Study of Meson Transition Form Factors at BESIII and A2

August 26, 2019

Max Lellmann

Hadron-China 2019, NKU, Tianjin

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

BESIII

A2

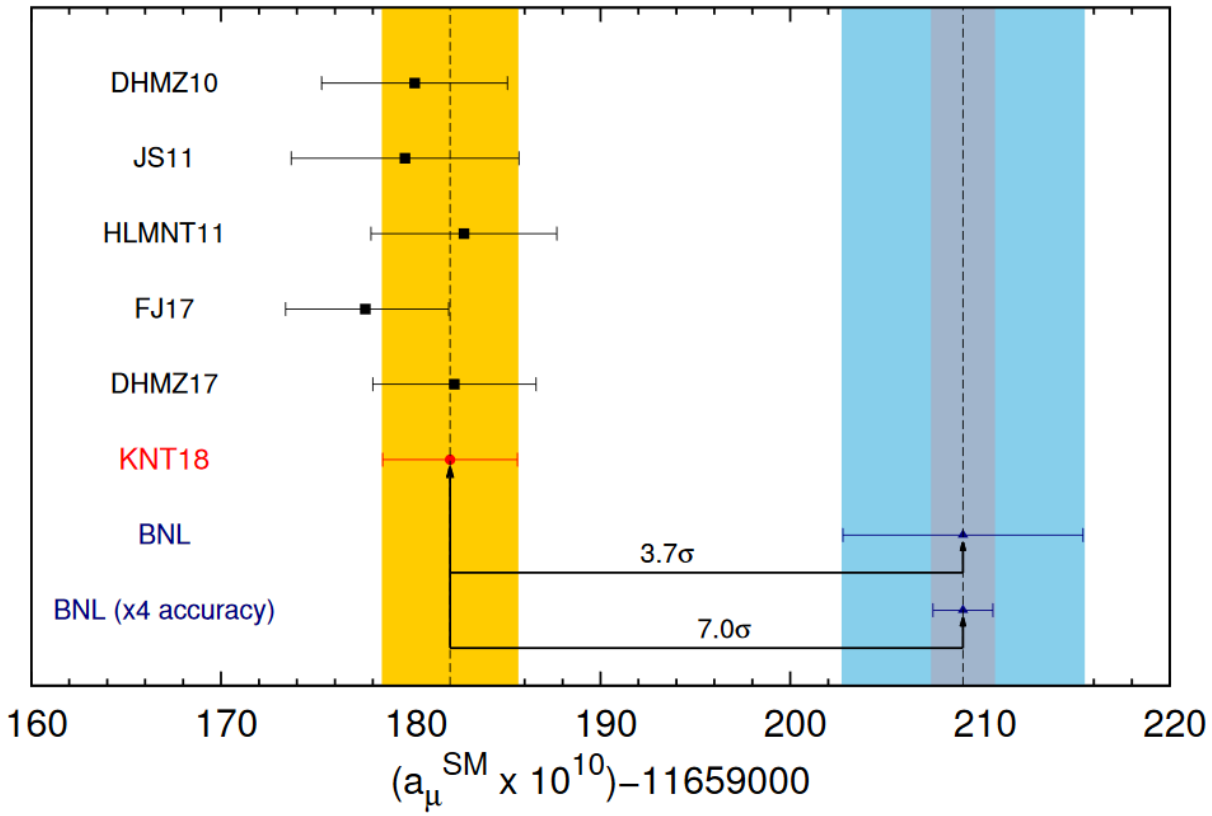
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

Motivation – Muon Anomalous Magnetic Moment

- Anomalous magnetic Moment: $a_\mu = \frac{(g-2)_\mu}{2}$
- 0.5 ppm accuracy in experiment and theory
  - Theory: $(11659182.04 \pm 3.65) \times 10^{-10}$
    (Phys. Rev. D79 (2018) 114025)
  - Exp. (BNL): $(11659208.9 \pm 6.3) \times 10^{-10}$
    (Phys. Rev. D73 (2006) 072003)
- Discrepancy between SM prediction and experiment observed
- New measurement at FermiLab and J-PARC
- **SM prediction needs to be improved**

Keshavarzi, Nomura, Teubner Phys.Rev. D79 (2018) 114025



Motivation – Muon Anomalous Magnetic Moment

Increase precision of

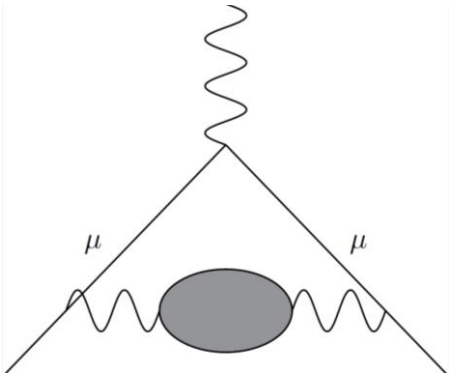
$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{Strong}}$$

Hadronic contributions limit SM prediction!

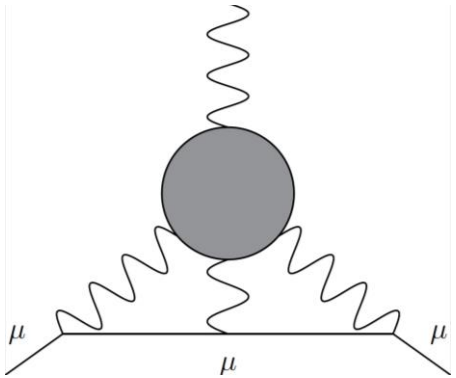
- **Fix parameters with experimental input**
- Hadronic Vacuum Polarization:
  - Related to hadronic R value
- Hadronic Light-by-Light scattering
  - Largest relative uncertainty
  - Depends on knowledge of hadrons coupling to photons

Standard model contribution	a_μ x 10^{11}
QED	116 584 718.971(0.075)
EW	153.6 (1.0)
Strong	
HVP - LO	**6894.6 (32.5)**
HLbL - LO	**103.4 (28.8)**

Hadonic Vacuum Polarization (HVP)



Hadronic Light-by-Light scattering (HLbL)



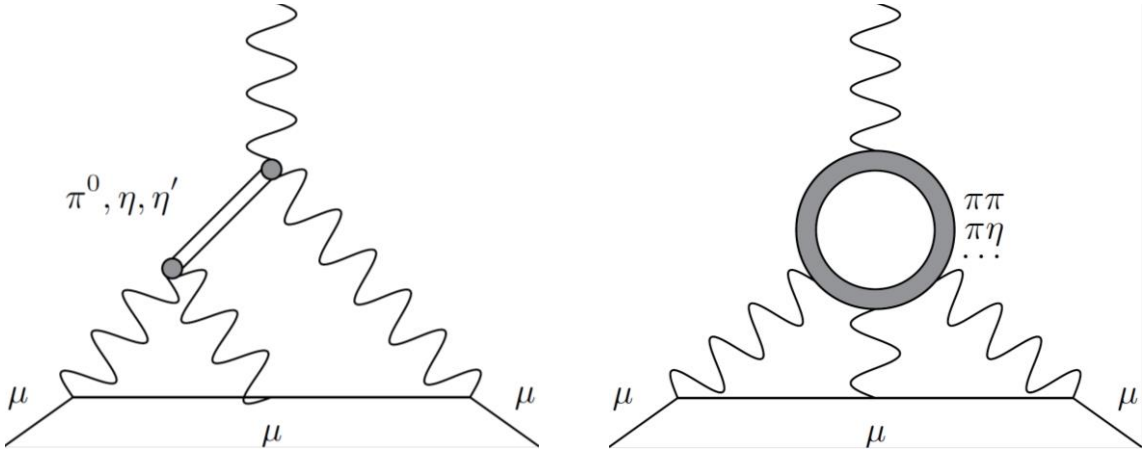
Phys. Rev. D 97, (2018) 036001 Phys.Rev. D88 (2013) 053005 Jegerlehner, arXiv:1711.06089 [hep-ph]

Relevant Processes and Energies for HLbL

Counting Scheme: (de Rafael, Phys.Lett.B322, 239, 1994)

Dominant processes are

- Pseudo scalar meson exchange
- Meson loop contribution



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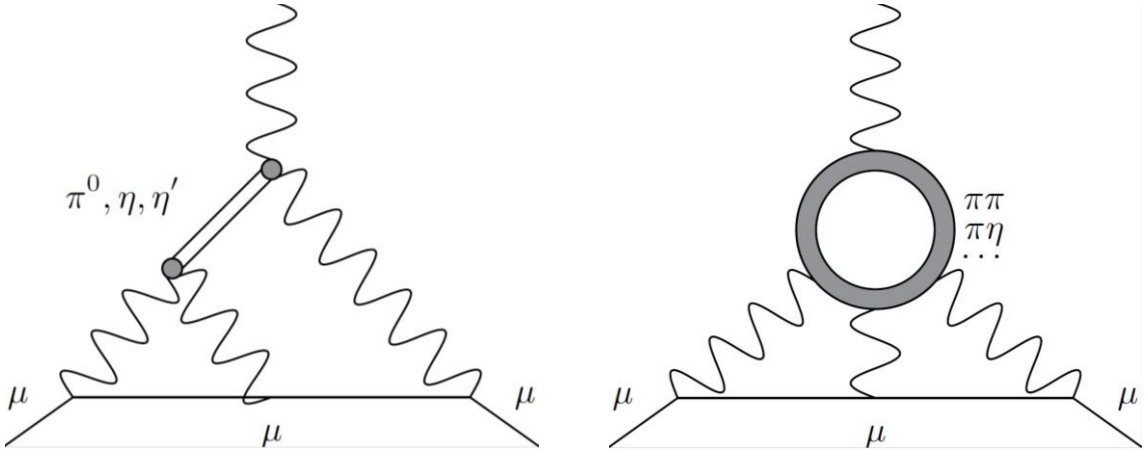
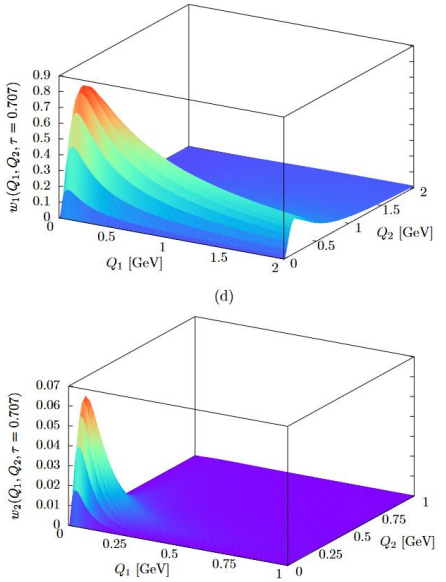


Contribution of neutral pion by 3D integral over Formfactor and weight functions:

$$a_\mu^{\mathrm{HLbL};\pi^0(1)} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^{1} d\tau\, w_1(Q_1, Q_2, \tau) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_1^2, -(Q_1+Q_2)^2) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_2^2, 0)$$

$$a_\mu^{\mathrm{HLbL};\pi^0(2)} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^{1} d\tau\, w_2(Q_1, Q_2, \tau) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_1^2, -Q_2^2) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-(Q_1+Q_2)^2, 0)$$

Relevant Energies:
0.25 GeV – 1.25 GeV



Nyffeler, Phys.Rev.D94,053006, 2016

How to Measure Transition Form Factors

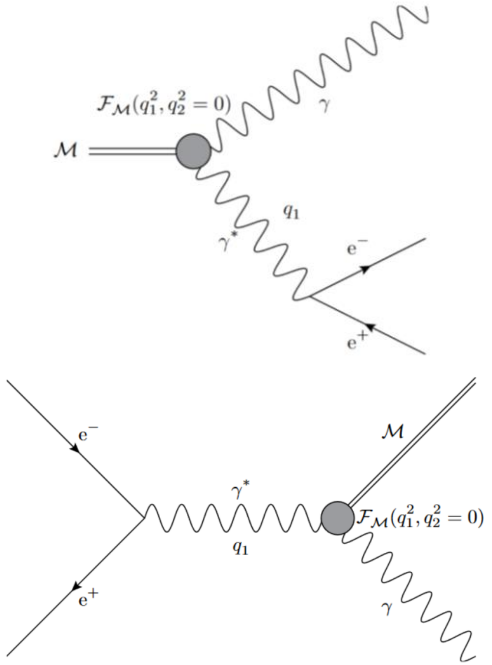
Time-like Transition Form Factors:

- Dalitz decay:

$$q^2 = m(e^+e^-)^2 < M^2$$

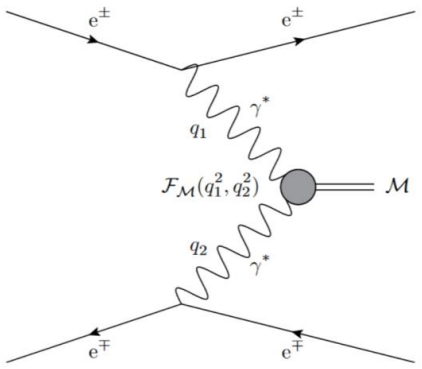
- Radiative production:

$$q^2 = s > M^2$$



Space-like Transition Form Factors:

- Two-Photon scattering:



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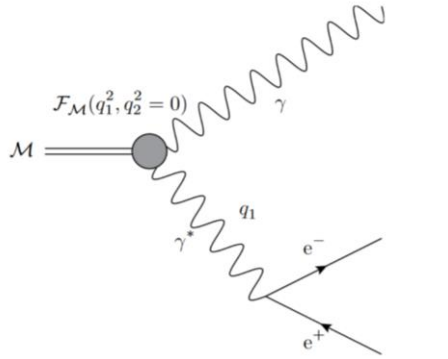

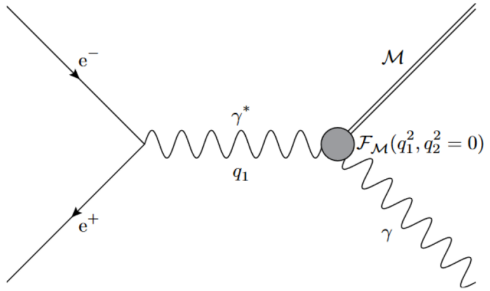

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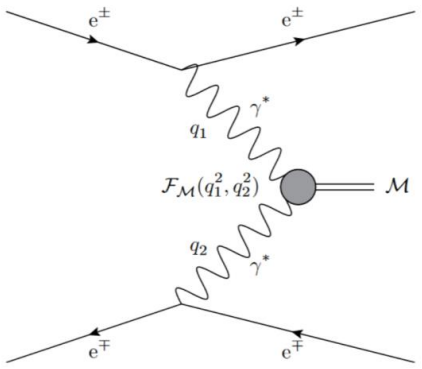

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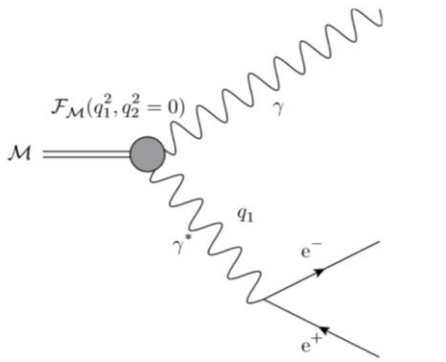

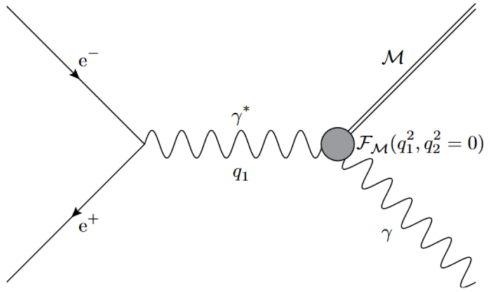

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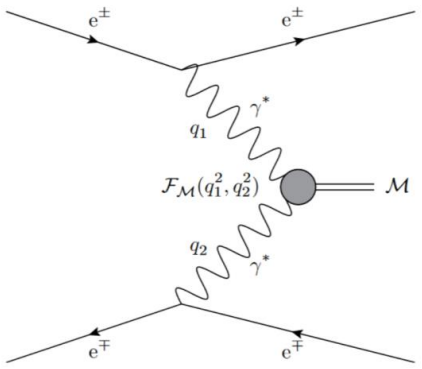
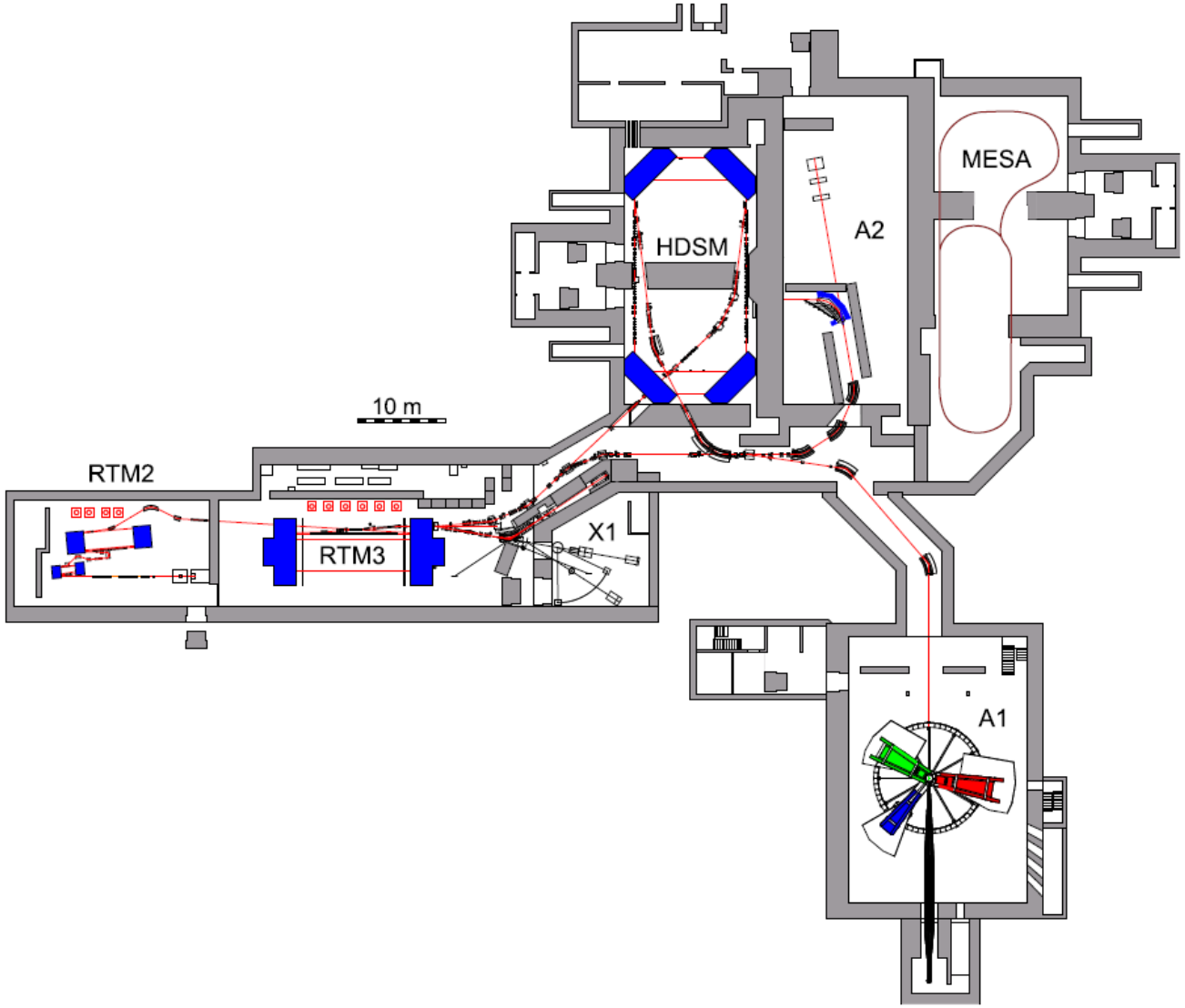


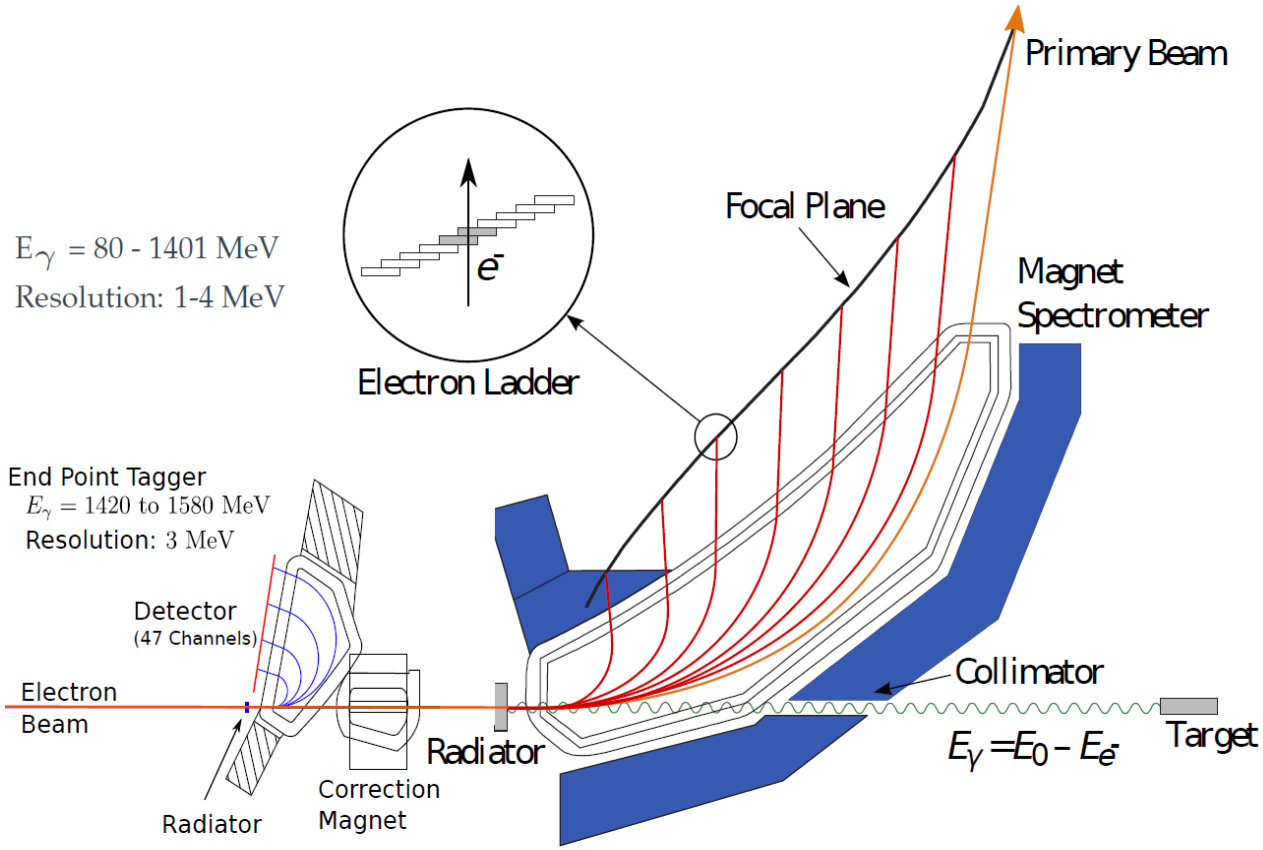
A2 at MAMI

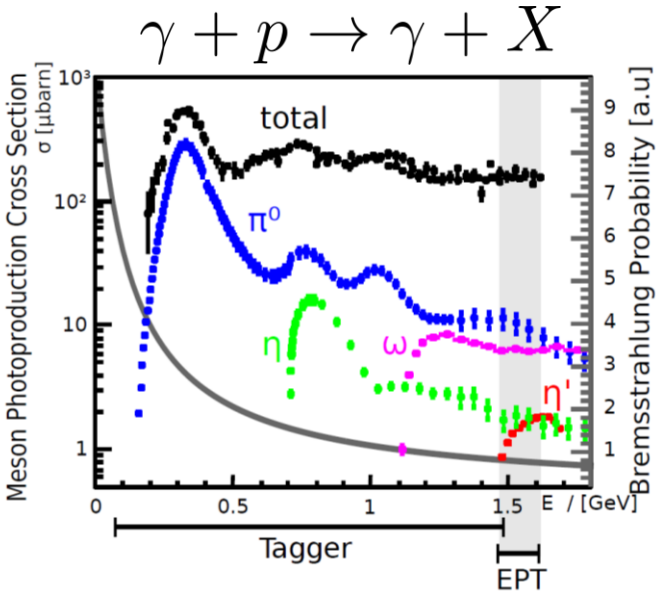


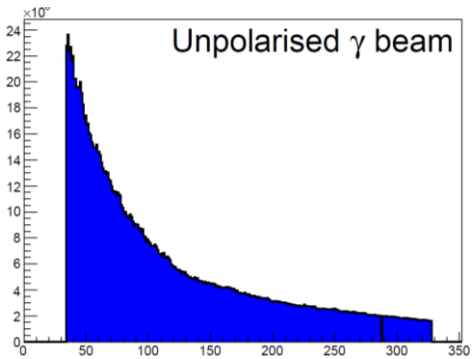
- **Ma**inzer **Mi**krotron
- (Un)polarized electron beam
- Quasi continuous (100% duty factor) and very stable beam
- Linac and 3 RTMs → 885 MeV
- HDSM (MAMI C) → 1604 MeV

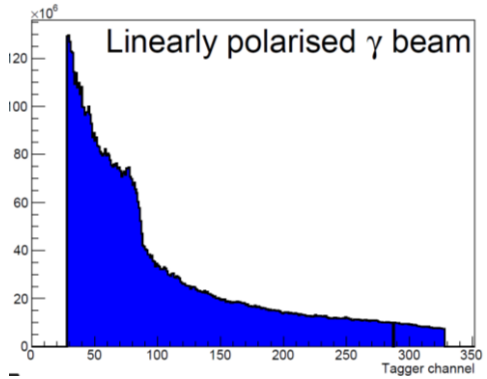
A2 at MAMI

Glasgow Photon Tagger + End Point Tagger: radiator + electron → bremsstrahlung photons



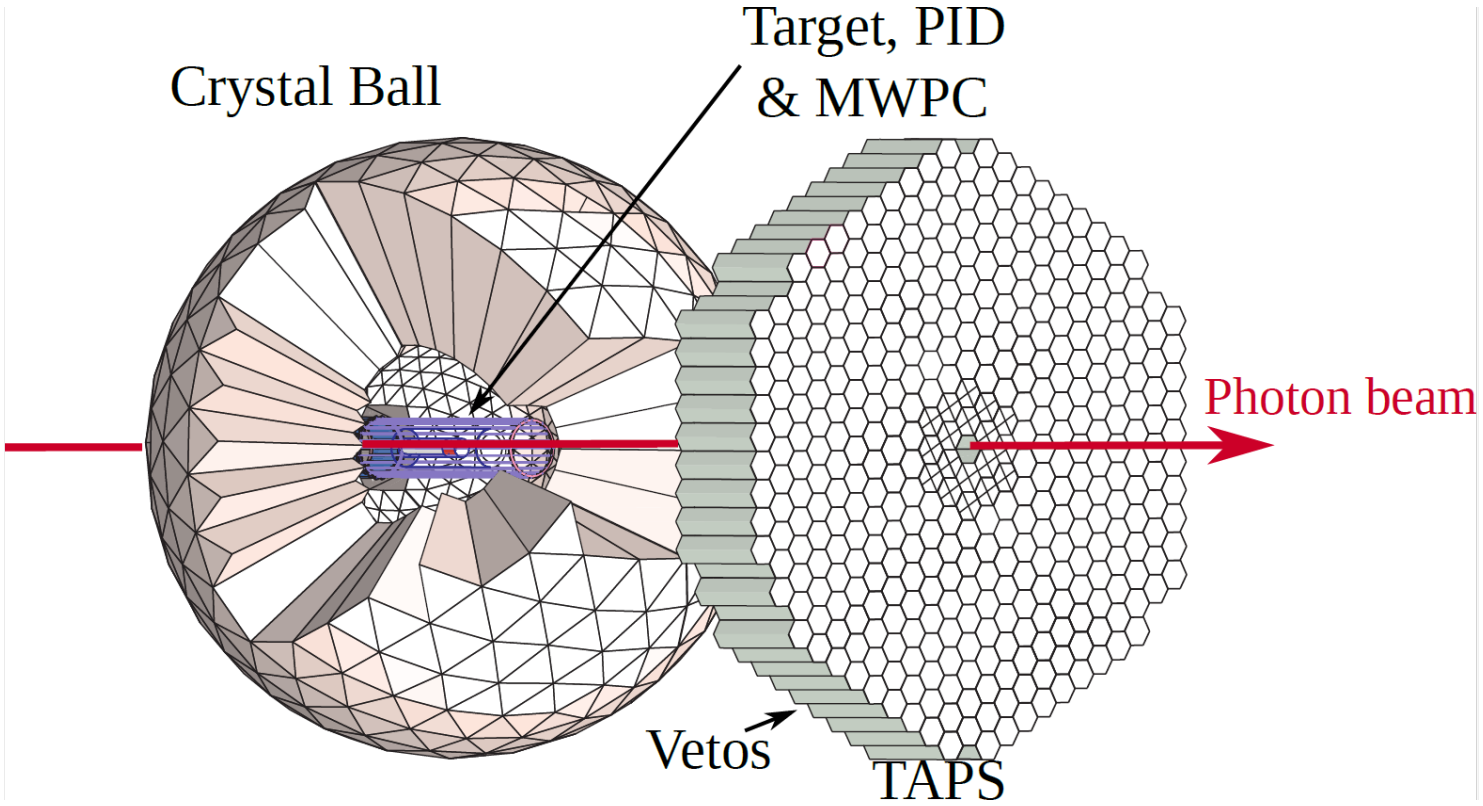






A2 at MAMI

- Crystal Ball –TAPS setup
- Photon Beam: Energies up to 1580 MeV



Targets:
- Cryogen: **LH_2**, LD_2, ^3He, ^4He
- Solid: C, Al, Pb, …
- Polarized Targets Optional

Crystal Ball:
- 672 NaI Crystals
- 24 PID paddles
- 2 Multiwire proportional chambers

Two Arms Photon Spectrometer (TAPS):
- 366 BaF_2 and 72 $PbWO_4$ crystals
- Veto Paddles

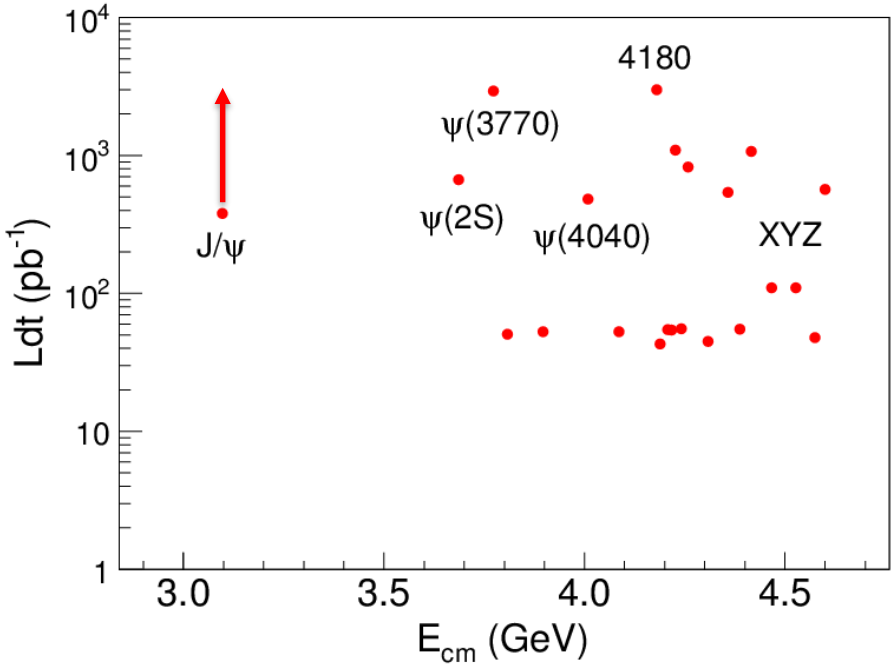
BESIII at BEPCII

- Operated at BEPCII electron-positron collider:

$$2.0\,\mathrm{GeV} \leq \sqrt{s} \leq 4.6\,\mathrm{GeV}$$

- Design luminosity achieved

$$\mathcal{L} = 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1} \quad \text{at} \quad \sqrt{s} = 3.773\,\mathrm{GeV}$$



Data taking for:

- Charmonium spectroscopy and charm physics
- Light hadron spectroscopy
- R - and τ-mass-scan

BESIII at BEPCII

Muon Chambers:
- **8-9 layers of RPCs**
- **1.4-1.7 cm resolution**
- **P > 400 MeV**

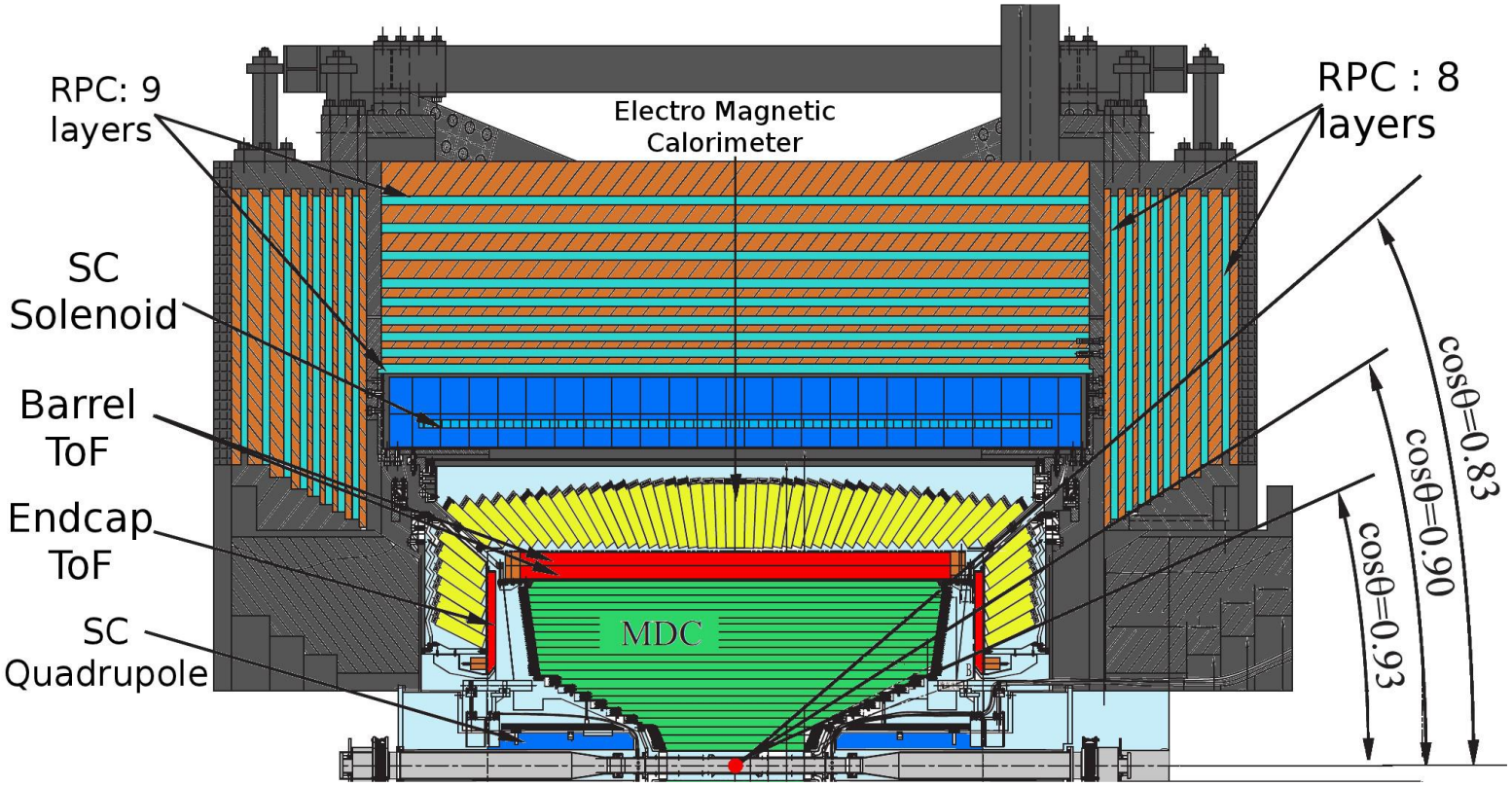
Superconducting Solenoid:
- 1T magnetic field

Electromagnetic Calorimeter:
- 6240 CsI(Tl) crystals
- 2.5% energy resolution
- 0.5 – 0.7 cm spatial resolution

Time-of-Flight System:
- 90 – 110 ps resolution

Drift Chamber:
- 0.5% momentum resolution
- 6% dE/dx resolution

Nucl.Instrum.Meth. A614 (2010) 345-399



Time-like Transition Form Factors

Possible reactions to produce hadrons:

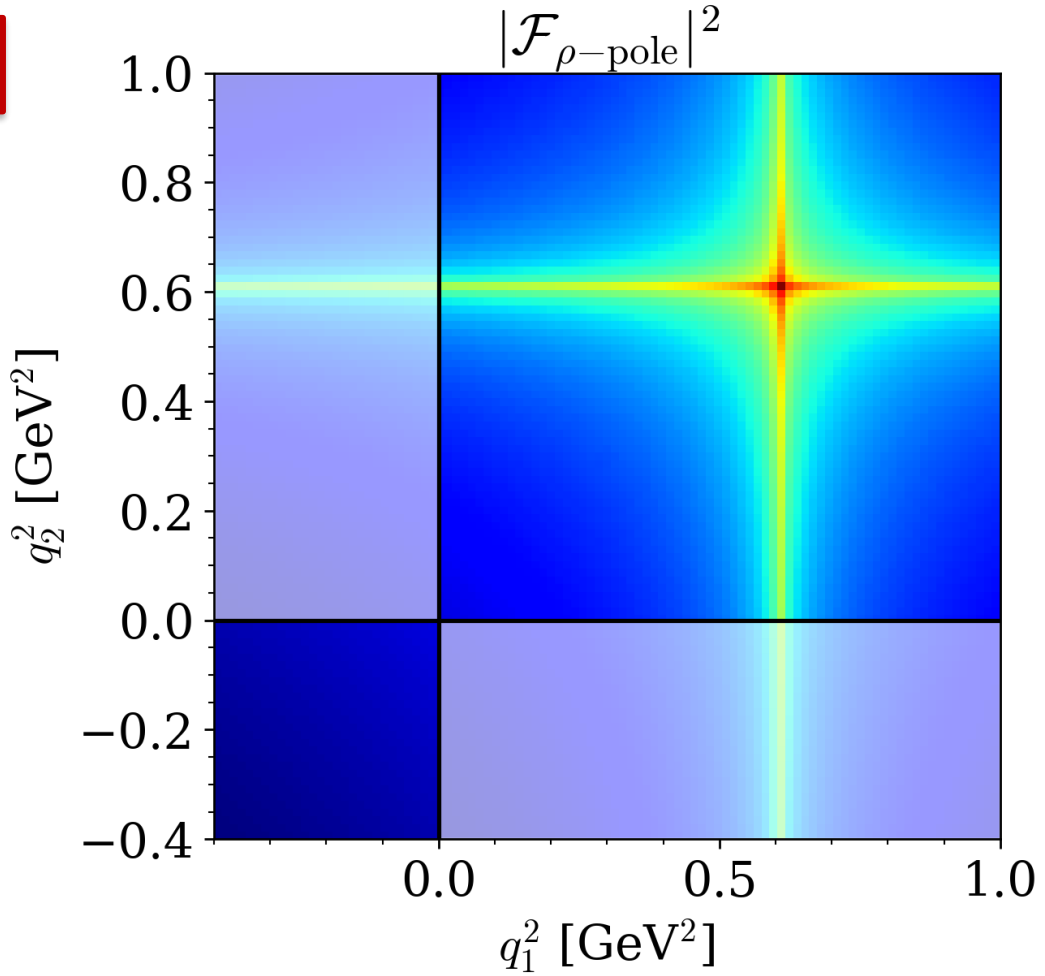
$\gamma + p \to p + X$ $\quad J/\psi \to \gamma + X \quad e^+e^- \to \gamma X$

Accessing the TFF from the decay rate:

$$\frac{d\Gamma(A \to e^+e^- B)}{dq^2 \Gamma(A \to B\gamma)} = \{\mathrm{QED}\}|\mathcal{F}_{AB}|^2$$

Possible Channels (examples for neutral pion):

- $\pi^0 \to e^+e^-\gamma$ **or** $e^+e^- \to \gamma\pi^0$
  - $\sqrt{q_1^2} = m(e^+e^-) \qquad \sqrt{q_2^2} = 0$
- $\omega \to e^+e^-\pi^0$
  - $\sqrt{q_1^2} = m(e^+e^-) \qquad \sqrt{q_2^2} = m(\omega)$



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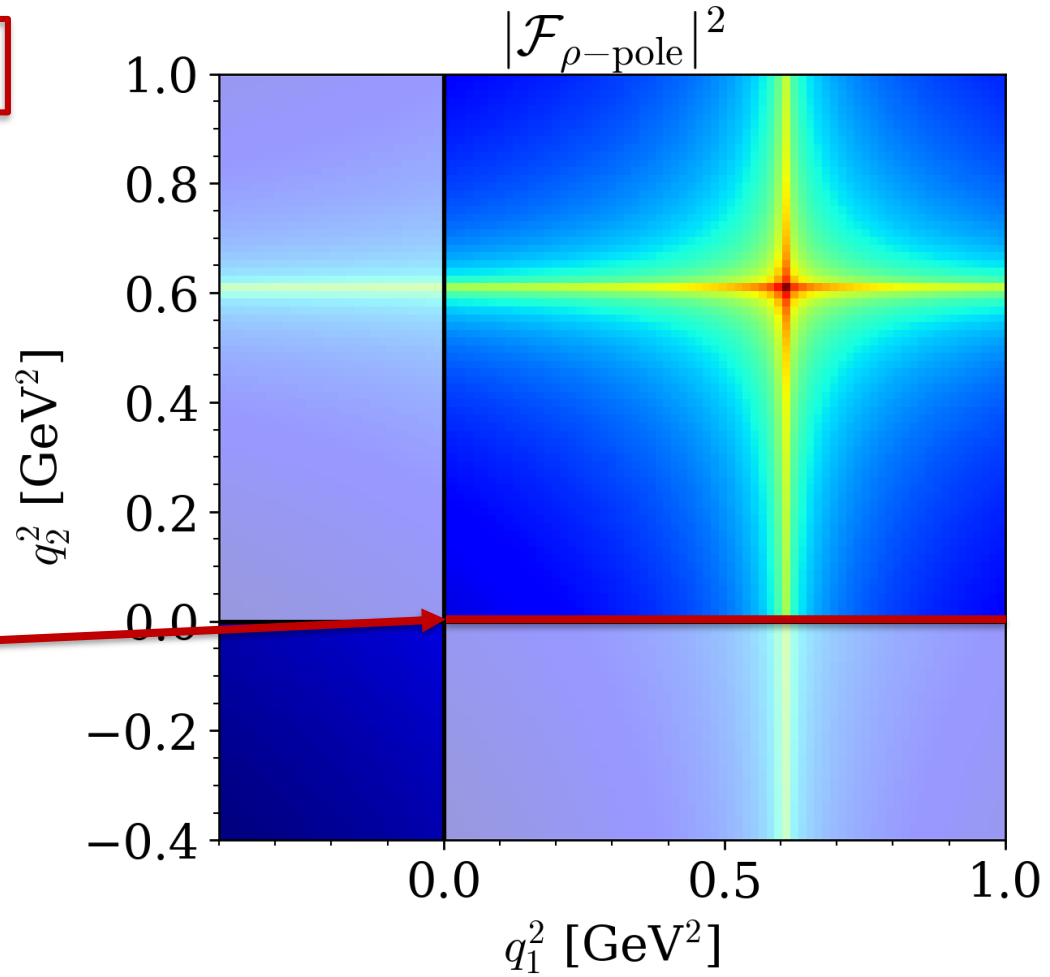

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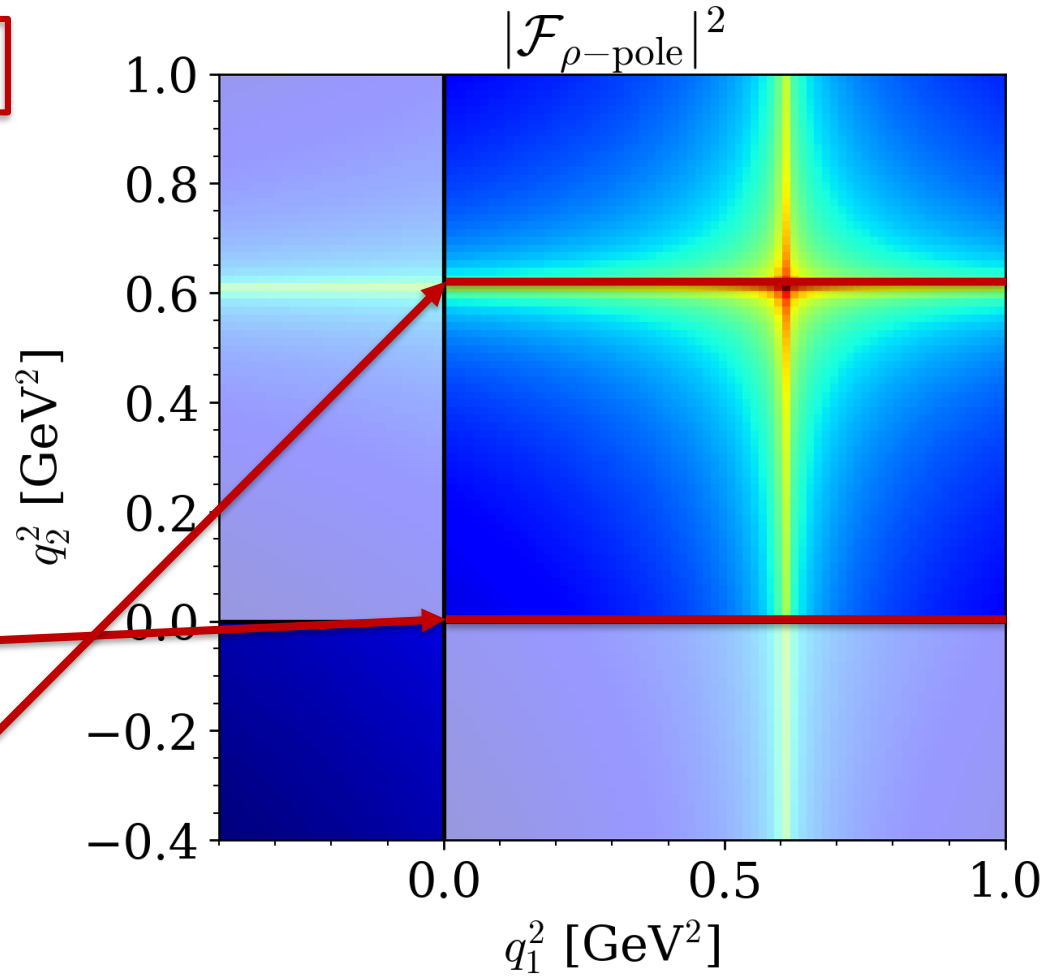


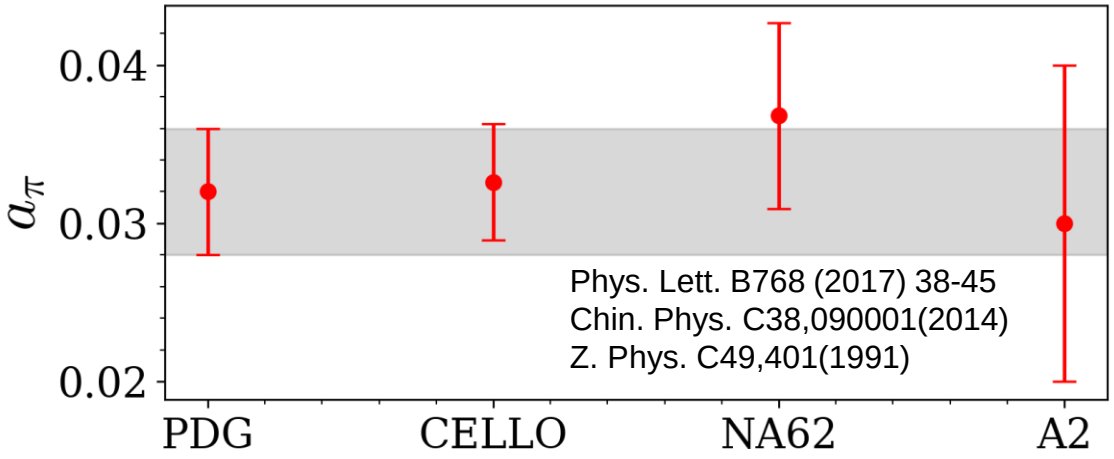
Time-like TFFs at A2: $\pi^0 \to e^+ e^- \gamma$

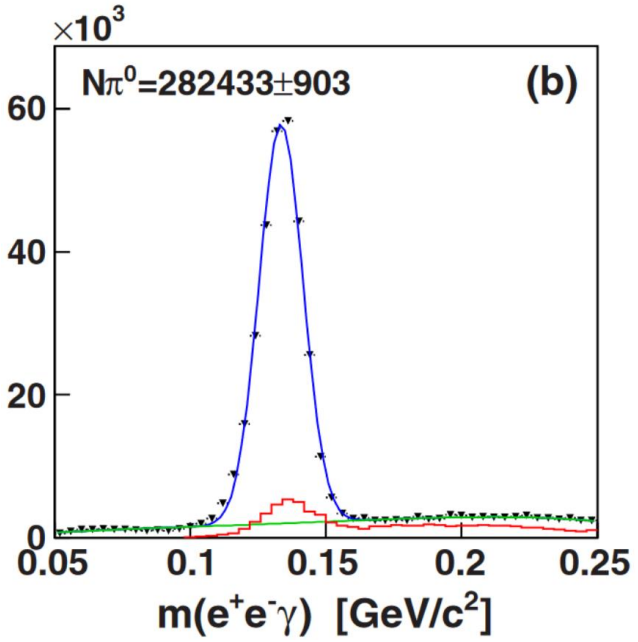
A2 publication: (Phys.Rev. C95 (2017) no.2, 025202)

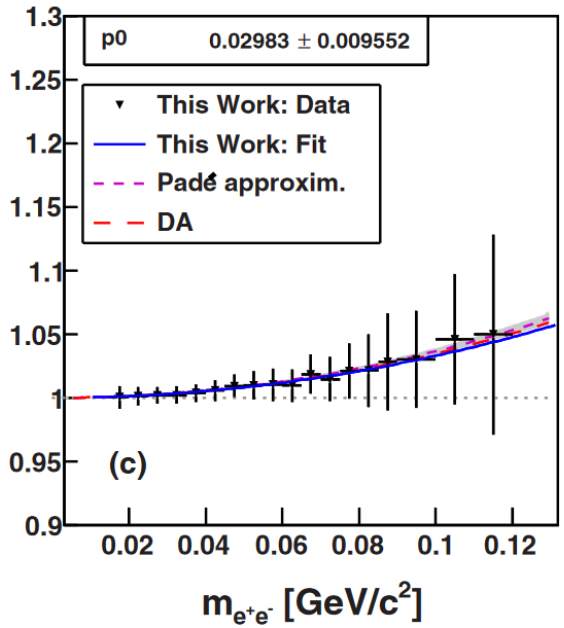
- 4×10^5 signal events
- QED with radiative corrections
- VMD inspired approach for comparison:

$$\mathcal{F}_{\mathrm{VMD}} = -\frac{\Lambda_V^2}{\Lambda_V^2 - q^2 - i\Gamma_V\Lambda_V} \approx 1 + \Lambda^{-2}q^2$$

- $a_\pi = \Lambda^{-2} \cdot m_{\pi^0}^2 = 0.03(1)$





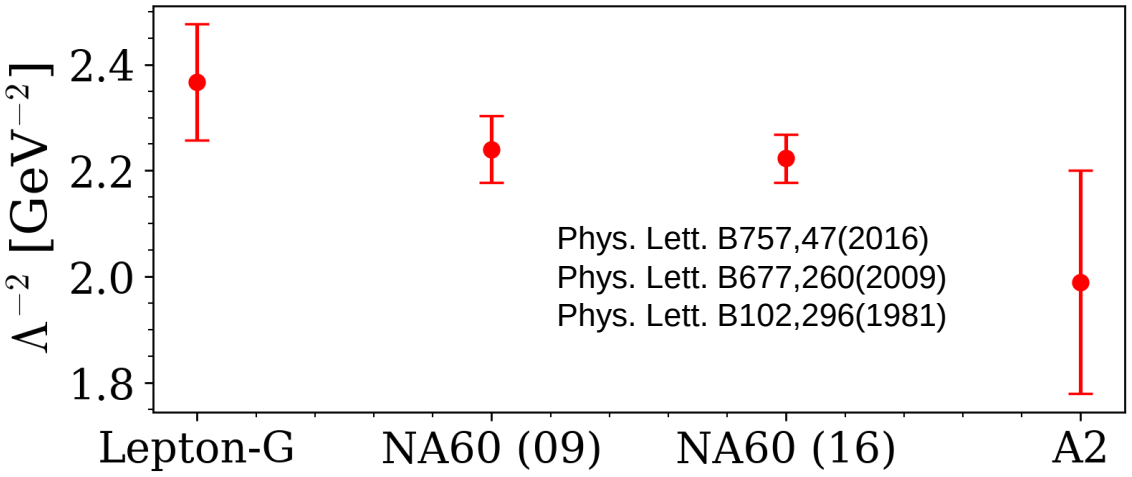


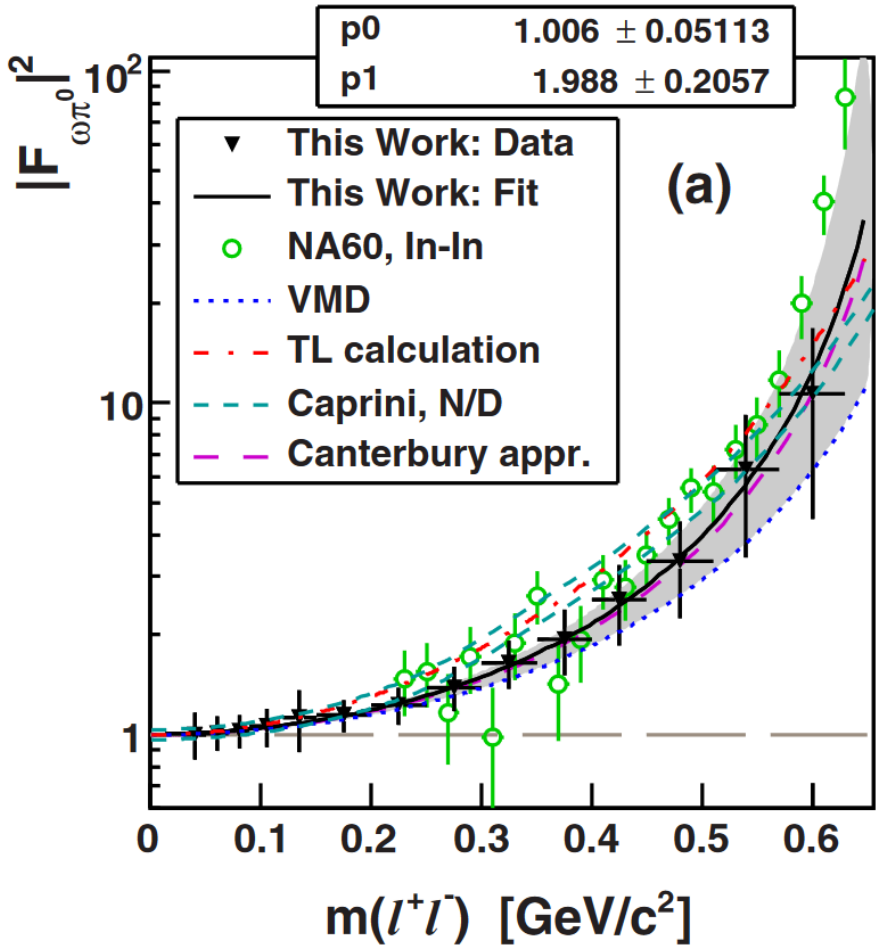
Ongoing A2 project to match PDG precision

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

A2 publication: (Phys. Rev. C95 (2017), 035208)

- Theory and experimental results disagree
- 1100 signal events extracted
- First measurement with electrons
- $\Lambda^{-2} = (1.99 \pm 0.21)\,\mathrm{GeV}^2$

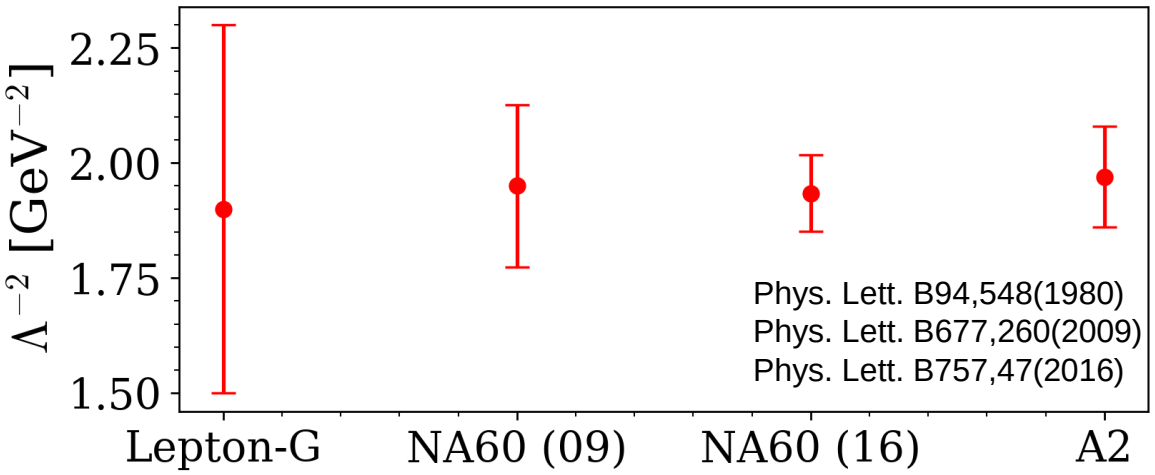


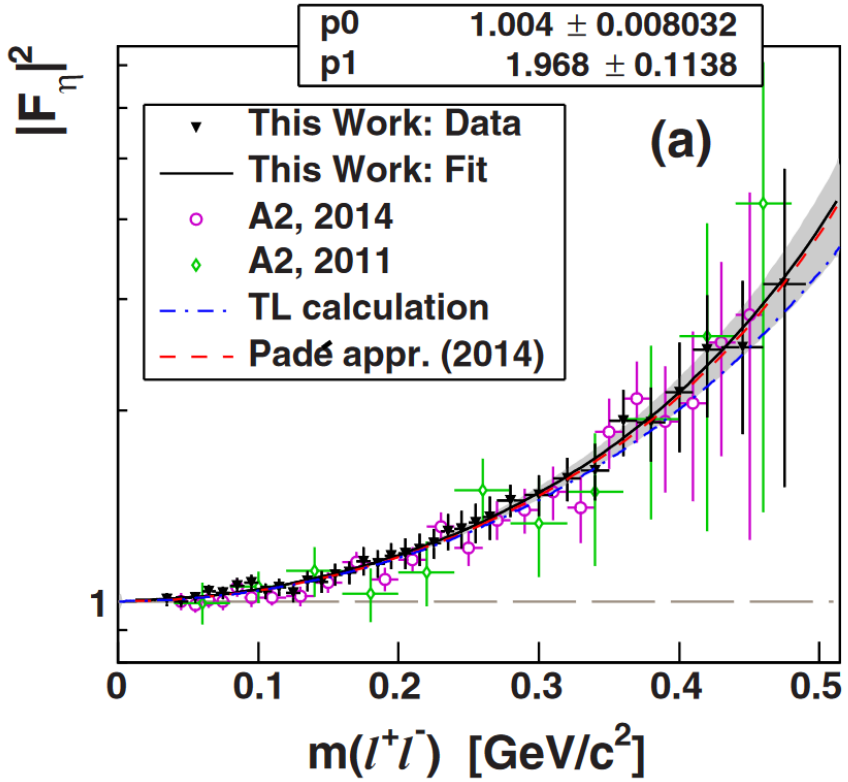


$\eta \to e^+ e^- \gamma$

A2 publication: (Phys. Rev. C95 (2017), 035208)

- 5.4×10^4 signal events
- Systematic uncertainty for individual data points
- $\Lambda^{-2} = (1.97 \pm 0.11)\,\mathrm{GeV}^2$

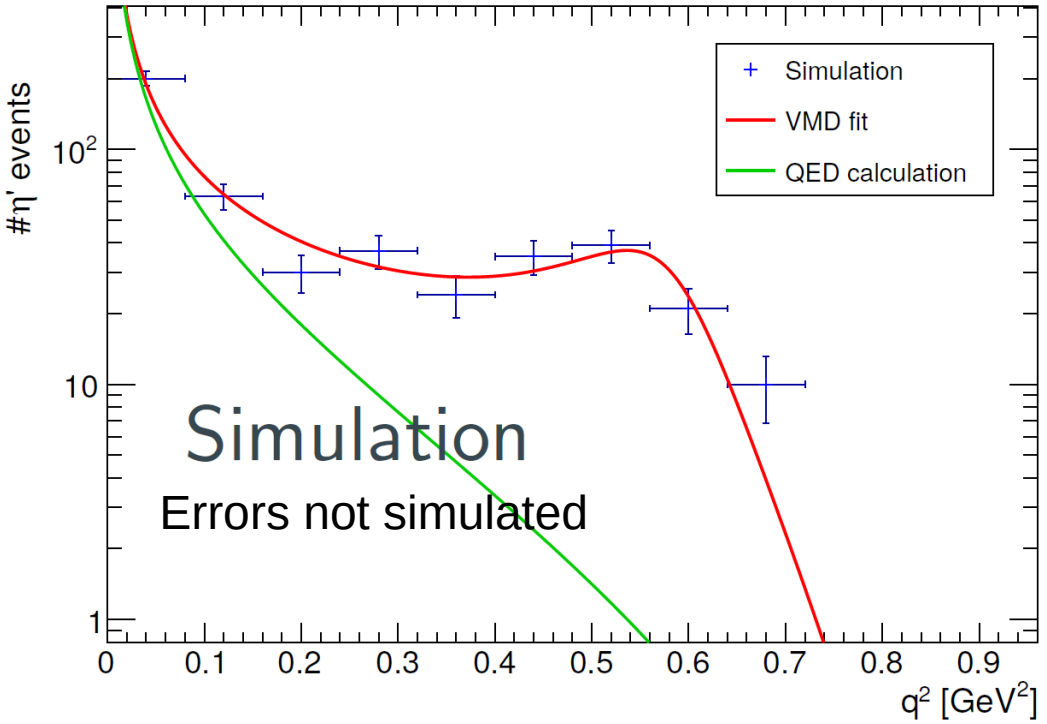




$\eta' \to e^+ e^- \gamma$

Ongoing A2 project:

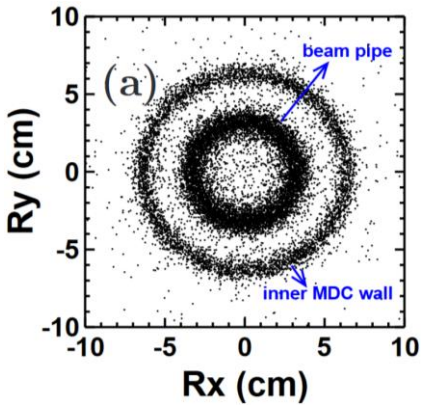
- 10 weeks of beamtime with end-point tagger
- More than 6 million η‘ produced
- Covers momentum transfer up to 0.7 GeV²
  - **includes ρ pole**
- Competitive with BESIII results

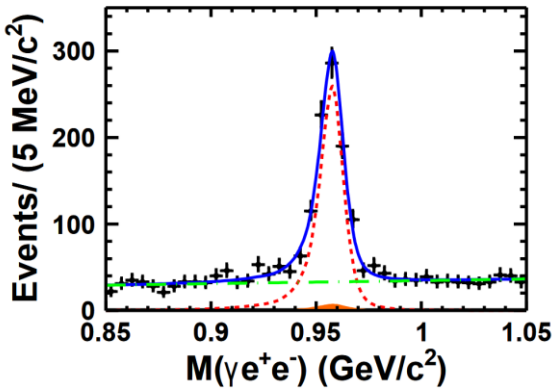


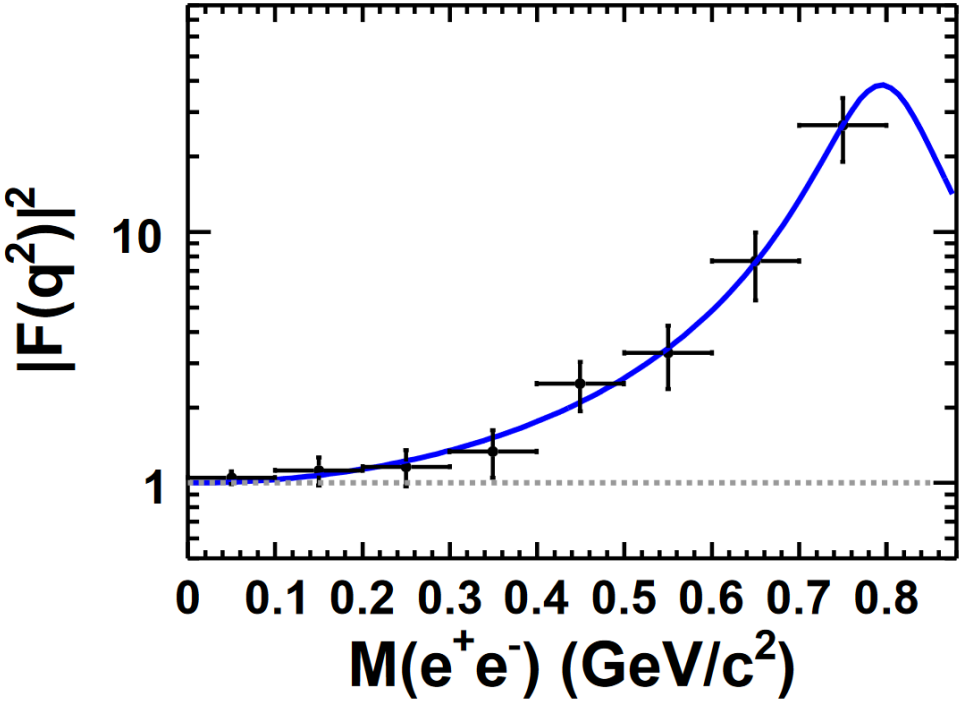
Time-like TFFs at BESIII: $\eta' \to e^+ e^- \gamma$

BESIII publication: Phys.Rev. D92 (2015) no.1, 012001

- $J/\psi \to \gamma\eta' \to \gamma e^+ e^- \gamma$
- 850 events extracted
- $\Lambda^{-2} = (1.60 \pm 0.17_{\text{stat.}} \pm 0.08_{\text{sys.}})\,\text{GeV}^{-2}$
- Based on ~1.3 billion J/ψ
  - new 10 billion J/ψ data set available!
- Photon conversion background suppressed by vertex fit

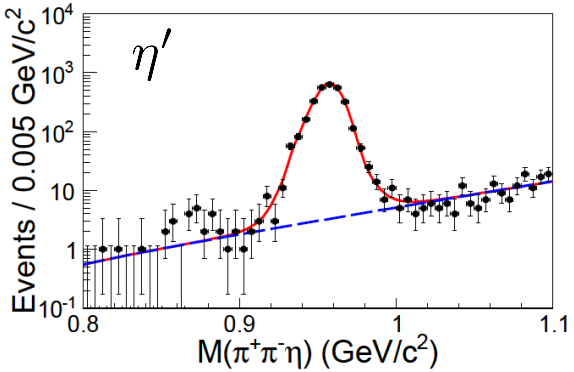


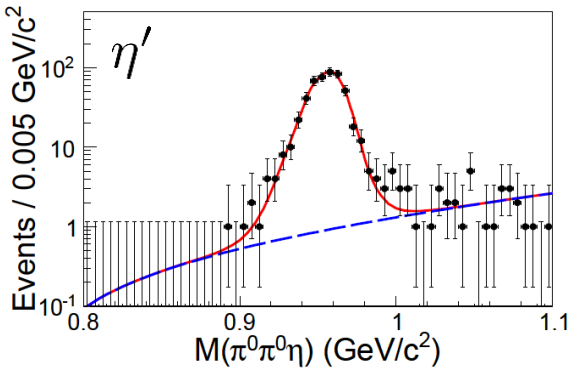


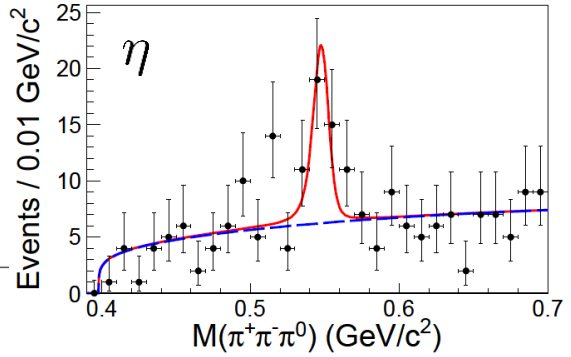


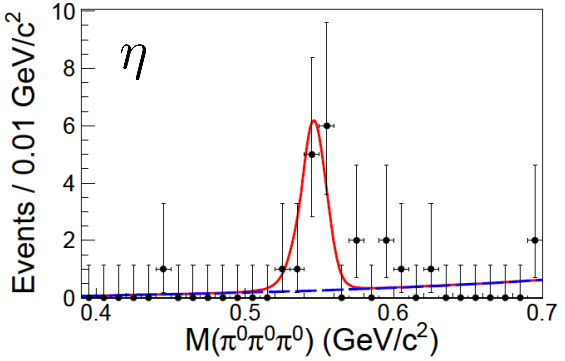
$\psi(2S) \to \gamma(\pi^0, \eta, \eta')$

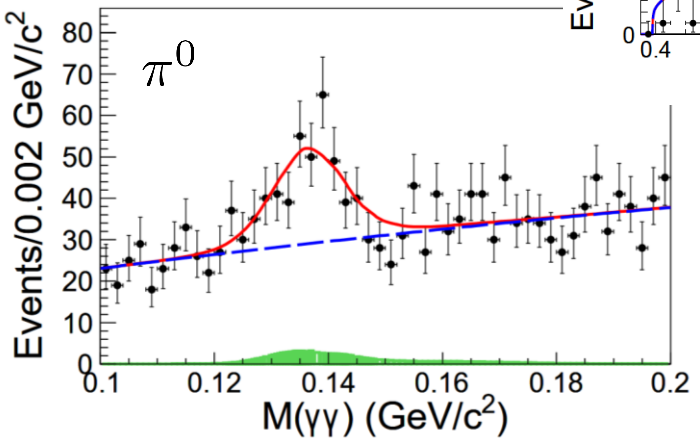
- Study radiative charmonium transitions
- Measurement of branching ratios
- Clear signal of $\psi(2S) \to \gamma(\pi^0, \eta, \eta')$
- Statistical significance:
  - π^0 : $6.7\,\sigma$
  - η : $7.3\,\sigma$
  - η' : $> 10\,\sigma$









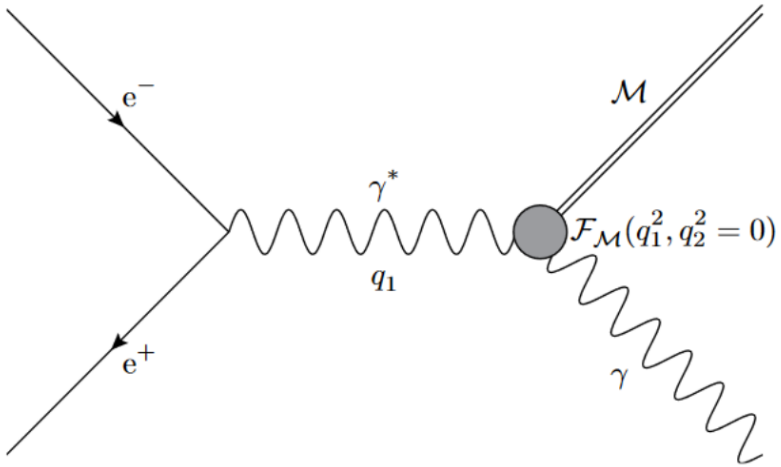


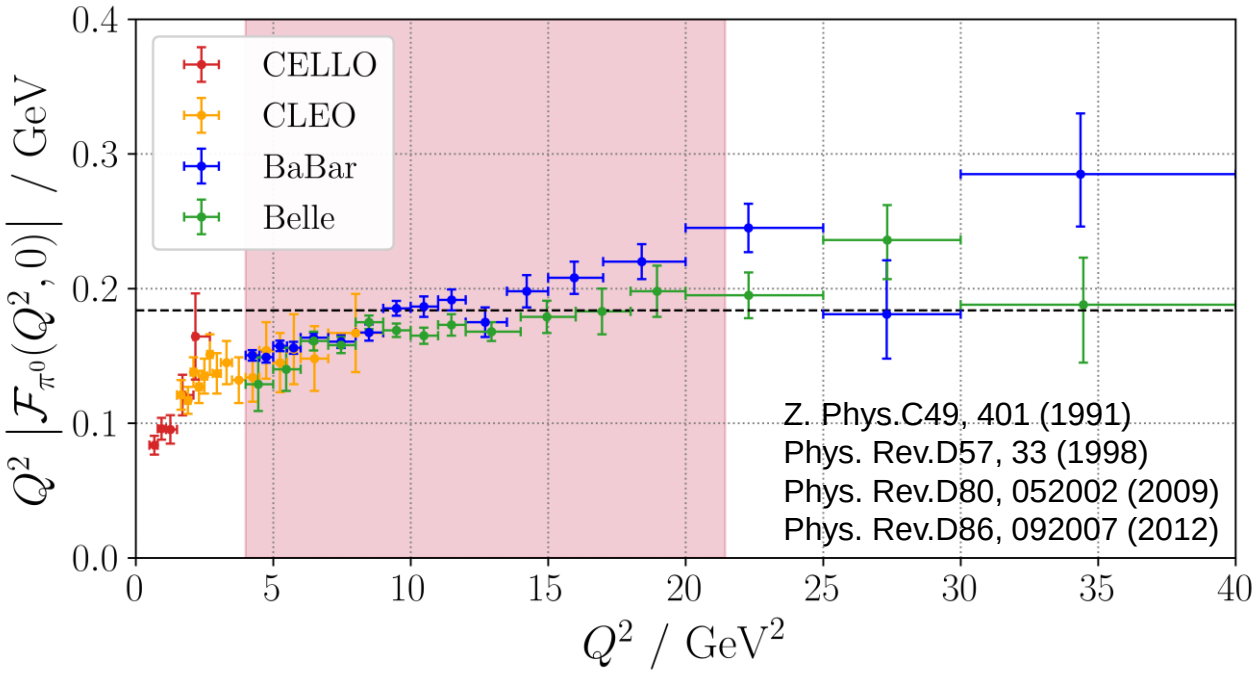
Phys. Rev. D96 (2017) no.5, 052003

$e^+e^- \to \gamma(\pi^0, \eta, \eta')$

BESIII ongoing project:

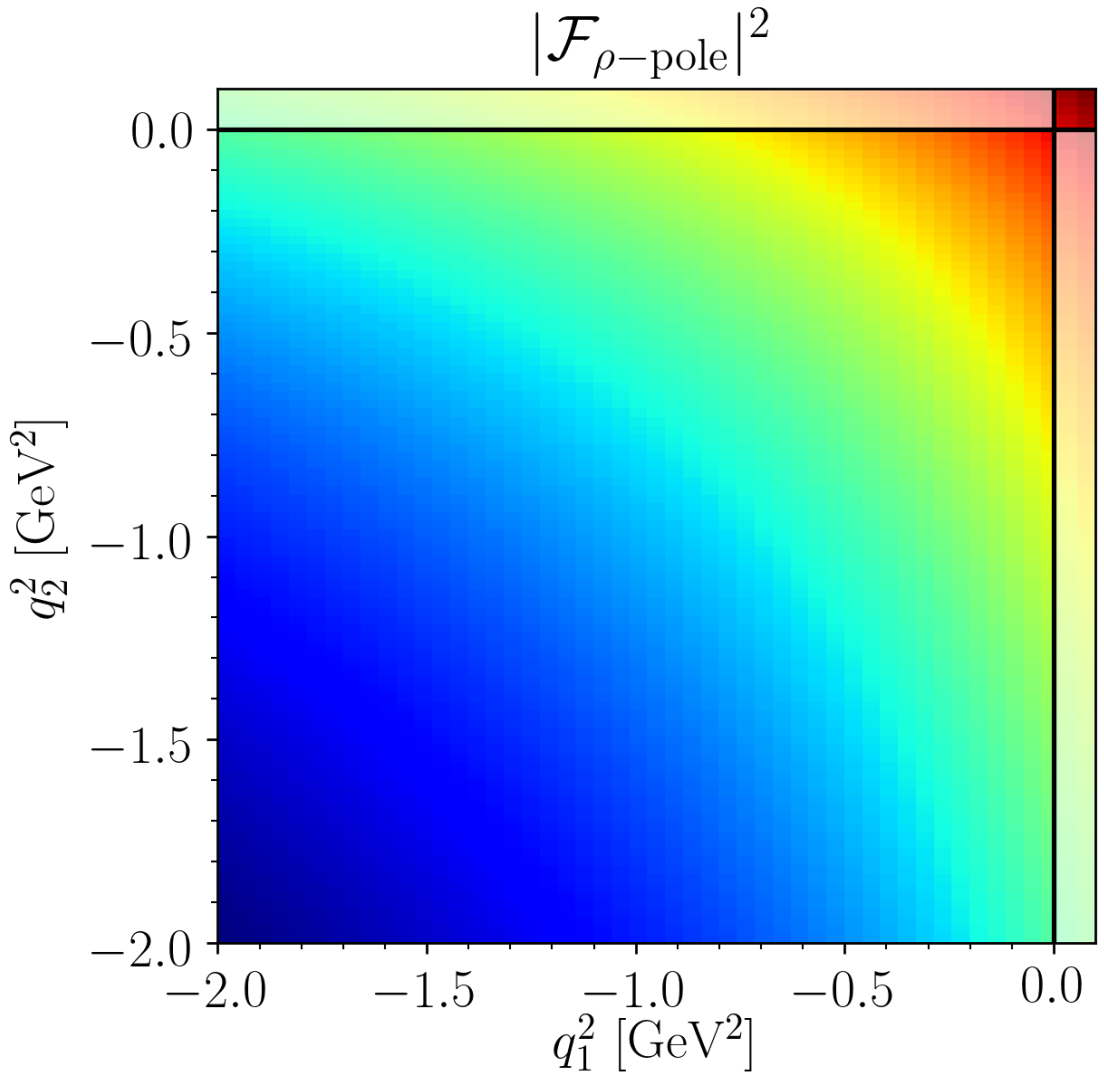
- Measurement at high virtualities
- Time- and Space-like TFF equal at large virtualities
- Check Brodsky-Lepage-Limit (pQCD)
- Shed light on BaBar-Belle puzzle



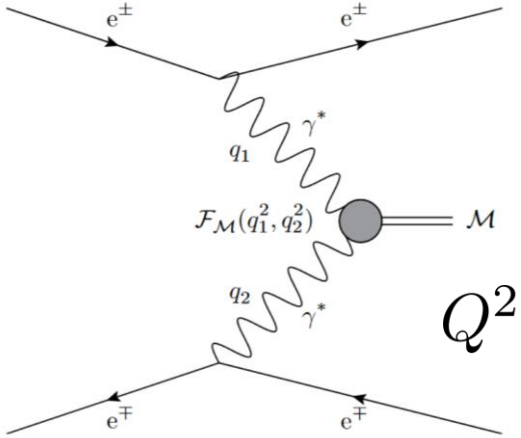


- Photon signature mimicked by photo conversion inside wire chamber
- First measurement of time-like TFF of the neutral pion in this momentum transfer region

Space-like Transition Form Factors



Two-Photon scattering process:



$$Q^2 = -q^2 = -(p - p')^2$$

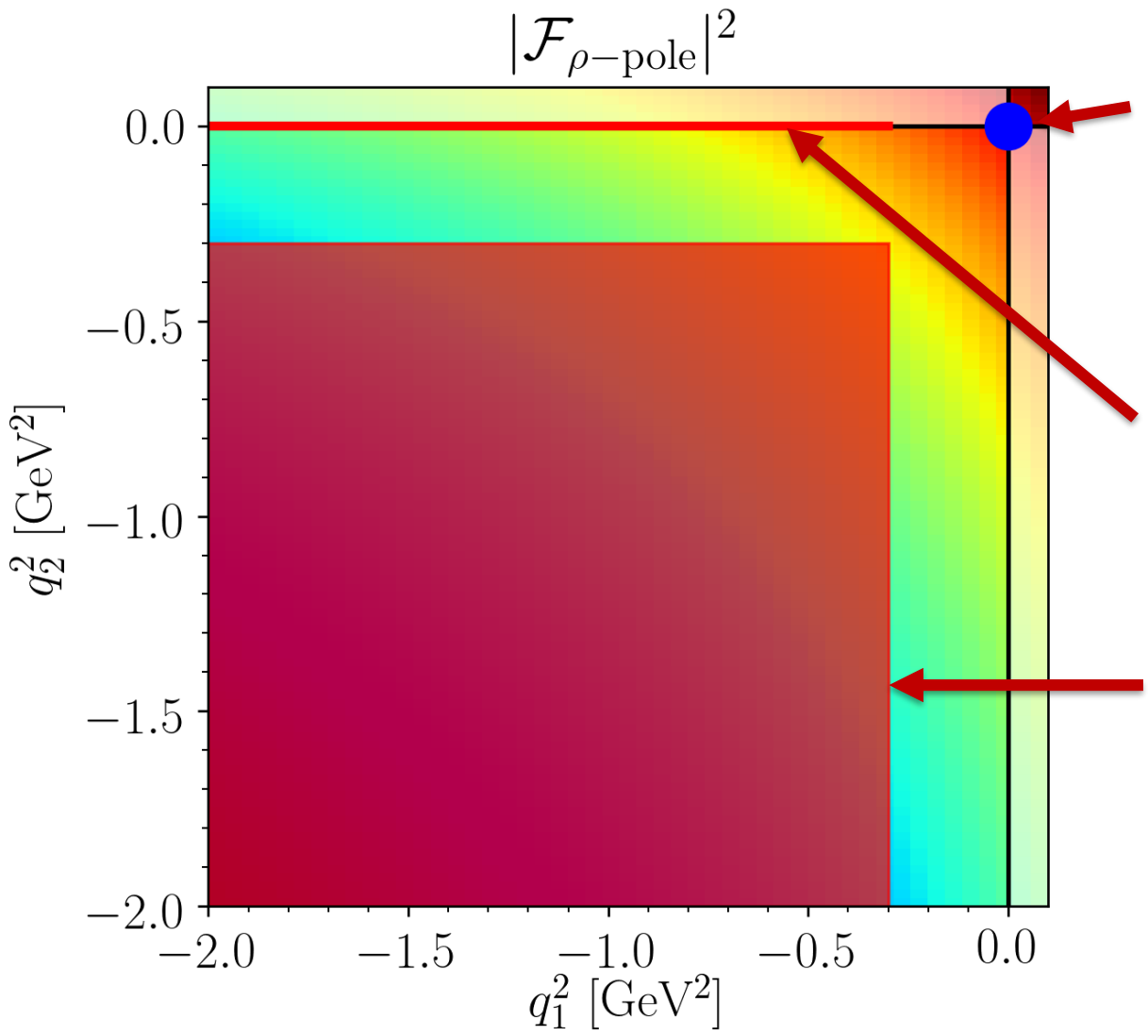
Divide by point like cross section to obtain TFF:

$$\frac{d^2\sigma}{dQ_1^2 dQ_2^2} = \left(\frac{d^2\sigma}{dQ_1^2 dQ_2^2}\right)_{\text{QED}} \cdot |\mathcal{F}(Q_1^2, Q_2^2)|^2$$

Traditional form of presentation (Brodsky-Lepage):

$$(Q_1^2 + Q_2^2) \cdot |\mathcal{F}(Q_1^2, Q_2^2)| \to \text{const.}$$

Space-like Transition Form Factors



Three different kinematics: $Q^2 \approx 4EE' \sin^2 \frac{\theta}{2}$

1. **Un-Tagged Measurement:**
   - Both Leptons scatter at small angles
   - $Q_1^2 = Q_2^2 = 0$
   - Spectroscopy purposes

2. **Single-Tagged Measurement:**
   - One lepton scatters at a small angle
   - Study TFF dependence on one virtuality
   - $Q_1^2 = -(p - p')^2 \qquad Q_2^2 = 0$

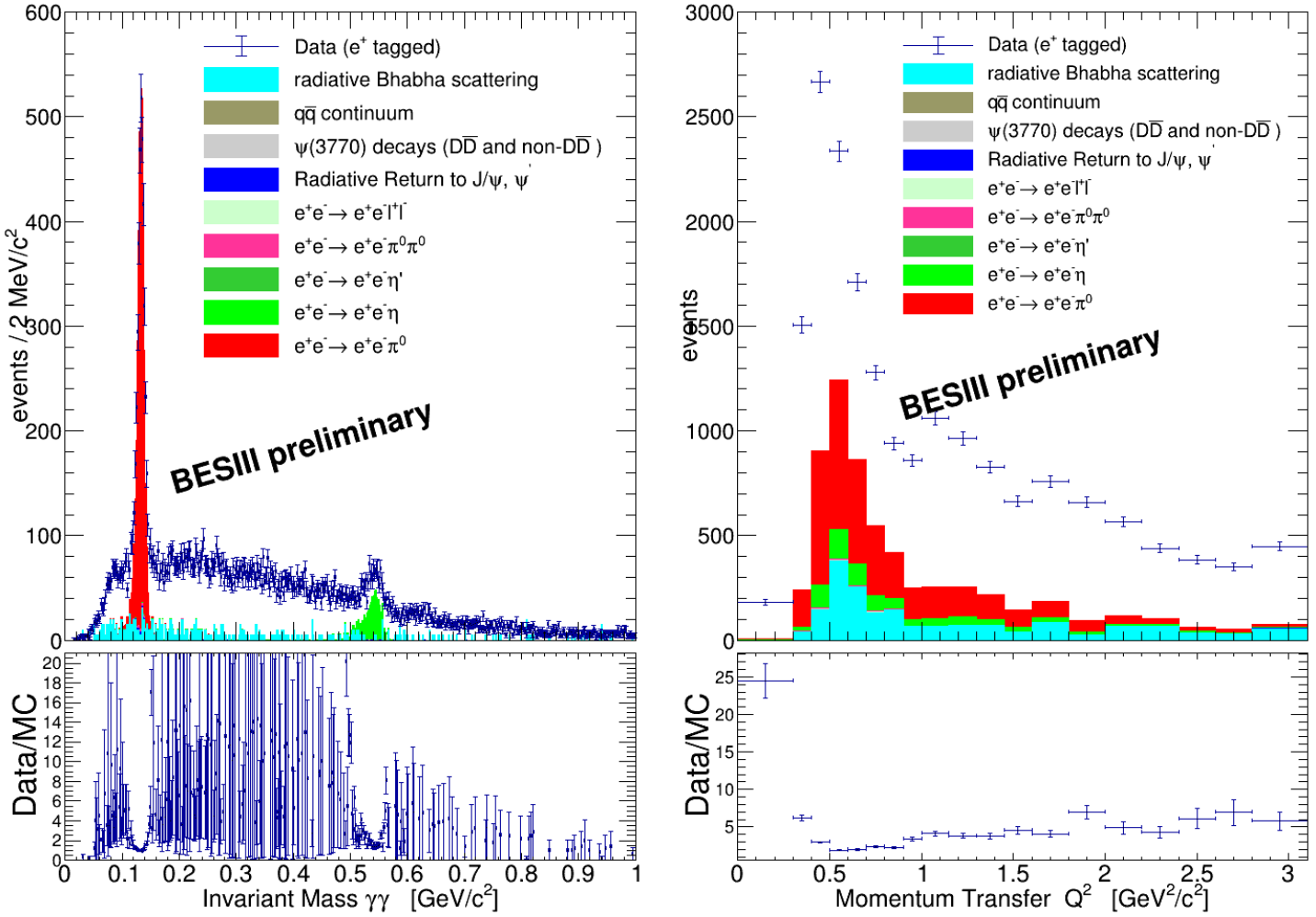
3. **Double-Tagged Measurement**
   - Both leptons scatter into active detector material
   - Study full momentum dependence of TFF
   - Tiny cross section

Space-like π^0 Transition Form Factor

- Single-Tag measurement
  - One charged track, two photons
  - Cut on missing polar angle
  - Constraint on photon helicity angle
  - Reduction of radiative effects:

$$R_\gamma = \frac{\sqrt{s} - E^{\mathrm{CMS}}_{e\pi^0} - p^{\mathrm{CMS}}_{e\pi^0}}{\sqrt{s}} < 0.05$$

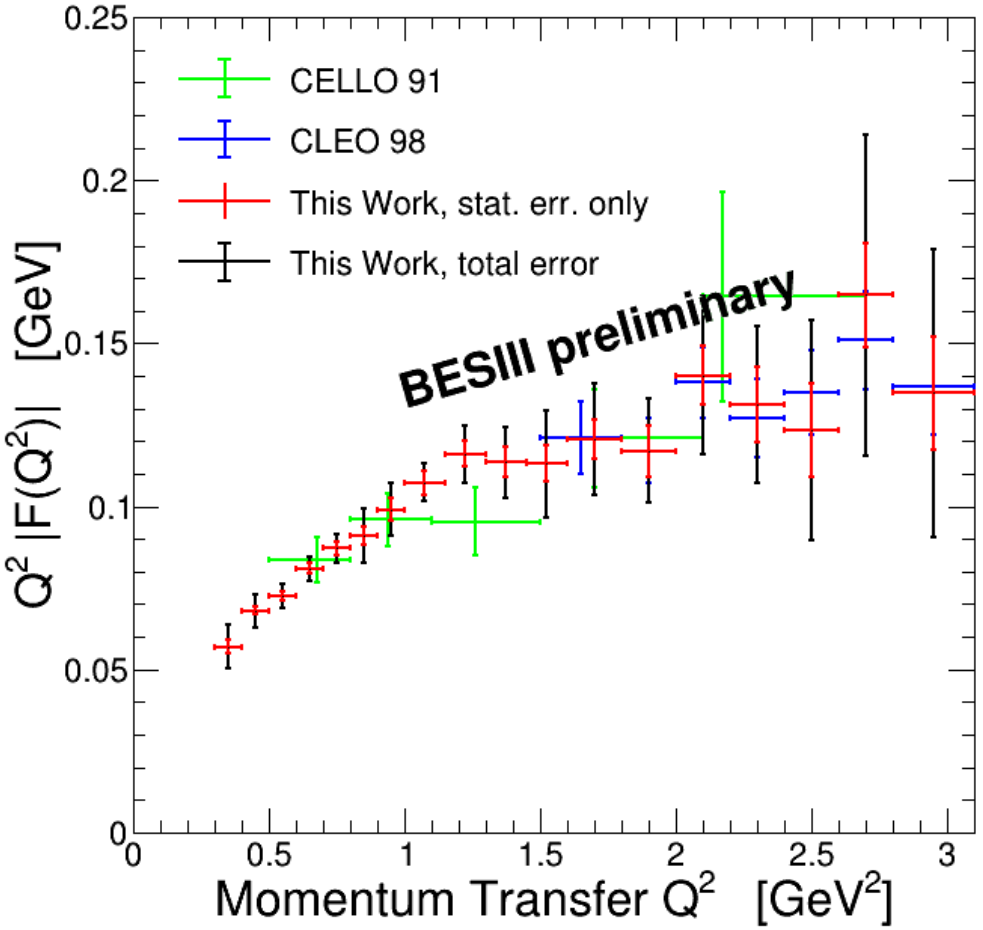
- Clear signals for π and η
- Q^2 from 0.3 GeV² to 3.1 GeV²
- Data driven background subtraction



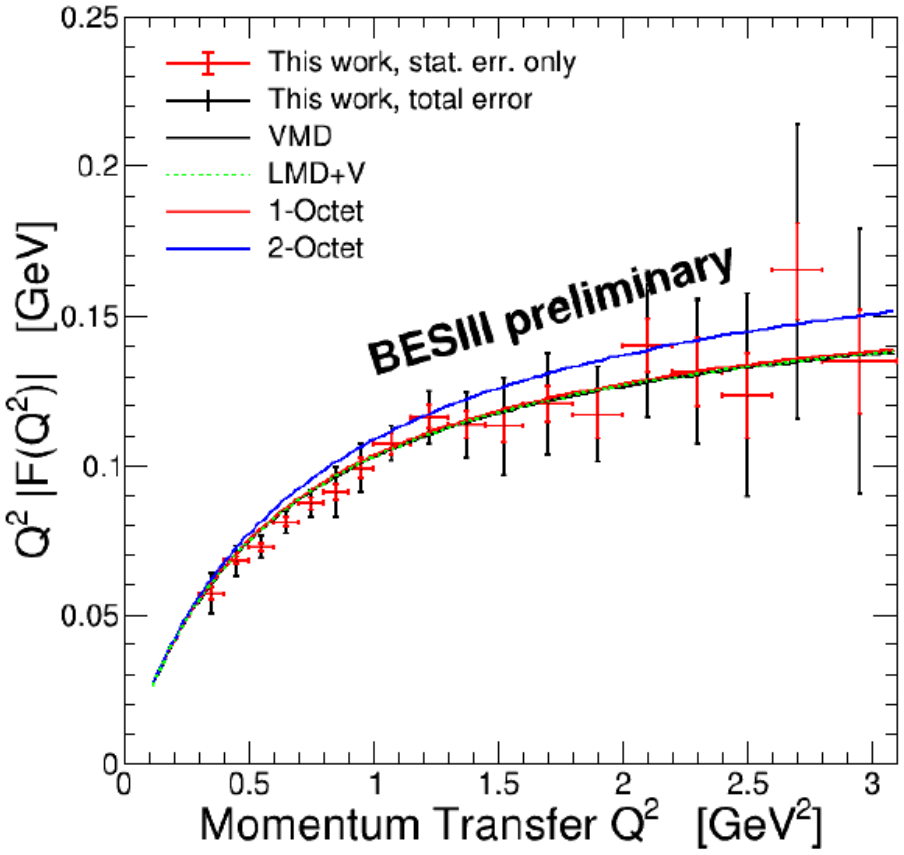
Space-like π^0 Transition Form Factor

Comparison to previous measurements

- Systematic uncertainty 3.9% to 30%
  - Dominated by background subtraction
- Good agreement to previous measurements
- First measurement below 0.5 GeV²
- Unprecedented accuracy below 1.5 GeV²
- Competitive above 1.5 GeV²



Space-like π^0 Transition Form Factor



$$F_{\mathrm{VMD}}(Q^2) = -\frac{N_c}{12\pi^2 F_\pi}\frac{M_V^2}{M_V^2+Q^2}$$

$$F_{\mathrm{LMD+V}}(Q^2) = -\frac{F_\pi}{3}\frac{h_1 Q^4 - h_5 Q^2 + h_7}{(M_{V1}^2+Q^2)(M_{V1}^2+Q^2)M_{V1}^2 M_{V2}^2}$$

Knecht,Nyffeler Phys. Rev. D65 (2002) 0730

$$F_{\mathrm{n-Octet}}(Q^2) = -\frac{N_c}{12\pi^2 F_\pi} + \sum_{i=1}^{n}\frac{4\sqrt{2}h_{Vi}f_{Vi}}{3F_\pi}Q^2(D_{\rho_i}-D_{\omega_i})$$

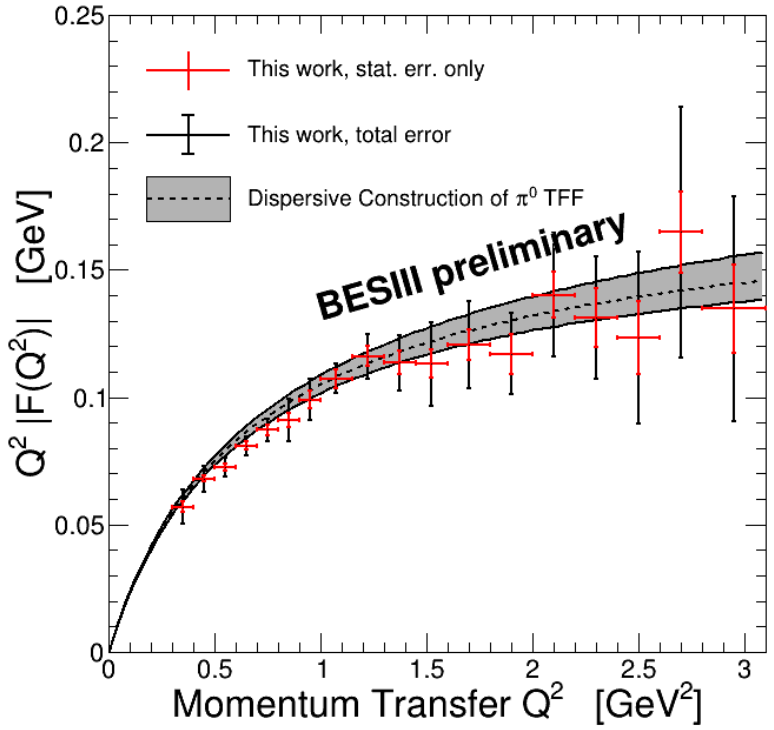
Czyz et al. Phys. Rev. D55 (2012) 094010

- Parameters fixed according to publications
- Agreement with result:

$$\chi^2_{\mathrm{VMD}} = 8.48$$
$$\chi^2_{\mathrm{LMD+V}} = 8.62$$
$$\chi^2_{\mathrm{1-Octet}} = 9.54$$
$$\chi^2_{\mathrm{2-Octet}} = 24.14$$

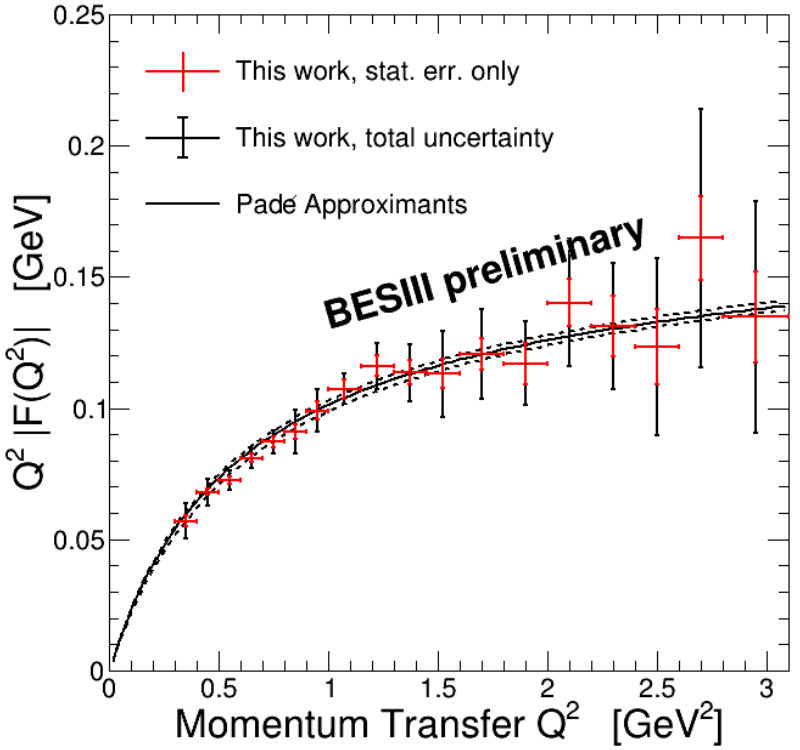
Space-like π^0 Transition Form Factor

Comparison to data driven theory



- Construct spacelike TFF using time-like results in dispersive calculations

Hoferichter et al., Phys. Rev. Lett. 121, 112002 (2018)



- Fit <u>previous</u> measurements with Padé approximants
  - Model independent
  - Estimate of systematic uncertainties

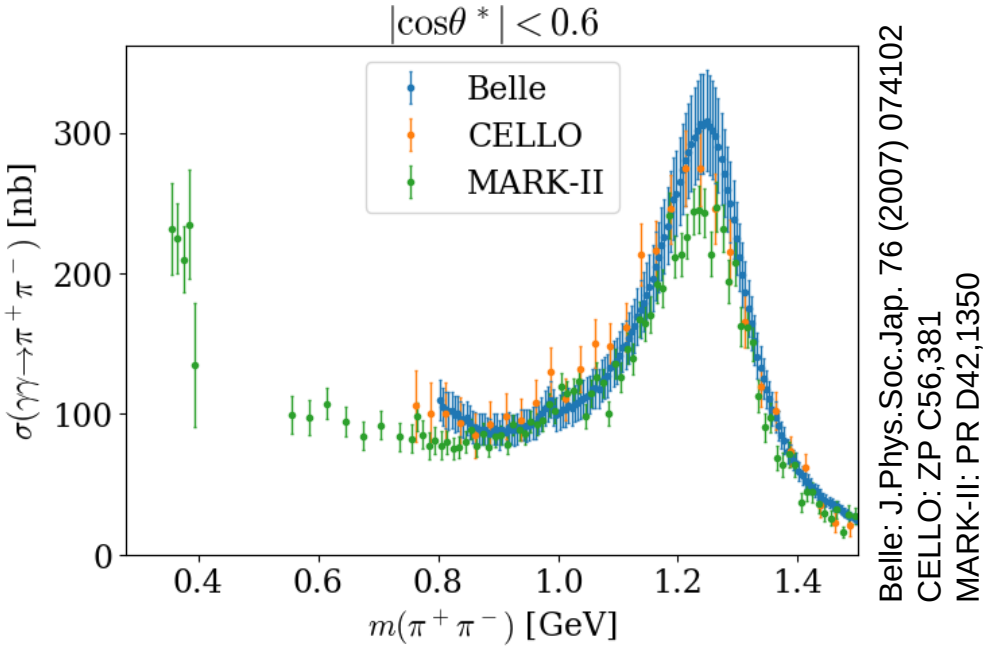
Masjuan et al., Phys. Rev. D86, 094021

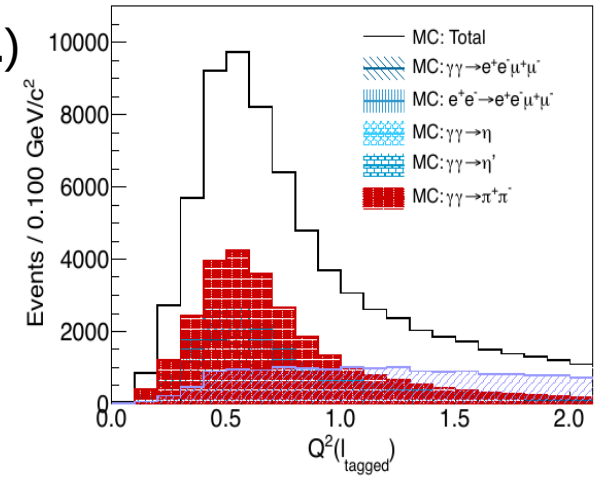
Outlook

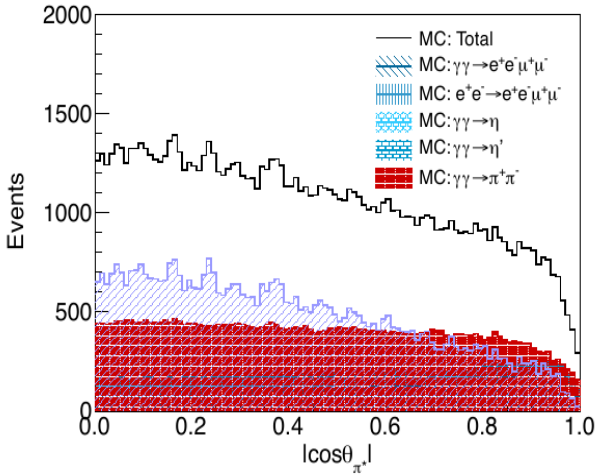
- **Un-Tagged Measurements**
  - Determination of radiative width

- **Single-Tagged Measurements**
  - Complete TFF study of single mesons states (η, η')
  - First single-tagged measurement of $\pi^+\pi^-$
    - Full helicity angle coverage
    - Mass coverage from two-pion threshold to 2 GeV
  - Two-Meson studies in neutral channels ($\pi\pi, \pi\eta, \eta\eta$)
  - Investigation of higher multiplicity states ($3\pi, 4\pi$ ...)

- **Double-Tagged Measurements**
  - Single mesons (π^0, η, η') studies for $Q^2 < 2$ GeV
  - ~100 events expected for π^0
  - Smaller Q² region as BaBar η' TFF measurement







Summary

A2 and BESIII ...

- … are great facilities to the properties of light mesons at high precision

- A2 is able to deliver high quality measurements of time-like TFFs of light mesons
  - Time-like TFF measurement for π^0, η available
  - Ongoing efforts to measure η' TFF and improve π^0 TFF measurement

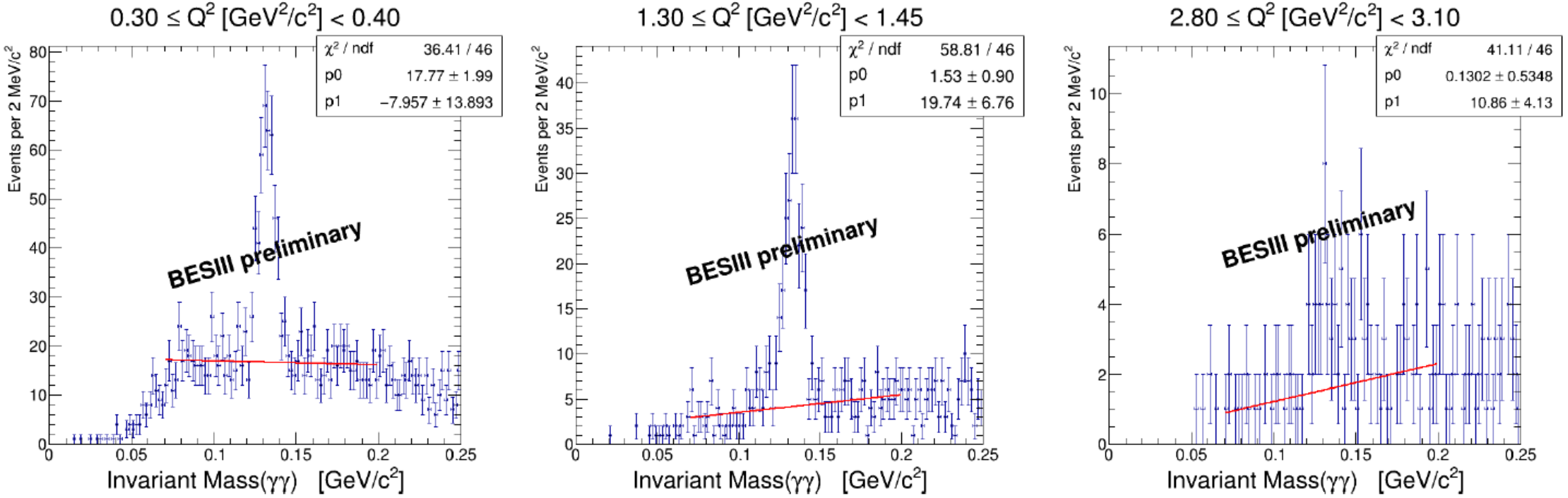
- BESIII is suitable for measurements of singly virtual space-like TFFs of the lightest mesons in the relevant Q^2 range for a_μ with unprecedented accuracy
  - Most accurate measurement of space-like π^0 TFF
  - First results of single-tagged measurements of meson pairs expected soon
  - Double-Tagged measurements of space-like TFFs started

- **Both experiments contribute significantly to the SM prediction of a_μ !**

谢谢 for your attention!

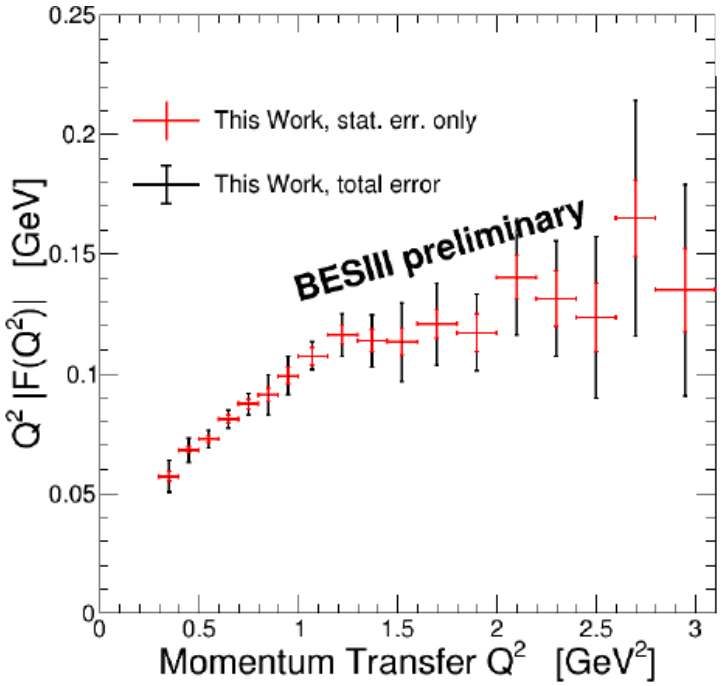
Back-up

- MC distribution do not describe data
  - Use data-driven, sideband-like background subtraction method
- Fit invariant mass distribution for each Q^2 bin in $0.07 \leq \mathrm{IM}_{\gamma\gamma}\ [\mathrm{GeV}/c^2] \leq 0.2$
  - Exclude peak region from fit $(0.115 \leq \mathrm{IM}_{\gamma\gamma}\ [\mathrm{GeV}/c^2] \leq 0.151)$
  - Count number of events in peak region above fitted background



Back-up

	Source	Contribution
External	Tracking efficiency	0.25%
	Photon detection efficiency	1%
	Luminosity	0.25%
Analysis	$q_{\text{tag}} \cdot \cos\theta_{\text{miss}} < -0.99$	0.1% – 3.1%
	$\cos\theta_{\text{H}} < 0.8$	0.2% – 4.5%
	$\lvert\Delta\phi_{\gamma\gamma}\rvert < \frac{\pi}{2}$	negligible
	$\lvert\Delta\theta_{\gamma\gamma} - 0.01 q_{\text{tag}}\rvert > 0.02$	0.3% – 9.8%
	$R_{\gamma} < 0.05$	1.0% – 7.7%
	Reconstruction efficiency	1.6% – 17.2%
Background subtraction	Signal shape	0.1% – 1.9%
	Event counting	0.1% – 11.1%
	Background shape	0.2% – 21.0%
Total		**3.9% – 30.0%**



- Contributions added in quadrature
- Full correlation between contributions of analysis conditions and background subtraction assumed

Error estimate does not consider radiative effects

- To be evaluated with recently released Ekhara 3.0 (arXiv:1805.07756)