UNIVERSITY OF LIVERPOOL

4th Liverpool Workshop on Muon Precision Physics, November 11-13, 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

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Outline

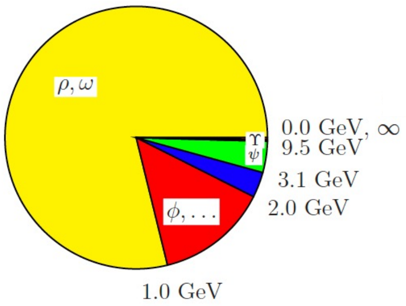
- Current situation data-driven HVP for $(g-2)_\mu$
- Radiative corrections and ISR measurements
- Breaking news from Orsay September workshop
- Status of BESIII analysis of $e^+e^- \to \pi^+\pi^-$
- Conclusions

R Measurements and Hadronic Vacuum Polarization

Hadronic vacuum polarization

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

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



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

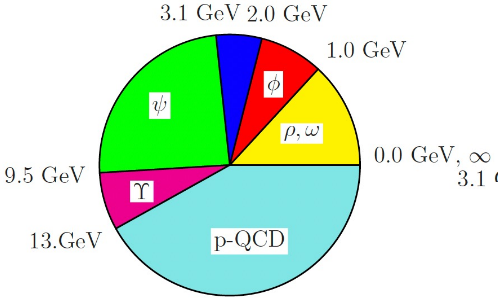
$$\sigma_{had}(s) = \sigma_{\text{tot}}(e^+e^- \to \text{Hadrons})$$

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

Running electromagnetic fine structure constant

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

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



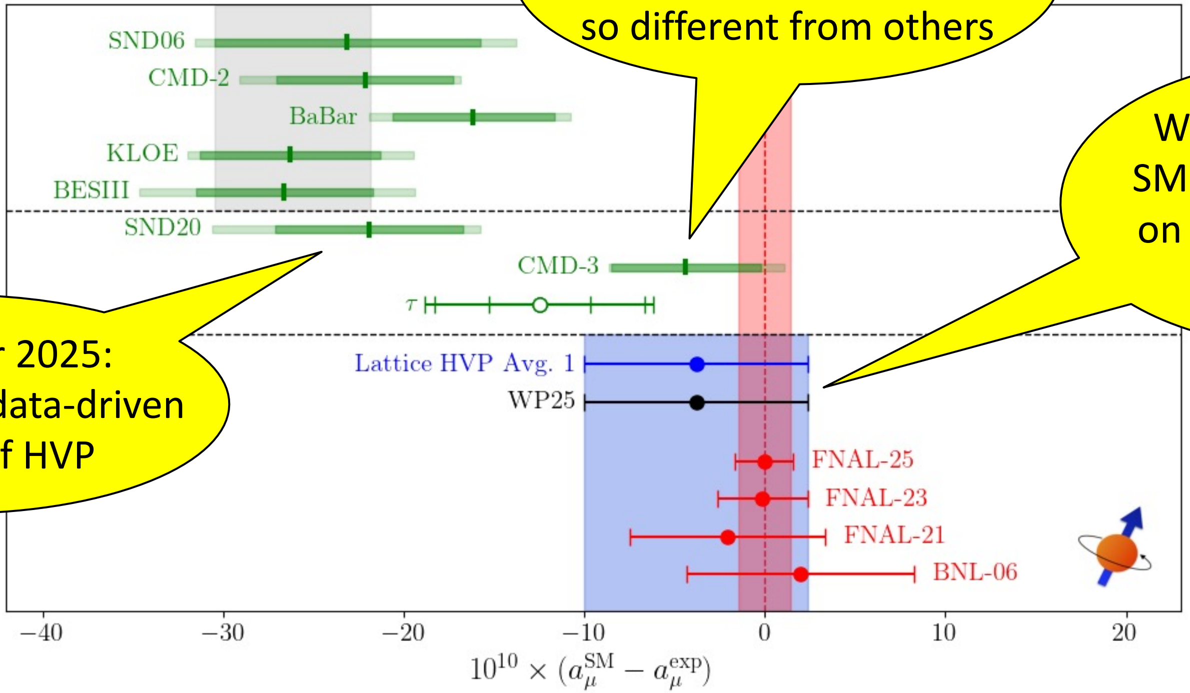
→ **relevant mass range < 13 GeV**

Whitepaper '25: Lattice QCD-based SM-Prediction for (g-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

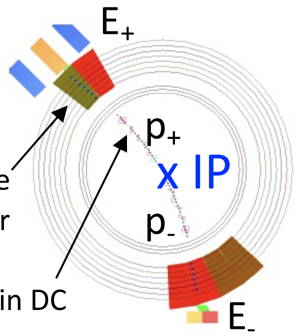
2023 Shock: CMD-3 @ Novosibirsk $e^+e^- \to \pi^+\pi^-$

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

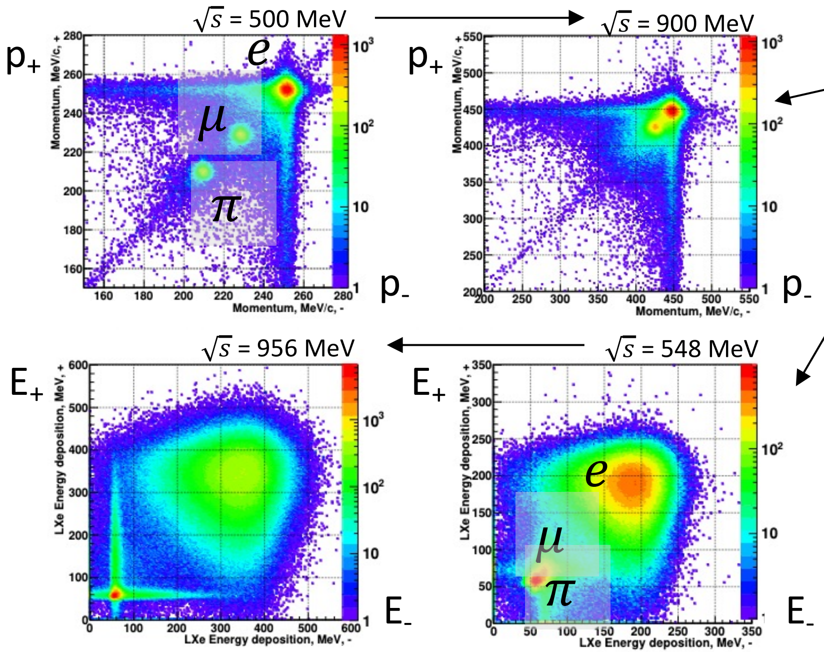
energy release in calorimeter

tracks in DC

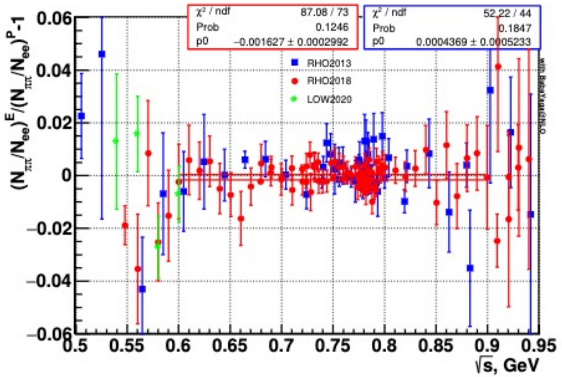


Most impressive feature: ππ/ee ratio determined independently by two complementary methods

- Momentum based
- Calorimetric



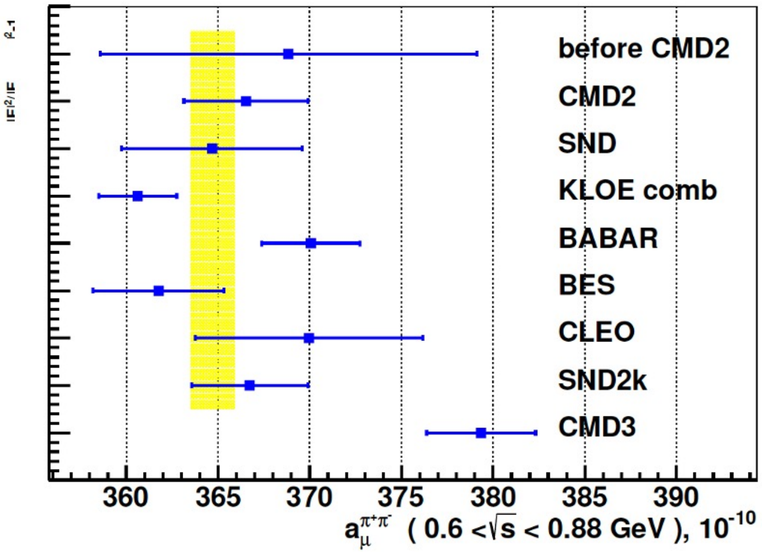
agreement ~ 0.2% around rho peak



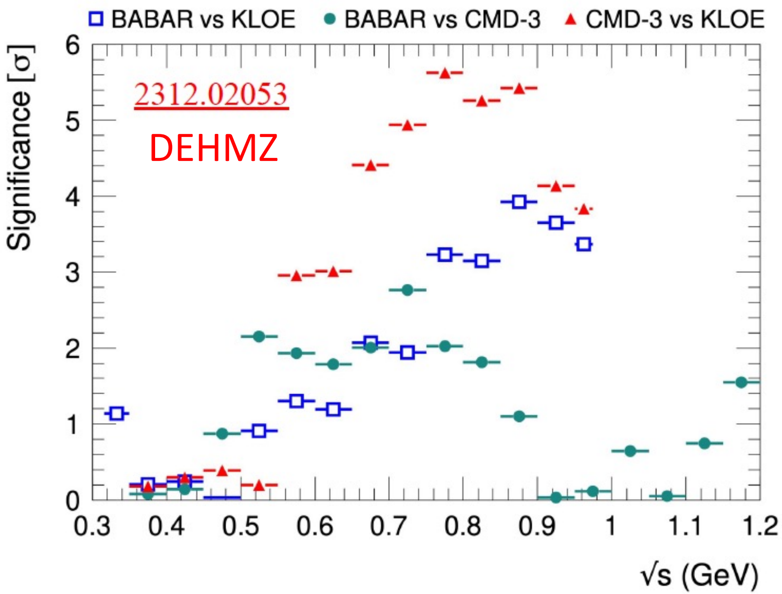
PRL 132 (2024) 231903
PRD 109 (2024) 112002

CMD-3 Compatibility with other Experiments for HVP Integral

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



Deviation between data sets (in statistical significance)



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

CMD-3 Compatibility with other Experiments for HVP Integral

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

Insights into CMD2/CMD3 difference

- We don't have means to do a full scale CMD-2 analysis – we can only get some hints about the potential sources of difference
- The radiative corrections are not the suspects.
- Suspect #1. Subtraction of cosmic background

  At CMD-3 we've developed better method to count cosmic background. Now we know that CMD-2 method had unaccounted systematic error (but we can't estimate it).

  The CMD-2 cosmic background was much larger: 6% - 15% compare to 0.12% for CMD-3
- Suspect #2. Event separation based on energy deposition

  CMD-3: LXe only ($5X_0$) and full calo ($13X_0$), observed very different behavior/systematics; might be able to take CsI only data

  CMD-2: CsI only ($8X_0$), systematics were estimated
- Suspect #3. Trigger. (correction was small, but could be …)

  Cmd2 had only one trigger with DC (4-6 superlayers), Z-chamber (2 layers) and CsI calorimeter with 40 MeV threshold in coincidence. Efficiency was studied assuming no correlations for π^+ and π^-. Correlated missing of both tracks could be – we have it with CMD-3

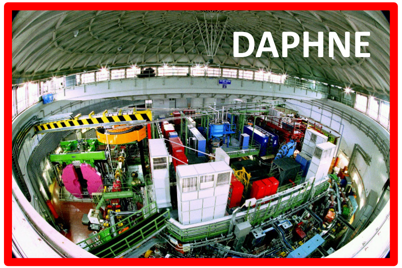
All above was discussed at the previous presentations – we did not see large effects

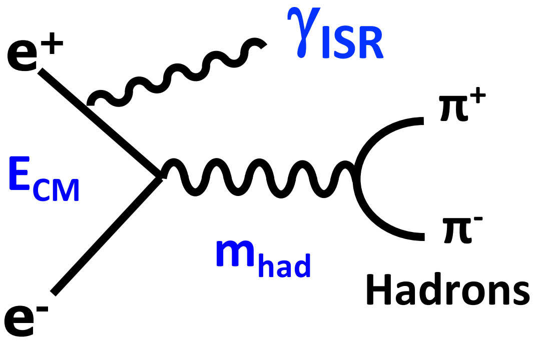
E. Solodov(BINP) VIII Plenary Workshop of the Muon g-2 Theory Initiative. Update-News from CMD-3 9

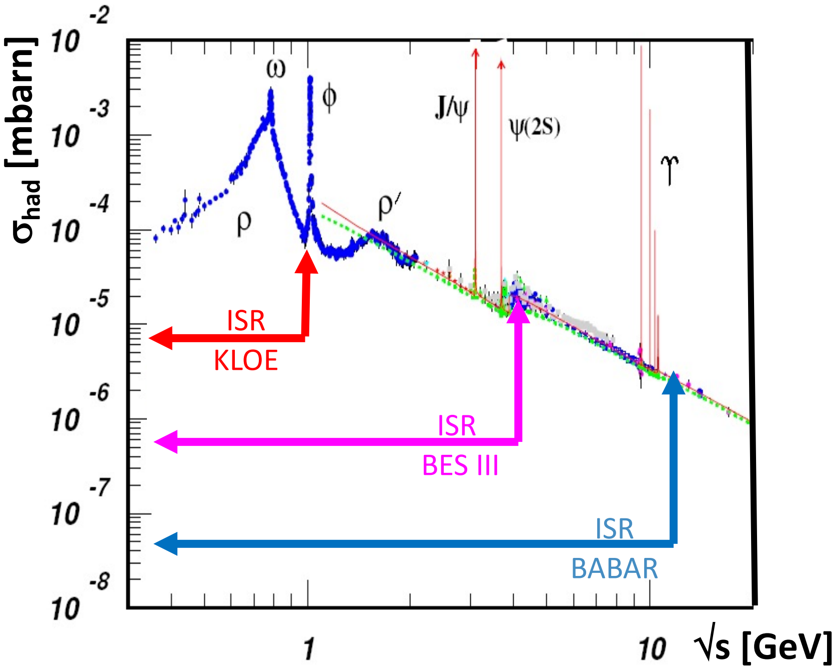
→ **No explanation !?**

Radiative Corrections and Initial State Radiation (ISR)

Measurements on R – Energy Scan vs. Initial State Radiation







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

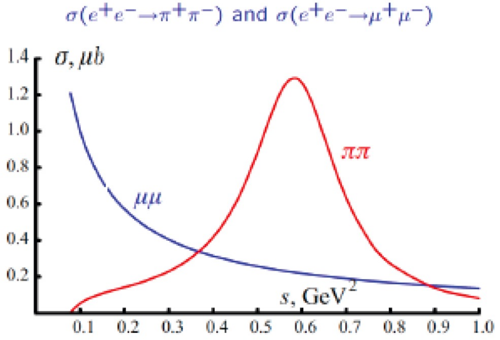
`PHOKHARA event generator`

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, …)

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

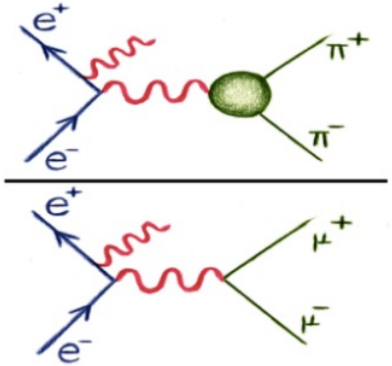


2) normalization to μ+μ-γ events, i.e. R ratio (ππγ/μμγ)

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

→ requires high statistics of μ+μ-γ

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

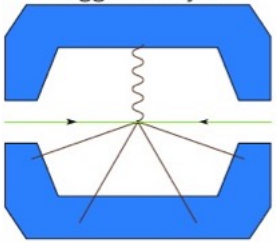


Overview Experiments

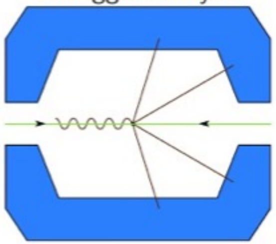
Experiment	Published Method	Normalization	Separation π - μ
KLOE $\sqrt{s}\sim 1$ GeV	ISR untagged ISR tagged ISR untagged	Luminosity + H_{rad} Luminosity + H_{rad} $\mu+\mu-\gamma$	Kinematics Track Kinematics Track Kinematics Track
BABAR $\sqrt{s}\sim 10$ GeV	ISR tagged	$\mu+\mu-\gamma$	Particle ID
BESIII $\sqrt{s}\sim 4$ 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

With (large Θ) and without (small Θ) ISR photon detection

Tagged analysis



Untagged analysis

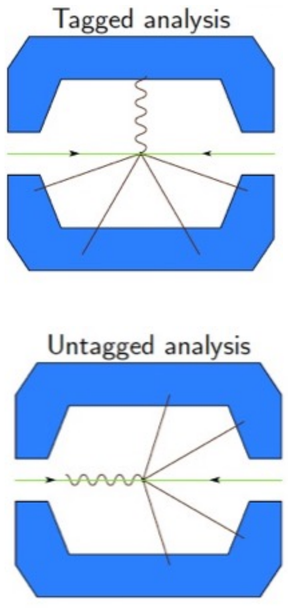


Overview Experiments

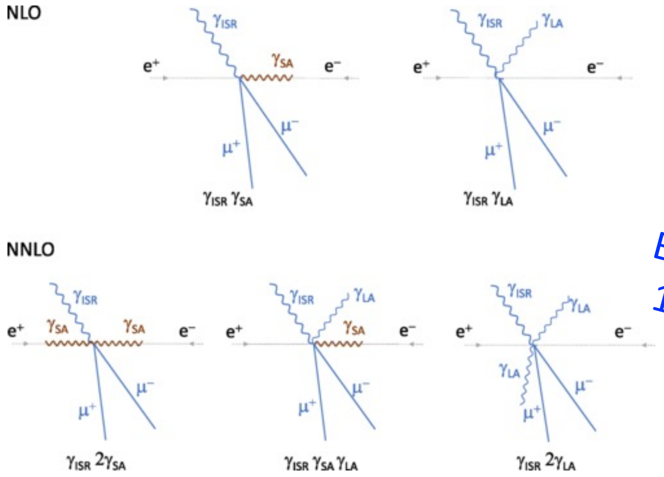
Experiment	Publis…	…malization	Separation π - μ
KLOE $\sqrt{s}\sim 1$ GeV		…osity + H_{rad} …sity + H_{rad} …μ-γ	Kinematics Track Kinematics Track Kinematics Track
		…-γ	Particle ID
		… + H_{rad}	Particle ID (ML)
…			
C…	…n < ~1 GeV	e+e-	Kinematics Track Kinematics EMC
SND	Scan < ~1 GeV	e+e-	Kinematics EMC

Diverse set of methods,
cms energies,
normalizations, selections
→ Systematic uncertainties
(obviously) underestimated

With (large Θ) and without (small Θ) ISR photon detection

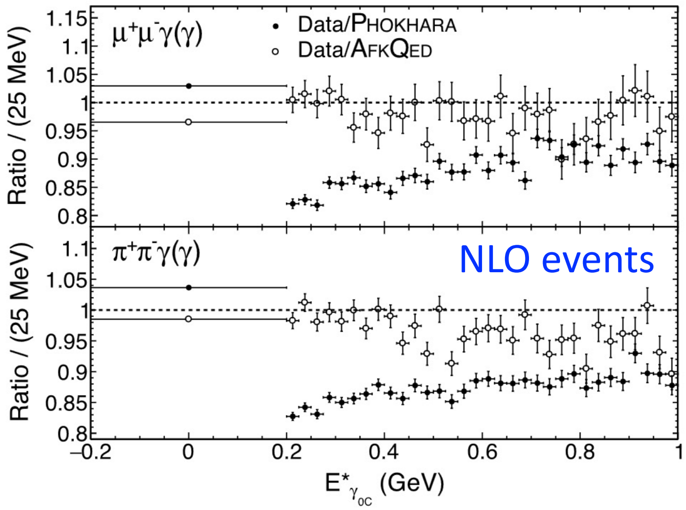


BABAR Radiative Correction Studies (2023)



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)

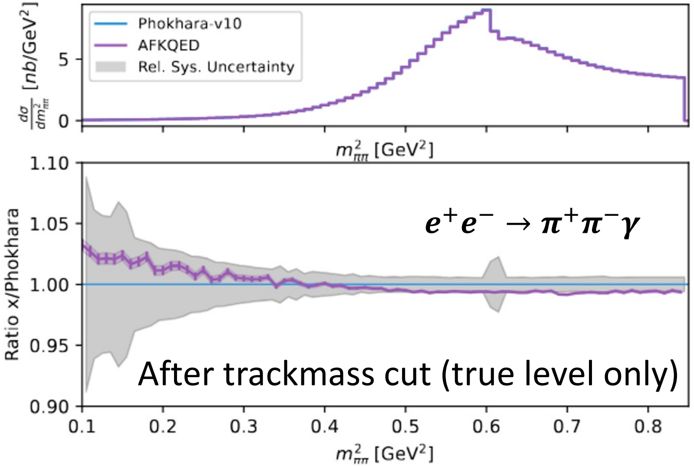
Eur. Phys. J. C 84, 721 (2024) → **claim: possibly large effects on BESIII and KLOE analyses!**

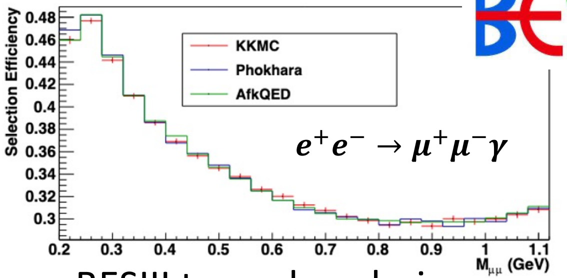
KLOE / BESIII Response to PHOKHARA Shortcomings

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

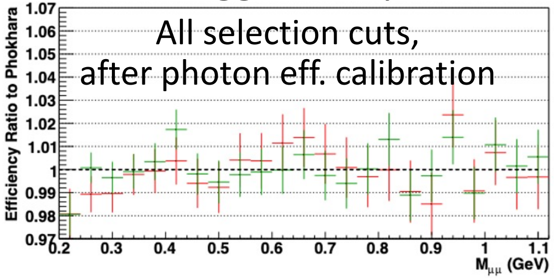
Comparison of Phokhara vs. KKMC for $e^+e^- \to \mu^+\mu^-\gamma$

KLOE tagged analysis





BESIII tagged analysis



Whitepaper muon g-2 2025

→ No indication of large systematic effects (beyond uncertainties) due to Phokhara limitations !

The need for improved radiative corrections

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 $\pi^+\pi^-\gamma$)

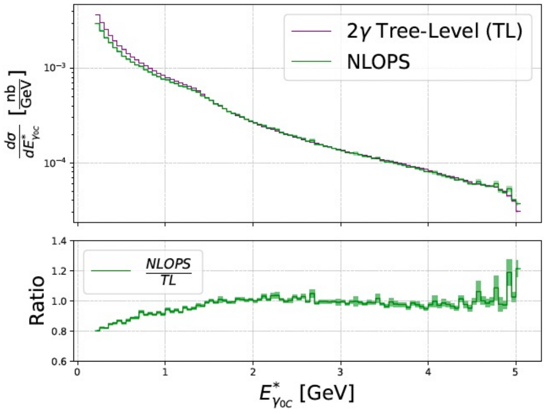
→ **Controlled treatment of Final State Radiation effects**

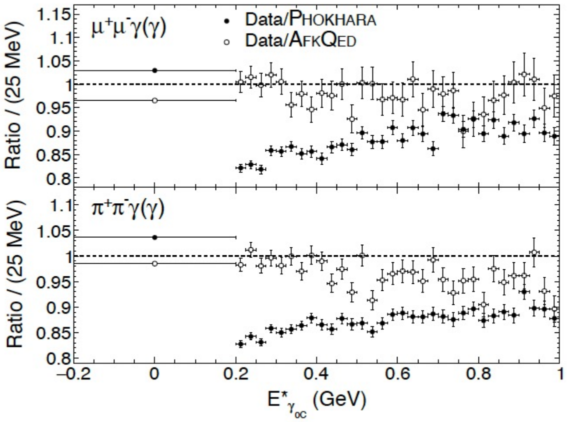
→ **Efforts coordinated within the RadioMontecarlow initiative**

→ **Strong interplay between Theory and Experiment**

Fulvio Piccini @ Orsay

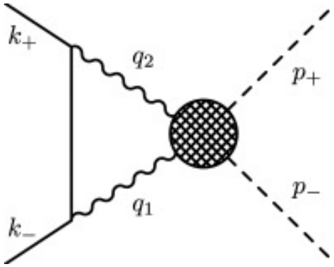
First results from new BABAYAGA@NLO
→ seems to confirm findings of BABAR regarding PHOKHARA limitations





Final State Radiation

As a by-product of the CMD-3 analysis, the importance of an accurate treatment of FSR was studied



Effects beyond scalar QED (sQED) of utmost importance, especially in box diagrams

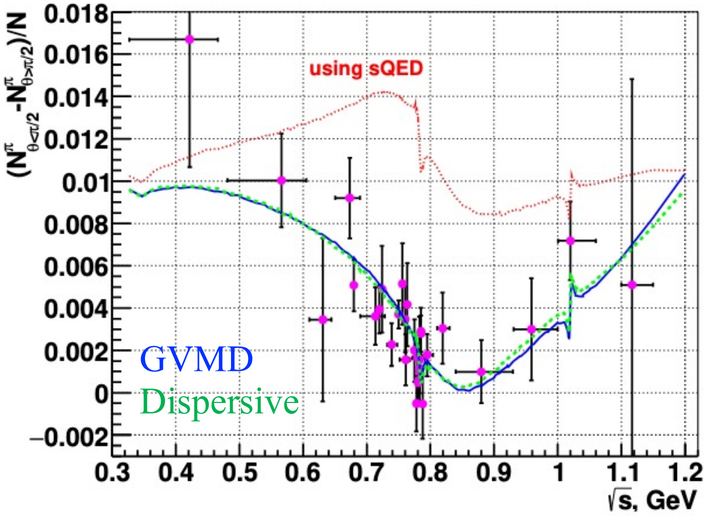
→ excellent agreement btw. GVMD calculation and dispersive treatment as well as CMD-3 data

→ implementation in ISR generators most important!

PLB833 (2022) 137283

Forward-backward asymmmetry is a most sensitive parameter:

$$A = \frac{N_{\theta<\pi/2} - N_{\theta>\pi/2}}{N_{\theta<\pi/2} + N_{\theta>\pi/2}}$$



Breaking News from 2025 Orsay Workshop and Outlook

NEW

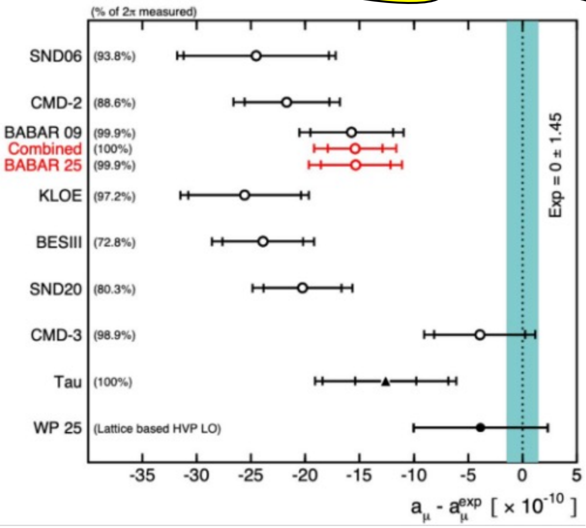
New BABAR ISR Measurement of $e^+e^- \to \pi^+\pi^-$

Andreas Pinto @ Orsay

New Large-Angle BABAR analysis :
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.

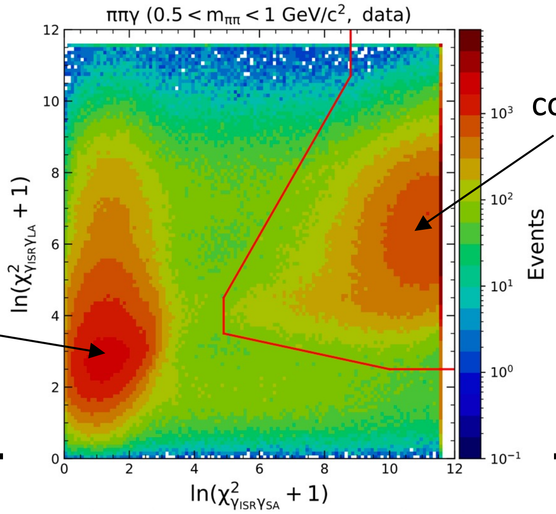


- Central region: systematic error 0.37%, statistical error (from fit) similar to 2009 analysis
- Statistical error dominates in threshold region

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

- **Innovative new approach**:
  Separation of $e^+e^- \to e^+e^-/\mu^+\mu^-/\pi^+\pi^-\gamma$ via template fits to polar angle distributions

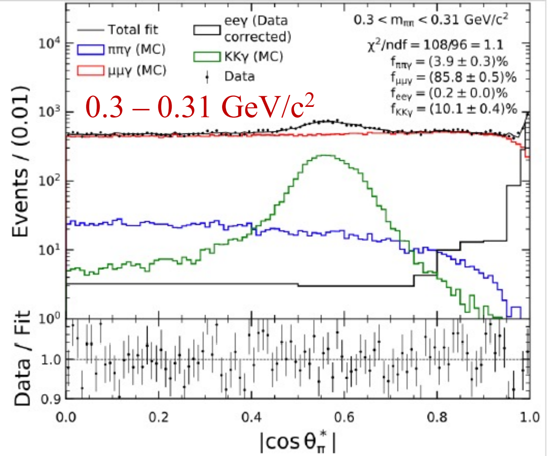
- **NLO fits for 2 high-energetic photons:**
  1 $\gamma_{ISR\text{-}LA}$ + 1 $\gamma_{ISR\text{-}SA}$ versus 1 $\gamma_{ISR\text{-}LA}$ + 1 $\gamma_{ISR\text{-}LA}$

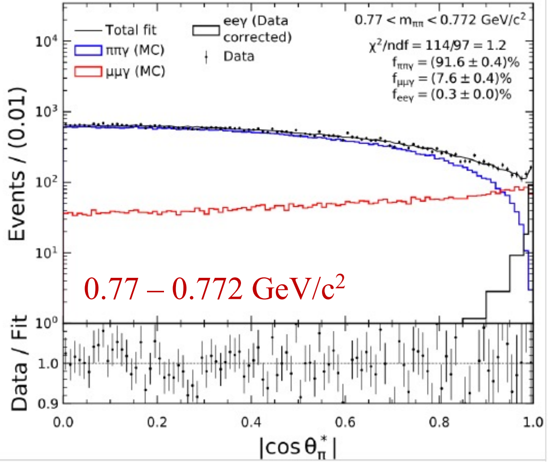


ISR-FSR configuration

ISR-ISR configuration

Suppress background via 2D χ^2 – cut (< 5%)





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

Normalization to μμγ channel

→ introduce ISR Luminosity $L_{ISR} = L_{inv}\, x\, H_{rad}$

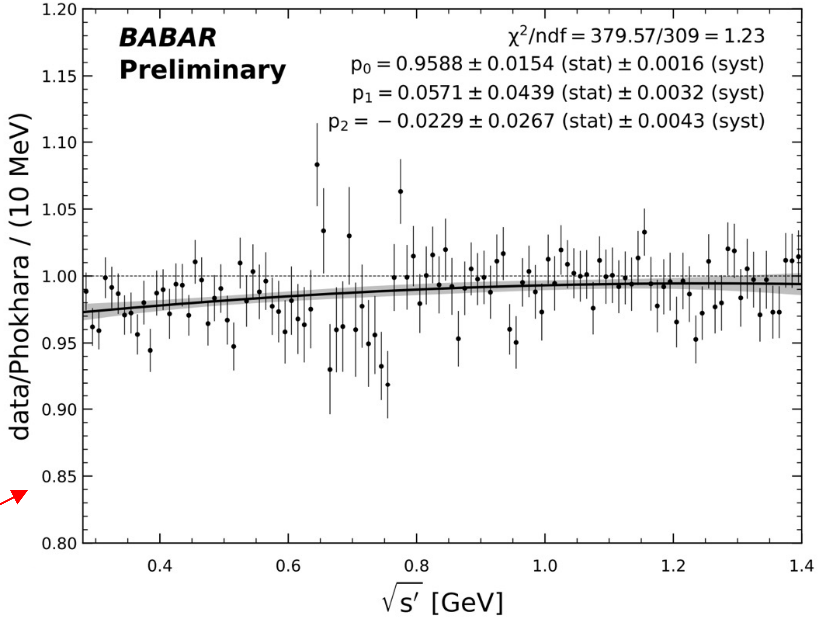
Unfolded spectrum

$$\frac{dL^{\rm eff}_{\rm ISR}}{d\sqrt{s'}} = \frac{dN^{\rm ISR}_{\mu\mu}/d\sqrt{s'}}{\epsilon_{\mu\mu}(\sqrt{s'})\ \sigma^0_{\mu\mu}(\sqrt{s'})}$$

Acceptance   Born cross section

ISR μμγ spectrum not taken from data, but from Phokhara Monte-Carlo !!!

$$\frac{dN^{\rm ISR}_{\mu\mu}/d\sqrt{s'}}{\epsilon_{\mu\mu}(\sqrt{s'})} = \underbrace{\frac{dN^{\rm MC\ gen}_{\mu\mu}}{d\sqrt{s'}}}_{\text{Phokhara spectrum at generation level}} \times \underbrace{(1 - f_{\rm LO\ FSR})}_{\text{removes the LO FSR contribution}} \times \underbrace{f_{\mu\mu}(\sqrt{s'})}_{\text{2nd order polynomial fit to data/MC}}$$

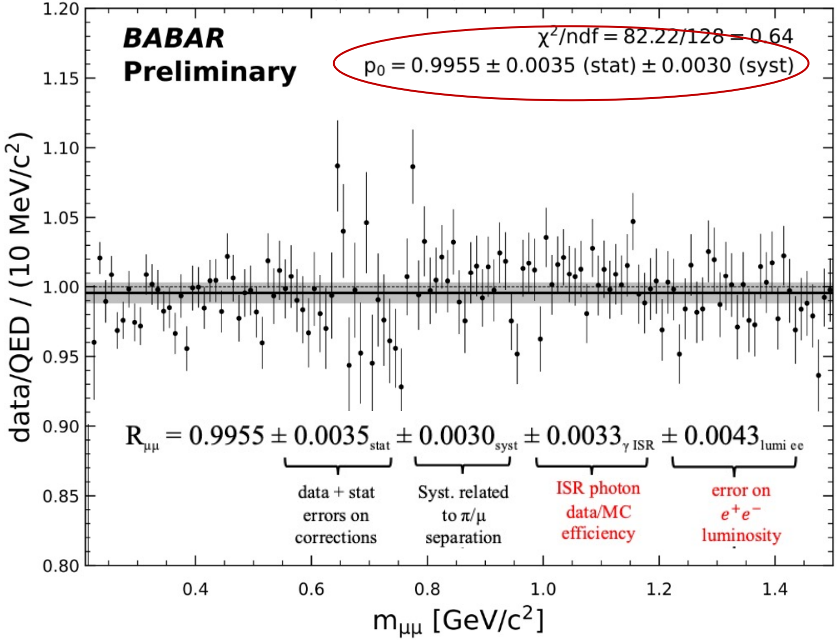


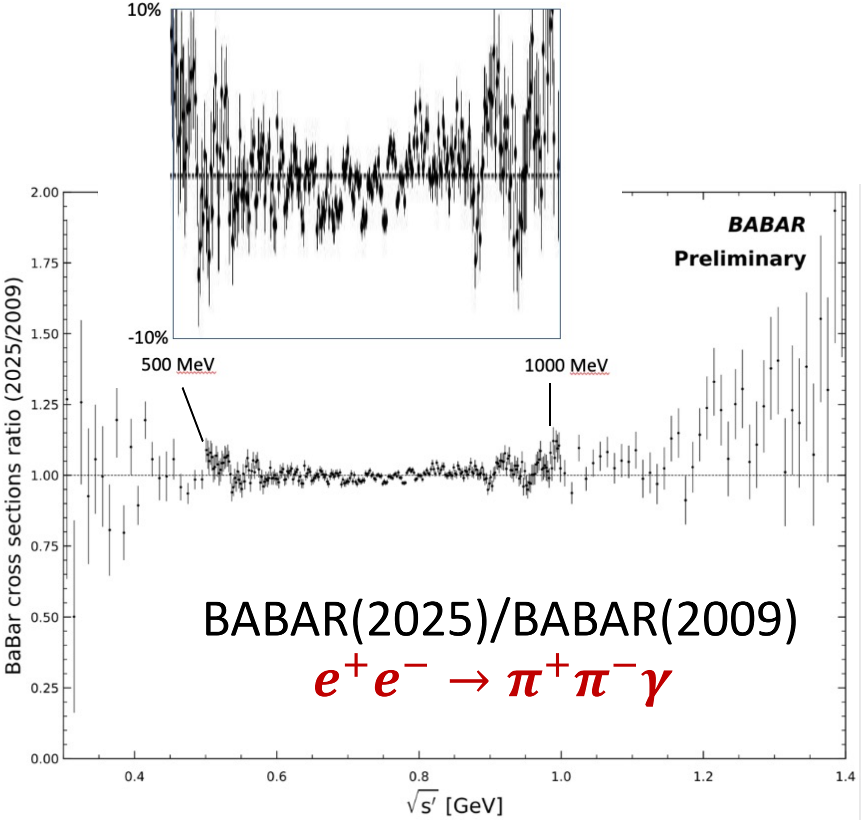
New BABAR ISR Measurement of $e^+e^- \to \pi^+\pi^-$

Andreas Pinto @ Orsay

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

BABAR(2025)/MC Phokhara





BABAR(2025)/BABAR(2009)

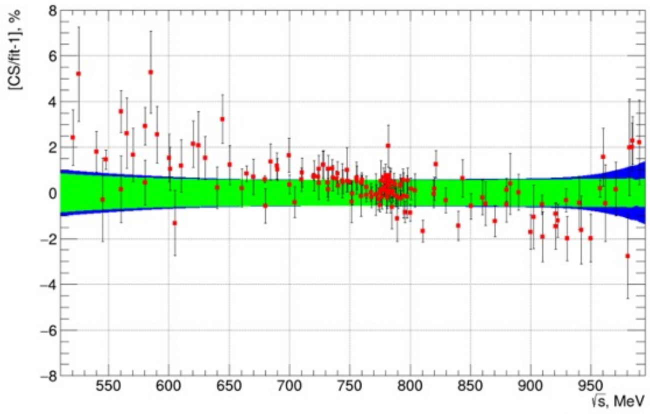
$e^+e^- \to \pi^+\pi^-\gamma$

NEW

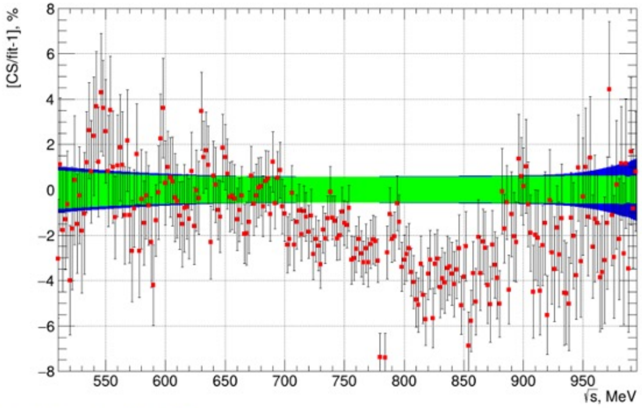
New SND Measurement of $e^+e^- \rightarrow \pi^+\pi^-$ (energy scan)

- 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)

CMD-3(2022)/SND(2025)



BABAR(2009)/SND(2025)



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

-0.6 σ

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

+1.8 σ

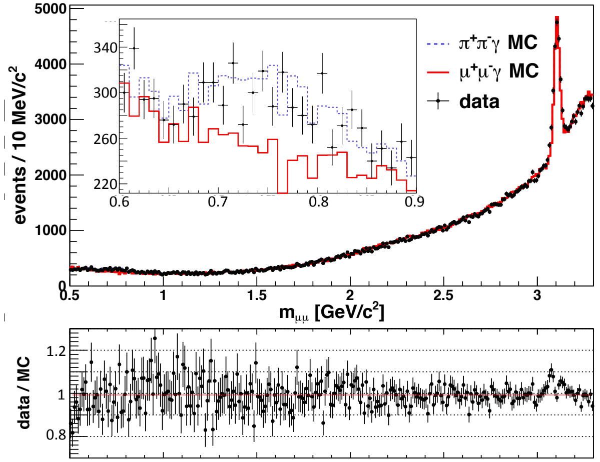
BaBar: $a_\mu \times 10^{10} = 423.87 \pm 2.06$

New BESIII Analysis of 2π Channel

Published BESIII Analysis

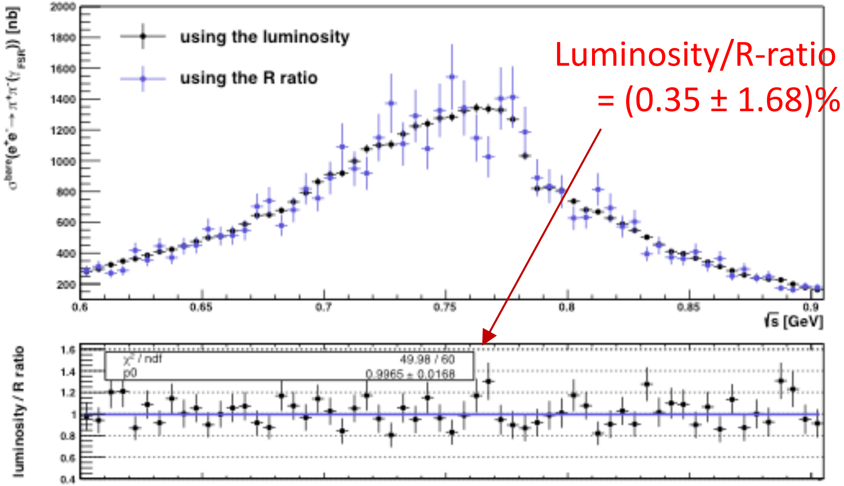
PLB753 (2016) 629
PLB812 (2021) 135982

- Tagged analysis based on 2.9/fb sample taken at cms. energy of 3.773 GeV
- 4C kinematic fit (tagged ISR photon used in fit)
- π/μ separation based on neural network (ANN)



- Selecting muons using ANN
- Perfect agreement with QED prediction

- Normalization to Luminosity / radiator function
- Normalization to μμγ limited by muon statistics



Status BESIII Experiment

- Energy and luminosity upgrade
- New cGEM inner drift chamber
- New small angle tagger cZDD (Mainz!)

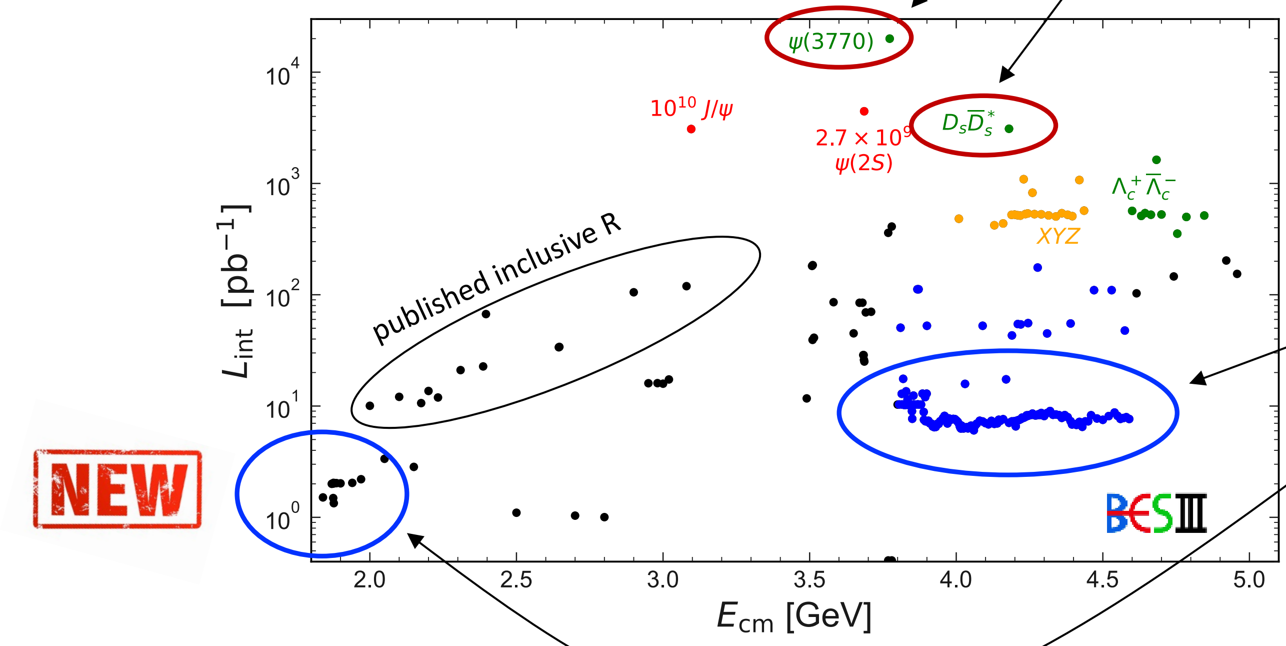
3.773 GeV sample 2.9/fb → 20.0/fb

3.1/fb at 4.18 GeV

ISR

exclusive channels

inclusive analysis



>100 energy points in open charm region

13 energy points 1.84 – 2.0 GeV

Inclusive R via energy scan

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

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

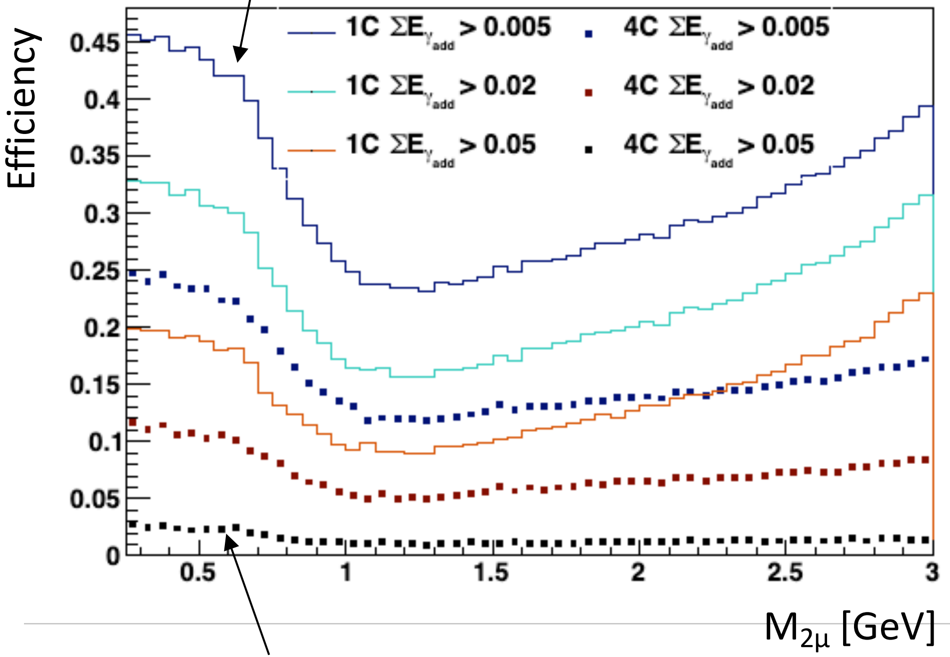
First half next year: expect new result!
adding 3.1/fb of data at $\sqrt{s}$=4.18 GeV;
1C kinematic fit → much less sensitive towards MC limitations of rad. corrections,
some minor additional improvements (0.7%);
keep ML-based PID (π-μ sepratation)

Next step: final result based on existing data set of 20/fb of data at $\sqrt{s}$=3.77 GeV;
1C kinematic 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
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 → 0.3
Sum	**0.9 → 0.7**

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

1C kinematic fit

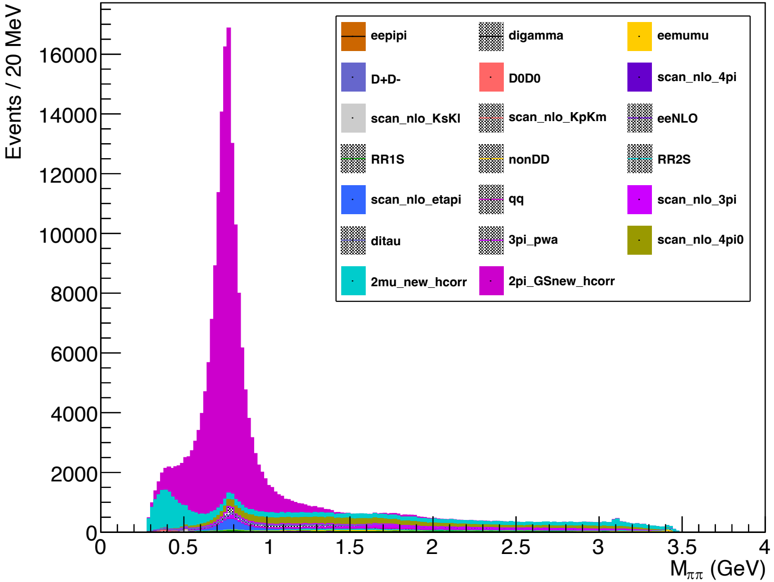


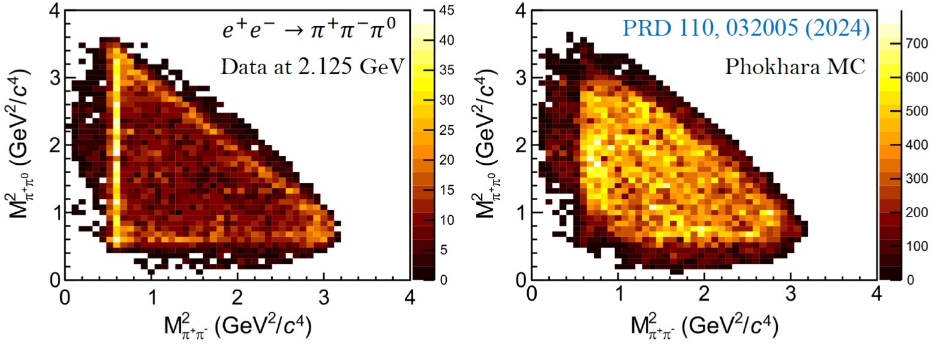
4C kinematic fit (published result)

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

Background BESIII Analysis

Price to pay in case of 1C kinematic fit (rather than 4C)
→ significantly larger background contribution, especially non-radiative $e^+e^- \rightarrow \pi^+\pi^-\pi^0$





Insufficient description of internal dynamics observed in Phokhara event generator for high cms energies:

- Already observed at lower energies in scan data
- Dedicated PWA analysis within bachelor project

Status of new BESIII Analysis

- Blinding and unblinding strategy defined and implemented
- Event selection criteria are defined and frozen
- Various data-MC corrections being finalized
- Deadtime corrections for Bhabha channel (luminosity) being investigated
- Preparing documentation for internal review

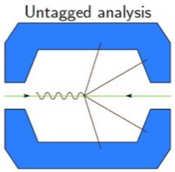
Philosophy of upcoming new BESIII analysis → Implement as many cross checks as possible:

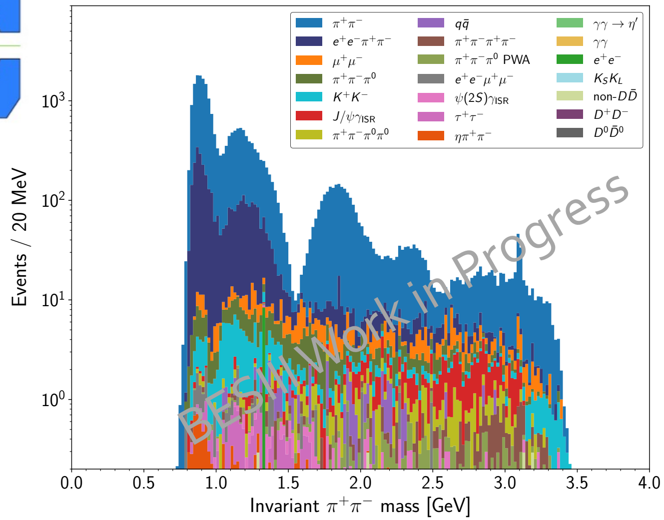
- 1C kinematic fit vs. 4C with entirely different background conditions
- cms energy of 3.77 GeV (2.9/fb) vs. 4.18 GeV (3.1/fb)
- Three normalization methods
  - Luminosity and radiator function (standard method)
  - $\pi\pi\gamma$ / $\mu\mu\gamma$
  - Template fits to polar angle distributions

Other highly-relevant BESIII Analysis

Untagged analysis (mass range > 1 GeV)

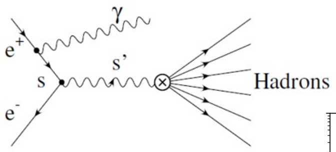
- Improvement in statistics wrt. BABAR
- Severe background conditions
- PhD project of Yasemin Scheelhaas in final stage

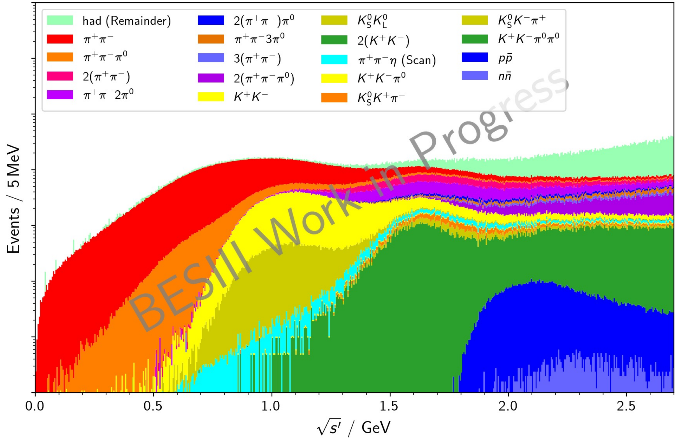




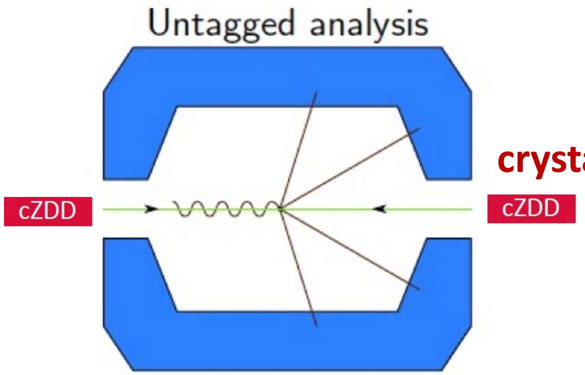
Inclusive R measurement via ISR (mass range <2 GeV)

- First-time measurement (after BABAR attempts)
- Currently based on 1-track selection
- Reduced dependence on Inclusive MC (> 97% efficiency)
- Few-percent precision achieved after unfolding
- PhD project of Thomas Lenz in final stage





Installation of a Tagging Detector at BESIII: cZDD

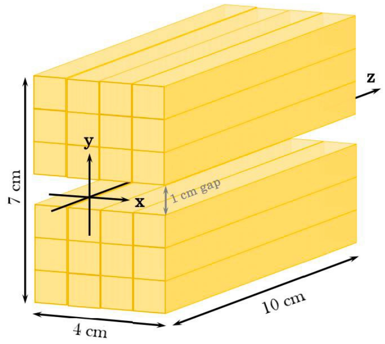


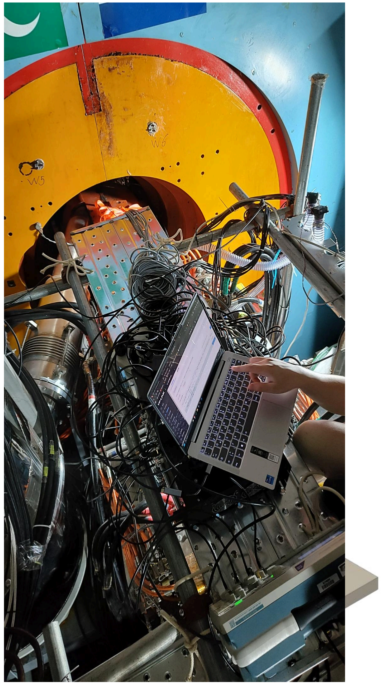
crystal Zero Degree Detector

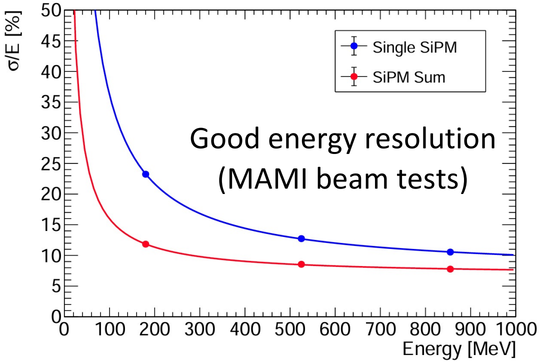
2 half detectors with 12 LYSO crystals each (SiPM) (on both sides), retractable

→ PANDA sampling ADC for SiPM readout

→ can also be used as luminosity detector







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
  - new BABAR data confirms previous BABAR result (in conflict with FNAL g-2)
  - will be exciting to see next upcoming new results (BESIII, expected 2026)

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

- Experiments (BABAR, BELLE-II, BESIII, CMD-3, KLOE, SND) targeting ~0.5% precision

A lot of effort needed to bring data-driven HVP determination back to business, but given the efforts on theory side and exchange among/with experimentalists (e.g. this meeting), we can be optimistic !

Never give up …

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 $\mu^+\mu^-\gamma$	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	Luminosity	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%
CMD-3	Energy scan	[illegible]	[illegible]	overall improvements	0.3%
SND	[illegible]	[illegible]	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, …