Working to solve the muon g-2 puzzle

Perspectives for a measurement of the pion form factor with 0.5% precision at BESIII

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with Prof. Dr. Achim Denig and Dr. Riccardo Aliberti
on behalf of the **CRC1660 - B03 Project**

BESIII DFG Deutsche Forschungsgemeinschaft Hadrons Nuclei CRC 1660 JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U

Precision tests of the SM

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \longrightarrow \text{gauge fields}$$

$$+ i\bar{\psi} \not{D} \psi + h.c. \longrightarrow \text{interactions}$$

$$+ y_{ij}\, \bar{\psi}_i \phi \psi_j + h.c. \longrightarrow \text{Yukawa coupling}$$

$$+ |D_\mu \phi|^2 - V(\phi) \longrightarrow \text{Higgs sector}$$

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WHY?

Search for deviations, possible new physics, and validation of the theory.

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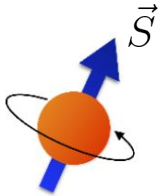

Leptons of the SM

Interacts with external magnetic fields

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{S}$$

g-factor => OBSERVABLE

Magnetic moment of the (electron, muon, tau…)

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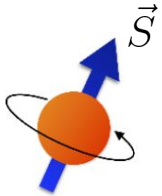

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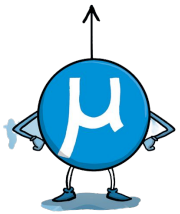
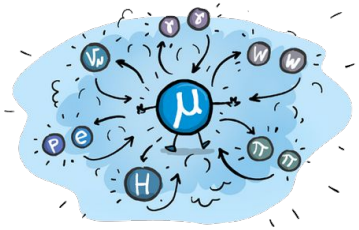
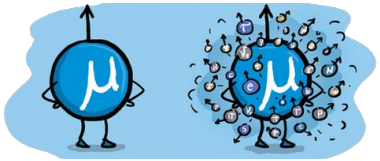


$g = 2$

Inclusion of SM interactions





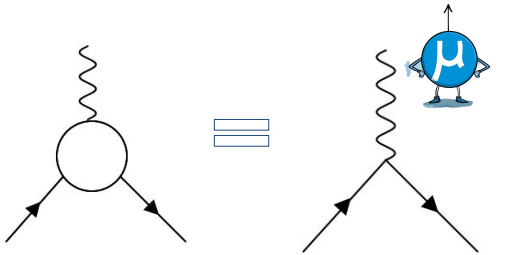
$g = 2$ $\quad g \neq 2$

Anomalous Magnetic Moment

$$a_\mu = \frac{g-2}{2}$$

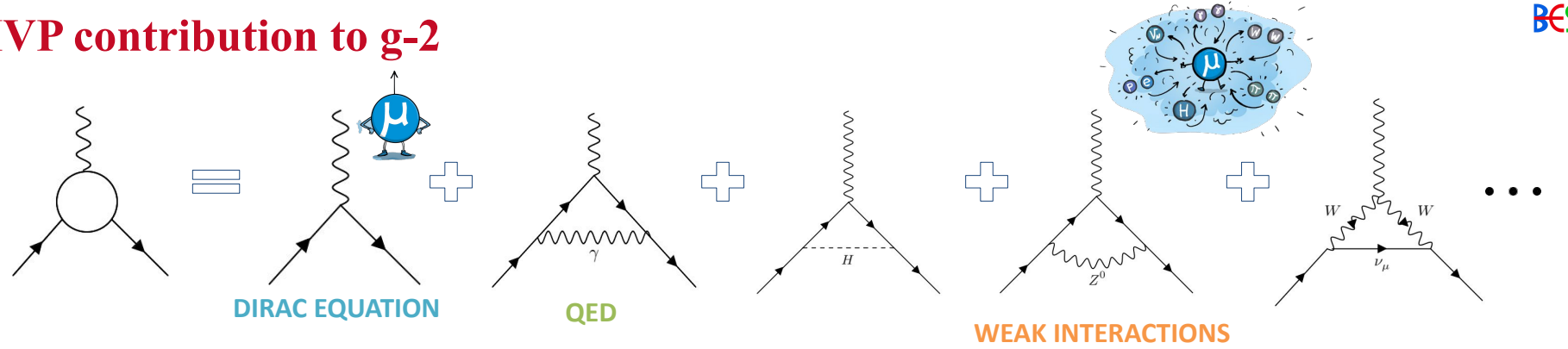
by Jorge Cham

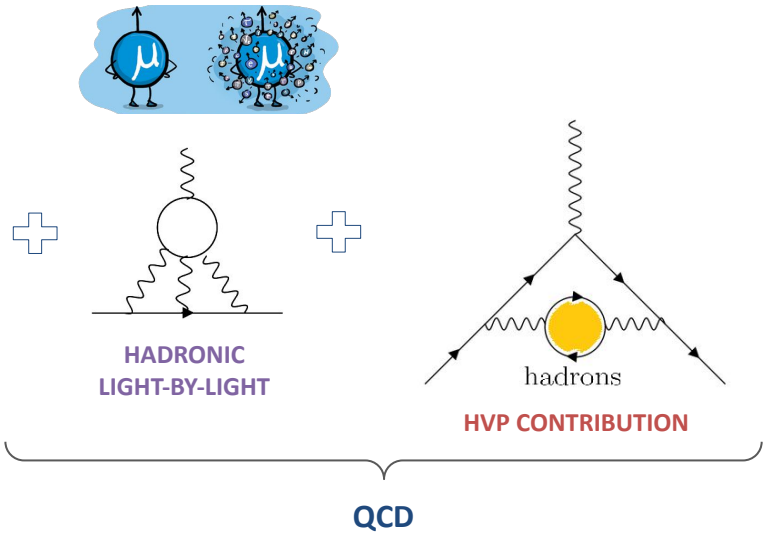
HVP contribution to g-2



DIRAC EQUATION

HVP contribution to g-2





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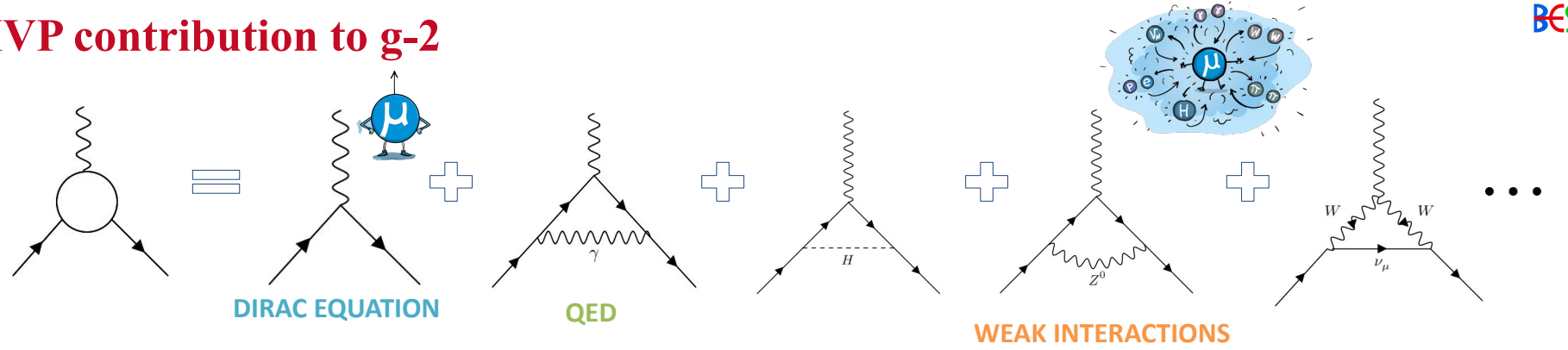
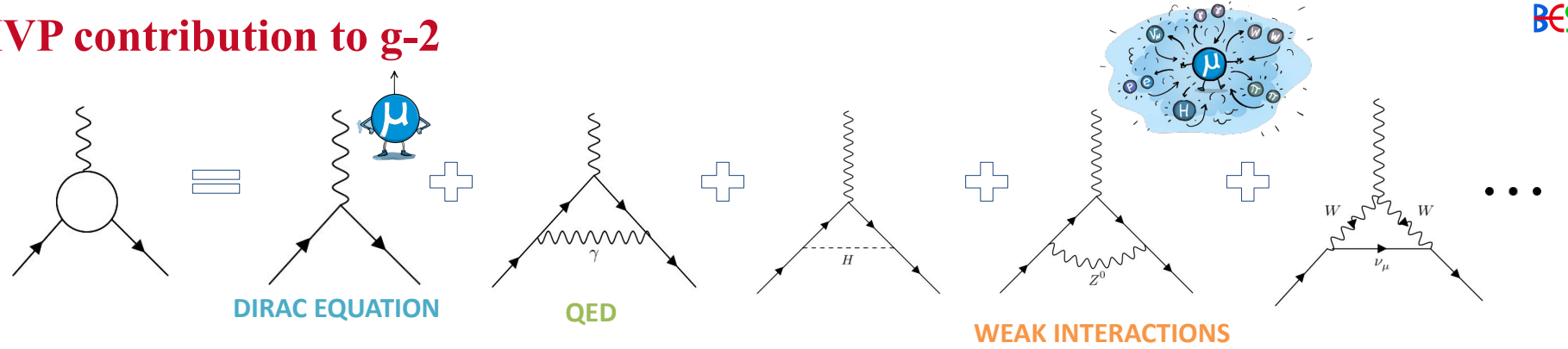


Hadronic vacuum polarization (HVP) is responsible for ~90% of the uncertainty in SM prediction to muon g-2 (WP20).

It can be computed following different approaches:

- Dispersive/data-driven approach;
- Lattice QCD approach.

HVP contribution to g-2



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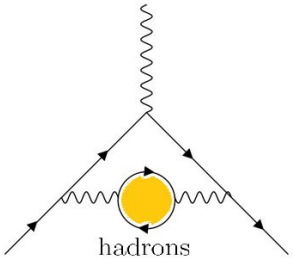
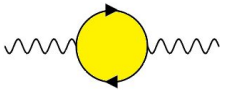
Data-driven approach



The HVP contribution is related to the **imaginary part** of the **2-point correlator of EM quark currents**



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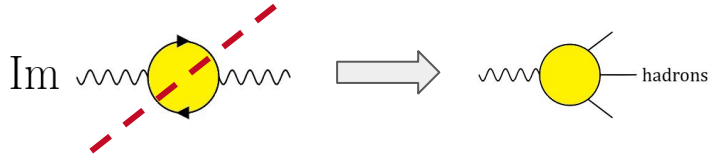
from **Optical Theorem**



HADRONIC CROSS SECTIONS

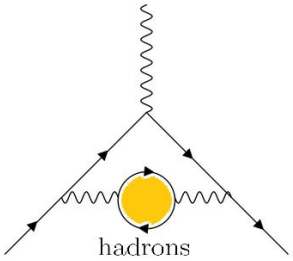
Dispersive Relation

$$a_\mu^{\rm HVP,\,LO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{\hat{K}(s)}{s^2} R_{\rm had}(s)$$

$$R_{\rm had}(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

Experimental data! (inclusive/exclusive inputs)

Data-driven approach



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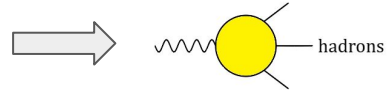

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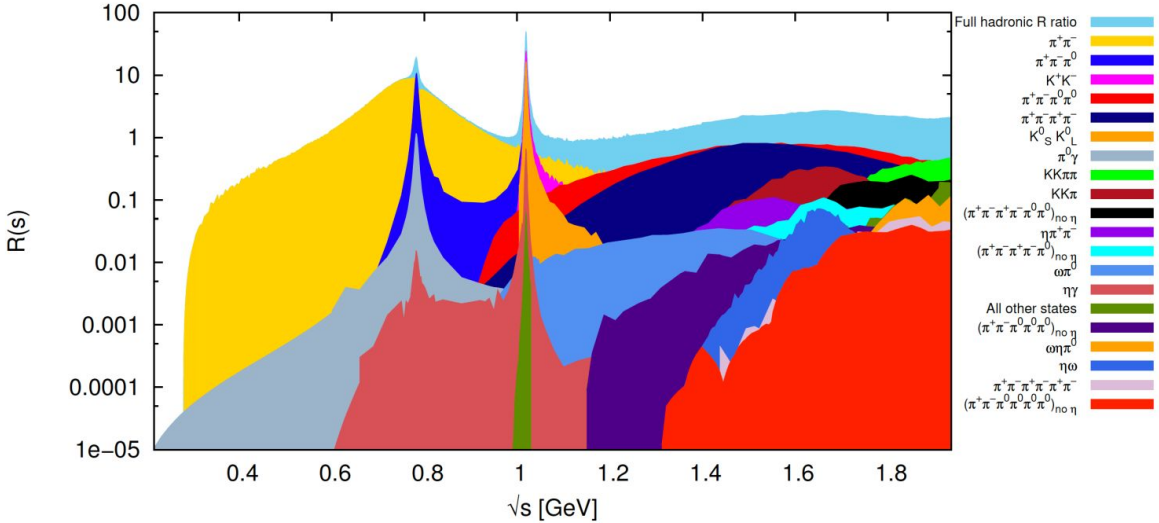
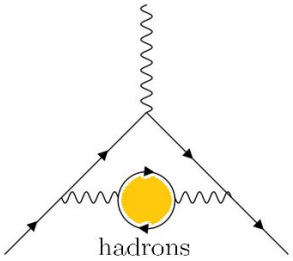
Due to the **QED Kernel function** (*K(s)*), the major contribution to this integral comes from the low-energy regime, which is dominated by the **$\pi^+\pi^-$ channel**



[Keshavarzi, Nomura, Teubner (KNT19). 1802.02995]

Data-driven approach



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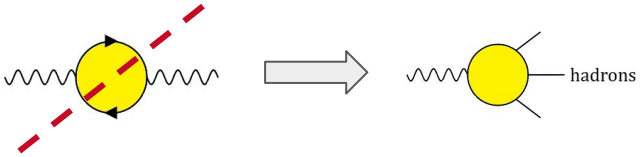

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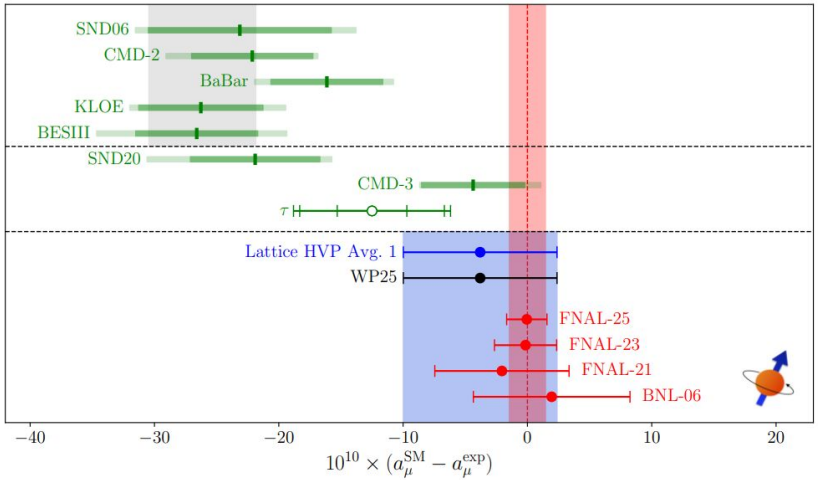

[Aliberti et al. (WP25), 2505.21476]

Tensions in the HVP data-driven results between **different $\pi^+\pi^-$ datasets** inputs.

Tension between HVP and Lattice computations comes mostly from the **$\pi^+\pi^-$ channel contribution.**

[BBGKMP, 2306.16808]

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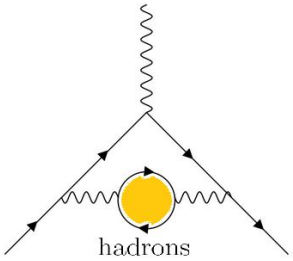

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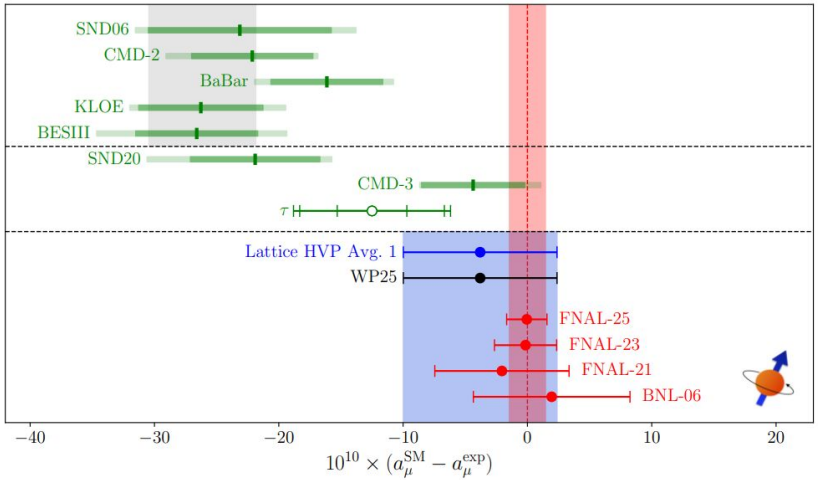
BESIII on the way to provide **new data inputs** for the HVP discussion in g-2!



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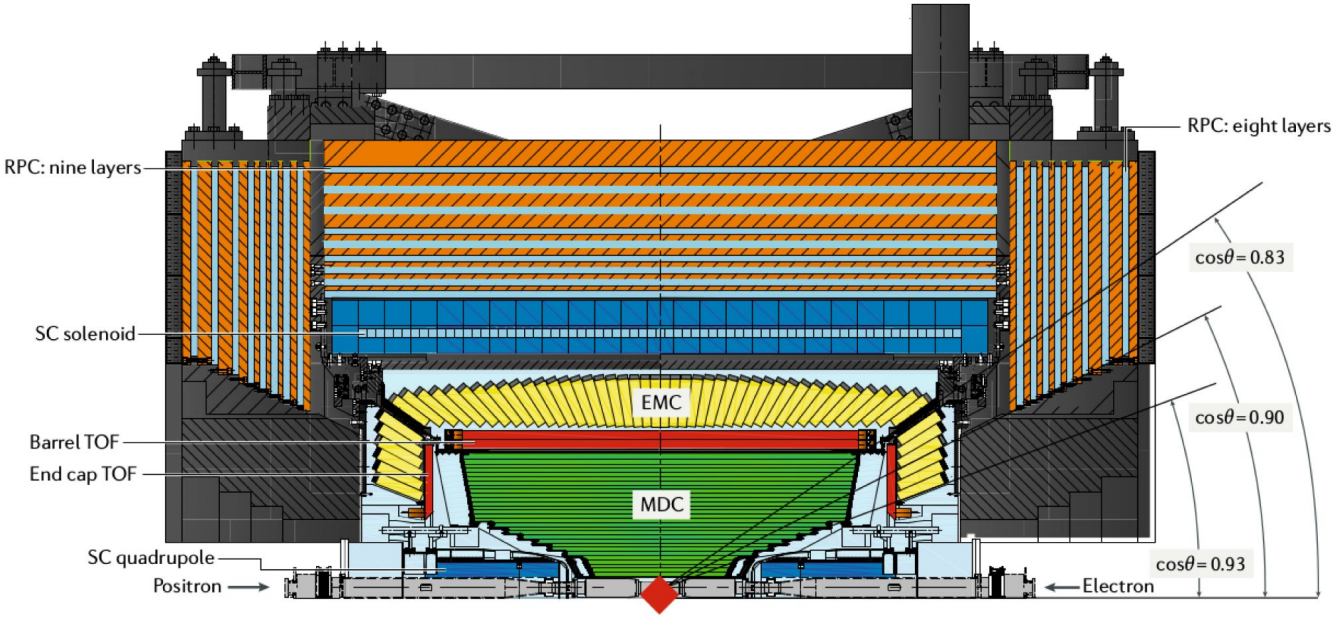
BESIII Detector

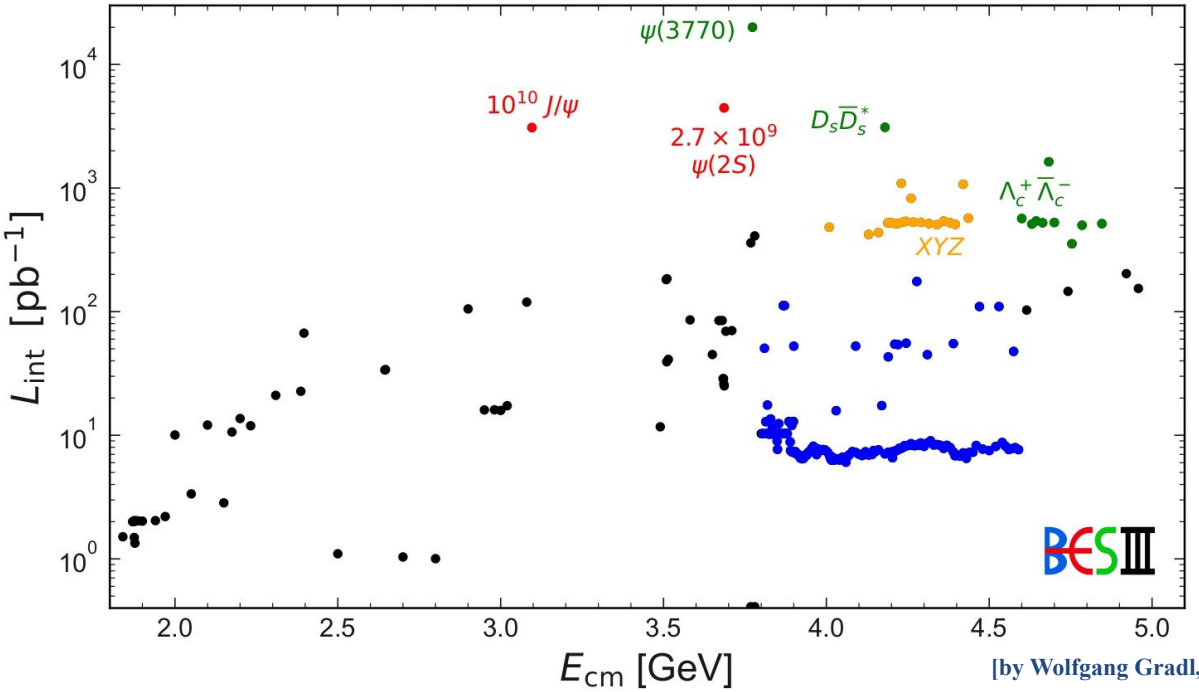
[BESIII Collaboration, 0911.4960]



- Experiment located at **BEPCII** (Beijing, China)
- Symmetric electron-positron beams with c.m. energy between **1.84~4.95 GeV**.
- Maximum luminosity reaches **1.2×10^{33}cm^{-2} s^{-1}**.

- Multilayer drift chamber (MDC).
- Time-of-Flight system (TOF).
- Electromagnetic calorimeter (EMC).
- Resistive plate chamber Muon counter (MUC).

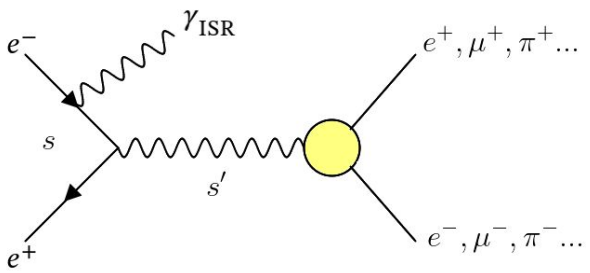
BESIII data samples



[by Wolfgang Gradl, 2024]

- **20 fb^{-1}** taking at **$\sqrt{s}$ = 3.773 GeV.**
- **13 scan points at in 1.84 ~2.00 GeV**, and inclusive measurement of R(s).
- **More than 100 scan points** in the open charm region.

Initial State Radiation (ISR)



The **Initial State Radiation (ISR)** is an experimental technique to evaluate hadronic cross sections in fixed cms energy experiments

$$e^+ + e^- \to \text{final state} + (\gamma)$$

$$M^2_{\rm had} = s' = s - 2\sqrt{s}E_\gamma$$

- When compared to the **scan method**, ISR technique has the advantage that one can perform many of the systematic studies for the whole spectrum once.
- This process is **suppressed by a factor of α/π**, when compared with the Born (LO) cross-section;
- Requires **high luminosity** experiments to compensate for the emission of the additional photon.
- Possible to perform a **large angles** and **small angles** analysis.

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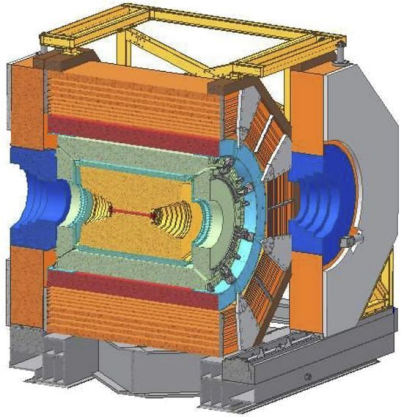

Photon can be emitted:

- Inside the **detector**;
- Along the **beam pipe**;

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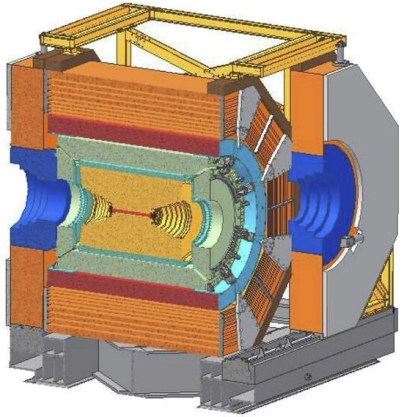

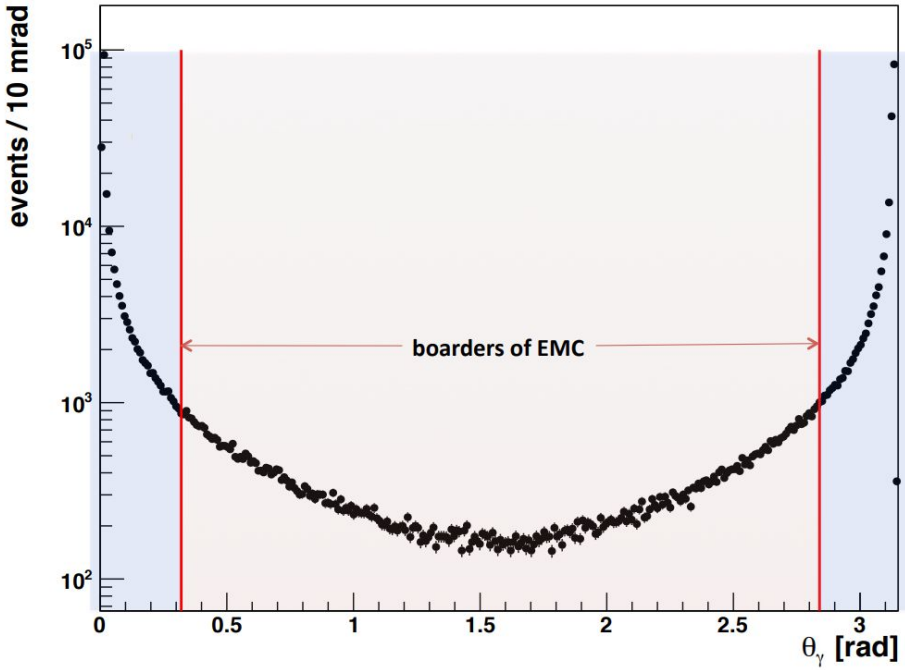

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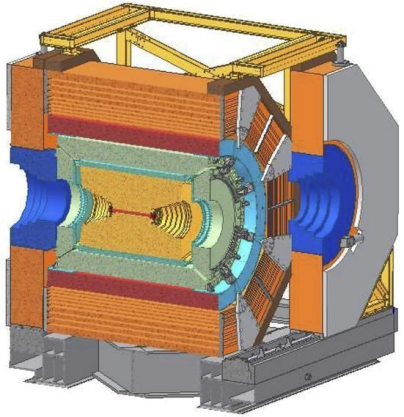

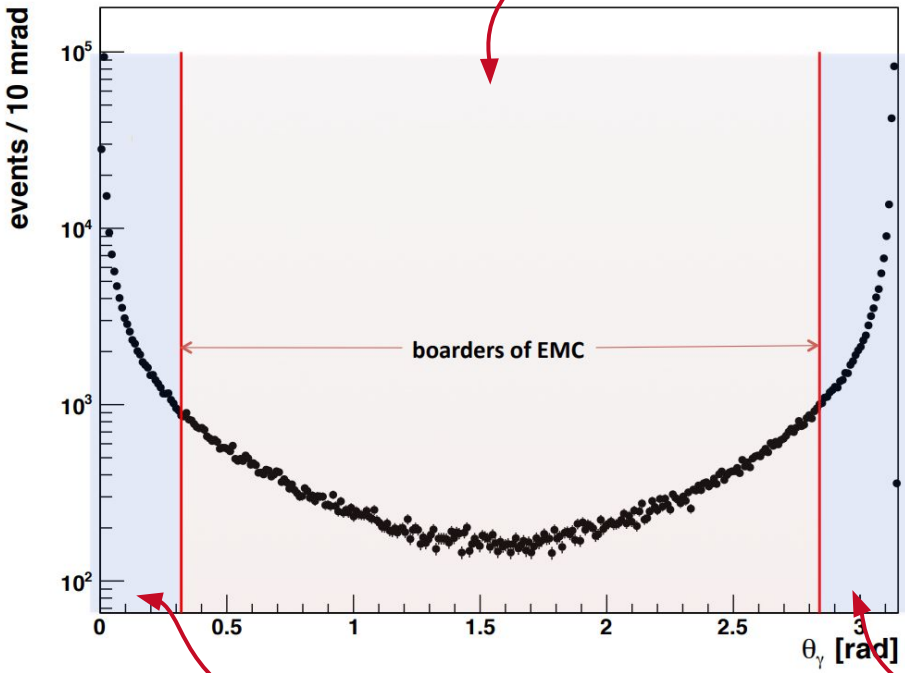

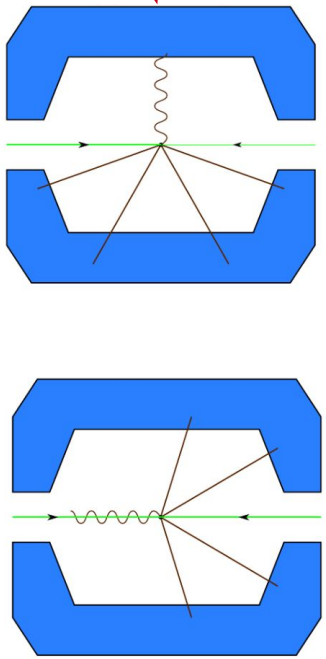

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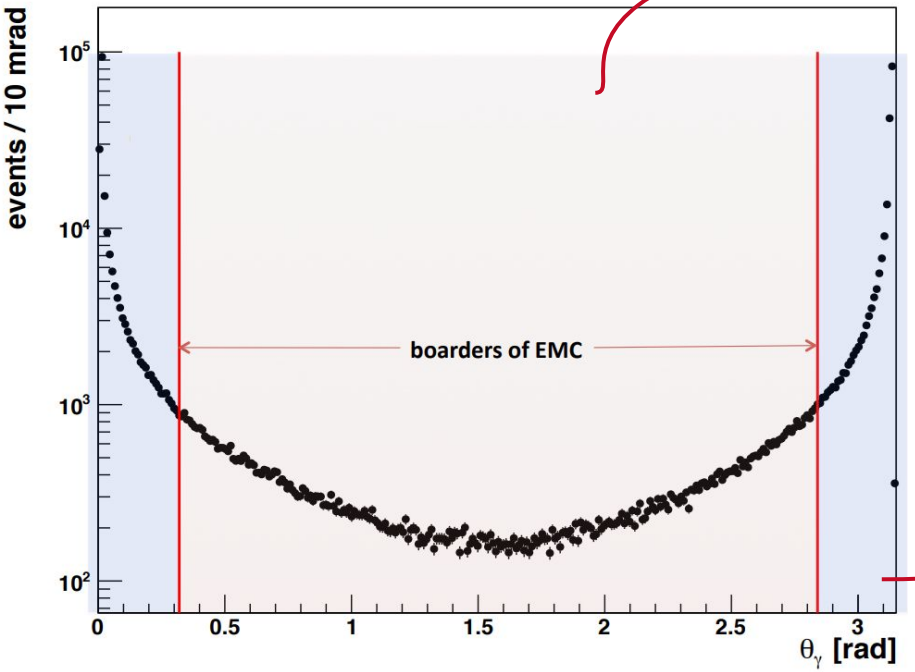
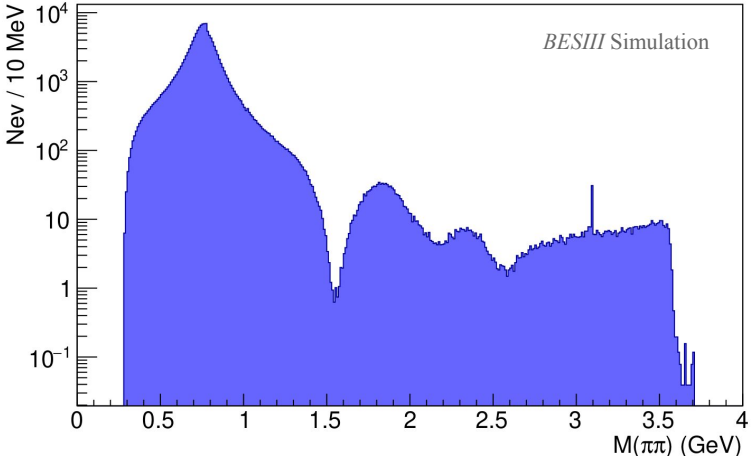
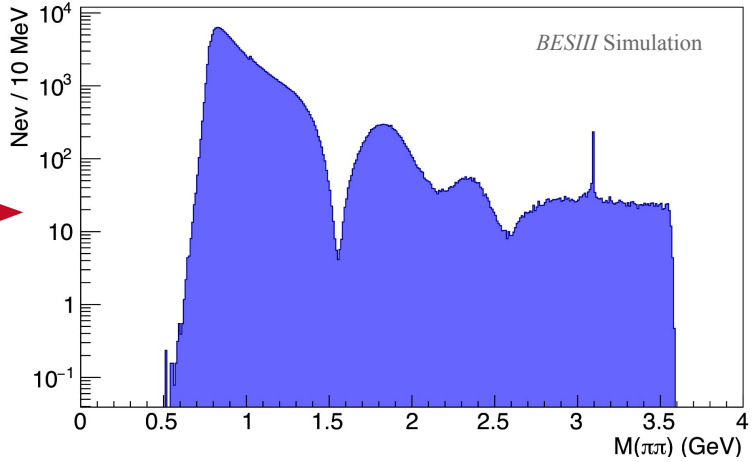




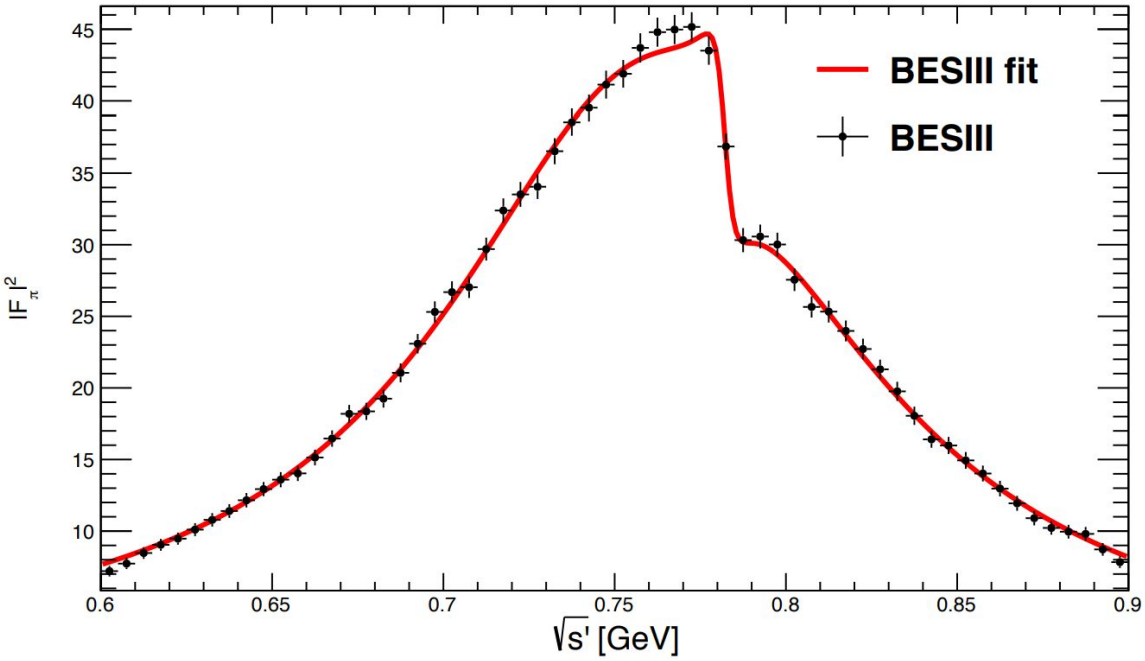


Large angle analysis is important for the data in the **low mass region**!

Previous measurement from BESIII

First measurement from BESIII published in 2016 **[BESIII Collab. Phys.Lett.B753 (2016) 629]**.

- **Event Selection**: required 2 charged tracks inside the detector, and requires tagging the photon in large angles;
- Machine Learning technique (**ANN**) to separate Pions and Muons in final state;
- Measurement performed in **[600, 900] MeV**;
- **0.9%** precision achievement in this measurement.



Status on Pion Form Factor measurement

On going **ISR analysis** being carried on by Riccardo Aliberti:

- Estimated final result with accuracy of **~0.7%**.
- Integrated luminosity **~ 6 fb^{-1}**.
- Normalization to **integrated luminosity**.
- **Blind analysis** implemented.

Cross checks being carried out:

- Perform previous measurement with different Kinematic Fits: **4C → 1C**.
- Apply same method at different c.m. energies: **3.773→4.178 GeV**.
- Measure the luminosity with a new method to reduce its uncertainty.
- Compare the normalizations with the **integrated luminosity** and **$\mu^+\mu^-$ events**.

$$e^+e^- \to \pi^+\pi^-(\gamma_{\rm ISR})$$

sources	Uncertainty (%)
Photon efficiency	0.2 → 0.0
Tracking efficiency	0.3 → 0.2
Pion ANN efficiency	0.2
Pion e-PID efficiency	0.2 → 0.0
Angular acceptance	0.1
Background subtraction	0.1
Unfolding	0.2
FSR correction $\delta_{\rm FSR}$	0.2
Vacuum polarization correction $\delta_{\rm vac}$	0.2
Radiator function	0.5
Luminosity $\mathcal{L}_{\rm int}$	0.5 → 0.3
Sum	**0.9 → 0.7**

Final Pion Form Factor measurement at BESIII

New **ISR analysis** using **20 fb^{-1}** at **$\sqrt{s}$ = 3.773 GeV**.

- Estimated final result with accuracy of **~0.5%**.
- **Full ψ(3770) dataset from BESIII**.
- Normalization to **$\mu^+\mu^-$ events**.
- **Blind analysis** implemented.

Future cross checks:

- Precise Measurements with different fits: **4C → 1C**.
- Study separation of **π/μ** using **ANN** and **angular fits**.
- Compare the normalizations with the **integrated luminosity** and **$\mu^+\mu^-$ events**.
- Compare results obtained with data sets taken in different rounds.

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- Estimated final result with accuracy of **~0.5%**.
- **Full ψ(3770) dataset from BESIII**.
- Normalization to **$\mu^+\mu^-$ events**.
- **Blind analysis** implemented.

Future cross checks:

- Precise Measurements with different fits: **4C → 1C**.
- Study separation of **π/μ** using **ANN** and **angular fits**.
- Compare the normalizations with the **integrated luminosity** and **$\mu^+\mu^-$ events**.
- Compare results obtained with data sets taken in different rounds.

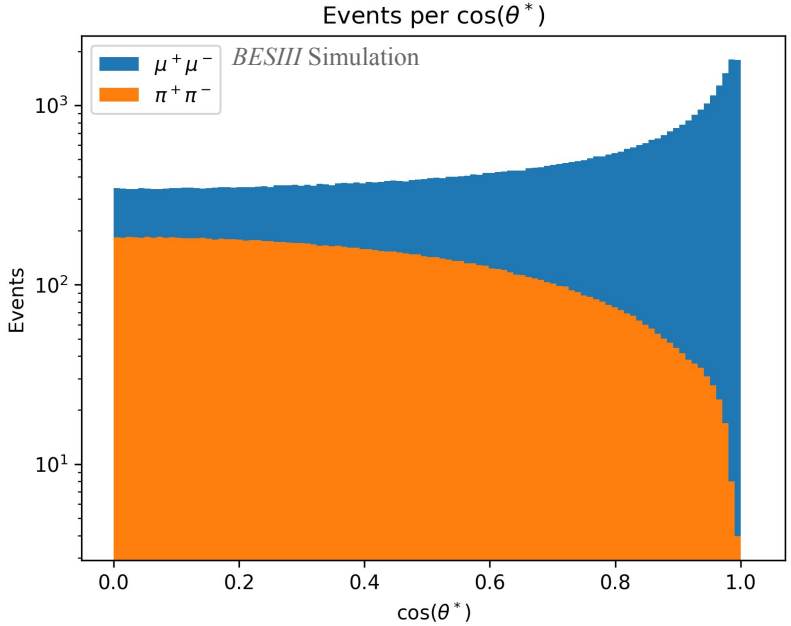
$$e^+e^- \to \pi^+\pi^-(\gamma_{\mathrm{ISR}})$$

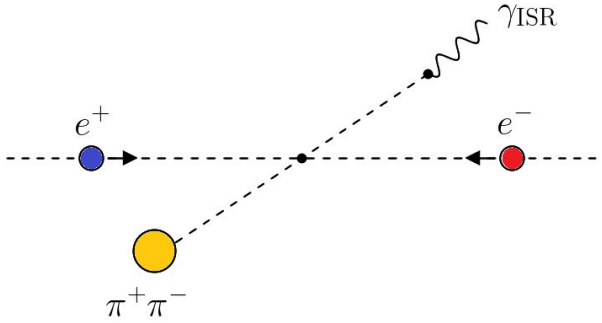
sources	Uncertainty (%)
Photon efficiency	0.2 → 0.0
Tracking efficiency	0.3 → 0.2
Pion ANN efficiency	0.2
Pion e-PID efficiency	0.2 → 0.0
Angular acceptance	0.1
Background subtraction	0.1
Unfolding	0.2
FSR correction δ_{FSR}	0.2
Vacuum polarization correction δ_{vac}	0.2
Radiator function	0.5 → 0.0
Luminosity $\mathcal{L}_{\mathrm{int}}$	0.5 → 0.0
Sum	**0.9 → 0.5**

Angular distributions with ISR - Pions and Muons

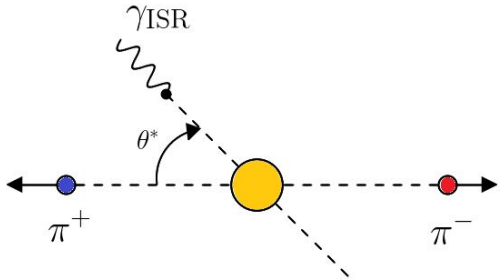
New idea to separate pions and muons in final states!

- originally proposed by the BaBar Collaboration.
- Due to **different spins** in the final states, pions and muons have different angular distributions in ISR events.

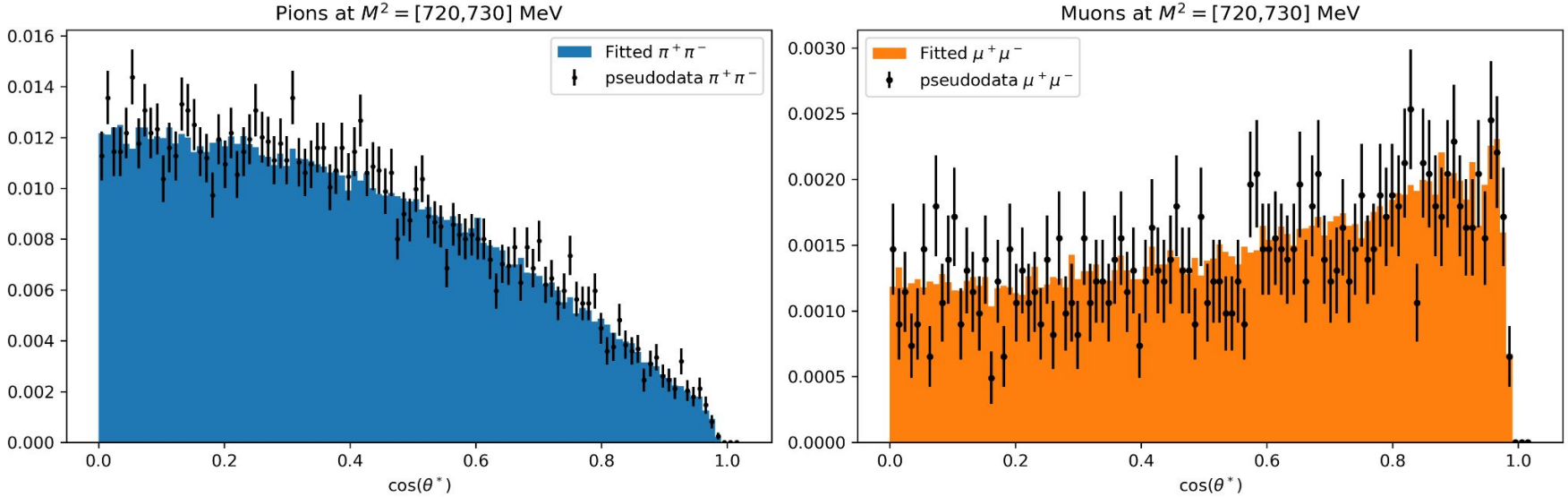




Change to the pions/muons
CM frame!



Angular distributions with ISR - Pions and Muons

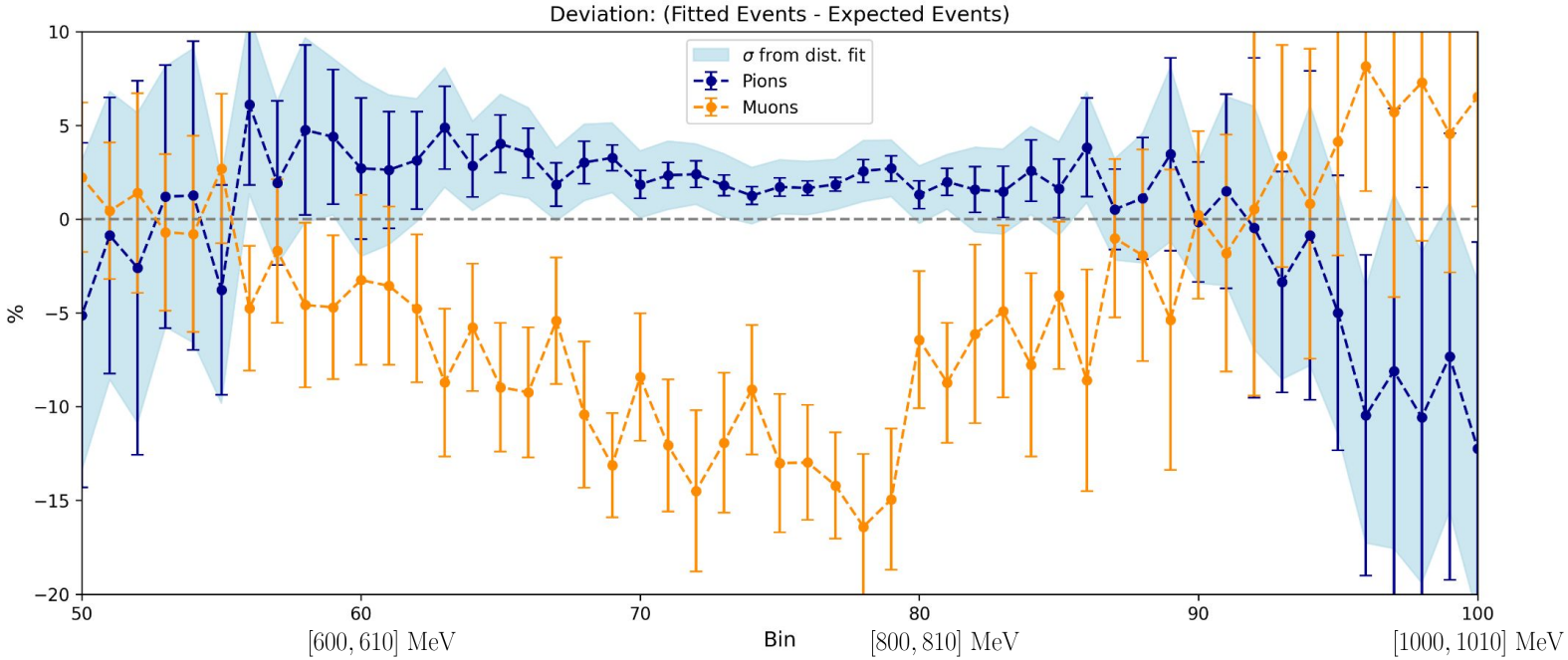


We are investigating, in the level of **Monte Carlo simulated data**, the application of this new method in **BESIII**:

- Looking for dependence of the fits with the mass-binnings/**invariant mass of the final states**;
- Looking for dependence of the fits with the total integrated luminosity — **statistics** — of the data sample.
- Studies performed fitting a pseudo-data generated from the MC distributions;

Angular distributions with ISR - Pions and Muons

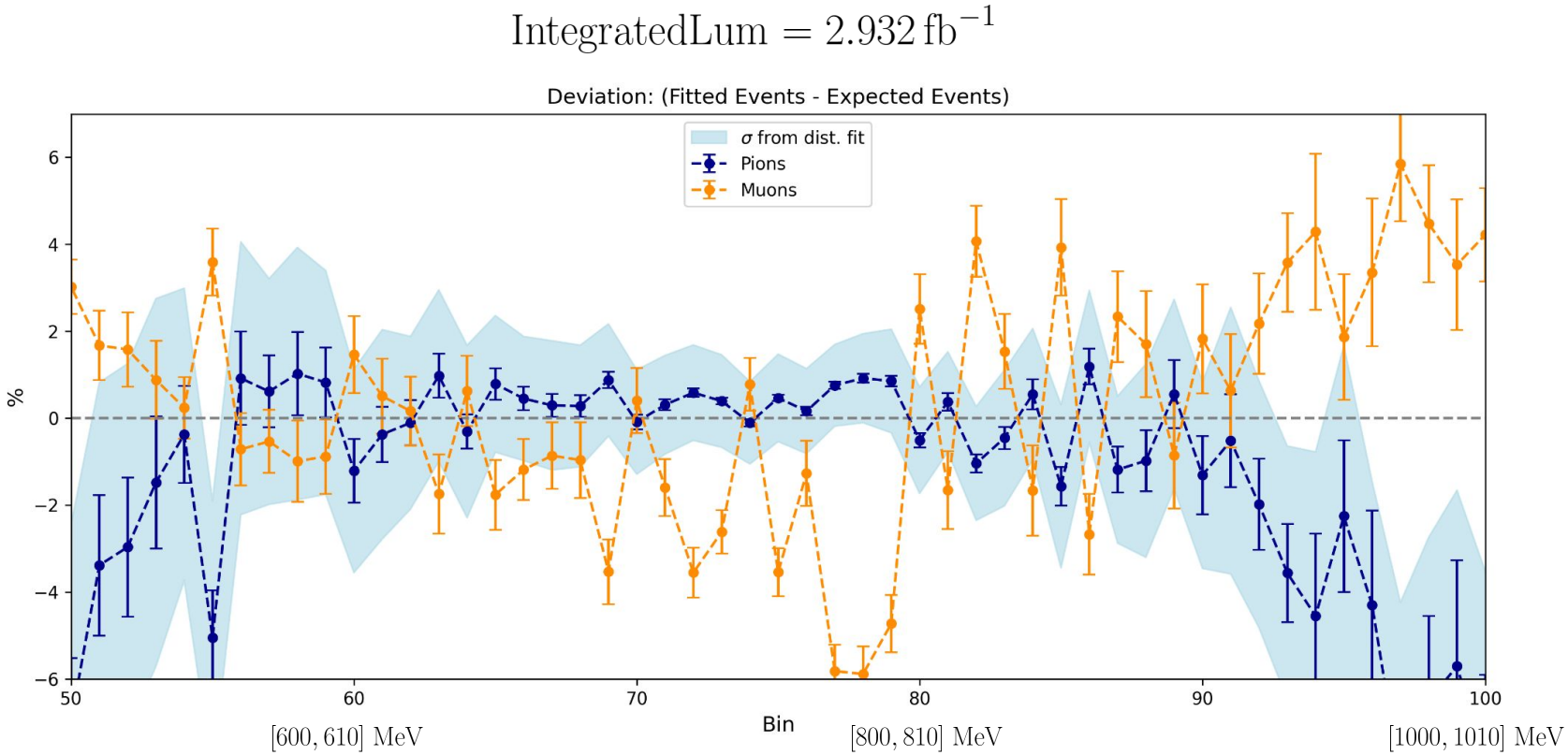
$$\text{IntegratedLum} = 2.932\,\text{fb}^{-1} \;/\; 4$$



Blue band: represents the standard deviation (sigma) from the 1000 samples generated for each mass bin.

Error bars: represent the error in the determination of the parameter in the Gaussian distribution fit.

Angular distributions with ISR - Pions and Muons



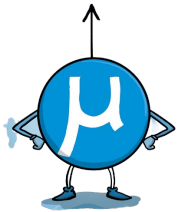
Blue band: represents the standard deviation (sigma) from the 1000 samples generated for each mass bin.

Error bars: represent the error in the determination of the parameter in the Gaussian distribution fit.

BESIII DFG Deutsche Forschungsgemeinschaft Hadrons Nuclei CRC1660 JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U


JCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis
Eighth Plenary Workshop of the Muon g-2 Theory Initiative
8th to 12th of Sept. 2025
Auditorium
Pierre Lehmann
(Bat 200)
200
ACCUEIL

Thank you!



Extras - Backup

R(s) measurement with ISR below 2 GeV

New idea: determining hadronic invariant mass using **only energy from the ISR photon**!

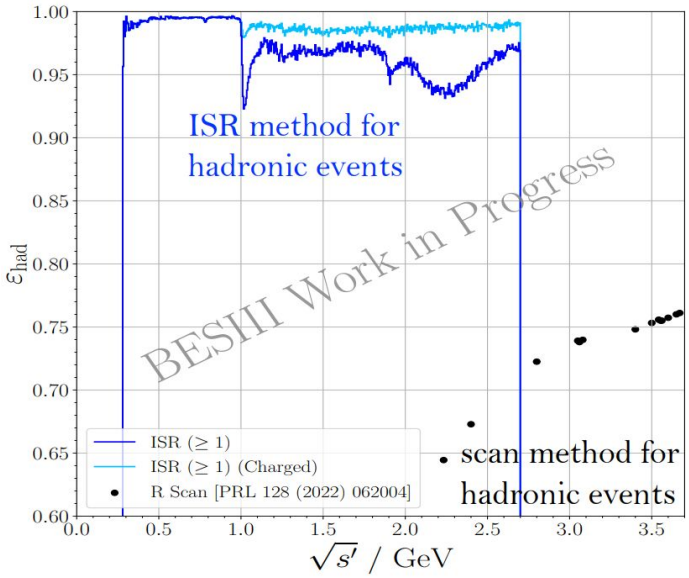
Simple event selection: 1 high-energetic photon emitted in large angles, and 1 charged track.

Advantages of the method:

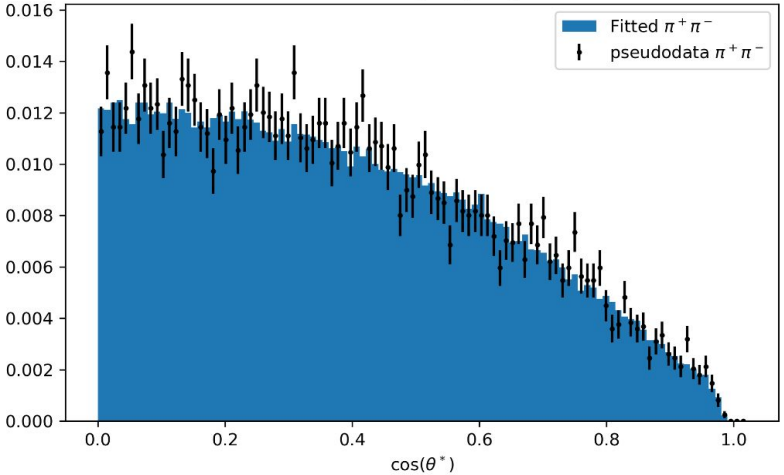
- Very high efficiency due to boost of ISR photon;
- Less reliant on description of hadronic MC;
- Single measured down to threshold;
- Fully inclusive for FSR and higher order ISR;

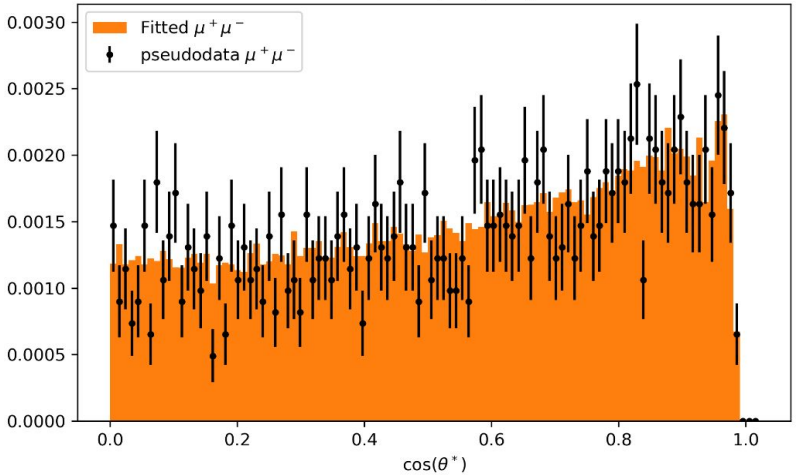
Challenges of the method:

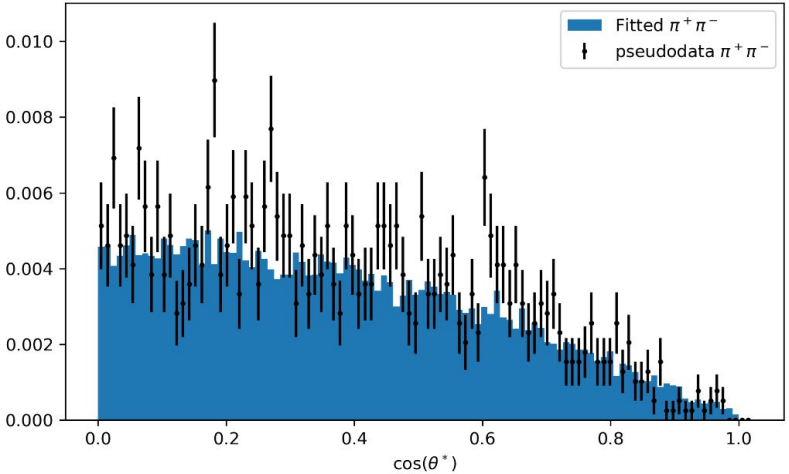
- Significant QED backgrounds due to their higher cross section: **dedicated PID needed**;
- Background from non-ISR hadronic events: **dedicated vetoes**;
- Limited resolution due to high energy of ISR photon.

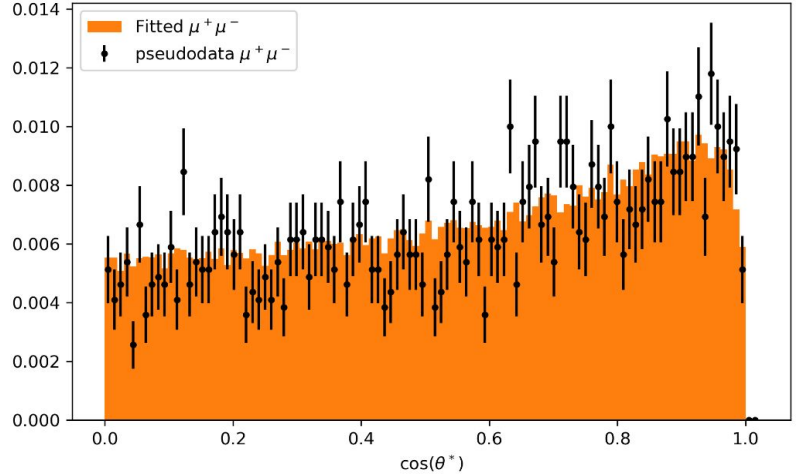


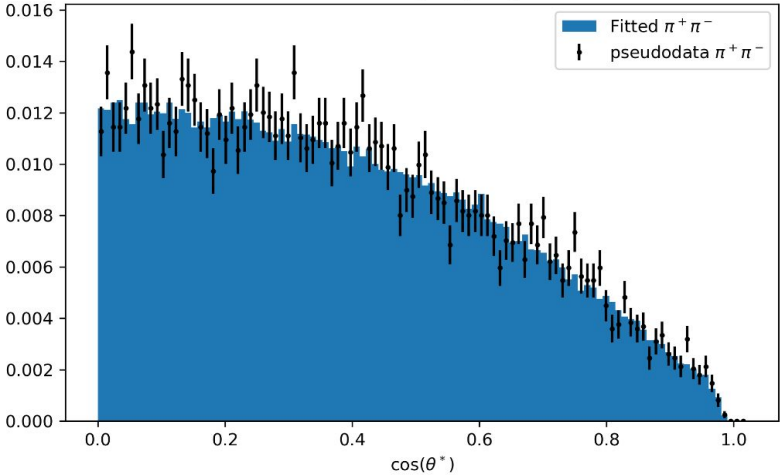
analysis being carried on by Thomas Lenz


Pions at $M^2 = [720,730]$ MeV
Fitted $\pi^+\pi^-$
pseudodata $\pi^+\pi^-$
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0.0
0.2
0.4
0.6
0.8
1.0
$\cos(\theta^*)$


Muons at $M^2 = [720,730]$ MeV
Fitted $\mu^+\mu^-$
pseudodata $\mu^+\mu^-$
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
0.0
0.2
0.4
0.6
0.8
1.0
$\cos(\theta^*)$


Pions at $M^2 = [520,530]$ MeV
Fitted $\pi^+\pi^-$
pseudodata $\pi^+\pi^-$
0.010
0.008
0.006
0.004
0.002
0.000
0.0
0.2
0.4
0.6
0.8
1.0
$\cos(\theta^*)$


Muons at $M^2 = [520,530]$ MeV
Fitted $\mu^+\mu^-$
pseudodata $\mu^+\mu^-$
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
0.0
0.2
0.4
0.6
0.8
1.0
$\cos(\theta^*)$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pseudodata $\pi^+\pi^-$
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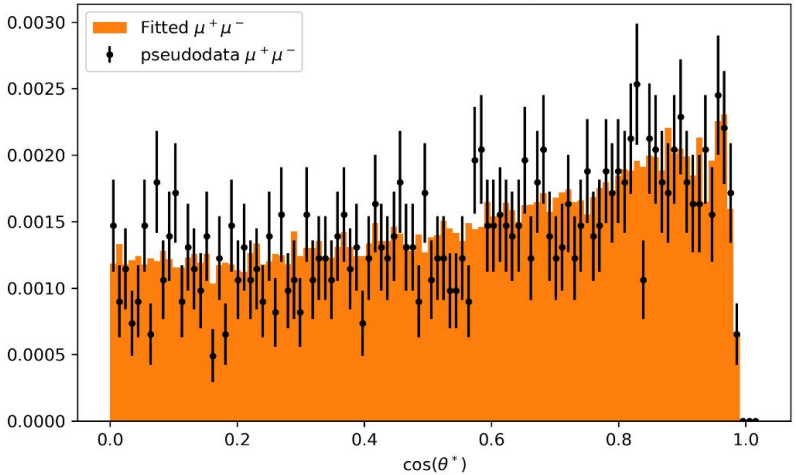
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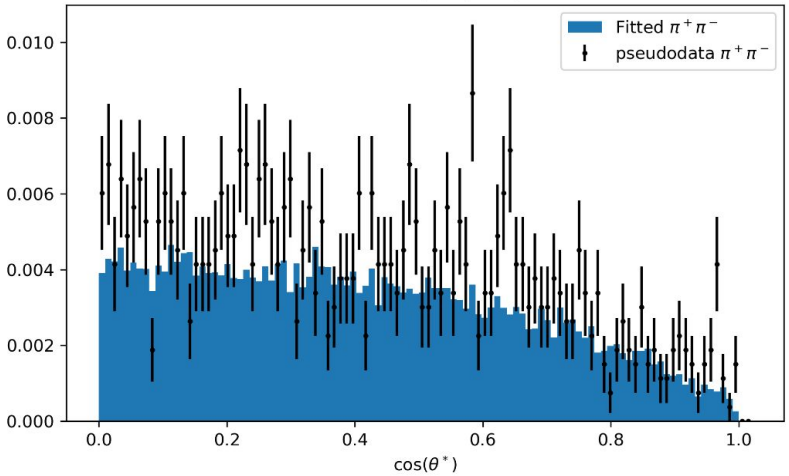
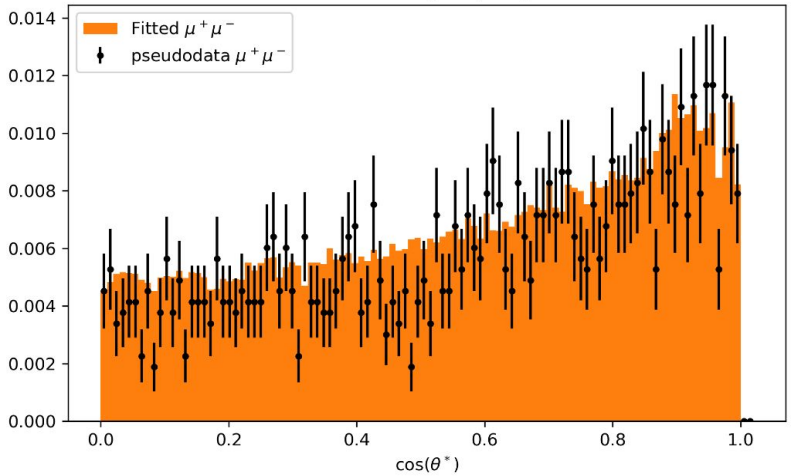

Pions at $M^2 = [970,980]$ MeV
Fitted $\pi^+\pi^-$
pseudodata $\pi^+\pi^-$
0.010
0.008
0.006
0.004
0.002
0.000
0.0
0.2
0.4
0.6
0.8
1.0
$\cos(\theta^*)$


Muons at $M^2 = [970,980]$ MeV
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pseudodata $\mu^+\mu^-$
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0.010
0.008
0.006
0.004
0.002
0.000
0.0
0.2
0.4
0.6
0.8
1.0
$\cos(\theta^*)$