Status of the KLOE new $\pi\pi\gamma$ analysis

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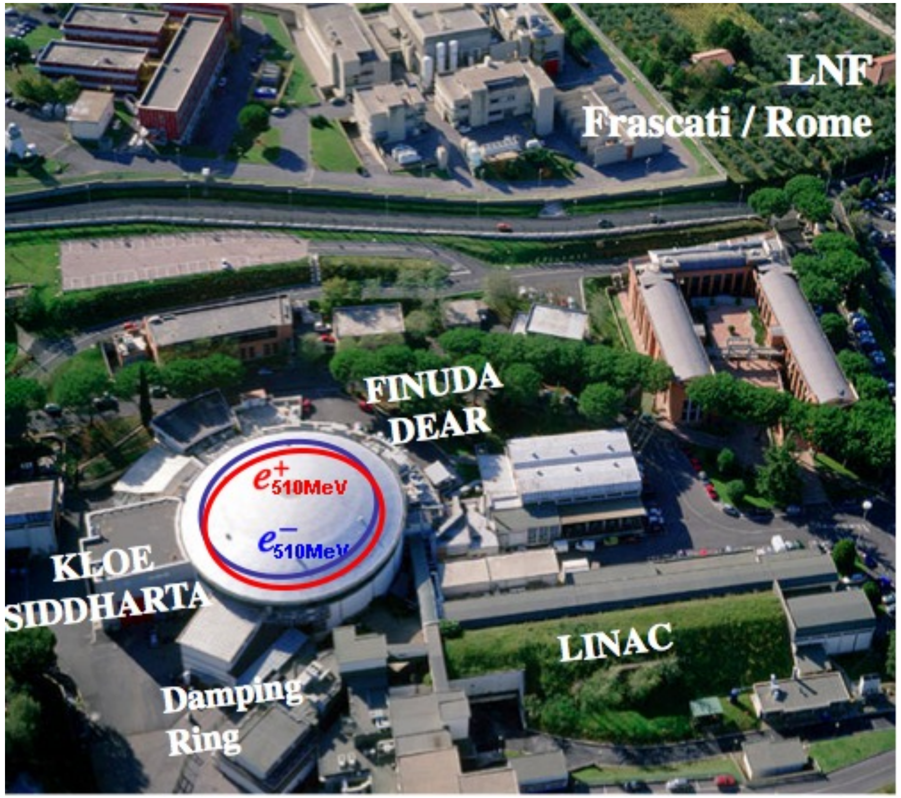
(on behalf of the *ppg group*)

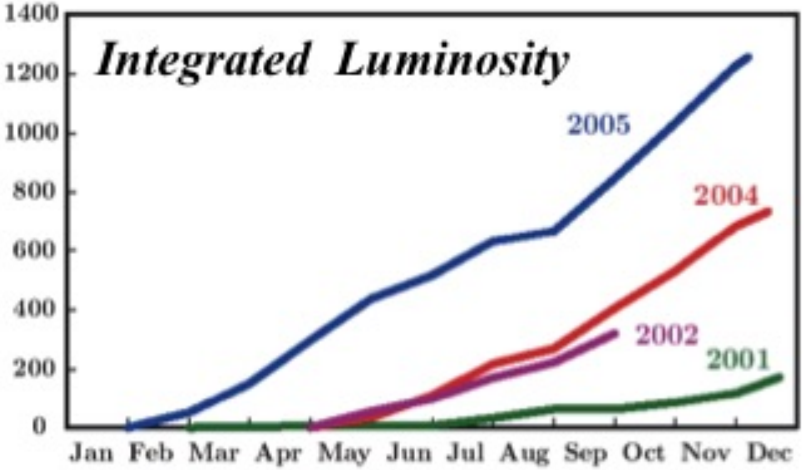
8 November 2023

DAΦNE facility: a ϕ factory



e^+e^- collider @ $\sqrt{s} = m_\phi \simeq$ 1.02 GeV

Peak luminosity L_{peak} = 1.4 × 10^{32} $cm^{-2}s^{-1}$



2005-2006:

⇒ Total KLOE int. lum.: $\int L dt \sim 2.1\ fb^{-1}$

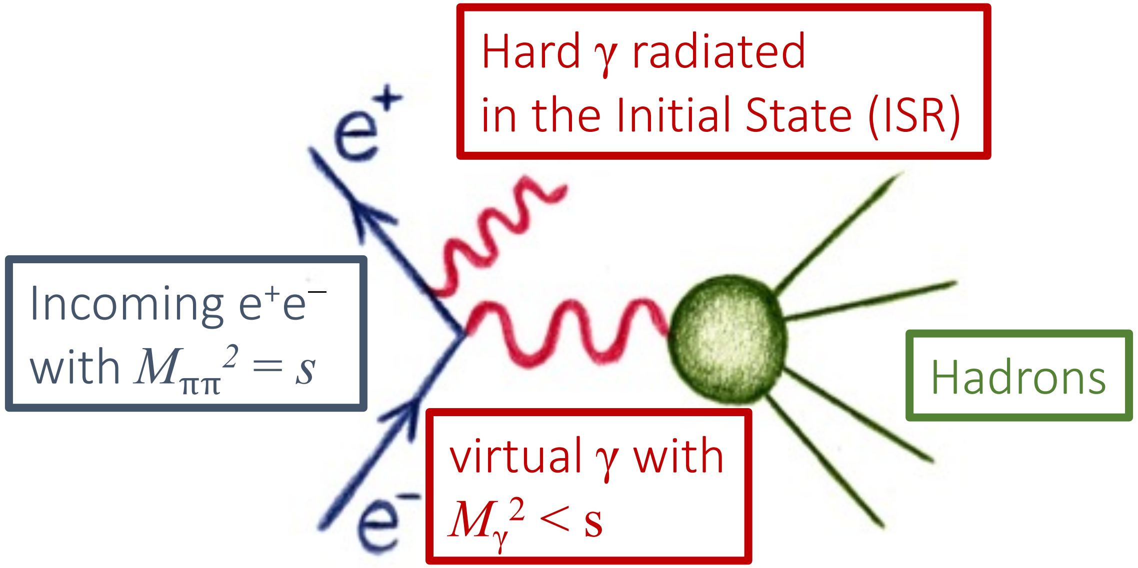
2006:

⇒ Scan 4 points around m_ϕ

⇒ 250 pb^{-1} at $\sqrt{s}$ = 1 GeV

Radiative return method

In the particle factories hadronic cross sections measured as a function of the hadronic *c.m.* energy.
⇒ Radiative return to energies below the collider energy $\sqrt{s}$



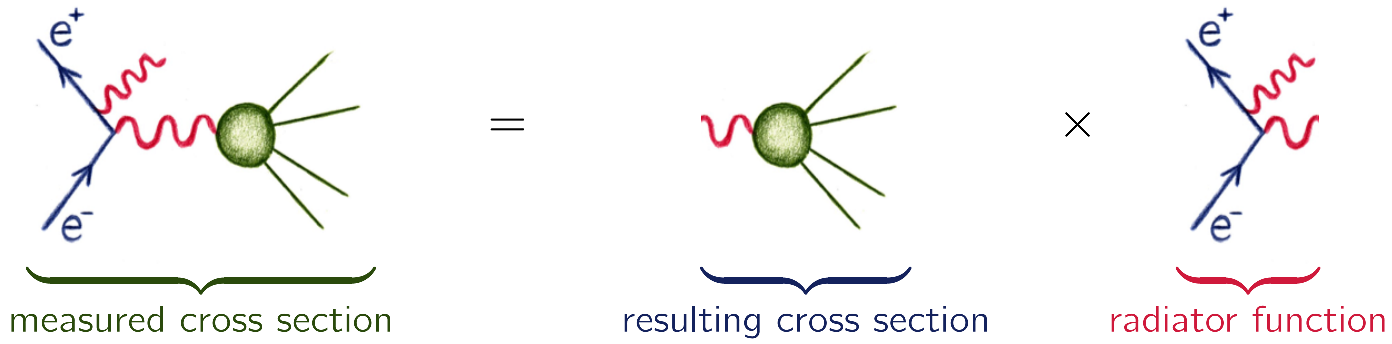
Emission of hard γ in bremsstrahlung process reduces available energy
⇒ hadronic system.

Initial State Radiation

Relate the measured differential cross section $d\sigma_{had+\gamma}/dM_{had}^2$ to hadronic cross section σ_{had}

⇒ radiator function $H(s,M_{had}^2)$

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



Precise estimation of radiator function $H(s,M_{had}^2)$ from PHOKHARA Monte Carlo event generator.

KLOE ISR measurements: normalizations

1) Absolute normalization

Normalize cross section from independent luminosity measurement using Bhabha events:

$$\frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} = \frac{N^{\mathrm{sel}} - N^{bkg}}{\Delta M^2_{\pi\pi}} \cdot \frac{1}{\varepsilon_{sel}} \cdot \frac{1}{\int L dt}$$

Total cross section:

$$\sigma_{\pi\pi}(M^2_{\pi\pi}) = s \cdot \frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} \frac{1}{H(s, M^2_{\pi\pi})}$$

2) Normalization with muons

Normalize $\pi\pi\gamma$ sample in each energy bin with $\mu\mu\gamma$ events:

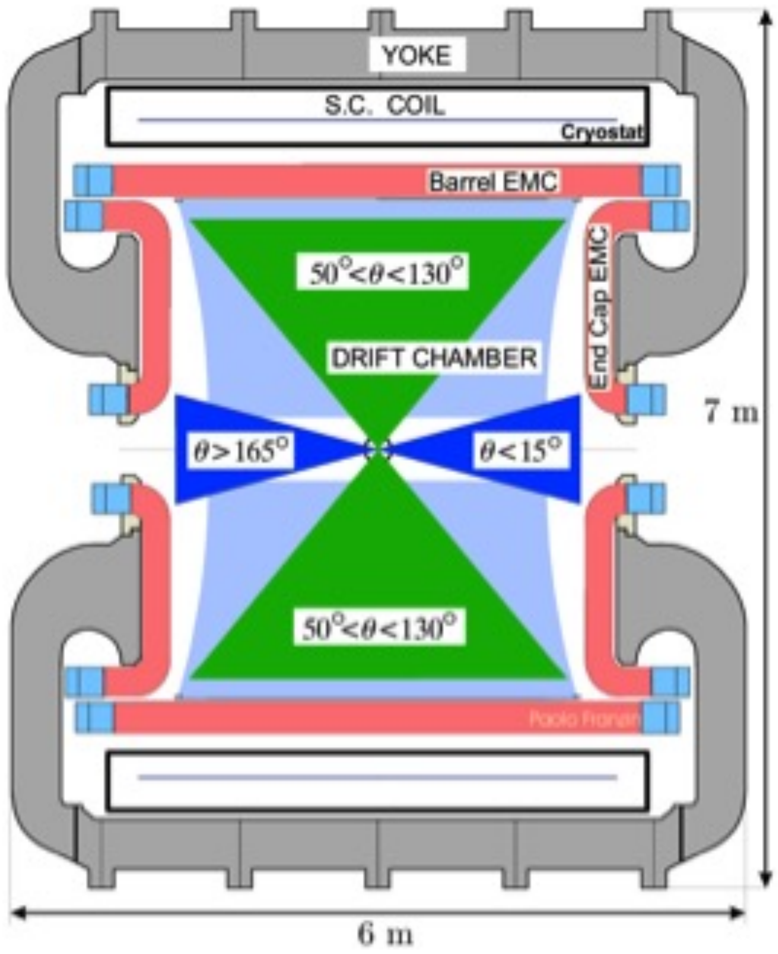
$$|F_{2\pi}(s')|^2 = \frac{4(1+2m^2_\mu/s')\beta_\mu}{\beta^3_\pi} \cdot \frac{(d\sigma_{\pi\pi\gamma}/dM^2_{\pi\pi})}{(d\sigma_{\mu\mu\gamma}/dM^2_{\mu\mu})}$$

The cross section:

$$\sigma_{\pi\pi}(s') = \frac{\pi\alpha^2\beta^3_\pi}{3s'}|F_{2\pi}(s')|^2$$

Removal of systematic effects and radiative corrections

KLOE ISR measurements: Small Angle cuts



2 pion (muon) tracks at large angles $50^o < \theta_{\pi,\mu} < 130^o$

1) Photons at small polar angles

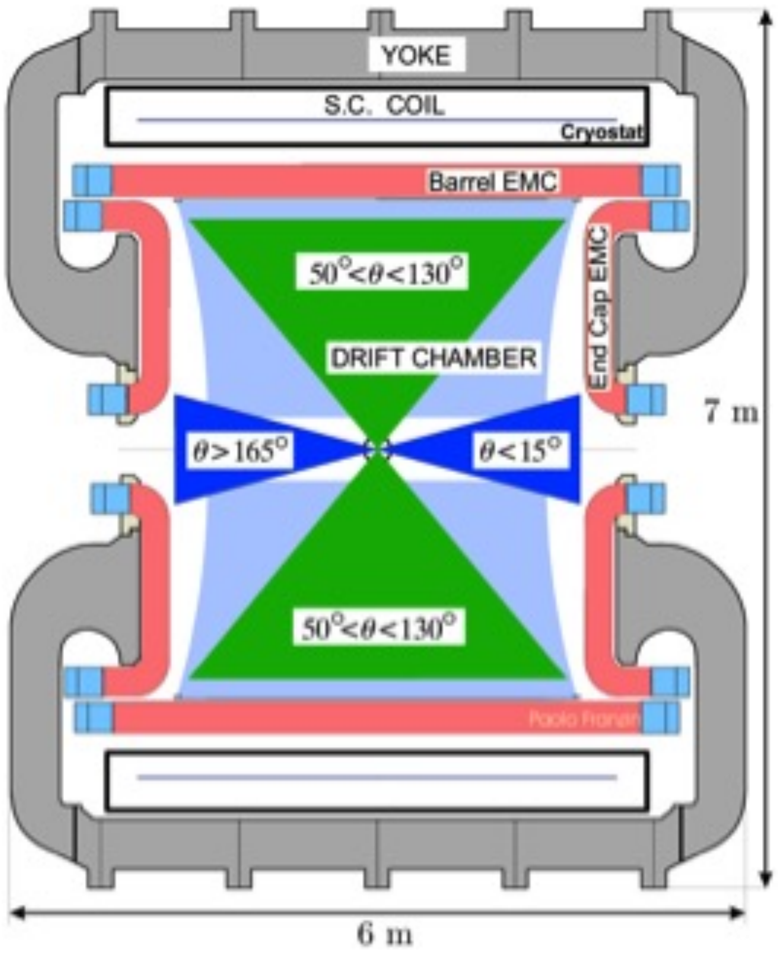
$\theta_{miss} < 15^o$ or $\theta_{miss} > 165^o$

- High statistics for ISR events
- Low Final State Radiation γ contribution
- Suppression of $\phi \to \pi^+\pi^-\pi^0$ background photon
- Photon momentum from kinematics:

$$\vec{p}_\gamma = \vec{p}_{miss} = -(\vec{p}_+ + \vec{p}_-)$$

- Threshold region not accessible

KLOE ISR measurements: Large Angle cuts



2 pion (muon) tracks at large angles $50^o < \theta_{\pi,\mu} < 130^o$

2) Photons at large polar angles

$50^o < \theta_\gamma < 130^o$

- Lower signal statistics
- Higher FSR contribution
- Photon detection possible (4-momentum constraints)
- Threshold region accessible
- More $\phi \to \pi^+\pi^-\pi^0$ background
- Irreducible background from $\phi \to f_0\gamma \to \pi^+\pi^-\gamma$

The KLOE analyses

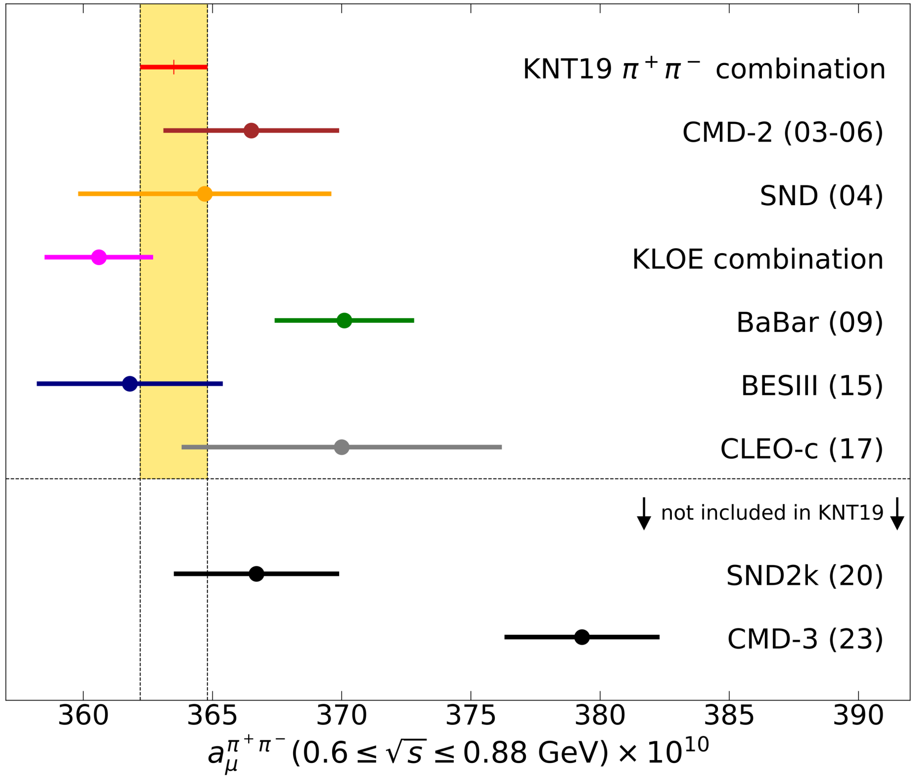
- KLOE08: 60 points between 0.35 and 0.95 GeV^2,
  based on 240.0 pb^{-1} data taken in 2002 (*Phys. Lett. B670 (2009) 285*)
  (small angle photon cuts, normalization to Bhabha and PHOKHARA radiator)

- KLOE10: 75 points between 0.1 and 0.85 GeV^2,
  based on 232.6 pb^{-1} data taken in 2006 with @ 1.00 GeV (*Phys. Lett. B700 (2011) 102*)
  (large angle photon cuts, normalization to Bhabha and PHOKHARA radiator)

- KLOE12: 60 points between 0.35 and 0.95 GeV^2,
  based on 240.0 pb^{-1} data taken in 2002 (*Phys. Lett. B720 (2013) 336*)
  (small angle photon cuts, normalization to $\mu\mu$ events)

Status of $\sigma(e^+e^- \to \pi^+\pi^-)$

Discprepancies in the dominant experimental $a_\mu^{\pi\pi}$ contribution



Long standing tension between KLOE and BaBar ($\simeq$ 2.8σ)

New CMD3 measurement of $a_\mu^{\pi\pi}$ (Feb 2023)
Tension with BaBar ($\simeq$ 2.3σ) and with KLOE ($\simeq$ 5.1σ)

a_μ^{HVP} [No CMD3] = $(684.5 \pm 4.0) \times 10^{-10}$
limited by tensions between KLOE and BaBar
and precision of $\sigma(e^+e^- \to \pi^+\pi^-)$

The status demands for clarification

The uncertainties and the plan

Syst. errors (%)	KLOE08 $\Delta^{\pi\pi}a_\mu$ abs [4]	KLOE12 $\Delta^{\pi\pi}a_\mu$ ratio
Background Filter (FILFO)	negligible	negligible
Background subtraction	0.3	0.6
Trackmass	0.2	0.2
Particle ID	negligible	negligible
Tracking	0.3	0.1
Trigger	0.1	0.1
Unfolding	negligible	negligible
Acceptance ($\theta_{\pi\pi}$)	0.2	negligible
Acceptance (θ_π)	negligible	negligible
Software Trigger (L3)	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
Vacuum Polarization	0.1	-
FSR treatment	0.3	0.2
Rad. function H	0.5	-
Total theory systematics	0.6	0.2
Total systematic error	0.9	0.7

Still ≃ 1.7 fb^{-1} (~25 million $\pi\pi\gamma$ events) from 2004-2005 data

KLOE23 => experimental and theoretical efforts for a new $\pi\pi\gamma$ analysis
- analysing the 1.7 fb^{-1} data
- improved analysis techniques
- blind analysis

KLOE12: $0.3\%_{stat} \oplus 0.2\%_{th} \oplus 0.7\%_{syst}$
$\sim 0.8\%_{tot}$

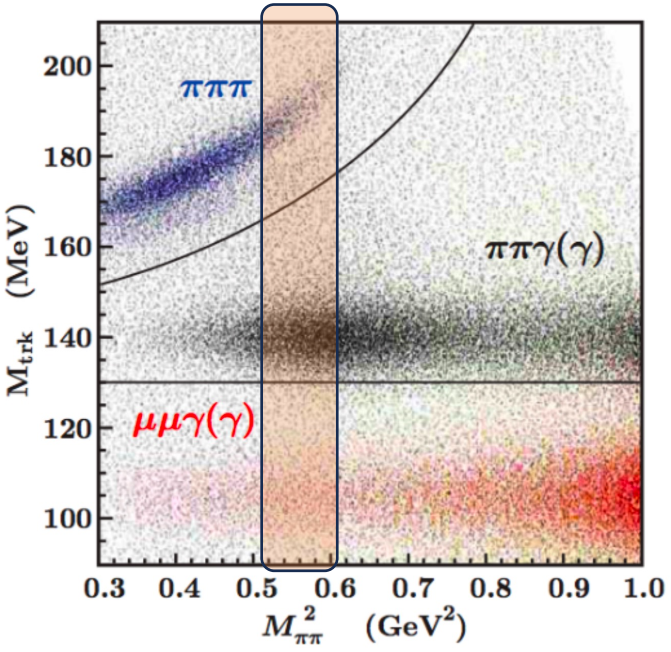
KLOE23$_{(goal)}$: $0.1\%_{stat} \oplus 0.2\%_{th} \oplus 0.3\%_{syst}$
$\sim 0.4\%_{tot}$

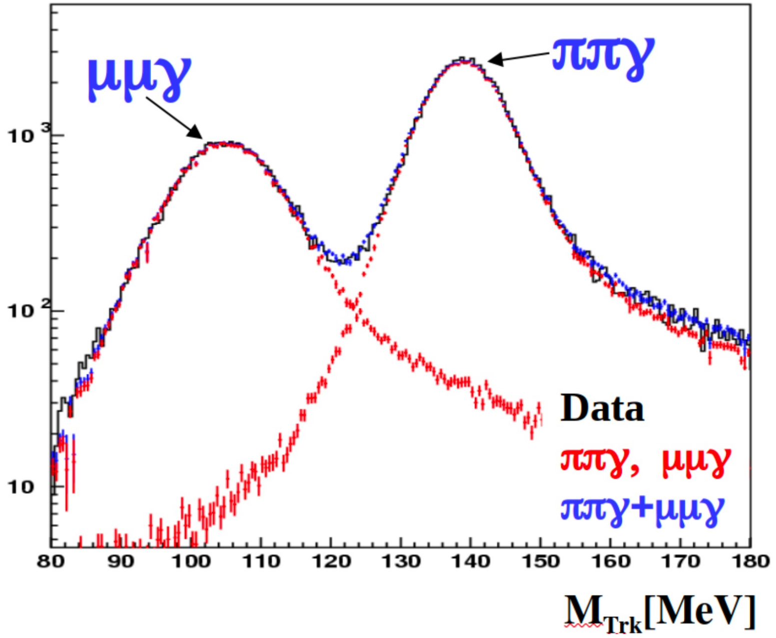
Trackmass and the background estimation

Trackmass (M_{trk}) 4-momentum conservation under the hypothesis of 2 charged tracks with equal mass and a photon

$$\left(\sqrt{s} - \sqrt{p_+^2 + M_{trk}} - \sqrt{p_-^2 + M_{trk}}\right)^2 - (p_+ - p_-)^2 = 0$$

- cut away background from $\pi^+\pi^-\pi^0$ and to separate π and μ.



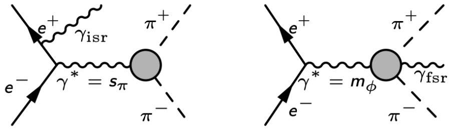
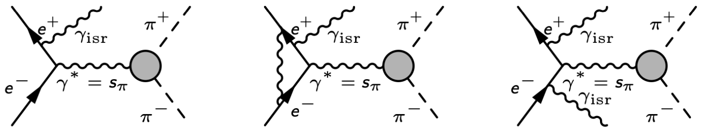
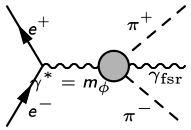
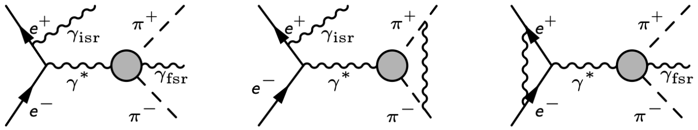


A refined new background subtraction procedure:
- additional and combined variables for discrimination
- confirming at ~1% level the previous estimation

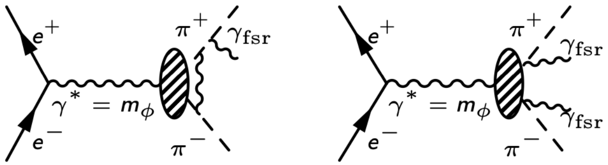
Great experimental effort to improve the background understanding

PHOKHARA generator

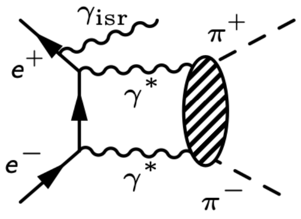
Simulation of $e^+e^- \rightarrow \pi^+\pi^-\gamma(\gamma)$ and $e^+e^- \rightarrow \mu^+\mu^-\gamma(\gamma)$, with photons emitted at Initial State Radiation (ISR) and Final State Radiation (FSR).
Employed to extract the radiator function $H(s,M_{had}^2)$

LO	
ISRNLO	
IFSLO	ISRNLO + 
IFSNLO	IFSLO + 

FSRNLO (Next-to-Leading-Order FSR)



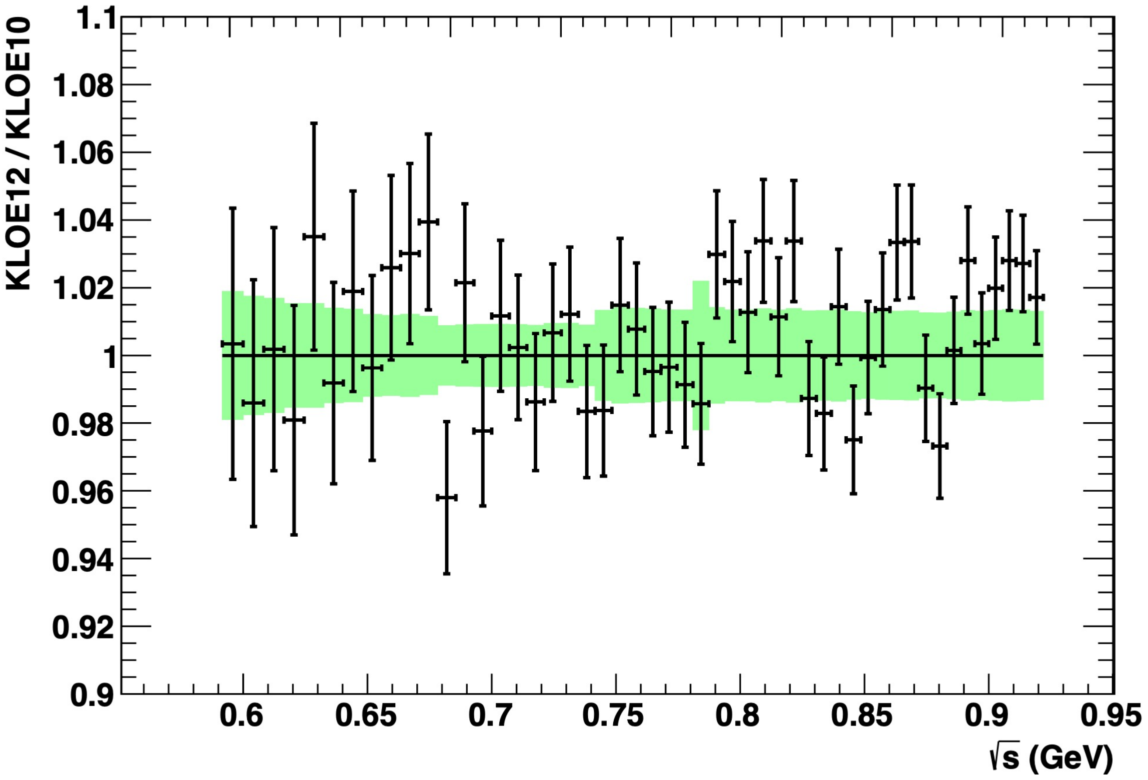
TVP (Two Virtual Photons)



Theory efforts in implementing all the relevant contributions at < 1%

Comparing $H(s,M_{had}^2)$ with data

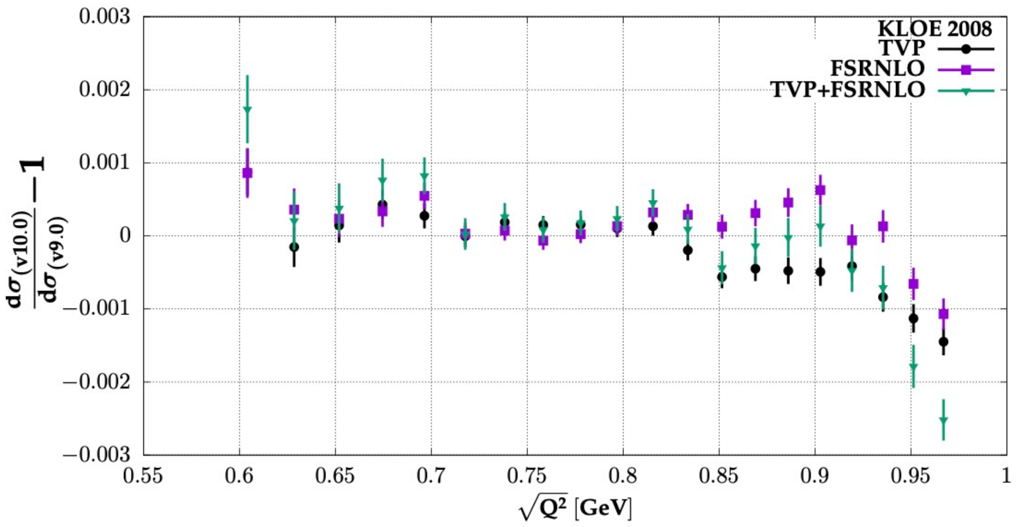
Comparison between KLOE10 results (using H and normalization to Bhabha events) and KLOE12 (normalization of π over μ events): cross check of the radiator function

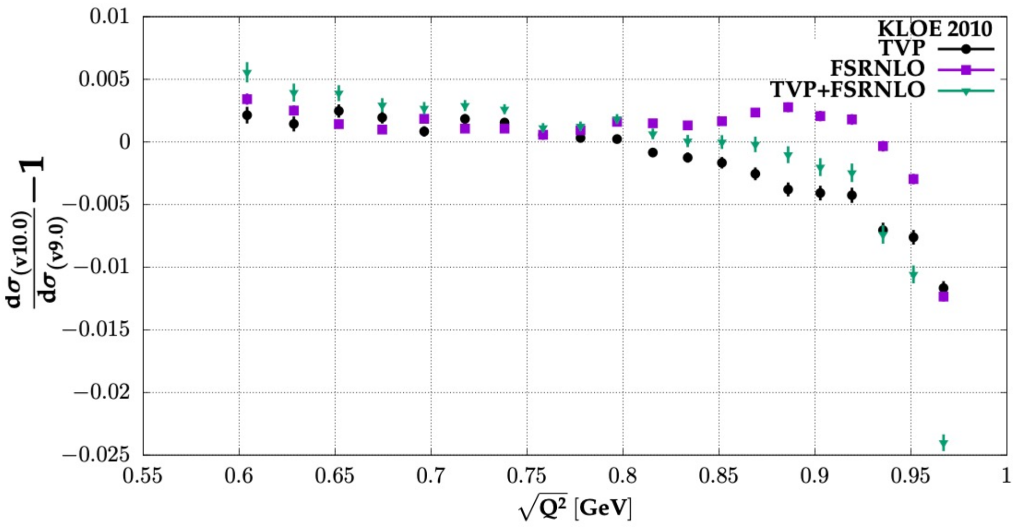


Compatible with 0.5% theoretical precision.

Further checks on PHOKHARA

PHOKHARA10 adds both NLO FSR contributions (FSRNLO) and contributions with two virtual photons (TVP)





- For KLOE08 (SA) the new contribution accounts for ~0.2%
- For KLOE10 (LA) the effect is of ~0.5% in the range of $0.6 < \sqrt{Q^2} < 0.92$ GeV

Campanario et al., Phys. Rev. D 100, 2019

Unfolding of the $Q^2_{\pi\pi}$ distribution

- To retrieve ${Q^2_{\pi\pi}}^{true}$ from ${Q^2_{\pi\pi}}^{meas}$: $N_i^{true} = \sum_{j=1}^{\mathcal{J}} \mathcal{P}(C_i|E_j) \cdot N_j^{meas}$
- Two approaches for KLOE08 and KLOE12 taken to find the smearing matrix
  1. Directly from Monte Carlo simulation, under the unitarity condition
  2. Calculated using the D'Agostini iterative procedure (bayesian approach)

G. D'Agostini, Meth. in Phys. Res. A362, 1995

- New unfolding method using Tikhonov regularisation with Singular Value Decomposition (SVD) implemented

Unfolding Approach	$\mathcal{I}[(Q^2_{\pi\pi})^{true}]/\mathcal{I}[(Q^2_{\pi\pi})^{meas}] - 1$
Matrix Multiplication	-3×10^{-5}
Iterative Bayes	7×10^{-5}
Singular Value Decomposition	2×10^{-4}
Target KLOE23 Precision	4×10^{-3}

Effect on $a_\mu^{\pi\pi}$ of unfolding the $Q^2_{\pi\pi}$ is negligible for the KLOE23 accuracy goal

Blinding for KLOE23 analysis

- Blinding procedure should not preclude consistency checks between data and Monte Carlo
- Blinding for KLOE23 is not trivial: new ad hoc solution must be found

- Use blinded data sets: removing events with constant probability inside each $Q^2{}_{\pi\pi}$ bins does not influence procedures at fixed $Q^2{}_{\pi\pi}$ slice but alters final value of $a_\mu{}^{\pi\pi}$

- The effect on $a_\mu{}^{\pi\pi}$ is ±6% with respect to true value in simulations
  ⇒ blinding offset much larger than KLOE23 target precision

Summary and outlook

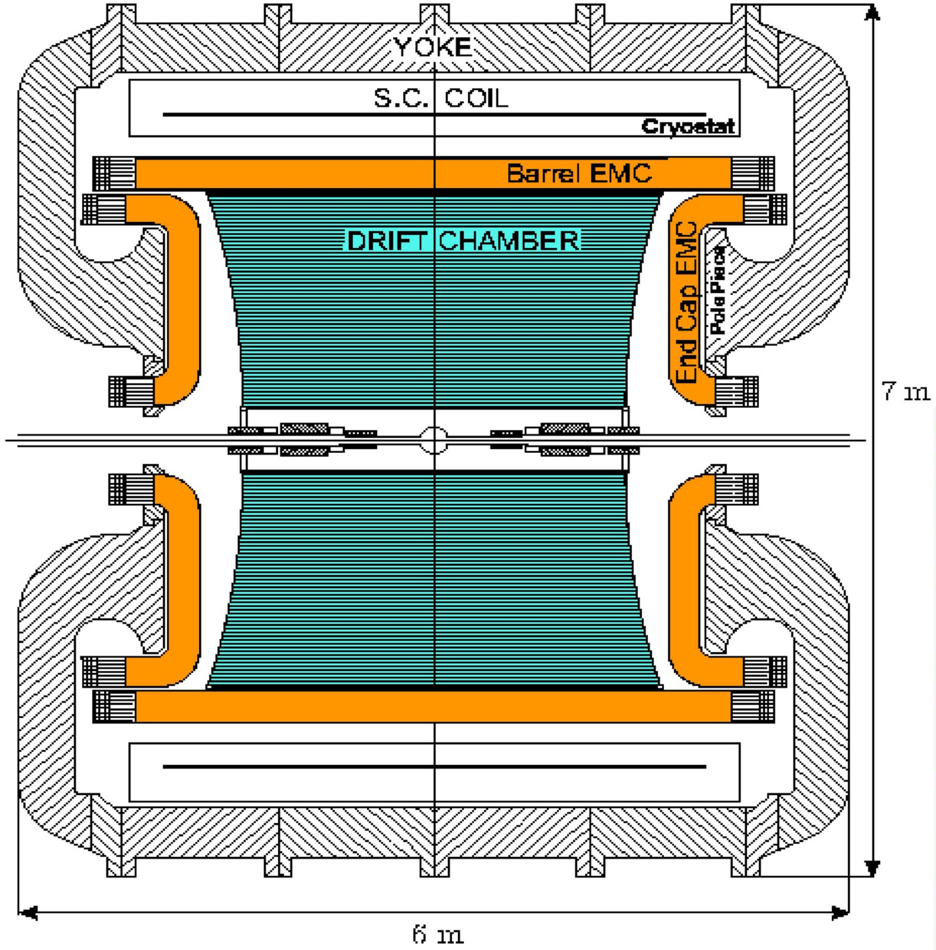
- New analysis of 2004/2005 KLOE data set initiated (1.7 fb^{-1}): KLOE23
- Multiple aspects addressed with high and unbiased accuracy
    - Starting from the estimated higher errors of KLOE08 and KLOE10
    - Seeking new causes of possible inaccuracy
    - Accurate studies on blinding
- KLOE analyses uses PHOKHARA5 generator for radiative corrections
- New efforts to add dominant NNLO contributions in PHOKHARA started
    - Ideas to extend BABAYAGA generator to ISR processes

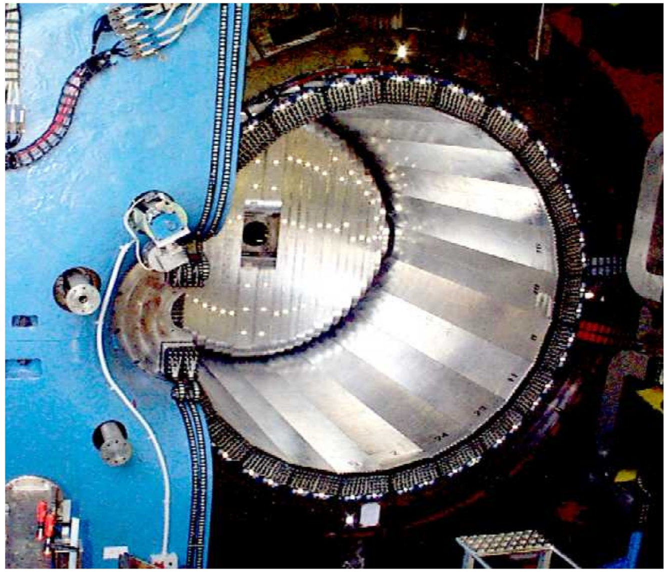
- Wide experimental and theoretical works to perform a blind analysis to get results at the ~0.4% total error on $a_\mu^{\pi\pi}$

LEVERHULME TRUST

Backup

KLOE detector



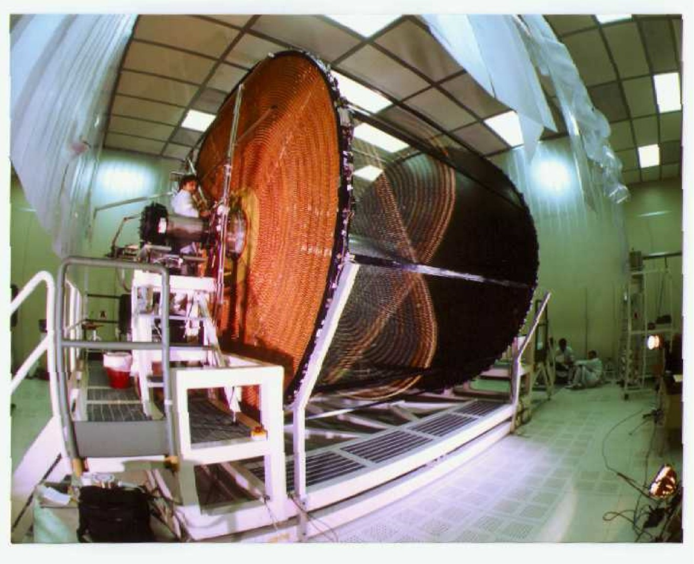


EM Calorimeter

$\sigma_t = 54\ \text{ps}/\sqrt{E\ [GeV]} \oplus 100\ \text{ps}$

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

Time resolution



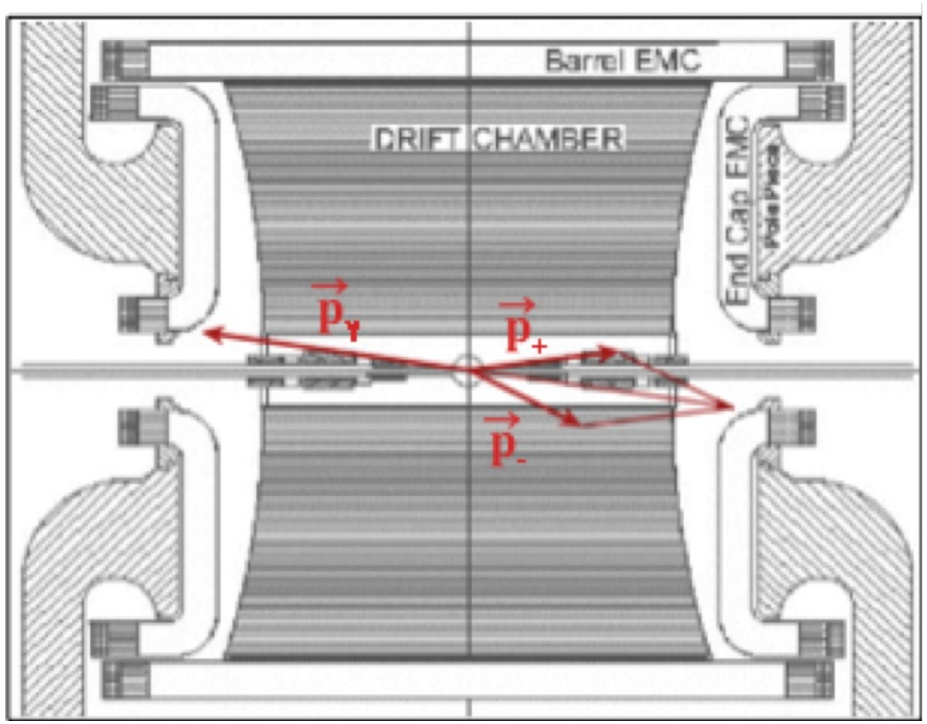
Drift Chamber

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

$\sigma_p/p = 0.4\%$

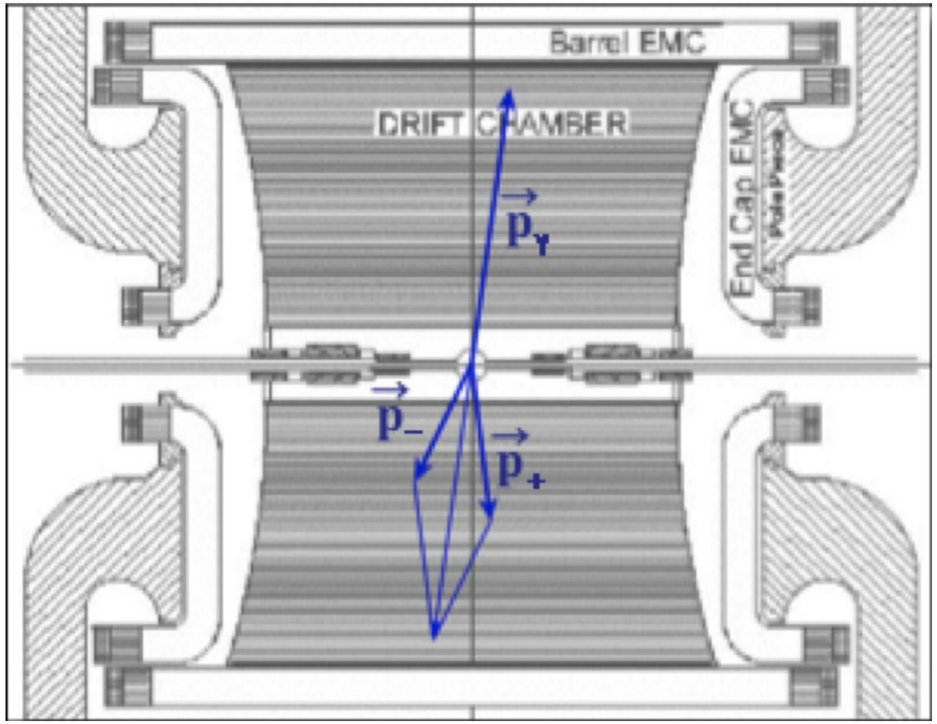
Momentum resolution

The threshold region



Untagged photon

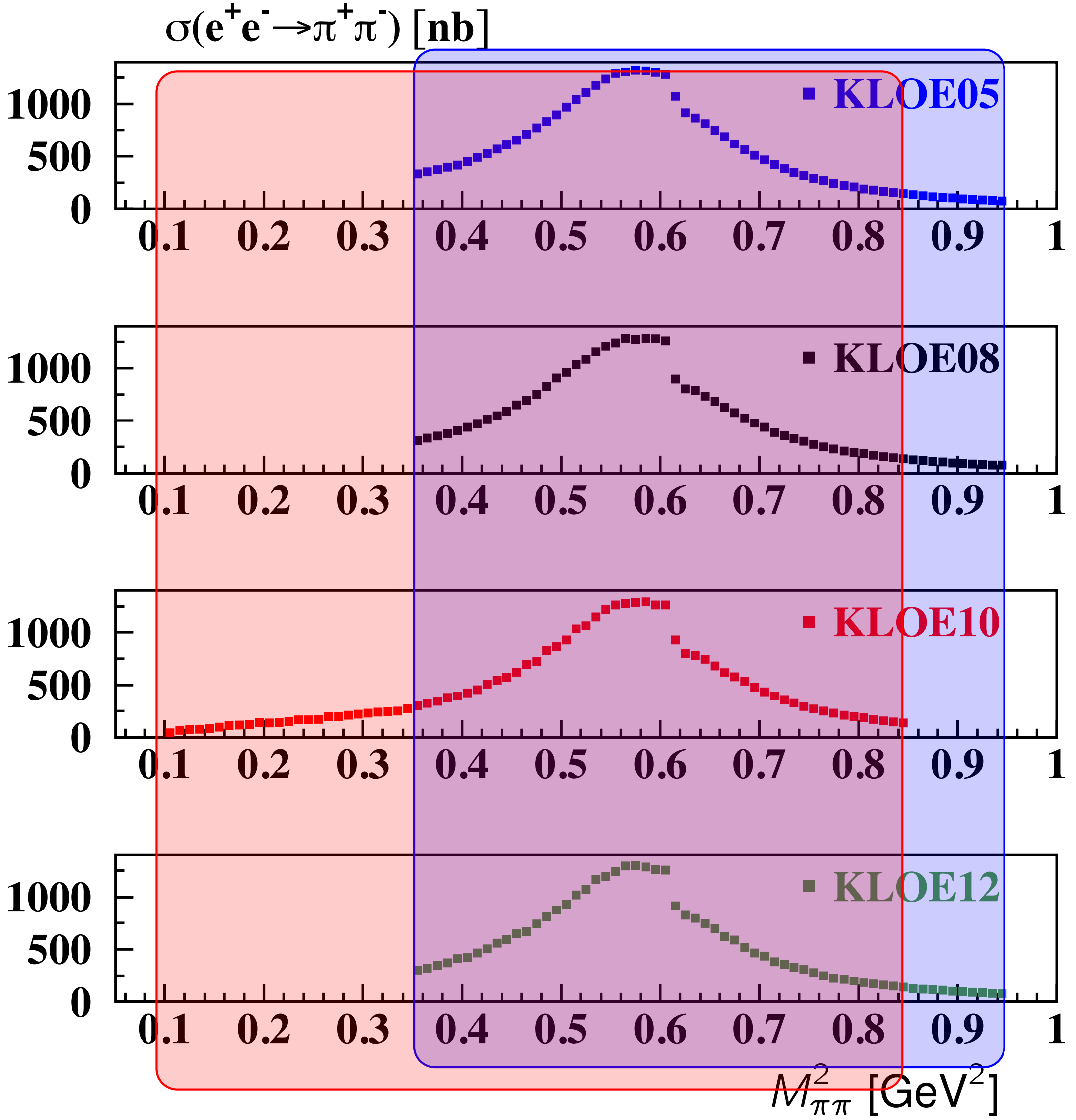
- High statistics, small background
- No FSR photons
- Only higher masses accessible



Tagged photon

- Access to hadronic threshold region
- Background at high masses

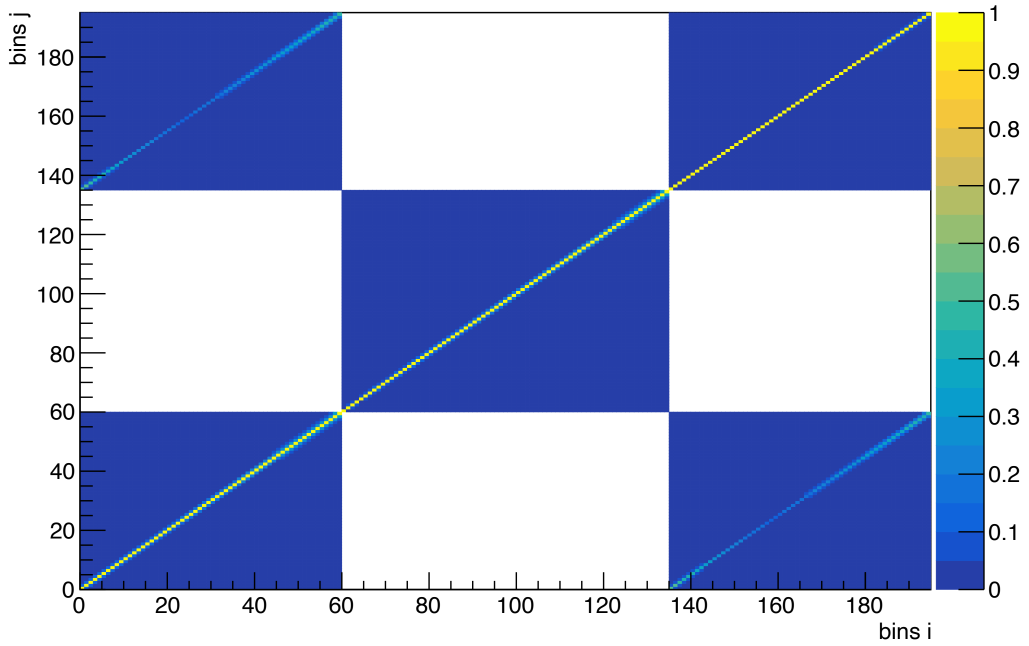
KLOE analyses



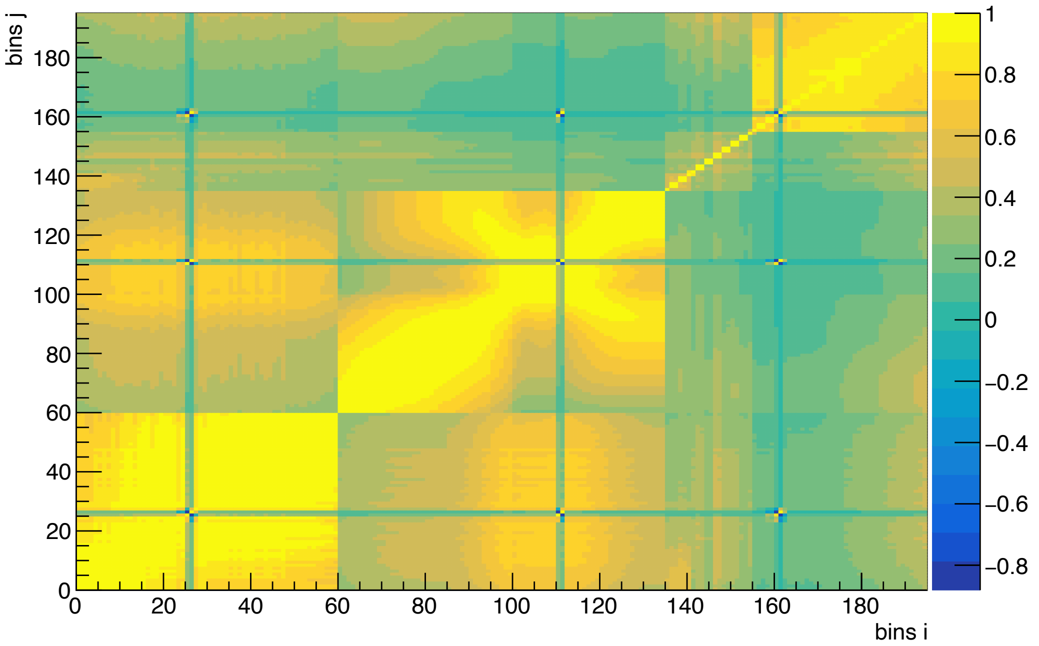
Combination of the KLOE results

With the help of Alex Keshavarzi and Thomas Teubner, we managed to construct the statistical and systematic correlation matrices for the $60 + 75 + 60 = 195$ data points of the KLOE08, KLOE10 and KLOE12 analyses:

Statistical correlation matrix:



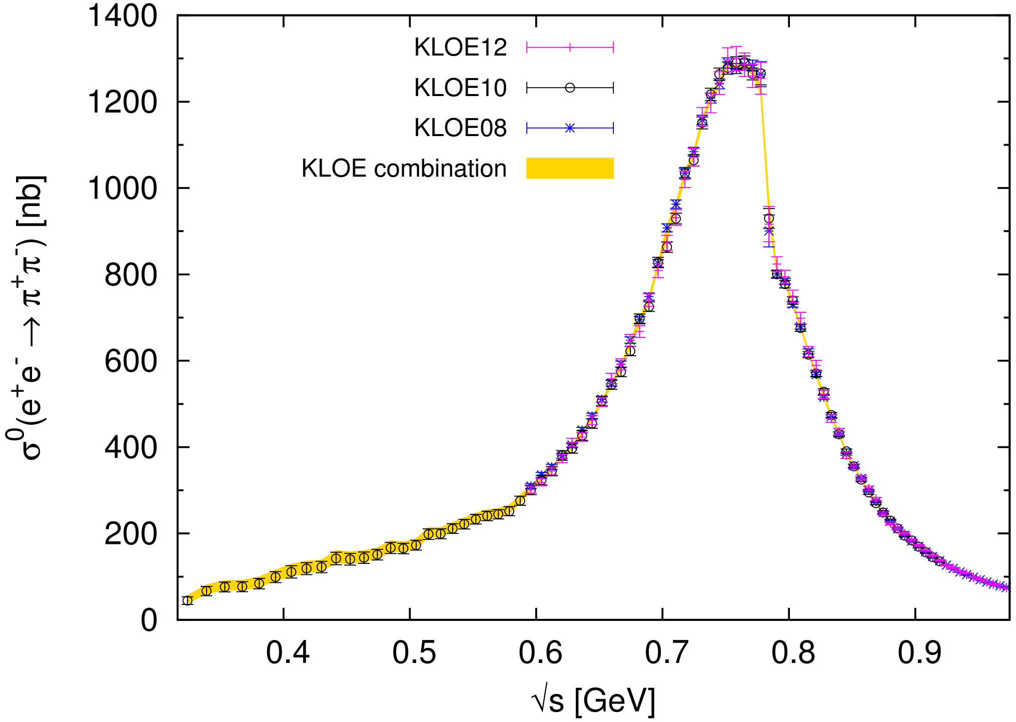
Systematic correlation matrix:

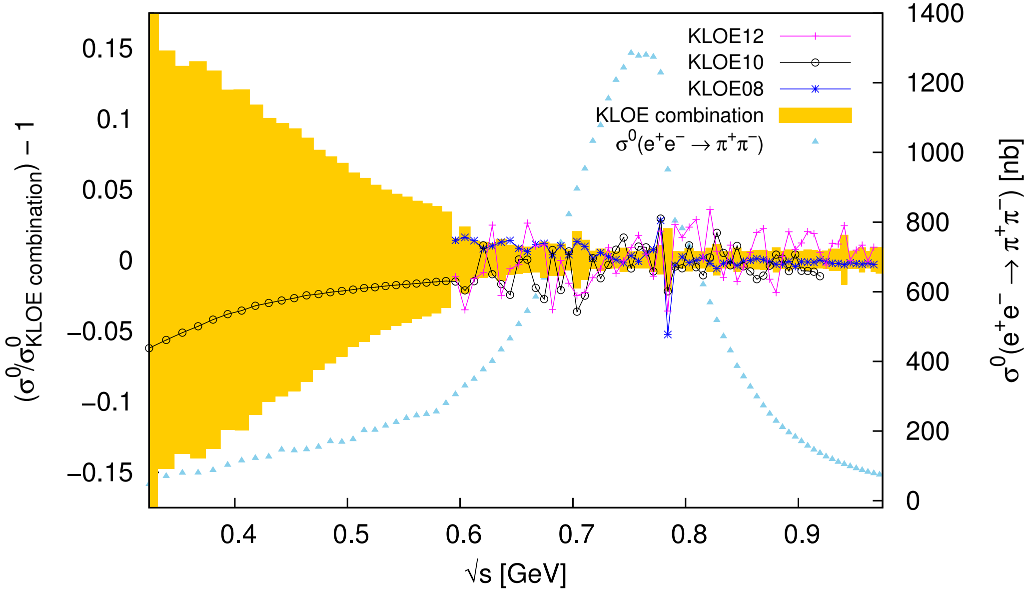


http://www.lnf.infn.it/kloe/ppg/ppg_2018/ppg_2018.html

Combination of KLOE reults

Using the correlation matrices, it was possible to perform a combination of the three KLOE datasets (JHEP 1803 (2018) 173, arXiv:1711.03085):



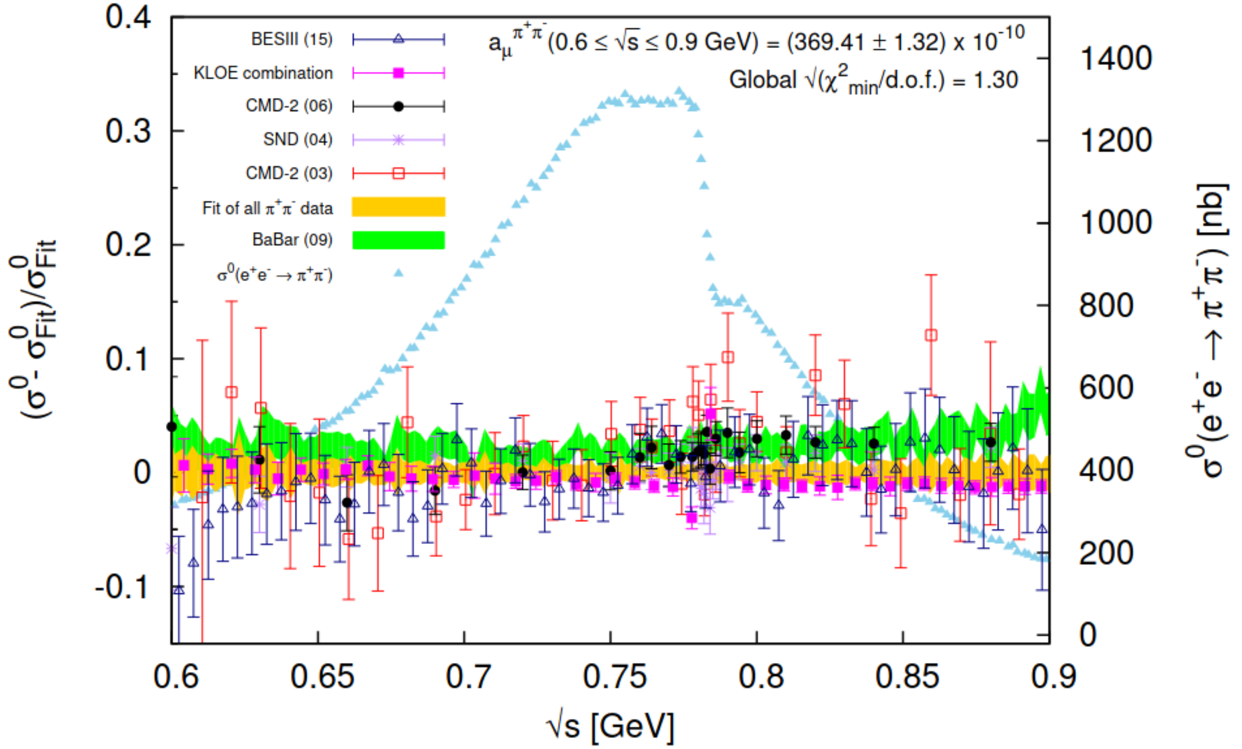


Plugging this in the dispersion integral for $a_\mu^{\pi\pi}$, one obtains in the range of $0.10 < s < 0.95$ GeV^2

$$a_\mu^{\pi^+\pi^-} \quad = \quad (489.8 \pm 1.7_{\text{stat}} \pm 4.8_{\text{sys}}) \times 10^{-10}$$

The BaBar-KLOE discrepancy

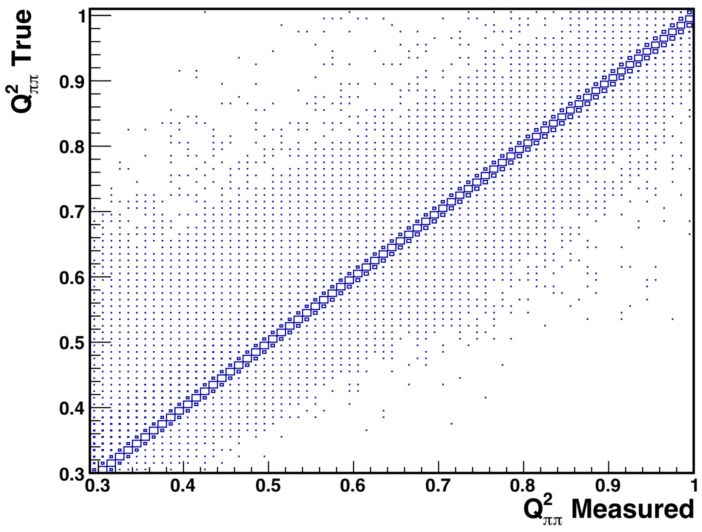
The tension between the two most precise measurements of the 2π-channel spoils the resulting uncertainty on a_μ^{HLO}:



[KNT2018, Phys. Rev. D 97, 114025 (2018)]

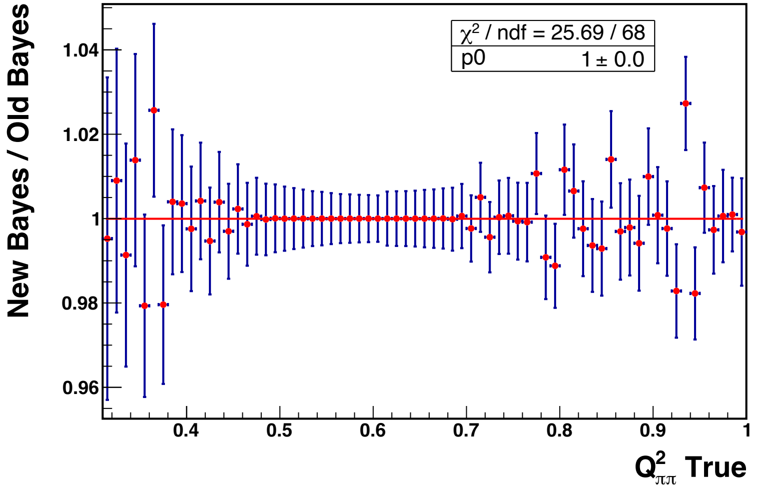
A better understanding of this "BaBar-KLOE"-puzzle would contribute to a reduced uncertainty in the a_μ^{HLO}-evaluation!

New Unfolding: RooUnfold



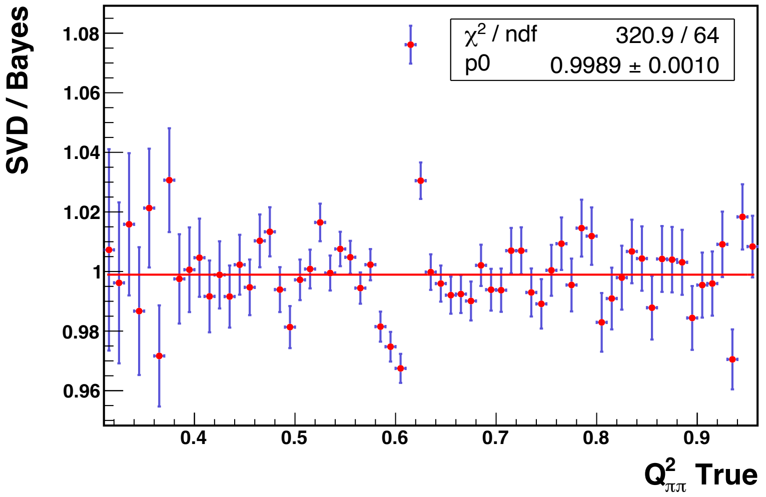
1. RooUnfoldBayes class:
new bayesian unfolding procedure

- Negligible difference with respect to the KLOE08 approach



2. RooUnfoldSvd class:
Tikhonov unfolding method

- finding the n that minimizes
$$||R \cdot n - m||^2 + \tau||Cn||$$
C: curvature matrix



Slide from S. Müller

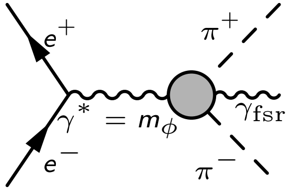
Final State Radiation

Final state radiation

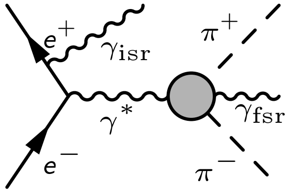
Cross section in dispersion integral should be inclusive with respect to FSR:

Definitions:

- **LO FSR:**
  Emission of one photon in the final state, no ISR.



- **NLO FSR:**
  One photon from ISR and one photon from FSR.



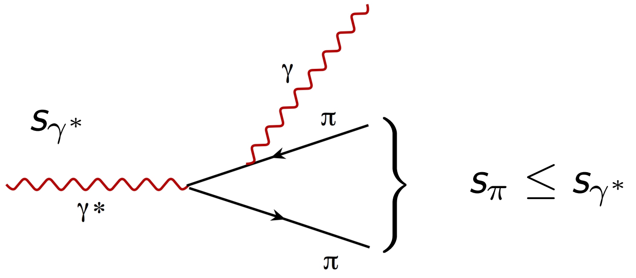
In the analyses, it is not possible to distinguish whether photon comes from initial or final state.
FSR corrections are estimated with PHOKHARA MC generator (sQED $\times$ VMD).

Slide from S. Müller

Final State Radiation

Final State Radiation (2)

The presence of FSR shifts the observed value of s_π (evaluated from the 2 pion tracks' momenta) away from the invariant mass squared of the virtual photon s_{γ^*}:



Leading order FSR is considered as background in the KLOE analyses. In this case, the event should sit at $M^2_{\pi\pi} = M^2_{ee} = s$, outside the energy range considered in the analyses.

Next-to-leading order FSR events in which there is both a photon from the initial state and a photon from the final state need to be included (they correspond to the desired LO-FSR for the cross section $e^+e^- \to \pi^+\pi^-$ after the division by the radiator function).

Slide from S. Müller

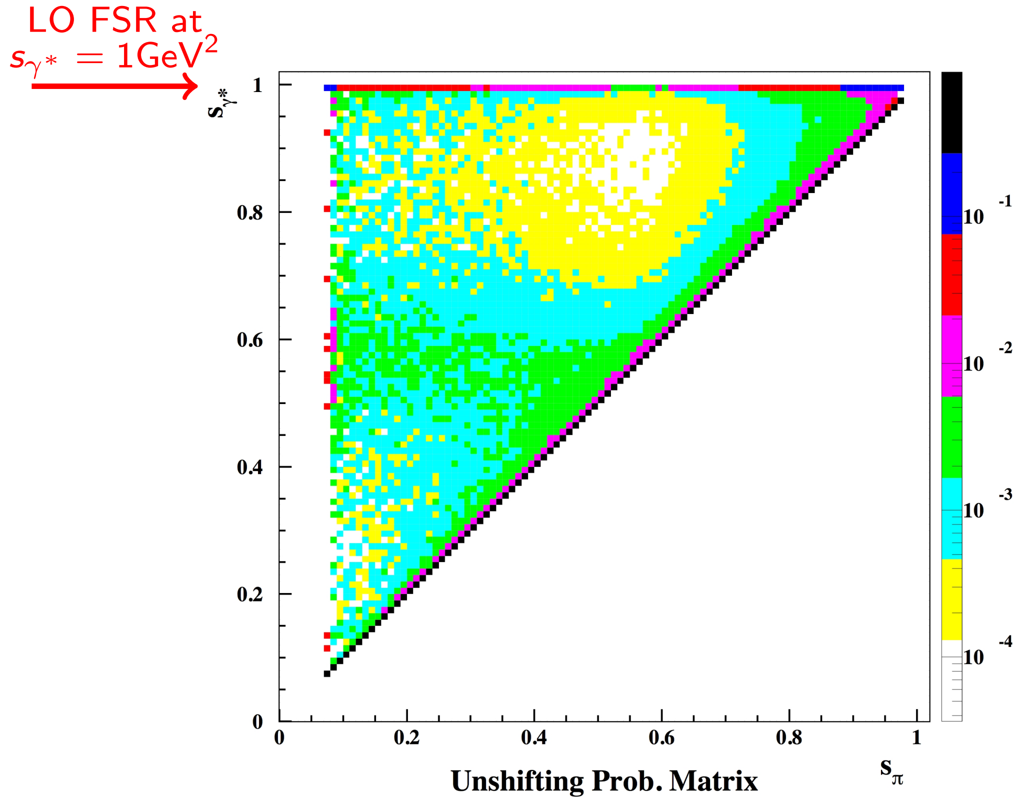
Final State Radiation

Final State Radiation (3)

Redistribute events to obtain "unshifted" distribution: $N_i^{s_{\gamma^*}} = \sum_{j=1}^{n} P(N_i^{s_{\gamma^*}} | N_j^{s_\pi}) \cdot N_j^{s_\pi}$

$P(N_i^{s_{\gamma^*}} | N_j^{s_\pi})$ obtained using dedicated version of PHOKHARA5 which allows to label whether photons come from ISR or FSR (*Phokhara_omega*).

This procedure also removes events from LO FSR from the spectrum by shifting them to $M_{ee}^2 = s = 1\,\text{GeV}^2$.



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  - Absolute normalization and normalization with the muons
  - Blind analysis
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  - Starting from the estimated higher errors of KLOE08 and KLOE10
  - Seeking new causes of possible inaccuracy
  - Extremely accurate study of analysis blinding
- KLOE analyses uses PHOKHARA5 generator for radiative corrections
  - Radiator function (KLOE08 and KLOE10)
  - Treatment of final state radiation
  - New terms in PHOKHARA10 work in progress (… should not change existing KLOE results)
- New efforts to add dominant NNLO contributions in PHOKHARA started
  - Ideas to extend BABAYAGA generator to ISR processes