Study of the background mixing algorithm for ECAL

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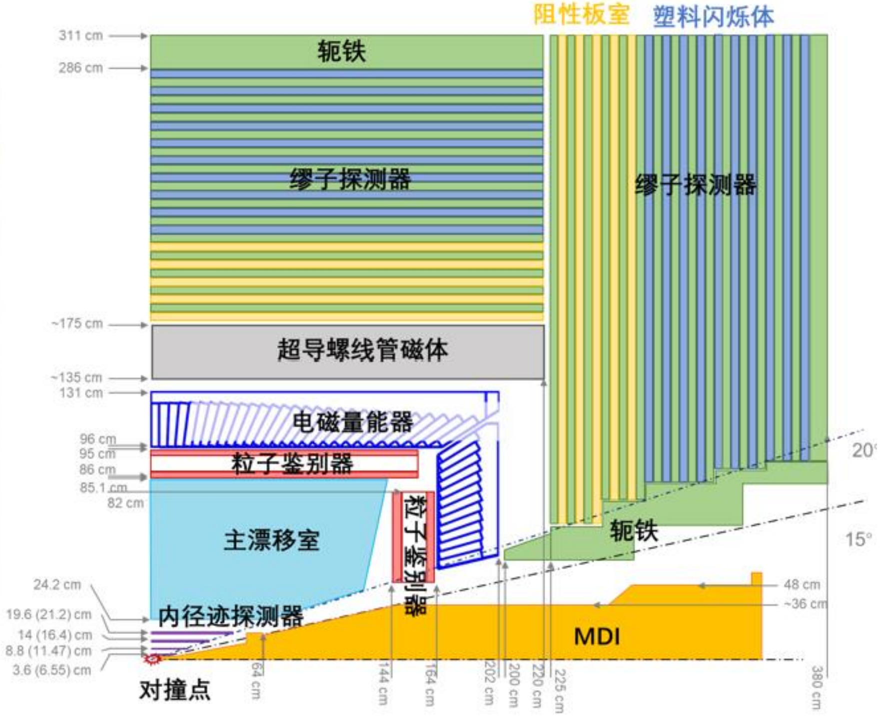
Outline

I. Motivation
II. Single-Event Check
III. Physics Validation
IV. Summary

Super Tau-Charm Facility (STCF)

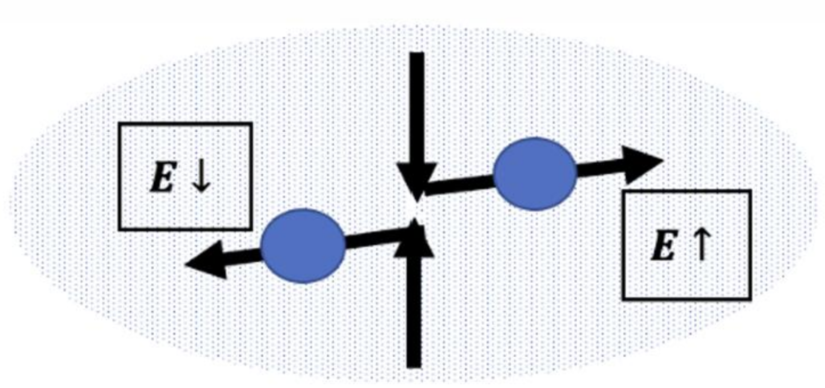
- Electron-positron collider experiment
- High luminosity：beyond $0.5 \times 10^{35}\ cm^{-2} \cdot s^{-1}$ @ 4GeV
- Wide energy region：center-of-mass energy range of 2~7 GeV



From Luminosity to Detector Reality: The Background Challenge

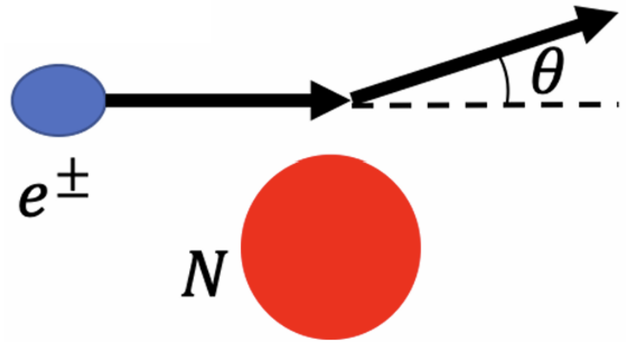
- **The High-Luminosity Trade-off**
  - Peak Lumi > $0.5 \times 10^{35}\ cm^{-2} \cdot s^{-1}$ @ 4GeV

  → High statistics, but severe beam-induced backgrounds.
- **Background Sources**
  - Beam-Gas (e^+/e^- with residual gas)
  - Touschek Effect (Intra-beam scattering)
  - Physics Background (γγ / Bhabha)
- **Why "Mixing" is Mandatory**
  - Pure signal ≠ Real data
  - Overlay time-correlated backgrounds onto signals
  - Enable realistic digitization & test reconstruction robustness



Touschek effect: dominant background

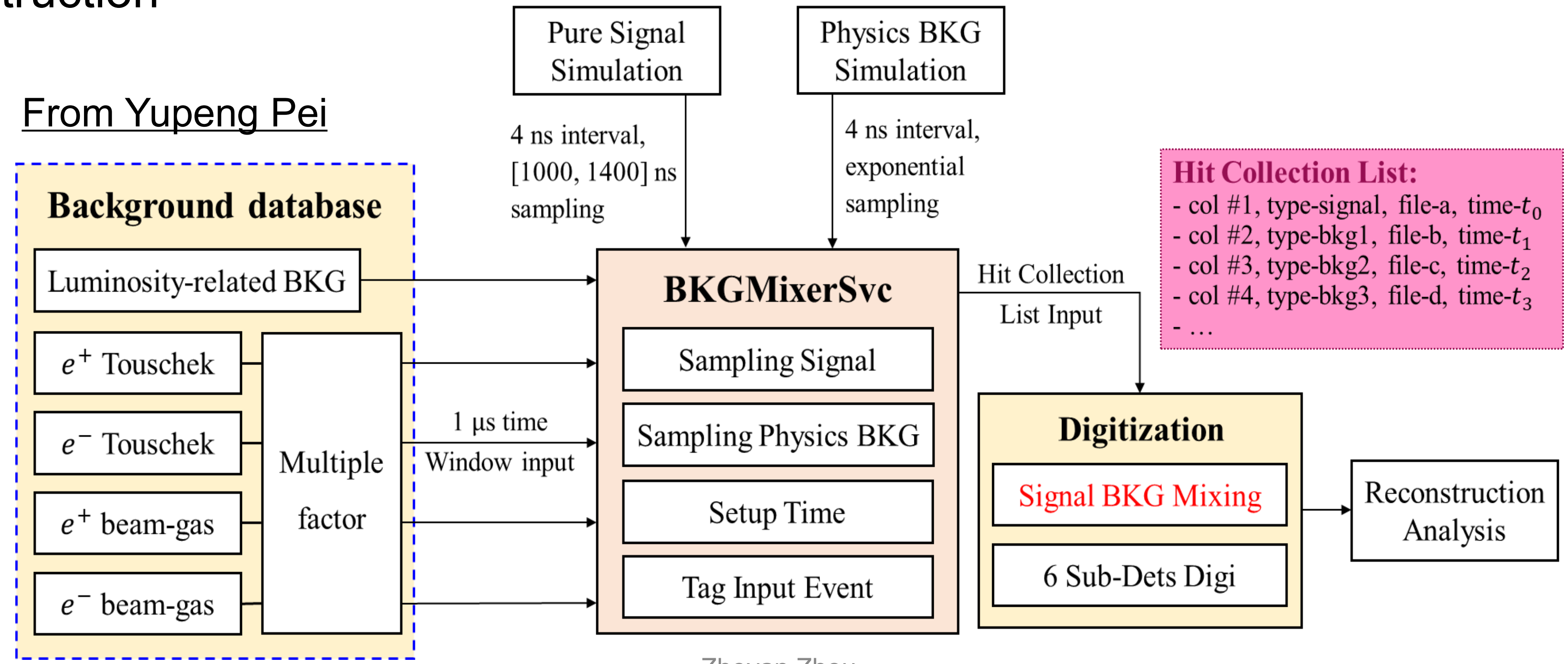
Beam-Gas Effect



Background Mixing Service

Baseline Background Mixing Pipeline

- **Build Database** – Independent simulation of each background source
- **Sample on demand** – Per signal event, sample hits from libraries within readout window
- **Mix & digitize** – Overlay signal + sampled backgrounds at preset ratios → digitization → reconstruction



Baseline: A Bottleneck in ECAL Digitization

- ECAL digitization dominates mixed-background processing time
  - ECAL with background: **~14.74 s/evt** — **41**× no-bkg cost
  - All other detectors: **≤ 1.40 s/evt**
- Root cause: Too many background hits in ECAL
- **→ ECAL is the bottleneck → calls for Fast-Mixing for ECAL**

100 $\psi(2S) \rightarrow \pi^+\pi^- J/\psi(\rightarrow \mu^+\mu^-)$ events

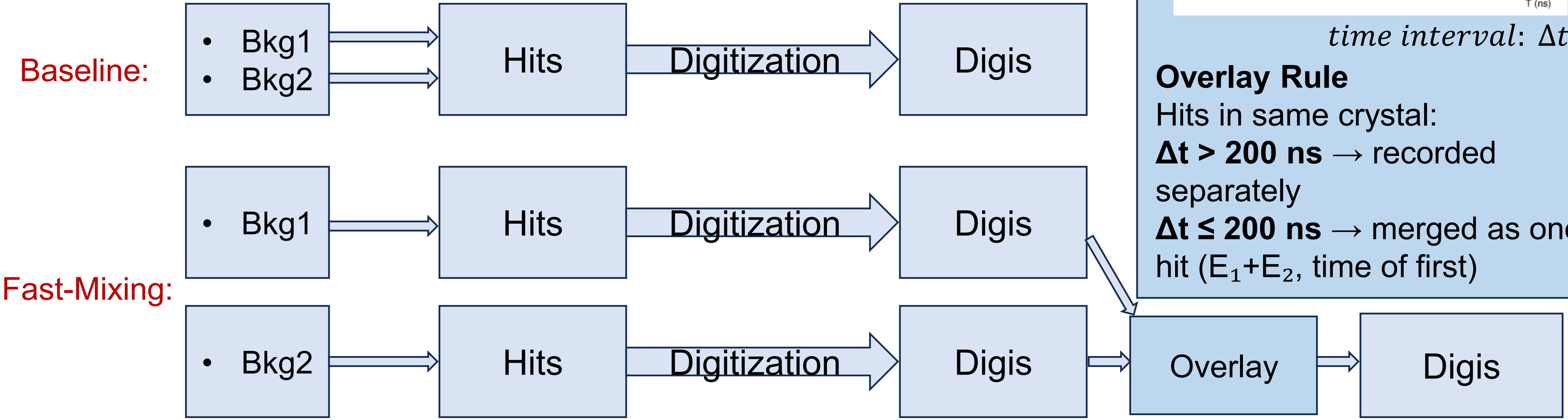
Detector	No Bkg (s)	With Bkg (s)	Sequential read (s)
ITKW	24.0	78.3	29.0
MDC	17.5	140.0	28.4
RICH	17.1	24.5	18.6
DTOF	16.8	29.7	17.96
ECAL	35.6	1473.9	1414.8
MUD	17.2	--	--
All Detector	42.6	1876.2	1344.6

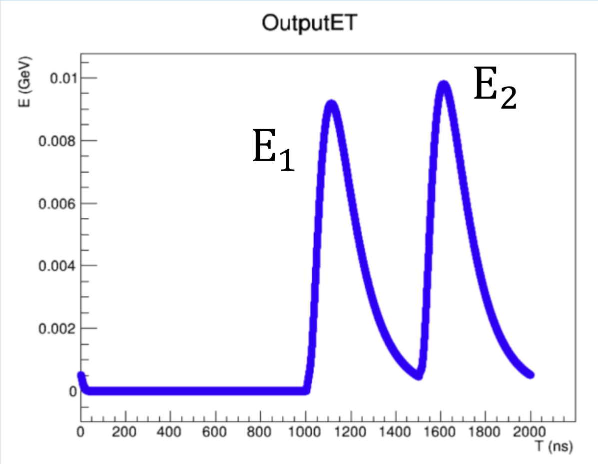
Y. Pei, STCF Digitization & Simulation Biweekly, 19 Jun 2025, Indico

From **Baseline** to **Fast-Mixing**

Fast-Mixing

- **Principle:** Pre-digitized background database → on-demand sampling & mixing
- **Validation:** Standalone tests confirm relative validity





time interval: Δt

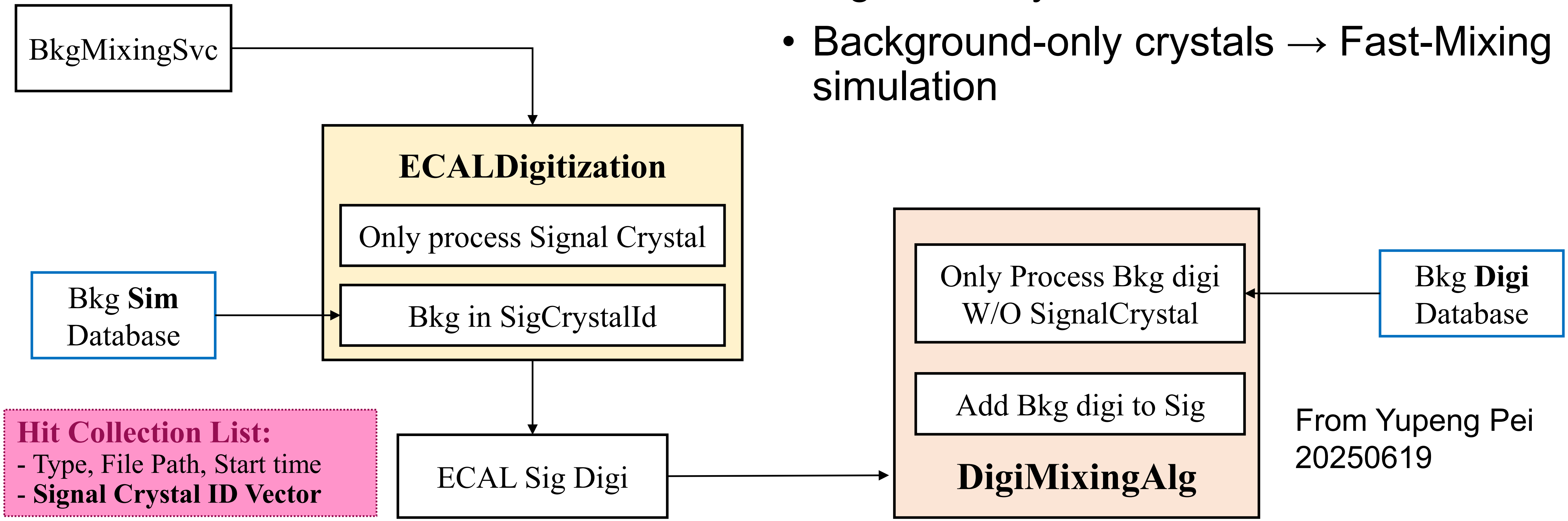
Overlay Rule
Hits in same crystal:
Δt > 200 ns → recorded separately
Δt ≤ 200 ns → merged as one hit (E_1+E_2, time of first)

Fast-Mixing Service

ECAL digitization time: 14.7 s/evt [Baseline] → 1.30 s/evt [FastMix]

Hybrid strategy:

- Signal-hit crystals → Baseline simulation
- Background-only crystals → Fast-Mixing simulation

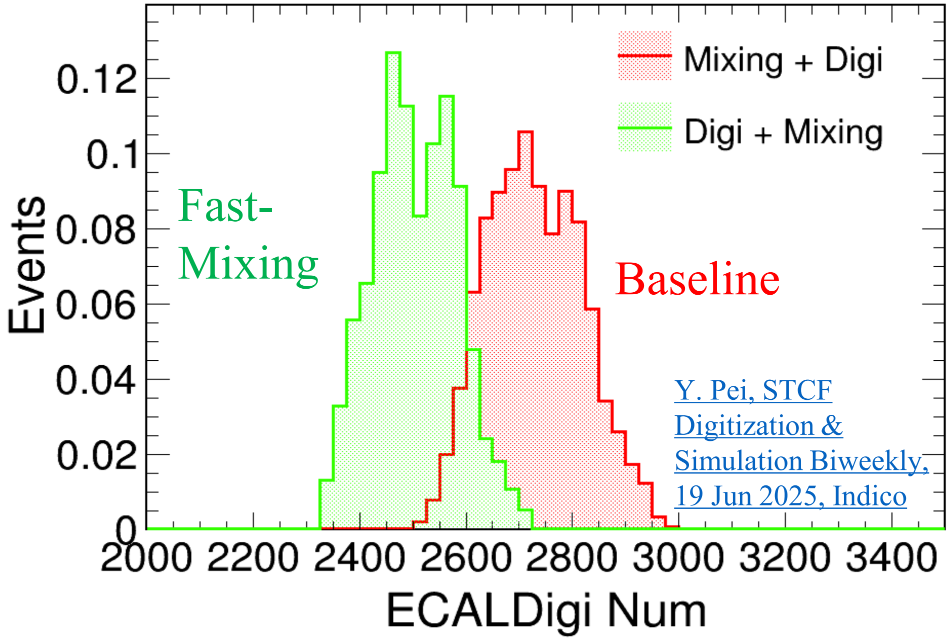


From Yupeng Pei 20250619

Single-Event Check

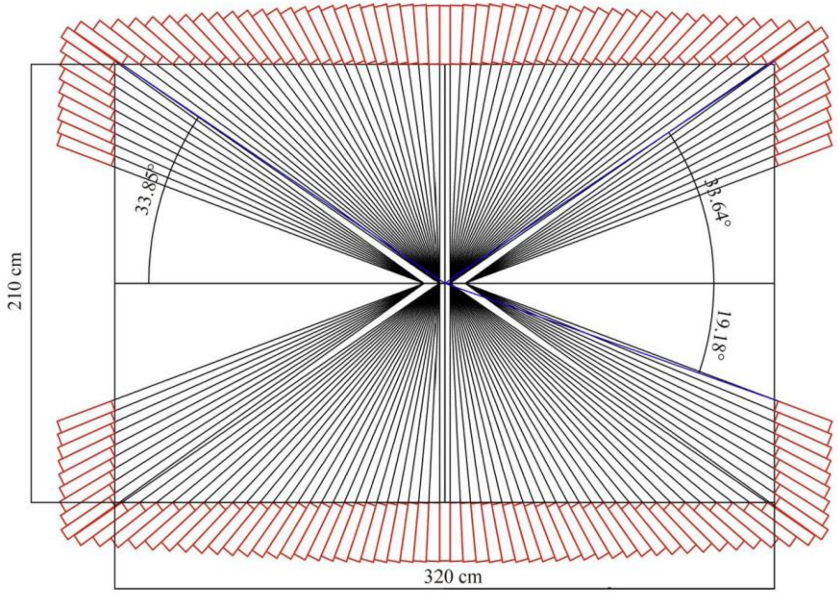
Fast-Mixing Service

- **Issue**: ECAL Digi distribution shows a clear leftward shift versus baseline.
- **Comparison**: Fast-Mixing shifts the Digi count distribution to lower values.



Single-Event Check：To identify origin of differences between Baseline and Fast-Mix

Signal	ρπ decay channel
Background Sources	e^+/e^- Touschek effect (2 background), generated by V7c3
Method	Compare Hit Map on barrel ECAL



The ECAL Layout Design

Difference Hit Map: Baseline vs Fast-Mixing

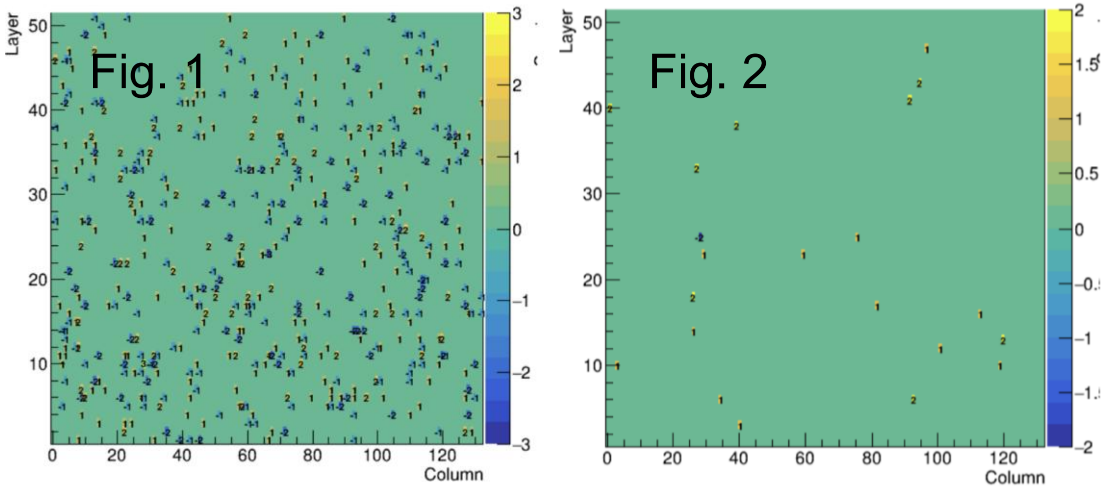
Method

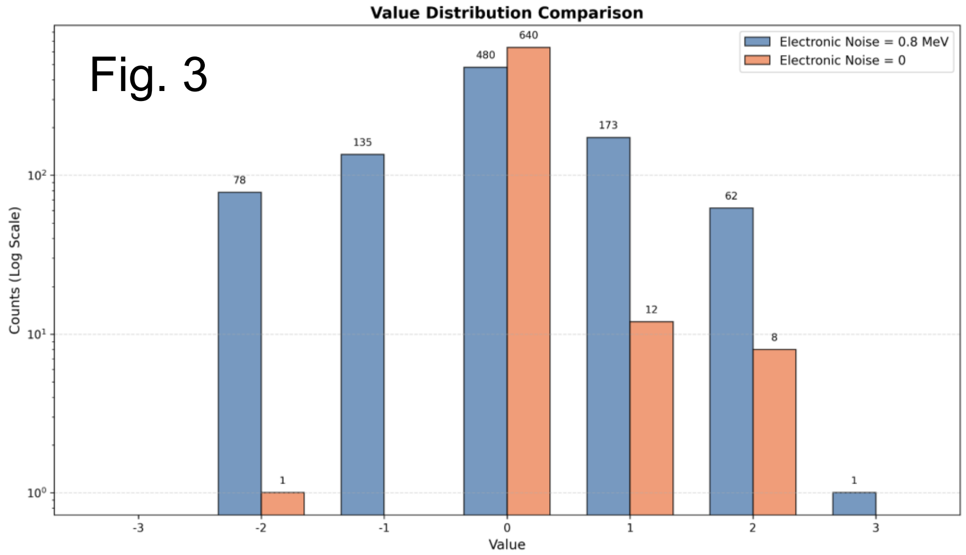
- Per-crystal digi-count difference (Baseline − Fast-Mixing) mapped onto ECAL
  - Fig. 1: with electronic noise (0.8 MeV)
  - Fig. 2: without electronic noise (0 MeV)
  - Fig. 3: Hit-count difference histogram (noise vs no noise)
- Crystals grouped by difference; examined with hit-level energy & time info

Conclusion

- Fast-Mixing operates as expected
- All differences understood, originating from digitization effects:
  - 0.8 MeV noise + 2 MeV threshold → stochastic hit classification (even for single hit)
  - Two background hits in same crystal → noise added twice (small fraction)

Hit-Count Difference (Baseline − Fast-Mixing)





From Single-Event Check to Physics Validation

Recap

- Baseline and Fast-Mixing differ in how they handle background mixing in ECAL
- Previous single-event studies attribute the differences to electronic noise near the 2 MeV threshold
- These differences are predominantly low-energy and may affect photon reconstruction

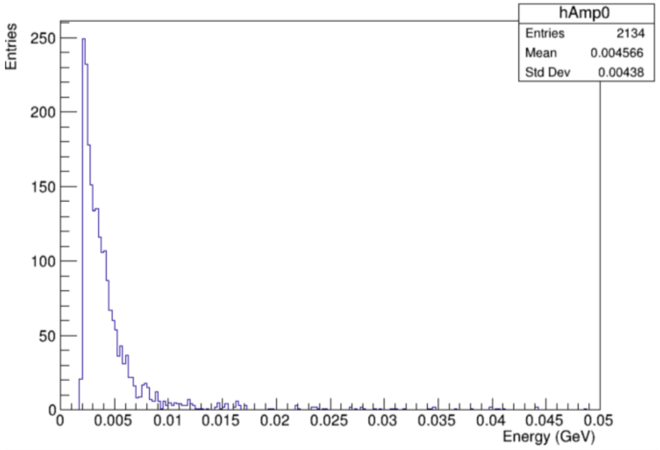
Objective

- Assess whether the two mixing modes produce consistent physics results.

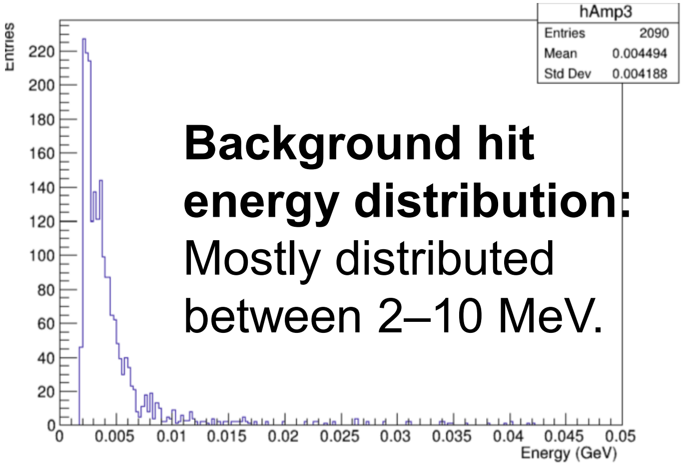
Approach

- Channel: $\Sigma^+ \rightarrow p\gamma$
- Compare: cutflow and distributions of key physics variables

Baseline Digi Energy



Fast-Mixing Digi Energy



Background hit energy distribution: Mostly distributed between 2–10 MeV.

Study of the Decay $\Sigma^+ \to p\gamma$ via $J/\psi \to \Sigma^+\bar{\Sigma}^-$

Measurement of the Absolute Branching Fraction

STCF benchmark physics for baryon radiative decay

- **Single Tag (ST)**

Reconstruct the decay

$$\bar{\Sigma}^- \to \bar{\mathrm{P}}\,\pi^0$$

to tag the process

$$J/\psi \to \Sigma^+\bar{\Sigma}^-$$

The ST yield is given by:

$$N_{\mathrm{ST}} = N_{J/\psi\to\Sigma^+\bar{\Sigma}^-} \times \mathcal{B}_{\bar{\Sigma}^-\to\bar{\mathrm{P}}\pi^0} \times \varepsilon_{\mathrm{ST}}$$

- **Double Tag (DT)**

On the recoil side of the ST events, reconstruct

$$\Sigma^+ \to p\gamma.$$

The DT yield is:

$$N_{\mathrm{DT}} = N_{J/\psi\to\Sigma^+\bar{\Sigma}^-} \times \mathcal{B}_{\bar{\Sigma}^-\to\bar{\mathrm{P}}\pi^0} \times \mathcal{B}_{\Sigma^+\to p\gamma} \times \varepsilon_{\mathrm{DT}}$$

- **Absolute Branching Fraction**

The absolute branching fraction is determined by:

$$\mathcal{B}_{\Sigma^+\to p\gamma} = \frac{N_{\mathrm{DT}}}{N_{\mathrm{ST}}} \times \frac{\varepsilon_{\mathrm{ST}}}{\varepsilon_{\mathrm{DT}}}$$

ST decay card

```
Decay J/psi
1.0 Sigma+ anti-Sigma- PHSP;
Enddecay

Decay Sigma+
0.5157 p+ pi0 PHSP;
0.4831 n0 pi+ PHSP;
0.0012 p+ gamma PHSP;
Enddecay

Decay anti-Sigma-
1.0 anti-p- pi0 PHSP;
Enddecay

Decay pi0
1.0 gamma gamma                    PHSP;
Enddecay

End
```

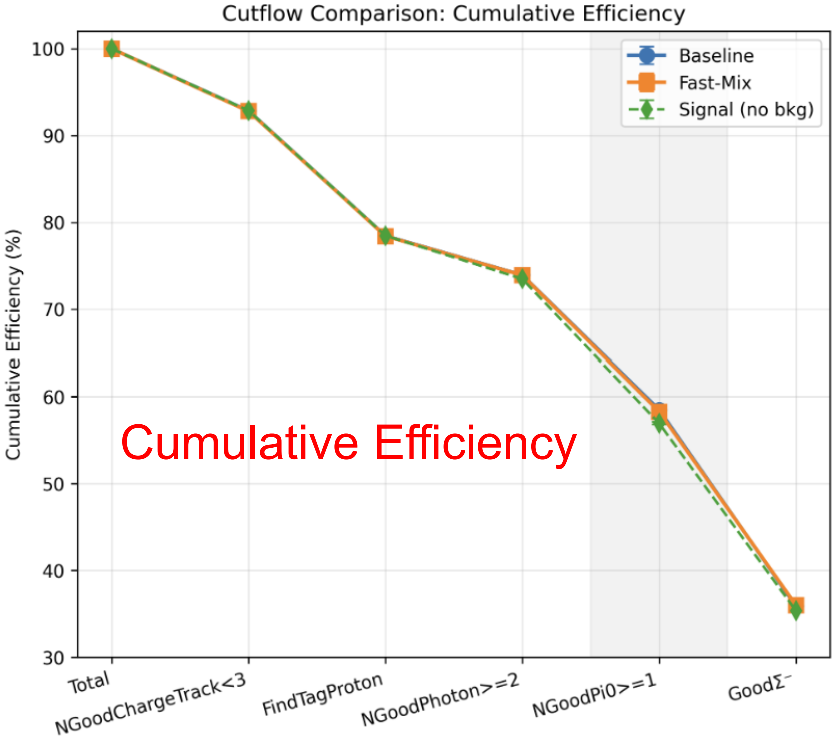
DT decay card

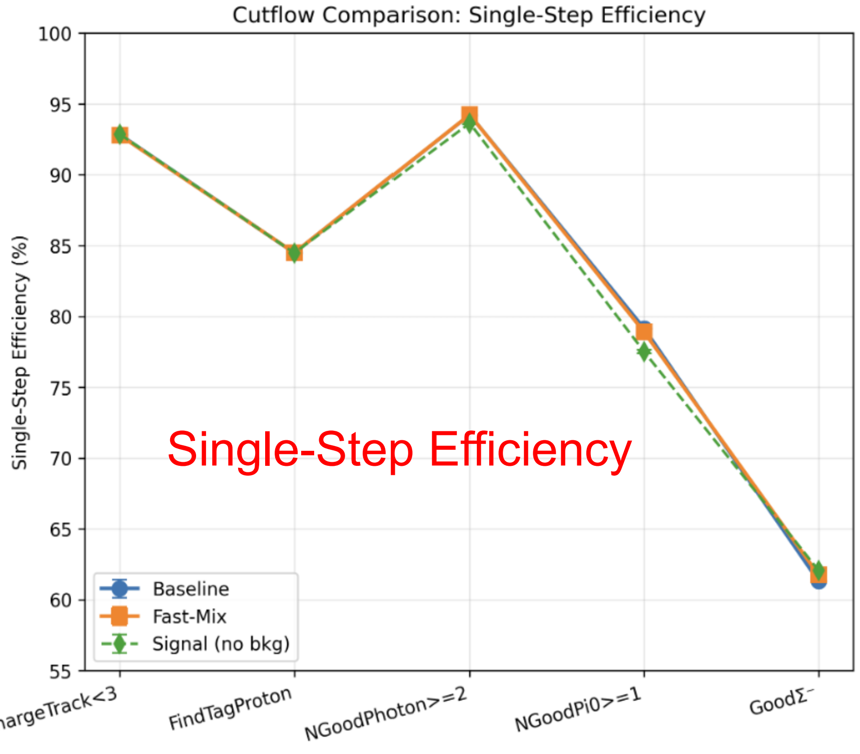
```
Decay J/psi
1.0 Sigma+ anti-Sigma- PHSP;
Enddecay

Decay Sigma+
1.0 p+ gamma PHSP;
Enddecay

Decay anti-Sigma-
1.0 anti-p- pi0 PHSP;
Enddecay

Decay pi0
1.0 gamma gamma                    PHSP;
Enddecay

End
```

Baseline vs Fast-Mixing: Cutflow Comparison

Sample: ST sample, **with ECAL beam background only**

- Baseline and Fast-Mixing show **no significant difference** in cutflow or key physics variables
- All observed deviations are **within statistical uncertainty (< 0.2%, < 2σ)**
- **Conclusion:** Fast-Mixing is statistically equivalent to Baseline for ST sample analysis.

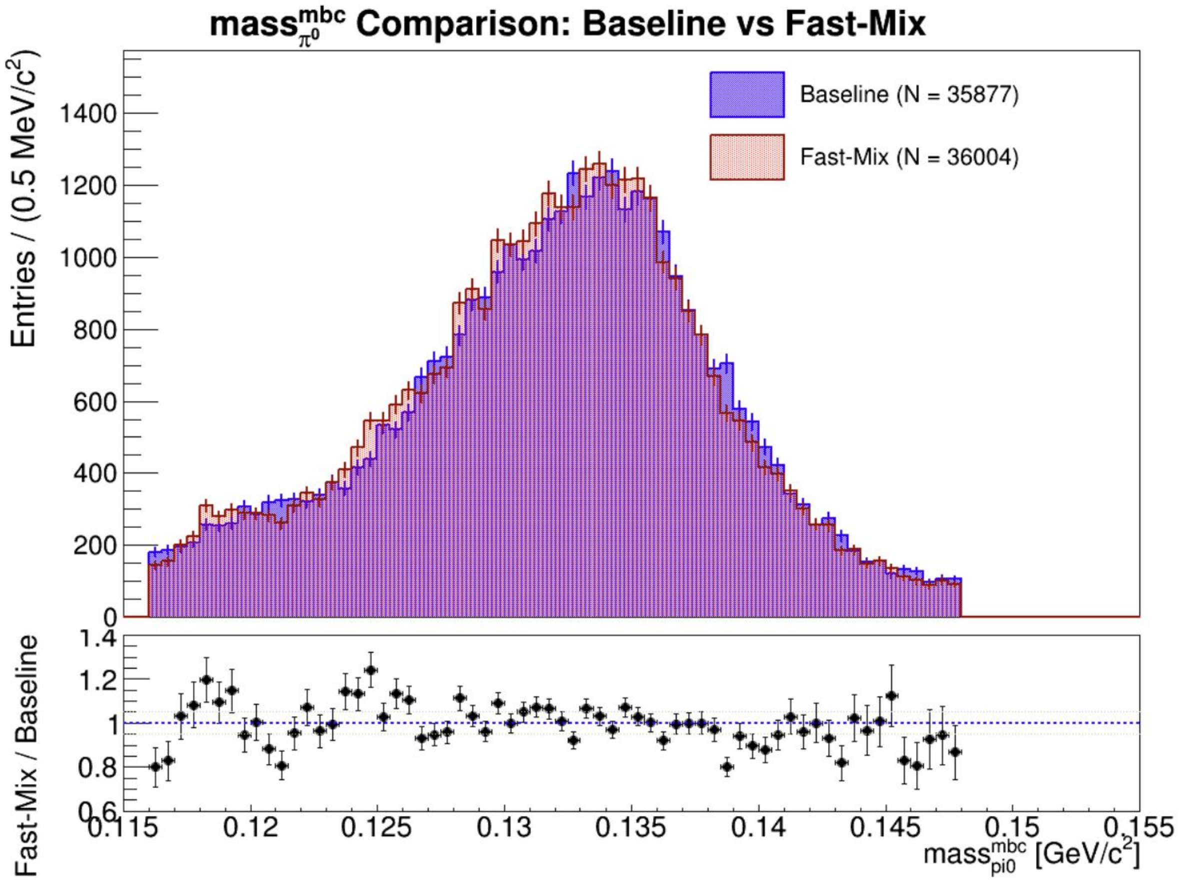




Physics Validation: π^0 Matching

Sample: ST sample after Σ^- selection

- **π^0 Matching Criterion**
  A reconstructed π^0 is matched to the MC-truth π^0 if $\Delta\theta < 8^\circ$
- **Matching Efficiency**
  - Baseline: 90.01%
  - Fast-Mix: 90.14% → **consistent within statistical uncertainty**
- **Distribution**
  Invariant mass distribution of selected π^0 candidates (see right panel) — good agreement between Baseline and Fast-Mixing



Baseline vs Fast-Mixing: Cutflow Comparison

Sample: DT sample, **with ECAL beam background only**

- **Results:**

	Baseline		Fast-Mixing		Signal	
Cut	Efficiency	Single-step efficiency	Efficiency	Single-step efficiency	Efficiency	Single-step efficiency
ST Effciency	36725(36.73%)	36.73%	36698(36.70%)	36.70%	36041(36.04%)	36.04%
DT Event selection	28739(28.74%)	78.25%	28763(28.76%)	78.38%	28173(28.17%)	78.17%
FindDTBakEvent	1283(1.28%)	4.46%	1371(1.37%)	4.77%	1155(1.16%)	4.10%
FindDTSigEvent	27456(27.46%)	95.54%	27392(27.39%)	95.23%	27018(27.02%)	95.90%

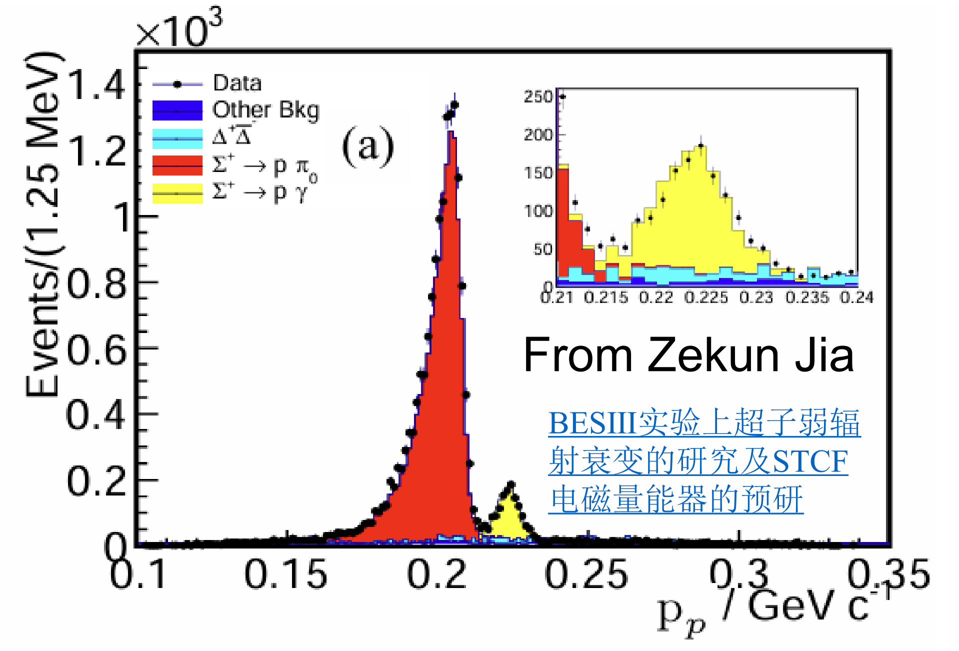
- All differences are within statistical uncertainty (< 0.4%, < 2σ)
- Baseline and Fast-Mixing show consistent results across the full cutflow
- **Conclusion:** Fast-Mixing is statistically equivalent to Baseline for DT sample analysis.

Physics Validation: Proton Momentum

DT Sample: Proton Momentum Check

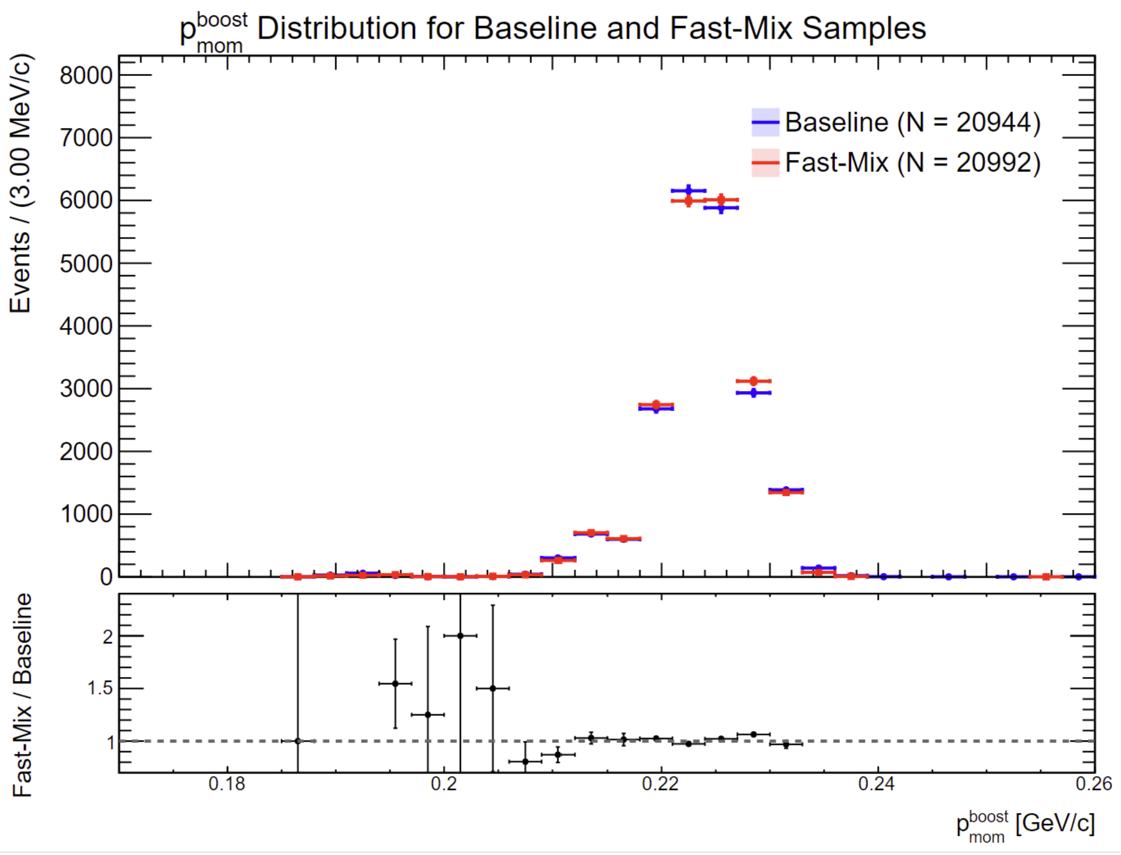
- **Variable:** Proton momentum in Σ^+ rest frame ($\Sigma^+ \to p\gamma$)
- **Comparison:** Baseline vs Fast-Mixing
- **Result:** Two distributions agree well

Fast-Mixing validated for proton momentum in DT sampl



From Zekun Jia

[BESIII实验上超子弱辐射衰变的研究及STCF电磁量能器的预研]()



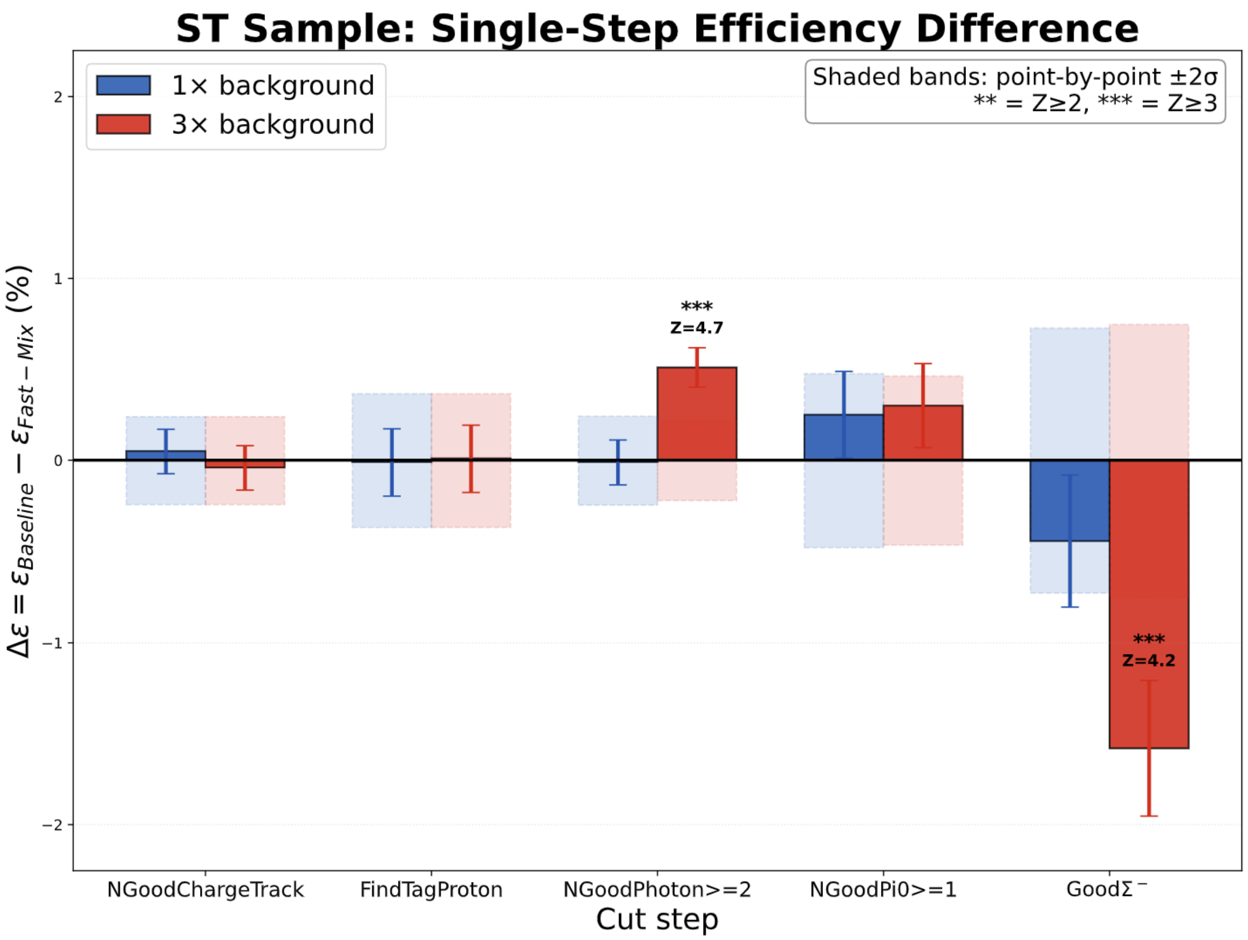
From 1× to 3× Background

ST Sample: Single-Step Efficiency Difference

- **Method:**
  - Efficiency difference per cut step:

    $$\Delta\varepsilon = \varepsilon_{\text{Baseline}} - \varepsilon_{\text{Fast-Mixing}}$$

  - Statistical uncertainties propagated
- **Results:**
  - **1× bkg:** All Δ within ±2σ → **consistent.**
  - **3× bkg:** Deviations emerge at NGoodPhoton>=2 and accumulate to Z=4.2 at Good Σ
- **Conclusion:**
  - Fast-Mixing validated at nominal background; higher bkg requires further study



Physics Check: Baseline vs Fast-Mixing (3× Background)

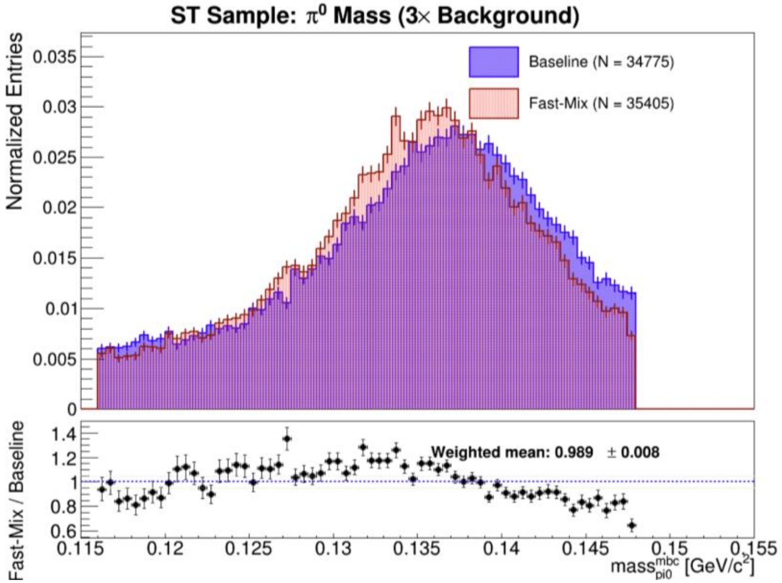
ST Sample: π⁰ Invariant Mass

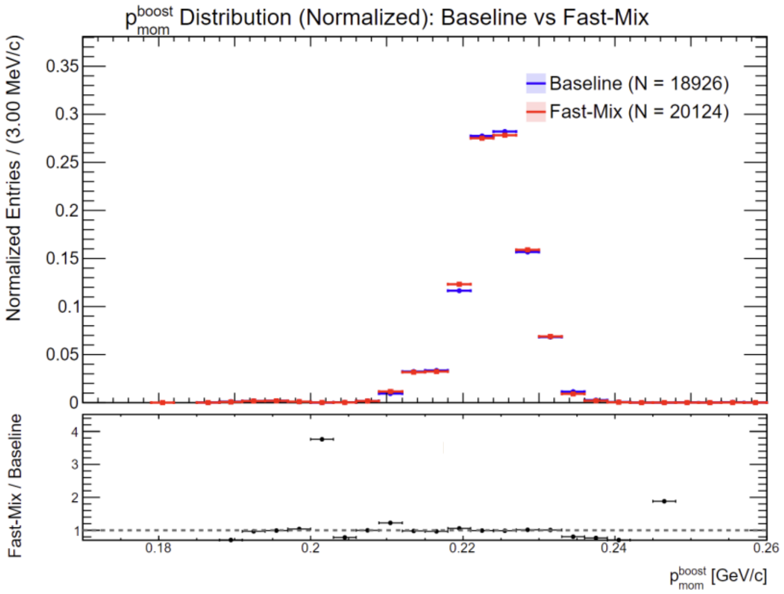
- **Conclusion**: Fast-Mixing shows deviation from Baseline
- **Reason**: π⁰ reconstructed via ECAL (π⁰→γγ); background hits affect photon reconstruction
- **Expectation**: Higher background enhances the difference between the two mixing service
- To do: Check photon energy spectra

DT Sample: Proton Momentum

- Conclusion: ✓ Shapes are consistent
- Reason: Proton reconstructed via MDC (charged track); independent of ECAL
- Expectation: Both samples remain consistent

Conclusion: At 3× background level, a visible difference in the shape of the π⁰ invariant mass spectrum is observed between Fast-Mixing and Baseline.





Summary

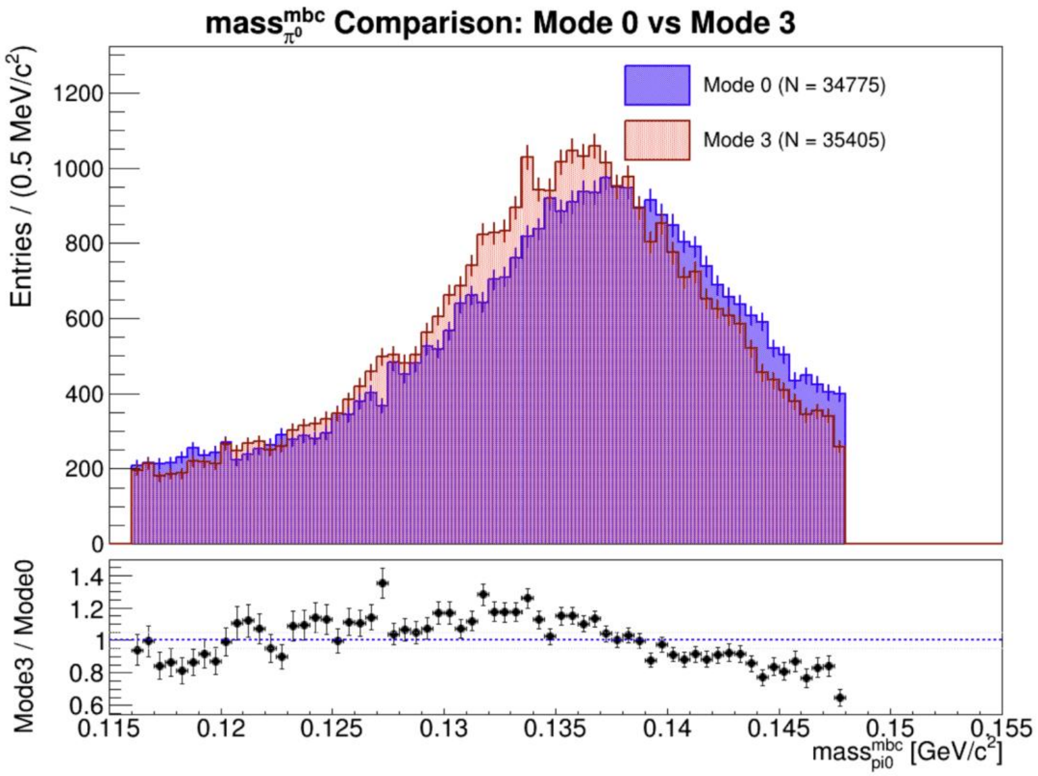
- **Motivation:** Fast-Mixing is proposed to accelerate MC production. Validation against Baseline is required before deployment — particularly its impact on physics observables under various background conditions.
- **Speed:** ~11× faster (14.8 → 1.30 s/evt) via pre-digitized background libraries
- **Origin:** Baseline–Fast-Mixing differences traced to electronic noise near 2 MeV threshold
- **Physics Validation** [$\Sigma^{+} \to p\gamma$]
  - **1× background:** Baseline and Fast-Mixing agree within statistics (ST & DT samples)
  - **3× background:** Discrepancies emerge in photon/π^0 cuts and accumulate, affecting signal efficiency
- **Conclusion:** Fast-Mixing validated at nominal background; higher background requires further study
- **To do:** Extend validation to charge-conjugate channels

ST Efficiency_ecalbkgonly_3bkg

	Baseline_3bkg		Fast-Mixing_3bkg		Signal	
Cut	Efficiency	Single-step efficiency	Efficiency	Single-step efficiency	Efficiency	Single-step efficiency
Total event	100000(100%)	-	100000(100%)	-	100000(100%)	-
NGoodChargeTrack<3	92808(92.81%)	92.81%	92847(92.85%)	92.85%	92867(92.87%)	92.87%
FindTagProton	78448(78.45%)	84.53%	78476(78.48%)	84.52%	78455(78.46%)	84.48%
NGoodPhoton>=2	75005(75.01%)	95.61%	74630(74.63%)	95.10%	73471(73.47%)	93.65%
NGoodPi0>=1	60037(60.04%)	80.04%	59509(59.51%)	79.74%	56948(56.95%)	77.51%
Good$\bar{\Sigma}^-$	34775(34.78%)	57.92%	35405(35.41%)	59.50%	35345(35.35%)	62.07%

Other check [ST sample - π^0 Matching Performance]

- **Sample:** ST (Single-Tag) sample after $\bar{\Sigma}^-$ selection
  - π^0 **Matching Criterion:** A reconstructed π^0 is considered correctly matched if the angular difference between the reconstructed π^0 and the MC-truth π^0 is **< 8°**
  - **Matching Efficiency:**
    - Mode 0: **84.96%**
    - Mode 3: **87.45%**
  - **Distribution:** Invariant mass distribution of selected reconstructed π^0 candidates is shown in the right panel



DT Efficiency _ecalbkgonly_3 x bkg

Results of sample [Add beam background only to the ECAL detector]:

	Mode0_ecalbkgonly		Mode3_ecalbkgonly		Signal	
Cut	Efficiency	Single-step efficiency	Efficiency	Single-step efficiency	Efficiency	Single-step efficiency
ST Effciency	35206(35.21%)	35.21%	36011(36.01%)	36.01%	36041(36.04%)	36.04%
DT Event selection	26761(26.76%)	76.01%	27813(27.81%)	77.23%	28173(28.17%)	78.17%
FindDTBakEvent	1874(1.87%)	7.00%	1538(1.54%)	5.53%	1155(1.16%)	4.10%
FindDTSigEvent	24887(24.89%)	93.00%	26275(26.28%)	94.47%	27018(27.02%)	95.90%

Cut条件	效率	单步效率
ST效率	39.58%	
DT事例挑选	33.77%	85.32%
$\chi^2_{5C} < \chi^2_{4\gamma}$	32.15%	95.20%
$\chi^2_{5C} < 30$	26.19%	81.46%
衰变长度要求	18.00%	68.73%
光子匹配	17.96%	99.78%

- Results from Yong Song:

Efficiency of DT Case Selection is 33.77%

- Note: Not directly comparable — based on different samples.

Sample	Generator	Purpose
DT sample	mDIY	Calibrate (ε_{DT})
ST sample	mDIY	Calibrate (ε_{ST})

Other check [DT sample - proton momentum]_ecalbkg0nly_3bkg

- **Sample:** DT (Double-Tag) sample
- **Variable:**
  Reconstructed proton momentum in the Σ^+ rest frame
  (i.e., the momentum of the proton from $\Sigma^+ \to P\gamma$ decay, boosted to the Σ^+ rest system)