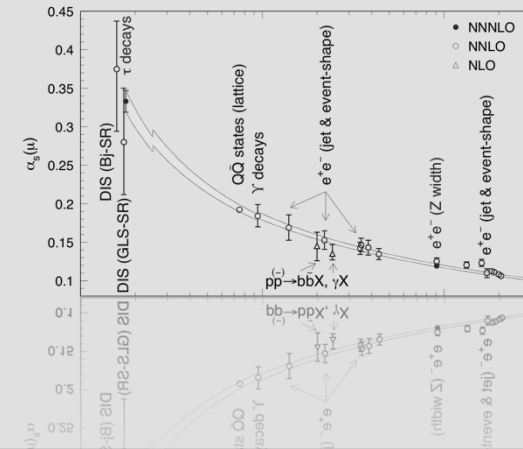




Clean measurements in the charged-lepton flavour sector can probe new physics at scales up to hundreds of TeV and above

Some deviations in flavour sector seen – none large enough to claim discovery – but very interesting to be followed up

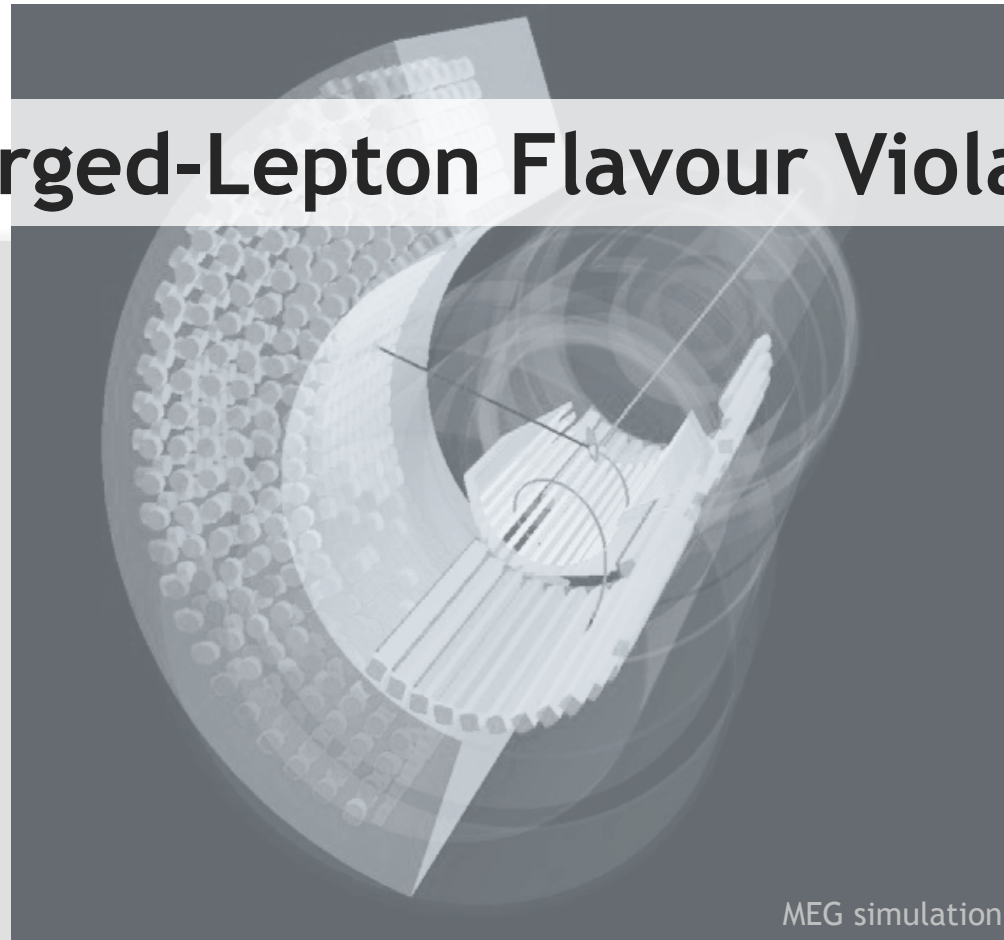
For this talk, I have been asked to discuss:

1. Charged-lepton flavour violation
 2. Lepton electric dipole moments and CP violation
 3. Recent tau physics results
 4. Muon anomalous magnetic moment
- + Conclusions

Absence of the decays $\mu \rightarrow e\gamma$ and $\tau \rightarrow \mu\gamma$ established, in the early days, that μ and τ were new elementary leptons, and not electron excitations

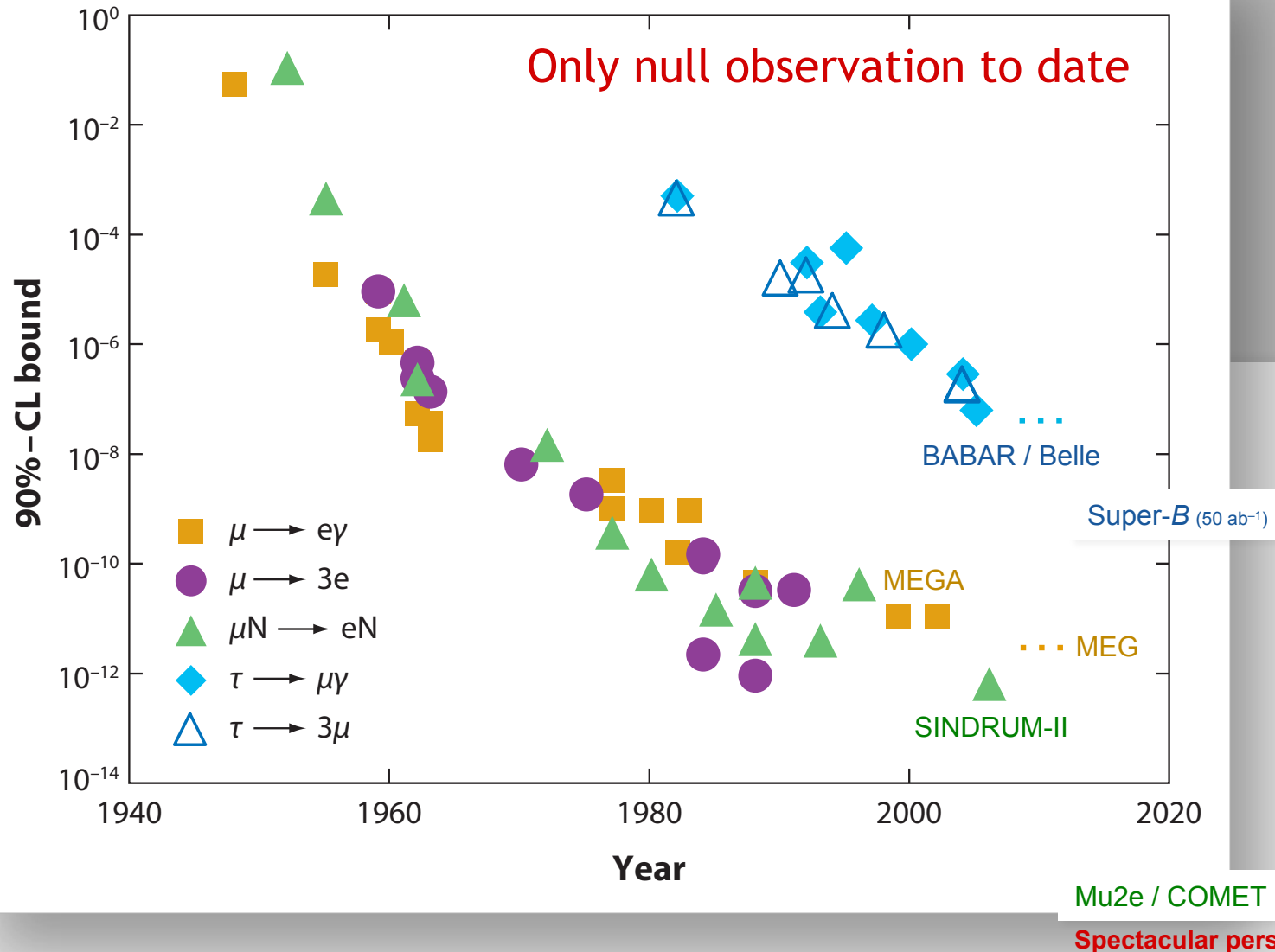
In analogy to the GIM mechanism, absence of $\mu \rightarrow e\gamma$ also required to introduce the muon neutrino to cancel flavour changing neutral currents (Feinberg 1958, prior to ν_μ discovery in 1962)

Charged-Lepton Flavour Violation



Charged-Lepton Flavour Violation

Marciano et al., Annu. Rev. Nucl. Part. Sci. 58, 315 (2008)

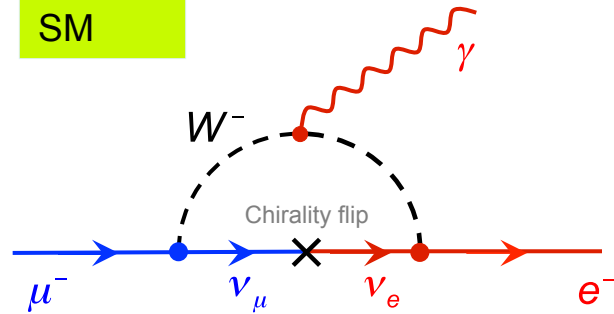


Mu-to-e Flavour Violation

Minimal SM: $m_\nu = 0 \rightarrow$ strictly zero transitions between lepton flavours

SM extension to $m_\nu \neq 0 \rightarrow$ unobservable tiny LFV rates predicted (GIM)

SM



$$\text{BR}(\mu^- \rightarrow e^- \gamma) \Big|_{\text{SM}} \simeq \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2$$

$$< 10^{-54}$$

$$(< 10^{-40} \text{ for } \tau^- \rightarrow \mu^- \gamma)$$

Generic NP contribution

$$\text{BR}(\mu^- \rightarrow e^- \gamma) \Big|_{\text{generic NP}} \simeq \frac{3\alpha}{32\pi} \left(|A_L|^2 + |A_R|^2 \right)$$

where $A_{L(R)}$ are radiative transition dipole amplitudes (dim-5 amplitude)

For generic new physics, parametrise:

$$A_L = A_R = \frac{16\sqrt{2}\pi^2}{G_F \Lambda_{\text{NP}}^2} \Rightarrow \Lambda_{\text{NP}} > 300 \text{ TeV}$$

Also: $\text{BR}_{\text{NP}}(\mu \rightarrow eee) \sim \alpha_{\text{QED}} \times \text{BR}_{\text{NP}}(\mu \rightarrow e \gamma)$

$\rightarrow$ Search for charged-LFV probes new physics without SM contamination !

Prior best limit on $\mu^+ \rightarrow e^+ \gamma$ by MEGA experiment (LAMPF, 1999): $B < 1.2 \times 10^{-11}$

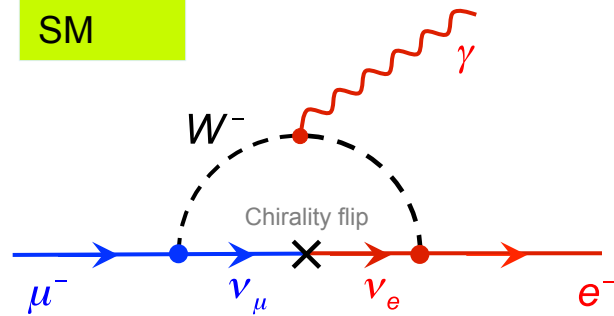
Mu-to-e Flavour Violation

Minimal SM: $m_\nu = 0 \rightarrow$ strictly zero transitions between lepton flavours

SM extension to $m_\nu \neq 0 \rightarrow$ unobservable tiny LFV rates predicted (GIM)

Flavour Changing Neutral Current

SM



$$\text{BR}(\mu^- \rightarrow e^- \gamma)_{\text{SM}} \simeq \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2$$

$$< 10^{-54}$$

$$(< 10^{-40} \text{ for } \tau^- \rightarrow \mu^- \gamma)$$

Generic NP contribution

Can vary significantly
with chosen new
physics amplitudes

$\text{BR}(\mu^- \rightarrow e^- \gamma)_{\text{generic}} = \frac{1}{32\pi} (|A_L|^2 + |A_R|^2)$

where $A_{L(R)}$ are radiative transition dipole amplitudes (dimensionless)

For generic new physics we parametrise:

$$A_{L(R)} = \frac{1}{\Lambda_{\text{NP}}^2} \Rightarrow \Lambda_{\text{NP}} > 300 \text{ TeV}$$

Also: $\text{BR}_{\text{NP}}(\mu \rightarrow e \gamma) \sim 170 \times \text{BR}_{\text{NP}}(\mu \rightarrow e e e)$

$\rightarrow$ Search for charged-LFV probes new physics without SM contamination !

Prior best limit on $\mu^+ \rightarrow e^+ \gamma$ by MEGA experiment (LAMPF, 1999): $B < 1.2 \times 10^{-11}$

The MEG $\mu^+ \rightarrow e^+ \gamma$ Experiment at PSI

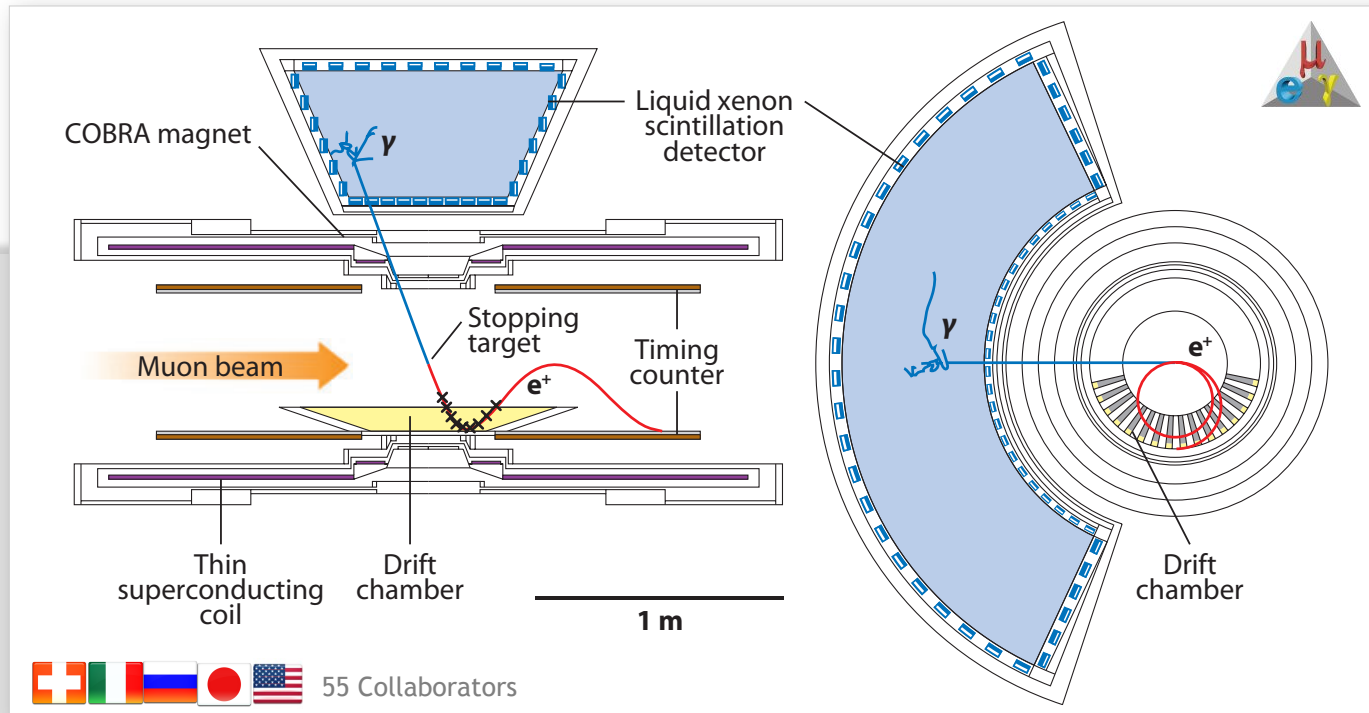
PSI π E5 produces 29 MeV surface μ^+ at 3×10^7 Hz rate hitting on thin stopping target

Signal reconstruction:

- Stopped μ^+ beam: monoenergetic
- Back-to-back and in-time $e-\gamma$
- Exploit E_γ , E_e , $T_{e\gamma}$, $\theta_{e\gamma}$, $\phi_{e\gamma}$ in combined fit

Background sources:

- Radiative $\mu^+ \rightarrow e^+ \gamma \nu \nu$ (RMD)
- Accidental photon coincidence from RMD, bremsstrahlung, or e^+ annihilation in flight



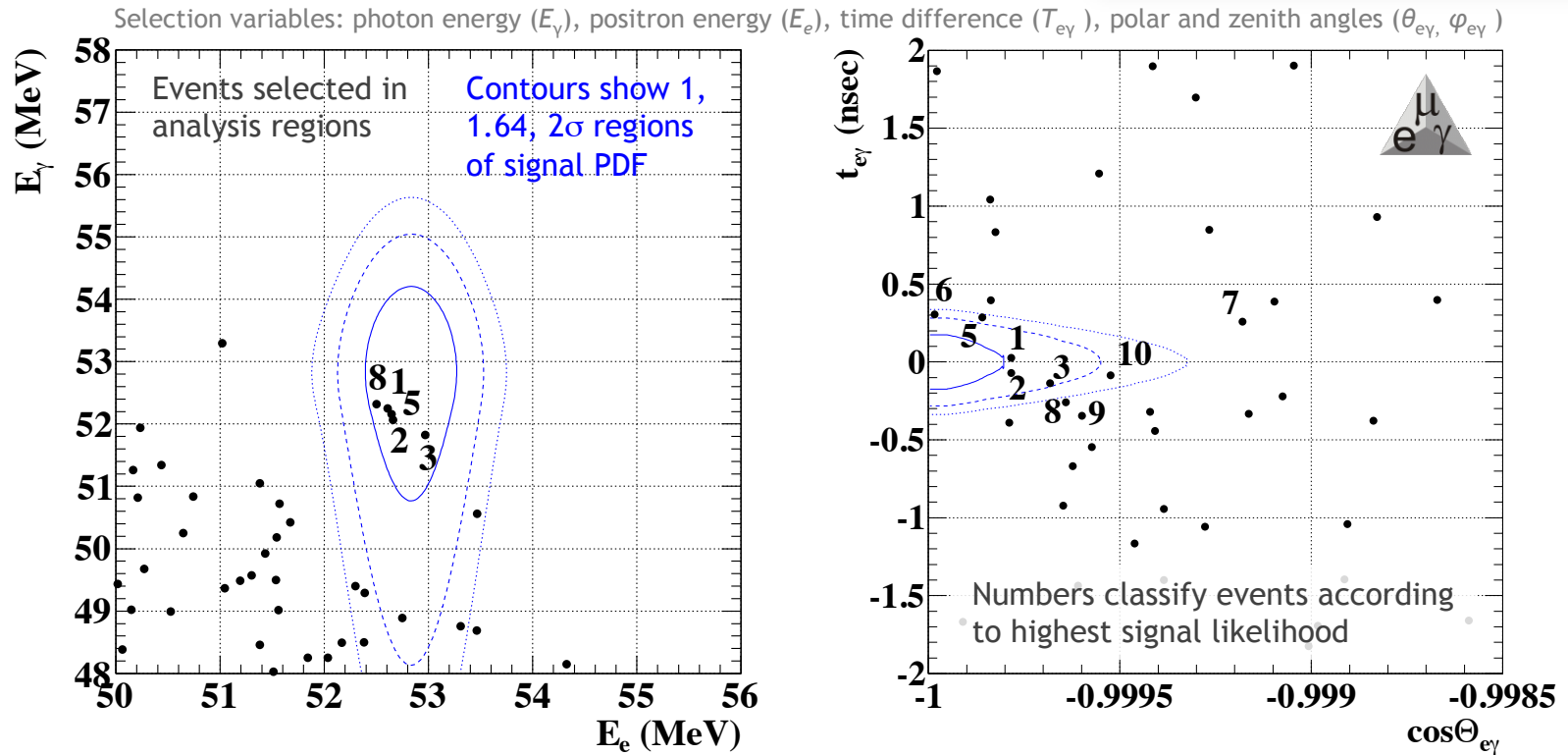
Sketch of MEG experiment

10% solid angle coverage

Situation after Preliminary Analysis of 2009 Data*

* two months stable data taking in 2009

MEG (Sawada), PoS ICHEP2010, 263 (2010)



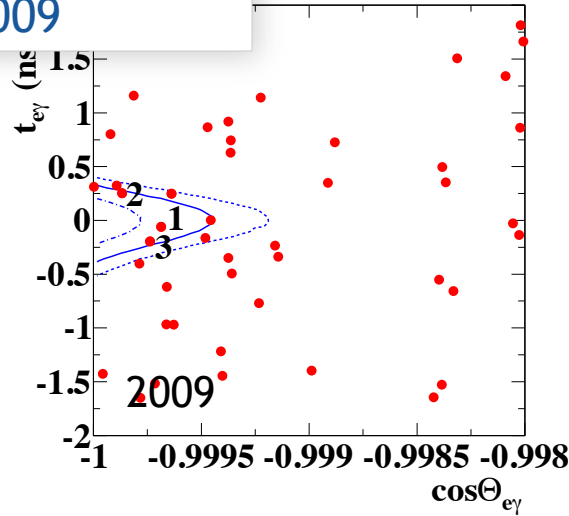
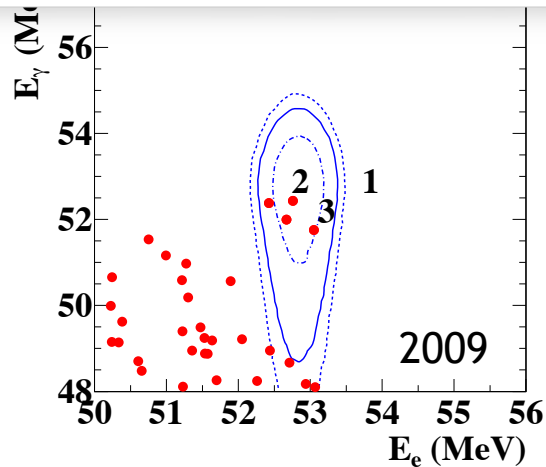
Unbinned maximum likelihood fit gave slight signal excess and 90% CL upper limit:

$$\text{BR}(\mu^+ \rightarrow e^+ \gamma) < \begin{cases} 1.5 \cdot 10^{-11} & \text{(observed)} \\ 6.1 \cdot 10^{-12} & \text{(expected for no signal)} \end{cases}$$

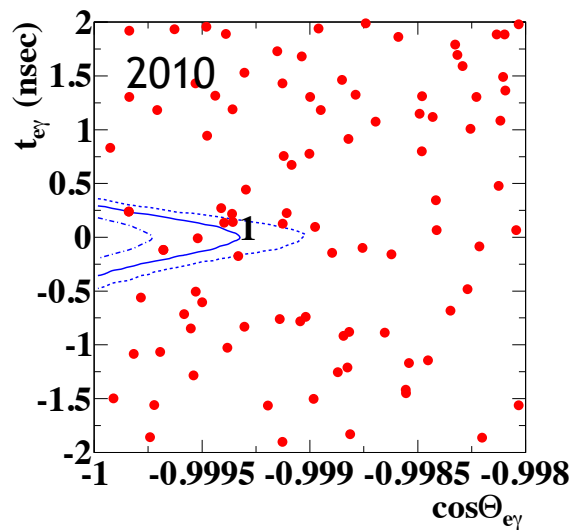
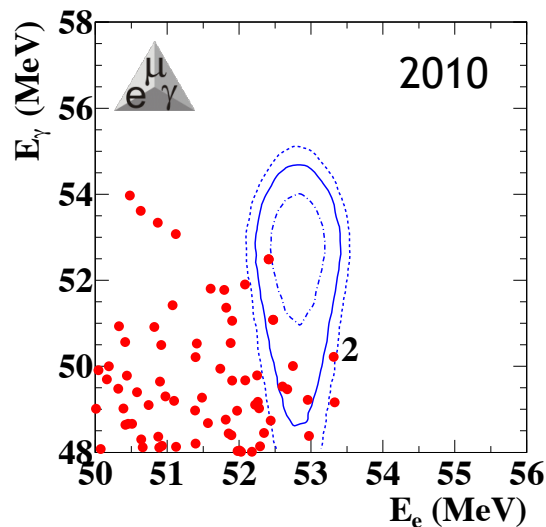
Combined Analysis of 2009 and 2010 Data

Total of 1.8×10^{14} μ^+ decays in the target,
2010 about twice statistics of 2009

MEG arXiv:1107.5547, T. Mori at EPS-HEP-2011



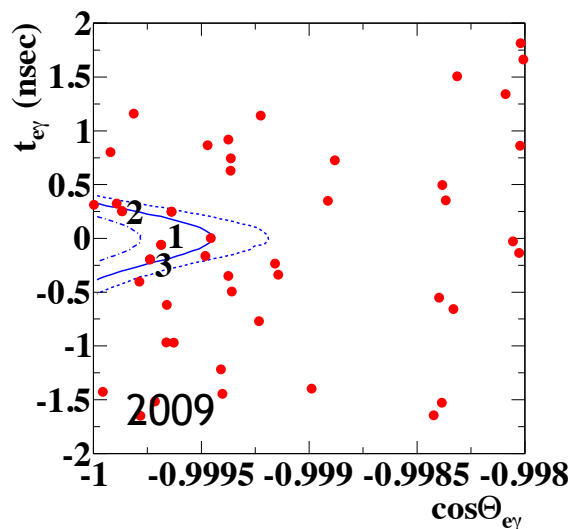
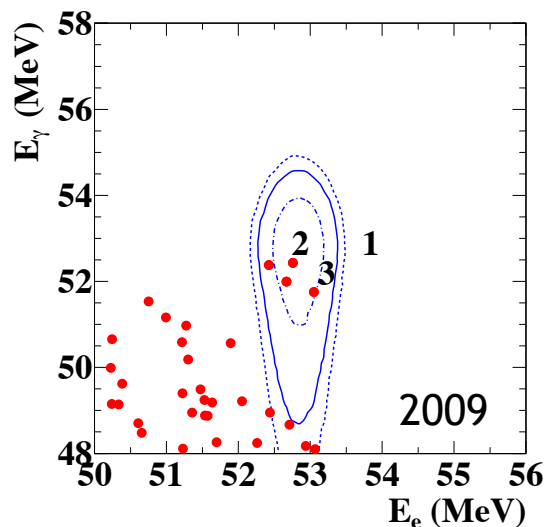
Excess in 2009
data confirmed by
reanalysis
(Background-only p-
value: 8%)



However, not
reproduced in
2010 data

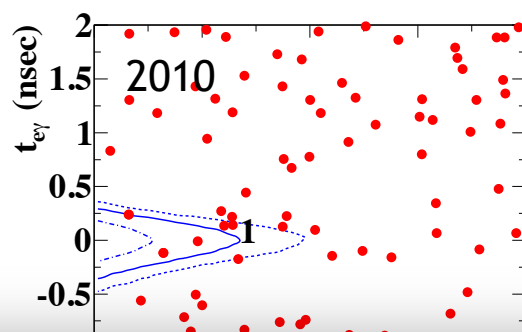
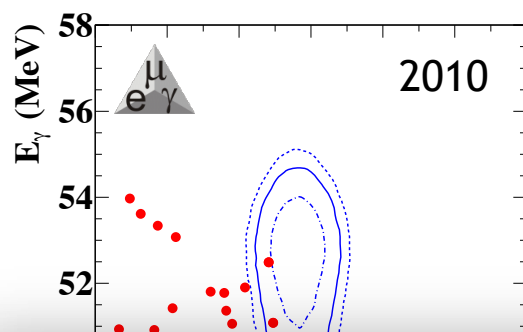
Combined Analysis of 2009 and 2010 Data

MEG arXiv:1107.5547, T. Mori at EPS-HEP-2011



Excess in 2009
data confirmed by
reanalysis

(Background-only p-
value: 8%)



However, not
reproduced in
2010 data

5 times better than
previous limit !

90% CL (Feldman-
Cousins) upper limit:

$$\text{BR}(\mu^+ \rightarrow e^+ \gamma) < \begin{cases} 2.4 \cdot 10^{-12} & \text{(observed)} \\ 1.6 \cdot 10^{-12} & \text{(expected for no signal)} \end{cases}$$

Full Analysis of 2009 and 2010 Data

MEG arXiv:1107.5547, T. Mori at EPS-HEP-2011

Systematic uncertainties in PDF and normalisation factors are small and will partly decrease with more statistics

MEG continues data taking in 2011+2012 to explore $\mu^+ \rightarrow e^+ \gamma$ up to the design sensitivity of $O(\text{a few } 10^{-13})$

Excess in 2009 data confirmed by reanalysis

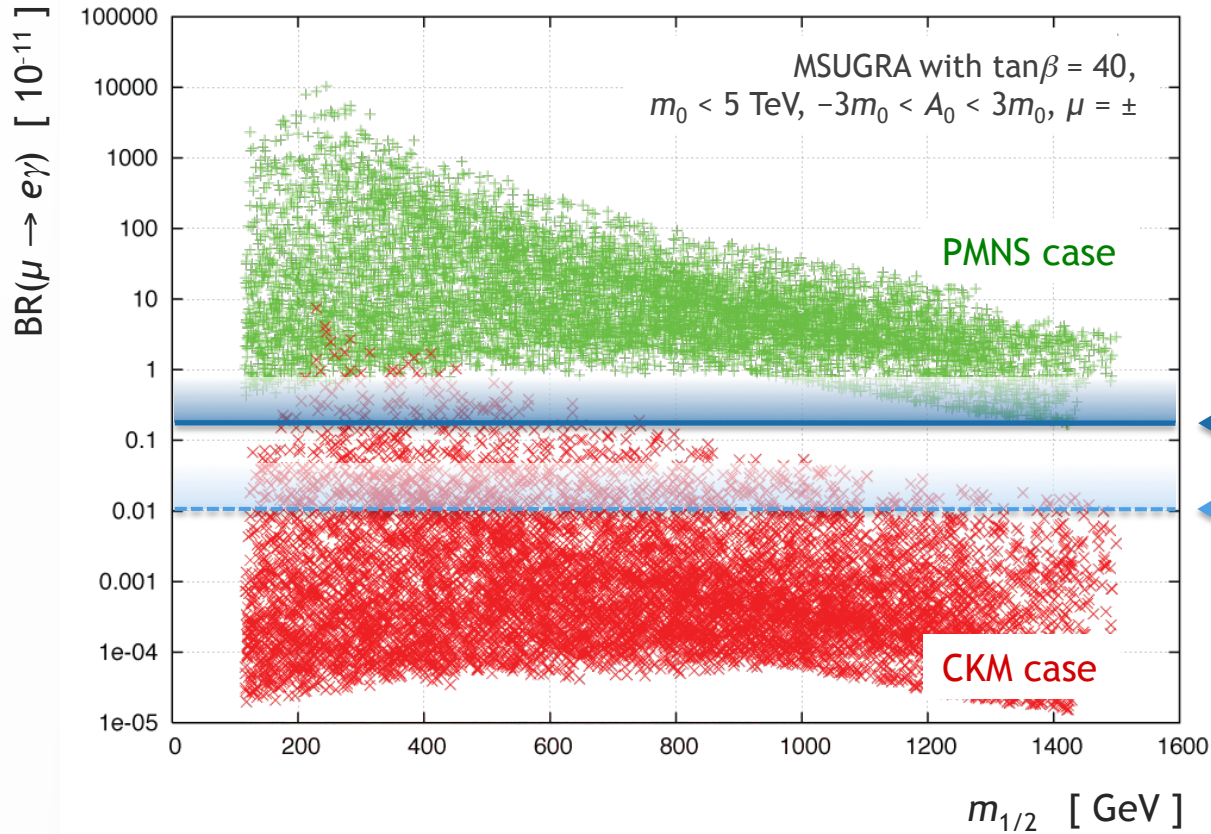
However, not reproduced in 2010 data

90% CL (Feldman-Cousins) upper limit:

$$\text{BR}(\mu^+ \rightarrow e^+ \gamma) < \begin{cases} 2.4 \cdot 10^{-12} & \text{(observed)} \\ 1.6 \cdot 10^{-12} & \text{(expected for no signal)} \end{cases}$$

Full Analysis of 2009 and 2010 Data

Calibbi *et al.*, hep-ph/0605139



Interpretation in terms of SUSY-GUT SO(10) MSUGRA models:

- CKM case: min. mixing
- PMNS case: max. mixing

← MEG 2009+2010

← MEG 2009-2012

90% CL (Feldman-Cousins) upper limit:

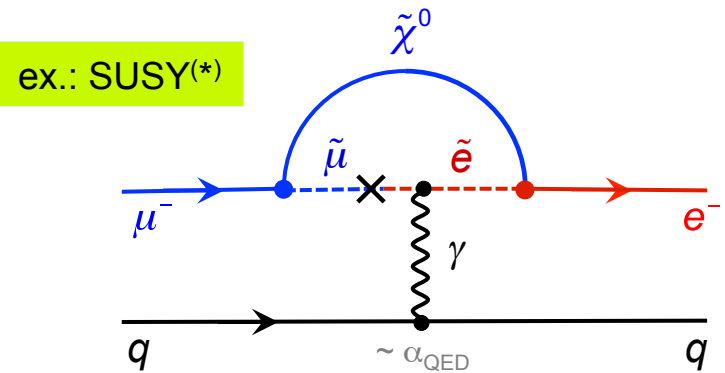
$$\text{BR}(\mu^+ \rightarrow e^+ \gamma) < \begin{cases} 2.4 \cdot 10^{-12} & \text{(observed)} \\ 1.6 \cdot 10^{-12} & \text{(expected for no signal)} \end{cases}$$

μ - e Conversion

Neutrinoless muon capture: $\mu \rightarrow e$ conversion via recoil against nucleus: $\mu^- N \rightarrow e^- N$

Principle:

1. Stopped muon captured by atom
2. There: decay or capture or μ - e conversion
3. Conversion gives single monoenergetic electron
(104.96 MeV for Al, 95.56 MeV for Au)



Simplicity and distinctive signature (**very low background e rate at 105 MeV**) allows extremely high rates and thus very sensitive measurement

Observable: $R_{\mu e}(A, Z) = \frac{\Gamma(\mu^- + N(A, Z) \rightarrow e^- + N(A, Z))}{\Gamma(\mu^- + N(A, Z) \rightarrow \text{all muon captures})}$

Dependence on A, Z , can be exploited to distinguish NP models after discovery

Best current limit from SINDRUM-II (PSI): $R_{\mu e}(\text{Au}) < 7 \times 10^{-13}$ (90% CL)

SINDRUM-II EPJ C 47, 337 (2006)

(*) Also: possible enhanced sensitivity to SUSY Higgs exchange compared to $\mu \rightarrow e \gamma$ (Kitano *et al.*, hep-ph/0308021) $\rightarrow$ use to discriminate between models

μ -e Conversion

A muon converts to an electron while recoiling against a nucleus: $\mu N \rightarrow e N$

New physics sensitivity compared to $\mu \rightarrow e \gamma$ for generic dipole dominance models ~ 390 times lower for Al target

[Classes of models involving μ -N exchange may enhance μ -e conversion over $\mu \rightarrow e \gamma$]

$\rightarrow \text{BR}(\mu \rightarrow e \gamma) < 10^{-13}$ requires $R_{\mu e}(\text{Al}) < 3 \times 10^{-16}$

Forthcoming experiments: Mu2e @ FNAL, COMET @ J-PARC

Goal: sensitivity down to $\sim 2 \times 10^{-17}$ with data-taking by 2018

[Requires 5×10^{19} muons - approaching #grains of sand on earth... (R. Bernstein, Pittsburgh 2011)]

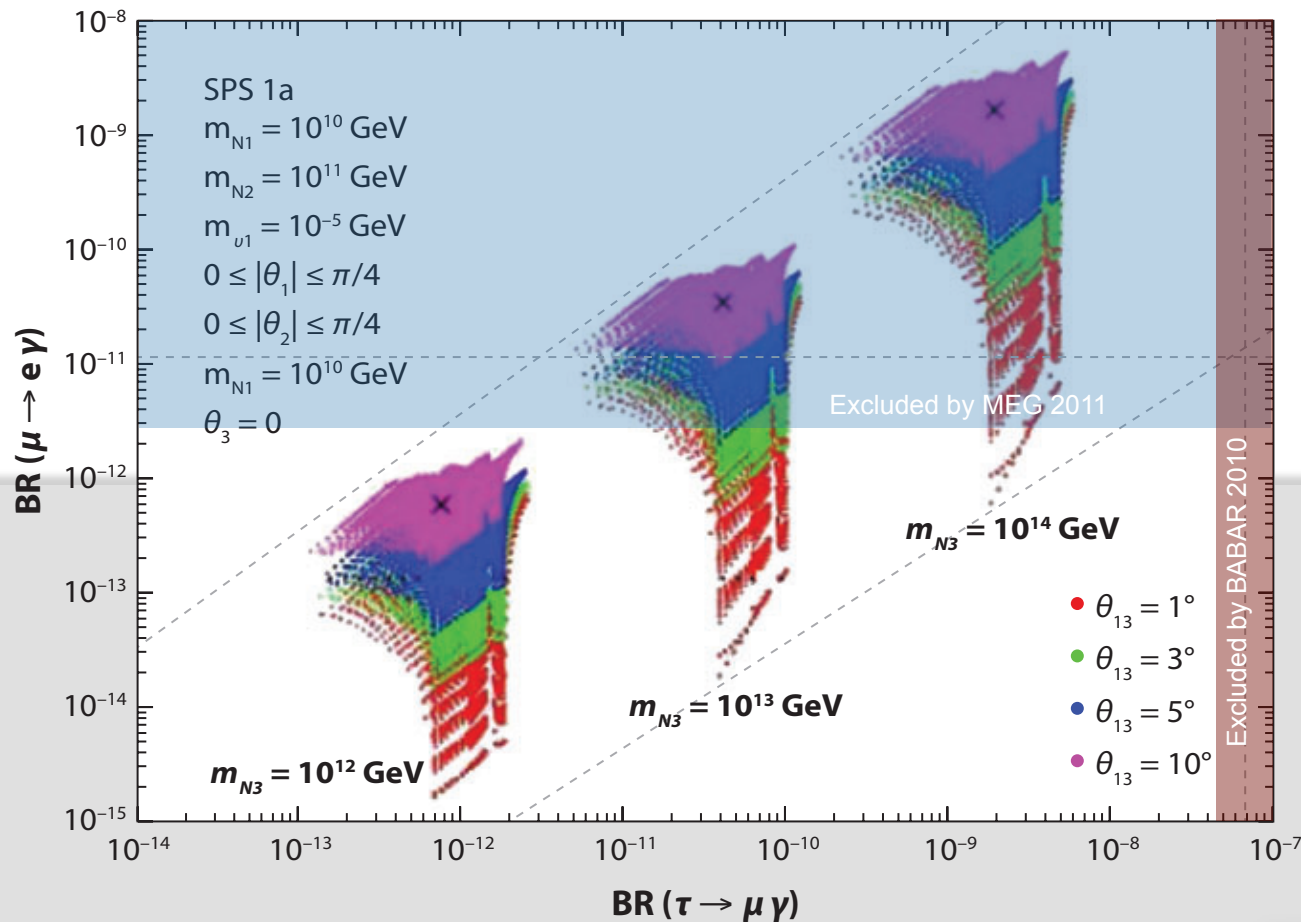
Se, e.g., Cirigliano *et al.*, arXiv:0904.0957

Best current limit from SINDRUM-II (PSI): $R_{\mu e}(\text{Au}) < 7 \times 10^{-13}$ (90% CL)

SINDRUM-II EPJ C 47, 337 (2006)

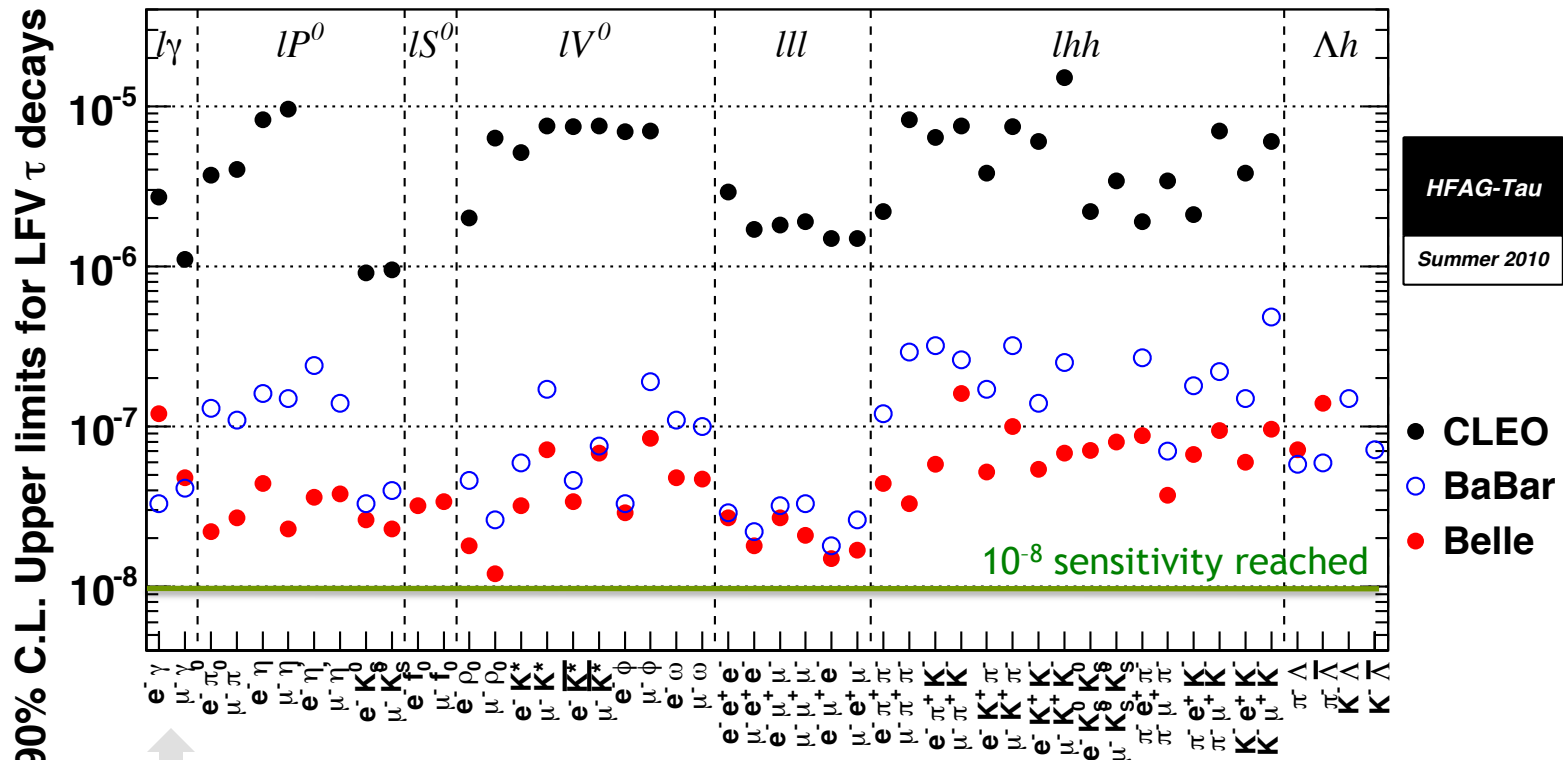
Lepton Flavour Violation in Tau Decays

LFV in tau decays (= neutrinoless tau decays) is searched for in a large variety of modes at the B -factories with sensitivity to different new physics scenarios



CMSSM model point with 3 massive RH N for various $m(N_3)$ and θ_{13}

Heavy Flavour Averaging Group, Summer 2010



$$\text{BR}(\tau^- \rightarrow \ell^- \gamma) < \begin{cases} 3.3 \cdot 10^{-8} & (e) \\ 4.4 \cdot 10^{-8} & (\mu) \end{cases}$$

Belle's new limits almost ready, but not quite for LP 2011

BABAR: PRL 104, 021802 (2010) PRL 104, 021802 (2010)

Elementary particles are predicted to be non-spherical, distorted by an electric dipole moment (EDM)

However, as for charged lepton flavour violation, EDMs are predicted to be undetectably tiny in the SM

Thus, any hint for a non-zero EDM would be physics beyond the SM, and indeed many SM extensions predict EDMs that are detectable by current experiments

Electric Dipole Moments



EDM is *CP*-nonconserving:

$$H = -\mu \vec{B} \cdot \hat{S} - d \vec{E} \cdot \hat{S}$$

For magnetic moment:

$$P(\vec{B} \cdot \hat{S}) = \vec{B} \cdot \hat{S}$$

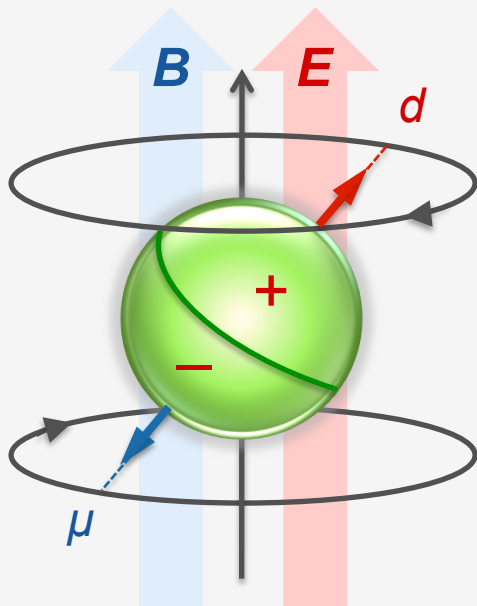
$$T(\vec{B} \cdot \hat{S}) = \vec{B} \cdot \hat{S}$$

For EDM:

$$P(\vec{E} \cdot \hat{S}) = -\vec{E} \cdot \hat{S}$$

$$T(\vec{E} \cdot \hat{S}) = -\vec{E} \cdot \hat{S}$$

Electric Dipole Moments



Precession frequency:

$$\omega_{\uparrow\uparrow} = \frac{2\mu B + 2dE}{\hbar}$$

$d \sim 5 \times 10^{-28}$ ecm gives:
 $\Delta f \sim 1$ nHz in 10 kV/cm field

Flip E field and measure
 frequency difference:

$$\Delta\omega = \omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow} = \frac{4dE}{\hbar}$$

Effective E field can be polarisation
 amplified (up to 10^6) in molecules

EDM is CP -
 nonconserving:

$$H = -\mu\vec{B} \cdot \hat{S} - d\vec{E} \cdot \hat{S}$$

For magnetic moment:

$$P(\vec{B} \cdot \hat{S}) = \vec{B} \cdot \hat{S}$$

$$T(\vec{B} \cdot \hat{S}) = \vec{B} \cdot \hat{S}$$

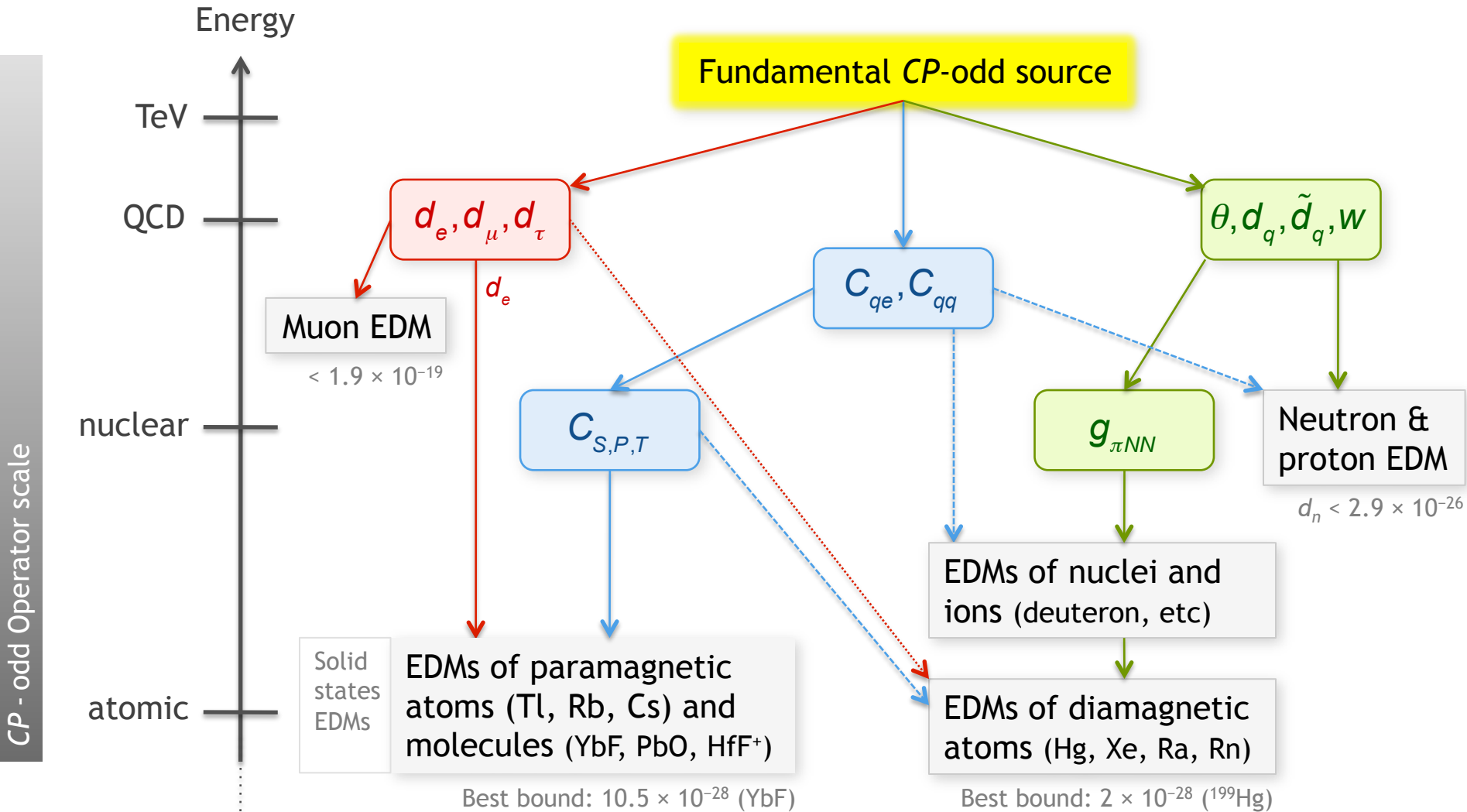
For EDM:

$$P(\vec{E} \cdot \hat{S}) = -\vec{E} \cdot \hat{S}$$

$$T(\vec{E} \cdot \hat{S}) = -\vec{E} \cdot \hat{S}$$

Origin of EDMs

Hierarchy of scales between CP -odd sources and generic classes of observable EDMs

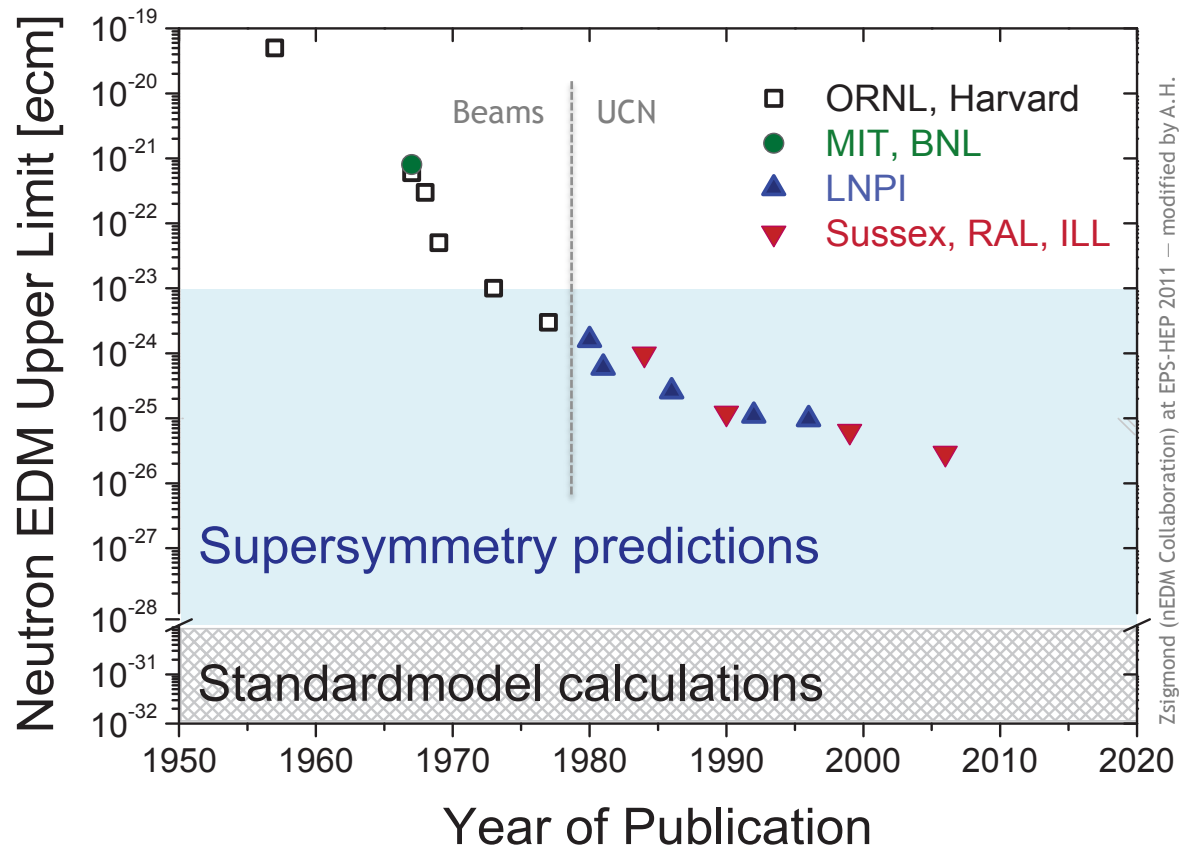


EDM - Experimental Programme

90% CL limits given

Neutron EDM

Best limit: $|d_n| < 2.9 \times 10^{-26} \text{ ecm}$ [Sussex-RAL-ILL Collaboration, PRL 97, 131801 (2006)]

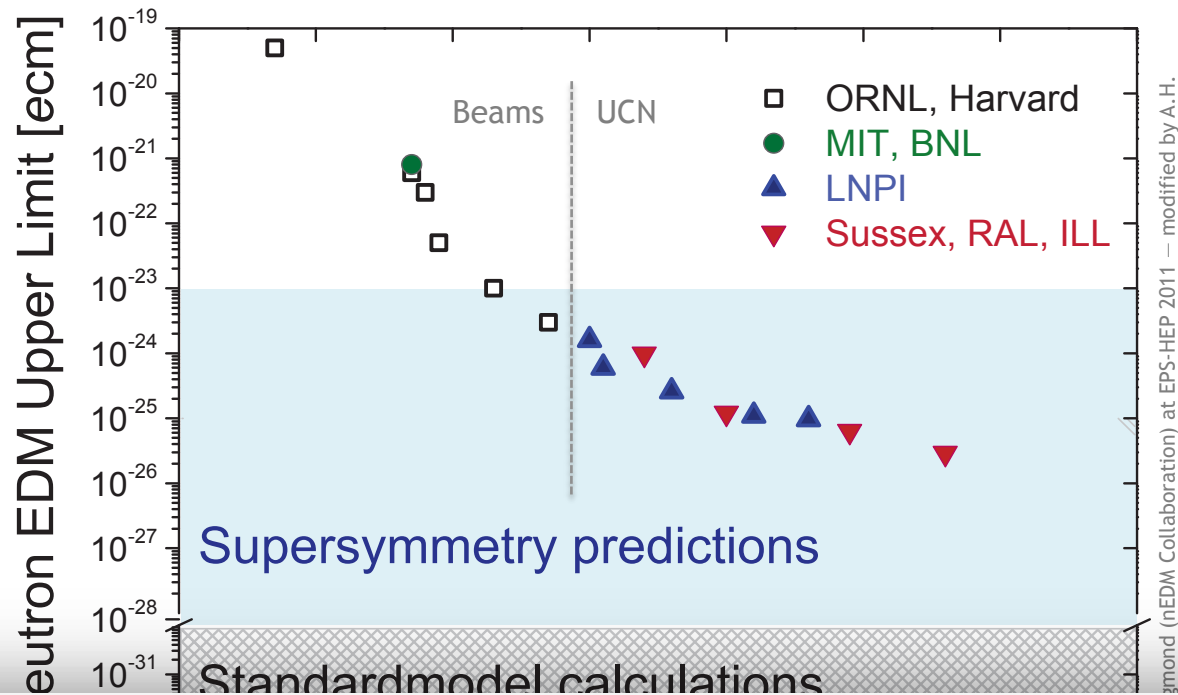


EDM - Experimental Programme

90% CL limits given

Neutron EDM

Best limit: $|d_n| < 2.9 \times 10^{-26} \text{ ecm}$ [Sussex-RAL-ILL Collaboration, PRL 97, 131801 (2006)]



Strong *CP* problem: $|d_n|$ limit translates into $|\bar{\theta}| \sim |d_n| \cdot 2 \times 10^{16} < 5 \times 10^{-10}$

SUSY *CP* problem: $|d_n| \sim 10^{-23} \text{ ecm} \cdot (300 \text{ GeV} / m_{\text{SUSY}})^2 \cdot \sin \phi_{\text{SUSY}}$

Why so small ?

EDM - Experimental Programme

90% CL limits given

Neutron EDM — best limit: $|d_n| < 2.9 \times 10^{-26} \text{ ecm}$ [RAL-Sussex-ILL, PRL 97, 131801 (2006)]

Forthcoming nEDM experiments	Group	No. of people	Sensitivity [10^{-26} ecm]	Due date	by K. Kirch, ETH at PANIC-2011
	nEDM at PSI n2EDM	~50	0.5 0.05	2013 2016	
	PNPI at ILL	~10-20	1	2012	
	CryoEDM at ILL	~25	0.3	2016	
	nEDM at SNS-ORNL	~90	0.03	2020	
	nEDM at RCNP at TRIUMF	~35	1 0.1 0.01	2014 2017 > 2020	

First nEDM data this year?
[Zsigmond at EPS-2011]

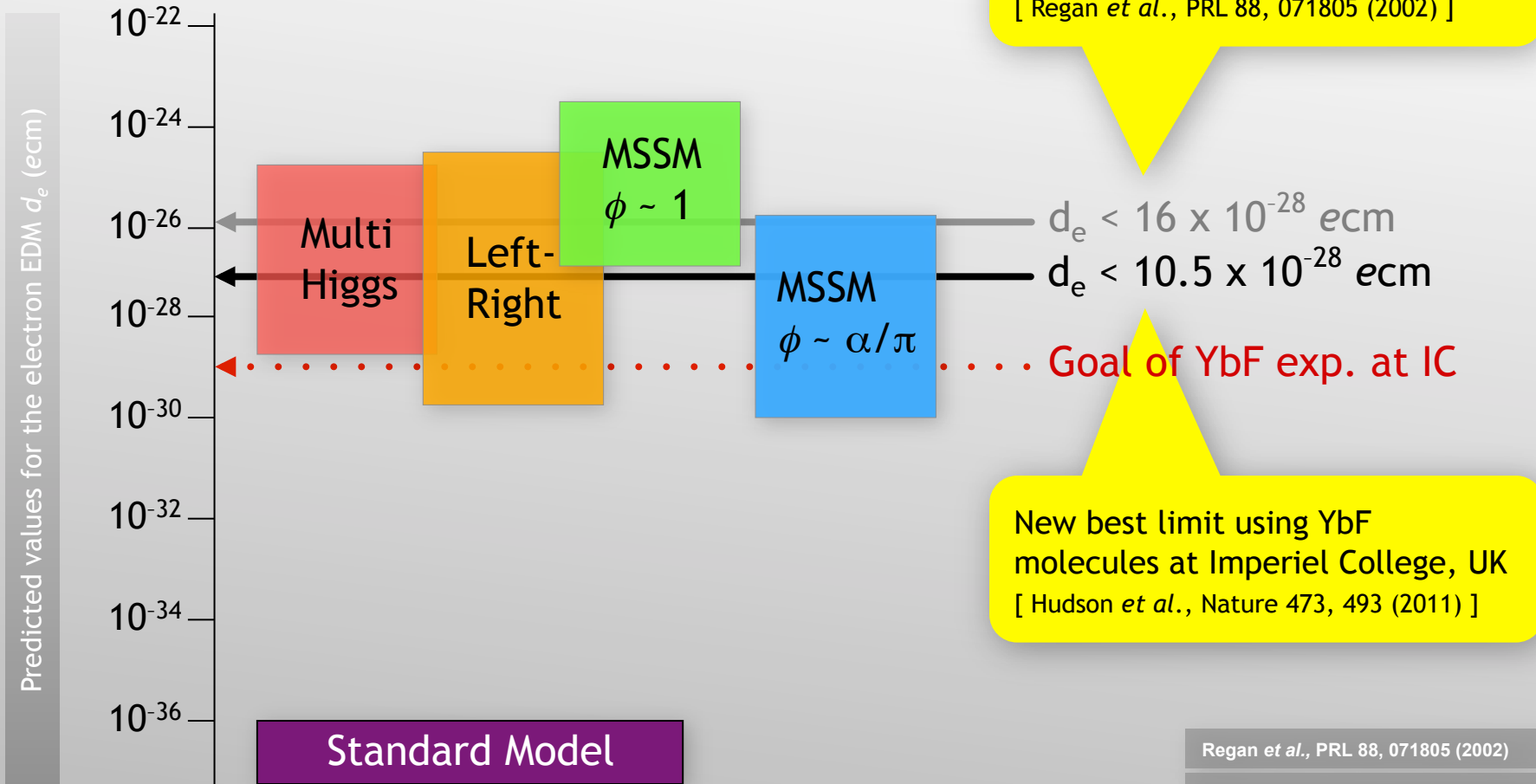
Proton / Deuterium EDM

Proposals at BNL, USA and Juelich, Germany for storage ring based pEDM measurement with sensitivity: 10^{-29} ecm

EDM - Experimental Programme

90% CL limits given

Electron EDM



Regan *et al.*, PRL 88, 071805 (2002)

Hudson *et al.*, Nature 473, 493 (2011)

Graph taken from: B. Sauer, IC

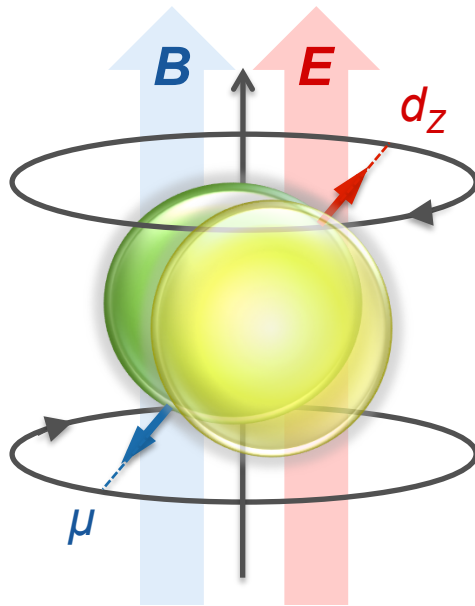
EDM - Experimental Programme

Hudson et al., Nature 473, 493 (2011)

Electron EDM - new measurement using paramagnetic YbF molecules

Schiff theorem: nonrelativistic system of electrostatically interacting charged particles (eg, atom) is fully shielded with respect to external E fields

Broken by magnetic, relativistic interactions and extended nucleons



→ Effective EDM: $d_z \sim (\eta^2 Z^3) \times d_e$

- Enhanced in heavy atoms / molecules
- $d_{\text{Tl}} \sim 585 \times d_e$ (exploited by Berkeley Tl experiment, 2002)
- $d_{\text{YbF}} \sim 1.4 \times 10^6 \times d_e$ (for 11 kV/cm field; earlier saturation than Tl)

Also systematic error advantage of YbF molecules over Tl (*motional magnetic field*)

But: much smaller production rate than Tl

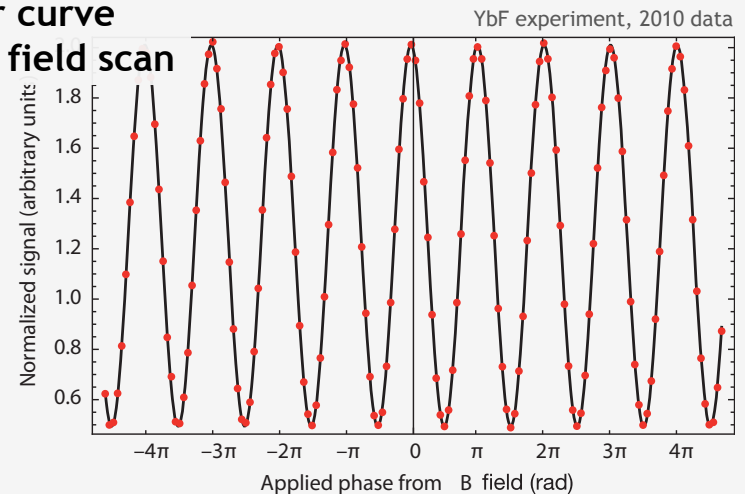
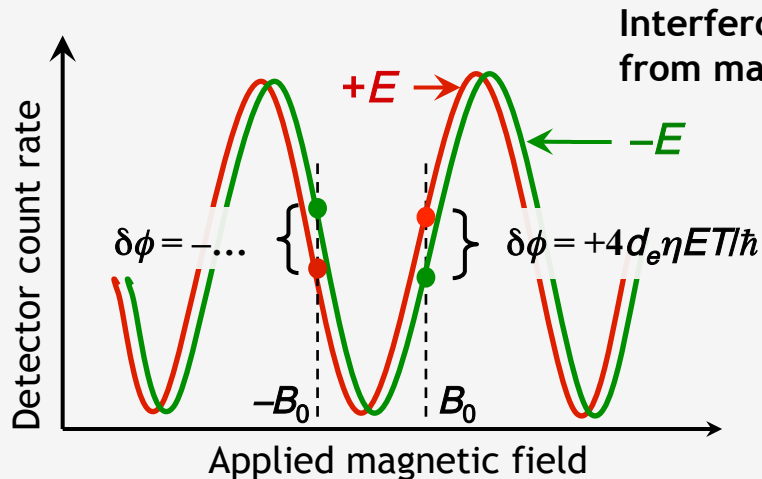
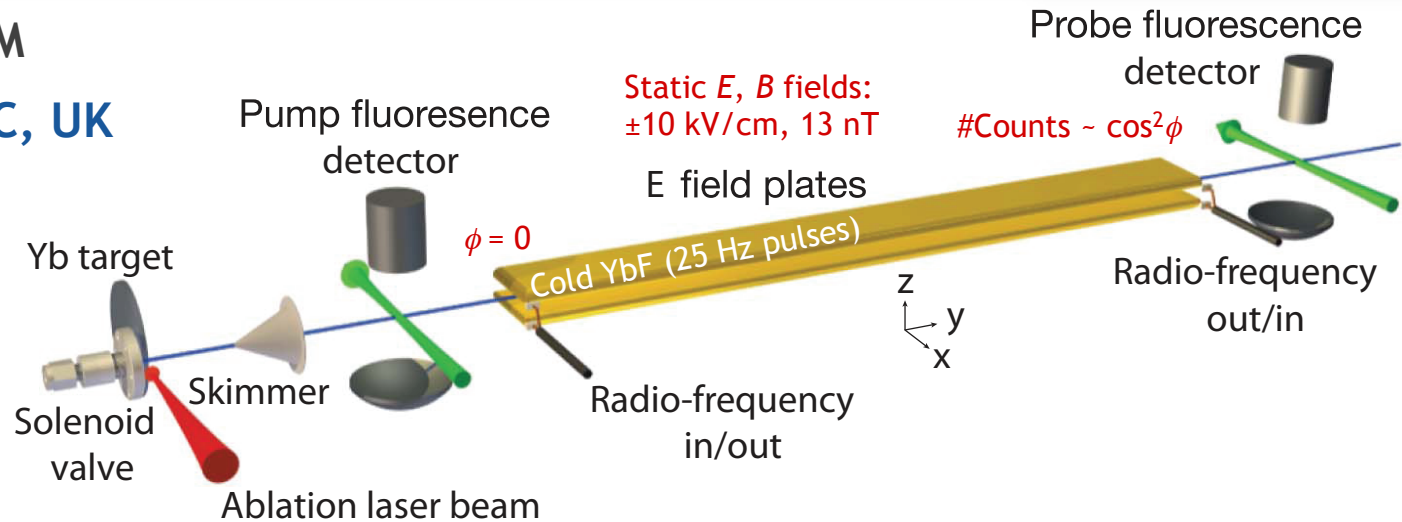
YbF exp. looks for spin interferometer phase shift of $F = 0, 1$ YbF hyperfine levels when E field is reversed

EDM - Experimental Programme

Hudson et al., Nature 473, 493 (2011)

Electron EDM

YbF @ IC, UK

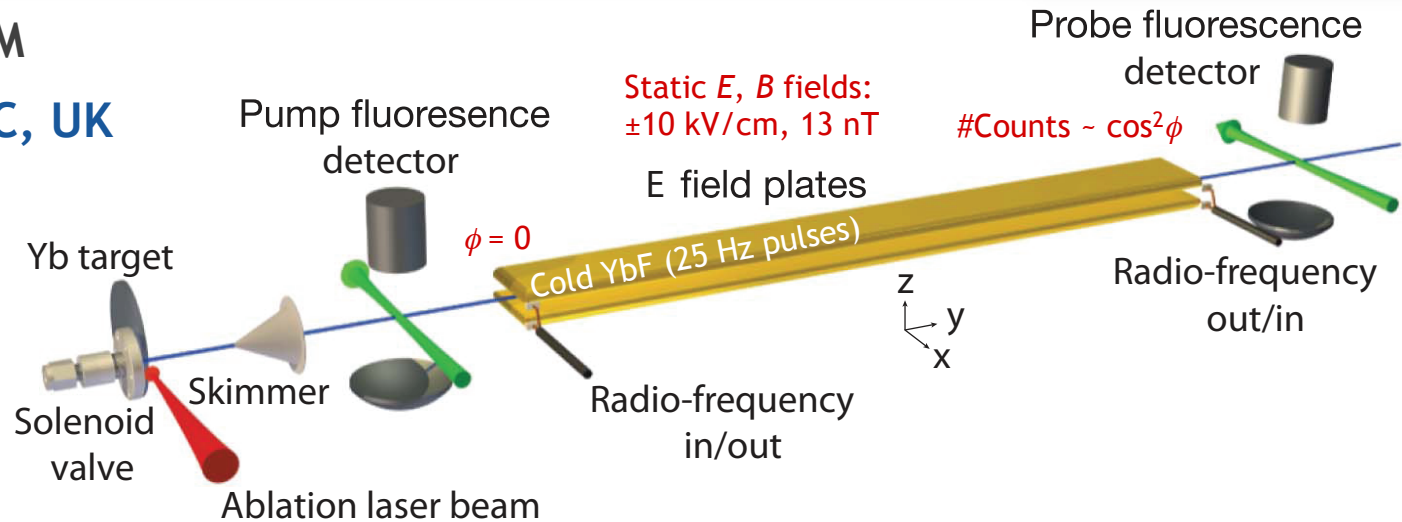


EDM - Experimental Programme

Hudson et al., Nature 473, 493 (2011)

Electron EDM

YbF @ IC, UK



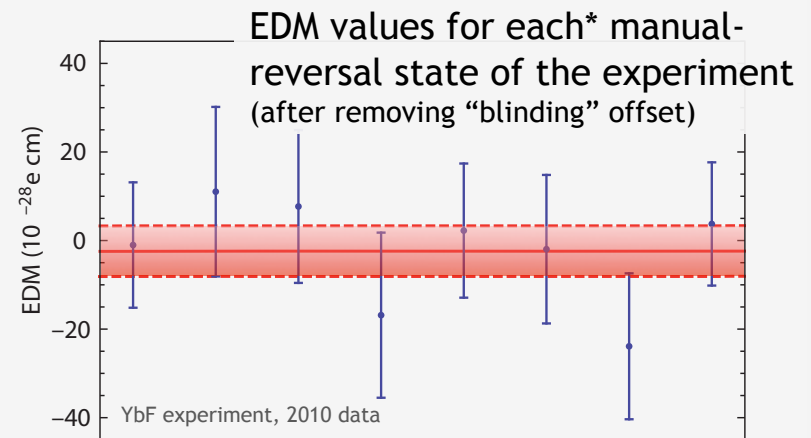
$$d_e = (-2.4 \pm 5.7_{\text{stat}} \pm 1.5_{\text{syst}}) \times 10^{-28} \text{ ecm}$$

$$|d_e| < 10.5 \times 10^{-28} \text{ ecm} \quad (90\% \text{ CL})$$

Statistics dominated

Largest systematic effect from E -field uncertainties

RF detuning phase shift and E reversal Stark shift corrected



*Swaps of HV, magnet and RF cables

EDM - Experimental Programme

Pioneering measurement with great potential in spite of relatively little improvement over Tl result from 2002

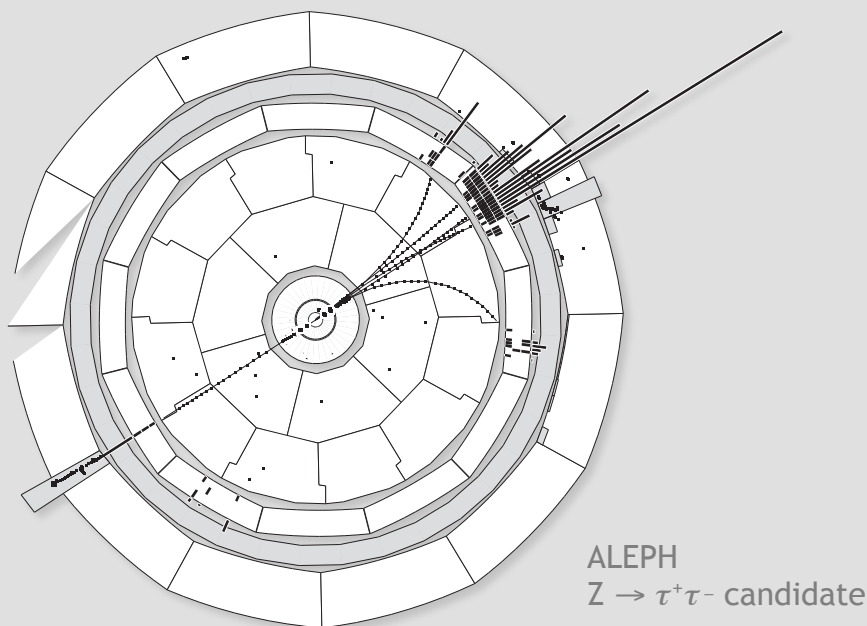
Measurement statistically limited, systematic errors reducible to $< 10^{-29}$ ecm

Factor of 10 sensitivity improvement within a few years, final goal is factor of 100

Several other EDM experiments, based on electron spin precession in atoms, molecules, molecular ions or solids, in progress

Fantastic combination work done by HFAG group - I will use a lot of their work here !

Tau-Lepton Physics



Tau-Lepton Physics

Last year was the 20th anniversary of the Tau Workshops (started in 1990 at Orsay)

During this period there was magnificent progress in tau physics through the LEP, CLEO, *B*-factories, BES, VEPP-2M, and neutrino experiments

Early meetings concentrated on consolidation of tau as a standard lepton without invisible decays and with universal couplings (precision experiments)

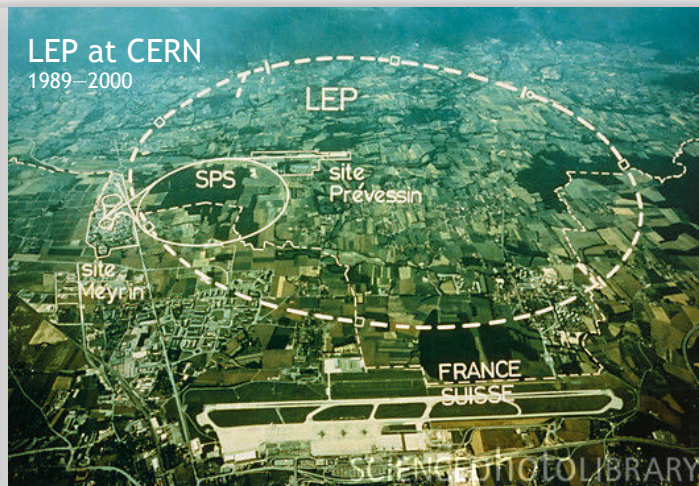
Increased data samples and better methods allowed to study electroweak and QCD physics leading to precision measurements of fundamental SM parameters, such as $\sin^2\theta_W$, α_S , $|V_{us}|$

CESR at Cornell, USA
1979–2008



~3.6 M $\tau\tau$
produced for
CLEO-I/II

LEP at CERN
1989–2000

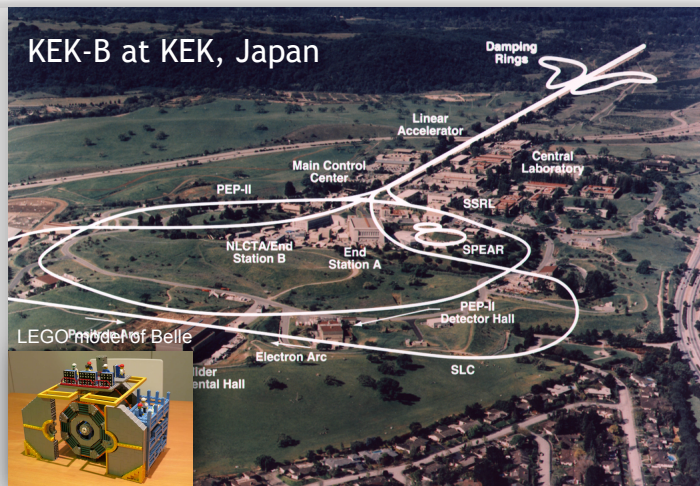


~165,000
 $Z \rightarrow \tau\tau$ per
experiment

Tau-Lepton Physics

Huge samples of roughly 500 M and 900 M tau pairs collected by **BABAR** and **Belle**
Experiments concentrate on rare modes and searches for new physics:

- Lepton flavour violation in tau decays
- Weak current universality tests (0.14% precision reached!), rare branching fractions
- “Second class currents” (isospin violation)
- CP violation
- Phenomenological work on determination of α_s and $|V_{us}|$ ($\rightarrow$ V. Lubicz’, T. Gershon’s talks) from tau branching fractions and spectral functions still actively pursued



B/τ Factories
at KEK and
SLAC

Searches for “Second Class Currents” in Tau Decays

“Second class currents” have spin-parity $J^{PG} = 0^{+-}, 0^{-+}, 1^{++}$ or 1^{--} and are proportional to u/d quark mass difference-squared

→ vanish in strict isospin limit

Branching ratios expected to be of order 10^{-5}

See, e.g., Nussinov-Soffer, arXiv:0806.3922 and references therein

Published BABAR limit with full statistics (470 fb^{-1})

$$B(\tau \rightarrow \nu + \eta\pi) < 9.9 \cdot 10^{-5} \text{ at 90\% CL}$$

BABAR, arXiv:1011.3917

Other second class current modes that are studied involve $\eta'\pi$ and $\omega\pi$ final states

CP Violation in Tau Decays

Due to mixing-induced CPV in K^0 system (ε_K), expect to see decay rate asymmetry

$$A_Q = \frac{\Gamma(\tau^+ \rightarrow K_S \pi^+ \bar{\nu}_\tau) - \Gamma(\tau^- \rightarrow K_S \pi^- \nu_\tau)}{\sum} \approx 2\text{Re } \varepsilon_K = (+0.33 \pm 0.01)\%$$

Bigi-Sanda, PLB 625, 47 (2005)

Deviations in A_Q should have NP origin as possible in, eg, multi-Higgs models

Kühn-Mirkes, PLB, 398, 407 (1997)

Results consistent with the SM found in $D^\pm \rightarrow K_S \pi^\pm$ [BABAR, PRD 83, 071103 (2011)]
and in angular analysis of $\tau^\pm \rightarrow K_S \pi^\pm \nu$ [Belle, arXiv:1101.0349]

New preliminary analysis of A_Q in $\tau^\pm \rightarrow K_S \pi^\pm (\geq 0\pi^0) \nu$ from BABAR using 476 fb⁻¹

- Electron and muon tags used
- Correction for different nuclear interaction cross sections of K^0 and $\bar{K}^0$
- Dominant systematic error from selection bias measured from data (stat. error)
- Raw asymmetry corrected for $K_S K^\pm (\geq 0\pi^0) \nu$ and $K^0 \bar{K}^0 \pi^\pm$ feed-through (assuming SM A_Q)

BABAR finds $A_Q = (-0.45 \pm 0.24 \pm 0.11) \%$, which deviates $\sim 3\sigma$ from SM

Tau Hadronic Spectral Functions and α_s

The measurement of complete vector and axial-vector tau hadronic spectral functions by ALEPH and OPAL triggered enormous activity on QCD studies

Precision determination of α_s from comparison of tau hadronic width with essentially pQCD

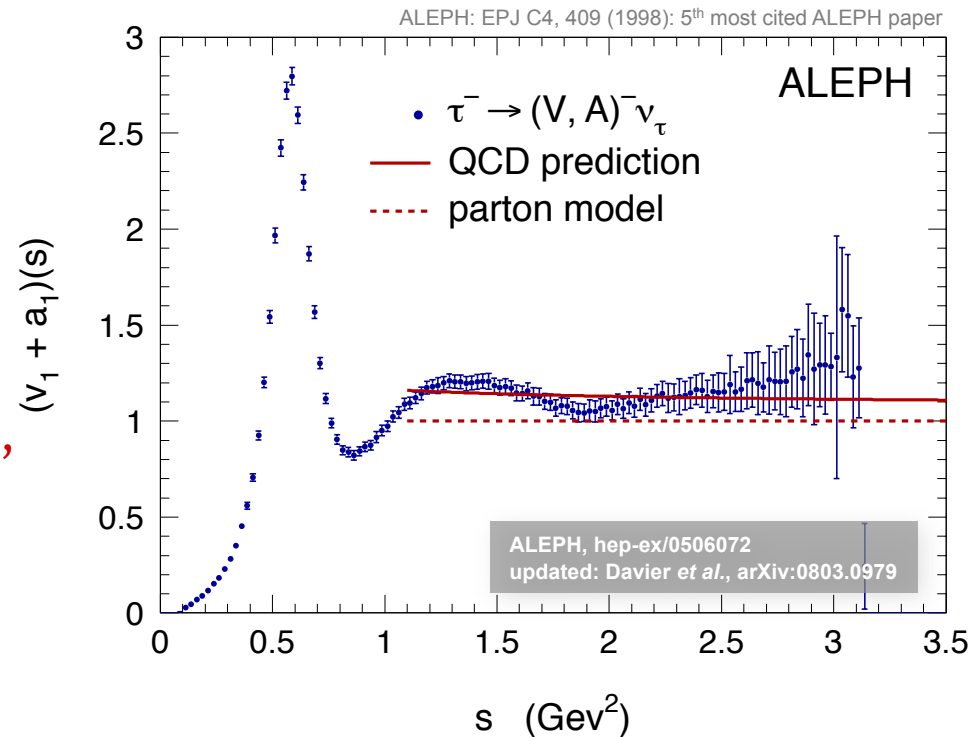
$$R_{\tau, V+A} = 3.4771 \pm 0.0084 \quad (\delta\sigma = 0.24\%)$$

HFAg, 2011

Benefits, as EW fit of Z hadronic width, from NNNLO perturbative calculation

Baikov *et al.*, arXiv:0801.1821

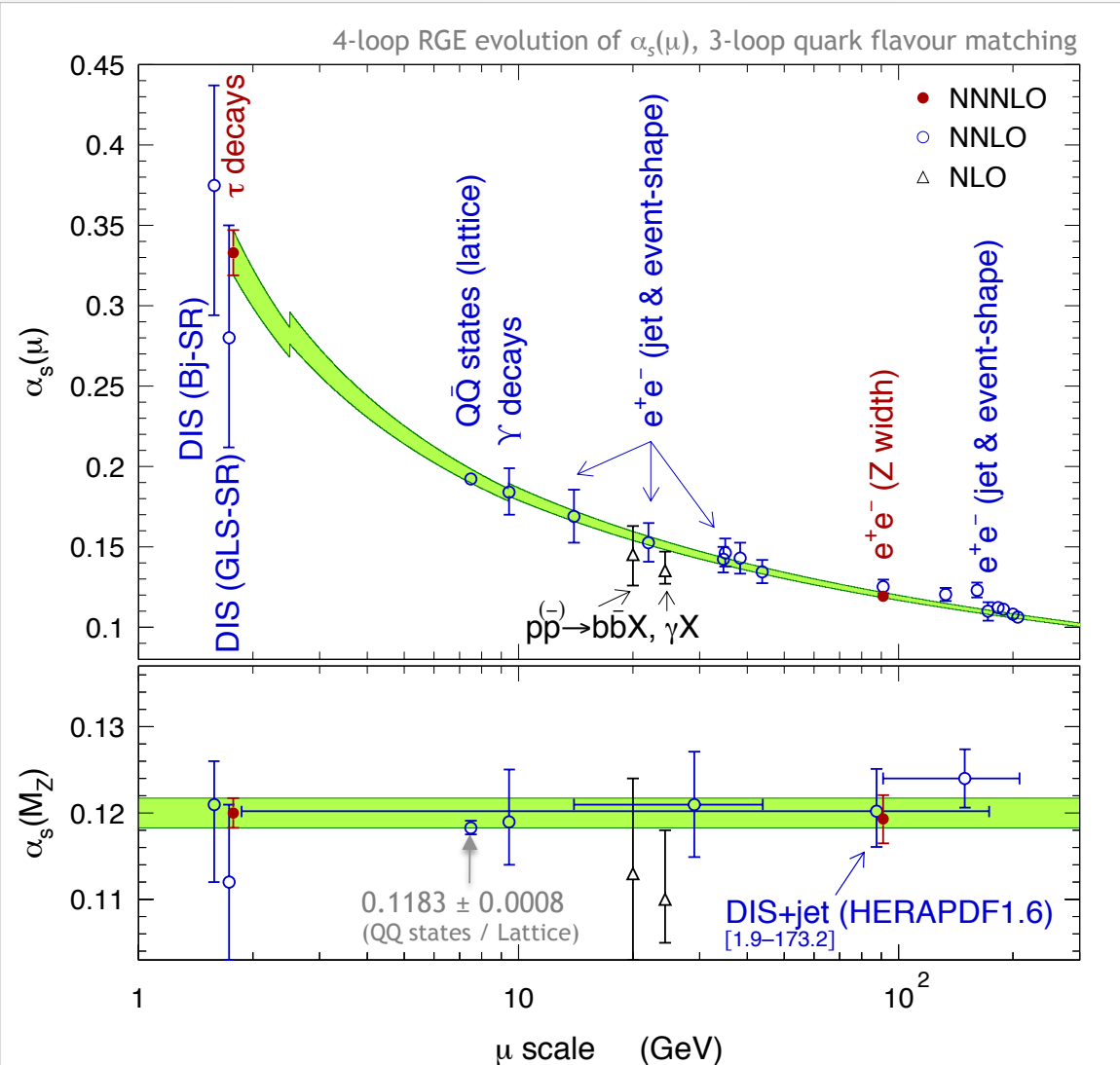
Nonperturbative contributions measured from data using “spectral moments” and found very small



Unfortunately, ambiguity in perturbative treatment does currently not allow to fully exploit the available precision

See, e.g.: Davier *et al.*, arXiv:0803.0979; Beneke-Jamin, arXiv:0806.3156; Menke, arXiv:0904.1796, and others

NNNLO Determination of α_s



Courtesy: Z. Zhang. Compilation from Bethke, arXiv:0908.1135

From combined fit of R_τ and spectral moments:

$$\alpha_s(M_Z) = 0.1200 \pm 0.0005_{\text{exp}} \pm 0.0008_{\text{theo}} \pm 0.0013_{\text{CIPT/FOPT}} \pm 0.0005_{\text{evol}} (0.0017_{\text{tot}})$$

Central value is arithmetic mean between CIPT and FOPT, with half the difference as syst. error

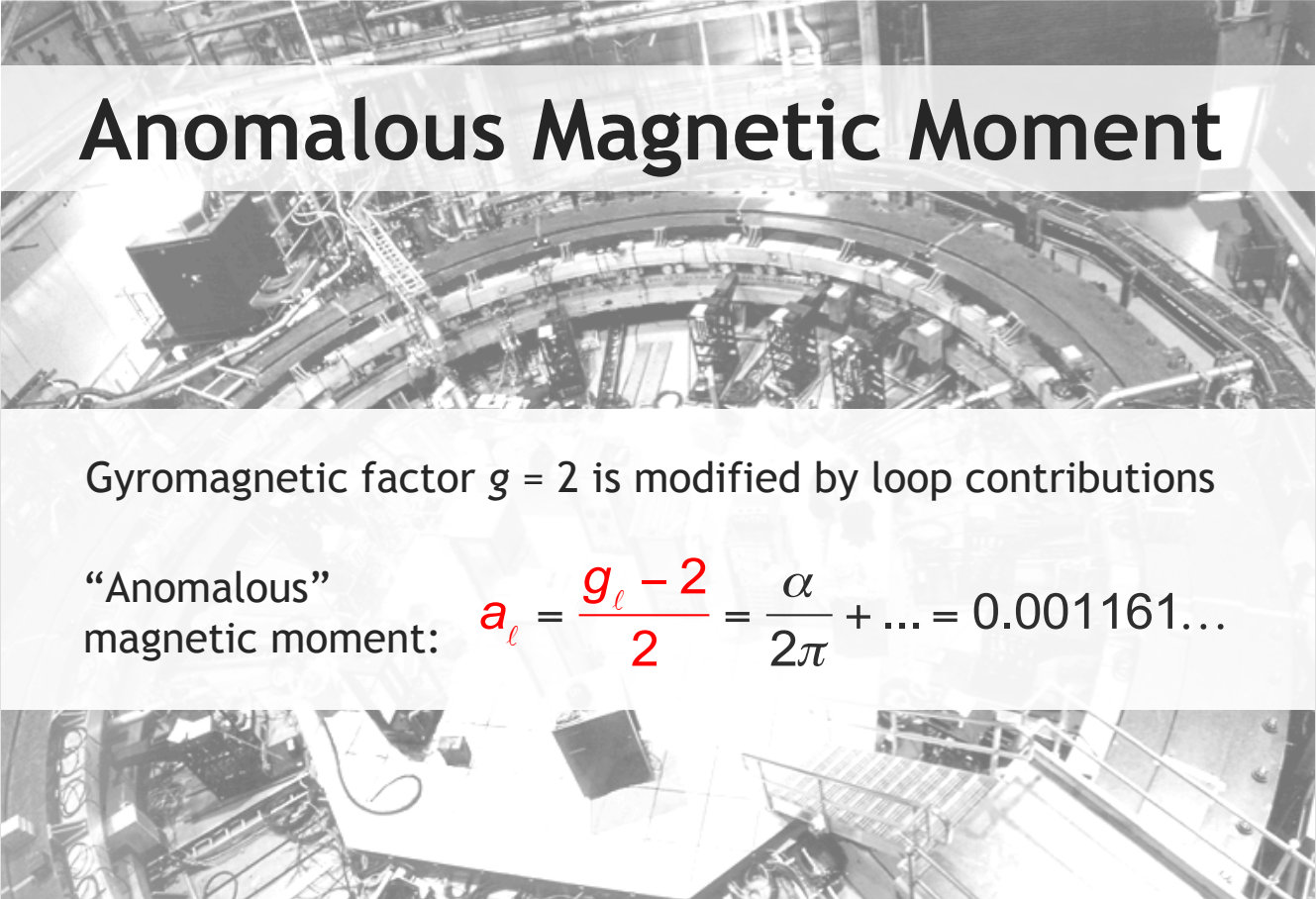
Modified from: Davier *et al.*, arXiv:0803.0979

Excellent agreement with NNNLO result from EW fit

$$\alpha_s(M_Z) = 0.1193 \pm 0.0028$$

Baak *et al.*, arXiv:1107.0975

Precise test of asymptotic freedom property of QCD



Anomalous Magnetic Moment

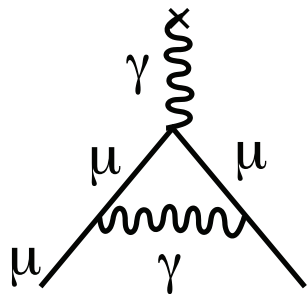
Gyromagnetic factor $g = 2$ is modified by loop contributions

“Anomalous”
magnetic moment: $a_\ell = \frac{g_\ell - 2}{2} = \frac{\alpha}{2\pi} + \dots = 0.001161\dots$

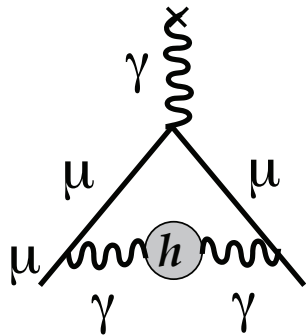
E821 at BNL

Loop contributions:

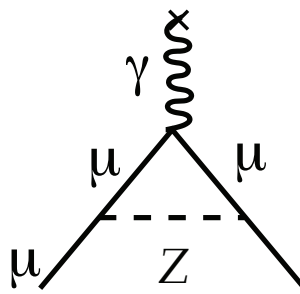
QED



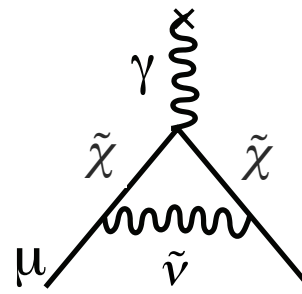
Hadronic



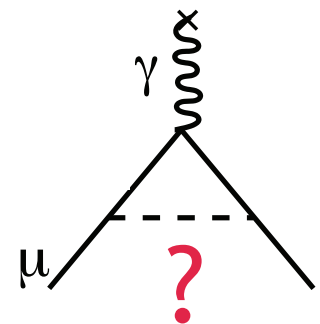
Weak



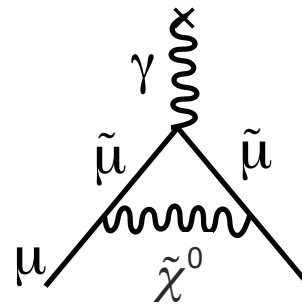
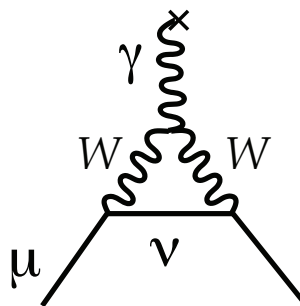
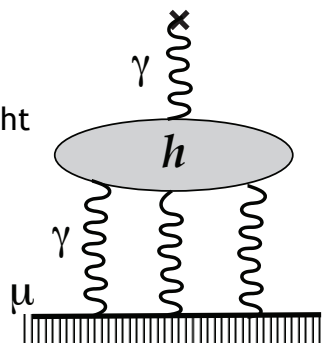
SUSY... ?



... or some unknown type of new physics ?



“Light-by-light scattering”



... or no effect on a_μ , but new physics at the LHC? That would be interesting as well !!



Measuring $(g - 2)_\mu$

For polarized muons moving in a uniform B field (perp. to muon spin and orbit plane), and vertically focused in E quadrupole field, the observed difference between spin precession frequency and cyclotron frequency is:

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

At “magic γ with $p_\mu = 3.09$ GeV
and assuming, $\mu\text{EDM} = 0$!

The experiment measures directly $(g - 2)/2$!

One actually measures: $a_\mu = R/(\lambda - R)$, $R = \omega_a/\omega_p$, $\lambda = \mu_\mu/\mu_p$



Measuring $(g - 2)_\mu$

World average (2006 - final BNL-E821 report):

$$a_\mu = 11\,659\,208.9\,(5.4)\,(3.3) \times 10^{-10}$$

...still statistics dominated !

E821, PRD 73, 072003 (2006)

Confronting Experiment with Theory

The Standard Model prediction of a_μ is decomposed in its physical contributions:

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

of which the
hadronic
contribution
has the **largest**
uncertainty:

$$a_\mu^{\text{QED}} = (11\,658\,471.809 \pm 0.015) \times 10^{-10}$$

$$a_\mu^{\text{had}} = (693.0 \pm 4.9) \times 10^{-10}$$

$$a_\mu^{\text{weak}} = (15.4 \pm 0.2) \times 10^{-10}$$

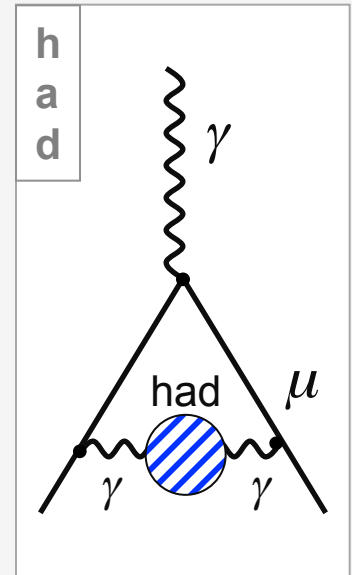
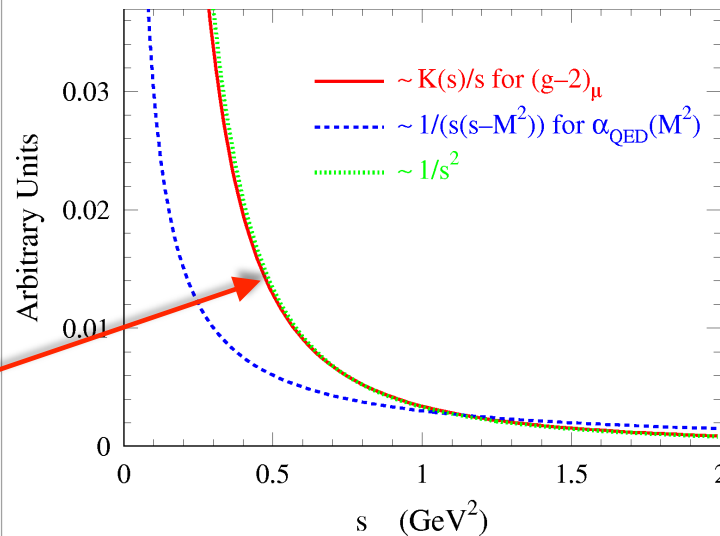
Hadronic Contribution

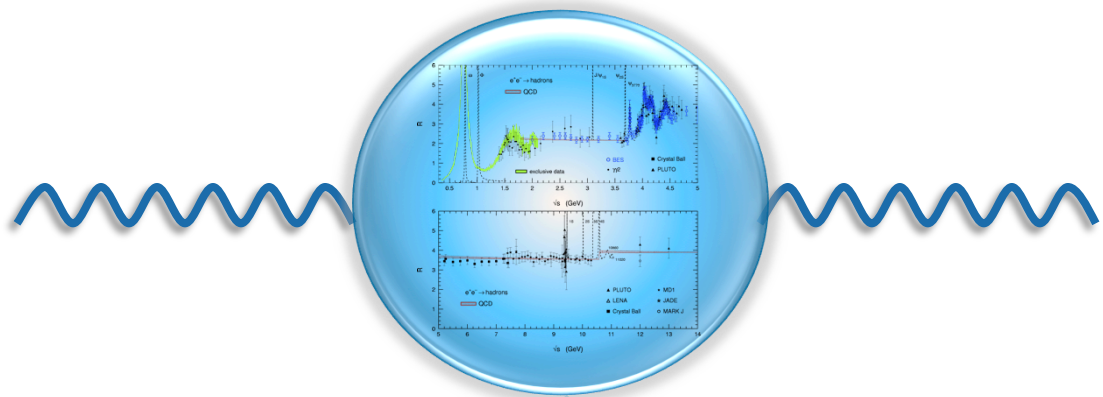
- Cannot be computed from first principles due to low-energy hadronic effects
- Fortunately, one can benefit from analyticity and unitarity to obtain real part of photon polarisation function from **dispersion relation over total hadronic cross section data**

$$12\pi \text{Im} \Pi_\gamma(s) = \frac{\sigma^{(0)}[e^+e^- \rightarrow \text{hadrons}]}{\sigma^{(0)}[e^+e^- \rightarrow \mu^+\mu^-]} \equiv R(s)$$

$$\text{Im}[\text{wavy line with shaded circle}] \propto |\text{wavy line with hadron blob}|^2$$

$$a_\mu^{\text{had,LO}} = \frac{\alpha^2}{3\pi^2} \int_{m_{\pi^0}^2}^{\infty} ds \frac{K(s)}{s} R(s)$$



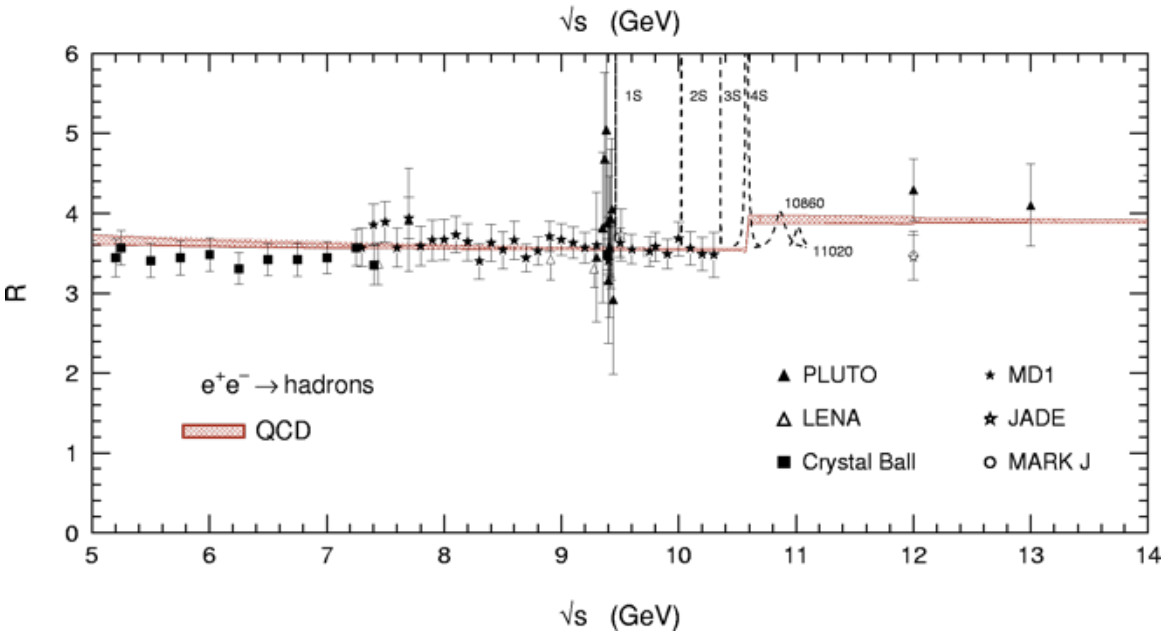
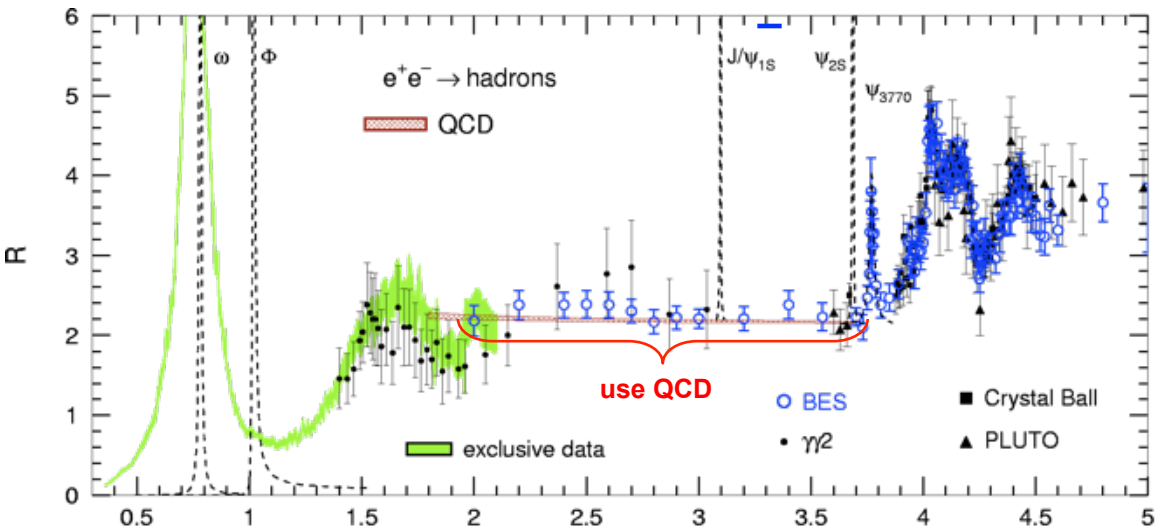


$$a_{\mu}^{\text{had,LO}} = \frac{\alpha^2}{3\pi^2} \int_{m_{\pi^0}^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

Huge 20-years effort by experimentalists and theorists to reduce error on lowest-order hadronic part

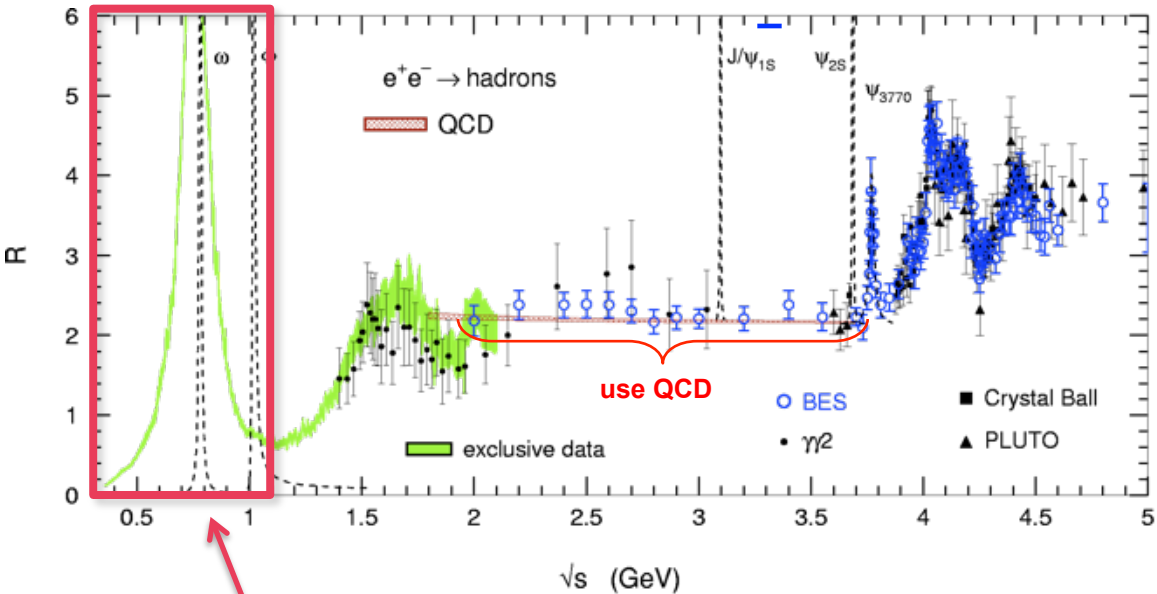
- Improved e^+e^- cross section data from Novosibirsk (Russia)
- More use of perturbative QCD
- Technique of “radiative return” allows to use data from Φ and B factories
- Isospin symmetry allows us to also use τ hadronic spectral functions

Plot not fully up to date - for illustration only



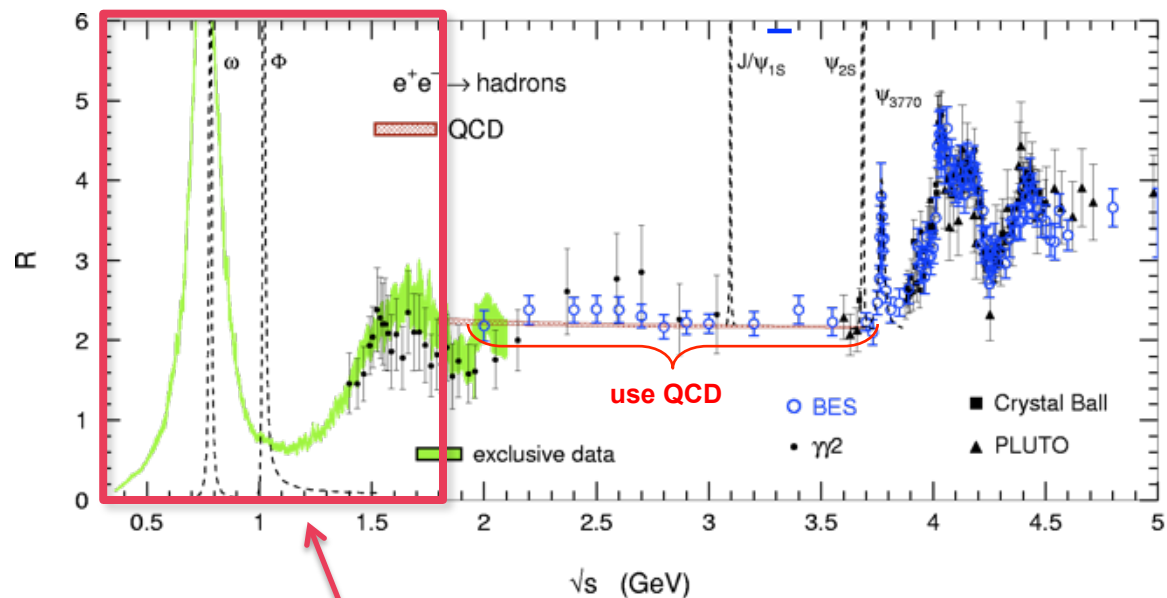
$$a_{\mu}^{\text{had,LO}} = \frac{\alpha^2}{3\pi^2} \int_{4m_{\pi}^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

Plot not fully up to date - for illustration only



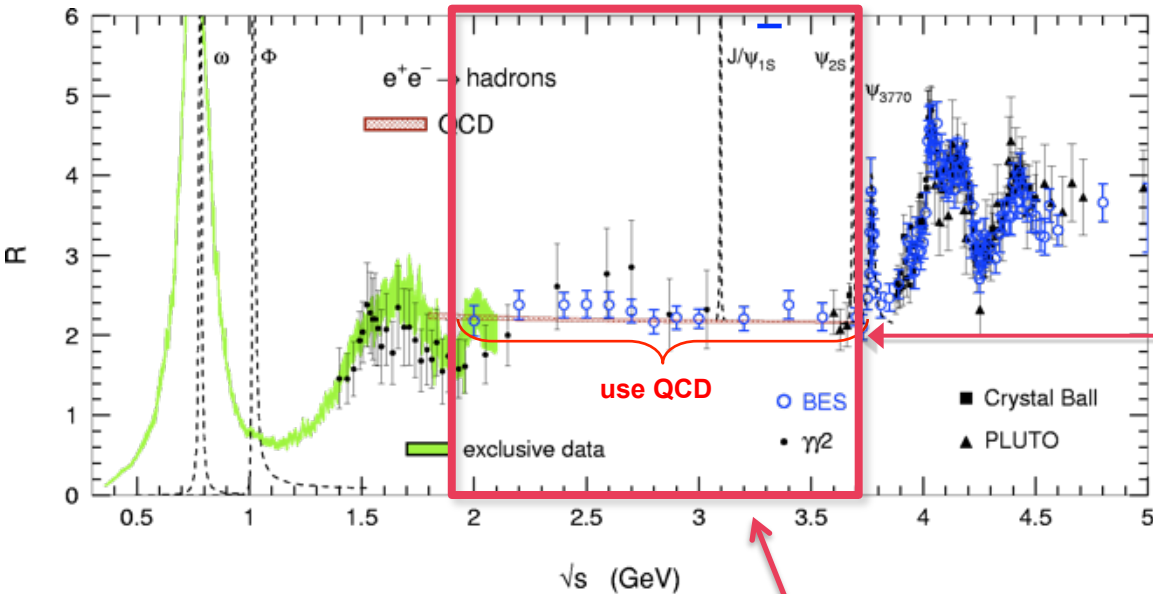
Due to the strongly decaying integration kernel, 73% of dispersion integral stems from $\pi^+\pi^-$ channel, which must be obtained from experiment

$$a_{\mu}^{\text{had,LO}} = \frac{\alpha^2}{3\pi^2} \int_{4m_{\pi}^2}^{\infty} ds \frac{K(s)}{s} R(s)$$



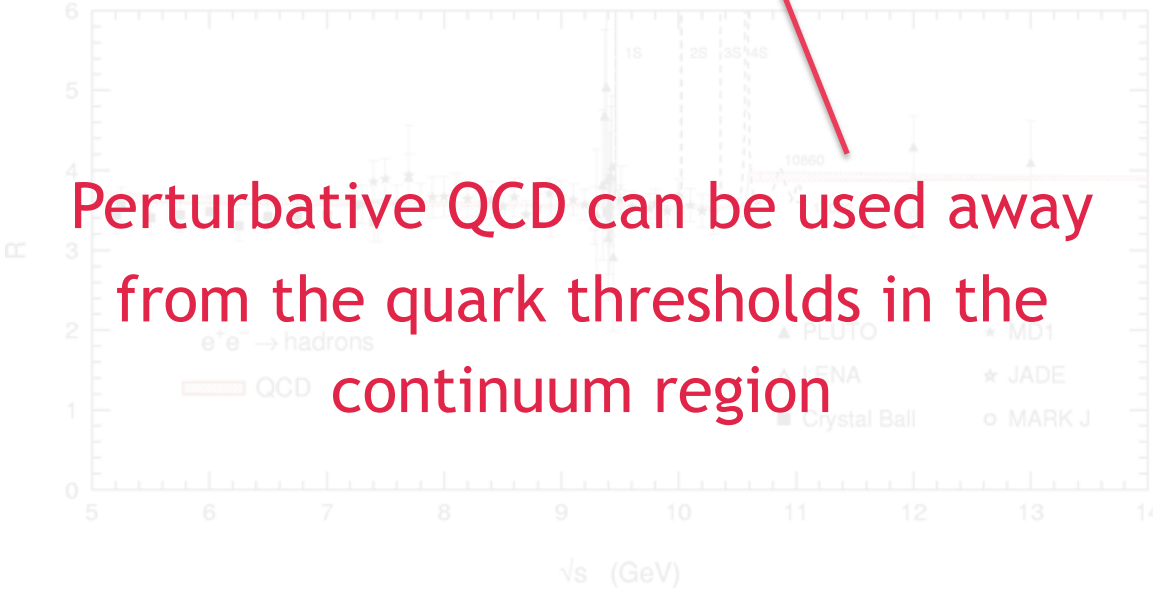
At low energy, the inclusive hadronic cross section is obtained by summing up to 26 exclusively measured final states, and by estimating unmeasured modes using isospin symmetry

$$a_{\mu}^{\text{had,LO}} = \frac{\alpha^2}{3\pi^2} \int_{4m_{\pi}^2}^{\infty} ds \frac{K(s)}{s} R(s)$$



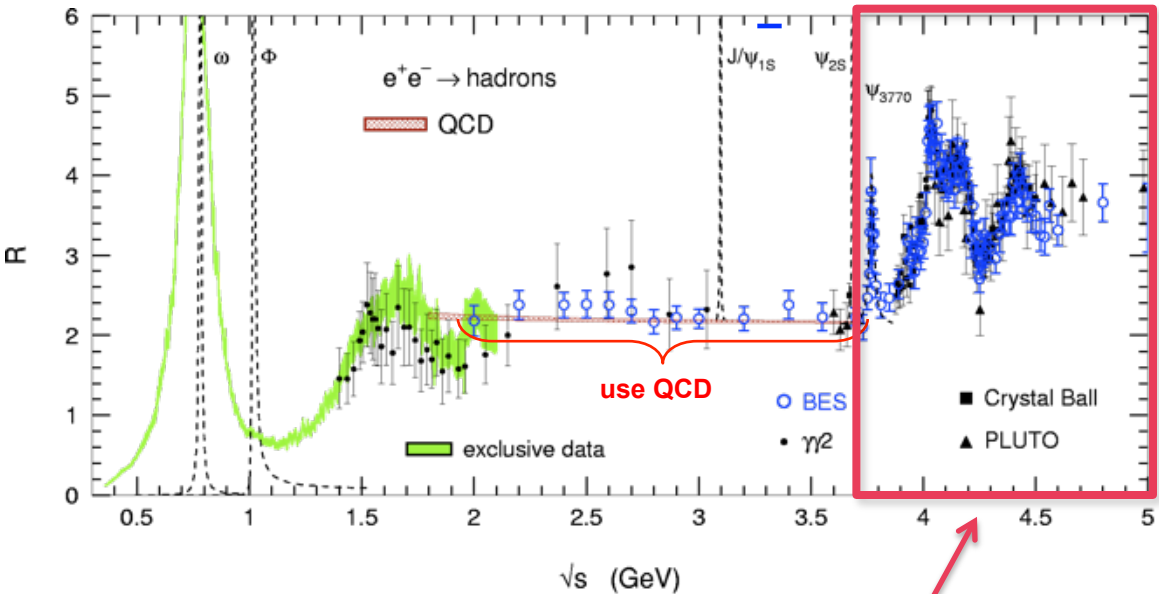
$$a_{\mu}^{\text{had,LO}} = \frac{\alpha^2}{3\pi^2} \int_{4m_{\pi}^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

Agreement between Data (BES) and pQCD (within correlated systematic errors)



Perturbative QCD can be used away from the quark thresholds in the continuum region

Plot not fully up to date - for illustration only



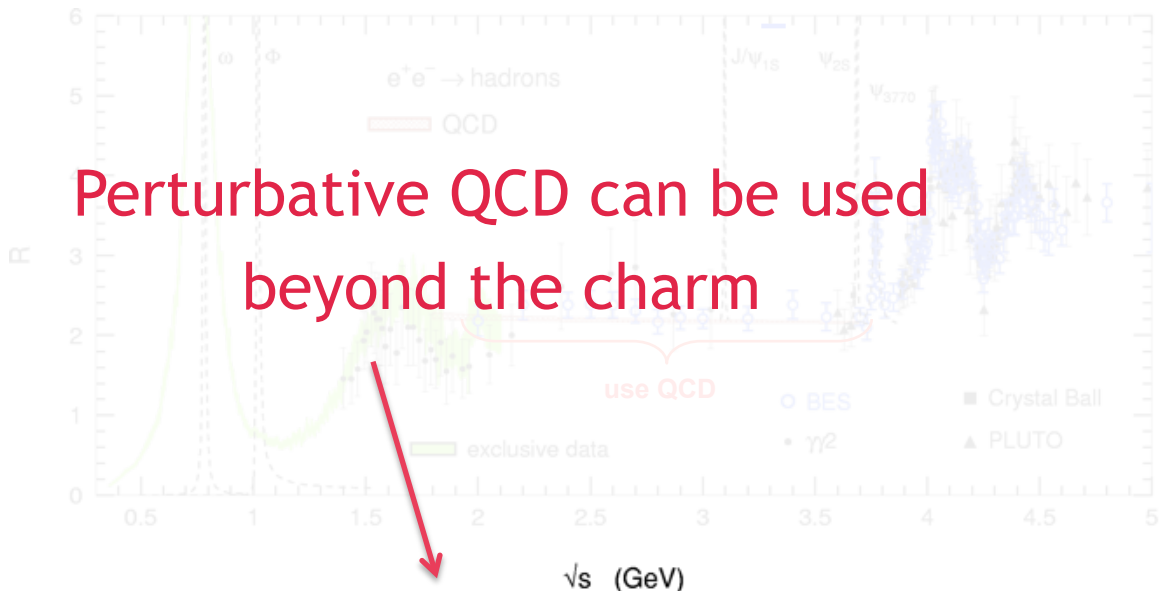
$$a_{\mu}^{\text{had,LO}} = \frac{\alpha^2}{3\pi^2} \int_{4m_{\pi}^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

Experimental data must be used in the charm anti-charm resonance region

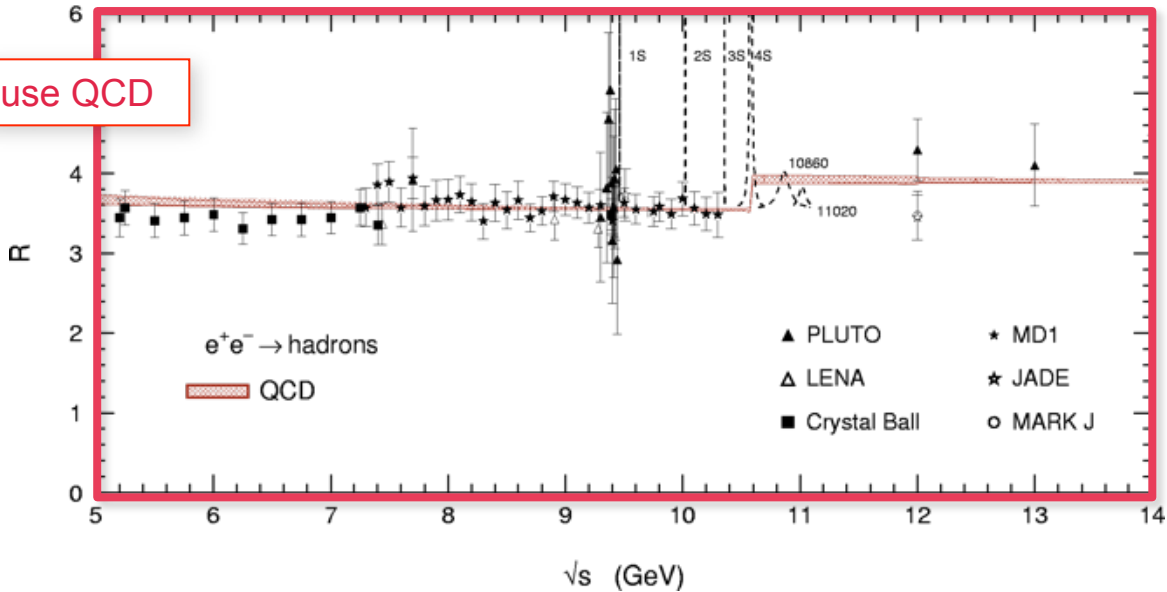


$$a_{\mu}^{\text{had,LO}} = \frac{\alpha^2}{3\pi^2} \int_{4m_{\pi}^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

Perturbative QCD can be used
beyond the charm

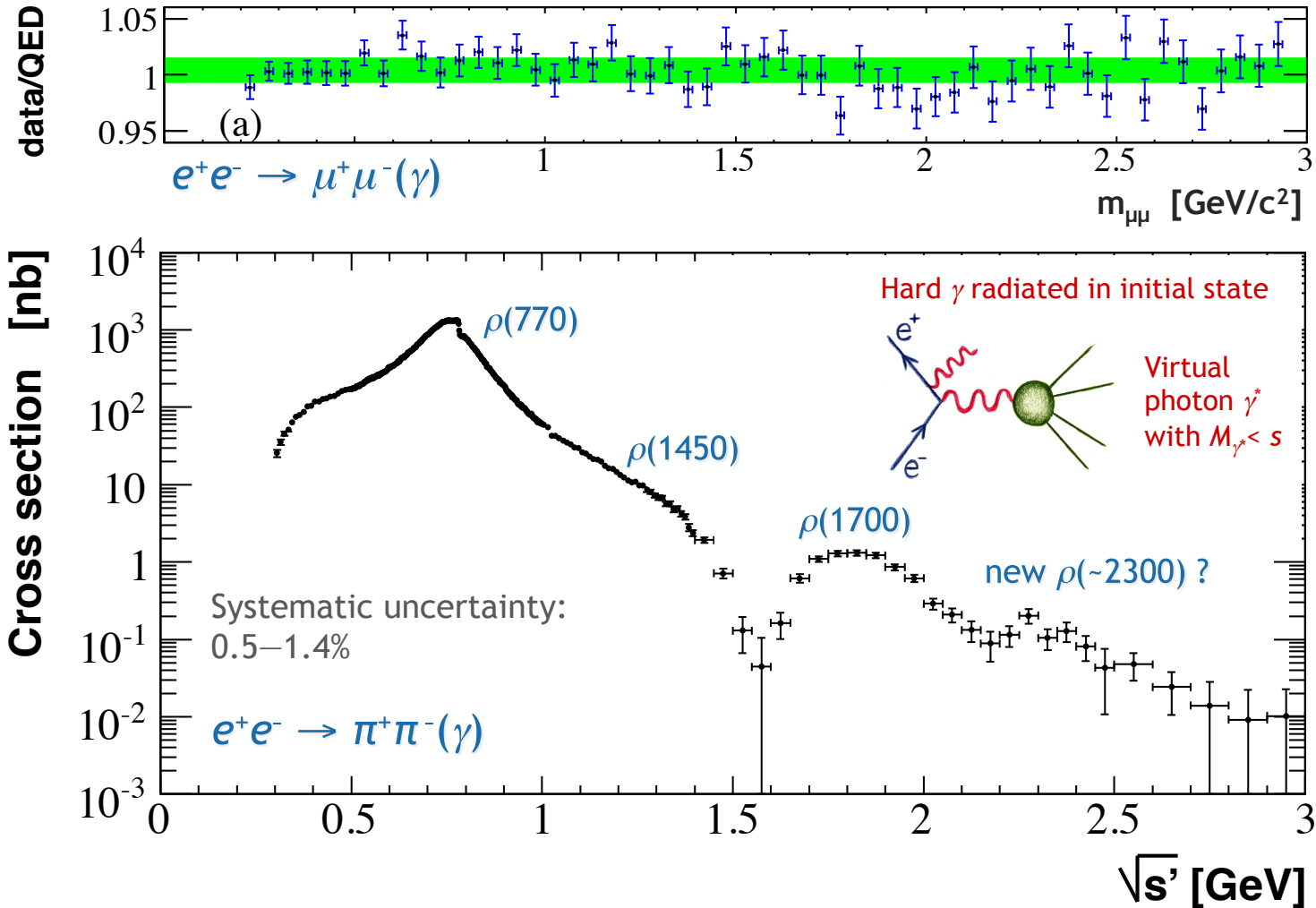


use QCD



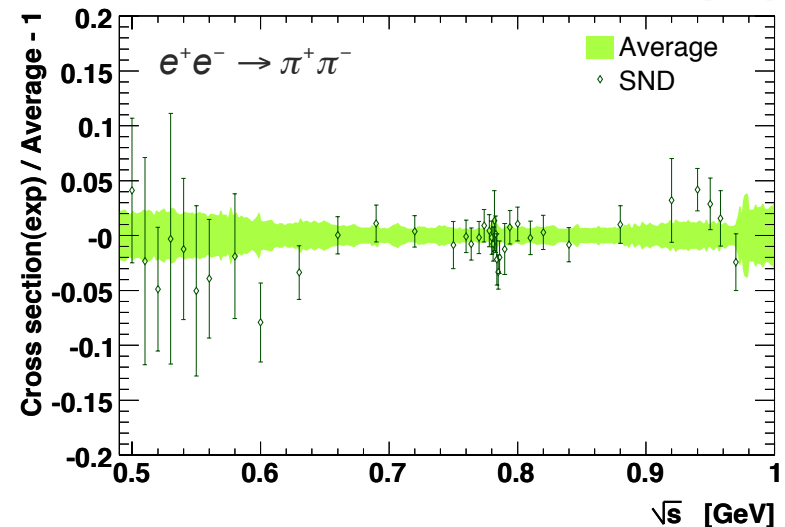
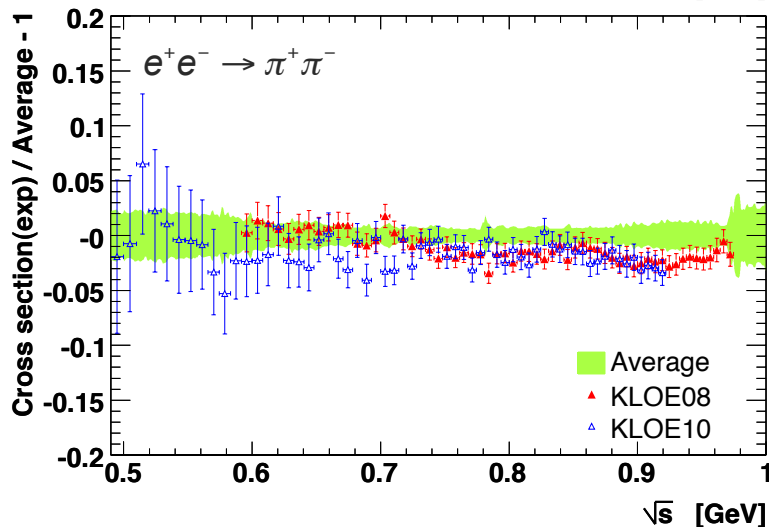
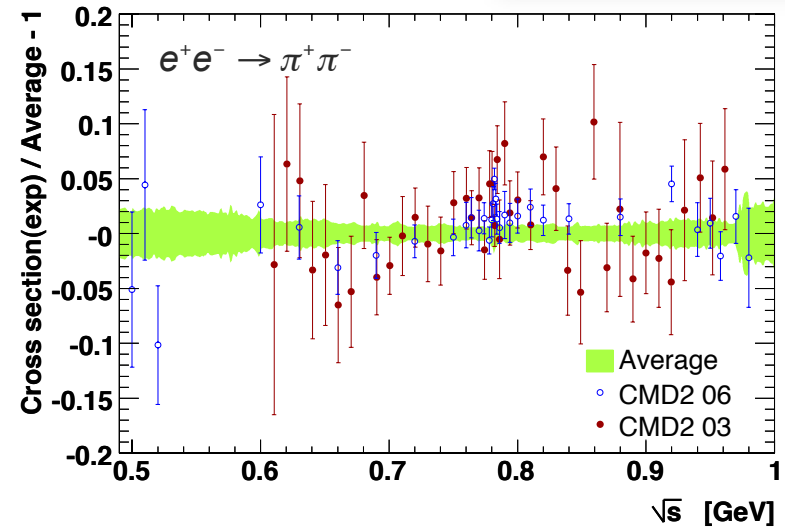
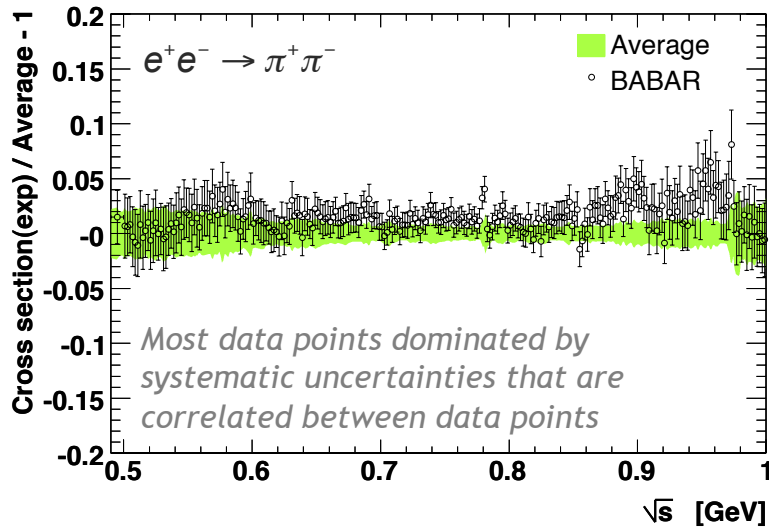
$e^+e^- \rightarrow \pi^+\pi^-(\gamma)$ Cross Section – *BABAR's tour de force*

BABAR, PRL 103, 231801 (2009)



Situation of Two-Pion Channel (e^+e^-)

Davier et al., EPJ C 71, 1515 (2011)



Brand new $e^+e^- \rightarrow \pi^+\pi^-(\gamma)$ – KLOE's *tour de force*

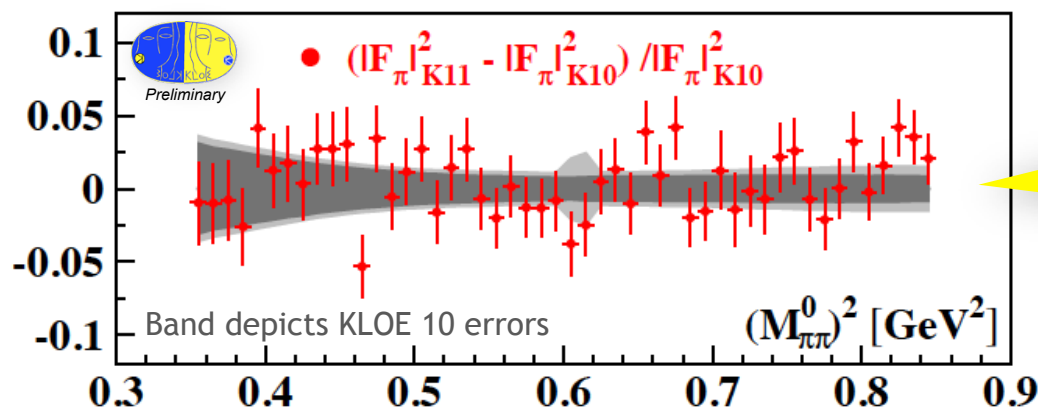
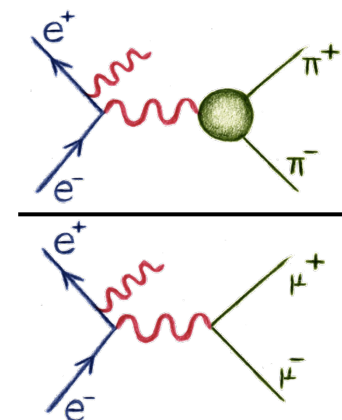
PRELIMINARY

G. Venanzoni (KLOE) at EPS 2011

So far KLOE published small and large-angle photon scattering results based on $\pi\pi(\gamma)$ data only, ie, requiring explicit insertion of QED radiator function

New result at EPS-2011 using $\pi\pi(\gamma) / \mu\mu(\gamma)$ ratio (as BABAR)

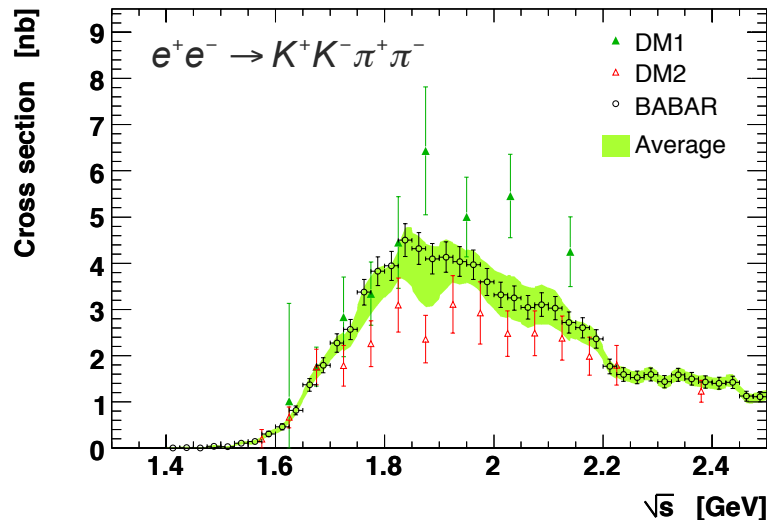
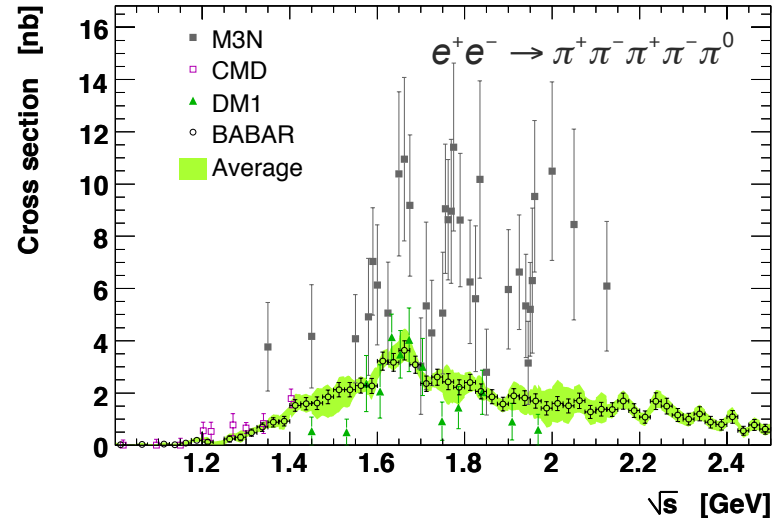
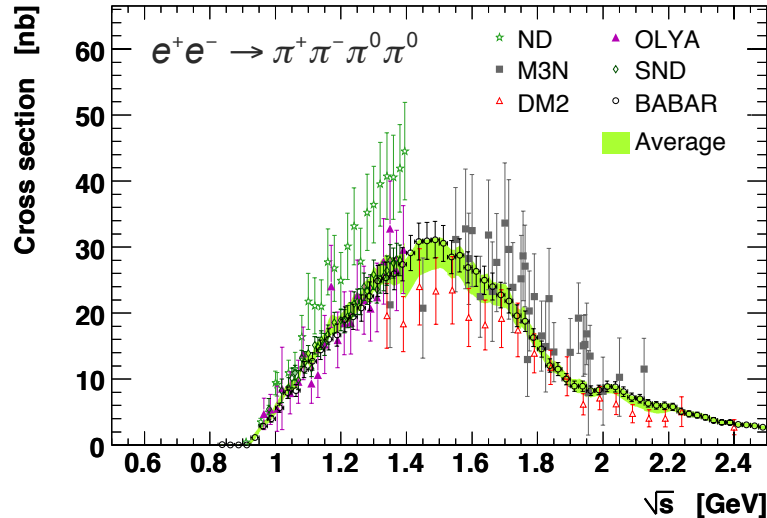
- Many corrections cancel: radiation, luminosity, vacuum polarisation
- However, crucially relies on well understood π / μ separation
- Statistics: 2002 data (239 pb⁻¹): 0.87 M $\mu\mu(\gamma)$ / 3.4 M $\pi\pi(\gamma)$ events
- Overall, excellent 1% systematic error achieved (BABAR: 0.5–1.0%)



Good agreement found!
This corroborates the earlier KLOE results and thus the discrepancy with BABAR (and τ data)

Examples for Rarer and High-Multiplicity Modes

Davier et al., EPJ C 71, 1515 (2011)

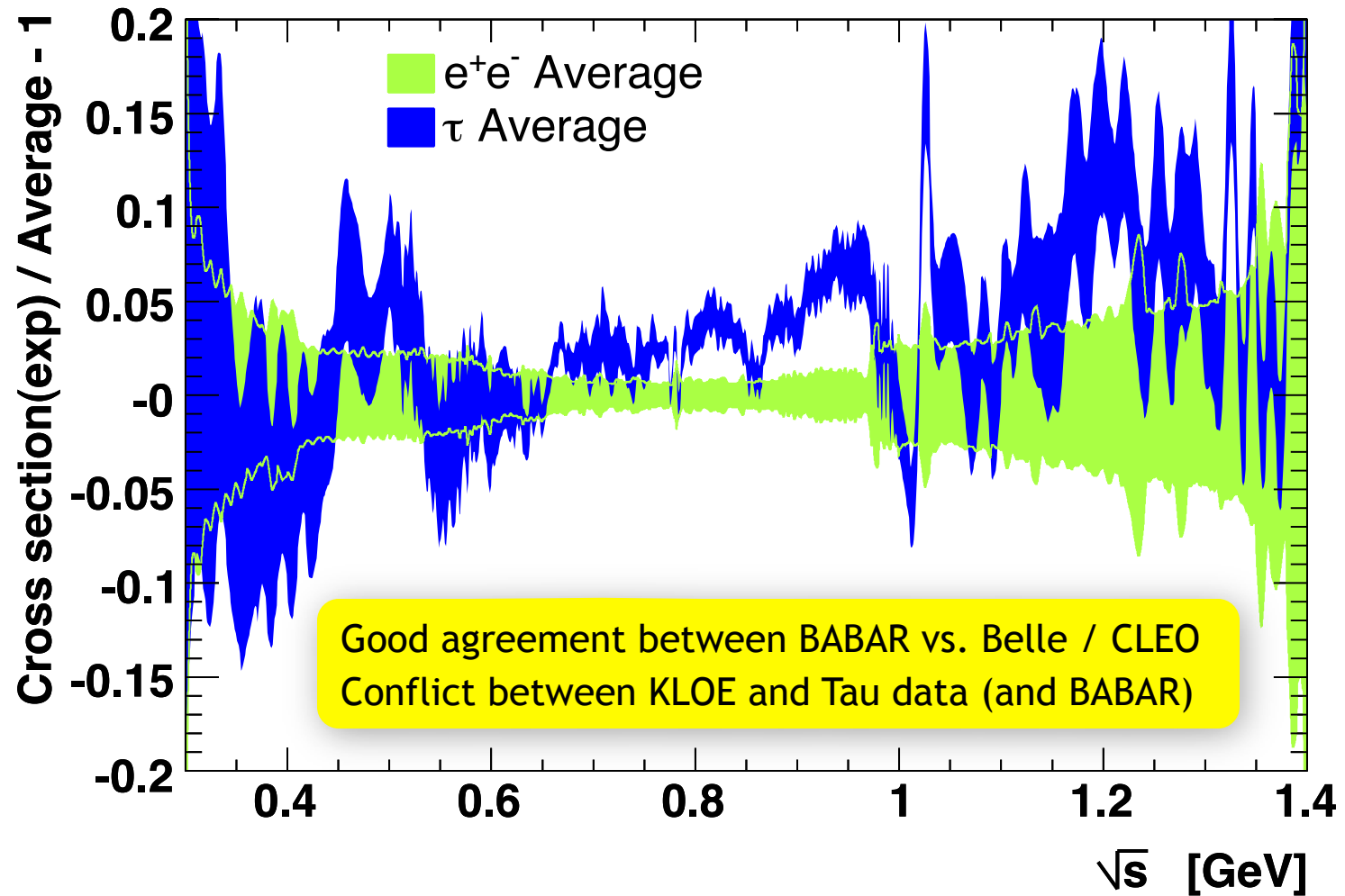


BABAR measured (almost) all the exclusive $e^+e^- \rightarrow$ hadrons modes
Many inconsistencies resolved
Huge impact on hadronic vacuum polarisation calculation

Can use precise **tau** data to improve a_μ prediction

What do the Tau data tell us?

Situation of Two-Pion Channel (e^+e^- vs. τ)



Adding all (28) Contributions Together

Hadronic LO term:

$$\Delta(\tau - e^+e^-) = 19.5 \pm 8.3 \text{ (2.4}\sigma\text{)}$$

$$a_{\mu}^{\text{had,LO}}[e^+e^-] = (692.3 \pm 4.2_{\text{ee+QCD}}) \times 10^{-10}$$

$$a_{\mu}^{\text{had,LO}}[\tau] = (701.5 \pm 3.5_{\tau} \pm 1.9_{\text{SU(2)}} \pm 2.4_{\text{ee+QCD}}) \times 10^{-10}$$

Davier et al., EPJ C 71, 1515 (2011)

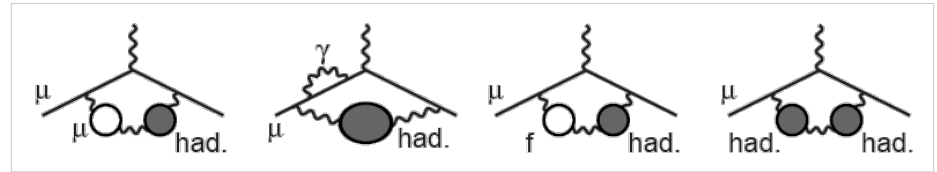
Hadronic NLO terms:

Vacuum polarization (1-loop) + additional photon or VP insertion

- Computed akin to LO part via dispersion integral with modified kernel function

$$a_{\mu}^{\text{had,NLO}} = -9.8(0.1) \times 10^{-10}$$

Hagiwara et al. 2010 (and others)



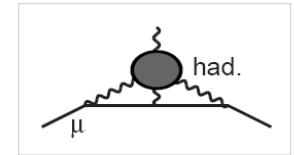
Light-by-light scattering

- Dispersion relation approach not possible (4-point function)
- Model-dependent calculations

$$a_{\mu}^{\text{had,LBL}} = +10.5(2.6) \times 10^{-10}$$

Prades-deRafael-Vainshtein (and others)

Jansen et al., arXiv:1103.4818



- Lattice results may be in reach (LO HVP ($u+d$ quarks only) computed to 3% accuracy)

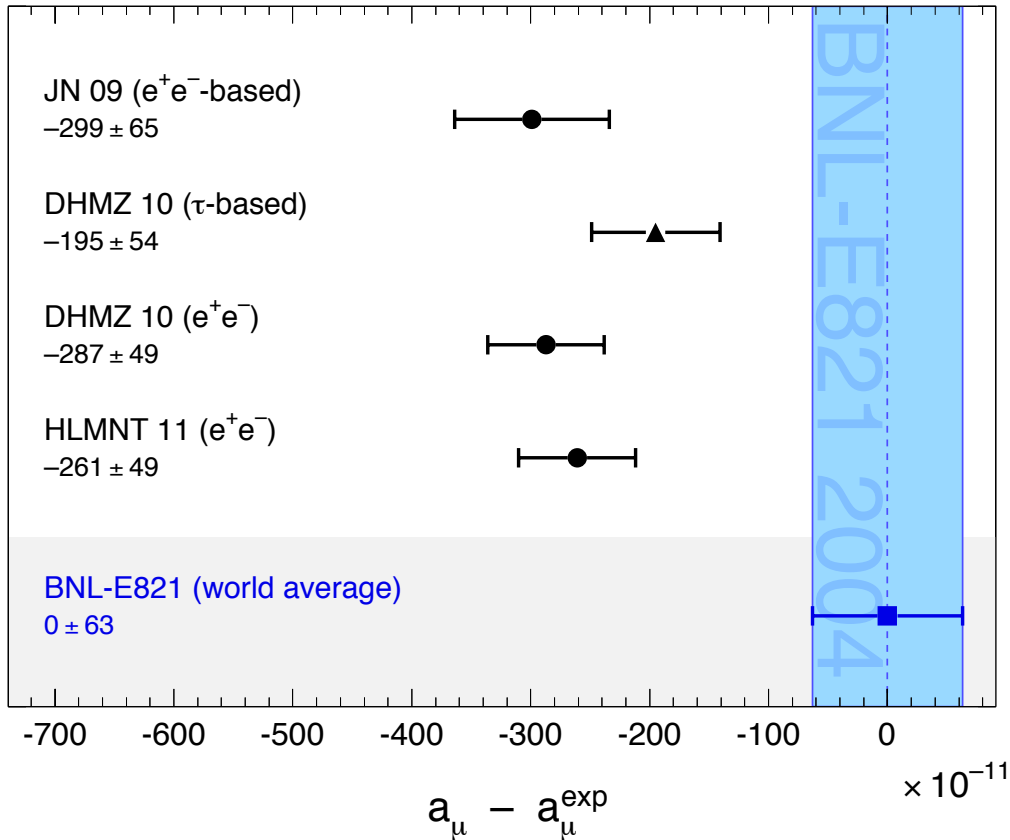
Results for Muon $g - 2$

$$a_{\mu}^{\text{SM}}[e^+e^-] = (11\,659\,180.2 \pm 4.2_{\text{had,LO}} \pm 2.6_{\text{NLO}} \pm 0.2_{\text{QED+weak}}) \times 10^{-10}$$

$$a_{\mu}^{\text{SM}}[\tau] = (11\,659\,189.4 \pm 4.7_{\text{had,LO}} \pm 2.6_{\text{NLO}} \pm 0.2_{\text{QED+weak}}) \times 10^{-10}$$

Davier *et al.*, EPJ C 71, 1515 (2011)

Status: summer 2011 (published results shown only)



BNL E821 (2004):

$$a_{\mu}^{\text{exp}} = (11\,659\,208.9 \pm 6.3) \times 10^{-10}$$

Difference: experiment – SM

$$a_{\mu}^{\text{exp}} - a_{\mu}^{\text{SM}} = (28.7 \pm 8.0) \times 10^{-10}$$

➔ 3.6 "standard deviations" (e^+e^-)

➔ 2.4 "standard deviations" (τ)

What could a $\Delta a_\mu \approx 30 \times 10^{-10}$ Deviation Tell Us?

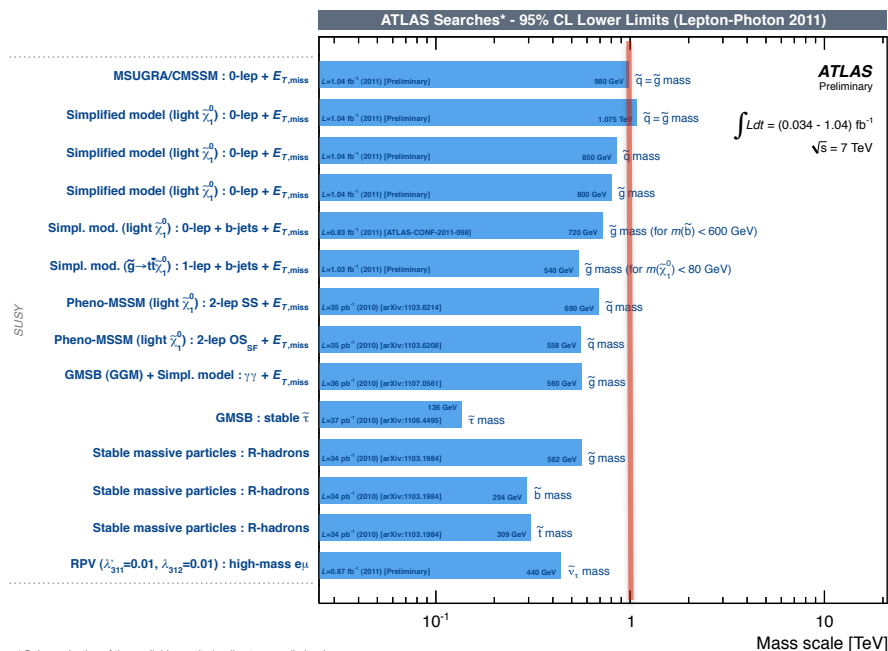
Amount of discrepancy in ballpark of SUSY with mass scale of several 100 GeV

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

But strong m_{SUSY} limits from LHC require large $\tan \beta$

Unfortunately, the situation stays non-conclusive

But: current discrepancy still limited by experimental uncertainty



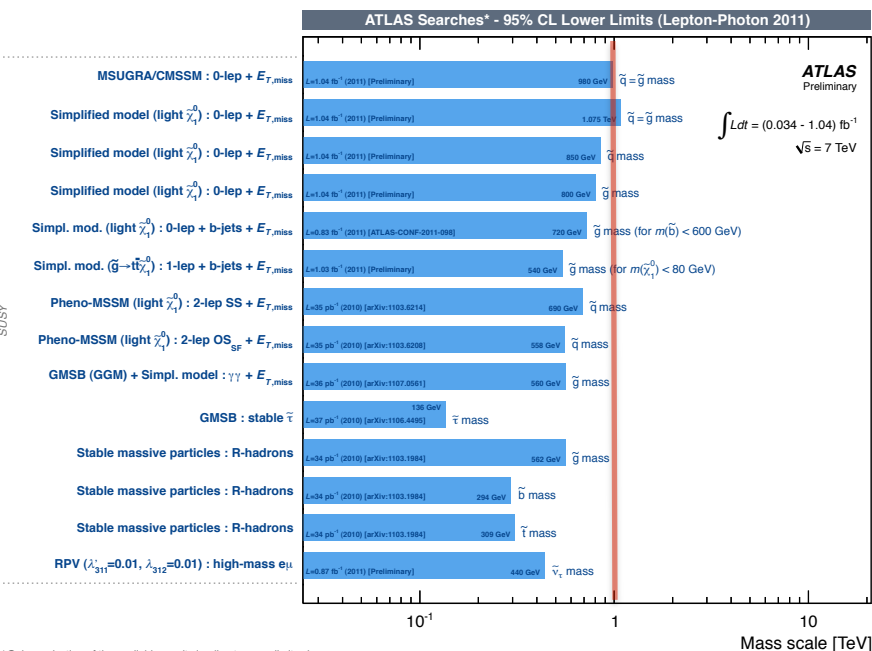
Fortunately, new experiments are being designed ...

What could a $\Delta a_\mu \approx 30 \times 10^{-10}$ Deviation Tell Us?

Amount of discrepancy in ballpark of SUSY with mass scale of several 100 GeV

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

But strong m_{SUSY} limits from LHC require large $\tan \beta$



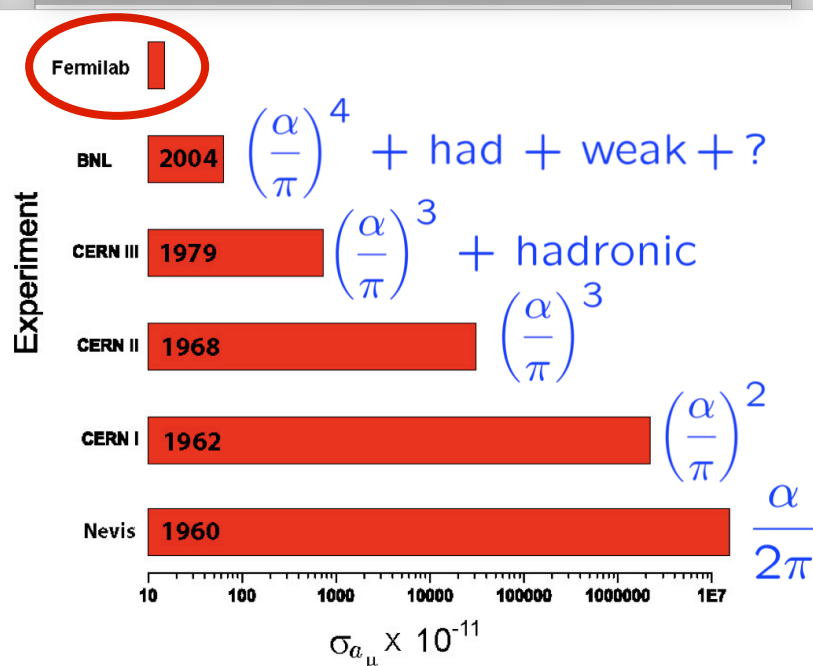
Proposals for new experiments E989 at FNAL (similar technique as E821) and at J-PARC (new: ultra-slow muons) with target of $\sigma \sim 1.6 \cdot 10^{-10}$

Final E989 proposal:

http://gm2.fnal.gov/public_docs/proposals/Proposal-APR5-Final.pdf

LOI: KEK_J-PARC-PAC2009-06

See also, e.g., Naohito SAITO (KEK), Seminar at DESY 2011



Summary

We all are passionately following ATLAS and CMS in their direct searches for EW symmetry breaking remnants and new physics at the TeV-scale energy frontier

Probing new physics orders of magnitude beyond that scale and helping to decipher possible TeV-scale new physics requires to work hard on the **intensity and precision frontiers**

Charged leptons offer an important spectrum of possibilities:

- LFV and EDM measurements have SM-free signals
- Current experiments and mature proposals promise orders of magnitude sensitivity improvements
- The muon $g-2$ **may** already show a deviation from the SM
- New physics models usually strongly correlate these sectors

Acknowledgment

I am most grateful to Alessandro Baldini, Swagato Banerjee, Robert Bernstein, Michel Davier, Tim Gershon, Herve Hiu Fai Choi, Yoshitaka Kuno, Alberto Lusiani, Bogdan Malaescu, James Miller, Toshinori Mori, Steven Robertson, Karim Trabelsi, Graziano Venanzoni and Zhiqing Zhang for their help with the preparation of this talk.

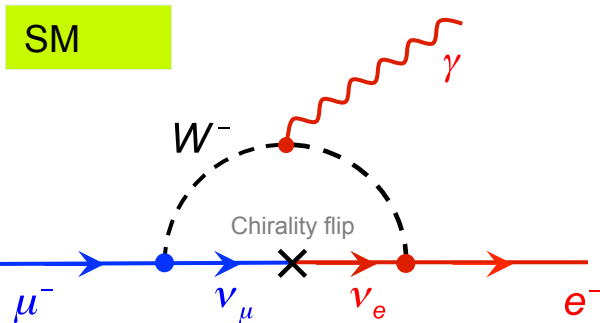
Extra slides...

Mu-to-e Flavour Violation

Minimal SM: $m_\nu = 0 \rightarrow$ strictly zero transitions between lepton flavours

SM extension to $m_\nu \neq 0 \rightarrow$ unobservable tiny LFV rates predicted (GIM)

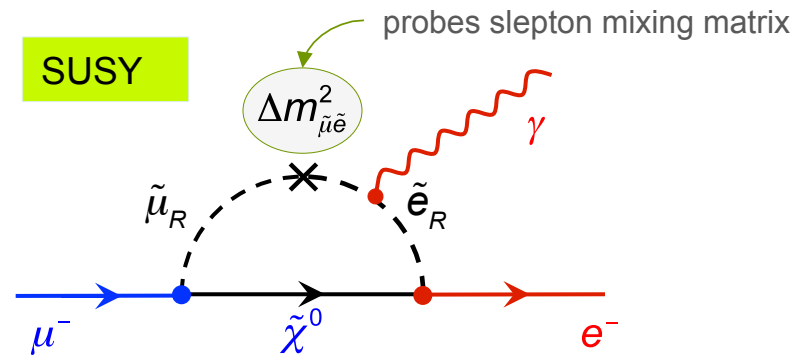
Flavour Changing Neutral Current



$$\text{BR}(\mu^- \rightarrow e^- \gamma)_{\text{SM}} \simeq \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2$$

$$< 10^{-54}$$

$$(< 10^{-40} \text{ for } \tau^- \rightarrow \mu^- \gamma)$$



$$\text{BR}(\mu^- \rightarrow e^- \gamma)_{\text{SUSY}} \sim 10^{-5} \left[\underbrace{\frac{\Delta m_{\tilde{e}\mu}^2}{\bar{m}_\ell^2}} \right]^2 \left(\frac{100 \text{ GeV}}{m_{\text{SUSY}}} \right)^4 \tan^2 \beta$$

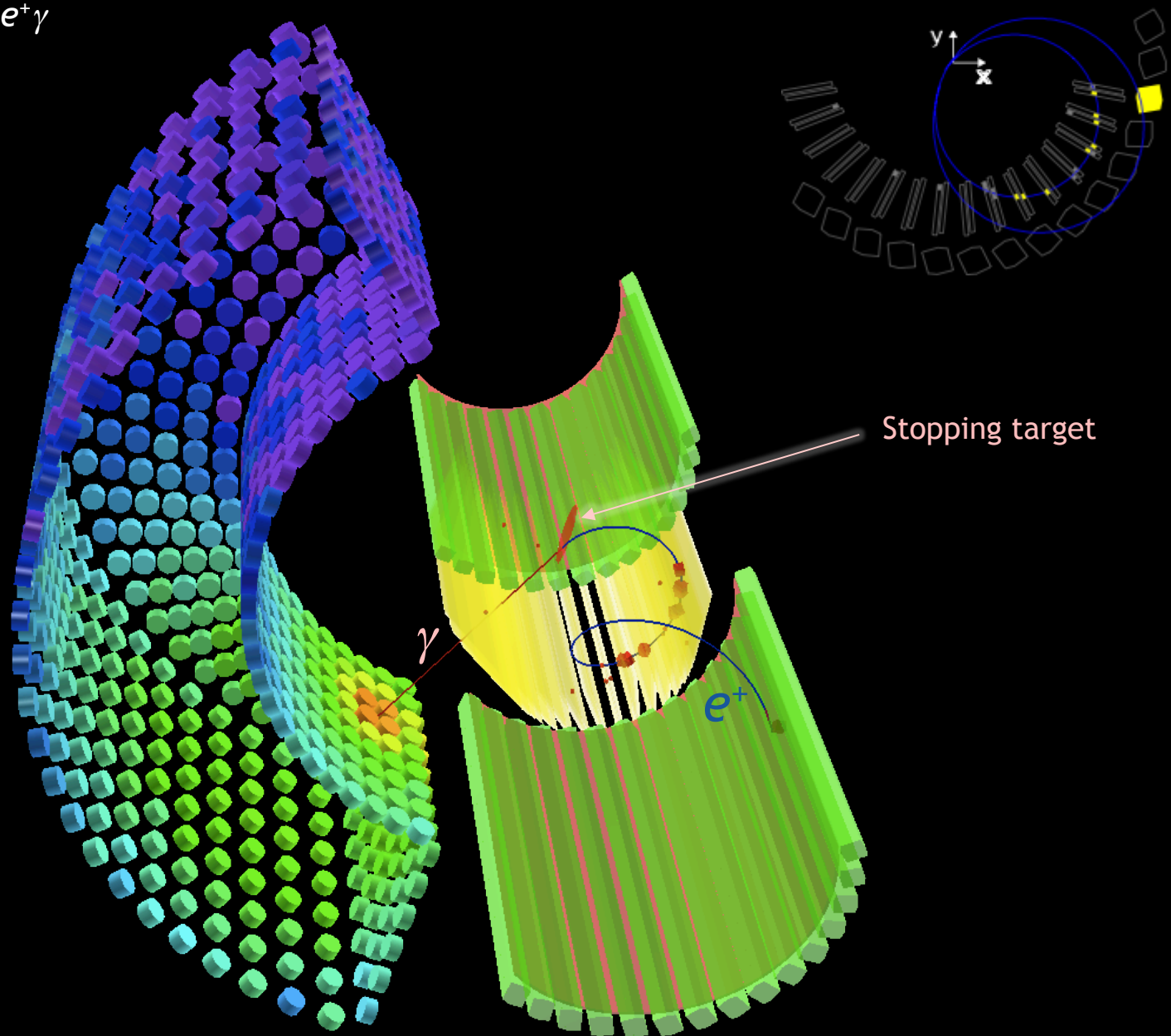
In seesaw related
to $\ln(M_{\nu R}/M_{\text{Planck}})$

$\rightarrow$ Search for charged-LFV probes new physics without SM contamination !

Prior best limit on $\mu^+ \rightarrow e^+ \gamma$ by MEGA experiment (LAMPF, 1999): $B < 1.2 \times 10^{-11}$

MEGA, PRL
83, 1521 (1999)

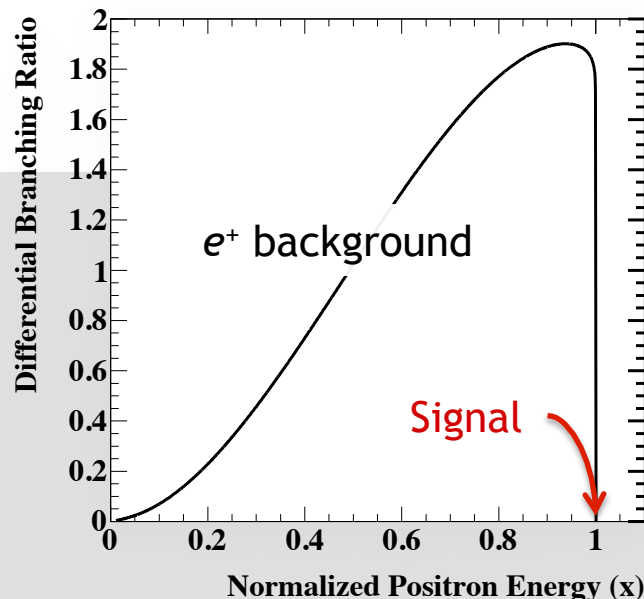
MEG display of $\mu^+ \rightarrow e^+ \gamma$
candidate event



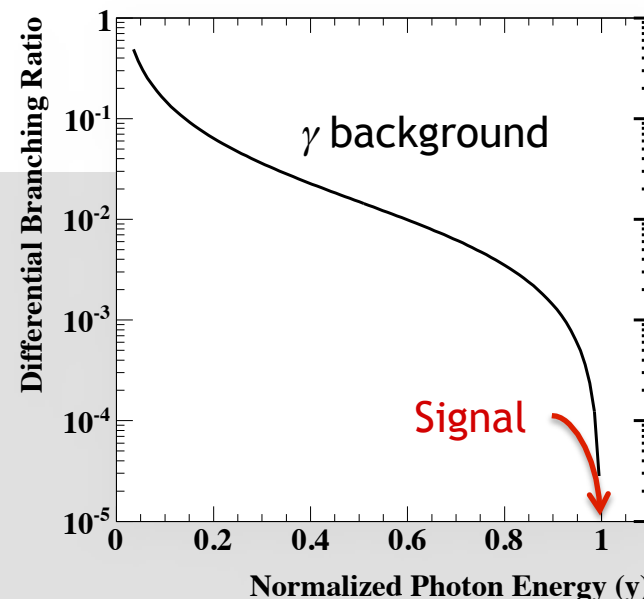
Full Analysis of 2009 and 2010 MEG Data

Total of 1.8×10^{14} μ^+ decays in the target, 2010 about twice statistics of 2009

- Improved time resolution in 2010, but slightly worse tracking resolution (noise)
- Precision improvements over prelim. 2009 analysis: calibration & alignment, gradient B -field (0.2%), more data-driven performance measurements
- Blind unbinned maximum likelihood analysis using E_γ , E_e , $T_{e\gamma}$, $\theta_{e\gamma}$, $\phi_{e\gamma}$ with PDFs mostly derived from data, fitting signal + RMD + accidental bkg. components

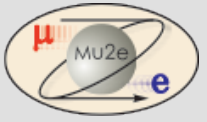


Must cope with high e^+ rate



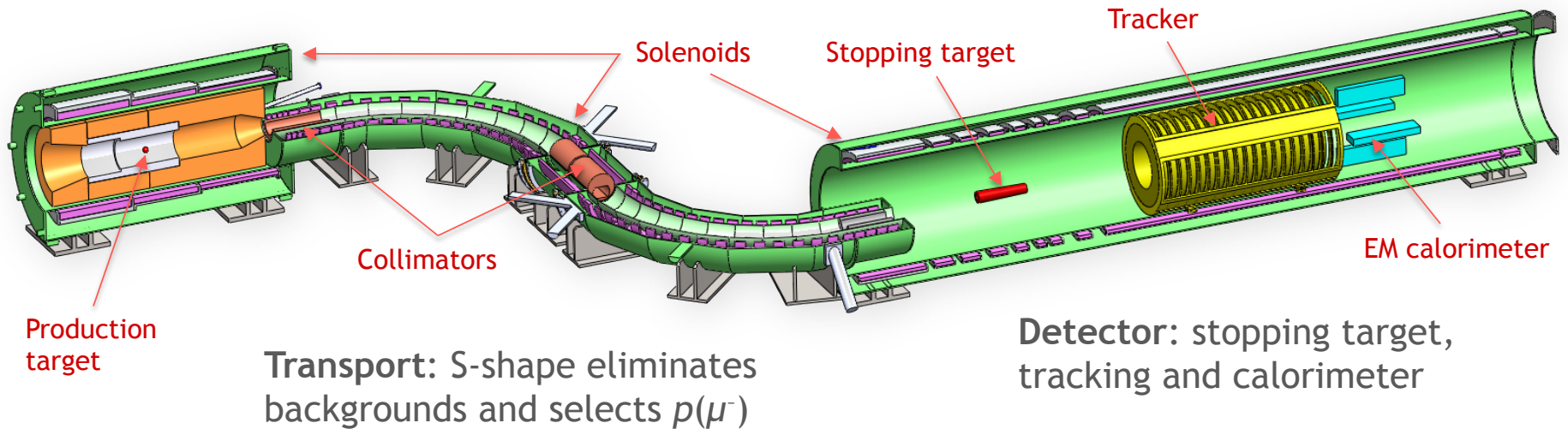
Good γ resolution most critical

Mu2E (FNAL) Overview



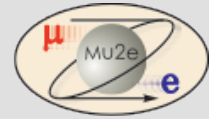
Production: magnetic bottle traps π 's which decay into accepted μ 's

See: <http://mu2e.fnal.gov/> and, e.g.,
R. Bernstein, Pittsburgh Seminar, Feb 2011

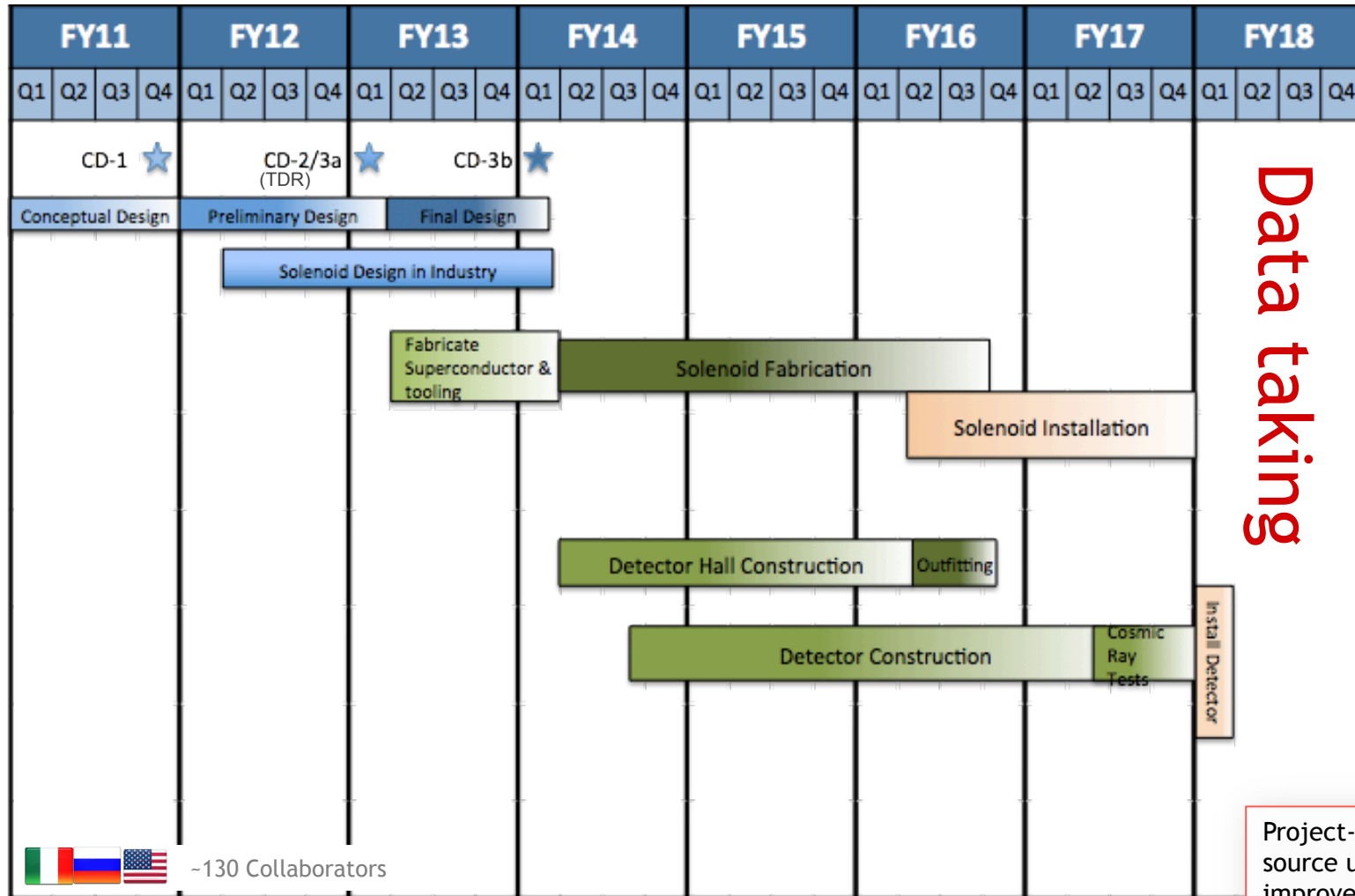


- **Pulsed Beam:** eliminate prompt backgrounds (e.g., radiative π capture), 0.6 MHz, 10^{-10} pulse extinction after 0.7 μ s, use late muonic atom decays ($\tau \sim 1 \mu$ s) for measurement
- **Gradient B -fields:** guide muons, increase muon acceptance, evacuate loopers
- **Detection:** atoms pass through tracker and stop in calorimeter, e^- helix in gradient field
- **Expected backgrounds:** $R_{\mu e} = 10^{-16} \rightarrow \sim 4 \text{ signal} / 0.2 \text{ bkg. events}$ (RPC, decay-in-orbit)
- **Multiple ring structure at FNAL:** no interference with NOvA running

Mu2E (FNAL) Schedule



US\$ 200 M total cost at CD-0



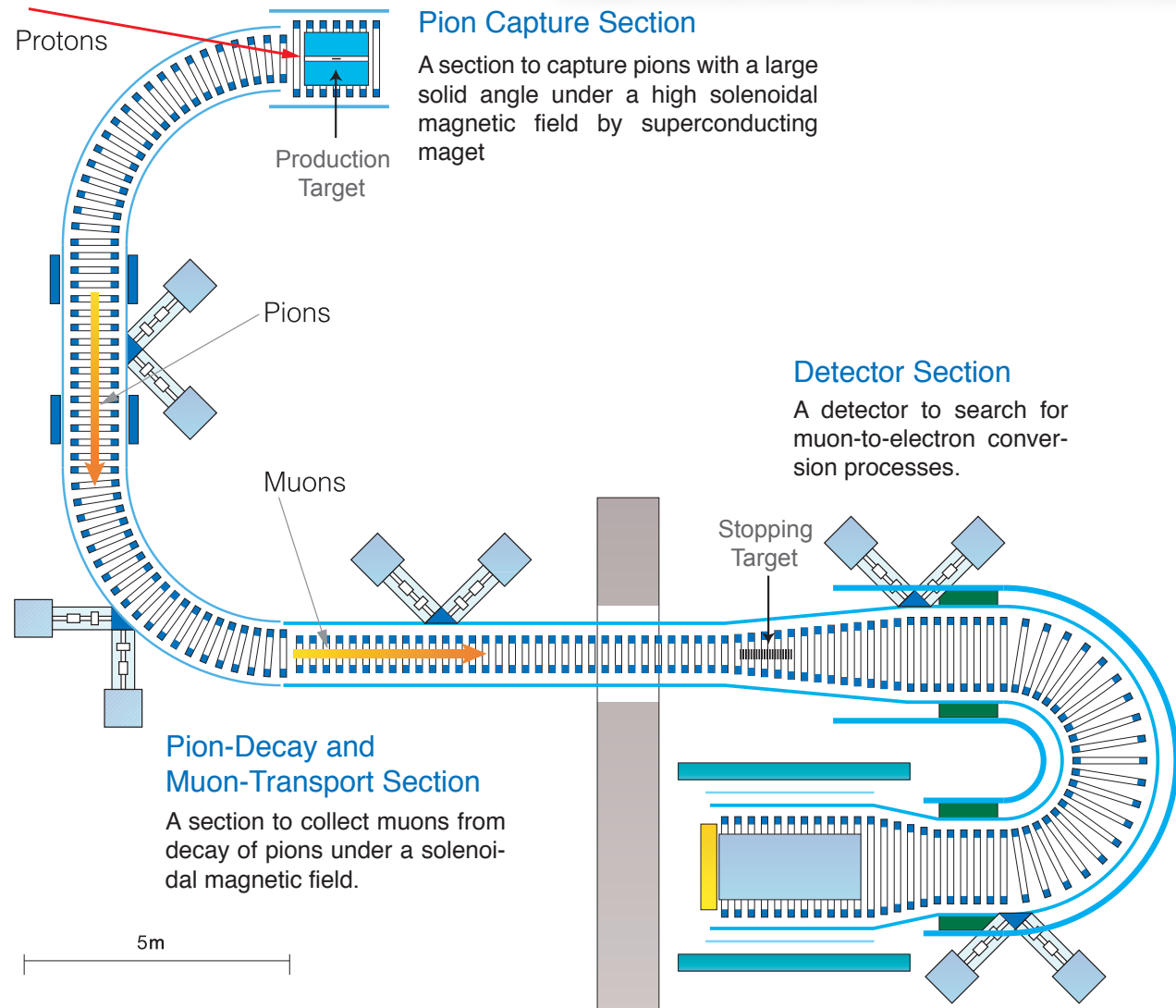
Project-X proton source upgrade may improve additional 2 orders of magnitude

COMET (J-PARC) Overview

COMET, TDR, KEK Report 2009-10 and update (courtesy: Y. Kuno)

Similar design features as Mu2e:

- Sensitivity: $R_{\mu e} \sim 3 \times 10^{-17}$
- Pulsed proton beam
- Efficient π collection around proton target
- (~850 protons with 8 GeV required to produce 1 muon)
- Curved solenoids for muon charge and momentum selection
- C-shaped (as opposed to S-shaped) transport for better p_μ selection
- C-shaped detector section eliminates low- E DIO e and protons



COMET (J-PARC) Overview

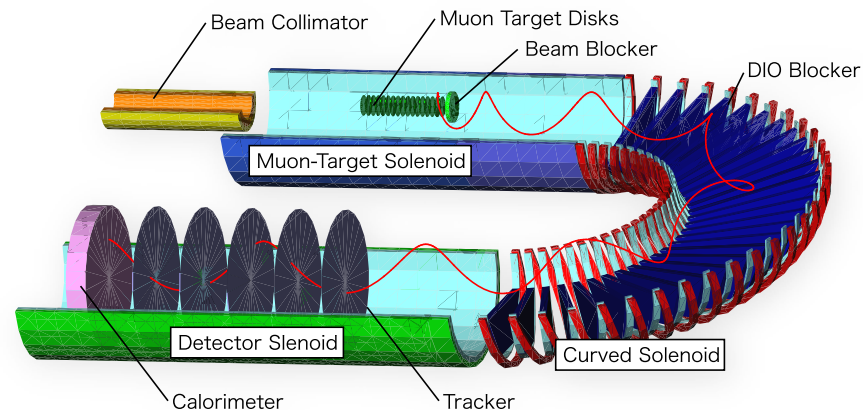
COMET, TDR, KEK Report 2009-10 and update (courtesy: Y. Kuno)

Similar design features as Mu2e:

- Sensitivity: $R_{\mu e} \sim 3 \times 10^{-17}$
- Pulsed proton beam
- Efficient π collection around proton target
(~850 8 GeV protons required to produce 1 muon)
- Curved solenoids for muon charge and momentum selection
- C-shaped (as opposed to S-shaped) transport for better p_μ selection
- C-shaped detector section eliminates low- E DIO e and protons

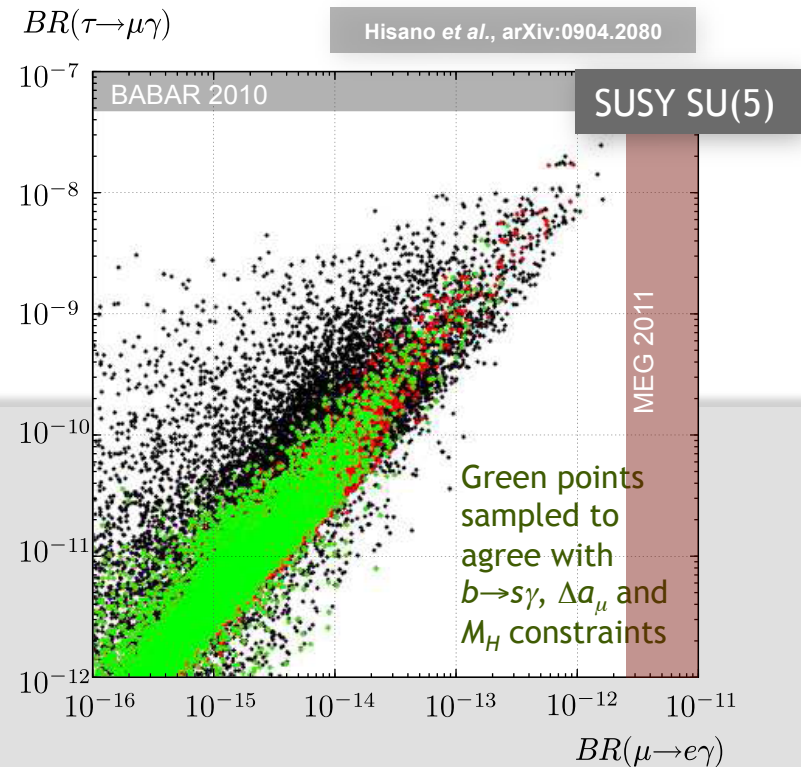
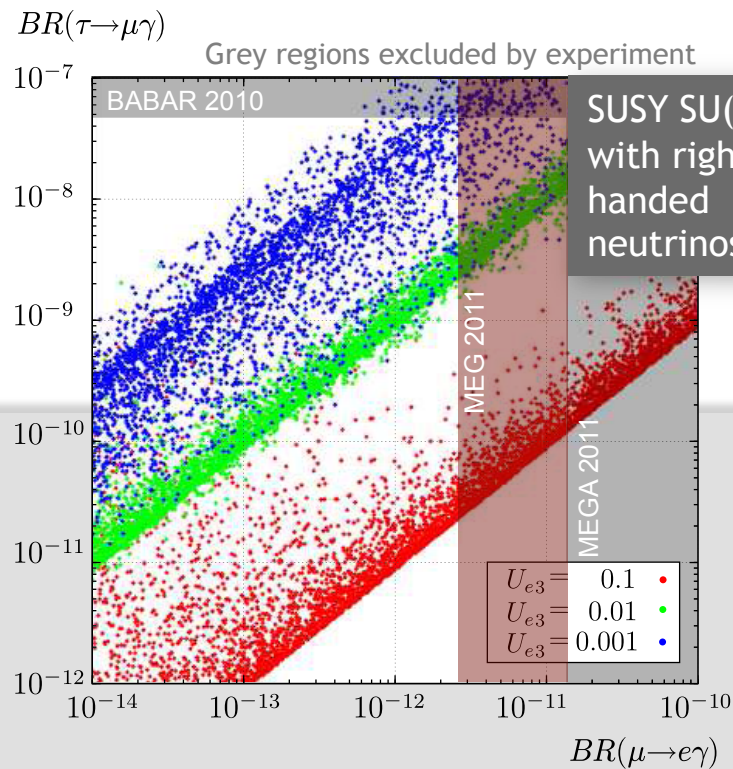
Schedule:

- Stage-1 approval obtained in 2009 (CDR)
- TDR expected end of 2011
- Superconducting magnet design biggest challenge
- Pion capture tested with MuSIC (Osaka)
- Request funding in 2014/2015
- Data taking in 2018
- Upgrade project to PRISM (with muon storage ring) expecting sensitivity of $R_{\mu e} \sim 3 \times 10^{-19}$



Lepton Flavour Violation in Tau Decays

LFV in tau decays (= neutrinoless tau decays) is searched for in a large variety of modes at the B -factories with sensitivity to different new physics scenarios

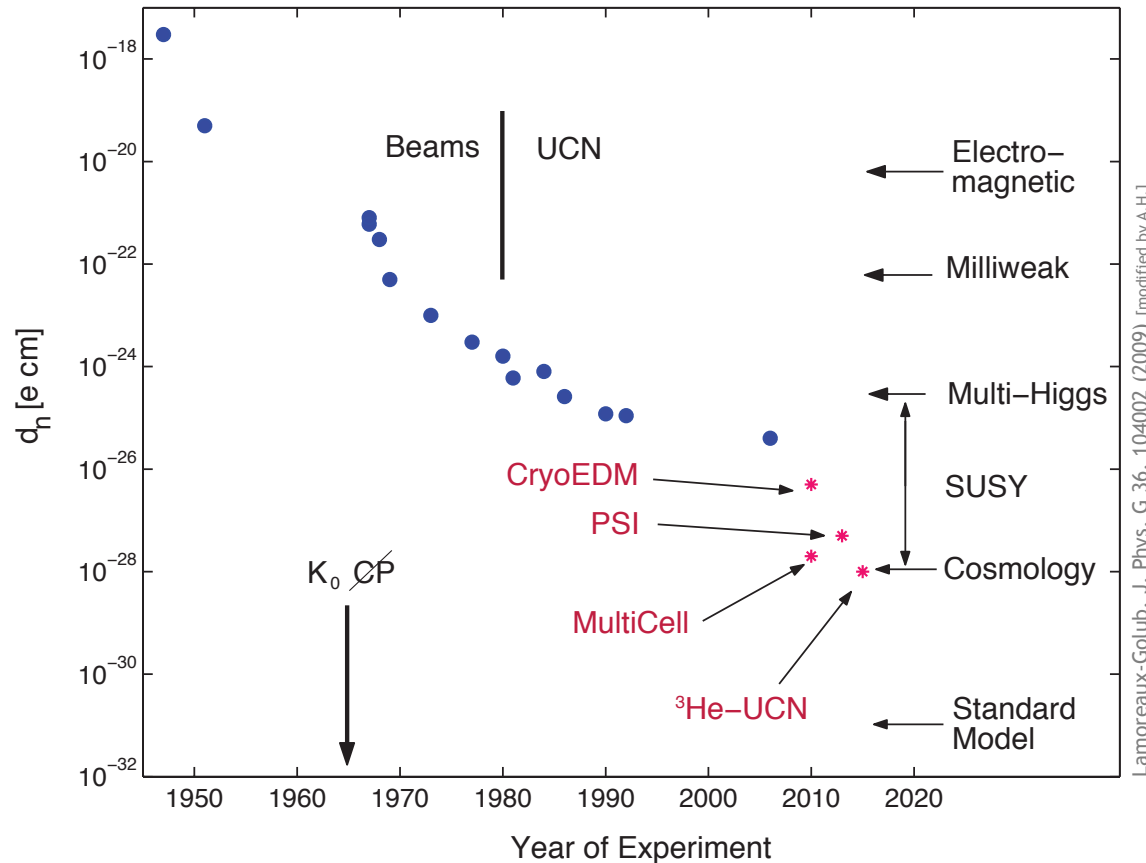


EDM - Experimental Programme

90% CL limits given

Neutron EDM

Best limit: $|d_n| < 2.9 \times 10^{-26} \text{ ecm}$ [RAL-Sussex-ILL Collaboration, PRL 97, 131801 (2006)]



Lamoreaux-Golub, J. Phys. G 36, 104002 (2009) [modified by A.H.]

EDM - Experimental Programme

90% CL limits given

See, e.g., Y. Semertzidis at Patras Workshop, 2011

Proton / Deuterium EDM

Proposals at BNL, USA and Juelich, Germany for storage ring based pEDM measurement with sensitivity: 10^{-29} ecm

Radial E field, aligned spin and momentum vectors at magic momentum (0.7 GeV for protons)

Similar new physics sensitivity as for neutrons, **but better precision!**



EDM - Experimental Programme

90% CL limits given

Muon g-2 Collaboration, PRD 80, 052008 (2009)

Muon EDM

Best limit: $|d_\mu| < 1.9 \times 10^{-19} \text{ ecm}$ [Muon g-2 Collaboration, PRD 80, 052008 (2009)]
Factor of 5 improvement over CERN experiment [Bailey *et al.*, Phys. G4, 345 (1978)]

If new physics scales with lepton mass, $|d_\mu| \gg |d_e|$, but may need sensitivity of 10^{-23} ecm to be competitive with current $|d_e|$ limits

Relative spin precession frequency modified by EDM:
$$\vec{\omega}_{\text{EDM}} = -\frac{Q_\mu d_\mu}{2m_\mu} \left(\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} \right)$$

EDM creates a vertical component of spin polarisation that oscillates with amplitude proportional to $|d_\mu|$

Measurement uses in addition to positron scintillators other detectors sensitive to the vertical decay-electron position. Final result dominated by systematic uncertainties

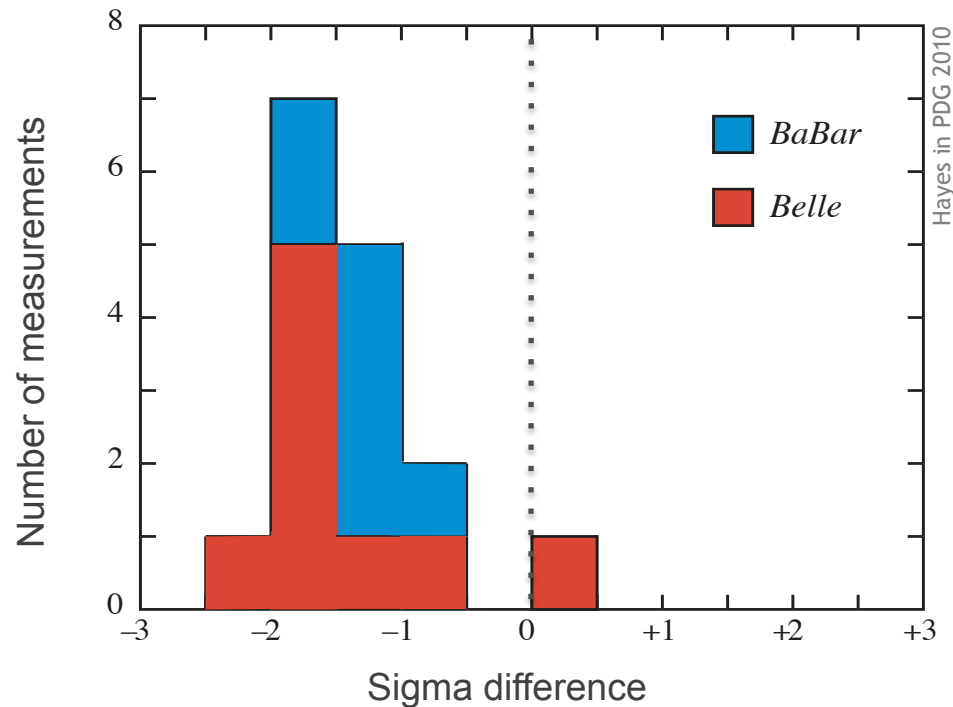
Limit reveals that $|d_\mu|$ contribution to a_μ must be smaller than $0.5 (+0.51 / -0.33) \times 10^{-11}$

Fermilab E989 / J-PARC g-2/EDM expect to improve sensitivity to $O(10^{-21})$

J-PARC g-2/EDM experiment can run in magic- γ ($p_\mu(B, E) \sim 125 \text{ MeV}$) *and* $E=0$ modes

Tau Branching Fractions

Large amount of new branching fraction measurement by BABAR and Belle.
Significant improvement in modes with kaons (but also a few inconsistencies)

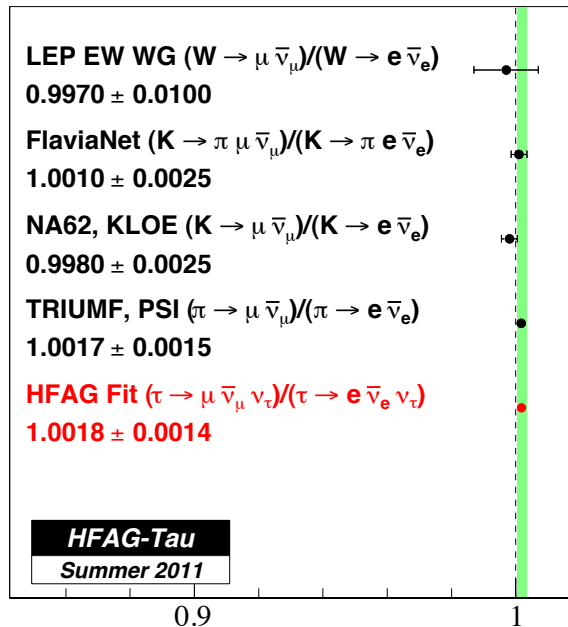


General trend observed between earlier and BABAR/Belle measurements
→ not understood; leads, a.o., to smaller strange hadronic width of tau

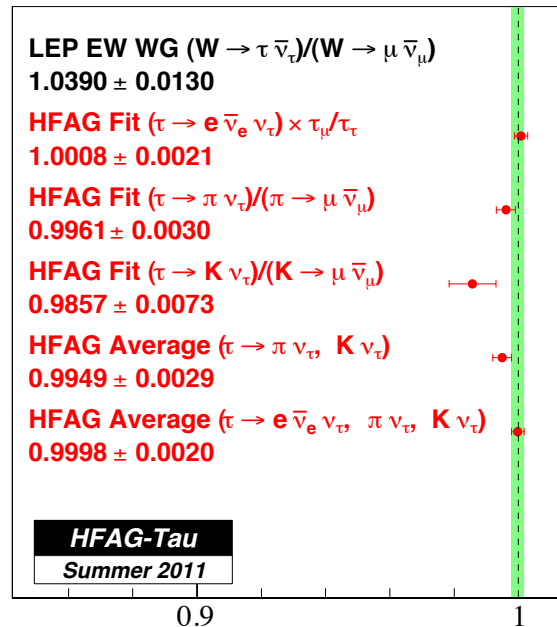
Tau Leptonic Charged Current Couplings

Probe new physics by testing the **universality** of charged weak couplings using tau branching fractions into leptons and tau lifetime

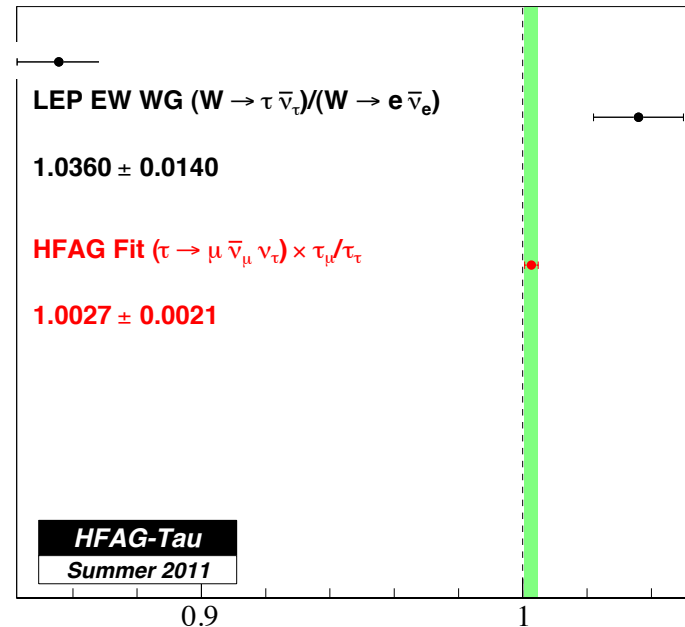
$$|g_\mu/g_e|$$



$$|g_\tau/g_\mu|$$

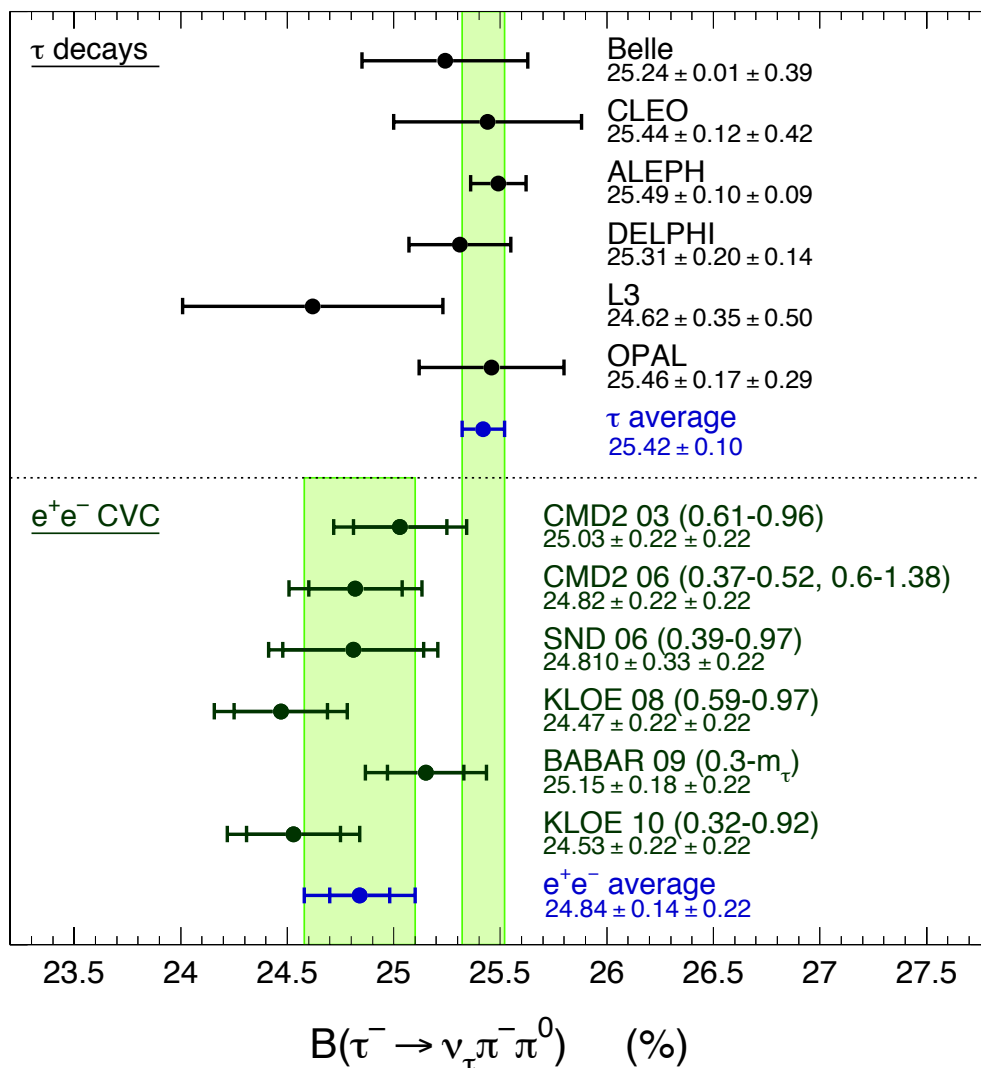


$$|g_\tau/g_e|$$



Down to 0.14% test of $e-\mu$ universality, compared to $\sim 0.28\%$ from $\Gamma_{Z \rightarrow ee/\mu\mu}$, and 0.13% for the effective weak axial coupling $g_{A,e/\mu}$

Predict Tau Branching Ratios from e^+e^- Data (CVC)



$$BR_{\tau^- \rightarrow \pi^- \pi^0 \nu_\tau}^{\text{CVC}} \propto \int_0^{m_\tau^2} ds \text{ kin}(s) \cdot \sigma_{e^+e^- \rightarrow \pi^+ \pi^-}^{\text{IB-corrected}}(s)$$

IB corrections of $+0.69 \pm 0.22$ applied for $\pi^+ \pi^0$

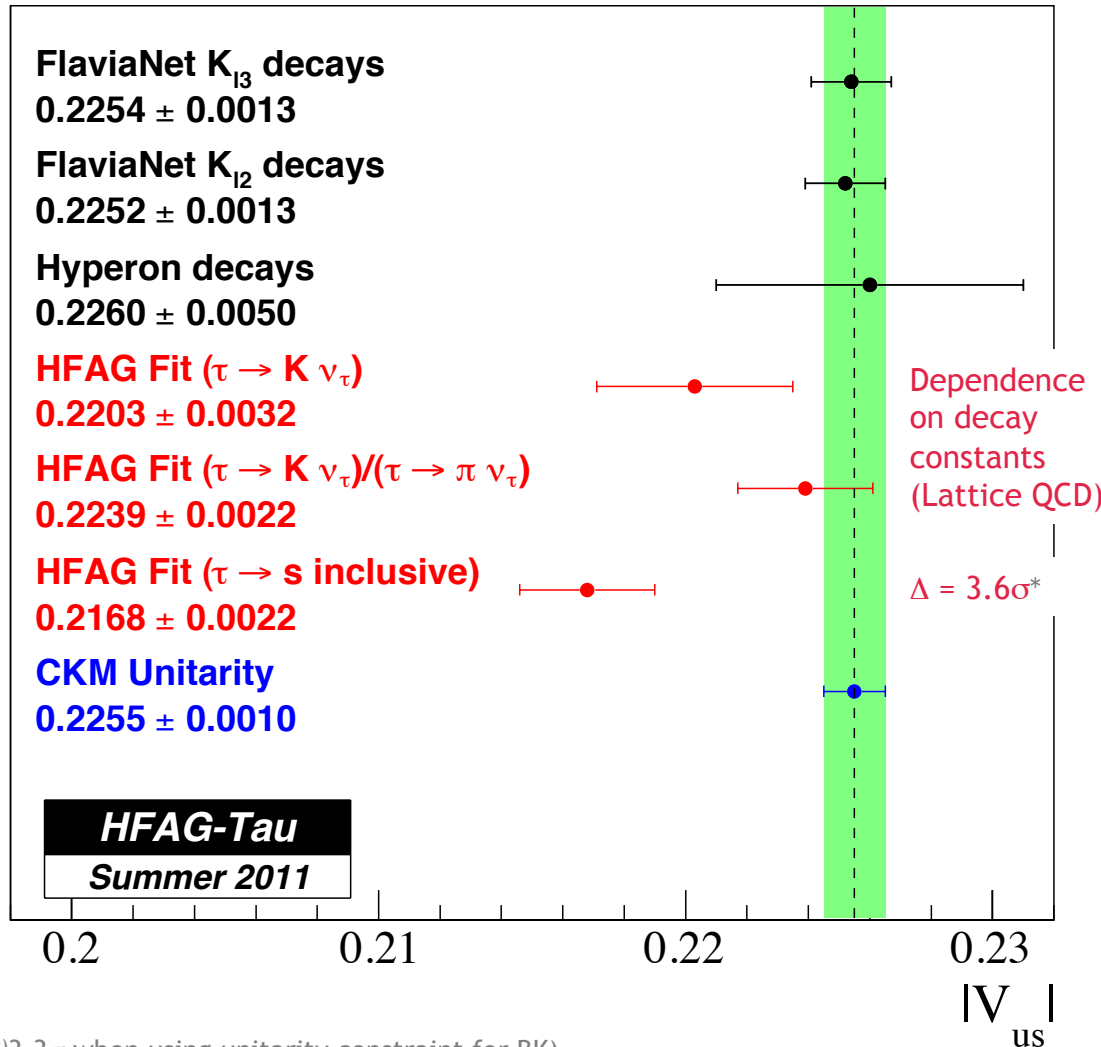
Difference: $BR[\tau^-] - BR[e^+e^- \text{ (CVC)}]$:

Mode	$\Delta(\tau - e^+e^-)$	“Sigma“
$\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$	$+0.58 \pm 0.28$	2.1
$\tau^- \rightarrow \pi^- 3\pi^0 \nu_\tau$	-0.03 ± 0.09	0.3
$\tau^- \rightarrow 2\pi^- \pi^+ \pi^0 \nu_\tau$	$+0.69 \pm 0.22$	3.2

CVC predictions of $\pi^+ \pi^0$ much improved with BABAR data and reevaluated IB corrections (4.5σ previously) !

Davier et al, arXiv:0906.5443 (2009)

$|V_{us}|$ Determination from Strange Tau Decays



Inclusive analysis uses:

$$|V_{us}|^2 = \frac{R_{\tau,S}}{\frac{R_{\tau,V+A}}{|V_{ud}|^2} - \delta R_\tau^{\text{Theory}}(\alpha_s, m_s)}$$

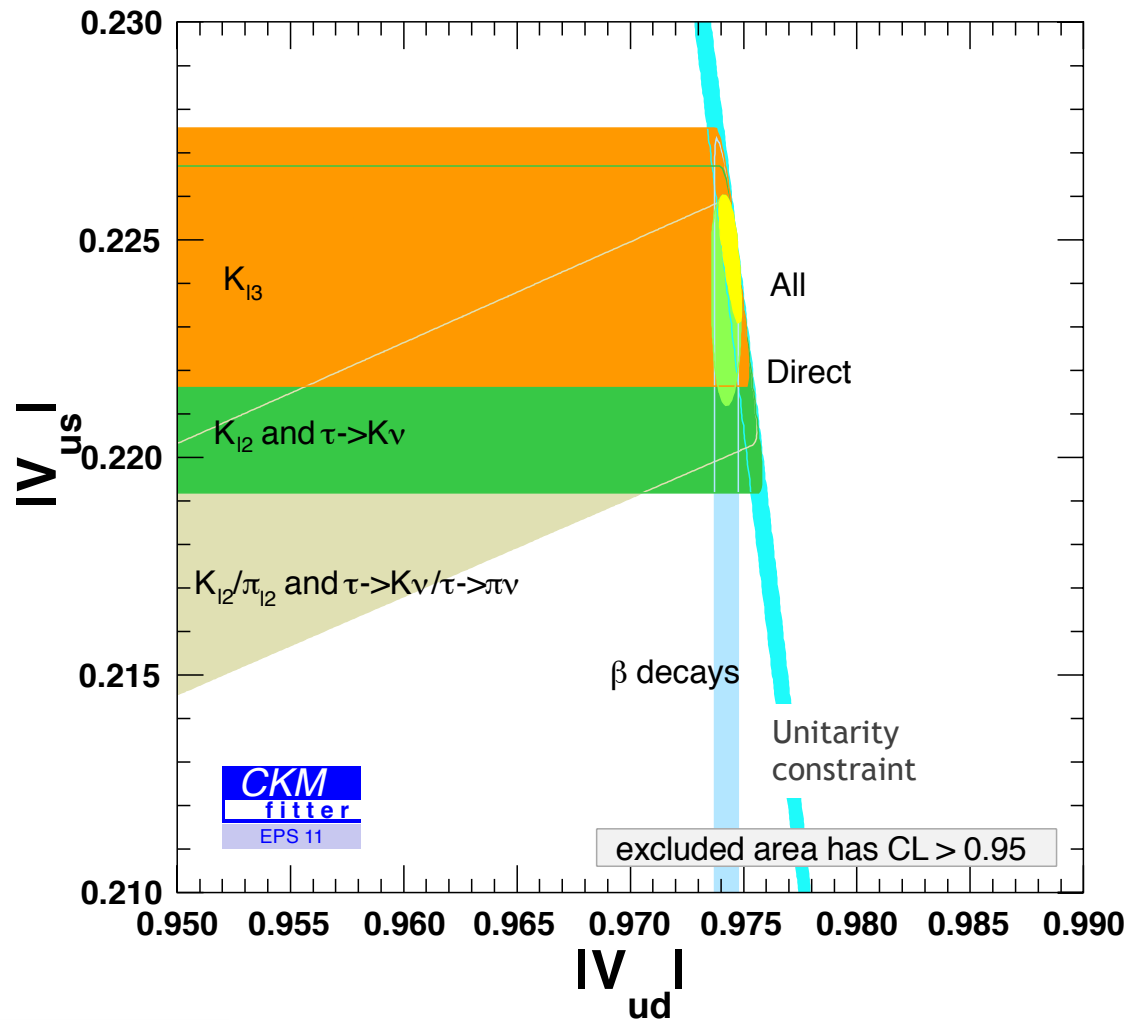
Dependence on $|V_{ud}|$, and theoretical dependence on α_s and m_s (problematic behaviour of perturbative series)

May miss yet unmeasured modes, compatibility can be tested with full strange spectral function

Trend of smaller branching ratios from B -factories. Without B -factory data, $|V_{us}|$ would increase to ~ 0.2213 .

Almost competitive accuracy with lepton K decays $\rightarrow$ unexpected in earlier days !

$|V_{us}|$ Determination from Strange Tau Decays

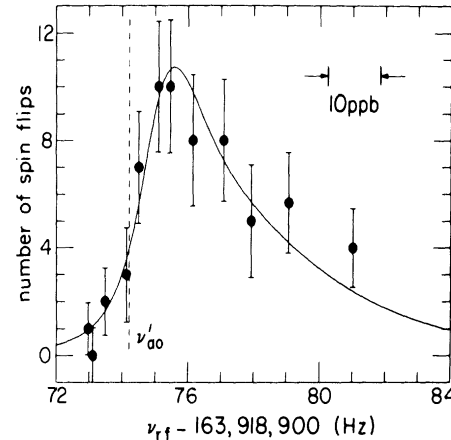


First row of CKM matrix shows good agreement with unitarity

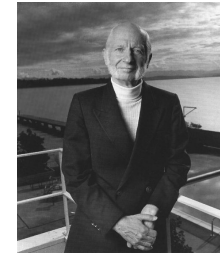
The Electron Anomalous Magnetic Moment

Schwinger's (et al.) prediction agreed (and still agrees) beautifully with experiment:

For the electron a_e , a series of Nobel price winning experiments was performed, using e^-/e^+ capture in a Penning trap



Electron spin resonance near 141 GHz versus the frequency of an exciting radiofrequency field.



Dehmelt, capturing single positrons for months

$$a_e^{\text{exp}} = 0.0011596521882(30)$$

Dyck-Schwinberg-Dehmelt
PRL 59, 26–29 (1987)

$$a_e^{\text{SM}} = \frac{\alpha}{2\pi} - 0.328478444 \left(\frac{\alpha}{\pi} \right)^2 + 1.181234 \left(\frac{\alpha}{\pi} \right)^3 - 1.7502 \left(\frac{\alpha}{\pi} \right)^4 + \underbrace{1.7 \times 10^{-12}}_{\text{hadronic \& EW effects}}$$

Kinoshita-Nio,
PRD 70, 113001 (2004)

Most precise determination of α to date: $\alpha^{-1} = 137.03599877(40)$ (quantum Hall:
137.03600300(270))

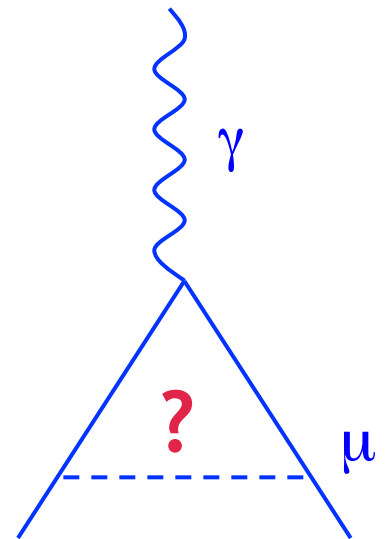
Probing New Physics

The experimental precision for a_μ will be worse than for a_e , so why do it ?

- In lowest order, where mass effects appear, contributions from heavy virtual particles scale as $m_{e/\mu}^2$:

$$a_\ell^{\text{NP}}(\Lambda_{\text{NP}}) \propto \mathcal{O}\left(\frac{m_\ell^2}{\Lambda_{\text{NP}}^2}\right) \quad \Rightarrow \quad \frac{a_\mu^{\text{NP}}}{a_e^{\text{NP}}} \propto \mathcal{O}\left(\frac{m_\mu^2}{m_e^2}\right) \approx 43,000$$

- Loose about a factor of 800 in experimental precision



$\Rightarrow a_\mu$ should be roughly 50 times more sensitive to NP than a_e !

a_τ even more sensitive, but insufficient experimental accuracy

The Muon $g - 2$ in the Standard Model

QED contribution

Computed up to 4th order
(5th order estimated)

$$a_{\mu}^{\text{QED}} \approx 11,658,471.809(0.015) \times 10^{-10}$$

Using α from latest α_e
[Gabrielse et al. PRL 97, 030802, 2006]

$$= (11,614,097.3 + 41,321.8 + 3,014.2 + 38.1 + 0.4) \times 10^{-10}$$

1st order known since 1948
[J. Schwinger, PR73(48)416]

Up to 3rd order
known analytically

4th order known numerically
[T. Kinoshita et al, 1980's]

5th order estimated recently, T. Kinoshita
& M. Nio, PRD 73, 053007, 2006

The Muon $g - 2$ in the Standard Model

Electroweak contribution a_μ^{weak} suppressed by $\frac{\alpha}{\pi} \frac{m_\mu^2}{m_W^2} \sim 10^{-9}$ (!)
 Computed to 2nd order

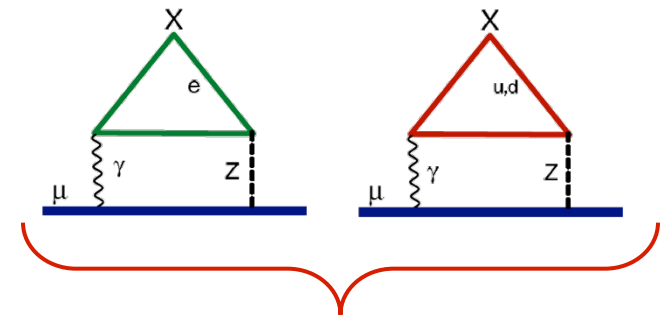
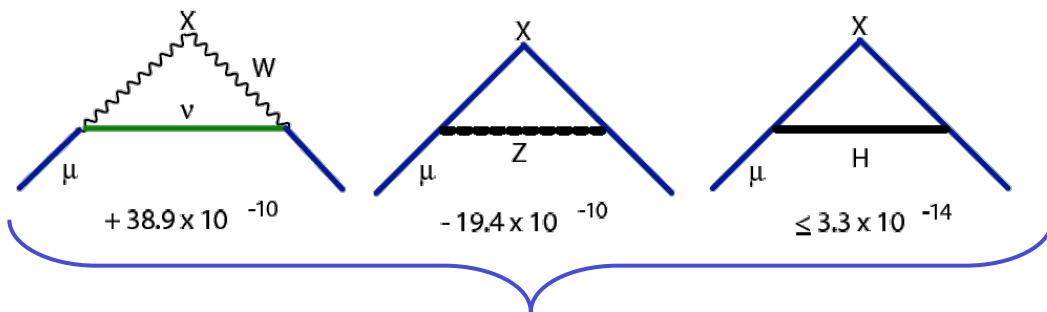
$$a_\mu^{\text{weak}} = \frac{G_\mu m_\mu^2}{8\sqrt{2}\pi^2} \left(\frac{5}{3} + \frac{1}{3} (1 - 4\sin^2 \theta_W) + \mathcal{O}\left(\frac{m_\mu^2}{m_W^2}\right) + \mathcal{O}\left(\frac{m_\mu^2}{m_H^2}\right) \right) = +19.5 \times 10^{-10}$$

1-loop

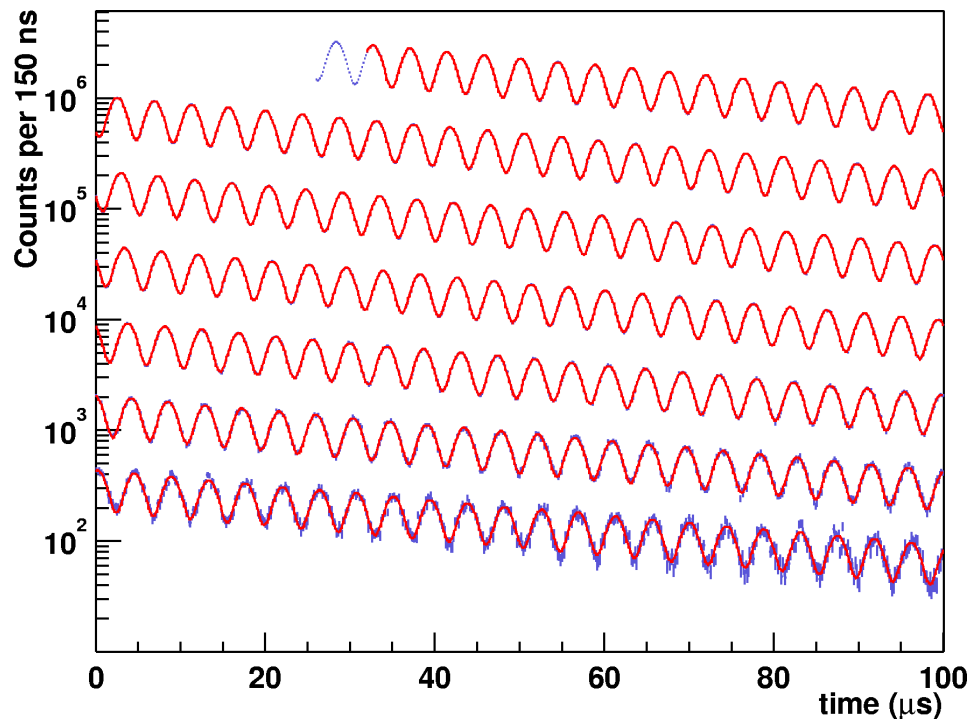
Czarnecki et al.,
 PRD 52, 2619 (1995)
 PRL 76, 3267 (1996)

2nd order contribution surprisingly large: $a_\mu^{\text{weak}} = -4.1(0.2) \times 10^{-10}$
 (due to large logs: $\ln[m_Z / m_\mu]$)
 2-loop

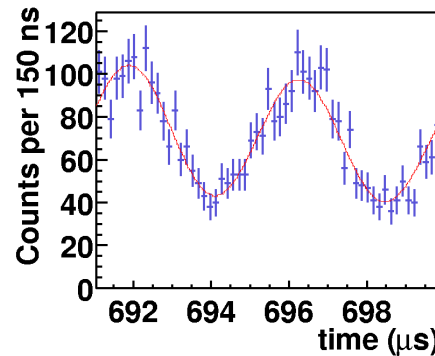
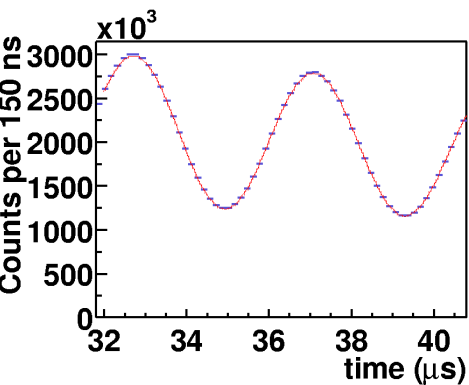
Note that between a_μ and a_e , the same sensitivity factor as for new physics applies here



The BNL Muon $g - 2$ Experiment



Observed positron rate in successive 100 μ s periods



Difference between spin precession and cyclotron frequency:

$$\vec{\omega}_a = \frac{e}{m_\mu c} \vec{a}_\mu \vec{B}$$

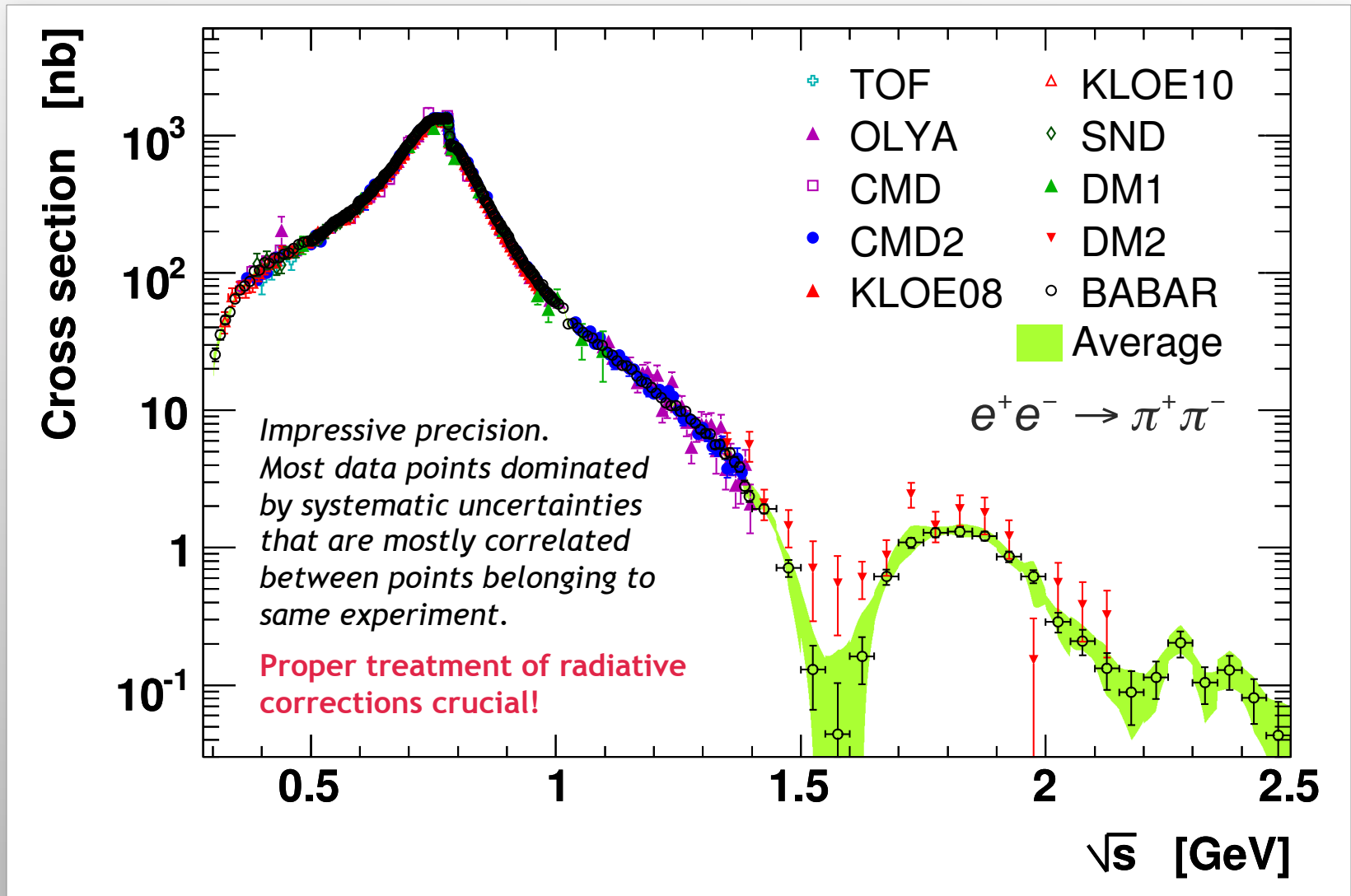
obtained from fit to:

$$N(t) = N_0 e^{-t/\gamma\tau} [1 + A \sin(\omega_a t + \phi)]$$

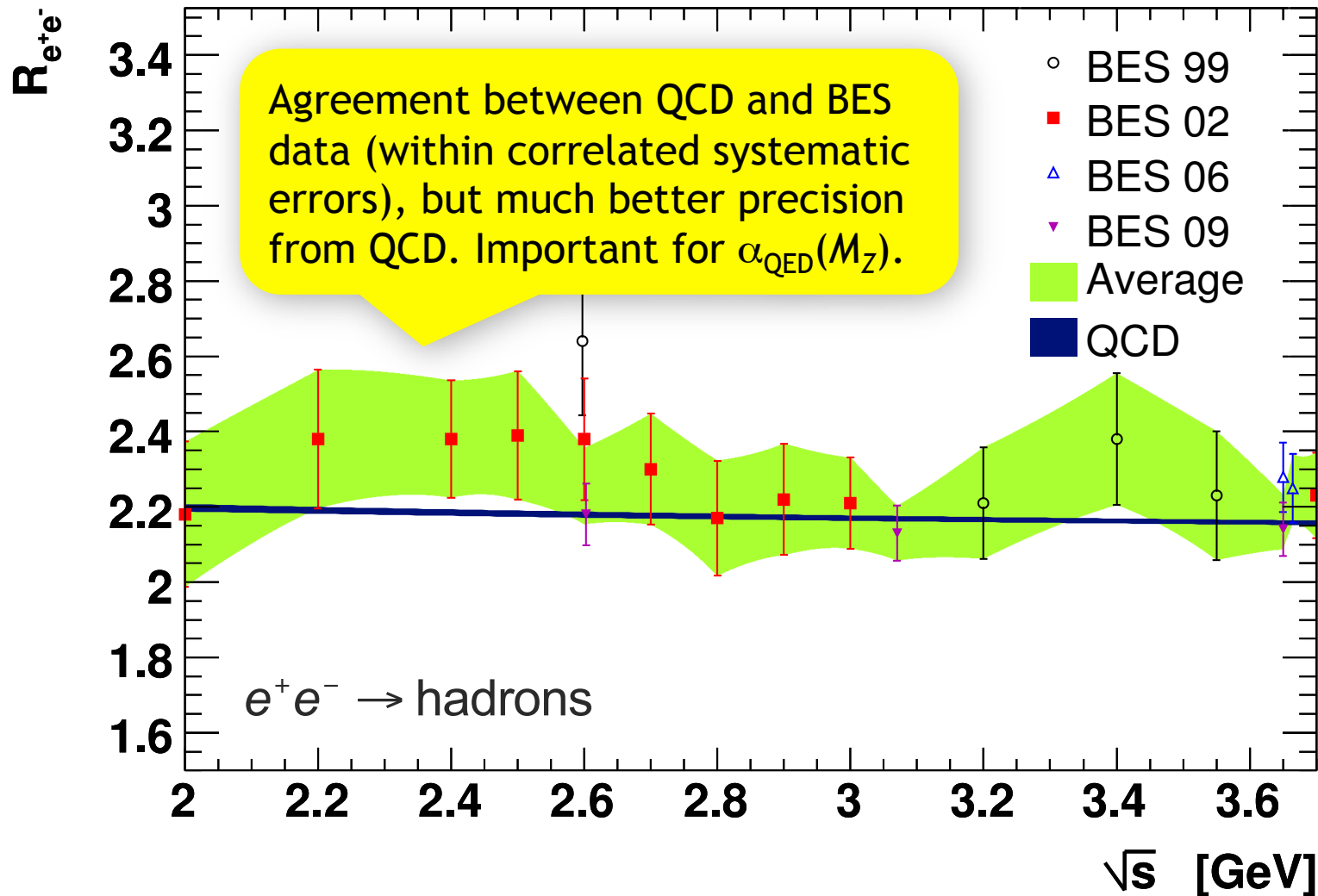
B -field from precise NMR probe

Plot taken from: E821 ($g - 2$), hep-ex/0202024

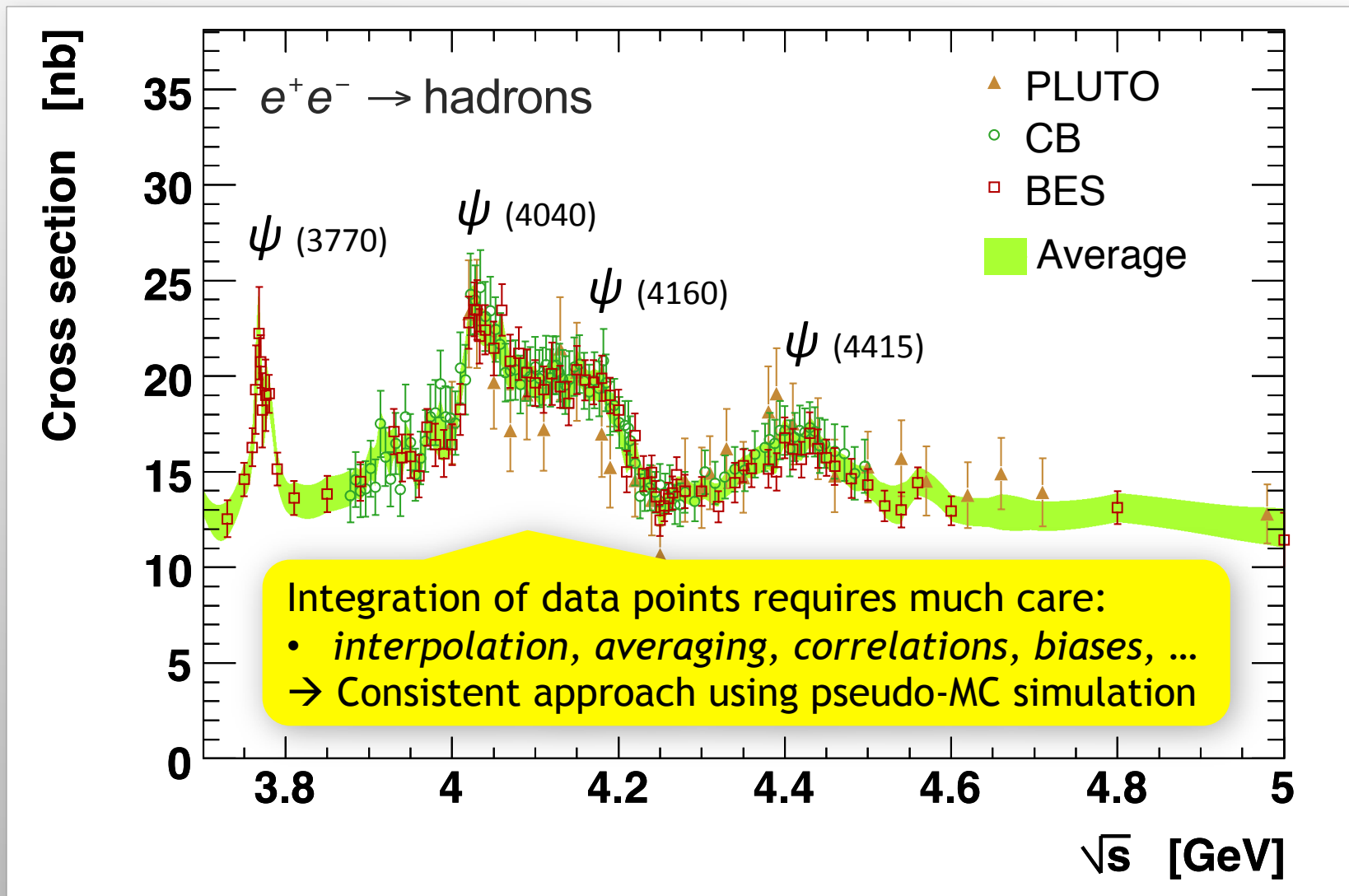
$e^+e^- \rightarrow \pi^+\pi^-$ Cross Section – *Compilation*



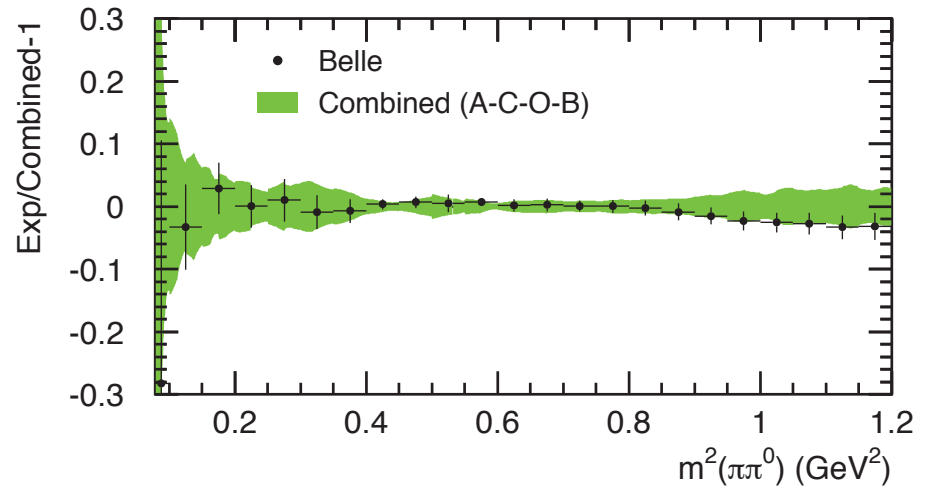
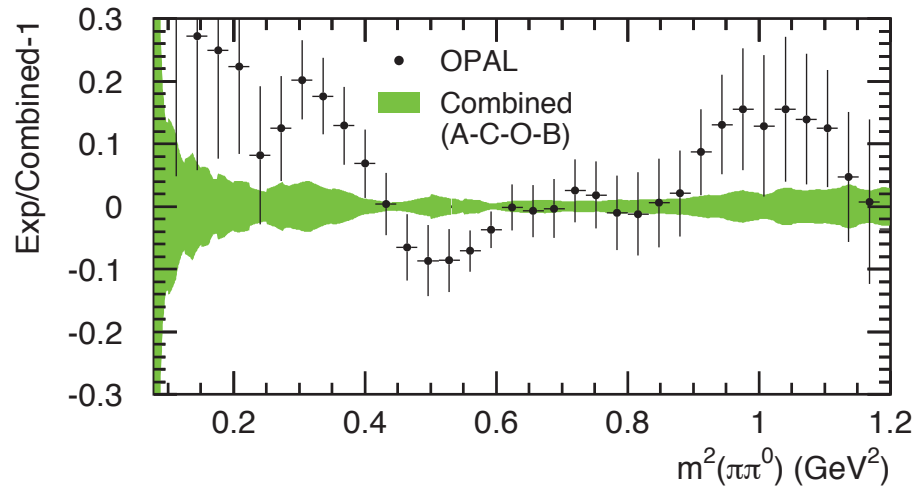
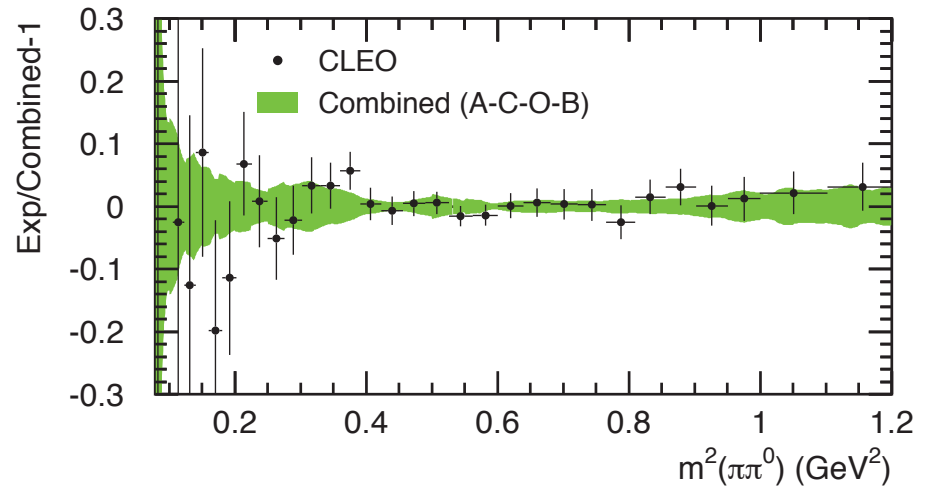
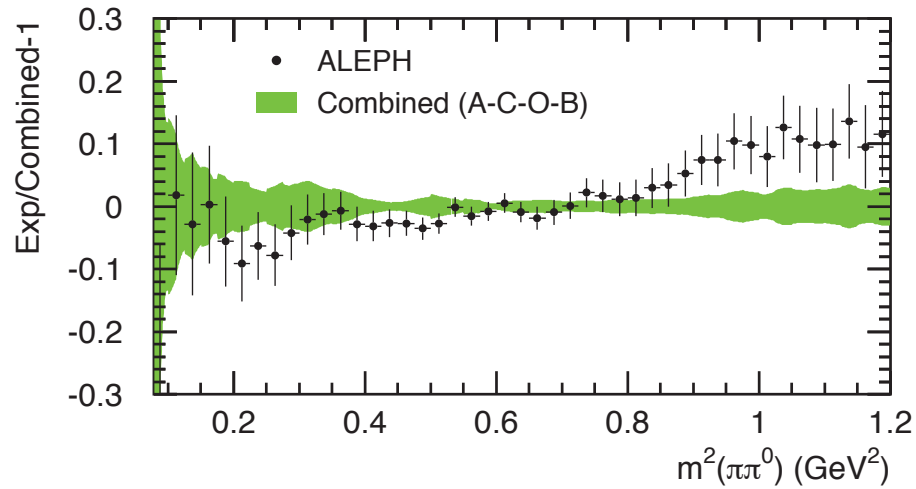
Inclusive Cross Section below $D\bar{D}$ Opening



Inclusive Cross Section above $D\bar{D}$ Opening



Situation of Two-Pion Channel (τ)



Can use precise **tau** data to improve a_μ prediction

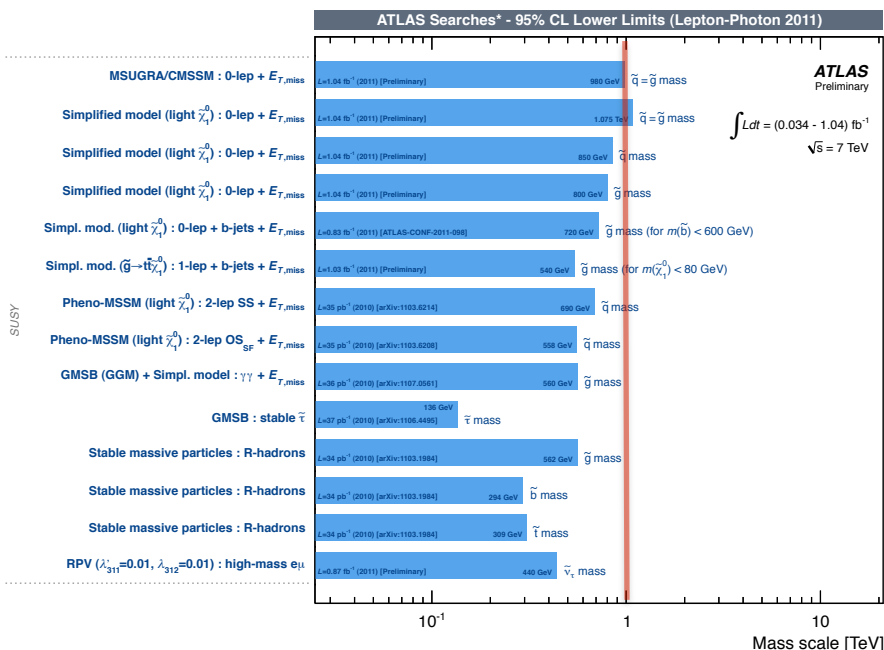
- In practice, used for 2π and 4π channels with isospin rotation
- Tau spectral functions measured by ALEPH, Belle, CLEO, OPAL
- Excellent precision of tau data. Branching ratio (ie, spectral function normalisation) for $\tau \rightarrow \pi\pi^0\nu$ known to 0.4%.
- Invariant mass spectrum requires unfolding using detector simulation, which is however under good control
- Main experimental challenge: abundance and shape modeling of feed-through from other tau final states
- Main theoretical challenge: **isospin breaking**
Radiative corrections, charged vs. neutral mass splitting and electromagnetic decays: $(-3.2 \pm 0.4)\%$ correction to a_μ^{had}

What could a $\Delta a_\mu \approx 30 \times 10^{-10}$ Deviation Tell Us?

Amount of discrepancy in ballpark of SUSY with mass scale of several 100 GeV

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

But strong m_{SUSY} limits from LHC require large $\tan \beta$



Alternative recent scenario involves “dark photons”

→ Light vector boson from dark matter sector coupling to SM through mixing with photon

Coupling to charged particles with strength $\epsilon \cdot e$

$$\Delta a_\mu^{\text{dark } \gamma} \approx \frac{\alpha}{2\pi} \epsilon^2 \cdot F \left(\frac{m_{\text{dark } \gamma}}{m_\mu} \right)$$

which, for $\epsilon \approx 0.001$ – 0.002 and $m_{\text{dark } \gamma} \approx 10$ – 100 MeV , can provide a solution for the discrepancy

Searches for the dark photon in that mass range are currently underway at Jefferson Lab, USA, and MAMI in Mainz, Germany

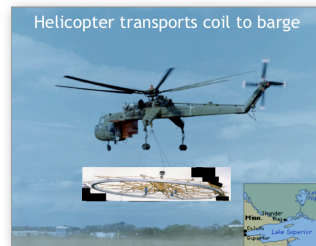
Pospelov, PRD 80, 095002 (2009)
Tucker-Smith and Yavin, PRD 83, 101702 (2011)

A Future for the Muon $g-2$

Unfortunately, the situation stays non-conclusive

But: current discrepancy still limited by experimental uncertainty

Proposal for new experiment E989 at FNAL with precision target of $1.6 \cdot 10^{-10}$

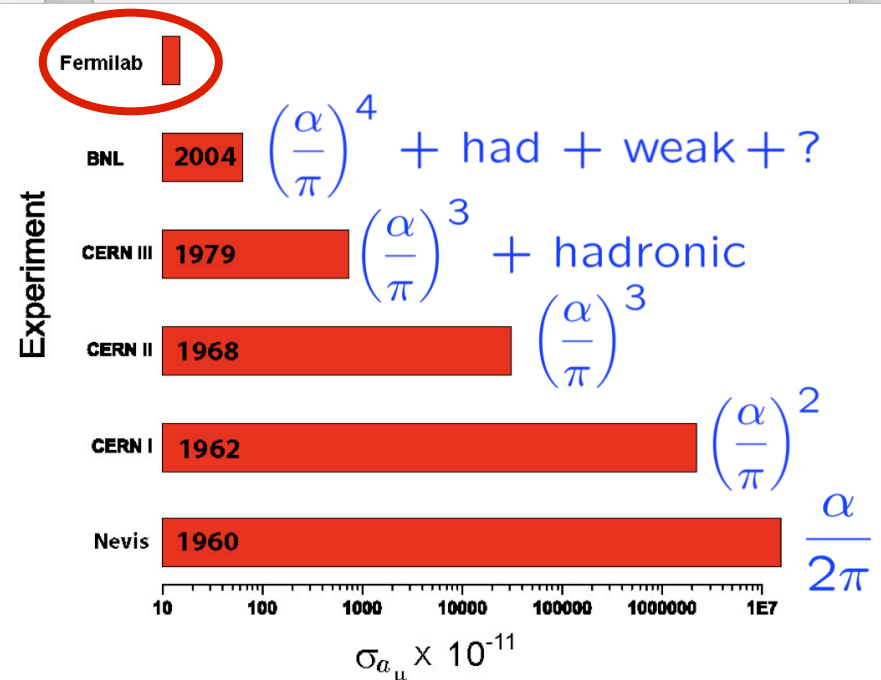


Alternative proposal of similar precision at J-PARC without magic γ and no E field, requiring ultra-slow muons generated from laser-ionised muonium atoms

Final E989 proposal:
http://gm2.fnal.gov/public_docs/proposals/Proposal-APR5-Final.pdf

LOI: KEK_J-PARC-PAC2009-06
 See also, e.g., Naohito SAITO (KEK), Seminar at DESY 2011

Fortunately, improvements are in view !



A Future for the Muon $g-2$

Final E989 proposal: http://gm2.fnal.gov/public_docs/proposals/Proposal-APR5-Final.pdf

Proposal for new experiment E989 at Fermilab with precision target of $1.6 \cdot 10^{-10}$ (factor ~ 20 increase in statistics)

Fermilab
E989
<http://gm2.fnal.gov>

- Relocate E821 (BNL) storage ring to Fermilab (12 T weight)
- Continue “magic-gamma” technique
- Interlink several proton rings at Fermilab
 - Higher proton rate, less protons per bunch than at BNL
 - 900 m pion decay line (BNL: 80 m) $\rightarrow$ less pion “flash” at muon ring injection
 - Zero-degree muons $\rightarrow$ 5–10 times larger muon yield per proton as BNL
 - 5–10 times as many muons stored per hour as BNL
- Improved detectors against signal pileup, new electronics, better shimming to reduce B -field variations, more improvements over BNL
 - $\rightarrow$ Expect ~ 2.5 (3) times reduced systematic error on B -field (ω_a)
- Can run parasitic to main injector experiments (e.g. NOVA)
- Experiment approved Jan 2011

A Future for the Muon $g-2$

Final E989 proposal: http://gm2.fnal.gov/public_docs/proposals/Proposal-APR5-Final.pdf

Proposal for new experiment E989 at Fermilab with precision target of $1.6 \cdot 10^{-10}$ (factor ~20 increase in statistics)

**Fermilab
E989**
<http://gm2.fnal.gov>

Helicopter transports coil to barge



Fermilab (12 T weight)

ilab

than at BNL

und at muon ring injection

muon yield per proton as BNL

r as BNL

leanup, new electronics, better

more improved

Projected E989 timeline as of Feb 2011

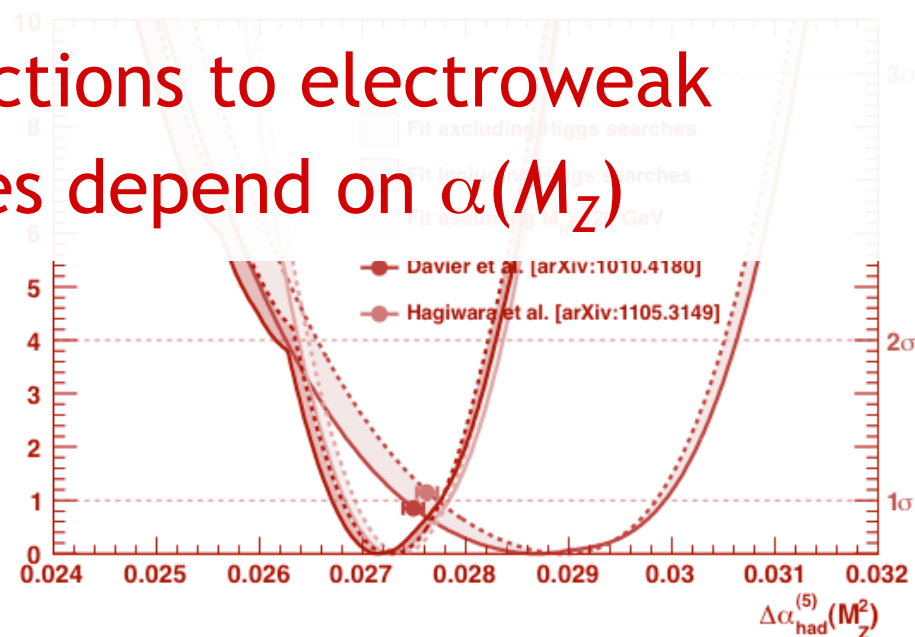
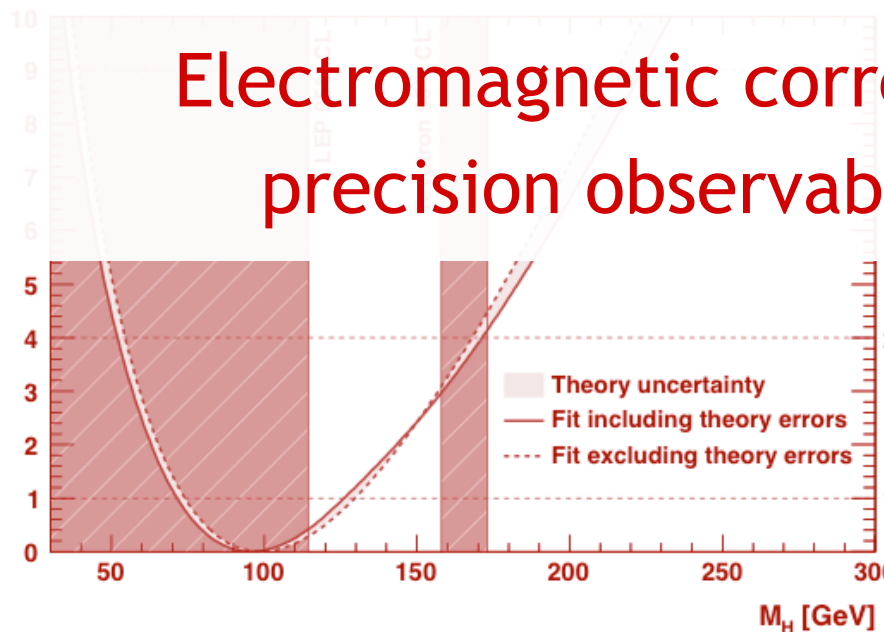
[L. Roberts at INT workshop, Seattle, 28 Feb 2011]

	2012												2013												2014												2015												
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D													
Engineer/construct building and tunnel																																																	
Disassemble and transport storage ring																																																	
Reassemble storage ring and cryogenics																																																	
Beamline and target modifications																																																	
Shim field, install detectors, commission																																																	



There is also the Running of α_{QED} !

Electromagnetic corrections to electroweak precision observables depend on $\alpha(M_Z)$



$$\alpha(s) = \frac{\alpha(0)}{1 - \Delta\alpha(s)} \quad \text{with: } \Delta\alpha(s) = \Delta\alpha_{\text{lep}}(s) + \Delta\alpha_{\text{had}}(s) = -4\pi\alpha \operatorname{Re} \left[\Pi_\gamma(s) - \Pi_\gamma(0) \right]$$



There is also the Running of α_{QED} !

Same principle as for $g-2$: energy-dependent vacuum polarisation effects screen the bare electromagnetic coupling. Leptonic contributions computed via QED, hadronic contributions obtained from dispersion relation, requiring precise data and QCD

*Due to -40% correlation between $\Delta\alpha_{\text{had}}(M_Z)$ and M_H in the global electroweak fit, the change in the central value increases M_H and reduces tension between fit and LEP bound.



There is also the Running of α_{QED} !

New evaluation of hadronic contribution:

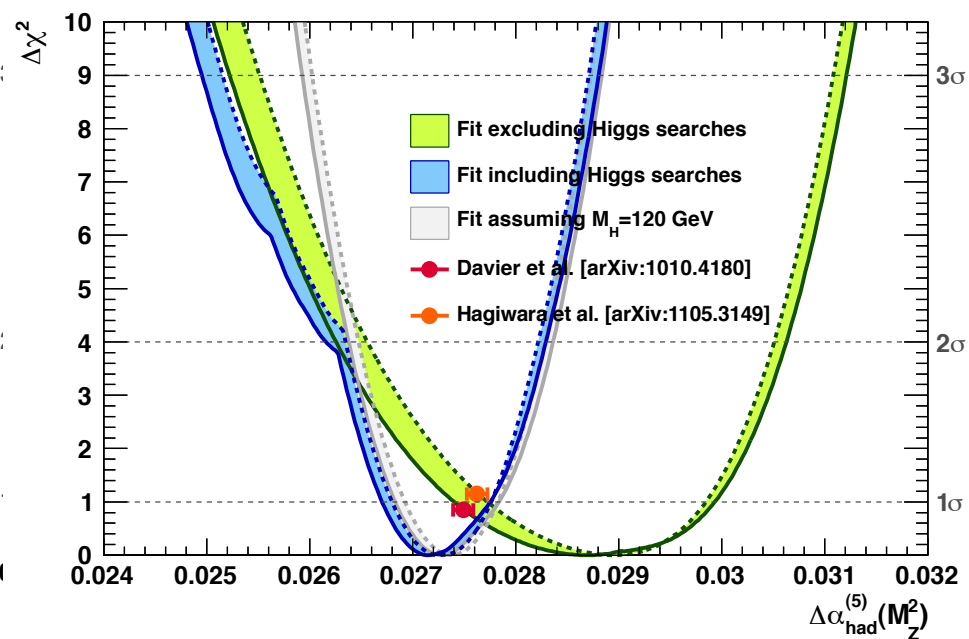
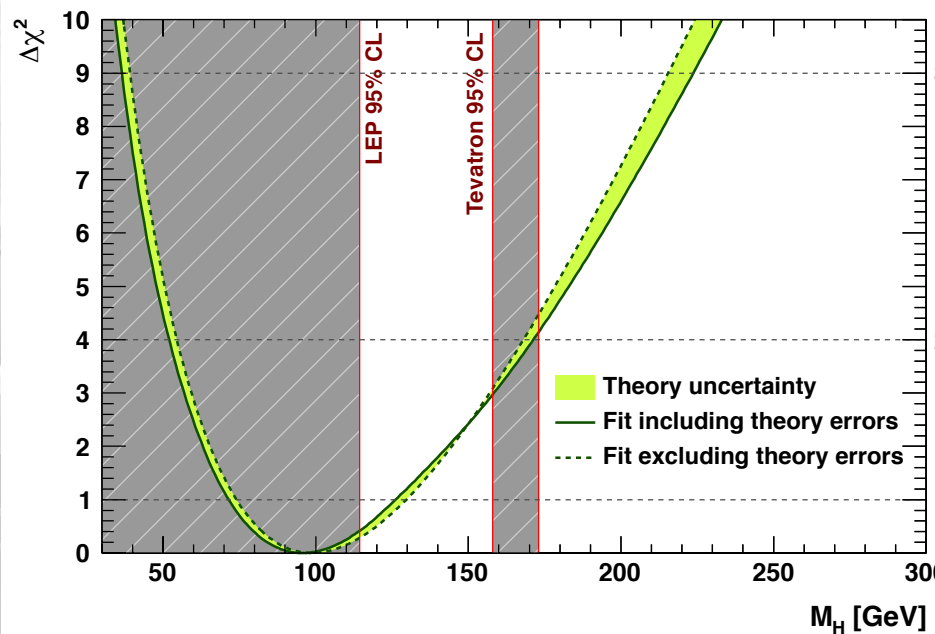
$$\Delta\alpha_{\text{had}}^{(5)}(M_Z) = 0.02749 \pm 0.00010$$

reduces EM coupling strength, thus increasing Higgs mass estimate from global electroweak fit by +12 GeV, which reduces tension with LEP bound*

*Due to -40% correlation between $\Delta\alpha_{\text{had}}(M_Z)$ and M_H in the global electroweak fit, the change in the central value increases M_H and reduces tension between fit and LEP bound.



There is also the Running of α_{QED} !



$$\begin{aligned}
 p_T(\mu) &= 18 \text{ GeV} \\
 p_T^{\text{vis}}(\tau_h) &= 26 \text{ GeV} \\
 m_{\text{vis}}(\mu, \tau_h) &= 47 \text{ GeV} \\
 m_T(\mu, E_T^{\text{miss}}) &= 8 \text{ GeV} \\
 E_T^{\text{miss}} &= 7 \text{ GeV}
 \end{aligned}$$



Run Number: 160613, Event Number: 9209492

Date: 2010-08-03 02:12:37 CEST

At LHC, τ 's are important probes for new physics

$Z \rightarrow \tau\tau$ Candidate in 7 TeV Collisions

