$\sigma(e^+e^-\rightarrow \text{hadrons}+\gamma)$

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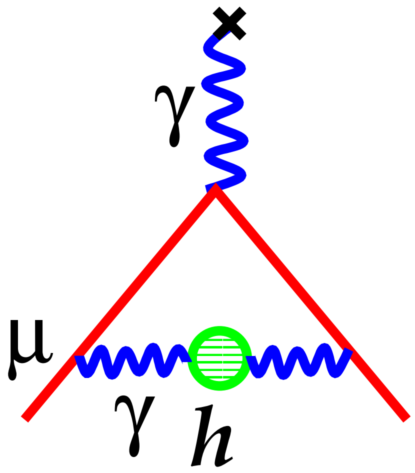
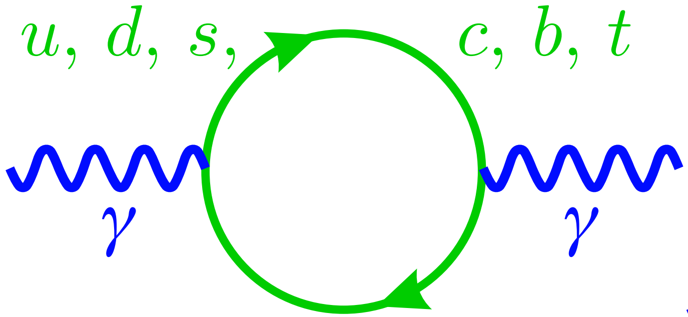
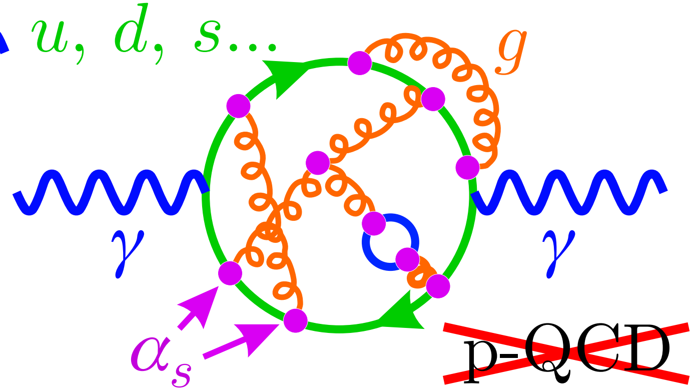
1. Why measure σ(hadrons+γ)
2. $\sigma_{\text{had}}(s')$ at fixed s
3. Advantages
4. Disadvantages
5. First results from KLOE
6. What next for KLOE

The question: "is there a discrepancy between standard model estimates and measurements" is important enough to warrant any possible check.
"Radiative return" due to initial state radiation, allows the measurement of hadro-production for $2m_\pi < s' < s$, at fixed collider s.

Recall that to calculate of a_μ we need the vacuum polarization corrections due to quark loops:







which cannot be calculated for low s, but

$$\Im\Pi(s)/\pi \quad = \quad s\sigma(e^+e^- \to \mathrm{hadr})/(16\pi^3\alpha^2)$$

$$\delta a_\mu^{\mathrm{had,lo}} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty}\sigma_{e^+e^-\to\mathrm{hadr}}(s)K(s)\mathrm{d}s.$$

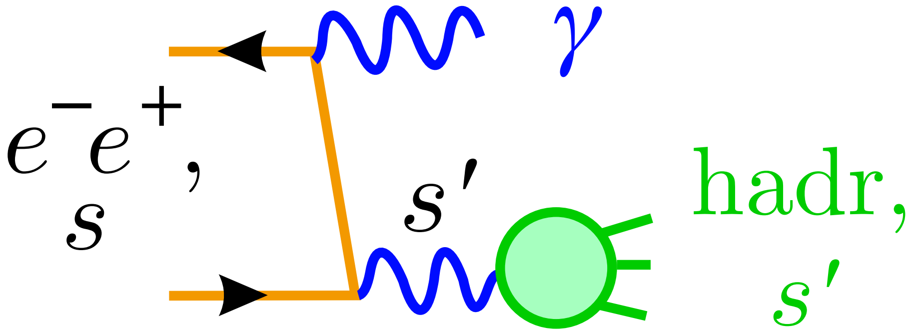
$K(s) \approx 1/s$, *i.e.* enhance low s. Some authors substitute:

$$\sigma_{e^+e^-\to\,\mathrm{hadr}}(s) \Rightarrow \frac{4483.124}{4483.124}\,\frac{s}{s}\,\sigma_{\,\mathrm{hadr}}(s) = \frac{R_{\,\mathrm{hadr}}}{s\times 4483.124}.$$

$1/(s\times 4483.124)$ $(4\pi\,\alpha^2/3s)$ is the lowest order QED cross section for e^+e^- annihilation into massless muons.

"Radiative return" due to initial state radiation, gives us the possibility of measuring hadro-production for $2m_\pi < s' < s$, at fixed collider s.

To lowest order the **ISR ONLY** amplitude is ($W^2 = s$):



from which

$$\frac{\mathrm{d}\sigma(\mathrm{hadrons} + \gamma)}{\mathrm{d}s_\pi \mathrm{d}\cos\theta_\gamma} = \frac{\alpha}{\pi s}\sigma_{\mathrm{hadr}}(s') \left[\frac{s^2 + s'^2}{s'(s - s')}\frac{1}{\sin^2\theta} - \frac{s - s'}{2s'}\right]$$

Binner, Kühn and Melnikov

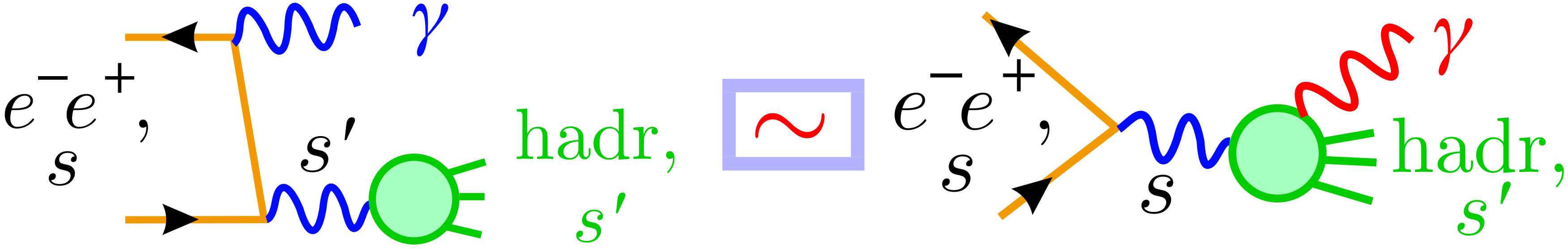
Example: hadr=$\pi^+\pi^-$, $s' = s_\pi = M^2_{\pi^+\pi^-}$.

$$\frac{\mathrm{d}\sigma(\pi\pi\gamma)}{\mathrm{d}s_\pi \mathrm{d}\cos\theta_\gamma} \sim \sigma(e^+e^- \to \pi^+\pi^-,\ s_\pi) \times \sigma(e^+e^- \to \gamma\gamma,\ s)$$

Advantages

1. Do not need to operate the collider at different energies
2. The overall energy scale, at least in a detector like KLOE is established at W=m_ϕ and applies to all values of M(hadr)
3. The luminosity is measured at fixed energy, for the entire data set, avoiding painful corrections

Disadvantages I.

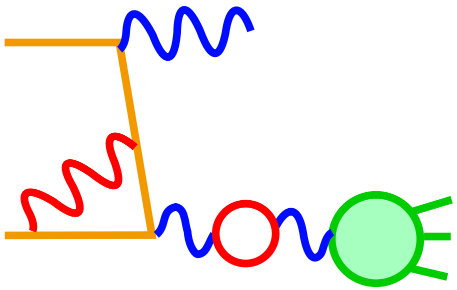


$s_\gamma = s'$ $\qquad\qquad$ $s_\gamma = s \neq s'$

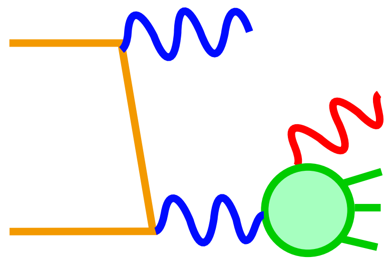
FS radiation is $\mathcal{O}(1)$ background to σ of interest!

Cannot distinguish two processes, need precise estimates.

Must also remove - correct for



and properly retain



Disadvantages II.

One must perform an absolute measurement of a cross section which is only a tiny fraction of the total cross section

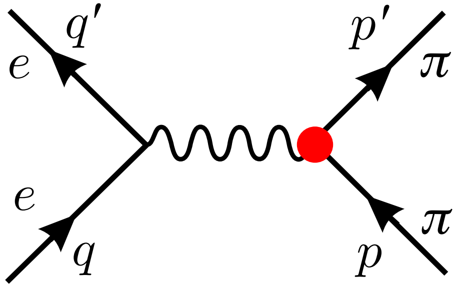
At KLOE, σ(Bhabha)$\sim$100 μb

σ(hadrons)$\sim$3 μb

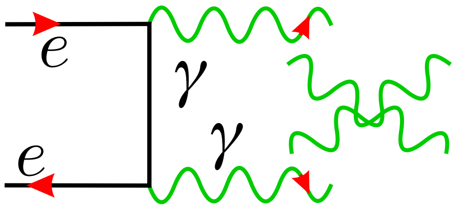
$\sigma(\pi^+\pi^-\gamma)\sim$0.01 μb

$e^+e^-\to\pi^+\pi^-,\ \gamma\gamma,\ \gamma\pi^+\pi^-$

$$\mathfrak{M} \propto e^2 J_e^\mu A_\mu \frac{1}{s}(p'-p)^\nu A_\nu F_\pi(s)$$

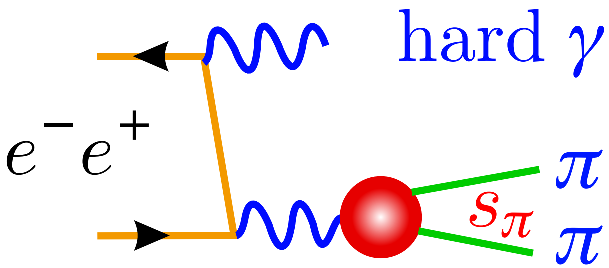


$$\sigma_{\pi\pi} = \frac{\pi\,\alpha^2}{3s}\,\beta^3\,|F_\pi(s)|^2$$



$$\overline{|\mathfrak{M}|^2} = 2e^4\left(\frac{u}{t}+\frac{t}{u}\right)$$

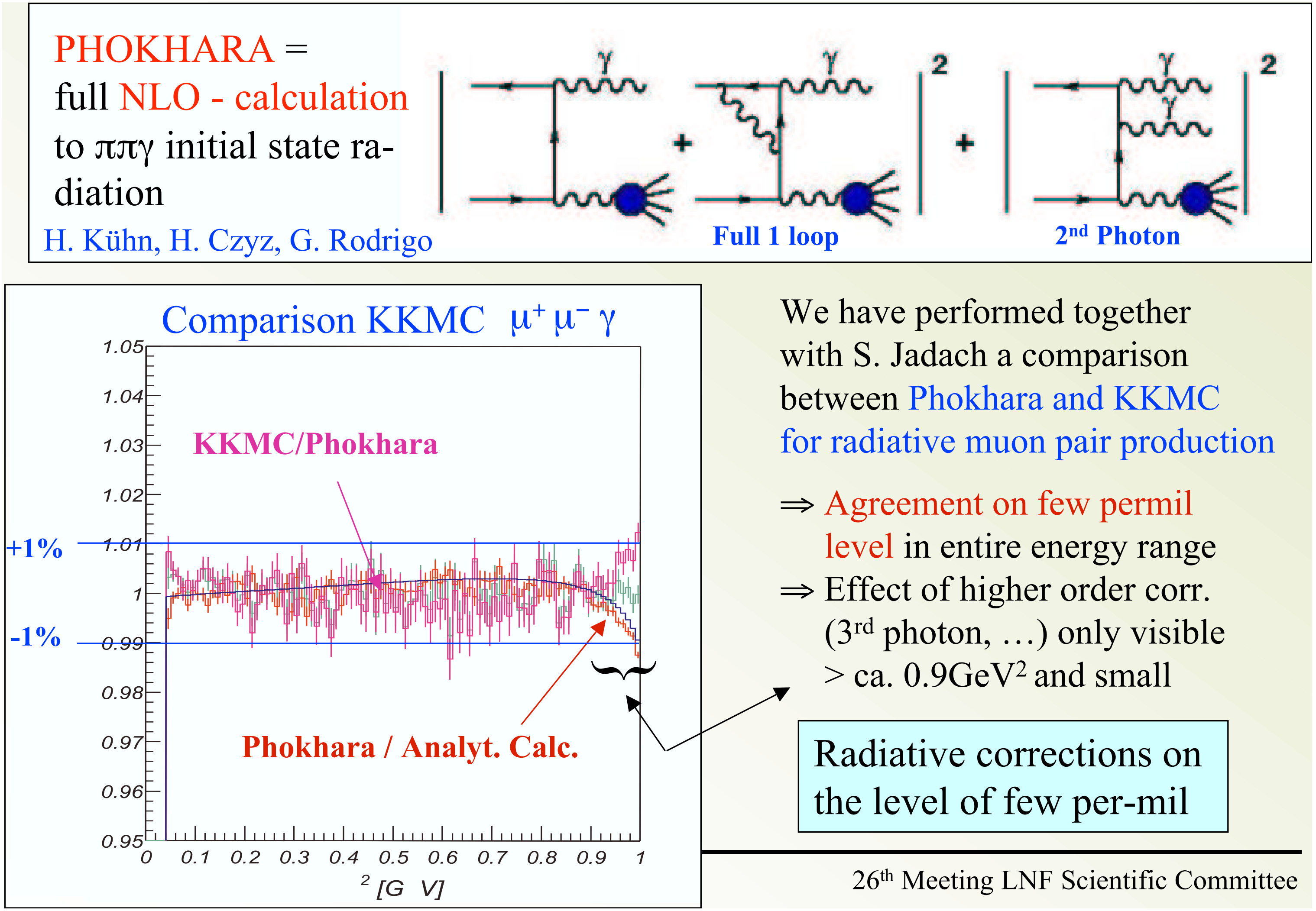
$$\frac{d\sigma_{\gamma\gamma}}{d\cos\theta} = \frac{2\pi\alpha^2}{s}\,\frac{1+\cos^2\theta}{\sin^2\theta}$$



$$\frac{d\sigma(\pi\pi\gamma)}{ds_\pi d\cos\theta_\gamma} = \frac{\alpha}{\pi s}\,\sigma_{\pi\pi}(s_\pi)\left[\frac{s^2+s_\pi^2}{s_\pi(s-s_\pi)}\,\frac{1}{\sin^2\theta} - \frac{s-s_\pi}{2s_\pi}\right]$$

Radiative corrections

ISR. This is a well understood process and we have the appropriate, tested tools for dealing with it.

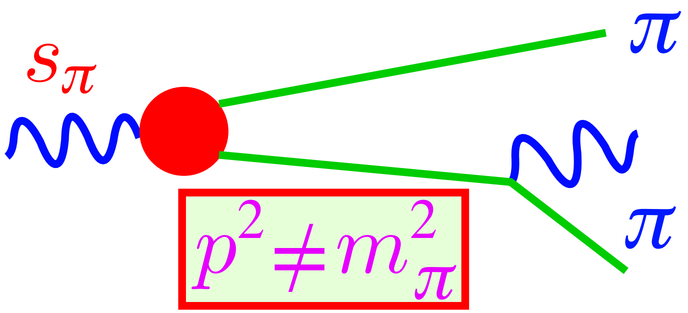


this is tex

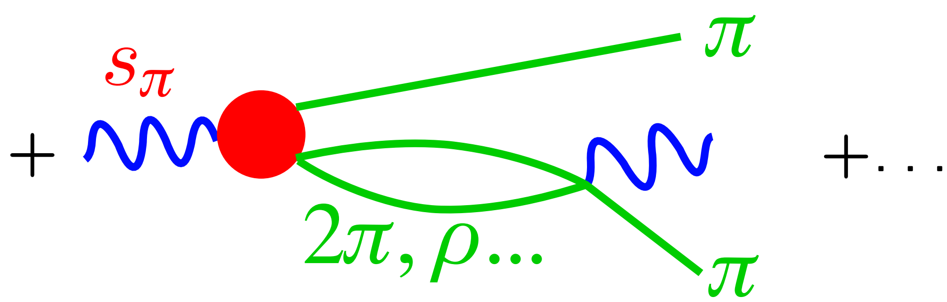
Vacuum Polarization

This is the same for everybody and presumably very well understood, today. The question is to apply it, correctly, to data and whatever normalizing process is used to get $\mathcal{L}$ (usually Bhabha scattering).

FSR 1. Hard photon

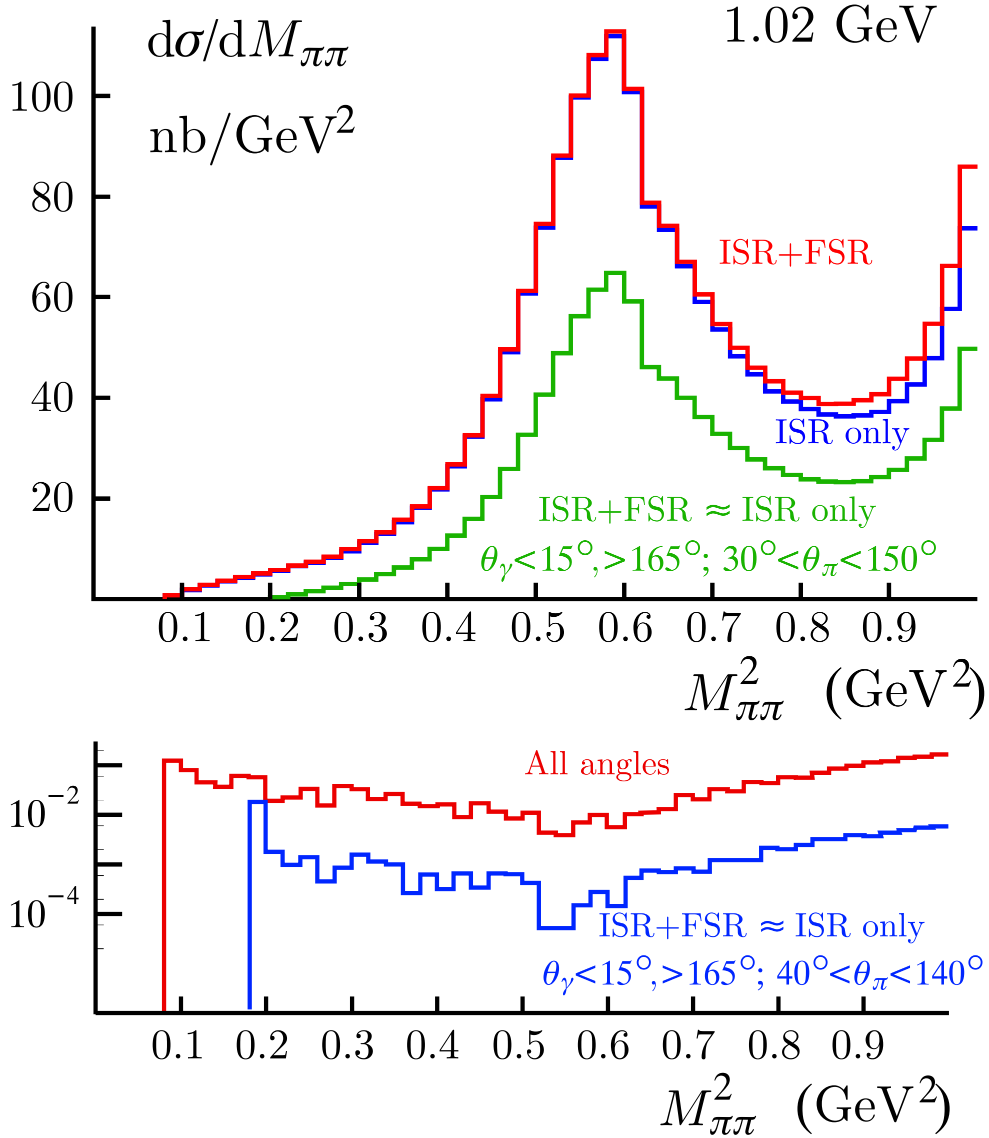


Therefore also



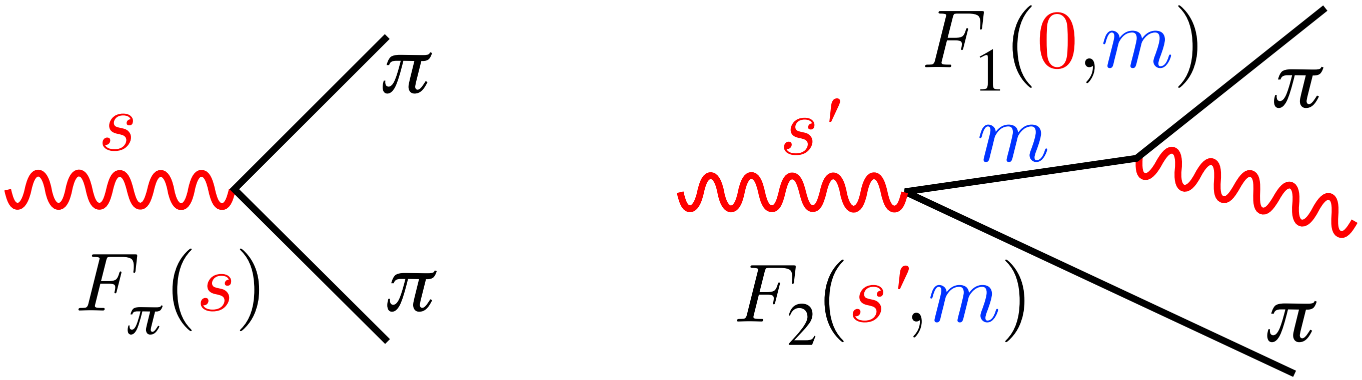
Ways out?

Take only small angle γ, ISR dominates, FSR not important.



But small s_{had} is lost

Simultaneously measure 3 "form factors", F_π, F_1, F_2. Inclusive σ preferred. (F.J.)



A truly inclusive measurement, as recommended, is never possible. Background channels invalidate the measurement. There are possible compromises, but with poorer statiscs.

Otherwise try χPT calculations. In any case 3-body processes are suppressed, $\sim 1/32\pi^2$. Likewise $\rho\pi\gamma$ small. It is quite reasonable to begin with point like pions and correct the result (G.I.)

FSR 2. Soft photons

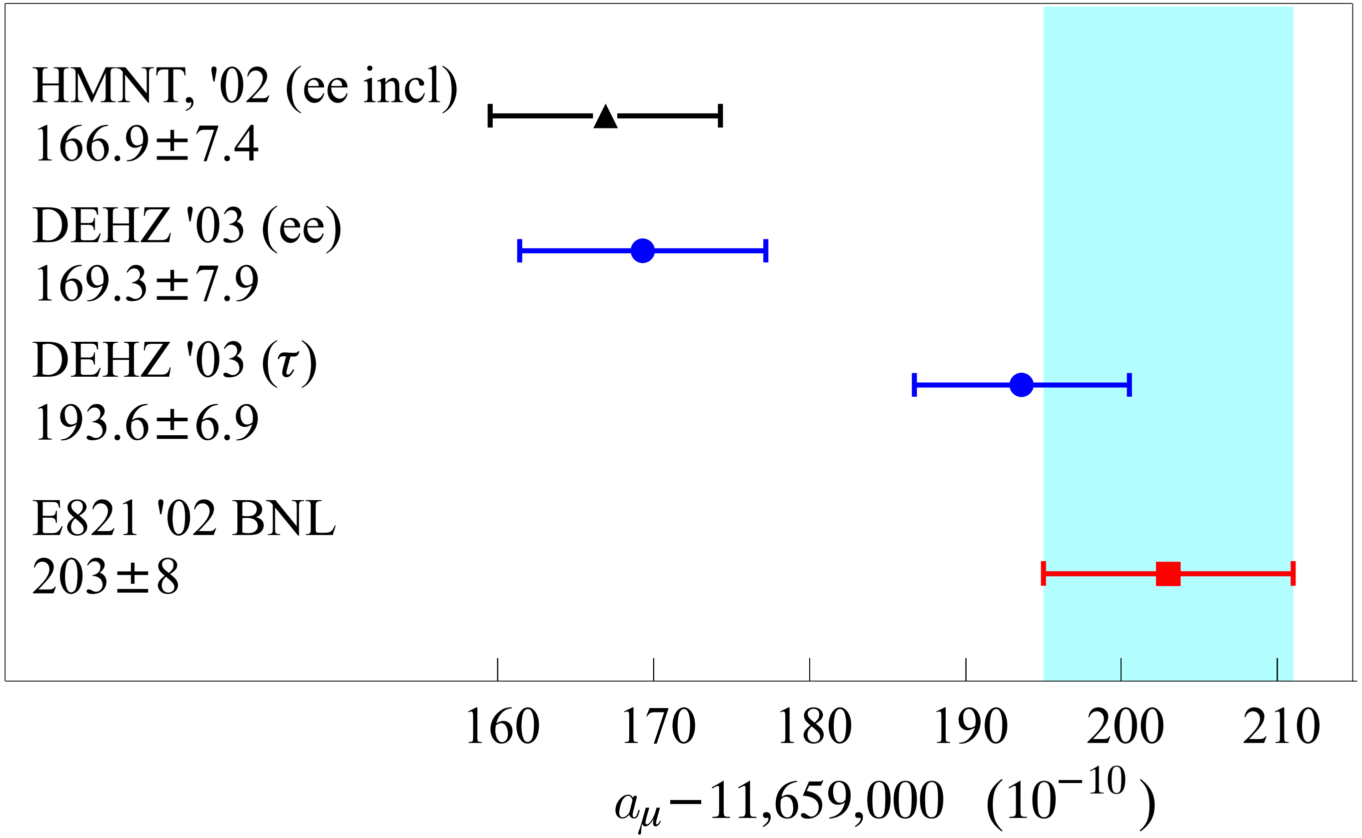
This refers to the presence of soft radiation in the final state, together with radiation of a hard photon by the initial electron-positron which allows one to measure $\sigma(s' < s)$. One needs proper modelling to ensure that whatever FSR has been removed by the event selection criteria, is reintroduced for a proper measurement to get to the muon anomaly.

Not Quite Final Results from KLOE

I am reporting now on a precision measurement of the $\pi^+\pi^-$ cross section around the ρ region, performed with KLOE, with 2 million $\pi^+\pi^-\gamma$ events
I wish to remind you why our first effort is concentrated in this energy region by showing the impact of related measurements on a_μ.
Let us remember that out of a contribution to a_μ of $\sim 685\times10^{-10}$, $\sim 441\times10^{-10}$ is due to the $\pi^+\pi^-$ channel, whose best measurement comes from CMD-2 at Novosibirsk with 110,000 events and a combination of τ data, in the $\pi^\pm\pi^0$ channels, from LEP and CESR, which appear to disagree.

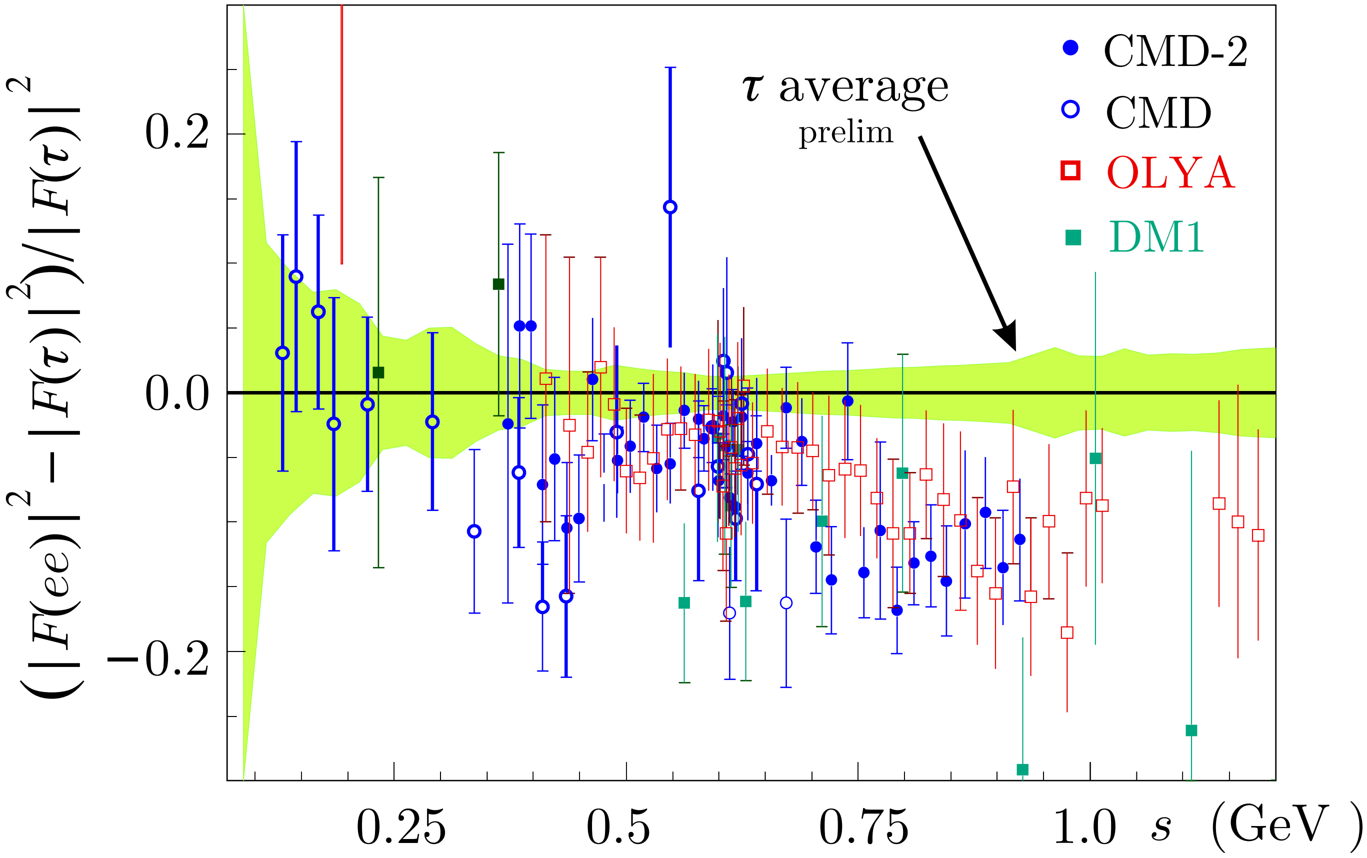
KLOE contributions

1. a_μ. Comparison of measurement and calculations.



The situation is somewhat embarrassing: we can't say if there is agreement with experiment. . . there is possibly a problem with τ-e^+e^- data.

2. e^+e^- data are clearly lower than τ extracted info, around the ρ region

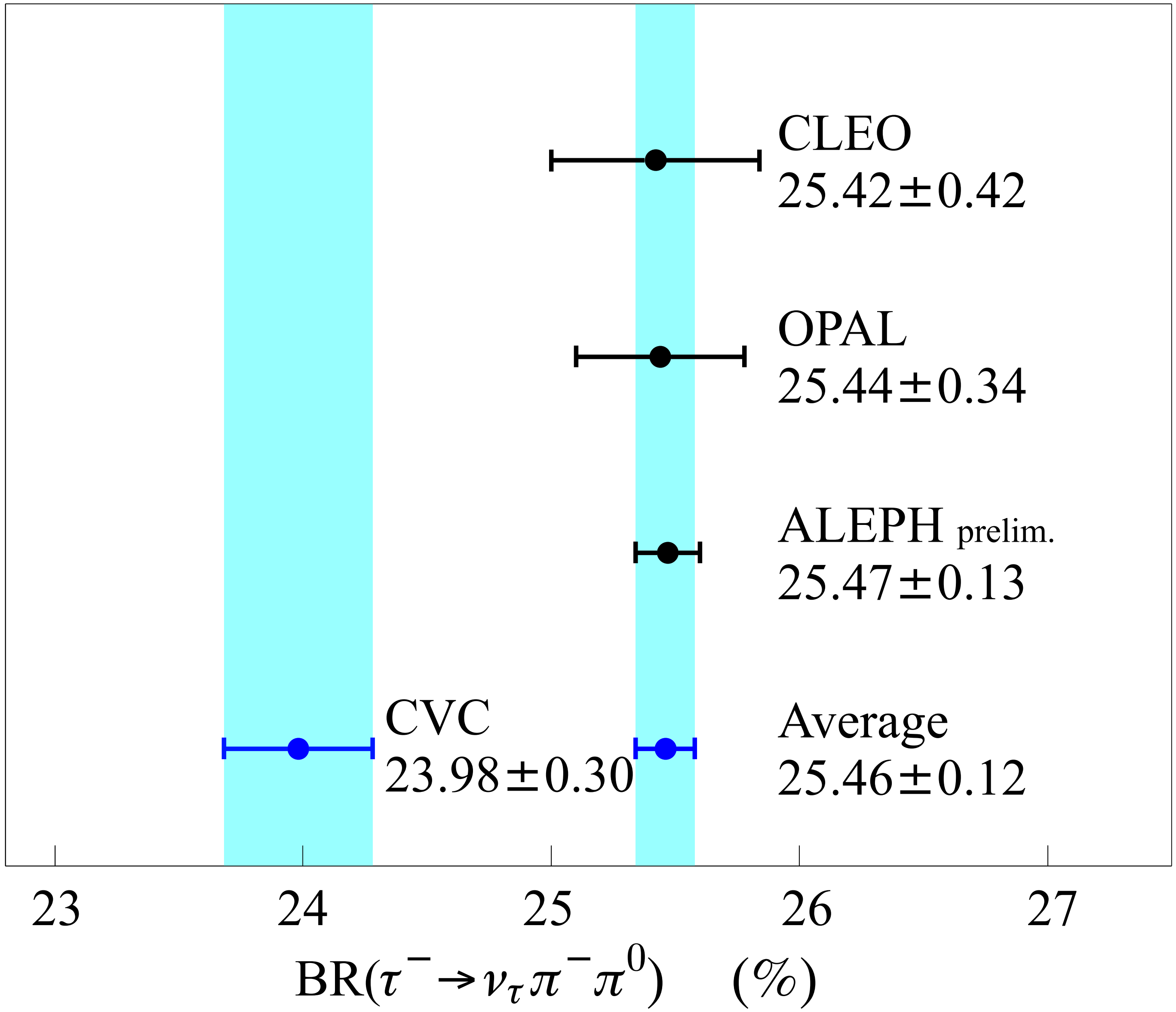


$$\Delta a_\mu(\tau - e^+e^-) = (24.3 \pm 7.9_{\text{exp}} \pm 3.8_{\text{rad}} \pm 2.8_{I-\text{spin}}) \times 10^{-10}$$

2.6 σ discrepancy

The disagreement is in fact stronger, when comparing BR:

~6% or ~4.6σ. 6% is a rather large I-spin violation!



KLOE can

e^+e^- - data with CMD-2 results

2) Cross check the central value of $a_\mu^{hadr} = (\,684.7 \pm 6.0_{exp} \pm 3.6_{rad}\,) \times 10^{-10}$

➡ At which precision can we be significant /competitive?

Benchmark measurement

CMD-2 '01 : systematic error = 0.6%

$a_\mu^{2\pi} = (\,368.1 \pm 2.6_{stat} \pm 2.2_{syst}\,) \times 10^{-10}$

to be compared

KLOE statistics :

2001: factor 20 more data

⇒ will be dominated by systematics!

KLOE systematics:

$$\delta a_\mu \approx \delta a_\mu^{hadr} = \sqrt{\underbrace{(\delta a_\mu^{2\pi})^2}_{\text{KLOE}} + \underbrace{(\delta a_\mu^{Rest})^2}_{\pm 5.1 \times 10^{-10}}} = \begin{cases} \pm 6.3_{exp} \times 10^{-10} & @\ 1\%\ \text{precision} \\ \pm 9.0_{exp} & 2\%\ \text{precision} \\ \pm 12.2_{exp} & 3\%\ \text{precision} \end{cases}$$

KLOE *systematics???*

KLOE

$e^+e^-\to\pi^+\pi^-\gamma$ simplified

To lowest order, *but* only ISR, Binner, Kühn and Melnikov give:

$$\frac{\mathrm{d}\sigma(\pi\pi\gamma)}{\mathrm{d}s_\pi \mathrm{d}\cos\theta_\gamma} = \frac{\alpha^3}{3s^2}\,|F_\pi(s_\pi)|^2\,\beta_\pi^3\,\left[\frac{s^2+s_\pi^2}{s_\pi(s-s_\pi)}\frac{1}{\sin^2\theta} - \frac{s-s_\pi}{2s_\pi}\right]$$

where $s_\pi = M_{\pi\pi}^2$ and $\beta_\pi = \sqrt{1-4m_\pi^2/s_\pi}$ is the pion velocity in the $\pi\pi$ system.

Integrating over $\cos\theta$, from $x_1 = \cos\theta_1$ to $x_2 = \cos\theta_2$ $(\theta_1 > \theta_2)$ we get:

$$\frac{\mathrm{d}\sigma(\pi\pi\gamma)}{\mathrm{d}s_\pi} = \frac{\alpha^3}{3ss_\pi}\,|F_\pi(s_\pi)|^2\;\beta_\pi^3\times$$

$$\left[\frac{1}{2}\frac{s^2+s_\pi^2}{s(s-s_\pi)}\left(\log\frac{1+x_2}{1-x_2}+\log\frac{1-x_1}{1+x_1}\right)-\frac{s-s_\pi}{2s}(x_2-x_1)\right]$$

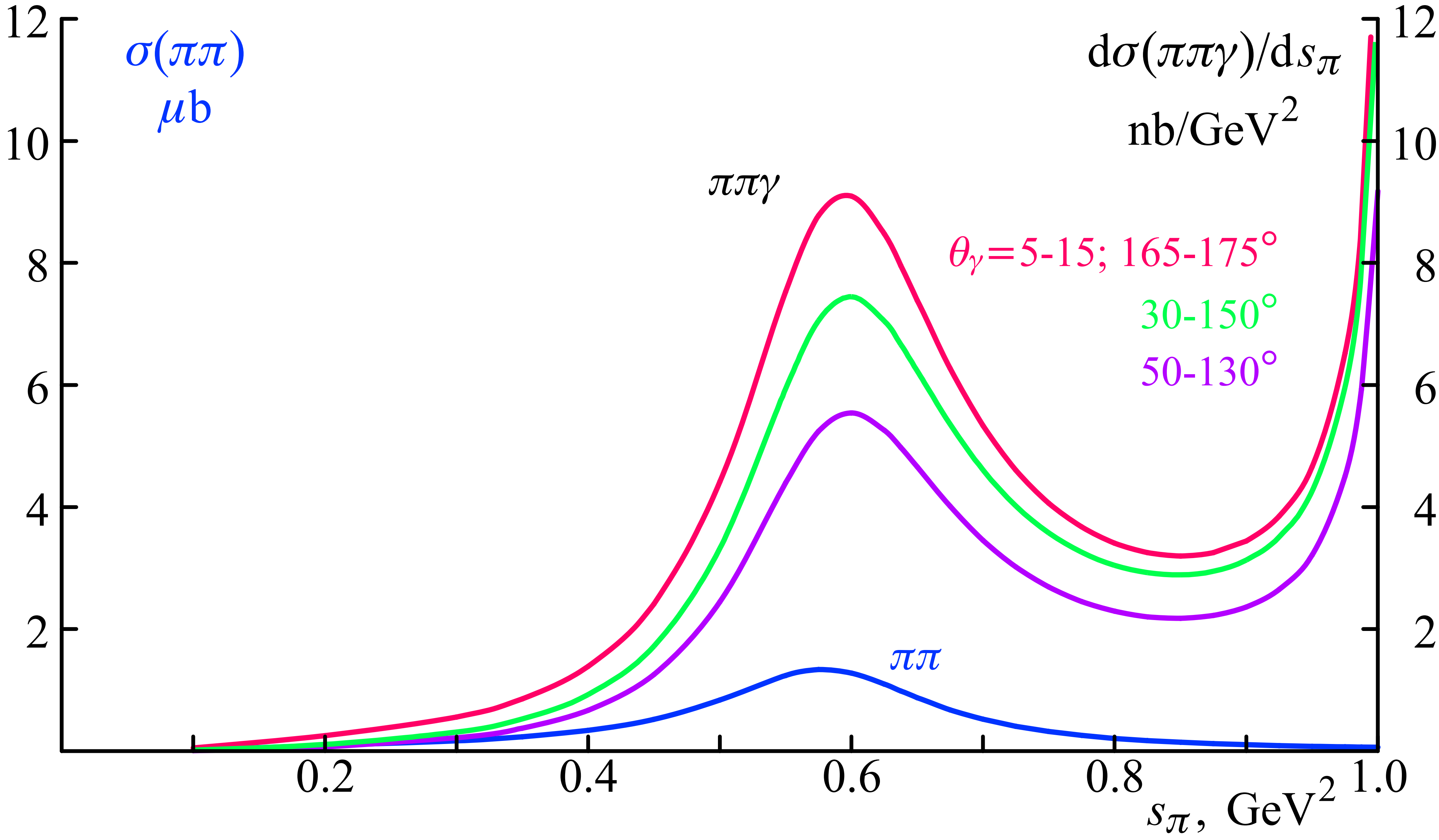
For $\theta < \theta_\gamma < 180 - \theta$, $x = \cos\theta$

$$\frac{\mathrm{d}\sigma(\pi\pi\gamma)}{\mathrm{d}s_\pi} = \frac{\alpha^3}{3ss_\pi}\,|F_\pi(s_\pi)|^2\;\beta_\pi^3\left[\frac{s^2+s_\pi^2}{s(s-s_\pi)}\,\log\frac{1+x}{1-x} - \frac{s-s_\pi}{2s}\,2x\right]$$

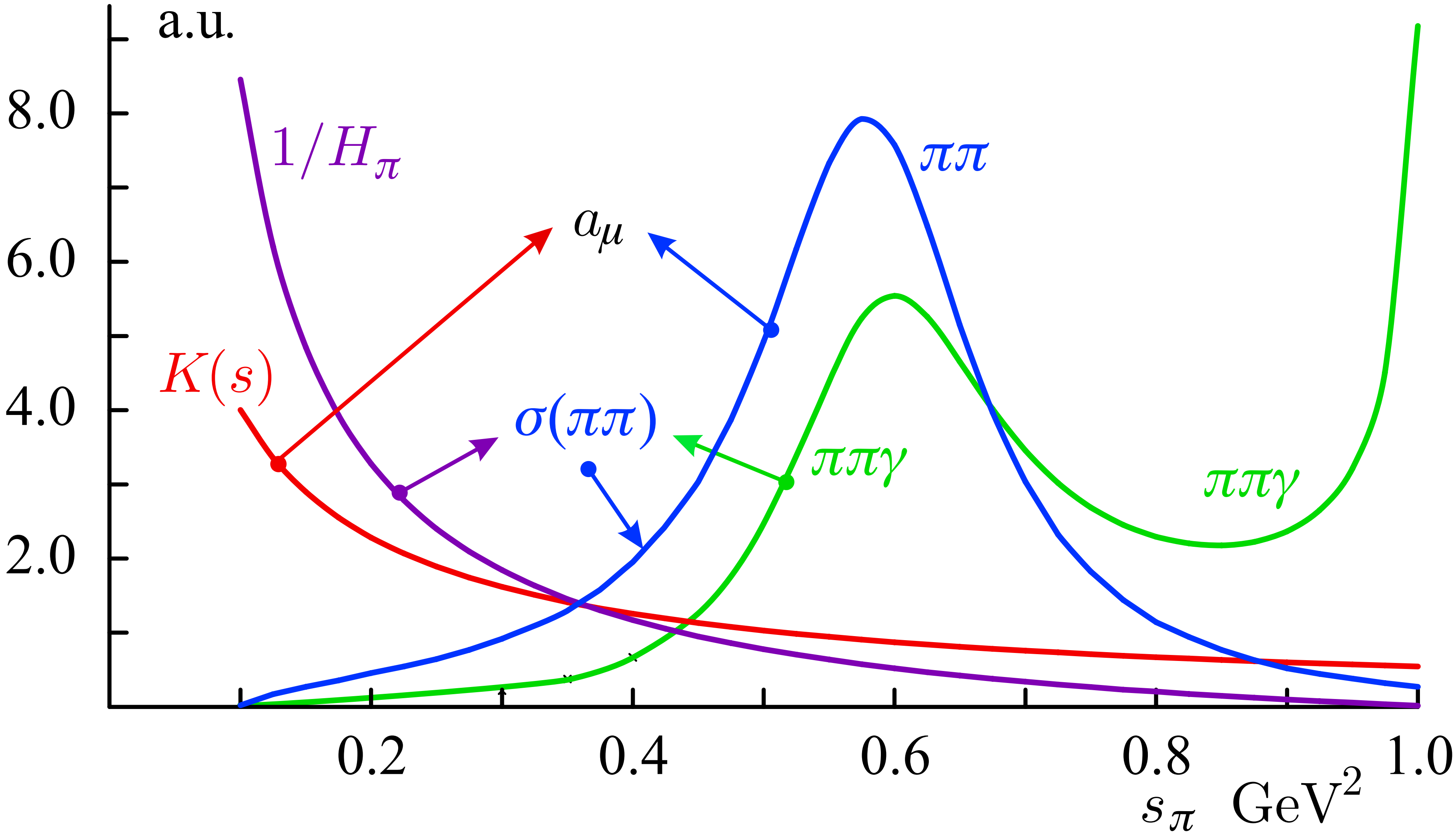
$$= \frac{\alpha}{s\pi}\left[\frac{s^2+s_\pi^2}{s(s-s_\pi)}\,\log\frac{1+x}{1-x} - \frac{s-s_\pi}{s}\,x\right]\sigma(\pi\pi,\,s_\pi)$$

$$= H \times \sigma(\pi\pi,\,s_\pi)$$

Definition of H, the radiator function.



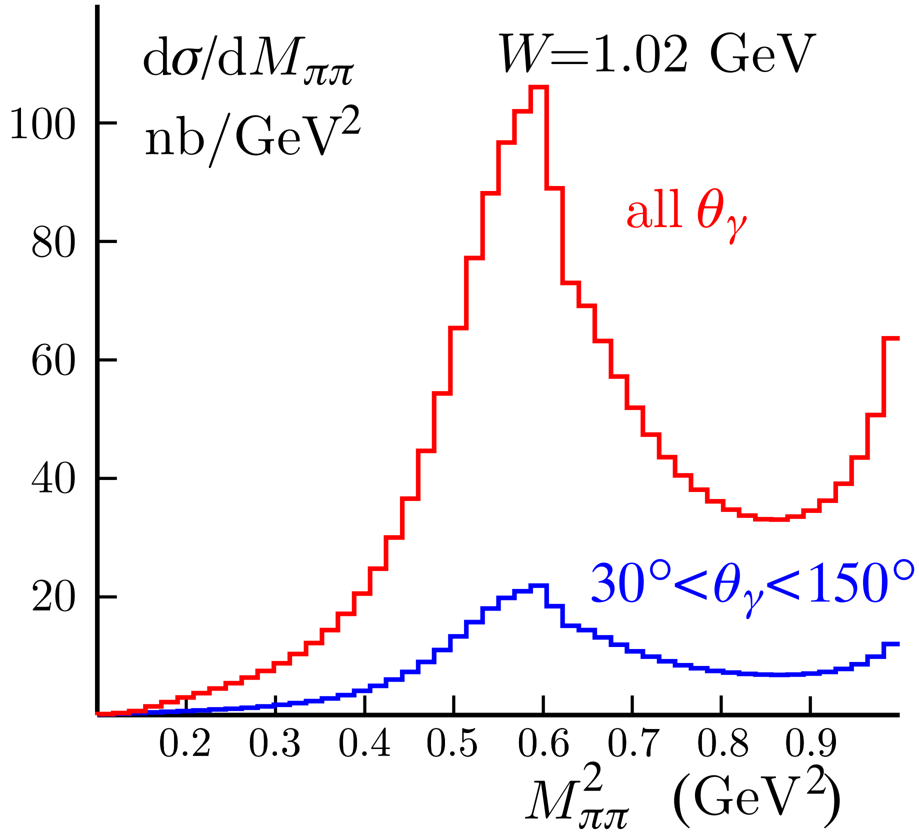
$\sigma(\pi\pi)$
μb
$d\sigma(\pi\pi\gamma)/ds_\pi$
nb/GeV^2
$\pi\pi\gamma$
θ_γ=5-15; 165-175°
30-150°
50-130°
$\pi\pi$
12
10
8
6
4
2
0.2
0.4
0.6
0.8
1.0
s_π, GeV^2

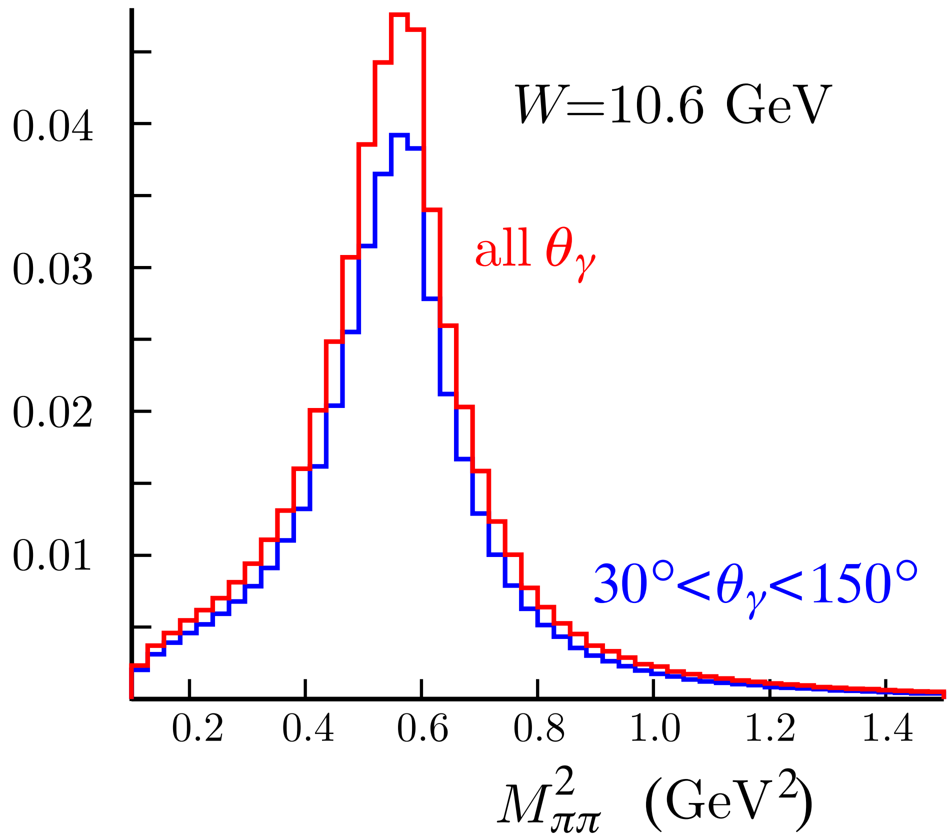


$$\frac{\delta a_\mu}{a_\mu} \sim 1.45 \frac{\delta \overline{\sigma_{\pi\pi\gamma}}}{\overline{\sigma_{\pi\pi\gamma}}}$$

From PHOKARA

$e^+e^-\to\pi^+\pi^-\gamma;\ 30^\circ<\theta_\pi<150^\circ$



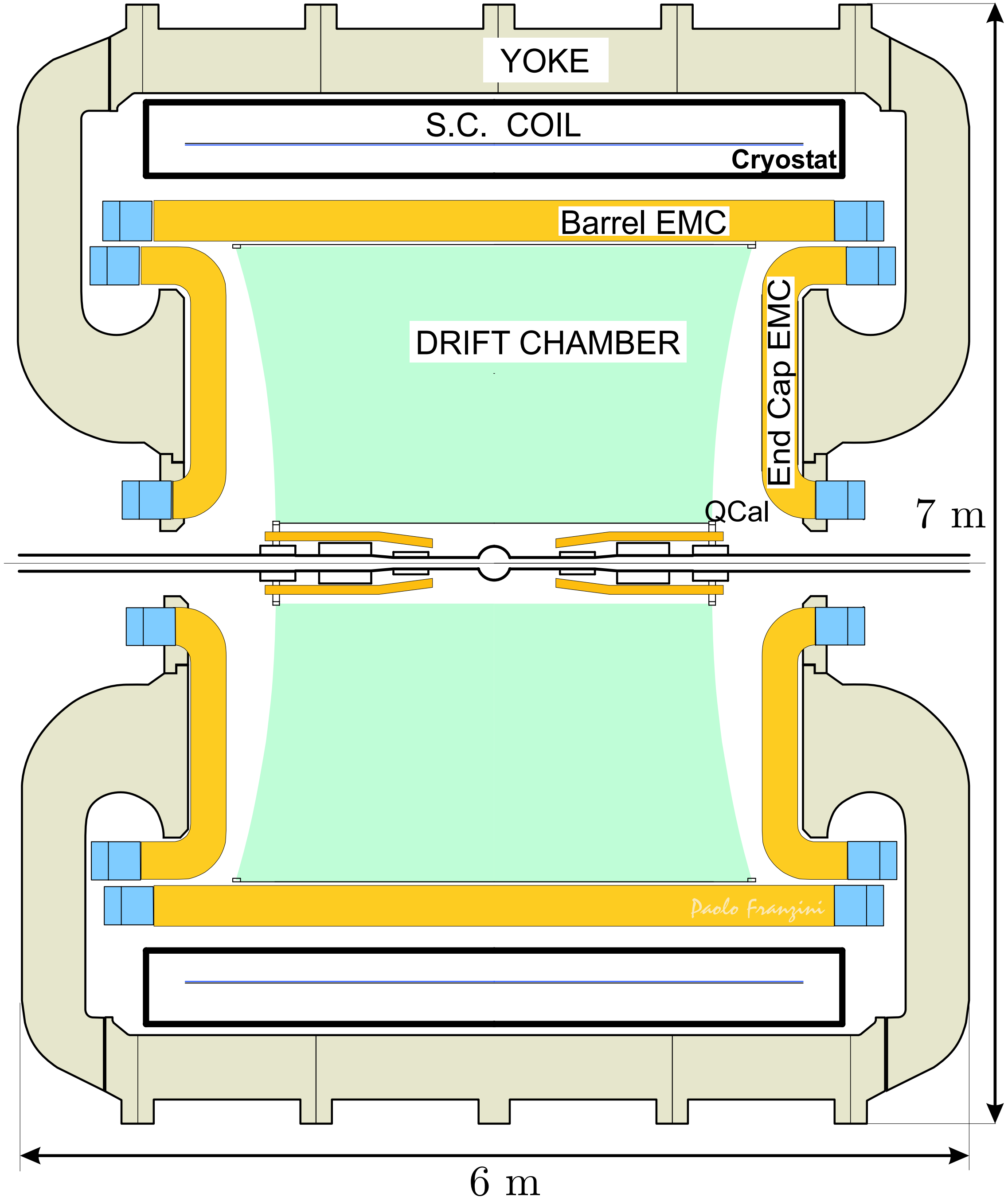


Magnet
SC Coil, B=0.6 T

EM Calor.
Pb–scint fiber
4880 pm

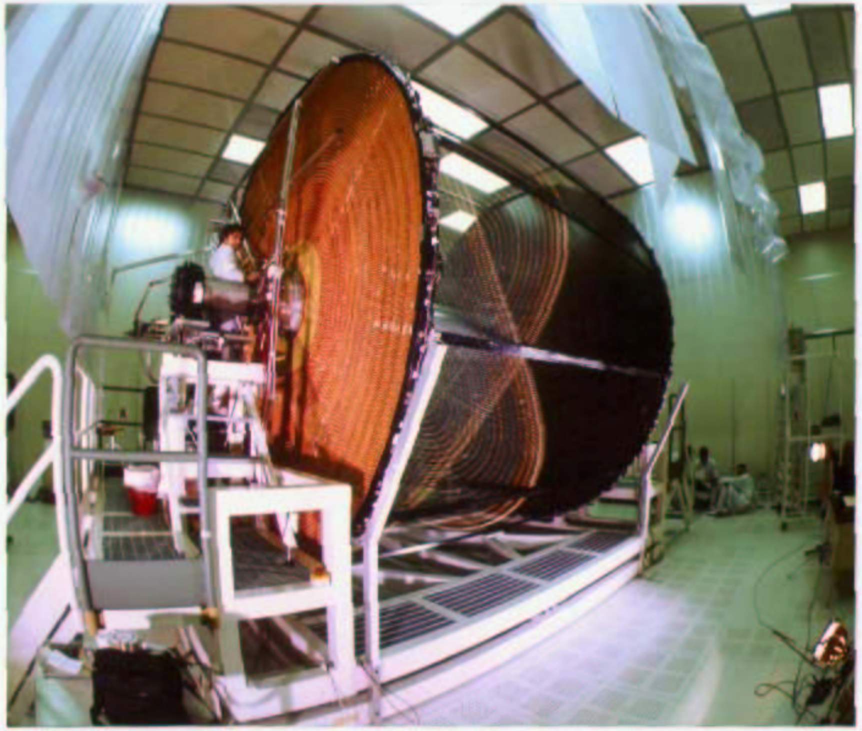
Drift Ch.
12582 sense wires
52140 tot wires

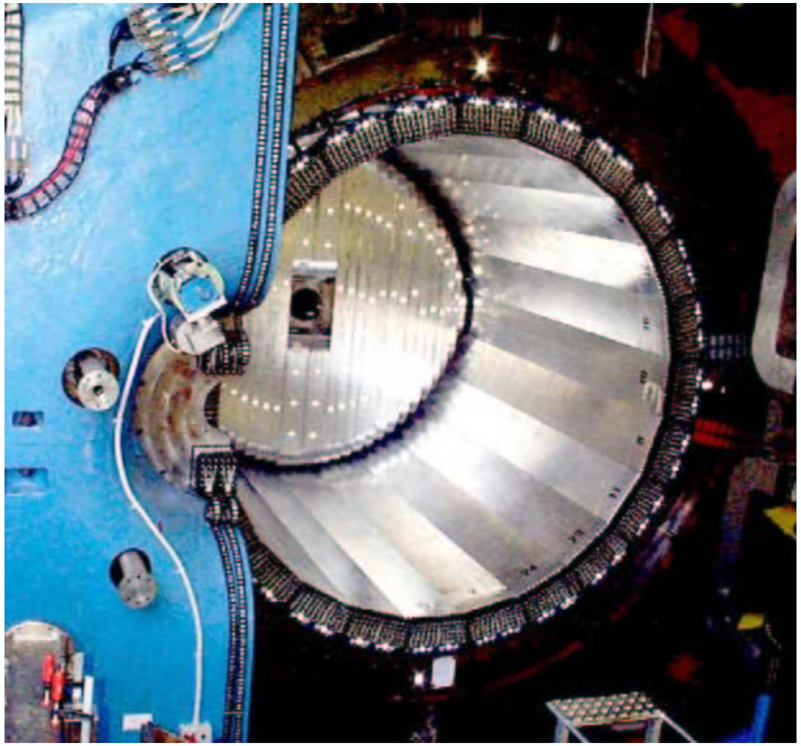
Al-Be beam pipe
r=10 cm, 0.5 mm thick



$\sigma_E/E = 5.7\% / \sqrt{E(GeV)}$
$\sigma_T = 54\ ps / \sqrt{E(GeV)} \oplus 50\ ps$
(Bunch length contribution subtracted from constant term)

Driftchamber





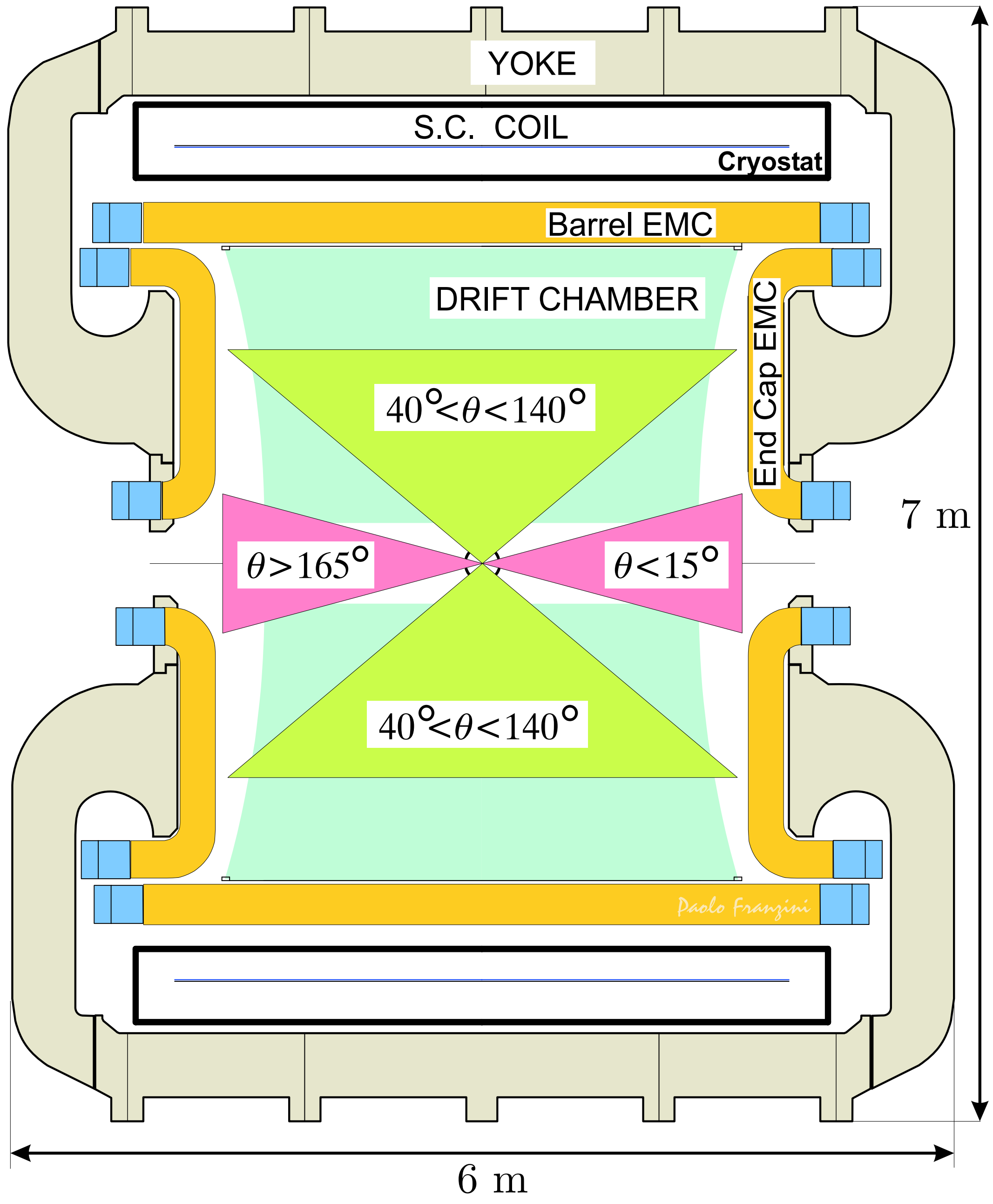
$\sigma_p/p = 0.4\%$ (for 90^0 tracks)
$\sigma_{xy} \approx 150\ \mu m$, $\sigma_z \approx 2$ mm

Electromagnetic calorimeter

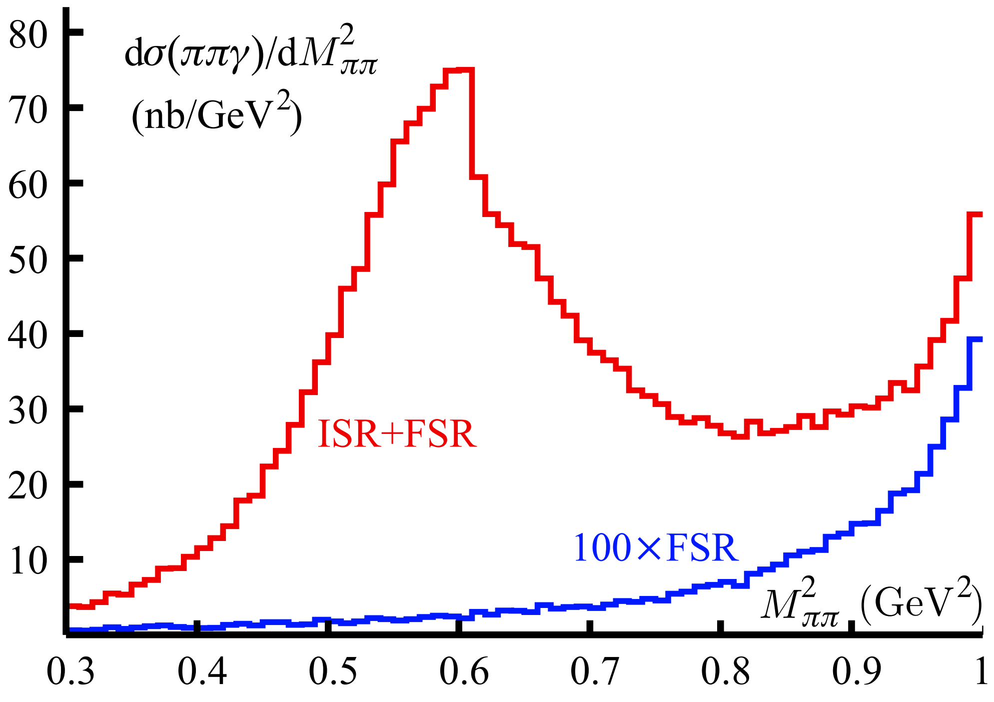
The photon momentum and angle are obtained from $\vec{p}_\gamma = -(\vec{p}_{\pi^+} + \vec{p}_{\pi^-})$.

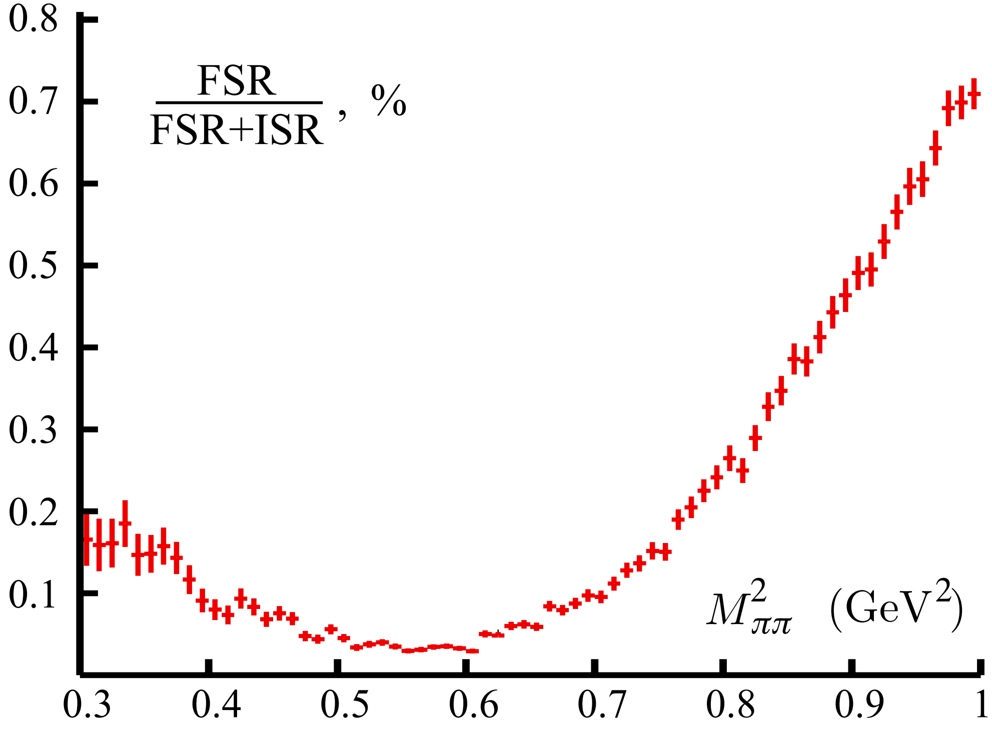
Photons with $\theta < 15^\circ$ ($> 165^\circ$) from the interaction region do not reach the calorimeter.

Pions are accepted for $40^\circ < \theta_\pi < 140^\circ$.



PHOKHARA for KLOE angular regions





FSR contribution is negligible for

$$\theta_\gamma < 15^\circ \ (> 165^\circ)$$
$$40^\circ < \theta_{\pi^+\pi^-} < 140^\circ$$

$$\frac{d\sigma(\pi^+\pi^-\gamma)}{dM^2_{\pi\pi}} = \frac{N^{obs} - N^{bkg}}{\Delta M^2_{\pi\pi}} \times \frac{1}{\epsilon_{sel} \times \epsilon_{acc}} \times \frac{1}{\mathcal{L}}$$

Signal

$e^+e^-\to\pi^+\pi^-\gamma$ $\sigma\sim$5-25 nb

Some background processes

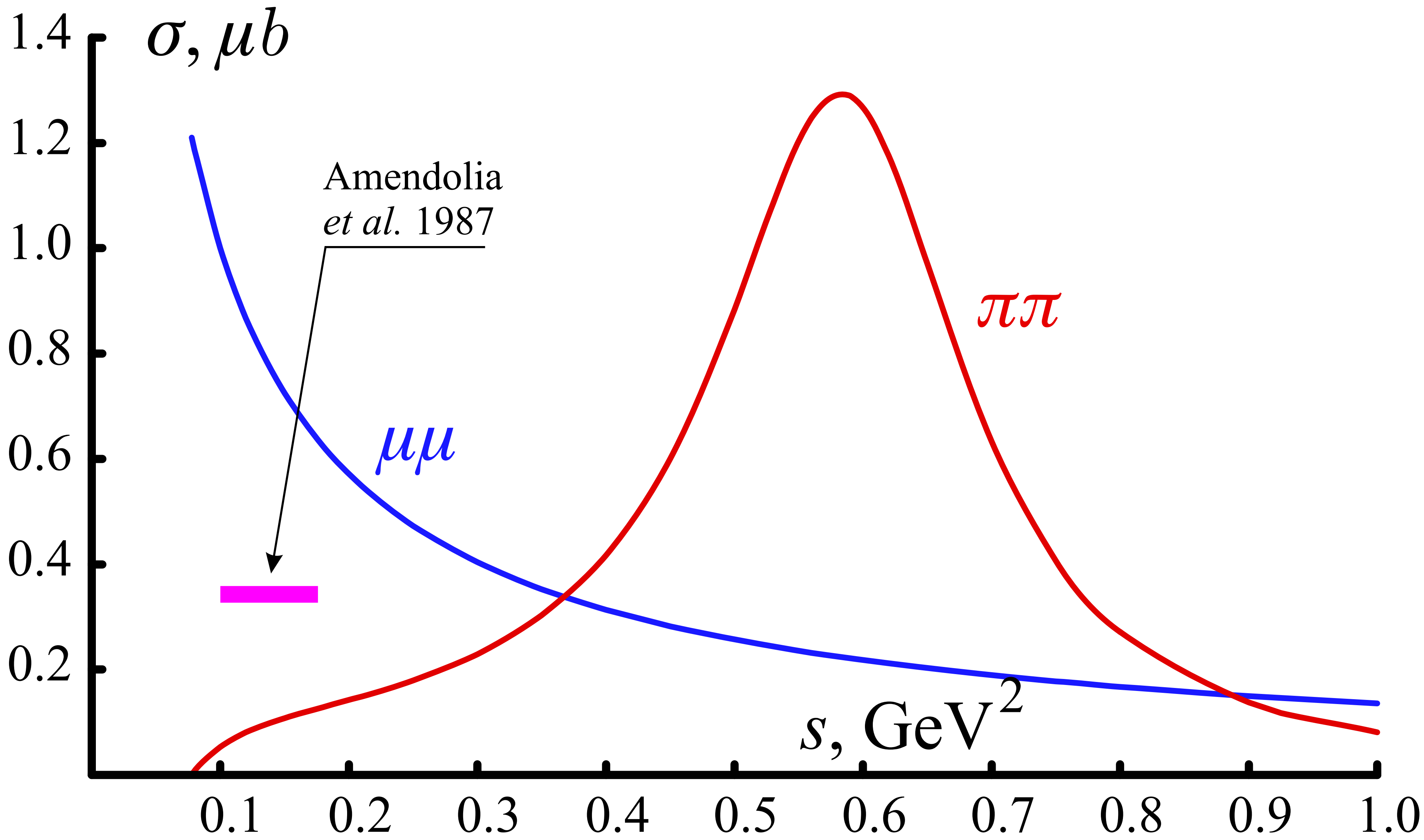
$e^+e^-\to\phi\to K_S K_L$, $K_S\to\pi^+\pi^-$, K_L does not decay, $\sigma\sim 0.4\mu$b

$e^+e^-\to\phi\to\rho\pi\to\pi^+\pi^-\pi^0$, $\sigma\sim 0.5\mu$b

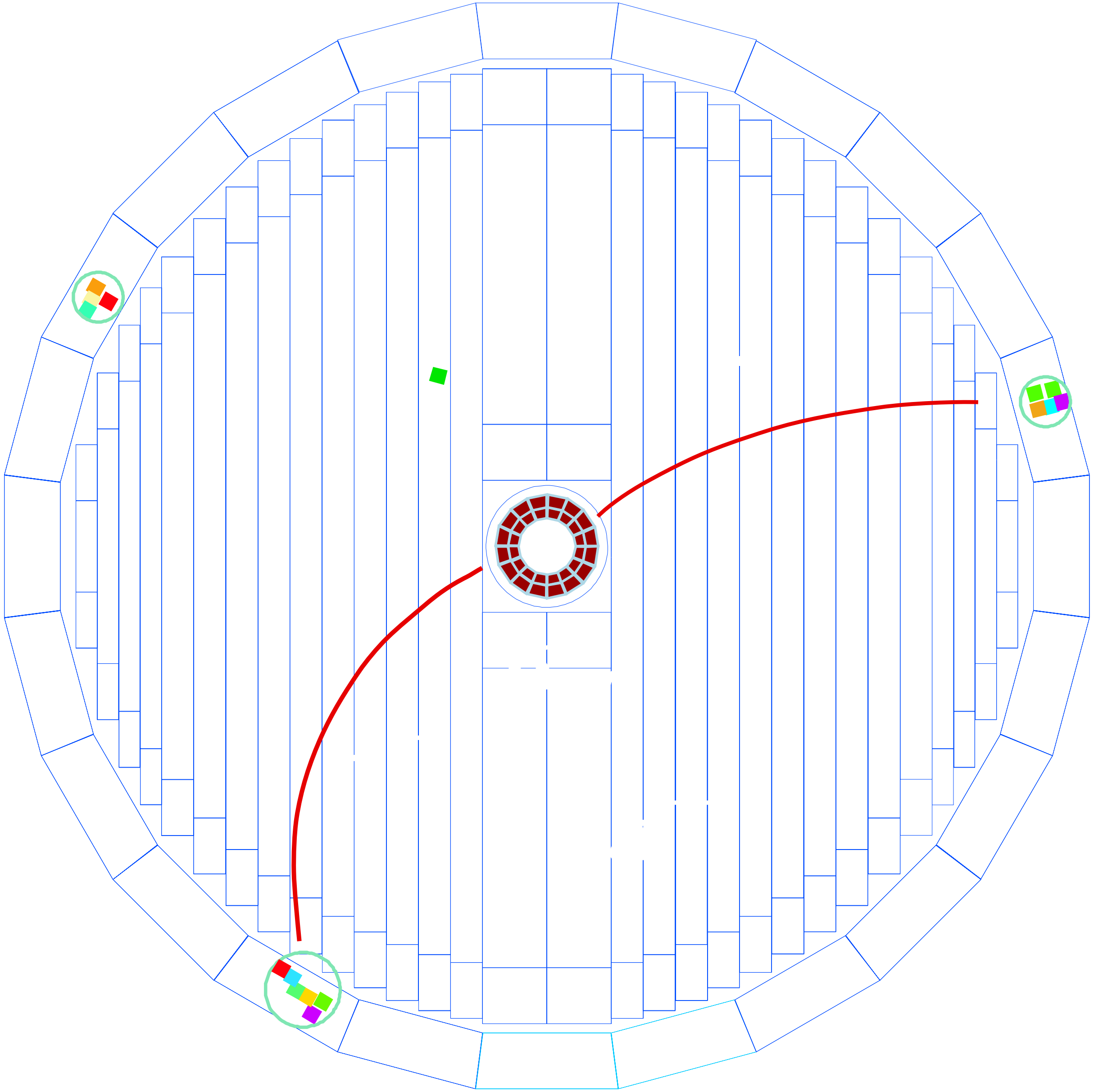
Radiative Bhabha $\sim$a fraction of μb – (large e^+e^- angles)

$e^+e^-\to\mu^+\mu^-\gamma$: for $s' <$600 MeV $\sigma(\mu\mu\gamma)$ is larger than $\sigma(\pi^+\pi^-\gamma)$.

$\sigma(e^+e^-\to\pi^+\pi^-)$ and $\sigma(e^+e^-\to\mu^+\mu^-)$



Event candidate, probably $\pi^+\pi^-\pi^0$



$\pi^+\pi^-\gamma$ events are selected requiring two opposite charged particles in the drift chamber, rather loosely coming from the interaction point. Most background events, such as $\phi \to K_S \to \pi^+\pi^- + K_L$ not decaying and $\phi \to \pi^+\pi^-\pi^0$, are removed early in reconstruction by kinematics and cuts on m_x, computed from

$$\left(M_\phi - \sqrt{p_+^2 + m_x^2} - \sqrt{p_-^2 + m_x^2}\right)^2 - (\vec{p}_+ + \vec{p}_-)^2 = 0,$$

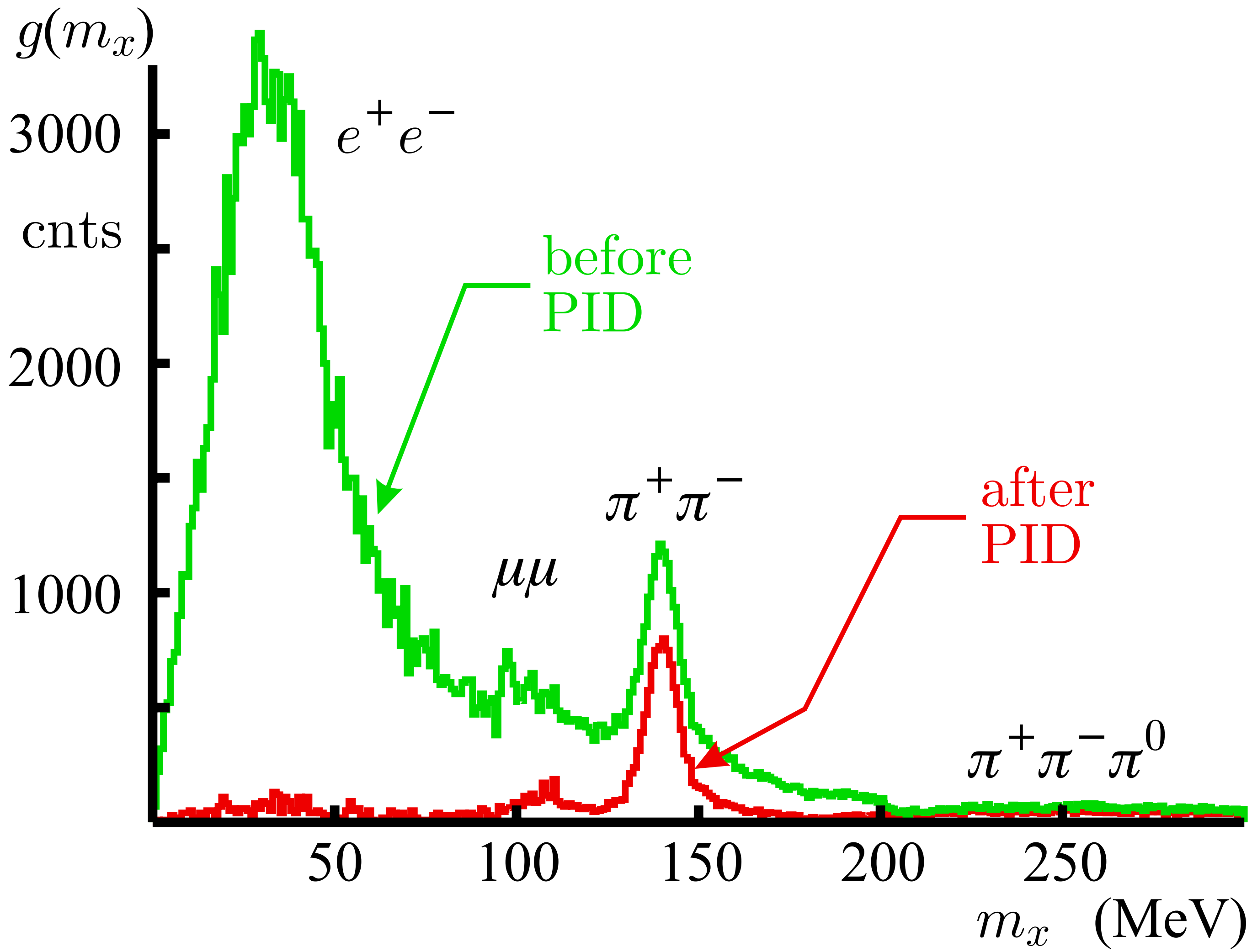
i.e. assuming that a pair of same mass particles are produced according to $e^+e^- \to x^+x^-\gamma$.

We do not want to apply restrictive kinematical requirements, or insist on multiple photon detection, to avoid imposing restrictive cuts on soft radiation, to be later corrected.

The observed mass, m_x, spectrum for the accepted two track events is shown below

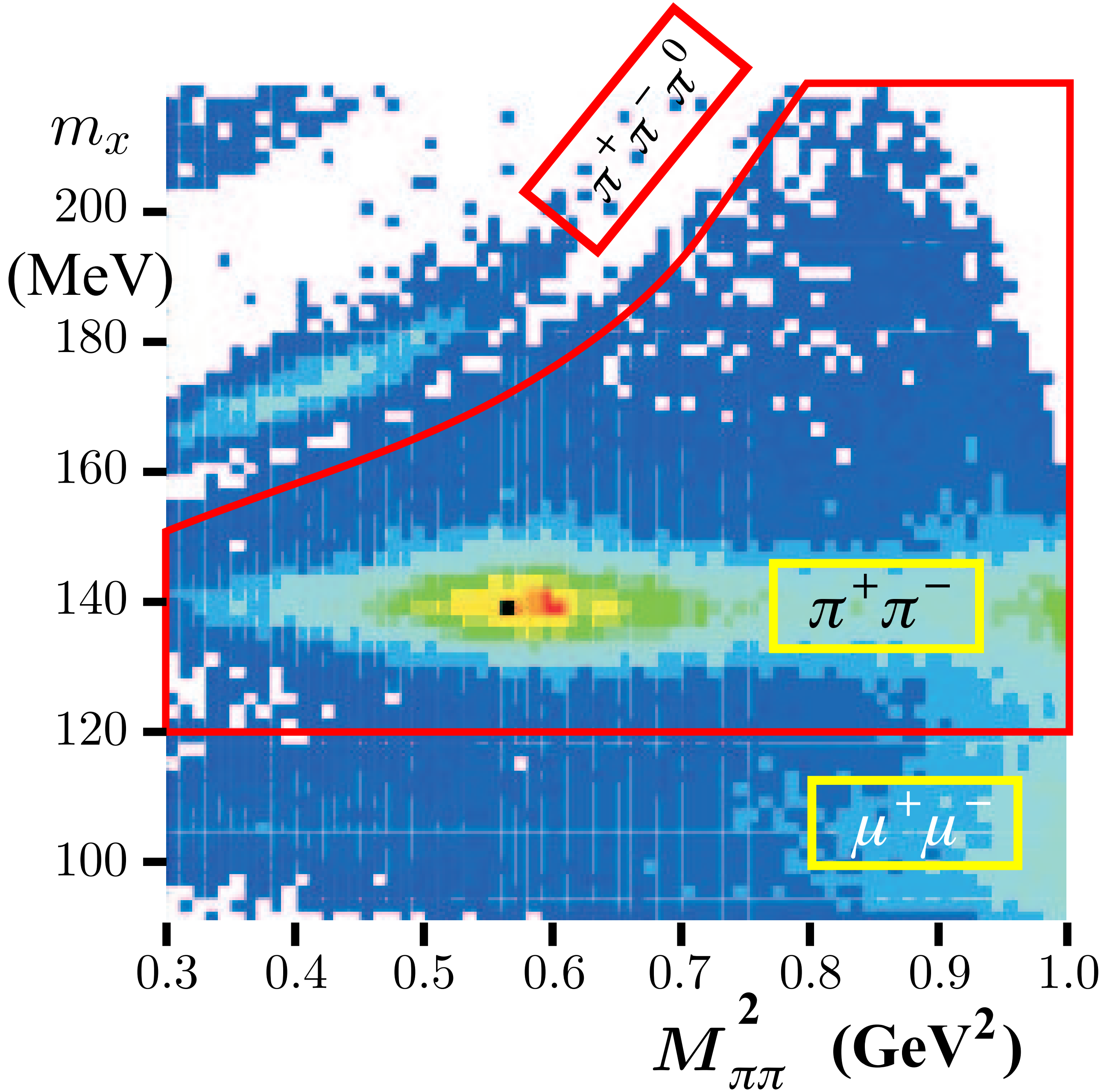
Particle identification is obtained with an estimator that uses time of flight, compared to momentum, and the energy deposit pattern in the EM calorimeter. Its effectiveness is apparent. At least one of the two particle must be a pion, ~95% of the signal is retained.

m_x spectrum for candidates



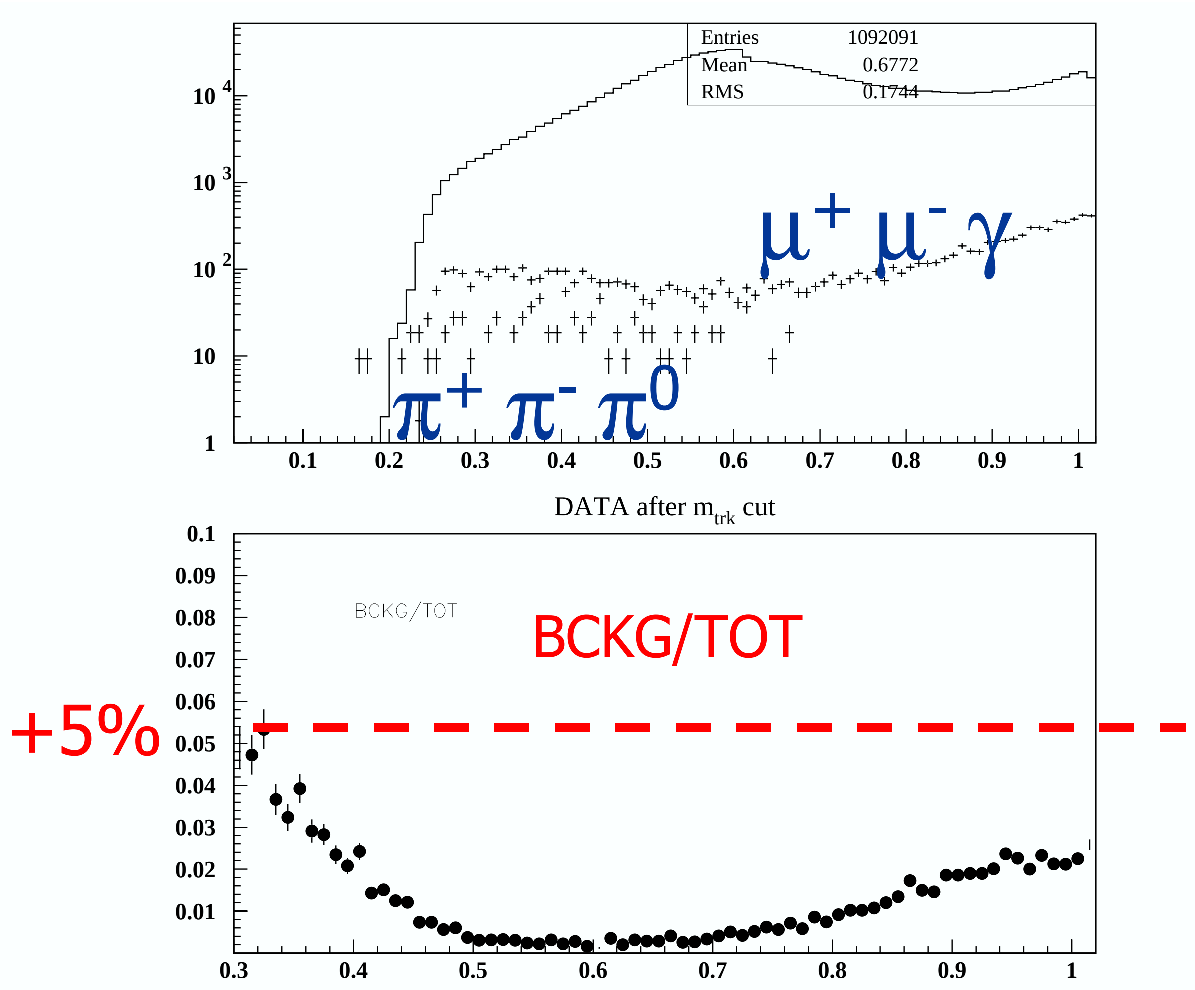
Distribution in the $\{M^2,\ m_x\}$ plane

Fiducial region in the $\{M_{\pi^+\pi^-},\ m_x\}$ plane.

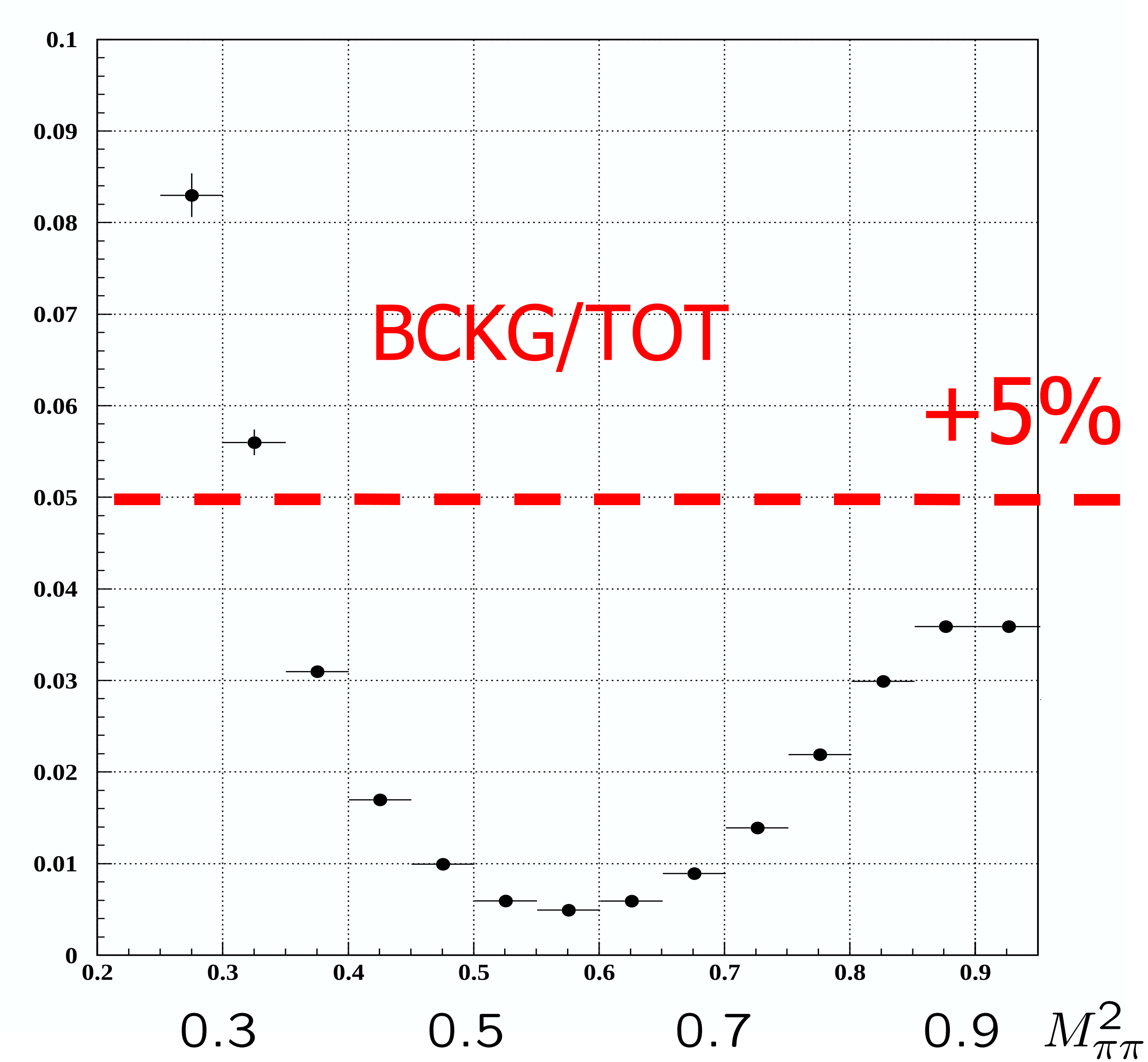


$\pi^+\pi^-\pi^0$ and $\mu^+\mu^-\gamma$ background subtraction

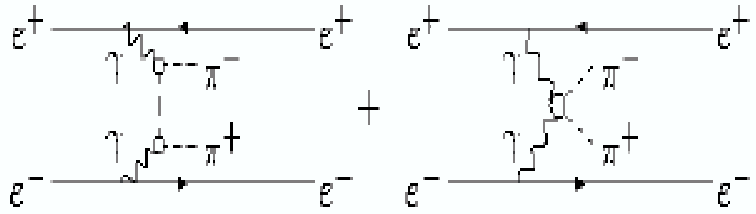
Backgrounds are estimated from data and subtracted. Monte Carlo simulations are in excellent agreement

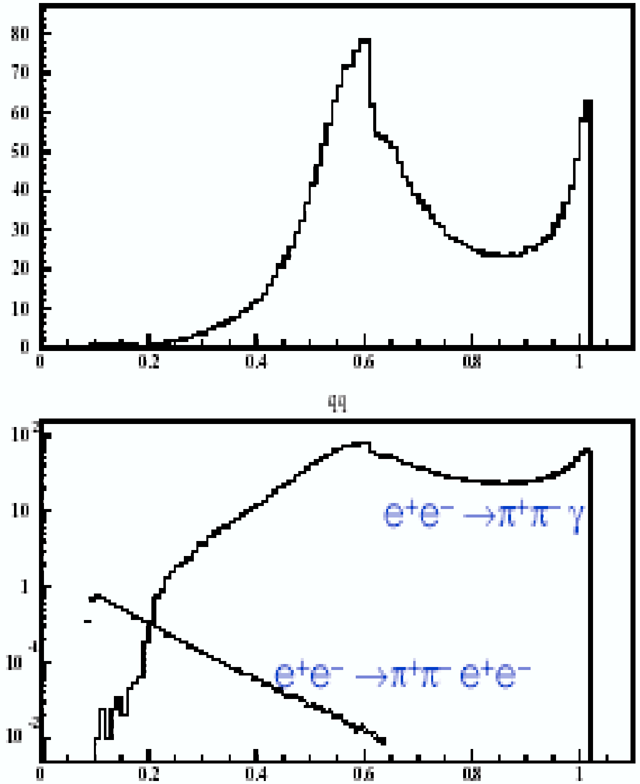


Radiative Bhabha, $e^+e^-\gamma$, background



This process could represent a background for our analysis if electron and positron go along the beam pipe.





From MC (old MC generator from F. Anulli), we expect a background contribution at low Q^2 values.

Background is removed by m_x cut.

Efficiencies

Trigger

Includes CR veto

Reconstr. Filter

filfo

Event Classification

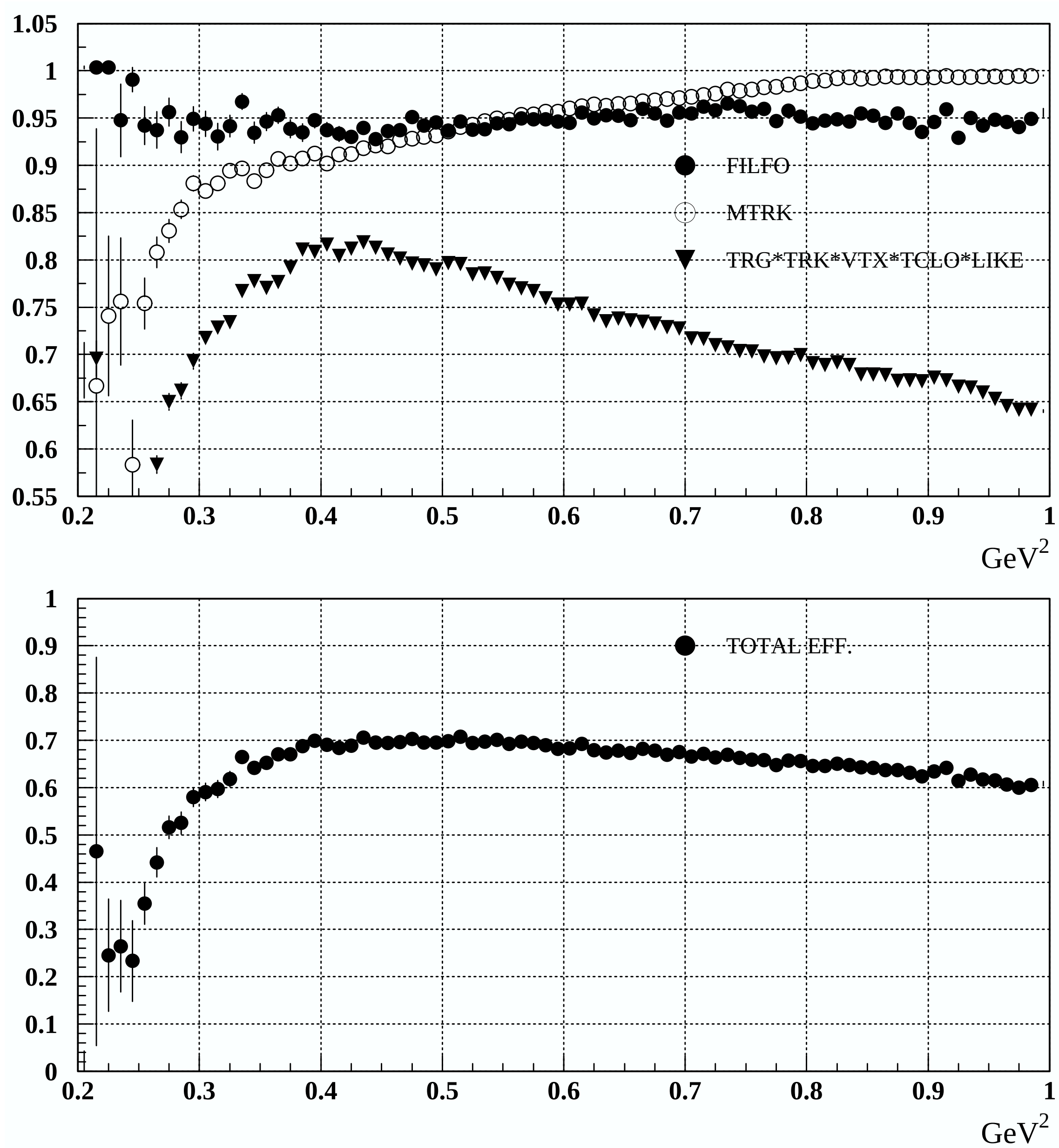
Track eff, vertex eff

PID

like

m_x

mtrk

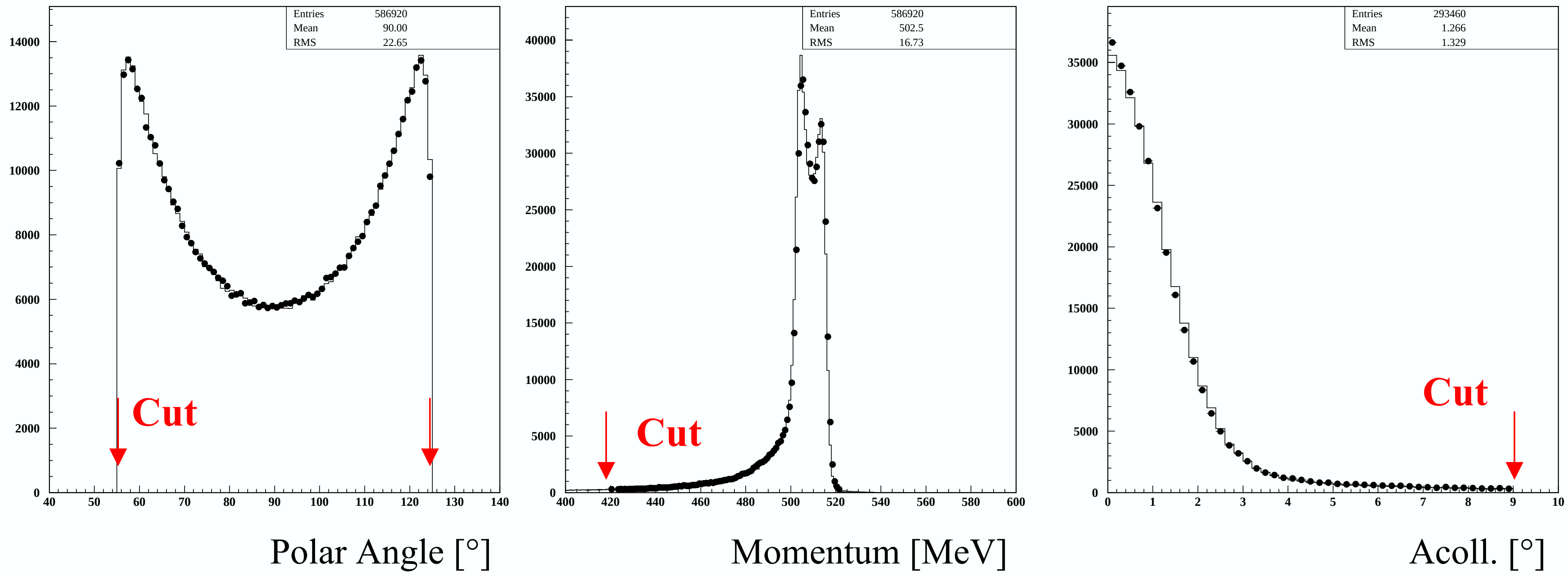


Measuring the luminosity

Acceptance:

Comparison DATA – MC to understand systematic effect
Normalize to same number of events

—— Monte Carlo (BABAYAGA)
* Data Points (1.1pb^{-1})



Only Polar Angle makes an non-negligible effect, the other distributions are "safe" what concerns systematics

SUMMARY LUMI SYSTEMATIC ERROR

Theory	0.5%	
Acceptance	0.3%	correct by 0.28%
Knowledge $\sqrt{s}$	0.1%	
Background	0.1%	correct by 0.53%
Tracking	0.1%	
Clustering	0.1%	correct by 0.23%
Trigger	<0.1 %	correct by 0.51%

Total 0.5% th., 0.4% exp. $\ominus$ 0.6%

Luminosity comparisons

BHABHA

1. BABAYAGA (Pavia, Carloni et al.)
2. BHAGEN (Modified Berends)

σ(VLAB, 1)=428.8±0.3 nb

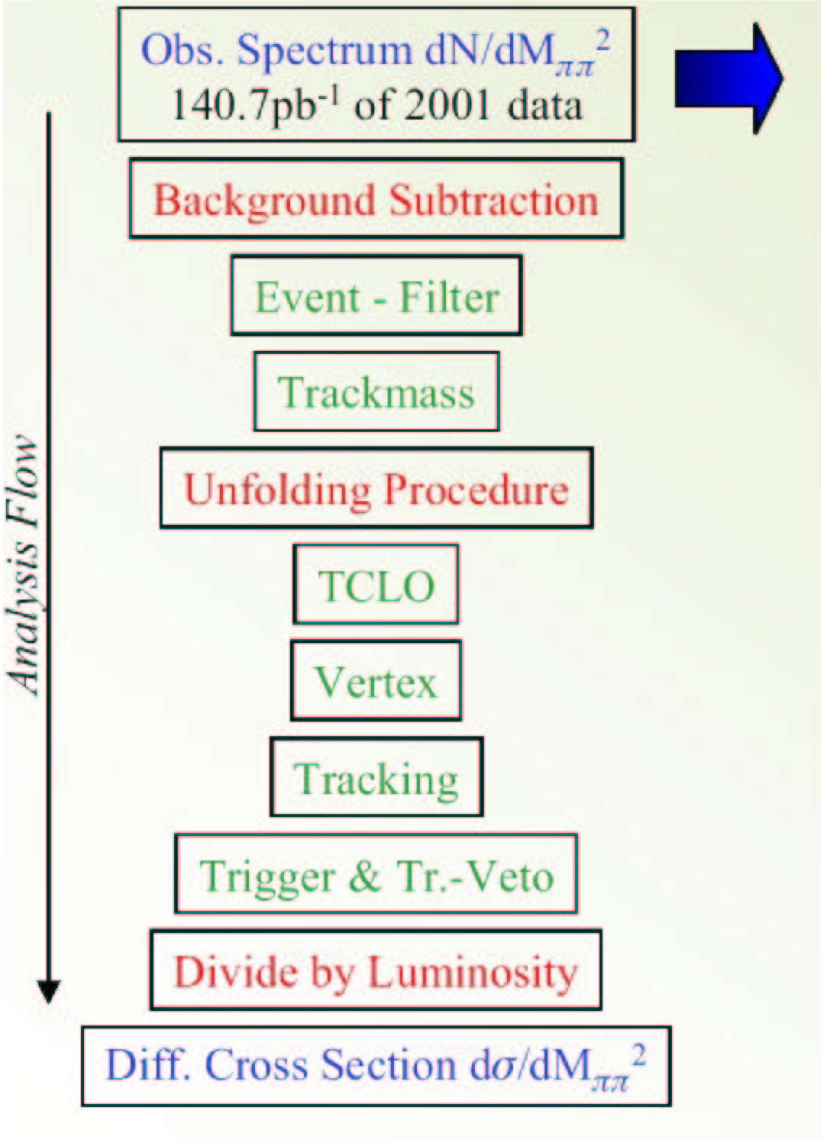
σ(VLAB, 1)=428.5±0.3 nb

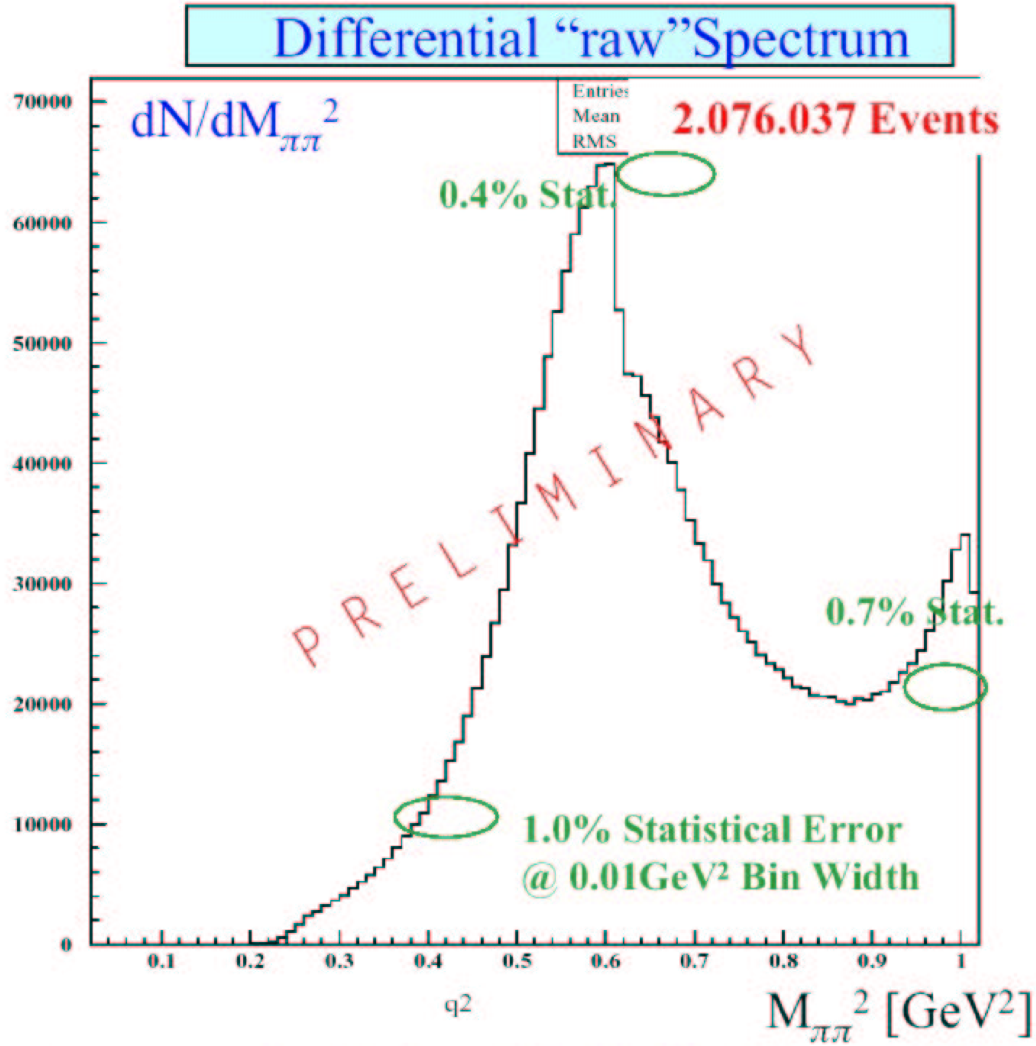
diff. 0.1±0.1 %

Large angle $\gamma\gamma$. $45^\circ < \theta_\gamma < 135^\circ$, σ=120 nb

$|\mathcal{L}(\text{BHABHA})-\mathcal{L}(\gamma\gamma)|$=0.2 %

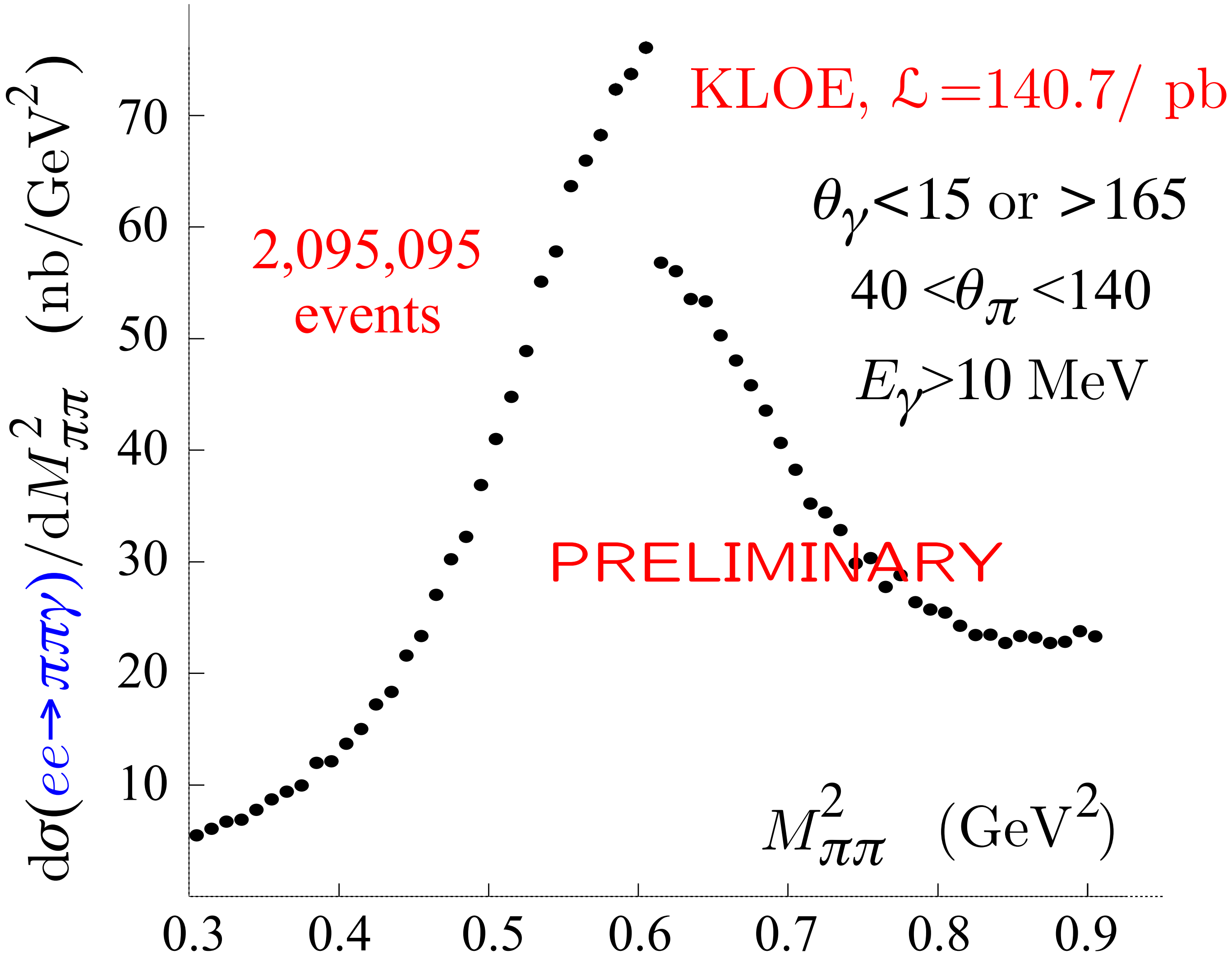
$\sigma(\pi^+\pi^-\gamma)$





Acceptance: $\theta_{\pi\pi}<15^o$ ($\theta_{\pi\pi}>165^o$), $40^o<\theta_\pi<140^o$, $E_\Sigma>10$ MeV

KLOE dipion mass resolution has been unfolded from the spectrum after all corrections



PION FORM FACTOR

From

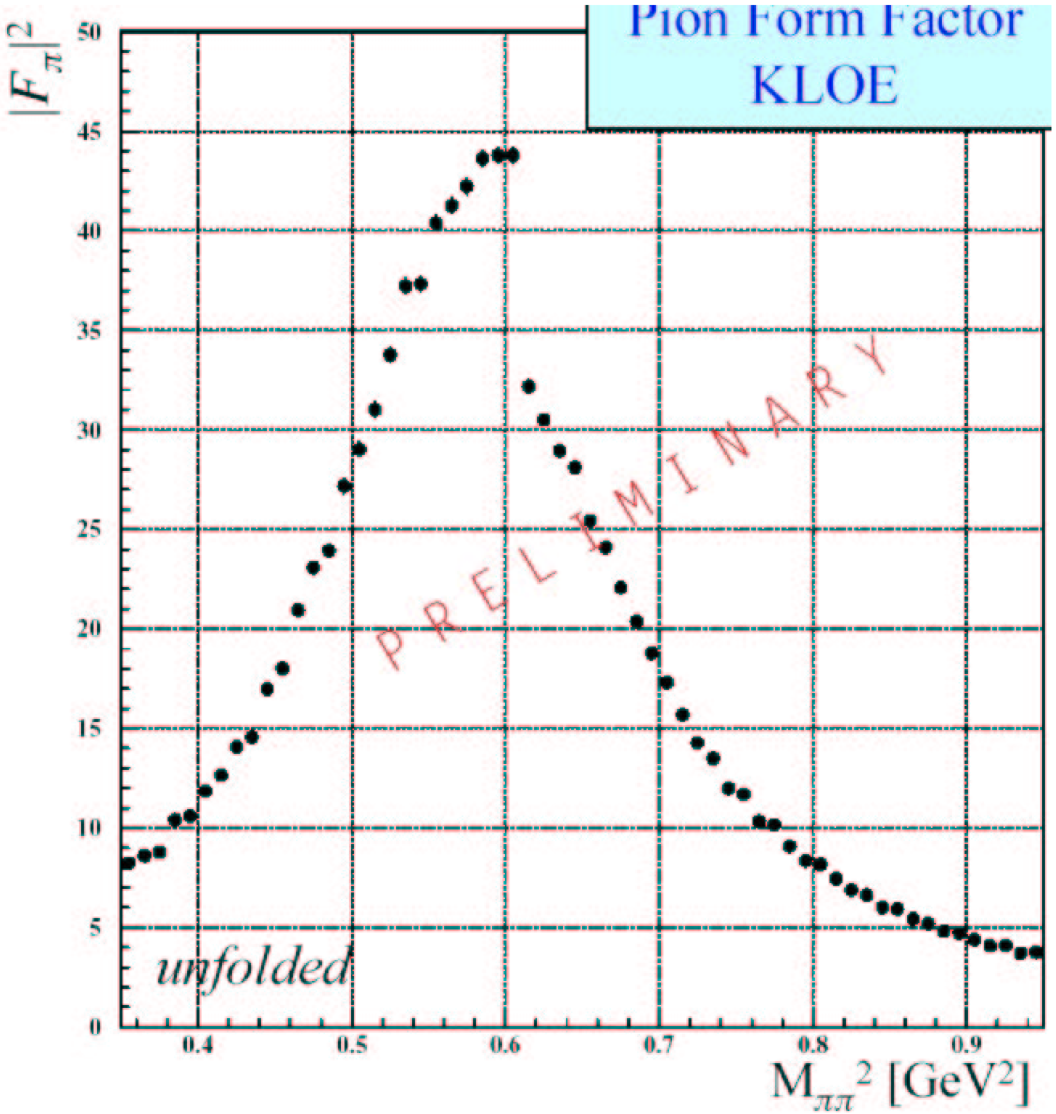
$$\sigma(\pi^+\pi^-, s_\pi) = \frac{1}{H}\frac{\mathrm{d}\sigma(\pi\pi\gamma)}{\mathrm{d}s_\pi}$$

and

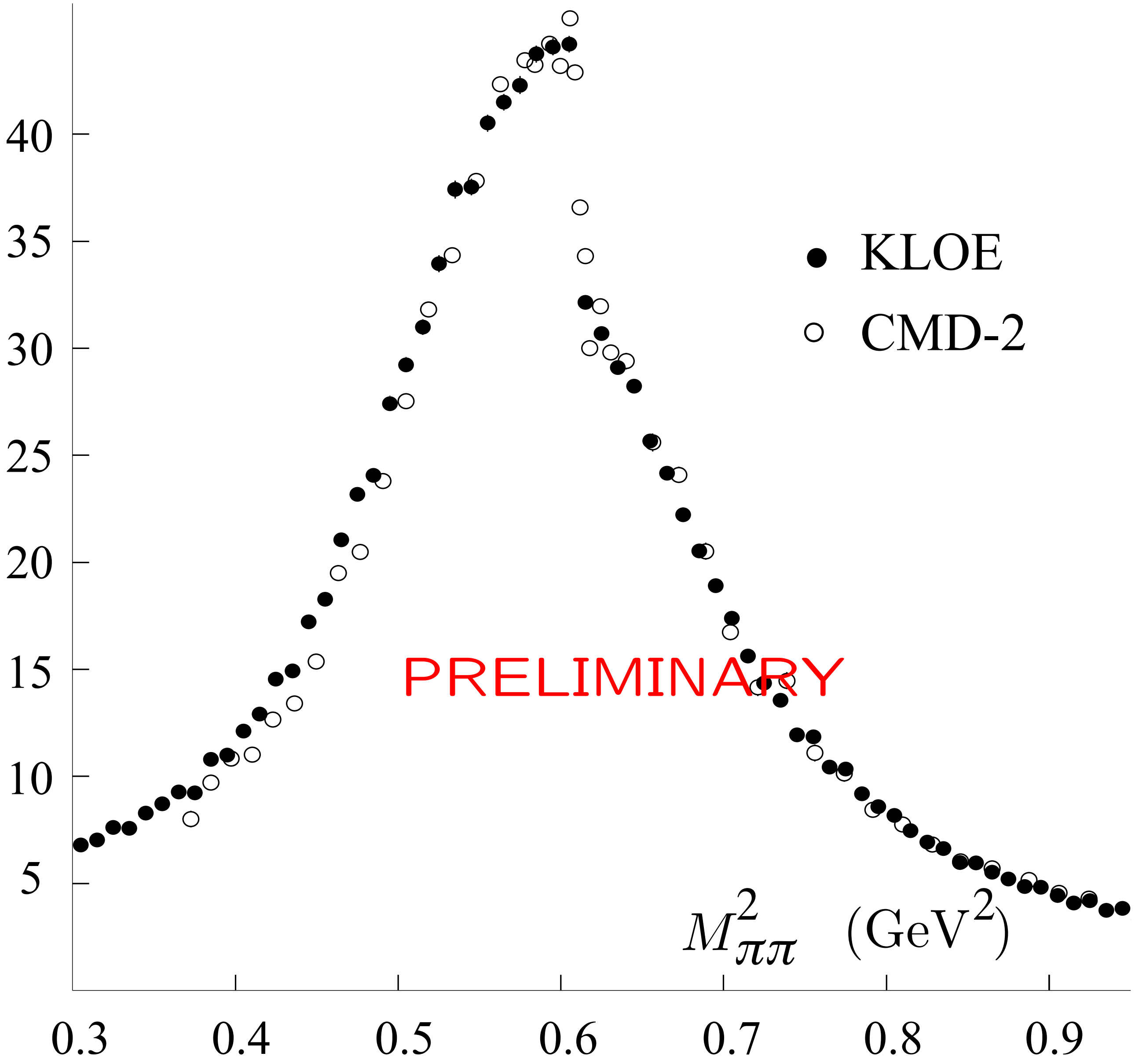
$$\sigma(\pi^+\pi^-, s_\pi) = \frac{\pi\alpha^2}{3e_\pi}\beta^3|f_\pi|^2$$

we get the pion form factor.

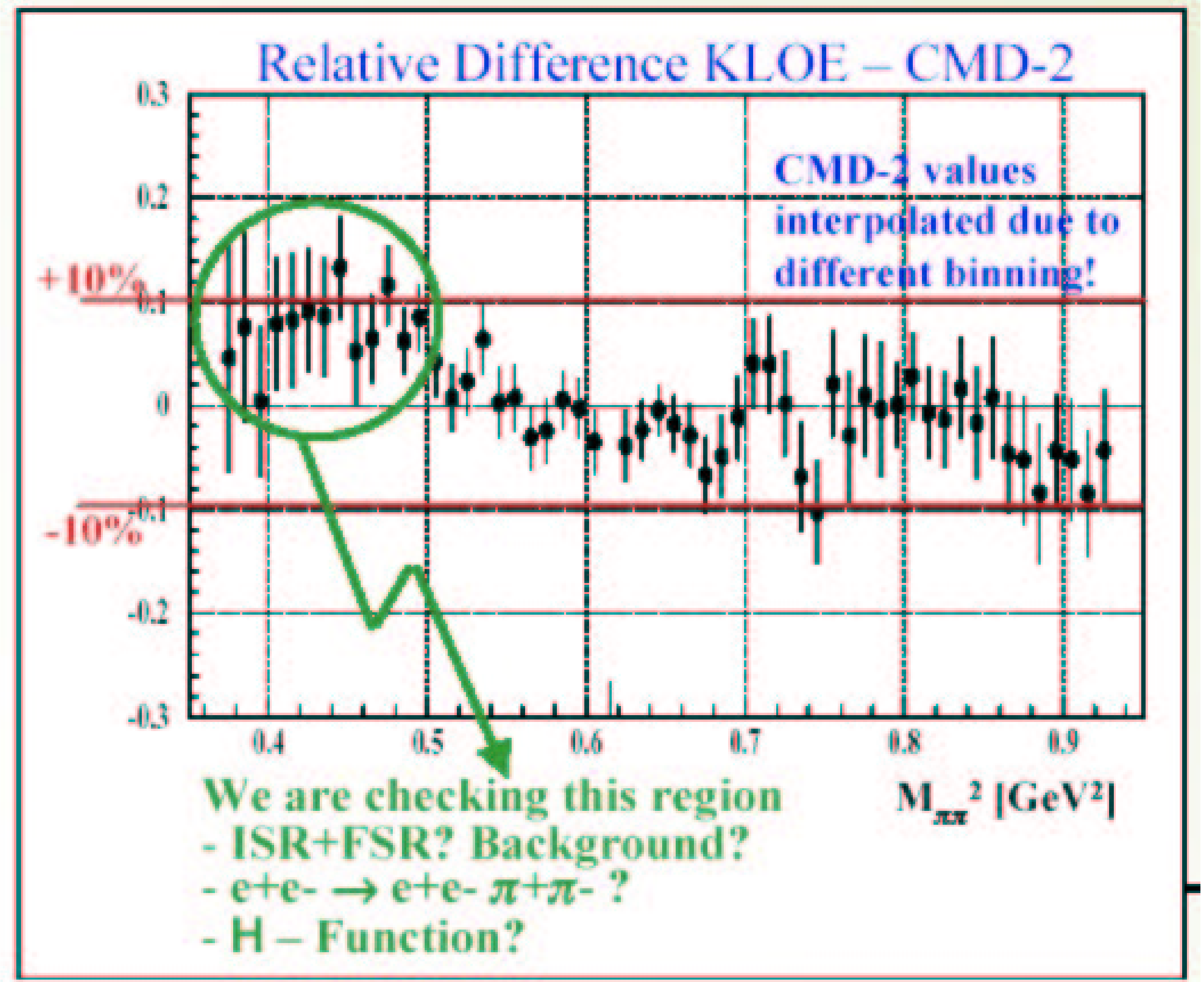
$H(s_\pi)$ is obtained from PHOKHARA with F_π=1.



The KLOE $e^+e^-\to\pi^+\pi^-$ cross section extracted from the measured $\pi^+\pi^-\gamma$ cross section above, compared with CMD-2 results.



A discrepancy at low mass is evident
PRELIMINARY!



a_μ

$$a_\mu \propto \int \sigma(s_\pi) K(s_\pi) \mathrm{d}s$$

* our calculation, we use values w/o FSR and VP correc. (like us)

KLOE — **PRELIMINARY**

Δa_μ=424.7 — 0.30< $M^2_{\pi\pi}$ <0.95 GeV^2

Δa_μ=381.4 — 0.37< $M^2_{\pi\pi}$ <0.93 GeV^2

Δa_μ=240.1 — 0.50< $M^2_{\pi\pi}$ <0.93 GeV^2

CMD-2 (Δa_μ=368.1)

Δa_μ=376.7* — 0.37< $M^2_{\pi\pi}$ <0.93 GeV^2

Δa_μ=241.4* — 0.50< $M^2_{\pi\pi}$ <0.93 GeV^2

1/2 % agreement with CMD-2 above 0.5 GeV^2

VP and FSR corrections need checking!

Radiative Corr. H ($M_{\pi\pi}^2$) (Phokhara)

↑

Systematic errors are still under evaluation!

Contributions from:

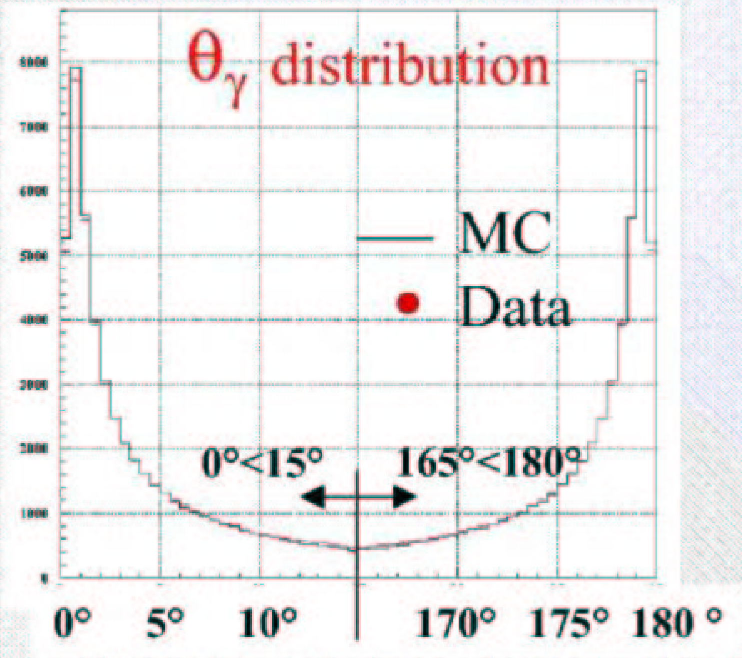
Luminosity

almost

0.5% Theory ⊕ 0.4% Exper.

PRELIMINARY

Acceptance Cuts



Good agreement Data - MC

Efficiencies

Effects are expected to be around on few tenths of % for each items

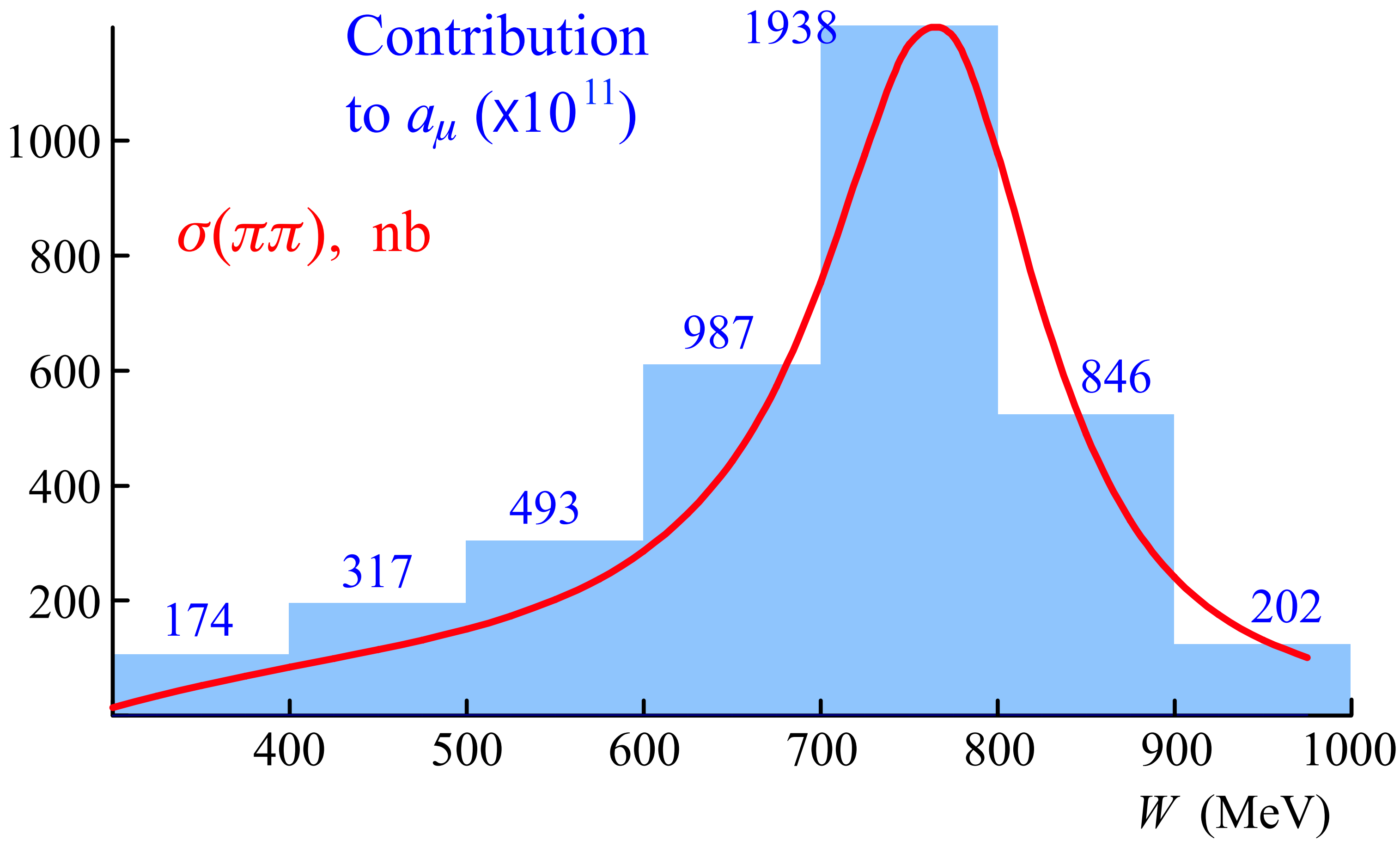
Trigger	**0.2%**
Tracking	**0.3%**
Vertex	**< 2%**
Ev.-Filter	**< 0.5%**
Trackmass	**0.2%**

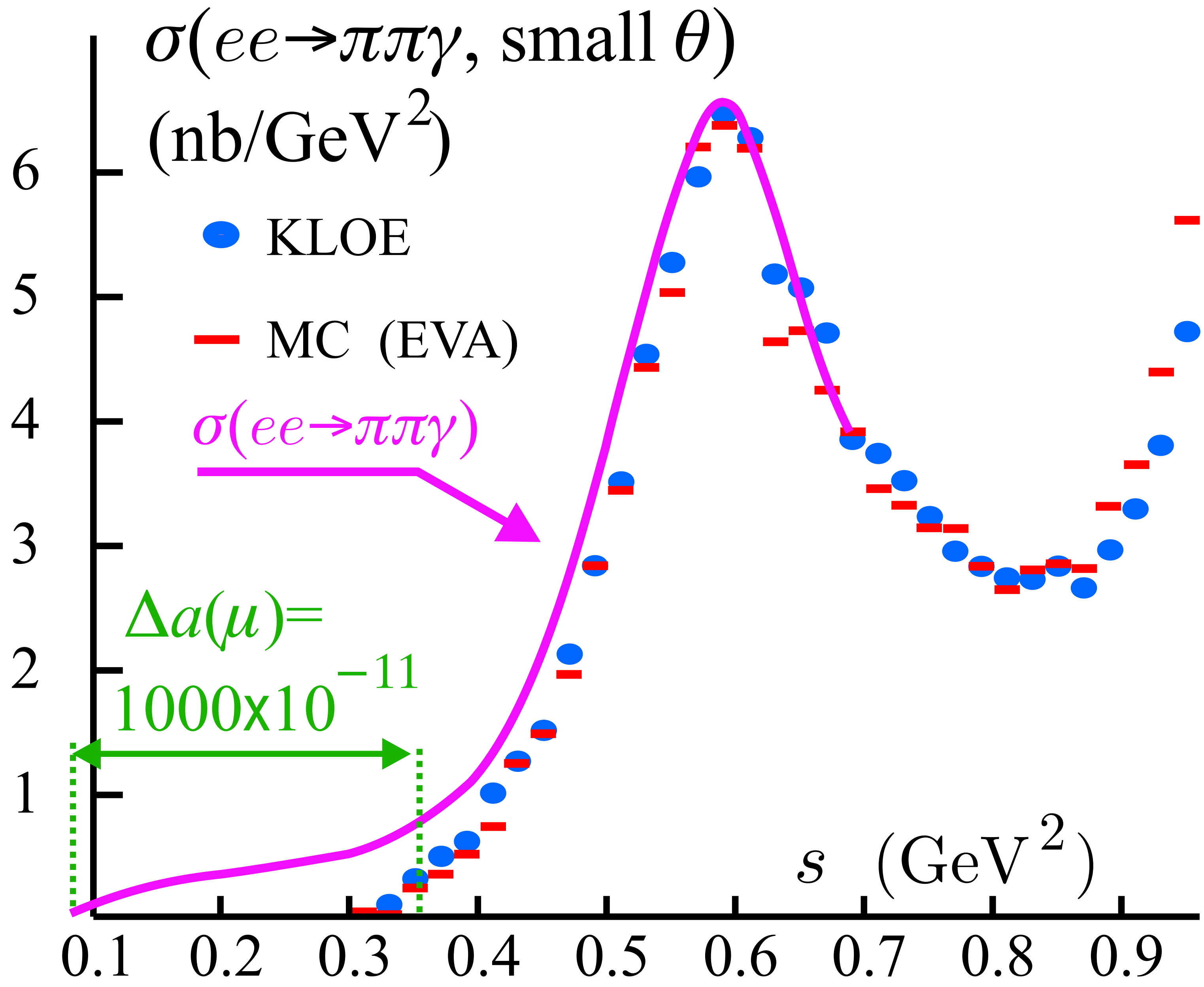
PRELIMINARY

What's next for KLOE

Measure large photon angle region

1. Access The Low Mass Region





σ(ee→ππγ, small θ)
(nb/GeV²)
KLOE
MC (EVA)
σ(ee→ππγ)
Δa(μ)=
1000x10⁻¹¹
s (GeV²)
6
5
4
3
2
1
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

There have been no recent measurement of $\sigma(e^+e^-\to\pi^+\pi^-)$ at small mass. It is worth noting however that the region from threshold to $M_{\pi\pi} < 600$ MeV ($s_\pi <$0.36 GeV^2, contributes $\sim$80 $\times$ 10^{-10} to the muon anomaly.

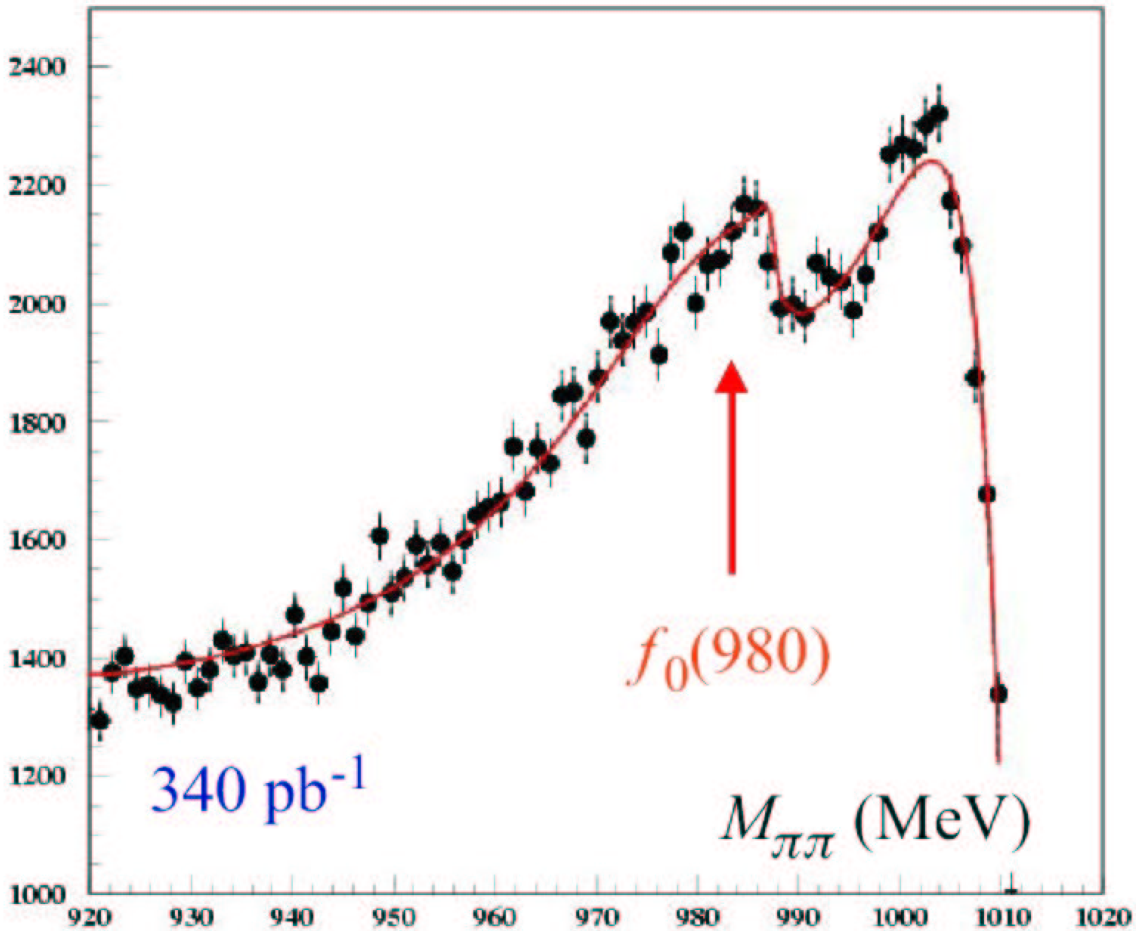
By choosing small values for θ_γ we removed some problems with FSR but lost the pions recoiling against the photon, inside the unaccessible forward and backward cones.

By going to the large angle photon region, KLOE will recover this portion of the cross section.

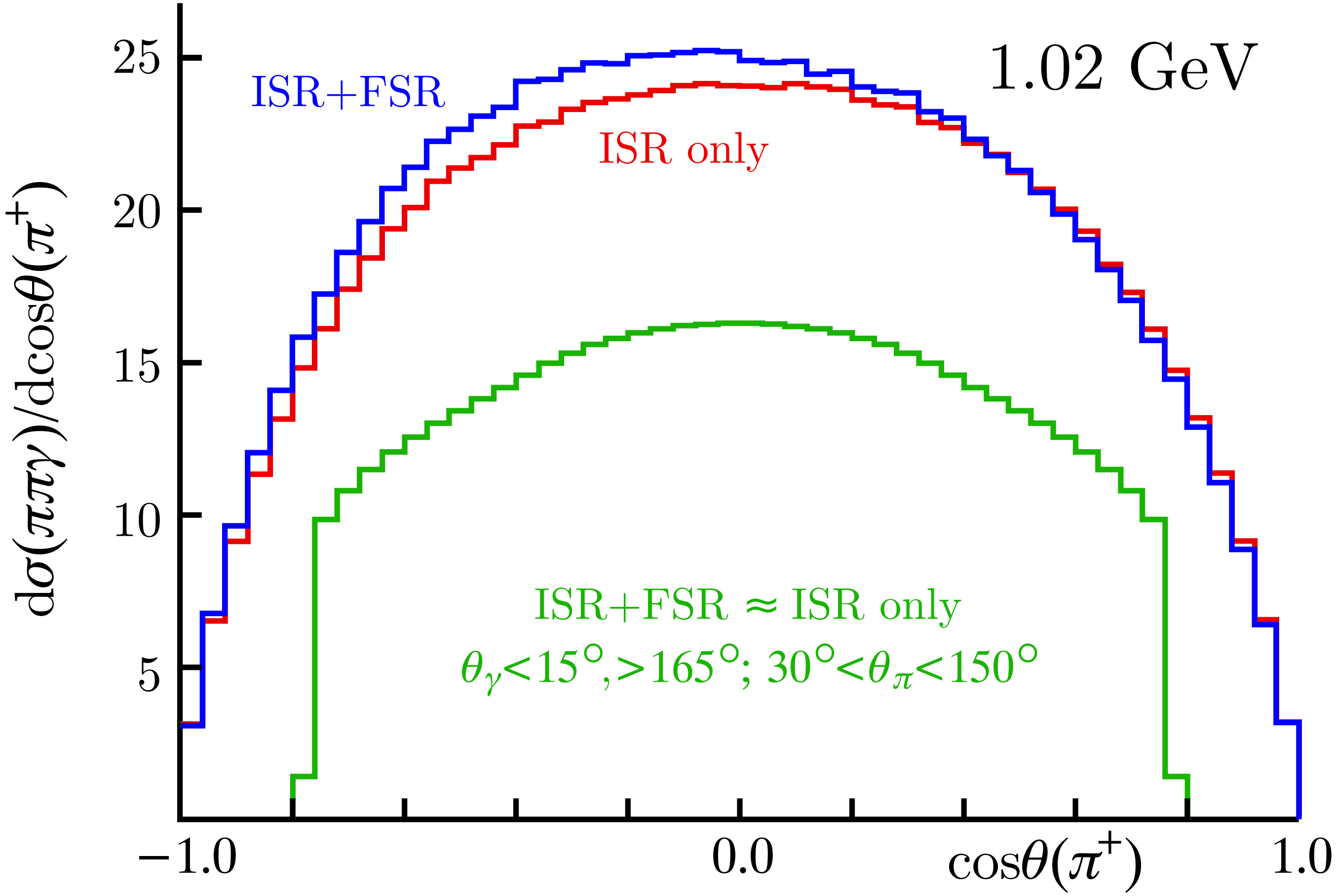
2. At large angle we can also study the scalar meson contribution to σ(hadrons) proposed by Narison.

Photon tag
i.e. photon is detected
$45^\circ < \theta_\gamma < 145^\circ$

Fit improves if a σ contribtion is added



3. Measure pion angular distribution.



With more information it will also be possible to clarify the validity of present modelling of FSR or learn how to deal with it better.