Status of $e^+e^- \to \pi^+\pi^-(\gamma)$ with the ISR method

47th B2GM
DS F2F meeting

- Samples and selection
- Analysis strategy and χ^2 distributions from kinematic fitting
- Tracking inefficiency study
- Impact of hiE3
- Summary
- Team members and assignment

Presented by:

Qingyuan Liu[1]

Jan. 31, 2024

1. Department of Physics and Astronomy, University of Hawaii

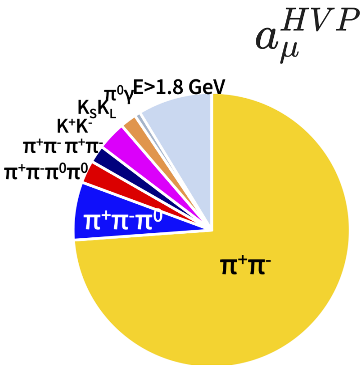
UNIVERSITY of HAWAIʻI® MĀNOA

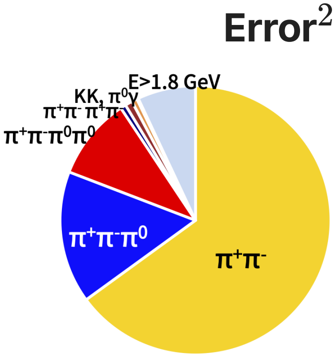
Introduction: muon g-2 and $e^+e^- \to \pi^+\pi^-$ cross section

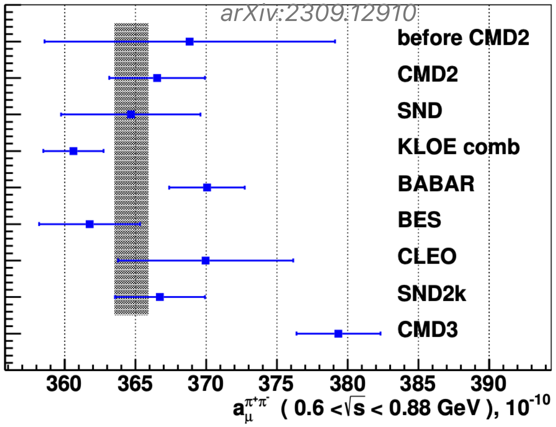
- Anomalous magnetic moment of muon:

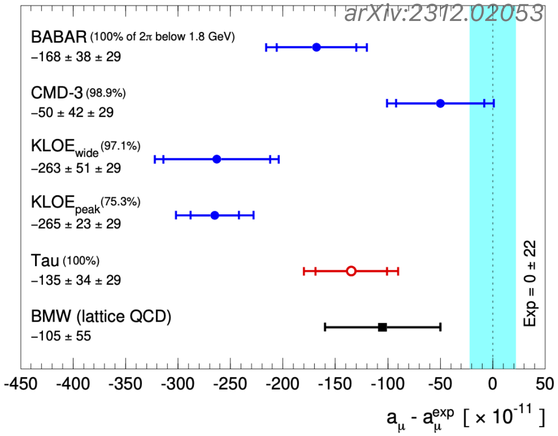
$$a_\mu^{SM} = (g_\mu - 2) = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HVP} + a_\mu^{HLBL}$$

- Its uncertainty is dominated by Hadronic Vacuum Polarization (HVP) which can be calculated
  - from Lattice QCD
  - or $\sigma^{bare}(s)$ of $e^+e^- \to \gamma^* \to hadrons(\gamma)$ and the dispersion relation
    - $e^+e^- \to \pi^+\pi^-$ contribution > **73%** of $\mathrm{a}_\mu^{\mathrm{HVP,LO}} = \frac{1}{4\pi^3}\int_{\mathrm{S_{th}}}^{\infty} \mathrm{ds\,K(s)}\sigma^{\mathrm{bare}}(\mathrm{s})$ [1]
      - Ambiguity among previous measurements: KLOE, BaBar, CMD-3
  - Discrepancy between Lattice QCD and the dispersive









1. *Phys. Rev. 168 (1968) 1620–1622*

Samples and selection

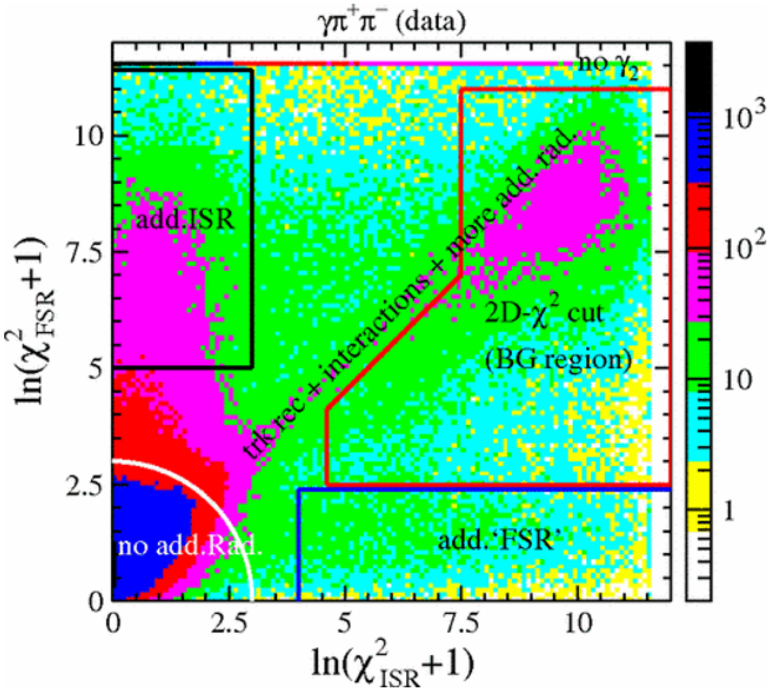
- Data for sanity check: $1.856\,\mathrm{fb}^{-1}$, run 5349 - 5399 in exp. 12
- MC samples (MC15rd_b)
  - **hhISR** and `mumu`: all 4S good runs in exp. 12: $54.388\,\mathrm{fb}^{-1}$
    - **hhISR**: `pipi`, pipipi0, k+k-, k0k0
  - Other backgrounds: the same run range as in data
    - **qqbar** with ISR(**uubar**, **ddbar**, **ssbar**, **ccbar**, **mixed**, **charged**), **tautau**, **gg**, **ee**, **llxx**
- Preliminary selection ← **HiE** trigger line
  - ISR (highest E^* in case of multiple candidates)
    - with $E^*_{ISR} > 2$ GeV, and in **ECL inner barrel** region: **(32.2+5, 128.7-5)**
  - The optional photon:
    - All clusters in **CDC acceptance** (smallest χ^2_{FSR} in case of multiple candidates)
  - Two tracks:
    - $dr < 2.0$ cm, $|dz| < 5.0$ cm and $p > 1.0$ GeV in **KLM inner barrel** region
    - PID(`pionID_noSVD` or `muonID_noSVD`) > 0.01
  - $M_{2-track} < 3.5$ GeV
  - Kinematic: Prob(χ^2_{ISR})>0, not optimized yet

Analysis strategy and χ^2 distributions

Follow BaBar's approach [Phys. Rev. D 86, 032-13]

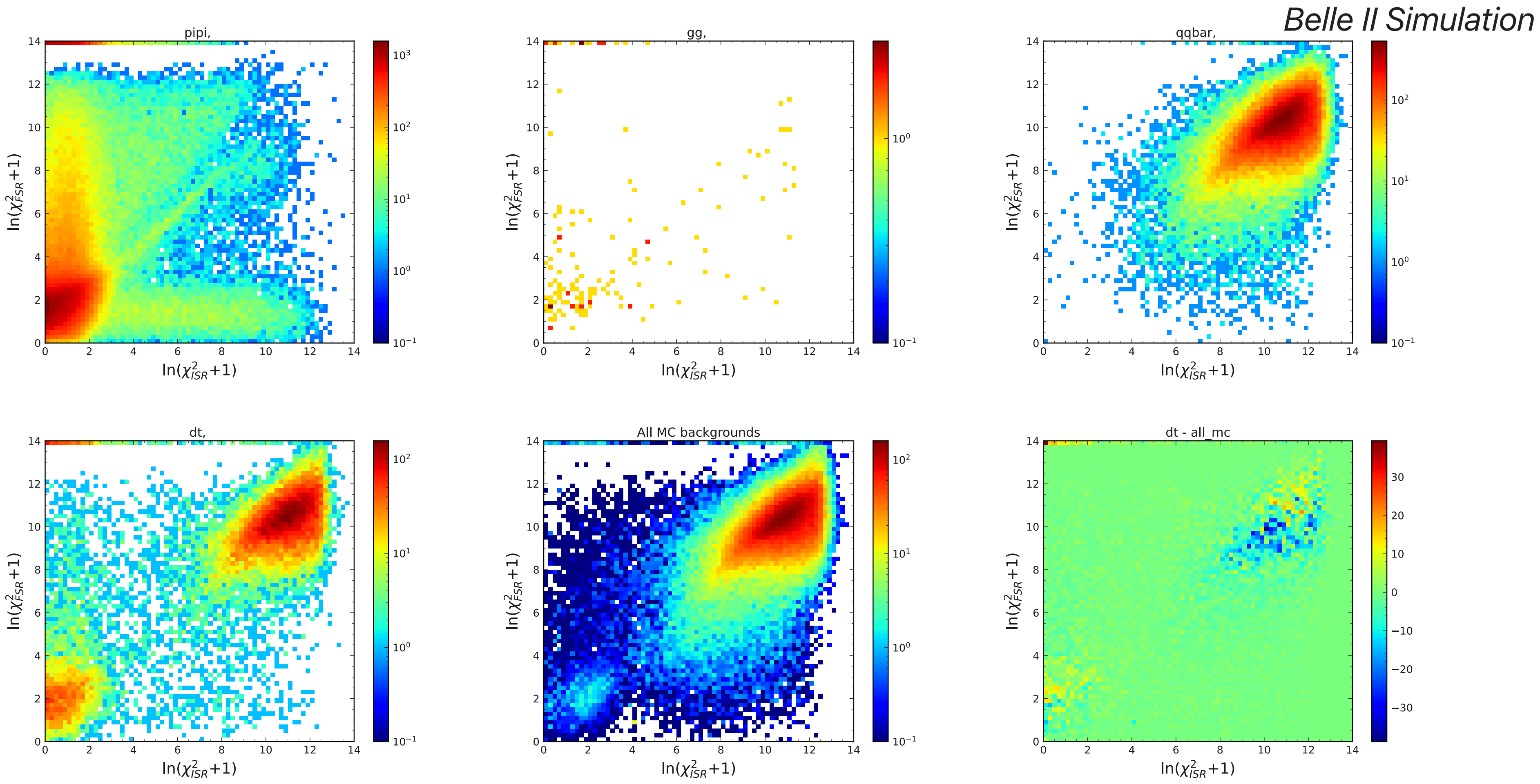
- Measure the R ratio of $e^+e^- \to \pi^+\pi^-(\gamma)$ cross section to $e^+e^- \to \mu^+\mu^-(\gamma)$ with the ISR method
  - Illustrating Belle II potential with LS1 dataset
  - Systematic dominated: ~0.5%
- Double kinematic fits for S/B separation and for disentangling QED corrections:
  - **2C "ISR" fit** for all events
    - 3 measured particles: *2 tracks* and γ_{isr}
      - ISR energy not used
    - Assume 1 unmeasured photon (ISR) along the beam (HER/LER)
  - **3C "FSR" fit** only for events with γ_2 reconstructed
    - 4 measured particles: *2 tracks*, γ_{isr} and γ_2
      - ISR energy not used
- PID to separate $\mu\mu$/$\pi\pi$/KK

BaBar's result for $0.5 < M_{\pi^+\pi^-} < 1.0$



Analysis strategy and χ^2 distributions

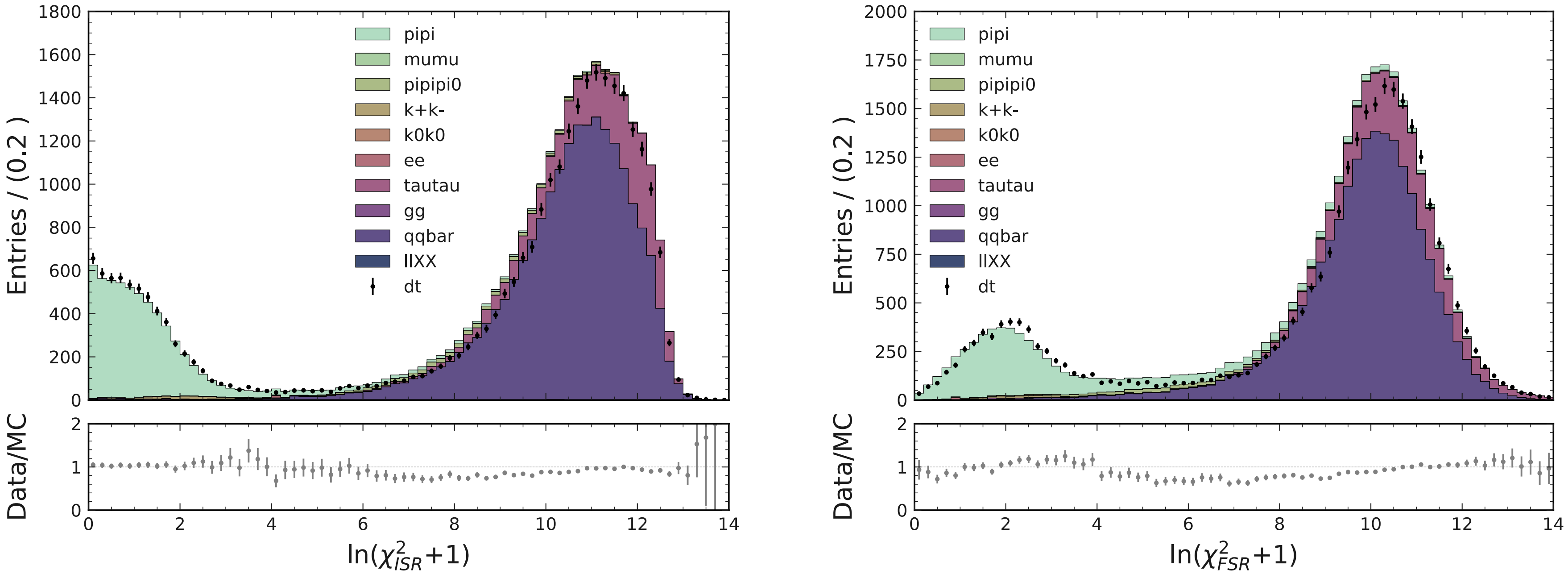
χ^2 distributions for $\pi^+\pi^-(\gamma)$



Analysis strategy and χ^2 distributions

χ^2 distributions for $\pi^+\pi^-(\gamma)$

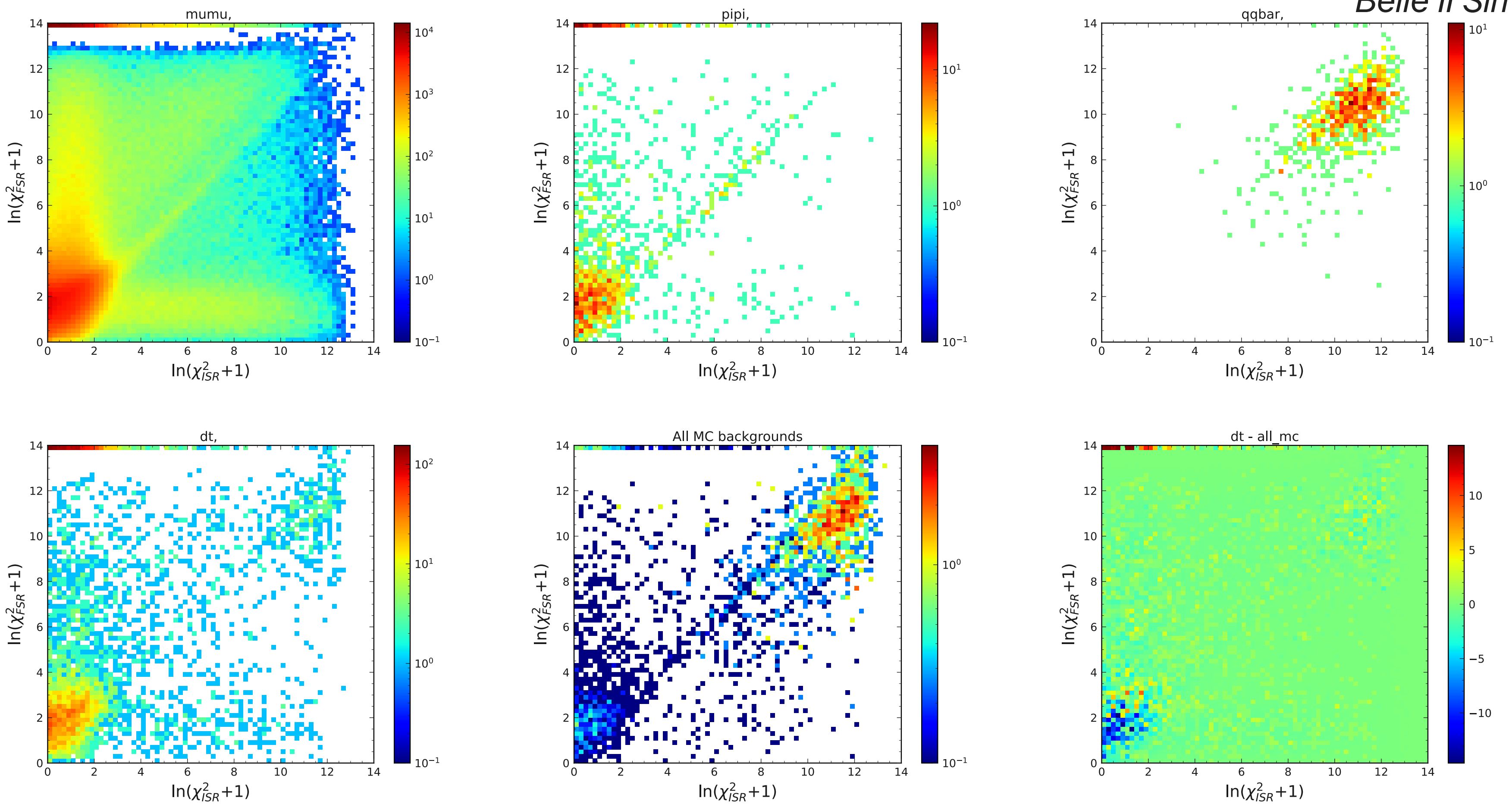
χ^2_{ISR}(2C fit) shows good data-MC agreement, and χ^2_{FSR}(3C fit) indicates mismodelling of γ_2 (FSR or NLO large-angle ISR)



Analysis strategy and χ^2 distributions

χ^2 distributions for $\mu^+\mu^-(\gamma)$

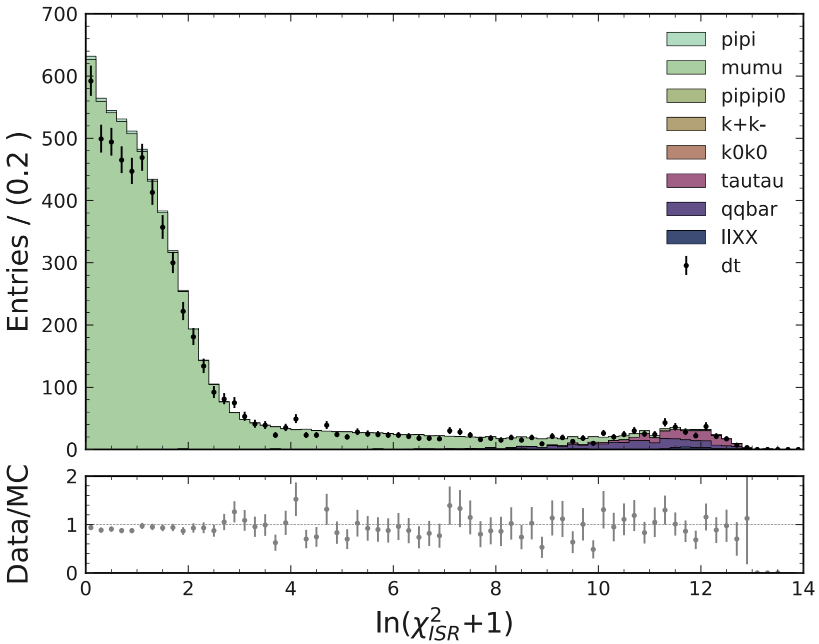
Belle II Simulation

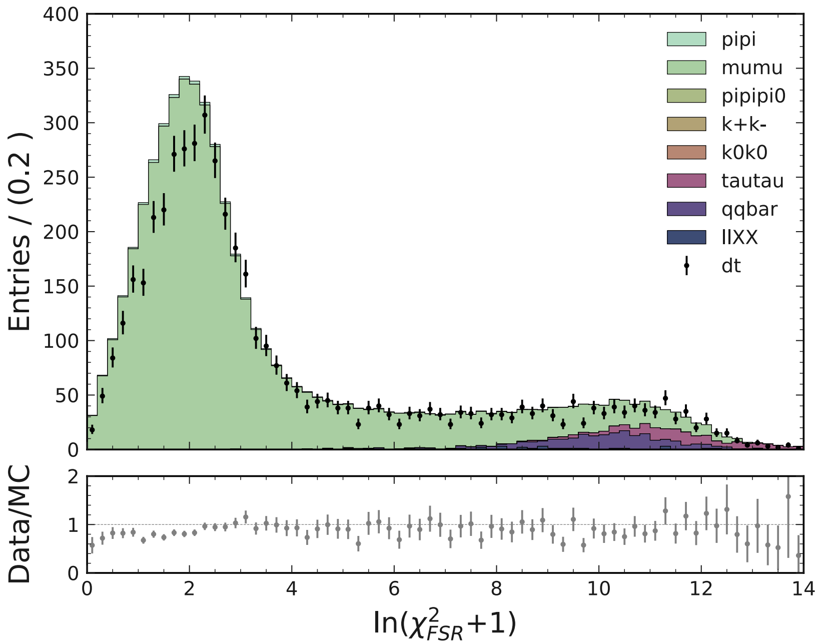


Analysis strategy and χ^2 distributions

χ^2 distributions for $\mu^+\mu^-(\gamma)$

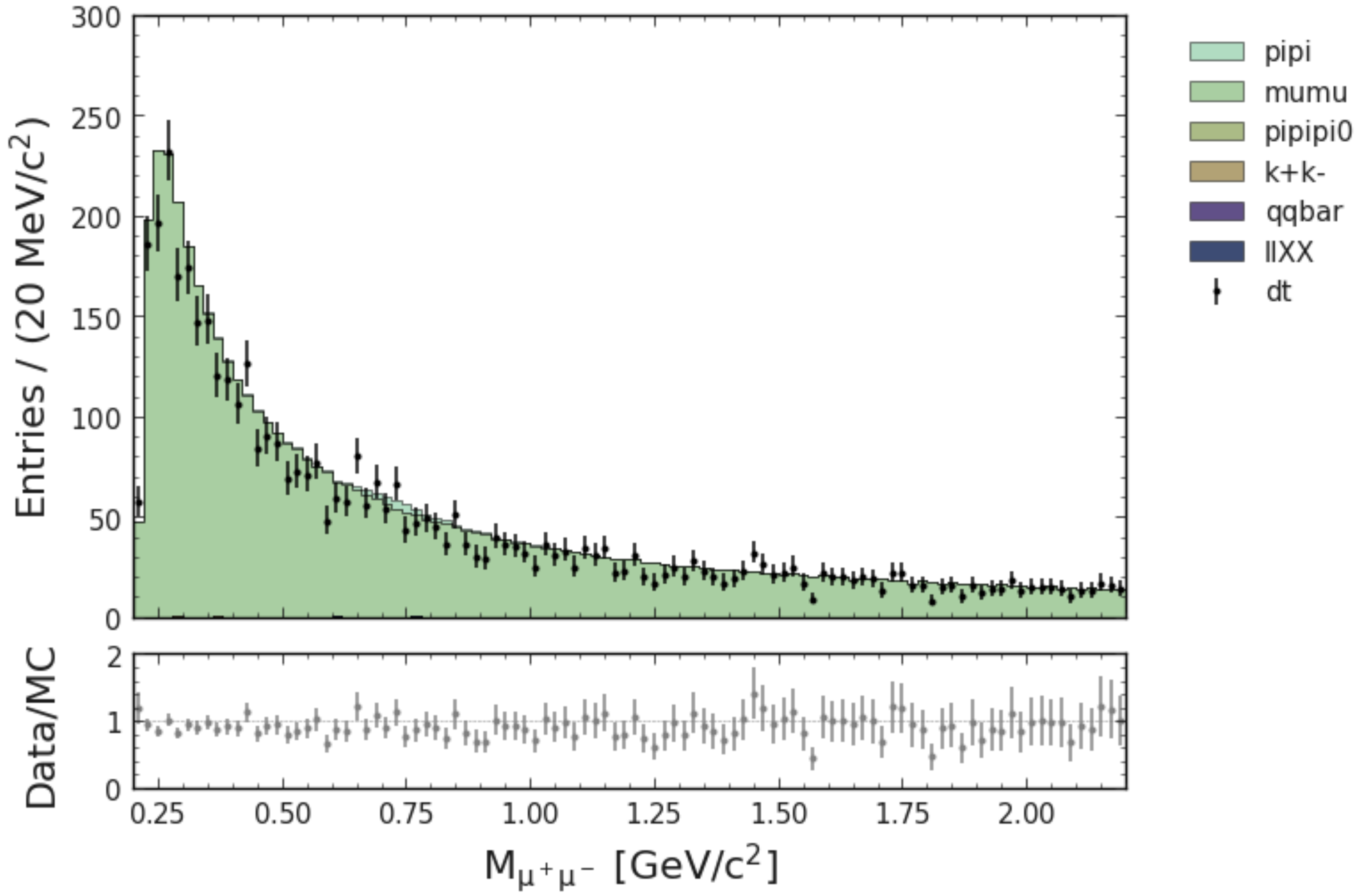
χ^2_{FSR}(3C fit) similar to the $\pi\pi$ channel, but χ^2_{ISR}(2C fit) shows worse data-MC agreement: muonID?





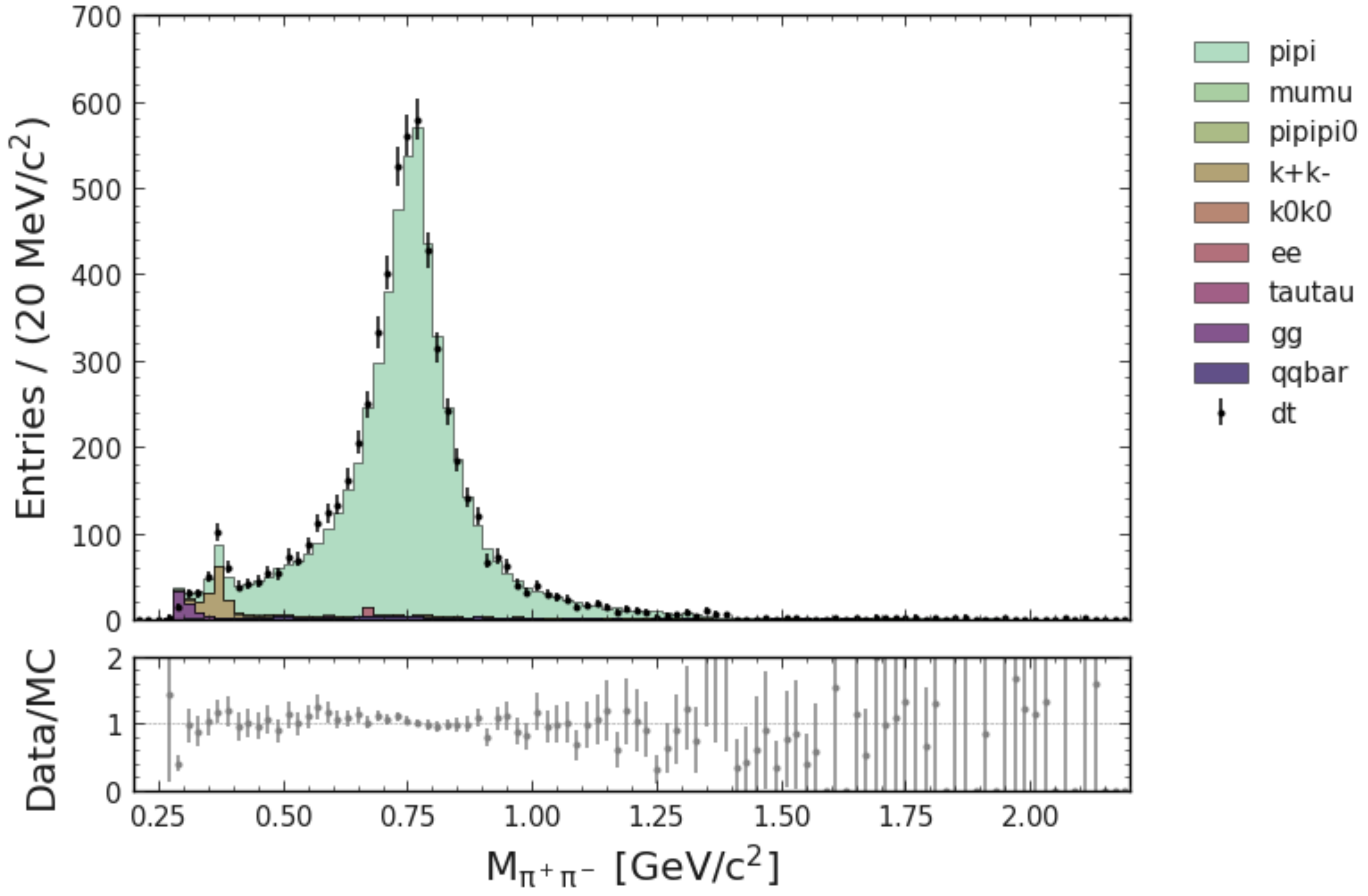
$M_{\mu^+\mu^-}$ spectrum

- All exp12 good runs scaled down to 1.856/fb, 2C OrcaKinFitProb > 0



$M_{\pi^+\pi^-}$ spectrum

- All exp12 good runs scaled down to 1.856/fb, 2C OrcaKinFitProb > 0
- New channels in hhISR are not included yet (have to be removed from qqbar)



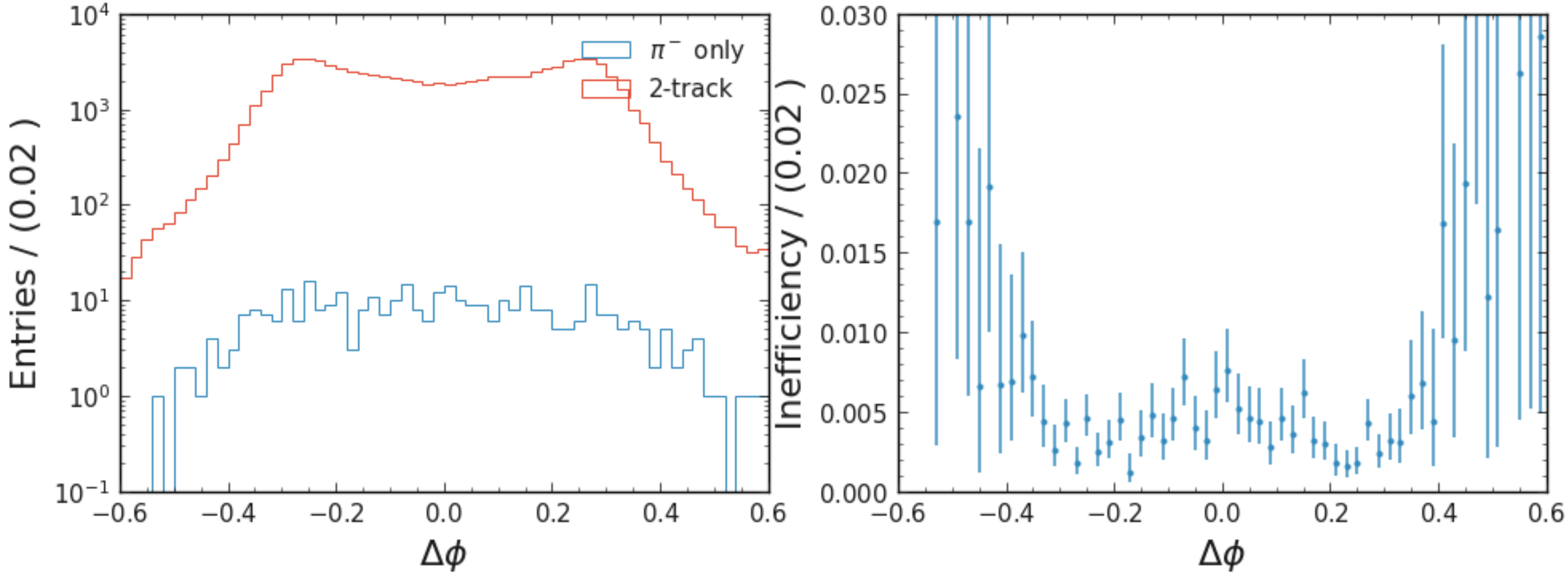
Tracking inefficiency study

Efficiency conditional on one reconstructed track is almost there and study on correlated track loss is ongoing.

- Using MC truth to select events for efficiency estimate.
  - Dedicated n-tuples with `p > 0.5 GeV` and `ISR in CDC acceptance`
    - **ISR and only one track** is required to be **reconstructed** $\rightarrow$ measure the reconstruction **inefficiency of the other track**
    - Kinematic fit to constrain the recoil as a pion/muon to get χ^2_{1C} for signal selection
  - MC track pair requirements: `p > 1 GeV` and `in KLM inner barrel` (47+5, 122-5)
  - Reference for the data driven method
- Using additional variables (χ^2_{1C}, θ_{recoil}, ...) to derive a similar efficiency.
- Efficiency (single-track) conditional on π^+: $\frac{N_{2-track}}{N_{2-track}+N_{\pi^+ only}}$, where **N** is number of events
- Efficiency (single-track) conditional on π^+ or π^-: $\frac{2N_{2-track}}{2N_{2-track}+N_{\pi^+ only}+N_{\pi^- only}}$
- Target: $\frac{\text{efficiency (data driven)}}{\text{efficiency (MC truth based)}} \approx 1$ for $\Delta\phi$ ($\equiv \phi^+ - \phi^-$) and $M_{2tracks}$ distributions

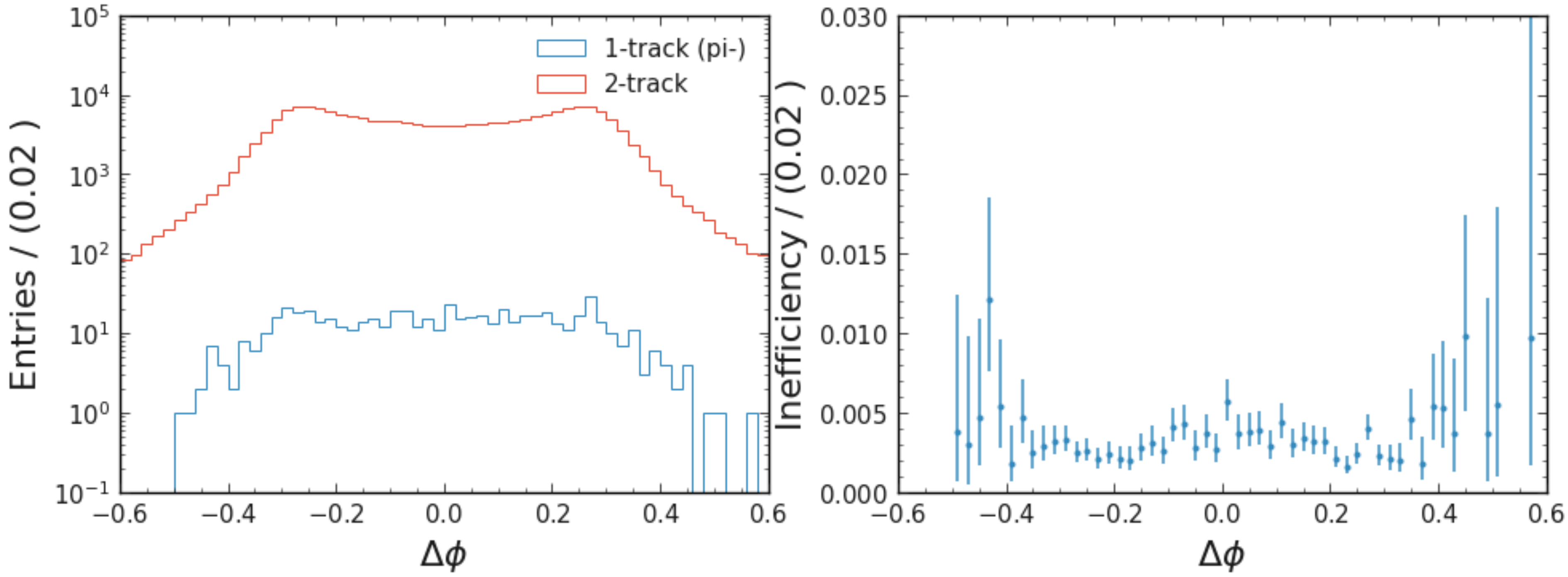
Inefficiency (data-driven) conditional on π^- reconstruction

- ISR in ECL inner barrel, tracks in KLM inner barrel, $p_\pi > 1$ and $\chi^2_{1C} < 1$
- Using reconstructed π^- and predicted π^+ in the 2-track events



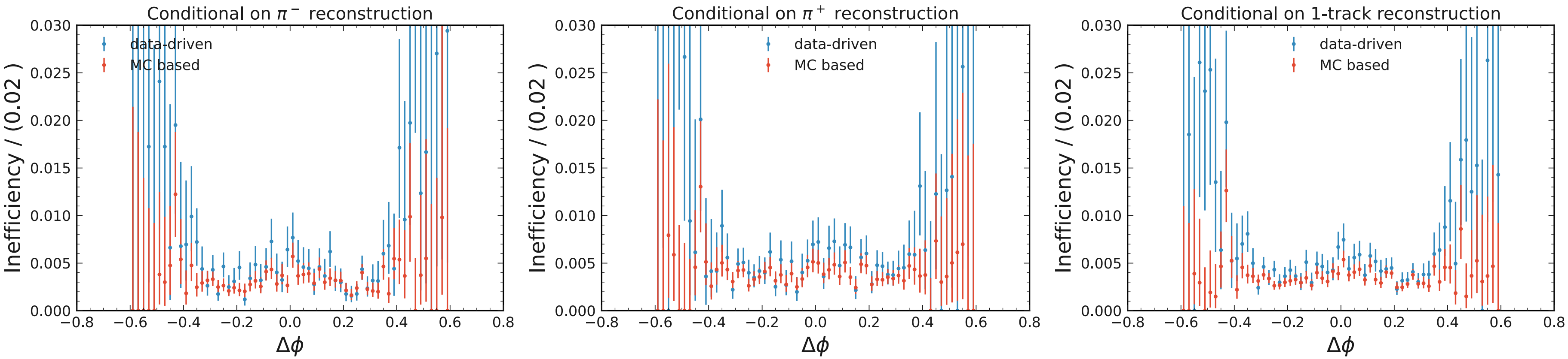
Inefficiency (MC truth based) vs $\Delta\phi$ conditional on π^- reconstruction

- ISR in ECL inner barrel, tracks in KLM inner barrel, $p_\pi > 1$ in n-tuples
- The same requirements on the primary MC track particles



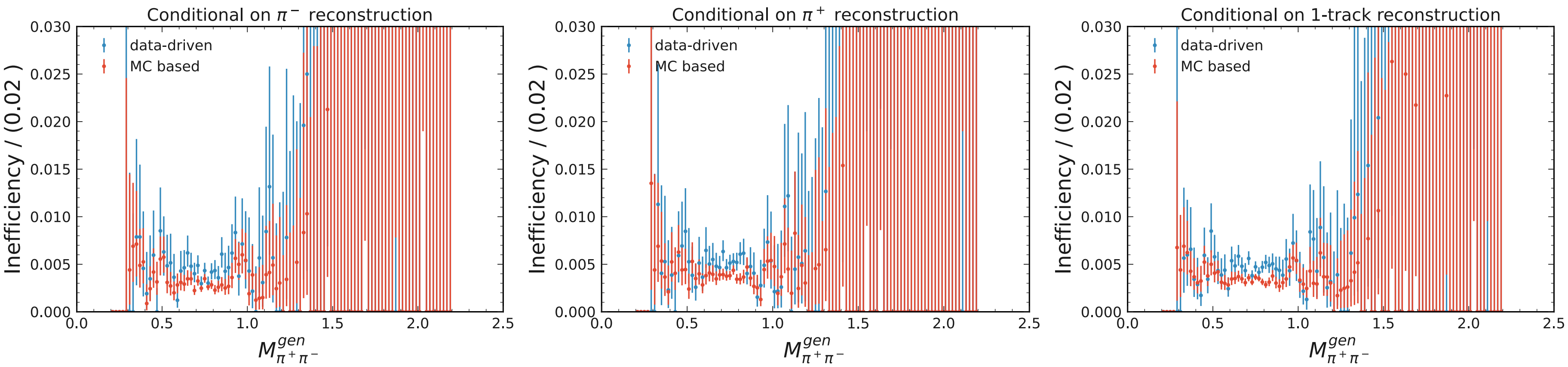
Uncorrelated track inefficiency vs $\Delta\phi$

- Data-driven method agrees with the MC based within statistical erros
  - might slightly overestimate the inefficiency



Uncorrelated track inefficiency vs $M^{gen}_{\pi^+\pi^-}$

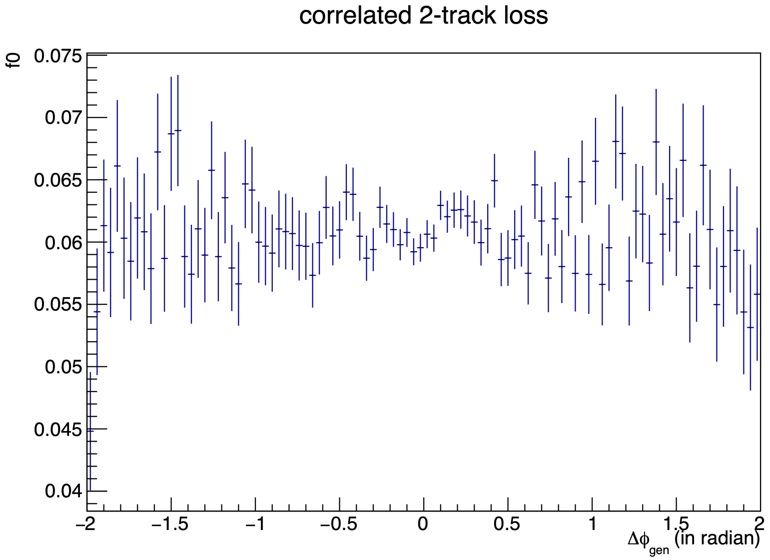
- Data-driven method agrees with the MC based within statistical erros
  - might slightly overestimate the inefficiency



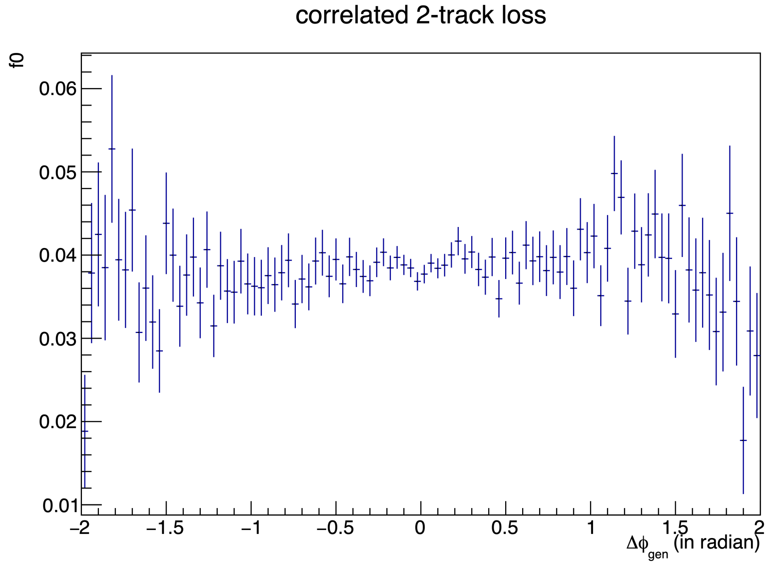
Correlated 2-track loss

- **Very preliminary** study with $p_T > 0.1$, $dr < 2.5$ and $|dz| < 5$ for $\mu\mu$
  - using generator level variables
- Correction factor: $f_0 = \frac{N_0}{N} - \frac{N_1^2}{4NN_2}$,
  - N_0, N_1, N_2 are numbers of events with zero, one and two tracks
  - $N = N_0 + N_1 + N_2$

ISR in CDC acceptance

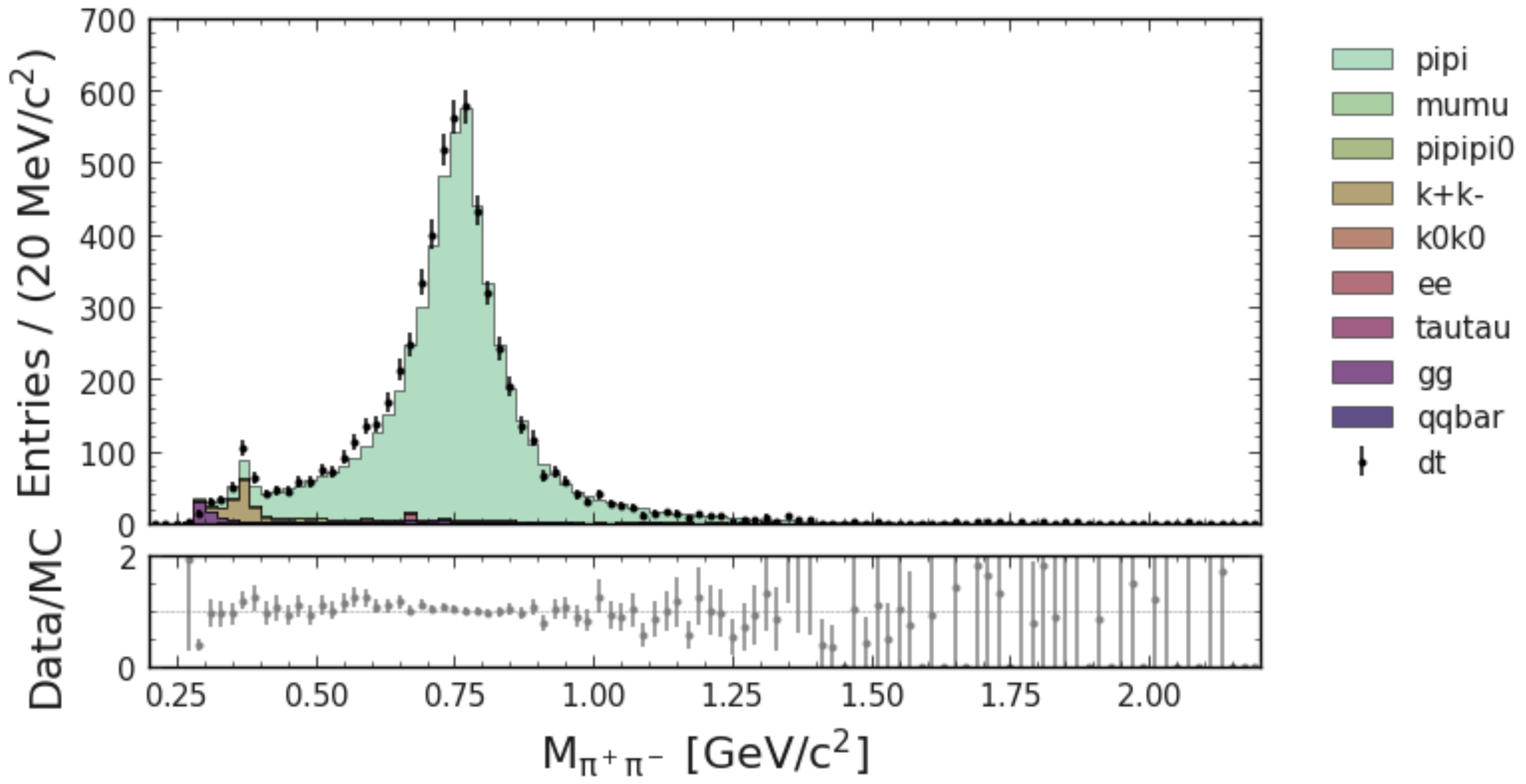


ISR in ECL acceptance



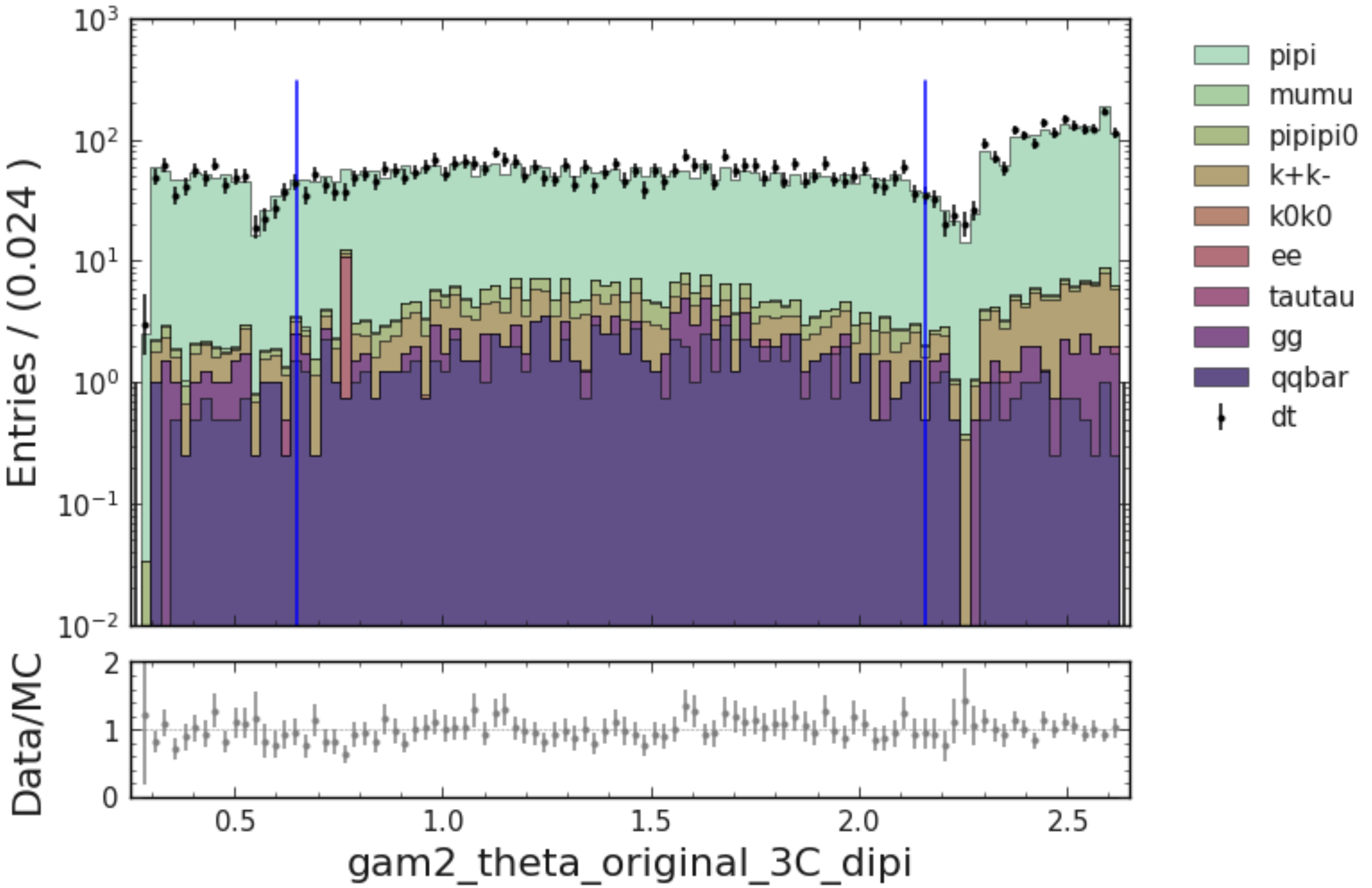
Impact of hiE3 on future studies

- Doesn't affect the current analysis with LS1 dataset
- Estimated using γ_2 distributions (dedicated trigger study is ongoing)
  - Compared to `hiE`, `hiE3` will use **clusters in ECL endcaps** to **veto radiative Bhabha**
    - This veto can kill our signals with both γ_{ISR} and γ_2 reconstructed
- Include more signal events with γ_2 by the χ^2 cut: $\log(\chi^2_{2C}+1) < 4$ or $\log(\chi^2_{3C}+1) < 3.5$



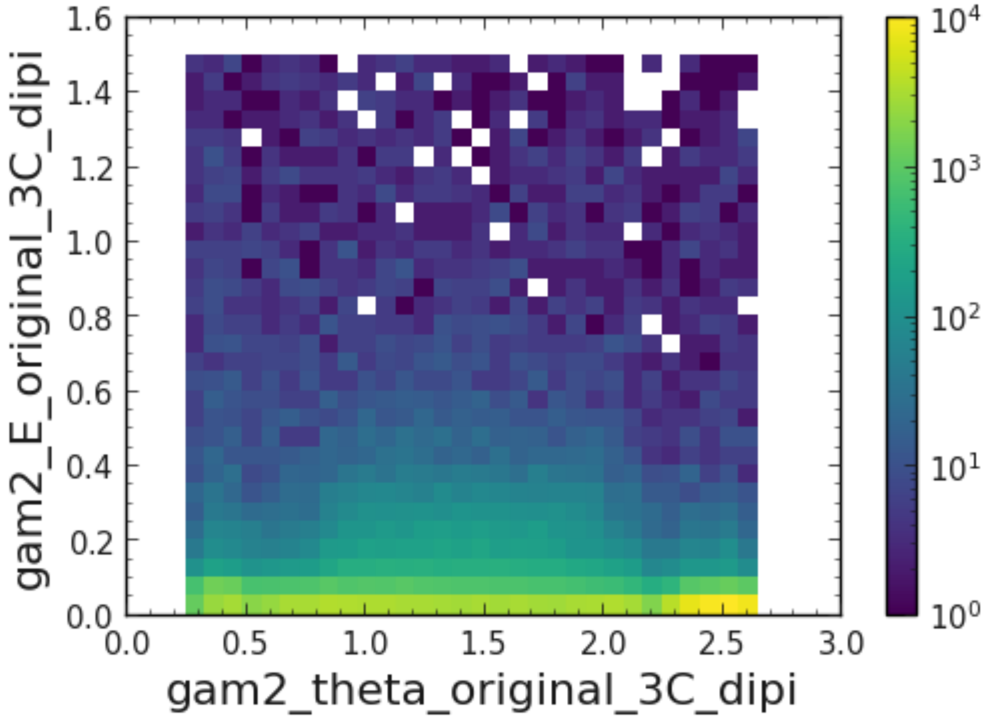
γ_2 spectrum

- ECL inner barrel: (0.65, 2.16)



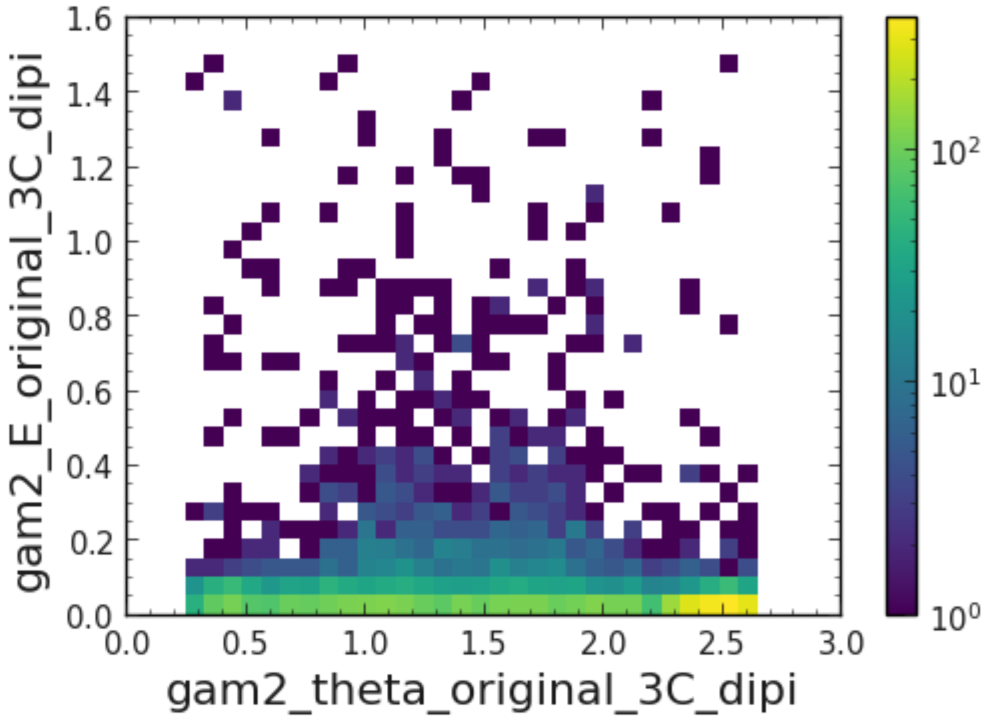
E_{γ_2} vs θ_{γ_2} of the signal MC

- Influence of hiE3 (endcap $E_2 > 0.1$ GeV): 2.45 + 0.04 - 0.04%
- $E_2 > 1$ GeV for Bhabha veto: 0.51 + 0.02 - 0.02%



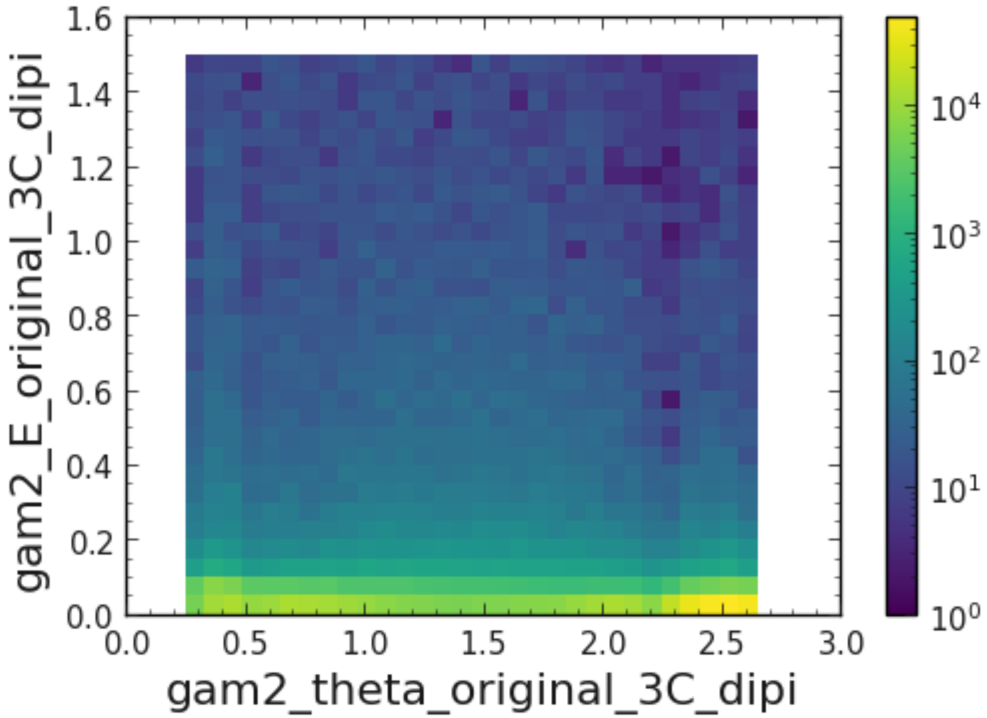
E_{γ_2} vs θ_{γ_2} in data (1.856/fb)

- Influence of current hiE3 (endcap $E_2 > 0.1$ GeV): 1.66 + 0.18 - 0.16%
- $E_2 > 1$ GeV for Bhabha veto: 0.45 + 0.10 - 0.08%



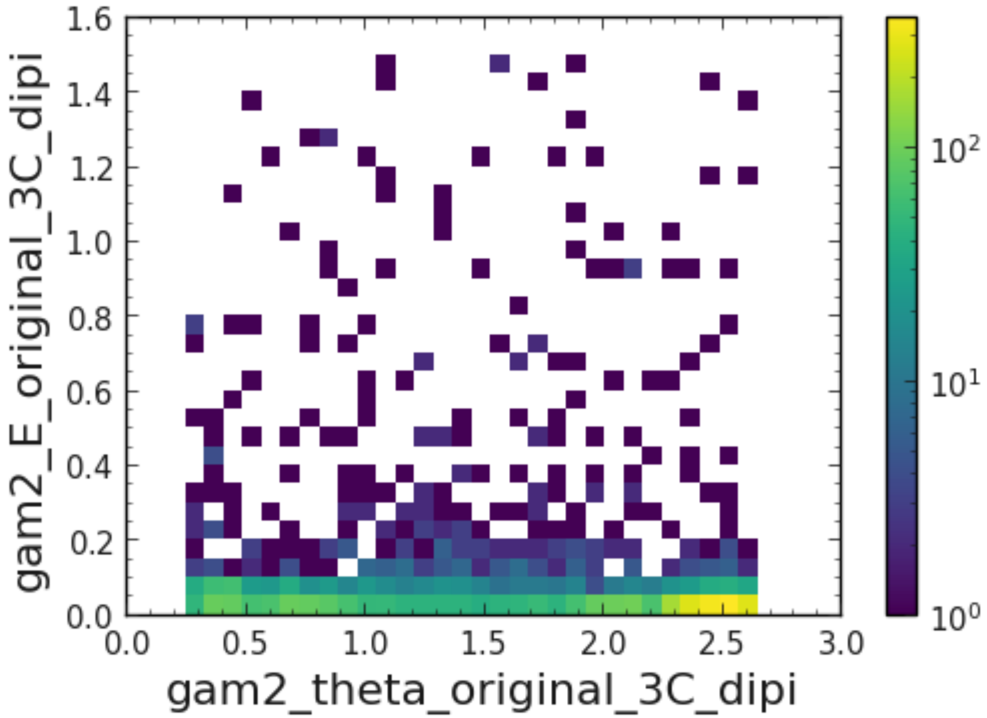
dimu E_{γ_2} vs θ_{γ_2} in signal MC

- Influence of current hiE3 (endcap $E_2 > 0.1$ GeV): 2.15 + 0.02 - 0.02%
- $E_2 > 1$ GeV for Bhabha veto: 0.41 + 0.01 - 0.01%

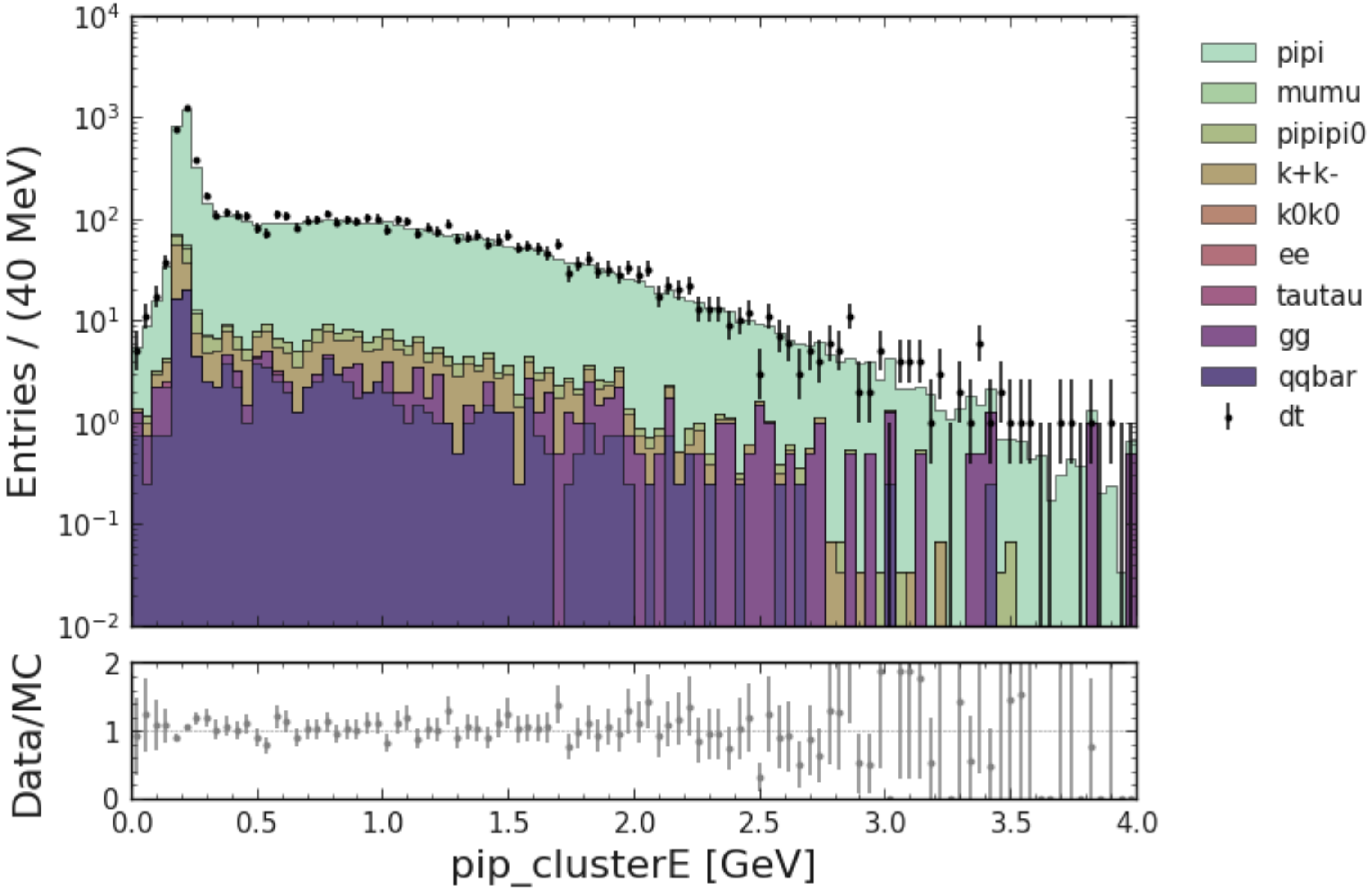


dimu E_{γ_2} vs θ_{γ_2} in data

- Influence of current hiE3 (endcap $E_2 > 0.1$ GeV): 2.09 + 0.22 - 0.20%
- $E_2 > 1$ GeV for Bhabha veto: 0.45 + 0.11 - 0.09%

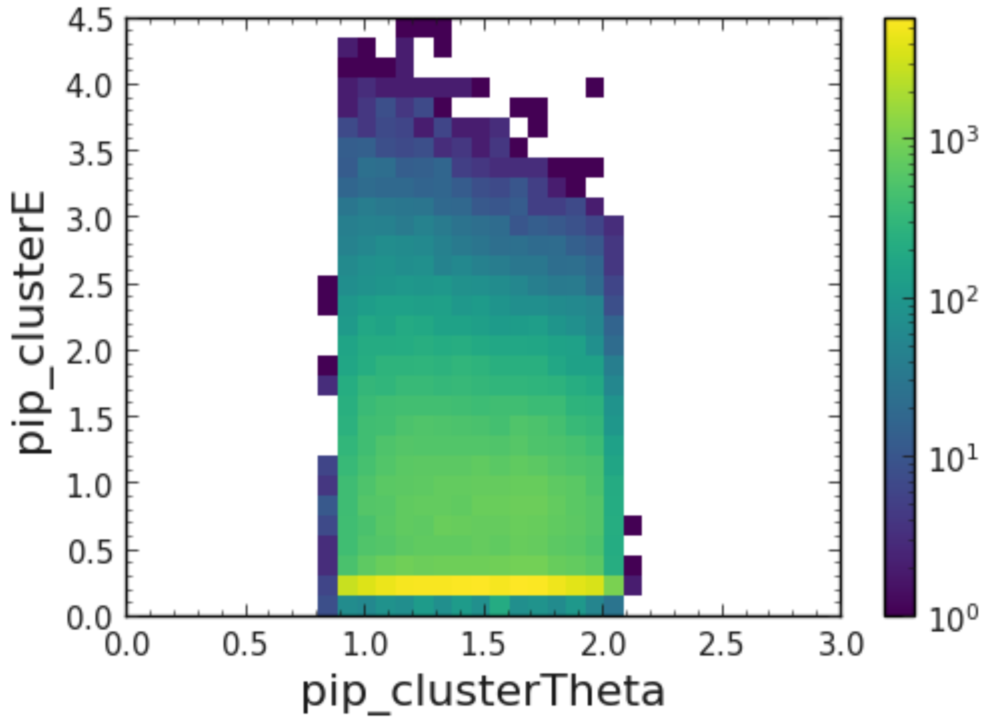


Matched cluster of tracks



E vs θ for track matched clusters

- Looks fine if we only use ISR in barrel region
- Might lead to large inefficiency if we also include ISR events in ECL endcaps



Summary

- Preliminary selection to start studies on correction factors of the analysis
  - Good agreement between data and MC for the 2C fit of $\pi\pi$ channel, but some discrepancy observed in $\mu\mu$ channel
  - Much worse modelling of the additional large angle photon
- The data-driven method to estimate conditional tracking inefficiency has been introduced and tested on both channels (Results on $\mu\mu$ in backup)
- New hiE3 trigger ($E_{cluster2} > 1$ GeV) will not affect current analysis and only has limited (per mill) effect in future data taking
  - However it depends on the selection. Will be a big problem if tracks hitting ECL endcaps are needed

Team members and assignment

Recently, we welcomed new teammates from Nankai, IITH and Duke.

- Tracking correction:
  - Prof. Jim Libby (IITM), Dr. Qingyuan Liu (Hawaii), and Mr. Gaurav Sharma (IITM)
- Trigger correction:
  - Dr. Qingyuan Liu (Hawaii), Prof. Junhao Yin (Nankai)
- PID correction:
  - Prof. Saurabh Sandilya (IITH) + students and Prof. Anselm Vossen (Duke) + students
- χ^2 selection and background: Duke, Hawaii, IITM

Backup

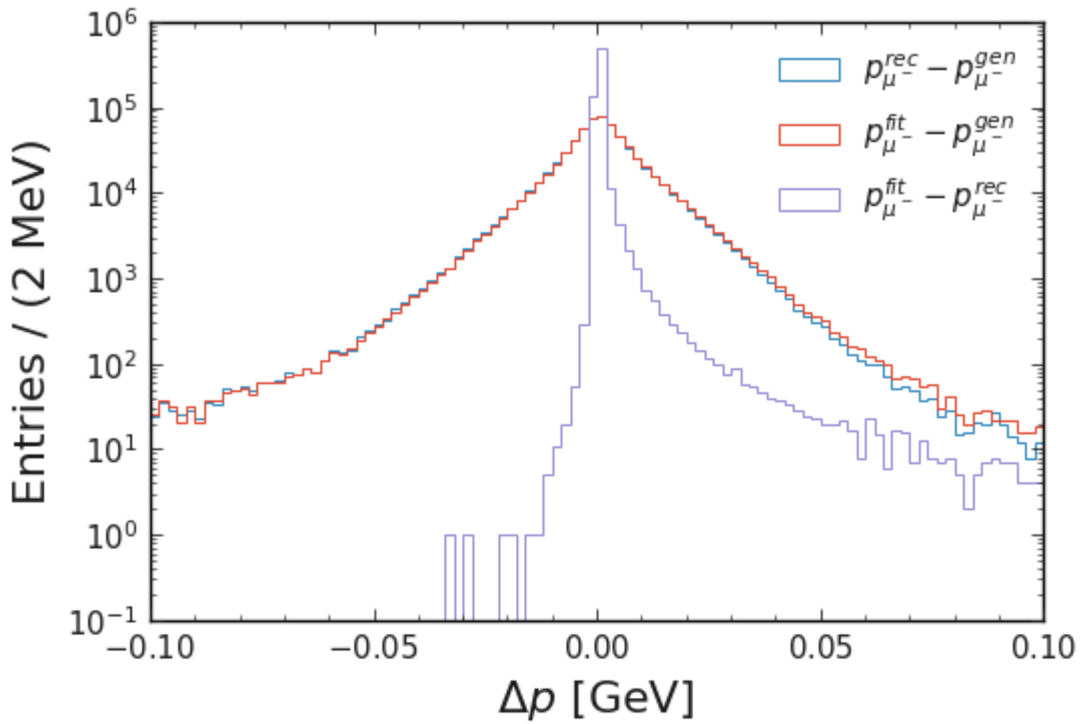
- Results from all 4S runs in exp. 12 (proc13, release-06)

Check $\mu\mu$ channel with the old ntuples of < 2/fb MC samples

- Only for the case $\mu^-\gamma_{isr}$ reconstructed

P_{μ^-} doesn't change much

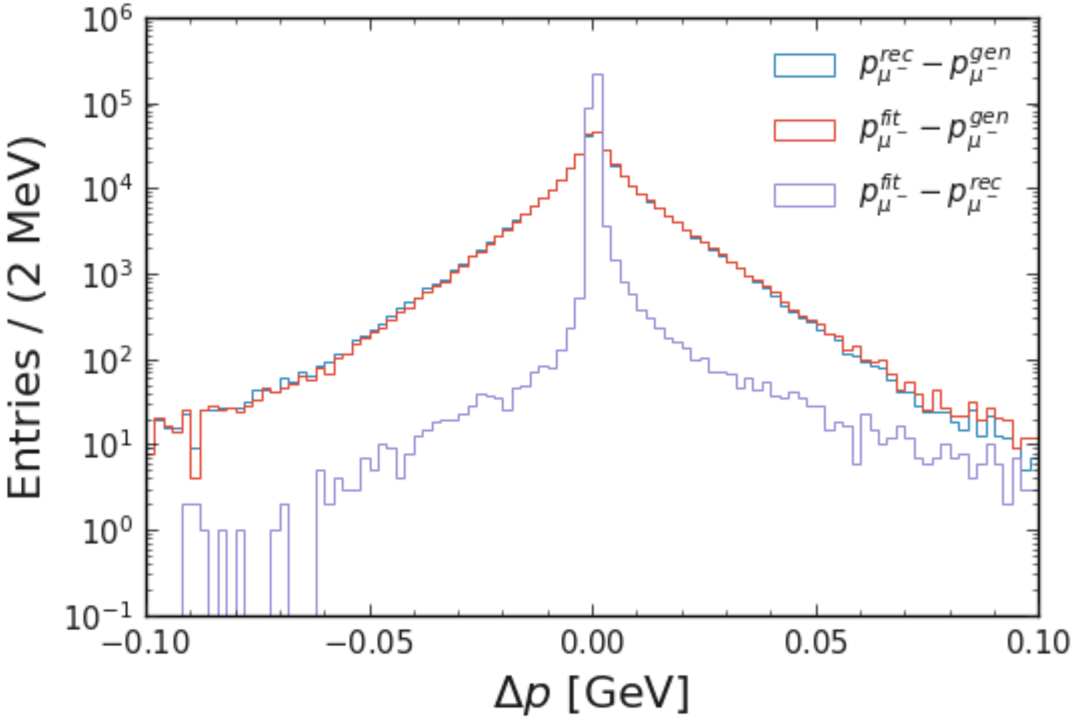
```
Residuals for ['mum_p_original_2CHER_dipi', 'mu_p_1Cm_dimu'] vs mc_pim_p:
Entries: 654552.0, Mean: 5.0e-04, Std: 1.2e-02, Median: 4.4e-04
Entries: 654410.0, Mean: 8.1e-04, Std: 1.2e-02, Median: 6.0e-04
Entries: 655370.0, Mean: 7.9e-04, Std: 2.3e-03, Median: 7.7e-04
```



P_{μ^-} doesn't change much

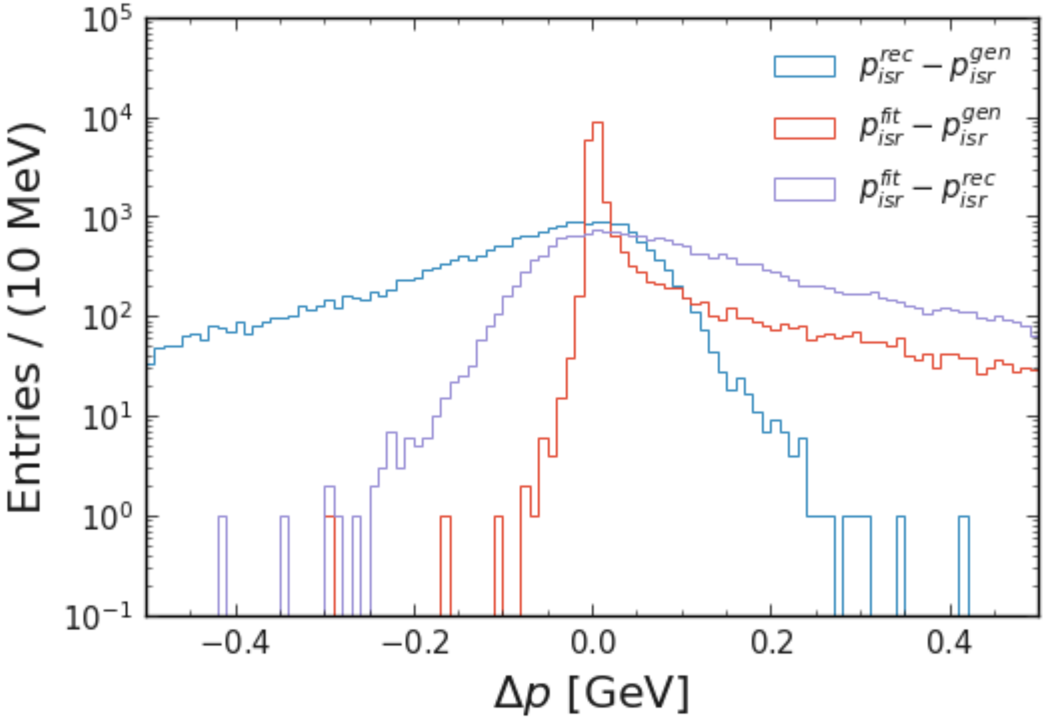
- $nGenGamma < 2$

```
Residuals for ['mum_p_original_2CHER_dipi', 'mu_p_1Cm_dimu'] vs mc_pim_p:
Entries: 318635.0, Mean: 5.7e-04, Std: 1.4e-02, Median: 3.6e-04
Entries: 318420.0, Mean: 8.4e-04, Std: 1.4e-02, Median: 4.4e-04
Entries: 318938.0, Mean: 6.6e-04, Std: 3.2e-03, Median: 6.5e-04
```



P_γ can be higher after 1C fit

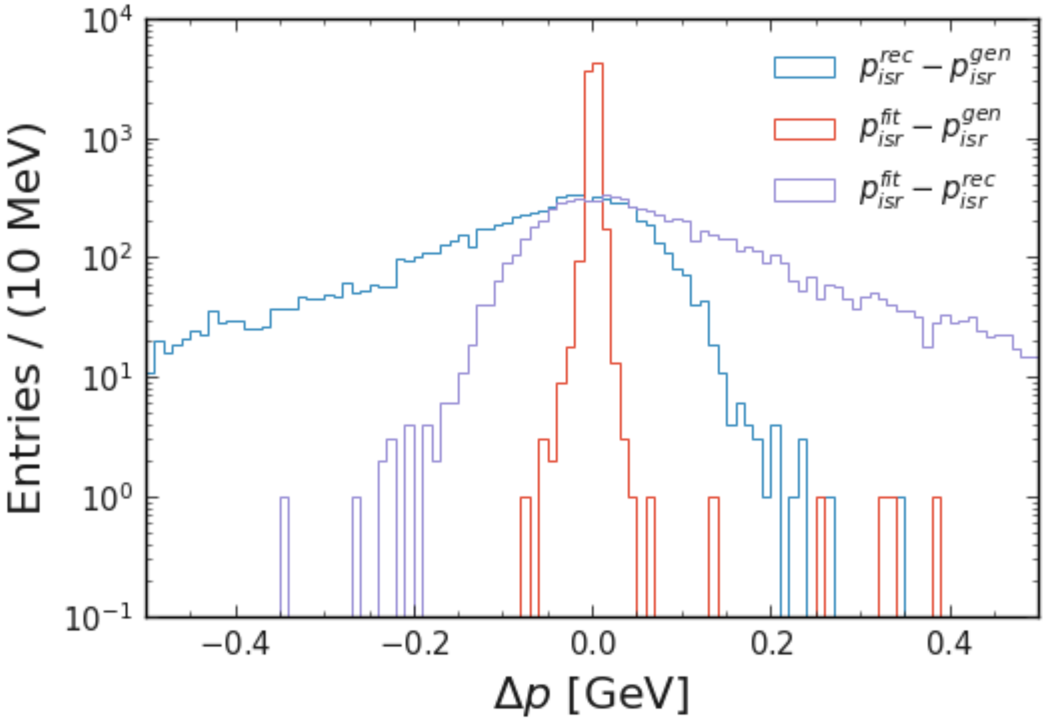
```
Residuals for ['isr_p_original_2CHER_dipi', 'isr_p_1Cm_dimu'] vs mc_isr_
p:
Entries: 20956.0, Mean: -7.6e-02, Std: 1.3e-01, Median: -4.6e-02
Entries: 21392.0, Mean: 3.8e-02, Std: 8.9e-02, Median: 5.3e-03
Entries: 19572.0, Mean: 1.0e-01, Std: 1.4e-01, Median: 7.3e-02
```



P_γ can be higher after 1C fit

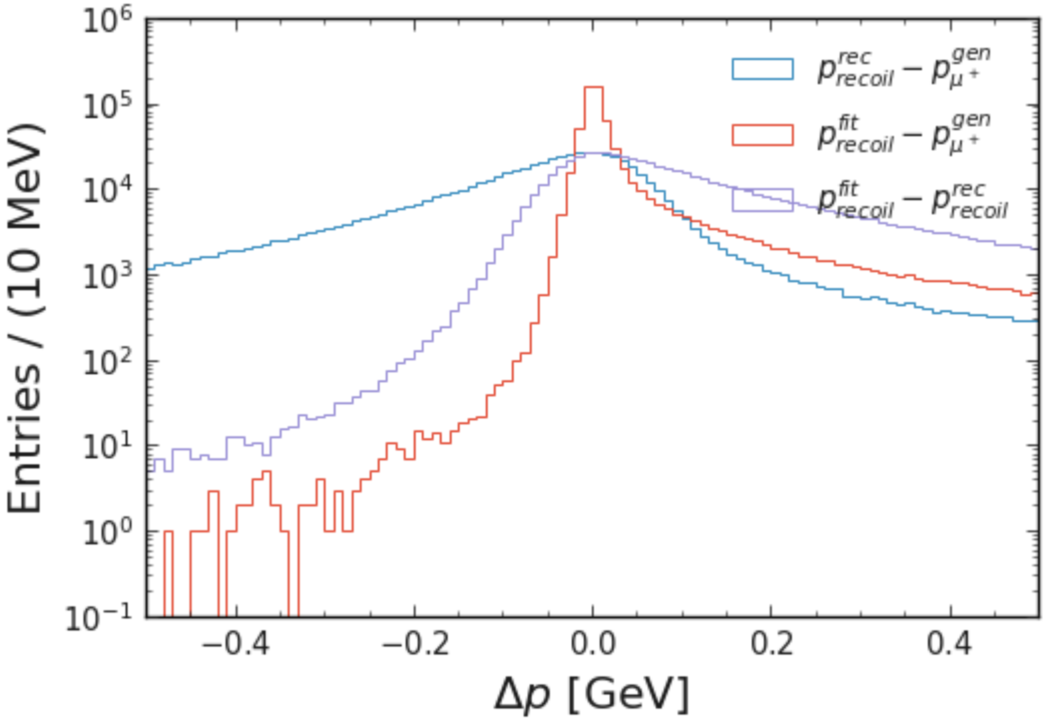
- `nGenGamma<2`

```
Residuals for ['isr_p_original_2CHER_dipi', 'isr_p_1Cm_dimu'] vs mc_isr_
p:
Entries: 7699.0, Mean: −7.6e−02, Std: 1.3e−01, Median: −4.6e−02
Entries: 8286.0, Mean: 6.7e−04, Std: 9.6e−03, Median: 8.9e−04
Entries: 7696.0, Mean: 7.7e−02, Std: 1.3e−01, Median: 4.7e−02
```



Similay behaviour for the recoil

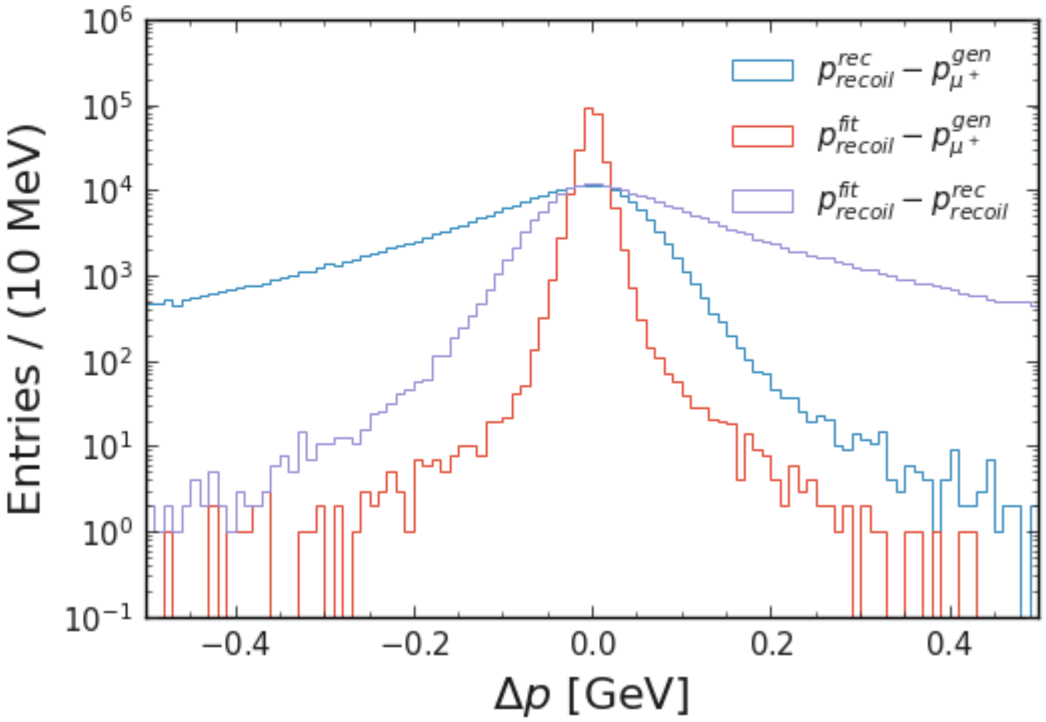
```
Residuals for ['recoil_p_original_1Cm', 'recoil_p_1Cm_dimu'] vs mc_pip_p:
Entries: 604850.0, Mean: -6.1e-02, Std: 1.4e-01, Median: -3.8e-02
Entries: 615865.0, Mean: 3.1e-02, Std: 8.0e-02, Median: 4.7e-03
Entries: 603277.0, Mean: 9.9e-02, Std: 1.3e-01, Median: 6.4e-02
```



Similay behaviour for the recoil

- `nGenGamma<2`

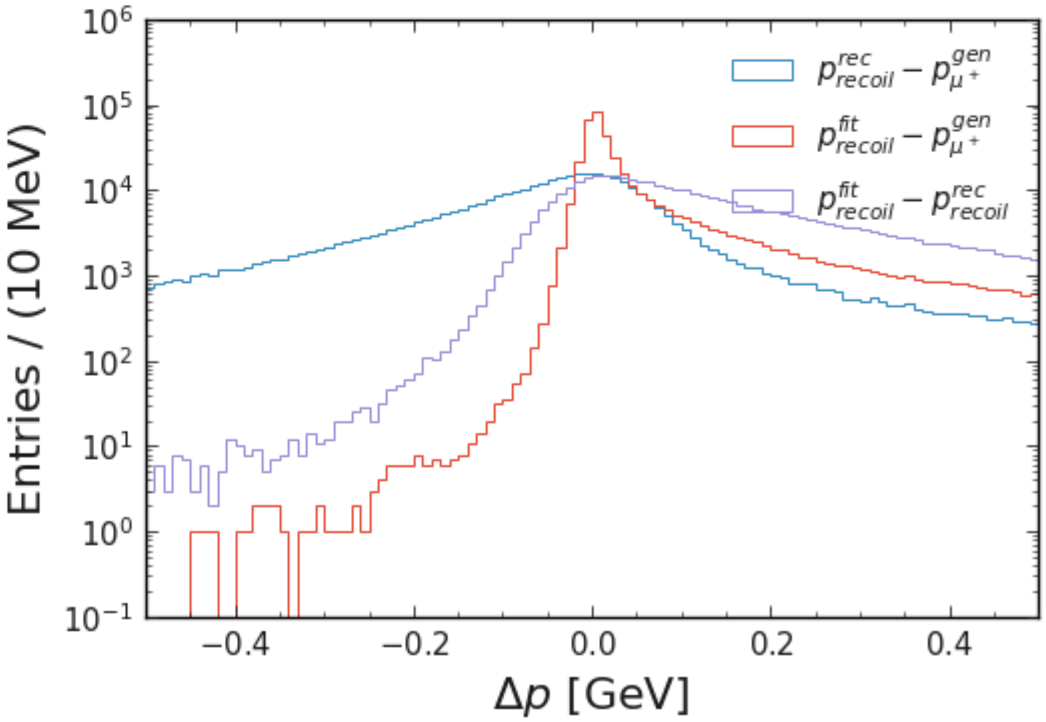
```
Residuals for ['recoil_p_original_1Cm', 'recoil_p_1Cm_dimu'] vs mc_pip_p:
Entries: 231469.0, Mean: -7.2e-02, Std: 1.2e-01, Median: -4.2e-02
Entries: 242200.0, Mean: -1.2e-03, Std: 1.5e-02, Median: -1.5e-03
Entries: 231605.0, Mean: 7.1e-02, Std: 1.2e-01, Median: 4.1e-02
```



Similay behaviour for the recoil

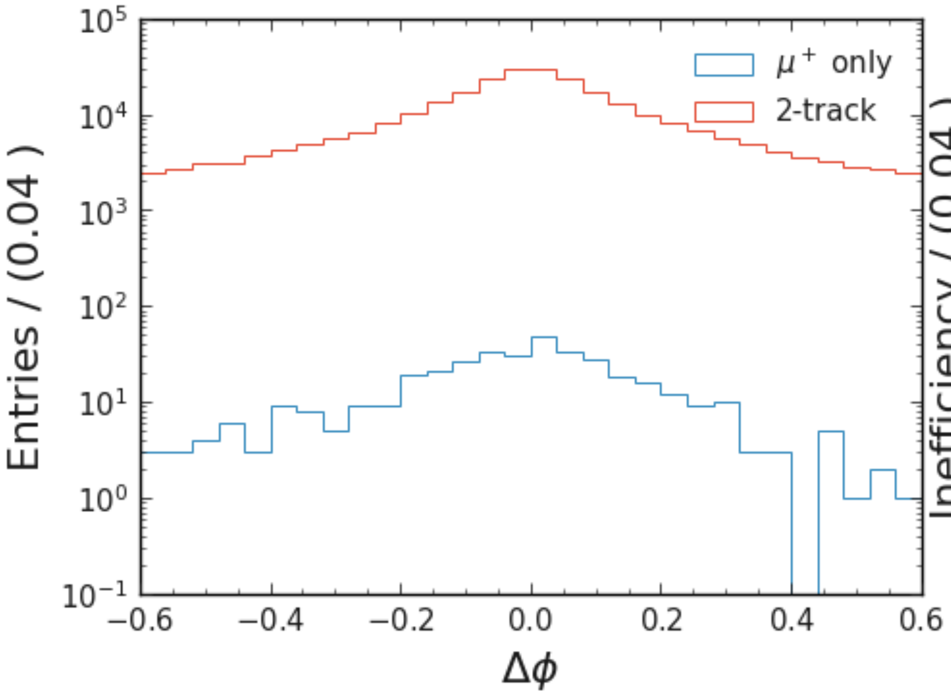
- `nGenGamma>=2`

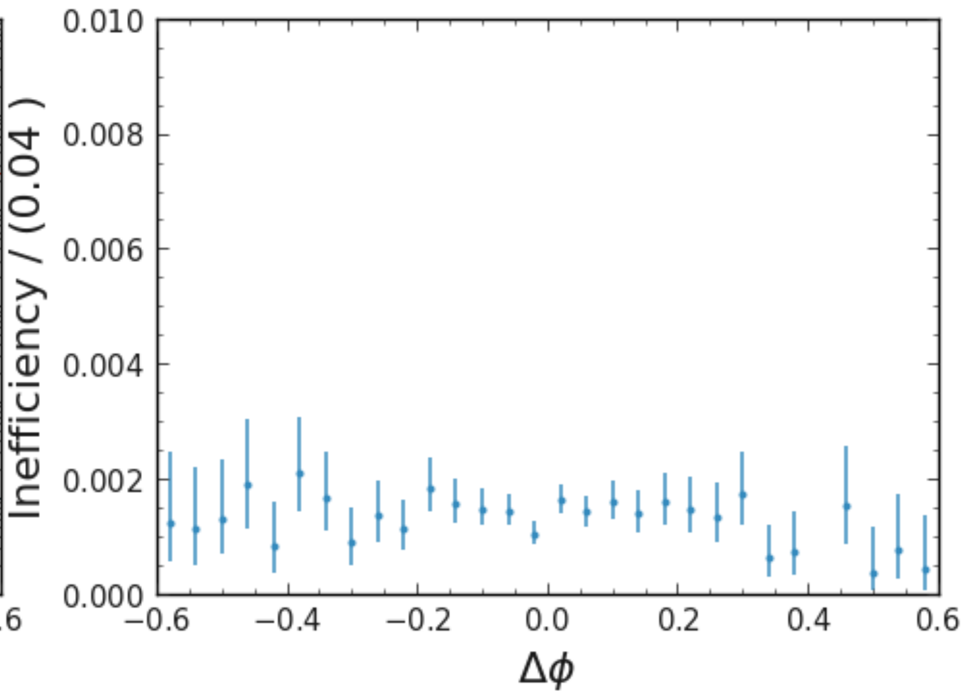
```
Residuals for ['recoil_p_original_1Cm', 'recoil_p_1Cm_dimu'] vs mc_pip_p:
Entries: 373381.0, Mean: -5.3e-02, Std: 1.5e-01, Median: -3.6e-02
Entries: 373665.0, Mean: 5.1e-02, Std: 9.7e-02, Median: 1.1e-02
Entries: 371672.0, Mean: 1.2e-01, Std: 1.4e-01, Median: 8.1e-02
```



Inefficiency (data-driven) conditional on μ^+ reconstruction

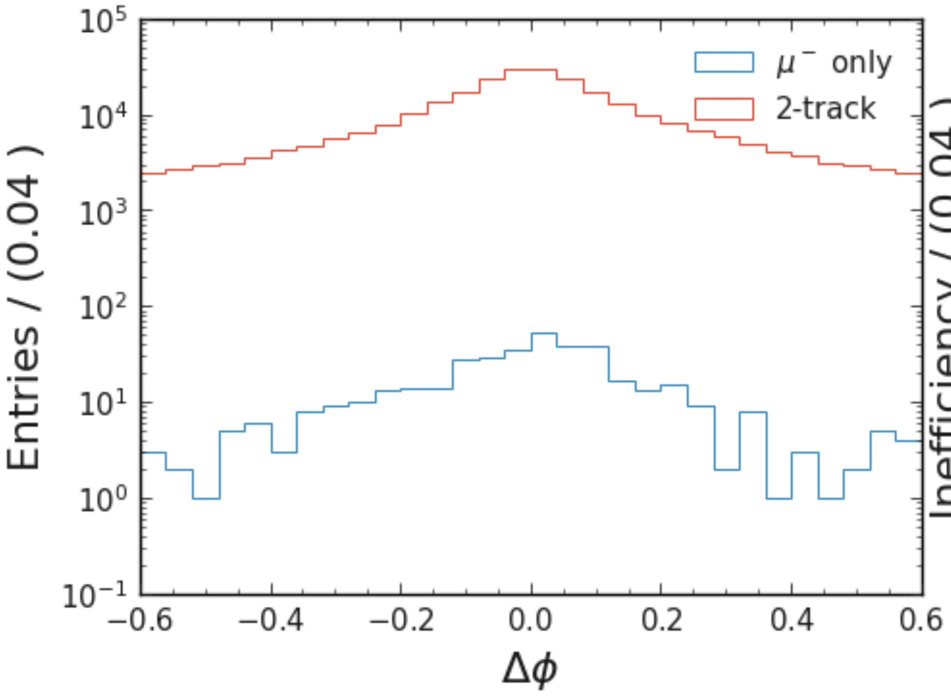
- ISR in ECL inner barrel, tracks in KLM inner barrel, $p_\mu > 1$ and $\chi^2_{1C} < 1$
- Using reconstructed μ^+ and predicted μ^- in the 2-track events

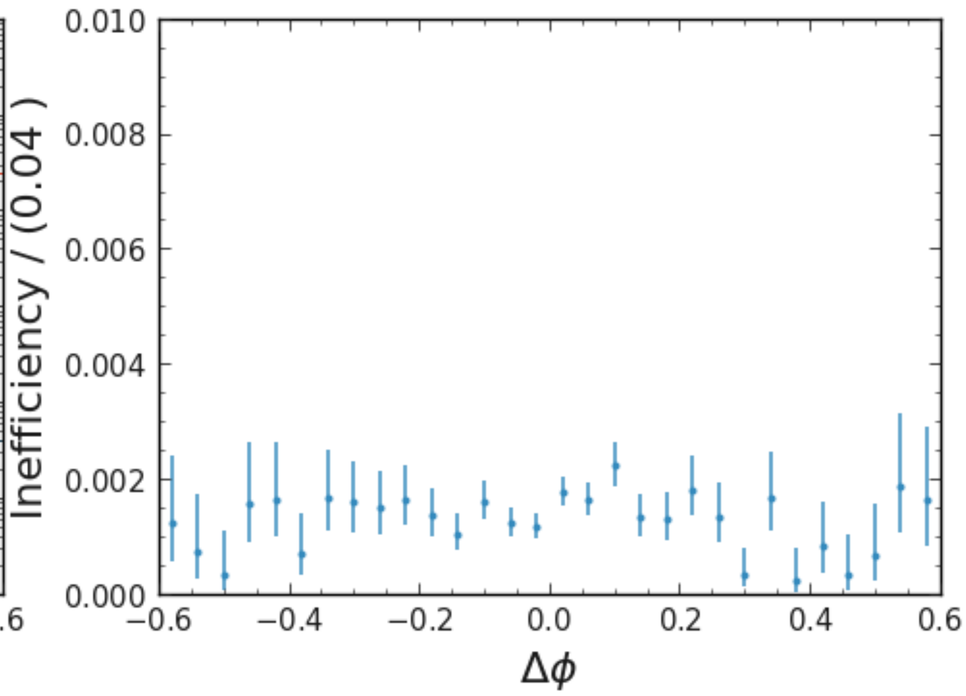




Inefficiency (data-driven) conditional on μ^- reconstruction

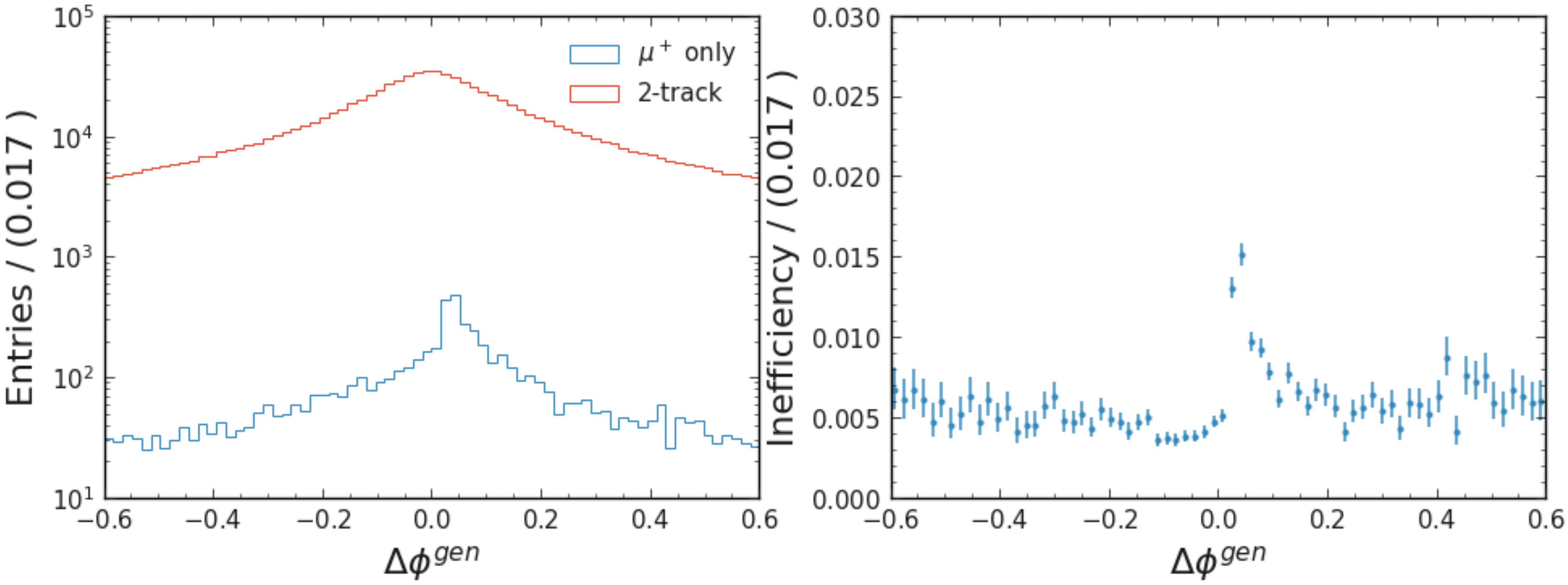
- ISR in ECL inner barrel, tracks in KLM inner barrel, $p_\mu > 1$ and $\chi^2_{1C} < 1$
- Using reconstructed μ^- and predicted μ^+ in the 2-track events





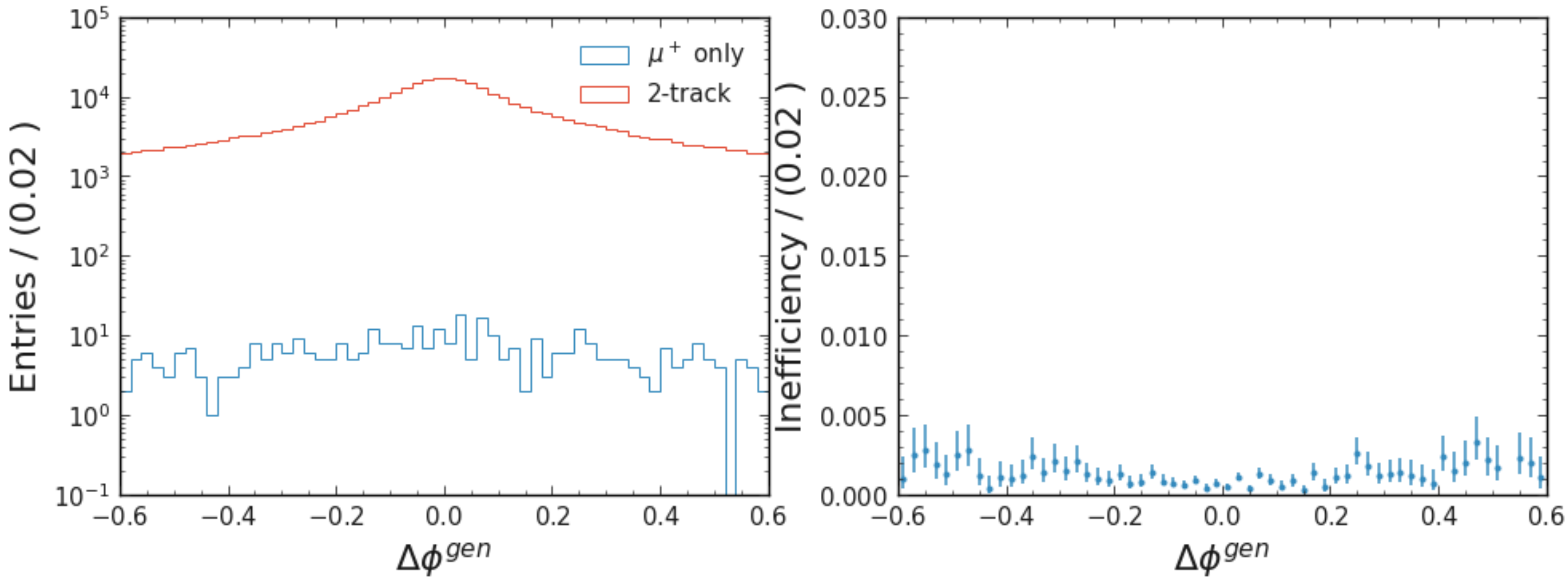
Inefficiency (data-driven) conditional on μ^+ reconstruction

- ISR and tracks in CDC acceptance and $p_\mu > 1$ in n-tuples
- The same requirments for the predicted track and $\chi^2_{1C} < 1$



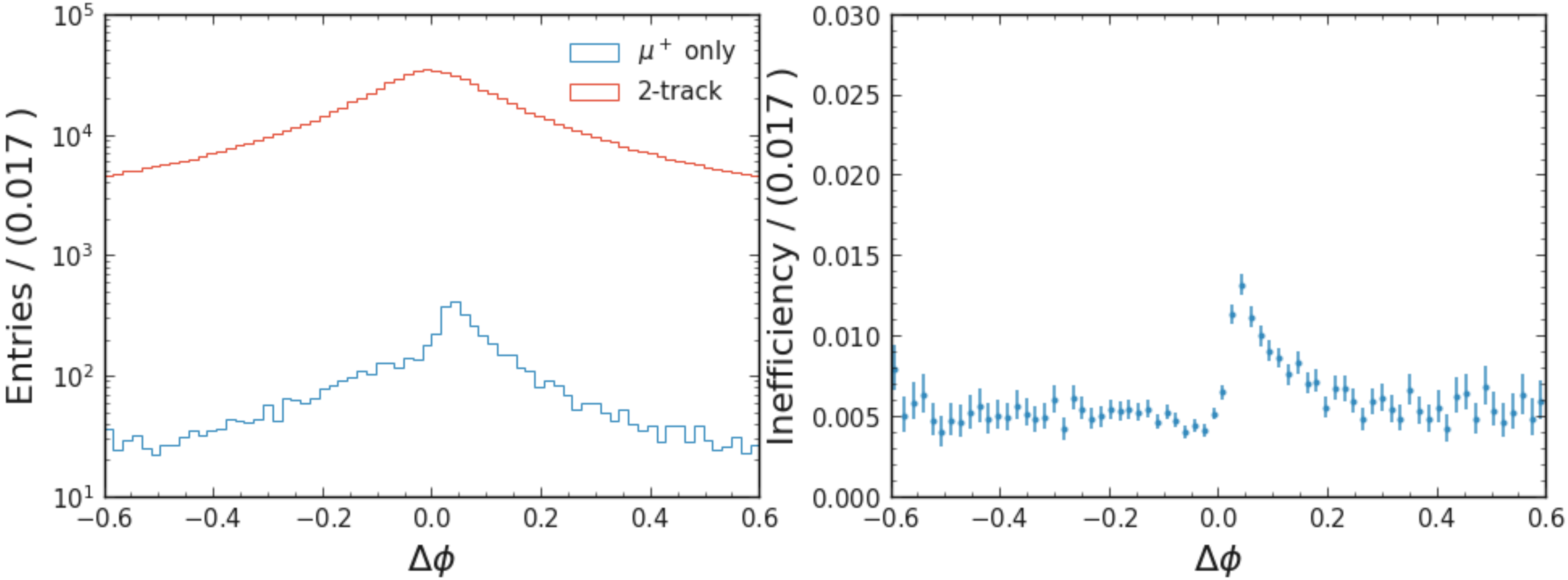
Inefficiency (data-driven) conditional on μ^+ reconstruction

- ISR in ECL inner barrel and tracks in KLM inner barrel and $p_\mu > 1$ in n-tuples
- The same requirments for the predicted track and $\chi^2_{1C} < 1$



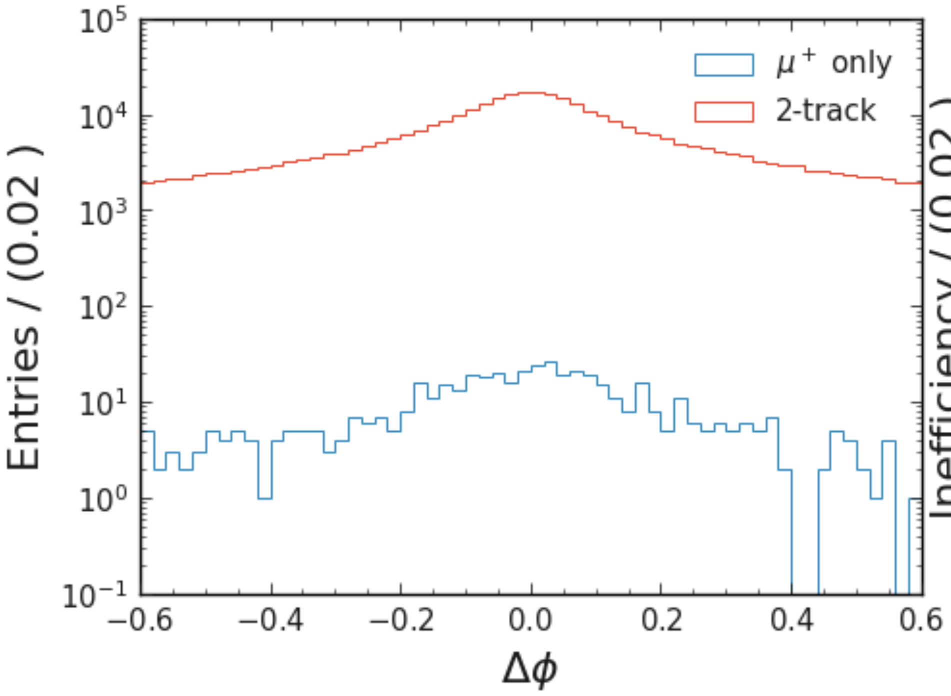
Inefficiency (data-driven) conditional on μ^+ reconstruction

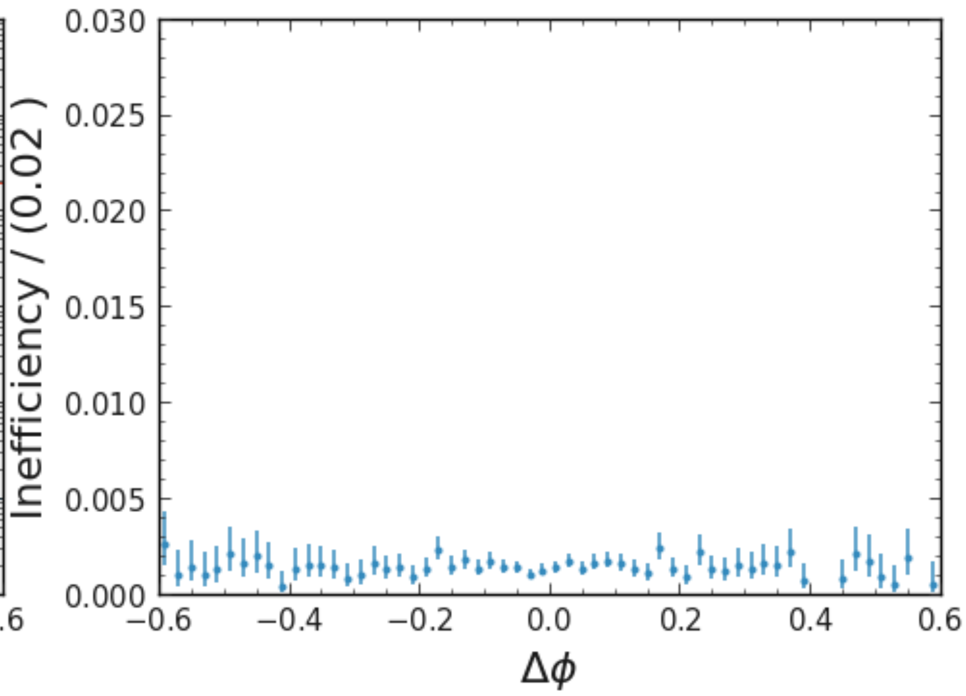
- ISR and tracks in CDC acceptance and $p_\mu > 1$ in n-tuples
- The same requirments for the predicted track and $\chi^2_{1C} < 1$



Inefficiency (data-driven) conditional on μ^+ reconstruction

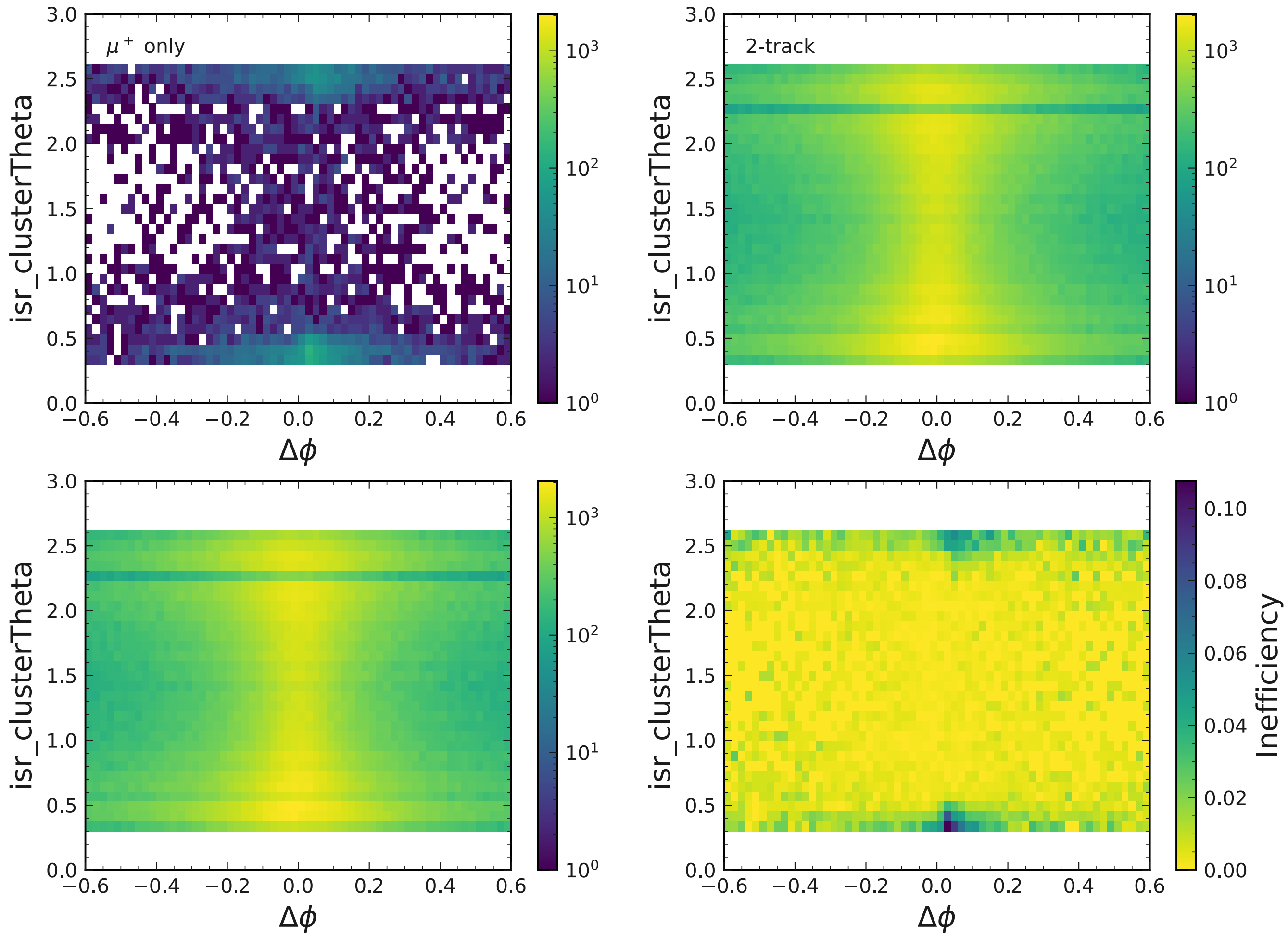
- ISR in ECL inner barrel and tracks in KLM inner barrel and $p_\mu > 1$ in n-tuples
- The same requirments for the predicted track and $\chi^2_{1C} < 1$





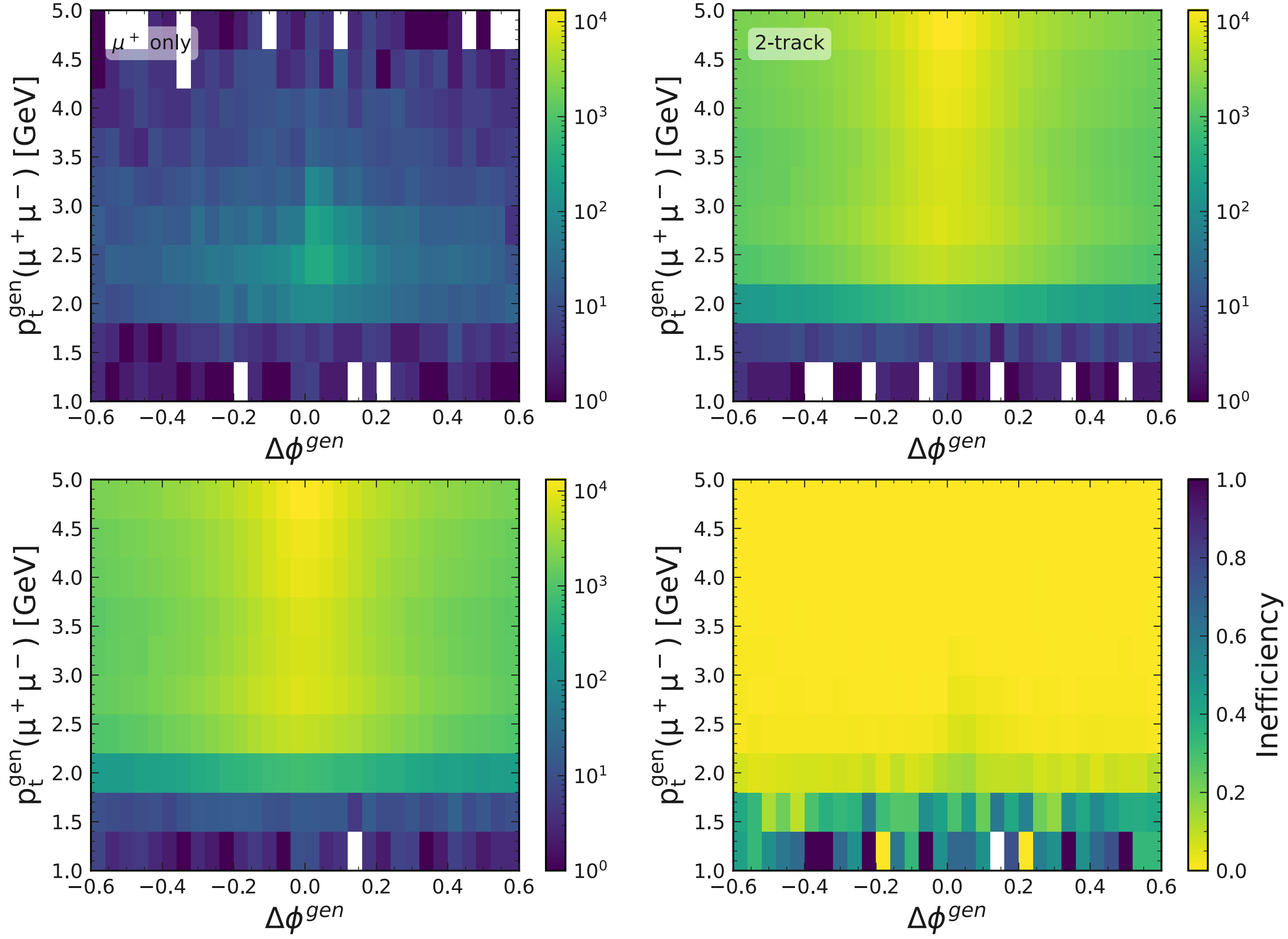
θ_{ISR} v.s. $\Delta\phi$

- Requiring θ_{ISR} in ECL inner barrel ([0.65, 2.16]) will remove the inefficiency peak around $\Delta\phi = 0.05$



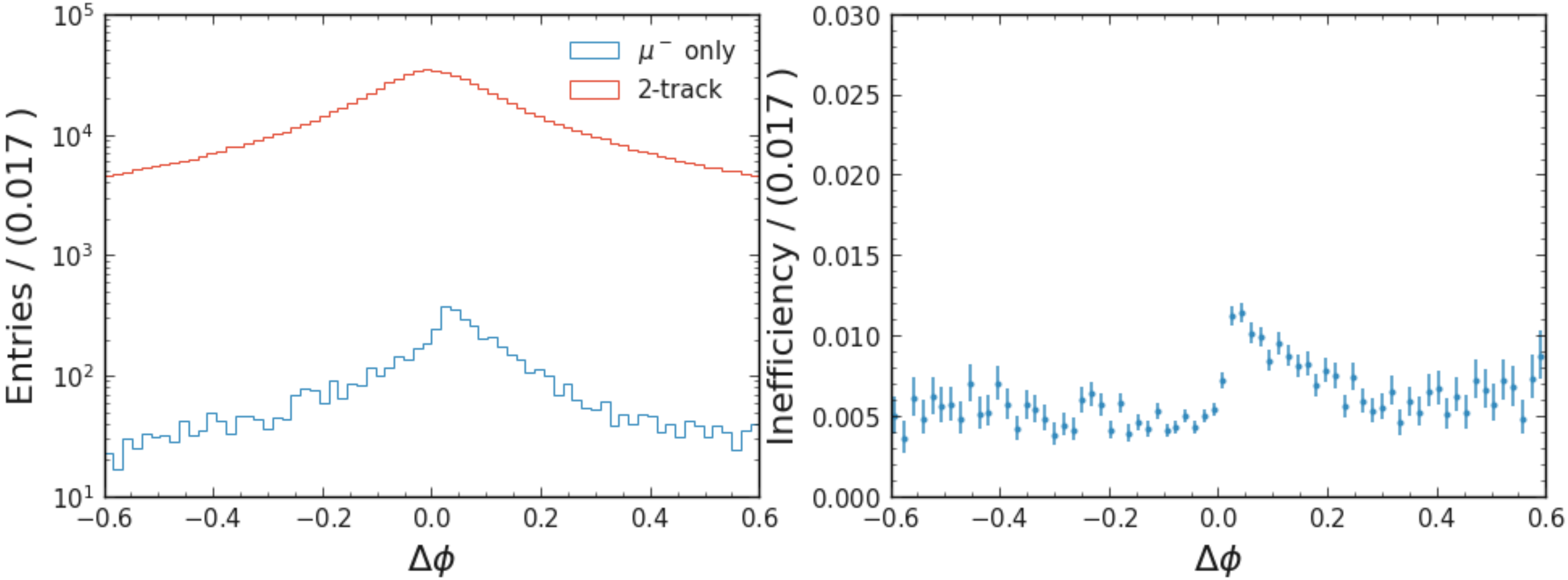
$p_T(\mu^+\mu^-)$ V.S. $\Delta\phi$

- Larger inefficiency around $|\Delta\phi^{gen}| = 0.5$ is due to low p_T of one track



Inefficiency (data-driven) conditional on μ^- reconstruction

- ISR and tracks in CDC acceptance and $p_\mu > 1$ in n-tuples
- The same requirments for the predicted track and $\chi^2_{1C} < 1$



Inefficiency (data-driven) conditional on μ^- reconstruction

- ISR in ECL inner barrel and tracks in KLM inner barrel and $p_\mu > 1$ in n-tuples
- The same requirments for the predicted track and $\chi^2_{1C} < 1$