KLOE $\pi^+\pi^-\gamma/\mu^+\mu^-\gamma$ analysis

Introduction slides

Lorenzo Cotrozzi on behalf of the KLOE 2π HVP group

Muon biweekly| 12/01/2026 | Liverpool

UNIVERSITY OF LIVERPOOL

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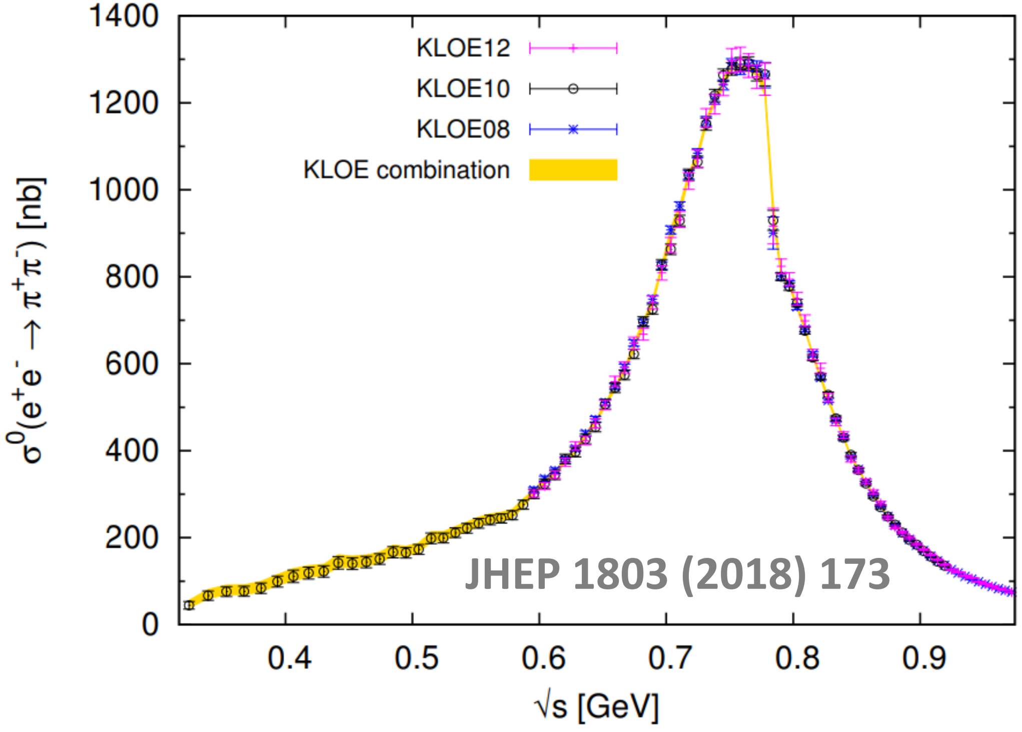
Outline

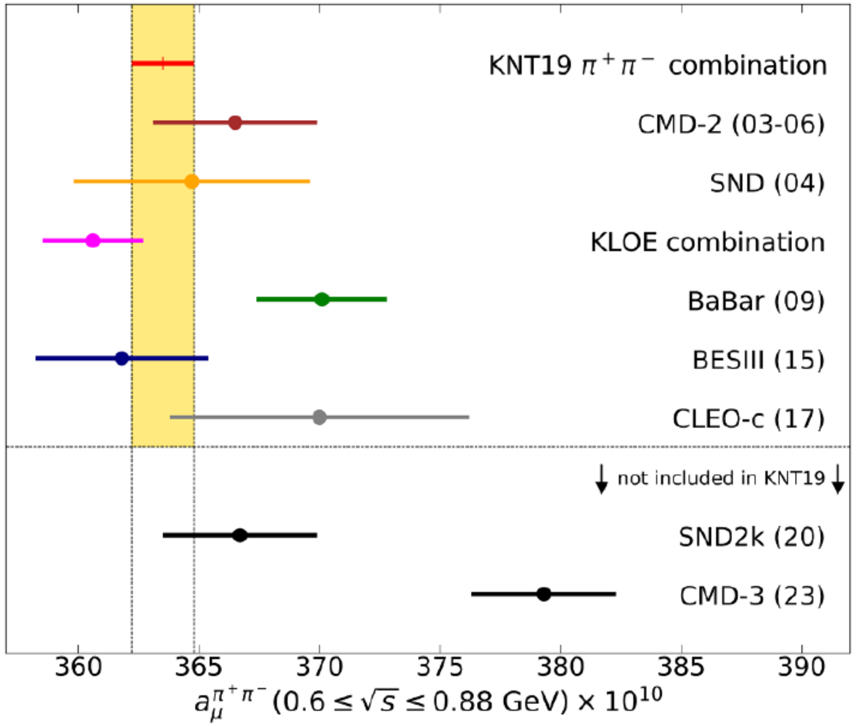
- Overview of the KLOE-nxt analysis
- Computing strategy to preserve data
- Connections with theoretical efforts in Liverpool

KLOE 2π HVP analysis

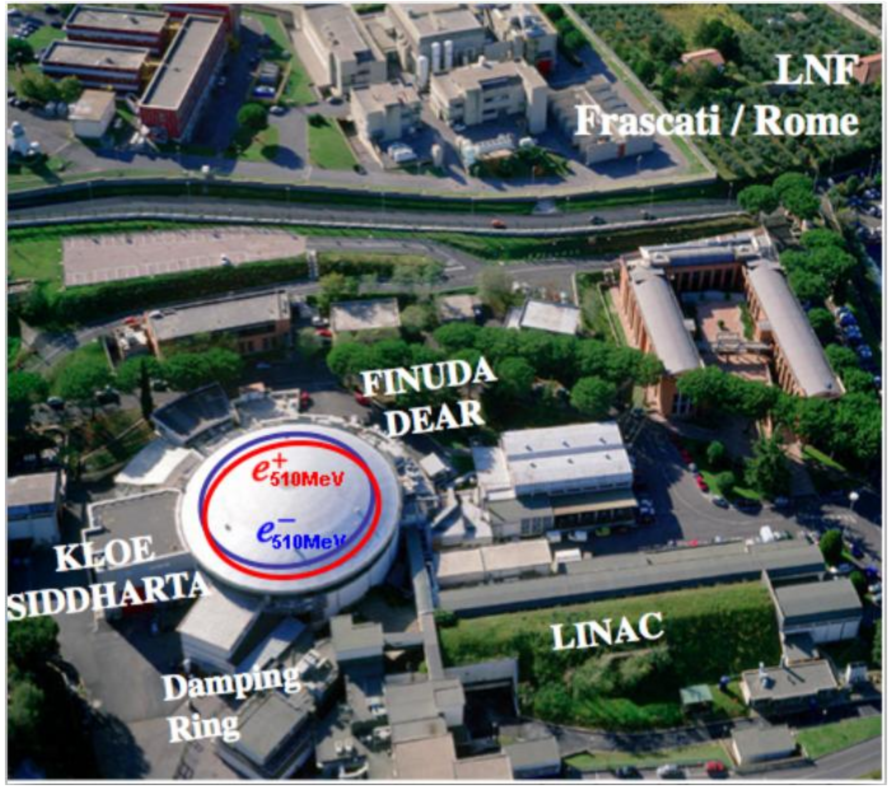
Data-driven approach for the theoretical prediction of a_μ^{HLO}:

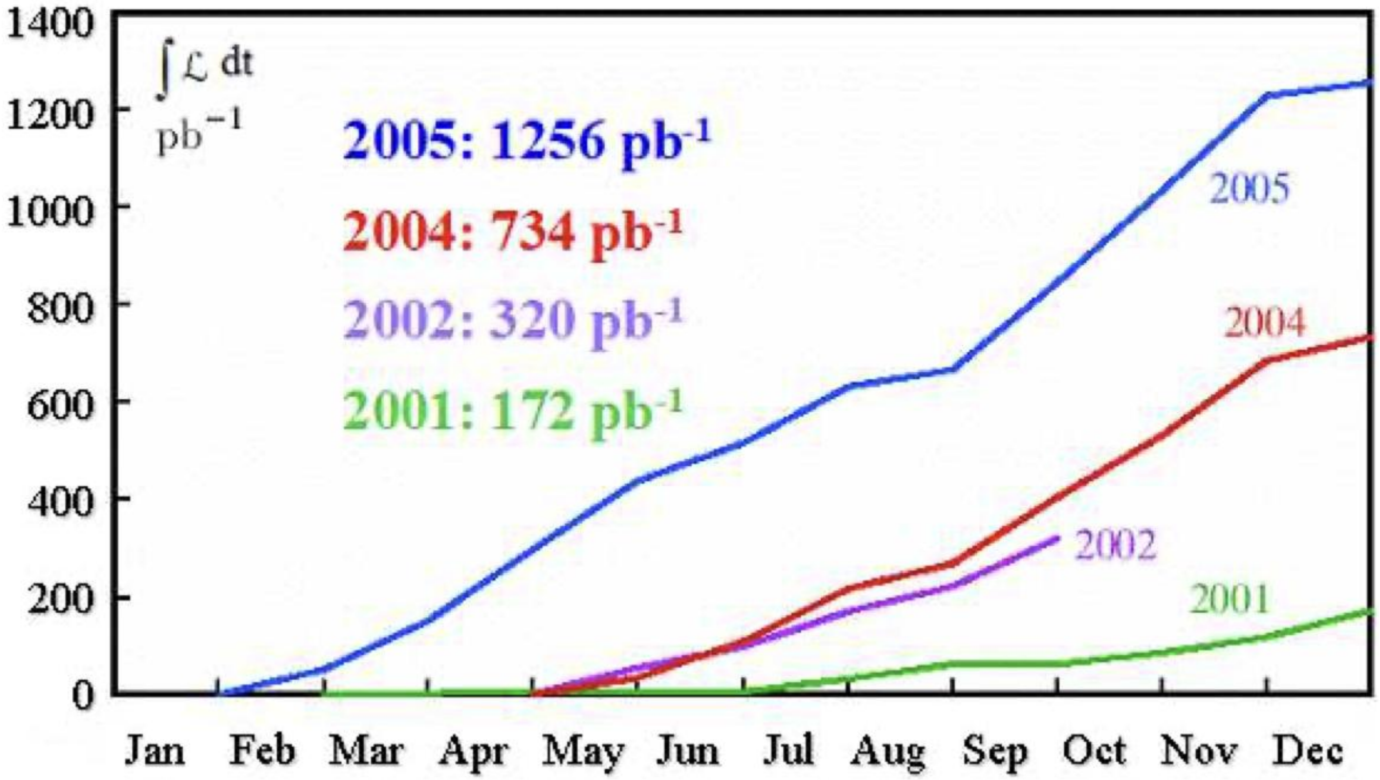
- Experimental input from $\pi^+\pi^-$ channel contributes as $\sim 75\%$
- Long-standing tension (2.8σ) between KLOE and BaBar; recent CMD-3 in tension with both (5.1σ and 2.3σ resp.)
- KLOE operated at $\sqrt{s} = 1020$ MeV using method of ISR return





KLOE data campaign



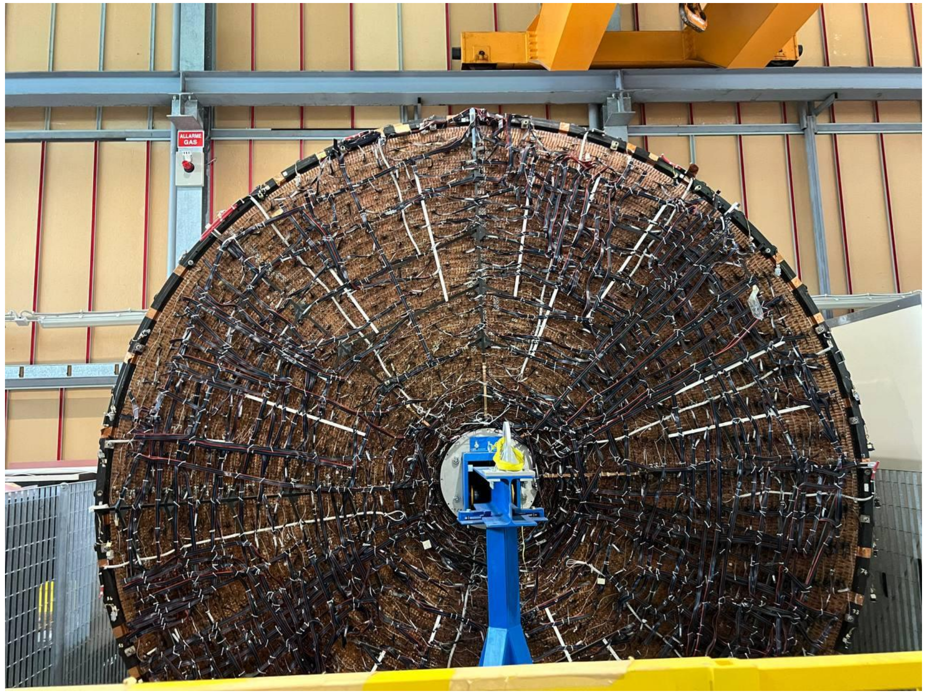


- Total of 2.4 fb^{-1} collected from 2001 to 2006: mostly on ϕ peak ($\sim$ 1020 MeV), small portion collected in 2006 off-peak
- KLOE detectors: drift chamber and electromagnetic calorimeter, continuously monitored and calibrated on-site, inserted in 0.52 T solenoidal magnetic field

KLOE detectors

Very good performances, continuously calibrated while running

Drift chamber

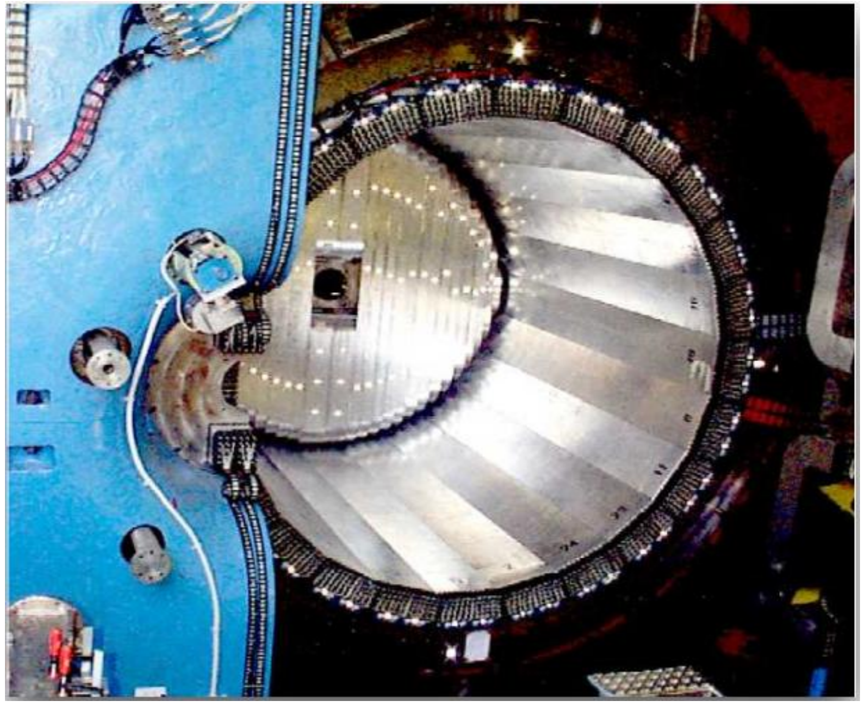


Excellent momentum resolution:

$$\sigma_p/p = 0.4\%$$

$$\sigma_{r\phi} = 150\mu\text{m}, \sigma_z = 2\text{mm}$$

EM Calorimeter



Excellent time resolution:

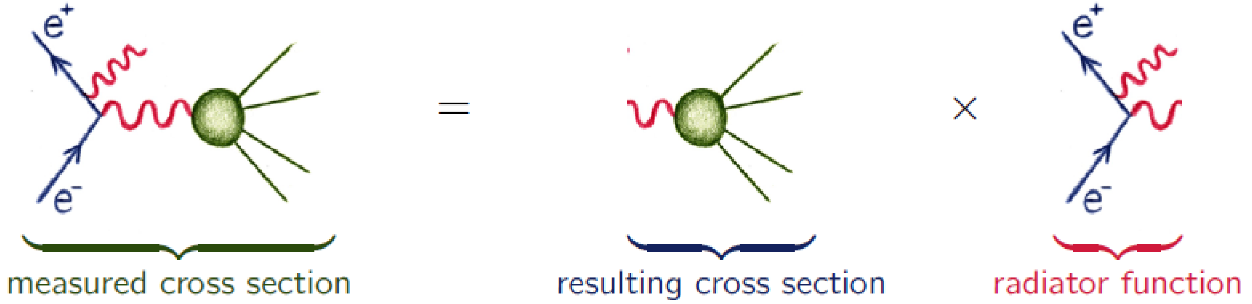
$$\sigma_t[\text{ps}] = 54/\sqrt{E[\text{GeV}]} \oplus 140$$

$$\sigma_E/E = 5.7\%/\sqrt{E[\text{GeV}]}$$

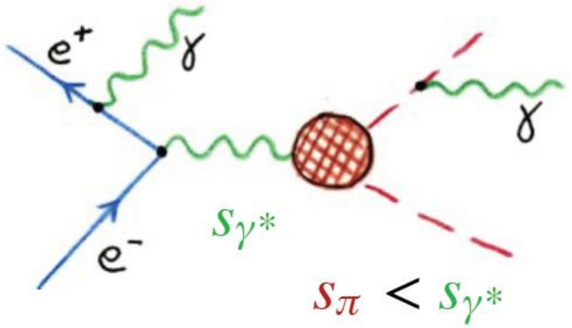
Method of Initial State Return

- ISR technique to scan $\sqrt{s}$: radiator function $H\left(s, M_{had}^2\right)$ relates differential cross section $e^+e^- \rightarrow \pi^+\pi^-\gamma$ to $e^+e^- \rightarrow \pi^+\pi^-$

$$\frac{d\,\sigma(e^+e^- \to \mathrm{had} + \gamma)}{d\,M_{\mathrm{had}}^2} = \frac{\sigma(e^+e^- \to \mathrm{had}, M_{\mathrm{had}}^2)}{s} \times H(s, M_{\mathrm{had}}^2)$$



- Phokhara MC calculates: ISR at NLO; Radiative corrections such as vacuum polarisation and FSR



Normalisation to muon ISR

Two methods to extract cross section:

- KLOE08, KLOE10: absolute **normalisation to luminosity** (from Bhabha events):

$$\frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} = \frac{N - N_{bkg}}{\Delta M^2_{\pi\pi}} \cdot \frac{1}{\varepsilon} \cdot \frac{1}{\int L\,dt} \rightarrow \sigma_{\pi\pi}(M^2_{\pi\pi}) = s \cdot \frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} \cdot \frac{1}{H(s, M^2_{\pi\pi})}$$

- KLOE12: normalize $\pi\pi\gamma$ sample with $\mu\mu\gamma$ events → for each energy bin:

$$|F_{2\pi}(s')|^2 = \frac{4(1+2m^2_\mu/s')\beta_\mu}{\beta^3_\pi} \cdot \frac{d\sigma_{\pi\pi\gamma}/dM^2_{\pi\pi}}{d\sigma_{\mu\mu\gamma}/dM^2_{\mu\mu}} \rightarrow \sigma_{\pi\pi}(s') = \frac{\pi\alpha^2\beta^3_\pi}{3s'} \cdot |F_{2\pi}(s')|^2$$

Advantage of **muon ISR normalization**: systematic effects and radiative corrections cancel!

Total uncertainty on Radiative Effects	
$a^{\pi\pi}{}_{\mu\mu}$ abs	0.1% + 0.3% + 0.5%
$a^{\pi\pi}{}_{\mu\mu}$ ratio	/ + 0.3% + /

New KLOE-nxt analysis

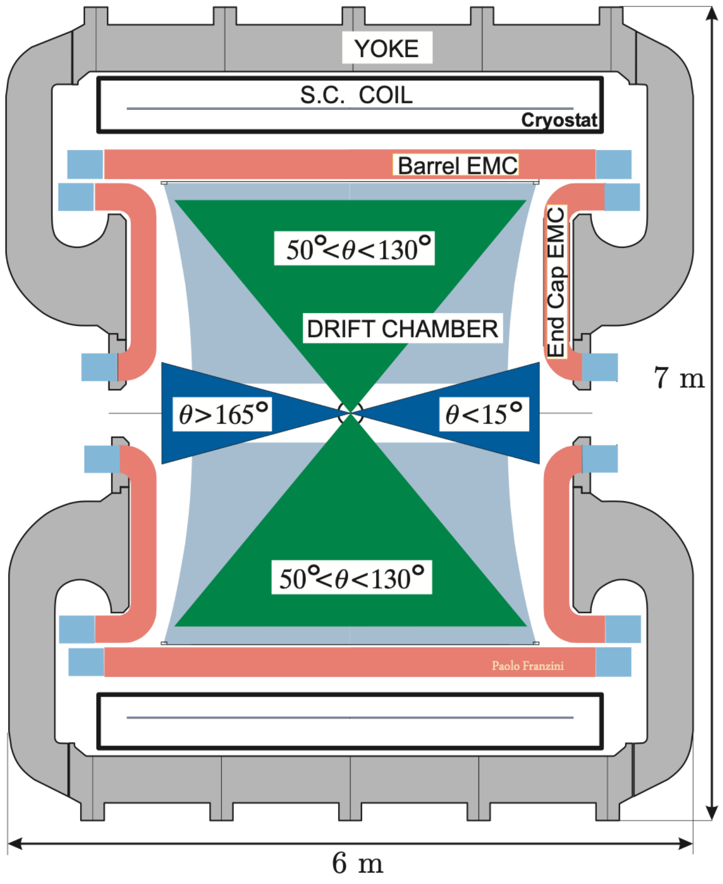
- 1.7 fb^{-1} from 2004/2005 data, with 25 million $\pi\pi\gamma$ events (7 times more statistics than published analyses, never analyzed before) + 232 pb^{-1} from 2006 off-peak data for additional cross checks and systematic studies
- Small Angle (SA) selection cuts on undetected photons:

$$\theta_\gamma < 15° \quad \text{or} \quad \theta_\gamma > 165°$$

- 2 pions (muons) at large angle:

$$50° < \theta_{\pi,\mu} < 130°$$

- Normalized to $\mu\mu\gamma$
- We're tackling many aspects of the analysis to reach a two-fold improvement on $a_\mu^{\pi\pi}$ uncertainty w.r.t. KLOE12 → goal of 0.4% total uncertainty
- Many new analysis techniques and also much theory work

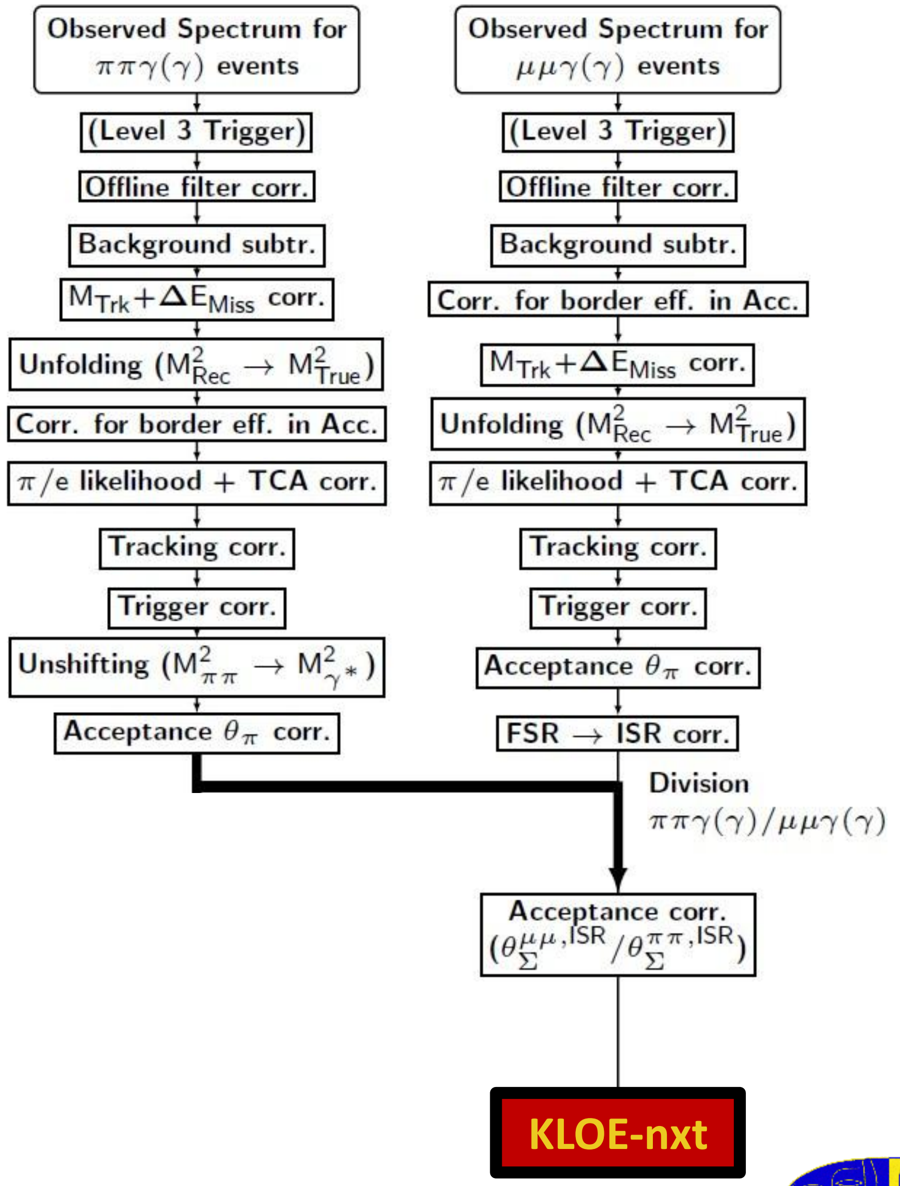


KLOE-nxt workflow

The analysis will be performed on pions, muons for normalization and bhabha events for luminosity/QED test

Many aspects of the analysis are led and carried out by Liverpool (see Estifa'a's presentation at the biweekly last year) but there is also a heavy involvement of colleagues from Pisa and Dresden

New procedure since KLOE12: blinding



KLOE-nxt roadmap

Tracking
Luminosity (for QED test)
Unfolding
Detector efficiency
Background subtraction
Blinding

- We're tackling many aspects of the analysis using new techniques: improved evaluations of the efficiencies, Data-MC comparisons, new BDT for PID, …

- Background subtraction was the dominant systematic in KLOE12: goal to improve it by a factor of x3

- KLOE12: $0.3\%_{stat} \oplus 0.2\%_{th} \oplus 0.7\%_{syst} =\sim 0.8\%_{total}$
  KLOE-nxt goal: $0.1\%_{stat} \oplus 0.2\%_{th} \oplus 0.3\%_{syst} =\sim 0.4\%_{total}$

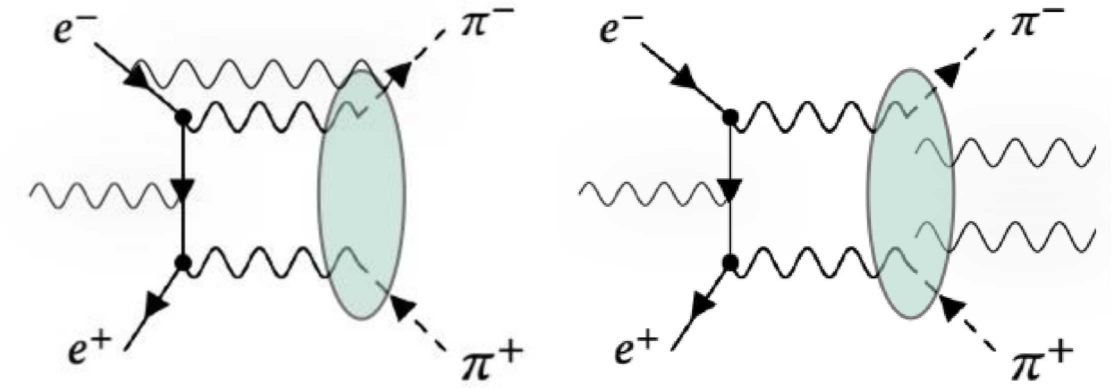
Our new computing strategy/plans

The analysis was heavily slowed down due to computing issues in the INFN-LNF laboratories. With careful recovery procedures, data was available again in Summer 2025. We have developed plans for long-term backups of KLOE files and analysis code, e.g.:

- Porting the KLOE code on Linux machines (INFN-CNAF), where we now plan to finish the analysis after comparisons of results on IBM vs Linux. Monte Carlo code ported to Linux as well.
- Codes maintained on GitLab repository
- Streamlined the procedure to run reconstruction jobs for root-tuples: the analysis has resumed, with gradual transition to Linux

Theoretical work

- In parallel with the analysis work, our collaborators on the theory side have been working to improve the current MC generators
- Building on work published in the RadioMonteCarLow2 report [2024, R. Aliberti et al]
- Towards Phokhara NNLO: incorporate GVMD; ongoing work on 2-loop scattering amplitudes that build full NNLO predictions



See latest updates at the muon biweekly: https://indico.ph.liv.ac.uk/event/2183/

Summary

- The KLOE-nxt workflow has been defined, with the analysis being carried out in a blinded fashion and mostly led by Liverpool
- The goal is a threefold reduction of the statistical uncertainty and twofold reduction of systematic uncertainty w.r.t. KLOE12, in order to reach $\sim 0.4\%$ on $a_\mu^{HLO-2\pi}$
- Much work was also required on the computing side to recover and preserve data in INFN
- Combined experimental efforts with theory collaborators to develop NNLO Monte Carlo generator → A rich analysis program!

THANK YOU FOR YOUR ATTENTION!

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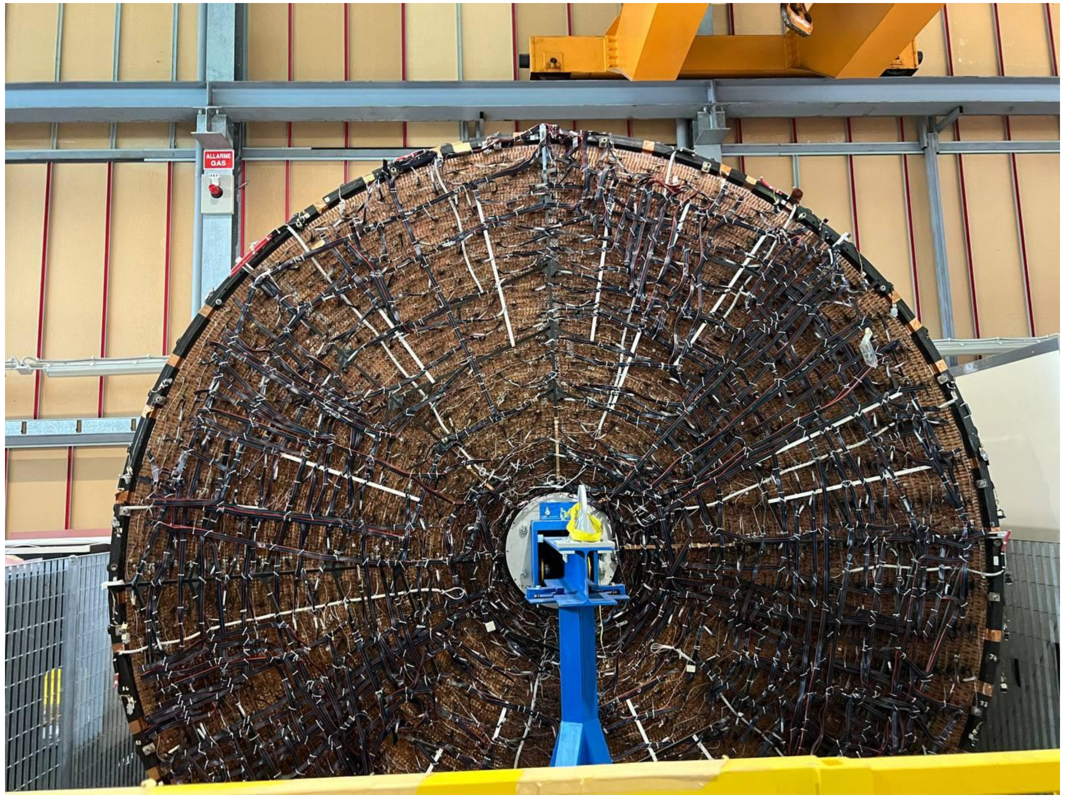
BACKUP

KLOE detectors: drift chamber



Full stereo cylinder (3.3m long, 2m radius) surrounding beam pipe hole of 25cm in radius

Chamber filled with 90% helium, 10% isobutane

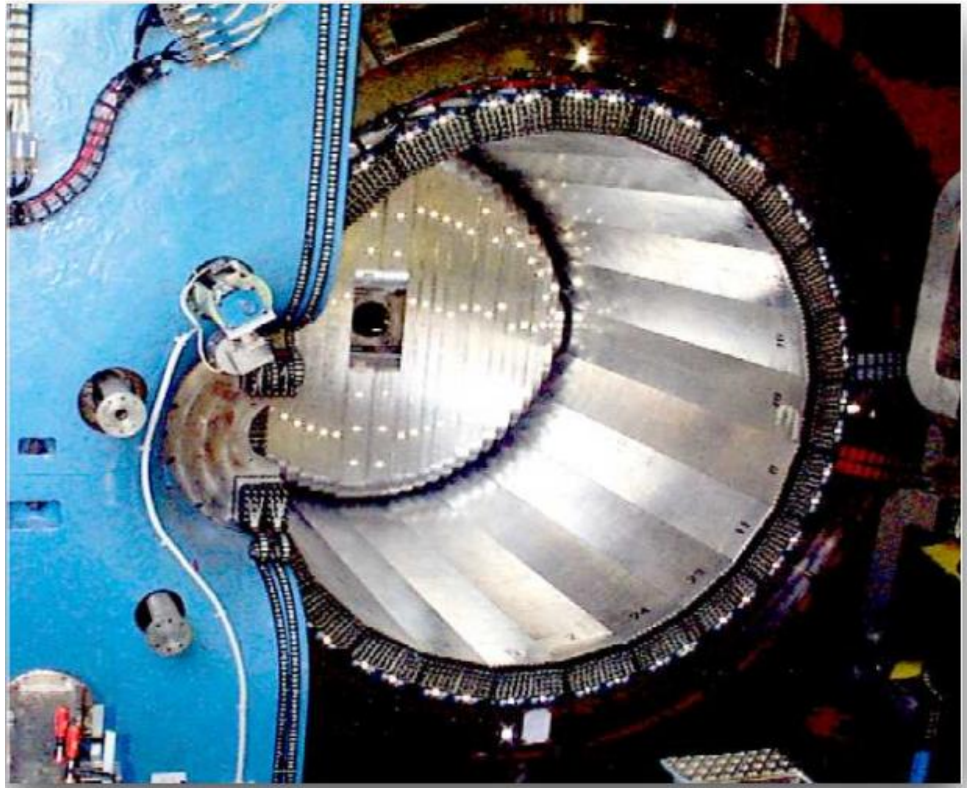
52’140 wires organized in different layers: in each layer, wires are parallel; wires of different layers have different stereo angle → good σ_z

Described in 2002 Paper

Excellent momentum resolution:

$$\sigma_p/p_T = 0.4\%, \sigma_{r\phi} = 150\mu\text{m}, \sigma_z = 2\text{mm}$$

KLOE detectors: EM calorimeter



98% solid angle coverage: 24 modules form the barrel, 32 modules form the end-cap

Sampling calorimeter with lead passive layers and scintillating fibers, read out by light guides into PMTs

5 layers of calorimeter modules organized in $4.4 \times 4.4 \mathrm{cm}^2$ areas

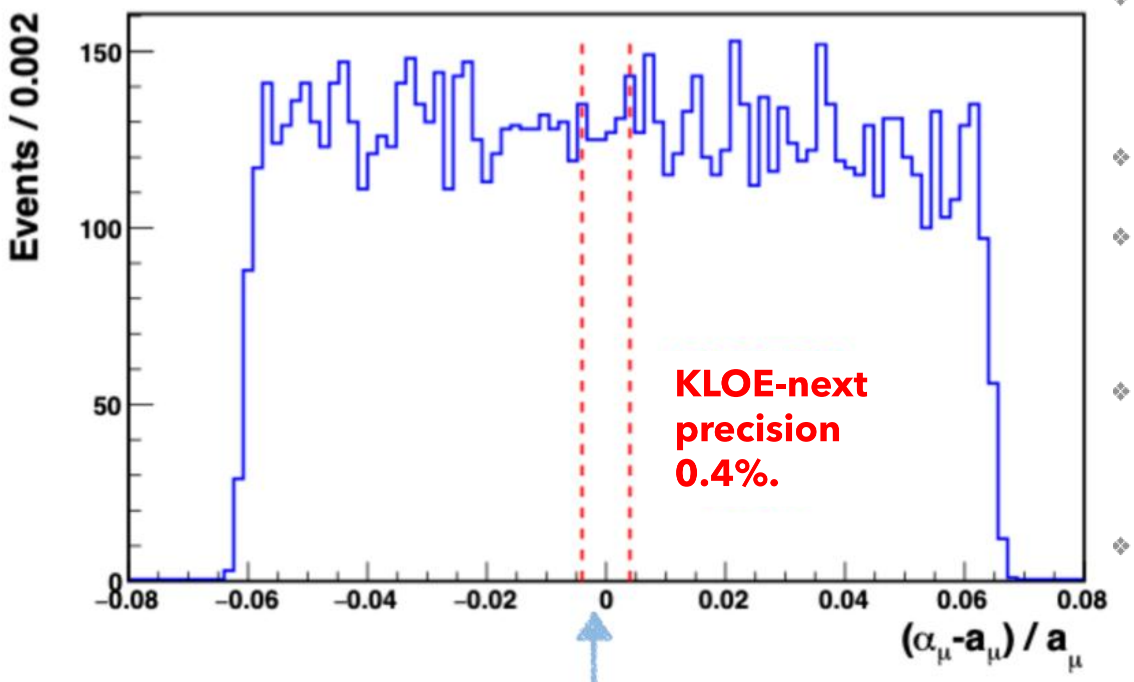
Detect photons in the energy range [20, 500] MeV

Described in 2002 Paper

Excellent time resolution:

$$\sigma_t[\mathrm{ps}] = 54/\sqrt{E[\mathrm{GeV}]} \oplus 140,\ \ \sigma_E/E = 5.7\%/\sqrt{E[\mathrm{GeV}]}$$

A BLINDED ANALYSIS

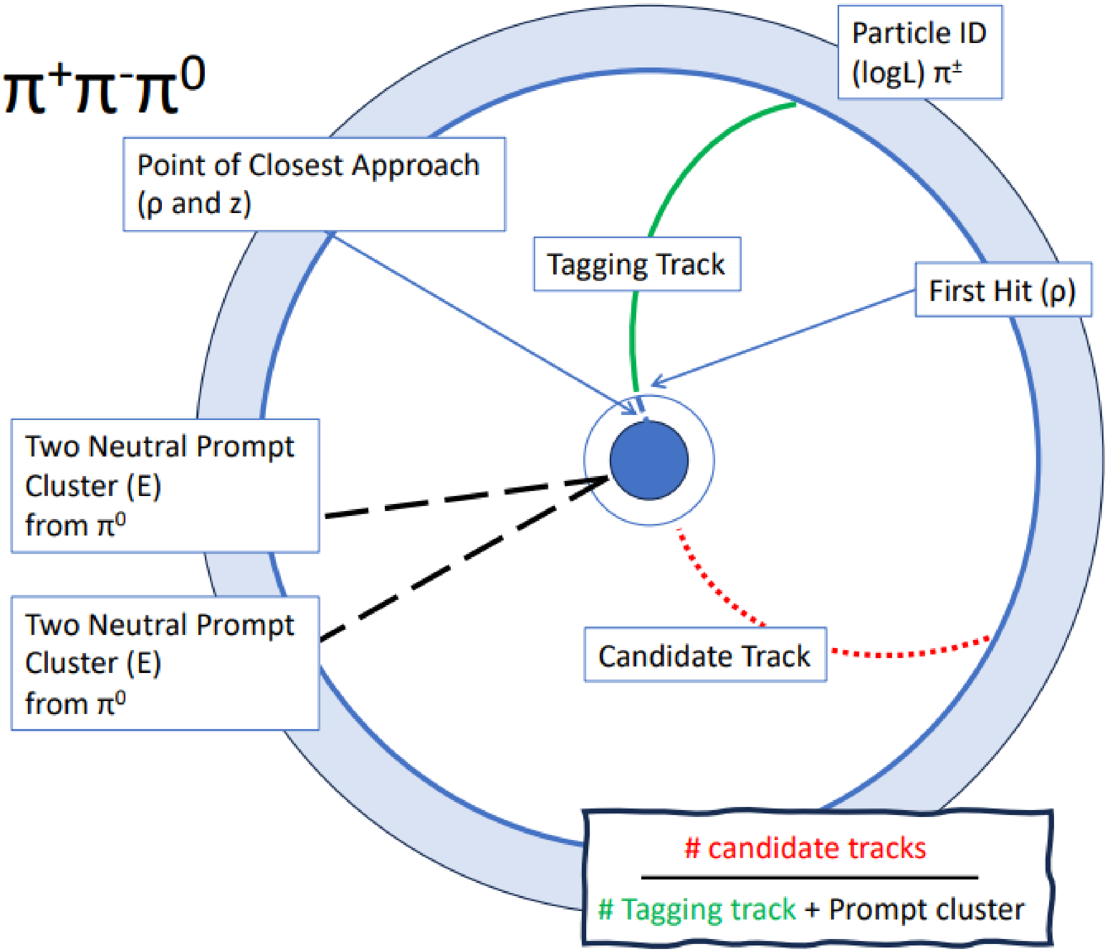


Blinded value of a_μ is $\pm 6\%$ with respect to true value in simulations. Blinded offset is much larger than KLOE-next precision

Blinding procedure has been documented and undergone an internal review process.

- 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.**

Tracking efficiency



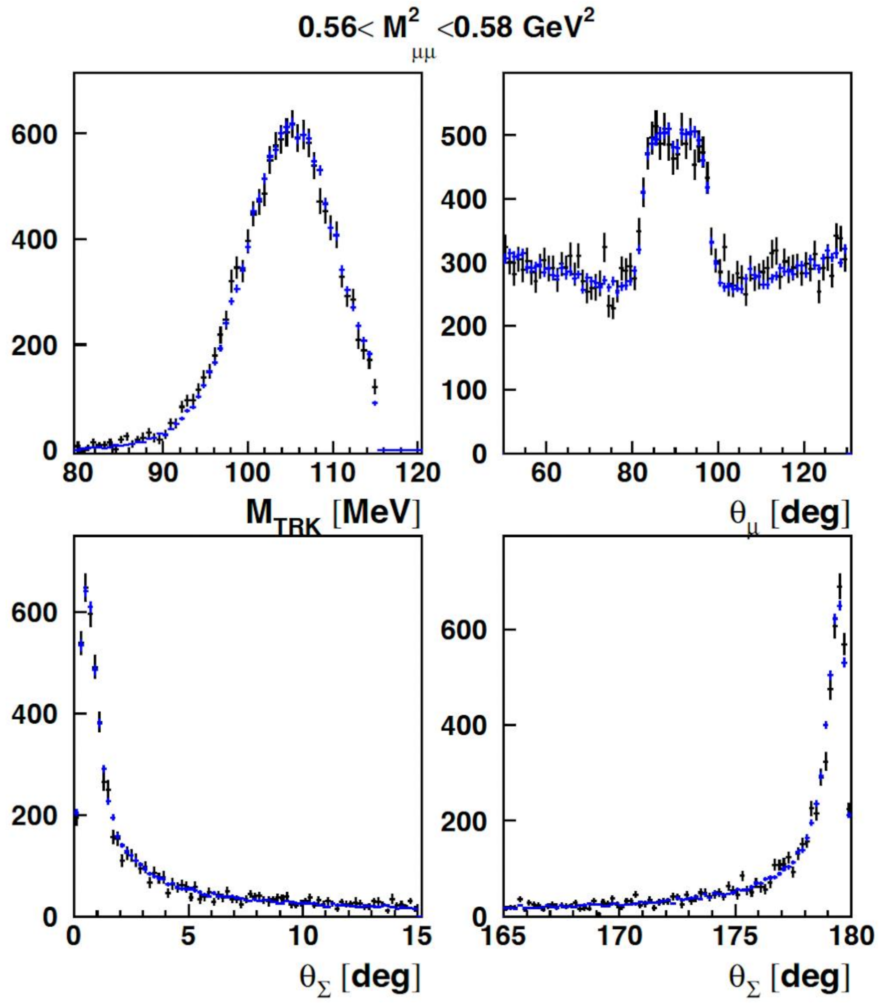
Goals:

- Extract tracking efficiency (MC and data)
- Study different samples which cover different momentum ranges: $\pi^+\pi^-\pi^0, \pi^+\pi^-, \pi^+\pi^-\gamma$

Work so far:

- Reproduce old selection and results
- UFO DSTs for Data; 3pi MC samples to compare with

Data/MC tuning



Goals:

- Determine how well Data and MC agree on various distributions
- Investigate and understand any discrepancies
- Comprehensively improve MC simulation

Work so far:

- On STENTU and PROD2NTU $\pi^+\pi^-\pi^0$ samples
- Positive and negative particles studied separately

Background subtraction overview

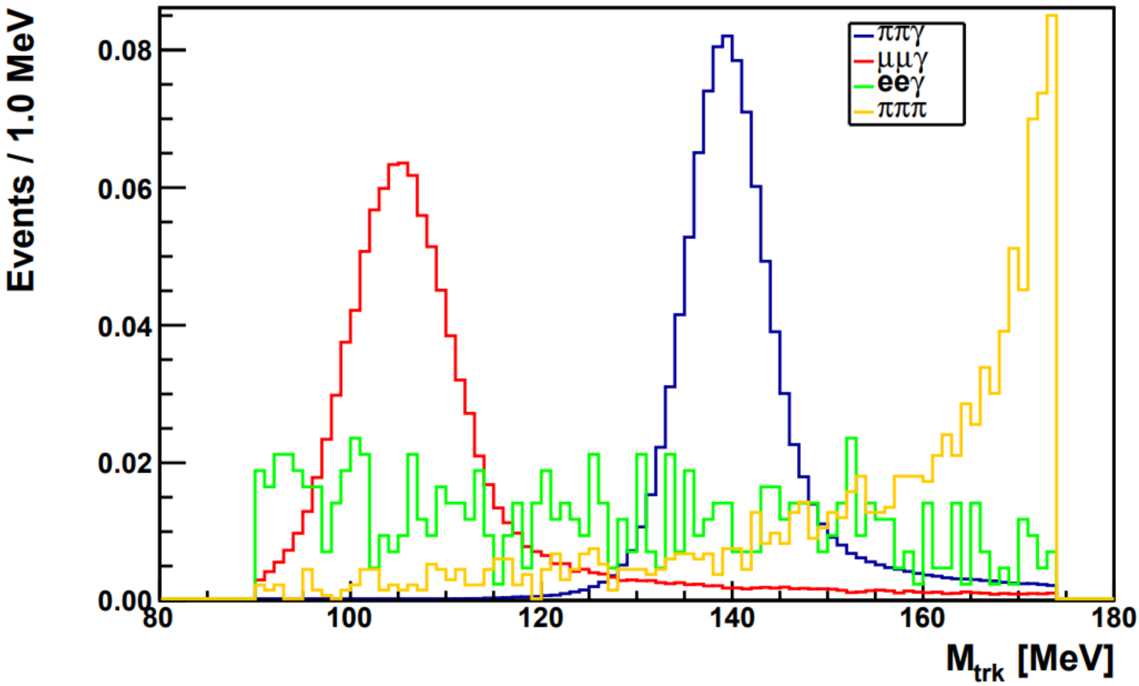
Current subtraction procedure described in [Lorenzo Punzi's Master's Thesis]

Goals:

- Select signal $\pi^+\pi^-\gamma$, suppress background sources: $\pi^+\pi^-\pi^0$, $e^+e^-\gamma$, $\mu^+\mu^-\gamma$
- Apply selection cuts on M_{trk}
- Estimate fraction of surviving background events and subtract it

For each slice i of Q^2:

- Estimate f_B^i (see how in the next slide)
- $f_B^i = f_{\mu\mu\gamma}^i + f_{ee\gamma}^i + f_{\pi\pi\pi}^i$
- Scale number of data events by $\left(1 - f_B^i\right)$

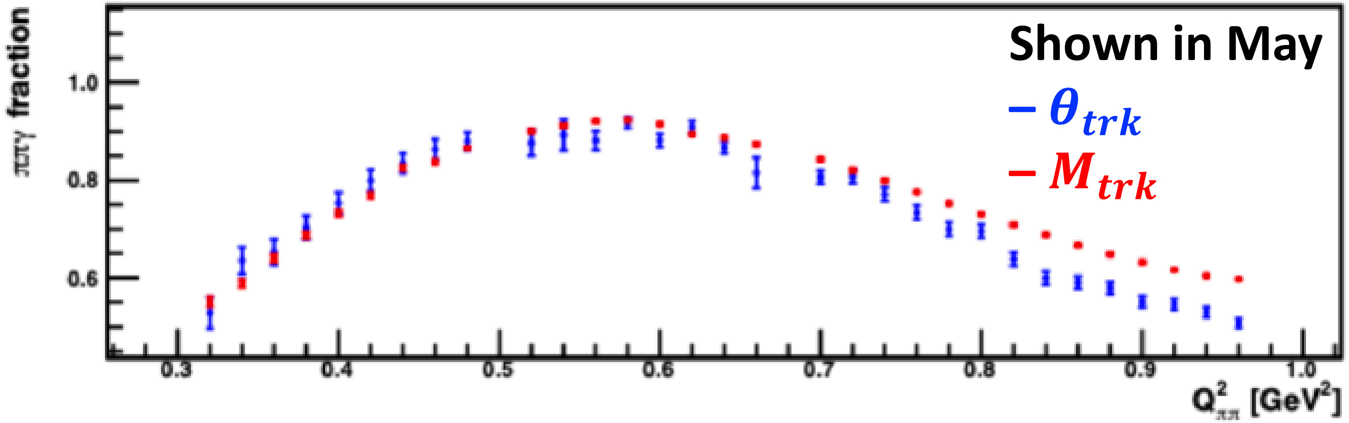


Background subtraction: strategies

How to estimate f_B^i:

1. Choose a variable, e.g. M_{trk} (as in previous analyses)
2. Fit the data distribution of M_{trk} to a weighted sum of MC samples
3. Binned maximum likelihood fit, on the full M_{trk} range, yield fractions of each source of background in data

Procedure should be independent on chosen variable, but we observed inconsistency when choosing θ_{trk} (polar angle of charged track). Investigations on hold until we progress with tuning



We're pursuing other avenues, e.g. BDT for π/μ discrimination