

Updates from the KLOE $e^+e^- \rightarrow \pi^+\pi^-\gamma$ analysis

Lorenzo Cotrozzi (University of Liverpool)

on behalf of the KLOE 2π HVP group

8th g-2 Theory Initiative workshop | 08/09/2025 | Orsay



LEVERHULME
TRUST _____

Outline

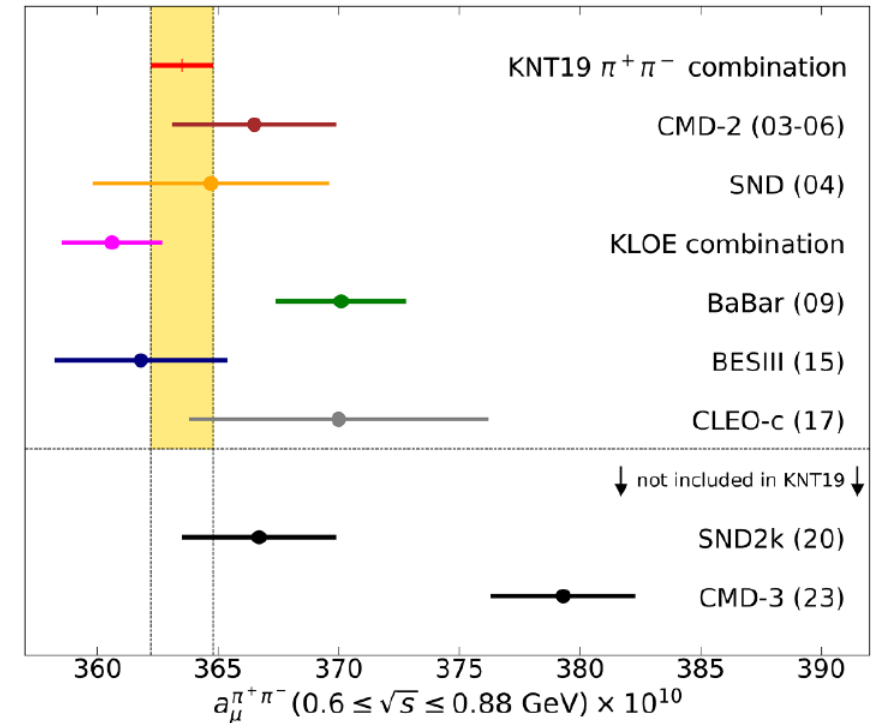
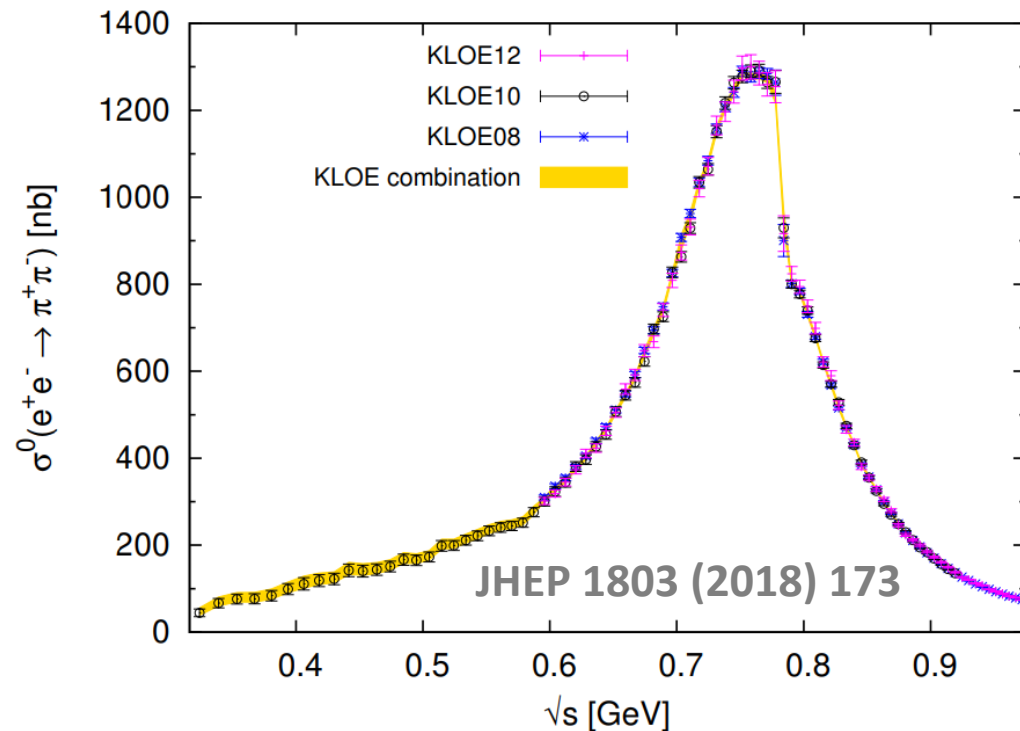
- Overview of the KLOE-nxt analysis
- Major computing downtime last year
- New computing plans and strategies
- Investigations on radiative corrections (WP25)
- Theoretical efforts: Phokhara NNLO



KLOE 2π HVP analysis

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

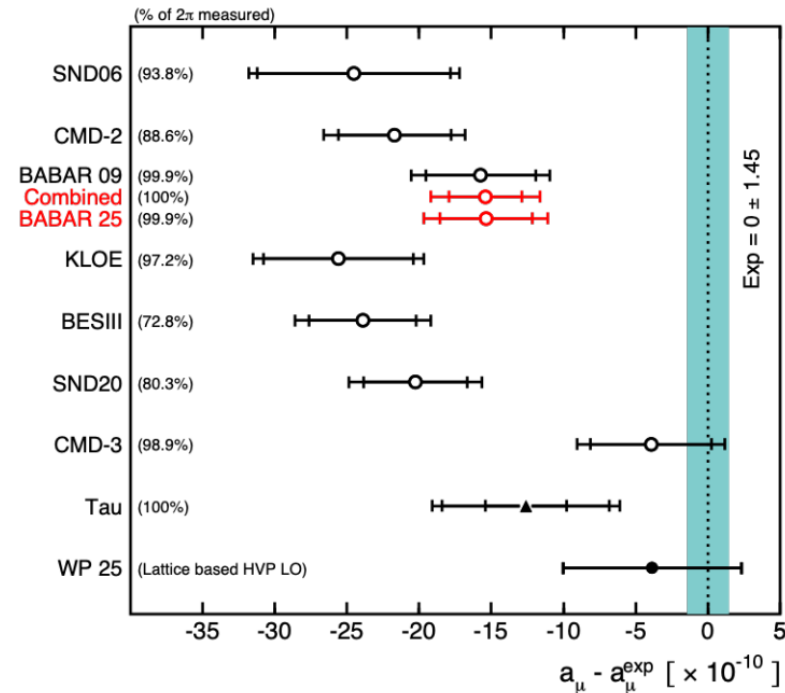
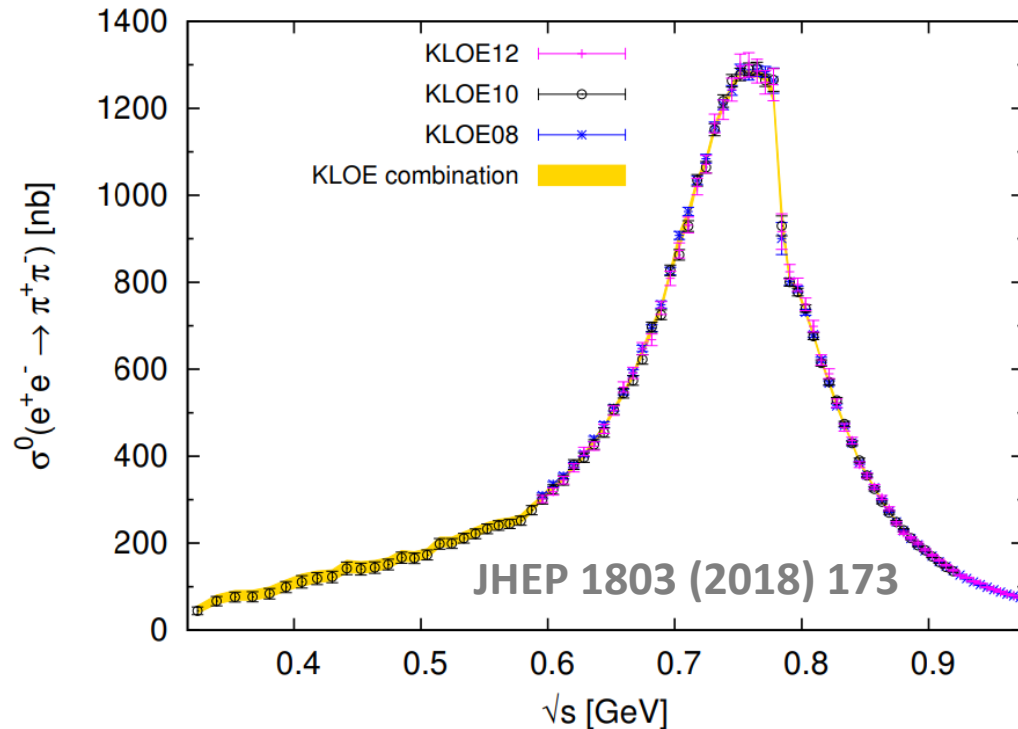
- Experimental input from $\pi^+\pi^-$ channel contributes as $\sim 75\%$
- Long-standing tension (2.8σ) between KLOE and BaBar; recent CMD-3 in tension with both (5.1σ and 2.3σ resp.)
- KLOE operated at $\sqrt{s} = 1020$ MeV using method of ISR return



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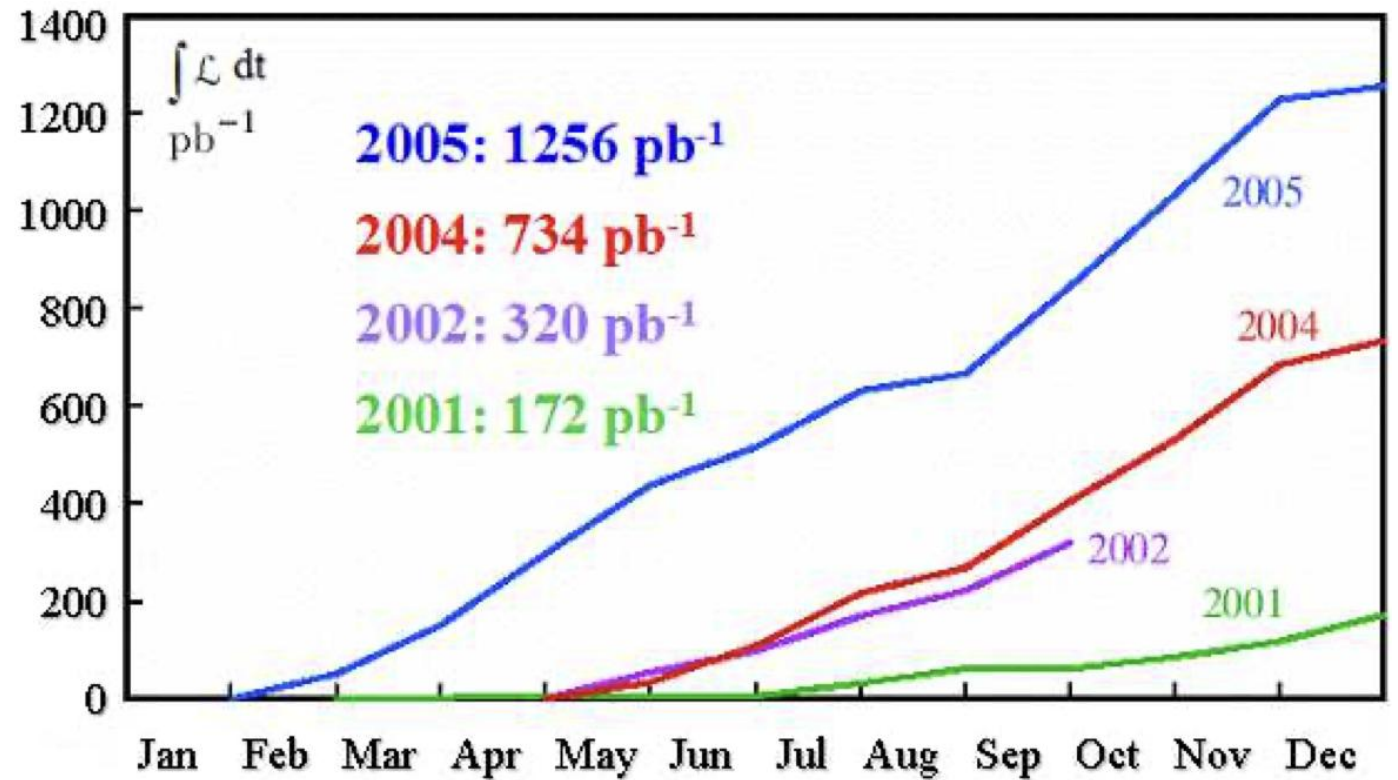
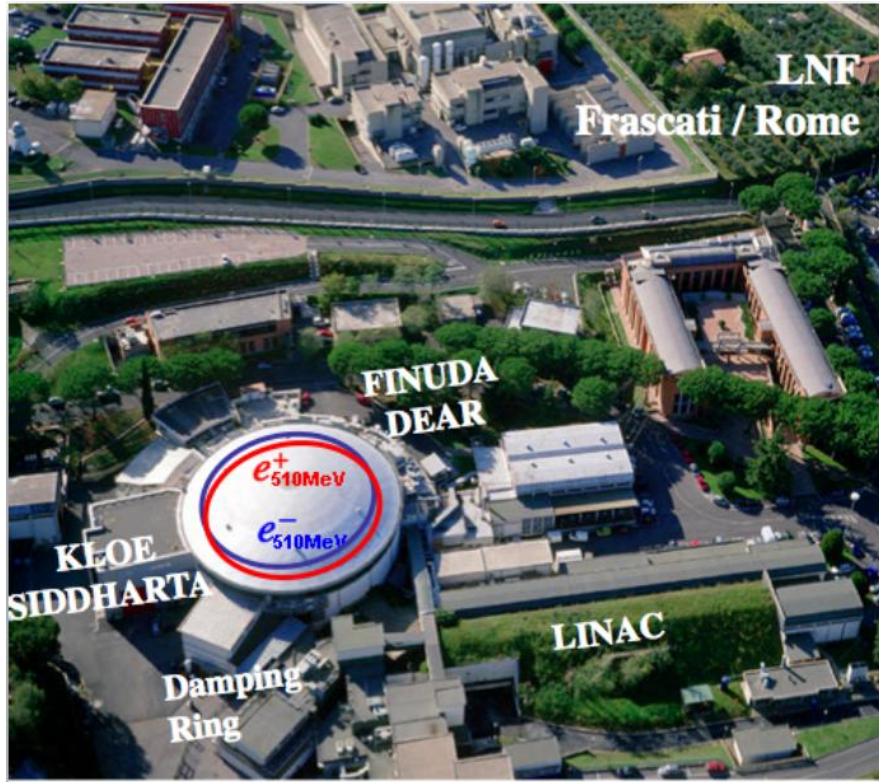


New: BABAR result presented at Lepton Photon 2025 ([talk](#), [review](#))

Also see earlier talk by A. Pinto



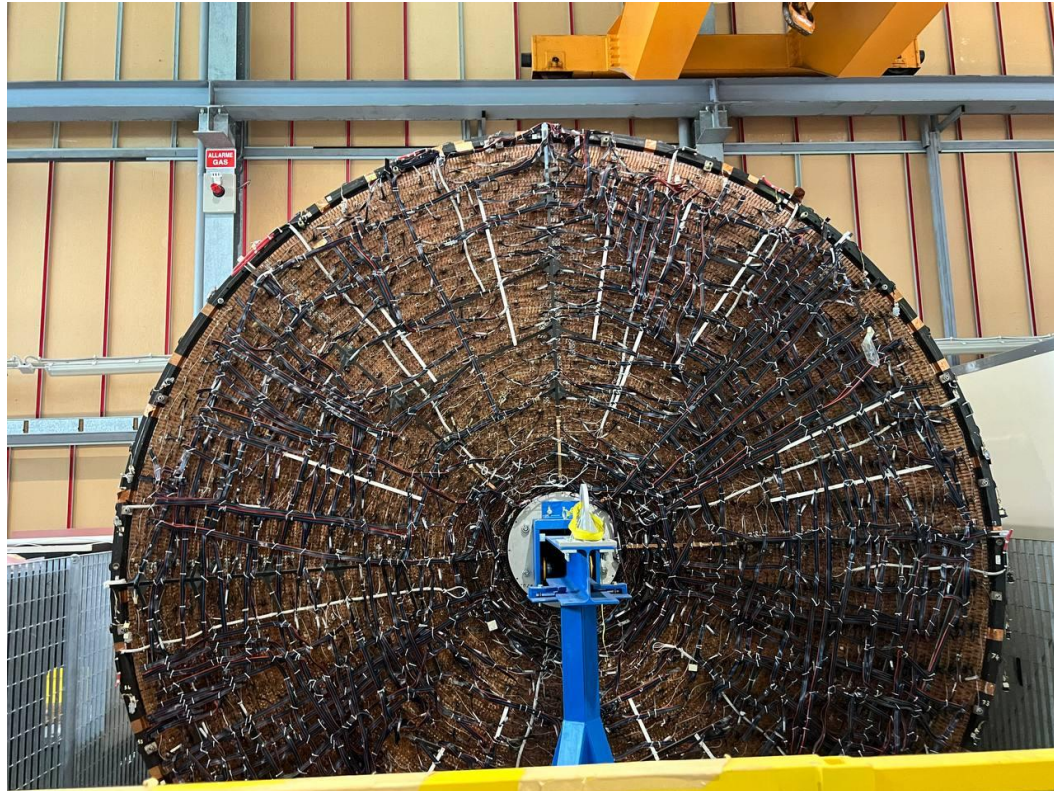
KLOE data campaign



- Total of 2.4 fb^{-1} collected from 2001 to 2006: mostly on ϕ peak ($\sim 1020 \text{ MeV}$), 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: 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 \rightarrow 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

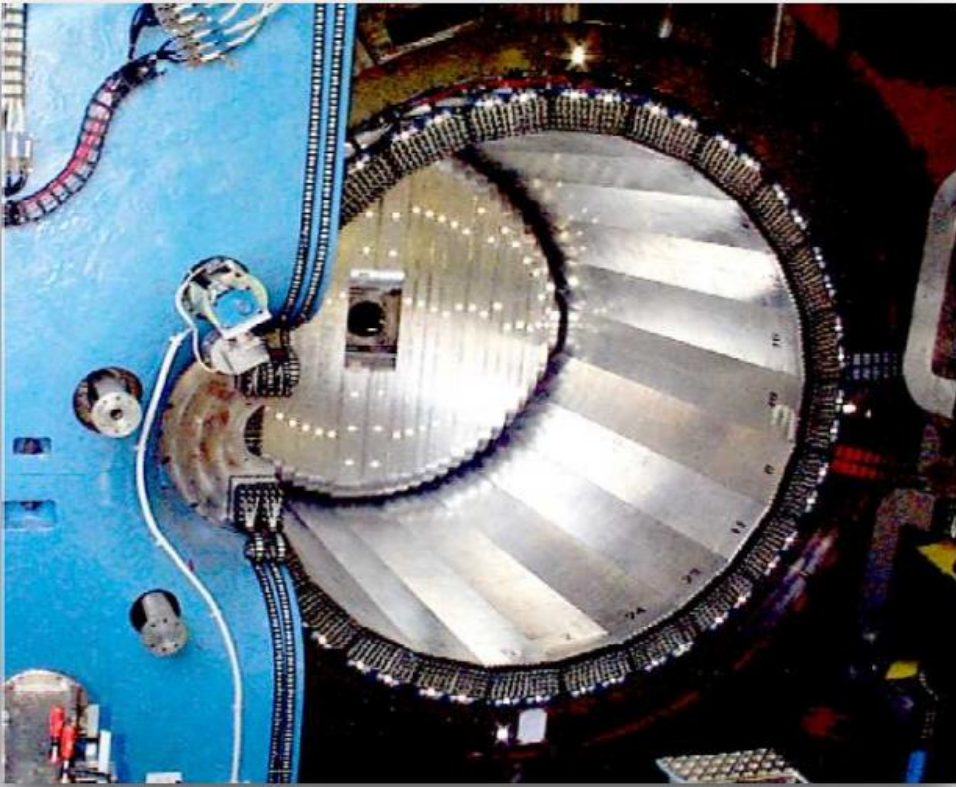
98% solid angle coverage: 24 modules form the barrel,
32 modules form the end-cap

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

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

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

Described in [2002 Paper](#)



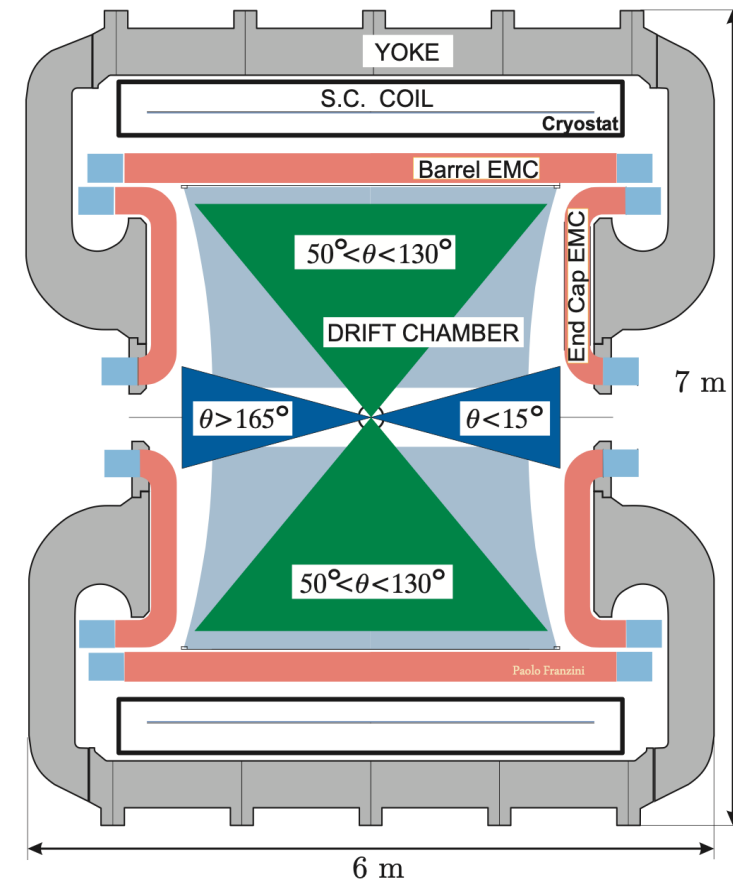
Excellent time resolution:

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



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:
 $\theta_\gamma < 15^\circ$ or $\theta_\gamma > 165^\circ$
- 2 pions (muons) at large angle:
 $50^\circ < \theta_{\pi,\mu} < 130^\circ$
- 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

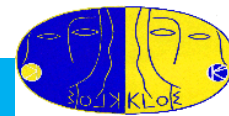
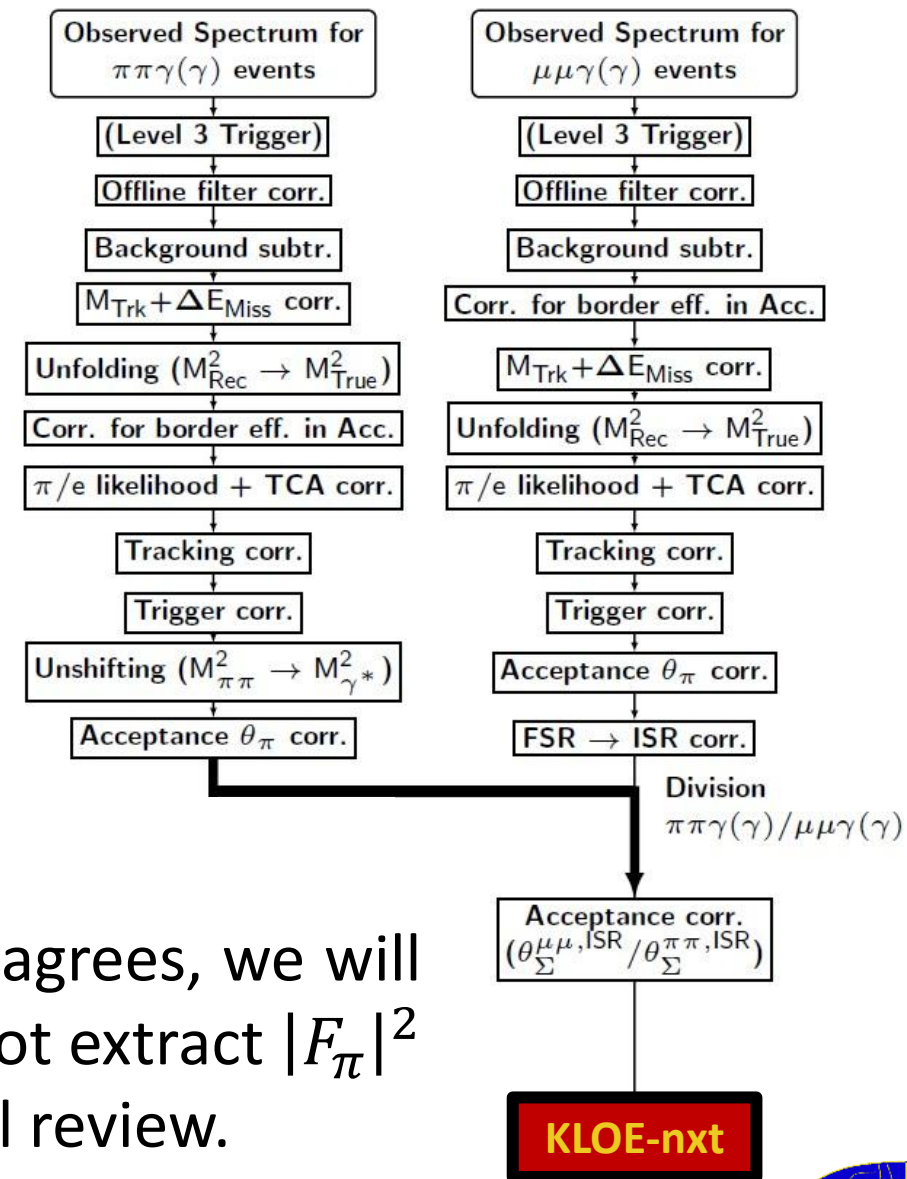
Details on previous and current analyses presented by Estifa'a Zaid at the last T.I. workshop ([slides](#))

New procedure since KLOE12: **Blinding**

Blinding method:

- From each Q^2 bin, remove small fraction of events unknown to analyzers
- Fixed Q^2 distributions not affected; the integral, instead, is blinded. $|F_\pi|^2$ not accessible.
- We also have «working root-tuples», not blinded, to extract efficiencies

Upon completion of the analysis, if the whole group agrees, we will unblind. A level of honesty is assumed: we agree to not extract $|F_\pi|^2$ beforehand. The procedure has gone through internal review.



KLOE-nxt roadmap

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

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

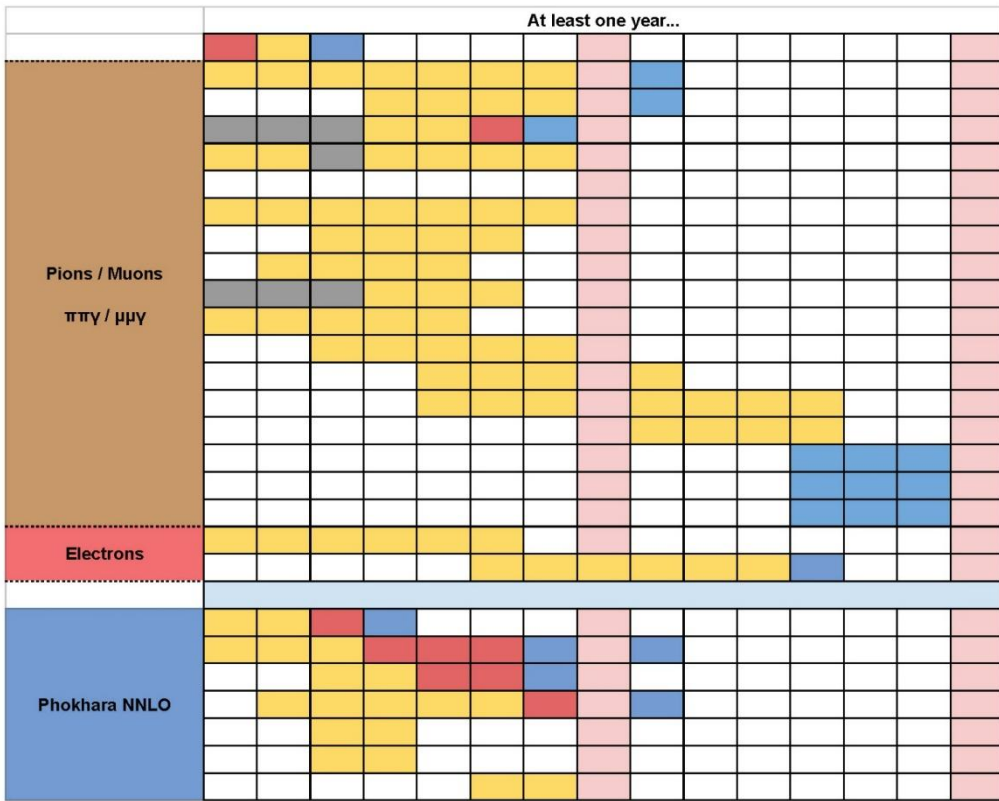
□ Background subtraction was the dominant systematic in KLOE12:
goal to improve it by a factor of x3

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



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- KLOE12: $0.3\%_{stat} \oplus 0.2\%_{th} \oplus 0.7\%_{syst} = \sim 0.8\%_{total}$
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Computing issues 2024/2025

- The analysis was heavily slowed down due to computing issues in the INFN-LNF laboratories. We spent great part of the year recovering access to KLOE 2004/5/6 data and elaborating a new strategy for backup and analysis → porting to Linux (see next slide).
- We needed to restore access to two partitions of the IBM tape library, DB2 database, and other machines/subsystems
- Careful but steady recovery of tapes: currently saving DSTs and raw files on data disks and transferring to INFN-CNAF tapes/disks. More interventions are still needed to restore 100% of the data.



Our new computing strategy/plans

While recovering access to data, we worked on the following:

- Plans for long-term backups of KLOE files and analysis code
- We are in the process of 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

We can now run reconstruction jobs again to produce root-tuples: the analysis has resumed, with gradual transition to Linux



Impact of missing RC on KLOE analyses

For WP25 we provided updated plots since last year's presentation from Graziano ([slides](#)), to investigate the impact of missing NNLO in Phokhara, as questioned by BaBar.

[DHLMZ 2024](#)

Details of the study:

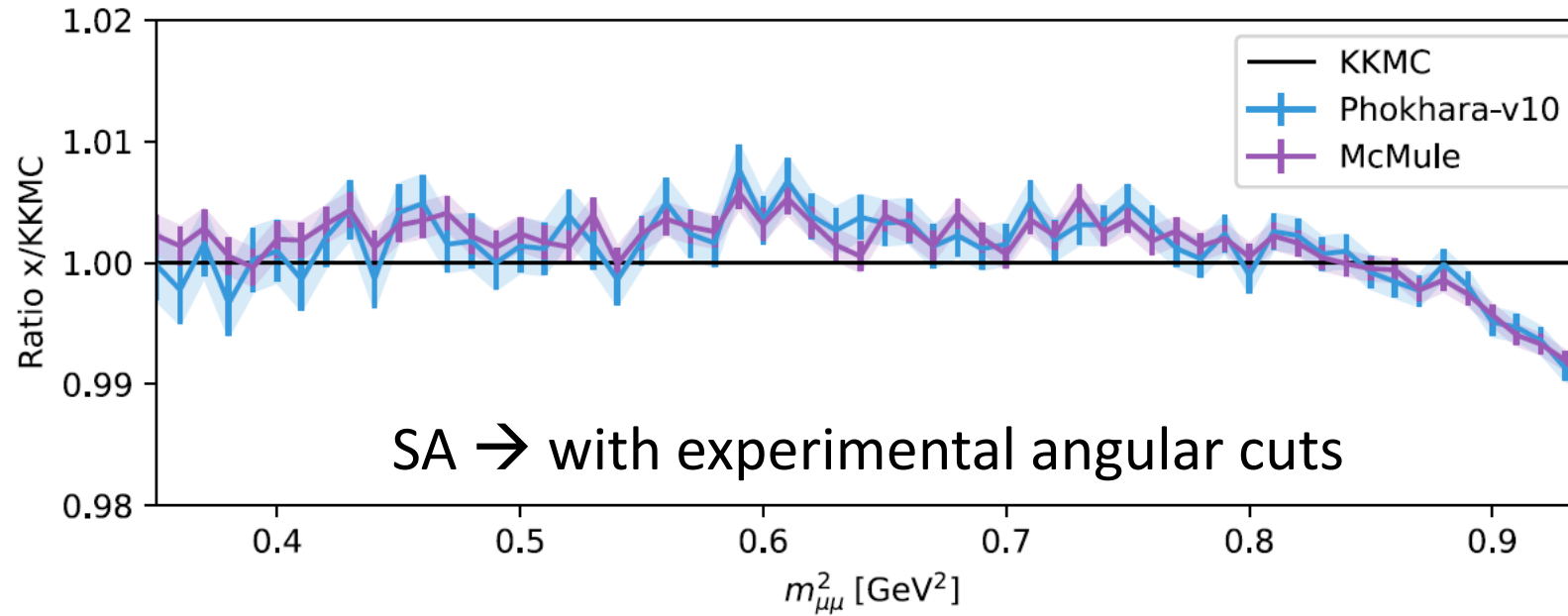
- Tested the effect of radiative corrections (RCs) in tuned comparisons between available MC generators w.r.t. Phokhara v10 @NLO.
- Tested different selection cuts, where RCs have different impacts: small angle (SA) acceptance (undetected photons); large angle (LA) acceptance (detected photons) with or without additional trackmass cut m_{trk}
- $\mu\mu\gamma(\gamma)$ with ISR+FSR; $\pi\pi\gamma(\gamma)$ in ISR only due to limitations of other generators

Caveat:

To isolate ISR and FSR RC effects: VP was switched off; detector effects (like smearing of momenta) were not included. So far, only Phokhara has been interfaced with detector simulation in GEANT, so this will be a next step.



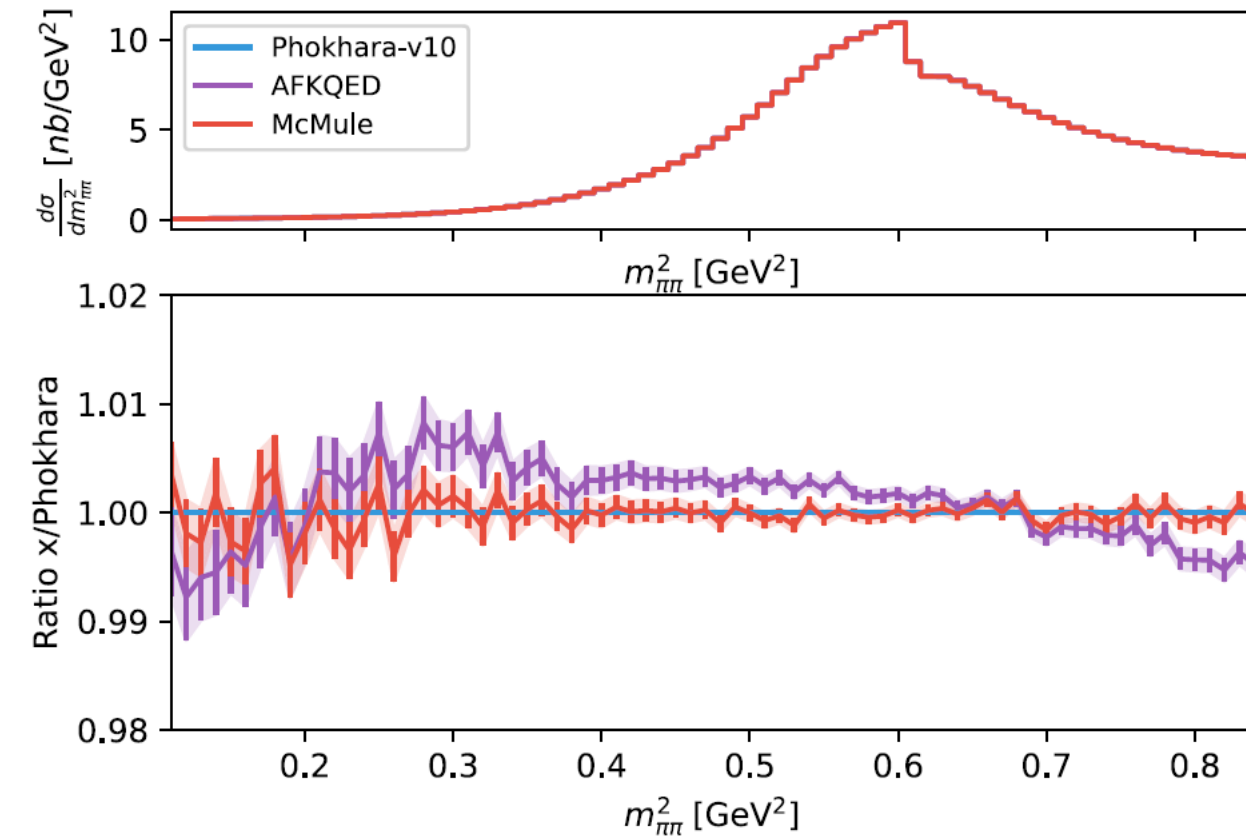
$\mu\mu\gamma$ SA scenario: ISR+FSR



- Agreement between Phokhara and McMule; differences below 0.5% between Phokhara and KKMC for most of the spectrum
- No trackmass cut yet (can be sensitive to RC): it will be done in future studies
- Due to missing exponentiation, differences reach few % in the inclusive case (before SA selection), but the effect is negligible for a_μ^{HLO}



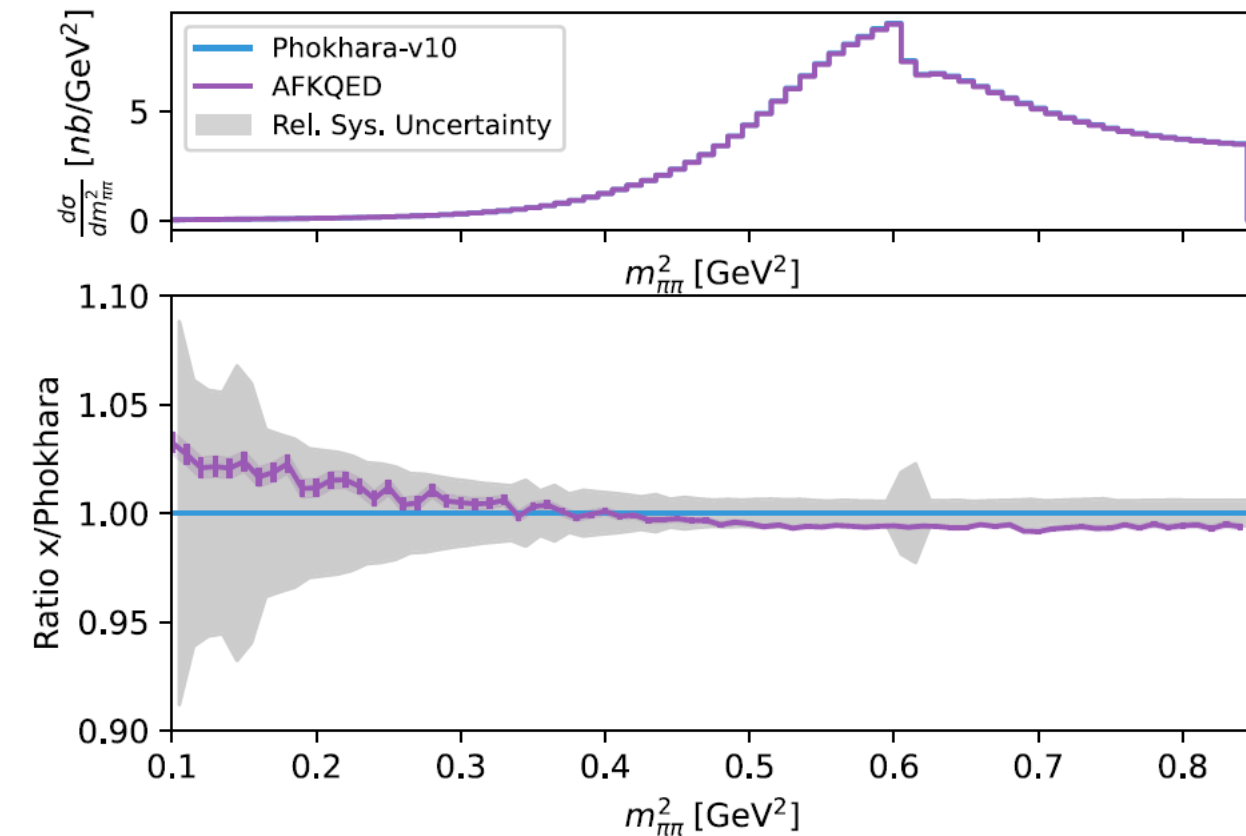
$\pi\pi\gamma$ LA scenario: ISR only



- Excellent agreement between Phokhara and McMule \rightarrow Confirmation of correct implementation of NLO matrix elements
- Around the ρ peak, agreement better than 0.5%



$\pi\pi\gamma$ LA scenario and m_{trk} cut: ISR only



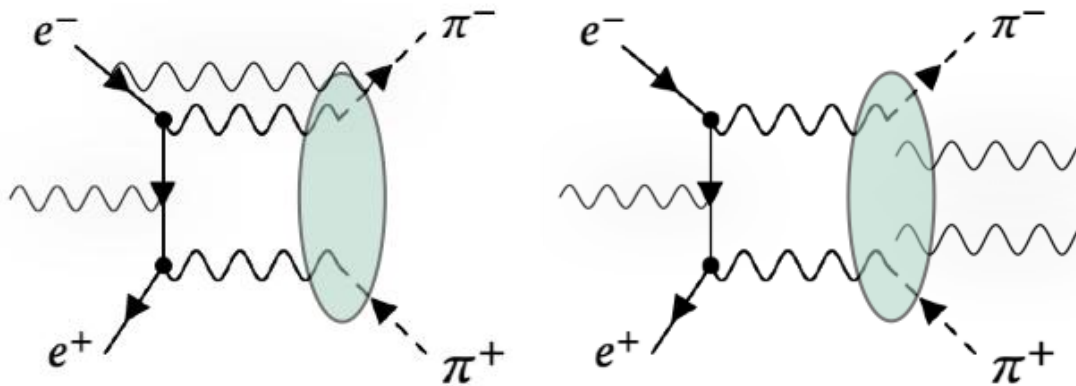
- m_{trk} is sensitive to (N)NLO effects
- Around the ρ peak, agreement of $\sim 1\%$
- Below 0.4 GeV^2 , effects due to different treatment of RCs
- Relative systematic uncertainties taken from KLOE10 analysis. Phokhara-AfkQed differences are within this band, but there is a clear need for improvement to NNLO MC

KLOE-nxt will however be (at least initially) SA



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 talk by Pau at this workshop tomorrow and [paper on arXiv](#)

See EPS contributions by [Pau](#) and [Jérémy](#)



Summary

- ❑ The KLOE-nxt workflow has been defined, with the analysis being carried out in a blinded fashion
- ❑ 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 $a_{\mu}^{HLO-2\pi}$
- ❑ Because of computing issues (not yet fully solved), our analysis has been on hold for more than a year while we fleshed out the plan
- ❑ Improved statistics of studies on RC effects impacting old analyses
- ❑ Combined experimental efforts with theory collaborators to develop NNLO Monte Carlo generator → A rich analysis program!



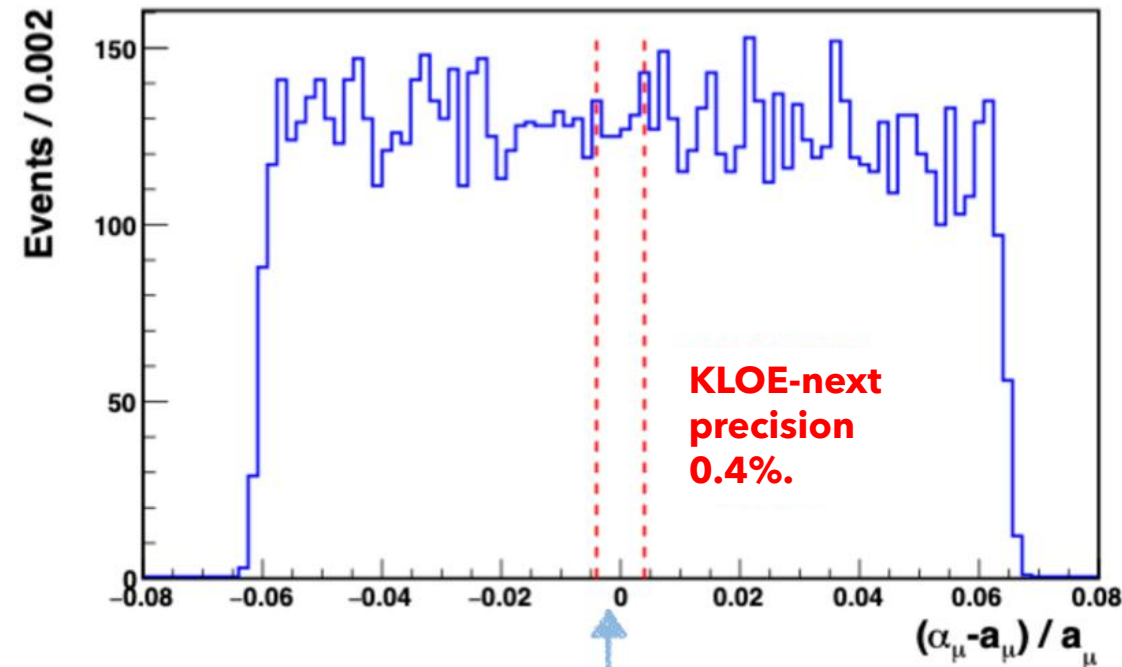
THANK YOU FOR YOUR ATTENTION!



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BACKUP

A BLINDED ANALYSIS



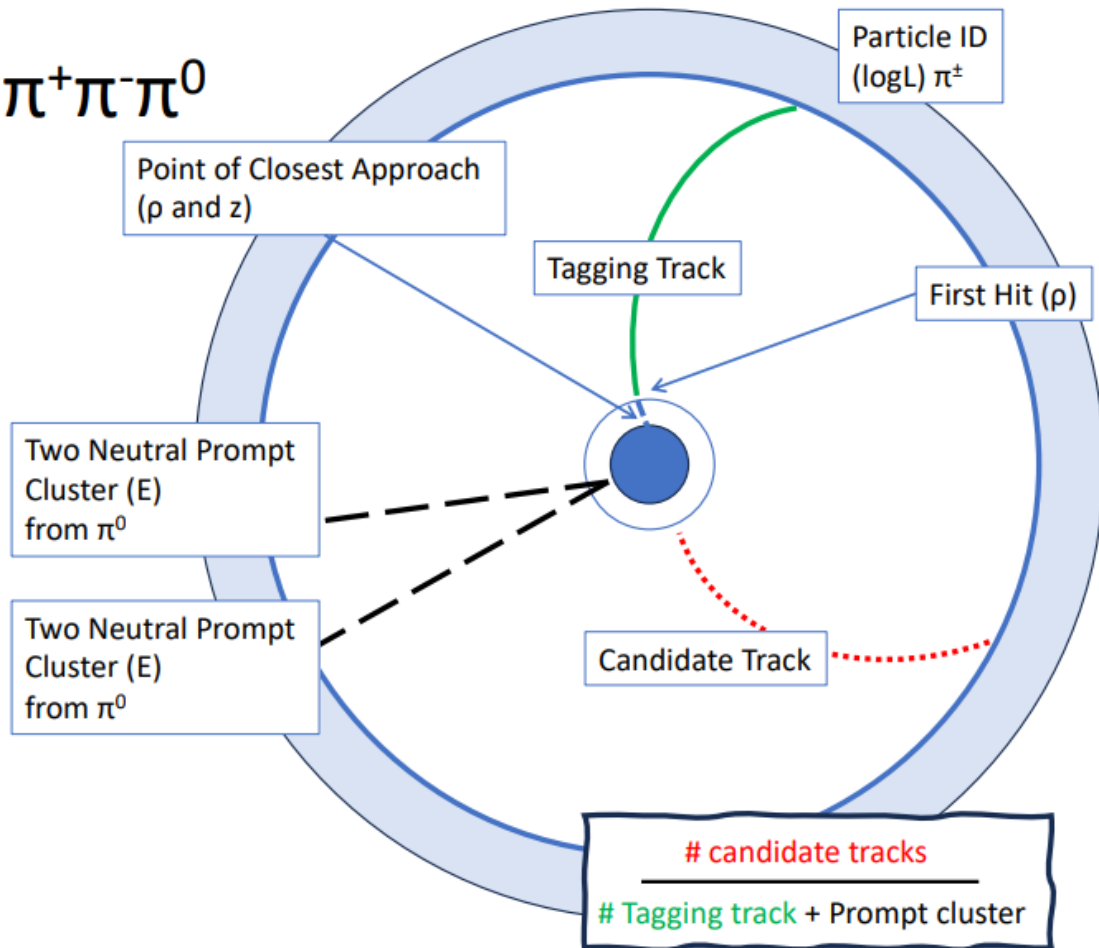
Blinded value of a_μ is $\pm 6\%$ with respect to true value in simulations. Blinded offset is much larger than KLOE-next precision

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 $Q_{\pi\pi}^2$ or $Q_{\mu\mu}^2$ slice in data.
 - ❖ This modifies the measured differential cross section and thus

$$a_{\pi\pi} \propto \int ds \dots \sigma_{\pi\pi}(s) \text{ whilst having no affect on distributions at fixed } Q^2 \text{ bins.}$$
- ❖ 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:

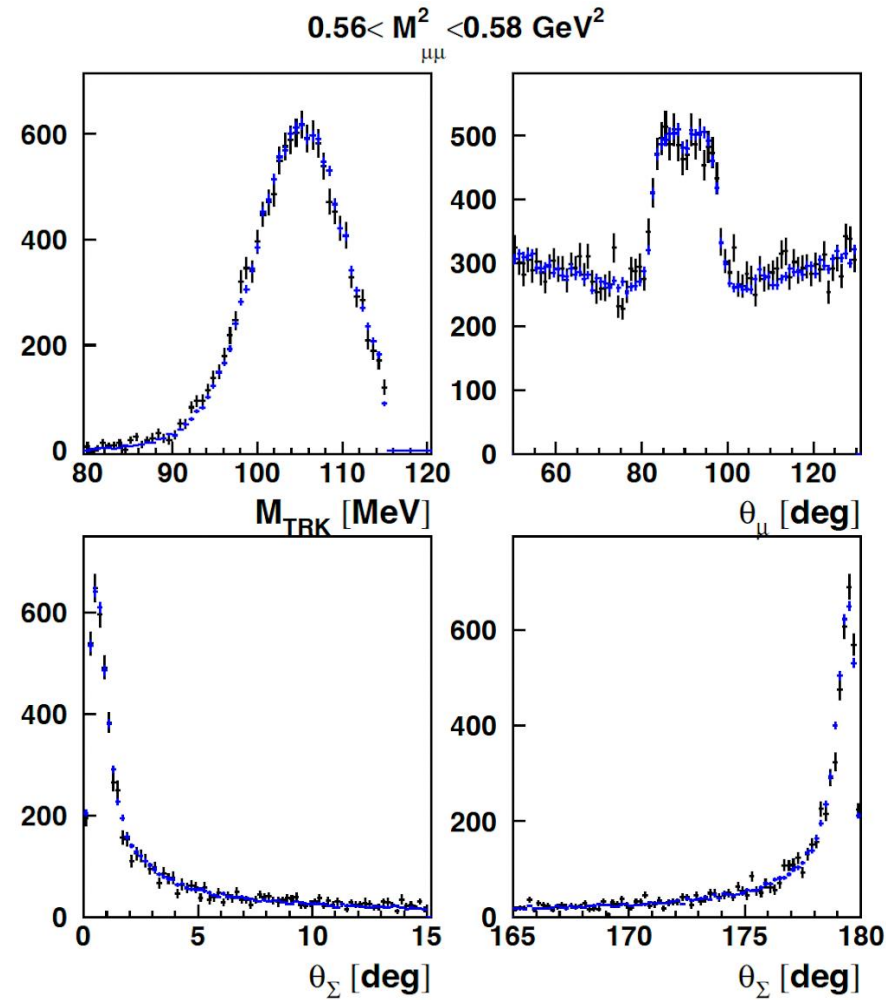
- Extract tracking efficiency (MC and data)
- Study different samples which cover different momentum ranges: $\pi^+\pi^-\pi^0$, $\pi^+\pi^-$, $\pi^+\pi^-\gamma$

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

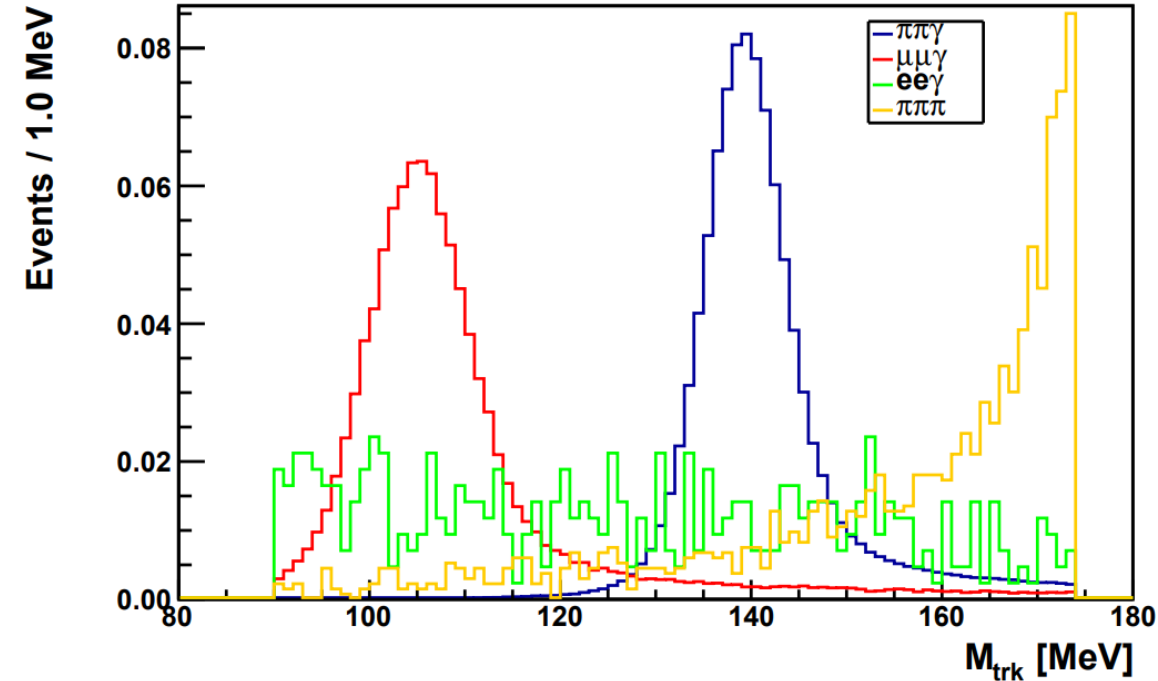
Current subtraction procedure described in [Lorenzo Punzi's Master's Thesis](#)

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 $(1 - f_B^i)$

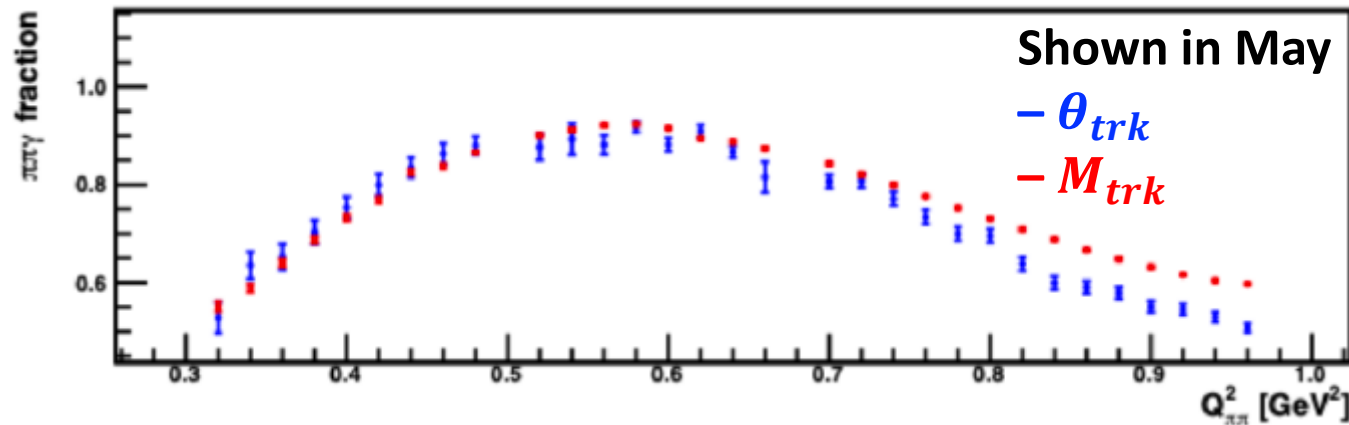


Background subtraction: strategies

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

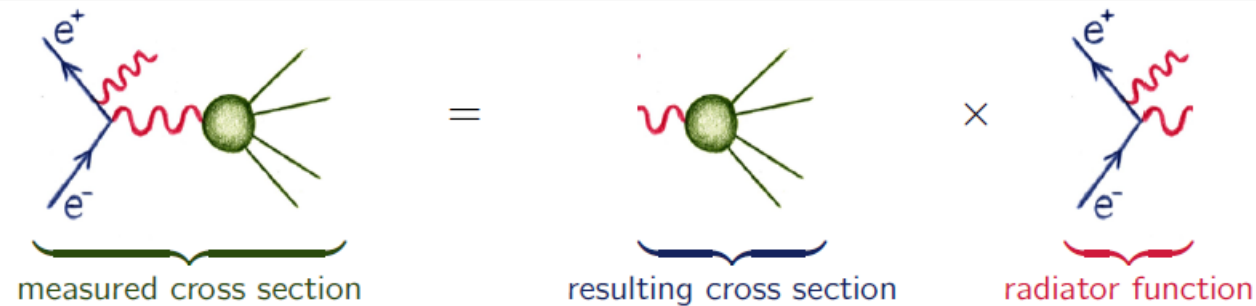


We're pursuing other avenues, e.g. BDT for π/μ discrimination

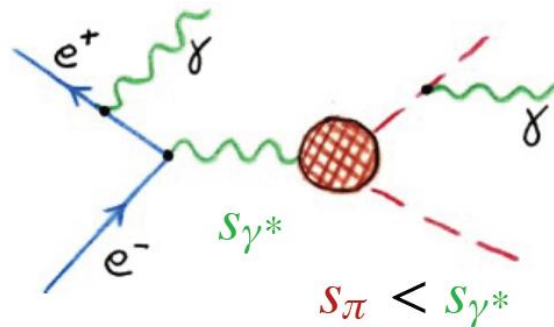


- ISR technique to scan \sqrt{s} : radiator function $H(s, M_{had}^2)$ relates differential cross section $e^+e^- \rightarrow \pi^+\pi^-\gamma$ to $e^+e^- \rightarrow \pi^+\pi^-$

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



- 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):

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

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

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

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

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

