Fundamental Symmetries Overview

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NPAC

Theoretical Nuclear, Particle, Astrophysics & Cosmology

http://www.physics.wisc.edu/groups/particle-theory/

NSAC Subcommittee, September 2012

Outline

I. *2007 Recommendation: “Targeted program”*
II. *Post 2007 Developments*
III. *Scientific & programmatic implications*
IV. *Outlook*

I. 2007 LRP Recommendation

2007 NSAC Long Range Plan

RECOMMENDATION III

We recommend a targeted program of experiments to investigate neutrino properties and fundamental symmetries. These experiments aim to discover the nature of the neutrino, yet-unseen violations of time-reversal symmetry, and other key ingredients of the New Standard Model of fundamental interactions. Construction of a Deep Underground Science and Engineering Laboratory is vital to U.S. leadership in core aspects of this initiative.

2007 NSAC Long Range Plan

Scientific Questions

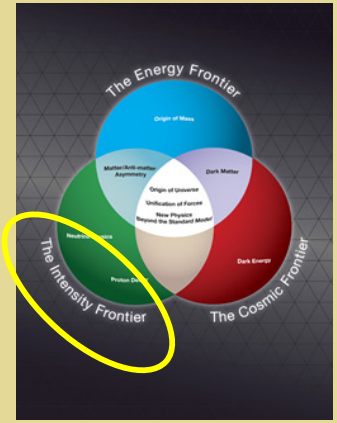
Fundamental Symmetries and Neutrinos

- What is the nature of the neutrinos, what are their masses, and how have they shaped the evolution of the universe?
- Why is there now more visible matter than antimatter in the universe?
- What are the unseen forces that were present at the dawn of the universe but disappeared from view as the universe evolved?

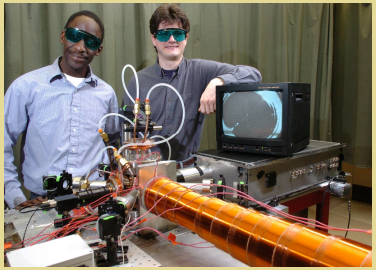
Four Components

EDM searches: *BSM CPV, Origin of Matter*	***$0\nu\beta\beta$ decay searches:*** *Nature of neutrino, Lepton number violation, Origin of Matter*
Lepton accelerators: *SM Precision Tests, BSM "diagnostic" probes*	***Smaller scale:*** *Weak decays, m_ν, "dark photons", non-Newtonian gravity, theory…*

Three Frontiers



Energy Frontier

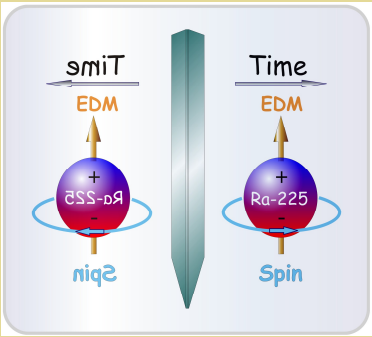


Precision Frontier or Intensity Frontier

Astro-Cosmo Frontier

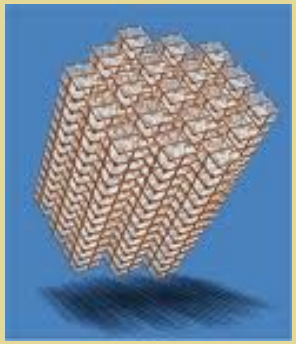
Intensity Frontier: Rare Processes

EDM Searches



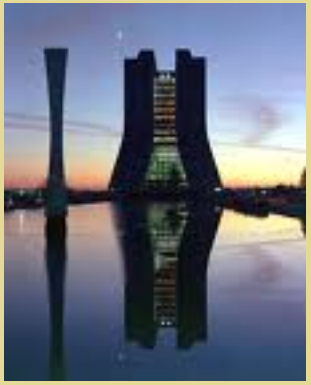
- *nucleon*
- *atoms*
- *leptons*

$0\nu\beta\beta$ Searches



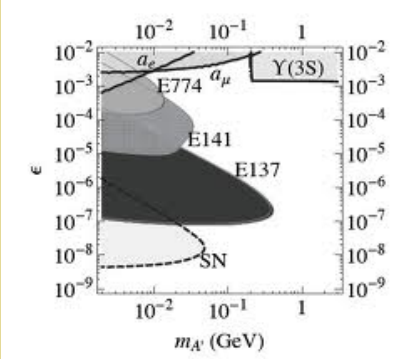
- *Cuore*
- *Exo*
- *Majorana*
- *SNO +*

CLFV Searches



- *mu2e*
- *PRIME*
- *EIC*

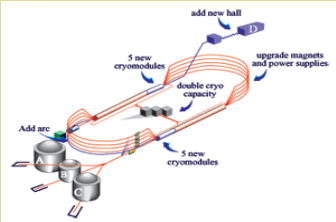
Dark Forces



- *J Lab*
- *Mainz*

Intensity Frontier: Precision Tests

PV Electron Scattering



- *Q-Weak*
- *12 GeV Moller*
- *PV DIS*

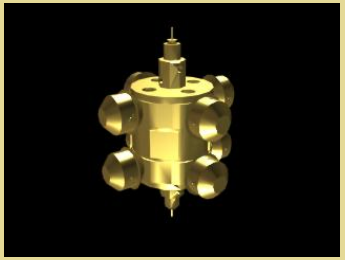
Muons

- *g_μ-2*
- *μA->eA*

Weak Decays

- *n decay correlations*
- *nuclear β decay*
- *pion decays*
- *muon decays*

Torsion Balances



- *Equiv Prin Tests*
- *Non-grav forces*

Neutrinos

- *oscillations*
- *β & $\beta\beta$ decay*

II. Post-2007 Developments

Post 2007 Developments: Major NP Experimental Achievements

- *New limit on ^{199}Hg EDM : Seattle*
- *New limit on $\tau_{0\nu\beta\beta}$: EXO*
- *Determination of θ_{13} : Daya Bay, RENO*
- *β-asymmetry "Big A" : UCNA LANL*
- *Successful completion of Q-Weak: J Lab*
- *New determination of τ_{μ} : MuLAN @ PSI*

Post 2007 Developments: Intensity Frontier International Context

- *New limit on electron EDM: YbF Sussex*
- *Lamb shift in muonic H: PSI*
- *New Limits on $\mu \rightarrow e\gamma$: PSI*

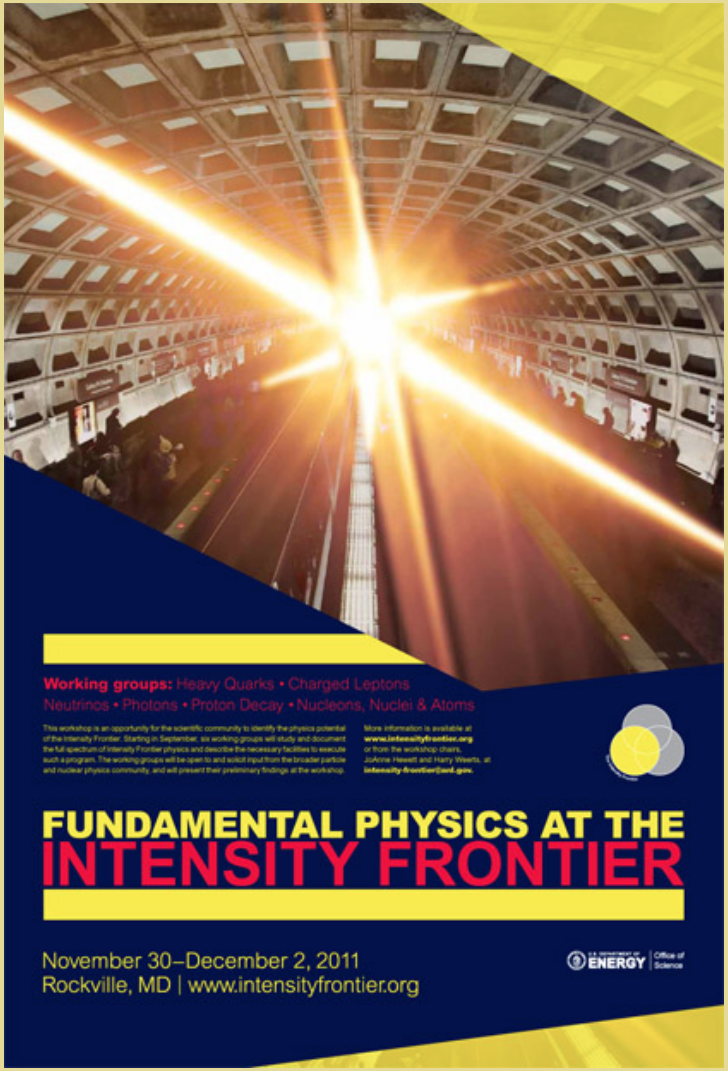
Post 2007 Developments: High Energy & Astrophysics Frontiers

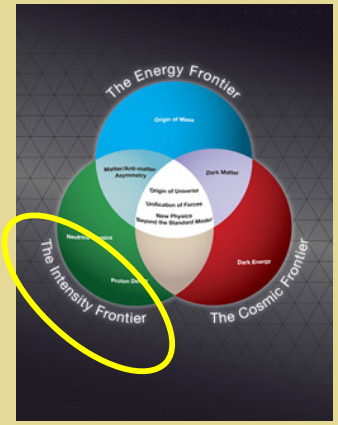
- *Observation of ~ 125 GeV particle: LHC*
- *Collider Anomalies: Tevatron, LHCb*
- *New limits on BSM candidates : LHC*
- *Positron excesses: PAMELA, Fermi*

Post 2007 Developments: U.S. Facilities & Program

- *DUSEL $\rightarrow$ Sanford Lab (see HGR talk)*
- *Long Baseline Neutrino Exp't descope (HGR talk)*
- *HEP emphasis on Intensity Frontier: new synergy with between NP and HEP*
- *NSAC Neutron Subcommittee Report: nEDM now R&D rather than MIE; refined β-decay priorities*
- *Muon g-2: HEP construction at FNAL, NP research*
- *Operation of the FNPB @ ORNL*
- *Theory: BSM NP collaboration*

Intensity Frontier Workshop & WP





Working Groups

- Charged Leptons
- Heavy Quarks
- Hidden Sector Photons, Axions, & WISPS
- Neutrino
- Nucleons / Nuclei / Atoms
- Proton Decay

Leading NP Role

Post 2007 Developments: International Facilities & Program

- *Initiation of several nEDM experiments: ILL, PSI, Munich, TRIUMF (UCN sources)*
- *New τ_n measurements: ILL, Munich,…*
- *Construction of PERC n-decay detector (Vienna/Heidelberg)*
- *Muon physics @ JPARC: $\mu \rightarrow e$, g_μ-2, d_μ*
- *Mainz: funding for high-intensity, low-energy pol'd e^-*
- *SNO Lab: $0\nu\beta\beta$*
- *European Spallation Source: fundamental neutron physics ?*

Post 2007 Developments: New Ideas

- *"Dark photons": J Lab, Mainz*
- $e \rightarrow \tau$ *: EIC*
- *Reactor* ν *deficit & short baseline oscillation studies: KamLAND, Daya Bay….*

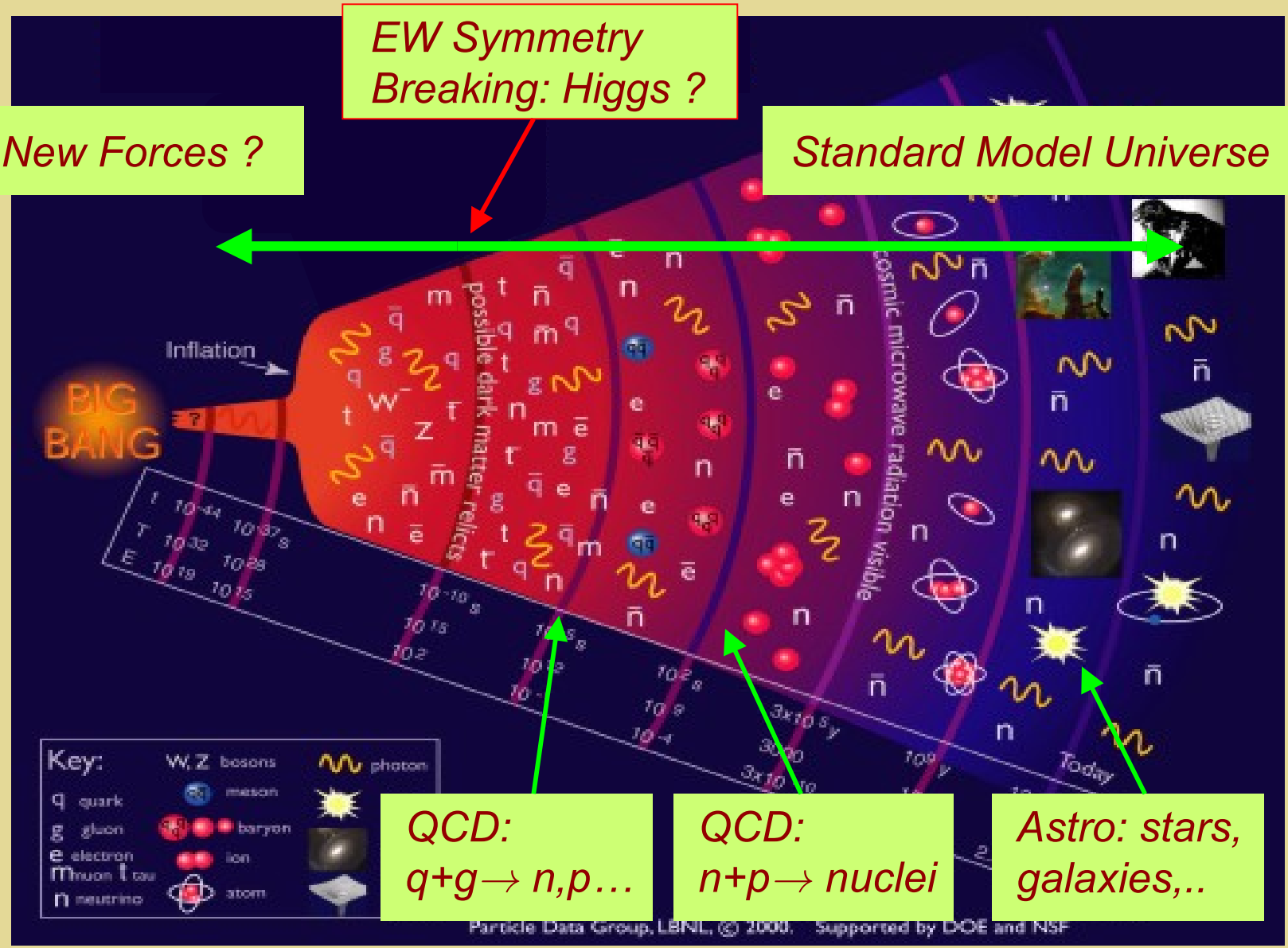
III. Implications

Implications: Underground Science

- *Upcoming talks by HGR, KMH, SJF*

Implications: New Standard Model

Symmetries & Cosmic History



EW Symmetry Breaking: Higgs ?

New Forces ?

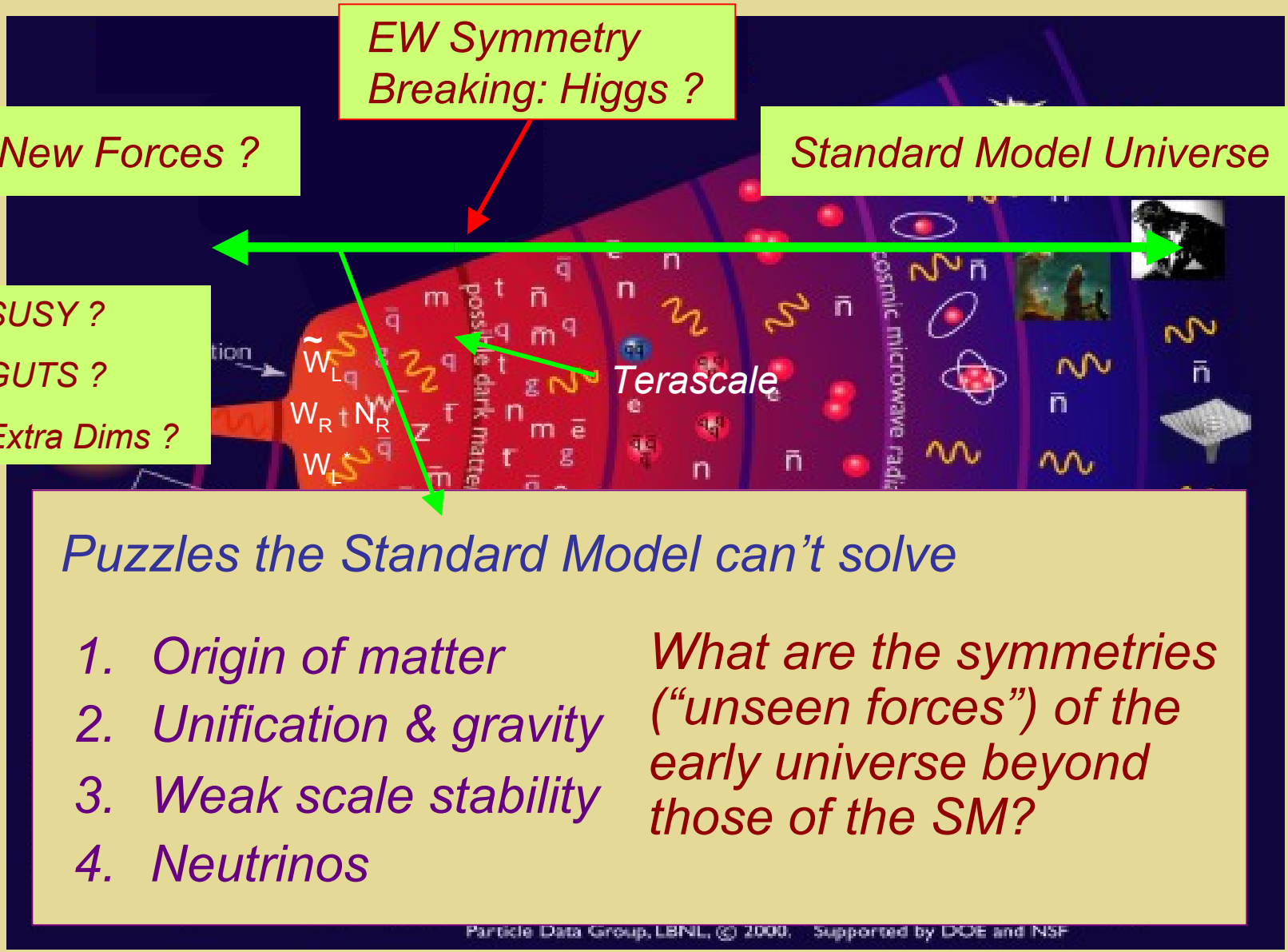
Standard Model Universe

QCD: q+g→ n,p…

QCD: n+p→ nuclei

Astro: stars, galaxies,..

Symmetries & Cosmic History



EW Symmetry Breaking: Higgs ?

New Forces ?

Standard Model Universe

SUSY ?

GUTS ?

Extra Dims ?

Terascale

Puzzles the Standard Model can't solve

1. *Origin of matter*
2. *Unification & gravity*
3. *Weak scale stability*
4. *Neutrinos*

What are the symmetries ("unseen forces") of the early universe beyond those of the SM?

Implications: CPV & LNV Searches

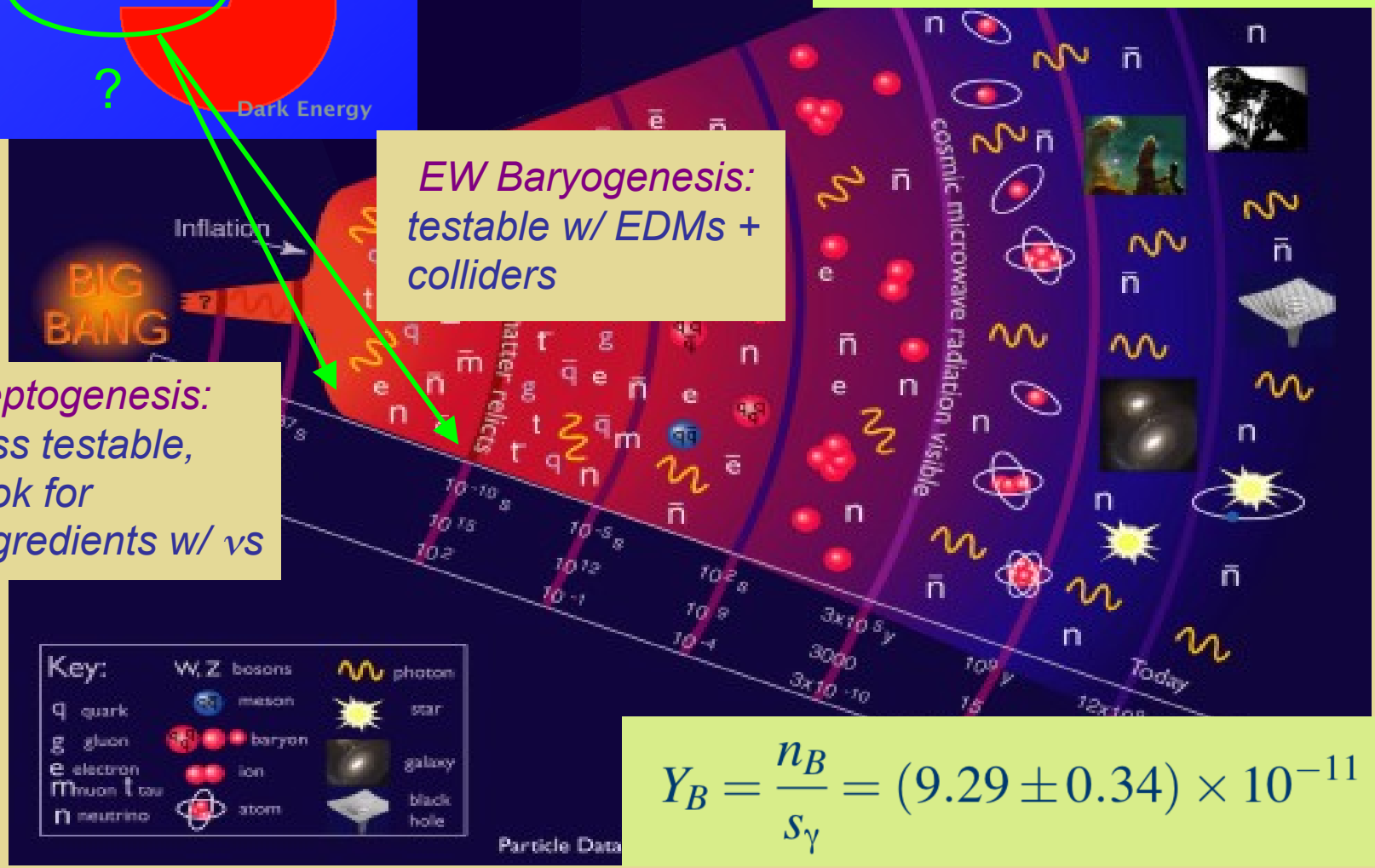
- *Baryogenesis*
- *Scale of BSM physics*
- *Nature of the neutrino* ← *HGR, SJF*

What is the Origin of Matter

Baryogenesis: When? CPV? SUSY? Neutrinos?

EW Baryogenesis: testable w/ EDMs + colliders

Leptogenesis: less testable, look for ingredients w/ νs



$$Y_B = \frac{n_B}{s_\gamma} = (9.29 \pm 0.34) \times 10^{-11}$$

EDMs: New CPV?

In units of e cm, selected EDM limits are:

Particle	EDM limit	System	SM Prediction	New Physics
e	10.5×10^{-28}	YbF	10^{-38}	10^{-27}
μ	1.1×10^{-19}	rest frame $\vec{E}$	10^{-35}	10^{-22}
τ	3.1×10^{-16}	$e^+e^- \to \tau^+\tau^-\gamma$	10^{-34}	10^{-20}
p	6.5×10^{-23}	TlF molecule	10^{-31}	10^{-26}
n	2.9×10^{-26}	UCN	10^{-31}	10^{-26}
^{199}Hg	3.1×10^{-29}	atom cell	10^{-33}	10^{-28}

Post 2007

BF Talk

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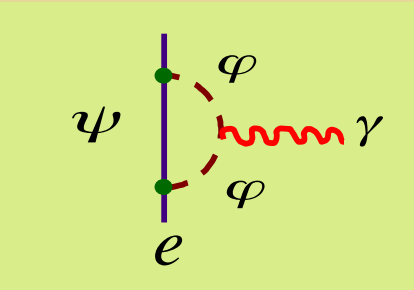
*

* but θ_{QCD}

Mass Scale Sensitivity



$\sin\phi_{CP} \sim 1 \;\to\; M > 5000$ GeV

$M < 500$ GeV $\to\; \sin\phi_{CP} < 10^{-2}$

EDMs: New CPV?

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- *SM "background" well below new CPV expectations **
- *New expts: 10^2 to 10^3 more sensitive*

** but θ_{QCD}*

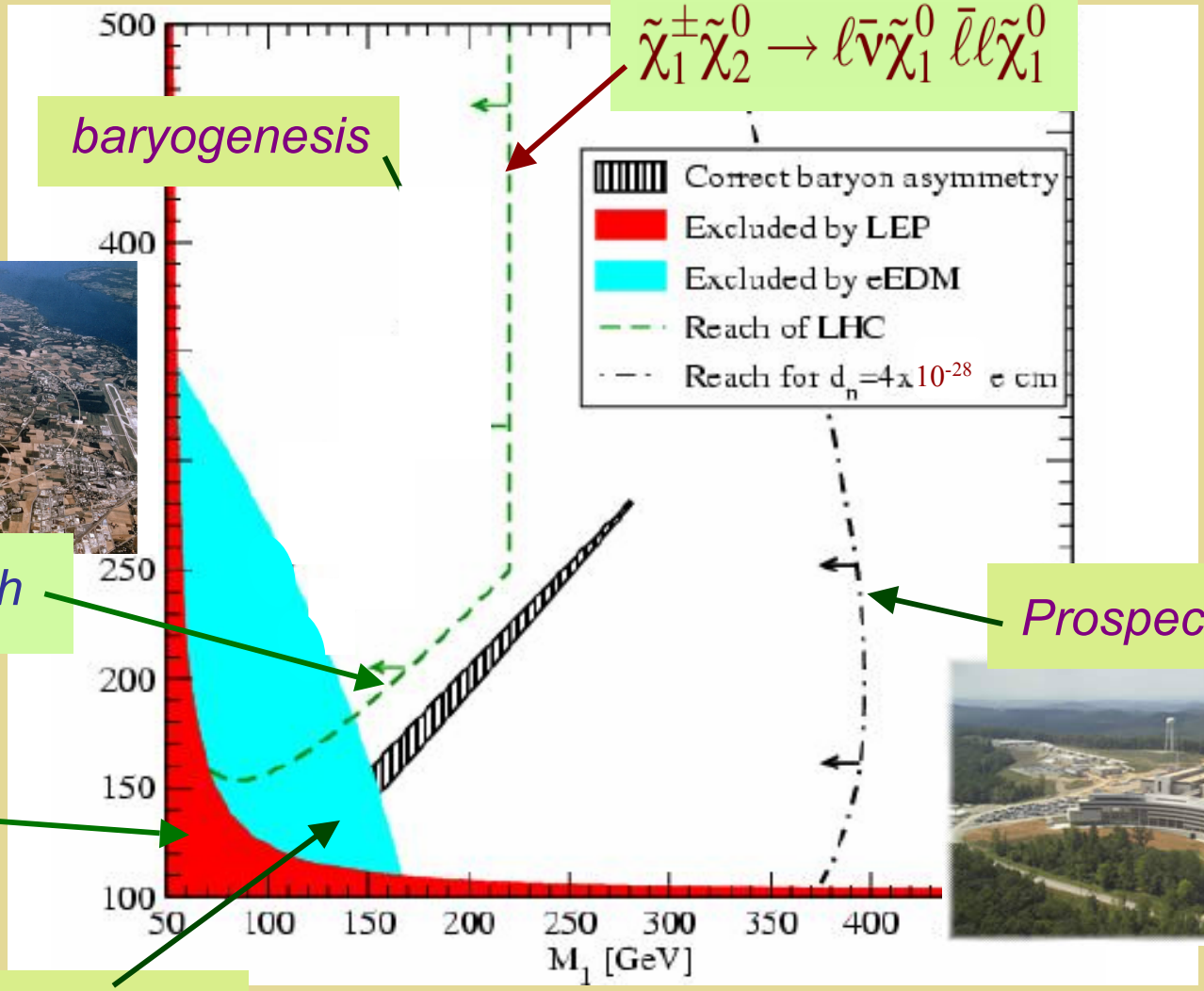
A non-exhaustive list:

Leptonic EDMs		Hadronic EDMs	
System	Group	System	Group
Cs (trapped)	Penn St.	n (UCN)	SNS
Cs (trapped)	Texas	n (UCN)	ILL
Cs (fountain)	LBNL	n (UCN)	PSI
YbF (beam)	Imperial	n (UCN)	Munich
PbO (cell)	Yale	^{199}Hg (cell)	Seattle
HBr^+ (trapped)	JILA	^{129}Xe (liquid)	Princeton
PbF (trapped)	Oklahoma	^{225}Ra (trapped)	Argonne
GdIG (solid)	Amherst	^{213,225}Ra (trapped)	KVI
GGG (solid)	Yale/Indiana	^{223}Rn (trapped)	TRIUMF
muon (ring)	J-PARC	Proton (ring)	BNL

+ TRIUMF

+ COSY (deuteron)

MSSM Baryogenesis: EDMs & LHC



LHC reach

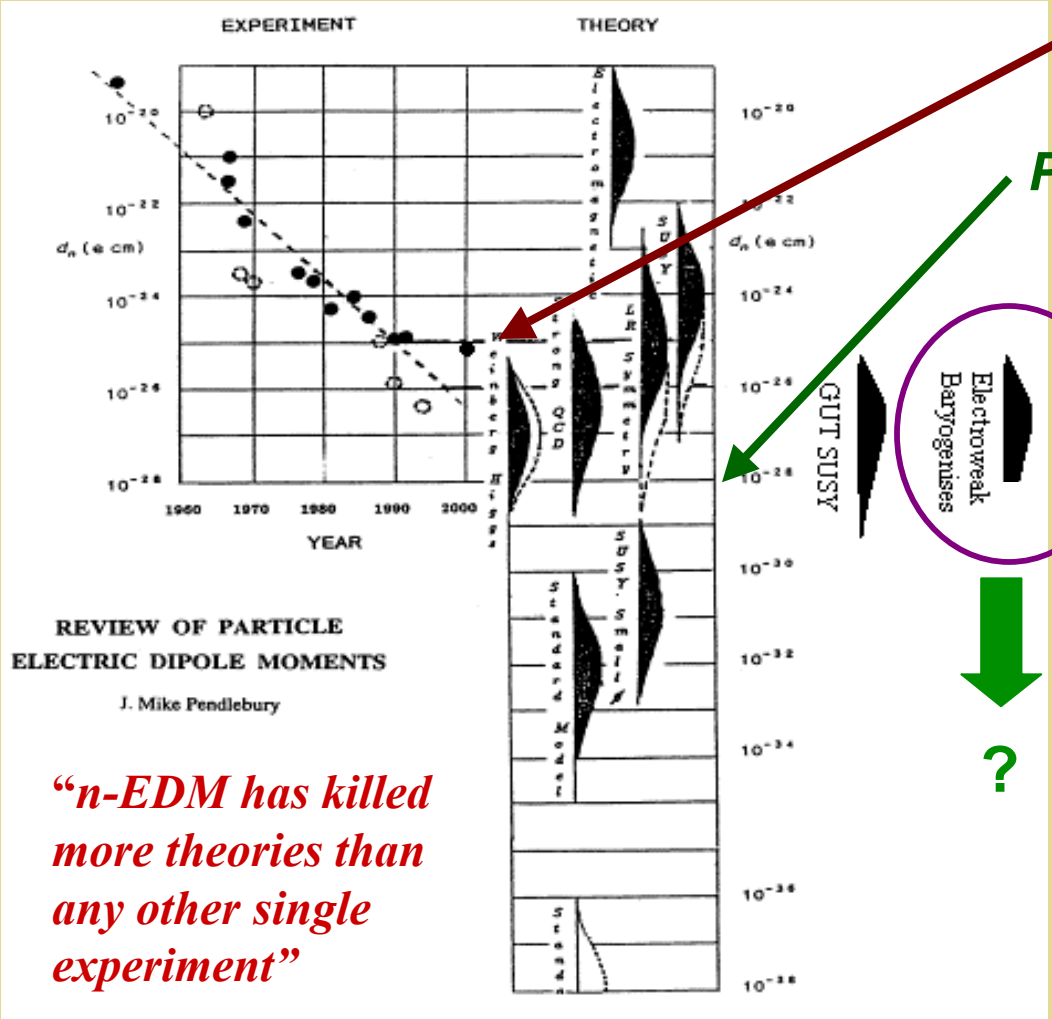
LEP II excl

Present d_e

Prospective d_n

Cirigliano, Profumo, R-M

EDMs: What We May Learn



"n-EDM has killed more theories than any other single experiment"

Present n-EDM limit

Proposed n-EDM limit

?

Matter-Antimatter Asymmetry in the Universe: MSSM

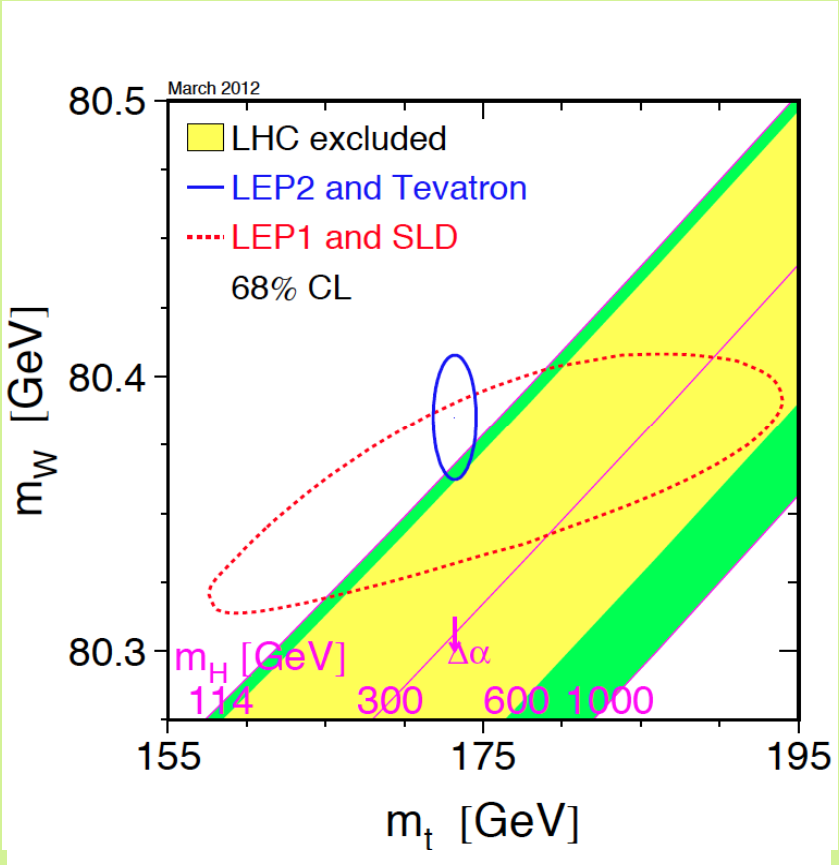
Theory: How robust ? Can EDMs kill EW baryogenesis ?

Implications: LHC & Precision Tests

- *Muon g-2* ← *DH Talk*
- *J Lab electroweak* ← *KP Talk*
- *Weak decays* ← *DH Talk*

Intensity & Energy Frontiers

LEP EW Working Group



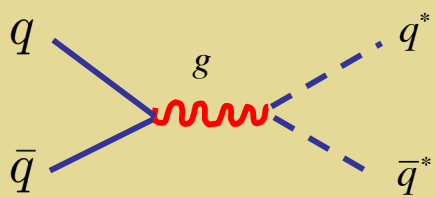
Precision Frontier:

- *Precision ~ Mass scale*
- *Look for pattern from a variety of measurements*
- *Identify complementarity with collider searches*
- *Special role: SM suppressed processes*

Stunning SM Success

LHC BSM Challenge: Disentangling Scenarios

Pair production of KK quarks



$q^* \to q + \gamma^*$ *UED*

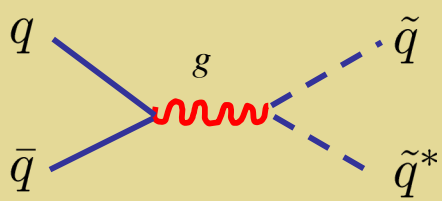
Additional challenges:

- *Determining spin*
- *Determining SU(N) quantum numbers*

"LHC inverse problem"

$\not{E}_T$

Pair production of squarks



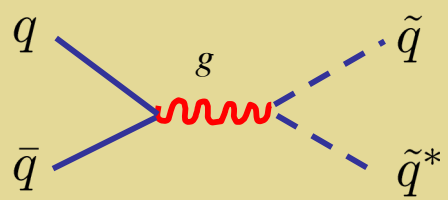
$q \to q + \chi \to \ell + \nu + q + \tilde{\chi}_1^0$

Final state: 2j + $\not{E}_T$, 2j + ℓ + $\not{E}_T$

What complementary info from other two frontiers ?

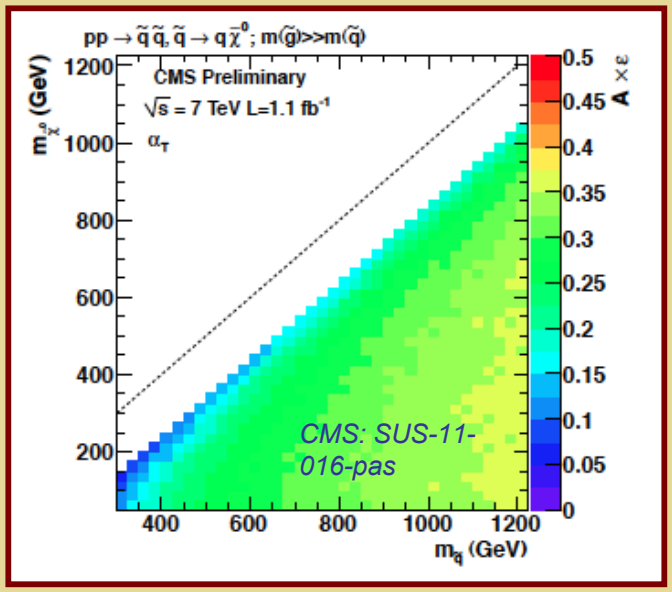
LHC BSM Challenge: Light but Compressed ?

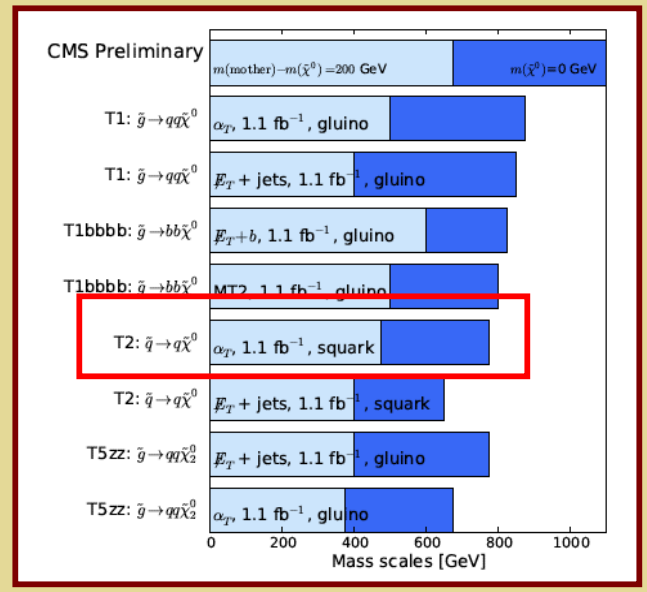
Pair production of squarks



$$\tilde{q} \to q + \tilde{\chi}_1^0$$
$$\tilde{q} \to q' + \tilde{\chi}^{\pm} \to \ell + \nu + q' + \tilde{\chi}_1^0$$

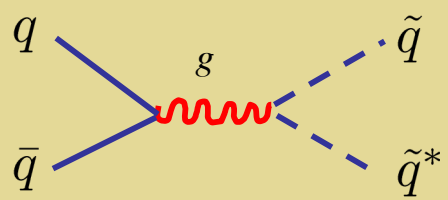
Final state: 2j + $\not{E}_T$, 2j + ℓ + $\not{E}_T$





LHC BSM Challenge: Light but Compressed ?

Pair production of squarks



$$\tilde{q} \to q + \tilde{\chi}_1^0$$
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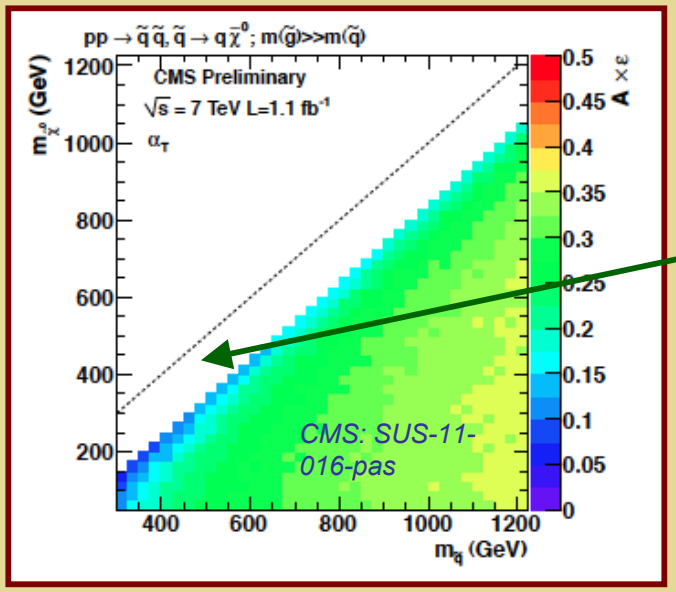
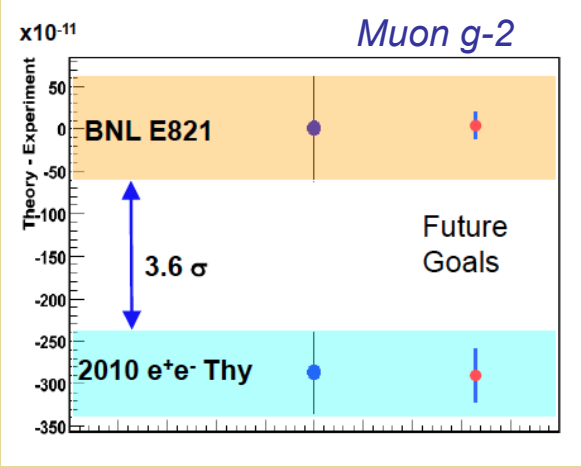
Final state: 2j + $\not{E}_T$, 2j + ℓ + $\not{E}_T$

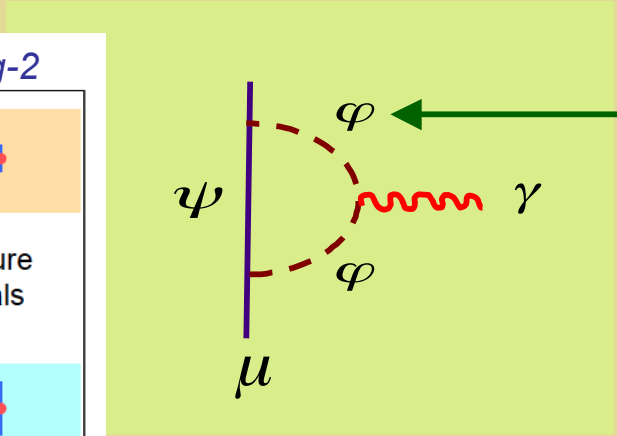


No exclusion yet (jets analysis): is sub-TeV SUSY hiding here?

If so, will it show up in precision tests ?

New Particles in Loops ?

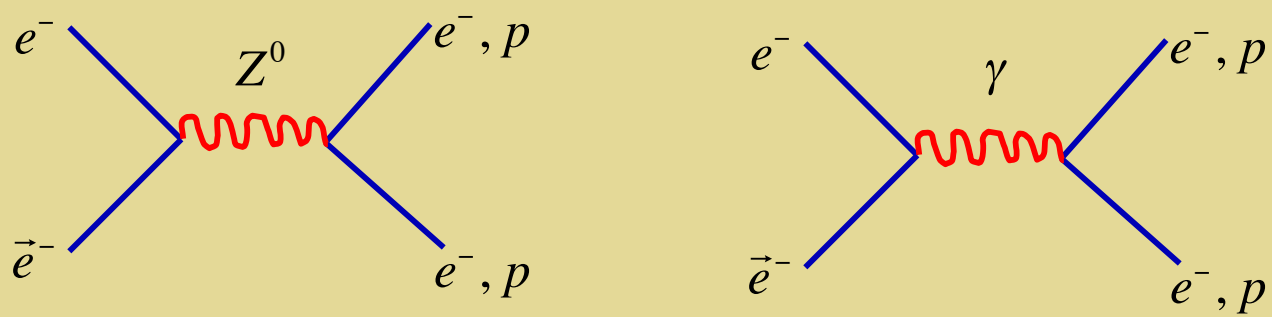




- *Smuon (SUSY)*
- *Leptoquark*
- *"Dark photon"*
- *Heavy Z'*
- *Extended scalar sector*

D. Hertzog TSI 2012

Parity-Violation & Weak Charges



Parity-Violating electron scattering

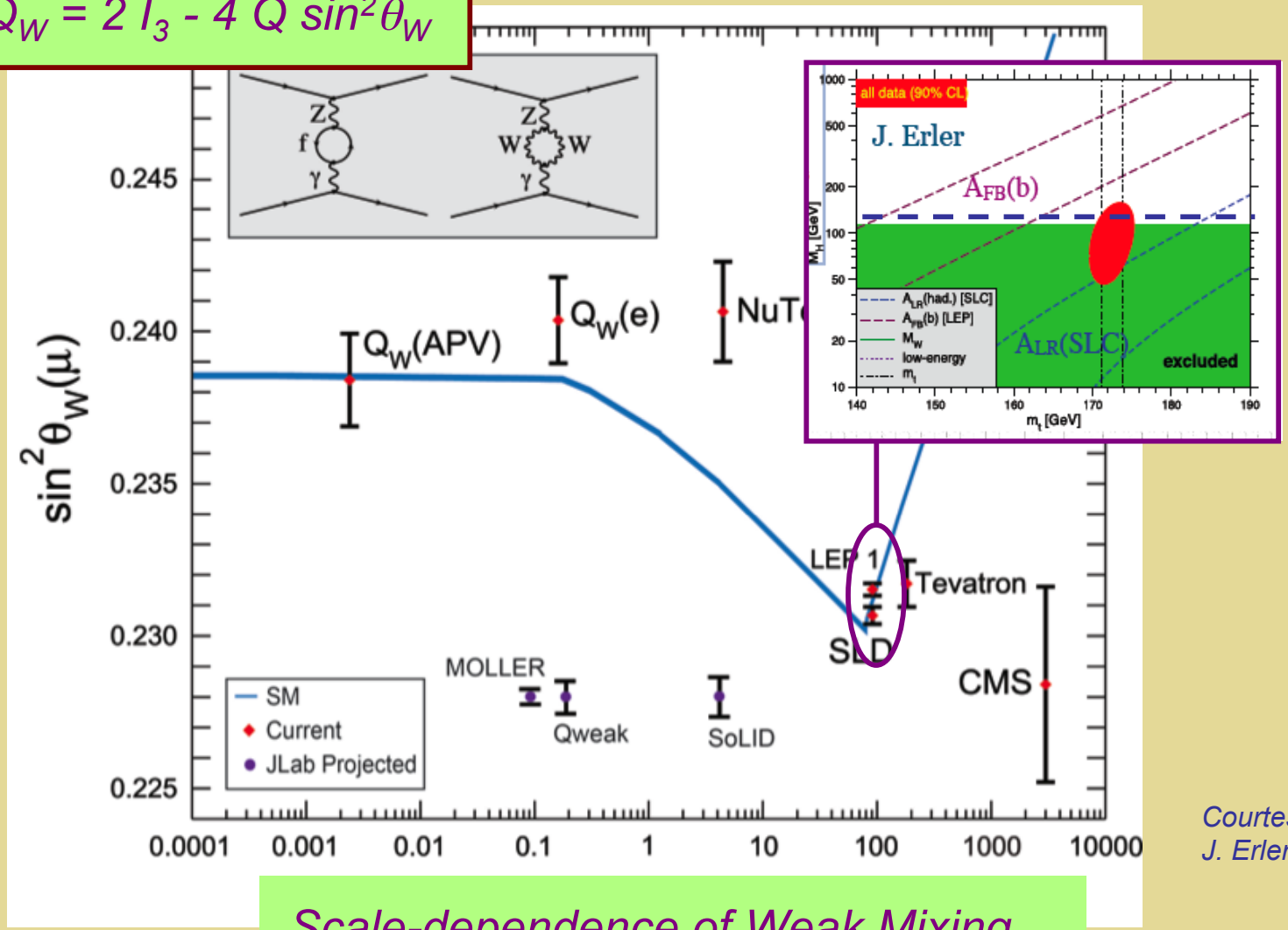
$$A_{PV} = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W + F(Q^2,\theta)\right]$$

Atomic parity-violation

$$E_1^{PV} / \beta = i\, e\, \mathcal{M} \times 10^{-11}\, a_0\, (Q_W / N) / \beta$$

PV Electron Scattering: Weak Mixing

$Q_W = 2\, I_3 - 4\, Q \sin^2\theta_W$

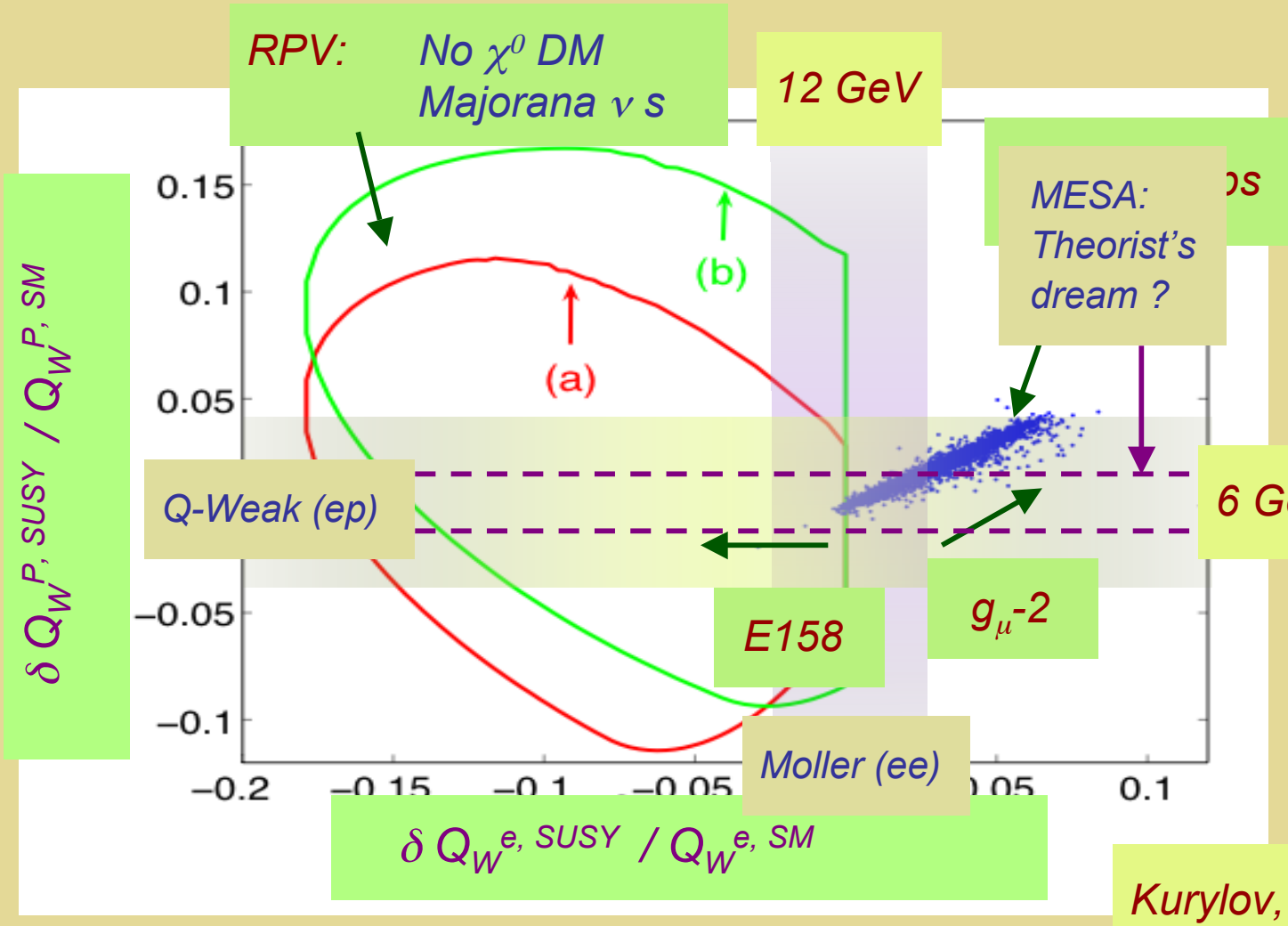


Courtesy J. Erler

Scale-dependence of Weak Mixing

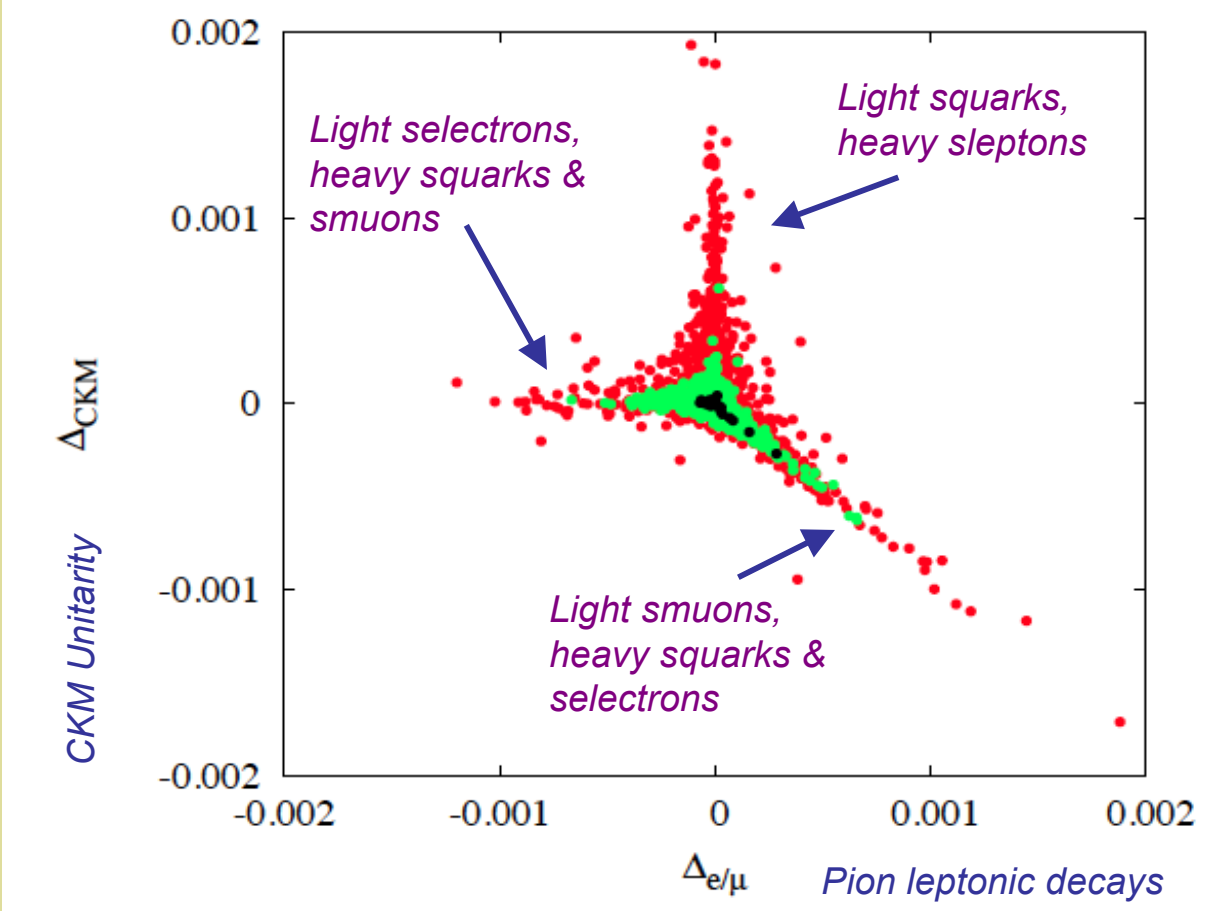
Marciano & Czarnecki; Erler & R-M

PV Electron Scattering: BSM Diagnostic



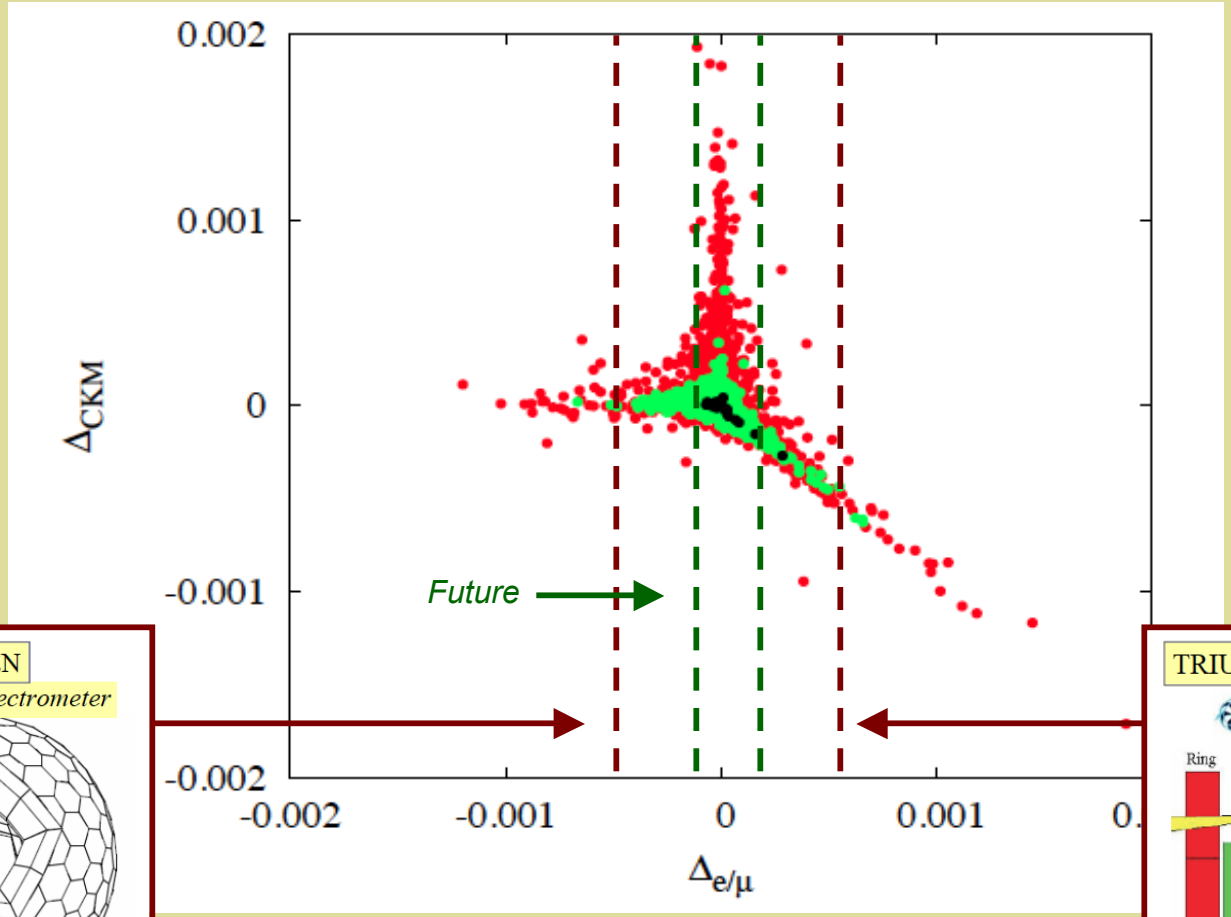
Kurylov, RM, Su

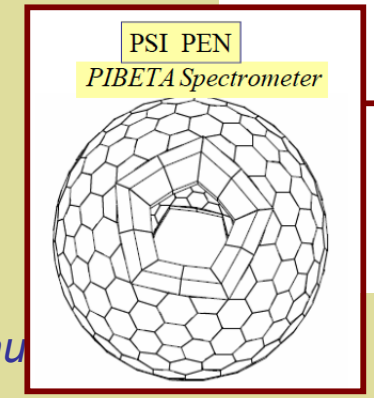
Weak Decays : Diagnostic Tool

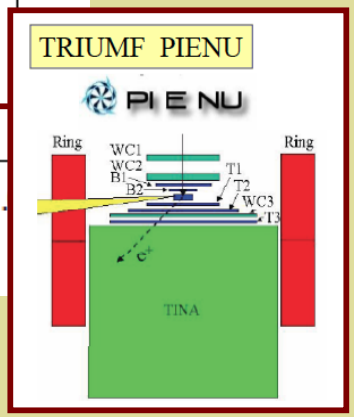


Bauman, Erler, R-M

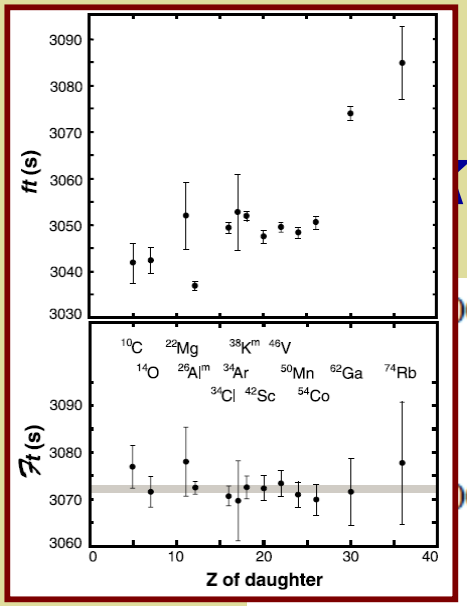
Weak Decays: Diagnostic Tool

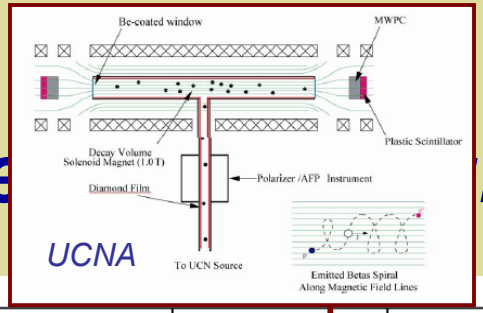


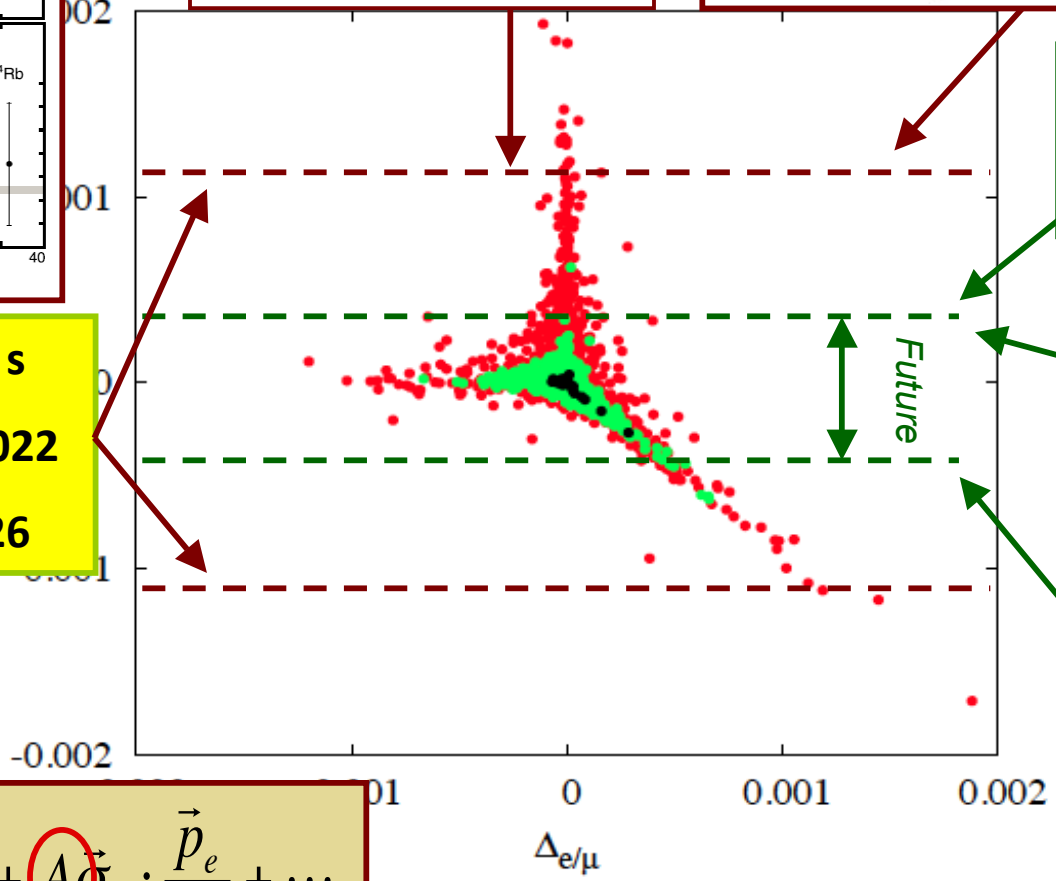




Bau





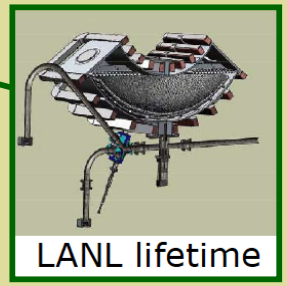


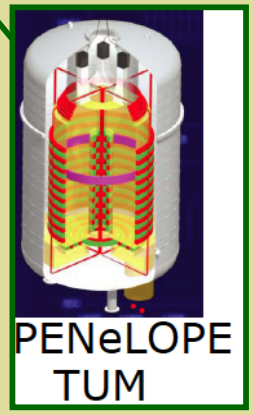
Ft **= 3072.08 ± 0.79 s**

V_{ud} = 0.97425 ± 0.00022

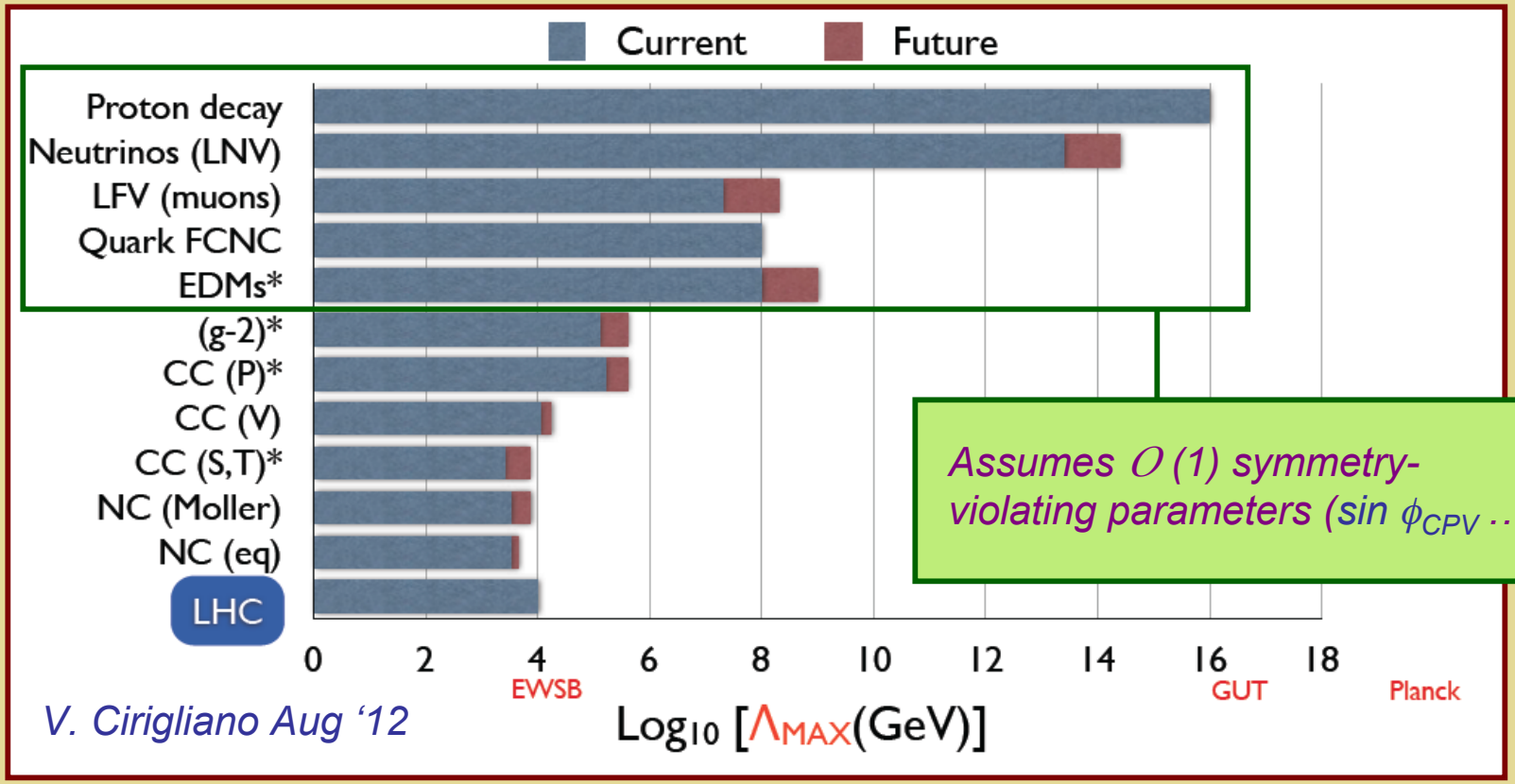
b_F = -0.0022 ± 0.0026

$$dW \propto 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + A\vec{\sigma}_n \cdot \frac{\vec{p}_e}{E_e} + \cdots$$





Implications: BSM Mass Reach



Assumes $\mathcal{O}(1)$ symmetry-violating parameters (sin ϕ_{CPV} …)

V. Cirigliano Aug '12

Implications: New Ideas

- *"Dark photons": J Lab, Mainz*
- $e \to \tau$ *: EIC*
- *Reactor* ν *deficit & short baseline oscillation studies: KamLAND, Daya Bay….*
- *Theory: BSM NP*

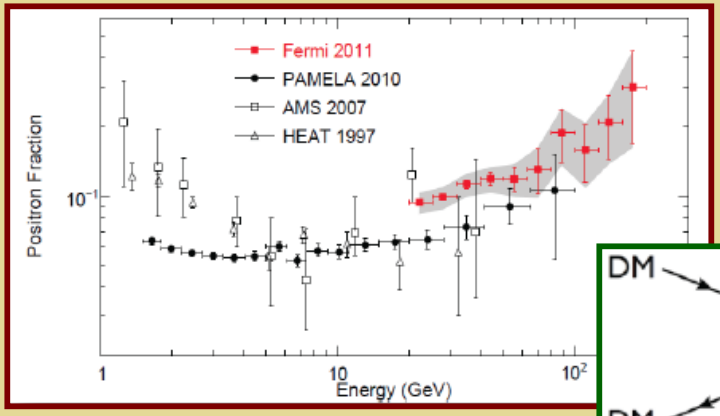
Implications: "Dark Photons"

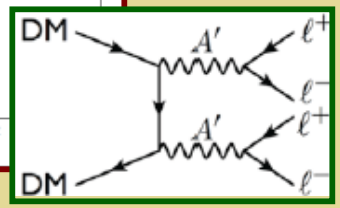
What is it ?

- *The A' : massive U(1) gauge boson that mixes w/ γ*
- *Mixing parameter: ε*

How motivated ?

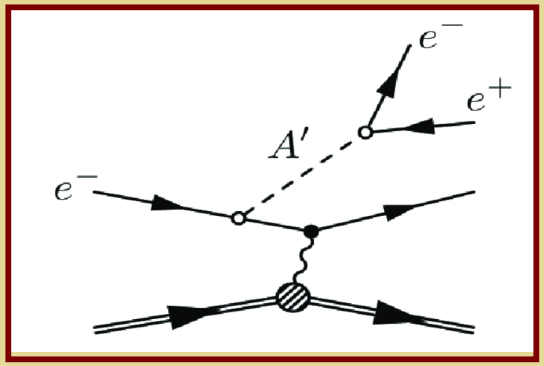
- *Muon g-2 deviation*
- *Positron excess*





How probed ?

- *Electron beam: look for e+ e- excess*
- *FEL*



Implications: "Dark Photons"

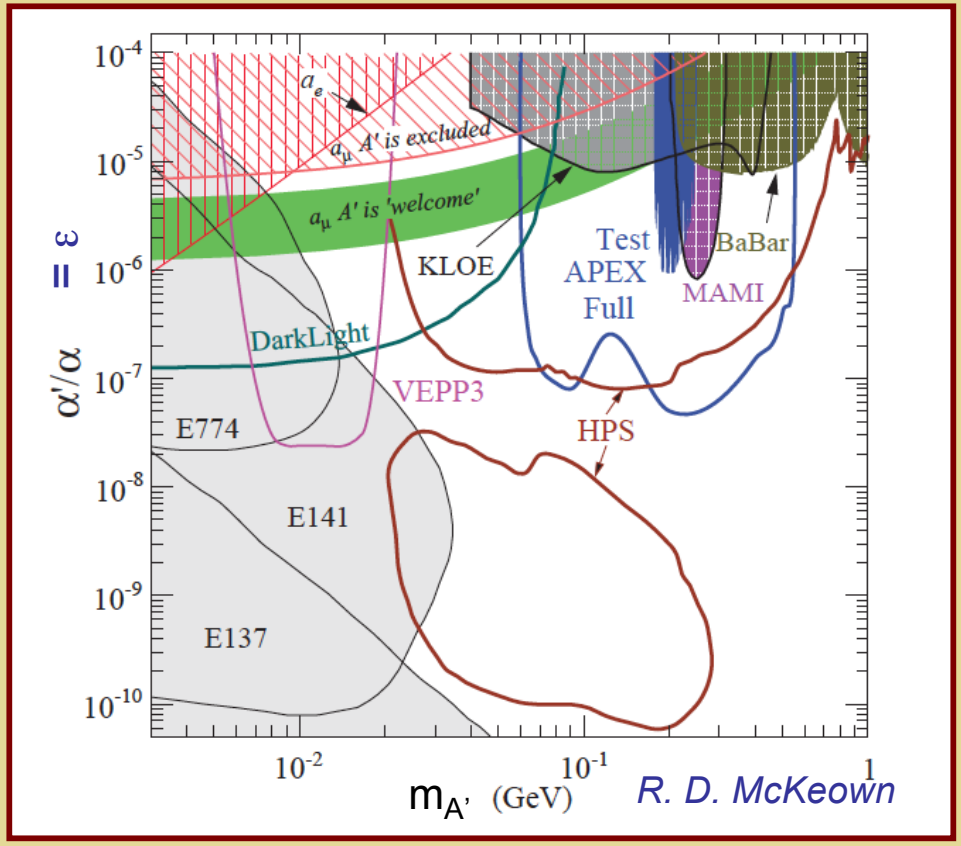
Experiments & Constraints

Jefferson Lab:

- *APEX*
- *Heavy Photon Search ("HPS")*
- *Dark Light (FEL)*

Mainz:

- *MAMI*
- *FEL*



R. D. McKeown

Implications: Facilities & Programs

- *Interface with HEP: heightened visibility for NP program*
- *EDMs: "let 1000 experiments bloom…" : recognition of discovery potential of nEDM*
- *Charged leptons, neutrons & international context: J Lab EW program unique*
- *FRIB: Opportunities for development*

IV. Outlook

Future Directions: Short & Longer Term

- *Uniqueness of fundamental symmetry tests: EDM, $0\nu\beta\beta$, LFV*
- *Complementary to HEP: LHC & heavy flavors*
- *International leadership: charged leptons, symmetry tests*
- *Dynamic science: new results, new ideas*

Four Components

EDM searches: *BSM CPV, Origin of Matter*	***$0\nu\beta\beta$ decay searches:*** *Nature of neutrino, Lepton number violation, Origin of Matter*
Lepton accelerators: *SM Precision Tests, BSM "diagnostic" probes*	***Smaller scale:*** *Weak decays, m_ν, "dark photons", non-Newtonian gravity, theory…*

Constrained Budgets

EDM searches:

BSM CPV, Origin of Matter

$0\nu\beta\beta$ decay searches:

Nature of neutrino, Lepton number violation, Origin of Matter

Lepton acc

SM Precision T
"diagnostic" pr

ler scale:

decays, m_ν, "dark
s", non-Newtonian
gravity, theory…

Risk: loss of US NP leadership in major discoveries

Constrained Budgets

EDM searches:

er

Risk: loss of US NP leadership in two textbook experiments

$0\nu\beta\beta$ decay searches:

Nature of neutrino, Lepton number violation, Origin of Matter

Lepton accelerators:

SM Precision Tests, BSM "diagnostic" probes

Smaller scale:

Weak decays, m_ν, "dark photons", non-Newtonian gravity, theory…

Constrained Budgets

EDM searches: *BSM CPV, Origin of Matter*	*C… s:* *N…* *n…* *M…*
Lepton accelerators: *SM Precision Tests, BSM "diagnostic" probes*	*Smaller scale:* *Weak decays, m_ν, "dark photons", non-Newtonian gravity, theory…*

Risk: loss of US NP response to new developments (dark γ, reactor ν deficit…)

Overall Outlook

- *Vital, robust, and growing component of NP*
- *High potential for discovery and insight*
- *High visibility beyond borders of NP and US*
- *Field with a long-term outlook*
- *Funding needed to maintain strength of the four components*

Back Up Slides

NSAC Neutron Subcommittee

nEDM

1) We recommend that the nEDM collaboration immediately focus the bulk of its efforts on a well-structured and strategically targeted R&D plan to address the outstanding technical issues.
2) We recommend that ORNL and Los Alamos National Laboratory (LANL) jointly establish an external standing Technical Review Committee (TRC) to review the R&D progress and to report periodically to the management of both institutions.
3) We recommend that long-lead-time procurements be contingent upon resolution of the major outstanding technical issues in the measurement technique.
4) We recommend that the agencies provide continued support for a period of two years given implementation of the aforementioned recommendations.
5) We recommend, in the event that major outstanding R&D issues remain unresolved after two years, that consideration be given to discontinuing the Major Item of Equipment (MIE) Project and re-evaluating the US strategy for achieving a precise neutron EDM measurement.

NSAC Neutron Subcommittee

Other Programs

6) We recommend strong support for the NPDGamma experiment as the highest priority measurement in hadronic parity-violation, and urge that every effort be made to reach the design goal, an asymmetry determination of one part in 10^8.

7) We recommend continued support for the UCNA experiment at LANL to improve the measurement precision of the A-coefficient by exploring a cost-effective and expeditious path to the original design sensitivity of 0.2%. We further recommend parallel R&D to develop the experiment to measure the a-coefficient with the Nab spectrometer, with a sensitivity of 0.1%.

8) We recommend that high priority be given to acquiring new data with the cold beam-based lifetime measurement at the National Institute for Standards and Technology (NIST), following its planned improvements.

9) We recommend that consideration be given to establishing a standing committee to review and prioritize various initiatives in US fundamental neutron science.

FS & N Chicago Meeting: Aug '12

Draft Rec's

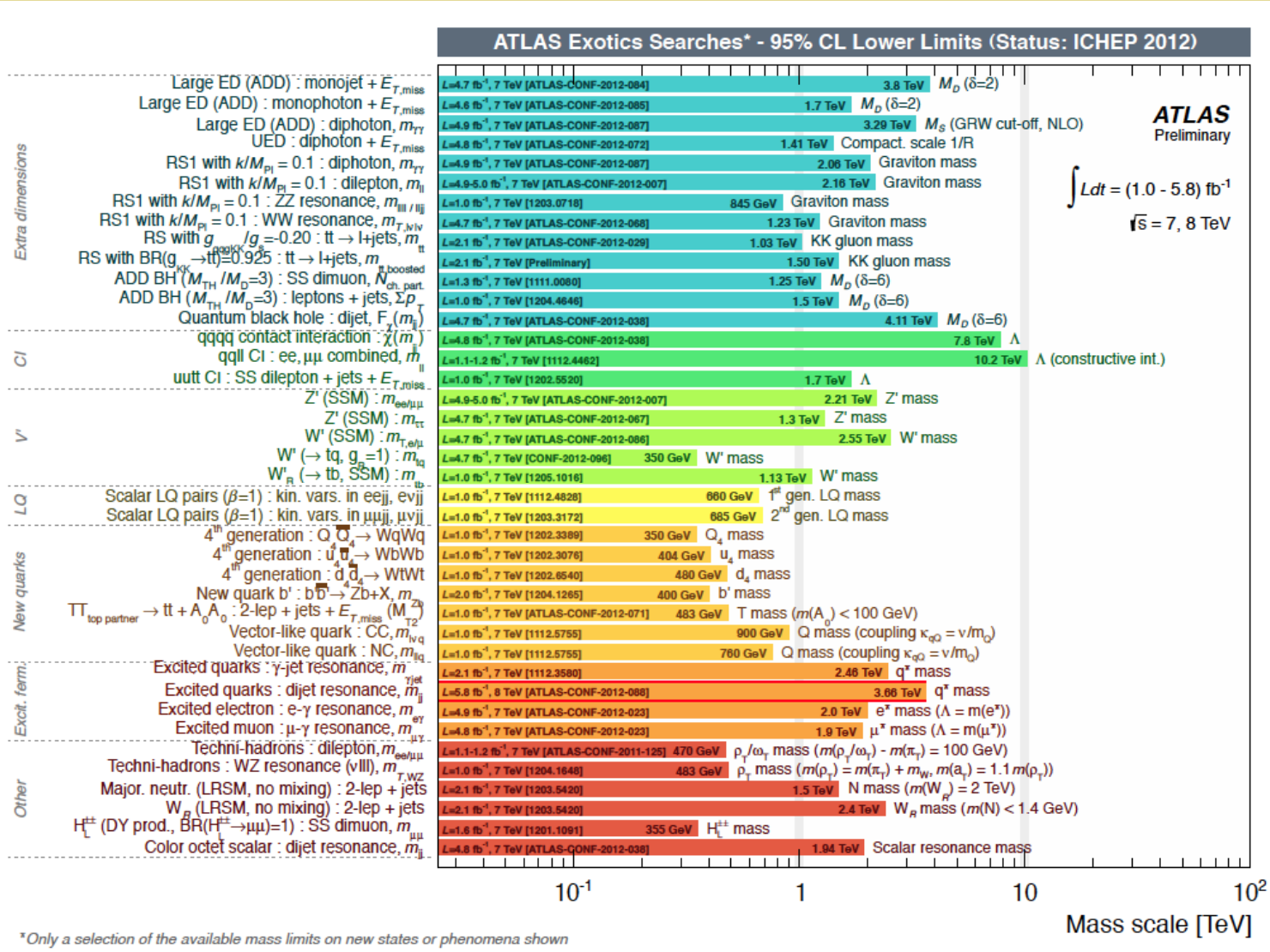
Recommendation 1: The community strongly endorses the recommendation of the 2007 Long Range Plan and subsequent, supporting, documents such as the 2012 NAS Nuclear Physics Report, the 2011 NAS Assessment of Science Proposed for DUSEL, and the 2011 NSAC Neutron subcommittee report. The 2007 Long Range Plan recommendation was:

Recommendation 2: The federal research investment in fundamental symmetries and neutrinos should be commensurate with the tremendous scientific opportunities and discovery potential in this area.

Recommendation 3: In order to ensure the long-term health of Fundamental Symmetries and Neutrinos Research, it is necessary to establish and maintain a balance between funding construction of new experiments and the needs of university and laboratory-based research programs performing existing experiments and developing new ideas and measurements that may have high impact.

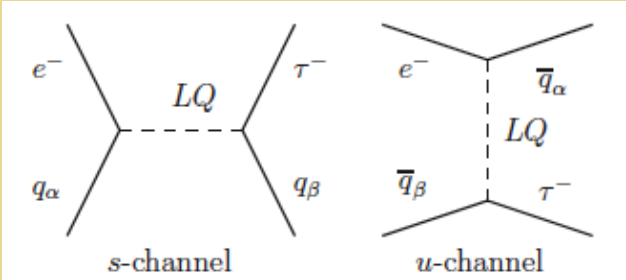
+ Theory

General LHC BSM Limits: "Exotica"



τ CLFV w/ Leptoquarks: EIC & HERA

HERA & EIC

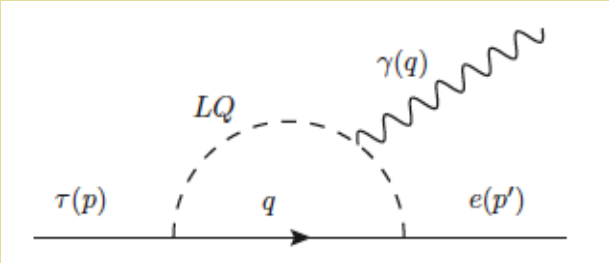


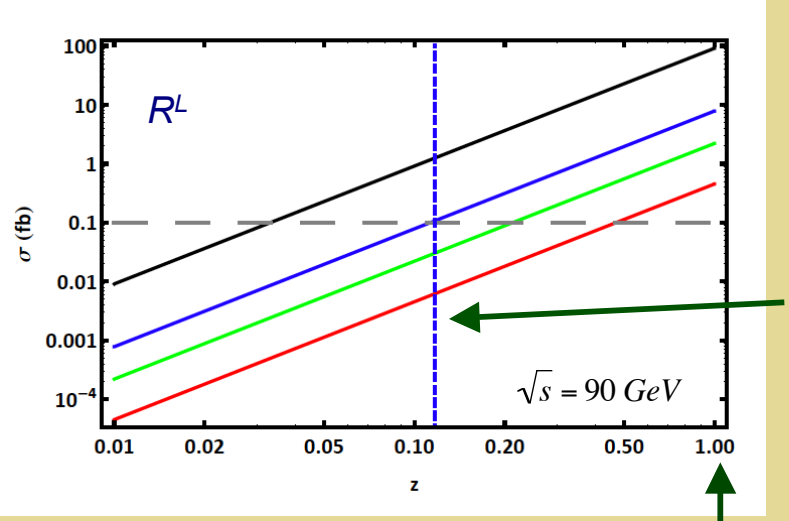
General Classification

$$\mathcal{L} = h_2^L \bar{u} \ell R_2^L + h_2^R \bar{q} i \tau_2 e R_2^R + \tilde{h}_2 \bar{d} \ell \tilde{R}_2^L + g_1^L \bar{q}^c i \tau_2 \ell S_1^L$$
$$+ g_1^R \bar{u}^c e S_1^R + \tilde{g}_1 \bar{d}^c e \tilde{S}_1^R + g_3 \bar{q}^c i \tau_2 \vec{\tau} \ell S_3 + h_1^L \bar{q} \gamma^\mu \ell U_{1\mu}^L$$

Extend HERA reach & compete with super B factories w/ 10 to 100 fb^{-1}

Rare Decays





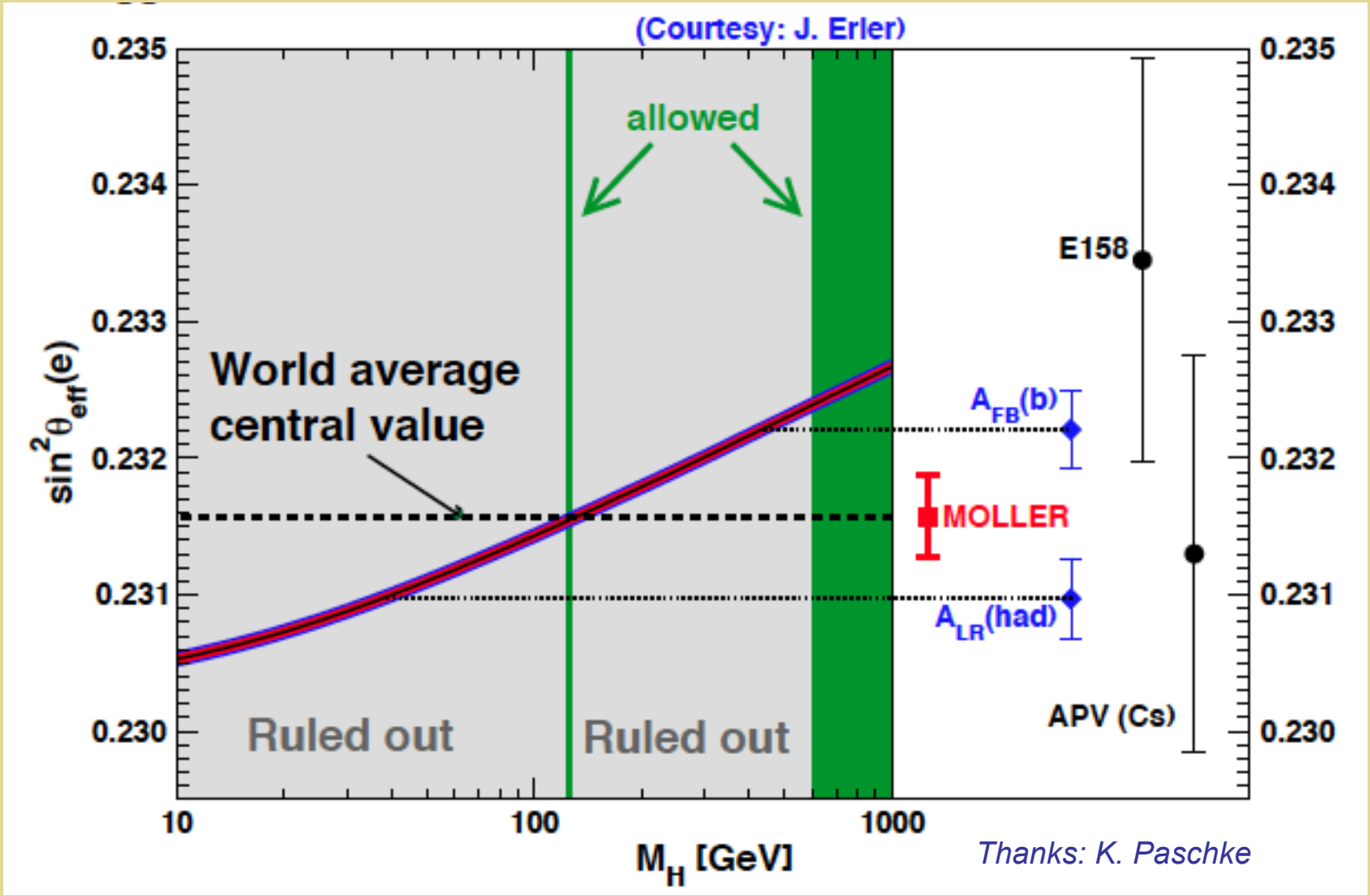
$\tau \to e\ \gamma$

HERA

$z = (\lambda^2 / M^2) / (\lambda^2 / M^2)_{HERA}$

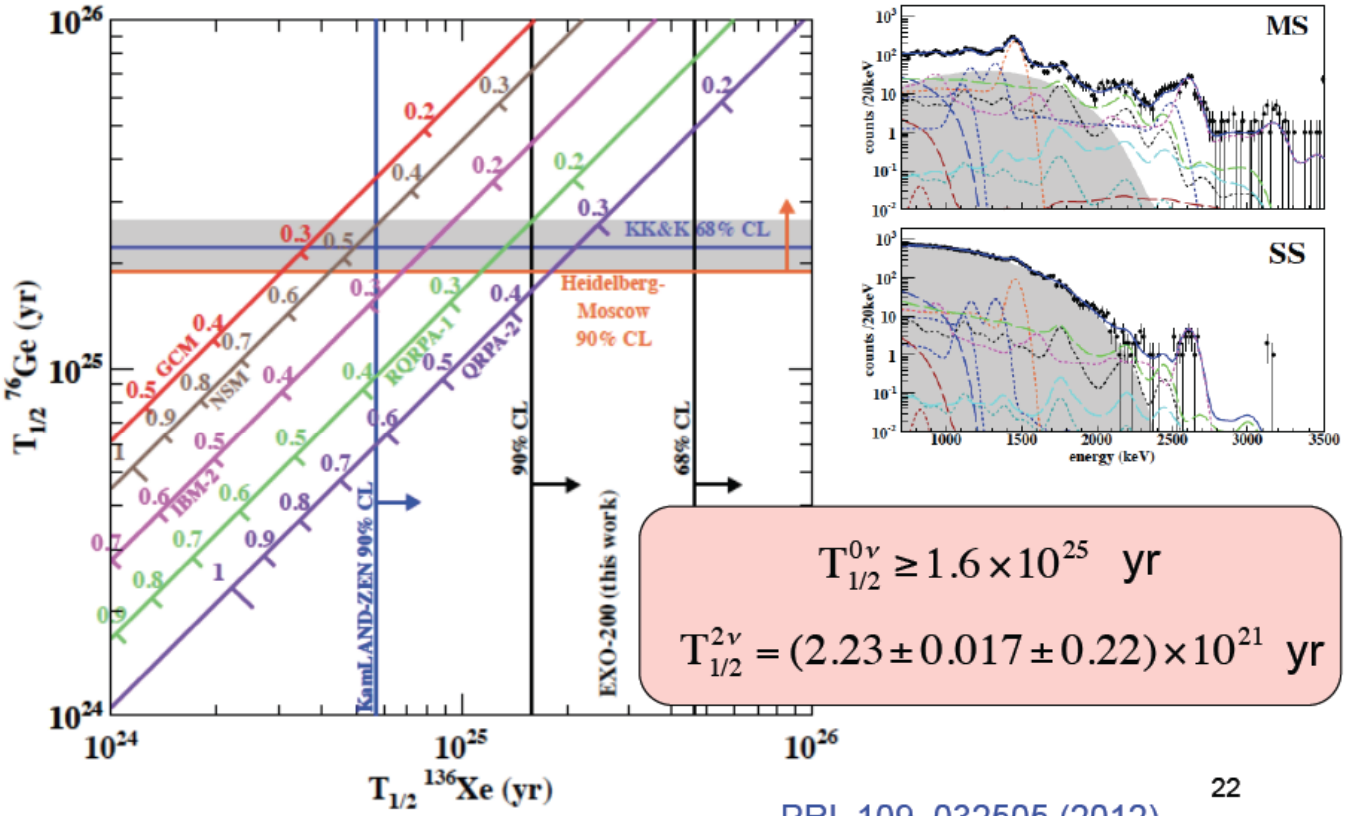
Gonderinger, R-M JHEP 1006:045

PVES & Higgs Mass



Thanks: K. Paschke

EXO Result



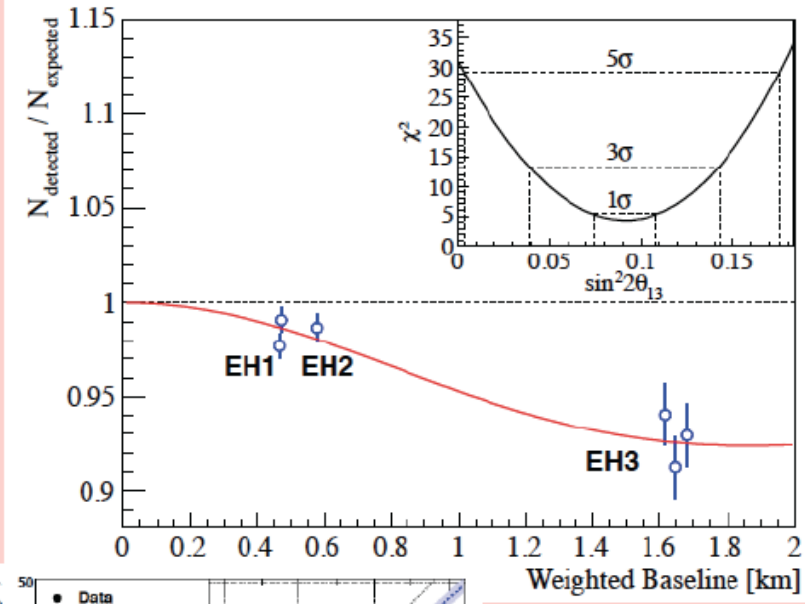
$$T^{0\nu}_{1/2} \geq 1.6 \times 10^{25} \text{ yr}$$

$$T^{2\nu}_{1/2} = (2.23 \pm 0.017 \pm 0.22) \times 10^{21} \text{ yr}$$

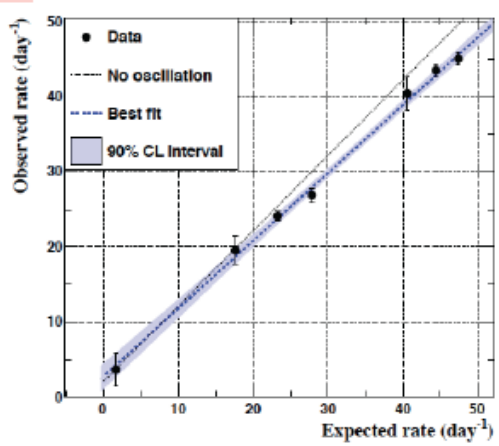
PRL 109, 032505 (2012)

Thanks: HGR

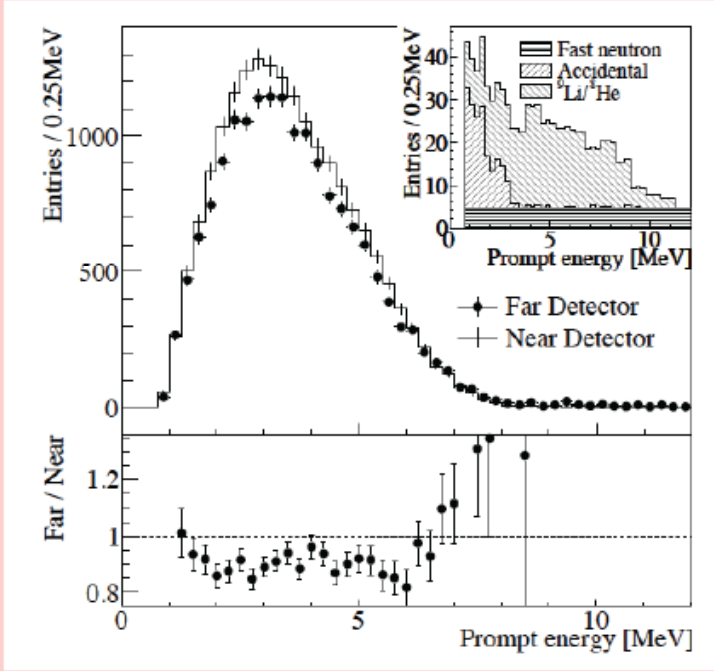
Θ_{13} Results



Daya Bay



Double Chooz

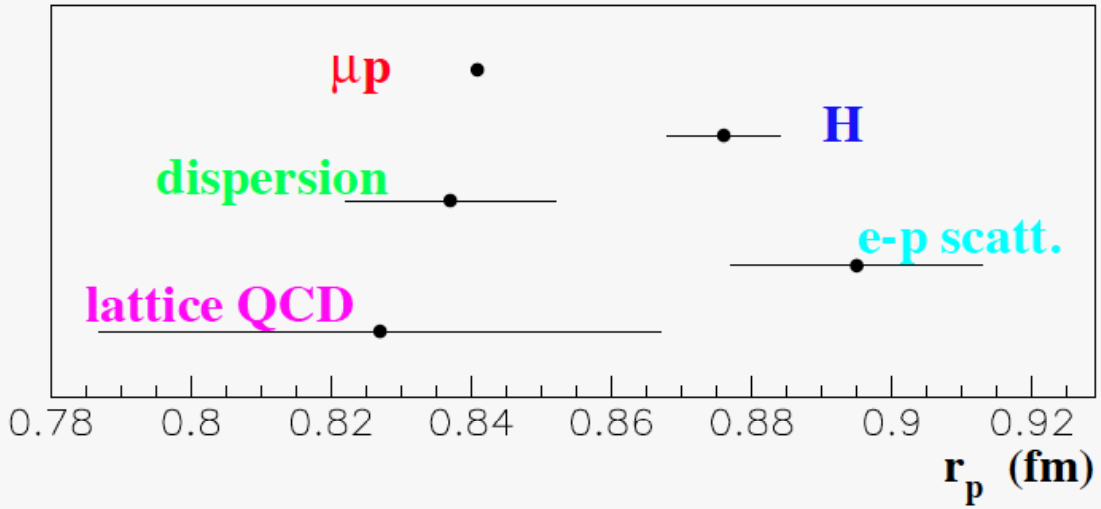


RENO

Thanks: HGR

Muonic Hydrogen & Proton Radius

Proton radius puzzle



- Pohl et al., submitted to Nature
- Mohr at al., Rev. Mod. Phys. **80** 633 (2008)
- Belushkin et al., Phys. Rev. C **75** 035202 (2007)
- Sick, Phys. Lett. B **576** 62 (2003)
- Wang et al., Phys. Rev. D **79** 094001 (2009)

The origin of the discrepancy?

- QED th. in μp: 60 δ(theory)
- QED th. in H: 25 δ(theory)
- 1S-2S in H: thousends of σ
- 2S-8S in H: 5 σ
- new physics?

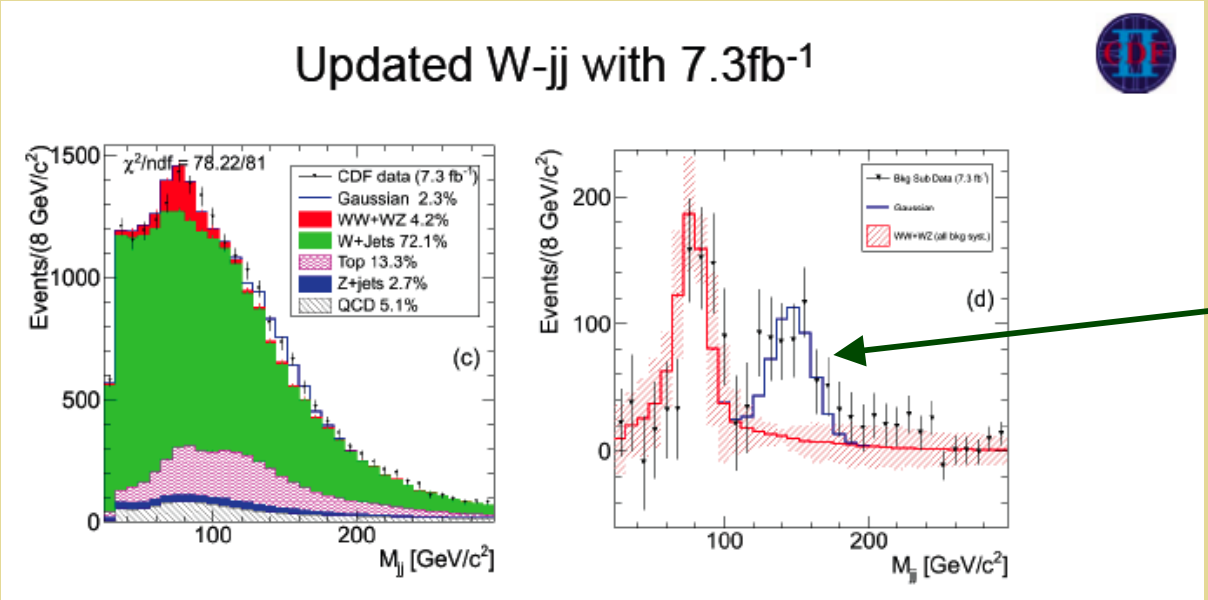
Interesting confrontation with

- e-p scattering
- dispersion analysis

Collider Anomalies:

Tevatron anomalies: W + jj

G. Punzi, Blois '11



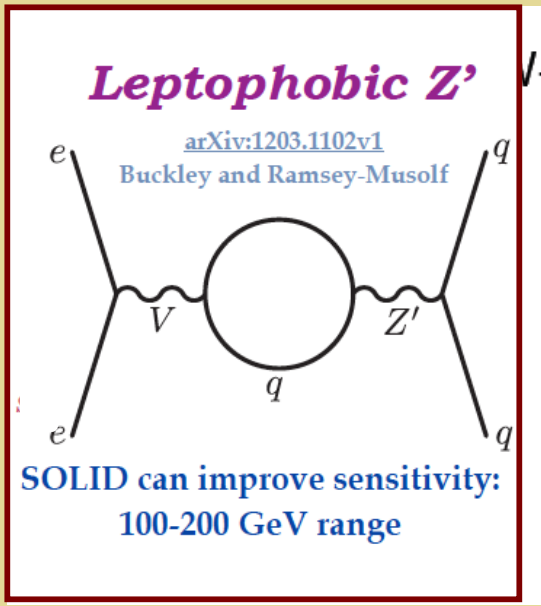
Close to 5σ

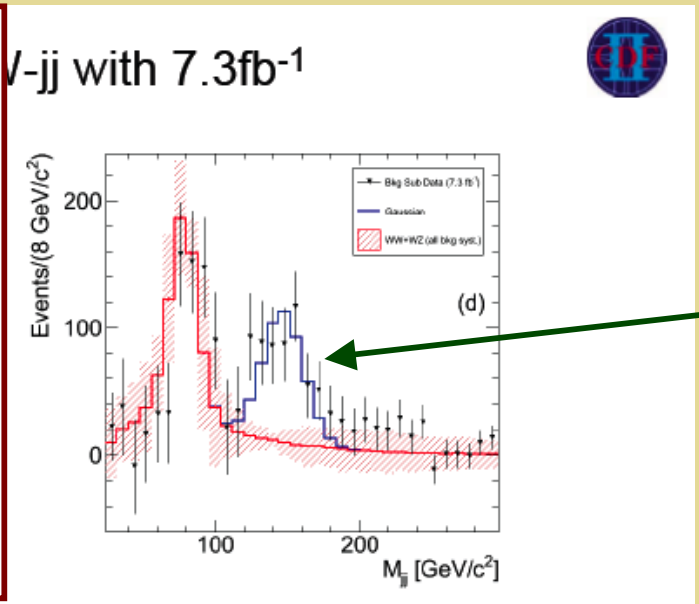
- *BSM ? Leptophobic Z', RPV SUSY,…*
- *SM/QCD: tops? Subtraction of W + (n> 3) j ?*

Collider Anomalies: Low-energy diagnostics

Tevatron anomalies: W + jj

G. Punzi, Blois '11





Close to 5σ

- *BSM ? Leptophobic Z', RPV SUSY,…*
- *SM/QCD: tops? Subtraction of W + (n> 3) j ?*

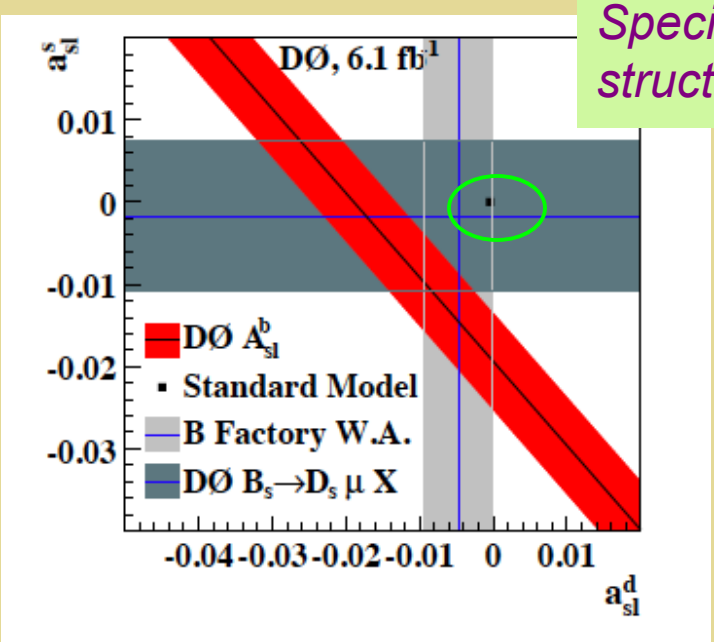
B Physics

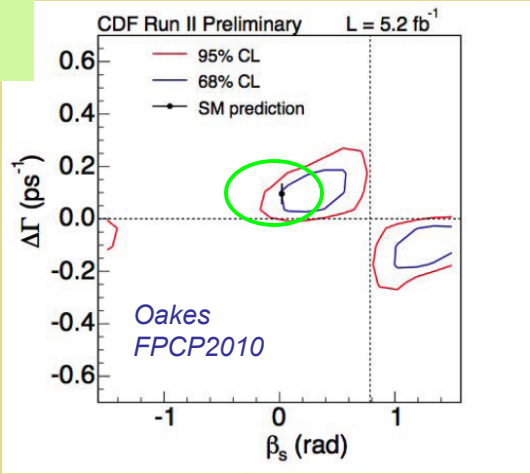
D0: like sign dimuon asymmetry

CDF: $B_s \to J/\psi + \phi$

$$\phi_s^{J/\psi\phi} = -2\beta_s^{SM} + \phi_s^{\Delta}$$

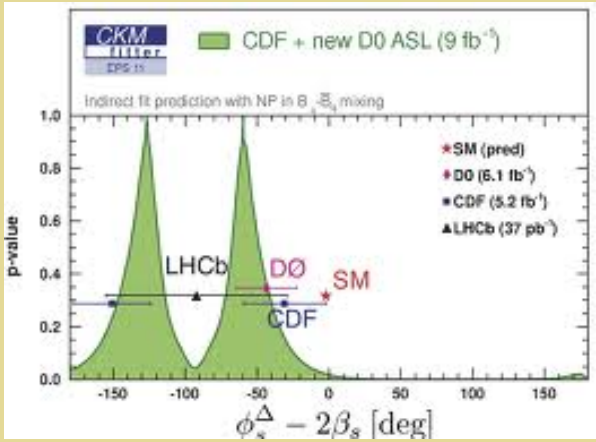
Special flavor structure ?





$$a_{sl}^q = \frac{\Gamma(\bar{B}_q^0(t) \to \mu^+ X) - \Gamma(B_q^0(t) \to \mu^- X)}{\Gamma(\bar{B}_q^0(t) \to \mu^+ X) + \Gamma(B_q^0(t) \to \mu^- X)}$$

$$a_{sl}^q = \frac{|\Gamma_q^{12}|}{|M_q^{12}|} \sin\phi_q = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$$



Baryogenesis: Ingredients

Sakharov Criteria

- *B violation*
- *C & CP violation*
- *Nonequilibrium dynamics*

Sakharov, 1967

Anomalous B-violating processes

SM Sphalerons: ✔

$$\Gamma(A+B\to C)\neq\Gamma(\bar{A}+\bar{B}\to\bar{C})$$

EDMs

SM CKM CPV: ✖

Prevent washout by inverse processes

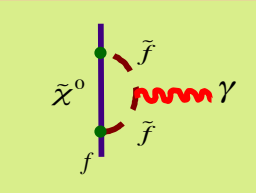
LHC: Scalars

SM EWPT: ✖

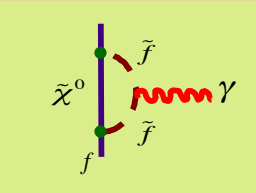
EDMs: Complementary Searches

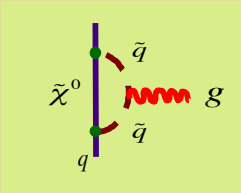
Improvements of 10^2 to 10^3

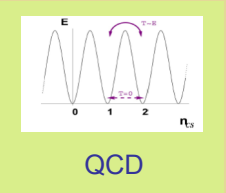
Electron



Neutron

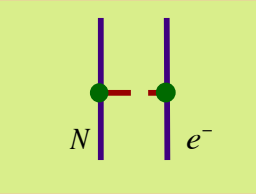


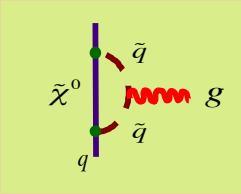


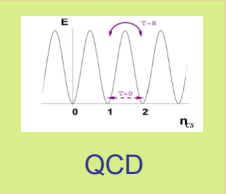


QCD

Neutral Atoms

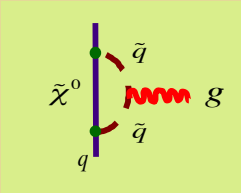


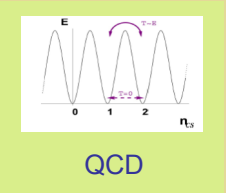




QCD

Deuteron





QCD