Achim Denig

Institute for Nuclear Physics
PRISMA Cluster of Excellence
Johannes Gutenberg University Mainz

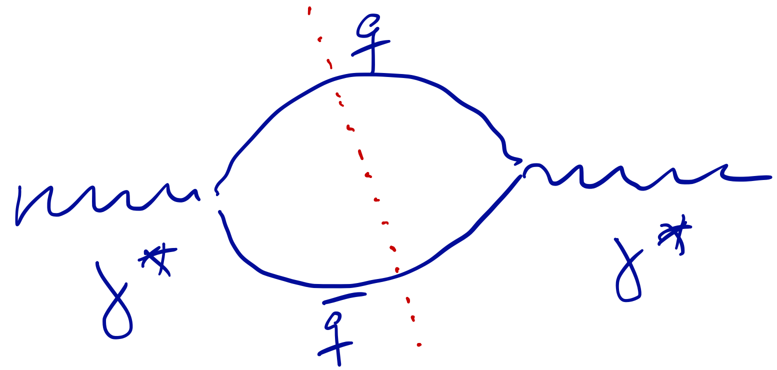
Measuring the Hadronic Contribution to $(g\text{-}2)_\mu$

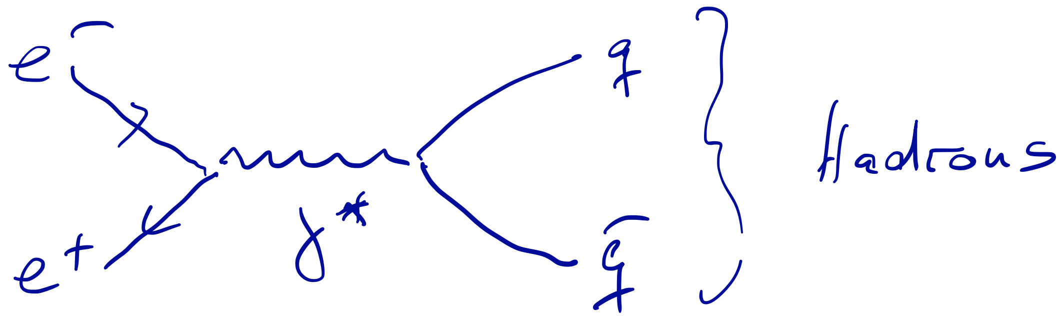
Part I: R_{had} Measurement

Part II: Meson Transition Form Factors

International School on Muon Dipole Moments and Hadronic Effects
BINP Novosibirsk, Sept 17 – 21, 2018

Reminder of Yesterday's Lecture



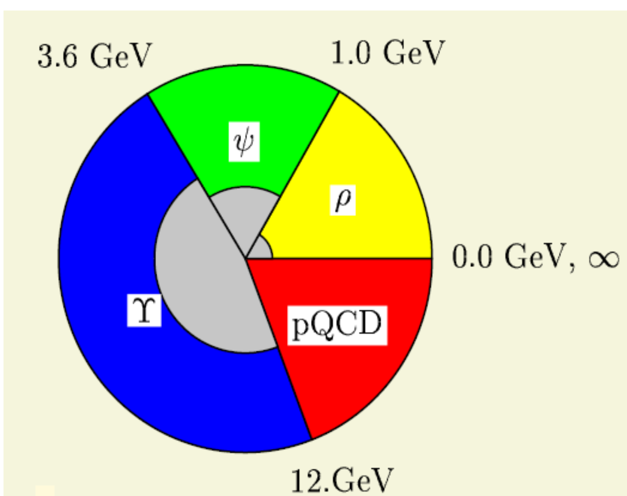


Reminder of Yesterday's Lecture

Running fine structure constant

$$\alpha_{\mathrm{em}}(s) = \frac{\alpha(0)}{(1 - \Delta\alpha_{\mathrm{em}}(s))}$$

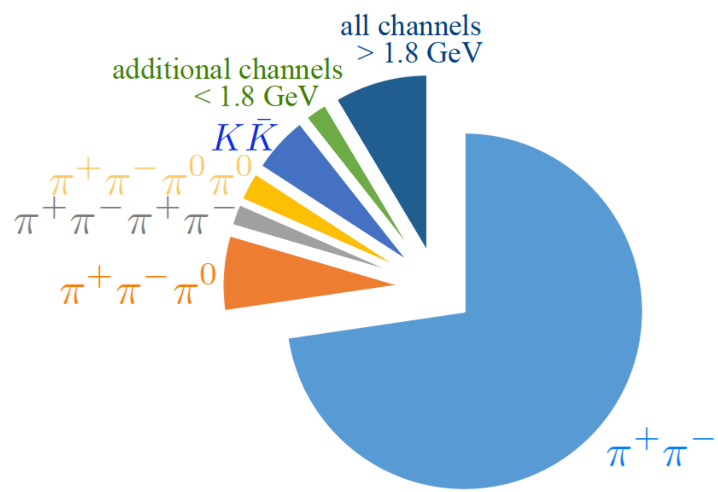
$$\Delta\alpha_{\mathrm{had}}^{(5)}(s) = -\frac{\alpha s}{3\pi} \int_{4m_\pi^2}^{E_{\mathrm{cut}}^2} \!\!\!\!\!\!\! P \;\; ds' \frac{R_\gamma^{\mathrm{data}}(s')}{s'(s'-s)}$$



Anomalous magnet moment of the muon

$$a_\mu = (g-2)_\mu / 2$$

$$a_\mu^{HVP} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma_{had}$$



Outline

Part I: R_{had} Measurements

- R measurements via Initial State Radiation

Part II: Measurements of Meson Transition Form Factors

- Hadronic Light-by-Light Contribution to $(g\text{-}2)_\mu$
- Meson Transition Form Factors at e+e- Colliders
- Production of $J^{PC}=1^{++}$ States in e+e- Annihilation

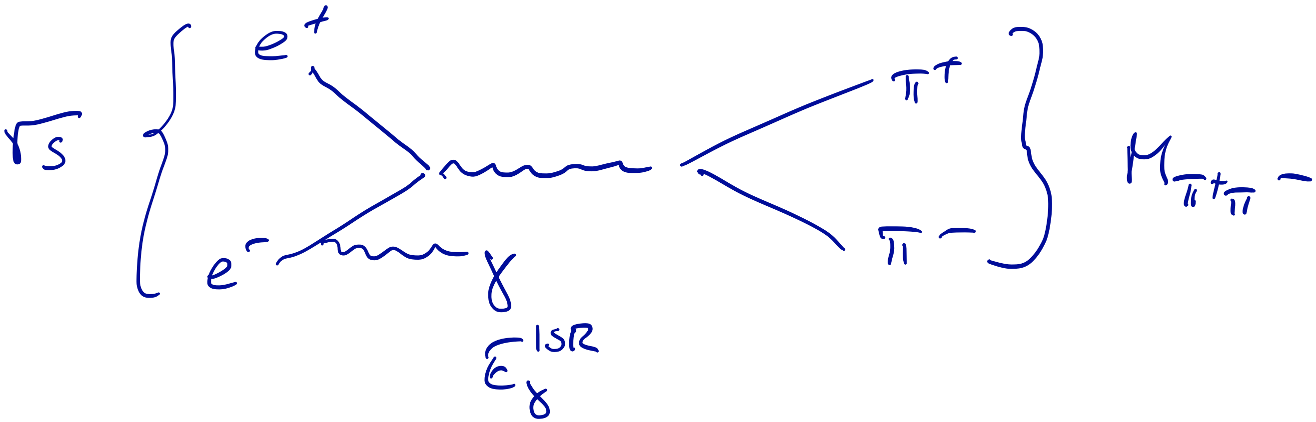
Summary (of both parts)

Hadronic Cross Section Measurements via Initial State Radiation

Initial State Radiation (ISR)

Baier, Fadin (1968)
Baier, Khoze (1965)
Arbuzov (1998)
Benayoun et al. (1999)
Binner et al. (1999)

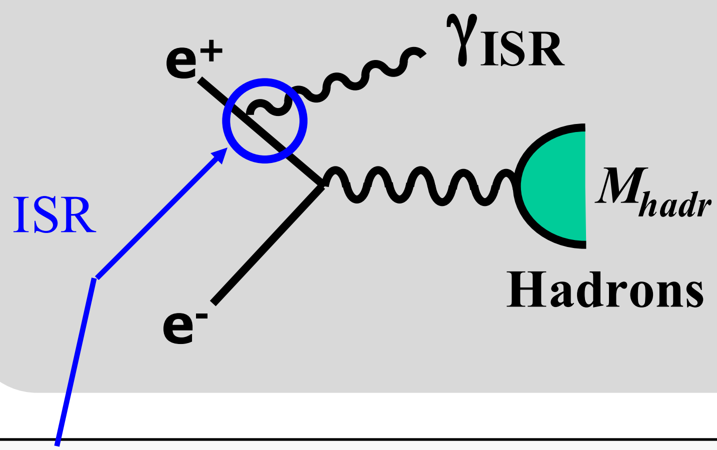
Complementary ansatz to traditional energy scan:
Consider events with **Initial State Radiation (ISR)**



Initial State Radiation (ISR)

Baier, Fadin (1968)
Baier, Khoze (1965)
Arbuzov (1998)
Benayoun et al. (1999)
Binner et al. (1999)

Complementary ansatz to traditional energy scan:
Consider events with **Initial State Radiation (ISR)**



'Radiative Return' to low-lying resonances
Normalization to thoeretical radiator function

$$\frac{d\sigma_{rad}}{dM^2_{Hadr}} = \frac{d\sigma(e^+ e^- \rightarrow \text{Hadrons} + \gamma_{ISR})}{dM^2_{Hadr}}$$

for $M_{Hadr}^2 < s$

MC- Generator PHOKHARA = NLO
J. Kühn, H. Czyż, G. Rodrigo

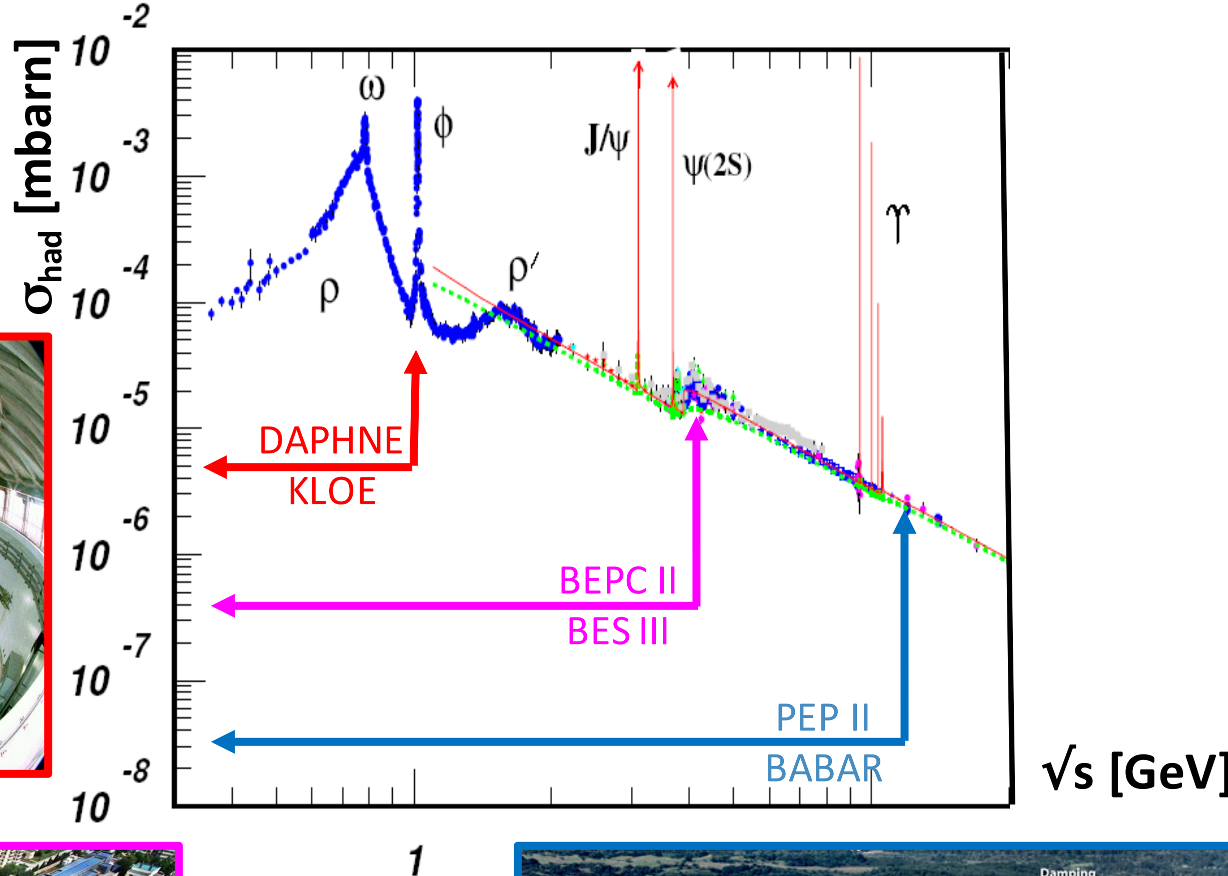
$$M^2_{Hadr} \frac{d\sigma_{rad}}{dM^2_{Hadr}} = \sigma_{Born}(s) \times H(s)$$

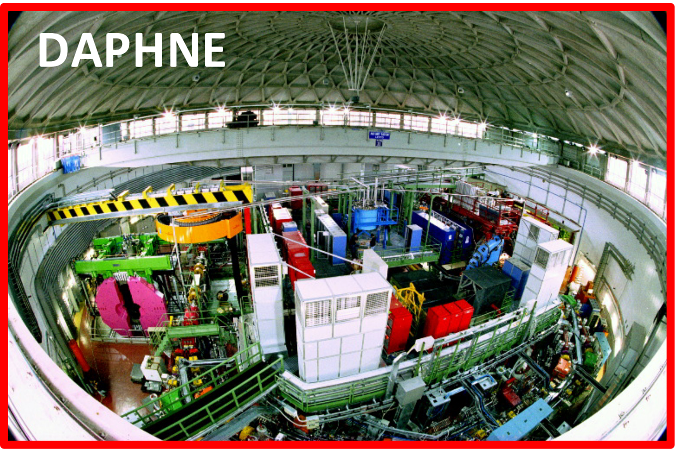
Radiator-Function

PHOKHARA 9.2: PRD94 (2016) 034033
All references at http://ific.uv.es/~rodrigo/phokhara/

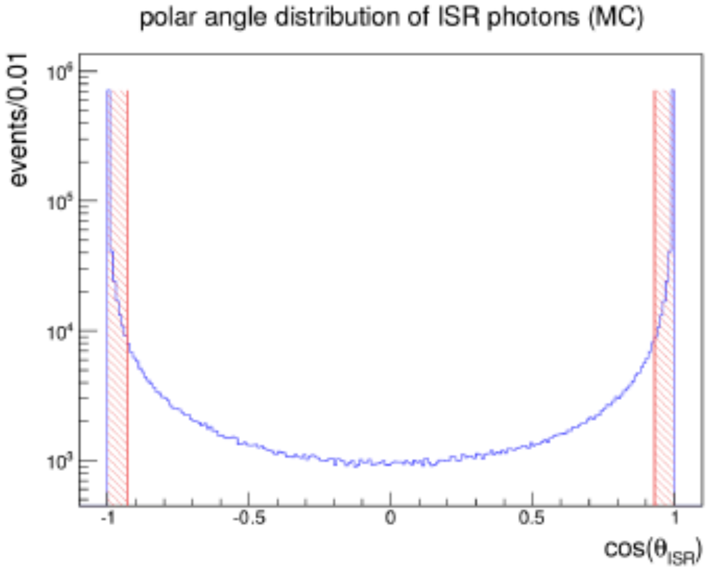
8

Initial State Radiation (ISR)





Initial State Radiation (ISR)



Tagged analysis:

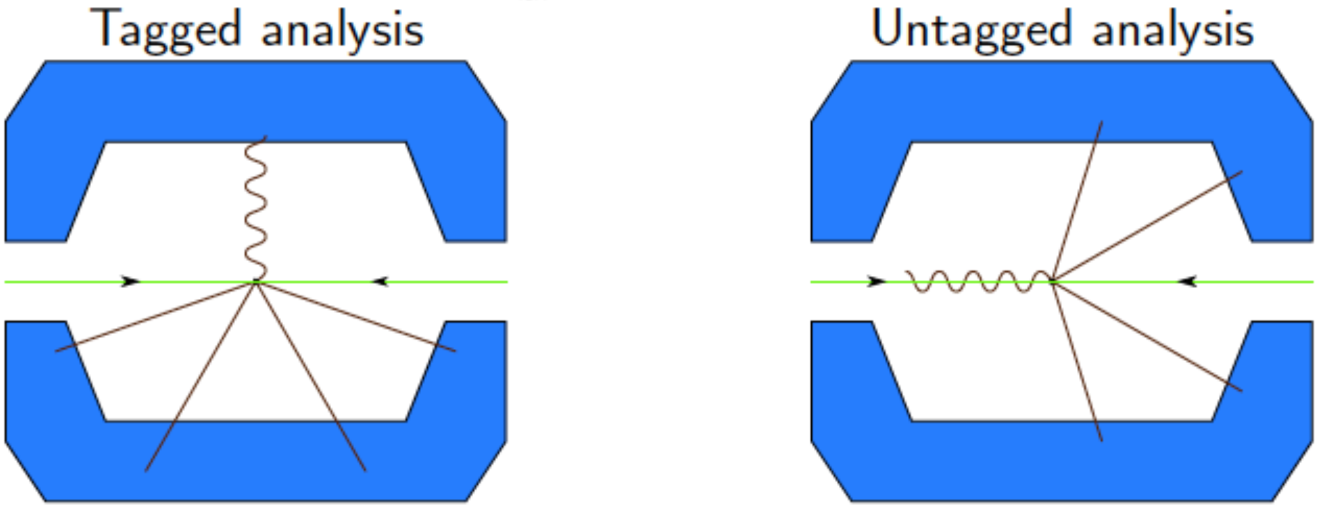
ISR photon measured in Calorimeter

- Increased amount of Final State Radiation (FSR)

Untagged analysis:

No ISR detection; cut on missing momentum

- Threshold mass region not accessible

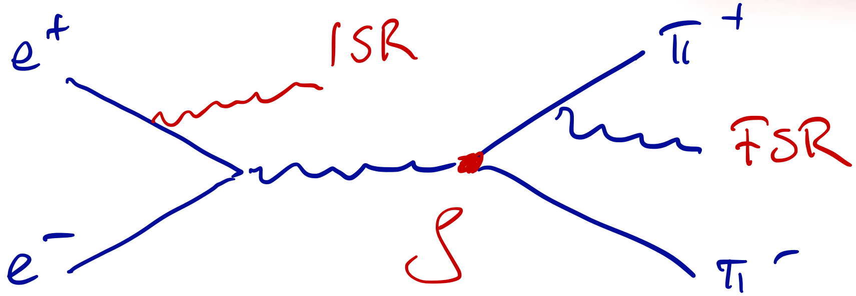


V. P. Druzhinin, S. I. Eidelman, S.I. Serednyakov, and E. P. Solodov
Rev. Mod. Phys. 83, 1545 (2011)

11

Final State Radiation (FSR)

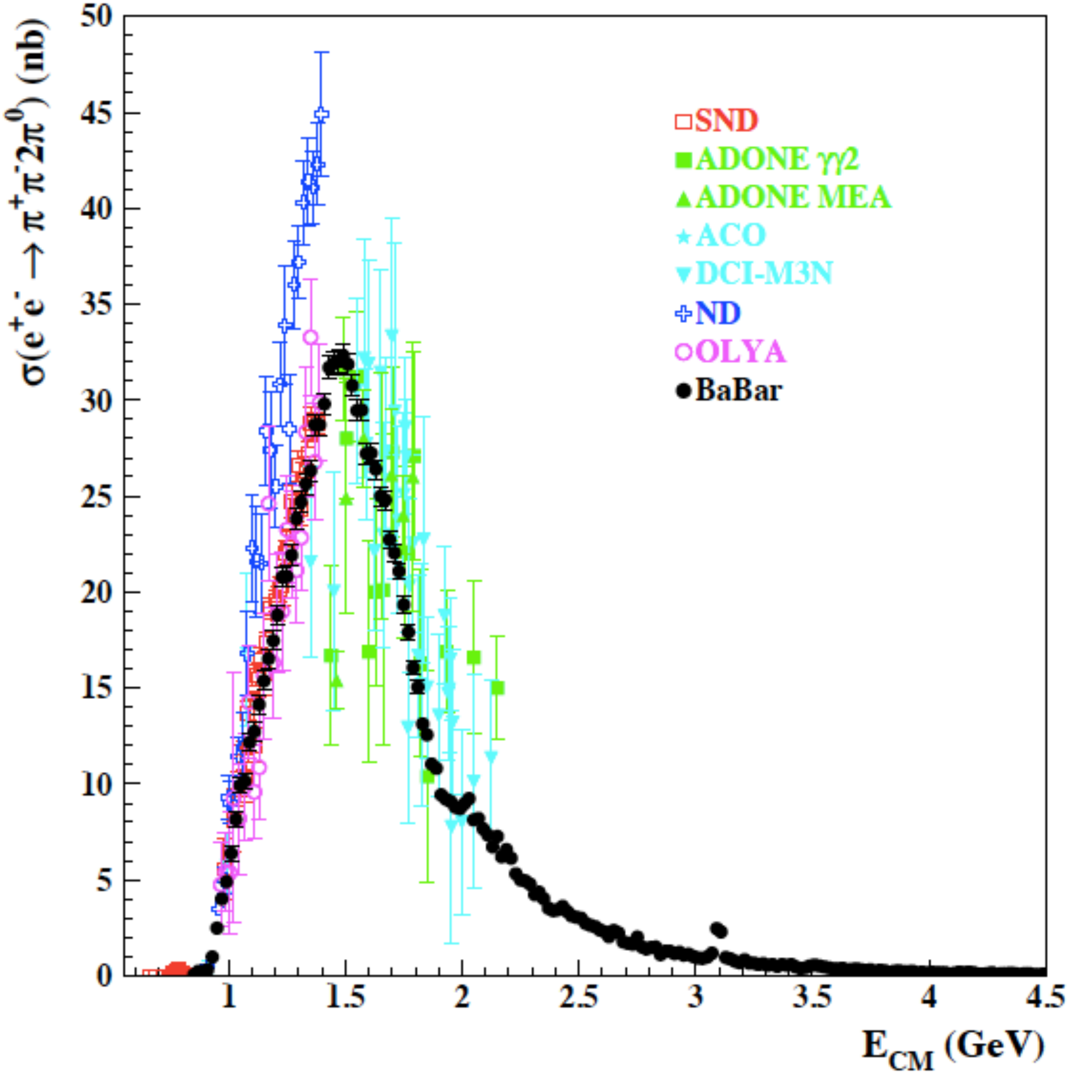
Do you expect FSR radiation effects to be of similar size as ISR in case of hadronic events ?



NEW

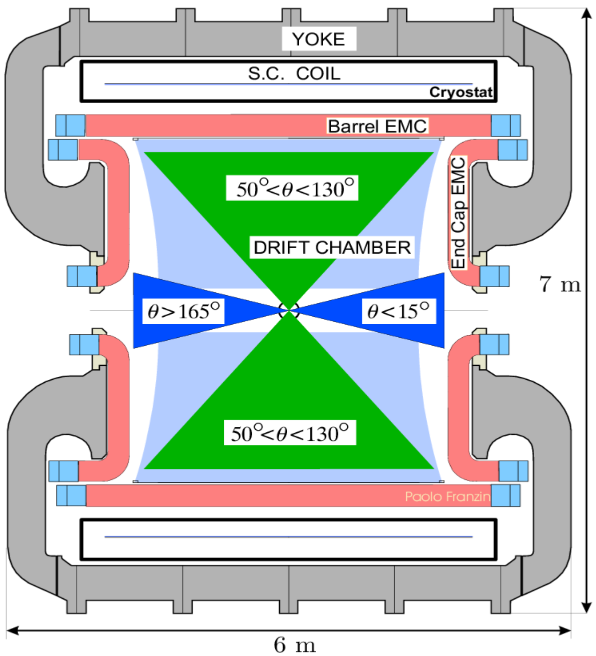
BABAR: $e^+e^- \to \pi^+\pi^-2\pi^0\gamma_{ISR}$

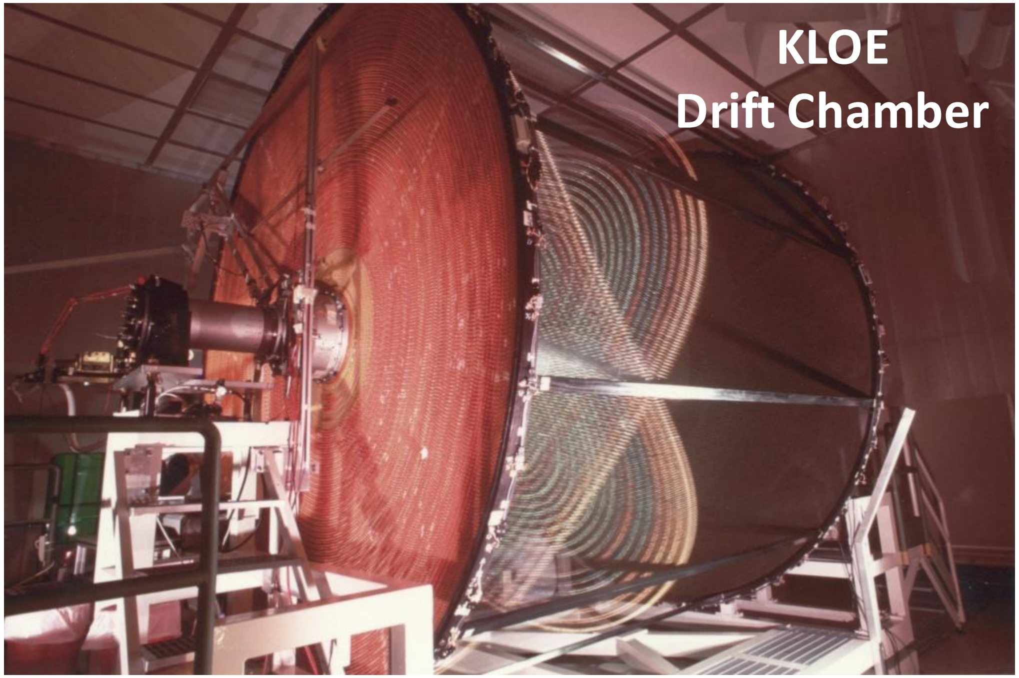
JG|U



- Tagged ISR analysis (2017)
- Huge improvement over existing data sets suffering from normalization issues

ISR@KLOE: $e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$



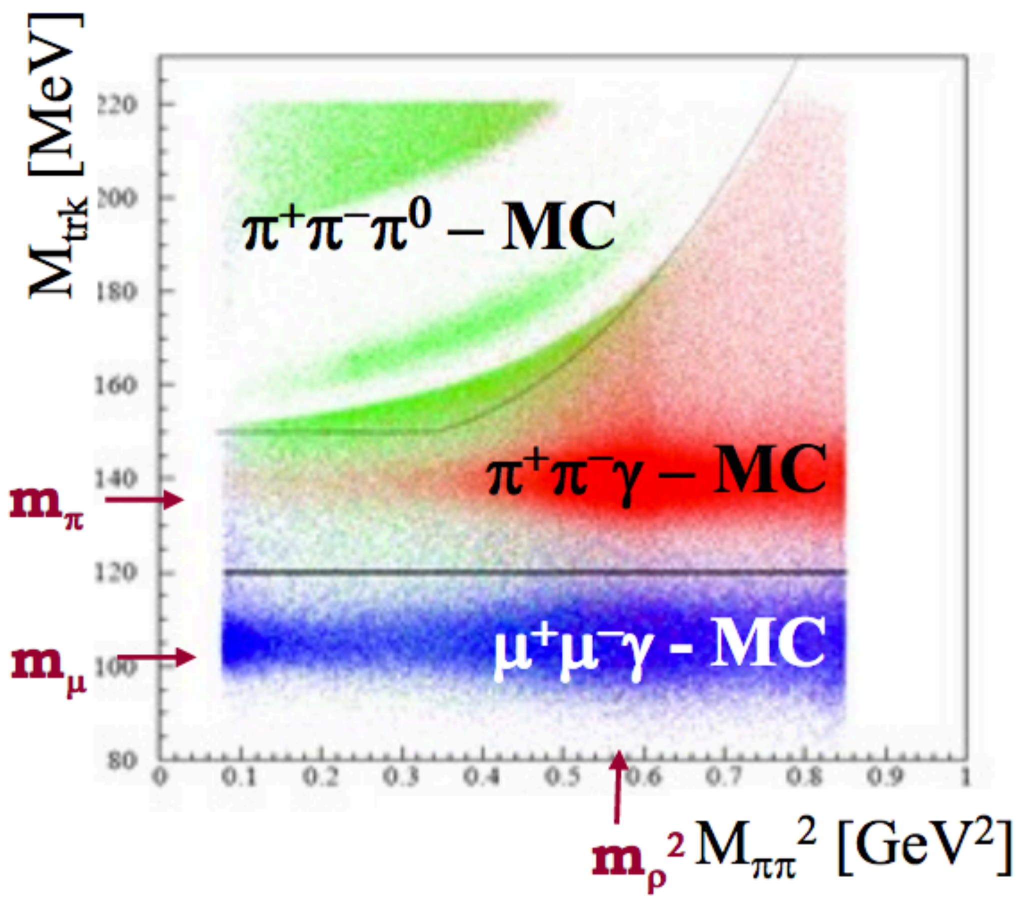


Publication	Mode	Normalization	Int. Luminosity*
Phys.Lett. B606 (2005) 12	untagged	Radiator	141 pb^{-1}
Phys.Lett. B670 (2009) 285	untagged	Radiator	240 pb^{-1}
Phys.Lett. B700 (2011) 102	tagged	Radiator	232 pb^{-1}
Phys.Lett. B720 (2013) 336	untagged	$\mu^+\mu^-\gamma$	240 pb^{-1}

*full KLOE statistics 2,500 pb^{-1}

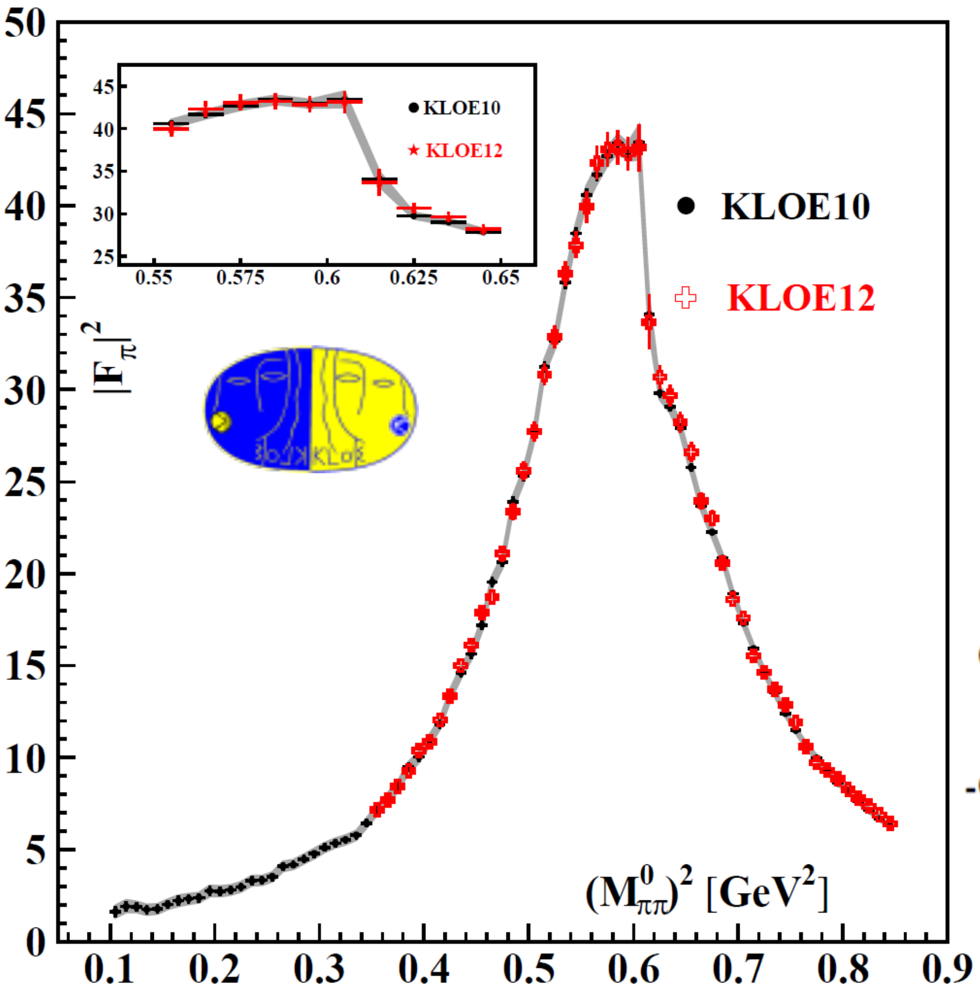
ISR@KLOE: $e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$

Track mass: $$\left(M_\phi - \sqrt{\vec{p}_1^{\,2} + M_{trk}^2} - \sqrt{\vec{p}_2^{\,2} + M_{trk}^2}\right)^2 - (\vec{p}_1 + \vec{p}_2)^2 = q_\gamma^2 = 0$$



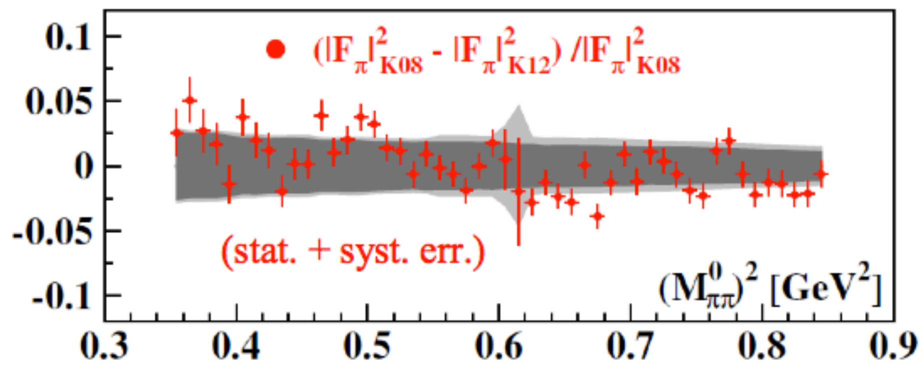
Derive this formula

ISR@KLOE: Pion Form Factor

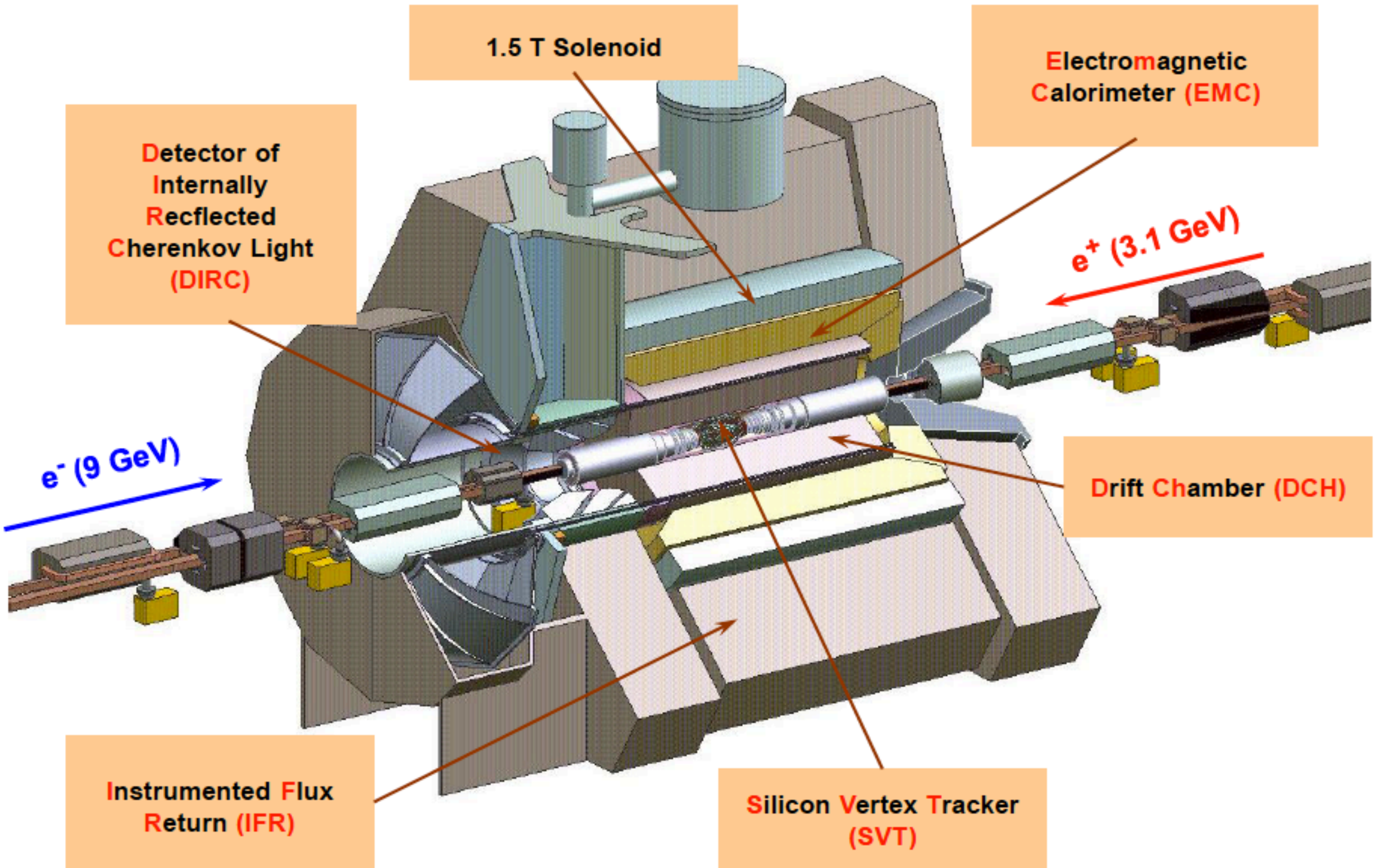


Features

- Below 1% systematic. uncertainties
- Coverage from threshold to 1 GeV
- Agreement btw. KLOE data sets within systematic uncertainties
  → Cross check for Radiator and Luminosity



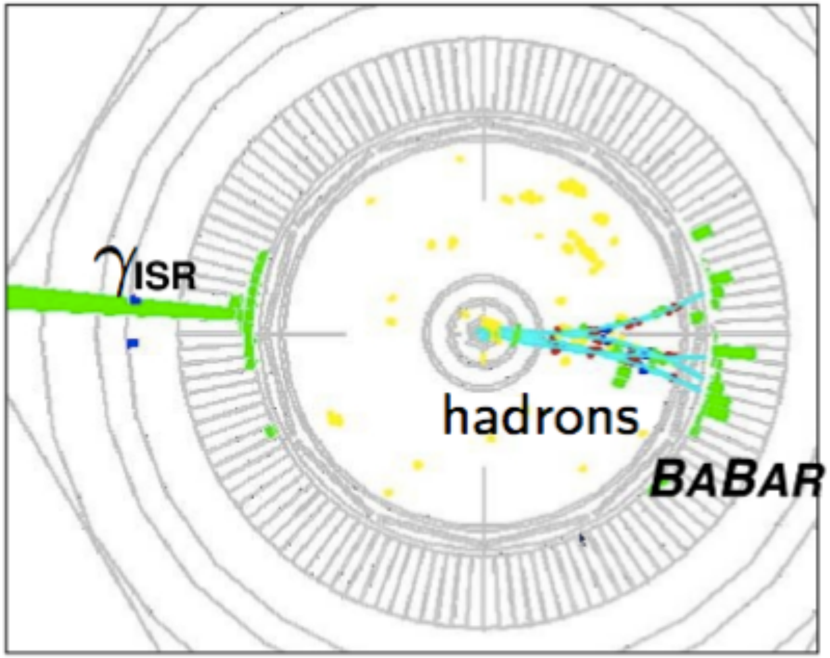
The BABAR-Experiment



Achim Denig

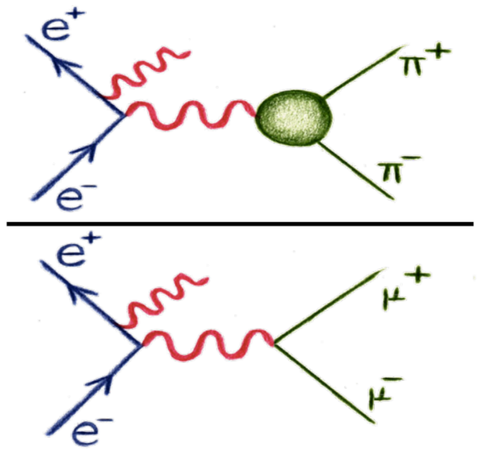
ISR@BABAR

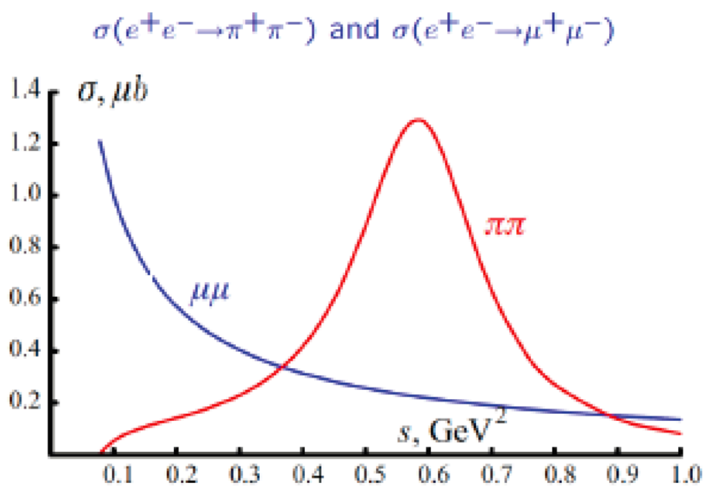
ISR Selection

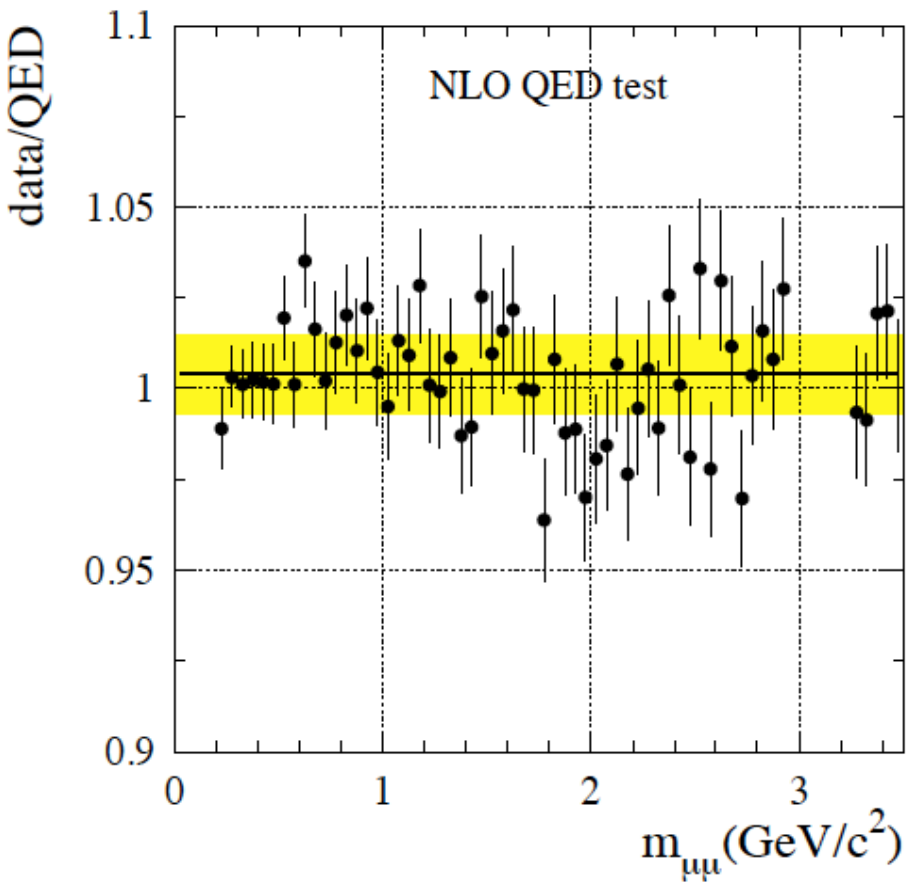


- **Detected high energy photon E_γ>3 GeV**
  → strong background subtraction
- **Event topology: back-to-back signature**
  → high geometrical acceptance
- **Kinematic fit including ISR**
  → very good energy resolution
- **Continous measurement from threshold to ~5 GeV**
  → provides common consistent systematic uncertainty

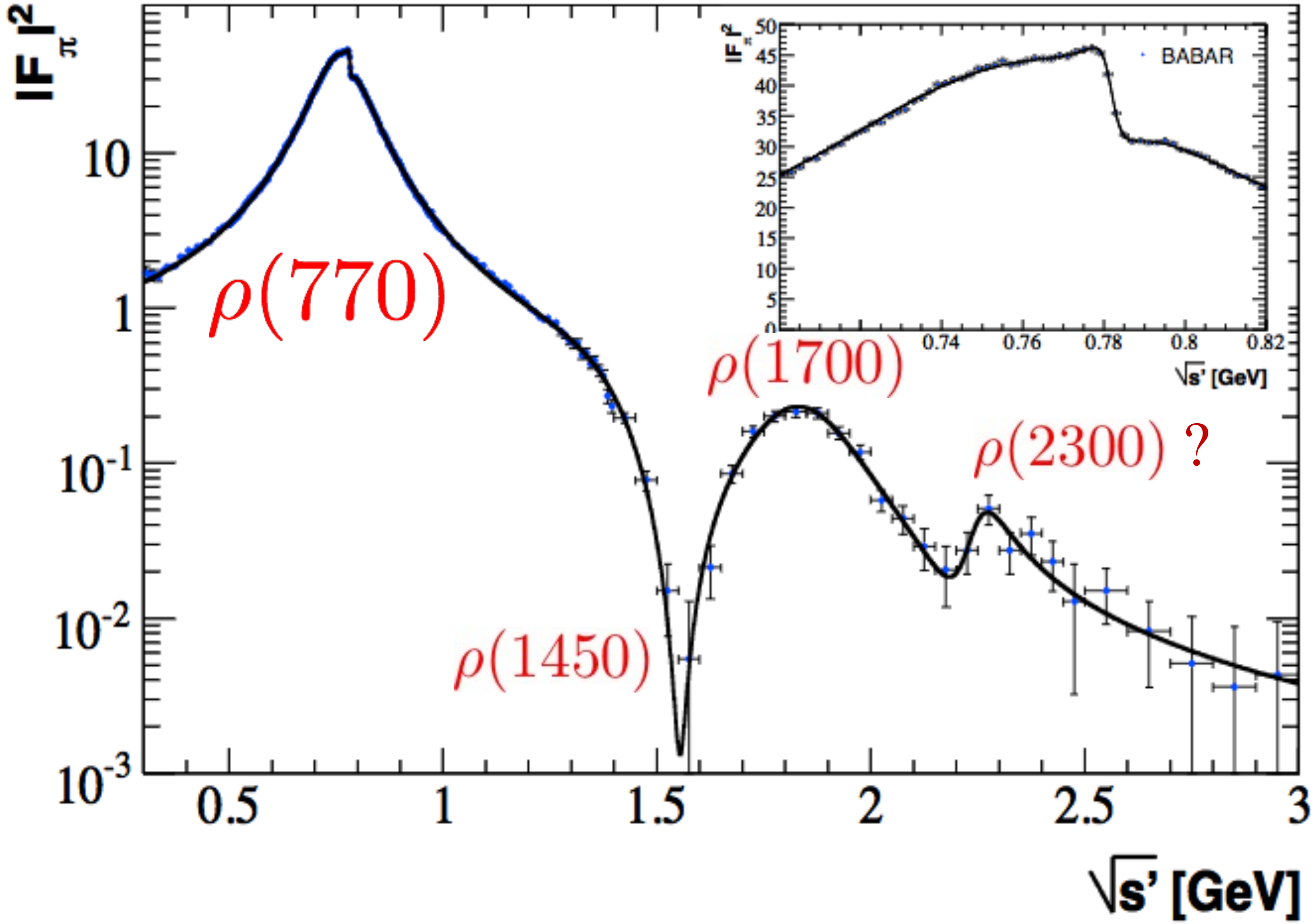
ISR@BABAR: Muon Normalization







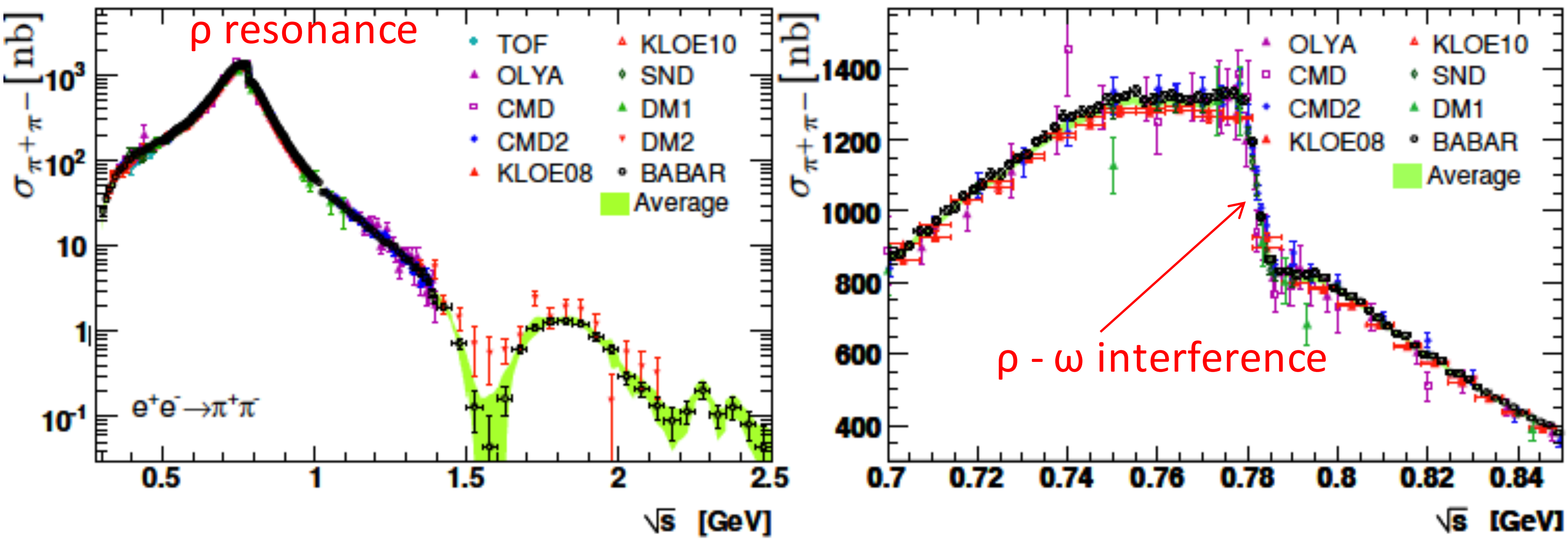
BABAR: Pion Form Factor



systematic. Uncertainty 0.5 – 1.4 %

BABAR, PRL 103, 231801 (2009)

Most relevant Channel: $e^+e^- \rightarrow \pi^+\pi^-$

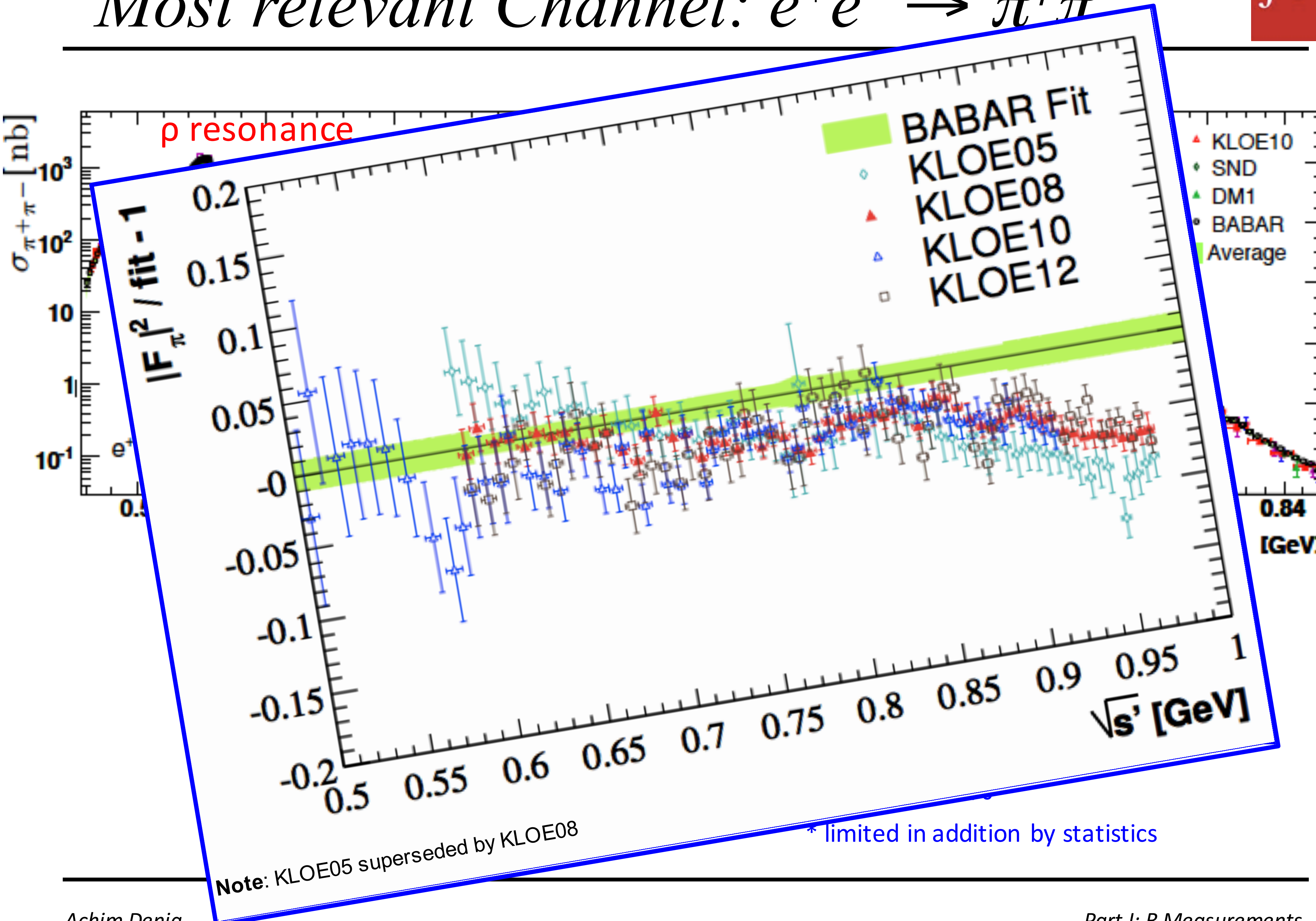


Systematic Uncertainties

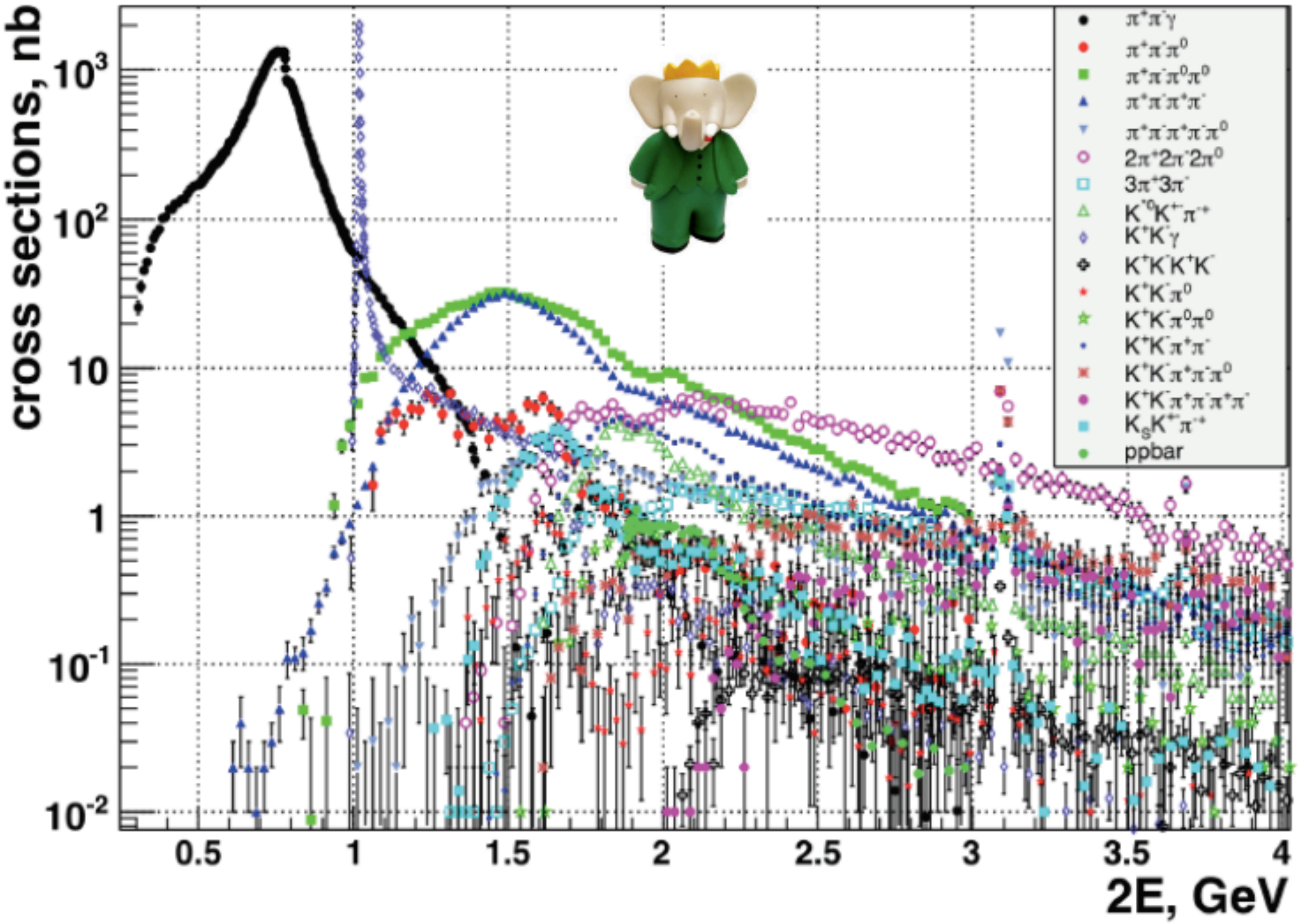
- BABAR 0.5%
- KLOE 0.8%
- CMD2 0.8%*
- SND 1.5%*

* limited in addition by statistics

Most relevant Channel: $e^+e^- \rightarrow \pi^+\pi^-$



Summary of ISR Results



Precision:

2π: < 1%

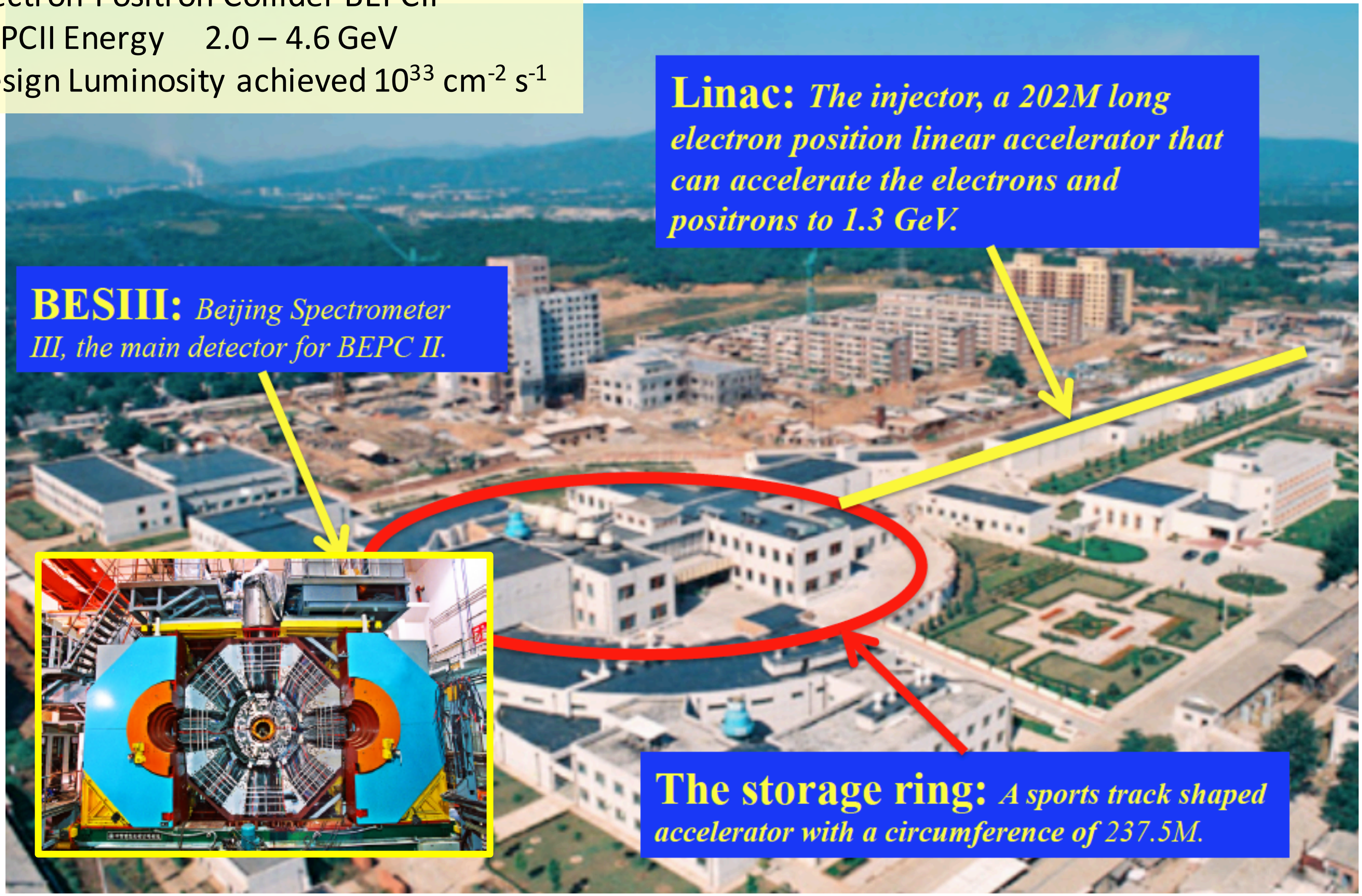
3π: ~10%

4π: ~ 3%

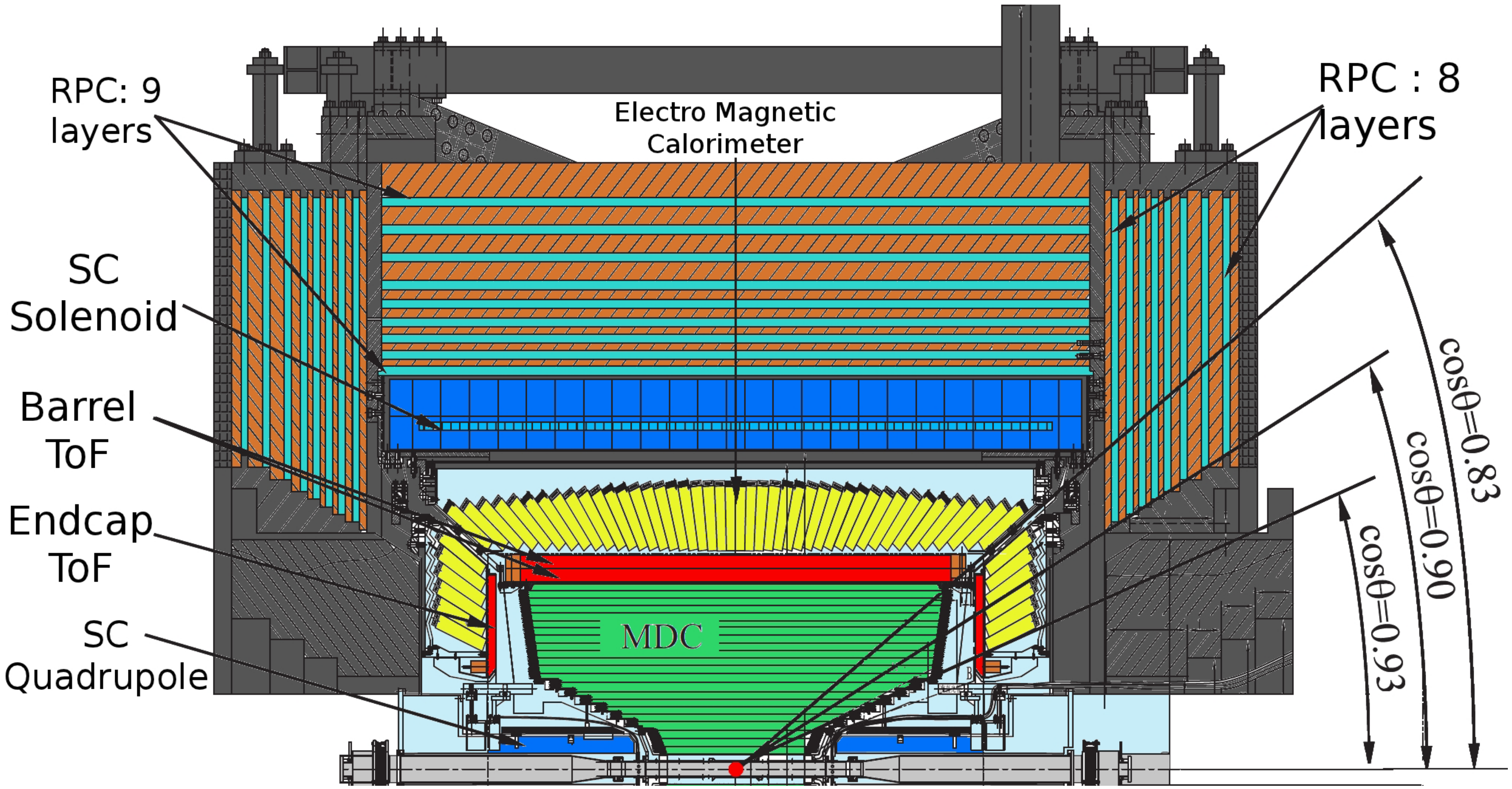
≥ 5π: 10% and higher

BESIII Experiment @ BEPCII

Electron-Positron Collider BEPCII
BEPCII Energy 2.0 – 4.6 GeV
Design Luminosity achieved 10^{33} cm^{-2} s^{-1}

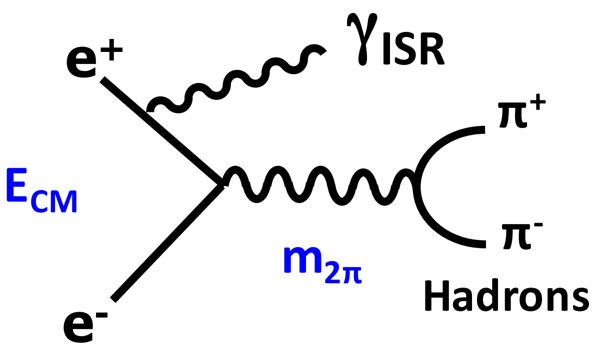


BESIII Experiment @ BEPCII

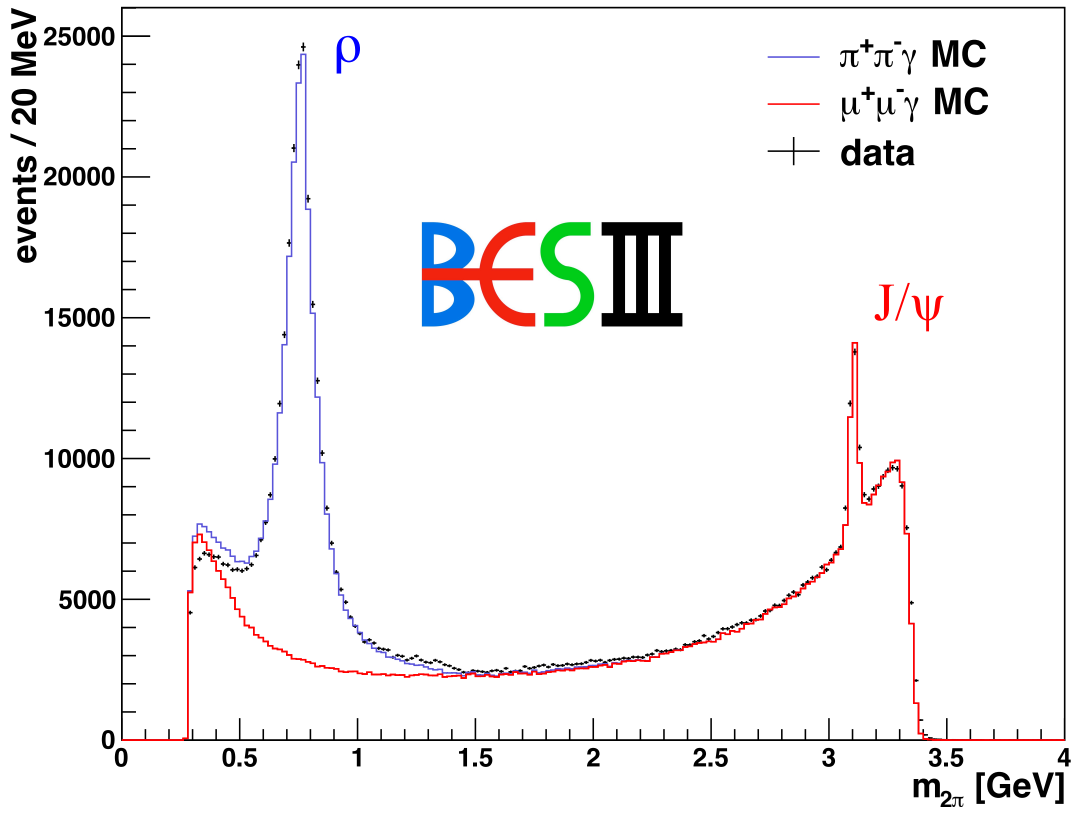


BESIII ISR Analysis: $e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$

Initial State Radiation



Event yield after acceptance cuts **only**

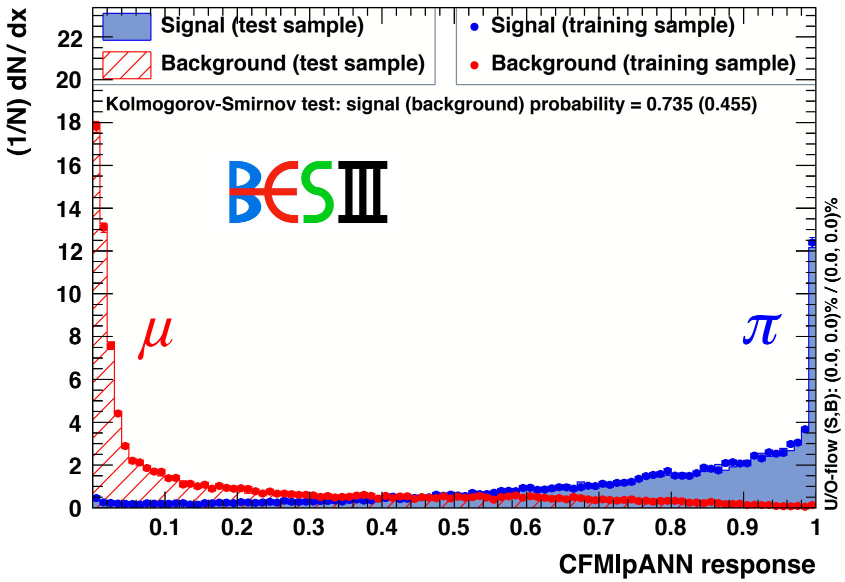


Features:

- $\psi(3770)$ data only (2.9 fb^{-1})
- no dedicated background subtraction
- tagged ISR photon

Pion Muon Separation needed
→ TMVA methods!

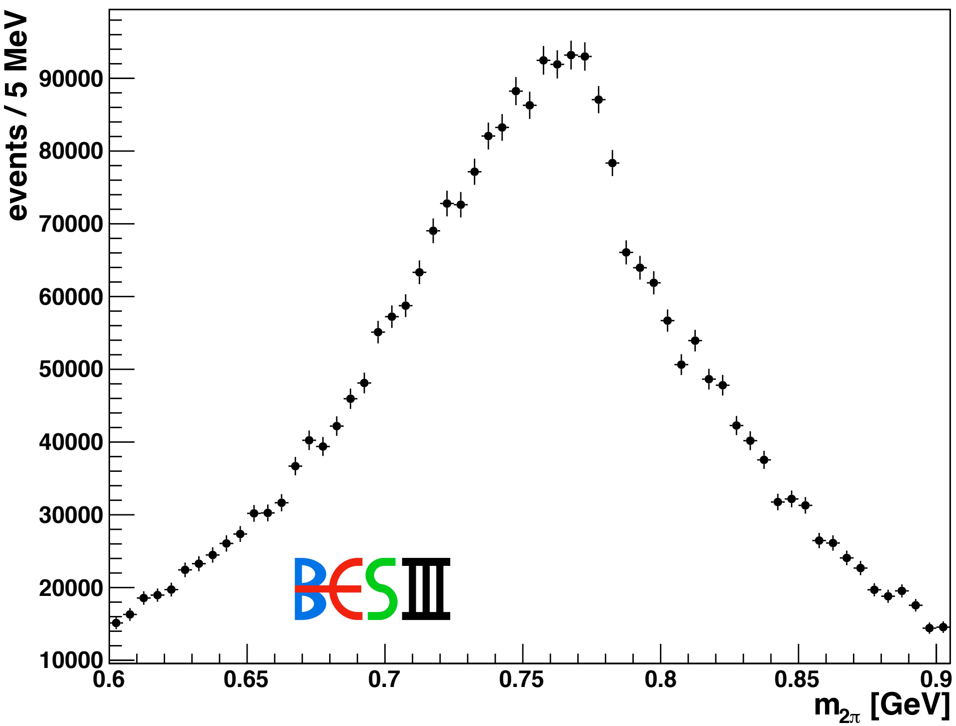
$e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$: π - μ Separation



TMVA method (Neural Network):

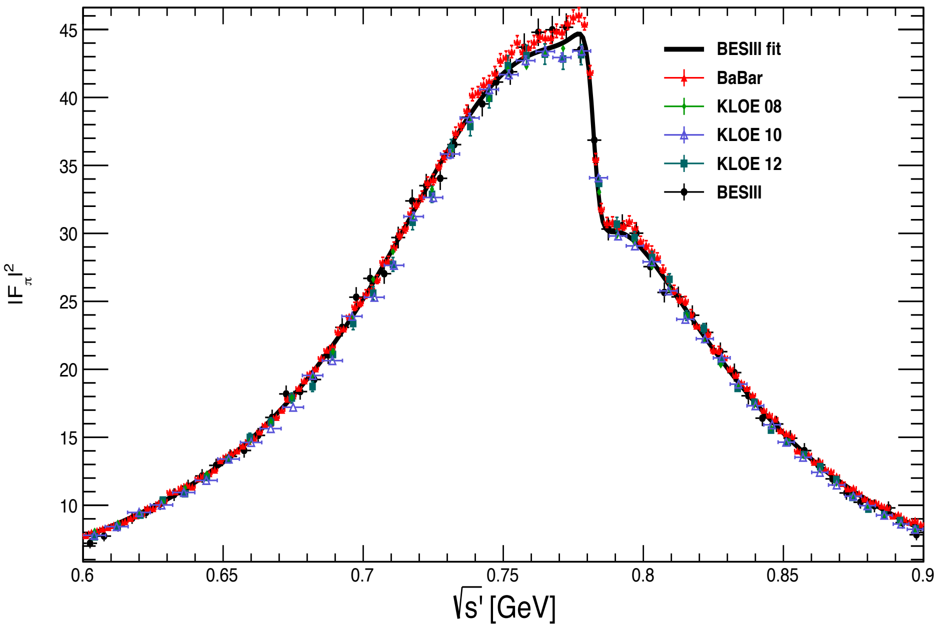
- trained using μμγ and ππππγ MC events
- information based on track level
- efficiency matrix (p,Θ) for data, MC
- corrected for data - MC differences
- cross checked for different TMVA methods

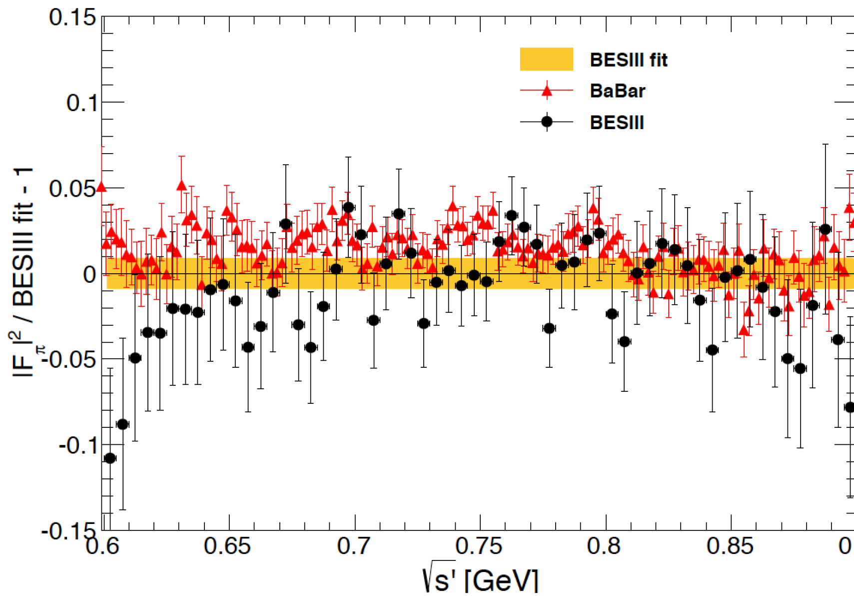
Event yield ππγ after π-μ separation

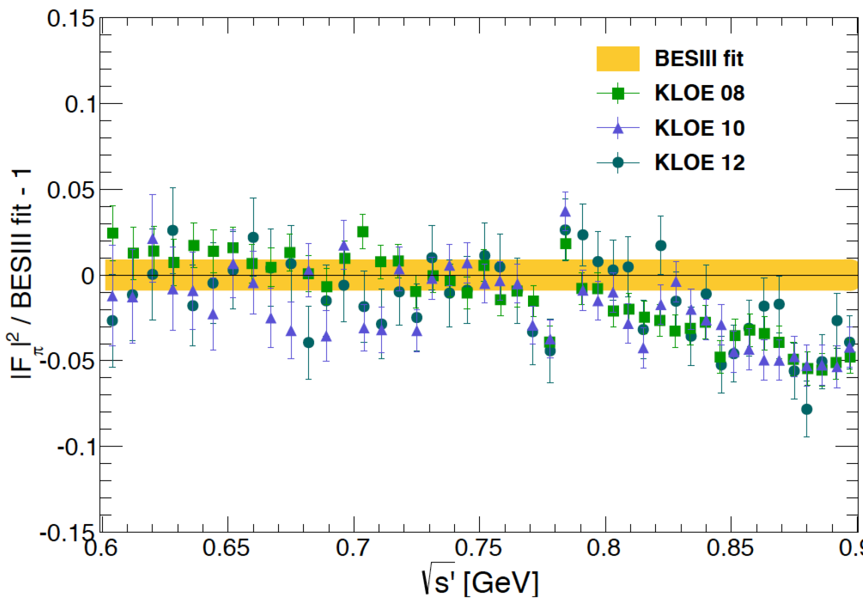


Comparison with existing Data

Pion Form Factor F_π





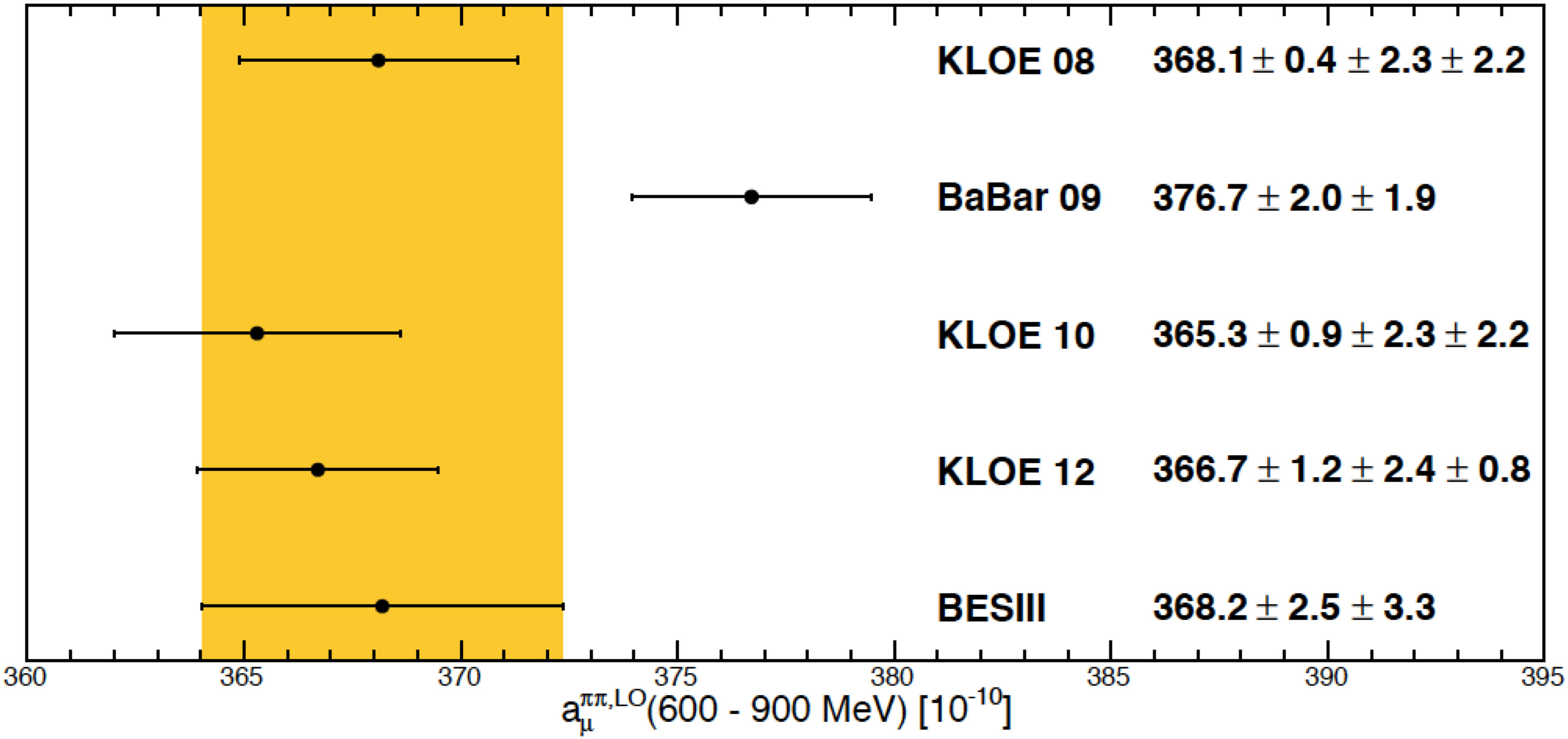


0.9 % accuracy

normalization to luminosity / radiator function

Impact on Hadronic Vacuum Polarization

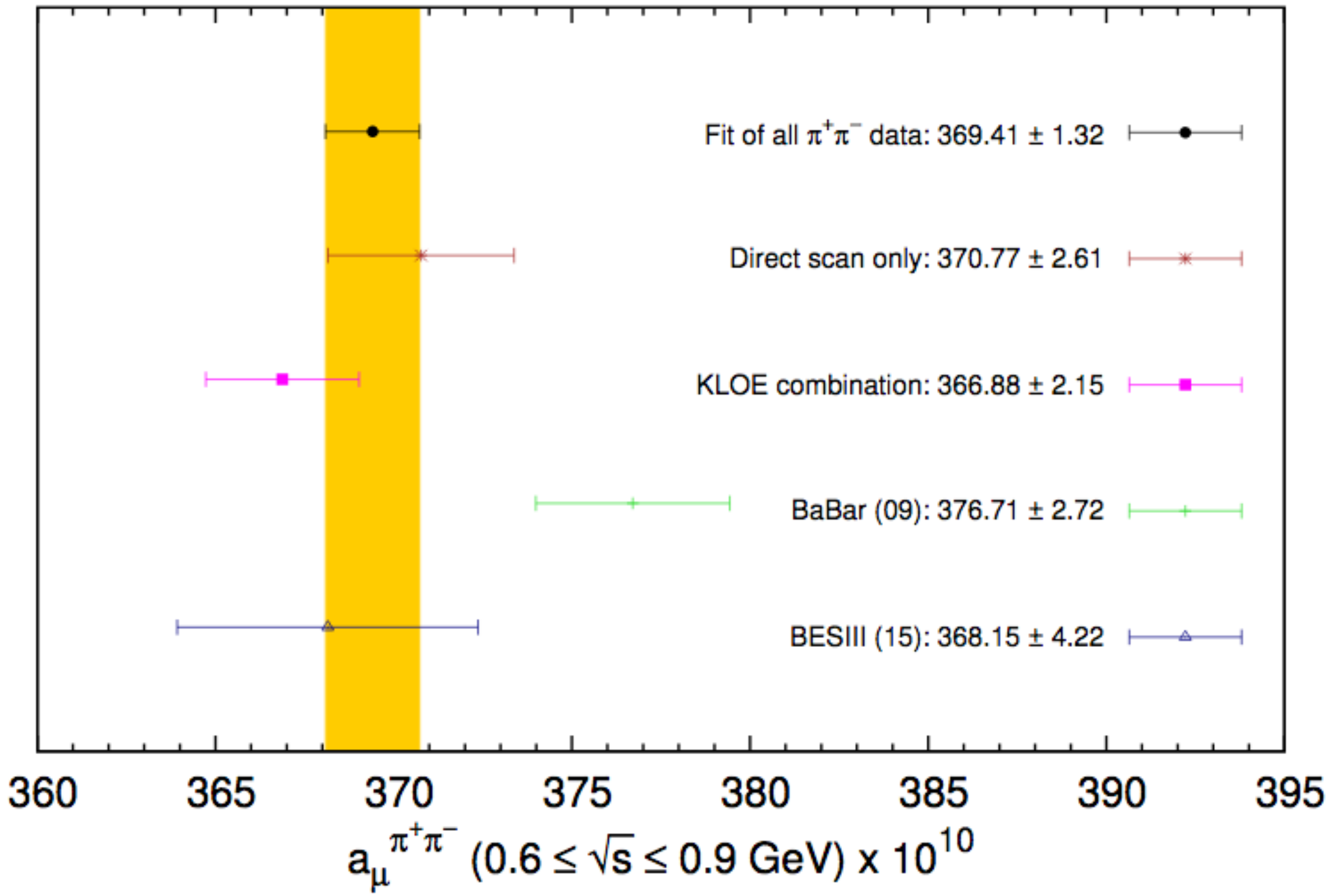
PLB753 (2016)



Good agreement found with KLOE !

BES III confirms the $(g\text{-}2)_\mu$ deviation at 3 …4 sigma level !!!

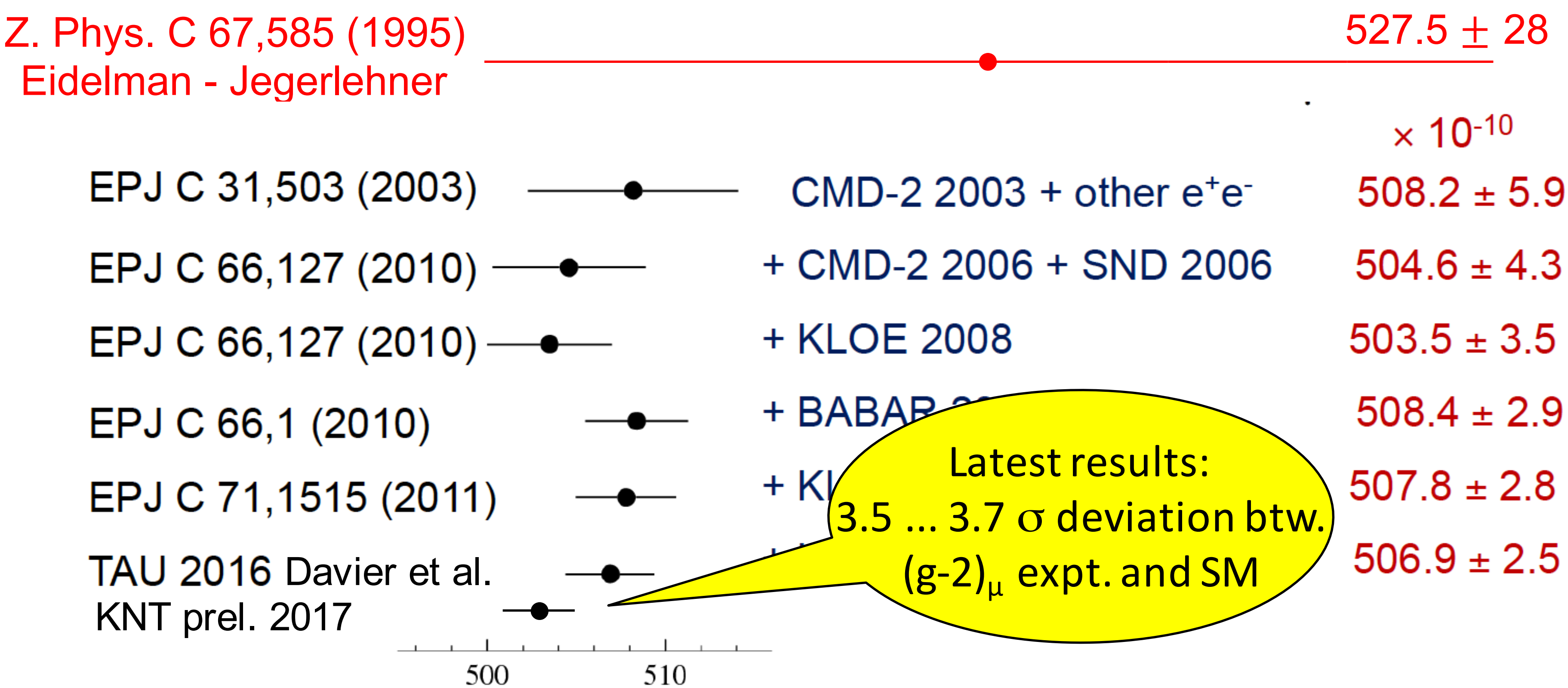
Impact on Hadronic Vacuum Polarization



Mandatory to understand KLOE-BABAR-BES III discrepancy !!!

New data (energy scan!) from VEPP-2000 eagerly awaited !!!

Improvement in 2π Contribution to $(g\text{-}2)_\mu$



Complementarity ISR Experiments

*** top, ** good, * fair

	KLOE	BABAR	BES III
Energy range covered	*	***	***
Available Statistics	***	***	**
Resolution DC	***	**	**
Threshold for untagged method	***	*	**
FSR model uncertainty	*	***	**

one might argue about certain points – also often energy-dependent

Hadronic Light-by-Light Contribution to $(g\text{-}2)_\mu$

Standard Model Prediction of $(g\text{-}2)_\mu$

Hadronic contribution **non-perturbative,** the **limiting** contribution

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had} = (11\,659\,180.2 \pm 4.9) \cdot 10^{-10}$$

Teubner et al. '11

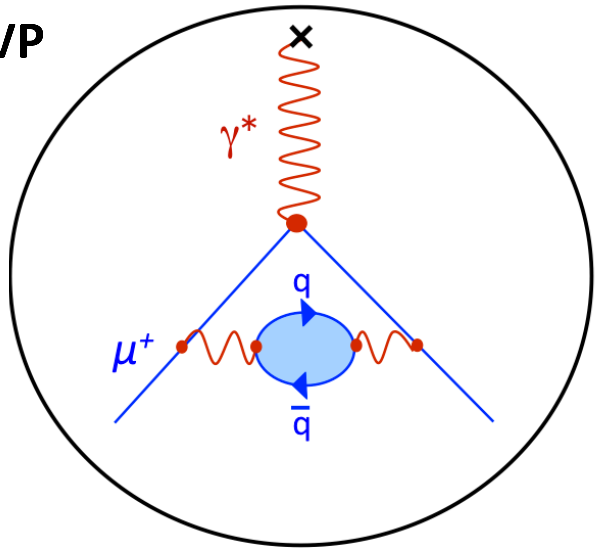
Keshavarzi et al. 2018

→ **HVP**: Hadronic Vacuum Polarization $(693.27 \pm \mathbf{2.46}) \cdot 10^{-10}$

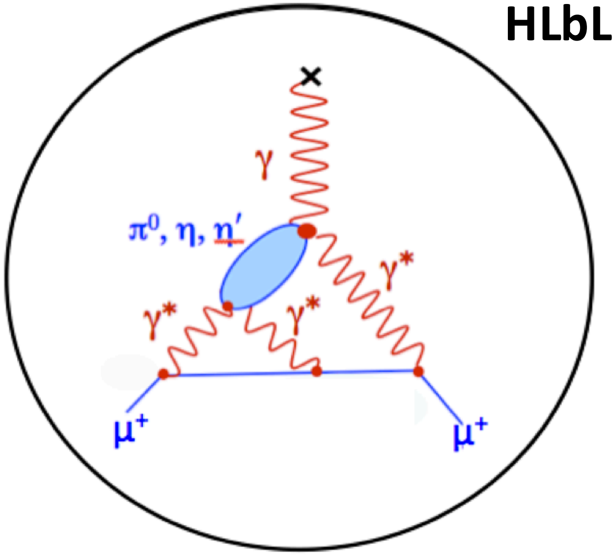
NLO $(-9.8 \pm \mathbf{0.1}) \cdot 10^{-10}$; NNLO $(1.2 \pm \mathbf{0.01}) \cdot 10^{-10}$)

→ **HLbL**: Hadronic Light-by-Light $(9.8 \pm \mathbf{2.6}) \cdot 10^{-10}$

HVP



HLbL



Hadronic Light-by-Light $(g\text{-}2)_\mu$

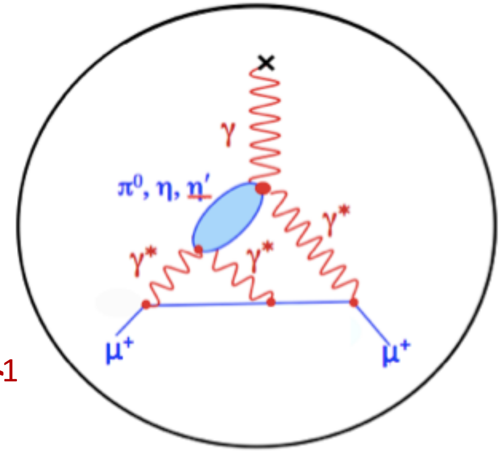
Leading contributions are pole contribution from π^0, η, η'

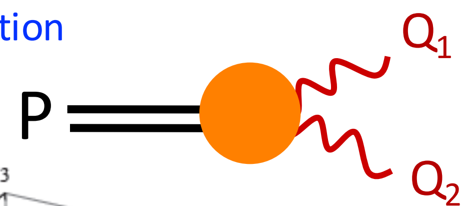
2D integral representation

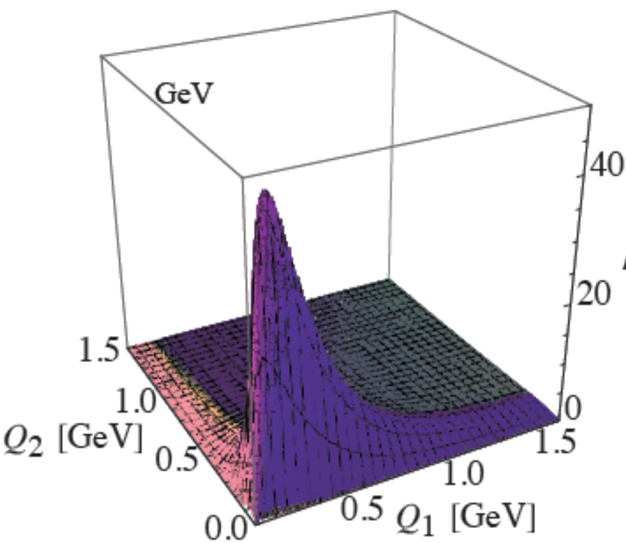
$$a_\mu^{\mathrm{HLbL};\pi^0} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \sum_i w_i(Q_1,Q_2)\, f_i(Q_1,Q_2)$$

weighting function — form factor

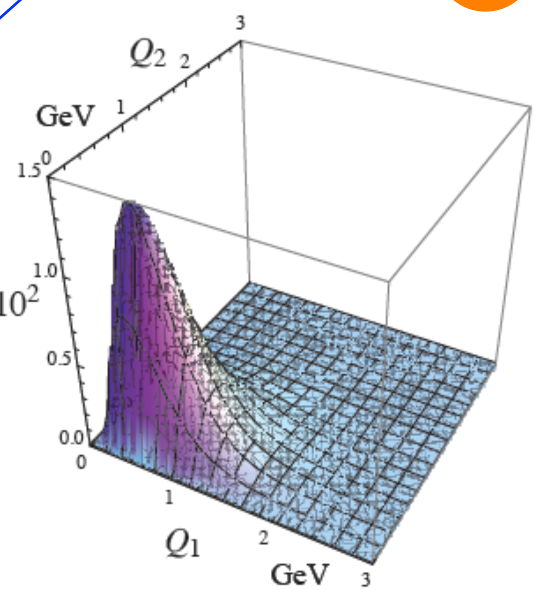
[Knecht, Nyffeler 2002]







Pseudoscalar Mesons



Axial Vector Mesons

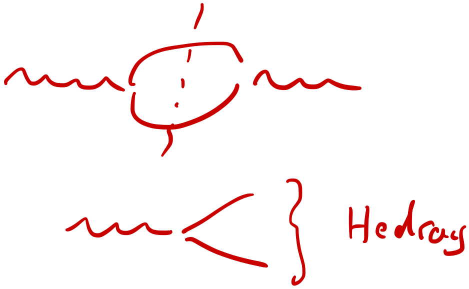
→ Need doubly virtual form factors of π^0, η, η' at low Q^2

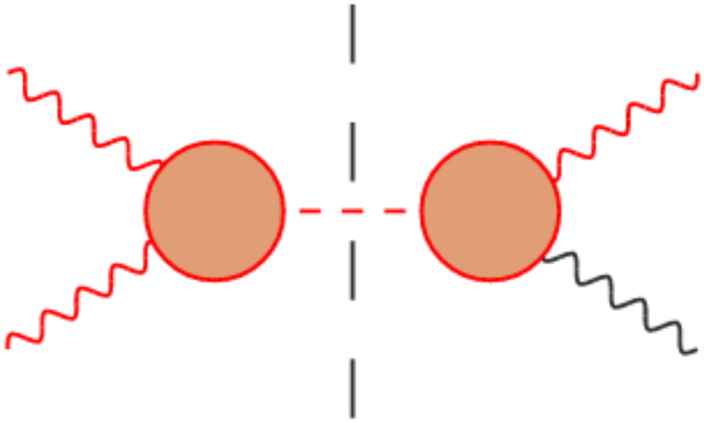
Data-Driven Approaches $F(Q^2, 0)$

Dispersive Approaches for a_μ^{HLbL}

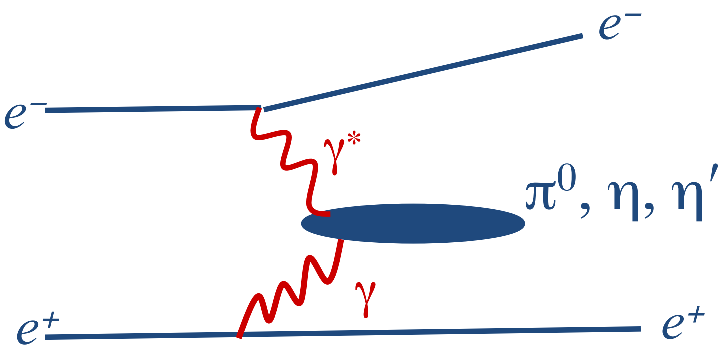
[Colangelo, Hoferichter, Kubis, …2014, 2015]
[Pauk, Vanderhaeghen, 2015, 2016]

- Describe dominating contributions with dispersion relations
- Remaining contributions calculated classically (model-dependent)
- Relate to measurable quantities
- Relate singly-virtual TFFs with double-virtual TFFs
- Goal: 10 … 20% of HLbL uncertainty
- **Reduced model-dependence**



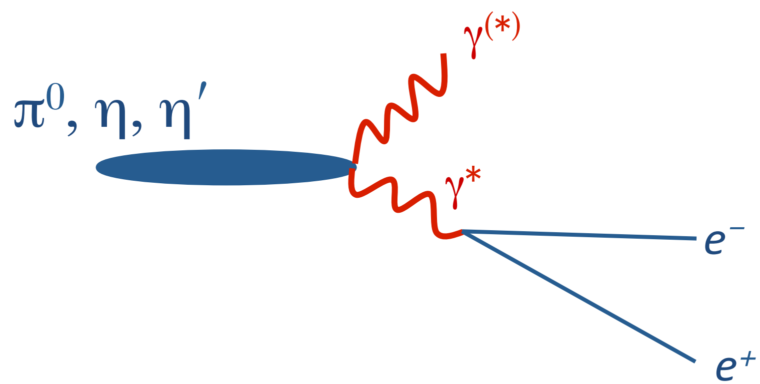


Transition Form Factors



Spacelike Measurement

at BES III: $Q^2 = 0.3 - 3.1\ GeV^2$
no previous precision data



Timelike Measurement

$Q^2 < M^2_{Meson}$

Meson Transition Form Factors at e+e- Colliders

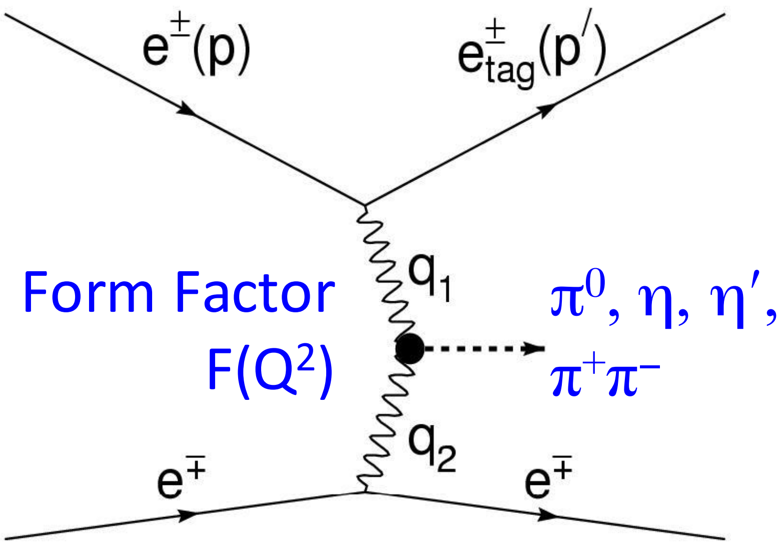
Spacelike FFs $\gamma\gamma^* \rightarrow P$

Single Tag Method

Selection criteria

- 1 electron (positron) detected
- 1 positron (electron) along beam axis
- Meson fully reconstructed

→ **cut on angle of missing momentum**



Momentum transfer

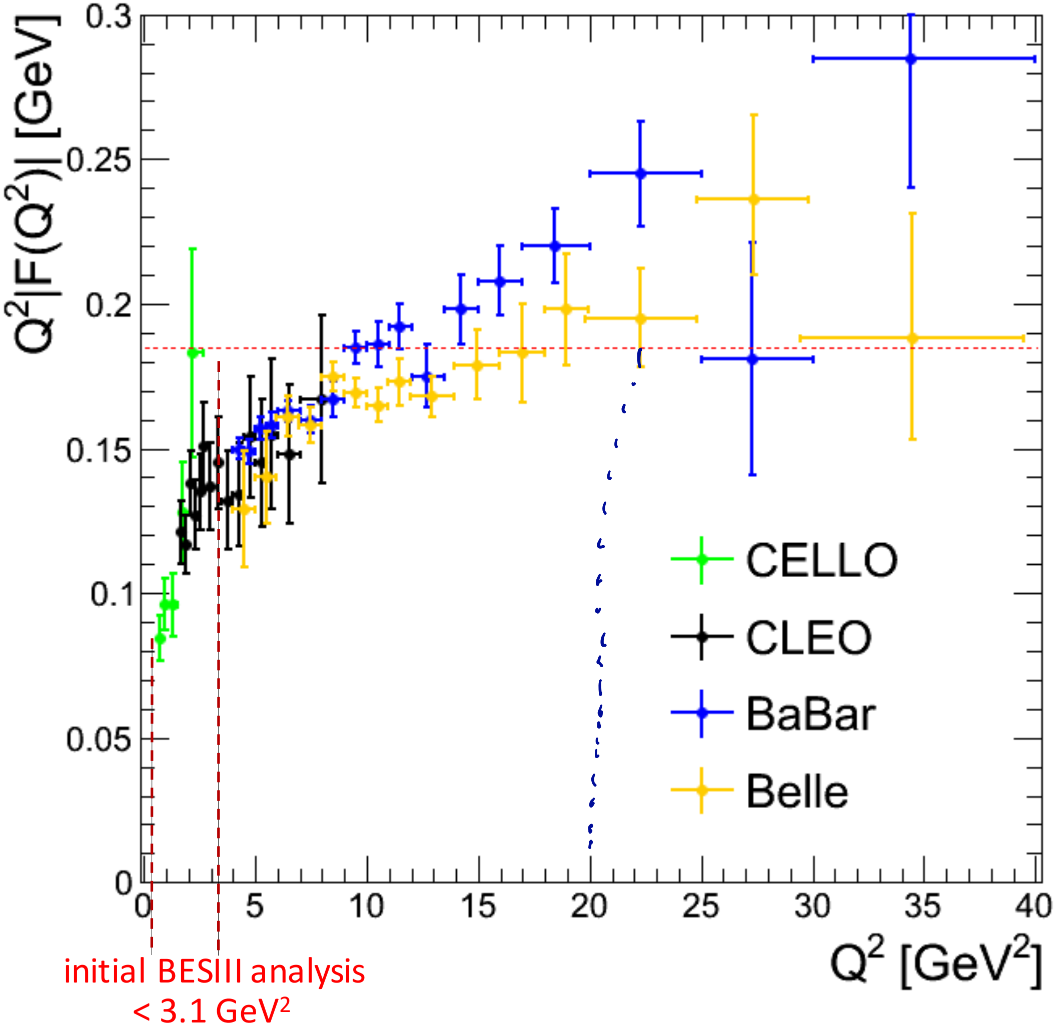
- tagged: $Q^2 = -q_1^2 = -(p - p')^2$
  → Highly virtual photon
- untagged: $q^2 = -q_2^2 \sim 0\ \mathrm{GeV}^2$
  → Quasi-real photon

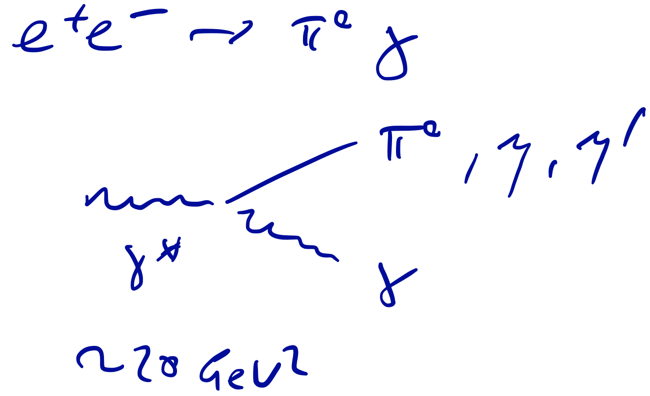
$$Q^2 = 4 \cdot E \cdot E' \cdot \sin^2(\theta/2)$$

EKHARA event generator
Czyż, Ivashyn

Existing Data on SL Transition FFs

$e^+e^- \rightarrow e^+e^- \pi^0$





Features:

- recent high-Q^2 data from BABAR and BELLE $Q^2 > 4$ GeV^2
- above 1.5 GeV^2 data from CLEO
- below 1.5 GeV^2 data from CELLO

Meson Distribution Amplitudes

Meson Structure:

Transition form factors F give access to the meson distribution amplitudes (DA) $\Phi(x,Q^2)$ important for many QCD processes

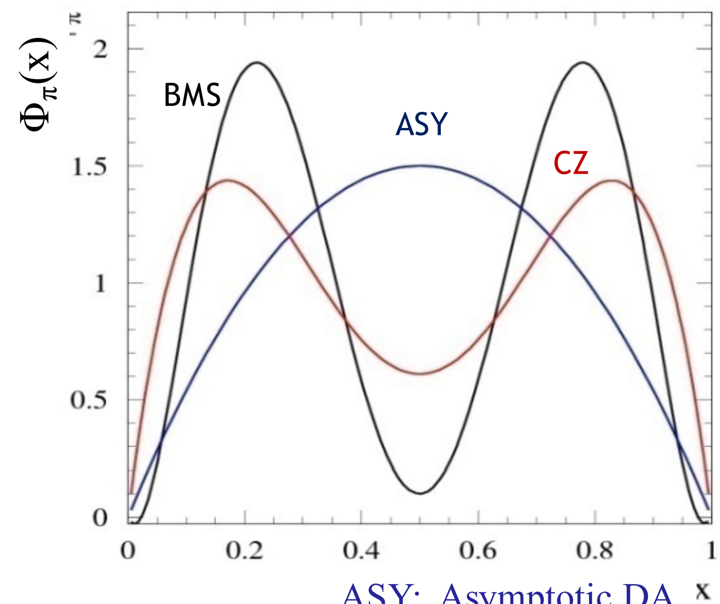
(x: fraction of the meson momentum carried by one of the quarks)

$$F(Q^2) = \int T(x,Q^2)\ \Phi(x,Q^2)\ dx$$

hard scattering amplitude for $\gamma\gamma \rightarrow qq$

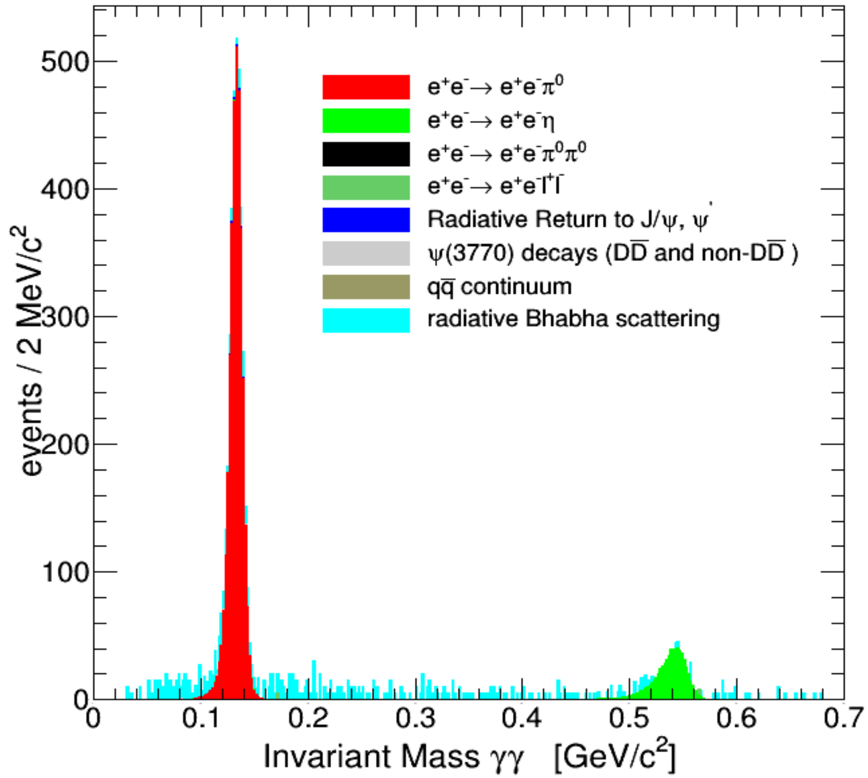
Nonperturbative pion distribution amplitude DA for $\gamma\gamma \rightarrow \pi/\eta^{(\prime)}$

Pion distribution amplitude



ASY: Asymptotic DA
CZ: Chernyak-Zhitnitsky DA
BMS: Bakulev-Mikhailov-Stefanis DA

BES III Analysis: $e^+e^- \rightarrow e^+e^- \pi^0$



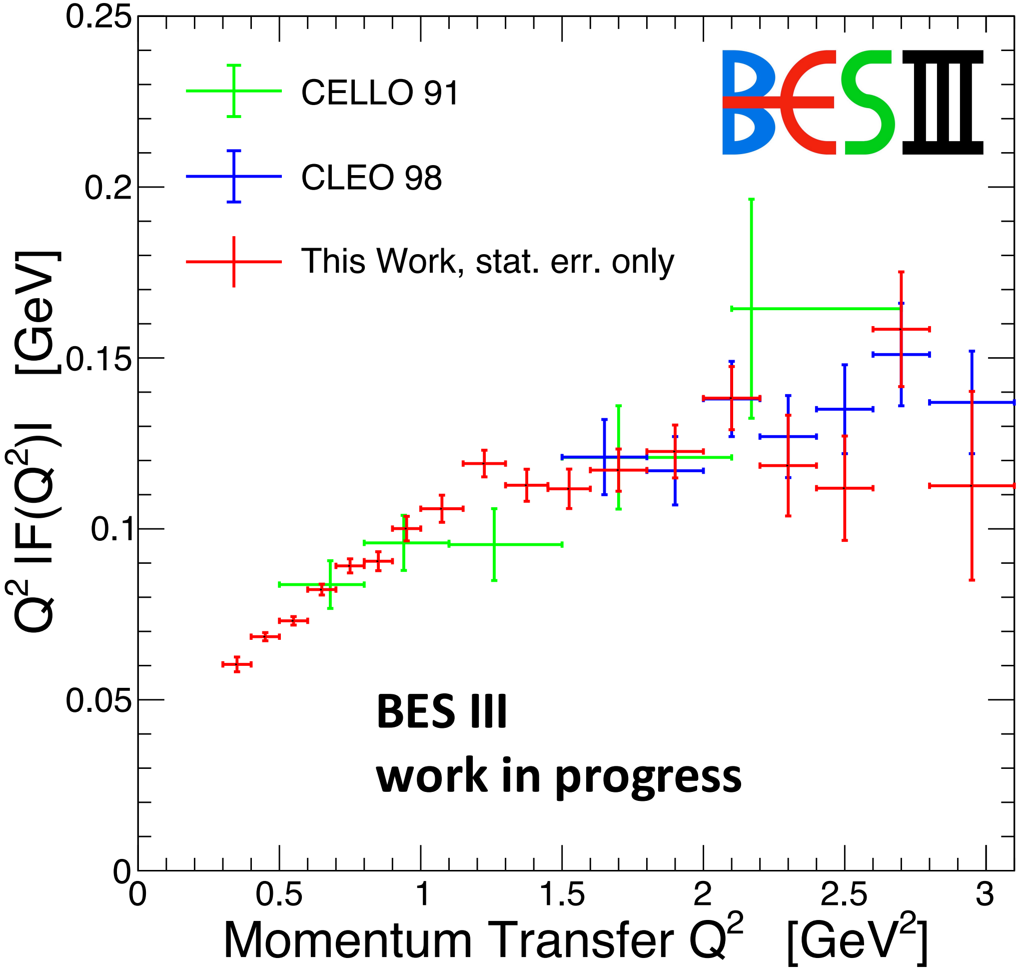
Event Selection:

- exactly one lepton candidate
- at least two, max four photons
- Helicity angle cos $\Theta_H > 0.8$
- Kinematic cuts to reject ISR background

→ **cut on angle of missing momentum**

Strategy: Count π^0 yield in bins of Q^2 → $d\sigma/dQ^2$ → Form factor $F(Q^2)$

BES III Analysis: $\gamma\,\gamma^* \rightarrow \pi^0$



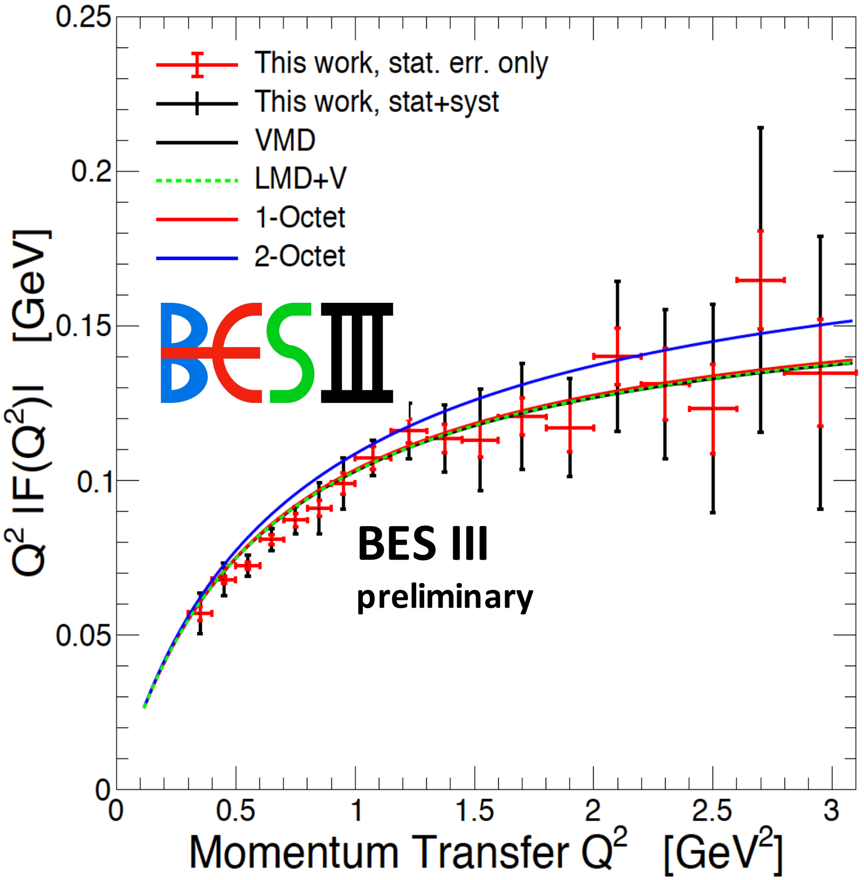
- L_{int}: 2.92 fb^{-1}
- Extract TFF for $0.3 \leq Q^2[GeV^2] \leq 3.1$

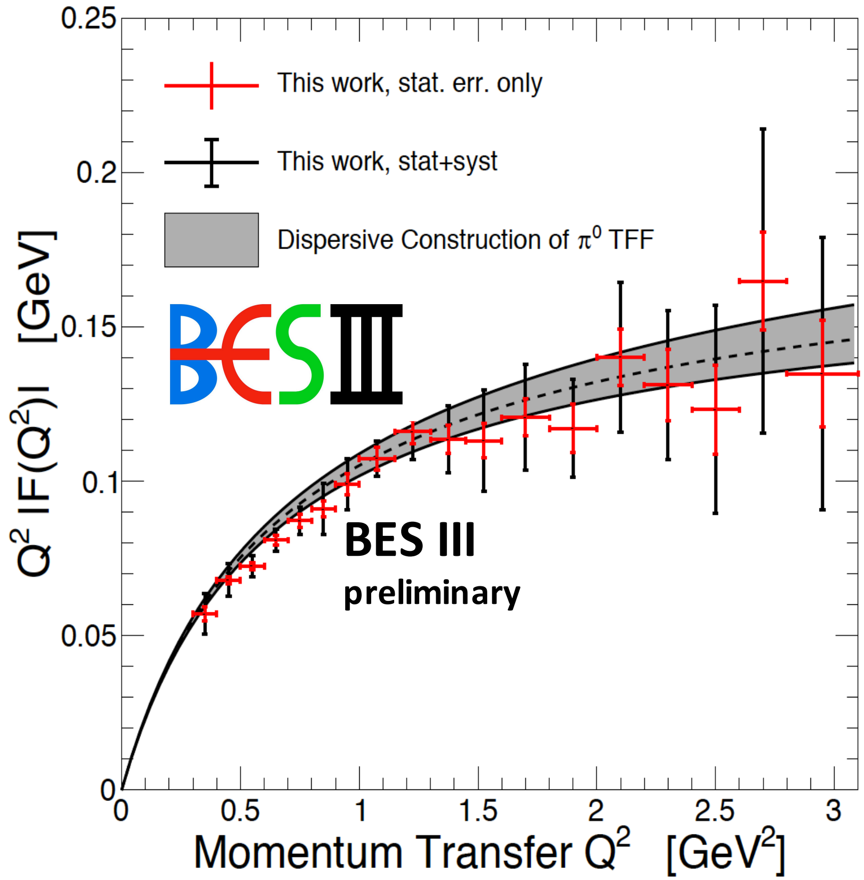
→ **Unprecedented Accuracy $Q^2 < 1.5\ GeV^2$**

→ **Challenges Hadronic Models**

BES III Analysis: $\gamma\,\gamma^* \rightarrow \pi^0$

→ Challenges Hadronic Models

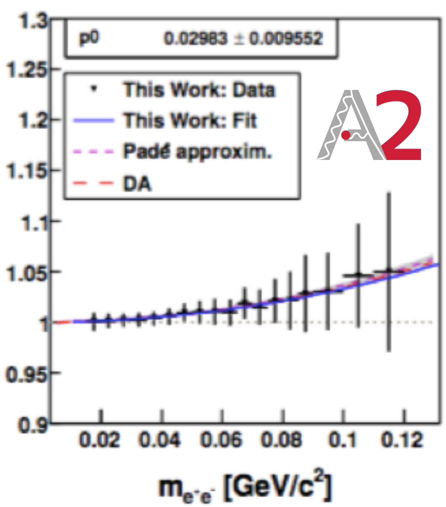


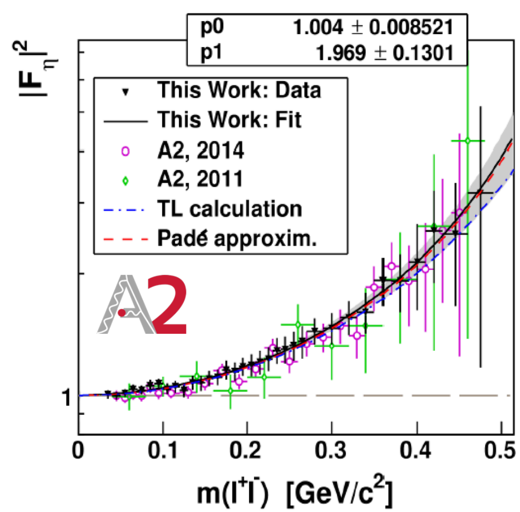


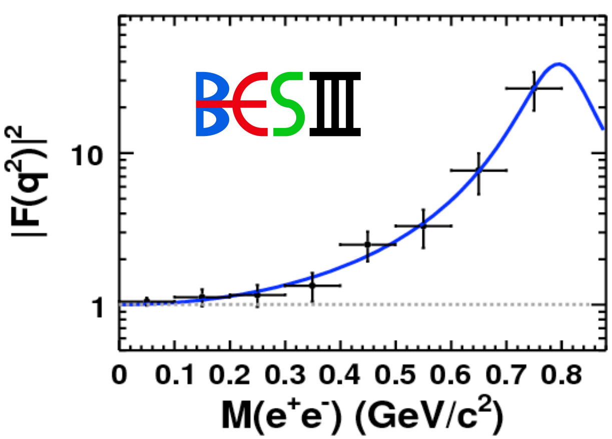
Further TFF Measurements

- Preliminary results for $\gamma\gamma^* \to \pi^+\pi^-$ from BES III expected soon
- Experiments (BABAR, BES III, BELLE II) embark on first measurements with two virtual photons (double-tag)
- Timelike TFFs from meson decays at various meson facilities worldwide (MAMI, COSY, JLAB, BES III, Frascati, BELLE II, CERN-SPS, ...)

$\pi^0 \to \gamma\gamma^*$ $\eta \to \gamma\gamma^*$ $\eta' \to \gamma\gamma^*$





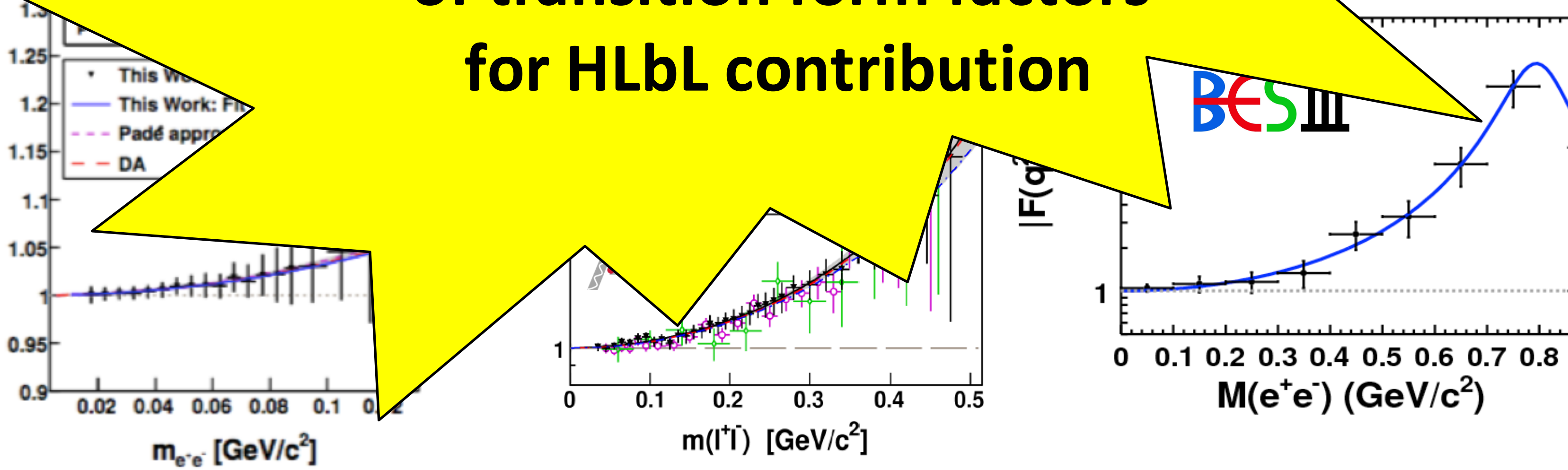


Further TFF Measurements

- Preliminary results for $\gamma\gamma^* \to \pi^+$ ... from BES ... pected soon
- Experiments (BAB... BES III, BELL... easur... nts with two virtual ph... uble...
- Time...
  (MAMI, ...

$\pi^0 \to$ ... $\to \gamma\gamma^*$

Major experimental progress on all fields in understanding of transition form factors for HLbL contribution



Production of

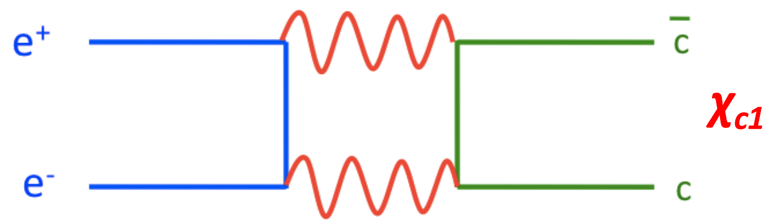
$J^{PC}=1^{++}$

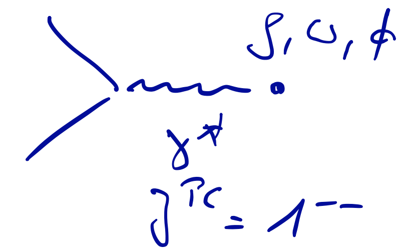
State in e+e- Annihilation

Production $e^+e^- \to \chi_{c1}$

$$e^+e^- \to 1^{++}$$

1^{--}





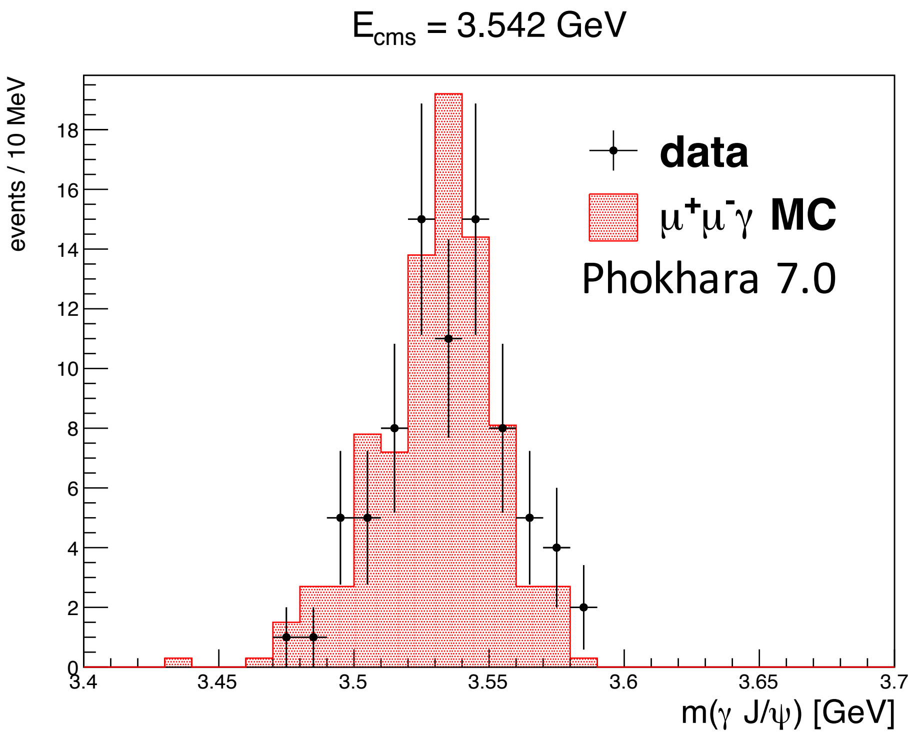
- **χ_{c1} Parameters:** Mass χ_{c1} = 3.5107 GeV
  Width χ_{c1} = 0.86 MeV
  Main decay channel (35% BR): $\chi_{c1} \to \gamma\, J/\Psi$

→ **Signal process: $e^+e^- \to \gamma\, J/\psi \to \gamma\, \mu^+\mu^-$**

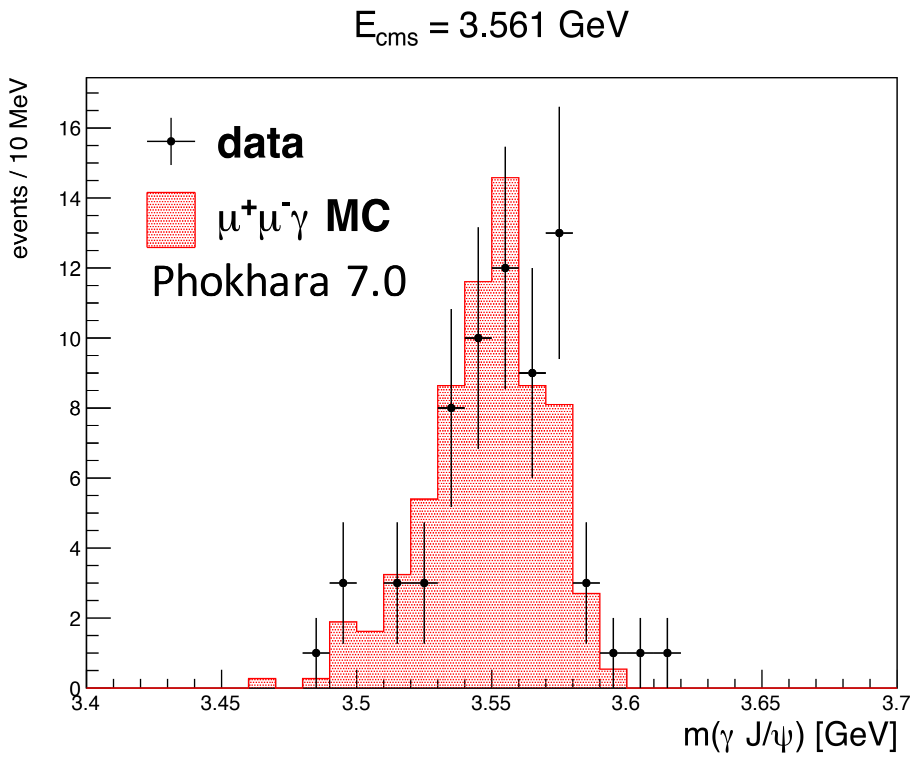
Irreducible background process: ISR production of J/ψ

ISR Background $e^+e^- \rightarrow \mu^+\mu^-\gamma_{ISR}$

31 MeV above signal



50 MeV above signal

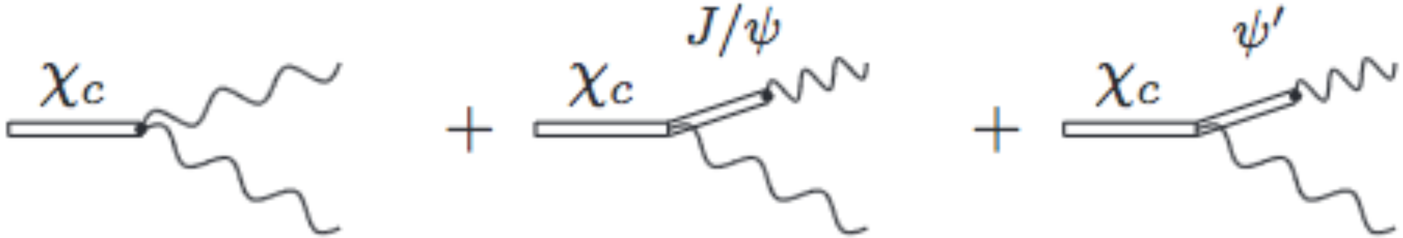


- excellent agreement, no indication of additional background
- effective cross section background 20.6 pb

Electronic Width of χ_{c1}

Czyz, Kühn, Trasc, arXiv:1605.06803

Interference effects lead to a value for Γ_{ee} for χ_{c1} of 0.41 eV



J. Kaplan, H.Kühn, PLB78 (1978) 252

Vector Meson Dominance (without ψ') predicts Γ_{ee} for χ_{c1} of 0.46 eV

used for our beam time proposal

N. Kivel and M. Vanderhaeghen, JHEP 02, 032 (2016)

Soft Collinear Theory Γ_{ee} for χ_{c1} is 0.09 eV

A.D., F.-K. Guo, C. Hanhart, A. Nefediev, PLB 736, 221 (2016)

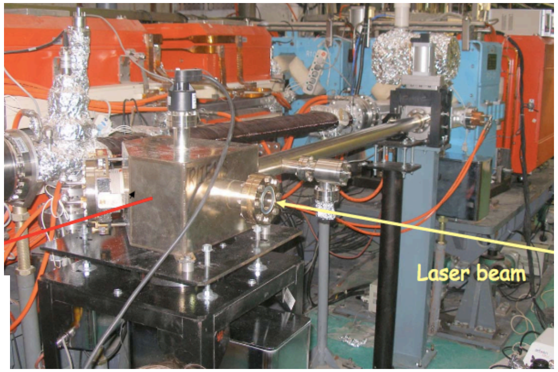
Vector Meson Dominance (without ψ') predicts Γ_{ee} for χ_{c1} of 0.1 eV

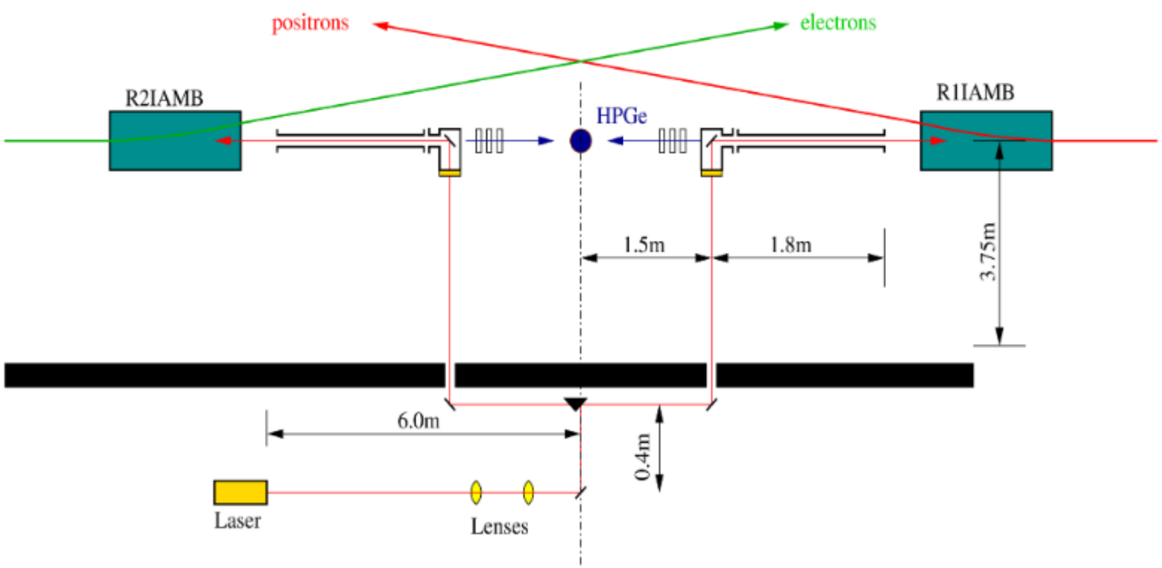
Data Taking Plan at BES III $e^+e^- \to \chi_{c1}$

3 weeks of data taking (> 300 pb^{-1})

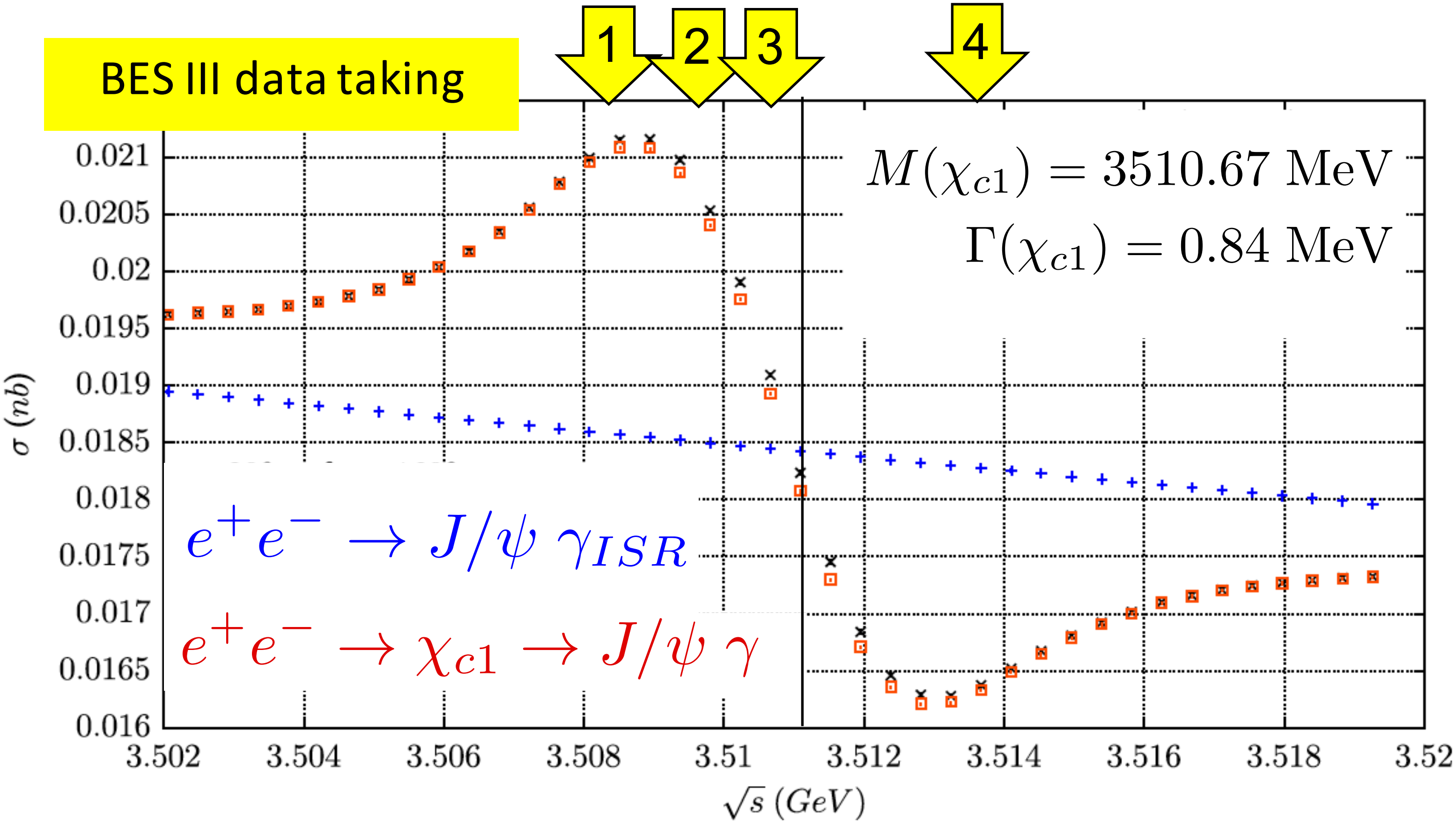
- Potential to observe 5 sigma effect (assuming no phase!)
  Beam energy spread, ISR effects included in calculation

- Beam Energy Measurement System
  Compton Backscattering developed by
  Novosibirsk group
  <<10^{-4} accuracy





Signal Cross Section $e^+e^- \to \chi_{c1}$



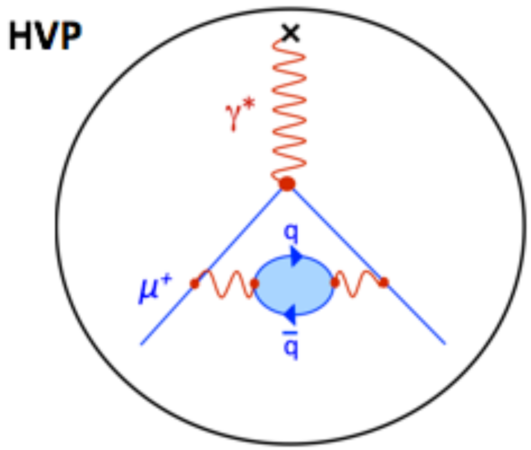
Effect of the resonance ~ 10%

Conclusions

and

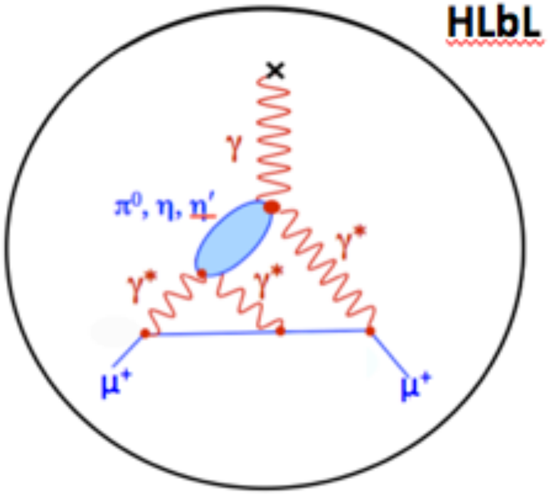
Outlook

Conclusions HVP



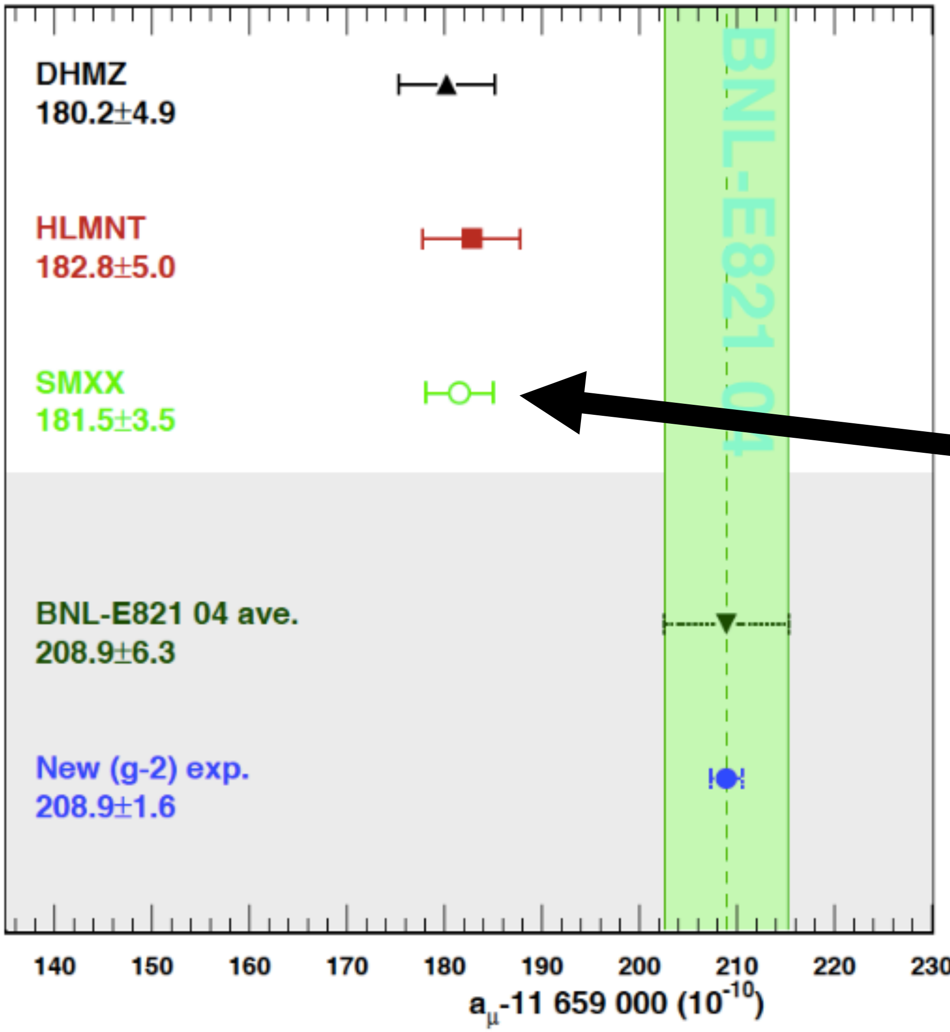
- Dispersion relation to relate hadronic cross section measurements to HVP contribution to g-2 of the muon
- Energy scan experiments at Novosbirsk < 2 GeV and Beijing < 5 GeV
- Initial State Radiation (ISR) at e+e- particle factories:
  KLOE, BABAR, BES III, BELLE (II)
- Extremely impressive progress in the field

Conclusions HLbL



- Up to some years considered as sub-leading hadronic contribution
  → not any more !
- Hadronic models (VMD-like) used for calculation → uncertainty ?
- Dispersion relations are now worked out: data-driven approach !
  → requires measurements of meson transition form factors P→ γγ
- Extremely impressive progress in the field

Conclusions



Expectation for the final reduction of SM uncertainty already now achieved

Whitepaper (2013)
arxiv:1311.2198

g-2
A phantastic field to work on