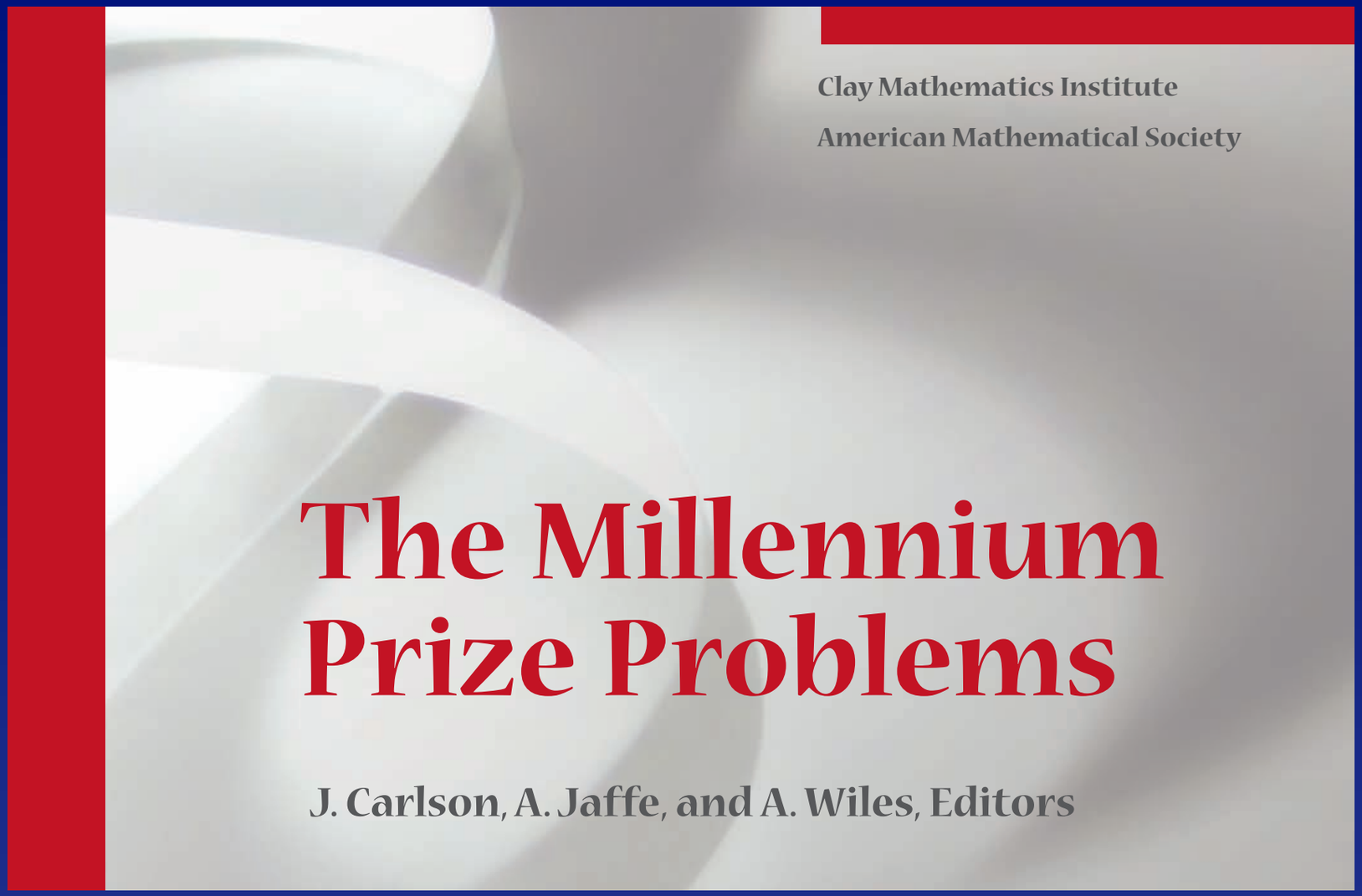
Beyond Confinement

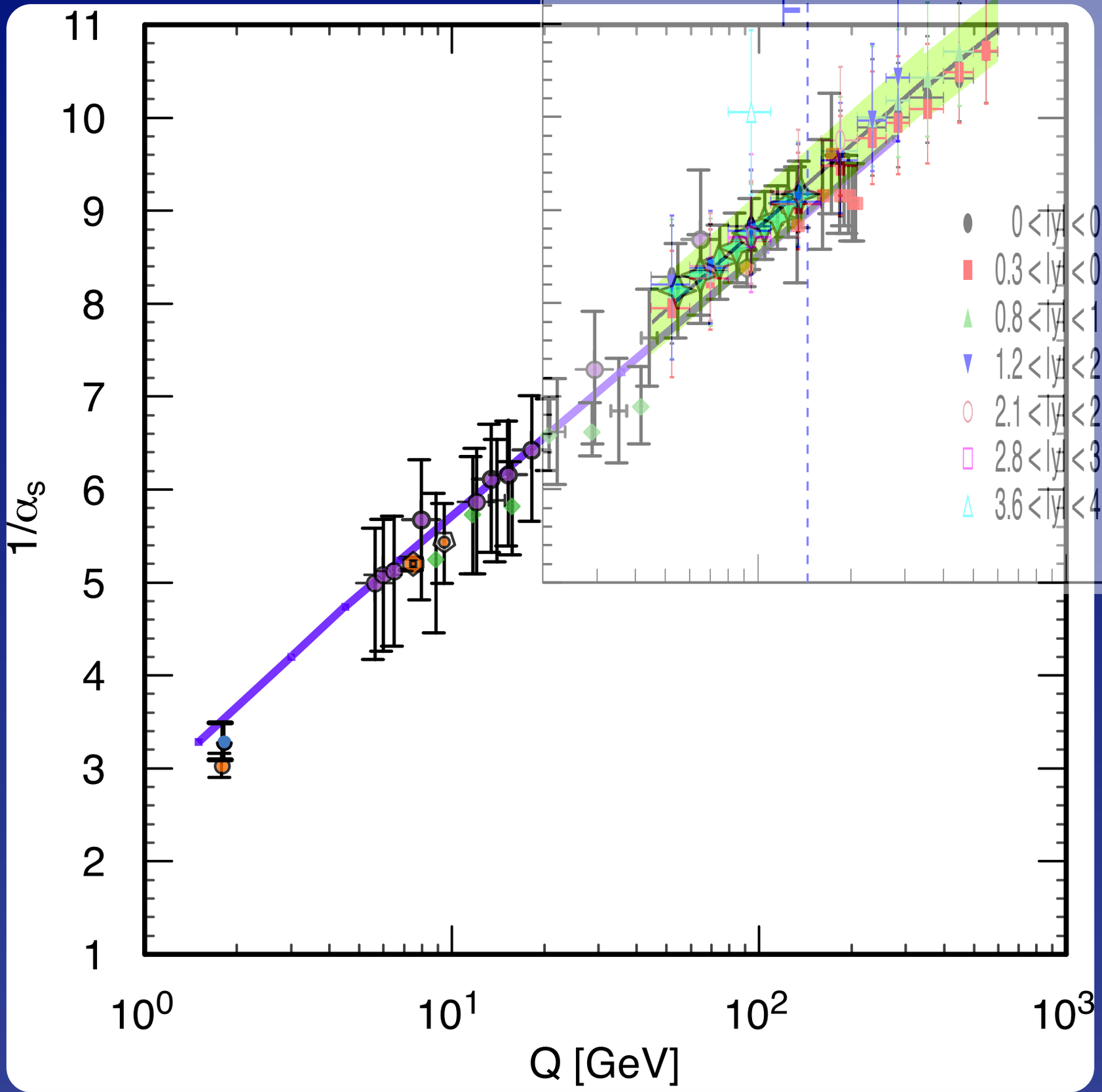
Chris Quigg
Fermi National Accelerator Laboratory · TUM

Quark Confinement & Hadron Spectrum X · TU-München · 12.X.2012

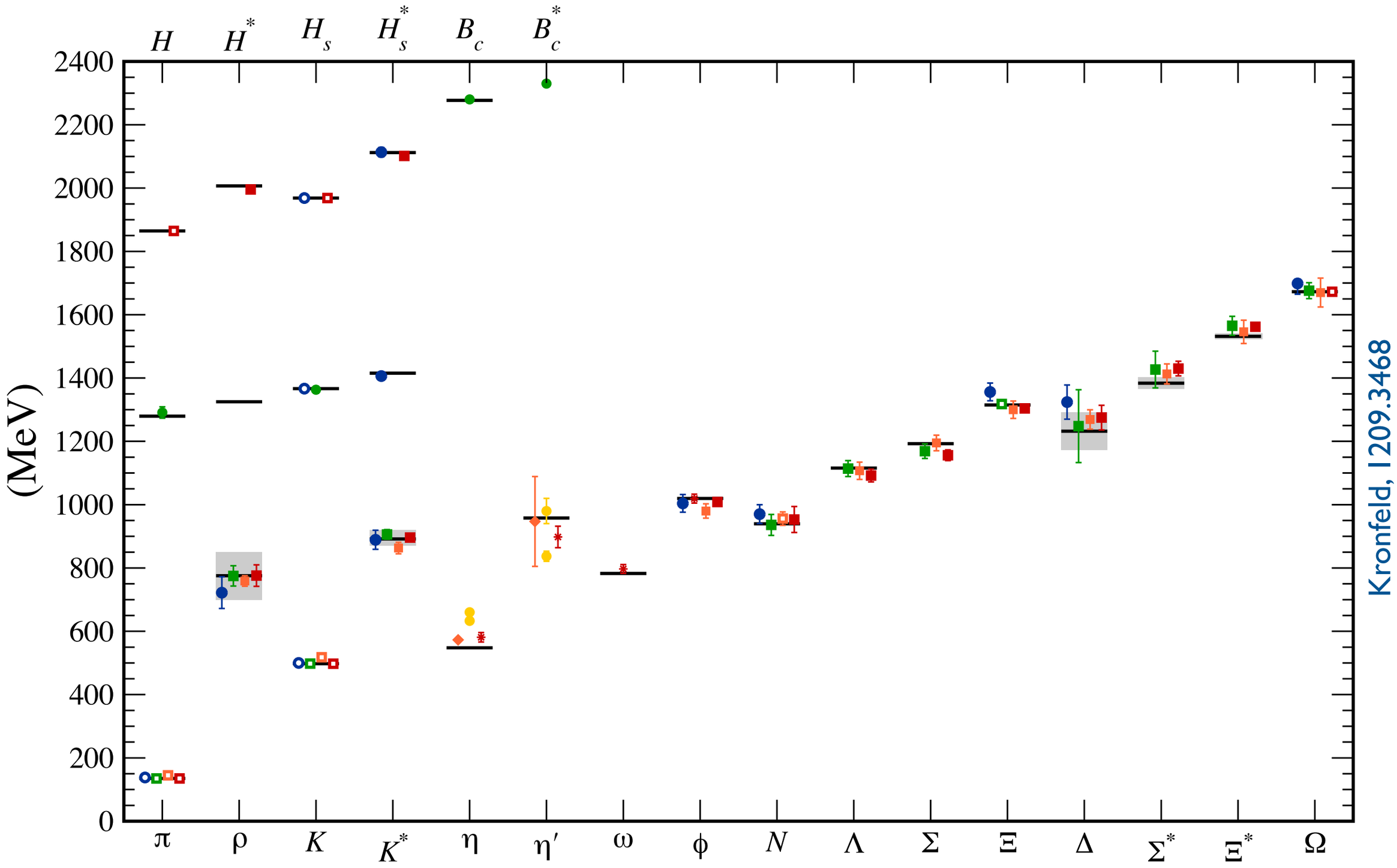


YANG–MILLS EXISTENCE AND MASS GAP. *Prove that for any compact simple gauge group G, a non-trivial quantum Yang–Mills theory exists on $\mathbb{R}^4$ and has a mass gap $\Delta > 0$. Existence includes establishing axiomatic properties at least as strong as those cited in* [**45, 35**].

Evolution of α_s



Hadron masses from (2+1)-flavor LQCD



sum of parts

rest energy

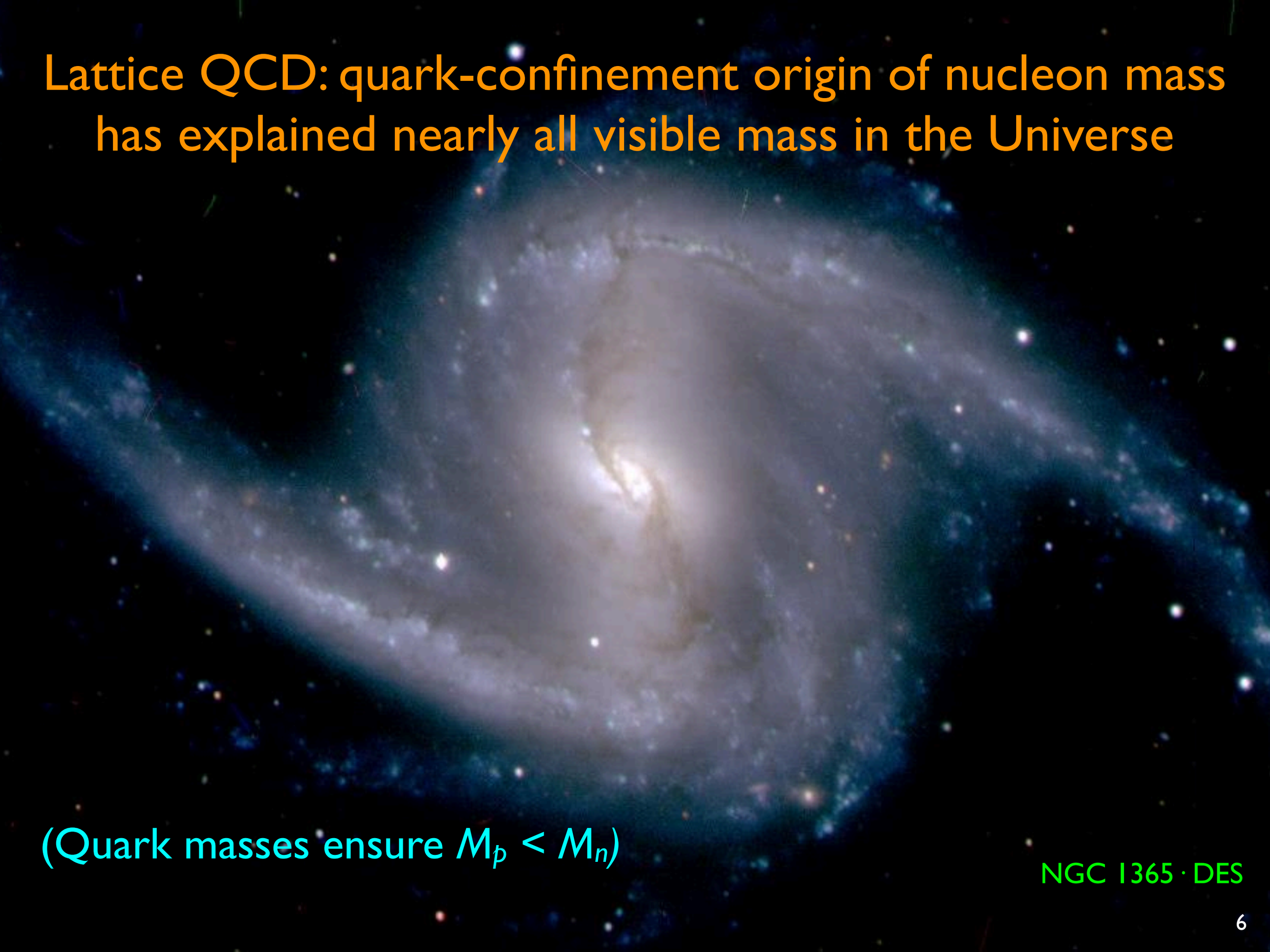
Nucleon mass: exemplar of $m = E_0/c^2$

up and down quarks contribute few %

$$3\,\frac{m_u + m_d}{2} = 10 \pm 2\ \mathrm{MeV}$$

χPT: $M_N \hookrightarrow$ 870 MeV for massless quarks

Lattice QCD: quark-confinement origin of nucleon mass has explained nearly all visible mass in the Universe

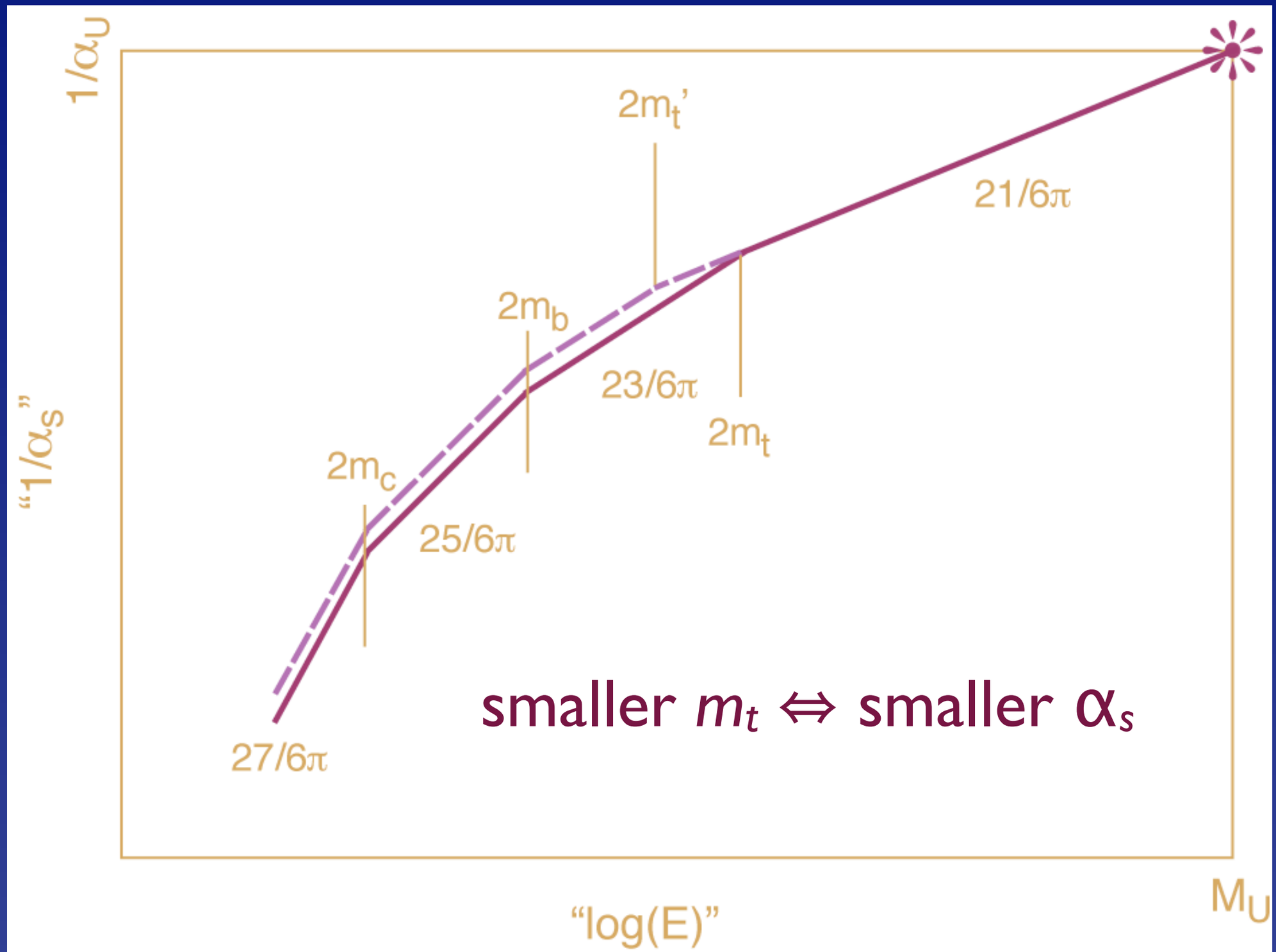


(Quark masses ensure $M_p < M_n$)

NGC 1365 · DES

Quark masses matter in other ways!

m_t influences low-energy value of α_s



$$1/\alpha_s(2m_c) \equiv (27/6\pi)\ln(2m_c/\Lambda)$$

$$\Lambda_{\mathrm{QCD}}(\mathrm{GeV}) = \text{const.} \left(\frac{m_t}{1\ \mathrm{GeV}}\right)^{2/27}$$

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

calculable on lattice

from dimensional transmutation

quark masses, EM self-energy

$$M_{\mathrm{proton}} \propto m_t^{2/27}$$

Let all quark masses → 0 …

QCD could be complete, up to M_{Planck}

… but that doesn't prove it must be

Prepare for surprises!

How Might QCD Crack?

(Breakdown of factorization)

Free quarks / unconfined color

New kinds of colored matter

Quark compositeness

Larger color symmetry containing QCD

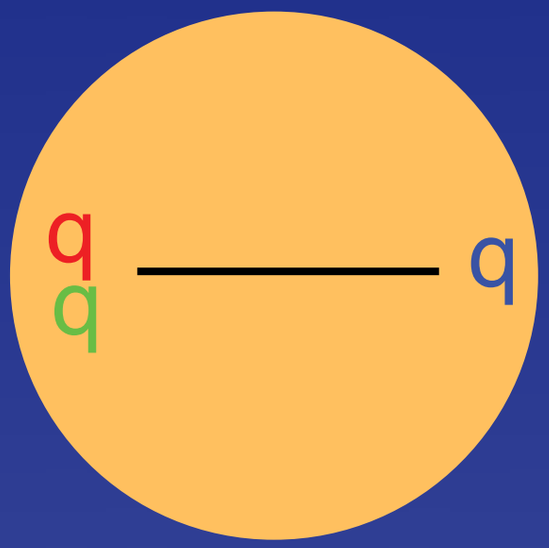
New phenomena within QCD?

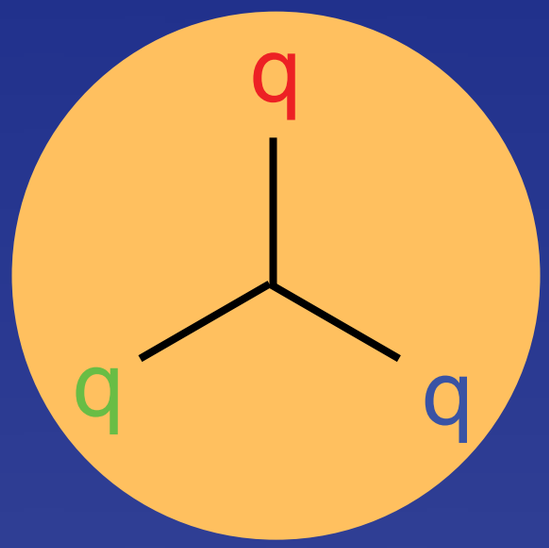
Multiple production beyond diffraction + short-range order?

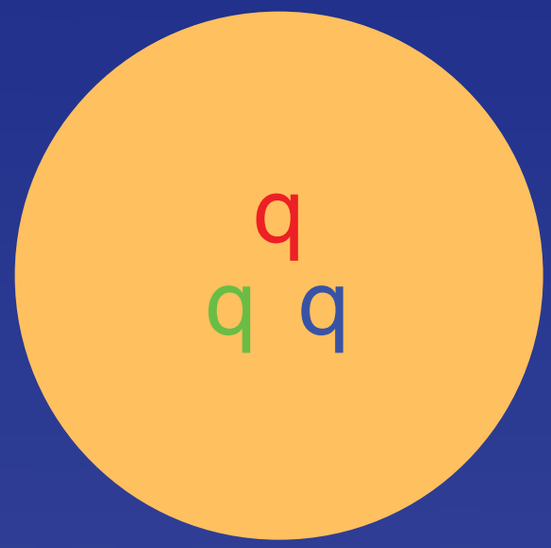
High density of few-GeV partons … thermalization?

Long-range correlations in y?

Unusual event structures …







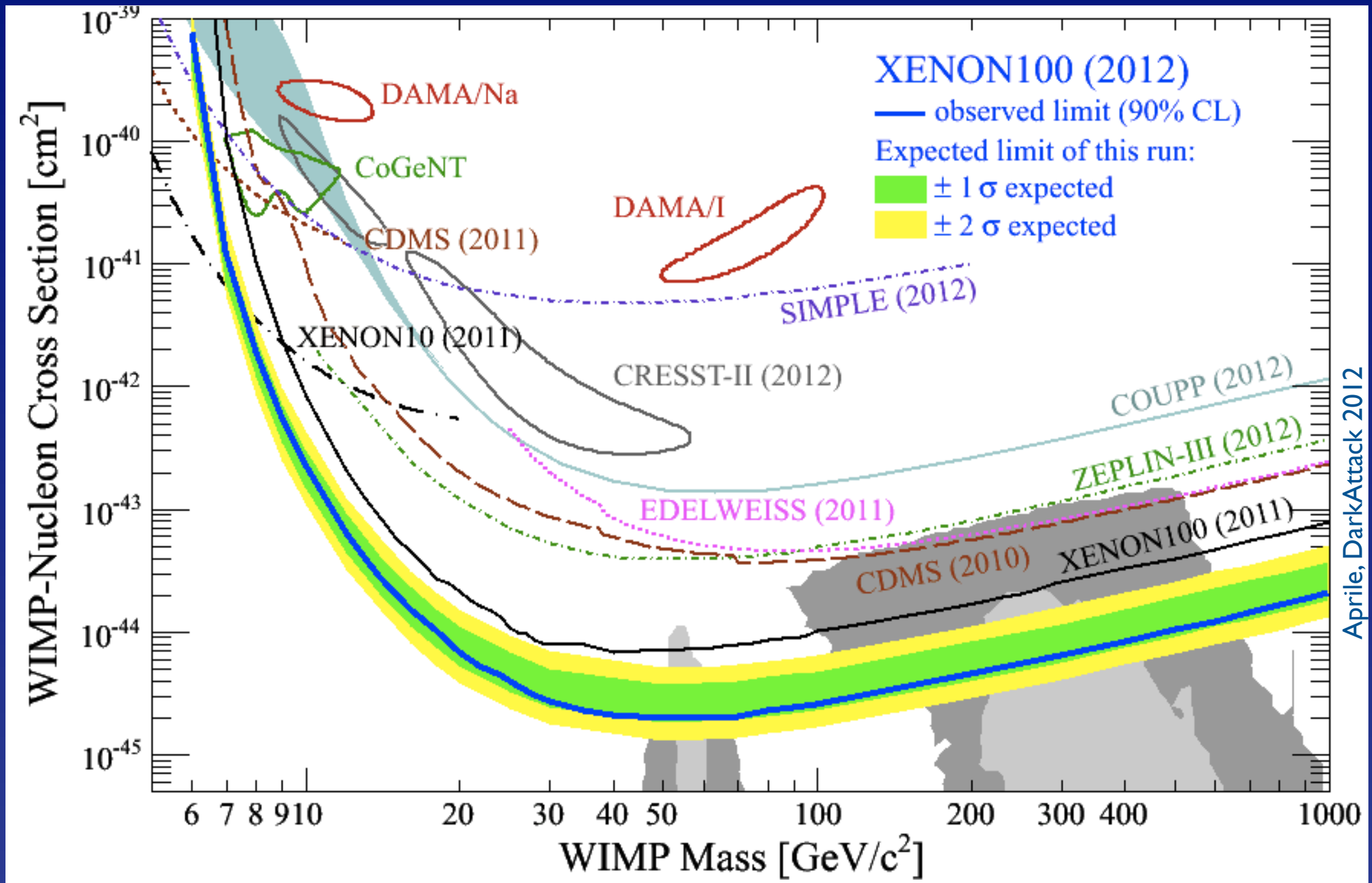
Bjorken (2010)

The CP under our mattress: *Strong CP Problem*

© Tomasz Sienicki

If Peccei–Quinn symmetry, where are the axions?

Direct Dark Matter Searches



Upper Limit (90% C.L.) is 2 x 10^{-45} cm^2 for 55 GeV/c^2 WIMP

Dark matter searches and nucleon structure

Scale of SUSY expectations set by (spin-independent) σ

Neutralino WIMP: σ attributed to Higgs exchange

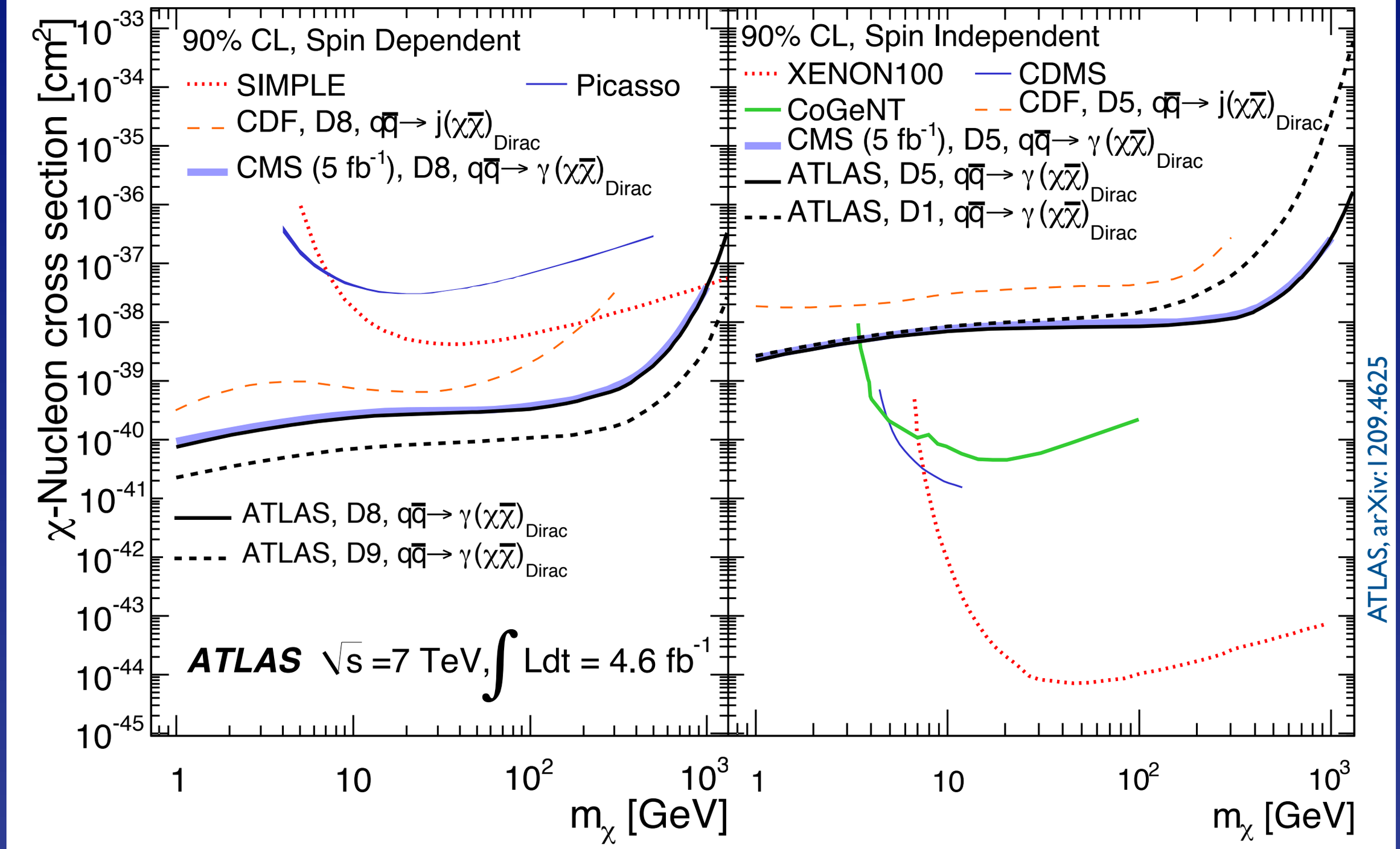
How does *H* interact with nucleon?

H coupling to heavy flavors: *s*, *b*, …

x 2-3 variation among lattice calculations

Experimental attention, perhaps theoretical reconception

Generic Collider Dark Matter Searches



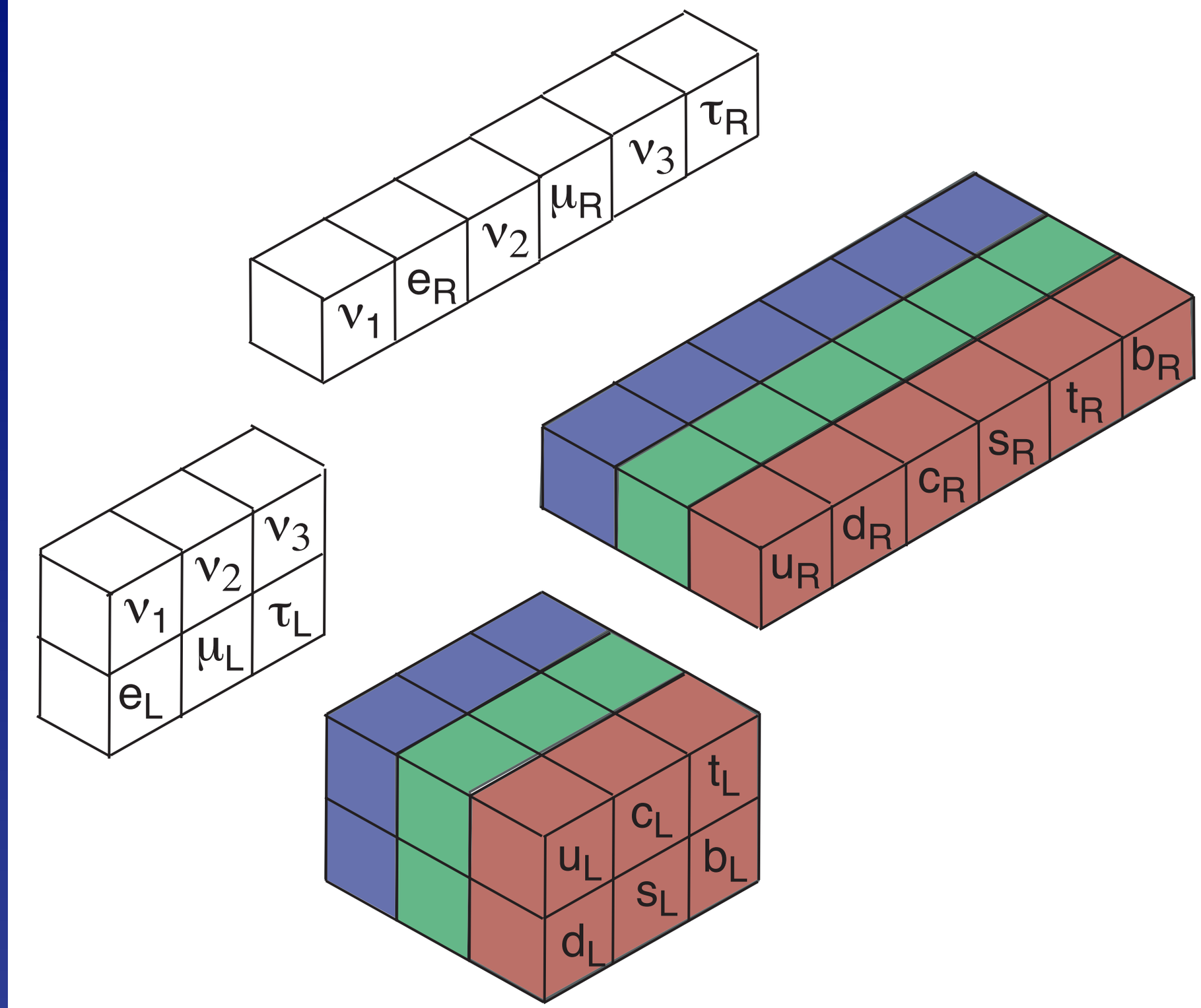
Bai-Fox-Harnik, *JHEP* 1012 (2012) 048

Electroweak Theory

To good approximation …
3-generation V–A
GIM suppresses FCNC
CKM quark-mixing matrix describes CPV

Gauge symmetry validated in $e^+e^- \rightarrow W^+W^-$

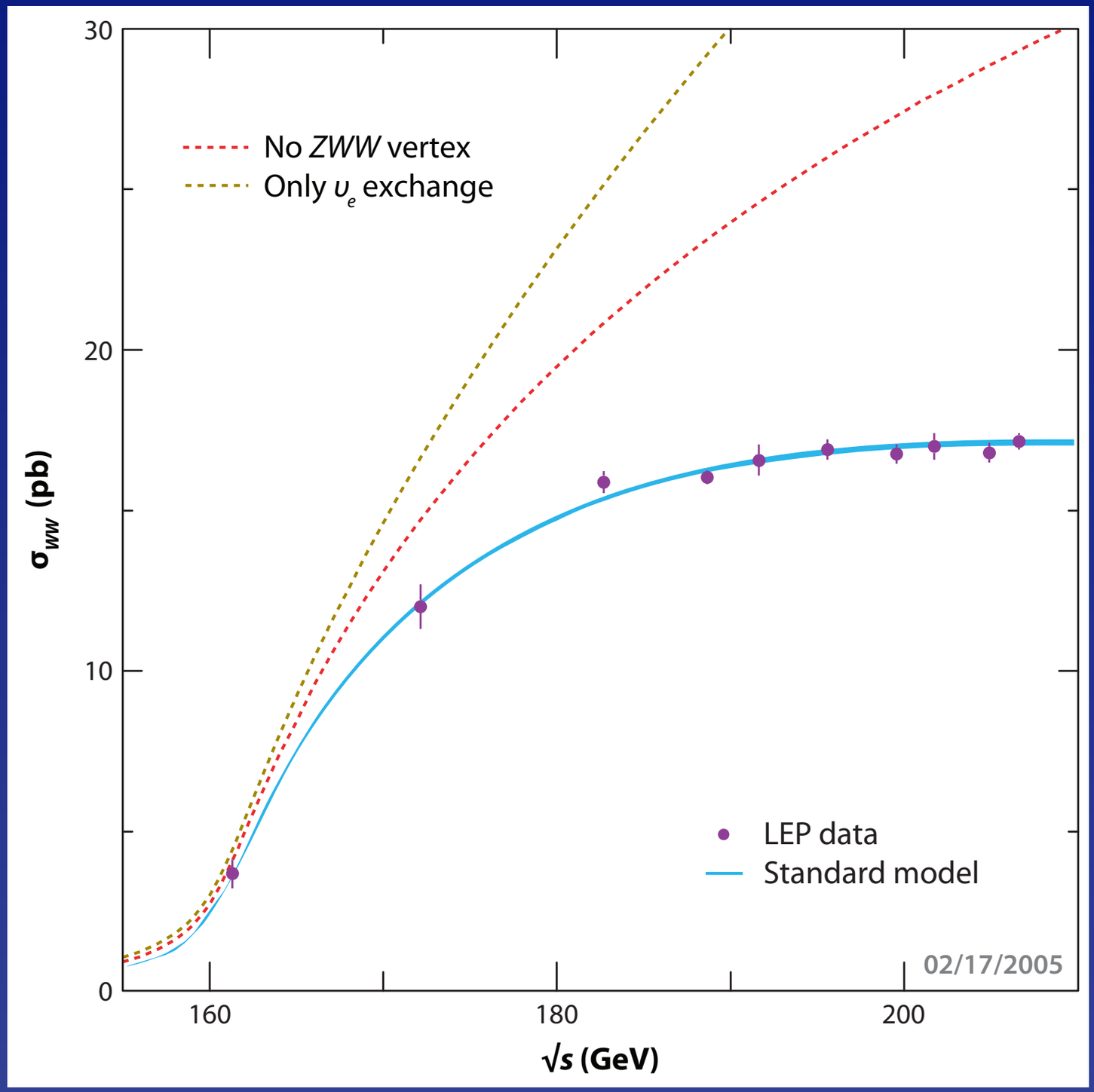
Tested as quantum field theory at per-mille level



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

Gauge symmetry (group-theory structure) tested in

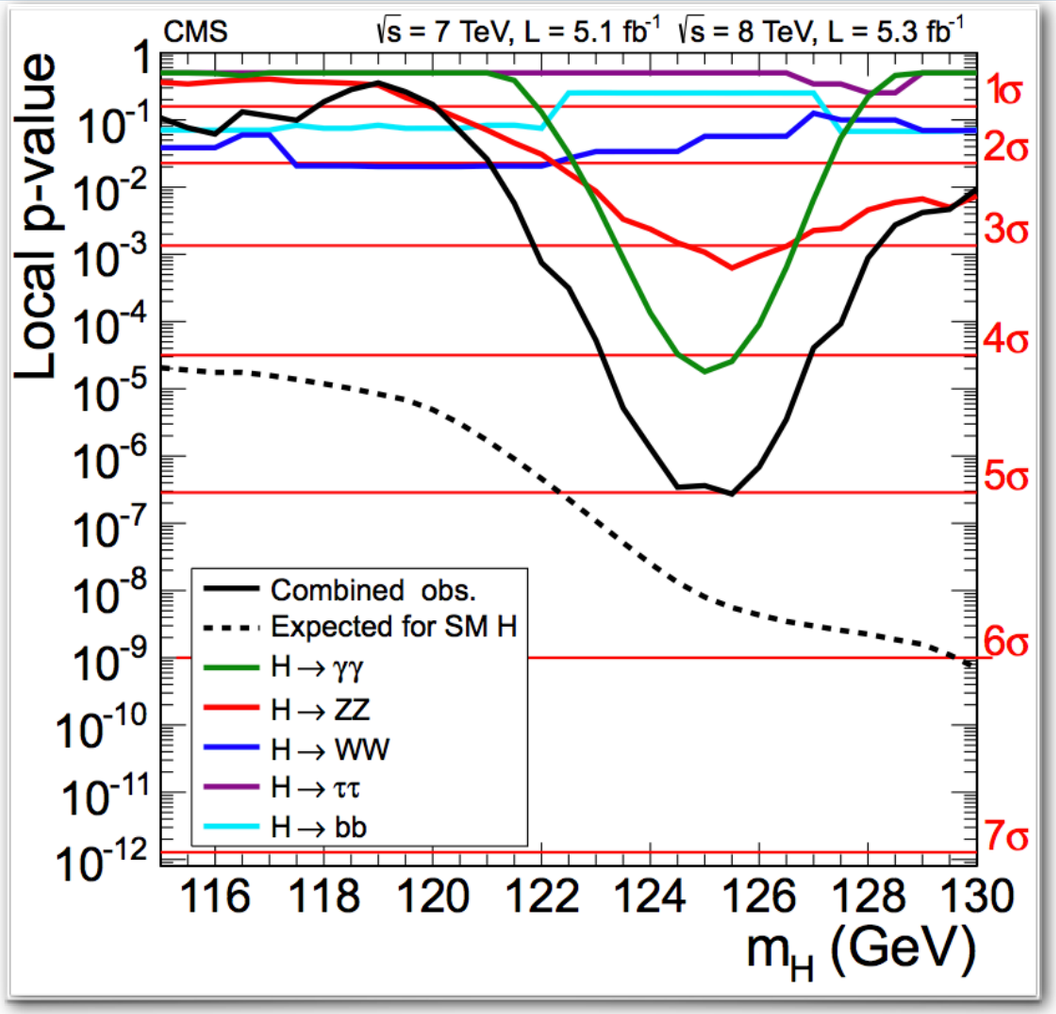
$$e^+e^- \longrightarrow W^+W^-$$



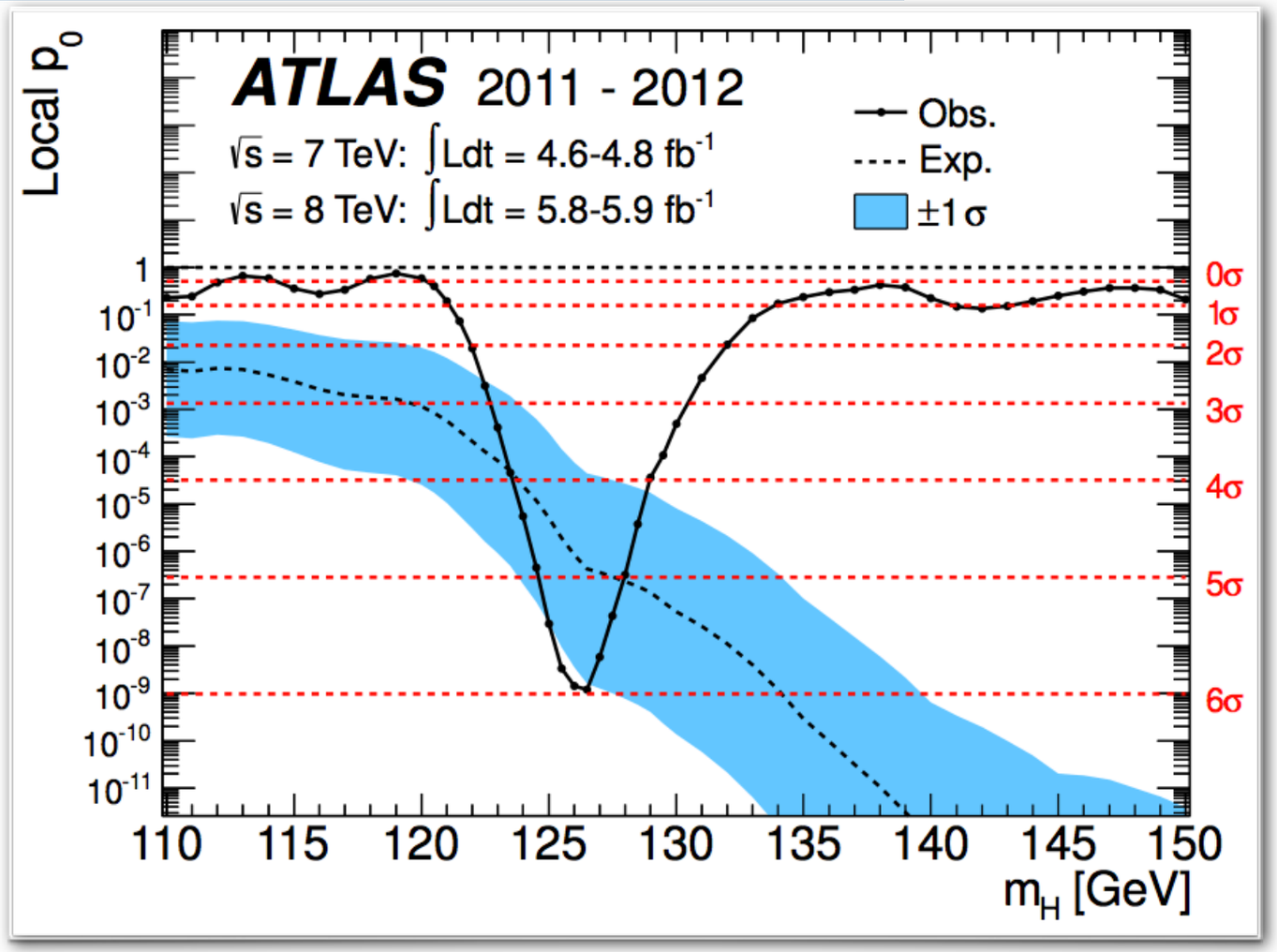
A hitherto unknown agent hides electroweak symmetry

- A force of a new character, based on interactions of an elementary scalar
- A new gauge force, perhaps acting on undiscovered constituents
- A residual force that emerges from strong dynamics among electroweak gauge bosons
- An echo of extra spacetime dimensions

(To what extent) Have we found it?



arXiv:1207.7235v1 [hep-ex]



arXiv:1207.7214v1 [hep-ex]

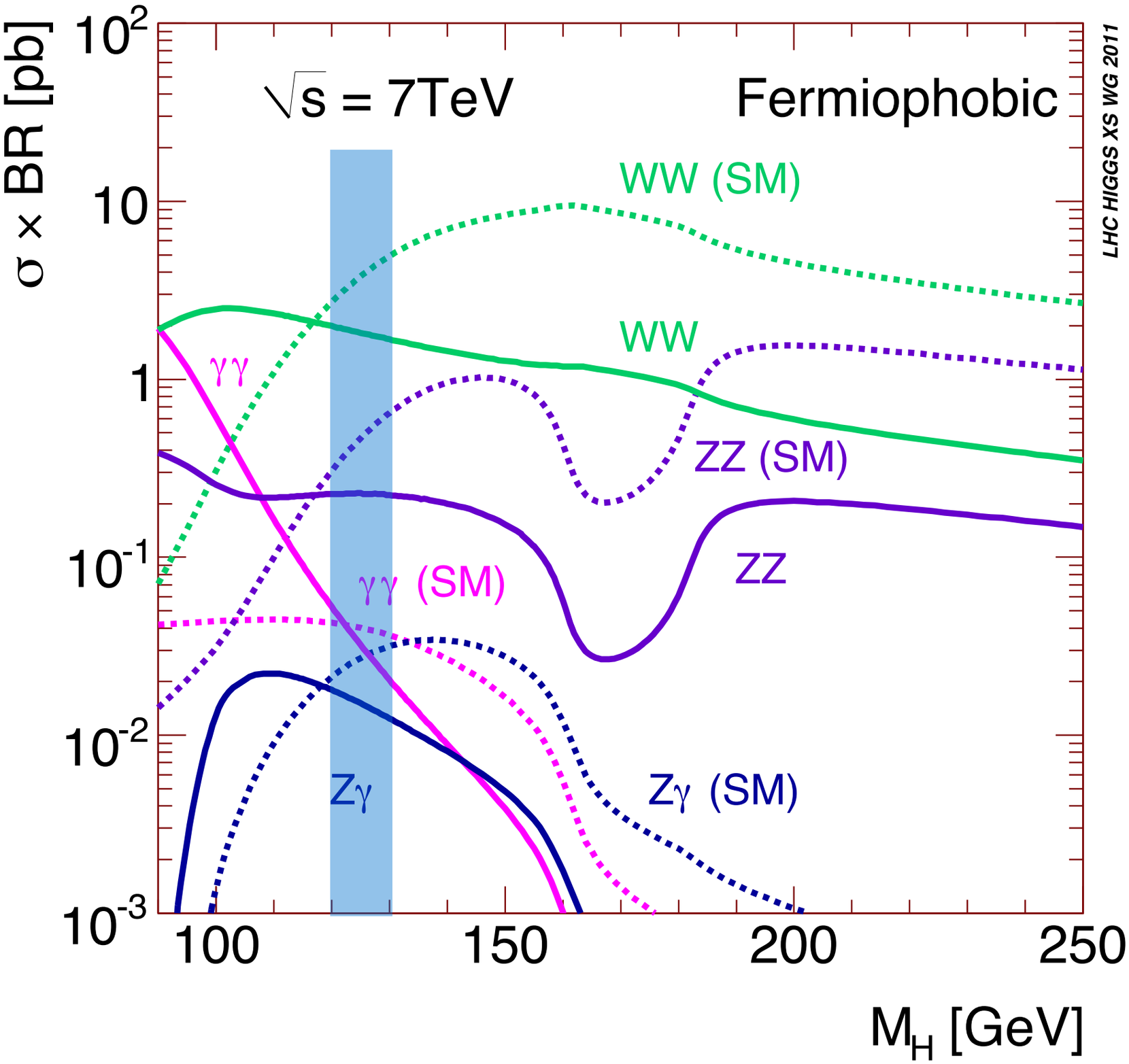
Fully accounts for EWSB (W, Z couplings)?

Couples to fermions?

Top from production,

need direct observation for b, τ

Distinguishing SM, bosogamous Higgs bosons



Fully accounts for EWSB (W, Z couplings)?

Couples to fermions?

Top from production,

need direct observation for b, τ

Accounts for fermion masses?

Fermion couplings $\propto$ masses?

Are there others?

Quantum numbers?

SM branching fractions to gauge bosons?

Decays to new particles?

All production modes as expected?

Implications of $M_H \approx 126$ GeV?

Any sign of new strong dynamics?

Why does discovering the agent matter?

Imagine a world without a symmetry-breaking (Higgs) mechanism at the electroweak scale

Without a Higgs mechanism …

Electron and quarks would have no mass

QCD would confine quarks into protons, etc.

Nucleon mass little changed

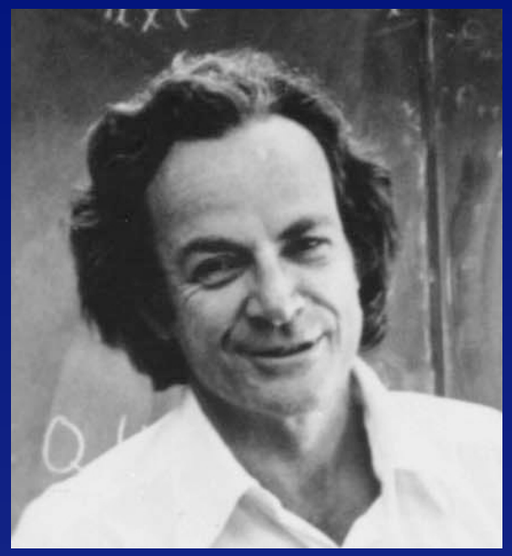
Surprise: QCD would hide EW symmetry,

give tiny masses to W, Z

Massless electron: atoms lose integrity

No atoms means no chemistry, no stable composite structures like liquids, solids, …

arXiv:0901.3958



Why does the muon weigh?

gauge symmetry allows

$$\zeta_e \left[(\overline{e_{\mathsf{L}}} \Phi) e_{\mathsf{R}} + \overline{e_{\mathsf{R}}} (\Phi^\dagger e_{\mathsf{L}}) \right] \rightsquigarrow m_e = \zeta_e v/\sqrt{2}$$

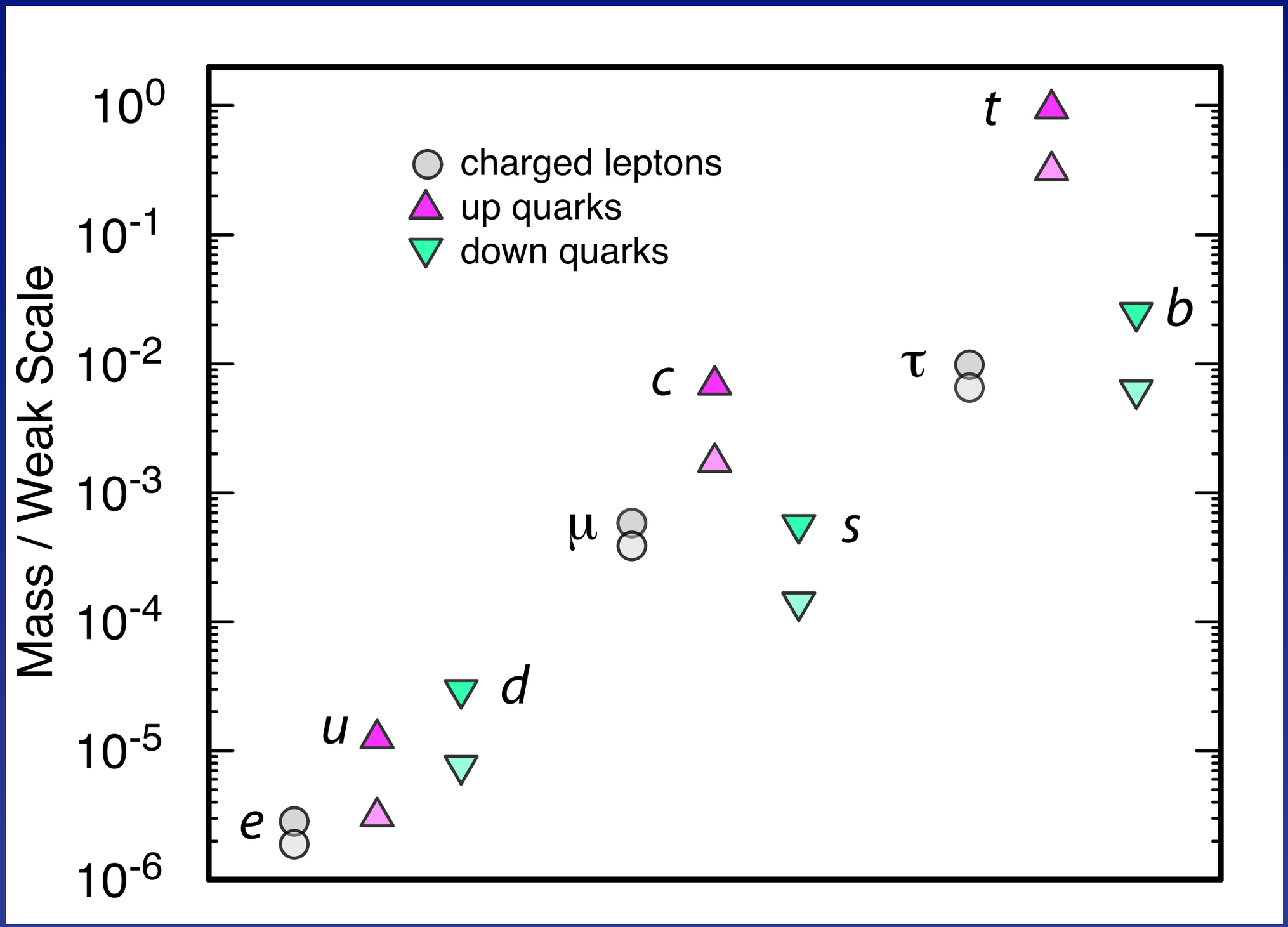
after SSB

What does the muon weigh?

ζ_e : picked to give right mass, not predicted

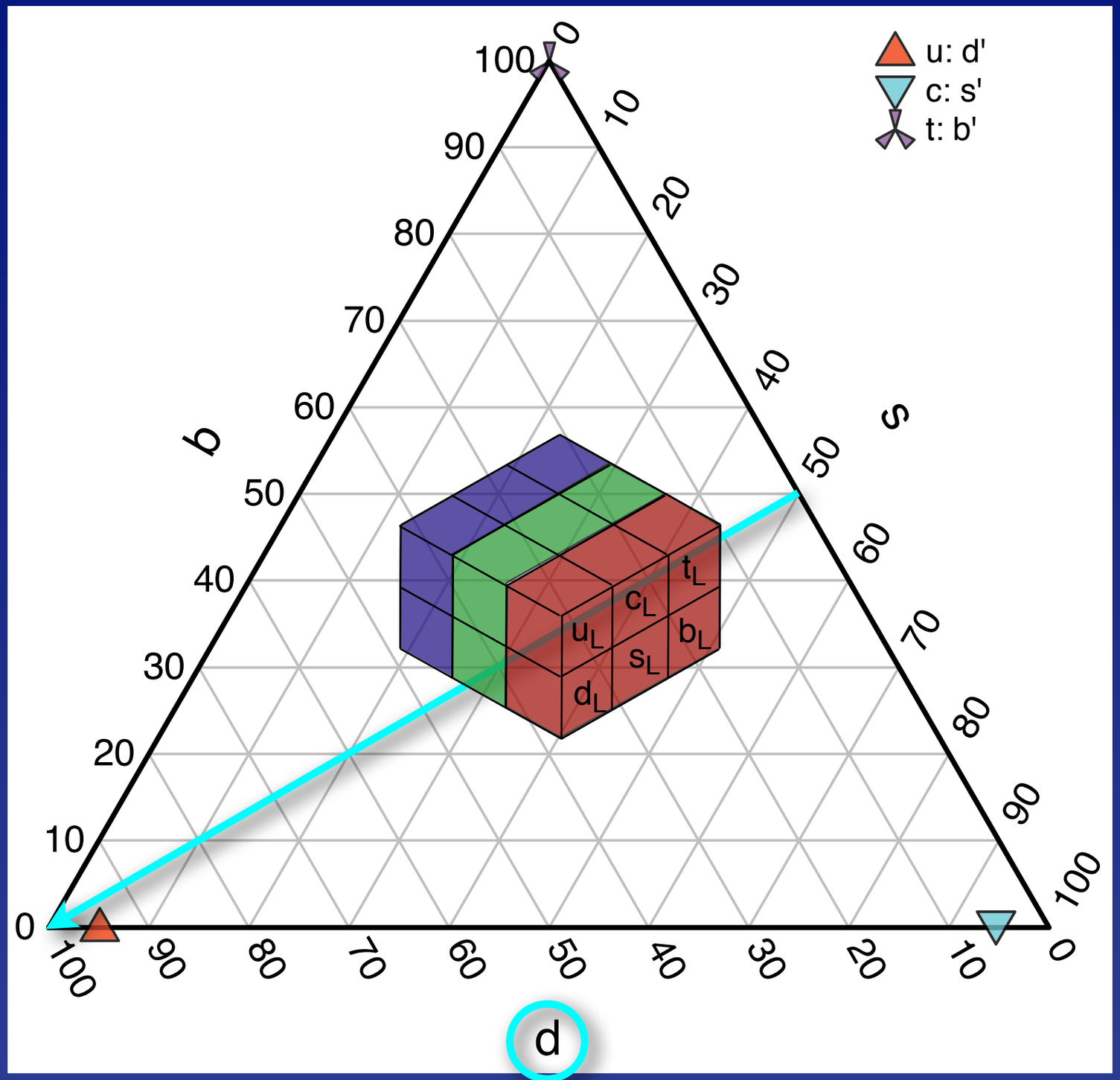
fermion mass implies physics beyond the standard model

Fermion Masses



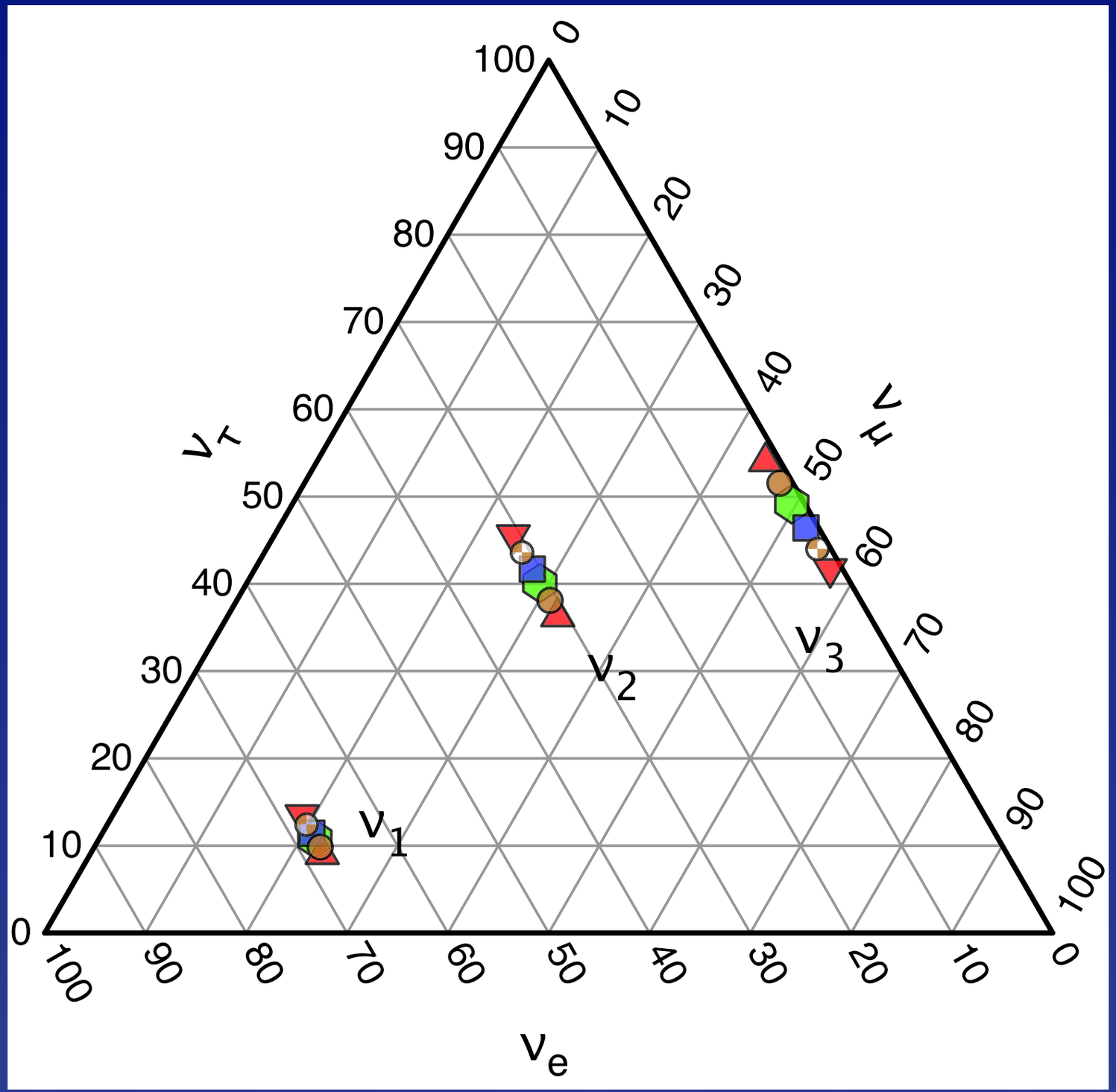
Running mass $m(m)$ … $m(U)$

Quark family patterns: *generations*



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

Neutrino family patterns

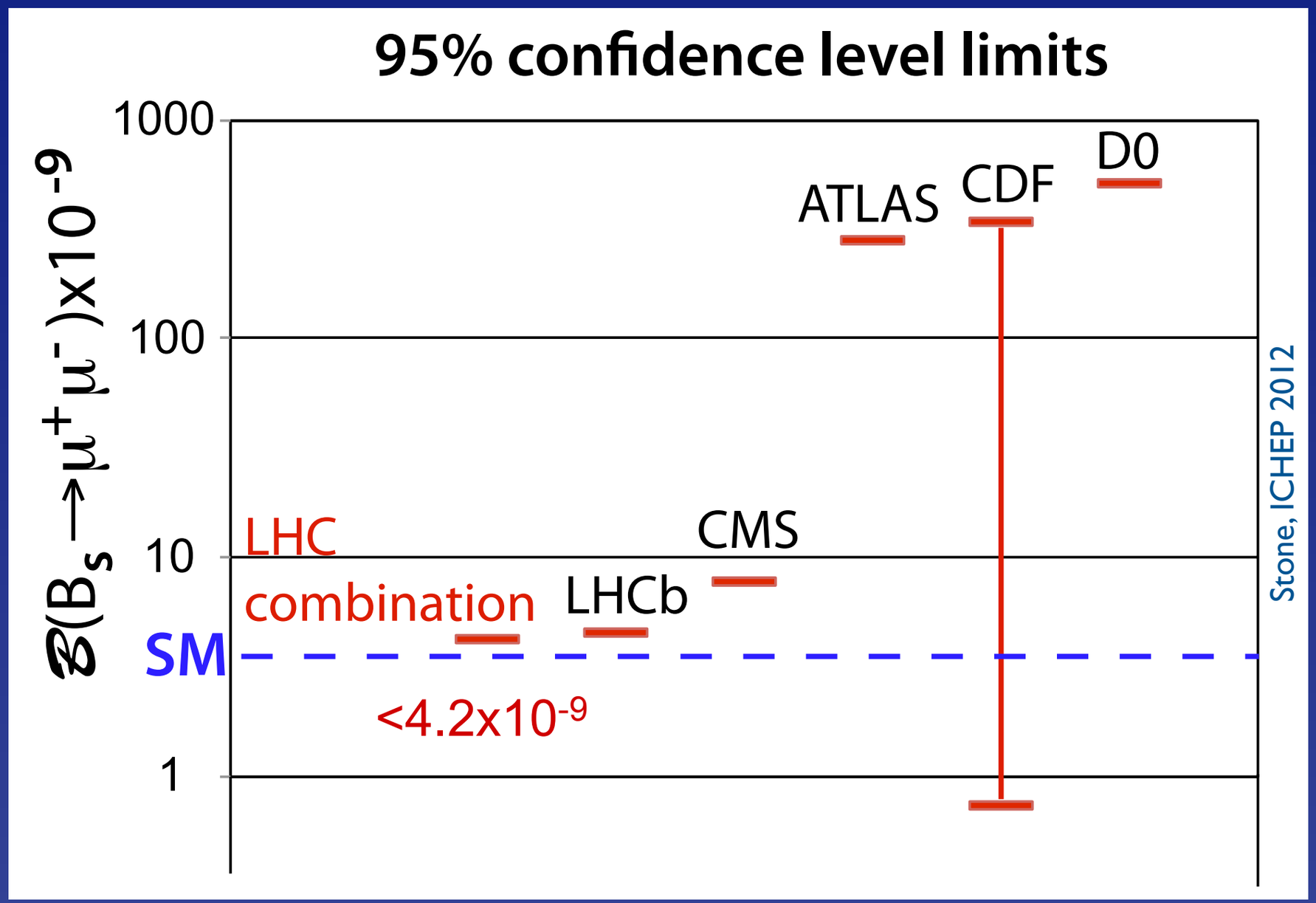


The unreasonable effectiveness of the standard model

arXiv:0907.3187

SM: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.5 \pm 0.2) \times 10^{-9}$

MSSM: $\mathrm{BR}(B_s \to \mu^+\mu^-) \propto \frac{m_b^2 m_t^2}{M_A^4} \tan^6 \beta$



Triangle-2000 meeting 'Nonperturbative methods in field and string theory',
Copenhagen, June 21, 2000

WAGER ON SUPERSYMMETRY

for ten years ahead

QUESTION: Do you think that in ten years from now, that is by noon C.E.T. June 21st, 2010, at least one supersymmetric partner of any of the known particles will be experimentally discovered? [The term "discovered" means that it is universally recognized by the community, as judged by an independent committee of three wise men/ladies appointed by the sides.]

Please put your name (in block letters) accompanied by your signature in one of the three columns below, marked as "**yes**", "**no**" or "**abstained**".

By signing "yes" or "no" you promise to deliver a bottle (75cl) of good cognac at a price of not less than $50, in case you are wrong.

By signing "abstained" you acknowledge that you either do not care, or have not thought about it, but still you'd like to be informed in the year 2010 who has been a prophet ten years ago, and to gain the right to sheepishly participate in drinking the cognac purchased by those who have honorably lost the bet.

Your signature in one of the first two columns entitles you to ask for a copy of the present agreement.

The party of winners organizes a meeting of all involved in this wager not later than in June 2011. At this meeting the cognac bought by the losers will be jointly consumed.

Yes, SUSY partners will be discovered	No, they won't	abstained
SEMENOFF kogan ** Jan Ambjorn A.Tseytlin D.S.Berman Kingsley Lee	Peter Orland Petrov Klein FADDEEV G. 't Hooft *) G.C. Rossi K. Yoshida P.H. Damgaard E. Lirits is I. Mishustin I. Klebanov M.A. Vazquez-Mozo C. Hofman Holger Bech Nielsen	MAKEENKO Neuberger

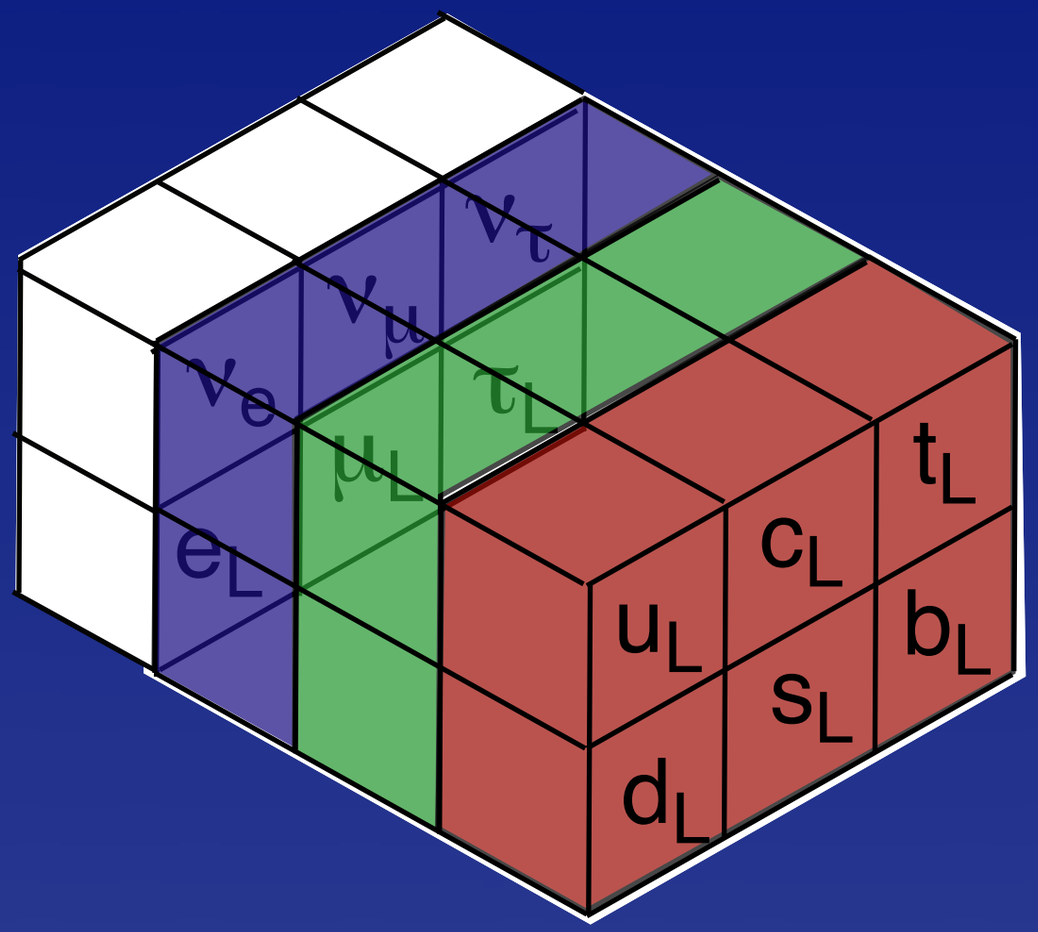
(continue signatures on the other side, if necessary)

*) But each side will claim victory

**) But it may be not as exciting as if neither SUSY, nor Higgs will be discovered.

A Unified Theory?

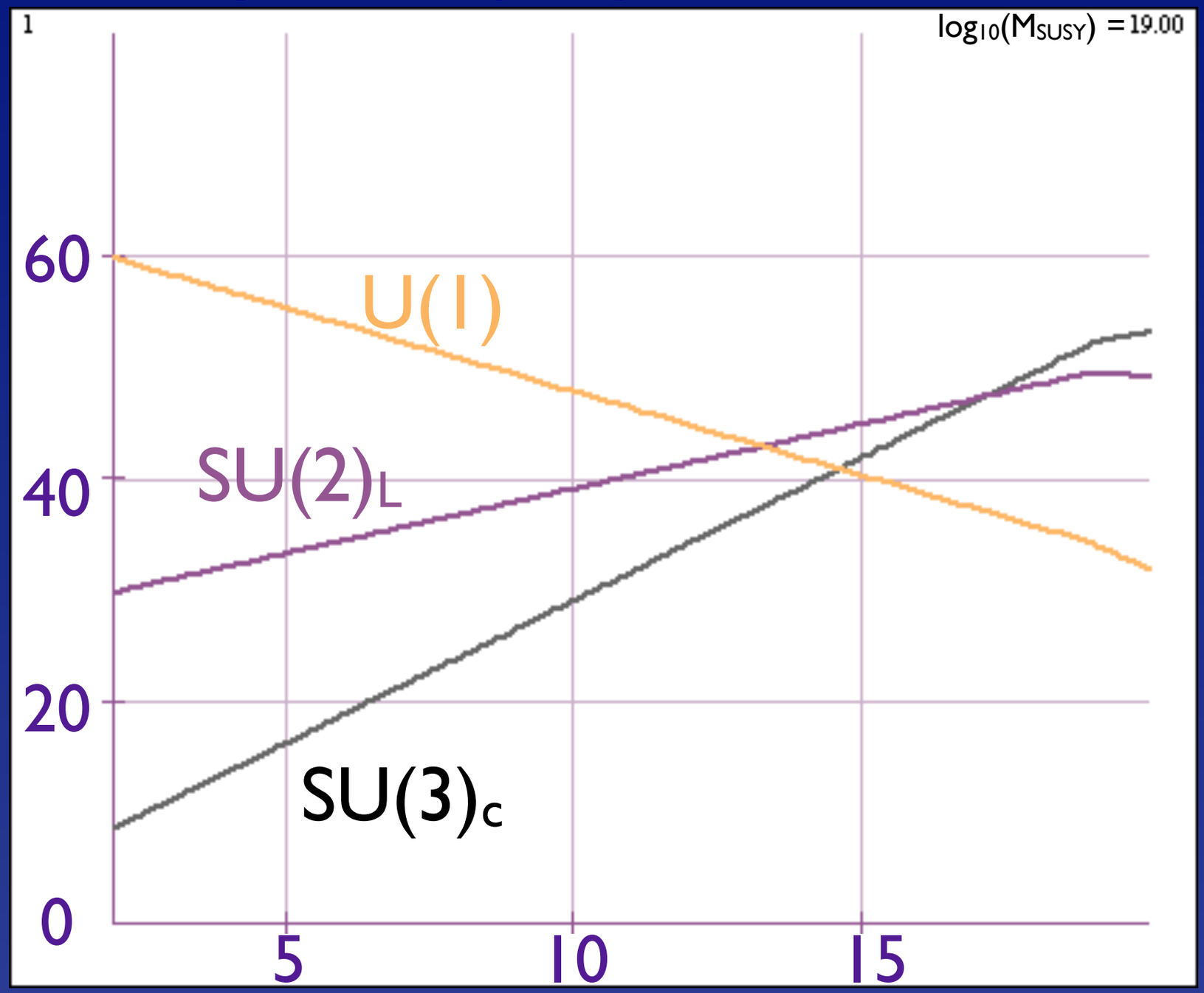
Why are atoms so remarkably neutral?



Coupling constant unification?

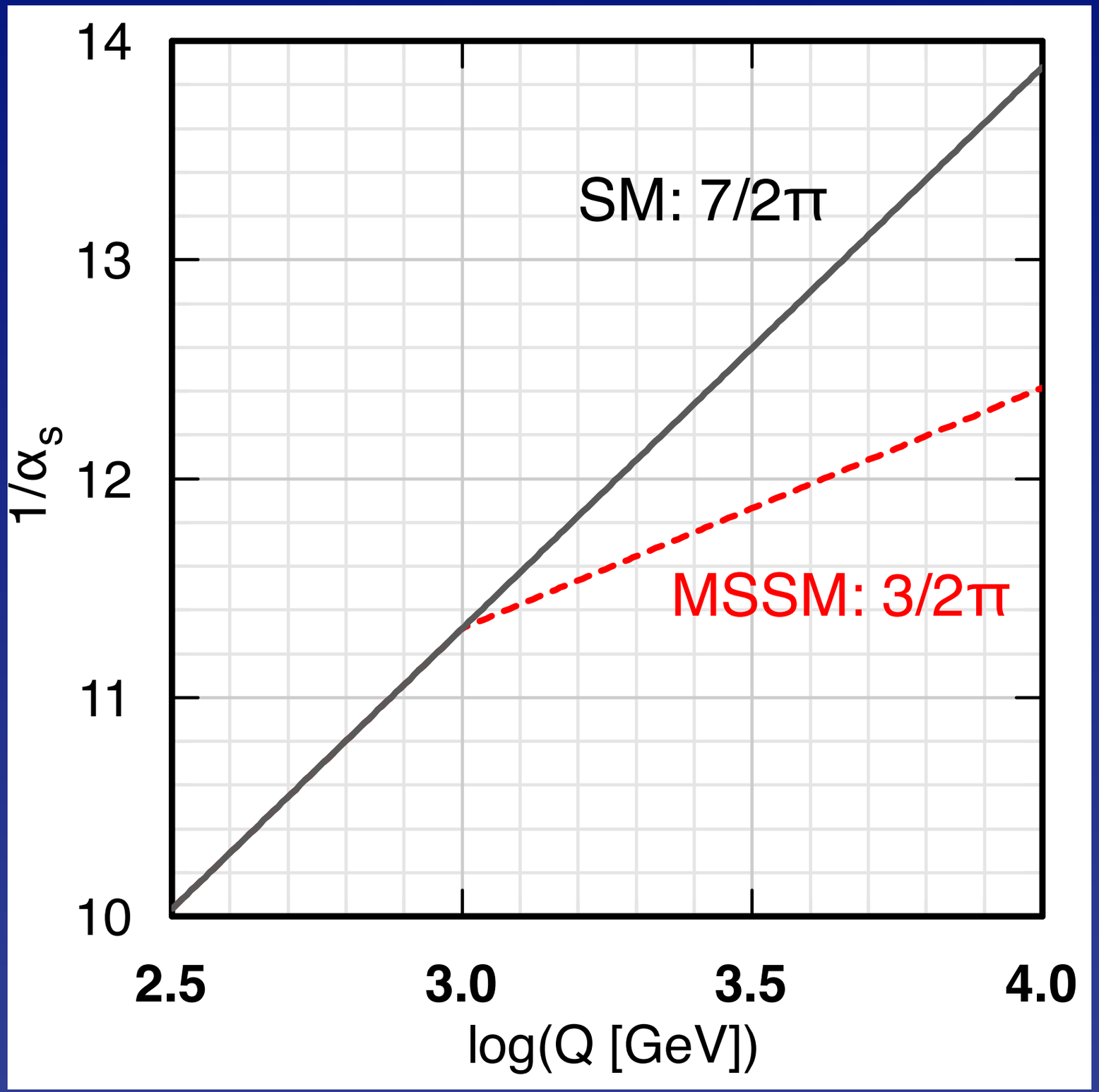
Extended quark–lepton families:
proton decay!

Different running of $U(1)_Y$, $SU(2)_L$, $SU(3)_c$ gives possibility of coupling constant unification



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

Goal: Measure change in slope for onset of SUSY?



Issues for the Future (Now!)

1. What is the agent of EWSB? Is there a Higgs boson? Might there be several?
2. Is the Higgs boson elementary or composite? How does it interact with itself? What triggers EWSB?
3. Does the Higgs boson give mass to fermions, or only to the weak bosons? What sets the masses and mixings of the quarks and leptons? *(How) is fermion mass related to the electroweak scale?*
4. Are there new flavor symmetries that give insights into fermion masses and mixings?
5. What stabilizes the Higgs-boson mass below 1 TeV?

Issues for the Future (Now!)

6. Do the different CC behaviors of LH, RH fermions reflect a fundamental asymmetry in nature's laws?
7. What will be the next symmetry we recognize? Are there additional heavy gauge bosons? Is nature supersymmetric? Is EW theory contained in a GUT?
8. Are all flavor-changing interactions governed by the standard-model Yukawa couplings? Does "minimal flavor violation" hold? If so, why?
9. Are there additional sequential quark & lepton generations? Or new exotic (vector-like) fermions?
10. What resolves the strong CP problem?

Issues for the Future (Now!)

11. What are the dark matters? Any flavor structure?
12. Is EWSB an emergent phenomenon connected with strong dynamics? How would that alter our conception of unified theories of the strong, weak, and electromagnetic interactions?
13. Is EWSB related to gravity through extra spacetime dimensions?
14. What resolves the vacuum energy problem?
15. (When we understand the origin of EWSB), what lessons does EWSB hold for unified theories? … for inflation? … for dark energy?

Issues for the Future (Now!)

16. Are there new phenomena in strong interactions?
17. What explains the baryon asymmetry of the universe? Are there new (CC) CP-violating phases?
18. Are there new flavor-preserving phases? What would observation, or more stringent limits, on electric-dipole moments imply for BSM theories?
19. (How) are quark-flavor dynamics and lepton-flavor dynamics related (beyond the gauge interactions)?
20. At what scale are the neutrino masses set? Is the neutrino its own antiparticle? Are there sterile νs?
21. Is there a case for a Higgs factory?
22. How are we prisoners of conventional thinking?

Vielen Dank! Viel Spaß in München!