R Measurements

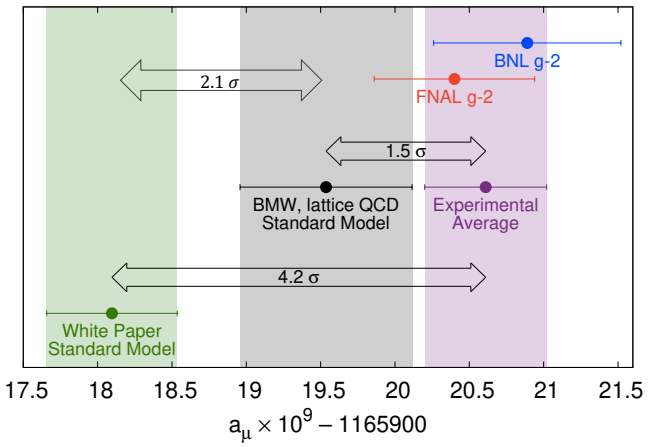
Experimental Inputs to HVP

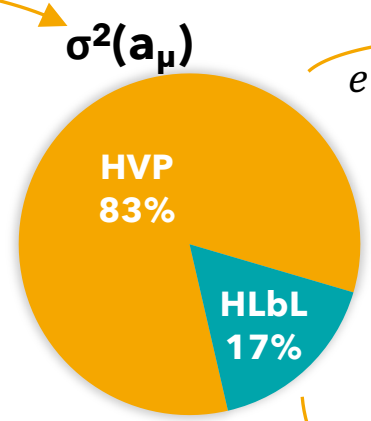
Riccardo Aliberti

Muon4Future Workshop

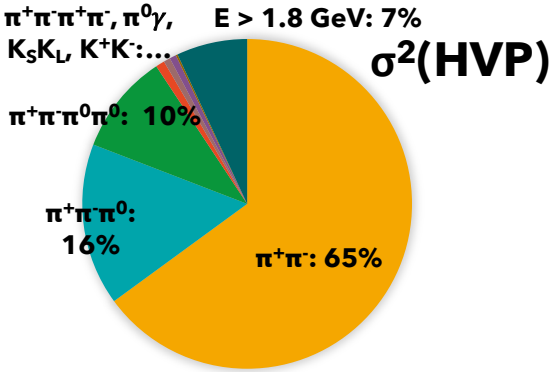
Venezia, 29-31 Mai 2023

Muon (g-2): SM and Experiment





$e^+e^- \to had$



[Data from: Phys.Rep 887 (2020) 1-166]

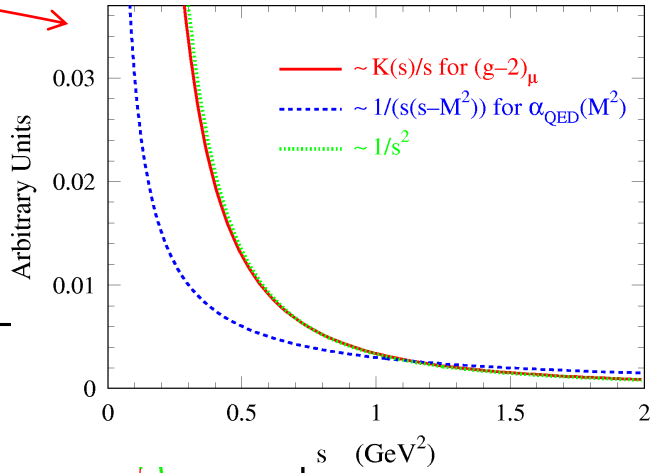
$\gamma^{(*)}\gamma^{(*)} \to hadrons$

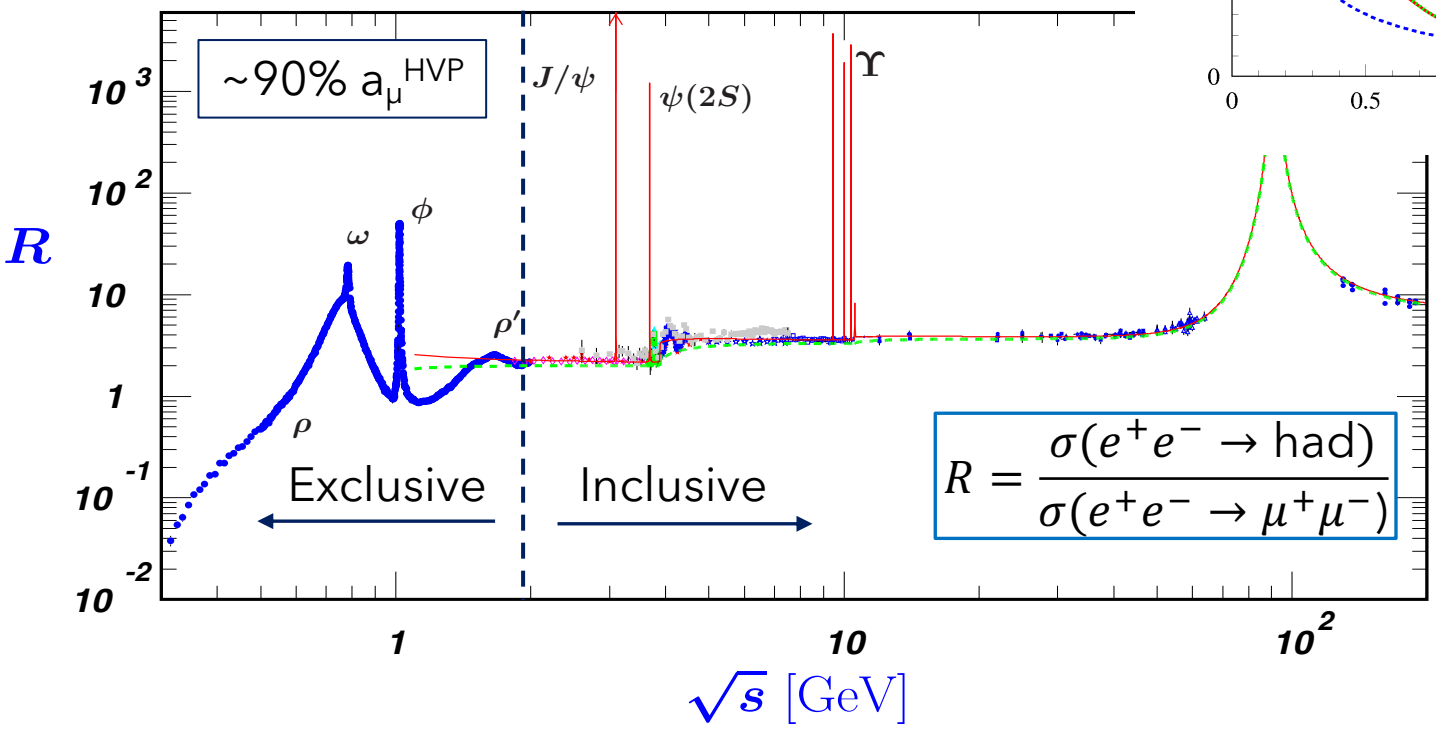
- FNAL confirms tension with (dispersive) SM (4.2σ!)
- Uncertainty dominated by HVP and HLbL
- Tension also between Lattice and Dispersive HVP
- Better understanding strictly needed!

R Measurements and HVP

[Brodsky, de Rafael, 1988]

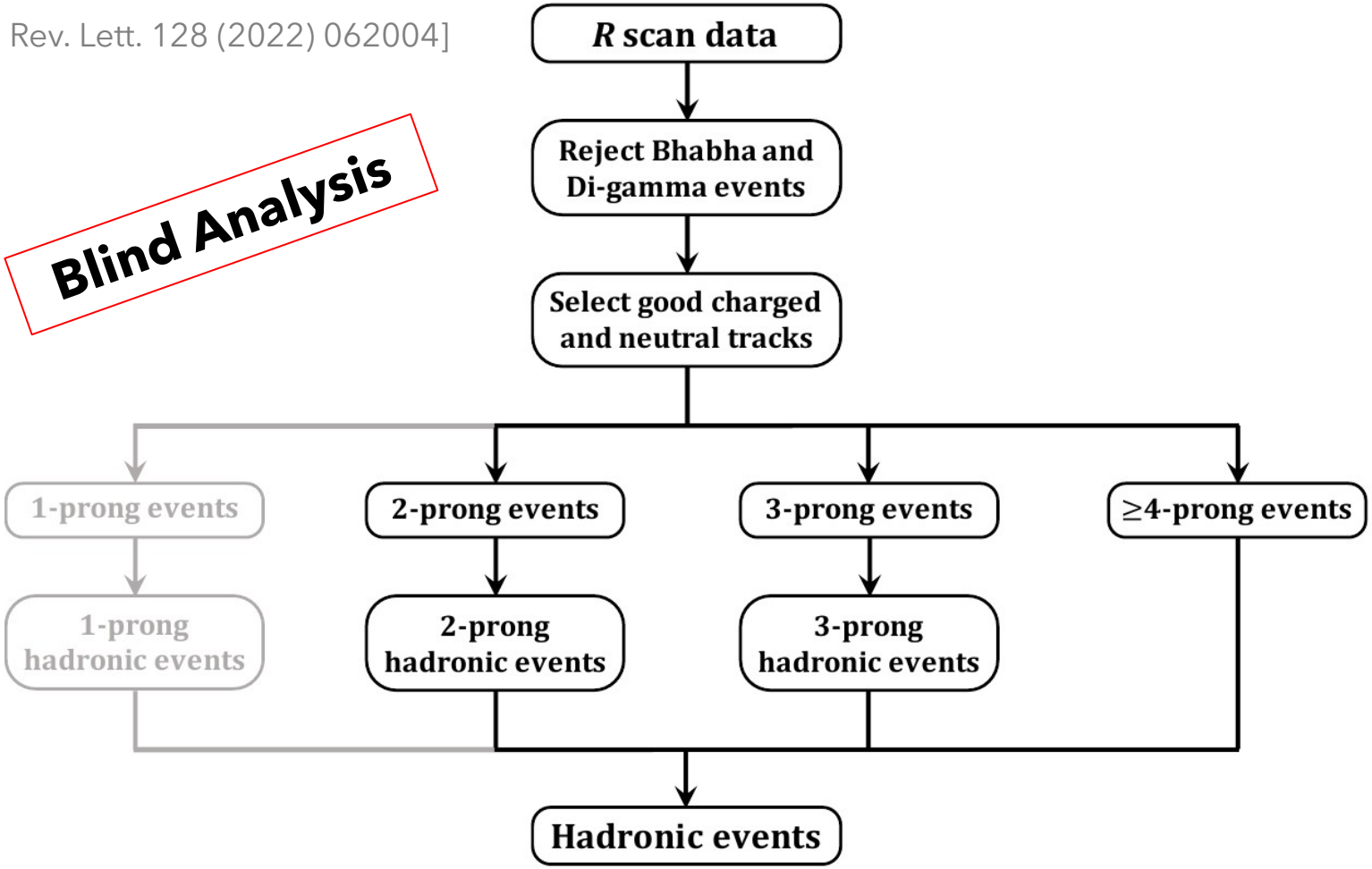
$$a_\mu^{HVP,LO} = \frac{1}{3}\left(\frac{\alpha}{\pi}\right)^2 \int_{m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$





Inclusive R Measurement at BESIII

[Phys. Rev. Lett. 128 (2022) 062004]



Inclusive R Measurement at BESIII

[Phys. Rev. Lett. 128 (2022) 062004]

Dataset
14 energy points
$2.2 \leq \sqrt{s} \leq 3.7$ GeV
$>10^5$ had. events

Background contributions
- Evaluated with MC:
  - Babayaga, Phokhara, KKMC (ee,μμ,gg,tt)
  - BdkRC, Diag36, Galuga, Ekhara (ee -> ee + X)
- Beam related background

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

Normalization
$\sigma_{\mu\mu}(s) = 86.85$ nb/s

Luminosity
Large angle Bhabha

Radiative corrections
- Two schemes tested
  - Feynman diagram
  - Structure functions
- Agreement better 1.4%

Inclusive R Measurement at BESIII

[Phys. Rev. Lett. 128 (2022) 062004]

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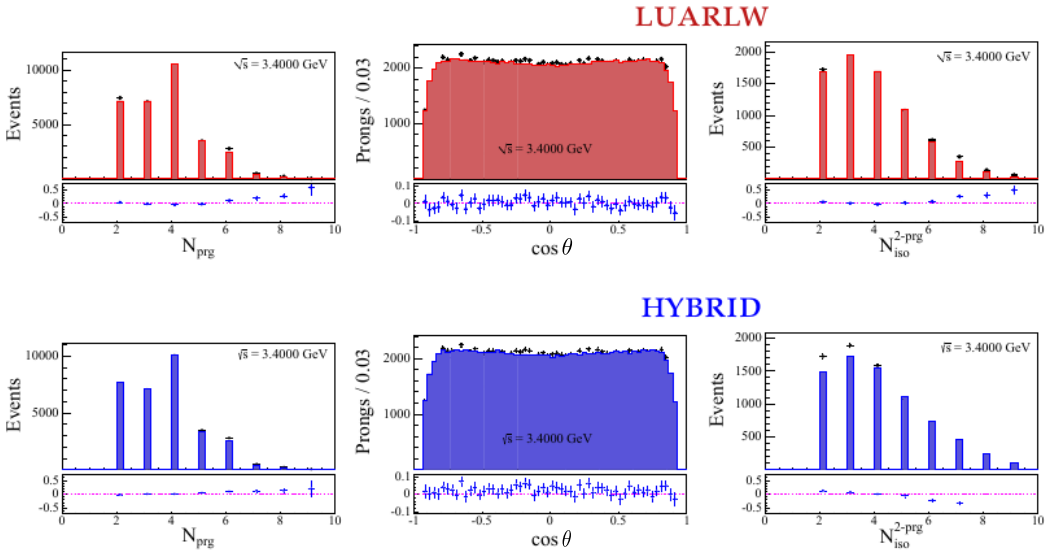

Efficiency

Ratio of generated and reconstructed events

Fully inclusive generator

- Lund Area Law
  - Low energy hadronization
  - Continuum, ISR, $J^{PC}=1^{--}$ resonances
  - Tuned to data

Hybrid generator

- Phokhara (10 excl. processes)
- ConExc (60 excl. proc. measured)
- Lund Area Law (unknown)

Inclusive R Measurement at BESIII

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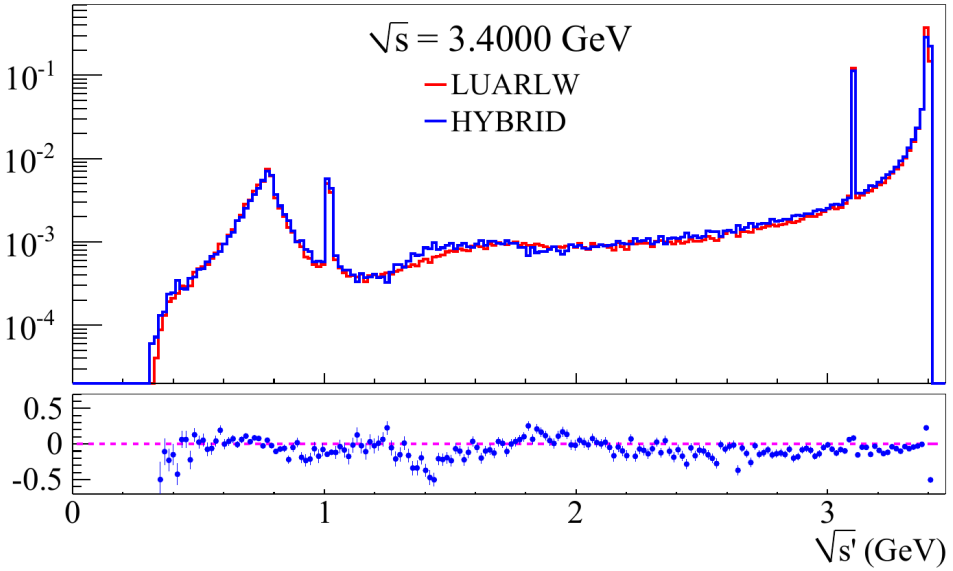

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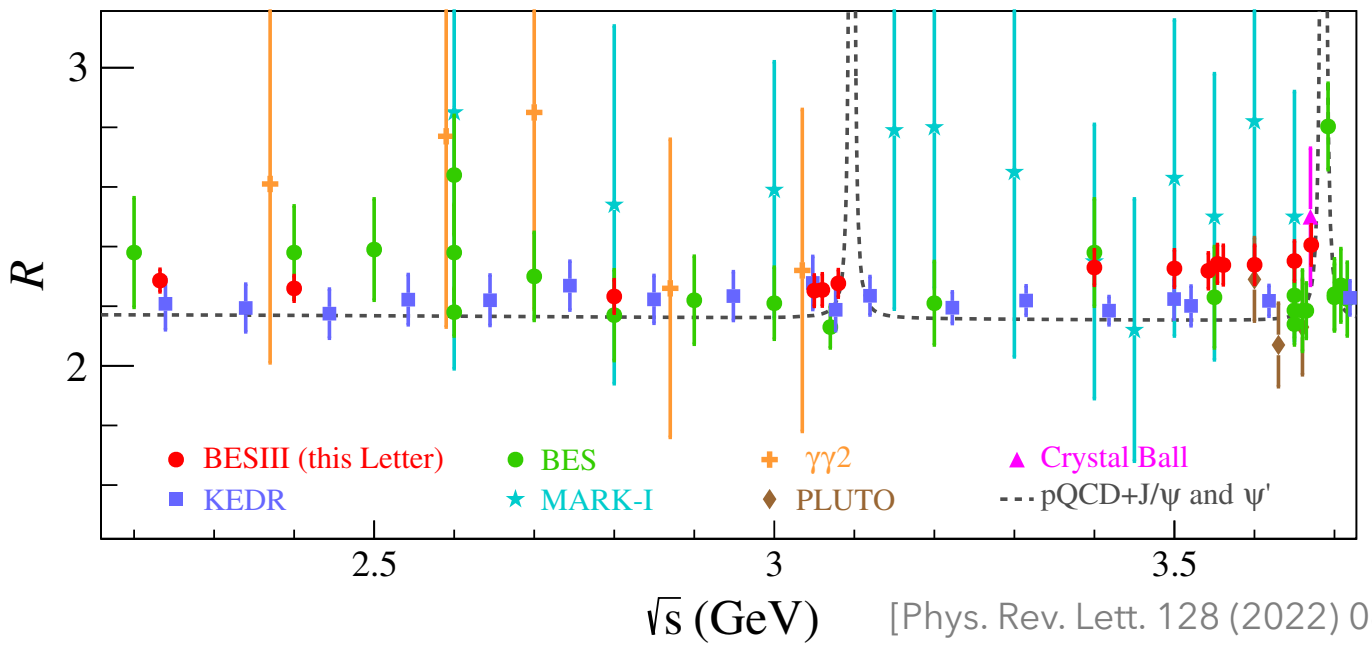
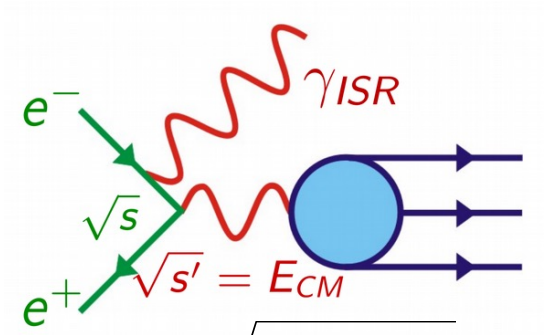


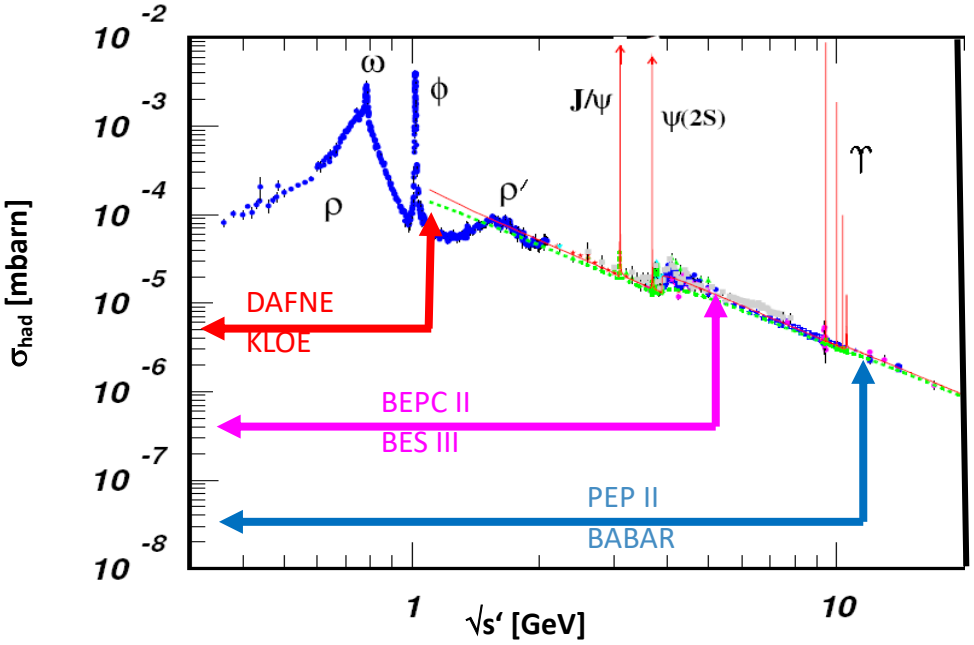
[Phys. Rev. Lett. 128 (2022) 062004]

- **Accuracy better than 2.6%** below 3.1 GeV and better than 3% above
- Exceeding pQCD predictions (2.7σ above 3.4 GeV)
- More to come in near future:
  - Result with **just 14 energy points out of 130**
  - Feasibility studies for **low energy (<2 GeV) measurement via ISR**

Initial State Radiation: Scan at Fixed Energy



$$\sqrt{s'} = \sqrt{s - 2\sqrt{s}E_\gamma}$$



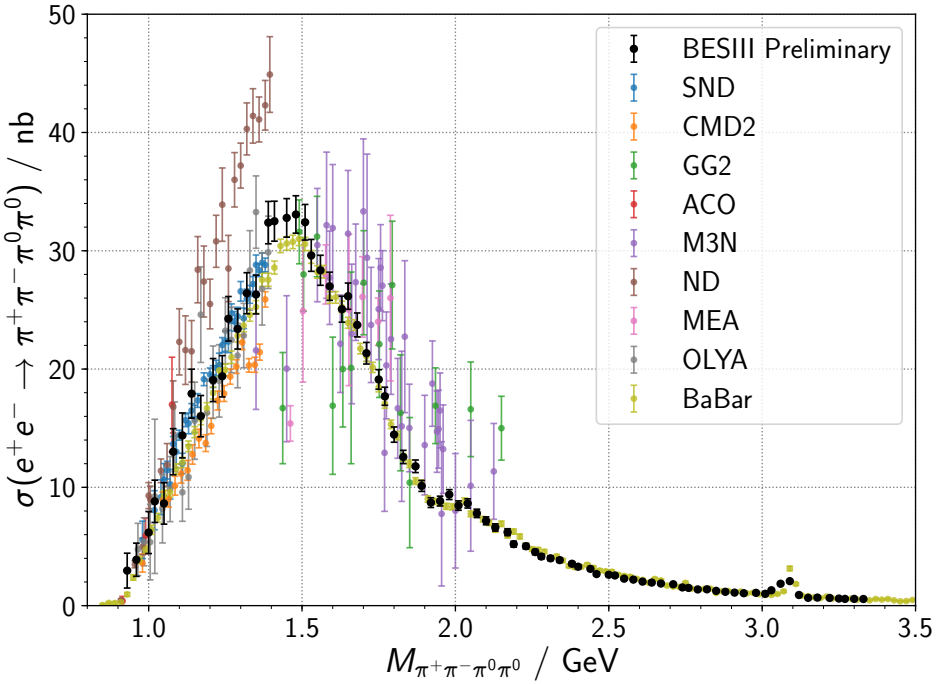
Initial-State Radiation:

- Effectively reduces √s
- Emission suppressed by $\frac{\alpha}{\pi}$

$$\frac{d\sigma_{ISR}(\sqrt{s'})}{d\sqrt{s'}} = \frac{2\sqrt{s'}}{s} W\left(s, E_\gamma, \theta_\gamma\right) \sigma(\sqrt{s'})$$

- Radiator function relates ISR to non-radiative process
- Frequent concern: Final-State Radiation (FSR) accounted?

Initial State Radiation: Scan at Fixed Energy



- ✓ Access to threshold region
- ✓ Normalization fixed over full range
- ✓ Consistent data-taking conditions
- ✗ Limited energy resolution
- ✗ Knowledge of radiator function
- ✗ FSR contributions

HVP evaluation <2 GeV mostly determined by ISR:

- $\pi^+\pi^-$ (80%): KLOE (0.6%) & BaBar (0.7%) | CMD2&3(0.8%) & SND (1%)
- $\pi^+\pi^-\pi^0$ (7%): BaBar (1.3%) | SND (4%)
- K^+K^- (3%): BaBar (1.2%) | CMD3 (2%), SND (7%)

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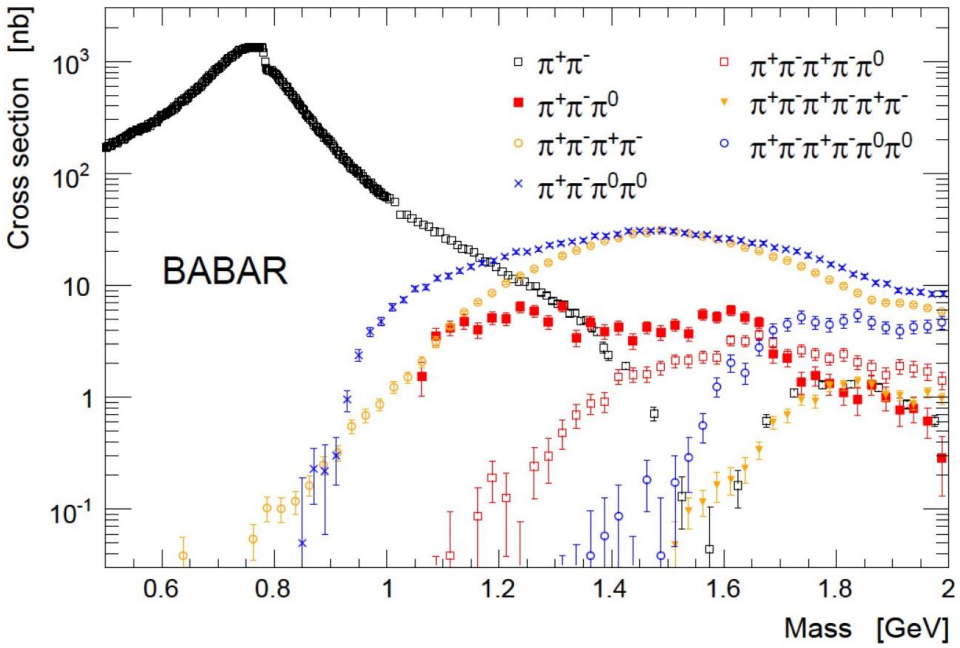

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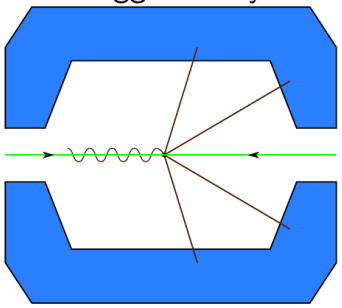
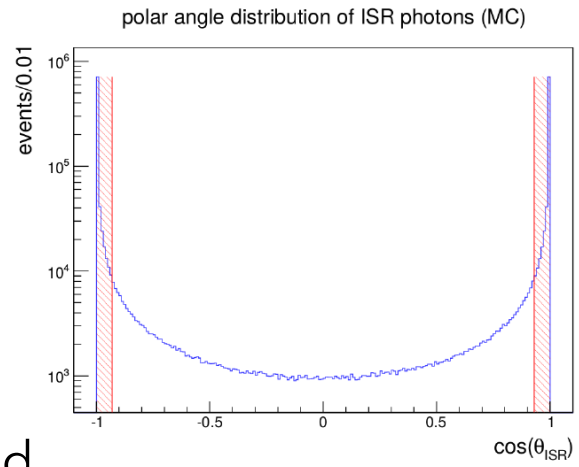
Initial State Radiation: Analysis Strategy

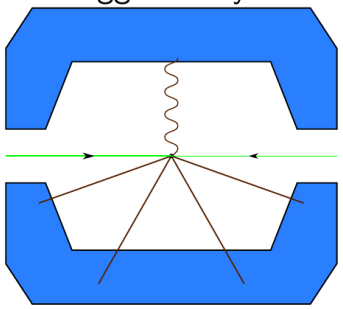
Detect full hadronic system

Untagged analysis





Tagged analysis



ISR photon undetected

- High statistics, small background
- No FSR
- Only higher masses accessible

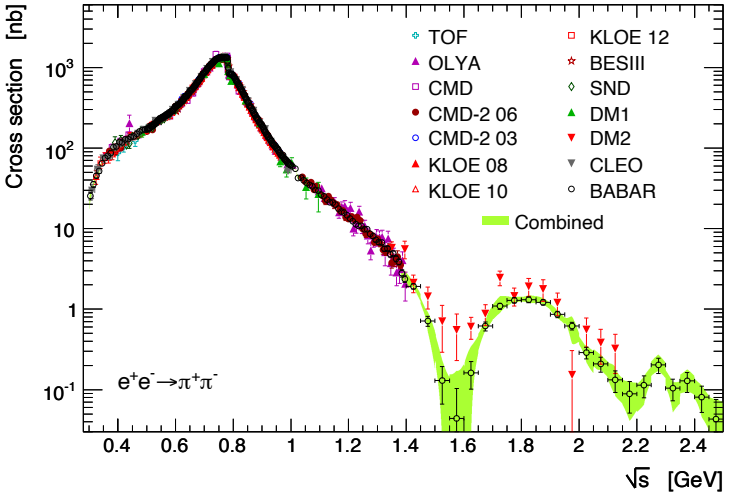
ISR photon detected

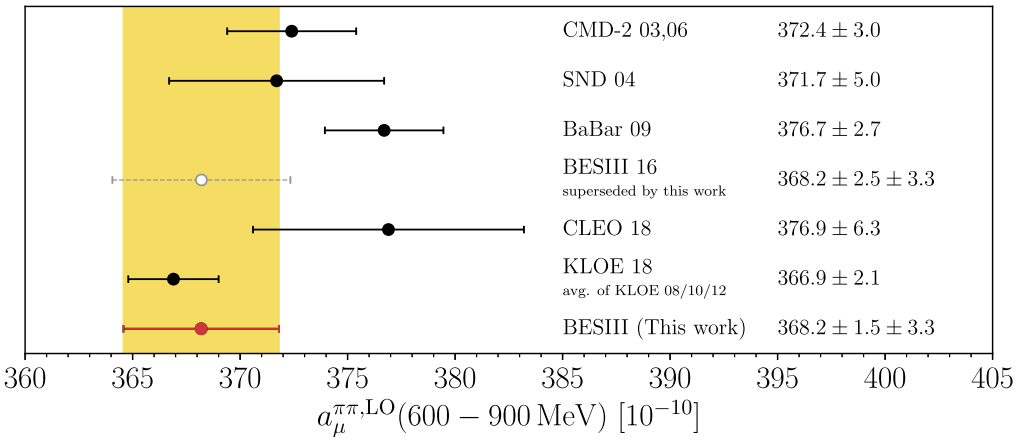
- Access to had. threshold region
- Background at high masses

Untagged analysis energy thresholds

KLOE ~350 MeV | BESIII ~800 MeV | BaBar ~3 GeV

$e^+e^- \to \pi^+\pi^-$: The Golden Channel





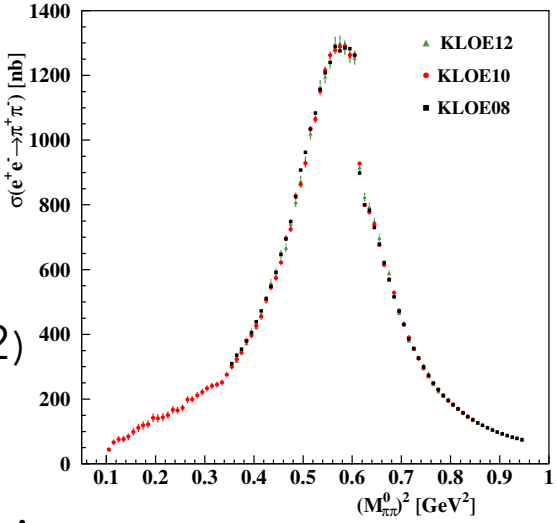
- Largest contributor to both HVP and σ_{HVP}
- KLOE, BaBar, and BESIII ISR measurement ($\delta a_\mu/a_\mu \leq 1\%$)
- Long standing KLOE-BaBar discrepancy
- ISR technique, but different analysis strategy

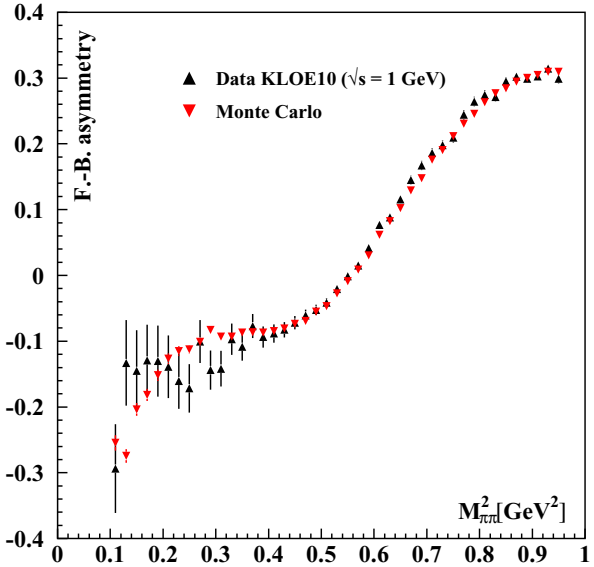
$e^+e^- \to \pi^+\pi^-$: KLOE

Several measurements, result as combination:

- Untagged analysis of 140 pb^{-1} @ m_Φ (KLOE05)
  [KLOE Collaboration Phys.Lett.B 606 (2005)]
- Untagged analysis of 240 pb^{-1} @ m_Φ (KLOE08)
  [KLOE Collaboration Phys.Lett.B 670 (2009)]
- Tagged analysis of 250 pb^{-1} @ 1 GeV (KLOE10)
  [KLOE Collaboration Phys.Lett.B 700 (2011)]
- KLOE08 with normalization to $e^+e^- \to \mu^+\mu^-$ (KLOE12)
  [KLOE Collaboration Phys.Lett.B 720 (2013)]

KLOE





Systematic uncertainties:

- Experimental: 0.6%
  (Background, Tracking, Luminosity)
- Theory: 0.5% ⊕ 0.2%
  (Radiator function, **FSR**)

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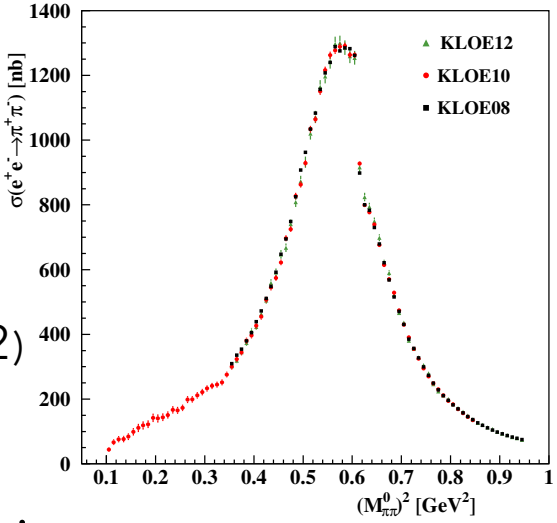
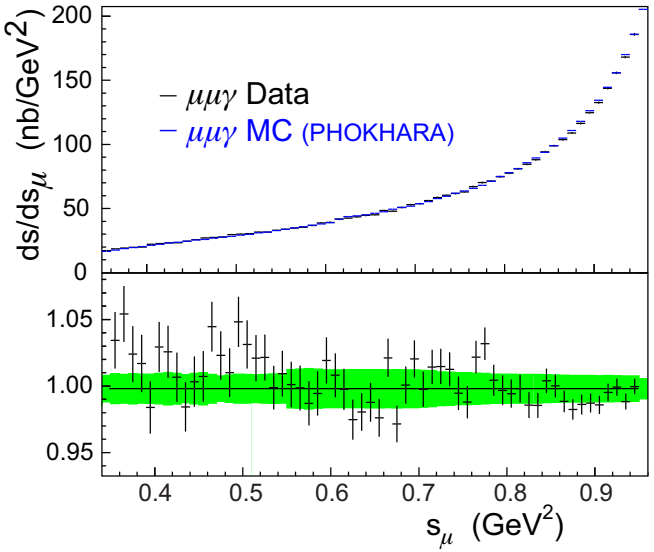




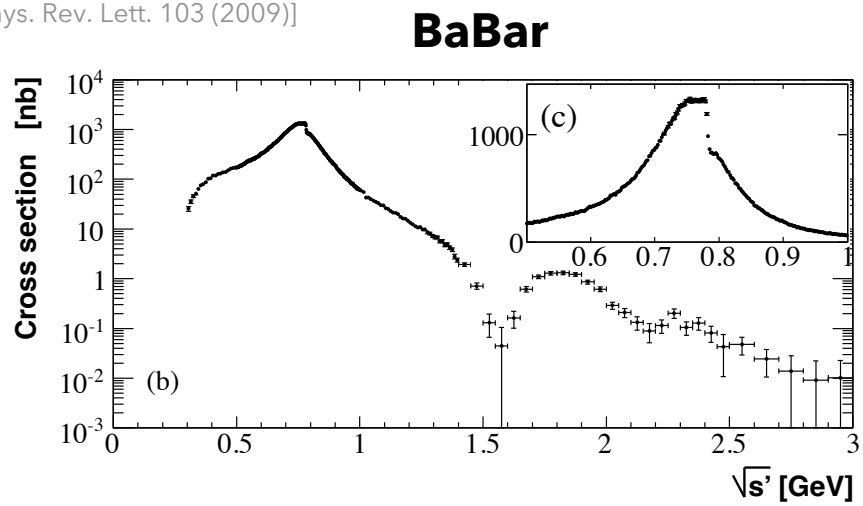
Systematic uncertainties:

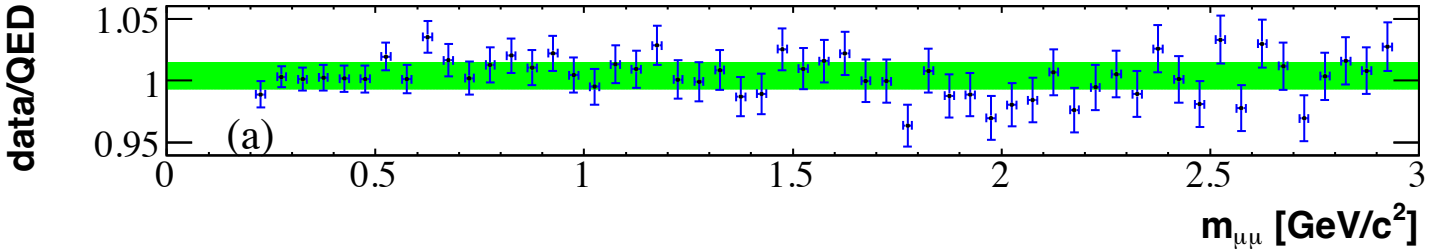
- Experimental: 0.7%
  (Background)
- Theory: ~~0.5%~~ $\oplus$ 0.2%
  (~~**Radiator function**~~, FSR)

$e^+e^- \to \pi^+\pi^-$: BaBar

Single measurement: [BaBar Collaboration Phys. Rev. Lett. 103 (2009)]

- Tagged strategy
- 232 fb^{-1} @ $\Upsilon(4S)$
- **Normalization to $e^+e^- \to \mu^+\mu^-$**
- PID for π/μ separation
- Kinematic Fit ($\pi^+\pi^-\gamma(\gamma)$)
- Direct estimate of FSR contribution





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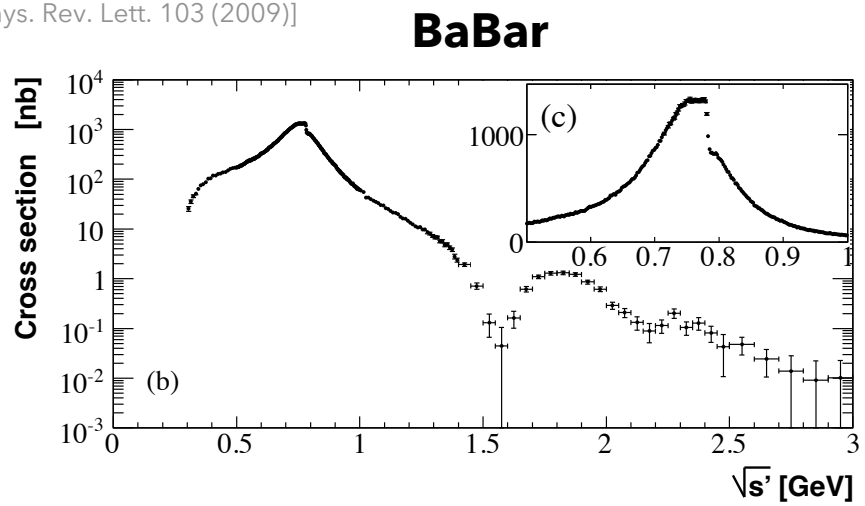
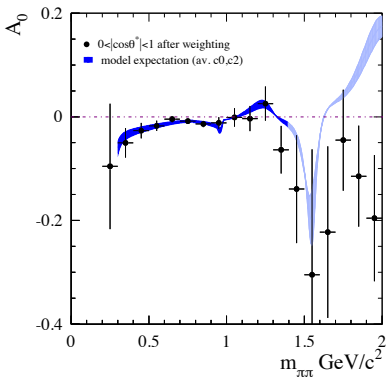
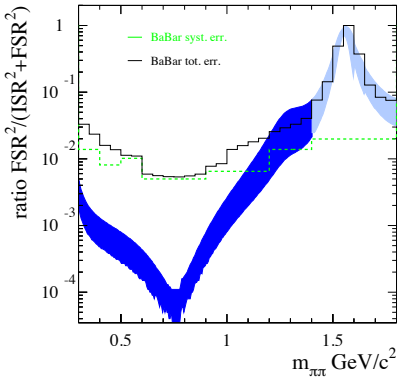
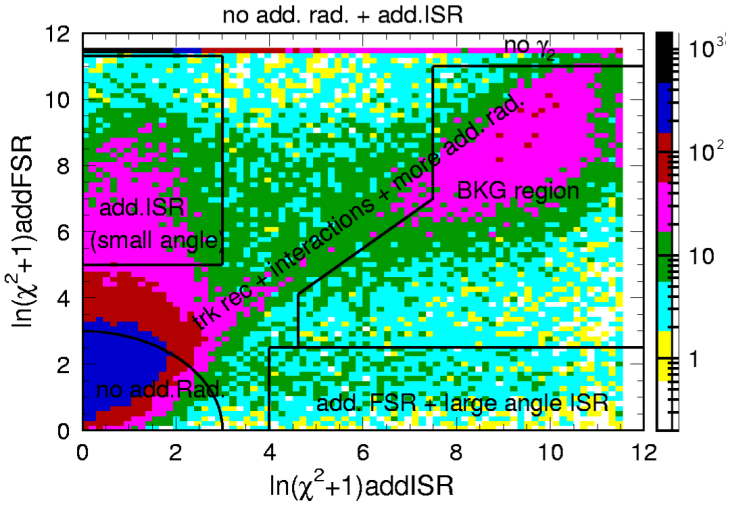


[BaBar Collaboration Phys. Rev. D 92 (2015)]

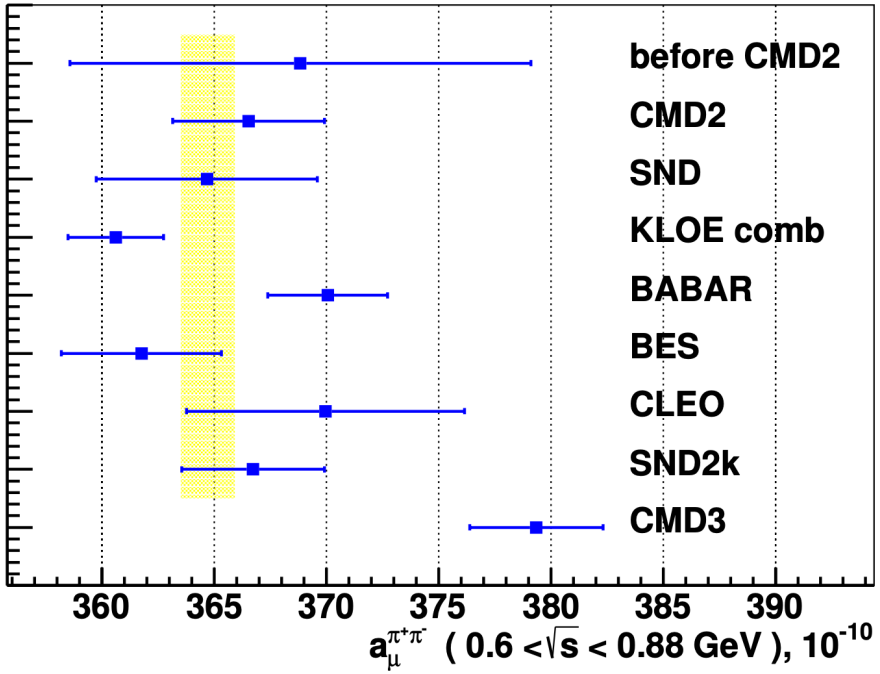






The CMD-3 "Earthquake"

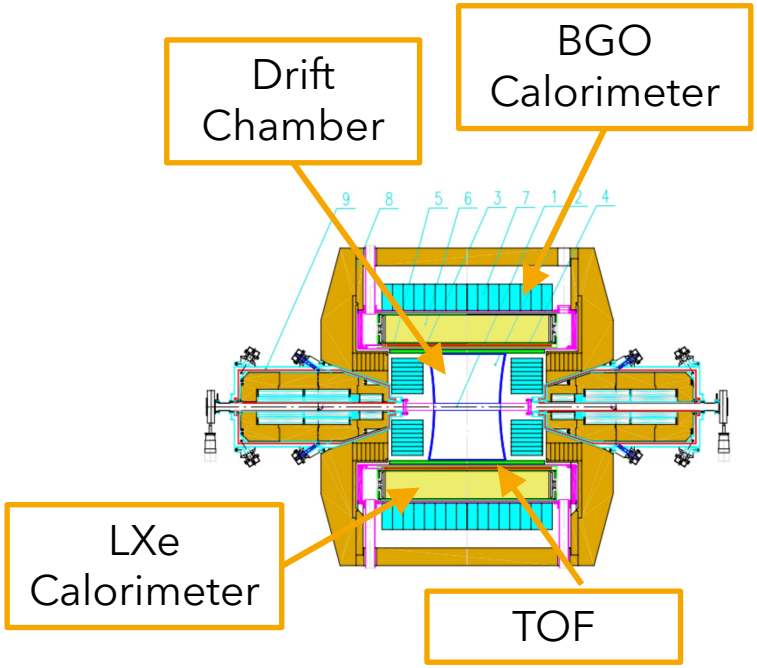
- New result on arXiv in February (arXiv:2302.08834)
- Energy scan measurement
- 0.8% precision
- Puzzling picture
  - BaBar: ~2.3σ
  - KLOE: ~5σ
  - CMD2/SND2k: ~2.9σ



- **Significant tension with most of the previous measurement**

CMD-3 Analysis Strategy

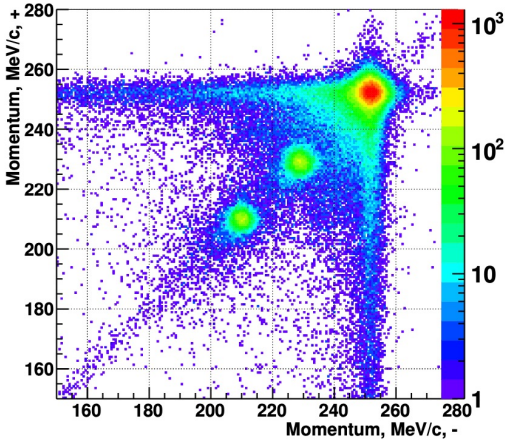
- VEPP-2000 collider
- CM energies up to 2 GeV
- Three data sets used:
  - RHO2013, 18 pb^{-1} (<1 GeV)
  - RHO2018, 45 pb^{-1} (<1 GeV)
  - LOW2020, 1 pb^{-1} (<0.6 GeV)
- Different data taking conditions:
  - Lower magnetic field (2013)
  - Upgraded detector and accelerator (2018)
  - Cross checks on the results



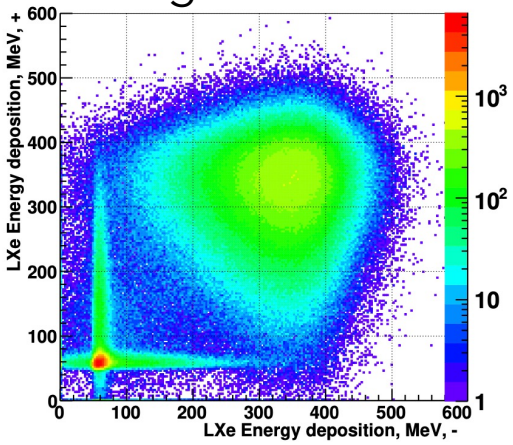
CMD-3 Analysis Strategy

- Simple selection conditions
  - Back-to-back topology
  - Timing
- Independent signal extraction by fit to:

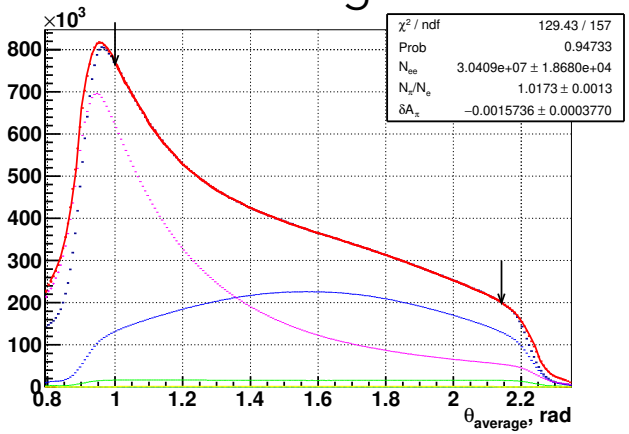
Track Momenta



Energies in LXe

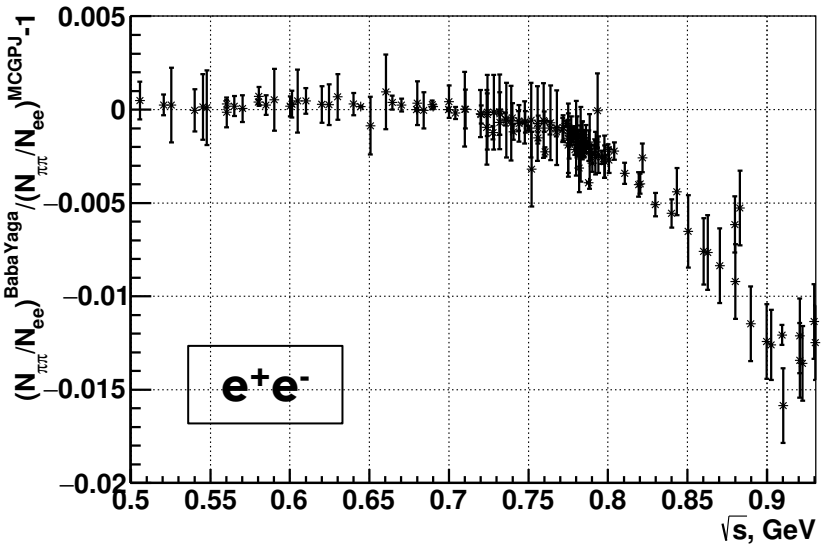


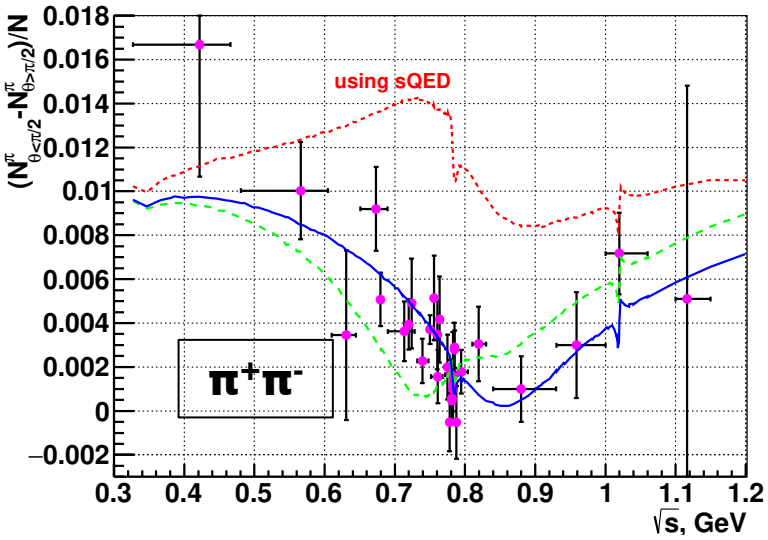
Track Angles



- Normalization to Bhabha scattering events (e^+e^-)

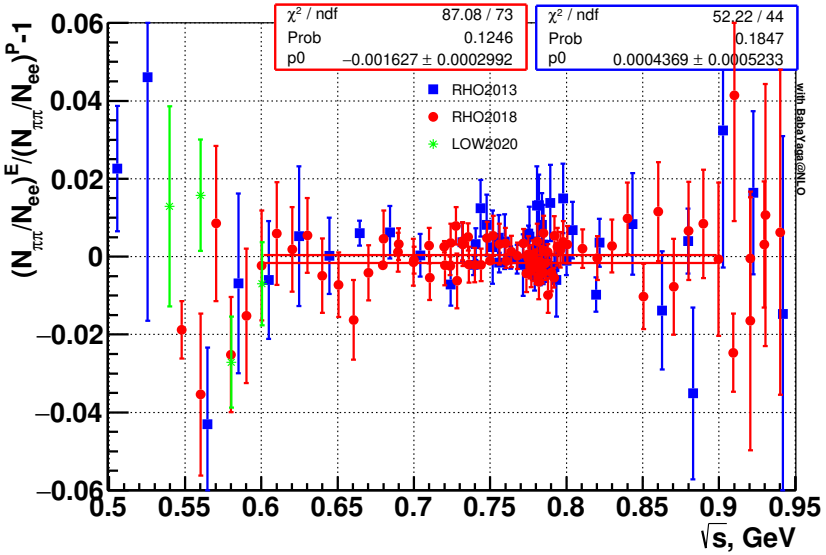
CMD-3: Checks and Results

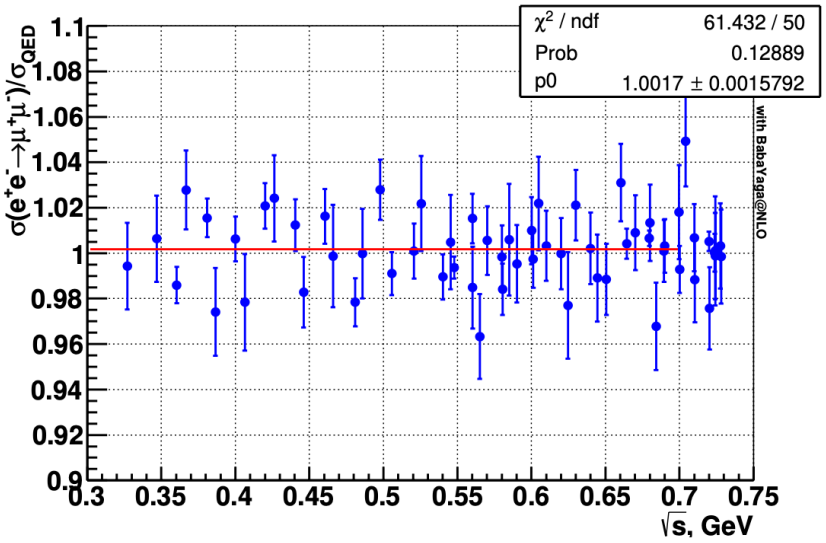




- Several checks on data-generator(s) consistency
  - Babayaga@NLO instead of MCGPJ for e+e-
  - Improved description of ISR-FSR interference in 2π (asymmetry)

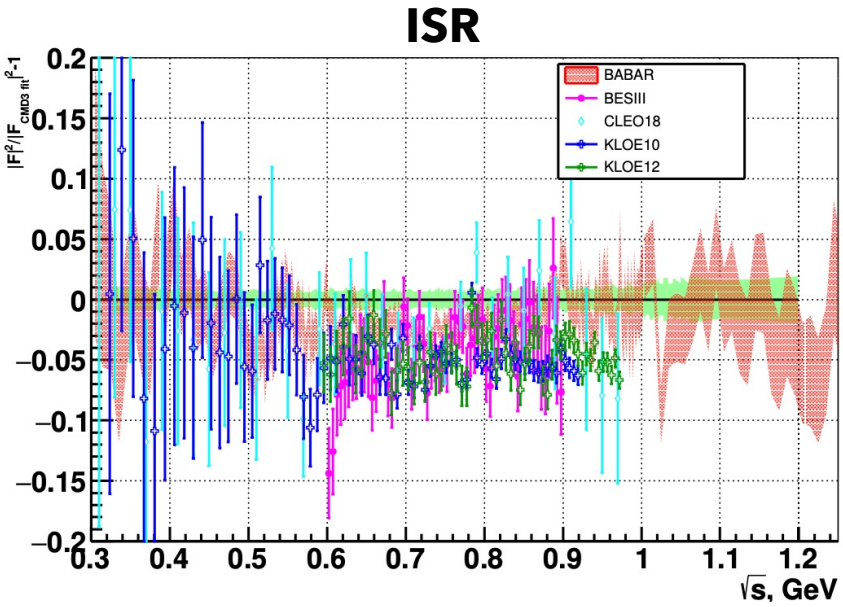
CMD-3: Checks and Results

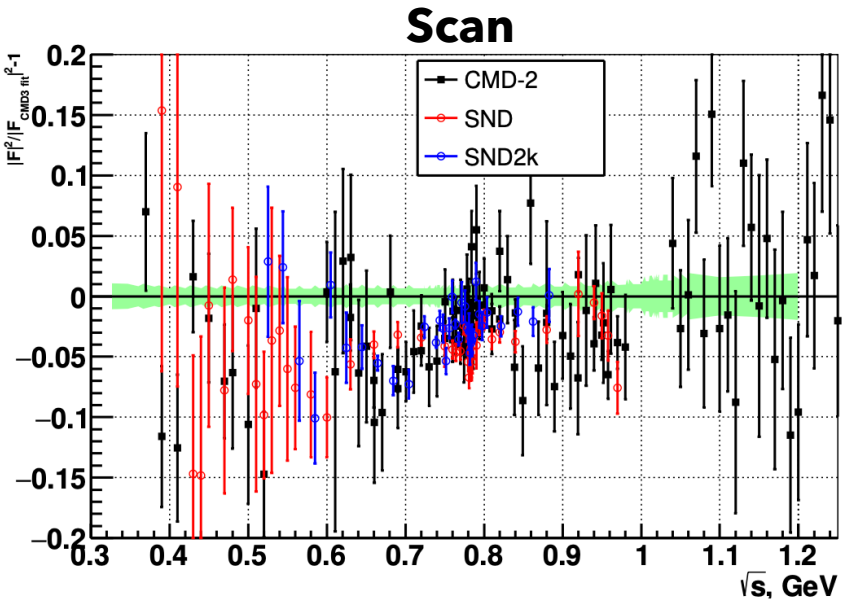




- Comparison between data sets and methods:
  - Agreement at 0.1% level
- Di-muon cross section vs. QED prediction:
  - Consistent within 0.1%

CMD-3: Checks and Results

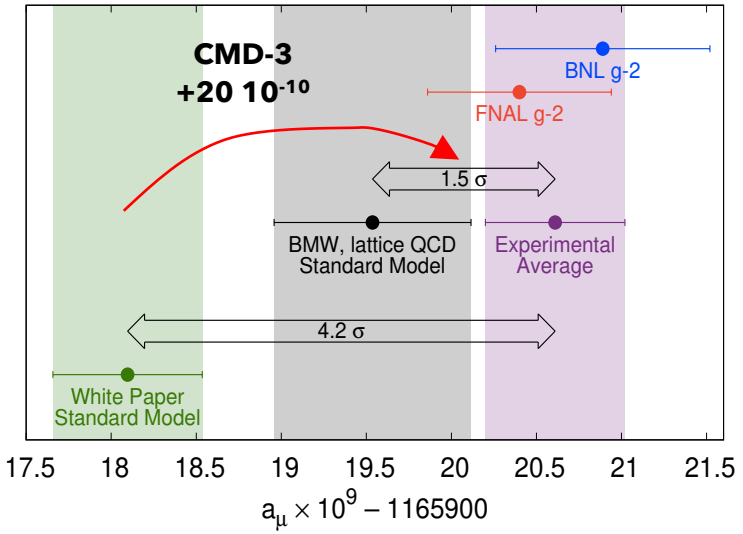


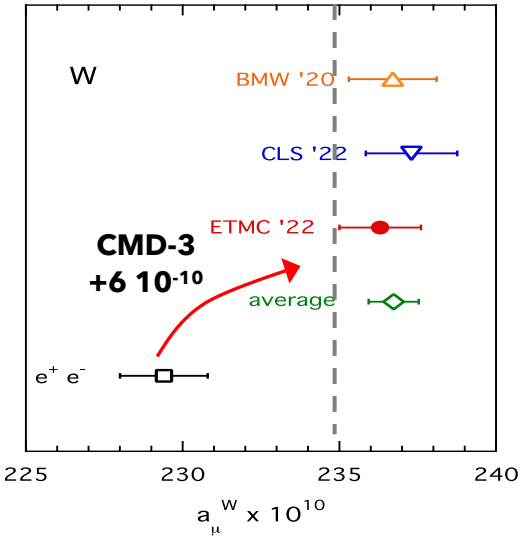


- Common (and flat) disagreement around ρ(770)
- Consistency at larger and smaller energies

Source of SND/CMD 2 vs 3 disagreement still unclear

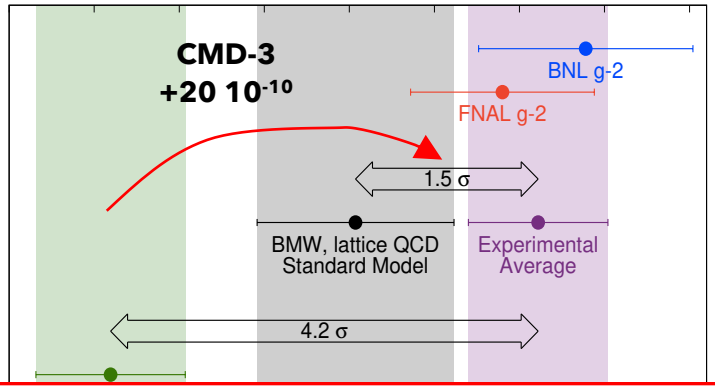
CMD-3: The End of the Story?

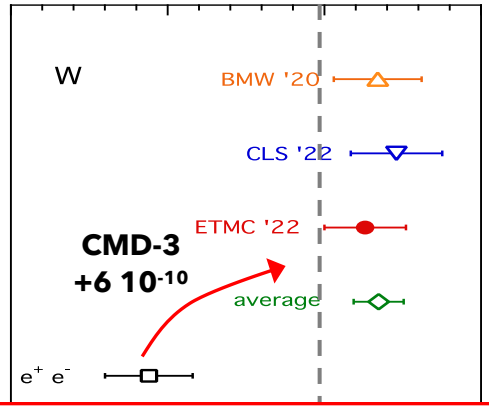




- CMD-3 result can fix BMWc/Exp – WP tension on a_μ
- Agreement also in the window quantity
- **But:**
  - What's the source of the CMD-2 vs CMD-3 difference?
  - Why were previous measurements in agreement?

CMD-3: The End of the Story?





Confirmation of CMD-3 result is needed!

New measurements on-going

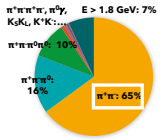
- Agreement also in the window quantity
- **But:**
  - What's the source of the CMD-2 vs CMD-3 difference?
  - Why were previous measurements in agreement?

Summary

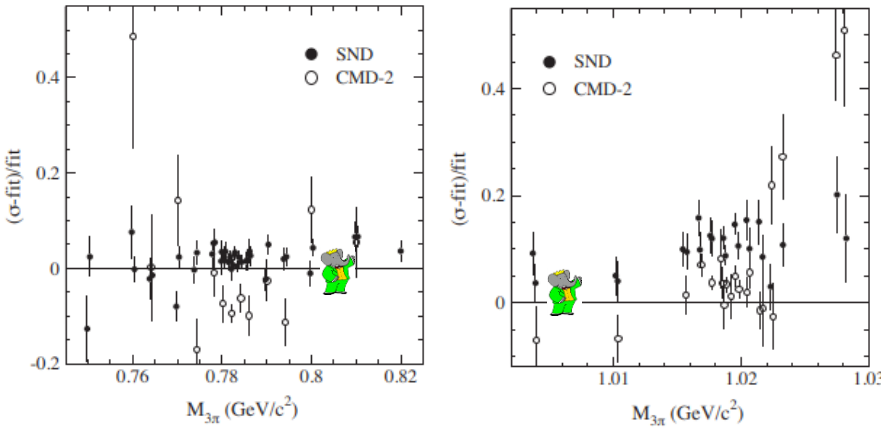
- R measurements crucial input to HVP
- Intriguing tensions in $(g-2)_\mu$:
  - Experiment – SM dispersive (e^+e^- data): 4.2σ
  - Lattice QCD – SM dispersive: 2.1σ
- Puzzling situation in 2π channel:
  - Long-standing KLOE-BaBar tension
  - New CMD 3 result
- New results on 2π channel to come "soon" from
  - Reanalysis of "old" data BaBar (2023), BESIII , KLOE
  - New data BESIII (20 fb^{-1}@ 3.77 GeV by 2024), Belle II

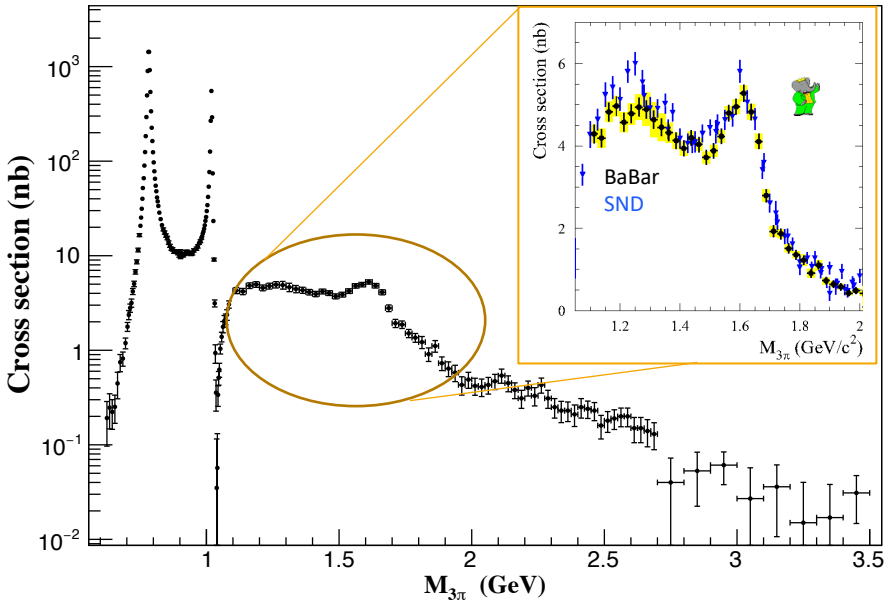
Backup

$e^+e^- \to \pi^+\pi^-\pi^0$: New BaBar Result!



[BaBar Collaboration *Phys.Rev.D* 104 (2021)





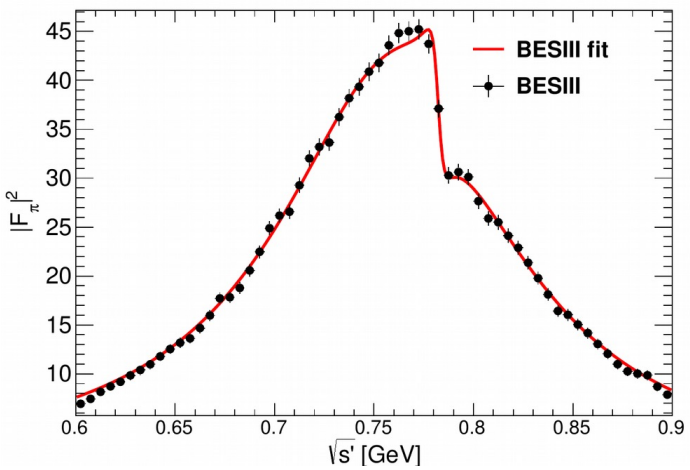
- Full dataset (5x wrt. 2004)
- Fit to VMD model → $B(\rho \to 3\pi) = (0.88 \pm 0.38) \times 10^{-4}$
- Up to 10% disagreement with SND/CMD2 results
- Strong reduction of uncertainty to a_μ

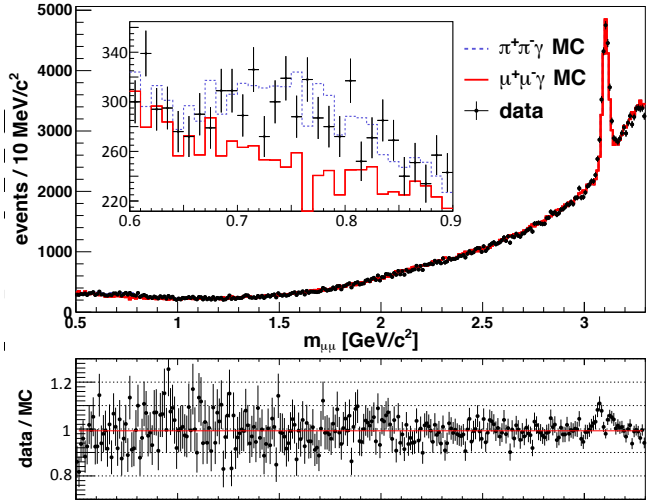
$$a_\mu^{3\pi}\,(E < 2\,\mathrm{GeV}) = (45.86 \pm 0.14 \pm 0.58)$$

$e^+e^- \to \pi^+\pi^-$: BESIII

Single measurement: [BESIII Collaboration Phys. Lett. B 753 (2016)]

- Tagged strategy
- 2.9 fb^{-1} @ ψ(3770)
- **Neural network for π/μ separation**
- Kinematic Fit ($\pi^+\pi^-\gamma$)

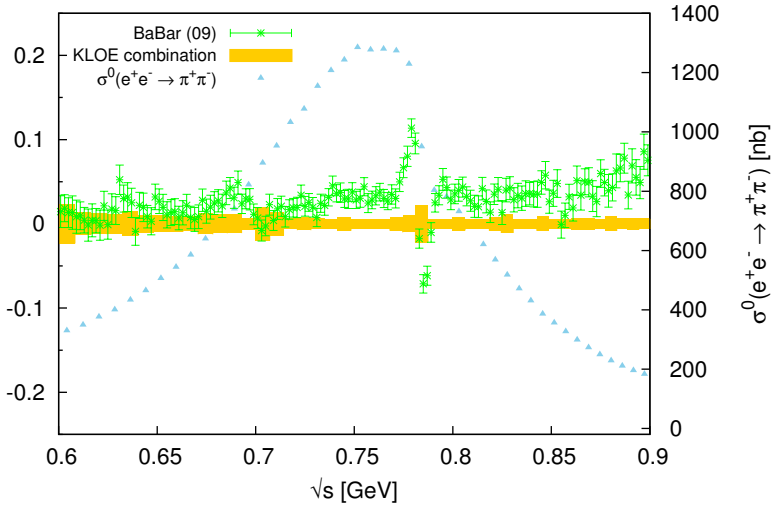


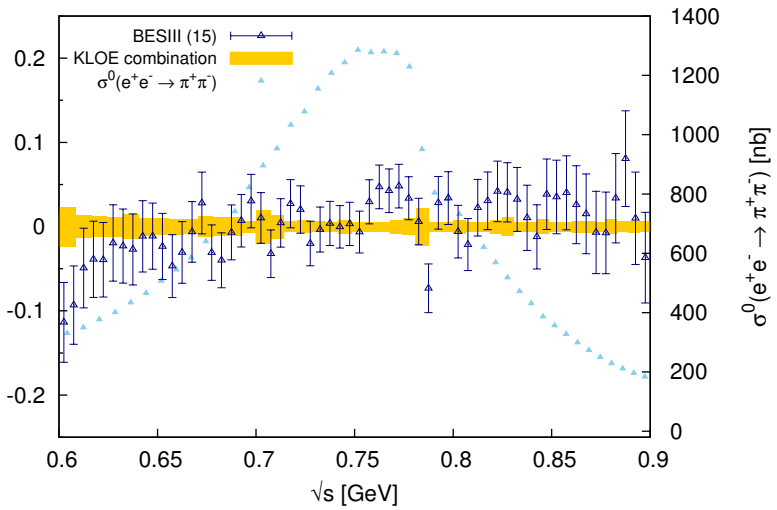


- Cross check QED prediction ($\mu^+\mu^-$)
  - ➢ Measurement of Γ_{ee} for J/ψ
- Measurement **statistically limited**
- Systematics dominated by radiator function (+ luminosity)

$e^+e^- \to \pi^+\pi^-$ in a Nutshell

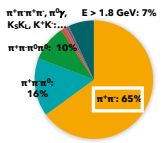
[Phys.Rep 887 (2020) 1-166]



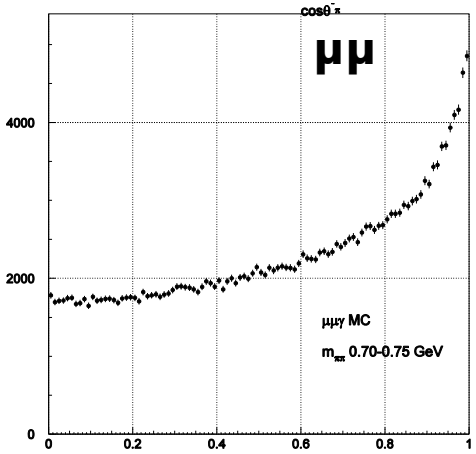


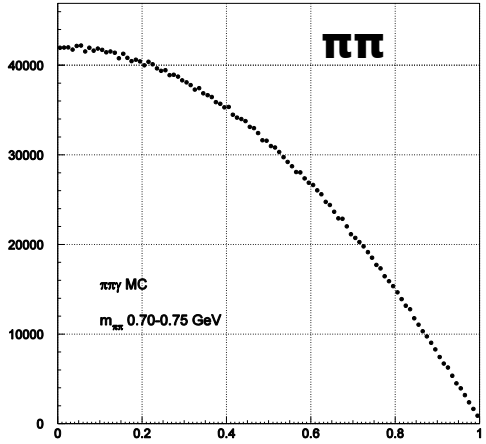
	KLOE	BaBar	BESIII
Final result	Combination	Single measurement	
Analysis type	Tag+Untag	Tagged	
π/μ separation	Track mass (kin)	PID	
Kinematic fit	No	$\pi^+\pi^-\gamma(\gamma)$	$\pi^+\pi^-\gamma$
Accuracy	0.6%	0.7%	1%

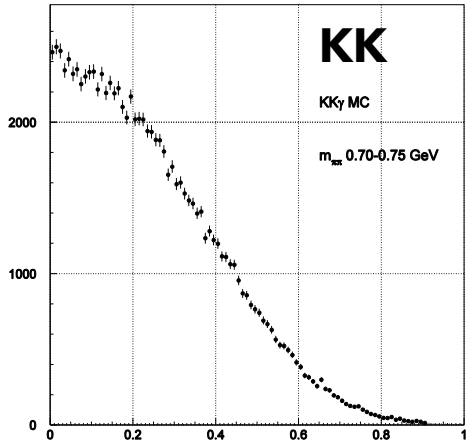
$e^+e^- \to \pi^+\pi^-$: Perspectives



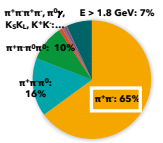
- Reanalysis of **full dataset** (2x)
- New approach to μμ/ππ/KK separation:
  - Minimal PID conditions (negligible systematics)
  - Fit angular distribution (ϑ^*) in ππ rest frame
- Larger angular and momentum acceptance (8x)
- **Results expected in 2023**

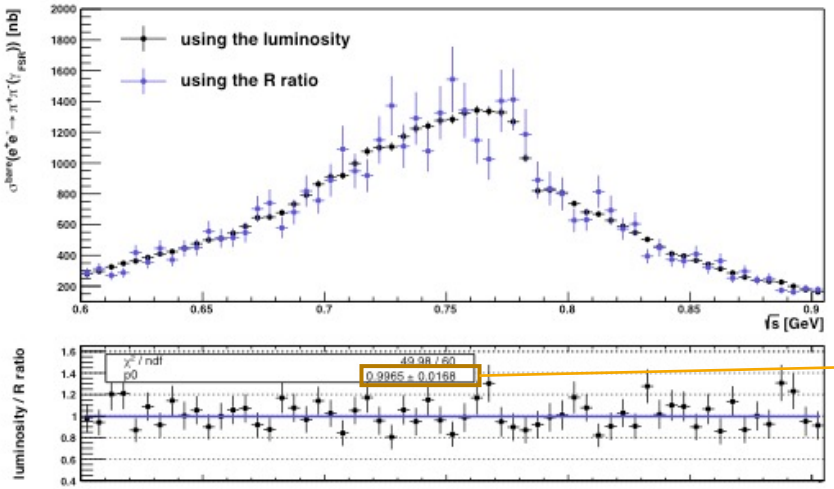






$e^+e^- \to \pi^+\pi^-$: Perspectives



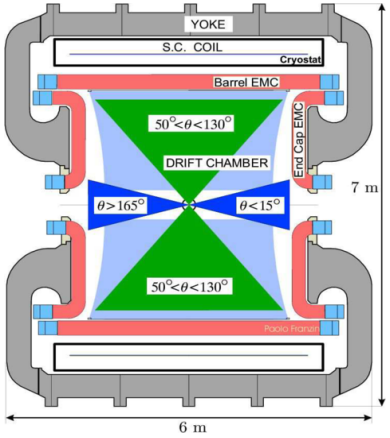


Agreement at 0.3% level
Statistics limited!

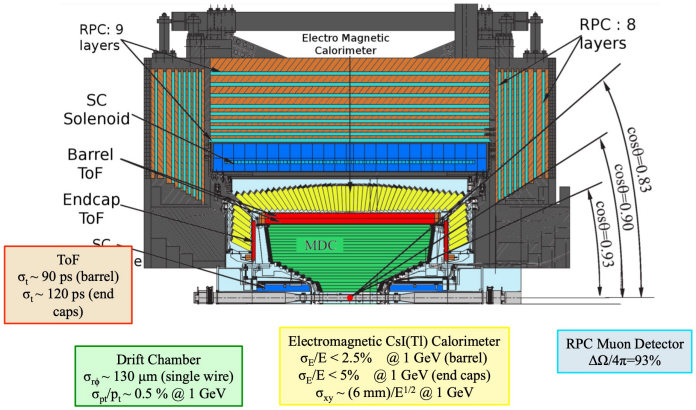
- **Plan to achieve 0.5% accuracy**
- New analysis on going:
  - Several strategies under test
  - Detailed study of 2γ events (ISR@NLO & ISR+FSR)
  - First results in 1-1.5 years
- Data taking @ ψ(3770): 2.9 → 20 fb^{-1} (2024)

Experiments Comparison

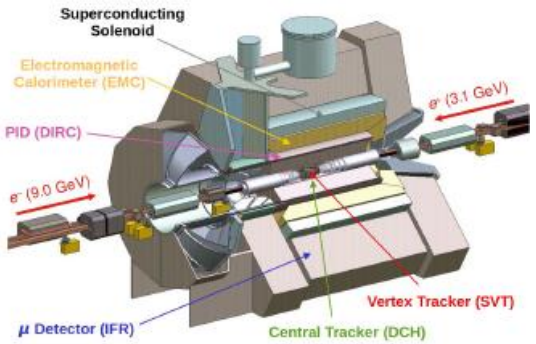
KLOE @ DAFNE



BESIII @ BEPC II

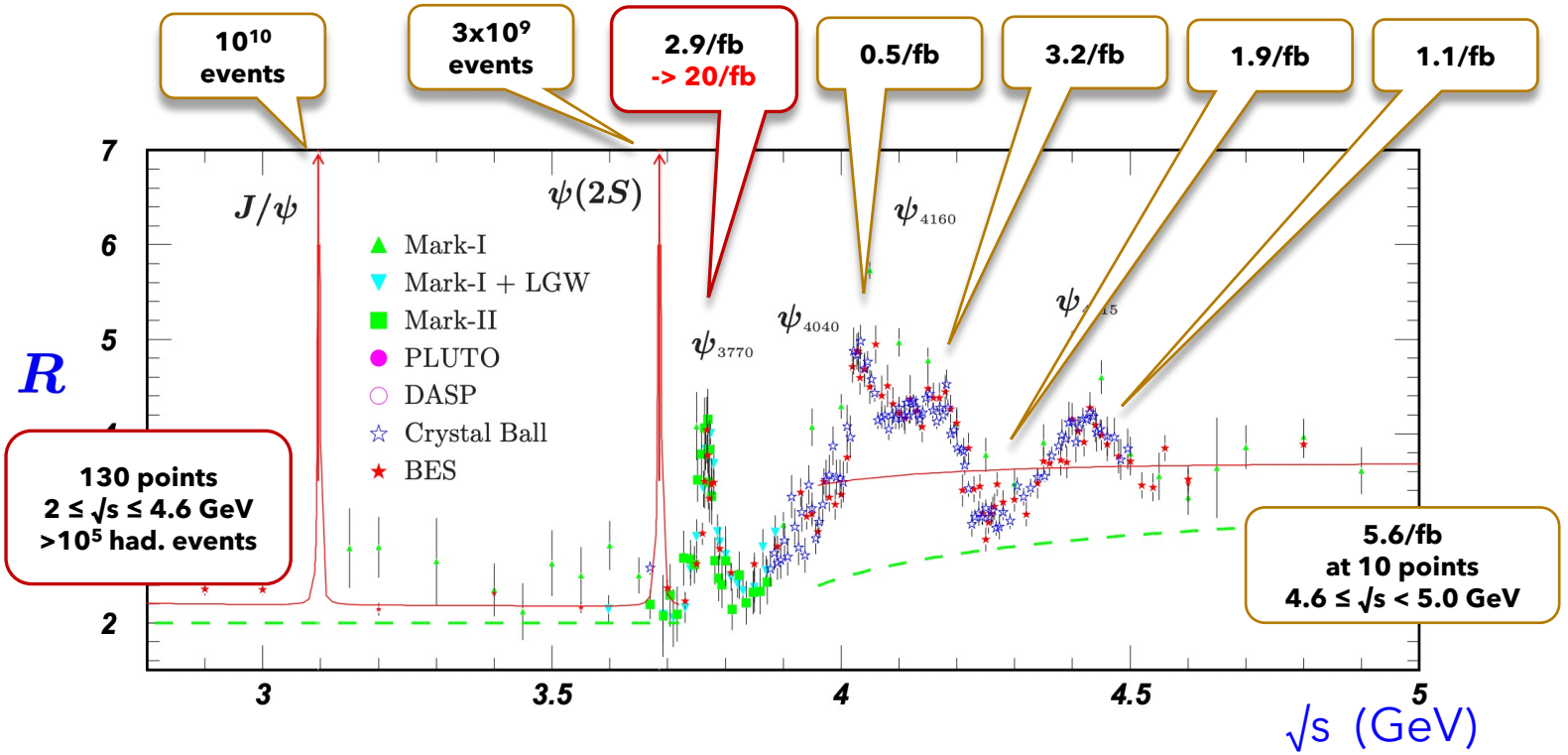


BaBar @ PEP II



- Experiments at colliders with different energy ranges
  - ~1 GeV (KLOE), 2-5 GeV (BESIII), ~10.5 GeV (BaBar)
- Symmetric vs asymmetric beam collisions
- Large drift chamber in KLOE → No need for unfolding!
- Impact of FSR (at lower masses) proportional to beam energy

Inclusive R measurement at BESIII



- Symmetric e^+e^- collider
- Working in Tau-Charm energy region (2 – 5 GeV)
- Broad physics spectrum