



JOHANNES GUTENBERG
UNIVERSITÄT MAINZ



THE LOW-ENERGY FRONTIER
OF THE STANDARD MODEL

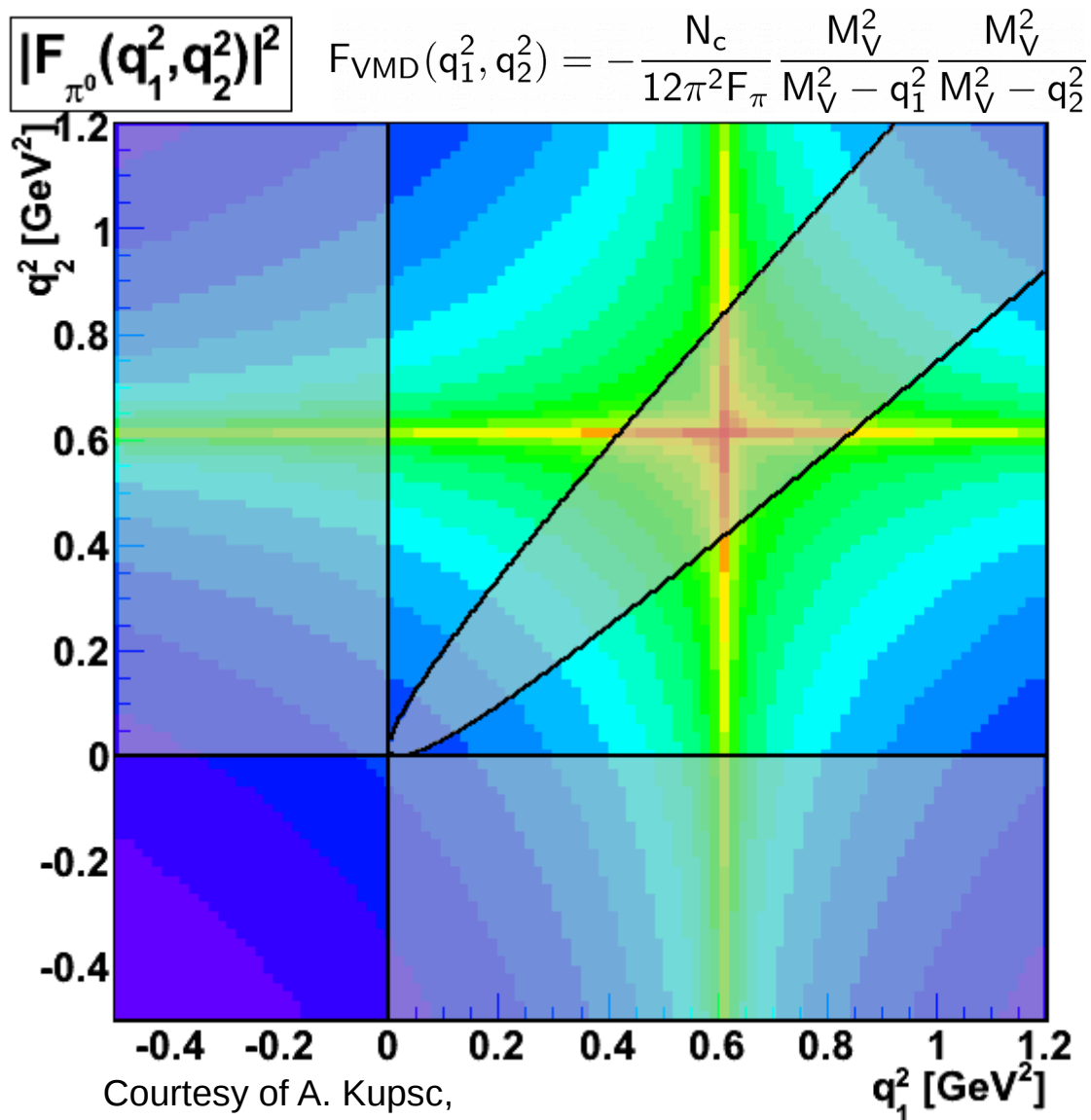


Measurements of electromagnetic transition form factors

June 5, 2017 | Christoph Florian Redmer

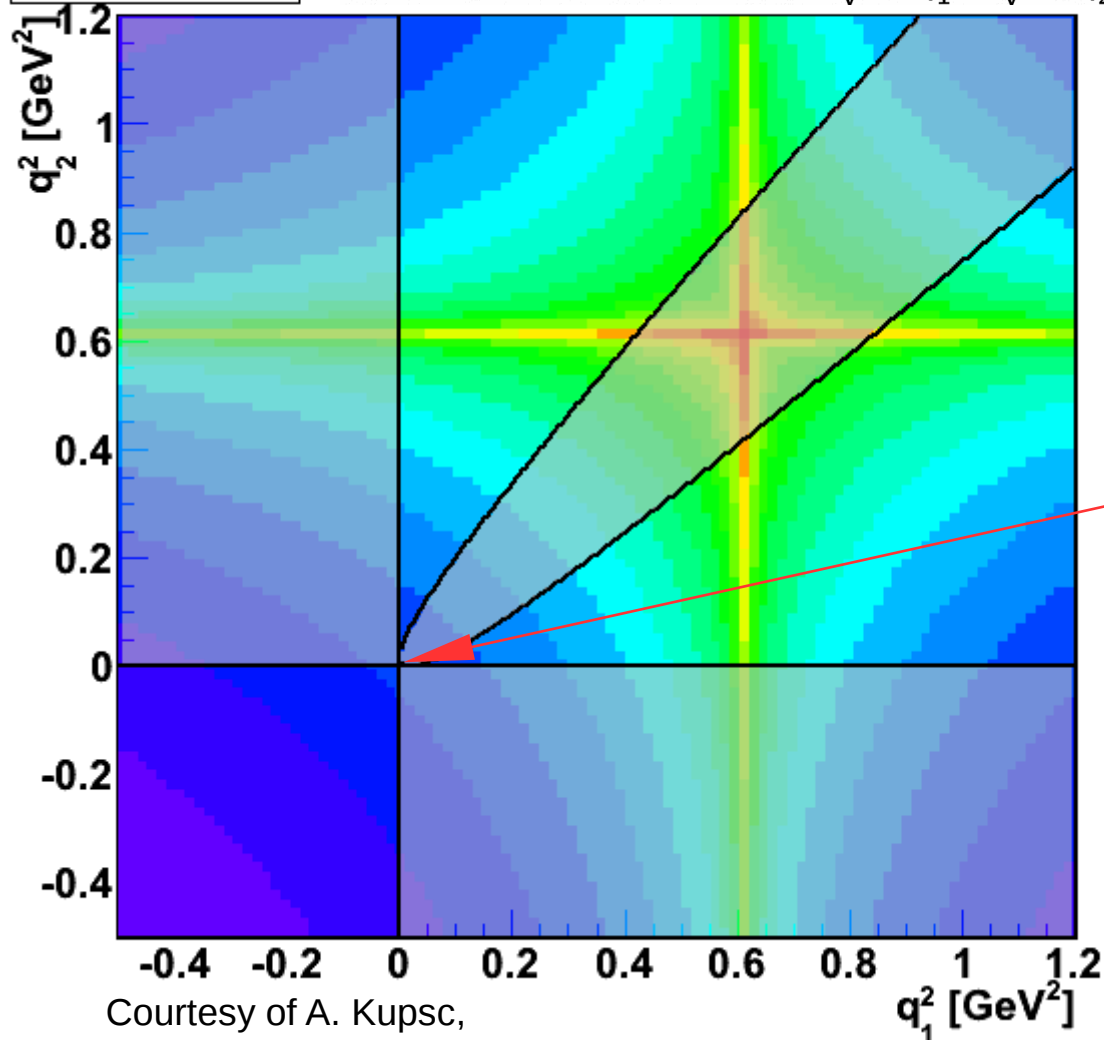
First Workshop of the Muon $g-2$ Theory Initiative

π^0 Transition Form Factor



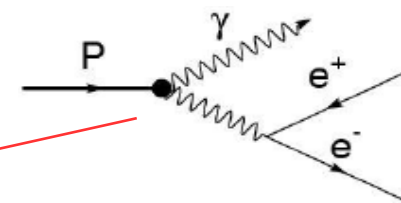
π^0 Transition Form Factor

$$|F_{\pi^0}(q_1^2, q_2^2)|^2 \quad F_{\text{VMD}}(q_1^2, q_2^2) = -\frac{N_c}{12\pi^2 F_\pi} \frac{M_V^2}{M_V^2 - q_1^2} \frac{M_V^2}{M_V^2 - q_2^2}$$

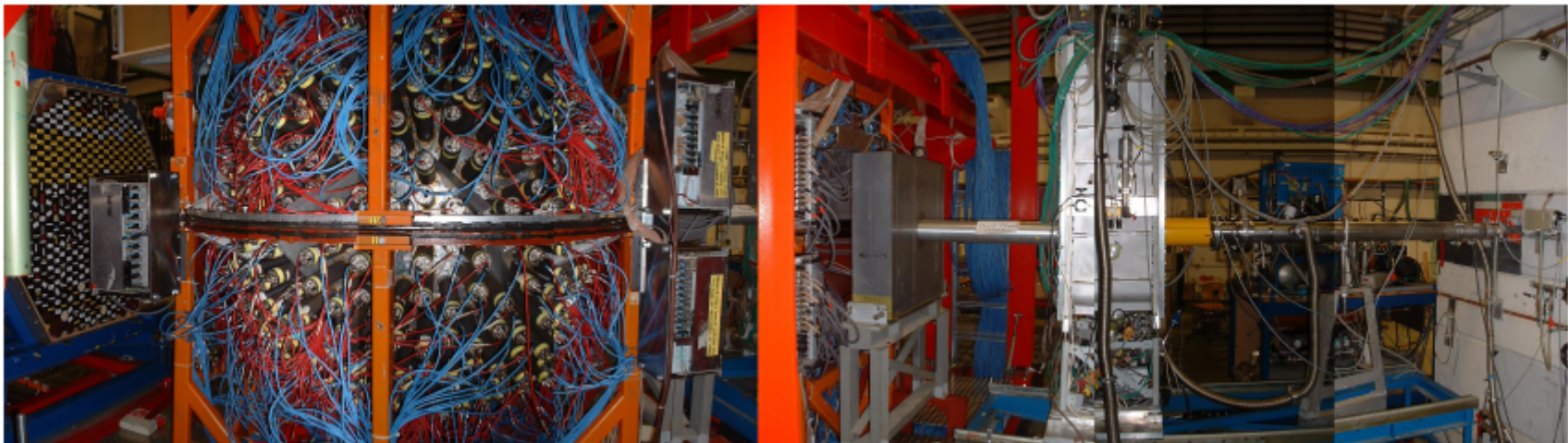


Time – like:

- Dalitz decays
- $0 < q^2 < M^2$



- TFF as deviation from the QED solution for the decay rate
- Usually parameterized in the linear form $F_{\pi^0\gamma}(m_{ee}) = 1 + a_\pi \frac{m_{ee}^2}{m_{\pi^0}^2}$
- Best value from Dalitz decay: SINDRUM-I $0.025(14)_{\text{stat}}(26)_{\text{syst}}$ Phys.Rev.D45 (1992) 1439
- PDG value dominated by space-like CELLO result
 - Includes model-dependent extrapolation
- New measurement by A2 collaboration
 - Photo-induced meson production with Crystal Ball and Taps detectors

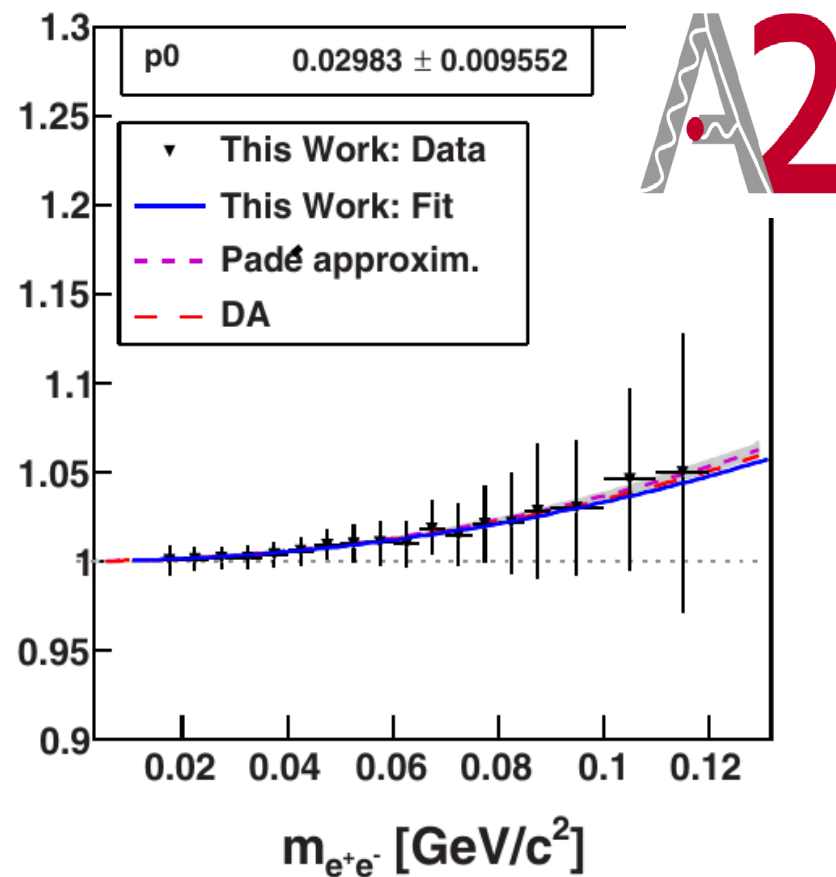


- ~ 0.4 M events reconstructed
- Radiative corrections taken into account
- Slope parameter: $a_\pi = 0.030 \pm 0.010_{tot}$
- Good agreement with data-driven approaches
- New measurement ongoing
 - To match PDG accuracy

- NA62 published at the same time:

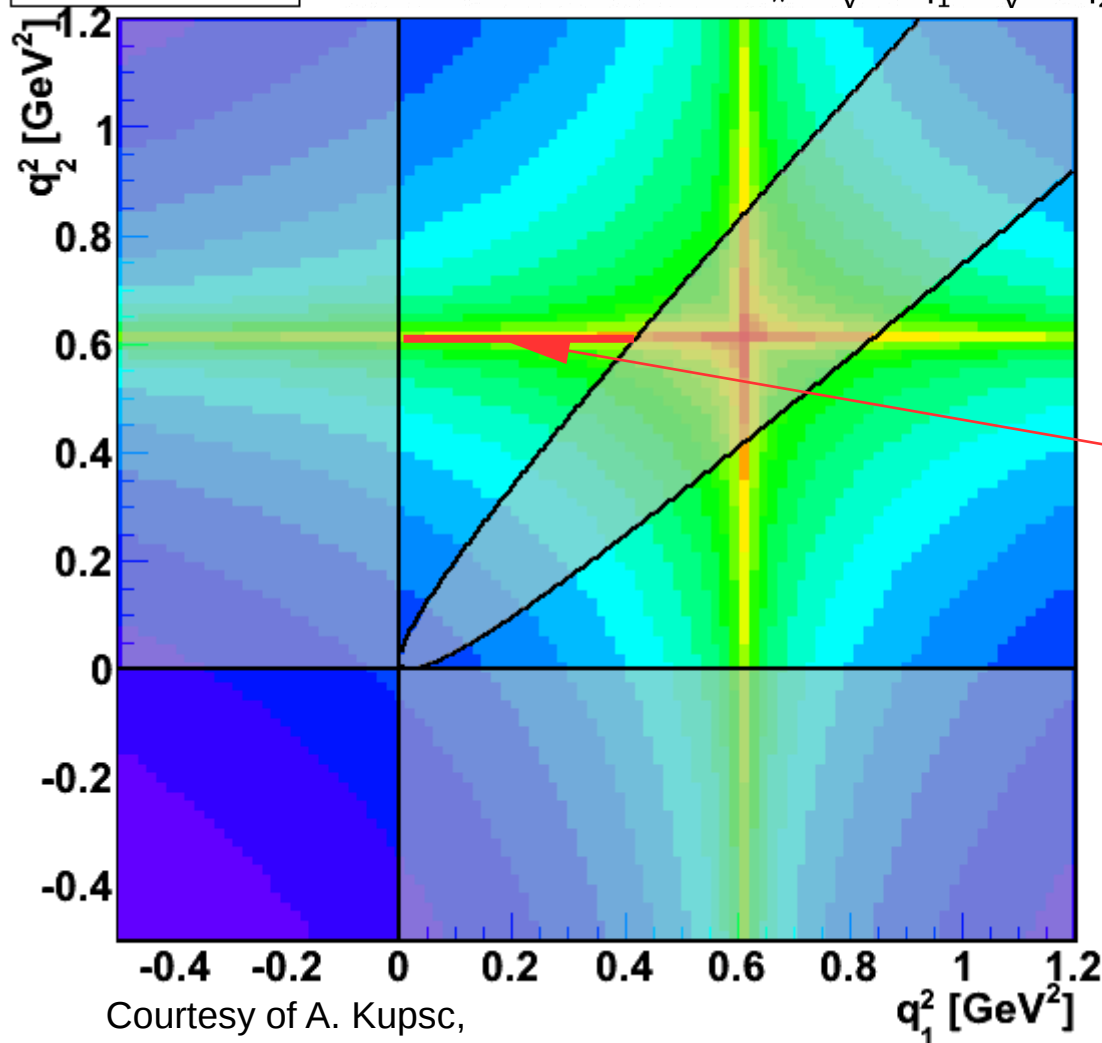
- 1.1 M events
- Slope parameter: $a_\pi = 0.0368 \pm 0.0057_{tot}$

C. Lazzeroni et al., Phys. Lett. B768 (2017) 38



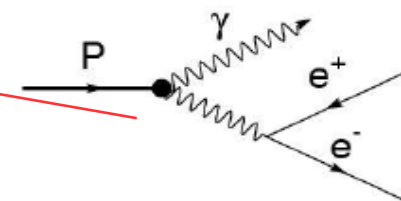
P. Adlarson et al., Phys. Rev. C95 (2017) 025202

$$|F_{\pi^0}(q_1^2, q_2^2)|^2 \quad F_{\text{VMD}}(q_1^2, q_2^2) = -\frac{N_c}{12\pi^2 F_\pi} \frac{M_V^2}{M_V^2 - q_1^2} \frac{M_V^2}{M_V^2 - q_2^2}$$



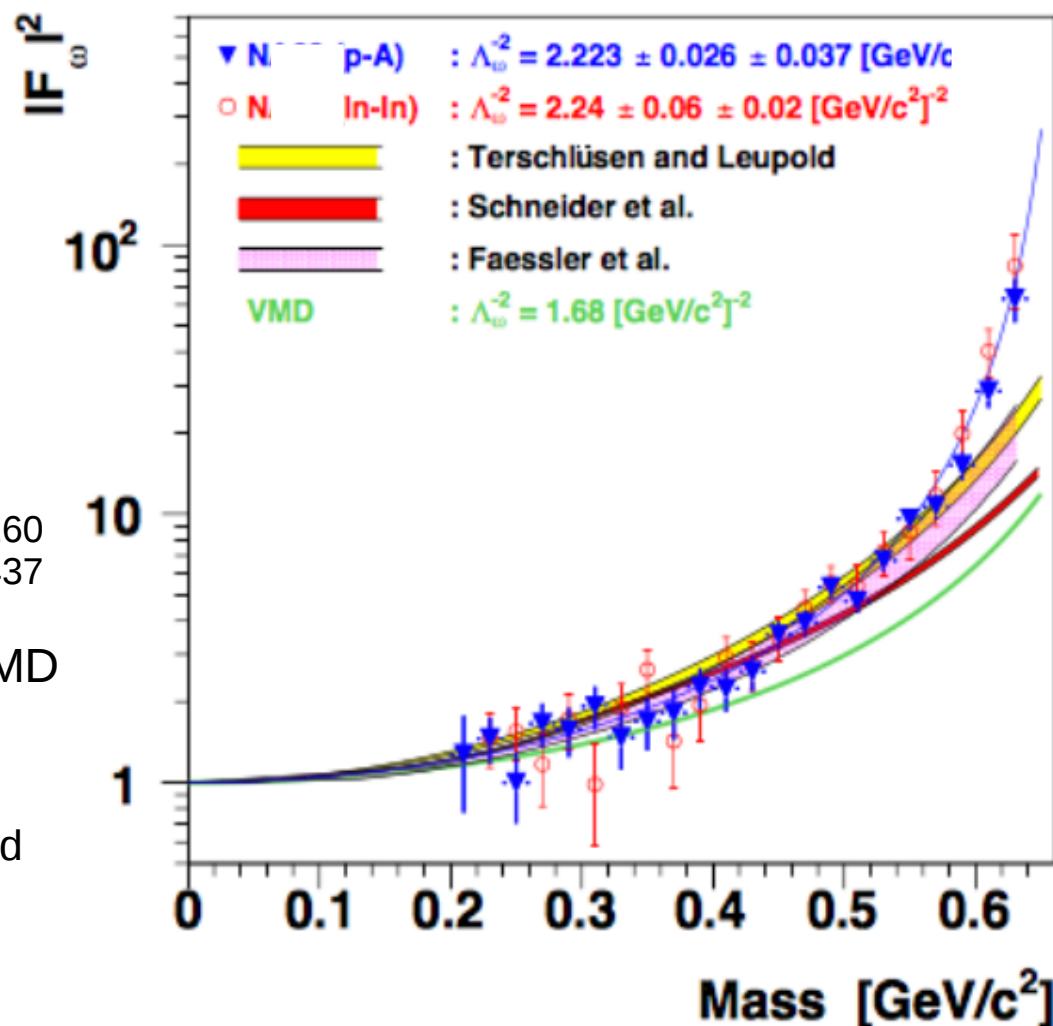
Time – like:

- Dalitz decays
- $0 < q^2 < M^2$



$$\omega \rightarrow \pi^0 |^+ |^-$$

- So far mostly muon dalitz decay
- Best precision provided by NA60
Phys.Lett B677(2009)260
Phys.Lett B757(2016)437
- At the time unexpected deviation from VMD
- New approaches developed
 - Highest mass data points still not understood



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



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

■ ~ 1100 events reconstructed

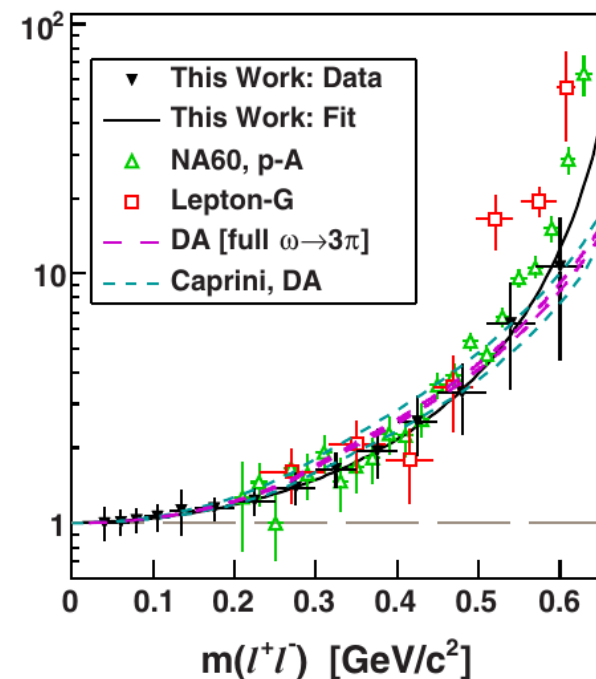
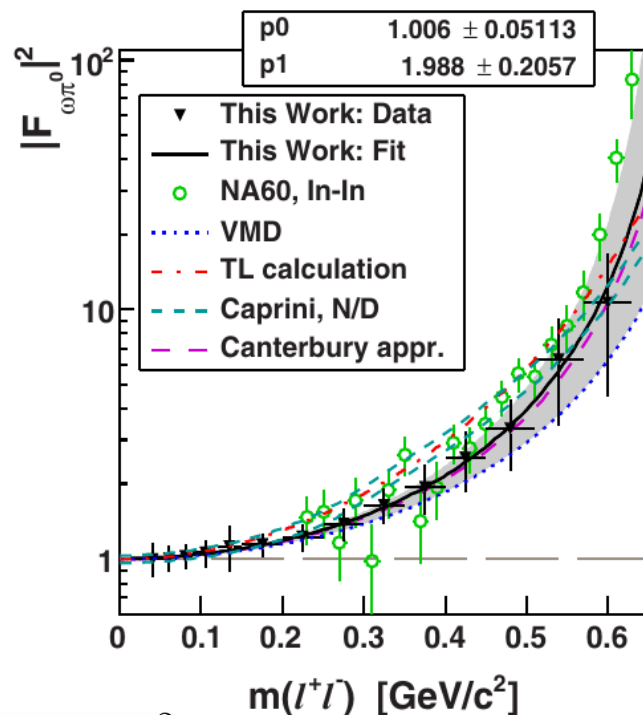
■ Slope: $\Lambda_{\omega\pi^0}^{-2} = (1.99 \pm 0.21_{tot}) GeV^{-2}$

■ Lower than previous measurements ($\omega \rightarrow \pi^0 \mu^+ \mu^-$)

■ Consistent with NA60 (within errors)

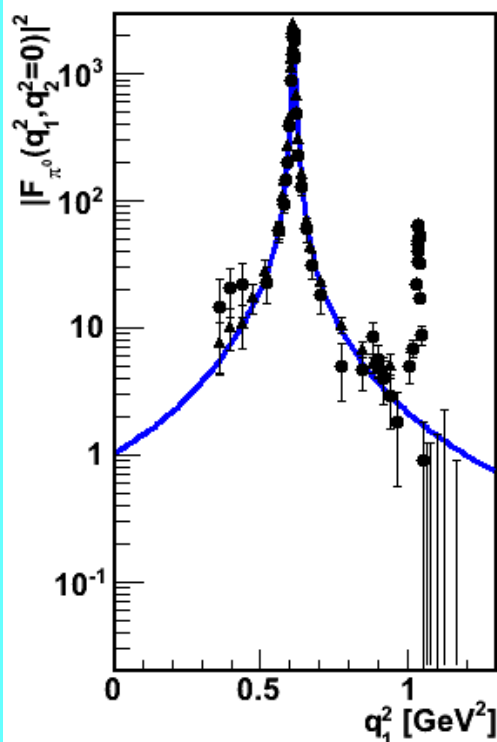
■ Good agreement with existing calculations

■ Small statistics at large m_{l+l-}



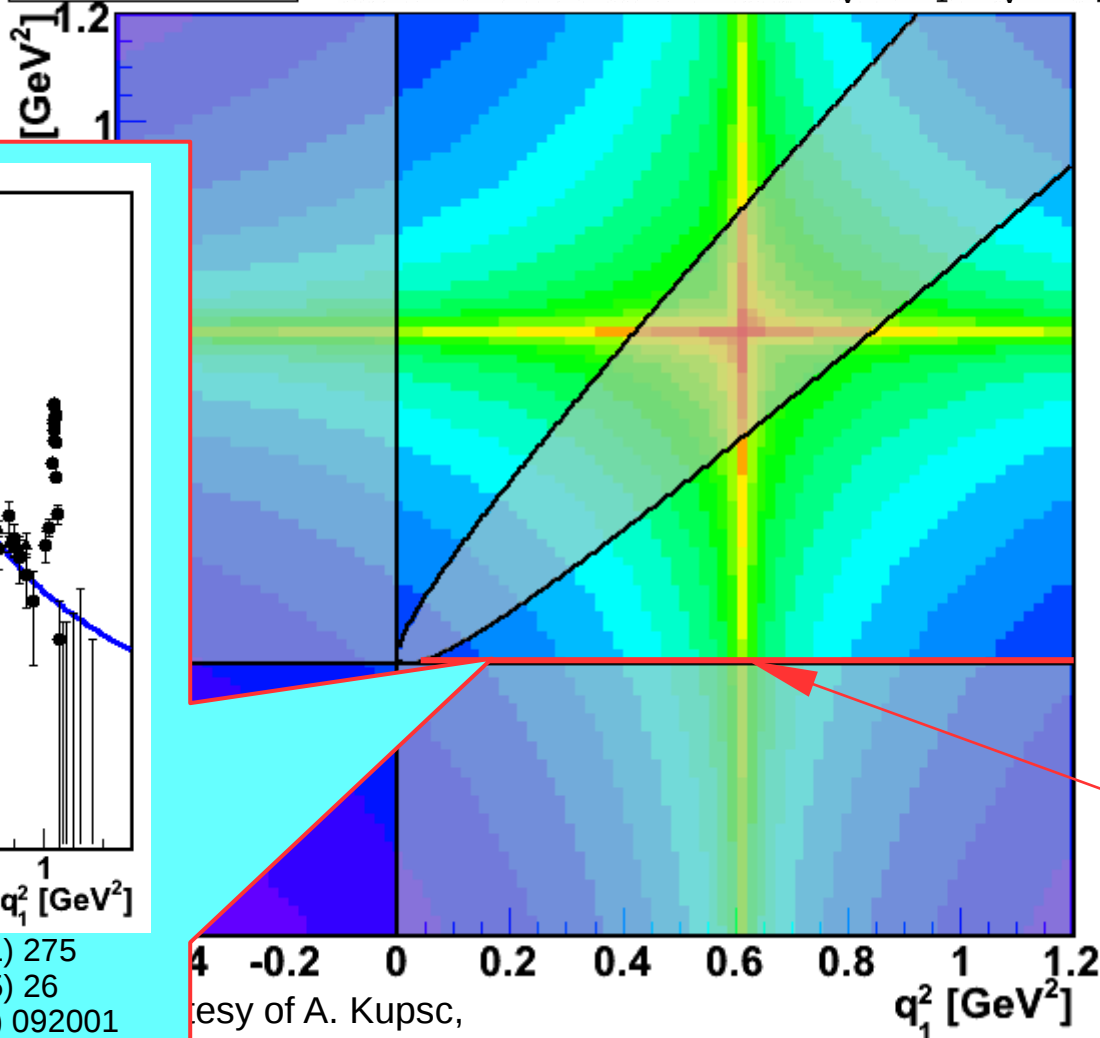
P. Adlarson et al., Phys. Rev. C95 (2017) 035208

$$|F_{\pi^0}(q_1^2, q_2^2)|^2 \quad F_{\text{VMD}}(q_1^2, q_2^2) = -\frac{N_c}{12\pi^2 F_\pi} \frac{M_V^2}{M_V^2 - q_1^2} \frac{M_V^2}{M_V^2 - q_2^2}$$



SND PLB504 (2001) 275
 CMD PLB605 (2005) 26
 SND PRD93 (2016) 092001

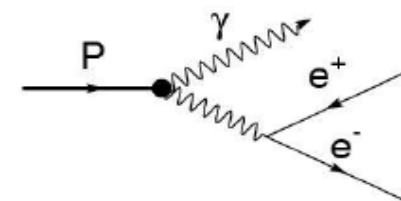
BESIII analysis around 15 GeV² ongoing



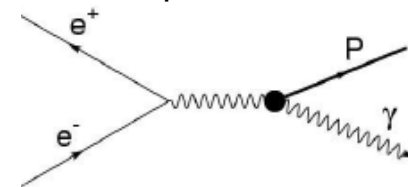
University of A. Kupsc,
 Kerala University

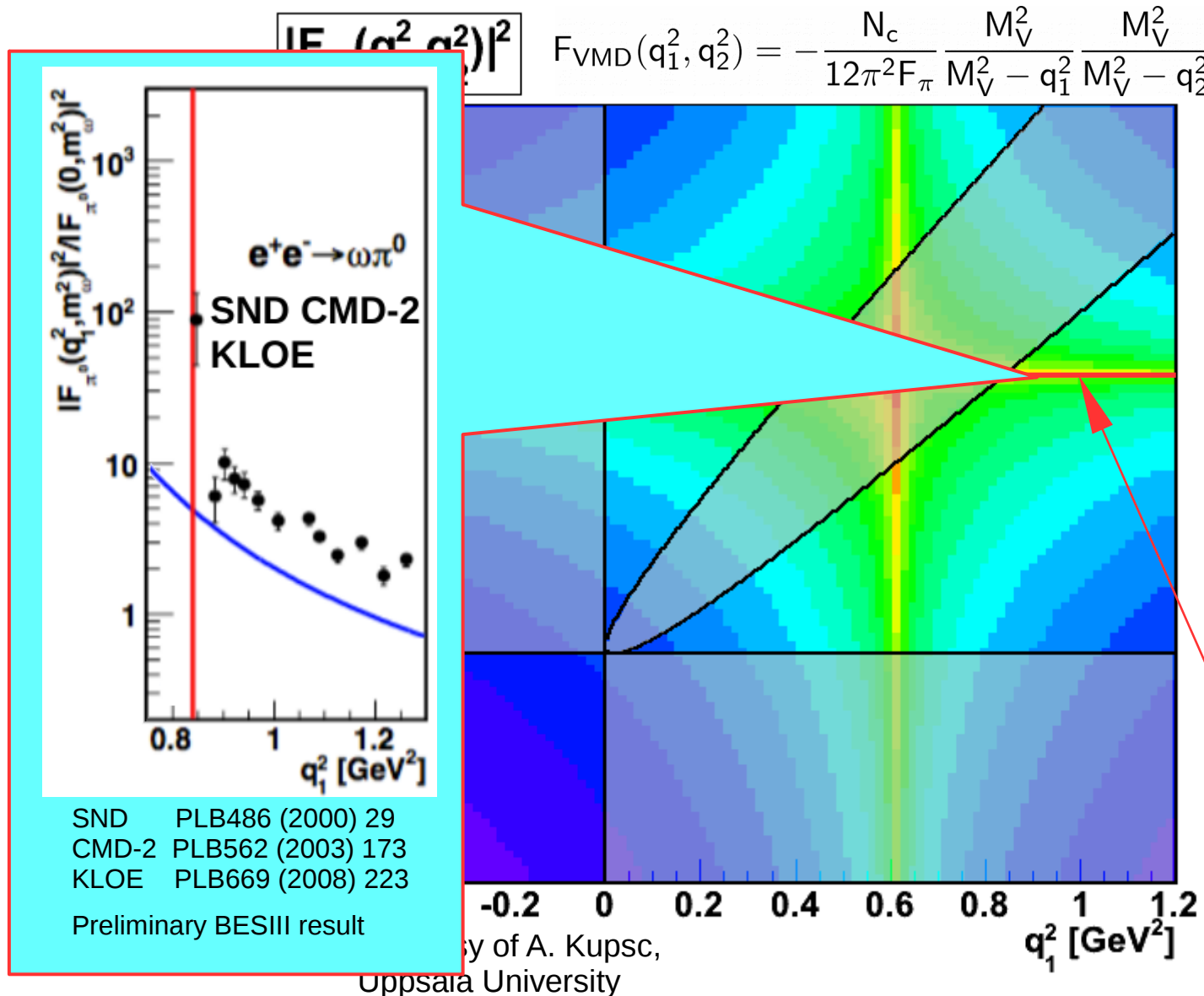
Time – like:

- Dalitz decays
- $0 < q^2 < M^2$



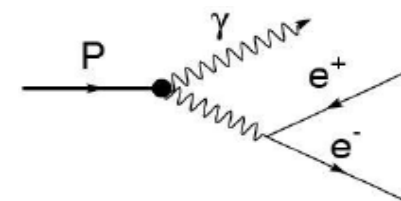
- e+e- Annihilation
- $q^2 = s > M^2$



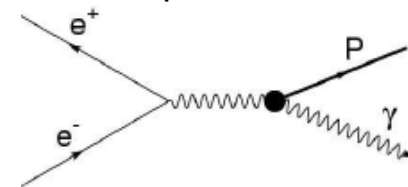


Time – like:

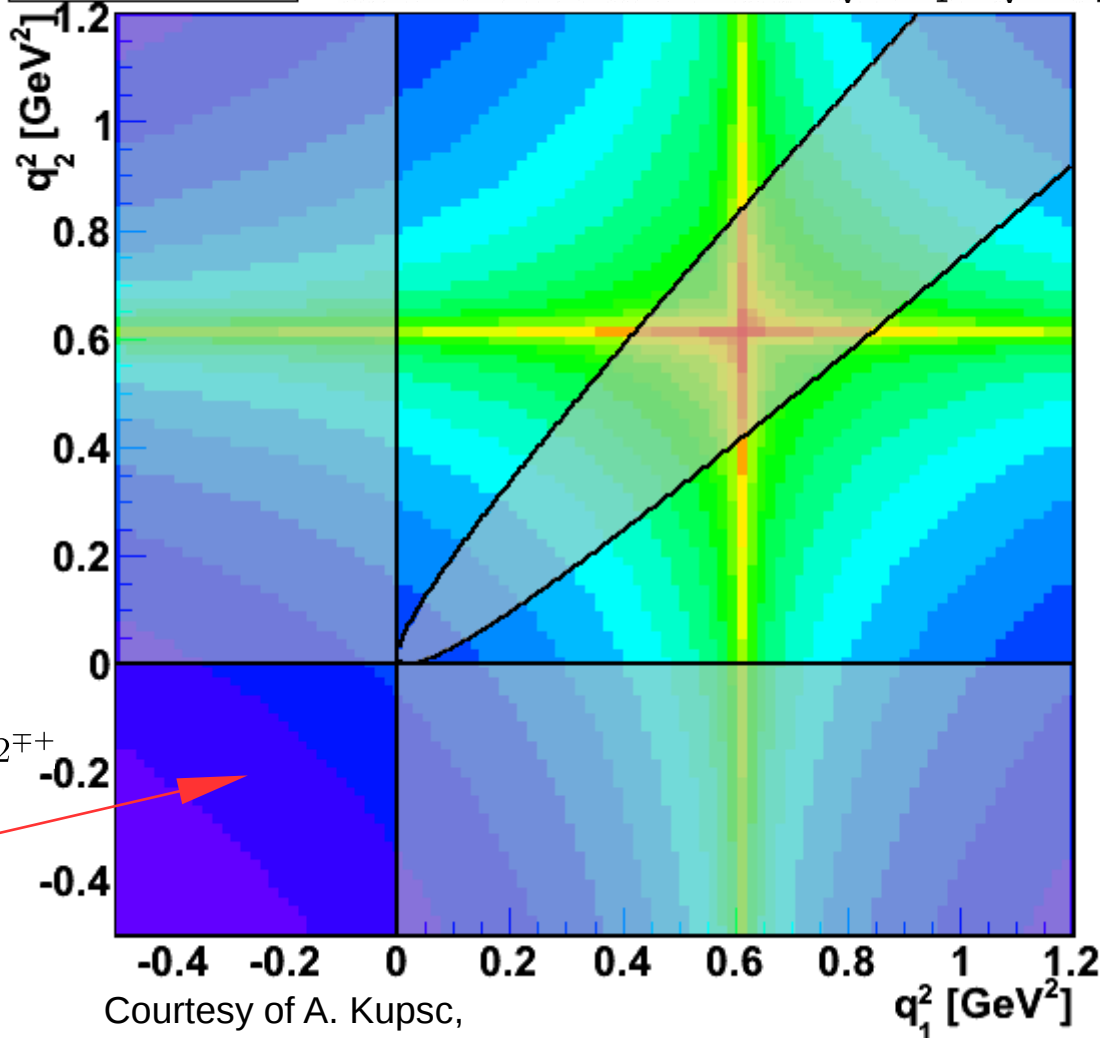
- Dalitz decays
- $0 < q^2 < M^2$



- e^+e^- Annihilation
- $q^2 = s > M^2$

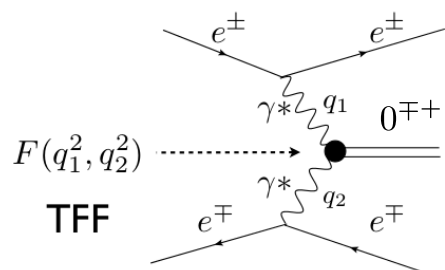


$$|F_{\pi^0}(q_1^2, q_2^2)|^2 \quad F_{\text{VMD}}(q_1^2, q_2^2) = -\frac{N_c}{12\pi^2 F_\pi} \frac{M_V^2}{M_V^2 - q_1^2} \frac{M_V^2}{M_V^2 - q_2^2}$$



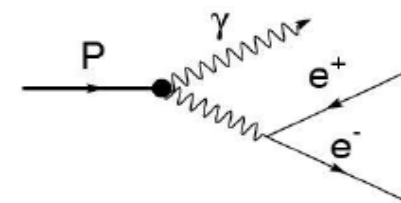
Space – like:

- Two-photon reactions
- $F(Q_1^2, Q_2^2)$, $Q^2 = -q^2$

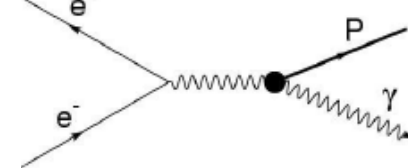


Time – like:

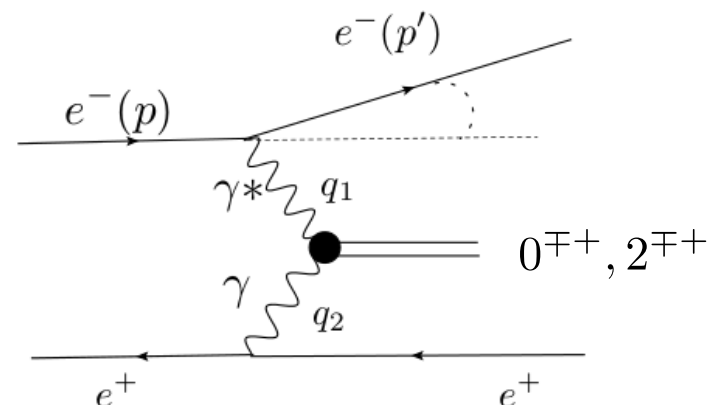
- Dalitz decays
- $0 < q^2 < M^2$



- e+e- Annihilation
- $q^2 = s > M^2$



- Reconstruct
 - only one scattered lepton
 - Produced system
- Unmeasured lepton from momentum conservation
 - Require scattering angle to be small
 - Small virtuality
- $F(q_1^2, q_2^2) \rightarrow F(q_1^2, 0) \rightarrow F(q^2)$

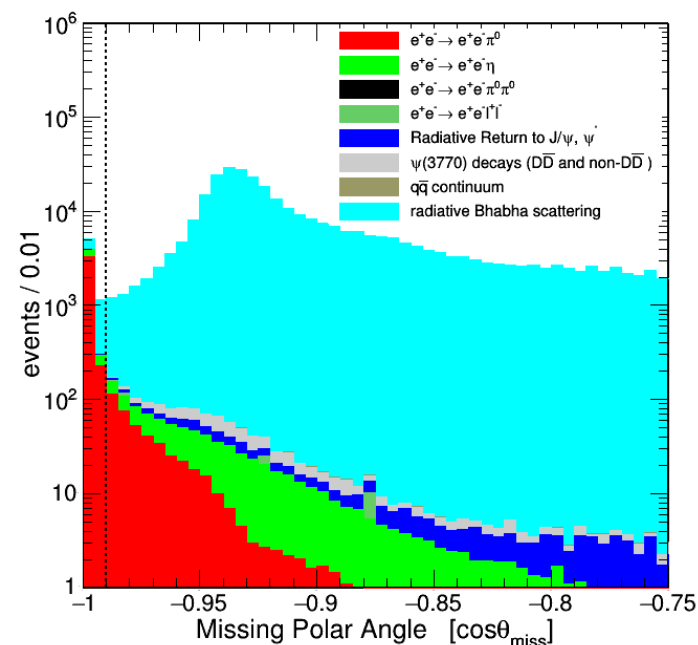


Example: π^0 transition form factor at BESIII

Monte Carlo, $L_{\text{int}} : 2.93 \text{ fb}^{-1} @ \Psi(3770)$

Tagged Lepton: e^+

Reconstructed decay: $\pi^0 \rightarrow \gamma\gamma$

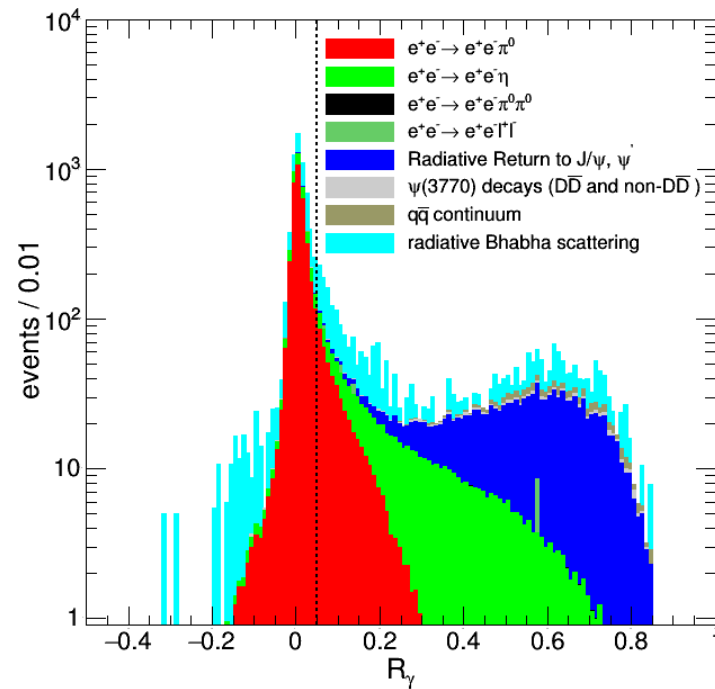
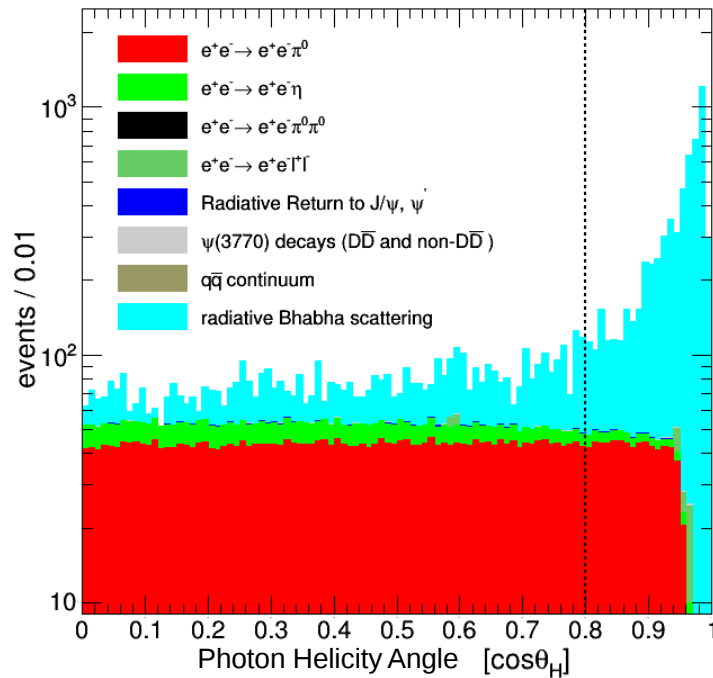


JGU Space-like π^0 Transition Form Factor



BESIII Monte Carlo, $\Psi(3770)$

$L_{\text{int}} : 2.93 \text{ fb}^{-1}$, Tagged Lepton: e^+



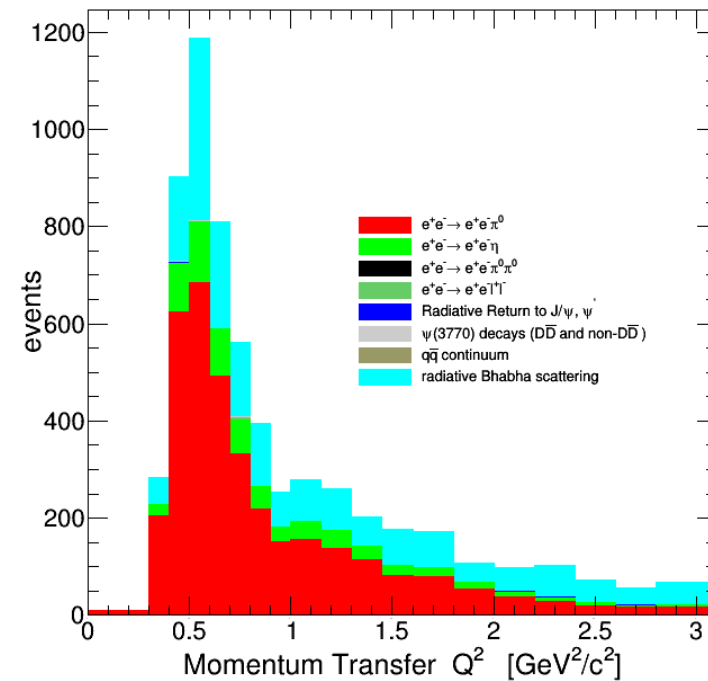
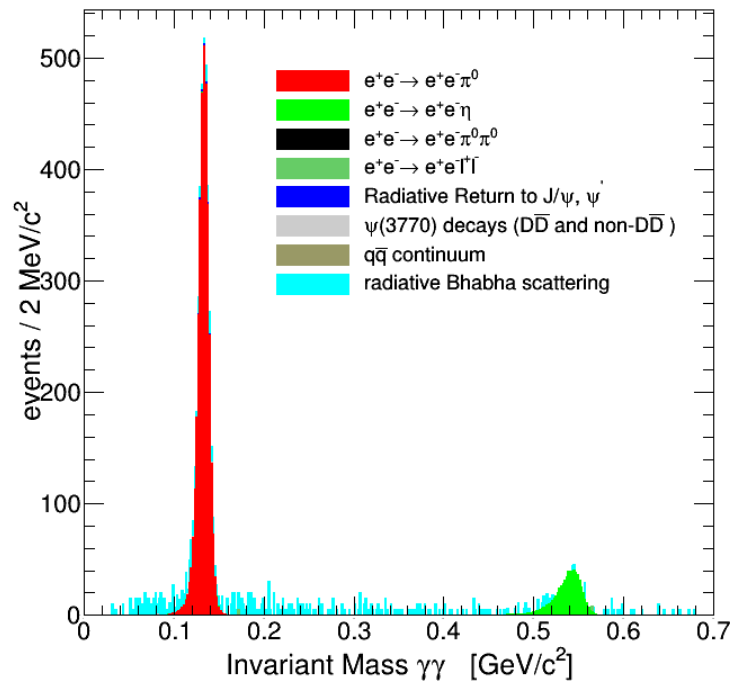
- Exactly one lepton
- Two to four photons
- $\cos\theta_{\text{untagged}} < -0.99$
- $\cos\theta_{\text{Helicity}} < 0.8$

- $R_\gamma = \frac{\sqrt{s} - E_{e^\pm\pi^0}^{\text{CMS}} - p_{e^\pm\pi^0}^{\text{CMS}}}{\sqrt{s}} > 0.05$
- Suppresses radiative background
- Rejects hadronic background

JGU Space-like π^0 Transition Form Factor

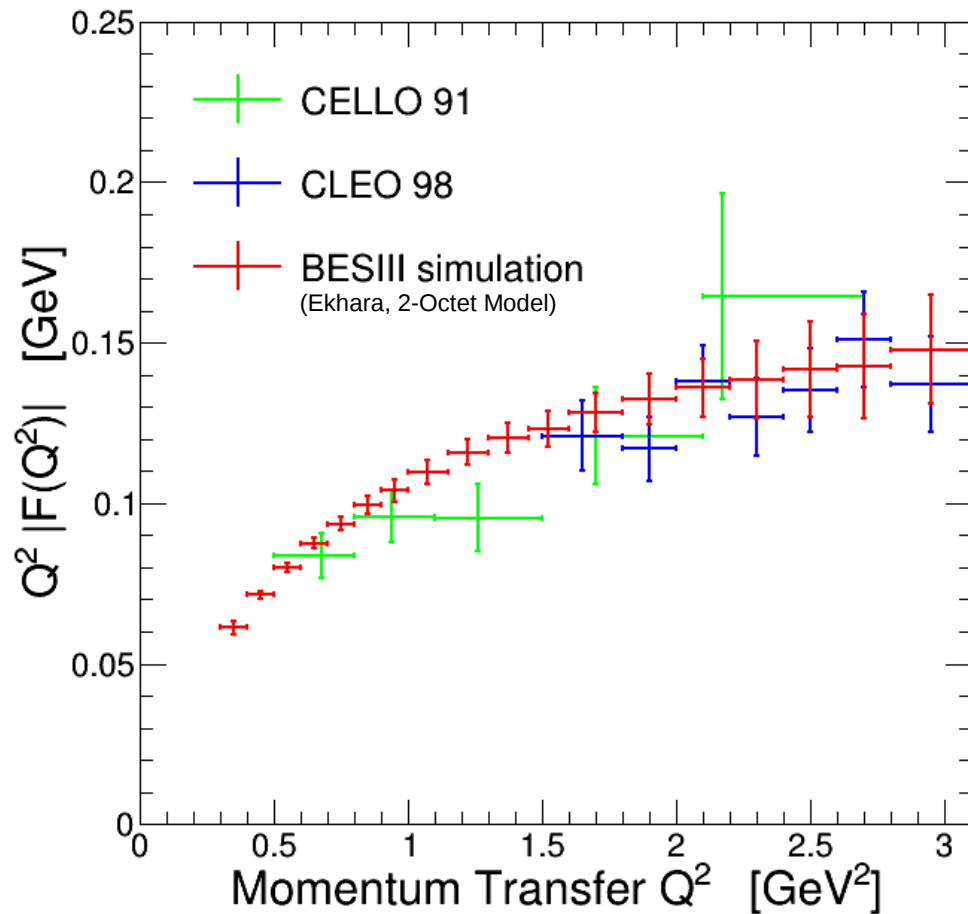


BESIII Monte Carlo, $\Psi(3770)$
 $L_{\text{int}}: 2.93 \text{ fb}^{-1}$, Tagged Lepton: e^+



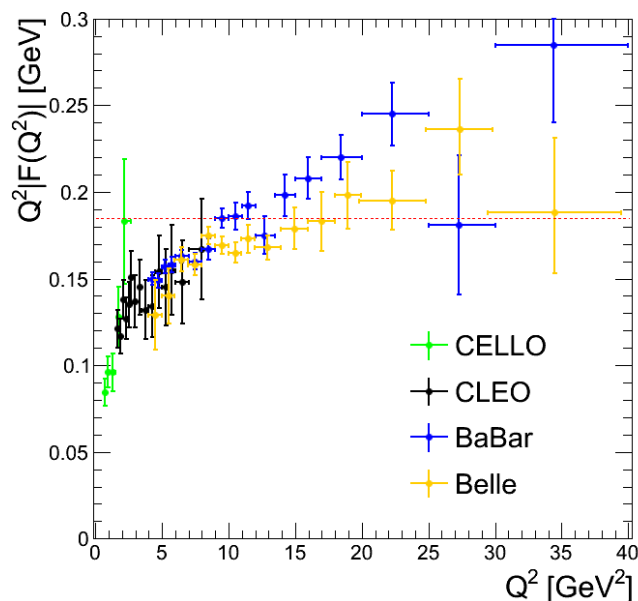
- Analysis useful for π^0 and η
- Monte Carlo description of background incomplete
- Bkg subtr. by counting π^0 yield per Q^2 bin
- Divide out point-like cross section for $|F(Q^2)|^2$

JG|U Space-like π^0 Transition Form Factor

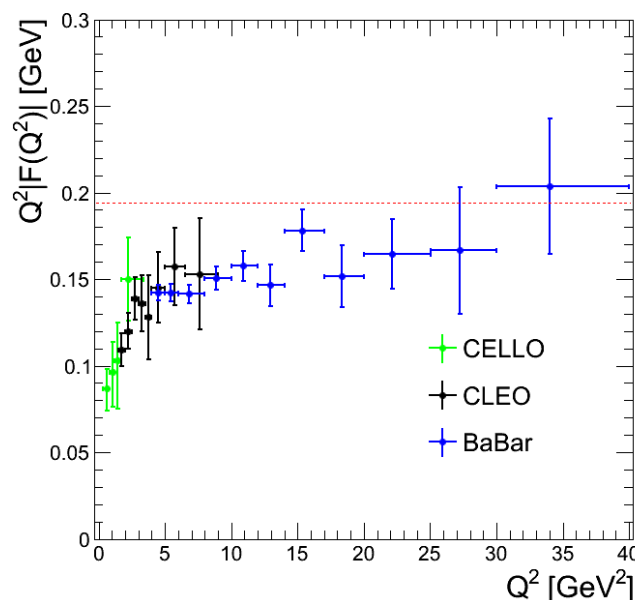


- 2.9 fb⁻¹ at $\Psi(3770)$ analyzed
- Covering $0.3 \leq Q^2 [\text{GeV}^2] \leq 3.1$
- Unprecedented accuracy below 1.5 GeV²
- Competitive accuracy up to 3.1 GeV²
- Systematics dominated by background subtraction
- Potential issues
 - 2nd virtuality
 - Radiative corrections

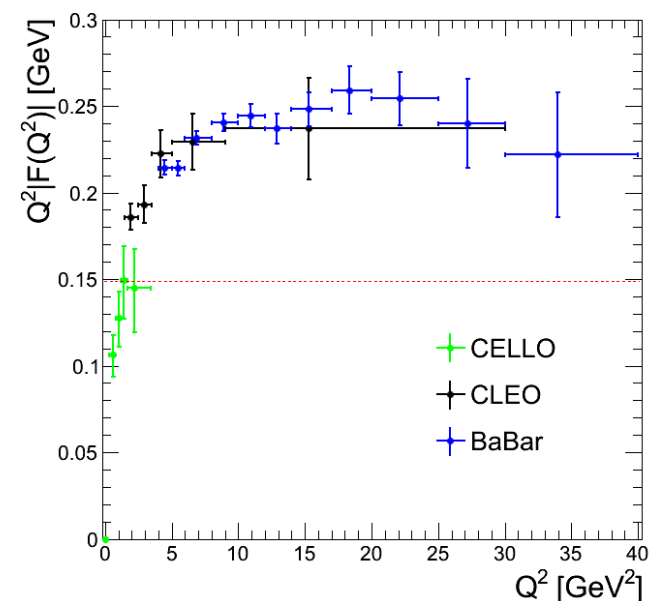
$$e^+e^- \rightarrow e^+e^- \pi^0$$



$$e^+e^- \rightarrow e^+e^- \eta$$



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



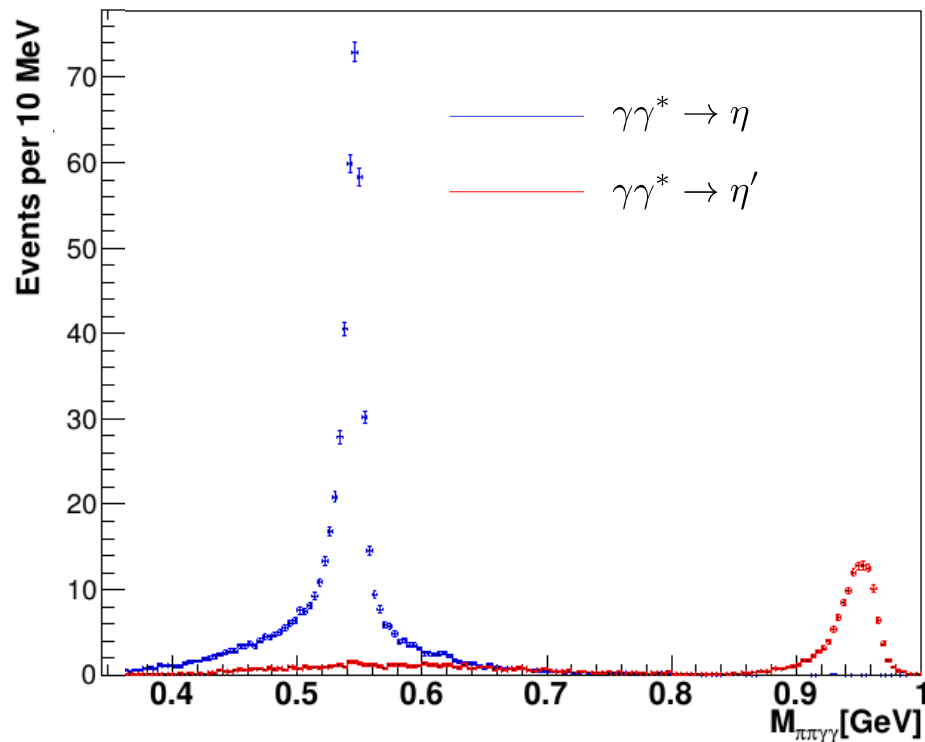
- Recent results from B-factories cover only large Q^2 ($5 < Q^2 [\text{GeV}^2] < 40$)
- Discrepancy for π^0 between BaBar and Belle
- Data scarce at lowest Q^2
- Region of relevance for $(g-2)_\mu$

CELLO: Z.Phys.C49 (1991) 401
 CLEO: Phys.Rev.D57 (1998) 33
 BaBar: Phys.Rev.D80 (2009) 052002
 Phys.Rev.D84 (2011) 052001
 Belle: Phys.Rev.D86 (2012) 092007

JG|U Space-like η, η' Transition Form Factor



BESIII Simulation: $2.9 fb^{-1}$ @ 3.773 GeV

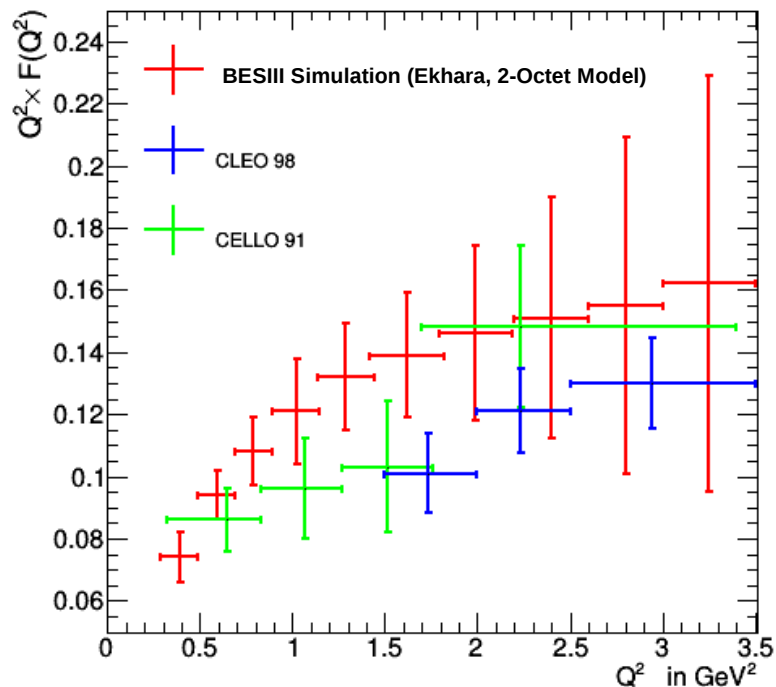


- $\eta \rightarrow \pi^+ \pi^- \pi^0$
- $\eta' \rightarrow \pi^+ \pi^- \eta$
- Select:
 - one electron or positron
 - two oppositely charged pions
 - two photons
- $\cos\theta_{\text{untagged}} > 0.99$
- Reject hadronic background
- Mass window cuts on $\gamma\gamma$ invariant mass
- Kinematic fit
- Relatively small background contamination

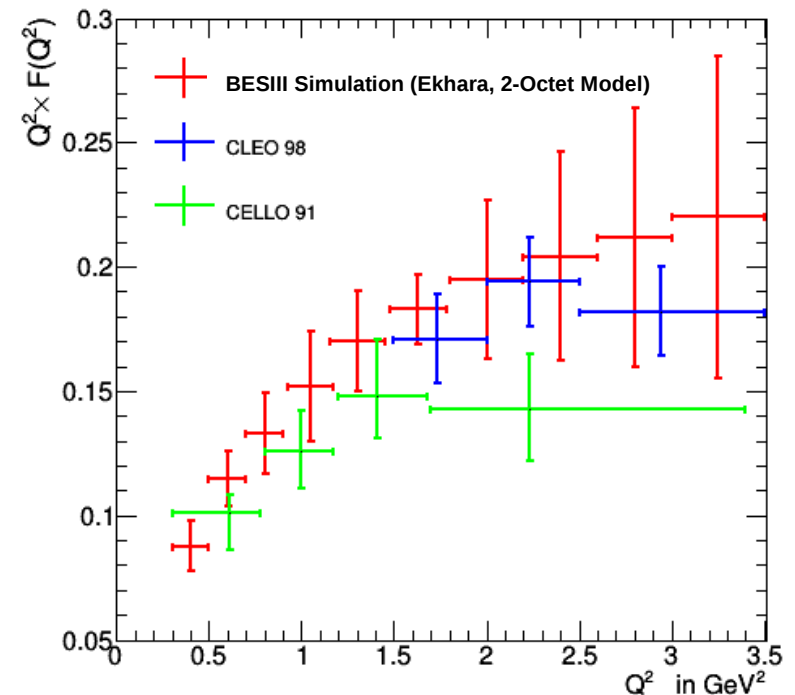
JG|U Space-like η, η' Transition Form Factor

BESIII

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



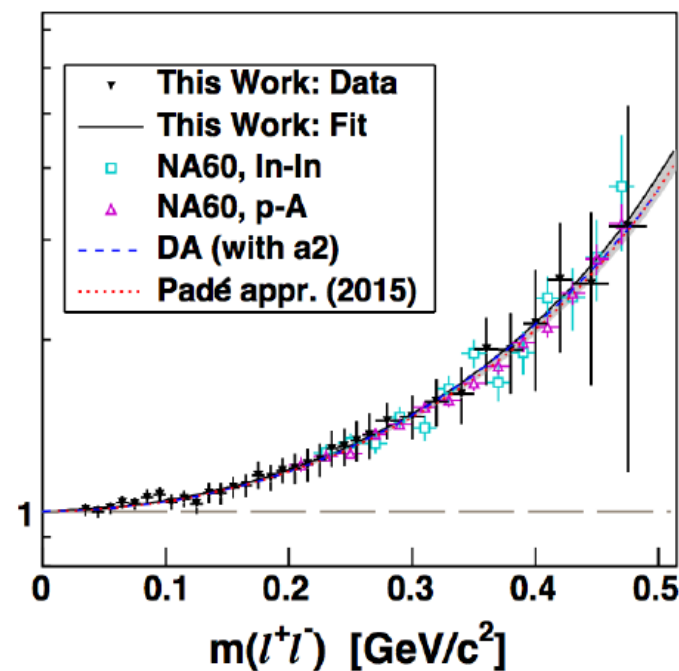
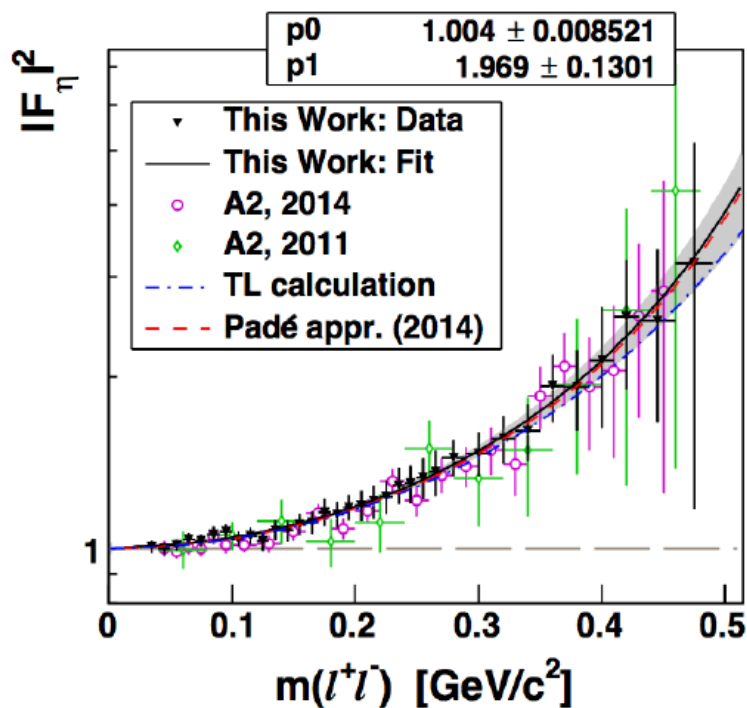
$$F_{\eta', \gamma, \gamma^*}(Q^2)$$



- Statistics compatible to previous measurements
 - only one decay channel of η and η' analyzed at BESIII
 - more data available ($\times 3.5$)
- Systematic studies to be done

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

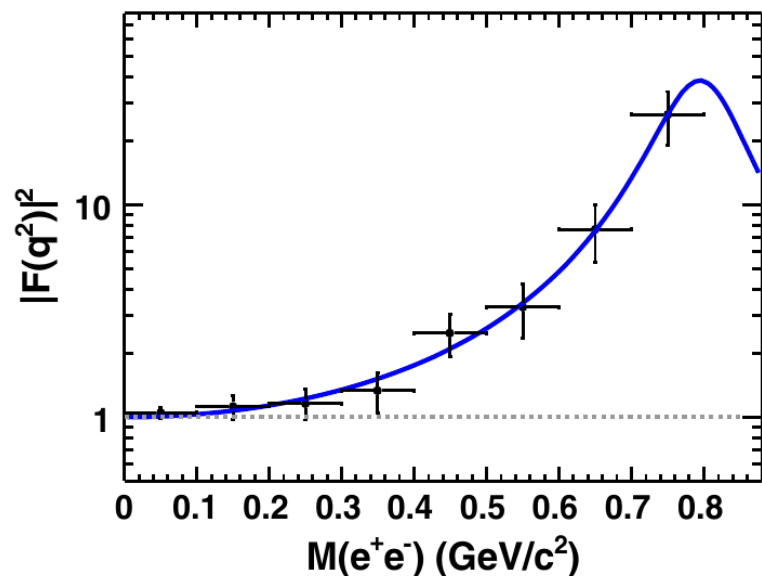
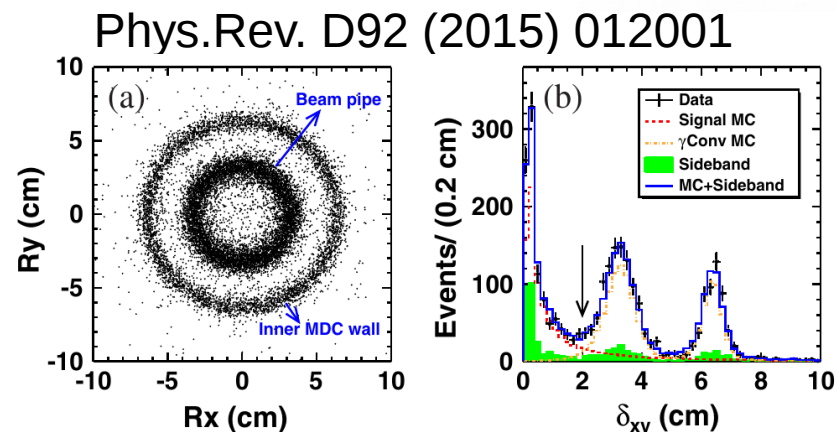
- New data taking / analysis at A2 $\gamma p \rightarrow p \gamma e^+ e^-$
- 540000 events reconstructed
- $\Lambda_{\eta\gamma}^{-2} = (1.97 \pm 0.13_{\text{tot}}) \text{GeV}^{-2}$ (normalization $|F_\eta(0)|^2 = 1$ as result of the fit)
 - Improved accuracy w.r.t. previous A2 and NA60 In-In measurements
 - Good agreement with previous measurements and theory



A2

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

- Reconstructed from $J/\psi \rightarrow \gamma \eta'$
- Using $1.3 \cdot 10^9 J/\psi$ decays
- 864 ± 36 Dalitz events detected
 - **First measurement!**
- Main Background: Photon conversion



$$F_{\eta'} = \frac{\Lambda^2(\Lambda^2 - \gamma^2)}{(\Lambda^2 - q^2)^2 - \Lambda^2\gamma^2}$$

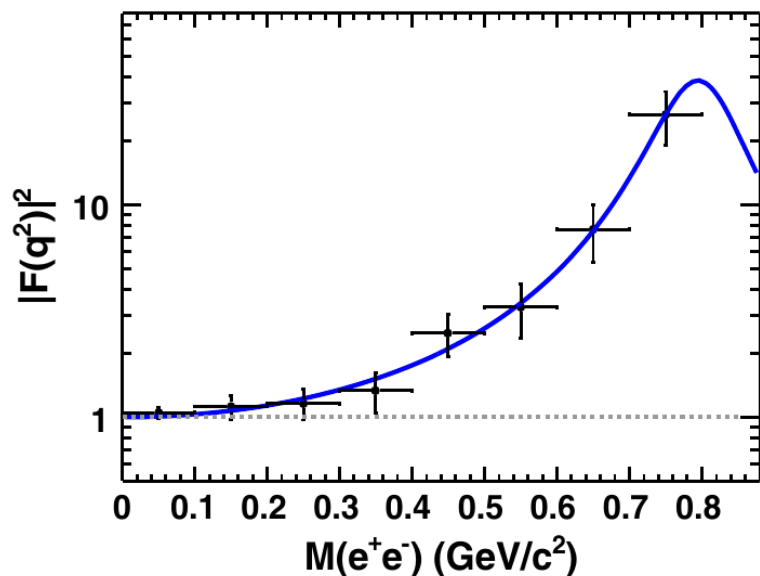
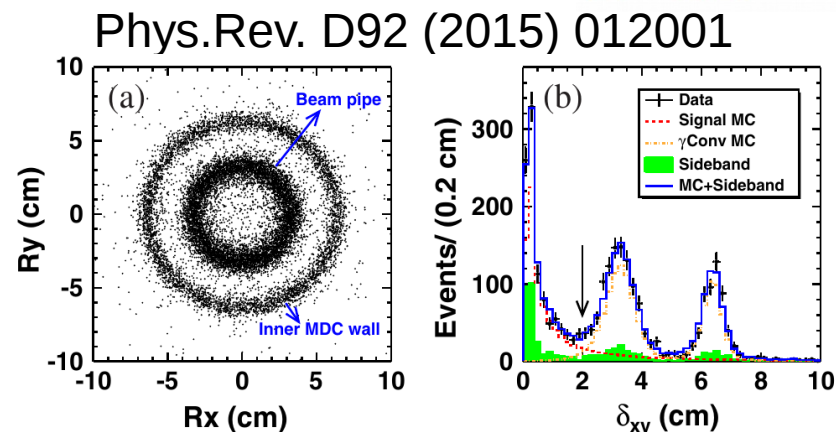
$$\Lambda = (0.79 \pm 0.04_{\text{stat}} \pm 0.02_{\text{syst}}) \text{ GeV}$$

$$\gamma = (0.13 \pm 0.06_{\text{stat}} \pm 0.03_{\text{syst}}) \text{ GeV}$$

- Precision on the level of space-like extrapolation
- Improvement over muon Dalitz decays

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- Precision on the level of space-like extrapolation
- Improvement over muon Dalitz decays

A2 result of similar accuracy expected soon!

■ Time-like Transition Form Factor

■ Dalitz decays

- Provided by A2, NA60, NA62, BESIII, KLOE(-2), CLAS

■ e^+e^- annihilation

- Provided by CMD, SND, KLOE, BESIII

■ Space-like Transition Form Factor

■ Two-photon reactions

- New measurements: BESIII, KLOE-2