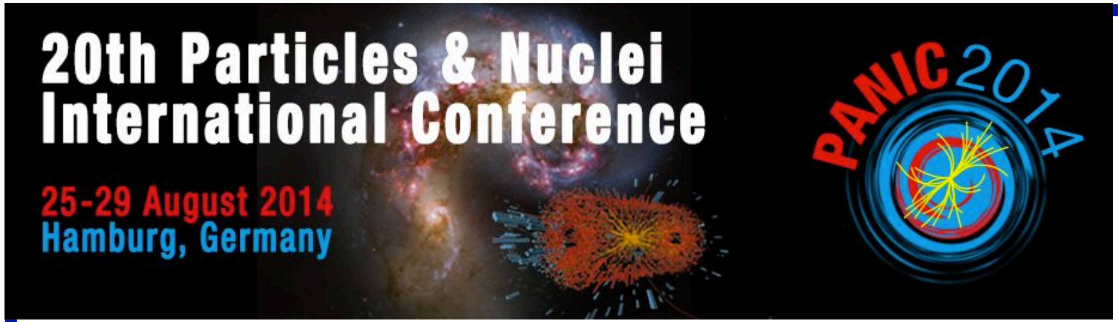

20th Particles & Nuclei International Conference

25-29 August 2014
Hamburg, Germany

UHH DESY

Tests of the Standard Model at low energies: $(g\text{-}2)_{\mu}$ *and Dark Photons*

Achim Denig

Institute for Nuclear Physics
Johannes Gutenberg University Mainz

mami MAINZER MIKROTRON

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

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

Anomalous Magnetic Moment of the Muon

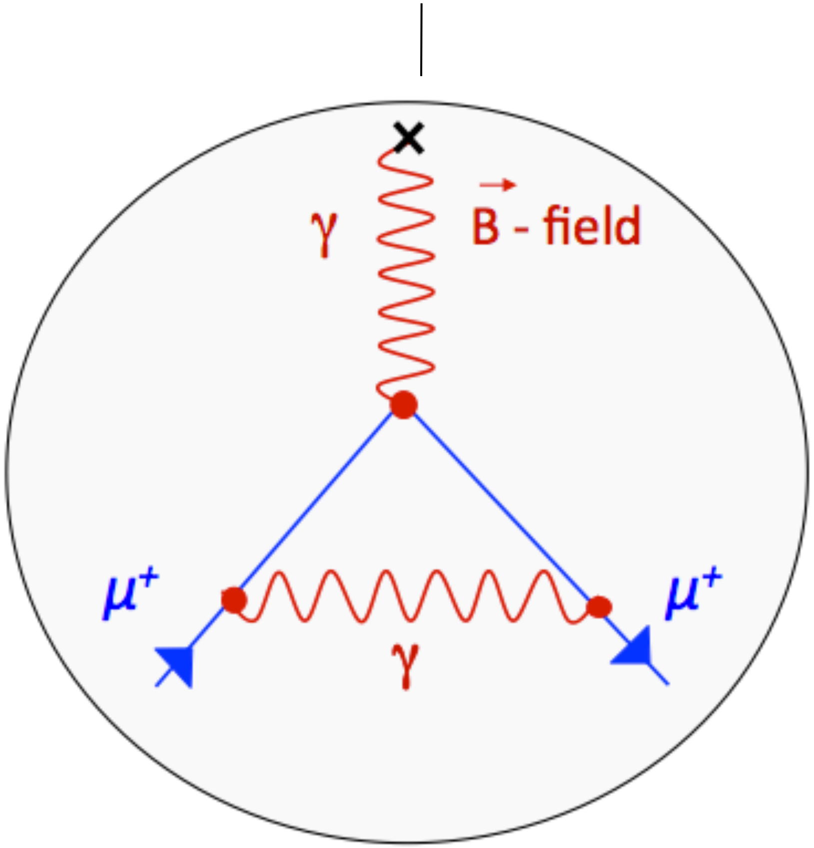
$(g\text{-}2)_\mu$

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

Magnetic Moment: $\vec{\mu} = \mu_B \; g \; \vec{S}$

$a_\mu^{SM} = (g\text{-}2)_\mu / 2 = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had} = (\,11\,659\,182.8 \pm 4.9\,) \cdot 10^{-10}$

Teubner et al ’11



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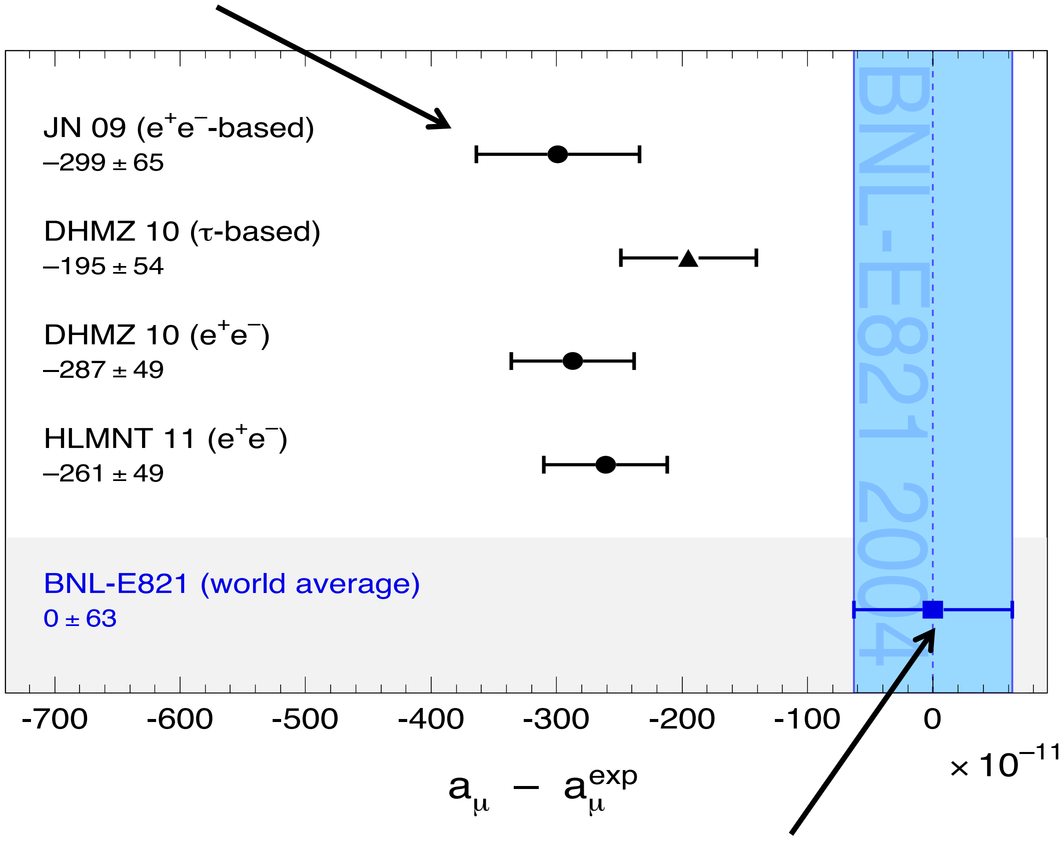

BNL/E821 measurement $a_\mu^{exp} = (11\,659\,208.9 \pm 6.3) \cdot 10^{-10}$

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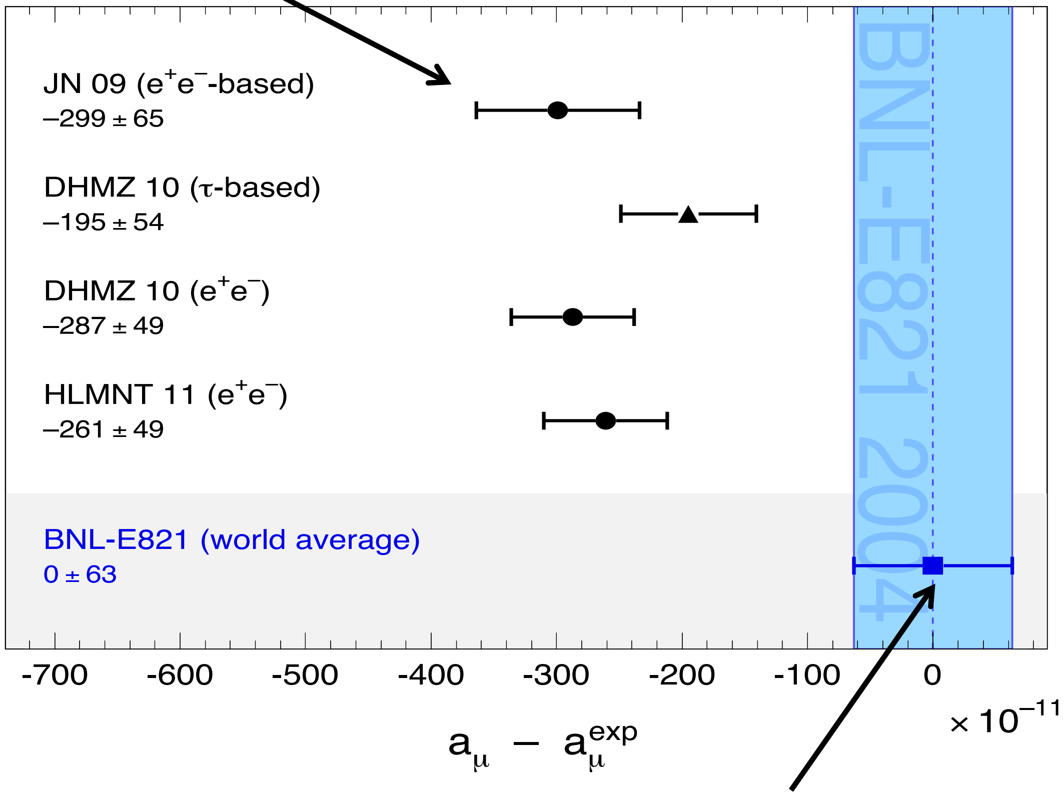

$\Delta a_\mu = a_\mu^{exp} – a_\mu^{SM} =$

$(26.1 \pm 8.0) \cdot 10^{-10}$ $(3.3\ \sigma)$

Error(s) or New Physics ?

BNL/E821 measurement $a_\mu^{exp} = (\,11\,659\,208.9 \pm 6.3\,) \cdot 10^{-10}$

$(g\text{-}2)_\mu$ and BSM Physics

Note: **Discrepancy twice as large as a_μ^{weak} !**

Expect $\Delta a_\mu^{BSM} = 26 \cdot 10^{-10} \sim a_\mu^{weak}$ x *couplings* x $\left(\frac{m_W}{m_{BSM}} \right)^2$

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Testing a very wide range of BSM models

$m_{BSM} \sim O(m_W)$, SUSY

$$\Delta a_\mu^{\text{SUSY}} \approx +13 \cdot 10^{-10}\, \text{sgn}(\mu) \left(\frac{100 \text{ GeV}}{m_{\text{SUSY}}} \right)^2 \tan\beta$$

Increasing tension with LHC data, non-traditional SUSY models viable

Stöckinger et al ’13

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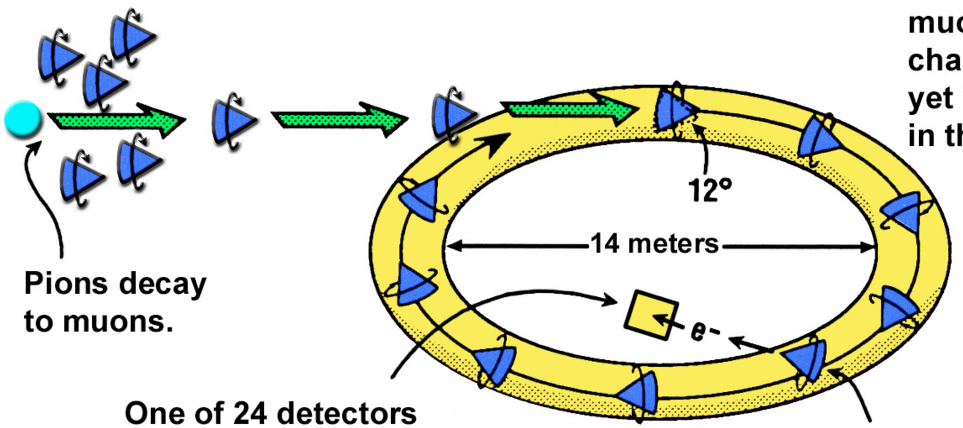
Increasing tension with LHC data, non-traditional SUSY models viable

Stöckinger et al ’13

m_{BSM} << $O(m_W)$,
e.g. Dark Photon
coupling << $\alpha_{em}/4\pi$

later

Direct Measurement of $(g\text{-}2)_\mu$



After each circle, muon's spin axis changes by 12˚, yet it keeps on traveling in the same direction.

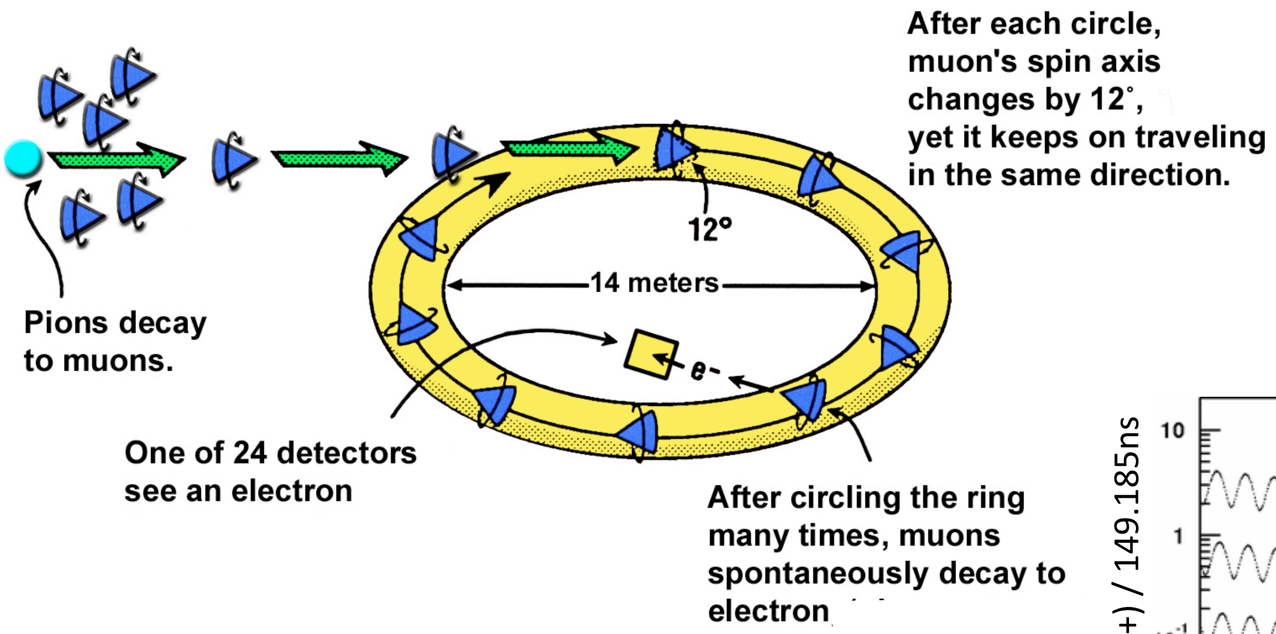
Pions decay to muons.

One of 24 detectors see an electron

After circling the ring many times, muons spontaneously decay to electron

N:
ENT

Direct Measurement of $(g\text{-}2)_\mu$



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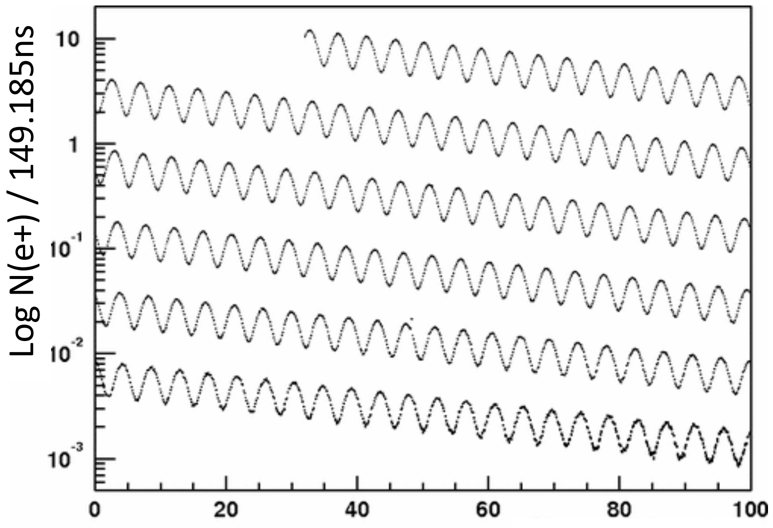
Positron counting rate (log scale)



time/ µs

$$\boxed{\omega_a = \omega_S - \omega_C = a_\mu \cdot \frac{e\,B}{m}}$$

ω_C: Cyclotron frequency

ω_S: Spin precession frequency

$$a_\mu^{exp} = (\,11\,659\,208.9 \pm 5.4_{stat} \pm 3.3_{syst}\,) \cdot 10^{-10}$$

BNL E821 '06

BNL → FNAL, A new $(g\text{-}2)_\mu$ Experiment

Upcoming $(g\text{-}2)_\mu$ Measurements

Naohito Saito

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$

BNL/FNAL Approach

J-PARC Approach

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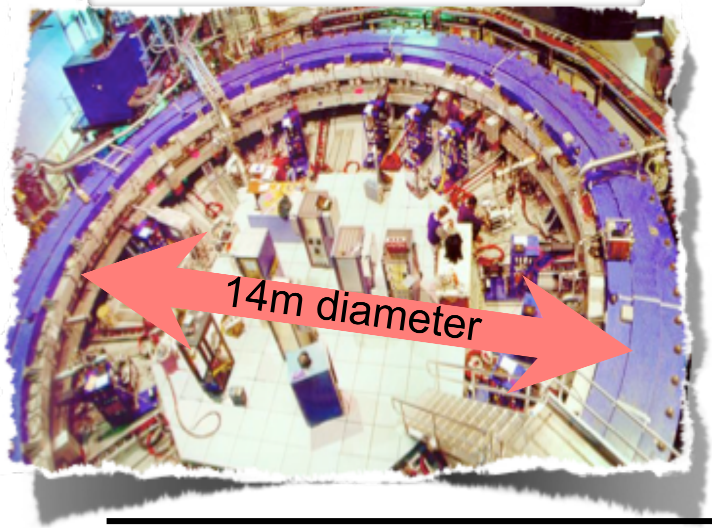
$$\gamma_{\text{magic}} = 29.3$$

$$p_{\text{magic}} = 3.09 \text{ GeV}/c$$



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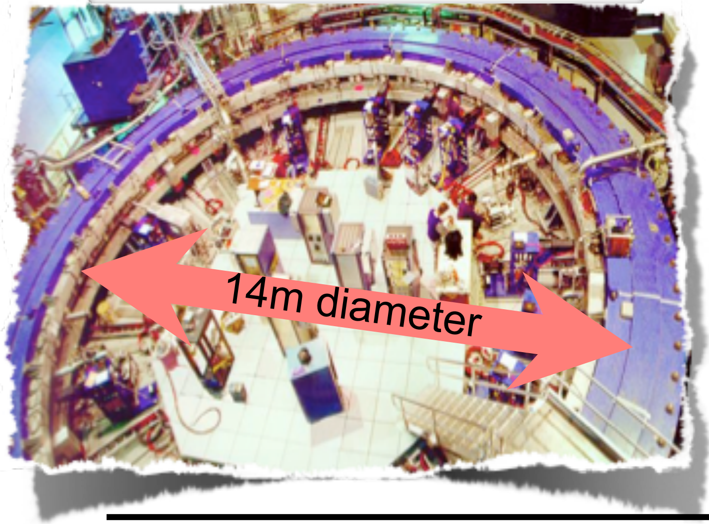
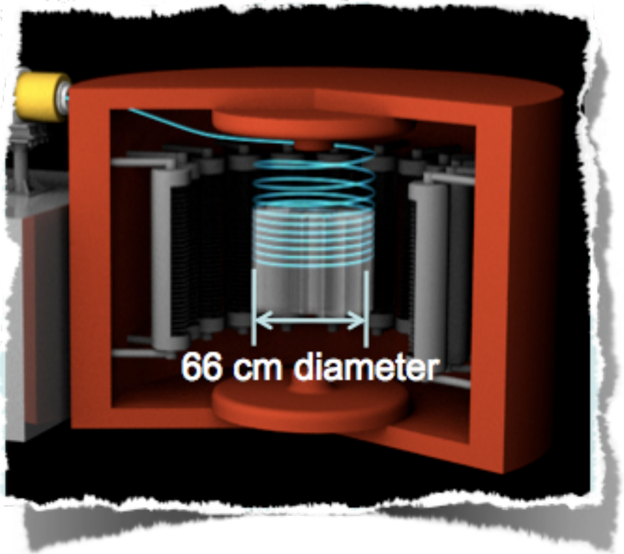


J-PARC Approach

$$\vec{E} = 0$$



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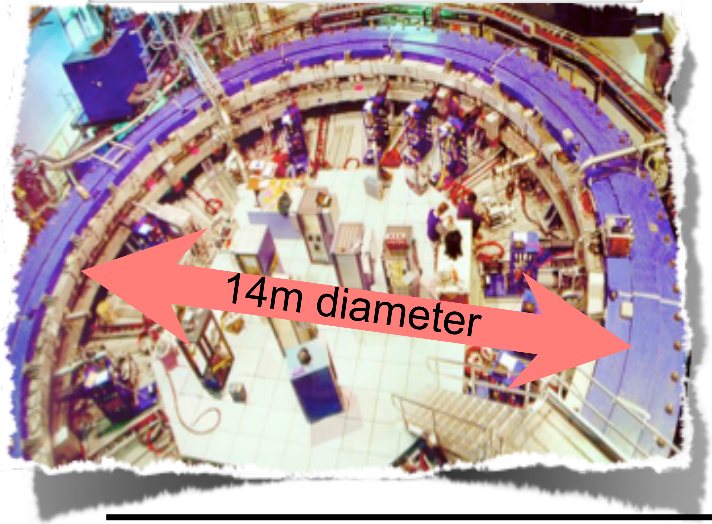

$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

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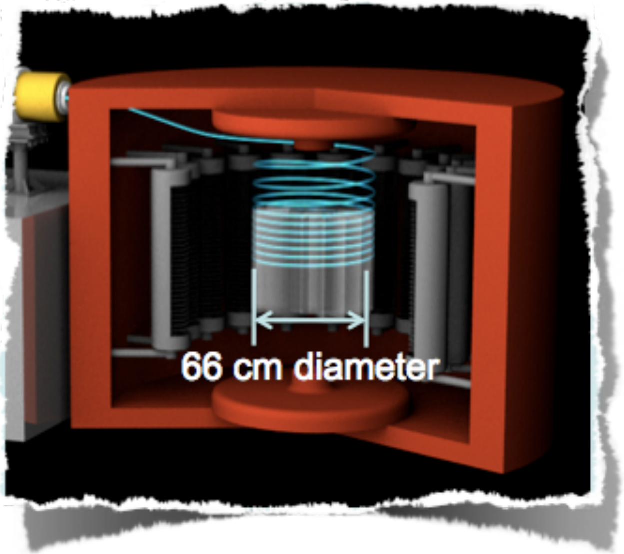

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BNL/FNAL Approach

- concept at FNAL as BNL/CERN
- higher muon statistics
- less pion contamination
- better control of systematics

J-PARC Approach

- table top experiment
- ultra-cold muons
- injection in 3T MRT magnet
- even larger muon statistics

Factor 4 improved accuracy

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

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

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had} = (11\,659\,182.8 \pm 4.9) \cdot 10^{-10}$$

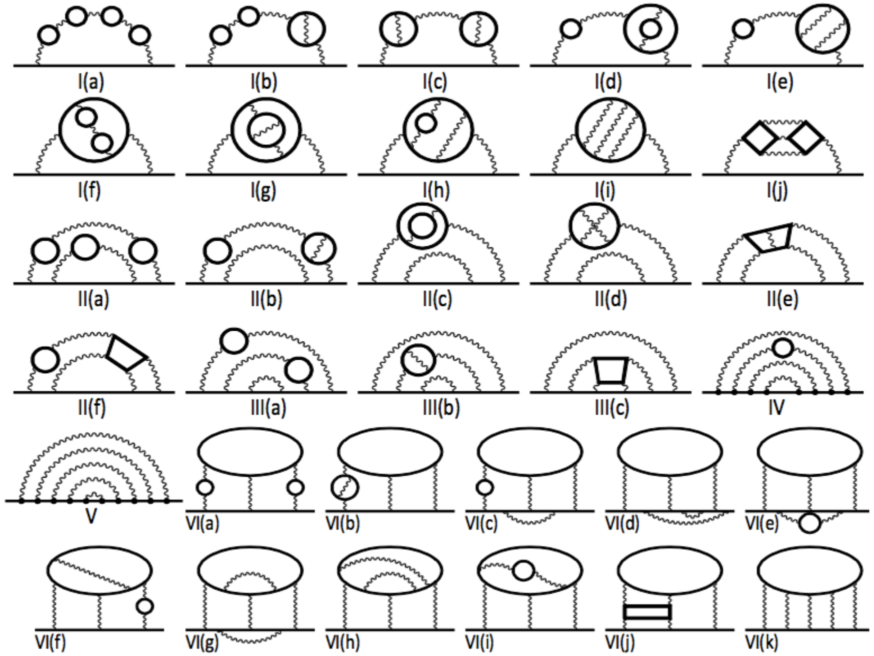
Czarnecki et al.

$(15.4 \pm \mathbf{0.2}) \cdot 10^{-10}$

Kinoshita et al. '12

$(11\,658\,471.808 \pm \mathbf{0.015}) \cdot 10^{-10}$

10th
12672
diagrams



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

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

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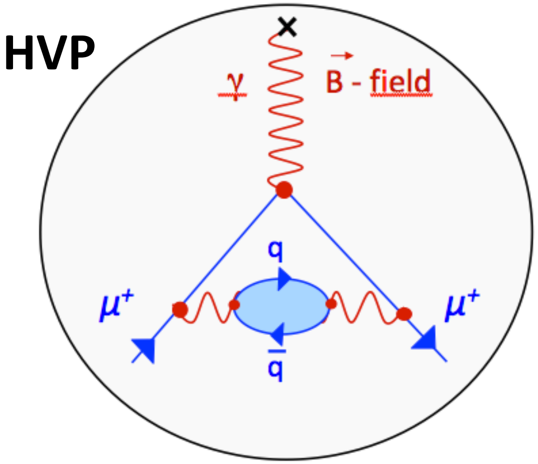
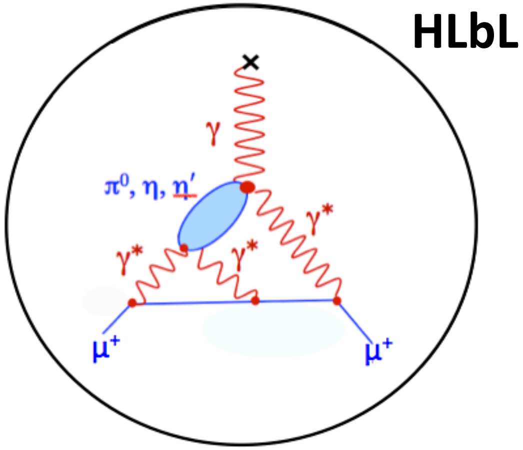
Teubnernet al. ‘11

→ **HVP**: Hadronic Vacuum Polarization (692.3 ± **4.2**) · 10^{-10}

NLO Hadronic Vacuum Polarization (-9.8 ± **0.1**) · 10^{-10}

→ **HLbL**: Hadronic Light-by-Light (10.5 ± **2.6**) · 10^{-10}





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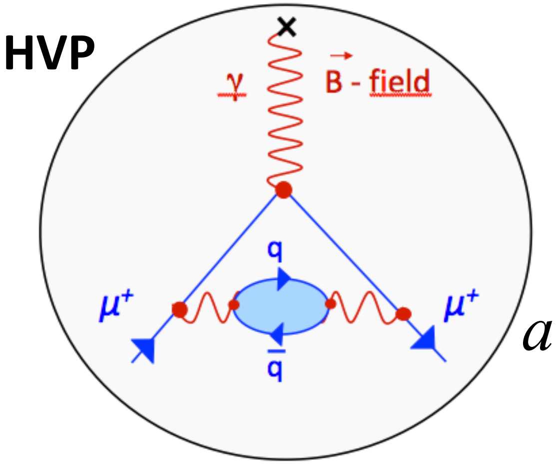


$$a_\mu^{HVP} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\,\sigma_{had}$$

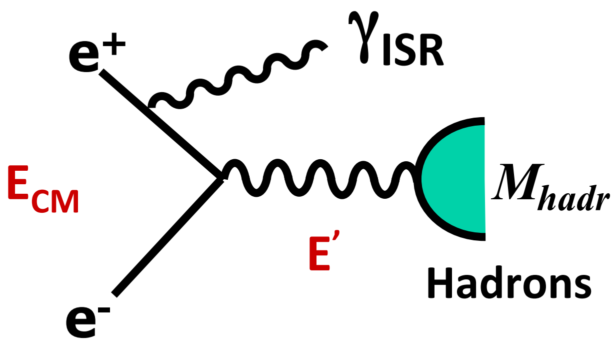
$$\sigma_{had} = \sigma(\,e^+e^- \rightarrow \; hadrons\,)$$

~ 1/s → Data below ~3 GeV needed!

Initial State Radiation

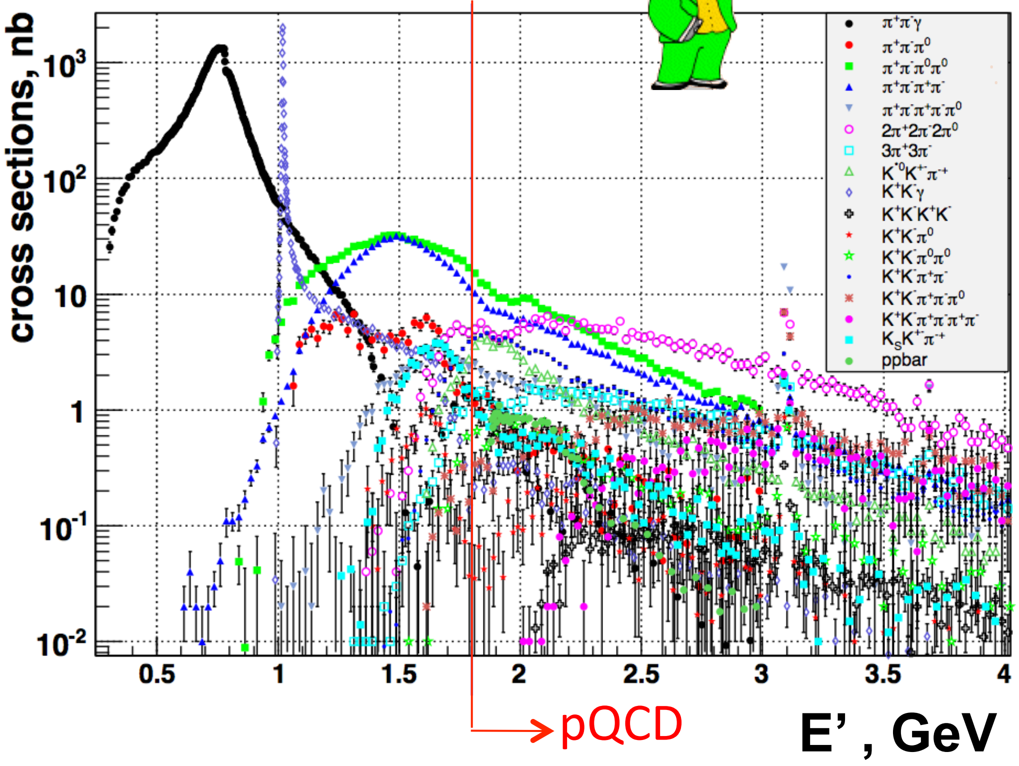
Rev. Mod. Phys. 83, 1545–1588 (2011)

Initial State Radiation (ISR) aka Radiative Return



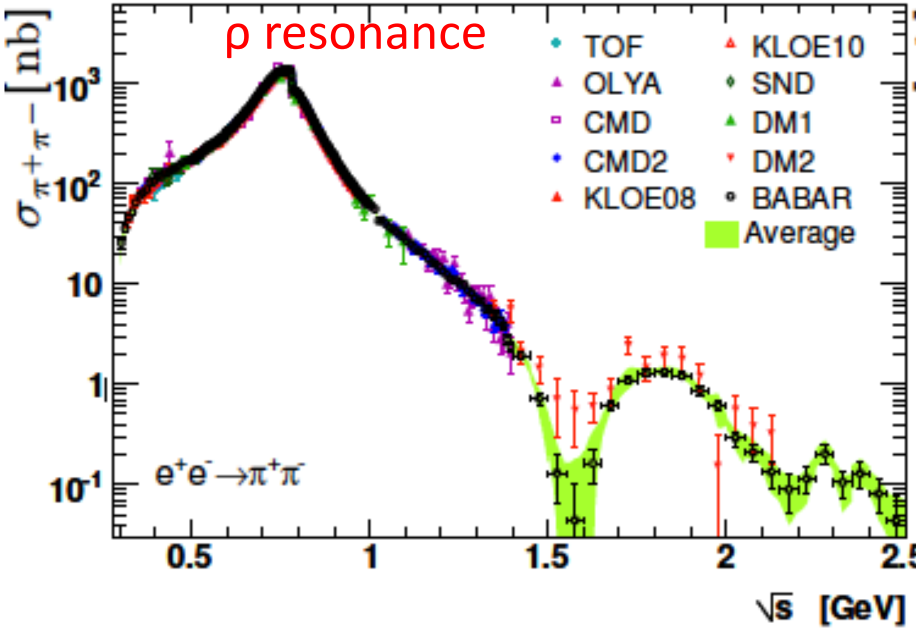
- Pioneered by KLOE '05
- Needs **no** systematic variation of beam energy (particle factories!)
- High statistics thanks to high integrated luminosities

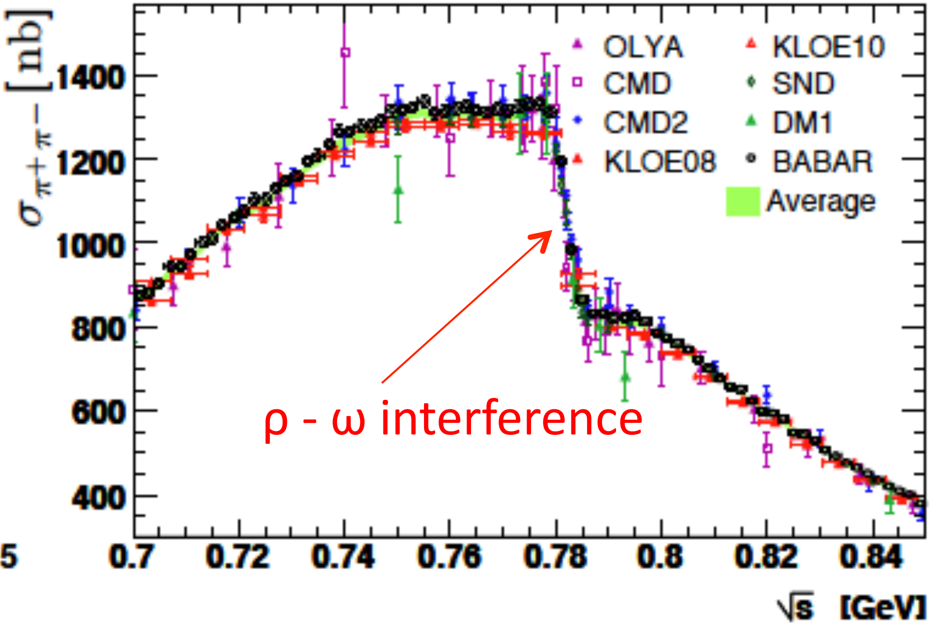
ISR spectra measured by **BABAR**



→ Entire E range <E_{CM} accessible

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



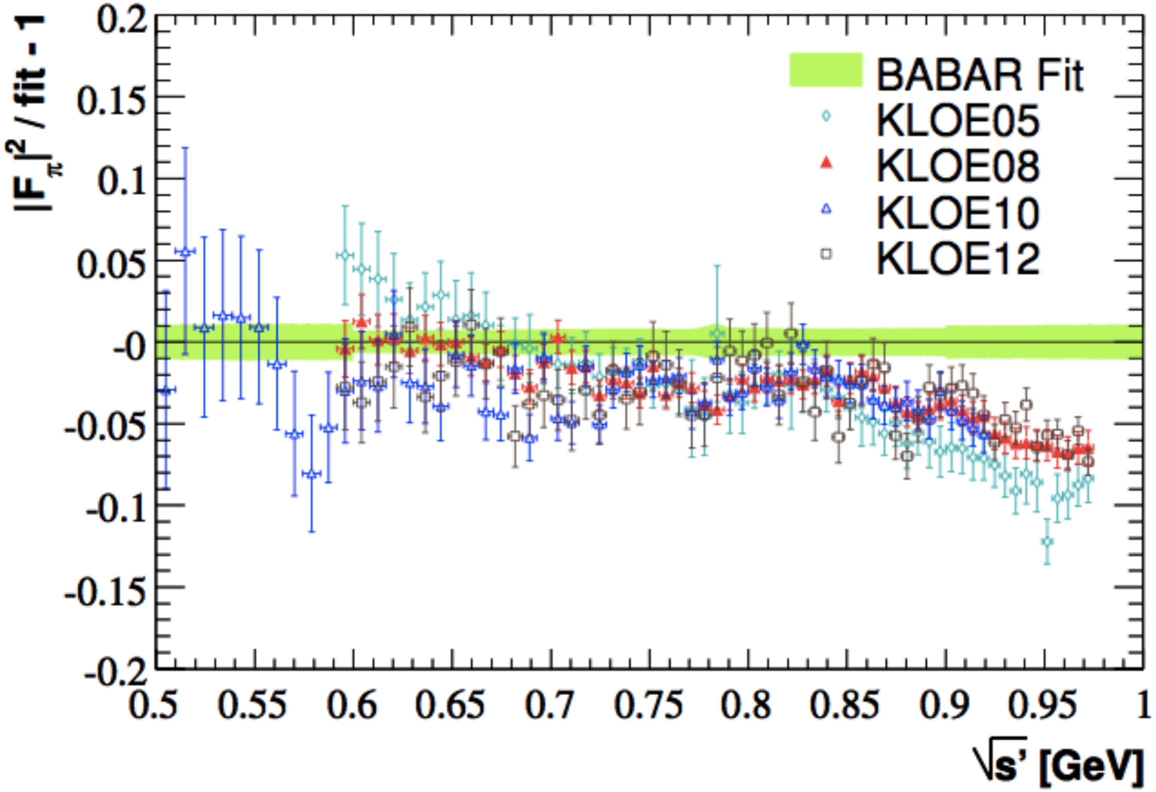


Systematic Uncertainties

- BABAR 0.5%
- KLOE 0.8%
- CMD2 0.8%*
- SND 1.5%*

* limited in addition by statistics

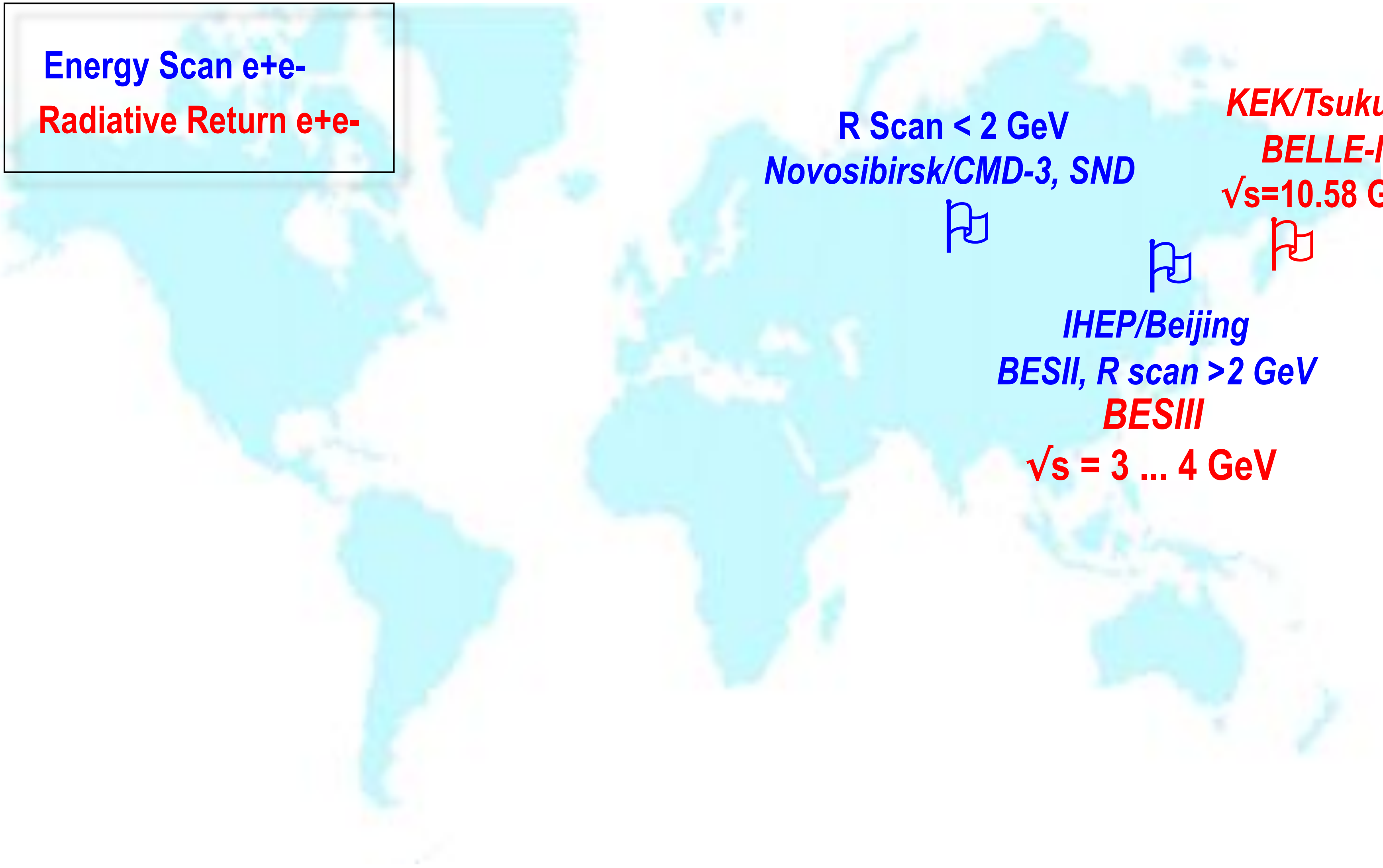
Most relevant Channel: $e^+e^- \rightarrow \pi^+\pi^-$



Note: KLOE05 superseded by KLOE08

- KLOE and BABAR dominate the world average
- Relatively large systematic differences, esp. above ρ peak
- Knowledge of a_μ^{had} dramatically limited due to this difference

Future Hadronic Cross Section Measurem.



Energy Scan e+e-

Radiative Return e+e-

R Scan < 2 GeV

Novosibirsk/CMD-3, SND

KEK/Tsukuba

BELLE-II

√s=10.58 GeV

IHEP/Beijing

BESII, R scan >2 GeV

BESIII

√s = 3 ... 4 GeV

Future Hadronic Cross Section Measurem.

Energy Scan e+e-

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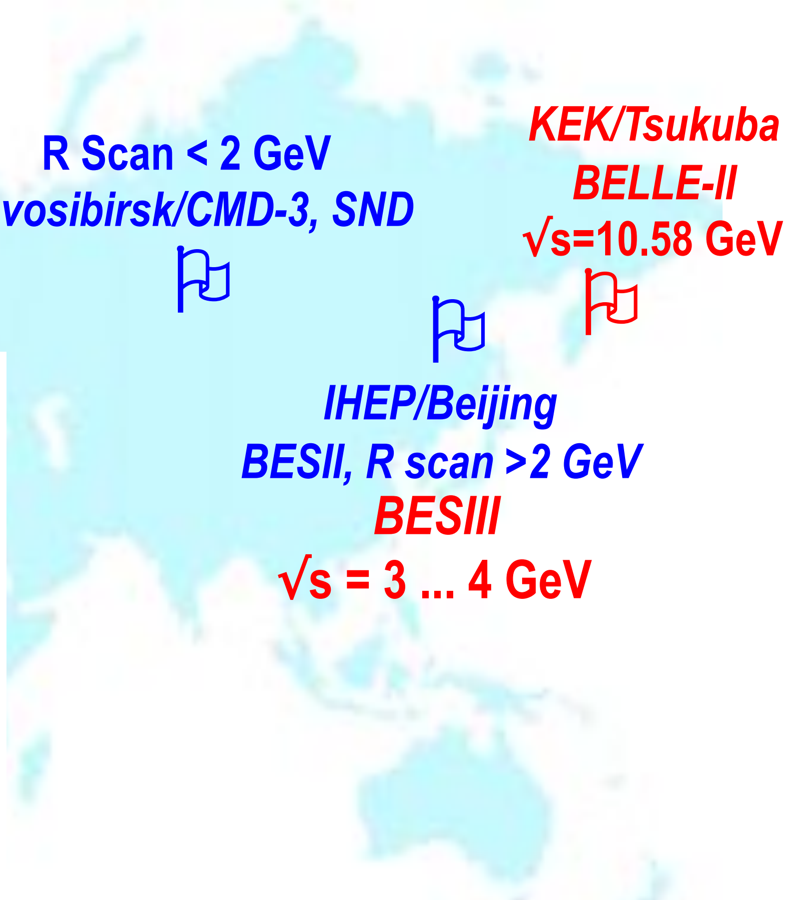

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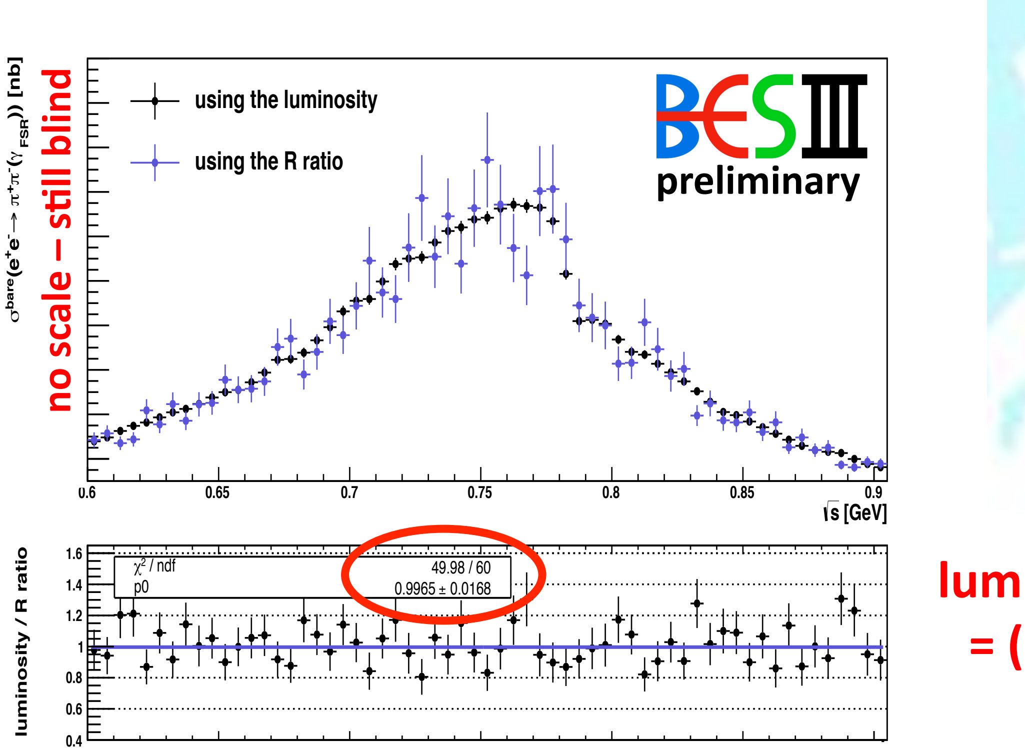
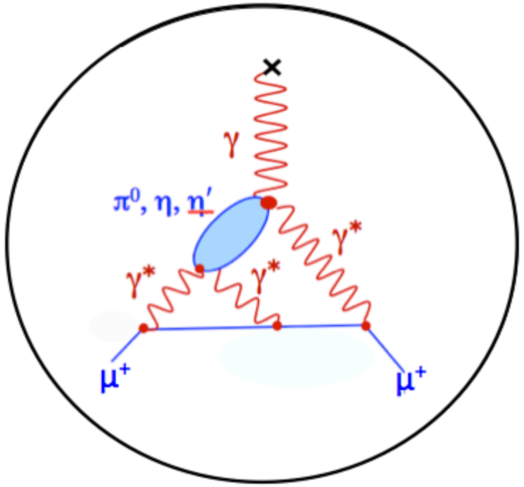


no scale – still blind

luminosity / R ratio
= (0.35 ± 1.68) %

limited by low $\mu\mu\gamma$ statistics

Hadronic Light-by-Light Scattering



a_μ^{HLbL} =(10.5 ± **2.6**) · 10^{-10}

Prades et al.

Based on phenomenological theoretical models (different groups find significantly larger values/errors)

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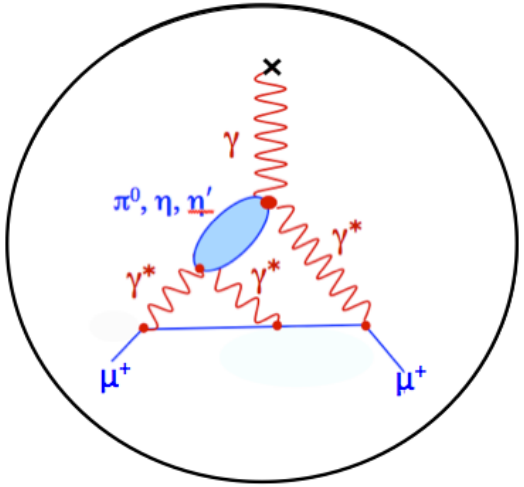

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Prades et al.

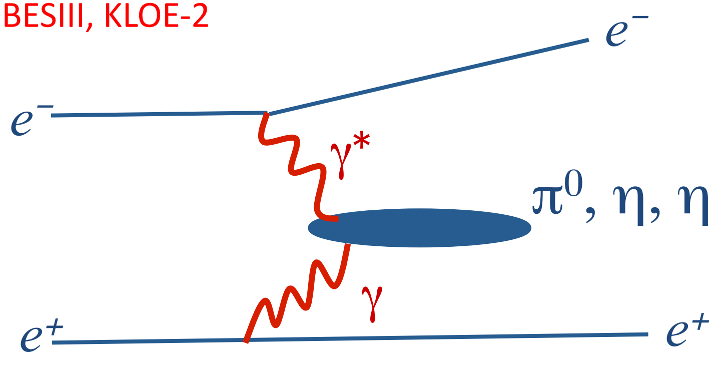
Based on phenomenological theoretical models (different groups find significantly larger values/errors)

Relation ?

⇔

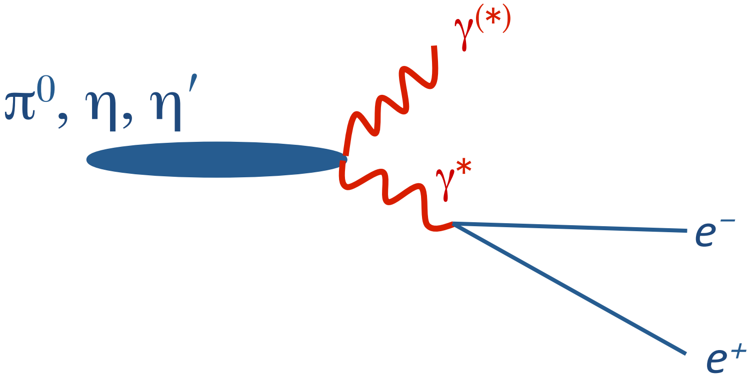
Exp. Input ?

BESIII, KLOE-2



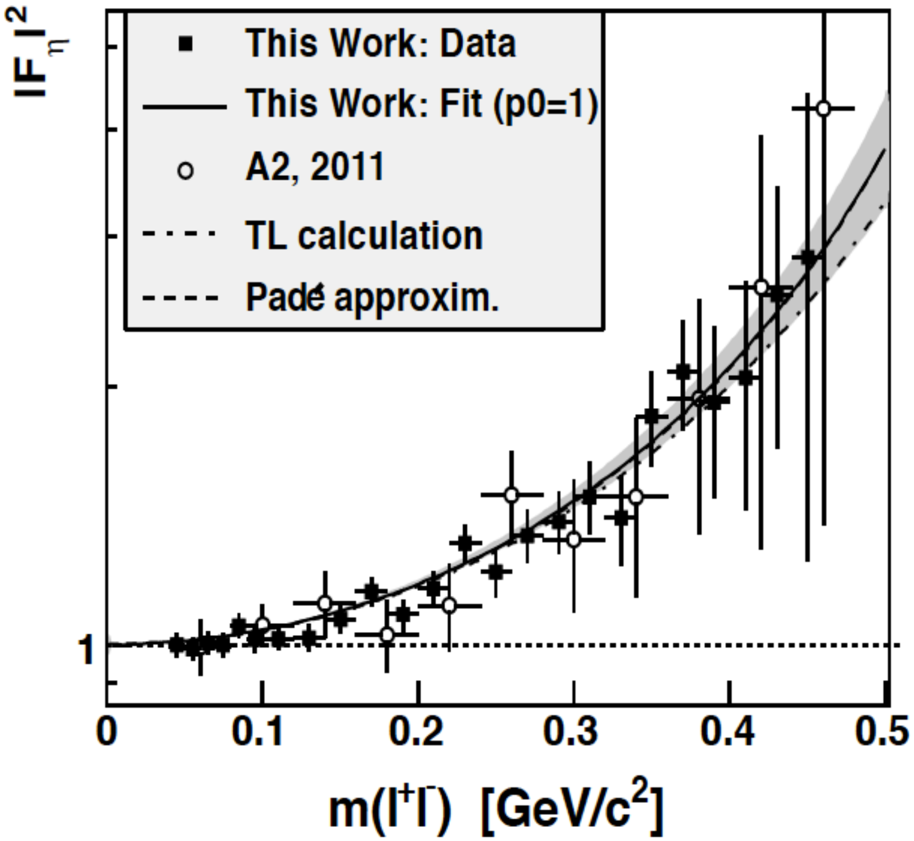
Dispersion Relations being developed using expt. input from γγ-scattering ! **Form Factors $F(Q^2)$!**

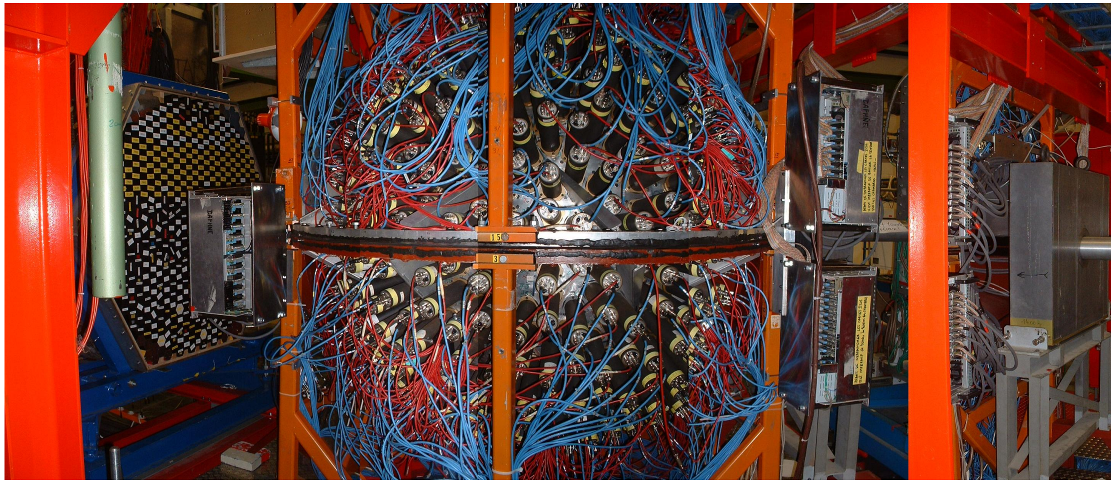
Vanderhaeghen et al., Colangelo et al. ‘14

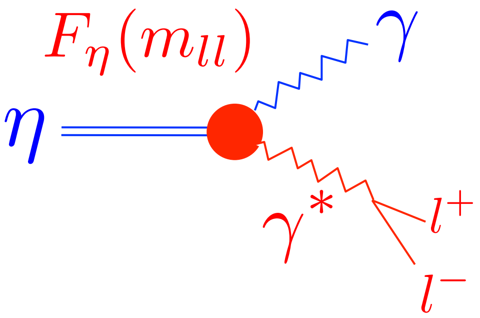


Crystal Ball: TL FF $\eta \to e^+e^-\gamma$

S. Prakhov, M. Unverzagt et al. (A2 collab.) '14







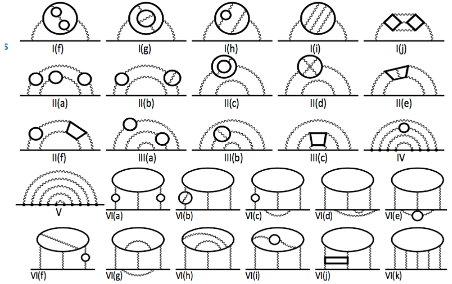
TL calculation: S. Leupold, C. Terschlüsen
Padé calculation: R. Escribano, P. Masjuan, P. Sanches-Puertas

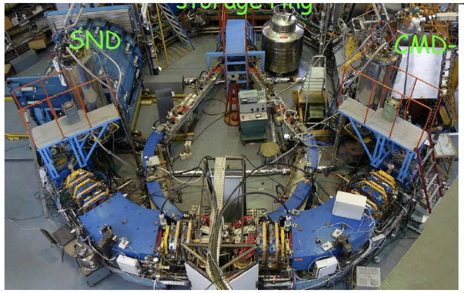
VMD pole model:
$\Lambda^{-2}=(1.95 \pm 0.15_{stat} \pm 0.10_{syst})$ GeV^{-2}

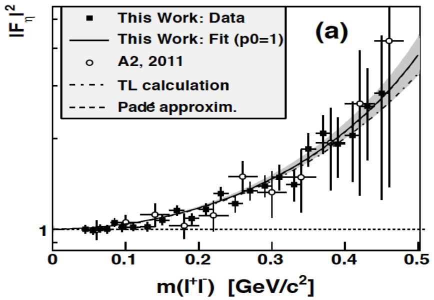
Conclusions & Outlook $(g\text{-}2)_\mu$

$(g\text{-}2)_\mu$ Experiment: Reduction of error by factor 4 !

$(g\text{-}2)_\mu$ Theory: Reduction of error by factor 2 !





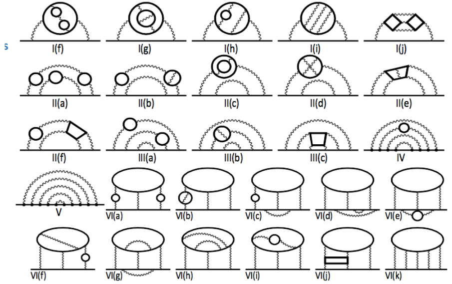


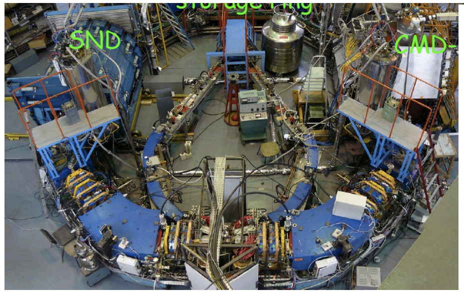
Conclusions & Outlook $(g\text{-}2)_\mu$

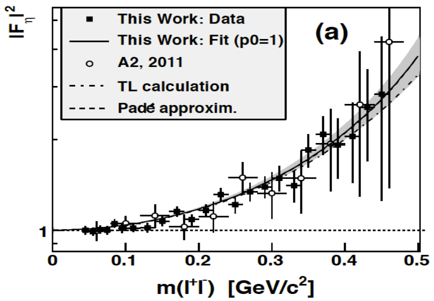
(g-2)$_\mu$ Experiment: Reduction of error by factor 4 !

Establish deviation at >>5σ level

(g-2)$_\mu$ Theory: Reduction of error by factor 2 !



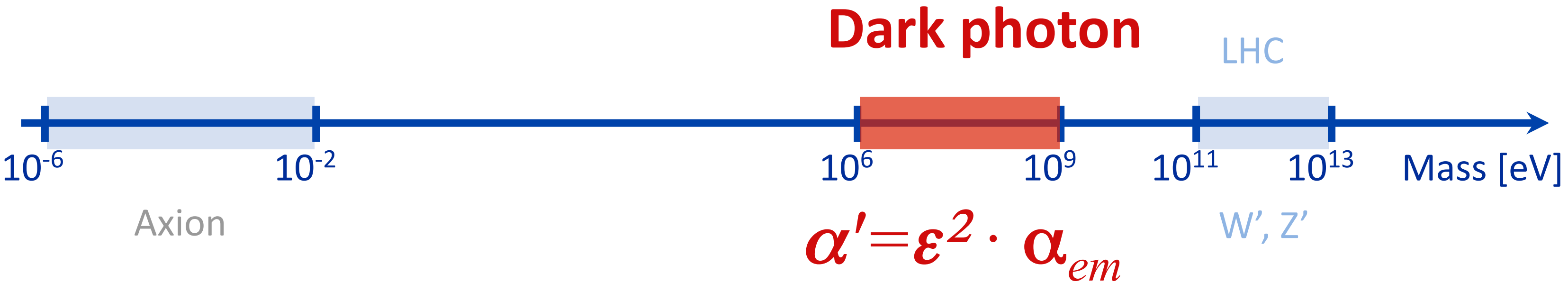




The
Dark Photon

Dark Photon Search

New massive force carrier of extra U(1)$_d$ gauge group; predicted in almost all string compactifications



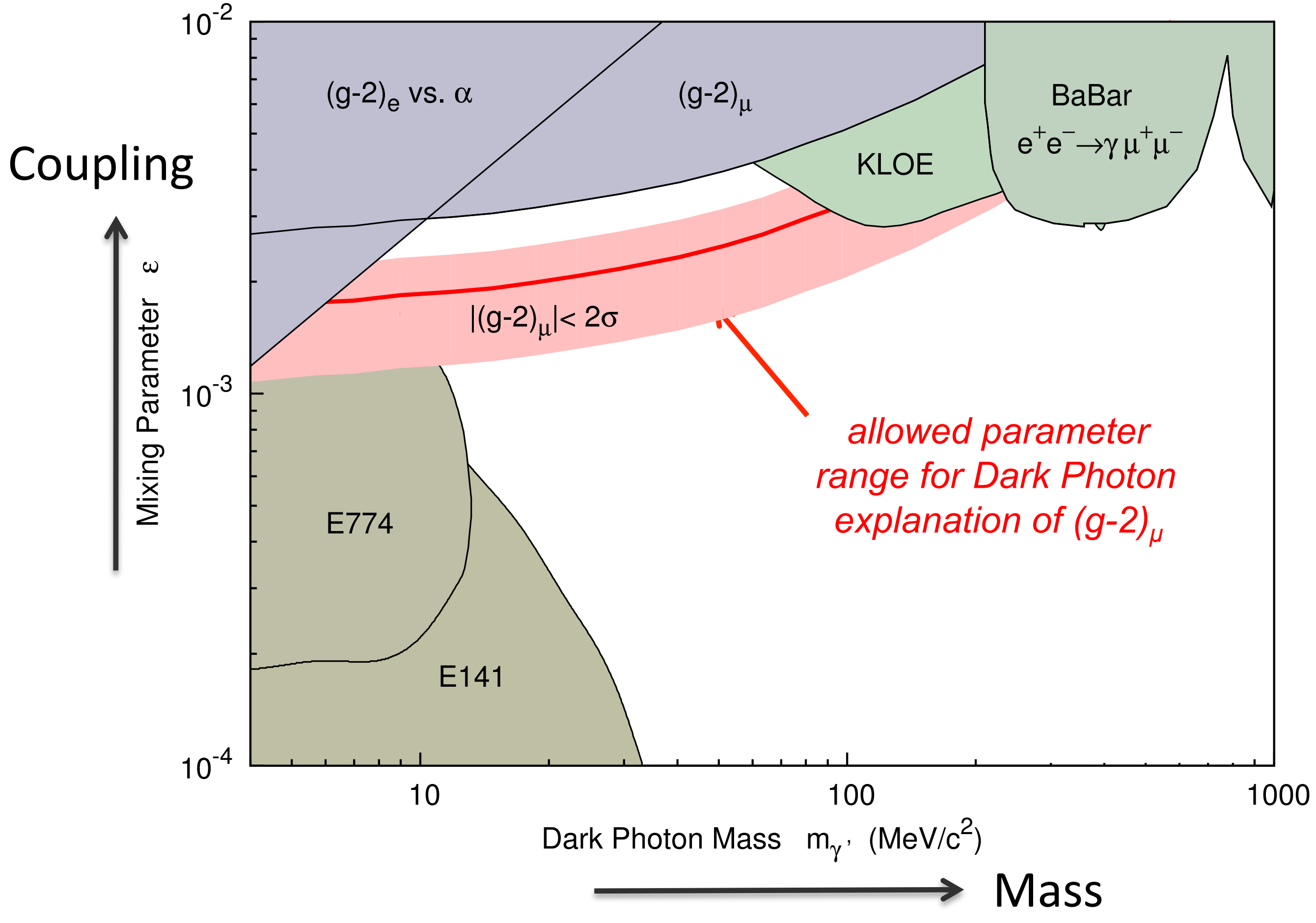
Search for the O(GeV/c^2) mass scale in a world-wide effort

- Could explain large number of **astrophysical anomalies**
  `Arkani-Hamed et al. (2009)`
  `Andreas, Ringwald (2010); Andreas, Niebuhr, Ringwald (2012)`

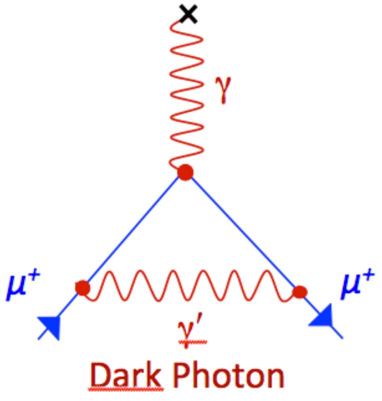
- Could explain presently seen **deviation of >3σ** between **(g-2)$_\mu$** Standard Model prediction and direct (g-2)$_\mu$ measurement
  `Pospelov(2008)`

The $(g\text{-}2)_\mu$ Parameter Range

Status 2011



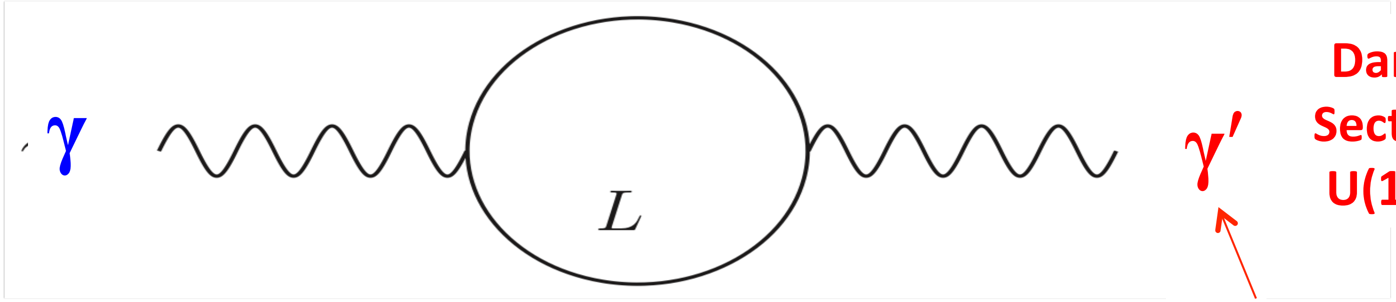
allowed parameter range for Dark Photon explanation of $(g\text{-}2)_\mu$



Kinetic Mixing and the Dark Sector

Holdom 86

A portal to relate the dark sector to the SM world (coupling ~ ε^2)



Standard Model Sector U(1)

Dark Sector $U(1)_d$

Heavy Charged Leptons *L*
(carry $U(1)_d$ charge)

Dark Photon
(aka A′, U, Z_d, ...)

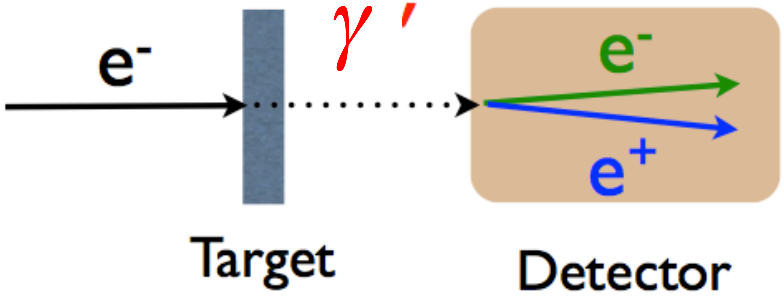
Features à la Arkani-Hamed: A theory of Dark Matter

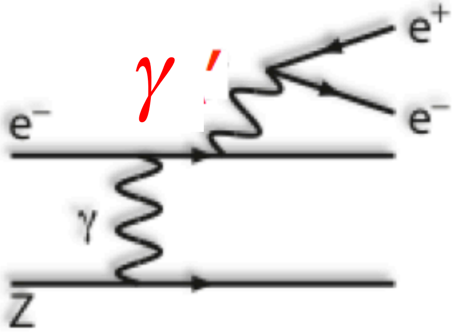
- More than one Dark Matter particle → Dark Sector
- dm + dm → e+e- explains positron excess
- Astrophysical anomalies (PAMELA, FERMI, DAMA/LIBRA, INTEGRAL, ...) suggest dark photon mass on GeV mass scala (and lighter than $2M_p$)

Searches using Fixed-Target Experiments

Low-energy, high-intensity accelerators (MAMI, JLAB) are ideally suited for Dark Photon searches!

Bjorken, Essig, Schuster, Toro (2009)





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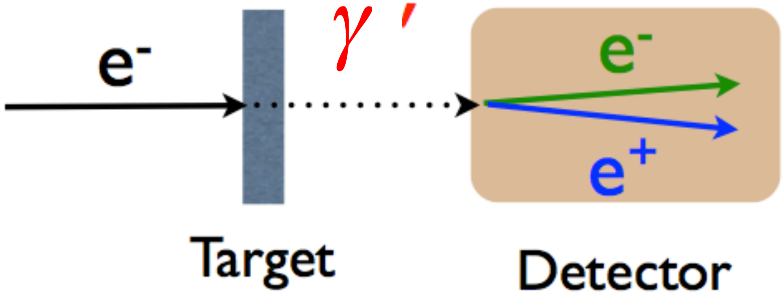
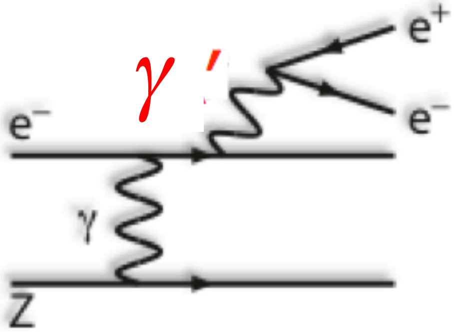
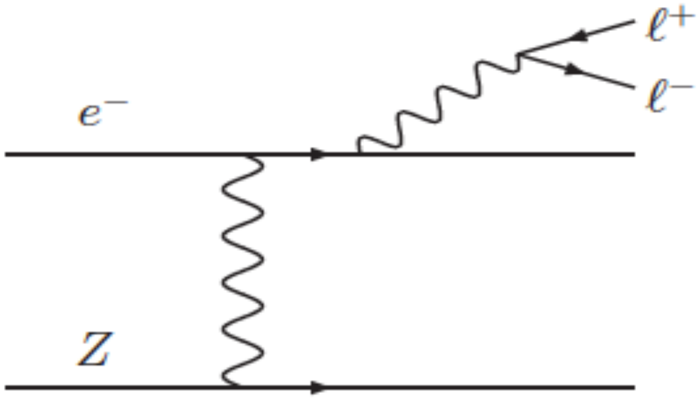
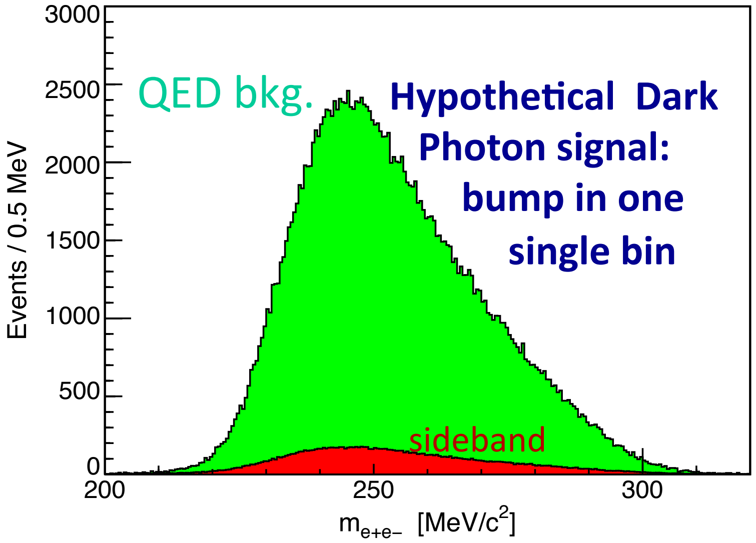




QED background processes:



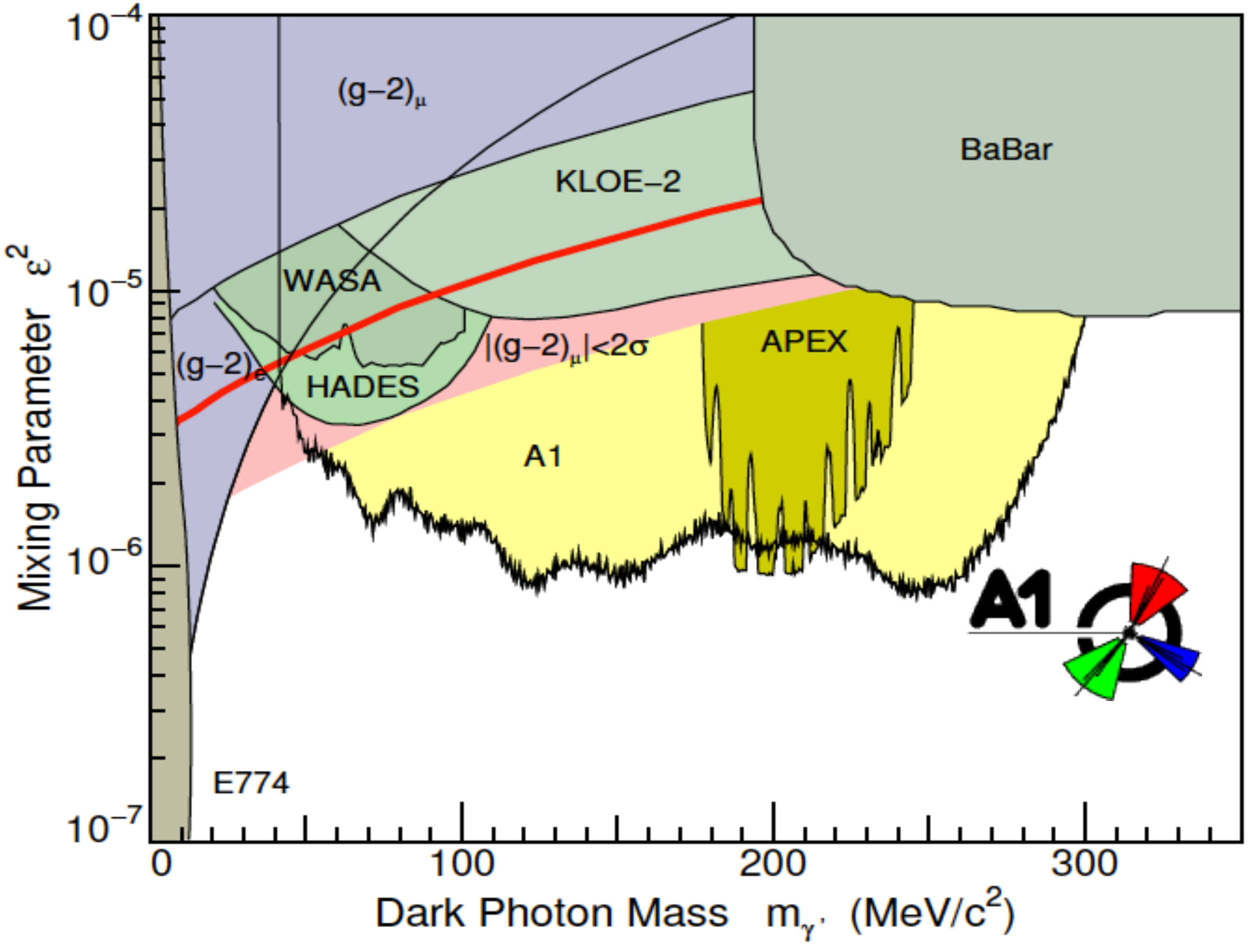
(a)

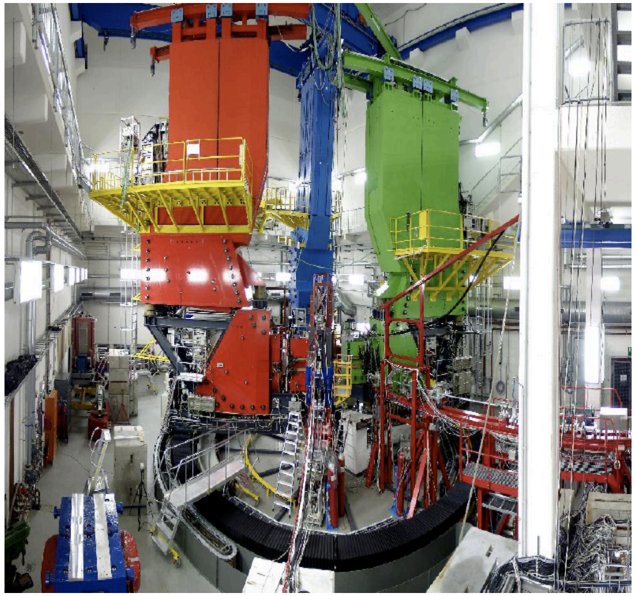


Hypothetical Dark Photon signal: bump in one single bin

MAMI Results (A1 collaboration)

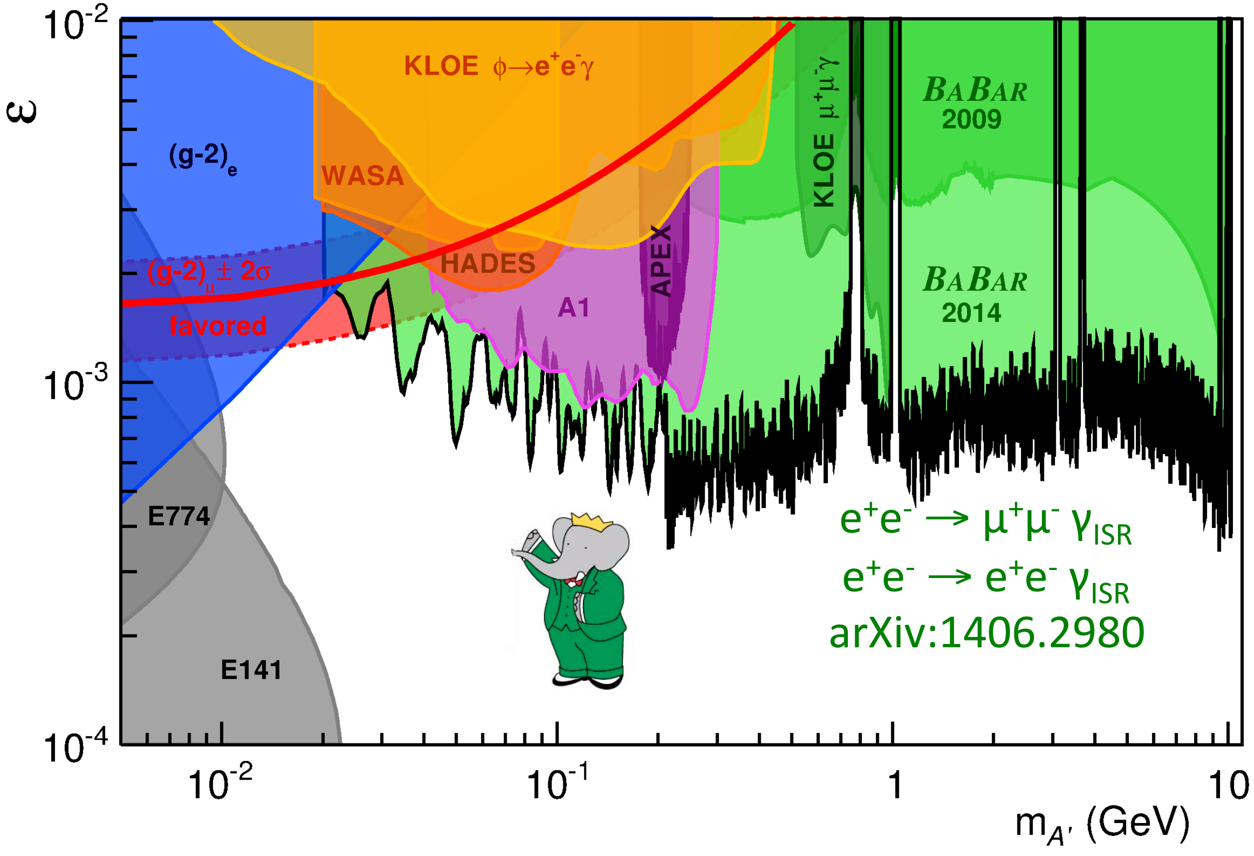
Phys. Rev. Lett. 112 (2014), 221802

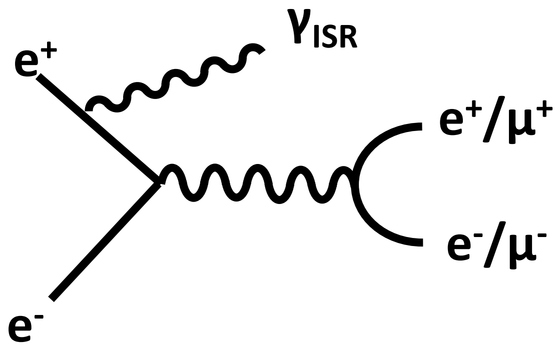




3 weeks of beamtime

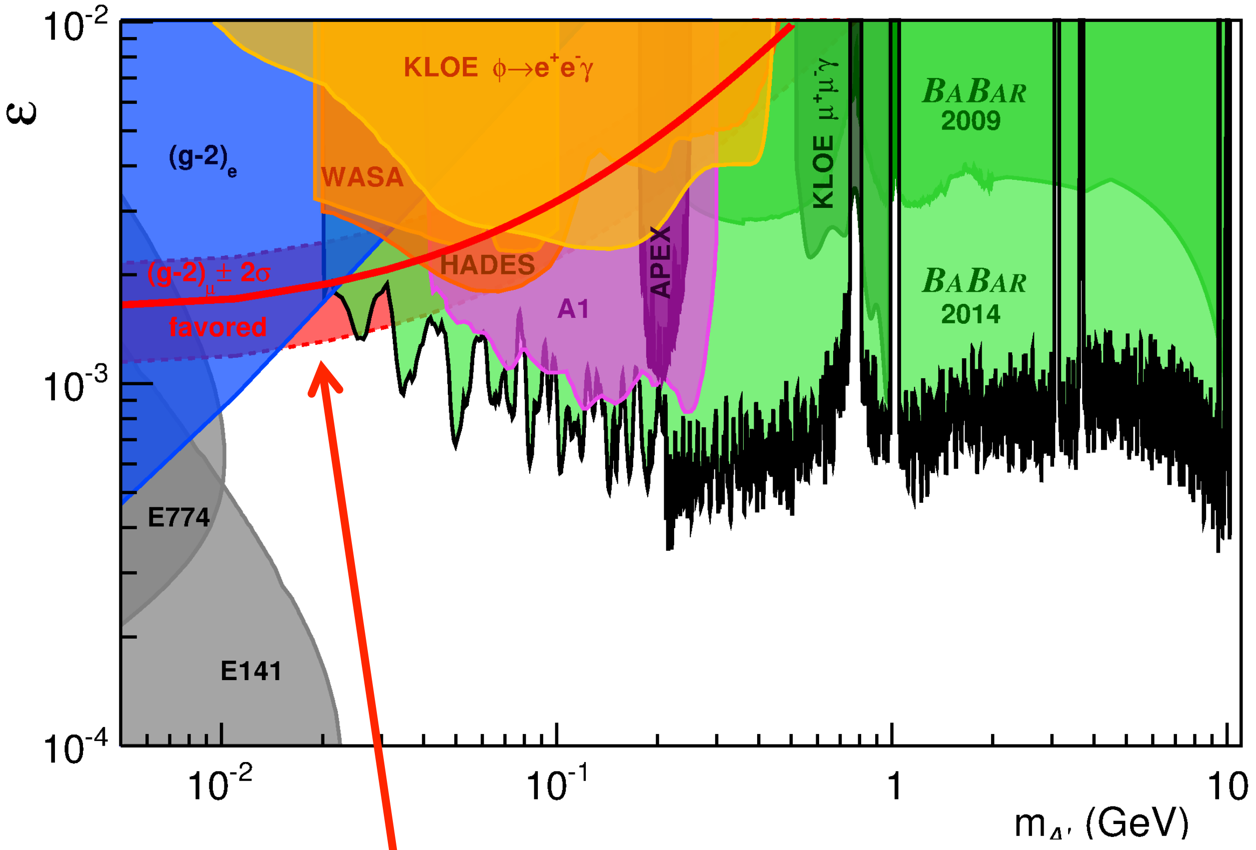
BABAR Dark Photon Search (arXiv:1406.2980)





Analysis of the full data set
(10 years)

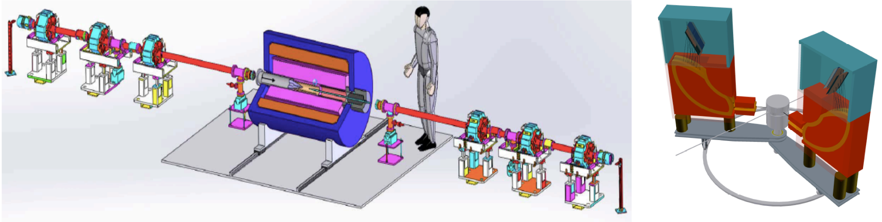
BABAR Dark Photon Search (arXiv:1406.2980)



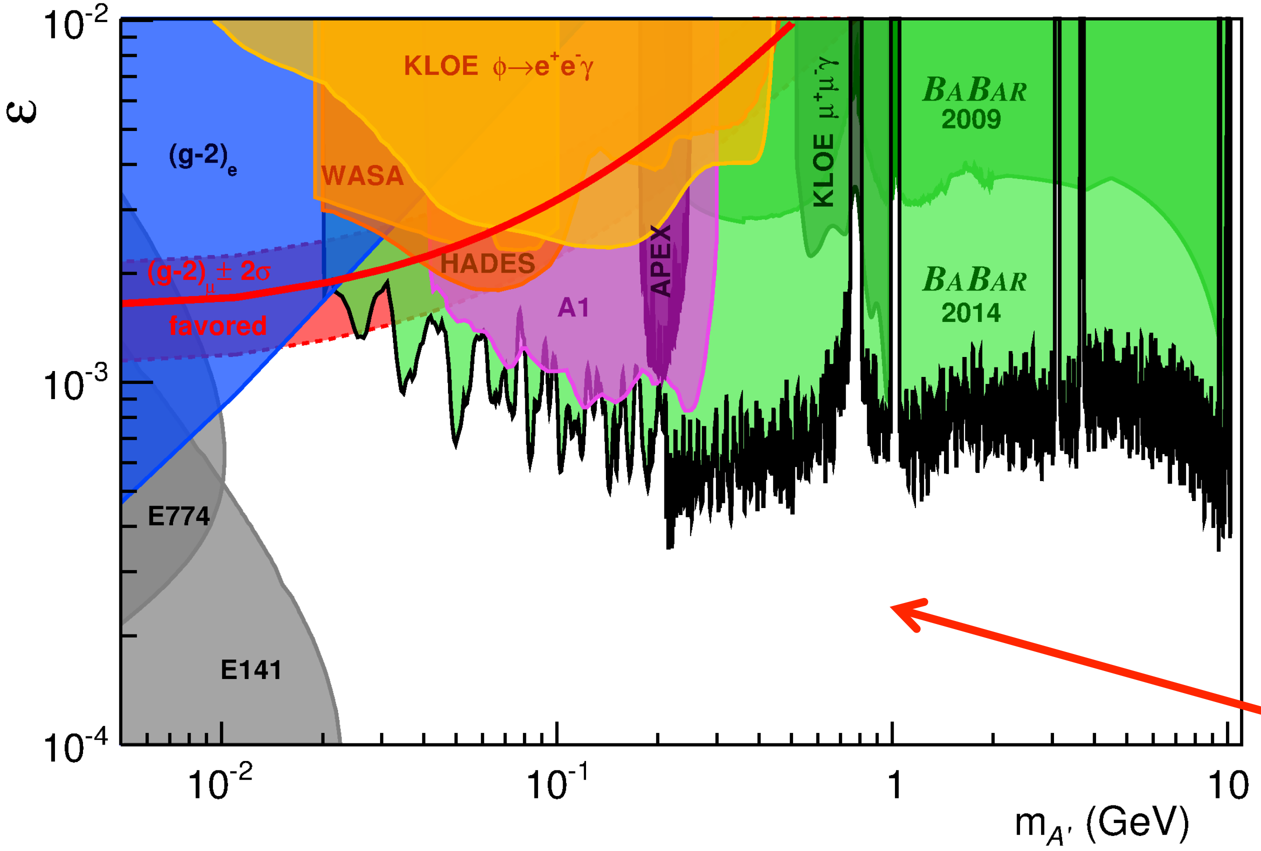
Remaining $(g-2)_\mu$ welcome region!?

Dark Light @ JLAB

MESA @ Mainz



BABAR Dark Photon Search (arXiv:1406.2980)

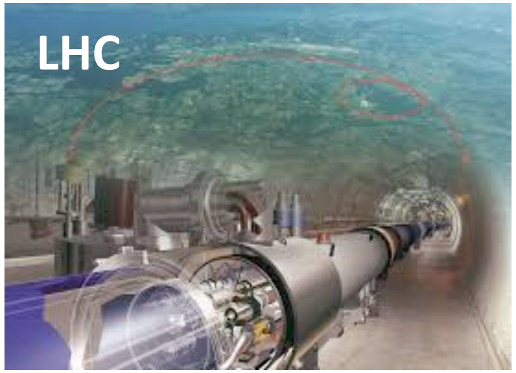


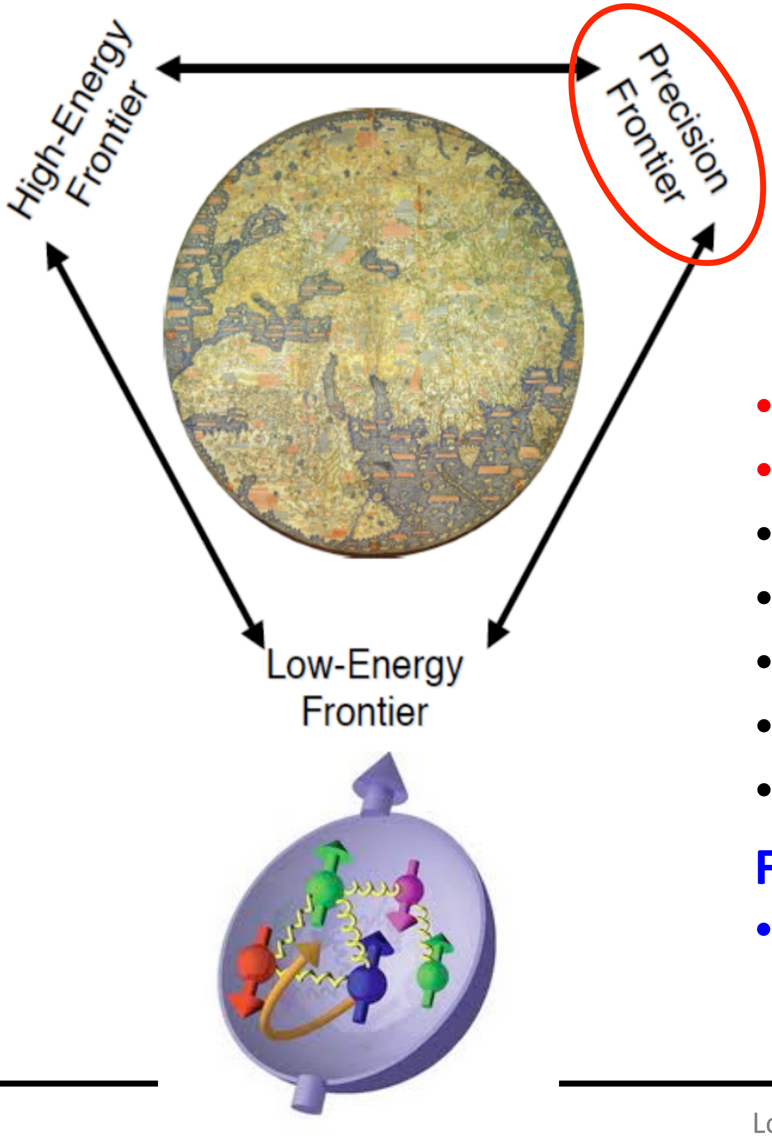
Entire remaining white region (JLAB APEX, HPS)

Interesting in view of dark sector

Conclusions

The Frontiers of Particle Physics





- $(g-2)_\mu$
- New light gauge bosons
- Proton radius puzzle
- EDMs
- LFV (e.g. $\mu \rightarrow e\gamma$)
- Flavour CKM Physics
- ……

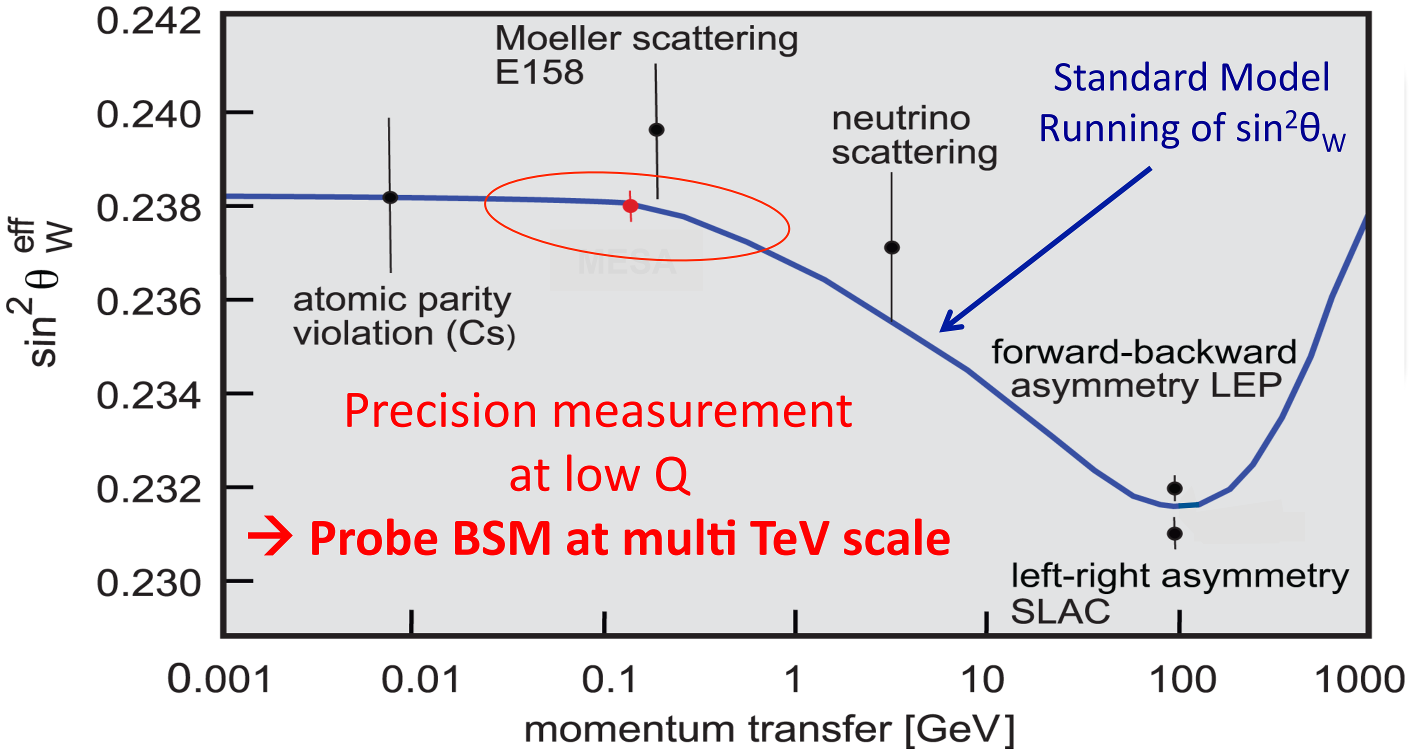
Future:

- low-energy $\sin^2 Q_W$

EW Mixing Angle $sin^2\Theta_W$ at Low Energies

$$\sin^2\Theta_W = (e/g)^2 = 1 - (M_W/M_Z)^2$$

A quantity which incorporates $SU(2)_L xU(1)_Y$ + Higgs Mechanism+ Renormalizability



Standard Model Running of $\sin^2\theta_W$

Precision measurement at low Q

→ **Probe BSM at multi TeV scale**

Parity Violating Electron Scattering

Scattering of longitudinally polarized electrons on protons / electrons

→ **Z boson exchange** introduces **parity-violating effect**
→ Measure **parity-violating Left-Right cross section asymmetry A_{LR}**

$$A_{LR} = \frac{\sigma(e\uparrow) - \sigma(e\downarrow)}{\sigma(e\uparrow) + \sigma(e\downarrow)} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W - \underset{\substack{\uparrow \\ \text{hadron structure}}}{F(Q^2)}\right)$$

$$Q_W = 1 - 4\sin^2\theta_W(\mu)$$

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$$Q_W = 1-4\sin^2\theta_W(\mu)$$

hadron structure

3 projects at JLAB (1.2 GeV, 11 GeV) and MESA/Mainz (0.1 GeV):

- **QWEAK@JLAB (6 GeV), data taking finished**
- **P2@MESA (0.1 GeV), in preparation**
- **Moeller@JLAB (11 GeV), in preparation**

PANIC2020 :

$\Delta\sin^2\theta_W$ 4 x 10^{-4}

(Thursday afternoon session)

Thank you!


NEW HADRONS
DARK MATTER PARTICLES
EXTRA DIMENSIONS
CP VIOLATION
MATTER ANTIMATTER OSCILLATIONS
HIGGS BOSON
EXOTIC PARTICLES
WZ PRODUCTION
TOP QUARK PROPERTIES
SUPER-SYMMETRY
W MASS

Additional slides

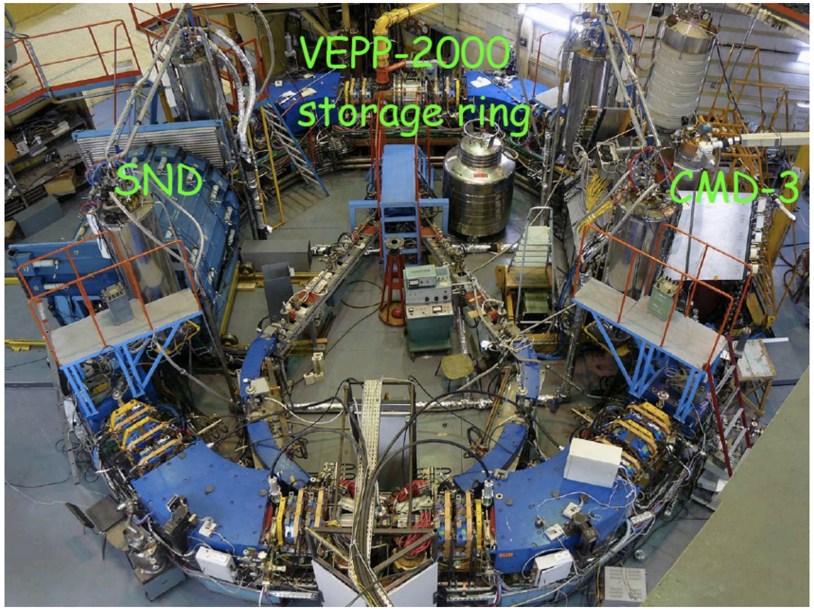
Energy Scan < 2 GeV at Novosibirsk

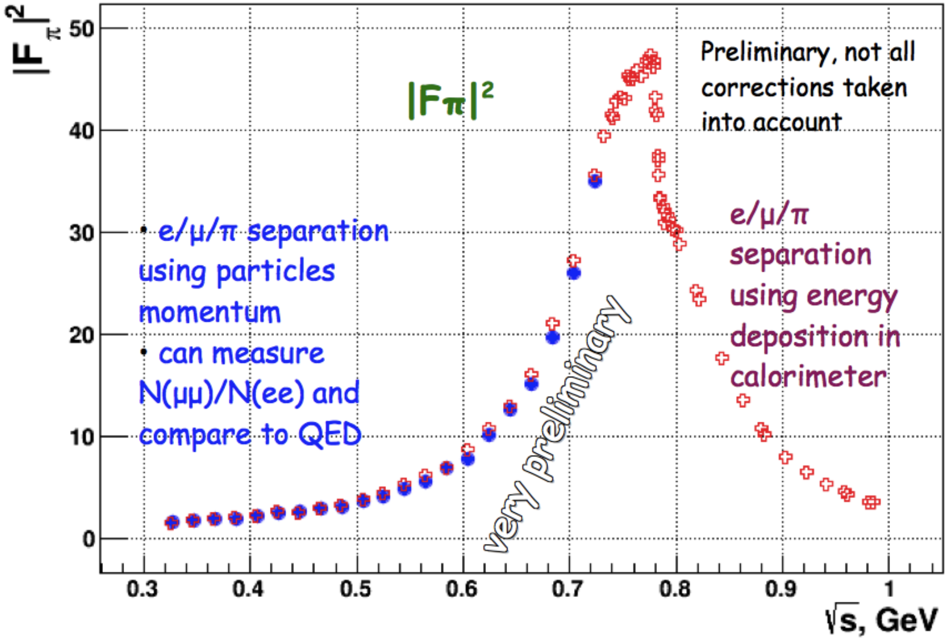
VEPP-2000 (since 2010):

- Classical energy scan technique, no ISR
- Upgrade of detectors CMD-3, SND,
- $L_{max} = 10^{32}\ cm^{-2}\ s^{-1}$ at 2 GeV, 20% reached

→ concept of round beams

→ already now competitive in statistics





Preliminary, not all corrections taken into account

- e/μ/π separation using particles momentum
- can measure N(μμ)/N(ee) and compare to QED

e/μ/π separation using energy deposition in calorimeter

Absolute μ+μ-γ cross section measured with 0.5% accuracy!

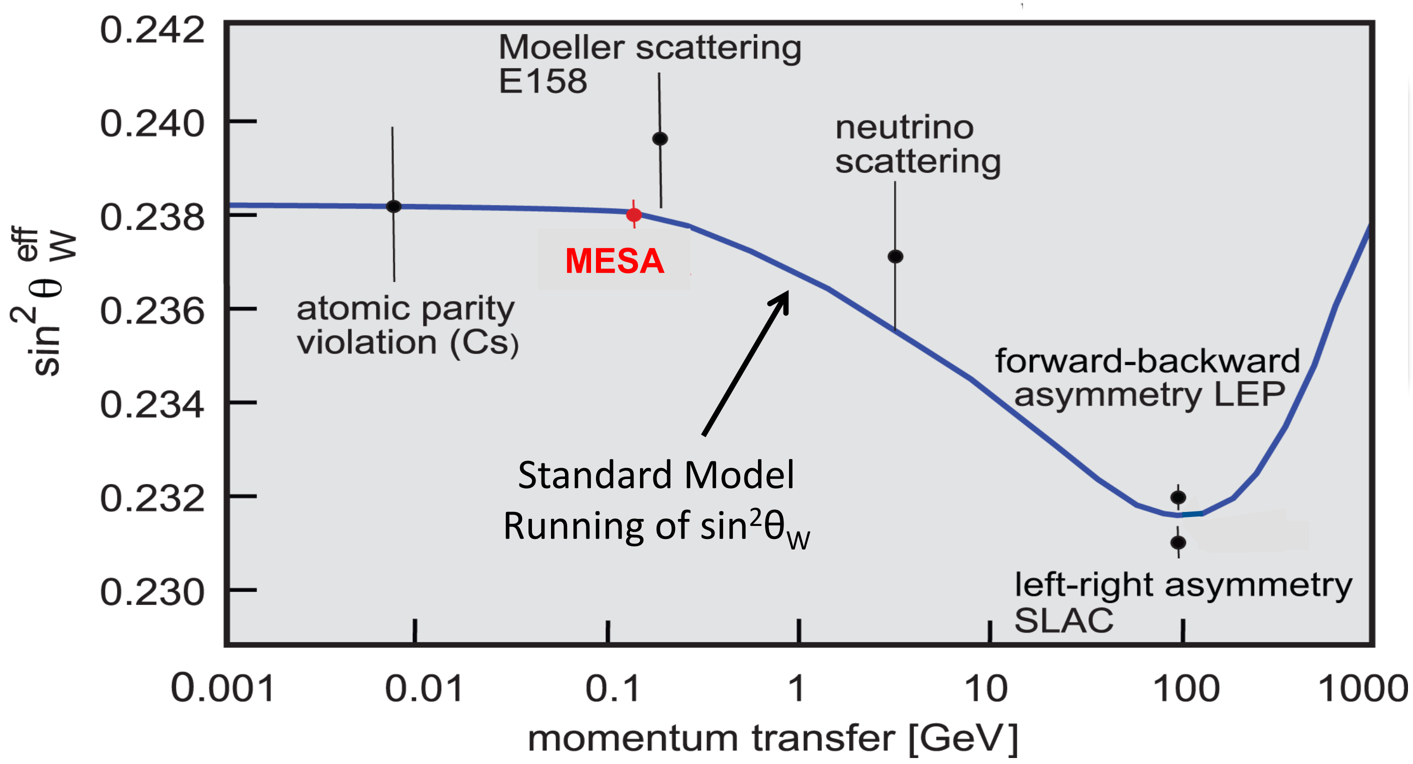
MESA contribution to $\sin^2\theta_W$

Scattering of long. polarized electrons (150 MeV) on protons

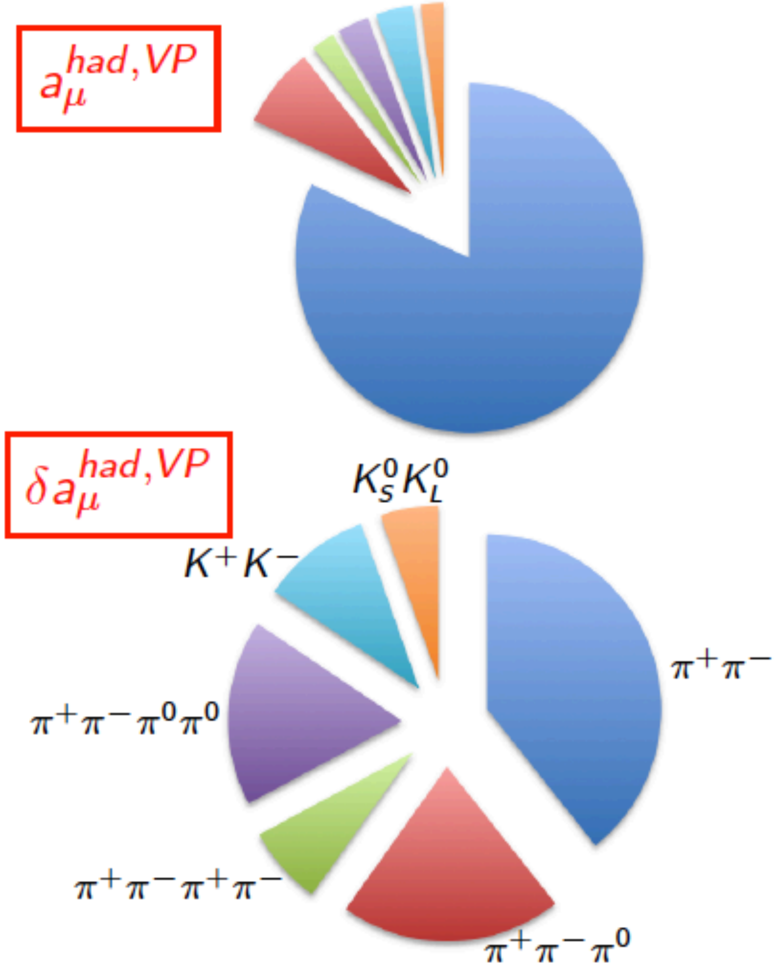
→ **Z boson exchange** introduces **parity-violating effect**

→ Measure **Parity-violating Left-Right cross section asymmetry A_{LR} of 20×10^{-9}**

MESA: $\Delta\sin^2\theta_W = 4 \times 10^{-4}$



Summary (g-2)$_\mu$



Future improvement of a_μ^{had} ?

1st priority:
Clarify situation regarding $\pi^+\pi^-$
(KLOE vs. BABAR puzzle)

2nd priority:
Measure 3π, 4π channels

3rd priority:
$K\bar{K}$ and higher multiplicities

Dark Photon Search in a world-wide Effort

WASA@COSY
HADES@GSI

Dalitz decays pseudoscalar mesons

$\pi^0 \rightarrow e^+e^-\gamma$
$\eta \rightarrow e^+e^-\gamma$

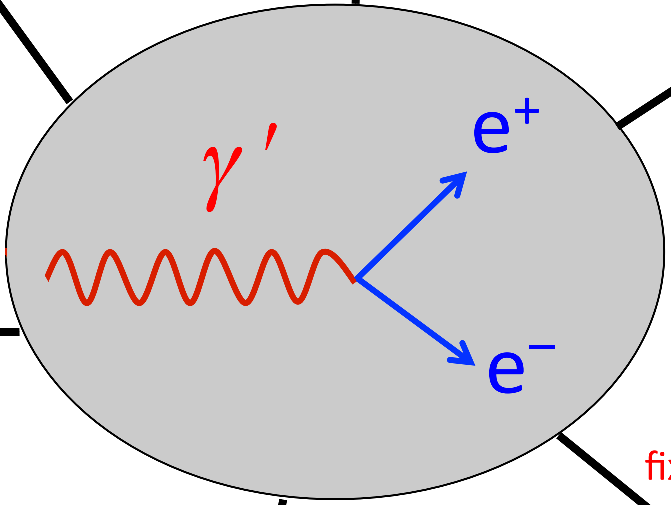
KLOE, BABAR, BESIII@Beijing

e+e- particle factories
ISR production of γ'

KLOE@Frascati
BABAR@SLAC

Radiative meson decays

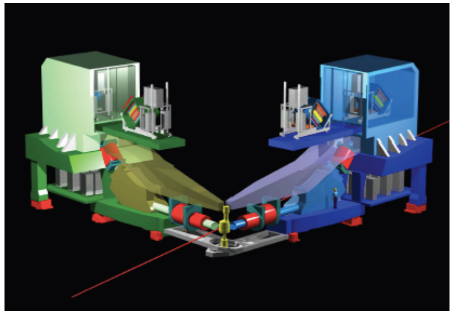
$\Phi \rightarrow \eta e^+e^-$
$\Upsilon(4S) \rightarrow \mu^+\mu^-\gamma$



APEX @ JLAB

fixed target

HR spectrometer
+ septum magnet
→ extend MAMI range



fixed target

Dark Light @ JLAB
MESA@Mainz

Low mass region < 50 MeV

fixed target

HPS@ JLAB

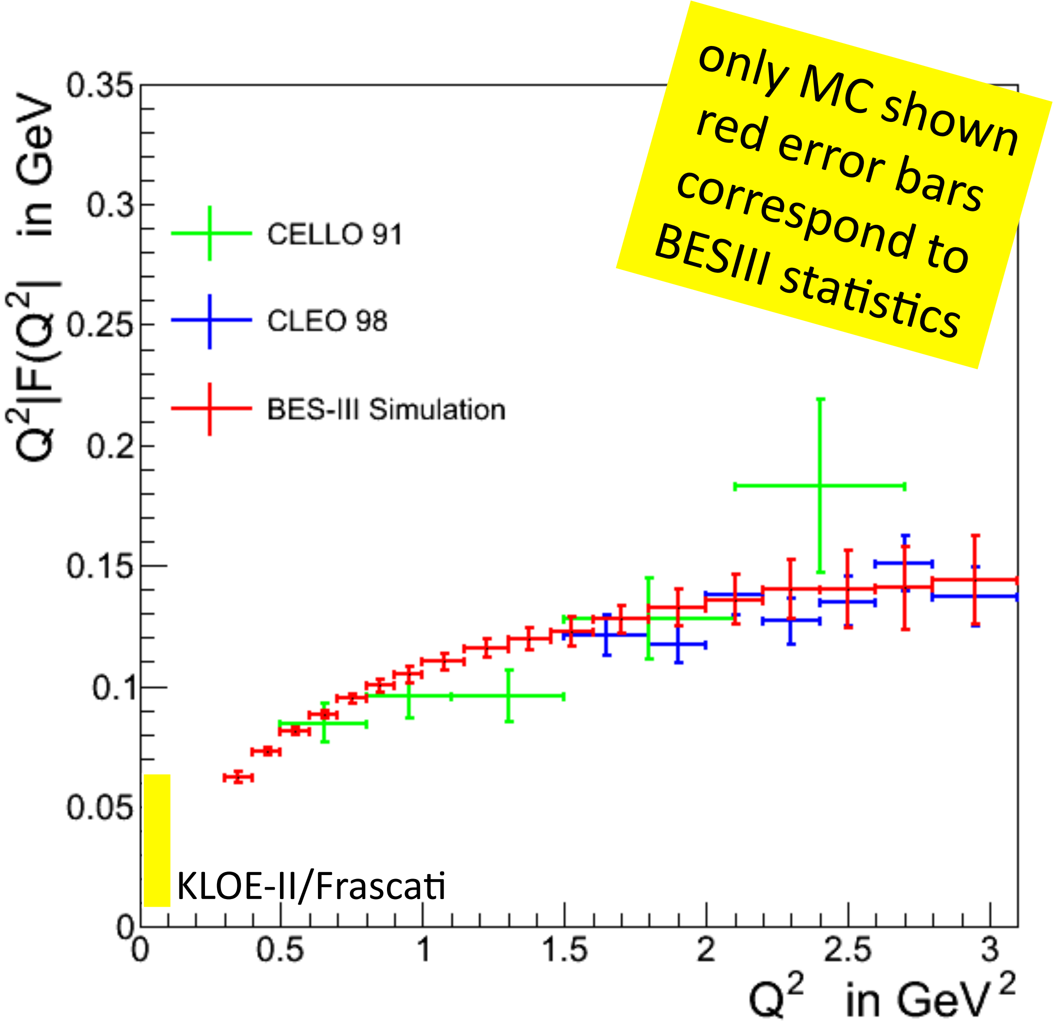
Hall B, 2015

Displaced vertex technique
→ sensitivity to low ε region;
Si vertex trigger, $PbWO_4$ EMC

BESIII

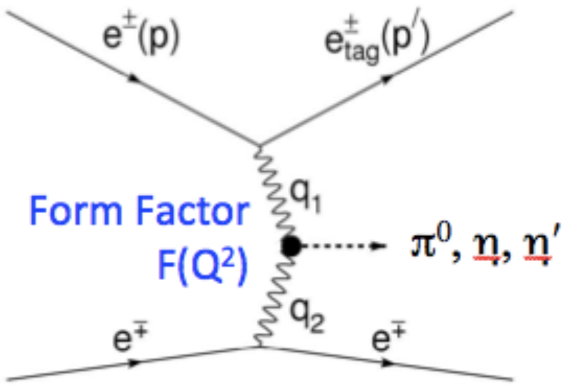
BESIII preliminary

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL



only MC shown red error bars correspond to BESIII statistics

Single Tag Method



Form Factor $F(Q^2)$

Unprecedented accuracy $Q^2 < 1.5$ GeV^2

most relevant range for HLbL

Outline

Anomalous Magnetic Moment of the Muon $(g\text{-}2)_\mu$

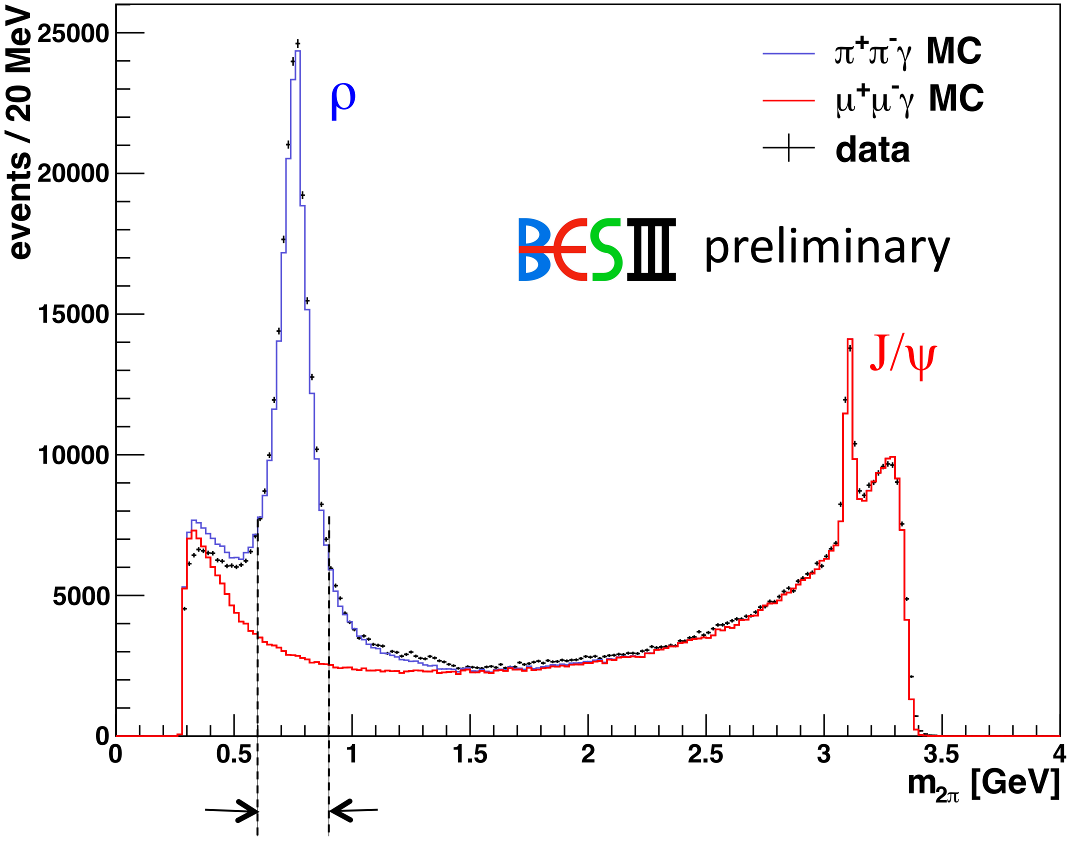
- $(g\text{-}2)_\mu$ Overview
- Experiment: Towards a New Measurement of $(g\text{-}2)_\mu$
- SM Prediction: Hadronic Vacuum Polarization
  Hadronic Light-by-Light Contribution

Dark Photons

- Overview
- Recent Searches for the Dark Photon

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

Event yield after acceptance cuts **only**



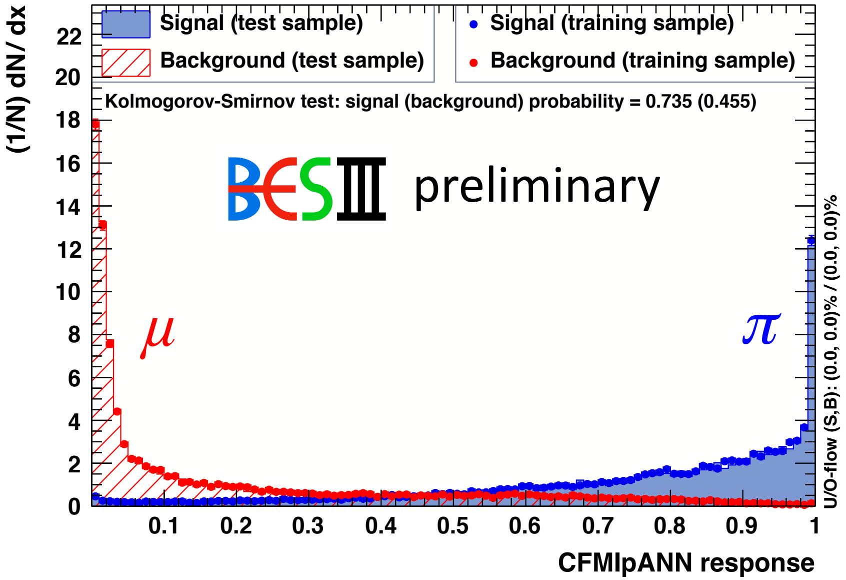
initial publication
600 – 900 MeV

Features:

- $\psi(3770)$ data only (2.9 fb^{-1})
- no dedicated background subtraction
- tagged ISR photon

→ large statistics of e+e- → ππγ events
→ background dominated by e+e- → μμγ
→ data – MC differences visible

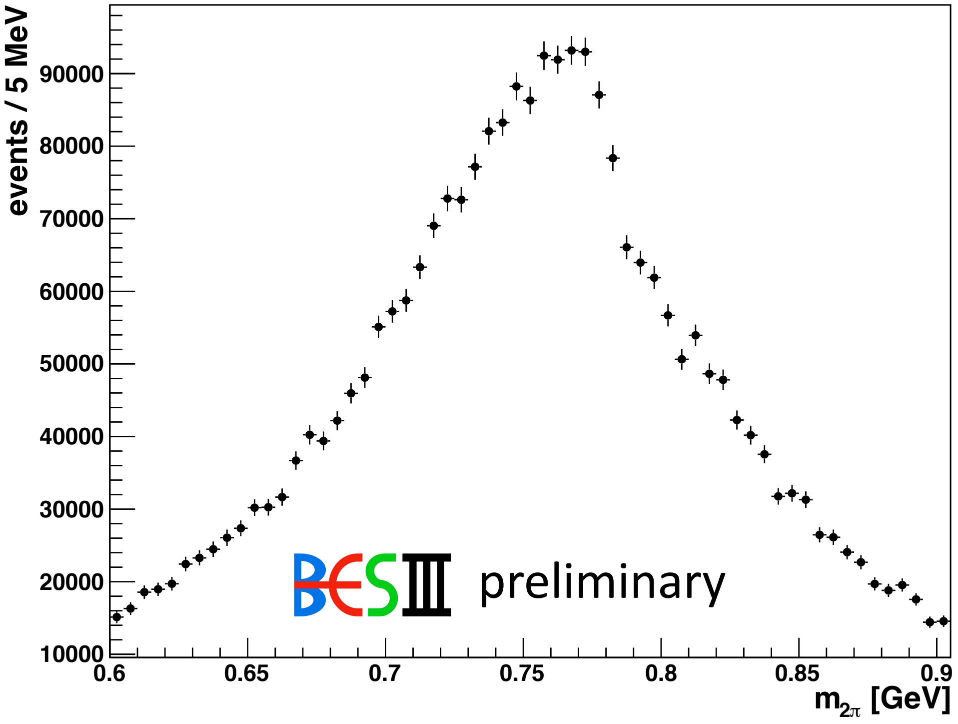
$e^+e^- \rightarrow \pi^+\pi^-\gamma_{ISR}$: π - μ Separation



TMVA method (Neural Network):

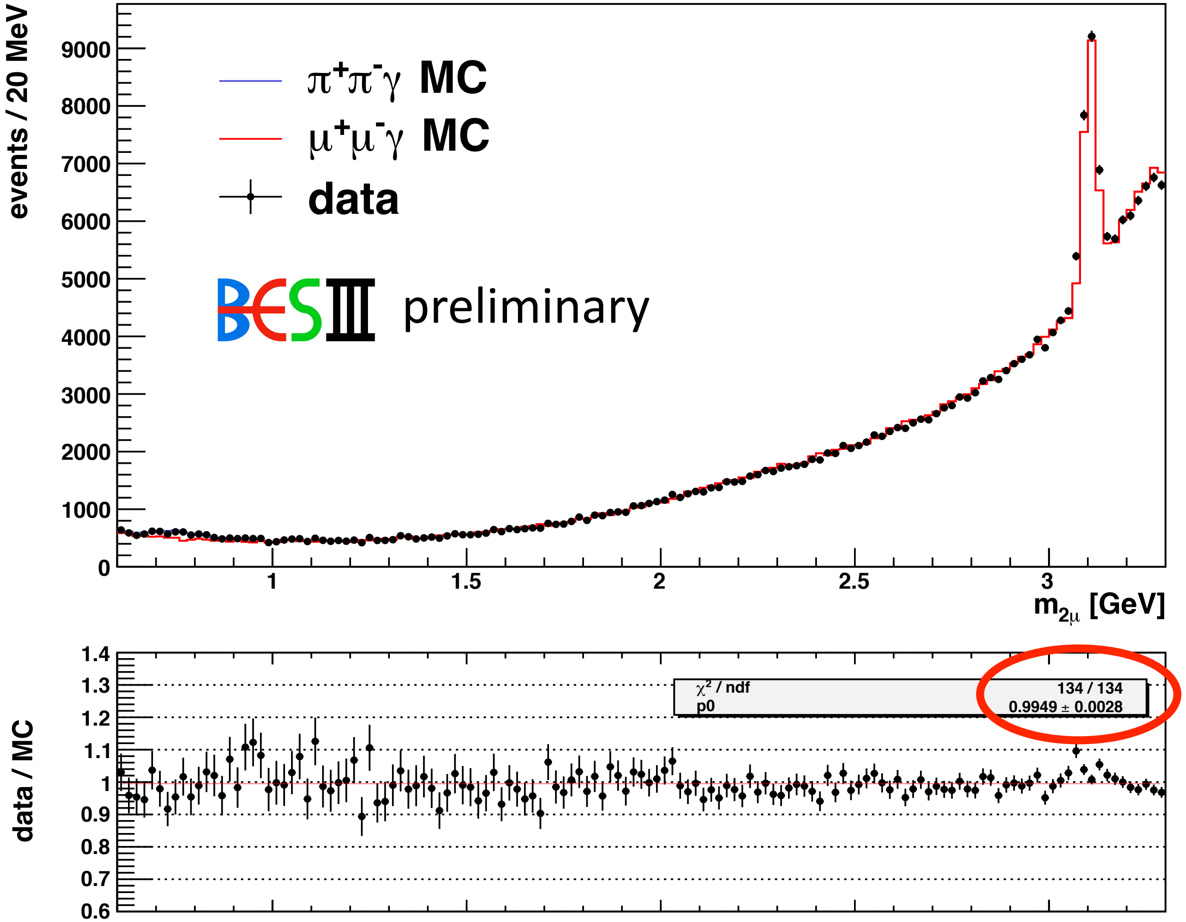
- trained using μμγ and ππππγ MC events
- information based on track level
- efficiency matrix (p,Θ) for data, MC
- correct for data - MC differences
- cross checked for different TMVA methods

Event yield ππγ after π-μ separation



Measurement of $\mu^+\mu^-\gamma$: Data vs. QED

Event yield μμγ after π-μ separation
and all efficiency corrections



Features:

- background from ππγ very small
- PHOKHARA accuracy <0.5%
- luminosity measurement based on Bhabha ev., 1.0% accuracy

→ excellent agreement with QED

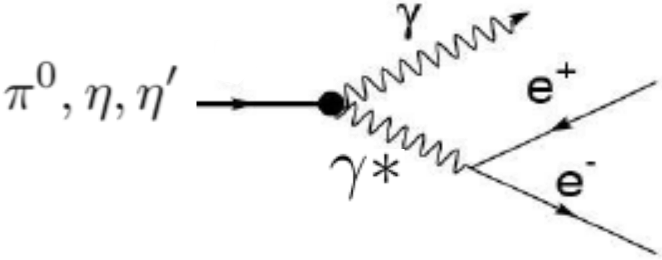
Δ(MC/QED-data) = (0.51 ± 0.28) %

→ accuracy on 1% level as needed to be competitive !

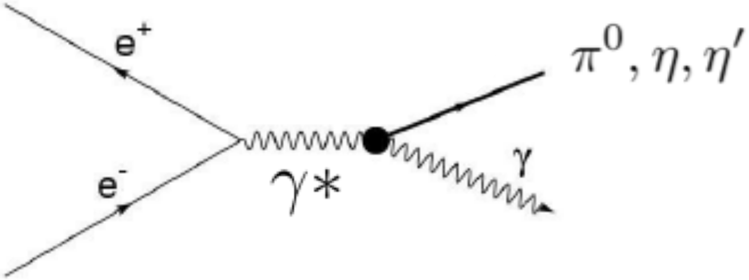
Meson Transition Form Factors $P \rightarrow \gamma^* \gamma^{(*)}$

Time-like transition form factors:

- Dalitz decays
  - $0 < q^2 < M_P^2$

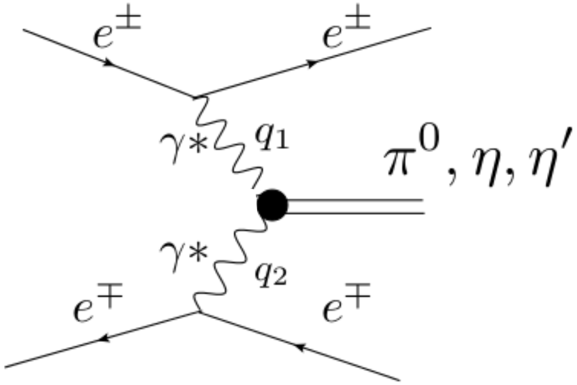


- Annihilation process
  - $q^2 = s > M_P^2$



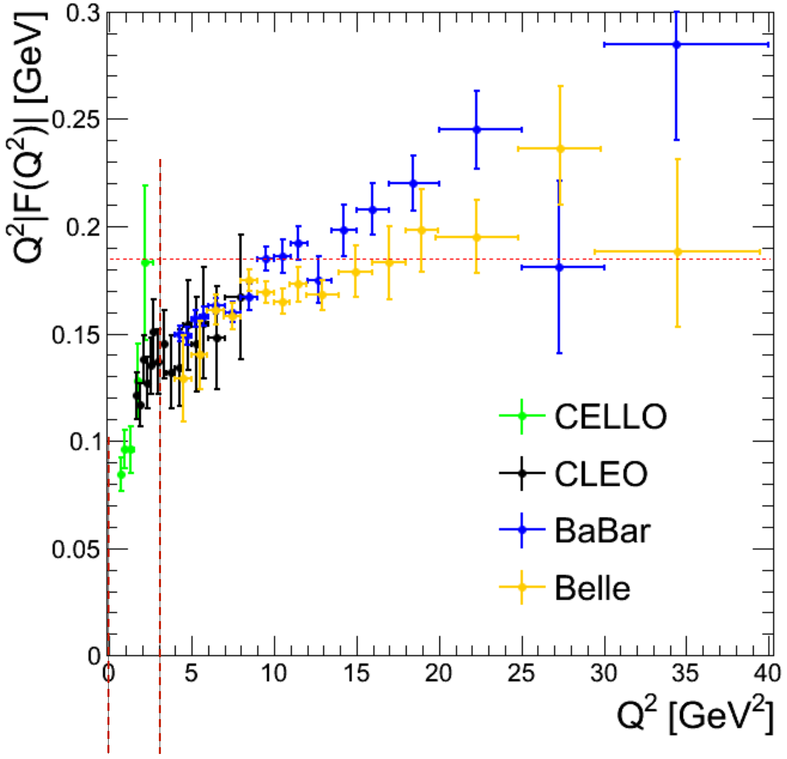
Space–like transition form factors:

- Two-photon production of mesons in e+e-



Existing Data on SL Transition Form Factors

$e^+e^- \rightarrow e^+e^- \pi^0$



initial BESIII publication
< 3.1 GeV^2

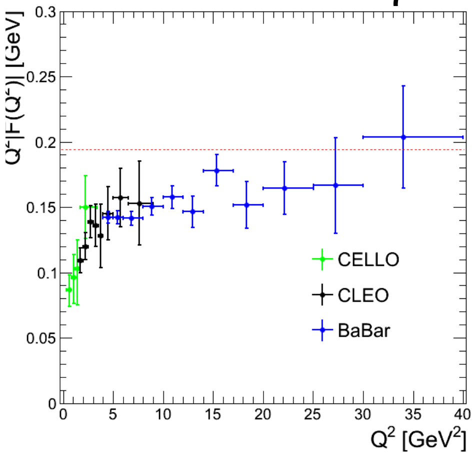
Features:

- recent high-Q^2 data from BABAR and BELLE $Q^2 > 4$ GeV^2
- above 1.5 GeV^2 data from CLEO
- below 1.5 GeV^2 data from CELLO, very poor accuracy

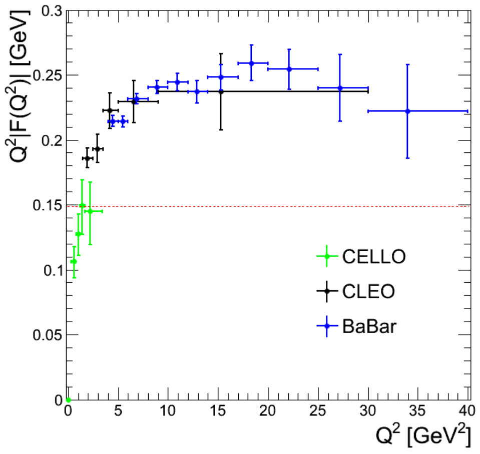
→ low Q^2 range not covered
most relevant for HLbL contribution to $(g\text{-}2)_\mu$

→ most relevant channels: π^0, η, η', $\pi\pi$

$e^+e^- \rightarrow e^+e^- \eta$



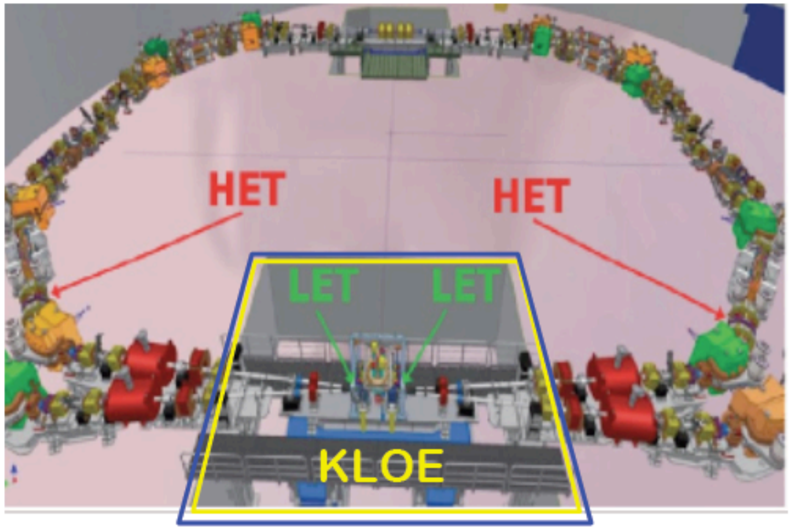
$e^+e^- \rightarrow e^+e^- \eta'$



Impact of KLOE-II

Future

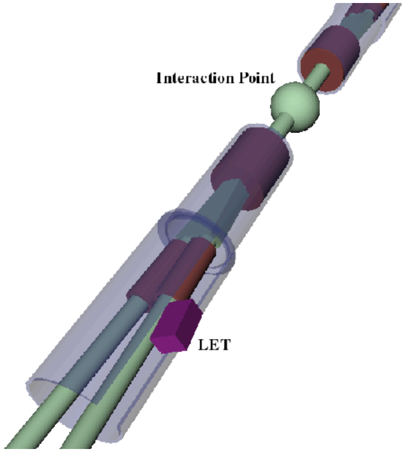
Installation of dedicated tagging detectors close to beam pipe



$e^+e^- \rightarrow e^+e^- + X$

taggers

KLOE

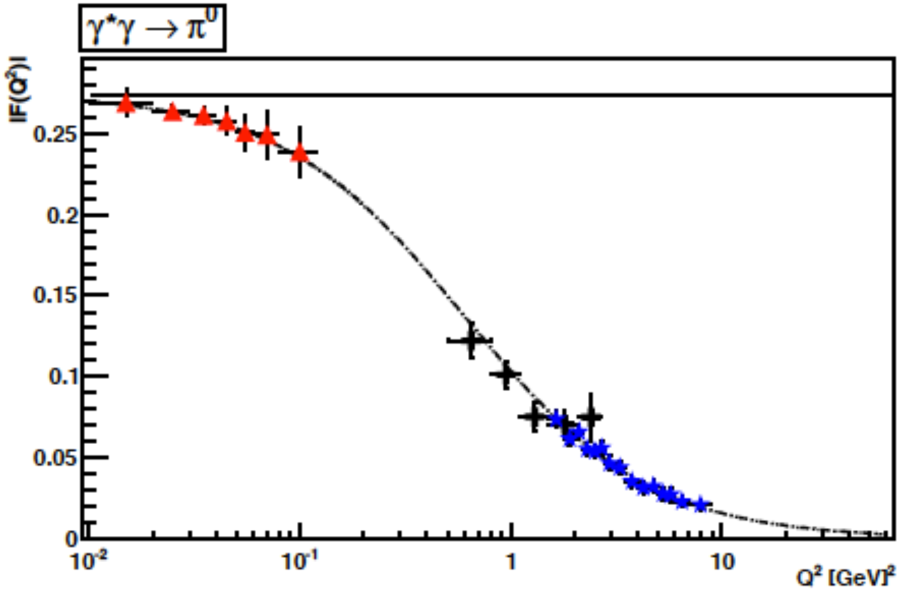


LET (Low Energy tagger)

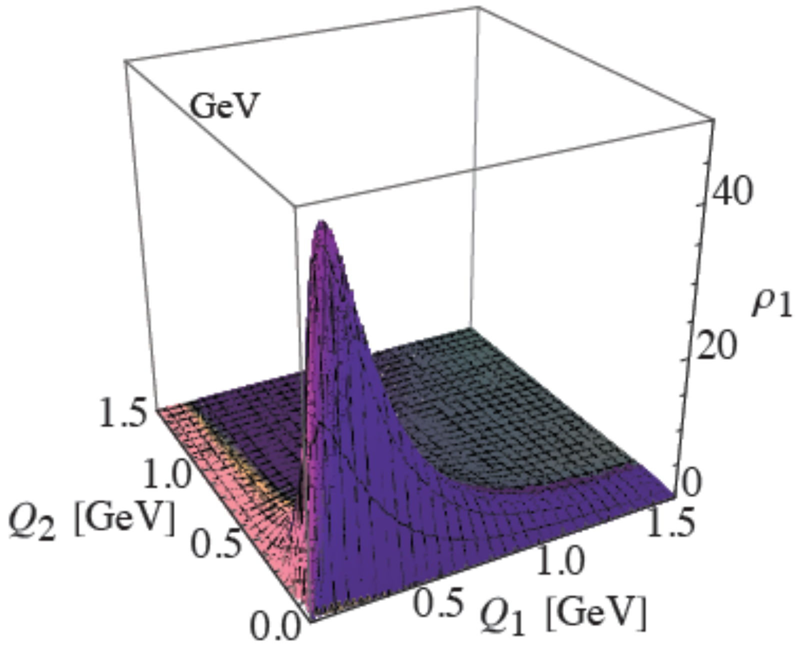
- inside KLOE (1 m from IP)
- energy range = 160-400 MeV

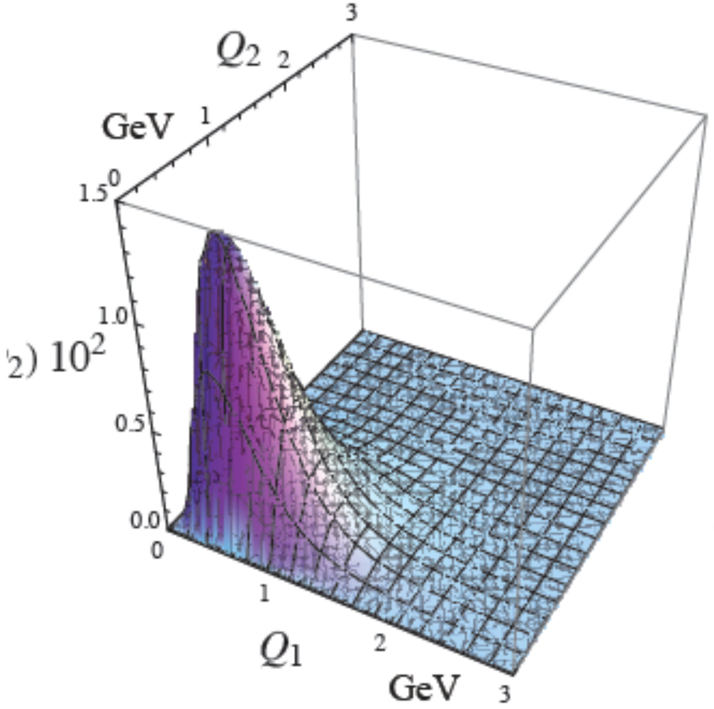
HET (High Energy tagger)

- after 1st dipole (11 m from IP)
- energy range = 420-495 MeV



Relevance for HLbL


Pseudoscalar Mesons

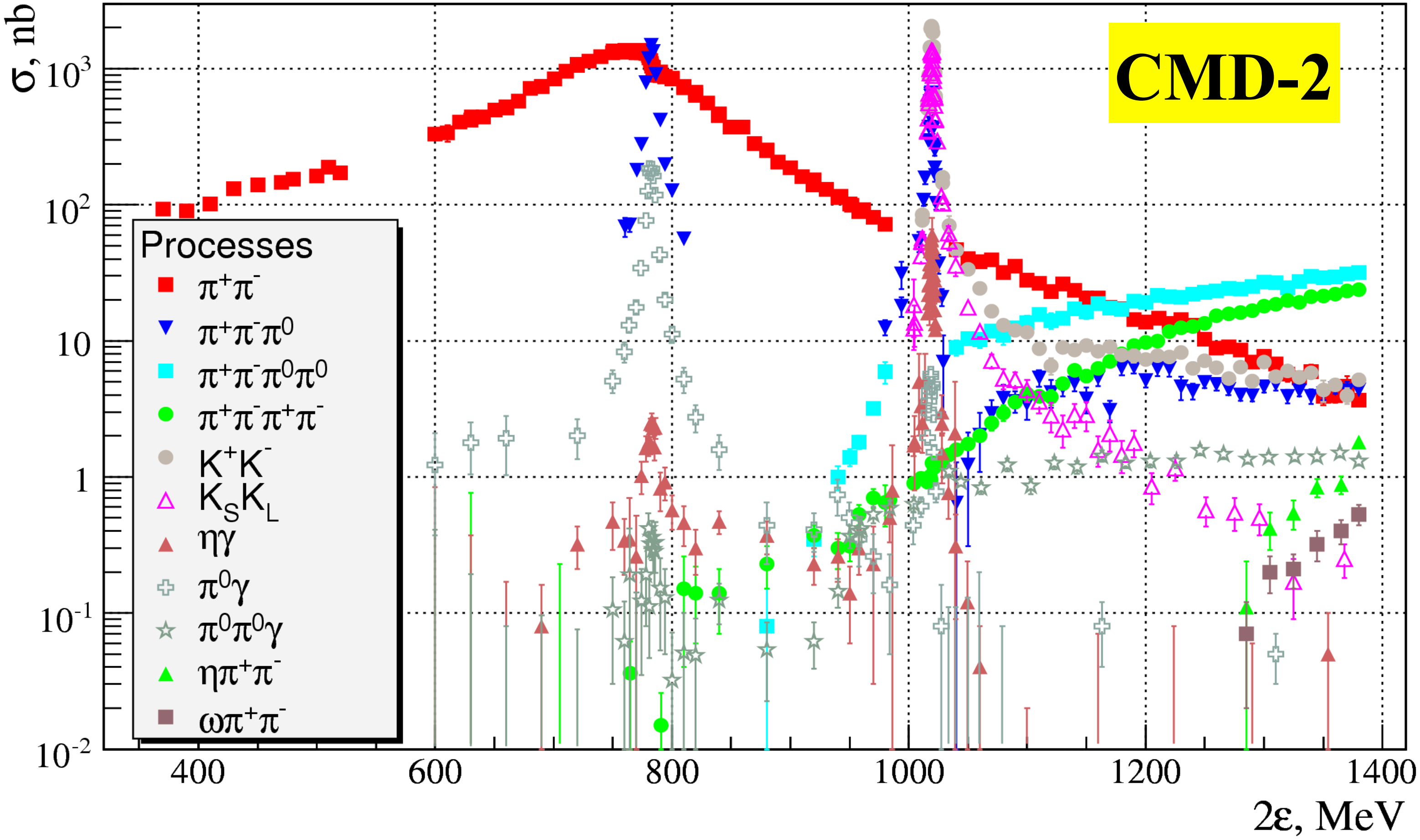

Axial Vector Mesons

Weighting functions dominate at low Q < 2 GeV !

courtesy: V. Pauk, JGU

Overview Novosibirsk Results

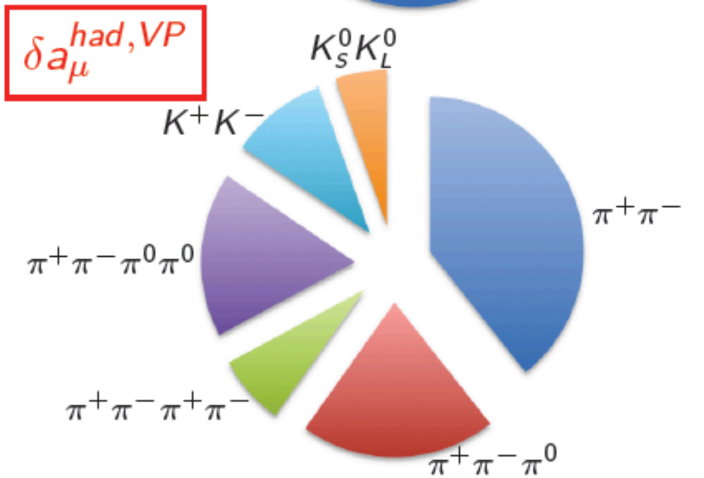
- **CMD-2: $\pi^+\pi^-$ <1%, higher multiplicities few % accuracy**
- **SND measurement of $\pi^+\pi^-$ with 1.2% accuracy**



Summary of ISR Results

Impact on $g_\mu - 2$: had. VP

$a_\mu^{VP,LO} = (692.3 \pm 4.2) \cdot 10^{-10}$



[data from Davier, EPJ **C** 71, 1515 (2011)]

$K_S^0 K_L^0$

BABAR not evaluated, yet

K^+K^-

BABAR reduces $\delta a_\mu^{had}(K^+K^-)$ by factor ≈ 3

$\pi^+\pi^-\pi^0\pi^0$

wait for *BABAR*, BESIII and CMD3 results

$\pi^+\pi^-\pi^+\pi^-$

BABAR reduces $\delta a_\mu^{had}(\pi^+\pi^-\pi^+\pi^-)$ by 40%

$\pi^+\pi^-$ & $\pi^+\pi^-\pi^0$

wait for BESIII and CMD3 results

Motivation: SUSY in CLFV and DMs

[From Tsutomu Mibe]

- **Large g-2 → Large CLFV**

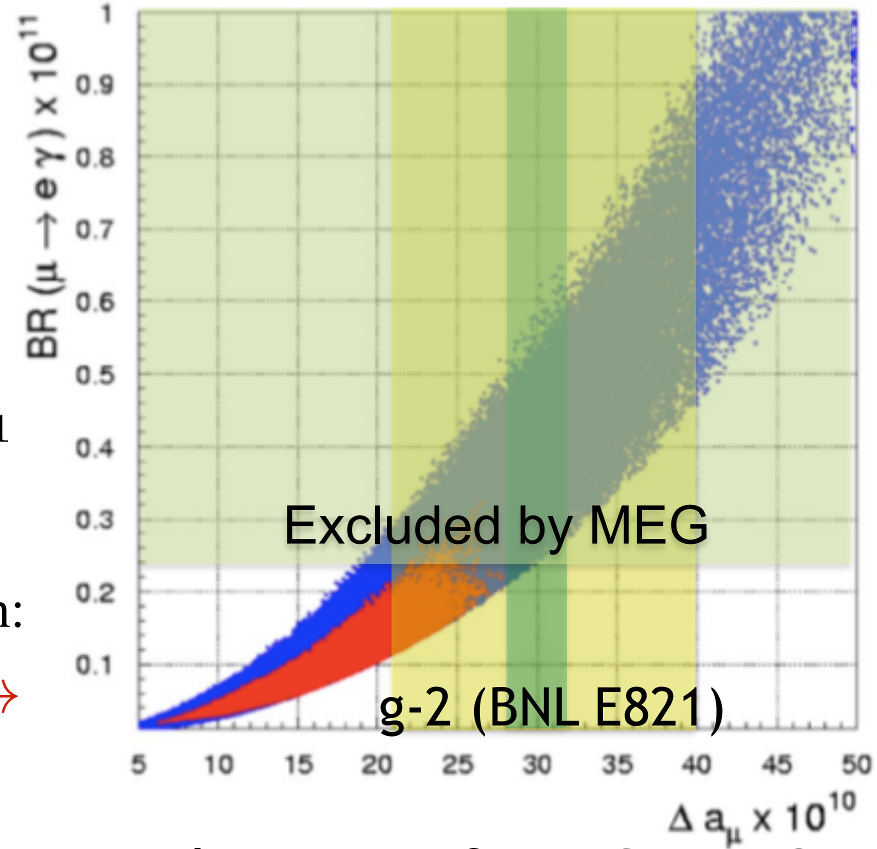
G. Isidori, F. Mescia, P. Paradisi, and D. Temes, PRD 75 (2007) 115019

Flavour physics with large tan β with a Bino-like LSP

$Br(\mu \to e\gamma) \times 10^{11}$

MEG limit now even:

$5.7 \times 10^{-13} \longrightarrow$



deviation from SM (g-2)

Lepton EDMs: d_μ vs. a_μ

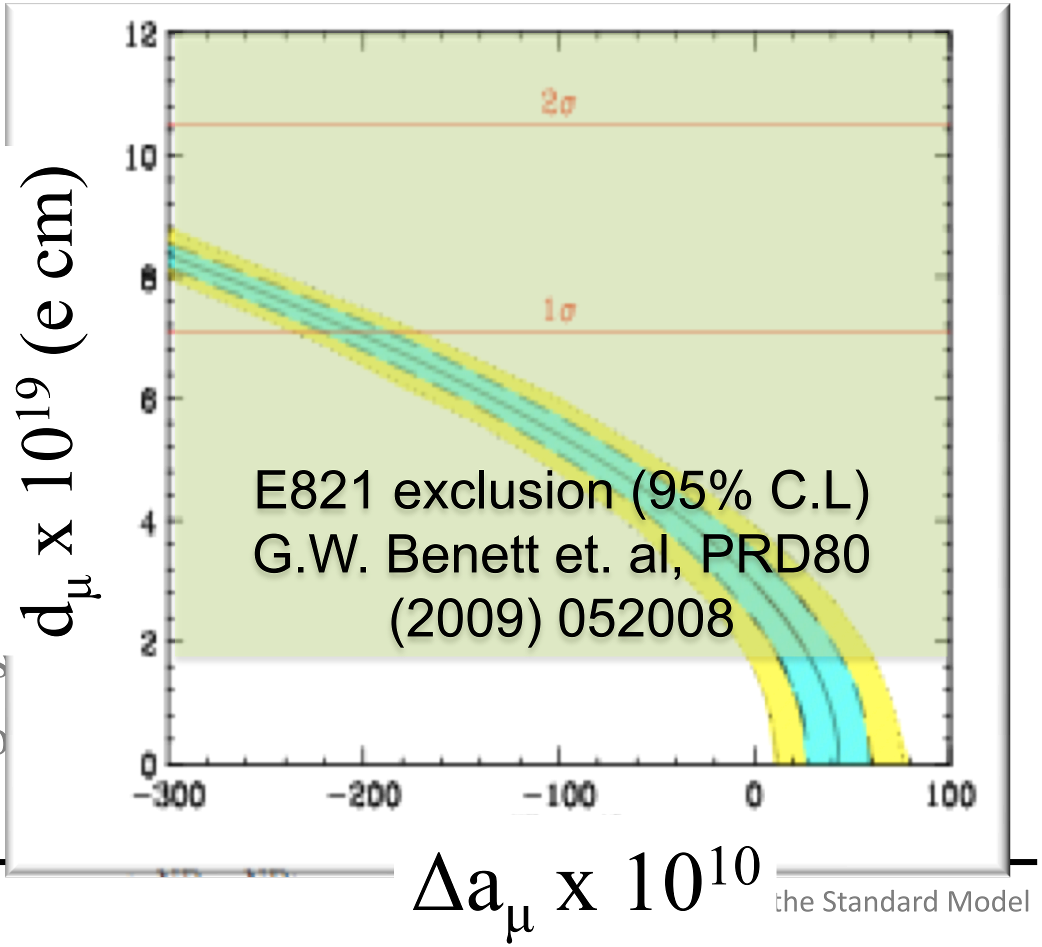
- One more reason to push for best possible muon EDM measurement:

μEDM could in principle fake muon AMM `The g-2 anomaly isn't' (Feng et al 2001)

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_\eta$$

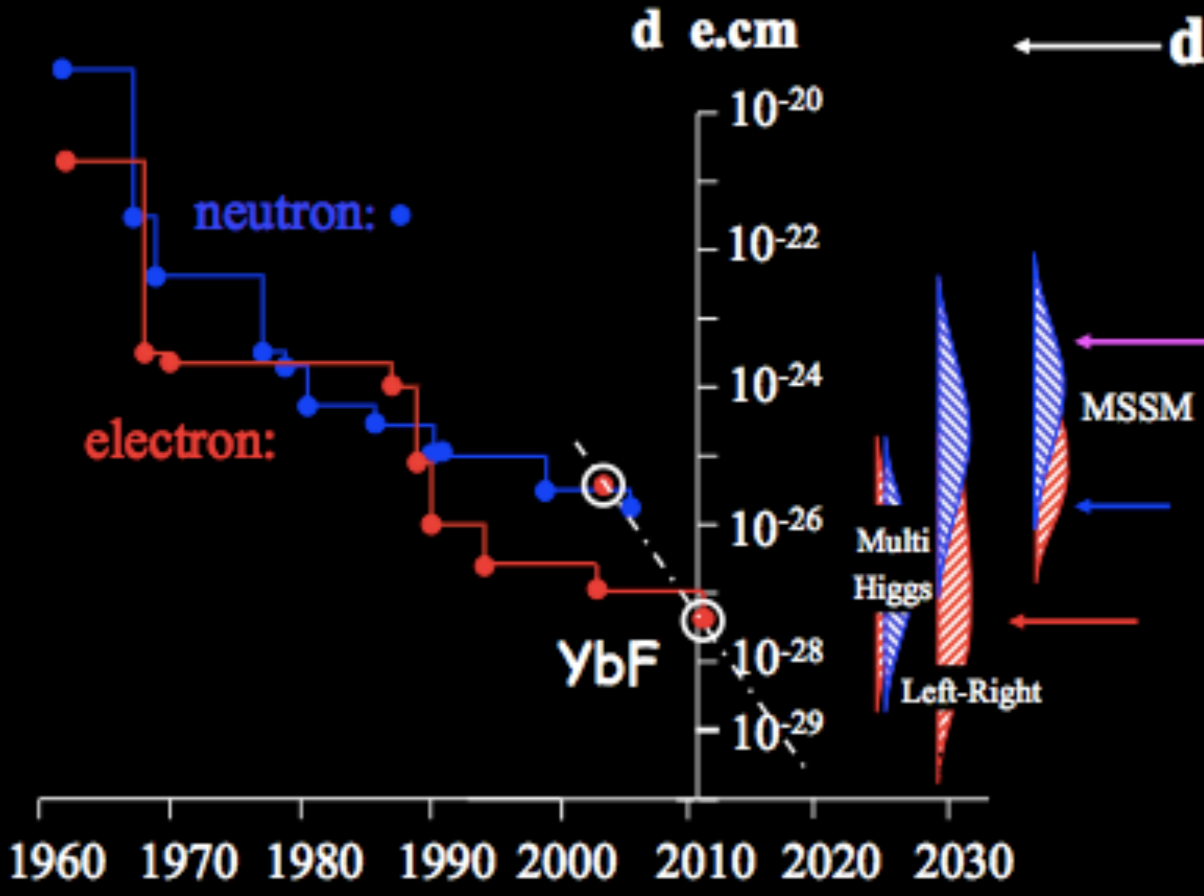
$$\omega = \sqrt{\vec{\omega}_a^2 + \vec{\omega}_\eta^2}$$

- Less befo



E821 exclusion (95% C.L)
G.W. Benett et. al, PRD80 (2009) 052008

Current status of EDMs



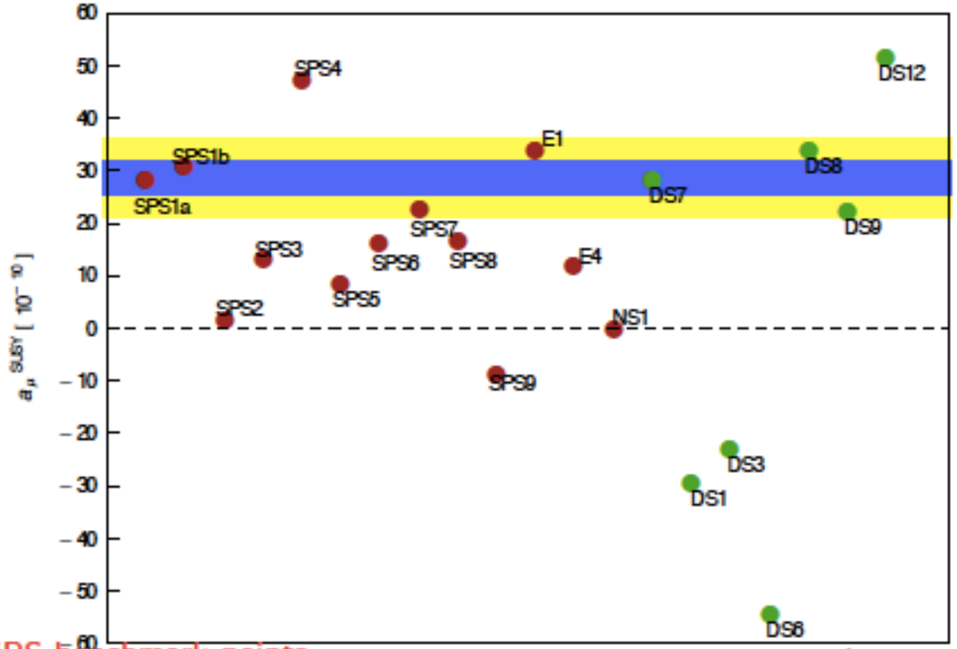
$d(\text{muon}) < 1.9\times10^{-19}$

$d(\text{proton}) < 5\times10^{-24}$

$d(\text{neutron}) < 3\times10^{-26}$

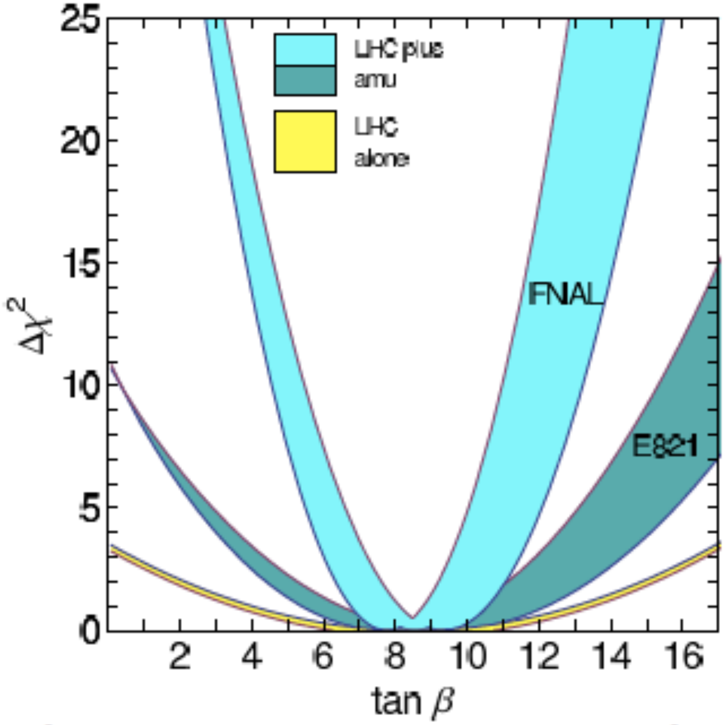
$d(\text{electron}) < 1\times10^{-27}$

Complementarity to LHC: a_μ central for BSM analyses



SPS benchmark points
[v.Weitershausen,Schäfer, Stöckinger-Kim,DS '10]

LHC Inverse Problem (300fb^{-1}) can't be distinguished at LHC
[Sfitter: Adam, Kneur, Lafaye, Plehn, Rauch, Zerwas '10]



[Hertzog, Miller, de Rafael, Roberts, DS '07]
[Miller, de Rafael, Roberts, DS '12]

- a_μ sharply distinguishes BSM models — here SUSY
- helps measure parameters