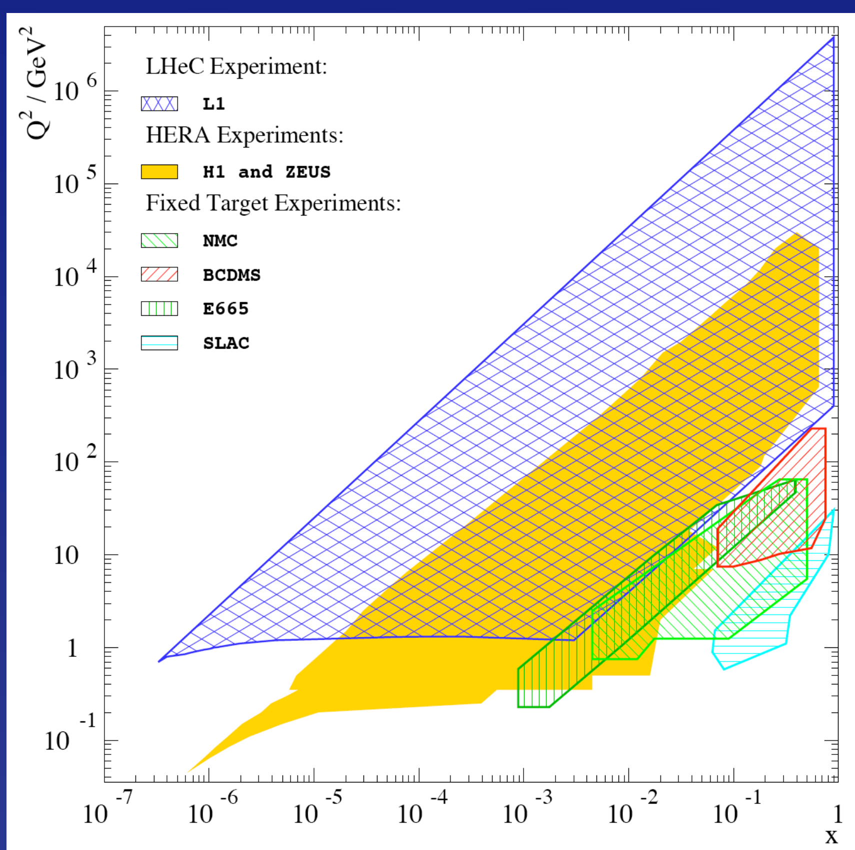
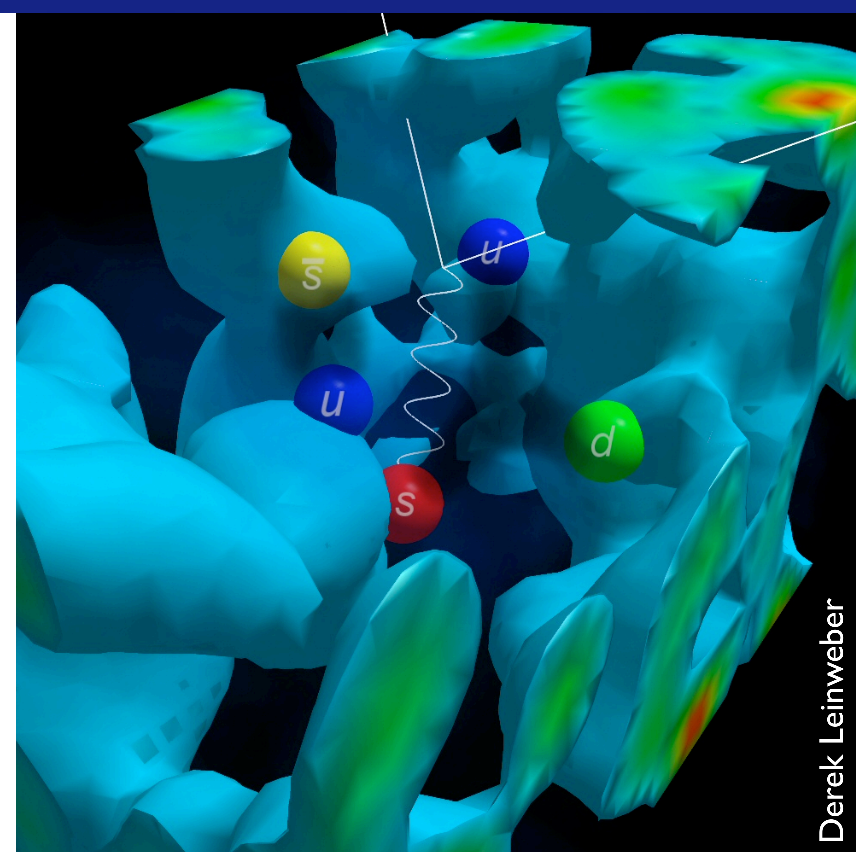
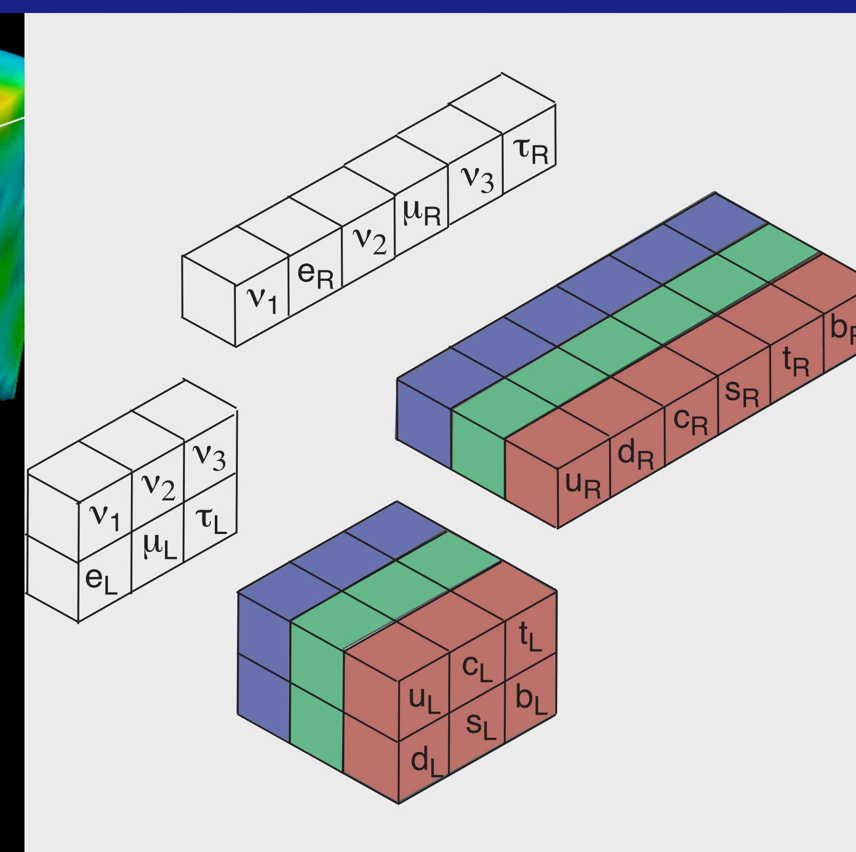
Particle Physics & LHeC

Chris Quigg

Fermi National Accelerator Laboratory

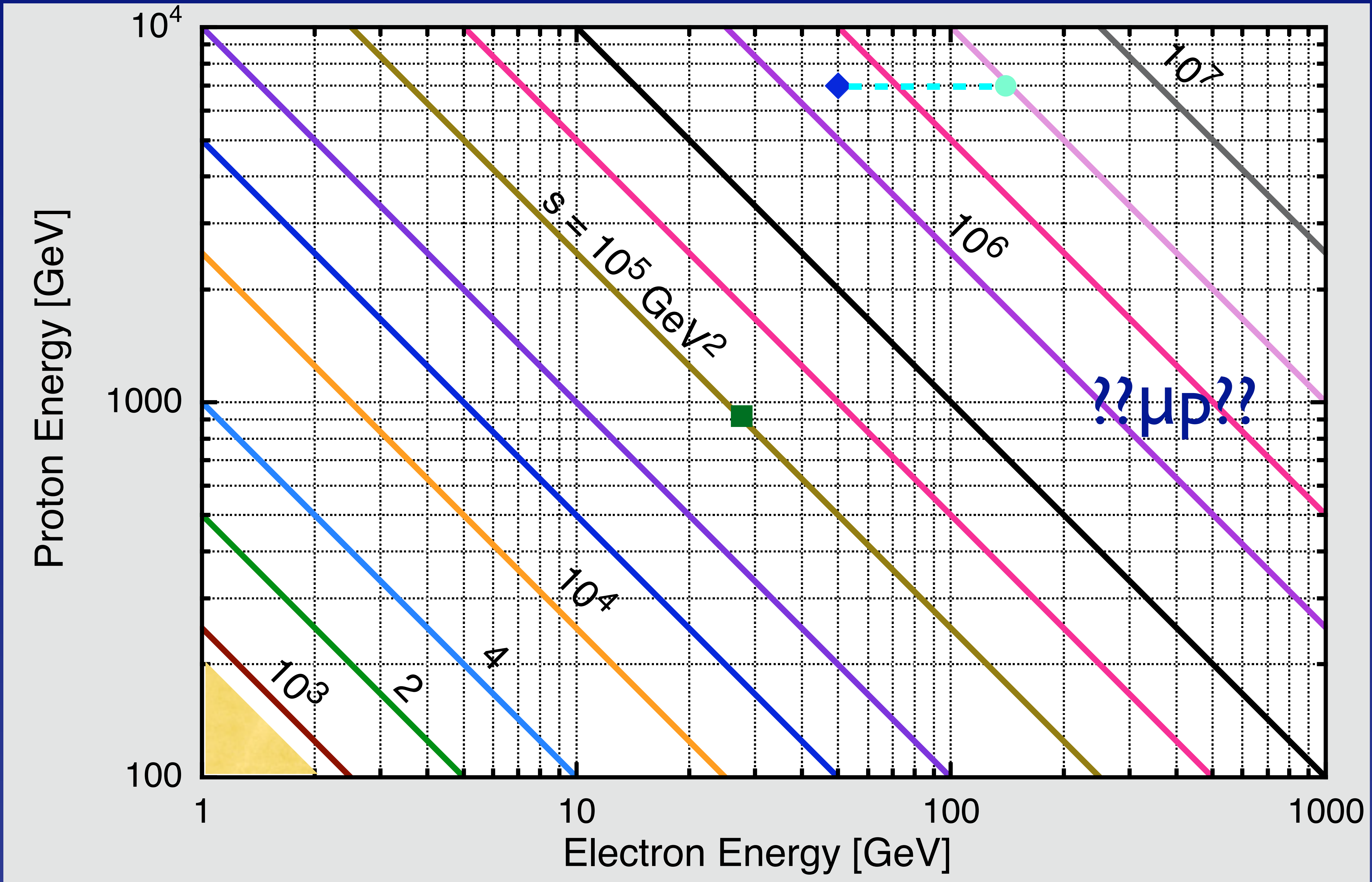






Divonne Workshop · 1.9.2009

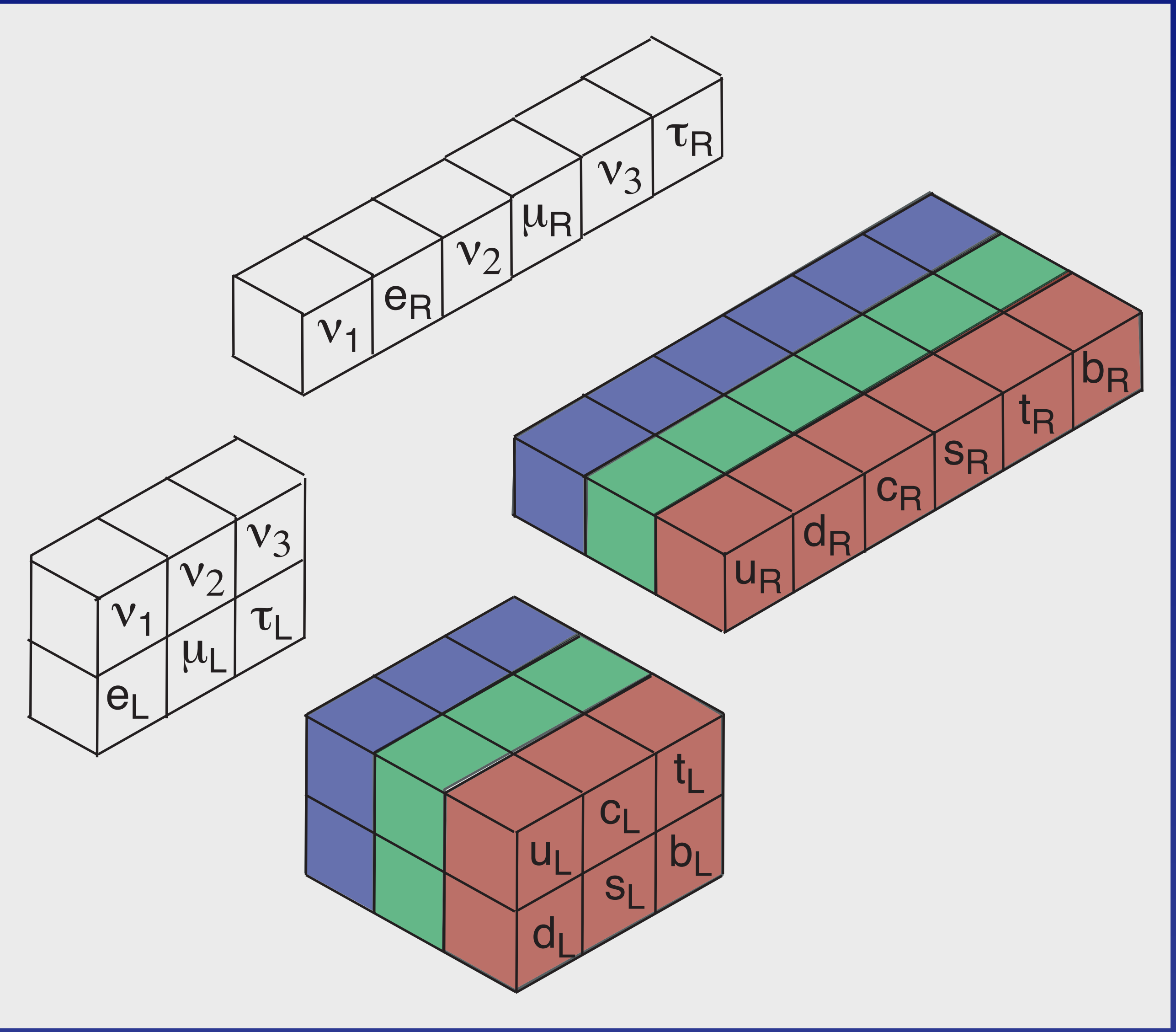
$$s \approx 4E_\ell E_p; \qquad E_\ell^{(f.t.)} = s/2M_p$$



Our Picture of Matter

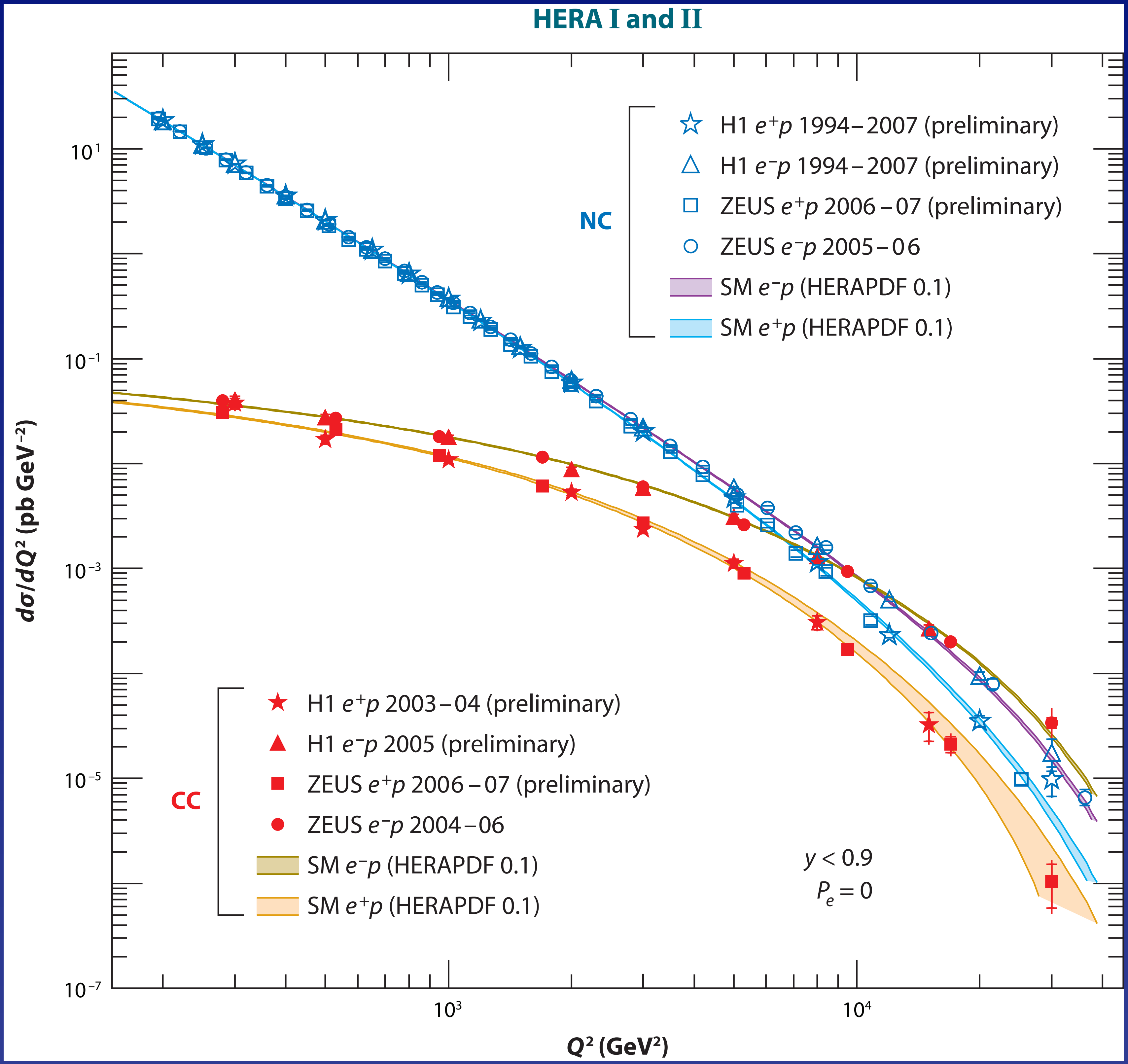
Pointlike ($r \leq 10^{-18}$ m) quarks and leptons

nanonanophysics



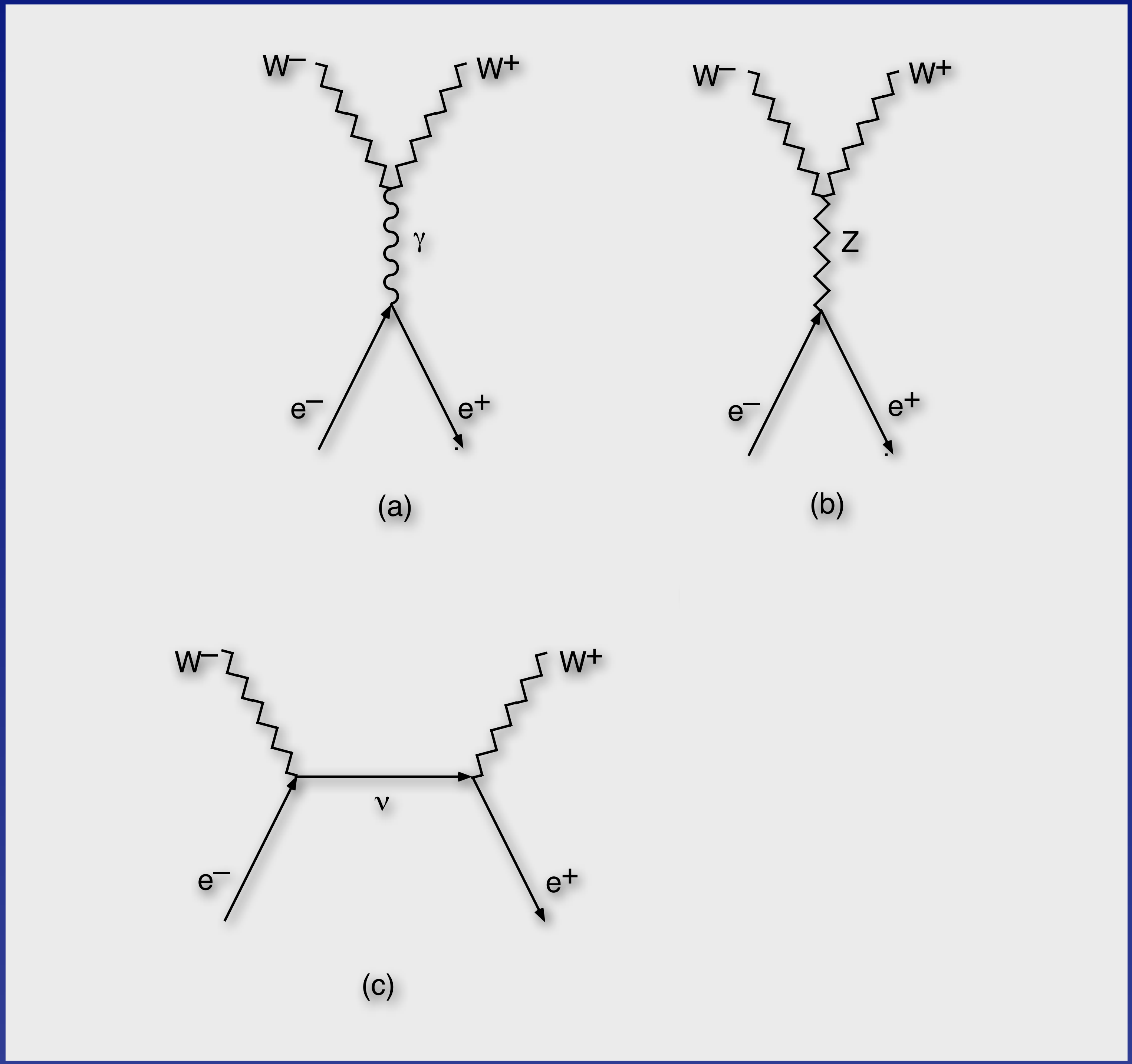
Interactions: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries

ep → eX and ep → υX: similar strengths

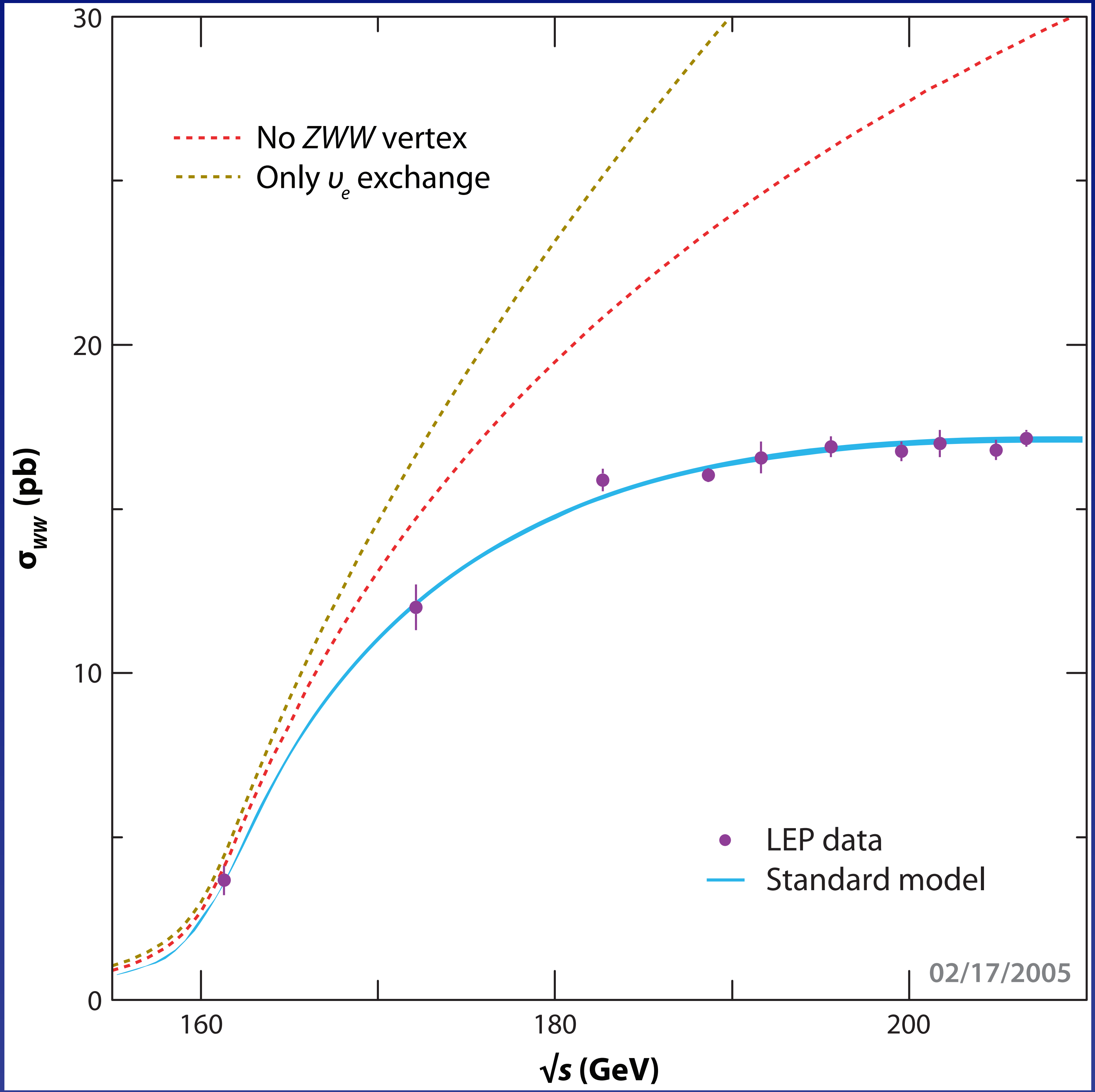


Gauge symmetry (group-theory structure) tested in

$e^+e^- \to W^+W^-$

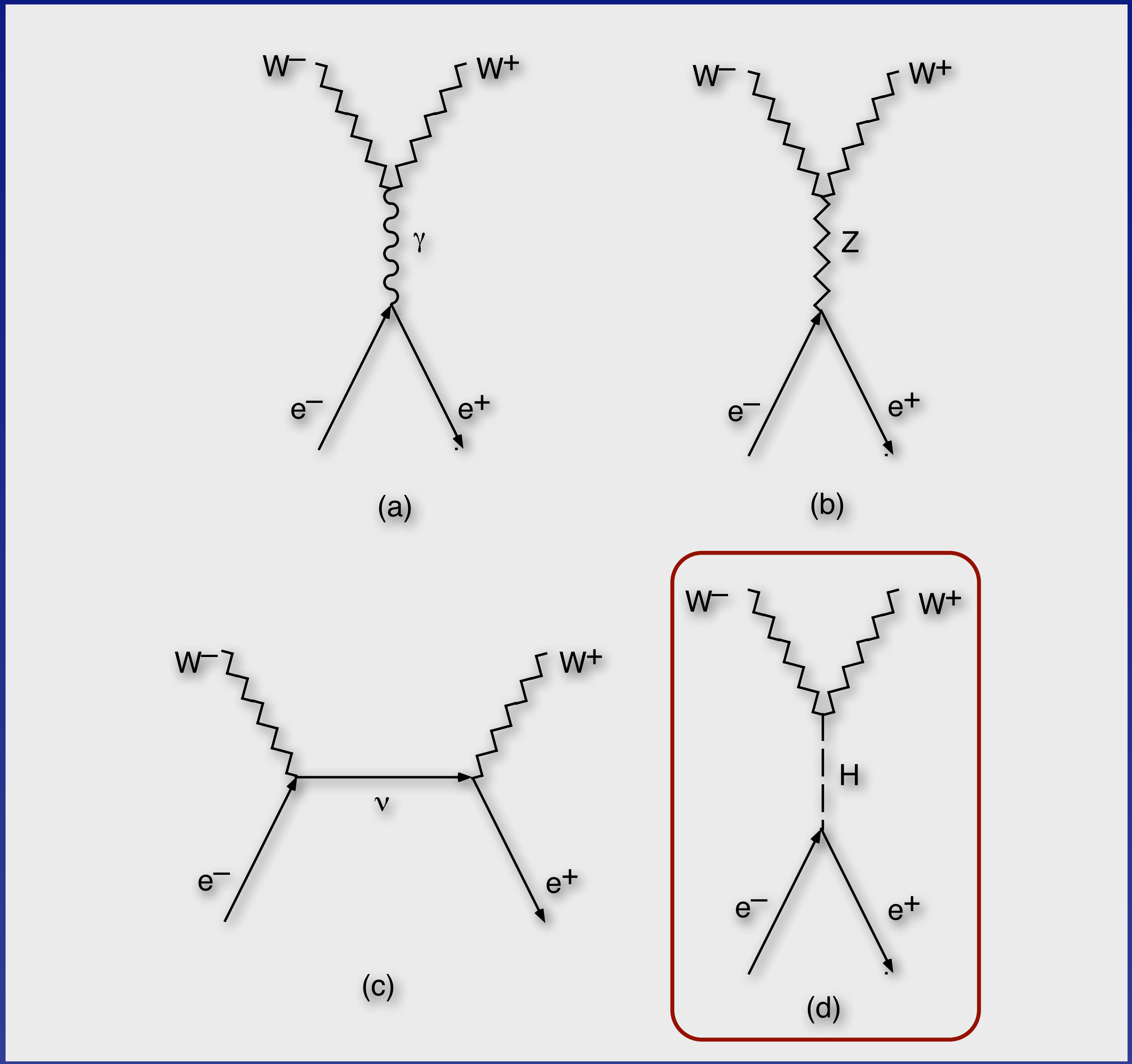


Validation of $SU(2)_L \otimes U(1)_Y$ gauge symmetry



Gauge symmetry (group-theory structure) tested in

$$e^+e^- \to W^+W^-$$

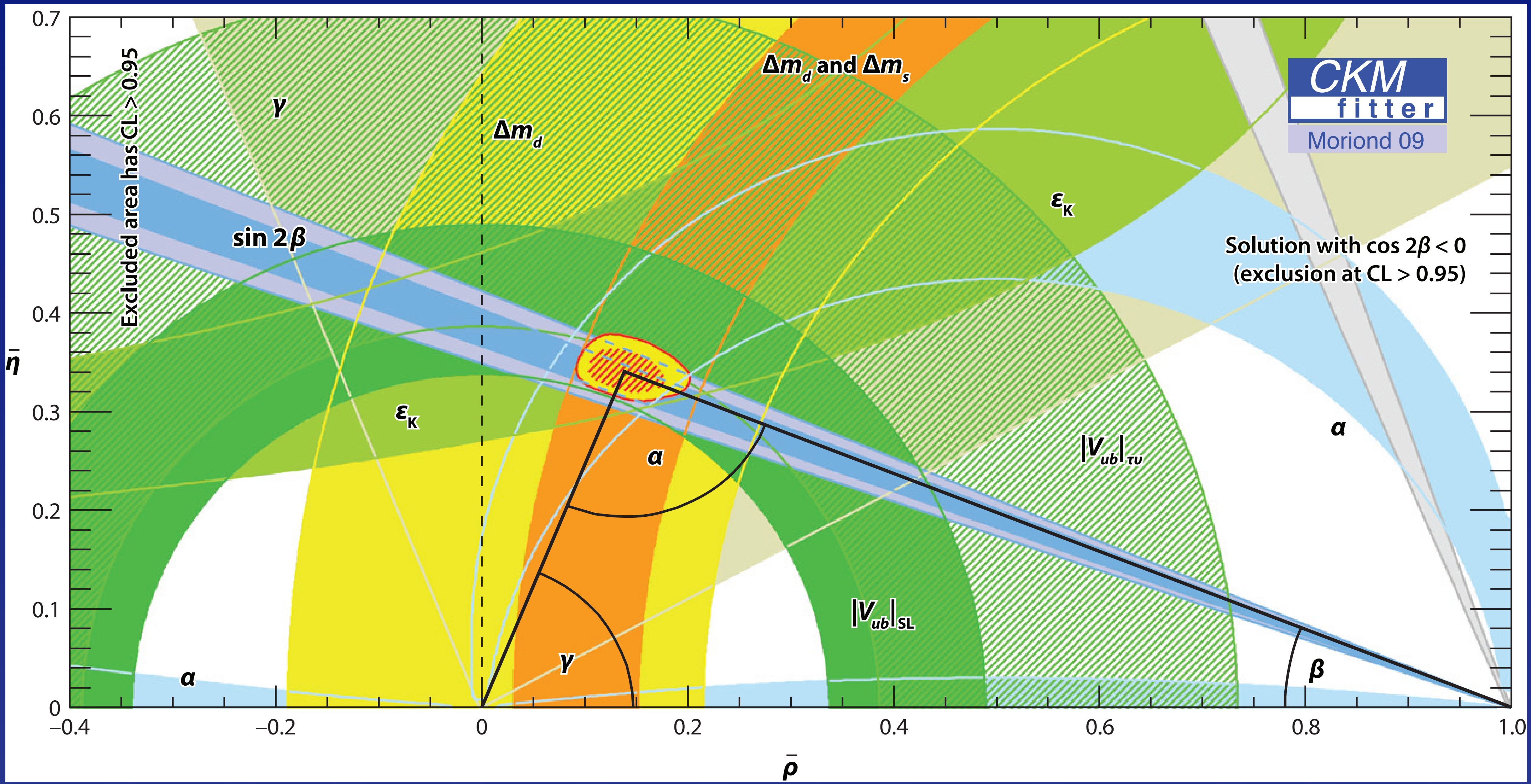


Massive weak bosons: Higgs boson

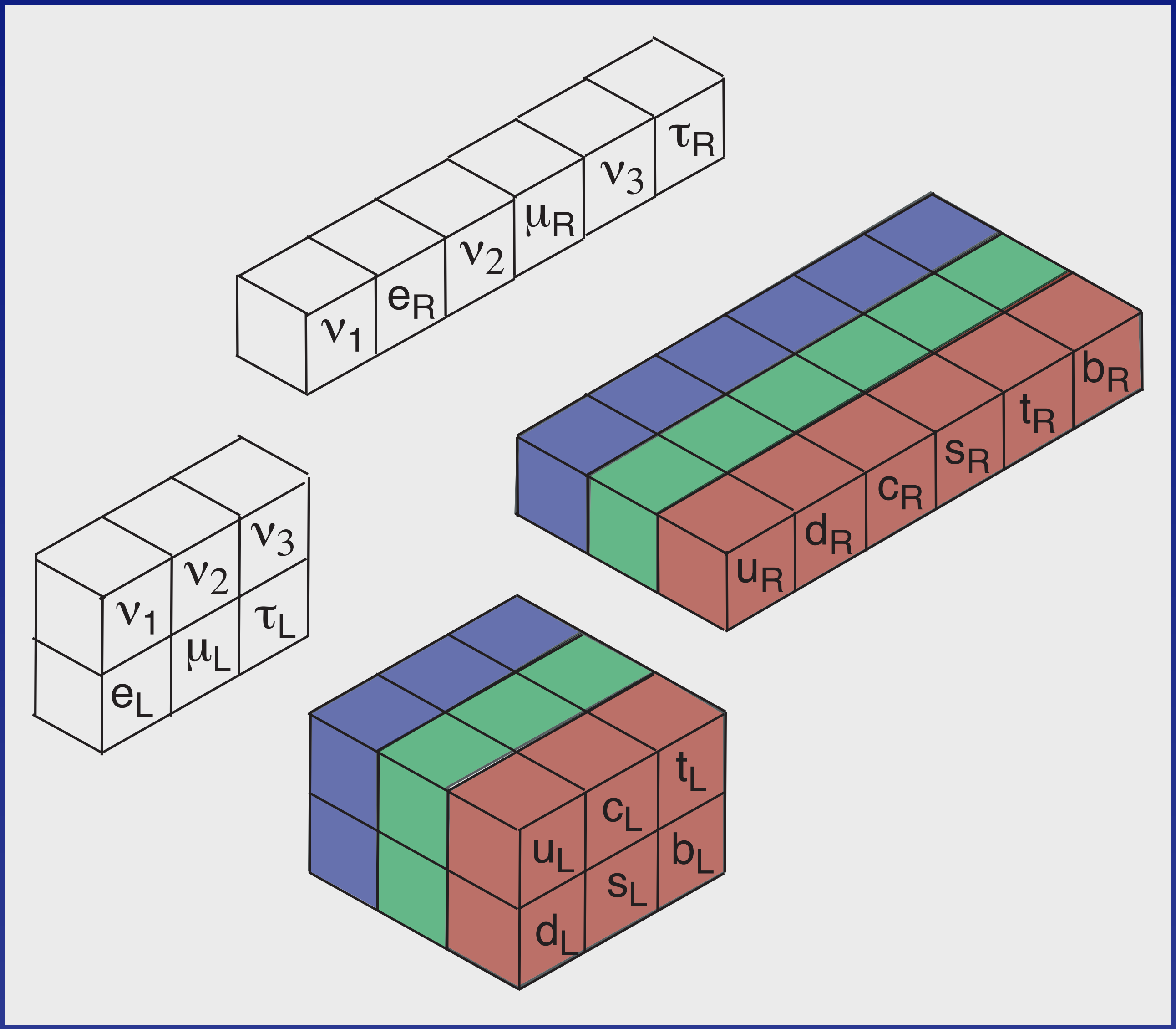
Meissner effect

$\propto G_F m_e E_{cm}$

Validation of CKM Quark Mixing Scheme

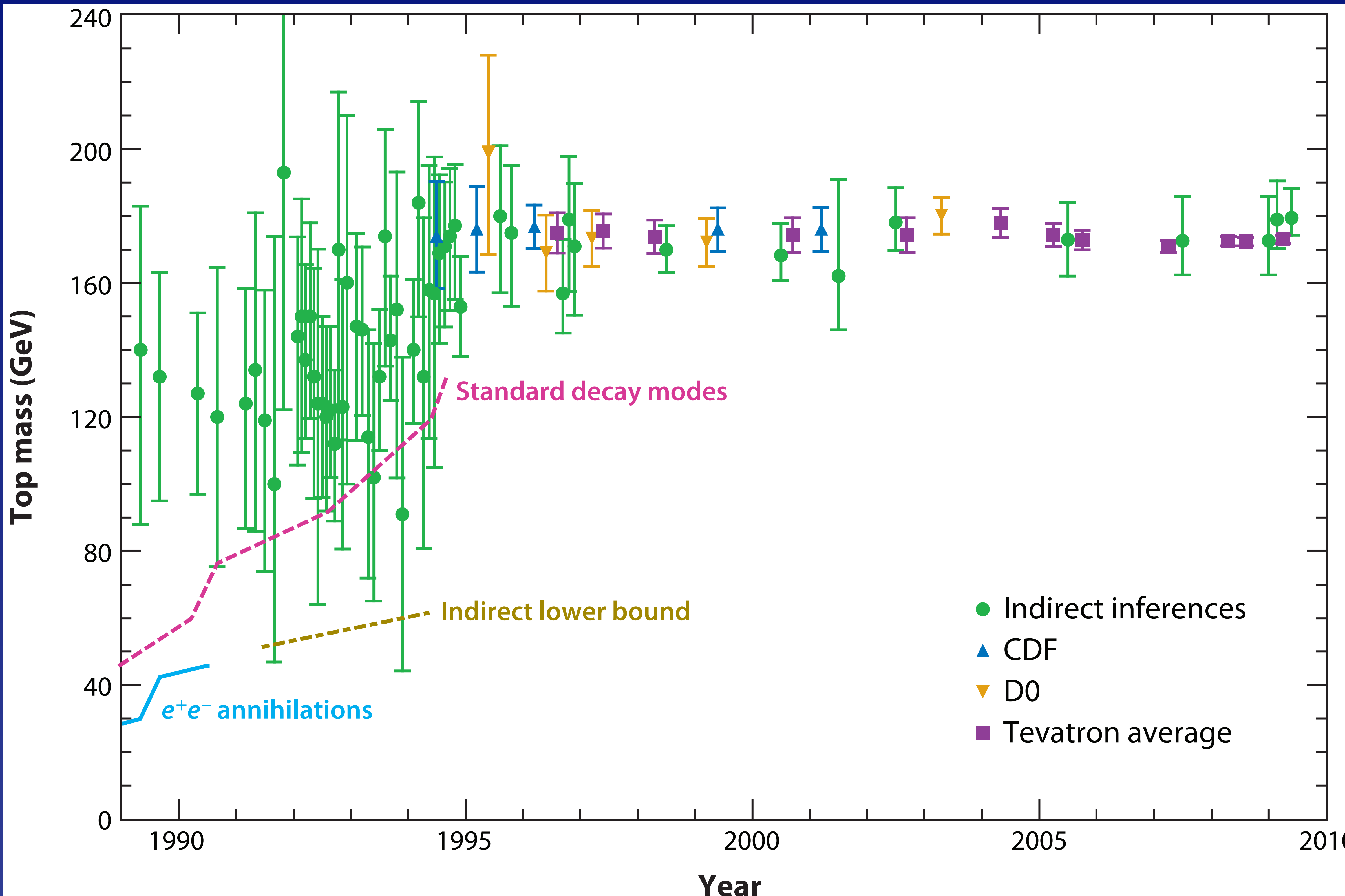


Are there right-handed weak interactions?

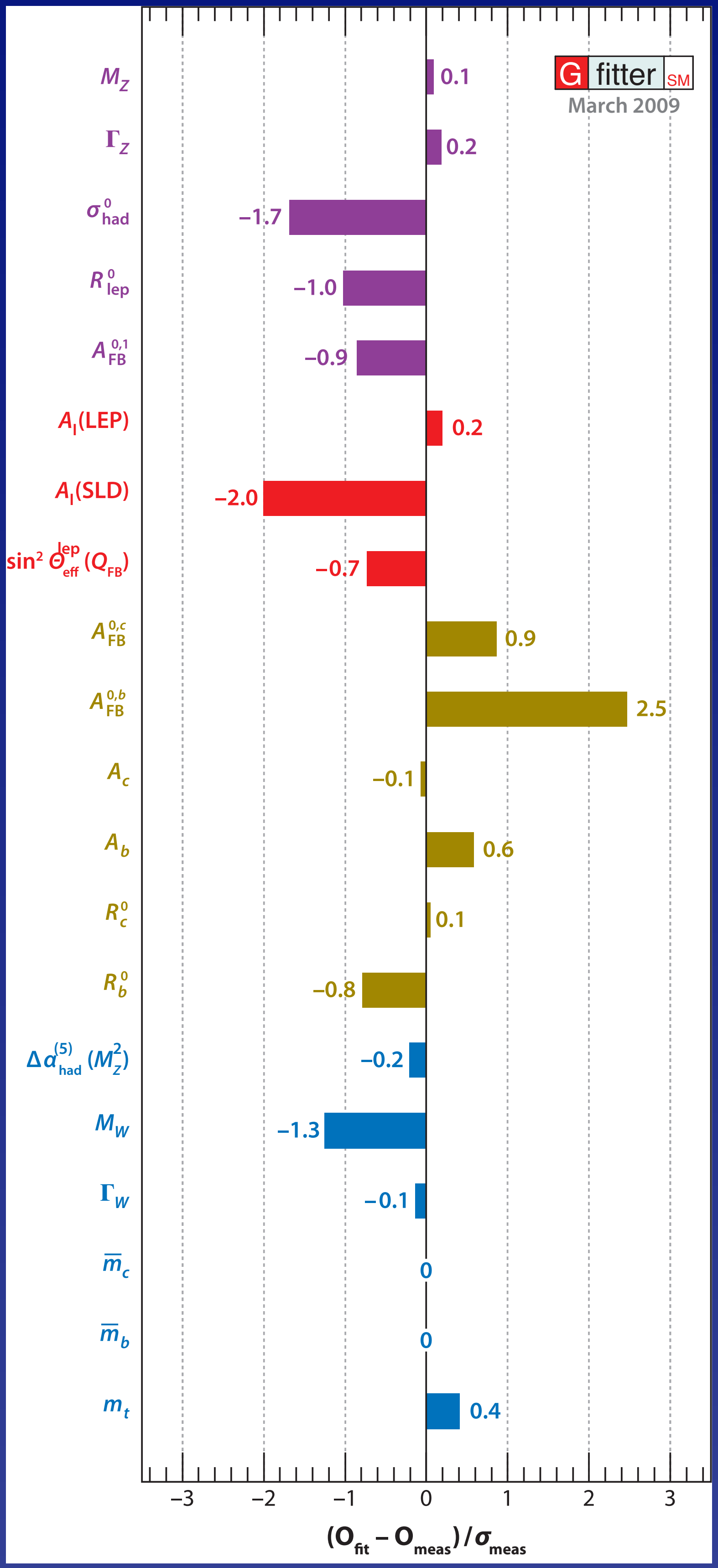


(case for polarization)

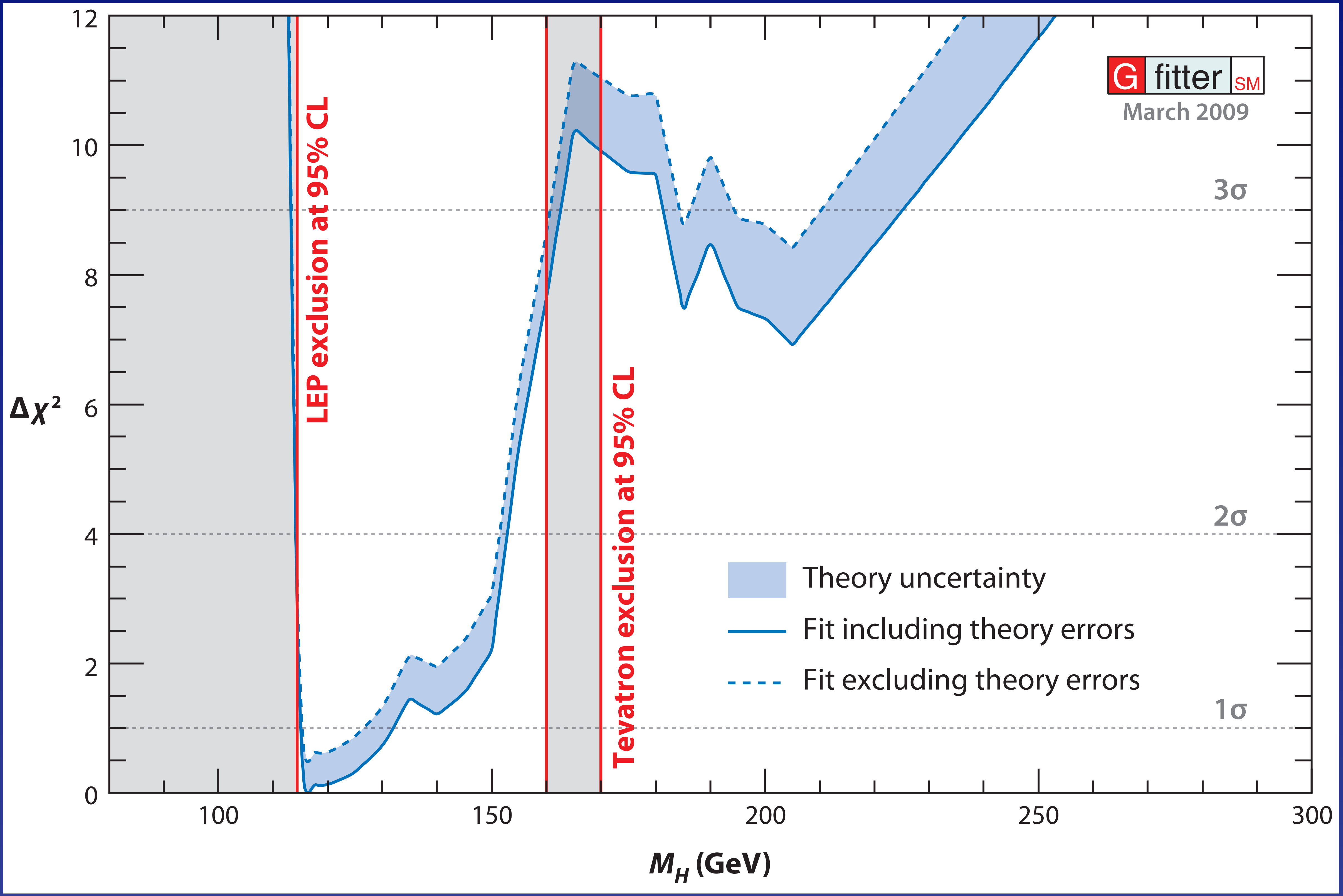
Inferring top mass from quantum corrections



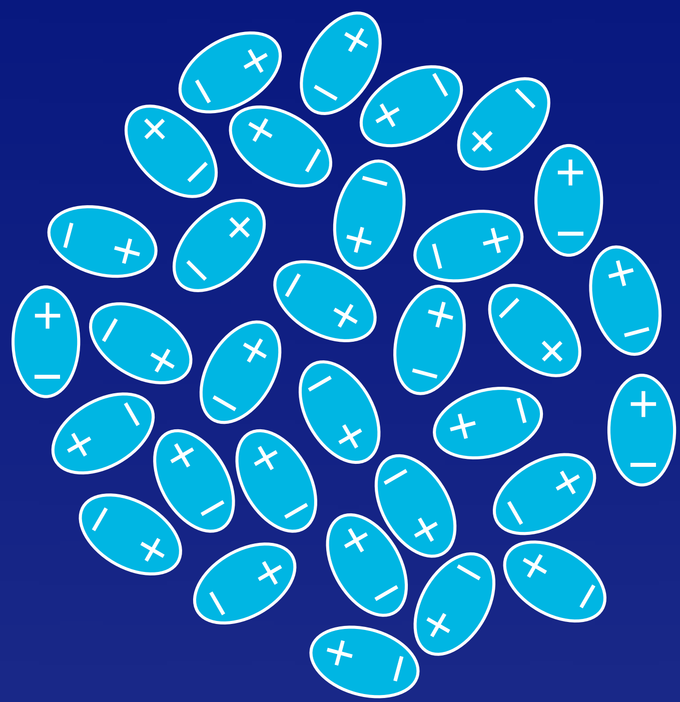
Testing electroweak theory as a quantum field theory

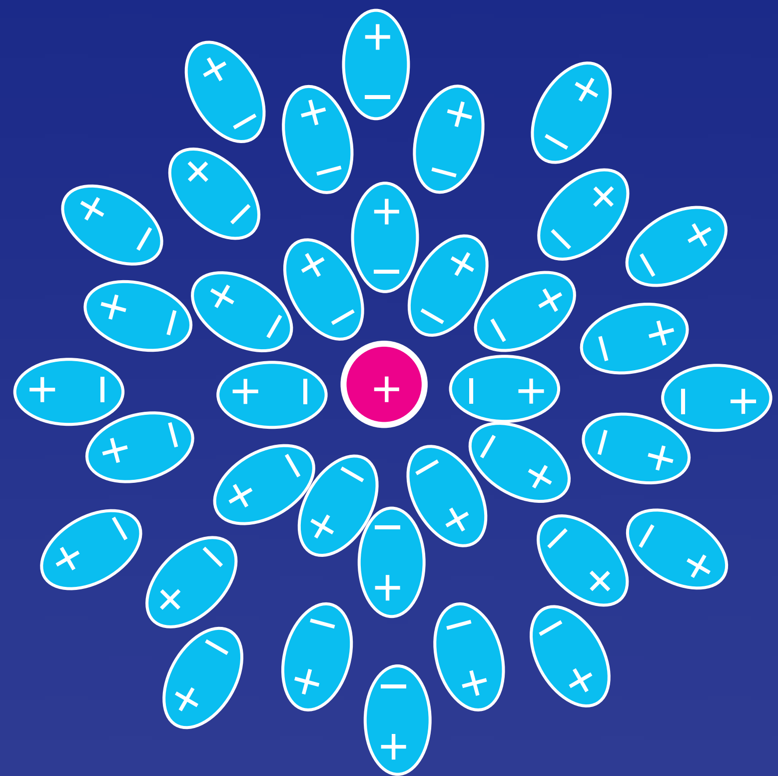


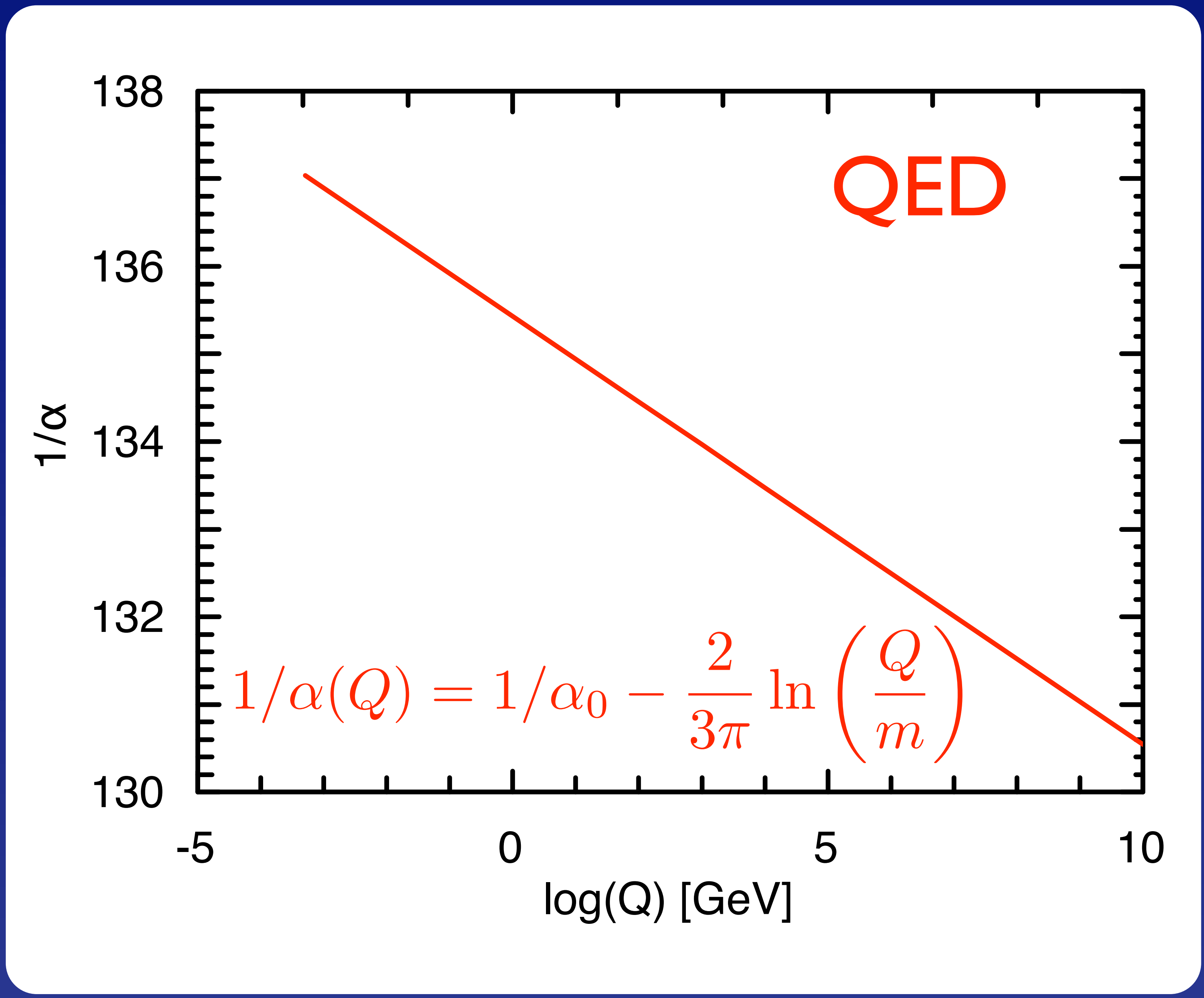
Where might *standard-model* Higgs boson be found?



Charge screening behavior of electrodynamics

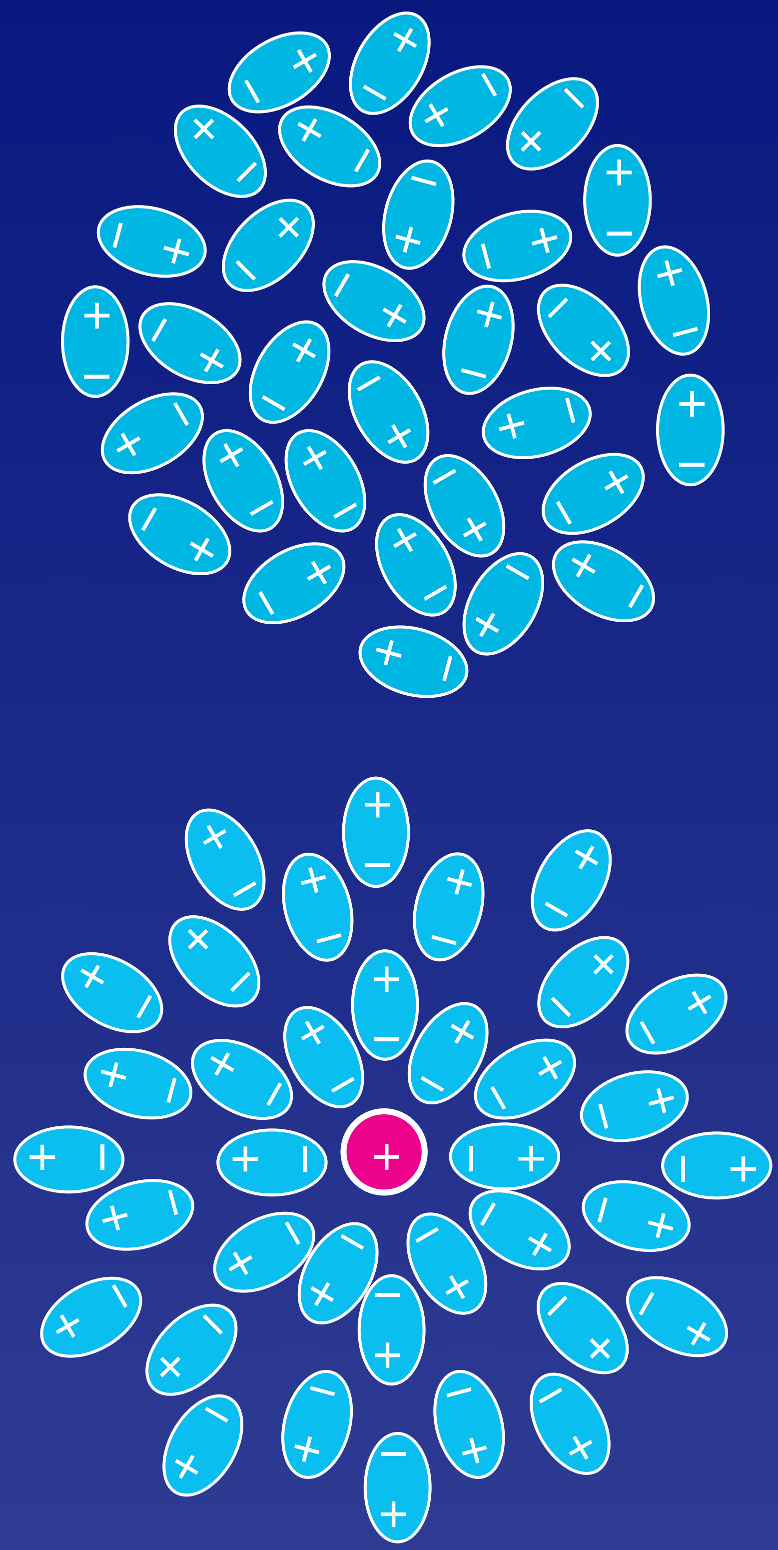


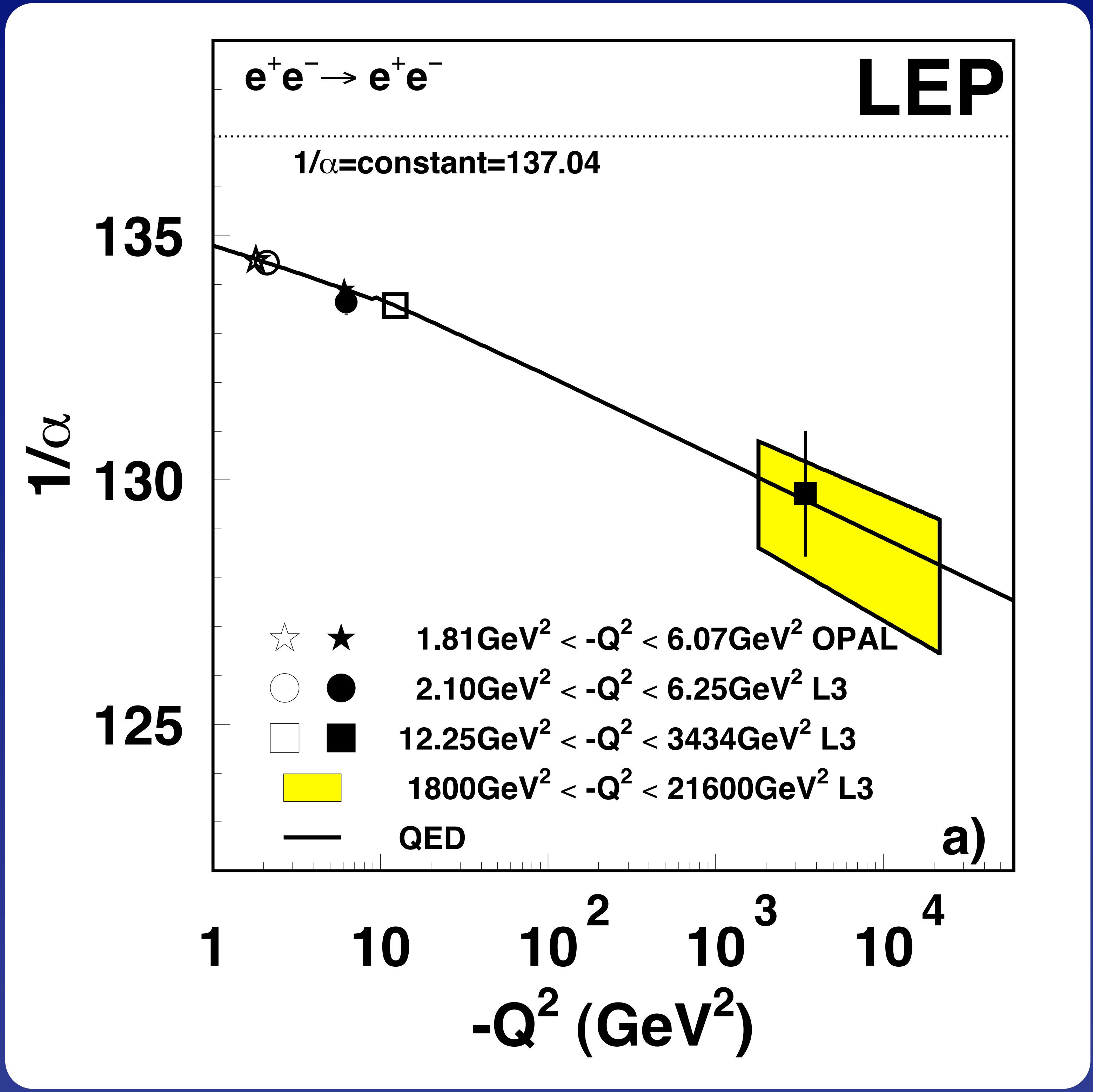




$Q_{eff} = Q/\epsilon,\ \epsilon > 1$

Charge screening behavior of electrodynamics





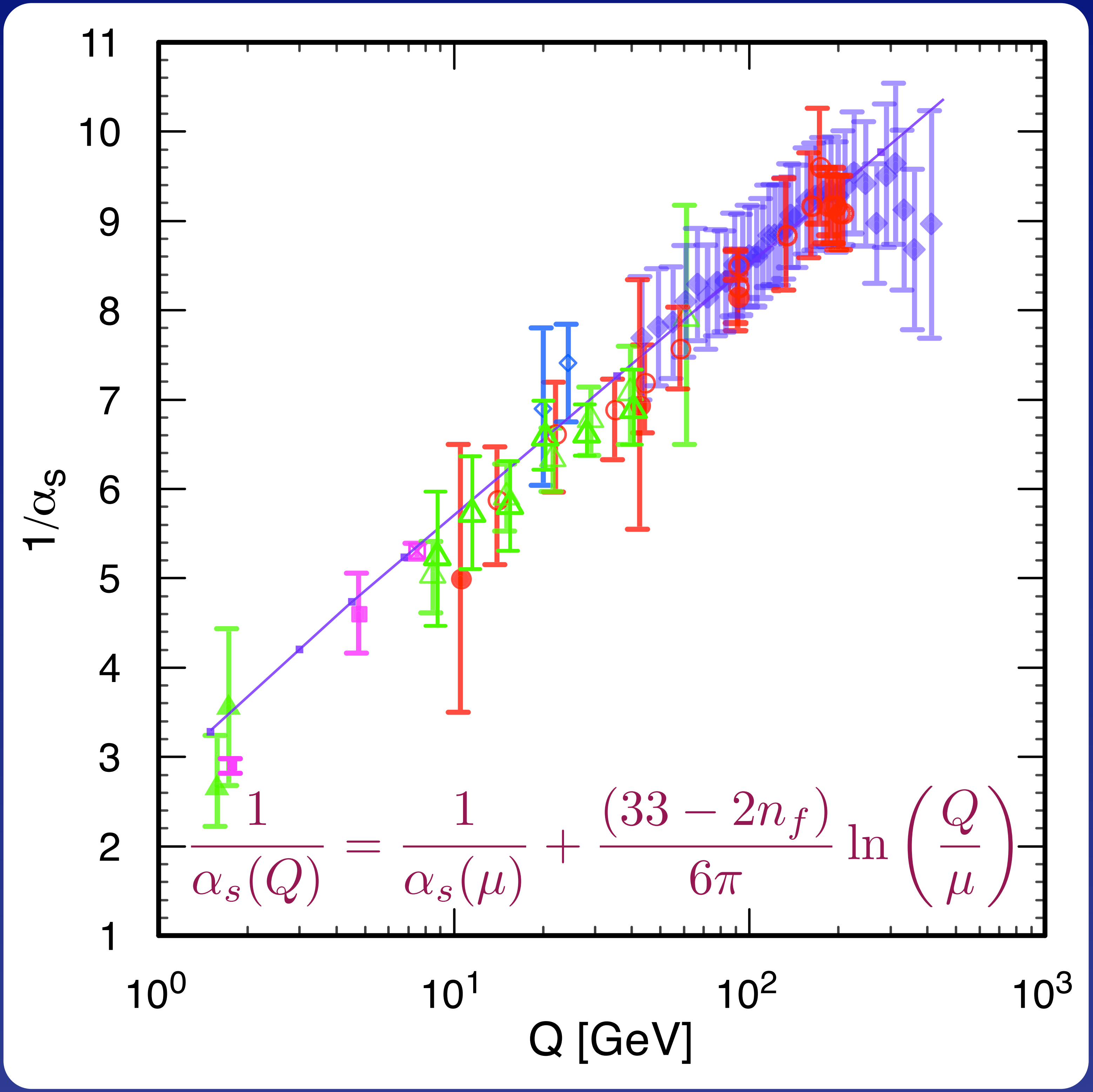
$Q_{eff} = Q/\epsilon,\ \epsilon > 1$

S. Mele, hep-ex/0601045

Color *antiscreening* behavior of chromodynamics

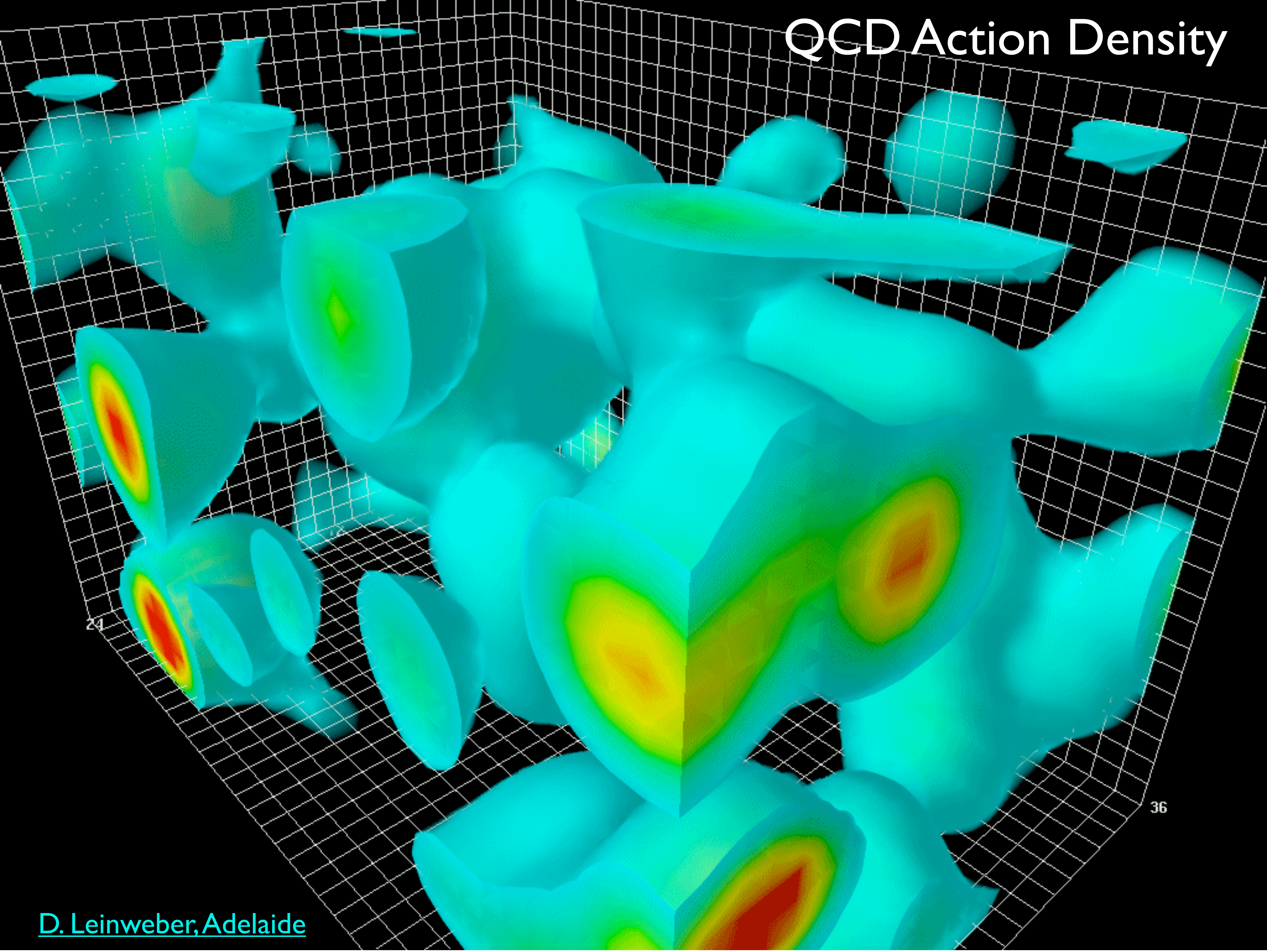
Color screening from quark pairs, camouflage from gluon cloud.

$\epsilon_{QCD} < 1$



S. Bethke, hep-ex/0606035

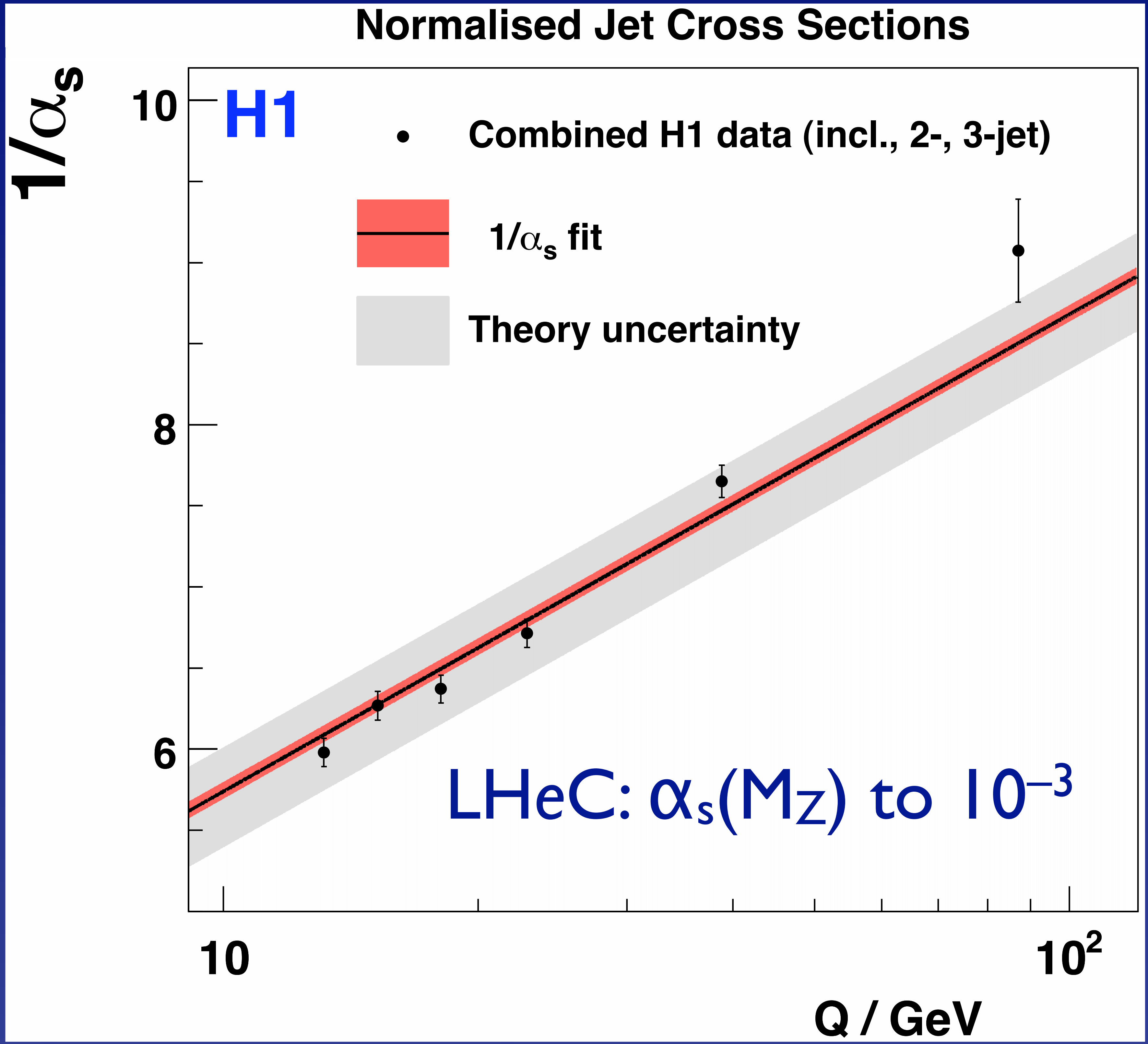
QCD Action Density



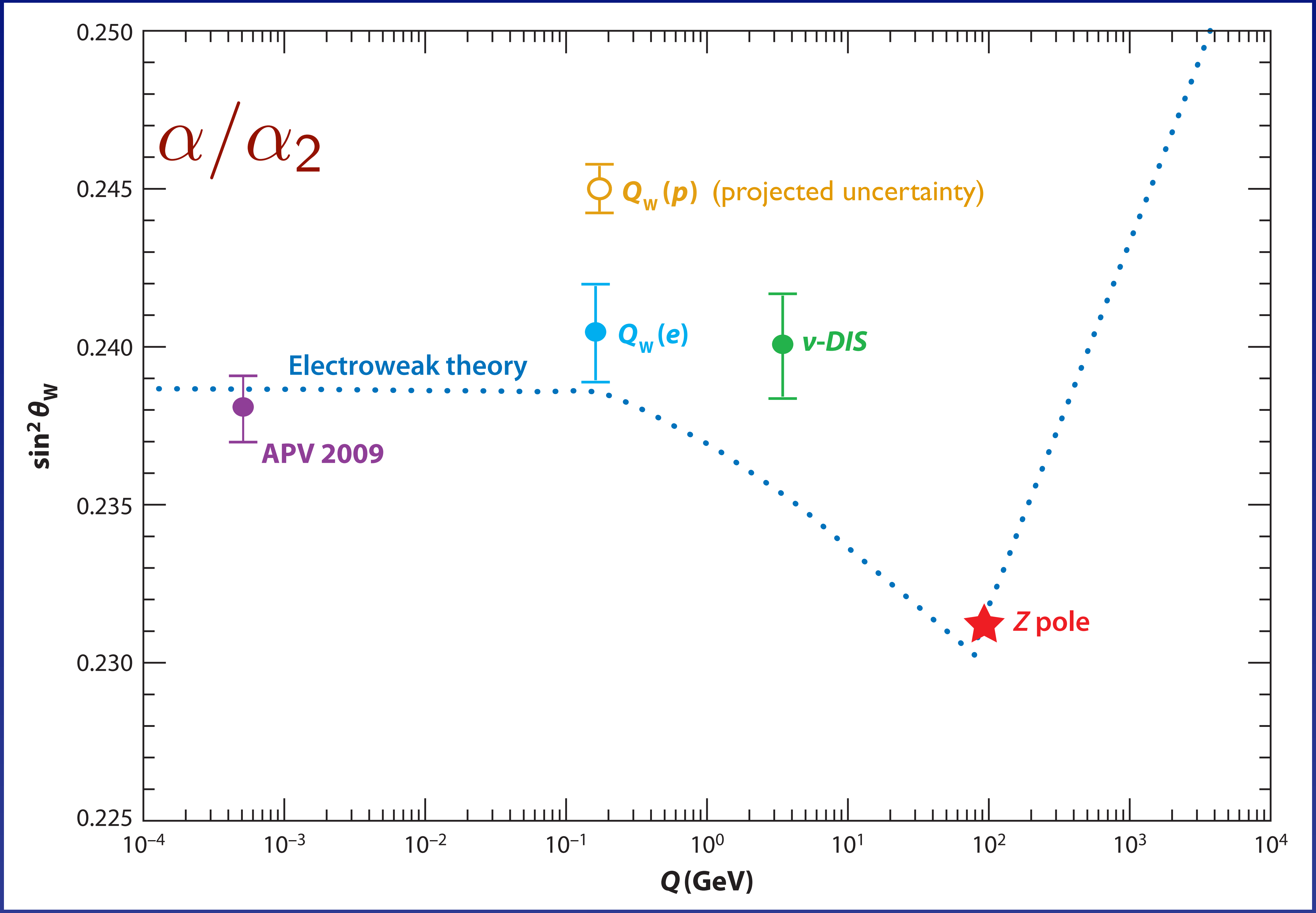
D. Leinweber, Adelaide

α_s: much recent progress (TH/EXP)

Example:

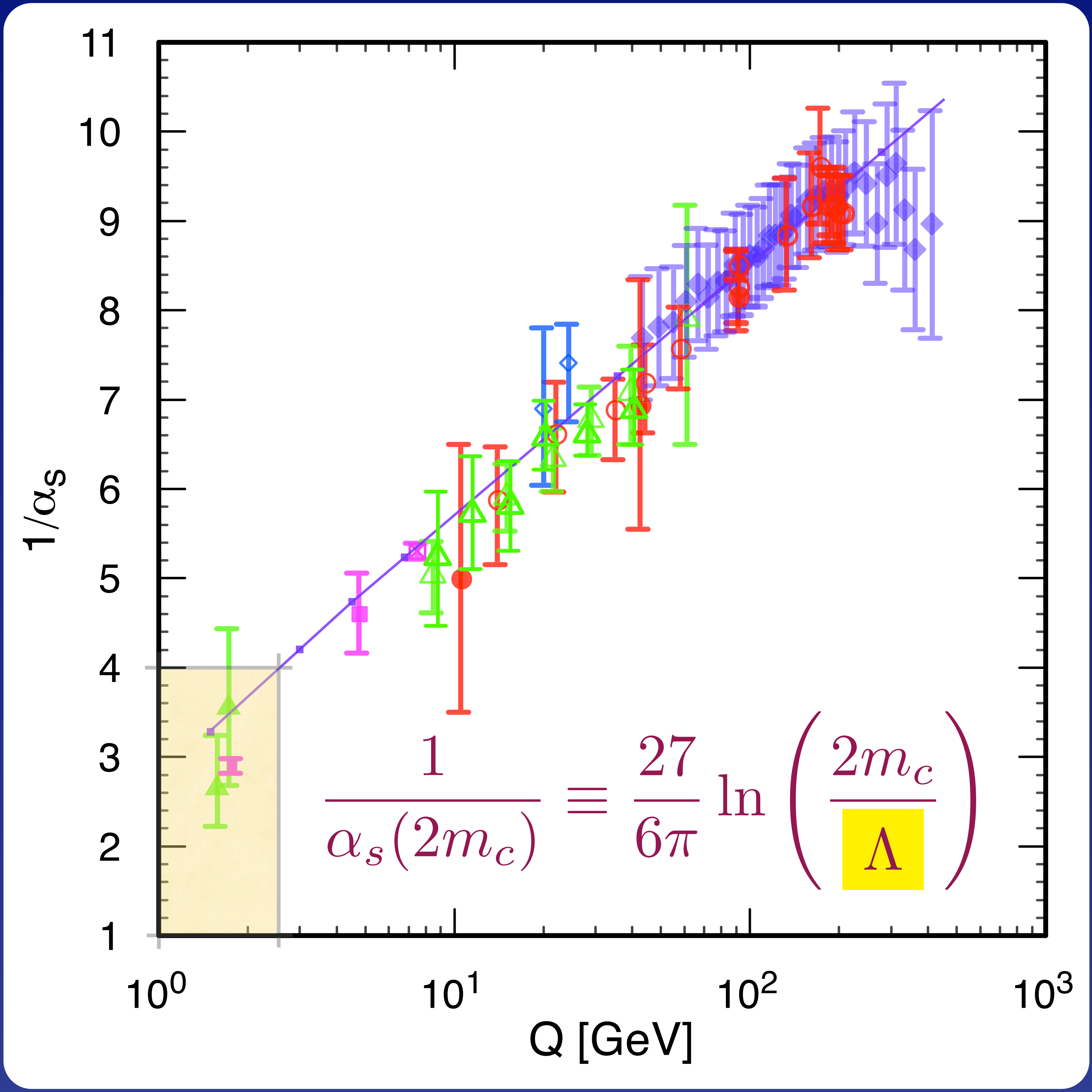


Low-energy evolution of weak mixing parameter



Dimensional transmutation

A dimensionful parameter is associated to the value of a dimensionless coupling constant



S. Bethke, hep-ex/0606035

Insight from QCD

$$M_{\text{proton}} = C \cdot \Lambda + \ldots$$

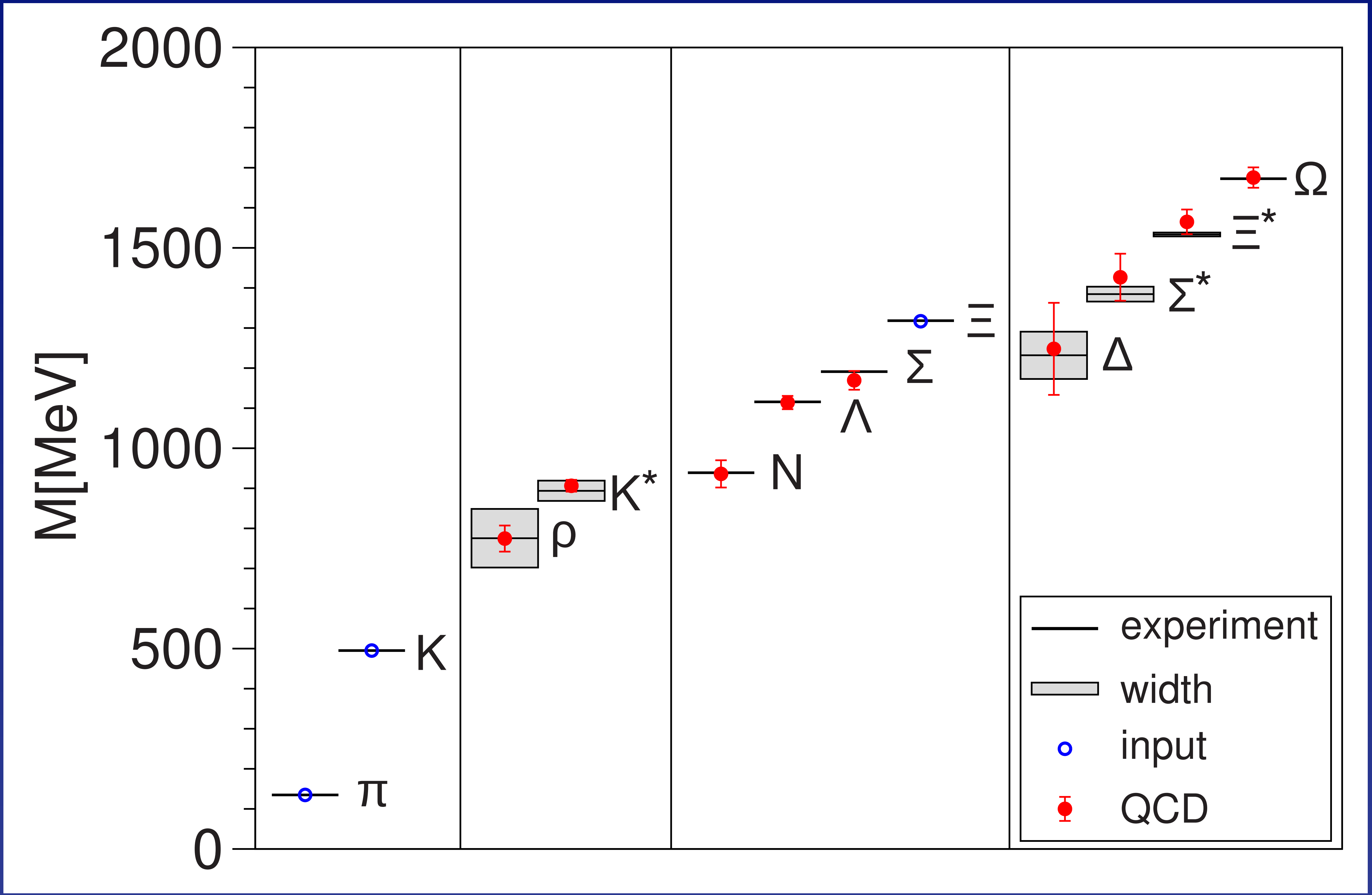
calculable on lattice

from dimensional transmutation

quark masses, EM self-energy

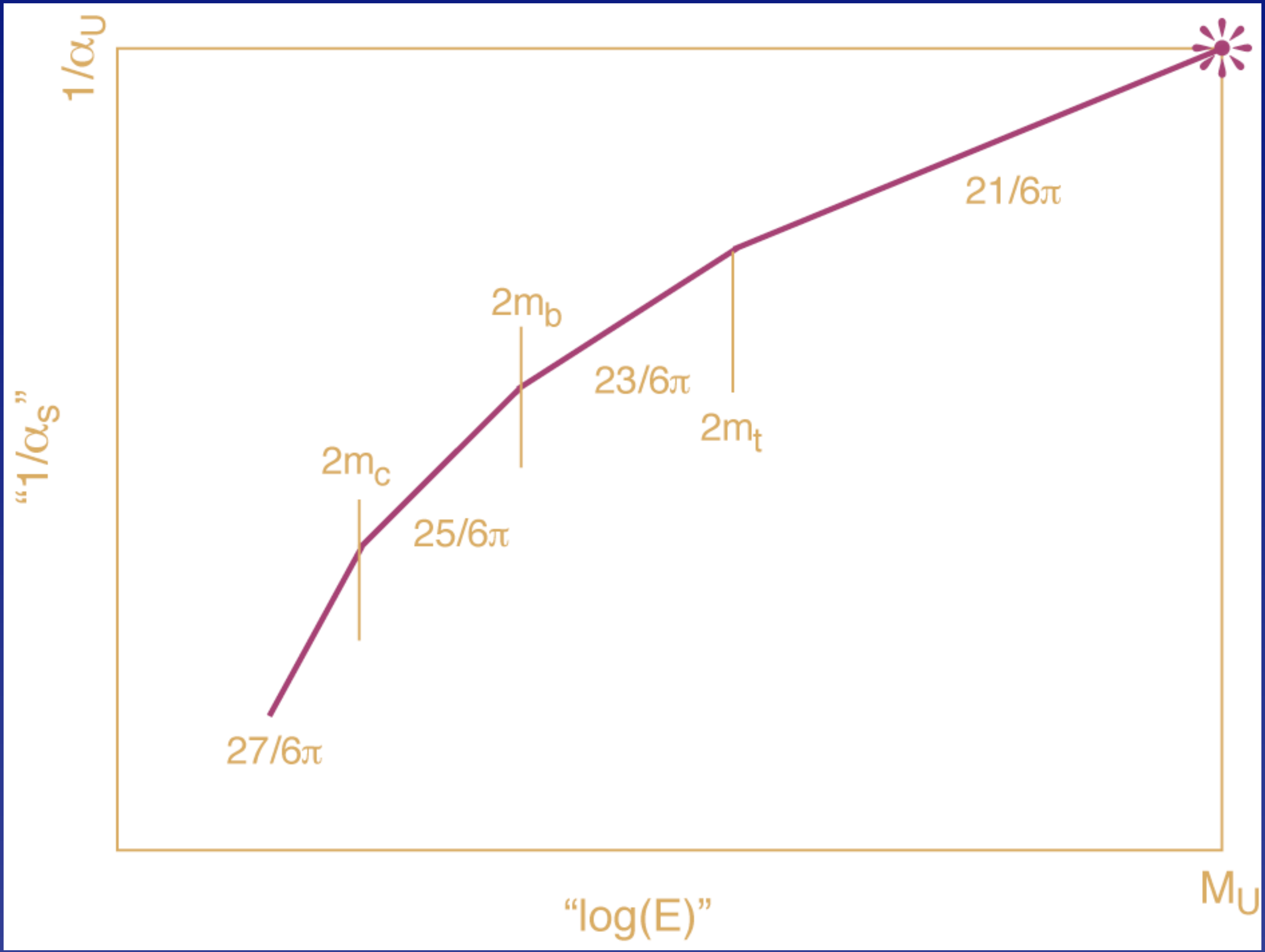
"Mass without Mass"

BMW: 2+1 dynamical quark flavors ~ 2008



Science 322: 1224 (2008)

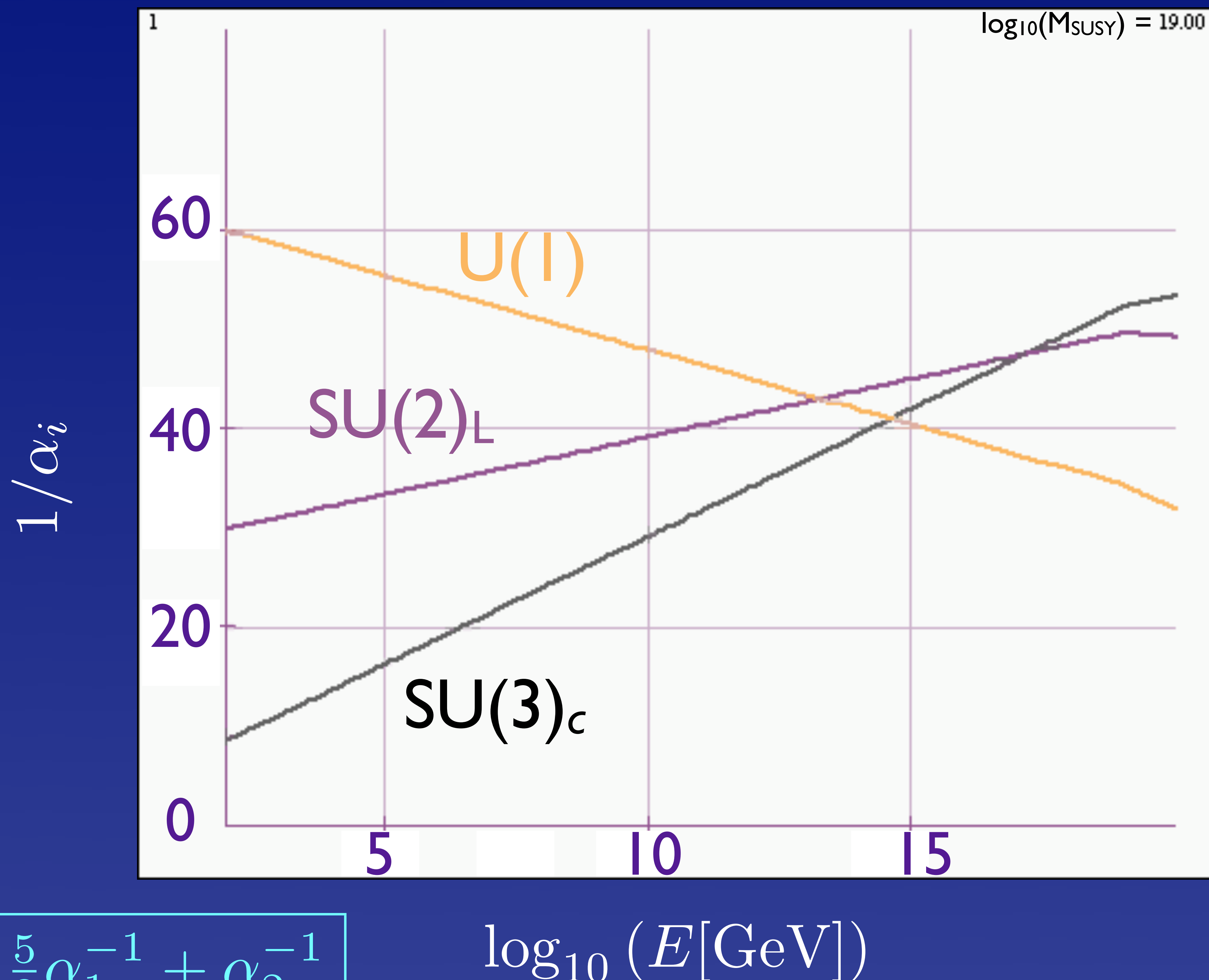
Measure change in slope at top threshold?



The Unity of Quarks & Leptons

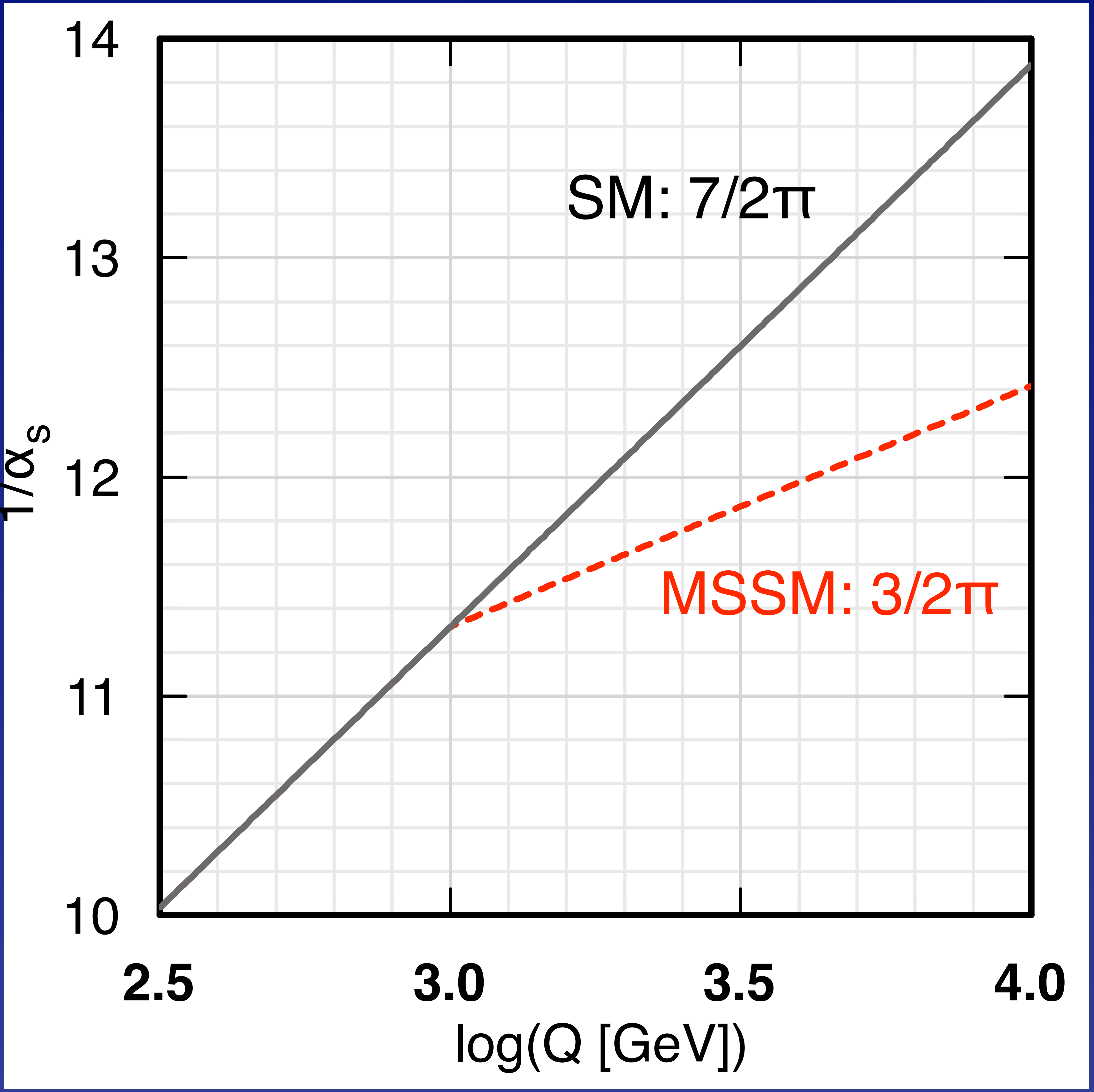
- What do quarks and leptons have in common?
- Why are atoms neutral?
- Which quarks with which leptons?
- Extended quark–lepton families: proton decay!

Different running of U(1)Y, SU(2)L, SU(3)c gives possibility of coupling constant unification



$$\alpha^{-1} = \frac{5}{3}\alpha_1^{-1} + \alpha_2^{-1}$$

Goal: Measure change in slope for onset of SUSY?



The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: *conditional upper bound*

$W_L^+ W_L^-, Z_L^0 Z_L^0, HH, HZ_L^0$ satisfy *s*-wave unitarity,

provided $M_H \leq \left(8\pi\sqrt{2}/3G_F\right)^{1/2} = 1$ TeV

- If bound is respected, perturbation theory is everywhere reliable
- If not, weak interactions among $W^\pm$, Z, H become strong on 1-TeV scale

New phenomena are to be found around 1 TeV

Imagine a world without a Higgs mechanism

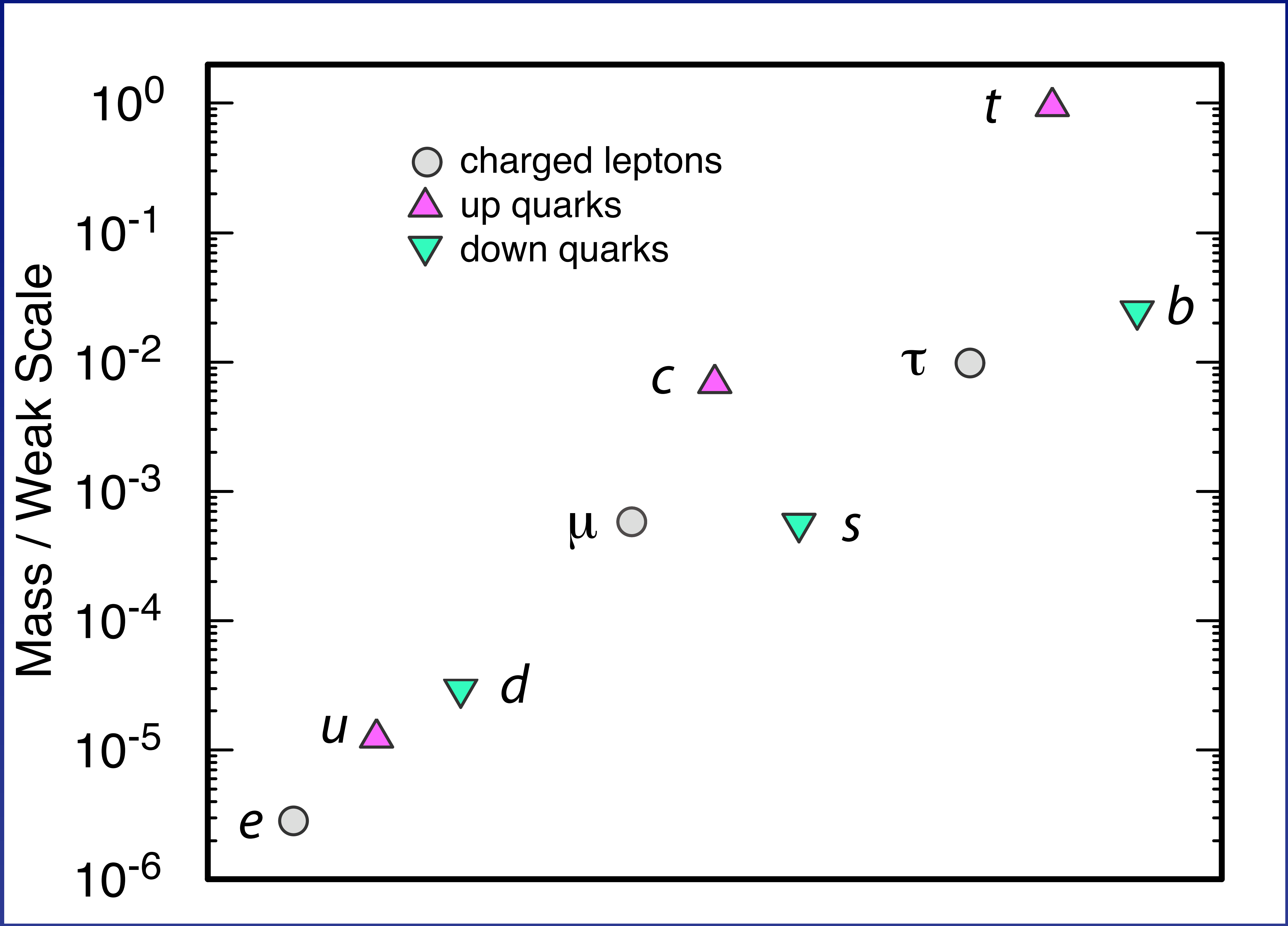
If electroweak symmetry were not hidden …

- Massless quarks and leptons
- QCD confines quarks into color-singlet hadrons
- *Nucleon mass little changed*
- QCD breaks EW symmetry, gives tiny W, Z masses; weak-isospin force doesn't confine
- *p might outweigh n:* rapid β-decay
  $\Rightarrow$ lightest nucleus is n … no hydrogen atom
- If light elements from BBN, ∞ Bohr radius
- No atoms means no chemistry, no stable composite structures like liquids, solids, …

… character of the physical world would be profoundly changed

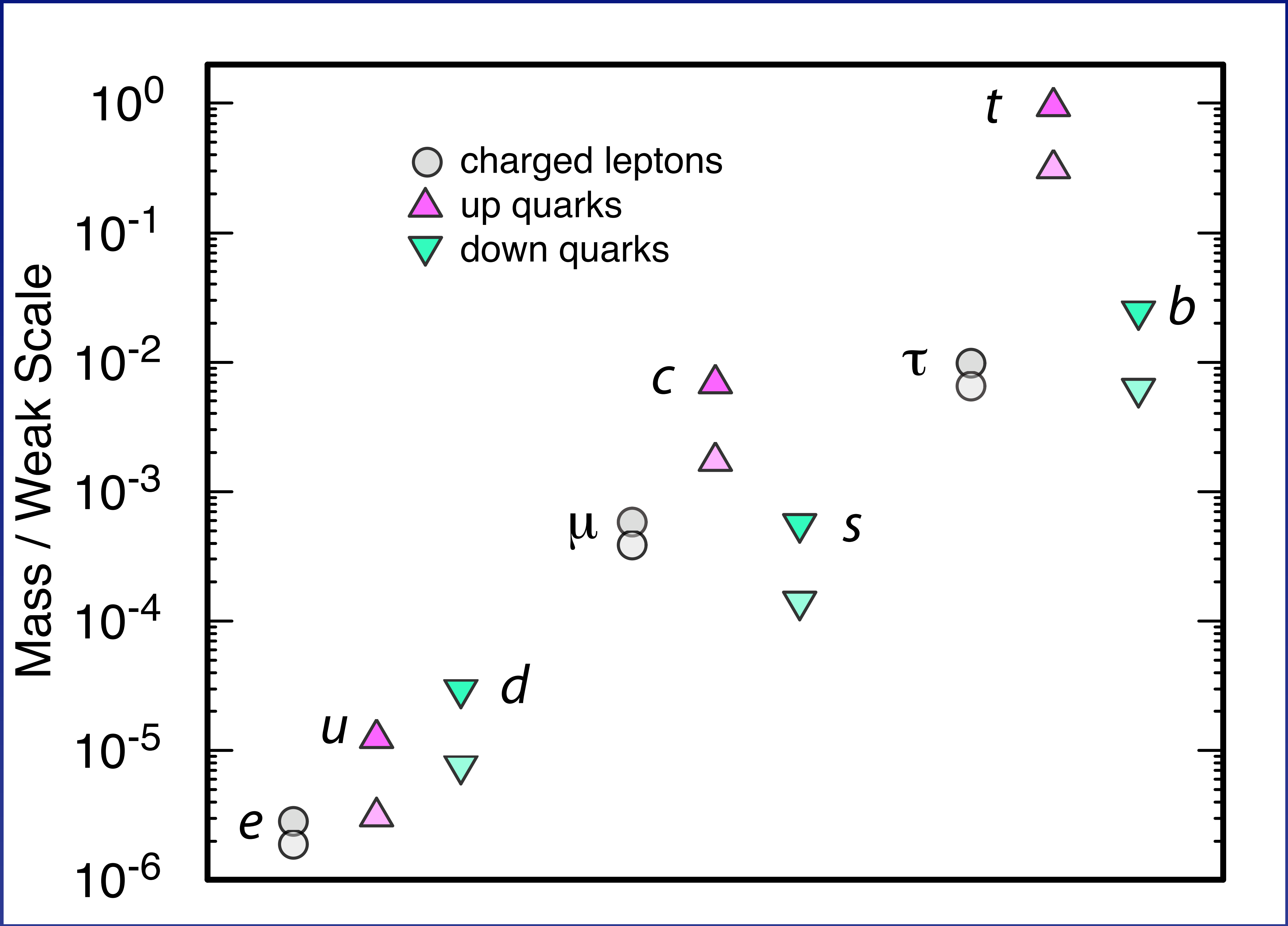
[arXiv:0901.3958]

Fermion Masses



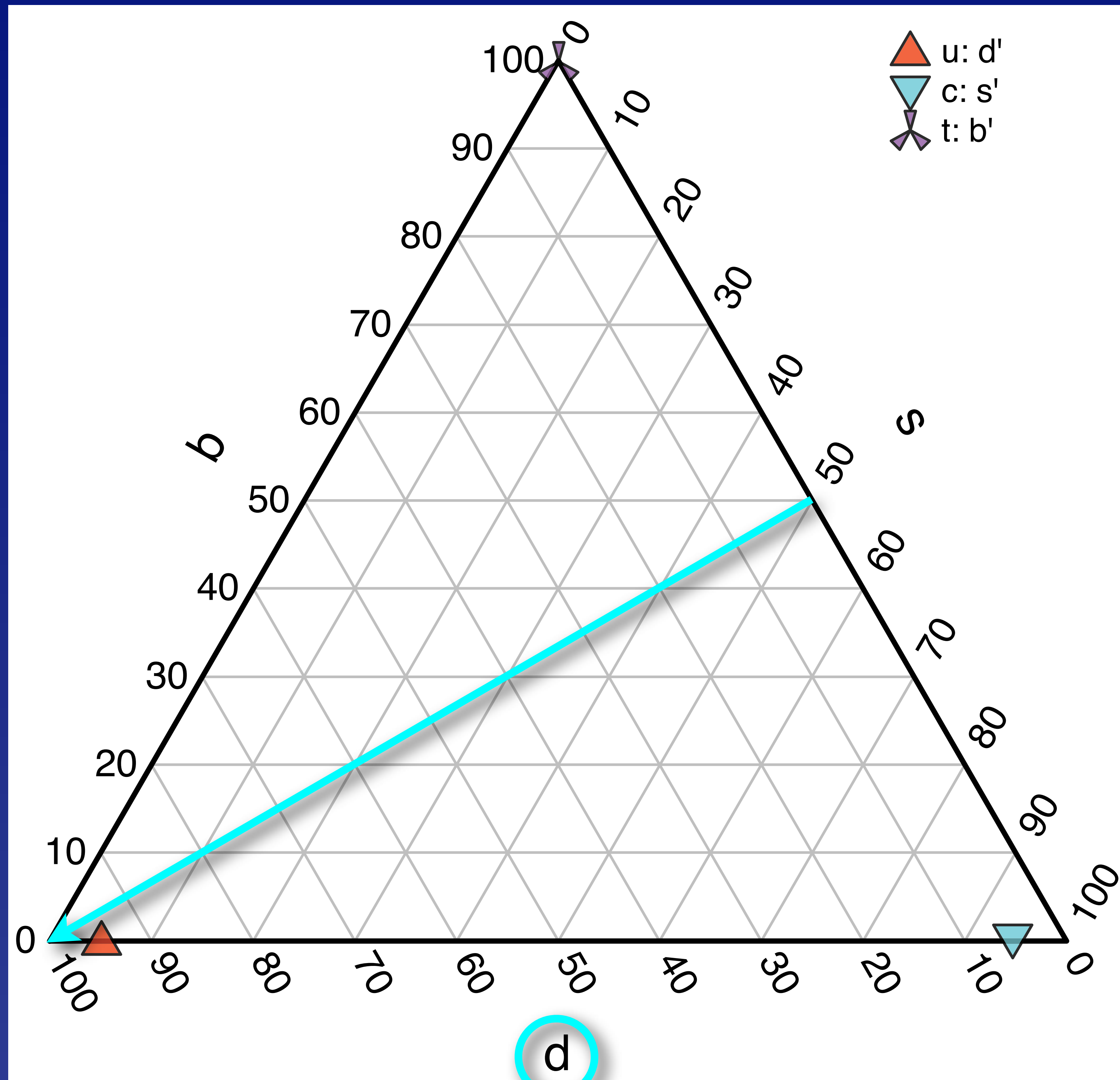
Running mass $m(m)$

Fermion Masses Run



Running mass *m*(*m*) … *m*(*U*)

Quark family patterns: *generations*



Veltman: Higgs boson knows something we don't know!

We have seen influence of Higgs boson in vacuum
Establishes "Higgs" couplings to W,Z

Weakly coupled (light Higgs boson)
or new strong dynamics?
Prepare for both lines …

No evidence yet for "Higgs" coupling to fermions

First evidence from $\mathrm{gg} \to \mathrm{H} \to \gamma\gamma$?

$(\rightsquigarrow \mathrm{Ht\bar{t}})$

LHeC: $\mathrm{W^+W^-} \to \mathrm{H} \to \mathrm{b\bar{b}}$

[arXiv:0905.3187]

Mass of the vacuum

Natural to neglect gravity in particle physics

Gravitational *ep* interaction ≈ 10^{-41} EM

But gravity is not always negligible …

Higgs field contributes uniform vacuum energy density

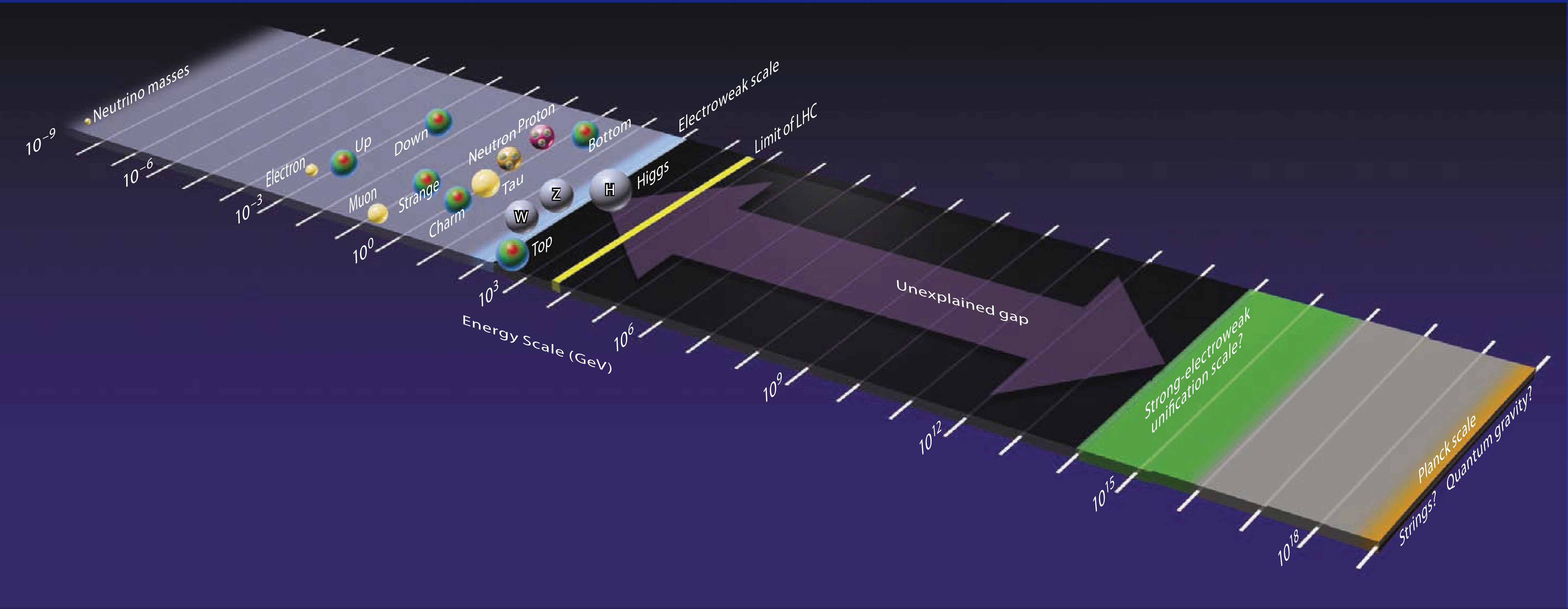
$$\varrho_H \equiv \frac{M_H^2 v^2}{8} \geq 10^8\ \text{GeV}^4 \qquad \approx 10^{24}\ \text{g cm}^{-3}$$

Critical density $\varrho_c \equiv \dfrac{3H_0^2}{8\pi G_{\text{Newton}}} \lesssim 10^{-29}\ \text{g cm}^{-3}$

How to separate EW, higher scales?

Does M_H < 1 TeV make sense?

The peril of quantum corrections – hierarchy problem



How to separate EW, higher scales?

Traditional: change electroweak theory to understand why M_H, electroweak scale $\ll M_{\text{Planck}}$

To resolve hierarchy problem: extend standard model on the 1-TeV scale …

$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

- composite Higgs boson
- technicolor / topcolor
- supersymmetry
- …

Ask instead why gravity is so weak, why $M_{\text{Planck}} \gg$ electroweak scale

A new conception of spacetime?

Could there be more spatial dimensions than we have perceived?

What is their size? their shape?

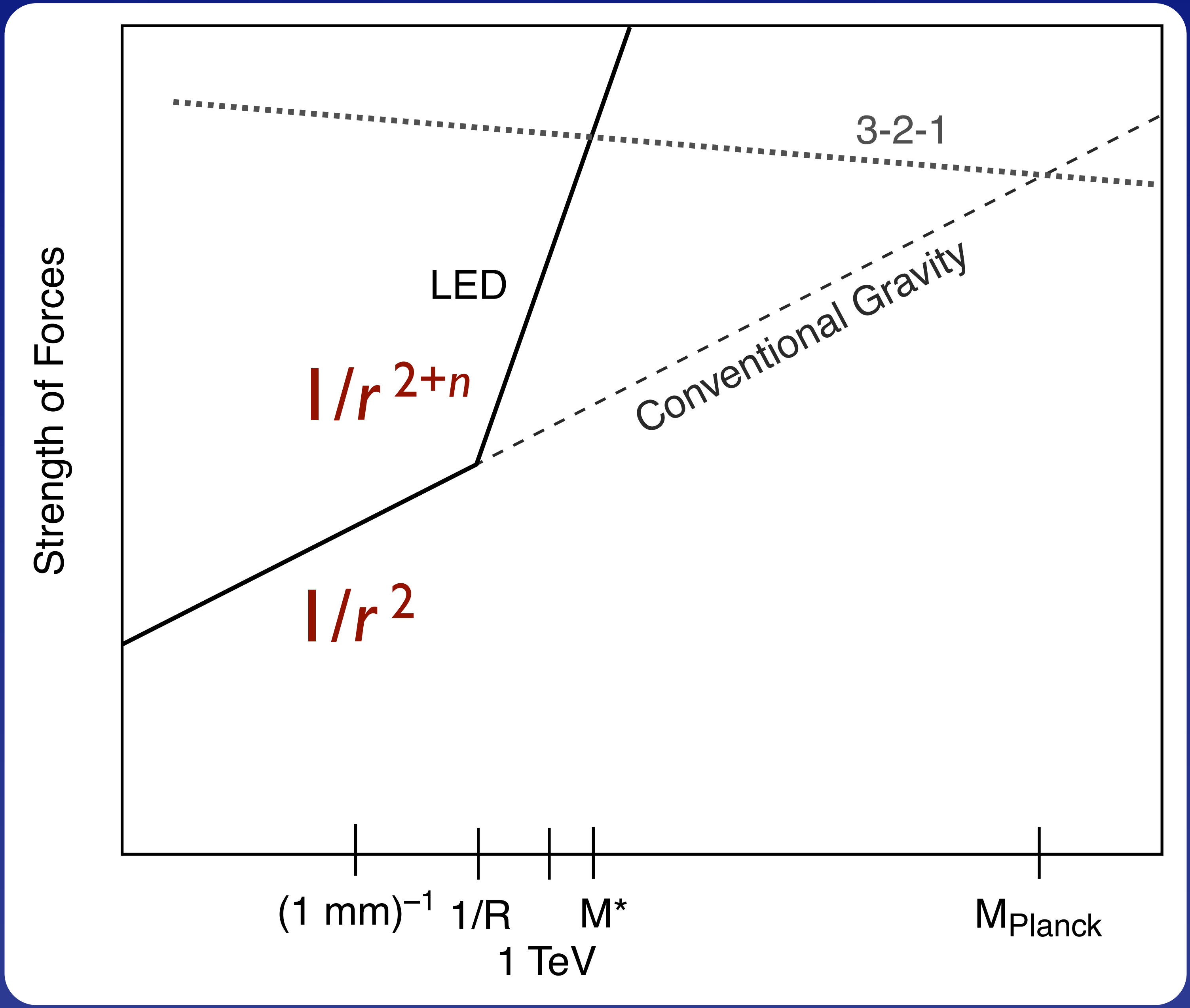
How do they influence the world?

How can we map them?

String theory needs 9 (10)

Suppose at scale R … gravity propagates in $4+n$ dimensions

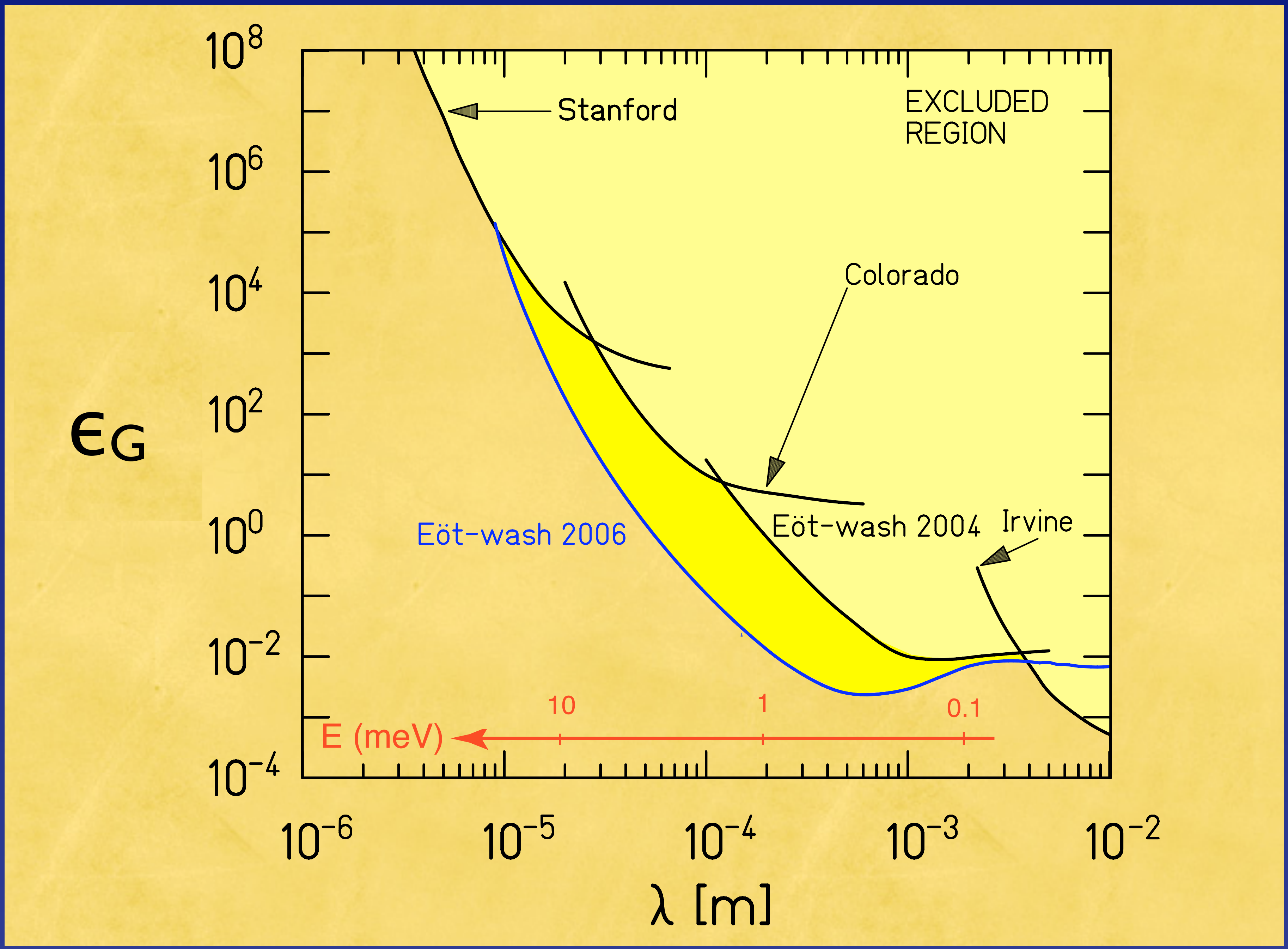
Gauss law: $G_N \sim M^{*-n-2}\ R^{-n}$ $\quad M^*$: gravity's true scale



M_{Planck} would be a mirage!

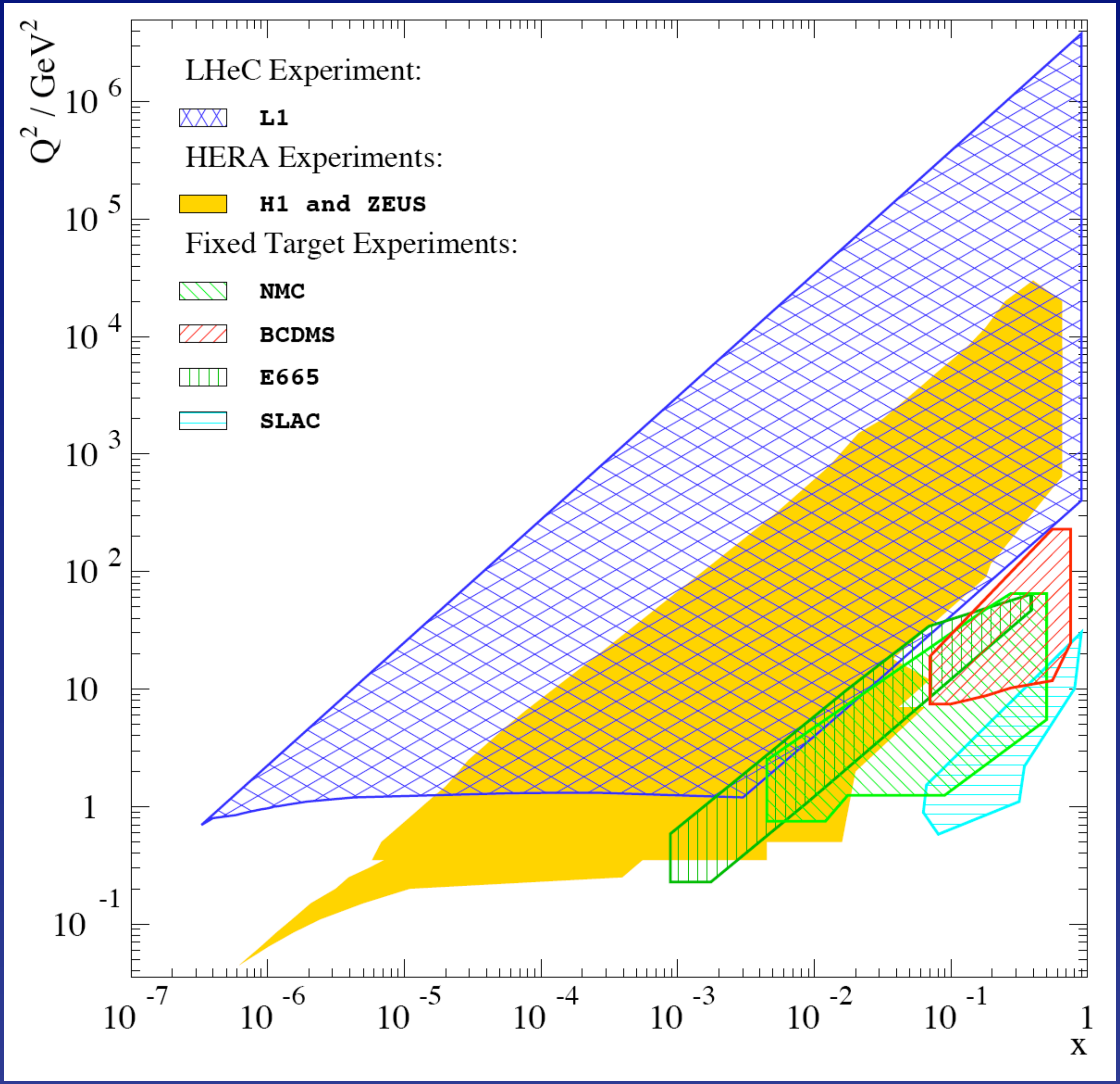
Gravity follows Newtonian force law down to $\lesssim 1$ mm

$$V(r) = -\int dr_1 \int dr_2 \frac{G_{\text{Newton}}\rho(r_1)\rho(r_2)}{r_{12}} \left[1 + \varepsilon_G \exp(-r_{12}/\lambda_G)\right]$$



Can we find evidence for graviton exchange, resonances?

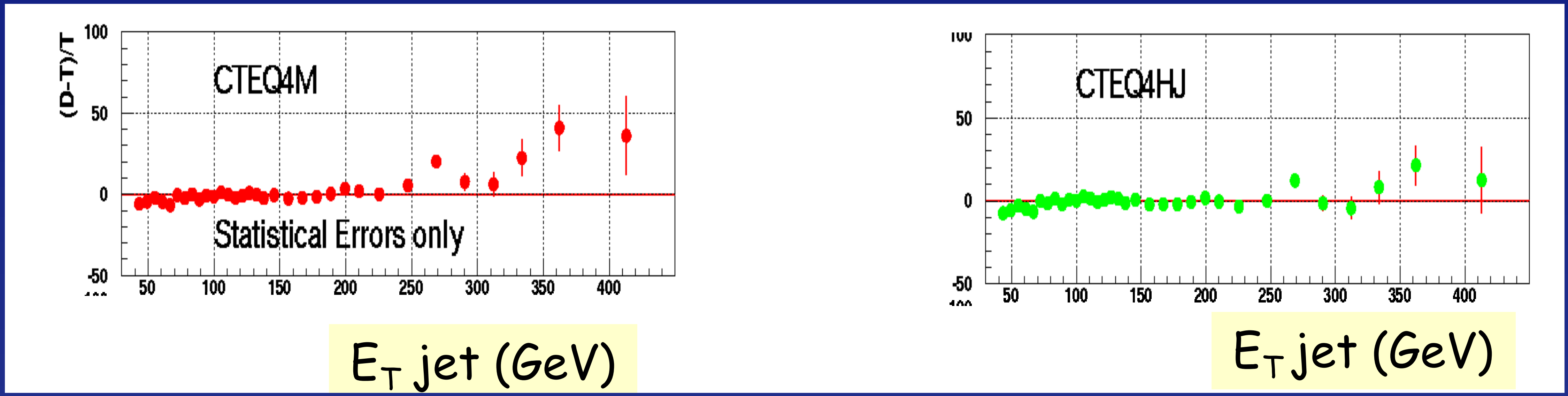
What is a proton?



momentum transfer × momentum fraction

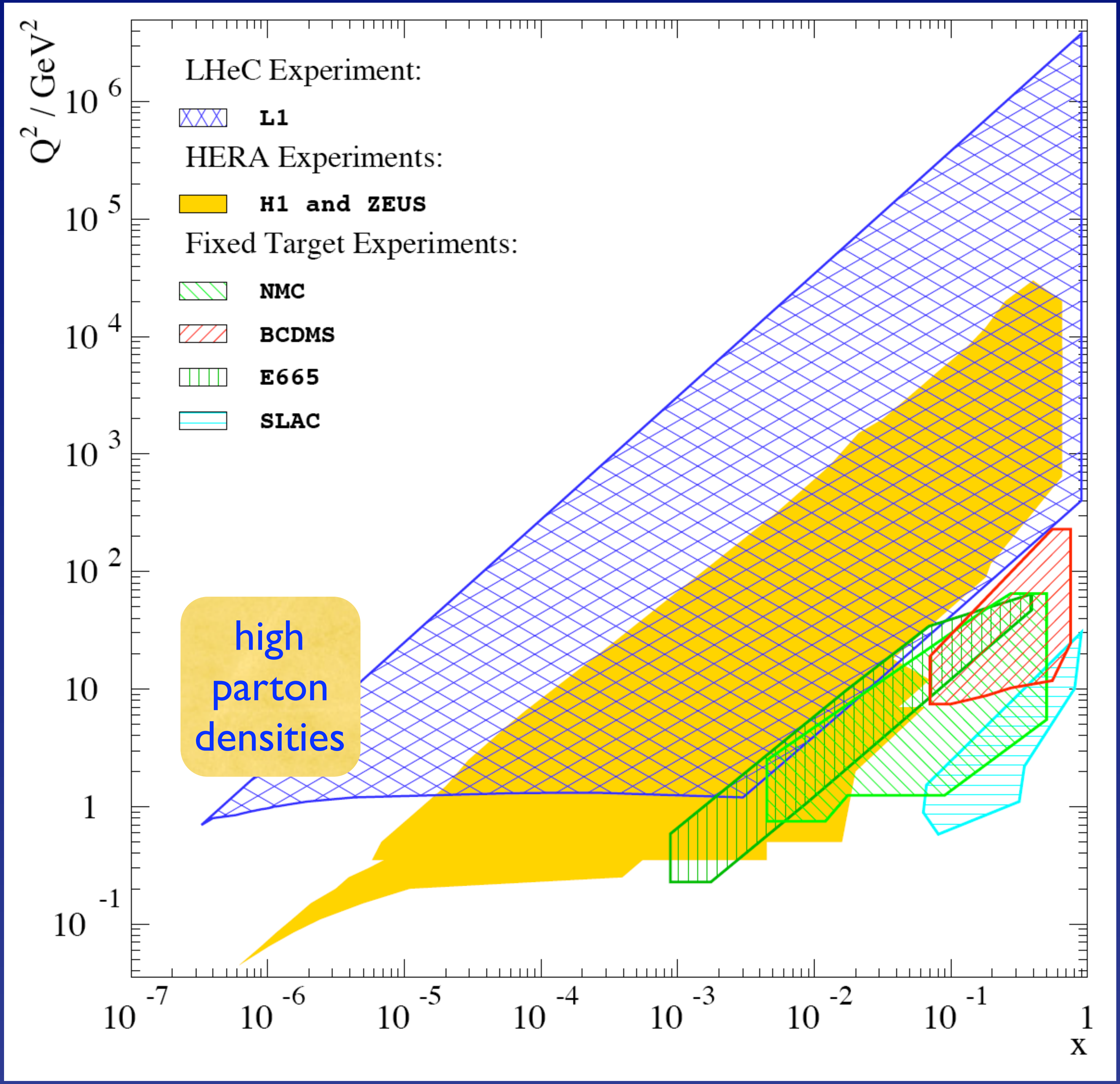
Is LHC vulnerable to illusory discoveries?

Oft-cited example: CDF high-E_T apparent excess



Reliable baseline (+uncertainties) obviously preferable …
… but can change running conditions to test hypotheses

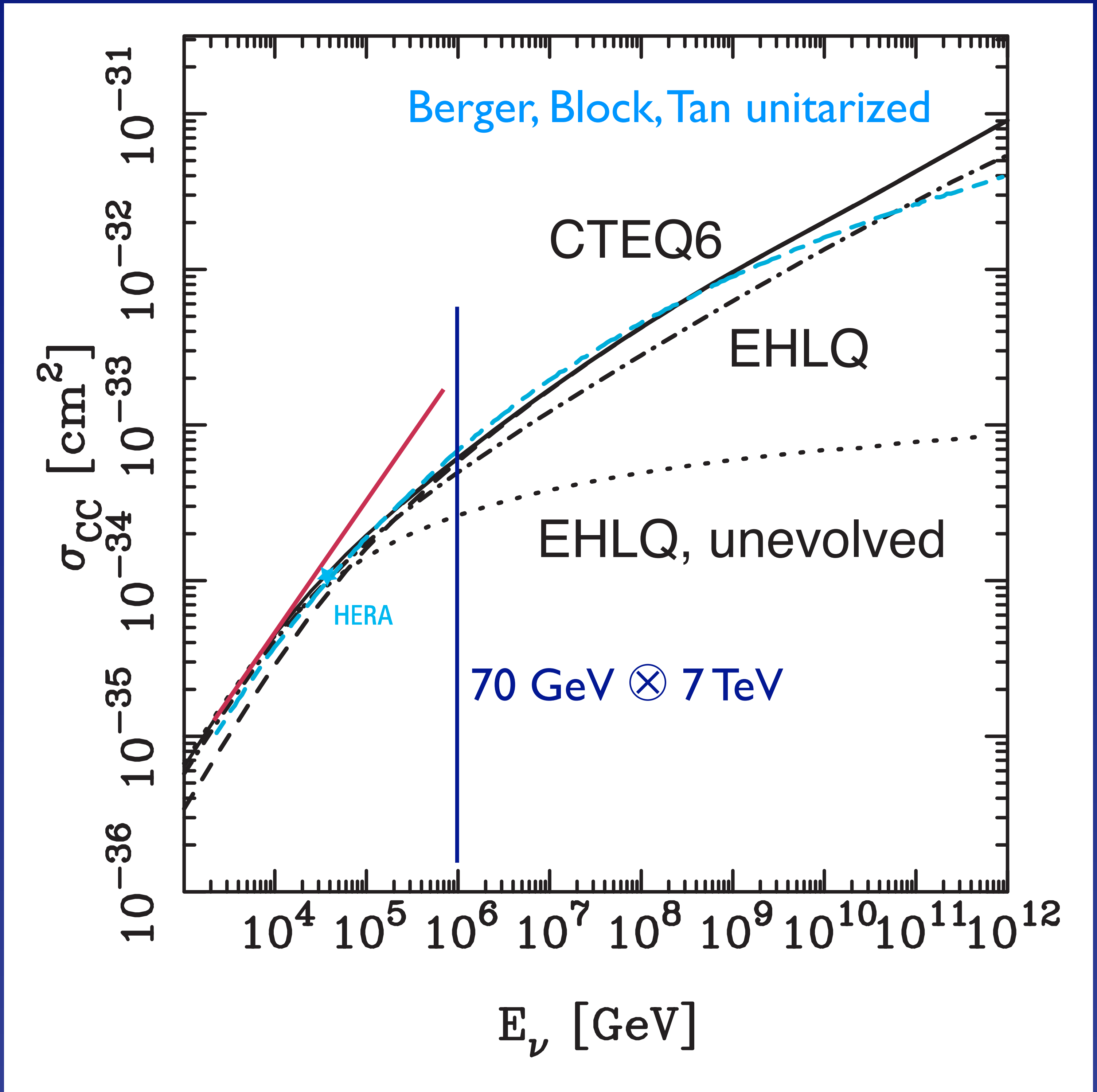
What is a proton?



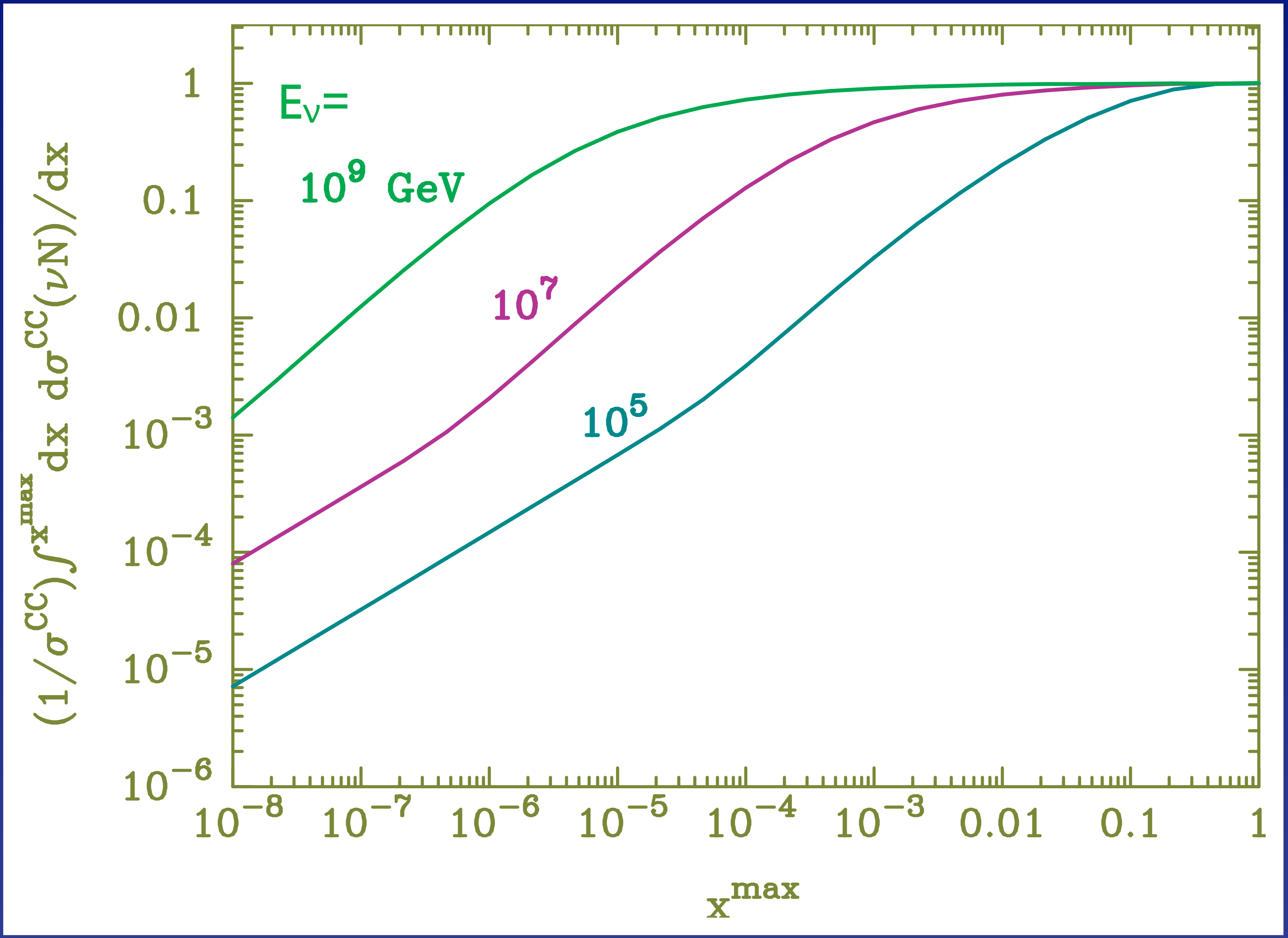
momentum transfer × momentum fraction

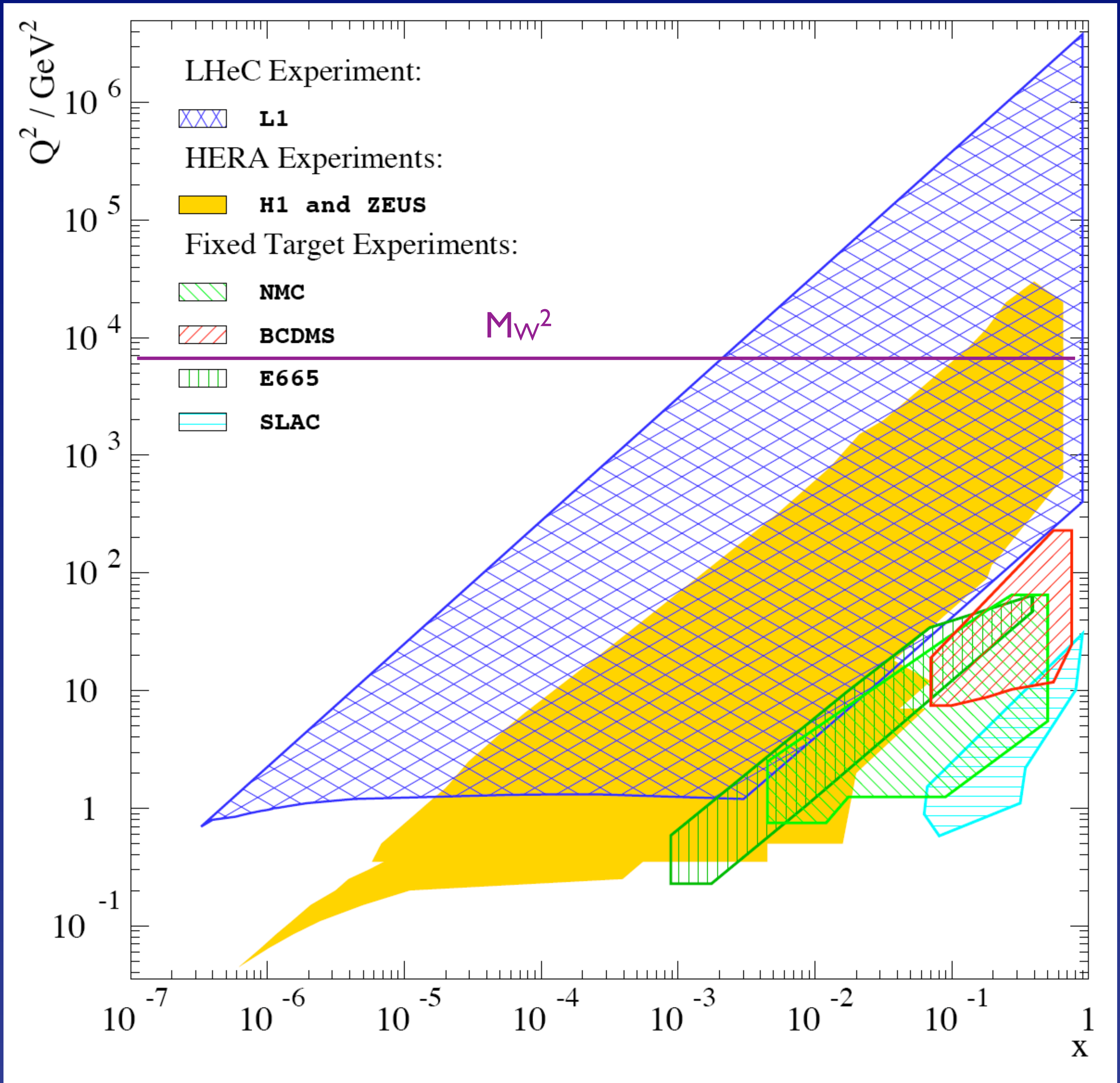
QCD influence on UHE ν detection: νN → μ+X

Importance of wee-x, high-Q^2 parton distributions

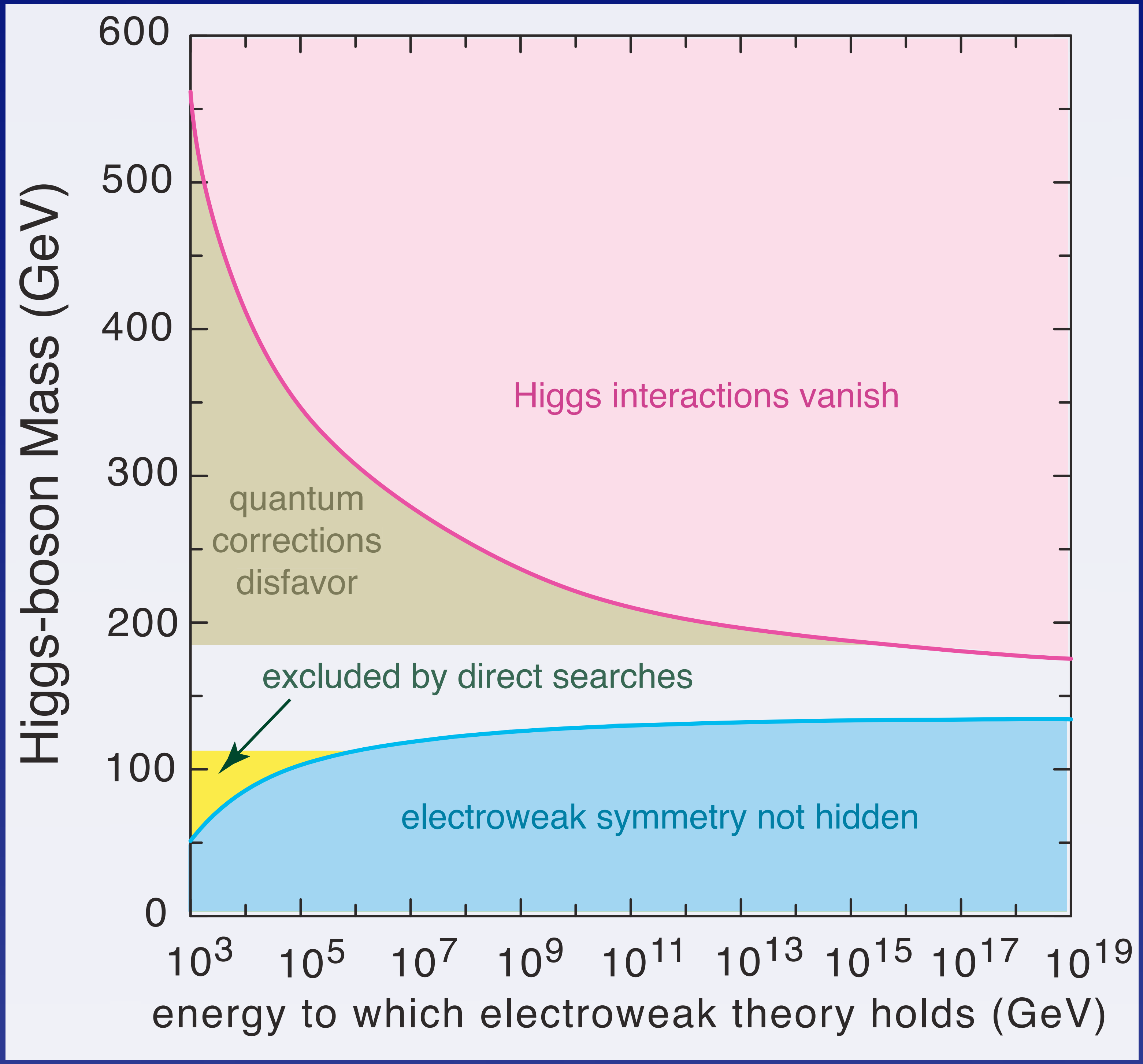


Where UHE σ(νN) arises




LHeC Experiment:
L1
HERA Experiments:
H1 and ZEUS
Fixed Target Experiments:
NMC
BCDMS
E665
SLAC
M_W^2
Q^2 / GeV^2
x

We think the electroweak theory is incomplete



also hierarchy problem, fermion masses, etc.

QCD could be complete, up to M_{Planck}

… but that doesn't prove it must be

Prepare for surprises!

10. SOME EXPERIMENTS ON MULTIPLE PRODUCTION

KENNETH G. WILSON

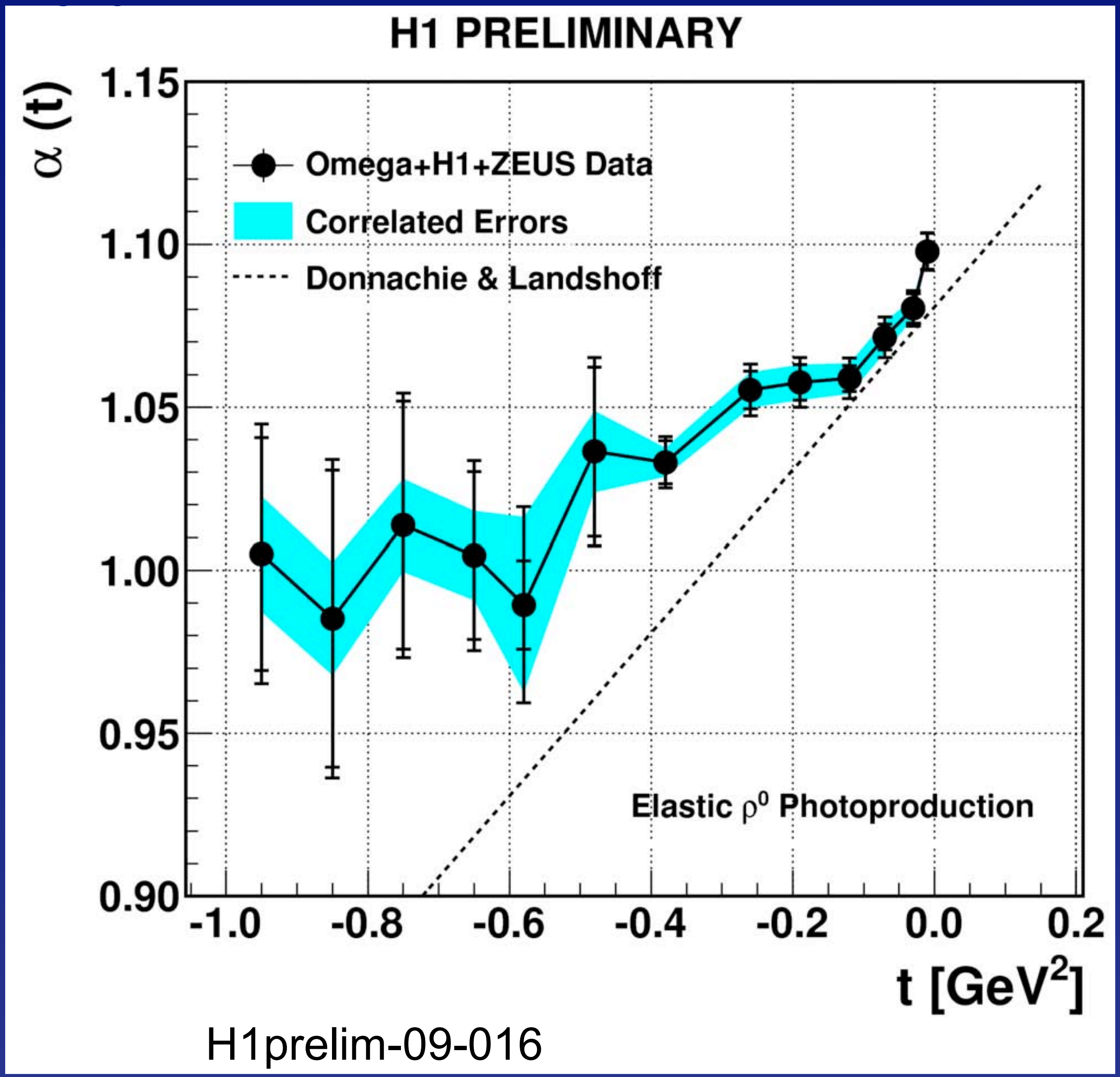
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

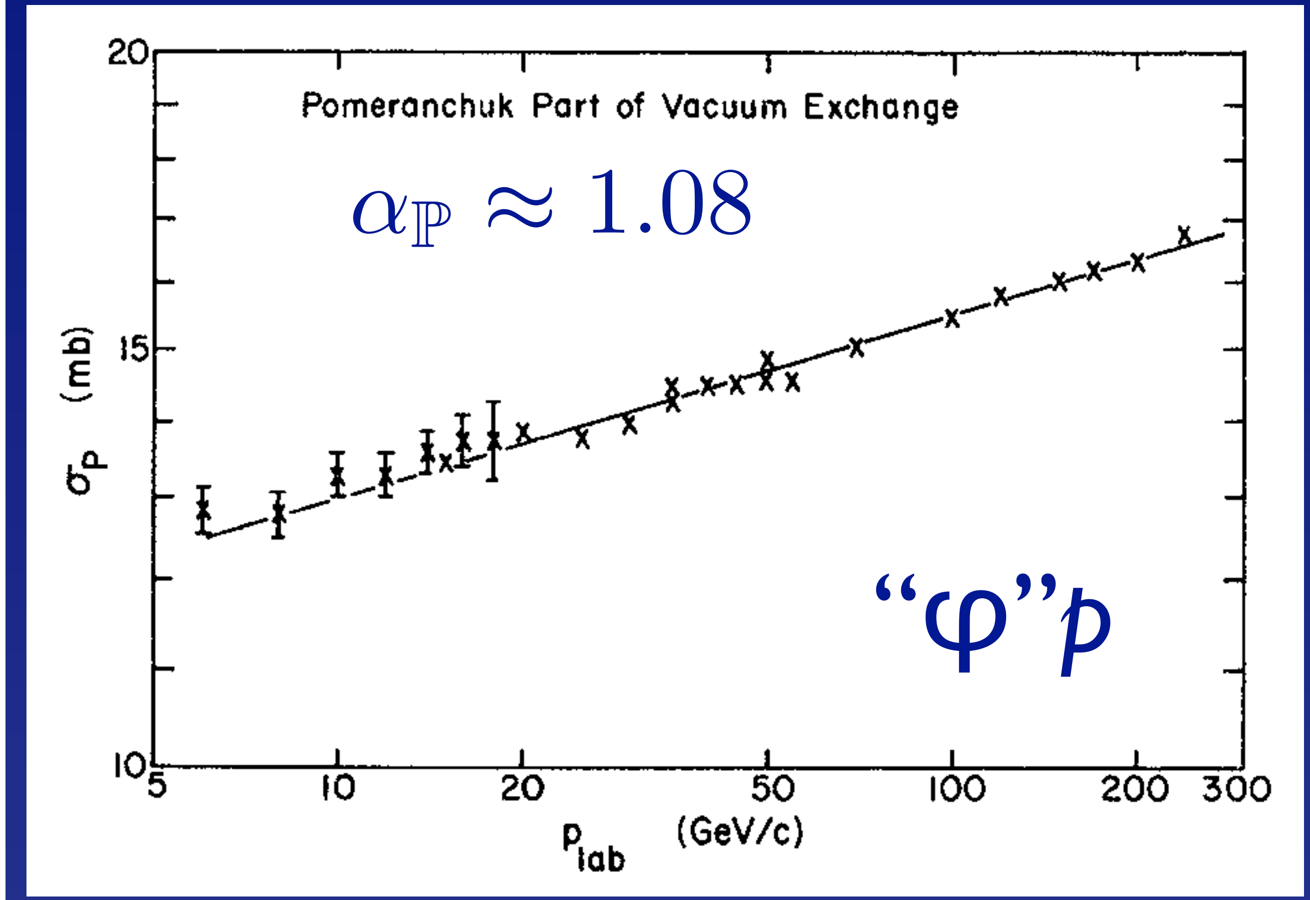
Might we see
unexpected event structure
in early LHC running?

Importance of canonical expectations
for multiplicities, correlations, topologies

Even without surprises, study of
soft collisions, underlying events
will pay great dividends
in understanding multiple production
and the search for new physics!

Soft Physics: the Pomeron





How realized in QCD (Pomeron ⇜⇝ gluons)?

How is Froissart bound realized?

$$\sigma_{\text{tot}} \leq C \cdot \ln^2 s$$

Not merely la physique rétro !

AdS/CFT Connection, holography, etc.

Powerful methods to solve strong-coupling problems that may give insight into real problems

Issue: theories we can solve are not exactly QCD, so what should we expect from these exercises?

Insights into strongly coupled theories?
Hints about universal behavior?
Reliable analogues for QCD?
(Direct tests of string theory?)

LHeC studies span an impressive range

Proton structure & QCD for LHC

QCD beyond parton-model comfort zone: small & large x

Novel lepton-quark interactions:

leptoquarks, R-parity–violating SUSY, …

Search for new interactions:

RH charged currents, eeqq contact terms,

graviton exchange, spin-2 resonances

Superpartners

New strong dynamics

Higgs-boson properties

Diffraction & soft physics

Nuclear effects

Connections …

Work hard!

Good luck!