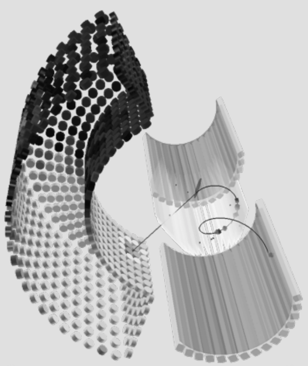
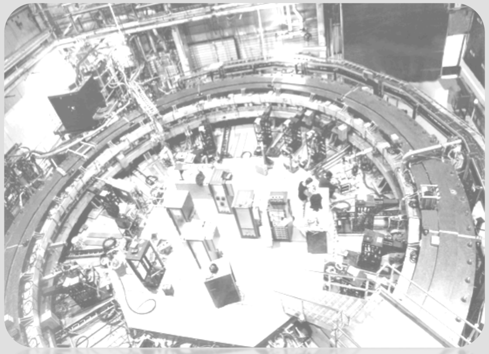
Charged-Lepton Flavour Physics

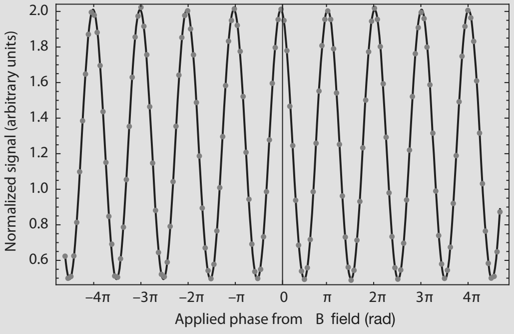
Andreas Hoecker (CERN)

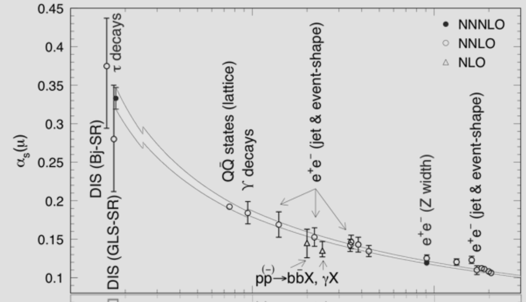
LAPP – Annecy, 2011

Lepton-Photon Symposium, Aug 22–27, 2011, Mumbai-India









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

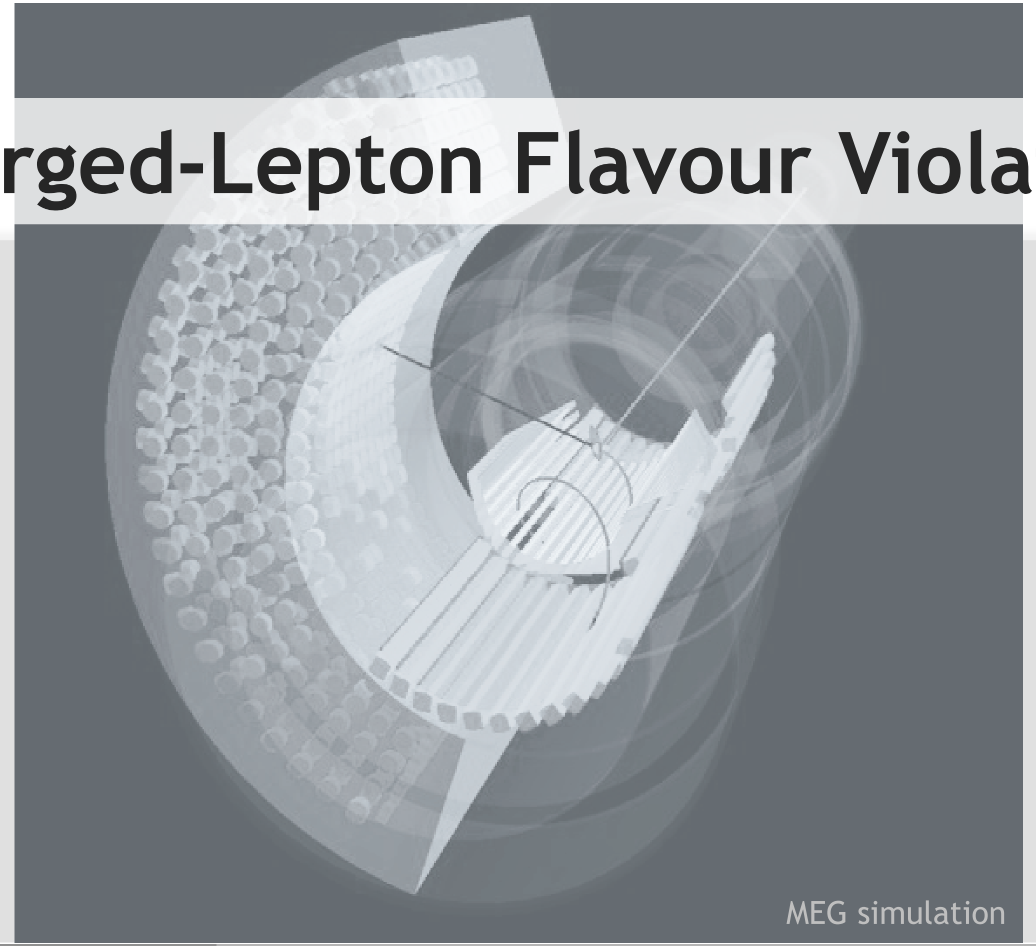
\+ Conclusions

E821 at BNL

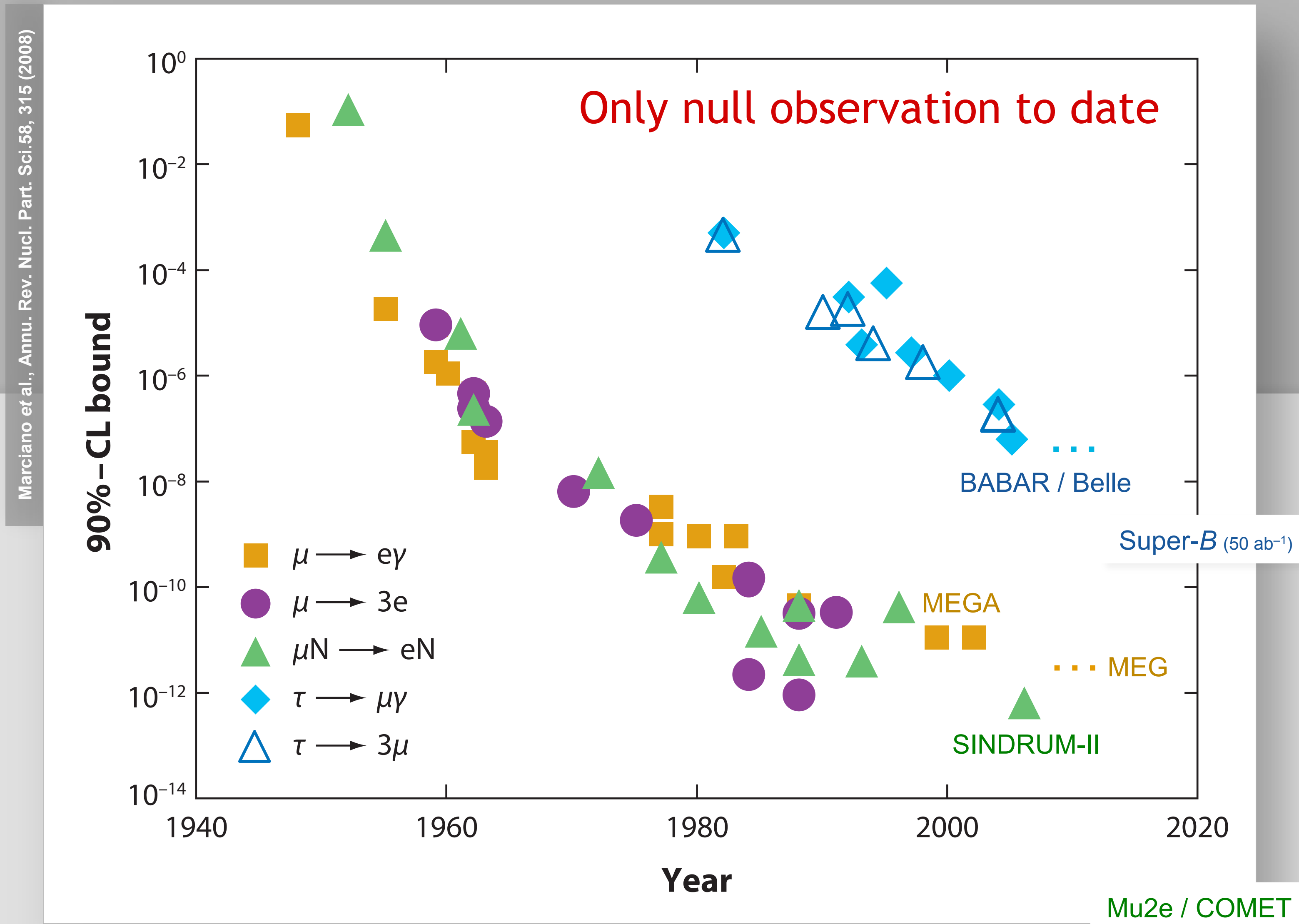
Absence of the decays $\mu \to e\gamma$ and $\tau \to \mu\gamma$ established, in the early days, that μ and τ were new elementary leptons, and not electron excitations

In analogy to the GIM mechanism, absence of $\mu \to e\gamma$ 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



Spectacular perspective !

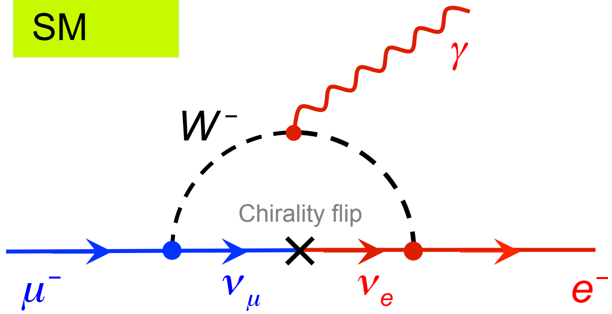
Mu-to-e Flavour Violation

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

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

Flavour Changing Neutral Current

SM



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

$$< 10^{-54}$$

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

Generic NP contribution

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

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

For generic new physics, parametrise:

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

Also: $\mathrm{BR_{NP}}(\mu \to eee) \sim \alpha_{\mathrm{QED}} \times \mathrm{BR_{NP}}(\mu \to e\gamma)$

→ Search for charged-LFV probes new physics without SM contamination !

Prior best limit on $\mu^+ \to e^+\gamma$ by MEGA experiment (LAMPF, 1999): $B < 1.2\times10^{-11}$

MEGA, PRL 83, 1521 (1999)

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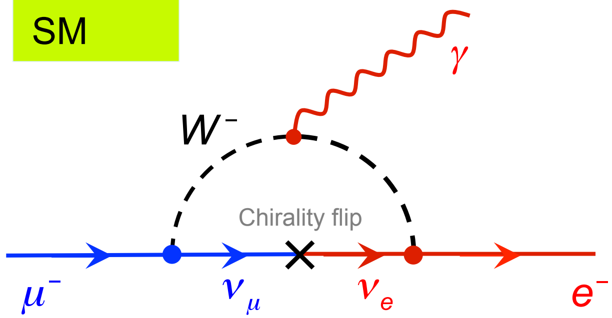

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$$< 10^{-54}$$

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

Generic NP contribution

Can vary significantly with chosen new physics amplitudes

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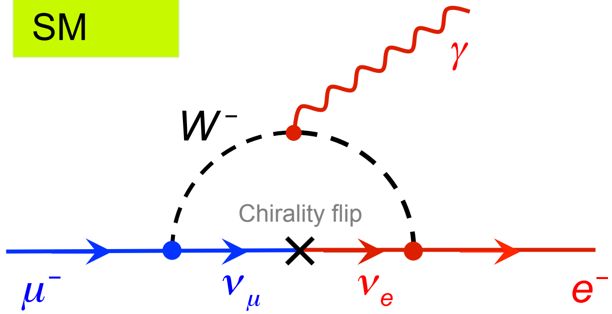
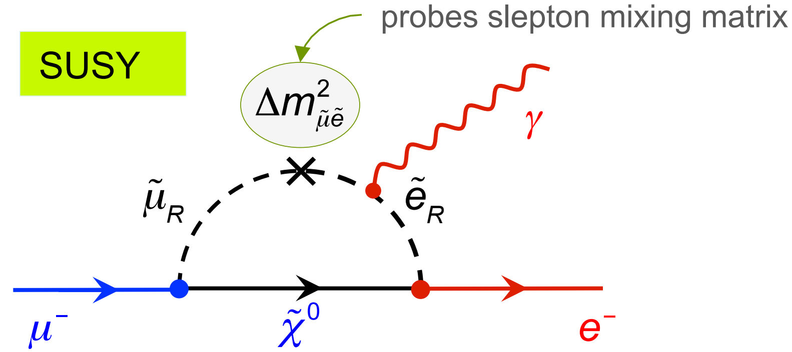


SUSY



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$< 10^{-54}$

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

$$\mathrm{BR}(\mu^- \to e^-\gamma)\Big|_{\mathrm{SUSY}} \sim 10^{-5}\left|\frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{\bar{m}^2_{\tilde{\ell}}}\right|^2 \left(\frac{100\ \mathrm{GeV}}{m_{\mathrm{SUSY}}}\right)^4 \tan^2\beta$$

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

→ Search for charged-LFV probes new physics without SM contamination !

Prior best limit on $\mu^+ \to e^+\gamma$ by MEGA experiment (LAMPF, 1999): $B < 1.2\times10^{-11}$

MEGA, PRL 83, 1521 (1999)

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

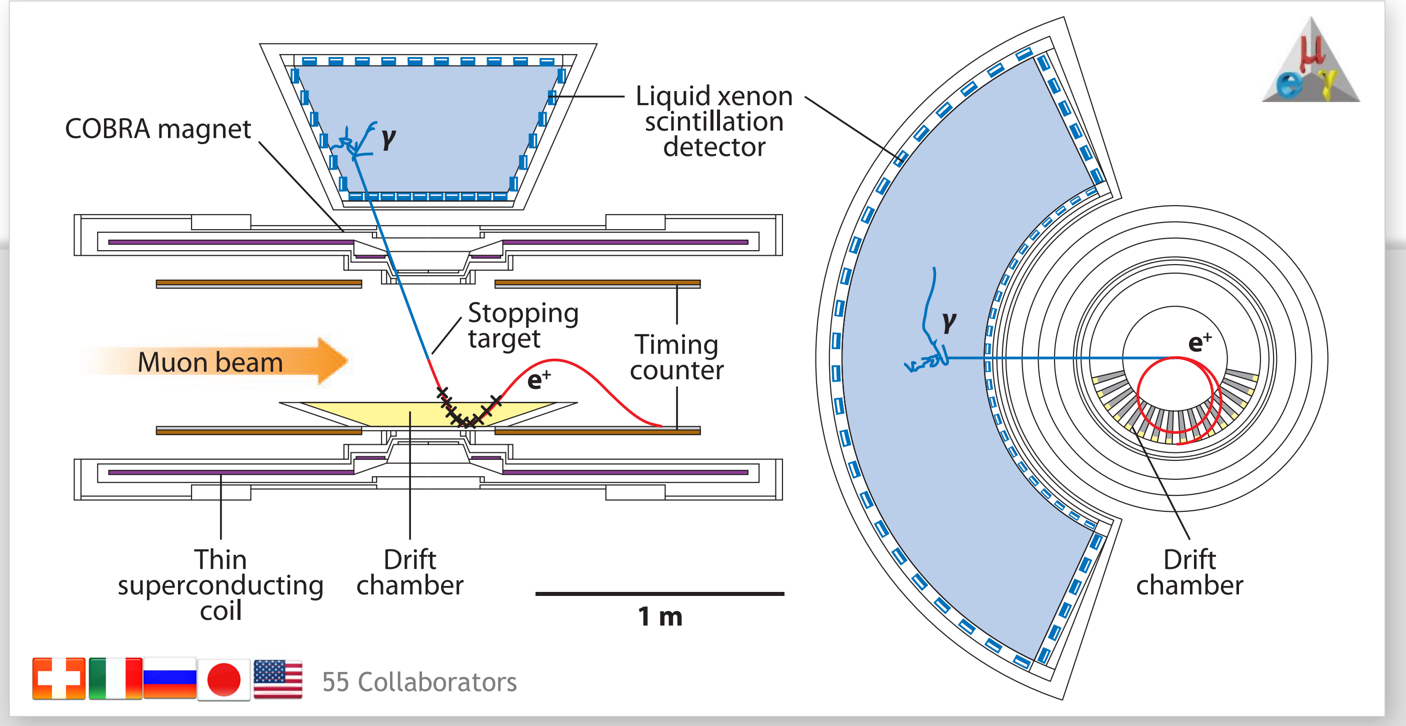
PSI πE5 produces 29 MeV surface μ^+ at $3{\times}10^7$ Hz rate hitting on thin stopping target

Signal reconstruction:

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

Background sources:

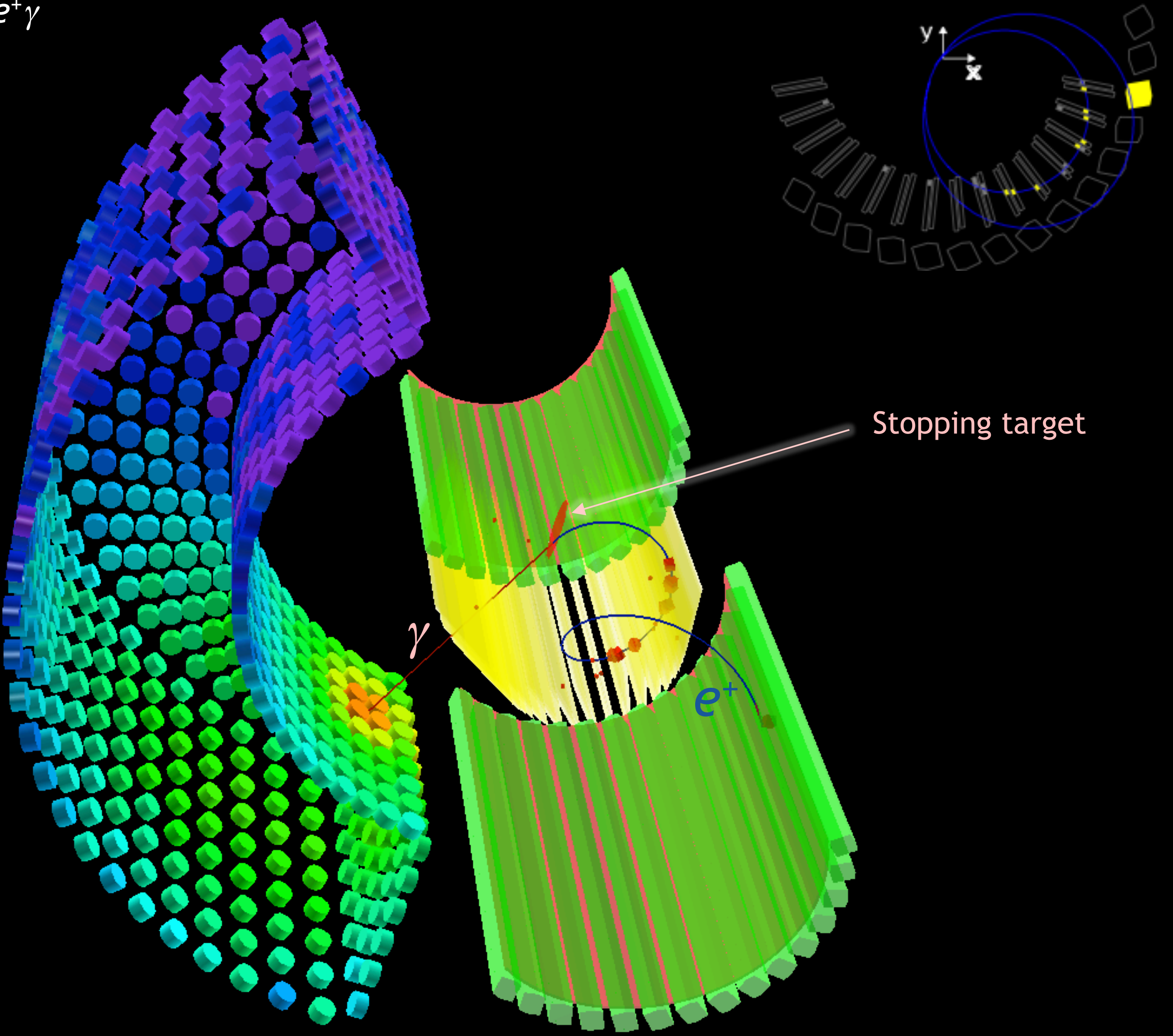
- Radiative $\mu^+ \to e^+\gamma\,\nu\nu$ (RMD)
- Accidental photon coincidence from RMD, bremsstrahlung, or e^+ annihilation in flight



Sketch of MEG experiment

10% solid angle coverage

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

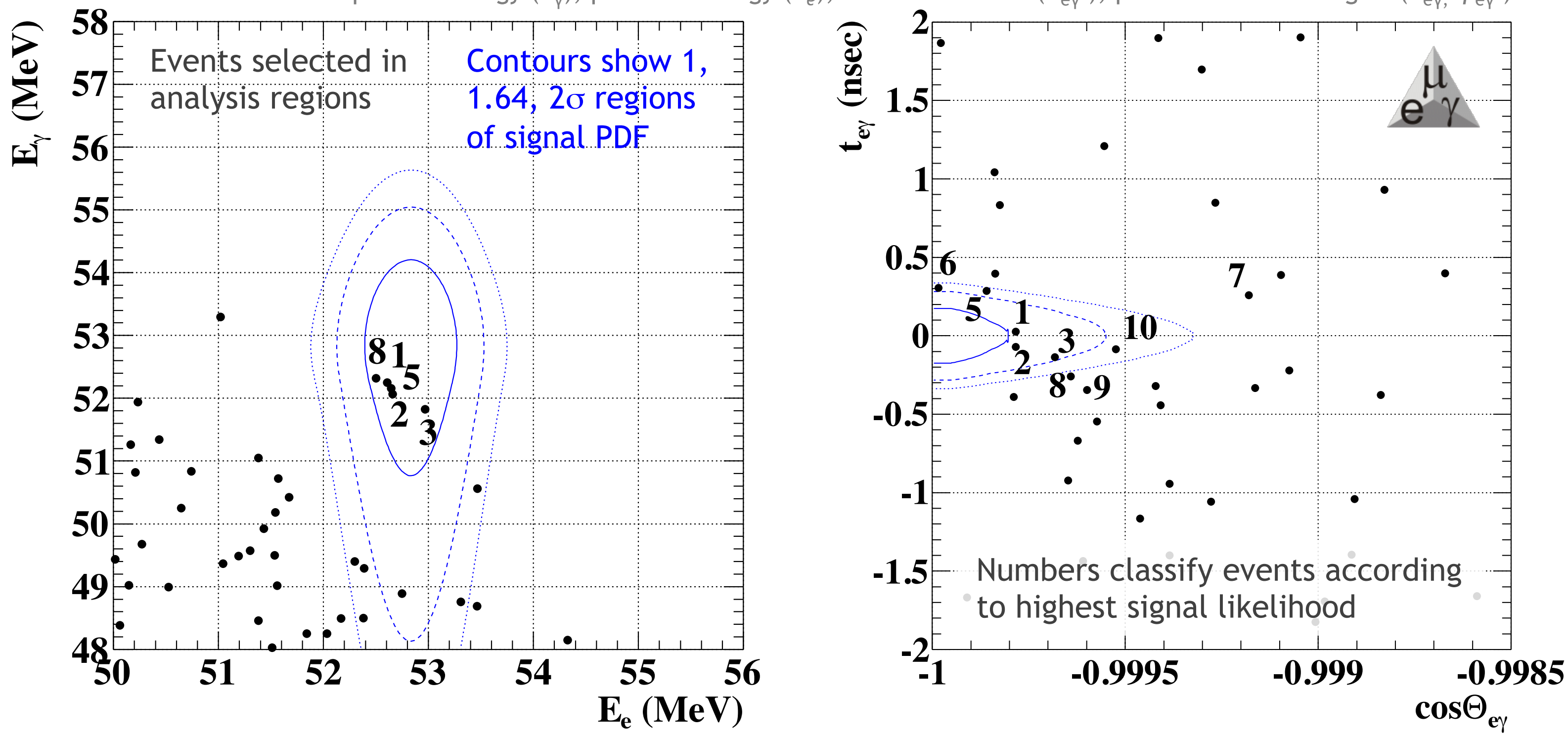


Situation after Preliminary Analysis of 2009 Data*

* two months stable data taking in 2009

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

Selection variables: photon energy (E_γ), positron energy (E_e), time difference ($T_{e\gamma}$), polar and zenith angles ($\theta_{e\gamma}$, $\varphi_{e\gamma}$)



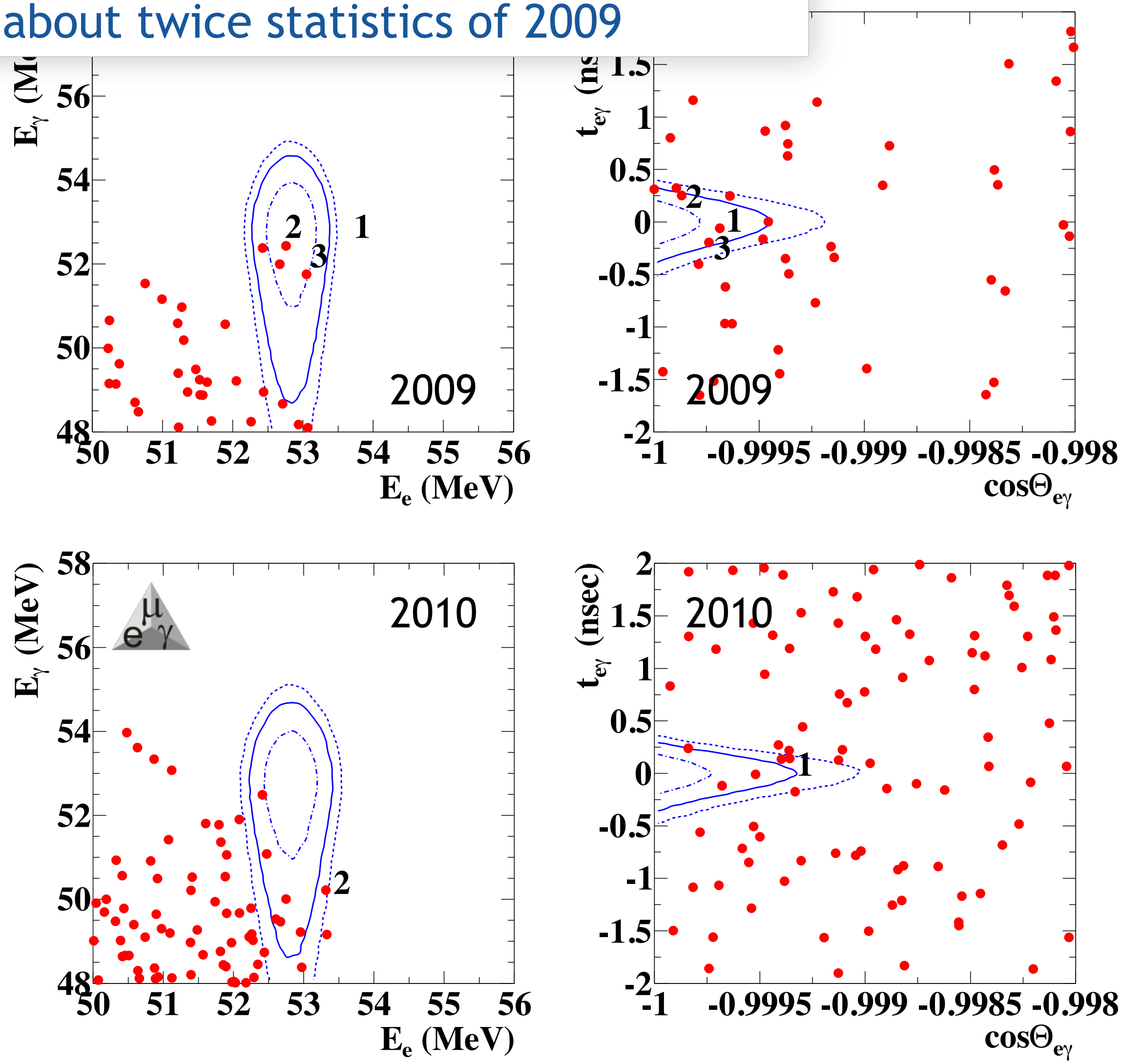
Unbinned maximum likelihood fit gave slight signal excess and 90% CL upper limit:

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

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

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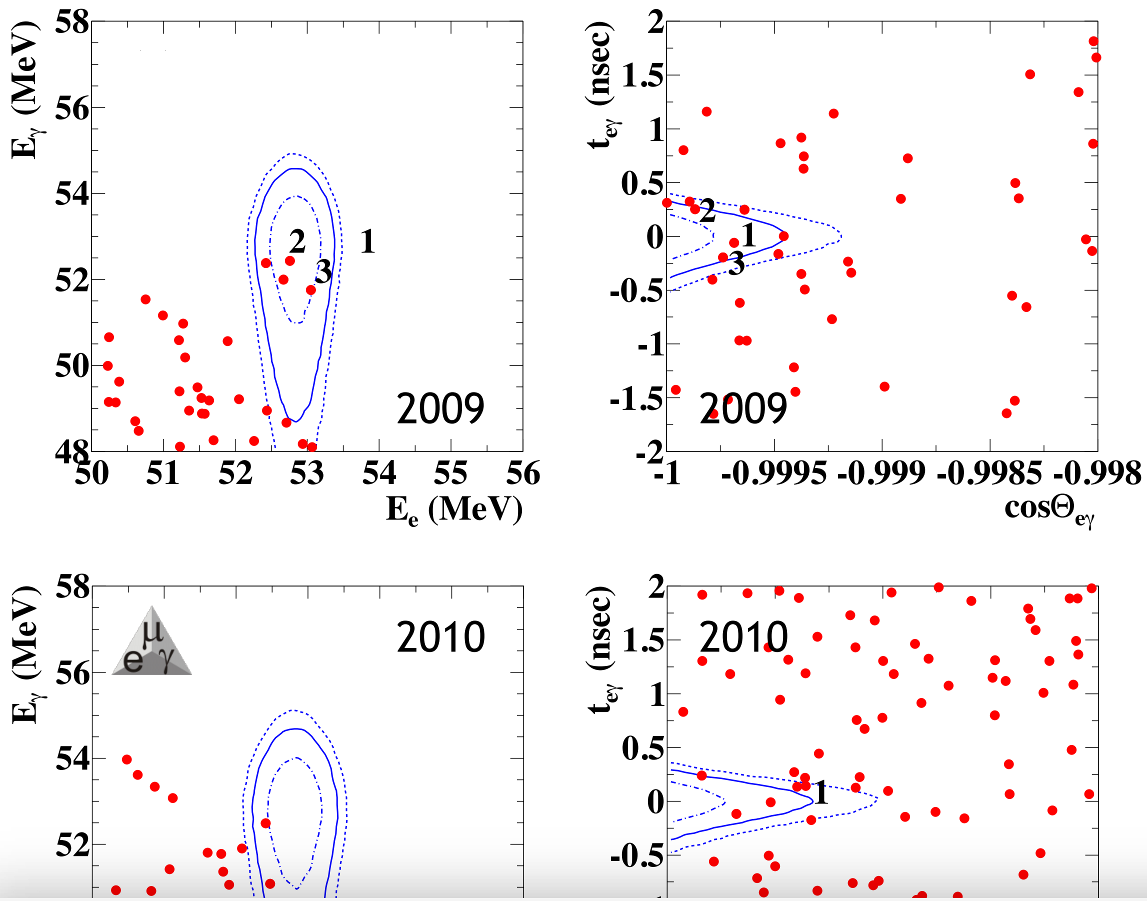


Excess in 2009 data confirmed by reanalysis

(Background-only p-value: 8%)

However, not reproduced in 2010 data

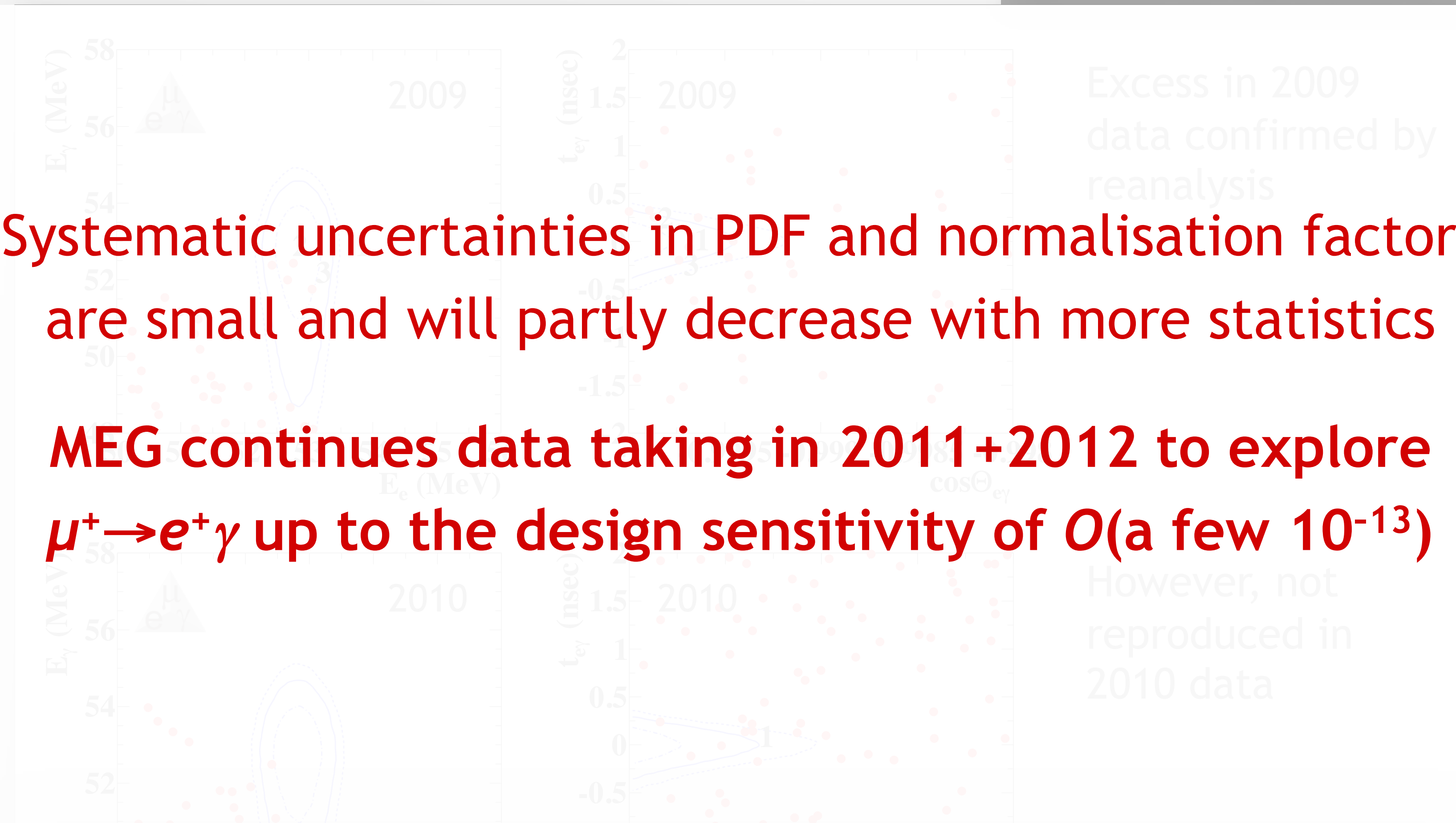
5 times better than previous limit !

90% CL (Feldman-Cousins) upper limit:

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

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

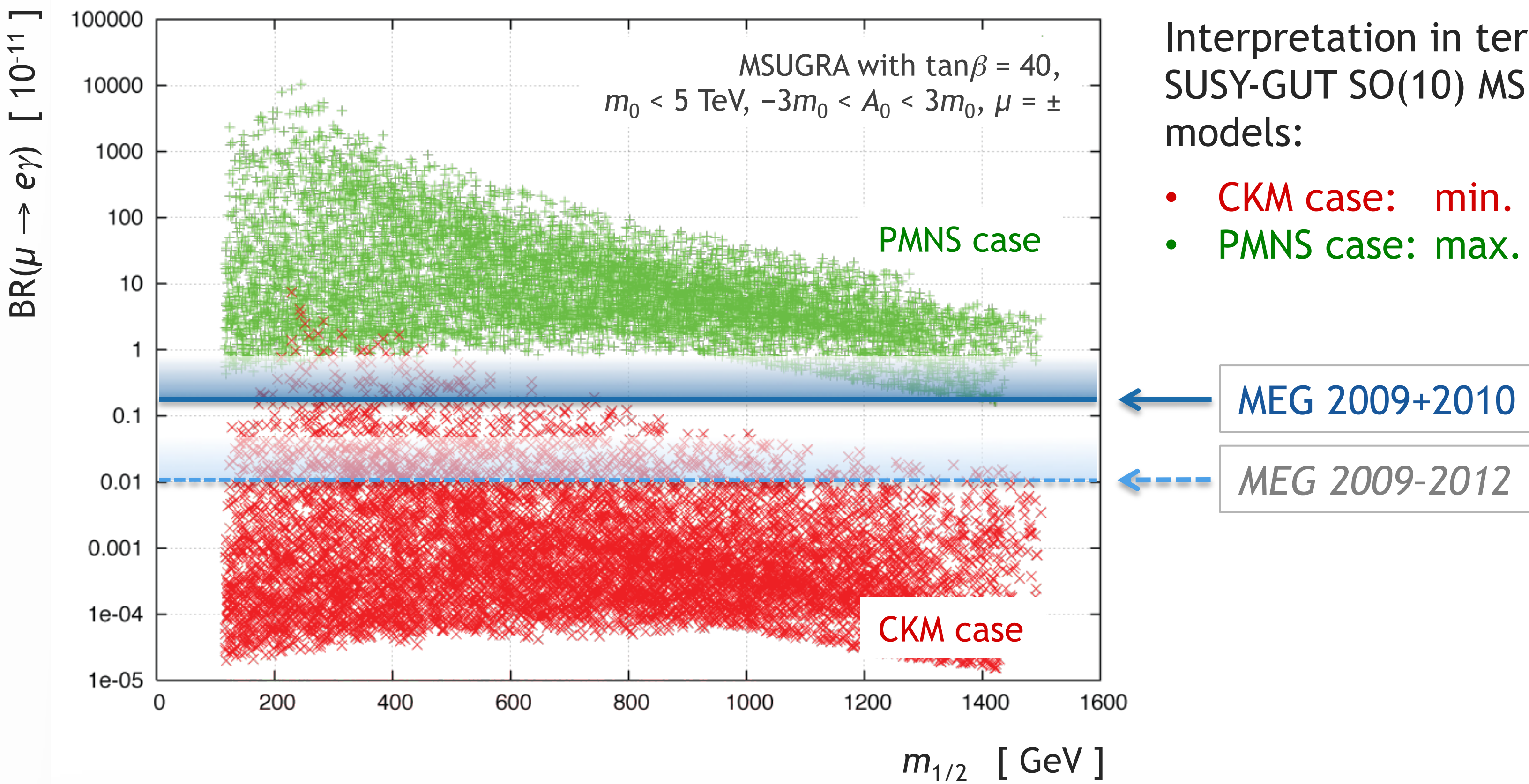
MEG continues data taking in 2011+2012 to explore $\mu^+ \to e^+\gamma$ up to the design sensitivity of O(a few 10^{-13})

90% CL (Feldman-Cousins) upper limit:

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

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

90% CL (Feldman-Cousins) upper limit:

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

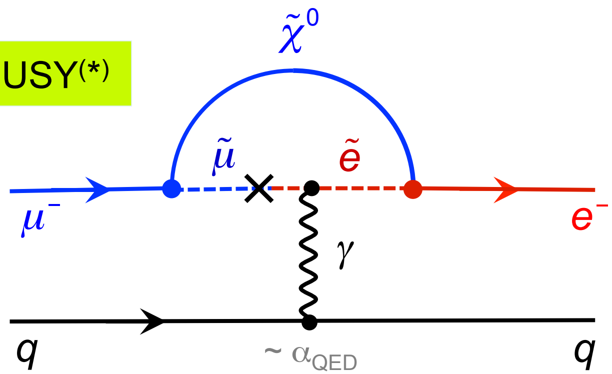
μ–e Conversion

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)

ex.: SUSY(*)



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): $R_{\mu e}(\mathrm{Au}) < 7\times10^{-13}$ (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) → use to discriminate between models

μ–e Conversion

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

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

→ BR($\mu \to e\gamma$) < 10^{-13} requires $R_{\mu e}$(Al) < 3×10^{-16}

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

Goal: sensitivity down to ~2×10^{-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

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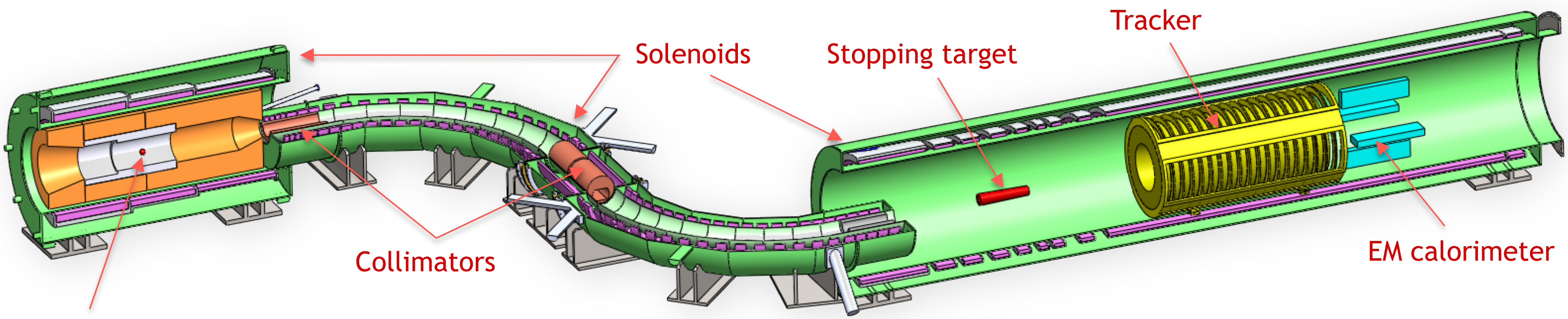
Mu2E (FNAL) Overview

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

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



Transport: S-shape eliminates backgrounds and selects $p(\mu^-)$

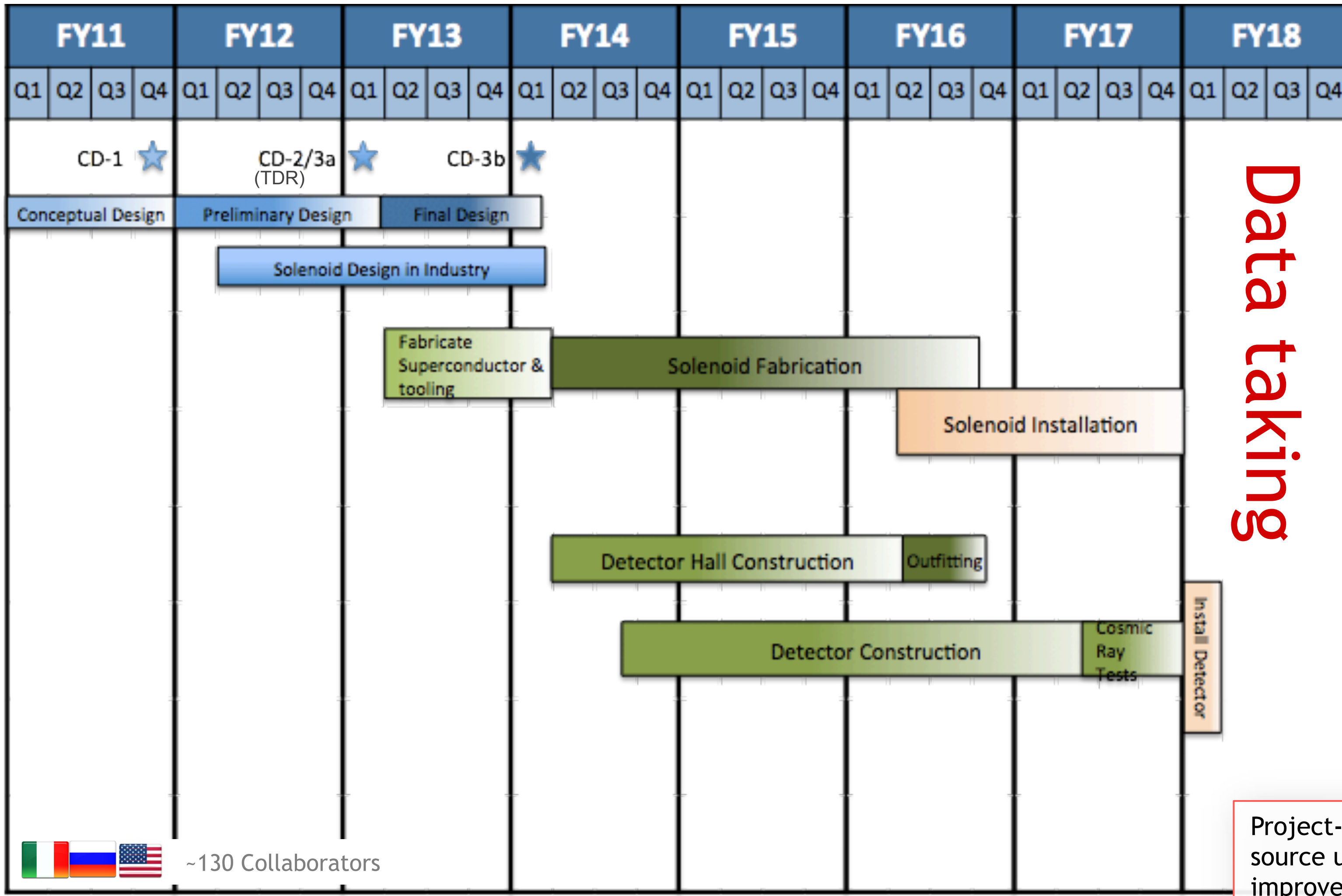
Detector: stopping target, tracking and calorimeter

Mu2e features

- **Pulsed Beam:** eliminate prompt backgrounds (e.g., radiative π capture), 0.6 MHz, 10^{-10} pulse extinction after 0.7 μs, use late muonic atom decays (τ ~1 μs) 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:** $R_{\mu e} = 10^{-16}$ → ~4 signal / 0.2 bkg. events (RPC, decay-in-orbit)
- **Multiple ring structure at FNAL:** no interference with NOvA running

Mu2E (FNAL) Schedule

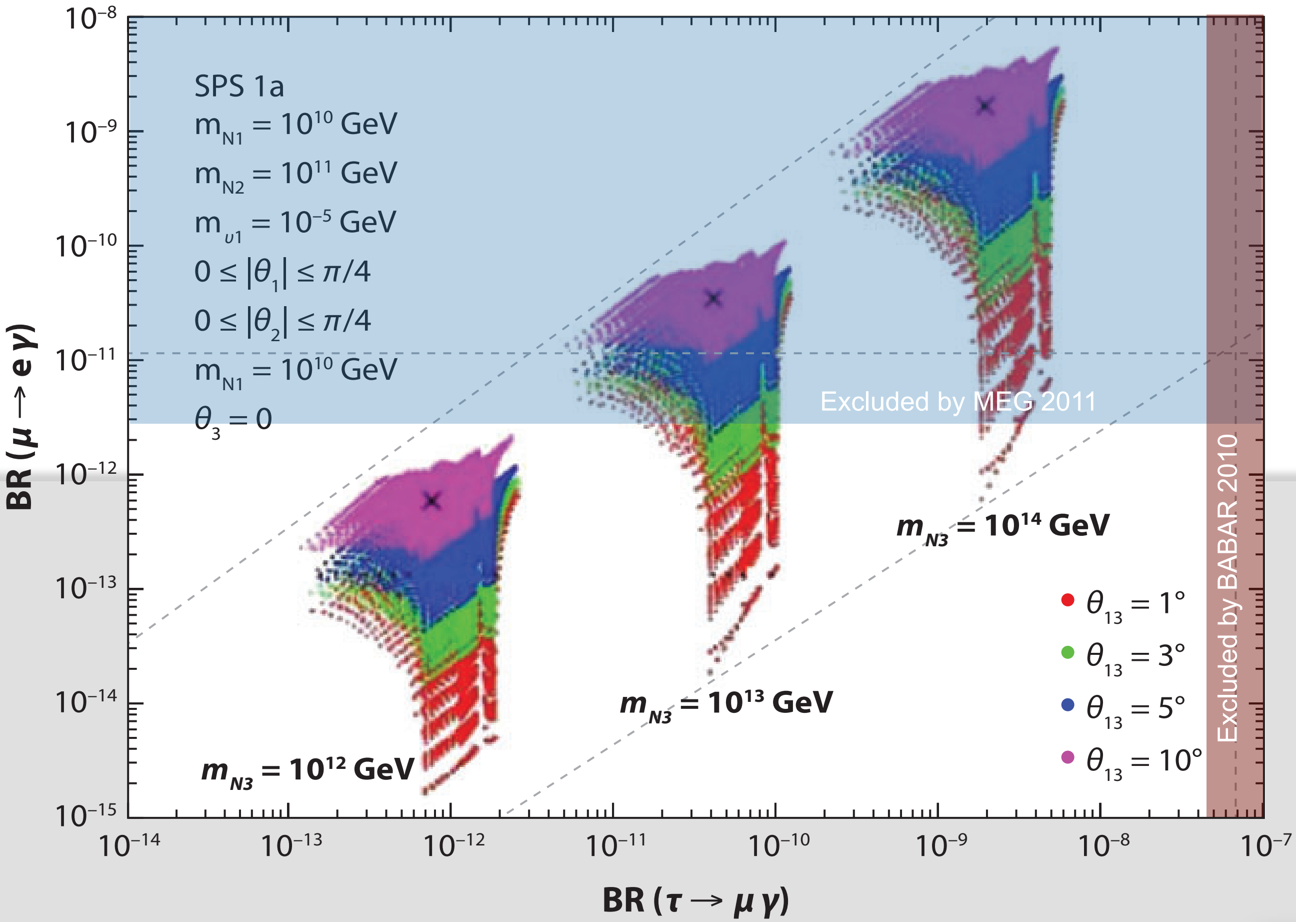
US$ 200 M total cost at CD-0



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

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

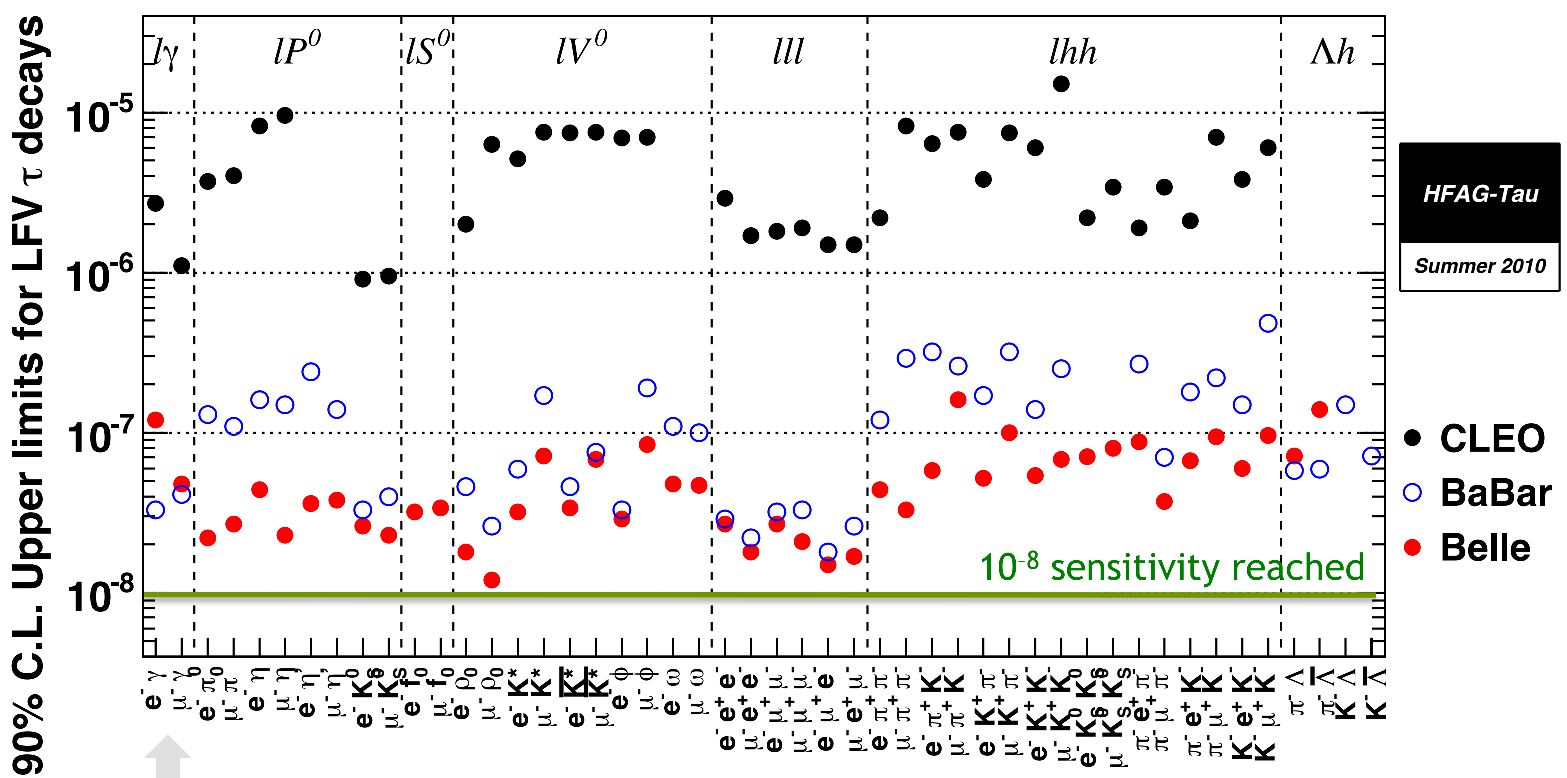


CMSSM model point with 3 massive RH *N* for various $m(N_3)$ and θ_{13}

Antusch *et al.*. JHEP 11, 90 (2006)

Compilation of Tau LFV Search Limits

Heavy Flavour Averaging Group, Summer 2010



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

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

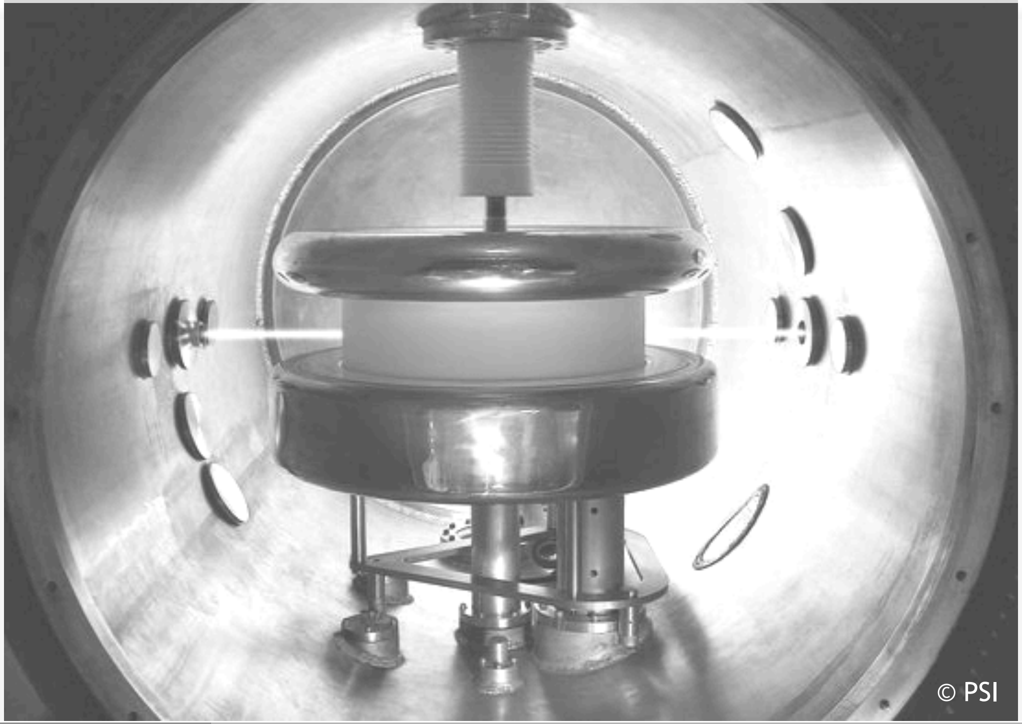
BABAR: PRL 104, 021802 (2010) PRL 104, 021802 (2010)

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:

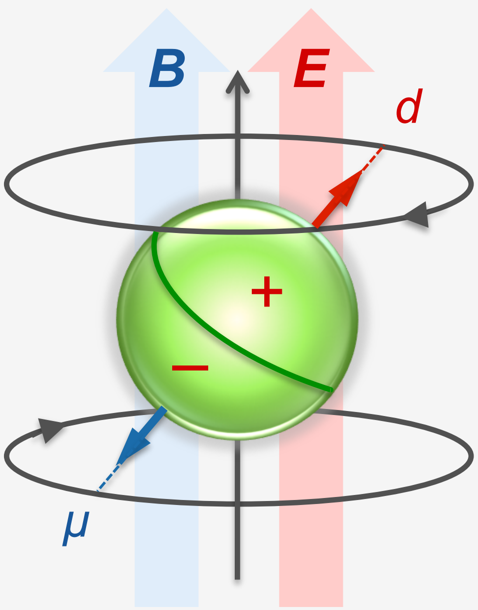
$$P(\vec{B} \cdot \hat{S}) = \vec{B} \cdot \hat{S}$$
$$T(\vec{B} \cdot \hat{S}) = \vec{B} \cdot \hat{S}$$

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

Basic measurement principle:



Precession frequency:

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

d ~ 5 × 10^{-28} ecm gives:
Δf ~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

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For magnetic moment:

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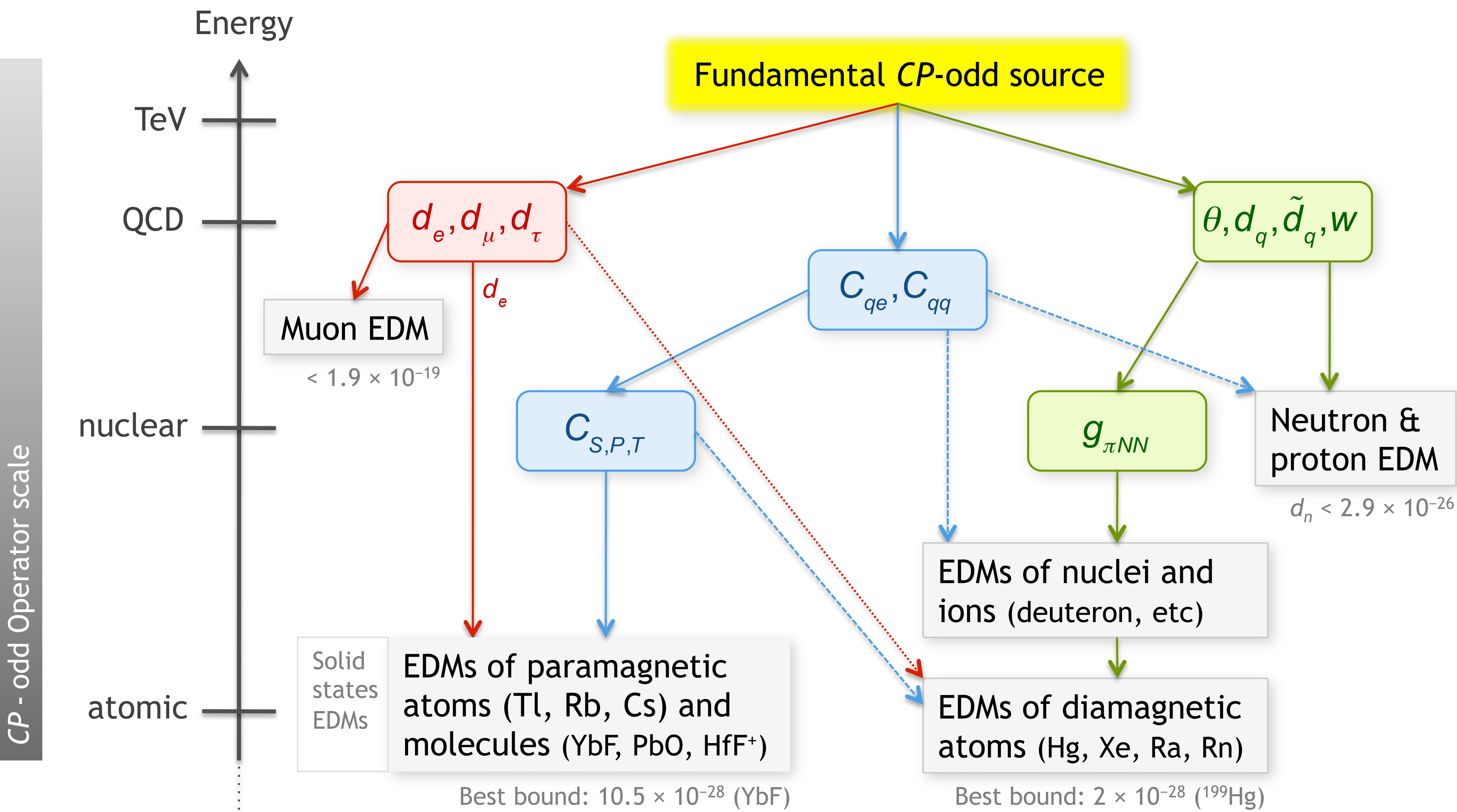
For EDM:

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

Origin of EDMs

Pospelov-Ritz, hep-ph/0504231
Raidal *et al.*, arXiv:0801.1826
K. Kirch talk at PANIC-2011
Michael Romalis

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

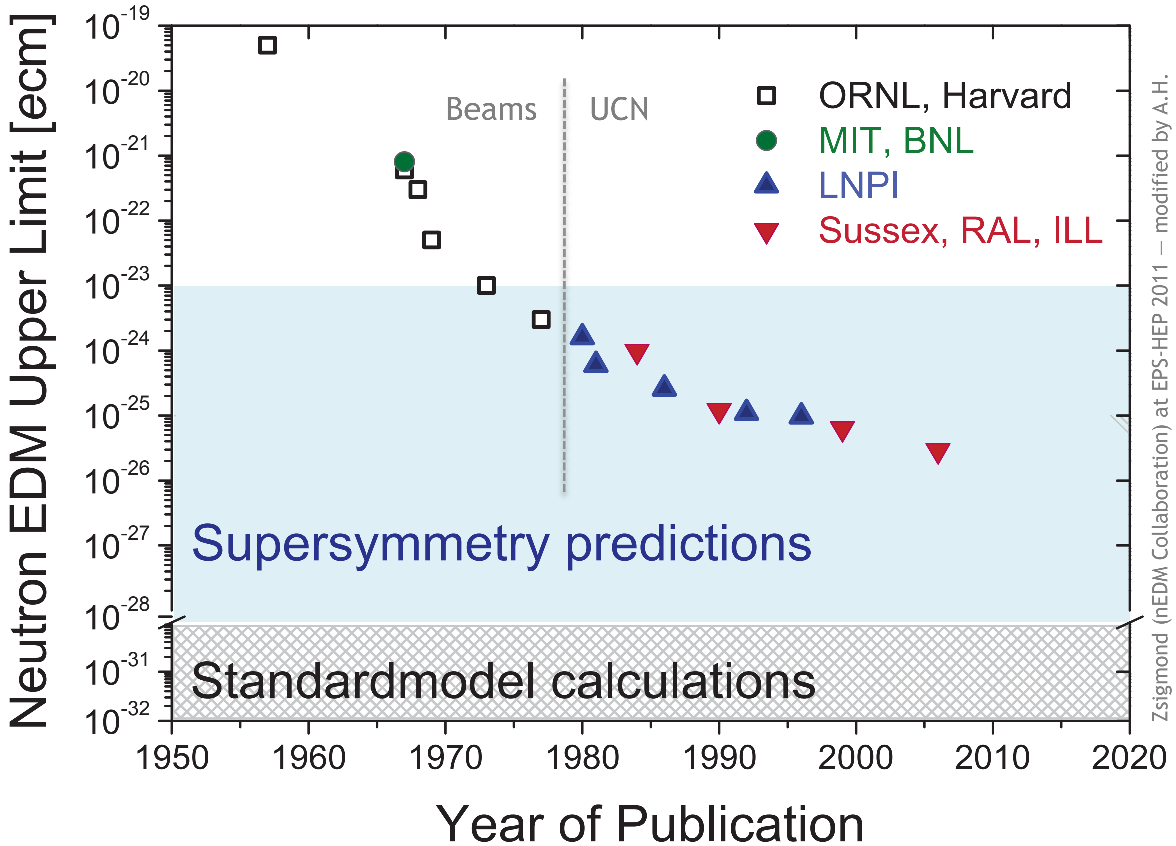


EDM - Experimental Programme

90% CL limits given

Neutron EDM

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



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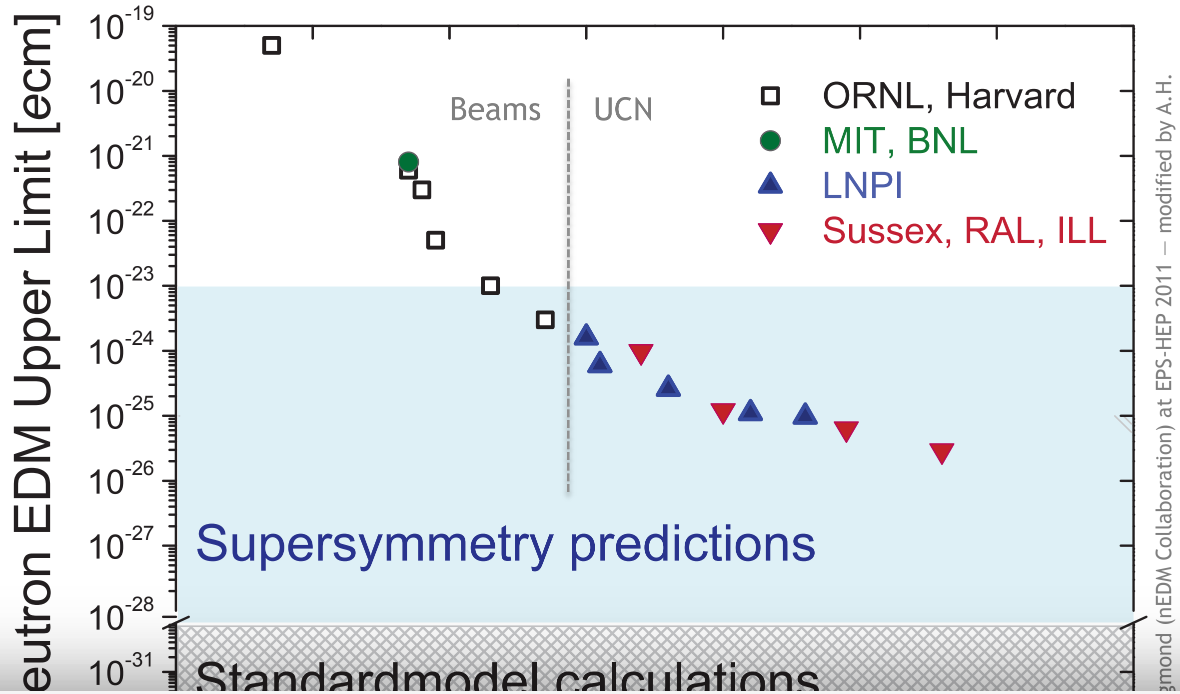

Strong *CP* problem: $|d_n|$ limit translates into $|\bar{\theta}| \sim |d_n| \cdot 2\times10^{16} < 5\times10^{-10}$

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

Why so small ?

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

Forthcoming nEDM experiments

Group	No. of people	Sensitivity [10^{-26} *e*cm]	Due date
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]

by K. Kirch, ETH at PANIC-2011

EDM – Experimental Programme

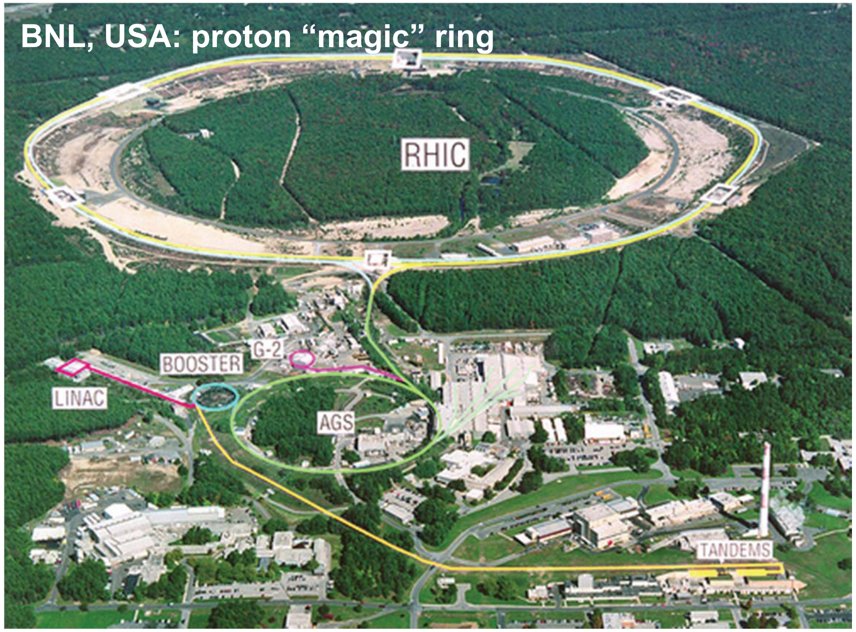
See, e.g., Y. Semertzidis at Patras Workshop, 2011

Proton / Deuterium EDM

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

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

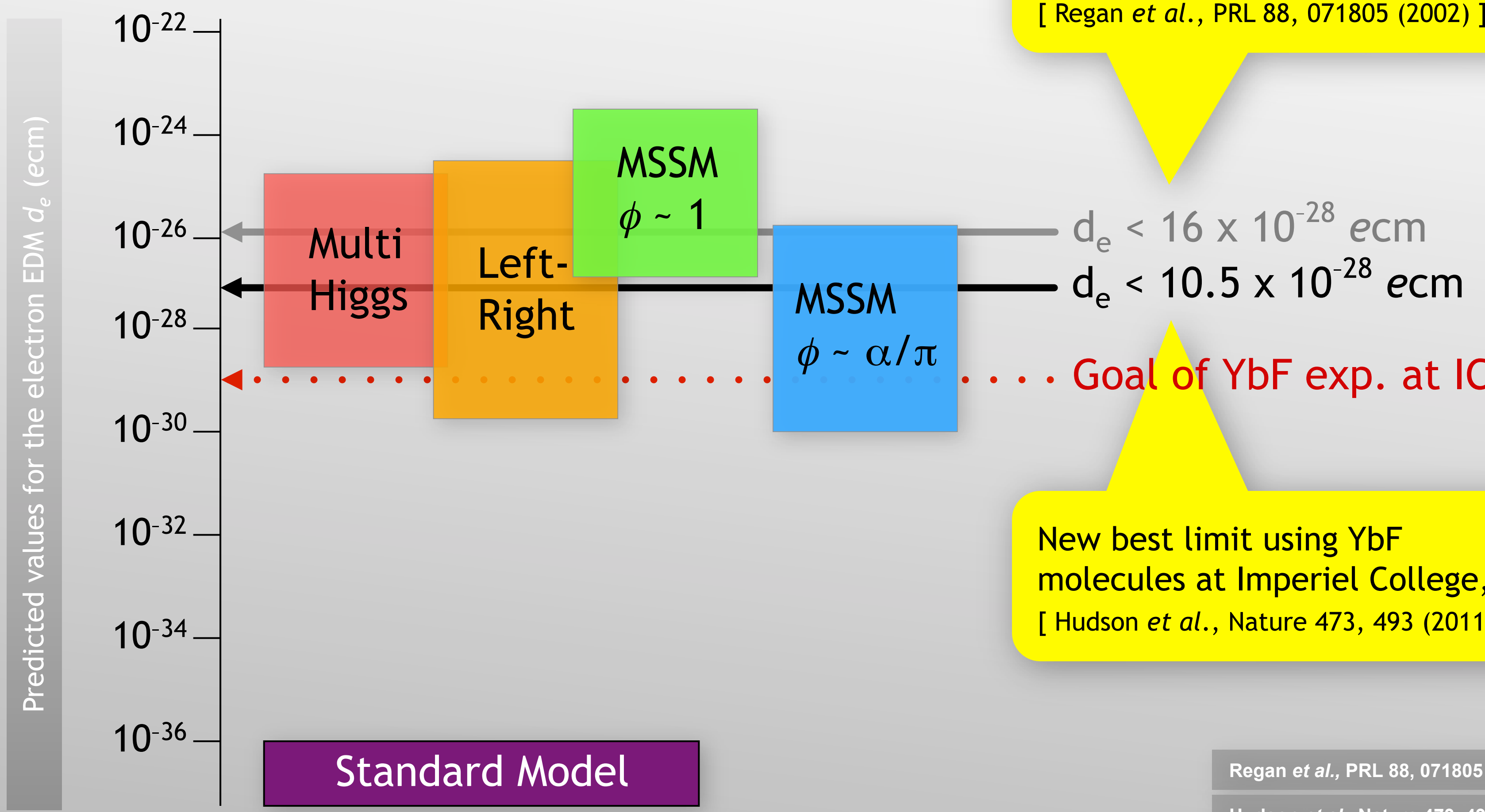
Similar new physics sensitivity as for neutrons, **but better precision**!



EDM - Experimental Programme

90% CL limits given

Electron EDM



Prior best limit obtained using Thallium (Tl) atoms at Berkeley
[Regan *et al.*, PRL 88, 071805 (2002)]

New best limit using YbF molecules at Imperiel College, UK
[Hudson *et al.*, Nature 473, 493 (2011)]

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

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

Graph taken from: B. Sauer, IC

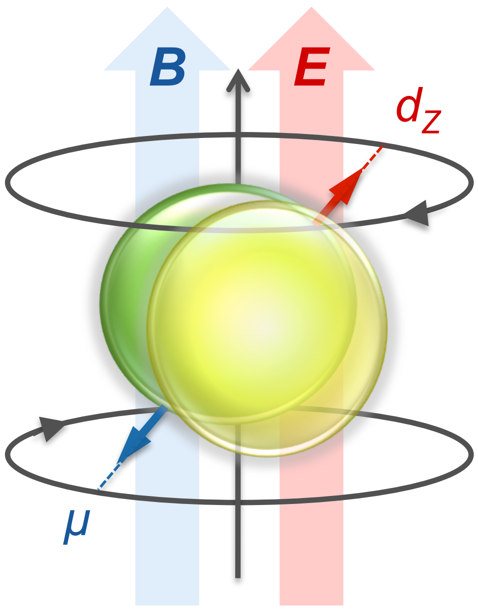
EDM - Experimental Programme

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
- $d_{Tl} \sim 585 \times d_e$ (exploited by Berkeley Tl experiment, 2002
- $d_{YbF} \sim 1.4{\times}10^6 \times d_e$ (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

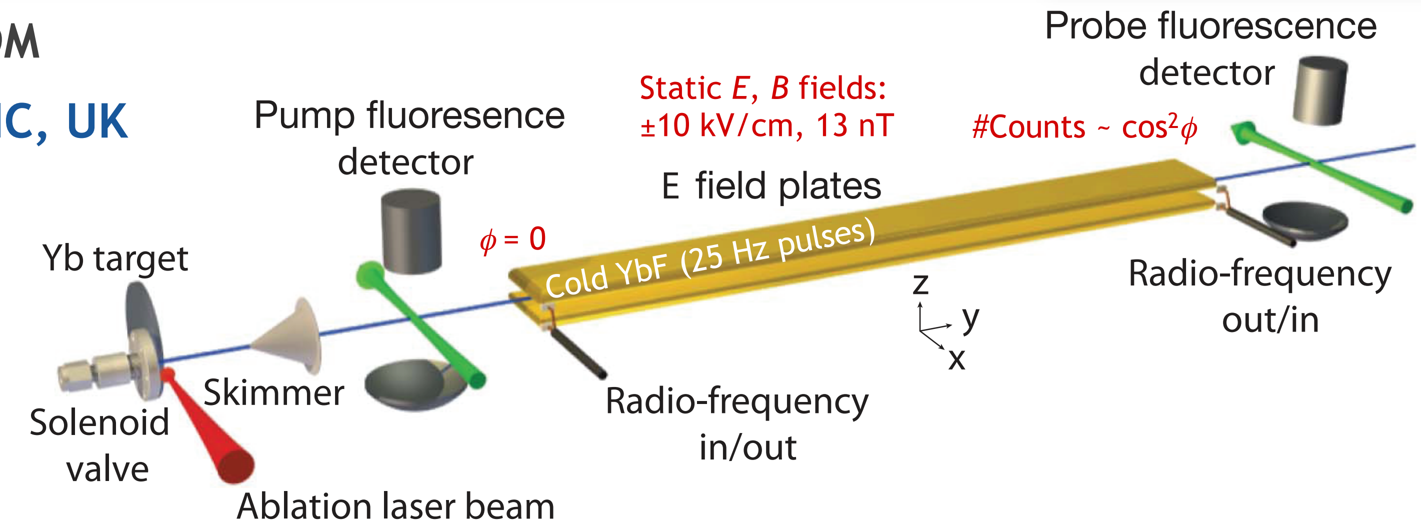
YbF exp. looks for spin interferometer phase shift of F = 0,1 YbF hyperfine levels when E field is reversed

EDM - Experimental Programme

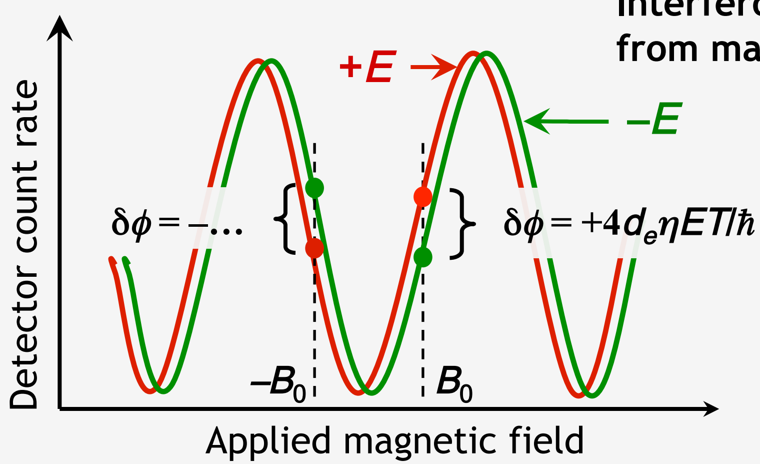
Hudson *et al.*, Nature 473, 493 (2011)

Electron EDM

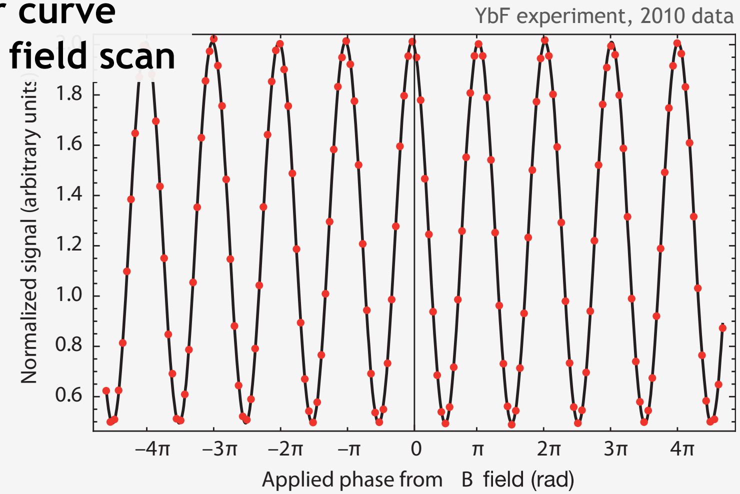
YbF @ IC, UK



Interferometer curve from magnetic field scan



Drawing taken from B. Sauer, IC

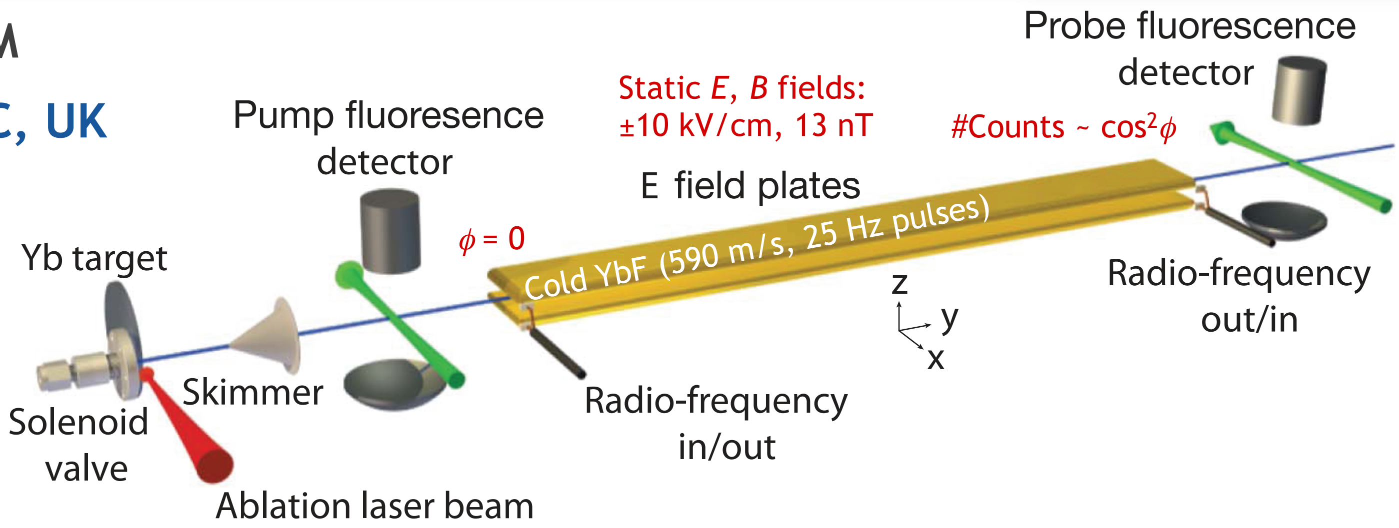


EDM - Experimental Programme

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

Electron EDM

YbF @ IC, UK



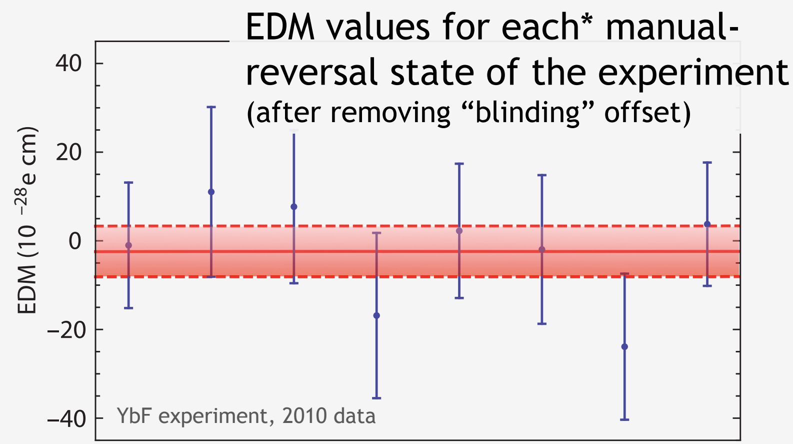
$d_e = (-2.4 \pm 5.7_{stat} \pm 1.5_{syst}) \times 10^{-28}\ ecm$

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

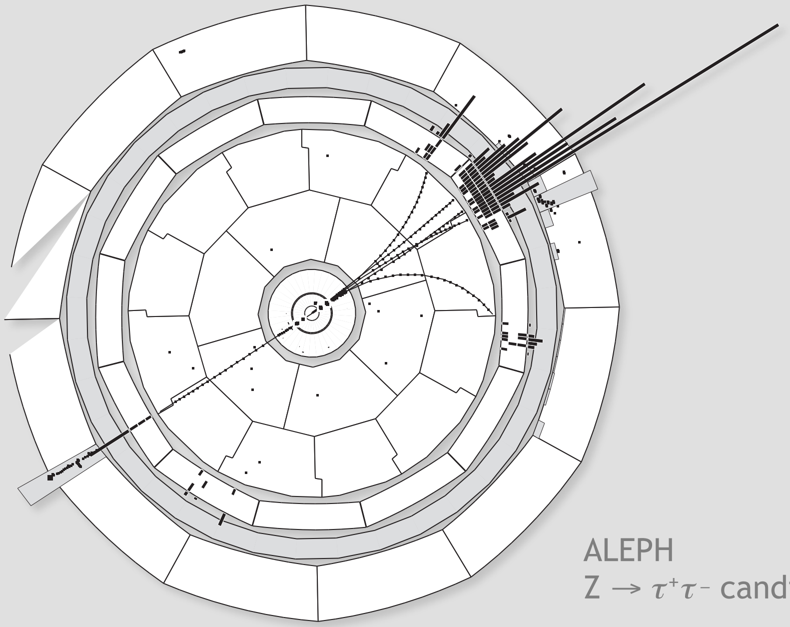
Measurement statistically limited, systematic errors reducible to < 10^{-29} *e*cm

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



ALEPH
$Z \to \tau^+\tau^-$ candidate

Tau-Lepton Physics

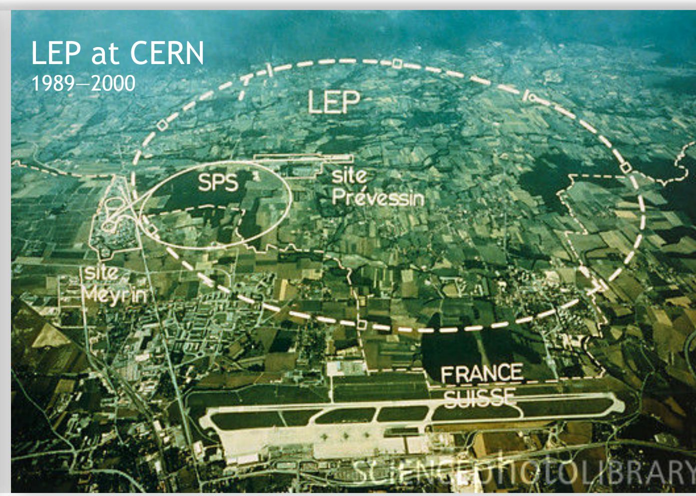
Last year was the 20th anniversary of the Tau Workshops (started in 1990 at Orsay)

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, $|V_{us}|$

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



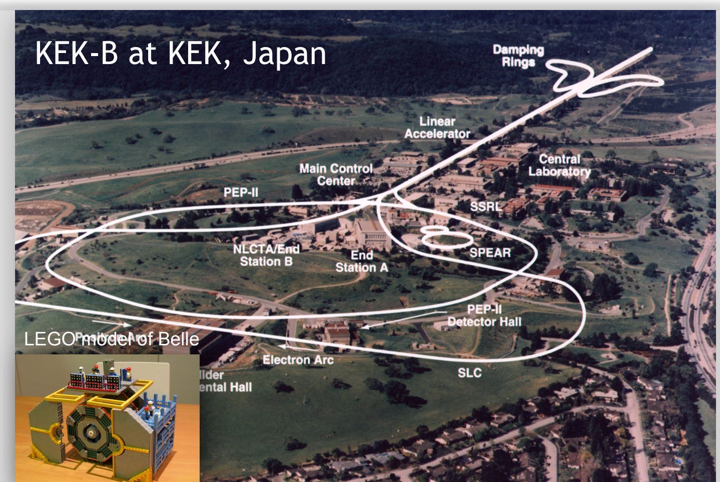
~165,000 $Z \rightarrow \tau\tau$ per experiment

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:

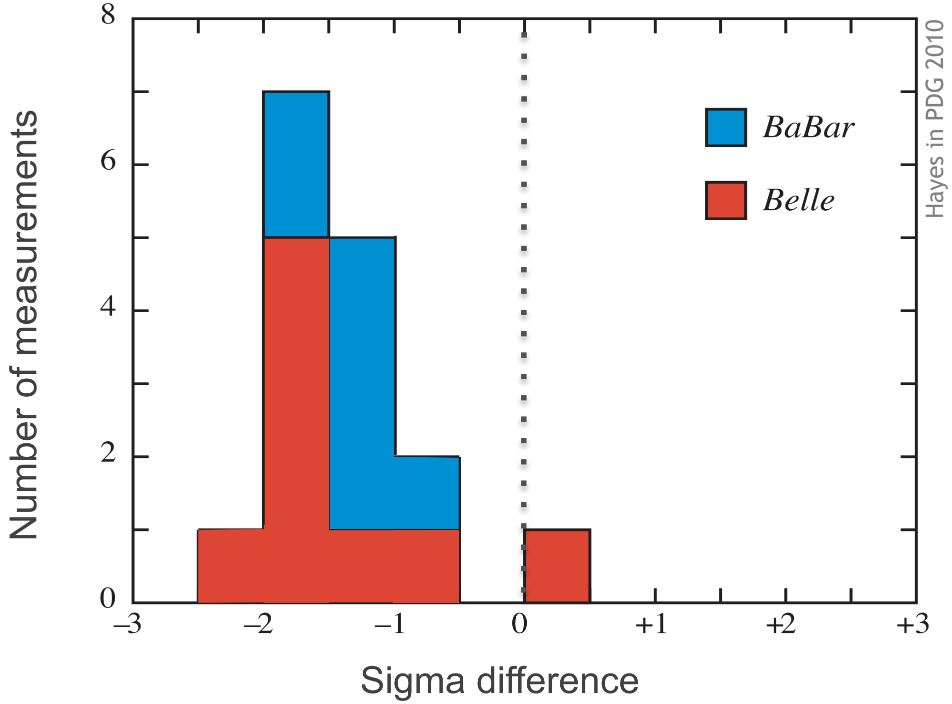
- Lepton flavour violation in tau decays
- Weak current universality tests (0.14% precision reached!), rare branching fractions
- "Second class currents" (isospin violation)
- *CP* violation
- Phenomenological work on determination of α_S and $|V_{us}|$ (→ V. Lubicz', T. Gershon's talks) from tau branching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



B/τ Factories at KEK and SLAC

Tau Branching Fractions

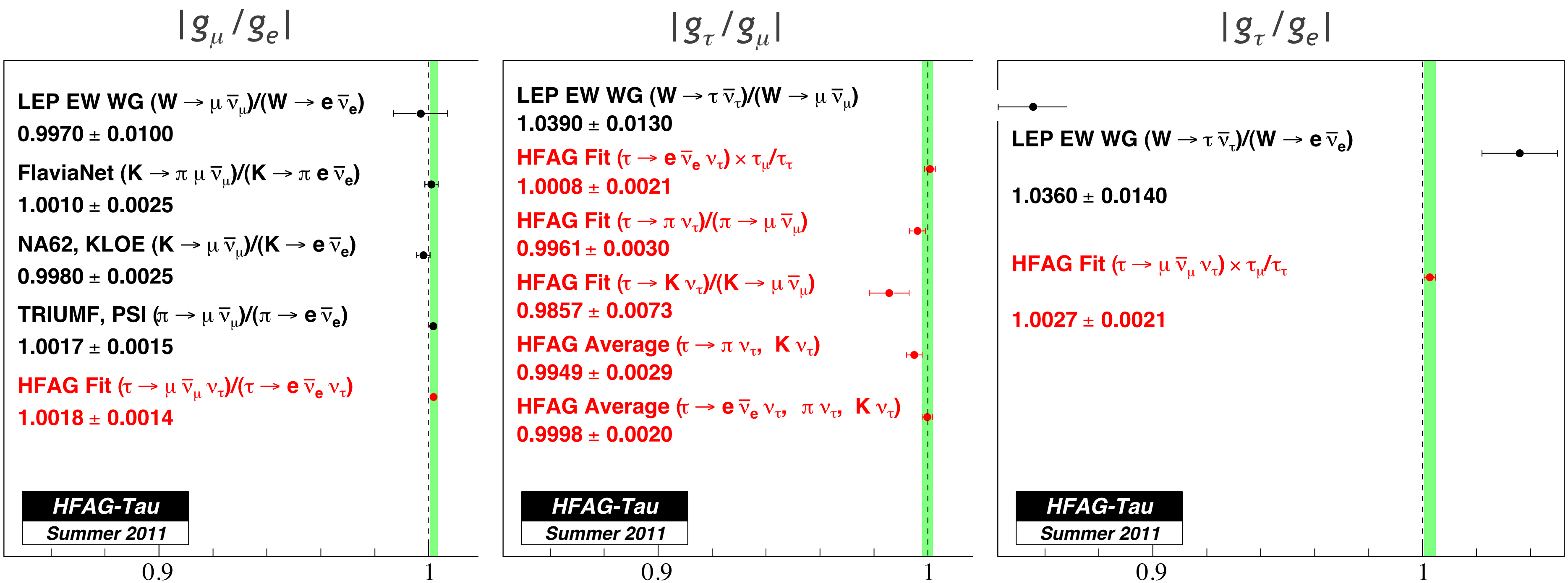
Large amount of new branching fraction measurement by BABAR and Belle.
Significant improvement in modes with kaons (but also a few inconsistencies)



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



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

LEP+SLC, Phys. Rept. 427, 257 (2006)

Searches for “Second Cass 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})

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

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^o system (ε_K), expect to see decay rate asymmetry

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

Bigi-Sanda, PLB 625, 47 (2005)

Kühn-Mirkes, PLB, 398, 407 (1997)

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

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

New preliminary analysis of A_Q in $\tau^\pm \to K_S \pi^\pm (\geq 0\pi^o)\nu$ from BABAR using 476 fb^{-1}

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

BABAR finds A_Q = **(−0.45 ± 0.24 ± 0.11) %**, which deviates ~3σ from SM

BaBar-PUB-11/009

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

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

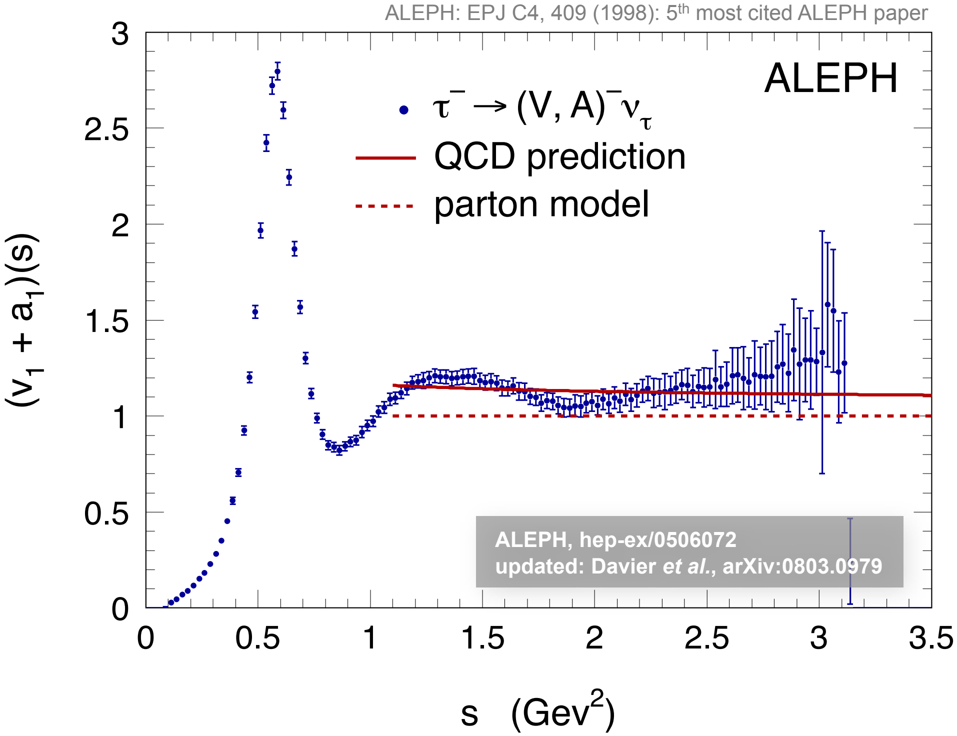
HFAG, 2011

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**

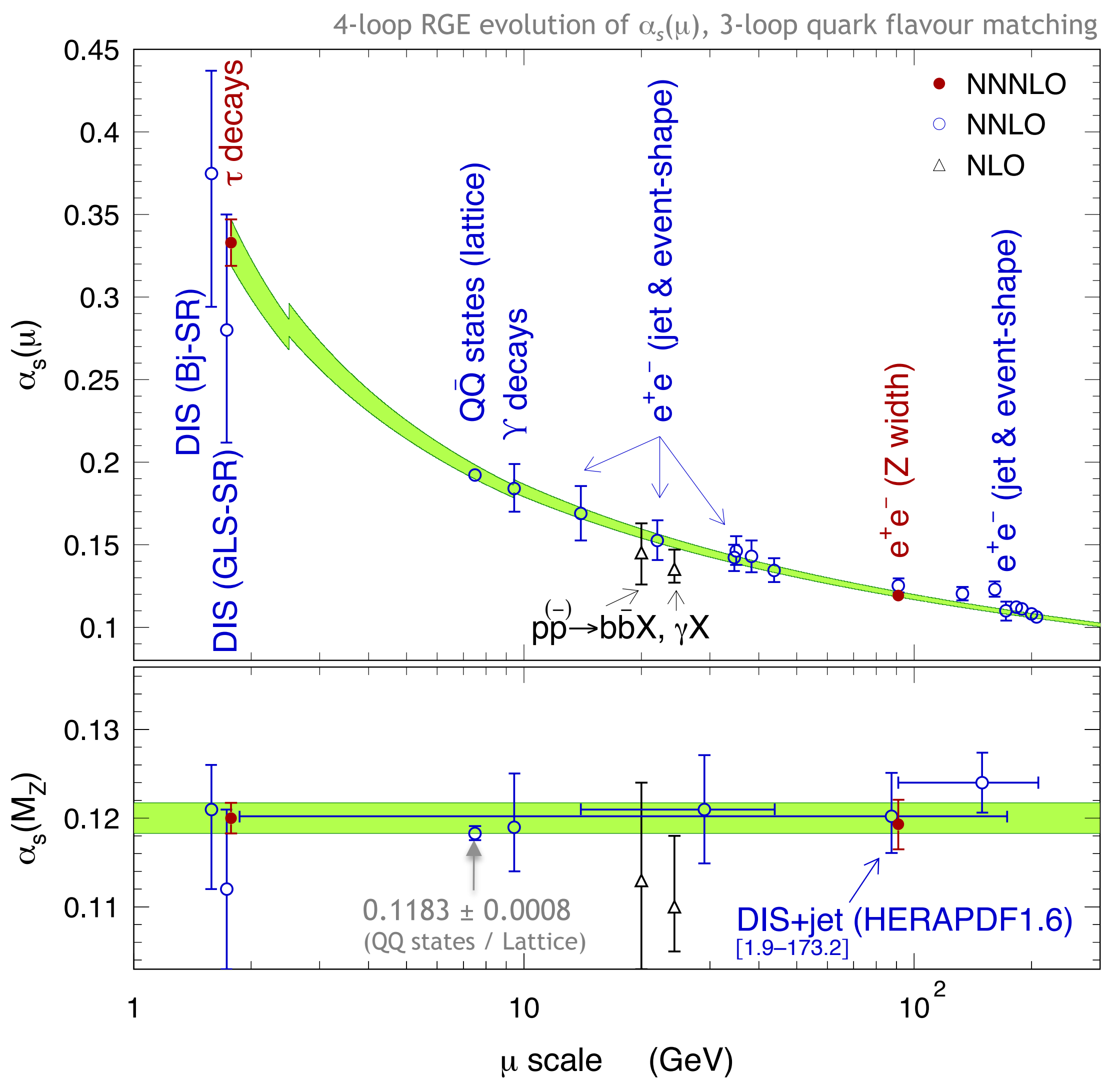
ALEPH: EPJ C4, 409 (1998): 5th most cited ALEPH paper



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:

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

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

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

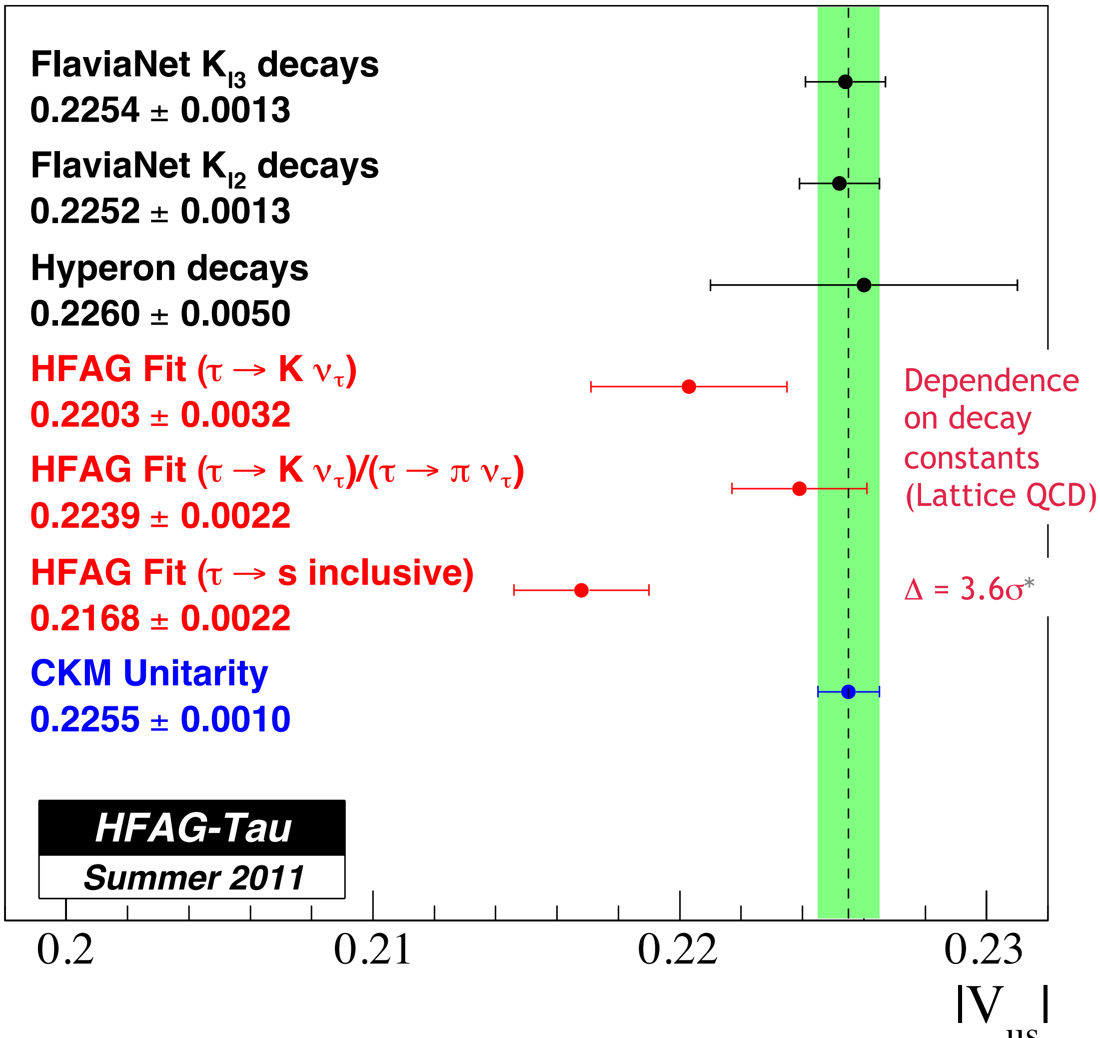
Excellent agreement with NNNLO result from EW fit

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

Baak *et al.*, arXiv:1107.0975

Precise test of asymptotic freedom property of QCD

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



(*)3.3σ when using unitarity constraint for BK)

Inclusive analysis uses:

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

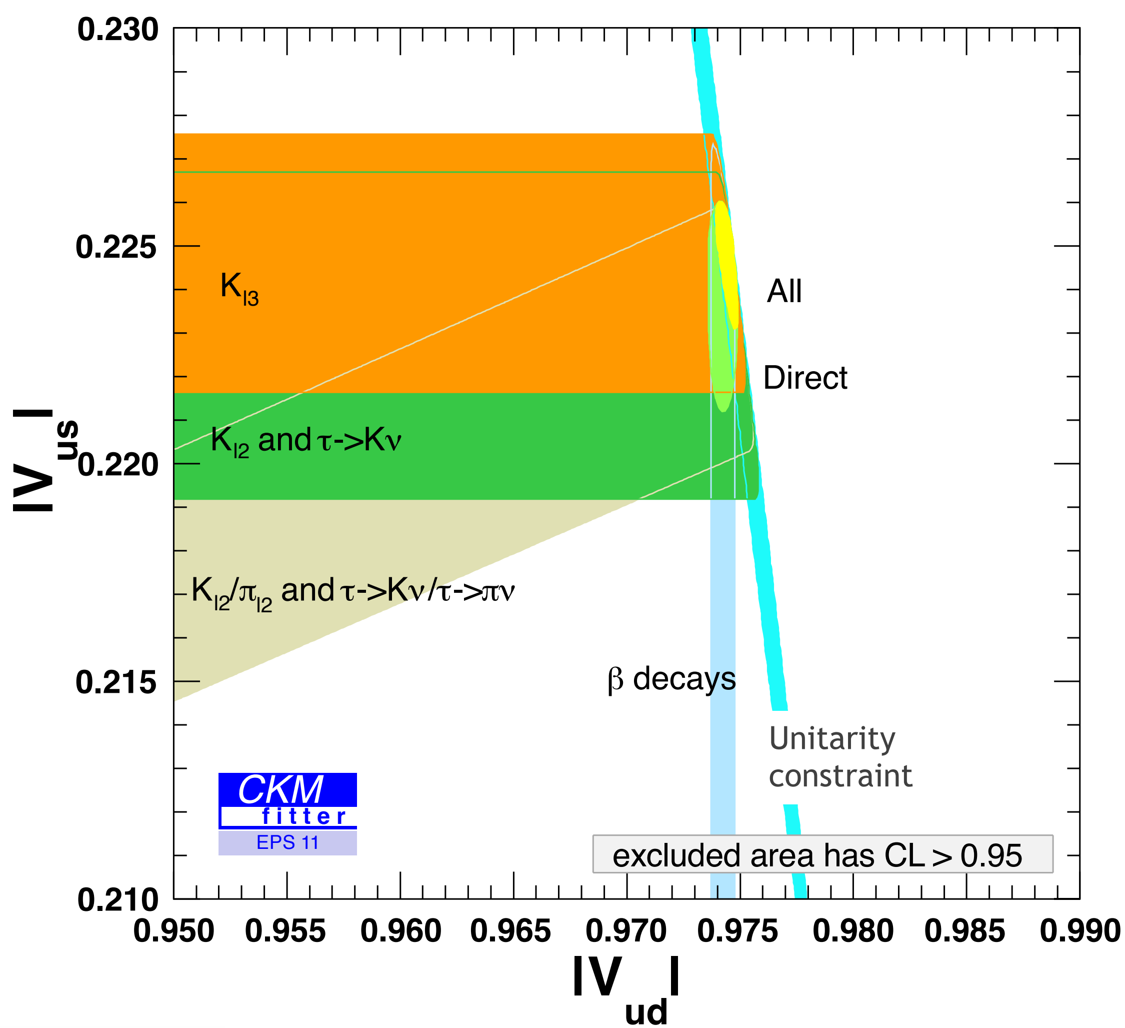
Dependence on $|V_{ud}|$, and theoretical dependence on α_S and m_s (problematic behaviour of perturbative series)

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 → unexpected in earlier days !

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



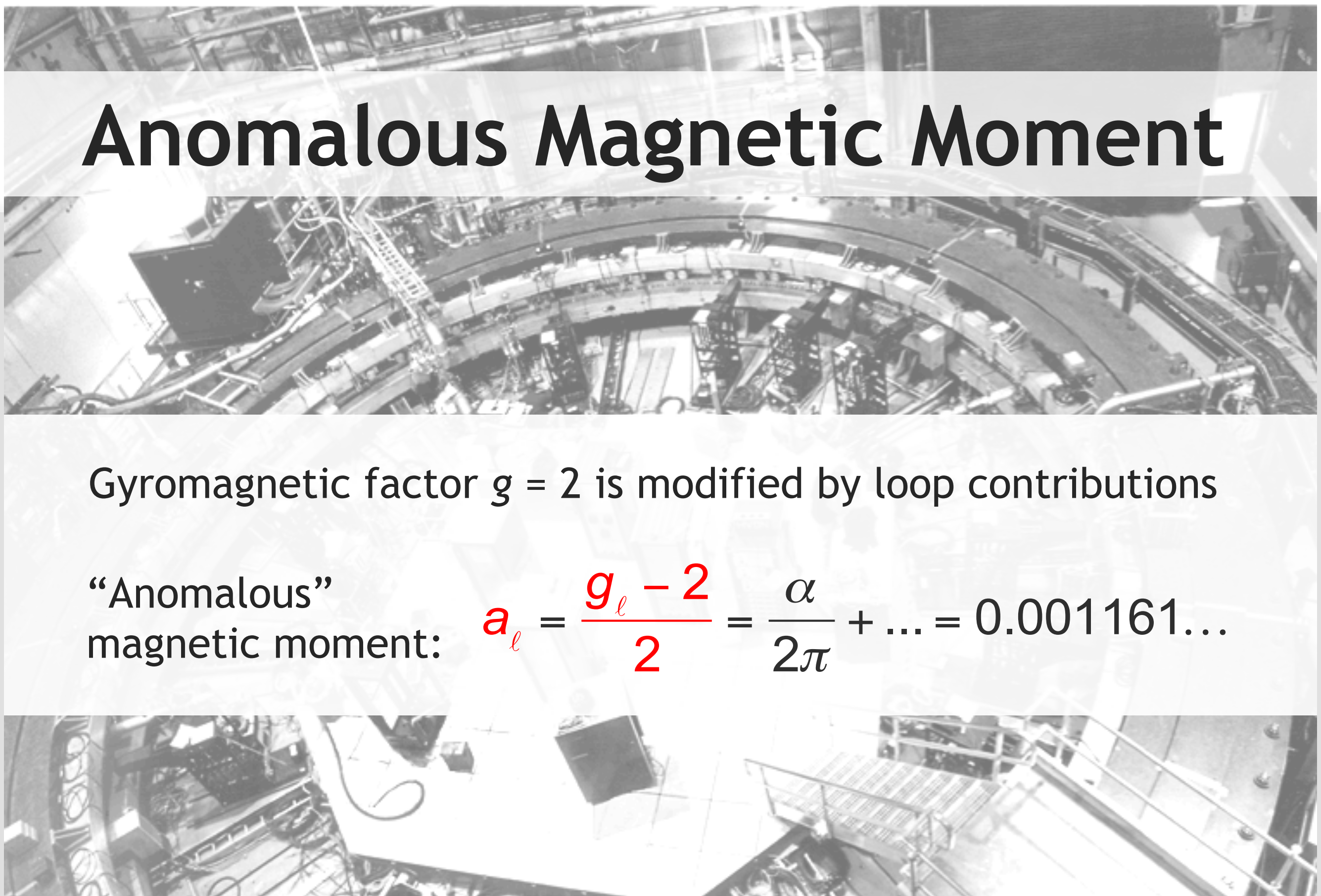
V. Niess at EPS 2011

First row of CKM matrix shows good agreement with unitarity

Anomalous Magnetic Moment

Gyromagnetic factor g = 2 is modified by loop contributions

"Anomalous" magnetic moment: $$a_\ell = \frac{g_\ell - 2}{2} = \frac{\alpha}{2\pi} + \ldots = 0.001161\ldots$$



E821 at BNL

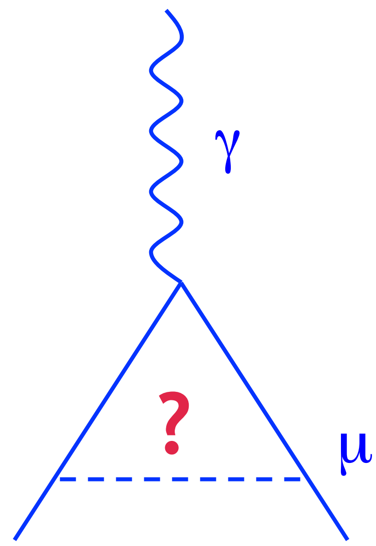
Probing New Physics

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 $m^2{}_{e/\mu}$:

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

- Loose about a factor of 800 in experimental precision



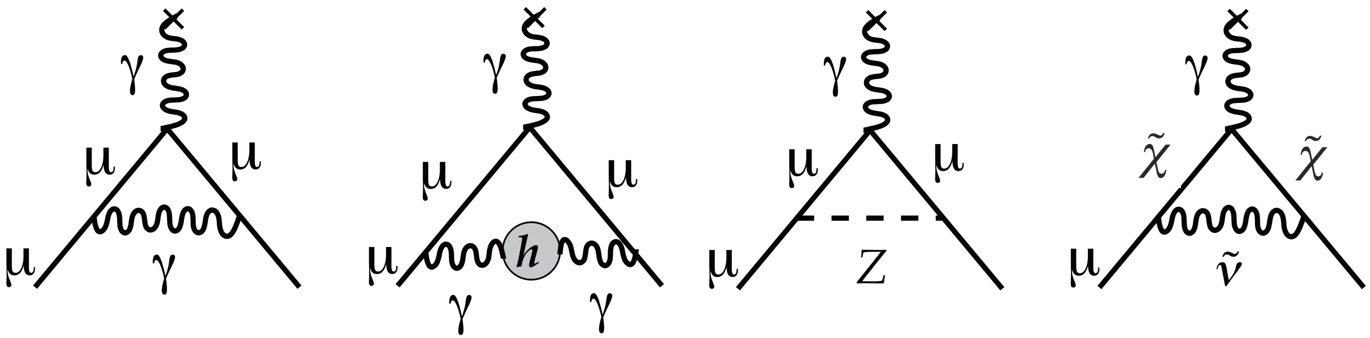
→ a_μ should be roughly 50 times more sensitive to NP than a_e !

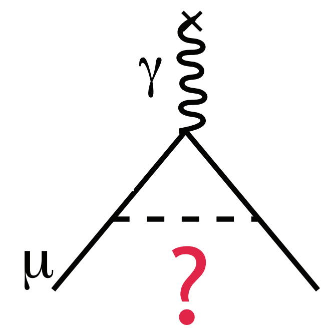
a_τ even more sensitive, but insufficient experimental accuracy

Loop contributions:

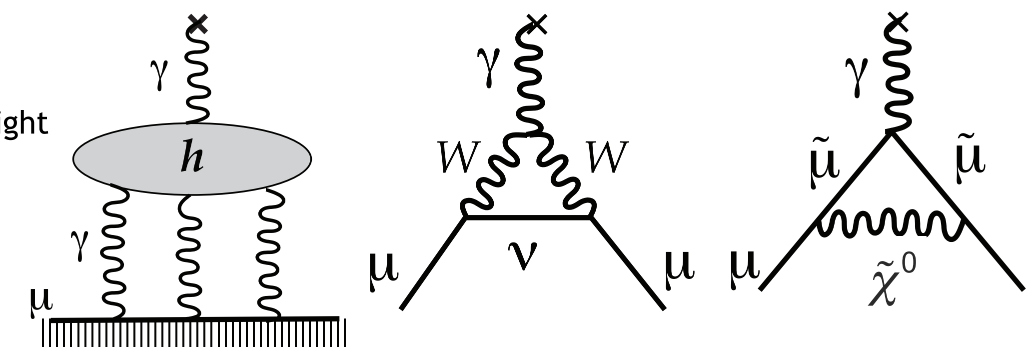
QED | Hadronic | Weak | SUSY… ?

… 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:

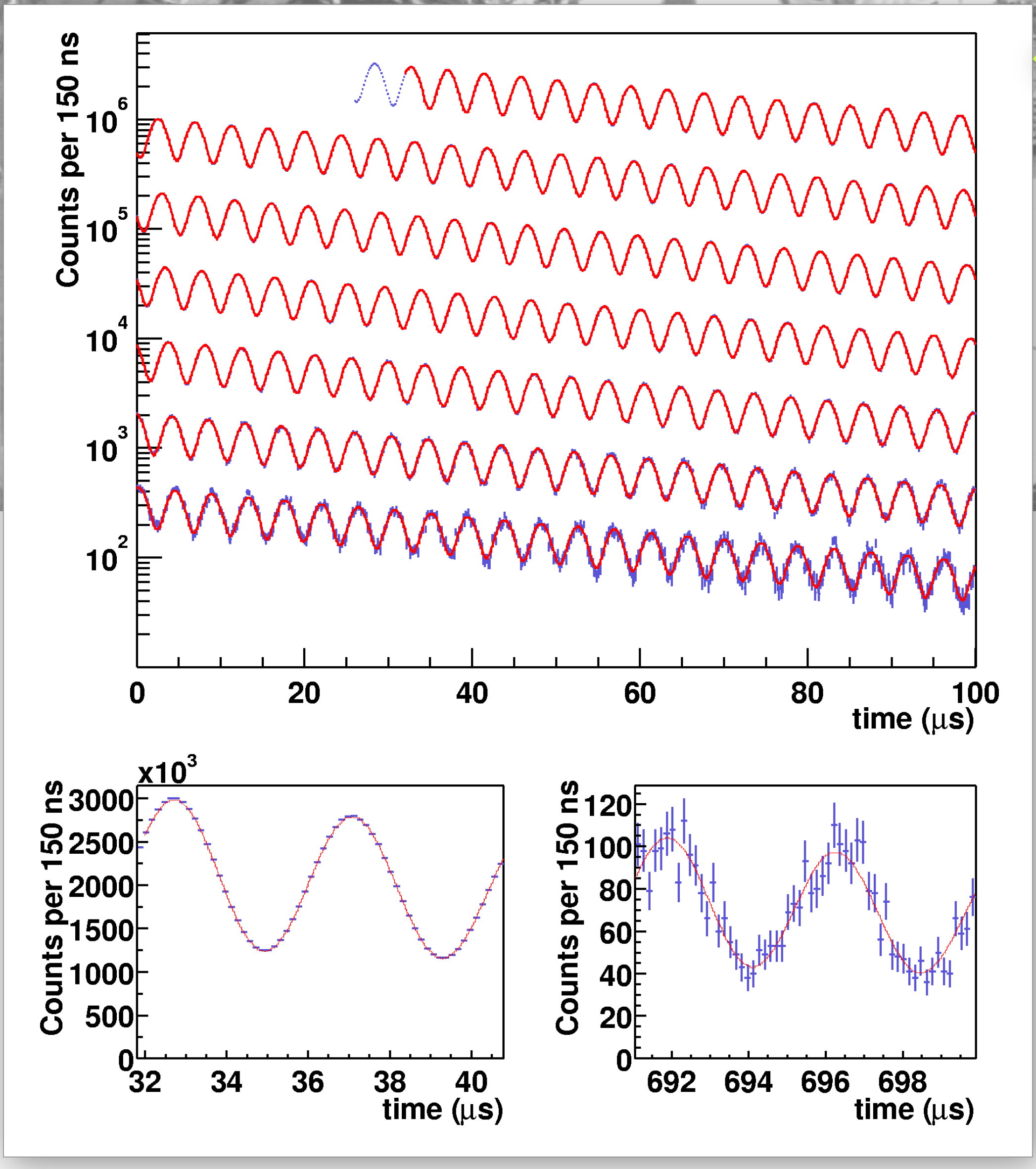
$$\vec{\omega}_a = \frac{e}{mc} a_\mu \vec{B}$$

At “magic γ with p_μ = 3.09 GeV and assuming, μEDM = 0 !

The experiment measures directly (g – 2)/2 !

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

The BNL Muon $g-2$ Experiment



Observed positron rate in successive 100μs periods

Difference between spin precession and cyclotron frequency:

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

obtained from fit to:

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

B-field from precise NMR probe

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

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:

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

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

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

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

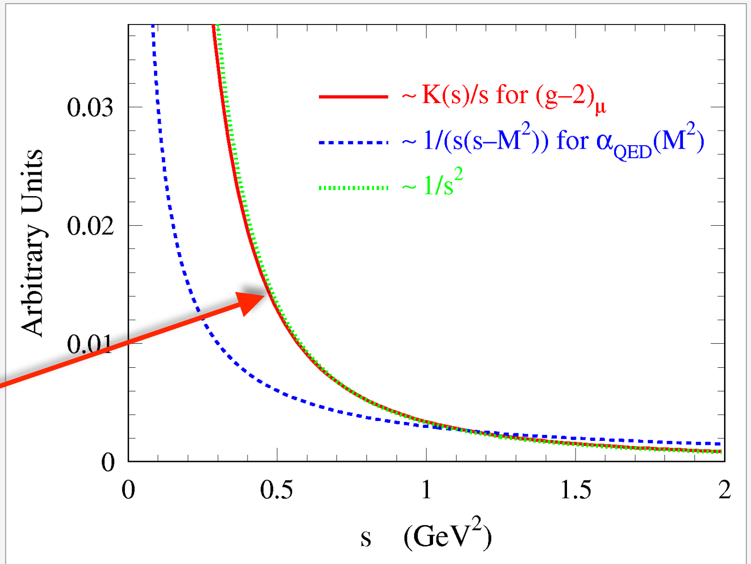
$$a_\mu^{\rm weak} = (15.4 \pm 0.2) \times 10^{-10}$$

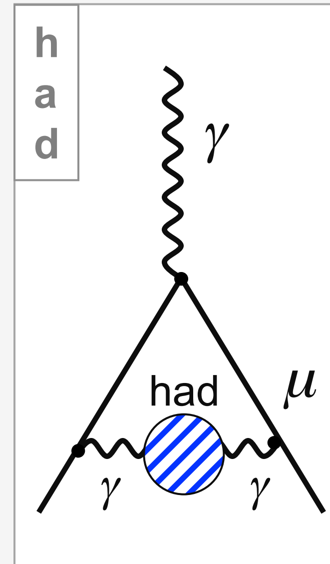
Hadronic Contribution

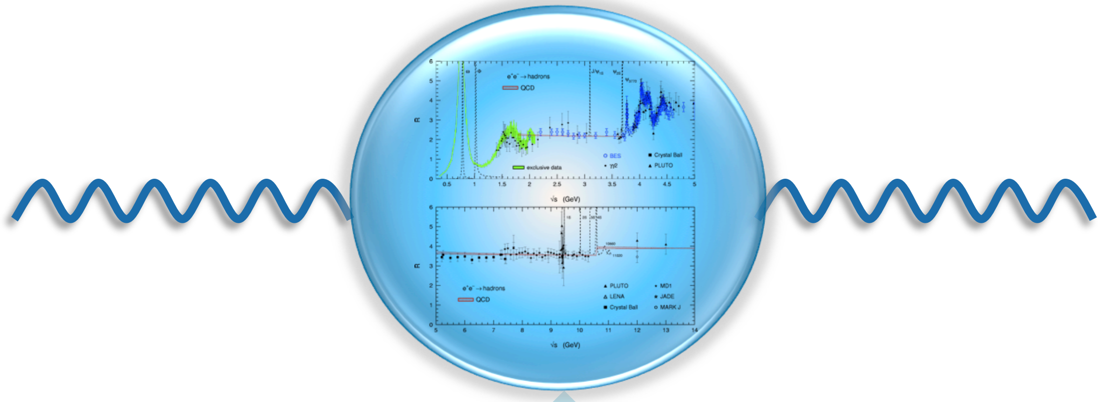
- Cannot be computed from first principles due to low-energy hadronic effects
- Fortunately, one can benefit from analyticity and unitarity to obtain real part of photon polarisation function from **dispersion relation over total hadronic cross section data**

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

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





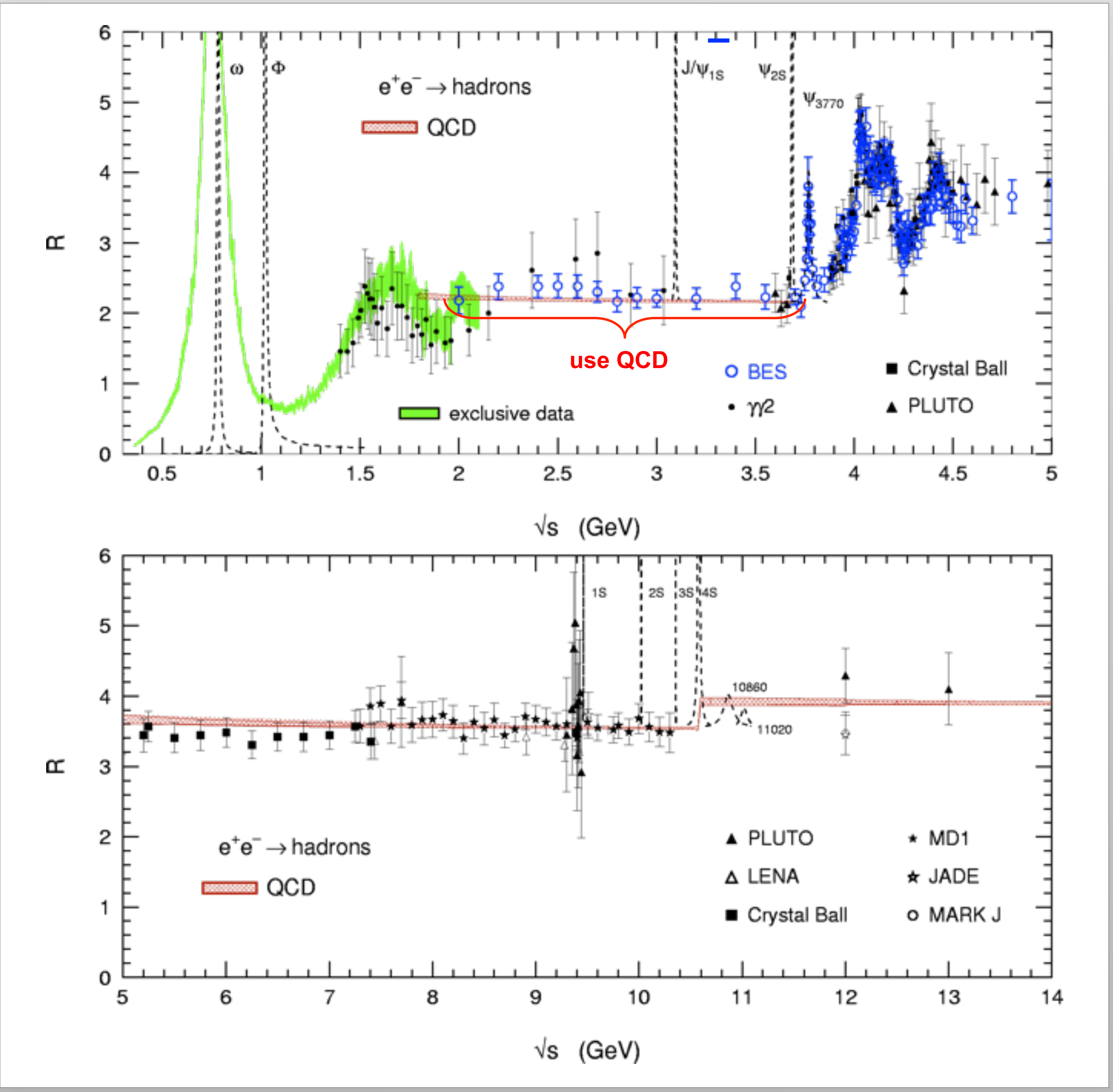


$$a_\mu^{\mathrm{had,LO}} = \frac{\alpha^2}{3\pi^2} \int_{m_{\pi^0}^2}^{\infty} ds \, \frac{K(s)}{s} \, R(s)$$

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

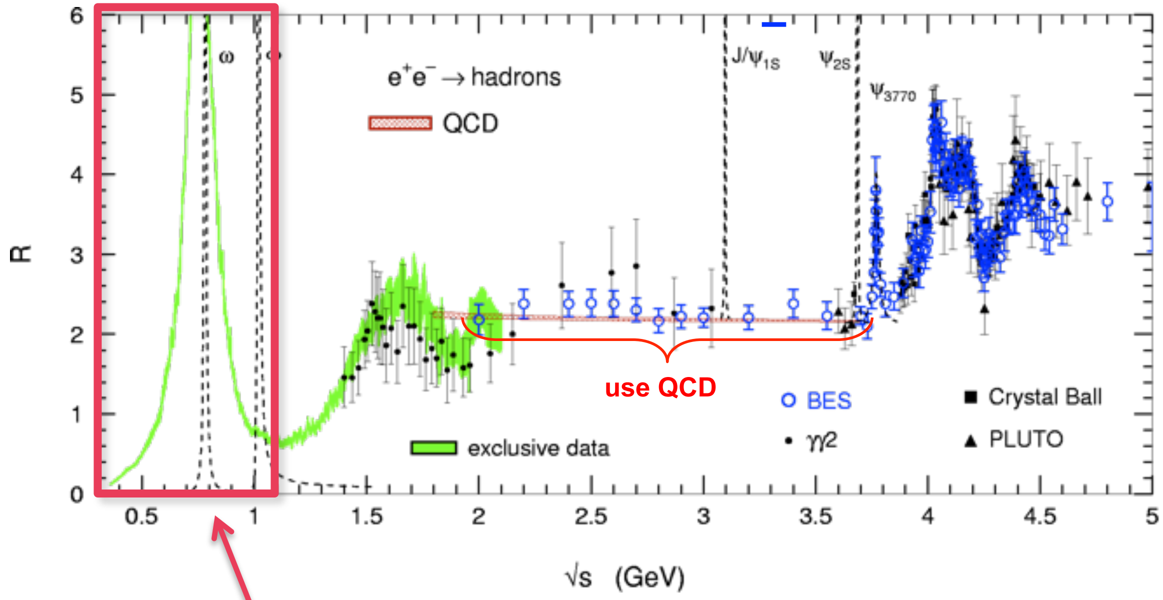
- **Improved e^+e^- cross section data** from Novisibirsk (Russia)
- More use of **perturbative QCD**
- Technique of "**radiative return**" allows to use data from Φ and B factories
- Isospin symmetry allows us to also use τ **hadronic spectral functions**

Plot not fully up to date – for illustration only



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

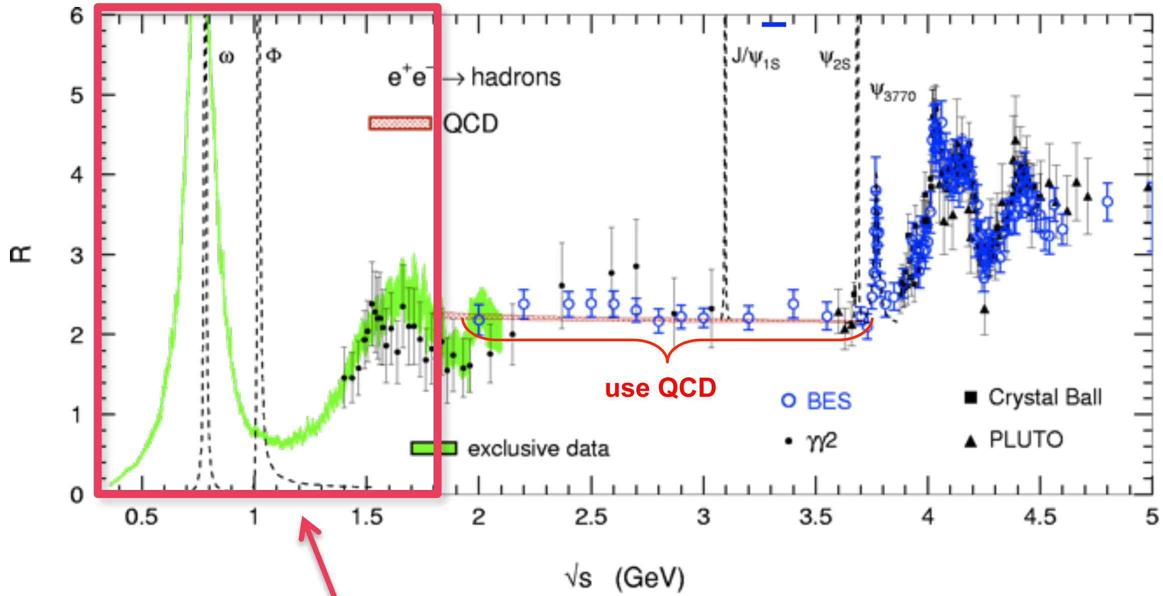
Plot not fully up to date – for illustration only



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

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

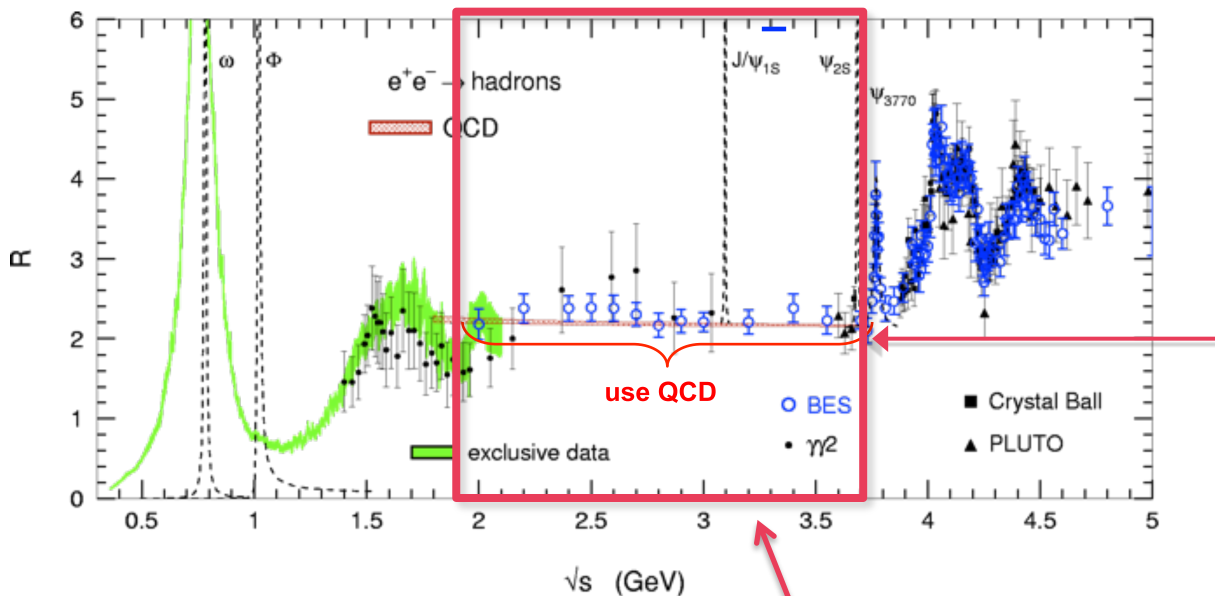
Plot not fully up to date – for illustration only



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

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

Plot not fully up to date – for illustration only

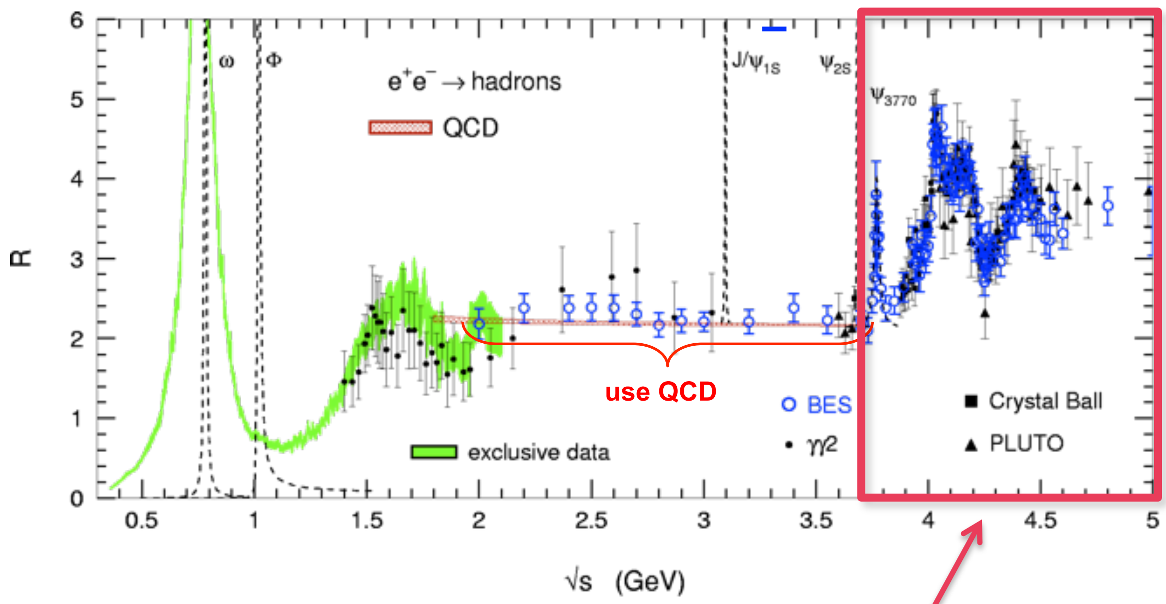


$$a_\mu^{\text{had,LO}} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

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



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

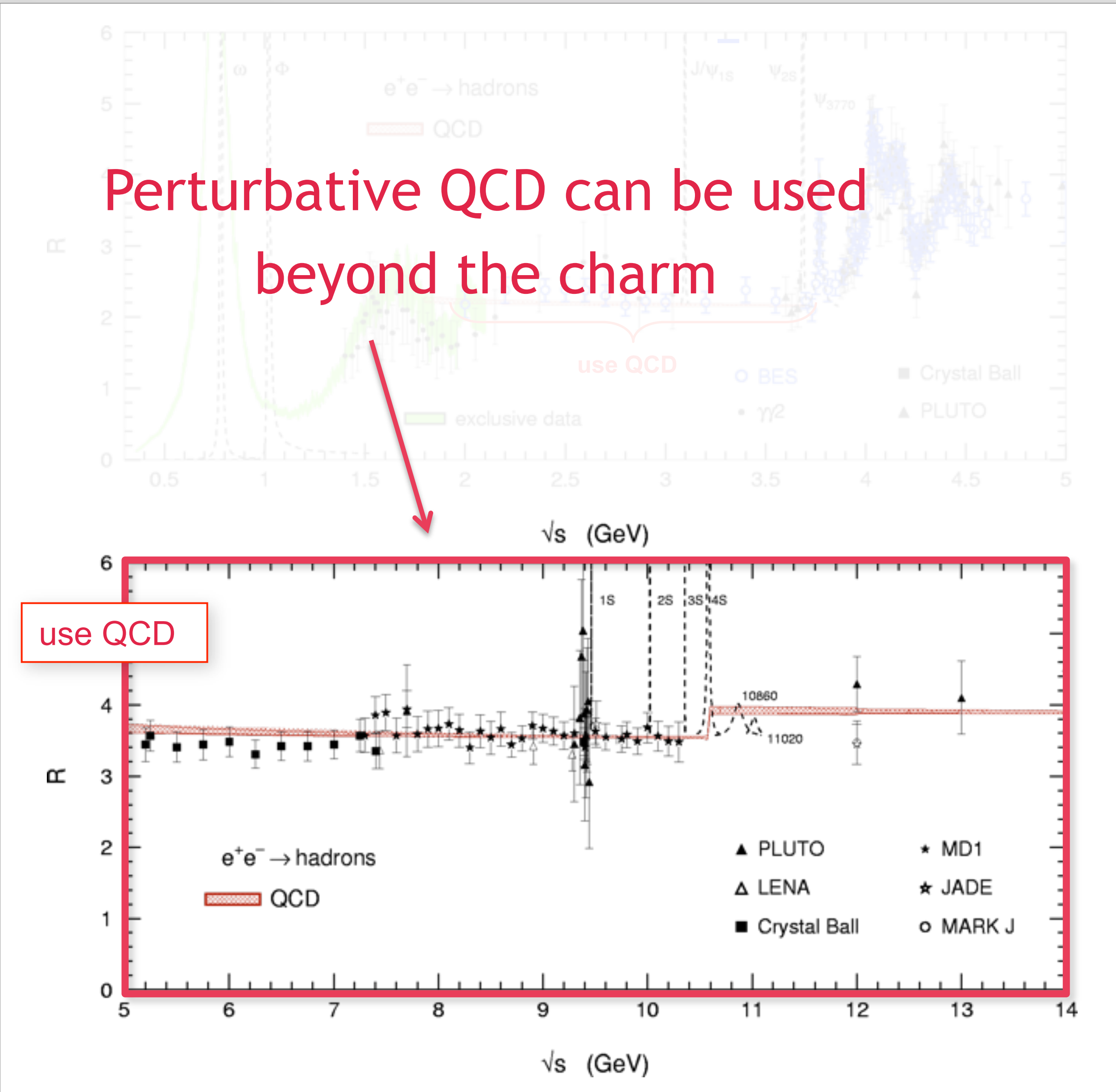
Experimental data must be used in the charm anti-charm resonance region

Plot not fully up to date – for illustration only

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

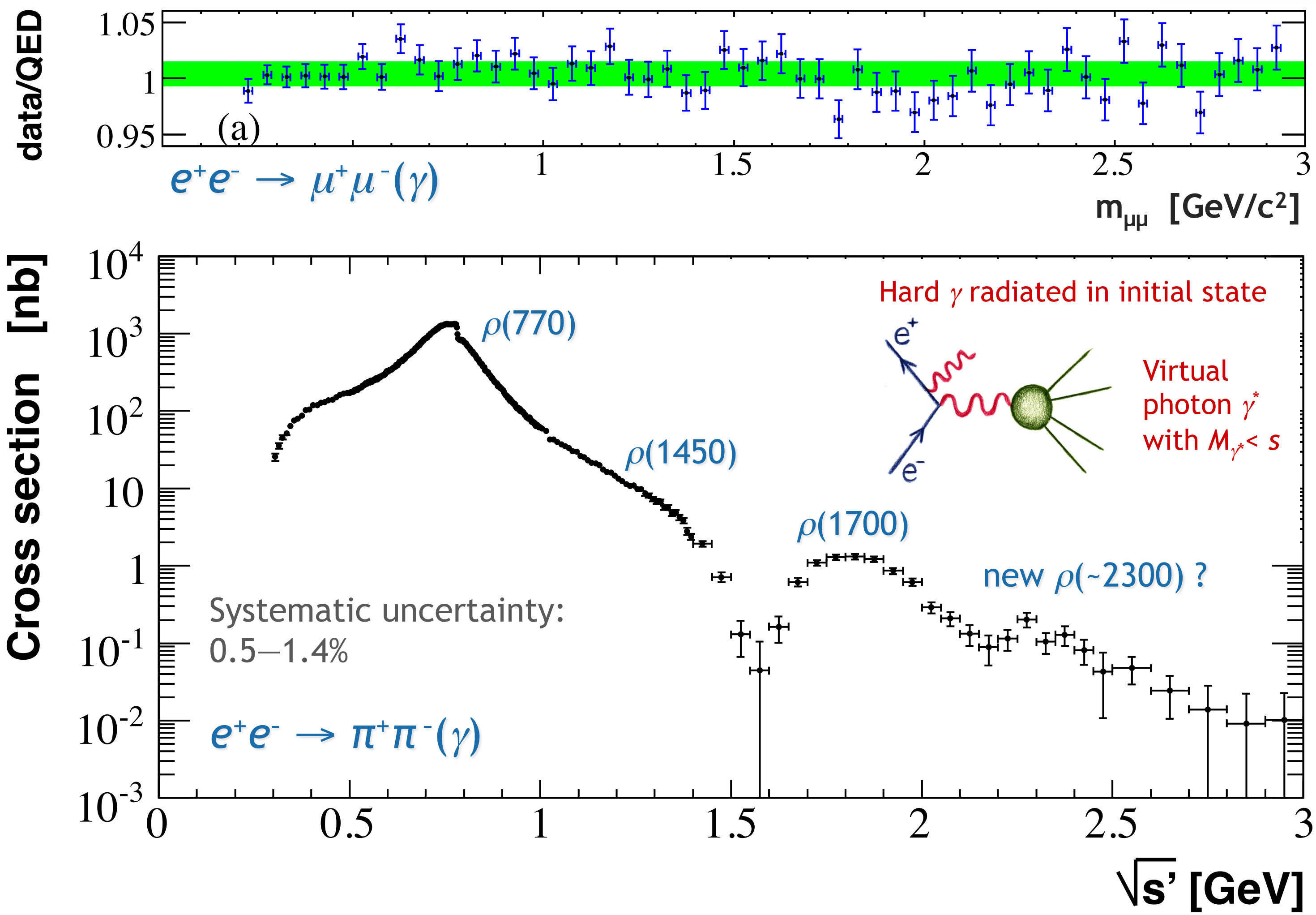
Perturbative QCD can be used beyond the charm

use QCD



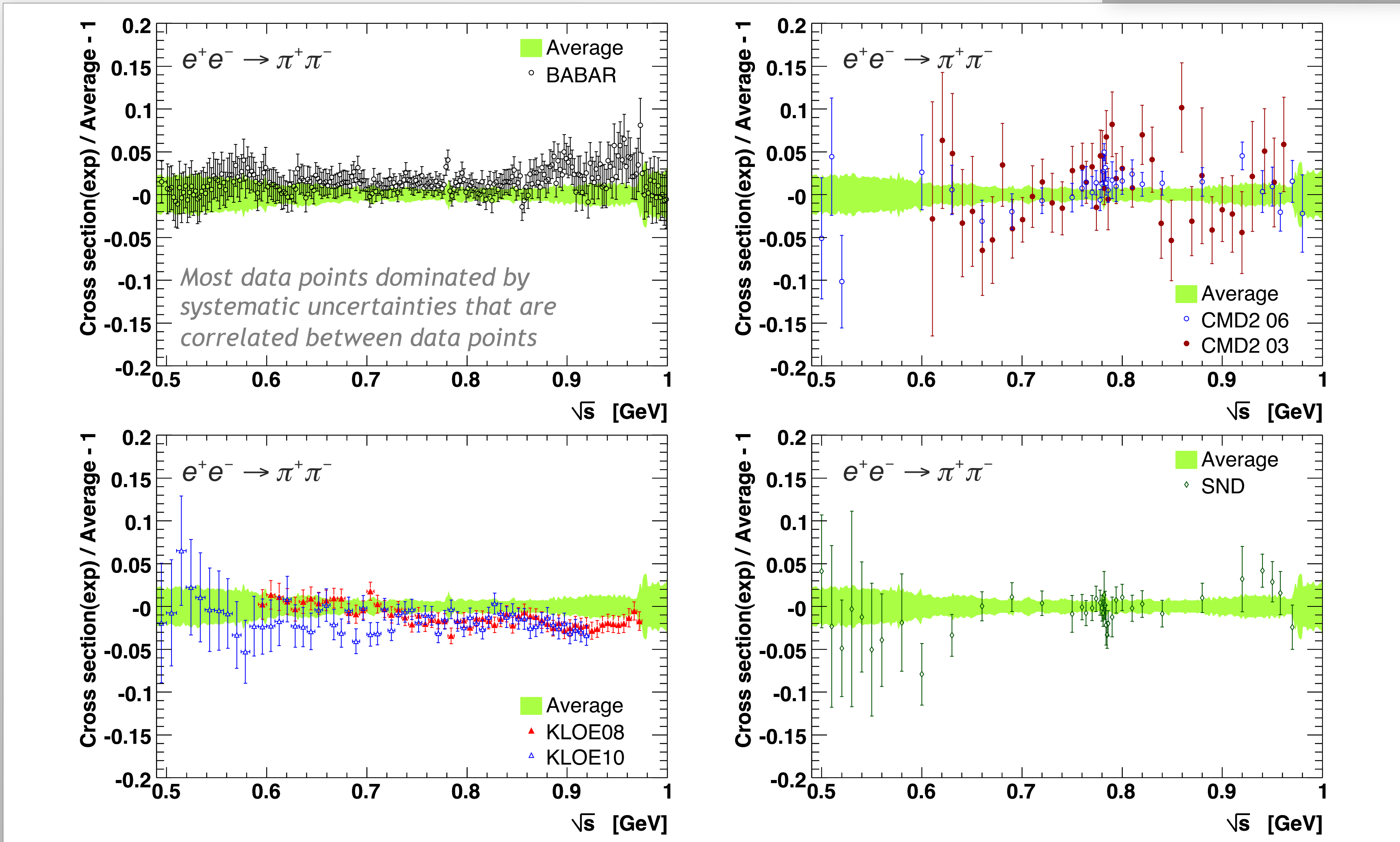
$e^+e^- \rightarrow \pi^+\pi^-(\gamma)$ Cross Section — *BABAR's tour de force*

BABAR, PRL 103, 231801 (2009)



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

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



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

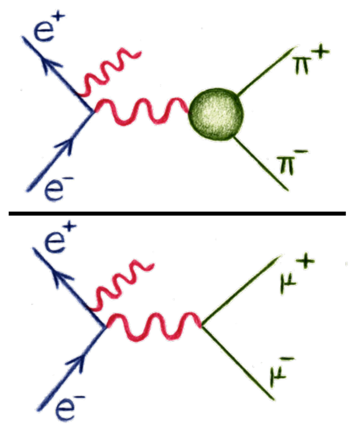
PRELIMINARY

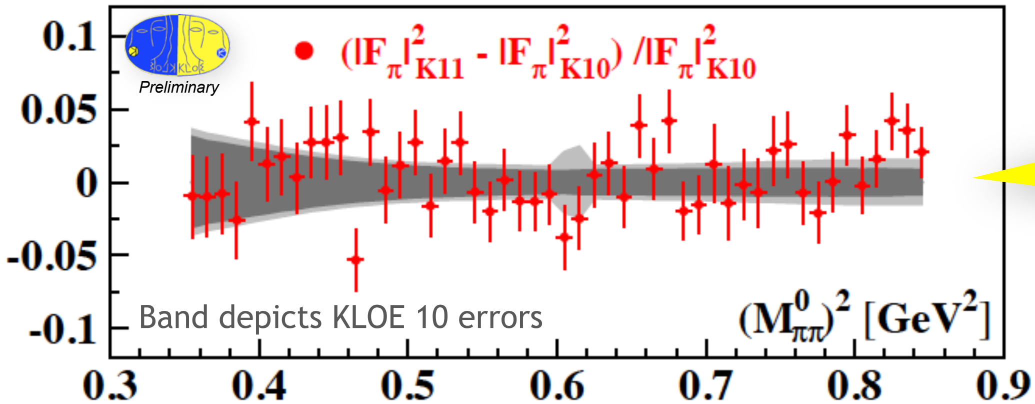
G. Venanzoni (KLOE) at EPS 2011

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%)

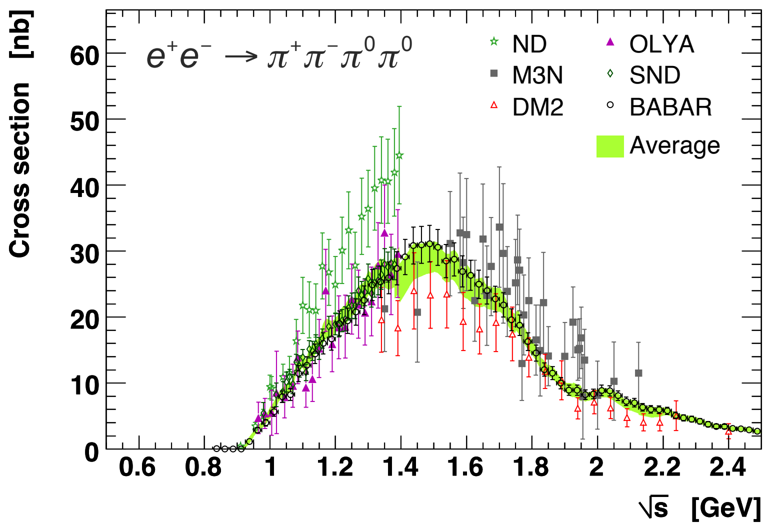


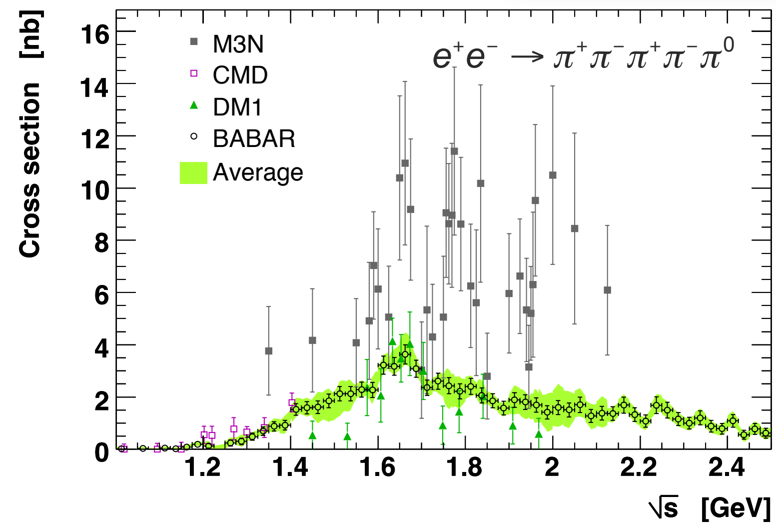


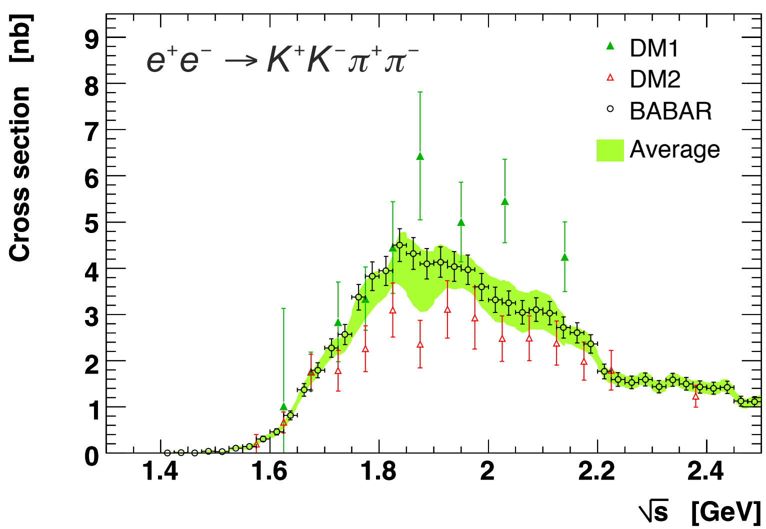
Good agreement found! This corroborates the earlier KLOE results and thus the discrepancy with BABAR (and τ data)

Examples for Rarer and High-Multiplicity Modes

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





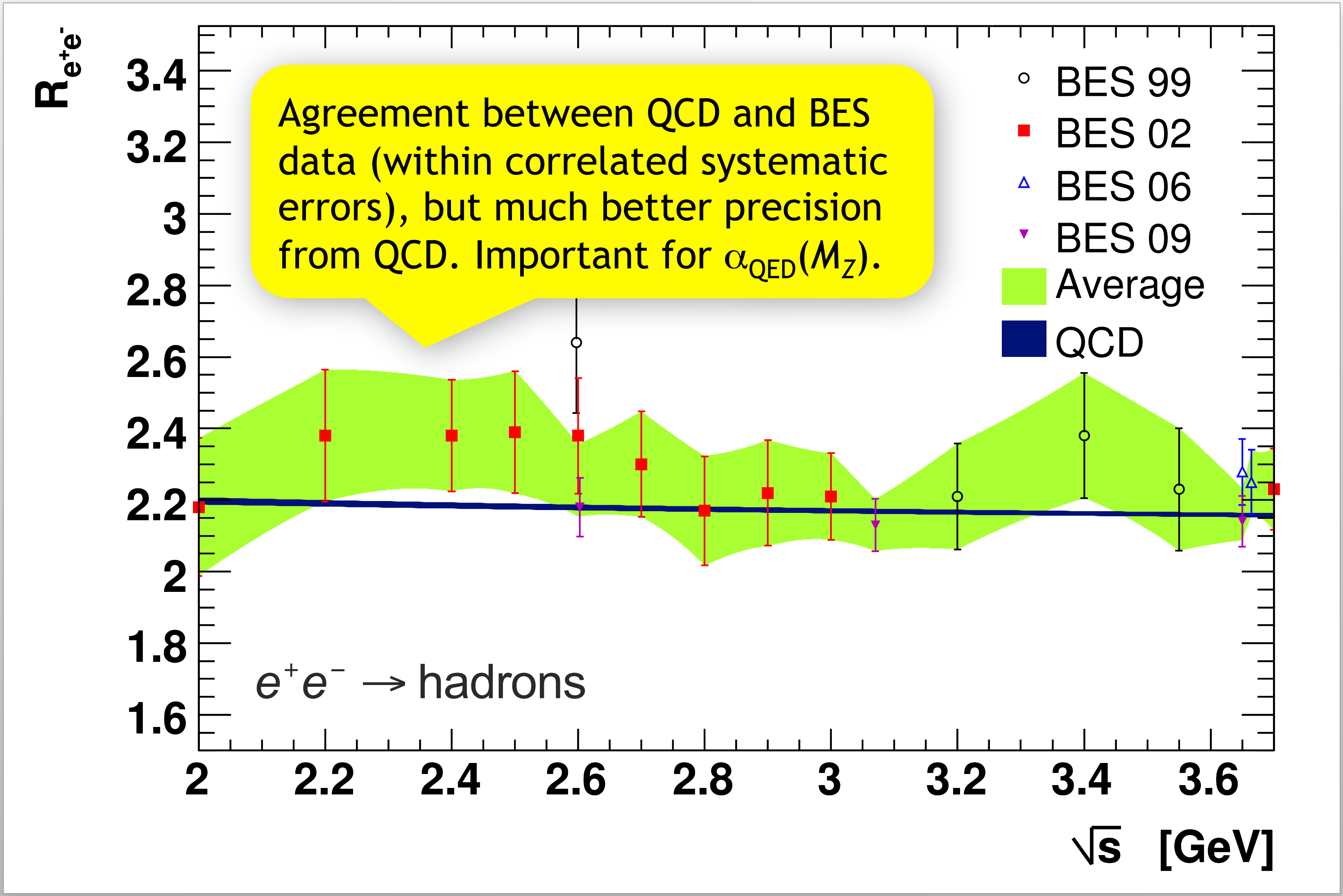


BABAR measured (almost) all the exclusive $e^+e^- \to$ hadrons modes

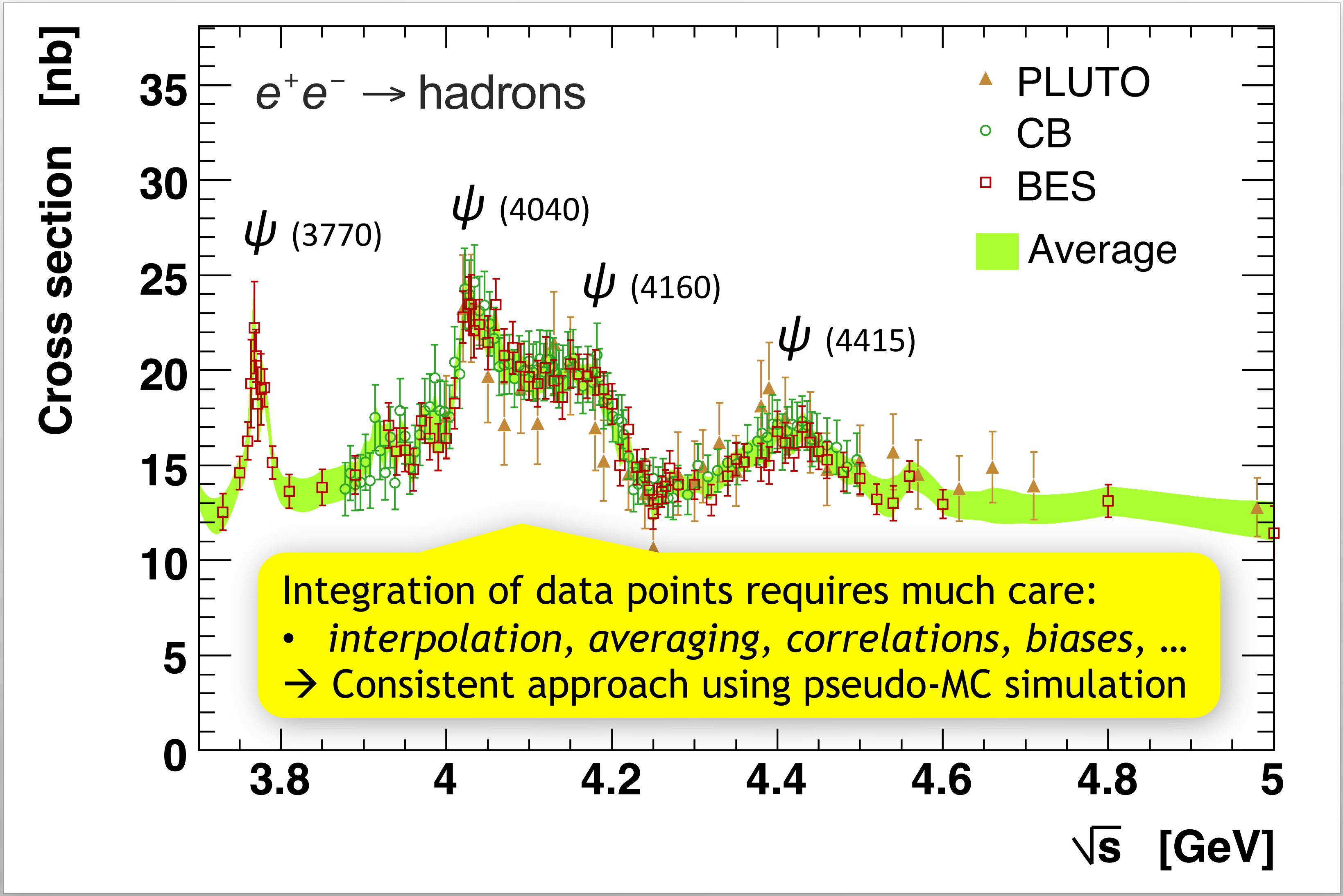
Many inconsistencies resolved

Huge impact on hadronic vacuum polarisation calculation

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



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



Integration of data points requires much care:

- *interpolation, averaging, correlations, biases, …*

→ Consistent approach using pseudo-MC simulation

Can use precise tau data to improve a_μ prediction

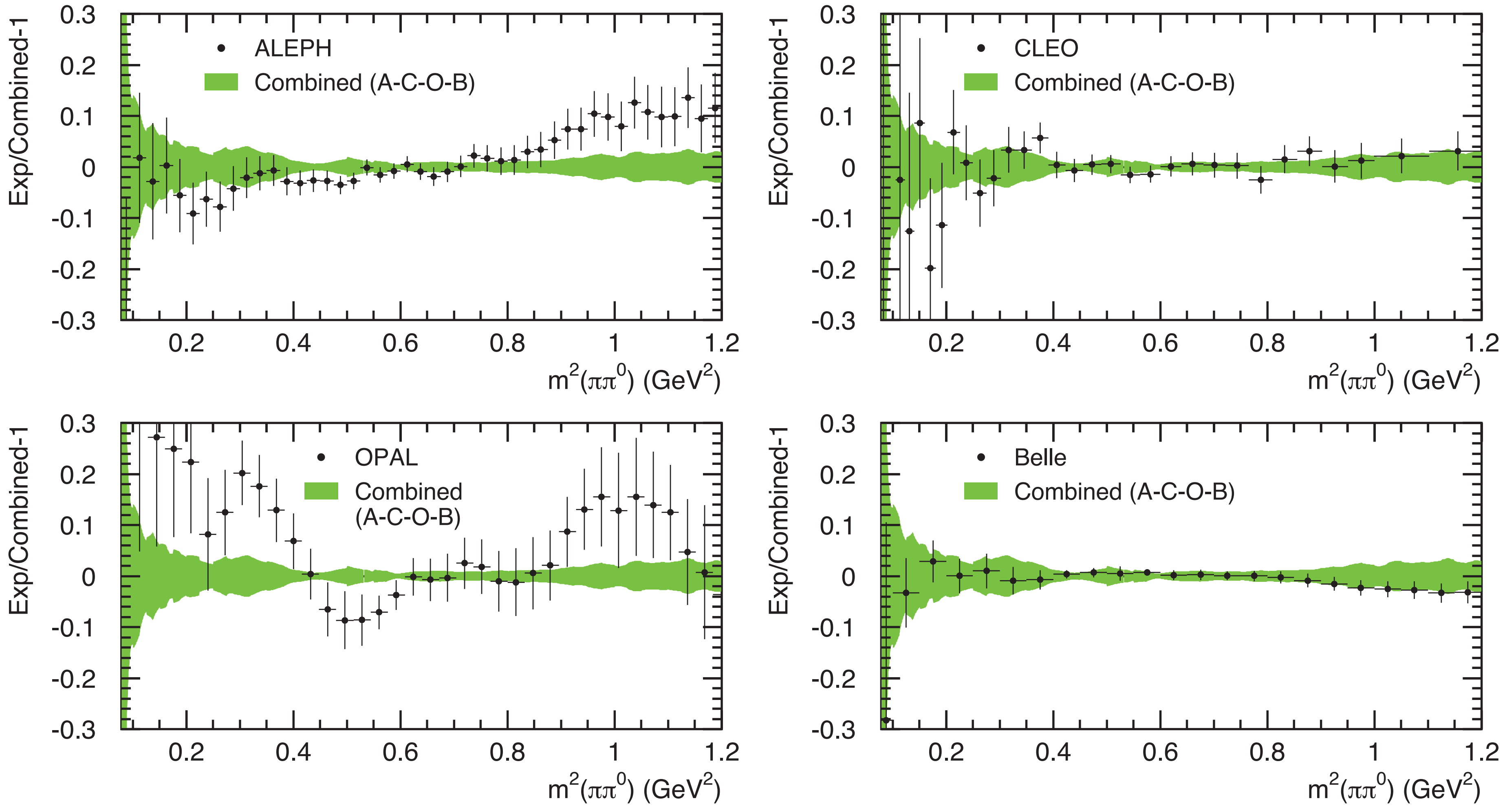
What do the Tau data tell us?

Can use precise tau data to improve a_μ prediction

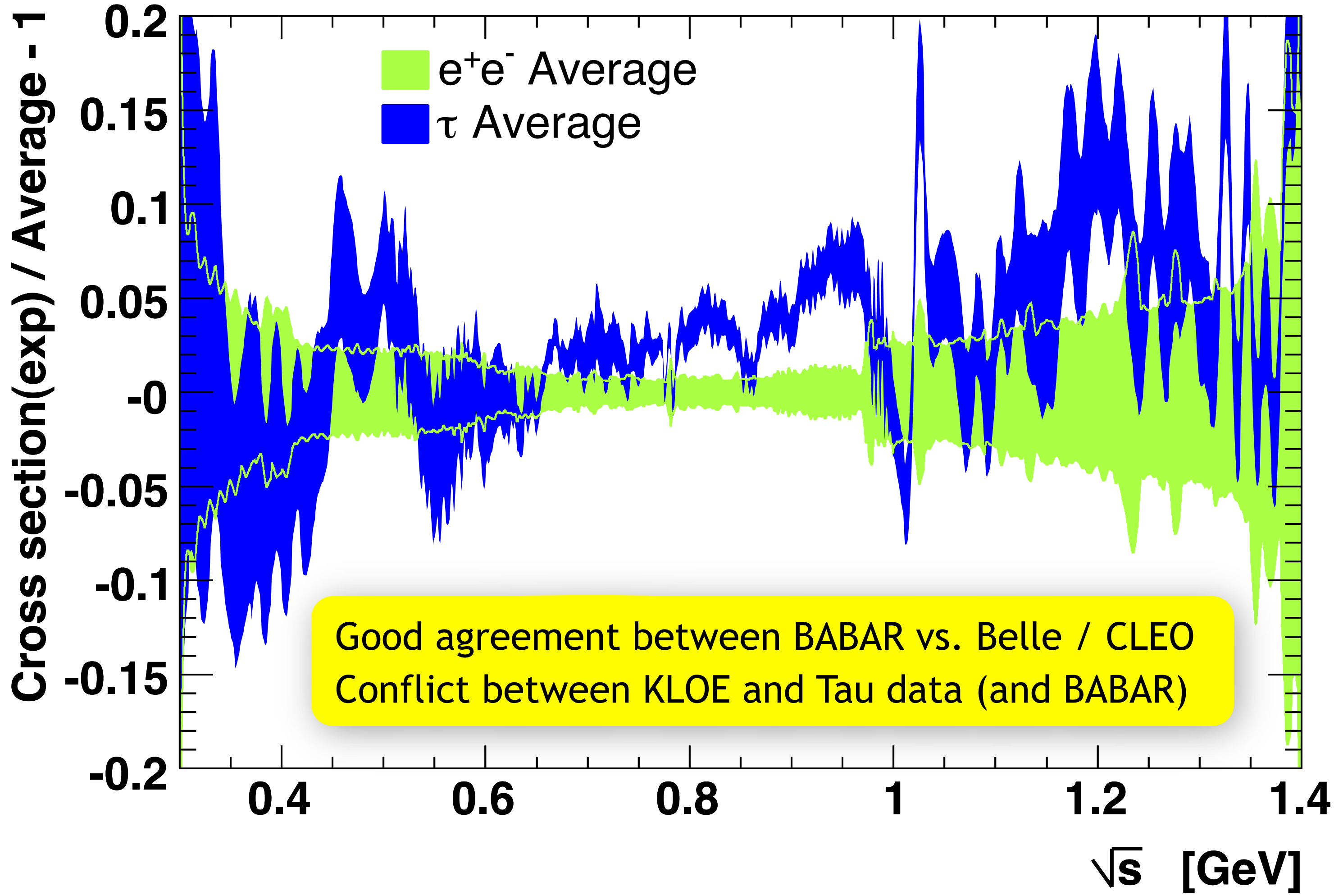
- In practice, used for 2π and 4π channels with isospin rotation
- Tau spectral functions measured by ALEPH, Belle, CLEO, OPAL
- Excellent precision of tau data. Branching ratio (ie, spectral function normalisation) for $\tau \to \pi\pi^0\nu$ known to 0.4%.
- Invariant mass spectrum requires unfolding 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 ± 0.4)% correction to a_μ^{had}

Situation of Two-Pion Channel (τ)



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



Good agreement between BABAR vs. Belle / CLEO
Conflict between KLOE and Tau data (and BABAR)

Adding all (28) Contributions Together

Hadronic LO term:

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

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

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

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

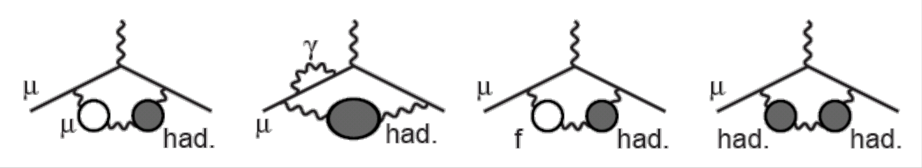
Hadronic NLO terms:

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

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

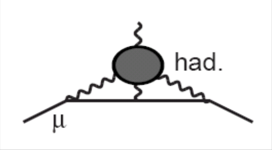
$$a_\mu^{\text{had,NLO}} = -9.8(0.1) \times 10^{-10}$$

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 ???)

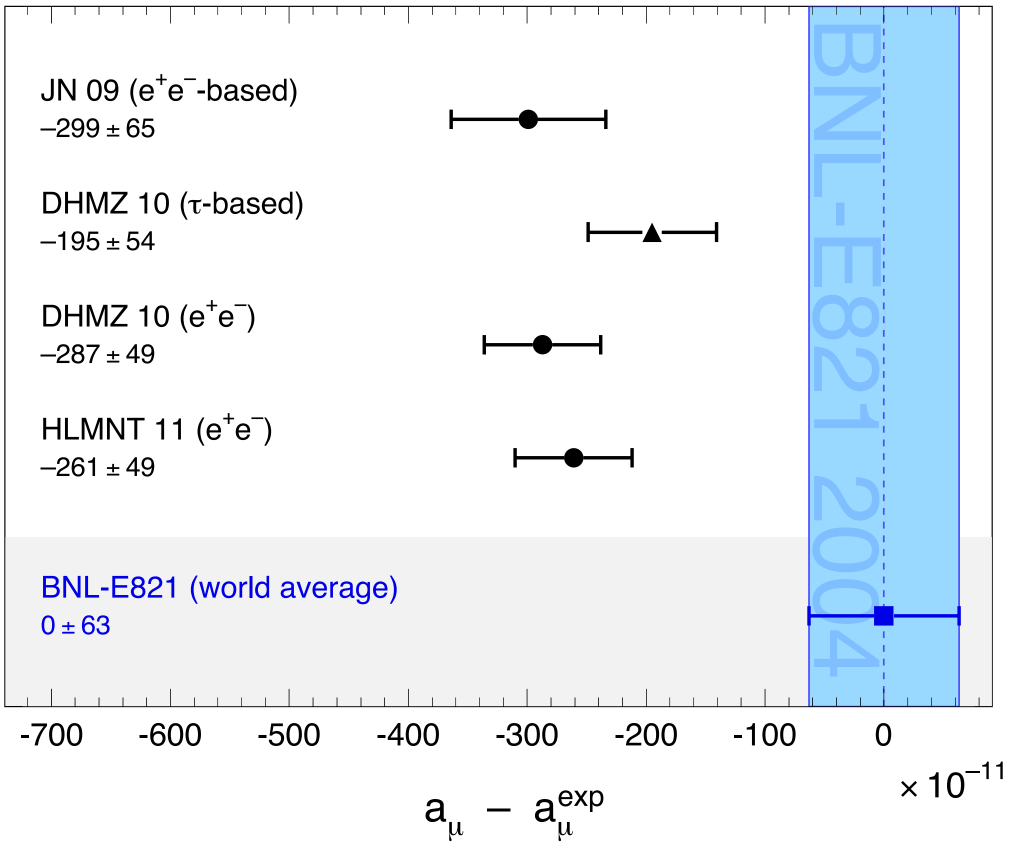
Results for Muon $g-2$

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

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

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

Status: summer 2011 (*published results shown only*)



BNL E821 (2004):
$a_\mu^{exp} = (11\,659\,208.9 \pm 6.3) \times 10^{-10}$

Difference: experiment – SM

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

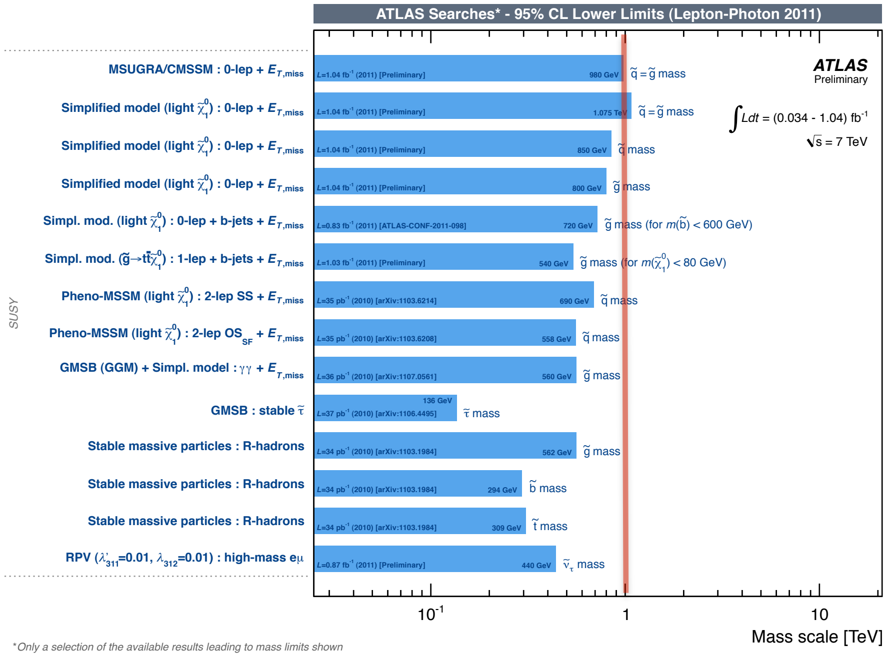
- ➡ 3.6 "standard deviations" (e^+e^-)
- ➡ 2.4 "standard deviations" (τ)

What could a $\Delta a_\mu \approx 30\times10^{-10}$ Deviation Tell Us?

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

$$\Delta a_\mu^{\rm SUSY} \approx +13\cdot10^{-10}\,{\rm sgn}(\mu)\left(\frac{100\ {\rm GeV}}{m_{\rm SUSY}}\right)^2 \tan\beta$$

But strong $m_{\rm SUSY}$ 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 $\varepsilon\cdot e$

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

which, for $\varepsilon \approx 0.001$—$0.002$ 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)

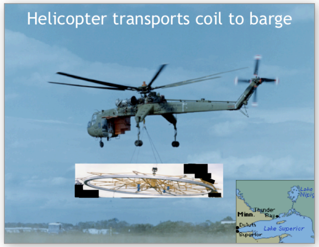
A Future for the Muon $g-2$

Unfortunately, the situation stays non-conclusive

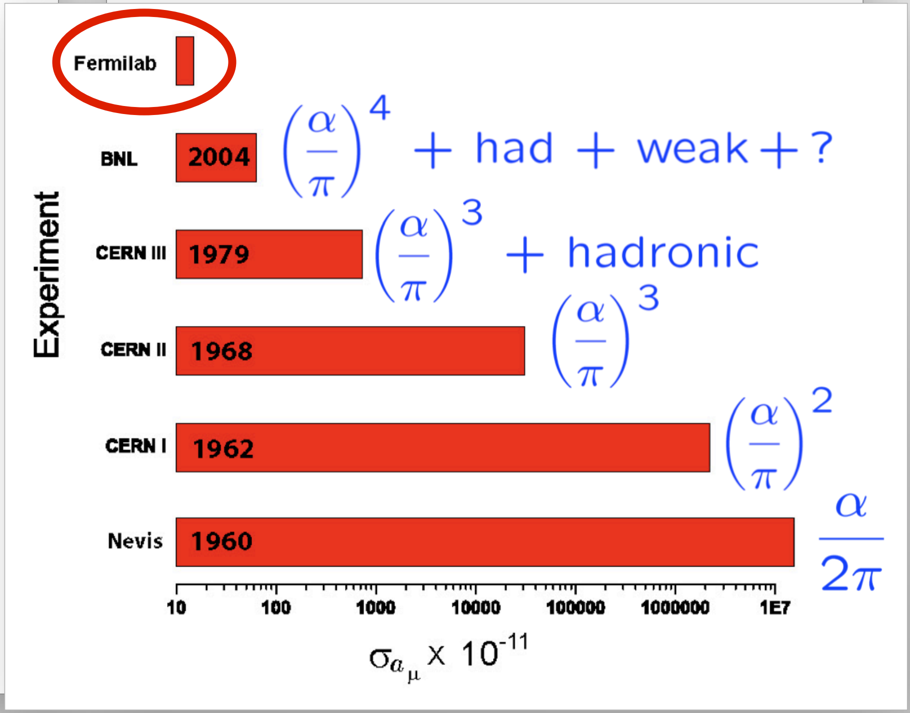
But: current discrepancy still limited by experimental uncertainty

Fortunately, improvements are in view !

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 proposall:
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

A Future for the Muon $g-2$

Final E989 proposall: 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) → less pion "flash" at muon ring injection
  - Zero-degree muons → 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

  → 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

Final E989 proposall: 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)

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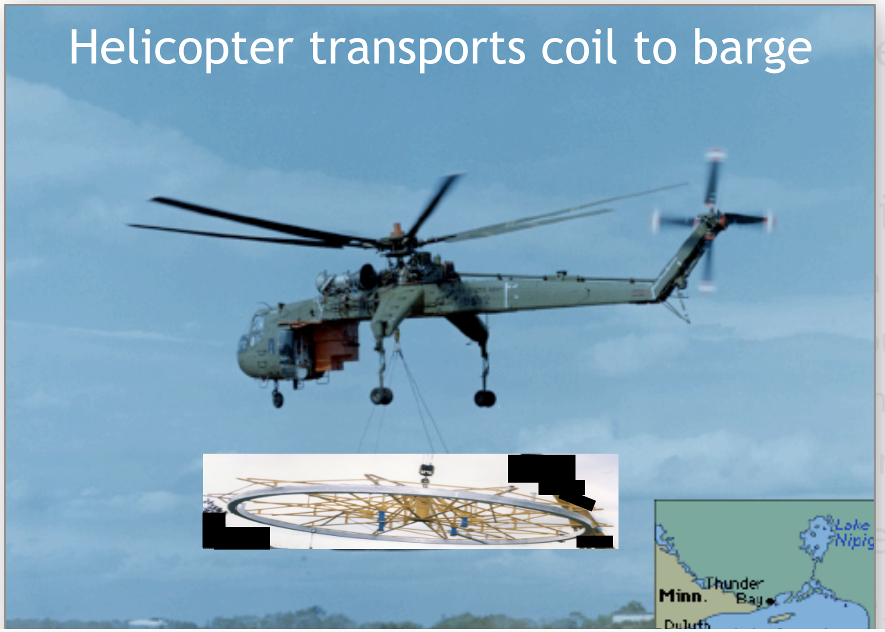
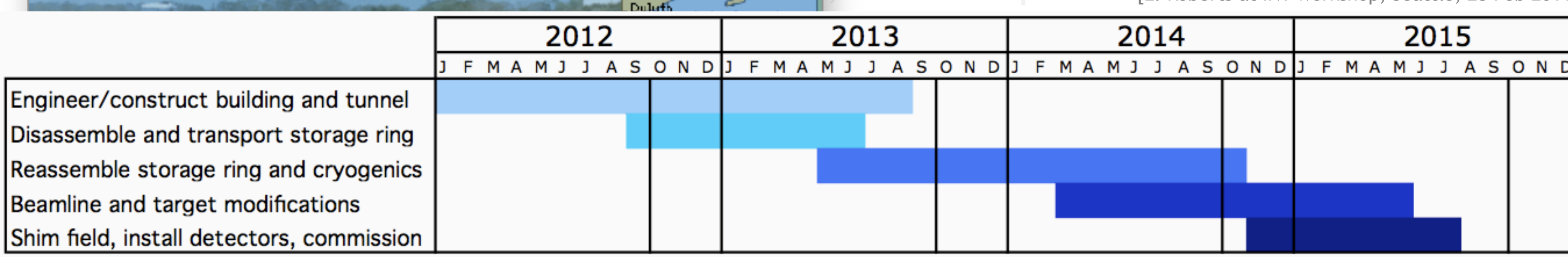


ermilab (12 T weight)
ilab
than at BNL
und at muon ring injection
uon yield per proton as BNL
r as BNL
up, new electronics, better
, more improve

Projected E989 timeline as of Feb 2011
[L. Roberts at INT workshop, Seattle, 28 Feb 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

E821 at BNL

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*.

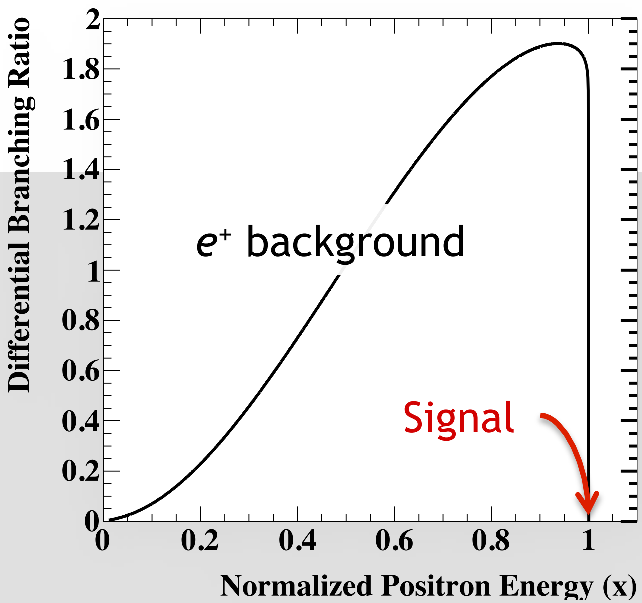
Extra slides…

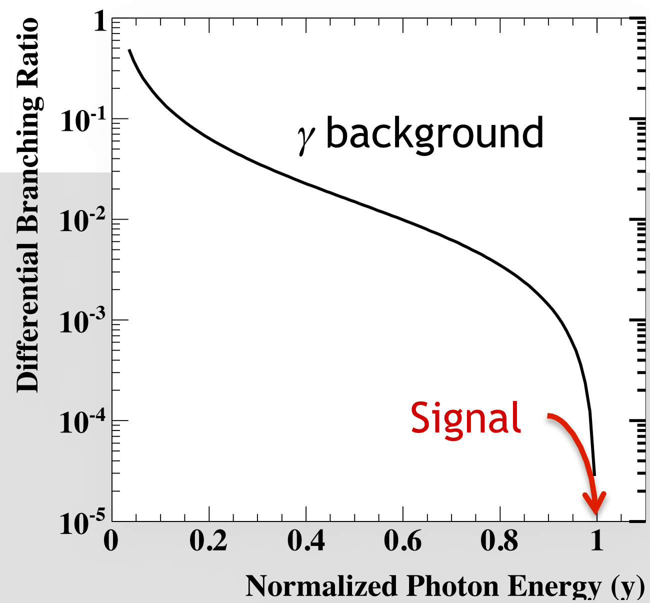
Full Analysis of 2009 and 2010 MEG Data

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, $T_{e\gamma}$, $\theta_{e\gamma}$, $\varphi_{e\gamma}$ with PDFs mostly derived from data, fitting signal + RMD + accidental bkg. components

Must cope with high *e*+ rate





Good γ resolution most critical

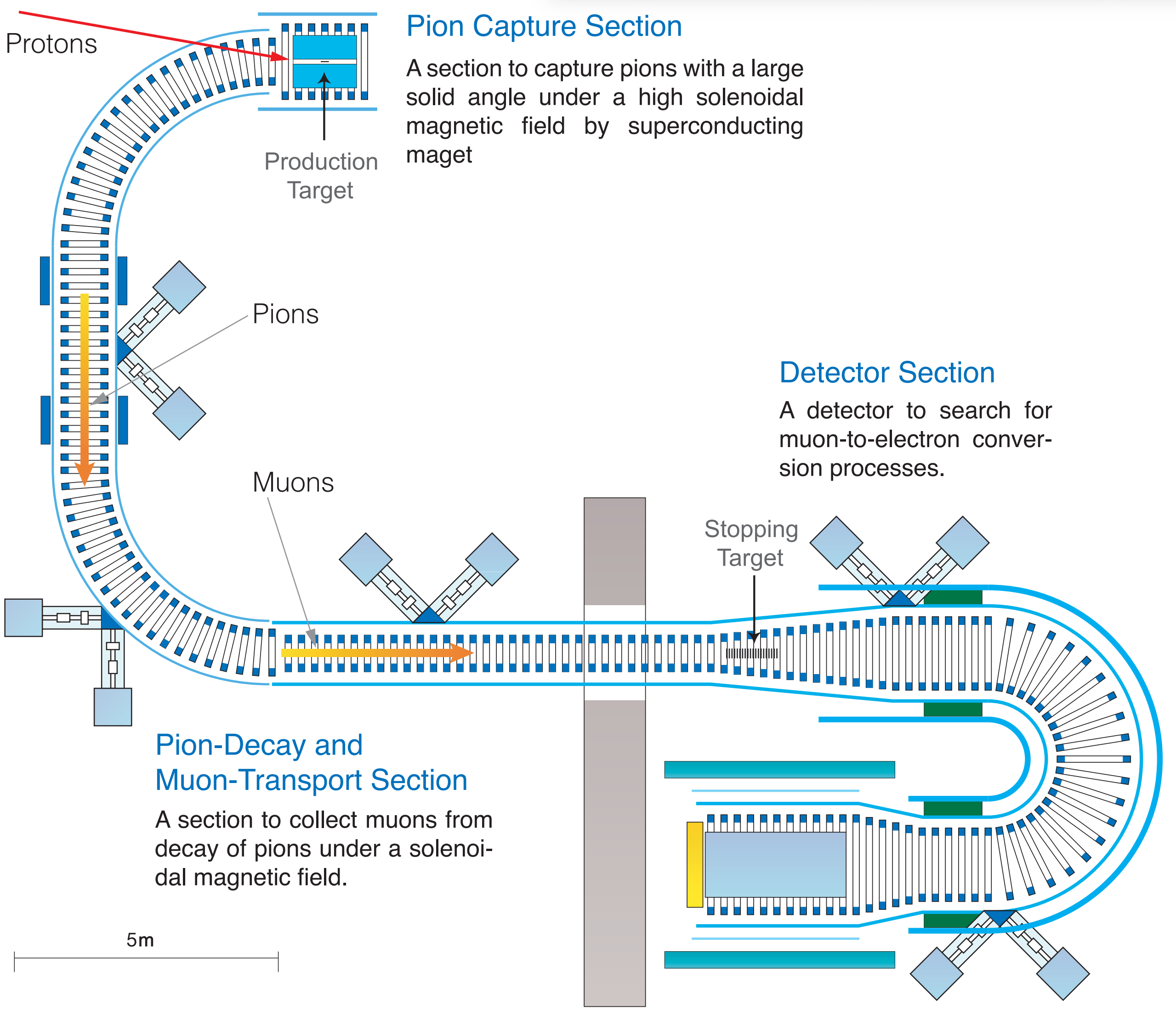
MEG arXiv:1107.5547, T. Mori at EPS-HEP-2011

COMET (J-PARC) Overview

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

Similar design features as Mu2e:

- Sensitivity: $R_{\mu e}$ ~ 3×10^{-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



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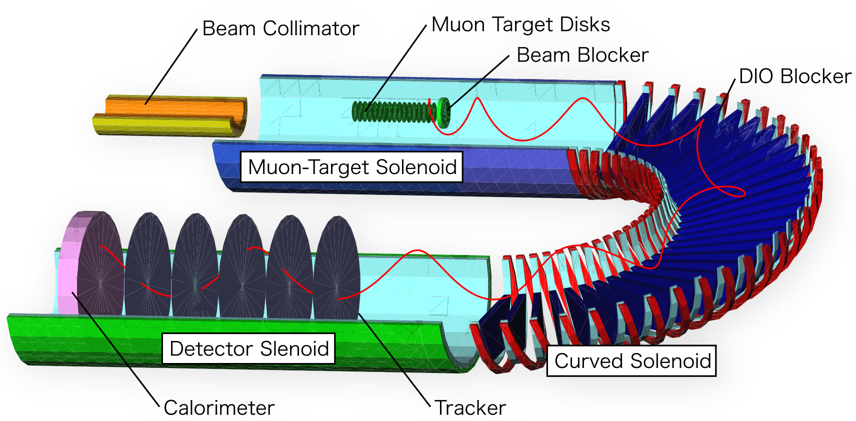
- Curved solenoids for muon charge and momentum selection
- C-shaped (as opposed to S-shaped) transport for better p_μ selection
- C-shaped detector section eliminates low-E DIO e and protons

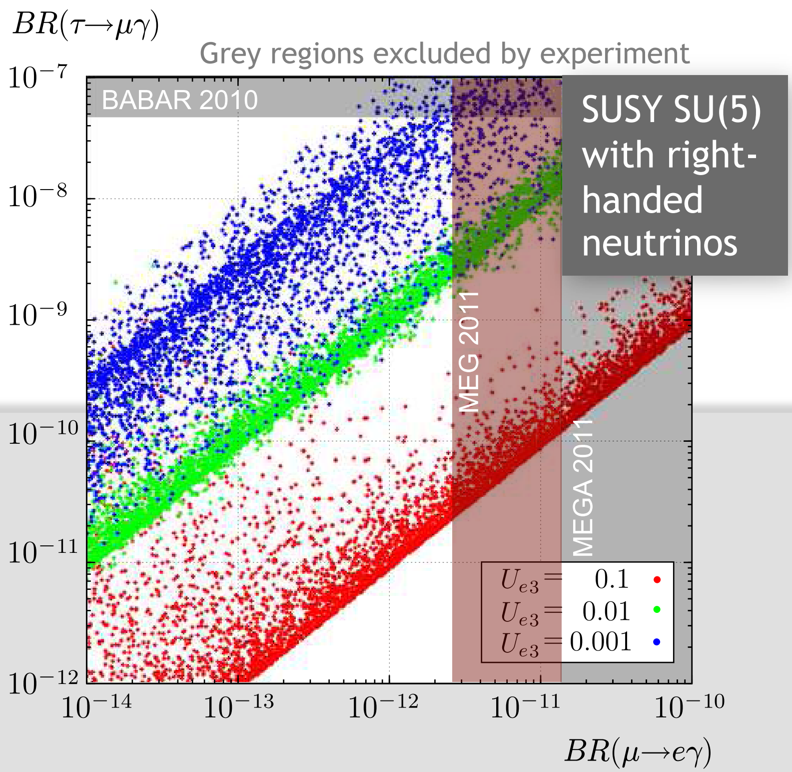
Schedule:

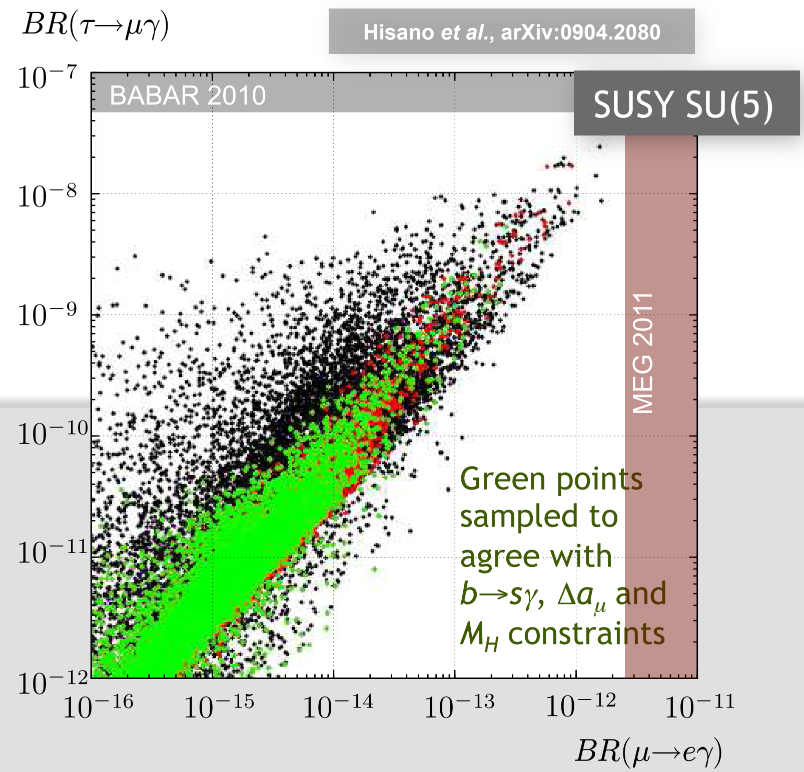
- Stage-1 approval obtained in 2009 (CDR)
- TDR expected end of 2011
- Superconducting magnet design biggest challenge
- Pion capture tested with MuSIC (Osaka)
- Request funding in 2014/2015
- Data taking in 2018
- Upgrade project to PRISM (with muon storage ring) expecting sensitivity of $R_{\mu e} \sim 3\times10^{-19}$



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



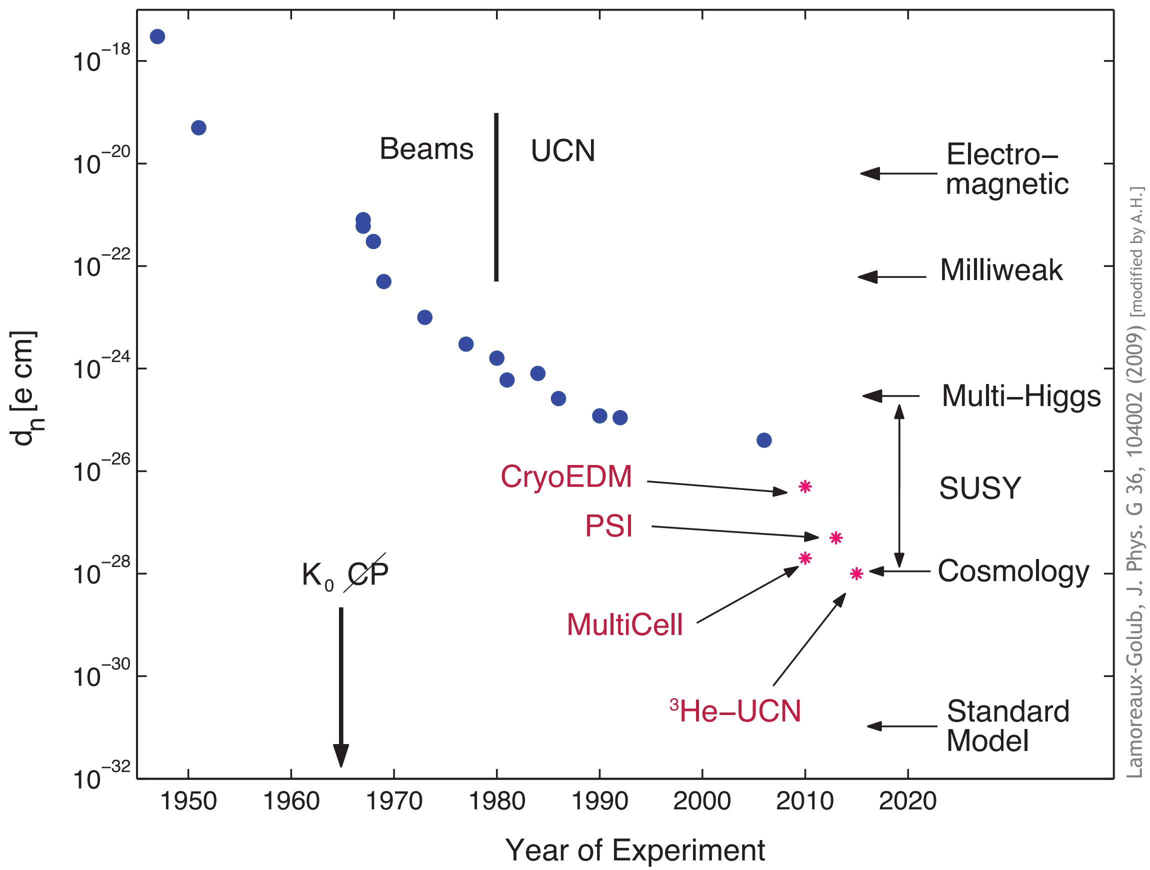


EDM - Experimental Programme

90% CL limits given

Neutron EDM

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



EDM - Experimental Programme

90% CL limits given

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

Muon EDM

Best limit: $|d_\mu| < 1.9 \times 10^{-19}$ *e*cm [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, $|d_\mu| >> |d_e|$, but may need sensitivity of 10^{-23} *e*cm to be competitive with current $|d_e|$ limits

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

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

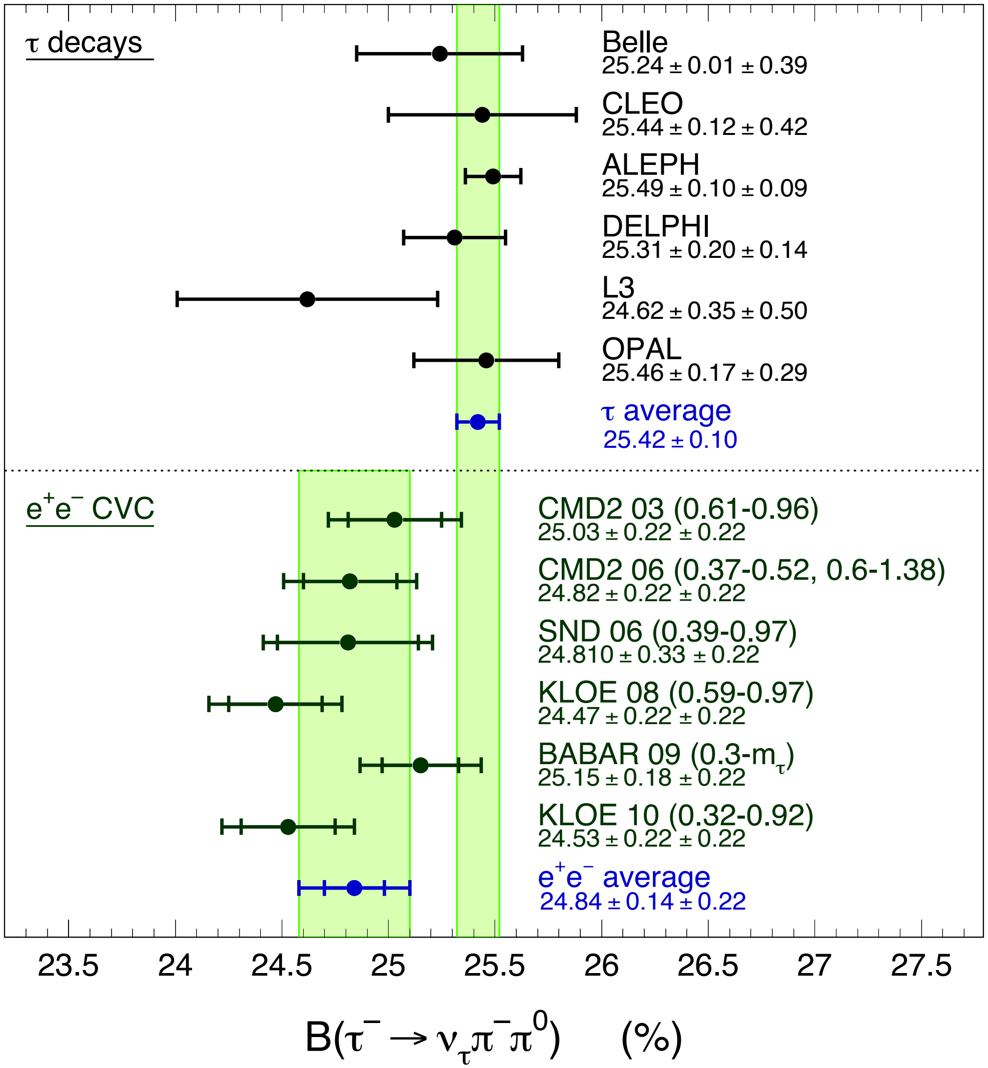
Measurement uses in addition to positron scintillators other detectors sensitive to the vertical decay-electron position. Final result dominated by systematic uncertainties

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 ($p_\mu(B, E)$ ~ 125 MeV) ***and*** E=0 modes

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



$$\mathrm{BR}^{\mathrm{CVC}}_{\tau^- \to \pi^- \pi^0 \nu_\tau} \propto \int_0^{m_\tau^2} ds\, \mathrm{kin}(s) \cdot \sigma^{\text{IB-corrected}}_{e^+e^- \to \pi^+\pi^-}(s)$$

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

Difference: BR[τ] – BR[e^+e^- (CVC)]:

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

The Muon $g-2$ in the Standard Model

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

QED contribution

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

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

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

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

Computed up to 2nd order

a_μ^{weak} suppressed by $\frac{\alpha}{\pi}\frac{m_\mu^2}{m_W^2} \sim 10^{-9}$ (!)

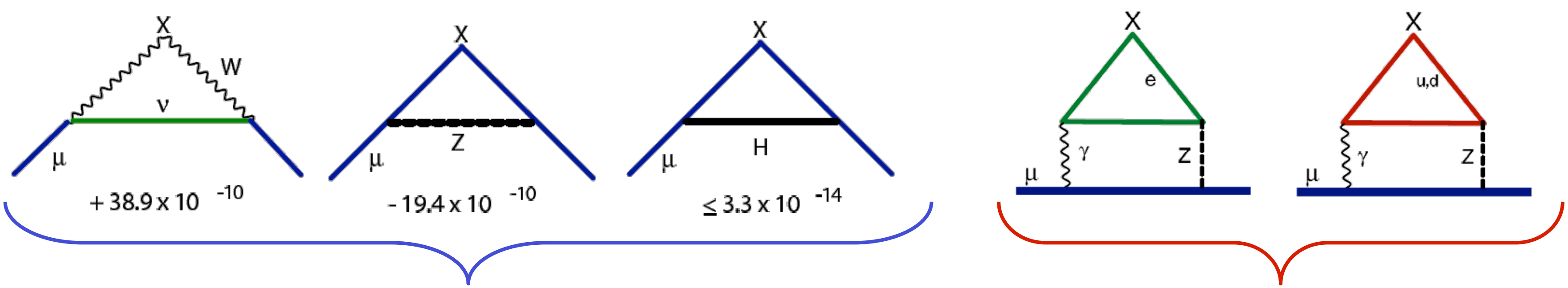
$$\underbrace{a_\mu^{\text{weak}}}_{\text{1-loop}} = \frac{G_\mu m_\mu^2}{8\sqrt{2}\pi^2}\left(\frac{5}{3}+\frac{1}{3}\left(1-4\sin^2\theta_W\right)+\mathcal{O}\left(\frac{m_\mu^2}{m_W^2}\right)+\mathcal{O}\left(\frac{m_\mu^2}{m_H^2}\right)\right) = +19.5\times10^{-10}$$

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

2nd order contribution surprisingly large: $\underbrace{a_\mu^{\text{weak}}}_{\text{2-loop}} = -4.1(0.2)\times10^{-10}$

(due to large logs: $\ln[m_Z / m_\mu]$)

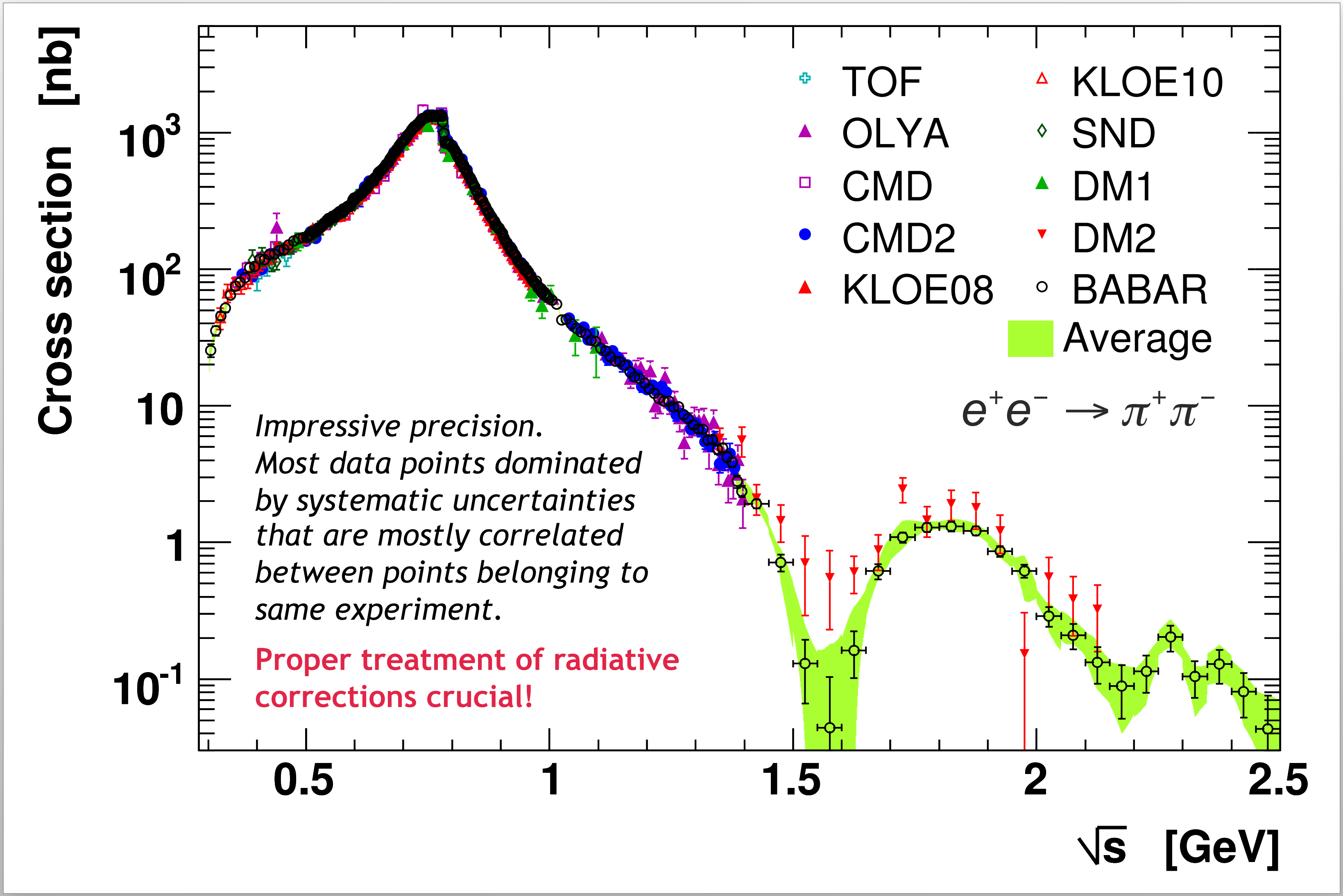
Note that between a_μ and a_e, the same sensitivity factor as for new physics applies here



1-loop [computed in 1972]

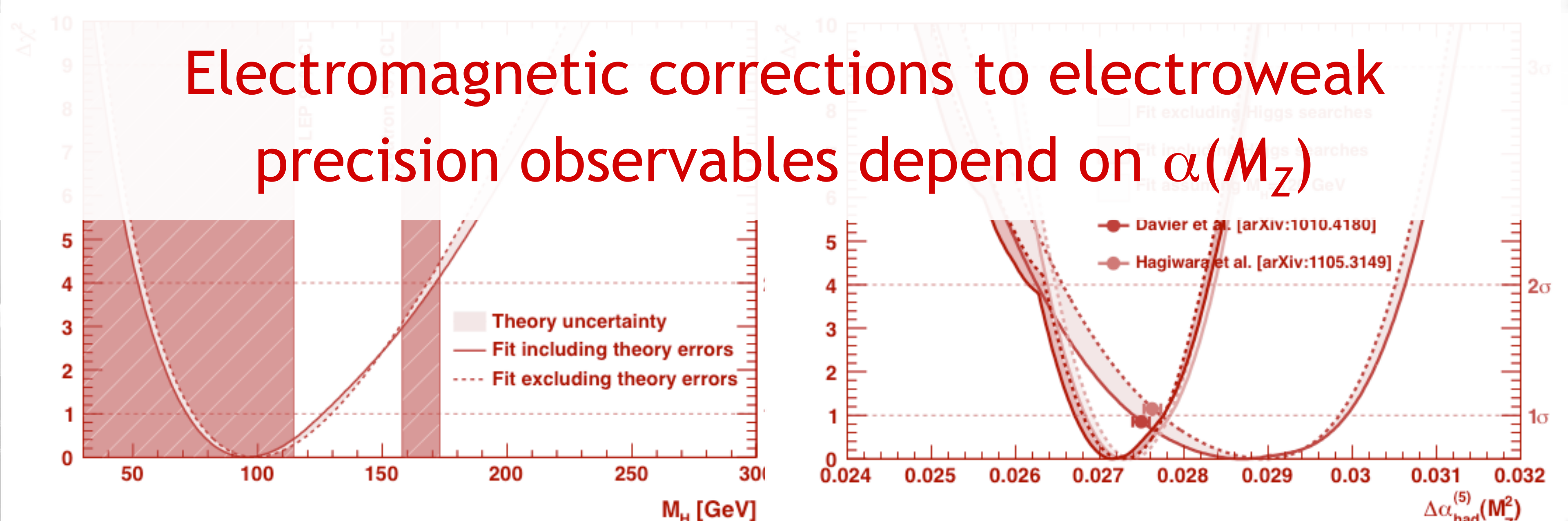
2-loop

$e^+e^- \to \pi^+\pi^-$ Cross Section — *Compilation*



There is also the Running of α_{QED} !

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



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

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 $\Delta\alpha_{had}(M_Z)$ 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} !

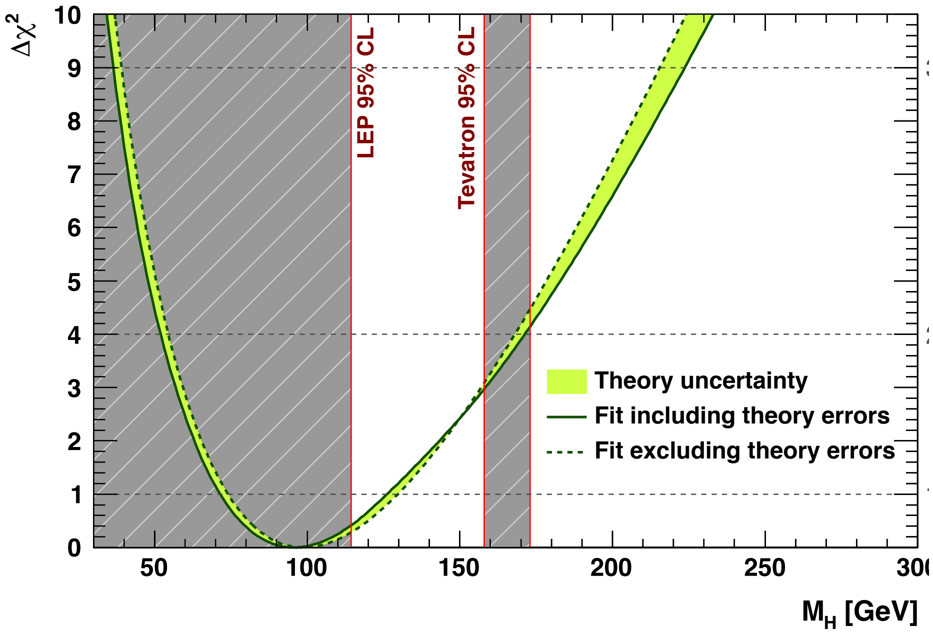
New evaluation of hadronic contribution:

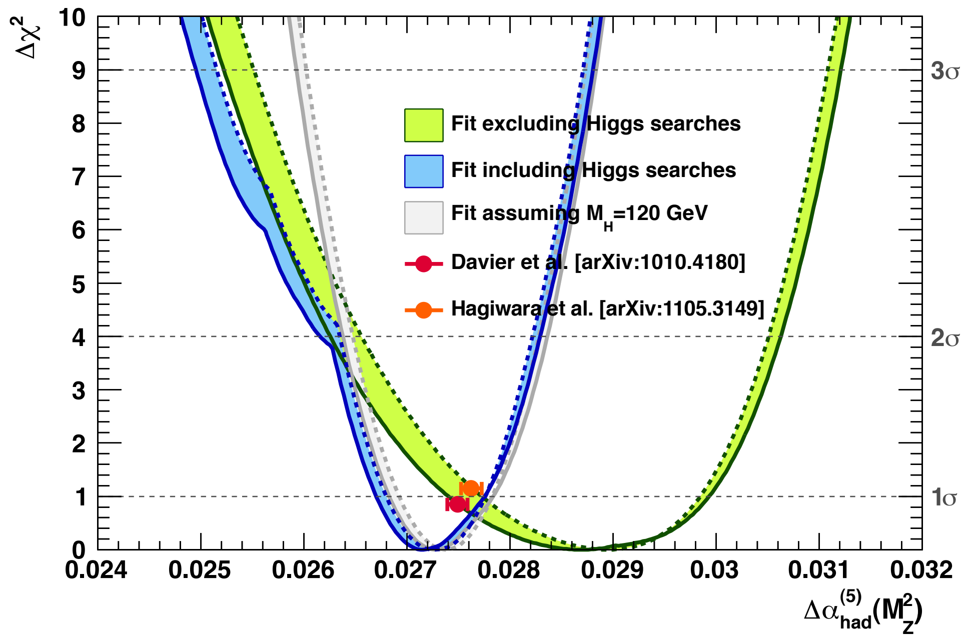
$\Delta\alpha_{had}^{(5)}(M_Z) = 0.02749 \pm 0.00010$

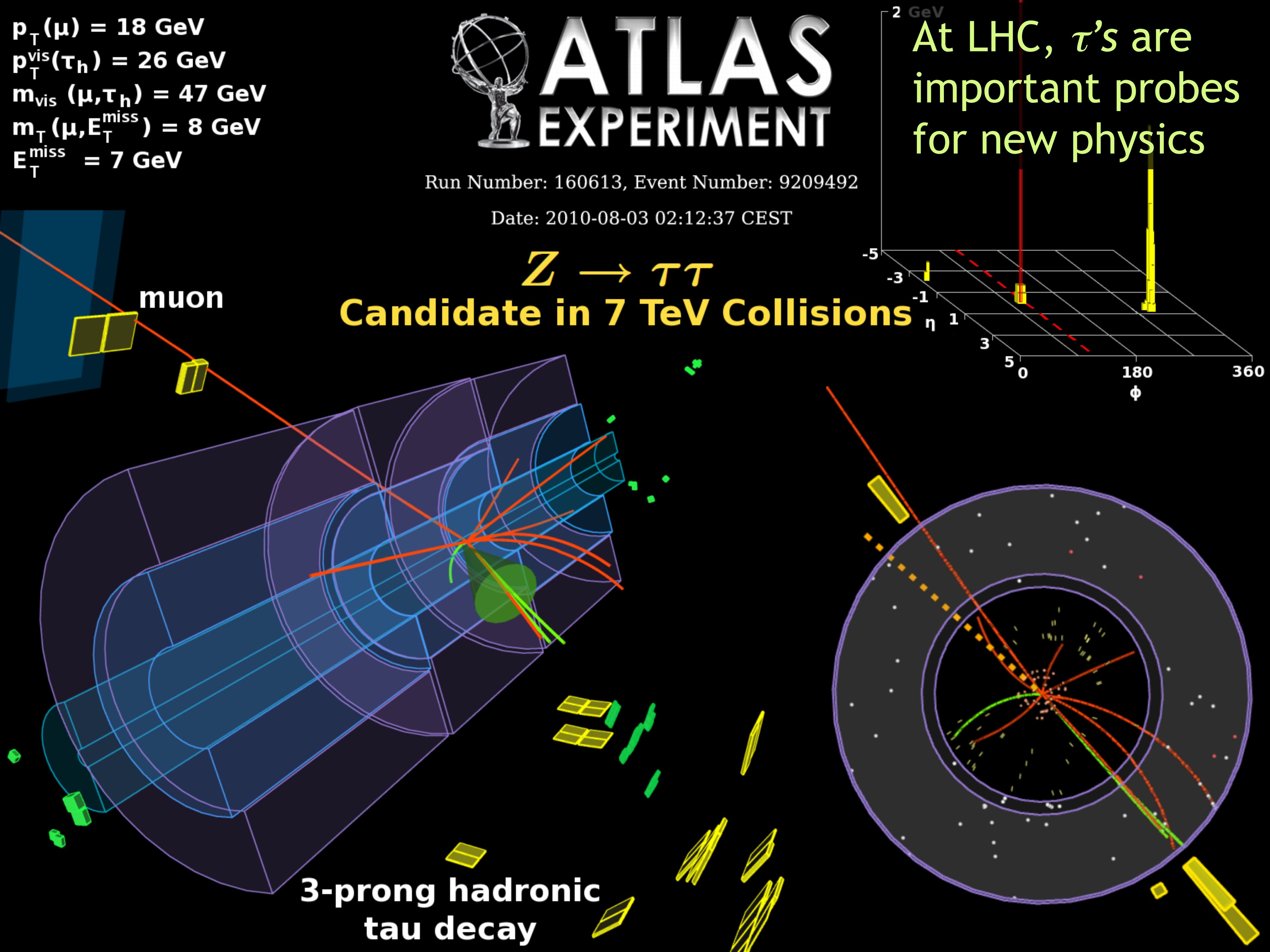
reduces EM coupling strength, thus increasing Higgs mass estimate from global electroweak fit by +12 GeV, which reduces tension with LEP bound*

*Due to–40% correlation between $\Delta\alpha_{had}(M_Z)$ 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} !







$p_T(\mu)$ = 18 GeV
$p_T^{vis}(\tau_h)$ = 26 GeV
$m_{vis}(\mu,\tau_h)$ = 47 GeV
$m_T(\mu,E_T^{miss})$ = 8 GeV
E_T^{miss} = 7 GeV
ATLAS EXPERIMENT
Run Number: 160613, Event Number: 9209492
Date: 2010-08-03 02:12:37 CEST
$Z \to \tau\tau$
Candidate in 7 TeV Collisions
muon
3-prong hadronic tau decay
At LHC, τ's are important probes for new physics
2 GeV
-5
-3
-1
1
3
5
η
0
180
360
φ