Workshop on Flavour Changing and Conserving Processes (FCCP2025)
Anacapri, September 29, 2025

Status of R measurements at low-energy e^+e^- colliders

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

FOR 5327

Hadrons CRC 1660 Nuclei

JG|U

Achim Denig
Institute for Nuclear Physics
Johannes Gutenberg University Mainz

R Measurements and Hadronic Vacuum Polarization

Marc Knecht

Hadronic vacuum polarization

Anomalous magnetic moment of the muon (g-2)$_\mu$

$$a_\mu^{HVP} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma_{\mathrm{had}}(s)$$

Running electromagnetic fine structure constant

$$\alpha_{\mathrm{em}}(M_Z^2) = \frac{1}{1-\Delta\alpha(M_Z^2)};$$

$$\Delta\alpha_{\mathrm{had}}^{(5)}(M_Z^2) \sim \int_{4\pi^2}^{\infty} ds\, \frac{R_{\mathrm{had}}(s)}{s(s-M_Z^2)}$$

$$\sigma_{had}(s) = \sigma_{\mathrm{tot}}(e^+e^- \rightarrow \mathrm{Hadrons})$$

$$R_{had} = \frac{\sigma_{had}(s)}{\sigma_{ee\rightarrow\mu\mu}(s)}$$

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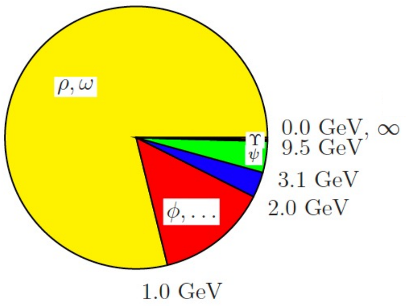

→ relevant mass range < 2...3 GeV
leading channel: $e^+e^- \to \pi^+\pi^-$
>70% contribution to a_μ^{HVP}

$$\boldsymbol{\sigma_{had}(s)} = \boldsymbol{\sigma_{\text{tot}}(e^+e^- \to \text{Hadrons})}$$

$$\boldsymbol{R_{had}} = \frac{\boldsymbol{\sigma_{had}(s)}}{\boldsymbol{\sigma_{ee\to\mu\mu}(s)}}$$

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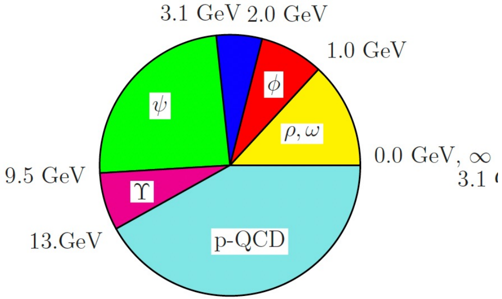
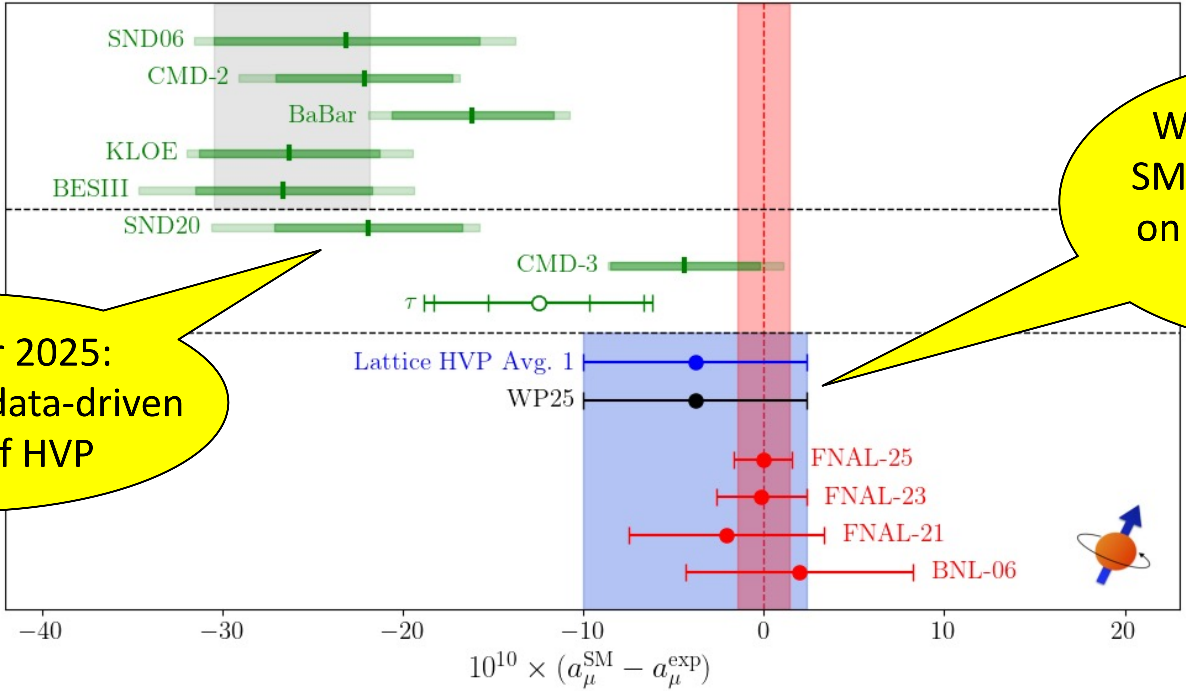


→ relevant mass range
< 13 GeV

Whitepaper ‘25: Lattice QCD-based SM-Prediction for $(g\text{-}2)_\mu$

Davide Giusti

After decades of SM g-2 calculations, for the first time dispersive determination not used any more



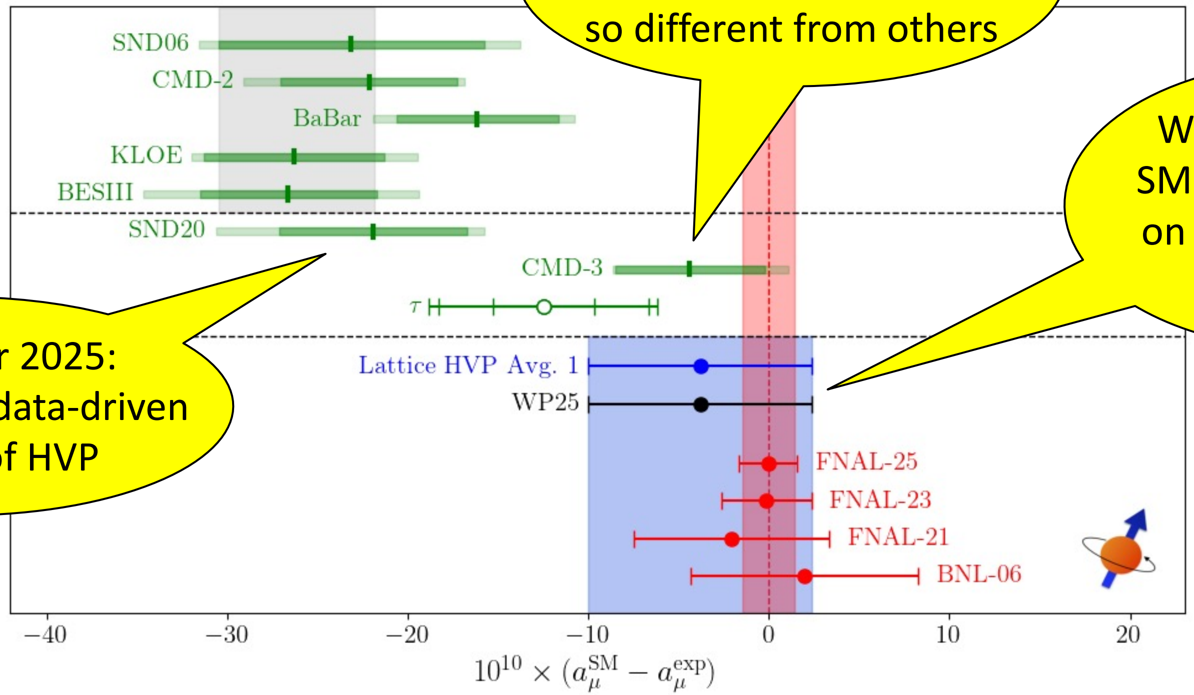
Whitepaper 2025: no average for data-driven estimate of HVP

Whitepaper 2025: SM prediction based on LQCD calculation for HVP

Whitepaper '25: Lattice QCD-based SM-Prediction for $(g\text{-}2)_\mu$

After decades of SM g-2 calculations, for the fi… …ion not used any more

CMD-3 measurement of $e^+e^- \rightarrow \pi^+\pi^-$ so different from others



Whitepaper 2025: SM prediction based on LQCD calculation for HVP

Whitepaper 2025: no average for data-driven estimate of HVP

2023 Shock: CMD-3 @ Novosibirsk $e^+e^- \to \pi^+\pi^-$

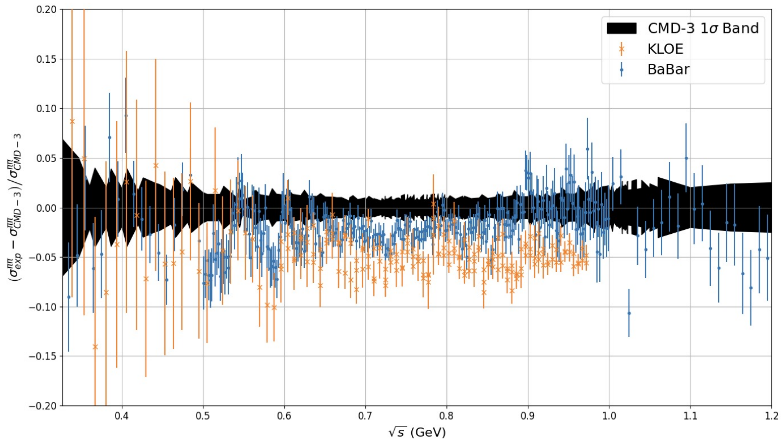
PRL 132 (2024) 231903
PRD 109 (2024) 112002

- New result from CMD-3 collaboration @ VEPP-2000 collider in Novosbirsk
- Energy scan (from threshold up to 1.2 GeV) method, no ISR!
- Form factor extraction via selection of ππ/ee ratio
- Highest statistics data sample of all experiments, systematic uncertainty 0.7% on ρ peak

$$|F_\pi|^2 = \left(\frac{N_{\pi^+\pi^-}}{N_{e^+e^-}} - \Delta^{bg}\right) \cdot \frac{\sigma^0_{e^+e^-} \cdot (1+\delta_{e^+e^-}) \cdot \varepsilon_{e^+e^-}}{\sigma^0_{\pi^+\pi^-} \cdot (1+\delta_{\pi^+\pi^-}) \cdot \varepsilon_{\pi^+\pi^-}}$$

→ Significant deviation from previous ISR and energy scan experiments (CMD-2)! Why?

Courtesy Aidan Wright



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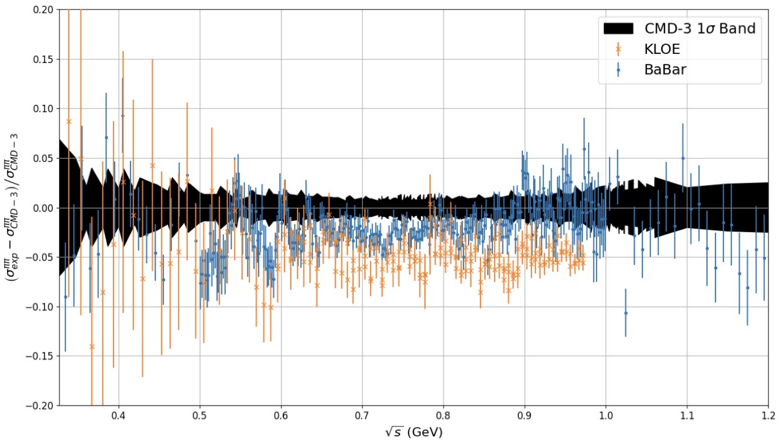
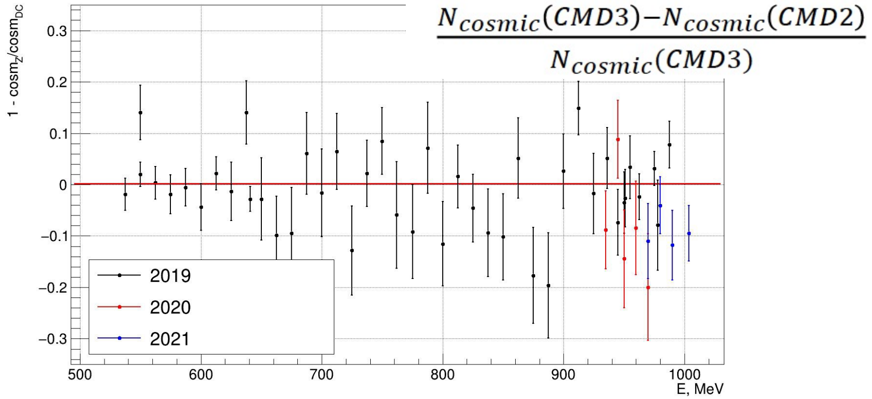


Background from cosmic ray events as a possible explanation for CMD-2/CMD-3 difference?



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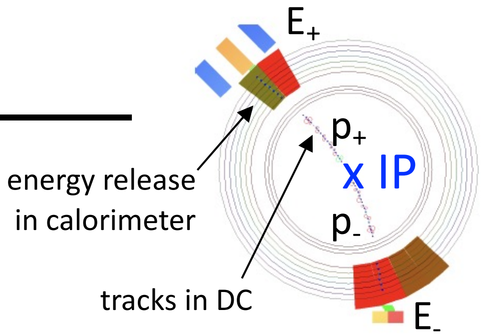
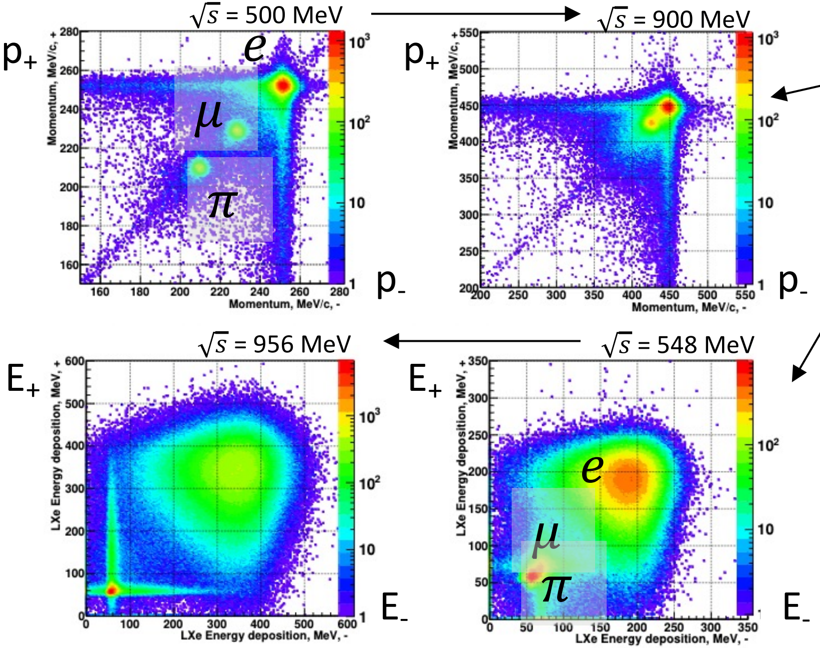


Scrutiny of CMD-3 result within the Theory Initiative

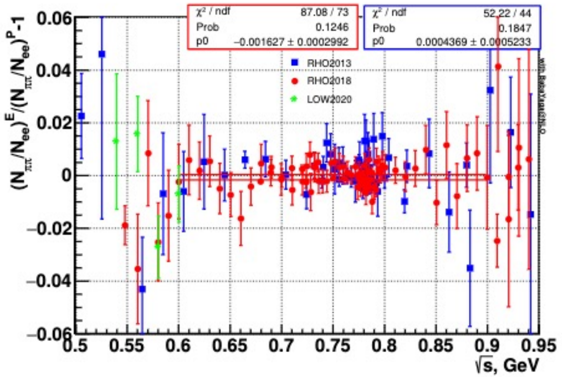
- Very open replies by F. Ignatov → no major showstopper observed
- Very powerful analysis with many and impressive internal cross checks
- Monte-Carlo generator for energy scan cannot be independently varified



Most impressive feature: ππ/ee ratio determined independently by two complementary methods

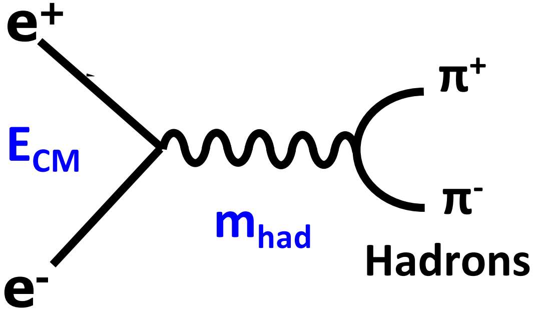
- Momentum based
- Calorimetric

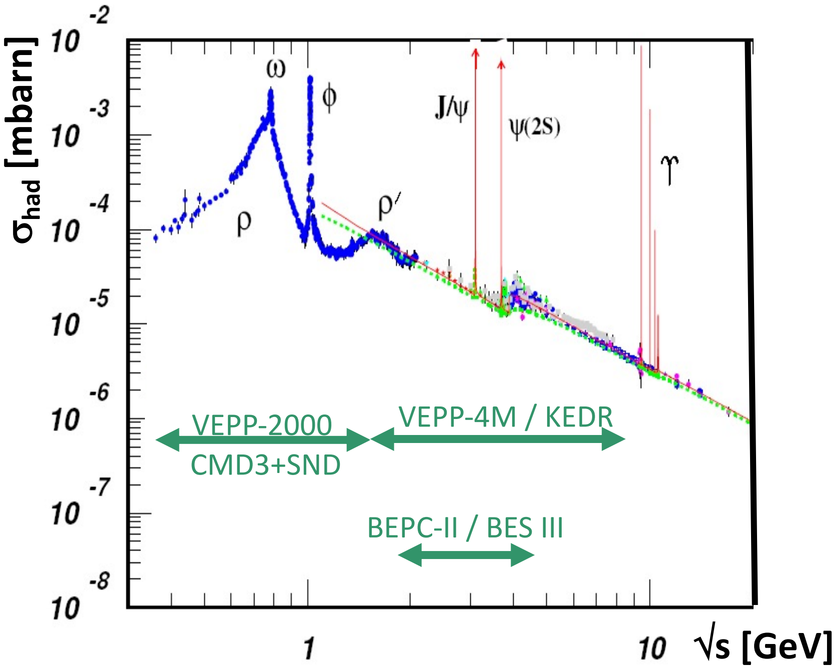
agreement ~ 0.2% around rho peak



The alternative Method: Initial State Radiation (ISR)

Measurements on R – Energy Scan vs. Initial State Radiation





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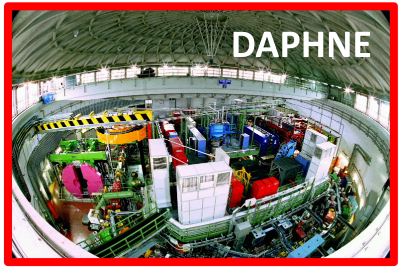

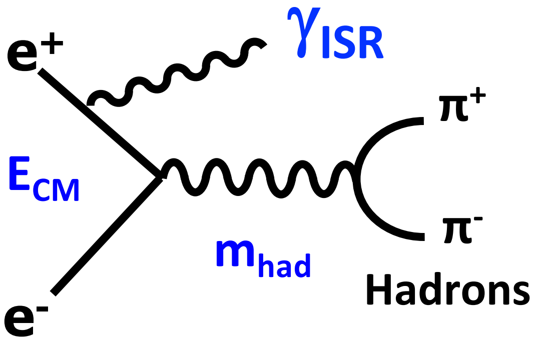

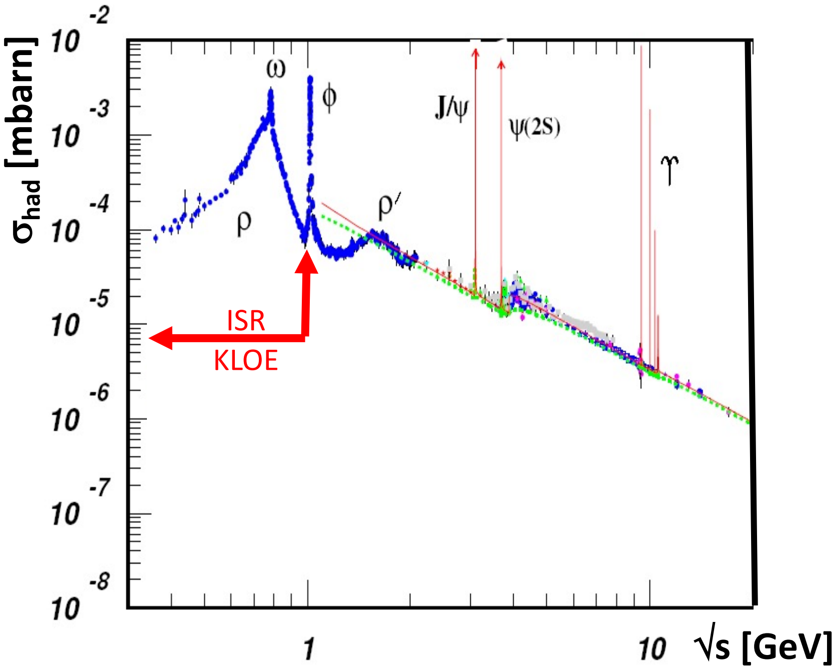

- No systematic variation of E_{beam}
- High statistics thanks to high luminosity
- Radiative corrections (H_{rad})

PHOKHARA event generator

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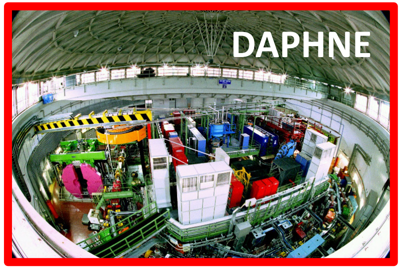

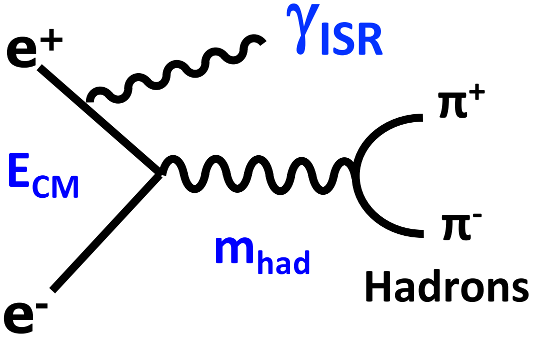

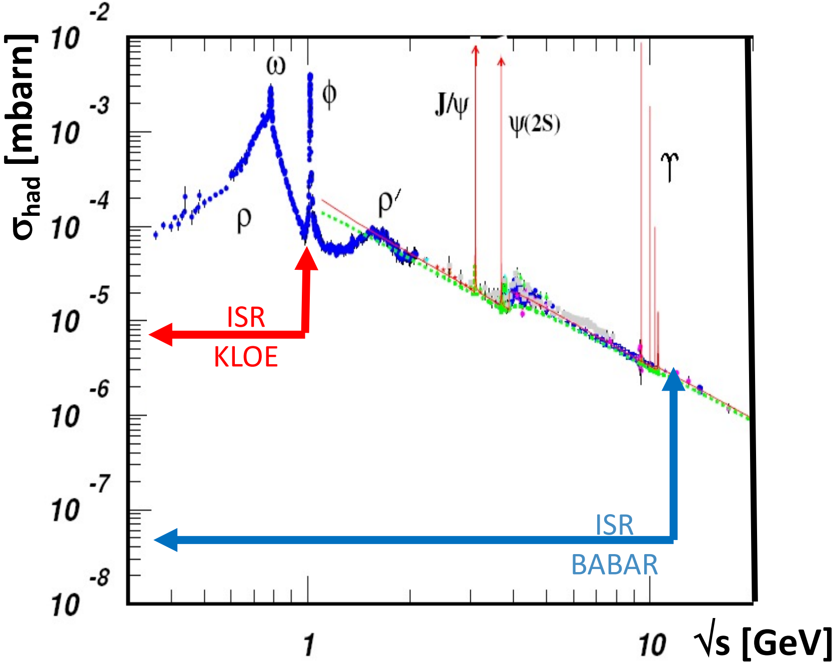

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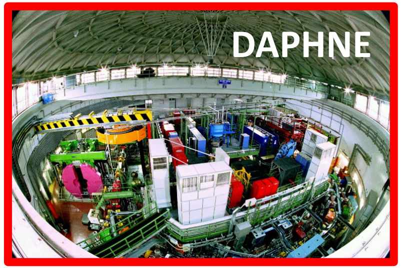

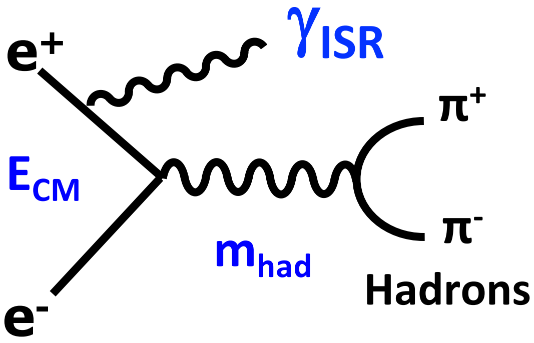

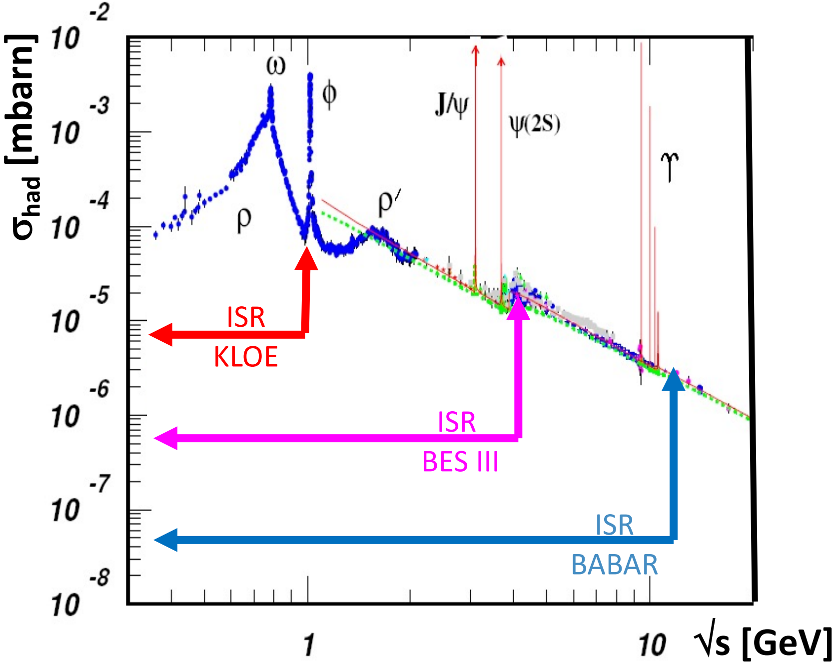

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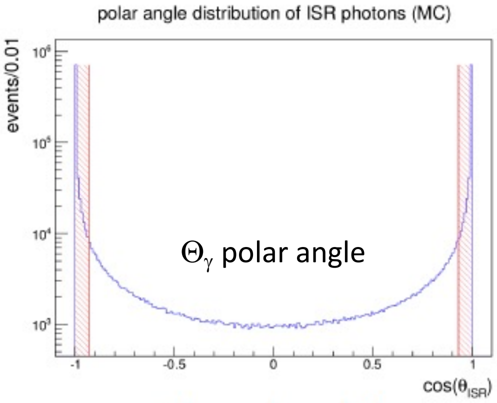
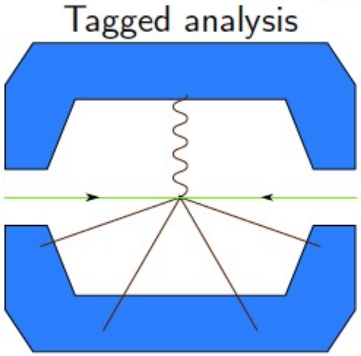
Initial State Radiation – tagged vs. untagged

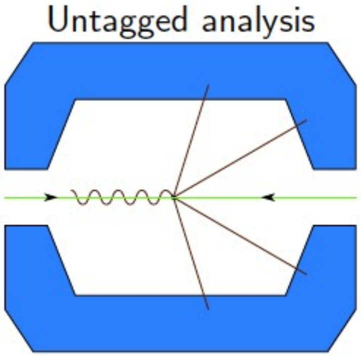


Tagged analysis:
ISR photon measured in Calorimeter

Untagged analysis:
No ISR detection; cut on missing momentum

+ exclusive reconstruction
- increased background
- reduced statistics
+ mass range $\sqrt{s'} < E_{CM}$





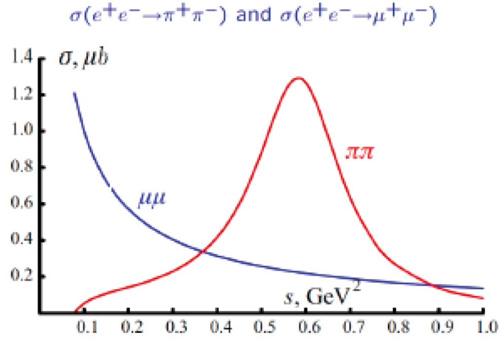
+ reduced background
+ very high statistics (x5)
- mass range $E_{th} < \sqrt{s'} < E_{CM}$
  KLOE: E_{th} = ~0.6 GeV
  BESIII: E_{th} = ~1 GeV
  BABAR: E_{th} = ~3 GeV

Initial State Radiation - Normalization

Two independent normalization methods:

1) normalization to L_{int} (obtained from Bhabha events) and H_{rad}; subtraction of background (μ+μ-γ, …)

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



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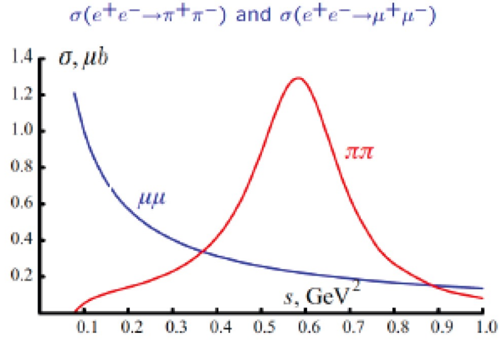
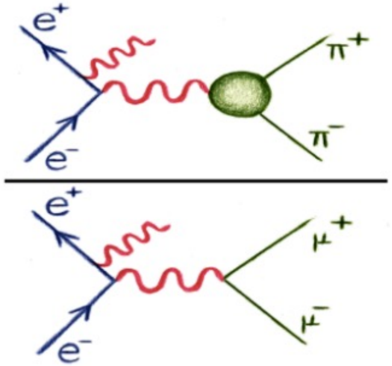


2) normalization to μ+μ-γ events, i.e. R ratio (ππγ/μμγ)

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

→ requires high statistics of μ+μ-γ

$$R = \frac{N_{\pi^+\pi^-}}{N_{\mu^+\mu^-}} \cdot \frac{\varepsilon_{\mu^+\mu^-} \cdot \left(1+\delta^{FSR}_{\mu^+\mu^-}\right)}{\varepsilon_{\pi^+\pi^-} \cdot \left(1+\delta^{FSR}_{\pi^+\pi^-}\right)}$$



Overview Experiments

Experiment	Published Method	Normalization	Separation π - μ
KLOE $\sqrt{s}\sim 1$ GeV	ISR untagged ISR tagged ISR untagged	Luminosity + H_{rad} Luminosity + H_{rad} μ+μ-γ	Kinematics Track Kinematics Track Kinematics Track
BABAR $\sqrt{s}\sim 10$ GeV	ISR tagged	μ+μ-γ	Particle ID
BESIII $\sqrt{s}\sim 4$ GeV	ISR tagged	Luminosity + H_{rad}	Particle ID (ML)
BELLE-II $\sqrt{s}\sim 10$ GeV			
CMD-2/CMD-3	Scan < ~1 GeV	e+e-	Kinematics Track Kinematics EMC
SND	Scan < ~1 GeV	e+e-	Kinematics EMC

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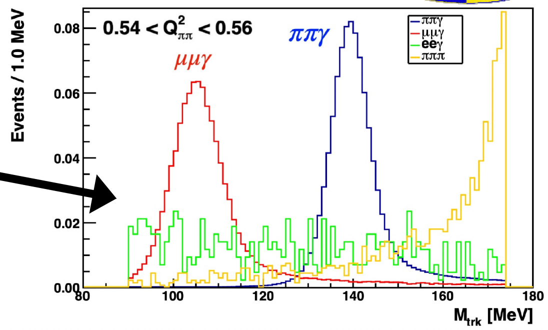
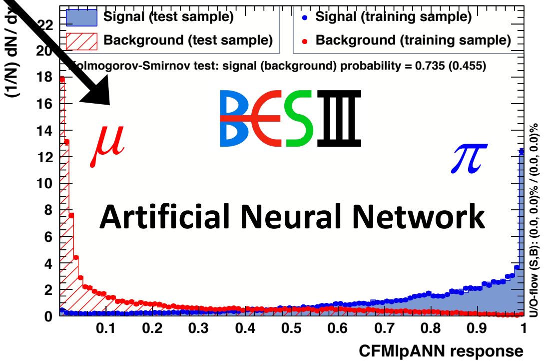
Trackmass x+x-γ





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		μ-γ	Kinematics Track
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BELLE-II $\sqrt{s}\sim 10$ GeV			
CMD-2/CMD-3	Scan < ~1 GeV	e+e-	Kinematics Track Kinematics EMC
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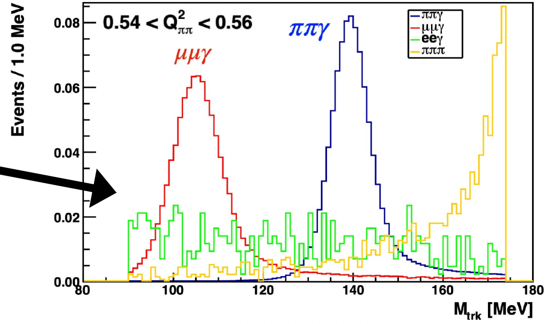
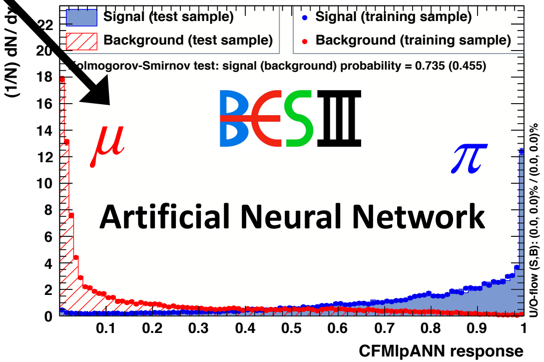
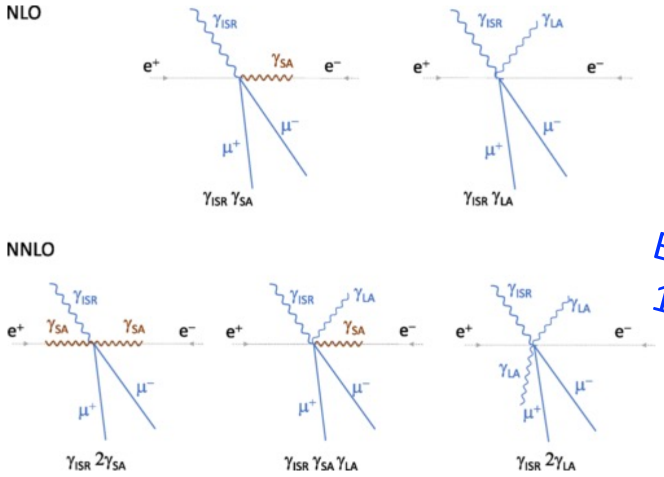
Diverse set of methods,
cms energies,
normalizations, selections

Trackmass x+x-γ



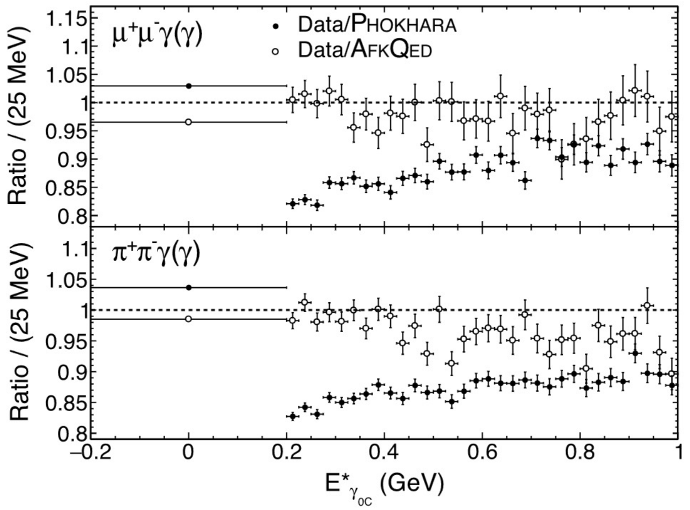


BABAR Radiative Correction Studies (2023)



BABAR analysis requires 1 photon at large angle

Phys. Rev. D 108, L111103



Detailed study of NLO and NNLO radiative corrections

- Kinematic fits for $\pi^+\pi^- \gamma_{ISR,LA}\,\gamma\,(\gamma)$, $\mu^+\mu^- \gamma_{ISR,LA}\,\gamma\,(\gamma)$
- Comparison with PHOKHARA (NLO full correction) and AfkQED (collinear approximation beyond LO) generators

→ NNLO radiation observed at 3.5% level (missing in PHOKHARA)

→ Phokhara prediction for small angle ISR photons at NLO too high by ~25% (AfkQED fits better to data)

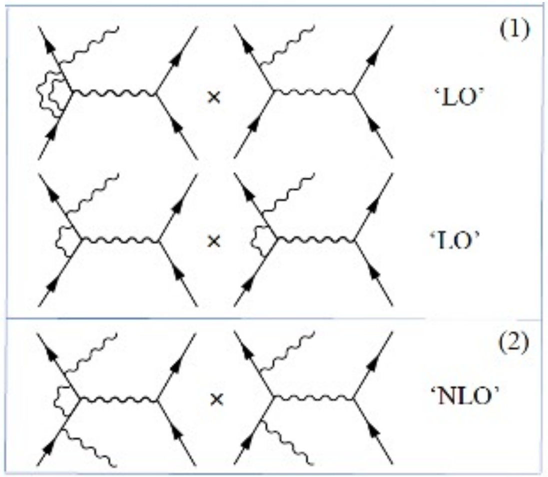
Possible Consequences from BABAR Findings (?)

Eur. Phys. J. C 84, 721 (2024)

BABAR: - rather inclusive selection and therefore weak dependence from PHOKHARA
→ small effect on published BABAR result due to PHOKHARA NLO limitations
- however: in original BABAR 2π paper 2% correction applied to AfkQED due to statement that PHOKHARA provides better NLO correction → only valid for acceptance (?)

KLOE/BESIII: - less inclusive selection regarding NLO
→ claim: large effects due PHOKHARA NLO limitations of up to 3.2% in the case of BESIII

However, scenarios need to be taken into account:
1: NNLO interference terms (1) dominate → large effects
2: NNLO interference terms (2) dominate
→ significantly reduced effects on experimental analyses
So far no explicit calculation of these NNLO interference effects



KLOE / BESIII Response to PHOKHARA Shortcomings

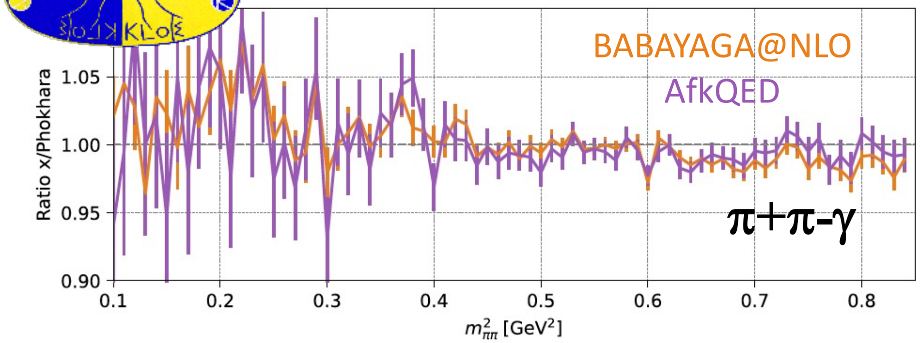
Investigation of kinematic cuts, which are sensitive to NLO corrections: Trackmass (KLOE), χ^2 (BESIII)

Radio-MonteCarlow Initaitive with detailed comparisons

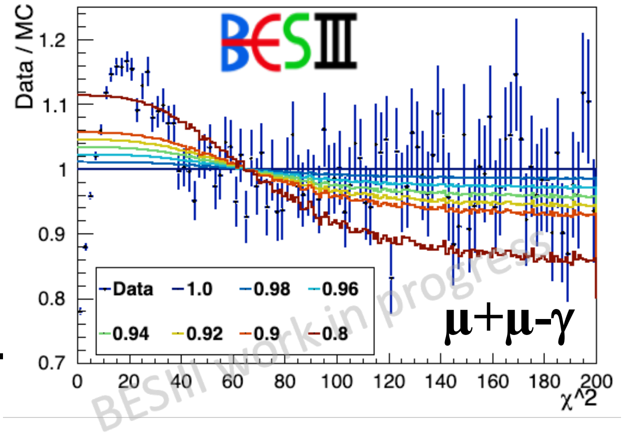
- **KLOE** has presented a **good agreement between various MC generators** for realistic acceptance cuts and also in the case of the kinematic trackmass cut for KLOE-10
- **BESIII** has carried out a **full detector simulations for various MC generators** and a **data-PHOKHARA comparison for $e^+e^- \rightarrow \mu^+\mu^-\gamma$ in the χ^2 distribution**; furthermore it has been demonstrated that the published analysis is **largely inclusive in higher order corrections**

→ **scenario 2 from DHLMZ23 paper strongly preferred**

Ratio to Phokhara including Trackmass cut



Data-Phokhara comparison for χ^2 distribution



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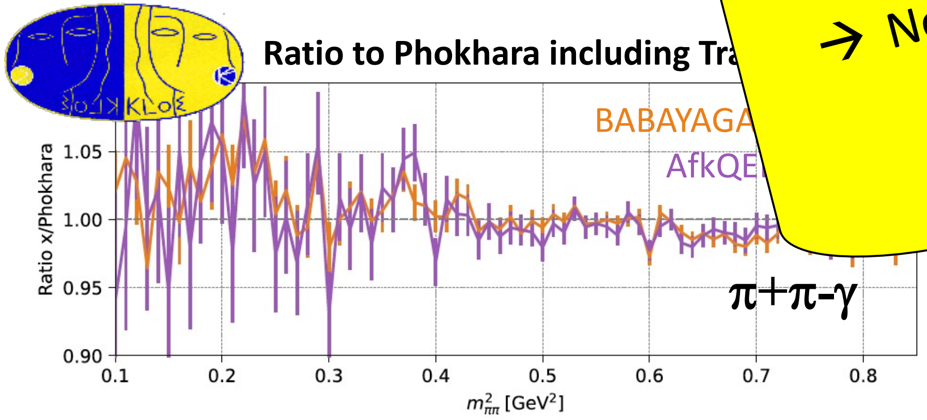
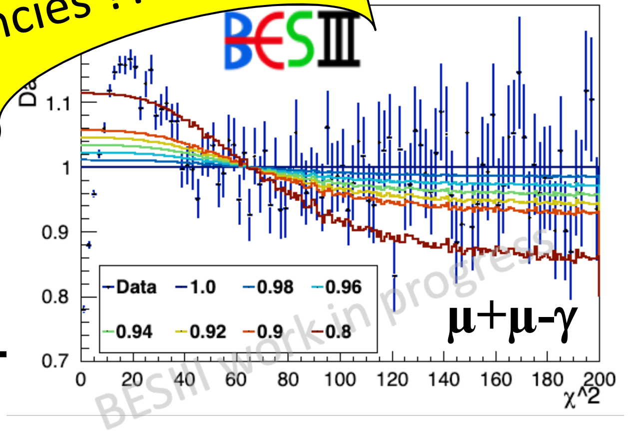
→ **scenario 2 from DHLMZ23 paper strongly** ...

News from 2024 KEK workshop:
Phokhara limitations likely not impacting KLOE/BESIII
→ No viable explanation for discrepancies ?!

Ratio to Phokhara including Tra ...



... n for χ^2 distribution



09/25: Orsay Workshop Muon g-2 Theory Initiaitve

The need for improved radiative corrections

Andrea Gurgone
Fulvio Piccini

ISR: for hadronic channels (especially two-pion channel) no independent cross check to Phokhara !
Energy scan: no independent cross check to MCGPJ generator !

→ **Development of new MC generators of utmost importance for the field**
PHOKHARA@NNLO, McMule, Sherpa, BABAYAGA@NLO (including $\pi^+\pi^-\gamma$)

→ **Controlled treatment of Final State Radiation effects**

→ **Efforts coordinated within the RadioMontecarlow initiative**

→ **Strong interplay between Theory and Experiment**

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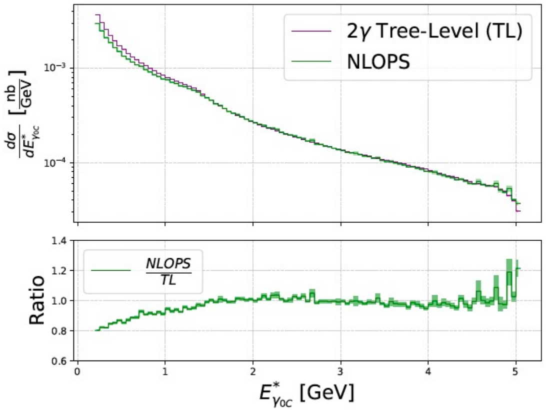
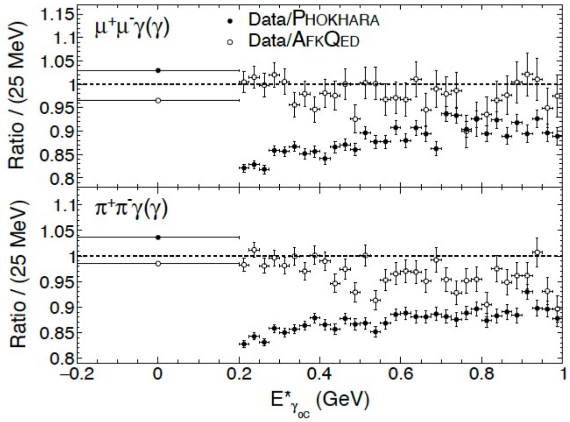
Fulvio Piccini @ Orsay

First results from new BABAYAGA@NLO
→ seems to confirm findings of BABAR regarding PHOKHARA liminations





Breaking News from 2025 Orsay Workshop and Outlook

NEW

New BABAR ISR Measurement of $e^+e^- \rightarrow \pi^+\pi^-$

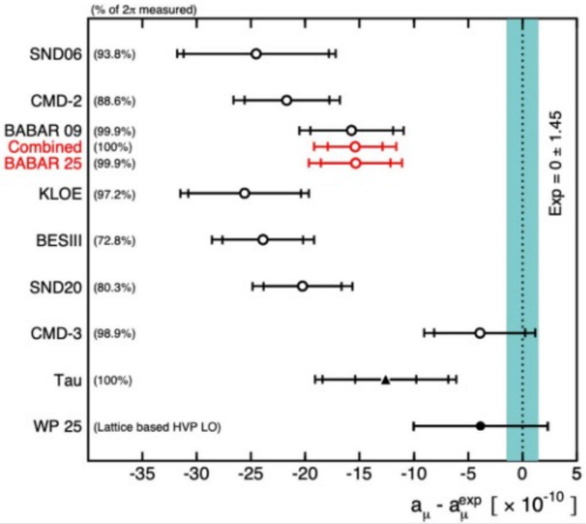
Andrés Pinto

Andreas Pinto @ Orsay

New analyses :
Factor x2 more statistics
Independent π - μ separation

- New **blind BaBar analysis** (460 fb^{-1}) confirms the $\pi^+\pi^-$ contribution to a_μ.
- Independent method (angular fits, no PID) removes dominant 2009 systematic.
- Unblinded $\mu\mu\gamma$ spectrum agrees with QED, validating the approach.
- $\pi\pi$ cross section consistent with 2009, with **reduced systematics** in 0.5–1.4 GeV.

- Results:
  - Below 0.5 GeV: $a_\mu^{\pi\pi} = (58.0 \pm 5.5\,(\text{stat.}) \pm 1.7\,(\text{syst.})) \times 10^{-10}$
  - 0.5–1.4 GeV: $a_\mu^{\pi\pi} = (456.2 \pm 2.2\,(\text{stat.}) \pm 1.7\,(\text{syst.})) \times 10^{-10}$
- Robustness shown by excellent agreement with 2009.



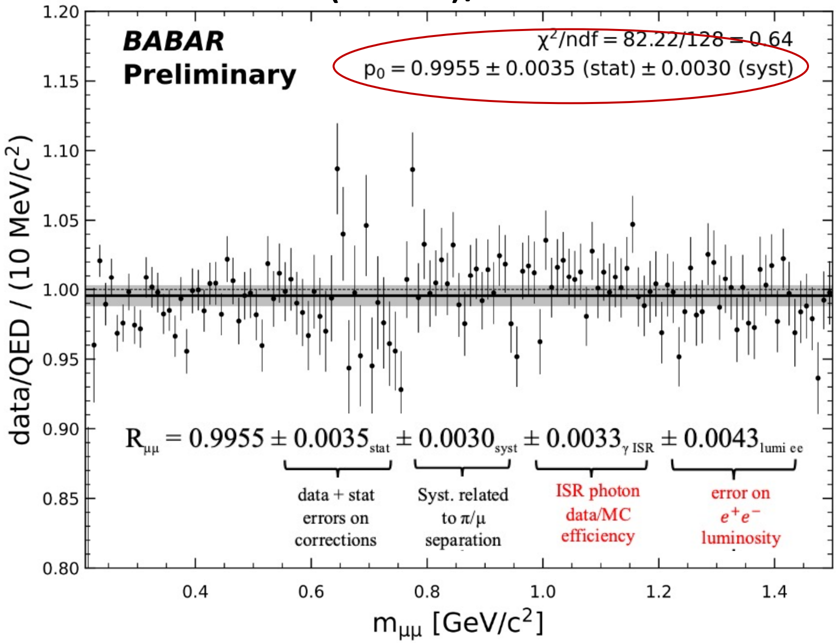
- Central region: systematic error 0.37%, statistical error (from fit) similar to 2009 analysis
- Statistical error dominates in threshold region

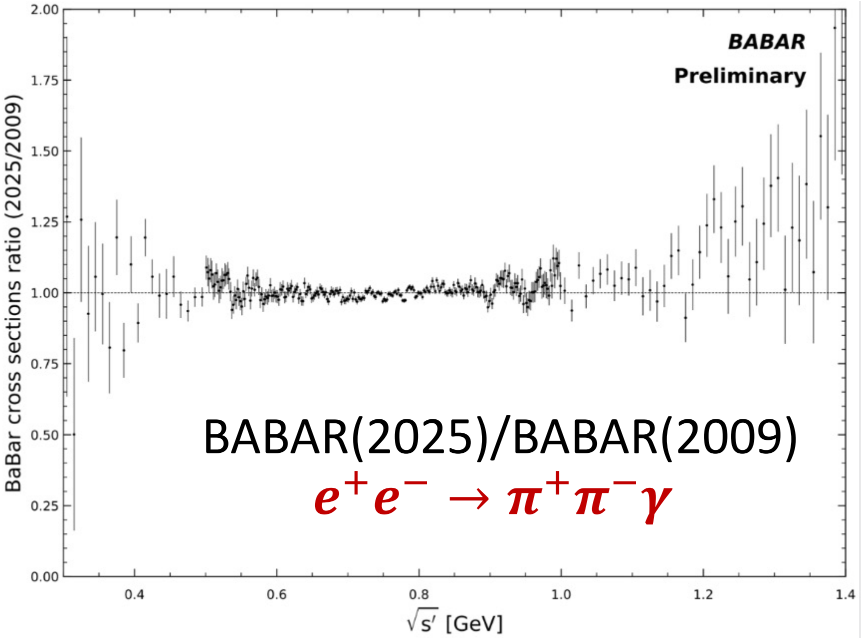
New BABAR ISR Measurement of $e^+e^- \to \pi^+\pi^-$

Andrés Pinto @ Orsay

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

BABAR(2025)/MC Phokhara





BABAR(2025)/BABAR(2009)

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

NEW

New BABAR ISR Measurement of $e^+e^- \to \pi^+\pi^-$

Andreas Pinto @ Orsay

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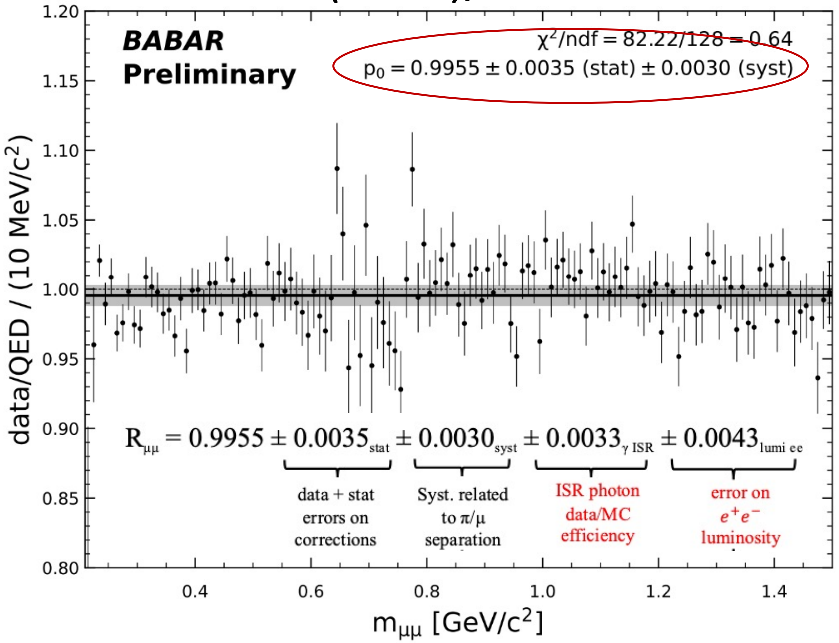
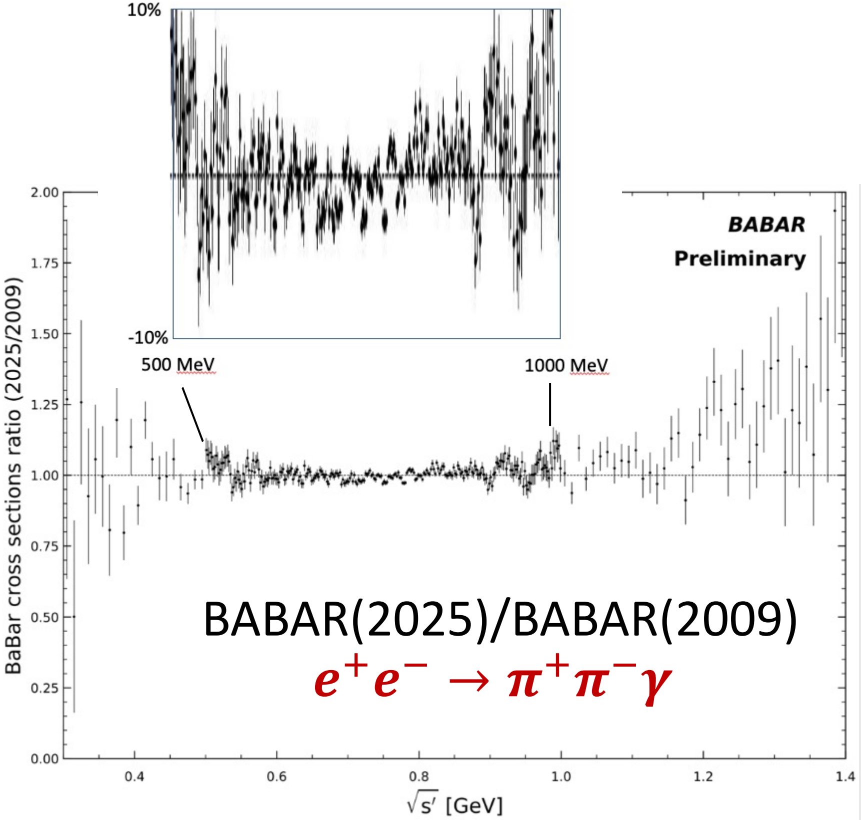


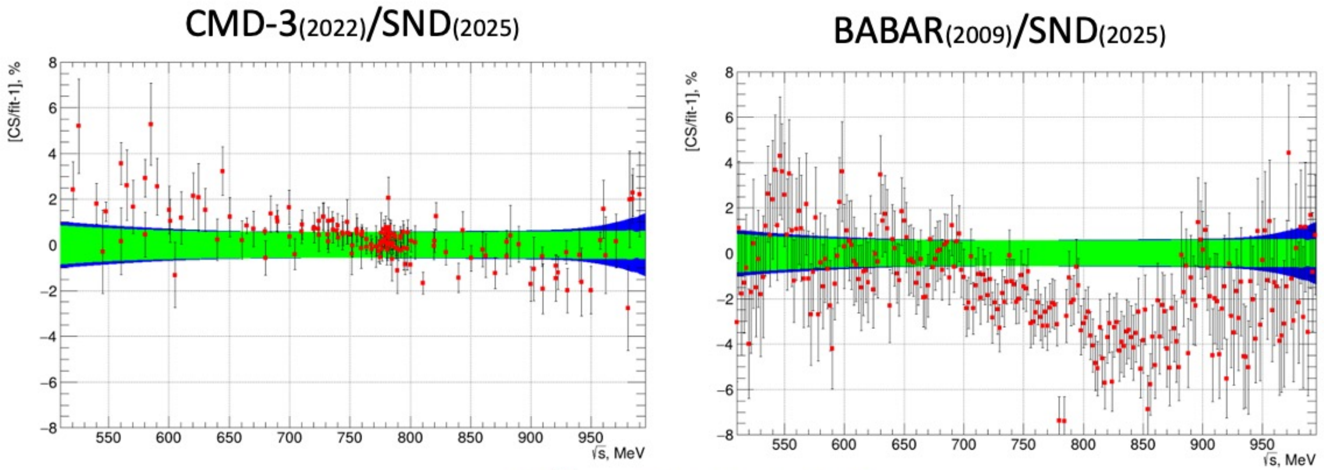


BABAR(2025)/BABAR(2009)

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

New SND Measurement of $e^+e^- \to \pi^+\pi^-$ (energy scan)

- New SND analysis based on 90/pb of data collected in 2018 (factor x20 compared to SND20)
- New selection algorithm, systematic uncertainty of 0.7%
  → higher cross section compared to previous analysis (SND20)
  → „ application of the current analysis techniques to (previous) data results in better agreement"
- Cross check on 2% level with 2019 data
- In dispersion integral
  -0.6σ wrt. CMD-3
  +1.8σ wrt. BABAR(09)



-0.6 σ

$a_\mu \times 10^{10} = 431.11 \pm 3.52$ vs.

+1.8 σ

CMD-3: $a_\mu \times 10^{10} = 433.62 \pm 3.76$ BaBar: $a_\mu \times 10^{10} = 423.87 \pm 2.06$

Overview Experiments – Past and Future

Experiment	Published Method	Normalization	Separation π - μ - e	Future
KLOE	ISR untagged ISR tagged ISR untagged	Luminosity Luminosity $\mu+\mu-\gamma$	Kinematics Track Kinematics Track Kinematics Track	ISR untagged $\mu+\mu-\gamma$ statistics x 7
BABAR	ISR tagged	$\mu+\mu-\gamma$	Particle ID	ISR tagged, separation by polar angle, statistics x 2
BESIII	ISR tagged	Luminosity	Particle ID (ML)	ISR tagged, $\mu+\mu-\gamma$, statistics x 7, 1C kin. fit
BELLE-II				ISR tagged, $\mu+\mu-\gamma$, Particle ID
CMD-3	Energy scan	e+e-	Kinematics Track Kinematics EMC	overall improvements
SND	Energy scan	e+e-	Kinematics EMC	overall improvements ML for π – e separation

Overview Experiments – Past and Future

Experiment	Published Method	Normalization	Separation π - μ - e	Future	
KLOE	ISR untagged ISR tagged ISR untagged	Luminosity Luminosity μ+μ-γ	Kinematics Track Kinematics Track Kinematics Track	ISR untagged μ+μ-γ statistics x 7	0.4%
BABAR	ISR tagged	μ+μ-γ	Particle ID	ISR tagged, separation by polar angle, statistics x 2	0.5%
BESIII	ISR tagged	...inosity	Particle ID (ML)	ISR tagged, μ+μ-γ, statistics x 7, 1C kin. fit	0.5%
BELLE-II				ISR tagged, μ+μ-γ, Particle ID	0.5%
			Kinematics Track Kinematics EMC	overall improvements	0.3%
	...rgy scan	e+e-	Kinematics EMC	overall improvements ML for π – e separation	0.7%

New analyses in preparation:
New MC generators, new techniques,
awareness to (N)NLO issues, ...

Upcoming new ISR BESIII Measurement of $e^+e^- \to \pi^+\pi^-$

Existing BESIII tagged ISR result based on 2.9/fb of data at $\sqrt{s}$=3.77 GeV - 4C kinematic fit

0.9% systematic uncertainty

sources	Uncertainty (%)
Photon efficiency	0.2
Tracking efficiency	0.3
Pion ANN efficiency	0.2
Pion e-PID efficiency	0.2
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
Luminosity $\mathcal{L}_{\mathrm{int}}$	0.5
Sum	**0.9**

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First half next year: expect new result!

adding 3.1/fb of data at $\sqrt{s}$=4.18 GeV;

1C kinematic fit → much less sensitive towards MC limitations of rad. corrections,

some minor additional improvements (0.7%))

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
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Unfolding	0.2
FSR correction δ_{FSR}	0.2
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Luminosity $\mathcal{L}_{\text{int}}$	0.5 → 0.3
Sum	**0.9 → 0.7**

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adding 3.1/fb of data at $\sqrt{s}$=4.18 GeV;
1C kinematic fit → much less sensitive towards MC limitations of rad. corrections,
some minor additional improvements (0.7%))

Next years: final result based on existing data set of 20/fb of data at $\sqrt{s}$=3.77 GeV;
1C kinem. fit and normal. to μμγ (<0.5%)

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
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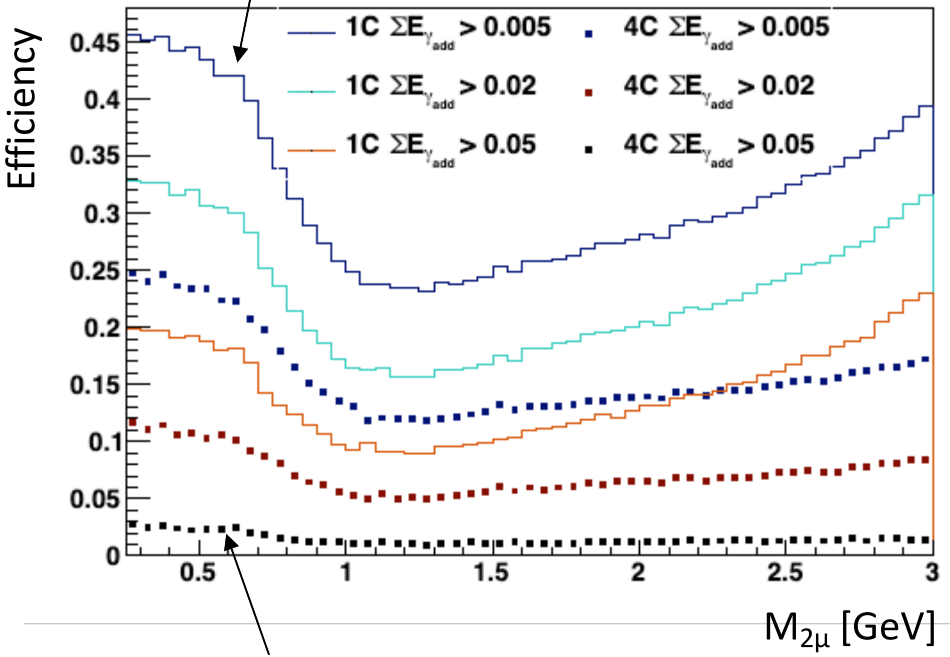
Upcoming new ISR BESIII Measurement of $e^+e^- \to \pi^+\pi^-$

1C kinematic fit

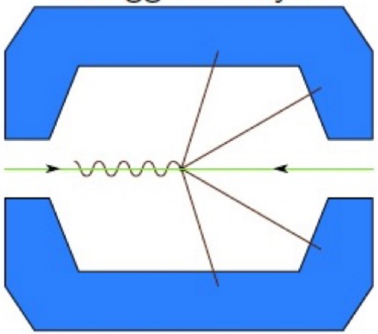


4C kinematic fit (published result)

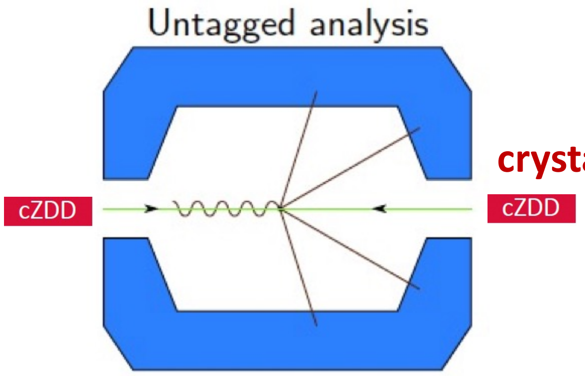
1C kinematic fit with much (x4) improved efficiency for NLO ISR photons
→ more inclusive for (N)NLO photons

Installation of a Tagging Detector at BESIII: cZDD

Untagged analysis

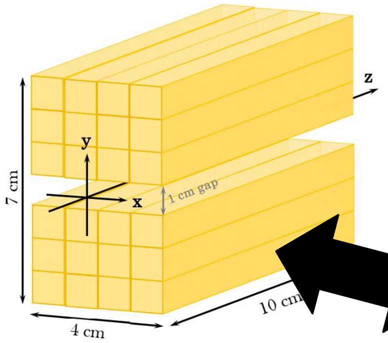


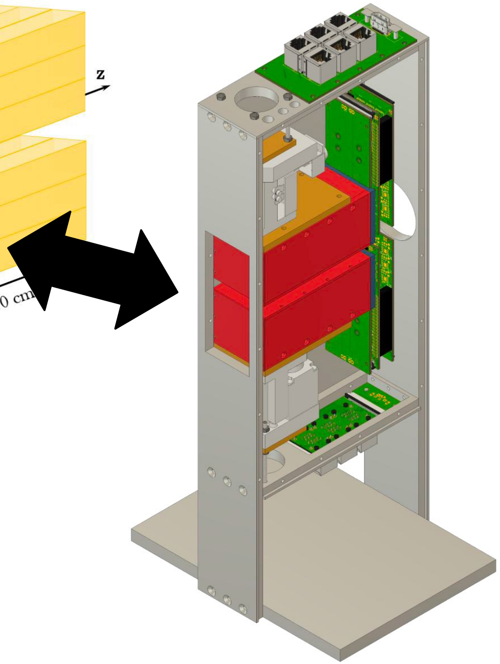
Installation of a Tagging Detector at BESIII: cZDD



crystal Zero Degree Detector

2 half detectors with 12 LYSO crystals each (SiPM) (on both sides), retractable
→ PANDA sampling ADC for SiPM readout
→ can also be used as luminosity detector





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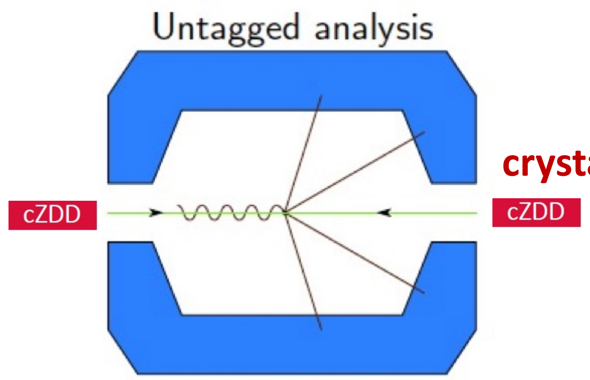

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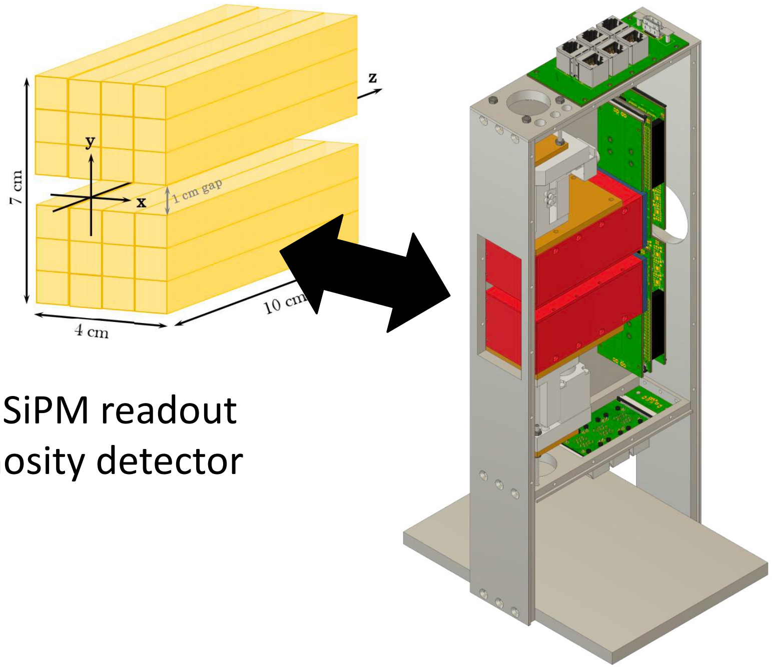
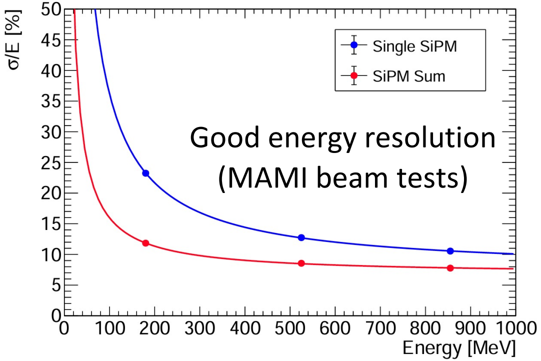
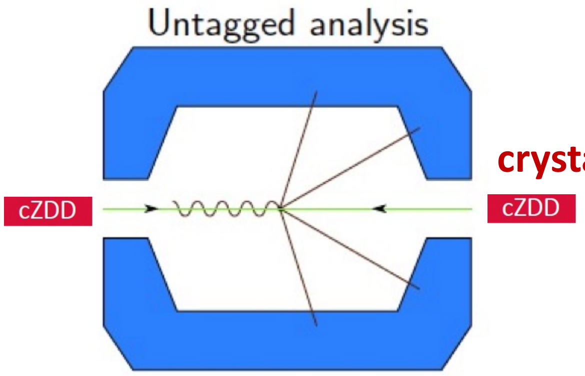
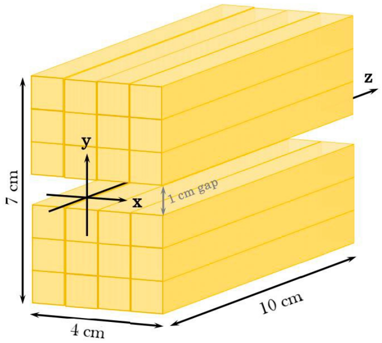


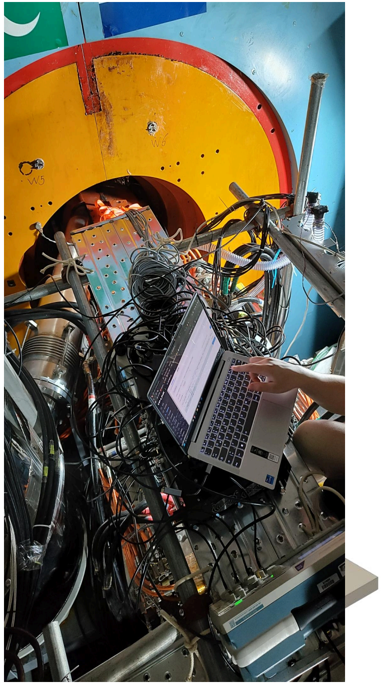


Installation of a Tagging Detector at BESIII: cZDD



crystal Zero Degree Detector





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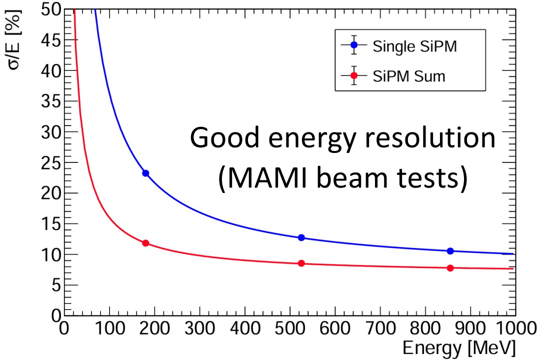


Installed in BESIII on Sept. 10th

→ cZDD detector will improve our capabilities for ISR physics (tagging of ISR photon, background subtraction, ...)

Conclusions

Conclusions

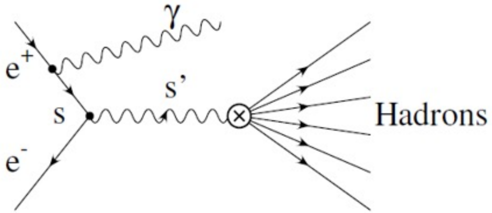
- New Lattice as well as CMD-3 results challenging previous e^+e^- data

  - difference in $\pi^+\pi^-$ between CMD-3 and other expts. to be understood
  - brand new BABAR data confirms previous result (in conflict with FNAL g-2)
  - will be exciting to see next upcoming new results (BESIII)

- Radiative corrections are a key issue → RadioMonteCarlow initiative!
  Comparison of existing MC codes should be possible shortly (finally!)
  New analysis algorithms designed to be resilient against MC limitations

- Have not covered other hadronic channels beyond $\pi^+\pi^-$- puzzles there as well

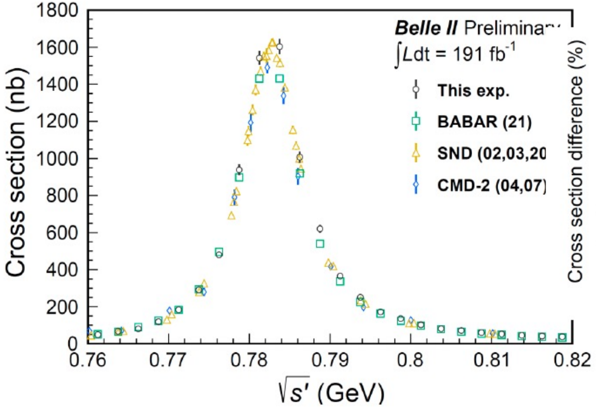
- Have not covered new inclusive ISR analysis at BESIII (with great potential for BELLE-II!)

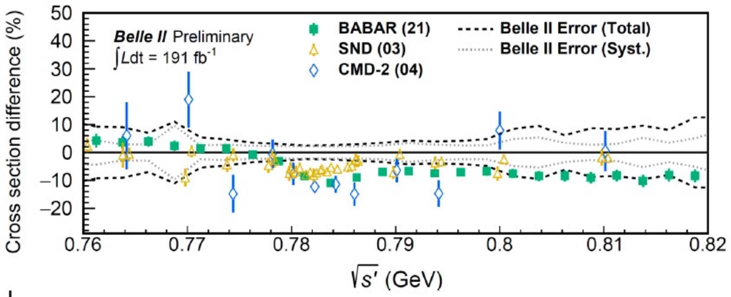


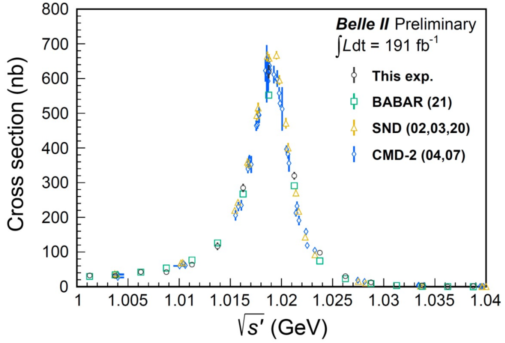
Thank you !

New BELLE-II Analysis of $e^+e^- \rightarrow \pi^+\pi^-\pi^0$

- First BELLE-II ISR analysis of hadronic process: $\pi^+\pi^-\pi^0$ channel, $(0.62 < \sqrt{s} < 1.8)$ GeV
  → systematic uncertainty: >2.2%
  → integral value higher by 2.5 sigma than BABAR
- Main limitation (~1.2% uncertainty): NLO radiative correction
  → confirmation of BABAR findings, however with limited consequences







5% ... 10% higher cross section than BABAR in ω region

NEW

CMD-3: $e^+e^- \to K_S K_L$

- Measurement 1.004 – 1.070 GeV
- 1.8% systematic uncertainty (BABAR 2.9%)
- Reconstruction of $K_S \to \pi^+\pi^-$
- Fit to cross section:

$$\sigma_{e^+e^-\to K_S^0 K_L^0}(s) = \frac{8\pi\alpha}{3s^{5/2}} p^3_{K^0} \left| \frac{g_{\rho\gamma} g_{\rho KK}}{D_\rho(s)} + \frac{g_{\omega\gamma} g_{\omega KK}}{D_\omega(s)} + \frac{g_{\phi\gamma} g_{\phi KK}}{D_\phi(s)} + A_{\rho',\omega',\phi'} \right|^2,$$

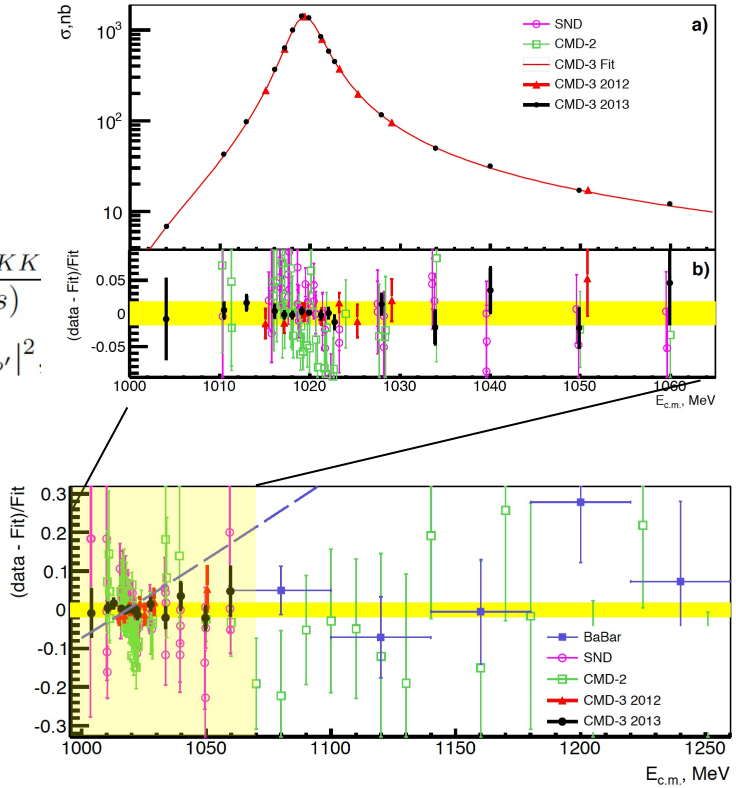
$$|g_{V\gamma}| = \sqrt{\frac{3m_V^3 \Gamma_{Vee}}{4\pi\alpha}}; \; |g_{VKK}| = \sqrt{\frac{6\pi m_V^2 \Gamma_V B_{VKK}}{p^3_{K^0}(m_V)}},$$

$$D_V(s) = m_V^2 - s - i\sqrt{s}\Gamma_V(s)$$

$$\Gamma_V(s) = \Gamma_V \sum_{V\to f} B_{V\to f} \frac{P_{V\to f}(s)}{P_{V\to f}(m_V^2)}$$

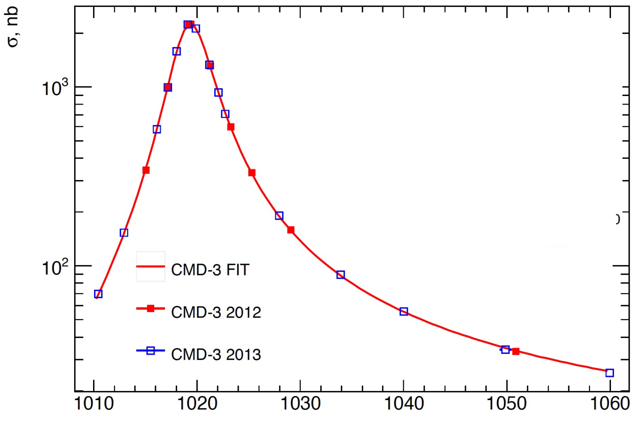
- Overall good agreement

Phys.Lett. B760 (2016) 314



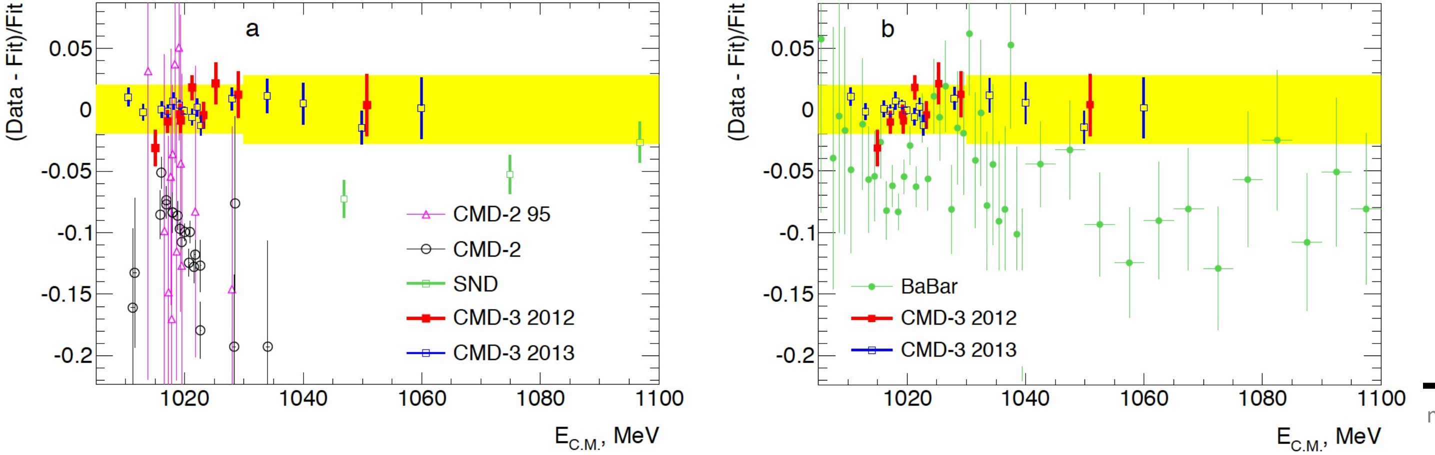
CMD-3: $e^+e^- \to K^+K^-$

NEW



Phys.Lett. B779 (2018) 64

- Measurement 1.010 – 1.060 GeV
- 2.0% systematic uncertainty
  (BABAR 0.72 – 1.41 % in that range)
- Similar fit to cross section as for $K_S K_L$
  Parameters:
- New CMD-3 data above CMD-2 / BABAR
  ???



R_{incl} Measurement BESIII (2022)

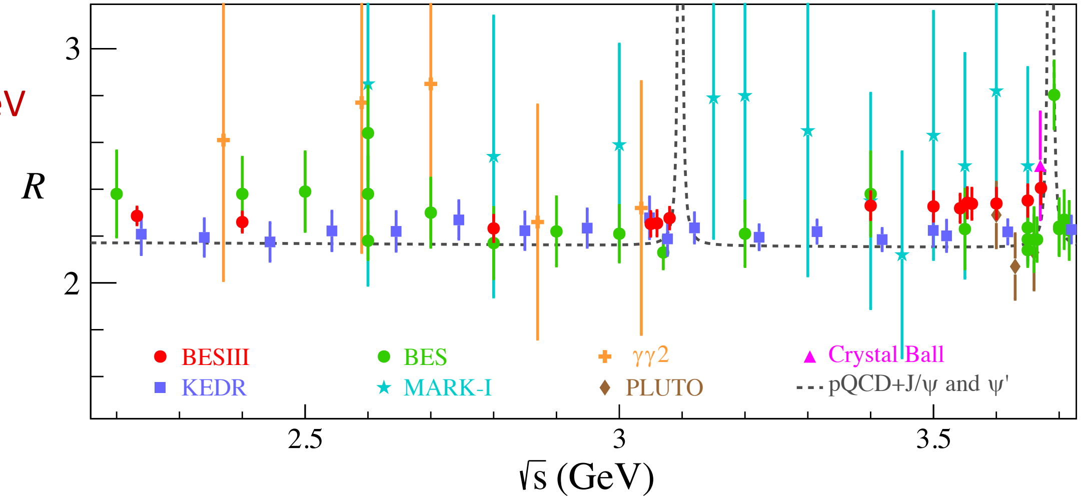
Phys. Rev. Lett. 128 (2022) 062004

$$R_{\text{had}}(s) = \frac{1}{\sigma_{\mu^+\mu^-}} \cdot \frac{N_{\text{had}} - N_{\text{bkg}}}{\mathcal{L} \cdot \varepsilon_{\text{had}} \cdot (1+\delta)}$$

Analysis strategy: select all events with ≥ 2 tracks

- Reject back-to-back 2-prong events (Bhabha, μ+μ-)
- Remaining background from ISR and QED events subtracted from MC

- Energy range covered: $2.2 < \sqrt{s} < 3.7$ GeV
- Statistical uncertainty <0.5%
  Systematic uncertainty <2.6% below 3.1 GeV
  ~3.0% above
- Above 3.4 GeV deviation observed with:
  - KEDR/Novosibirsk on the level of 1.9σ
  - pQCD theory on the level of 2.7σ



World's most precise R_{incl} measurement !
Some deviations from pQCD seen ?!
Much more data will be published shortly !

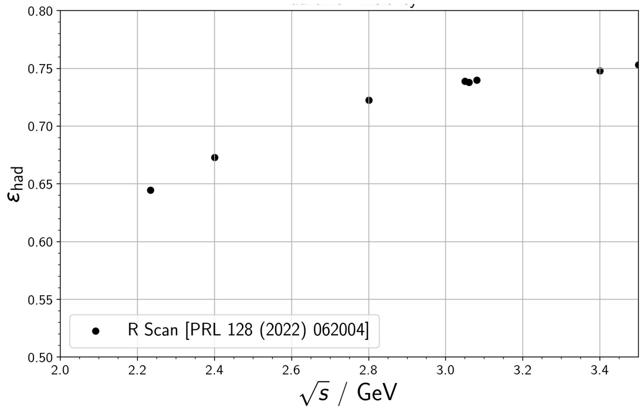
Messages learnt from Inclusive R Measurement

- Selection requires $\geq$ **2 tracks,** which are not back-to-back
- Detector acceptance starts **above 21°**

→ For low-multiplicity final hadronic states ($\pi^+\pi^-$, $\pi^+\pi^-\pi^0, \pi^+\pi^-\pi^0\pi^0$, ...), the probability to be not selected large relatively large

→ Total event efficiency at 60% .... 70% level

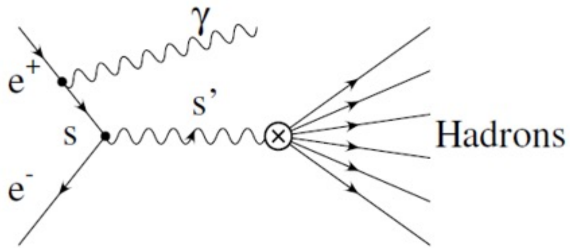
Efficiency



For the determination of the event efficiency, a precise MC generator for $e^+e^- \rightarrow Hadrons$ is needed (possible model dependence difficult to estimate)

Inclusive ISR with detection of ISR photon only

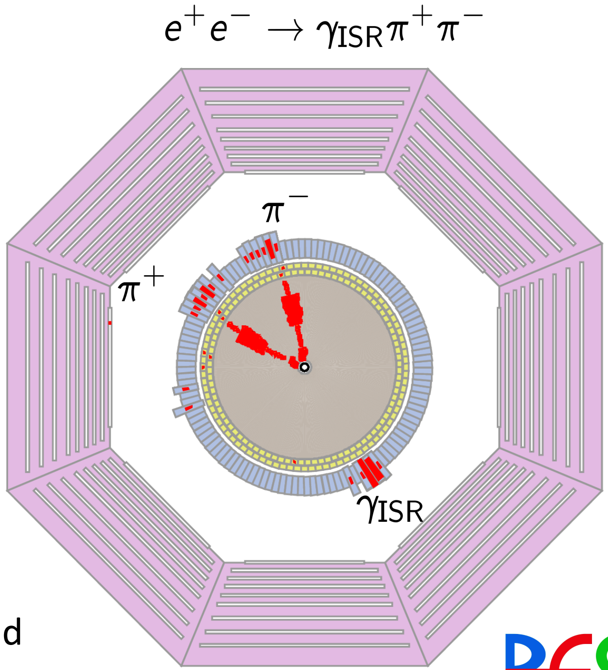
$$s' = m_{\rm had}^2 = s - 2E_\gamma\sqrt{s}$$



New Inclusive Approach using ISR

Event selection:

- **Select 1 high-energetic photon > 1.2 GeV ≡ ISR photon at large polar angle $|cos\Theta_{ISR}| < 0.8$**
  → Restricts hadronic mass spectrum < 2.7 GeV
- **Require (for time being) ≥ 1 charged track in the event**
  → Does currently not include fully neutral states (e.g. $e^+e^- \rightarrow \pi^0\gamma$)



- ISR boost confines particles into narrow cone
  → Very high detection efficiency
- Less reliant on description of hadronic MC
  → ISR description in MC under control
- Single measurement down to threshold (does not need scan)
- Measurement fully inclusive for Final State Radiation (FSR) and higher order corrections of ISR
- In principle able to measure fully neutral channels

New Inclusive Approach using ISR: Efficiency

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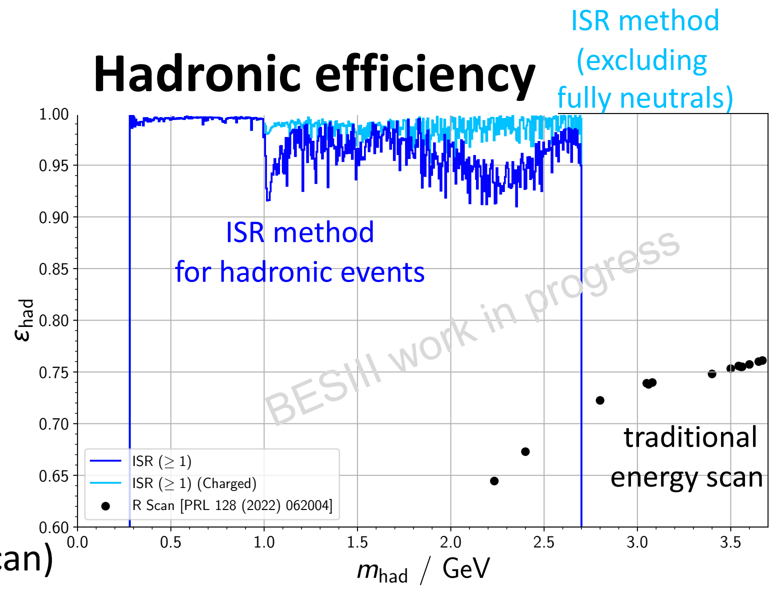
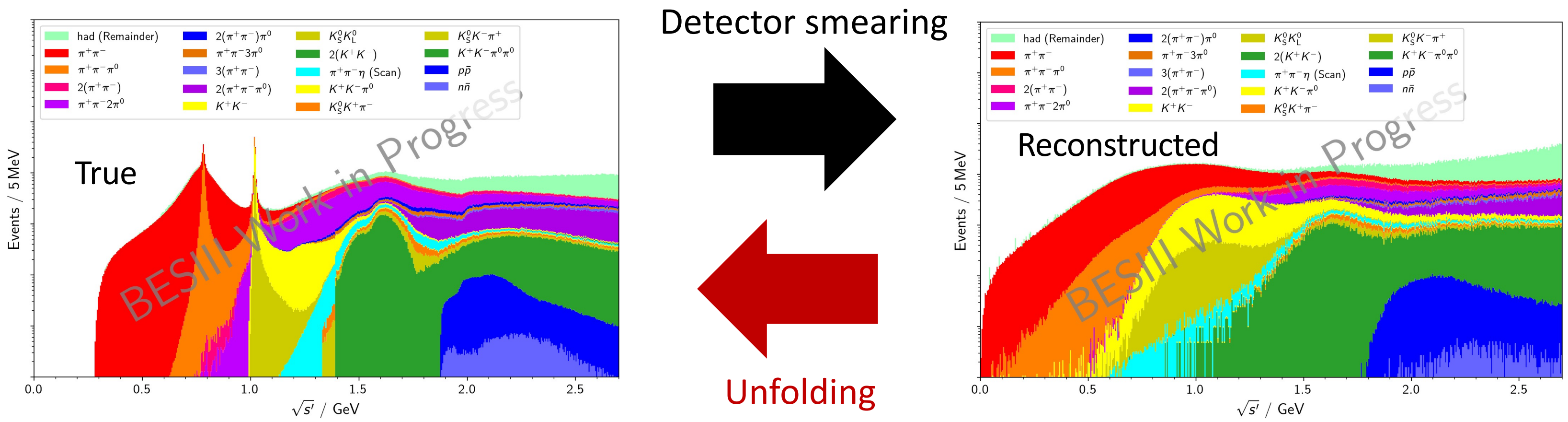


Unfolding from Detector Mass Resolution

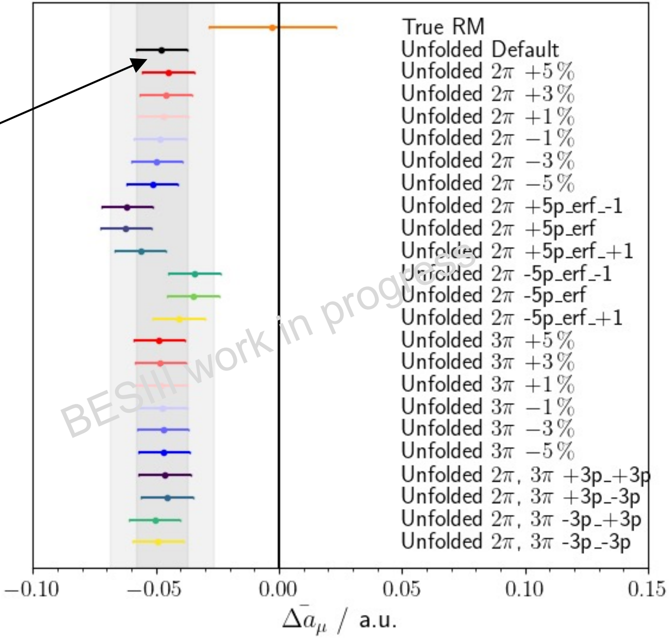


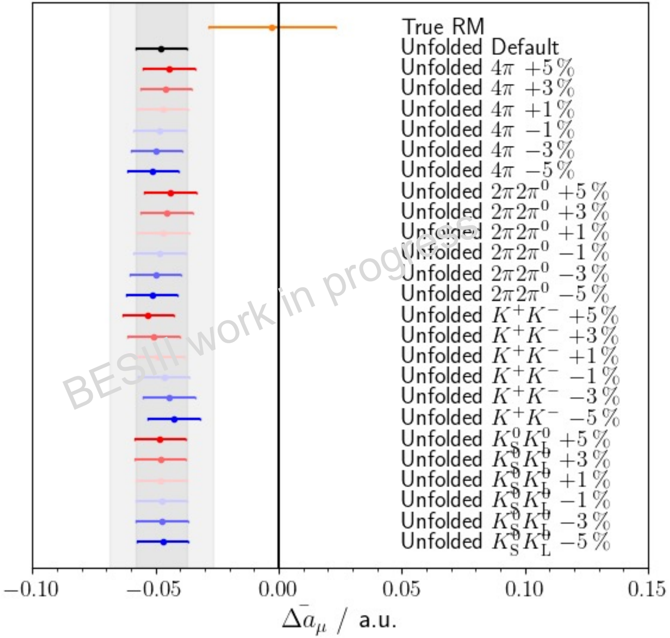
- Large smearing introduced by limited detector resolution
- Application of unfolding algorithms to recover the *true* spectrum
- Requires Monte-Carlo program to construct unfolding matrix – Response Matrix (RM)
- Systematically testing the bias in the unfolding procedure due to wrong input Monte-Carlo Pseudo Data (PD)

Unfolding from Detector Mass Resolution

- More than 50 cross section variations in input MC tested (e.g. up to ±5% variation of 2π cross section)
  → Very stable result for unfolded spectrum → variation well within percent level (=precision goal)

variations from 200 samples of pseudo data

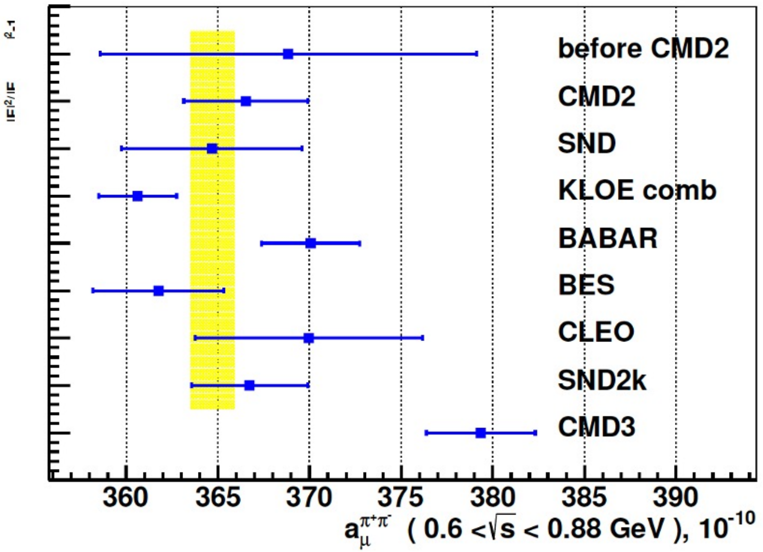




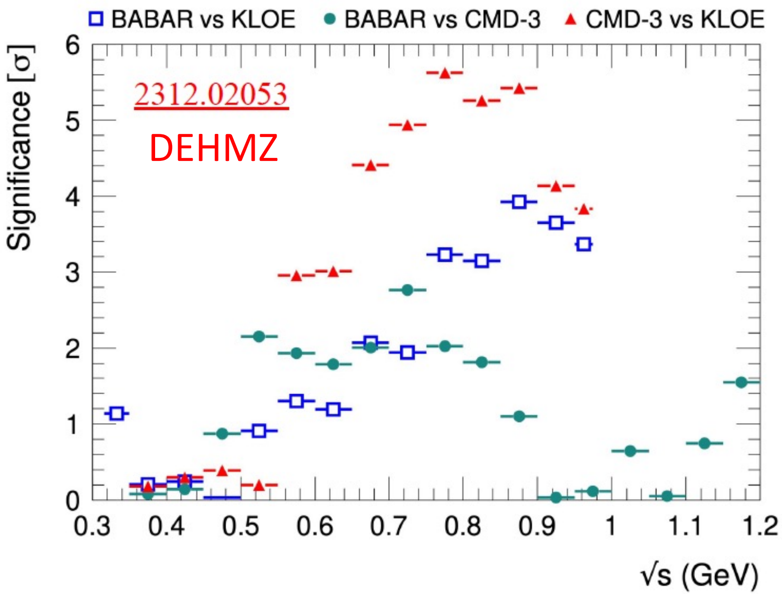
- **With larger data sets also conversion events might be used to significantly improve mass resolution**

CMD-3 Compatibility with other Experiments for HVP Integral

(g-2) Integral $a_\mu^{\pi\pi}$ (600 − 880 MeV)

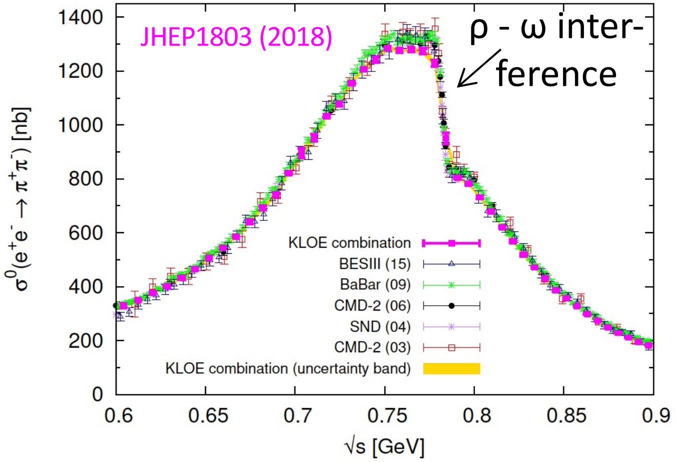


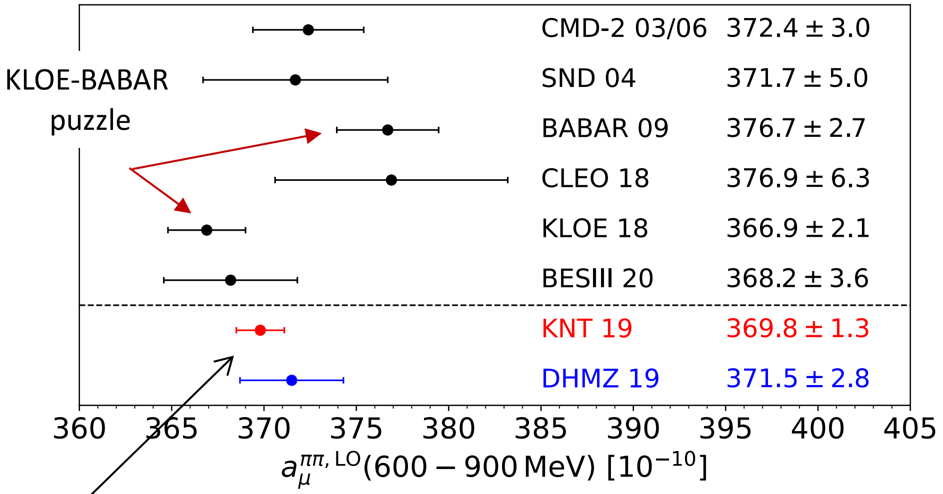
Deviation between data sets (in statistical significance)



→ Significant deviation from previous ISR <u>and</u> energy scan experiments (CMD-2)! Why?

Most relevant Channel: $e^+e^- \to \pi^+\pi^-$ (until 2023)





Systematic Uncertainties on ρ(770) peak

- ISR BABAR 0.5%
- ISR KLOE 0.6%
- ISR BESIII 0.9%
- Energy Scan CMD-2 0.8%*
  - * limited in addition by statistics

Most recent evaluations of HVP:

- Davier, Höcker, Malaescu, Zhang (DHMZ)
  - averaging via 2nd ord. polynomial interpolation
  - systematic correlat. propagated via pseudo-data (MC)
- Keshavarzi, Nomura, Teubner (KNT)
  - data subjected to a clustering procedure
  - fit over all data sets taking into account correlations

2020 Whitepaper Estimate of HVP

Merging of KNT, DHMZ esti... ...put from ChPT/dispersive fits: CHHKS for 2π, 3π channels;

Big debate up to 2023:
Who is right? KLOE or BABAR?

	DHMZ19	KNT19	Difference
	507.85(0.83)(3.23)(0.55)	504.23(1.90)	3.62
	46.21(0.40)(1.10)(0.86)	46.63(94)	−0.42
	13.68(0.03)(0.27)(0.14)	13.99(19)	−0.31
	18.03(0.06)(0.48)(0.26)	18.15(74)	−0.12
	23.08(0.20)(0.33)(0.21)	23.00(22)	0.08
K_L	12.82(0.06)(0.18)(0.15)	13.04(19)	−0.22
$\pi^0\gamma$	4.41(0.06)(0.04)(0.07)	4.58(10)	−0.17
Sum of the above	626.08(0.95)(3.48)(1.47)	623.62(2.27)	2.46
[1.8, 3.7] GeV (without $c\bar{c}$)	33.45(71)	34.45(56)	−1.00
J/ψ, $\psi(2S)$	7.76(12)	7.84(19)	−0.08
[3.7, ∞) GeV	17.15(31)	16.95(19)	0.20
Total $a_\mu^{\text{HVP, LO}}$	694.0(1.0)(3.5)(1.6)(0.1)$_\psi$(0.7)$_{\text{DV+QCD}}$	692.8(2.4)	1.2

:-((difference 3.62)

reasonable agreement (difference 1.2)

→ $a_\mu^{HVP,LO} = 693.1(2.8)_{\text{exp}}(2.8)_{\text{syst}}(0.7)_{\text{pQCD}} = 693.1(4.0) \times 10^{-10}$ Whitepaper estimate

experimental uncertainties: domitated by 2π uncertainty

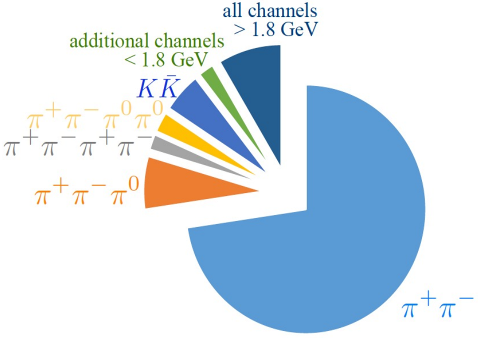
KLOE/BABAR tension: leaving out KLOE or BABAR, respectively

energy region [1.8;3.7] GeV; usage of pQCD by DHMZ, while KNT follows data-driven approach

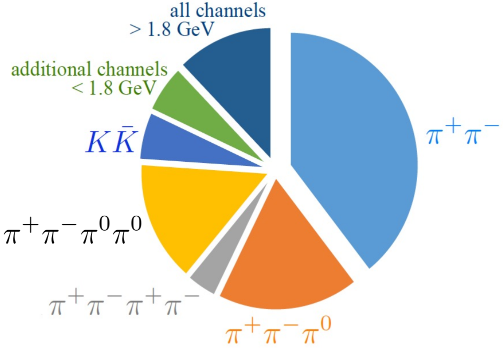
Hadronic Vacuum Polarization Contribution to (g-2)$_\mu$

Anomalous magnetic moment of the muon (g-2)$_\mu$

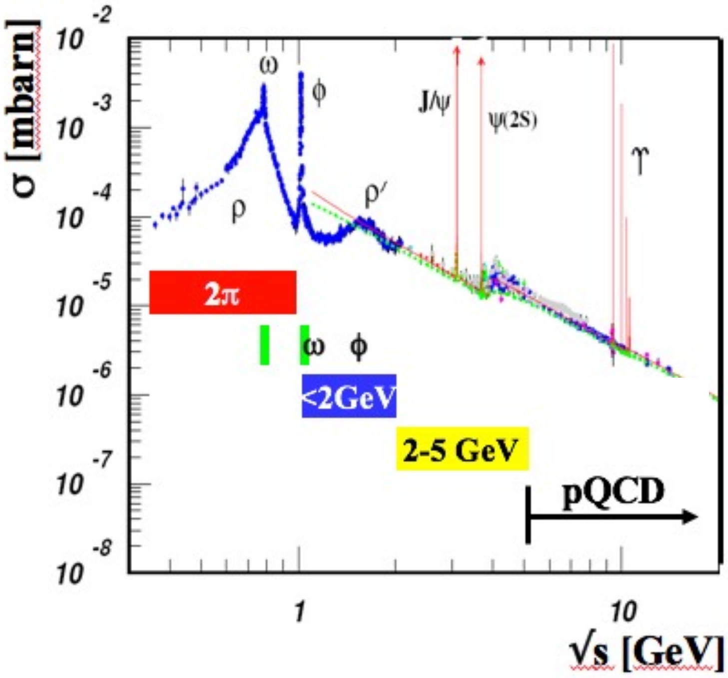
$$a_\mu^{HVP} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\, \boldsymbol{\sigma}_{\mathbf{had}}(\boldsymbol{s})$$



Contributions to HVP integral



Contributions to HVP error



Overview Experiments – Past and Future

Experiment	Published Method	Normalization	Separation π - μ - e	Future	
KLOE	ISR untagged ISR tagged ISR untagged	Luminosity Luminosity $\mu^+\mu^-\gamma$	Kinematics Track Kinematics Track Kinematics Track	ISR untagged $\mu^+\mu^-\gamma$ statistics x 7	0.4%
BABAR	ISR tagged	$\mu^+\mu^-\gamma$	Particle ID	ISR tagged, separation by polar angle, statistics x 2	<0.5%
BESIII	ISR tagged	…inosity	Particle ID (ML)	ISR tagged, $\mu^+\mu^-\gamma$, statistics x 7, 1C kin. fit	0.5%
BELLE-II				ISR tagged, $\mu^+\mu^-\gamma$, Particle ID	0.5%
			Kinematics Track Kinematics EMC	overall improvements	0.3%
	…rgy scan	e+e-	Kinematics EMC	overall improvements ML for π – e separation	0.6%

New analyses in preparation:
New MC generators, new techniques,
awareness to (N)NLO issues, …

NEW

Hadronic Cross Section Data after 2020 Whitepaper

- BESIII $\pi^+\pi^-$ (600 < $\sqrt{s}$ < 900) MeV, update of covariance matrix → central value unchanged
- Energy scan measurements above 2 GeV of multi-hadronic channels (spectroscopy)
- Total hadronic cross section measurement above 2 GeV

- New SND scans of $\pi^+\pi^-4\pi^0$ above 1 GeV (> 3% uncertainty)
- New SND scan of $\pi^+\pi^-$ channel, (525 < $\sqrt{s}$ < 883) MeV
  → systematic uncertainty > 600 MeV: 0.8%; after publications issues found

- New BABAR ISR data on $\pi^+\pi^-4\pi^0$, $2(\pi^+\pi^-)3\pi^0$, $KK\pi\pi\pi$
- New BABAR ISR analysis of $\pi^+\pi^-\pi^0$ channel, (0.62 < $\sqrt{s}$ < 3.5) GeV
  → systematic uncertainty: > 1.3%
  → fit to $M_{3\pi}$ including $\omega(782)$, $\omega(1420)$, $\omega(1680)$, $\phi(1020)$, $\rho(770)$

- First BELLE-II ISR analysis of hadronic process: $\pi^+\pi^-\pi^0$ channel, (0.62 < $\sqrt{s}$ < 1.8) GeV
  → systematic uncertainty: >2.2%
  → integral value higher by 2.5 sigma than BABAR
- Main limitation (~1.2% error): NLO rad. correction → confirmation of BABAR findings

Inclusive R Measurement

Above cms energies of ~ 2 GeV inclusive measurement of R_{had}
(large QED background below, low multiplicities)

Master formula:

$$R_{\text{had}}(s) = \frac{1}{\sigma_{\mu^+\mu^-}} \cdot \frac{N_{\text{had}} - N_{\text{bkg}}}{\mathcal{L} \cdot \varepsilon_{\text{had}} \cdot (1+\delta)}$$

Background Contributions

- Evaluated with MC:
  - BabaYaga@NLO, Phokhara, KKMC
    $e^+e^- \to e^+e^-, \mu^+\mu^-, \gamma\gamma, \tau^+\tau^-$
  - BdkRC, Diag36, Galuga, Ekhara
    $e^+e^- \to e^+e^- X$
- Beam related background

CMS Energy

- 14 points
- 2.2 GeV to 3.7 GeV
- > 10^5 had. events

Luminosity

Determined with large angle Bhabha scattering

Efficiency

Ratio of generated and reconstructed events from Monte-Carlo

Radiative Corrections

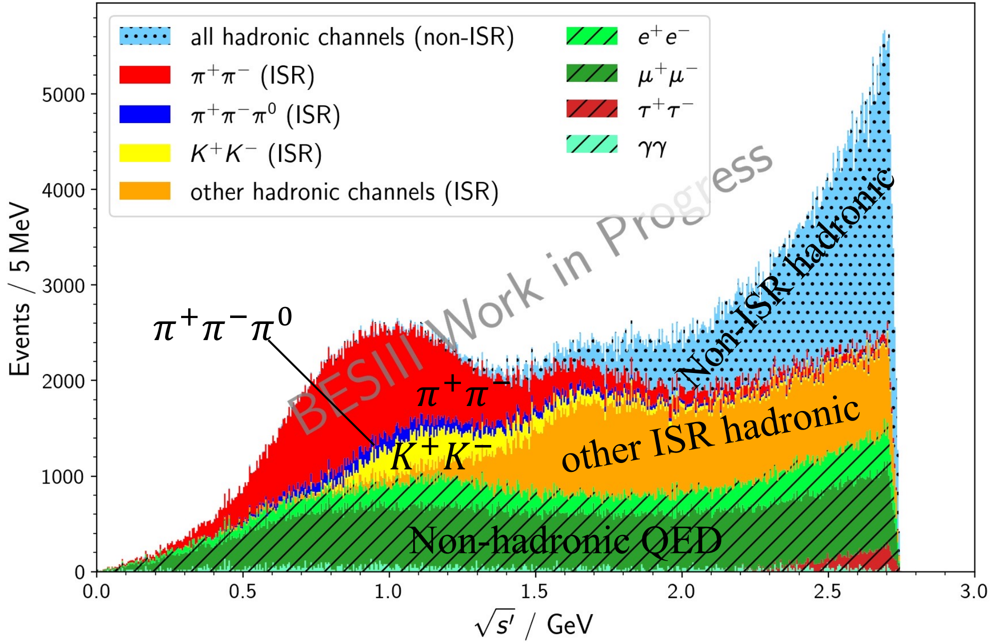
- Two schemes tested
  - Feynman diagram
  - Structure functions
- Agreement within 1.2 %

Analysis strategy: select all events with $\geq$ 2 tracks

- Reject back-to-back 2-prong events (Bhabha, Di-Muons)
- Remaining background from ISR and QED events ($e^+e^- \to e^+e^- / \mu^+\mu^-$) subtracted from MC

Hadronic Mass Spectrum

Mass spectrum after application of PID and meson veto



- Plots for $\sqrt{s} = 4.180$ GeV (3.1 / fb)
- No additional cuts using Muon Detector or other selection cuts

- Significant yield of hadronic events over QED background; hadronic non-ISR event yield small < 1.5 GeV
- However ... due to limited energy resolution of ISR photon, huge smearing effects (no ρ, ω, ϕ visible)

Improve Mass Resolution by using Photon Conversion Events

- Utilize conversion of ISR photon in detector material, especially the beam pipe

  Reduction of statistics

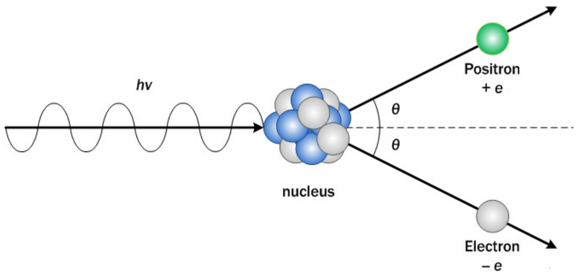
- Tracks of produced e^+e^- pair to be reconstructed in the MDC

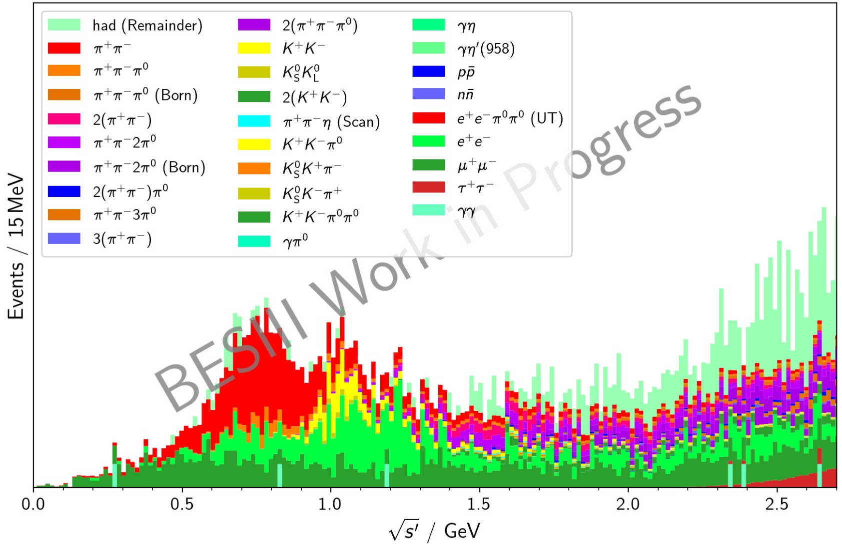
- Improvement of mass resolution by large factors

  → Narrow resonances now separately visible

- High potential for the new high-statistics data sets at BESIII, especially the 20/fb data sample being currently collected

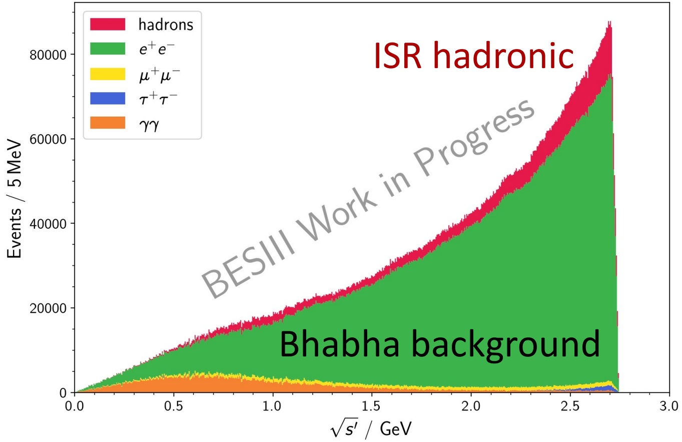
  → allows for cross checks between different analysis approaches

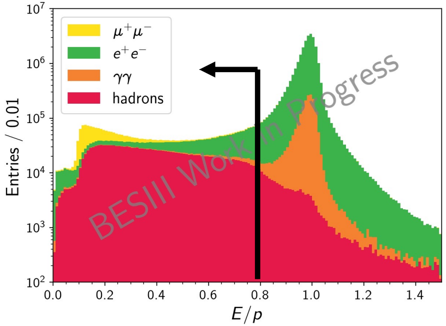




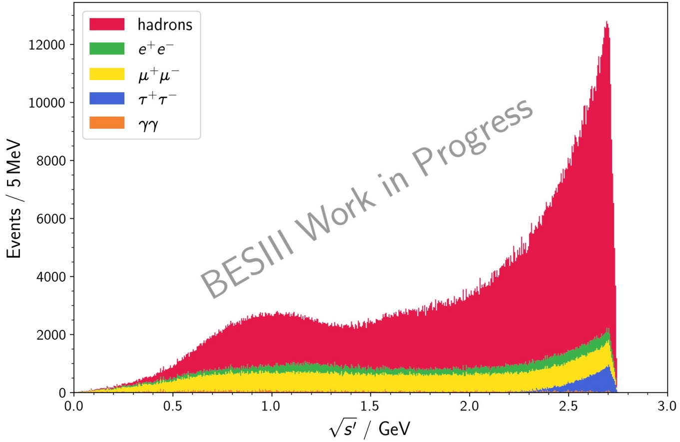
Challenge 1: Subtraction of QED Background

- Apply dedicated PID cuts, e.g. $E_{EMC} / |\vec{p}|$
- Subtract remaining QED events using MC simulation → High precision QED MC needed
  - ✓ BabaYaga@NLO ~0.1%: $e^+e^- \to e^+e^-(\gamma),\ \gamma\gamma(\gamma)$
  - ✓ Phokhara ~0.5%: $e^+e^- \to \mu^+\mu^-(\gamma)$
  - ✓ KKMC: $e^+e^- \to \tau^+\tau^-(\gamma)$



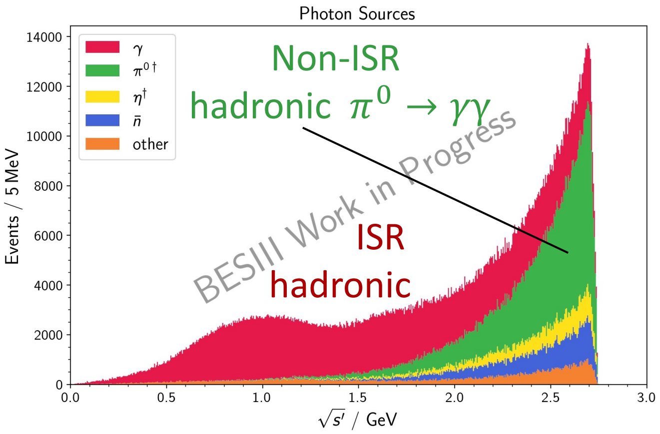


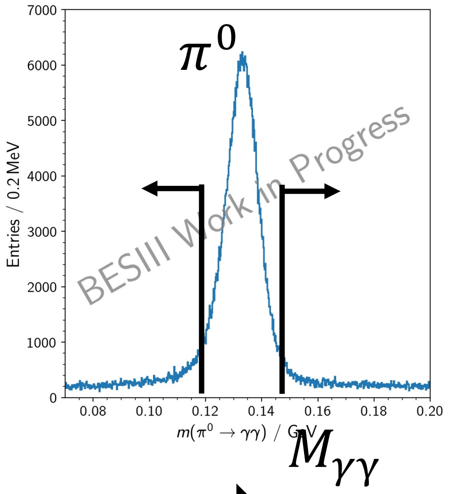
Dramatic reduction of Bhabha background

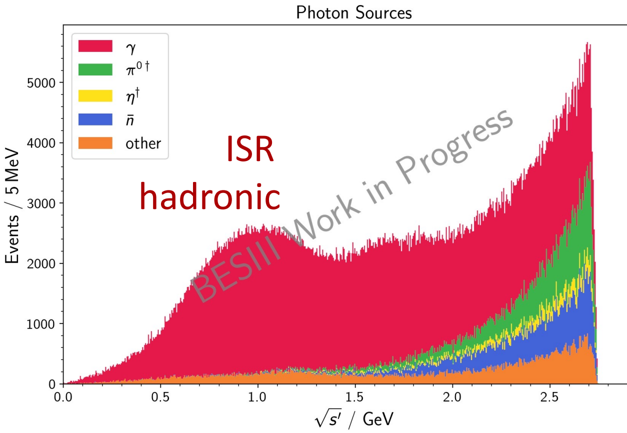


Challenge 2: Subtraction of Hadronic Non-ISR Events

- Very asymmetric two-photon decays of π^0 mesons, $\pi^0 \to \gamma\gamma$, can produce high-energetic photons
- Veto events, in which $\gamma\gamma$ invariant masses peaks around the π^0, η, η' mass



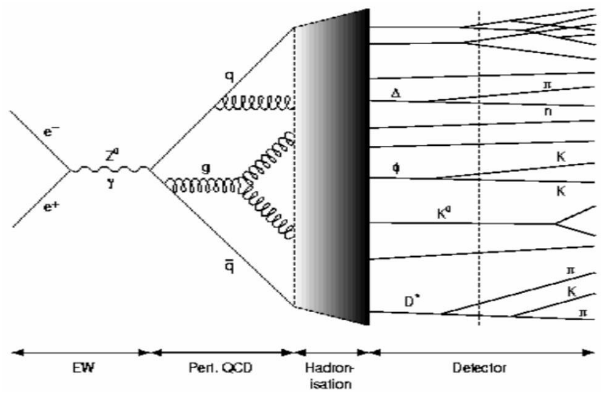




Two independent inclusive Monte-Carlo Generators

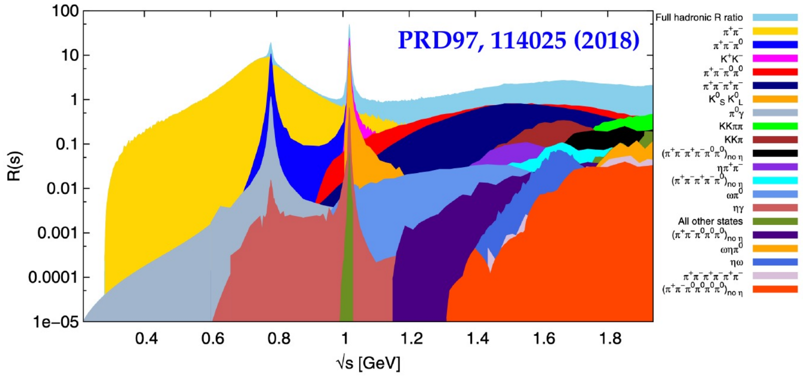
Fully theoretical MC production

- Development based on Jetset for low-energy experiments (LundAreaLaw)
- Simulation of resonances and continuum
- ISR and vacuum polarization implemented
- Kinematics of final hadrons tuned by experimental distributions (N_{trk}, N_γ, $\cos\Theta$, ...)



MC generator almost entirelybased on exptl. data

- PHOKHARA event generator (10 low-multiplicity channels 2π, 3π, 4π, $N\overline{N}$, ...) fitted to exptl. data
- CONEXC based purly on exptl. data (phase space), 47 channels



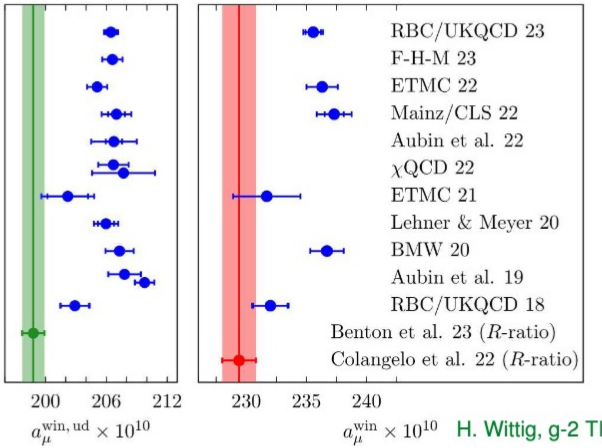
- Remaining channels simulated by LUARLW

After years of developments, tuning, and cross checks a deviation of better than 2.3% (including ISR) between the hybrid generator and LUARLW is found (major achievement)

Lattice QCD Windows Estimates

Serious deviation between data-driven evaluation of a_μ^{HVP} and intermediate-distance Lattice-QCD window

- weight function allows to relate Lattice-QCD window to total hadronic cross section
- weight function peaked at ~1.5 GeV
- ca. 1/3 of total a_μ^{HVP}, of which 60% given by $\pi^+\pi^-$
- selects ~28% of absolute $\pi^+\pi^-$ contribution
- need to explain deviation of 7 … 8×10^{-10}



H. Wittig, g-2 TI Worshop

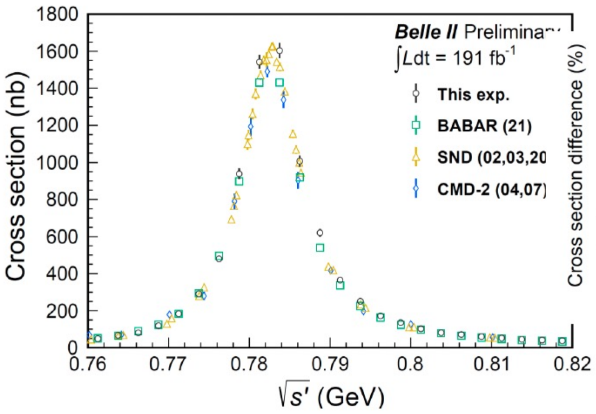
Explanation 1: Upscale π+π- data by >5% (flat), however this causes some conflict with BMW result for full a_μ^{HVP}

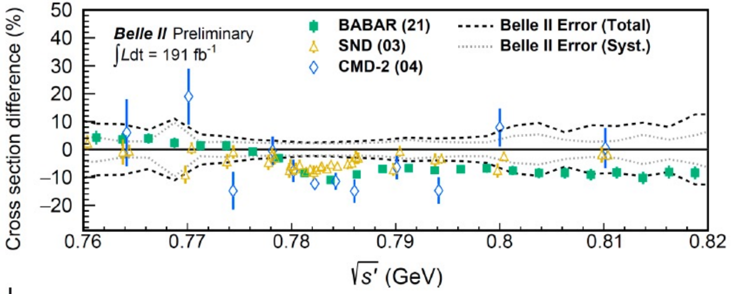
Explanation 2: Underestimated contributions > 1 GeV (higher multipl.), however would need to be large effect; hadronic particle not being observed by experiment, e.g. Sexaquark? arxiv:2206.13460

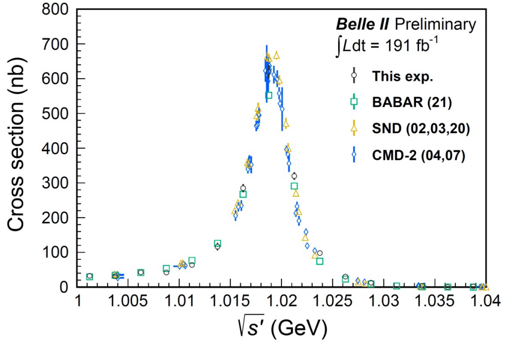
Explanation 3: Common systematic effect in Lattice-QCD and/or underestimated BMW21 result for full a_μ^{HVP}

New BELLE-II Analysis of $e^+e^- \to \pi^+\pi^-\pi^0$

- First BELLE-II ISR analysis of hadronic process: $\pi^+\pi^-\pi^0$ channel, ($0.62 < \sqrt{s} < 1.8$) GeV
  → systematic uncertainty: >2.2%
  → integral value higher by 2.5 sigma than BABAR
- Main limitation (~1.2% uncertainty): NLO radiative correction
  → confirmation of BABAR findings, however with limited consequences







5% ... 10% higher cross section than BABAR in ω region

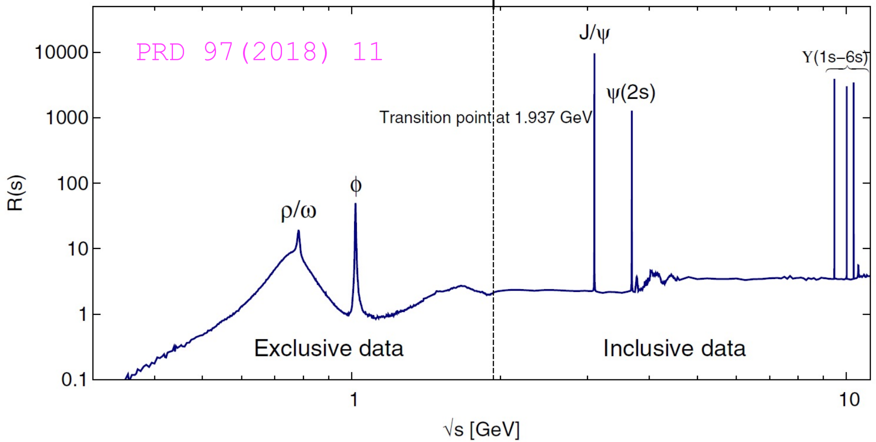
Measurements on R – Exclusive vs. Inclusive

Exclusive measurements (<2 GeV)

- Individually highly precise
- Energy scan or initial state radiation
- Large number of channels at higher energies
- Sum over multiple channels

Inclusive measurements (>2 GeV)

- Covers all possible channels
- Reliant on good Monte Carlo generator
- Only energy scan measurements
- Subtract QED background

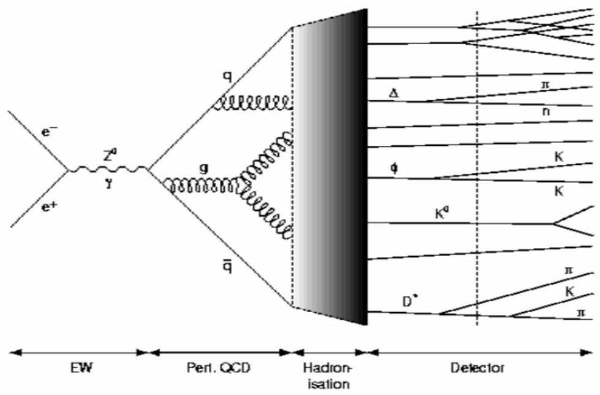


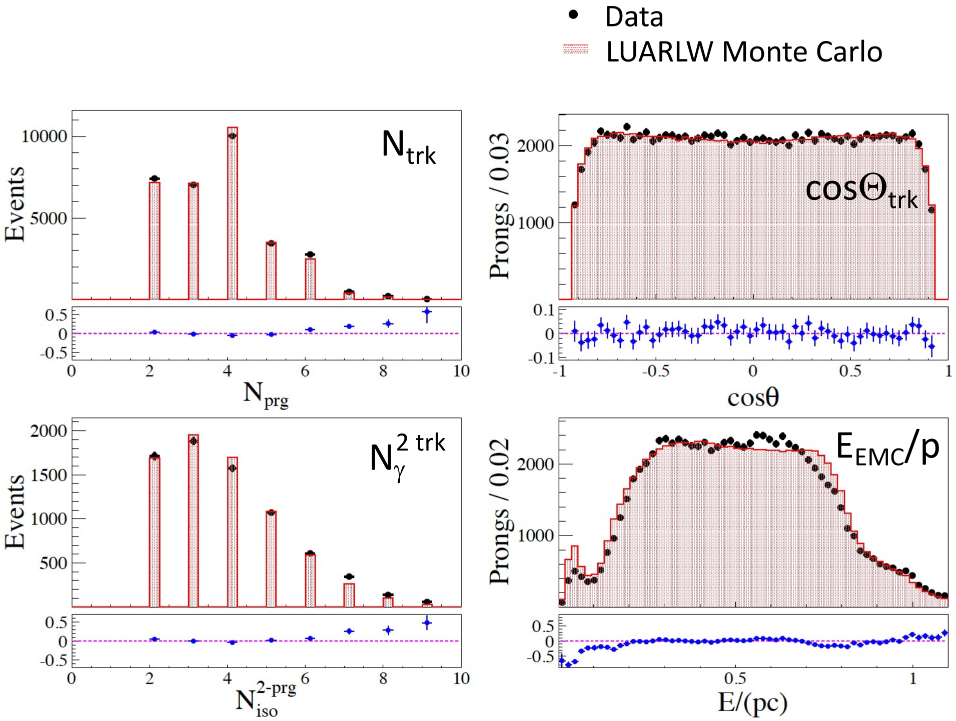
Some tension with KEDR data in the transition region around 2 GeV

Inclusive Monte-Carlo Production LUARLW

Fully theoretical MC production

- Development based on Jetset for low-energy experiments (LundAreaLaw)
- Simulation of resonances and continuum
- ISR and vacuum polarization implemented
- Kinematics of final hadrons tuned by experimental distributions

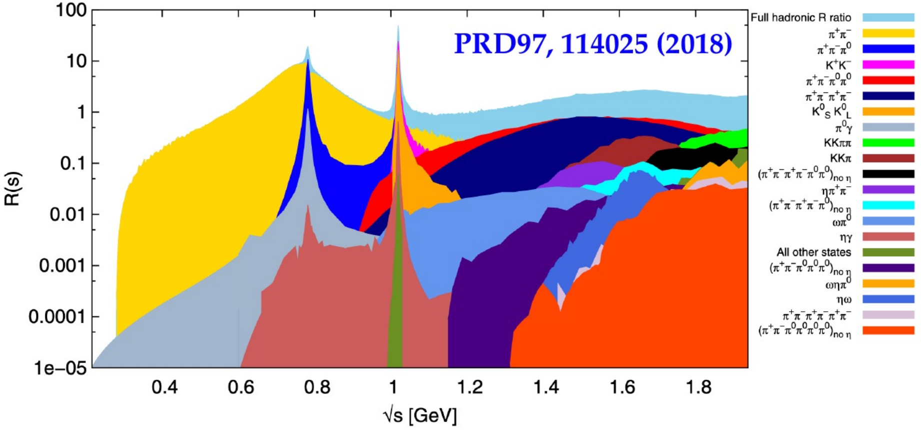




Hybrid Monte-Carlo Generator

MC generator based on experimental data (as much as possible)

- PHOKHARA event generator (10 low-multiplicity channels 2π, 3π, 4π, $N\bar{N}$, ...) fitted to exptl. data
- CONEXC based purly on exptl. data (phase space), 47 channels
- Remaining channels simulated by LUARLW



After years of developments, tuning, and cross checks a deviation of better than 2.3% (including ISR) between the hybrid generator and LUARLW is found (major achievement)

Whitepaper Estimate of HVP

- Merging of KNT, DHMZ estimates + input from ChPT/dispersive fits: CHHKS for 2π, 3π channels; determinations from FJ17 and BDJ10 (assuming hadronic models in global fit) not considered
- Observation that averaging procdures in KNT and DHMZ lead to large differences for individual channels (especially 2π) although total average in good agreement, which is accidental!

→ $a_\mu^{HVP,LO} = 693.1(2.8)_{\text{exp}}(2.8)_{\text{syst}}(0.7)_{\text{pQCD}} = 693.1(4.0) \times 10^{-10}$ Whitepaper estimate

- exp: experimental uncertainties: 2.8×10^{-10} domitated by 2π channel uncertainty

- syst: KLOE/BABR tension taken into account by estimating HVP leaving out KLOE or leaving out BABAR in evaluation: 2.8×10^{-10}

- pQCD: difference in energy region [1.8;3.7] GeV btw. KNT and DHMZ; usage of pQCD by DHMZ, while KNT follows data-driven approach: $.7 \times 10^{-10}$

2.8×10^{-10}

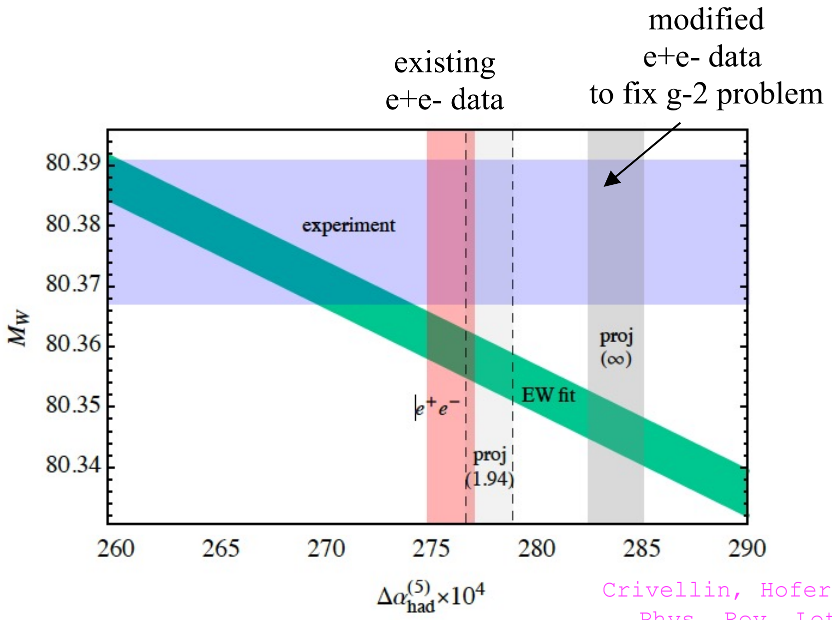
	DHMZ19	KNT19	Difference
$\pi^+\pi^-$	507.85(0.83)(3.23)(0.55)	504.23(1.90)	3.62 :-(
$\pi^+\pi^-\pi^0$	46.21(0.40)(1.10)(0.86)	46.63(94)	−0.42
$\pi^+\pi^-\pi^+\pi^-$	13.68(0.03)(0.27)(0.14)	13.99(19)	−0.31
$\pi^+\pi^-\pi^0\pi^0$	18.03(0.06)(0.48)(0.26)	18.15(74)	−0.12
K^+K^-	23.08(0.20)(0.33)(0.21)	23.00(22)	0.08
K_SK_L	12.82(0.06)(0.18)(0.15)	13.04(19)	−0.22
$\pi^0\gamma$	4.41(0.06)(0.04)(0.07)	4.58(10)	−0.17
Sum of the above	626.08(0.95)(3.48)(1.47)	623.62(2.27)	2.46
[1.8, 3.7] GeV (without $c\bar{c}$)	33.45(71)	34.45(56)	−1.00
$J/\psi, \psi(2S)$	7.76(12)	7.84(19)	−0.08
$[3.7, \infty)$ GeV	17.15(31)	16.95(19)	0.20
Total $a_\mu^{\text{HVP, LO}}$	$694.0(1.0)(3.5)(1.6)(0.1)_\psi(0.7)_{\text{DV+QCD}}$	692.8(2.4)	1.2

HVP and Electroweak Precision Physics

Artificially increasing e^+e^- cross sections (over full energy range) to mach a_μ^{exp}

→ Impact on running of fine structure constant $\Delta\alpha_{had}(M_Z^2)$

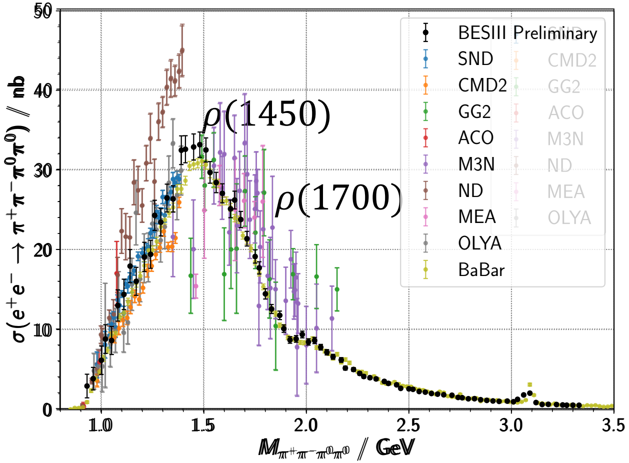
→ increasing deviation btw. EW fit and EW measurements (e.g. M_H, M_W, ...) ?!



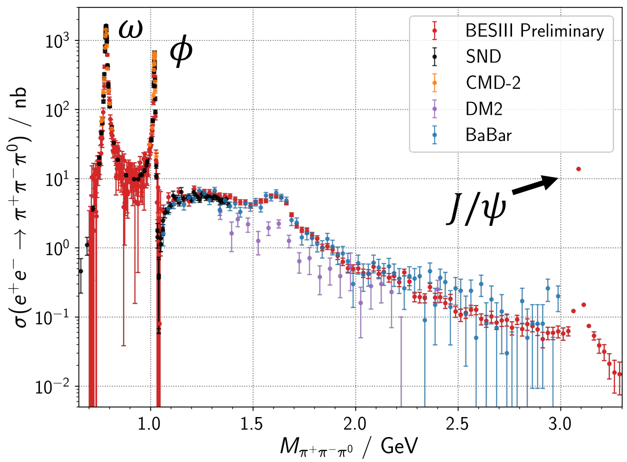
Crivellin, Hoferichter, Manzari, Montull
Phys. Rev. Lett. 125, 091801 (2020)

ISR: $e^+e^- \to \pi^+\pi^-\pi^0$, $e^+e^- \to \pi^+\pi^- 2\pi^0$

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



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



	fb^{-1}	$a_\mu^{4\pi}$ $[10^{-10}]$
Before		$16.76 \pm 1.31 \pm 0.20_{rad}$
BABAR	450	$17.9 \pm 0.1 \pm 0.06$
BESIII (prel.)	2.9	$18.63 \pm 0.27 \pm 0.57$

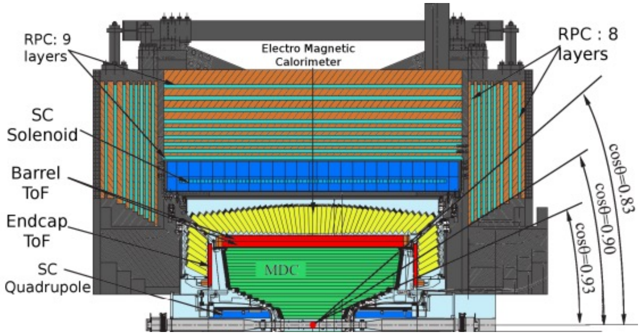
	$a_\mu^{3\pi}$ $[10^{-10}]$
Before$_{KNT18}$ (<2 GeV)	47.79 ± 0.89
BESIII (prel.)	$49.15 \pm 0.56 \pm 0.58$

Meson2021: Bastian Kubis

BESIII *Experiment at the tau-charm Factory BEPC-II*

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

- Symmetric e^+e^- collider
- Located at the BEPCII collider (Beijing, China)
- CMS energy: 2 GeV to 5 GeV
- Maximum luminosity: $1 \times 10^{33}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
- 93% coverage of the solid angle



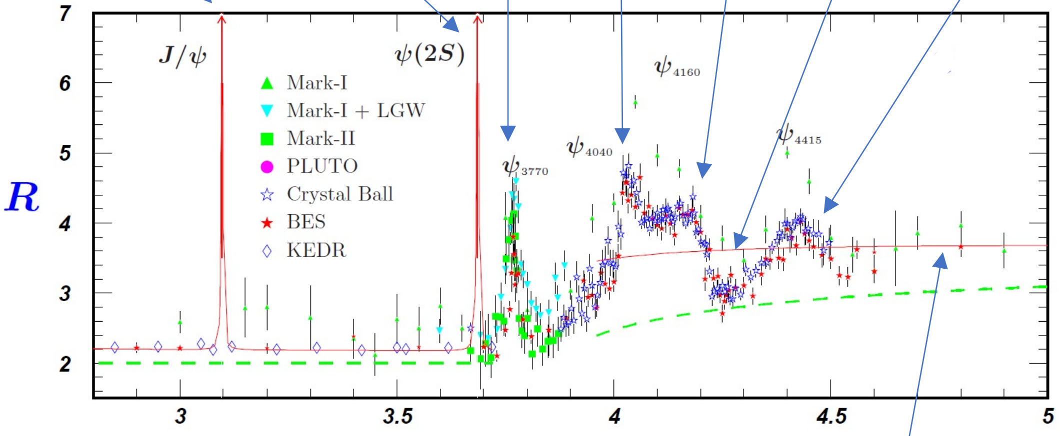
1×10^{10} Events

3×10^{9} Events

$2.9\ \mathrm{fb}^{-1}$

$20\ \mathrm{fb}^{-1}$ (2022)

$0.5\ \mathrm{fb}^{-1}$ $3.2\ \mathrm{fb}^{-1}$ $10.5\ \mathrm{fb}^{-1}$ $1.0\ \mathrm{fb}^{-1}$



130 points

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

$\gg$ 1×10^{5} had. Events each

$5.6\ \mathrm{fb}^{-1}$ at 10 points

$4.6\ \mathrm{GeV} \leq \sqrt{s} \leq 5.0\ \mathrm{GeV}$

Standard Model Prediction of $(g\text{-}2)_\mu$

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had} = (11\,659\,181.0 \pm 4.3) \cdot 10^{-10}$$

Czarnecki et al.

$(15.4 \pm \mathbf{0.2}) \cdot 10^{-10}$

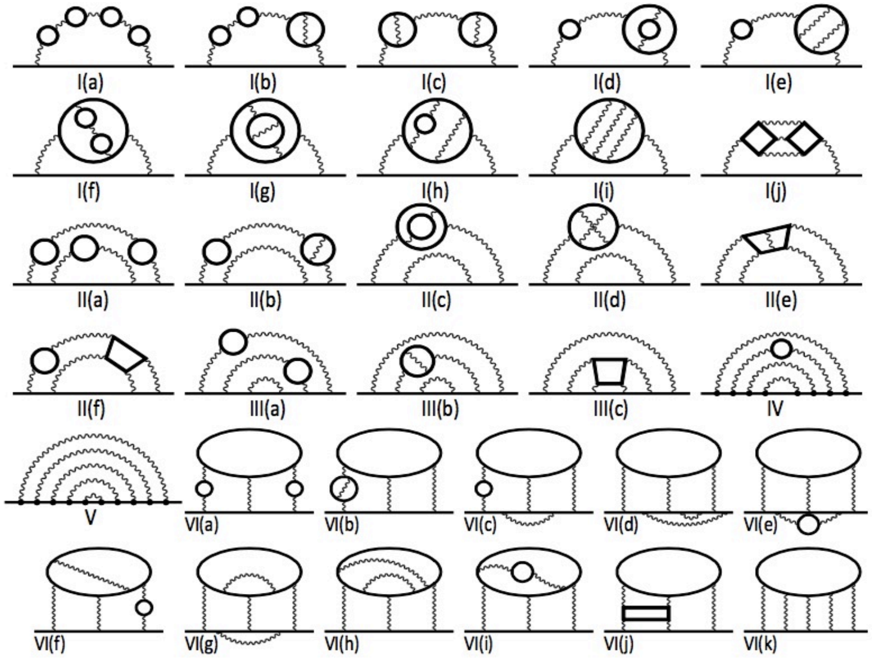
Kinoshita et al. '12

$(11\,658\,471.808 \pm \mathbf{0.015}) \cdot 10^{-10}$

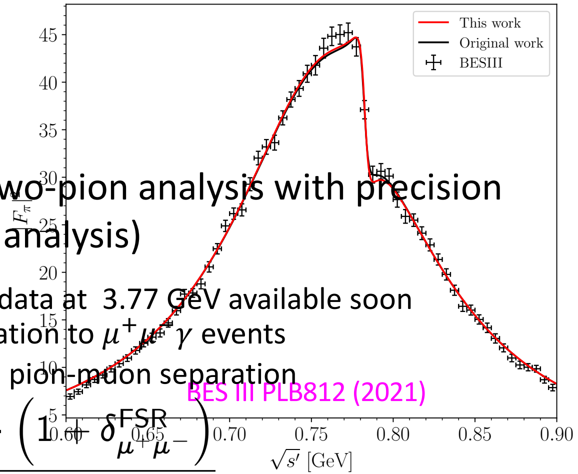
Absolute contribution dominated by QED

Uncertainty dominated by hadronic contribution

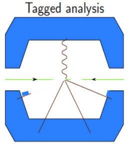
10th
12672
diagrams



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



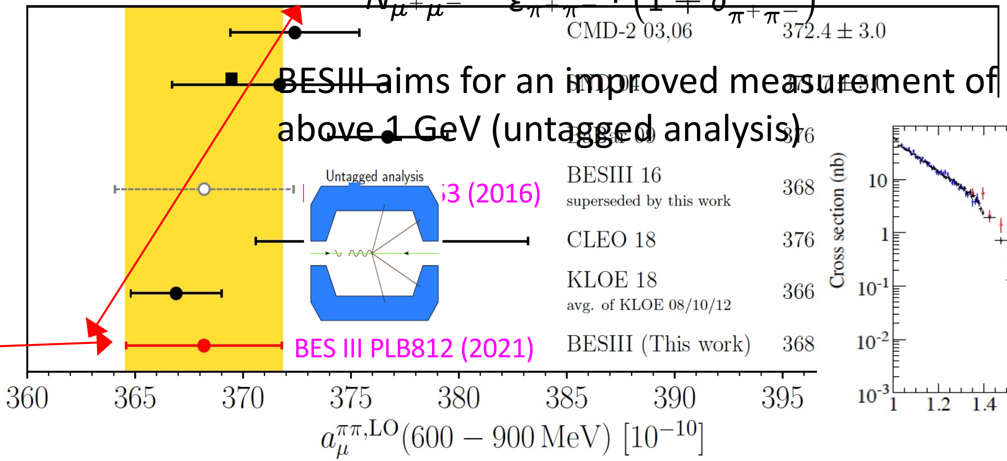
- BESIII aims for new two-pion analysis with precision goal of 0.5% (tagged analysis)



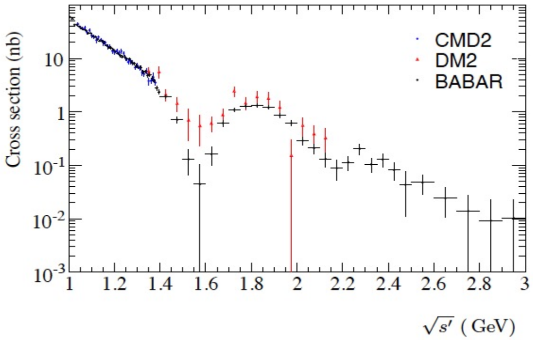
  - 20/fb of data at 3.77 GeV available soon
  - Normalization to $\mu^+\mu^-\gamma$ events
  - Improved pion-muon separation

$$R = \frac{N_{\pi^+\pi^-}}{N_{\mu^+\mu^-}} \cdot \frac{\varepsilon_{\mu^+\mu^-} \cdot \left(1 + \delta^{FSR}_{\mu^+\mu^-}\right)}{\varepsilon_{\pi^+\pi^-} \cdot \left(1 + \delta^{FSR}_{\pi^+\pi^-}\right)}$$

Source	BESIII 2016 2.9/fb (Update)
Photon efficiency	0.2
Pion tracking efficiency	0.3
Pion ANN efficiency	0.2
Pion e-PID efficiency	0.2
Angular acceptance	0.1
Background subtraction	0.1
Unfolding procedure	0.2
Luminosity $\mathcal{L}$	0.5
FSR correction	0.2
Vacuum polarization	0.2
Radiator function	0.5
Sum Systematics	**0.9**
Statistical error	**0.4**



- BESIII aims for an improved measurement of the mass range above 1 GeV (untagged analysis)



Whitepaper 2025: KLOE LA-Analysis