Hadronic Contributions to $(g-2)_\mu$

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New Vistas in Low-Energy Precision Physics
Mainz, 4-7 April 2016

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

- **Experimental:** $a^{exp}_\mu = 1165\ 920\ 8.9\ (6.3) \times 10^{-10}$ **(0.54 ppm)**

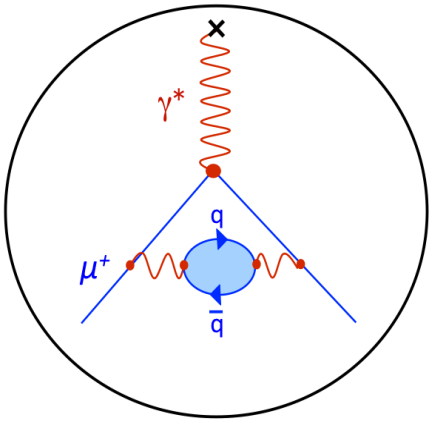
[BNL-E821: PRD 73 072003]

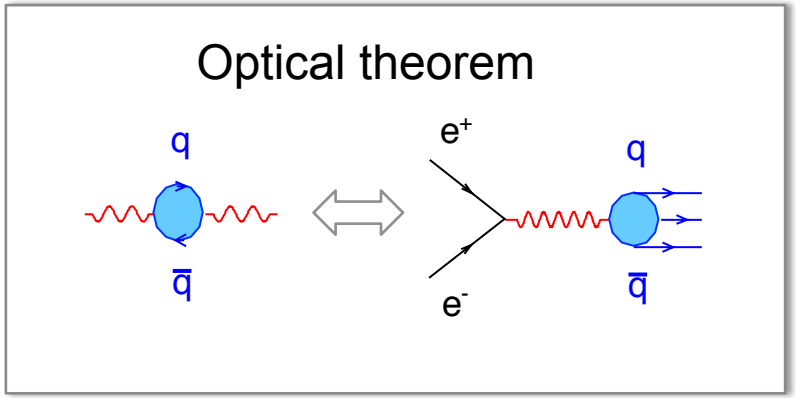
- **Standard Model prediction:** $a^{SM}_\mu = a^{QED}_\mu + a^{weak}_\mu + a^{had}_\mu$

Contribution	in units 10^{-10}	
QED(γ+lepton)	1165 847 1.8951 ± 0.0080	Kinoshita et.al. (2012)
EW	15.36 ± 0.10	Gnendiger, Stöckinger, Stöckinger-kim (2013)
HVP,LO	692.3 ± 4.2	Davier et. al. (2011)
HVP,NLO	-9.84 ± 0.07	Hagiwara et al. (2009)
HLbL	11.6 ± 4.0	Jegerlehner, Nyffler (2009)
Total	1165 918 1.3 ± 5.8	

Hadronic Contributions

Hadronic Vacuum Polarization





Dispersion integral

$$a_{\mu,LO}^{\mathrm{HVP}} = \frac{1}{4\pi^3}\int_{m_{\pi^0}}^{\infty} ds\, K(s)\, \sigma_{\mathrm{had}}(s)$$

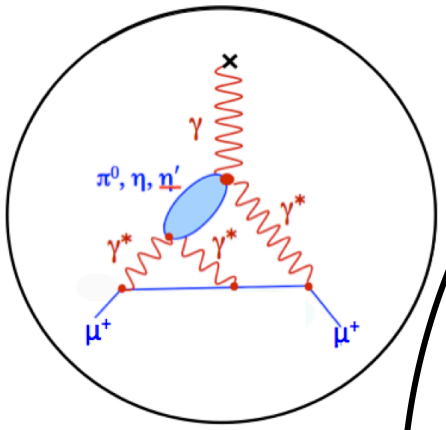
$\sigma_{\mathrm{had}} = \sigma(e^+e^- \rightarrow hadrons)$

~ 1/s → Low energy contributions important!

Kernel function ~ 1/s

Hadronic Contributions

Hadronic Light-by-Light

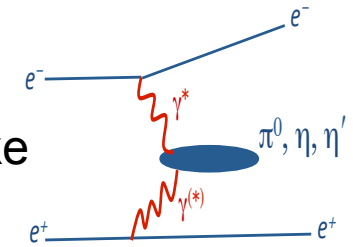


- Only model calculations so far
- Data-driven approach been developed

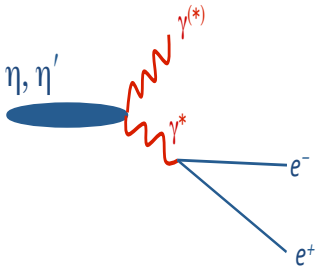
[Colangelo et al '14; Pauk, Vanderhaeghen '14]

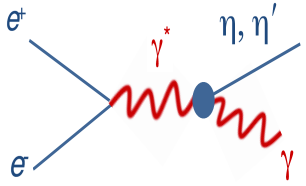
Transition form factors

Spacelike



Timelike



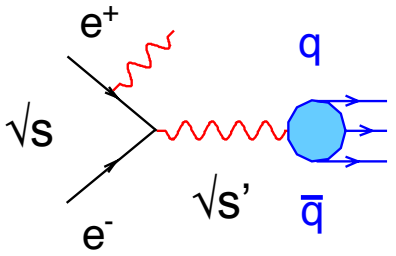


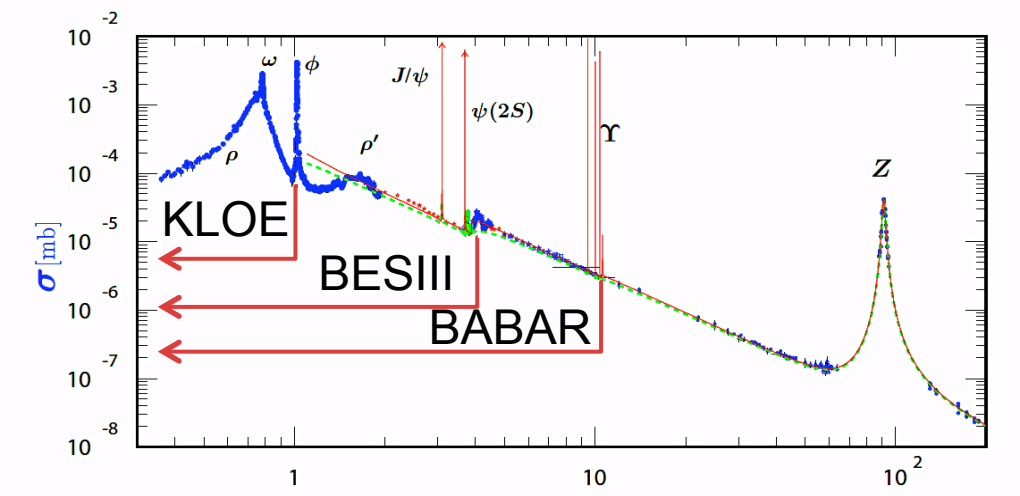
Hadronic Cross Section

$\sigma_{had}\,(e^+e^- \rightarrow \text{hadrons})$

Hadronic Cross Section

- **Energy Scan:**
  - CMD & SND at VEPP-2M & VEPP-2000 in Novosibirsk
  - BESIII at BEPCII in Beijing
- **Initial State Radiation:**
  - KLOE at DAϕNE in Frascati
  - BABAR at PEP-II in Stanford
  - BESIII at BEPCII in Beijing



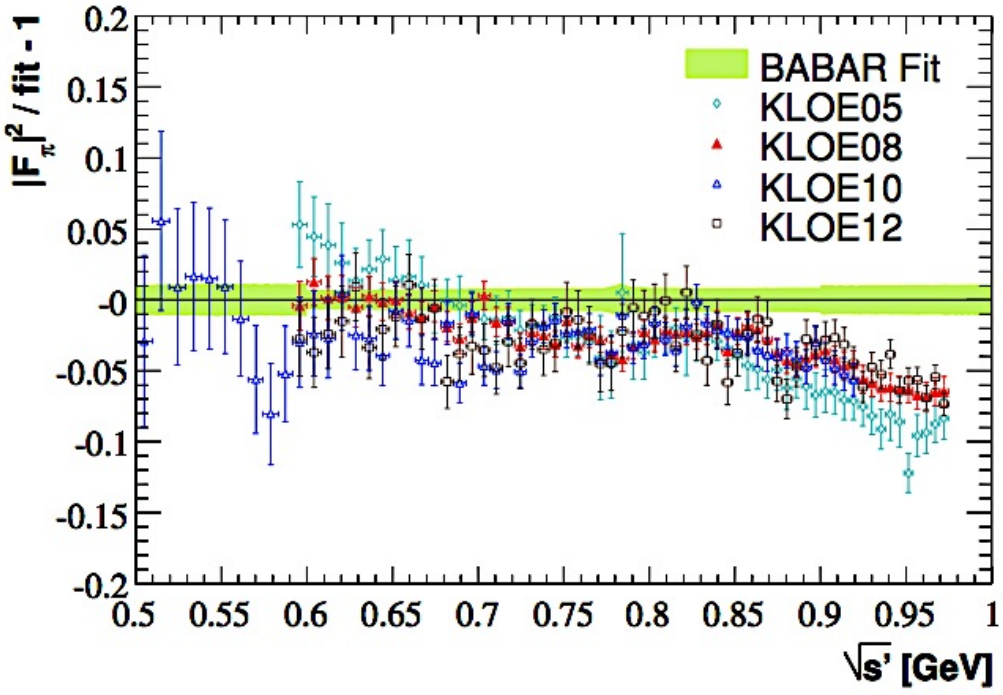


- Needs **no** systematic variation of beam energy
- High statistics thanks to high integrated luminosities

Most Relevant Channel:

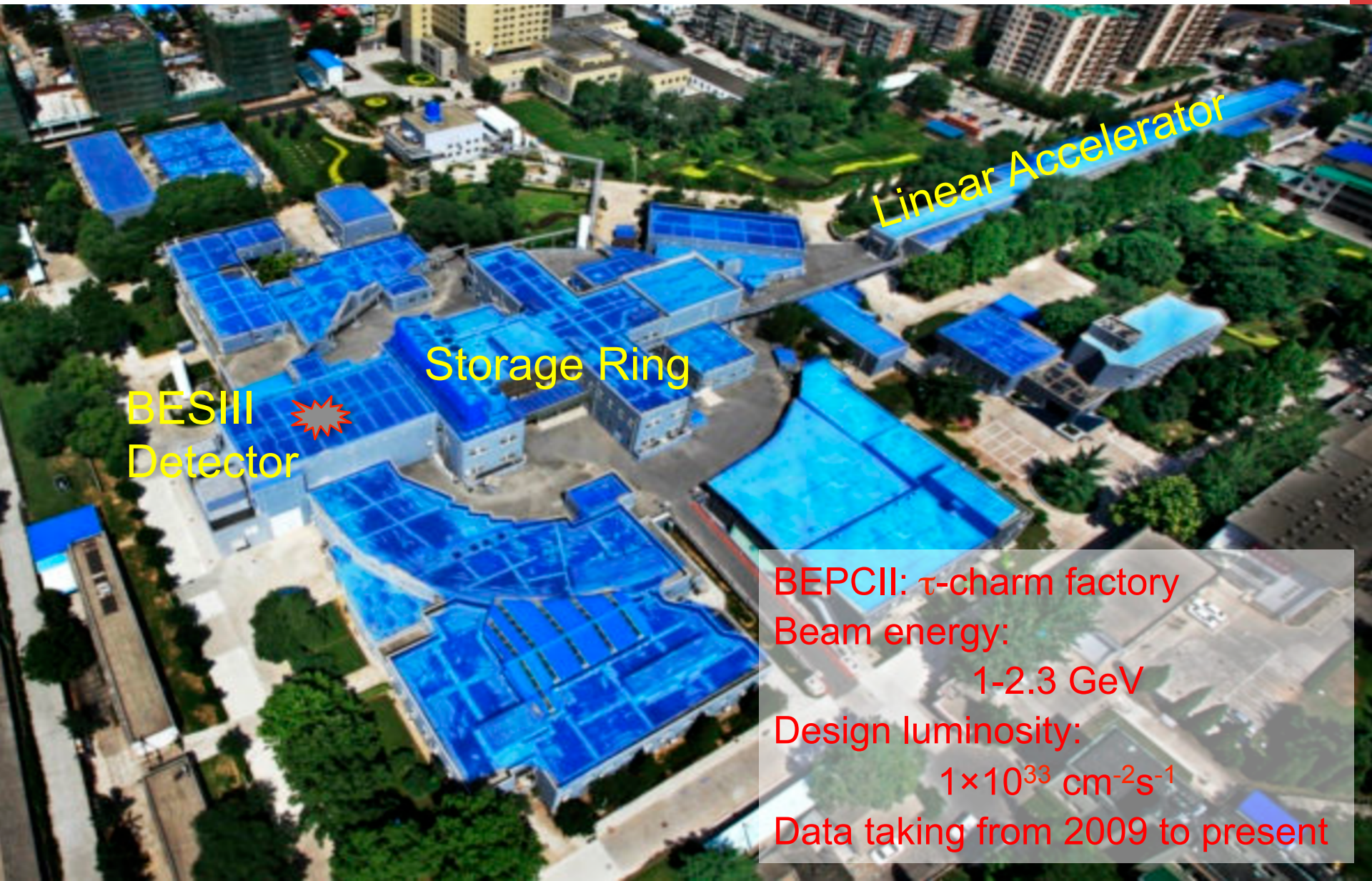
$e^+e^- \rightarrow \pi^+\pi^-$

- KLOE and BABAR dominate the world average
- Both with uncertainties smaller than 1%
- Relatively large systematic differences, especially above ρ peak
- Knowledge of a_μ^{had} dramatically limited due to this difference



***Note**: KLOE05 superseded by KLOE08*

Beijing Electron Positron Collider-II



BEPCII: τ-charm factory

Beam energy:

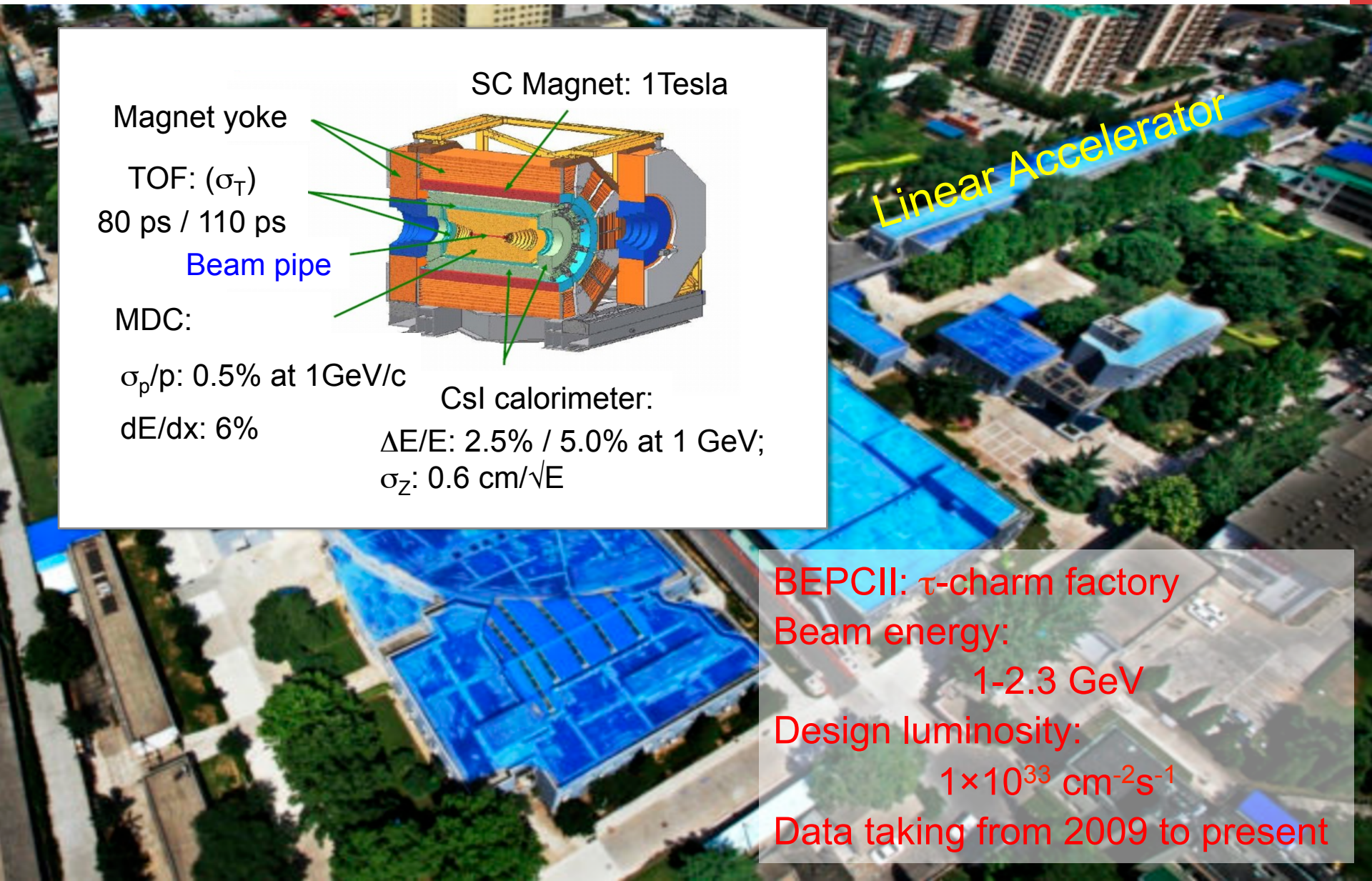
1-2.3 GeV

Design luminosity:

1×10^{33} $cm^{-2}s^{-1}$

Data taking from 2009 to present

Beijing Electron Positron Collider-II



BEPCII: τ-charm factory
Beam energy:
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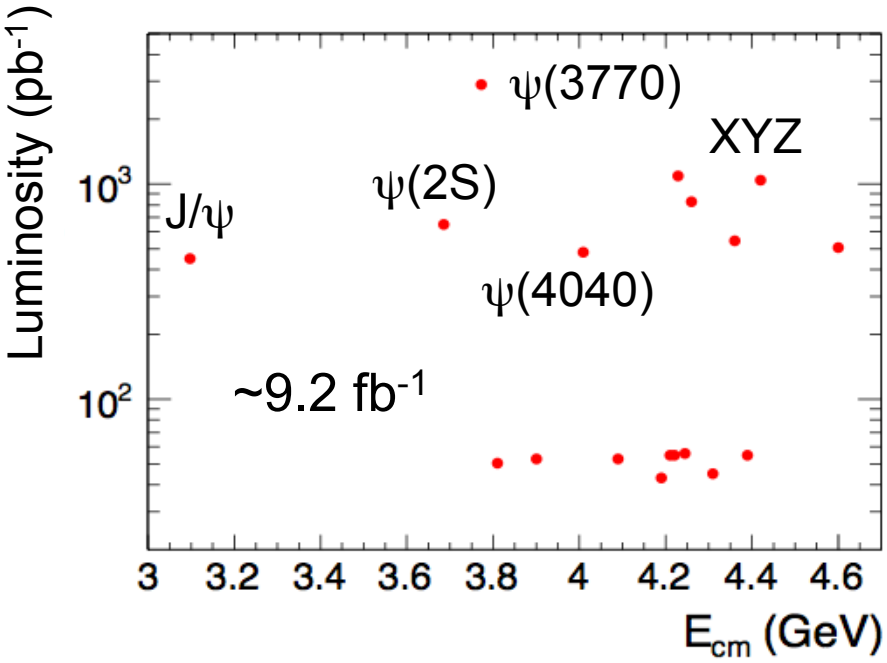
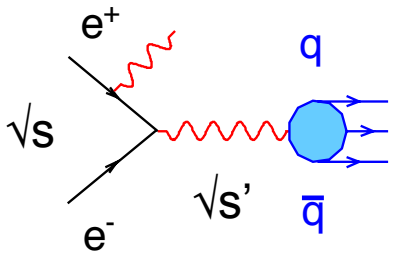
Data Samples for ISR Study

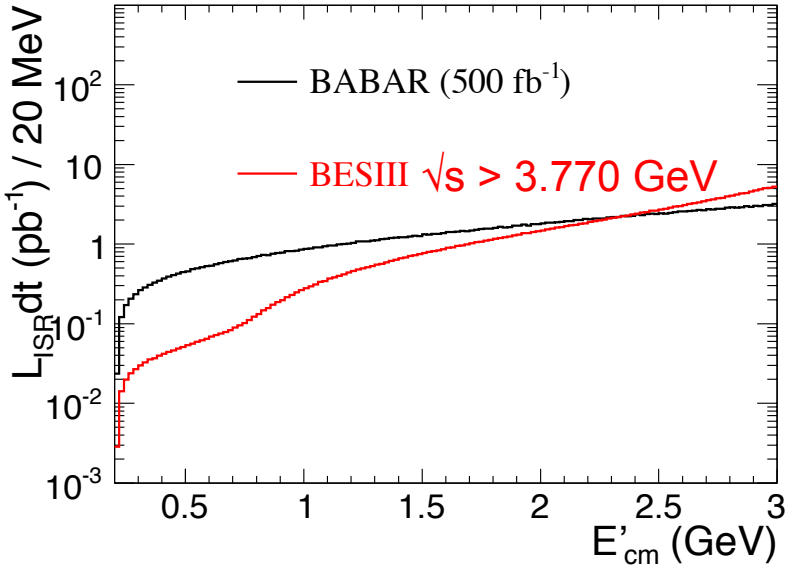


Scan data samples later



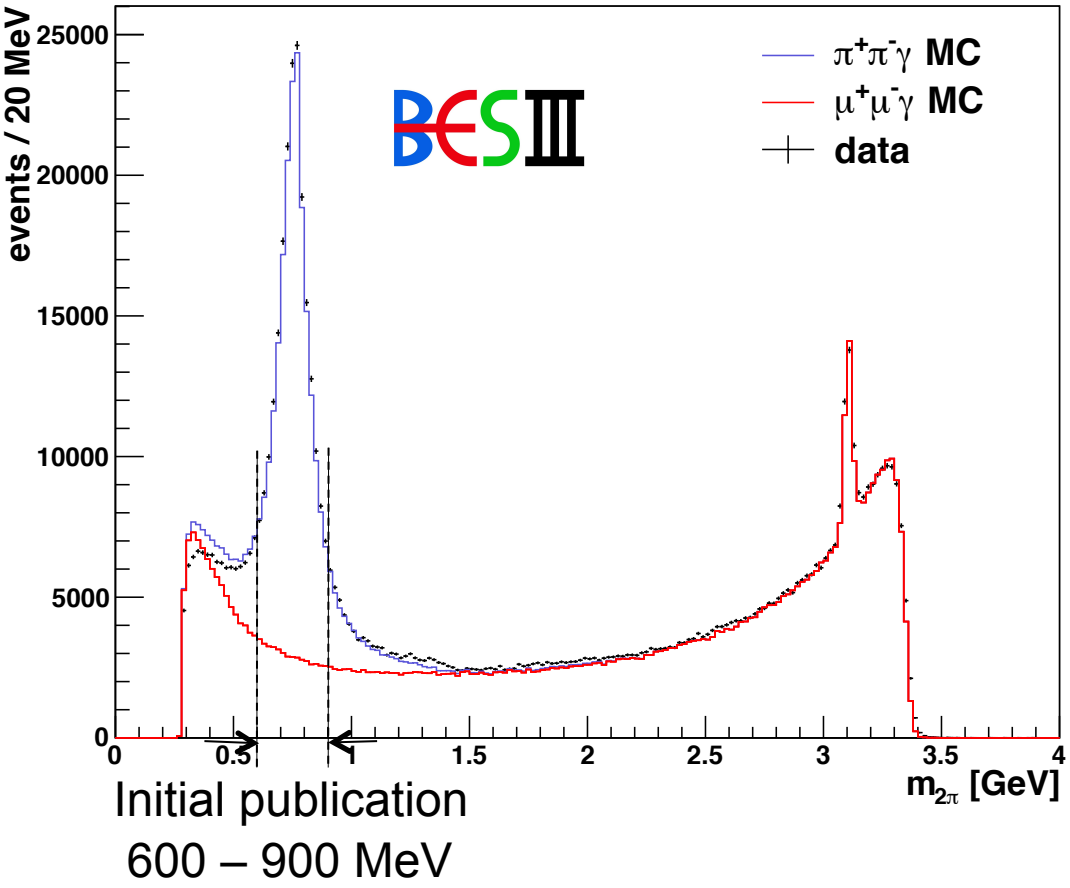
ISR luminosity = L dt x H_{rad}

Radiator function, well known



$e^+e^- \to \gamma_{ISR}\pi^+\pi^-$ at BESIII

Event yield after preliminary selection



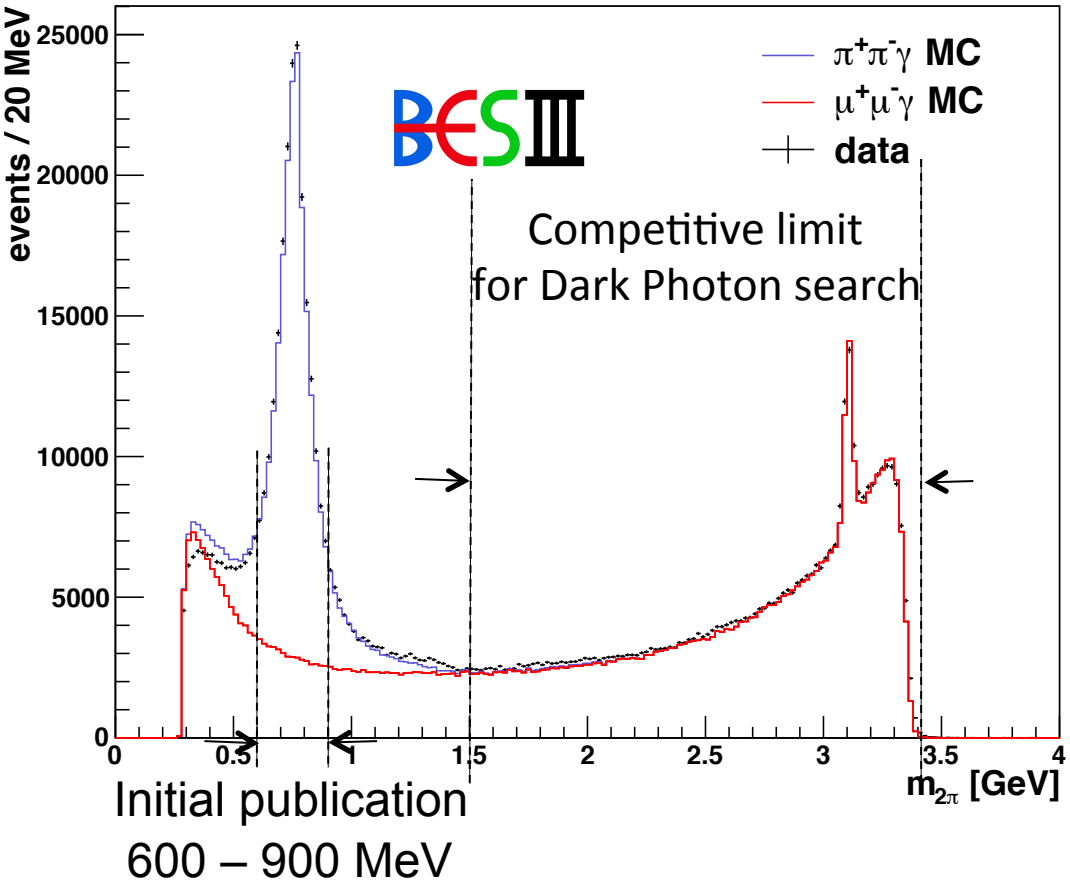
[Phys. Lett. B753 (2016) 629]

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

- $e^+e^- \to \gamma\pi^+\pi^-$: large statistics
- $e^+e^- \to \gamma\mu^+\mu^-$: dominate background
- Data - MC differences visible

$e^+e^- \to \gamma_{ISR}\pi^+\pi^-$ at BESIII

Event yield after preliminary selection



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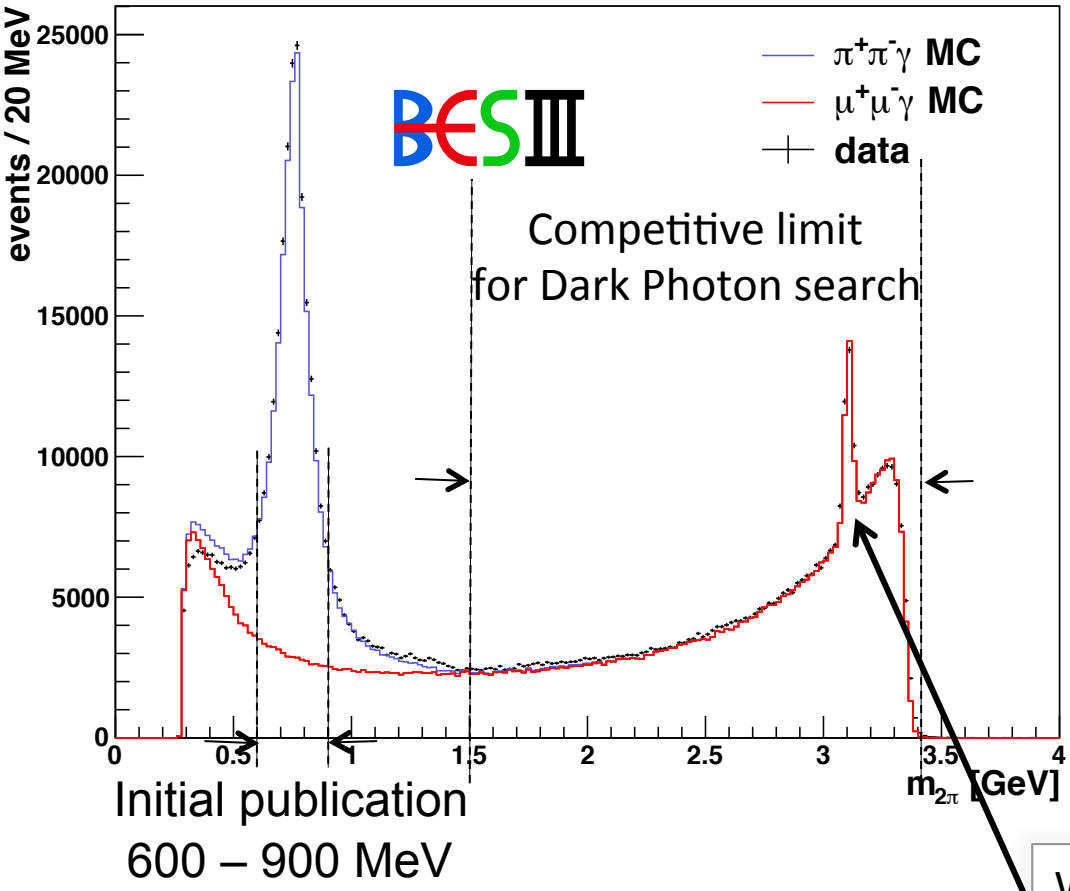

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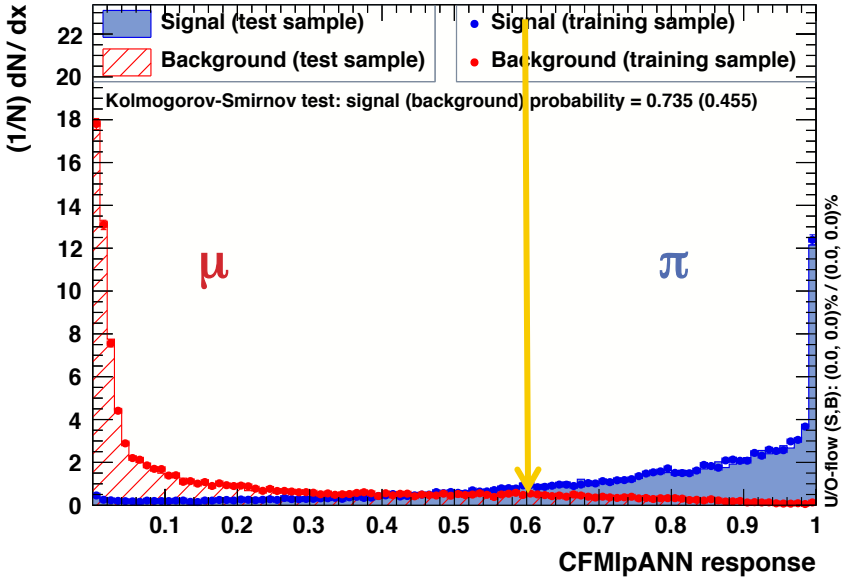
World's best measurement of Γ_{ee} of J/ψ

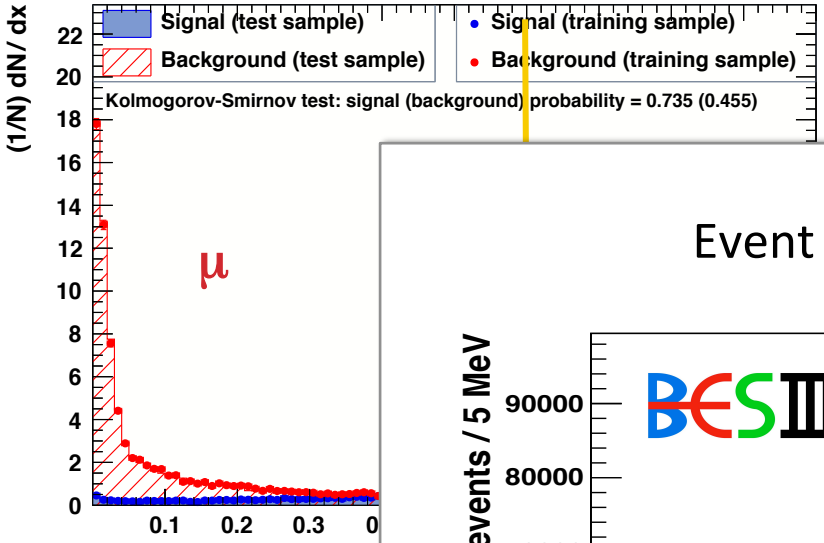
$e^+e^- \to \gamma_{ISR}\,\pi^+\pi^-$: π-μ separation



TMVA method (Neural Network):

- Trained using $\gamma\mu\mu$ and $\gamma\pi\pi$ MC events
- Information based on track level
- Efficiency matrix (p,θ) for data, MC
- Correct for data - MC differences
- Cross checked for different TMVA methods

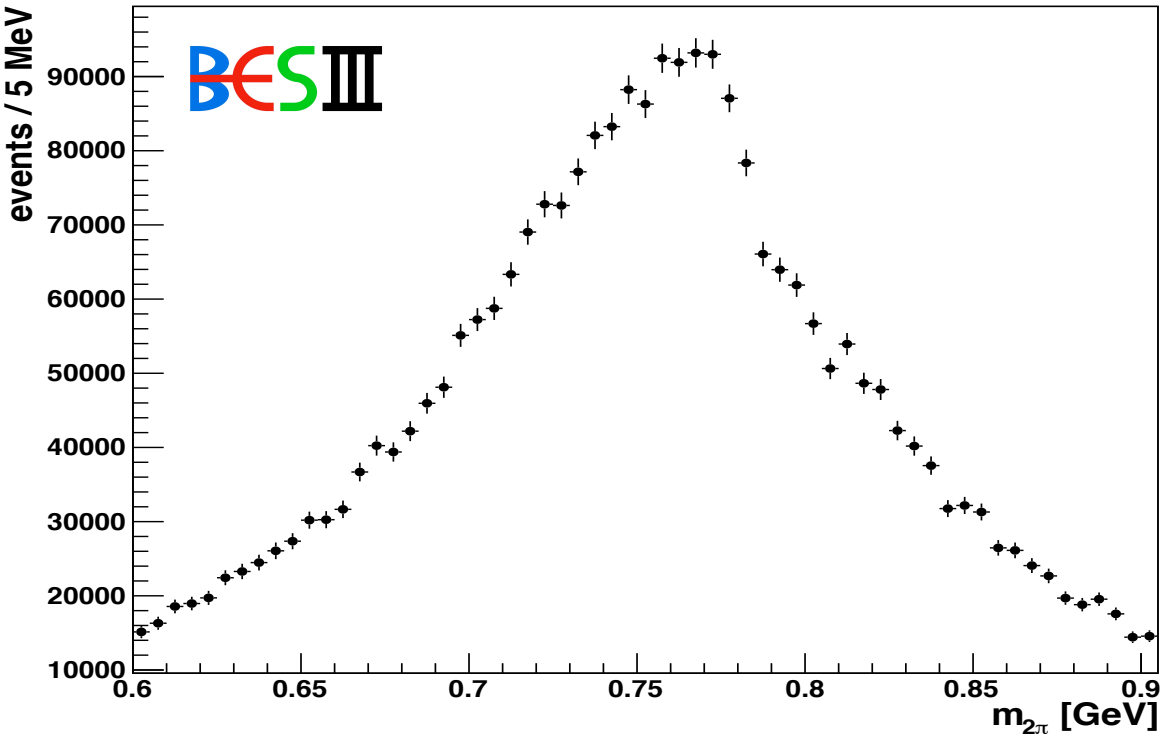
$e^+e^- \to \gamma_{ISR}\,\pi^+\pi^-$: π-μ separation



TMVA method (Neural Network):

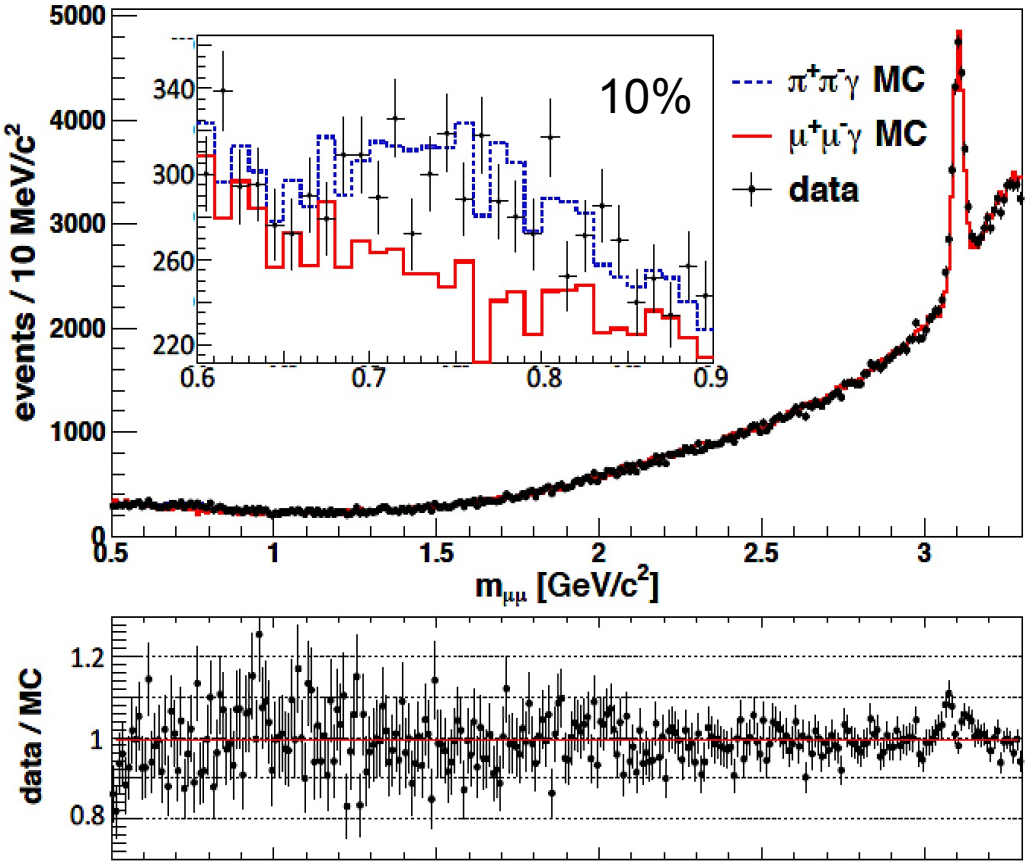
- Trained using $\gamma\mu\mu$ and $\gamma\pi\pi$ MC events

Event yield $\gamma\pi\pi$ after π-μ separation



QED Test: $e^+e^- \rightarrow \gamma\mu^+\mu^-$

Event yield $\gamma\mu\mu$ after π-μ separation and all efficiency corrections



- Background from $\gamma\pi\pi$ small
- PHOKHARA uncertainty < 0.5%
- Luminosity measurement based on Bhabha events, 0.5% accuracy

Δ(MC/QED-data) -1 = $(1.0 \pm 0.3_{stat} \pm 0.9_{syst})$ %

- Excellent agreement with QED
- Accuracy on 1% level as needed to be competitive !

$e^+e^- \to \pi^+\pi^-$ Cross section

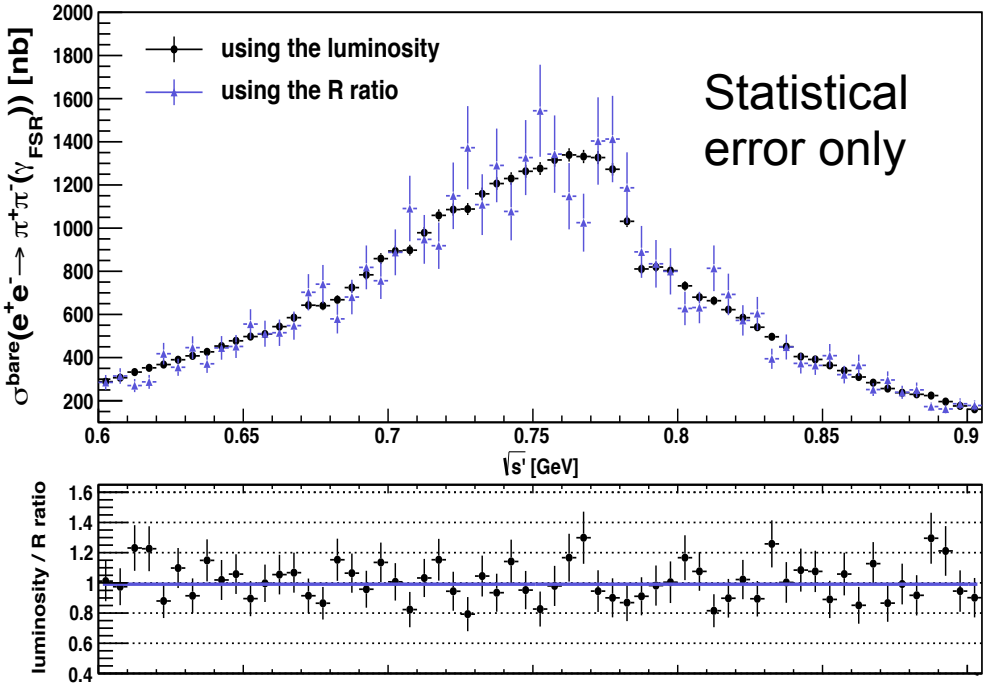
2 normalization methods:

- Normalization to L_{int} (obtained from Bhabha events)

$$\sigma^{\text{bare}}_{\pi\pi(\gamma)} = \frac{N_{\pi\pi\gamma} \cdot (1 + \delta^{\pi\pi}_{\text{FSR}})}{\mathcal{L}_{int} \cdot \epsilon^{\pi\pi\gamma}_{\text{global}} \cdot H(s) \cdot \delta_{vac}}$$

- Normalization to γμμ events, i.e. R ratio (γππ/γμμ)

L_{int}, H_{rad}, δ_{vac} cancel in ratio



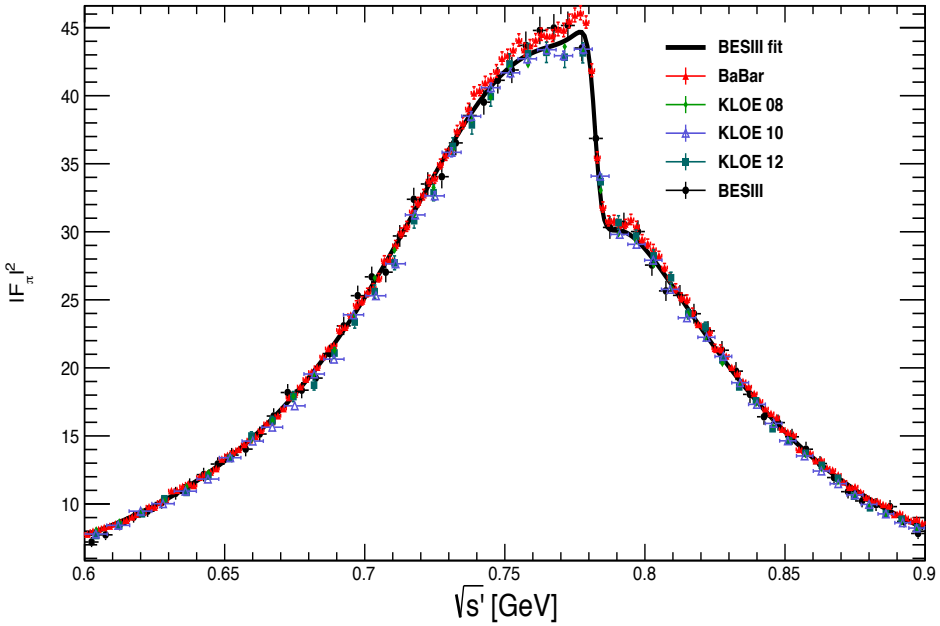
Good agreement between two methods

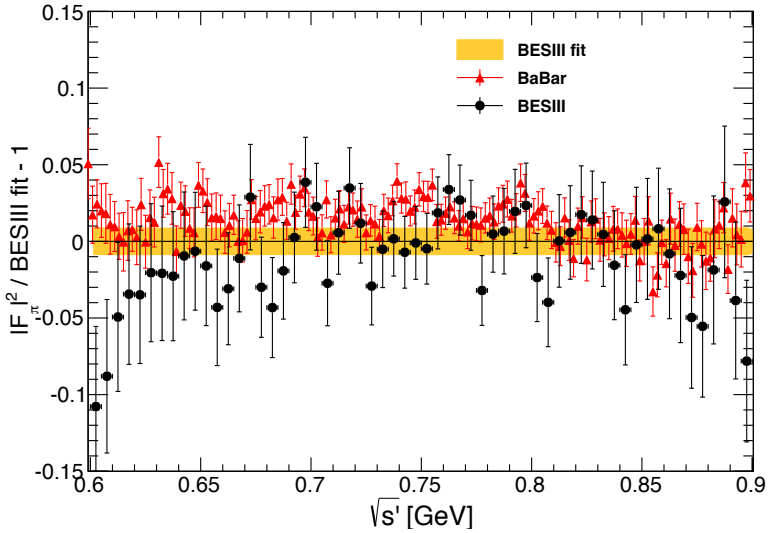
Luminosity / R ratio -1 = (0.85 ± 1.68) %

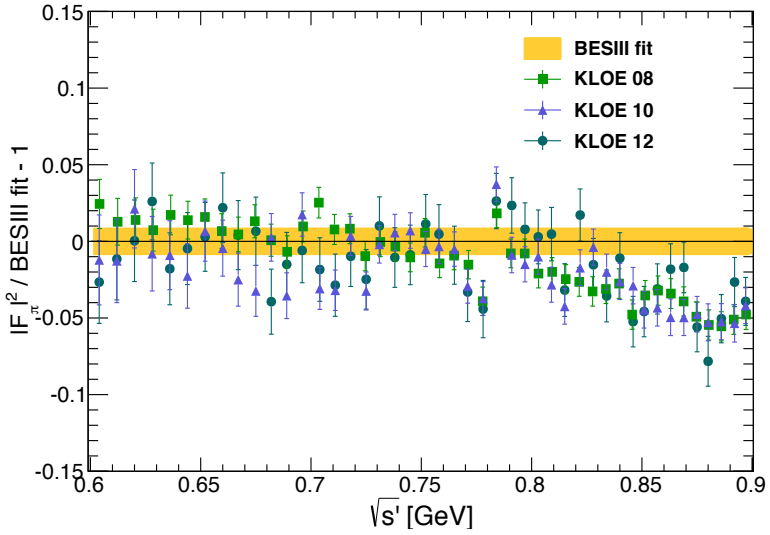
limited by low γμμ statistics

Compare with Existing Data

Pion Form Factor F_π

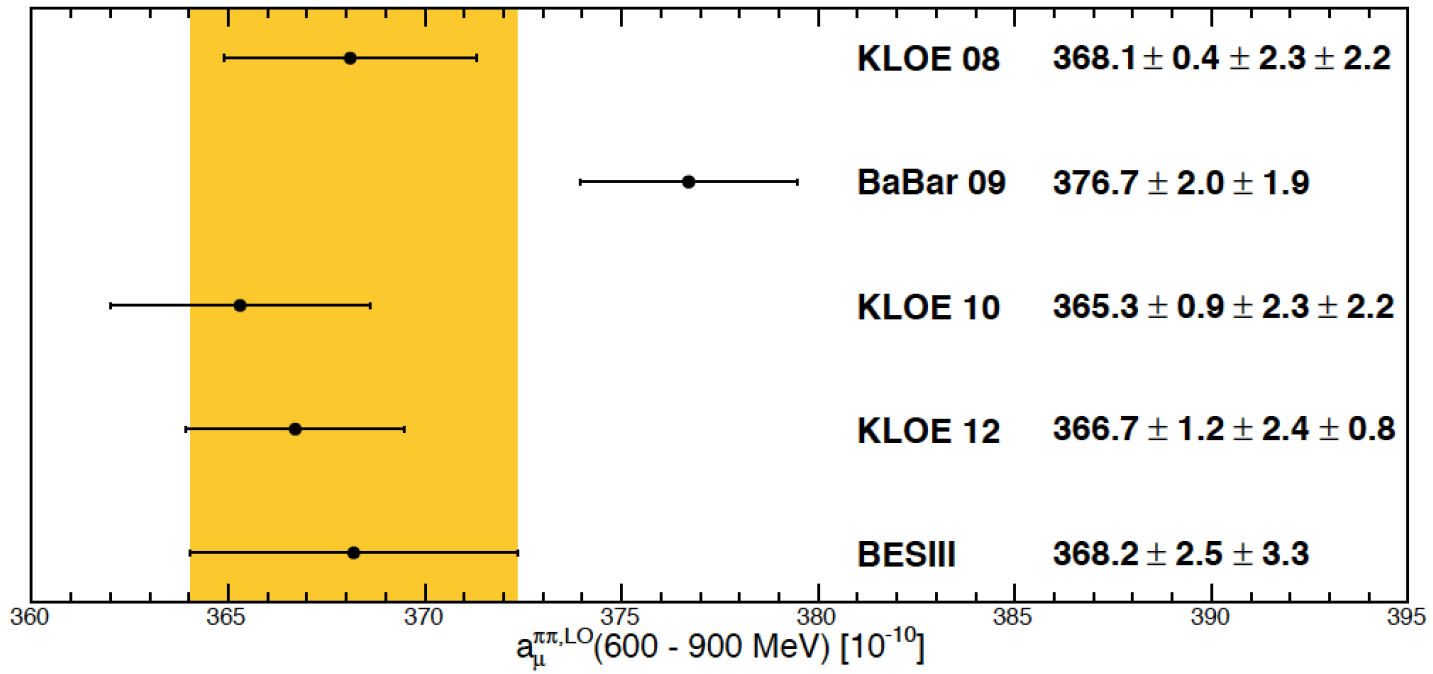






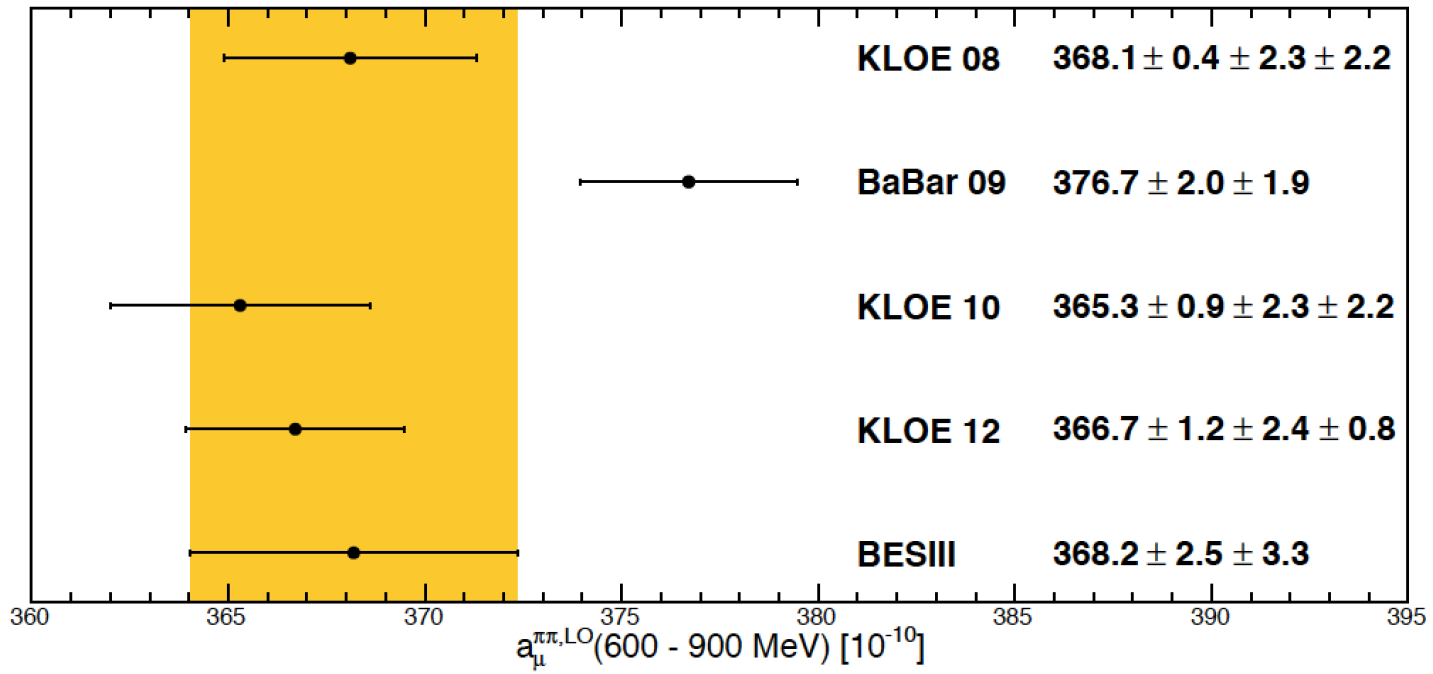
- 0.9 % accuracy (dominated by theory)
- Normalization to luminosity × radiator function
- Gounaris and Sakurai parameterization

Impact on a_μ^{HVP}



Deviation on $(g-2)_\mu$ between experimental and SM has been confirmed

Impact on a_μ^{HVP}



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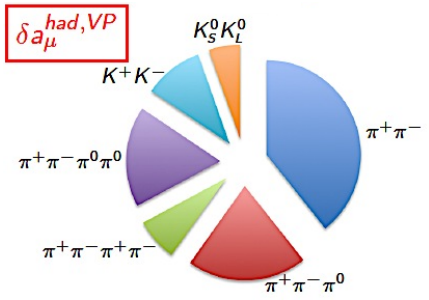


Study of $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-\pi^0\pi^0$ processes undergoing at BESIII

Energy Scan from 2.0 to 4.6 GeV

World's best measurement from BES/BESII with 5% ~ 8% total uncertainty (statistical uncertainty: 3% ~ 5%)

BESIII: aim at systematic uncertainty: 3.0%

151 energy points >10^5 hadronic events each → statistical error negligible

Energy region	Energy points	Note
2.400~3.400	4	Mini-scan
3.800~4.590	104	Fine-scan heavy charm resonant
2.000~3.080	21	R&QCD-scan
3.050~3.120	16	J/ψ-scan
3.542~3.600	5	τ-scan
3.650,3.671	2	ψ(3686)-scan

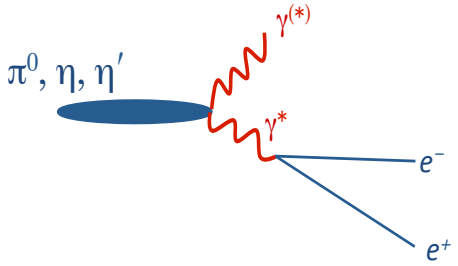
Reducing the uncertainty of $\alpha_{em}(M_Z^2)$ by a factor of 2

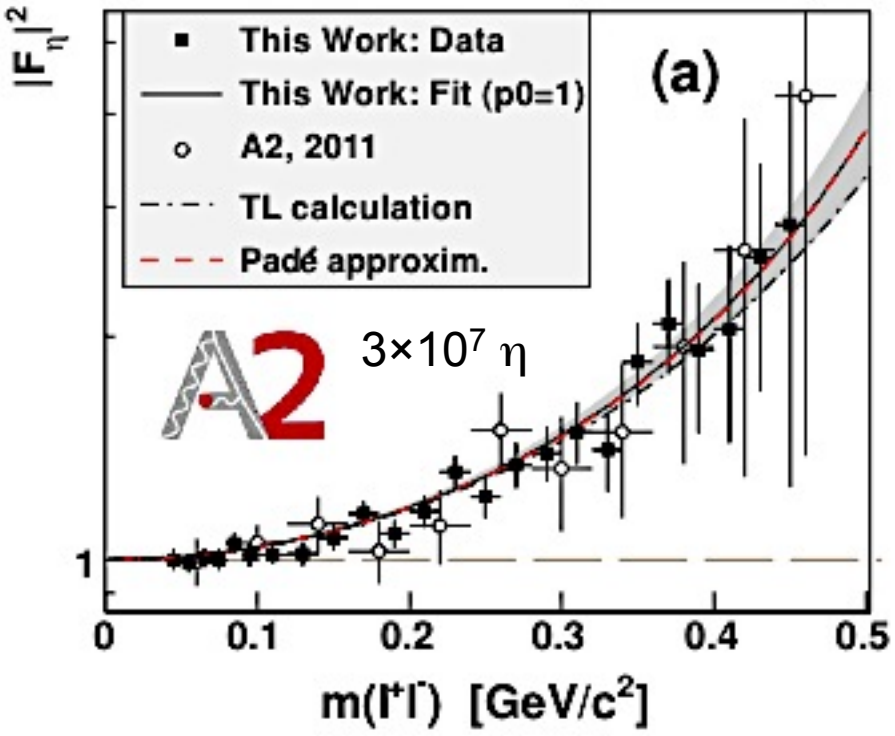
→ A new quantity of electroweak precision fits

Meson Transition Form Factor $|F(Q^2)|$

Timelike Transition FFs

$$\frac{d\Gamma(\eta \to l^+l^-\gamma)}{dm_{ll}\Gamma(\eta \to \gamma\gamma)} = [QED] \cdot |F_\eta(m_{ll})|^2$$





[Phys. Rev. C89 (2014) 044608]

Vector Meson Dominance Model:

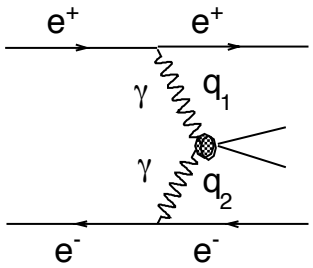
single-pole:

$F(q) = (1-q^2/\Lambda^2)^{-1}$

$\Lambda^{-2} = (1.95 \pm 0.15 \pm 0.10)\ \text{GeV}^{-2}$

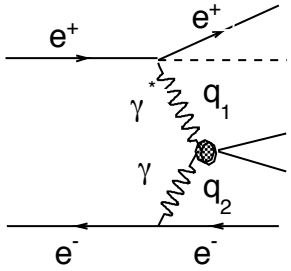
In good agreement with previous measurements!

Spacelike Transition FFs



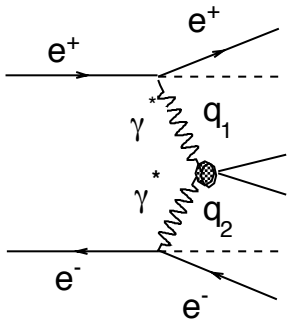
Untag:

- Only tag the hadron products, P_t-balance
- Q_i^2~0 GeV^2, quasi-real photon



Single tag:

- Tag the hadron products
- Tag only one lepton, missing momentum direction
- Q_1^2~0 GeV^2, $Q_1^2=-q_2^2$ GeV^2; highly virtual photon



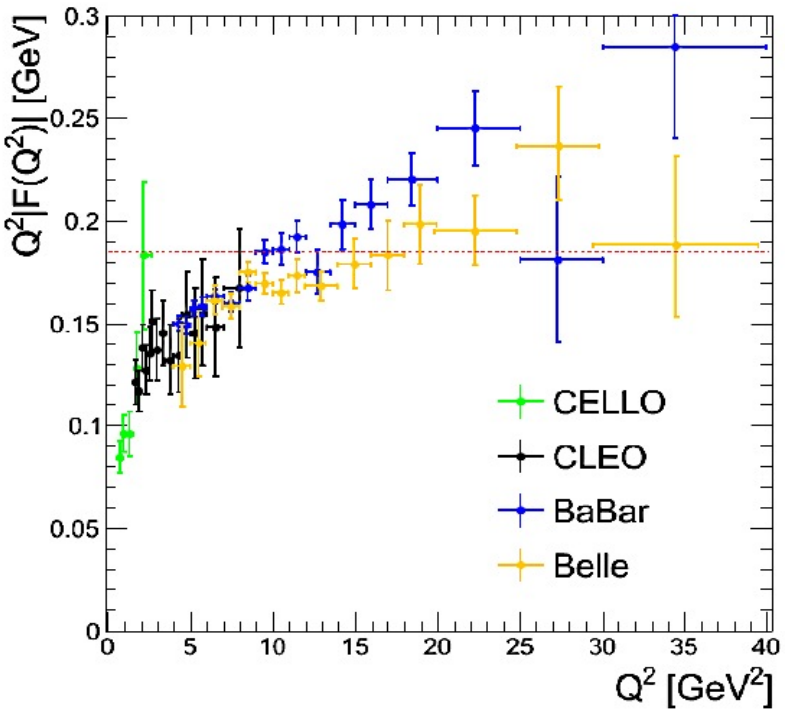
Double tag:

- Tag the hadron products
- Tag both leptons
- Both photons are virtual

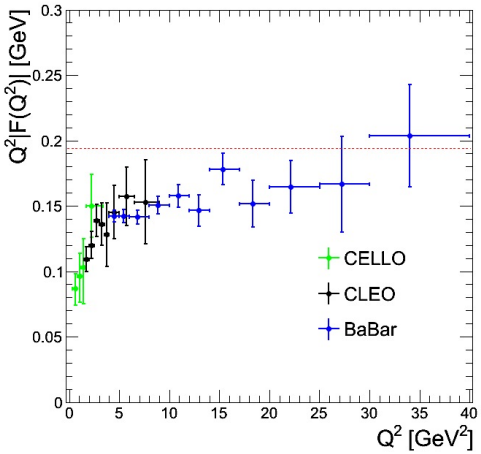
Input for data-driven approach

Existing Data on Spacelike TFFs

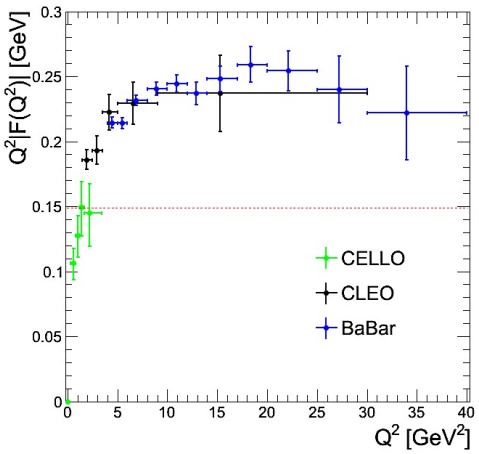
$e^+e^- \to e^+e^- \pi^0$



$e^+e^- \to e^+e^- \eta$



$e^+e^- \to e^+e^- \eta'$



- Recent results from BABAR and BELLE: $Q^2 > 4$ GeV^2
- CLEO: $Q^2 > 1.5$ GeV^2
- CELLO: $Q^2 < 1.5$ GeV^2 , very poor accuracy

Low Q^2 range not covered/precise

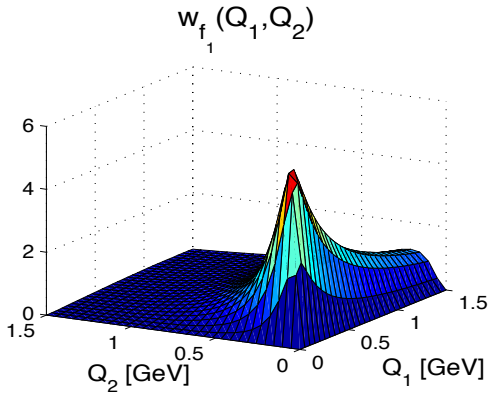
CELLO: Z. Phys. C 49 401 (1991)
CLEO: Phys. Rev. D57 33 (1998)
BaBar: Phys. Rev. D80 052002 (2009)
Belle: Phys. Rev. D86 092007 (2012)

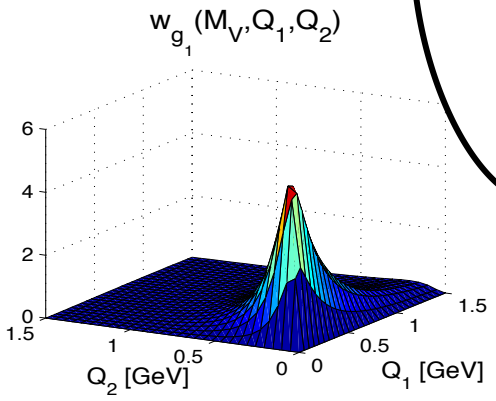
Relevant Q^2 Region

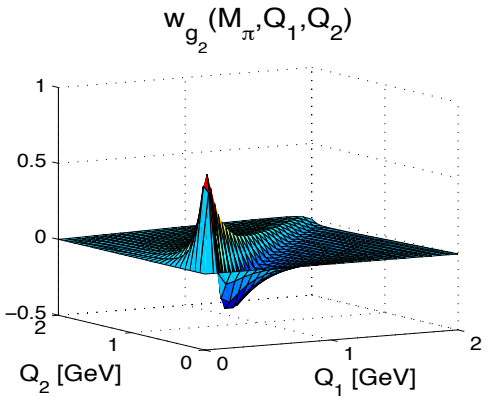
$$a_\mu^{\mathrm{HLBL};\pi^0} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \sum_i W_i(Q_1, Q_2)\, f_i(Q_1, Q_2)$$

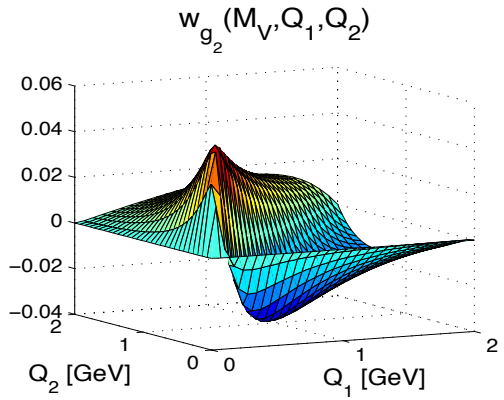
Form factor dependent

Universal weight functions









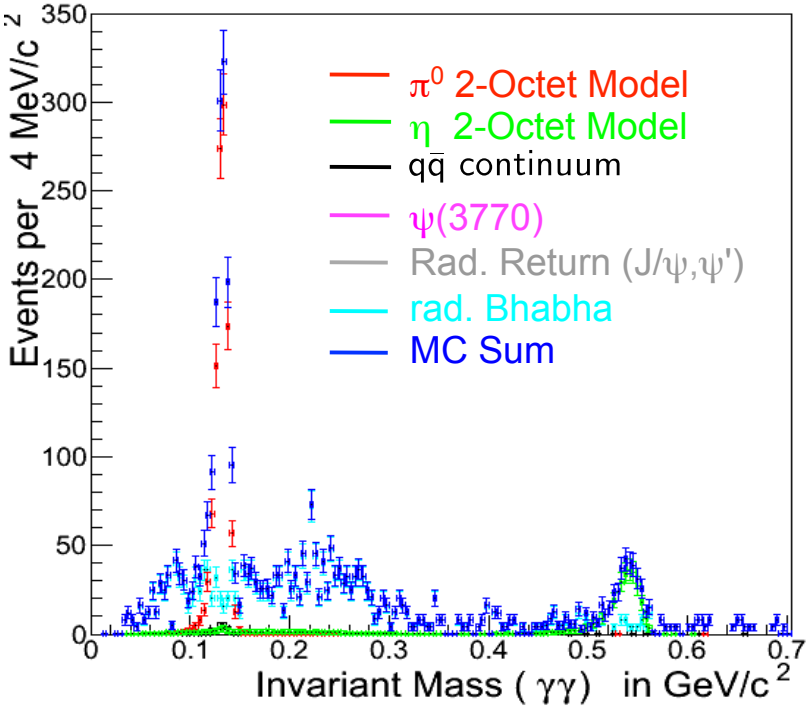
Relevant Q^2 region:
<1.5 GeV^2

[M. Knecht and A. Nyffeler: Phys. Rev. D 65, 073034 (2002)]

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

L_{int}: 927 pb^{-1} Tagged lepton: e^-

MC only, part of full statistics

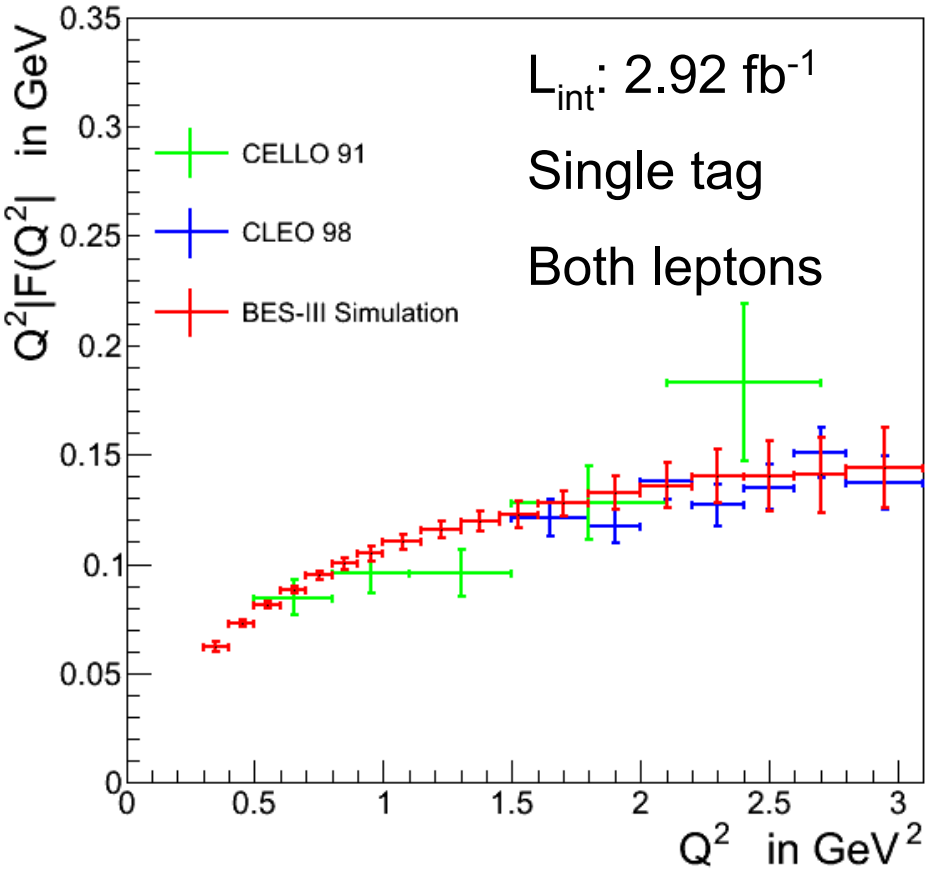


Event Selection:

- 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 $F(Q^2)$

Spacelike transition FFs: π^0



[CELLO: Z. Phys. C 49 401 (1991)]
[CLEO: Phys. Rev. D57 33 (1998)]

MC only, red error bars corresponding to BESIII statistics

Extract TFF for:

$0.3 \leq Q^2[\text{GeV}^2] \leq 3.1$

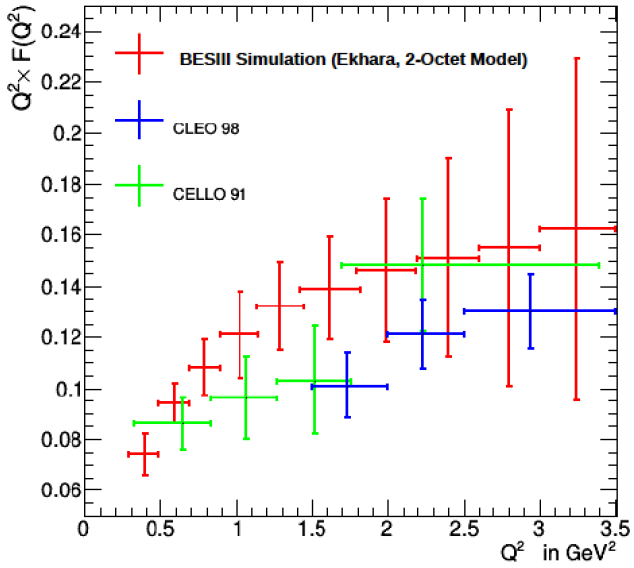
Significantly improves and extends data set below Q^2 = 1.5 GeV^2

Input for $(g\text{-}2)_\mu$!

Spacelike transition FFs: η / η´

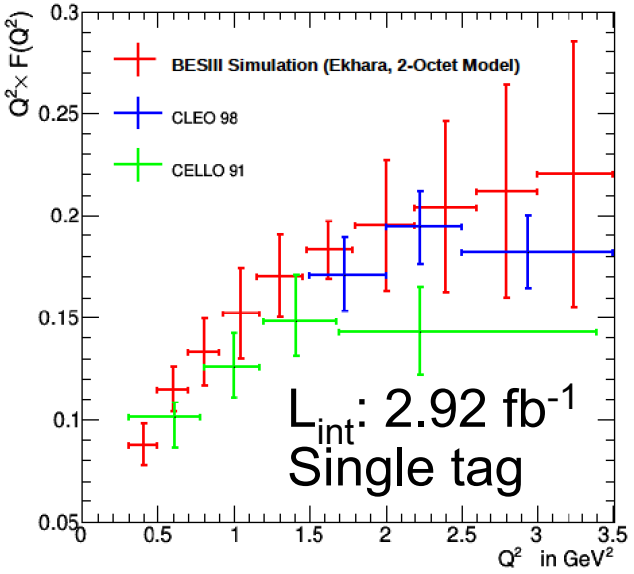
MC only, red error bars corresponding to BESIII statistics

$F_{\eta,\gamma,\gamma^*}(Q^2)$



$\eta \rightarrow \pi^+ \pi^- \pi^0 \rightarrow \pi^+ \pi^- \gamma\ \gamma$

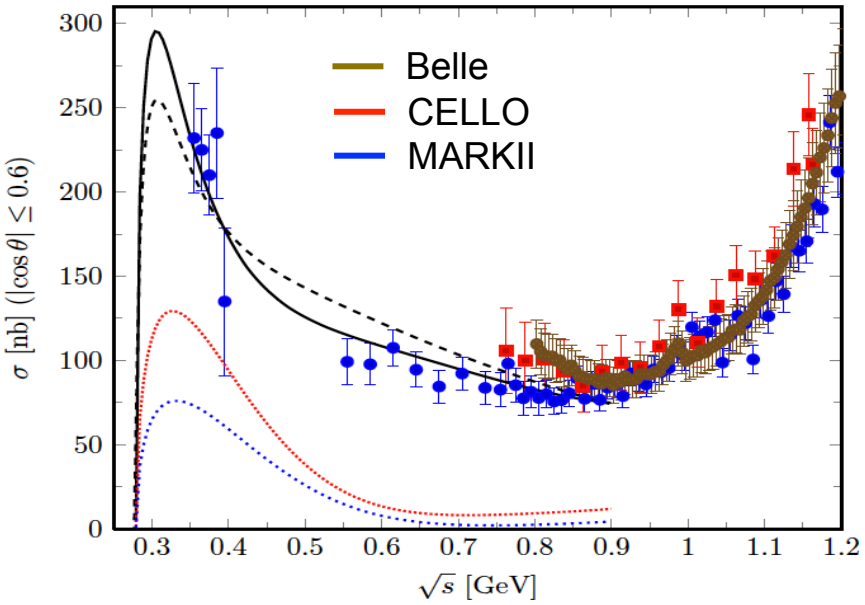
$F_{\eta',\gamma,\gamma^*}(Q^2)$



$\eta' \rightarrow \pi^+ \pi^- \eta \rightarrow \pi^+ \pi^- \gamma\ \gamma$

- Results competitive to previous measurement
- More data and more decay modes → order of magnitude improvement

$\gamma\gamma^* \rightarrow \pi^+\pi^-$ at BESIII



- All in two real photon case: $\gamma\gamma \rightarrow \pi^+\pi^-$
- In low mass region, only measurement come from MarkII

[MARKII: Phys. Rev. D42, 5, 1990]

[CELLO: Z. Phys. C56, 381, 1992]

[Belle: Phys. Rev. D75, 051101(R), 2007]

[N. Asmussen, P. Masjuan, M. Vanderhaeghen]

Access to:

Q^2 region: 0.2~2.0 GeV^2

$M_{\pi\pi}$: threshold~2.0 GeV

Conclusion

- Important results (to be expected) from BESIII for SM prediction of $(g-2)_\mu$
  - HVP: precision inclusive and exclusive measurements
  - HLbL: spacelike form factors measurement in relevant region
- Competing experiments: Frascati, Novosibirsk, Belle-II(?)
- Reduction of factor of 2 of the uncertainty of a_μ^{had} in reach

THANK YOU FOR YOUR ATTENTION!

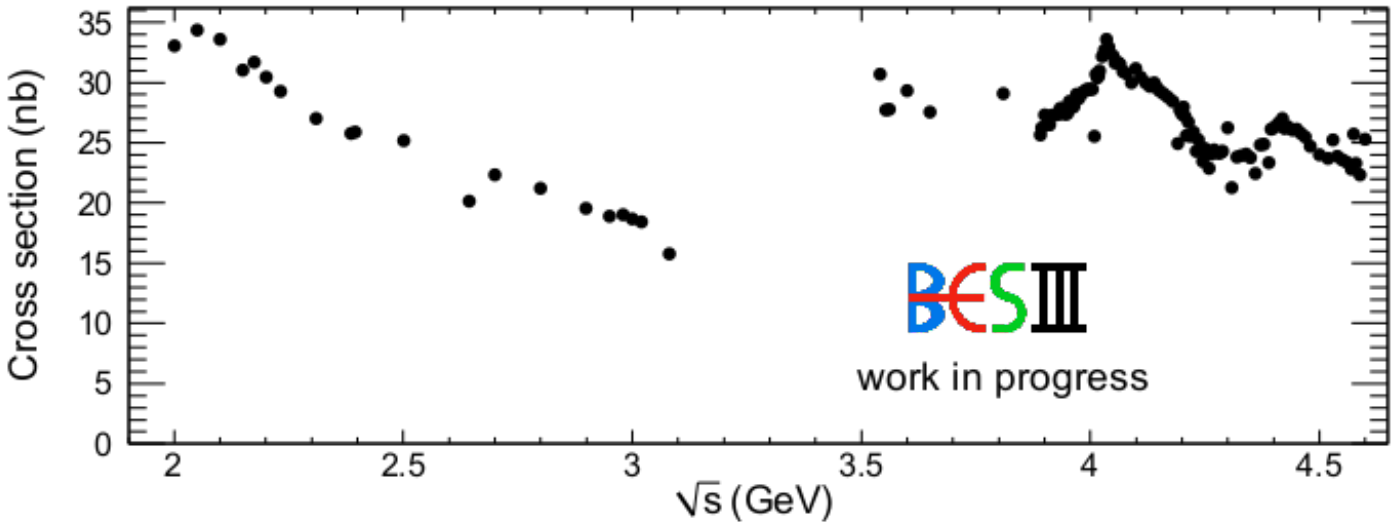
Backup slides

Energy Scan from 2.0 to 4.6 GeV

Reducing the uncertainty of $\alpha_{em}(M_Z^2)$ by a factor of 2

→ A new quantity of electroweak precision fits

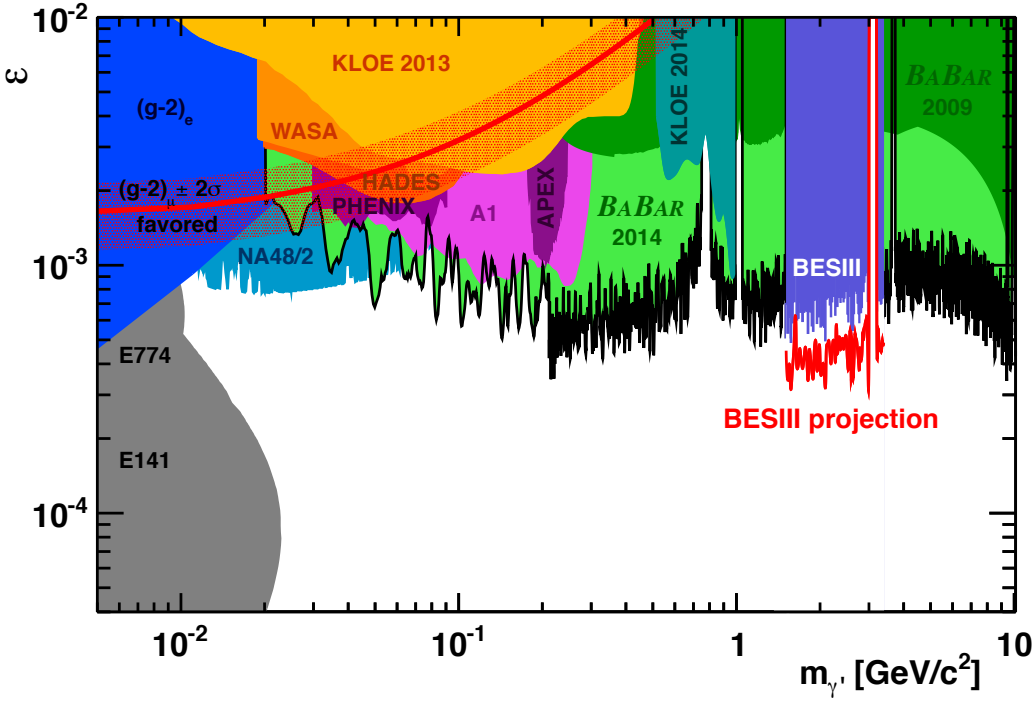
Online spectrum of R scan recently finished

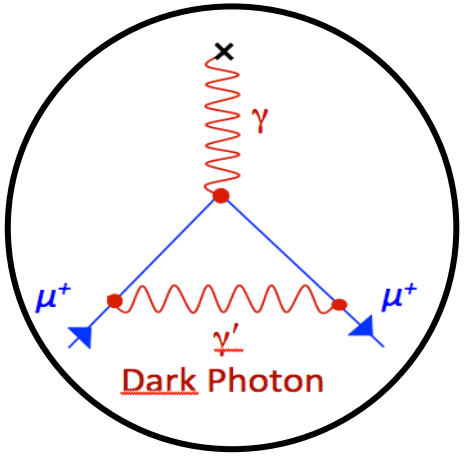


$R = \sigma_{had}/\sigma_{\mu\mu}$ with targeted systematic accuracy: 3.0%

- 125 scan points with >10^5 hadronic events each → statistical error negligible
- World's best measurement so far from BES /BESII with 5 ...8 % total error (with 3 ... 5% statistical error)

Dark photon and $(g-2)_\mu$





BESIII (Mass 1.5 -3.4 GeV/c^2)

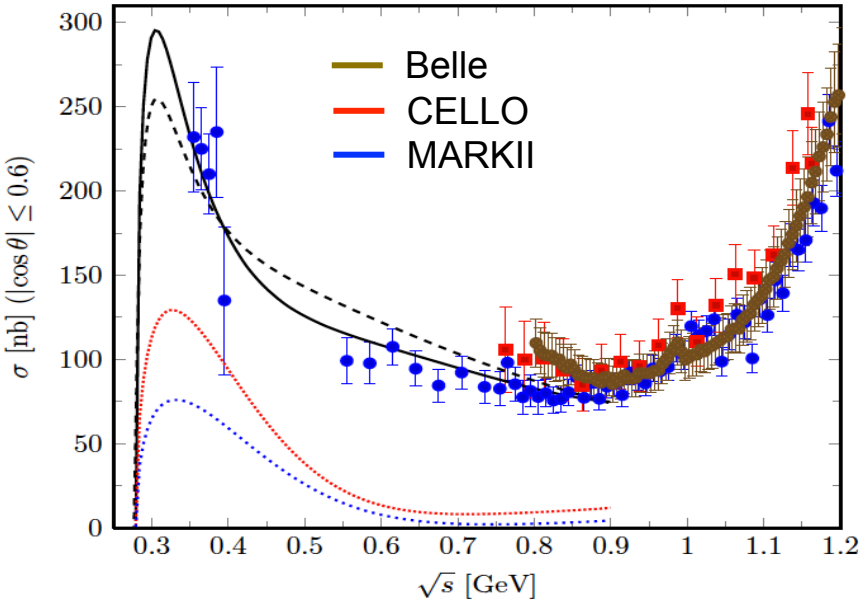
- Spin-off of pion FF analysis ($e^+e^- \rightarrow \gamma\mu^+\mu^-$ / γe^+e^-)

A1 / MAMI (Mass 30 – 855 MeV/c^2)

- Search in Bethe-Heitler process (eZ scattering)

$\gamma\gamma^* \rightarrow \pi^+\pi^-$ at BESIII

- Hadron form factor
- Resonance parameters for $0^{\pm+}$, 2^{++} states
- Pion polarizability, probe the structure of pion
- Re-scattering effect study at low mass region



[N. Asmussen, P. Masjuan, M. Vanderhaeghen]

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