HIM
HELMHOLTZ
Helmholtz Institute Mainz

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

SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

The Low-Energy Frontier of the Standard Model

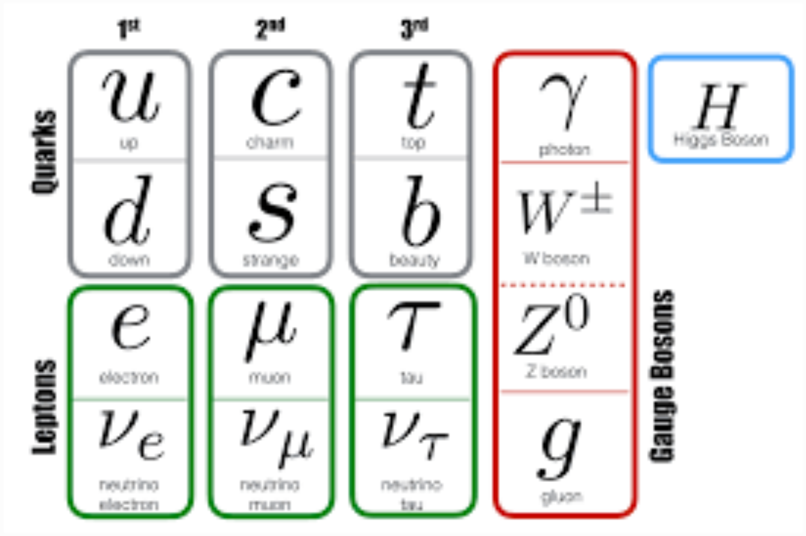
GSI

Achim Denig
GSI Colloquium
December 4, 2018

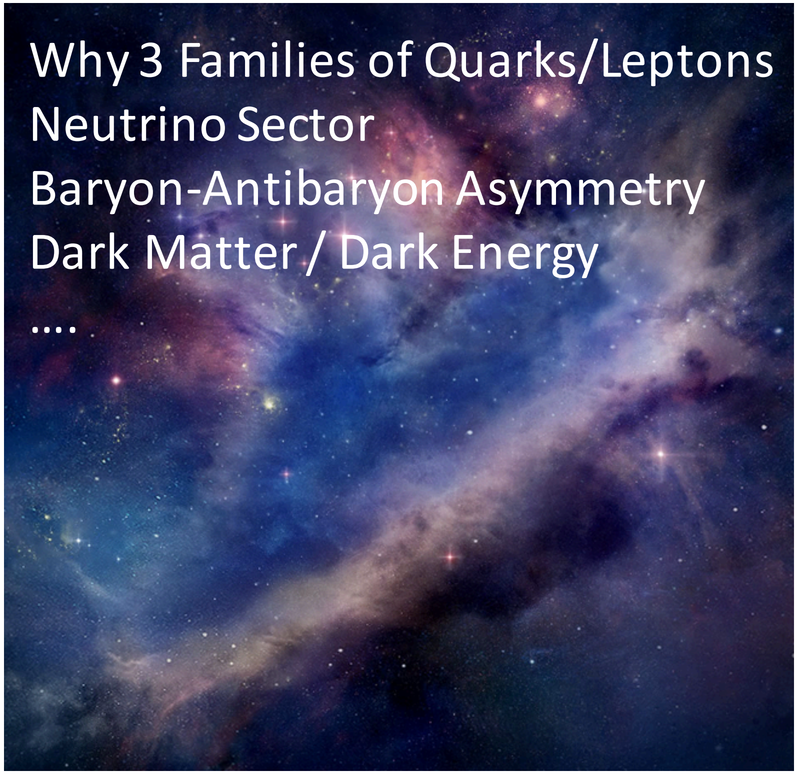
The Standard Model

Higgs discovery
→ Last particle of the Standard Model discovered


Nobel Prize 2013



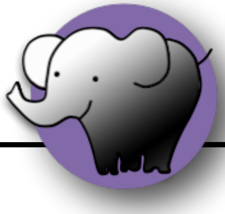
Problems of the Standard Model



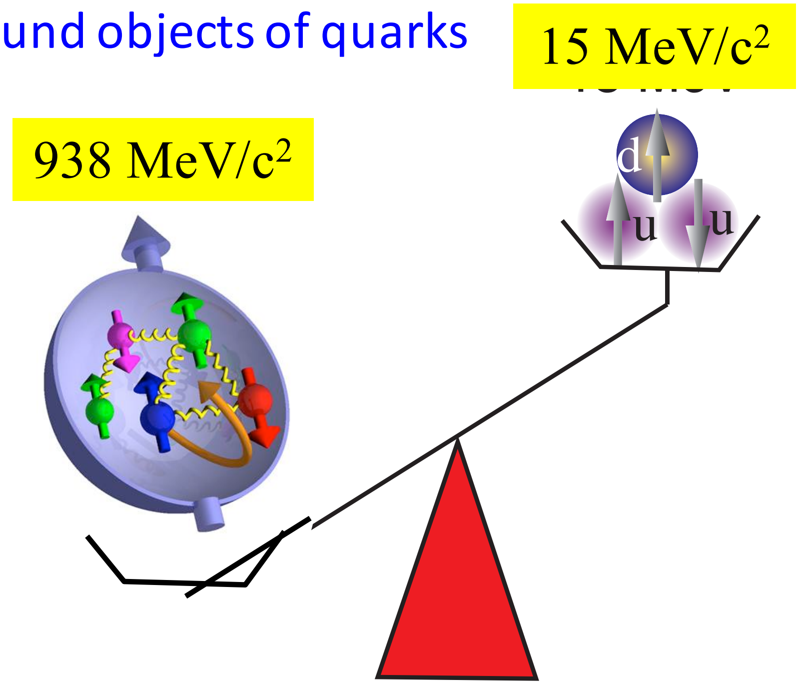
Why 3 Families of Quarks/Leptons
Neutrino Sector
Baryon-Antibaryon Asymmetry
Dark Matter / Dark Energy
….

Search for New Physics

Generally believed to consist of particles beyond the Standard Model

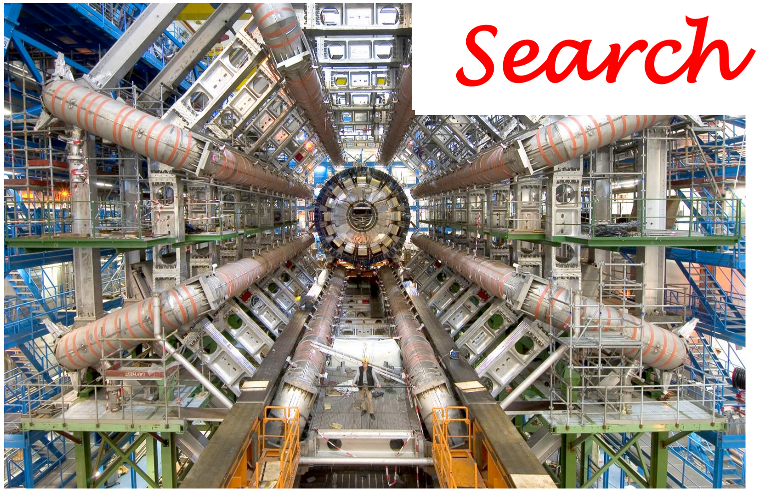


The World of Hadrons as bound objects of quarks



Understanding Low-Energy QCD

Frontiers in Nuclear & Particle Physics



Search for New Physics

High Energy Frontier
(e.g. LHC/CERN)

Precision Frontier

SFB 1044
THE LOW-ENERGY FRONTIER
OF THE STANDARD MODEL

$\sin^2\theta_W$

Proton Radius

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

Dark Photons

Low Energy Frontier

From Quarks and Gluons to Hadrons and Nuclei

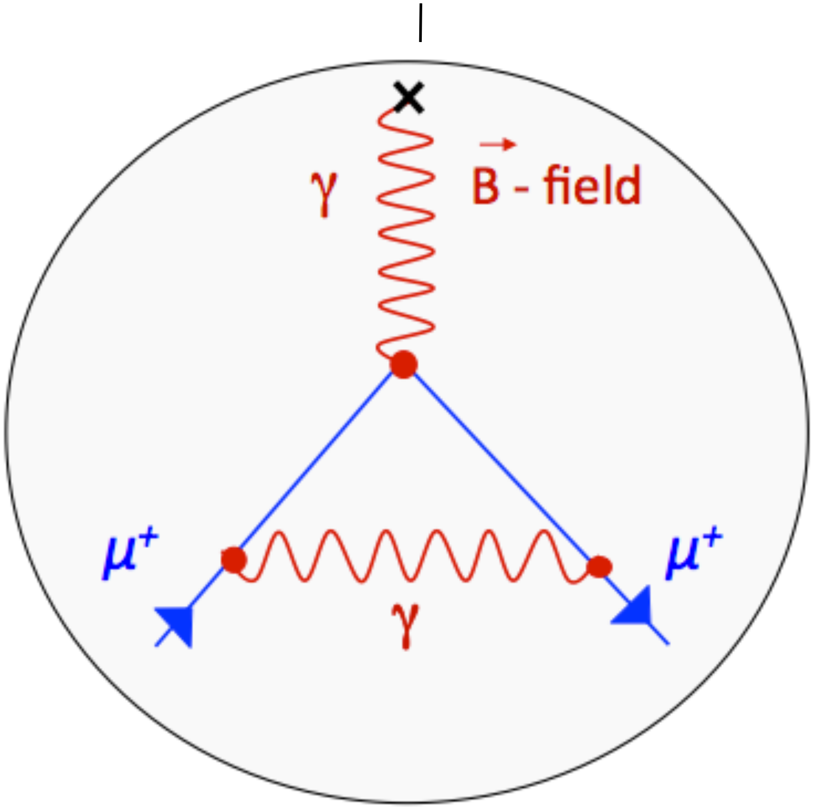
Anomalous Magnetic Moment of the Muon

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

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

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

QFT: $a_\mu^{SM} = (g\text{-}2)_\mu \,/\, 2 = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had}$



$g \neq 2$

≈ 2.00232

$\approx \alpha / \pi$

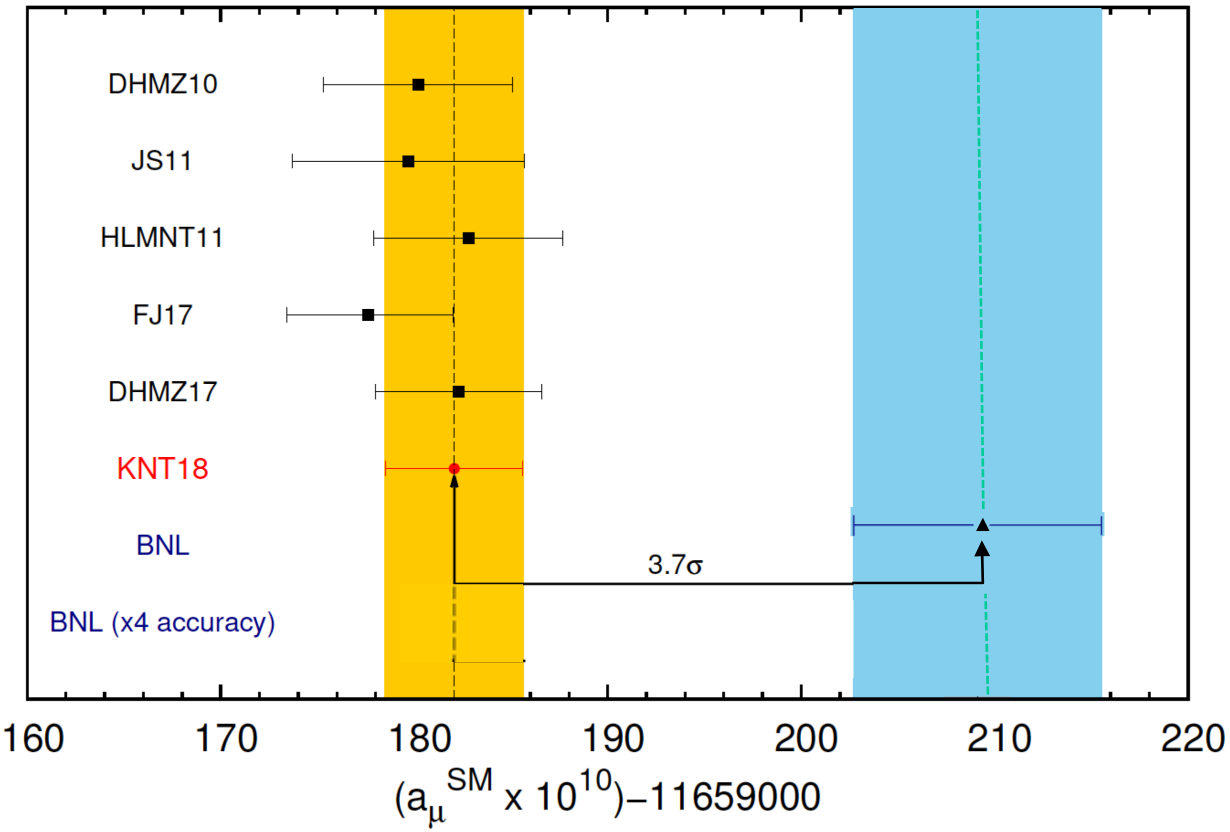
Julian Schwinger 1948
Nobel price 1965

$$\boxed{a_\mu = (g_\mu - 2)/2}$$

muon anomaly

Schwinger term contains
> 99% of total correction

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



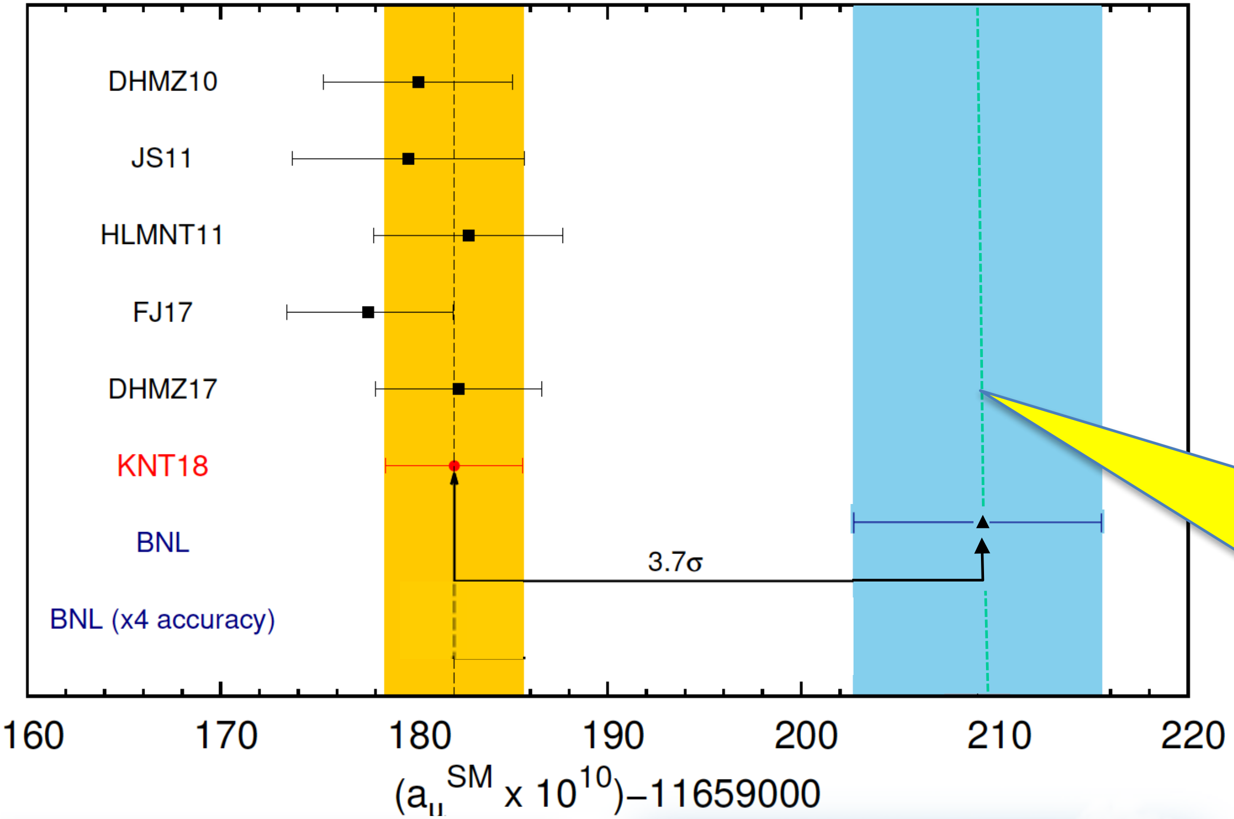
One of the most significant tests of the SM

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = (27.05 \pm 7.28) \cdot 10^{-10}$ (3.7σ) !!!

Keshavarzi et al. 2018

Errors or New Physics ???

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



BNL ring shipped
to Fermilab !
First result
expected in
spring 2019 !

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

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

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had} = (\,11\,659\,182.2 \pm 4.2\,)\cdot 10^{-10}$$

Czarnecki et al.

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

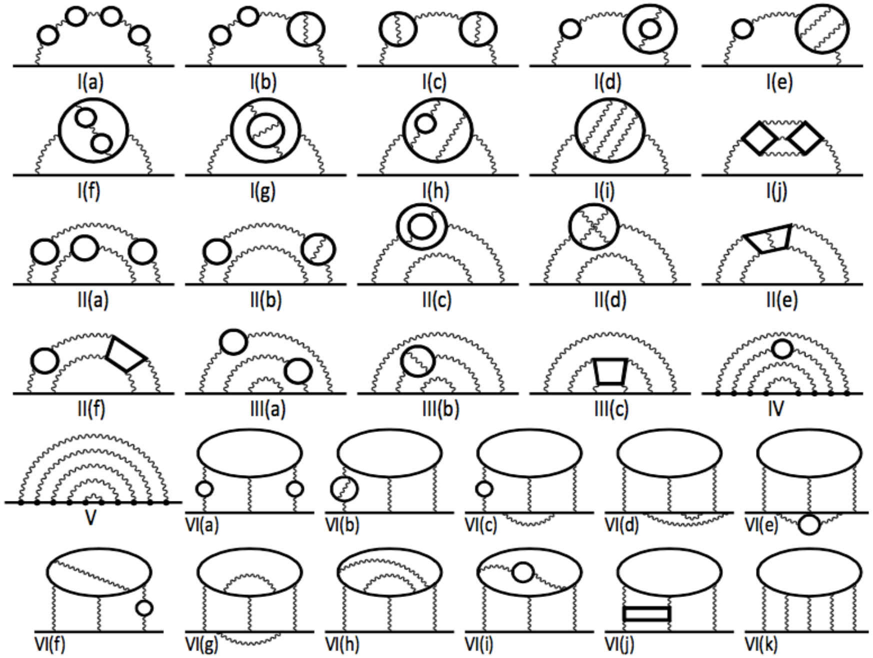
Kinoshita et al. ‘12

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

10th

12672

diagrams



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

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

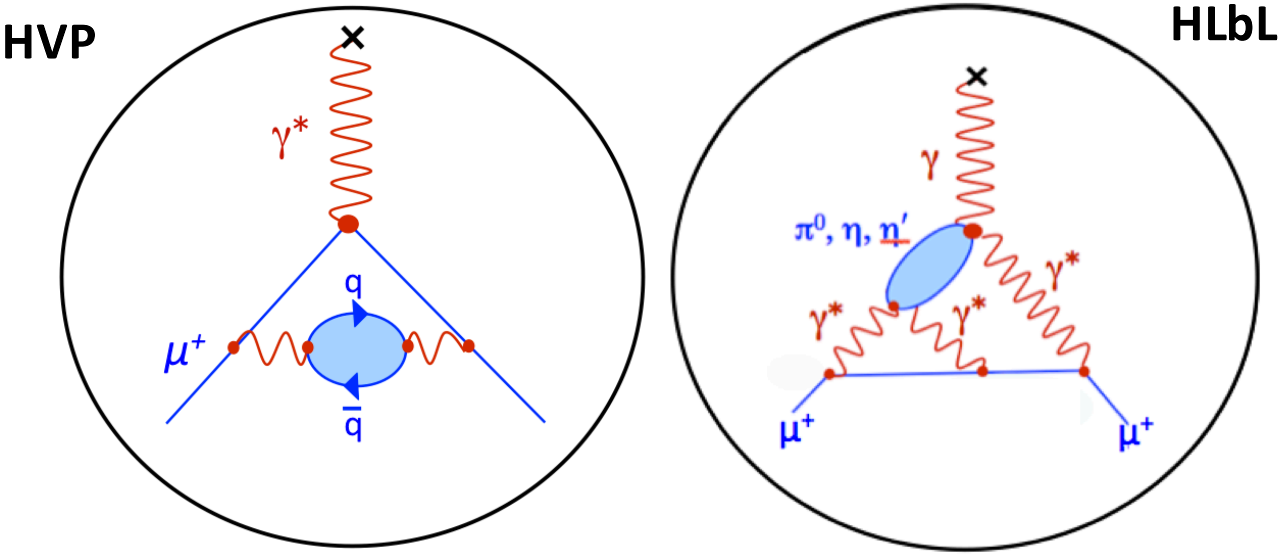
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had} = (\,11\,659\,180.2 \pm 4.2\,)\cdot 10^{-10}$$

Teubner et al. '11

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

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

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



Standard Model P edictio (g-2)$_\mu$

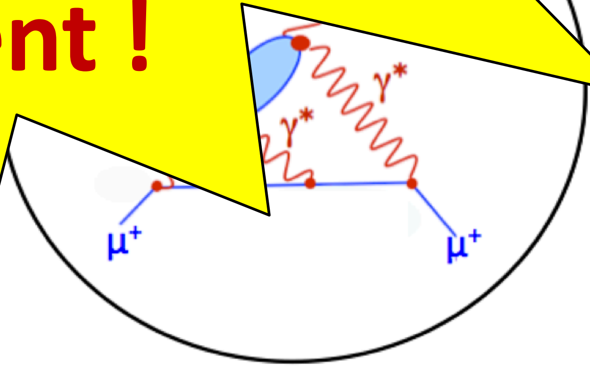
Hadronic cor tion **non-per** contrib n

a_μ^{SM} = a_μ weak ± 4.2) · 10^{-10}

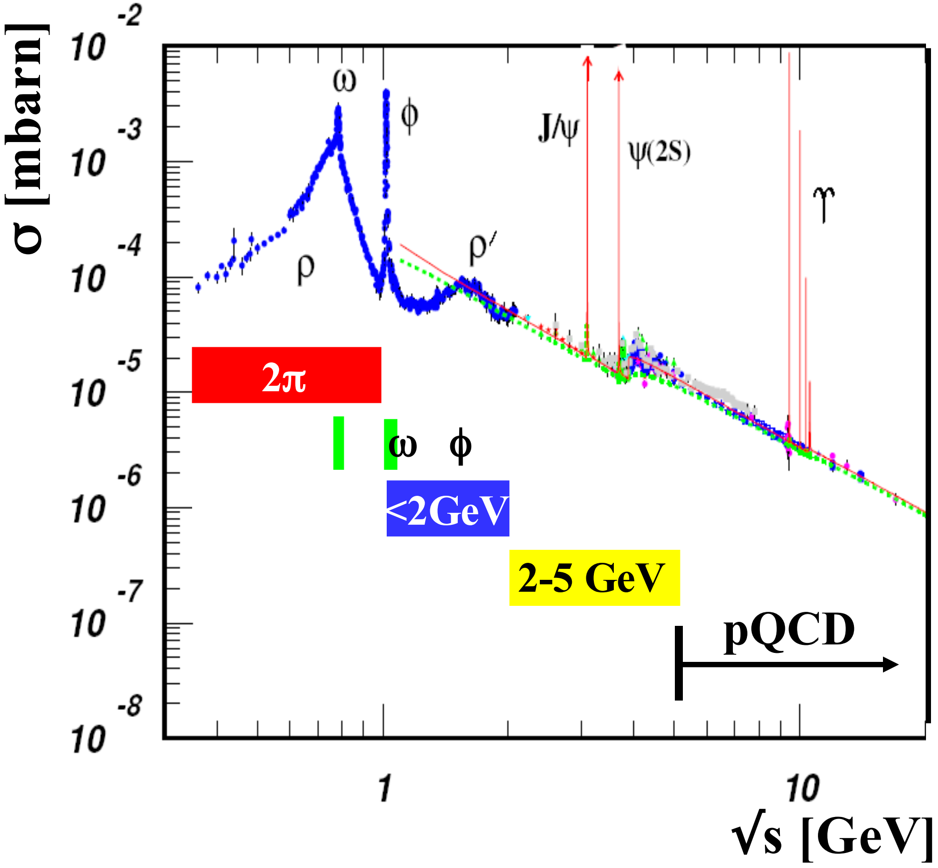
Improving hadronic contributions of utmost importance for interpretation of FNAL measurement !

10^{-10}

HLbL

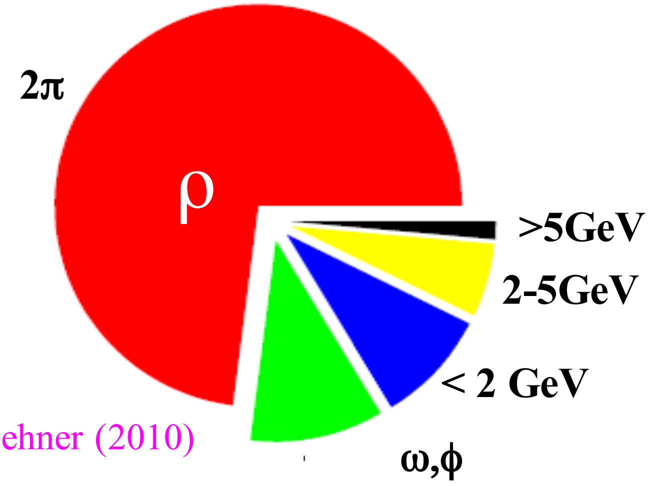


Hadronic Vacuum Polarization Contrib. to (g-2)$_\mu$



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

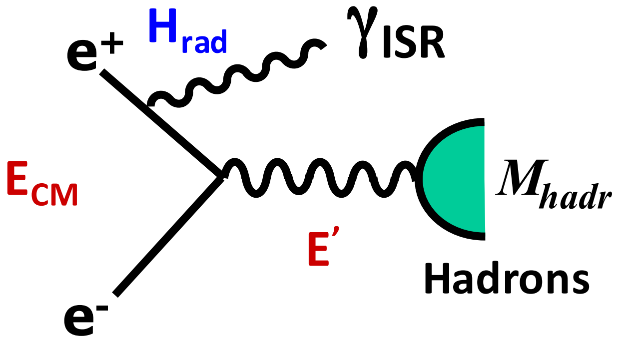
Intrinsic ~ 1 / s^2
low energy contributions
especially important!



Jegerlehner (2010)

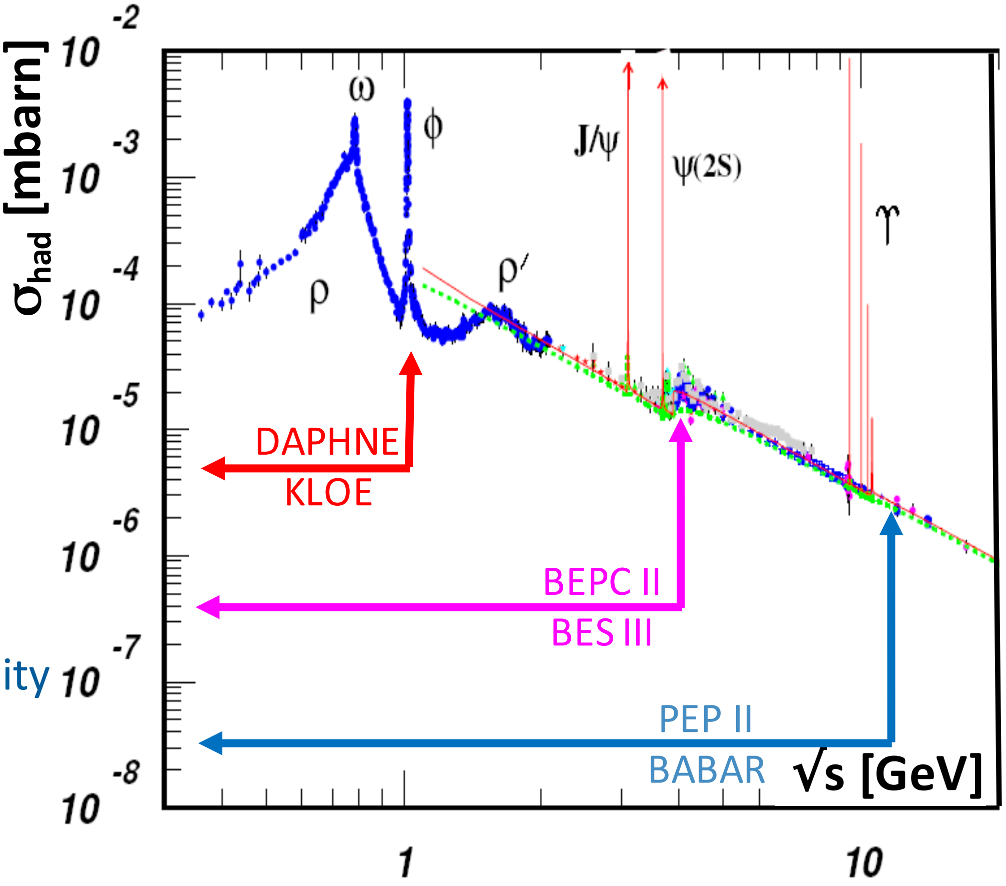
Initial State Radiation (ISR)

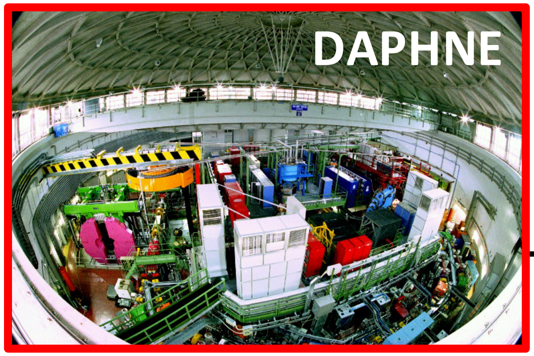
Initial State Radiation (ISR) aka Radiative Return

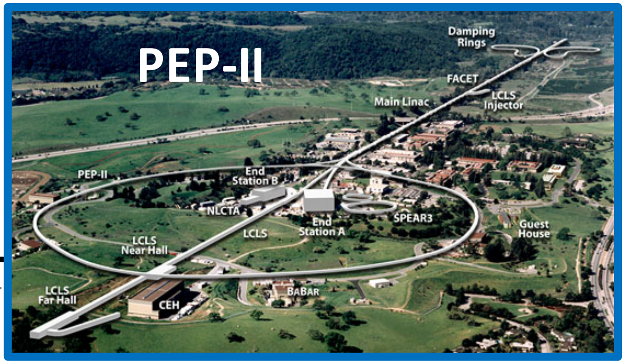


- No systematic variation of E_{beam}
- High statistics thanks to high luminosity
- Precise knowledge of radiative corrections mandatory (H_{rad})

PHOKHARA event generator

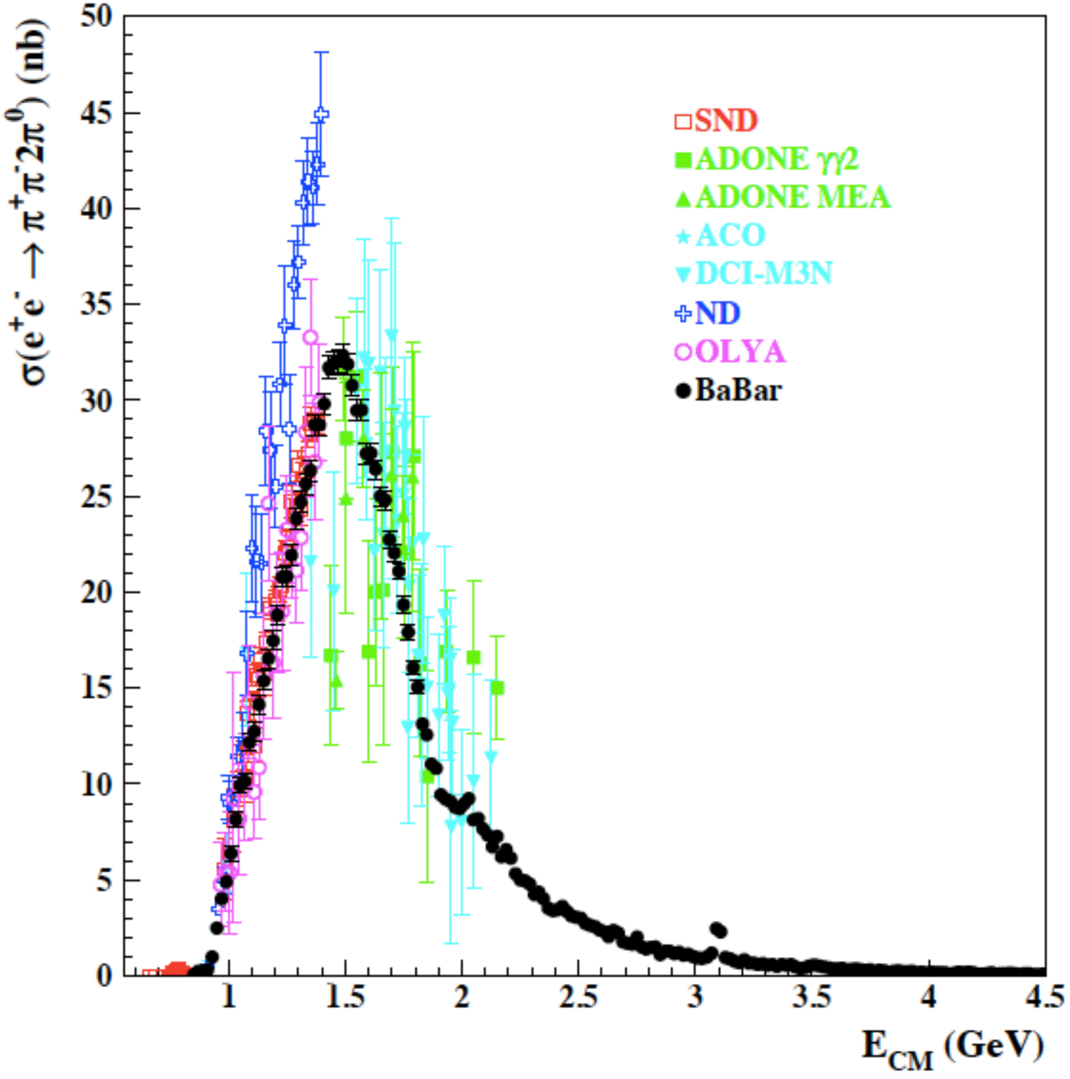






NEW

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



- Tagged ISR analysis (2017)

  `Phys. Rev. D96 (2017) 092009`

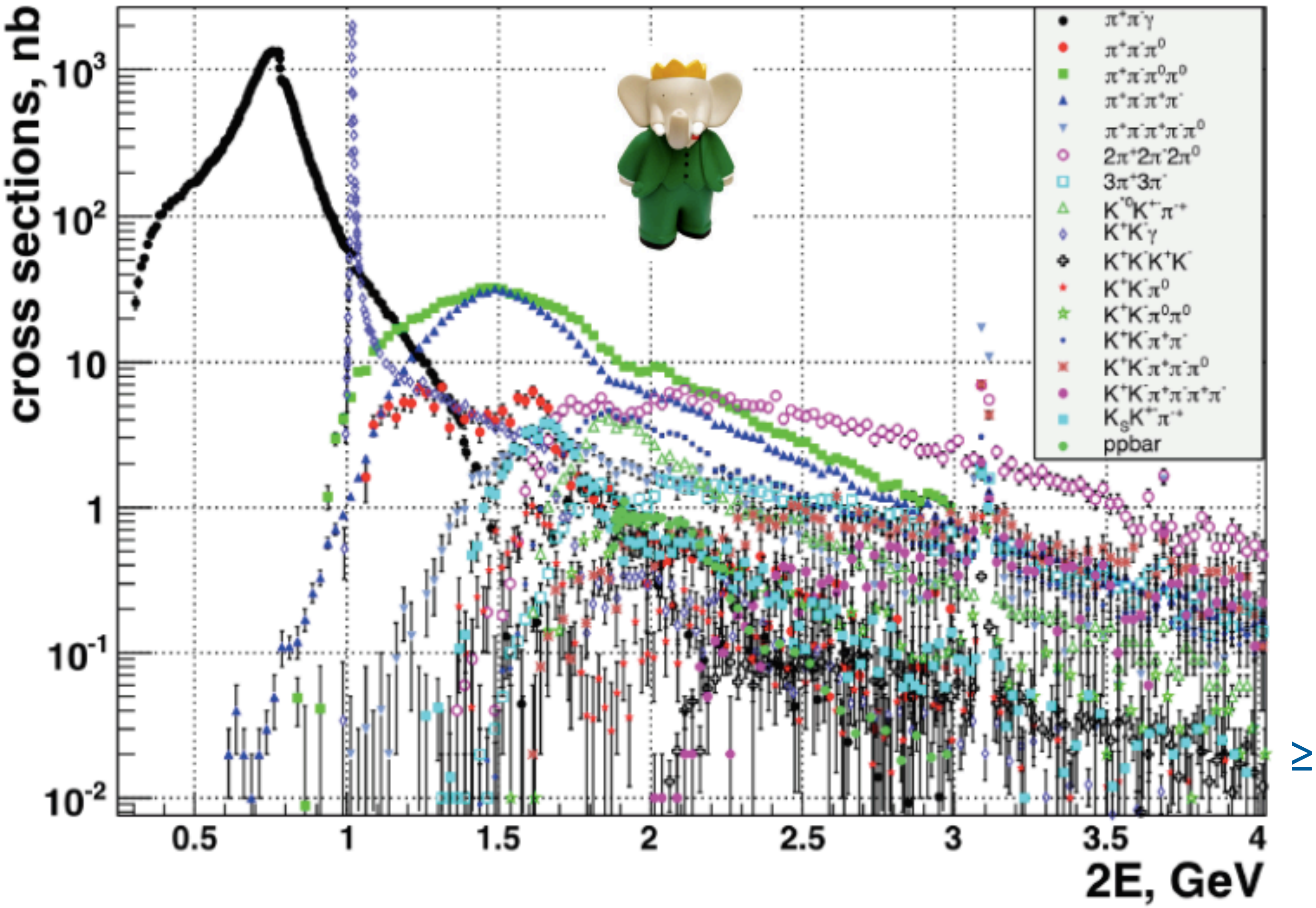
- Huge improvement over existing data sets suffering from normalization issues
- Main complications:

  1) neutral pion eff. determination

  2) understanding background from $e^+e^- \rightarrow \pi^+\pi^-3\pi^0$

- Confirmed by BES III analysis (preliminary)

BABAR *ISR Results*



Precision:

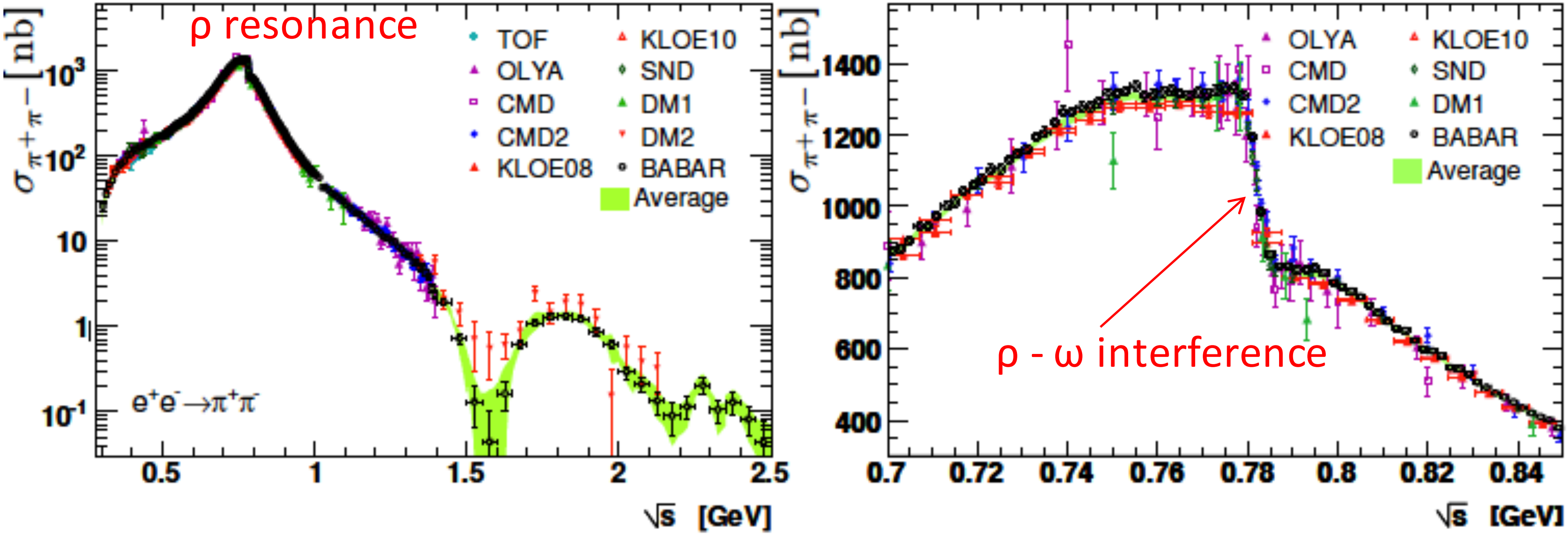
2π: < 1%

3π: ~10%

4π: ~ 3%

≥ 5π: 10% and higher

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



ρ resonance

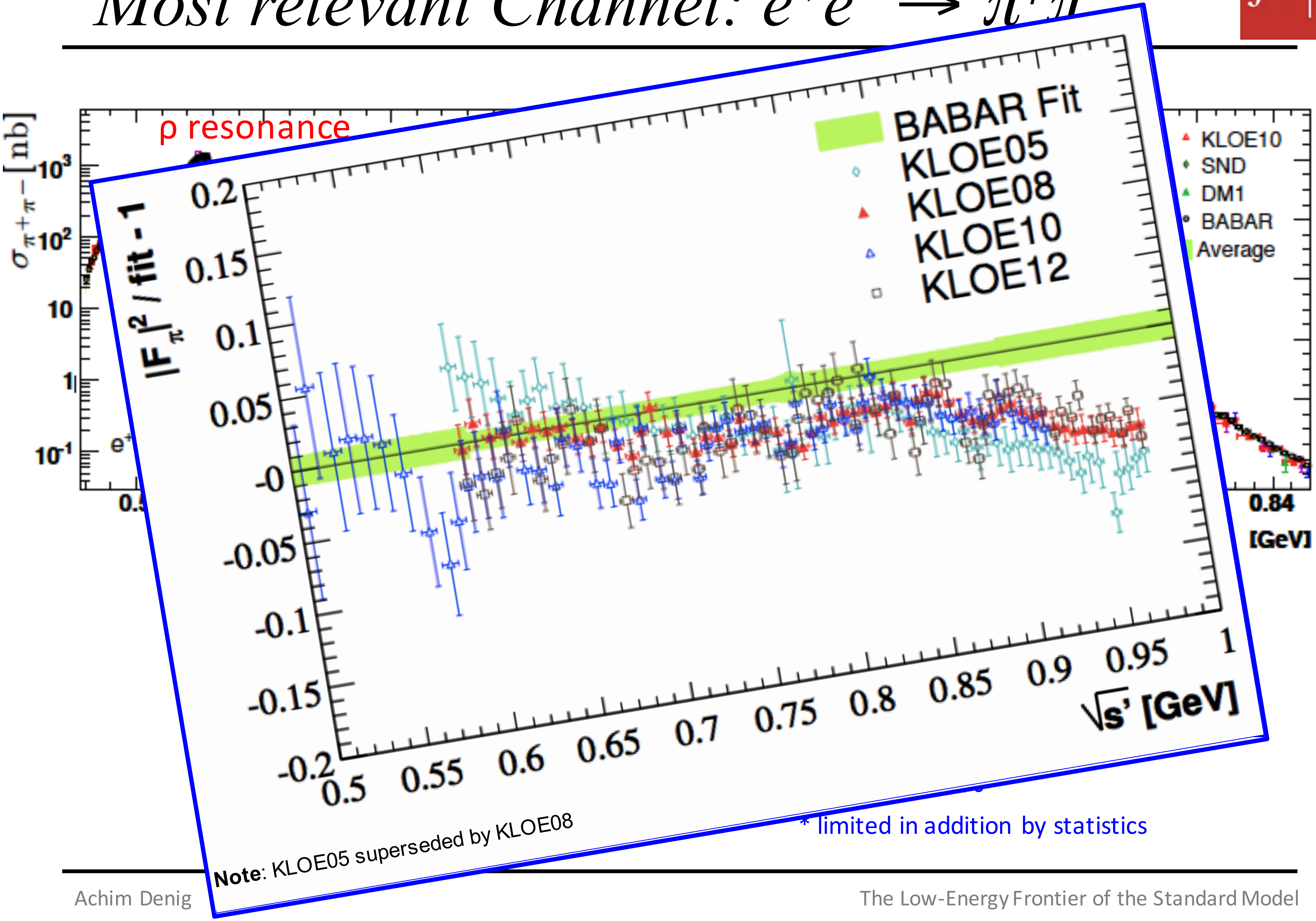
ρ - ω interference

Systematic Uncertainties

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

* limited in addition by statistics

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



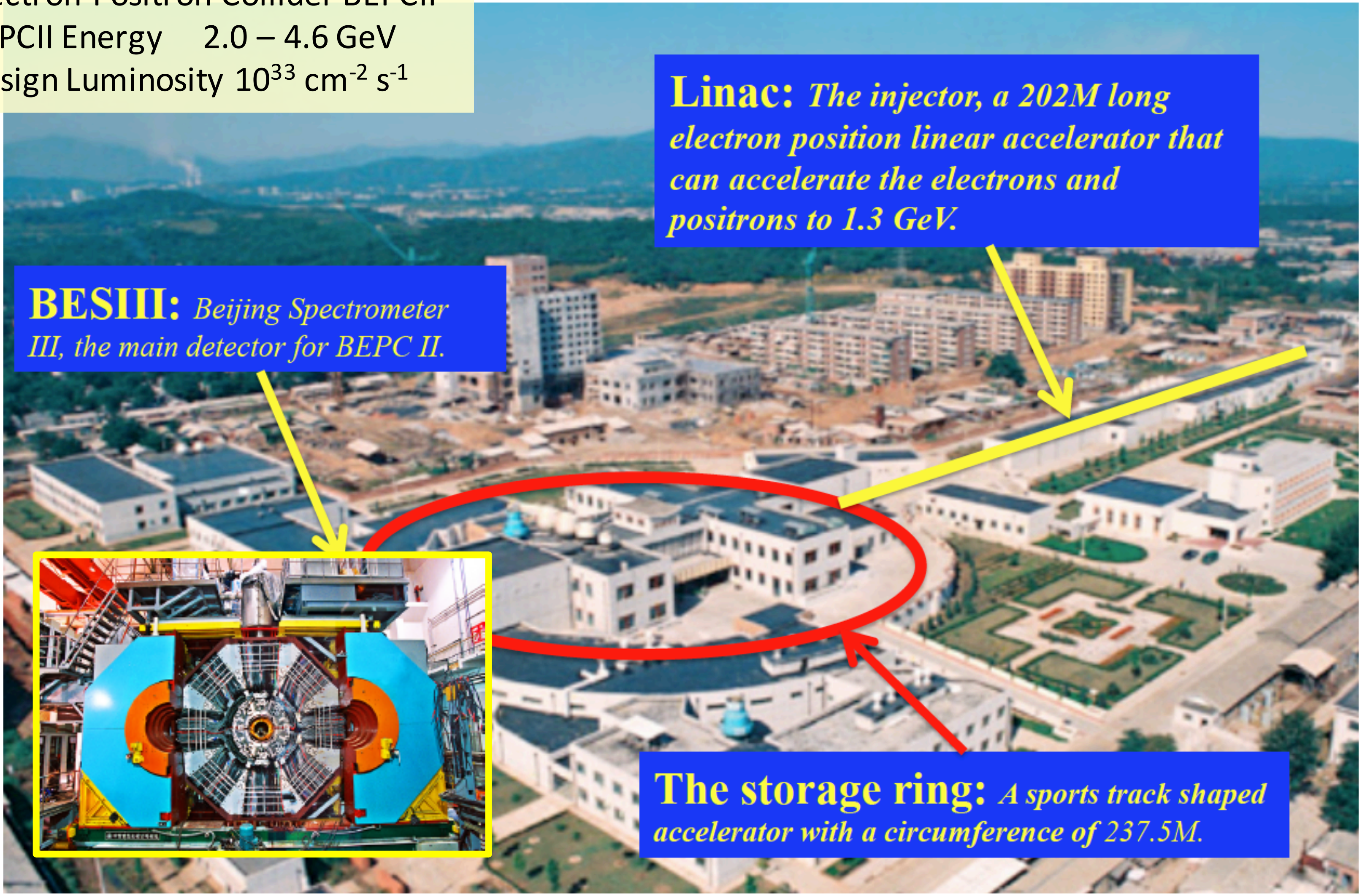
ρ resonance

Note: KLOE05 superseded by KLOE08

* limited in addition by statistics

BESIII Experiment @ BEPCII

Electron-Positron Collider BEPCII
BEPCII Energy 2.0 – 4.6 GeV
Design Luminosity 10^{33} cm^{-2} s^{-1}



Linac: *The injector, a 202M long electron position linear accelerator that can accelerate the electrons and positrons to 1.3 GeV.*

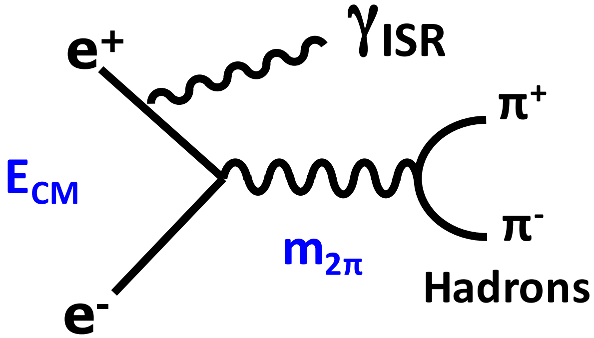
BESIII: *Beijing Spectrometer III, the main detector for BEPC II.*

The storage ring: *A sports track shaped accelerator with a circumference of 237.5M.*

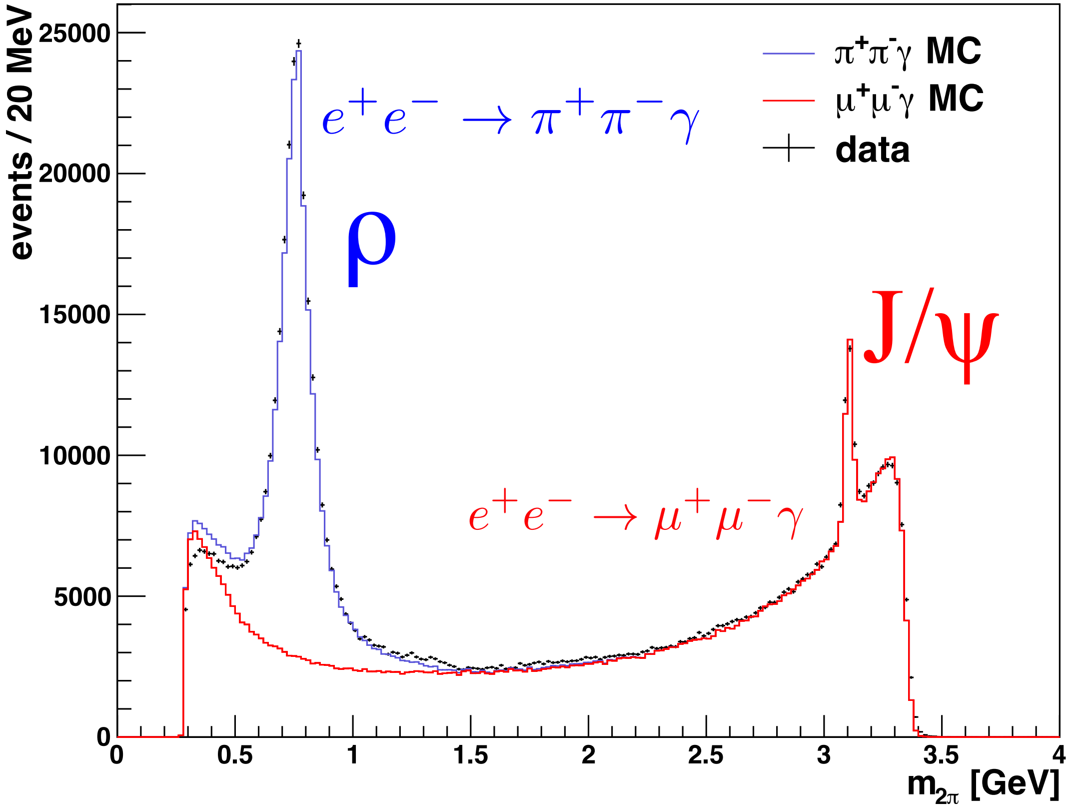
BESIII ISR Analysis: $e^+e^- \to \pi^+\pi^-\gamma_{ISR}$

Initial State Radiation, aka Radiative Return

Phokhara event generator:
H. Kühn, H. Czyz, G. Rodrigo
Experiment:
A.D., W. Kluge, G. Venanzoni



Event yield after acceptance cuts **only**

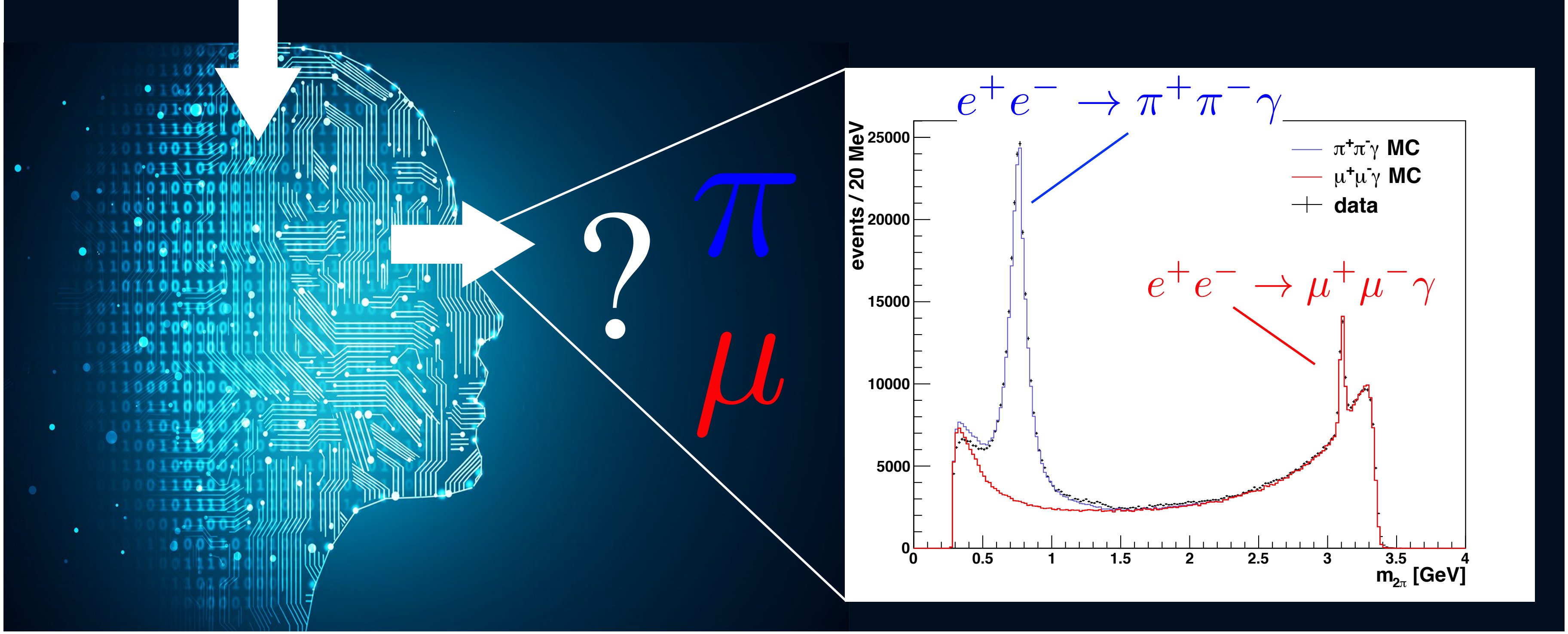


Pion Muon Separation needed
→ TMVA methods!

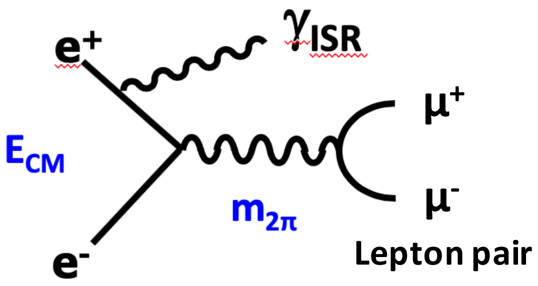
Pion – Muon Separation and Machine Learning

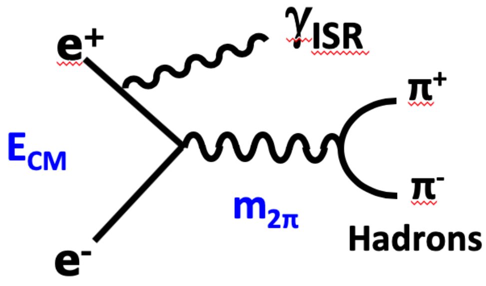
Artificial Neural Network:

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

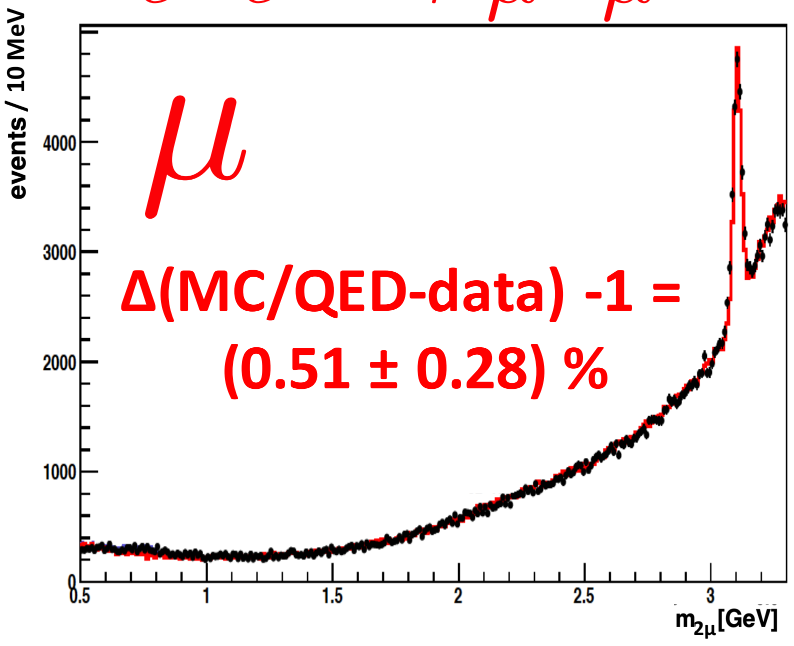


Pion – Myon Separation



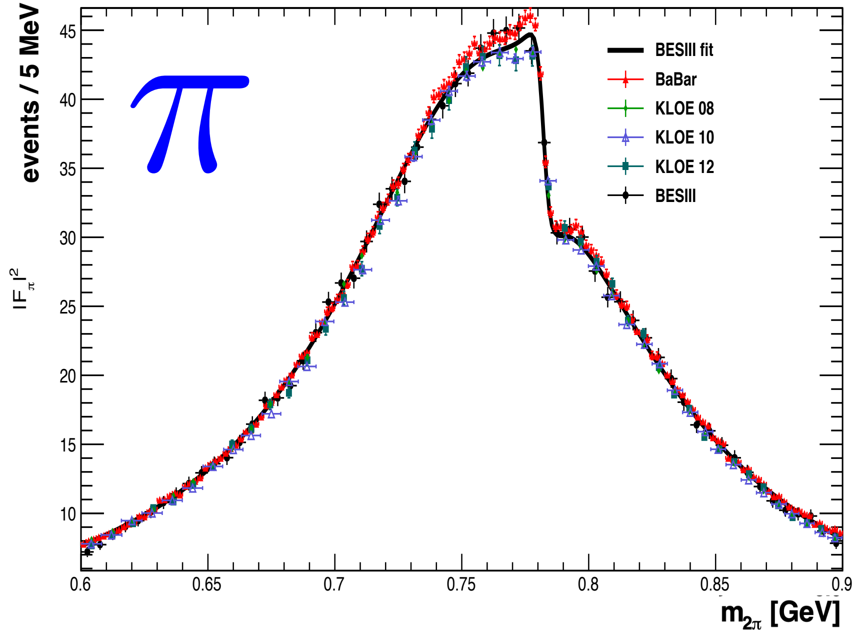


$$e^+e^- \rightarrow \mu^+\mu^-$$



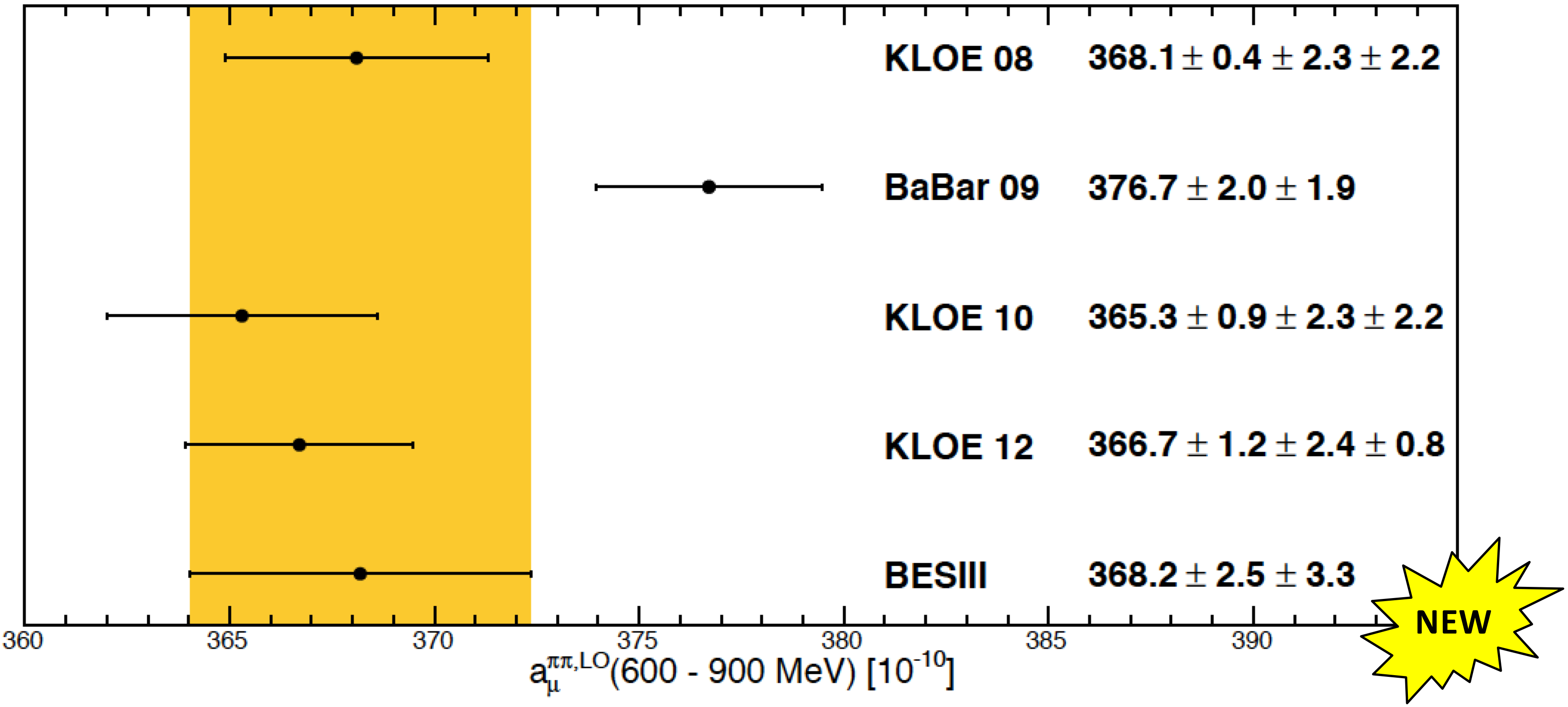
Δ(MC/QED-data) -1 = (0.51 ± 0.28) %

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



Impact on Hadronic Vacuum Polarization

BES III PLB753 (2016)



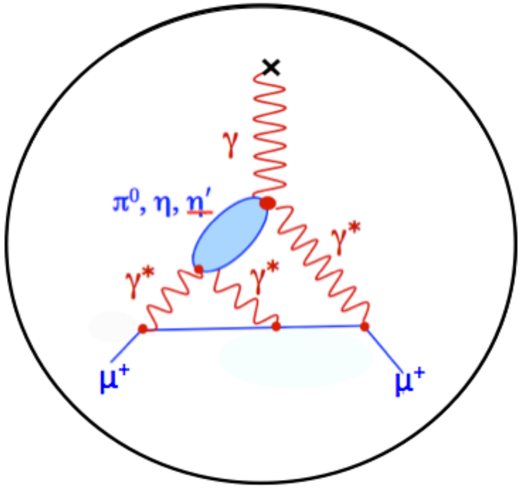
Good agreement with KLOE found !

BES III confirms the $(g\text{-}2)_\mu$ deviation at 3 …4 sigma level !!!

Hadronic Light-by-Light Scattering

HLbL: (10.5 ± **2.6**) · 10^{-10}
Prades, de Rafael, Vainshtein '09

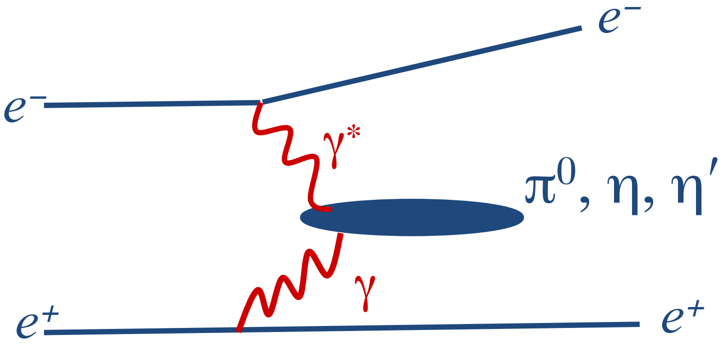
(13.6 ± **2.5**) · 10^{-10}
Melnikov, Vainshtein '09



Relation ?

⇔

Exp. Input !
Transition
Form Factors
$F(Q^2)$



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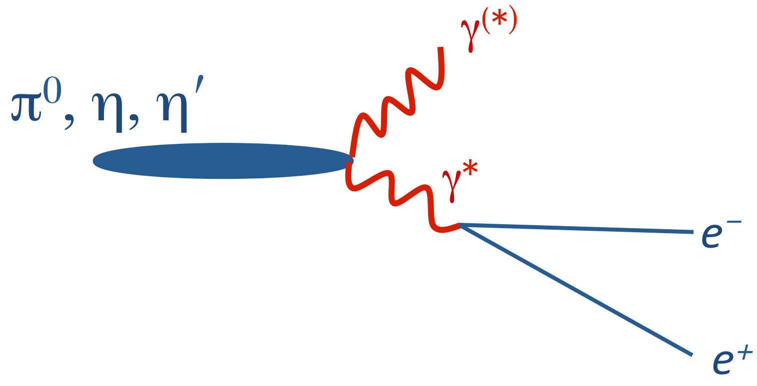
1044

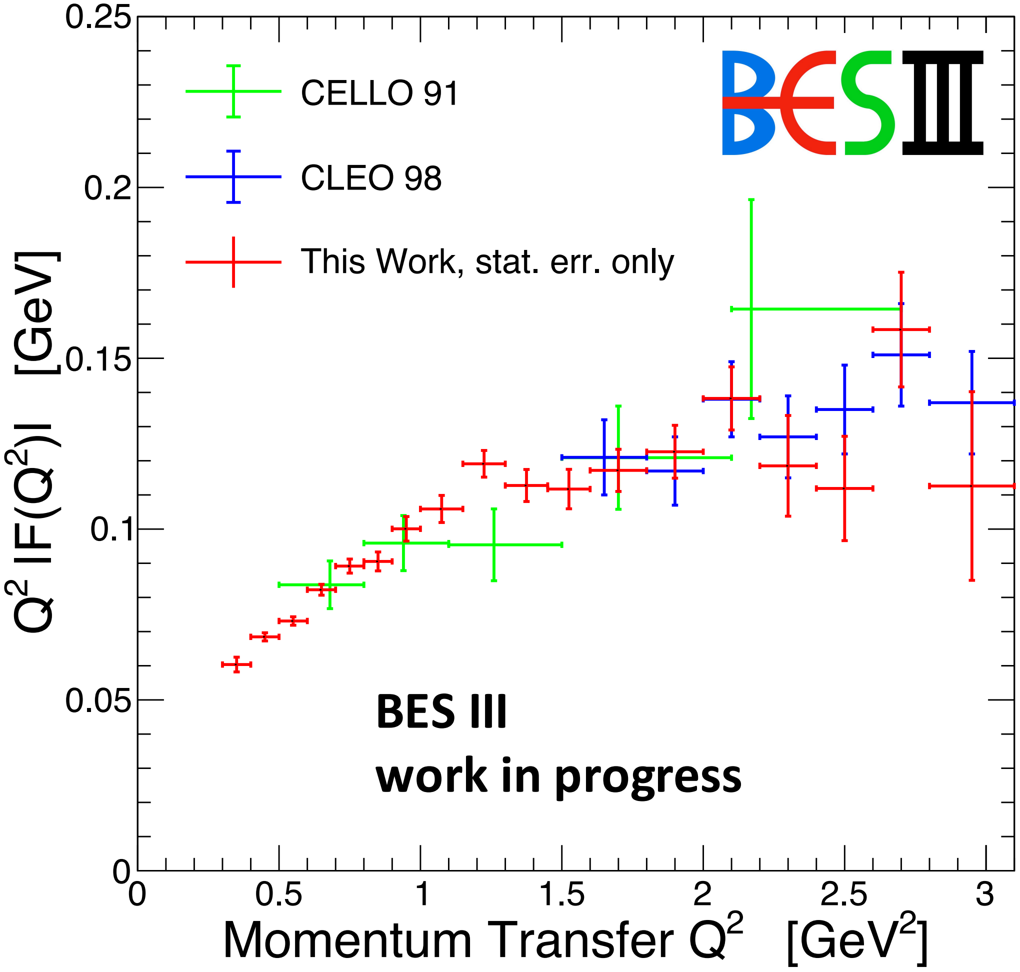


Future: data-driven approach!

Dispersion Relations being developed using experimental measurements of meson transition form factors!

Colangelo et al '14; Pauk, Vanderhaeghen '14

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

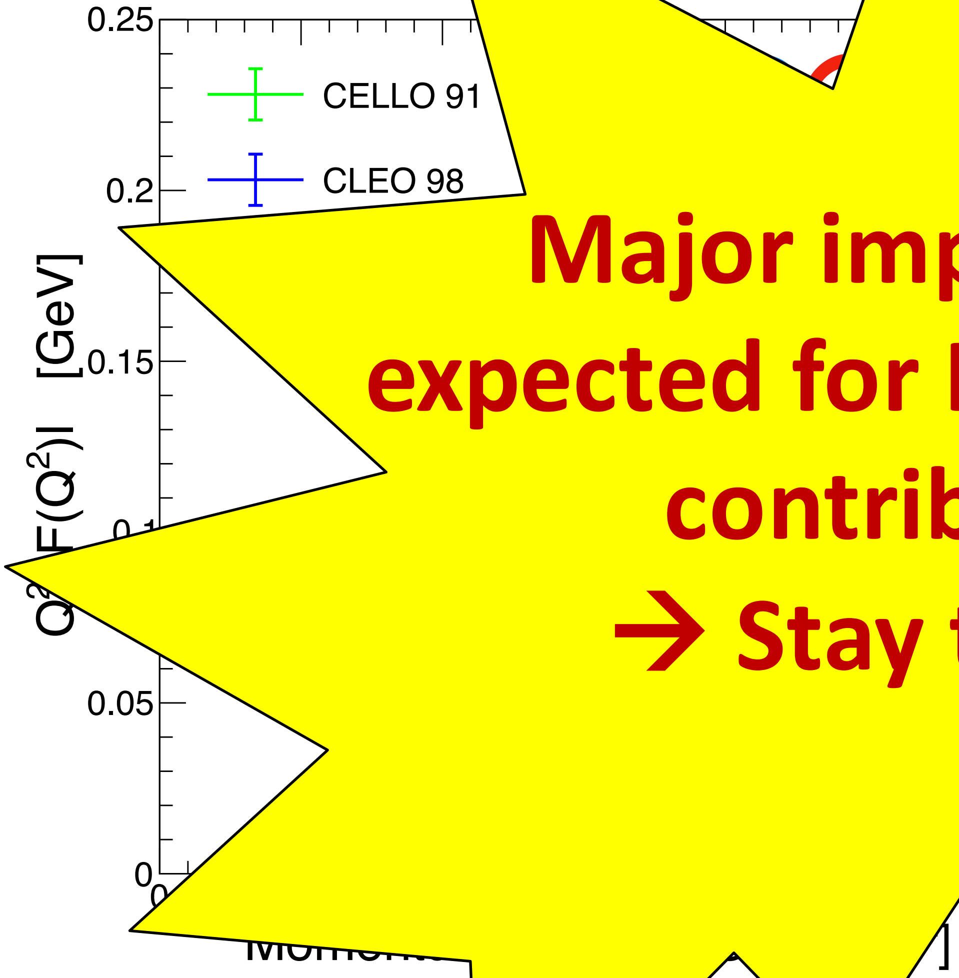


- L_{int}: 2.92 fb^{-1}
- Extract TFF for $0.3 \leq Q^2[GeV^2] \leq 3.1$

→ Unprecedented Accuracy $Q^2 < 1.5$ GeV^2

→ Challenges Hadronic Models

BES III Analysis: $\gamma\gamma^* \to \pi^0$



Major improvement expected for HVP and HLbL contributions

→ Stay tuned !!!

^{2}[GeV^2] ≤ 3.1

cy $Q^2 <$ 1. V^2

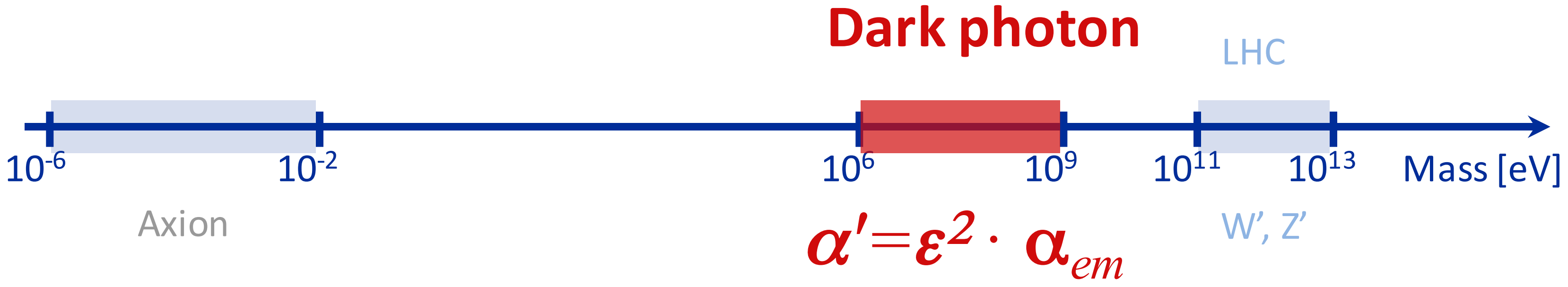
→ C ges Hadronic Models

The Dark Photon

as a possible Extension of the Standard Model

Dark Photon Search

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



$$\alpha' = \varepsilon^2 \cdot \alpha_{em}$$

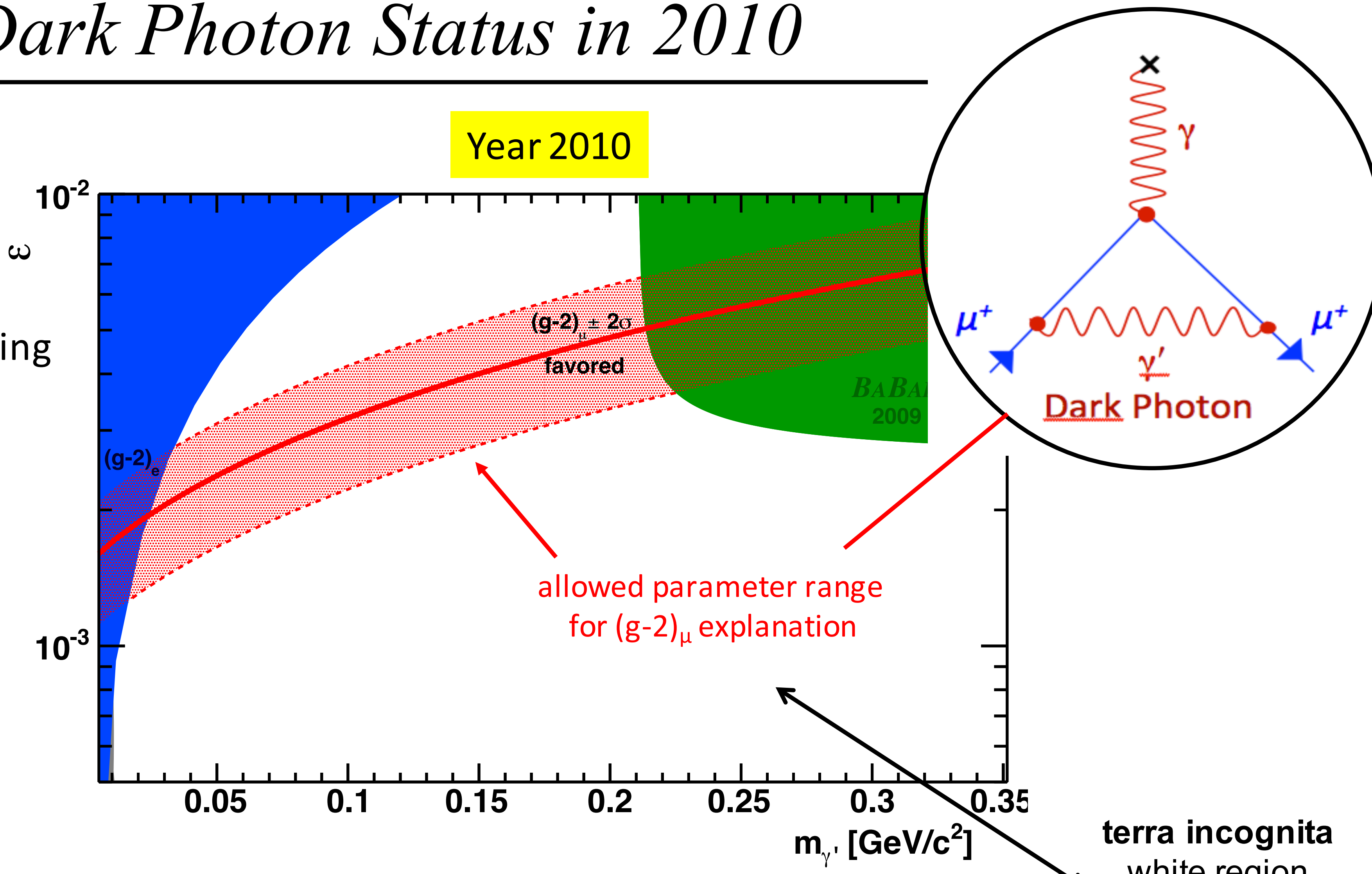
Search for the O(GeV/c^2) mass scale in a world-wide effort

- 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 3.6σ between (g-2)$_\mu$** Standard Model prediction and direct (g-2)$_\mu$ measurement
  Pospelov(2008)

Dark Photon Status in 2010

Year 2010



Coupling

Mass

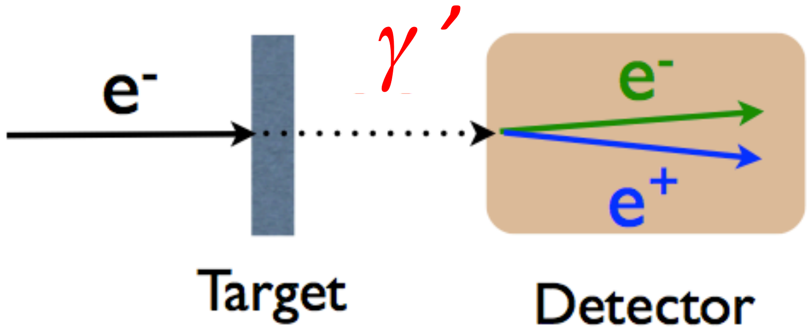
allowed parameter range
for $(g-2)_\mu$ explanation

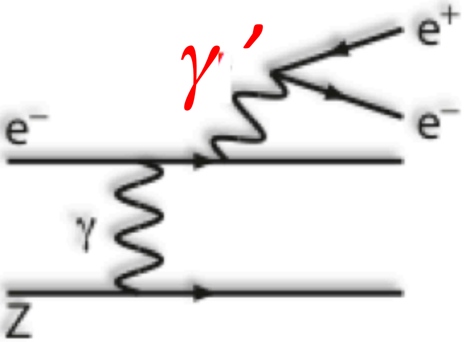
terra incognita
white region
motivated by
dark matter !

Searches using Fixed-Target Experiments

Bjorken, Essig, Schuster, Toro (2009)

Low-energy, high-intensity accelerators on the GeV scale are ideally suited for Dark Photon searches





m_{e+e-}

Bump hunting!

1. **High luminosity e- beam**
2. **Excellent mass resolution**
3. **Detection at small angles**

→ MAMI / JLAB
→ Spectrometers

Mainz Microtron MAMI

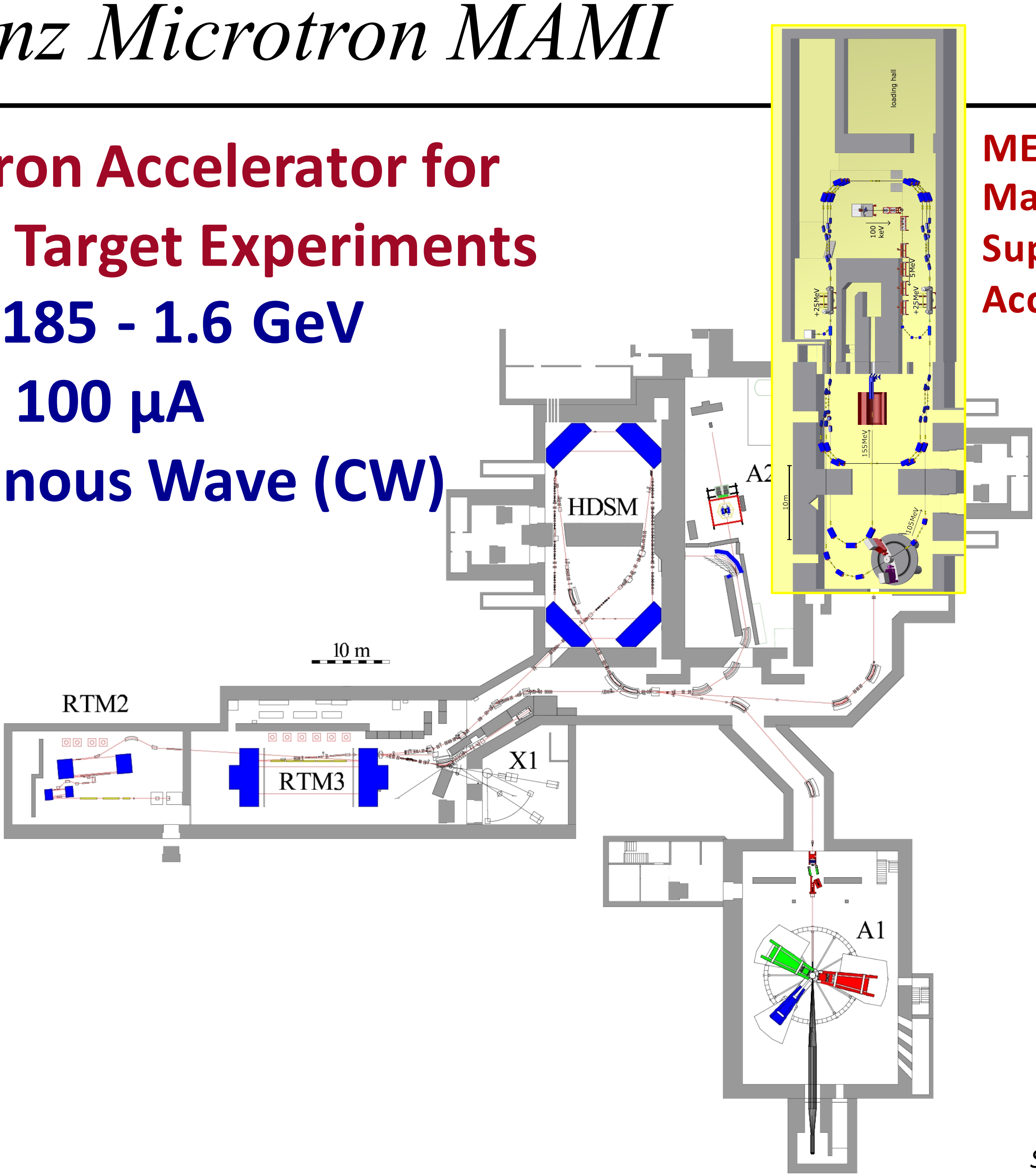
Electron Accelerator for Fixed Target Experiments

$E = 0.185 - 1.6$ GeV

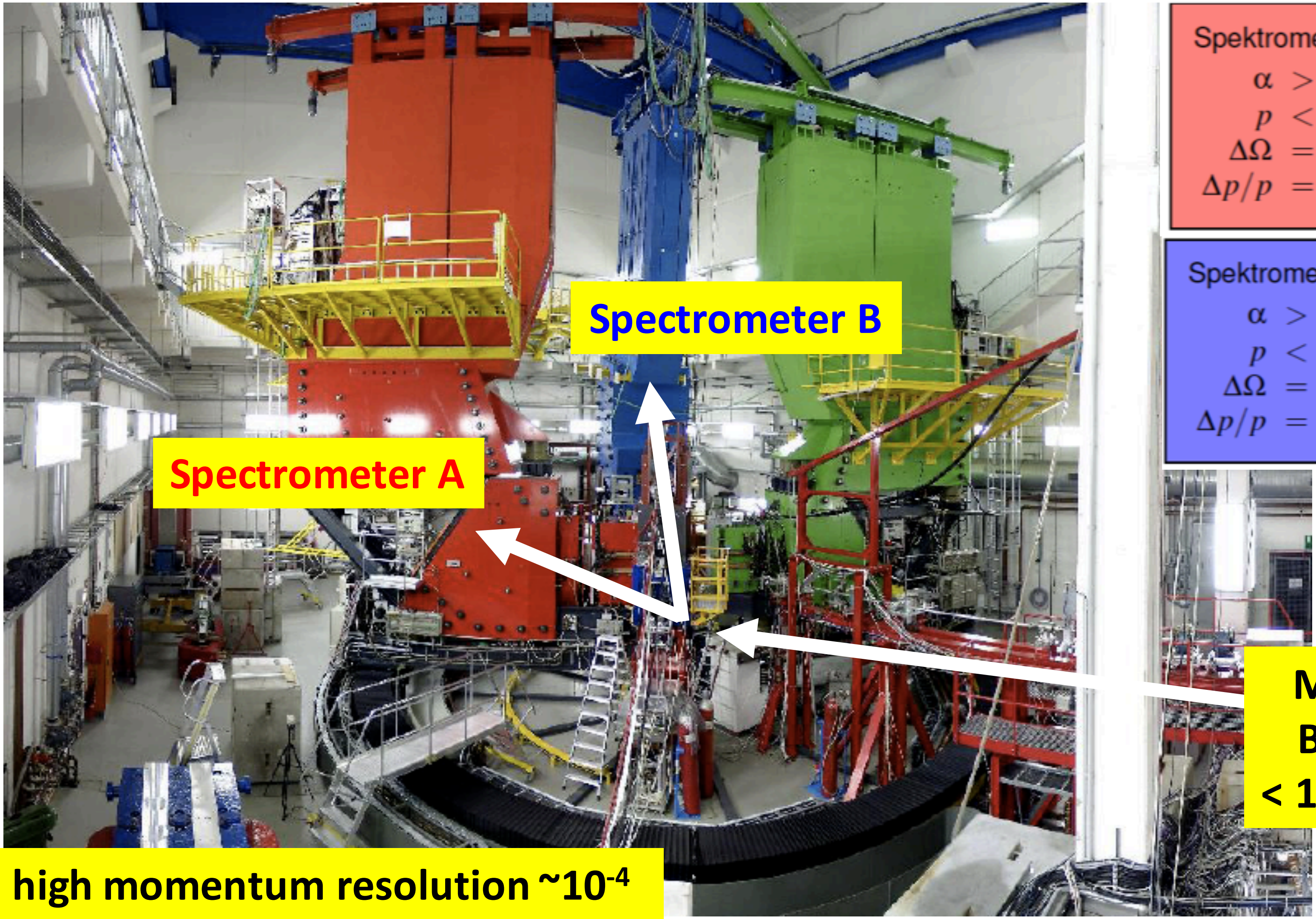
$I_{max} \sim 100\ \mu A$

Continous Wave (CW)

MESA
Mainz Energy-Recovering Superconducting Accelerator



A1 High Resolution Spectrometers



Spectrometer B

Spectrometer A

MAMI
Beam
< 1.6 GeV

high momentum resolution ~10^{-4}

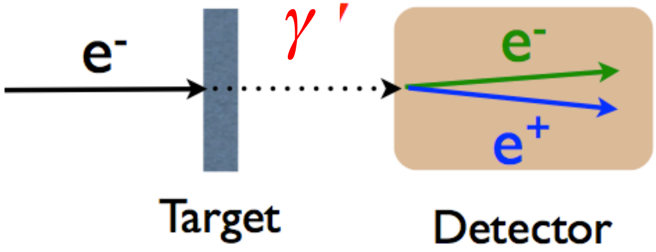
Spektrometer A:

$$\begin{aligned} \alpha &> 20^\circ \\ p &< 735\,\tfrac{\text{MeV}}{c} \\ \Delta\Omega &= 28\,\text{msr} \\ \Delta p/p &= 20\% \end{aligned}$$

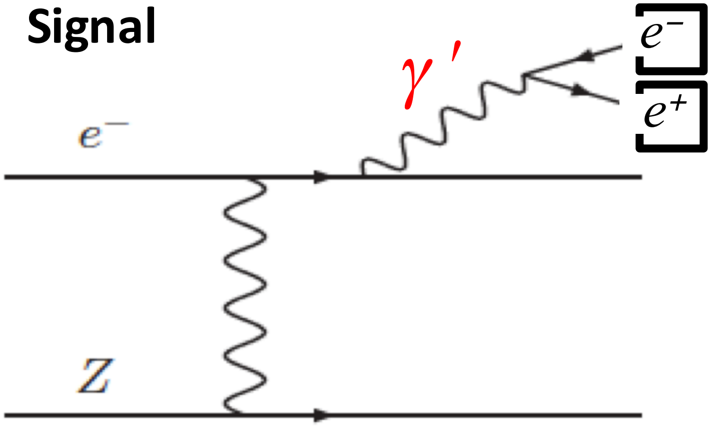
Spektrometer B:

$$\begin{aligned} \alpha &> 8^\circ \\ p &< 870\,\tfrac{\text{MeV}}{c} \\ \Delta\Omega &= 5.6\,\text{msr} \\ \Delta p/p &= 15\% \end{aligned}$$

Results from A1 Pilot Run (2011)



Signal



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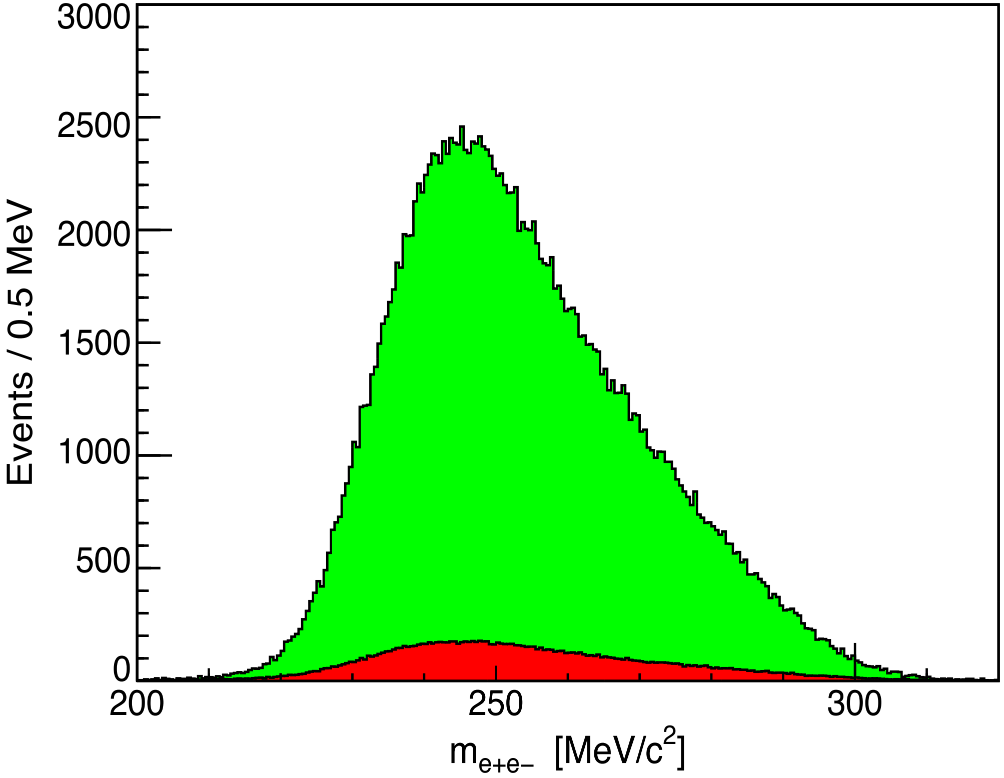
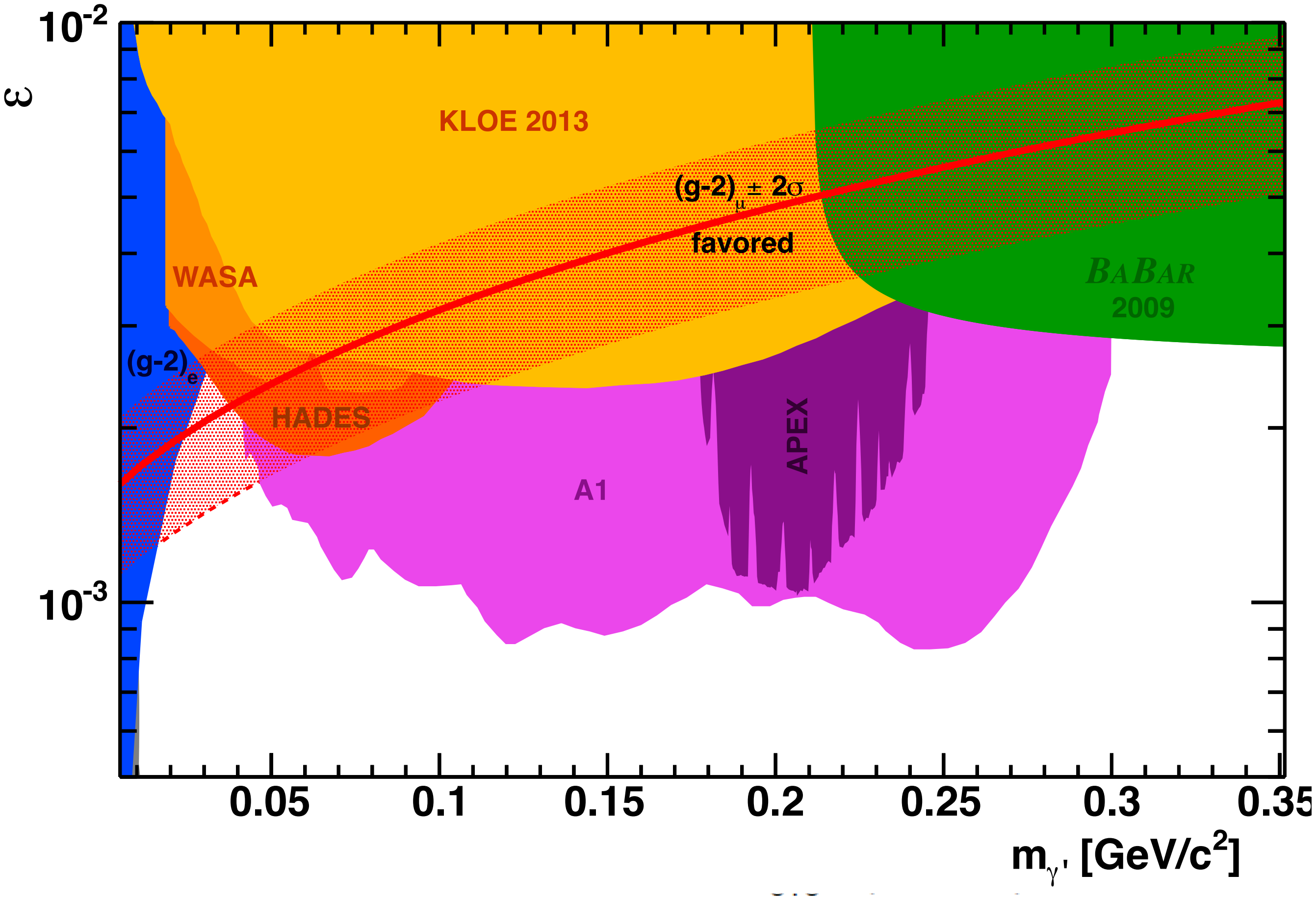
Background



Invariant Mass of e+e-

Results from A1

Merkel et al. [A1]
PRL '11
PRL '14

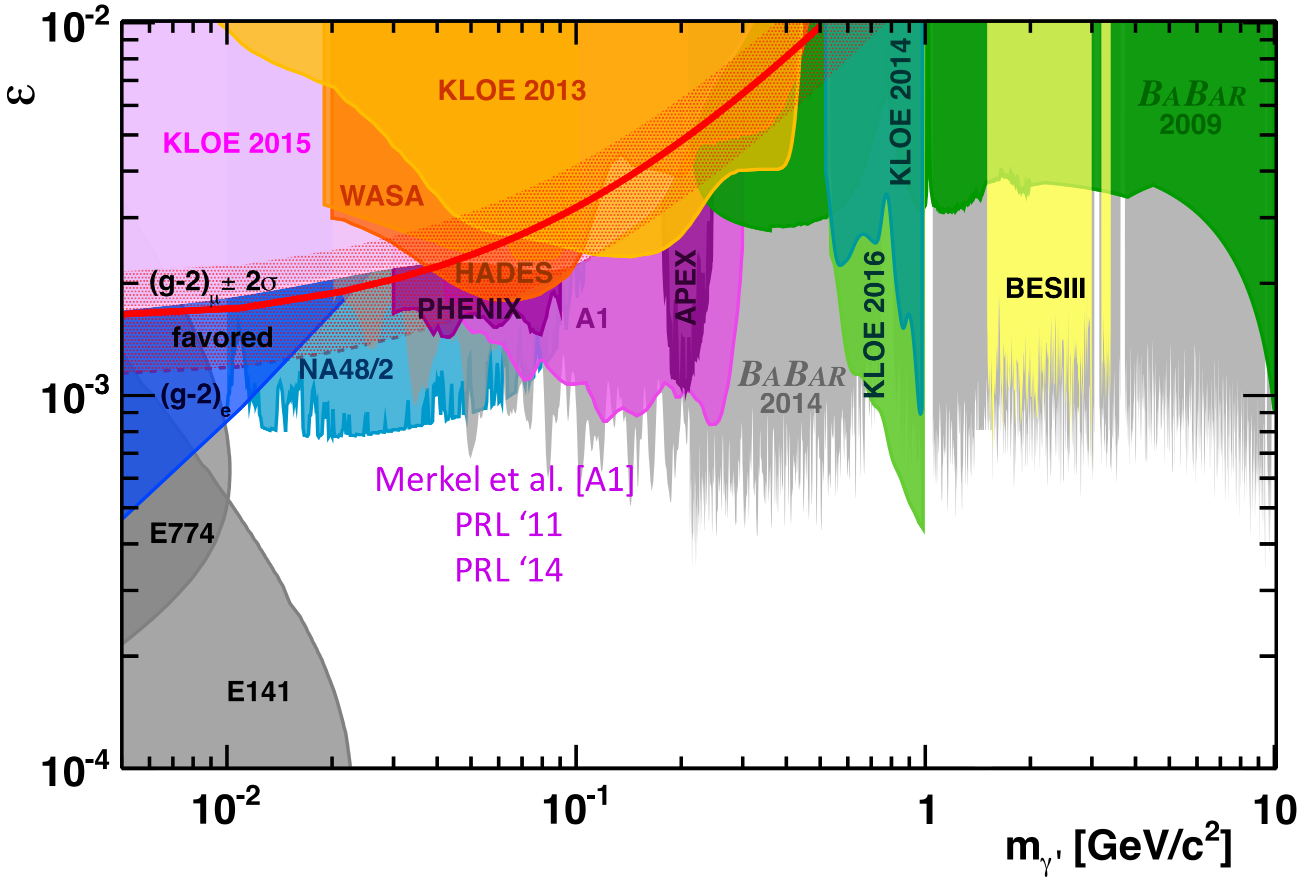


- E_{beam} 180 - 855 MeV
- 100 μA beam current
- Stack of Ta targets
- 22 kinematic settings
- O(1 month) of beam tim

→ at time of publication most stringent limit ruling out major part of the parameter range motivated by $(g-2)_\mu$

Results from A1/MAMI

Year 2017



Merkel et al. [A1]
PRL '11
PRL '14

→ at time of publication most stringent limit ruling out major part of the parameter range motivated by $(g\text{-}2)_\mu$

New Tool for Low-Energy Frontier: MESA

Mainz Energy-Recovering Superconducting Accelerator

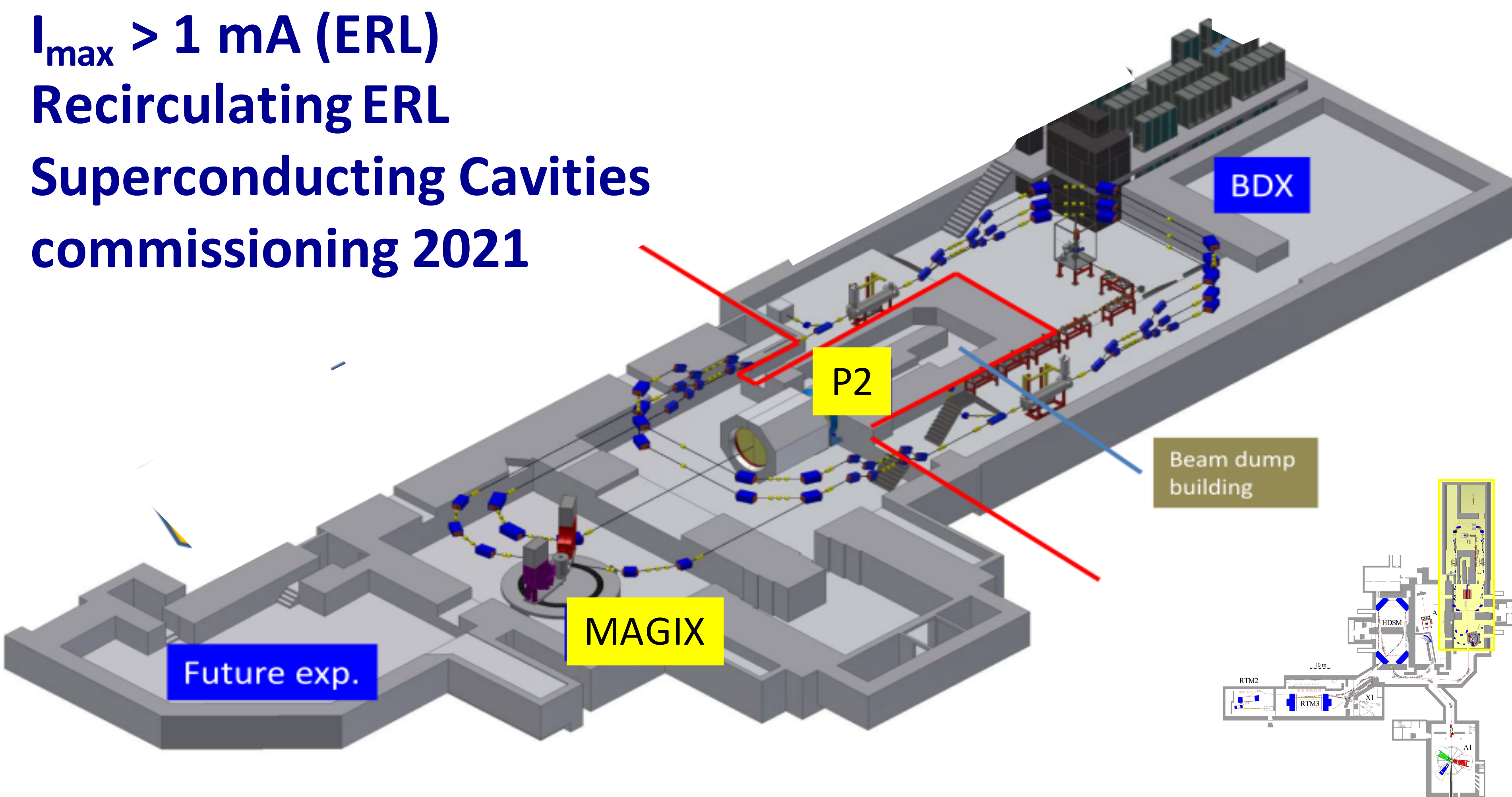
E_{max} = 155 MeV

I_{max} > 1 mA (ERL)

Recirculating ERL

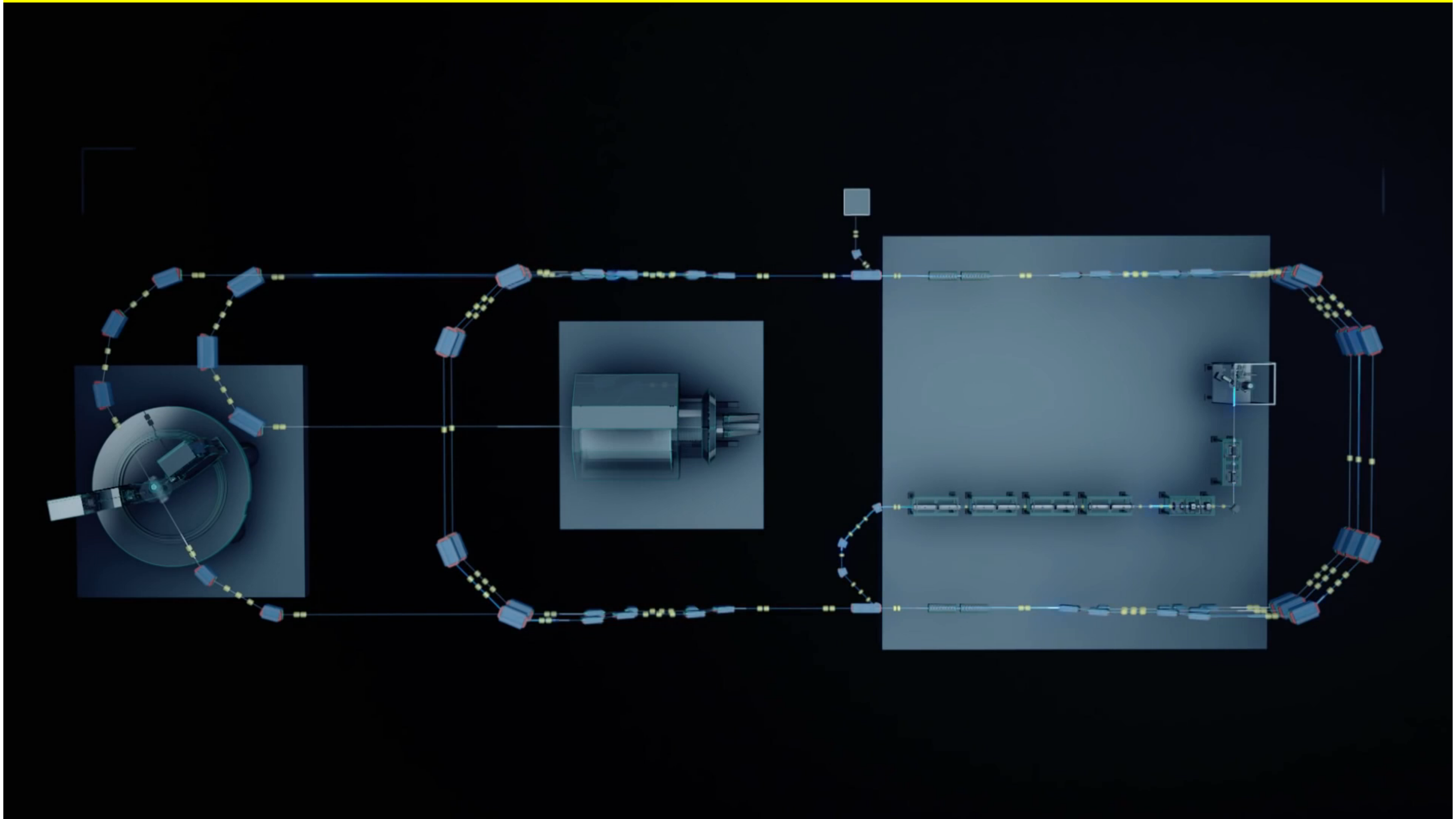
Superconducting Cavities

commissioning 2021



Internal Exper. MAGIX @ MESA ERL Mode

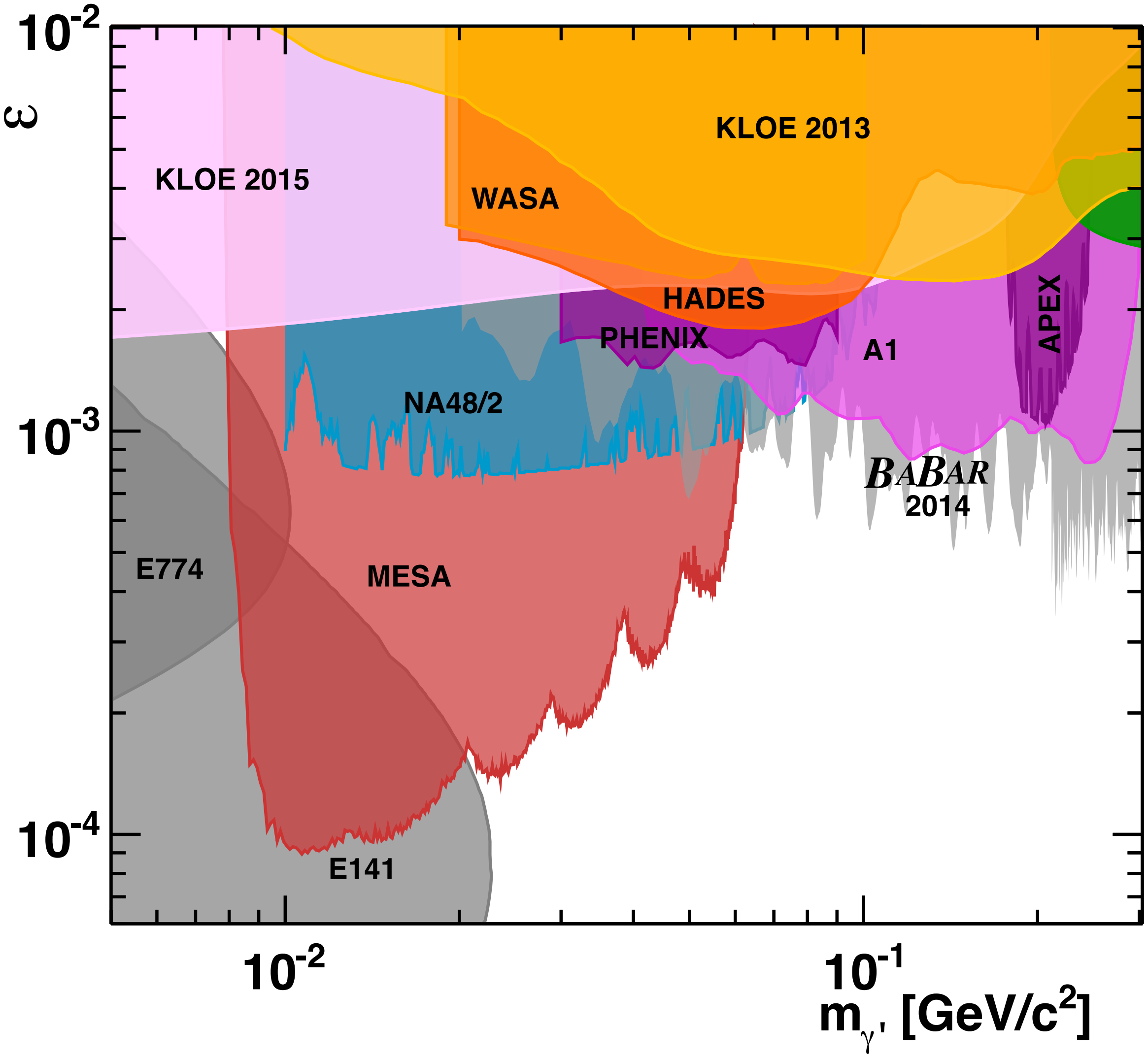
Operation of a high-intensity (polarized) ERL beam
in conjunction with light internal target
→ a novel technique in nuclear and particle physics
→ precise measurement of low momenta tracks at competitive luminosities



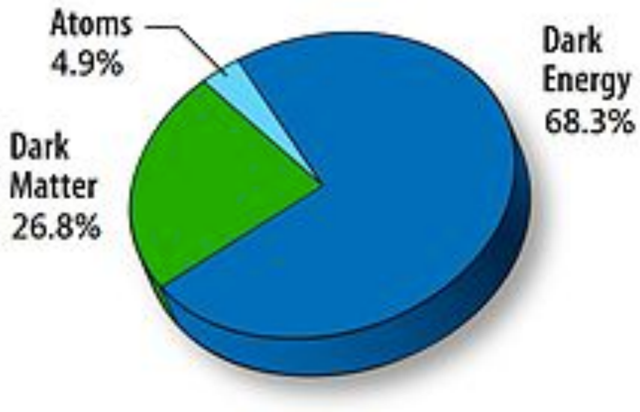
Dark Sector Searches at MAGIX

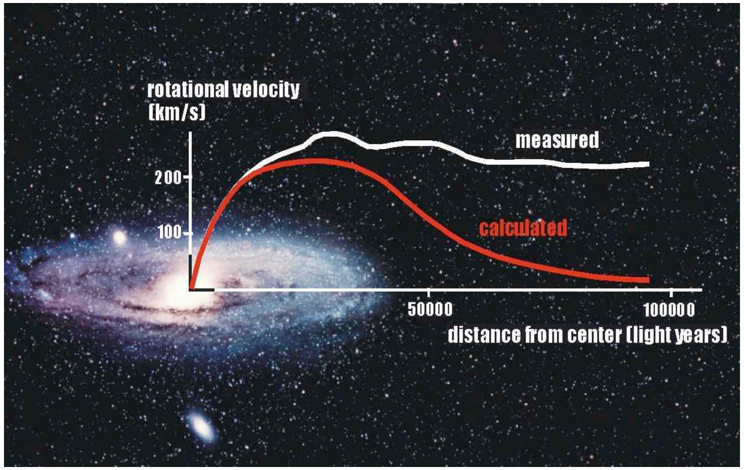
Features:

- Xe gas target
- Luminosity 10^{35} cm^{-2}s^{-1}
- 6 month of data taking



Light Dark Matter Search at MESA



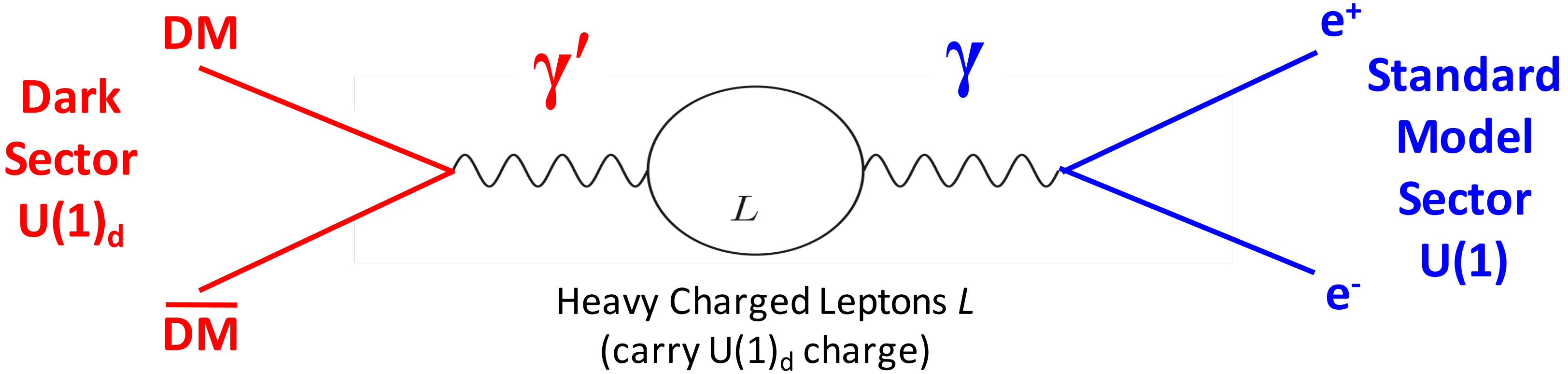


Dark Photon Relation to Dark Matter

Model 1: $m_{\gamma'} \ll m_{\text{DM}}$

Holdom [1986]

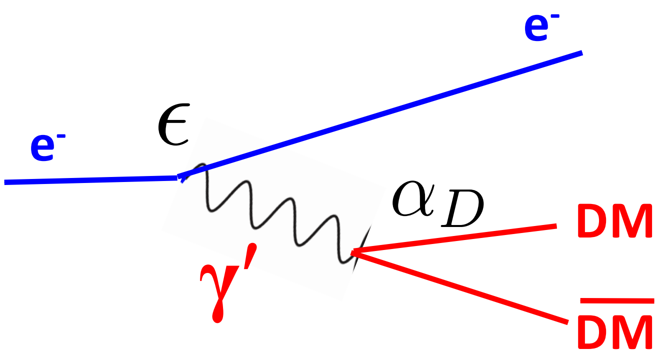
Dark Photon decaying into SM particles – coupling ϵ



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

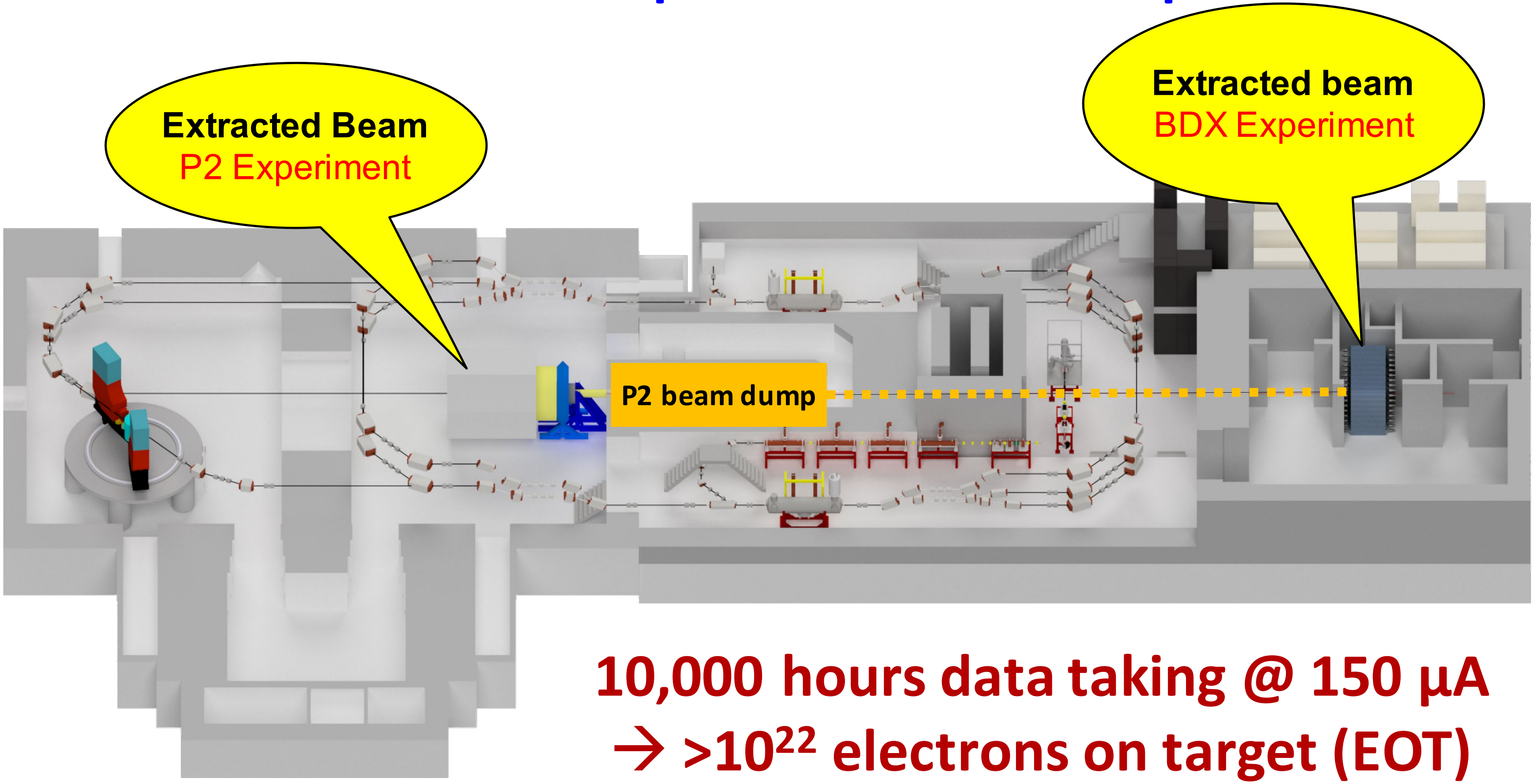
Model 2: $m_{\gamma'} > 2m_{\text{DM}}$

Dark Photon decaying into Dark Matter
→ invisible decay experiments
→ LDM detection



Beam Dump Experiment (BDX) @ MESA

Electron Scattering (MESA) on Beam Dump
→ Collimated pair of Dark Matter particles !



10,000 hours data taking @ 150 µA
→ >10^{22} electrons on target (EOT)

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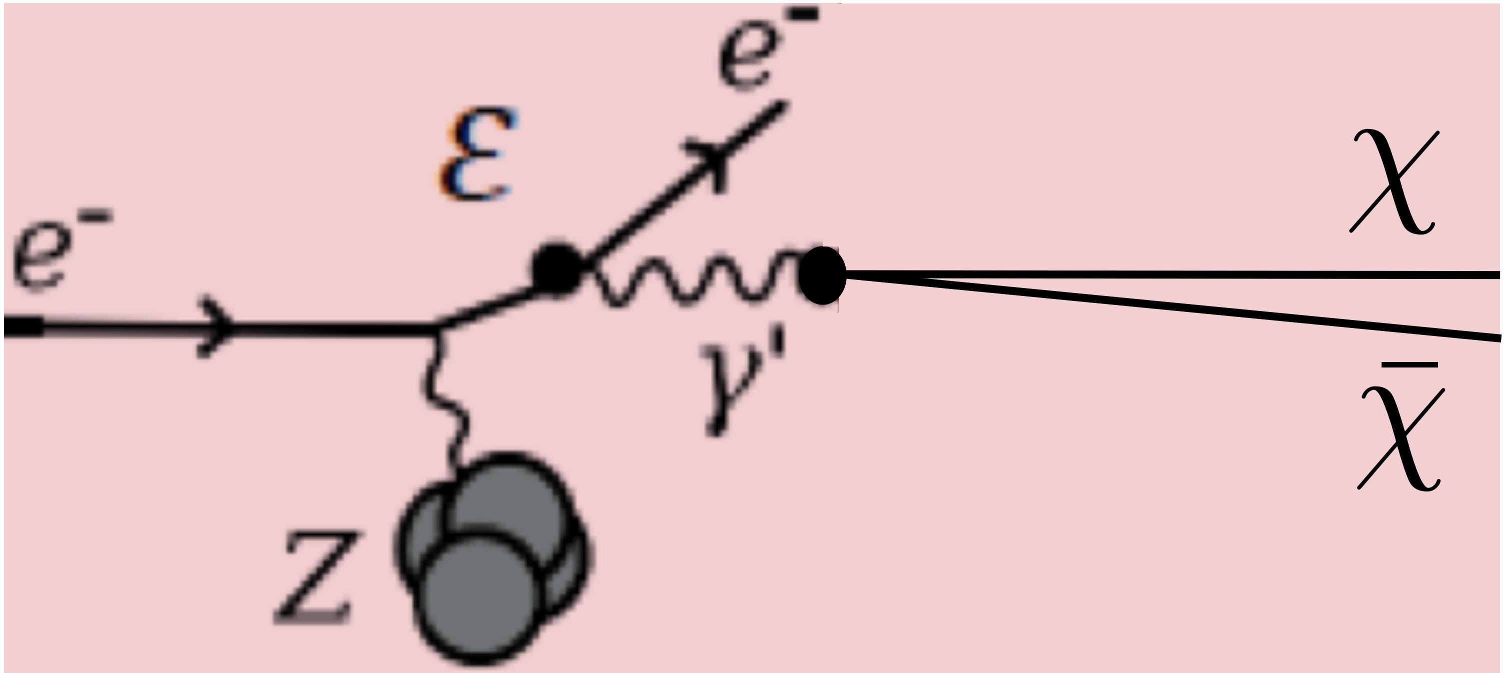

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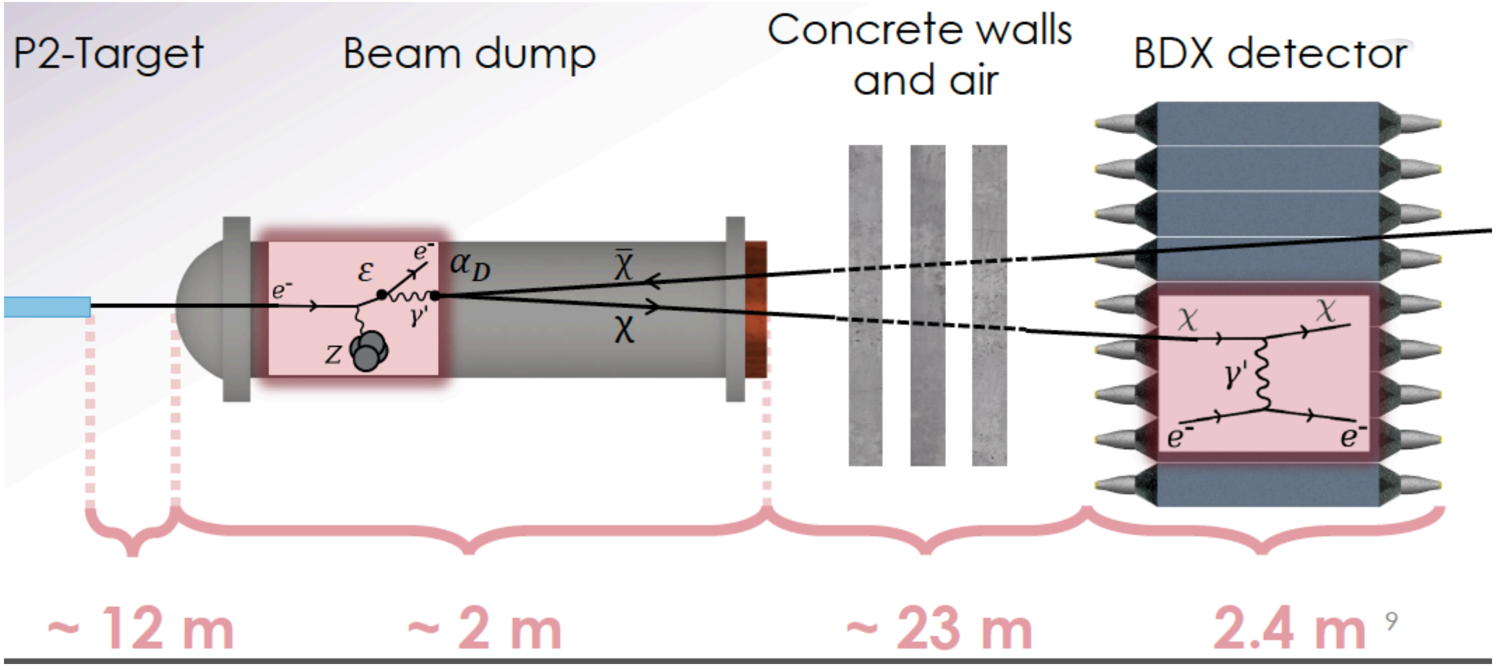

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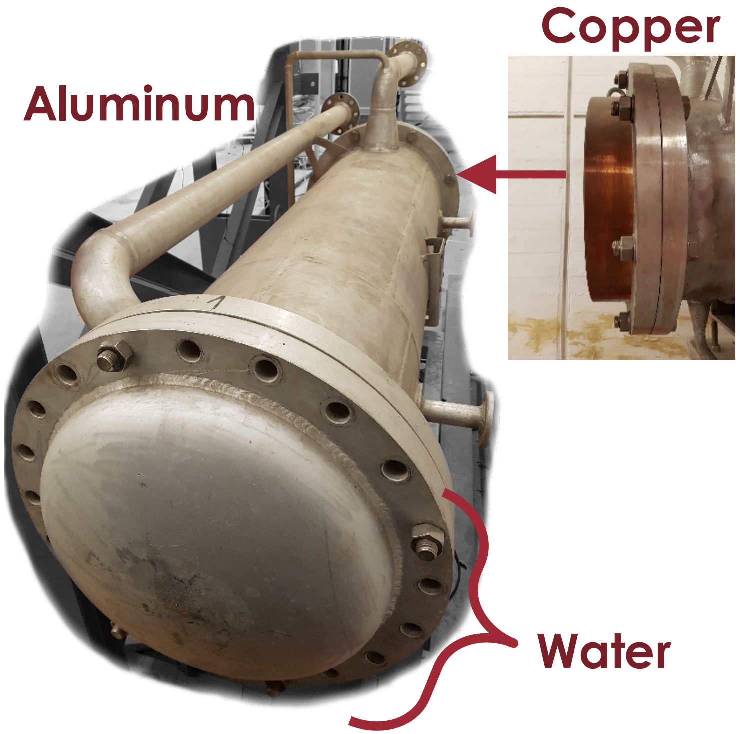
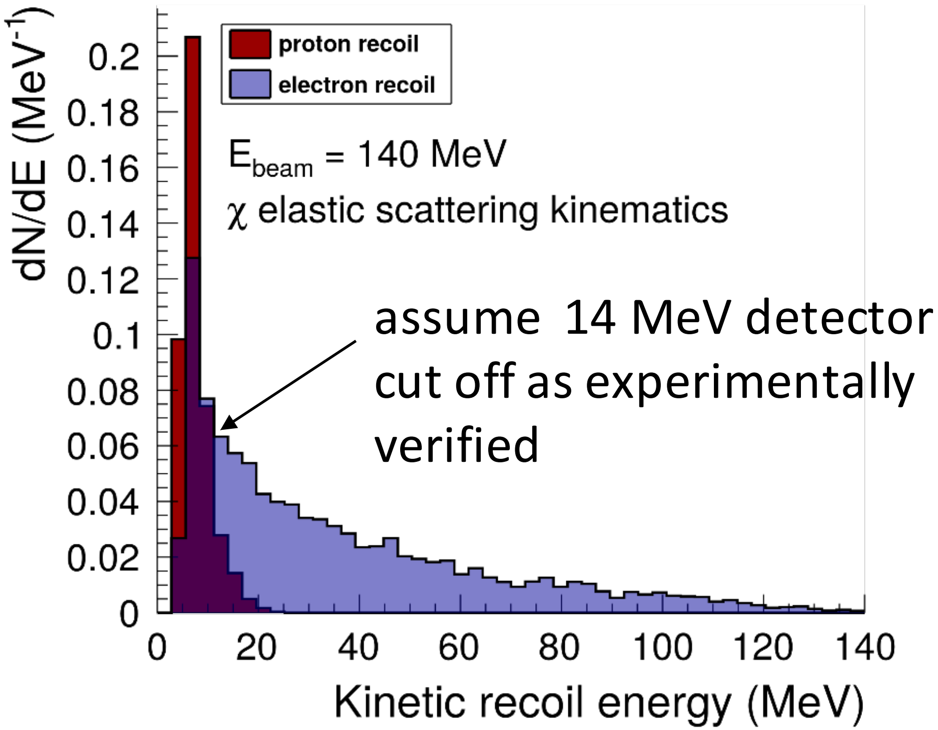
Simulation BDX @ MESA

- Full GEANT4 simulation (P2 target, beam dump, BDX detector volume, walls etc.)
- Addition of 2.5 mm W plate before beam dump to increase (dark) photon rate?
- No neutrino background due to low beam energy, reduced neutron background





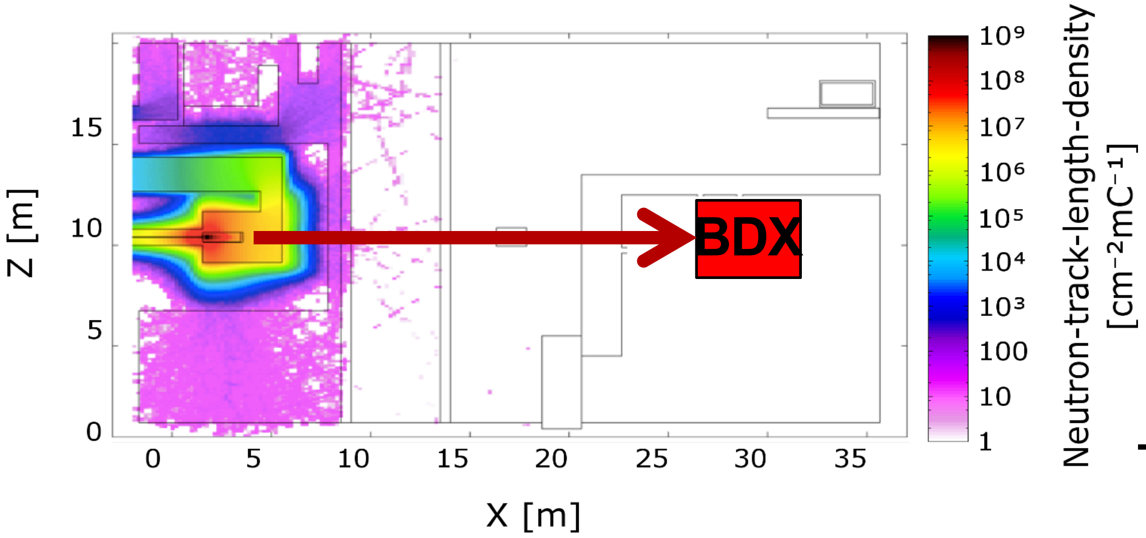
assume 14 MeV detector cut off as experimentally verified

Detector Concept for BDX @ MESA

Ideal Requirements:

1. Large Surface (Acceptance)
2. Large thickness (Int. Prob.)
3. High density (Int. Prob.)
4. Reliability (long running time)
5. Background rejection

- Cosmics
- Natural Backgrounds
- Beam Backgrounds (Neutrons)



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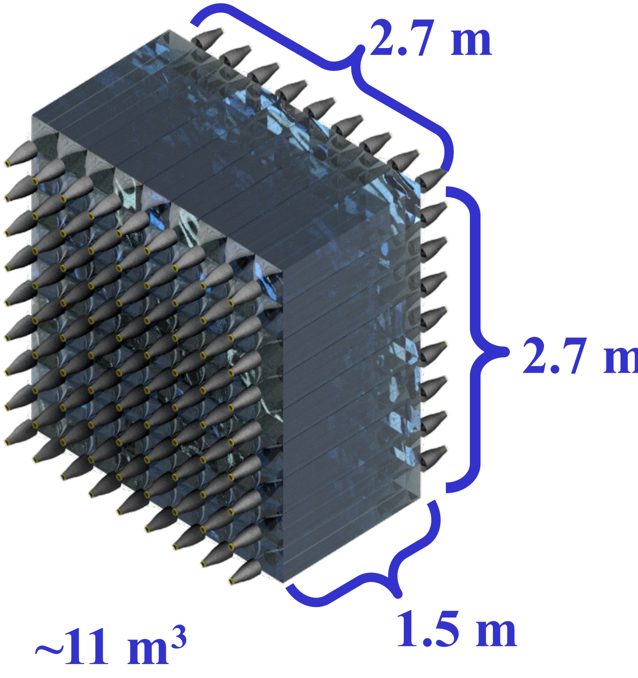
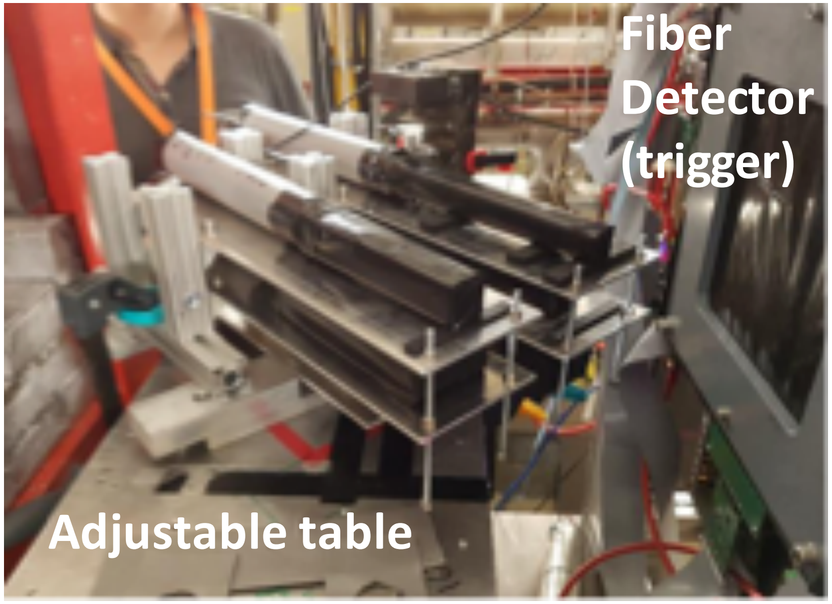


Baseline Concept

Inorganic crystal calorimeter (high density)

- Cherenkov (fast, no neutrons)
- Scintillator (higher light yield)

MAMI Test Beam for BDX @ MESA



14 MeV

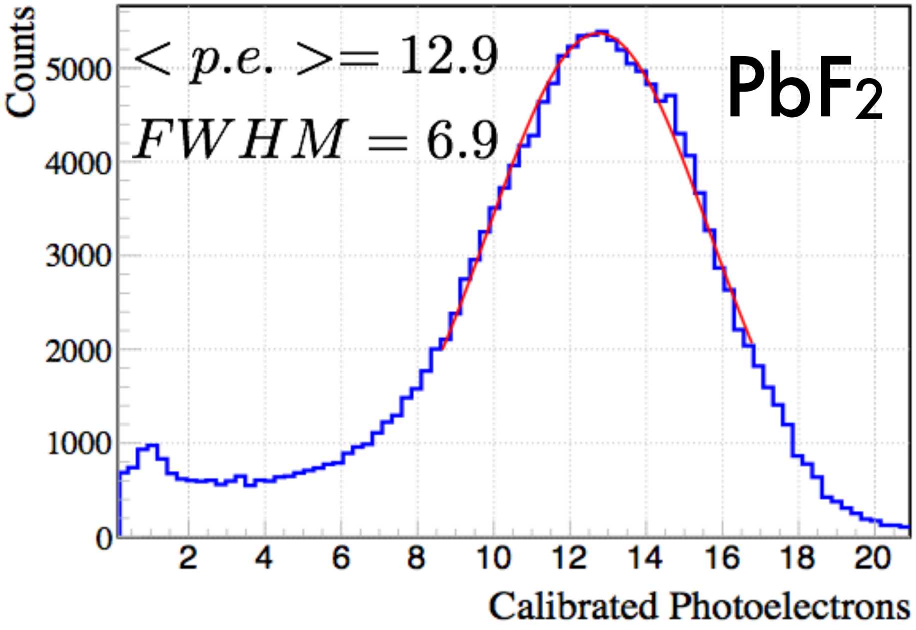
MAMI beam

Measurements:

Light Yield

Position dependence

PMT voltage scan



Crystals investigated

SF5 (Pb-Glass, Schott AG)

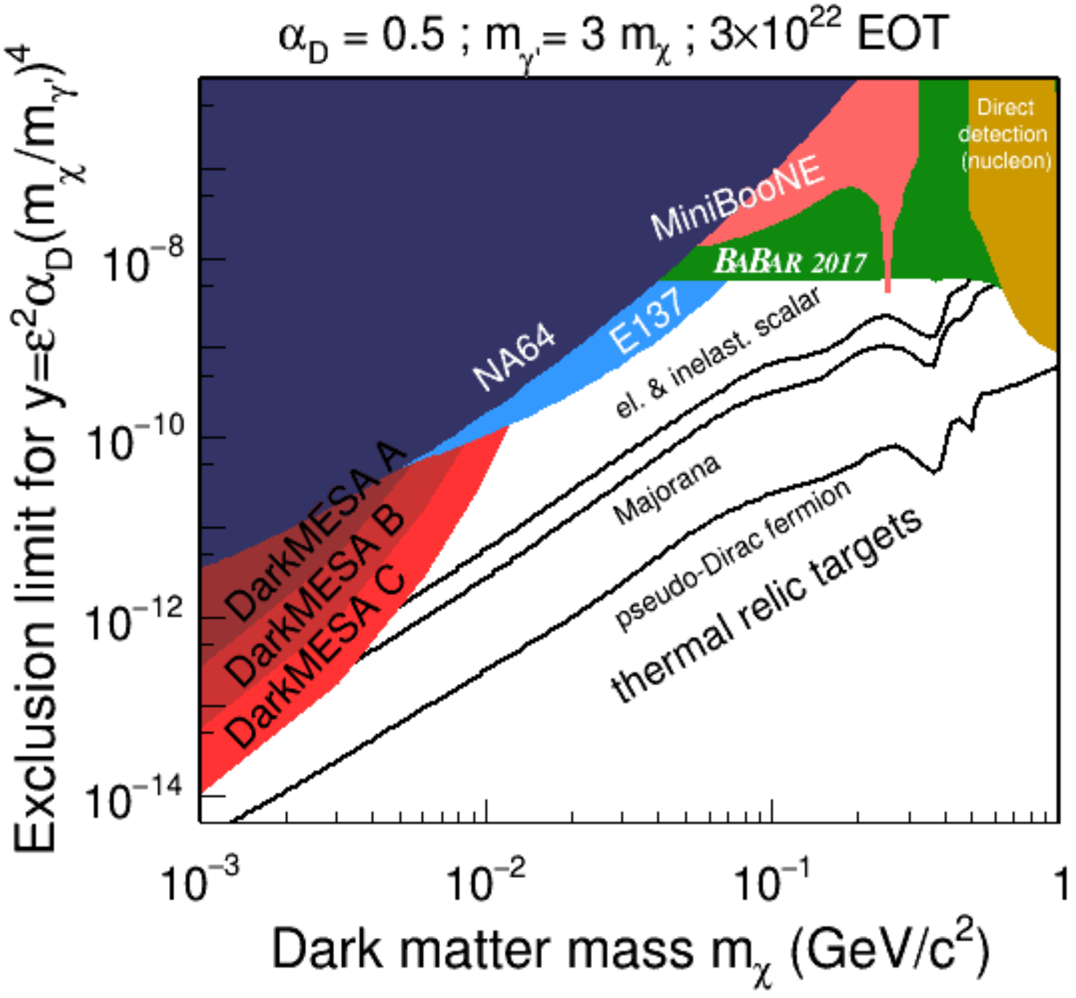
SF6 (Pb-Glass, Schott AG)

SF57HTultra (Pb-Glass, Schott AG)

BGO (from L3-LEP)

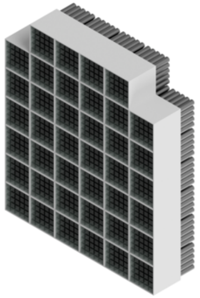
PbF_2 (from A4/MAMI)

MAMI Test Beam for BDX @ MESA

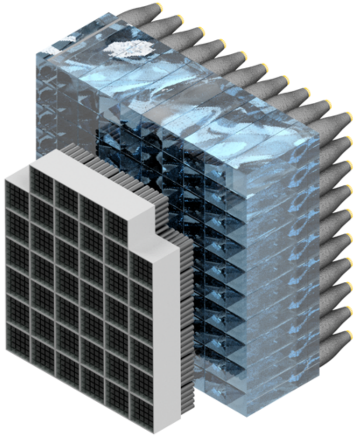


Detector layouts:

- Phase A: existing PbF2 crystals (A4 - 0.13 m^3 volume)
- Phase B: add aditional lead glass blocks (total volume 1m^3)
- Phase C: 11m^3 lead glass calorimeter

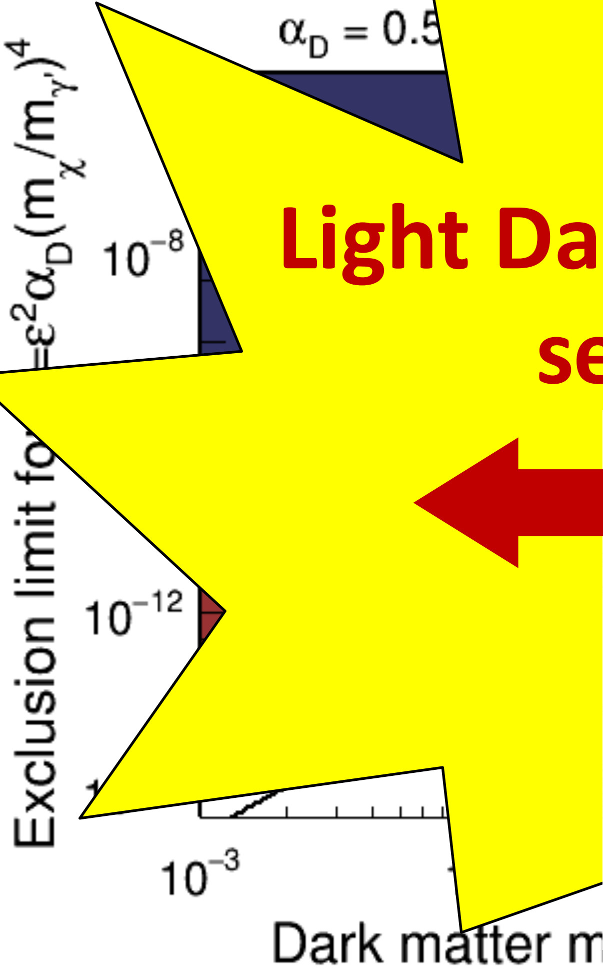


Phase 1



Phase 2

MAMI T st Beam f BDX @ MESA



puts:

xisti

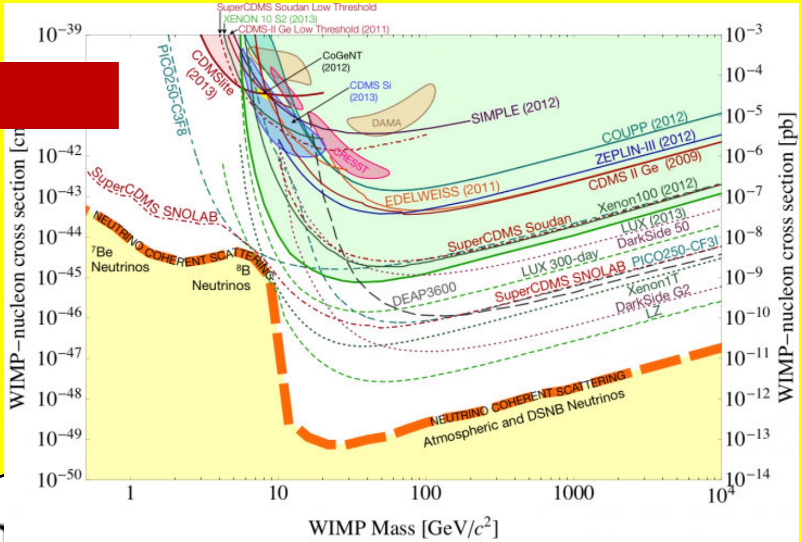
e)

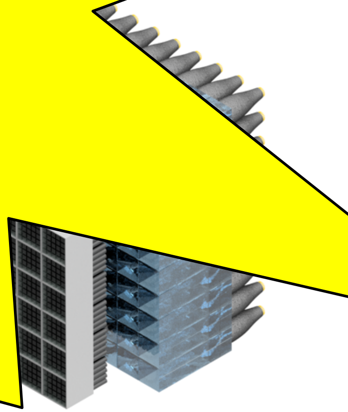
d glass

volume 1m³)

glass

Light Dark Matter Searches at MESA seems highly attractive





Phase 2

Conclusions

Conclusions

- **Hadron physics („The low-energy frontier of the SM“)** aims to understand the theory of strong interactions at low energies
  --> **Hadron physics also limiting precision tests of the SM**

- **Upcoming new $(g\text{-}2)_\mu$ experiment** at FNAL
  --> Needs **improved SM prediction**, i.e. form factor measurements
  --> Huge activity on a world-wide scale

- **No TeV-scale New Physics seen at LHC** !
  --> Focus **on low-energy extensions of the SM**
  --> **Dark Photon** searches as a global effort
  --> High-intensity accelerators like MESA with great potential
  --> Unique opportunities for the search for **low-mass Dark Matter**