59th International Winter Meeting
on Nuclear Physics
23-27 January 2023
Bormio, Italy

Measuring the hadronic contributions to the muon (g-2)

JG|U

Project TFF, Project XYZ, Project JRP, Project ALP, Project LBL
FOR 5327

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

Achim Denig
JGU Mainz

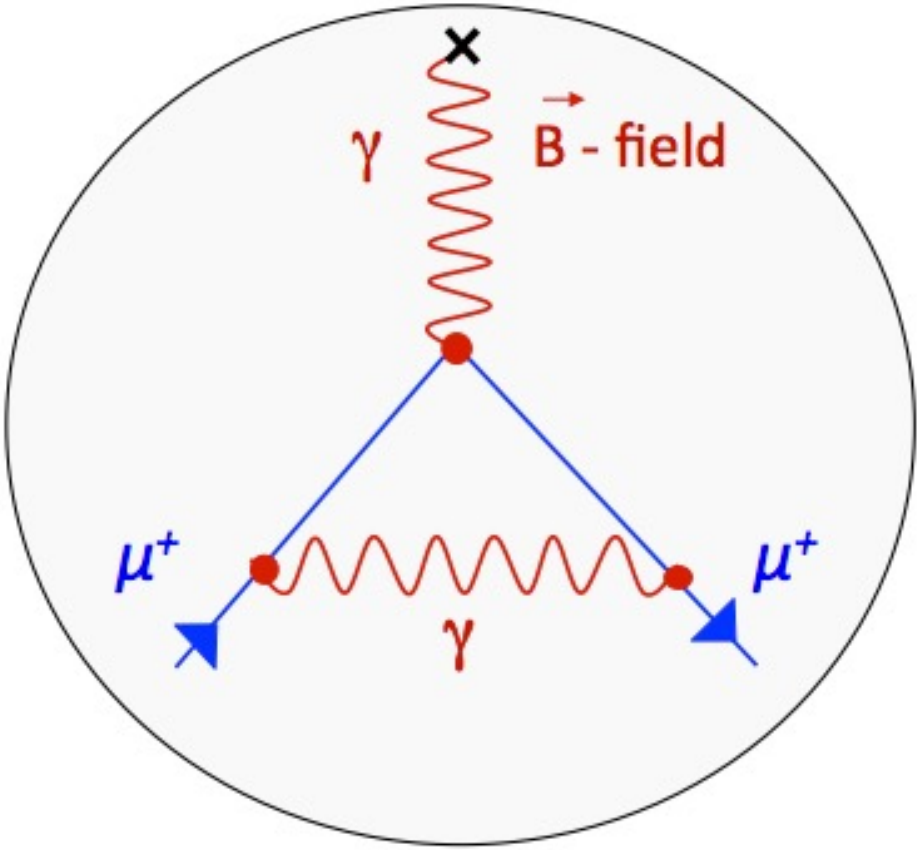
Muon Magnetic Moment: (g-2)$_\mu$

Confront a high-precision SM prediction with a high-precision measurement

Definition: $\vec{\mu} = \mu_B \cdot g \cdot \vec{S}$

Dirac: $g = 2$

SM (QFT): $a_\mu = (g-2)/2 \approx \alpha/\pi$



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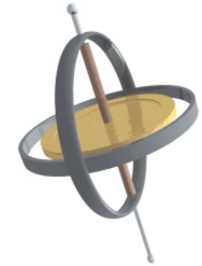
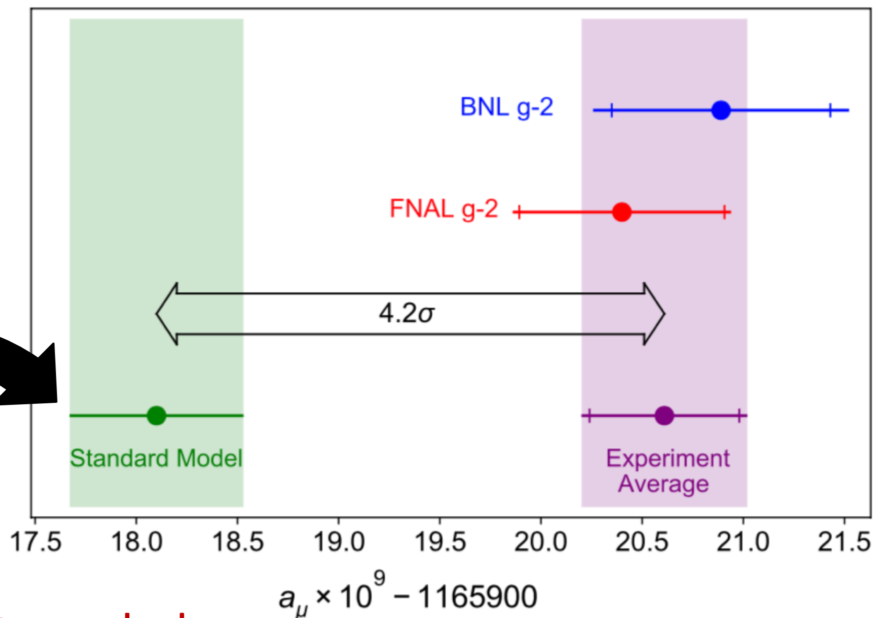


a_μ^{SM} = (11 659 181.0 ± 4.3) · 10^{-10}

a_μ^{exp} = (11 659 206.1 ± 4.1) · 10^{-10}



experimental input needed
→ this talk!

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

EW contributions: A **trimph** of perturbative QFT and computing

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$$

Czarnecki et al.

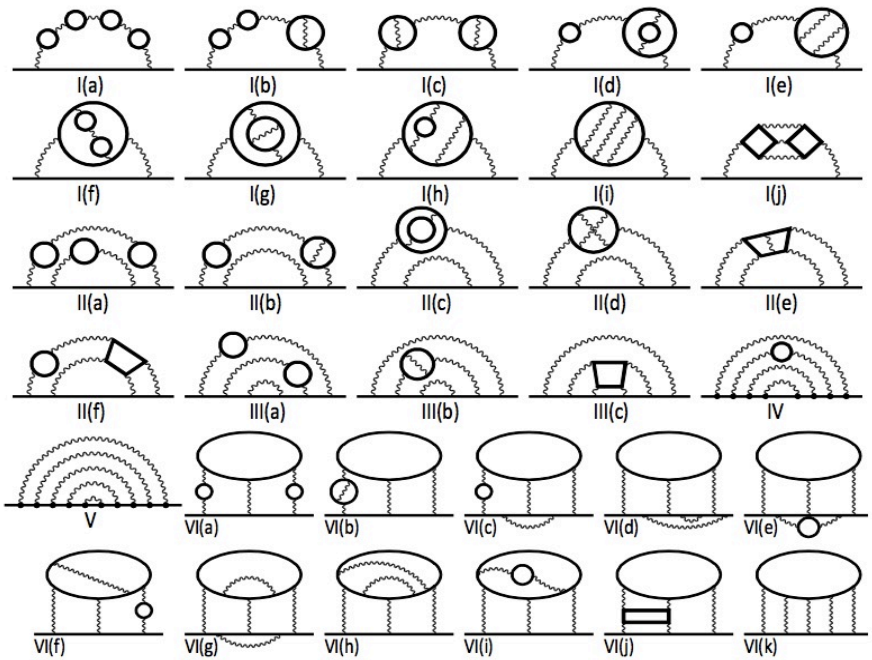
(15.4 ± **0.2**) · 10^{-10}

Kinoshita et al. '12

(11 658 471.808 ± **0.015**) · 10^{-10}

Absolute contribution dominated by QED
Uncertainty dominated by hadronic contribution

10th
12672
diagrams



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

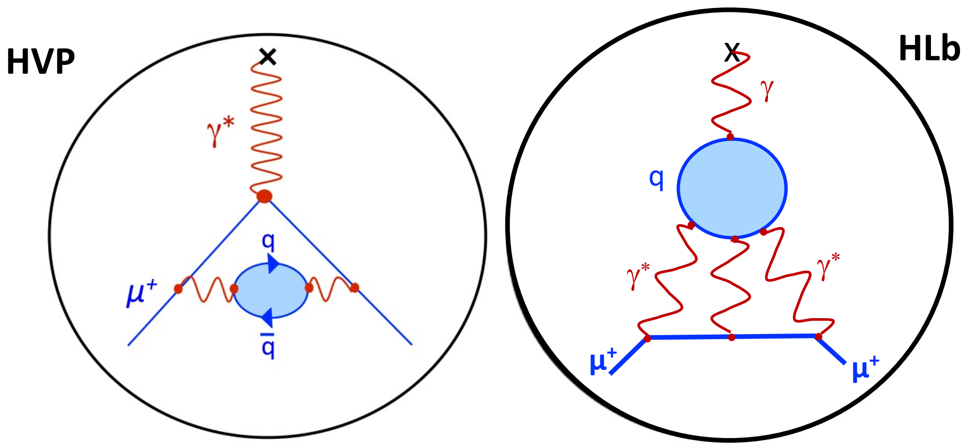
Hadronic contribution **non-perturbative,** the **limiting** contribution

$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$

→ **HVP**: Hadronic Vacuum Polarization (≅ **687 … 694** ± **2.4 … 4.1**) · 10^{-10}

	BDJ19	DHMZ19	FJ17	KNT19
$a_\mu^{\text{HVP, LO}} \times 10^{10}$	687.1(3.0)	694.0(4.0)	688.1(4.1)	692.8(2.4)

→ **HLbL**: Hadronic Light-by-Light (10.5 ± **2.6**) · 10^{-10} Glasgow „consensus“ value



NLO (-9.8 ± **0.1**) · 10^{-10};
NNLO (1.2 ± **0.01**) · 10^{-10}

$(g\text{-}2)_\mu$ Theory Initiative (since 2017)

196 pages, 103 figures


FERMILAB-PUB-20-207-T
INT-PUB-20-021
KEK Preprint 2020-5
MITP/20-028

CERN-TH-2020-075
IFT-UAM/CSIC-20-74
LMU-ASC 18/20
LTH 1234
LU TP 20-20
MAN/HEP/2020/003
PSI-PR-20-06
UWThPh 2020-14
ZU-TH 18/20

arXiv:2006.04822 [hep-ph] 8 Jun 2020

The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama[1,2,3], N. Asmussen[4], M. Benayoun[5], J. Bijnens[6], T. Blum[7,8], M. Bruno[9], I. Caprini[10], C. M. Carloni Calame[11], M. Cè[9,12,13], G. Colangelo[14], F. Curciarello[15,16], H. Czyż[17], I. Danilkin[12], M. Davier[18], C. T. H. Davies[19], M. Della Morte[20], S. I. Eidelman[21,22], A. X. El-Khadra[23,24], A. Gérardin[25], D. Giusti[26,27], M. Golterman[28], Steven Gottlieb[29], V. Gülpers[30], F. Hagelstein[14], M. Hayakawa[31,2], G. Herdoíza[32], D. W. Hertzog[33], A. Hoecker[34], M. Hoferichter[14,35], B.-L. Hoid[36], R. J. Hudspith[12,13], F. Ignatov[21], T. Izubuchi[37,8], F. Jegerlehner[38], L. Jin[7,8], A. Keshavarzi[39], T. Kinoshita[40,41], B. Kubis[36], A. Kupich[21], A. Kupść[42,43], L. Laub[14], C. Lehner[26,37], L. Lellouch[25], I. Logashenko[21], B. Malaescu[5], K. Maltman[44,45], M. K. Marinković[46,47], P. Masjuan[48,49], A. S. Meyer[37], H. B. Meyer[12,13], T. Mibe[1], K. Miura[12,13,3], S. E. Müller[50], M. Nio[2,51], D. Nomura[52,53], A. Nyffeler[12], V. Pascalutsa[12], M. Passera[54], E. Perez del Rio[55], S. Peris[48,49], A. Portelli[30], M. Procura[56], C. F. Redmer[12], B. L. Roberts[57], P. Sánchez-Puertas[49], S. Serednyakov[21], B. Shwartz[21], S. Simula[27], D. Stöckinger[58], H. Stöckinger-Kim[58], P. Stoffer[59], T. Teubner[60], R. Van de Water[24], M. Vanderhaeghen[12,13], G. Venanzoni[61], G. von Hippel[12], H. Wittig[12,13], Z. Zhang[18],

M. N. Achasov[21], A. Bashir[62], N. Cardoso[47], B. Chakraborty[63], E.-H. Chao[12], J. Charles[25], A. Crivellin[64,65], D. Deineka[12], A. Denig[12,13], C. DeTar[66], C. A. Dominguez[67], A. E. Dorokhov[68], V. P. Druzhinin[21], G. Eichmann[69,47], M. Fael[70], C. S. Fischer[71], E. Gámiz[72], Z. Gelzer[23], J. R. Green[9], S. Guellati-Khelifa[73], D. Hatton[19], N. Hermansson-Truedsson[14], S. Holz[36], B. Hörz[74], M. Knecht[25], J. Koponen[1], A. S. Kronfeld[24], J. Laiho[75], S. Leupold[42], P. B. Mackenzie[24], W. J. Marciano[37], C. McNeile[76], D. Mohler[12,13], J. Monnard[14], E. T. Neil[77], A. V. Nesterenko[68], K. Ottnad[12], V. Pauk[12], A. E. Radzhabov[78], E. de Rafael[25], K. Raya[79], A. Risch[12], A. Rodríguez-Sánchez[6], P. Roig[80], T. San José[12,13], E. P. Solodov[21], R. Sugar[81], K. Yu. Todyshev[21], A. Vainshtein[82], A. Vaquero Avilés-Casco[66], E. Weil[71], J. Wilhelm[12], R. Williams[71], A. S. Zhevlakov[78]

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[22] Lebedev Physical Institute, 53 Leninskiy Pr., Moscow 119333, Russia

Goal:

theory consensus value of muon g-2 SM prediction (most relevant hadronic contributions!)

- Working groups on HVP, HLbL, LatticeQCD, ...
- Five collaboration meetings and various workshops on subtopics
- Scrutiny of various theoretical evaluations


Edinburgh 2022

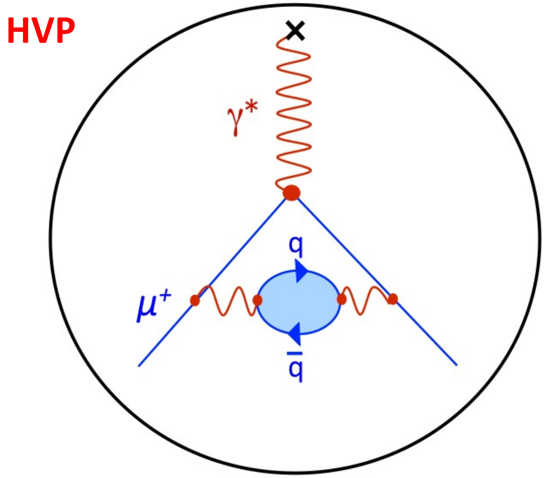

FNAL 2017


Mainz 2018


Seattle 2019

KEK (virtual) 2021

Hadronic Vacuum Polarization (HVP)

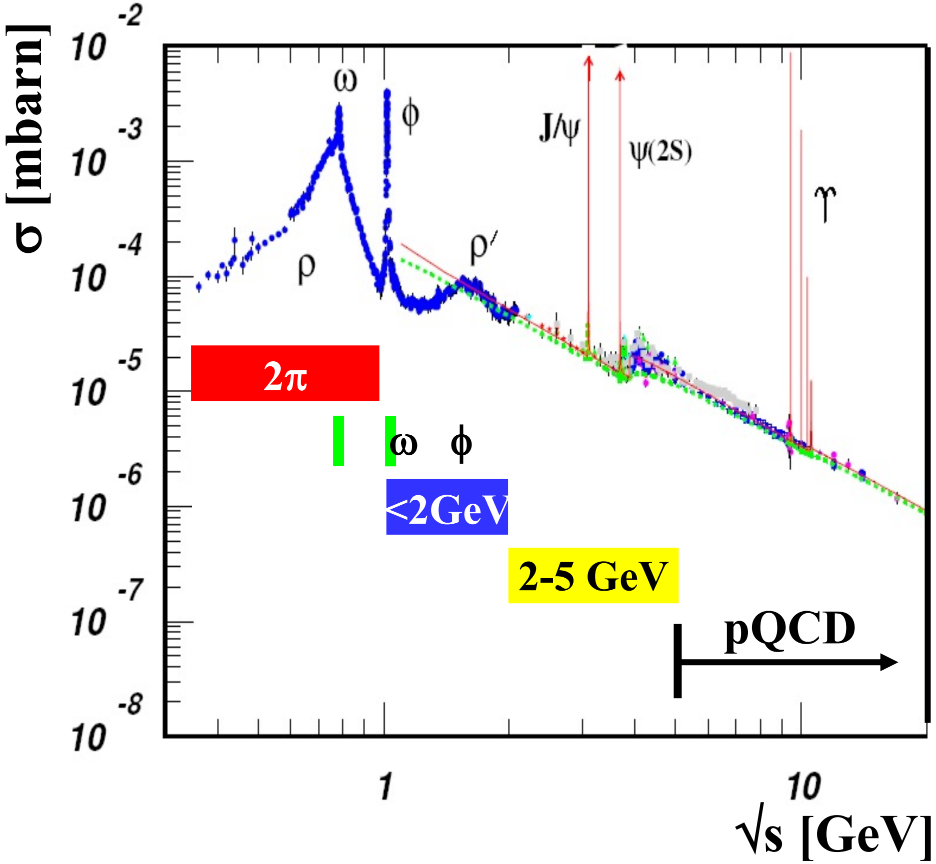


Estimate of (g-2) Theory Initiative
based on dispersive approach
(including higher orders):

(**693.1 ± 4.0**) · 10^{-10}

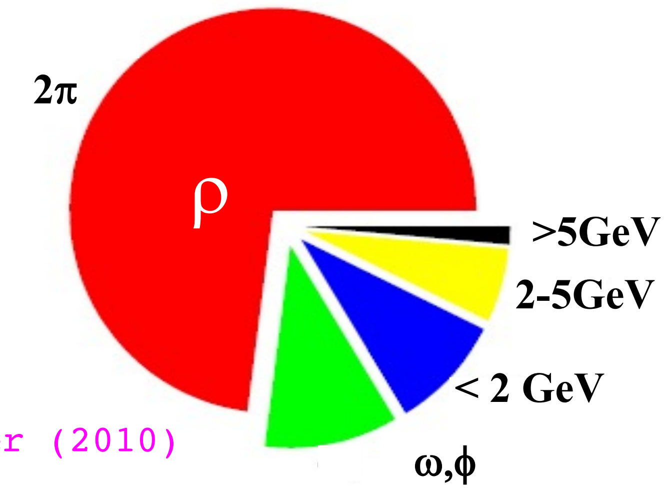
was (≅ 687 ... 694 ± 2.4 ... 4.1) · 10^{-10}

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



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

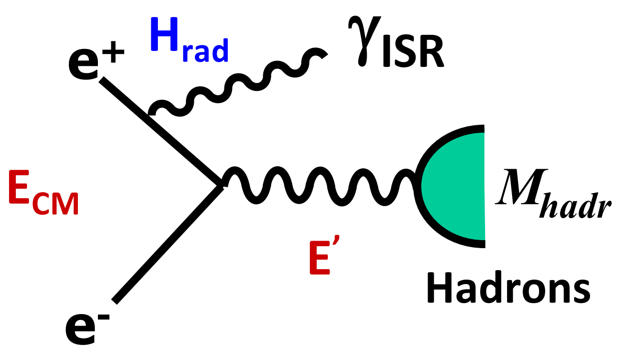
Intrinsic ~ 1 / s^2
low energy contributions
especially important!

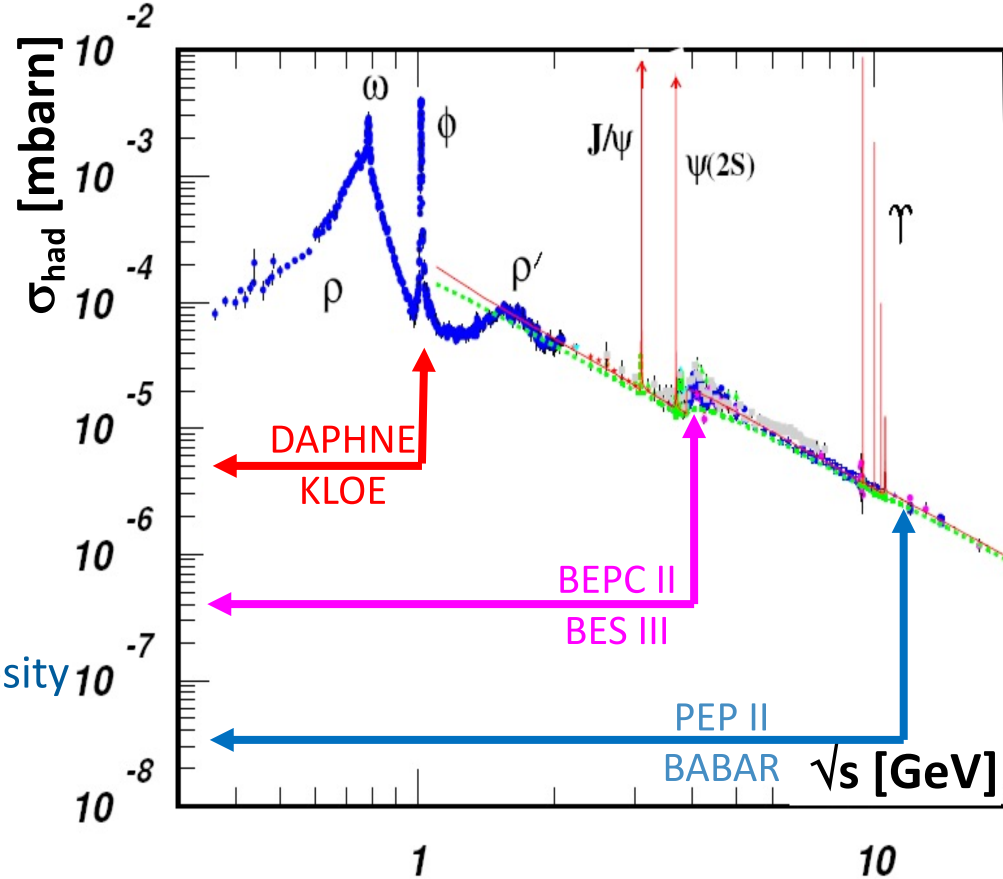


Jegerlehner (2010)

Initial State Radiation (ISR)

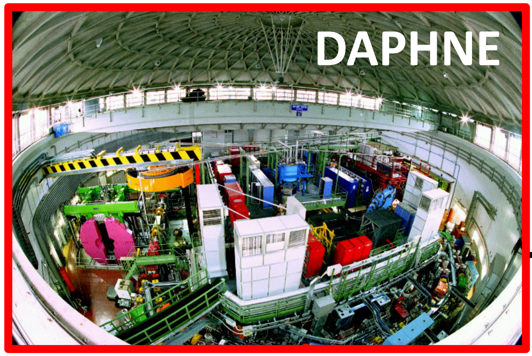
Initial State Radiation (ISR) aka Radiative Return

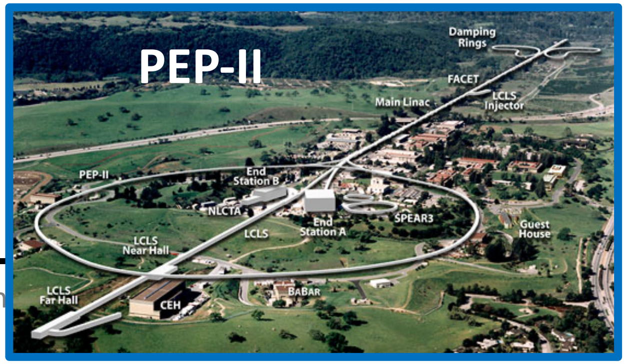




- No systematic variation of E_{beam}
- High statistics thanks to high luminosity
- Precise knowledge of radiative corrections mandatory (H_{rad})

PHOKHARA event generator

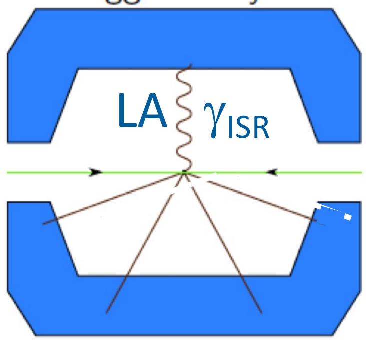




Initial State Radiation (ISR)

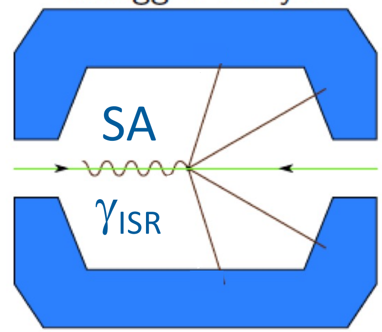
Tagged vs. untagged ISR analyses

Tagged analysis

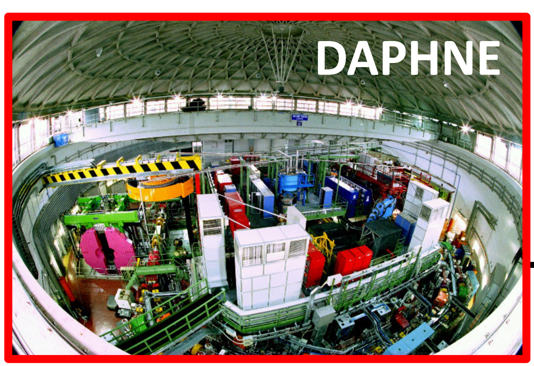


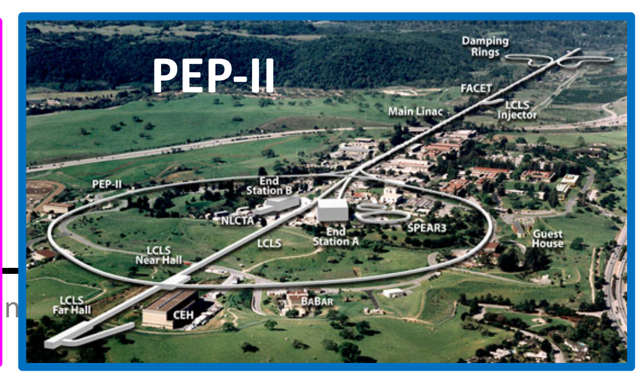
+ exclusive reconstruction
- increased background
- reduced statistics
+ mass range $\sqrt{s'} < E_{CM}$

Untagged analysis

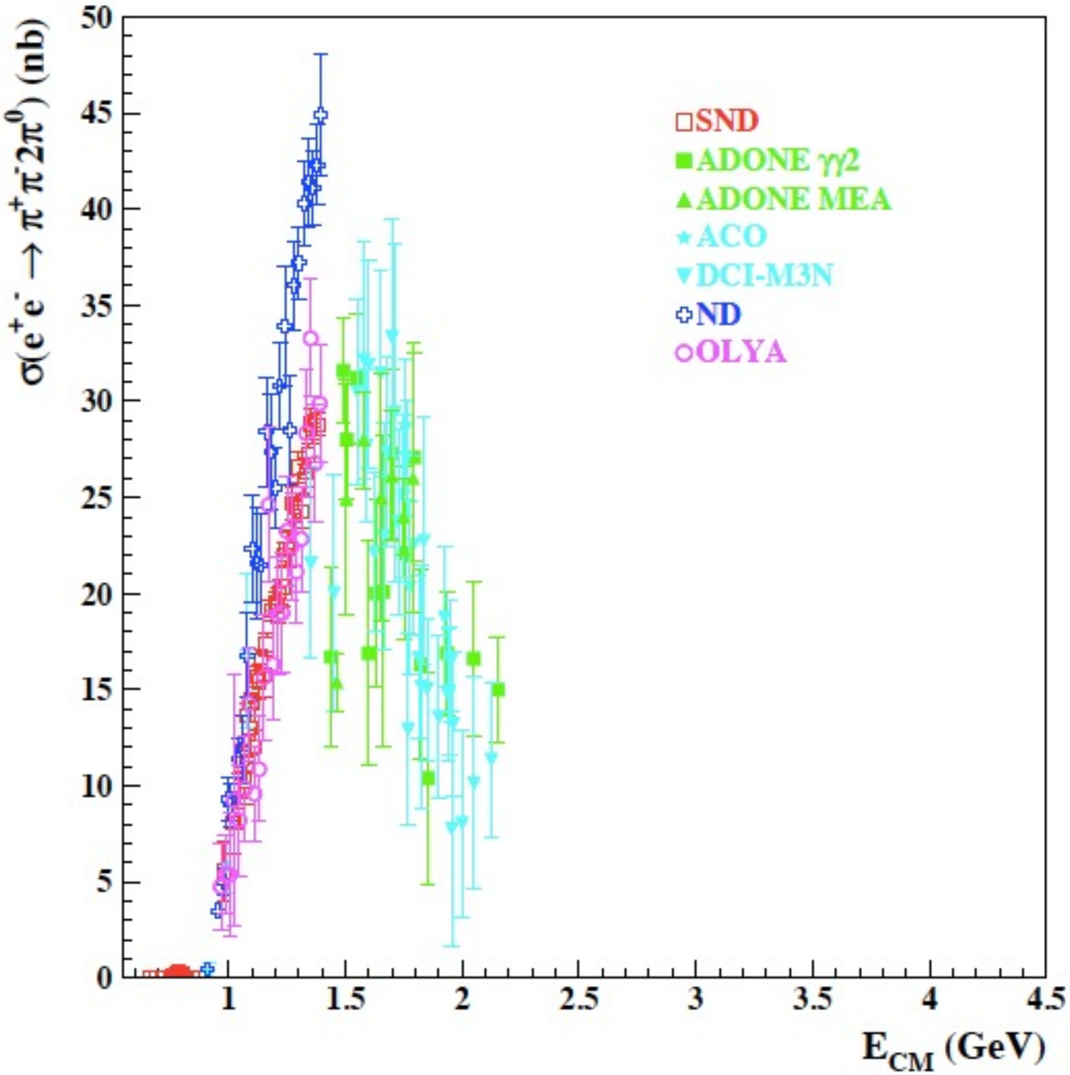


- cut on angle of missing momentum
+ reduced background
+ very high statistics (x5)
- mass range $E_{th} < \sqrt{s'} < E_{CM}$
  KLOE, E_{th} = ~0.6 GeV
  BESIII: E_{th} = ~1 GeV
  BABAR, E_{th} = ~3 GeV

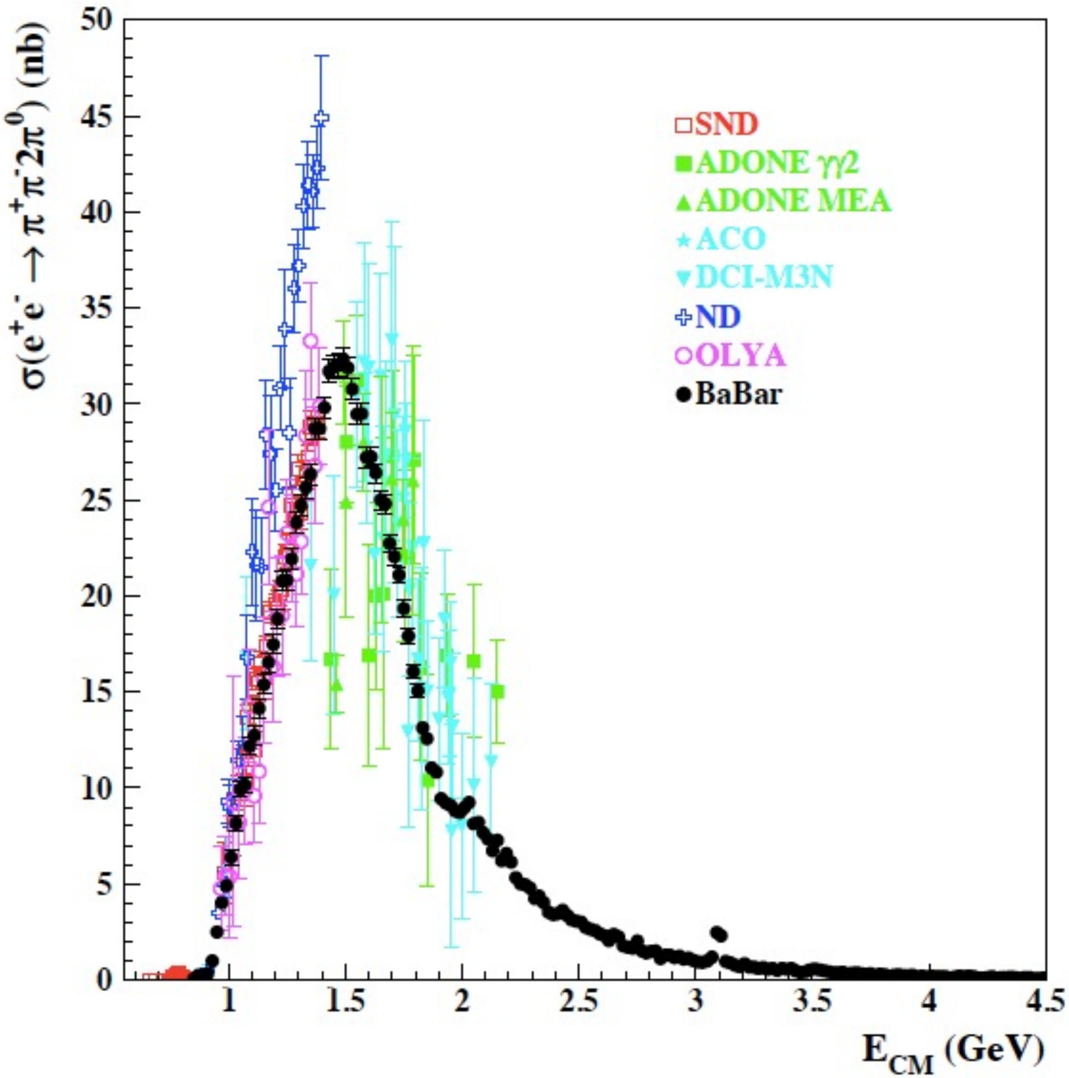




$BABAR: e^+e^- \to \pi^+\pi^- 2\pi^0 \gamma_{ISR}$

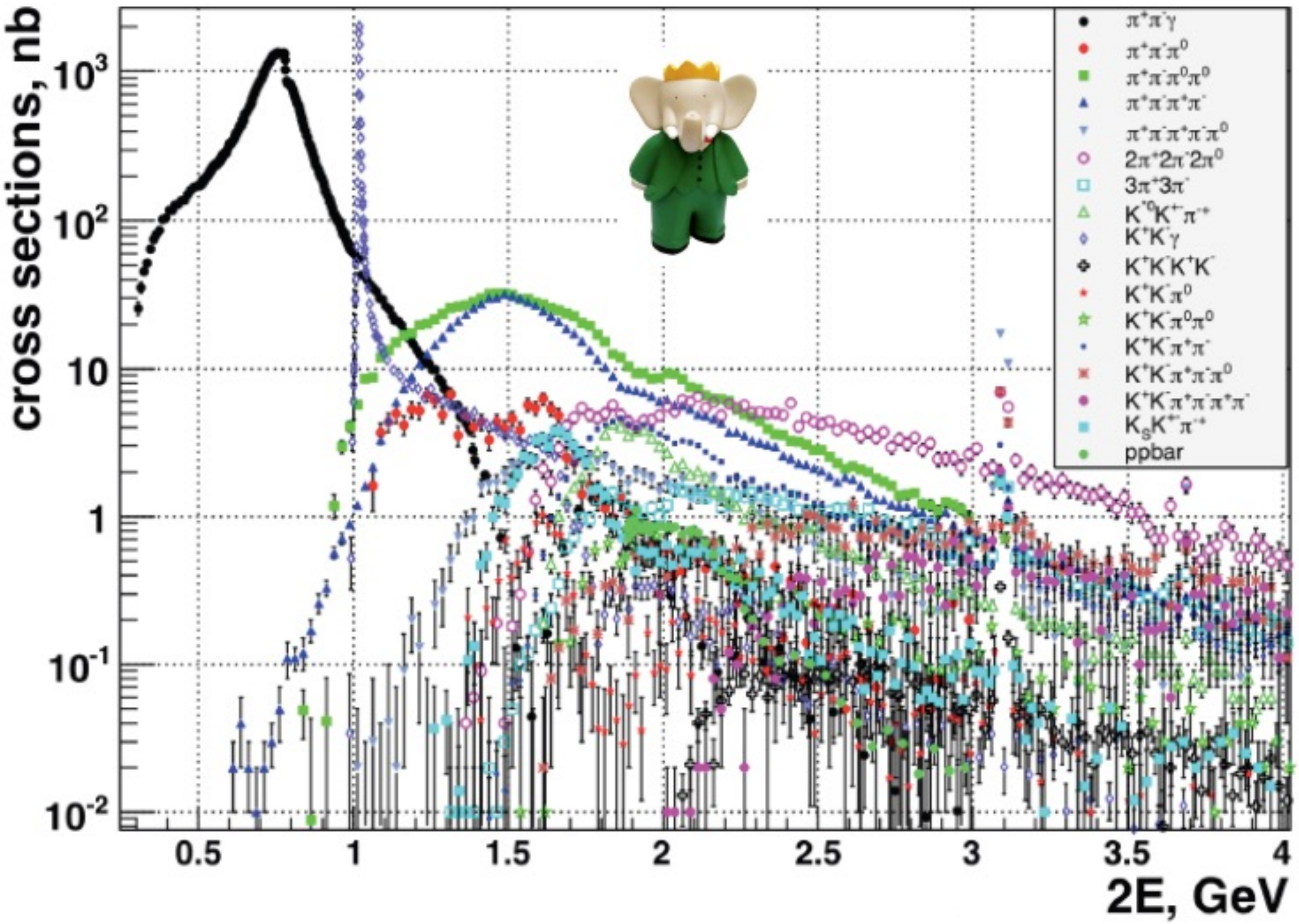


BABAR: $e^+e^- \to \pi^+\pi^-2\pi^0\gamma_{ISR}$



- Tagged ISR analysis (2017)
  Phys. Rev. D96 (2017) 092009
- Huge improvement over existing data sets suffering from normalization issues
- Confirmed by BES III analysis (preliminary)

BABAR ISR Results



Precision:

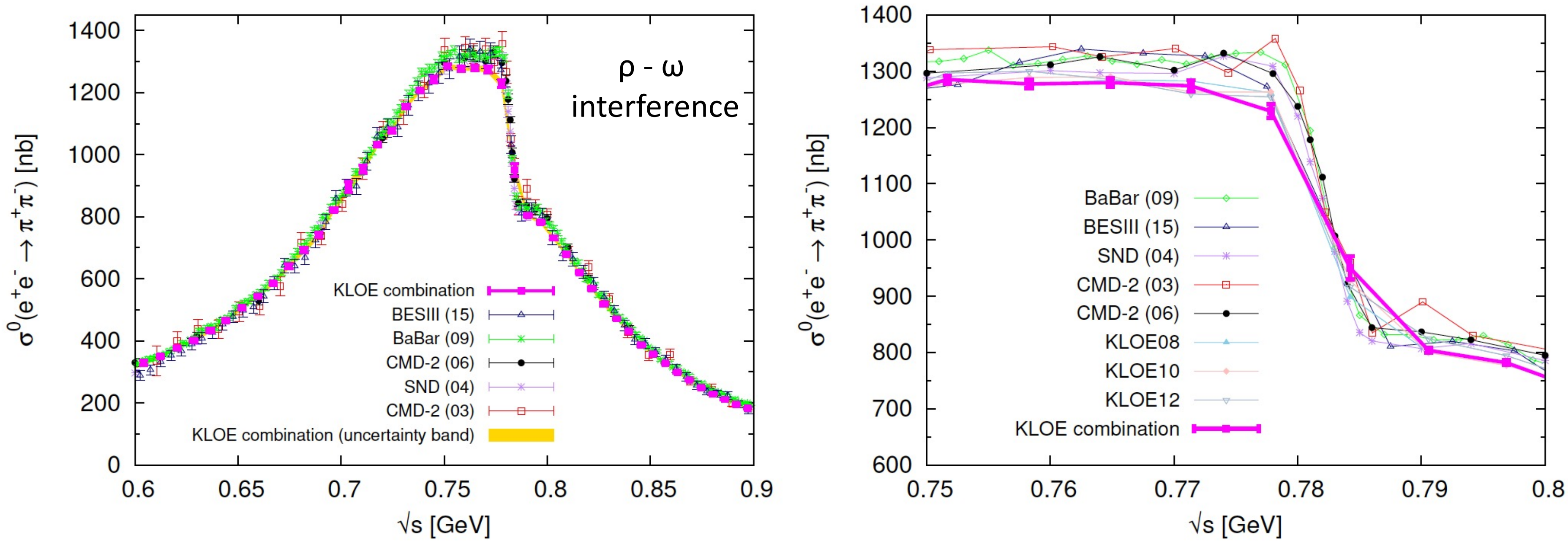
2π: < 1%

3π: ~10%

4π: ~ 3%

≥ 5π: 10% and higher

Most relevant Channel: $e^+e^- \to \pi^+\pi^-$

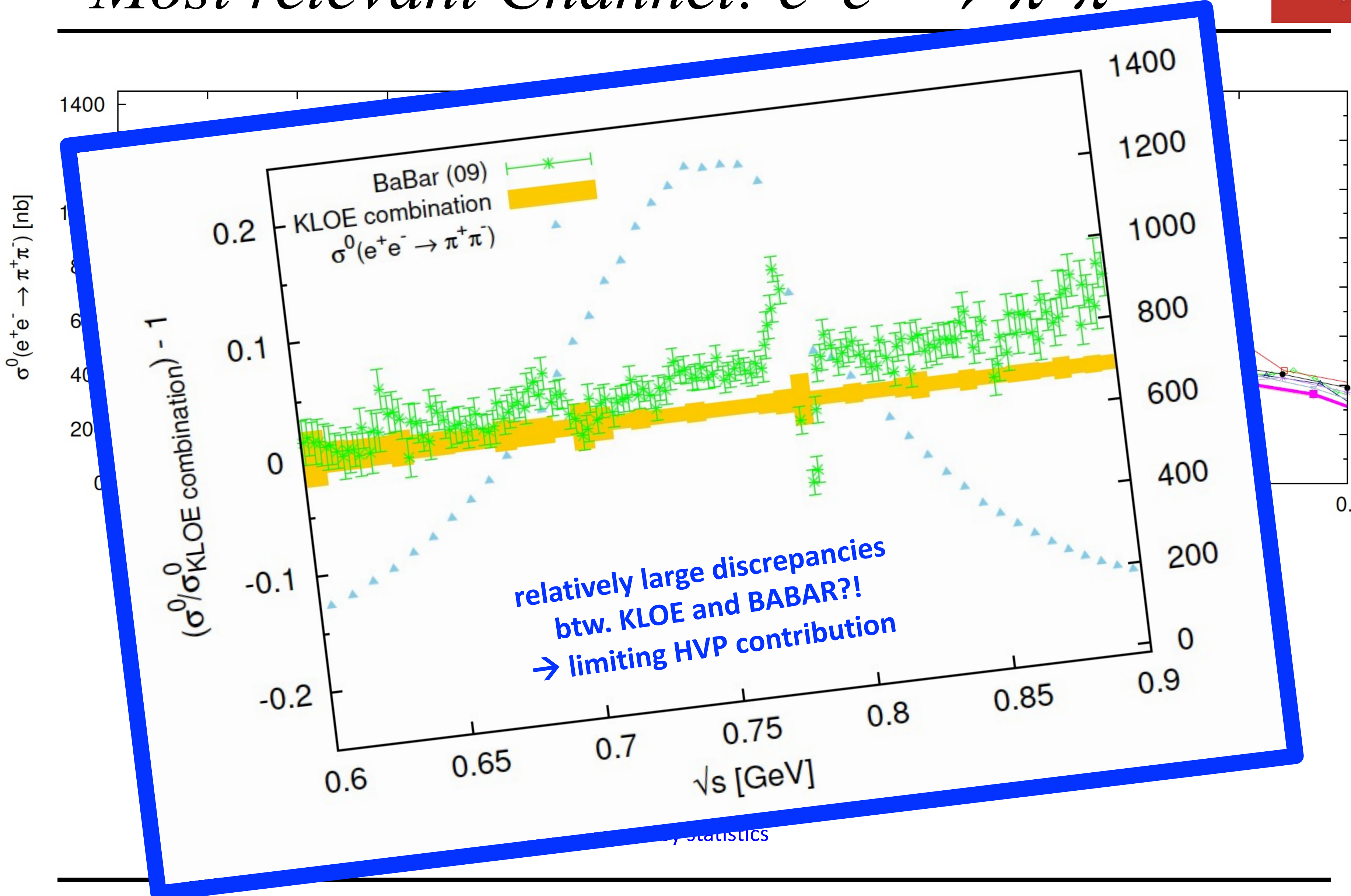


Systematic Uncertainties on ρ(770) peak

- ISR BABAR 0.5%
- ISR KLOE 0.6% (average of 3 analyses)
- ISR BESIII 0.9%
- Energy Scan CMD2 0.8%*

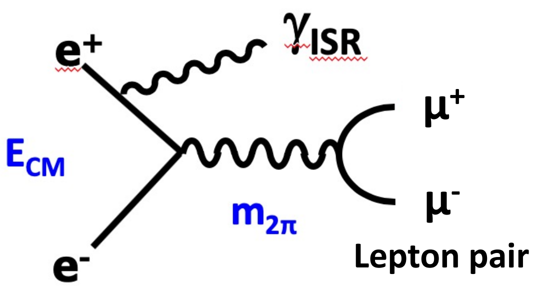
* limited in addition by statistics

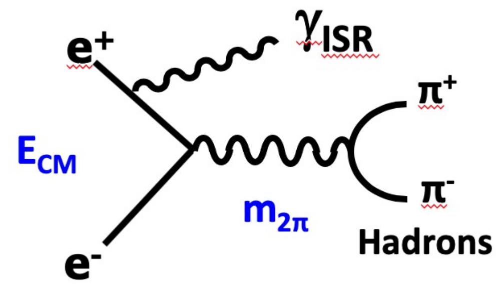
Most relevant Channel: $e^+e^- \rightarrow \pi^+\pi^-$



statistics

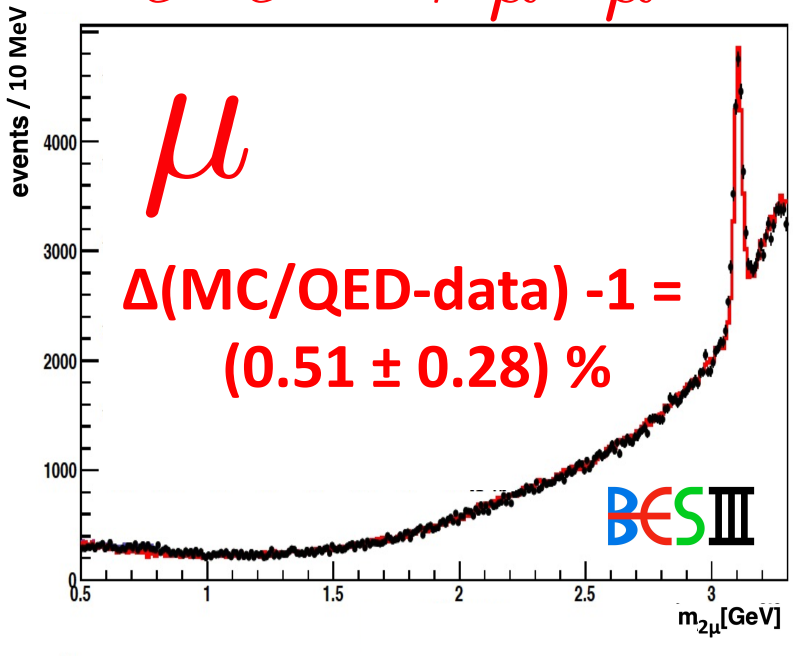
Pion-Muon Separation via Neural Network

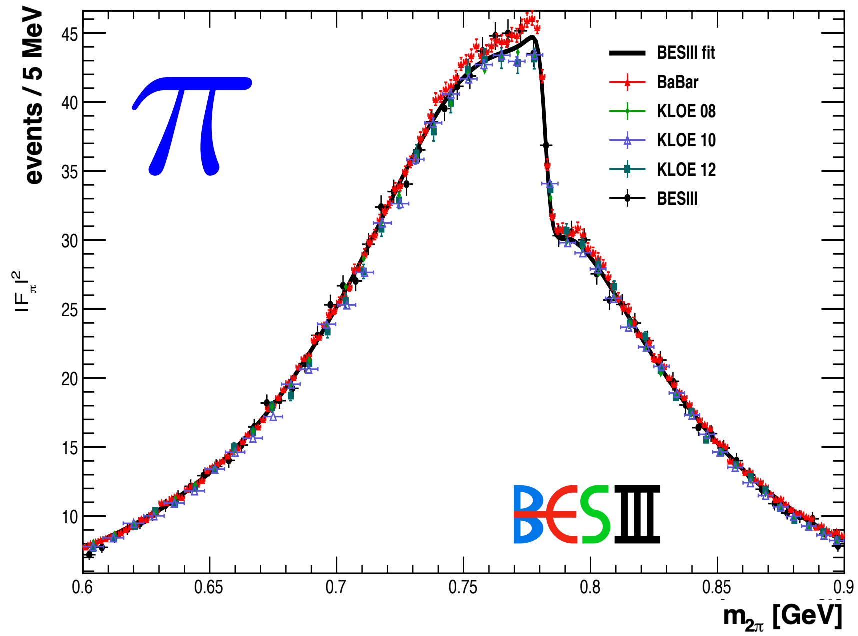




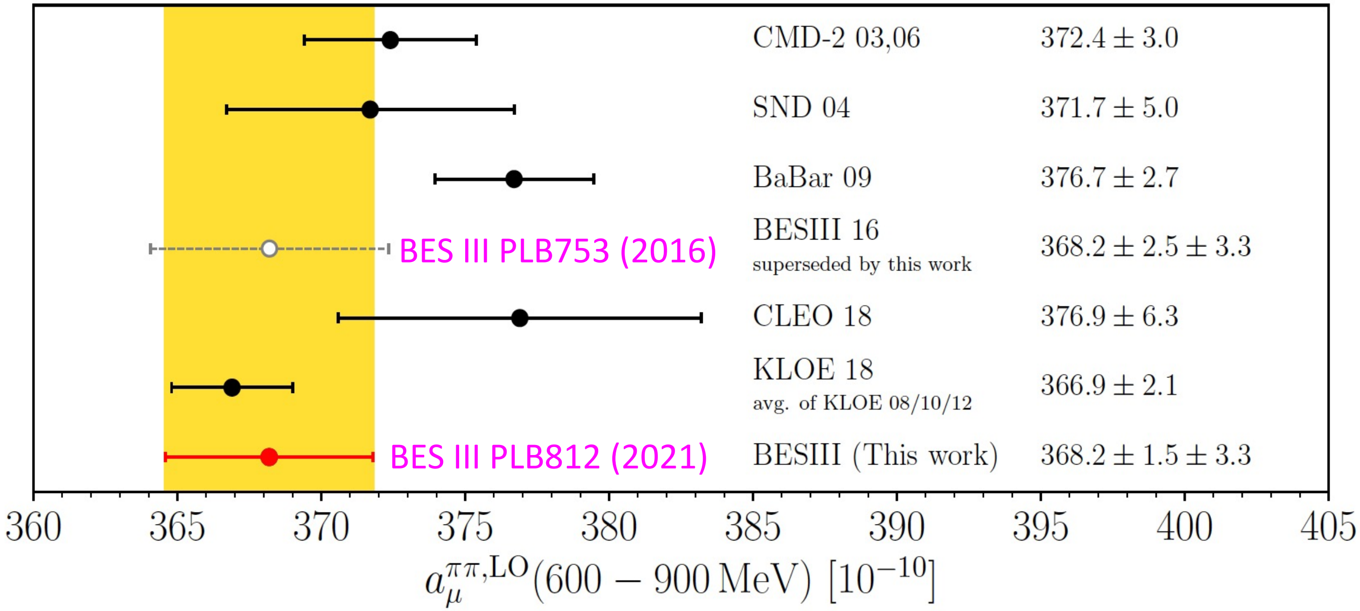
$e^+e^- \rightarrow \mu^+\mu^-$

$e^+e^- \rightarrow \pi^+\pi^-$





Knowledge of the 2π Contribution



Knowledge of 2π contribution to HVP largely limits accuracy of SM prediction to the muon g-2

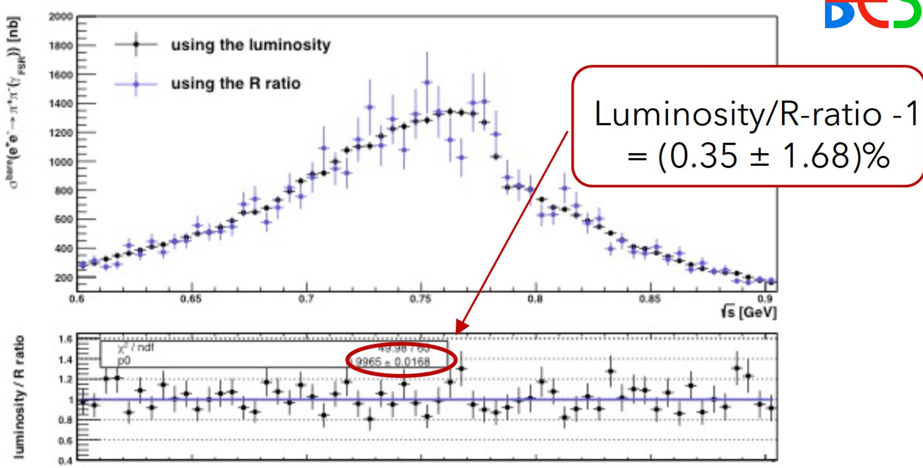
Near future will luckily see new measurements from BABAR, BESIII, CMD-3 and BELLE-II: Targeted accuracy 0.5% or lower!

New BESIII Analysis of 2π Contribution

New analysis (20 fb^{-1}@3.77 GeV) –> 0.5%

Measure ππγ/μμγ ratio

$$R = \frac{N_{2\pi\gamma}}{N_{2\mu\gamma}} \cdot \frac{\epsilon^{2\mu\gamma} \cdot \left(1 + \delta^{2\mu}_{FSR}\right)}{\epsilon^{2\pi\gamma} \cdot \left(1 + \delta^{2\pi}_{FSR}\right)}$$



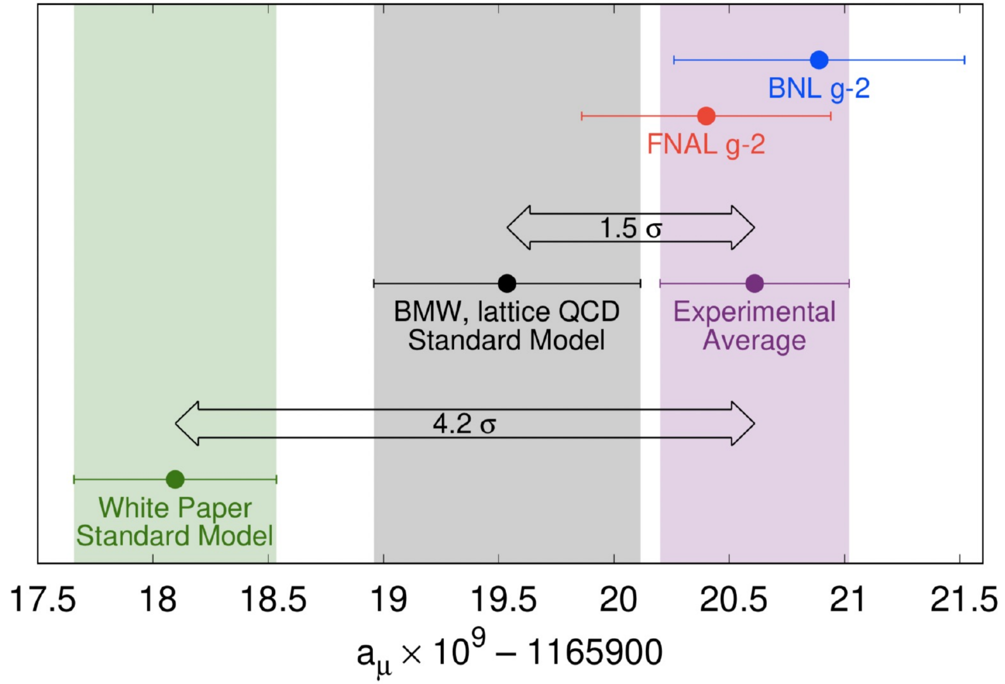
- Old analysis (2.9fb^{-1}) limited by μμγ statistics
- R ratio (main systematic contrib. drop!)
- Improved PID via machine learning

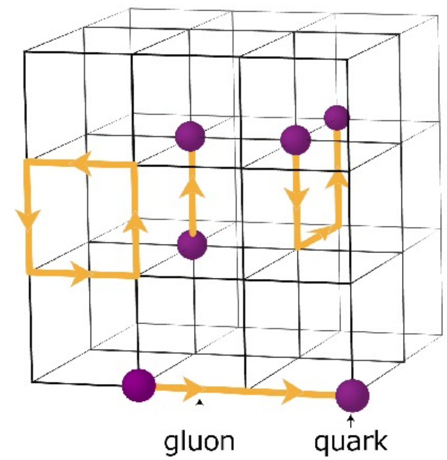
Source	BESIII 2016 2.9/fb (Update)	New analysis Normalization to $\mu^+\mu^-\gamma$ events
Photon efficiency	0.2	-
Pion tracking efficiency	0.3	0.2
Pion ANN efficiency	0.2	0.3
Pion e-PID efficiency	0.2	0.1
Angular acceptance	0.1	0.1
Background subtraction	0.1	0.1
Unfolding procedure	0.2	0.2
Luminosity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

Another Puzzle: Lattice vs. e^+e^- Data

First time ab-initio precision calculation of HVP contribution by means of Lattice QCD (BMW 2021)

Similar accuracy as dispersive data-based calculation





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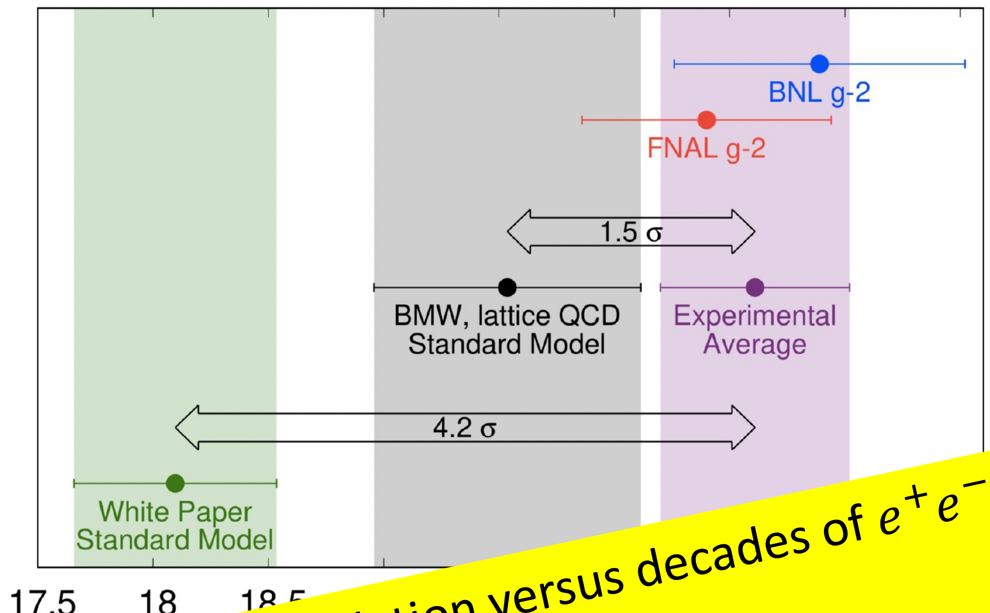
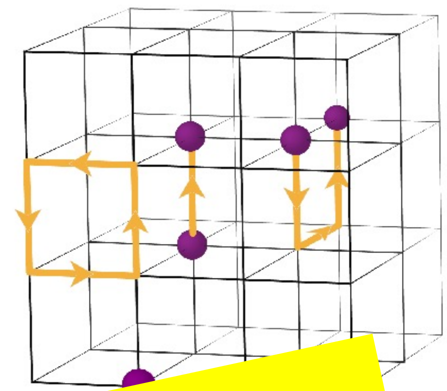




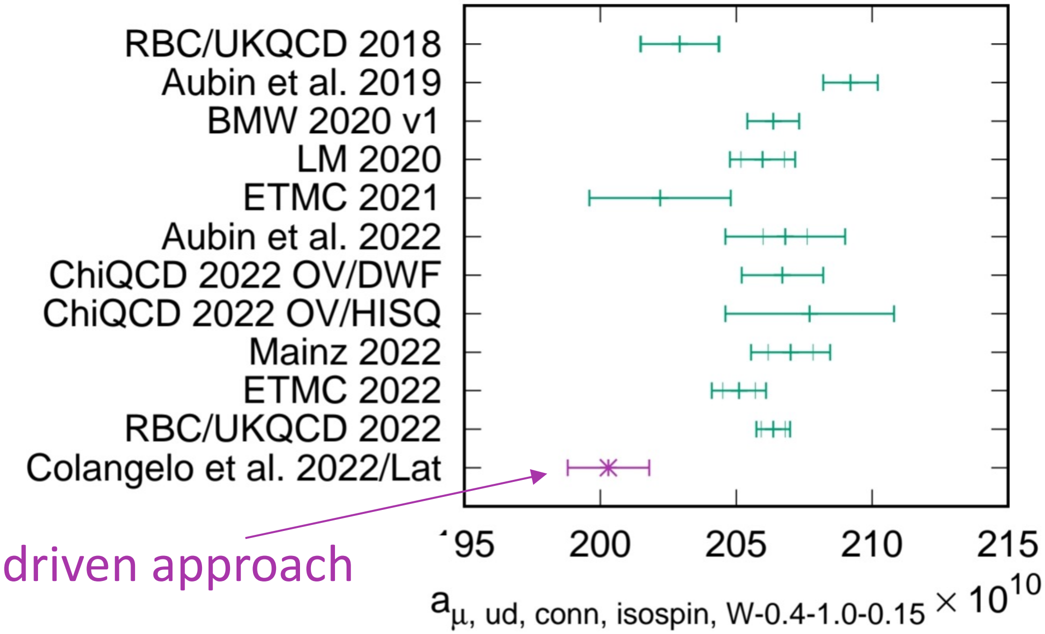
2021 opinion: one single calculation versus decades of e^+e^- experiments ….

2022 window fever !

Intermediate Window Fever …

Lattice QCD calculations (spacelike!) with largest systematic effects at small and long distances

→ **intermediate window (~1/3 of total HVP contribution)!**



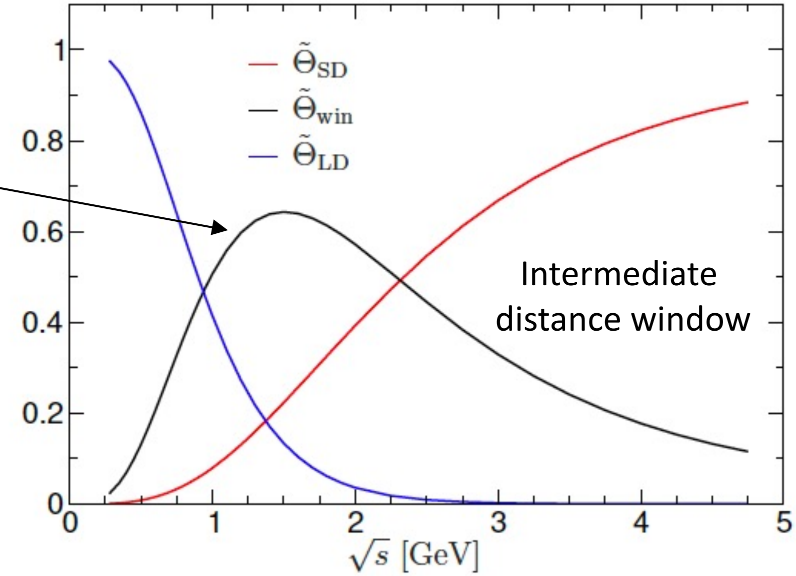
arxiv:2205.12963
Dispersive data-driven approach

Excellent agreement among all Lattice QCD calculations and disagreement with data-driven approach confirmed !

Another Puzzle: Lattice vs. e^+e^- Data

This is a very serious deviation !!!

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

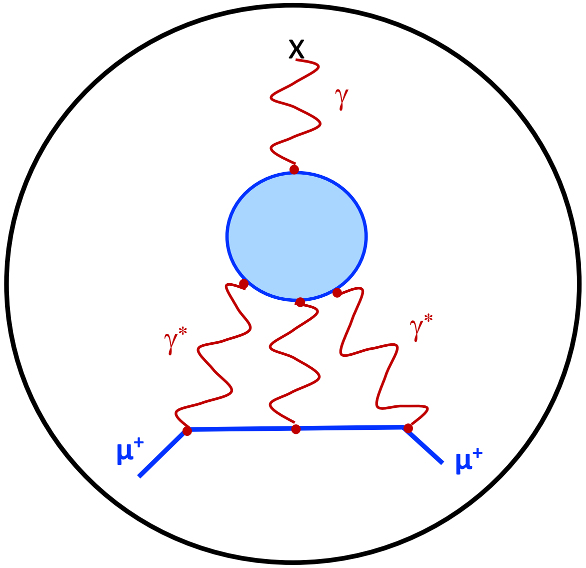


Explanation 1: Upscale π+π- data by >5% (flat), however this causes conflict with BMW result for full a_μ^{HVP}

Explanation 2: Underestimated contributions > 1 GeV (higher multiplicity state), however would need to be large effect; stable hexaquark?!

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

Hadronic Light-by-Light Contribution (HLbL)

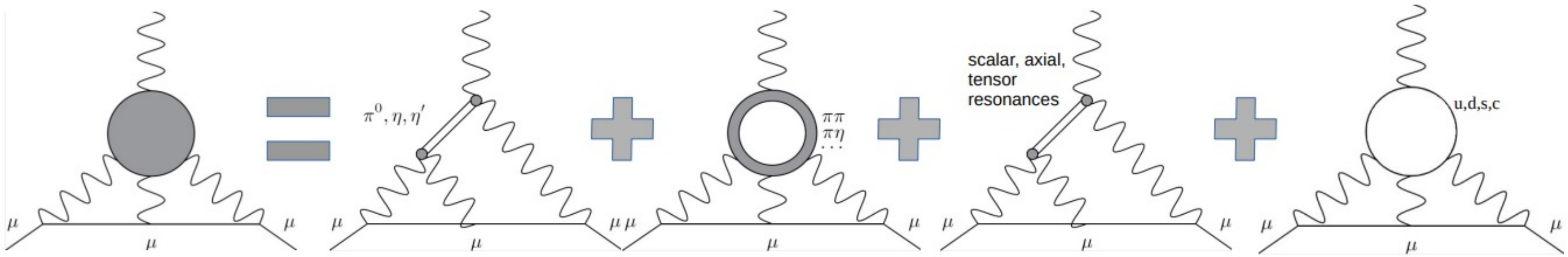


Estimate of (g-2) Theory Initiative:

(**9.2 ± 1.8**) · 10^{-10}

was (10.5 ± **2.6**) · 10^{-10}

HLbL and Impact of BESIII Data

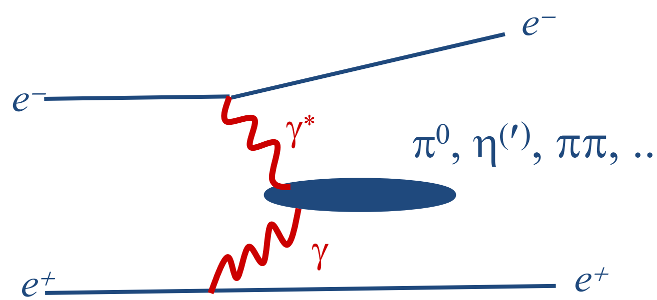


leading contribution

NEW

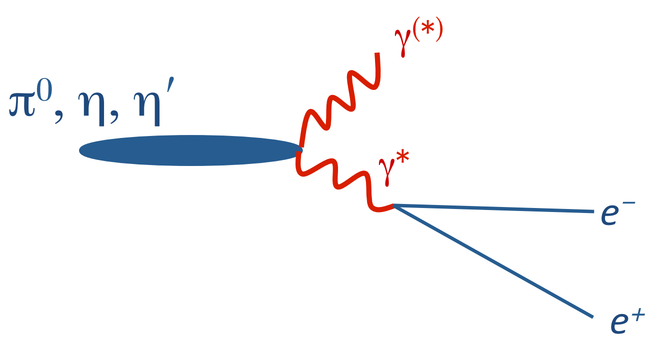
Data-driven approach!

Exp. Input:
Transition
Form Factors $F(Q^2)$
below ~ 2 GeV^2



BESIII

e^+e^- collider
$\sqrt{s}$ 2 ... 5 GeV



Hadronic Light-by-Light (g-2)$_\mu$

Leading contributions are pole contribution from π^0, η, η'

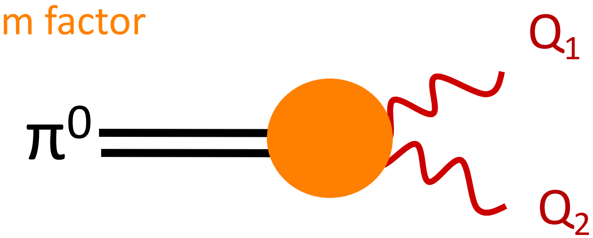
$$a_\mu^{\mathrm{HLbL};\pi^{0(1)}} = \int_0^\infty dQ_1 \int_0^\infty dQ_2 \int_{-1}^{1} d\tau \; w_1(Q_1, Q_2, \tau) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_1^2, -(Q_1+Q_2)^2) \mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_2^2, 0)$$

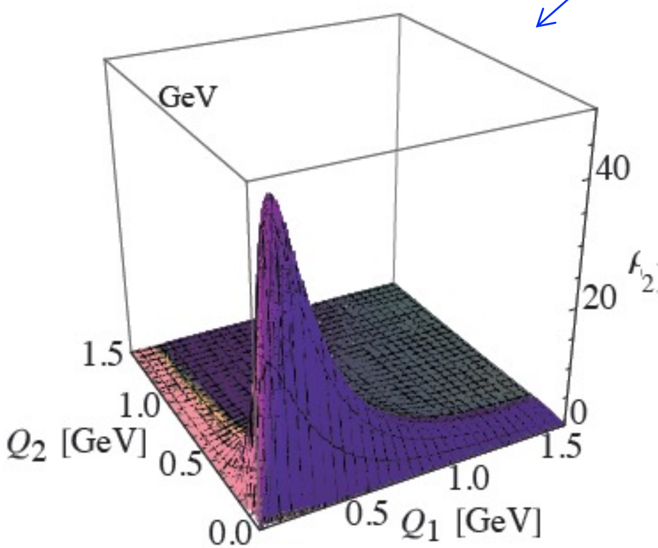
3D integral representation

weighting function

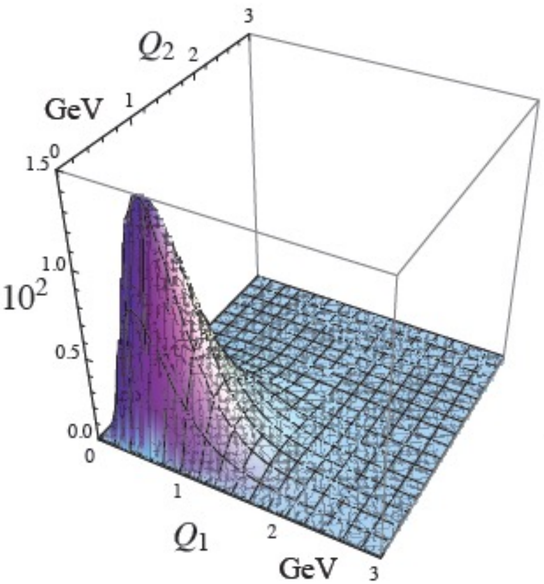
transition form factor

[Nyffeler 2016]





Pseudoscalar Mesons



Axial Vector Mesons

→ Need doubly virtual form factors of π^0, η, η' at low Q^2

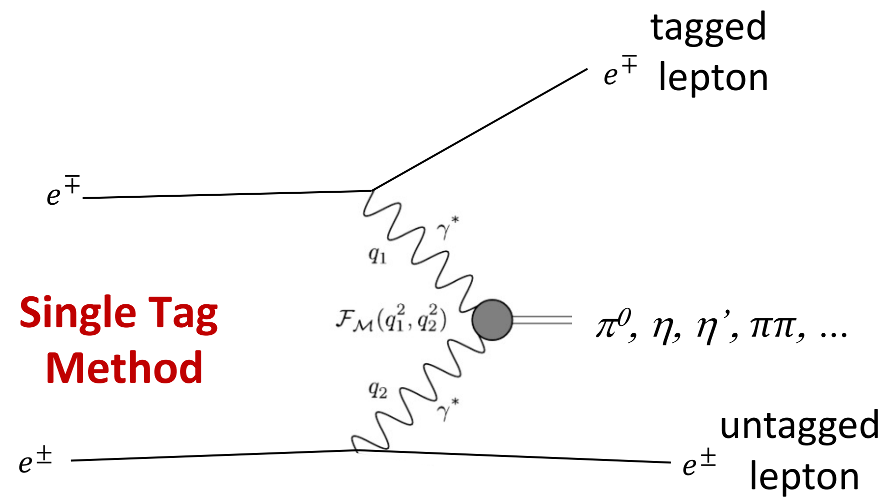
Two-Photon Physics Programme at BESIII

Selection criteria

- 1 electron (positron) detected
- 1 positron (electron) along beam axis
- Meson fully reconstructed

→ **cut on angle of missing momentum**

Single Tag Method



Momentum transfer

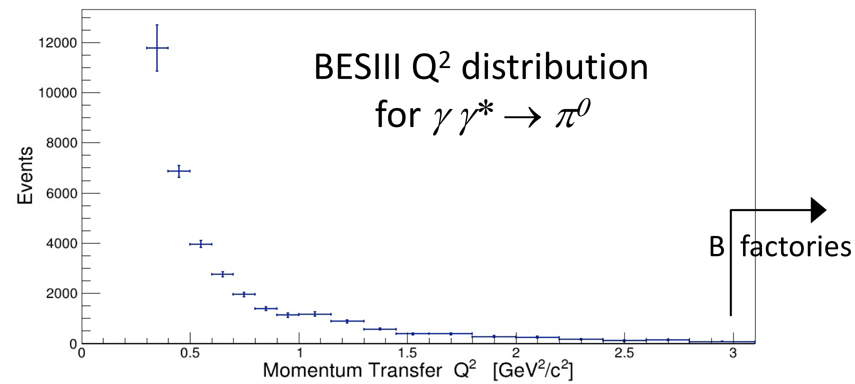
- tagged: $Q^2 = -q_1^2 = -(p - p')^2$

  → Highly virtual photon

- untagged: $q^2 = -q_2^2 \sim 0$ GeV^2

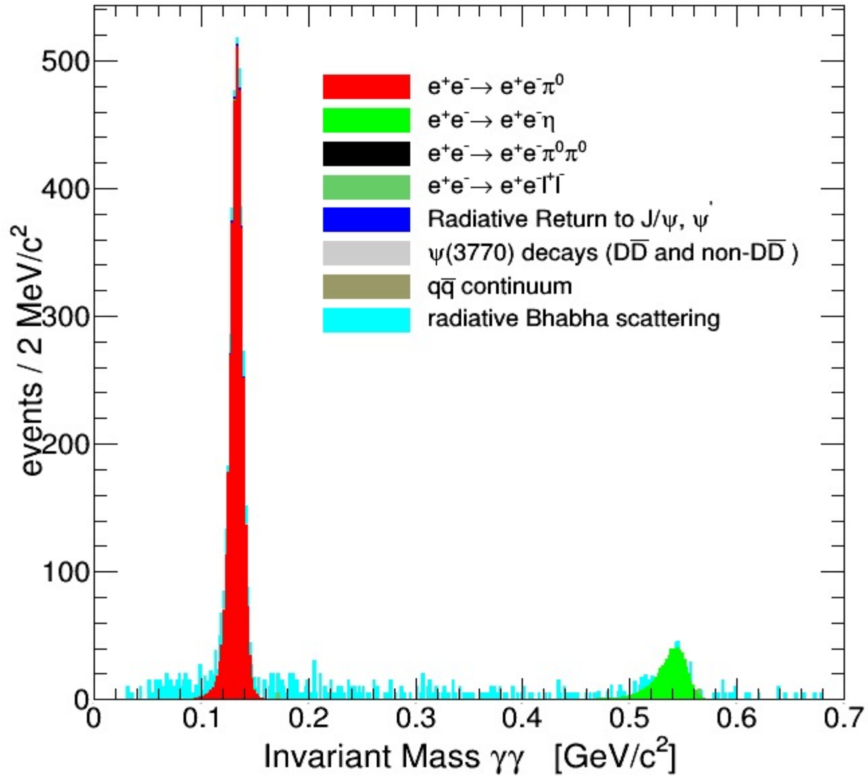
  → Quasi-real photon

EKHARA event generator



$$Q^2 = 4 \cdot E \cdot E' \cdot \sin^2(\theta/2)$$

BES III Analysis: $e^+e^- \to e^+e^- \pi^0$



Event Selection:

- exactly one lepton candidate
- at least two, max four photons
- Helicity angle cos $\Theta_H > 0.8$
- Kinematic cuts to reject ISR background

→ **cut on angle of missing momentum**

Strategy: Count π^0 yield in bins of Q^2 → $d\sigma/dQ^2$ → Form factor $F(Q^2)$

BES III Analysis: $\gamma\,\gamma^* \rightarrow \pi^0$

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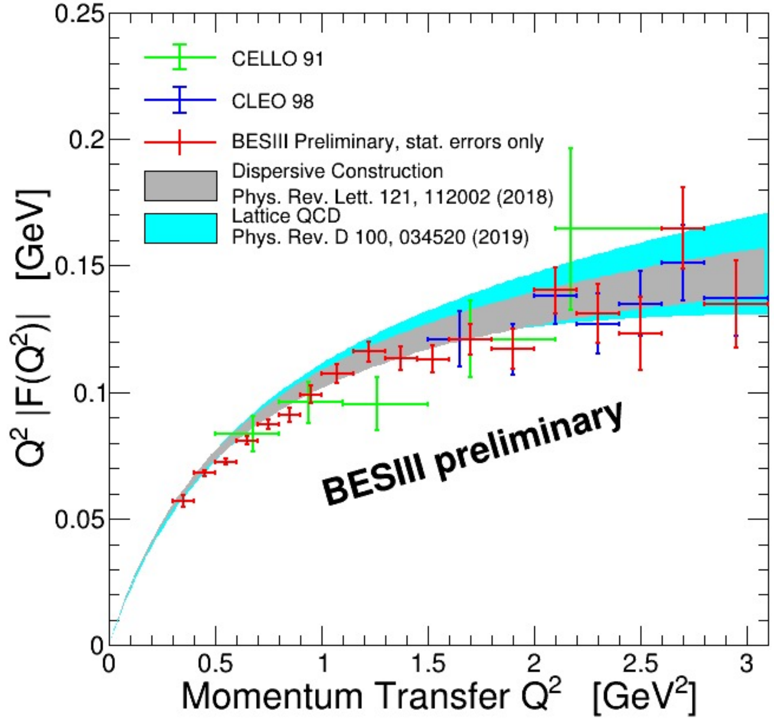


- $\sqrt{s}_{\mathrm{BESIII}} = 3.77$ GeV, L= 2.9/fb
- Unprecedented accuracy of BESIII
- Relevant Q^2 range for HLbL

→ **Very good agreement with recent dispersive analysis and of Lattice QCD calculation**

- Q^2 range below 0.3 GeV^2 accessible at BESIII with data from lower c.m. energy

similar results for η and η' TFFs;
first measurement ever ππ;
many other channels

Conclusions

Conclusions

- Interpretation of FNAL muon g-2 experiment calls for a detailed understanding of hadronic effects:
  - Hadronic Vacuum Polarization (HVP) contribution
  - Hadronic Light-by-Light (HLbL) contribution
- Following the standard approach to determine HVP contribution via dispersion relation shows a discrepancy of 4.2 σ between (g-2) SM theory and experiment:

  New Physics ?

- New lattice QCD calculation of HVP suggests lower discrepancy
  This tension between dispersive and lattice QCD approaches establishes a new HVP puzzle, for which currently no solution exists
- Close relation to running of e.m. fine structure constant and EW precision tests through global EW fits to the SM

Thank you !

g-2 is not an experiment
[not a number] –
It is a way of life ...

John Adams, former Director General CERN

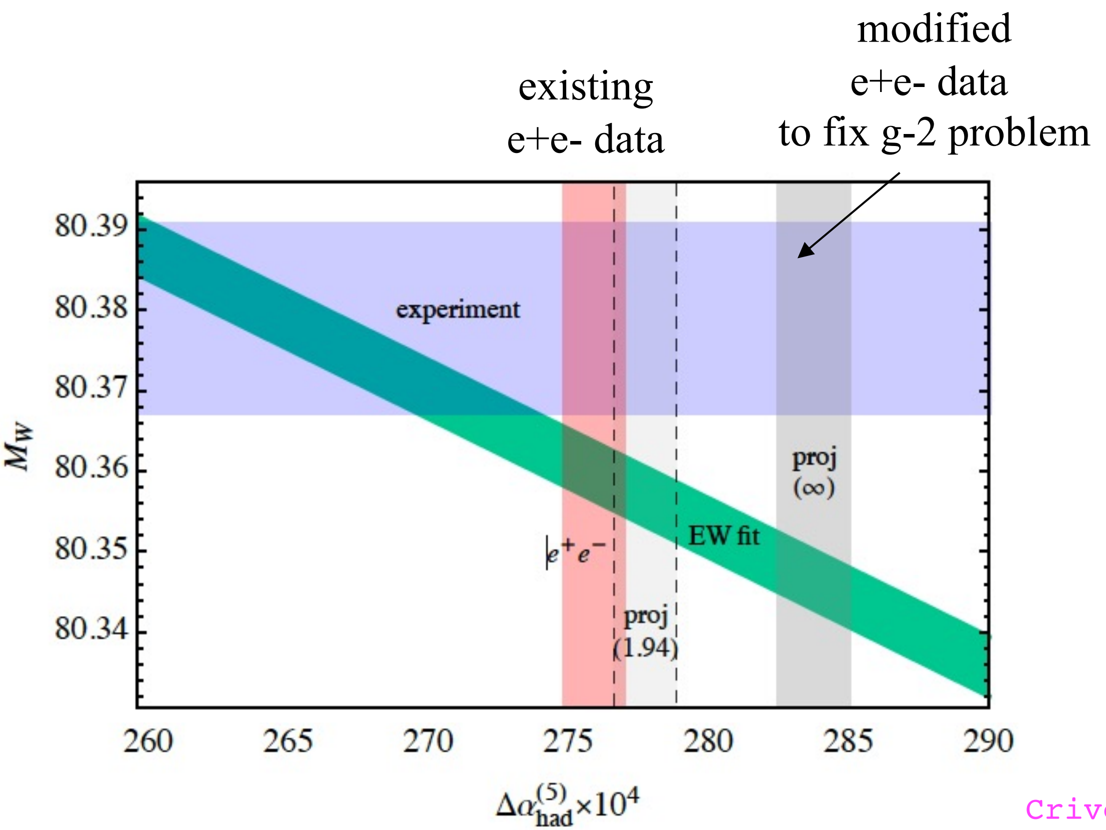
Backup

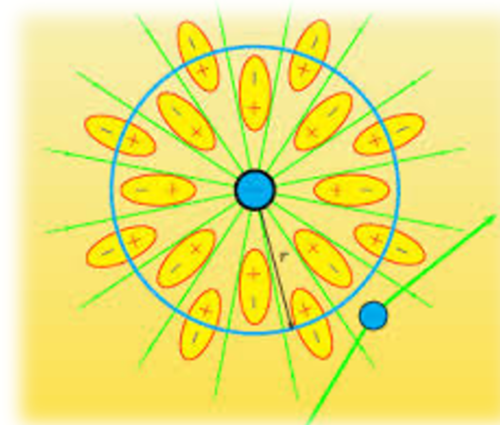
HVP and Electroweak Precision Physics

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

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

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





$$\alpha_{em}(s) = \frac{\alpha(0)}{(1-\Delta\alpha_{em}(s))}$$

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