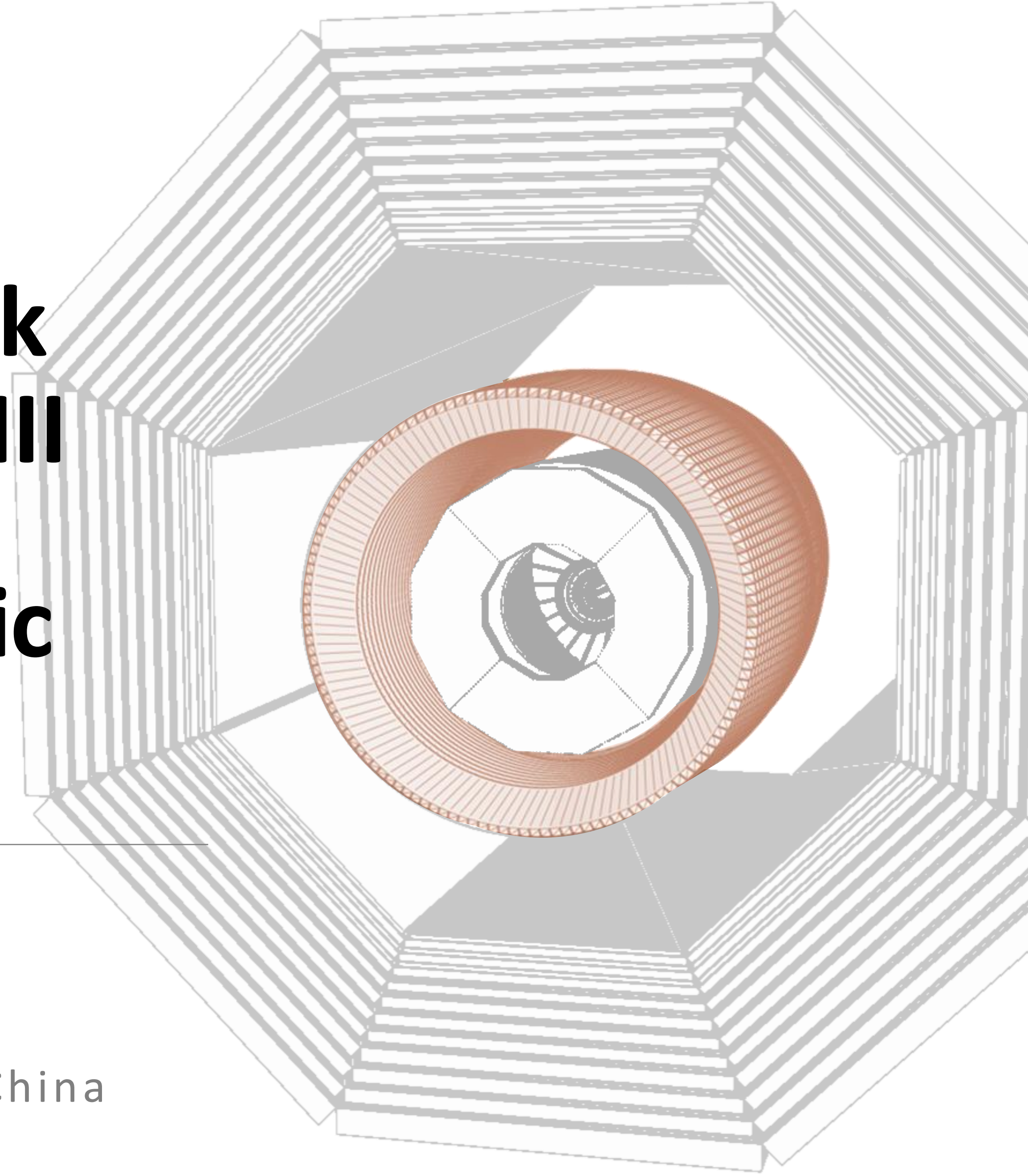
中国科学技术大学

Study of Hyperon Weak Radiative Decay at BESIII
&
R&D of Electromagnetic Calorimeter for STCF



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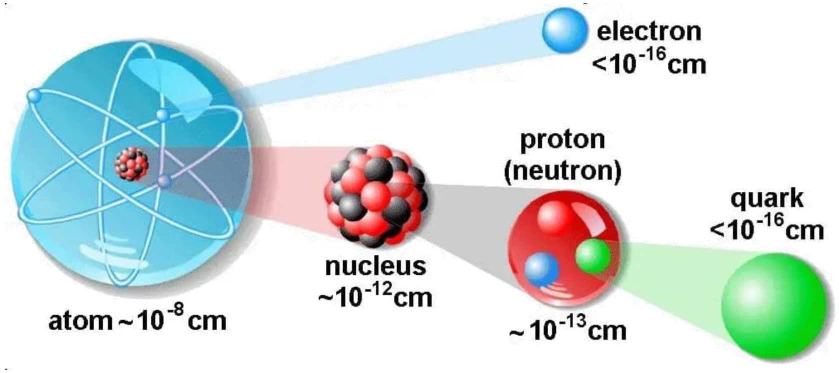
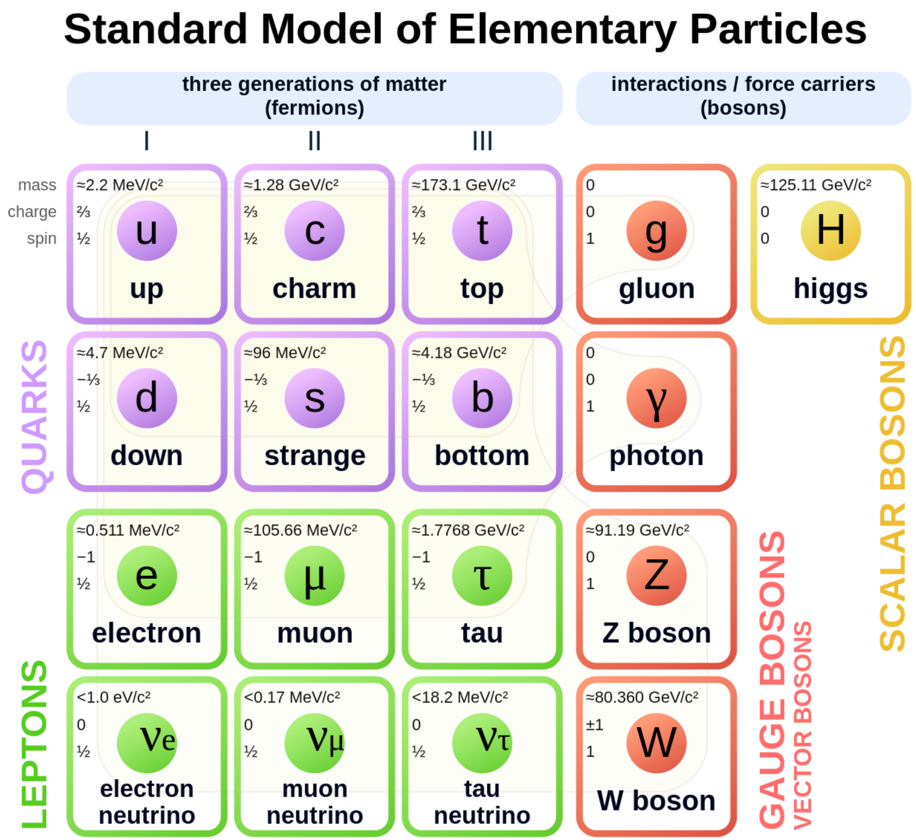
The Doctoral Dissertation Defense

Introduction

Standard Model

- The innermost structure of matter
  - Three generation of fermions
  - Four gauge bosons & Higgs boson
  - Hadrons formed by quarks and gluons
- Basic interactions among elementary particles
  - Strong: Quantum chromodynamics
  - Weak & Electromagnetic: Electroweak theory
  - Particle mass: Higgs mechanism

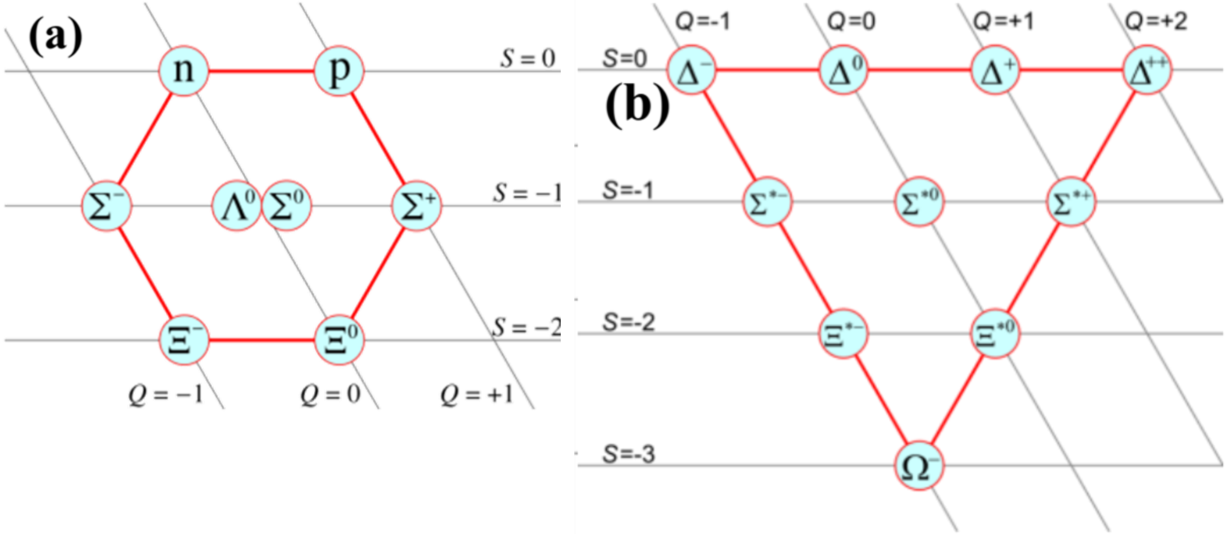


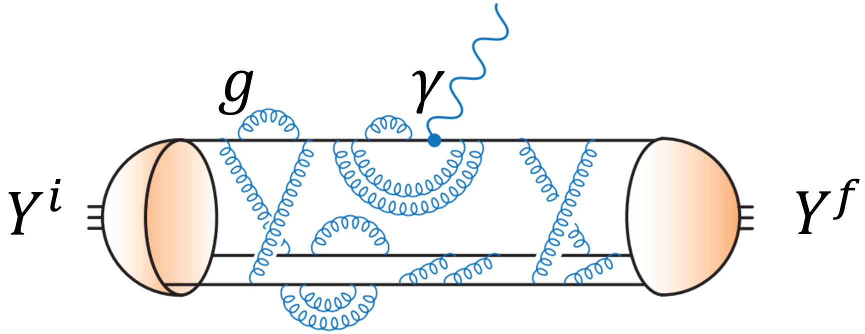


Introduction

Challenges facing the Standard Model

- The origin of hadron mass?
- Inner structure of hadrons?
- Hadron decay mechanism?
  - Significant non-perturbation QCD effects
  - Hyperon: baryons containing s quarks
  - Proving ground of basic symmetries: SU(3), CP
  - Decay of ground hyperons:
    - Weak hadronic decay ($\Sigma^+ \to p\pi^0$)
    - Semi-leptonic decay ($\Sigma^+ \to pe\nu_e$, $\Sigma^+ \to pee$)
    - Weak radiative decay (WRHD) ($\Sigma^+ \to p\gamma$)





Prog.Part.Nucl.Phys. 91 (2016), 1

Weak Radiative Hyperon Decays

Overview

- Flavor Changing Neutral Current process ($s \to d\gamma$ transition)
- A symphony of strong, weak and EM interaction
- Effective Lagrangian

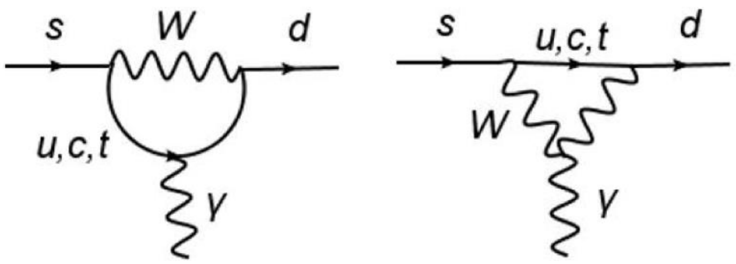
$$\mathcal{L} = \frac{eG_F}{2}\bar{Y}_f\left(a^{\mathrm{PC}} + b^{\mathrm{PV}}\gamma_5\right)\sigma^{\mu\nu}Y_i F_{\mu\nu}$$

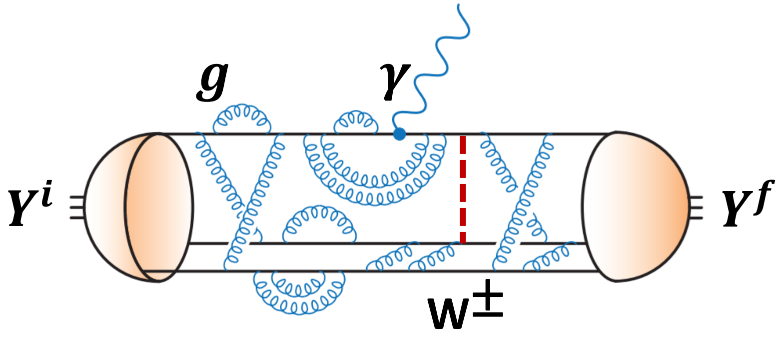
- Decay width & decay asymmetry

$$\Gamma = \frac{e^2G_F^2}{\pi}\left(|a|^2 + |b|^2\right)\cdot\left|\vec{k}\right|^3$$

$$\alpha_\gamma = \frac{2\mathrm{Re}(ab^*)}{|a|^2 + |b|^2}$$

$\Lambda \to n\gamma$	$\Xi^0 \to \Lambda\gamma$
$\Sigma^+ \to p\gamma$	$\Xi^0 \to \Sigma^0\gamma$
$\Sigma^0 \to n\gamma$	$\Xi^- \to \Sigma^-\gamma$
	$\Omega^- \to \Xi^-\gamma$

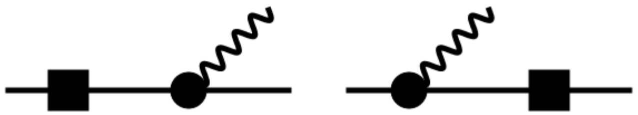




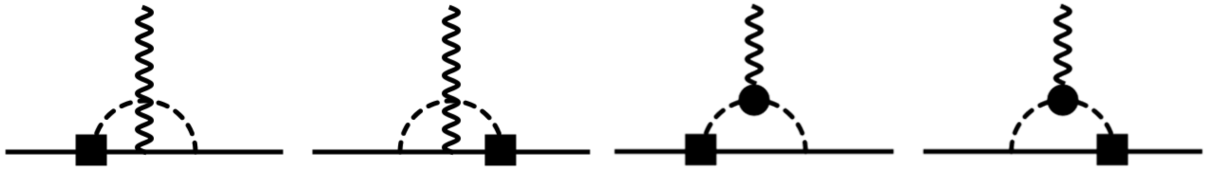
Weak Radiative Hyperon Decays

Effective Theory Point-of-view

- Hara's Theorem: $\alpha_{\gamma,\Sigma^+/\Xi^-} = 0$ under SU(3) symmetry
- Various predictions based on: VMD, Broken SU(3), Pole Model, Quark Model, NRCQM, Baryon ChPT …
- Topology diagrams based on baryon ChPT Sci.Bull. 67 (2022), 2298
  - LO contributions (parity conserving)



  - NLO contributions



■: share with weak hadronic decays

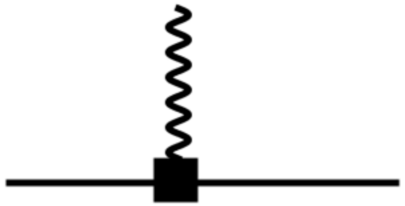
●: determined by octet baryon magnetic moments

Meson-Baryon interaction vertex: share with semi-leptonic decays

Weak Radiative Hyperon Decays

Effective Theory Point-of-view

- Unique contribution from “direct photon emission”
  - Need experiment input from $\Xi^0 \to \Lambda(\Sigma^0)\gamma$ or $\Lambda \to n\gamma$ process



$$\mathrm{Re}(b)_{\Xi^0\Sigma^0} = \sqrt{3}\mathrm{Re}(b)_{\Xi^0\Lambda} \qquad \mathrm{Re}(b)_{\Lambda n} = -\mathrm{Re}(b)_{\Xi^0\Lambda}$$

$$\mathrm{Re}(b)_{\Sigma^0 n} = -\sqrt{3}\mathrm{Re}(b)_{\Xi^0\Lambda} \qquad \mathrm{Re}(b)_{\Sigma^+ p} = \mathrm{Re}(b)_{\Xi^-\Sigma^-} = 0$$

Some Conclusions

- WRHDs contain the same FF information of hyperons as weak hadronic decay & semi-leptonic decay
- New FF contributions introduced by the decays sensitive to QCD models
- High precision experiment inputs are indispensable to understand the decay mechanism

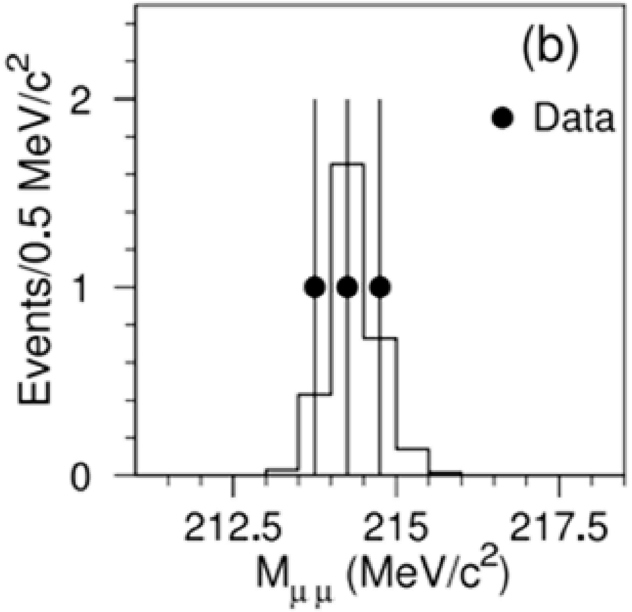
Weak Radiative Hyperon Decays

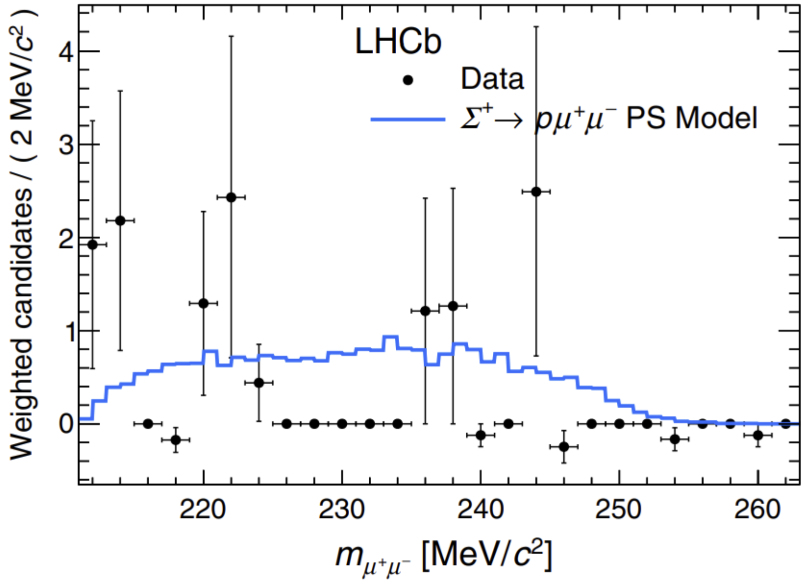
Physics Beyond the Scope of QCD Phenomenon

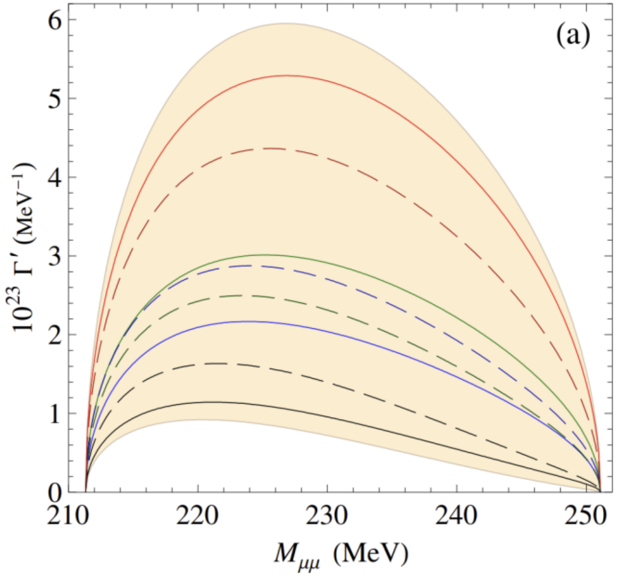
- New physics in $Y_i \rightarrow Y_f l^+ l^-$ decay
  - Smoke screen of new physics in $\Sigma^+ \rightarrow p\mu^+\mu^-$ decay

    Phys.Rev.Lett. 94 (2005) 021801, Phys.Rev.Lett. 120 (2018) 22, 221803
  - Experiment results of WRHDs provide SM expectations on such decays – narrowing the range for NP!

    JHEP 10 (2018) 040, JHEP 02 (2022) 178







Weak Radiative Hyperon Decays

Physics Beyond the Scope of QCD Phenomenon

- *CP* violation in radiative decays
  - *CP* violation in heavy flavor radiative decays extensively predicted under SM
    - Decrease as quark mass decreases
  - May be significantly enhanced by NP up to $\mathcal{O}(10)\%$

    Phys.Rev.Lett. 109 (2012), 171801, JHEP 01 (2013) 027, JHEP 04 (2017) 027, JHEP 08 (2017) 09
  - Extensive experimental studies on K, D and B meson decays

Channel	SM predicted A_{CP}
$K^+ \to \pi^+\pi^0\gamma$	$2\times10^{-6} - 1\times10^{-5}$
$K_L \to \pi^+\pi^-\gamma$	$10^{-4} - 10^{-3}$
$D \to \rho\gamma$	$\leq 2\times10^{-3}$
$b \to s\gamma$ $b \to d\gamma$	$(0.1-1)\%$ $(1-10)\%$
$B \to \rho\gamma$	$\sim10\ \%$

Decay Mode	Exp. A_{CP}	Decay Mode	Exp. A_{CP}
$K^\pm \to \pi^\pm\pi^0\gamma$	0.0000 ± 0.0012	$B^+ \to \eta K^+\gamma$	-0.12 ± 0.07
$D^0 \to \rho\gamma$	0.06 ± 0.15	$B^+ \to \phi K^+\gamma$	-0.13 ± 0.11
$D^0 \to \phi\gamma$	-0.09 ± 0.07	$B^+ \to \rho^+\gamma$	-0.11 ± 0.33
$D^0, \bar{D}^0 \to \bar{K}^*(892)^0\gamma$	-0.003 ± 0.020	$B^0 \to K^*(892)^0\gamma$	-0.006 ± 0.011
$B^+ \to K^*(892)^+\gamma$	0.014 ± 0.018	$B^0 \to K_2^*(1430)^0\gamma$	-0.08 ± 0.15
$B^+ \to X_s\gamma$	0.028 ± 0.019	$B^0 \to X_s\gamma$	-0.009 ± 0.018

Weak Radiative Hyperon Decays

Physics Beyond the Scope of QCD Phenomenon

- *CP* violation & WRHDs
  - Limited studies in baryon sector
  - Unified WRHD theory is the basis for related research
  - Two *CP* observables:

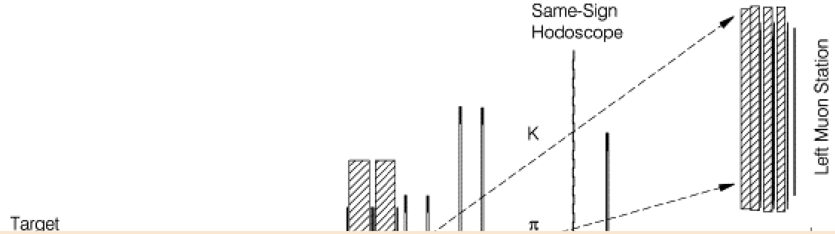
$$\Delta_{CP} = \frac{\mathrm{BF}_+ - \mathrm{BF}_-}{\mathrm{BF}_+ + \mathrm{BF}_-} \qquad A_{CP} = \frac{\alpha_+ + \alpha_-}{\alpha_+ - \alpha_-}$$

SM predictions on $\Sigma^+ \to p\gamma$	Δ_{CP}	A_{CP}
Phys.Rev.D 51 (1995), 227	$10^{-5} - 10^{-4}$	
Commun.Theor.Phys. 19 (1993) 475		$10^{-5} - 10^{-4}$
arxiv:2312.17568	2×10^{-5}	

Weak Radiative Hyperon Decays

Experiment Research Status

- Fixed target experiments govern the results before 2022
  (~23 papers from over 5 experiment groups)



MORE accurate measurements

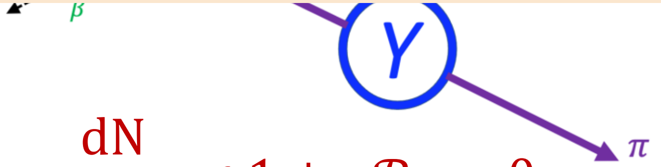
To solve the problems

Date	Expriment	BF ($\times10^{-3}$)	α_γ
2022	BESIII	$0.846 \pm 0.039 \pm 0.052$	$-0.160\pm0.101\pm0.046$
1994	E761	1.75 ± 0.15	-
1992	SPEC	1.78 ± 0.24	-

1987	SPEC	0.227 ± 0.102	-

$\Omega^- \to \Xi^-\gamma$

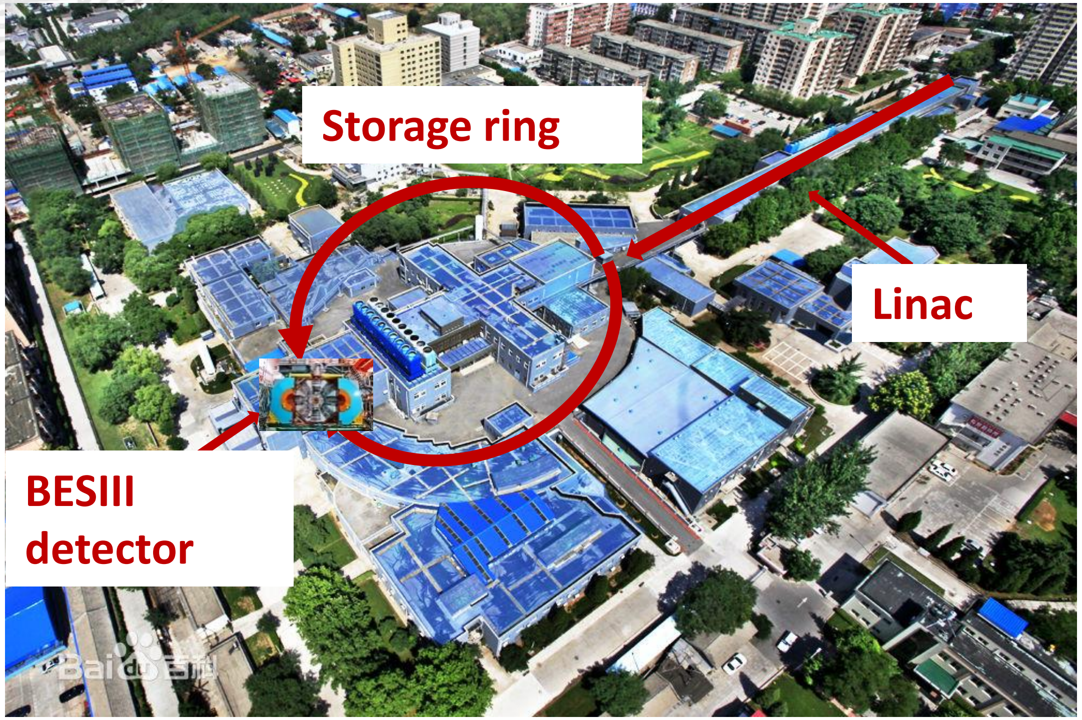
Date	Expriment	BF ($\times10^{-3}$)	α_γ
1994	E761	<0.46	-
1984	SPEC	<0.22	-
1979	SPEC	<0.31	-



$$\frac{dN}{d\cos\theta} \propto 1 + \alpha\mathcal{P}_Y\cos\theta$$

Studies on weak radiative hyperon decays at BESIII

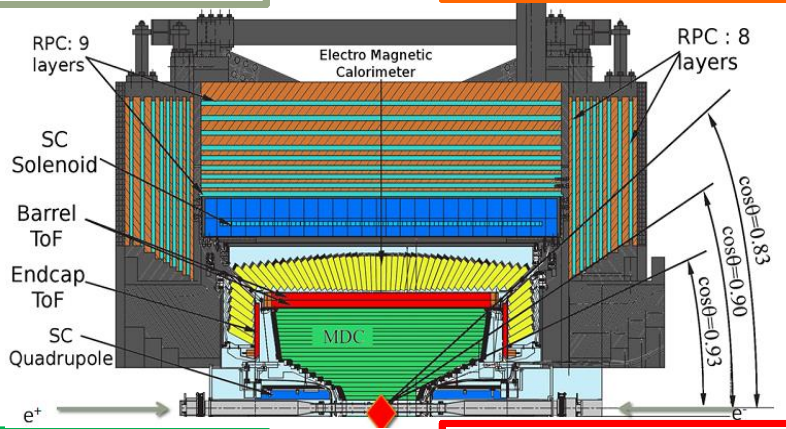
BEPCII & BESIII



- $E_{cm} = 1.84-4.95$ GeV
- Peak luminosity @ E_{cm}= 3.773 GeV: $\sim 1.1\times10^{33}$ $cm^{-1}s^{-1}$
- Circumference: 237.53 m
- Crossing angle: 2×11 mrad

Electromagnetic Calorimeter
- CsI(Tl): L=28 cm
- Barrel σ_E=2.5 %
- Endcap σ_E=5.0 %

Muon Counter
- RPC
- Barrel: 9 layers
- Endcap: 8 layers
- $\sigma_{spatial}$: 1.48 cm



Main Drift Chamber
- Small cell, 43 layer
- σ_{xy}=130 μm
- dE/dx~6 %
- σ_p/p= 0.5 % at 1 GeV

Time Of Flight
- Plastic scintillator
- σ_T(barrel): 68 ps
- σ_T(endcap): 110 ps
- (update to 60 ps with MRPC)

Hyperon Physics at BESIII

- Uniquely pair-produced hyperons from ψ decay, e.g. $e^+e^- \to J/\psi \to Y\bar{Y}$
- Over 70 million hyperon pair events collected from 2009-2019

Data sets	Number of J/ψ events ($\times 10^6$)
2009	224.0 ± 1.3
2012	$1\,088.5 \pm 4.4$
2018 2019	$8\,774.0 \pm 39.4$
Total	$10\,087 \pm 44$

Decay Channel	BF ($\times 10^{-3}$)	N_{evt} ($\times 10^6$)
$J/\psi \to \Lambda\bar{\Lambda}$	1.89 ± 0.09	19.1
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	1.07 ± 0.04	10.8
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	1.17 ± 0.03	11.8
$J/\psi \to \Sigma^-\bar{\Sigma}^+$	---	~15
$J/\psi \to \Xi^0\bar{\Xi}^0$	1.17 ± 0.04	11.8
$J/\psi \to \Xi^-\bar{\Xi}^-$	0.97 ± 0.08	9.8
Total		~78

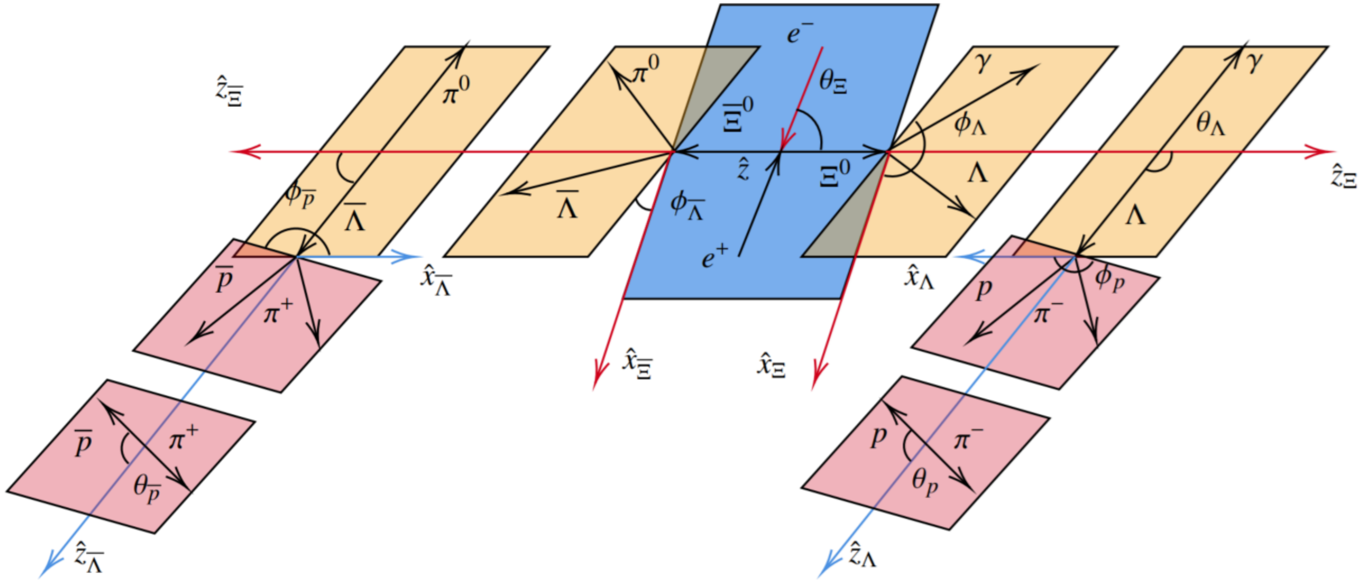
Hyperon Physics at BESIII

Decay Parameter Study

- Hyperon spin correlation & Decay parameter measurement
  - e.g. $e^+e^- \to J/\psi \to \Xi^0(\to \Lambda\gamma)\bar{\Xi}^0\left(\to \bar{\Lambda}\pi^0\right)$ $\Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$
  - Decay amplitude (Helicity):

$$\mathcal{W} = \sum_{\mu,\nu=0}^{3} \sum_{\mu'=0}^{3} \sum_{\nu'=0}^{3} C_{\mu\nu} a^{\Xi}_{\mu\mu'} a^{\Lambda}_{\mu'0} a^{\bar{\Xi}}_{\nu\nu'} a^{\bar{\Lambda}}_{\nu'0}$$

Helicity angles:
$\theta_\Xi, \theta_\Lambda, \phi_\Lambda, \theta_{\bar{\Lambda}}, \phi_{\bar{\Lambda}}, \theta_p, \phi_p, \theta_{\bar{p}}, \phi_{\bar{p}}$
Decay parameters:
$\alpha_{J/\psi}, \Delta\Phi_\Psi, \alpha_\Xi, \Delta\Phi_\Xi, \alpha_{\bar{\Xi}}, \Delta\Phi_{\bar{\Xi}}, \alpha_\Lambda, \alpha_{\bar{\Lambda}}$



Hyperon Physics at BESIII

Decay Parameter Study

- C: polarization and spin correlation matrix of $Y\bar{Y}$

$$C_{00} = 2(1+\alpha_\Psi \cos^2\theta_{\Xi^0}),\quad C_{20} = -C_{02},$$
$$C_{02} = 2\sqrt{1-\alpha_\Psi^2}\sin\theta_{\Xi^0}\cos\theta_{\Xi^0}\boxed{\sin(\Delta\Phi_\Psi)},\quad C_{22} = \alpha_\Psi C_{11},$$
$$C_{11} = 2\sin^2\theta_{\Xi^0},\quad C_{31} = -C_{13},$$
$$C_{13} = 2\sqrt{1-\alpha_\Psi^2}\sin\theta_{\Xi^0}\cos\theta_{\Xi^0}\cos(\Delta\Phi_\Psi),\quad C_{33} = -2(\alpha_\Psi + \cos^2\theta_{\Xi^0}),$$

- BESIII observation of non-zero $\Delta\Phi_\Psi$
  - Transverse polarization and spin-correlation between hyperon pairs Nature Phys. 15 (2019), 631

Decay	$\alpha_{J/\psi}$	$\Delta\Phi_\Psi$	Polarization (%)
$J/\psi \to \Lambda\bar{\Lambda}$	$0.475 \pm 0.002 \pm 0.003$	$0.752 \pm 0.004 \pm 0.007$	24.7
$J/\psi \to \Sigma^+\bar{\Sigma}^-$	$-0.508 \pm 0.006 \pm 0.004$	$-0.270 \pm 0.012 \pm 0.009$	16.4
$J/\psi \to \Xi^-\bar{\Xi}^+$	$0.586 \pm 0.012 \pm 0.010$	$1.213 \pm 0.046 \pm 0.016$	30.1
$J/\psi \to \Xi^0\bar{\Xi}^0$	$0.514 \pm 0.006 \pm 0.015$	$1.168 \pm 0.019 \pm 0.018$	32.1

- a: decay matrices of hyperons

$$\beta = \sqrt{1-\alpha^2}\sin(\Delta\Phi), \gamma = \sqrt{1-\alpha^2}\cos(\Delta\Phi)$$

- For $\frac{1}{2}^+ \to \frac{1}{2}^+ + 0^-$ decay ($\Xi^0 \to \Lambda\pi^0$)

$$a_h^{\Xi} = \begin{pmatrix} 1 & 0 & 0 & \alpha \\ \alpha\cos\phi\sin\theta & \gamma\cos\theta\cos\phi - \beta\sin\phi & -\beta\cos\theta\cos\phi - \gamma\sin\phi & \sin\theta\cos\phi \\ \alpha\sin\theta\sin\phi & \beta\cos\phi + \gamma\cos\theta\sin\phi & \gamma\cos\phi - \beta\cos\theta\sin\phi & \sin\theta\sin\phi \\ \alpha\cos\theta & -\gamma\sin\theta & \beta\sin\theta & \cos\theta \end{pmatrix}$$

- For $\frac{1}{2}^+ \to \frac{1}{2}^+ + 1^-$ decay ($\Xi^0 \to \Lambda\gamma$)

$$a_r^{\Xi} = \begin{pmatrix} 1 & 0 & 0 & -\alpha \\ \alpha\cos\phi\sin\theta & 0 & 0 & -\sin\theta\cos\phi \\ \alpha\sin\theta\sin\phi & 0 & 0 & -\sin\theta\sin\phi \\ \alpha\cos\theta & 0 & 0 & -\cos\theta \end{pmatrix}$$

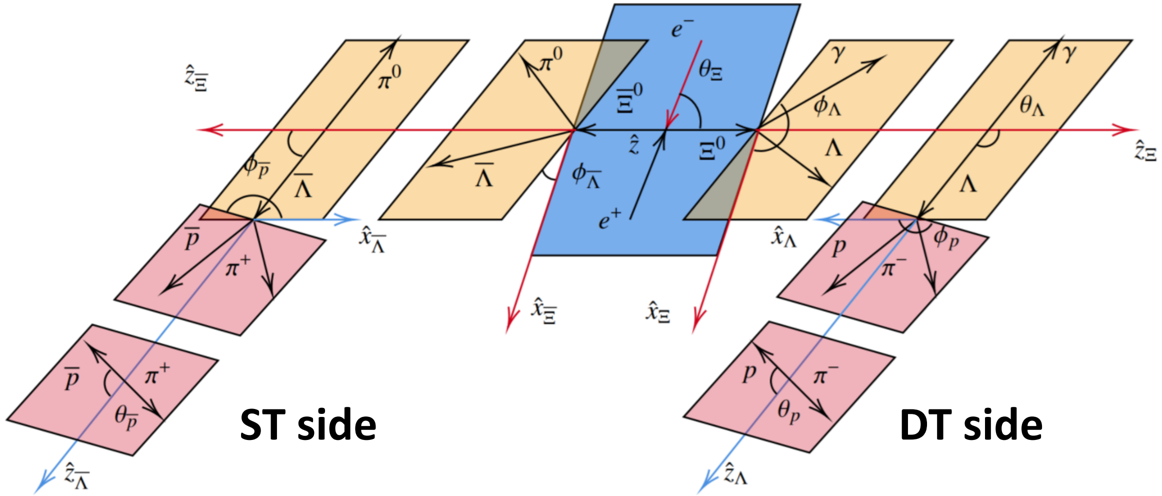
- Decay parameters fitted from amplitude
  - Sensitivity multiplicated by several times Chin. Phys. C 47 (2023), 093103

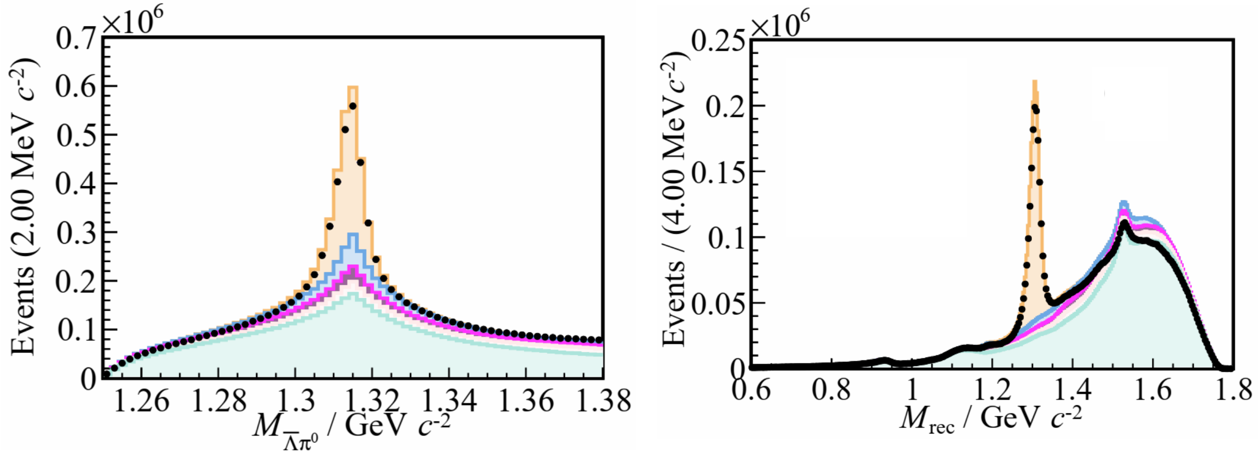
Hyperon Physics at BESIII

Absolute BF Measurement

- Double-tag method for BF measurement

$$\mathrm{BF} = \frac{N_{\mathrm{DT}}}{N_{\mathrm{ST}}} \times \frac{\varepsilon_{\mathrm{ST}}}{\varepsilon_{\mathrm{DT}}}$$





ST reconstruction

$M_{\bar{\Lambda}\pi^0}$

ST recoil

$\boldsymbol{M_{\mathrm{rec}} = M(\vec{P}_{\mathrm{cm}} - \vec{P}_{\bar{\Lambda}\pi^0})}$

Measurement of the Decay $\Sigma^+ \to p\gamma$

Datasets

- **Data**
  - 10 B J/ψ data accumulated in 2009-2019
- **MC sample**
  - 10 B J/ψ inclusive MC
  - Signal MC
    - 1 M DIY MC
    - 1 M PHSP MC
  - Exclusive MC
    - $J/\psi \to \Sigma^+\bar{\Sigma}^-, \Sigma^+ \to p\pi^0, \bar{\Sigma}^- \to \bar{p}\pi^0$: ~10 M, DIY
    - $J/\psi \to \Sigma^+\bar{\Sigma}^-, \Sigma^+ \to p\pi^0, \bar{\Sigma}^- \to \bar{p}\pi^0$: ~10 M, PHSP
    - $J/\psi \to \Sigma^+\bar{\Sigma}^-, \Sigma^+ \to p\pi^0, \bar{\Sigma}^- \to$ anything: 10 M, DIY

Input parameters for DIY MC Phys.Rev.Lett. 125 (2020) 5, 052004	
$\alpha_{J/\psi}$	-0.508
$\Delta\Phi_{\Psi}$	-0.270
$\alpha_{\Sigma^+\to p\pi^0}$	-0.980
$\alpha_{\Sigma^+\to p\gamma}$	-0.652

Measurement of the Decay $\Sigma^+ \to p\gamma$

Event Selection - ST

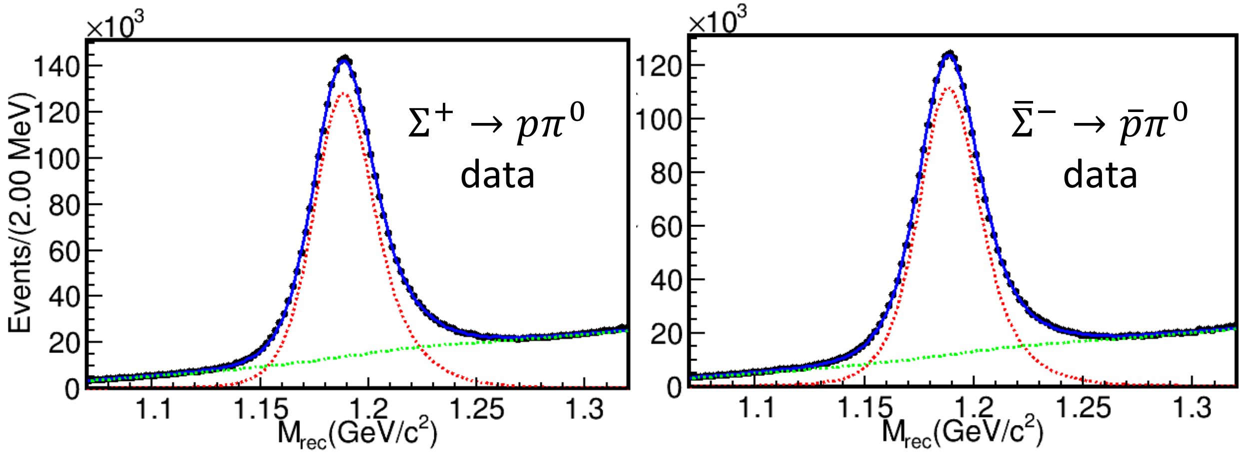
- **Charged tracks:**
  - $V_r < 2$ cm, $|V_z| < 10$ cm, $|\cos\theta| < 0.93$
  - $n_{\text{c.t.}} \leq 2$
- **Particle ID:**
  - $p/\bar{p}$ criteria:
    - prob(p) > prob(π) and prob(p) > prob(K)
    - Momentum > 0.5 GeV/c (Kinematic constraint)
  - $n_{\bar{p}} \geq 1$
- **Neutral tracks:**
  - Nominal energy&angular requirement
  - Angle between n.t. and c.t. larger than $10°$
  - Angle between n.t. and $\bar{p}$ larger than $20°$
  - $n_{\text{n.t.}} \geq 2$
- **π^0 Selection:**
  - Loop over all combinations of neutral tracks and preserve all π^0 candidates passing 1C fit
  - $116 < m_{\gamma\gamma} < 148$ MeV/c^2
- **$\bar{\Sigma}^-$ Selection:**
  - $\left|m_{\bar{p}\pi^0} - m_{\Sigma^+}\right| < 4.5$ MeV/c^2
  - $M_{\text{rec}} = \sqrt{\left(E_{\text{cm}} - E_{\bar{p}} - E_{\pi^0}\right)^2 - \left(\mathbf{p}_{\bar{p}} + \mathbf{p}_{\pi^0}\right)^2}$

Measurement of the Decay $\Sigma^+ \to p\gamma$

ST Fit

- Signal shape: truth matched signal MC shape $\otimes$ Gaussian
- $J/\psi \to \Delta^+\overline{\Delta}^-$ BKG shape: PHSP MC
- Residual BKG: 3rd order Chebychev polynomial
- Fit method: binned extended likelihood fit
- Fit range : $1.07 < M_{\mathrm{rec}} < 1.32\ \mathrm{GeV}/c^2$

	$\Sigma^+ \to p\pi^0$	$\bar{\Sigma}^- \to \bar{p}\pi^0$
ST Yield	$2\,509\,380 \pm 2301$	$2\,177\,771 \pm 2285$
$\varepsilon_{\mathrm{ST}}$ (%)	44.31	39.02
$\mathcal{B}$ ($\times 10^{-3}$)	1.078 ± 0.001	1.062 ± 0.001

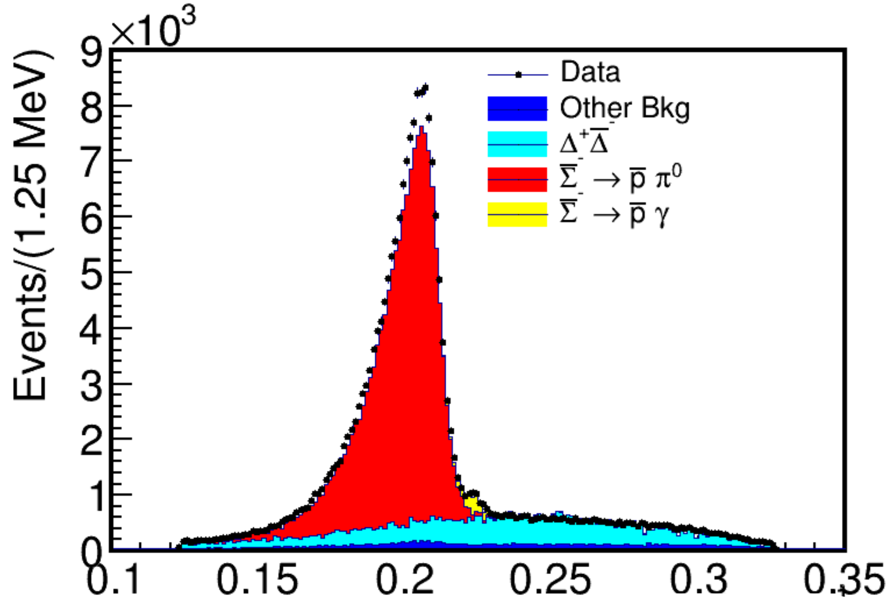


Measurement of the Decay $\Sigma^+ \to p\gamma$

Event Selection - DT

- **Object number:**
  - 1 proton
  - At least 1 photon candidate
- **Kinematic fit:**
  - $p\bar{p}\pi^0\gamma$ hypothesis
  - 5 constraints: the total 4-Momentum, π^0mass
  - Final state particles from ST are fixed
  - Loop over all signal photon candidates
  - Preserve the combination with the least χ^2_{5C}
- Use proton momentum in the Σ^+ CoM frame to extract DT signal (p_p)

- **Dominant background:**
  - $J/\psi \to \Sigma^+\bar{\Sigma}^-, \Sigma^+ \to p\pi^0, \bar{\Sigma}^- \to \bar{p}\pi^0$
  - $J/\psi \to \Delta^+\bar{\Delta}^-, \Delta^+ \to p\pi^0, \bar{\Delta}^- \to \bar{p}\pi^0$

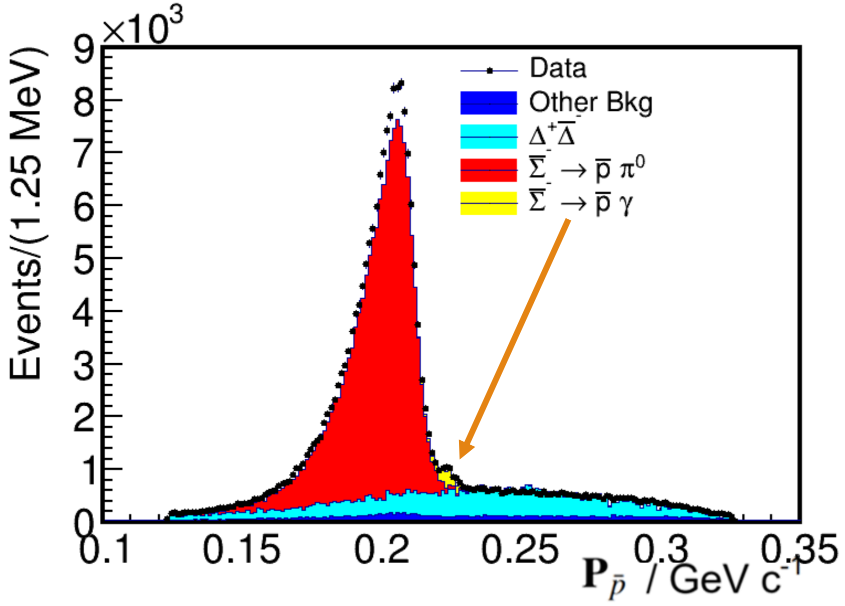


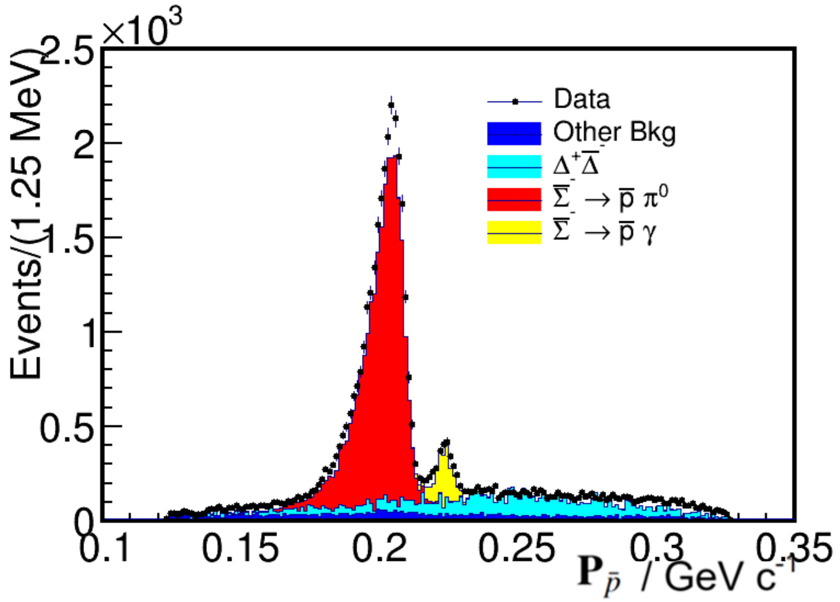
200 times the signal!

Measurement of the Decay $\Sigma^+ \to p\gamma$

DT Background Study

- Introduce 1 more photon into 5C fit
  - $\chi^2_{5C,4\gamma} > \chi^2_{5C,3\gamma}$
- Optimize χ^2_{5C} cut in signal region $0.21 < \mathrm{p}_p < 0.24\ \mathrm{GeV}/c$
  - Require $\chi^2_{5C} < 30$

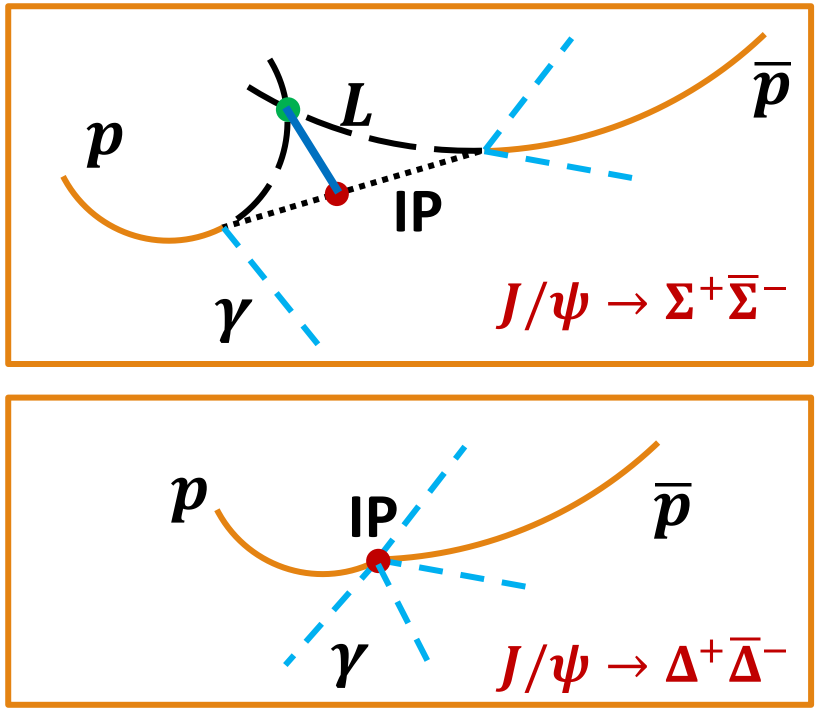


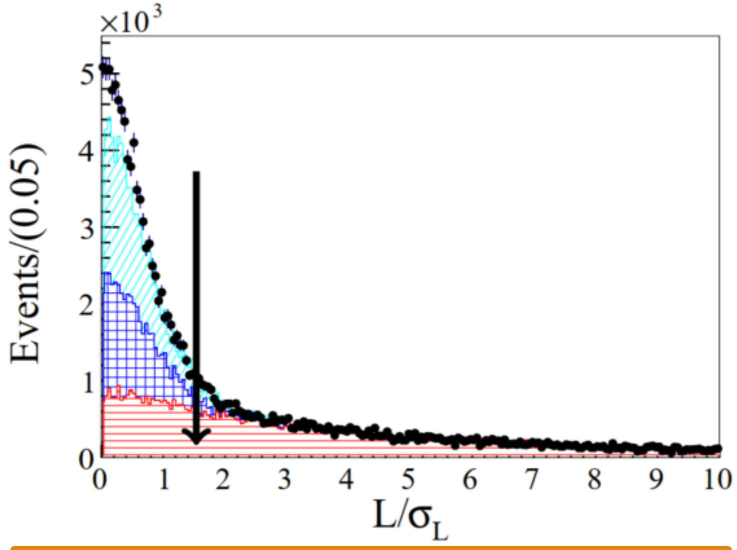


Measurement of the Decay $\Sigma^+ \to p\gamma$

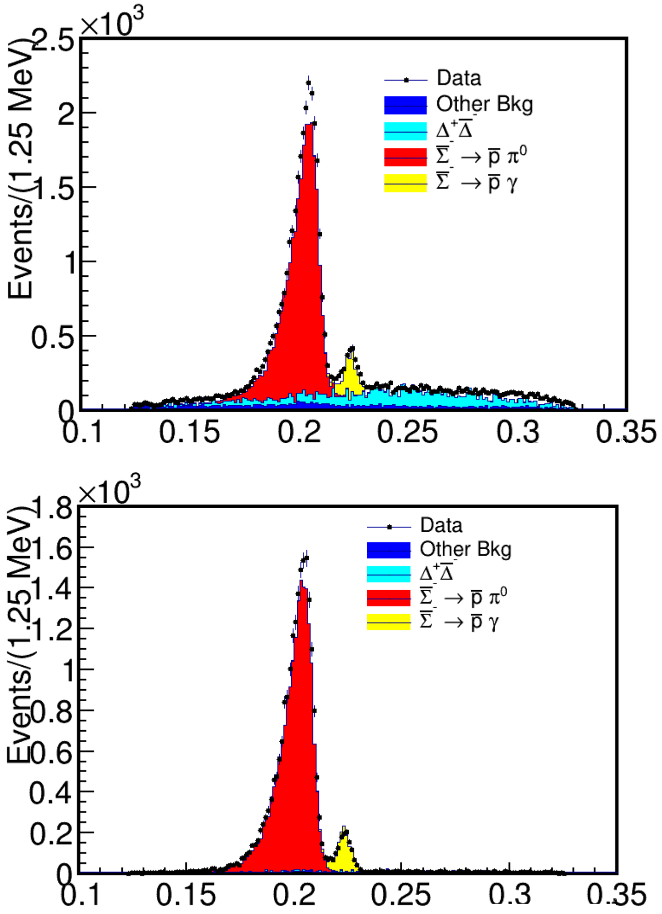
DT Background Study

- Major BKG: non-Σ^+ baryons' decay (e.g. $\Delta^+ \to p\pi^0$)
  - Significant life time difference
  - Define an effective decay length





- Signal efficiency > **78 %**
- Background rejection > **93 %**



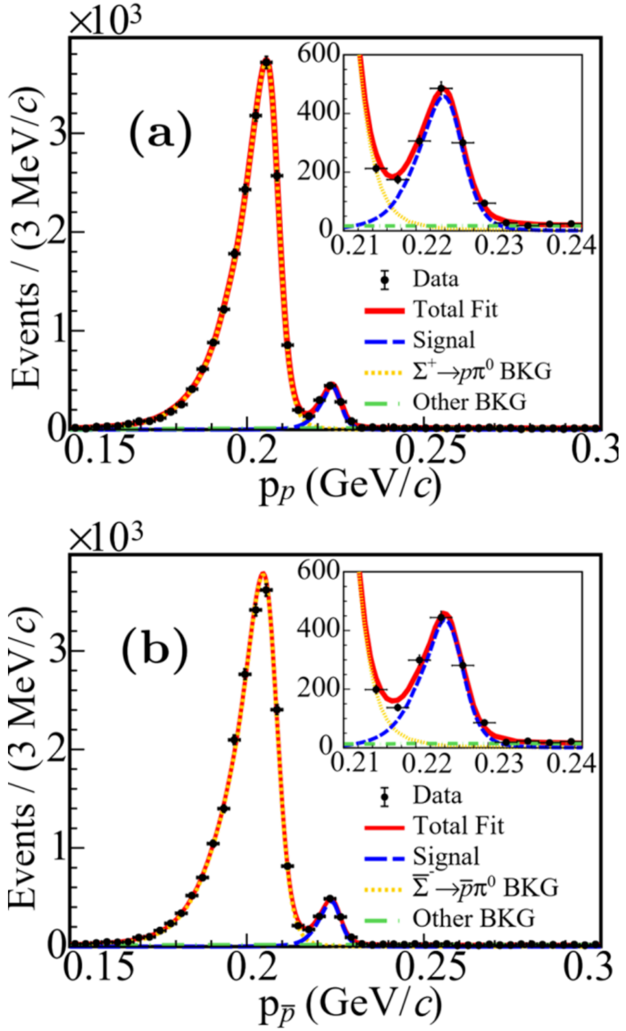
Measurement of the Decay $\Sigma^+ \to p\gamma$

DT Fit

- Fit method: unbinned extended maximum likelihood fit
- Fit range: $0.15 < \mathrm{p}_p < 0.30\ \mathrm{GeV}/c$
- signal MC shape: DIY MC
- $\Sigma^+ \to p\pi^0$ BKG shape: DIY MC

(both shapes) $\otimes$ Gaussian

- Residual BKG: 2nd order Chebychev polynomial
- Individual & simultaneous fits performed



Measurement of the Decay $\Sigma^+ \to p\gamma$

DT Fit

- DT branching fraction:

$$\mathrm{BF} = \frac{N_{\mathrm{DT}}}{N_{\mathrm{ST}}} \times \frac{\varepsilon_{\mathrm{ST}}}{\varepsilon_{\mathrm{DT}}}$$

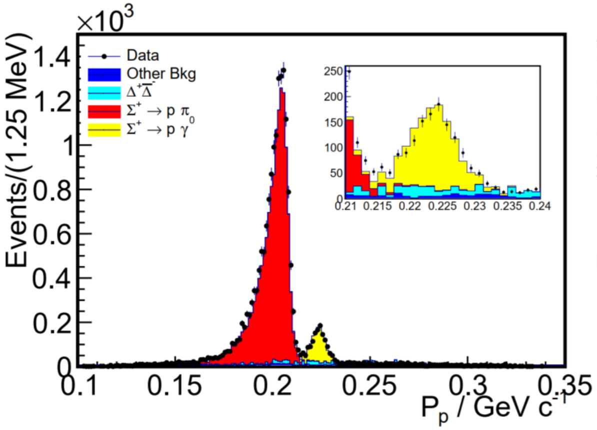
- Individual and simultaneous fit results consistent
- Individual BF of two charge conjugate channels differs only 0.31 σ

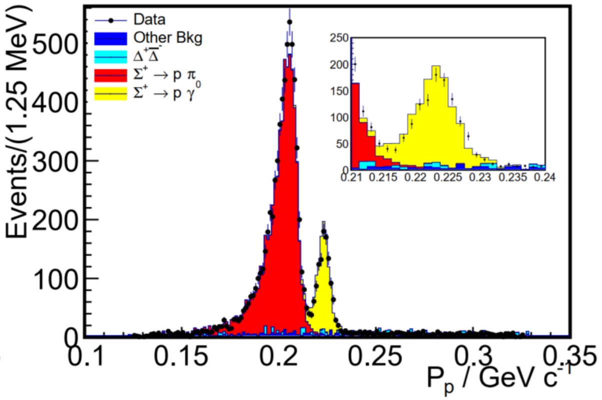
	$\Sigma^+ \to p\gamma$	$\bar{\Sigma}^- \to \bar{p}\gamma$
ST Yield	$2\,177\,771 \pm 2285$	$2\,509\,380 \pm 2301$
$\varepsilon_{\mathrm{ST}}$ (%)	39.02	44.31
$\varepsilon_{\mathrm{DT}}$ (%)	21.16	23.20
Individual BF	$(1.007 \pm 0.032) \times 10^{-3}$	$(0.994 \pm 0.030) \times 10^{-3}$
Simultaneous BF	$(0.997 \pm 0.021) \times 10^{-3}$	
Correction factor	0.998	0.999
Corrected individual BF	$(1.005 \pm 0.032) \times 10^{-3}$	$(0.993 \pm 0.030) \times 10^{-3}$
Corrected simultaneous BF	$(0.996 \pm 0.021) \times 10^{-3}$	

Measurement of the Decay $\Sigma^+ \to p\gamma$

Decay Asymmetry Parameter Measurement

- Further requirements to improve signal purity
- Signal region: $0.215 < p_p < 0.235$ GeV/c
- $\chi^2_\gamma < \chi^2_{\pi^0}$ cut: treat signal photon as missing particle and compare χ^2 under two hypotheses, $m_\gamma = 0$ or $m_{\pi^0} = 0.135$ GeV/c^2





Processes	$\Sigma^+ \to p\gamma$	$\bar{\Sigma}^- \to \bar{p}\gamma$
Signal	1137 ± 38	1225 ± 40
$\Sigma^+ \to p\pi^0$	101 ± 4	108 ± 5
Other BKG	76 ± 7	112 ± 9

Processes	$\Sigma^+ \to p\gamma$	$\bar{\Sigma}^- \to \bar{p}\gamma$
Signal	1026 ± 38	1076 ± 40
$\Sigma^+ \to p\pi^0$	58 ± 4	62 ± 4
Other BKG	53 ± 6	70 ± 7

Measurement of the Decay $\Sigma^+ \to p\gamma$

Decay Asymmetry Parameter Measurement

- Method: unbinned likelihood fit
- Input parameters: $\xi = (\theta_\Sigma, \theta_p, \phi_p, \theta_{\bar{p}}, \phi_{\bar{p}})$
- Likelihood construction:

$$\mathcal{L} = \prod_{i=1}^{N} \frac{\mathcal{W}_i(\xi, H)}{\mathcal{N}} \qquad \mathcal{N} = \frac{1}{N_{\mathrm{MC}}} \sum_{j=1}^{N_{\mathrm{MC}}} \mathcal{W}_i^{\mathrm{MC}}(\xi, H)$$

  - $\mathcal{W}_i$: differential cross section
  - $\mathcal{N}$: normalization factor based on PHSP MC
  - $H = \left(\alpha_{J/\psi}, \Delta\Phi_\Psi, \alpha_{\Sigma^+\to p\gamma}, \alpha_{\bar{\Sigma}^-\to\bar{p}\pi^0}\right)$
- Objective function minimization: MINUIT

- Objective function:

$$S = -\ln\mathcal{L}_{\mathrm{data}} + \ln\mathcal{L}_{\mathrm{bkg}}$$

- Construction of BKG likelihood:
  - $\Sigma^+ \to p\pi^0$ BKG: extracted from DIY MC ($5 \times N_{\mathrm{data}}$)
  - Other BKG: Use data in sideband region ($0.088 < \mathrm{p}_p < 0.1\ \mathrm{GeV}/c$, $0.204 < \mathrm{p}_p < 0.216\ \mathrm{GeV}/c$) to estimate
  - Number of BKG: obtained from individual DT fit
- Fit result of two c.c. process deviates 1.1 σ

Processes	$\Sigma^+ \to p\gamma$	$\bar{\Sigma}^- \to \bar{p}\gamma$
Individual fit	-0.587 ± 0.082	0.710 ± 0.076
Simultaneous fit	-0.651 ± 0.056	

Measurement of the Decay $\Sigma^+ \to p\gamma$

Systematic Uncertainty Study

Source	BF uncertainty (%)
Tracking and PID	0.4
Photon detection	0.3
$\chi^2 < 30$	0.8
$\chi^2_{5C} < \chi^2_{4\gamma}$	0.2
Decay length cut	0.4
Decay parameters	0.6
ST yield fit	0.4
Fit range	0.8
Signal shape	0.2
$\Sigma^+ \to p\pi^0$ shape	0.5
Polynomial background shape	0.8
Total Uncertainty	1.8

Source	α uncertainty
Tracking efficiency	0.001
Decay length cut	0.005
$\chi^2_{\gamma} < \chi^2_{\pi^0}$	0.006
Signal region cut	0.014
Background likelihood value	0.004
Background event number	0.002
Other decay parameters' uncertainty	0.011
Total uncertainty	0.020

Measurement of the Decay $\Xi^0 \to \Lambda\gamma$

Datasets

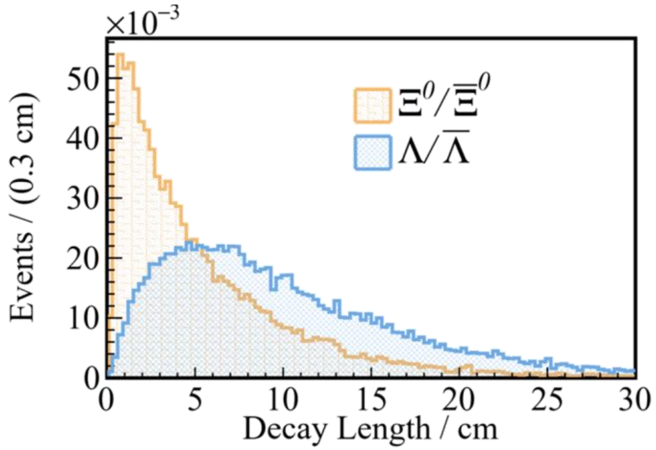
- **Data**
  - 10 B J/ψ data accumulated in 2009-2019
- **MC sample**
  - 10 B J/ψ inclusive MC
  - Signal MC for ST:
    - $J/\psi \to \Xi^0(\to \text{anything})\bar{\Xi}^0(\to \bar{\Lambda}\pi^0), \bar{\Lambda} \to \bar{p}\pi^+$: 20 M, DIY
  - Signal MC for DT:
    - $J/\psi \to \Xi^0(\to \Lambda\gamma)\bar{\Xi}^0(\to \bar{\Lambda}\pi^0), \bar{\Lambda} \to \bar{p}\pi^+$: 1.5 M, DIY, PHSP
  - Exclusive MC:
    - $J/\psi \to \Xi^0(\to \Lambda\pi^0)\bar{\Xi}^0(\to \bar{\Lambda}\pi^0), \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$: 0.5 B, DIY
    - $J/\psi \to \bar{\Lambda}\Sigma^0\pi^0$+c.c. MC: 20 M, DIY

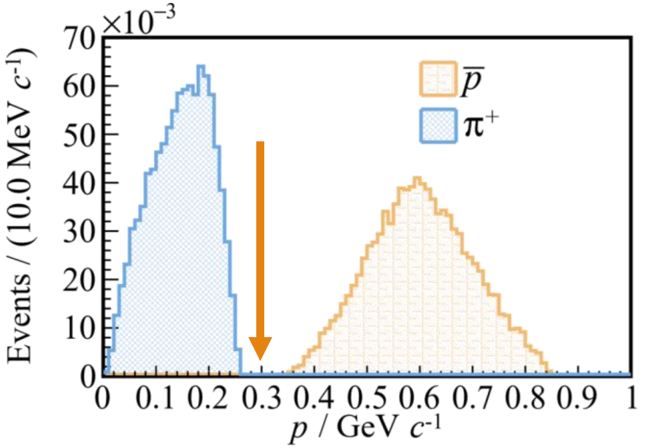
Input parameters for DIY MC Phys.Rev.D 108 (2023) 3, L031106	
$\alpha_{J/\psi}$	0.514
$\Delta\Phi_{\Psi}$	1.168
$\alpha_{\Xi^0\to\Lambda\pi^0}$	-0.375
$\Delta\Phi_{\Xi^0\to\Lambda\pi^0}$	0.005
$\alpha_{\bar{\Xi}^0\to\bar{\Lambda}\pi^0}$	0.379
$\Delta\Phi_{\bar{\Xi}^0\to\bar{\Lambda}\pi^0}$	-0.005
α_{Λ}	0.755
$\alpha_{\bar{\Lambda}}$	-0.745
$\alpha_{\Xi^0\to\Lambda\gamma}$	-0.749
$\alpha_{\bar{\Xi}^0\to\bar{\Lambda}\gamma}$	-0.749

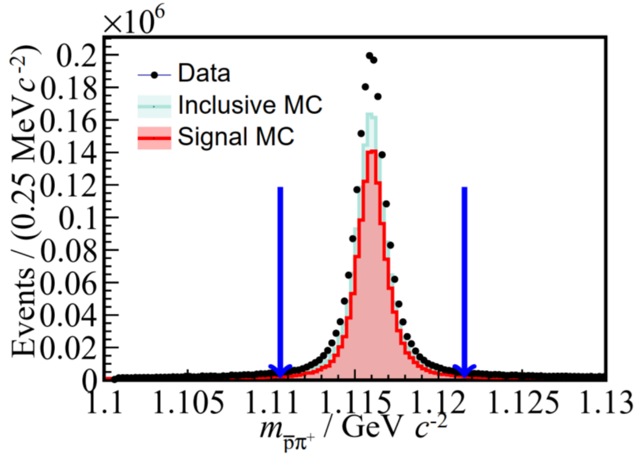
Measurement of the Decay $\Xi^0 \to \Lambda\gamma$

Event Selection - ST

- **Charged tracks:**
  - No requirements on V_r, V_z, $|\cos\theta|$
- **Particle ID:**
  - $p/\bar{p}$:
    - prob(p) > prob(π) and prob(p) > prob(K)
    - Momentum > 0.3 GeV/c
  - $\pi^{\pm}$: Tracks other than $p/\bar{p}$
- **$\bar{\Lambda}$ Reconstruction (all candidates preserved):**
  - Vertex fit on $\bar{p}\pi^+$ combinations
  - $|m_{\bar{p}\pi^+} - m_{\bar{\Lambda}}| < 6$ MeV/c^2



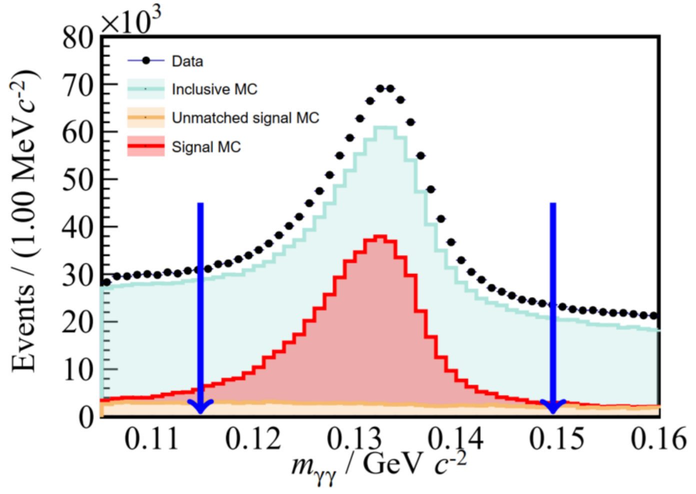


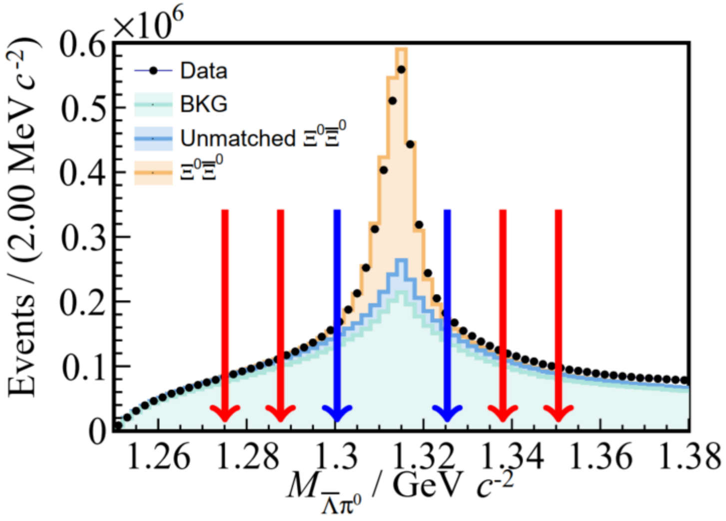


Measurement of the Decay $\Xi^0 \to \Lambda\gamma$

Event Selection - ST

- **Photons:**
  - Nominal energy&angular requirements
  - Angle between n.t. and c.t. ($\bar{p}$) larger than $10°$ ($20°$)
- **π^0 Selection (all candidates preserved):**
  - 1C kinematic fit on $\gamma\gamma$ combinations
  - $115 < m_{\gamma\gamma} < 150$ MeV$/c^2$
- **Object number:**
  - $N_{\bar{p}} \geq 1$, $N_{\pi^+} \geq 1$, $N_{\bar{\Lambda}} \geq 1$, $N_{\pi^0} \geq 1$
- **$\bar{\Xi}^0$ Selection**
  - $M_{\bar{\Lambda}\pi^0} = \sqrt{(E_{\bar{p}\pi^+} + E_{\pi^0})^2 - (\mathrm{p}_{\bar{p}\pi^+} + \mathrm{p}_{\pi^0})^2} - m_{\bar{p}\pi^+} + m_{\bar{\Lambda}}$
  - Signal region: $|m_{\bar{\Lambda}\pi^0} - m_{\bar{\Xi}^0}| < 12$ MeV$/c^2$





Measurement of the Decay $\Xi^0 \to \Lambda\gamma$

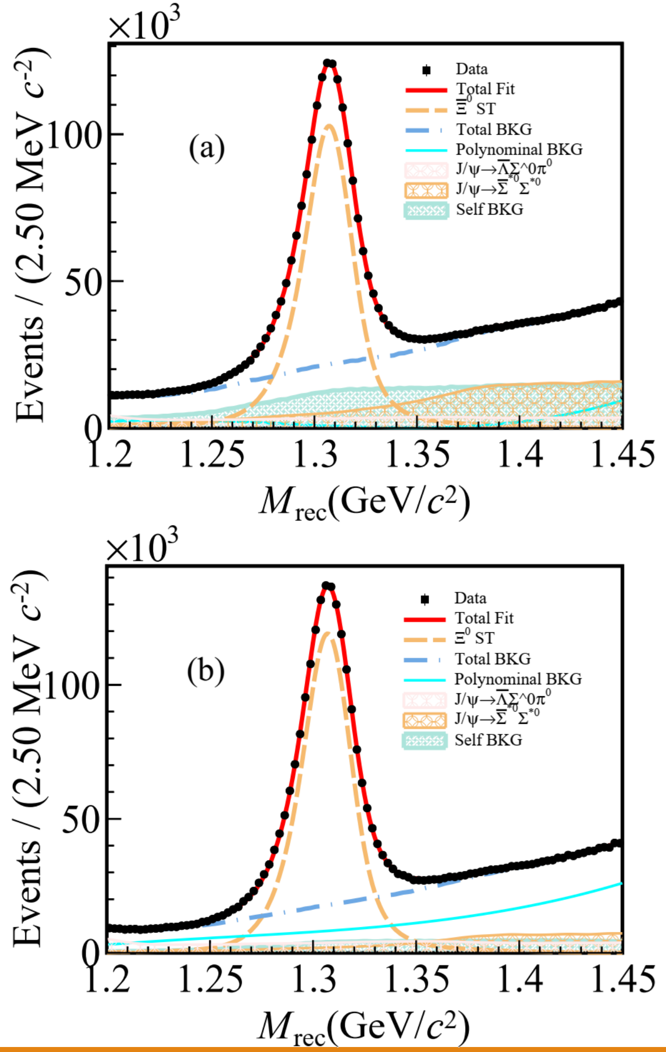
ST Fit

$$M_{\rm rec} = \sqrt{(E_{\rm cm} - E_{\bar{p}\pi^+} - E_{\pi^0})^2 - (\mathbf{p}_{\bar{p}\pi^+} + \mathbf{p}_{\pi^0})^2}$$

- Fit range: $1.20 < M_{\rm rec} < 1.45\ \mathrm{GeV}/c^2$
- Signal shape: truth matched signal MC shape $\otimes$ Gaussian
- Background shape:
  - Unmatched signal MC shape
  - $J/\psi \to \bar{\Lambda}\Sigma^0\pi^0$ + c.c. DIY MC shape
  - $J/\psi \to \Sigma^{*0}\bar{\Sigma}^{*0}$ PHSP MC shape
  - 3^{rd} order Chebyshev polynomial

} Bump-like BKG

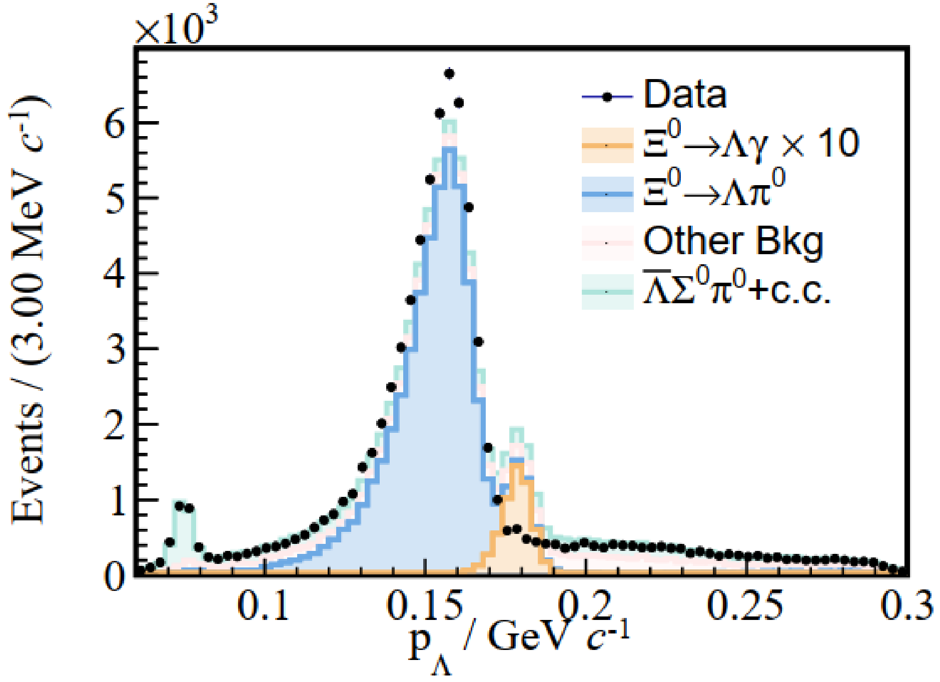
Continuum BKG



Measurement of the Decay $\Xi^0 \to \Lambda\gamma$

Event Selection - DT

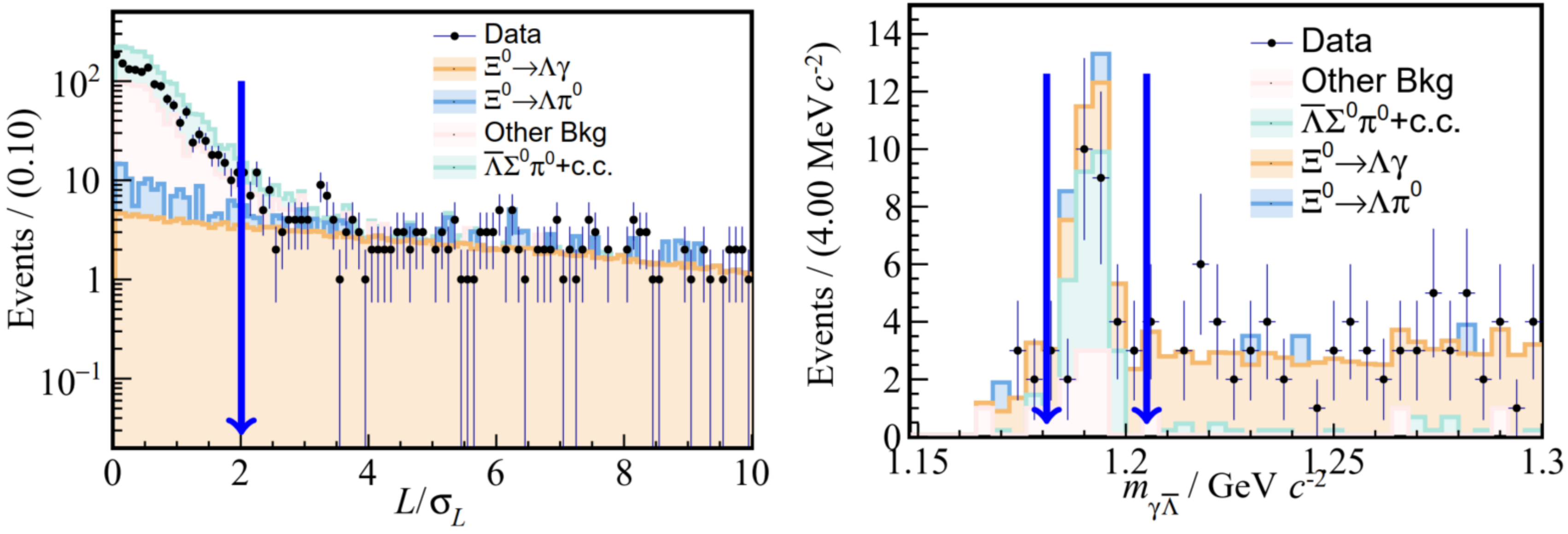
- Object numbers:
  - $N_p \geq 1$, $N_{\pi^-} \geq 1$, $N_{\mathrm{n.t.}} \geq 1$, $N_\Lambda \geq 1$
- $\Lambda\bar{\Lambda}\pi^0\gamma$ Kinematic fit:
  - 5 constraints: total 4-Momentum, π^0 mass
  - Minimizing χ^2_{5C}
- Use Λ momenta in the Ξ^0 CoM frame (p_Λ) to extract DT signal
  - p_Λ= 0.178 GeV/c for signal



Measurement of the Decay $\Xi^0 \to \Lambda\gamma$

DT Background Study

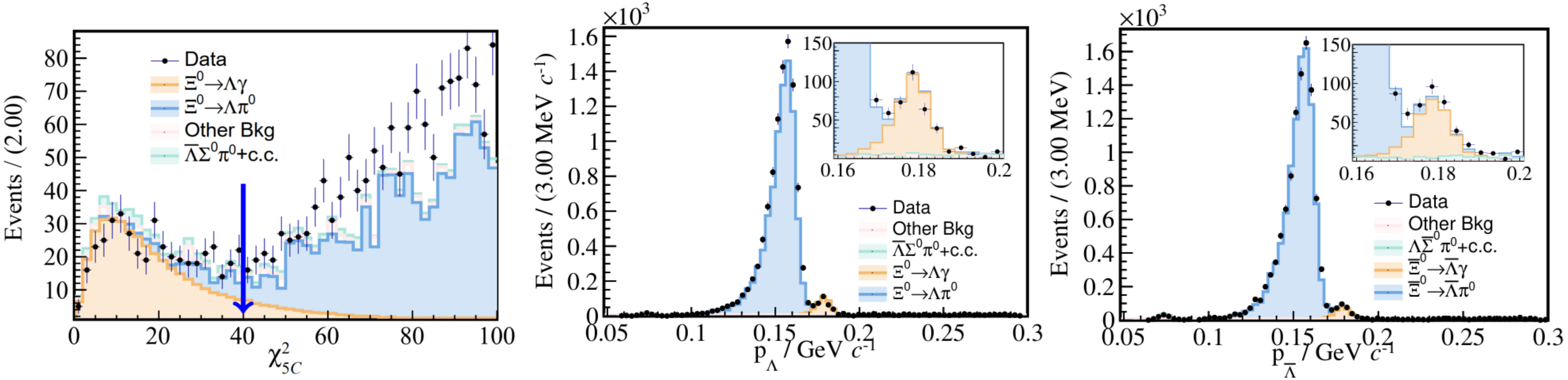
- For $\Sigma^{0(*)}$ associated background
  - Veto $L/\sigma_L < 2.0$
- For Σ^0 associated background
  - $m_{\gamma\bar{\Lambda}}$: The invariant mass of DT γ and ST $\bar{\Lambda}$
  - $|m_{\gamma\bar{\Lambda}} - m_{\bar{\Sigma}^0}| > 12\ \mathrm{MeV}/c^2$



Measurement of the Decay $\Xi^0 \to \Lambda\gamma$

DT Background Study

- General purpose optimization
  - $\chi^2_{5C} < 40$



Measurement of the Decay $\Xi^0 \to \Lambda\gamma$

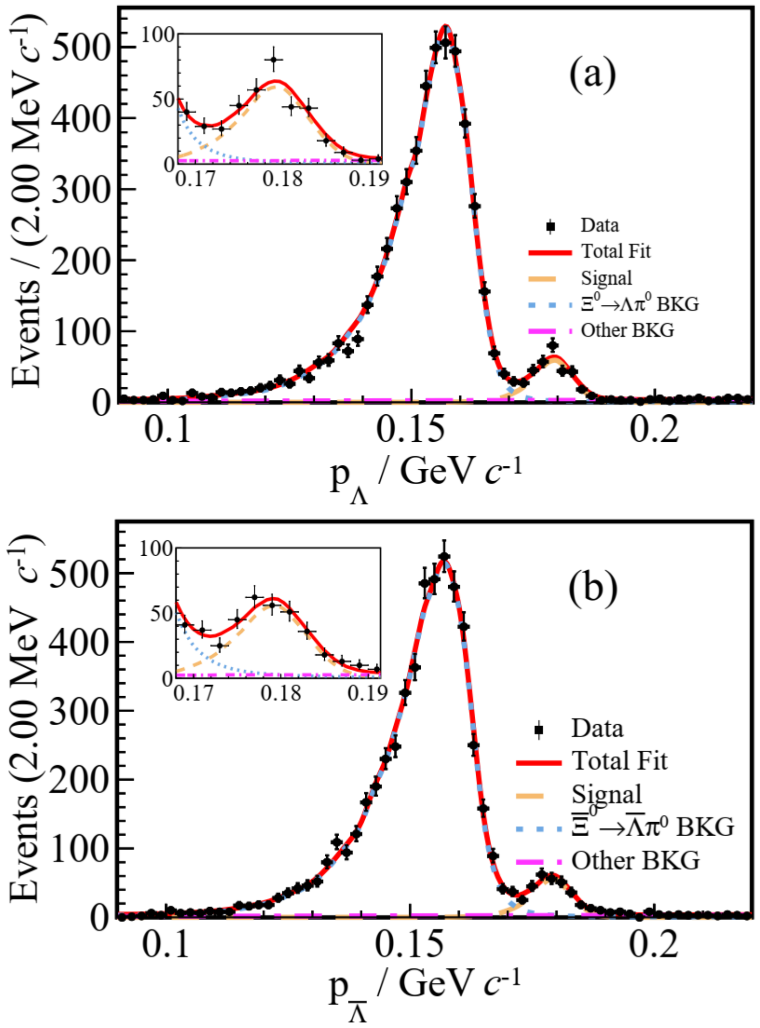
DT Fit

- Fit range: $0.1 < p_\Lambda < 0.25$ GeV/c
- Signal shape: DIY MC
- $\Xi^0 \to \Lambda\pi^0$ BKG shape: DIY MC

} $\otimes$ Gaussian

- Residual BKG: 1st order polynomial

Modes	$\Xi^0 \to \Lambda\gamma$	$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$
ST Yield	1 400 541 ± 1989	1 611 216 ± 2111
ε_{ST} (%)	17.61 ± 0.01	19.77 ± 0.01
ε_{DT} (%)	4.43 ± 0.02	4.77 ± 0.02
Individual BF	$(1.391 \pm 0.093) \times 10^{-3}$	$(1.344 \pm 0.099) \times 10^{-3}$
Simultaneous BF	$(1.379 \pm 0.068) \times 10^{-3}$	
Correction factor	1.032	1.014
Corrected individual BF	$(1.348 \pm 0.090) \times 10^{-3}$	$(1.326 \pm 0.098) \times 10^{-3}$
Corrected simultaneous BF	$(1.347 \pm 0.066) \times 10^{-3}$	

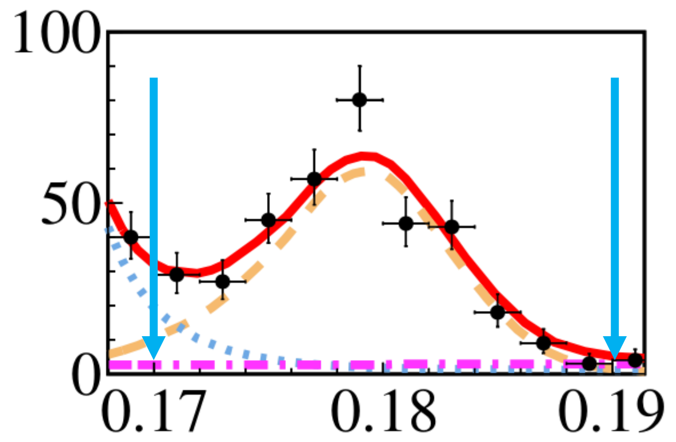


Measurement of the Decay $\Xi^0 \to \Lambda\gamma$

Decay Asymmetry Parameter Measurement

- Signal region for fit: $0.170 < p_\Lambda < 0.190$ GeV/c (3σ mass window)
- Construction of $\mathcal{L}_{\rm bkg}$:
  - $\Xi^0 \to \Lambda\pi^0$ BKG: DIY MC ($100 \times N_{\rm data}$)
  - Other BKG: Cocktail MC samples
    - $J/\psi \to \bar{\Lambda}\Sigma^0\pi^0$+c.c. DIY MC shape
    - $J/\psi \to \Sigma^{*0}\bar{\Sigma}^{*0}$ PHSP MC shape
  - Number of BKG: Obtained from DT fit
- Normalization factor obtained from DIY MC

$$\mathcal{N} = \frac{1}{N_{\rm MC}}\sum_{j=1}^{N_{\rm MC}}\frac{\mathcal{W}(\xi_i,H)}{\mathcal{W}(\xi_i,H_0)}$$



Processes	$\Xi^0 \to \Lambda\gamma$	$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$
Individual fit	-0.652 ± 0.092	0.830 ± 0.080
Simultaneous fit	-0.741 ± 0.062	

Measurement of the Decay $\Xi^0 \to \Lambda\gamma$

Systematic Uncertainties

Source	$\Xi^0 \to \Lambda\gamma$ (%)	$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$ (%)	Combined (%)
Selection Efficiency Related			
Proton tracking and PID	0.5	0.5	0.5
Pion tracking and PID	2.3	1.4	1.8
$\Lambda(\bar{\Lambda})$ reconstruction	0.9	1.1	1.0
Photon detection	0.4	0.4	0.4
$\chi^2_{5C} < 40$	0.5	0.1	0.3
Decay length requirement	1.3	1.8	1.6
$m_{\gamma\Lambda}$ requirement	0.2	0.0	0.1
Decay parameters	0.6	0.6	0.6
ST Fit Related			
Fit range	0.5	0.4	0.5
Bin width	0.5	0.6	0.6
Signal shape	0.2	0.2	0.2
Self background shape	0.2	0.7	0.5
Continuum background shape	1.5	1.9	1.7
Bump-like background	0.4	0.7	0.6
DT Fit Related			
Fit range	1.6	1.6	0.2
$\Xi^0 \to \Lambda\gamma$ MC shape	0.7	3.0	1.8
$\Xi^0 \to \Lambda\pi^0$ MC shape	0.4	0.4	0.4
Polynomial background shape	0.2	0.2	0.2
$\mathcal{B}_{\Lambda\to p\pi^-}$	0.8	0.8	0.8
Total Uncertainty	4.0	5.0	4.0

Source	$\Xi^0 \to \Lambda\gamma$	$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$	Combined
Selection Efficiency Related			
Track detection	0.001	0.001	0.001
$\chi^2_{5C} < 40$	0.001	0.002	0.002
Decay length requirement	0.001	0.001	0.001
$m_{\gamma\Lambda}$ requirement	0.001	0.001	0.001
Signal mass window	0.002	0.001	0.002
Fit Related			
$\Xi^0 \to \Lambda\pi^0$ background yield	0.008	0.014	0.010
Continuum background yield	0.006	0.012	0.009
Continuum background model	0.012	0.040	0.013
Input parameters' uncertainty	0.002	0.002	0.002
Total Uncertainty	0.016	0.044	0.019

Results and Discussion

	$\Sigma^+ \to p\gamma$	$\bar{\Sigma}^- \to \bar{p}\gamma$
$N_{\rm ST}^{\rm obs}$	2 177 771±2285	2 509 380±2301
$\varepsilon_{\rm ST}$ (%)	39.00±0.04	44.31±0.04
$N_{\rm DT}^{\rm obs}$	1189±38	1306±39
$\varepsilon_{\rm DT}$ (%)	21.16±0.03	23.20±0.03
Individual BF (10^{-3})	1.005±0.032	0.993±0.030
Simultaneous BF (10^{-3})	$0.996 \pm 0.021 \pm 0.018$	
Individual α_γ	−0.587±0.082	0.710±0.076
Simultaneous α_γ	$-0.652 \pm 0.056 \pm 0.020$	

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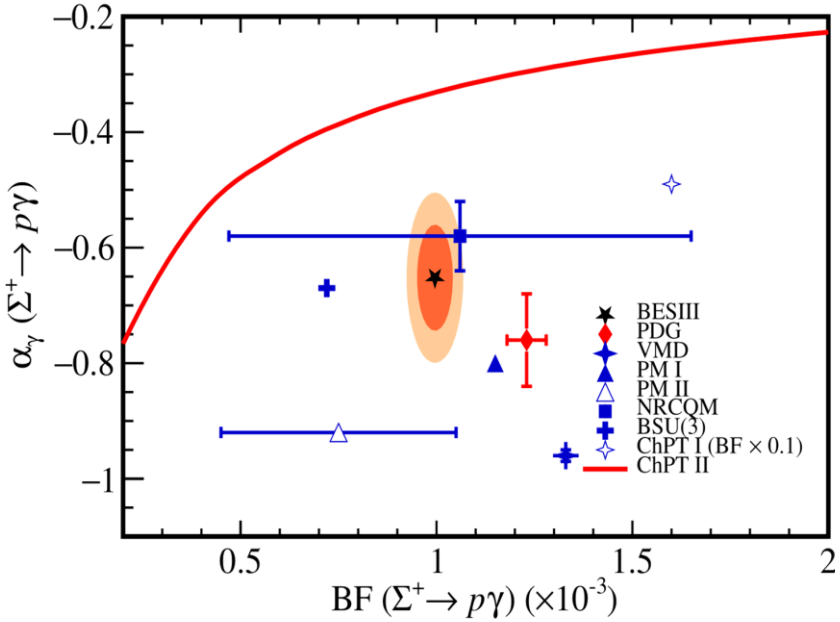
	$\Xi^0 \to \Lambda\gamma$	$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$
$N_{\rm ST}^{\rm obs}$	1 400 541±1989	1 611 216±2111
$\varepsilon_{\rm ST}$ (%)	17.61±0.01	19.77±0.01
$N_{\rm DT}^{\rm obs}$	308±21	330±25
$\varepsilon_{\rm DT}$ (%)	4.49±0.02	4.92±0.02
Individual BF(10^{-3})	$1.348 \pm 0.090 \pm 0.052$	$1.326 \pm 0.098 \pm 0.065$
Simultaneous BF(10^{-3})	$1.347 \pm 0.066 \pm 0.052$	
Individual α_γ	$-0.652 \pm 0.092 \pm 0.016$	$0.830 \pm 0.080 \pm 0.044$
Simultaneous α_γ	$-0.741 \pm 0.062 \pm 0.019$	

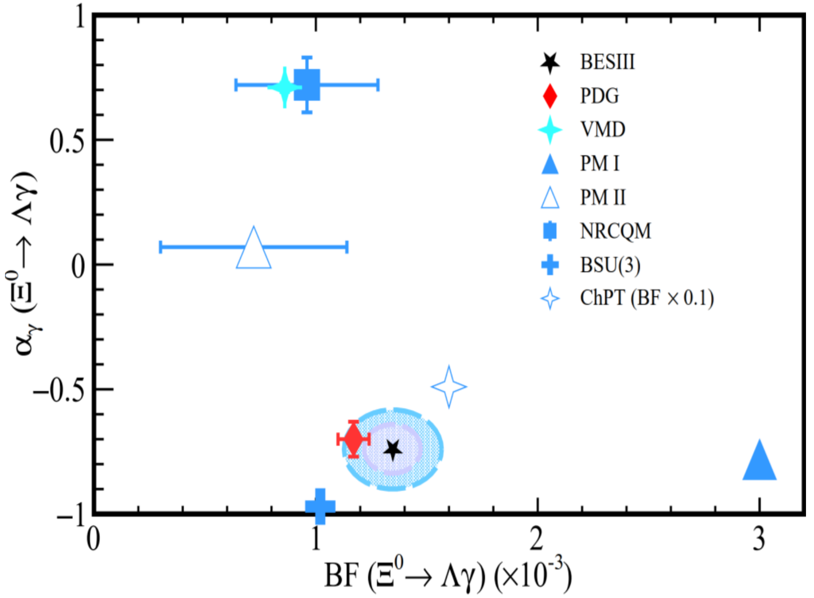
BAM-760, waiting for SP's approval

Results and Discussion

- $\Sigma^+ \to p\gamma$:
  - BF (α_γ) accuracy improved by $78\ \%$ ($34\ \%$)
  - BF deviates from PDG by $4.2\ \sigma$
- $\Xi^0 \to \Lambda\gamma$:
  - Competitive accuracy to PDG values

The first determination of absolute BFs
Precise α_γ with 100 times smaller statistics



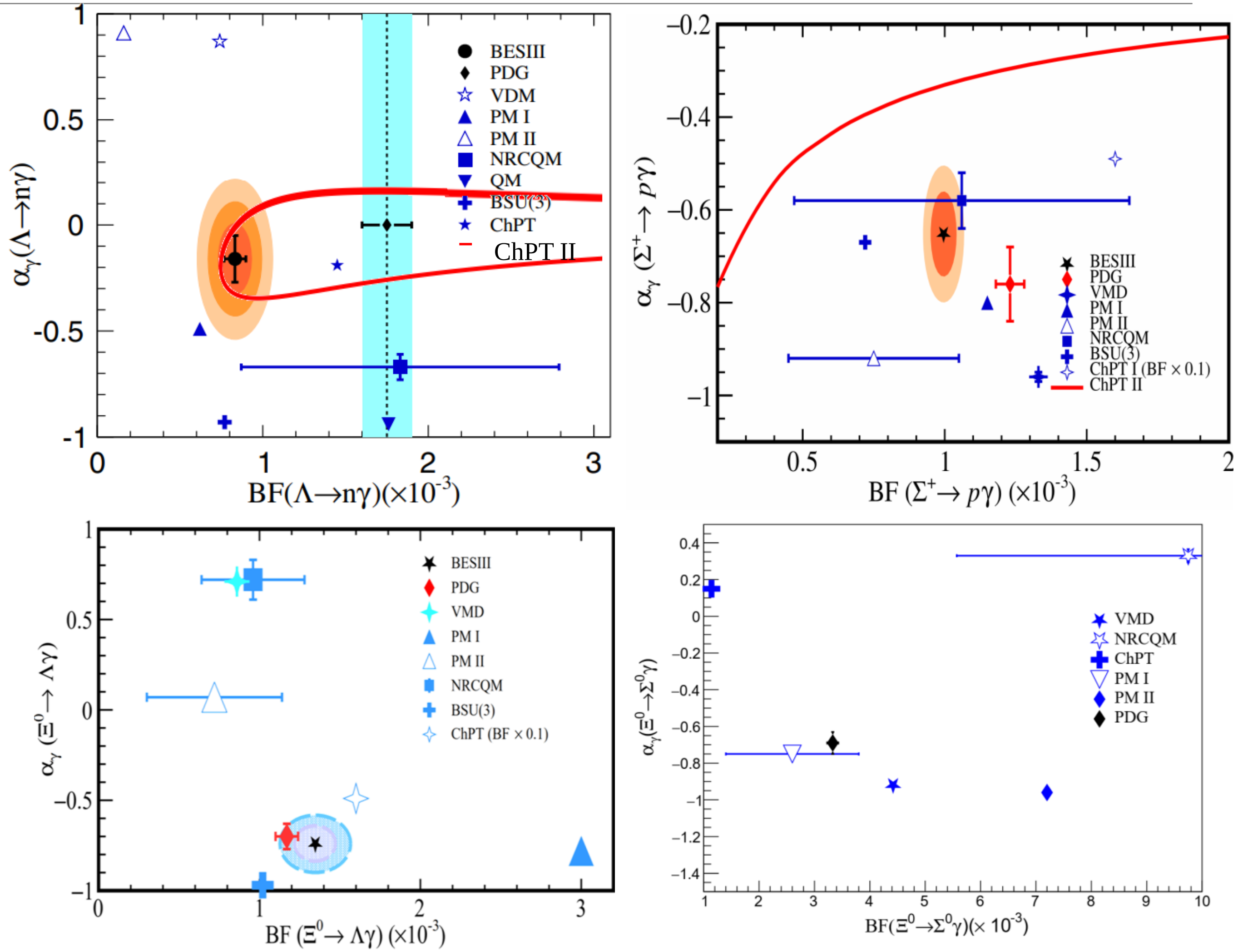


Results and Discussion

- Four established channels
- No QCD model succeeds in predicting these BF & α_γ results
- BESIII results have better accuracy/unbiasedness

$\Lambda \to n\gamma$	$\Xi^0 \to \Lambda\gamma$
$\Sigma^+ \to p\gamma$	$\Xi^0 \to \Sigma^0\gamma$
$\Sigma^0 \to n\gamma$	$\Xi^- \to \Sigma^-\gamma$
	$\Omega^- \to \Xi^-\gamma$

Promote the establishment of unified WRHD theory



Results and Discussion

- No evidence of *CP* violation within the limited statistics
  - Comparable accuracy to radiative meson decays
  - SM prediction: $10^{-5} - 10^{-4}$

	Δ_{CP}	A_{CP}
$\Sigma^+ \to p\gamma$	$0.006 \pm 0.011 \pm 0.004$	$0.095 \pm 0.087 \pm 0.018$
$\Xi^0 \to \Lambda\gamma$	$-0.033 \pm 0.049 \pm 0.031$	$-0.120 \pm 0.084 \pm 0.029$

- If there is an experiment with a statistics 100 times to BESIII
  - BF and α_γ measurement accuracy improved by ~10 times (statistical & systematic)
  - Expected sensitivity on *CP* violation reaches $\mathcal{O}(0.1) - \mathcal{O}(1)\%$
  - Validate unified WRHD theories & Test on NP enhanced *CP* violation

R&D on Electromagnetic Calorimeter of STCF

Super Tau-Charm Facility

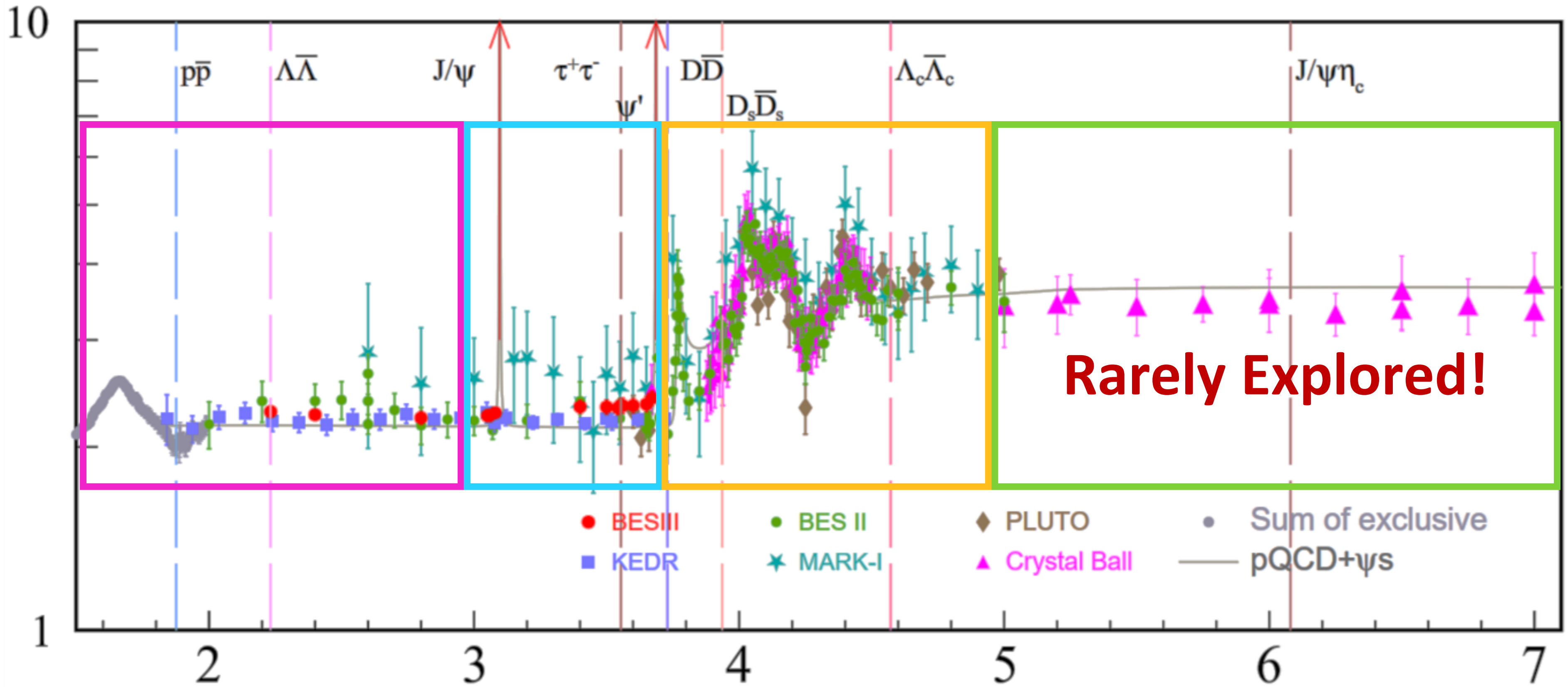
Hadron Physics at τ-charm energy region

- Nucleon/Hadron form factors
- Lightest multiquark states

- LH spectroscopy
- Gluonic and exotic
- Hyperon physics
- τ physics & Ditauonium

- XYZ particles
- CKM matrix & γ angle
- f_D and f_{D_s}
- D_0-$\overline{D}_0$ mixing
- Charm baryons

- New XYZ particle
- Multiquark state
- Di-charmonium state
- Charm baryons
- Hadron fragmentation

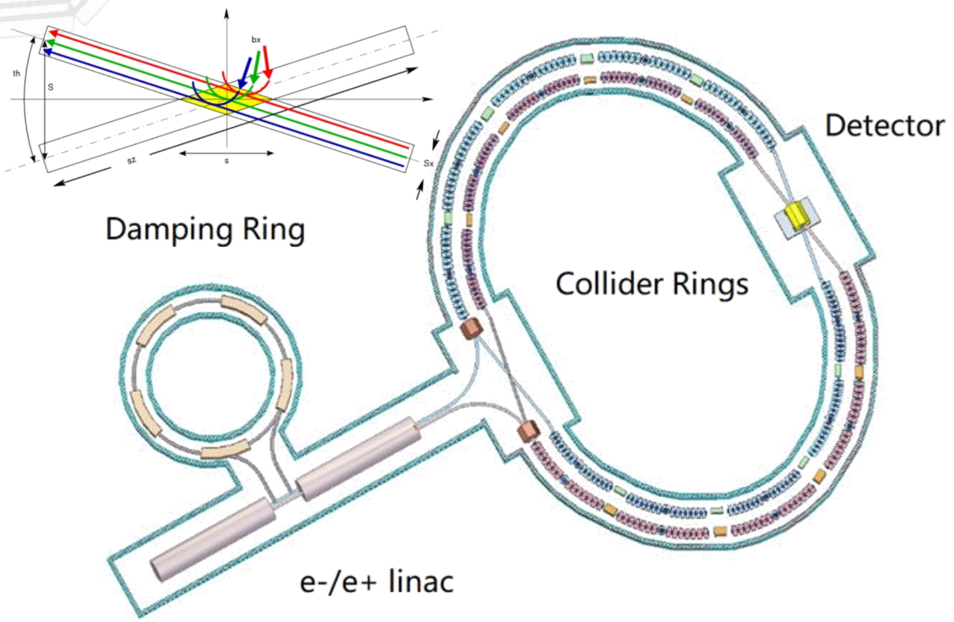


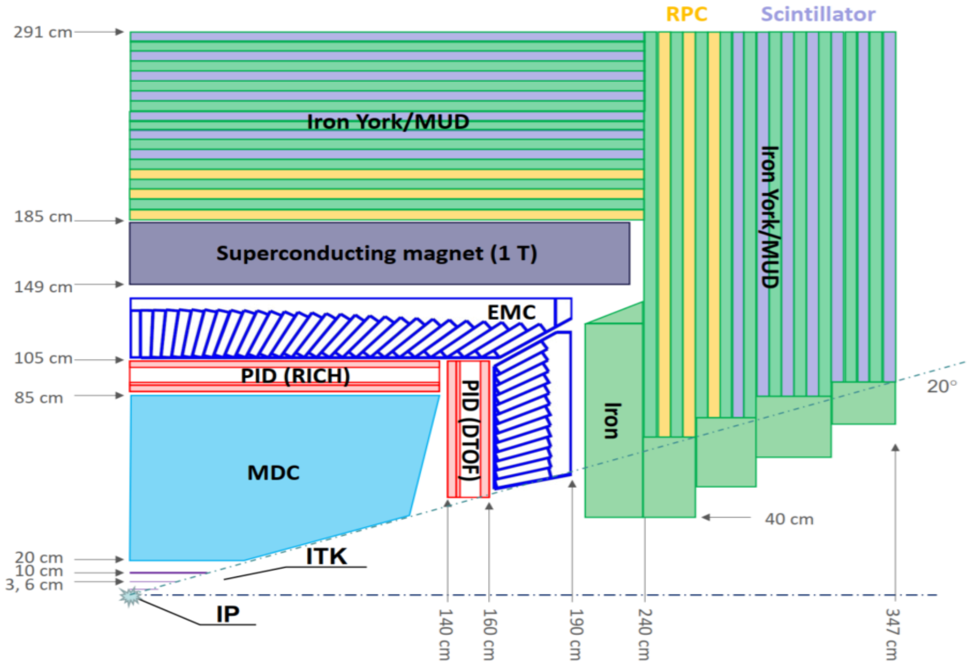
Super Tau-Charm Facility

Tackle challenges facing the SM with unprecedented statistics

Super Tau-Charm Facility

Project Overview

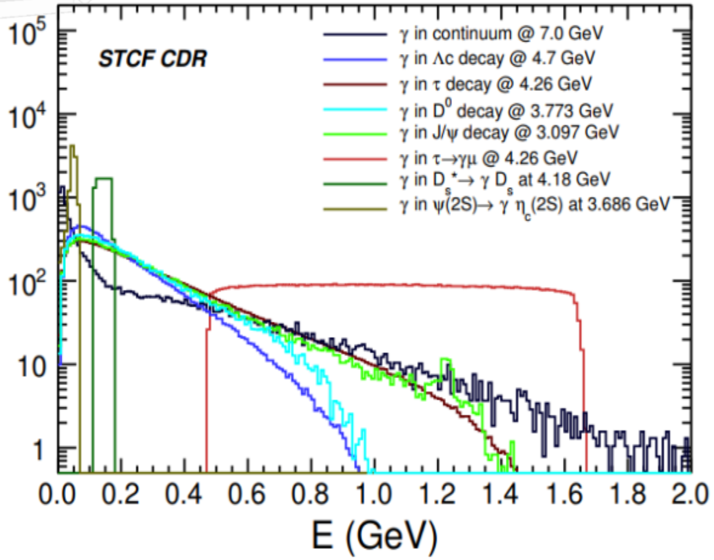


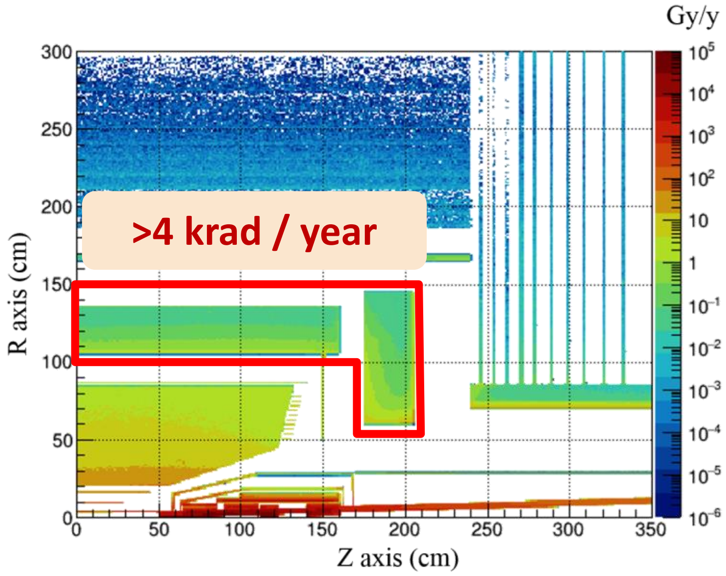


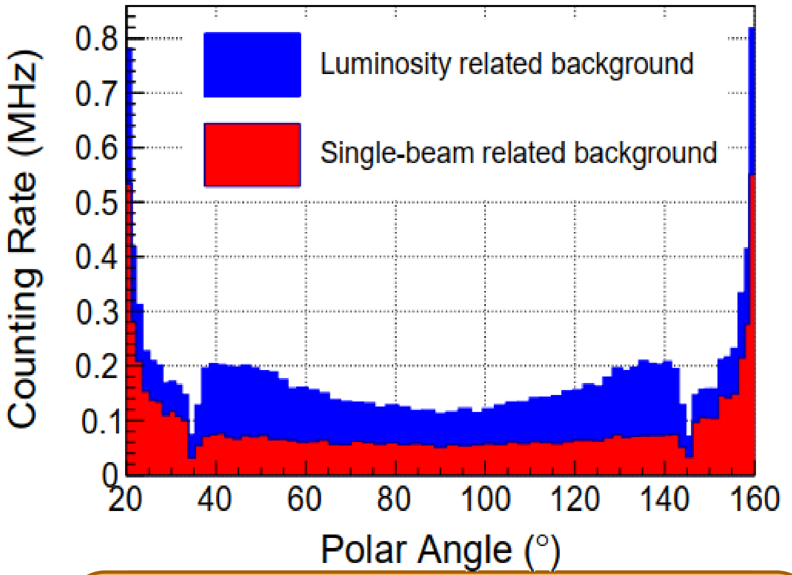
- Large Piwinski angle + Crab Waist
- Design $\mathcal{L} > 0.5\times10^{35}$ cm^{-2}s^{-1}
- $E_{cm} = 2-7$ GeV
- Potential for beam polarization

• < 0.25% X_0/ layer • $\sigma_{xy} < \sim 100$ μm	μRWELL/CMOS
• $\sigma_{xy} < 130$ μm • $\sigma_p/p \sim 0.5\%$ @ 1 GeV/c • dE/d$x \sim 6\%$	Drift Chamber
• π/K (and K/p) 3-4 σ separation up to 2 GeV/c	RICH & DTOF
• E range: 0.025−3.5 GeV • σ_E<2.5% @ 1 GeV • σ_x <6 mm @ 1 GeV • σ_t<0.8 ns @ 0.1 GeV	Pure CsI + APD
• 0.4–2 GeV π suppression > 30	RPC + Scint.

Challenges in Design and Operation







$E_{\gamma} =$ ~1 MeV – 3.5 GeV
Event Rate > 400 kHz

Large Dynamic Range & Fast Response

Average TID > 0.3 krad
Peaking TID > 40 krad

Radiation Tolerate

Beam background rate ~1 MHz per channel

Fast Response & Pile-up Recovery

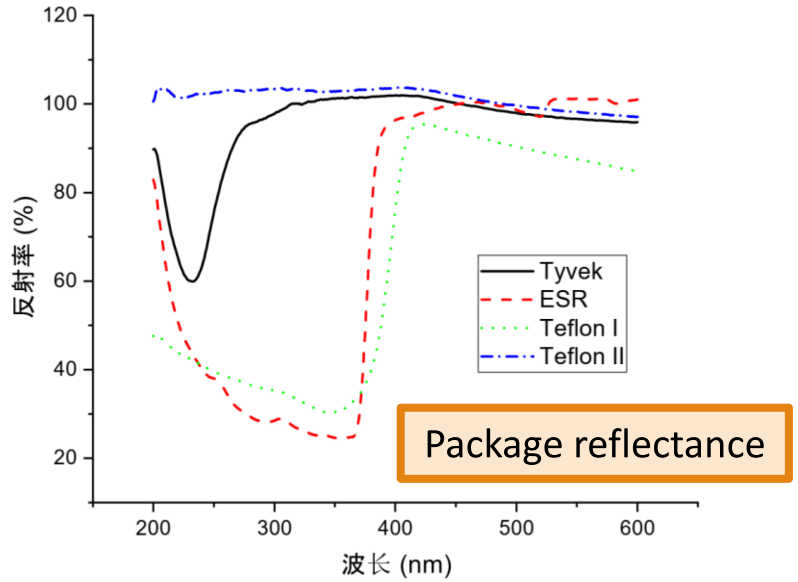
Introduction of STCF EMC

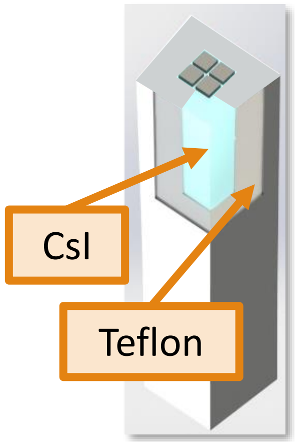
Detection Unit

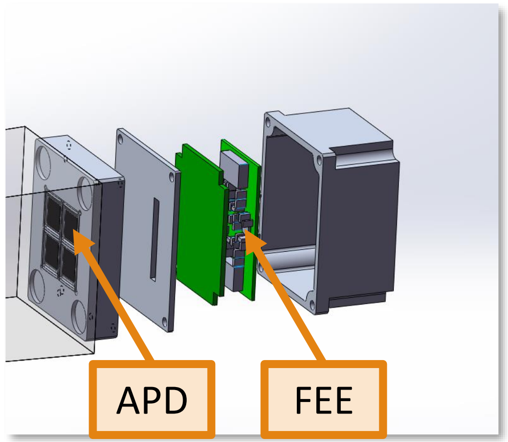
Radiation Hardness	100 krad	LYSO	BaF2	CsI	CsI(Tl)	BGO PWO	
Decay Time	10 – 30 ns	BaF2	PWO	CsI	LYSO	BGO	CsI(Tl)
Light Yield	2000 / MeV	CsI(Tl)	LYSO	BGO	CsI	BaF2	PWO
Price	\$4.6 / g	CsI CsI(Tl)		BaF2	PWO	BGO	LYSO

Magnetic Resistance		PD APD SiPM		
Dynamic range		PD	APD	SiPM
Q. E.	> 85%	APD PD		SiPM
SNR	1000 e/cm^2	SiPM	APD	PD

- Undoped CsI: $5 \times 5 \times 28\ \mathrm{cm}^3$
- $250\ \mu\mathrm{m}$ Teflon
- Si APD: $10 \times 10\ \mathrm{mm}^2 \times 4$

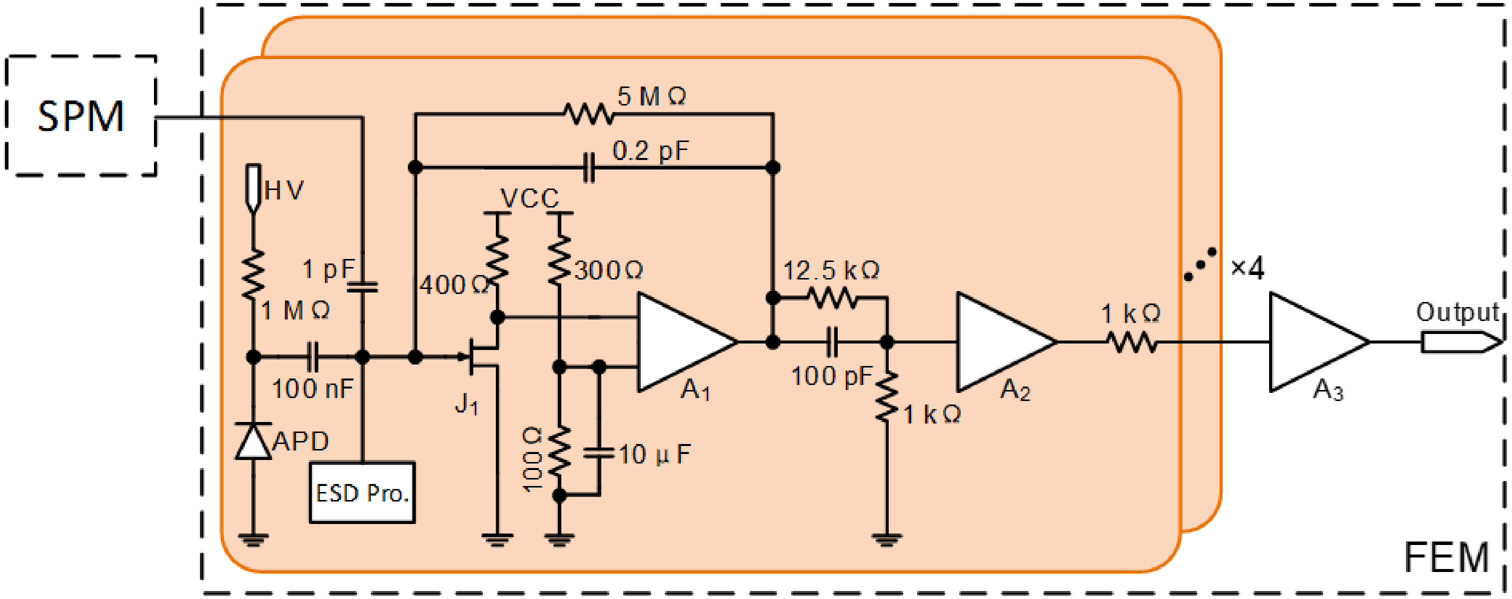






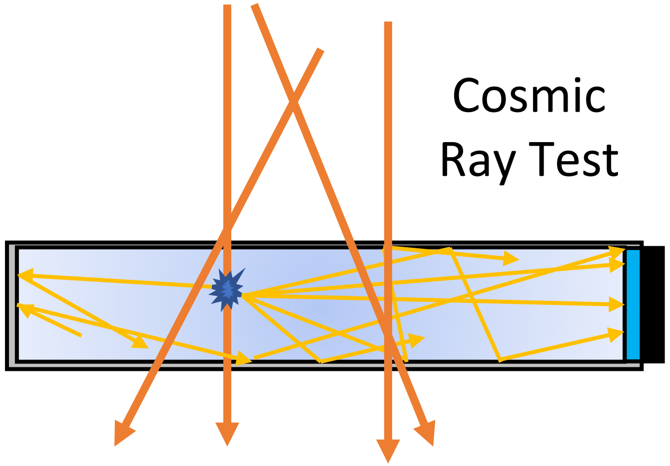
Introduction of STCF EMC
Frontend Electronics

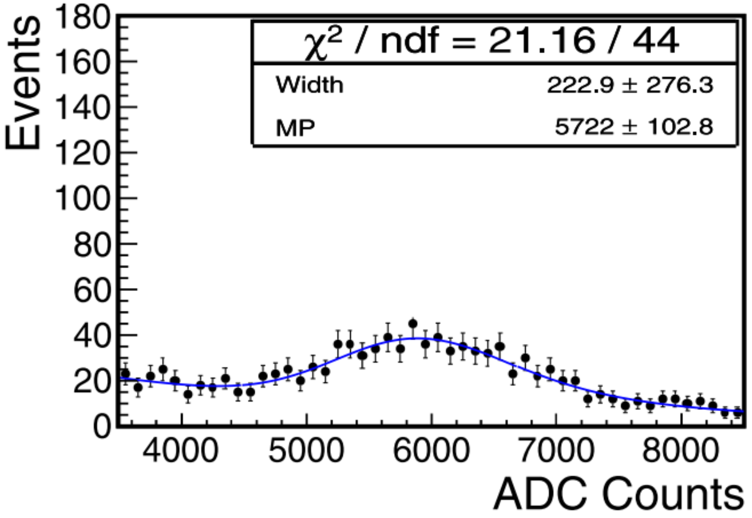
- CSA
  - High gain/Low gain: 33
  - Maximum charge: >7200 fC
  - Noise: 2.0 fC
- PZC
  - Decay time: 100 ns
- ADC
  - 80 MHz; 14 bit



Introduction of STCF EMC

Prototype Test



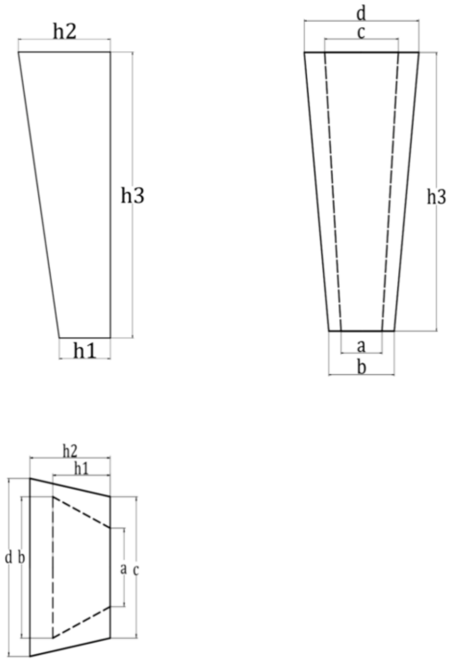


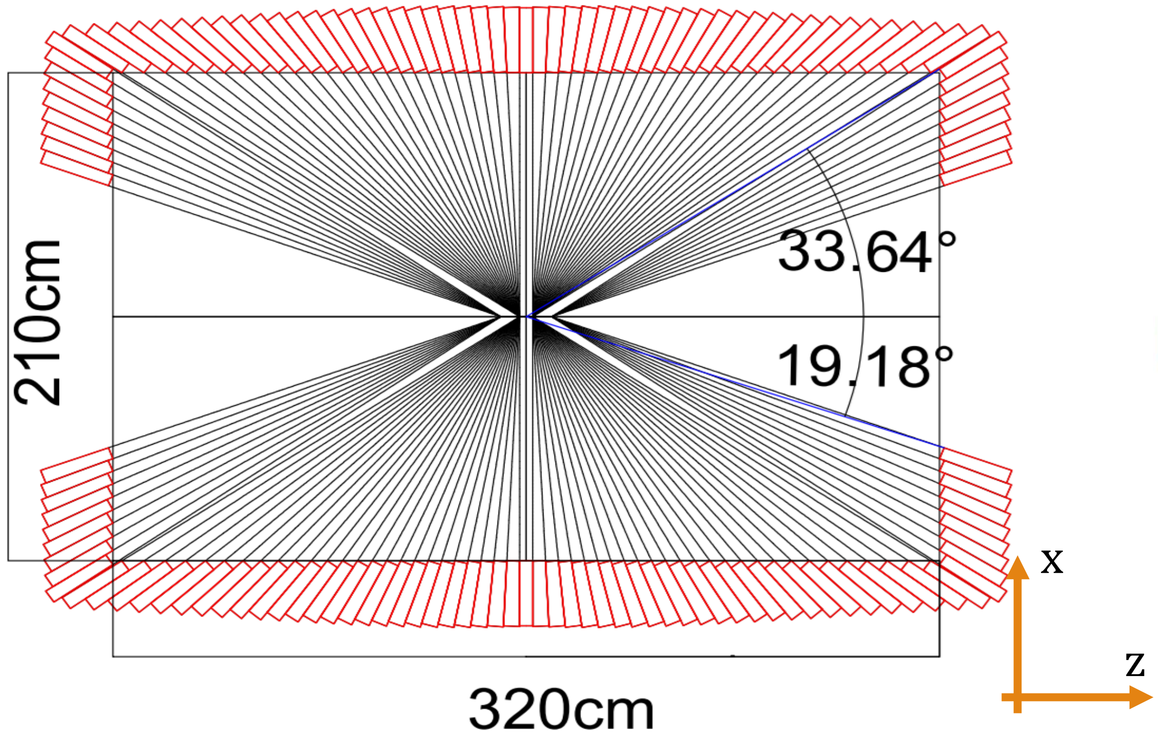
- Maximum LY = 155 pe/MeV
- Nominal LY ~100 pe/MeV
- Nominal $\sigma_{noise} = 1.0$ MeV

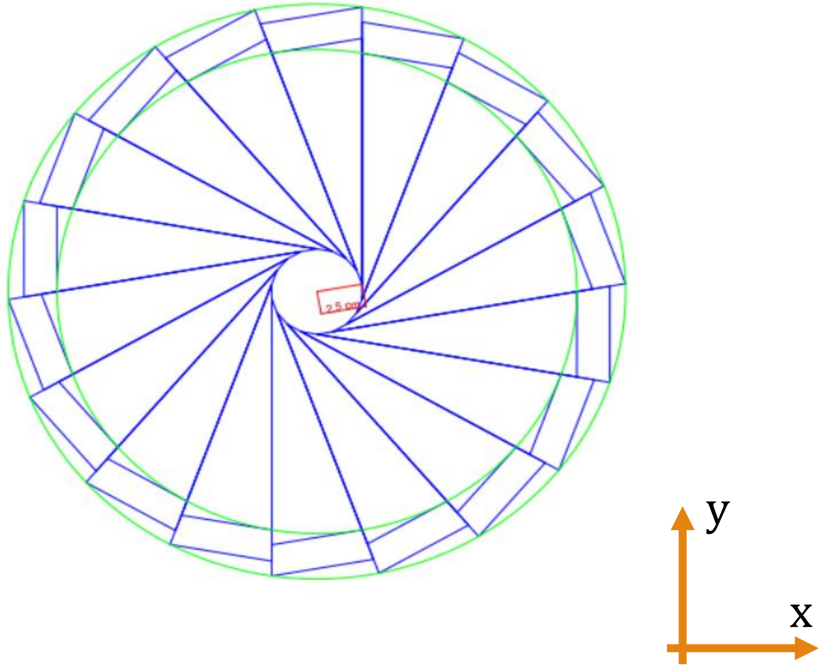
Introduction of STCF EMC

Full Geometry

- Barrel: 6732 crystals (51 × 132); Endcap: 969 crystals
- Non IP-oriented alignment to mitigate dead region



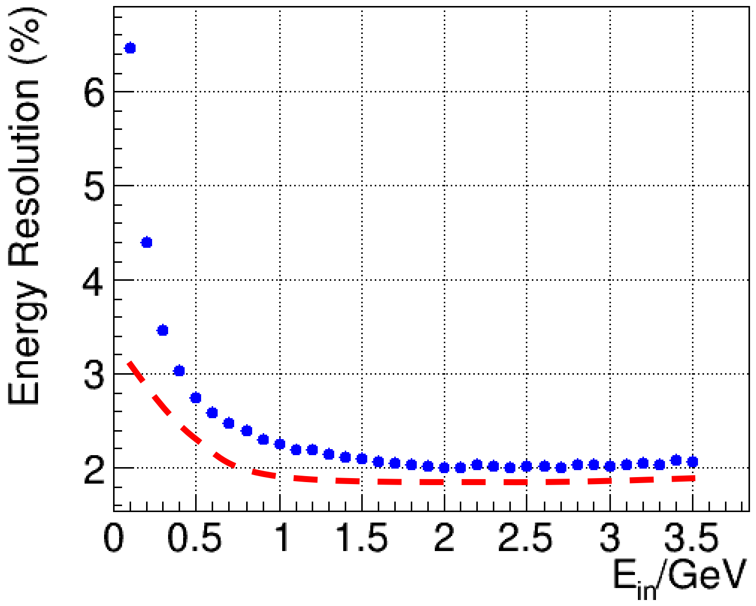


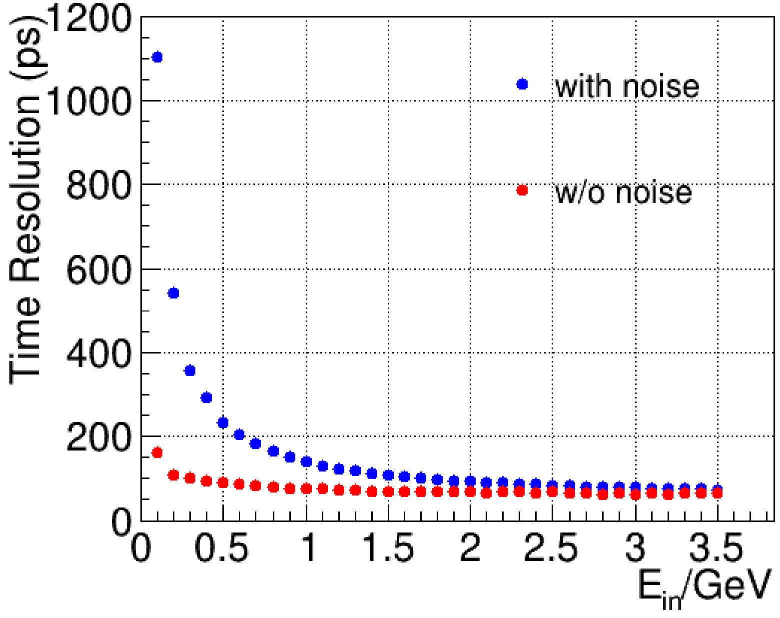


R&D on LY Enhanced Detection Unit

Motivation

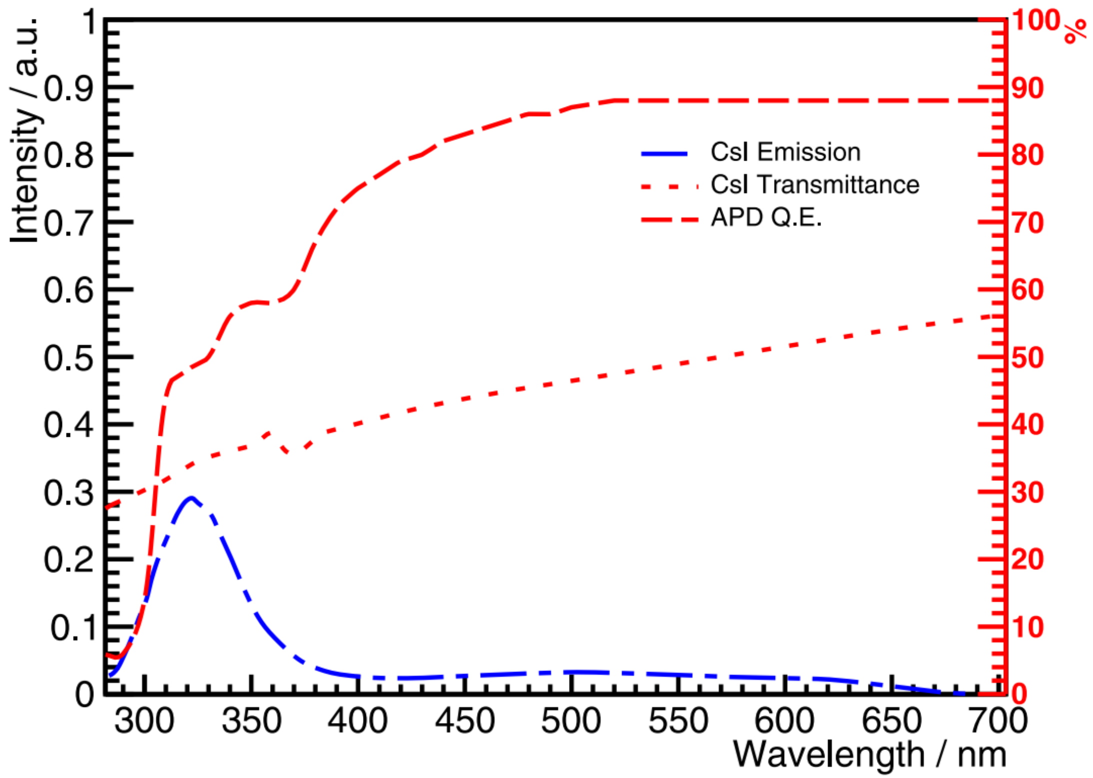
- Light yield – The bottleneck of EMC performance
  - Energy resolution of low energy photons
  - Time resolution
  - Pile-up recovery capability

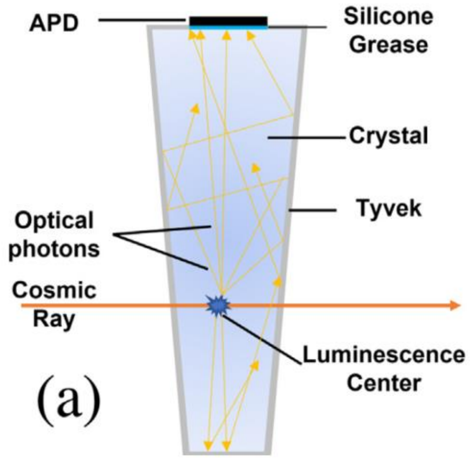




R&D on LY Enhanced Detection Unit
Light Transportation Simulation

- Speculation: LY subject to transmittance
- Validated by optical simulation @ Geant4





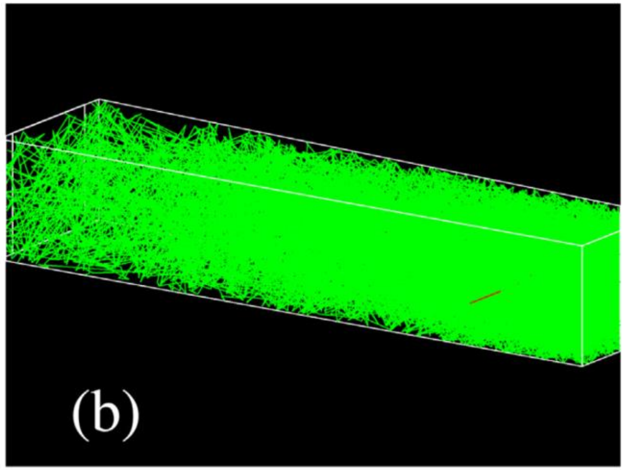


Table 1
Summary of the optical simulation parameters and result.

Component	UV	VIS
Generated ratio (%)	70	30
Absorption length (cm)	26.7	55.0
Q.E. (%)	48	89
Detected ratio (%)	31.53	68.47

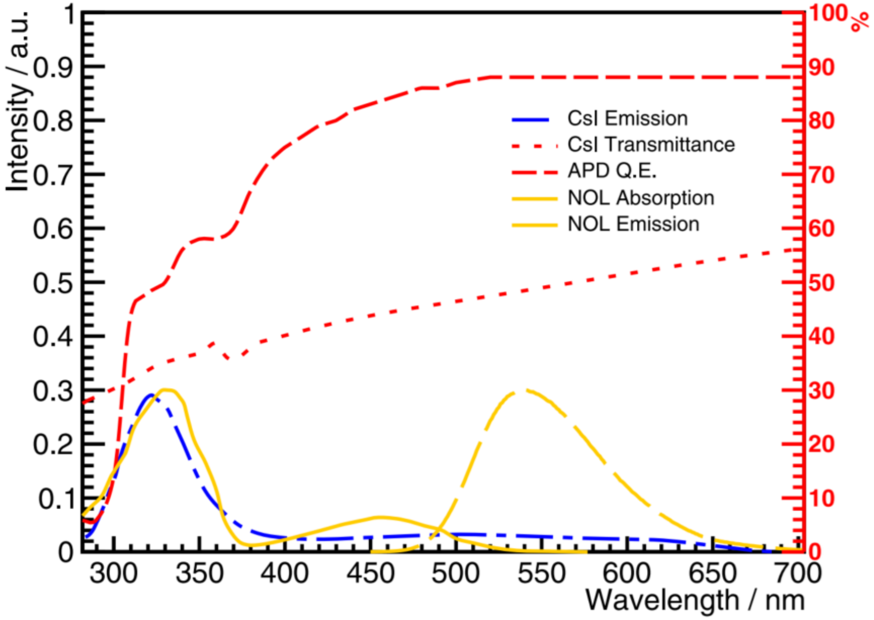
UV detection efficiency < 10 %

R&D on LY Enhanced Detection Unit

LY Enhancement method with WLS

- How to improve effective transmittance and Q.E. simultaneously?
- Increase scintillation wavelength during propagation – Coating WLS on crystal

NOL@LumInnoTech
- Q.E. > 95 %
- $\tau \approx 10$ ns

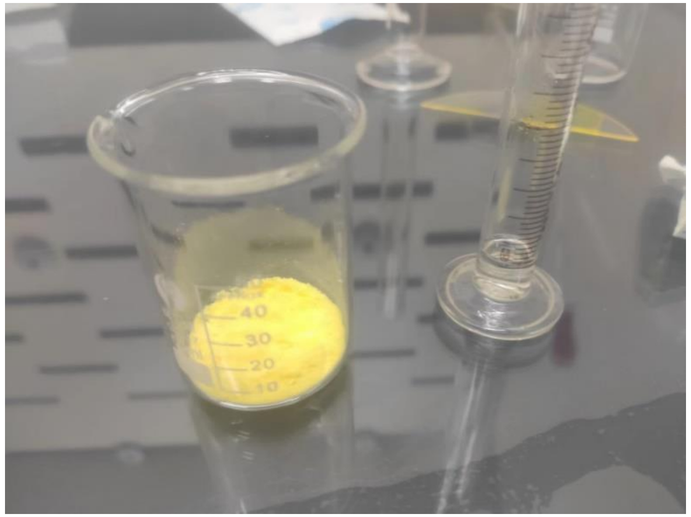


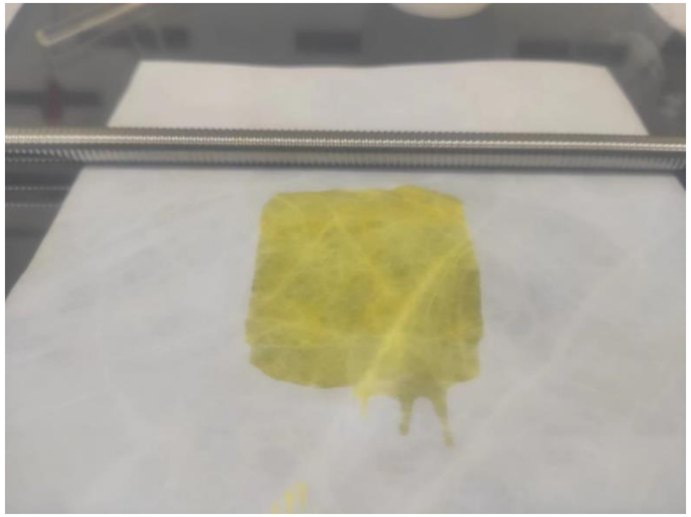
Scheme	L.Y. (p.e./MeV)	Relative ratio
No-coating scheme	143	
WLSP scheme	338	2.36
Alternative-1 scheme	179	1.25
Alternative-2 scheme	341	2.38

R&D on LY Enhanced Detection Unit

Experiment Validation: NOL coated Tyvek Film

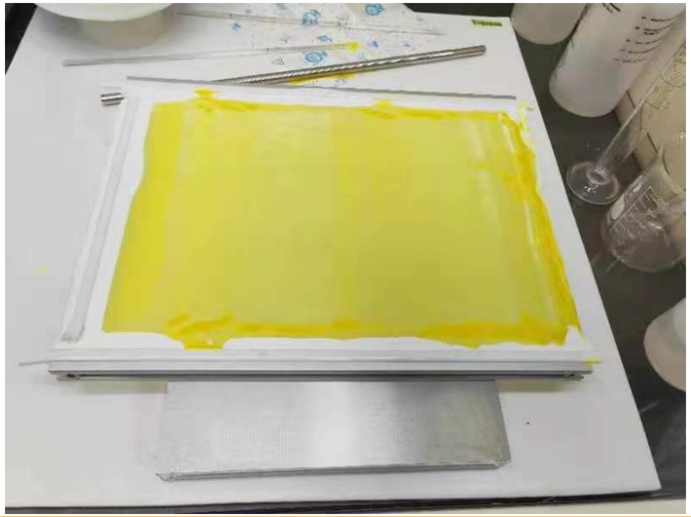
NOL Solution Preparation
- 0.4 g/ml
- Toluene solution





Film Spreading With Mayer-bar
- 200 μm wet film

Drying
- 40 μm film

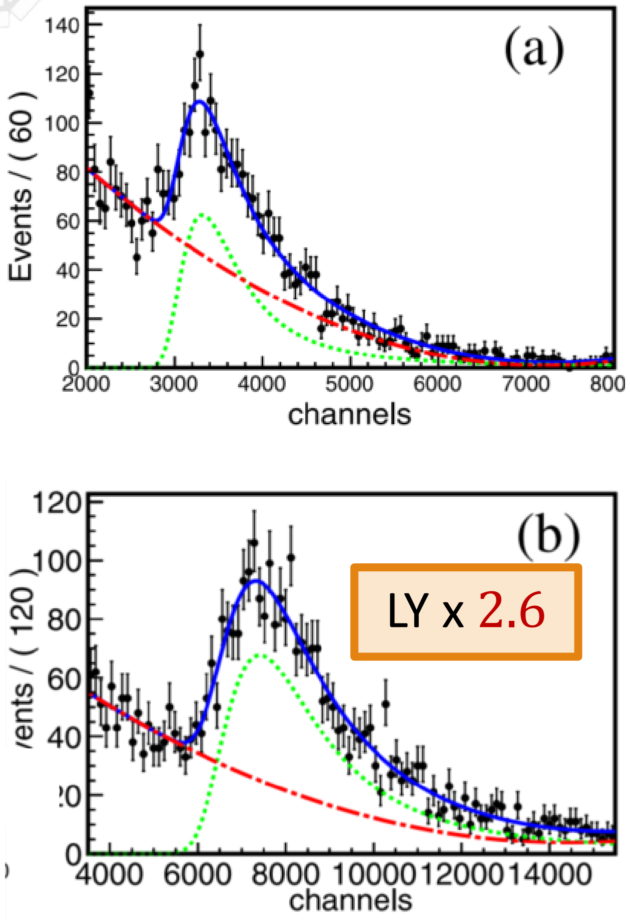


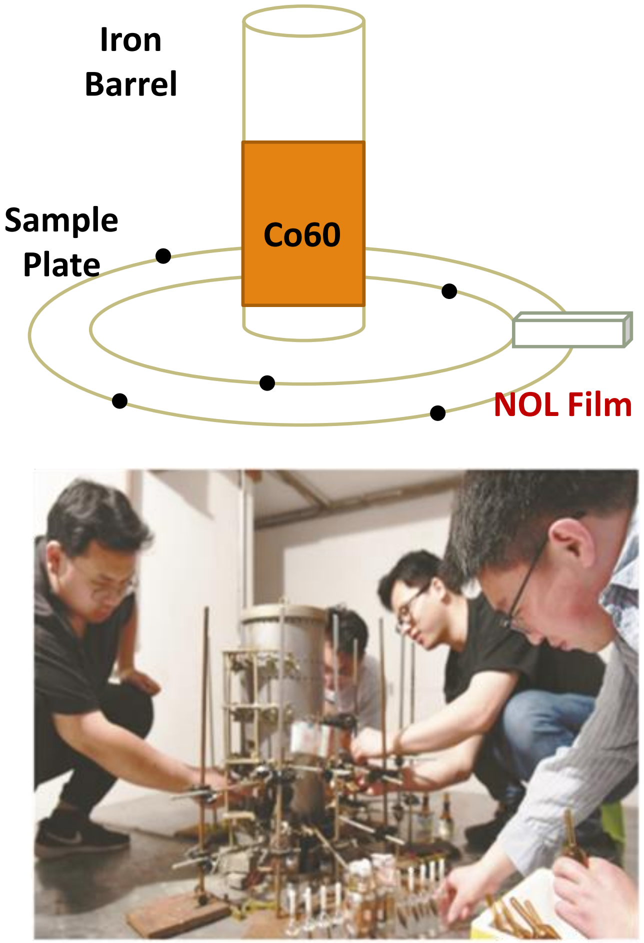
Assembling

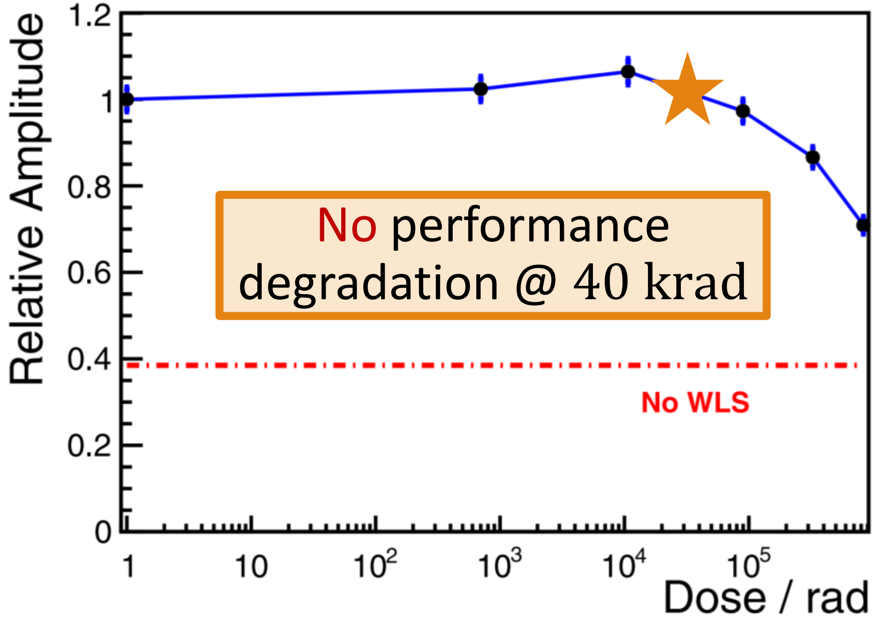
Z. K. Jia *et al*. Nucl.Instrum.Meth.A 1050 (2023), 168173

R&D on LY Enhanced Detection Unit

Experiment Validation: NOL coated Tyvek Film

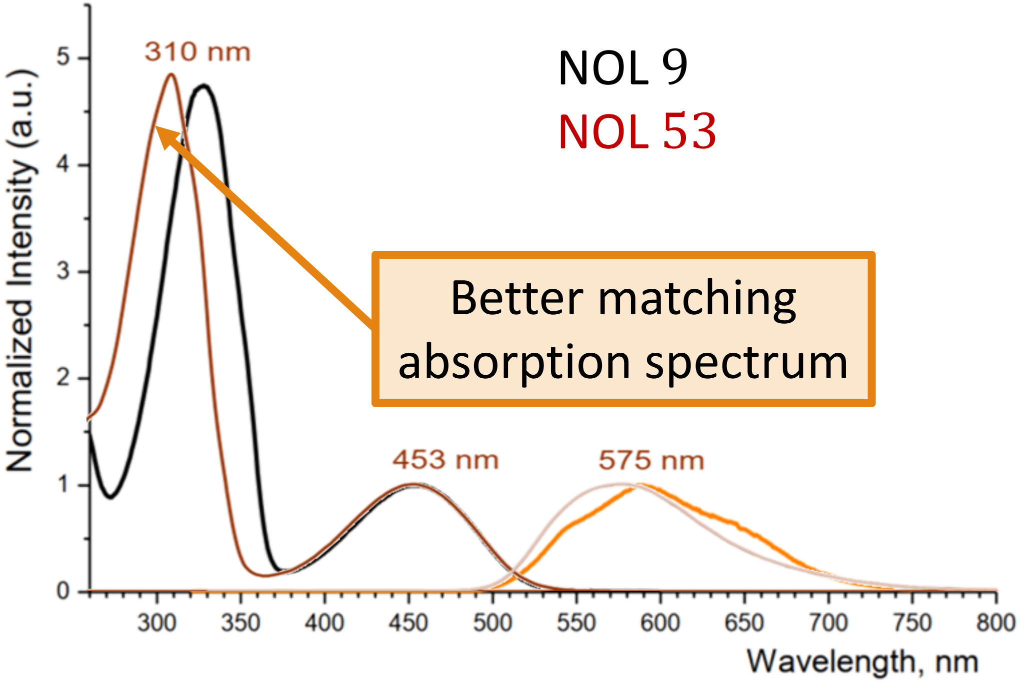






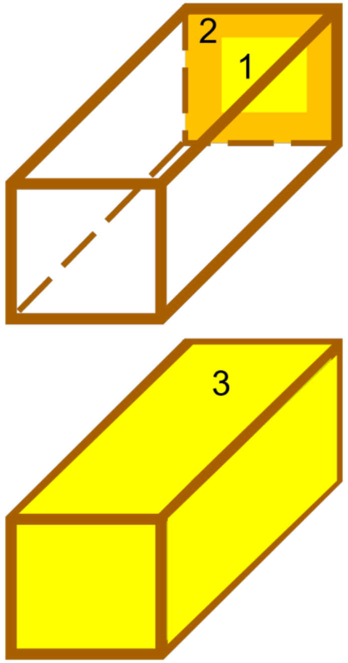
R&D on LY Enhanced Detection Unit

Mass Production: NOL Coated CsI Crystal



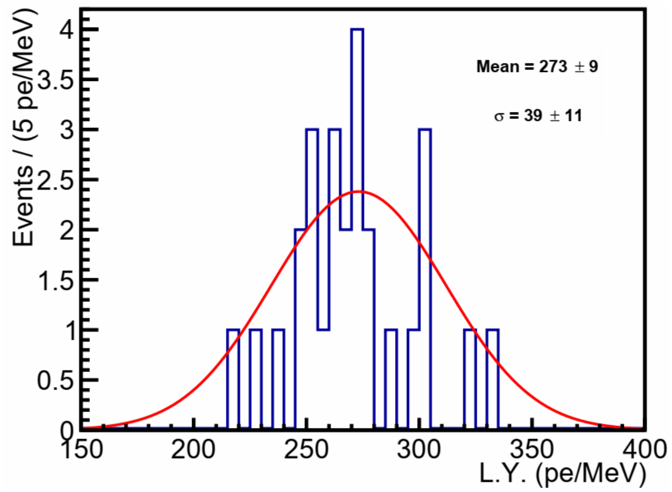
R&D on LY Enhanced Detection Unit

Mass Production: NOL Coated CsI Crystal



NOL Type	Painting Position	Dosage (g)	LY (pe/MeV)	Ratio
53	---	---	117	
	3	5	274	**2.3**
	3	10	303	2.6

- Nominal scheme: 5 g NOL-53 per crystal
- Average LY: 273 pe/MeV
- σ_{noise} = 1.0 MeV → 0.4 MeV
- σ_E @ 100 MeV: 6.4 % → 4.5 %



EMC Timing Performance Study

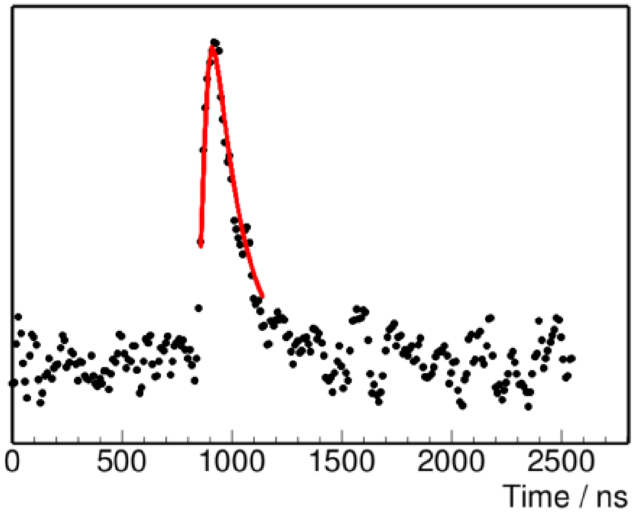
Time Resolution Derivation

- $\sigma_t \propto (\sigma_{\mathrm{intr}} \oplus \sigma_{\mathrm{noi}})$
- Define noise sequence $\vec{n} = \vec{y} - A\vec{f}(\tau)$. Require $\chi_T^2 = 0$, according to error propagation formula:

$$\chi_T^2(A,\tau) = \sum \left(\vec{y} - A\vec{f}(0) - A\vec{f}'(0)\tau\right)^{\mathrm{T}} S^{-1} \left(\vec{y} - A\vec{f}(0) - A\vec{f}'(0)\tau\right)$$

$$\sigma_{\mathrm{noi}} = \frac{2\vec{n}^{\mathrm{T}} S^{-1} \vec{f}'(0)}{A\vec{f}'^{\mathrm{T}}(0) S^{-1} \vec{f}'(0)}$$

- σ_{noi} influencing factors:
  - (time correlated) electronics noise $\vec{n}$ (proportional)
  - Signal amplitude A (anti-proportional)
  - Waveform slope f' (anti-proportional)



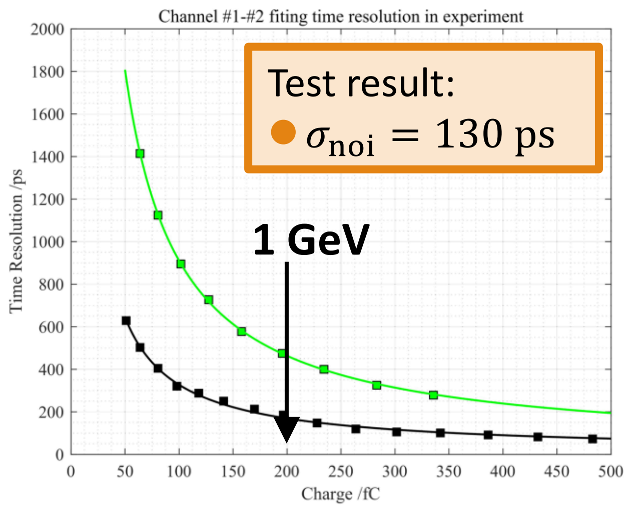
EMC Timing Performance Study

Electronics Scheme Upgrade

- Numerical studies on timing & amplitude measurement performance
  - Traditional electronics scheme: CSA + $(\mathrm{RC})^2$ shaping + ADC
  - New scheme: CSA + ADC + DSP (Template fit with least square method or optimal filtering)

$$\begin{pmatrix} \vec{f}(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{f}(0) & \vec{f}(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{f}'(0) \\ \vec{f}'(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{f}(0) & \vec{f}'(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{f}'(0) \end{pmatrix} \begin{pmatrix} A \\ A\tau \end{pmatrix} = \begin{pmatrix} \vec{f}(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{y} \\ \vec{f}'(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{y} \end{pmatrix}$$

Numerical Result	Time resolution (ps @ 200 fC)
CSA+$(\mathrm{RC})^2$ +correlated noise	492
CSA+$(\mathrm{RC})^2$	213
CSA	133

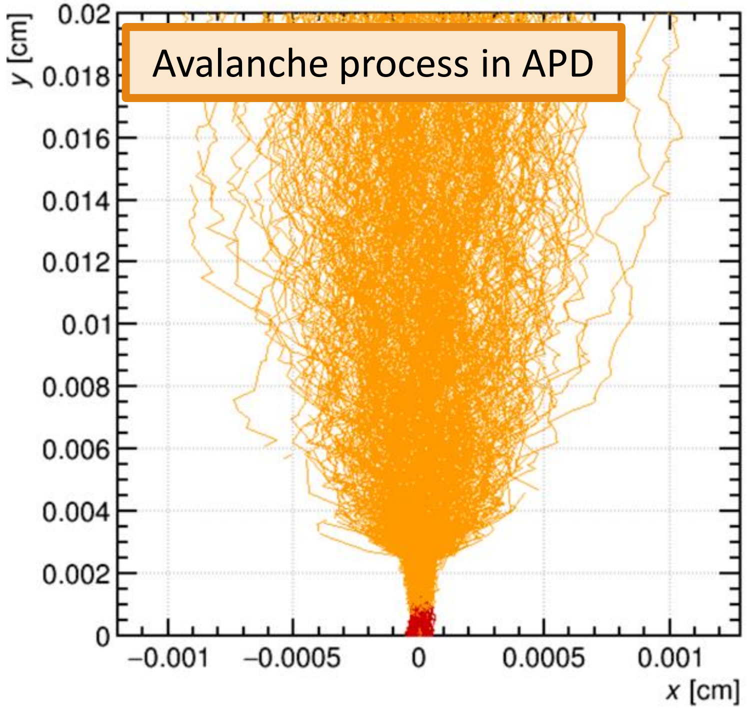


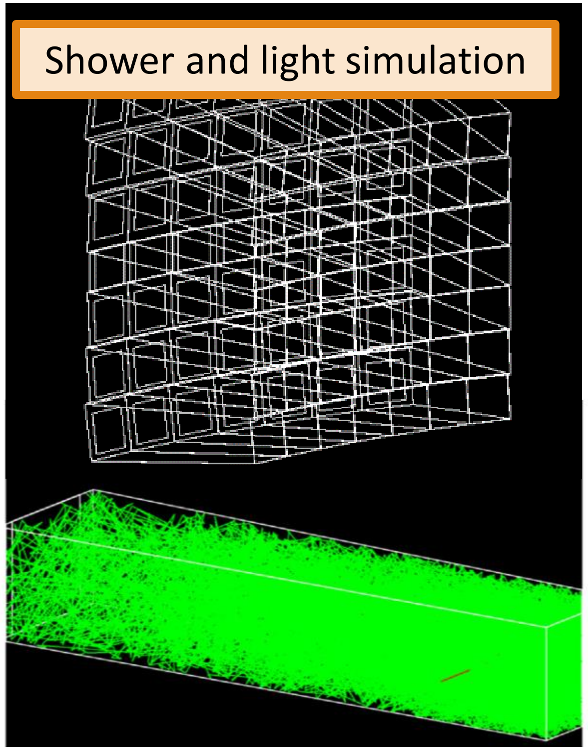
- Consistent amplitude SNR
- 2 times improved time resolution
- "Compact" electronics design

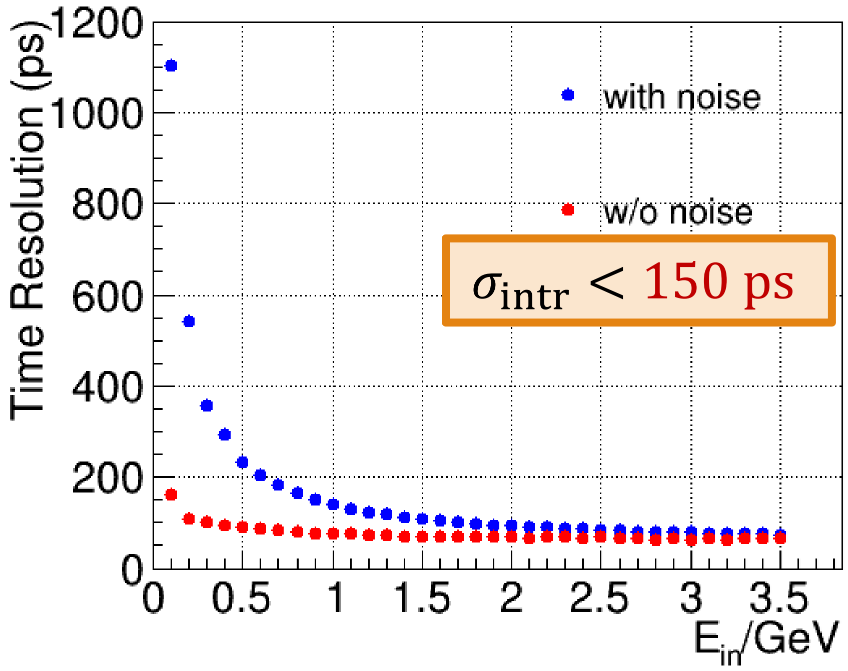
EMC Timing Performance Study

Other Intrinsic Factors

- σ_{intr}: APD avalanche, shower growth, light propagation…

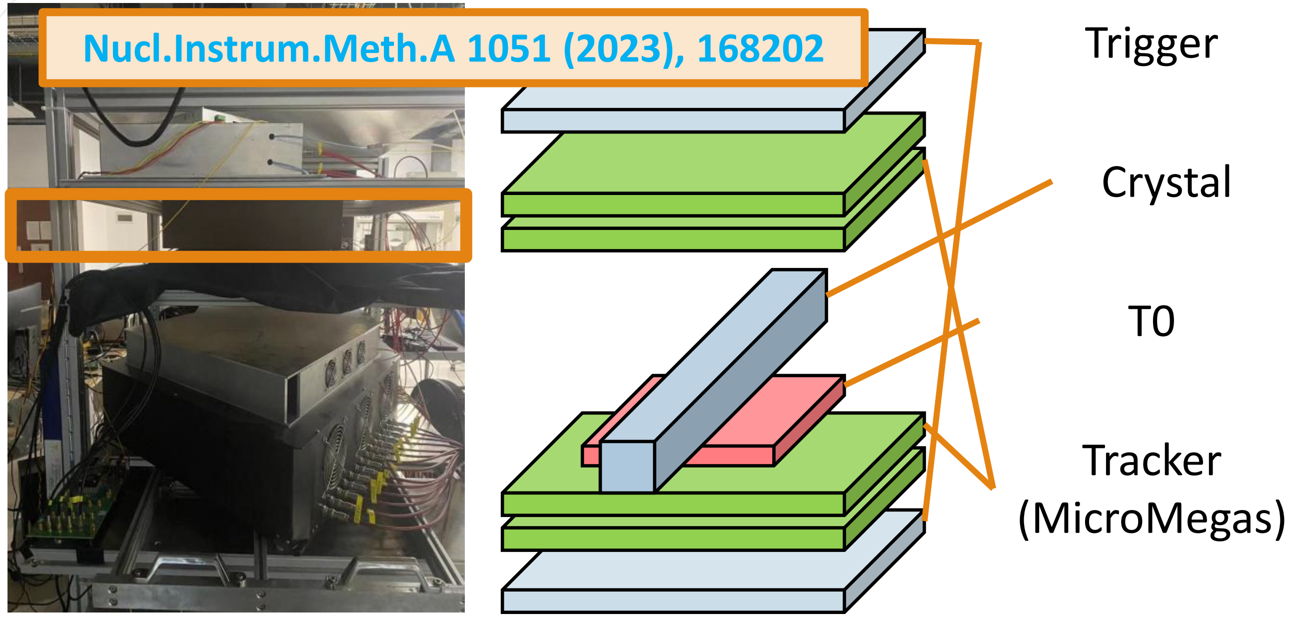


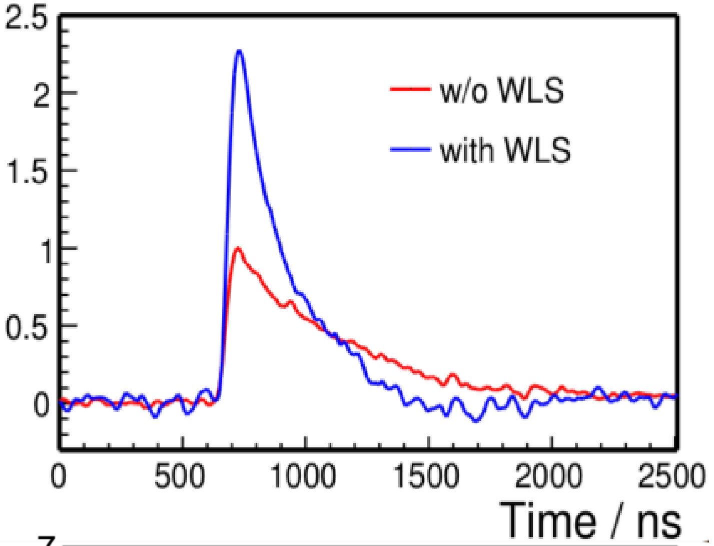


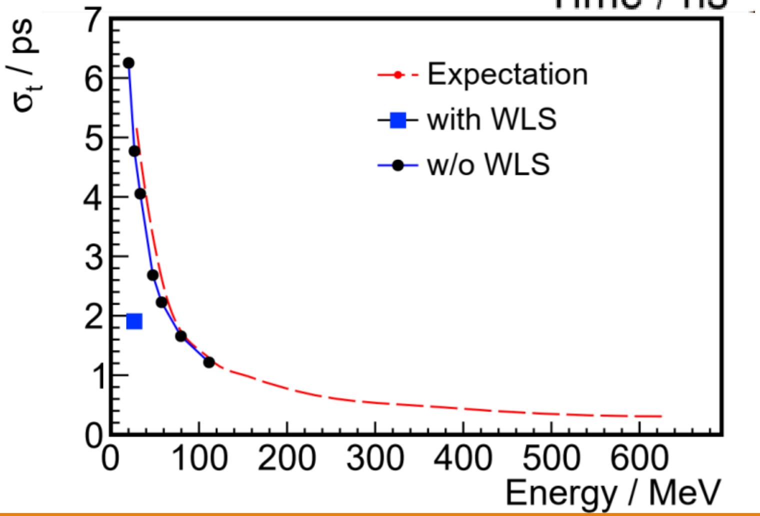


EMC Timing Performance Study

Time Resolution Measurement on Detection Unit







Much improved σ_t for new detection unit

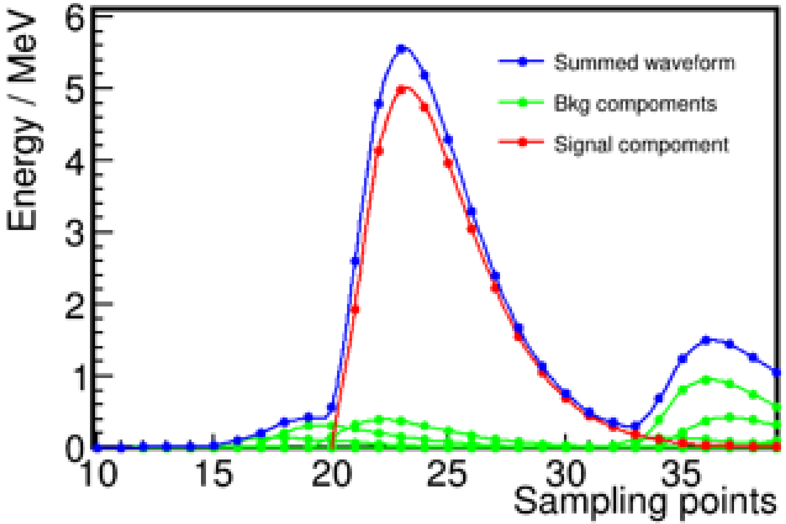
- σ_t: 5.0 ns $\rightarrow$ 2.0 ns @ 0.033 GeV (measured)
- σ_t = 0.7 ns @ 0.1 GeV (extrapolation)

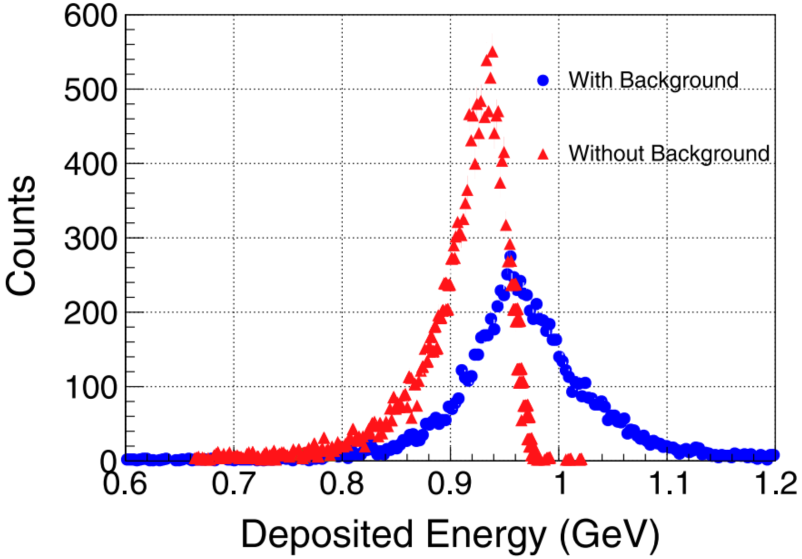
Critical for Event timing & Neutral PID

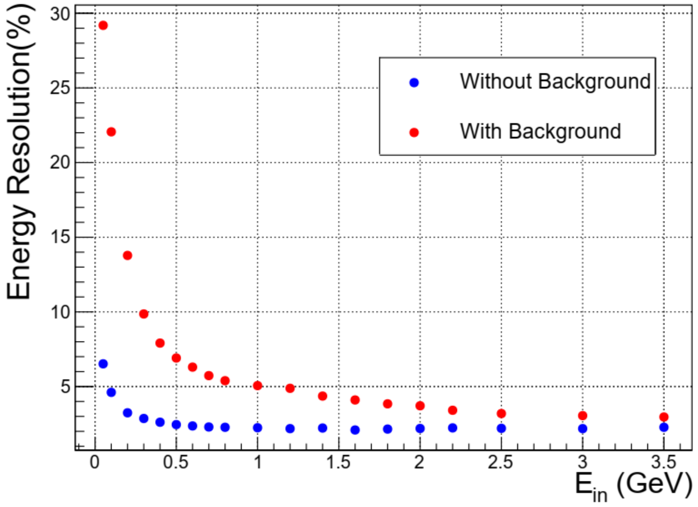
Studies on Pile-up Recovery Methods

Pile-up Induced Resolution Deterioration

- Fast crystal & electronics – Isolate background out of ~500 ns
- Signal waveform still deformed by 1 MHz beam background events



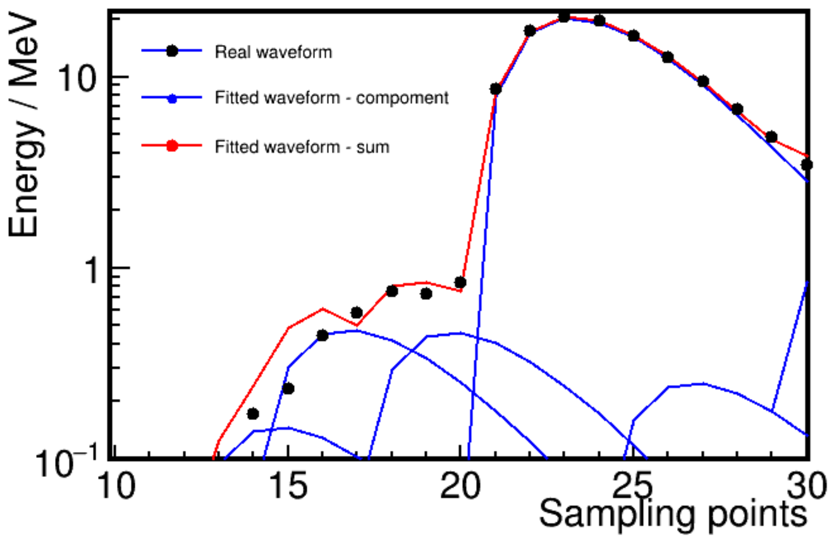


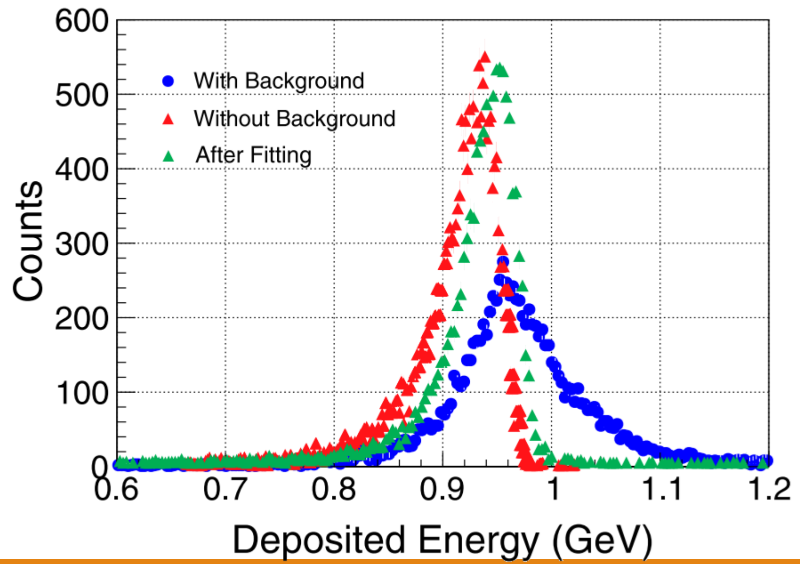


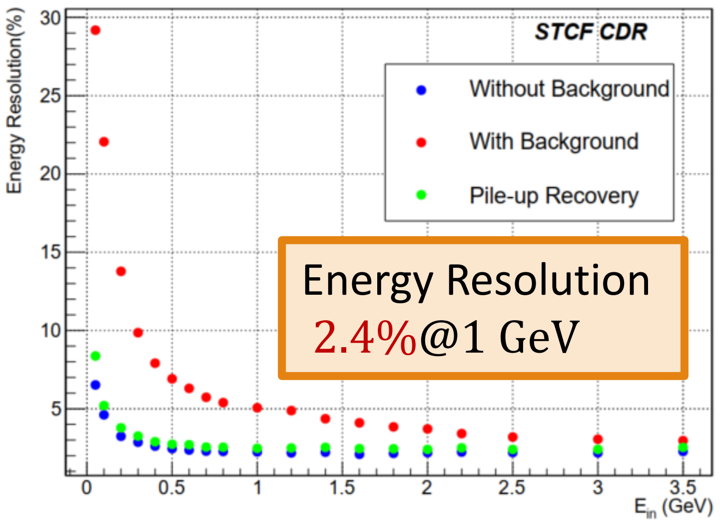
Studies on Pile-up Recovery Methods

Proof-of-Concept Algorithm

- MultiFit: $\chi^2_{\mathrm{MF}} = \left(\vec{y} - \vec{A}\boldsymbol{T}\right)^{\mathrm{T}} \left(\vec{y} - \vec{A}\boldsymbol{T}\right)$
  - $\vec{A}$: Amplitude vector
  - $\boldsymbol{T}$: Template matrix, adjacent column with fixed time interval
  - Utilize *fnnls* for minimization to avoid overfitting – noise level dependent threshold





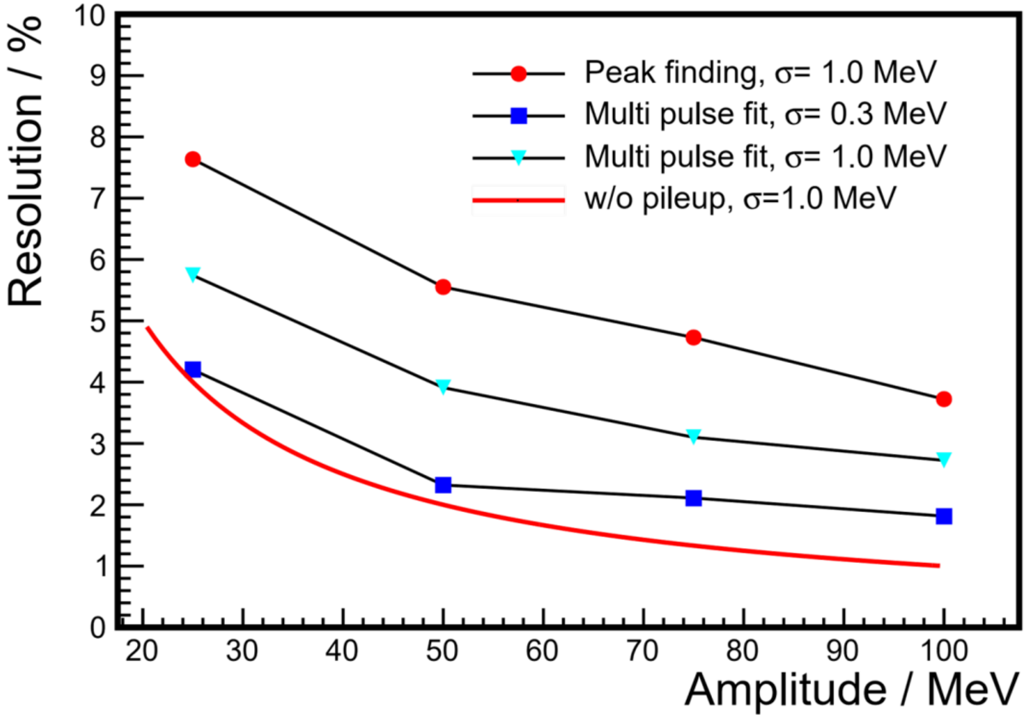


Energy Resolution
2.4%@1 GeV

Studies on Pile-up Recovery Methods

MultiFit with improved LY

- MultiFit threshold: $5\ \mathrm{MeV} \rightarrow 2.1\ \mathrm{MeV}$
- Amplitude resolution further recovered



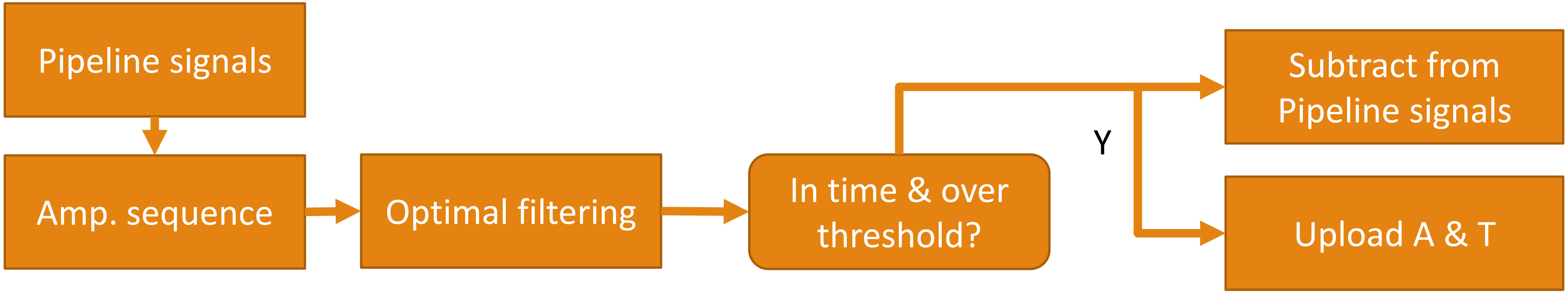
Studies on Pile-up Recovery Methods

An Online Pile-up Recovery Scheme

- Optimal filtering: Least-χ^2 fit w/o iteration

$$\begin{pmatrix} \vec{f}(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{f}(0) & \vec{f}(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{f}'(0) \\ \vec{f}'(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{f}(0) & \vec{f}'(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{f}'(0) \end{pmatrix} \begin{pmatrix} A \\ A\tau \end{pmatrix} = \begin{pmatrix} \vec{f}(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{y} \\ \vec{f}'(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{y} \end{pmatrix}$$

- Online application: point-by-point optimal filtering, pipeline processing



Summary

- EMC technique scheme
  - undoped CsI + APD + CSA-based Electronics
- Dedicated technology R&D
  - R&D on LY enhanced detection unit
  - EMC timing performance study
  - Pile-up recovery Methods
- Achieved performance indicators
  - 1.3 times improved LY – $30\ \%$ energy resolution improvement of $100\ \mathrm{MeV}$ photon
  - Time resolution: $1.9\ \mathrm{ns@33\ MeV} \rightarrow 0.7\ \mathrm{ns@100\ MeV}$ – critical for event timing & neutral PID
  - Pile-up discrimination threshold: $5\ \mathrm{MeV} \rightarrow 2.1\ \mathrm{MeV}$ – σ_E recovered to $< 2.5\%@1\ \mathrm{GeV}$

Fully meet experiment & physics requirements

Publications and Conference

	Authors	Title	Journal	Comments
1	M. Ablikim *et al.* (BESIII Collaboration)	Precision Measurement of the Decay $\Sigma^+ \to p\gamma$ in the Process $J/\psi \to \Sigma^+\bar{\Sigma}^-$	Phys. Rev. Lett. 130, 211901 (2023)	Primary Author
2	Z. K. Jia *et al.*	A light yield enhancement method using wavelength shifter for the STCF EMC	Nucl. Instrum. Methods A 1050, 168173 (2023)	First Author
3	Z. K. Jia *et al.*	Study of the Properties of GSO:Ce for Applications in Dual-Bolometers	IEEE Trans. Nucl. Sci. 70, 1301–1306 (2023)	First Author
4	Y. Song, Z. K. Jia *et al.*	Pure CsI electromagnetic calorimeter design for the Super Tau-Charm Facility	Nucl. Instrum. Methods A 1057, 168749 (2023)	Second Author
5	L. F. Luo, Z. K. Jia *et al.*	Study on time measurement for CSA-based readout electronics in STCF ECAL	JINST 17, P02034 (2022)	Second Author
6	Z. K. Jia *et al.*	Measurement of the Decay $\Xi^0 \to \Lambda\gamma$ decay with Entangled $\Xi^0\bar{\Xi}^0$ pairs		SP's Approval

	Title	Conference	Type
1	Design and Study of Electromagnetic Calorimeter for Super Tau-Charm Facility	TIPP 2021	Poster
2	Measurement of GSO:Ce Crystal's Scintillation Properties in Wide Temperature Range	16th SCINT, 2022	Poster
3	Design and Prototype Test of the Homogeneous Crystal EMC for STCF	全国粒子物理大会，2022	Oral
4	The Progress of Super Tau Charm Facility in China	31st Lepton Photon, 2023	Poster
5	R&D Progress of the STCF Electromagnetic Calorimeter	FTCF 2024	Oral

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  - My supervisor: 彭海平 教授
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- Special thanks to
  - 张云龙 教授，周小蓉 教授

谢谢！

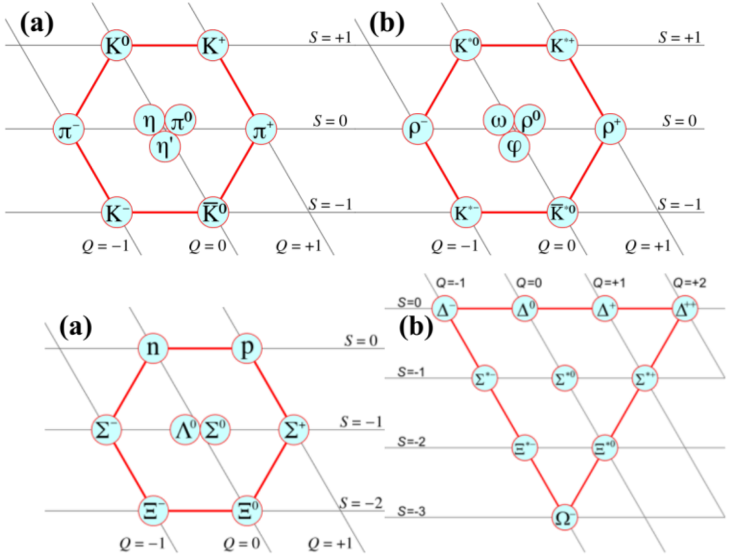
BACKUP

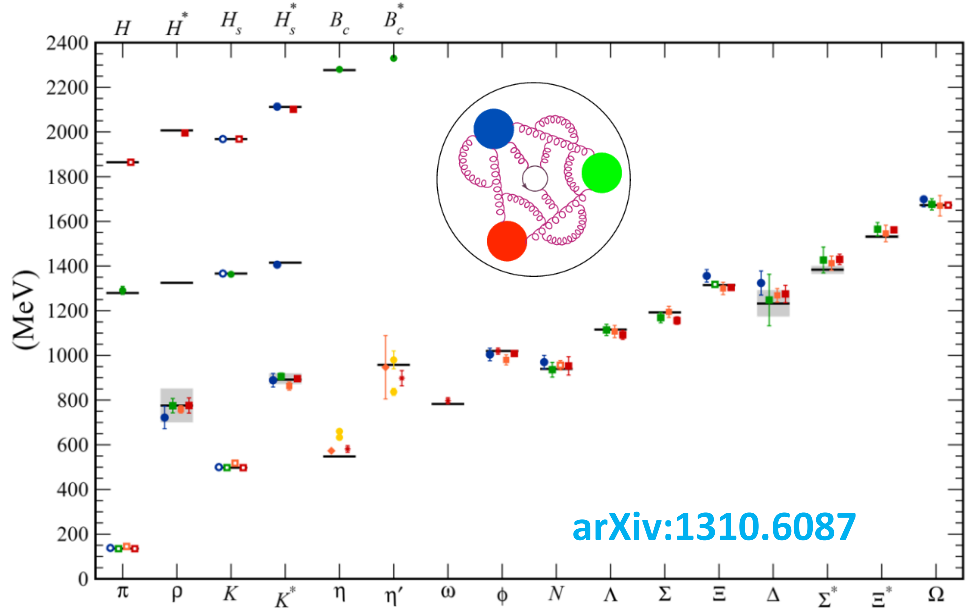
Introduction

Challenges facing the Standard Model

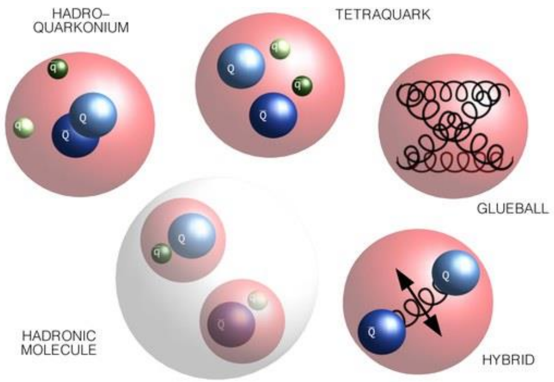
- The origin of hadron mass?
- Hadron classification beyond quark model
- Inner structure of hadrons?
- Hadron decay mechanism?
- ......

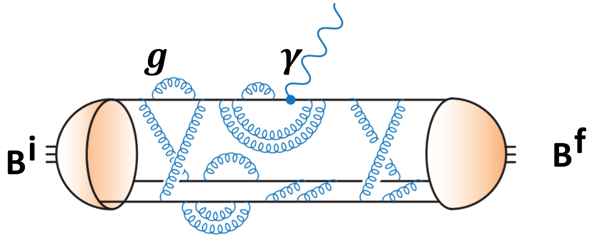
NPQCD effects





arXiv:1310.6087



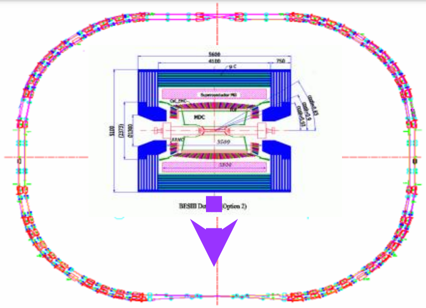


Prog.Part.Nucl.Phys. 91 (2016), 1

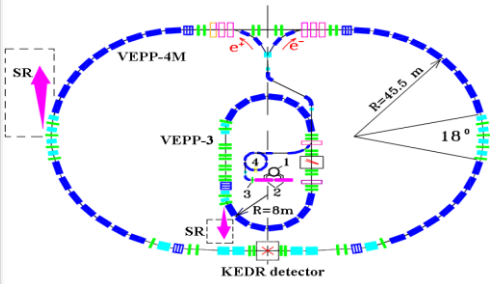
Introduction

Accelerator-based HEP Experiments

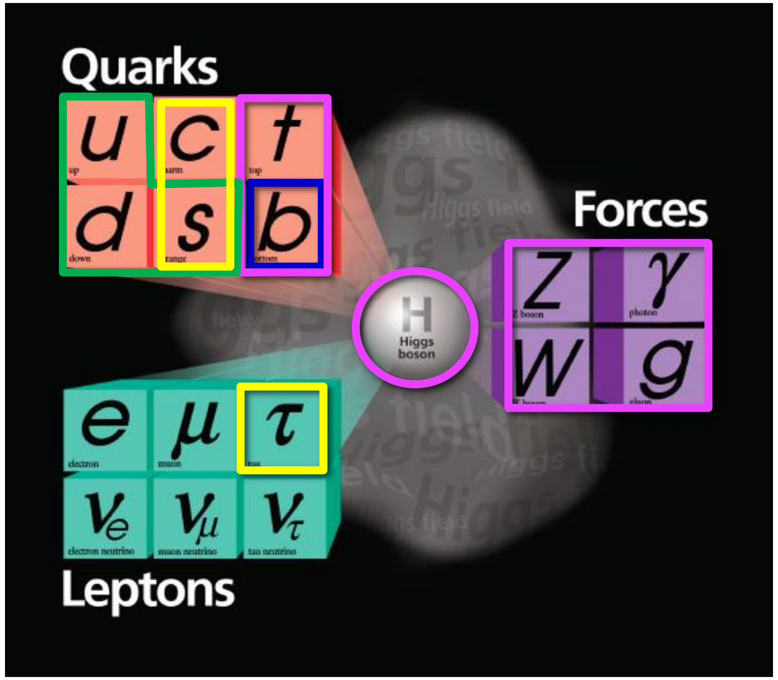
- Varied CME for studies on different fundamental particles
- BEPCII/BESIII: The only experiment operated at τ-charm energy region

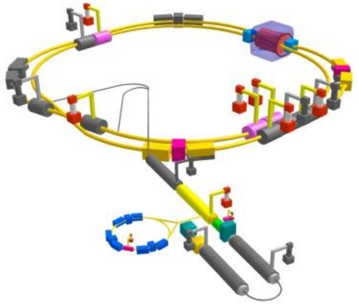


BEPCII BESIII

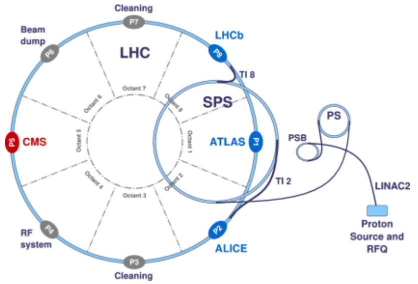


VEPP-4M CMD/SND/KEDR





SuperKEKB BelleII

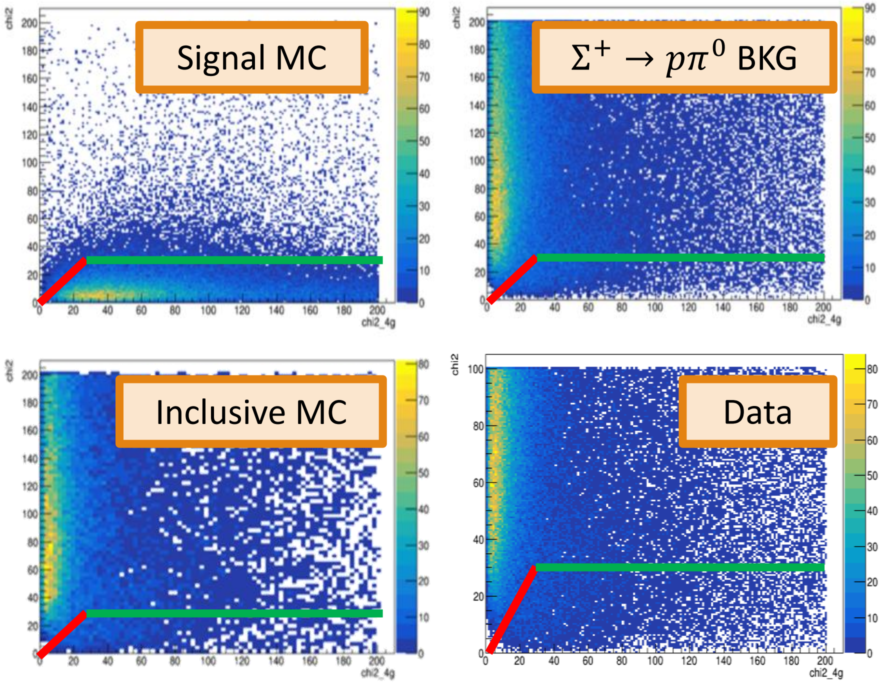


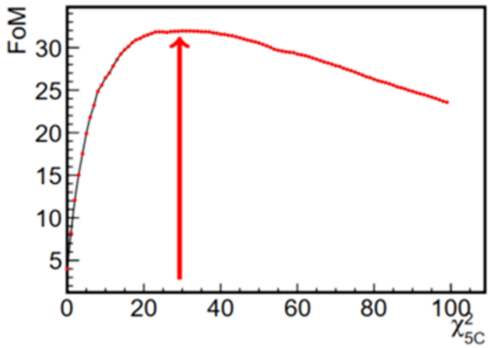
LHC ATLAS/CMS/ALICE/LHCb

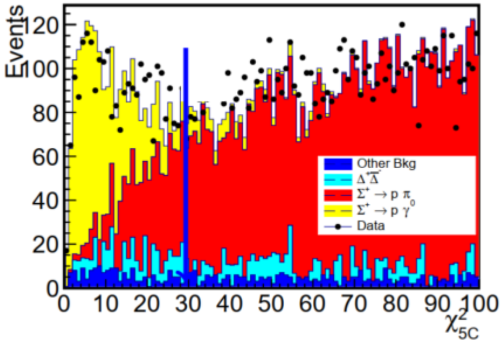
CPV in weak radiative decays

Reference	Channel	A_{CP}
Phys.Rev.D 49 (1994), 3771	$K^+ \to \pi^+\pi^0\gamma$	$2 \times 10^{-6} - 1 \times 10^{-5}$
Phys.Lett.B 315 (1993), 170	$K_L \to \pi^+\pi^-\gamma$	$10^{-4} - 10^{-3}$
JHEP 08 (2017), 091	$D \to \rho\gamma$	$\leq 2 \times 10^{-3}$
Nucl.Phys.B 367 (1991), 575 Phys.Rev.Lett. 79 (1997), 185	$b \to s\gamma$ $b \to d\gamma$	$(0.1 - 1)\%$ $(1 - 10)\%$
Eur.Phys.J.C 41 (2005), 173	$B \to \rho\gamma$	$\sim 10\ \%$

PhysRevLett.70.2529, PhysRevLett.109.191801, PhysRevLett.118.051801, PhysRevLett.119.191802


Signal MC
$\Sigma^+ \to p\pi^0$ BKG
Inclusive MC
Data
chi2
chi2_4g


FoM
χ^2_{5C}

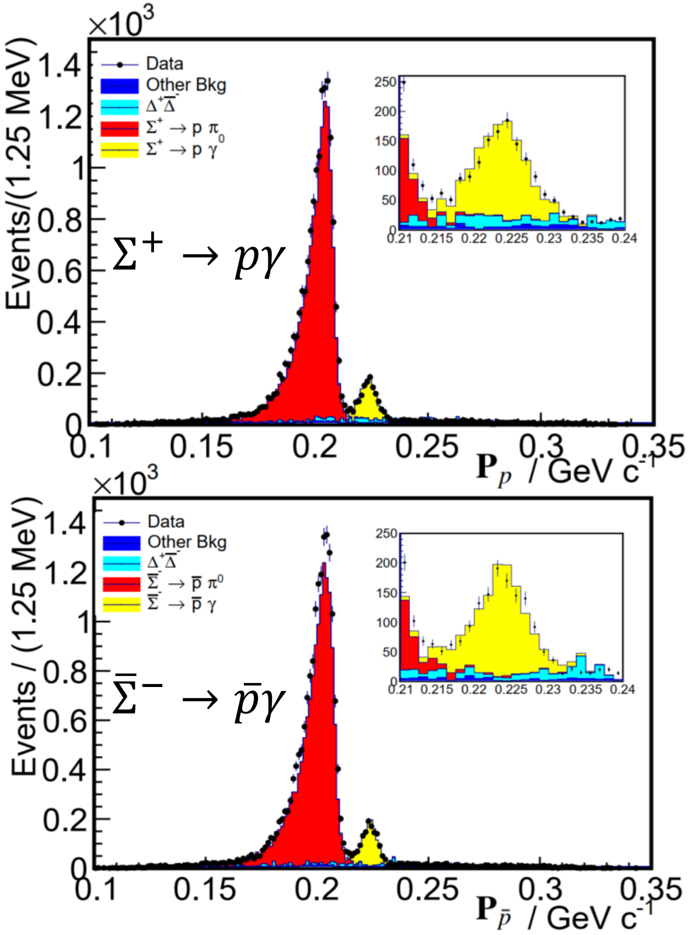

Events
Other Bkg
$\Delta\bar{\Delta}$
$\Sigma^+ \to p\ \pi_0$
$\Sigma^+ \to p\ \gamma$
Data
χ^2_{5C}

Double Tag Analysis

Cut Flow of DT

- Main difference comes from single tag
- Relative efficiency of DT selection consists

	$\Sigma^+ \to p\gamma$		$\bar{\Sigma}^- \to \bar{p}\gamma$	
cut	Absolute Efficiency (%)	Relative Efficiency (%)	Absolute Efficiency (%)	Relative Efficiency (%)
Single tag	39.02		44.31	
DT event selection	32.04	82.11	35.17	77.84
$\chi^2_{5C} < \chi^2_{4\gamma}$	31.46	98.19	34.50	98.14
χ^2 <30	27.09	86.11	29.88	87.71
Decay length cut	21.18	78.18	23.22	77.72
Truth match	21.16	99.90	23.20	99.91



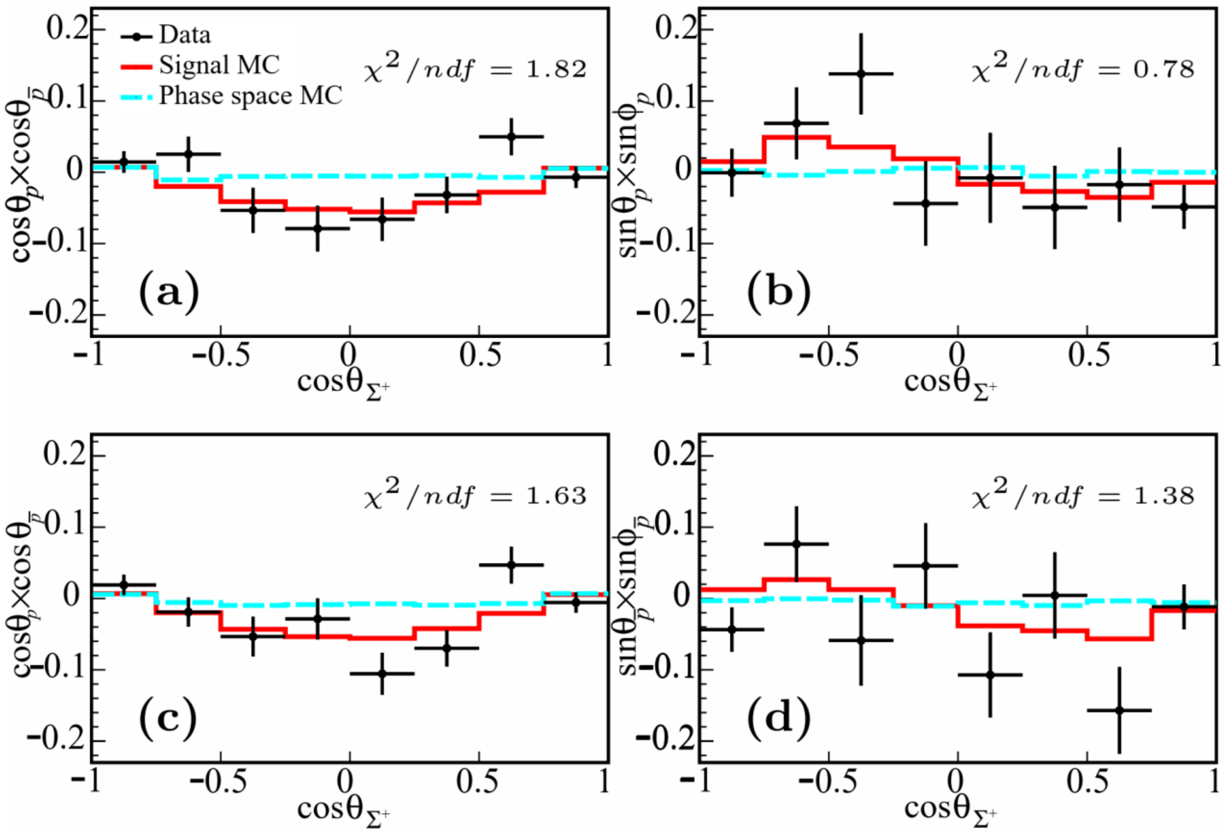
Measurement of the Decay $\Sigma^+ \to p\gamma$

Decay Asymmetry Parameter Measurement

Processes	$\Sigma^+ \to p\gamma$	$\bar{\Sigma}^- \to \bar{p}\gamma$
Individual fit	-0.587 ± 0.082	0.710 ± 0.076
Simultaneous fit	-0.651 ± 0.056	

$$M_1(\cos\theta_{\Sigma^+}) = \frac{m}{N}\sum_{i=1}^{N_k} \cos\theta_{\bar{p}}^i \cos\theta_p^i$$

$$M_2(\cos\theta_{\Sigma^+}) = \frac{m}{N}\sum_{i=1}^{N_k} \sin\theta_p^i \sin\phi_p^i$$



Measurement of the Decay $\Xi^0 \to \Lambda\gamma$

ST Fit

IO Check result of ST yield

	$\bar{\Xi}^0 \to \bar{\Lambda}\pi^0$	$\Xi^0 \to \Lambda\pi^0$
Input yield	1 348 646	1 528 602
Output yield	1347 906 $\pm$1754	1 528 861$\pm$1765
Divergence ($\times\ \sigma$)	-0.42	0.71
Divergence (%)	0.05	0.08

Fit result of data and resultant $\mathcal{B}_{J/\psi\to\Xi^0\bar{\Xi}^0}$

	$\bar{\Xi}^0 \to \bar{\Lambda}\pi^0$	$\Xi^0 \to \Lambda\pi^0$
Yield	1 400 541$\pm$1 989	1 611 216$\pm$2111
$\varepsilon_{\mathrm{ST}}$	17.61$\pm$0.01	19.77$\pm$0.01
$\mathcal{B}_{J/\psi\to\Xi^0\bar{\Xi}^0}$ ($\times 10^{-3}$)	1.240$\pm$0.002	1.271$\pm$0.002
Correction Factor	0.982	1.006
$\mathcal{B}_{J/\psi\to\Xi^0\bar{\Xi}^0,\mathrm{corr}}$ ($\times 10^{-3}$)	1.263$\pm$0.002	1.264$\pm$0.002

Double Tag Analysis

DT Yield Extraction

	$\Xi^0 \to \Lambda\gamma$		$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$	
Selection Criteria	Absolute Eff	Relative Eff	Absolute Eff	Relative Eff
ST selection (no truth match)	20.44%	20.44%	22.12%	22.12%
$N_p > 1$	19.24%	94.13%	20.40%	92.22%
$N_{\pi^-} > 1$	13.61%	70.74%	14.52%	71.18%
$N_\Lambda \geq 1$	10.47%	76.93%	11.13%	76.65%
$N_{\mathrm{n.t.}} \geq 1$	10.06%	96.08%	10.68%	95.96%
5C Kinematic fit	6.94%	68.99%	7.48%	70.04%
Veto $L/\sigma_L < 2.0$	5.75%	82.85%	6.18%	82.62%
$\lvert m_{\gamma\bar{\Lambda}} - m_{\bar{\Sigma}^0} \rvert > 12\ \mathrm{MeV}/c^2$	5.51%	95.83%	5.90%	95.47
$\chi^2_{5C} < 40$	4.44%	80.58%	4.77%	80.85%
Truth match	4.42%	99.54%	4.76%	99.79%

Processes	$\Xi^0 \to \Lambda\gamma$	$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$
Signal	283 ± 19	301 ± 17
$\Xi^0 \to \Lambda\pi^0$	50 ± 7	64 ± 8
Other BKG	38 ± 6	26 ± 5
Signal Purity (%)	76.3	77.0

Measurement of the Decay $\Xi^0 \to \Lambda\gamma$

Decay Asymmetry Parameter Measurement

Fit result of data

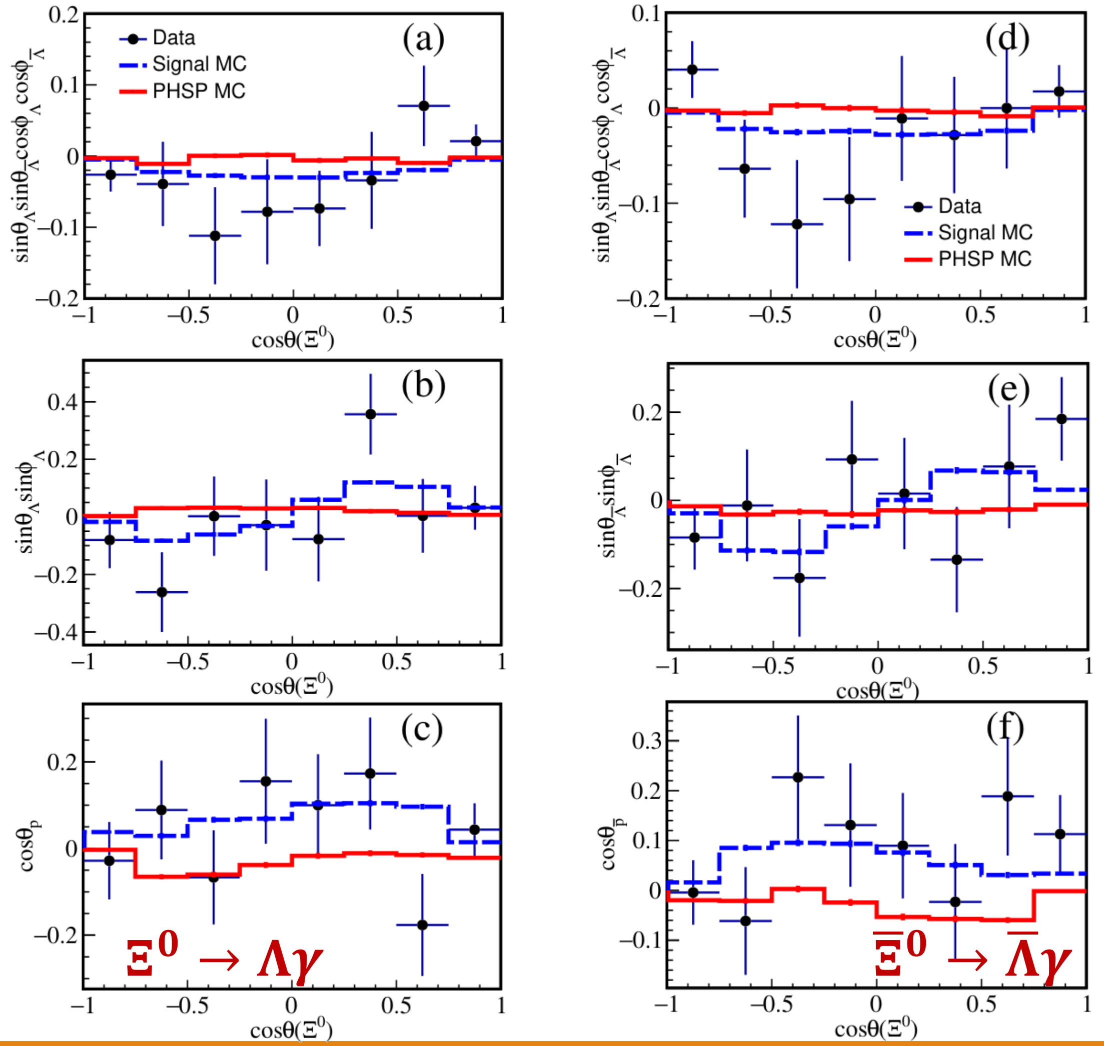
Processes	$\Xi^0 \to \Lambda\gamma$	$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$
Individual fit	-0.652 ± 0.092	0.830 ± 0.080
Simultaneous fit	-0.741 ± 0.062	

Decay Asymmetry visualization

- $C_{11,\Lambda}(\theta_{\Xi^0}) = \frac{m}{N}\sum_{i=1}^{N} x_{1,i}^{\bar{\Lambda}} x_{1,i}^{\Lambda}$
- $C_{02,\Lambda}(\theta_{\Xi^0}) = \frac{m}{N}\sum_{i=1}^{N} x_{0,i}^{\bar{\Lambda}} x_{2,i}^{\Lambda}$
- $C_{33,p}(\theta_{\Xi^0}) = \frac{m}{N}\sum_{i=1}^{N} x_{3,i}^{\bar{p}} x_{3,i}^{p}$

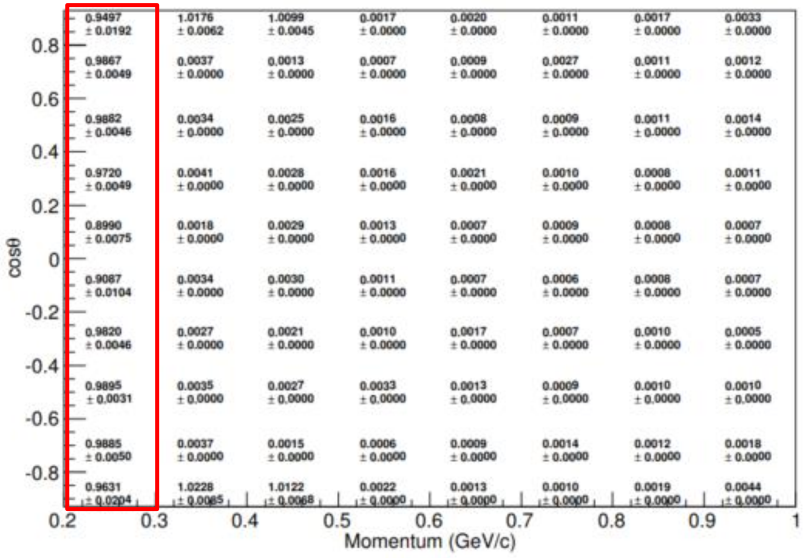
$x_0 = 1$
$x_1 = \sin\theta\cos\phi$
$x_2 = \sin\theta\sin\phi$
$x_3 = \cos\theta$

$\chi^2_{\text{PHSP}} = 1.31$ $\chi^2_{\text{Signal}} = 0.92$

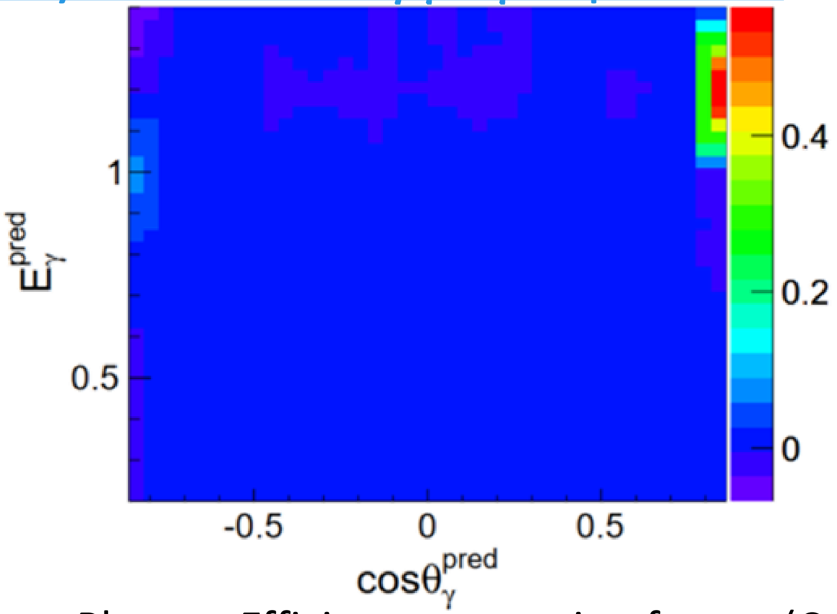


Tracking efficiency correction and uncertainty

- Based on previous work by BESIII software performance group
- Study of tracking and PID efficiency and uncertainty from $J/\psi \rightarrow p\bar{p}\pi^{+}\pi^{-}$
- Study of photon detection efficiency in $e^{+}e^{-} \rightarrow \gamma\mu^{+}\mu^{-}$ process



Proton PID correction factor (C) and uncertainty (σ)



Photon Efficiency correction factor (C-1)

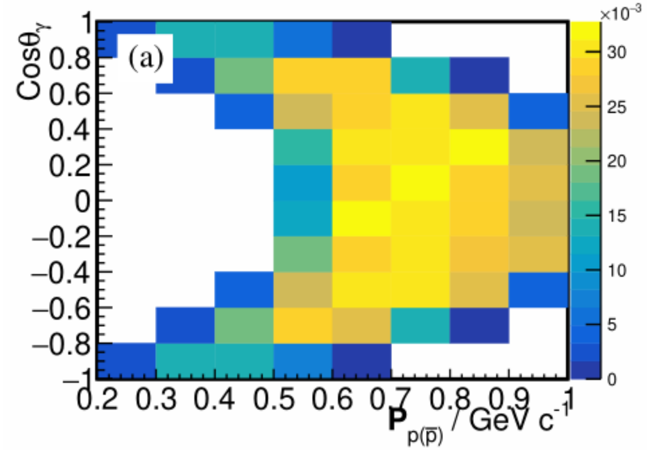
Tracking efficiency correction and uncertainty

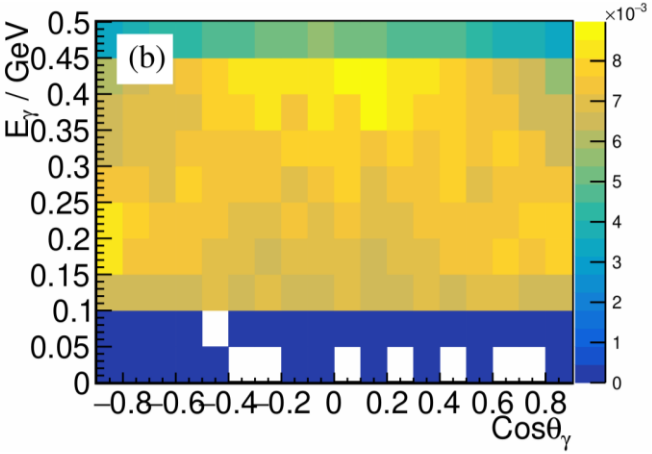
- The Momentum-angular 2D distribution of $p(\bar{p})$ and photon is obtained from signal MC
- The value of each bin called $w_{i,j}$. The average correction factor and unc

$$C = \sum_{i,j} C_{i,j} w_{i,j} \qquad \sigma^2 = \sum_{i,j} \sigma_{i,j}^2 w_{i,j}$$

- BF result is updated with average correction factor.

	Proton		Anti-proton		Photon
	Tracking	PID	Tracking	PID	Efficiency
$C-1$	7.34×10^{-5}	1.41×10^{-3}	-1.05×10^{-4}	0.21×10^{-3}	-3.16×10^{-3}
σ (%)	0.11	0.32	0.10	0.41	0.26





Systematic Uncertainty

Control sample selection: $J/\Psi \to \Sigma^+\bar{\Sigma}^-, \Sigma^+ \to p\pi^0, \bar{\Sigma}^- \to \bar{p}\pi^0$

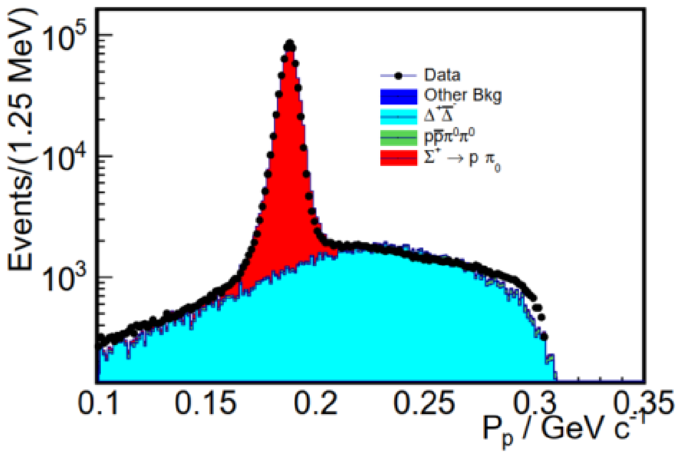
- The same ST analysis as signal
- For DT:
  - 1 proton
  - 1 anti-proton
  - At least 4 γ
  - 6C kinematic fit, $\chi^2_{6C} < 100$

Yield extraction:

- **Signal shape**: truth matched signal MC events
- **$J/\Psi \to \Delta^+\bar{\Delta}^-$ BKG shape**: PHSP MC

} MC Shape$\otimes$*Gaussian*

- **Residual BKG**: 2rd order Chebychev polynomial
- **Fit method**: binned extended likelihood fit
- **Fit range** :$0.10 < \mathbf{P}_p < 0.30\ GeV/c$



Angular distribution fit

- Exactly the same as signal

	$\Sigma^+ \to \pi^0 p$	$\bar{\Sigma}^- \to \pi^0 \bar{p}$
This work	-0.983 ± 0.003	1.000 ± 0.005
Previous work	$-0.998 \pm 0.037 \pm 0.009$	$0.990 \pm 0.037 \pm 0.011$

Systematic uncertainties

- $J/\psi \to \Sigma^+\bar{\Sigma}^-, \Sigma^+ \to p\pi^0, \bar{\Sigma}^- \to \bar{p}\pi^0$ control sample related uncertainty terms:
  - $\boldsymbol{\chi^2_{5C} < \chi^2_{4g}}$: A very similar cut ($\chi^2_{4\gamma} < \chi^2_{5\gamma}$)is performed on control sample. Take cut efficiency difference between data and MC as uncertainty

	DIY MC	Data
Cut Efficiency (%)	98.85	98.65
Divergence (%)	0.2	

  - **Decay length cut**: The same cut is applied to control sample. Also take cut efficiency difference as uncertainty

	DIY MC	Data
Cut Efficiency (%)	76.22	75.73
Divergence (%)	0.6	

  - $\boldsymbol{\chi^2_{5C}}$ cut:

	Yield w/o χ^2_{5C} cut	Yield with χ^2_{5C} cut	Relative Efficiency (%)
MC	536 405	455 393	84.90
Data	439 189	369 730	84.17

Systematic uncertainties

- Tracking and PID: 0.4% per track
- Photon selection: 0.3% per photon
- ST Yield: Change BKG shape from $J/\psi \to \Delta^{+}\bar{\Delta}^{-}$ BKG shape + 3rd order Chebychev polynomial to only the polynomial.
- **Fit range**: Change the fit range from
- $0.15 < \mathbf{P}_p < 0.30\ GeV/c$ to $0.13 < \mathbf{P}_p < 0.32\ GeV/c$ and $0.17 < \mathbf{P}_p < 0.28\ GeV/c$.

Range	BF(10^{-3})	Divergence (%)
$0.15 < \mathbf{P}_p < 0.30\,\mathrm{GeV}/c$	0.997	—
$0.13 < \mathbf{P}_p < 0.32\,\mathrm{GeV}/c$	1.005	0.82
$0.17 < \mathbf{P}_p < 0.28\,\mathrm{GeV}/c$	0.996	−0.07

- Fit model:
  - **Signal and $\Sigma^{+} \to p\pi^{0}$ BKG shape**: vary the parameters of convolved Gaussian by $\pm1\ \sigma$.
  - **Polynomial BKG:** change the function from 2nd order to 3rd order.

Systematic uncertainties

- Decay parameters:
  - $\boldsymbol{\alpha_{\Sigma^+\to p\pi^0}}$, $\boldsymbol{\alpha_\psi}$ **and** $\boldsymbol{\Delta\Phi}$: generate new DIY sample with these values varied by $\pm 1\ \sigma$. Compare the relative efficiency $\varepsilon_{DT}/\varepsilon_{ST}$.

	Relative Eff (%)	
	-1σ	+1σ
$\alpha_{\Sigma^+\to p\pi^0}$	52.77	52.59
$\Delta\Phi$	52.63	52.49
α_ψ	52.56	52.62
Nominal set	52.62	

  - $\boldsymbol{\alpha_{\Sigma^+\to p\gamma}}$: generate new DIY sample using $\alpha_{\Sigma^+\to p\gamma}$ measured in this work and check the efficiency difference.

	Nominal	**New**
Efficiency (%)	21.16	21.16

Systematic Uncertainty

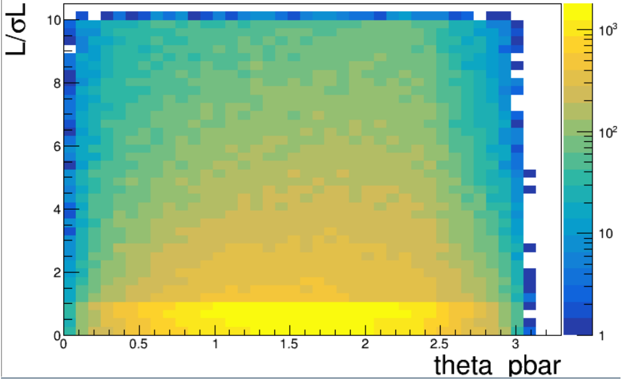
Angular distribution fit

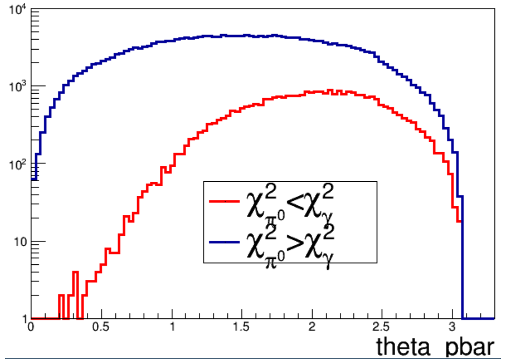
- How to decide whether a cut is angular dependent:

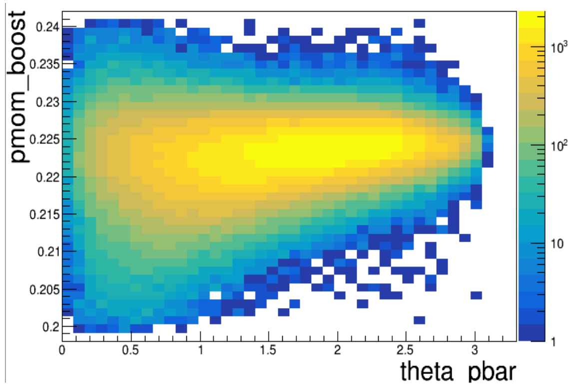
So the first step is to clarify whether a cut is ξ dependent or ξ independent. For PHSP signal MC, the differential cross-section is a constant. So moments defined in Eq. 17 and Eq. 18 are also constants when not considering the efficiency. If a cut changes the distribution of these two moments, it's considered as a ξ dependent cut. Specifically speaking, a χ^2 induced by one cut is defined based on the definition of the moments $M_{1,2}$:

$$\chi^2_{ang} = \frac{1}{2m}\sum_{i=1}^{m} \frac{(M_1'(\theta_i) - M_1(\theta_i))^2}{\sigma_1^2(\theta_i)} + \frac{(M_2'(\theta_i) - M_2(\theta_i))^2}{\sigma_2^2(\theta_i)} \qquad (19)$$

cut	χ^2_{ang}
Track selection	—
ST selection	0.28
$\chi^2_{5C} < \chi^2_{4\gamma}$	0.16
$\chi^2 < 30$	0.21
Decay length cut	5.12
$\chi^2_{3C,\gamma} < \chi^2_{3C,\pi^0}$	15.95
$0.215 < P_p < 0.235\,\mathrm{GeV}/c$	5.40







Systematic Uncertainty

Angular distribution fit

Likelihood value of BKG:

- **Number of BKG**: vary the number of event by $\pm 1\ \sigma$

	α	
	-1σ	+1σ
$N_{\Sigma^+\to p\pi^0}$	0.651	0.651
$N_{Other\ BKG}$	0.652	0.649
Nominal set	0.651	

- **Other BKG's likelihood value**: change sampling region from

$0.11 < \mathbf{P}_p < 0.16\ GeV/c,\ 0.24 < \mathbf{P}_p < 0.29\ GeV/c$

to

$0.10 < \mathbf{P}_p < 0.15\ GeV/c,\ 0.24 < \mathbf{P}_p < 0.29\ GeV/c$

or

$0.11 < \mathbf{P}_p < 0.16\ GeV/c,\ 0.25 < \mathbf{P}_p < 0.30\ GeV/c$

	α
Region nominal	0.651
Region 1	0.651
Region 2	0.647

$\alpha_{\Sigma^+\to p\pi^0}$, α_ψ and $\Delta\Phi$ uncertainty:
vary these values by $\pm 1\ \sigma$

	α	
	-1σ	+1σ
α_ψ	0.647	0.654
$\Delta\Phi$	0.651	0.651
$\alpha_{\Sigma^+\to p\pi^0}$	0.640	0.662
Nominal set	0.651	

Event selection efficiency:

- **Tracking efficiency**: Use corrected efficiency to sample the PHSP MC

$$r_\varepsilon = \frac{\varepsilon_p^{data} \times \varepsilon_{\bar{p}}^{data} \times \prod_{i=1}^{3} \varepsilon_{\gamma,i}^{data}}{\varepsilon_p^{MC} \times \varepsilon_{\bar{p}}^{MC} \times \prod_{i=1}^{3} \varepsilon_{\gamma,i}^{MC}}$$

The new set of PHSP MC is used to calculate the normalization factor and update the fit result

Event selection efficiency:

- **Decay length cut**: Perform the same angular distribution fit on control sample and check the result with or w/o decay length cut

	α	
	$\Sigma^+ \to p\pi^0$	$\bar{\Sigma}^- \to \bar{p}\pi^0$
w/o decay length cut	-0.988±0.003	1.000-0.003
with decay length cut	-0.983±0.003	1.000±0.005

- **$\chi^2_\gamma < \chi^2_{\pi^0}$ cut:** A customized cut on $\Sigma^+ \to p\pi^0$ control sample: $\chi^2_\gamma > \chi^2_{\pi^0}$* to check the difference on fit result
- **Signal region cut**: change signal region from $0.215 < \mathbf{P}_p < 0.235\ GeV/c$ to $0.214 < \mathbf{P}_p < 0.234\ GeV/c$ or $0.216 < \mathbf{P}_p < 0.236\ GeV/c$

	α
Region nominal	0.651
Region 1	0.665
Region 2	0.643

*The relative efficiency of this cut is 89.25% for signal MC and 87.25% for control sample

Systematic Uncertainties

Efficiency Correction

Particles need correction

- $\pi^{\pm}$, $\Lambda(\bar{\Lambda})$, π^0

(BAM-537, BAM-676, BAM-559)

Efficiency Correction with control sample

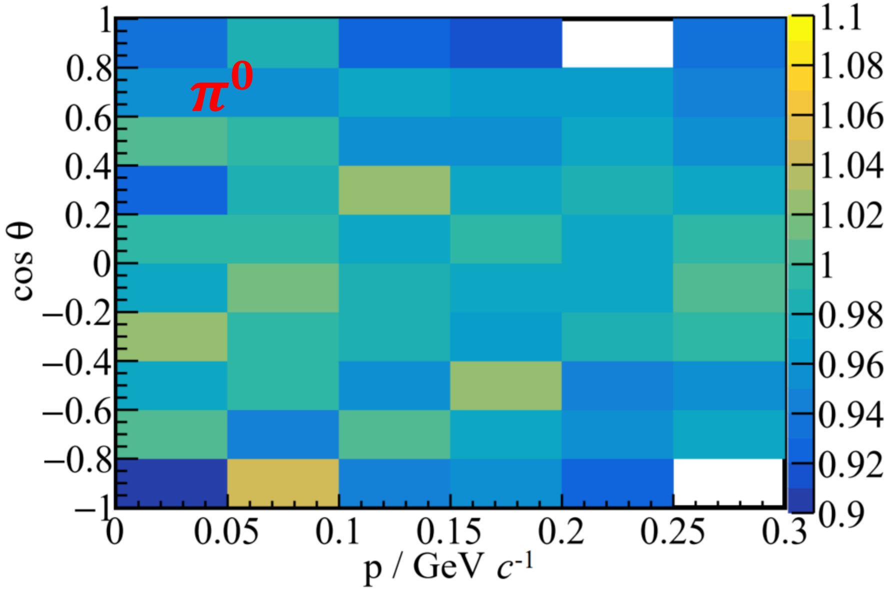
$$\varepsilon_{\mathrm{MC(data)}} = \frac{N_{\mathrm{detect}}}{N_{\mathrm{detect}} + N_{\mathrm{miss}}}$$

- Correction factor: $C = \frac{\varepsilon_{\mathrm{data}}}{\varepsilon_{\mathrm{MC}}}$
- *Syst.* Uncertainty after correction:

$$\sigma = \frac{\varepsilon_{\mathrm{data}}}{\varepsilon_{\mathrm{MC}}} \sqrt{\left(\frac{\sigma^2_{\varepsilon,\mathrm{MC}}}{\varepsilon^2_{\mathrm{MC}}} + \frac{\sigma^2_{\varepsilon,\mathrm{data}}}{\varepsilon^2_{\mathrm{data}}}\right)}$$

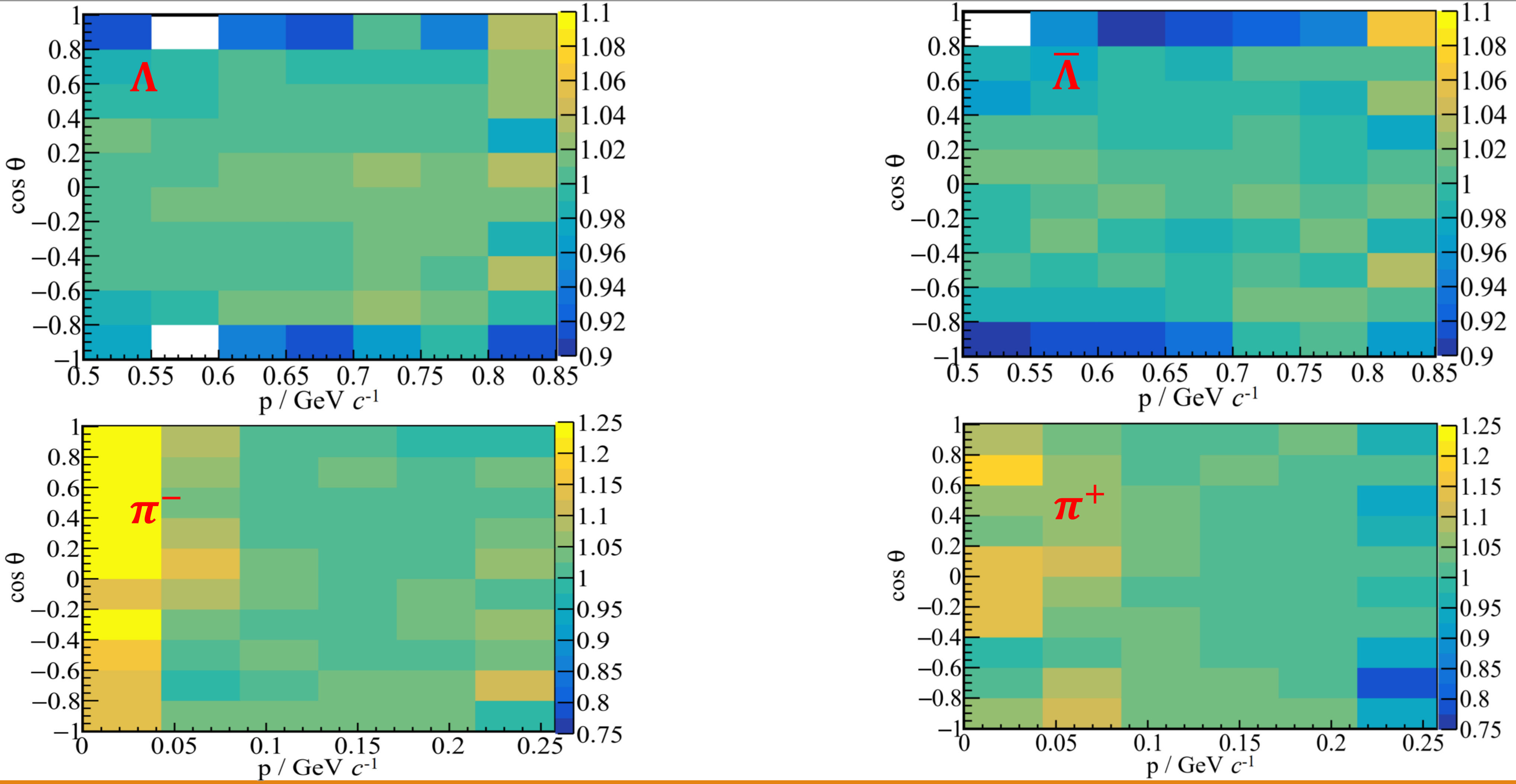
Selected Control samples*:

- $\pi^{\pm}$: $J/\psi \to \Xi^-(\to \Lambda\pi^-)\bar{\Xi}^+(\to \bar{\Lambda}\pi^+), \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$
- $\Lambda(\bar{\Lambda})$: $J/\psi \to \Xi^-(\to \Lambda\pi^-)\bar{\Xi}^+(\to \bar{\Lambda}\pi^+)$
- π^0: $J/\psi \to \Xi^0(\to \Lambda\pi^0)\bar{\Xi}^0(\to \bar{\Lambda}\pi^0)$



Systematic Uncertainties

Efficiency Correction



*: event selection procedure detailed in backup & memo

Systematic Uncertainties

Efficiency Correction

ST Correction Factor

	$\bar{\Xi}^0 \to \bar{\Lambda}\pi^0$	$\Xi^0 \to \Lambda\pi^0$
π^0	0.976	0.973
$\pi^\pm$	1.020	1.037
$\Lambda(\bar{\Lambda})$	0.989	0.993
Total	**0.982**	**1.006**

DT Correction Factor

	$\Xi^0 \to \Lambda\gamma$	$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$
$\pi^\pm$	1.045	1.028
$\Lambda(\bar{\Lambda})$	0.987	0.986
Total	**1.032**	**1.014**

Weighted by signal distribution

Particle detection uncertainty

- $p(\bar{p})$: Tong Chen's report
- **Photon**: BAM-511
- **Other objects**: This work

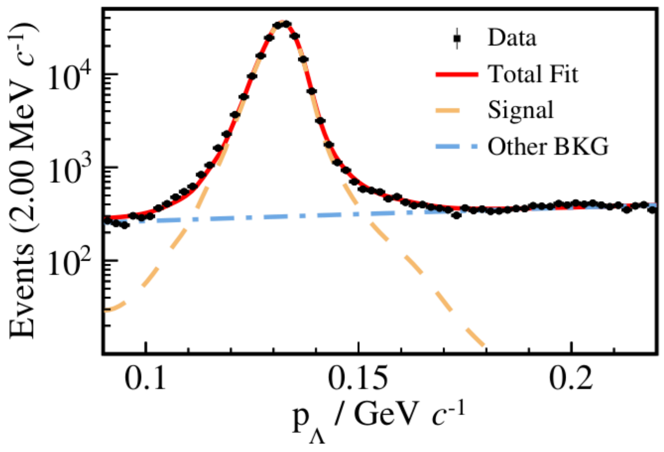
Weighted by signal distribution

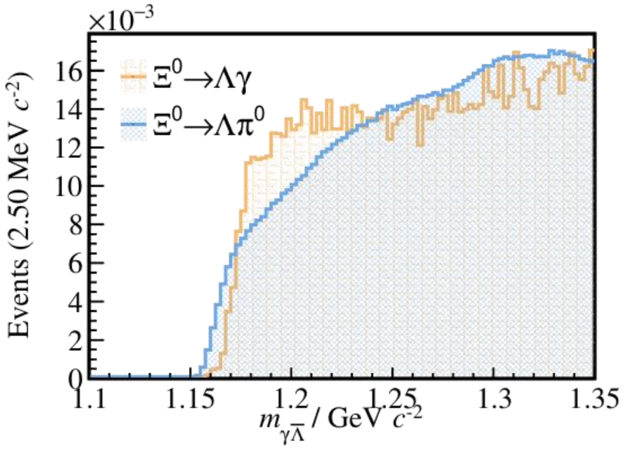
Source	$\Xi^0 \to \Lambda\gamma$ (%)	$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$ (%)
Proton tracking & PID	0.47	0.52
Pion detection	**2.3**	**1.4**
$\Lambda(\bar{\Lambda})$ detection	0.90	1.11
Photon detection	0.40	0.40

Systematic Uncertainties

BF Uncertainties

- **The control sample of $\Xi^0 \to \Lambda\pi^0$ decay**
  - **one more** photon at DT side
  - Event selection consistent with signal*
  - Extract yield from p_Λ
  - Efficiency difference between MC and data as syst. Uncertainty





- Decay length requirement, $\chi^2_{5C} < 40$:
  - Good signal-control sample consistency (BAM-559)
- $m_{\gamma\bar{\Lambda}}$ requirement
  - Modified to $\boldsymbol{m_{\gamma_h\bar{\Lambda}}}$ requirement

    --Photon decayed from **DT** π^0 with higher energy
  - Close efficiency between signal (**95.83%**) and control sample (**94.74%**)

	Decay length requirement	$m_{\gamma\bar{\Lambda}}$ requirement	$\chi^2_{5C} < 40$
MC (%)	77.49	94.74	80.61
Data (%)	78.53	94.59	81.03

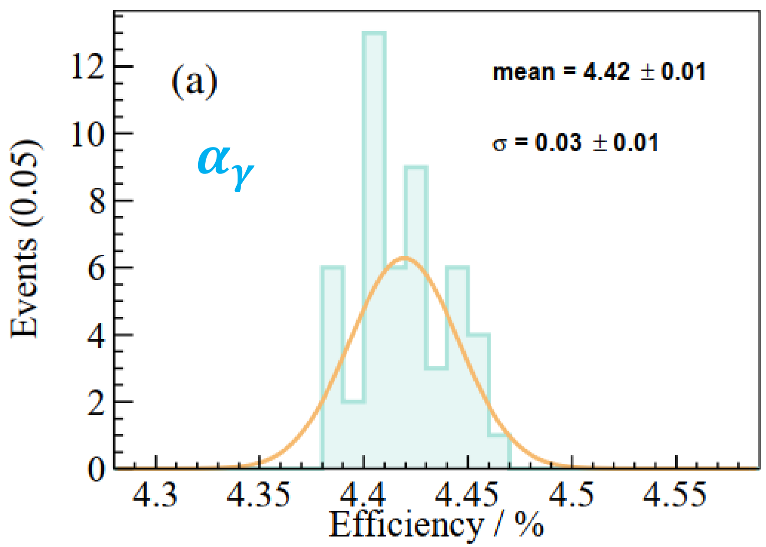
*: event selection procedure detailed in backup & memo

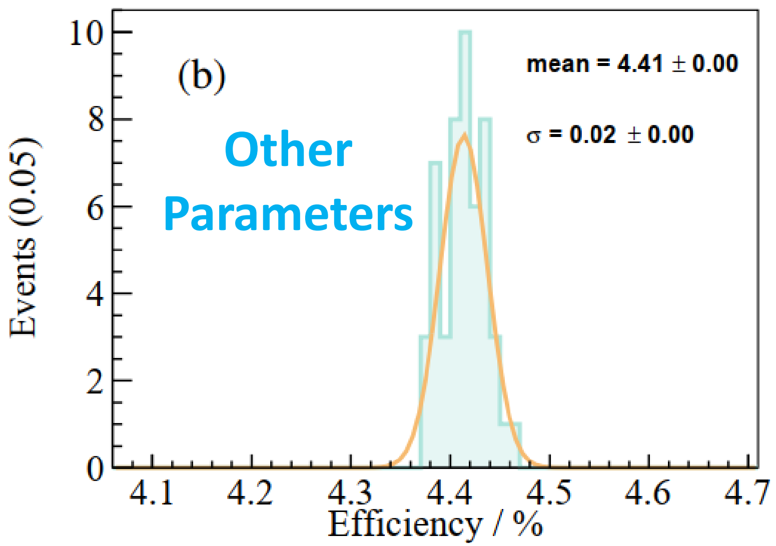
Systematic Uncertainties

BF Uncertainties

Decay parameters for MC Model

- BAM-537 & this work
- **100** sets of MC samples
- Randomly sampled decay parameters according to the uncertainty (**with correlation**)
- σ of pull distribution as uncertainty – **0.65%** in total





*: event selection procedure detailed in backup & memo

Systematic Uncertainties

BF Uncertainties

ST Fit uncertainties

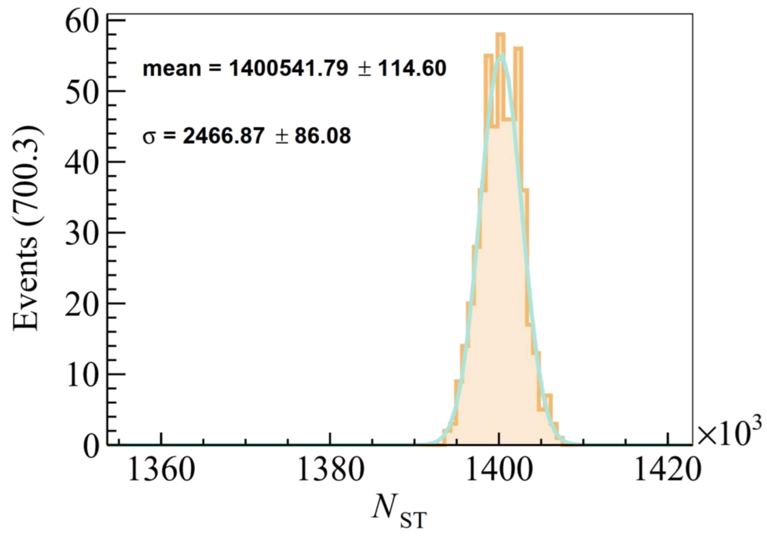
- Bin width (number):

Bin number	Yield
60	1 396 983
80	1 394 820
100	**1 400 541**
120	1 401 884
140	1 399 875

- Fit range:
  - Shift the fit range by $\pm 20\mathrm{MeV}/c^2$

Fit range (GeV/c^2)	[1.18,1.43]	[1.20,1.45]	[1.22,1.47]
Yield	1 406 703	1 400 541	1 407 123
Difference (%)	0.44	---	0.47

- Signal shape:
  - Sampling Gaussian parameters according to fit result (**with correlation**)
  - Repeat fitting by **500** times
  - σ of pull distribution as uncertainty



Systematic Uncertainties

BF Uncertainties

- Self BKG shape:
  - Convolve the same Gaussian as signal

	Yield
Before convolution	1 400 541
After convolution	1 403 034

- Continuum BKG shape:
  - Vary the order of polynomial

Polynomial order	Yield
2nd	**1 421 223**
3rd	**1 400 541**
4th	1 403 150

- Bump-like BKG
  - Removed from the fit one by one

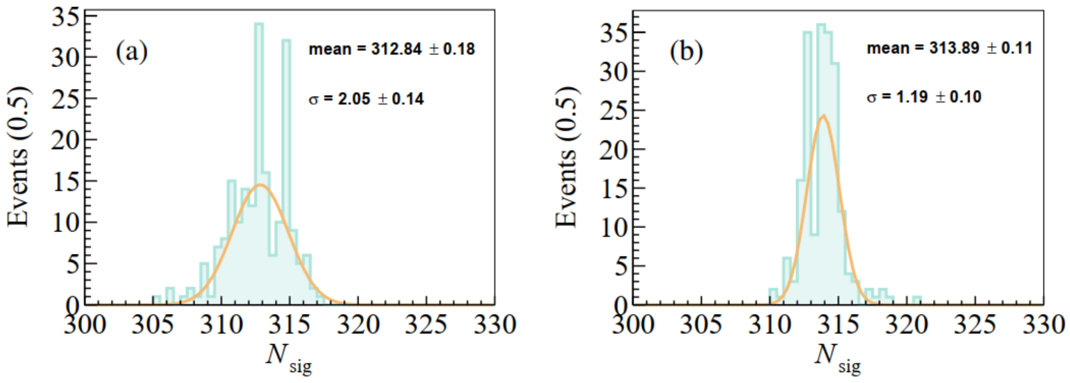
Removed term	Yield
---	**1 400 541**
$\bar{\Lambda}\Sigma^0\pi^0$ **BKG**	1 400 448
$\Sigma^{*0}\bar{\Sigma}^{*0}$ BKG	**1 406 727**

Systematic Uncertainties

BF Uncertainties

DT Fit uncertainties

- MC shapes of $\Xi^0 \to \Lambda\gamma$ and $\Xi^0 \to \Lambda\pi^0$
  - Sampling Gaussian parameters
  - Repeat fitting by 200 times
  - σ of pull distribution as uncertainty
- MC shapes of $\Xi^0 \to \Lambda\pi^0$
  - Consistent with $\Xi^0 \to \Lambda\gamma$



- Continuum BKG shape
  - Vary the order of polynomial

Polynomial order	Yield
1st	313
2nd	312

- Fit range
  - Shift the fit range

Fit range	Yield
(0.09,0.22)	313
(0.07,0.20)	315
(0.11,0.24)	318

Systematic Uncertainties

α_γ Uncertainties

Efficiency related uncertainties

- Particle detection efficiency
  - Utilizing **efficiency correction** results
  - **Reweight** MC sample
  - Update **Normalization factor**
  - **Negligible** influence (consistent with BAM-537)
- Decay length requirement, $\chi^2_{5C} < 40$, $\mathrm{m}_{\gamma\bar{\Lambda}}$ requirement:
  - Angular distribution fit on $\Xi^0 \to \Lambda\pi^0$ control sample
  - Only set $\boldsymbol{\alpha_{\Xi^0}}$ to be free

Original	Decay length requirement	$m_{\gamma\bar{\Lambda}}$ requirement	$\chi^2_{5C} < 40$
-0.380	-0.381	-0.382	-0.381

- Signal mass window:
  - Angular distribution fit on $\Xi^0 \to \Lambda\pi^0$ control sample
  - Loose mass window: $\mathbf{0.110 < p_\Lambda < 0.150}$ GeV/c
  - Tight mass window: $\mathbf{0.120 < p_\Lambda < 0.140}$ GeV/c (**3σ** mass window)
  - Only set $\boldsymbol{\alpha_{\Xi^0}}$ to be free

Mass window	$\boldsymbol{\alpha_{\Xi^0}}$
$\mathbf{0.110 < p_\Lambda < 0.150\ GeV}/c$	-0.380
$\mathbf{0.120 < p_\Lambda < 0.140\ GeV}/c$	-0.378

Systematic Uncertainties

α_γ Uncertainties

Fit related uncertainties

- Background Yield:
  - Varied by $\pm 1\sigma$

BKG Yield		α_γ
$\Xi^0 \to \Lambda\pi^0$ **BKG**	$+1\sigma$	-0.659
	-1σ	-0.644
Other BKG	$+1\sigma$	-0.657
	-1σ	-0.646
Nominal		**-0.652**

- Continuum BKG model:
  - ~~MC simulated distribution~~
  - Side band event ($\mathbf{0.075} < p_\Lambda < \mathbf{0.100}$ GeV/c, $\mathbf{0.204} < p_\Lambda < \mathbf{0.216}$ GeV/c)

BKG Model	α_γ
MC simulation	-0.652
Sideband	-0.639

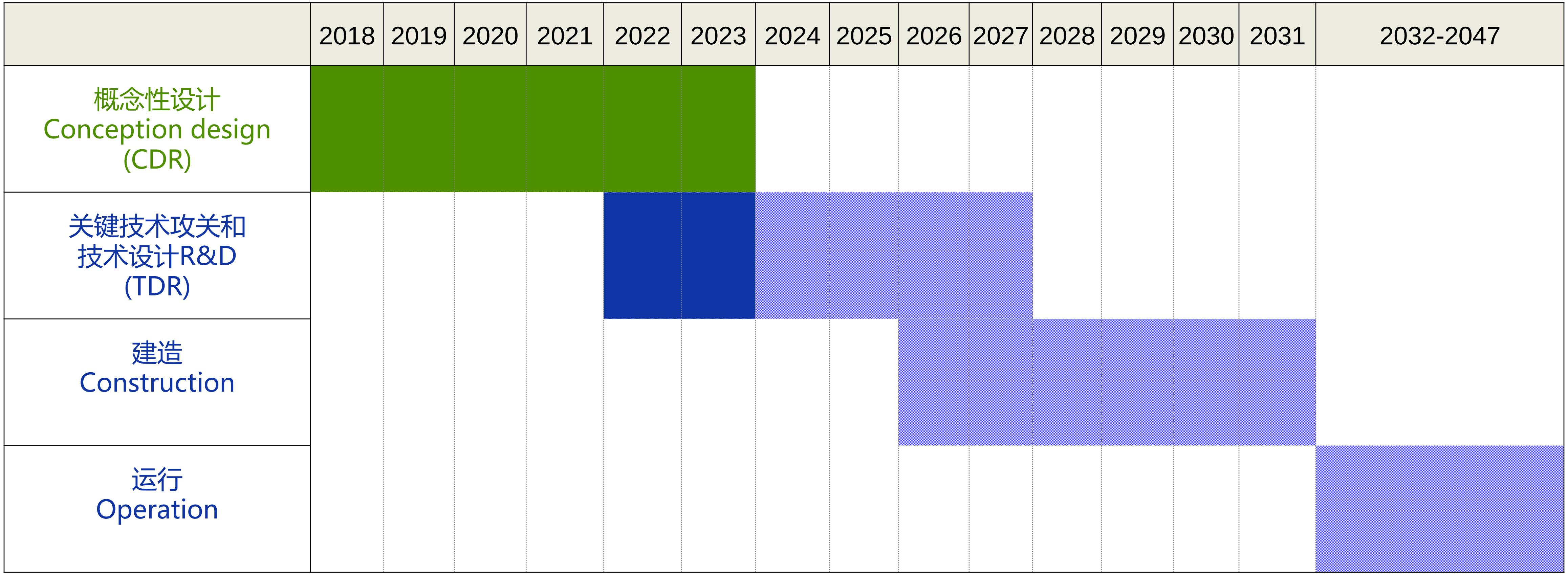
- Fixed parameters' uncertainty:
  - Referred from BAM-537
  - Sampling within uncertainty (**with correlation**)
  - Repeat the fit by 300 times
  - $\boldsymbol{\sigma}$ of pull distribution as uncertainty

Summary

- **First** measurement of $\Xi^0 \to \Lambda\gamma$ decay at BESIII
- **Competitive** sensitivity compared to the world average value
- **Consistent** BF and α_γ result with PDG

	$\mathcal{B}_{\Xi^0\to\Lambda\gamma}\,(\times 10^{-3})$	α_γ
$\Xi^0 \to \Lambda\gamma$	1.348±0.090±0.066	-0.652±0.092±0.016
$\bar{\Xi}^0 \to \bar{\Lambda}\gamma$	1.326±0.098±0.069	0.830±0.080±0.044
Combined	1.347±0.066±0.062	-0.741±0.062±0.019
PDG Value	1.17±0.07	-0.70 ± 0.07
Divergence ($\times\,\sigma$)	**1.55**	**0.57**

STCF Project



R&D Timeline

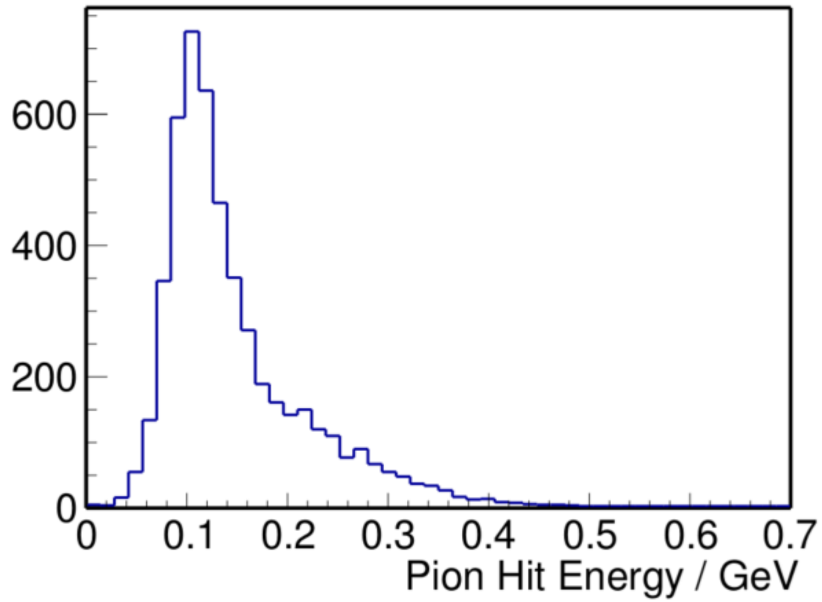
		2018	2019	2020	2021	2022	2023	2024
Conceptual Design								
Key Technology R&D	Timing Performance							
	Pile-up Recovery							
	Light Yield Enhancement							
Prototype Fabrication								
Beam Test								

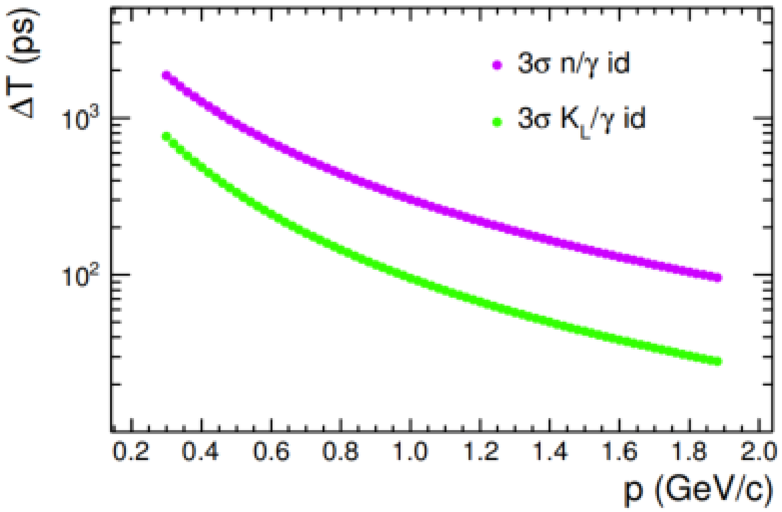
Homogenous Calorimeter Technical Routing

Technology	Experiment	Date	Depth	σ_E @ 1 GeV
NaI(Tl) + PMT	Crystal Ball	1983	$20X_0$	2.7%
BGO + PD	L3	1993	$22X_0$	2.1%
CsI + PMT	KTeV	1996	$27X_0$	2.0%
CsI + SiPM	Mu2e	?	$10X_0$	4.9%?
CsI(Tl) + PD	BaBar	1999	$16\text{-}18X_0$	2.7%
CsI(Tl) + PD	BELLE	1998	$16X_0$	1.8%
CsI(Tl) + PD	BESIII	2010	$15X_0$	2.5%
PWO + APD	CMS	1997	$25X_0$	3.0%
PWO + APD	PANDA	?	$22X_0$	2.5%

- Common routing: CsI(Tl) + PD
- Radiation hardness (<1 krad)
- Hit rate (< 1 kHz)

Time resolution requirements

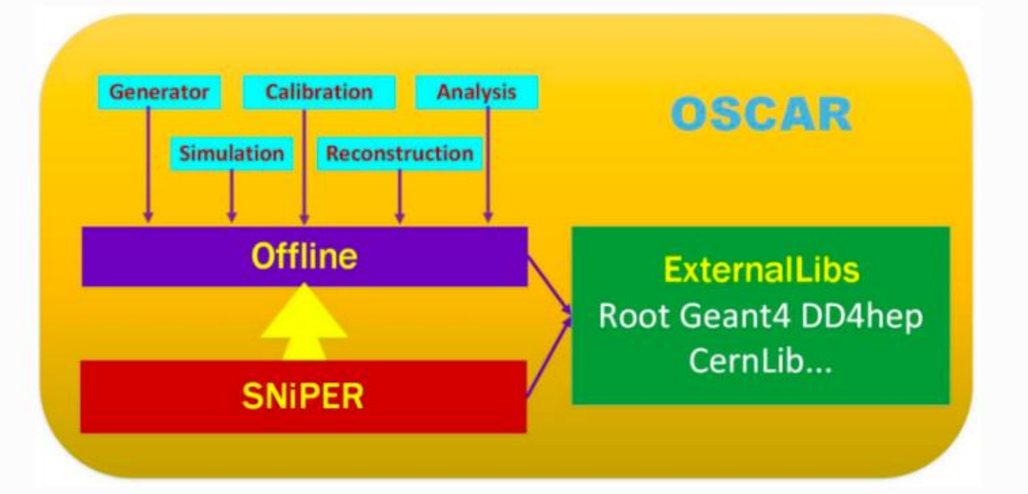


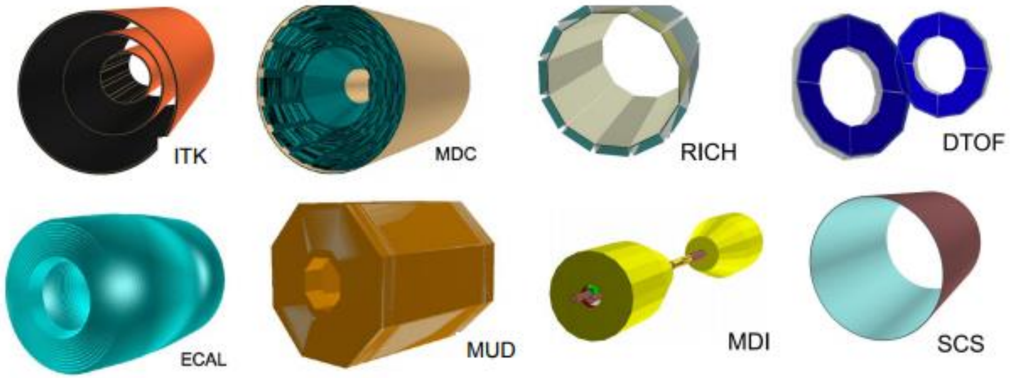


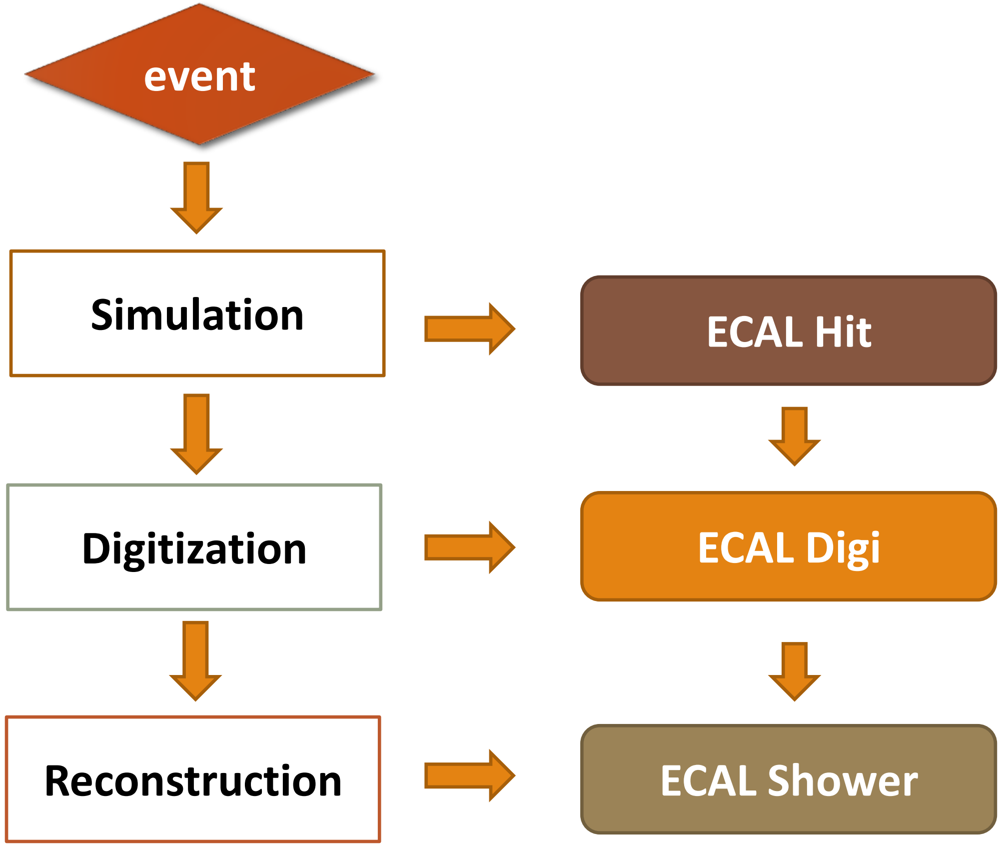
ECAL Software Development

Simulation Framework

- Conducted under Offline Software of Super Tau-Charm Facility



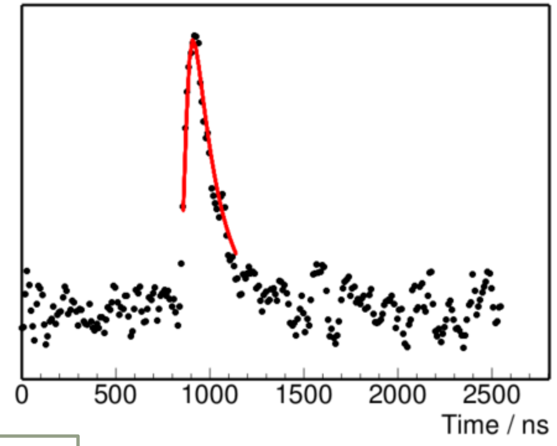




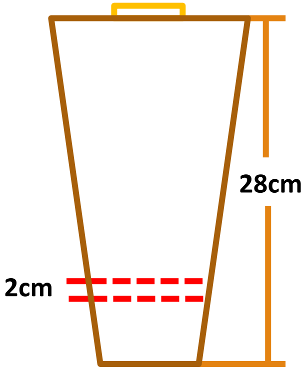
ECAL Software Development

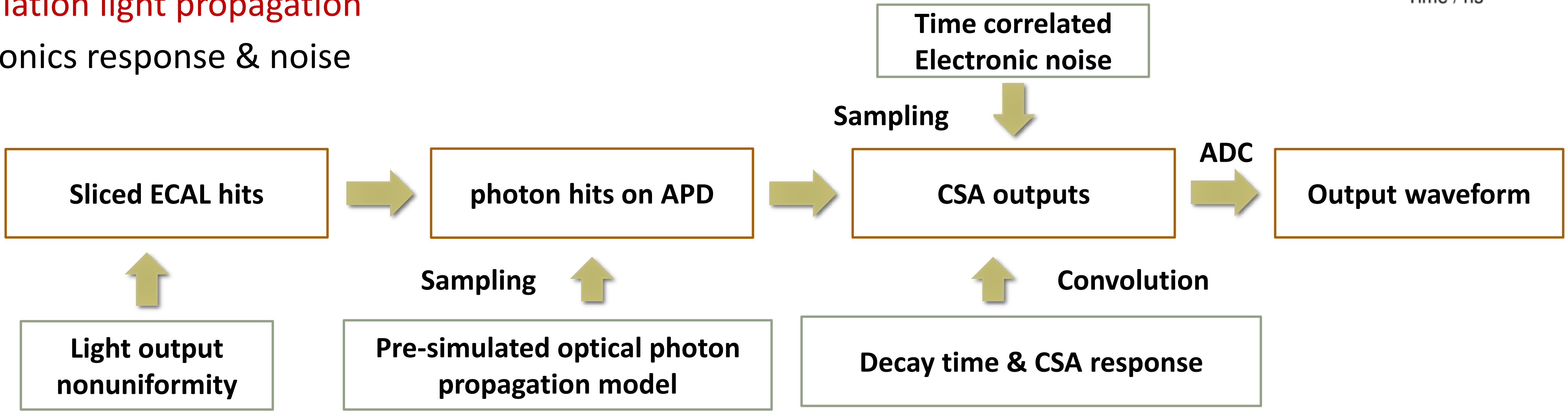
Simulation Framework

- **Sliced hit information (Data size reduced by 10 times)**
  - Layer width: 2 cm
  - Time bin width: 500 ps

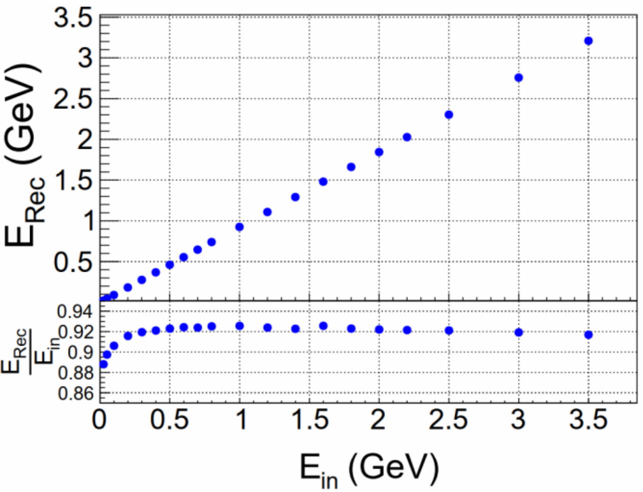


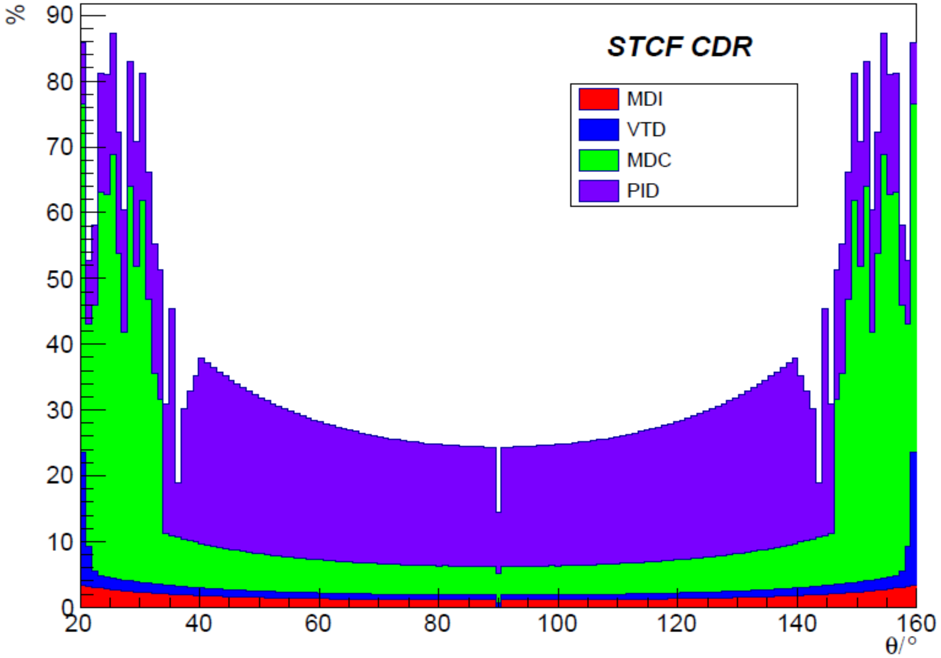
- **Complete digitization procedure**
  - Light output nonuniformity
  - Scintillation light propagation
  - Electronics response & noise
  - ADC

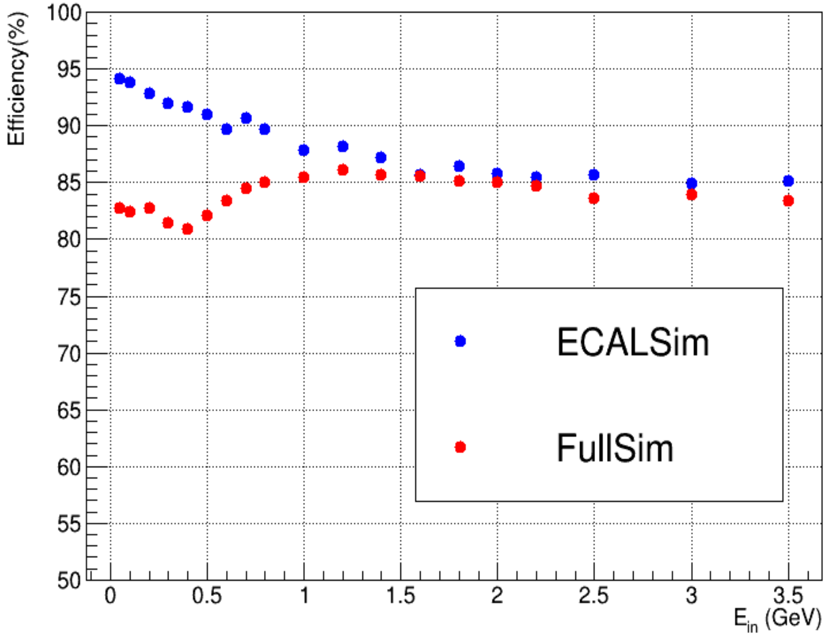




Energy resolution from material budget



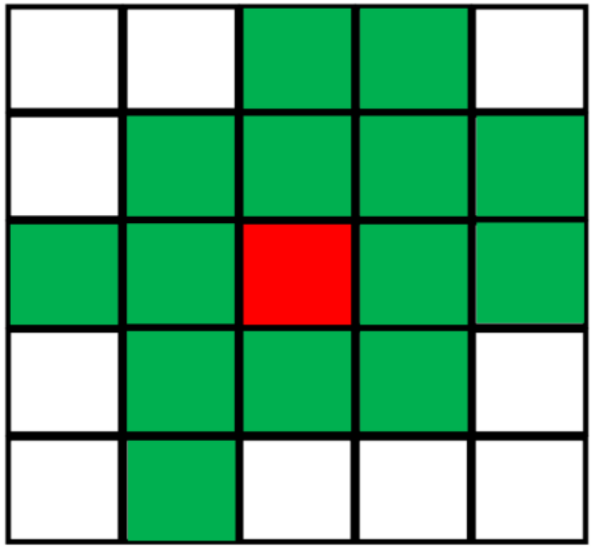




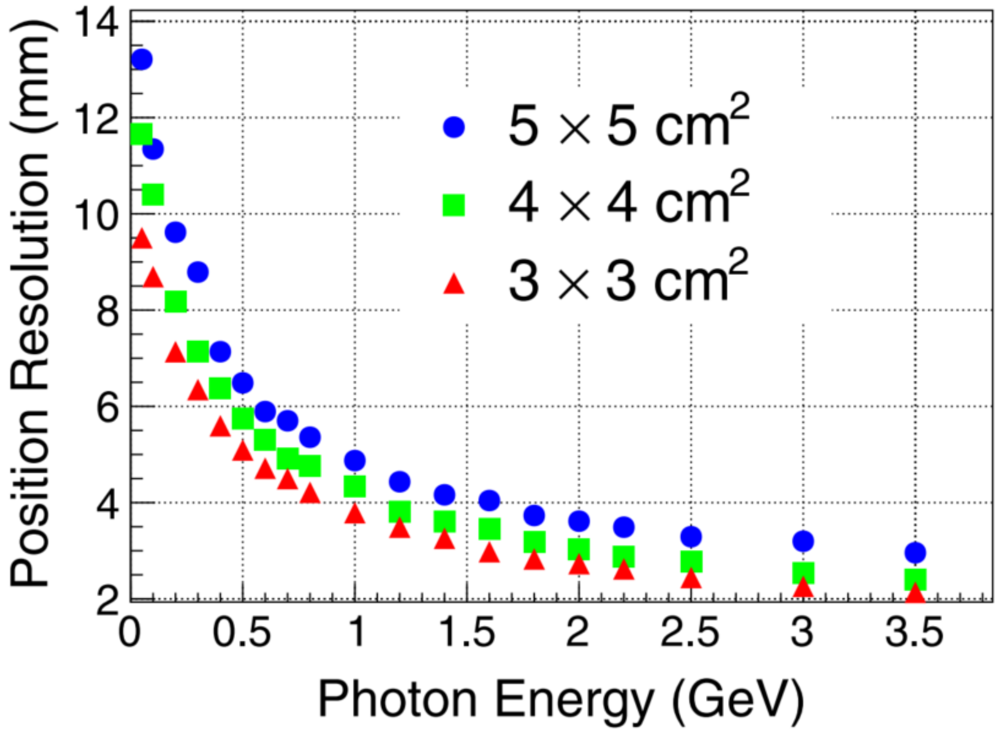
ECAL Conceptual Design

Position Resolution

Y. Song, **Z. K. Jia** *et al*. Nucl. Instrum. Methods A 1057, 168749 (2023)



$$X_c = \sum_j W_j(E_j) \cdot X_j / \sum_j W_j(E_j)$$



$$\sigma_x \approx \frac{R_M}{\sqrt{E/E_c}}$$

4.9 mm @ 1.0 GeV

Least Chi-square and Optimal Filtering

- Target function for least chi-square method:

$$\chi^2 = \sum_{i,j} (y_i - \sum_m A_m f(T_i + \tau_m) - p) S_{ij}^{-1} (y_j - \sum_m A_m f(T_j + \tau_m) - p)$$

- One possible way for minimization:

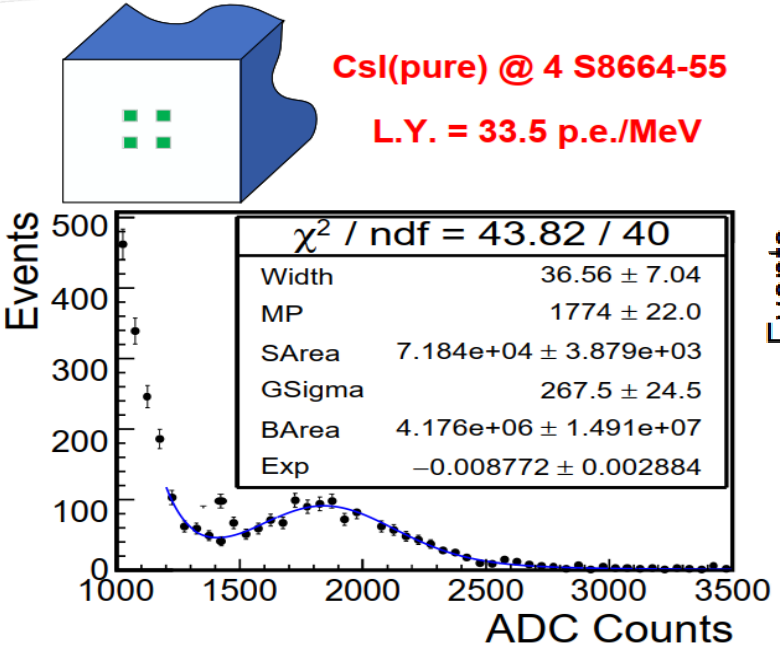
Replace $A\tau$ with B, rewrite it as:

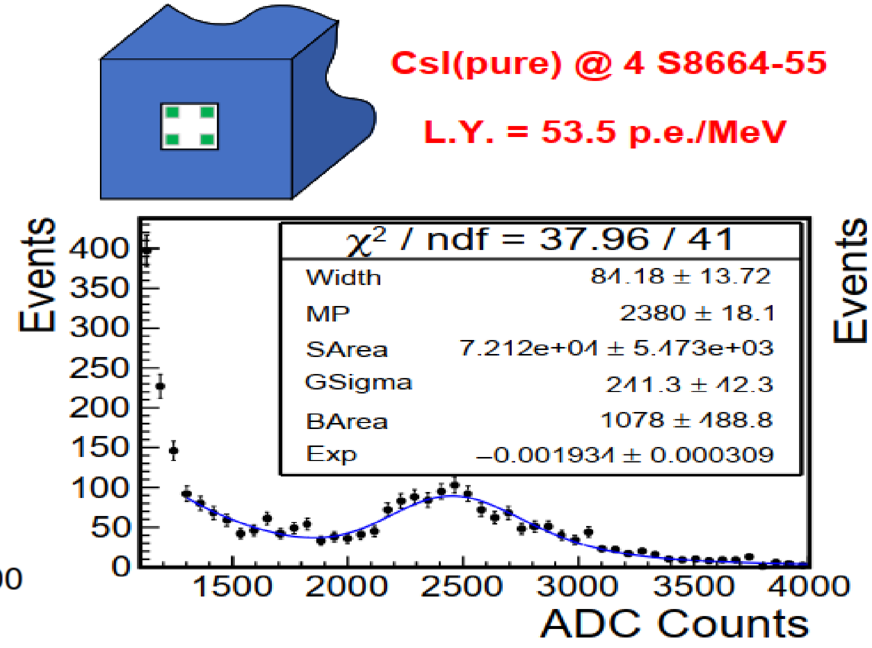
$$\begin{pmatrix} \mathbf{f}^{m\mathrm{T}}\mathbf{S}^{-1}\mathbf{f}^{m} & \mathbf{f}^{m\mathrm{T}}\mathbf{S}^{-1}\mathbf{f}'^{m} & \mathbf{f}^{m\mathrm{T}}\mathbf{S}^{-1}\mathbf{1} \\ \mathbf{f}'^{m\mathrm{T}}\mathbf{S}^{-1}\mathbf{f}^{m} & \mathbf{f}'^{m\mathrm{T}}\mathbf{S}^{-1}\mathbf{f}'^{m} & \mathbf{f}'^{m\mathrm{T}}\mathbf{S}^{-1}\mathbf{1} \\ \mathbf{1}^{\mathrm{T}}\mathbf{S}^{-1}\mathbf{f}^{m} & \mathbf{1}^{\mathrm{T}}\mathbf{S}^{-1}\mathbf{f}'^{m} & \mathbf{1}^{\mathrm{T}}\mathbf{S}^{-1}\mathbf{1} \end{pmatrix} \begin{pmatrix} A \\ B \\ p \end{pmatrix} = \begin{pmatrix} \mathbf{f}^{m\mathrm{T}}\mathbf{S}^{-1}\mathbf{y} \\ \mathbf{f}'^{m\mathrm{T}}\mathbf{S}^{-1}\mathbf{y} \\ \mathbf{1}^{\mathrm{T}}\mathbf{S}^{-1}\mathbf{y} \end{pmatrix}$$

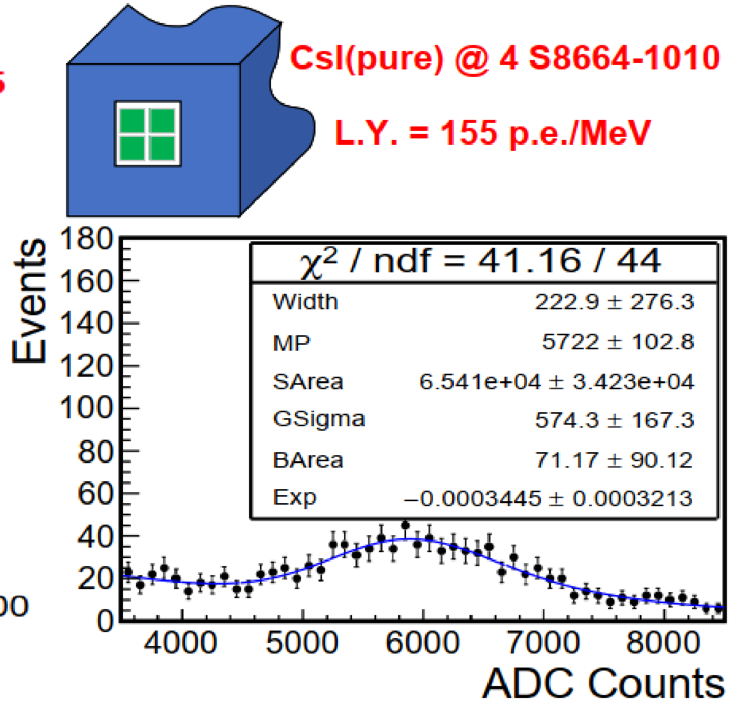
- Only iterate one time: optimal filtering

Key Technology R&D

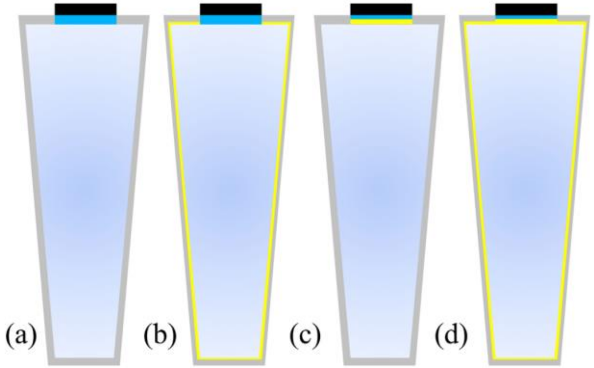
Light Yield Enhancement







- Proved the feasibility of L.Y. > 100 p.e./MeV
- Further improvement for better performance?

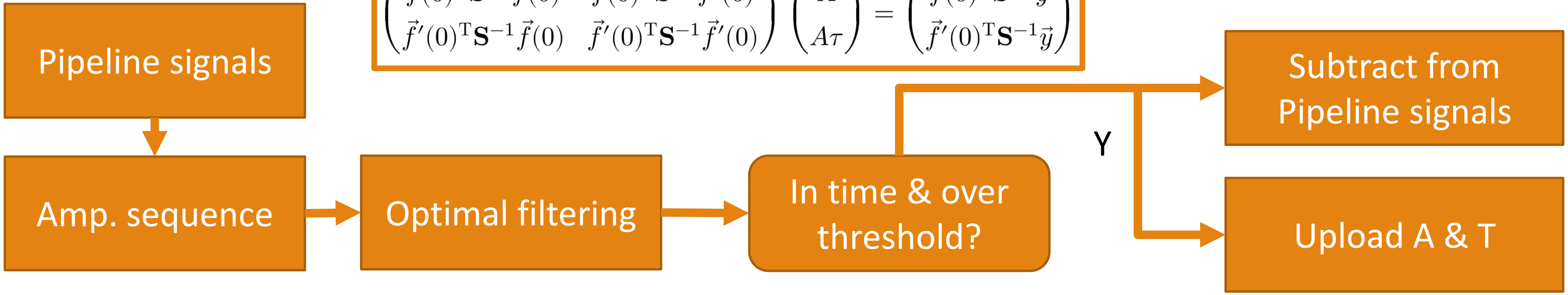

(a)
(b)
(c)
(d)

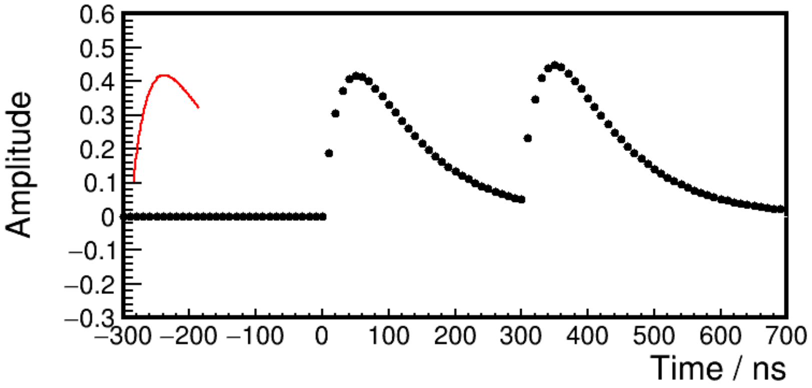
Studies on Pile-up Recovery Methods

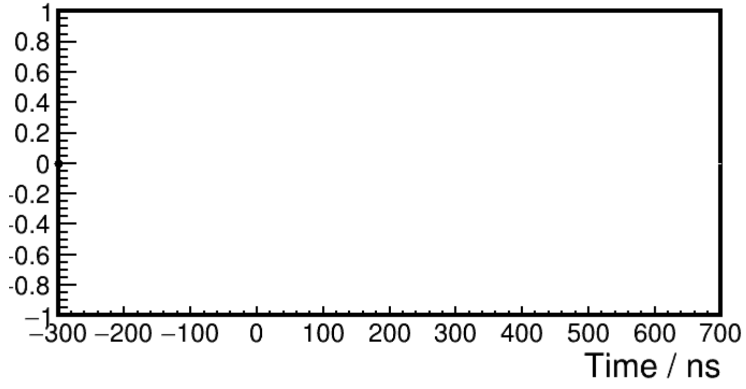
An Online Pile-up Recovery Scheme

- Optimal filtering: Least-χ^2 fit w/o iteration

$$\begin{pmatrix} \vec{f}(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{f}(0) & \vec{f}(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{f}'(0) \\ \vec{f}'(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{f}(0) & \vec{f}'(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{f}'(0) \end{pmatrix} \begin{pmatrix} A \\ A\tau \end{pmatrix} = \begin{pmatrix} \vec{f}(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{y} \\ \vec{f}'(0)^{\mathrm{T}}\mathbf{S}^{-1}\vec{y} \end{pmatrix}$$





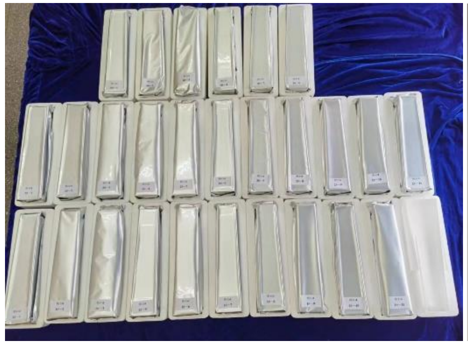


Prototype Fabrication and Beam Test

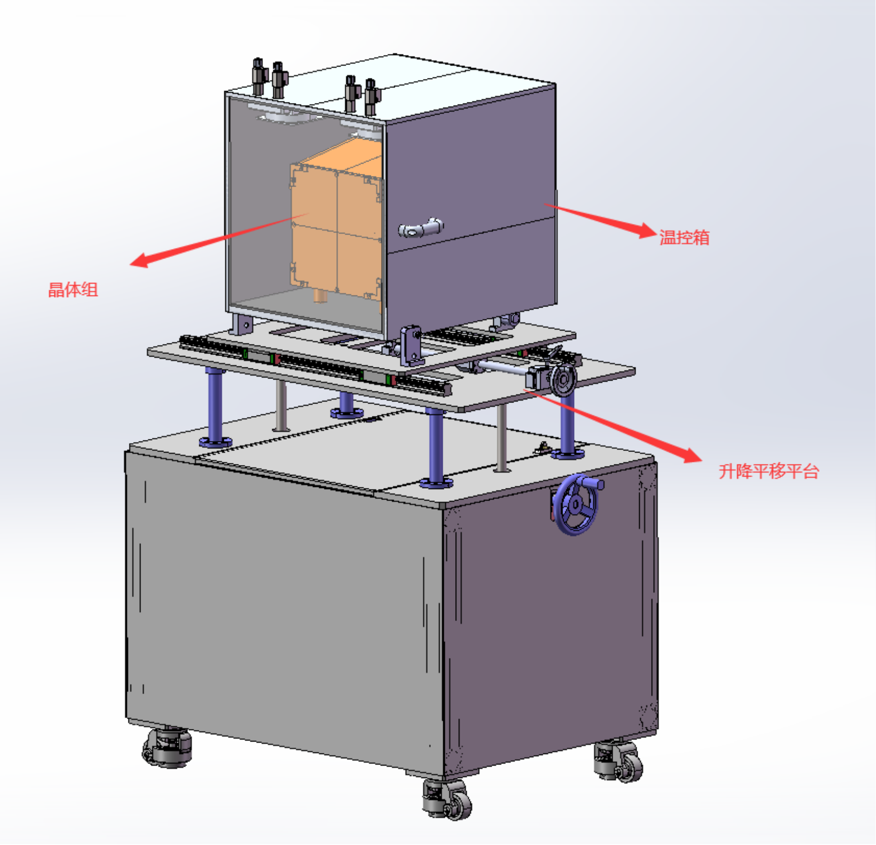
Prototype Fabrication (5x5 array)

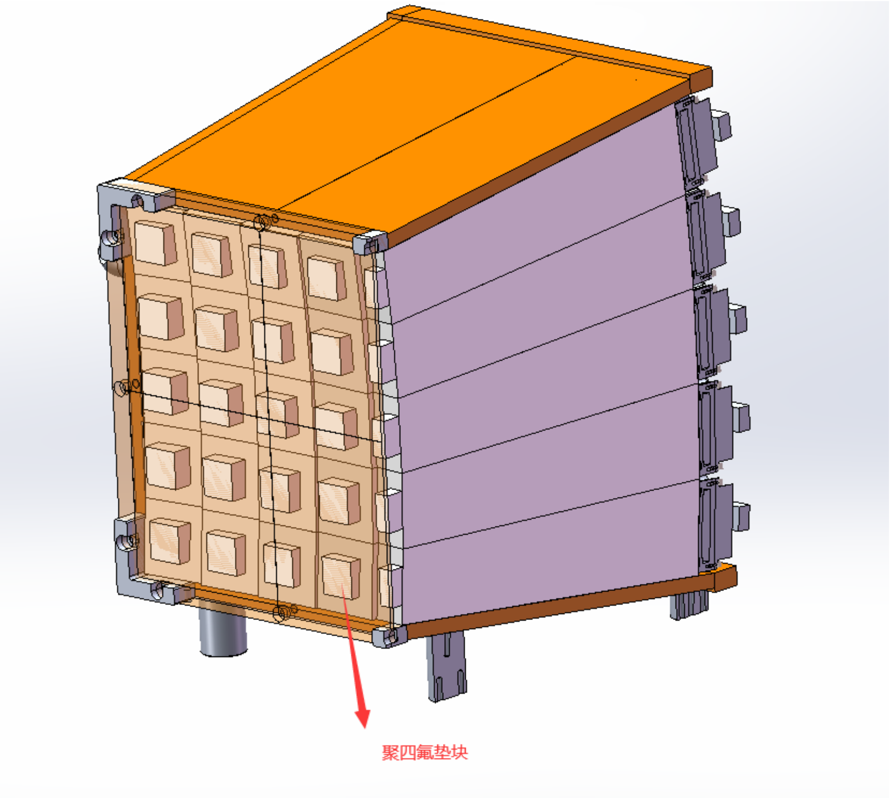
- ✓ CsI crystal, APD and NOL are ready
- ✓ Frontend electronics, Signal processing module and DAQ system are ready
- ☐ NOL coated crystals under processing
- ☐ Mechanical system in design

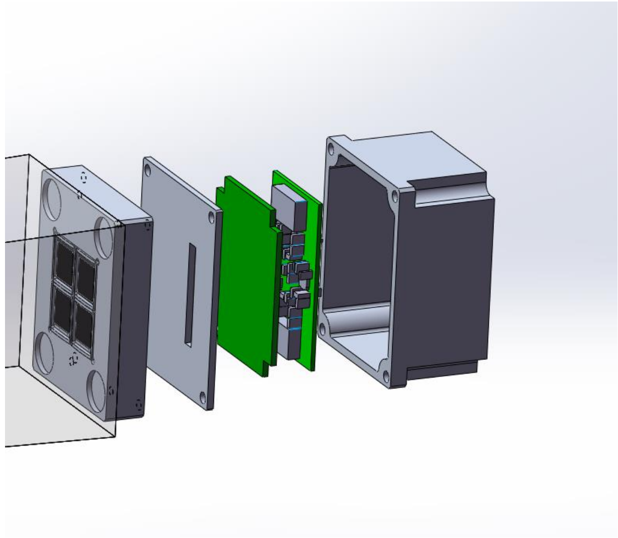
Beam test scheduled in July, 2024




Prototype Fabrication and Beam Test





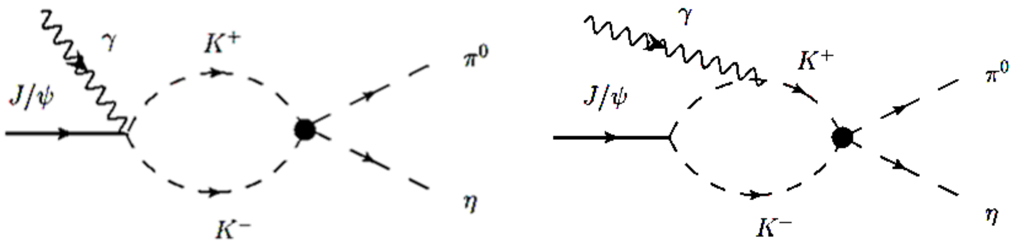


Amplitude Analysis on $J/\psi \to \gamma\pi^0\eta$ Decay

Physics Motivation

- Physics of $J/\psi \to \gamma + 1^{-}$ process
  - Isospin suppressed radiative process – better sensitivity on exotic states (if exist)
  - A test field for light meson production mechanism (FSI, CUSP, VMD, …)

Reference	$\mathrm{B}(J/\psi \to \gamma a_0(980), a_0(980) \to \pi^0\eta)$
Eur.Phys.J.A 56 (2020) 1, 23	0.48×10^{-7}
PhysRevD.101.014005	2.7×10^{-7}



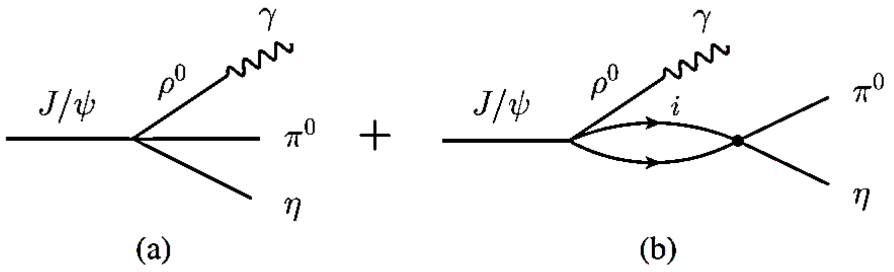


FIG. 5. $\pi^0\eta$ production driven by ρ^0 conversion. (a) tree level, (b) rescattering. The intermediate states are $i = K^+K^-, K^0\bar{K}^0, \pi^0\eta$.

Physics Motivation

- Physics of $J/\psi \to \pi^0(\eta) + 1^{+-}$ process
  - Rare knowledge about axial-vector mesons production & radiative decay
  - The first measurement on the BF of axial-vector meson-related decays

Decay Mode	BF Prediction PhysRevD.99.094020	BF from PDG
$J/\psi \to \eta h_1(1170)$	0.95×10^{-3}	**Absent**
$J/\psi \to \eta' h_1(1170)$	0.54×10^{-3}	
$J/\psi \to \eta h_1(1415)$	0.04×10^{-3}	
$J/\psi \to \eta' h_1(1415)$	2.35×10^{-3}	
$J/\psi \to \pi^0 b_1(1235)$	1.23×10^{-3}	$(2.3 \pm 0.6) \times 10^{-3}$

Decay Mode	Γ Prediction (keV) PhysRevD.77.034017	Experiment BF
$h_1(1170) \to \gamma\pi^0$	837 ± 134	**Absent**
$h_1(1415) \to \gamma\pi^0$	81 ± 18	
$b_1(1235) \to \gamma\pi^0$	180 ± 28	
$h_1(1170) \to \gamma\eta$	3.1 ± 0.9	
$h_1(1415) \to \gamma\eta$	438 ± 80	
$b_1(1235) \to \gamma\eta$	488 ± 70	

Analysis Method

- Partial wave analysis under the framework of covariant tensor amplitude
- General formula: $A = \psi_\mu(m_1)e^*_\nu(m_2)A^{\mu\nu} = \psi_\mu(m_1)e^*_\nu(m_2)\sum_i \Lambda_i U_i^{\mu\nu}.$

$$U^{\mu\nu}_{\gamma a_0} = g^{\mu\nu} f^{(a_0)}$$

$$U^{\mu\nu}_{(\gamma a_2)1} = \tilde{t}^{(a_2)\mu\nu} f^{(a_2)}$$

$$U^{\mu\nu}_{(\gamma a_2)2} = g^{\mu\nu} p^{\alpha}_{(\psi)} p^{\beta}_{(\psi)} \tilde{t}^{(a_2)}_{\alpha\beta} B_2(Q_{(\psi)\gamma a_2}) f^{(a_2)}$$

$$U^{\mu\nu}_{(\gamma a_2)3} = q^{\mu} p^{\alpha}_{(\psi)} \tilde{t}^{(a_2)\nu}_{\alpha} B_2(Q_{(\psi)\gamma a_2}) f^{(a_2)}$$

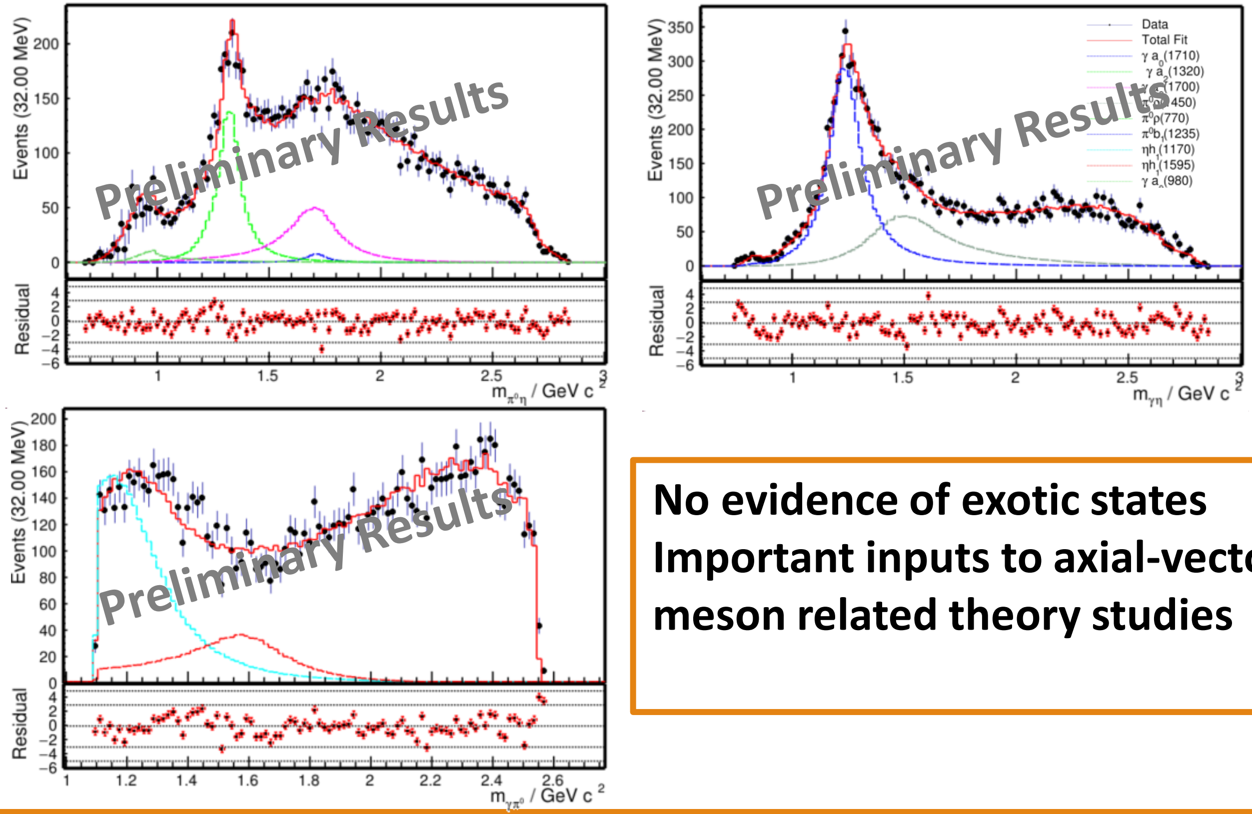
$$U^{\mu\nu}_{\pi^0(\eta)X} = \varepsilon^{\mu}_{\alpha\beta\gamma} p^{\alpha}_{(\psi)} \tilde{T}^{(1)\beta} \varepsilon^{\gamma\delta\sigma\nu} p_{(X)\delta} \tilde{t}^{(1)(X)}_{\sigma} f^{(X)}$$

$$U^{\mu\nu}_{\pi^0(\eta)X,SS} = \tilde{g}^{(X)\mu\nu} f^{(X)}$$

$$U^{\mu\nu}_{\pi^0(\eta)X,SD} = \tilde{t}^{(2)(X)\mu\nu} f^{(X)}$$

$$U^{\mu\nu}_{\pi^0(\eta)X,DS} = \tilde{T}^{(2)(\psi)\mu}_{\lambda} \tilde{g}^{(X)\lambda\nu} f^{(X)}$$

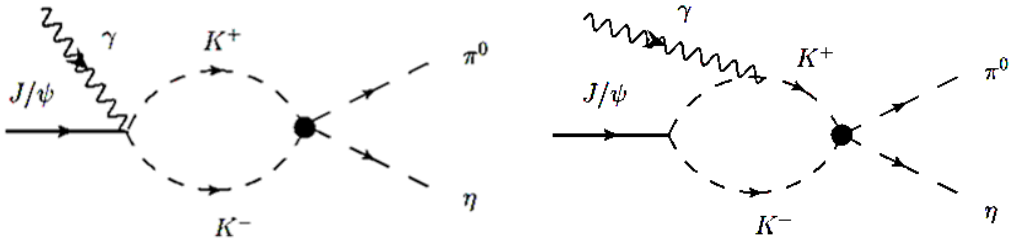
$$U^{\mu\nu}_{\pi^0(\eta)X,DD} = \tilde{T}^{(2)(\psi)\mu}_{\lambda} \tilde{t}^{(2)(X)\lambda\nu} f^{(X)}$$



No evidence of exotic states
Important inputs to axial-vector meson related theory studies

Physics Motivation & Analysis Method

- Physics of $J/\psi \to \gamma + 1^-$ process
  - Isospin suppressed radiative process – better sensitivity on exotic states (if exist)
  - A test field for light meson production mechanism (FSI, CUSP, VMD, …)
- Physics of $J/\psi \to \pi^0(\eta) + 1^{+-}$ process
  - Rare knowledge about axial-vector mesons production & radiative decay
  - The first measurement on the BF of axial-vector meson-related decays



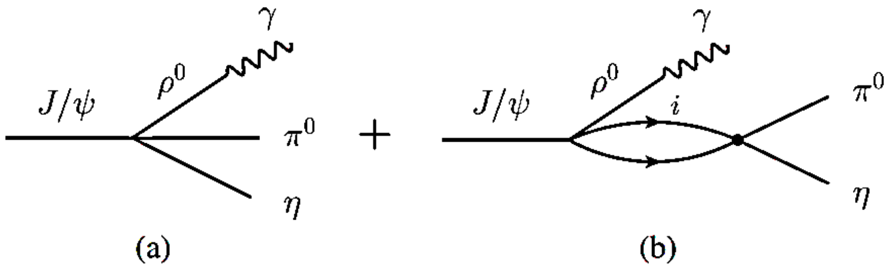
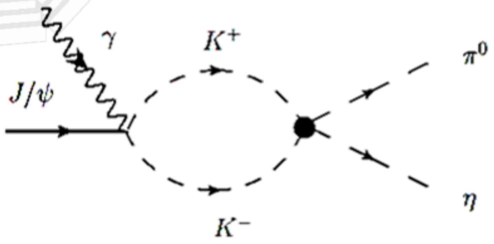
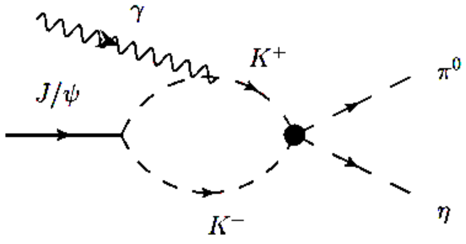
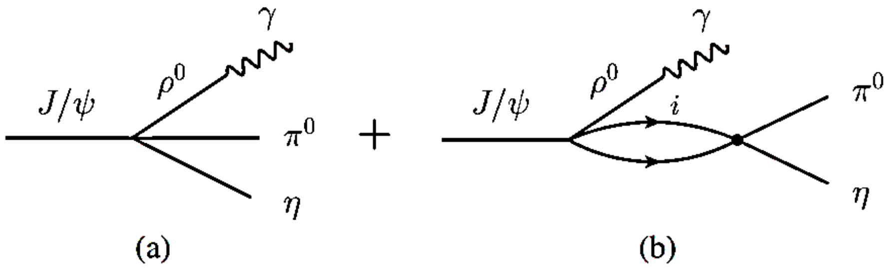


FIG. 5. $\pi^0\eta$ production driven by ρ^0 conversion. (a) tree level, (b) rescattering. The intermediate states are $i = K^+K^-, K^0\bar{K}^0, \pi^0\eta$.







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