UNIVERSITY OF LIVERPOOL

3rd Liverpool Workshop on Muon Precision Physics,
November 12-14, 2024

Status of hadronic cross section experiments 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

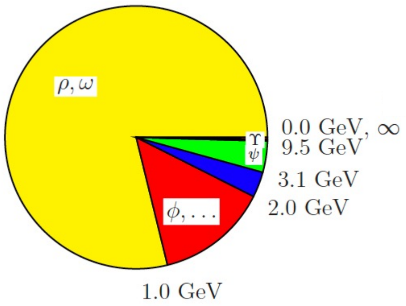
Achim Denig
Institute for Nuclear Physics
Johannes Gutenberg University Mainz

Hadronic Cross Section and Hadronic Vacuum Polarization

Hadronic vacuum polarization

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

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



→ **relevant mass range**
< 2...3 GeV

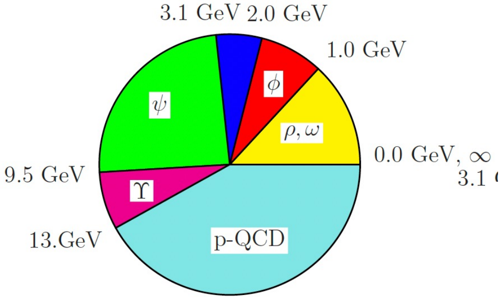
$$\boldsymbol{\sigma_{had}(s)} = \boldsymbol{\sigma_{\mathbf{tot}}(e^+e^- \rightarrow \mathbf{Hadrons})}$$

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

Running electromagnetic fine structure constant

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

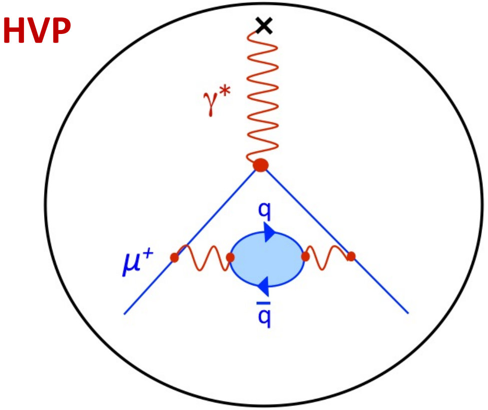
$$\Delta\alpha_{\mathrm{had}}^{(5)}(M_Z^2) \sim \int_{4\pi^2}^{\infty} ds\, \frac{\boldsymbol{R}_{\mathbf{had}}(\boldsymbol{s})}{s(s-M_Z^2)}$$



→ **relevant mass range**
< 13 GeV

Hadronic Vacuum Polarization (HVP) for $(g\text{-}2)_\mu$ from dispersive Analysis

$$a_\mu^{SM} = 11\,659\,181.0\,(4.3) \times 10^{-10}$$



Estimate of (g-2) Theory Initiative
based on dispersive approach
(including higher orders):

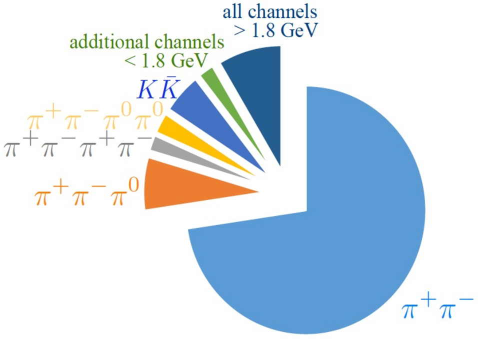
(**693.1 ± 4.0**) $\cdot 10^{-10}$

was (≅ 687 ... 694 ± 2.4 ... 4.1) $\cdot 10^{-10}$

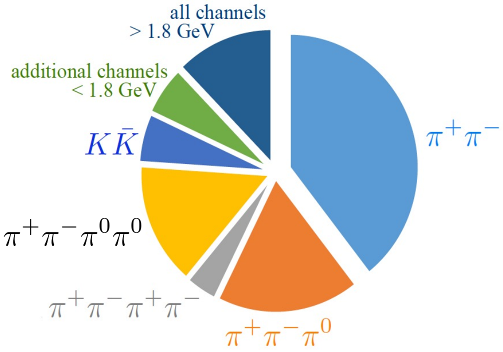
Hadronic Vacuum Polarization Contribution to (g-2)$_\mu$

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

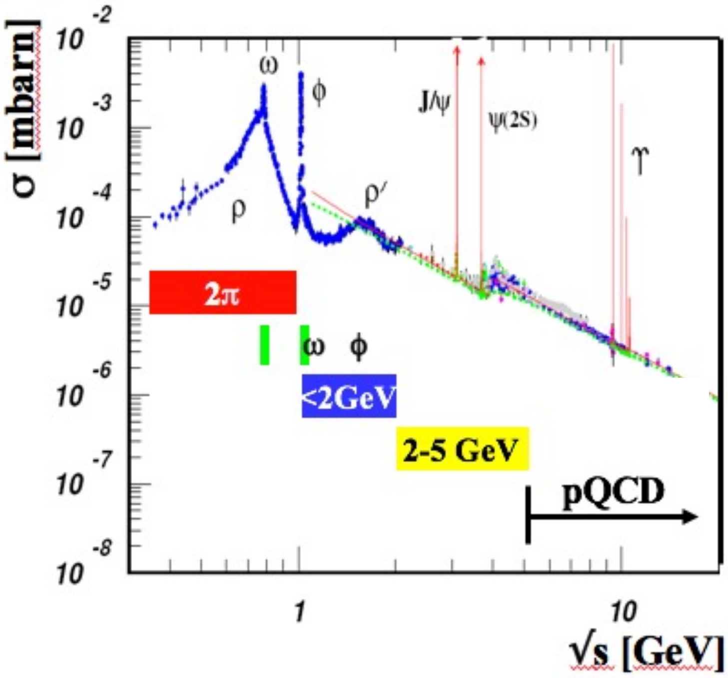
$$a_\mu^{HVP} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\, \boldsymbol{\sigma_{\mathrm{had}}(s)}$$



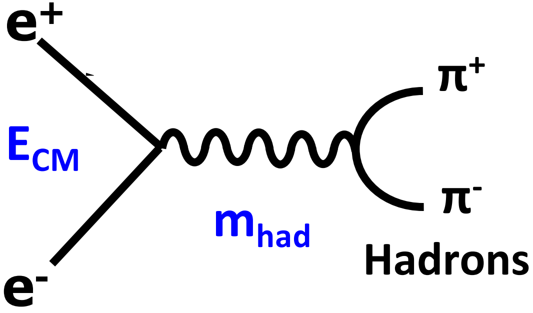
Contributions to HVP integral

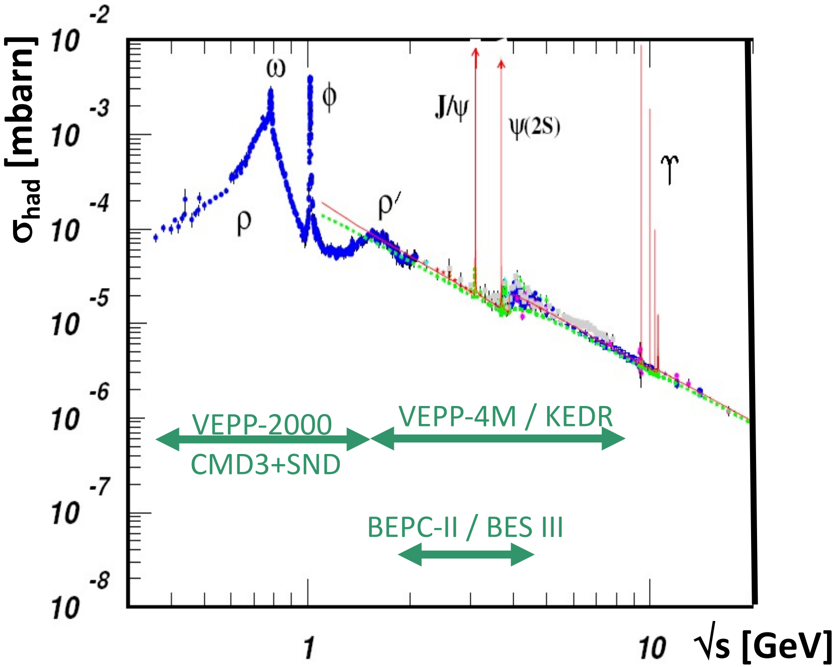


Contributions to HVP error

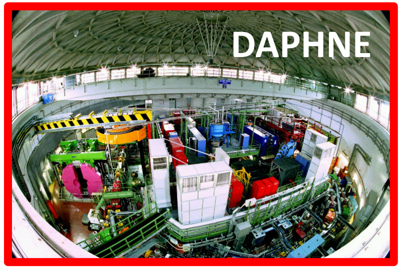


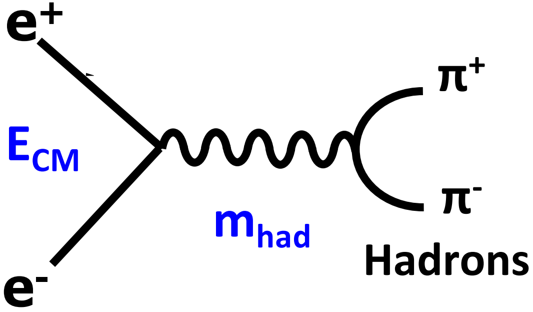
Measurements on R – Energy Scan vs. Initial State Radiation

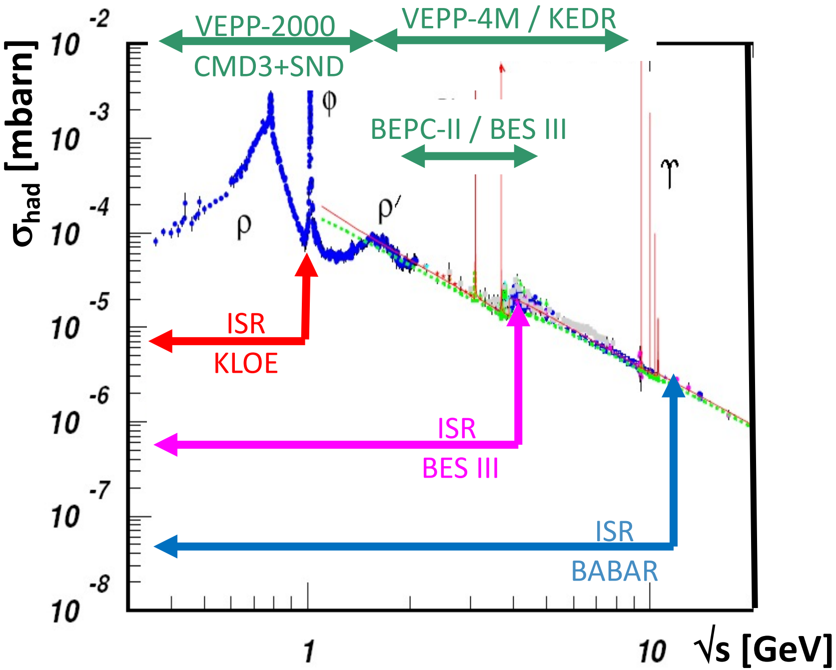




Measurements on R – Energy Scan vs. Initial State Radiation



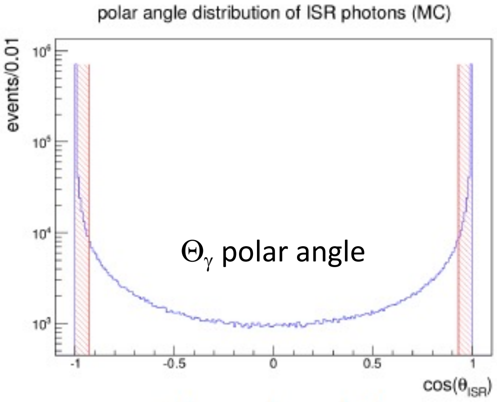




- No systematic variation of E_{beam}
- High statistics thanks to high luminosity
- Radiative corrections (H_{rad})

`PHOKHARA event generator`

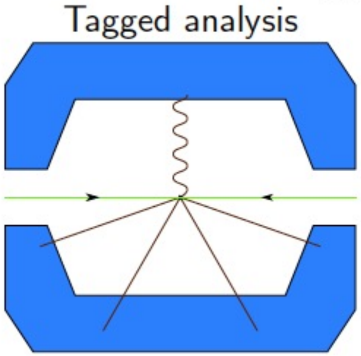
Initial State Radiation – tagged vs. untagged

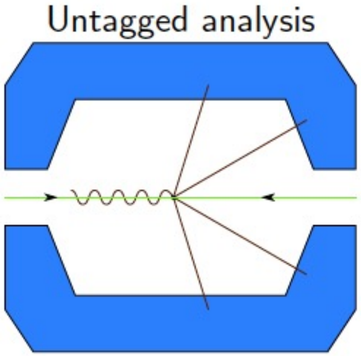


Tagged analysis:
ISR photon measured in Calorimeter

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

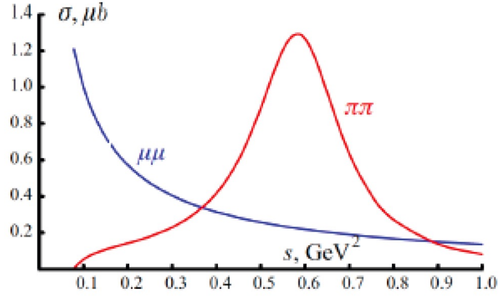
Initial State Radiation - Normalization

Two independent normalization methods:

1) normalization to L_{int} (obtained from Bhabha events) and H_{rad}; subtraction of background ($\mu^+\mu^-\gamma$, …)

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

σ(e⁺e⁻→π⁺π⁻) and σ(e⁺e⁻→μ⁺μ⁻)

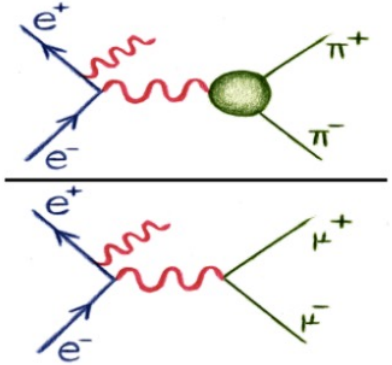


2) normalization to $\mu^+\mu^-\gamma$ events, i.e. R ratio ($\pi\pi\gamma/\mu\mu\gamma$)

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

→ requires high statistics of $\mu^+\mu^-\gamma$

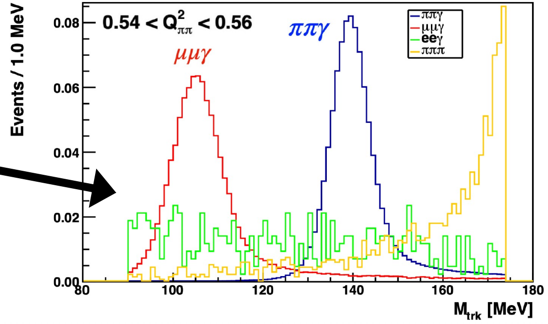
$$R = \frac{N_{\pi^+\pi^-}}{N_{\mu^+\mu^-}} \cdot \frac{\varepsilon_{\mu^+\mu^-} \cdot \left(1+\delta^{\text{FSR}}_{\mu^+\mu^-}\right)}{\varepsilon_{\pi^+\pi^-} \cdot \left(1+\delta^{\text{FSR}}_{\pi^+\pi^-}\right)}$$

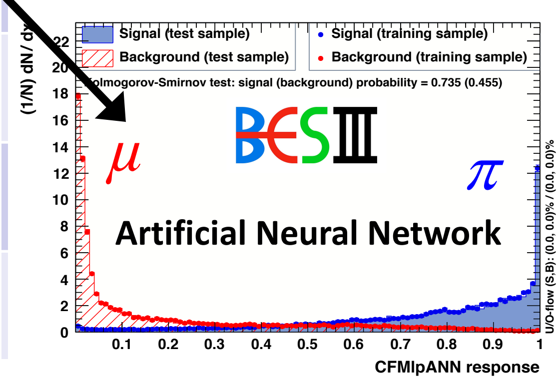


Overview Experiments

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

Trackmass x+x-γ



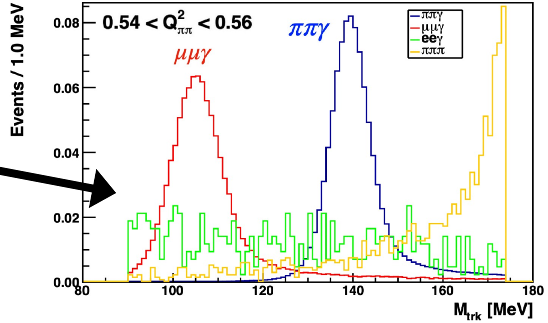


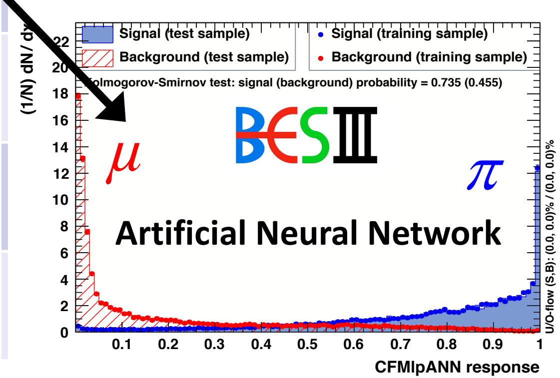
Overview Experiments

Experiment	Publish	rmalization	Separation π - μ
KLOE		osity + H_{rad} sity + H_{rad} μ-γ	Kinematics Track Kinematics Track Kinematics Track
	agged	μ+μ-γ	Particle ID
GeV	ISR tagged	Luminosity + H_{rad}	Particle ID (ML)
BELLE-II $\sqrt{s}$~10 GeV			
CMD-2/CMD-3	Scan < ~1 GeV	e+e-	Kinematics Track Kinematics EMC
SND	Scan < ~1 GeV	e+e-	Kinematics EMC

Diverse set of methods, cms energies, normalizations, selections

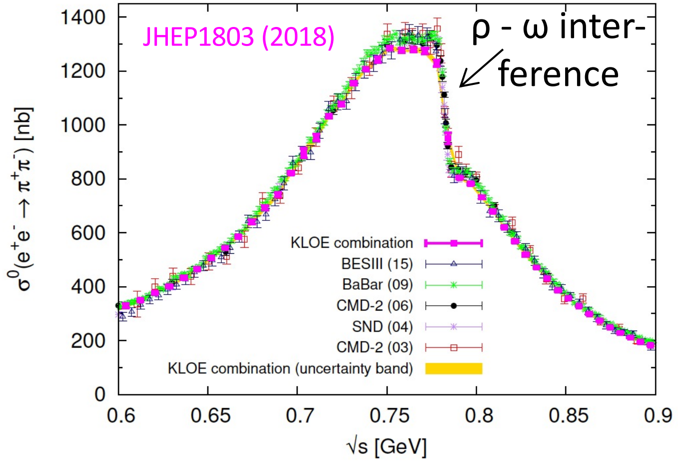
Trackmass x+x-γ

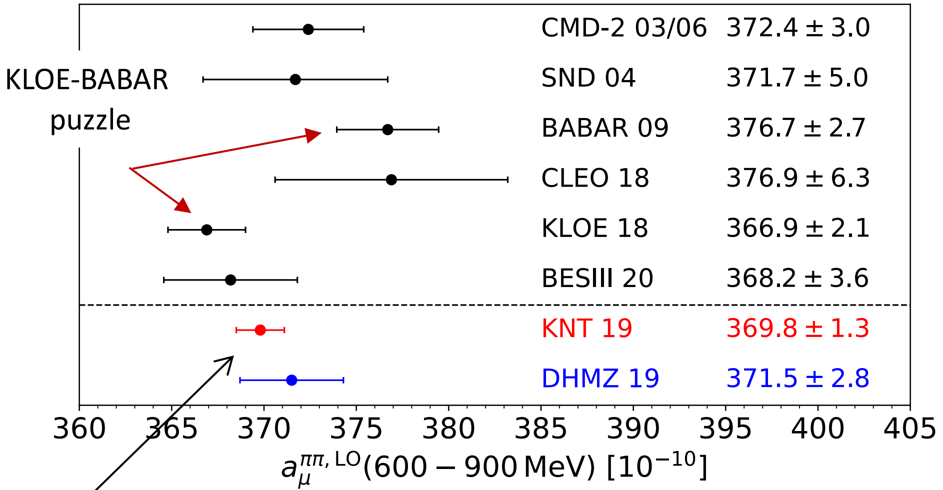




Artificial Neural Network

Most relevant Channel: $e^+e^- \rightarrow \pi^+\pi^-$ (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 estimates + input from ChPT/dispersive fits: CHHKS for 2π, 3π channels;

	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
$K_S K_L$	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
$J/\psi, \psi(2S)$	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

:-(

reasonable agreement

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

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?

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K_L	12.82(0.06)(0.18)(0.15)	13.04(19)	−0.22
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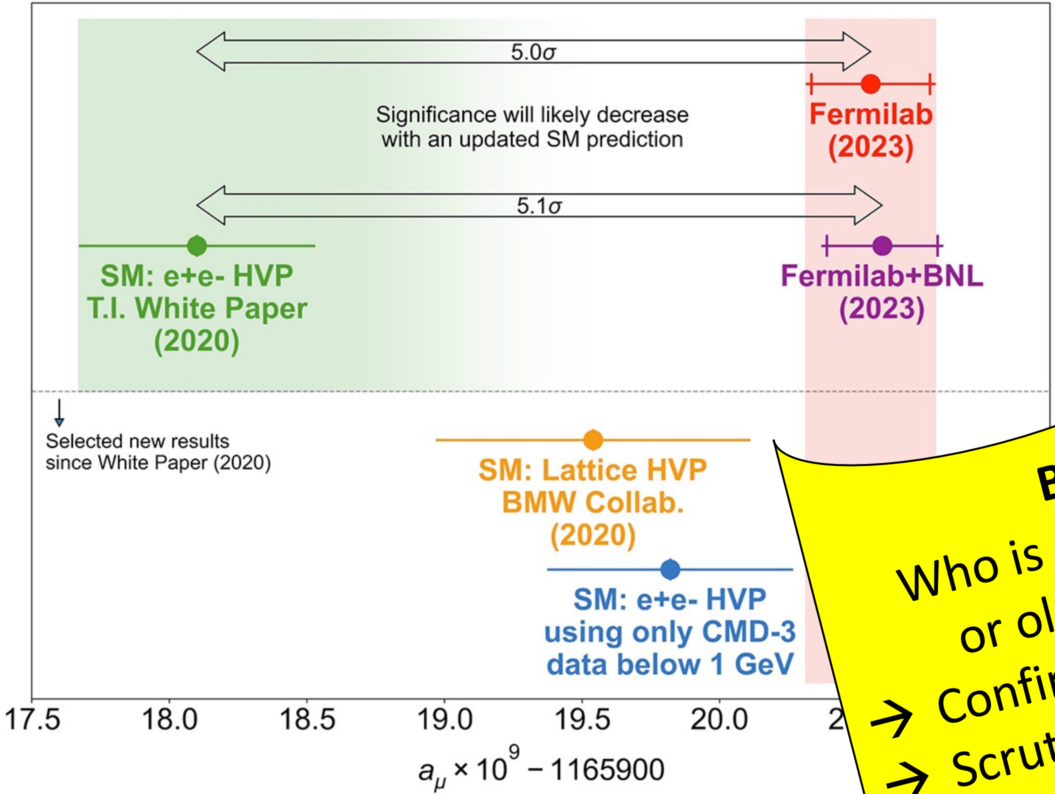
SM – *Theory vs. Experiment: $(g\text{-}2)_\mu$*



Post-2020 Whitepaper:

- **BMW Lattice QCD HVP**
- **CMD-3 data on π+π-**

Big debate now:
Who is right? CMD-3 **and** BMW
or older e+e- experiments?
→ Confirmation of BMW needed
→ Scrutiny of CMD-3 & old e+e- data

NEW

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

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

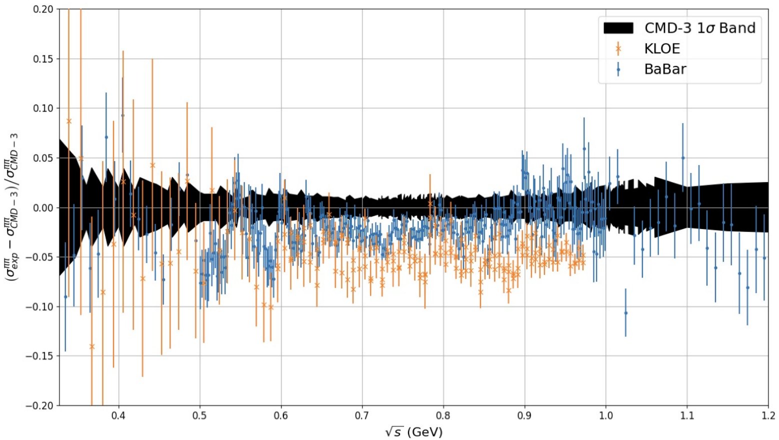
- New result from CMD-3 collaboration @ VEPP-2000 collider in Novosbirsk
- Energy scan (from threshold up to 1.2 GeV) method, no ISR!
- Form factor extraction via selection of ππ/ee ratio

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

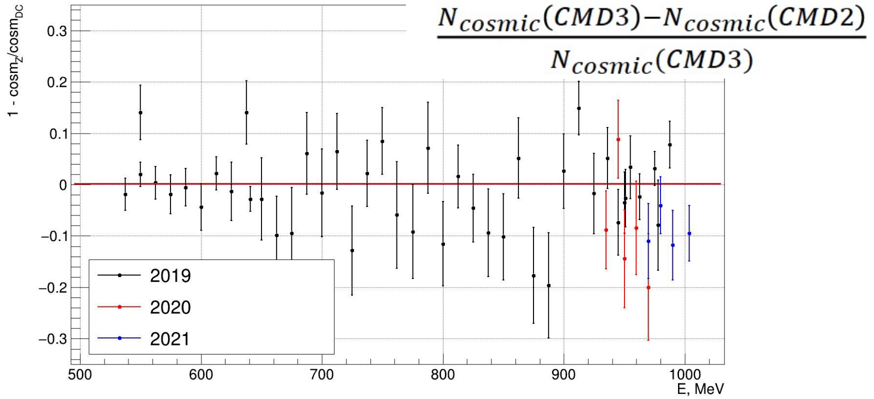
- Highest statistics data sample of all experiments, systematic uncertainty 0.7% on ρ peak

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

Courtesy Aidan Wright

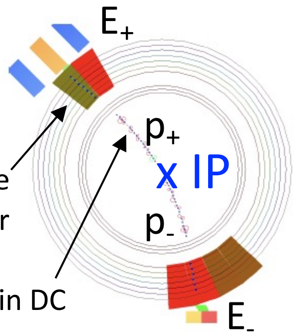


Background from cosmic ray events
as a possible explanation for CMD-2/CMD-3 difference?



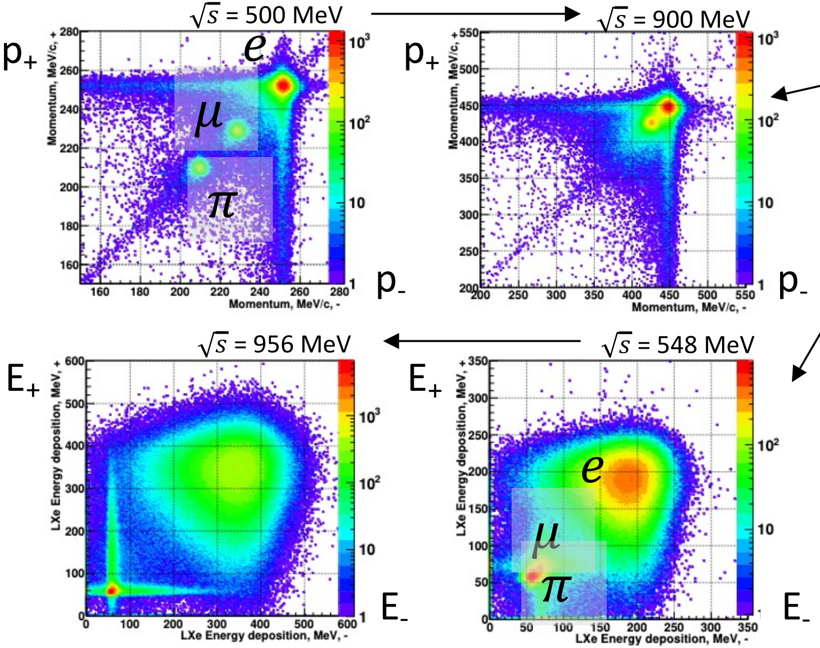
$$\frac{N_{cosmic}(CMD3) - N_{cosmic}(CMD2)}{N_{cosmic}(CMD3)}$$

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



Scrutiny of CMD-3 result within the Theory Initiative

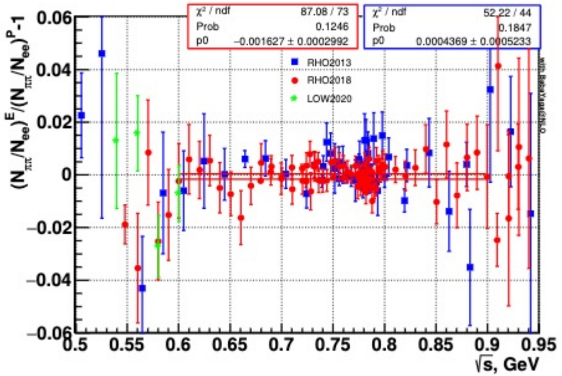
- Very open replies by F. Ignatov → no major showstopper observed
- Very powerful analysis with many and impressive internal cross checks
- Monte-Carlo generator for energy scan cannot be independently varified



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

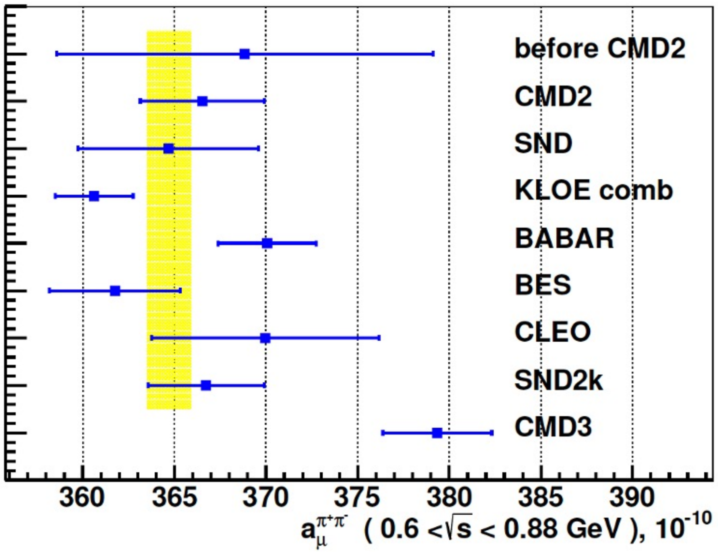
- Momentum based
- Calorimetric

agreement ~ 0.2% around rho peak

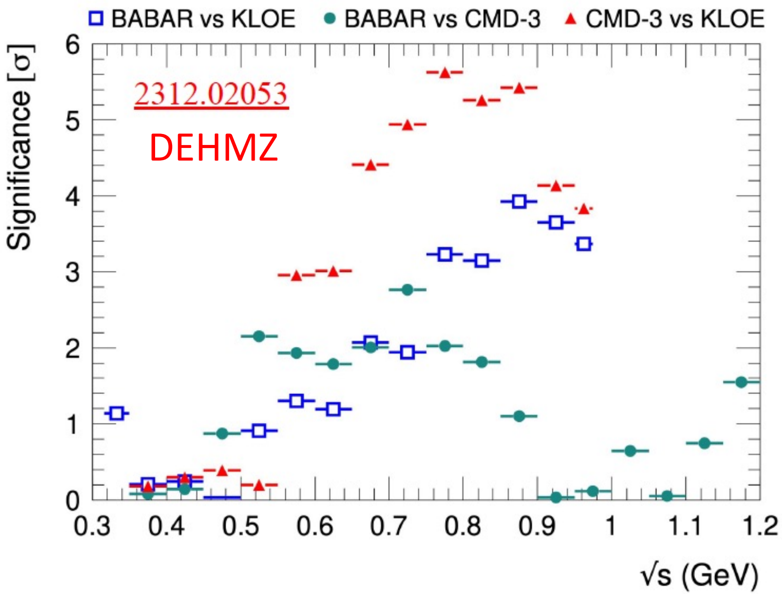


CMD-3 Compatibility with other Experiments for HVP Integral

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



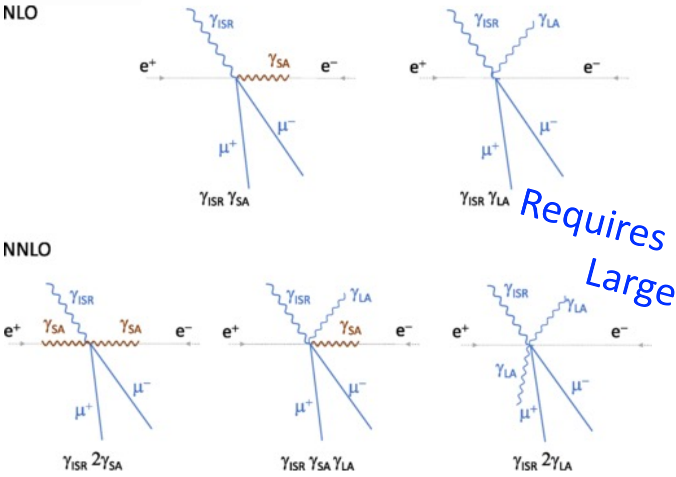
Deviation between data sets (in statistical significance)



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

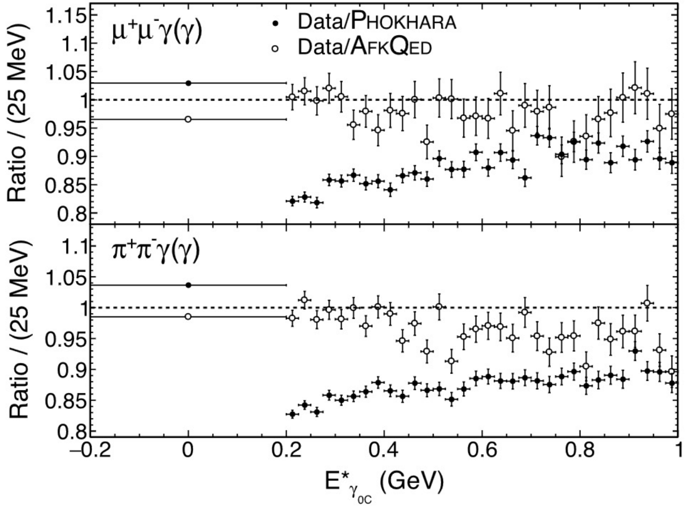
NEW

BABAR Radiative Correction Studies



Requires 1 photon at large angle
Large smearing effects

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)

NEW

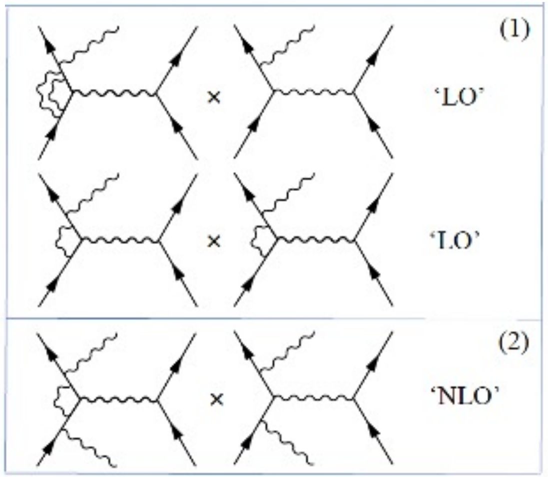
Possible Consequences from BABAR Findings (?)

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 → claim: 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



NEW

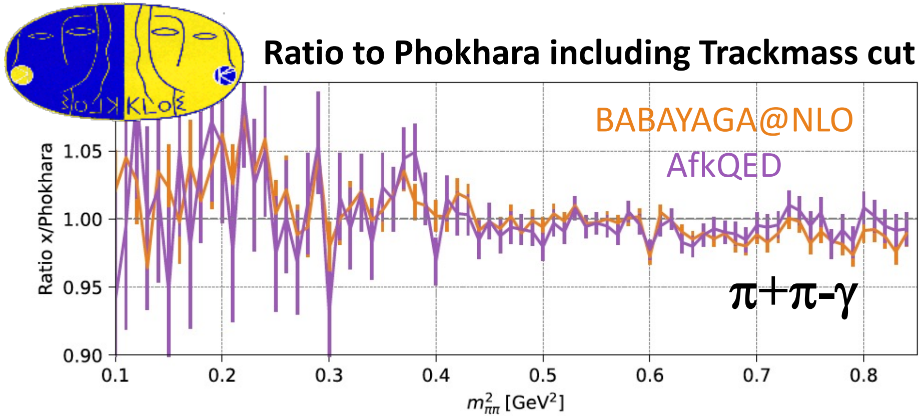
KLOE / BESIII Response to PHOKHARA Shortcomings

Investigation of kinematic cuts, which are sensitive to NLO corrections: Trackmass (KLOE), χ² (BESIII)

Radio-MonteCarlow Initaitive with detailed comparisons

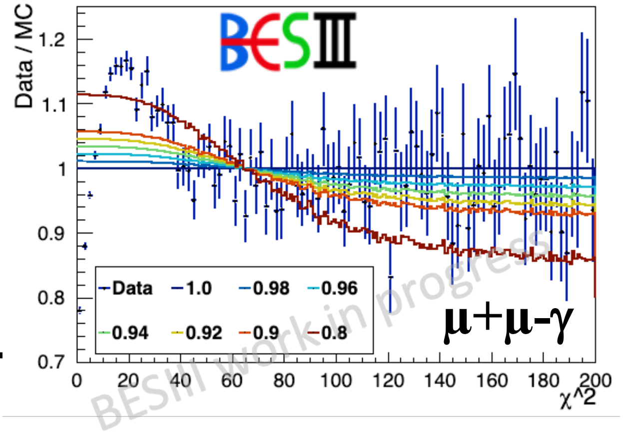
- **KLOE** has presented a **good agreement between various MC generators** for realistic acceptance cuts and also in the case of the kinematic trackmass cut for KLOE-10
- **BESIII** has carried out a **full detector simulations for various MC generators** and a **data-PHOKHARA comparison for $e^+e^- \rightarrow \mu^+\mu^-\gamma$ in the χ² 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 χ² distribution



NEW

09/24: KEK Workshop Muon g-2 Theory Initiaitve

KLOE / BESIII Response to PHOKHARA Shortcomings

Investigation of kinematic cuts, which are sensitive to NLO corrections: Trackmass (KLOE), χ² (BESIII)

Radio-MonteCarlow Initaitive with detailed comparisons

- **KLOE** has presented a **good agreement between various MC gen** ance cuts and also in the case of the kinematic trackmass cut for KLOE-10
- **BESIII** has carried out a **full detector simulations for vari** **KHARA comparison for $e^+e^- \to \mu^+\mu^-\gamma$ in the χ** that the published analysis is **largely inclusive in h**

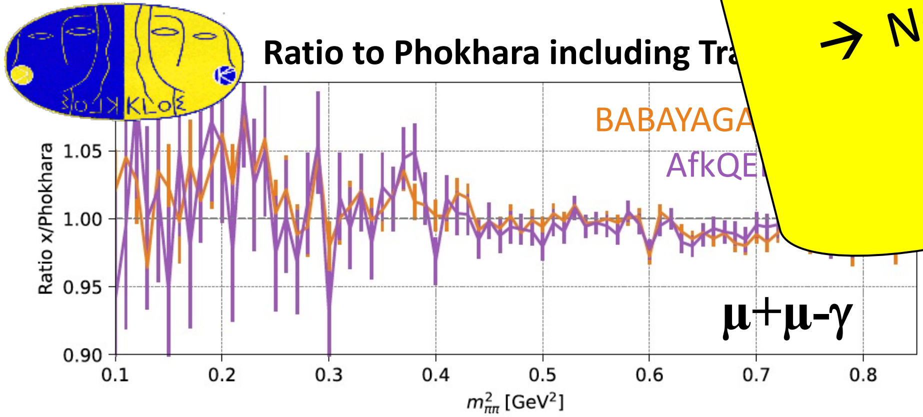
→ **scenario 2 from DHLMZ23 paper strongly**

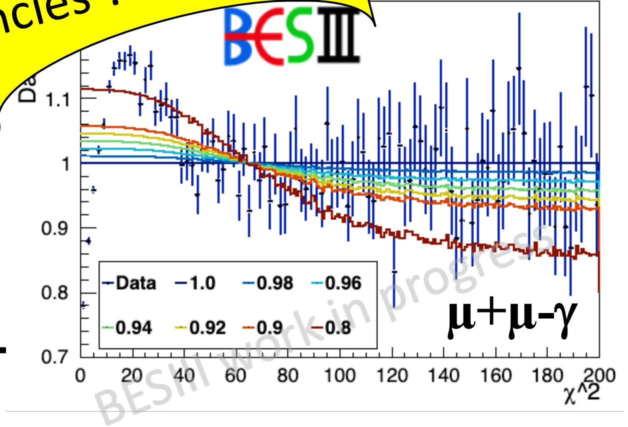
News from 2024 KEK workshop:

Phokhara limitations likely not impacting KLOE/BESIII

→ No viable explanation for discrepancies ?!

on for χ² distribution



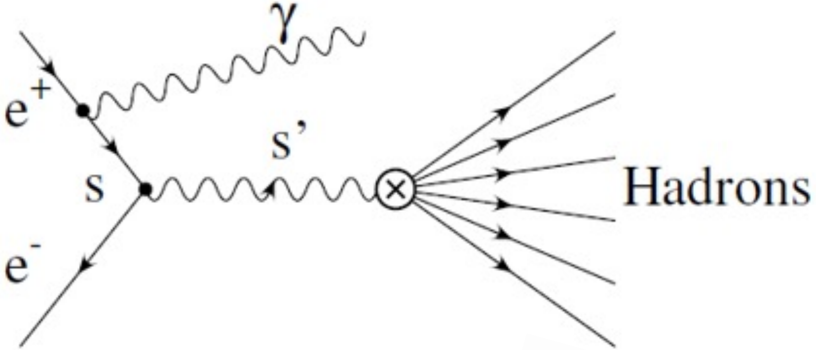


Overview Experiments – Past and Future

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	0.6%

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

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



Inclusive R-Measurement via Initial State Radiation

NEW

PhD N.J.P. Berger (2006, Stanford)
PhD project, Th. Lenz (JGU Mainz)

R_{incl} Measurement BESIII (2022)

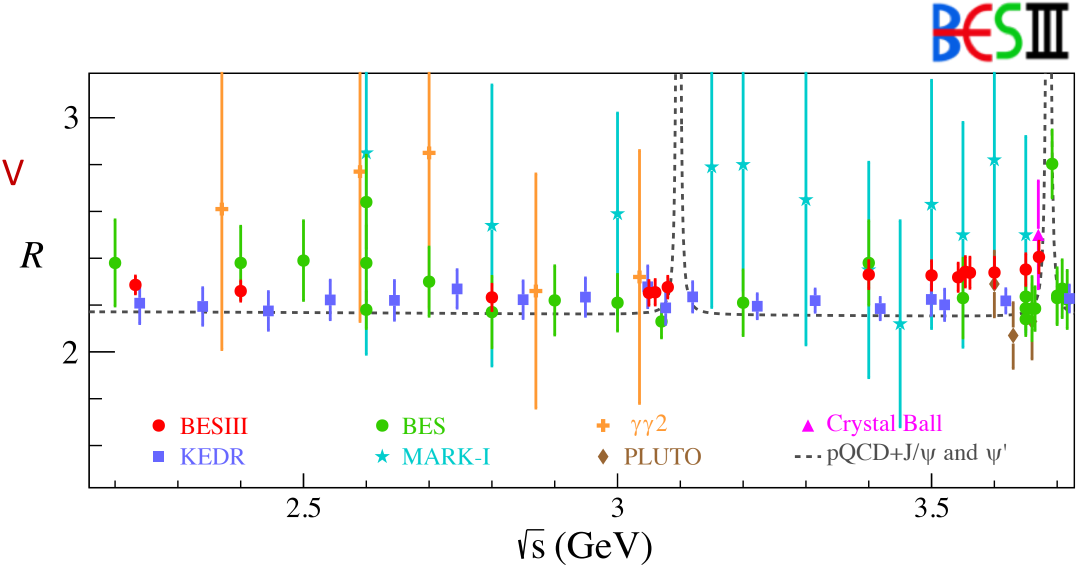
Phys. Rev. Lett. 128 (2022) 062004

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

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 !

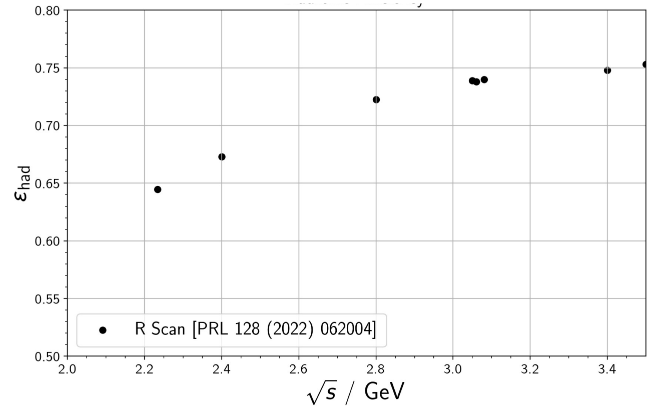
Messages learnt from Inclusive R Measurement

- Selection requires ≥ **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

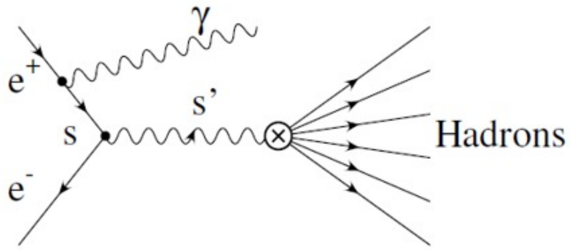
Efficiency



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

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



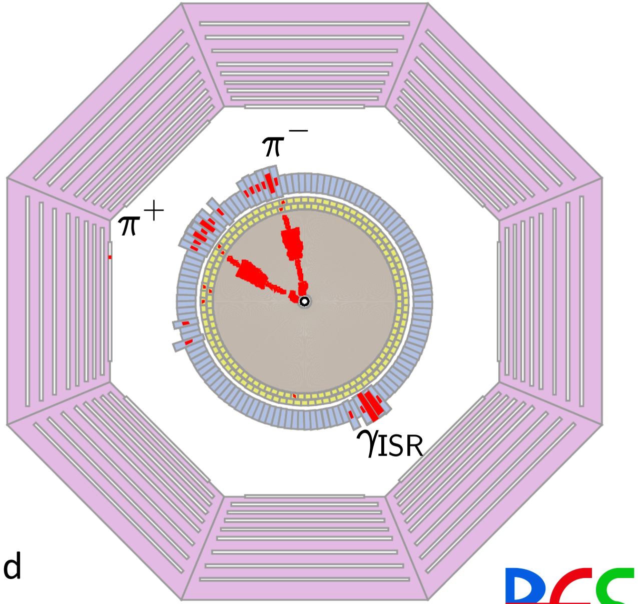
New Inclusive Approach using ISR

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

$e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^-$



New Inclusive Approach using ISR: Efficiency

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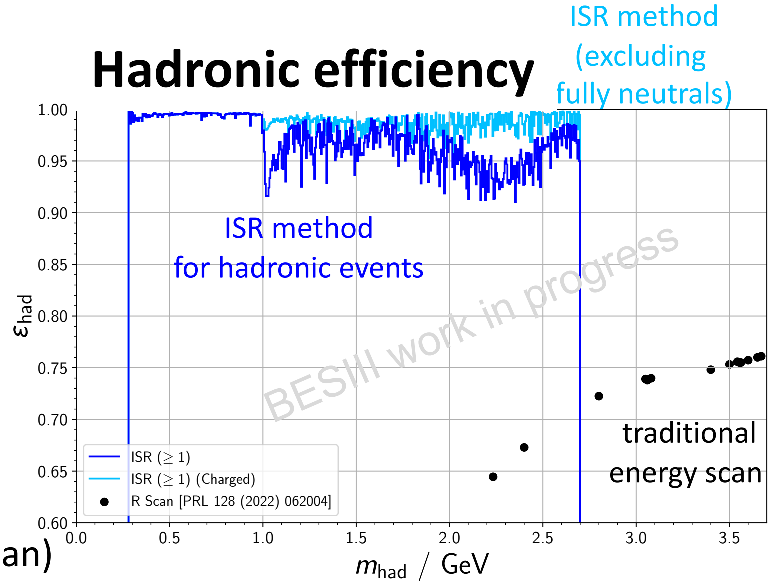
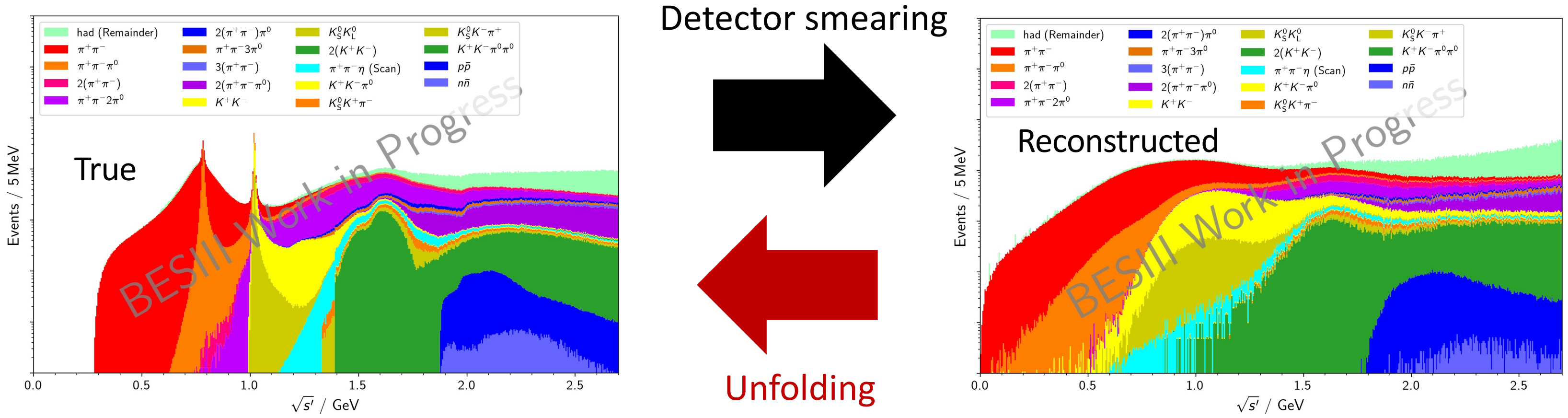

Hadronic efficiency

ISR method (excluding fully neutrals)

ISR method for hadronic events

traditional energy scan

Unfolding from Detector Mass Resolution

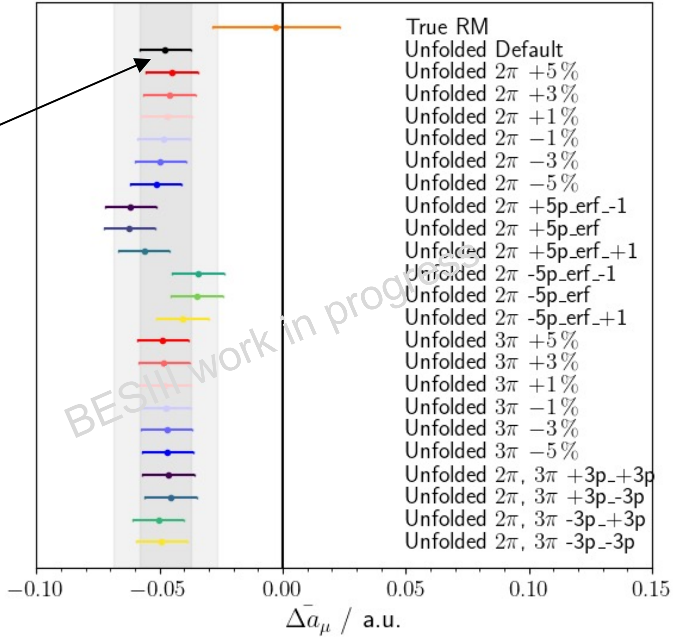


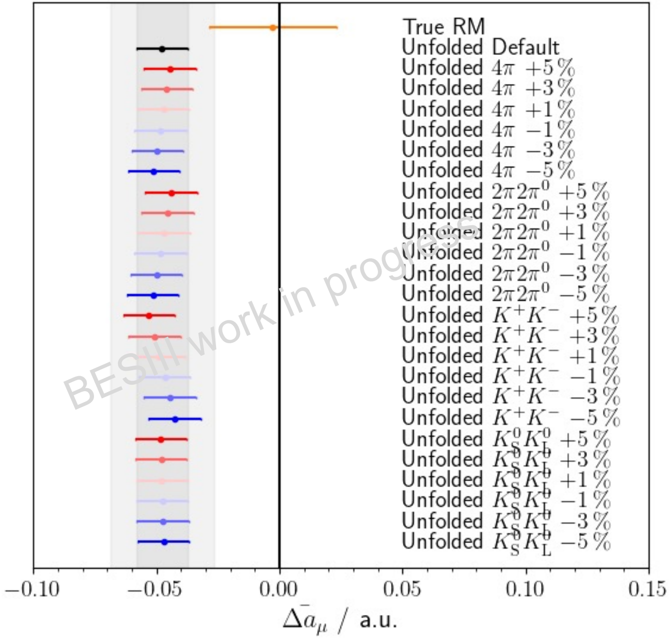
- Large smearing introduced by limited detector resolution
- Application of unfolding algorithms to recover the *true* spectrum
- Requires Monte-Carlo program to construct unfolding matrix – Response Matrix (RM)
- Systematically testing the bias in the unfolding procedure due to wrong input Monte-Carlo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

Conclusions

Conclusions

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

  - difference in $\pi^+\pi^-$ between CMD-3 and other expts. to be understood
  - radiative corrections are a key issue → RadioMonteCarlow initiative!

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

- Luckily, new e^+e^- data at the horizon

  - BABAR with fit to angular distributions for π/μ/e separation
  - KLOE with full KLOE statistics
  - BESIII with 20/fb data sample (normalization to μμ), new ideas R_{incl} via ISR
  - BELLE-II has joined the team of ISR experiments
  - further cross checks by CMD-3 and new SND data from energy scan

Thank you !