Tau Physics status at Super Tau Charm Facility

Workshop on Tau physics at Belle II and STCF

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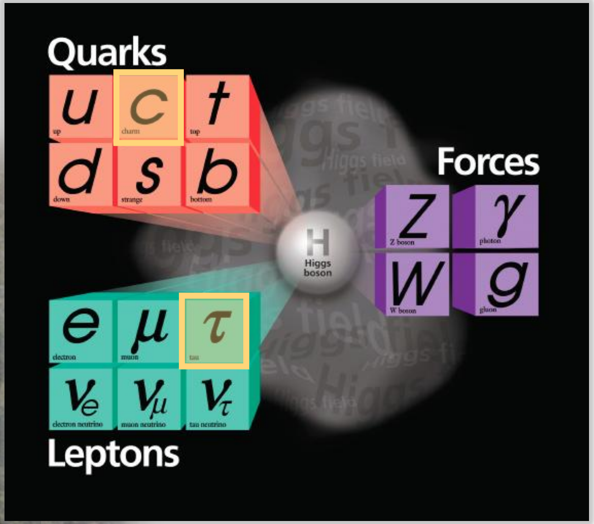
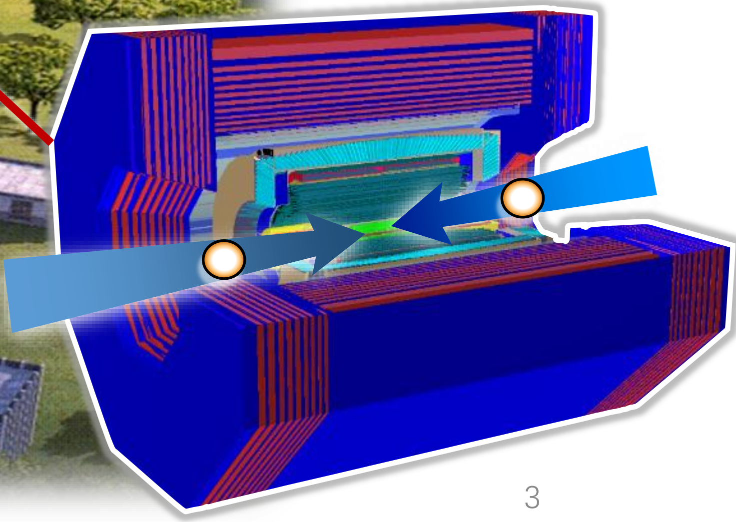
Outline

- Overview about the Super Tau Charm Facility (STCF).
- Physics requirements and detector design.
- Offline software, reconstruction algorisms.
- **Preliminary studies for Tau Physics at STCF.**
  - ✓ MC simulation.
  - ✓ List for the on-going/planned Tau Physics study at STCF.
    - Studies based on $\rho\rho$ decay channel: EDM; Quantum Entanglement.
    - Study based on $\pi\pi\pi\nu$ decay channel: tau reconstruction enhanced by vertex constrain
    - Charged lepton flavor violating (cLFV) study based on $\boldsymbol{\tau \to \gamma\mu}$ and $\boldsymbol{\tau \to \mu\mu\mu}$ channels.
    - CP Violation (CPV) in $\boldsymbol{\tau}$ decay.

Overview about the STCF

Next generation of symmetric electron-positron colliding factory, producing massive tau lepton and charm hadrons, to unravel the mystery of how quarks form matter and the symmetries of fundamental interactions.

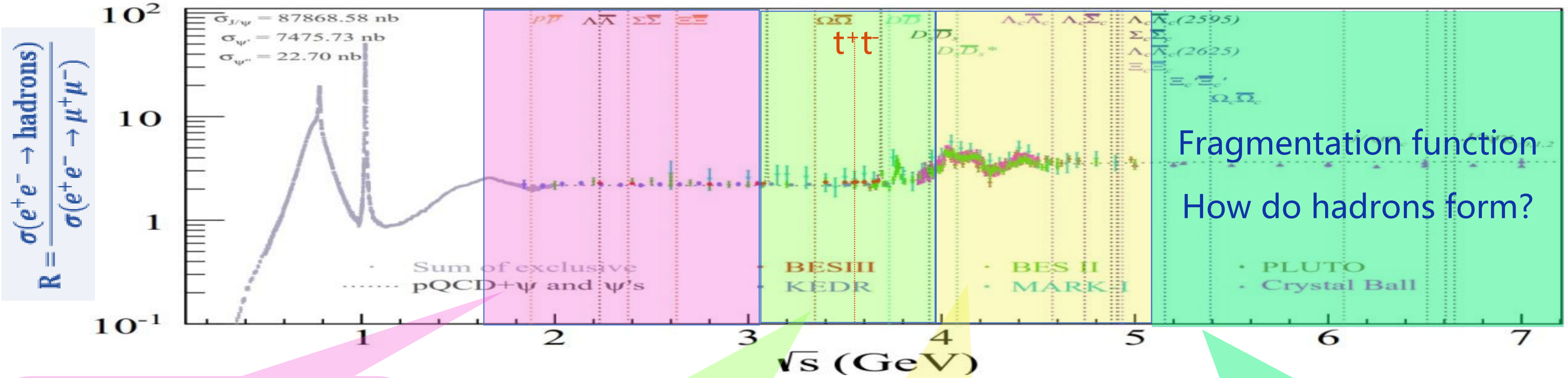




- E_{cm} = 2-7 GeV, $\mathcal{L} > 0.5\times10^{35}$ cm^{-2} s^{-1}.
- Site: Hefei’ s suburban "Future Big Science City”.

Physics potential

- Covering transiting energy scale for (non) perturbation QCD
- Redundant resonances, large yield for Di-charmonium states, tau pairs productions
- Multiquark states (with/without s quark), Gluonic states, etc.
- …



- Nucleon/Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark
- MLLA/LPHD and QCD sum rule predictions

- LH spectroscopy
- Gluonic and exotic
- LFV and CPV
- Rare/forbidden decays
- Physics with τ lepton

- XYZ particles
- Physics with D mesons
- f_D and f_{Ds}
- D_0-D_0 mixing
- Charm baryons

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

- **Fundamental symmetry test**

Hyperon/τ CP-violation

$K^0 - \bar{K}^0$ CPT

Lepton flavor violation

- **Mystery of color confinement**

Hadron spectrum

Hadron structure

Hadron fragmentation

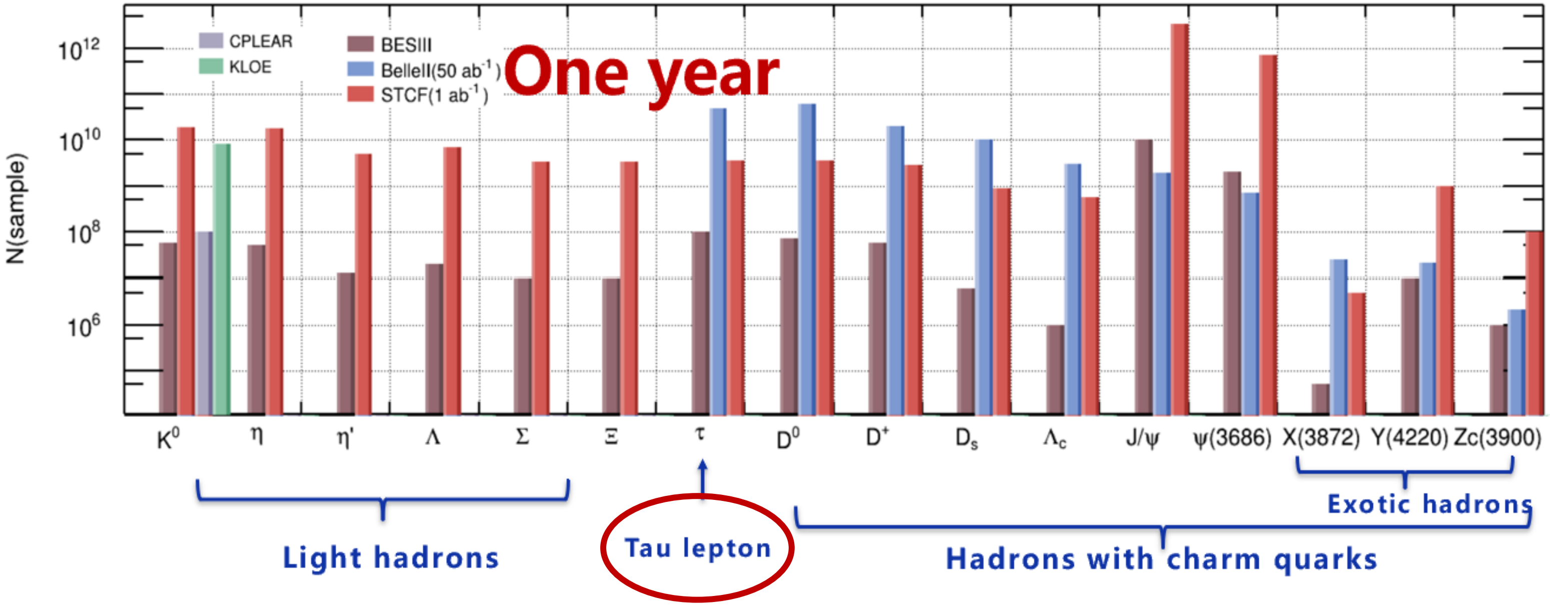
- **Precision measurements**

R value, τ mass, α_{EM}, α_S

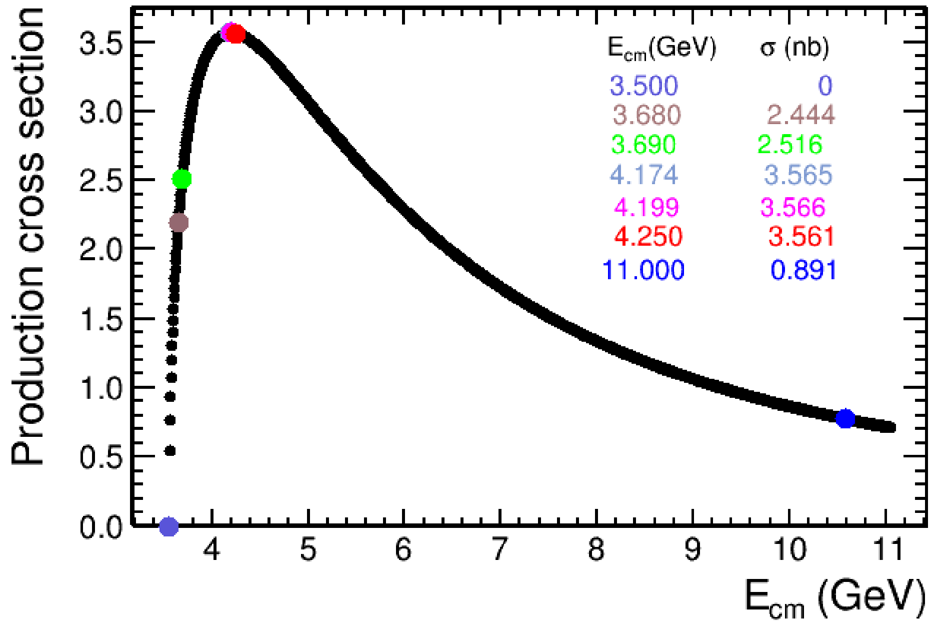
CKM matrix elements

Prospected statistics from STCF

- **STCF: Electron-positron collider, $\sqrt{s}$ covering 2-7 GeV, with peak luminosity reach over 0.5×10^{35} cm^{-2} s^{-1} → Integrated luminosity ~1 ab^{-1}.**
- **Thousand billions of ψ events, billions of (quantum correlated) hyperon, charmonium, tau lepton pairs will be produced, in a wider energy range.**



Tau pair production cross section

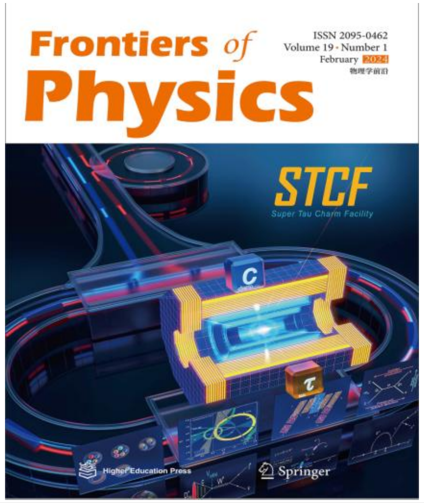


- **Tau event rate: $\sim 3.5\times10^{9}$ per year ($\sqrt{s}=4.26$GeV)**
- **$\sim 1.9\times10^{9}$ per year ($\sqrt{s}=7GeV$)**

Prospected physics sensitivity

- Compare prospected sensitivity of STCF (via fast simulation) with the world best result → Placed requirements on detector performances.

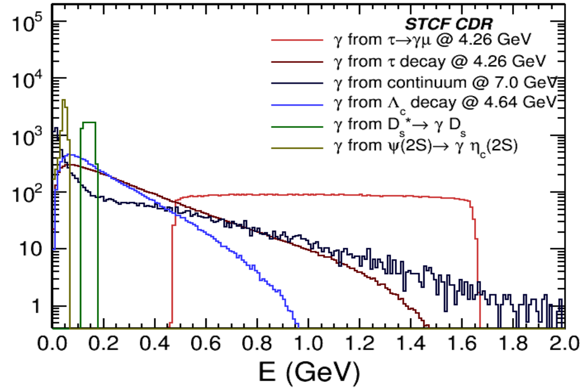
Physics goal	Observable	BESIII	Current world best	STCF prospect(1 ab^{-1})
Fundamental Symmetry	A_{CP} in hyperon decay	0.005	0.005	$\mathcal{O}(10^{-4})$
	weak phase in hyperon decay	1.2°	1.2°	0.04°
	Δ_{CP} in tau decay	-	0.25%	$\mathcal{O}(10^{-3})$
	EDM of hyperon	-	$\mathcal{O}(10^{-16})$ ecm	$\mathcal{O}(10^{-21})$ ecm
	EDM of tau	-	$\mathcal{O}(10^{-17})$ ecm	$\mathcal{O}(10^{-18})$ ecm
	cLFV in $\tau \to \mu\mu\mu$	-	2.1×10^{-8}	$\mathcal{O}(10^{-9})$
	cLFV in $J/\psi \to e\mu$	4.5×10^{-9}	4.5×10^{-9}	$\mathcal{O}(10^{-11})$
	cLFV in $J/\psi \to e\tau$	7.5×10^{-8}	7.5×10^{-8}	$\mathcal{O}(10^{-10})$
Quark Confinement	$N_{Y(4260)/Z_c/X(3872)}$	$10^7/10^6/10^4$	$10^6/10^5/10^6$	$10^9/10^8/10^6$
	Pentaquarks	-	P_cs in $J/\psi p(\Lambda)$	$\sigma_{J/\psi pp} \simeq 4$ fb
	Di-charmonium	-	di-ψ	$\sigma_{J/\psi c\bar{c}} \simeq 10$ fb
	$N_{J/\psi/\psi(3686)}$	$10^{10}/10^9$	$10^{10}/10^9$	$10^{12}/10^{11}$
	Collins effects	0.3	0.3	$\mathcal{O}(10^{-3})$
	Baryon form factors	10%	10%	$\mathcal{O}(10^{-2})$
Physical Quantities	R value	3%	3%	$\mathcal{O}(10^{-3})$
	tau mass	160 keV	120 keV	$\mathcal{O}(10)$ keV
	$\lvert V_{us}\rvert$	-	1%	$\mathcal{O}(10^{-3})$
	$\lvert V_{cd}\rvert$	1.2%	1%	$\mathcal{O}(10^{-3})$
	$\lvert V_{cs}\rvert$	1.4%	1.4%	$\mathcal{O}(10^{-3})$
	Sys. unc. of γ from D decay	0.4°	0.4°	0.1°
	α_s	-	1.5%	$\mathcal{O}(10^{-3})$

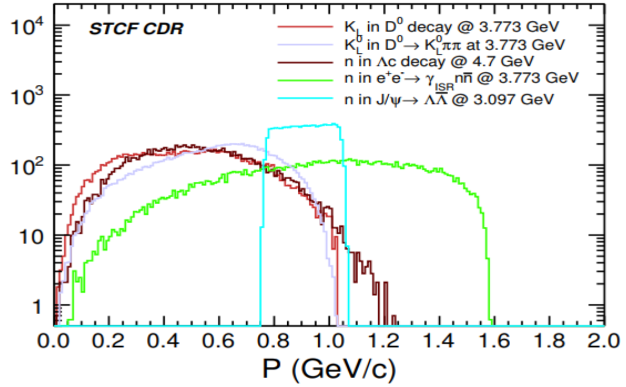


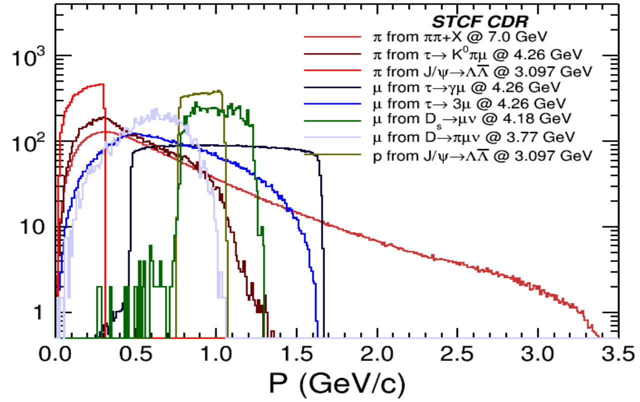
Process	Physics Interest	Optimized Subdetector	Requirements
$\tau \to K_s\pi\nu_\tau$, $J/\psi \to \Lambda\bar{\Lambda}$, $D_{(s)}$ tag	CPV in the τ sector, CPV in the hyperon sector, Charm physics	ITK+MDC	acceptance: 93% of 4π; trk. effi.: $> 99\%$ at $p_T > 0.3$ GeV/c; $> 90\%$ at $p_T = 0.1$ GeV/c $\sigma_p/p = 0.5\%$, $\sigma_{\gamma\phi} = 130\ \mu$m at 1 GeV/c
$e^+e^- \to KK + X$, $D_{(s)}$ decays	Fragmentation function, CKM matrix, LQCD etc.	PID	π/K and K/π misidentification rate $< 2\%$ PID efficiency of hadrons $> 97\%$ at $p < 2$ GeV/c
$\tau \to \mu\mu\mu$, $\tau \to \gamma\mu$, $D_s \to \mu\nu$	cLFV decay of τ, CKM matrix, LQCD etc.	PID+MUD	μ/π suppression power over 30 at $p < 2$ GeV/c, μ efficiency over 95% at $p = 1$ GeV/c
$\tau \to \gamma\mu$, $\psi(3686) \to \gamma\eta(2S)$	cLFV decay of τ, Charmonium transition	EMC	$\sigma_E/E \approx 2.5\%$ at $E = 1$ GeV $\sigma_{pos} \approx 5$ mm at $E = 1$ GeV
$e^+e^- \to n\bar{n}$, $D_0 \to K_L\pi^+\pi^-$	Nucleon structure Unity of CKM triangle	EMC+MUD	$\sigma_T = \frac{300}{\sqrt{p^3(\mathrm{GeV}^3)}}$ ps

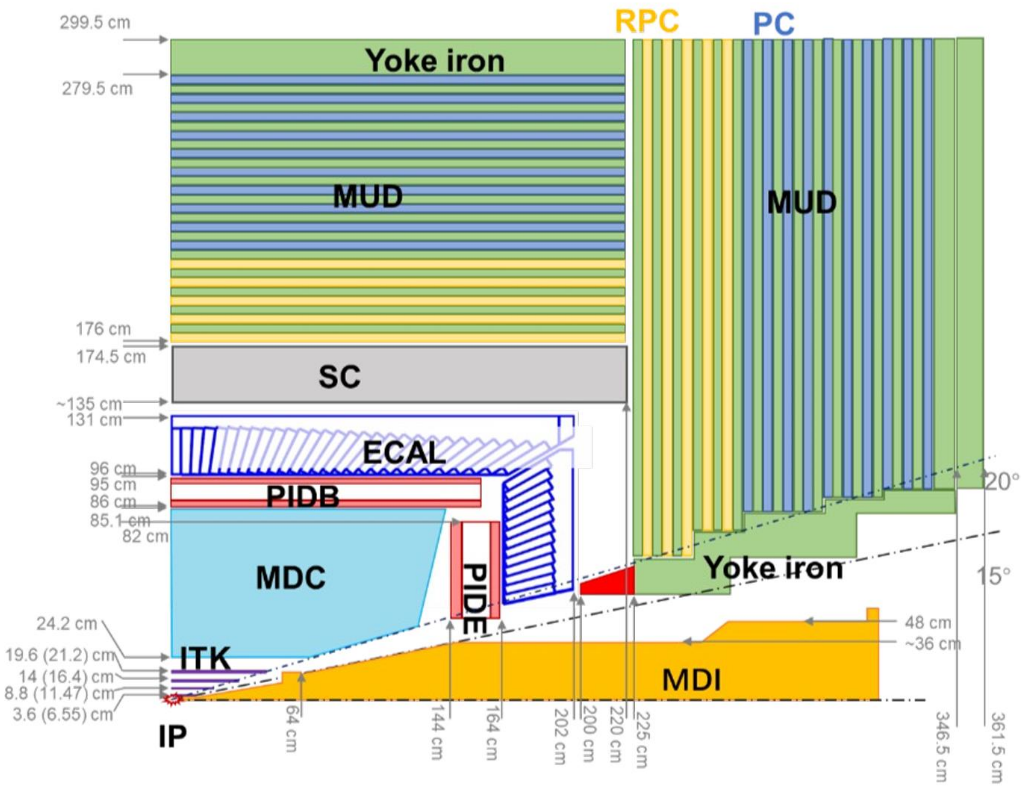
M. Achasov, et al., STCF conceptual design report (Volume 1): Physics & detector, Front. Phys. 19(1), 14701 (2024)

Demands on detectors









ITK

<0.25%X0 / layer

σ_{xy}< 100 μm

MDC

σ_{xy}< 130 μm; σp/p ~ 0.5% @ 1 GeV; dE/dx~6%

PID

π/K (and K/p) >97% up to 2 GeV/c @mis-ID rate 2%

EMC

E range: 0.025-3.5 GeV

σ_E @ 1 GeV: 2.5% in barrel, 4% at endcaps; Pos. Res. : ~ 5mm; σ_t<300ps

MUD

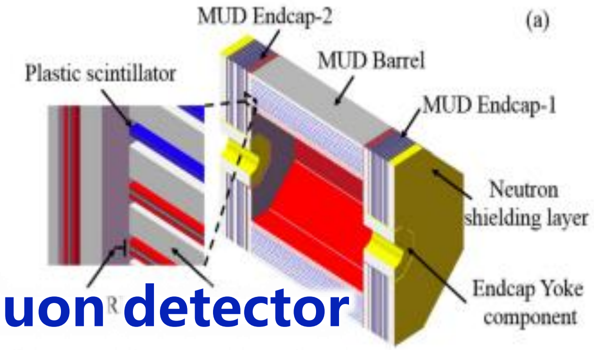
0.4 - 1.8 GeV

π suppression >30

Requirement:

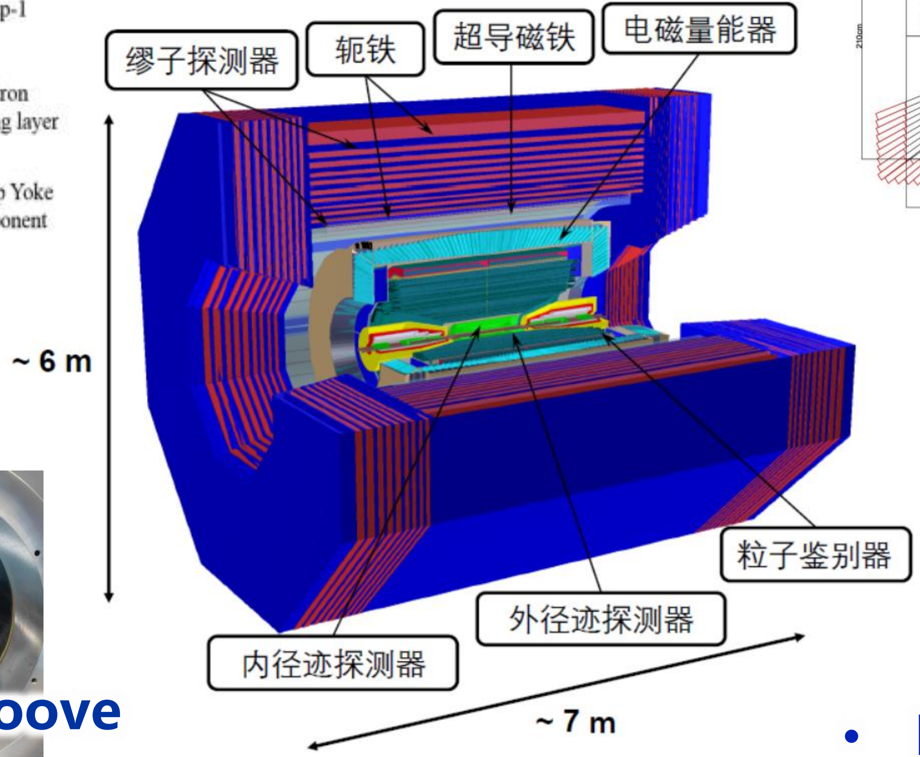
- High detection efficiency and good resolution
- Superior PID ability
- Tolerance to high rate/background environment

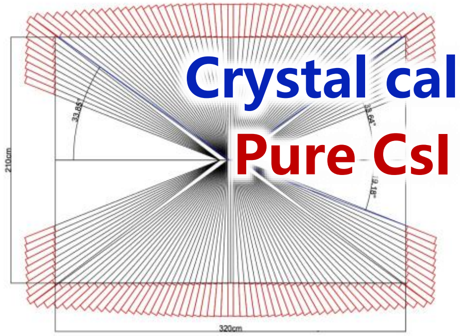
Detector system



Muon detector

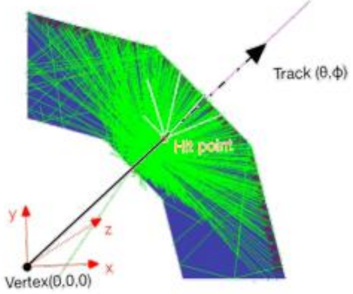
RPC+Plastic scintillator





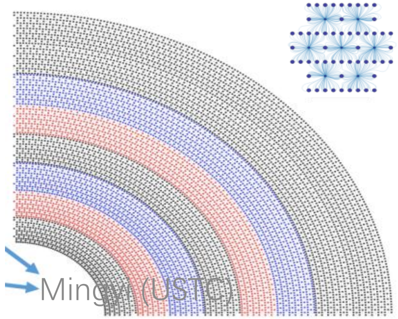
Crystal calorimeter

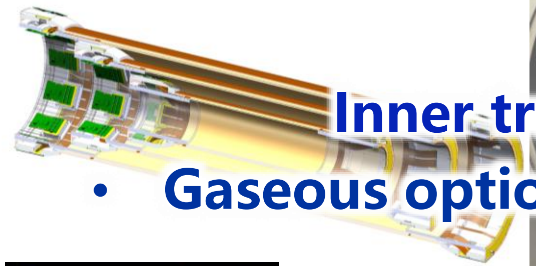
Pure CsI + APD



PID system

- **Barrel: DTOF**
- **Endcap: DTOF/RICH/ASHIPH**

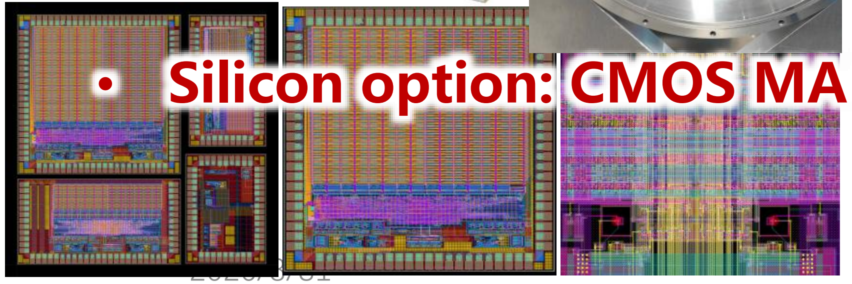




Inner tracker

- **Gaseous option : u-RGroove**

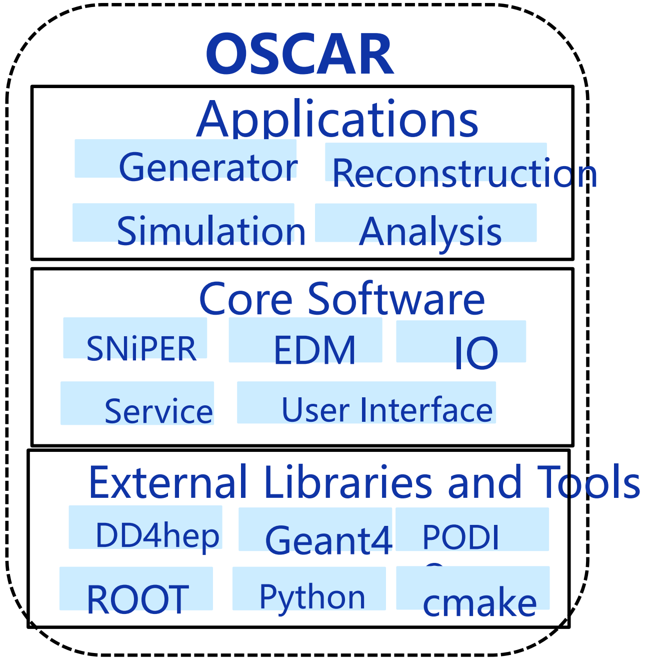
- **Silicon option: CMOS MAPS**



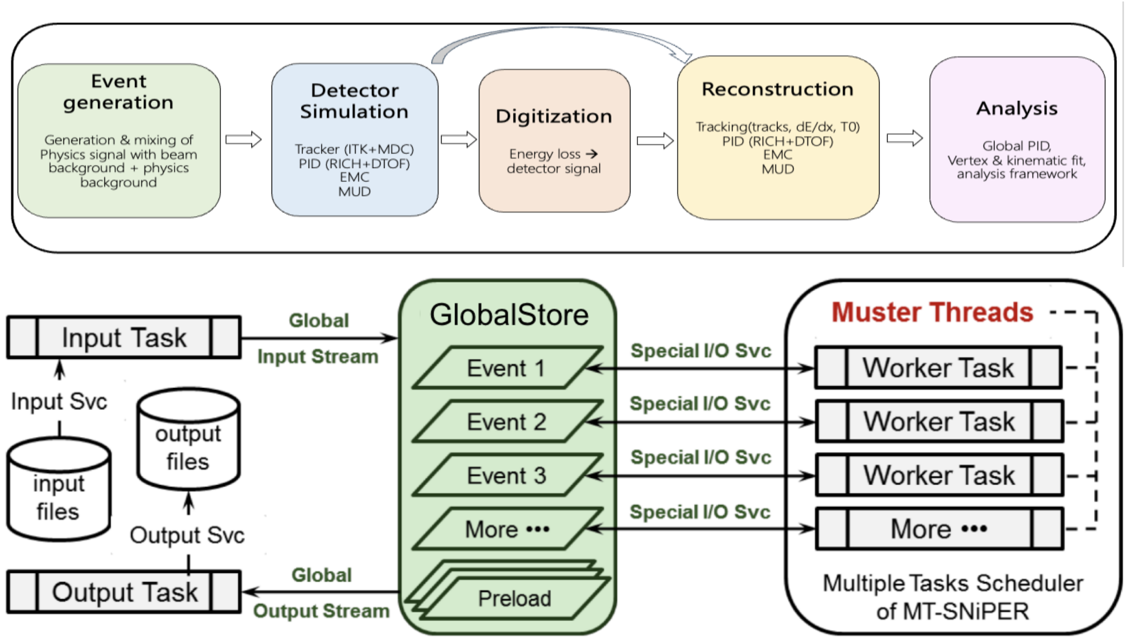
Central tracker: MDC

Offline data analysis software

- Offline Software System of Super Tau-Charm Facility (OSCAR, current ver. 2.7.0)
  - External Interface+ Framework +Offline
- SNiPER framework provides common functionalities for whole data processing
- Offline including Generator, Simulation, Calibration, Reconstruction and Analysis

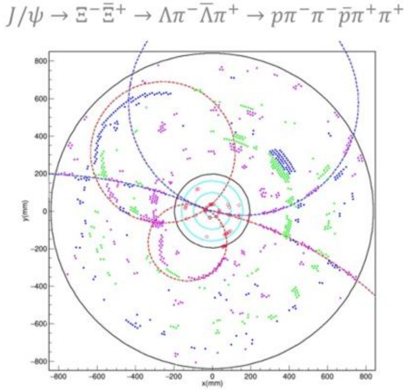


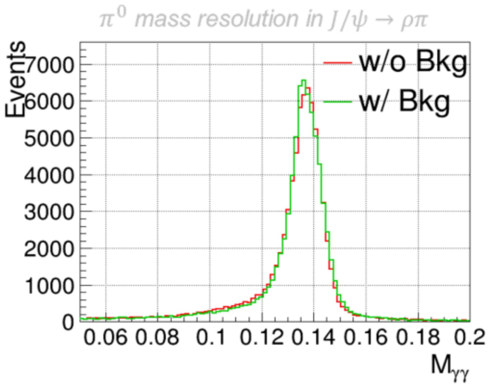
W.H. Huang et al 2023 JINST 18 P03004

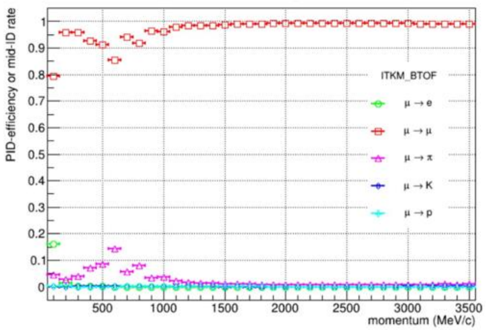


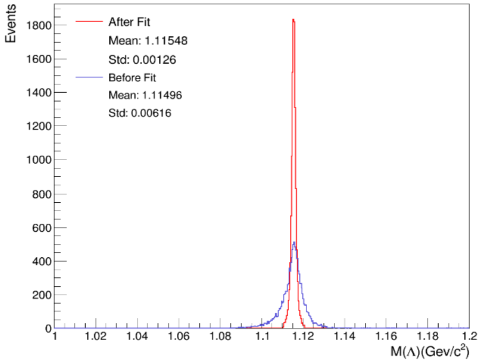
Full simulation chain by Oscar

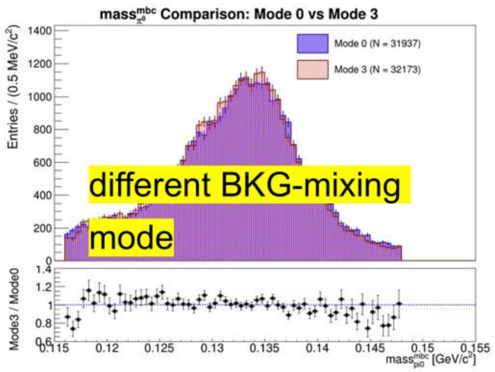
Full simulation chain: Truth + Detector response + Digitization + Reconstruction + Analysis







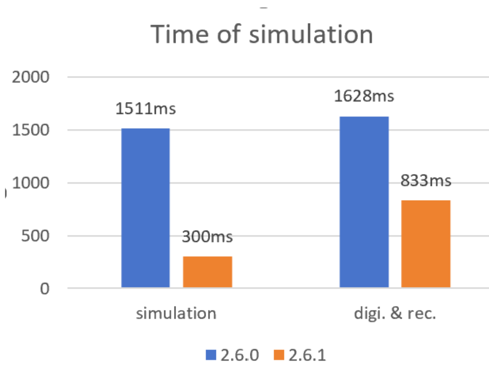


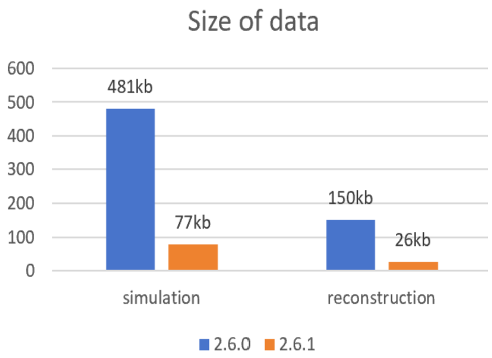


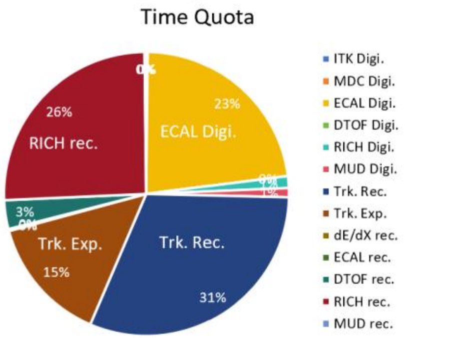
- ✓ **Charged track reconstruction**
- ✓ **Neutral particle reconstruction**
- ✓ **Particle identification**
- ✓ **Kinematic fit**
- ✓ **Beam background mixing**

External generators combined in Oscar：

- Babayaga (Babar， $\mu^+\mu^-, \gamma\gamma$)
- **Madgraph5 + Pythia8 ($\tau\tau$, with ISR/FSR)**
- Ekhara, Diag36, Gluga (Di photon)
- KKMC + EvtGen (Charmonium decay)
- LundArlw, Pythia (Hadronic)



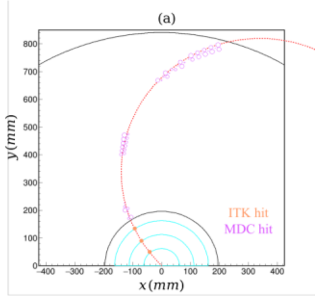


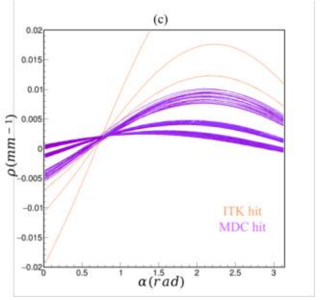


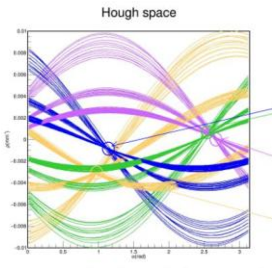
- **Optimization/speed up for simulation/digitization**

Tracking reconstruction

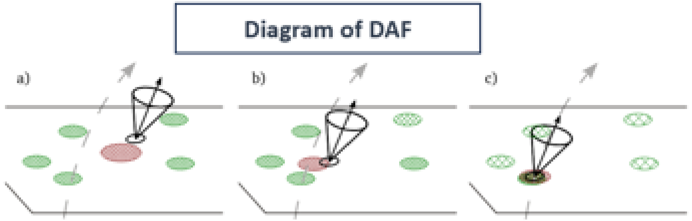
- Tracking system works in a **1T magnetic field**
- **Combined information from ITK(M) and MDC.**
- Algorithm: Hough transform + DAF in Genfit2 + GNN

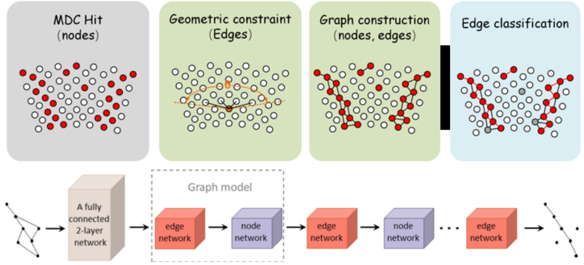


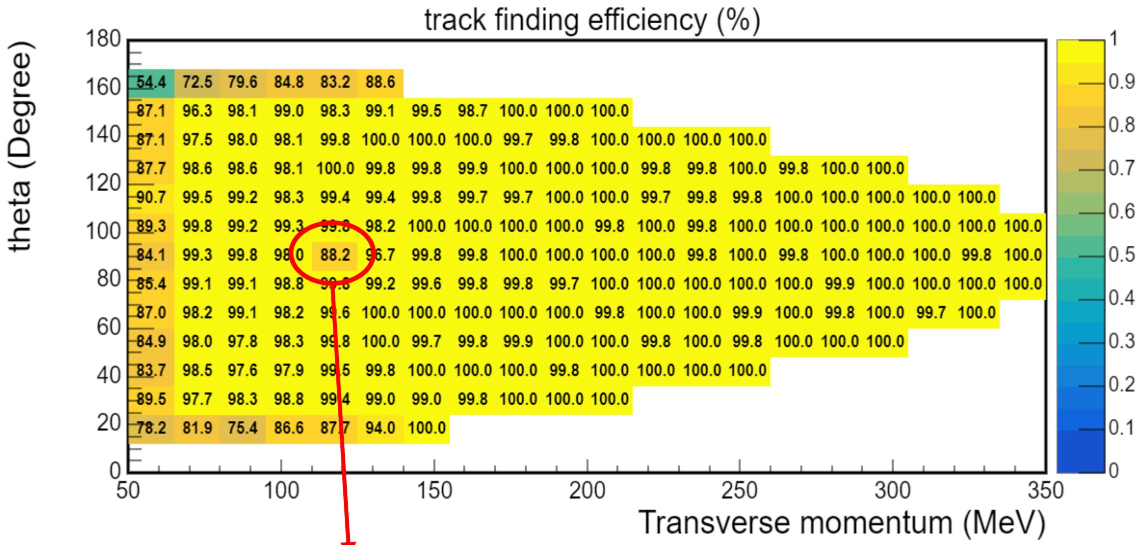


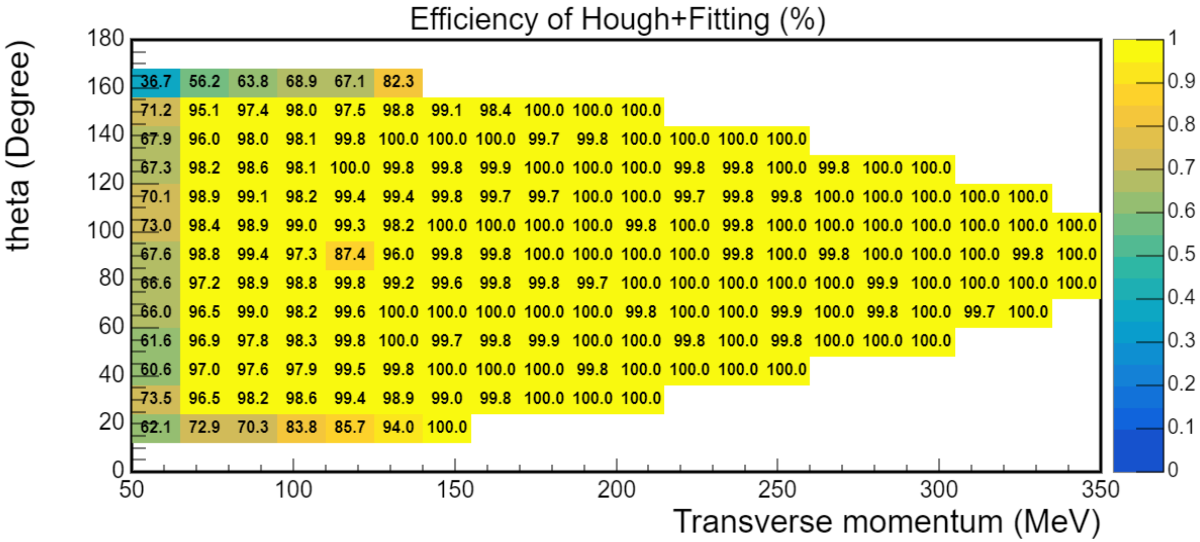


An example of 4 tracks(π+π-μ+μ-)





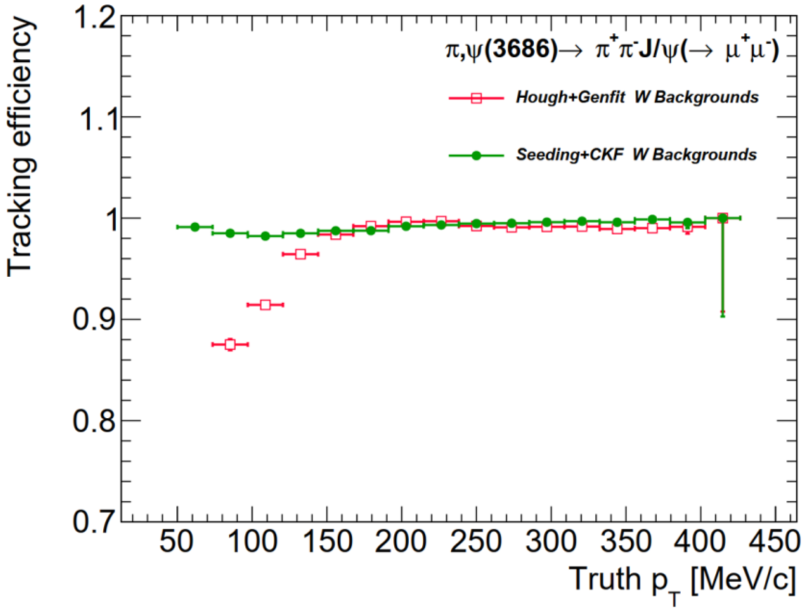


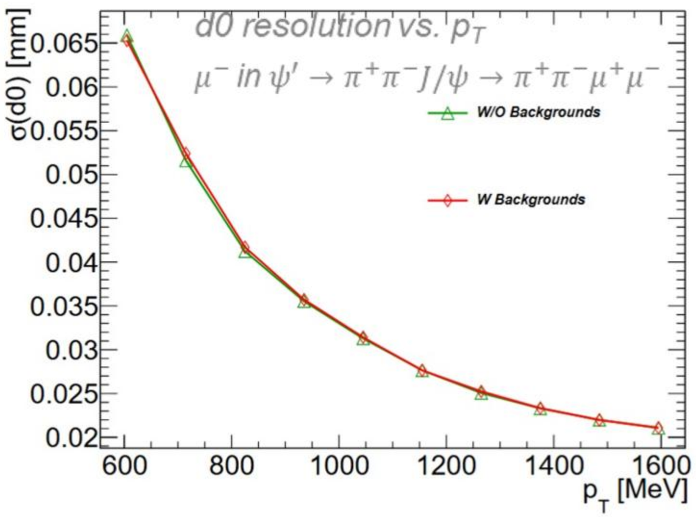


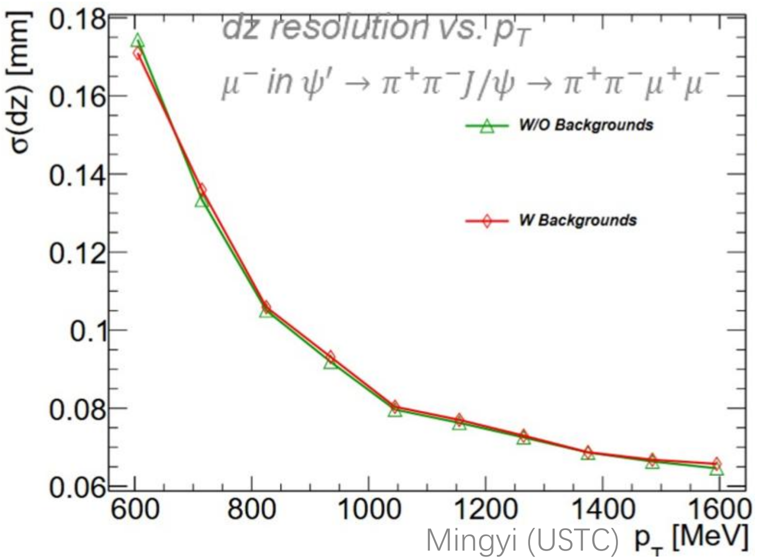
Circling tracking at z=0, difficult to distinguish the charge

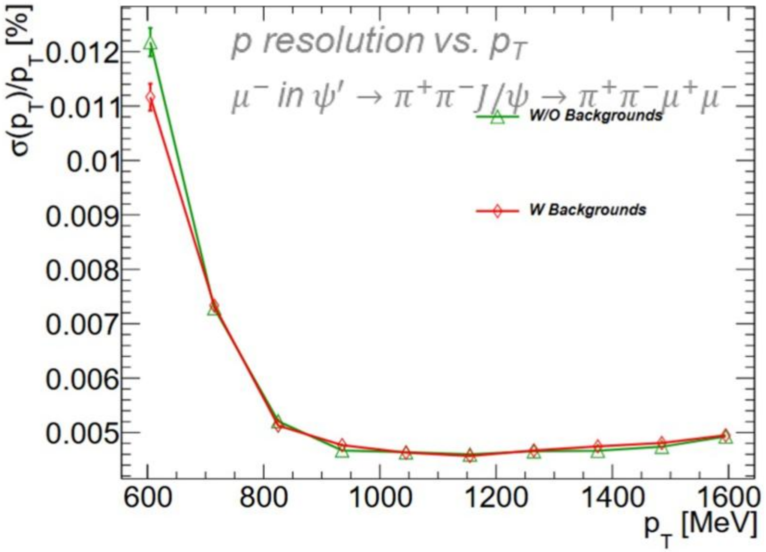
Tracking performance

- **Tracking efficiency:**
  - reaches **90%** with 1 time background **@100MeV**;
  - ~99% with 1 time background @300MeV;
- **Impact parameter and momentum resolution:**
  - d0 resolution ~32 um, z0 resolution ~ 85 um
  - Momentum resolution better than 0.5% at 1GeV/c



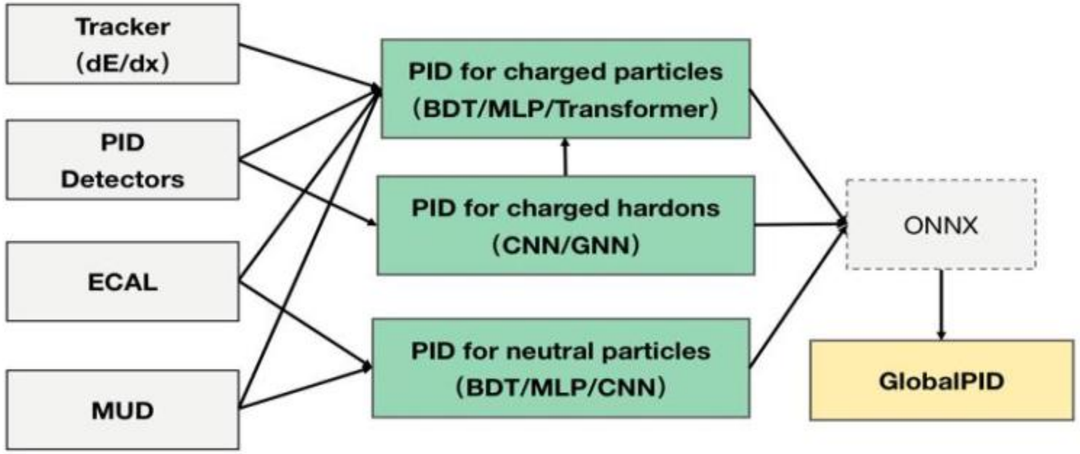






Particle identification

- Two methods for PID
- **A global PID** algorithm based on **machine learning (default)**



- **A combined PID** algorithm with **weighted likelihood**

Combined likelihood $\mathcal{L}_h = \prod_{det} \mathcal{L}_{det,h}$

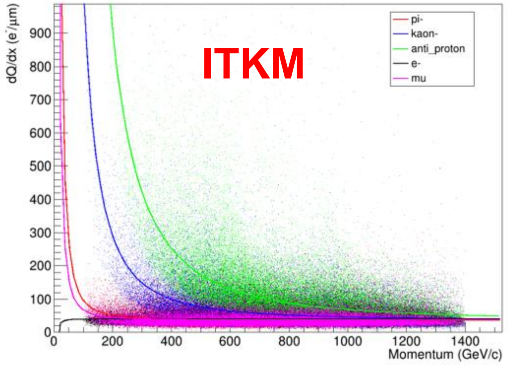
Likelihood ratio $p(h) = \dfrac{P_{\text{prior},h}\mathcal{L}_h}{\sum_h P_{\text{prior},h}\mathcal{L}_h}$

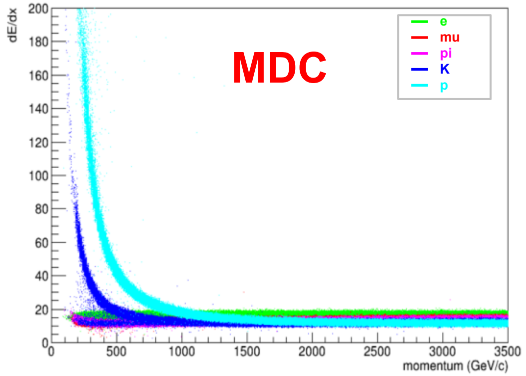
Detector	Feature	Description
Track	'Charge'	Reconstructed particle charge
	'Mom_x', 'Mom_y', 'Mom_z'	Particle momentum along the x, y, and z directions
	'HelixPar_d0'	Distance between the reference point and the point ($p0$) on the helix closest to it in the x–y plane
	'HelixPar_ϕ'	Azimuthal angle of the line connecting the helix circle center and the reference point in the x–y plane
	'HelixPar_cpa'	Inverse of the track transverse momentum, with the sign determined by the charge of the track
	'HelixPar_z0'	z coordinate of the point $p0$ on the helix closest to the reference point in the x–y plane
	'HelixPar_tanl'	Helix slope ($\frac{p_z}{p_t}$)
BTOF	'Likelihood_e'	Likelihood assuming the particle is an electron
	'Likelihood_μ'	Likelihood assuming the particle is a muon
	'Likelihood_k'	Likelihood assuming the particle is a kaon
	'Likelihood_π'	Likelihood assuming the particle is a pion
	'Likelihood_p'	Likelihood assuming the particle is a proton
dEdX	'dEdXsep'	χ^2 values under five particle hypotheses
ECAL	'NumHits'	Number of hits in the ECAL
	'Energy'	Reconstructed particle energy
	'ESeed'	Energy of the seed crystal
	'E3x3'	Local shower energy in 3×3 crystal around the seeding crystal
	'E5x5'	Local shower energy in 5×5 crystal around the seeding crystal
	'Position_x', 'Position_y', 'Position_z'	Spatial coordinates of the shower
	'SecondMoment'	Second matrix
	'LateralMoment'	Lateral matrix
	'ZernikeMoment{2,0}', 'ZernikeMoment{4,2}'	Zernike matrix (2×0 and 4×2)
MUD	'θ'	Polar angle
	'ϕ'	Azimuthal angle in the x–y plane
	'HitNum'	Number of hits in the MUD
	'RPCHitNum'	Number of hits in the RPC
	'PSHitNum'	Number of hits in the plastic scintillator detector
	'MaxHit'	Number of hits in the layer with the maximum occupancy
	'MaxHitLayer'	Index of the layer with the maximum number of hits
	'MudExp'	Probability of being identified as a muon
	'IsMuon'	Muon identification result (1 for muon, 0 otherwise)
DTOF	'logL_e'	Log-likelihood under the electron hypothesis
	'Logl_μ'	Log-likelihood under the muon hypothesis
	'Logl_π'	Log-likelihood under the pion hypothesis
	'Logl_k'	Log-likelihood under the kaon hypothesis
	'Logl_p'	Log-likelihood under the proton hypothesis

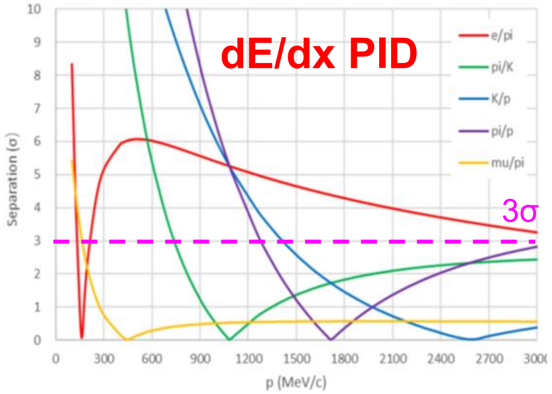
Table 1: Detector features employed in global particle identification.

Subdetector PID performance

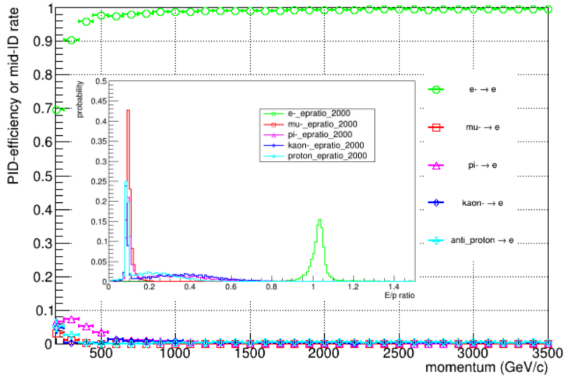
- **dQ/dx, dE/dx**







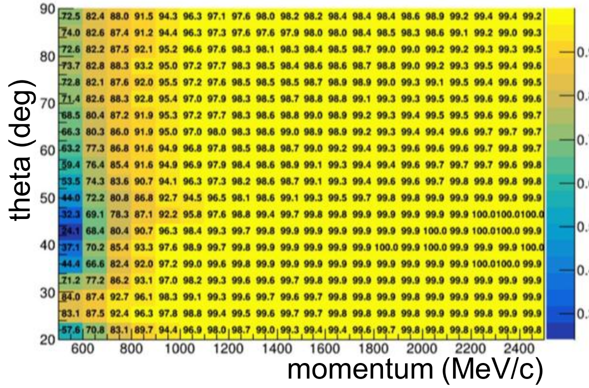
- **Electron ID（ECAL）**



➢ **pi/K**： >3σ at p<750 MeV/c, >2σ at p>2 GeV/c

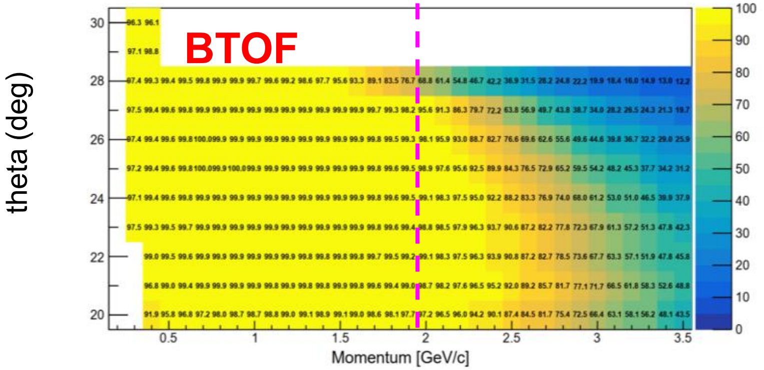
➢ **mu/pi**： >3σ at p<150 MeV/c; **e/pi**： >3σ except 120-250 MeV/c

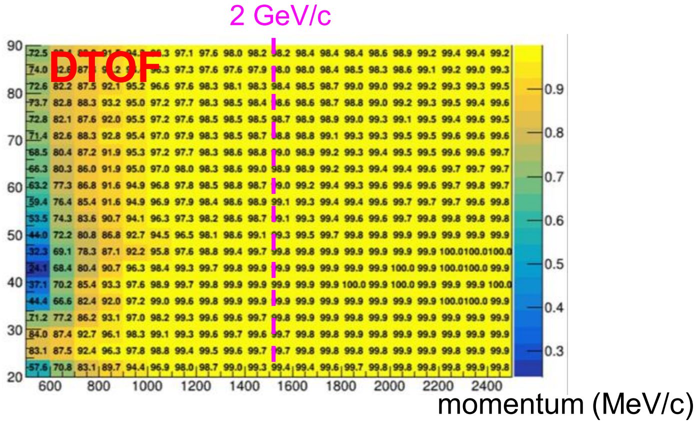
- **Muon ID（MUD&ECAL）**



➢ **>95% muon efficiency with pion mis-ID=3% at p>1 GeV/c**

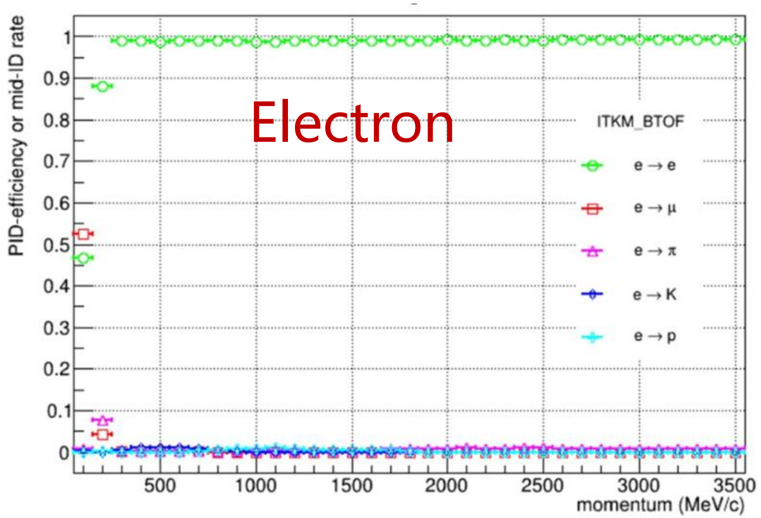
Pion efficiency with kaon mis-ID=2%

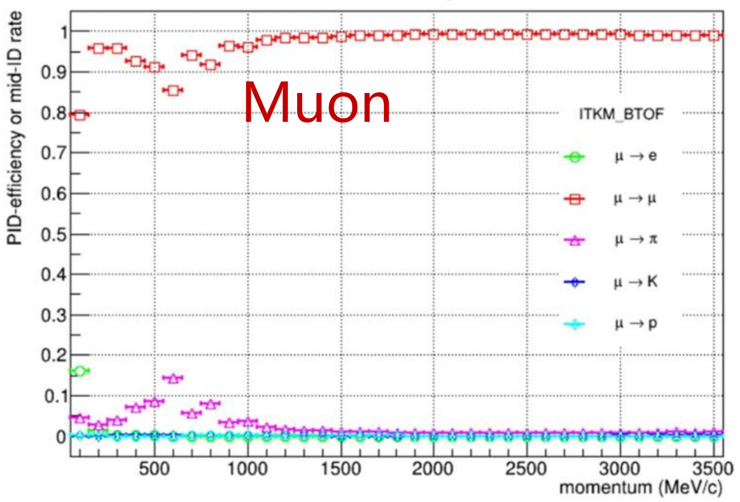


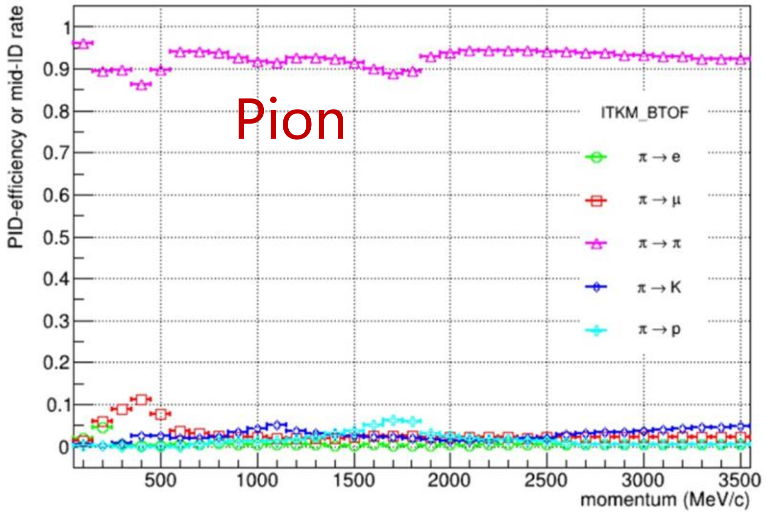


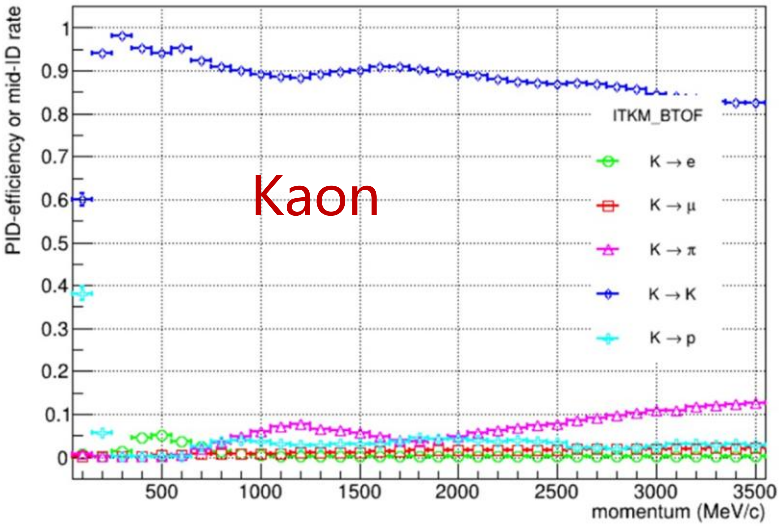
➢ **>97% pion efficiency with kaon mis-ID=2% at p<2 GeV/c**

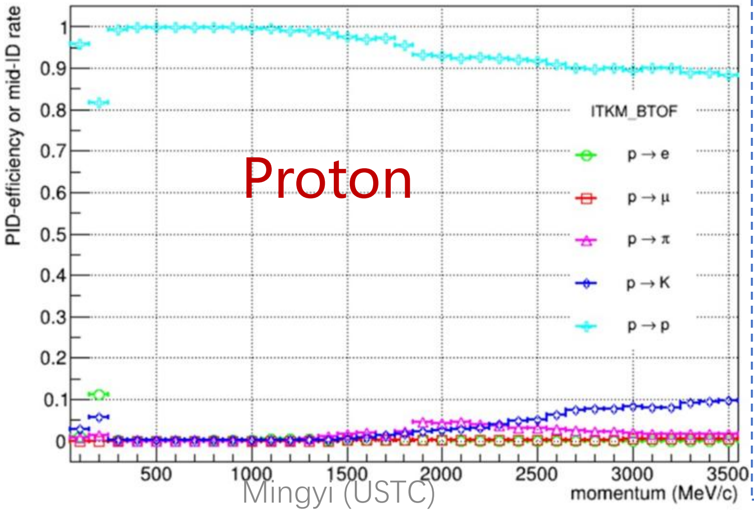
Global PID performance



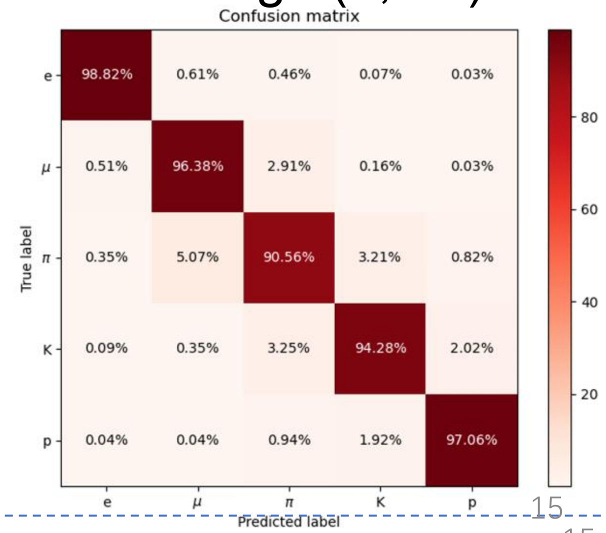








Overall ID/mis-ID efficiency with momentum range (0,3.5) GeV



Tau Physics at STCF: topic list

Topic	Fast Simulation	Full Simulation
Tau lepton EDM	CPC49 113001 (2025)	On going
Quantum entanglement within $\tau^+\tau^-$ pair	-	On going
Tau lepton reconstruction via $\tau \to \pi\pi\pi\nu_\tau$	-	On going
Charged lepton flavor violation via $\tau \to \mu\gamma$	Eur. Phys. J. C 83, 908	On going
Charged lepton flavor violation via $\tau \to \mu\mu\mu$	-	On going
Radiative decay $\tau \to \pi\nu_\tau\gamma$	-	On going
CP violation via $\tau \to \pi\nu_\tau K_s$	CPC45 053003 (2021)	On going
τ mass measurement	-	On going
$D_s^+ \to \tau^+\nu_\tau$ & $\lvert V_{cs}\rvert$ measurement	Eur. Phys. J. C 82, 310	On going
α_s via $\tau \to l\nu_l\nu_\tau$ vs $\tau \to \pi\pi^0\nu_\tau$	-	On going

MC simulation

- Tau pair production $\boldsymbol{e^+e^- \to \tau^+\tau^-}$: Simulated via MadGraph5.
- Tau decay:

Decay channel	MC Tool
$\tau \to e\nu_e\nu_\tau$ (Br: 17.4%)	• Decay chain embedded in MadGraph5. • With the "taudecay_UFO" modeling package. • Full spin correlation between tau and its decay products are considered. • Interference between different tau polarization states are considered.
$\tau \to \mu\nu_\mu\nu_\tau$ (Br: 17.8%)	
$\tau \to \pi\nu_\tau$ (Br: 10.8%)	
$\boldsymbol{\tau \to \pi\pi^0\nu_\tau}$ (Br: 25.5%)	
$\tau \to \pi\pi^0\pi^0\nu_\tau$ (Br: 9.3%)	
$\tau \to \pi\pi\pi\nu_\tau$ (Br: 9.0%)	
Other channels (Total Br: 10.2%)	Pythia8 (with spin correlation ON)

- ISR/FSR photon: Pythia8.
- Detector/Digitization/Reconstruction via OSCAR.

Study of $\rho\rho$ decay mode

- Signal: $\tau^+\tau^- \to \rho^+\rho^-\bar{\nu}_\tau\nu_\tau \to \pi^+\pi^-2\pi^0\bar{\nu}_\tau\nu_\tau$
- Major backgrounds – Other tau decay modes, e.g.:

$$a^+\rho^-/\rho^+a^- \to \pi^+\pi^-3\pi^0,\ a^+\pi^-/\pi^+a^- \to \pi^+\pi^-2\pi^0,\ \rho K^*,\ \text{etc.}$$

- Object selection:

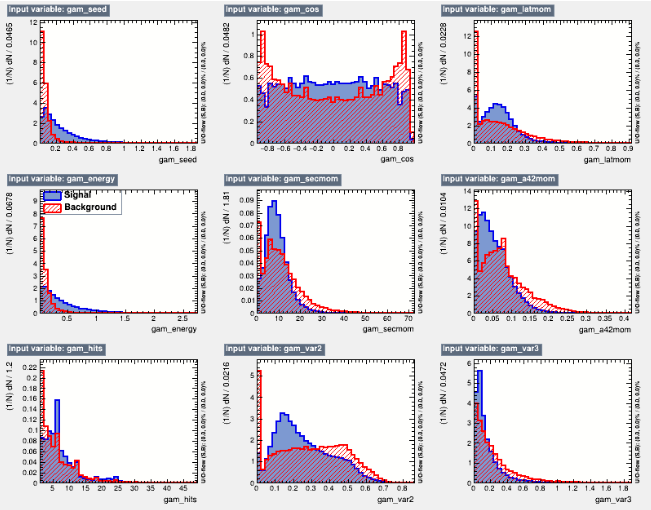
  → γ **energy** $\boldsymbol{E > 0.05\ GeV}$ **(endcap),** $\boldsymbol{E > 0.025\ GeV}$ **(barrel)**

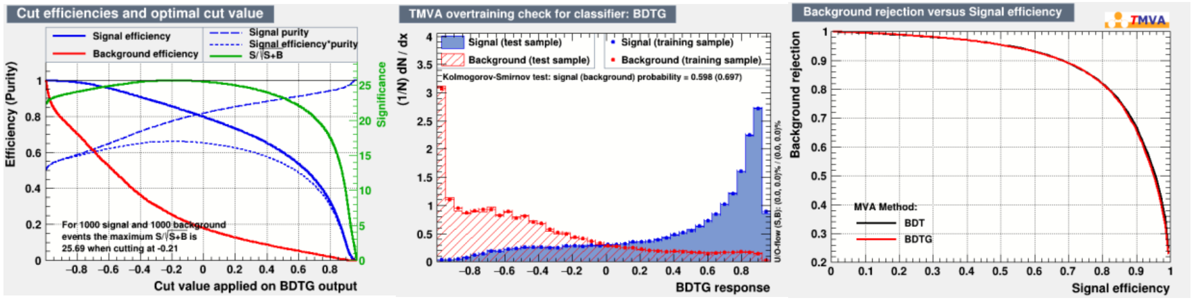
  → **Geometric acceptance (detector constrain):** $\boldsymbol{20^\circ < \theta < 160^\circ}$

  → **Use BDTG to Select** $\boldsymbol{\pi^0}$ **gamma from other gamma (ISR gamma: low energy, forwarded)**

Input variables, e.g.:

- E deposited in center crystal.
- Total energy.
- Secondary energy.
- …

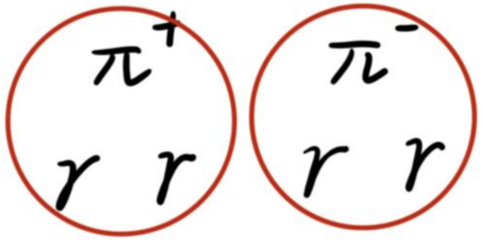




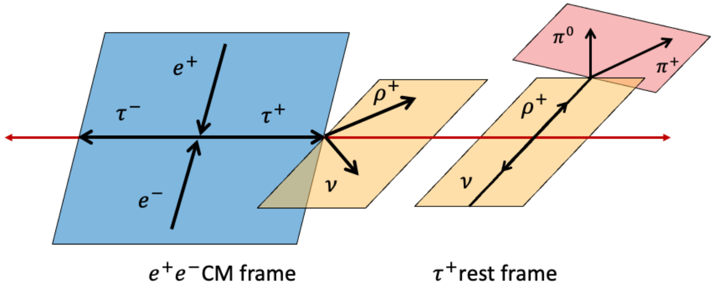
- ❑ Retaining about 80% π^0 gamma and 20% BKG gamma.
- ❑ Efficiency : SGN channel(25.2%), Inclusive channel(7.3%).

Study of $\rho\rho$ decay mode

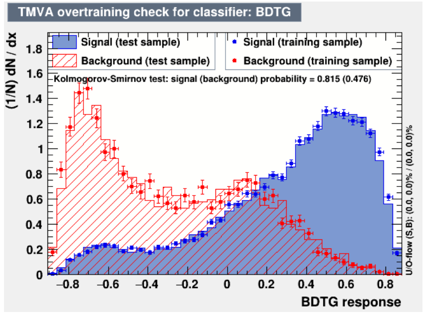
- ❑ Object requirement: $N_{\pi^+} = 1$, $N_{\pi^-} = 1$, $N_\gamma = 4$.



- ❑ Tau reconstruction
  - Group 4γ to $2\pi^0$ (by mass constrain).
  - Pairing π^0 with π^+/π^-, solve the ν energy-momentums:
    - ✓ Energy-momentum conservation (4 equation).
    - ✓ Mass constraints of τ (2 equation).
    - ◆ One can solve the missing ν momentums: yet, with a two-folded ambiguity.
    - ✓ Kinematic constraints:



$$p_{\nu(1)} + p_{\nu(2)} < \frac{E_{total}}{2},\ 0.115\text{GeV} < m_{\pi^0} < 0.150\text{GeV},\ 0.6\text{GeV} < m_{\pi\pi^0} < 1.0\text{GeV}.$$



- ❑ Event level BDTG to further separate SGN from BKG.
- ❑ Combine vertex information/implement ML technique to optimize the tau reconstruction.

Study based on $\rho\rho$ decay mode: EDM

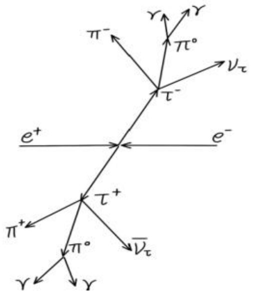
Prospect at STCF ($@\sqrt{s} = 4.26\text{GeV}$):

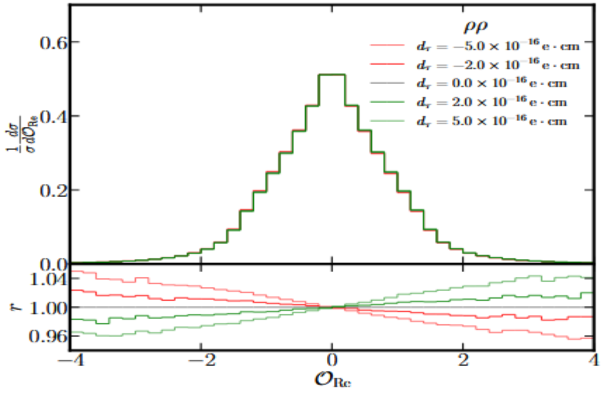
- 3.5×10^9 tau pairs with 1 year data taking
- Feasibility study (fast simulation):
  - Signal events ($\rho\rho$ mode): 2.2×10^8
  - Signal yield after selection: 1.4×10^7 (efficiency: 6.3%, purity: 80.0%)
- Full simulation is on-going

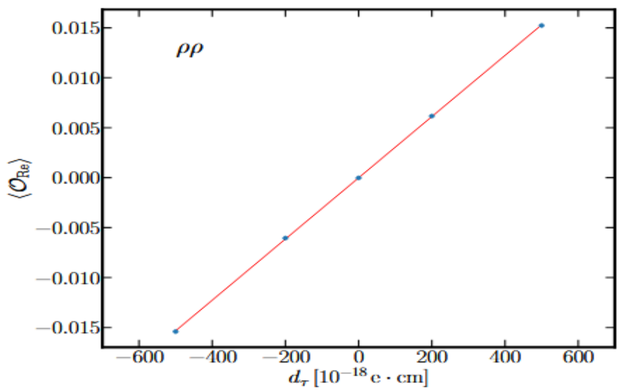
Chin. Phys. C 49,113001

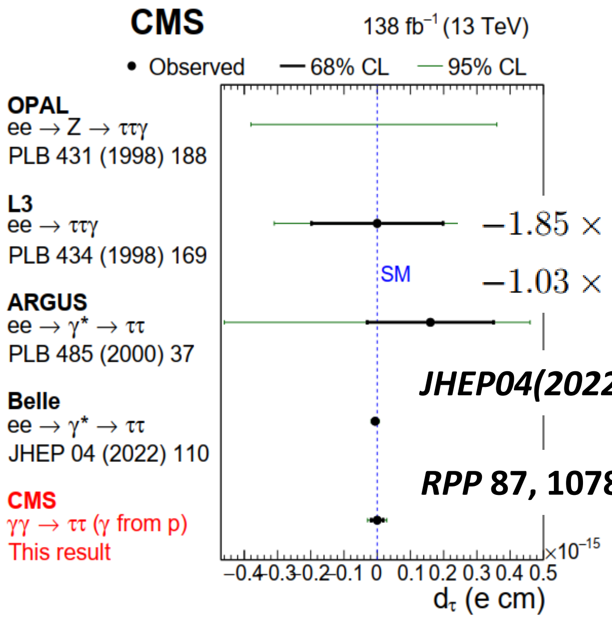
$$\langle \mathcal{O}_{\text{Re}} \rangle = a_{\text{Re}} \cdot \text{Re}\,(d_\tau) + b_{\text{Re}}, \quad \langle \mathcal{O}_{\text{Im}} \rangle = a_{\text{Im}} \cdot \text{Im}\,(d_\tau) + b_{\text{Im}}$$

Mode	a^i_{Re} $[(10^{-18} e \cdot \text{cm})^{-1}]$	b^i_{Re}	$\delta\langle \mathcal{O}_{\text{Re}} \rangle^i$
$\pi\pi$	$1.16 \times 10^{-5} \pm 2.80 \times 10^{-7}$	$2.15 \times 10^{-5} \pm 9.52 \times 10^{-5}$	2.128×10^{-4}
$\rho\rho$	$3.06 \times 10^{-5} \pm 1.43 \times 10^{-7}$	$-1.85 \times 10^{-5} \pm 4.87 \times 10^{-5}$	1.088×10^{-4}









$$-1.85 \times 10^{-17} < \text{Re}(d_\tau) < 0.61 \times 10^{-17}\ \text{ecm},$$
$$-1.03 \times 10^{-17} < \text{Im}(d_\tau) < 0.23 \times 10^{-17}\ \text{ecm}.$$

JHEP04(2022)110

RPP **87, 107801 (2024)**

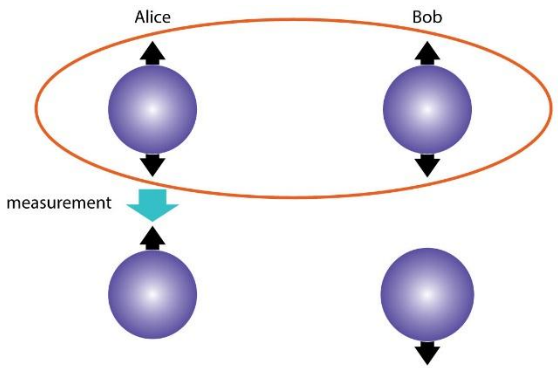
STCF prospected:

- $|d_\tau| < 3.89 \times 10^{-18}\ e \cdot \text{cm}$ for $\rho\rho$ channel.
- $|d_\tau| < 2.01 \times 10^{-17}\ e \cdot \text{cm}$ for $\pi\pi$ channel.

Study of $\tau^\pm \to \pi^\pm\pi^0\nu$: Quantum entanglement

Motivation:

- Entanglement is a critical phenomenon in QM.
- Validated by atomic and solid-state experiments @ low energy.

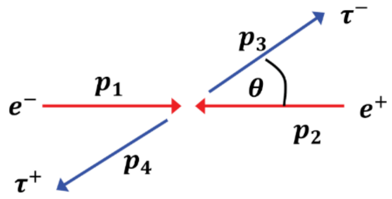


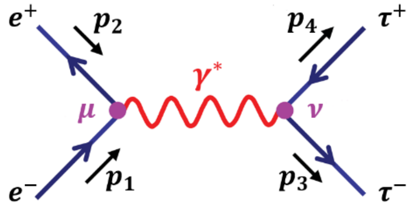
QE probing @ high energy physics gets more interesting these days:

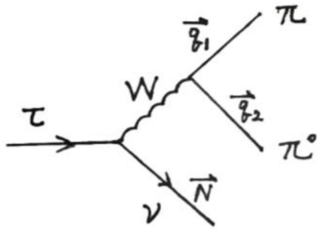
- ATLAS / CMS experiments observed QE within top-quark pairs, which leads the observation of toponium

  → **What about tau? Tauonium?**

✓ Quantum state tomography: Reconstruct the spin density matrix (SDM) based on decay products.

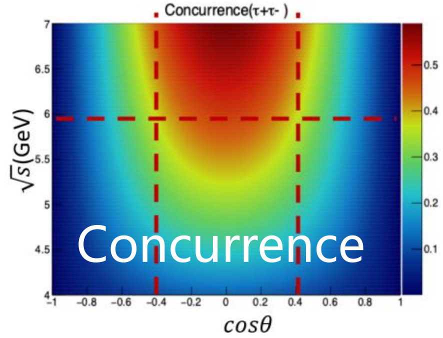


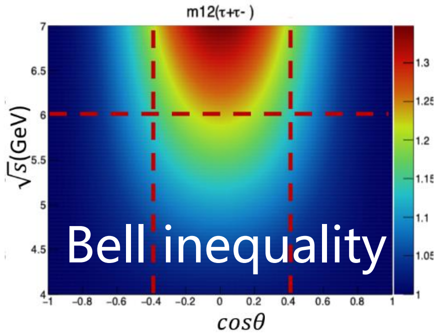




✓ Based on the SDM, place QE test

PRD 109, 032005 (2024)





$$\rho = \frac{1}{4}\left[\mathbf{1}_2 \otimes \mathbf{1}_2 + \sum_{i=1}^{3} B_i^+(\sigma_i \otimes \mathbf{1}_2) + \sum_{i=1}^{3} B_j^-(\mathbf{1}_2 \otimes \sigma_j) + \sum_{i,j=1}^{3} C_{ij}(\sigma_i \otimes \sigma_j)\right],$$

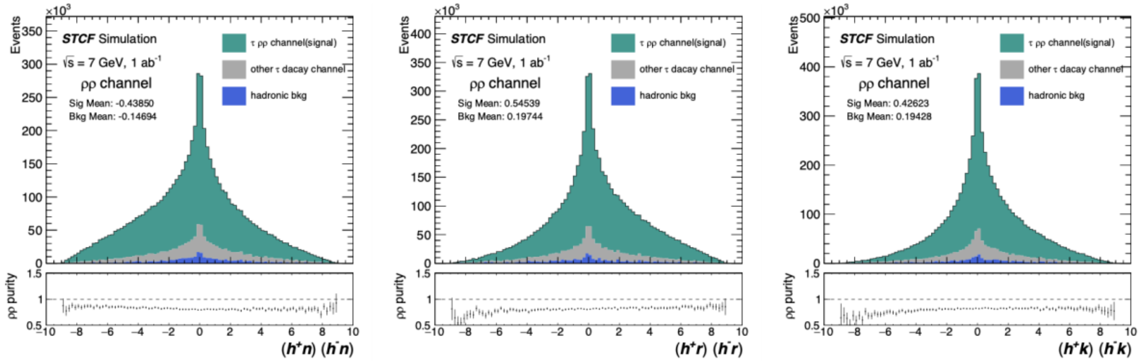
$$B_i^\pm = \frac{3}{\kappa_\pm}\frac{1}{\sigma}\int \mathrm{d}\Omega^\pm \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega^\pm}(\vec{n}^\pm \cdot \hat{e}_i),$$

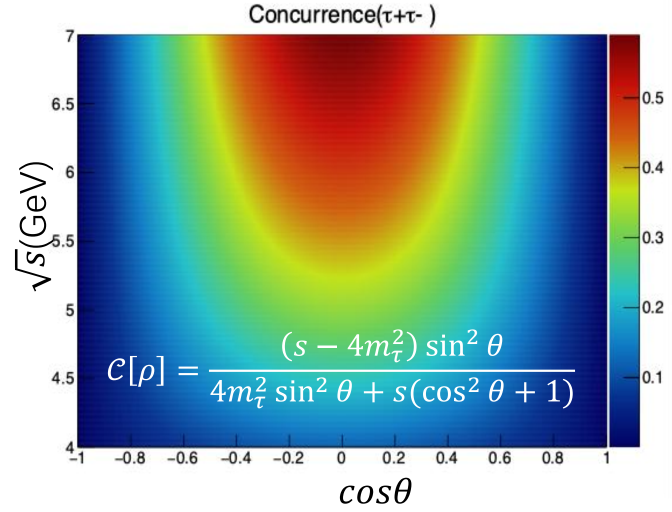
$$C_{ij} = \frac{9}{\kappa_+\kappa_-}\frac{1}{\sigma}\int \mathrm{d}\Omega^+\mathrm{d}\Omega^- \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega^+\mathrm{d}\Omega^-}(\vec{n}^+ \cdot \hat{e}_i)(\vec{n}^- \cdot \hat{e}_j)$$

- $\boldsymbol{h} \propto -[2(q^\mu N_\mu)\vec{\boldsymbol{q}} - (q^\mu q_\mu)\vec{\boldsymbol{N}}]$

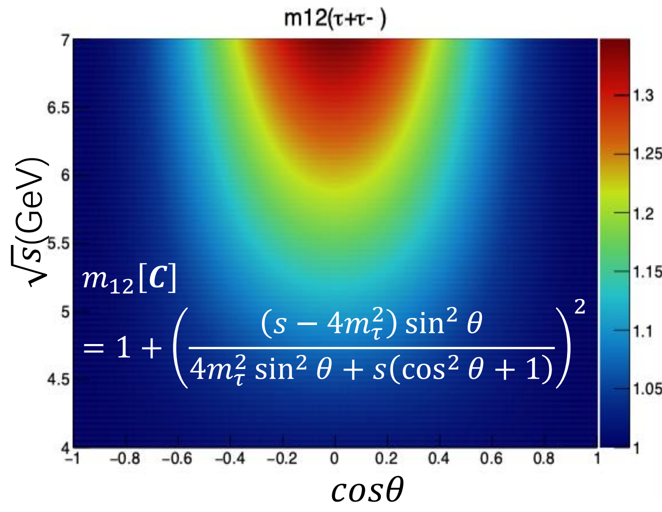
Study of $\tau^{\pm} \to \pi^{\pm}\pi^{0}\nu$: Quantum entanglement

- @7GeV, for enhancing entanglement significance
- Overall efficiency: 0.37% , Signal efficiency: 4.9% , Signal purity: 91.2%





- For systematics, we simulate the experimental resolution by varying ("smearing") the four-vectors of the charged and neutral particles.



- **The prospective value for tau pair concurrence under 1 ab^{-1}:**

$$\mathcal{C} = 0.31440 \pm 0.02249[stat.] \pm 0.01385[syst.]$$

Promising for a validation (>5σ) of the entanglement

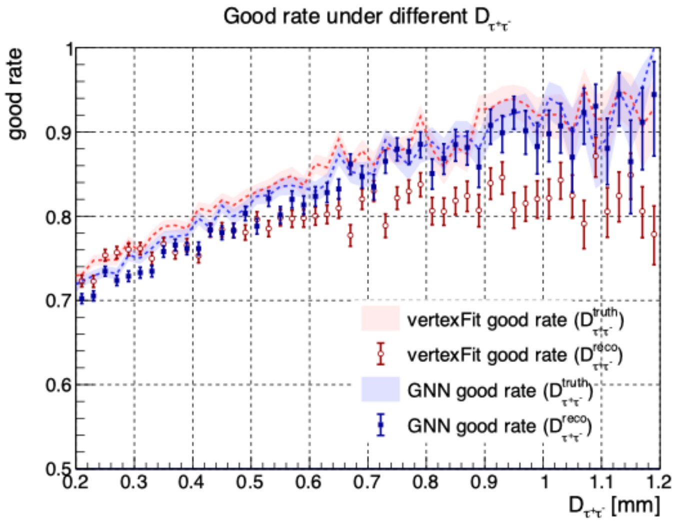
Study of $\tau^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}\nu$: vertex reconstruction

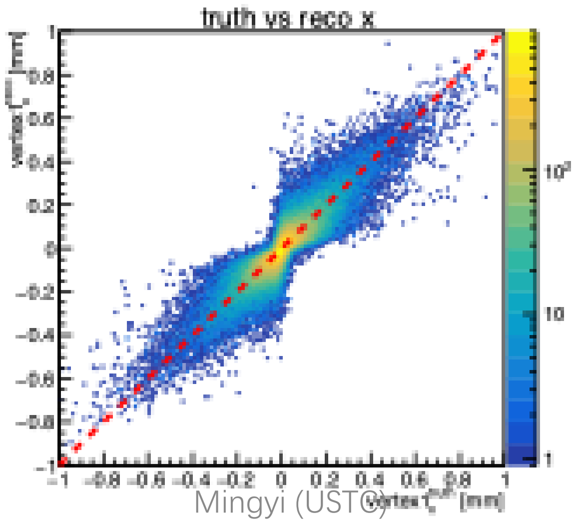
- 3 charged-tracks enabling the decay vertex fit.
- Tau vertices discriminate the two-folded results.
- Vertex reconstruction: GNN network
  - Vertex resolution improved:
  $53.1\ \mu m \to 34.8\ \mu m\ (\sigma_x); 67.7\ \mu m \to 63.8\ \mu m\ (\sigma_z)$
  - τ Double-Solution Selection Good Rate:
  $79.6\% \to 83.9\%$

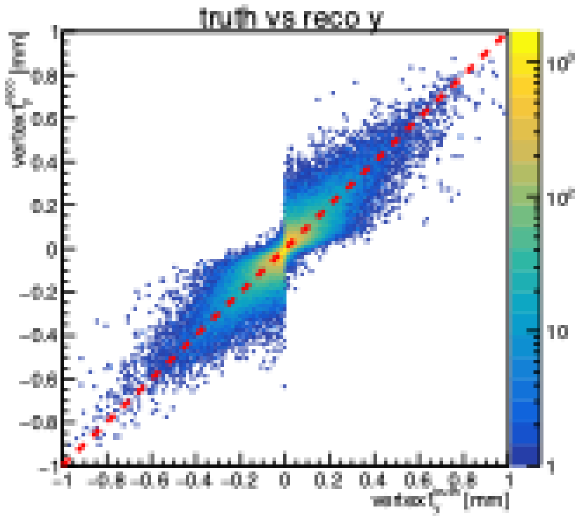
(As a reference, the good rate in the rho-rho channel is <60%)

Step	$a_1 a_1$ eff.(%)
Total events	-
N_{ch} = 6, total charge = 0	52.9
N_{π^+} = 3, N_{π^-} = 3	44.4
Particle pairing passed (vertex & kinematic)	59.3
τ momentum reconstruction passed	95.5
Overall	13.3

Overall efficiency: 13.3%, pairing correctness: 98.6%





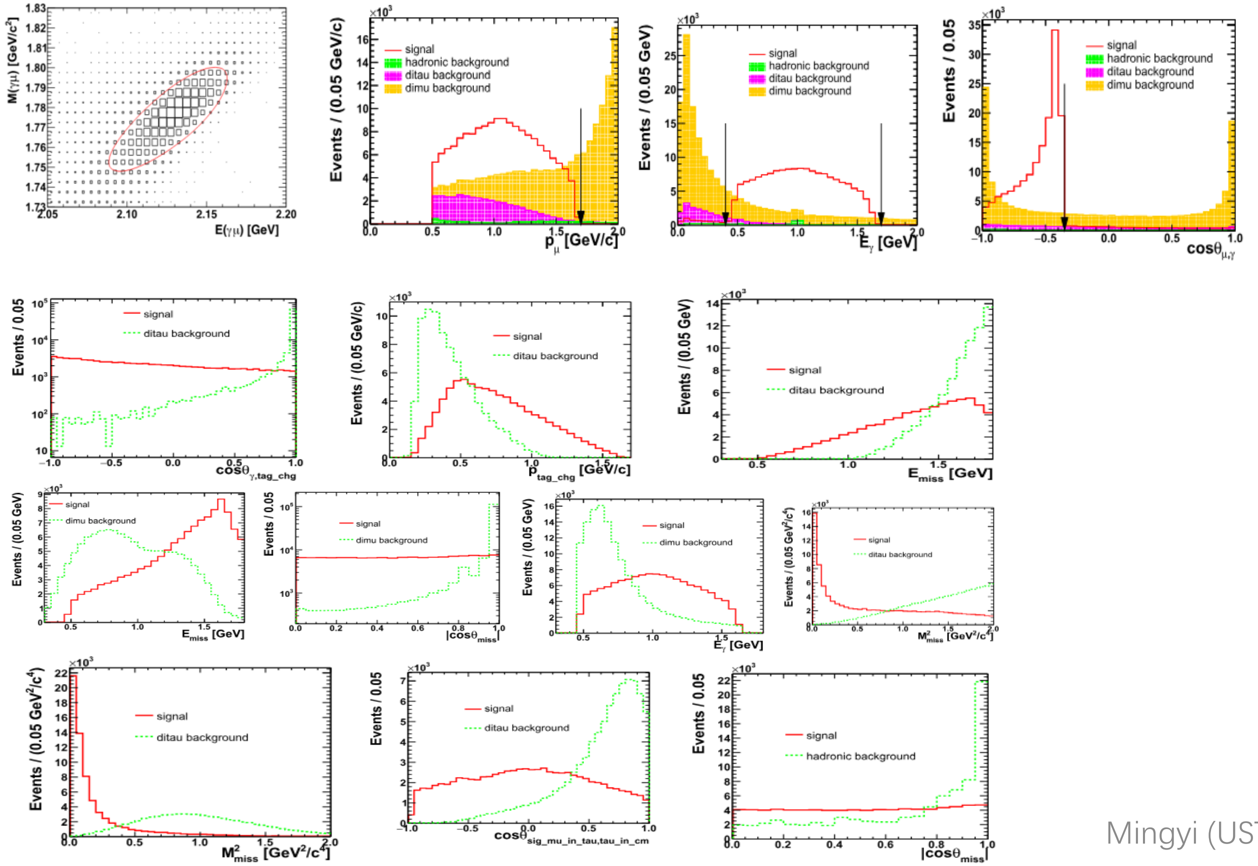


@7GeV

cLFV of $\tau \to \gamma\mu$ at STCF

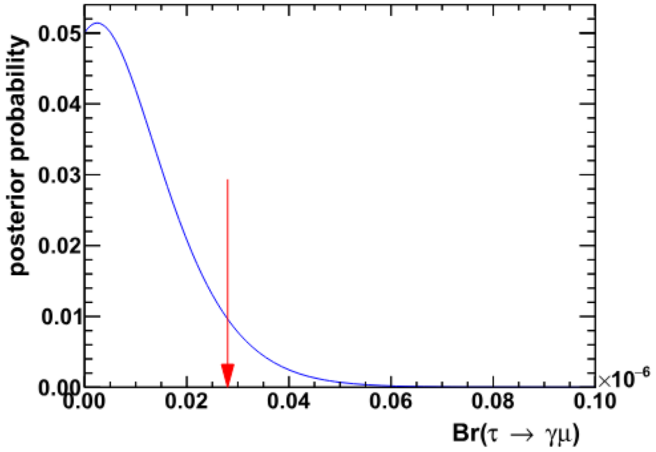
- Tag side: $\tau \to e\nu\bar{\nu},\ \pi\nu, \pi\nu\pi^0$; Signal side: $\tau \to \gamma\mu$.
- The energy of STCF can be adjusted to be just above the threshold of τ pair production:

$$\sigma \to max;\ E_{\gamma Radiative} \downarrow \to N_{\gamma Fake\ signal} \downarrow$$



Eur. Phys. J. C 83, 908

Tag mode	Selection criteria	N_{bkg} (ϵ) before	N_{bkg} (ϵ) after
$e^+\nu_e\bar{\nu}_\tau$	$\cos\theta_{sig\_\gamma,tag\_charged} < -0.2$	1.5×10^2 (2.6%)	0 (1.1%)
	$p_{tag\_charged} > 0.5\,GeV/c$		
	$E_{miss} < 1.7\,GeV$		
$\pi^+\bar{\nu}_\tau$	$E_{miss} > 0.7\,GeV$	1.4×10^4 (4.0%)	0.3 (0.5%)
	$\lvert\cos\theta_{miss}\rvert < 0.6$		
	$E_{sig\_\gamma} > 0.8\,GeV$		
	$M^2_{miss} < 0.050\,GeV^2/c^4$		
$\pi^+\pi^0\bar{\nu}_\tau$	$M^2_{miss} < 0.075\,GeV^2/c^4$	1.2×10^3 (2.6%)	1.2 (1.5%)
	$\cos\theta_{sig\_mu\_in\_tau,tau\_in\_cm} < 0.8$		
	$\lvert\cos\theta_{miss}\rvert < 0.9$		
Total		1.6×10^4 (9.2%)	1.5 (3.1%)

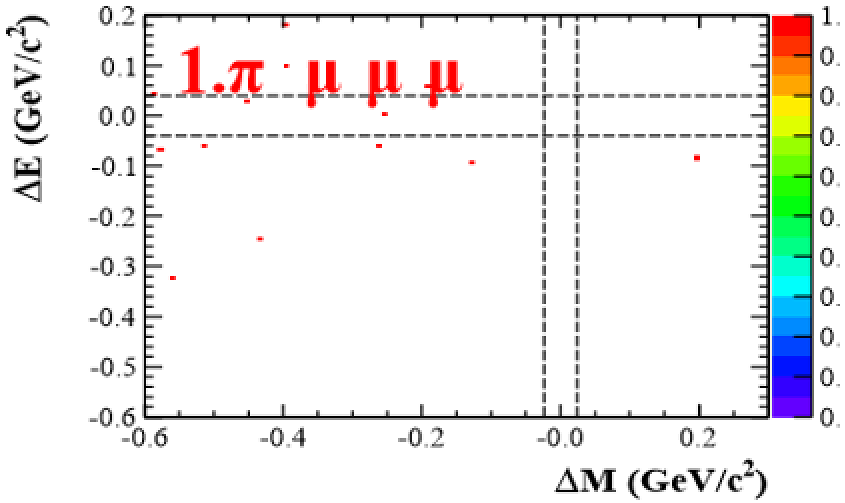


STCF with 1 ab^{-1}: $\mathcal{B}^{90}_{UL}(\tau \to \gamma\mu) < 2.8 \times 10^{-8}$

cLFV of $\tau \to \mu\mu\mu$ at STCF

Prospect at STCF:

- Signal side: $\tau \to 3\ leptons$
- Tag side: $\tau \to e\nu\bar{\nu},\ \mu\nu\bar{\nu},\ \pi\nu + n\pi^0$ ($\mathcal{B}r = 82\%$)
- Almost background free, sensitivity : $\mathcal{B}_{UL}^{90}(\tau \to \mu\mu\mu) \sim 1/\mathcal{L}$
- Best efficiency ($\tau \to \mu\mu\mu$): 22.5% (including the tag $\mathcal{BF}$)
- **STCF with 1 ab^{-1}:** $\mathcal{B}_{UL}^{90}(\tau \to \mu\mu\mu) < \frac{N_{UL}^{90}}{2\varepsilon N_{\tau\tau}} \sim 1.4 \times 10^{-9}$



Model	Ref.	$\tau \to \mu\mu\mu$	$\tau \to \gamma\mu$
SM + heavy Majorana	PRD 66.034008	$\mathbf{10^{-10}}$	10^{-9}
Non-universal Z'	PLB 547(3) 252	$\mathbf{10^{-8}}$	10^{-9}
SUSY + seesaw	PRL 89, 241802	$\mathbf{10^{-7}}$	10^{-10}
SM + 4th generation	JHEP 1009:104	$\mathbf{10^{-8}}$	10^{-8}

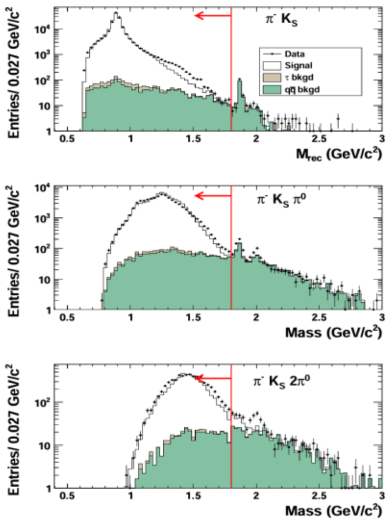
CPV in τ decay at STCF

- In **SM**, no direct CP violation in tau decays at the tree level. However, due to $\boldsymbol{K^0-\bar{K}^0}$ **mixing**, CPV appears in $\tau\to K_s\pi\bar{\nu}$, which is predicted to be

$$A_{cp}=\frac{\Gamma(\tau^+)-\Gamma(\tau^-)}{\Gamma(\tau^+)+\Gamma(\tau^+)}=(0.33+0.01)\%$$

- Experimentally, **BaBar** found evidence of CPV in $\tau\to K_s\pi\bar{\nu}$ decays, to be $A_{cp}=(-0.36\pm0.23\pm0.11)\%$

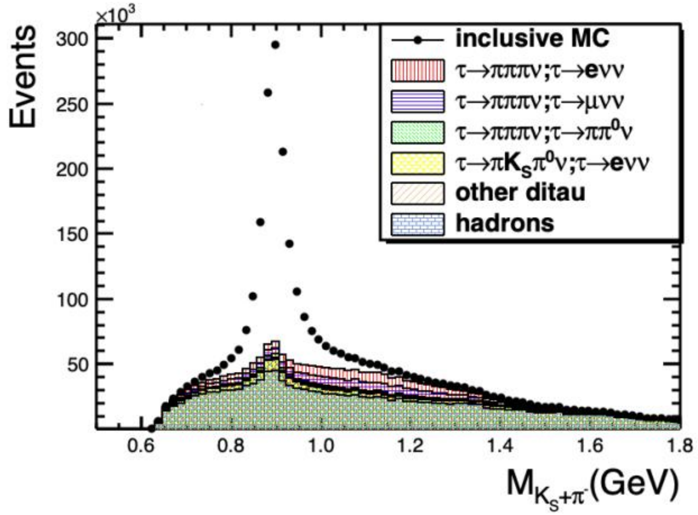
2.8σ deviation from SM prediction!

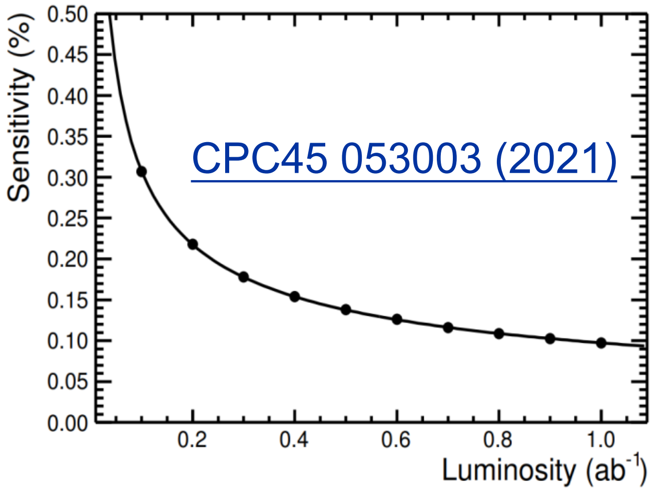


PRD 85, 031102 (2012)

Prospect at STCF:

- $e^+e^-\to\tau^+\tau^-$ at $\sqrt{s}=4.26$ GeV, $\tau_{tag}\to l\nu\nu$, $\tau_{sig}\to K_s\pi\nu$
- Optimized efficiency: 32.8%
- Using 1 ab^{-1} @ 4.26 GeV, sensitivity of CPV is determined with decay-rate difference between $\tau^+\to K_s\pi^+\nu_\tau$ and $\tau^-\to K_s\pi^-\bar{\nu}_\tau$, to be $\boldsymbol{\Delta A_{CP}\sim 0.097\%}$
- With 10 ab^{-1} data in $\sqrt{s}=4-5$ GeV : $\boldsymbol{\Delta A_{CP}\sim 0.031\%}$





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Summary

Recent status of STCF has been introduced

- Detector system design.
- Offline software and full simulation framework.
- Reconstruction algorithm.

Feasibility study for tau physics on STCF has been reported, yields promising sensitivity

- Quantum correlation and EDM study via $\rho\rho$ channel.
- Tau reconstruction enhancement via $3\pi^{\pm}$ decay channel.
- Charged flavor violation and CP violation study.

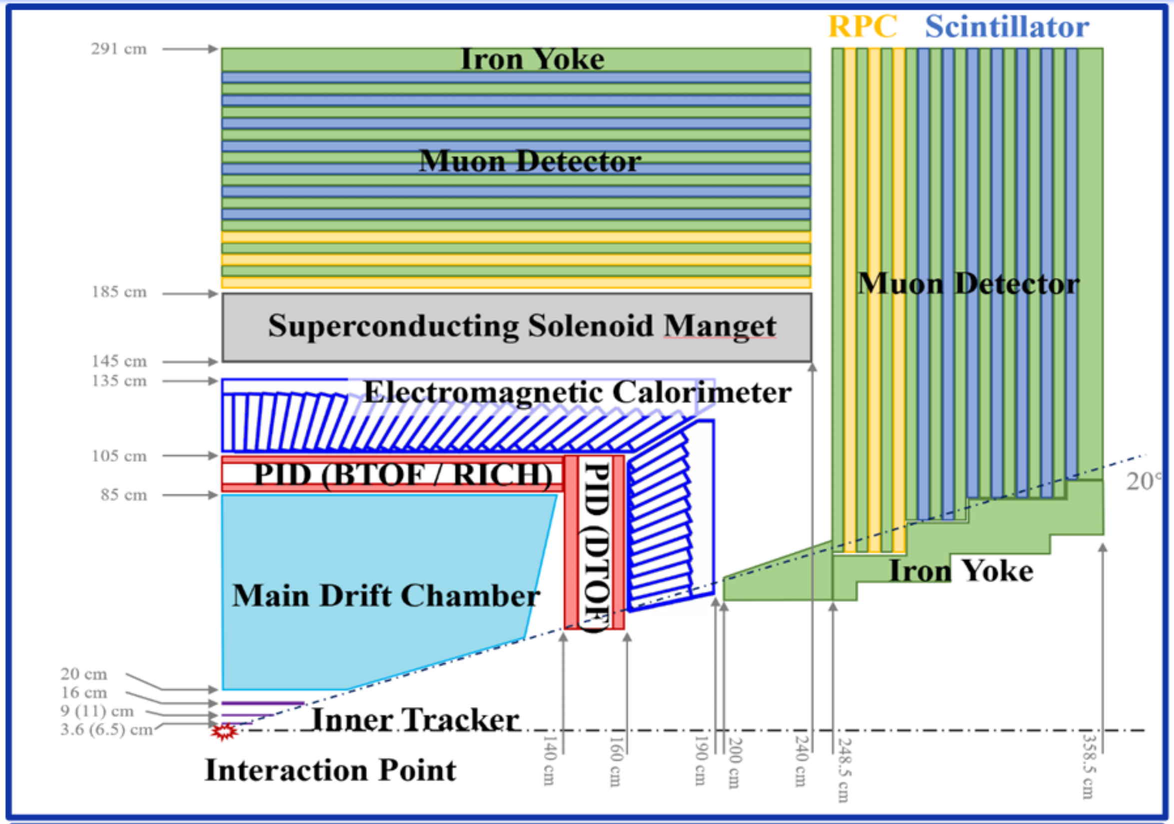
Thanks!

Backup

Prospected statistics from STCF

CME (GeV)	Lumi (ab^{-1})	Samples	σ(nb)	No. of Events	Remarks
3.097	1	J/ψ	3400	3.4×10^{12}	
3.670	1	$\tau^+\tau^-$	2.4	2.4×10^9	
3.686	1	$\psi(3686)$	640	6.4×10^{11}	
		$\tau^+\tau^-$	2.5	2.5×10^9	
		$\psi(3686) \to \tau^+\tau^-$		2.0×10^9	
3.770	1	$D^0\bar{D}^0$	3.6	3.6×10^9	
		$D^+\bar{D}^-$	2.8	2.8×10^9	
		$D^0\bar{D}^0$		7.9×10^8	Single tag
		$D^+\bar{D}^-$		5.5×10^8	Single tag
		$\tau^+\tau^-$	2.9	2.9×10^9	
4.009	1	$D^{*0}\bar{D}^0 + c.c$	4.0	1.4×10^9	$CP_{D^0\bar{D}^0} = +$
		$D^{*0}\bar{D}^0 + c.c$	4.0	2.6×10^9	$CP_{D^0\bar{D}^0} = -$
		$D_s^+D_s^-$	0.20	2.0×10^8	
		$\tau^+\tau^-$	3.5	3.5×10^9	
4.180	1	$D_s^{+*}D_s^-$+c.c.	0.90	9.0×10^8	
		$D_s^{+*}D_s^-$+c.c.		1.3×10^8	Single tag
		$\tau^+\tau^-$	3.6	3.6×10^9	
4.230	1	$J/\psi\pi^+\pi^-$	0.085	8.5×10^7	
		$\tau^+\tau^-$	3.6	3.6×10^9	
		$\gamma X(3872)$			
4.360	1	$\psi(3686)\pi^+\pi^-$	0.058	5.8×10^7	
		$\tau^+\tau^-$	3.5	3.5×10^9	
4.420	1	$\psi(3686)\pi^+\pi^-$	0.040	4.0×10^7	
		$\tau^+\tau^-$	3.5	3.5×10^9	
4.630	1	$\psi(3686)\pi^+\pi^-$	0.033	3.3×10^7	
		$\Lambda_c\bar{\Lambda}_c$	0.56	5.6×10^8	
		$\Lambda_c\bar{\Lambda}_c$		6.4×10^7	Single tag
		$\tau^+\tau^-$	3.4	3.4×10^9	
4.0–7.0	3	300-point scan with 10 MeV steps, 1 fb^{-1}/point			
> 5	2–7	Several ab^{-1} of high-energy data, details dependent on scan results			

Design indicators for detector



Major Performance Requirements

Acceptance: $94\% \times 4\pi$

Momentum res.: $\sigma_p/p \sim 0.5\%$ @ 1 GeV

Energy res. : $\sigma_E/E \sim 2.5\%$ @ 1 GeV

Hadron ID: $\pi/K \sim 4\sigma$ @ 2 GeV

Muon ID: eff. >95%, misrate <3.3% @1 GeV

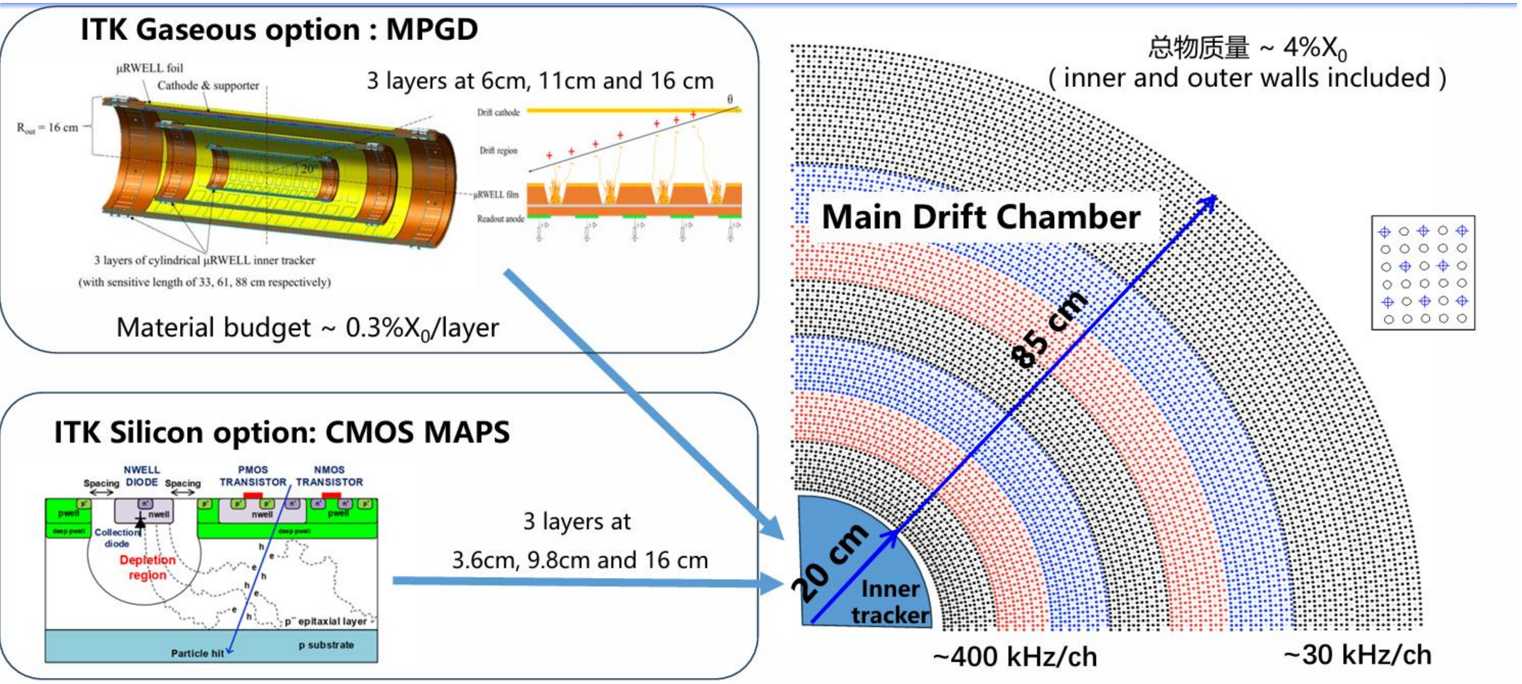
- Inner Tracker
  - MPGD: cylindrical uRGroove, $\sigma_x \sim 100\ \mu m$
  - Silicon: low-mass MAPS, $<0.3\% X_0$/layer
- Central Tracker ($\sigma_p/p \sim 0.5\%$ @ 1GeV)
  - Drift chamber with super-small cells, $\sigma_x < 130\ \mu m$
- PID System ($\pi/K \sim 4\sigma$ @ 2GeV)
  - Barrel: DIRC-like TOF ($\sigma_t \sim 30$ ps)
  - Endcap: RICH (<4mrad) or ASHIPH
- EMC
  - pCsI + APD: ($\sigma_E/E \sim 2.5\%$, $\sigma_x \sim 5$ mm, $\sigma_t \sim 300$ ps @ 1GeV)
- Solenoid ： 1 T
- Muon Detector (eff. >95%, mis-rate <3% @1GeV)
  - inner layers : glass RPC， > 300 Hz/cm^2
  - outer layers : scintillator strip + SiPM, ~ 2.4 m
- Trigger, DAQ, Clock and Data Transmission

Beam background at the inner most layer

~1 Mrad/y, $\sim 1 \times 10^{11}$ 1MeV n-eq/cm^2/y, ~1 MHz/cm^2

Tracking system: MDC + ITK

- Works in a **1T magnetic field**
- **MDC**: main drift tracker with large detection volume range 42 layers, 4 stereo super – layers, 4 axial super layers
- **ITK**: 4 layers of detectors with high counting rate capability
  - Placed in the area close to the beam pipe (3-20 cm)
  - Two options: MPGD/MAPS



Superlayer	Radius (mm)	Num. of Layers	Stereo angle (mrad)	Num. of Cells	Cell size (mm)
A	200.0	6	0	128	9.8 to 12.5
U	271.6	6	39.3 to 47.6	160	10.7 to 12.9
V	342.2	6	-41.2 to -48.4	192	11.2 to 13.2
A	419.2	6	0	224	11.7 to 13.5
U	499.8	6	50.0 to 56.4	256	12.3 to 13.8
V	578.1	6	-51.3 to -57.2	288	12.6 to 14.0
A	662.0	6	0	320	13.0 to 14.3
A	744.0	6	0	352	13.3 to 14.5
total	200 to 827.3	48		11520	

A further optimization of the tracking system is ongoing.