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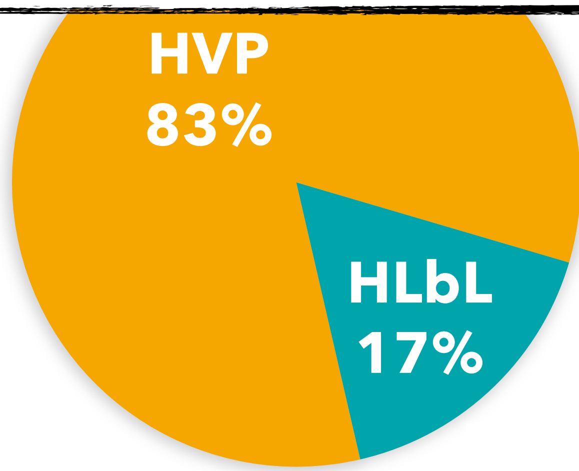
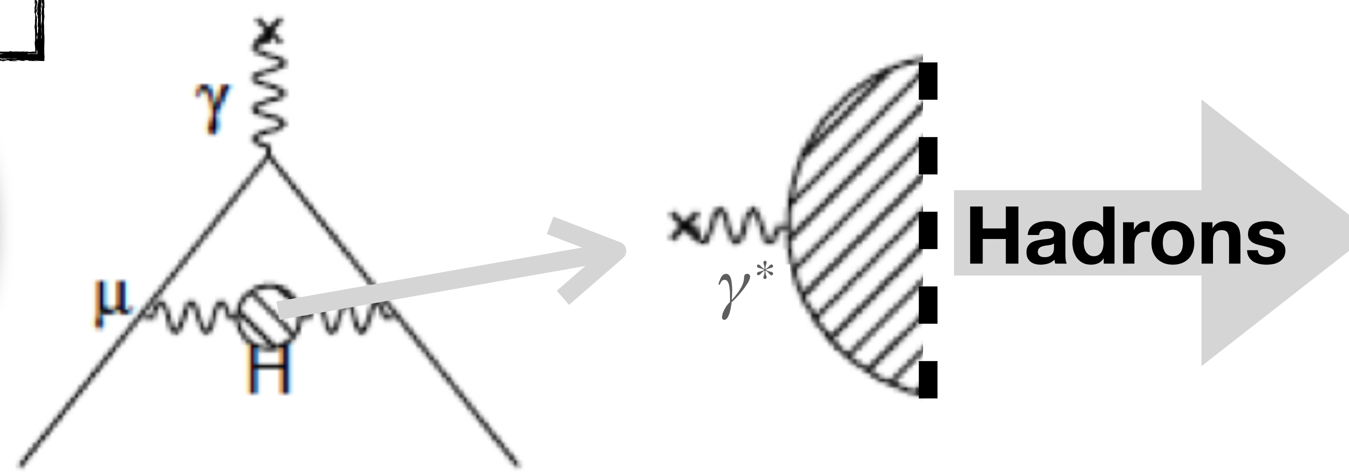
KLOE activity in Liverpool

Paolo Beltrame, Liverpool HEP Annual Meeting 18/19 May 2023

Hadronic contribution to *g*-2

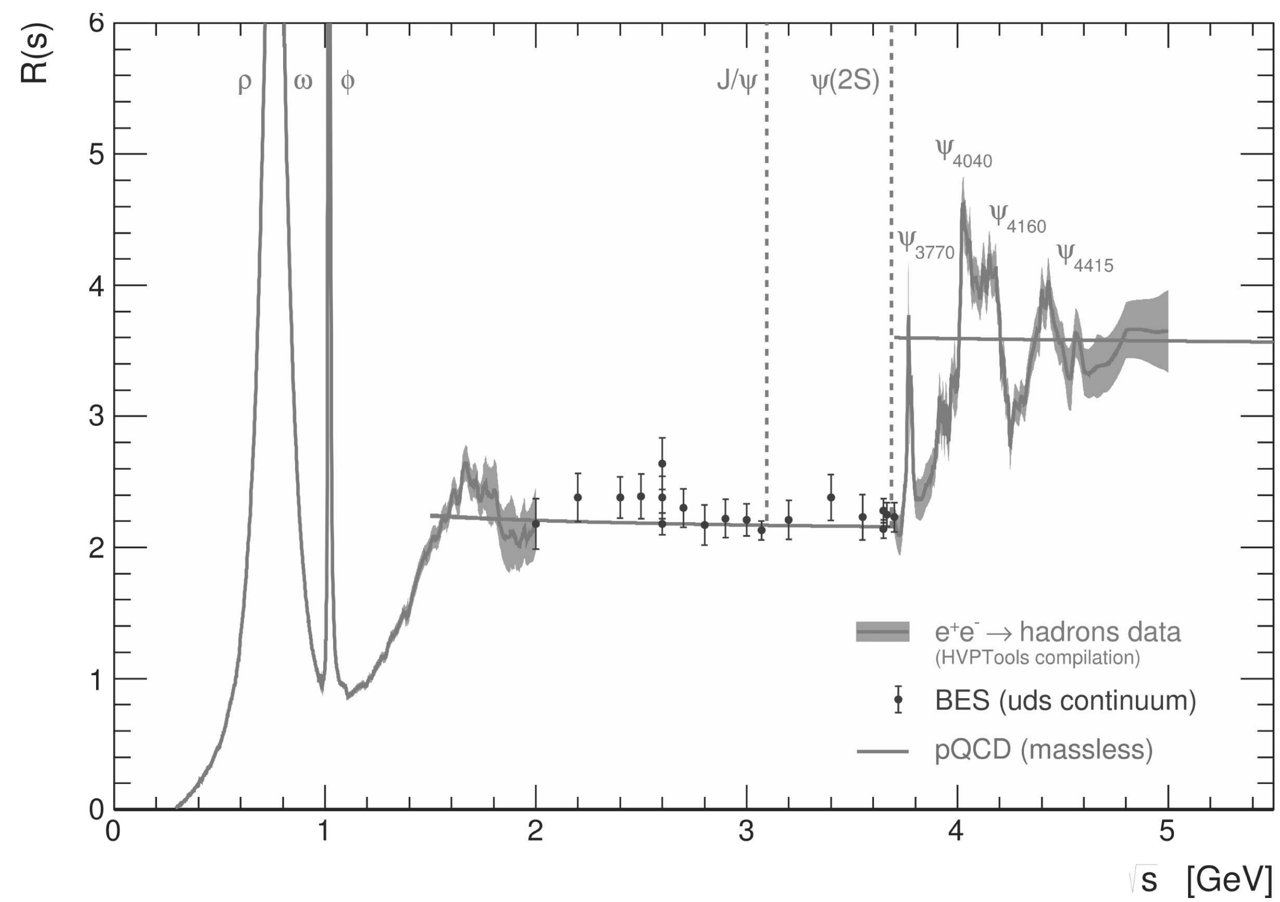
e^+e^- -> hadrons





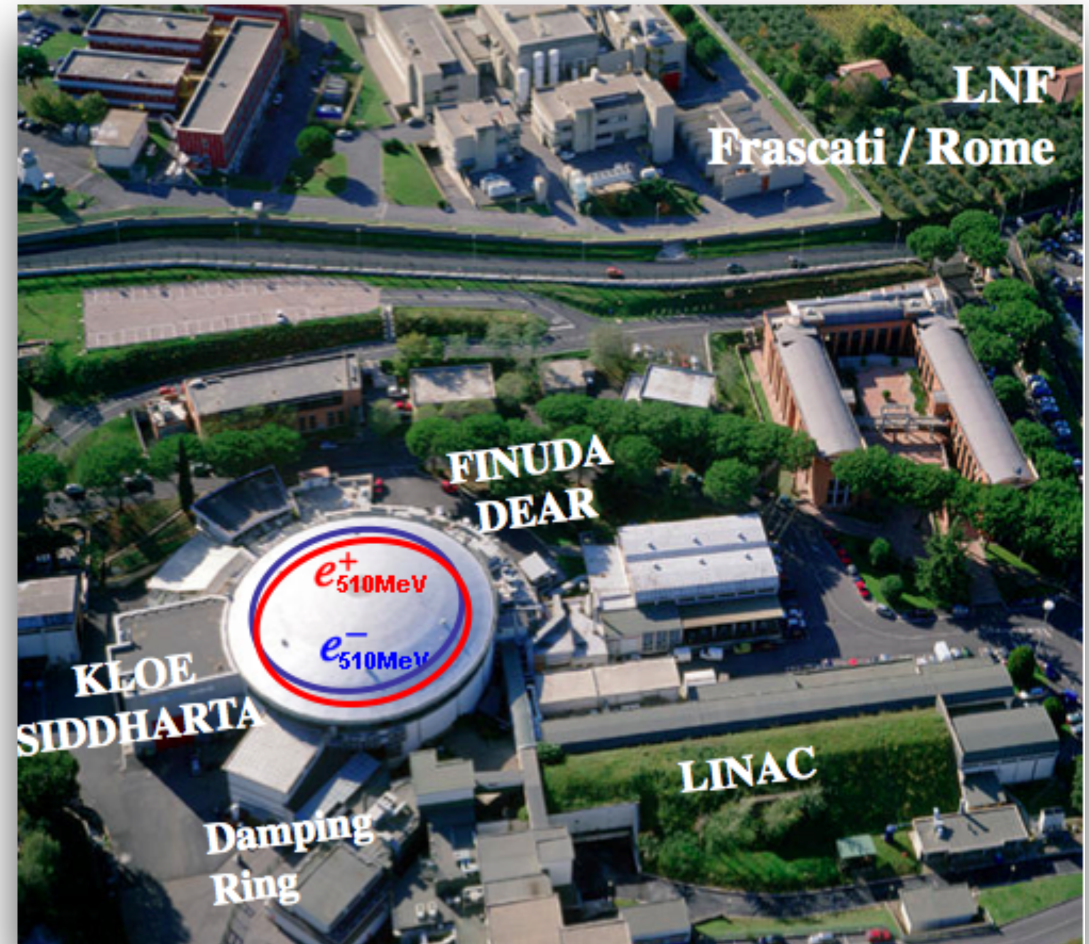
$\pi^+\pi^-$ => ~65%

$$a_\mu^{\pi\pi} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{\hat{K}(s) R_{\mathrm{had}}(s)}{s^2}$$

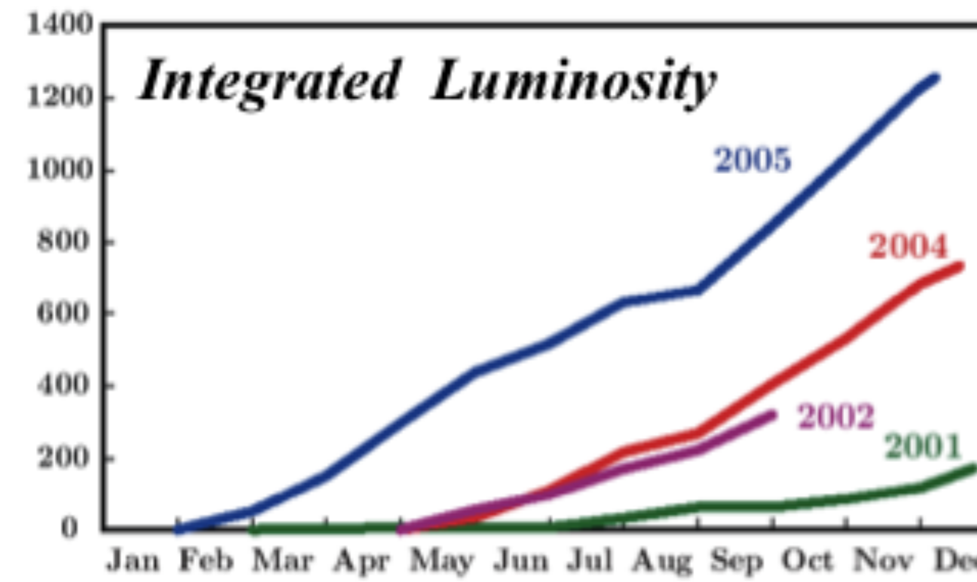


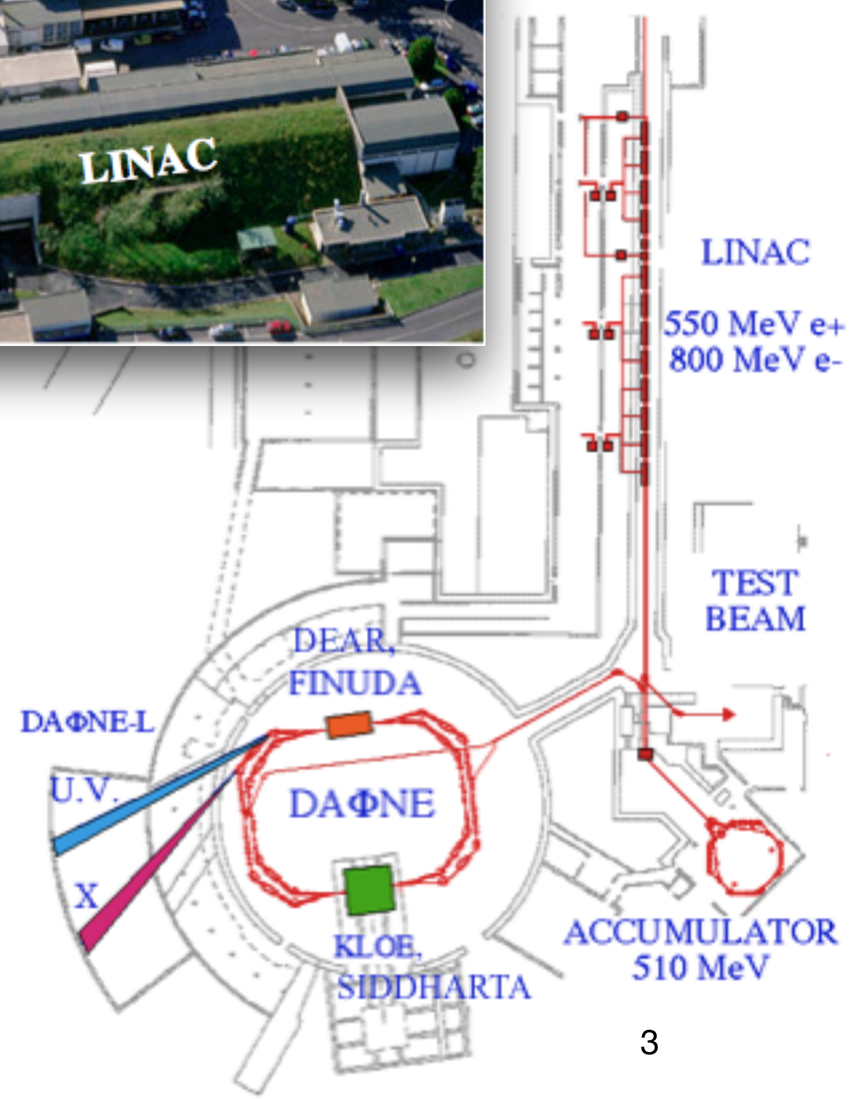
Experimental input required
by the theoretical calculation

DAΦNE: a ϕ factory



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





A. Total KLOE int. luminosity: 2.1 fb^{-1} [2001 - 2005]

B. And in 2006:
- Energy scan: 4 points around m_ϕ
- *Off-peak* data ($\sqrt{s}$ = 1. GeV): 250 pb^{-1}

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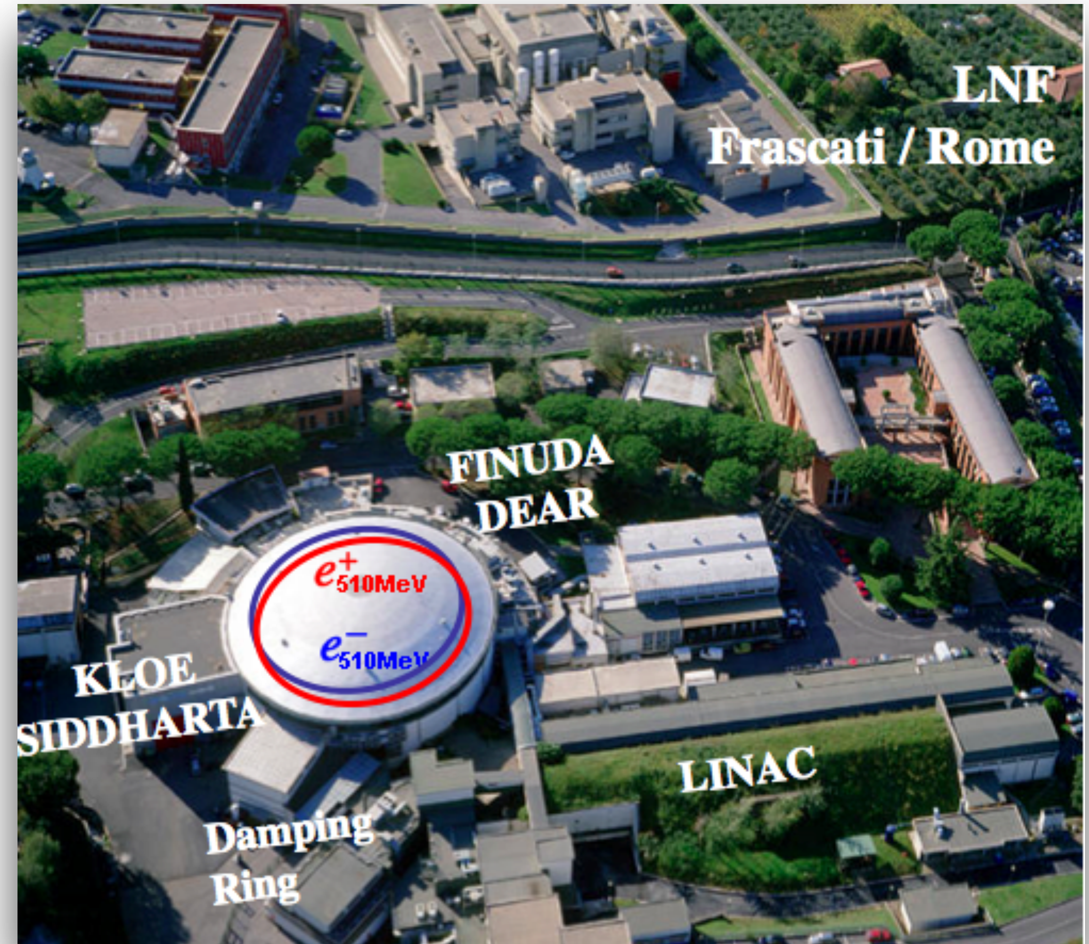

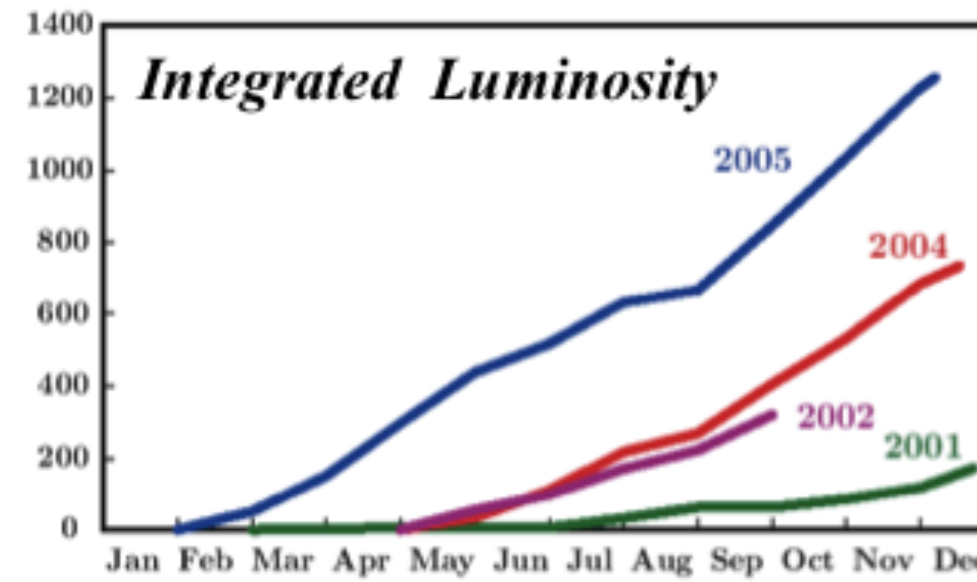

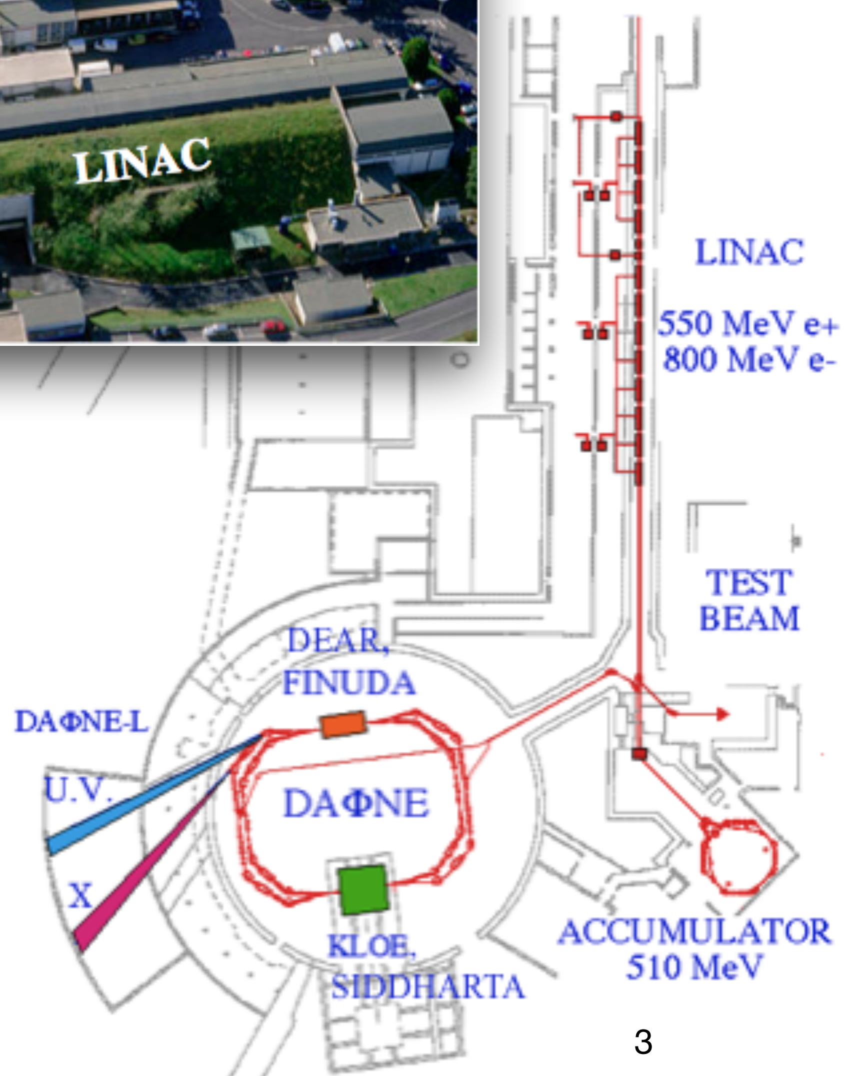

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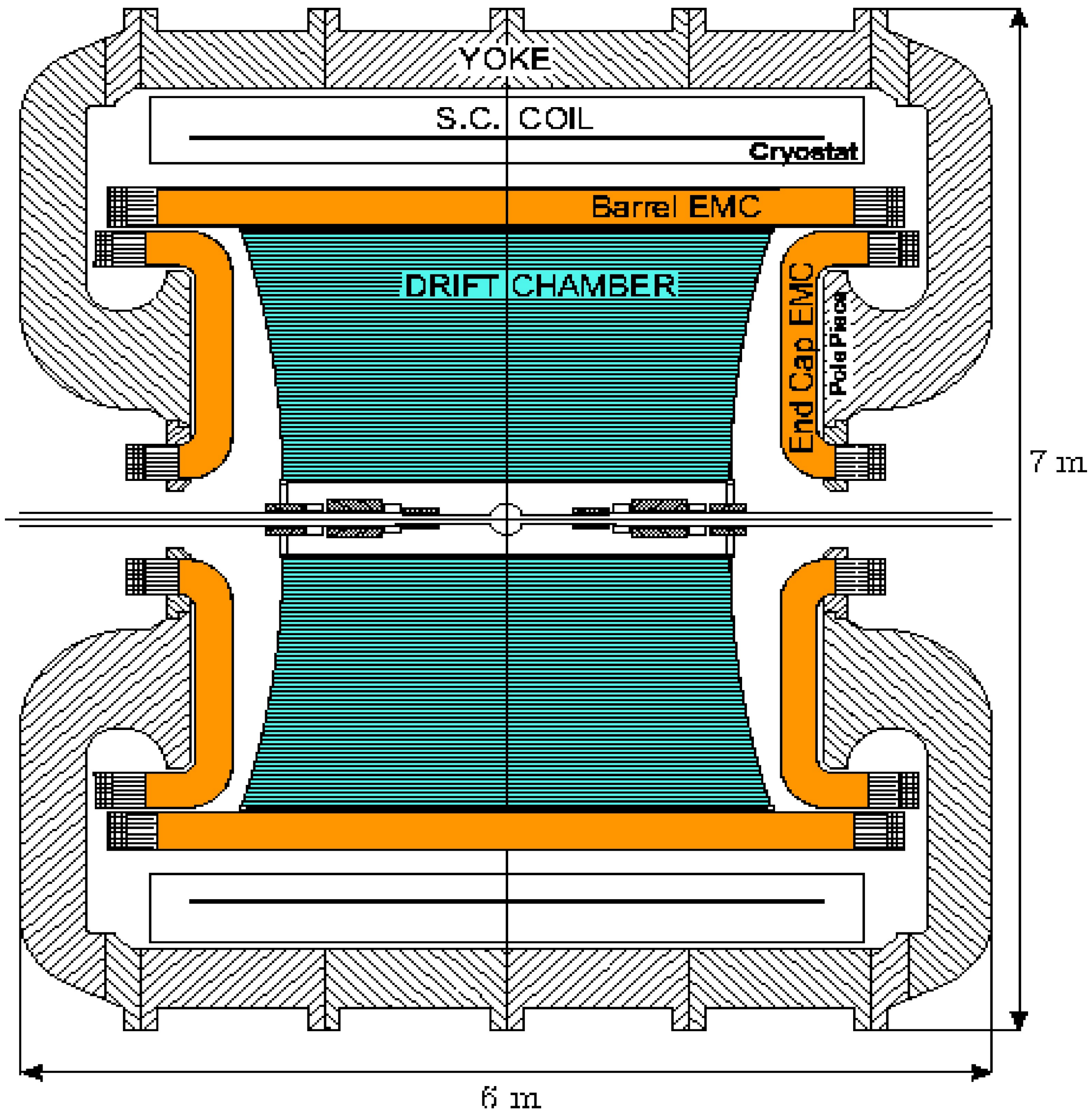
KLOE detector: Drift Chamber

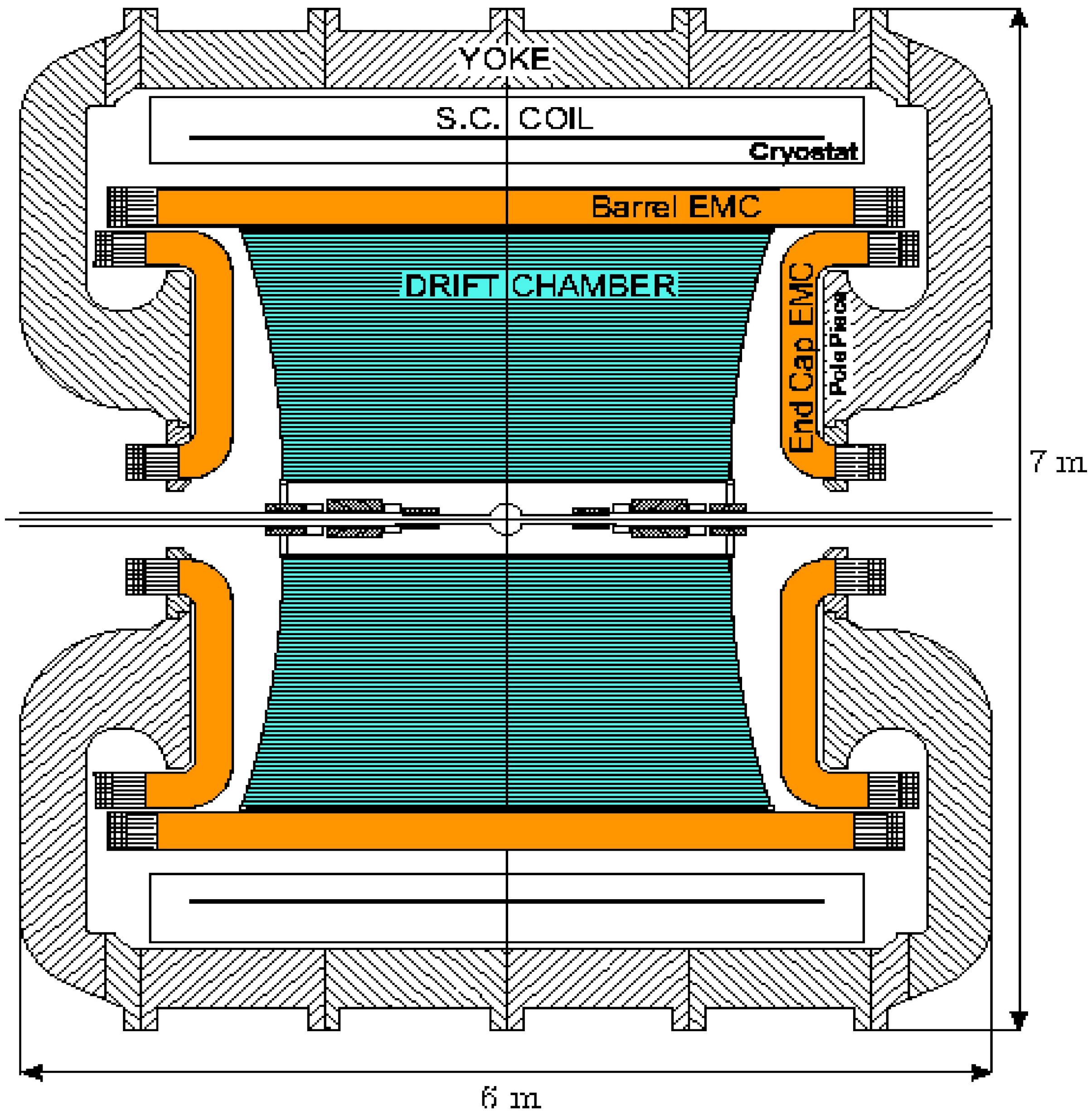


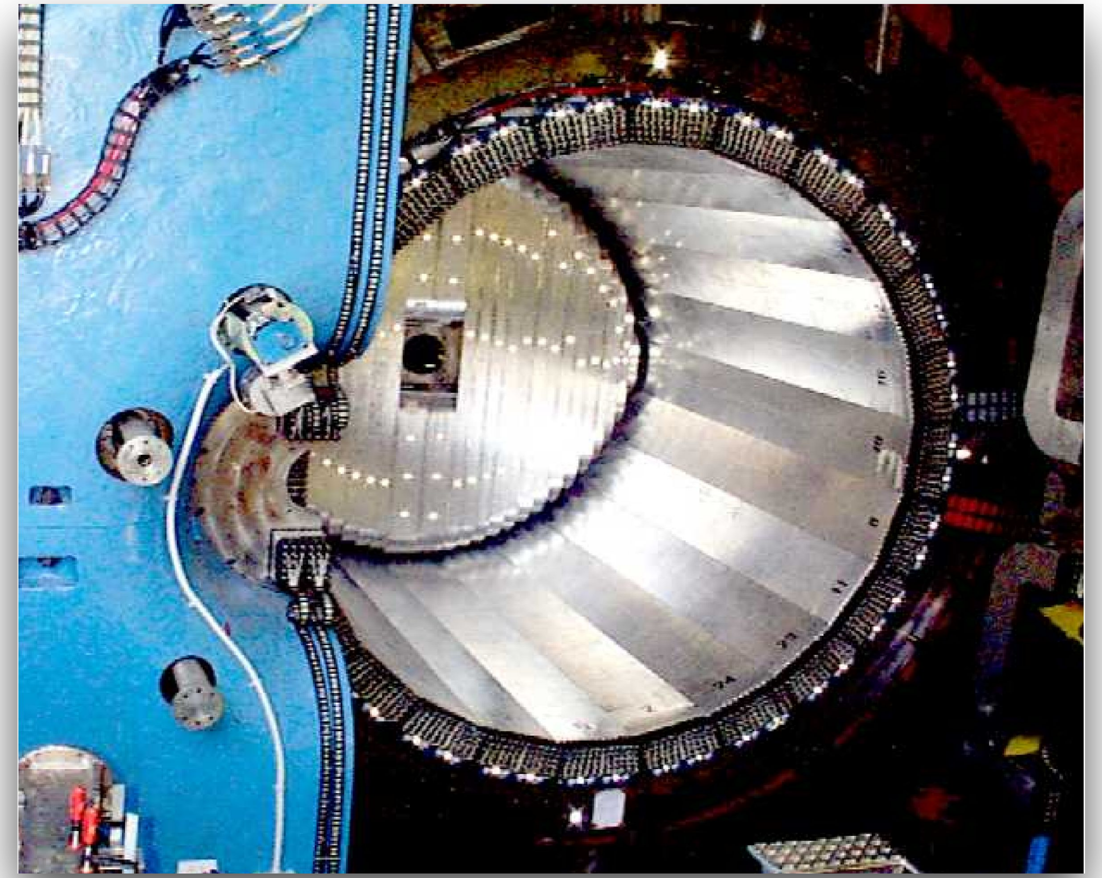
$\sigma_{r\phi}$ = 150 μm, σ_z = 2 mm

σ_p/p = 0.4%

Excellent momentum resolution

KLOE detector: Calorimeter





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

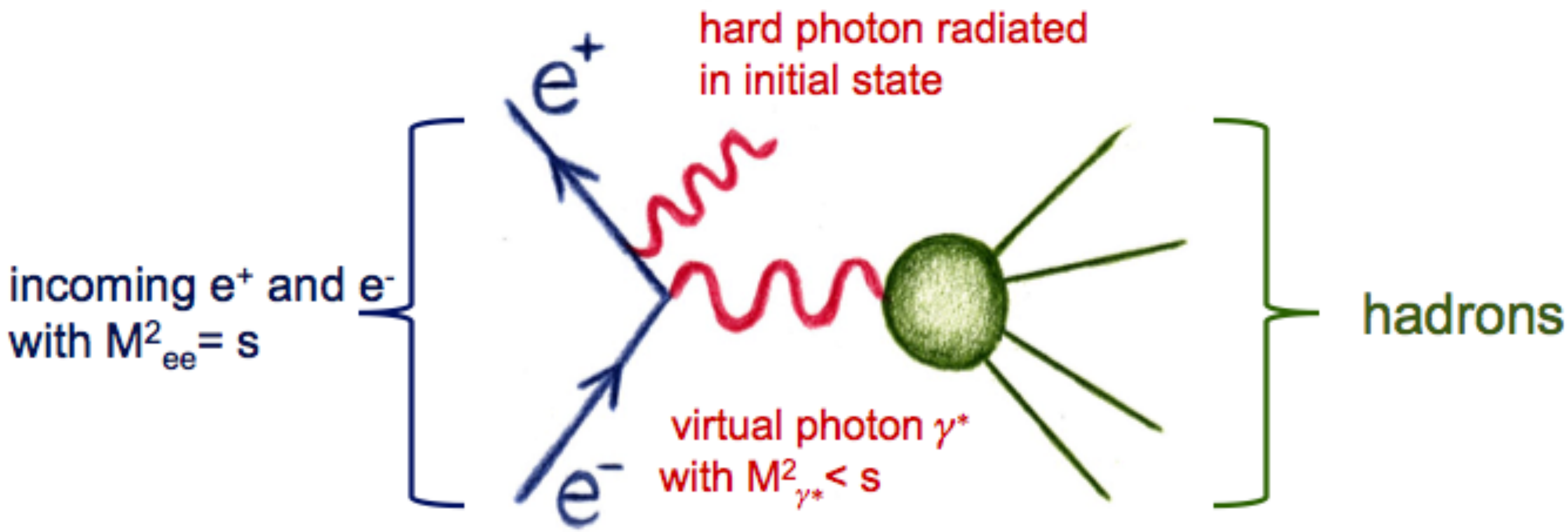
$\sigma_E/E = 5.7\%/\sqrt{E\ [\text{GeV}]}$

Excellent time resolution

Initial State Radiation

- Hadronic cross sections as a function of the hadronic c.m. energy.
- Particle factories works at fixed energy

=> Radiative Return -> energies below the collider energy $\sqrt{s}$

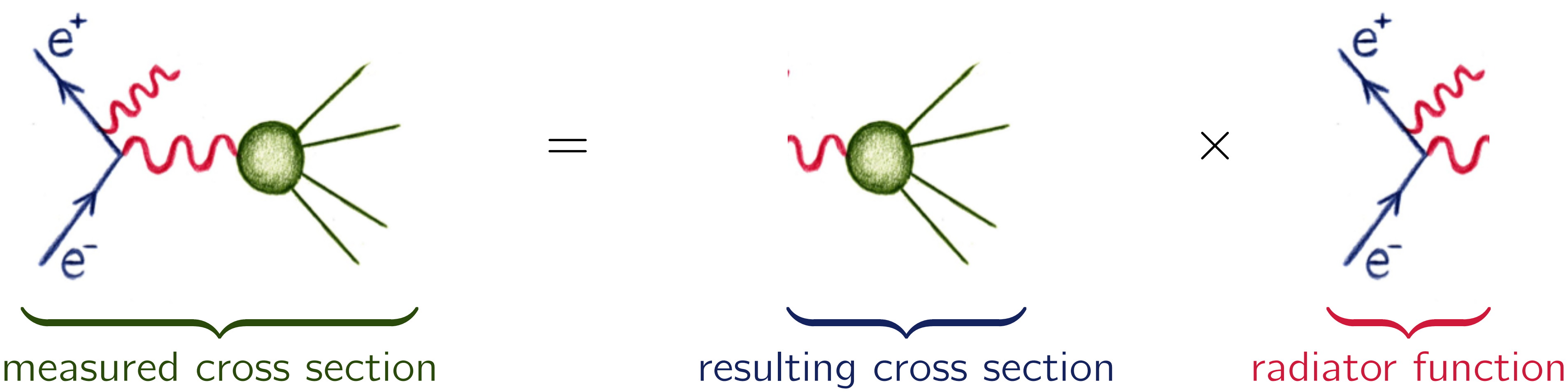


The emission of hard γ in the bremsstrahlung process reduces available energy to produce hadronic system.

Initial State Radiation

Radiator function $H(s,M_{had}^2)$ to relate measured differential cross section $d\sigma_{had+\gamma}/dM_{had}^2$ to hadronic cross section σ_{had}

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



Precise calculation of radiator function $H(s,M_{had}^2)$ event generator:

PHOKHARA Monte Carlo

Extremely detailed theory work!

ISR methods in KLOE (I)

Two methods to obtain the 2π-cross section:

1) Absolute normalisation: Normalise cross section from independent luminosity measurement using Bhabha events:

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

The total cross section is then obtained

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

ISR methods in KLOE (II)

Two methods to obtain the 2π-cross section:

2) Normalisation with muons: Normalise $\pi\pi\gamma$ sample in each energy bin with $\mu\mu\gamma$ events:

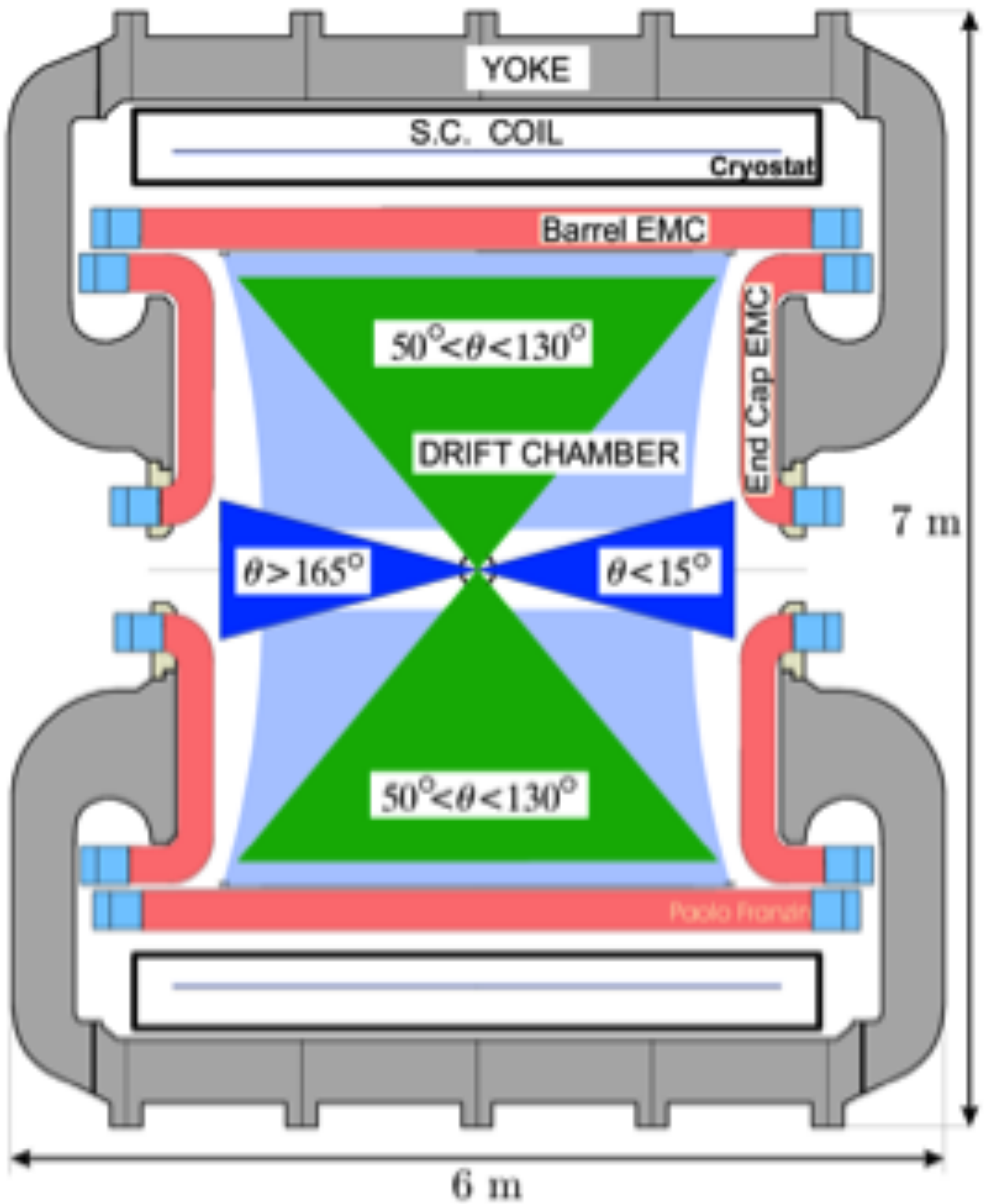
$$|F_{2\pi}(s')|^2 = \frac{4(1+2m_\mu^2/s')\beta_\mu}{\beta_\pi^3} \cdot \frac{(d\sigma_{\pi\pi\gamma}/dM_{\pi\pi}^2)}{(d\sigma_{\mu\mu\gamma}/dM_{\mu\mu}^2)}$$

The total cross section is then obtained

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

Advantage: Cancellation of systematic effects and radiative corrections

Selection cuts for analyses



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

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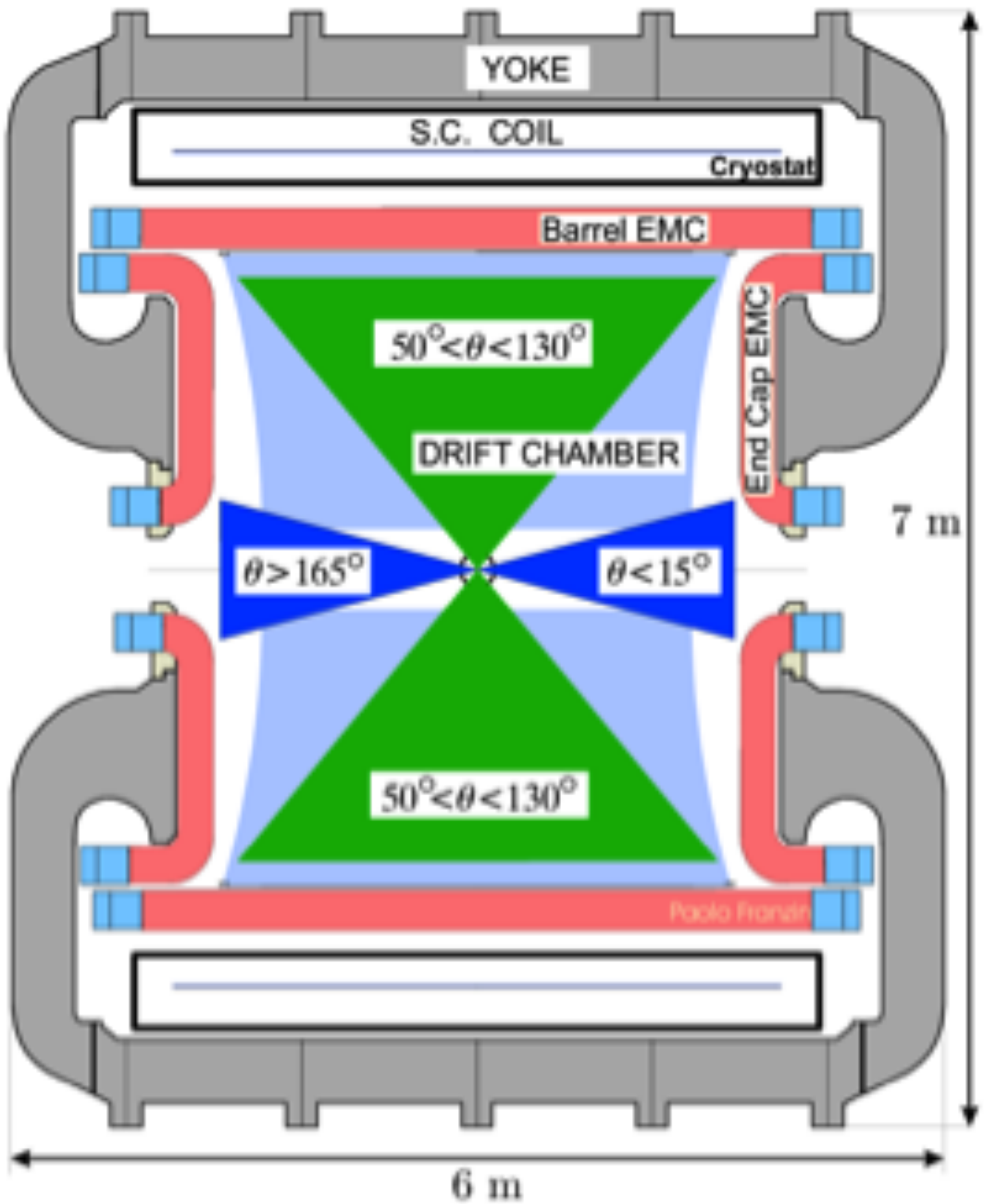
Selection cuts for analyses



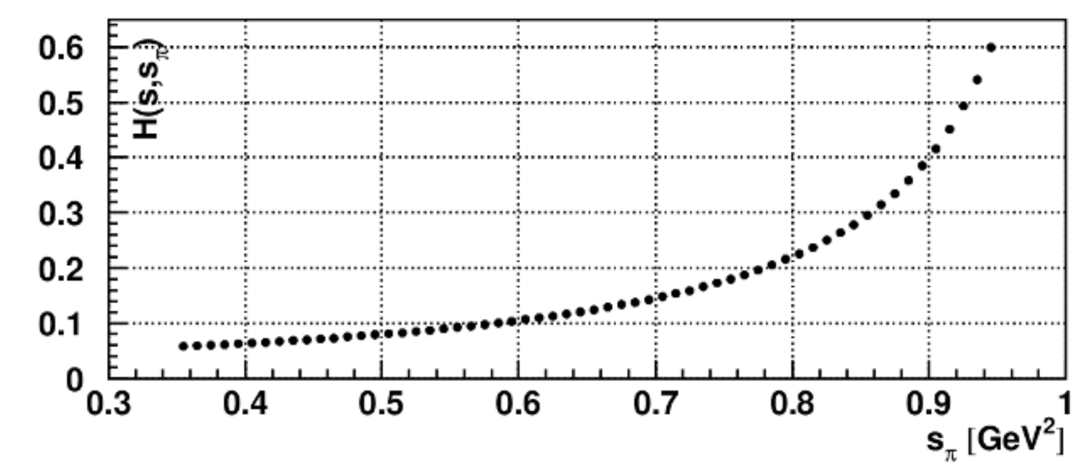
2 pion (muon) tracks at
$50° < \theta_{\pi,\mu} < 130°$
at Large Angle

Small angle photon selection
$\theta_{miss} < 15°$; $\theta_{miss} > 165°$

- high statistics for ISR events
- low FSR contribution
- suppression of $\phi \to \pi^+\pi^-\pi^0$ background
- photon momentum from kinematics:
  $\vec{p}_\gamma = \vec{p}_{miss} = -(\vec{p}^+ + \vec{p}^-)$
- threshold region not accessible

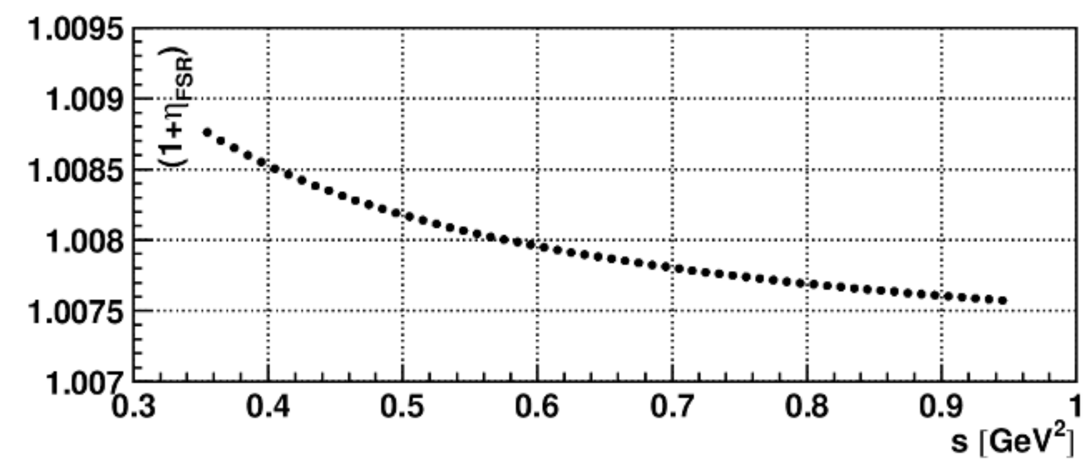
Radiative effects

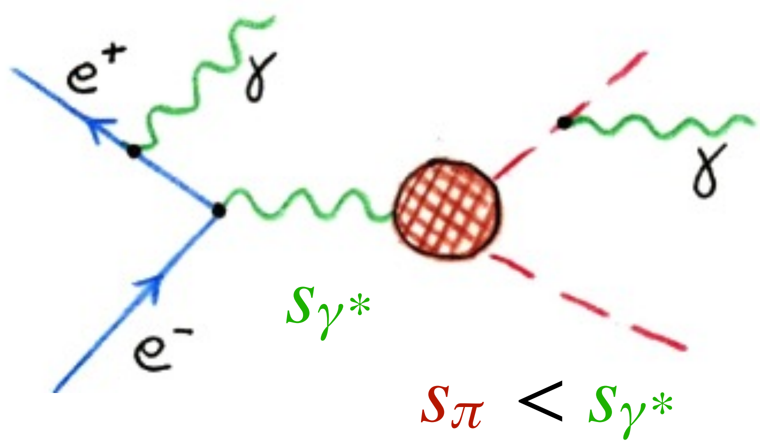
A. Radiator Function $H(s,s_\pi)$
=> ISR calculated at NLO-level
PHOKHARA Monte Carlo generator



B. Radiative Corrections

1. Vacuum Polarisation
   => to be removed to get the bare cross section => $\sigma^{\text{dress}}/\delta_{\text{VP}}(s)$
2. Final State Radiation
   => The $\sigma_{\pi\pi}$ cross section is inclusive of FSR





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% + /

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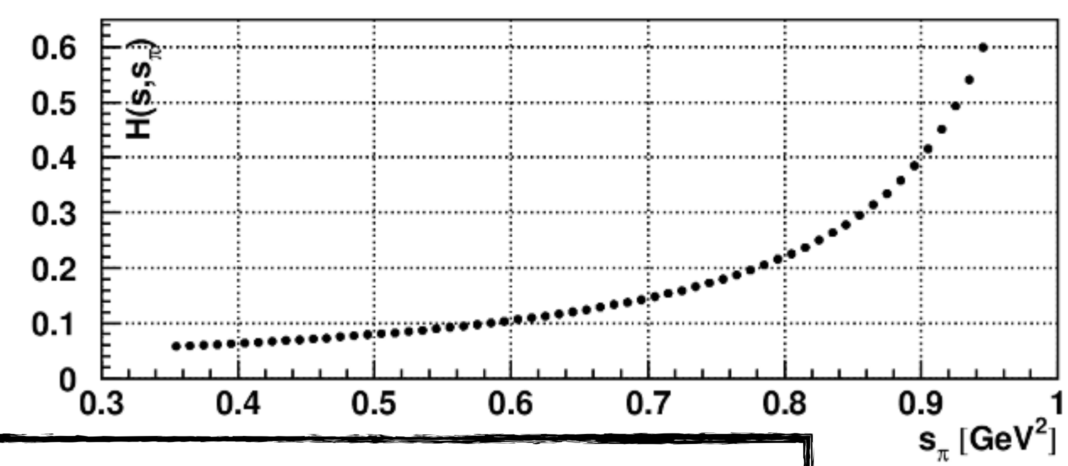
Radiative effects

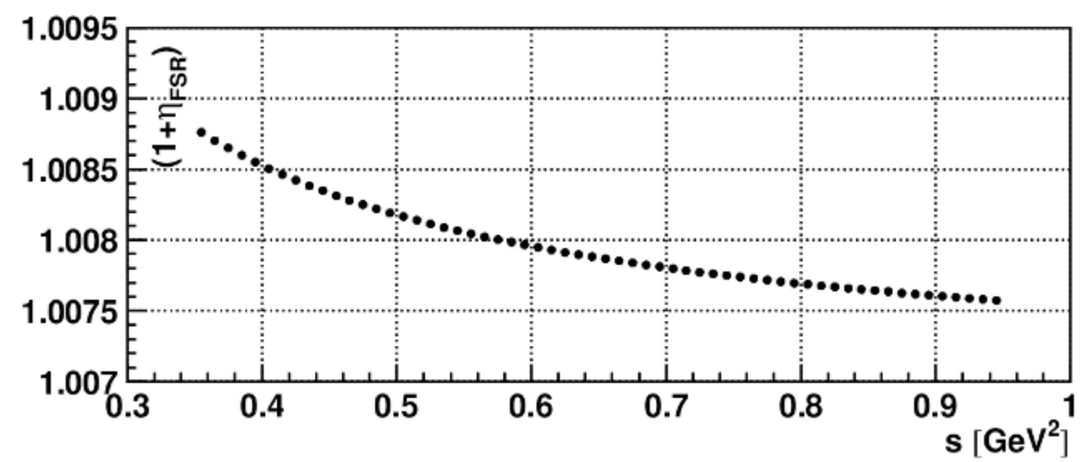
A. Radiator Function $H(s,s_\pi)$
=> ISR calculated at NLO-level
PHOKHARA Monte Carlo generator



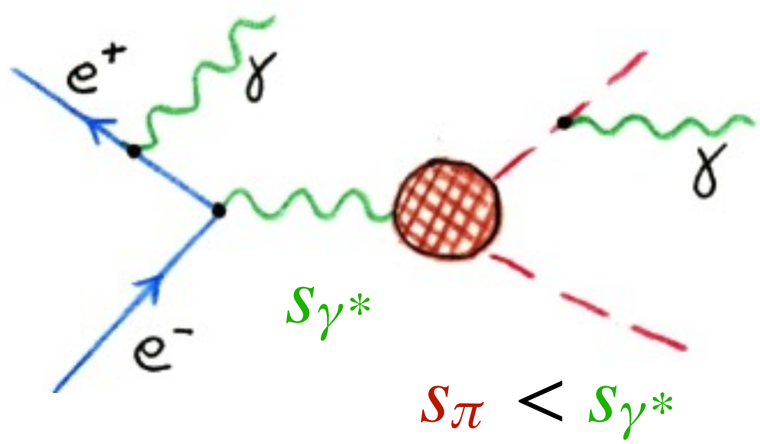
B. Radiative Corrections

Further theoretical and simulation works for improvements

1. Vacuum Polarisation
=> to be removed to get the bare cross section => $\sigma^{\text{dress}}/\delta_{\text{VP}}(s)$



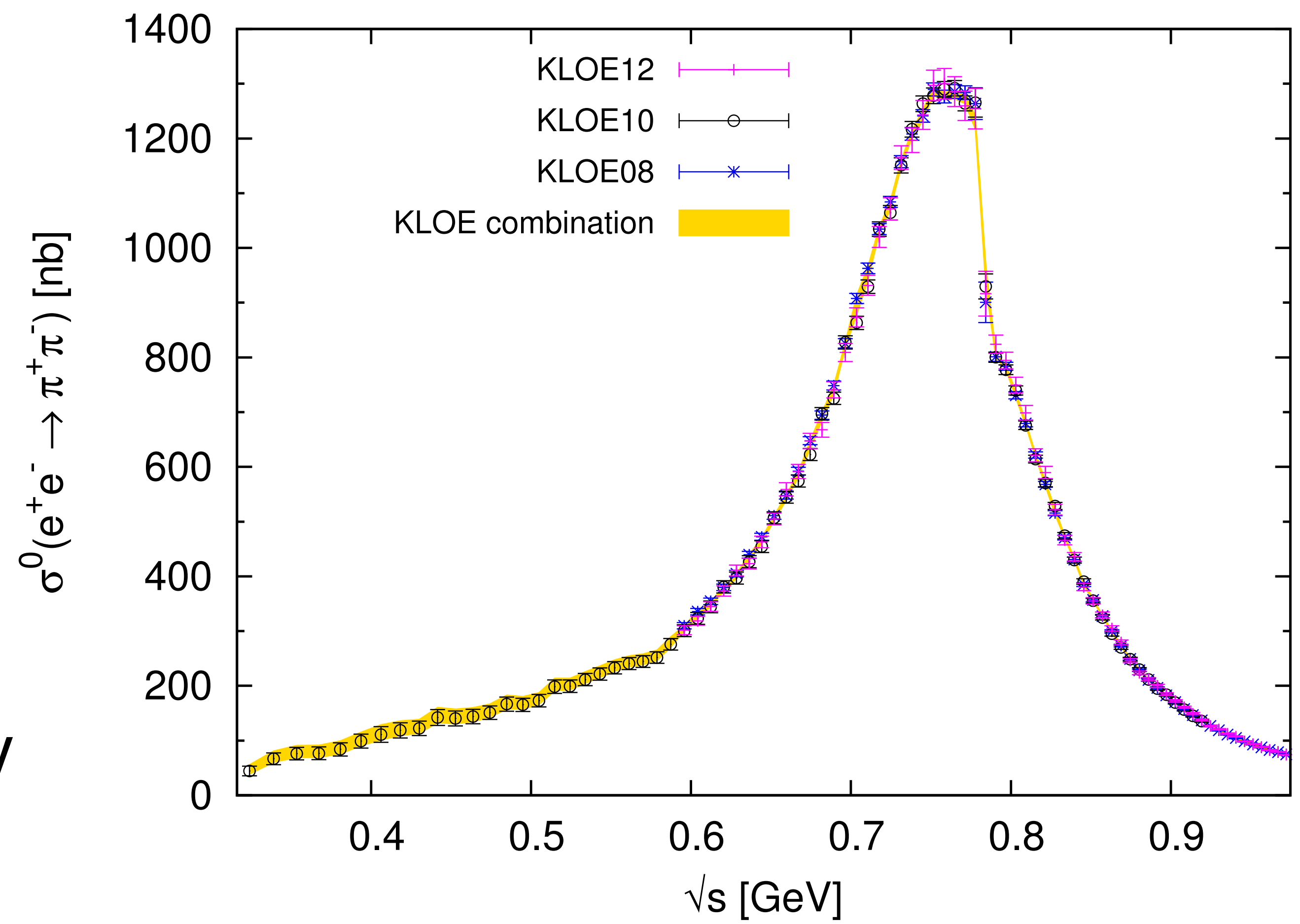
2. Final State Radiation
=> The $\sigma_{\pi\pi}$ cross section is inclusive of FSR



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% + /

KLOE analyses

- (*KLOE05*)
  Small Angle analysis of 140 pb^{-1} @ m_ϕ
  KLOE Coll. Phys. Lett. B 606 (2005)
- (***KLOE08***)
  Small Angle analysis of 240 pb^{-1} @ m_ϕ
  KLOE Coll. Phys. Lett. B 670 (2009)
- (***KLOE10***)
  Large angle analysis of 250 pb^{-1} @ 1 GeV
  KLOE Coll. Phys. Lett. B 700 (2011)
- (***KLOE12***)
  KLOE08 with normalisation to $e^+e^- \to \mu^+\mu^-$
  KLOE Coll. Phys. Lett. B 720 (2013)



Combination of three datasets
JHEP 1803 (2018) 173

$a_\mu^{\pi\pi}$ [$0.1 < s < 0.95$ GeV^2] =
$(489.8 \pm 1.7_{stat} \pm 4.8_{sys}) \times 10^{-10}$

Uncertainty

Syst. errors (%)	$\Delta^{\pi\pi} a_\mu$ abs [4]	$\Delta^{\pi\pi} a_\mu$ 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

Uncertainty

We want to improve…

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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

Summary and plans

- Determination of $a_\mu^{\pi\pi}$ at the sub-percent level
- Results in tension with other collaborations… to be clarified

A. Leverhulme International Professorship: G. Venanzoni
  - F. Ignatov P. Beltrame, E. Zaid;
    A. Kumari, N. Vestergaard, C. Devanne

B. Colleagues from the Theoretical Physics group: Prof. T. Teubner
  - W. T. Bobadilla, J. Paltrinieri
    T. Dave, P. Petit Rosas

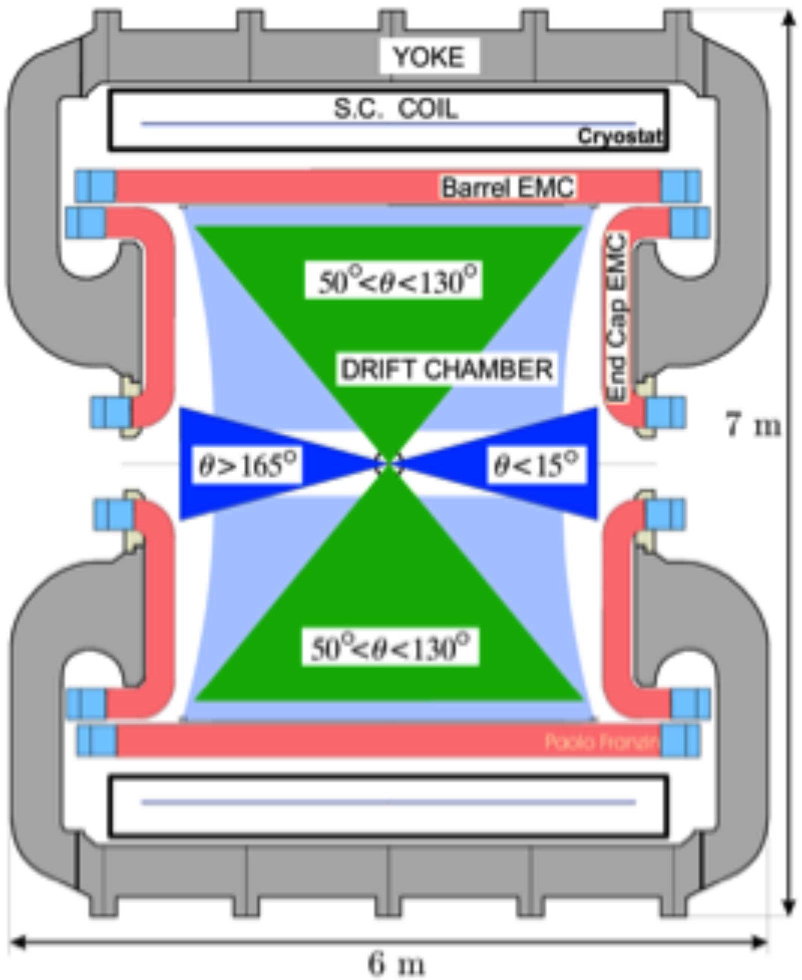
C. S. Müller, L. Punzi, A. Kupsc, O. Shekhovstova, A. Keshavarzi, W. Wislicki, A. Lusiani, J. Wiechnik

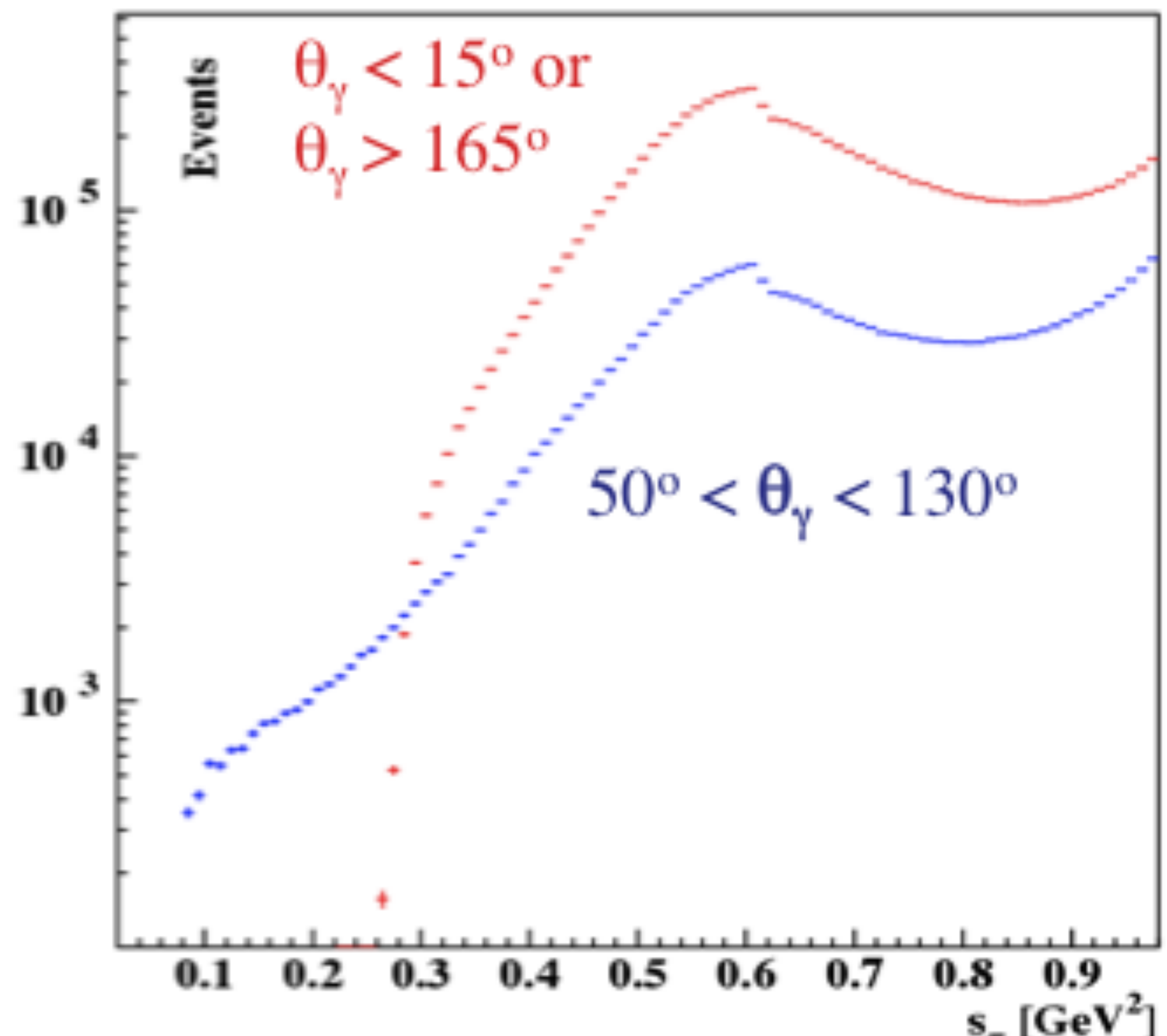
- Development of independent, modern software and algorithms
  => An independent robust analysis at the sub-percent level

Thank you!

Threshold region

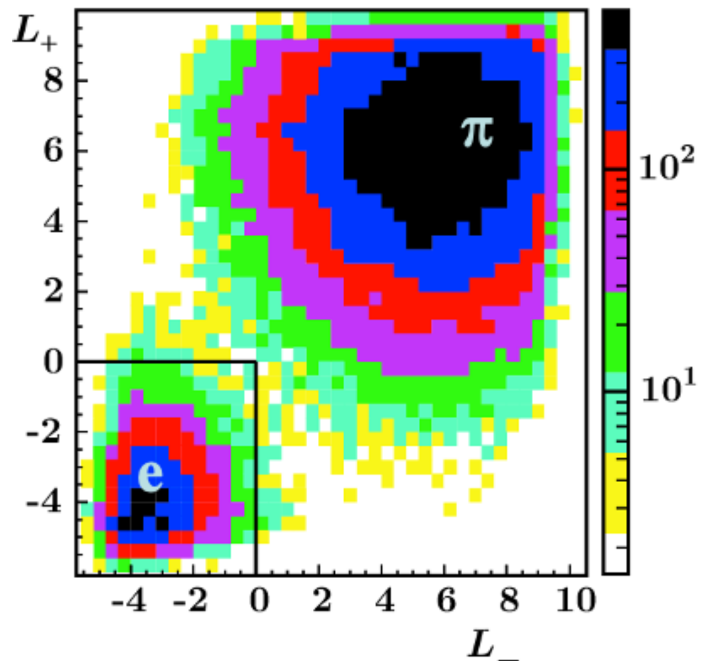
- Events at small energy ($M^2_{\pi\pi}$ < 0.35 GeV^2, $M_{\pi\pi}$ < 0.6 GeV) are suppressed for small angle analysis, but can be reached with the large angle analysis



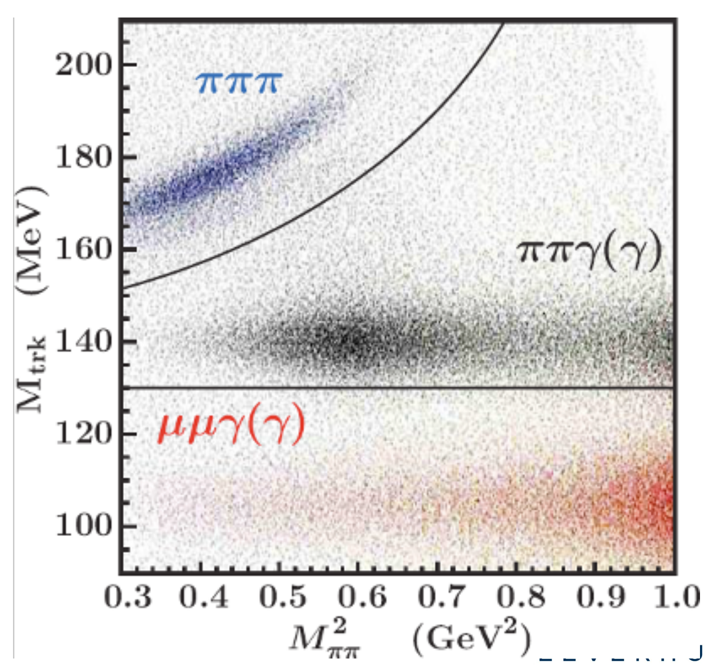


Signal Selection

- Two tracks at large polar angle from the IP
  => $\pi^+\pi^-\gamma$
- Background
  $e^+e^- \rightarrow e^+e^-\gamma$, $\mu^+\mu^-\gamma$, $\phi \rightarrow \pi^+\pi^-\pi^0$



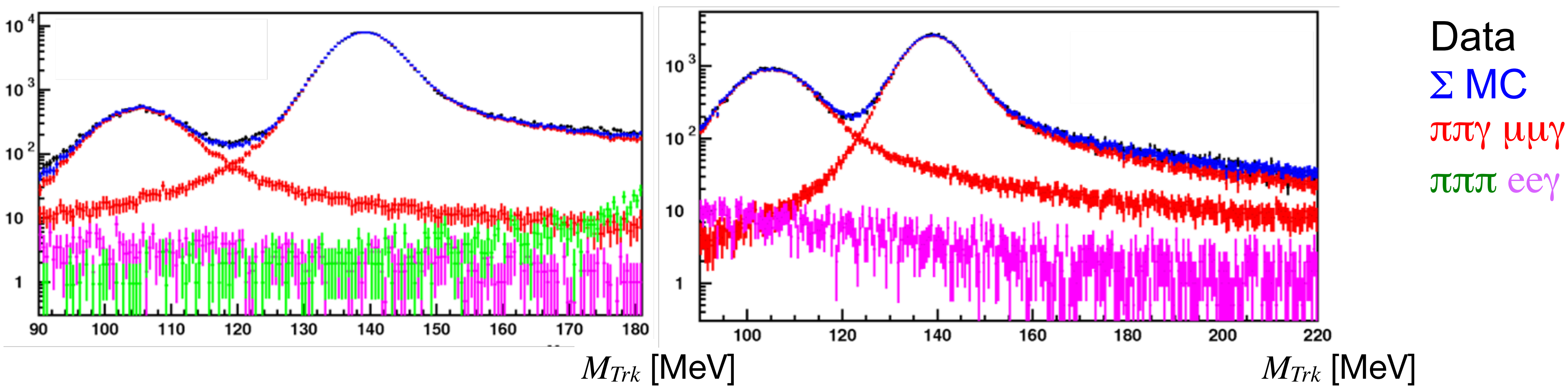
  - PID for π-e separation
    calorimeter and time of flight
  - Kinematic cuts:
    Trackmass: $e^+e^- \rightarrow x^+x^-\gamma$

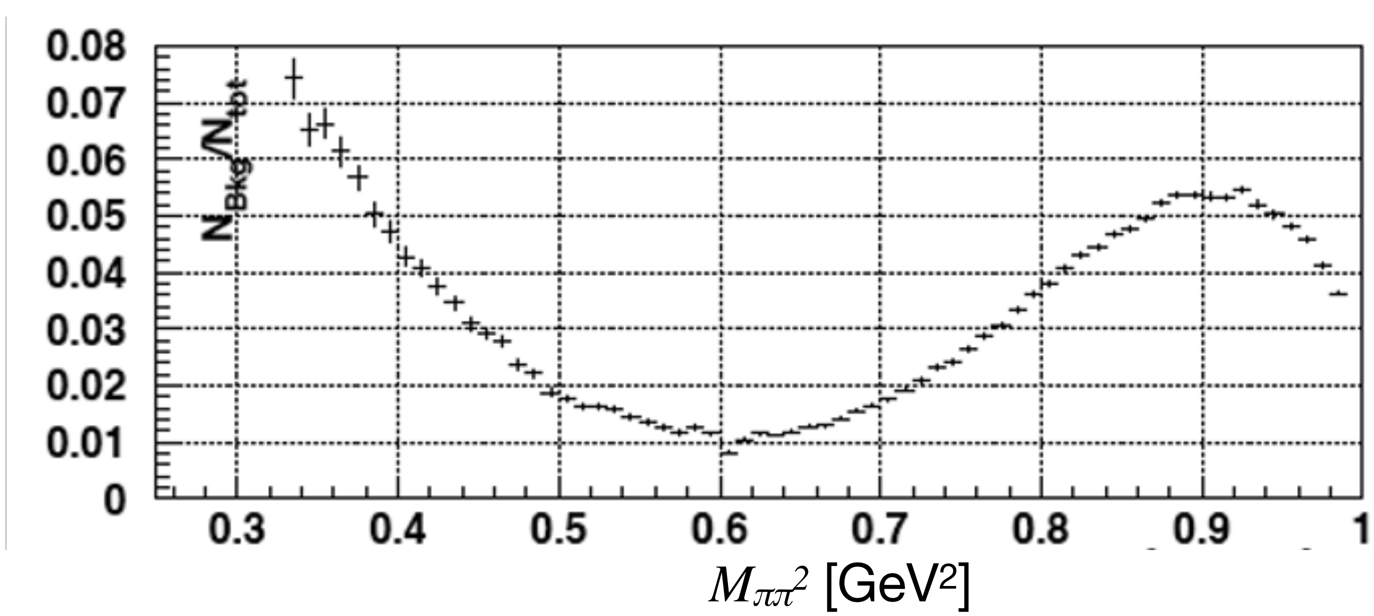


$$\left(\sqrt{s} - \sqrt{\vec{p}_{x+}^{\,2} + M_{trk}^2} - \sqrt{\vec{p}_{x-}^{\,2} + M_{trk}^2}\right)^2 - (\vec{p}_{x+} + \vec{p}_{x-})^2 = q_\gamma^2 = 0$$

Background subtraction

Main backgrounds obtained from MC shapes fitted to data distribution in M_{Trk} ($\pi\pi\gamma$ and $\mu\mu\gamma$, $\pi\pi\pi$, $ee\gamma$)





Total uncertainty on Background estimation	
$a^{\pi\pi}_{\mu\mu}$ abs	0.3 %
$a^{\pi\pi}_{\mu\mu}$ ratio	0.6 %

KLOE results