MITP Topical Workshop, June 4-7, 2024

The Evaluation of the Leading Hadronic Contribution to the Muon g-2: Consolidation of the MUonE Experiment and Recent Developments in Low Energy e^+e^- Data

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

JG|U

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Hadronic Cross Section and Hadronic Vacuum Polarization

Hadronic vacuum polarization

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

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

Running electromagnetic fine structure constant

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

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

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

$$\boldsymbol{R}_{had} = \frac{\boldsymbol{\sigma}_{had}(\boldsymbol{s})}{\boldsymbol{\sigma}_{ee\rightarrow\mu\mu}(\boldsymbol{s})}$$

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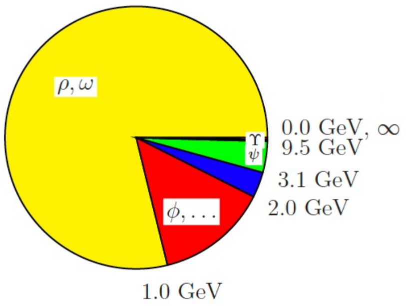

→ **relevant mass range < 2...3 GeV**

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

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

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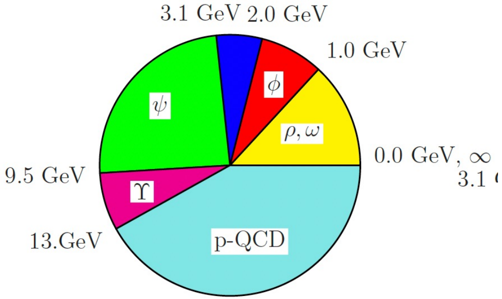
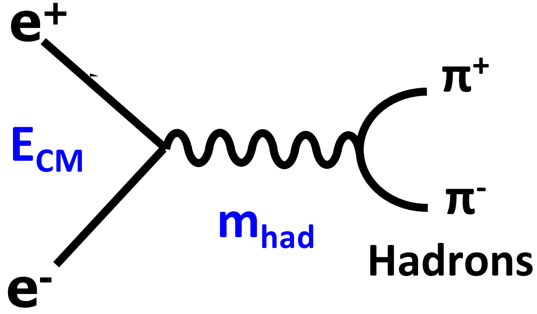
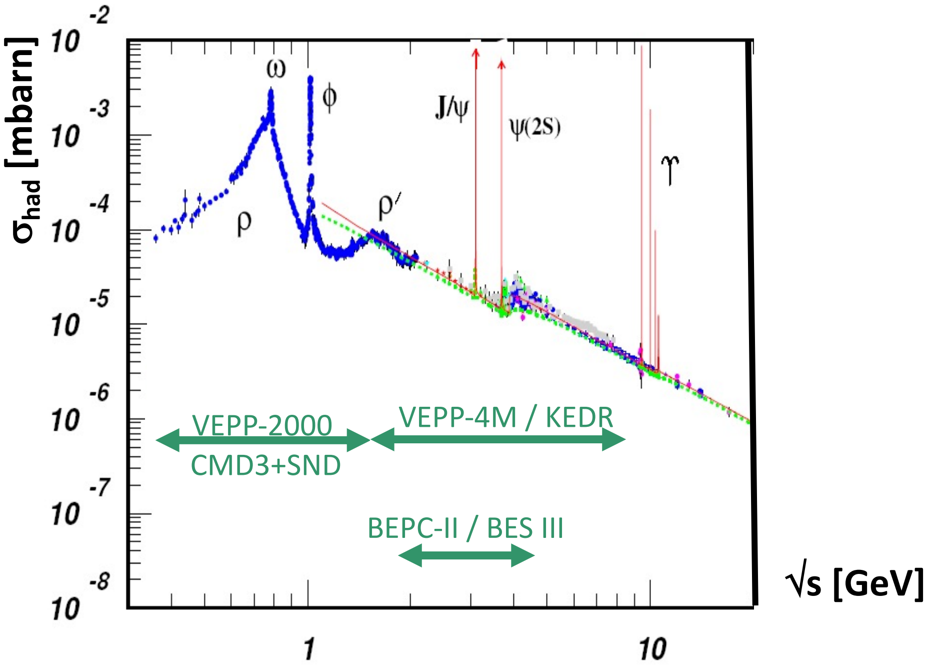


→ **relevant mass range < 13 GeV**

Measurements on R – Energy Scan vs. Initial State Radiation





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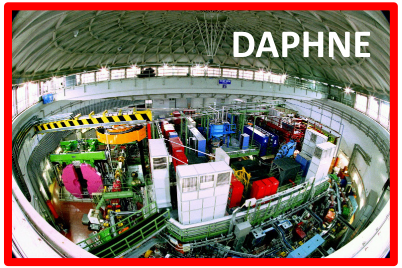

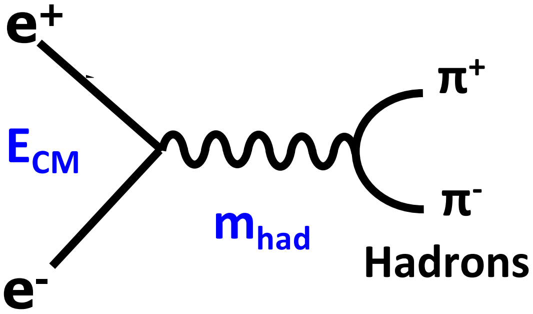

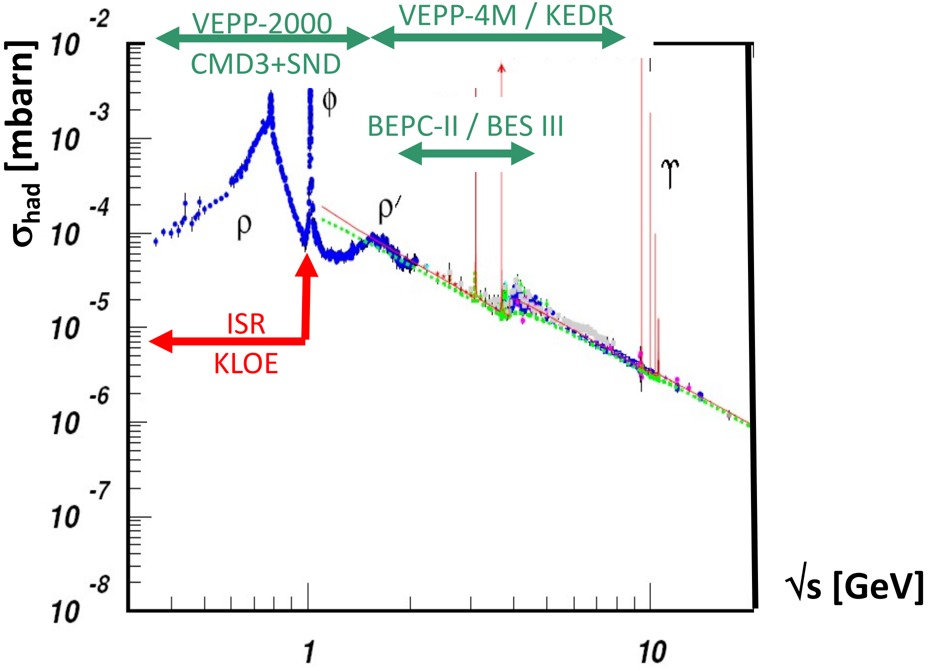

- No systematic variation of E_{beam}
- High statistics thanks to high luminosity
- Radiative corrections (H_{rad})

`PHOKHARA event generator`

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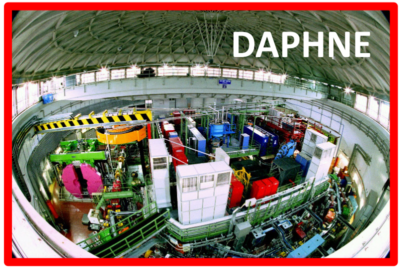

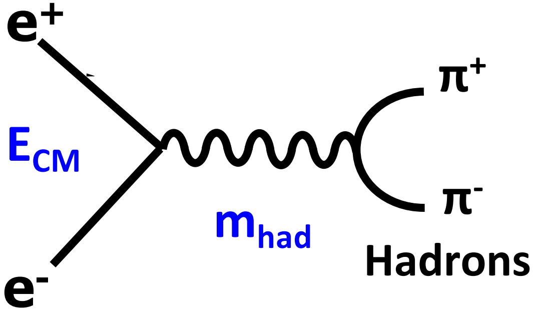

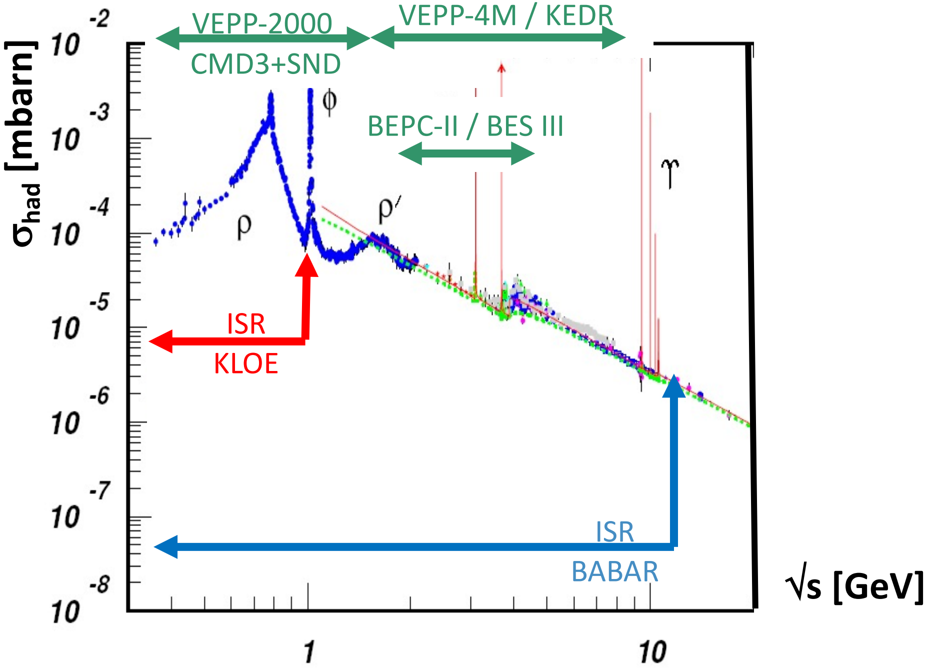

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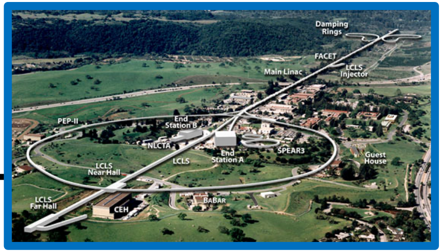

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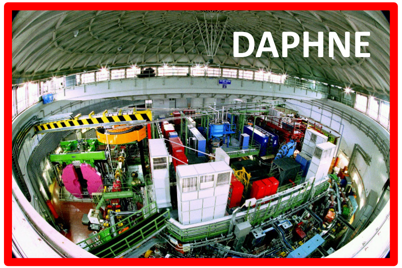

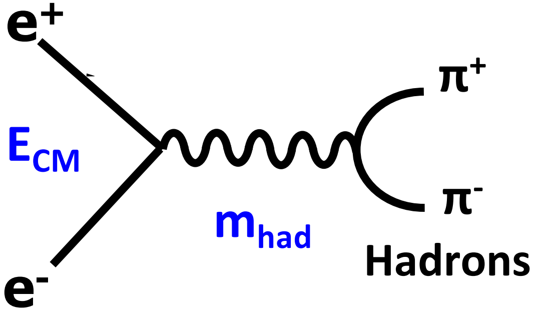

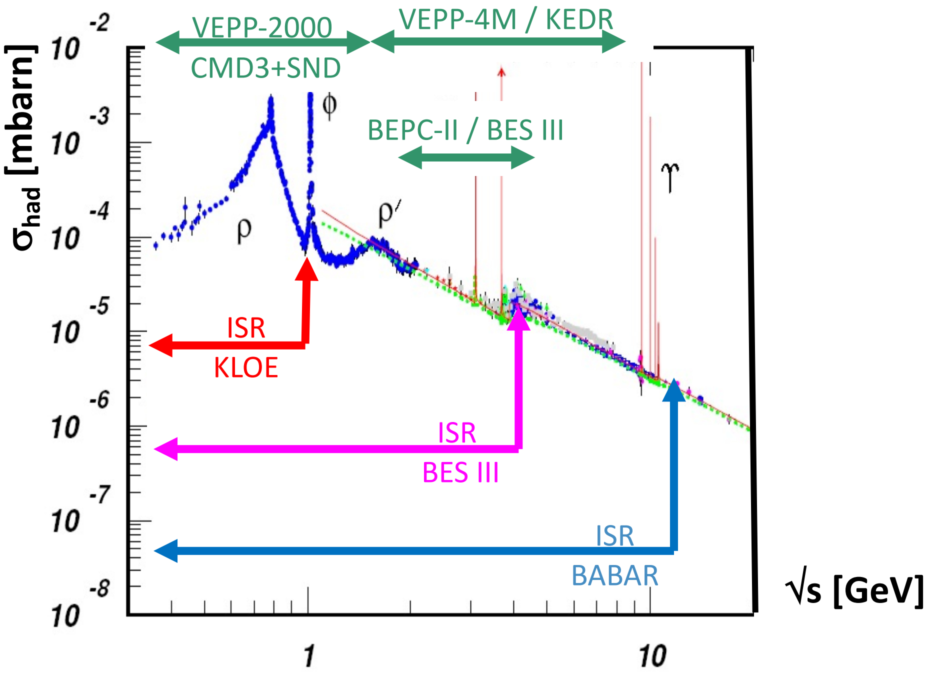

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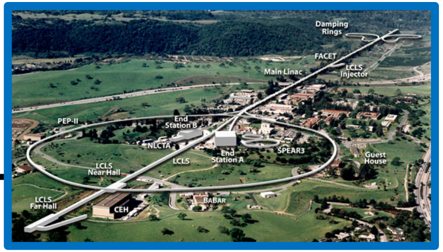
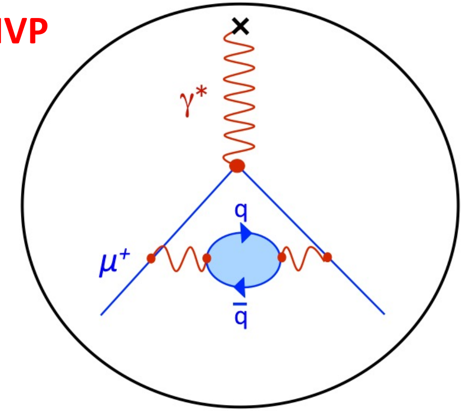


Hadronic Vacuum Polarization (HVP) for $(g\text{-}2)_\mu$ from dispersive Analysis

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

HVP



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

(**693.1** ± **4.0**) · 10^{-10}

was (≅ 687 ... 694 ± 2.4 ... 4.1) · 10^{-10}

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

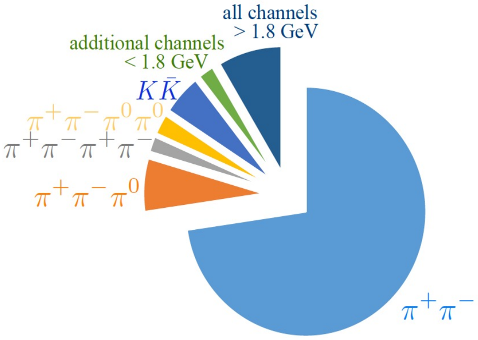
Optical theorem (unitarity) and analyticity:

Data-driven approach: *K(s):* known kernel function
s: energy^2

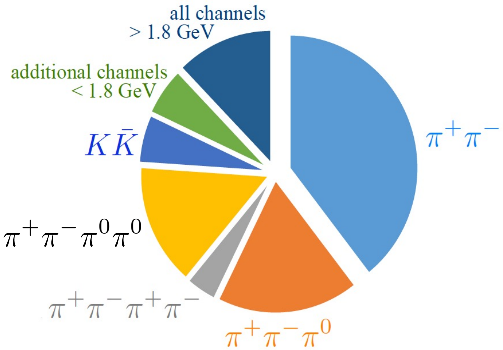
$$a_\mu^{HVP} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\, \boldsymbol{\sigma_{\mathrm{had}}(s)}$$

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

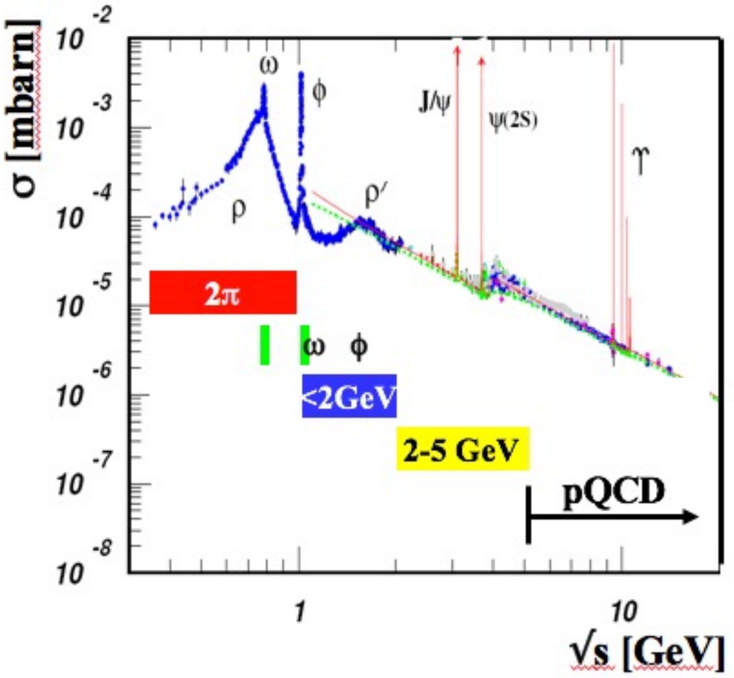
low energy contributions especially important!



Contributions to HVP integral

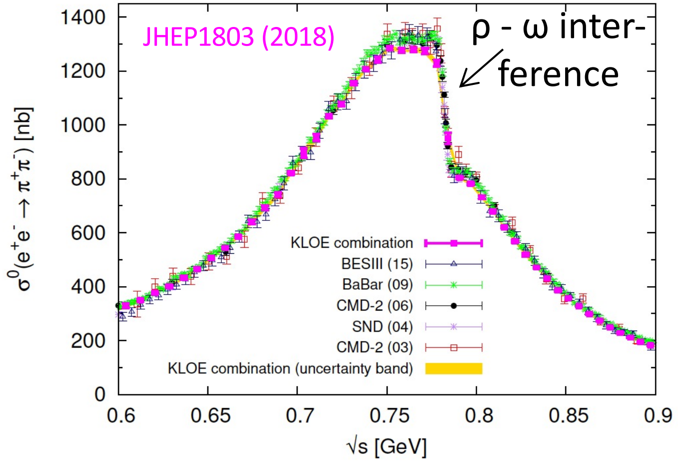


Contributions to HVP error



Status of e^+e^- hadronic cross section experiments

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 CMD2 0.8%*

  * limited in addition by statistics

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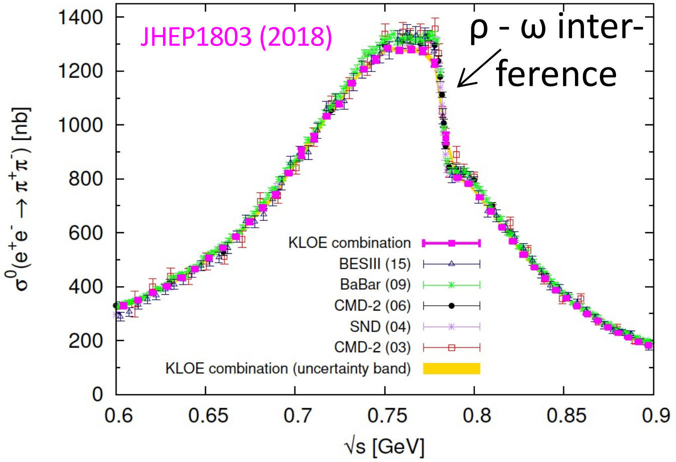

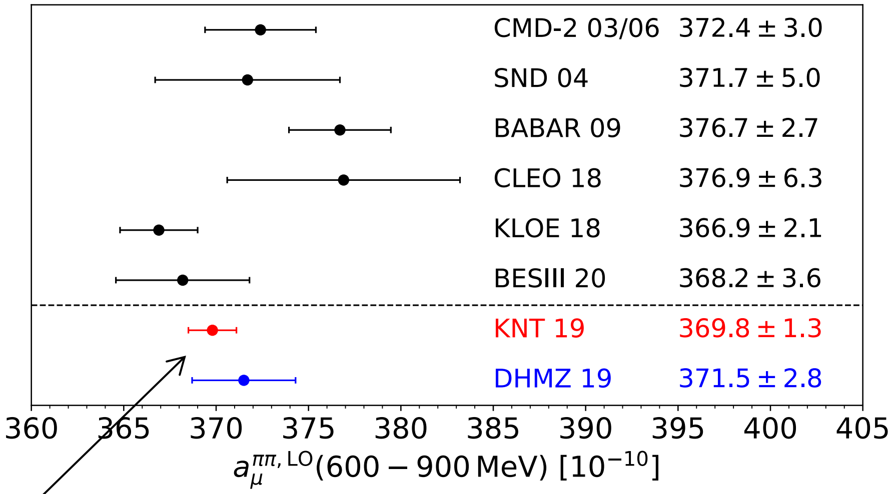

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Most recent evaluations of HVP:

- 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
$[3.7, \infty)$ 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

:-(

reasonable agreement

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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

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

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:-((3.62)

reasonable agreement (1.2)

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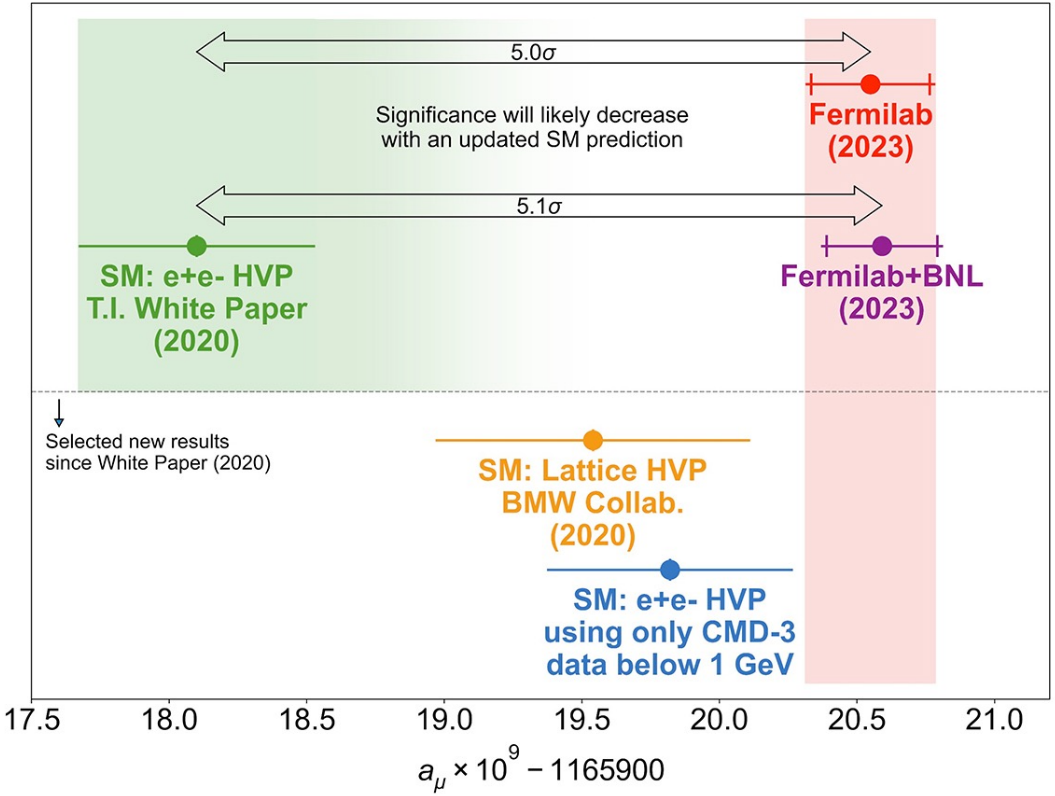
2024: SM – Theory vs. Experiment: $(g\text{-}2)_\mu$



Post-2020 Whitepaper:

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

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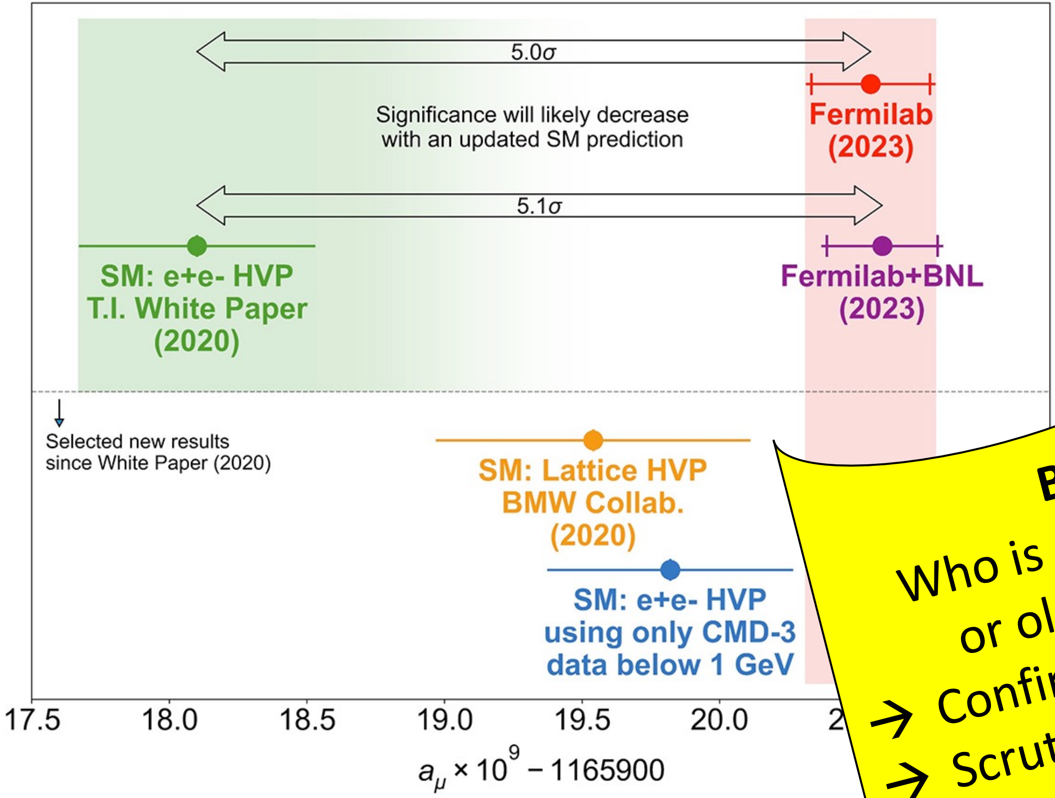


Post-2020 Whitepaper:
- **BMW Lattice QCD HVP**
- **CMD-3 data on π+π-**

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

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

arxiv:2302.08834

- 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

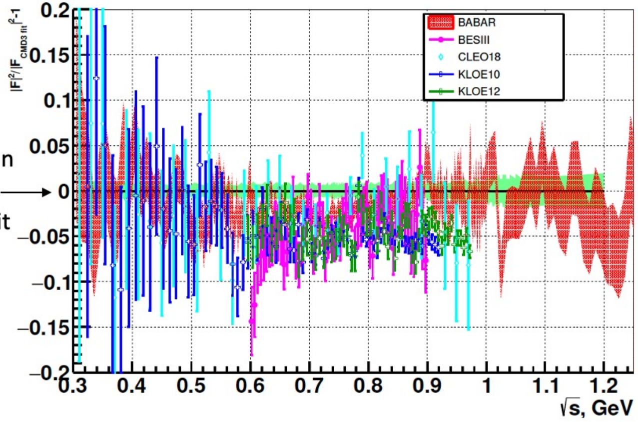
$$|F_\pi|^2 = \left(\frac{N_{\pi^+\pi^-}}{N_{e^+e^-}} - \Delta^{bg}\right) \cdot \frac{\sigma^0_{e^+e^-} \cdot (1+\delta_{e^+e^-}) \cdot \varepsilon_{e^+e^-}}{\sigma^0_{\pi^+\pi^-} \cdot (1+\delta_{\pi^+\pi^-}) \cdot \varepsilon_{\pi^+\pi^-}}$$

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

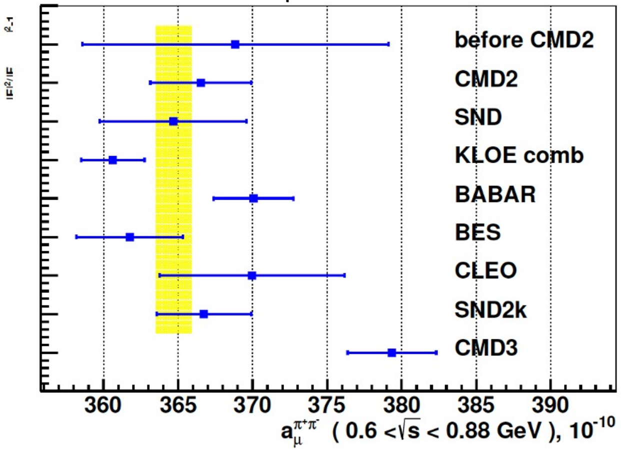
→ Significant deviation from previous ISR and energy scan experiments ! Why? No answer !

Differential spectrum

Deviation from CMD3 fit



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



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

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
- Unfortunately no (real) blind analysis

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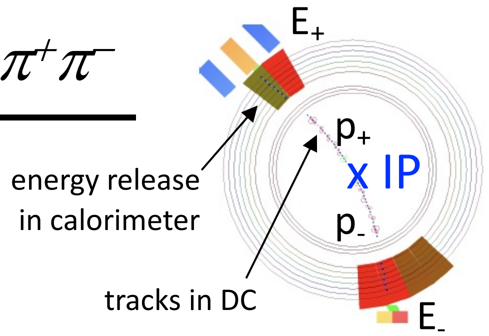

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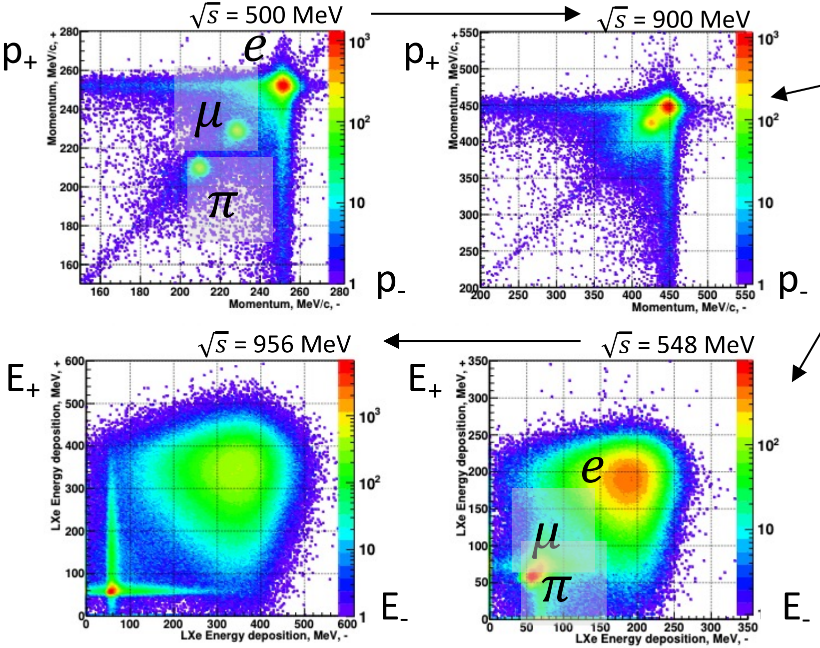
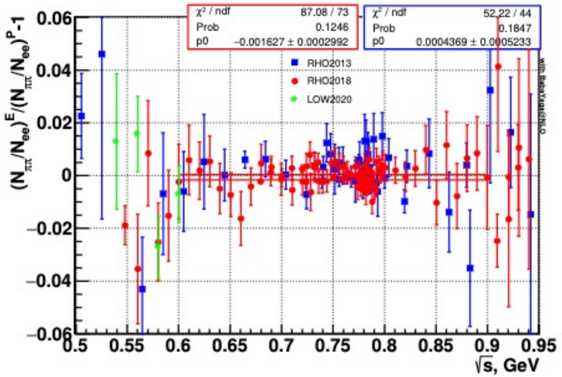
Most impressive feature: ππ/ee ratio determined independently by two complementary methods

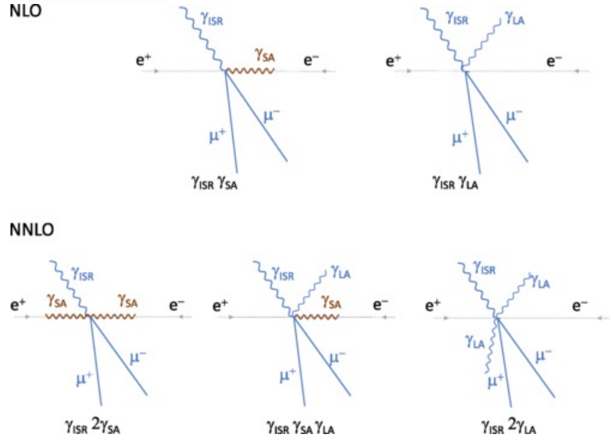
- Momentum based
- Calorimetric



agreement ~ 0.2% around rho peak

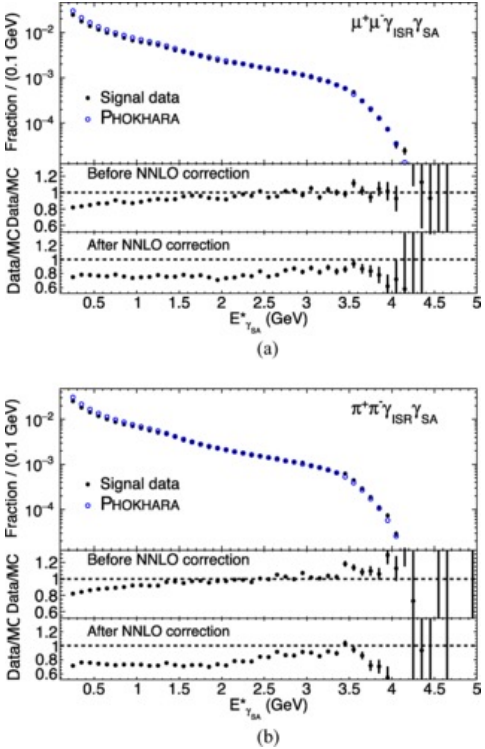


BABAR Radiative Correction Studies



Phys. Rev. D 108, L111103

Requires 1 photon at large angle
Large smearing effects



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 better)

NEW

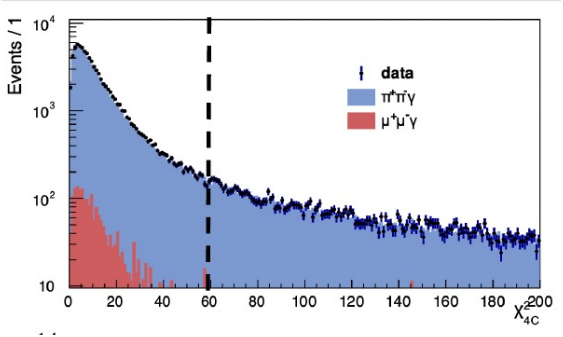
Possible Consequences from BABAR Findings (?)

JG|U

arXiv:2312.02053

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

KLOE/BESIII: - less inclusive selection regarding NLO
→ claim: possibly large effect due PHOKHARA NLO limitations,
BESIII: good agreement data-PHOKHARA in χ^2 distribution (?)



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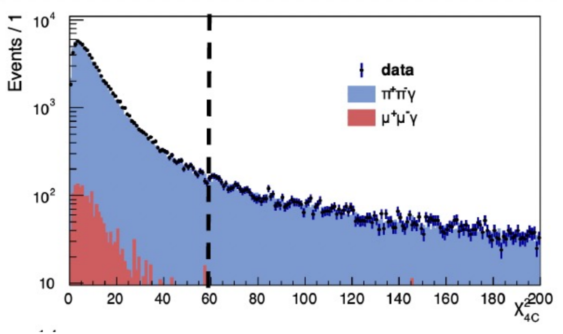
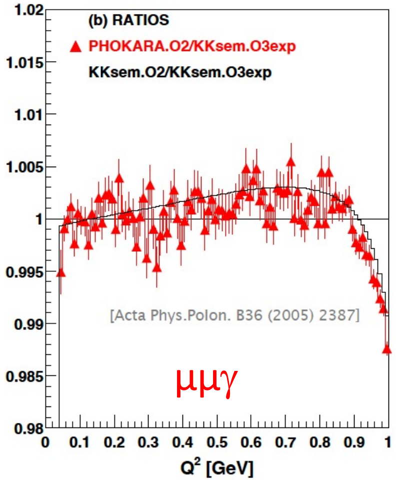


excellent PHOKHARA-KKMC comparison (?)



Hadronic Cross Section Data after 2020 Whitepaper

- BESIII $\pi^+\pi^-$ (600 < √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 < √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 < √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 < √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 via Energy Scan

Phys. Rev. Lett. 128 (2022) 062004

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 %

NEW

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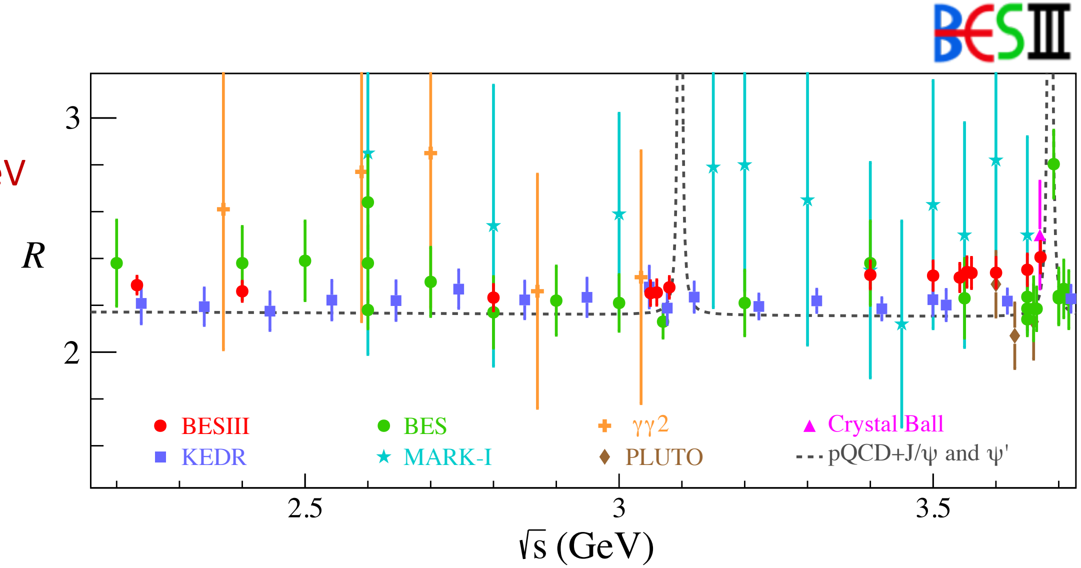
Analysis strategy: select all events with $\geq$ 2 tracks

- 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

New R_{incl} Measurement from BESIII

After years of developments, tuning, and cross checks two complementary inclusive MC generators (fully theoretical LUARLW, data-driven hybrid MC) have been found to be in agreement on a level of 2.3%

- 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 ?!

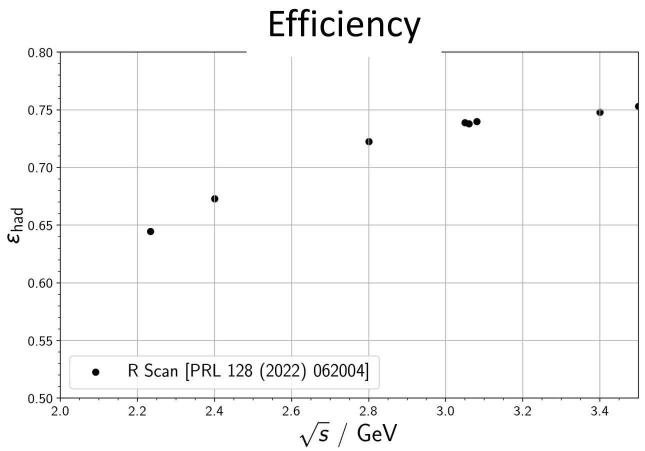
Next step: Analysis of high statistics energy scan in entire range 2.0 – 4.6 GeV

Messages learned from Inclusive R Measurement

Remember: - 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

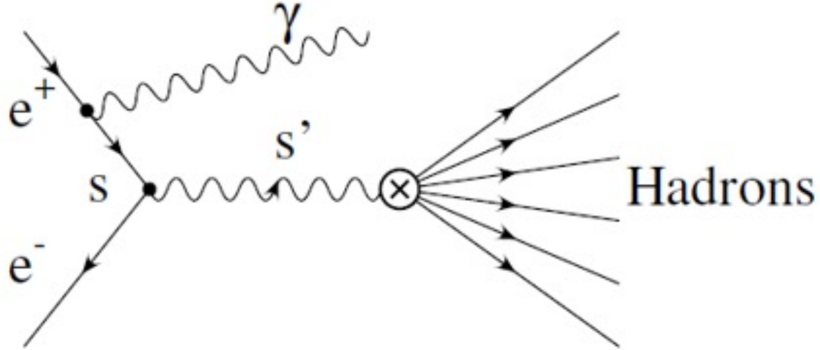
→ Total event efficiency at 60% .... 70% level



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

Is there a way to increase the detection efficiency?

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



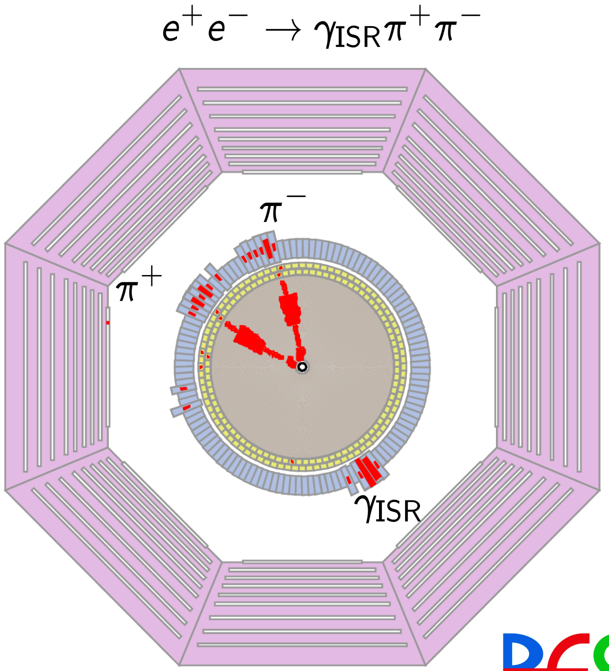
Inclusive R-Measurement via Initial State Radiation

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

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. $e^+e^- \rightarrow \pi^0\gamma$)



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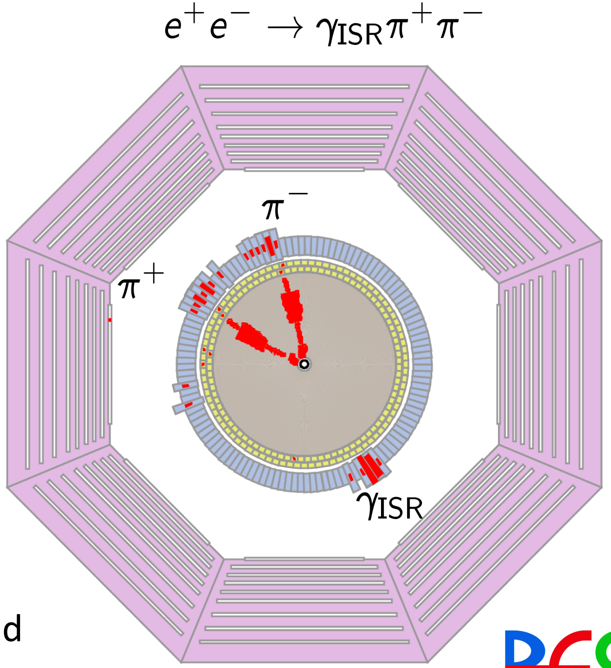

- ISR boost confines particles into narrow cone
  → Very high detection efficiency
- Less reliant on description of hadronic MC
  → ISR description in MC under control
- Single measurement down to threshold (does not need scan)
- Measurement fully inclusive for Final State Radiation (FSR) and higher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

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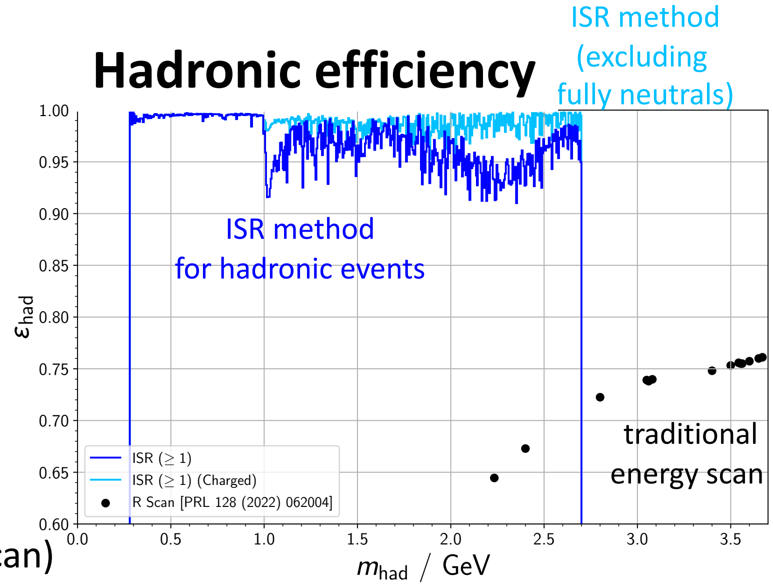

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New Inclusive Approach using ISR: Challenges

1) **Enormous background from QED processes**:

$$e^+e^- \to e^+e^-(\gamma)$$
$$e^+e^- \to \gamma\gamma(\gamma)$$
$$e^+e^- \to \mu^+\mu^-(\gamma)$$
$$e^+e^- \to \tau^+\tau^-(\gamma)$$

2) **Background from hadronic events, which are not ISR**, i.e. π^0 decays (only relevant for high hadr. masses)

3) Very **limited hadronic mass resolution** due to energy resolution of ISR photon detection
$\Delta E_{ISR}/E_{ISR} \approx 3\%/\sqrt{E_{ISR}[GeV]}$ (i.e. 30 MeV for $E_{ISR} = 1\ GeV$)

.... many more,
for instance **radiative corrections**

New Inclusive Approach using ISR: Challenges

1) **Enormous background from QED processes**:

   → apply dedicated PID (particle identification) cuts to distinguish hadrons from leptons, especially from electrons

$$e^+e^- \to e^+e^-(\gamma)$$
$$e^+e^- \to \gamma\gamma(\gamma)$$
$$e^+e^- \to \mu^+\mu^-(\gamma)$$
$$e^+e^- \to \tau^+\tau^-(\gamma)$$

2) **Background from hadronic events, which are not ISR**, i.e. π^0 decays (only relevant for high hadr. masses)

   → Dedicated cuts to veto meson decays, which mimick ISR photons

3) Very **limited hadronic mass resolution** due to energy resolution of ISR photon detection

   $\Delta E_{ISR}/E_{ISR} \approx 3\%/\sqrt{E_{ISR}[GeV]}$ (i.e. 30 MeV for $E_{ISR} = 1\ GeV$)

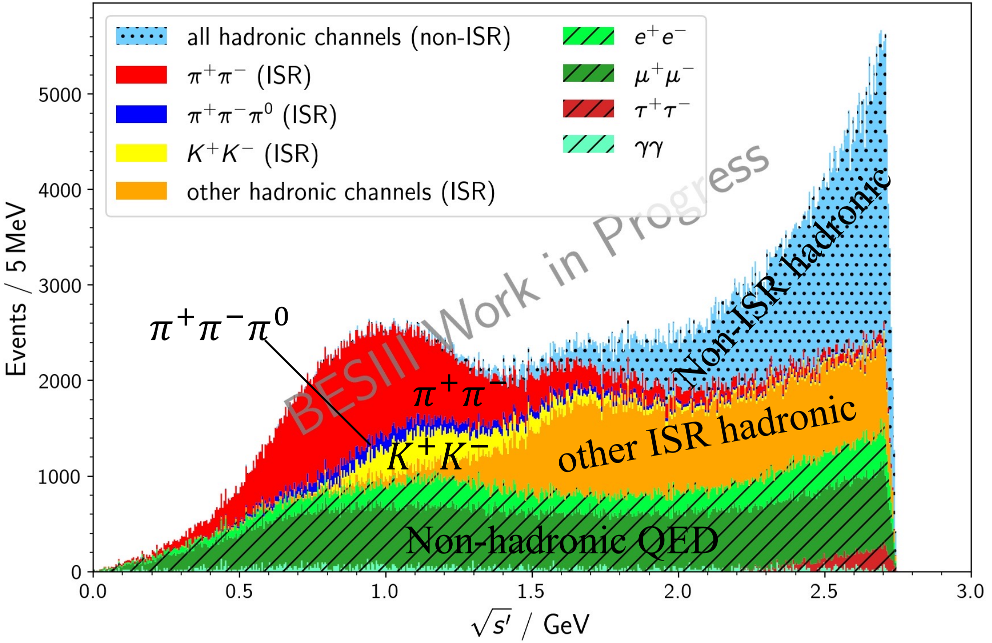
   → Unfolding of mass resolution using modern methods

.... many more,
for instance **radiative corrections**

Disclaimer:
Not allowed to show data!

Hadronic Mass Spectrum

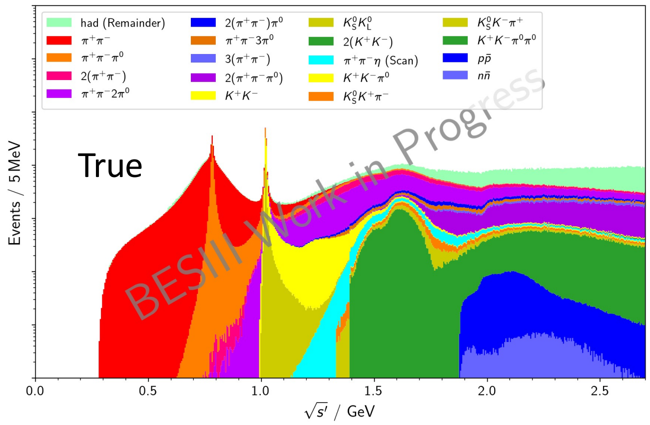
Mass spectrum after application of PID and meson veto



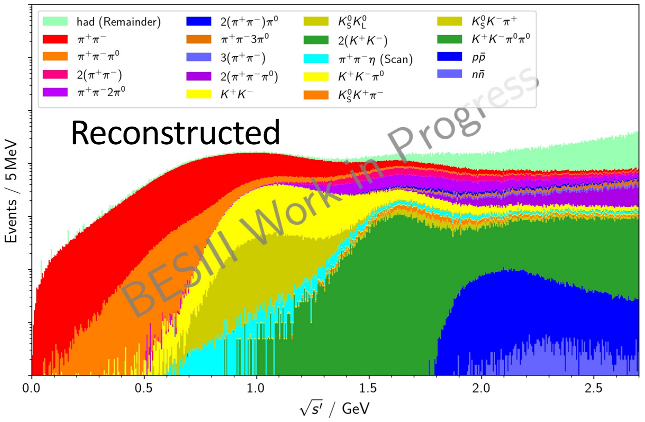
- Plots for $\sqrt{s} = 4.180$ GeV (3.1 / fb)
- No additional cuts using Muon Detector or other selection cuts

- 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)

Unfolding from Detector Mass Resolution



Detector smearing



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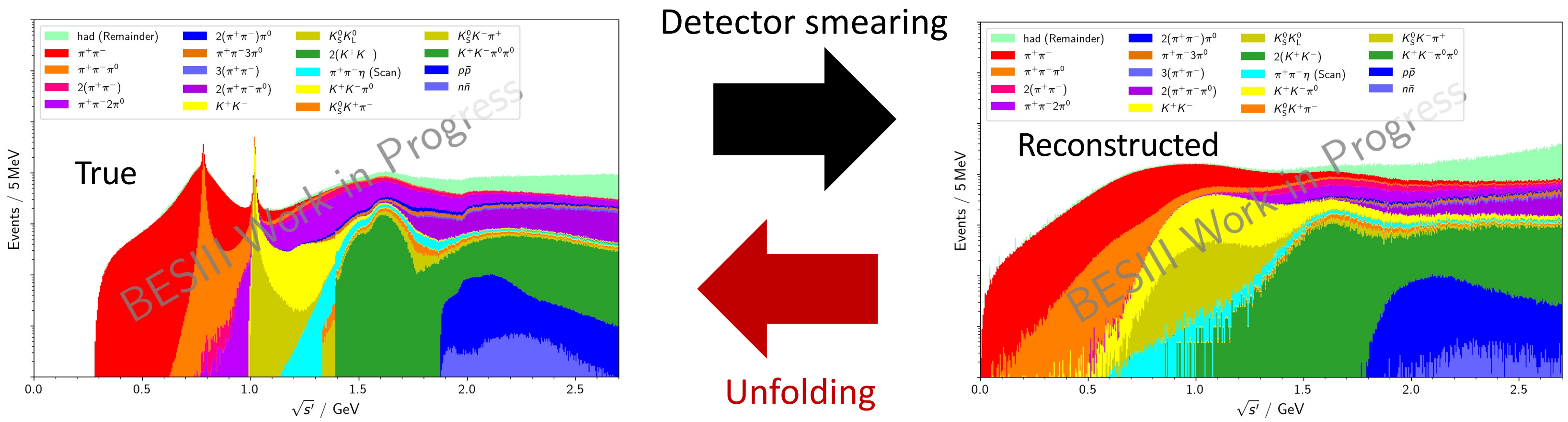


- Application of unfolding algorithms to arrive at true spectrum
- Requires Monte-Carlo program to construct unfolding matrix
- Systematically testing the bias in the unfolding procedure due to wrong input Monte-Carlo
  → observation: effect on dispersion integral for $(g\text{-}2)_\mu$ at the level of 0.3%
- With larger data sets also conversion events might be used to improve mass resolution

Improve Mass Resolution by using Photon Conversion Events

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

  Reduction of statistics

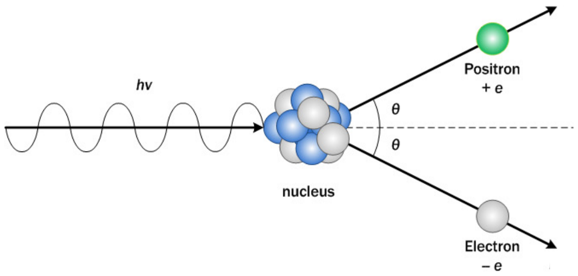
- Tracks of produced e^+e^- pair to be reconstructed in the MDC

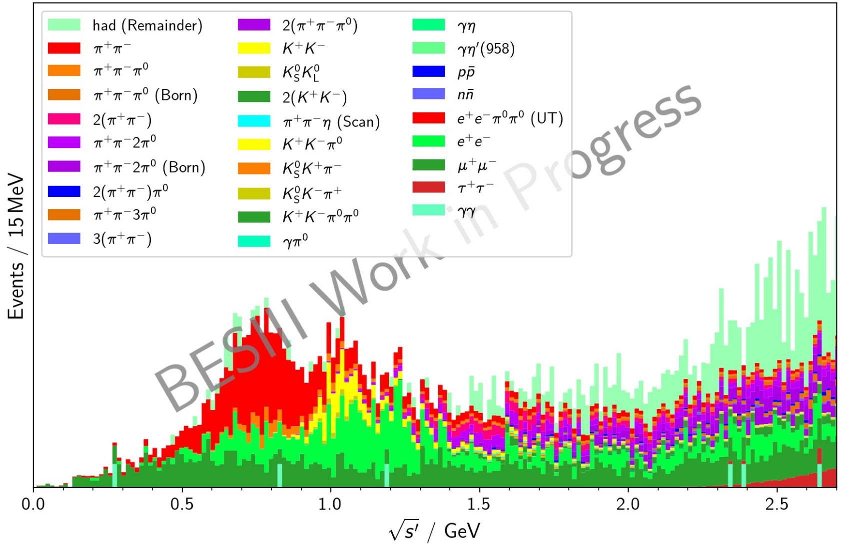
- Improvement of mass resolution by large factors

  → 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





Conclusions

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

  - radiative corrections are a key issue
  - difference between CMD-3 and other energy scan expts. to be understood

- 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

Conclusions

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My personal guess:
It will take some time to clarify issues, but not too long given the global efforts to cross check things

Thank you !