

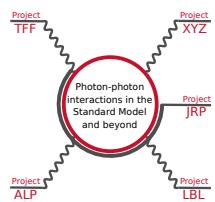


*Fifth Plenary Workshop of the Muon g-2 Theory Initiative,
The University of Edinburgh,
September 7, 2022*

Mainz gamma-gamma Programme for HLbL (A2/MAMI and BESIII)



Cluster of Excellence
PRISMA⁺
Precision Physics,
Fundamental Interactions
and Structure of Matter



*Achim Denig
Johannes Gutenberg University Mainz*

Outline

- Research Unit FOR5327 on Photon-Photon-Interactions
- Programme of Meson Transition Form Factor Measurements:
 - A2/MAMI (meson Dalitz decays)
 - BESIII/BEPC-II (photon-photon fusion reactions) → Christoph Redmer
- Observation of $e^+e^- \rightarrow \chi_{c1} (J^{PC} = 1^{++})$ at BESIII **NEW**
- Conclusions & Outlook

Muon g-2 related Activities @ Mainz

Experiment: Member of the FNAL muon g-2 experiment (Martin Fertl)



Theory

Hadronic Vacuum Polarization

- ISR measurements of exclusive hadronic cross sections @ BESIII (past BABAR, KLOE)
- Lattice QCD calculation of LO-HVP contribution
- Lattice QCD calculation of NLO-HVP contribution

Theory

Hadronic Light-by-Light

- Measurent of meson Transition Form Factors (TFFs) at BESIII and A2/MAMI
- Dispersive analyses and application of sum rules in the context of meson TFFs
- Lattice QCD calculation of HLbL contribution

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Combined efforts under one roof: DFG-funded Research Unit FOR5327

**"Photon-Photon interactions in the Standard Model and beyond -
exploiting the discovery potential from MESA to the LHC"**

(Spokespersons: AD, Marc Vanderhaeghen, 2022-2026, 3.6M€)

DFG
Deutsche
Forschungsgemeinschaft

FOR5327: Photon-Photon Interactions

Measurement of Meson
Transition Form Factors
(TFFs) at BESIII and A2/MAMI;
Dispersive Theory

Project
TFF

Project
XYZ

Project
JRP

Project
ALP

Project
LBL

Photon-photon
interactions in the
Standard Model
and beyond

Joint Research Project (JRP):
HLbL contribution to $(g-2)_\mu$



Project Leaders of the Research Unit

Co-Applicants

International Partners

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Measurement of Meson Transition Form Factors (TFFs) at BESIII and A2/MAMI; **Dispersive Theory**

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Exotic Meson Spectroscopy (XYZ particles) at BESIII exploiting **dispersive methods**

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**Joint Research Project (JRP):
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Exploiting the potential of the recent direct observation of **LBL scattering** at the LHC;

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Photon-photon interactions in the Standard Model and beyond



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FOR5327: Photon-Photon Interactions

Measurement of Meson Transition Form Factors (TFFs) at BESIII and A2/MAMI; **Dispersive Theory**

Project
TFF

Search for axion-like particles (ALPs) in $\gamma\gamma$ -processes at BESIII and ATLAS/LHC

Project
ALP

Photon-photon interactions in the Standard Model and beyond

Project
XYZ

Project
JRP

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Exotic Meson Spectroscopy (**XYZ** particles) at BESIII exploiting **dispersive methods**

**Joint Research Project (JRP):
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Exploiting the potential of the recent direct observation of **LBL scattering** at the LHC;



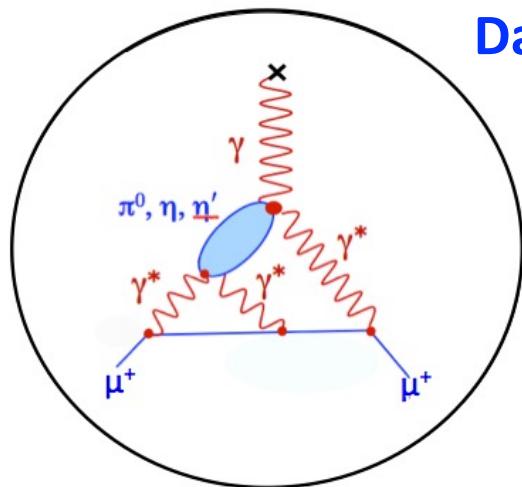
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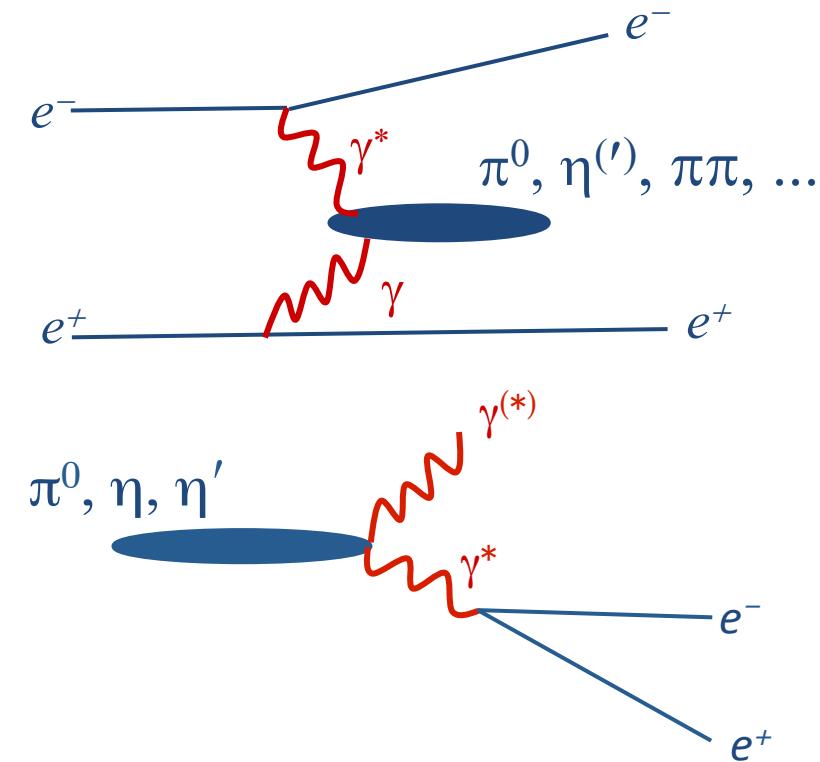
Meson Transition Form Factors and HLbL



Data-driven approach!



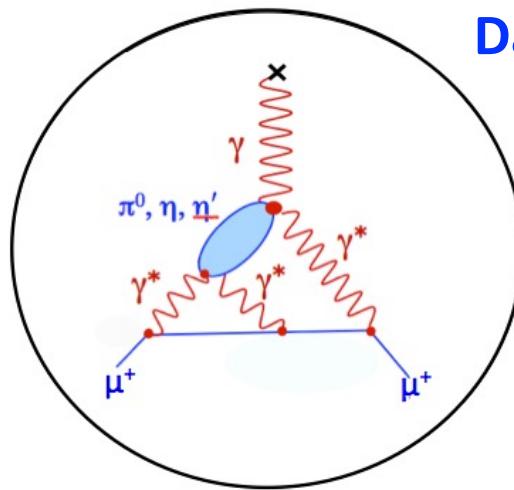
Exp. Input !
Transition
Form Factors $F(Q^2)$
below $\sim 2 \text{ GeV}^2$



BES III



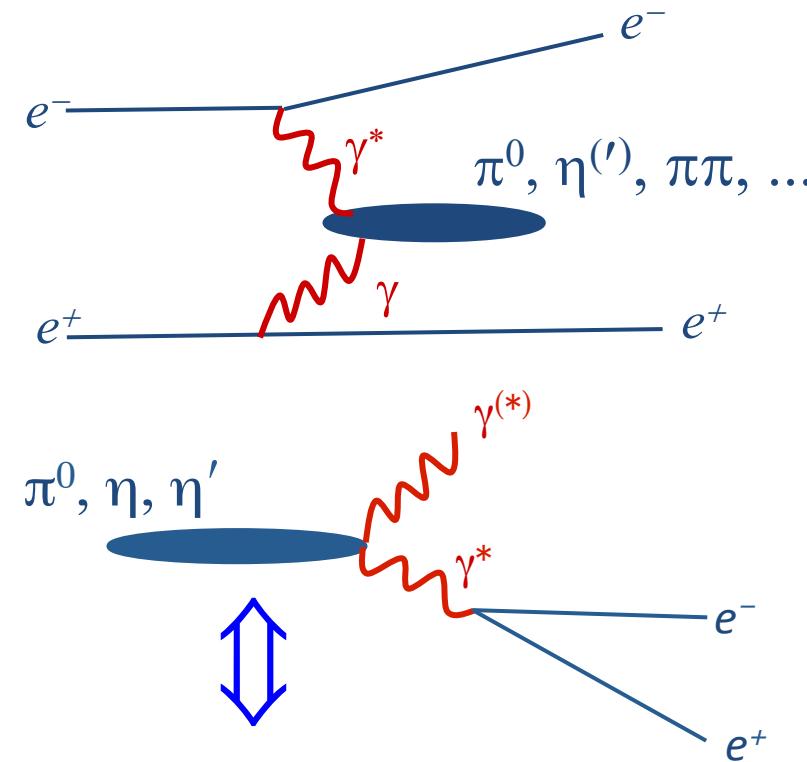
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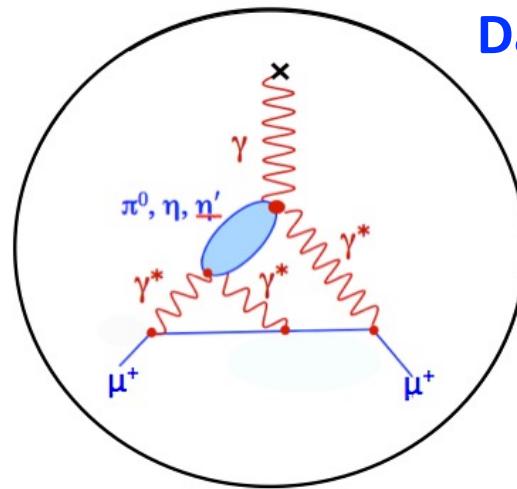


Problem: double-virtual TFFs needed,
for which no measurements exist yet!

Way out: use theory calculations
for double-virtual TFFs:

- Lattice QCD calculation
- Dispersive analyses

Meson Transition Form Factors and HLbL



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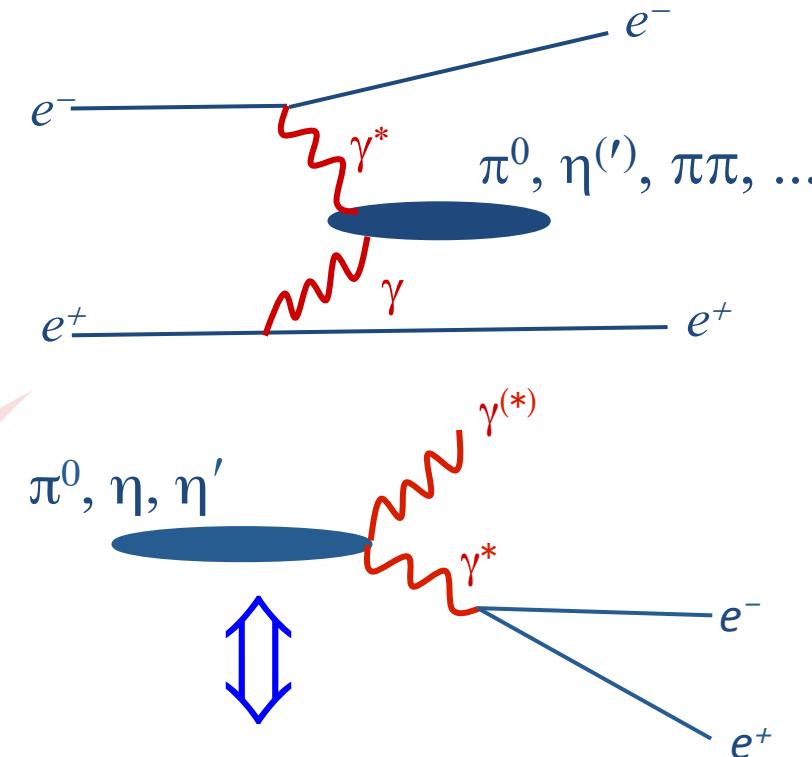


Exp. Input !
Transition
Form Factors $F(Q^2)$
below $\sim 2 \text{ GeV}^2$

Experimental challenges:

Now: measure single-virtual TFF and compare with theory assumption!

Future: provide measurements of double-virtual TFFs



BES III



Problem: double-virtual TFFs needed, for which no measurements exist yet!

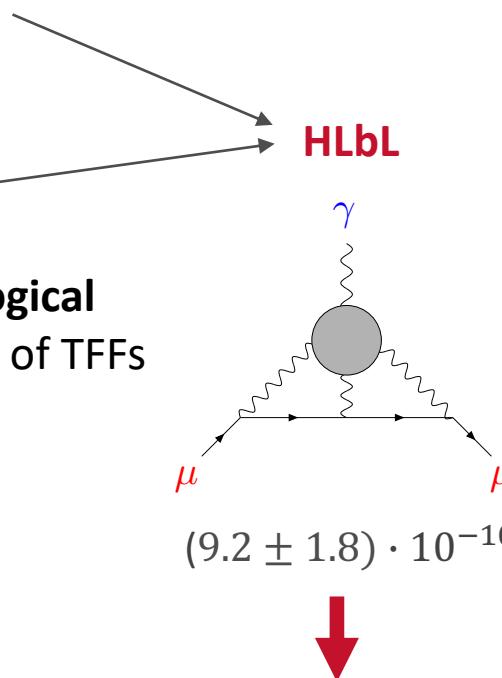
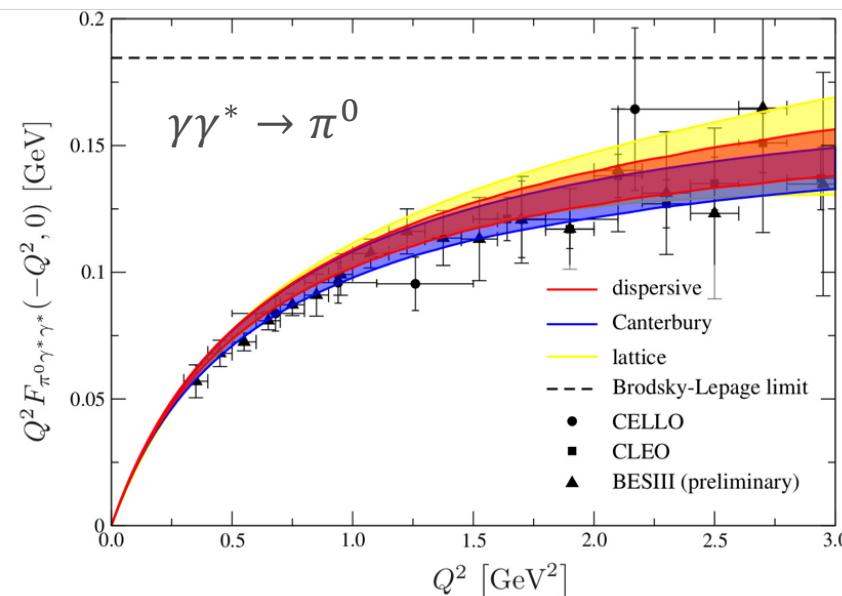
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Joint Research Project: HLbL Contribution to $(g-2)_\mu$

Direct new lattice QCD calculation of HLbL contribution with improved accuracy

Improved estimate of **single- und multi-meson channels** from **BESIII data (pseudo-scalar, $\pi\pi$, $f_1(1285)$, ...)** from **phenomenological analysis**, and from **lattice QCD calculations of TFFs**

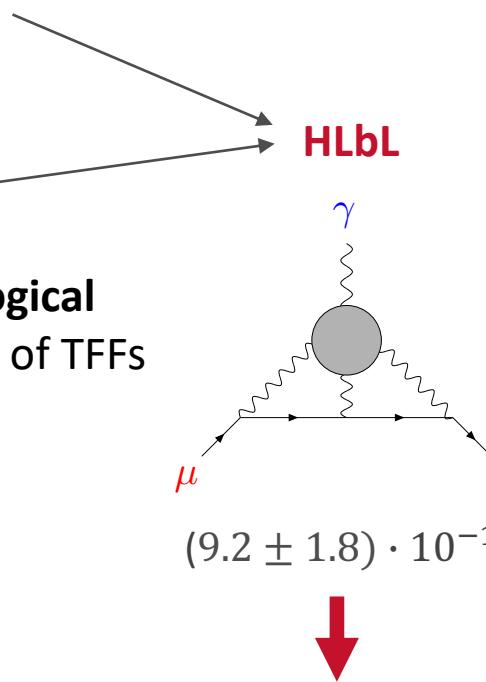
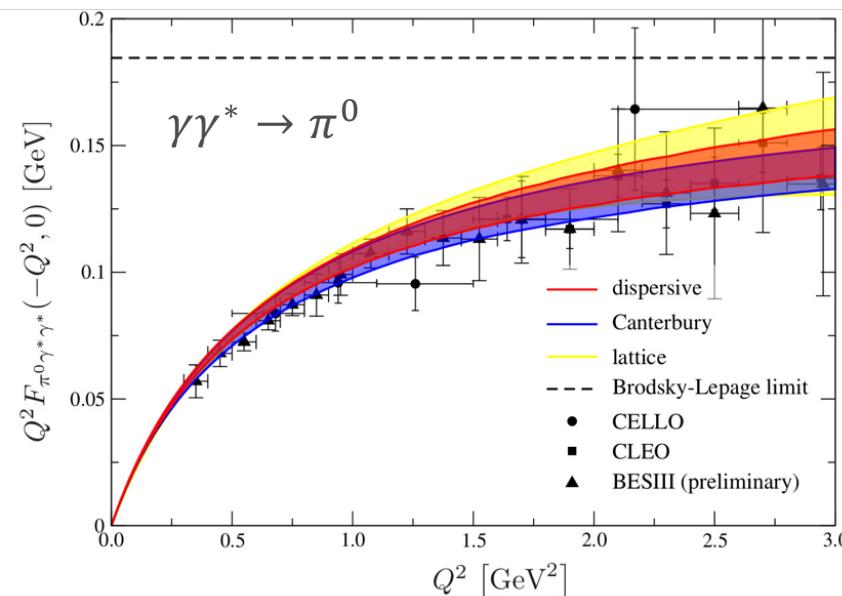


Goal: determine HLbL contribution with 10% relative uncertainty both in lattice QCD and in phenomenology

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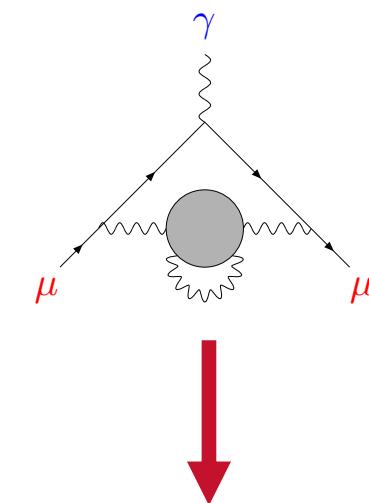
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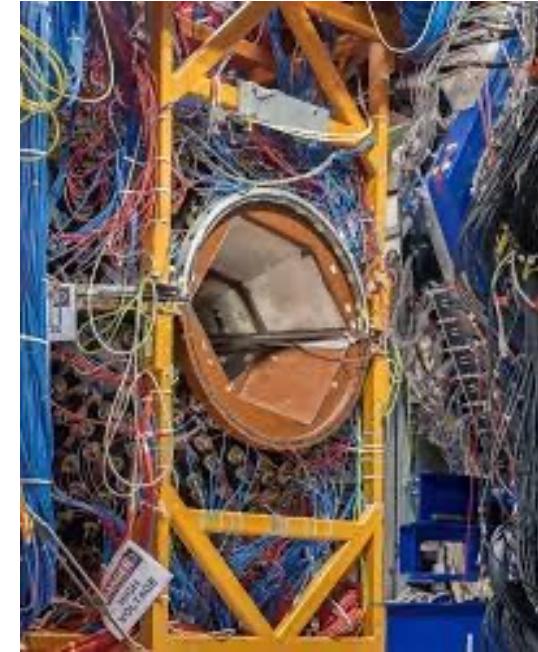
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EM corrections to LO - HVP



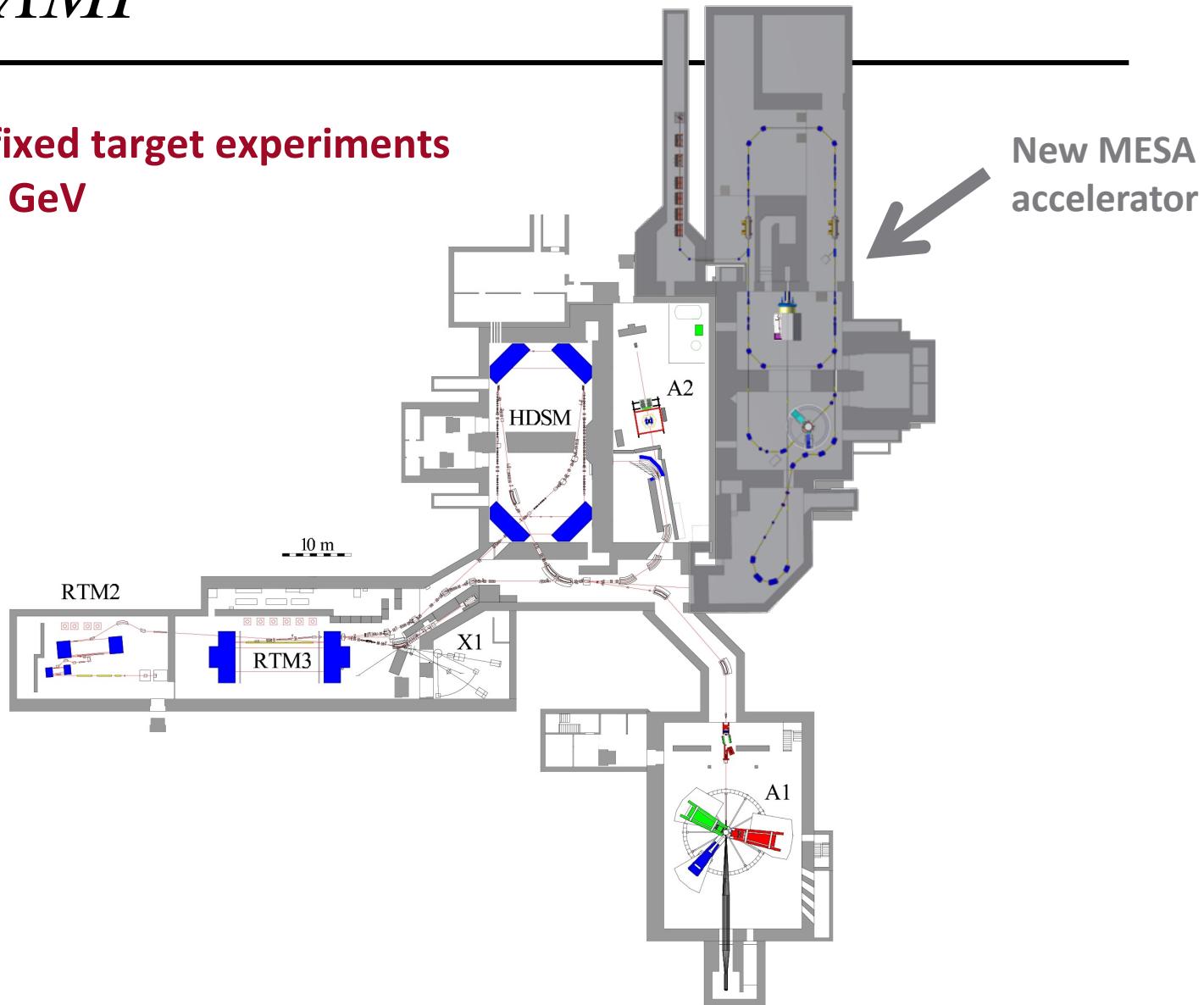
Goal: electromagnetic and iso-spin-breaking corrections to HVP contribution within lattice QCD

Potential for TFF Measurements at A2/MAMI



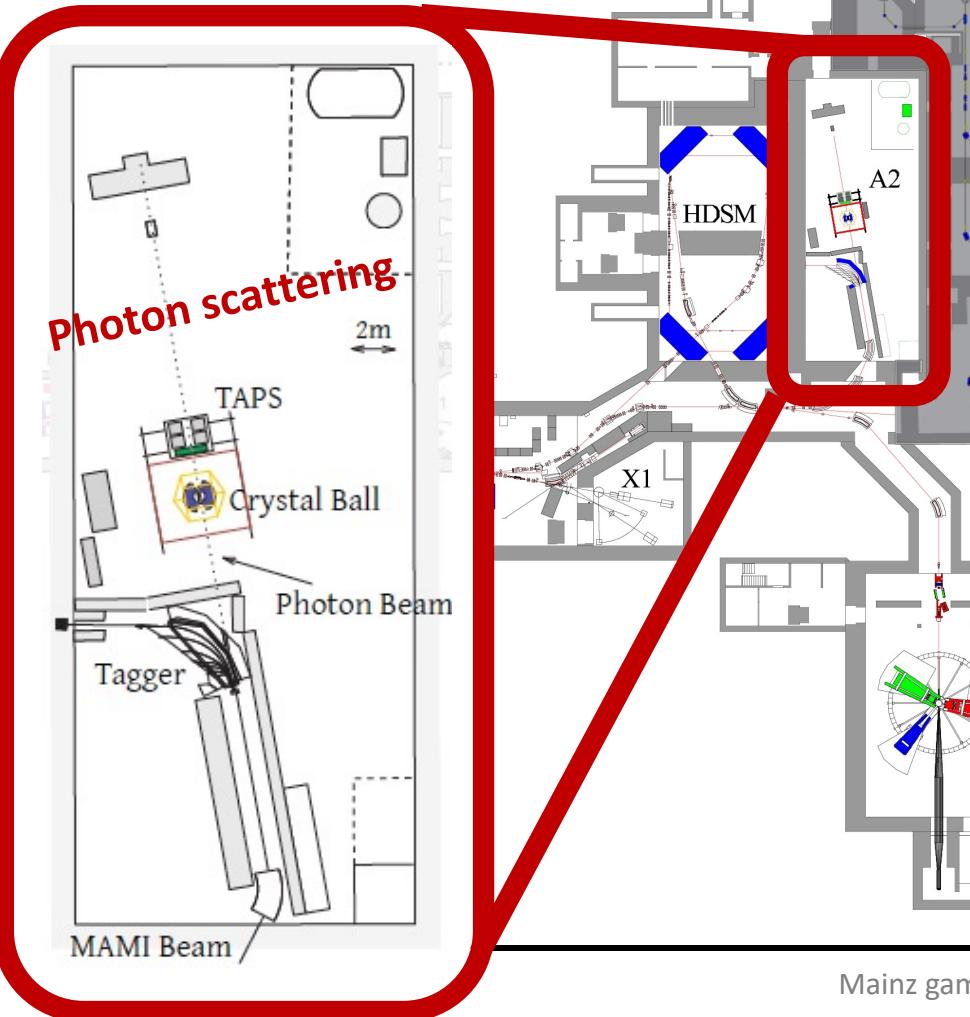
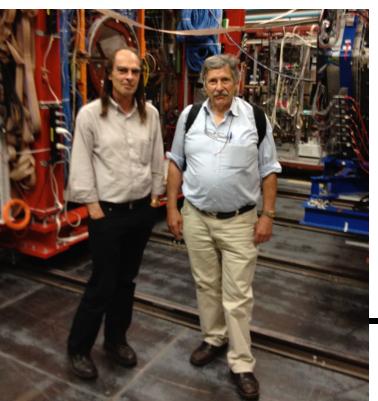
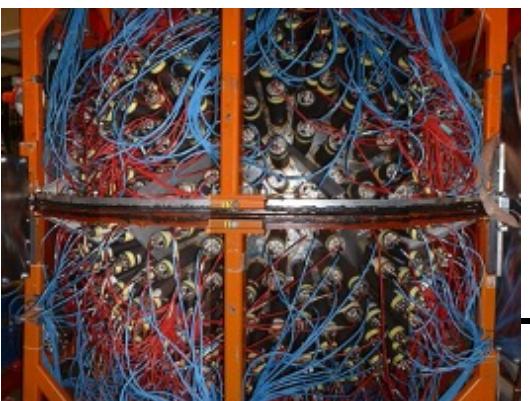
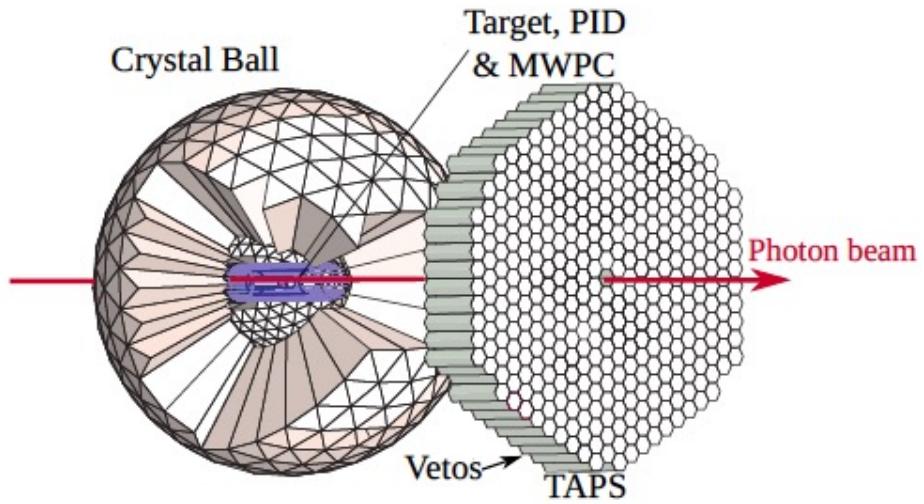
The Mainz Microtron MAMI

**High-intensity CW electron accelerator for fixed target experiments
with electron and photon beams: $E_{\max} = 1.6 \text{ GeV}$**



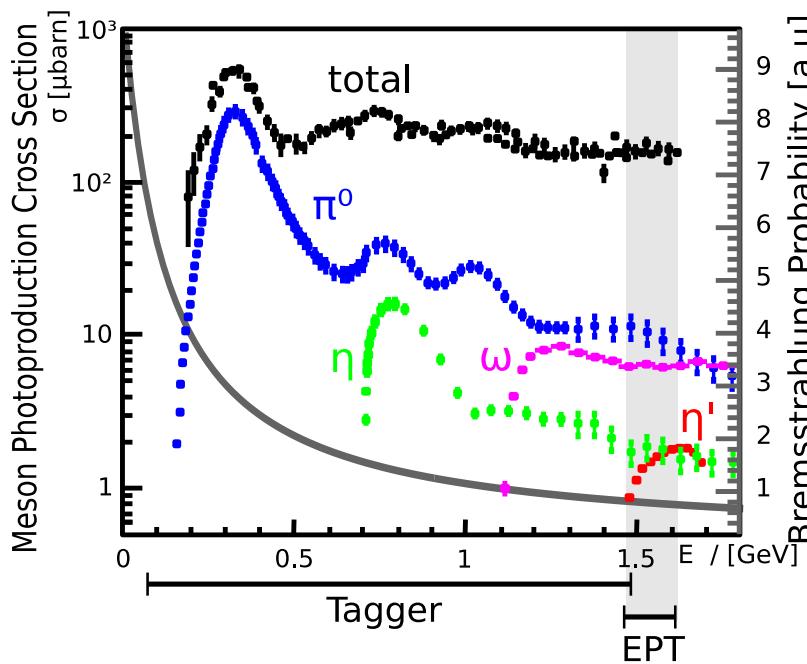
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Mainz gamma-gamma programme for HLbL

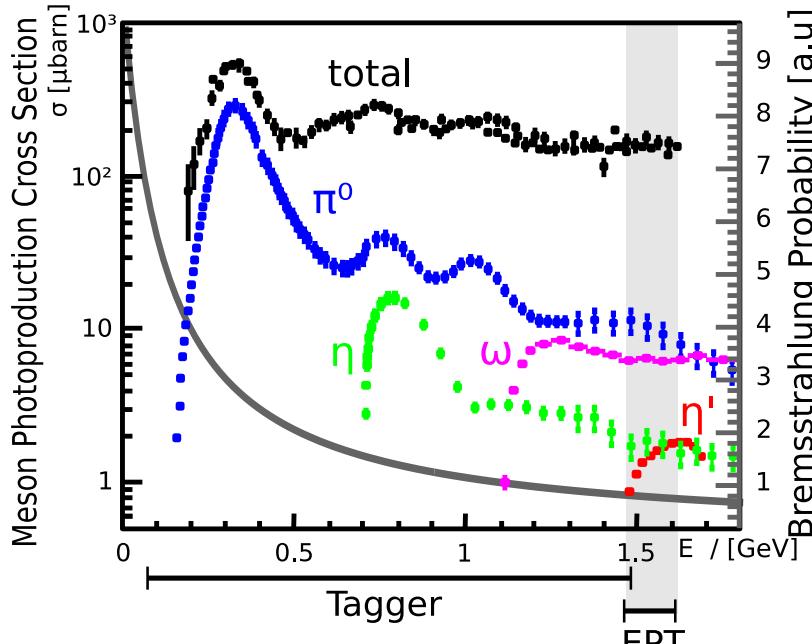
MAMI: a Meson Factory for Measurements of TFFs



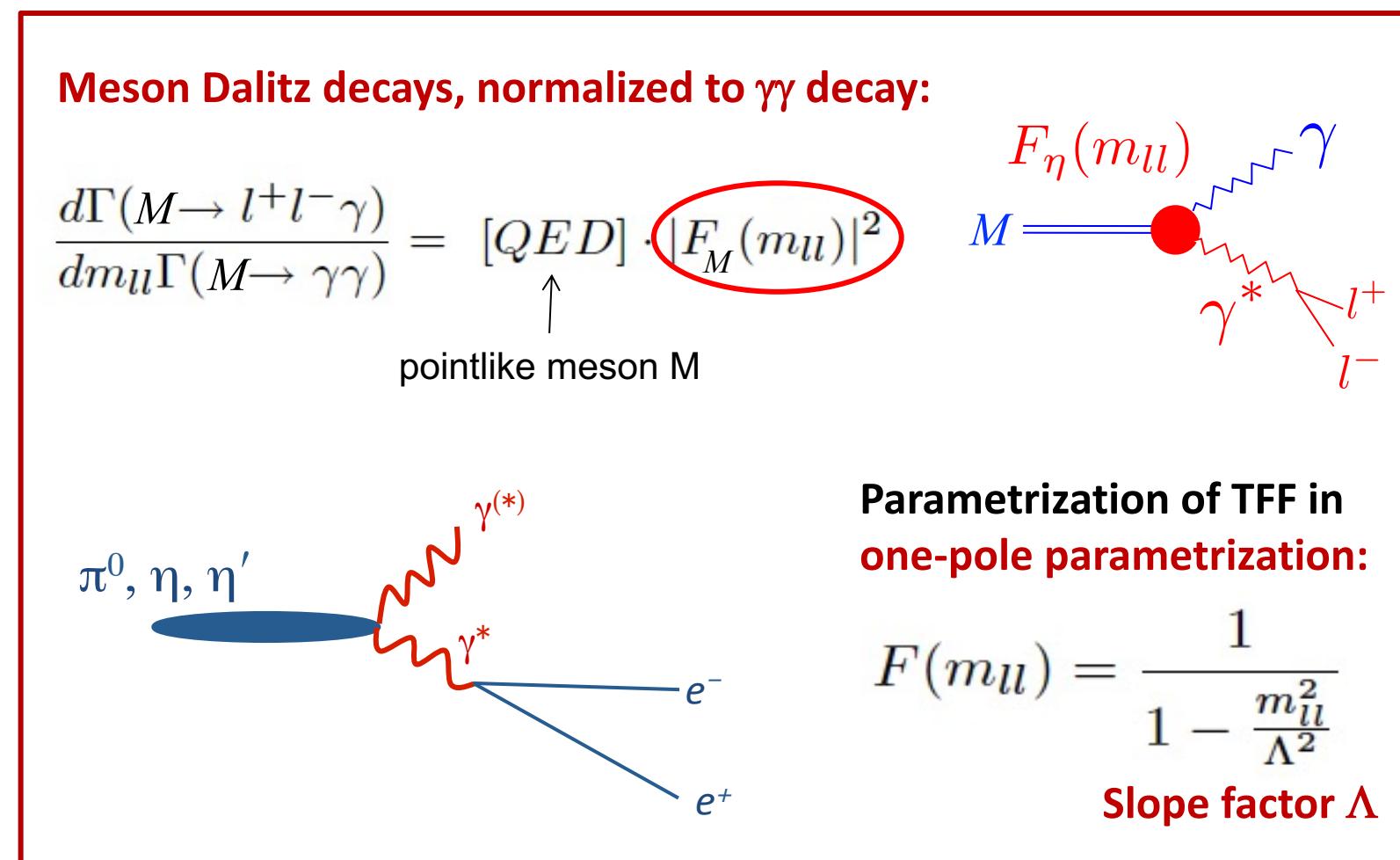
Depending on photon energy,
extremely large cross sections
for meson production on p target:
 $\sim 10^7 \dots 10^9$ mesons/beam time
(corresponding to ~ 3 weeks)

MAMI is a Meson factory
(e.g. world's best data on $\eta \rightarrow 3\pi^0$)

MAMI: a Meson Factory for Measurements of TFFs



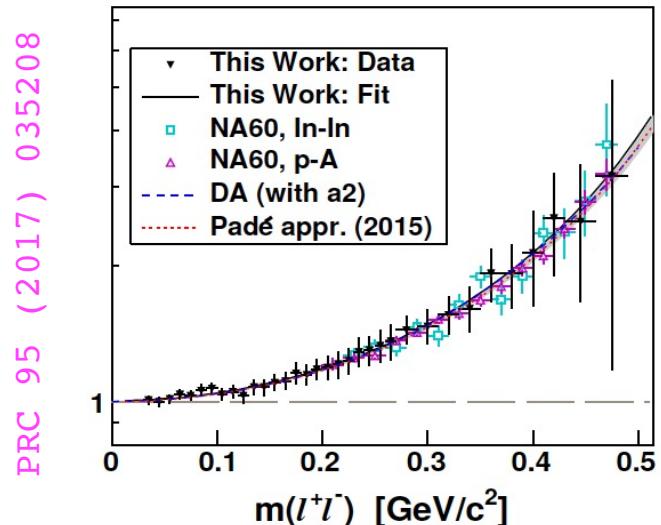
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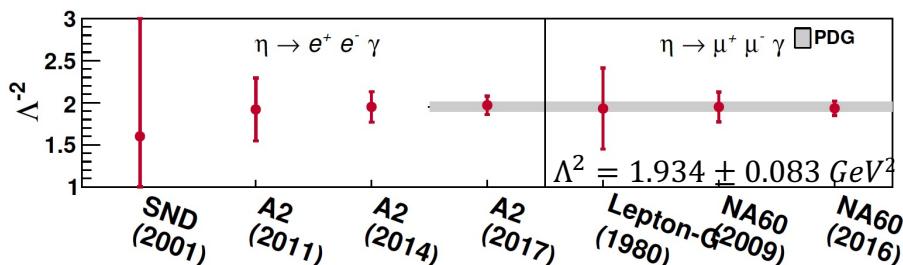
Timelike η and $\omega - \pi^0$ TFFs

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

with $\eta - \eta'$ mixing tool to study light-quark dynamics



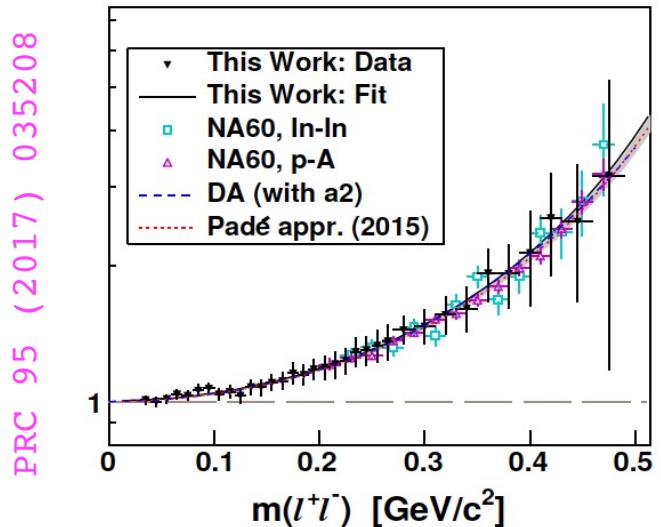
- $5.4 \cdot 10^4 \eta \rightarrow e^+ e^- \gamma$ events, most precise in $e^+ e^-$
- slope parameter: $\Lambda^2 = 1.97 \pm 0.11 \text{ GeV}^2$



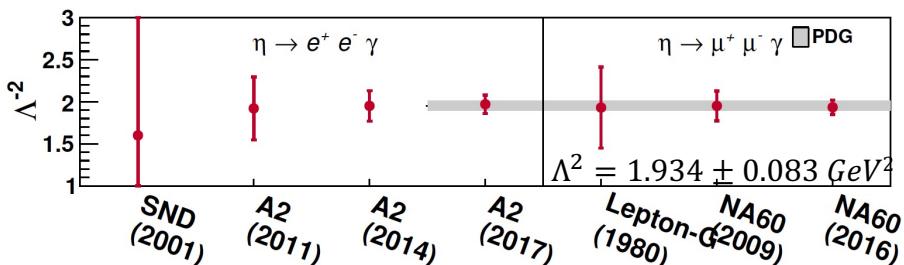
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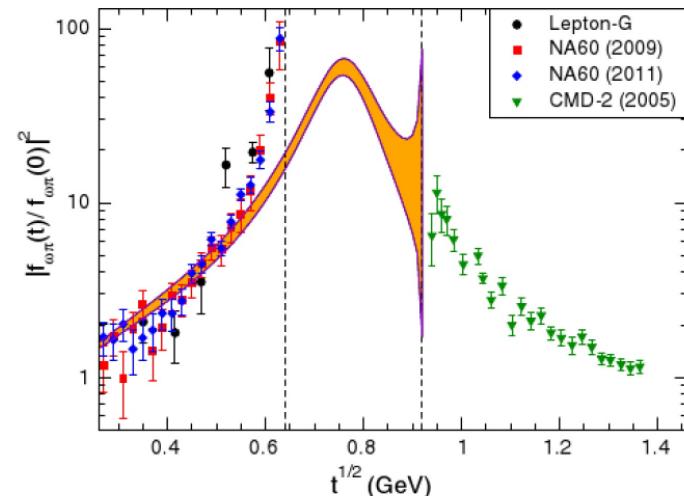


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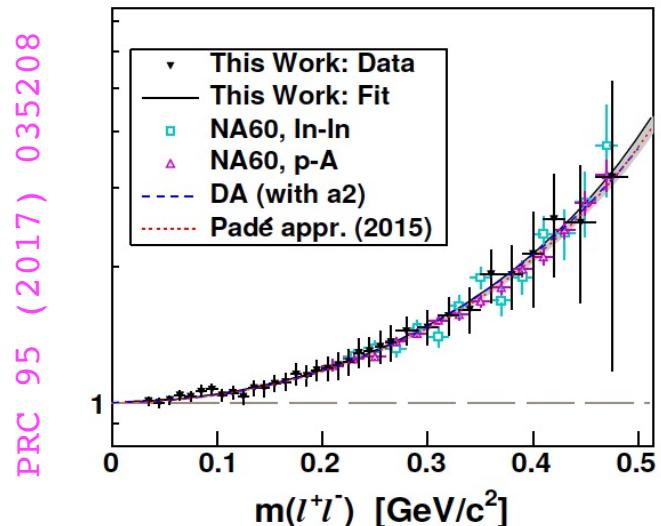
large deviation between NA60 and theoretical models?!



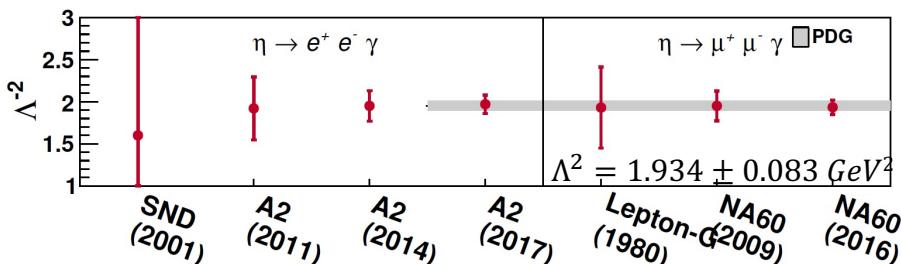
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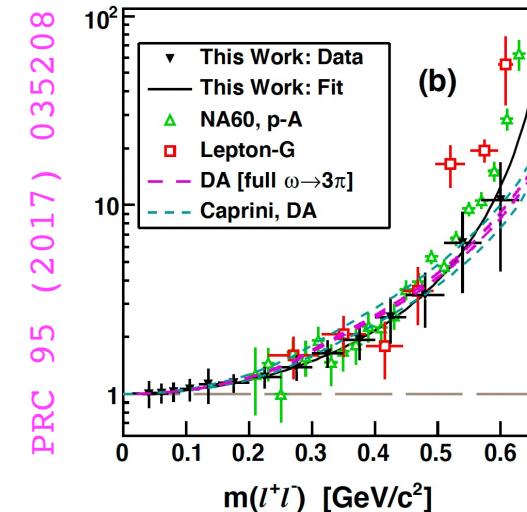


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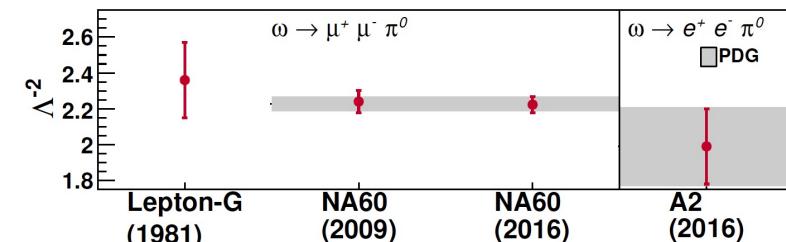
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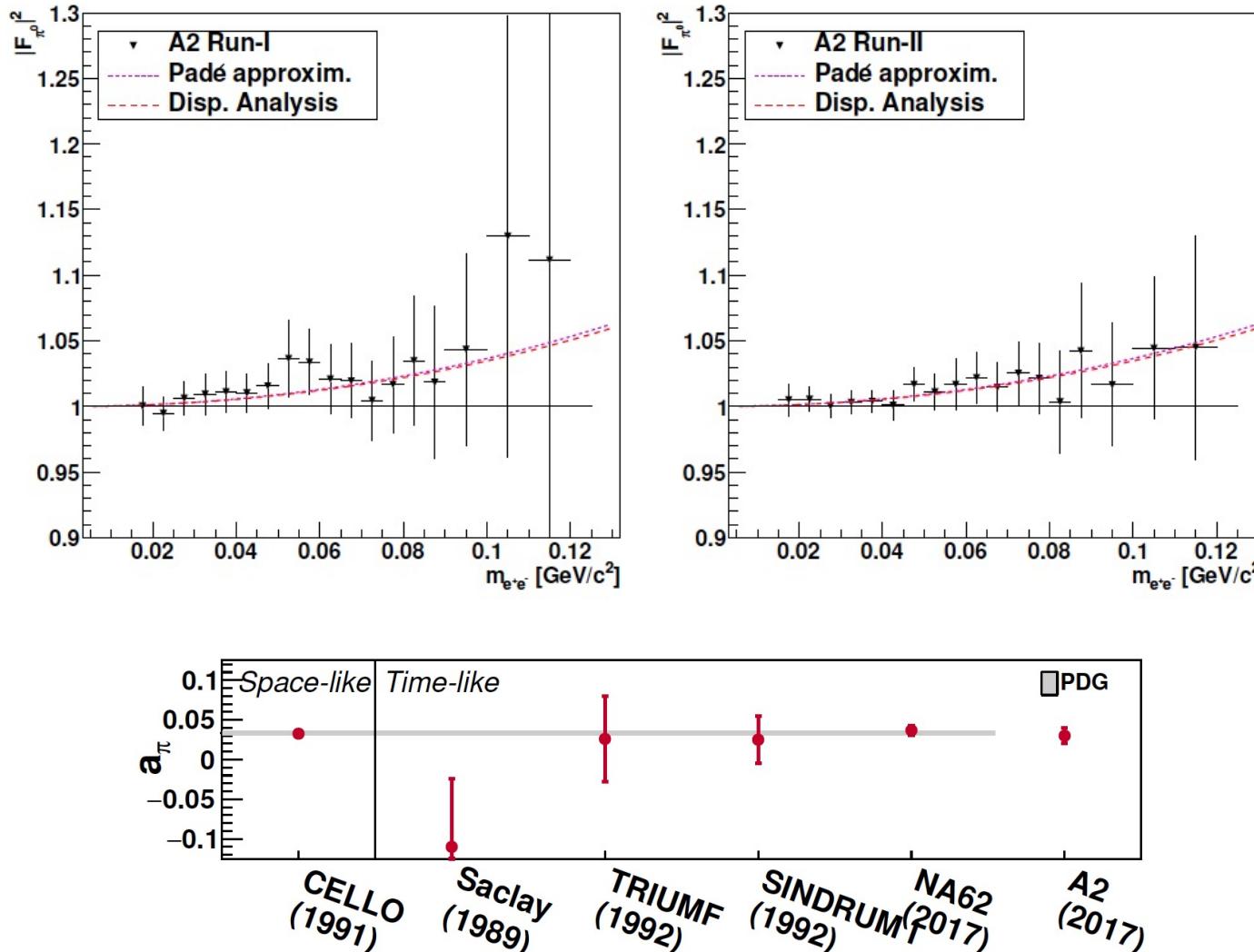
A2: 1100
 $\omega \rightarrow \pi^0 e^+ e^- \gamma$
events

- A2 data not yet competitive (**new data taking ongoing**)
- at given statistics no conflict with theoretical description



Further improvement in future by A2

Timelike Pion TFF: $\pi^0 \rightarrow e^+e^-\gamma$



Feasibility study already lead to first publication [Phys. Rev. C95 \(2017\) 02502](#)

- $4 \cdot 10^5 \pi^0 \rightarrow e^+e^-\gamma$ events
- slope parameter $a_\pi = 0.03 \pm 0.01$ with $a_\pi = m_\pi^2 \cdot \Lambda^{-2}$
- competitive with world's most precise NA62 analysis $a_\pi = 0.0370 \pm 0.0064$

Ongoing A2 project

- New data sample with 5.5 times larger statistics has been collected
- Aiming for world-leading accuracy of slope parameter measurement

Potential for Studying Photon-Photon- Interactions at BESIII

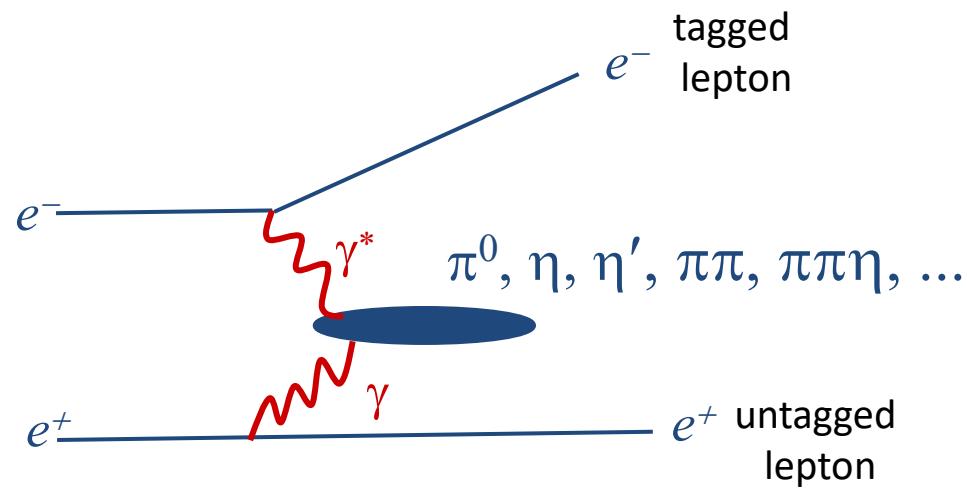


World's by far largest τ -charm dataset in e^+e^- annihilation:

- Symmetric e^+e^- collider
- Located at IHEP Beijing, China
- CMS energy: 2 GeV to 5 GeV
- Maximum luminosity: $1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

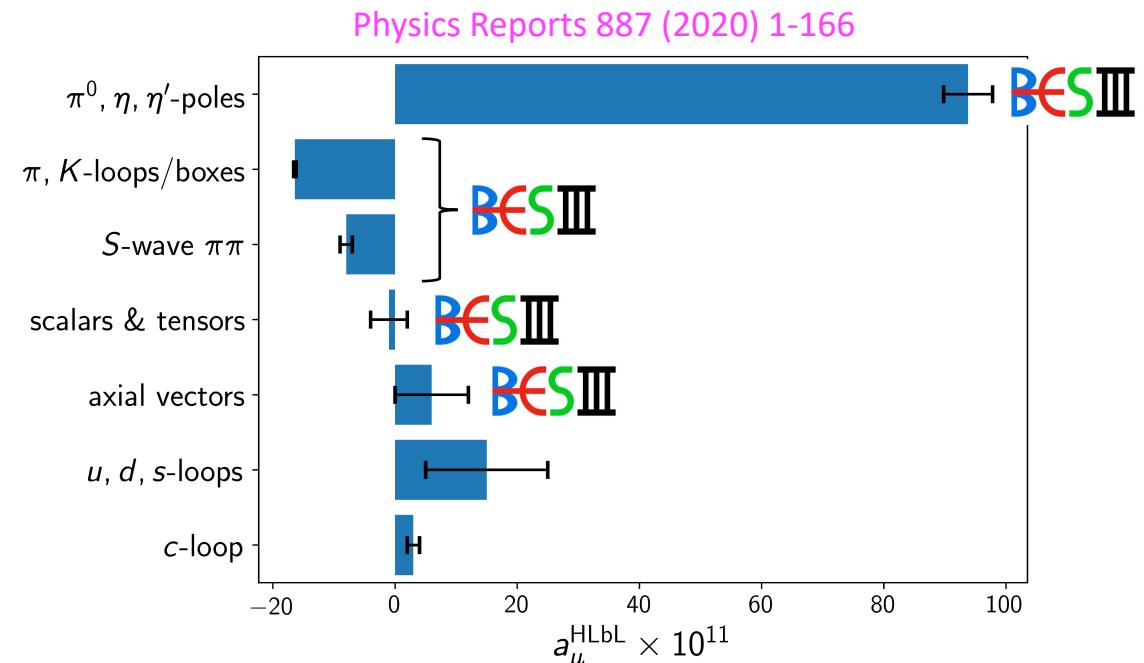
Two-Photon Physics Program at BESIII

**Meson Transition Form Factors (TFFs)
in photon-photon fusion reactions
Single Tag Method (space-like)**



$$Q^2 = 4 \cdot E \cdot E' \cdot \sin^2\left(\frac{\theta}{2}\right)$$

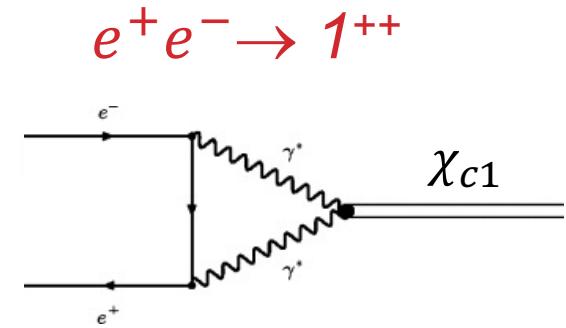
BESIII: $0.2 < Q^2 < 3 \text{ GeV}^2$; B factories: $Q^2 > 3 \text{ GeV}^2$



- The C-even states can be produced directly through a process with two virtual photons or neutral current reaction
- Up to now, in e^+e^- annihilation only vector resonances with $J^{PC}=1^{--}$ observed
- Experimental null searches so far for:
 $\eta, \eta', f_0(980), f_0(1300), f_2(1270), a_0(980), a_2(1320)$, and $X(3872)$ from Novosibirsk and BEPC-II
Recent evidence for the production of $f_1(1285)$ at SND/VEPP-2000 (2 events, 2.5σ)
- The production rate is proportional to the electronic width of the states (Γ_{ee}).

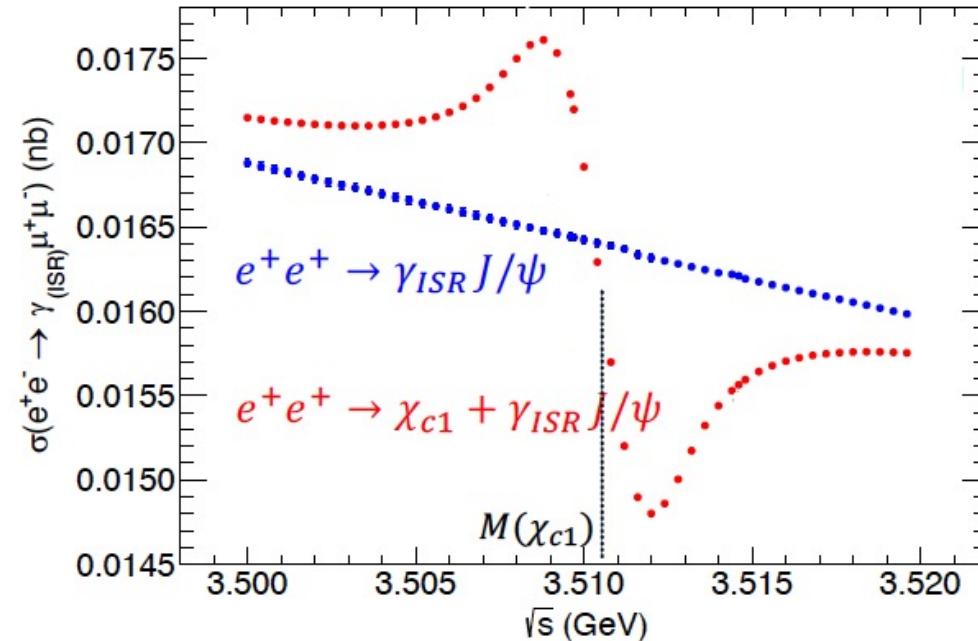
For the χ_{c1} state:

- Unitarity limit: $\Gamma_{ee} > 0.044$ eV Kaplan, Kühn, Phys. Lett. B78 (1978) 252
- Vector Dominance Model: $\Gamma_{ee} = 0.46$ eV; OR $\Gamma_{ee} \sim 0.1$ eV Kühn, Kaplan, Safiani, Nucl. Phys. B157 (1979) 125
A.D., Guo, Hanhart, Nefediev, Phys. Lett. B736 (2014) 221
- Non-relativistic QCD: $\Gamma_{ee} \sim 0.1$ eV Kivel, Vanderhaeghen, J. High. Energy Phys. 2 (2016) 32
- Latest prediction: $\Gamma_{ee} = 0.43$ eV; interference with background process! Czyz, Kühn, Tracz, Phys. Rev. D94 (2016) 034033



Prediction for $e^+e^- \rightarrow \chi_{c1}$ from Czyz, Kühn, Tracz

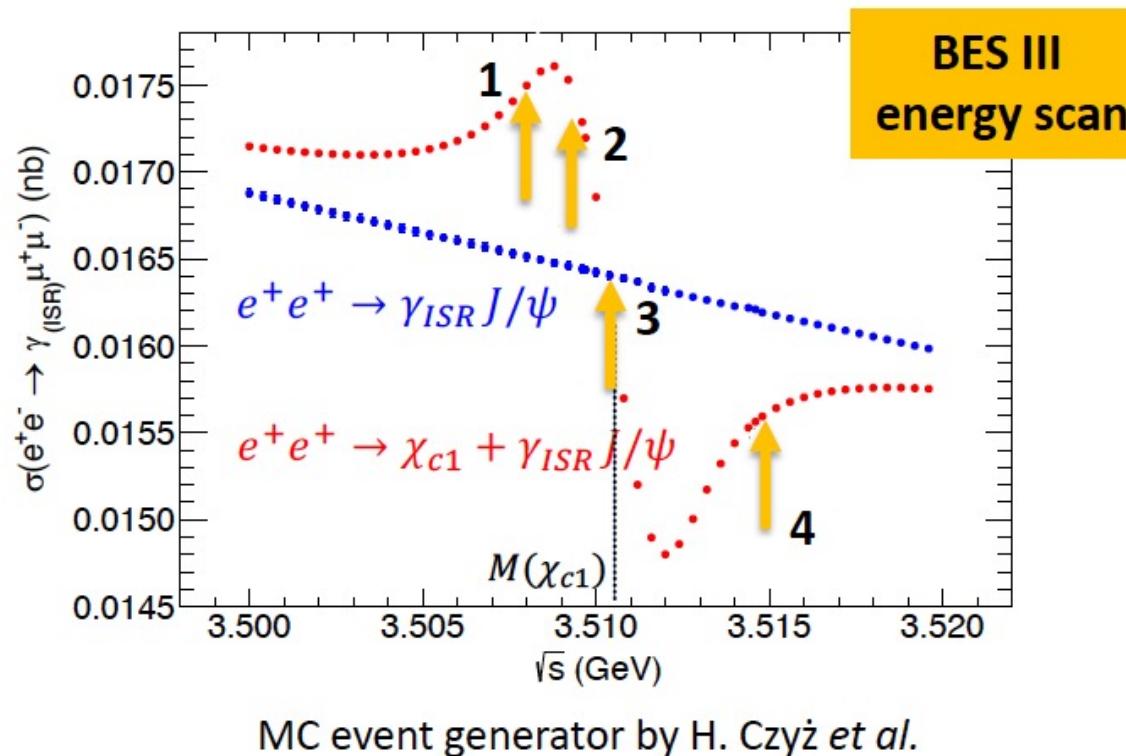
- Search for χ_{c1} in it's main decay channel (35% B.R.): $\chi_{c1} \rightarrow J/\psi \gamma \rightarrow \mu^+\mu^- \gamma$
- Large interference effects (phase angle ϕ) \rightarrow distortion of the total cross section
- Implemented in PHOKHARA event generator



MC event generator by H. Czyż *et al.*

Prediction for $e^+e^- \rightarrow \chi_{c1}$ from Czyz, Kühn, Tracz

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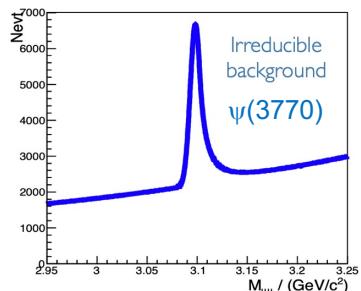
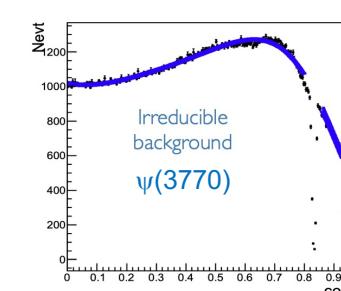
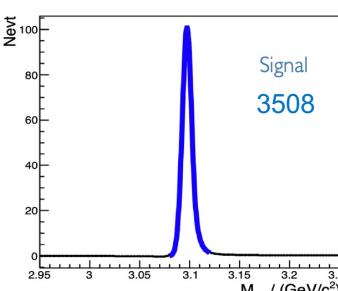
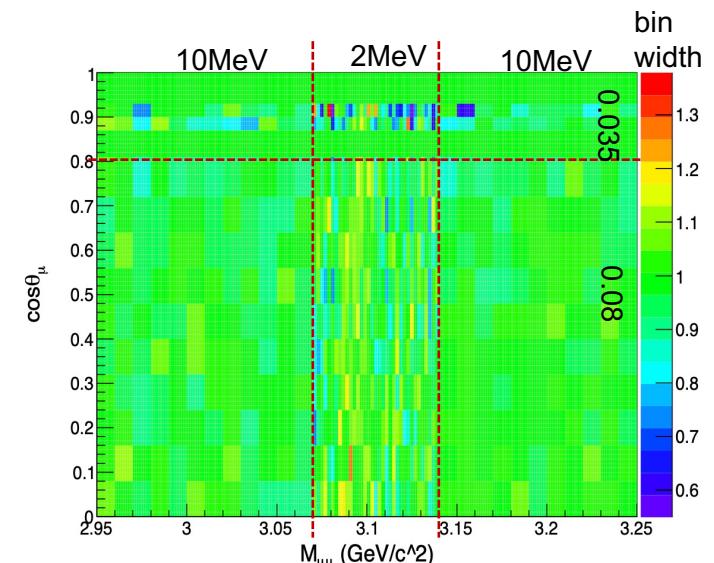
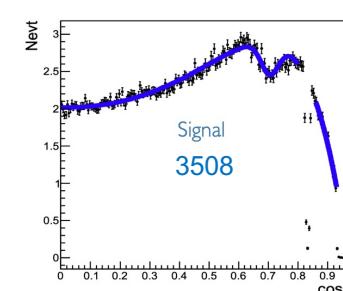


- BESIII energy scan around χ_{c1} mass
- Precise energy determination via BEMS (Compton backscattering measured in HP-Ge)

Data Sample	$E_{\text{cms}} [\text{GeV}]^*$	Lumi. [1/pb]
1	3.5080	$181.79 \pm 0.04 \pm 1.04$
2	3.5097	$39.29 \pm 0.02 \pm 0.22$
3	3.5104	$183.64 \pm 0.04 \pm 1.05$
4	3.5146	$40.92 \pm 0.02 \pm 0.23$

Analysis Strategy $e^+e^- \rightarrow \chi_{c1} \rightarrow \gamma J/\psi \rightarrow \gamma\mu^+\mu^-$

- Validate the description of the ISR background simulated with PHOKHARA generator by using:
 - High statistics data samples at $\psi(3770)$ and 4.178 GeV, $\sim 3 \text{ fb}^{-1}$ each
 - Off-peak data samples at 3.581 GeV and 3.670 GeV, $\sim 85 \text{ pb}^{-1}$ each
- Check $e^+e^- \rightarrow \chi_{c1}$ signal** by searching for excess (reduction) of events beyond ISR background both in:
 - $\mu^+\mu^-$ mass spectrum
 - Polar angle distribution of muon tracks

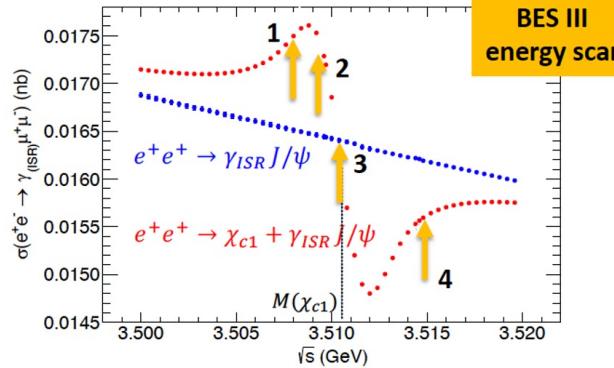
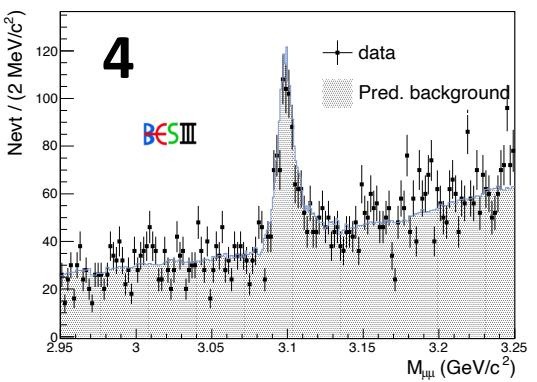
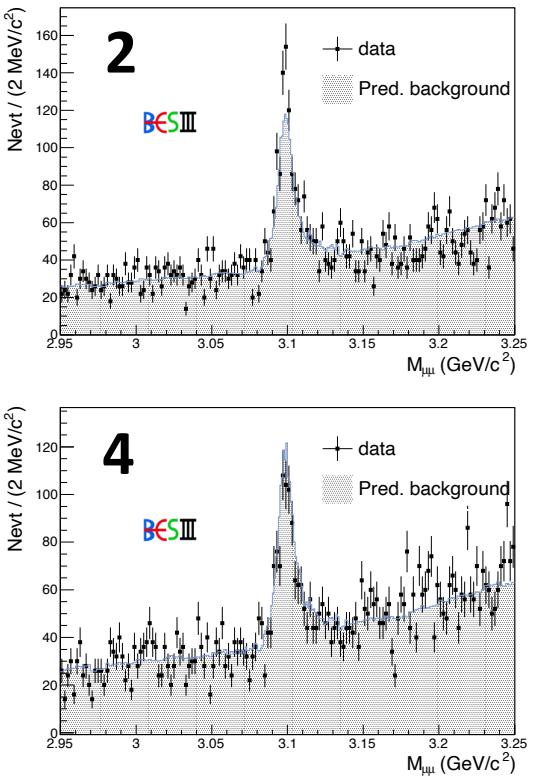
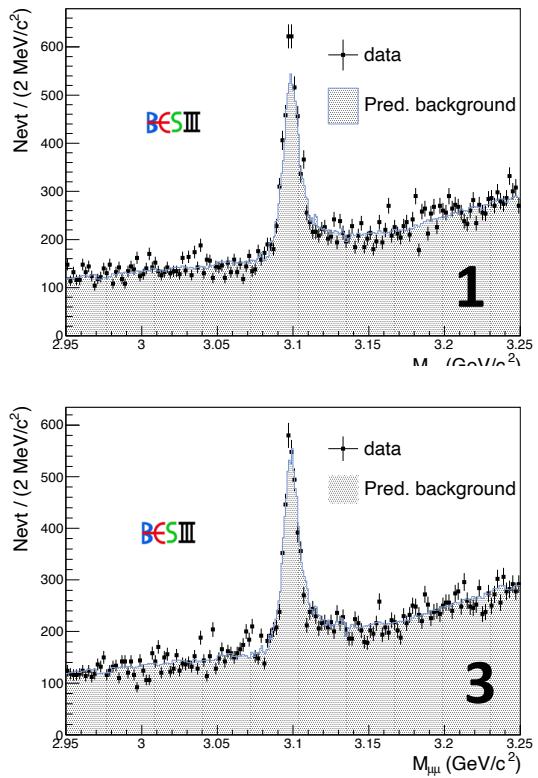
Projection on $M(\mu^+\mu^-)$ Projection on $|\cos\theta_\mu|$ 

Correction factors

- Two-dimensional fit to search for excess of events beyond ISR background

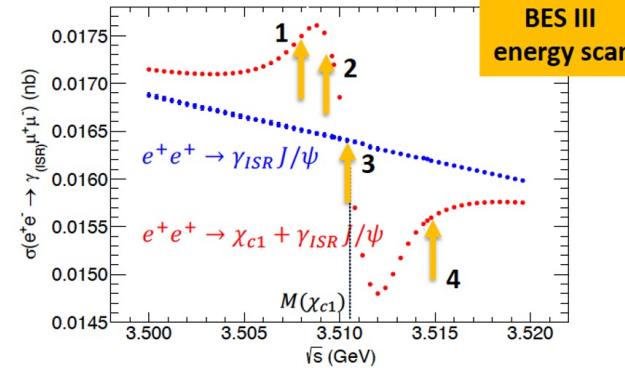
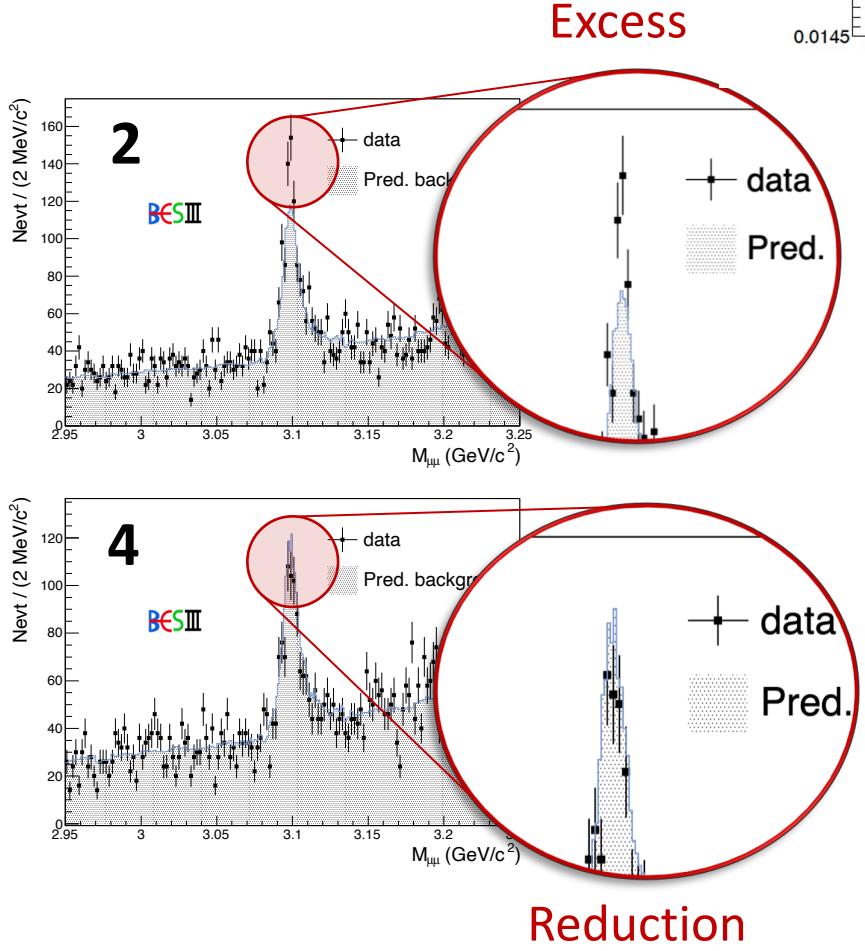
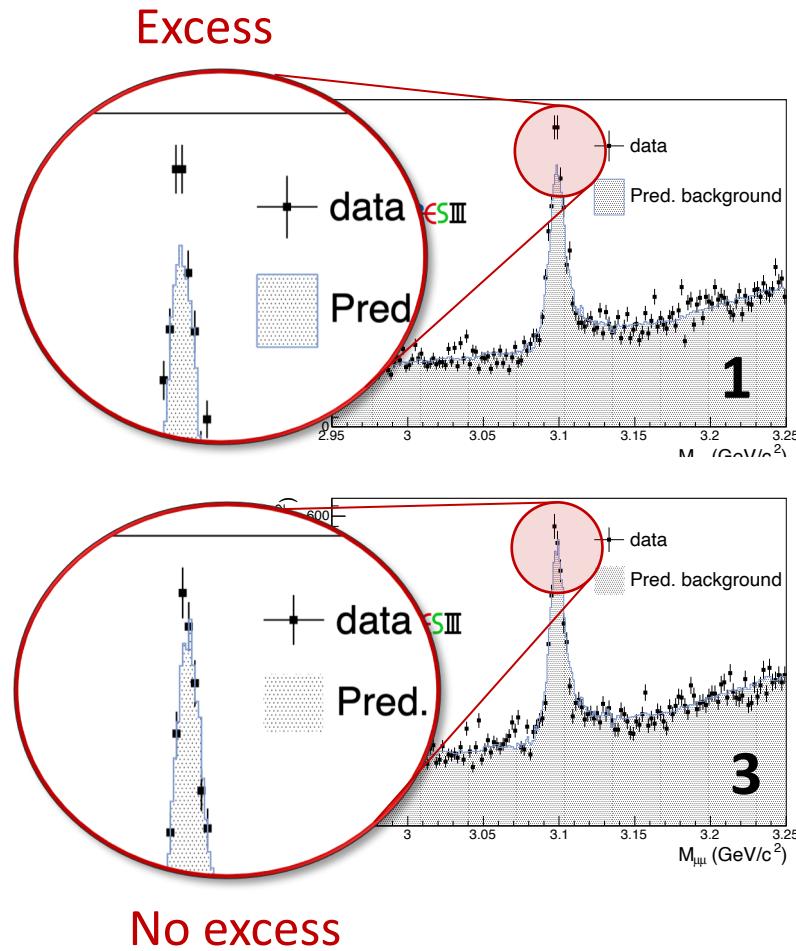
Mass Spectra $e^+e^- \rightarrow \gamma J/\psi$

Mass spectra of 4 scan points after calibration procedure:



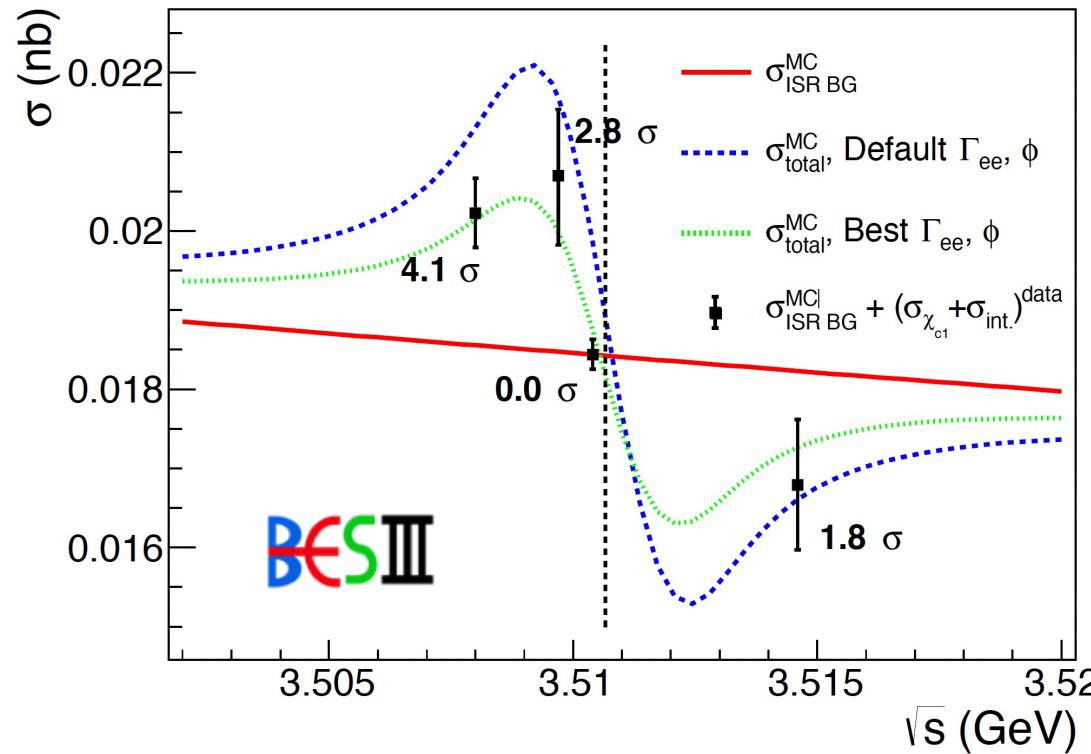
Mass Spectra $e^+e^- \rightarrow \gamma J/\psi$

Mass spectra of 4 scan points after calibration procedure:



Observation of $e^+e^- \rightarrow \chi_{c1}$ with 5.1σ Significance

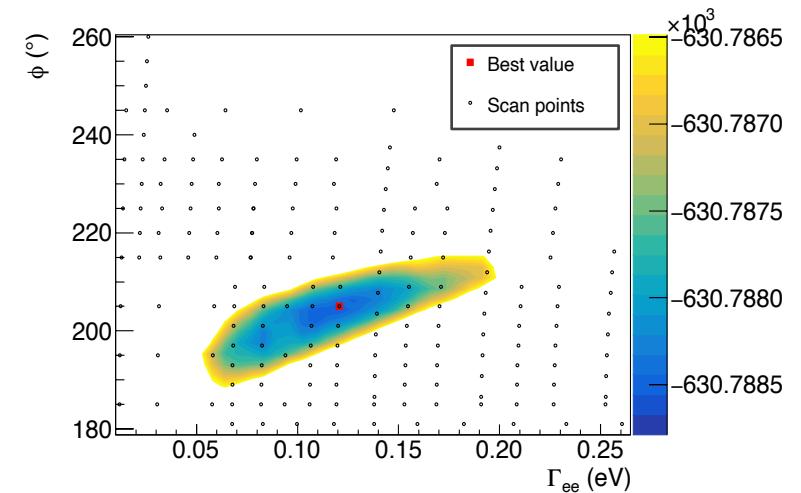
Combination of 4 energy points yields a significance of 5.1σ :
First observation of a non-vector resonance in e^+e^- annihilation!



NEW

Common fit to all 4 scan points
→ first measurement of Γ_{ee}

$$\Gamma_{ee} = 0.12^{+0.13}_{-0.08} \text{ eV}, \phi = 205^{\circ \pm 15.4^{\circ}}_{-22.4^{\circ}}$$



arxiv:2203.13782
accepted for publication in Phys. Rev. Lett.

Conclusions and Outlook

Conclusions

- New **Research Unit on Photon-Photon interactions** at JGU Mainz, bundles Mainz efforts in:
 - Lattice QCD calculations (HVP + HLbL)
 - Hadron Phenomenology (dispersion relations & sum rules)
 - Experiment aiming for improved TFFs (BESIII → Christoph Redmer & A2/MAMI)

Spin-offs besides HLbL for muon g-2: XYZ physics, LBL, Axion searches
- Successful track record and perspectives for **TFF measurements at A2/MAMI**
 - Upcoming new π^0 TFF
 - Upcoming new $\omega - \pi^0$ TFF
- **First observation of production of non-vector meson (χ_{c1}) at e^+e^- collider**
 - New avenue for investigations of hadrons in e^+e^- physics
 - Measure properties of conventional and exotic mesons in electron-positron collision, e.g. X(3872)
 - **Application of method for light-quark mesons → input for HLbL (g-2)_μ**