SCUOLA NORMALE SUPERIORE

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Status of the KLOE-NXT Analysis

9th Plenary Workshop of the Muon g-2 Theory Initiative

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on behalf of the KLOE-2 Collaboration

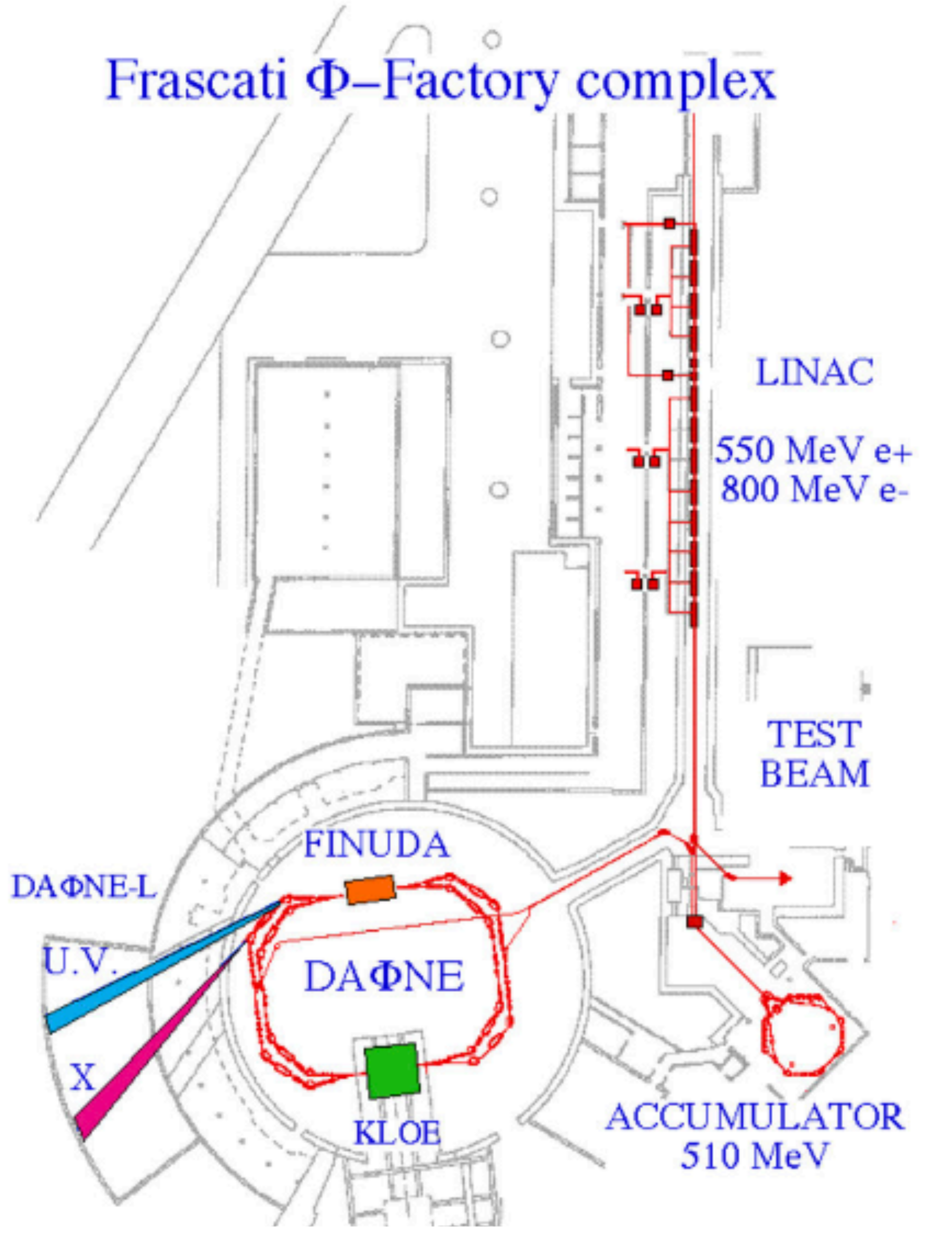
1) Scuola Normale Superiore, Pisa 2) INFN, Sezione di Pisa

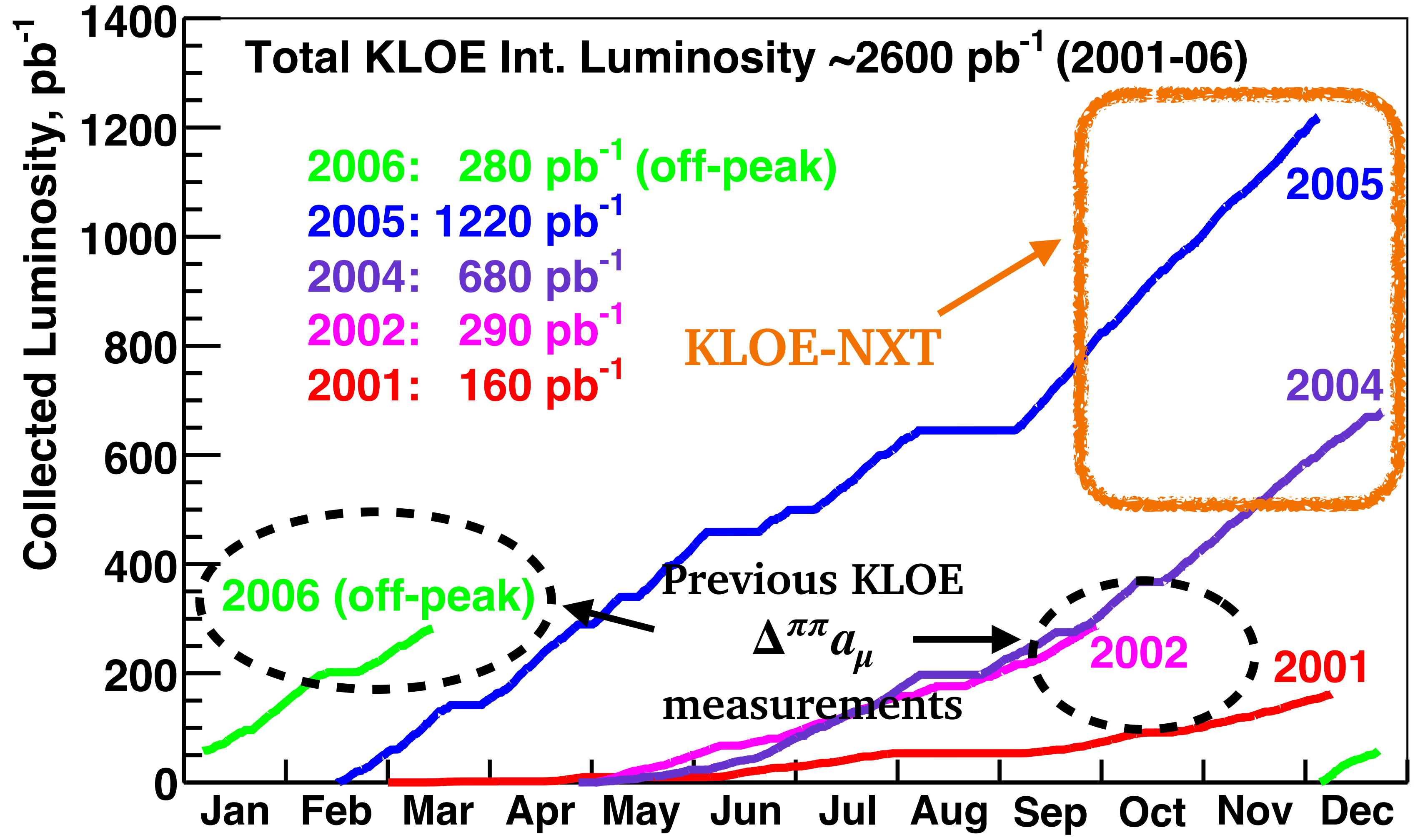
Old and New KLOE Analyses

What was done and what we aim for

The KLOE Experiment and DAΦNE @LNF

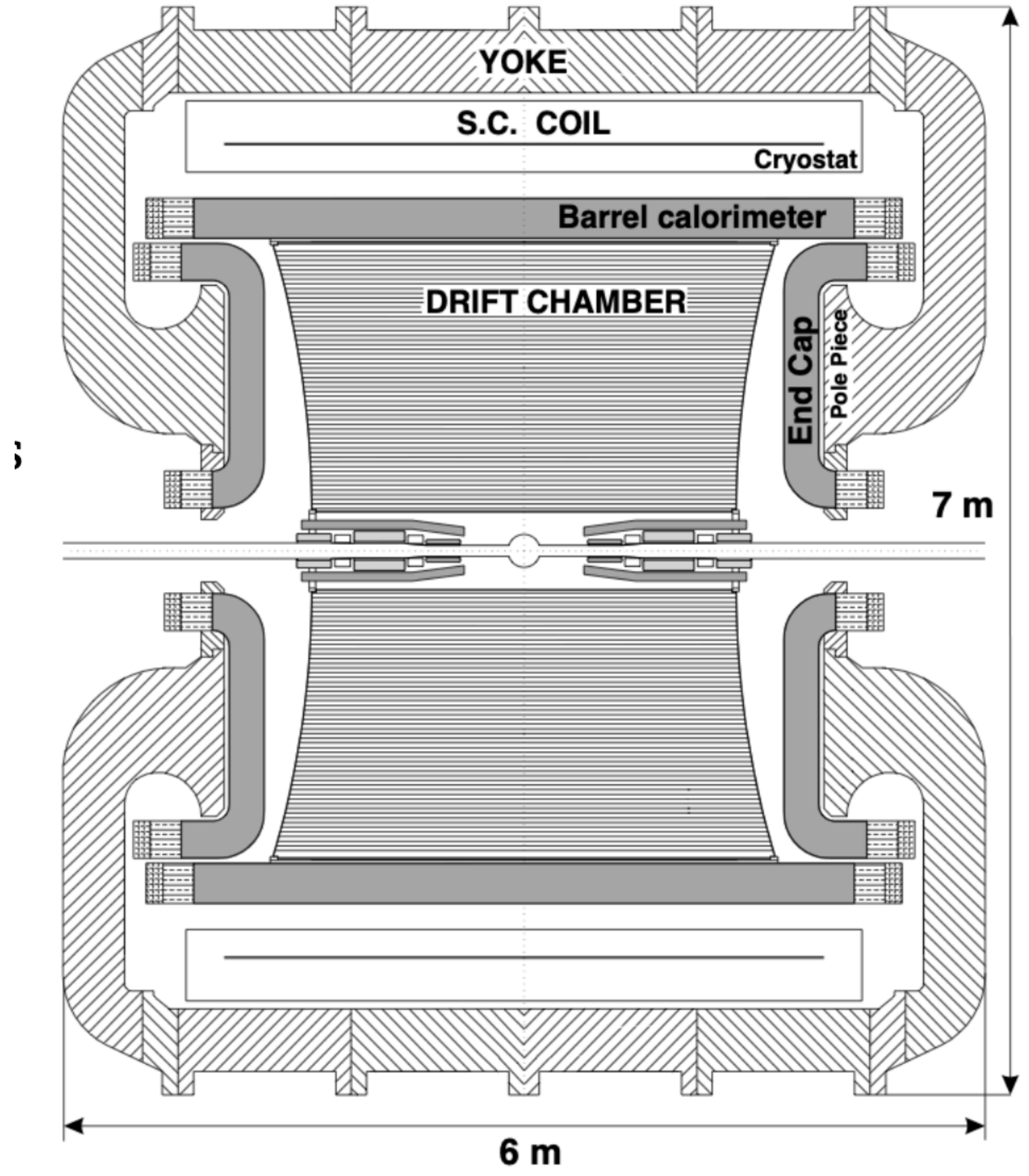
- KLOE-1 and KLOE-2 experiments located at the DAΦNE e^+e^- collider in Frascati, Italy → fixed c.m.s. energy of $m_\phi \simeq 1020$ MeV
- KLOE-1 data taking in 2002-2006, with 2.5 fb^{-1} on peak + 250 pb^{-1} off-peak ($\sqrt{s} \simeq 1000$ MeV) in 2006
- Maximum luminosity of ~ 8.5 pb^{-1}/day achieved in 2005
- Previous KLOE $\Delta^{\pi\pi}a_\mu$ measurements only used 240 pb^{-1} from 2002 (~3.5M $\pi\pi\gamma$ events) and 250 pb^{-1} from 2006
- There are still ~1.7 fb^{-1} of 2004-2005 data (~25M $\pi\pi\gamma$ events) to analyse **for a new $\Delta^{\pi\pi}a_\mu$ measurement**

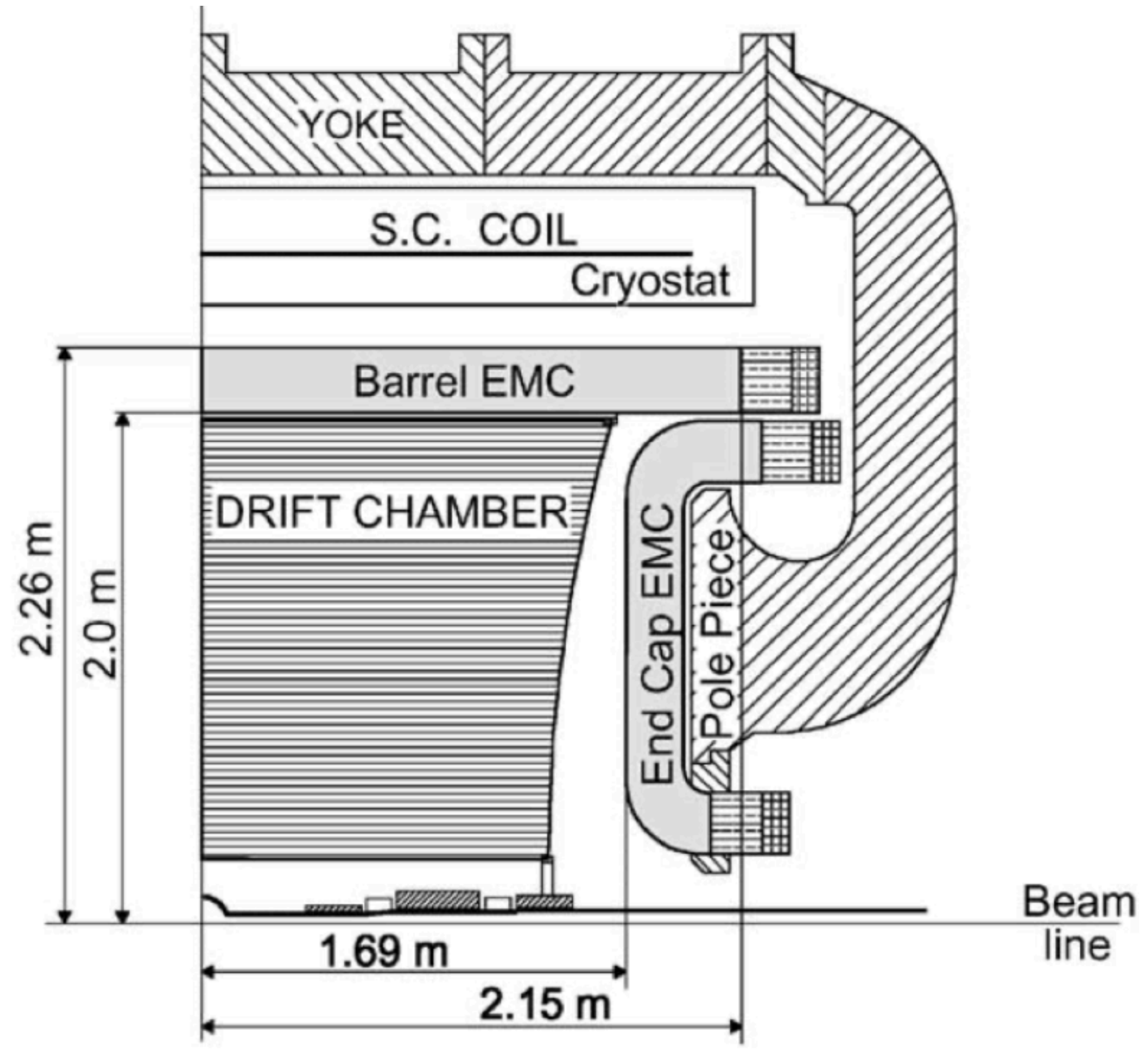




The KLOE Drift Chamber and Calorimeter

- Full stereo 3.3m x 2m (L x r) cylindrical drift chamber in 0.52T solenoidal magnetic field filled with 90% He - 10% Isobutane
- 50k+ wires (field:sense = 3:1) arranged in layers with varying stereo angles from 60 mrad to 150 mrad
- Resolutions achieved: $\sigma_{r\phi} \simeq 200\mu$m, $\sigma_z \simeq 2$mm, $\sigma_{vtx} \simeq 3$mm, $\sigma(p_T)/p_T \simeq 0.4\% \rightarrow$ excellent momentum resolution





- Sampling calorimeter (Barrel + Endcaps) comprised of Pb passive layers + scintillating fibre sensing layers
- Detects photons between 20 MeV - 500 MeV with 98% of 4π acceptance
- Readout using 5k photomultipliers, which feed trigger, ADCs and TDCs (allow measurement of coordinate along fiber)
- Resolutions achieved:
  - $\sigma(E)/E \simeq 5.7\,\%/\sqrt{E[\text{GeV}]}$
  - $\sigma_t = 54/\sqrt{E[\text{GeV}]} \oplus 100$ ps $\longrightarrow \sigma_z \simeq 9/\sqrt{E[\text{GeV}]}$ mm

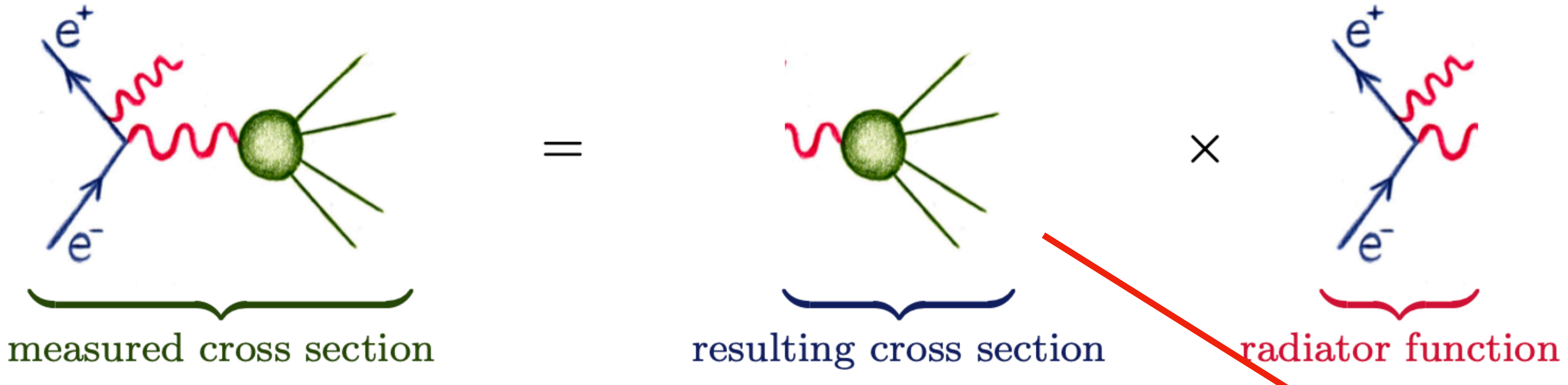
Previous KLOE $\Delta^{\pi\pi}a_\mu$ Analyses: KLOE08

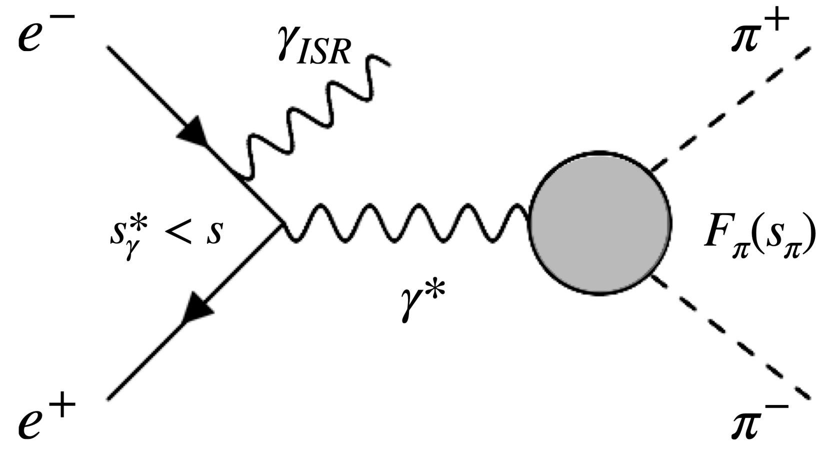
KLOE08

- Measure 60 points of s between 0.35 and 0.95 GeV^2
- Used 240.0 pb^{-1} form 2002 run
- 2 charged tracks (pions) at large angles $50^\circ < \theta_\pm < 130^\circ$
- *Untagged* photon at small angle (SA) from kinematics $\vec{p}_{miss} \equiv -\vec{p}_+ - \vec{p}_- \rightarrow \theta_\Sigma < 15^\circ \vee \theta_\Sigma > 165^\circ$
- Topology choice enhances ISR, suppresses FSR and $\phi \rightarrow \pi^+\pi^-\pi^0$ background
- Cannot reach dipion threshold $s = 4m_\pi$ (kinematics)
- Cross section from normalisation to luminosity (Bhabha) and correction with radiator (PHOKHARA v5)

$$s \cdot \frac{d\sigma(e^+e^- \rightarrow \pi^+\pi^-\gamma)}{ds_{\pi\pi}} = \sigma_{\pi\pi}(s_{\pi\pi}) \times H(s_{\pi\pi}, s)$$

$$\boxed{\frac{\mathrm{d}\,\sigma(e^+e^- \rightarrow \mathrm{had} + \gamma)}{\mathrm{d}\,M^2_{\mathrm{had}}} = \frac{\sigma(e^+e^- \rightarrow \mathrm{had}, M^2_{\mathrm{had}})}{s} \times H(s, M^2_{\mathrm{had}})}$$





$$\Delta^{\pi\pi}a_\mu = \frac{1}{4\pi^3}\int_{s_{min}}^{s_{max}} ds K(s)\sigma^0_{\pi\pi}(s)$$

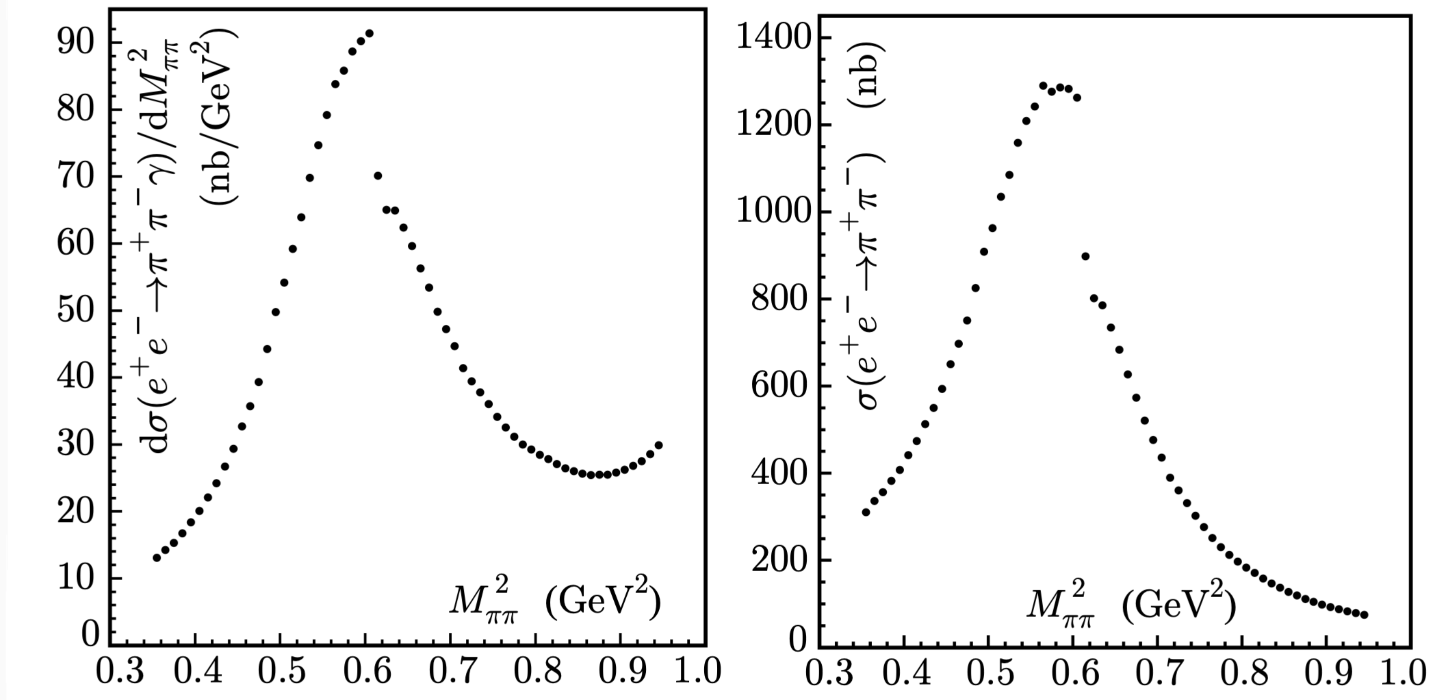
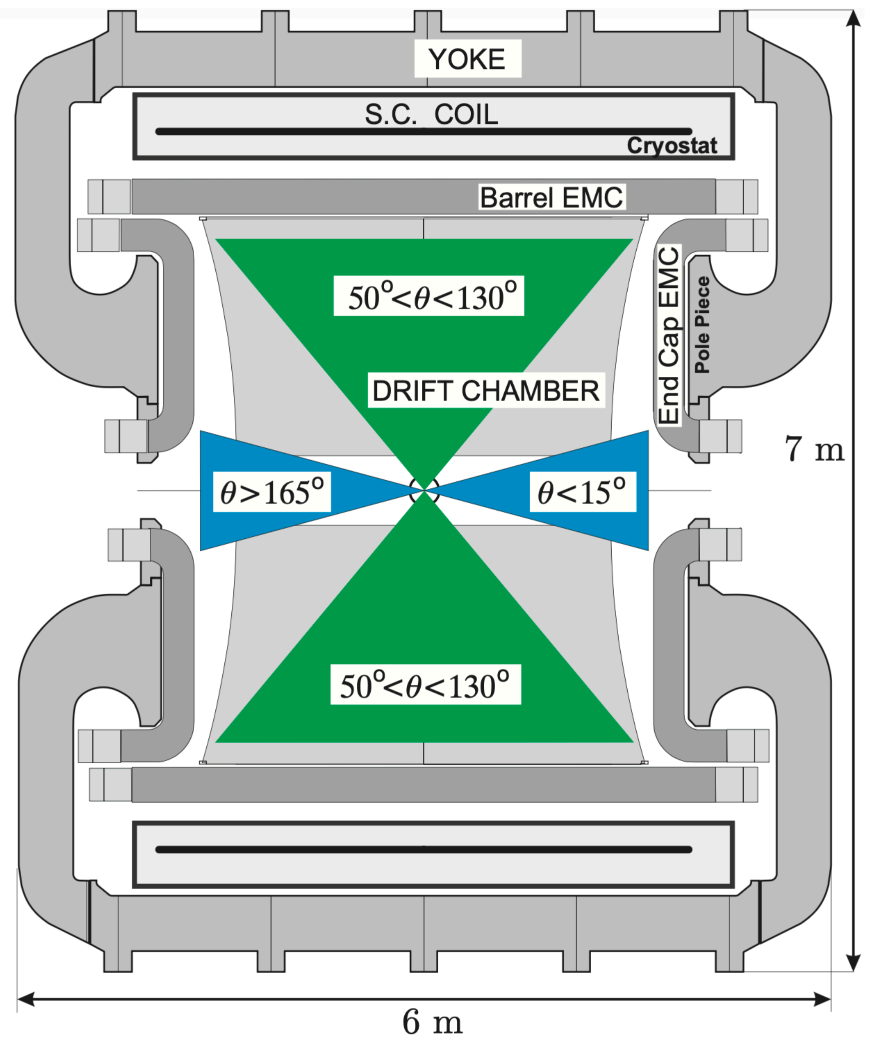
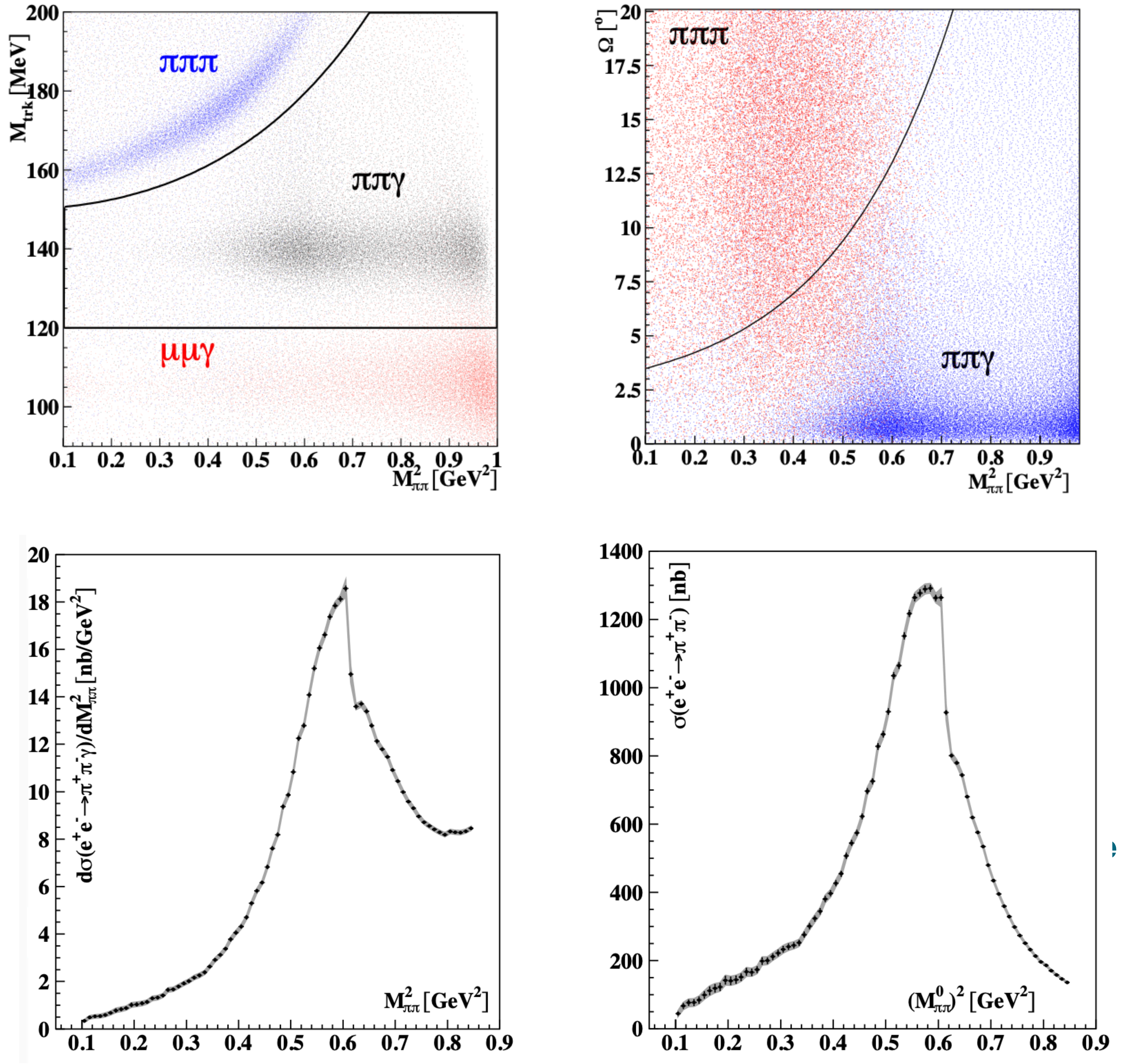


Figure 42: Left: Cross section for the $e^+e^- \rightarrow \pi^+\pi^-\gamma(\gamma)$ process, inclusive in θ_π and with $0^o < \theta_{\pi\pi} < 15^o$ or $165^o < \theta_{\pi\pi} < 180^o$. Right: *Bare* cross section for $e^+e^- \rightarrow \pi^+\pi^-$.



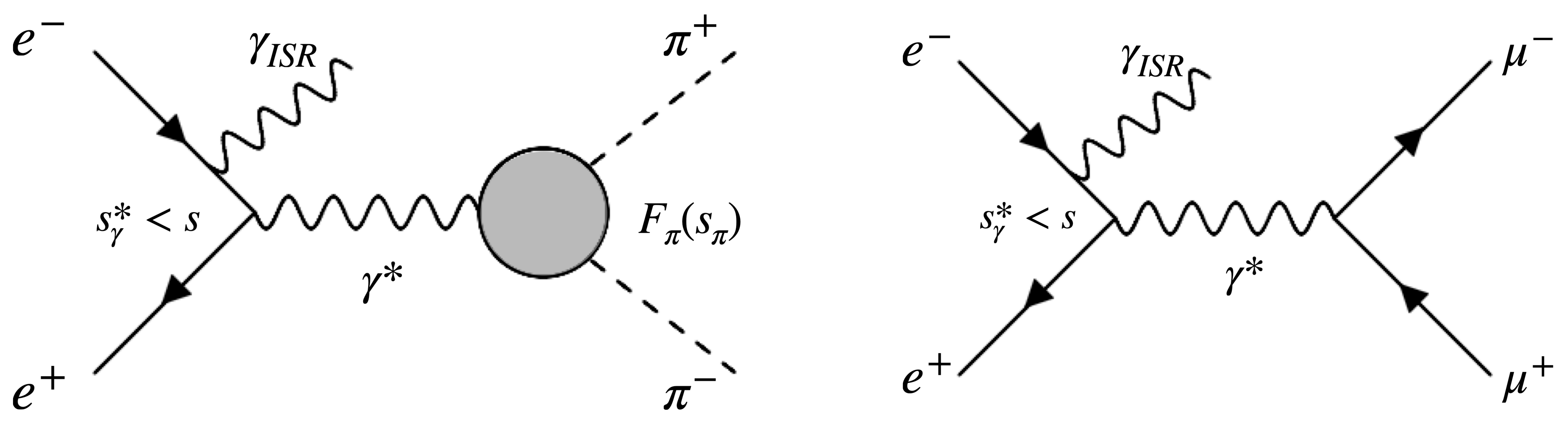
KLOE10

- Measure 75 points of s between 0.10 and 0.85 GeV^2
- 232.6 pb^{-1} from 2006 off-peak data ($\sqrt{s} \sim 1000$ MeV)
- 2 charged tracks (pions) at large angles $50^\circ < \theta_\pm < 130^\circ$
- **Tagged photon** detected at large angle using EMC $\rightarrow$ $50^\circ < \theta_\gamma < 130^\circ$
- Topology reaches much lower s at the cost of higher FSR and $\phi \rightarrow \pi^+\pi^-\pi^0$ background
- $\phi \rightarrow \pi^+\pi^-\pi^0$ background mitigated by being off the ϕ peak
- Cross section from normalisation to luminosity (Bhabha) and correction with radiator (PHOKHARA)

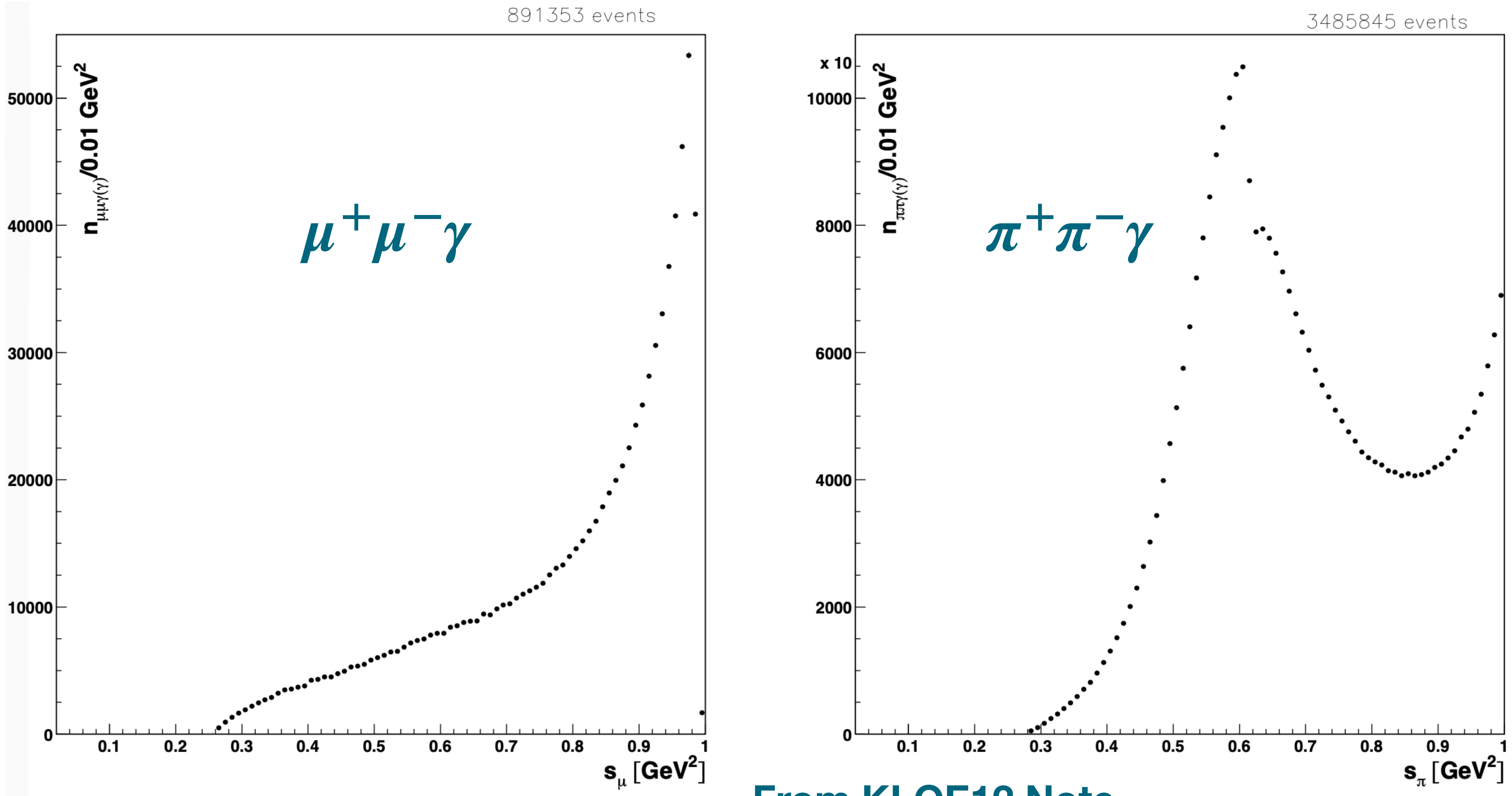


From KLOE10 Note

Previous KLOE $\Delta^{\pi\pi}a_\mu$ Analyses: KLOE12



$$\sigma_{\pi\pi(\gamma)}(s) = \sigma_{\mu\mu(\gamma)}(s)\frac{d\sigma^{ISR}_{\pi\pi\gamma}/ds}{d\sigma^{ISR}_{\mu\mu\gamma}/ds}$$



From KLOE12 Note

KLOE12

- Measure 60 points of s between 0.35 and 0.95 GeV^2
- Used 240.0 pb^{-1} form 2002 run
- 2 charged tracks (pions) at large angles $50^\circ < \theta_\pm < 130^\circ$
- *Untagged* photon at small angle (SA) from kinematics $\vec{p}_{miss} \equiv -\vec{p}_+ - \vec{p}_- \rightarrow \theta_\Sigma < 15^\circ \vee \theta_\Sigma > 165^\circ$
- Topology choice enhances ISR, suppresses FSR and $\phi \rightarrow \pi^+\pi^-\pi^0$ background
- Cannot reach dipion threshold $s = 4m_\pi$ (kinematics)
- **Normalise to $\mu^+\mu^-\gamma$ cross section** $\rightarrow$ "*ratio approach*"
- Compatible with KLOE08 and KLOE10 (see backup) despite different systematics

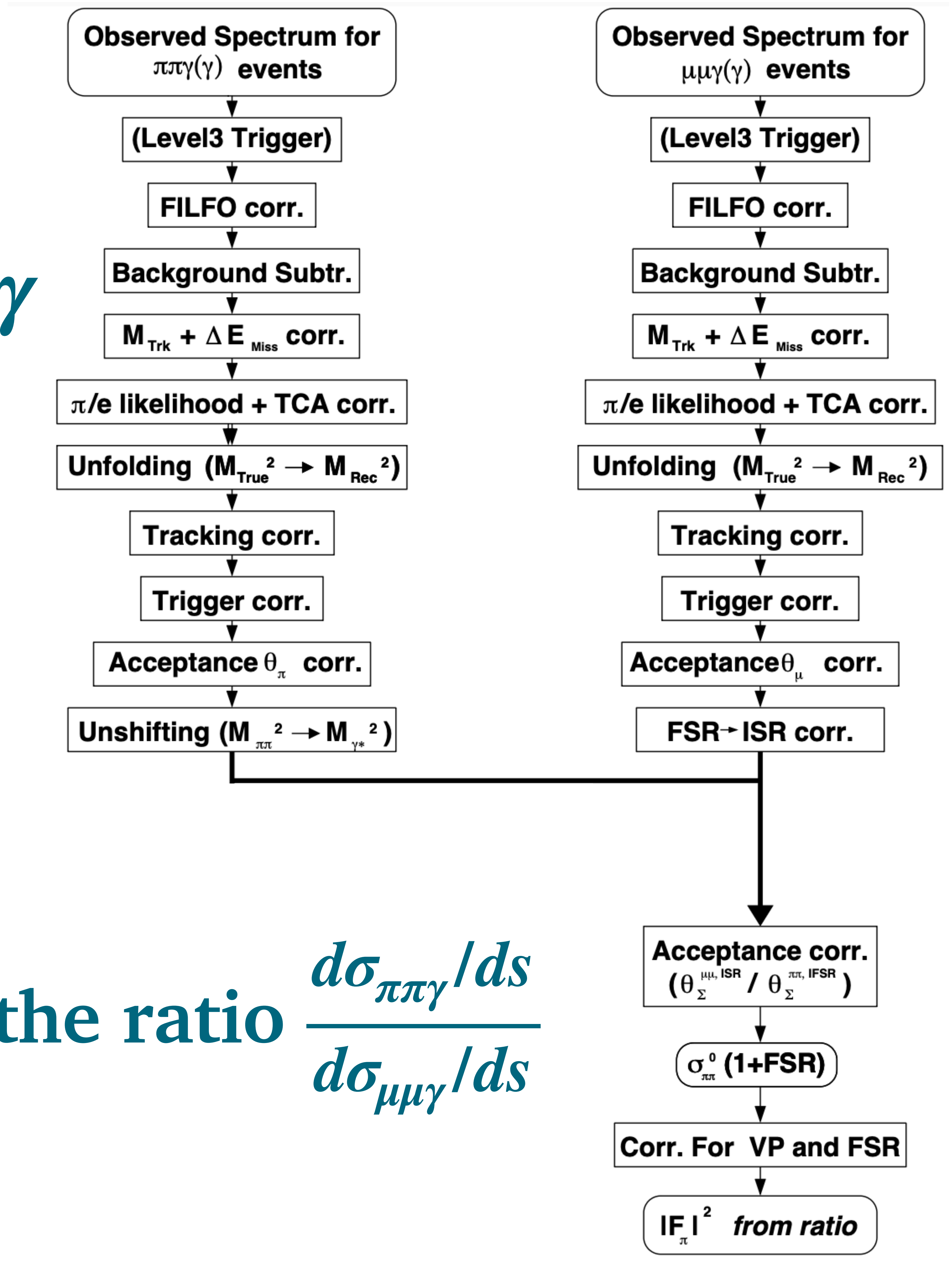
A New Measurement: *KLOE-NXT*

KLOE-NXT (goal)

- Measure 60 points of s between 0.35 and 0.95 GeV^2
- Same selections as KLOE08 and KLOE12
- Normalise to $\mu^+\mu^-\gamma$ cross section like KLOE12
- **Use $\sim$1.7 fb^{-1} from 2004-2005 runs (7x statistics)**
- Use 2006 off-peak dataset for cross-checks
- Use newer MC generators, e.g. PHOKHARA v10, BABAYAGA@NLO, etc
- Use updated reconstruction simulation
- Use new analysis strategies made possible by increased statistics
- ***Blind the analysis for the first time***

$\pi^+\pi^-\gamma$

$\mu^+\mu^-\gamma$



Take the ratio $\dfrac{d\sigma_{\pi\pi\gamma}/ds}{d\sigma_{\mu\mu\gamma}/ds}$

Precision Goal of *KLOE-NXT*

Syst Errors (%)	$a_\mu^{\pi\pi}$ absolute (KLOE08)	$a_\mu^{\pi\pi}$ ratio (KLOE12)	Goal KLOE-NXT
Background Filter (FILFO)	negligible	negligible	negligible
Background Subtraction	0.3	0.6	0.2
Trackmass	0.2	0.2	0.2
Particle ID	negligible	negligible	negligible
Tracking	0.3	0.1	0.1
Trigger	0.1	0.1	0.1
Unfolding	negligible	negligible	negligible
Acceptance ($\theta_{\pi\pi}$)	0.2	negligible	negligible
Acceptance (θ_π)	negligible	negligible	negligible
Software Trigger (L3)	0.1	0.1	0.1
Luminosity	$0.3\,(0.1_{th} \oplus 0.3_{exp})$	-	-
$\sqrt{s}$ dep. of H	0.2	-	-
Total exp. systematics	0.6	0.7	0.3
Vacuum Polarisation	0.1	-	-
FSR treatment	0.3	0.2	
ISR&FSR treatment			0.2
Rad. function H	0.5	-	-
Total theory systematics	0.6	0.2	0.2
Total systematic error	0.9	0.7	0.4

- With 7x statistics the final precision is expected to be limited by systematics
- Substantial increase in statistics should allow for improvement of systematics and additional cross checks
- One of the main systematics is background subtraction → **final goal is to reduce it by 3x, leveraging increased statistics and new methods**
- Final uncertainty goal:
  - KLOE12: $0.7\%_{syst} \oplus 0.2\%_{th} \oplus 0.3\%_{stat} = 0.8\%_{tot}$
  - KLOE-NXT goal: $0.3\%_{syst} \oplus 0.2\%_{th} \oplus 0.1\%_{stat} = 0.4\%_{tot}$

Most precise measurement by a single experiment to date!

Progress on *KLOE-NXT*

The work so far from our group

Computing Challenges!

- KLOE computing in LNF heavily relied on outdated IBM infrastructure, including the old tape library storing KLOE-1 data and software (analysis, reconstruction, …)

- Since 2023 KLOE computing has faced repeated failures of machines/subsystems, including two partitions of the old tape library, halting progress on the ongoing KLOE-NXT analysis → couldn't access most KLOE-1 data and software, e.g. detector reconstruction simulation

- Solutions were limited due to low personnel numbers and irreplaceable hardware

- Good news! Thanks to the effort of our group and the KLOE-2 computing personnel, recently:
    - 90% of KLOE-1 data has been migrated to CNAF computing center (Bologna)
    - One partition of the tape library has been fully restored (other is WiP)
    - New working environments have been setup both in CNAF and Liverpool, with git version control
    - KLOE software has been updated and ported to more "modern" Linux infrastructure
    - First KLOE-1 data re-processing and Monte Carlo production on Linux machines now complete!

Tuning of Monte Carlo Simulation

- KLOE $\sigma(e^+e^- \to \pi^+\pi^-)$ measurements rely on Monte Carlo simulations for background subtraction, efficiencies, … → **data-MC consistency is crucial for the analysis**

- Due to imperfect simulation of the KLOE detector (e.g. large Drift Chamber), additional corrections are needed to improve data/MC consistency

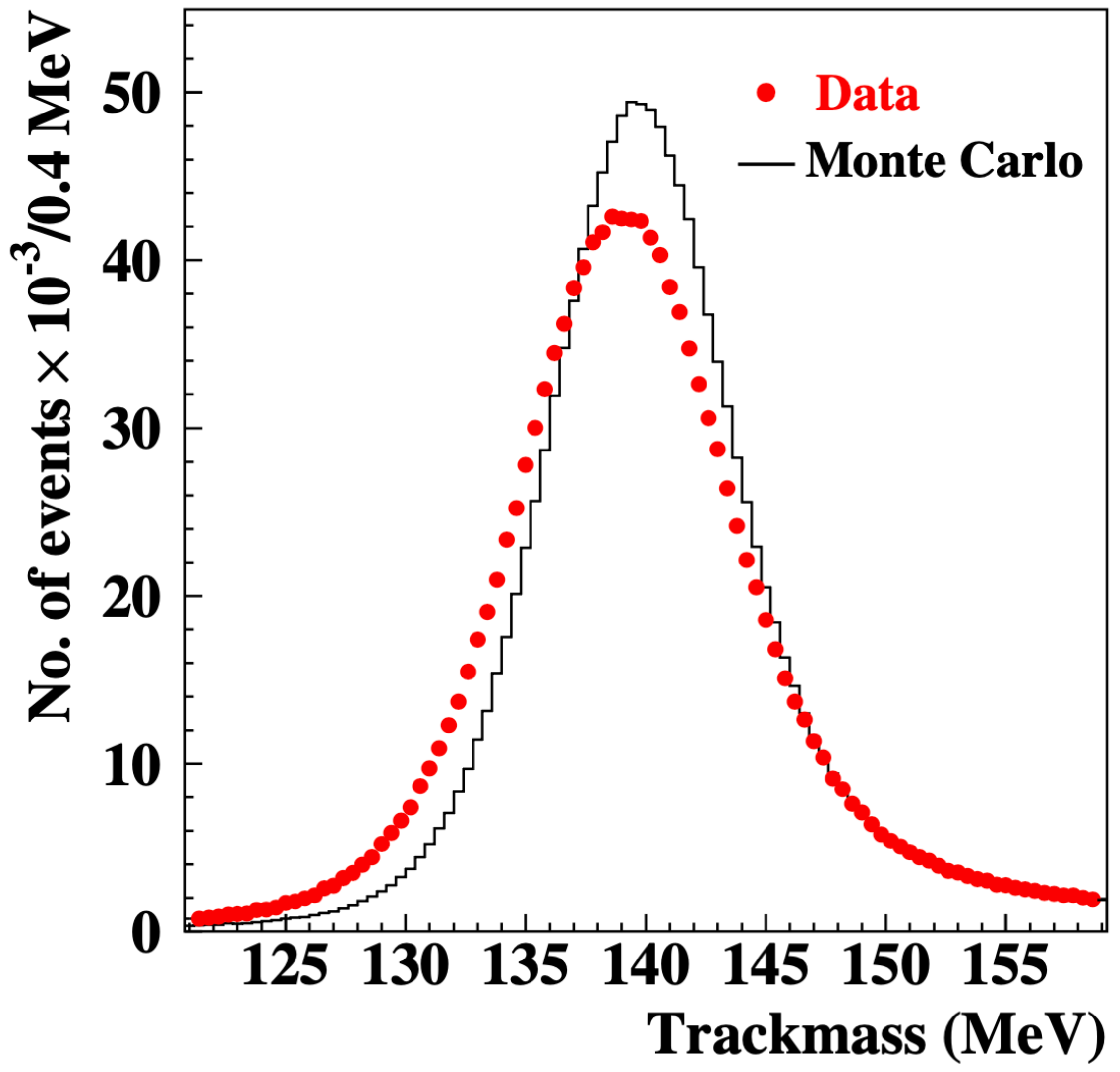
- KLOE08/KLOE12 analyses corrected MC by shifting/smearing the charged tracks' momenta $p^{\pm}_{x,y,z}$

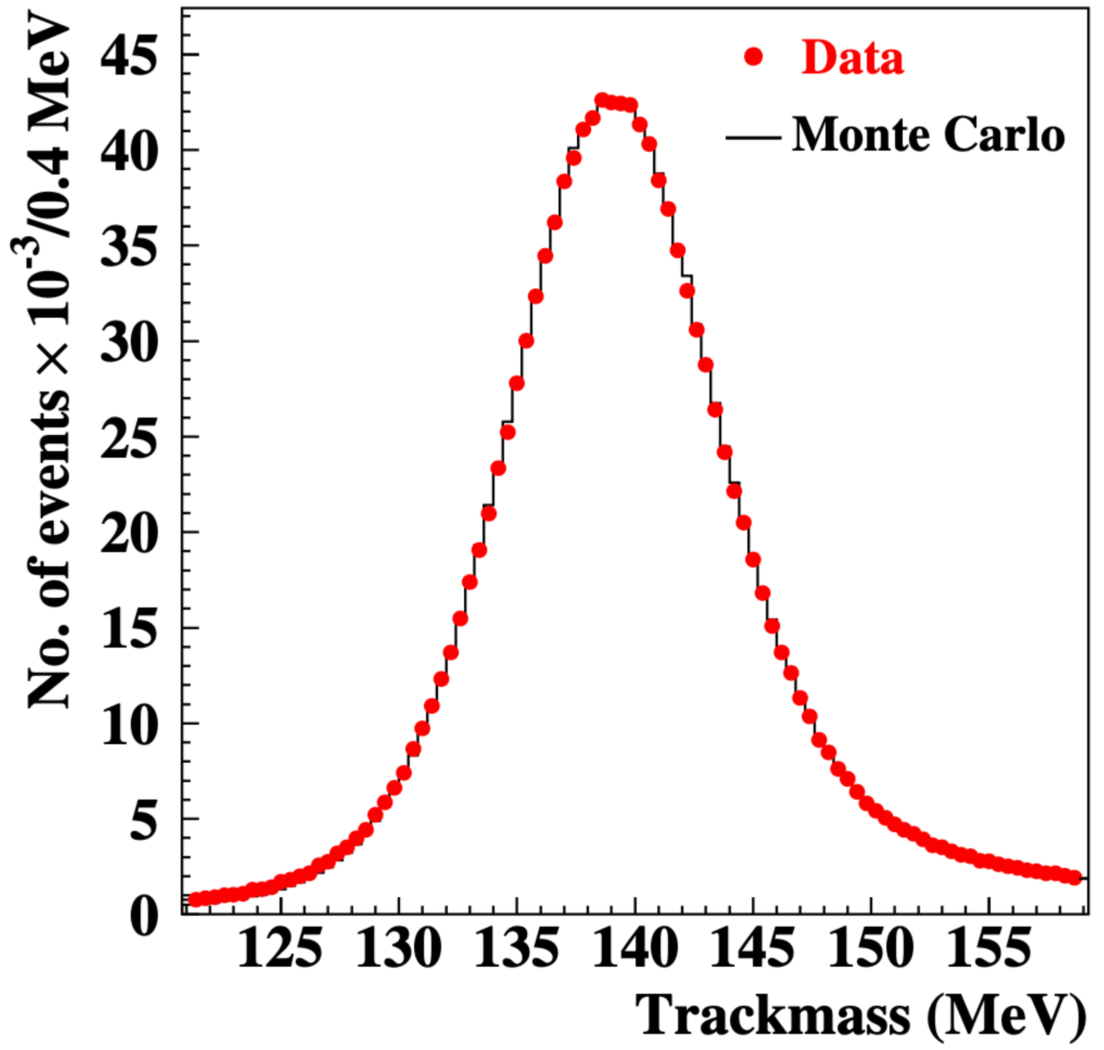
- Corrections were tuned by comparing $M^{\star}_{trk}$ distributions between data and Monte Carlo in the $\pi^+\pi^-\gamma$ signal channel

*Estimates mass of $X^{\pm}$ particle in events $e^+e^- \to X^+X^-(\gamma)$

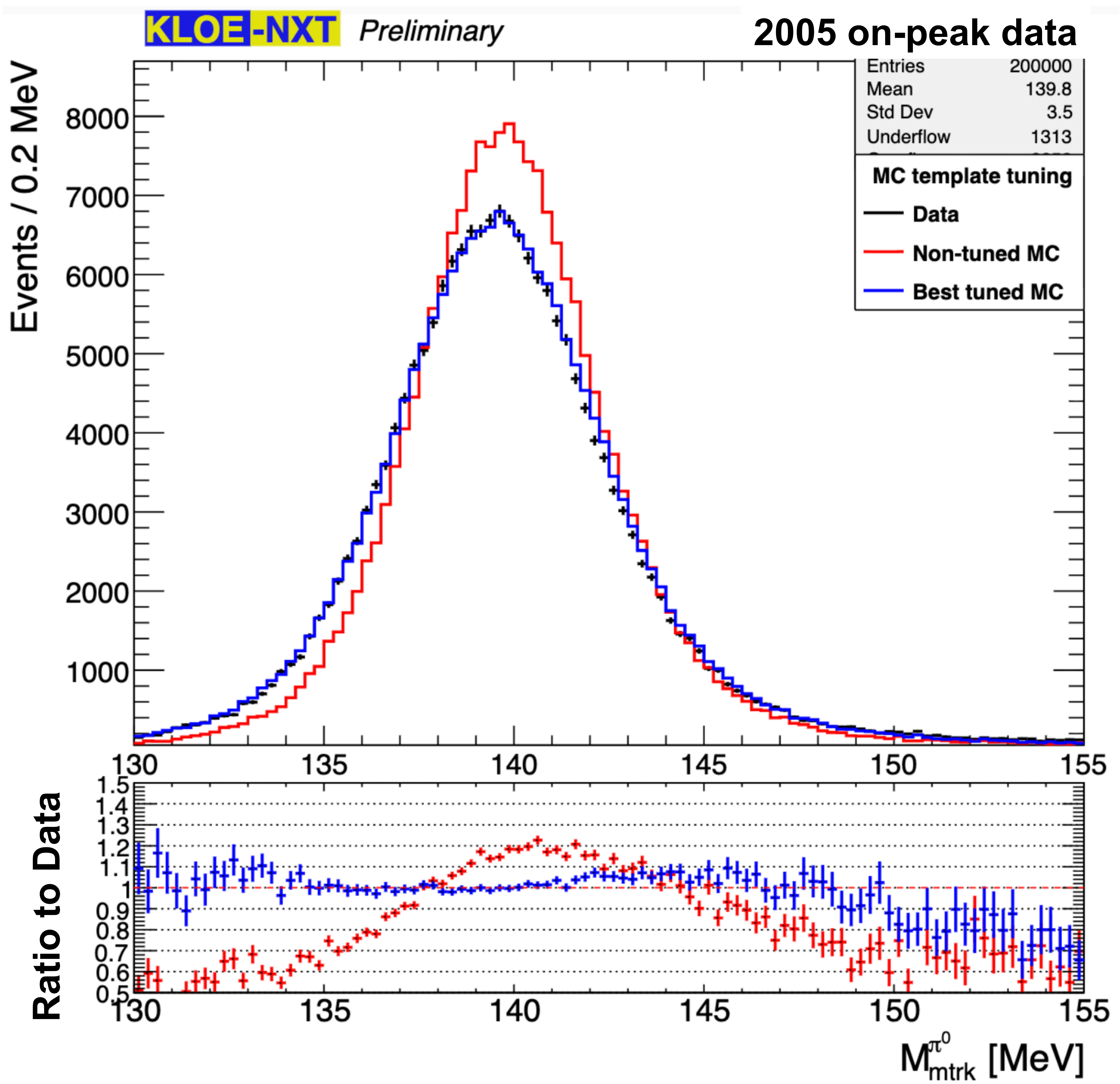
$$\left(E_\phi - \sqrt{p_+^2 + M_{trk}^2} - \sqrt{p_-^2 + M_{trk}^2}\right)^2 - \left|\vec{p}_\phi - \vec{p}_+ - \vec{p}_-\right|^2 \equiv 0$$

From B. Valeriani's PhD Thesis





Tuning of Monte Carlo Simulation

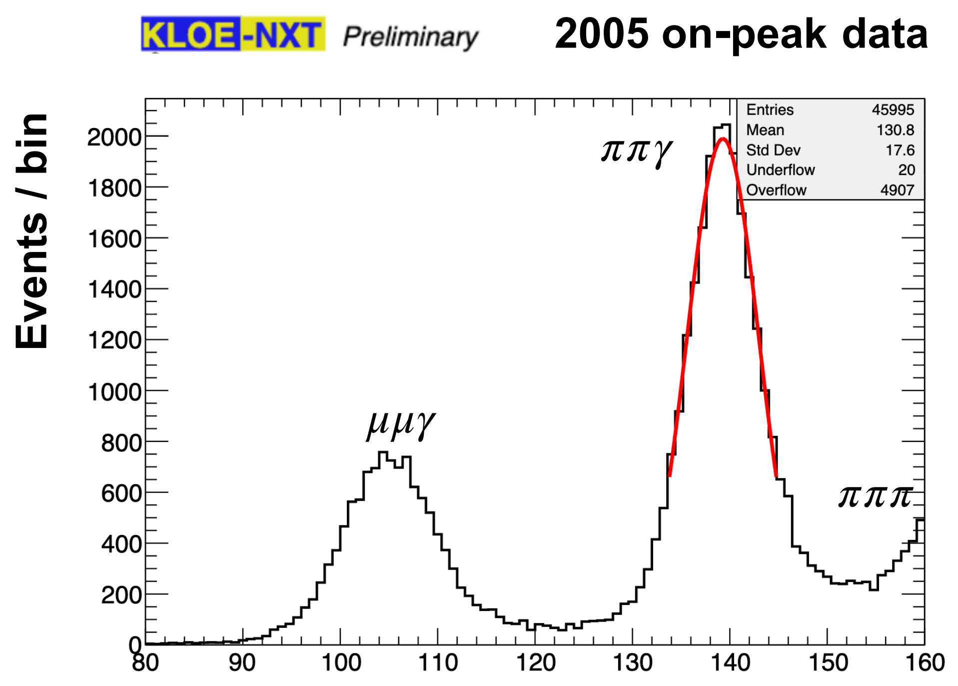


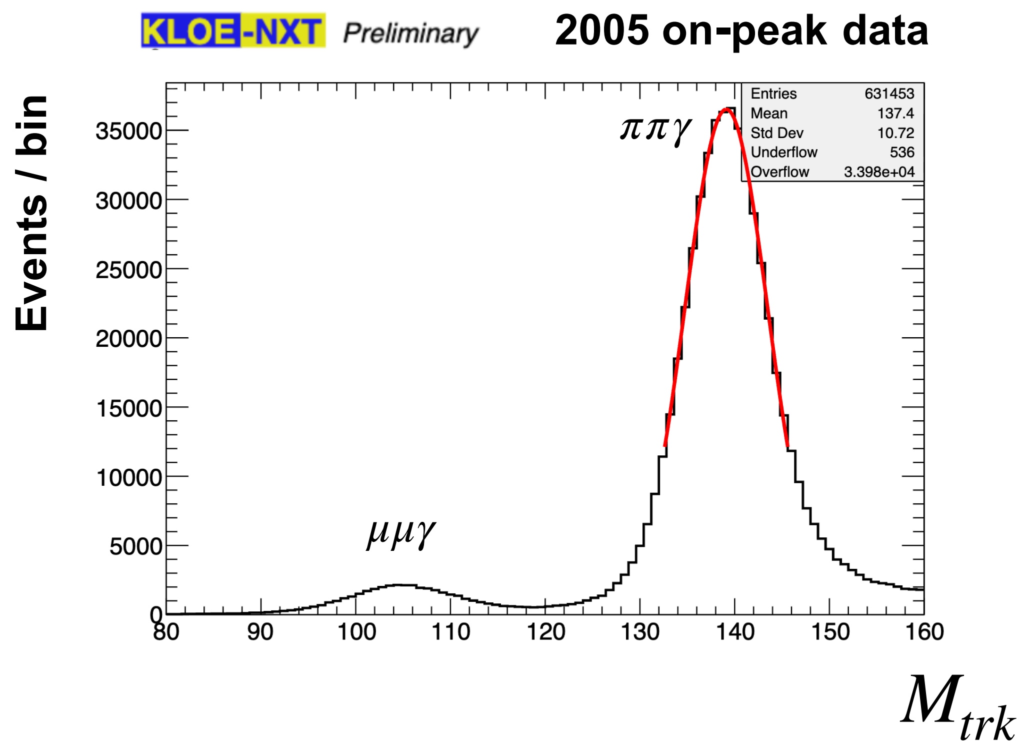
- **New tuning method currently being tested:**
  - Uses independent control channels such as $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-$ instead of signal channel $\pi^+\pi^-\gamma$
  - Corrections applied to lower level track variables $\{\kappa, \theta, \phi\}$ instead of $\{p_x, p_y, p_z\}$
- Multiplicative gaussian shifting/smearing applied on an event-by-event basis to Monte Carlo
- Correction defined by gaussian parameters $\{\mu, \sigma\}$ found via template $\chi 2$ fit of data M_{trk} distribution
- Promising results achieved, still work in progress

Tuning of Monte Carlo Simulation

- Apply the corrections tuned on $\pi^+\pi^-\pi^0$ **to the $\pi^+\pi^-\gamma$ channel** $\rightarrow$ the agreement between M_{trk} peak positions in data and MC clearly improves w.r.t. uncorrected MC and old tuning

- Work is in progress:
  - Parametrisation used for tuning
  - Values of parameters
  - Tail corrections ($t-$Student)
  - A priori tuning using expected resolution
  - Tuning as a function of $Q^2_{\pi\pi}$
  - Using collinear sample $\pi^+\pi^-$ and $\mu^+\mu^-$ for cross checks at higher momenta





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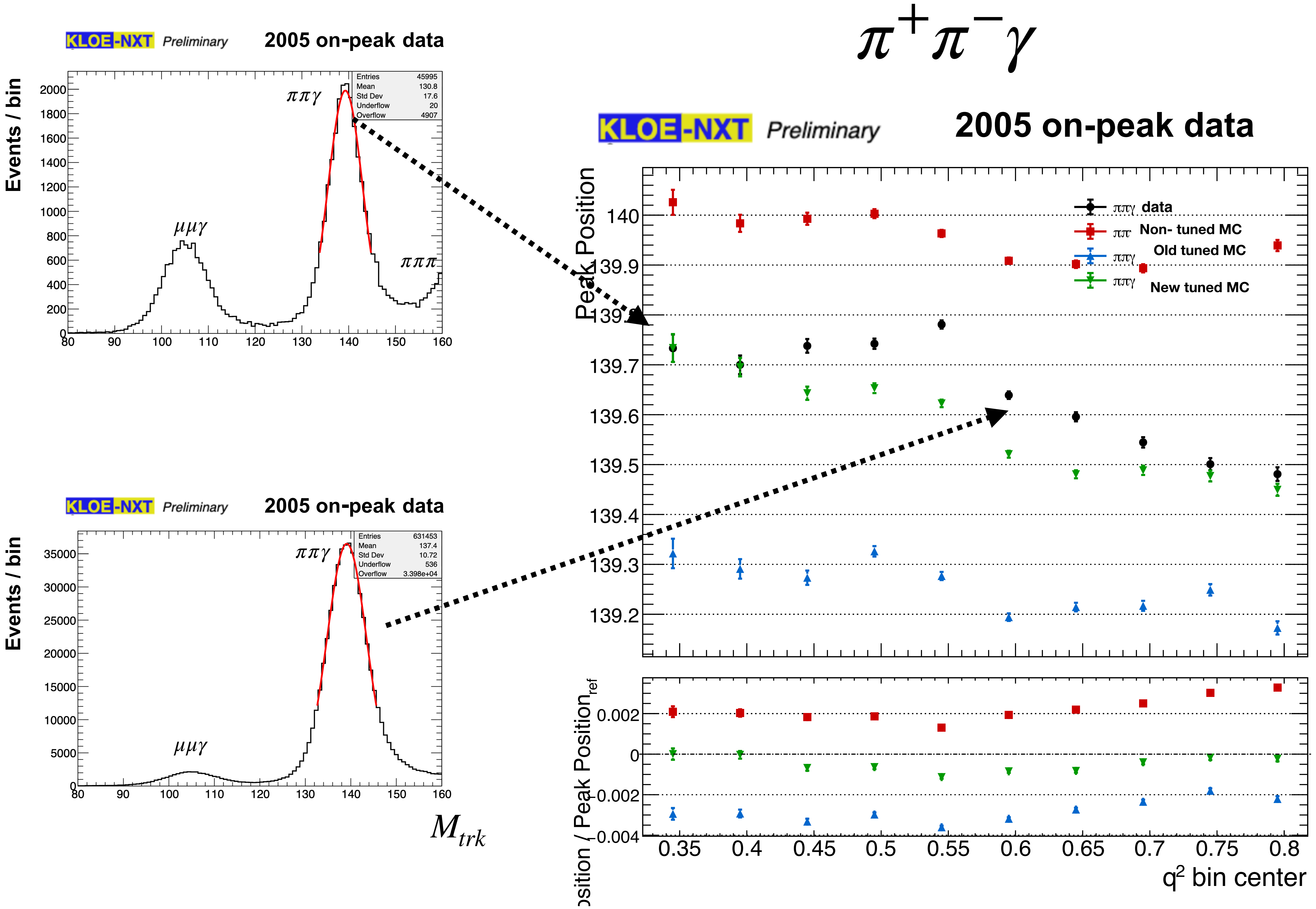


Background Fit and Subtraction

- A crucial step of the KLOE-NXT is **subtraction of residual background** from events surviving all selection cuts $\longrightarrow$ leading systematic uncertainty in KLOE12 (0.6% out of 0.7%)

- In case of $\pi^+\pi^-\gamma$ signal main surviving backgrounds are $\mu^+\mu^-\gamma$, $e^+e^-\gamma$, and $\pi^+\pi^-\pi^0$

- To subtract this background perform a maximum likelihood fit of the M_{trk} distribution of data using MC tuned templates of the M_{trk} distributions for $\pi^+\pi^-\gamma$, $\mu^+\mu^-\gamma$, $e^+e^-\gamma$, and $\pi^+\pi^-\pi^0$ $\rightarrow$ **one separate fit for each bin of $Q^2_{\pi\pi}$**

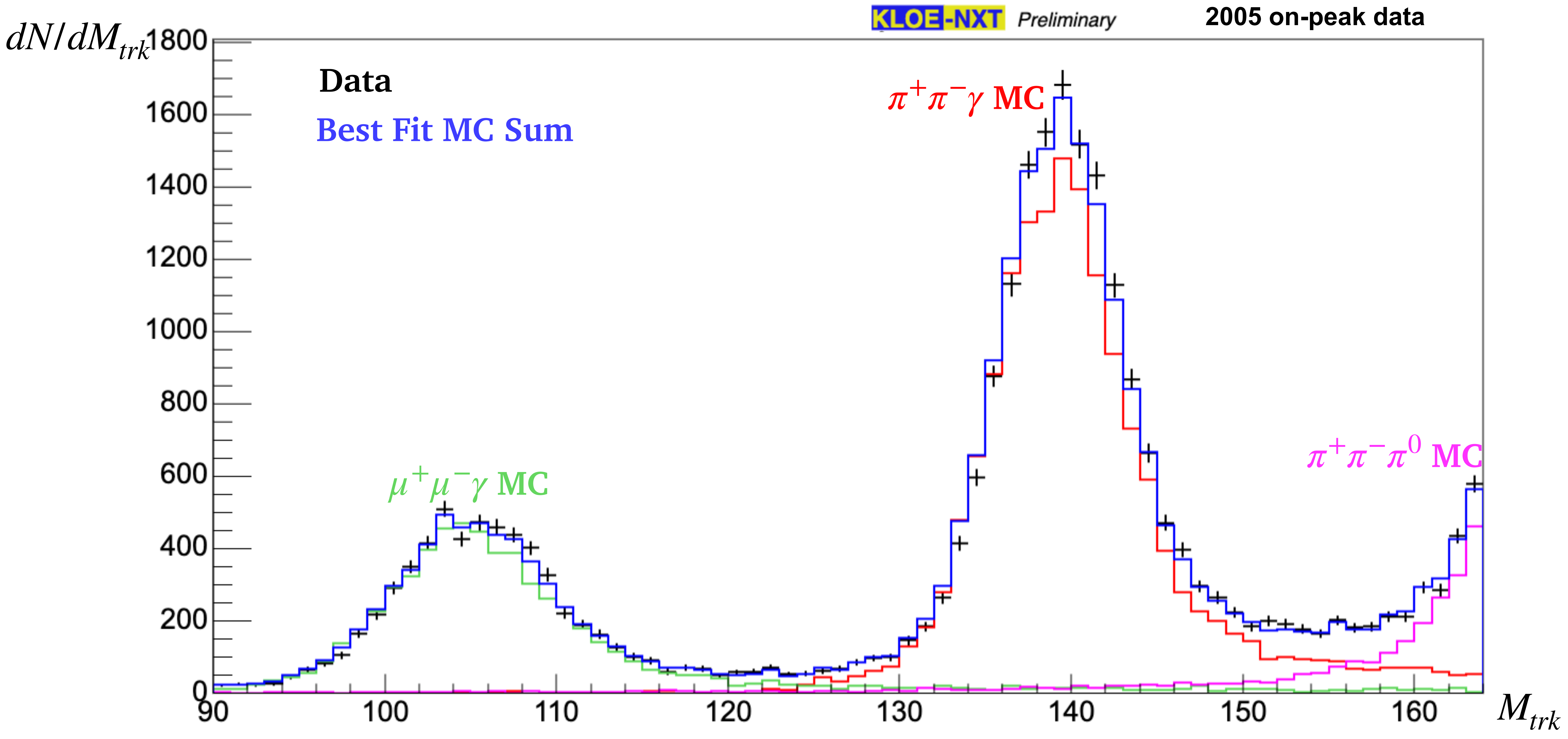
- Fit yields the respective fractions $f_{\pi\pi\gamma}, f_{\mu\mu\gamma}, f_{ee\gamma}, f_{\pi\pi\pi}$ keeping into account the finite statistics of the MC templates used

- Given the spectrum of observed events as a function of $Q^2_{\pi\pi}$, i.e. $dN_{obs}/dQ^2_{\pi\pi}$, we recover the signal $dN_{\pi\pi\gamma}/dQ^2_{\pi\pi}$ by subtracting the fraction of background in each bin i of $Q^2_{\pi\pi}$

$$N_{\pi\pi\gamma} = N_{obs} \cdot (1 - f_i^{bkg}) = N_{obs} \cdot (1 - f_i^{\mu\mu\gamma} - f_i^{ee\gamma} - f_i^{\pi\pi\pi})$$

Background Fit and Subtraction

- Example of a background fit in the bin $Q^2_{\pi\pi} \in [0.37, 0.38]$ GeV^2



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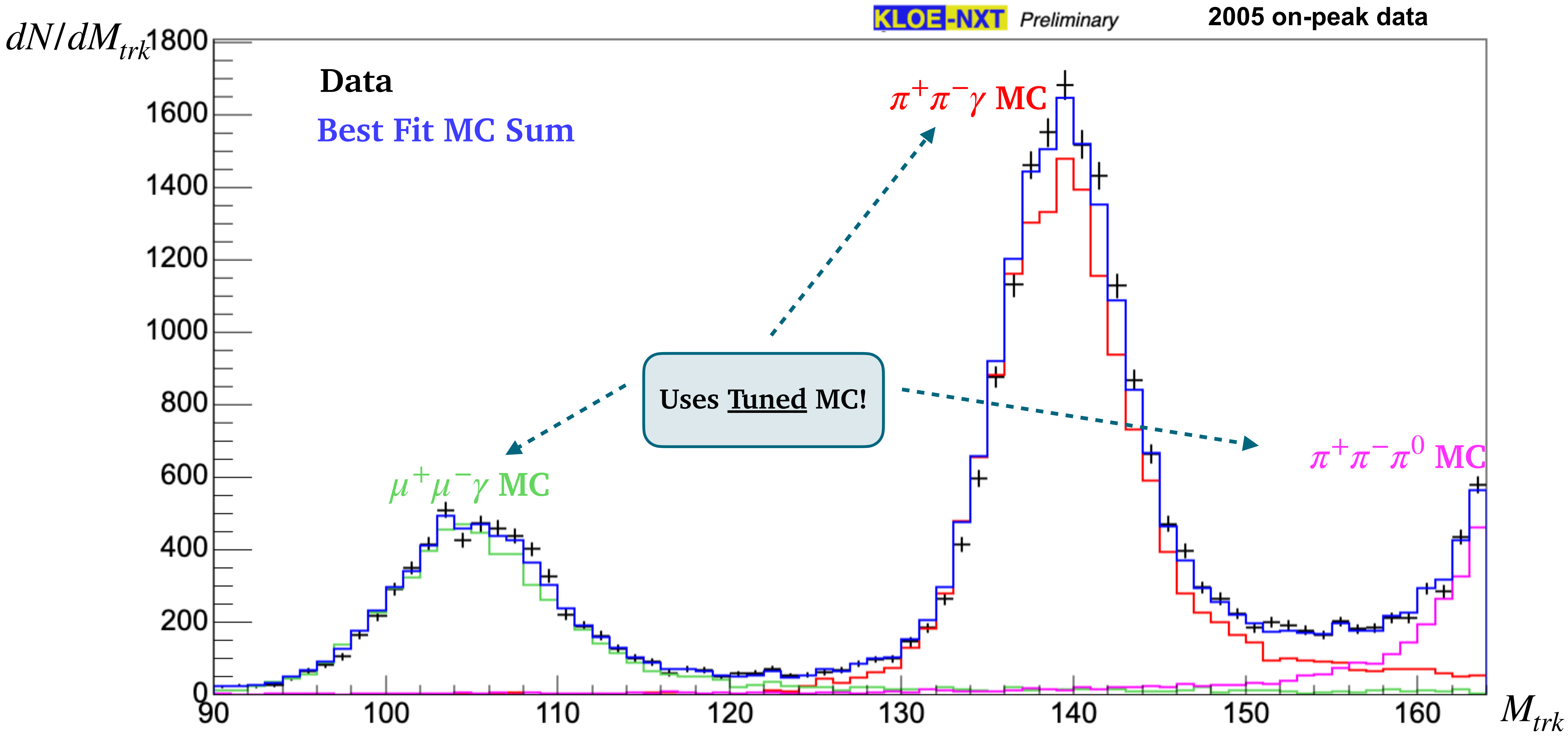
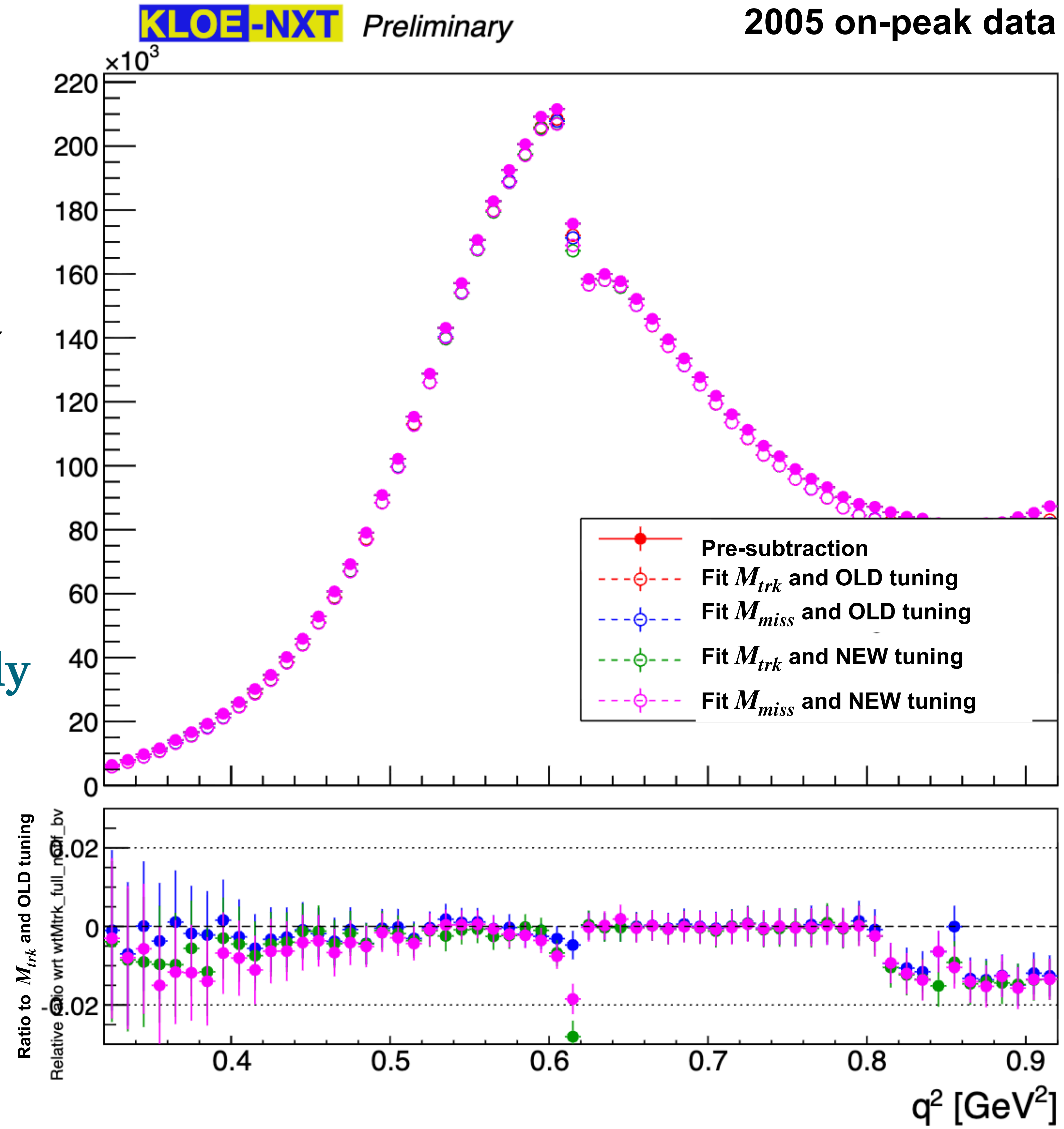


Background Fit and Subtraction

- For the first time the procedure has been cross checked…
  - Fitting on other variables, e.g. $M^{\star}_{miss}$
  - Using new tuning instead of old BV tuning
  - Using new generator BABAYAGA@NLO for the MC $\pi\pi\gamma$ and $\mu\mu\gamma$ templates
- Differences with respect to old procedure can be used to evaluate systematics
- Work is in progress on fitting **two or more variables simultaneously**
- Special care must be taken in order to correctly assign errors to subtracted spectrum following the procedure (currently showing statistical error only)



*Estimates missing invariant mass assuming $e^+e^- \to \pi^+\pi^-(X)$

$$M^2_{miss} = \left(E_\phi - \sqrt{p_+^2 + m_\pi^2} - \sqrt{p_-^2 + m_\pi^2}\right)^2 - \left|\vec{p}_\phi - \vec{p}_+ - \vec{p}_-\right|^2$$

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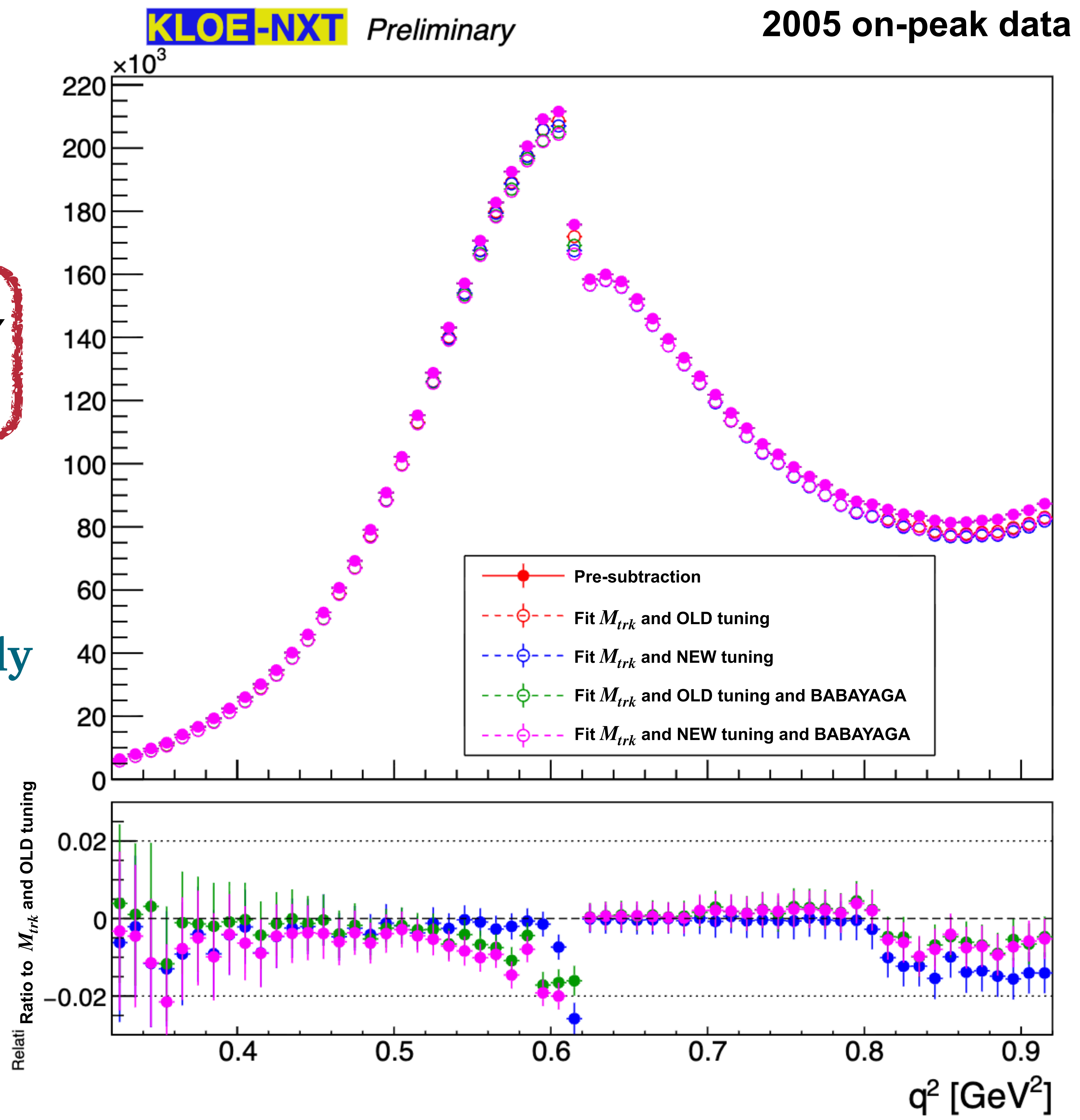

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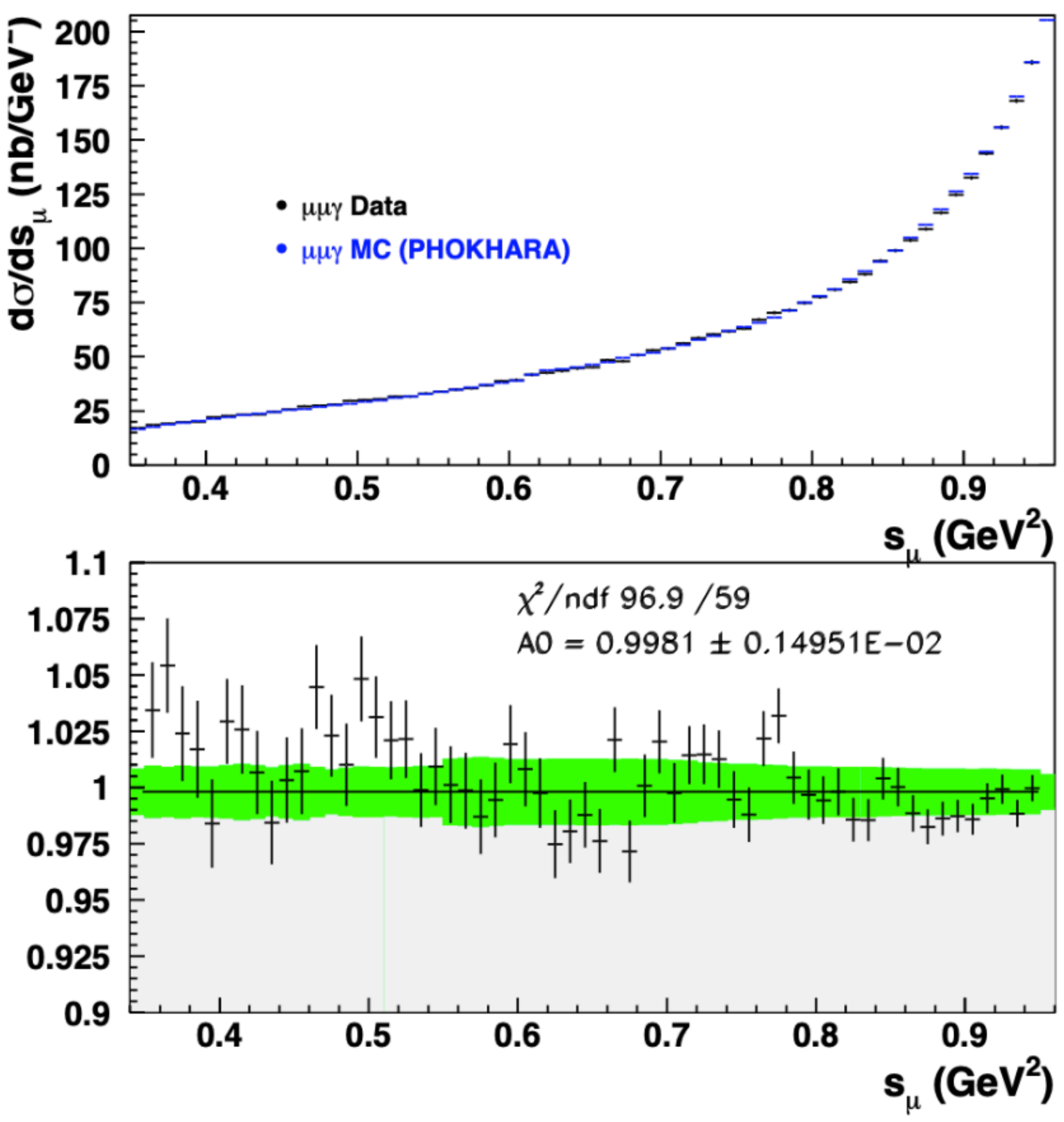
Luminosity Studies: Why Luminosity?

- Even in the *ratio approach* an important analysis cross check is the comparison between measured $\mu\mu\gamma$ cross section and expectation from QED
- This test requires **measuring *luminosity*** → Very Large Angle Bhabha (VLAB) events $e^+e^- \to e^+e^-$ used due to high statistics and excellent theoretical precision of the process (σ_{eff}^{VLAB})
- Previous luminosity measurement based on a 2006 KLOE study on 2001 data → we intend to:
  - Analyse 2002, 2004, 2005, and 2006 datasets separately
  - Use the latest version of the BABAYAGA@NLO MC generator
  - Perform an independent cross check using the $e^+e^- \to \gamma\gamma$ process
- Dedicated MC corrections to improve EMC cluster data/MC consistency are being studied

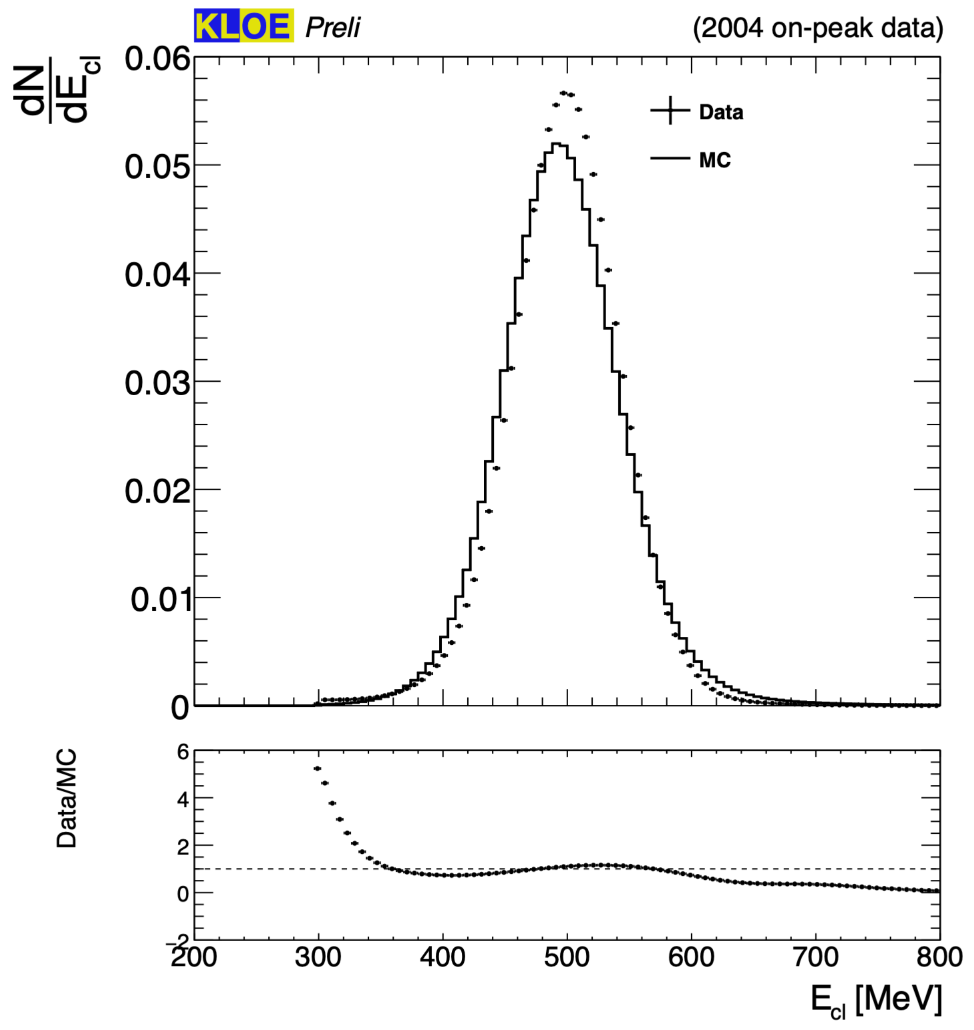
From KLOE12

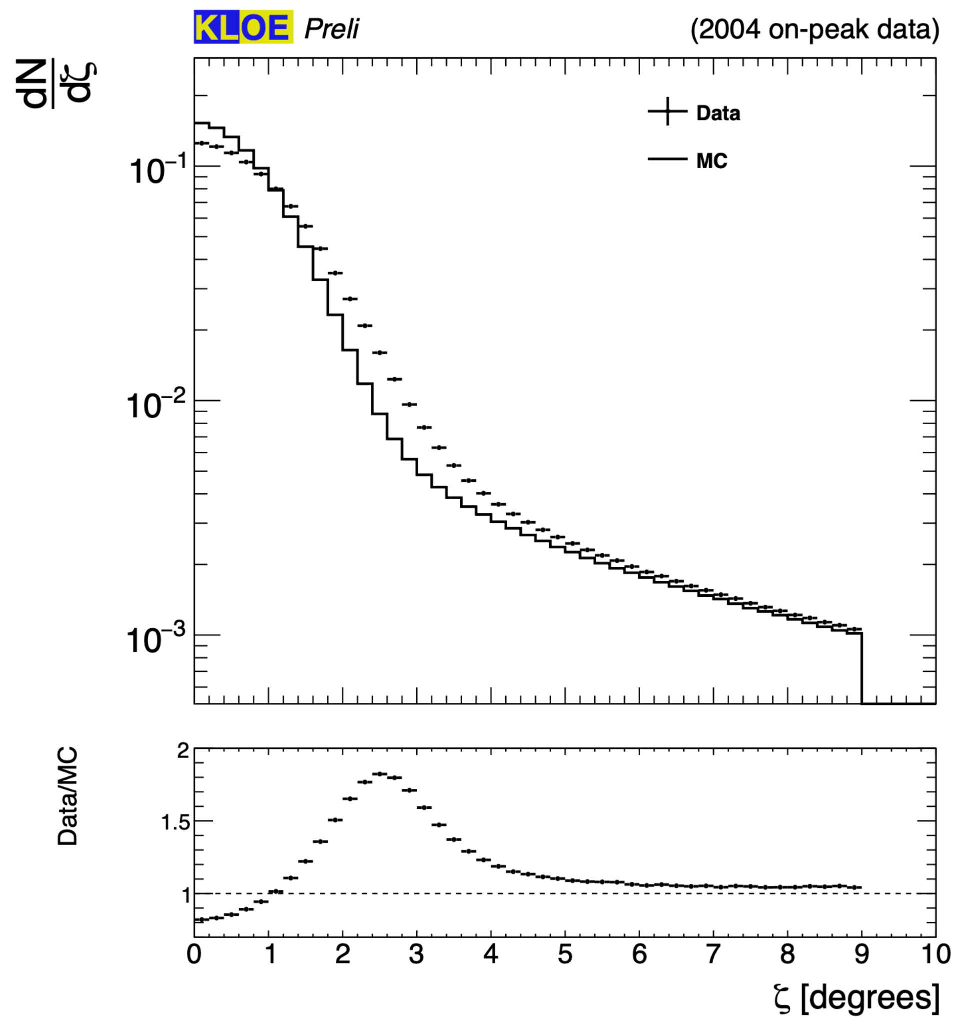


$$\int \mathscr{L} dt = \frac{N_{OBS}^{VLAB} - N_{bkg}^{VLAB}}{\sigma_{eff}^{VLAB}}$$

Luminosity Studies: Cluster Corrections

Before Corrections

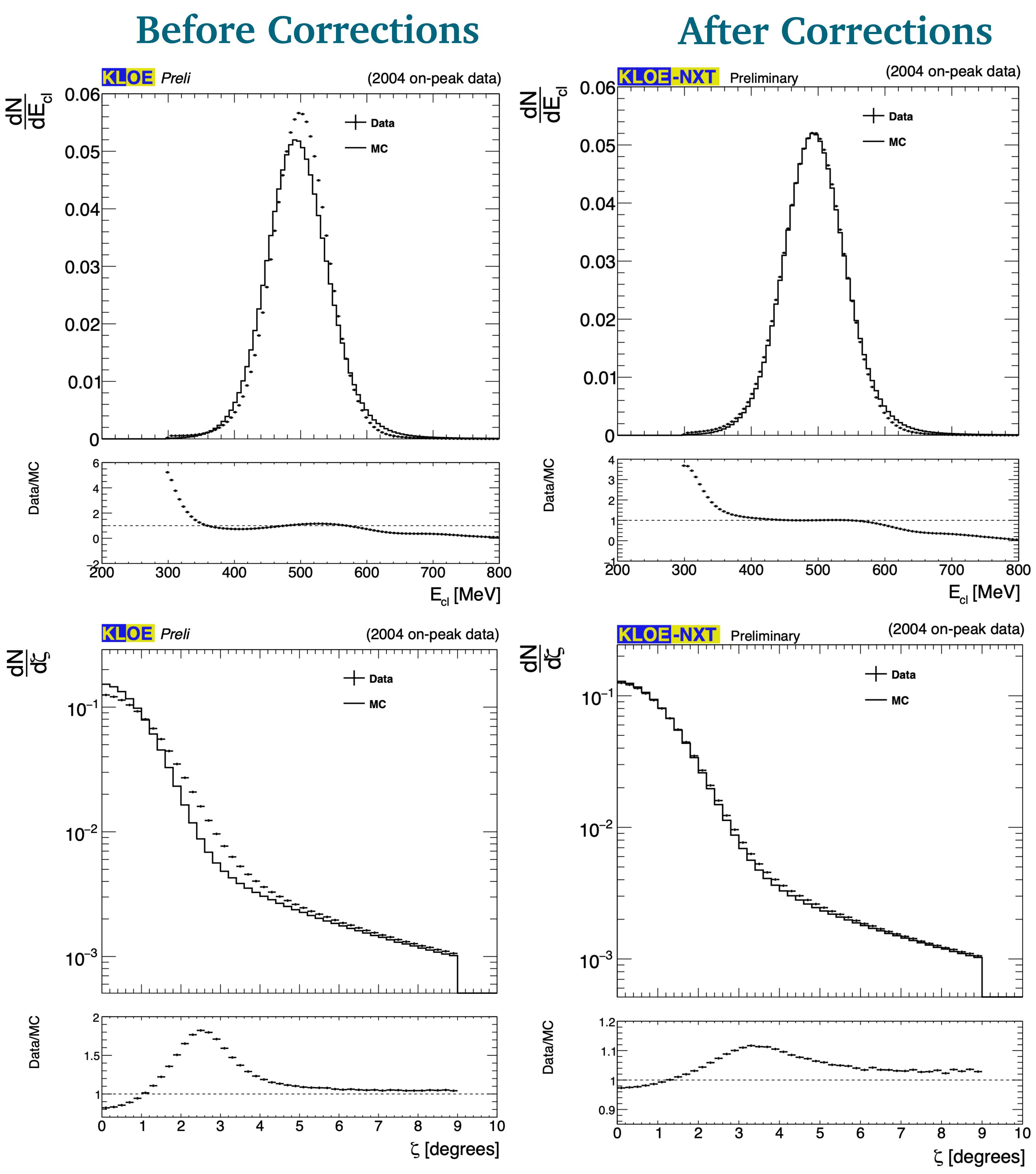




Acollinearity between clusters

- Corrections to Monte Carlo simulation of cluster position and energy are being developed
- For cluster energy a simple single Gaussian smearing is applied to data, obtained directly from a fit of both data and MC
- For cluster position, angles are corrected based on the data/MC discrepancy in resolution
- Cluster angles are compared with the extrapolated angle from the drift chamber track fit
- Discrepant data/MC θ resolutions are corrected with a double gaussian fit
- Working on evaluating the respective systematics

Luminosity Studies: Cluster Corrections



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Radiative Corrections

What can change with latest precision

Studies on Radiative Corrections

- The KLOE $\Delta^{\pi\pi}a_{\mu}$ analysis relied on PHOKHARA5 (almost full NLO) interfaced with GEANFI→ Importance of higher order effects (NNLO) [M. Davier *et al* EPJC 84 (2024) 7, 721][https://arxiv.org/pdf/2201.12102] and FSR beyond F×sQED [F. Ignatov and R. N. Lee, PLB833 (2022)137283] [G. Colangelo et al. JHEP 08 (2022) 295] have been strongly emphasised recently

- In the past two years our group has compared different generators (PHOKHARA10, BABAYAGA@NLO, KKMC,…) **at MC truth level** in $\pi^+\pi^-\gamma/\mu^+\mu^-\gamma \to$ see G. Venanzoni's presentation from 7th T.I. Plenary Workshop

- At MC truth level GVMD model (beyond sQED) seems to have negligible impact on $M^2_{\pi\pi}$ distribution at SA [P. Rosàs, O. Shekhovtsova, W.T.Bobadilla]

- Now Monte Carlo generations interfaced with GEANFI are available → comparisons **at reconstruction level for KLOE case are finally possible.**

Studies on Radiative Corrections

- The KLOE $\Delta^{\pi\pi}a_\mu$ analysis relied on PHOKHARA5 (almost full NLO) interfaced with GEANFI→ Importance of higher order effects (NNLO) [M. Davier *et al* EPJC 84 (2024) 7, 721][https://arxiv.org/pdf/2201.12102] and FSR beyond F×sQED [F. Ignatov and R. N. Lee, PLB833 (2022)137283] [G. Colangelo et al. JHEP 08 (2022) 295] have been strongly emphasised recently

- In the past two years our group has compared different generators (PHOKHARA10, BABAYAGA@NLO, KKMC,…) **at MC truth level** in $\pi^+\pi^-\gamma/\mu^+\mu^-\gamma$ → see G. Venanzoni's presentation from 7th T.I. Plenary Workshop

- At MC truth level GVMD model (beyond sQED) seems to have negligible impact on $M^2_{\pi\pi}$ distribution at SA [P. Rosàs, O. Shekhovtsova, W.T.Bobadilla]

- Now Monte Carlo generations interfaced with GEANFI are available → comparisons **at reconstruction level for KLOE case are finally possible.**

- We simulate analysis cuts and compare $\pi^+\pi^-\gamma$ and $\mu^+\mu^-\gamma$ simulations of:

  - PHOKHARA5 (used in previous analyses), ISR+FSR, partial fixed order NLO, VP , $F_\pi(s)$: F. Jegerlehner's 2003 + H. Czyz's custom parametrisation

  - BABAYAGA@NLO ISR+FSR, full fixed order NLO + PS, VP , $F_\pi(s)$: STRONG2020 default parametrisation

- PHOKHARA10 with latest improvements also interfaced with GEANFI recently → comparisons are under way!

- In $\pi^+\pi^-\gamma$ case we account for the different $F_\pi(s)$ parametrisations used by the different generators

- In the following I will show results for SA selection cuts (used for KLOE-NXT), LA scenario is WiP

Trackmass + Missing Mass Cut

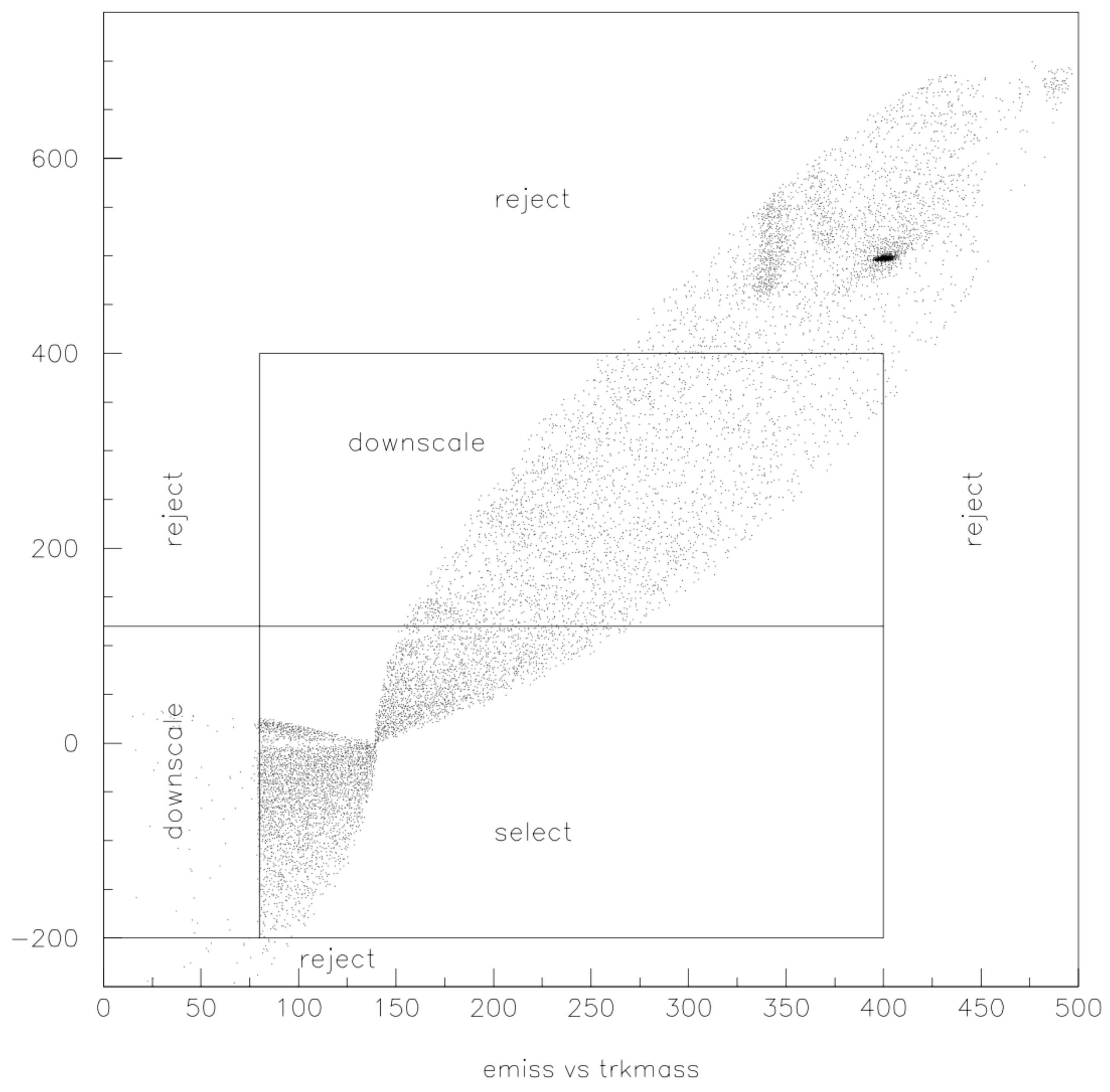
- In KLOE analyses cuts on $M_{trk} - M_{miss}$ plane select $\pi^+\pi^-\gamma$ and $\mu^+\mu^-\gamma$ events and suppress $\pi^+\pi^-\pi^0$ contamination
- Additionally, a final cut on M_{trk} was used to select the two separate channels:
  - $\pi^+\pi^-\gamma \longrightarrow 130 < M_{trk} < 250 - 105 \cdot \sqrt{1 - (M_{\pi\pi}/0.85)^2}$ MeV
  - $\mu^+\mu^-\gamma \longrightarrow M_{trk} < 115$ MeV
- These cuts on the tails of the M_{trk} distributions are sensitive to radiative corrections

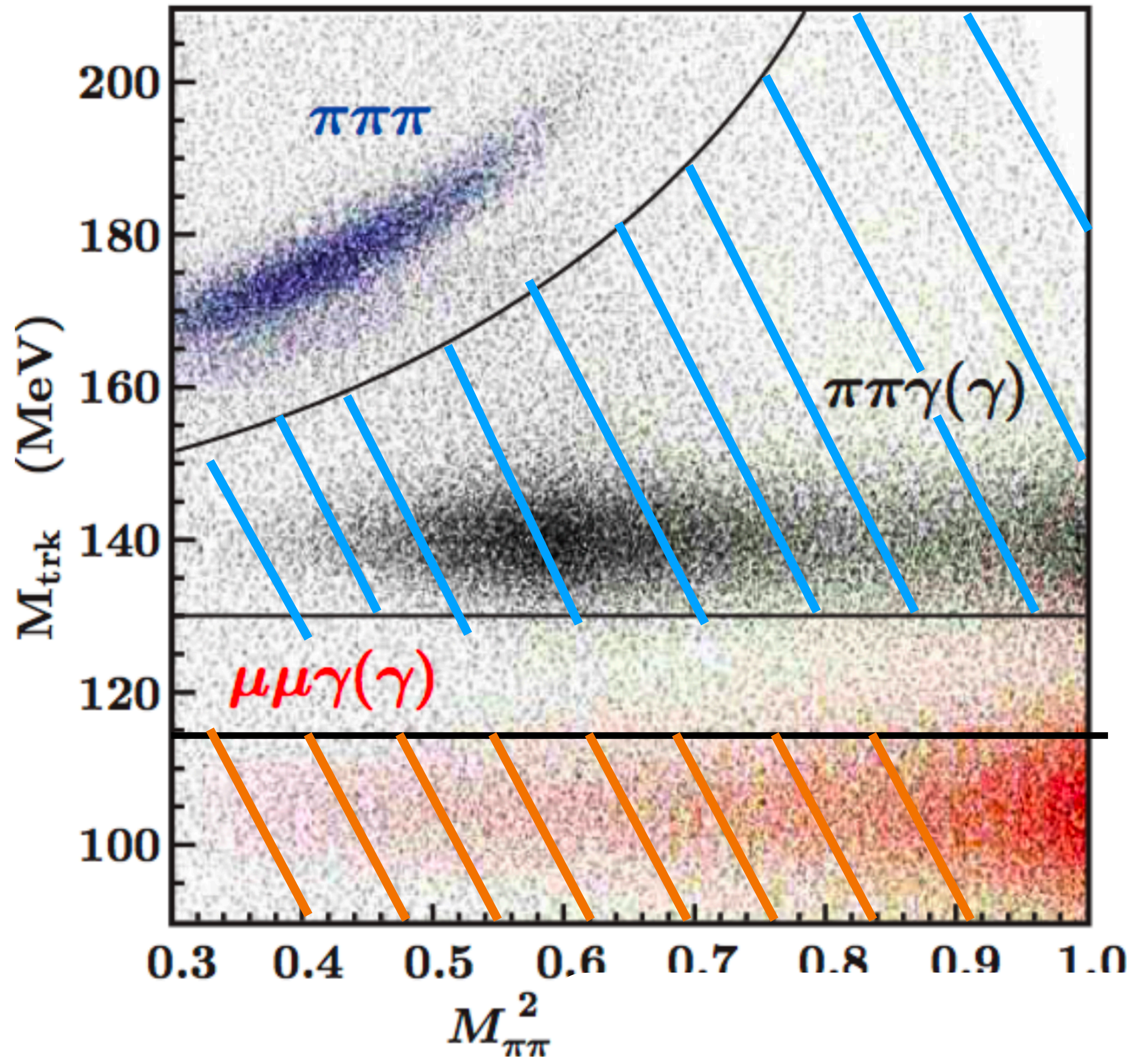
REMINDER

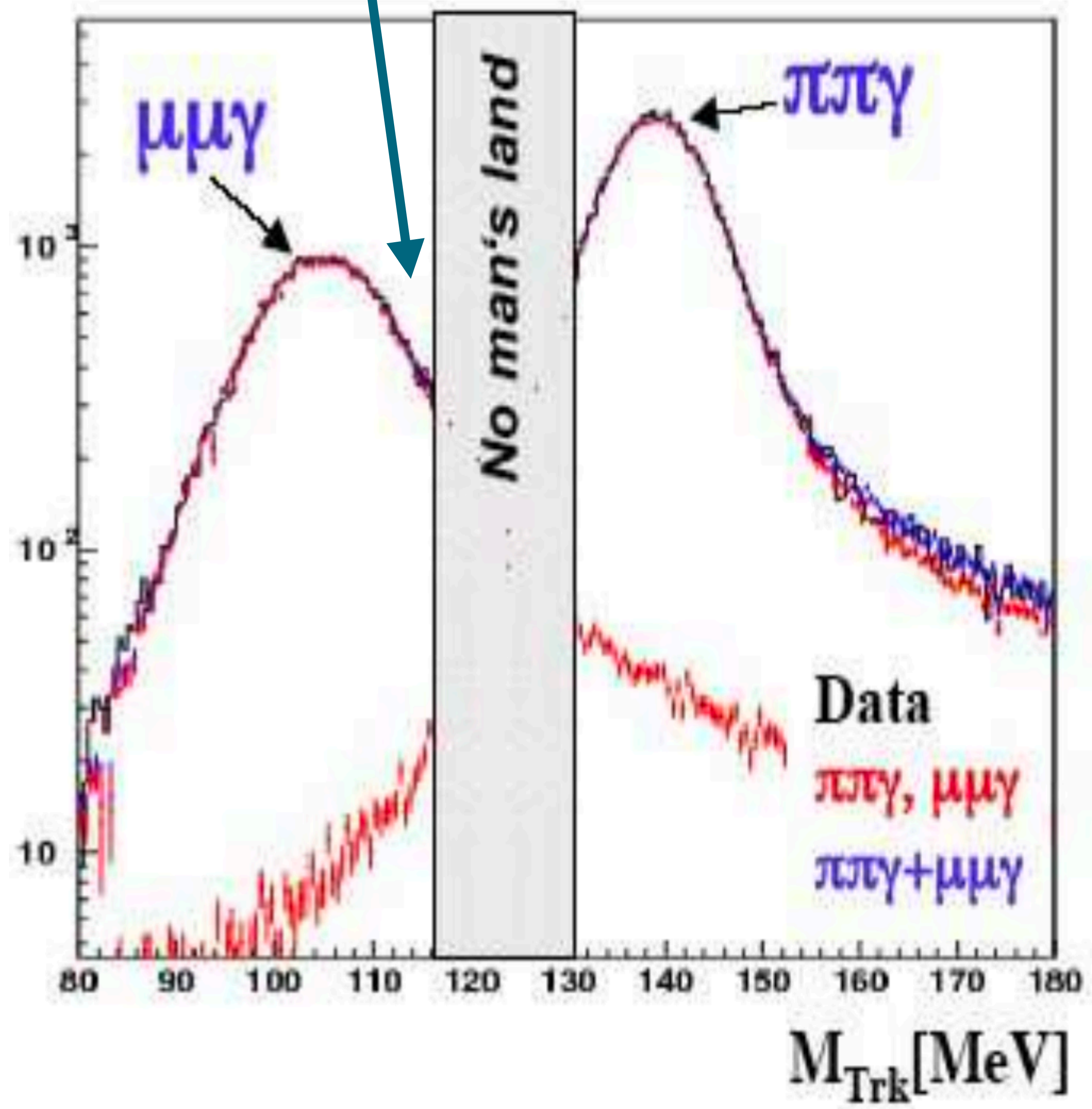
$$\left(E_\phi - \sqrt{p_+^2 + M_{trk}^2} - \sqrt{p_-^2 + M_{trk}^2}\right)^2 - \left|\vec{p}_\phi - \vec{p}_+ - \vec{p}_-\right|^2 \equiv 0$$

$$M_{miss}^2 = \left(E_\phi - \sqrt{p_+^2 + m_\pi^2} - \sqrt{p_-^2 + m_\pi^2}\right)^2 - \left|\vec{p}_\phi - \vec{p}_+ - \vec{p}_-\right|^2$$

Tight cut on $\mu^+\mu^-\gamma$!

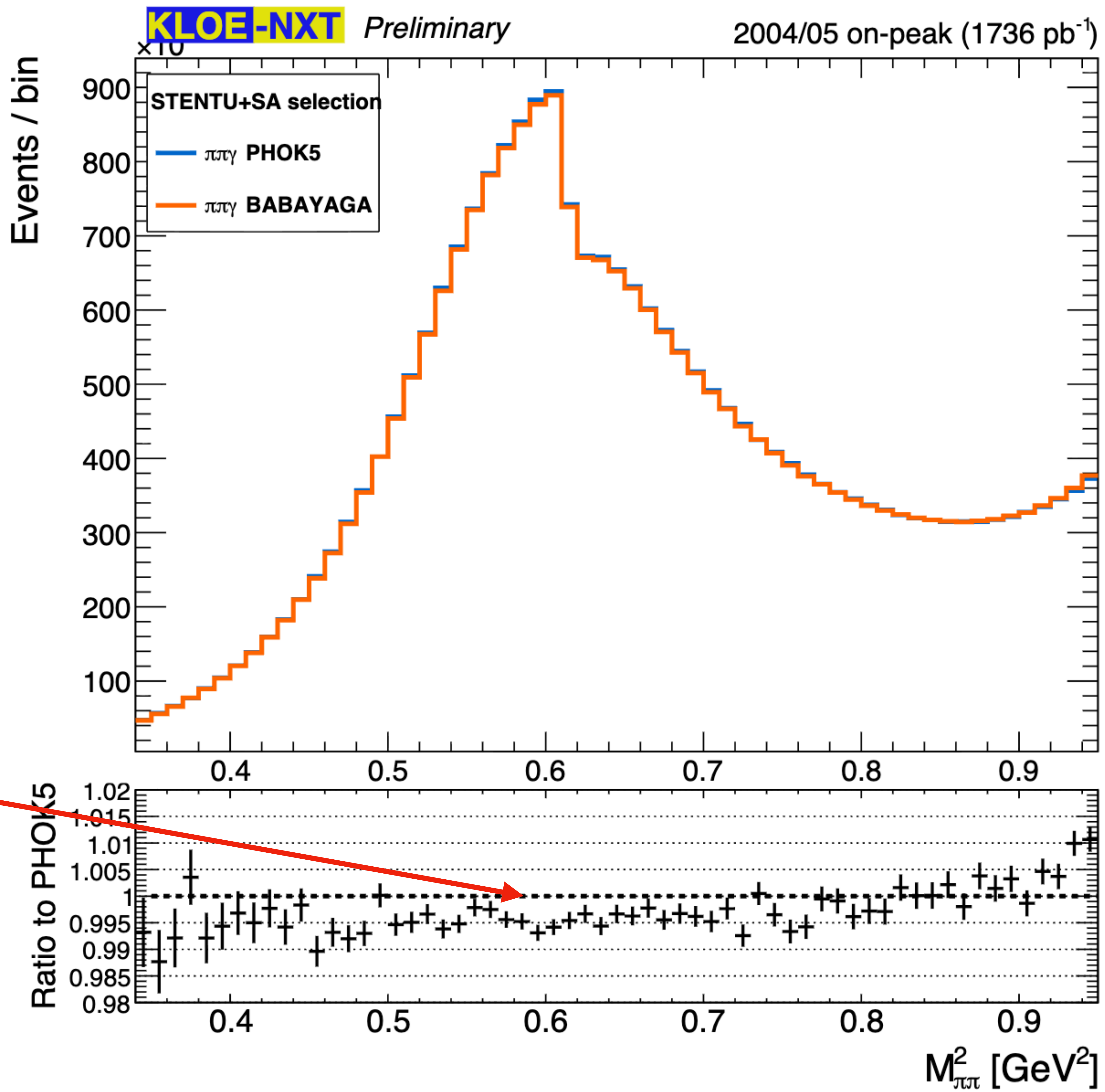






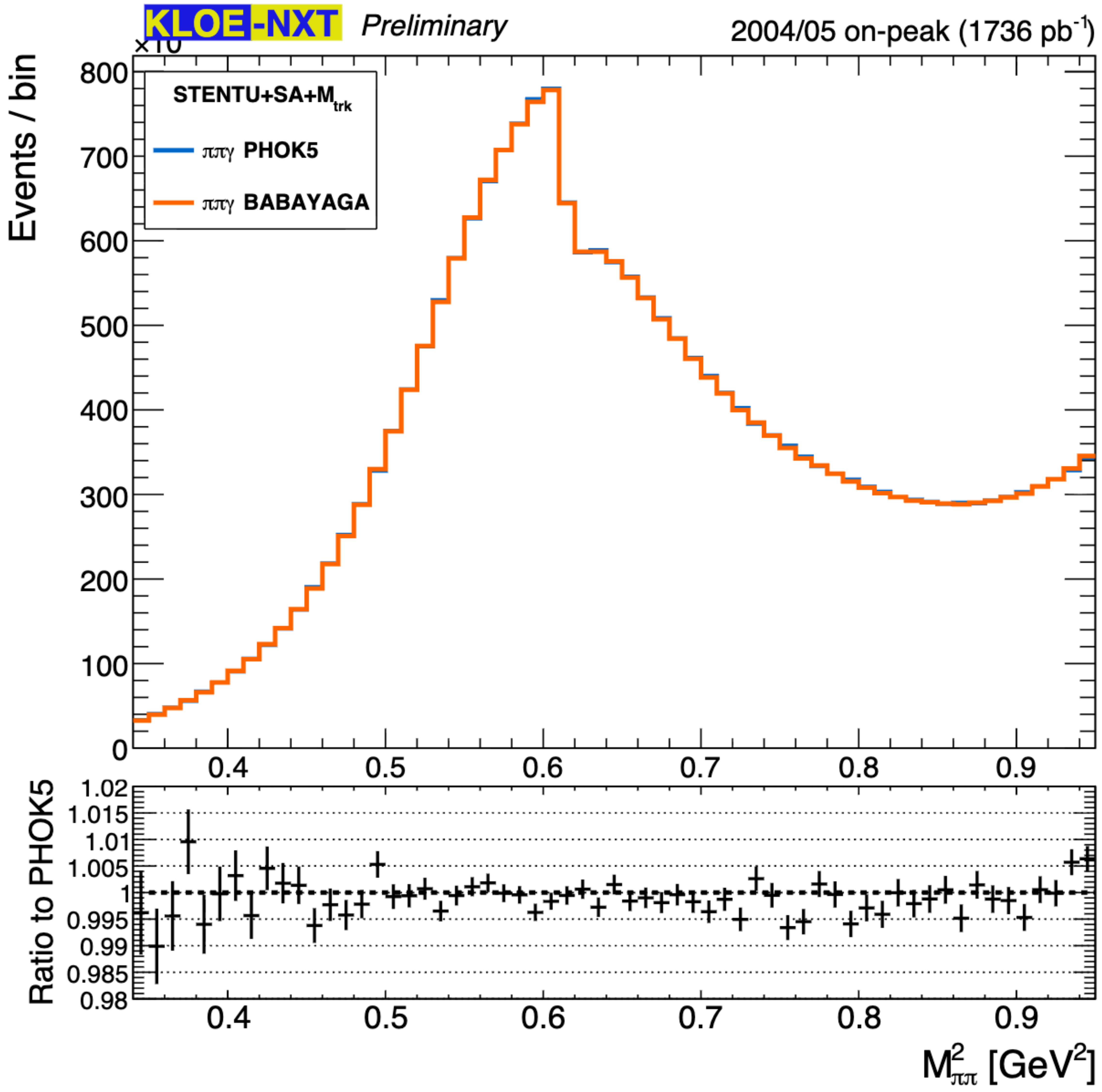
Comparison of $dN(\pi^+\pi^-\gamma)/dM^2_{\pi\pi}$ SA

- Apply only base selection + SA cut
  - Two reconstructed charged tracks
  - $50^\circ < \theta_\pm < 130^\circ$
  - $p_T > 130\ \text{MeV}\ \vee |p_z| > 90\ \text{MeV}$
  - $|z_{PCA}| < 7$ cm $\wedge\, \rho_{PCA} < 8$ cm $\wedge\, \rho_{FirstHit} < 50$ cm
  - $\mathscr{L}_+ > 0 \vee \mathscr{L}_- > 0$ (PID)
  - $\vec{p}_{miss} \equiv -(\vec{p}_- + \vec{p}_+) \rightarrow$ $\theta_{miss} < 15^\circ \vee \theta_{miss} > 165^\circ$ (SA)
- Discrepancy of 0.5% at the ρ peak



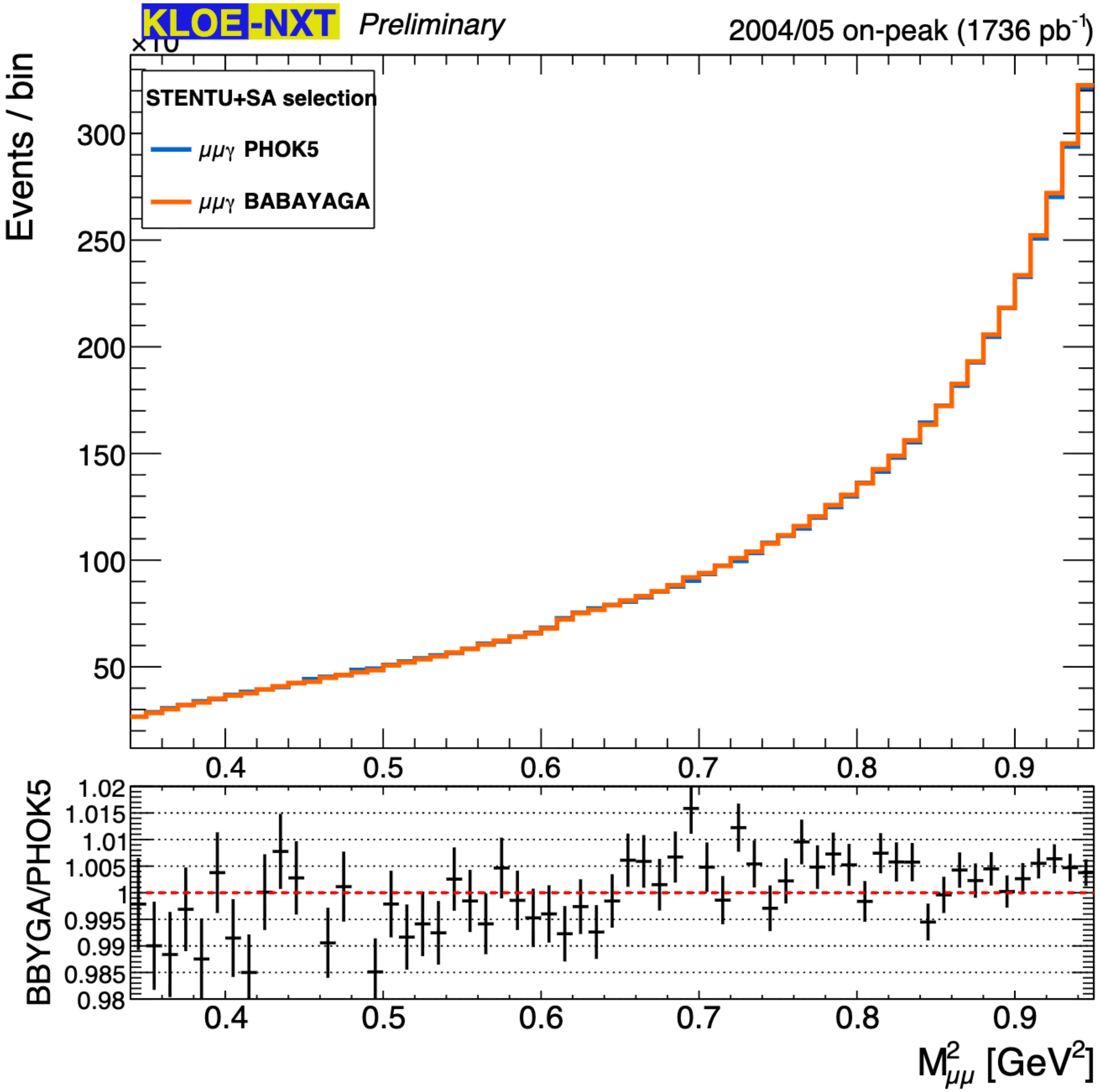
Comparison of $dN(\pi^+\pi^-\gamma)/dM^2_{\pi\pi}$ SA + M_{trk}

- Apply base selection + SA cut + M_{trk}/M_{miss} cut
  - Two reconstructed charged tracks
  - $50° < \theta_\pm < 130°$
  - $p_T > 130\ \text{MeV} \ \vee |p_z| > 90\ \text{MeV}$
  - $|z_{PCA}| < 7\ \text{cm} \ \wedge \rho_{PCA} < 8\ \text{cm} \ \wedge \rho_{FirstHit} < 50\ \text{cm}$
  - $\mathscr{L}_+ > 0 \vee \mathscr{L}_- > 0$ (PID)
  - $\vec{p}_{miss} \equiv -(\vec{p}_- + \vec{p}_+) \rightarrow \theta_{miss} < 15° \vee \theta_{miss} > 165°$ (SA)
  - $150\ \text{MeV} < |\vec{p}_-| + |\vec{p}_+| < 1020\ \text{MeV}$
  - $-220\ \text{MeV} < M_{miss} < 120\ \text{MeV}$
  - $130\ \text{MeV} < M_{trk} < 250 - 105 \cdot \sqrt{1 - (M_{\pi\pi}/0.85)^2}\ \text{MeV}$
- **Trackmass cut seems to *improve* agreement**
  → within 0.3%, quoted PHOKHARA5 uncertainty = 0.5%



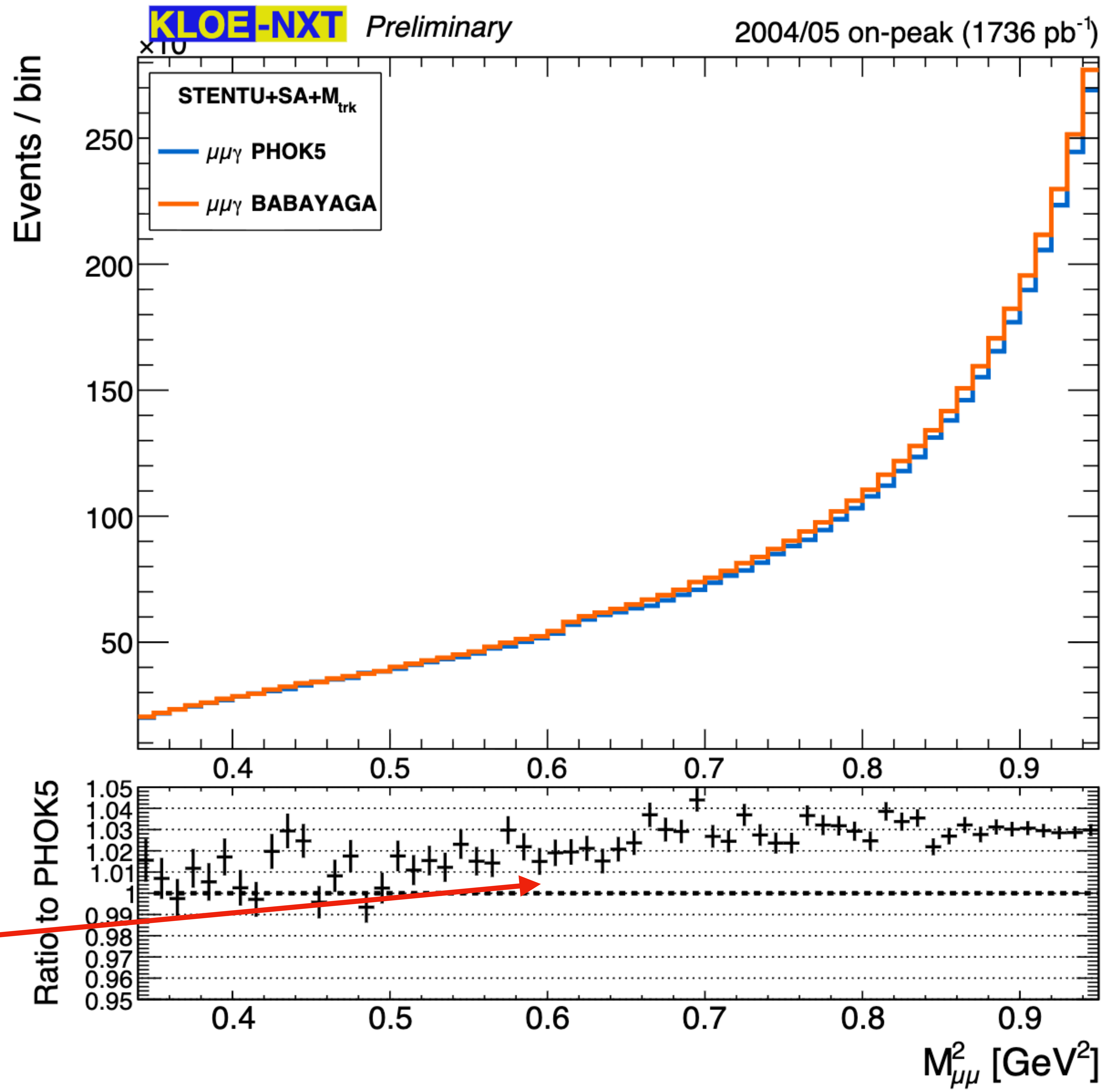
Comparison of $dN(\mu^+\mu^-\gamma)/dM^2_{\mu\mu}$ SA

- Apply only base selection + SA cut
  - Two reconstructed charged tracks
  - $50^\circ < \theta_\pm < 130^\circ$
  - $p_T > 130\ \text{MeV}\ \vee |p_z| > 90\ \text{MeV}$
  - $|z_{PCA}| < 7\text{ cm}\ \wedge \rho_{PCA} < 8\text{ cm}$ $\wedge\, \rho_{FirstHit} < 50\text{ cm}$
  - $\mathscr{L}_+ > 0 \vee \mathscr{L}_- > 0$ (PID)
  - $\vec{p}_{miss} \equiv -(\vec{p}_- + \vec{p}_+) \rightarrow$ $\theta_{miss} < 15^\circ \vee \theta_{miss} > 165^\circ$ (SA)
- 0.5% discrepancy above the ρ peak



Comparison of $dN(\mu^+\mu^-\gamma)/dM^2_{\mu\mu}$ SA + M_{trk}

- Apply only base selection + SA cut
  - Two reconstructed charged tracks
  - $50^\circ < \theta_\pm < 130^\circ$
  - $p_T > 130\ \text{MeV} \ \vee |p_z| > 90\ \text{MeV}$
  - $|z_{PCA}| < 7\text{ cm}\ \wedge \rho_{PCA} < 8\text{ cm}\ \wedge \rho_{FirstHit} < 50\text{ cm}$
  - $\mathscr{L}_+ > 0 \vee \mathscr{L}_- > 0$ (PID)
  - $\vec{p}_{miss} \equiv -(\vec{p}_- + \vec{p}_+) \rightarrow$
    $\theta_{miss} < 15^\circ \vee \theta_{miss} > 165^\circ$ (SA)
  - $150\ \text{MeV} < |\vec{p}_-| + |\vec{p}_+| < 1020\text{ MeV}$
  - $-220\ \text{MeV} < M_{miss} < 120\text{ MeV}$
  - $80 < M_{trk} < 115\text{ MeV}$
- M_{trk}/M_{miss} cut seems to enhance discrepancy, reaching 3% at high $M^2_{\mu\mu}$ (2% at ρ peak)



Conclusions and Outlook

- KLOE-NXT is the new $\Delta^{\pi\pi}a_\mu$ analysis by KLOE, using 1.7 fb^{-1} ($\sim$25M $\pi^+\pi^-\gamma$ events) of 2004/5 data: **7x increase in statistics**

- We expect to double precision w.r.t. KLOE12, providing the **most precise measurement of $\Delta^{\pi\pi}a_\mu$ below 1 GeV by single experiment**

- First reprocessing of data and dedicated MC generations on new Linux infrastructure achieved!

- New Monte Carlo correction approach is being developed for the analysis and compared with previous corrections

- Background fit and subtraction (leading systematic) are being expanded with different variables and multiple dimensions → currently being cross checked using different generators and tuning methods

- Luminosity is being measured on 2002,2004-2006 dataset with dedicated corrections and new MC

- New analysis so far shows good consistency with previous analyses

- **KLOE-NXT will be performed with a custom blinding procedure**

Conclusions and Outlook

- Impact of beyond-NLO Radiative Corrections on KLOE $\Delta^{\pi\pi} a_\mu$ is being evaluated at the **reconstruction level with realistic Small Angle selection criteria** by comparing `PHOKHARA5` (almost NLO) and `BABAYAGA@NLO` (NLOPS) interfaced with `GEANFI`.

- `PHOKHARA10` comparisons will also soon be completed

- Preliminary results suggest:

  - For $\pi^+\pi^-\gamma$ channel at SA, all observed effects lie within quoted `PHOKHARA` uncertainty (0.5%)

  - For $\mu^+\mu^-\gamma$ channel at SA, discrepancy of up to 3% (2% at ρ peak) after the trackmass cut

- These comparisons were done to check effects in *previous* analyses → The new KLOE-NXT analysis is blind, therefore **impact on the new analysis can be evaluated only *after* the unblinding**

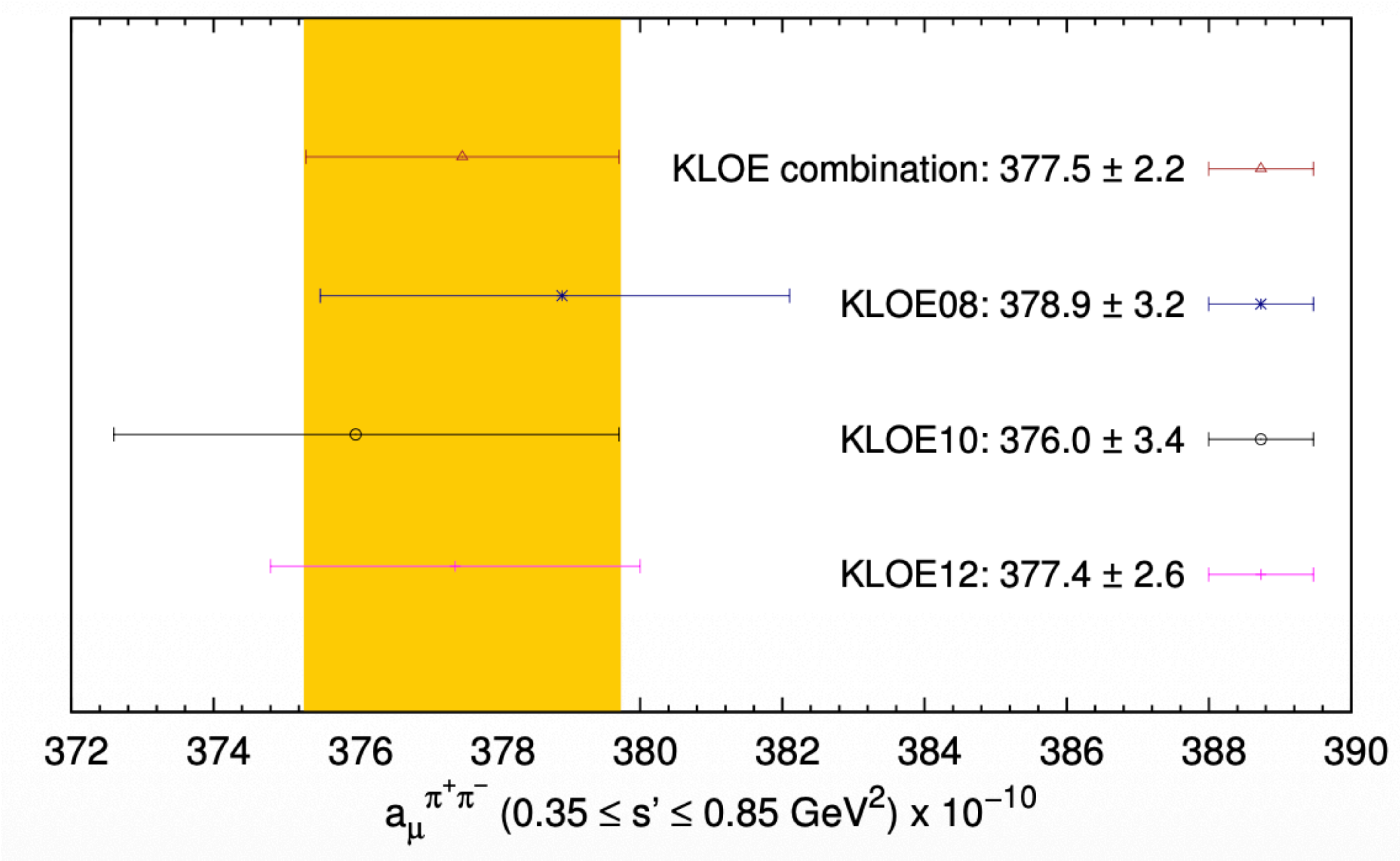
- Additional confirmation of radiative correction effects from `PHOKHARA` is needed and is WiP (see William's talk)

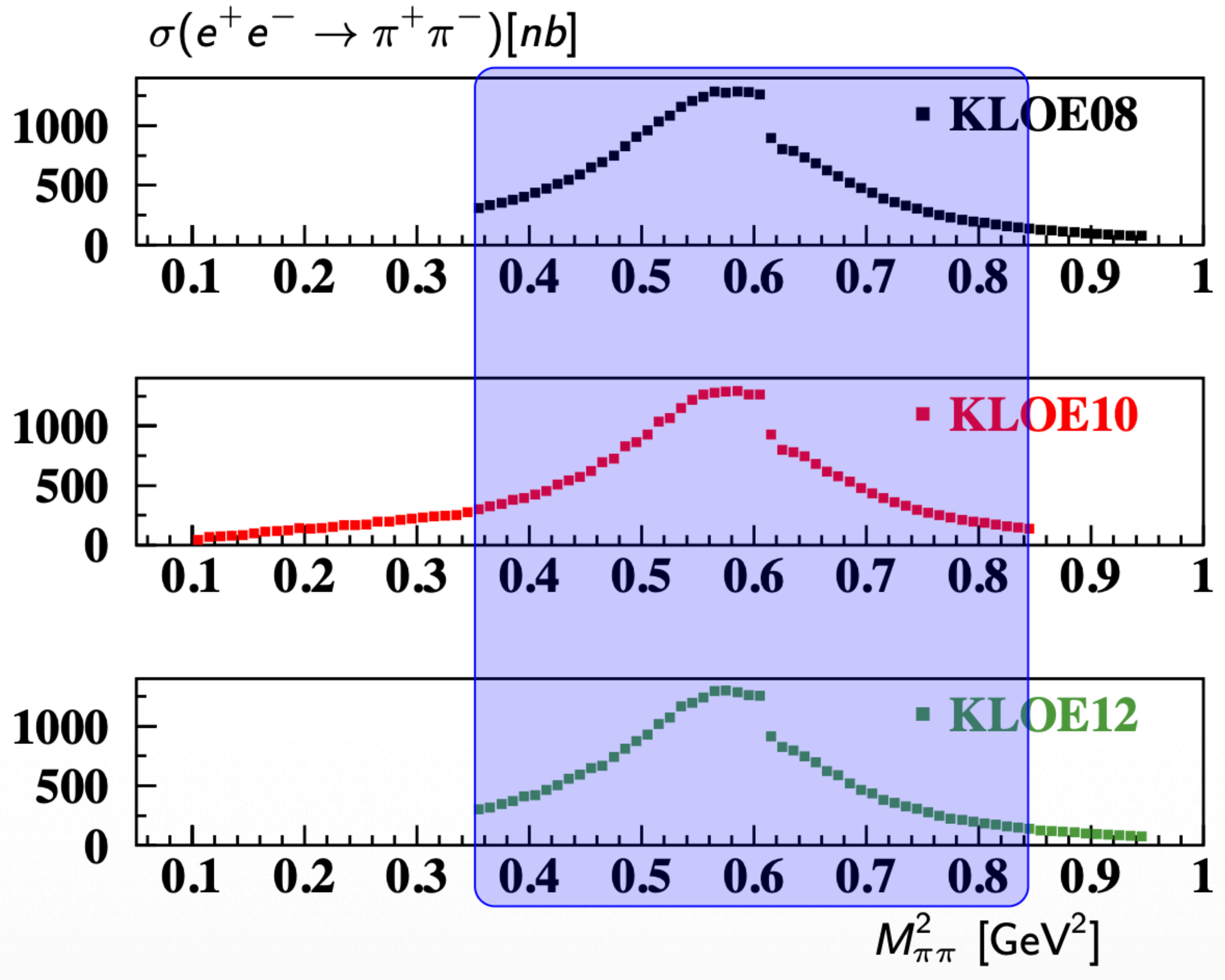
Thank You!

BACKUP

KLOE08/KLOE10/KLOE12 Consistency

(JHEP 1803 (2018) 173)





Old MC Corrections (KLOE08)

The following corrections have been applied to Monte Carlo momenta components p_i

$$p_i \quad \rightarrow \quad p_i/\zeta(\theta, s_\pi) \tag{B.1}$$

where

$$\zeta(\theta, s_\pi) = \begin{cases} c(\theta) - (1.2354 - 2.1833 s_\pi + 0.87765 s_\pi^2) 10^{-3} & if\ \theta > \pi/2 \\ c(\theta) & if\ \theta < \pi/2 \end{cases}$$

and

$$c(y) = (1. - 5 \cdot 10^{-4})(1 - (y/|y|(1 - e^{-|y|/0.07}) - 1)/2.5/510)\ ;\ y = \theta - 0.85 \tag{B.2}$$

If $s_\pi > 0.8\ GeV^2$ $c \rightarrow c - 0.0002$.

If $s_\pi < 0.8\ GeV^2$ the momenta of the positive (p_i^+) and negative track (p_i^-) are smeared ($p_i^{+,-} \rightarrow p^{+,-} \cdot smear_{+,-}$) according to

$$smear_+ = \begin{cases} 1 - 0.007x & 1/20\ of\ the\ events \\ 1 - 0.0018x & else \end{cases}$$

$$smear_- = \begin{cases} 1 - 0.007x & 1/20\ of\ the\ events \\ 1 - 0.0023x & else \end{cases}$$

where x is a random Gaussian variable (with mean 0 and sigma 1). Plots on the effect of these corrections on data-MC comparison for variables of significant interest can be found in [18].

Tuning of Monte Carlo Simulation

- Main smearing is Gaussian in curvature, $cot\theta$ and ϕ

$$x \to x \cdot \left(1 + Gaus\left(\mu_x, \sigma_x\right)\right) \quad x \in \{\kappa, cotan\theta, \phi\}$$

- A fraction of events (3%) are not smeared with a gaussian but with a t-Student distribution → improves consistency in tails

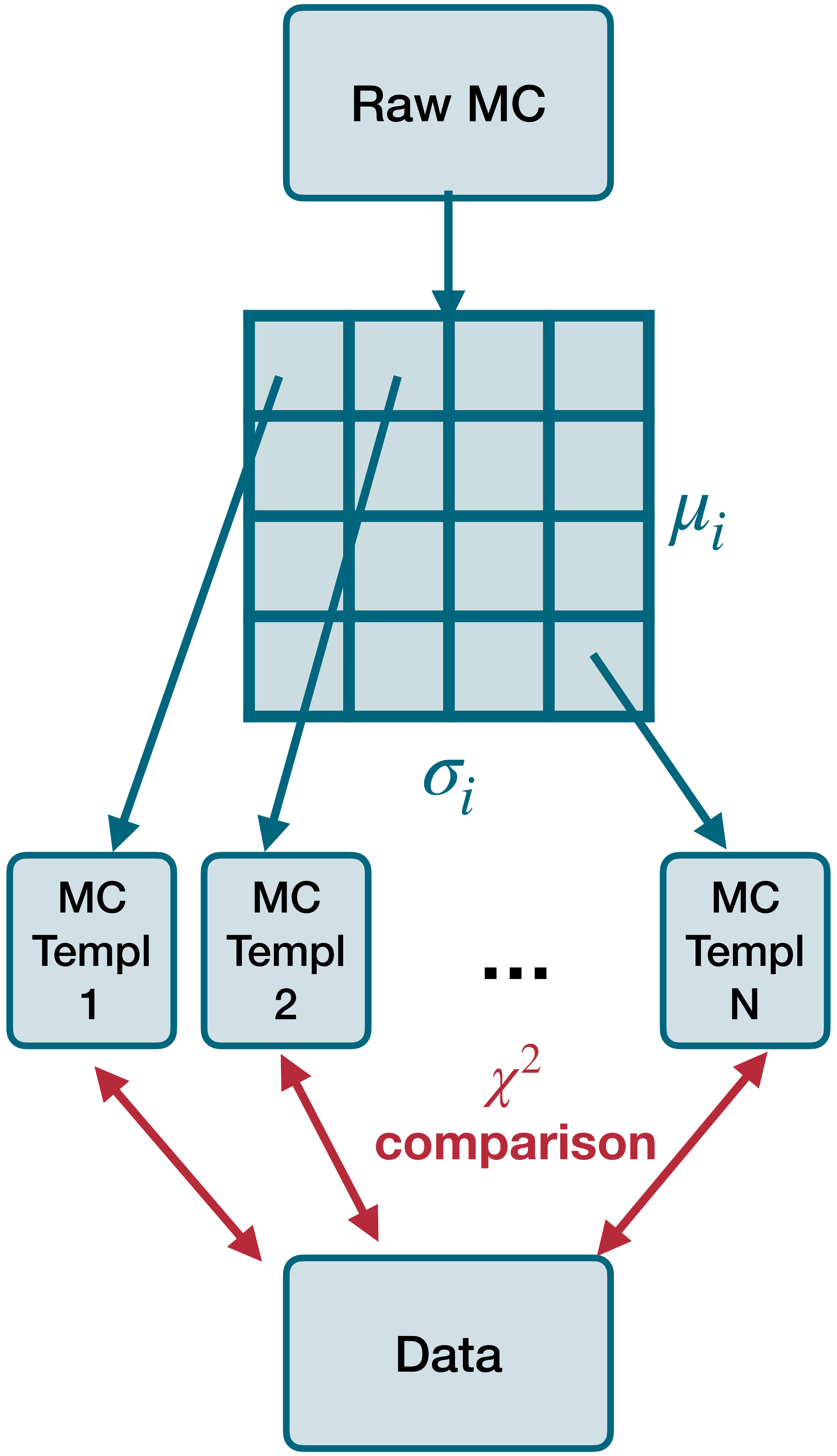
$$x \to x \cdot \left(1 + \mu_x + 4t\sigma_x\right) \qquad t \sim \mathcal{T}(\nu = 2) \qquad x \in \{\kappa, cotan\theta, \phi\}$$

- Fractions and parameters are subject to change, this is WiP

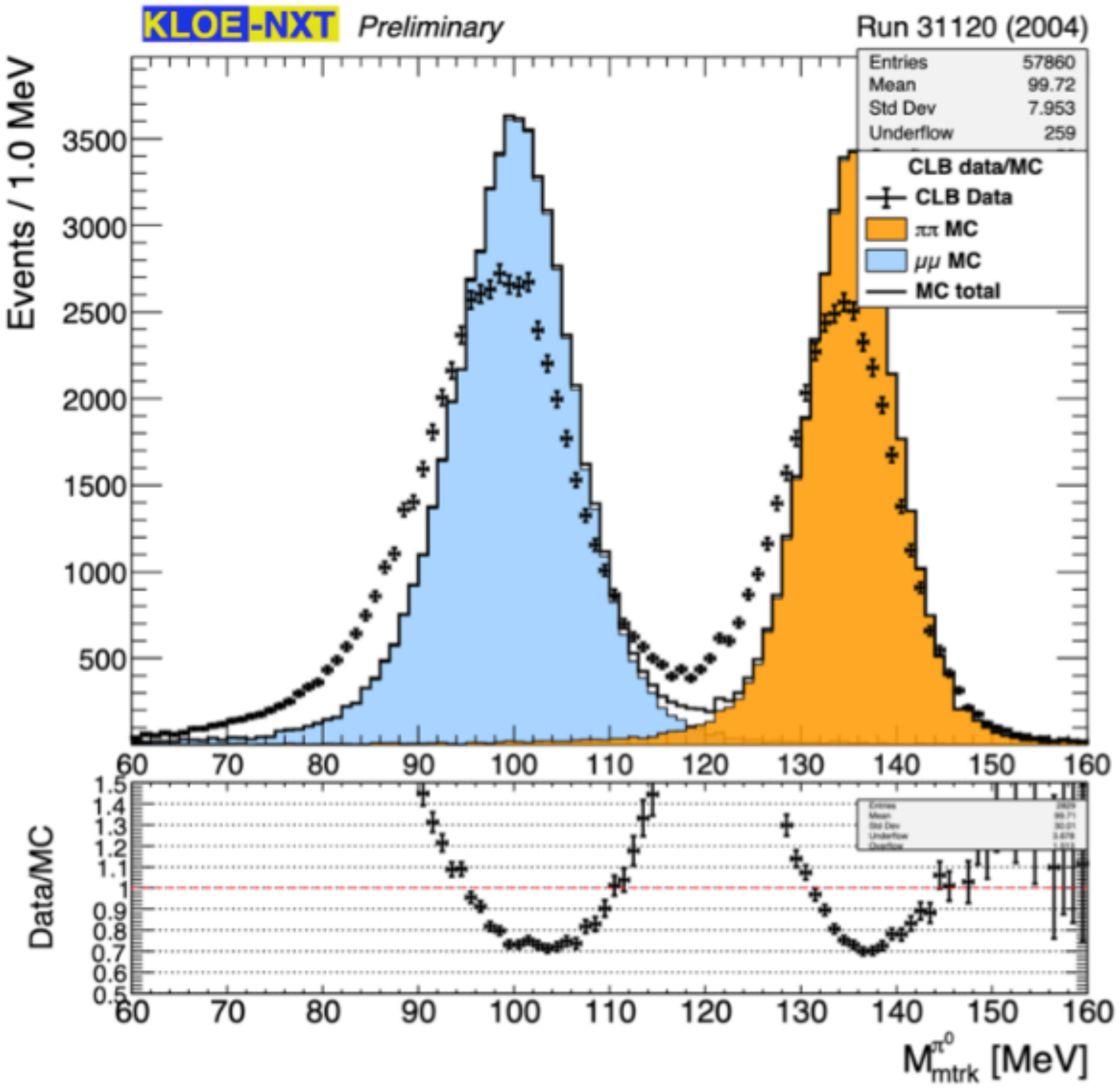
Tuning of Monte Carlo Simulation

- The parameters that fix the tuning are the coefficients $\{\mu_i^x, \sigma_i^x\}$ → we want to find the parameters that best improve data/MC empirical agreement

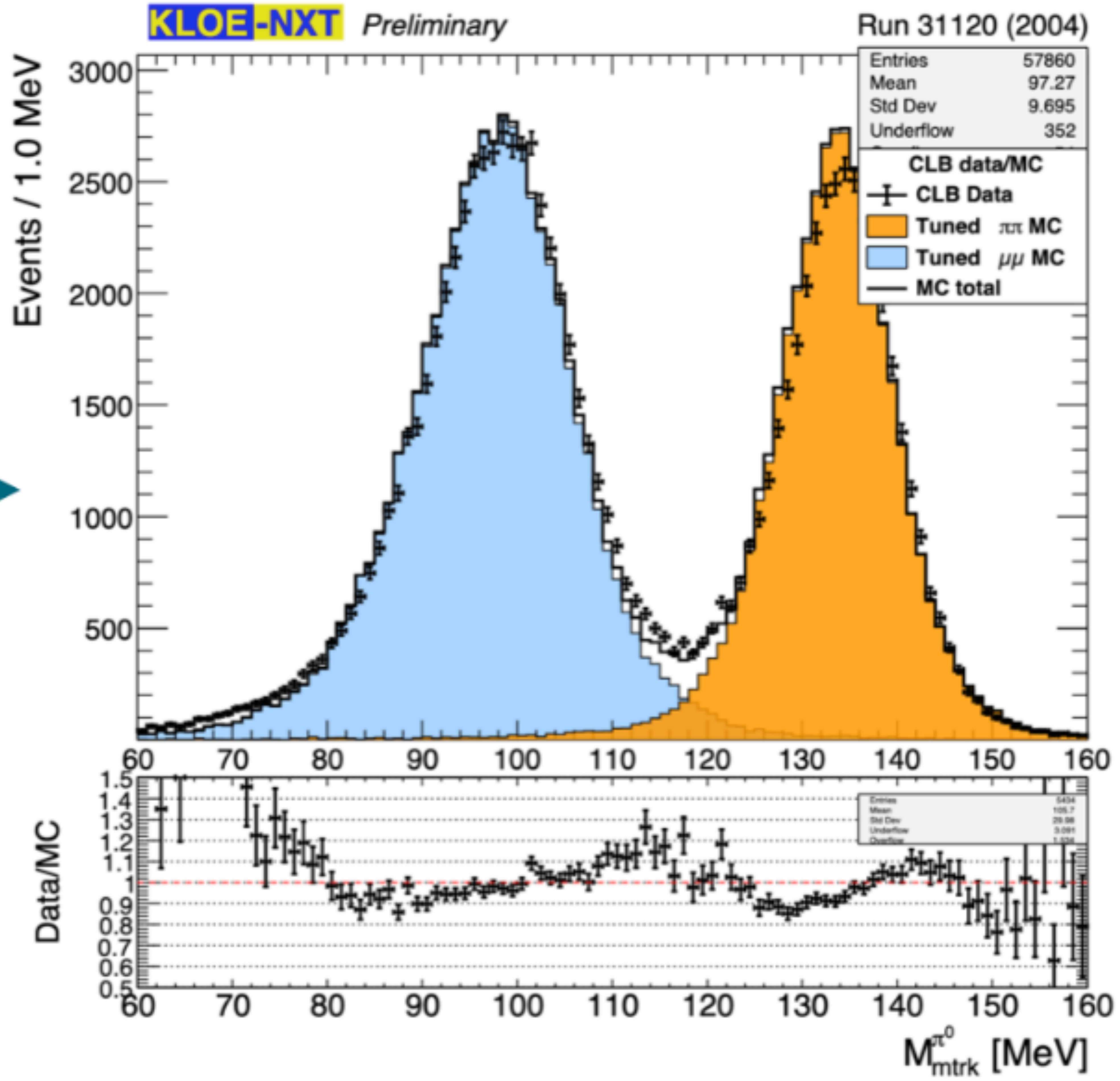
- Can be done through a **template fit:**
    - Start from a common Monte Carlo production that should simulate a data set and choose a grid of N values for the parameters $\{\mu_i^x, \sigma_i^x\}$.
    - For each point in the grid tune the MC sample with gaussian noise according to the parameters values at that grid point with different coefficient values → N different tuned MC samples
    - Choose the best tuned sample based on lowest discrepancy with data. Discrepancy is measured with a χ^2 comparison between data and MC histograms of variable (e.g. M_{trk}, $M_{trk}^{\pi^0}$,…)



Tuning of Monte Carlo Simulation



After applying tuning found with template fit on 3π stream



Background Subtraction

Three main backgrounds survive the cuts in addition to the signal ($\pi^+\pi^-\gamma$) :

$$e^+e^- \to \mu^+\mu^-\gamma(\gamma) \qquad e^+e^- \to e^+e^-\gamma(\gamma) \qquad e^+e^- \to \pi^+\pi^-\pi^0$$

The objective is estimating the total fraction f_B^i of background events in each bin i of $Q^2_{\pi\pi}$:

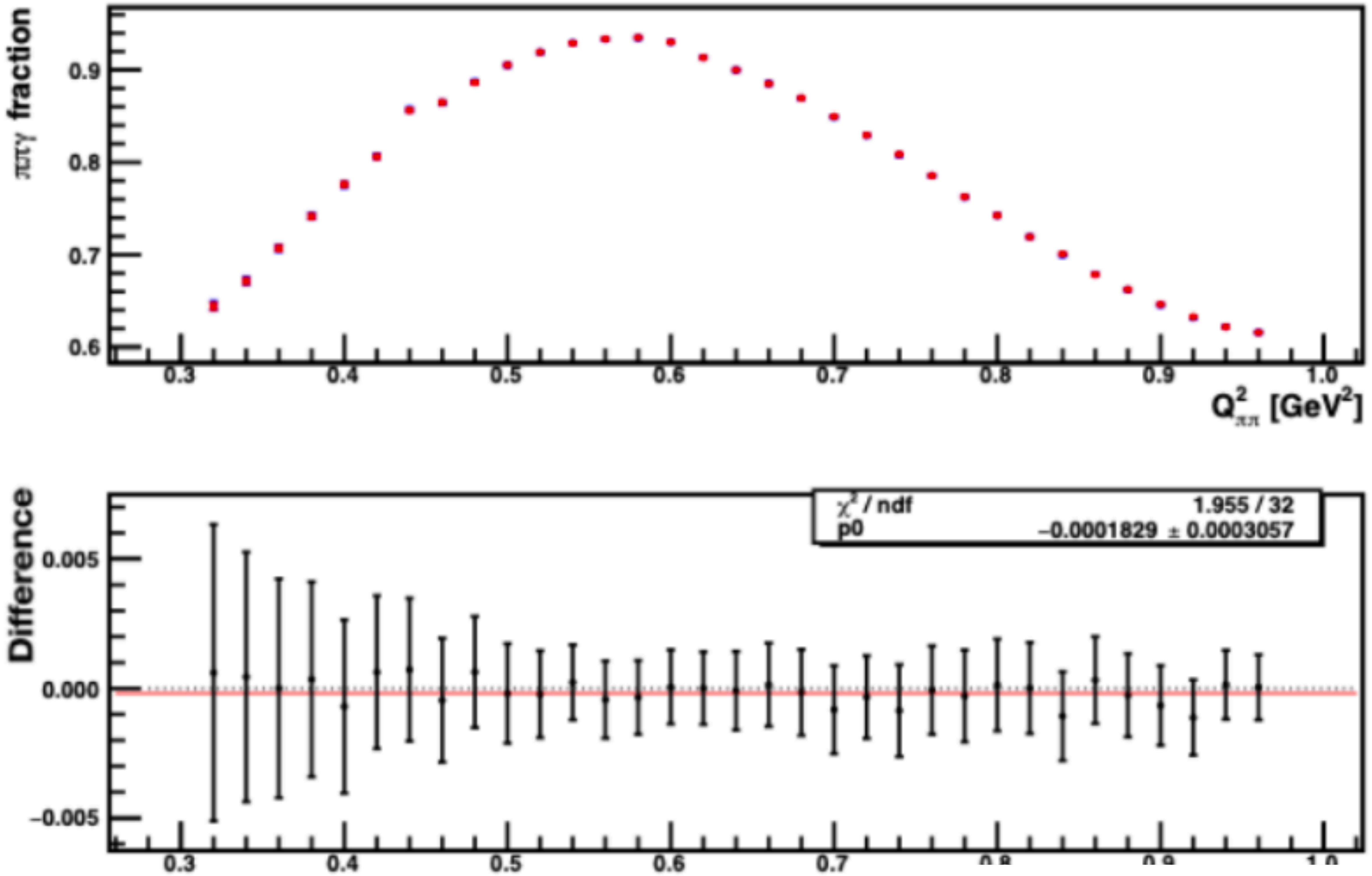
$$f_B^i = f^i_{\mu\mu\gamma} + f^i_{ee\gamma} + f^i_{\pi\pi\pi}$$

- Data M_{trk} distribution is fitted in each bin i with MC M_{trk} distributions to find the fractions F^i_α of each channel α.
- Fits are performed on the **entire range** of M_{trk} (no signal cut) to increase sensitivity.
- Fractions in the **signal region** of M_{trk} (f^i_α) are calculated using the weights w^i_α:

$$w^i_\alpha \equiv F^i_\alpha \frac{N^i_{dat}}{N^i_{mc,\alpha}} \quad \Longrightarrow \quad f^i_\alpha = w^i_\alpha \frac{n^i_{mc,\alpha}}{n^i_{dat}} = F^i_\alpha \frac{N^i_{dat}}{N^i_{mc,\alpha}} \frac{n^i_{mc,\alpha}}{n^i_{dat}}$$

Background Subtraction

- θ_{trk} can be used to perform a 2D fit with $M_{trk} \longrightarrow$ greater **consistency** constraining and better **precision** on the best fit fractions.
- The test yields promising results $\longrightarrow$ **fraction error decreased by** $\sim 30\%$!



(M_{trk}, θ_{trk}) and M_{trk} fitted $\pi\pi\gamma$ fractions ($F_{\pi\pi\gamma}$) as a function of $Q^2_{\pi\pi}$ on toy data.

Calorimeter Cluster Corrections

Correction of Z_{clu} in MC

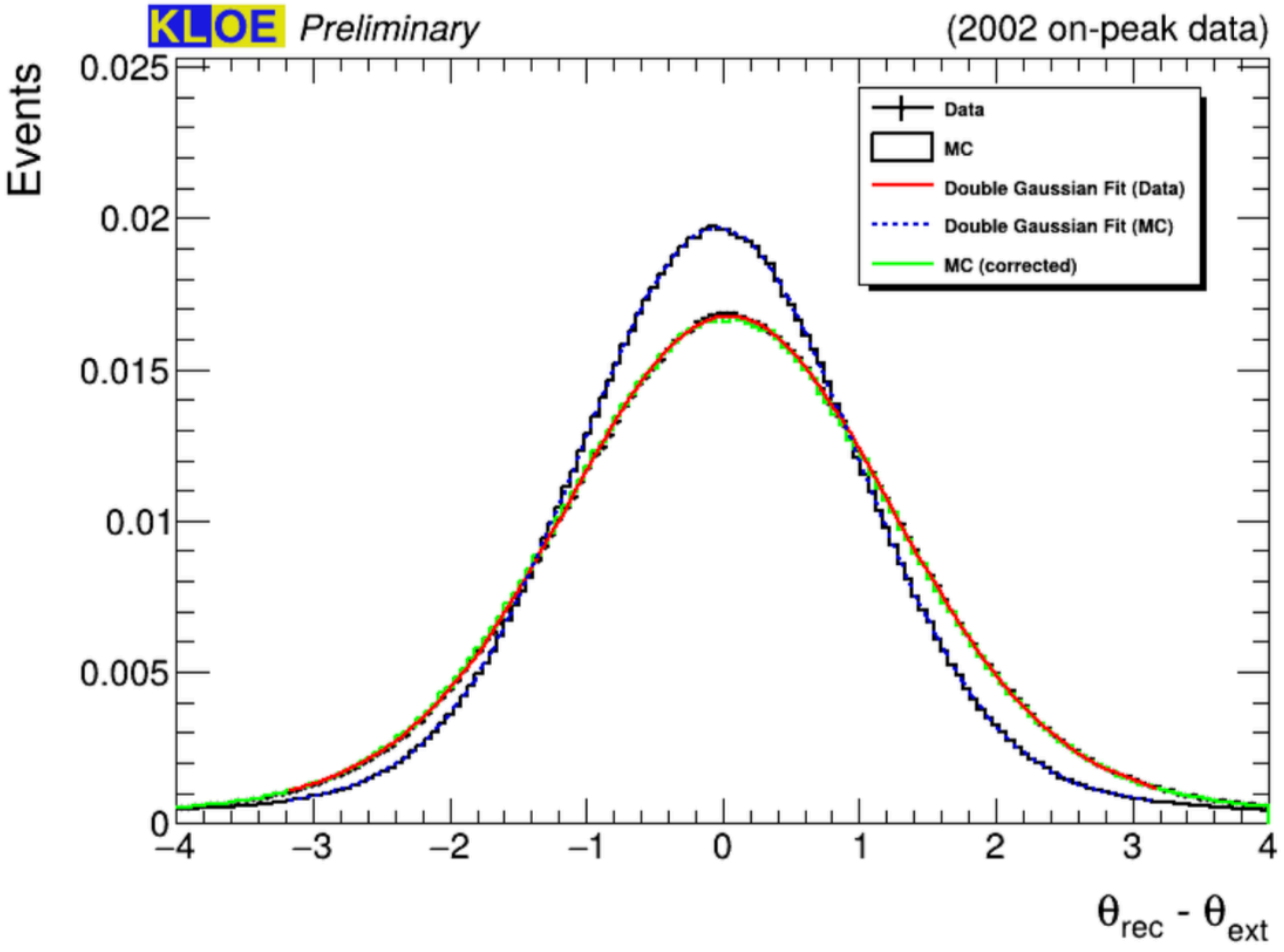
1: Define resolution by $\theta_{\text{rec}} - \theta_{\text{ext}}$ for data and MC VLAB clusters, where $\theta_{\text{rec}} = \cos^{-1}(Z_{\text{clu}_1}/r_{\text{clu},1})$ and $\theta_{\text{extrapolated}} = -\cos^{-1}(Z_{\text{clu}_2}/r_{\text{clu},2})$, i.e. the extrapolated cluster angle is antiparallel with respect to the reconstructed

2: Fit the resulting distributions from data and Monte Carlo separately with a double Gaussian, corresponding to a core plus a tail

3: Calculate the fraction of the distribution corresponding to the core by $A_{\text{core}} = \dfrac{A_{\text{core}} \cdot \sigma_{\text{core}}}{A_{\text{core}} \cdot A_{\text{core}} + A_{\text{tail}} \cdot A_{\text{tail}}}$

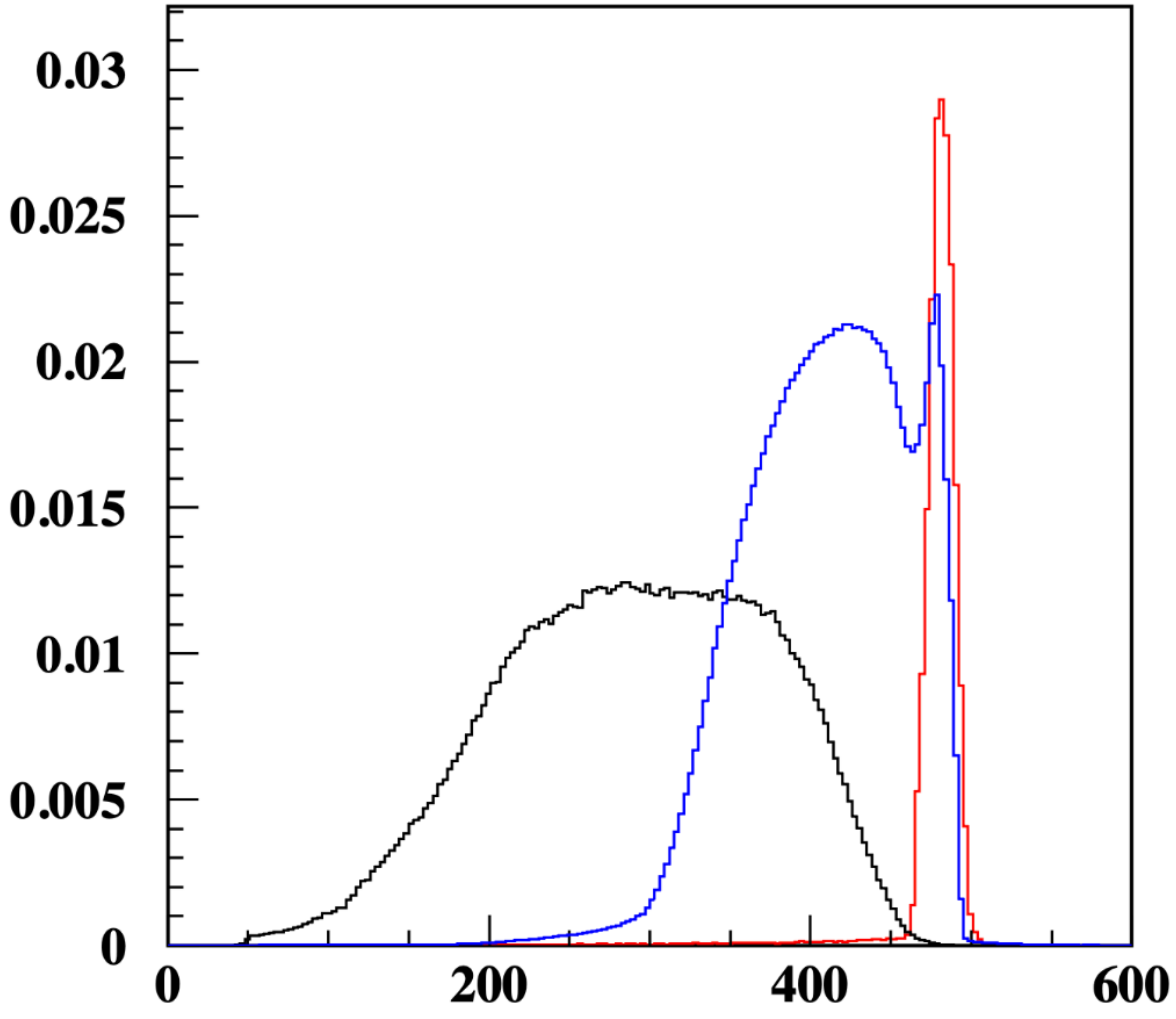
4: Draw a random number, x, between 0 and 1, if $x < A_{\text{core}}$, correct by $\theta_{\text{corrected}} = \theta + \mathcal{N}(0, \sigma_{\text{cor}})$ where $\sigma_{\text{cor}} = \sqrt{(\sigma^2_{\text{data,core}} - \sigma^2_{\text{MC,core}})}$, else if $x > A_{\text{core}}$, $\sigma_{\text{cor}} = \sqrt{(\sigma^2_{\text{data,tail}} - \sigma^2_{\text{MC,tail}})}$, and standard deviations and amplitudes are all extracted from the double Gaussian fit

5: Apply correction on all clusters by $Z_{\text{clu,corrected}} = r_{\text{clu}} \cdot \cos(\theta_{\text{corrected}})$



Tracking Efficiency

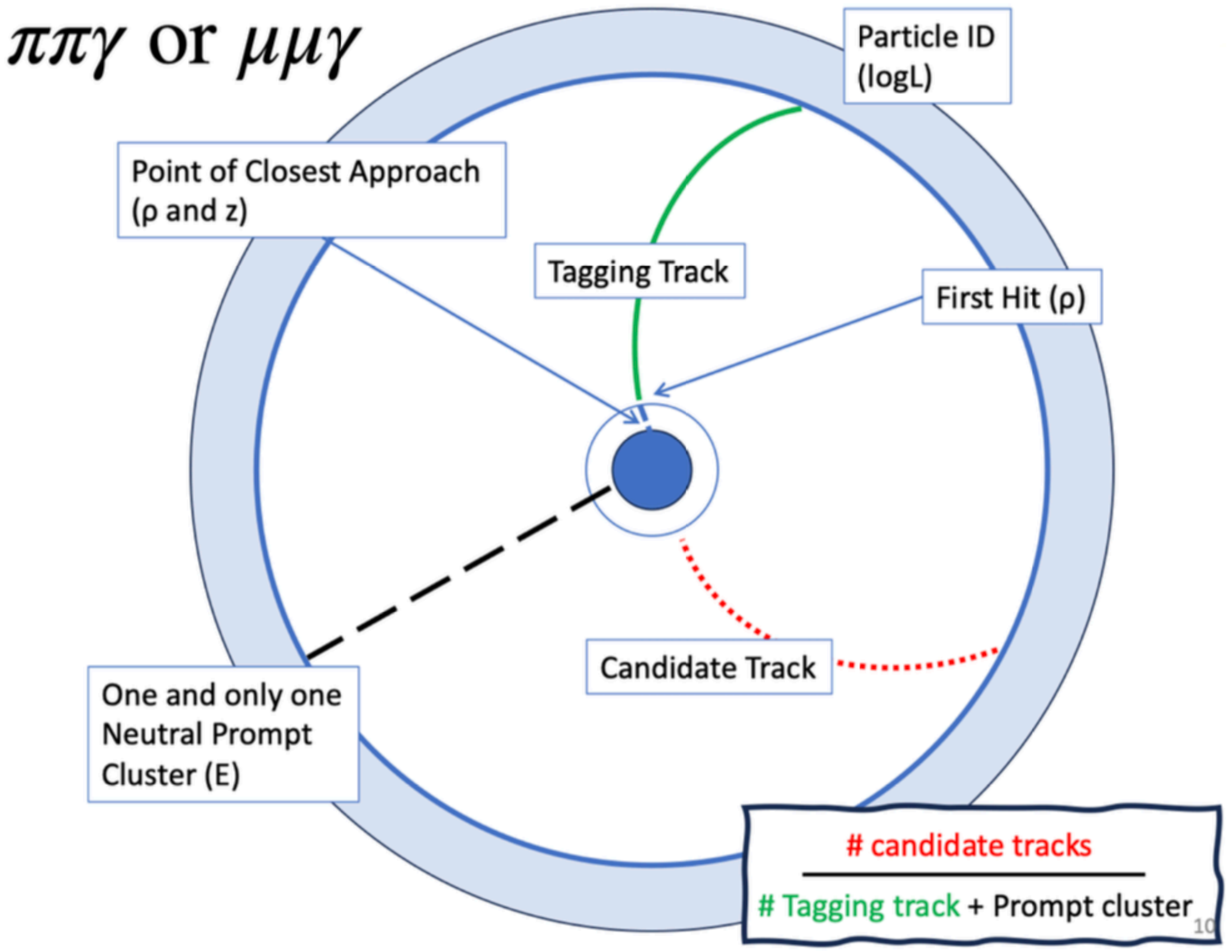
- An important systematic is related to tracking efficiency
- In order to span a wide range of momenta and evaluate systematic error, multiple channels are used
  - $\pi^+\pi^-\gamma$ and $\mu^+\mu^-\gamma$ (signal)
  - $\pi^+\pi^-\pi^0$
  - $\pi^+\pi^-$ (**new!**)
- Efficiency is evaluated both on data (with ad hoc selections) and on Monte Carlo simulation as a function of $M^2_{\pi\pi}$ and $M^2_{\mu\mu}$ respectively
- Efficiency studies currently underway to:
  - Optimise selections
  - Use newer Monte Carlo generators
  - Exploit collinear $\pi^+\pi^-$ events

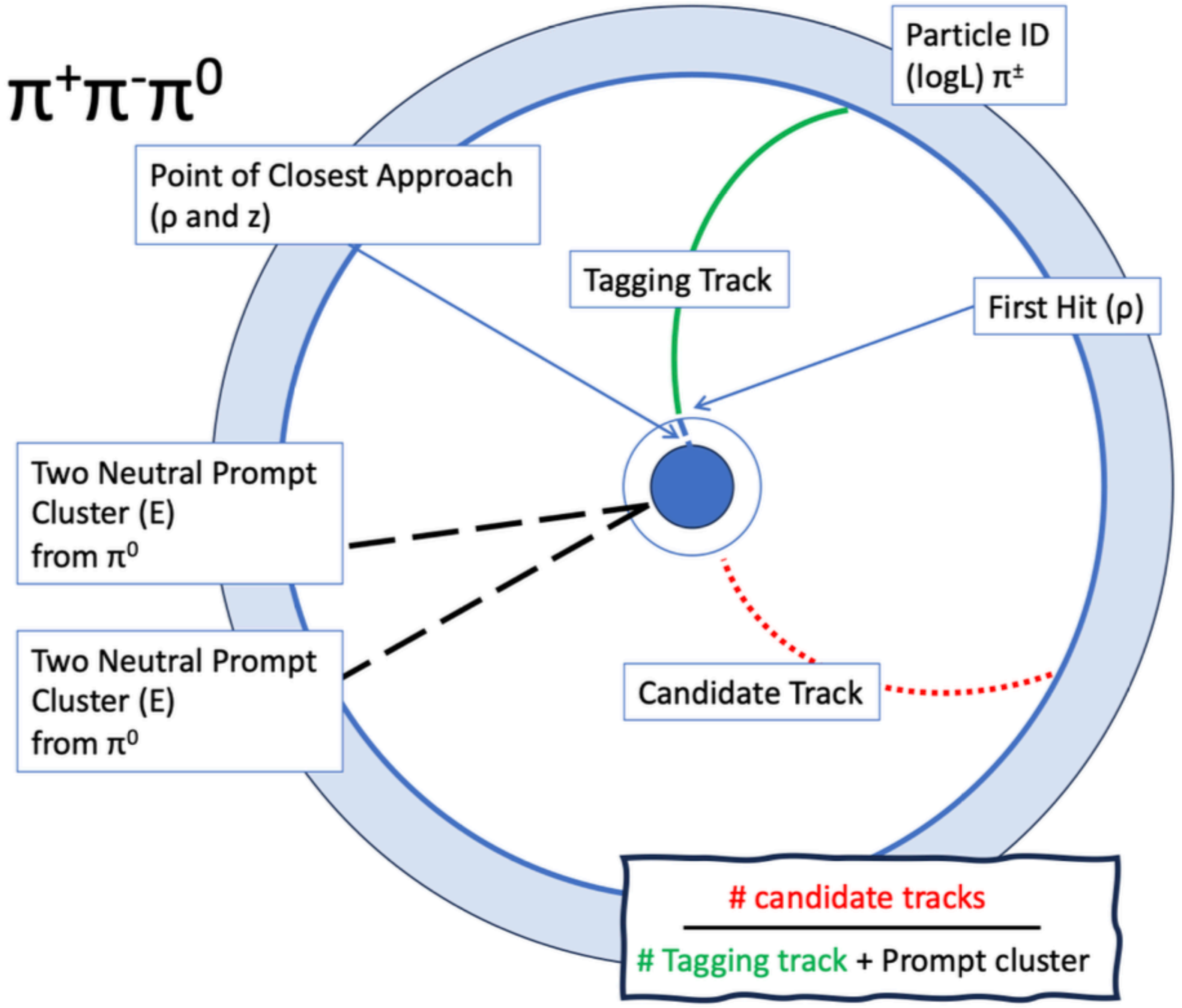


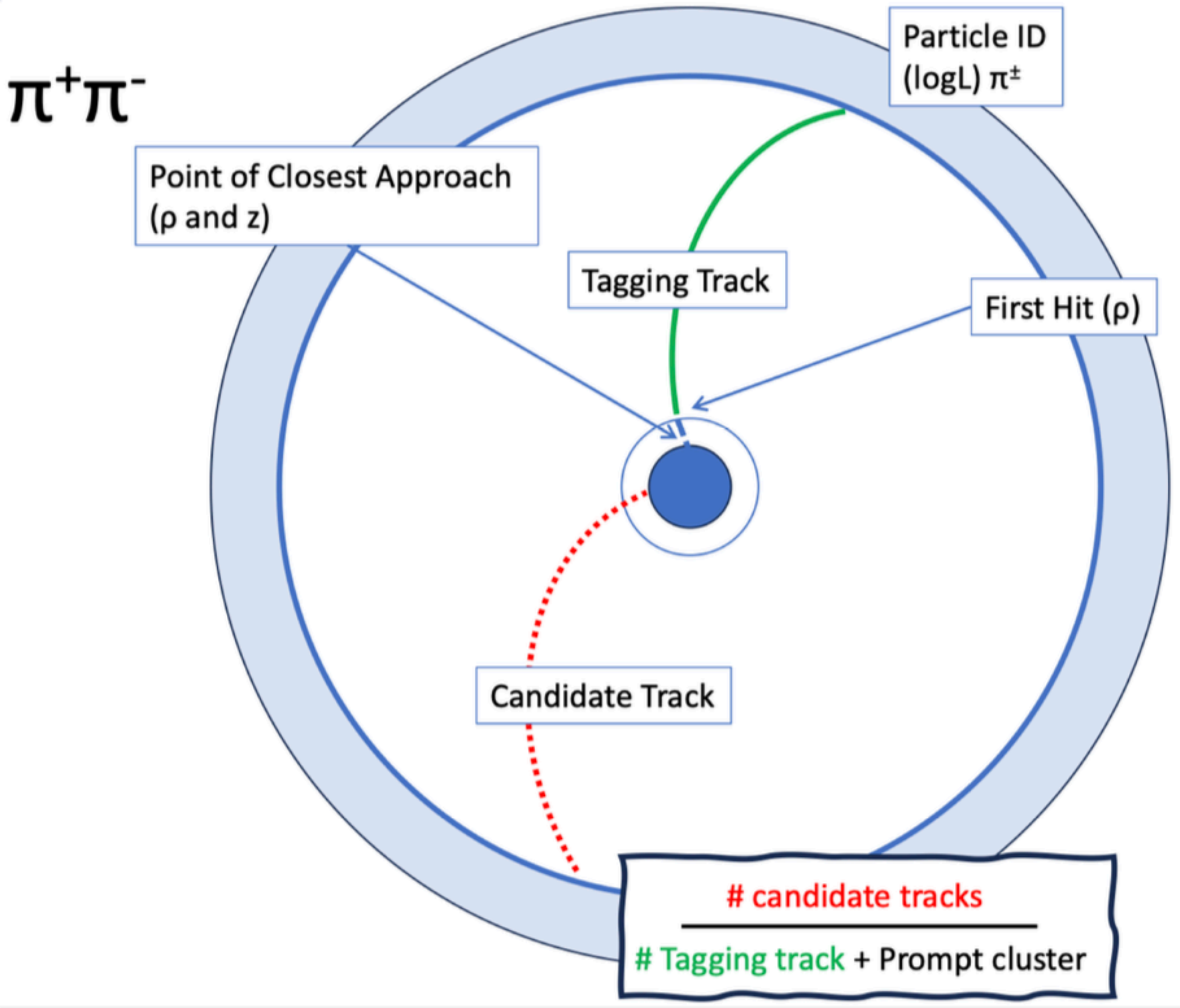
b) π^+, π^- momentum

Tracking Efficiency

- Different selections for different topologies:

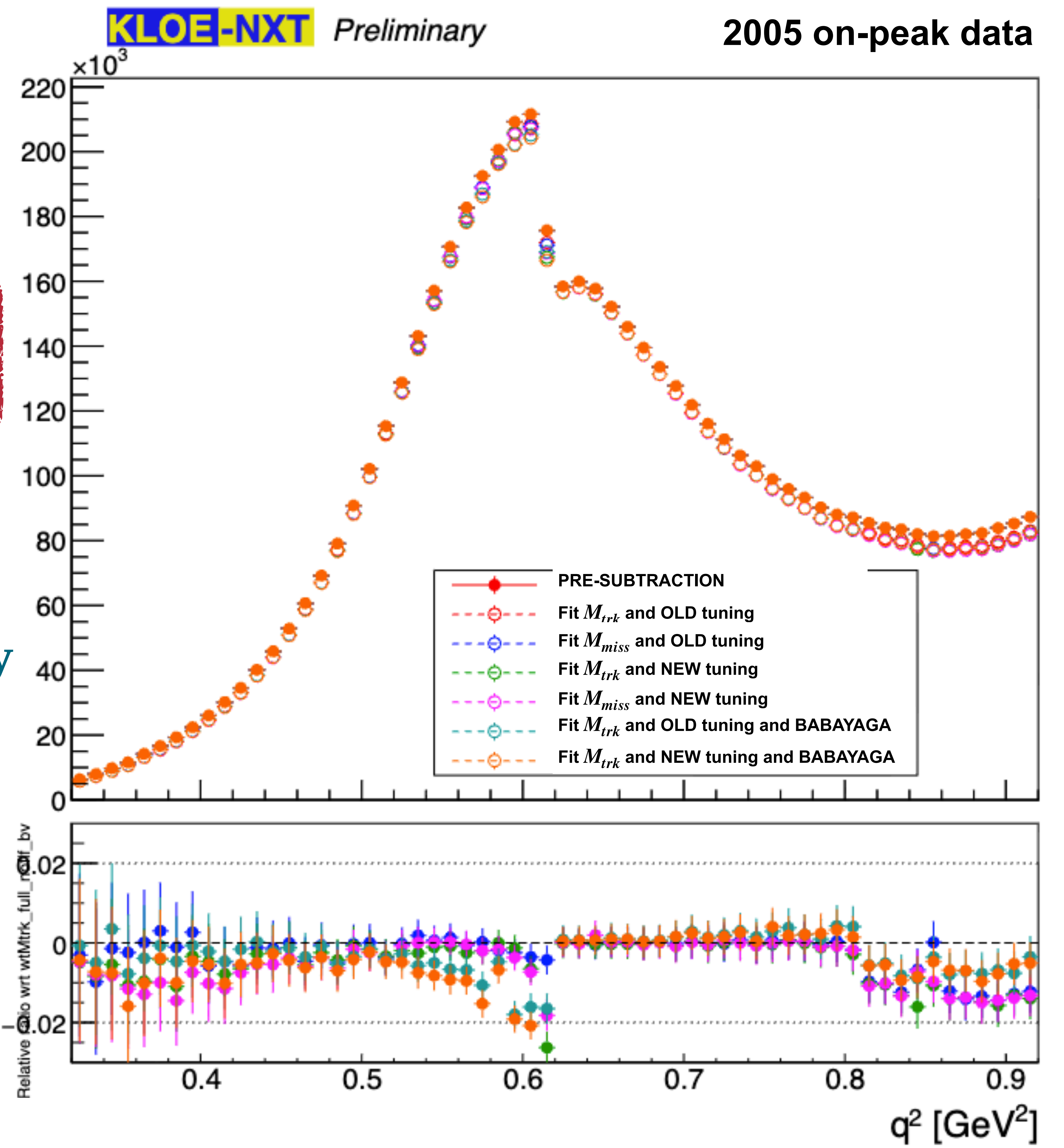






Background Fit and Subtraction

- For the first time the procedure has been cross checked…
  - Fitting on other variables, e.g. $M^{\star}_{miss}$
  - Using new tuning instead of old BV tuning
  - Using new generator BABAYAGA@NLO for the MC $\pi\pi\gamma$ and $\mu\mu\gamma$ templates
- Differences with respect to old procedure can be used to evaluate systematics
- Work is in progress on fitting **two or more variables simultaneously**
- Special care must be taken in order to correctly assign errors to subtracted spectrum following the procedure (currently showing statistical error only)

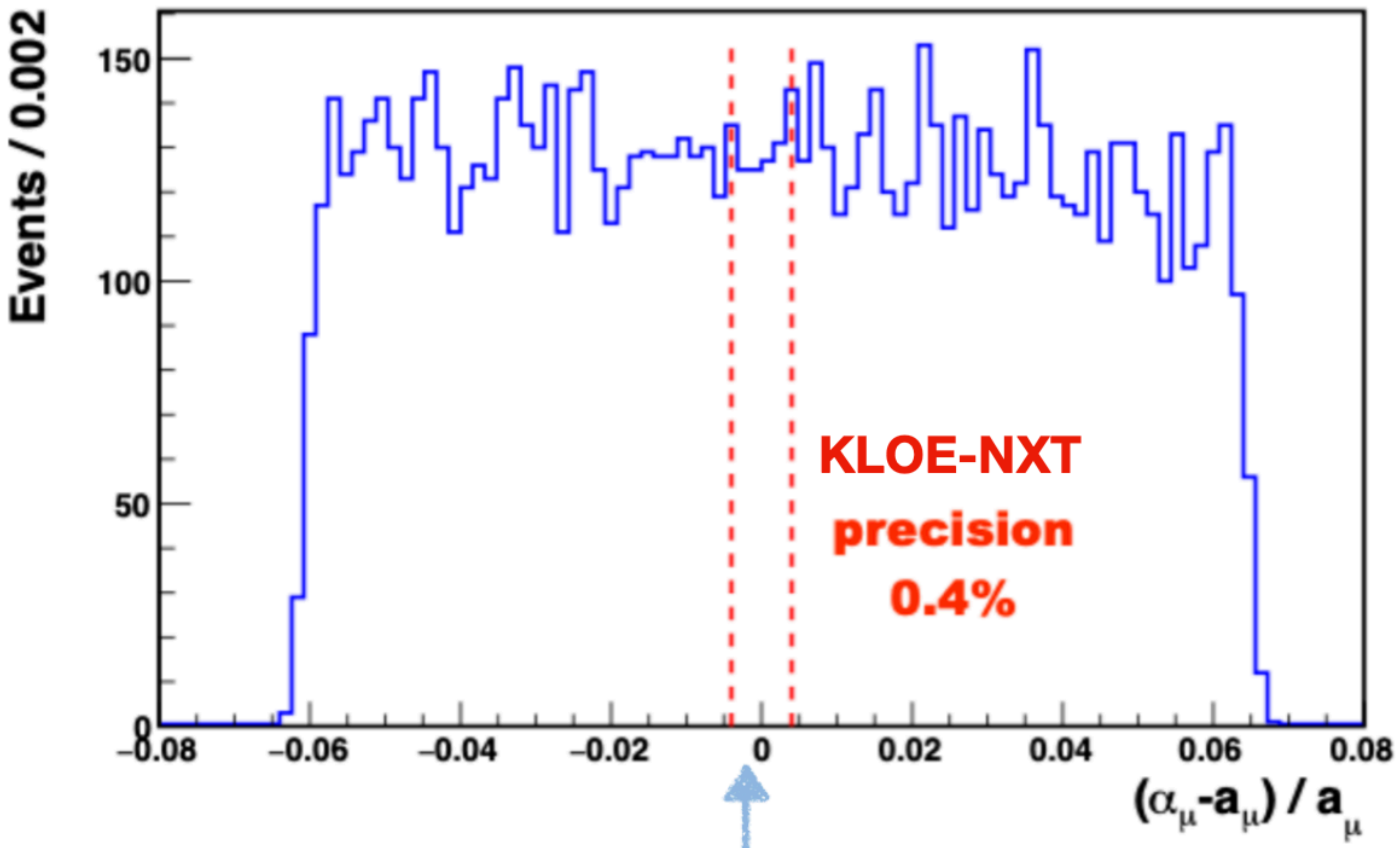


[★]Estimates missing invariant mass assuming $e^+e^- \to \pi^+\pi^-(X)$

$$M^2_{miss} = \left(E_\phi - \sqrt{p_+^2 + m_\pi^2} - \sqrt{p_-^2 + m_\pi^2}\right)^2 - \left|\vec{p}_\phi - \vec{p}_+ - \vec{p}_-\right|^2$$

Blinding

- The new KLOE analysis will be **conducted blindly** to ensure good practice and avoid bias throughout.
- This is not a trivial task and is the **first KLOE a_μ^{HLO} analysis to be blinded.**
- The aim of blinding is to shift the result of the analysis by a small amount without jeopardising the distributions of data and Monte Carlo.
- Two sets of root-tuples will be used in this analysis; **blinded and working (unblinded) root-tuples.**
- For the blinded root-tuples, proposed procedure is as follows:
  - **Removing a small, unknown (to the analysers) fraction of events from each $Q^2_{\pi\pi}$ or $Q^2_{\mu\mu}$ slice in data.**
  - This modifies the measured differential cross section and thus $a_{\pi\pi} \propto \int ds \ldots \sigma_{\pi\pi}(s)$ whilst having no affect on distributions at fixed Q^2 bins.
- Efficiencies are calculated on the working root-tuples ($|F_\pi|^2$ not accessible here).
- **Extraction of $|F_\pi|^2$ is done only on blinded root-tuples.**



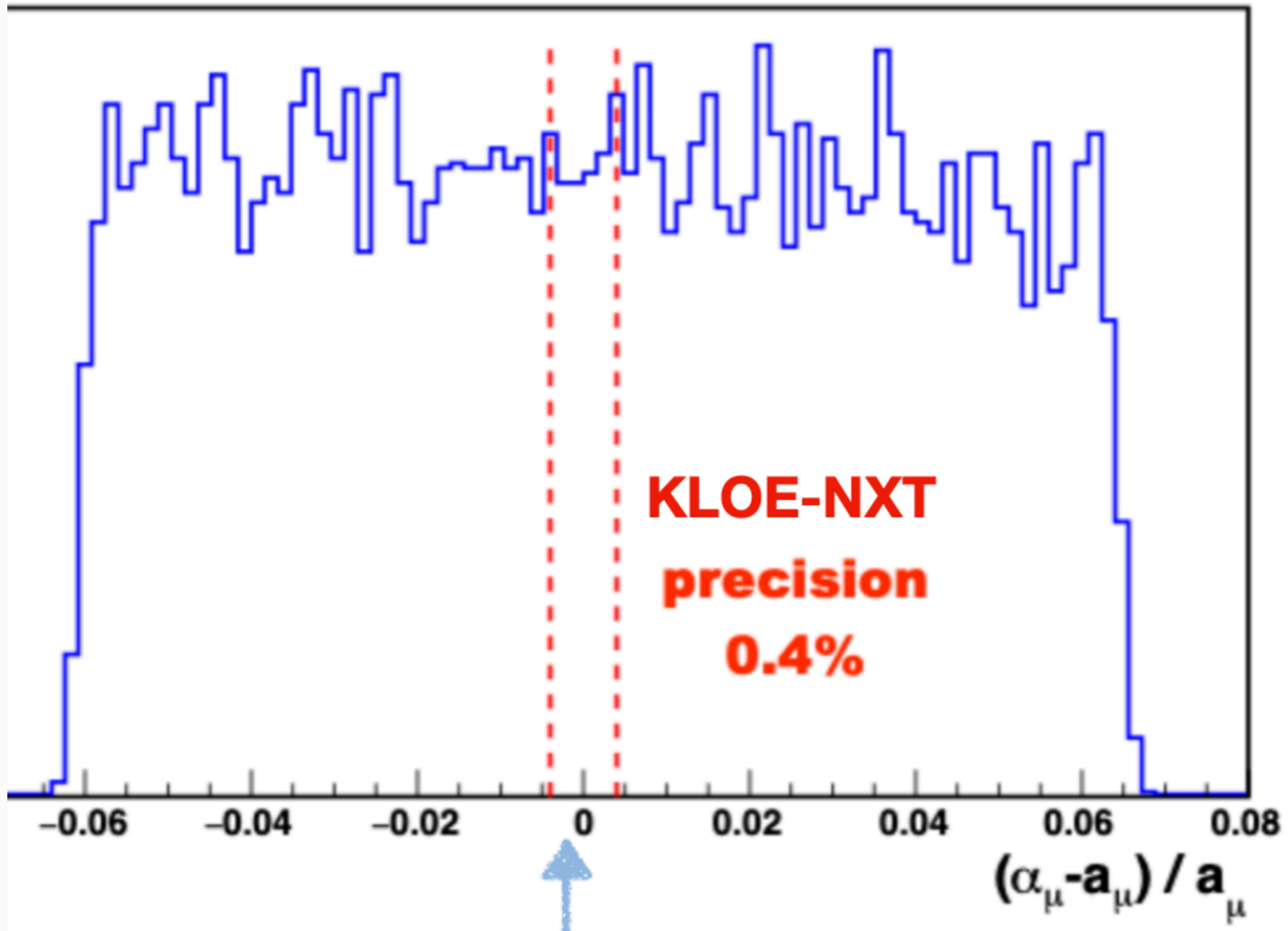
Blinded value of a_μ is ±6% with respect to true value in simulations. Blinding offset **much larger than target KLOE-NXT precision!**

Blinding

Efficiency Generation Routine

For simplicity instead of the efficiencies, which are close to 100%, the routine is expressed in terms of the inefficiencies $1-\mathcal{E}$

1) An inefficiency offset $\mathcal{E}_\pi^{off}$ is extracted between 1% and 7% for the whole $\Delta N_{\pi\pi\gamma}/\Delta Q^2_{\pi\pi\gamma}$ distribution.
2) For each bin i of the distribution, the specific $\mathcal{E}_i$ is uniformly extracted between $\pm 1\%$ with respect to this common offset
3) For the $\Delta N_{\mu\mu\gamma}/\Delta Q^2_{\mu\mu\gamma}$ distribution, $\mathcal{E}_\mu^{off}$ is not randomly extracted but is determined by imposing $\mathcal{E}_\mu^{off} = 8\% - \mathcal{E}_\pi^{off}$. This anticorrelates $\mathcal{E}_\mu^{off}$ and $\mathcal{E}_\pi^{off}$.
4) The $\mathcal{E}_i$ of the individual bins of $\Delta N_{\mu\mu\gamma}/\Delta Q^2_{\mu\mu\gamma}$ are then randomly generated from this $\mathcal{E}_\mu^{off}$ as in the $\pi\pi\gamma$ case: $\pm 1\%$ with respect to this offset.



Blinded value of a_μ is ±6% with respect to true value in simulations. Blinding offset **much larger than target** KLOE-NXT precision!

RC Study Selections

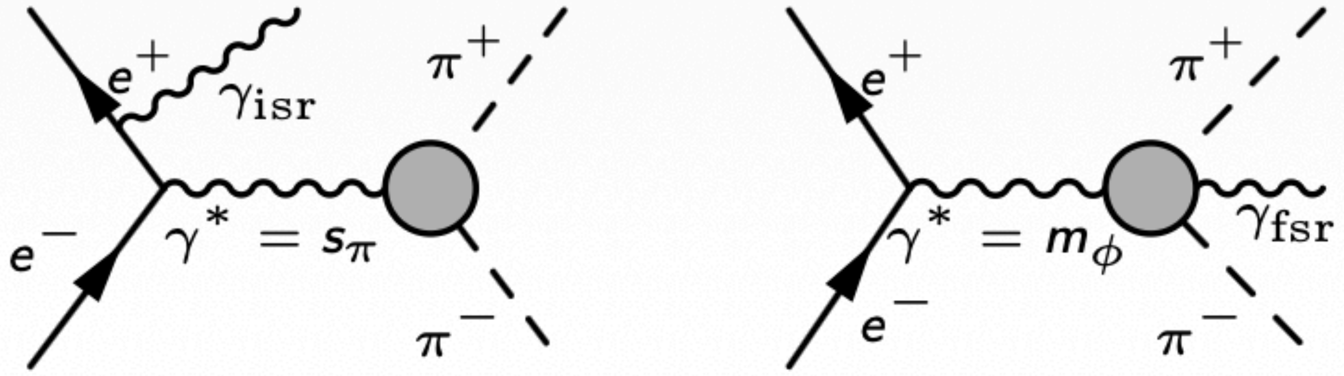
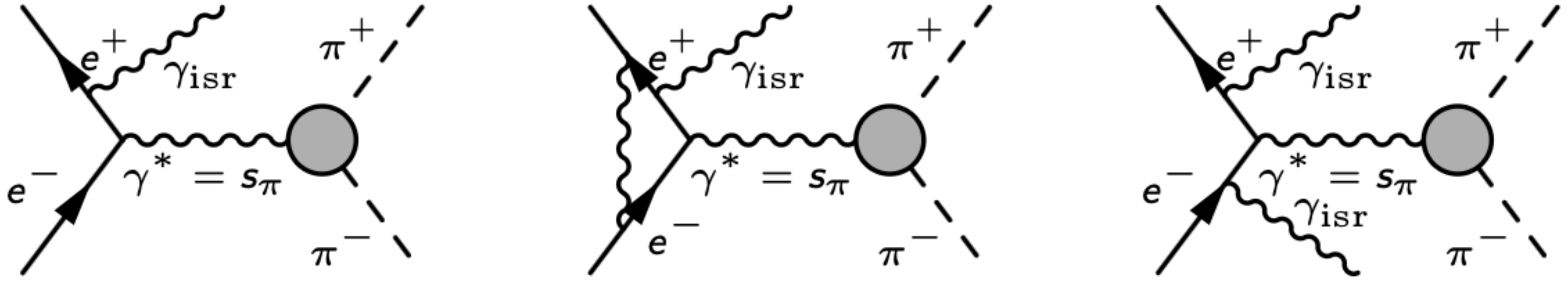
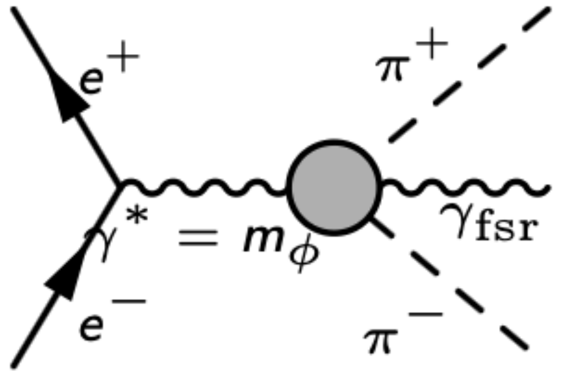
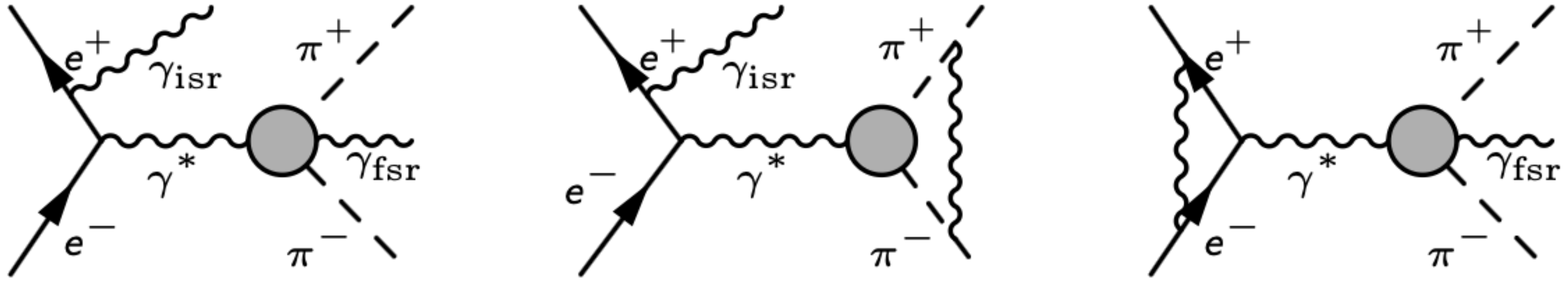
- $50^\circ < \theta_\pm < 130^\circ$
- $|p_t| > 160$ MeV or $|p_z| > 90$ MeV
- $|z_{PCA}| < 7$ cm
- $\rho_{firsthit} < 50$ cm and $\rho_{PCA} < 8$ cm
- $\mathscr{L}_- > 0 \vee \mathscr{L}_+ > 0$
- $\theta_{miss} < 15^\circ \vee \theta_{miss} > 165^\circ$ (SA) or $50^\circ < \theta_{miss} < 130^\circ$ (LA)
- PPGTAG selection (KLOE memo 305)
- $M_{miss} < 120$ MeV
- $M_{trk} > 130$ ($\pi\pi\gamma$) or $M_{trk} < 115$ MeV ($\mu\mu\gamma$)

STENTU selection

STENTU selection + SA or LA

STENTU + SA/LA + M_{trk} CUTS

$M^2_{\mu\mu}$ for $\mu\mu\gamma$ STENTU+SA+M_{trk} Cut

LO (fsr = 1, nlo = 0)	
ISRNLO (fsr = 0, nlo = 1)	
IFSLO (fsr = 1, nlo = 1)	ISRNLO + 
IFSNLO (fsr = 1, nlo = 1, fsrnlo = 1)	IFSLO + 

Radiator and VP

Radiator-Function $H(s,s_\pi)$ (ISR):

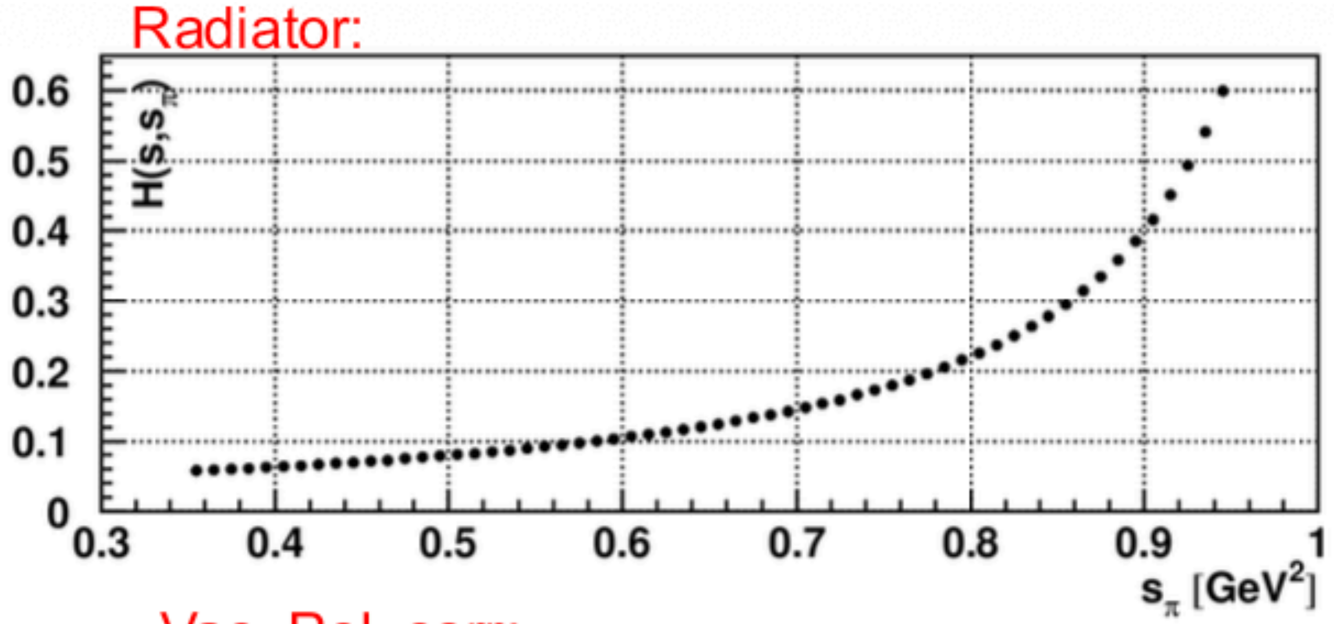
- ISR-Process calculated at NLO-level **PHOKHARA** generator

It cancels in the ratio to $\mu\mu\gamma$

(H.Czyż, A.Grzelińska, J.H.Kühn, G.Rodrigo, EPJC27,2003)

Precision: 0.5%

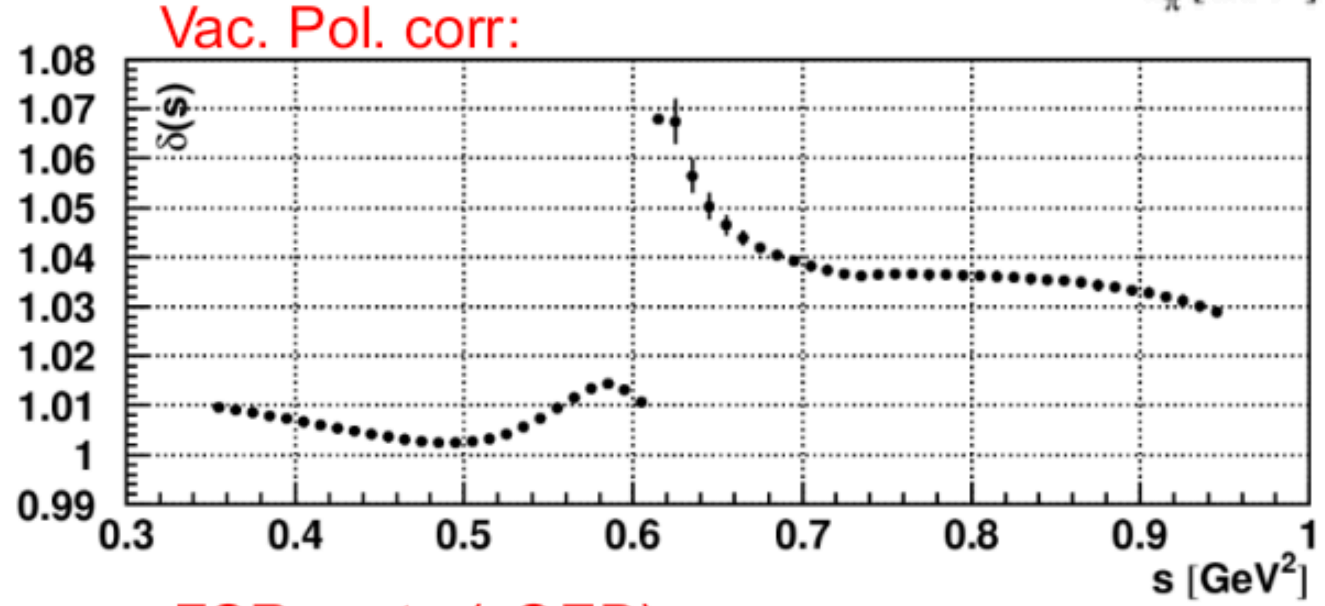
$$s \times \frac{d\sigma_{\pi\pi\gamma}}{ds_\pi} = \sigma_{\pi\pi}(s_\pi) \times H(s,s_\pi)$$



Radiative Corrections:

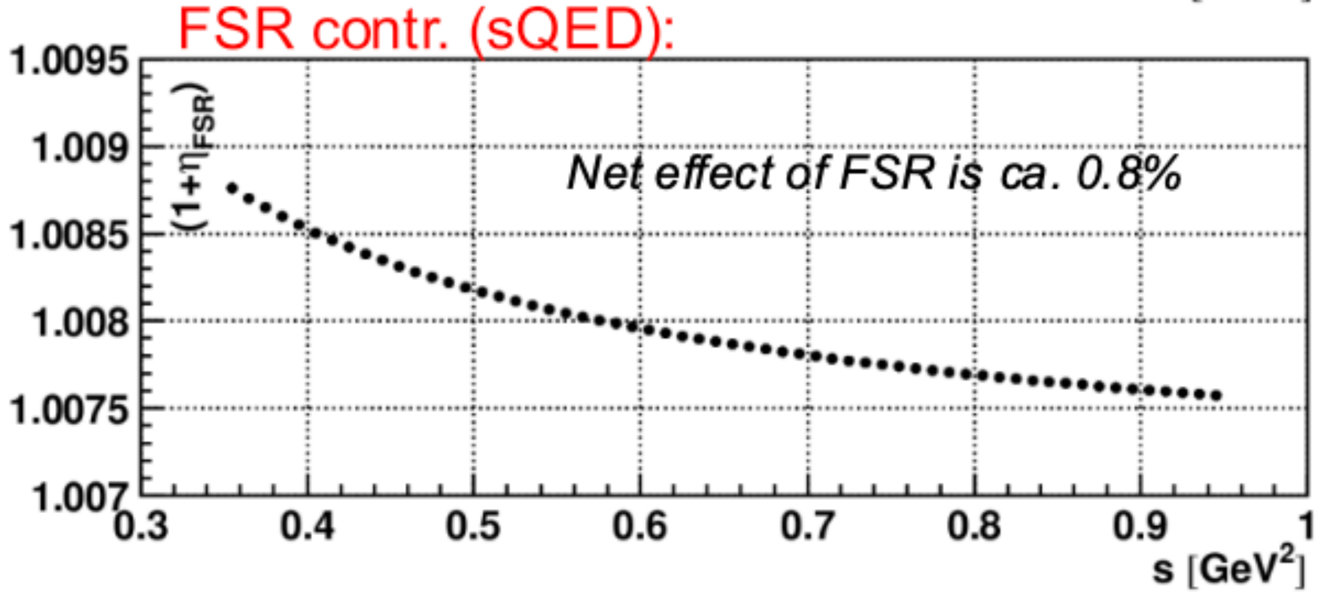
i) Bare Cross Section

divide by Vacuum Polarisation $\delta(\sigma)=(\alpha(\sigma)/\alpha(0))^2$

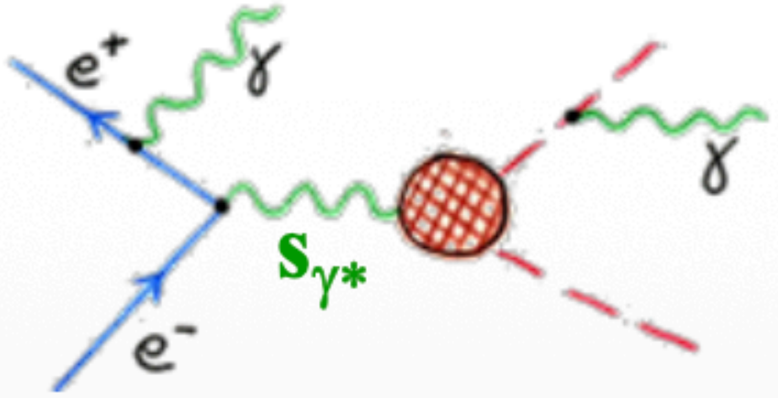


ii) FSR

Cross section $\sigma_{\pi\pi}$ must be incl. for FSR for use in the dispersion integral of a_μ



FSR corrections have to be taken into account in the efficiency eval. (Acceptance, M_{Trk}) and in the mapping $s_\pi \to s_{\gamma*}$



$\sigma_{\gamma*} > \sigma_{\pi\pi}$

22

(H.Czyż, A.Grzelińska, J.H.Kühn, G.Rodrigo, EPJC33,2004)