JOHANNES GUTENBERG UNIVERSITÄT MAINZ

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

BESIII

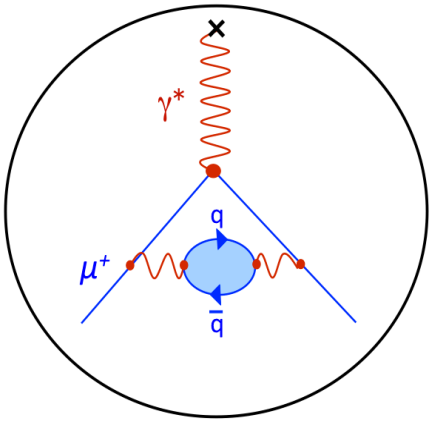
Experimental Inputs for the Hadronic Calculations of $(g-2)_\mu$

Yuping Guo

INSTITUT FÜR KERNPHYSIK
JOHANNES GUTENBERG-UNIVERSITÄT MAINZ

Hadronic Contributions

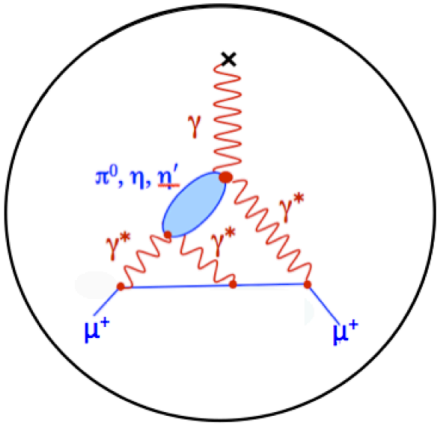
Hadronic Vacuum Polarization



692.3 ± 4.2

[Davier et. al. (2011)]

Hadronic Light-by-Light



11.6 ± 4.0

[Jegerlehner, Nyffler (2009)]

10.5 ± 2.6

[Prades et al. (2009)]

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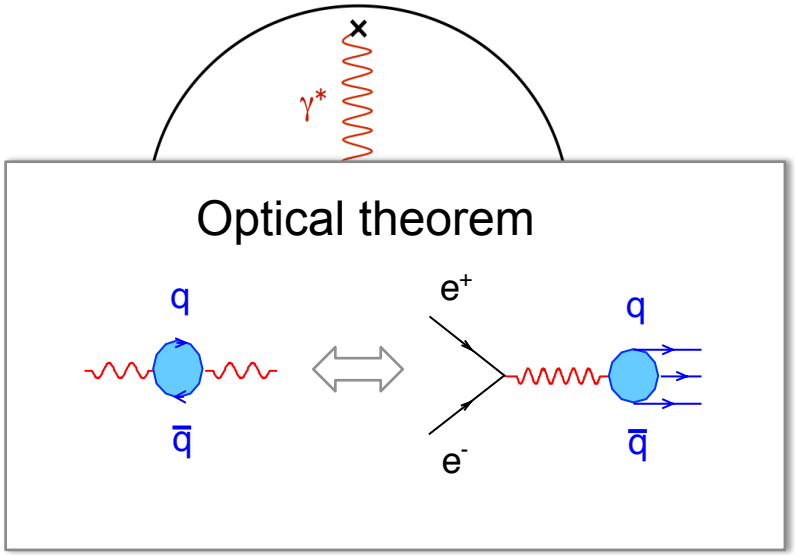

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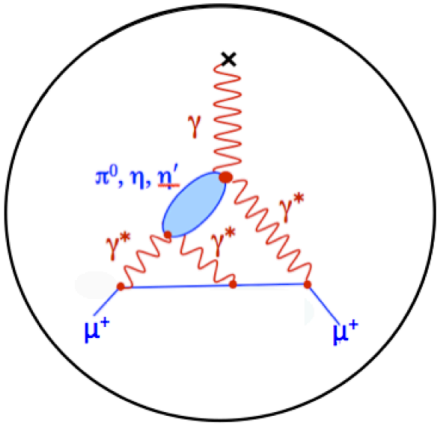
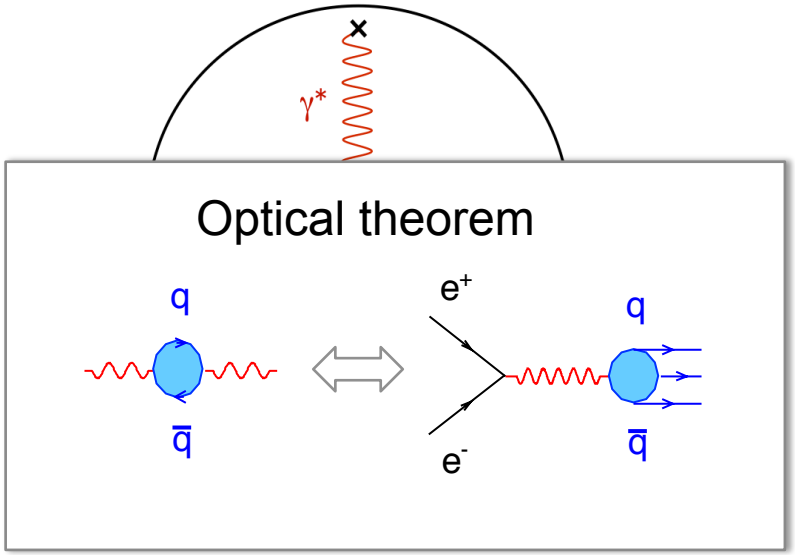


Dispersion integral

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

Hadronic Contributions

Hadronic Vacuum Polarization



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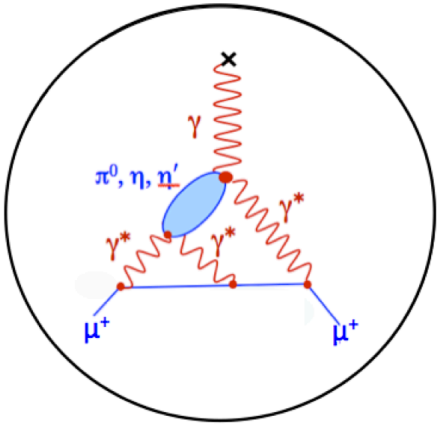

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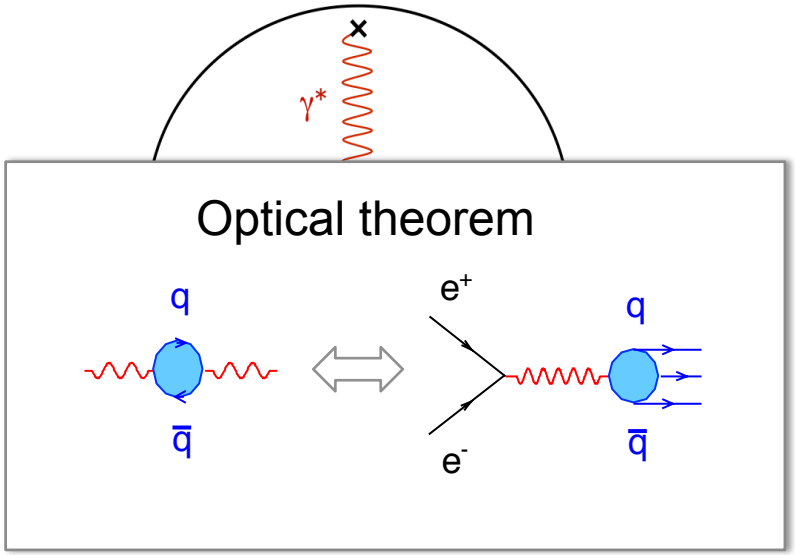
$\sigma_{\mathrm{had}} = \sigma(e^+e^- \rightarrow \textit{hadrons}) \sim 1/s$

Kernel function ~ 1/s

Hadronic Contributions

Hadronic Vacuum Polarization



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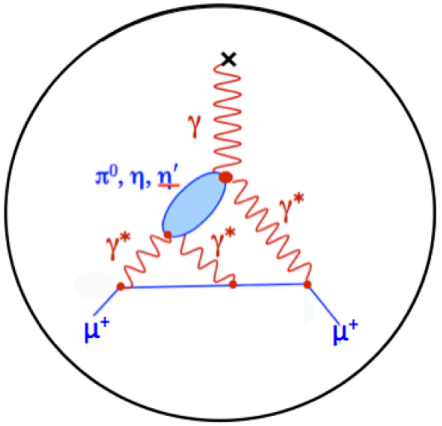

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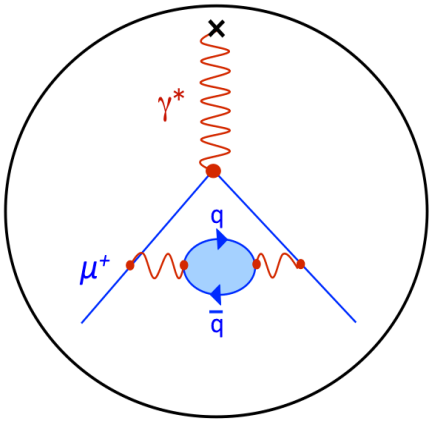
Kernel function ~ 1/s

Low energy contributions important!

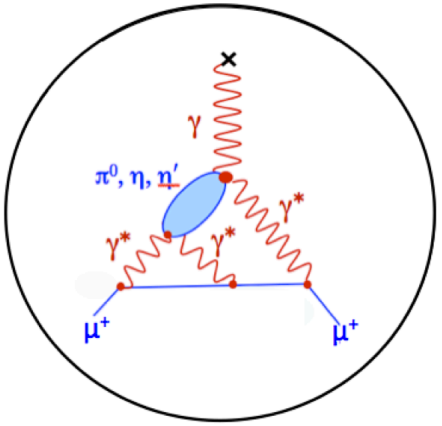
Hadronic Contributions

Hadronic Vacuum Polarization



Transition form factors
Helicity amplitute

Hadronic Light-by-Light

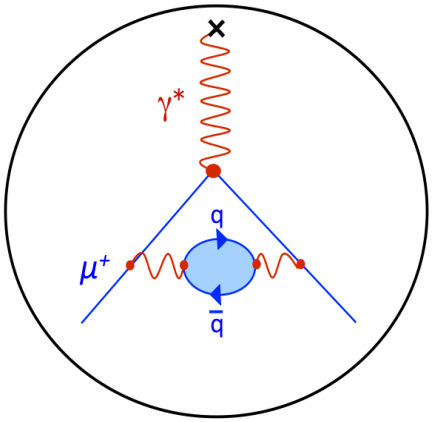


- Only model calculations so far
- Data-driven approach been developed

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

Hadronic Contributions

Hadronic Vacuum Polarization



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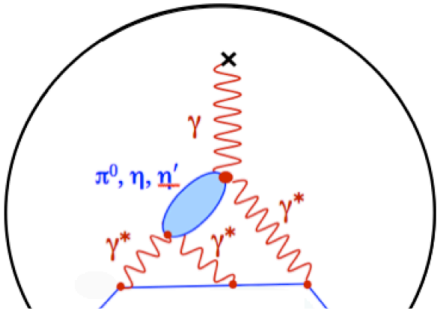
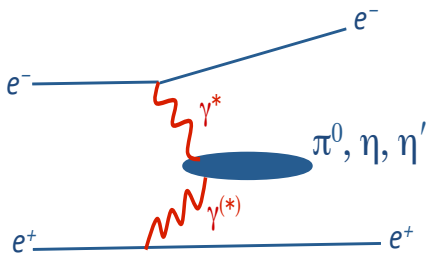
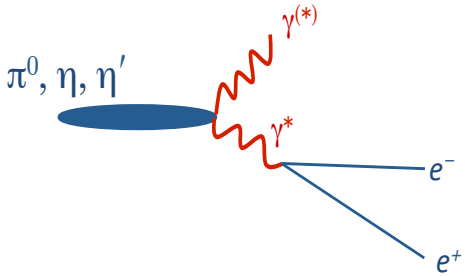


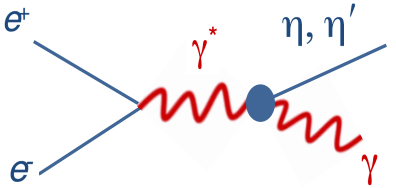
Transition form factors
Helicity amplitute

Spacelike



Timelike





Hadronic Cross Section

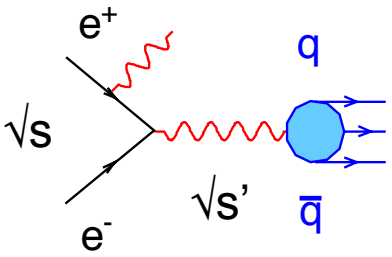
$\sigma_{had}\,(e^+e^- \rightarrow hadrons)$

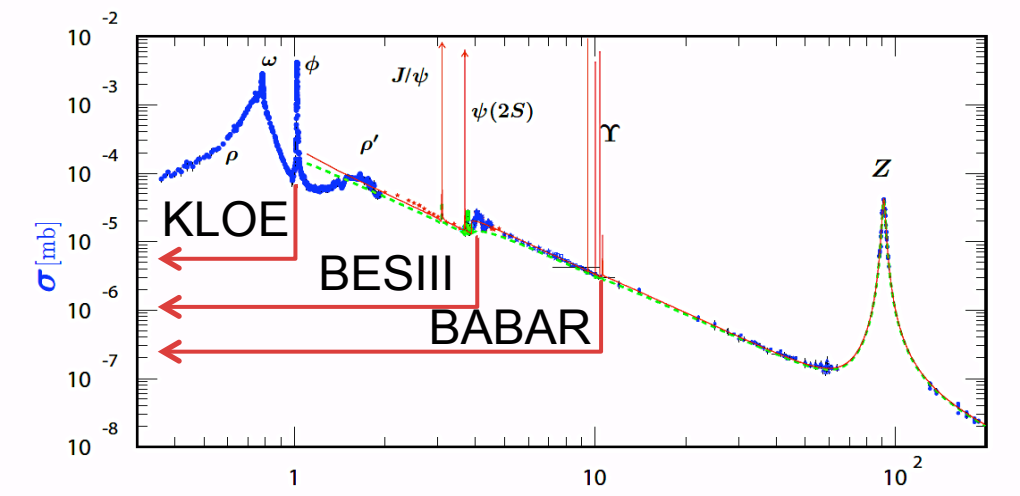
Hadronic Cross Section

- **Energy Scan:**
  - CMD & SND at VEPP-2M & VEPP-2000 in Novosibirsk
  - BESIII at BEPCII in Beijing

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

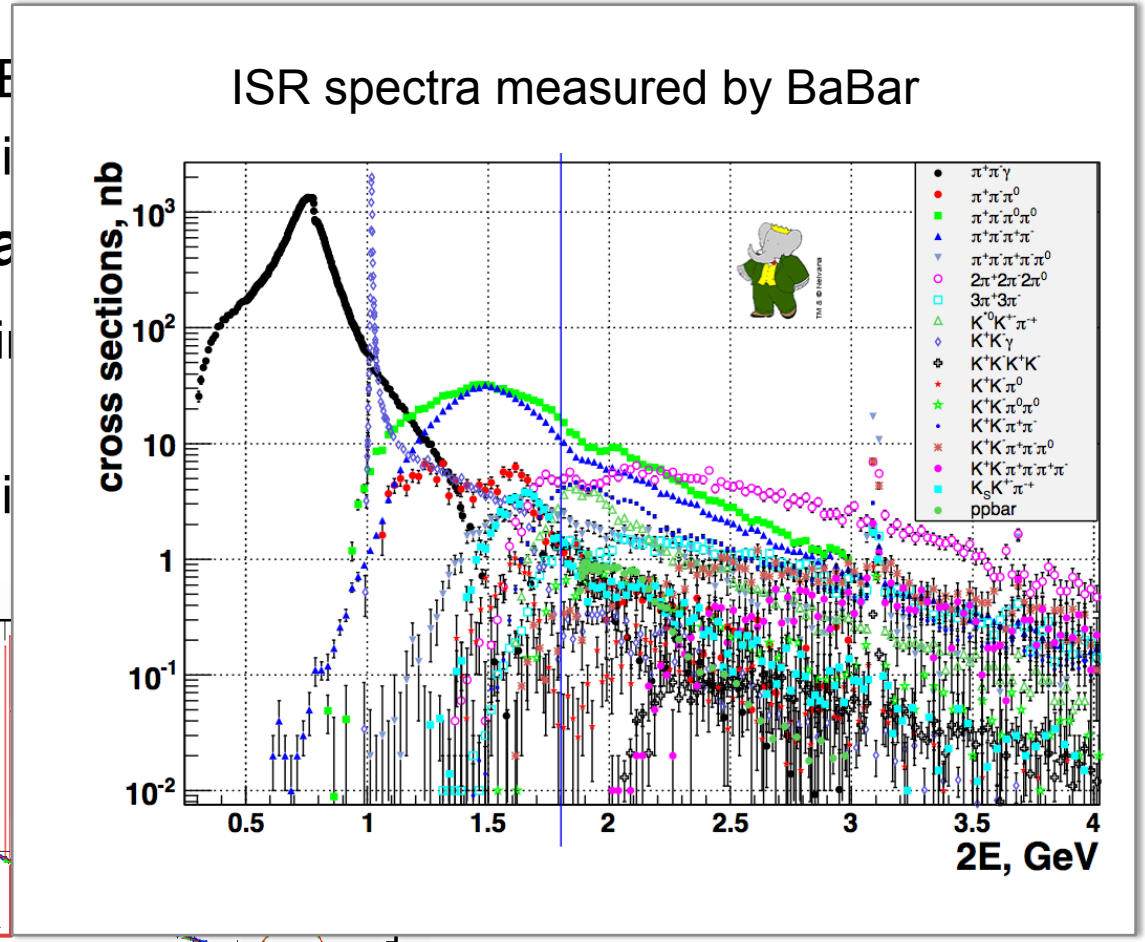


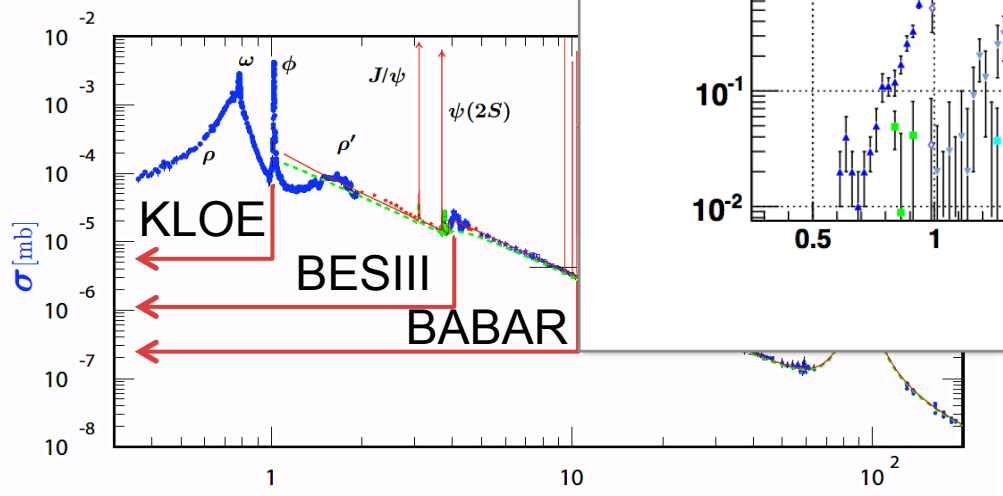


- Needs no systematic variation of beam energy
- High statistics thanks to high integrated luminosities

Hadronic Cross Section

- **Energy Scan:**
  - CMD & SND at VE
  - BESIII at BEPCII i
- **Initial State Radia**
  - KLOE at DAϕNE i
  - BABAR at PEP-II
  - BESIII at BEPCII i

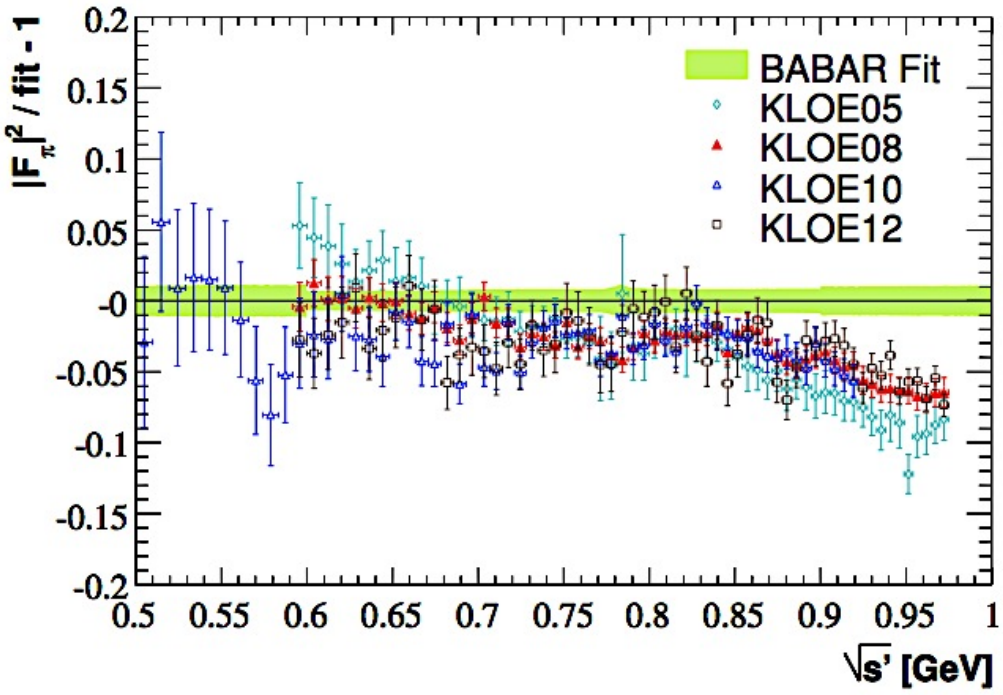




Most Relevant Channel:

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

- 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} $cm^{-2}s^{-1}$ (April 2016)

Data taking from 2009 to present

Beijing Electron Positron Collider-II

MUC: 9/8 layer RPC, $\sigma_{R\Phi}$: 2 cm

SC Magnet: 1Tesla

Magnet yoke

TOF: (σ_T)

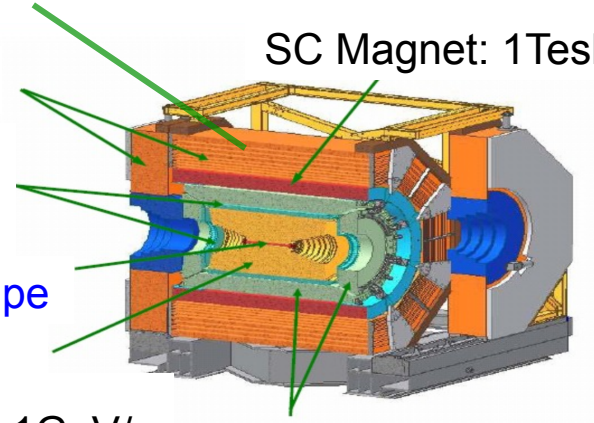
80 ps / 110 ps

Beam pipe

MDC:

σ_p/p: 0.5% at 1GeV/c

dE/dx: 6%



CsI calorimeter:

$\Delta E/E$: 2.5% / 5.0% at 1 GeV;

σ_Z: 0.6 cm/$\sqrt{E}$

Linear Accelerator

BEPCII: τ-charm factory

Beam energy:

1-2.3 GeV

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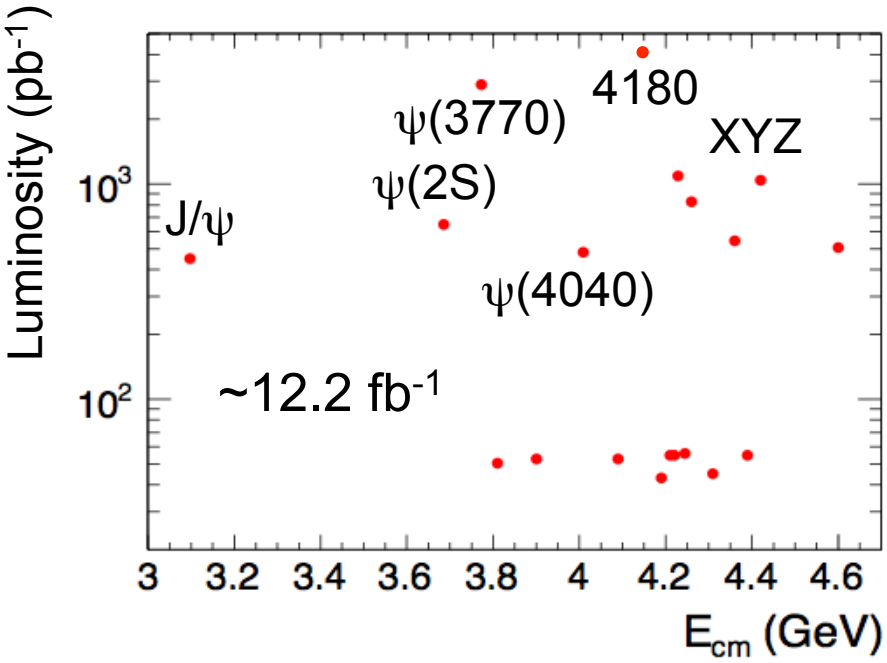
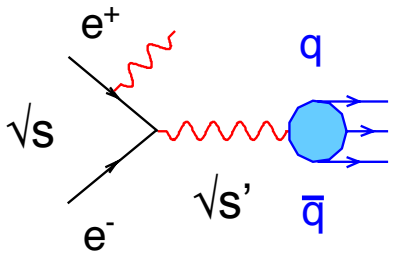
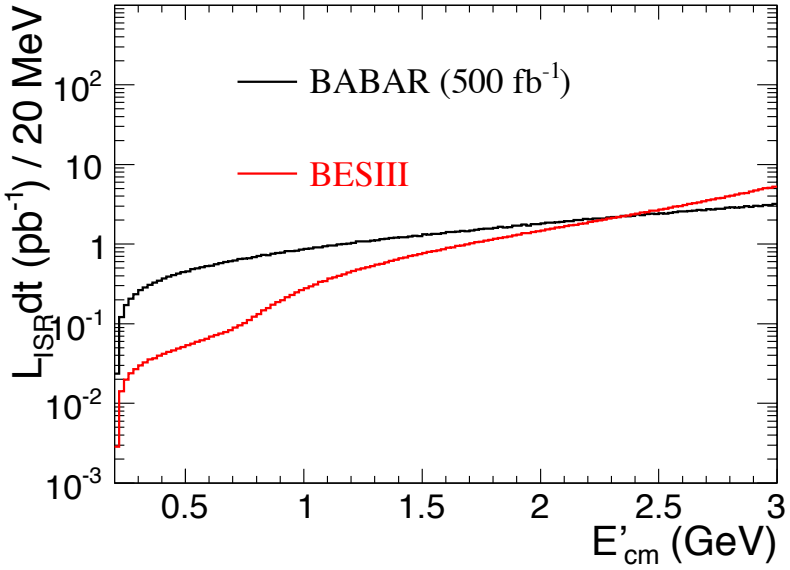
Data Samples for ISR Study





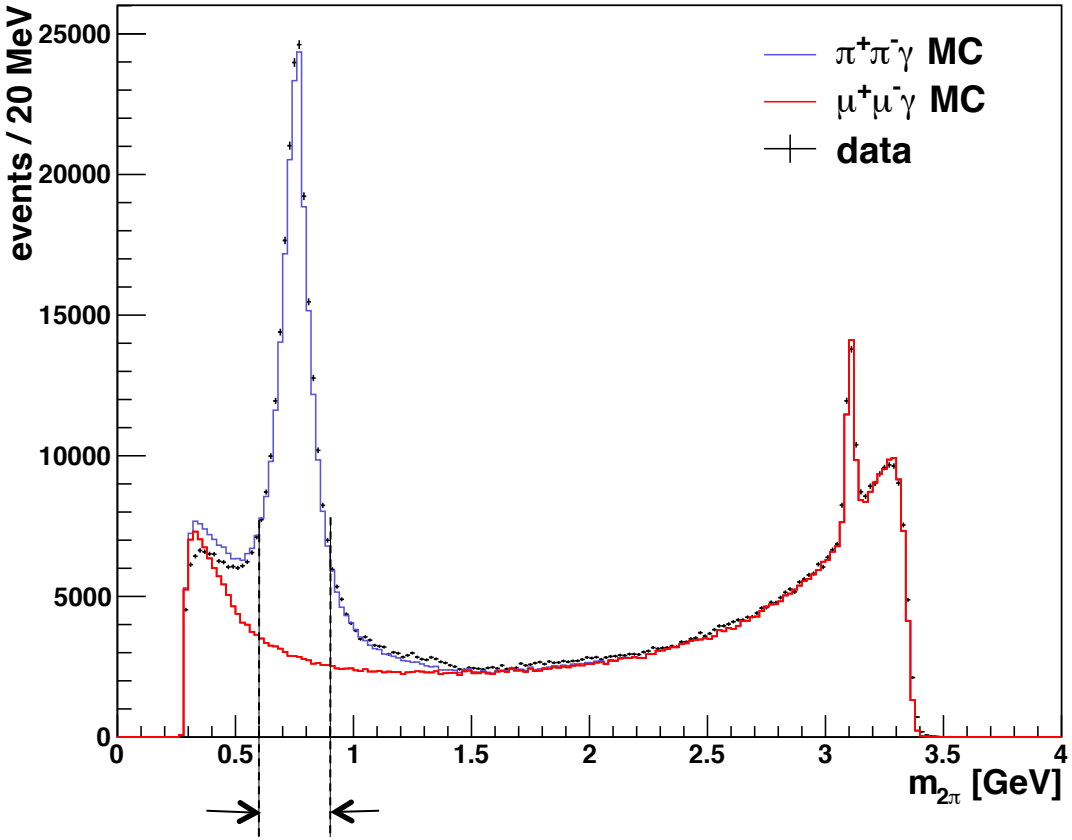
ISR luminosity = L dt x H_{rad}

Radiator function, well known



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

Event yield after preliminary selection



Initial publication
600 – 900 MeV

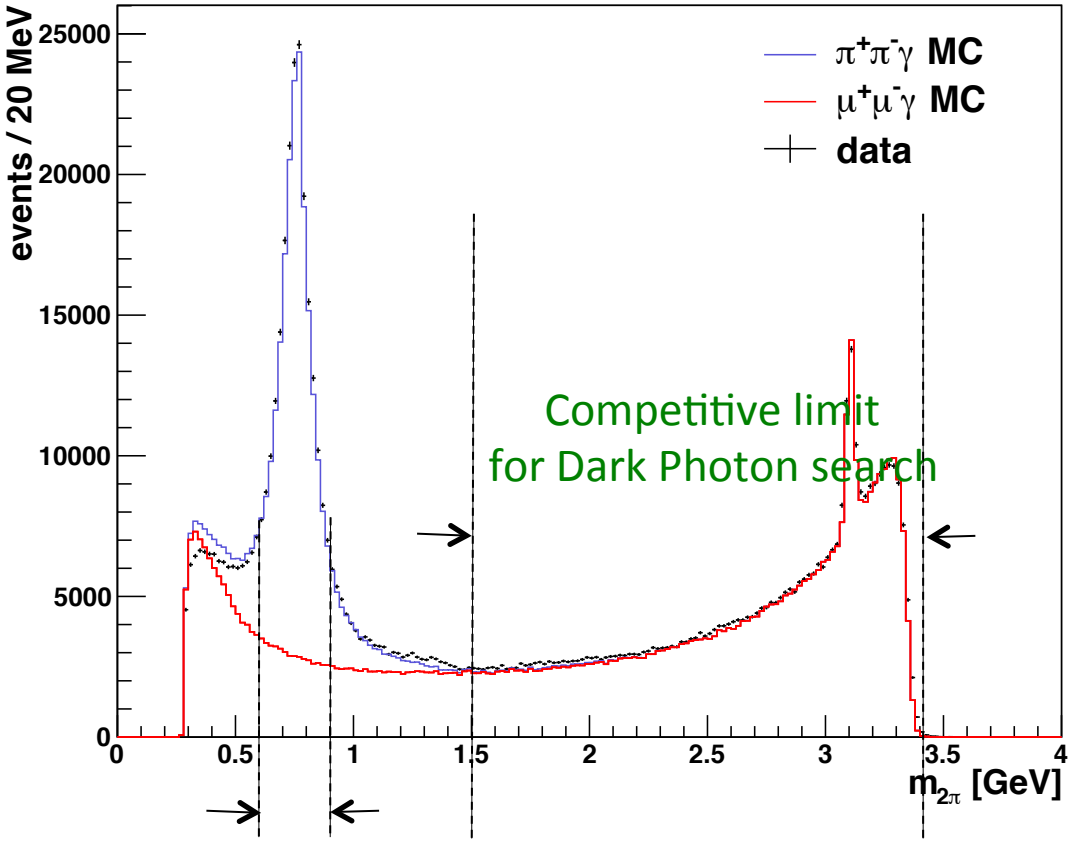
[Phys. Lett. B753 (2016) 629]

- $\psi(3770)$ data (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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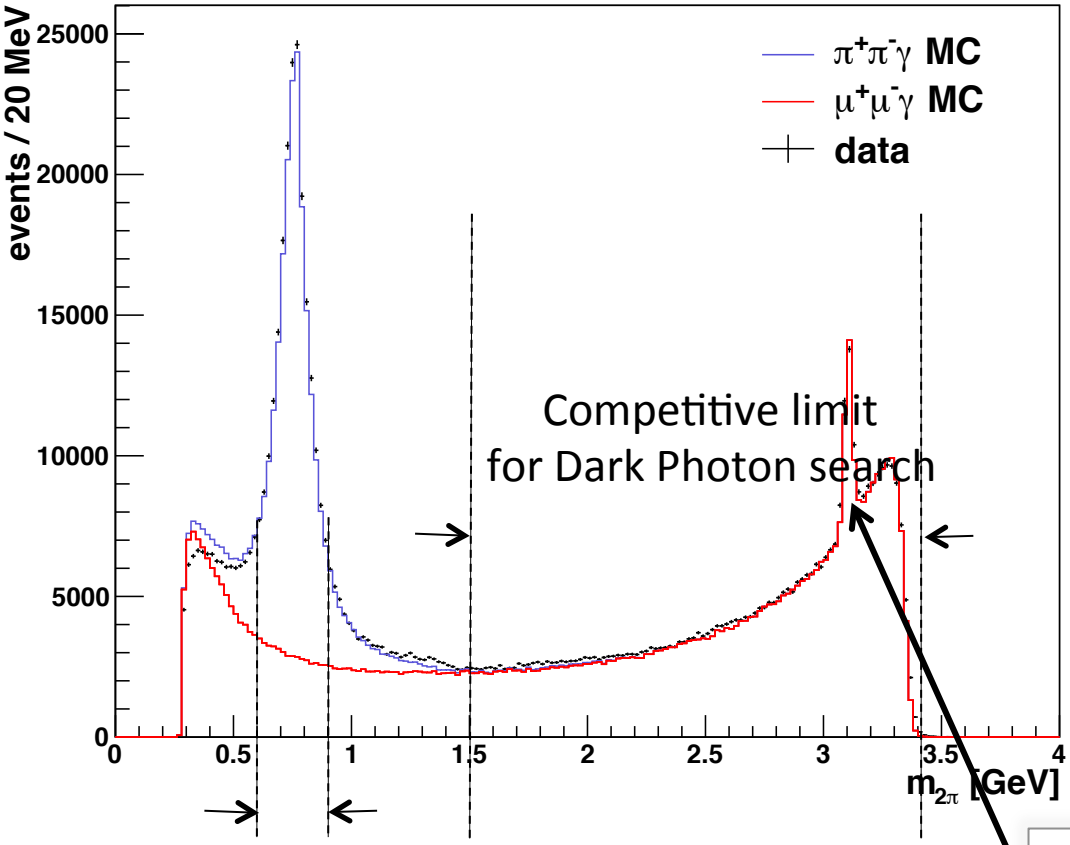

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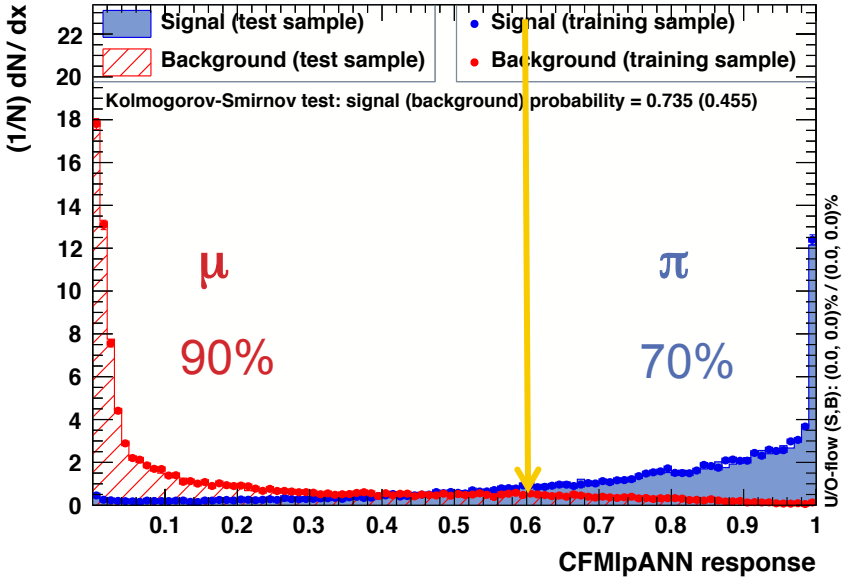
World's best measurement of Γ_{ee} of J/ψ

[Phys. Lett. B753 (2016) 629]

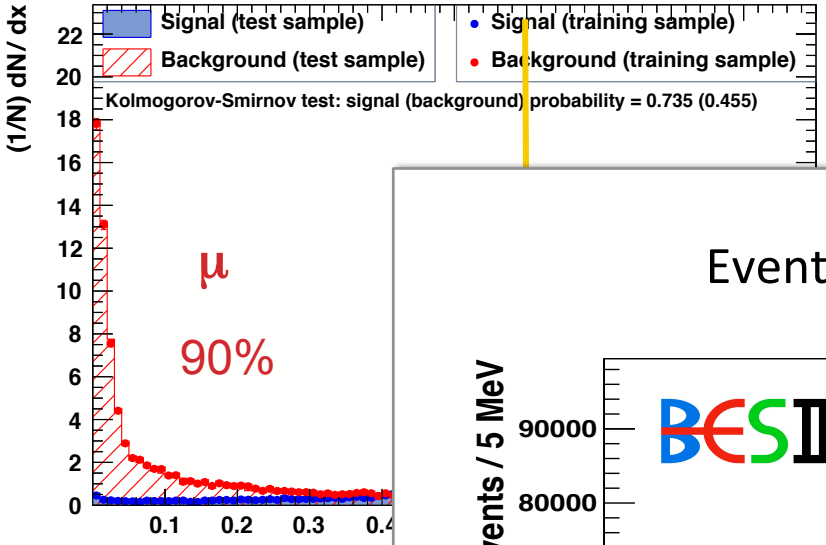
$e^+e^- \to \gamma_{ISR}\,\pi^+\pi^-$: π-μ separation



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

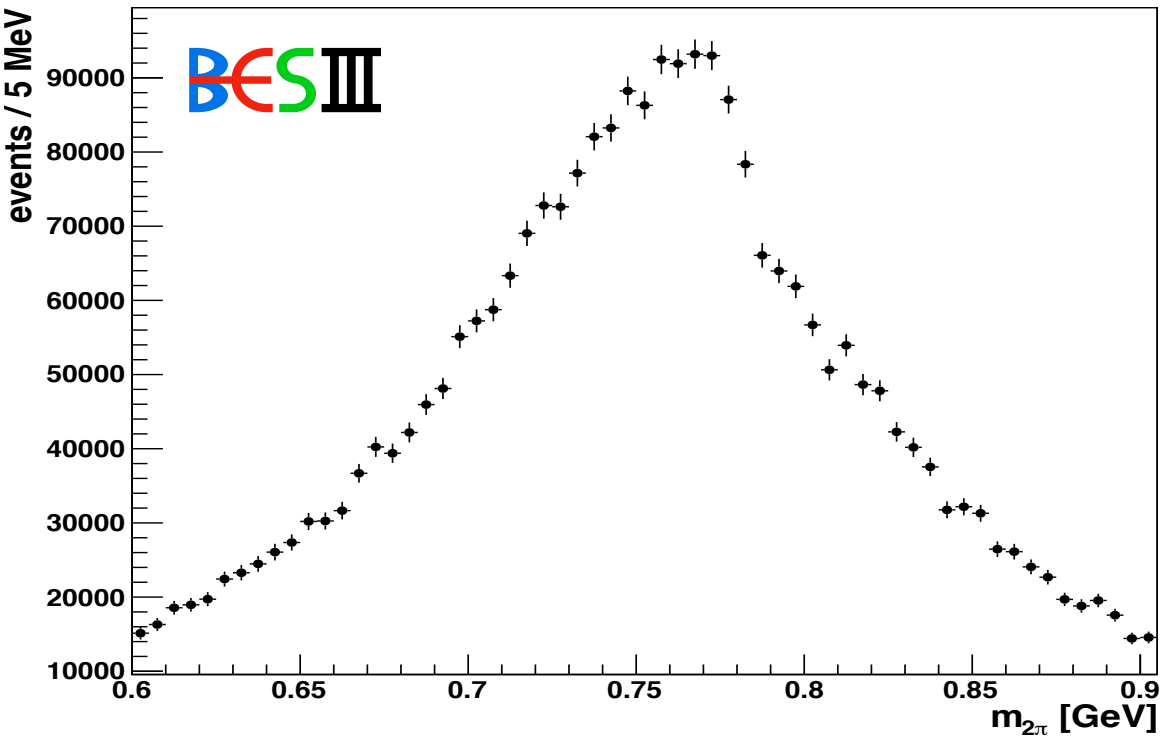


TMVA method (Neural Network):

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

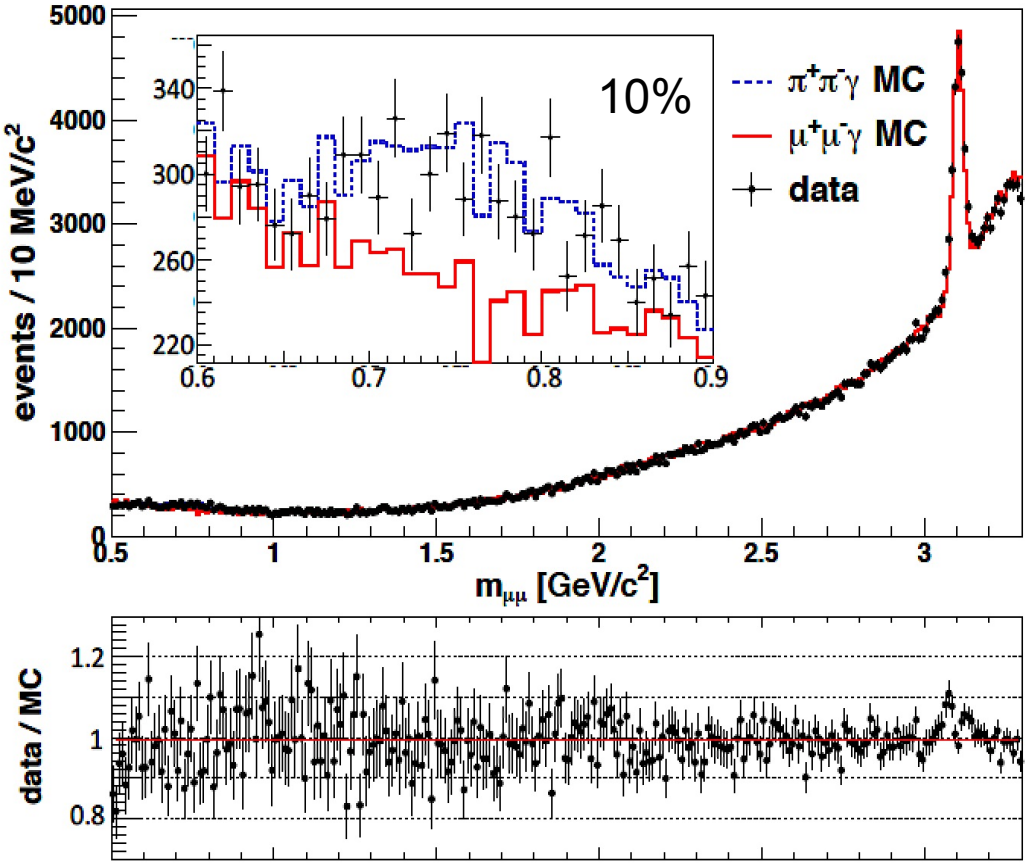
ods

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, 1.0% 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

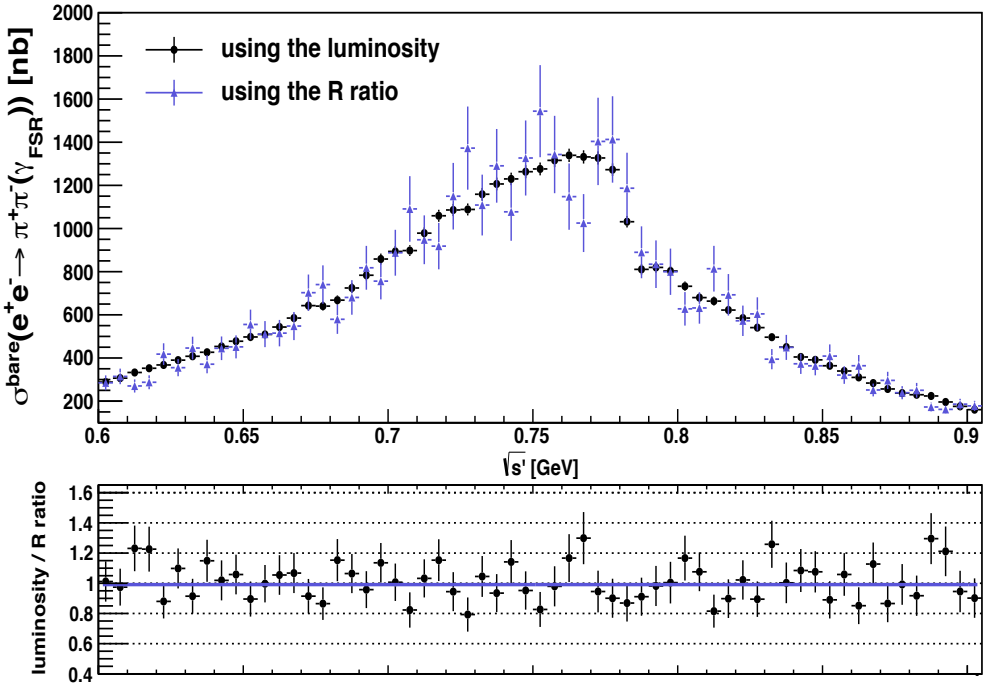
2 normalization methods:

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

$$\sigma_{bare}(e^+e^- \to \pi^+\pi^-) = \frac{N_{\pi\pi\gamma}}{L_{int} \cdot H_{rad} \cdot \delta_{vac} \cdot (1+\delta_{FSR})}$$

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

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



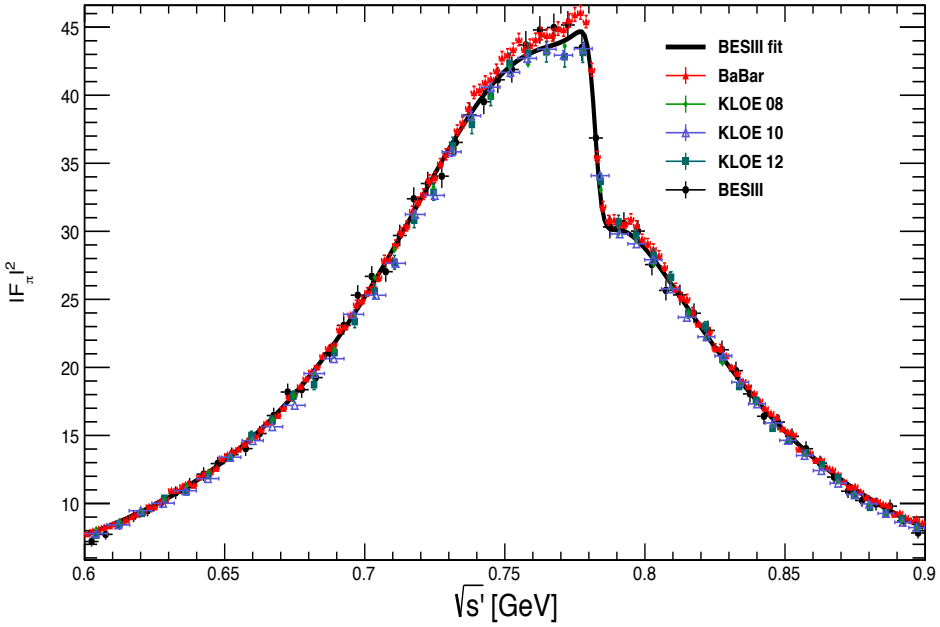
Good agreement between two methods

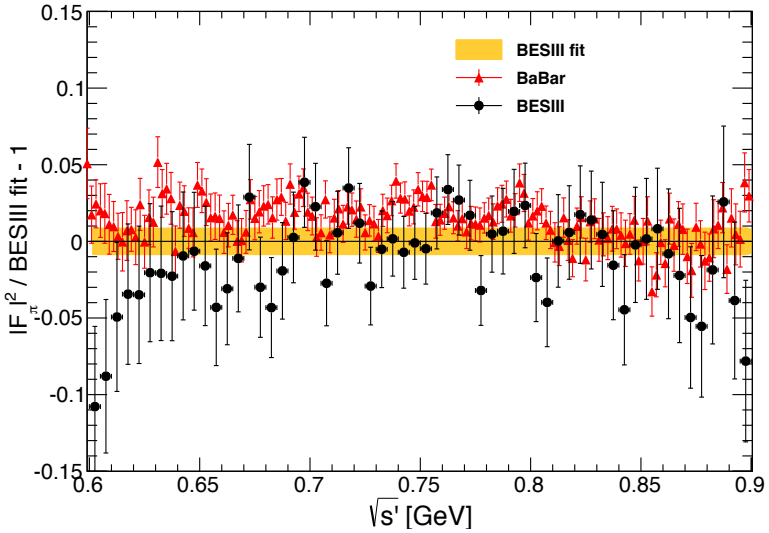
luminosity / R ratio -1
= (0.85 ± 1.68) %

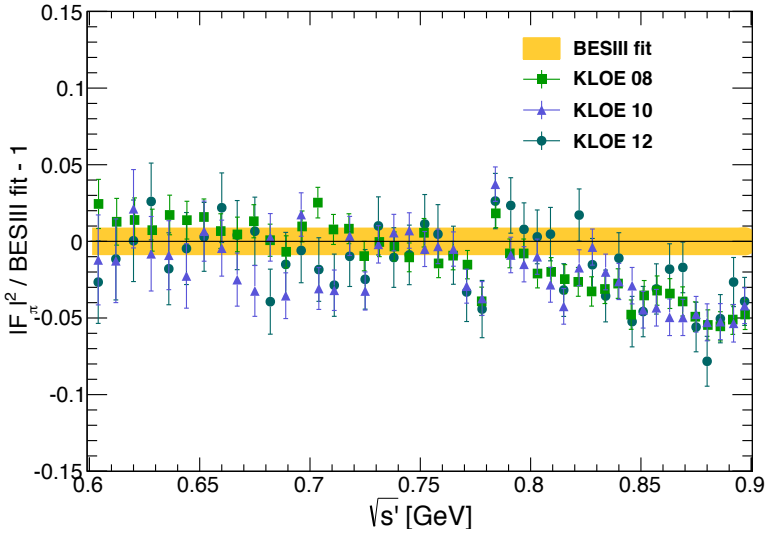
limited by low γμμ statistics

Compare with Existing Data

Pion Form Factor F_π

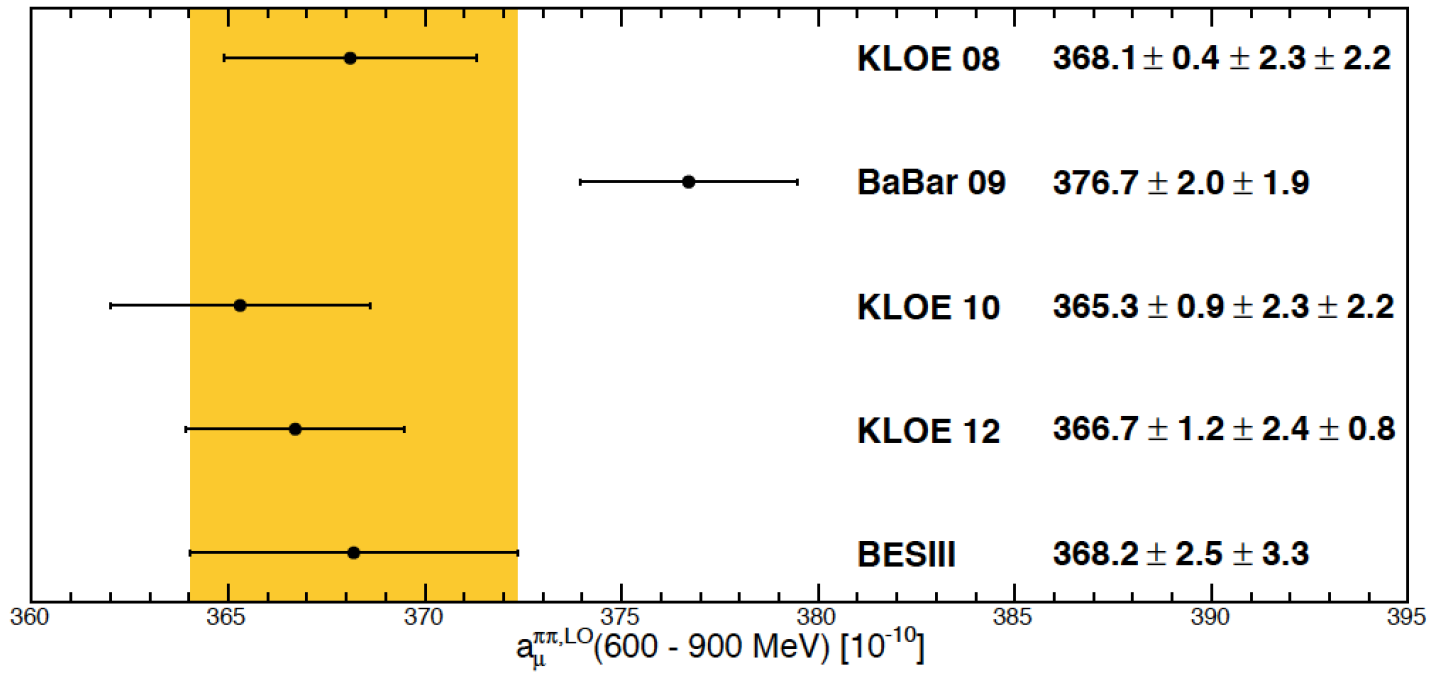






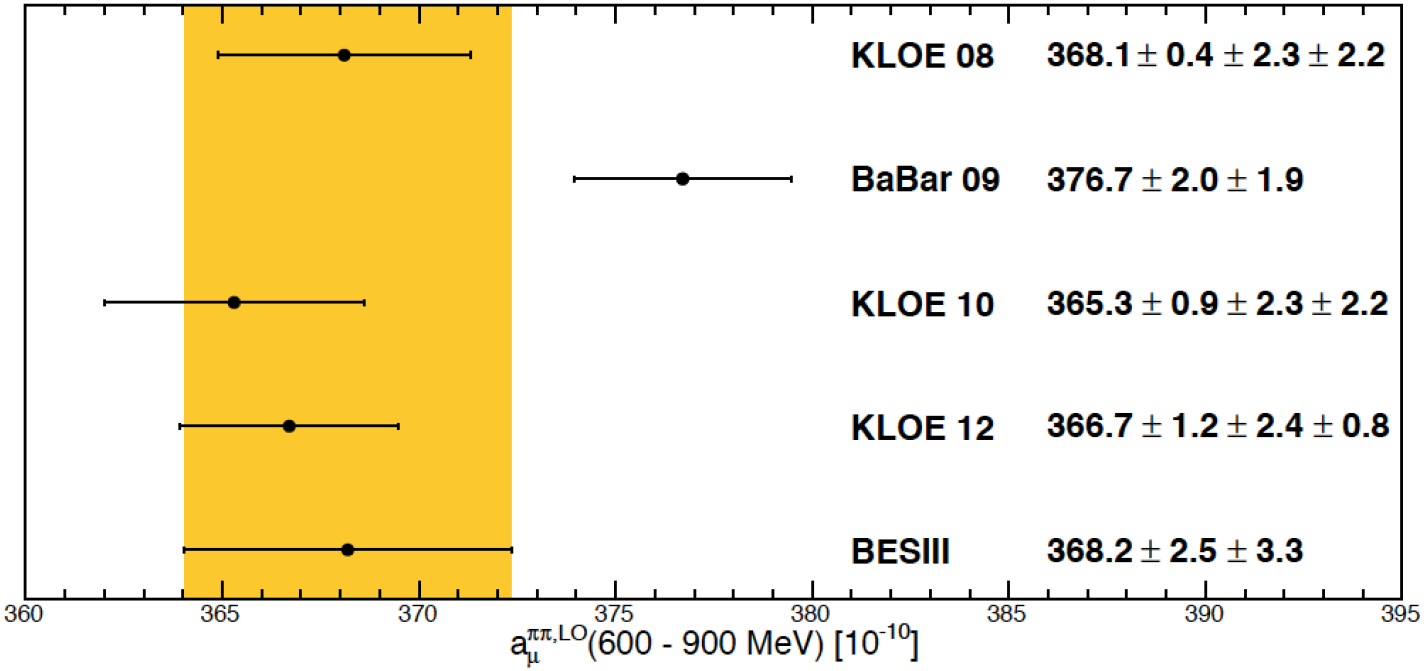
- Gounaris and Sakurai parameterization
- 0.9 % accuracy (dominated by theory)
- Normalization to luminosity × radiator function

Impact on a_μ^{HVP}



Deviation on $(g-2)_\mu$ between experimental and SM: 3-4 sigma

Impact on a_μ^{HVP}



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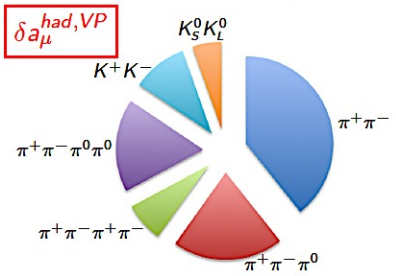


Study of $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-\pi^0\pi^0$ processes undergoing at BESIII

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 accuracy: 3.0%

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

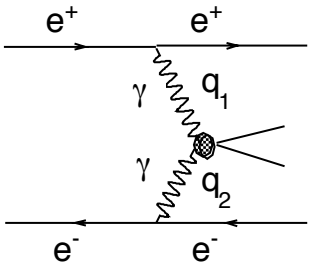
Energy region	Energy points	Note
2.400~3.400	4	Mini-scan
3.800~4.590	104	Fine-scan heavy charm resonant
2.000~3.080	21	R&QCD-scan
3.050~3.120	16	J/ψ-scan
3.542~3.600	5	τ-scan
3.650,3.671	2	ψ(3686)-scan

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

→ A new quantity of electroweak precision fits

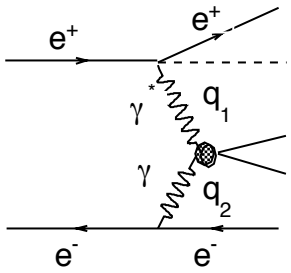
Meson Transition Form Factor $|F(Q^2)|$

Spacelike Transition FFs



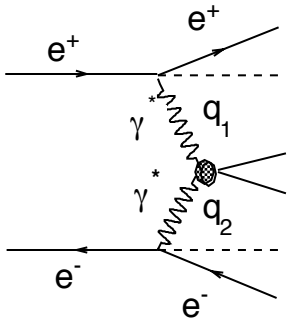
Untag:

- 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



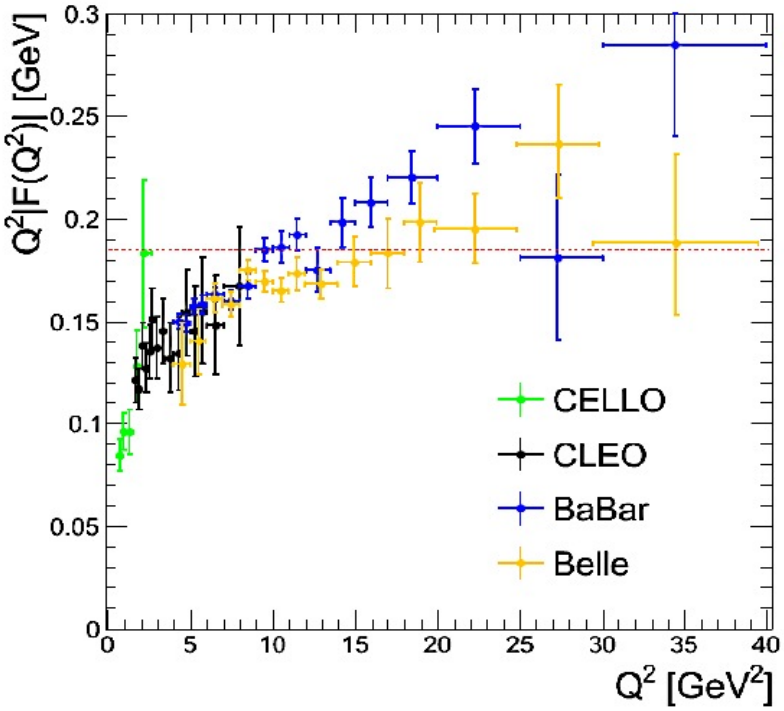
Double tag:

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

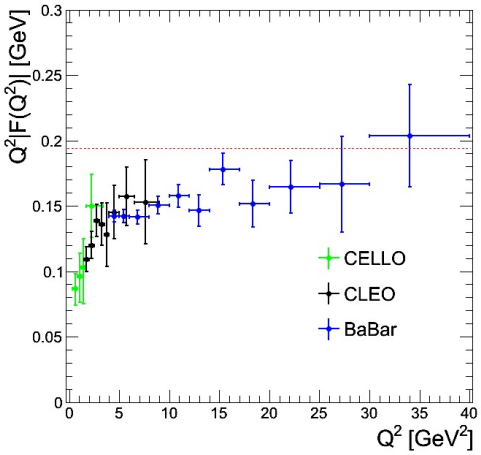
Input for data-driven approach

Existing Data on Spacelike TFFs

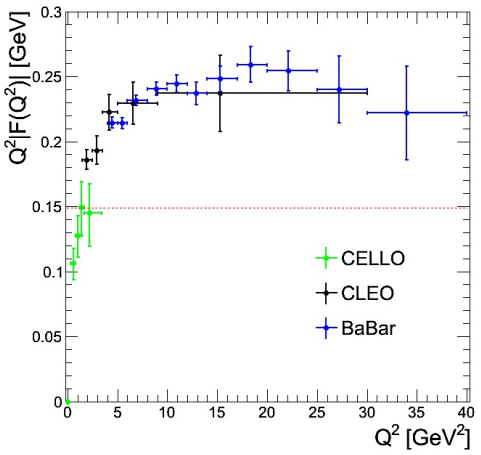
$e^+e^- \to e^+e^- \pi^0$



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



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



- 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

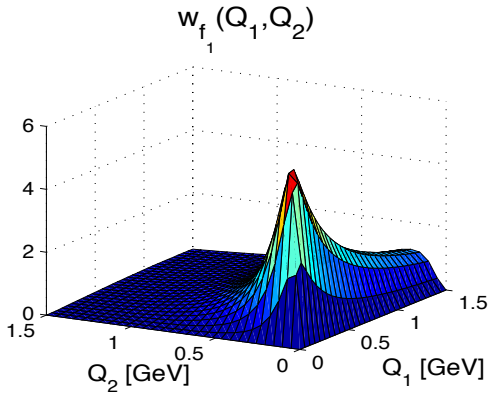
[CELLO: Z. Phys. C 49 401 (1991)]
[CLEO: Phys. Rev. D57 33 (1998)]
[BaBar: Phys. Rev. D80 052002 (2009)]
[Belle: Phys. Rev. D86 092007 (2012)]

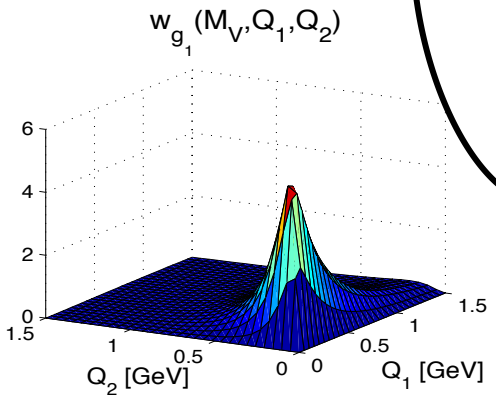
Relevant Q^2 Region

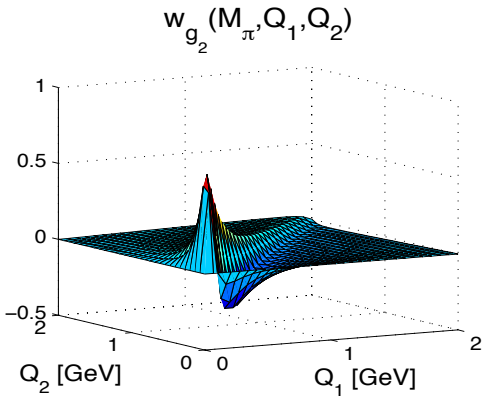
$$a_\mu^{\mathrm{HLBL};\pi^0} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \sum_i W_i(Q_1, Q_2)\, f_i(Q_1, Q_2)$$

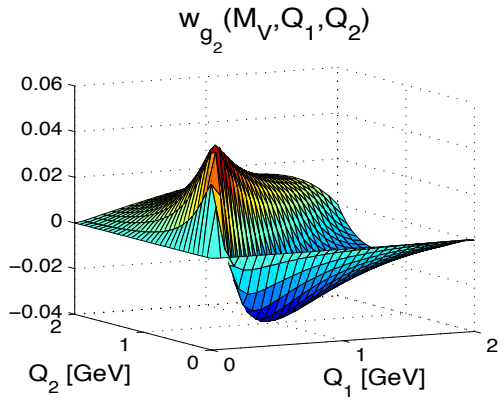
Form factor dependent

Universal weight functions









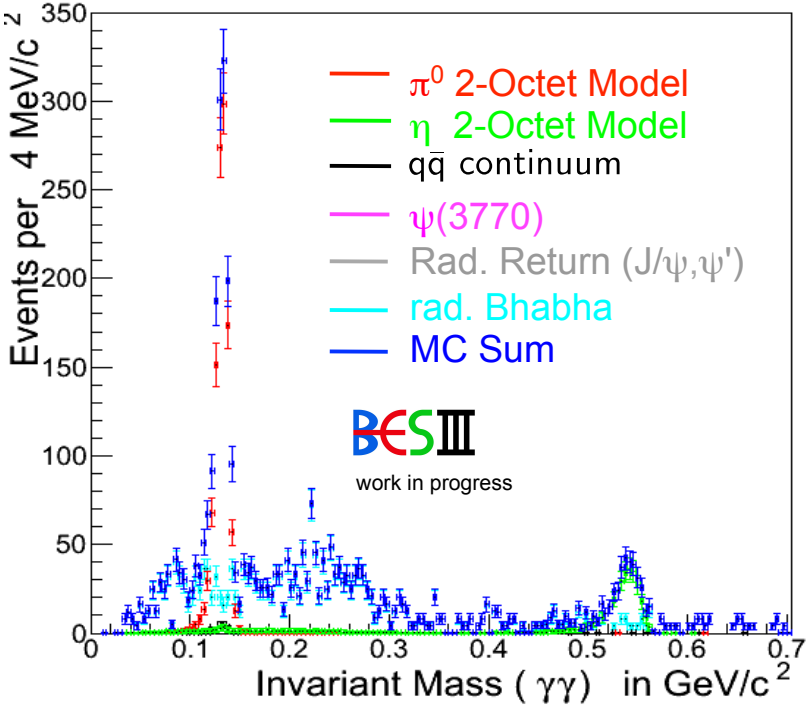
Relevant Q^2 region:
<1.5 GeV^2

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

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

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

MC only, part of full statistics



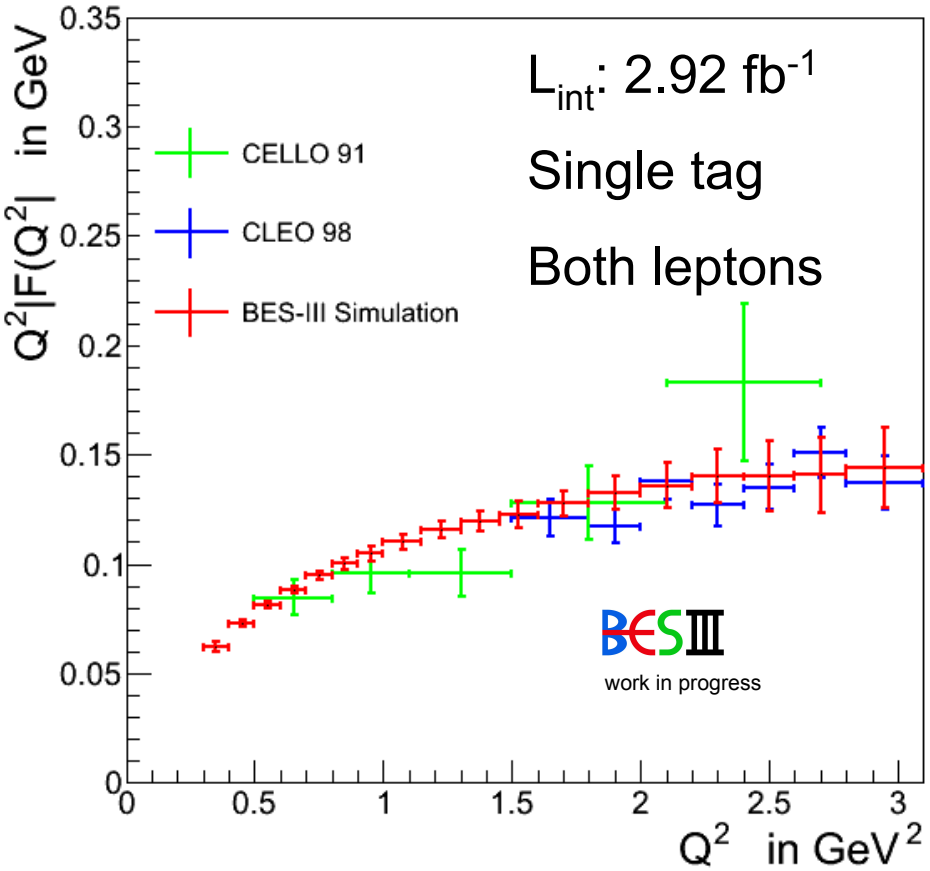
Event Selection:

- 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:

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

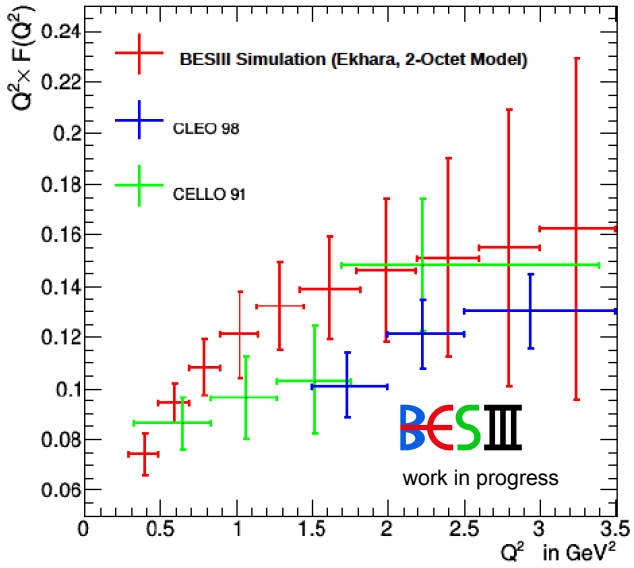
Significantly improves and extends data set below Q^2 = 1.5 GeV^2

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

Spacelike transition FFs: η / η'

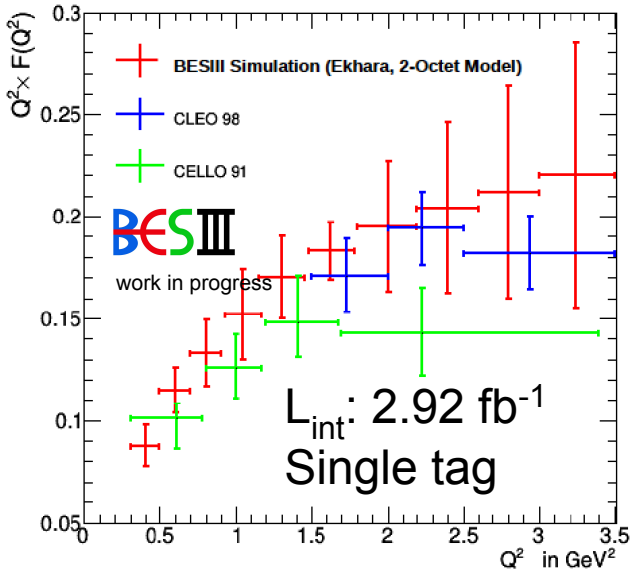
MC only, red error bars corresponding to BESIII statistics

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



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

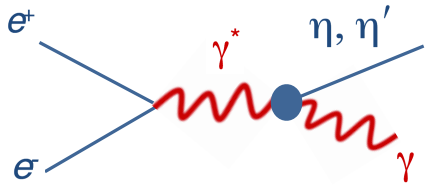
$F_{\eta',\gamma,\gamma^*}(Q^2)$



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

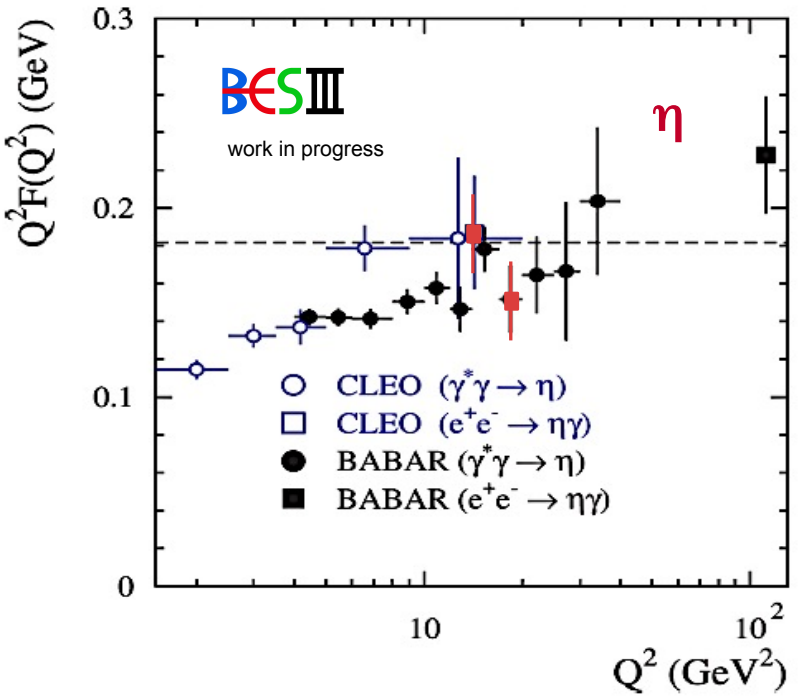
- Results competitive to previous measurement
- More data and more decay modes → order of magnitude improvement

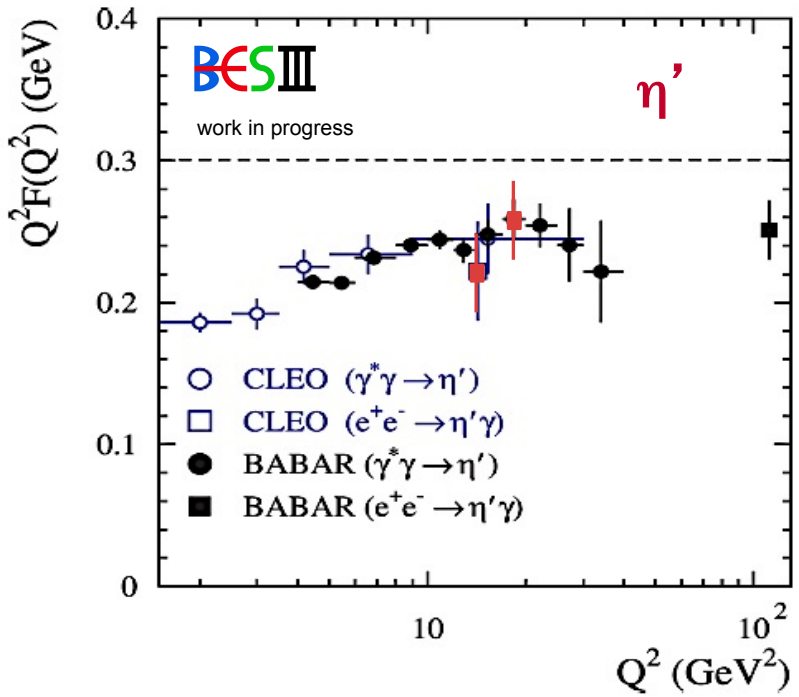
Timelike transition FFs



η and η' timelike TFF

$$\sigma_{e^+e^-\to\eta^{(\prime)}\gamma}(q^2) = \frac{2\pi^2\alpha^3}{3}(1-\frac{m_{\eta'}^2}{s})^3|F_{\eta'}(q^2)|^2$$

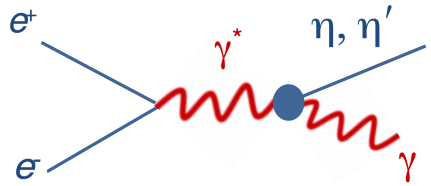


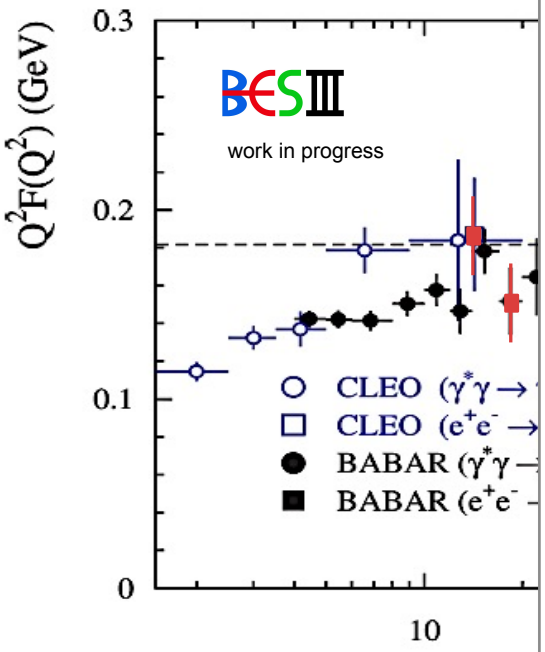


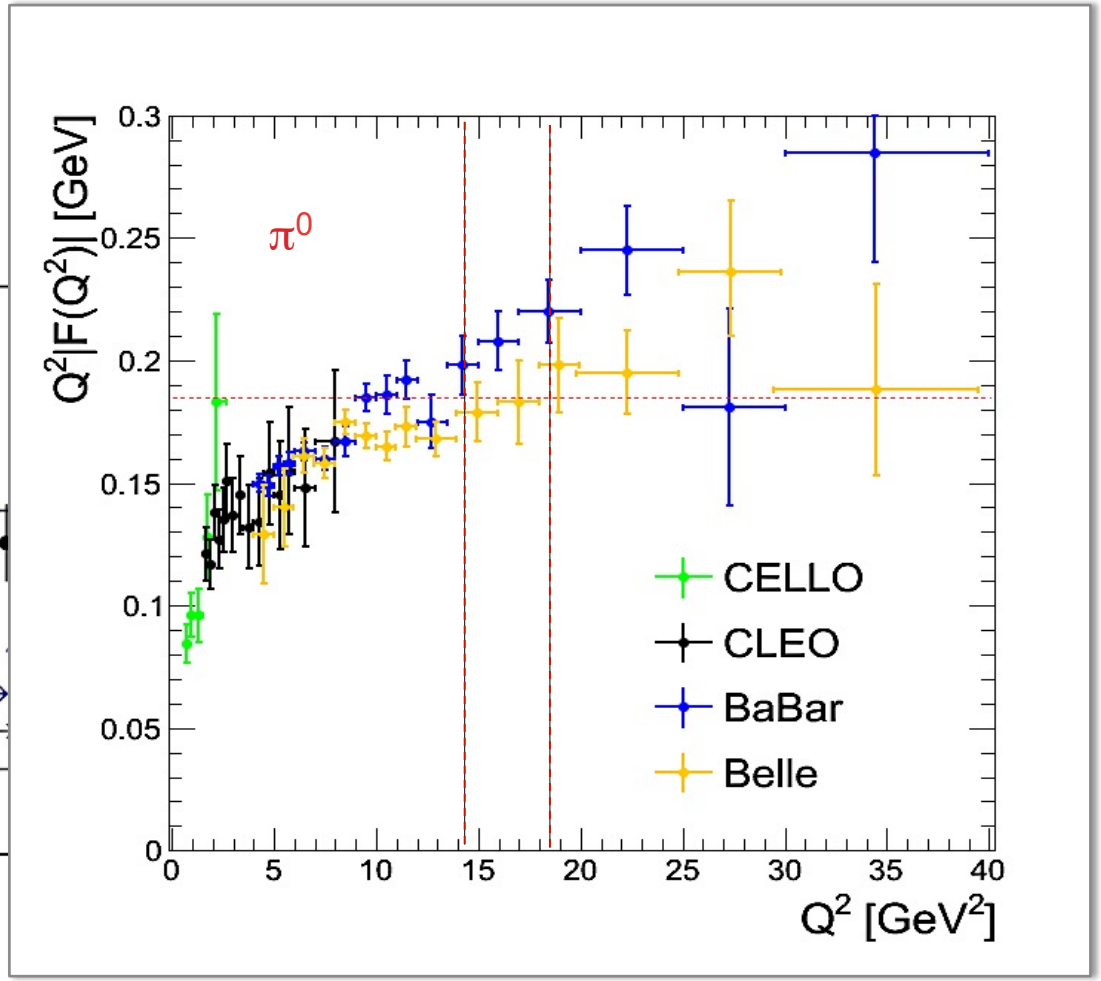
- <Q^2>: 18.5 GeV^2, 5.3 fb^{-1} from 4.0-4.6 GeV
- <Q^2>: 14.2 GeV^2, 2.9 fb^{-1} at 3.773 GeV

Position: arbitrary
Error: Corresponding to statistics

Timelike transition FFs



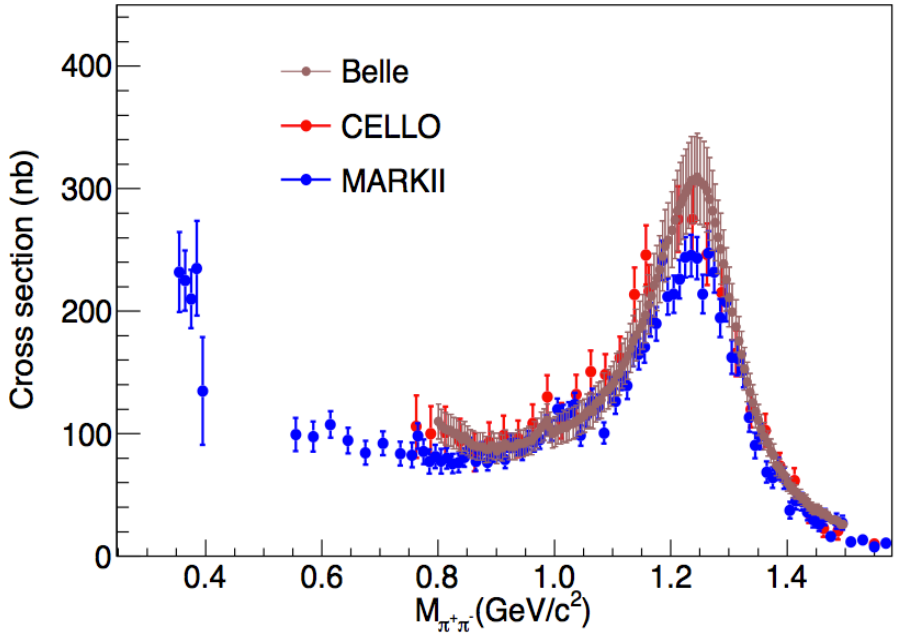




- $\langle Q^2 \rangle$: 18.5 GeV^2, 5.3 fb^{-1} from 4.0-4.6 GeV
- $\langle Q^2 \rangle$: 14.2 GeV^2, 2.9 fb^{-1} at 3.773 GeV

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

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

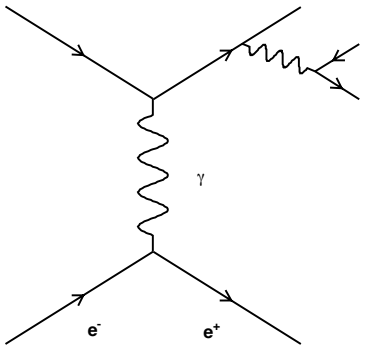


$\gamma\gamma^* \rightarrow \pi^+\pi^-$ at BESIII

Background dominated by $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ events:

1. Cross section about 6 times larger the signal process
2. μ/π ID needed

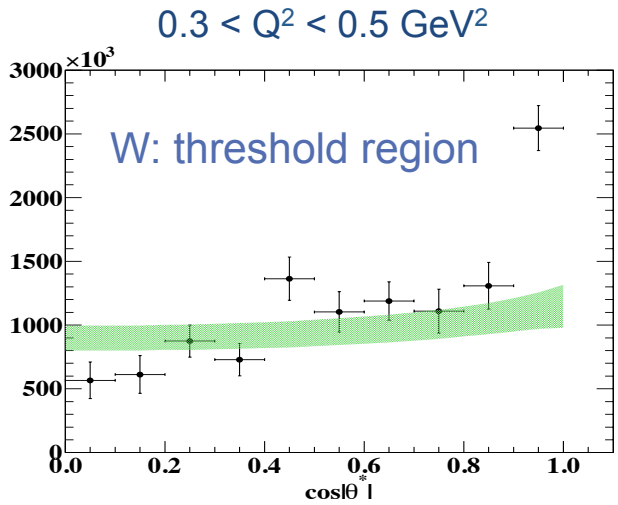
Background from vector mesons:

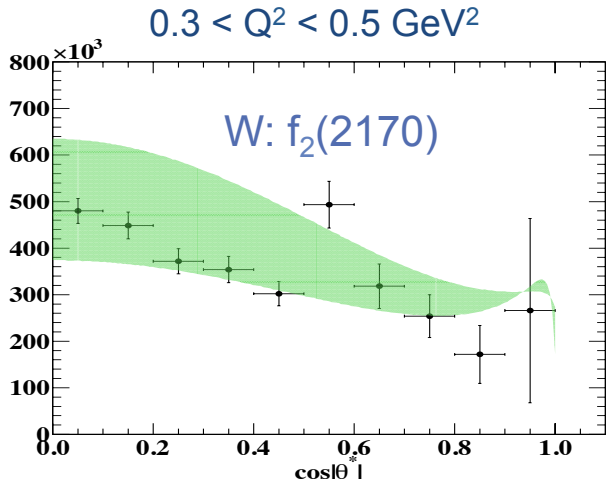


subtract use fit curve

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

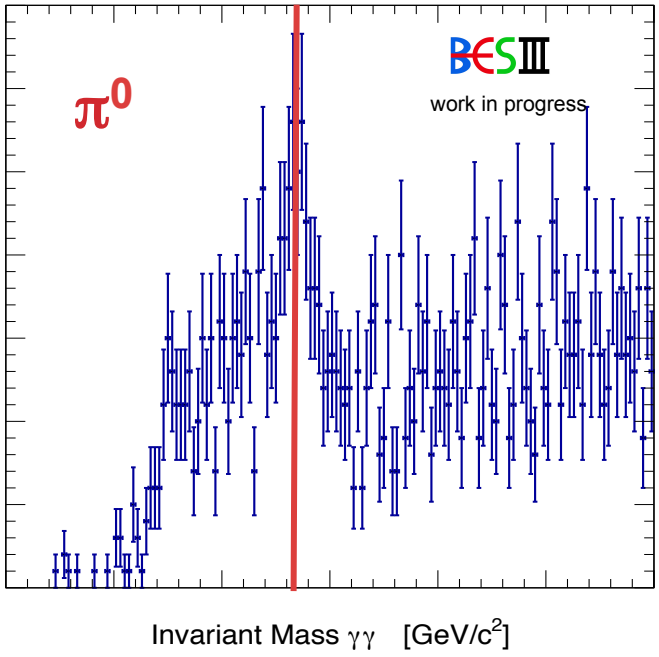
- First single tag measurement of $\pi^+\pi^-$channel
- Q^2: 0.1-3 GeV^2
- W: threshold-1.5 GeV/c^2
  - Obvious $f_2(1270)$ resonance
  - Can measure from threshold
- First complete coverage of the helicity angle of pion system

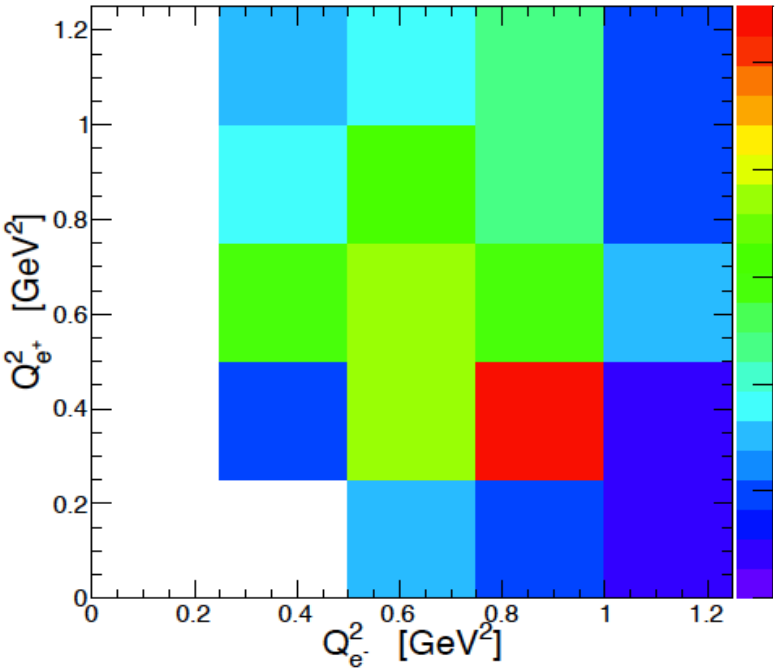




Spacelike transition FFs

Exploratory first double tag measurement: $\gamma^*\gamma^* \rightarrow \pi^0$





- Preliminary study shows feasible in most of the parameter space
- Further background suppression using multivariate analysis tool

Conclusion and Outlook

- Important results (to be expected) from BESIII for SM prediction of $(g-2)_\mu$
  - HVP: precision inclusive and exclusive measurements
    - $\pi^+\pi^-$, $\pi^+\pi^-\pi^0$, and $\pi^+\pi^-\pi^0\pi^0$ cross section
    - Inclusive hadronic cross section
  - HLbL: spacelike form factors measurement in relevant region
    - Form factors at low Q^2 region
    - First measurement of single tag $\gamma\gamma\rightarrow\pi^+\pi^-$
    - Doubly off-shell form factor
- Reduction of factor of 2 of the uncertainty of a_μ^{had} in reach

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THANK YOU FOR YOUR ATTENTION!