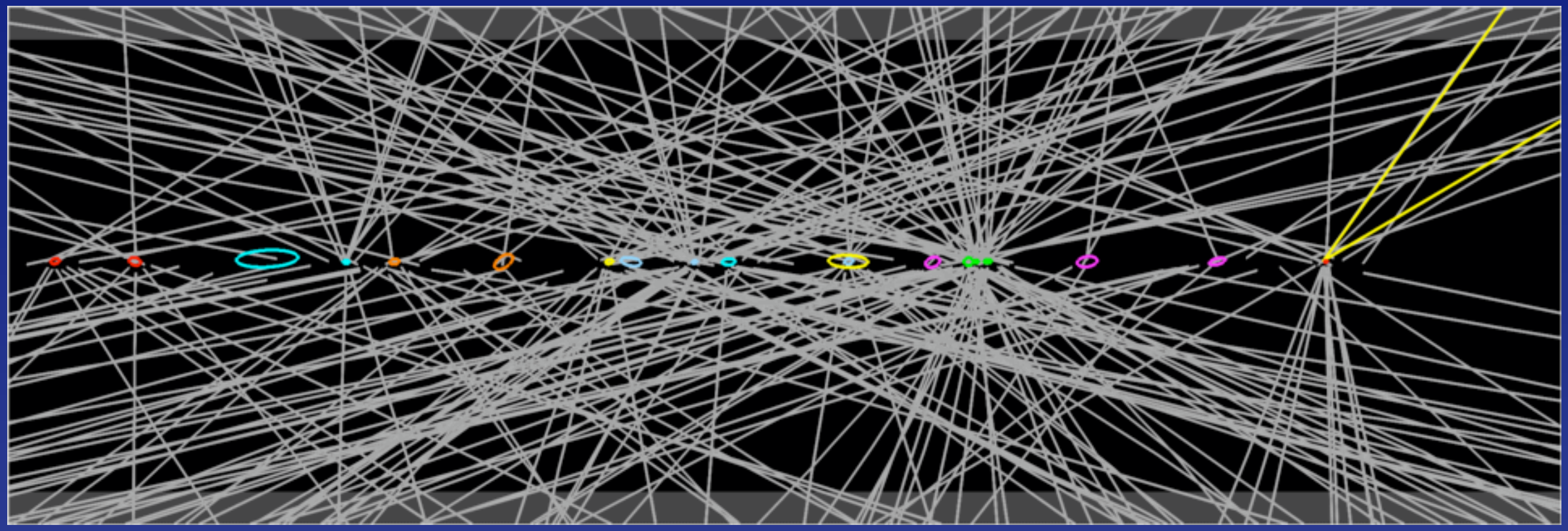
Particle Physics in a Season of Change

Chris Quigg
Fermi National Accelerator Laboratory



Hadron Collider Physics · Paris · 14 November 2011

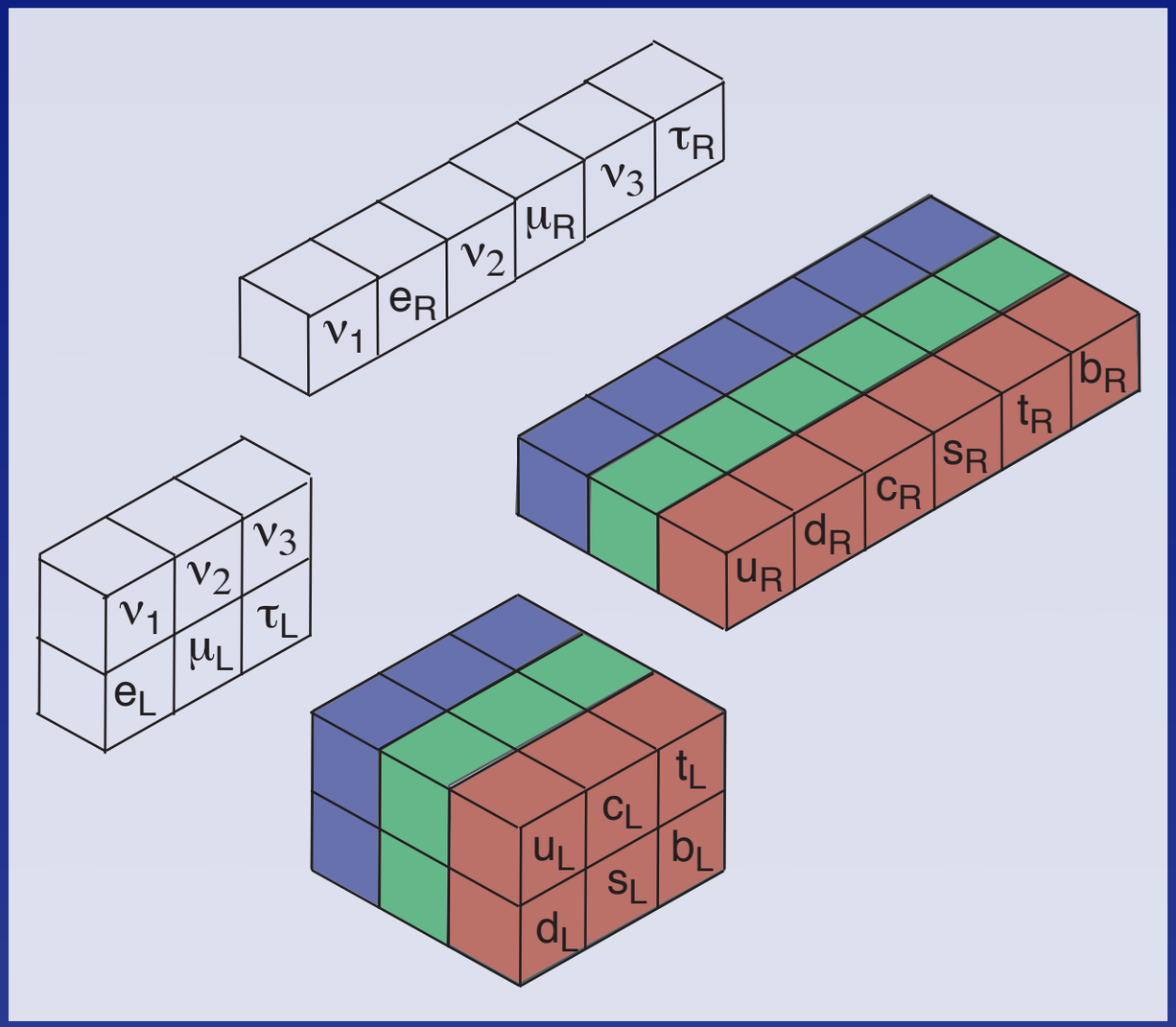
Explore

Search

Measure

Two New Laws of Nature +

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



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

Quantum Chromodynamics

Asymptotically free theory

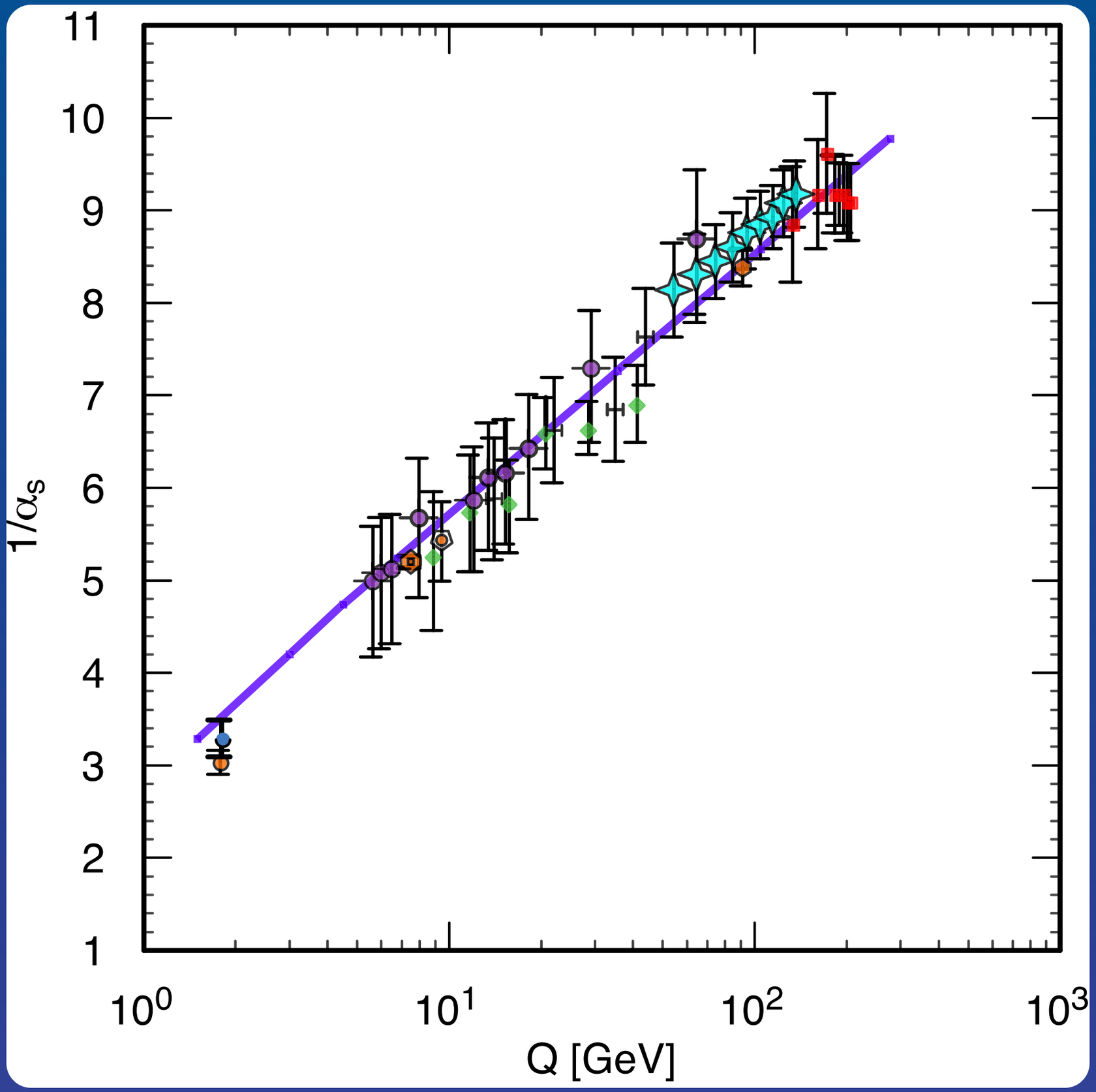
Many successes in perturbation theory to 1 TeV

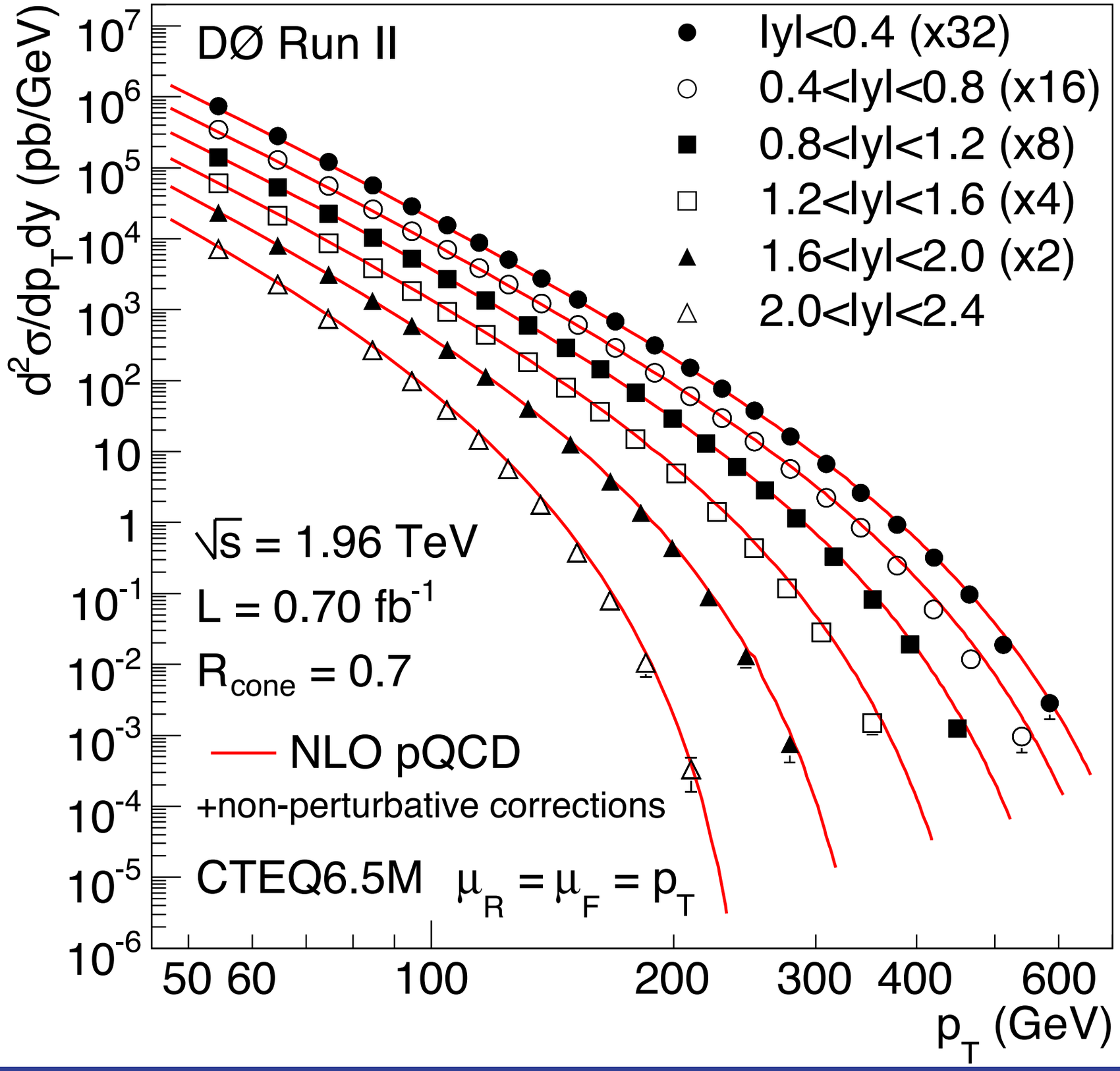
Growing understanding: nonperturbative regime

Quarks & gluons confined: evidence, no proof

No structural defects, but … *strong CP problem*

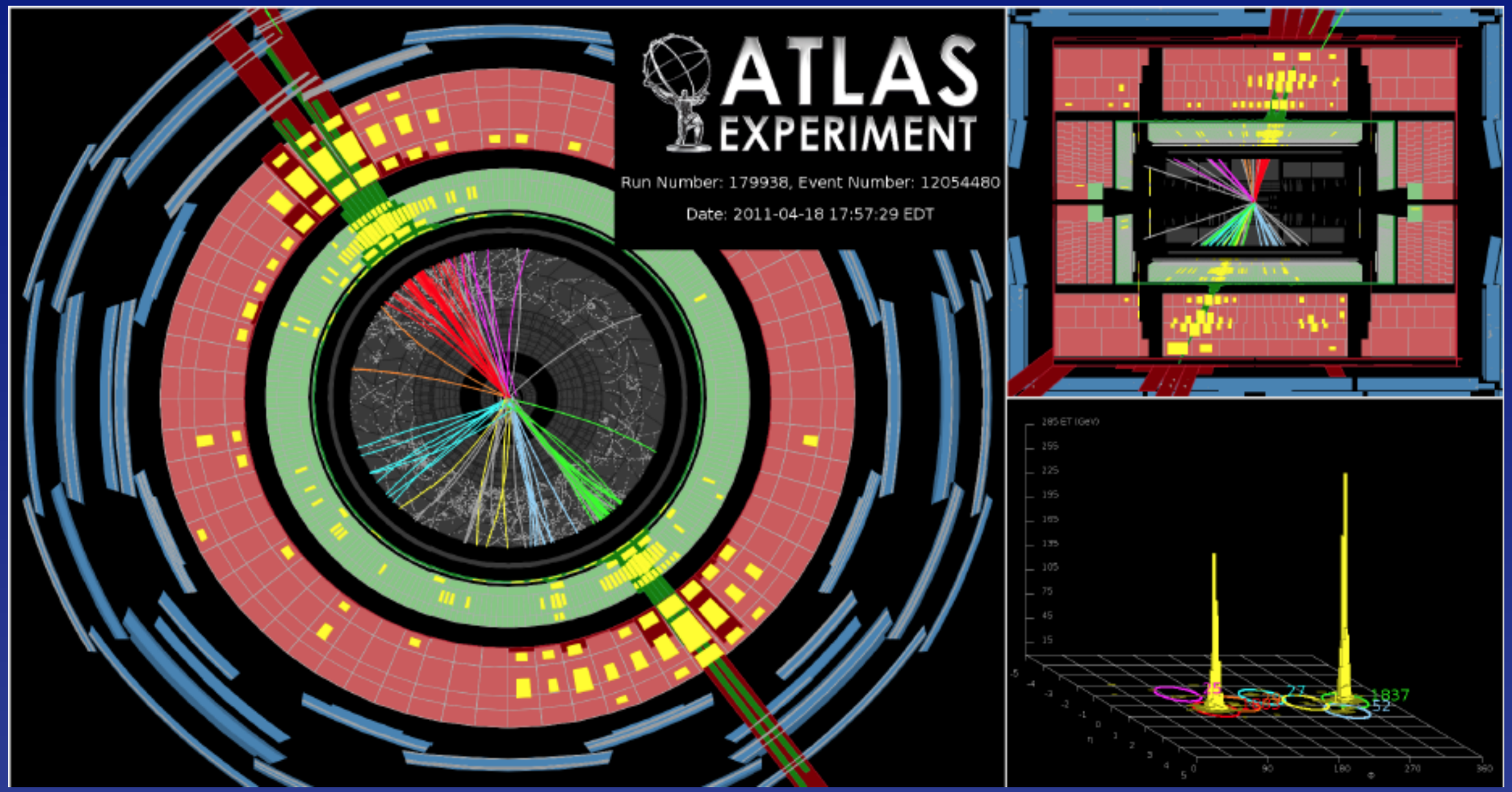
Evolution of the strong coupling




DØ Run II
|y|<0.4 (x32)
0.4<|y|<0.8 (x16)
0.8<|y|<1.2 (x8)
1.2<|y|<1.6 (x4)
1.6<|y|<2.0 (x2)
2.0<|y|<2.4
√s = 1.96 TeV
L = 0.70 fb-1
Rcone = 0.7
NLO pQCD
+non-perturbative corrections
CTEQ6.5M μR = μF = pT
d2σ/dpTdy (pb/GeV)
pT (GeV)

The World's Most Powerful Microscopes

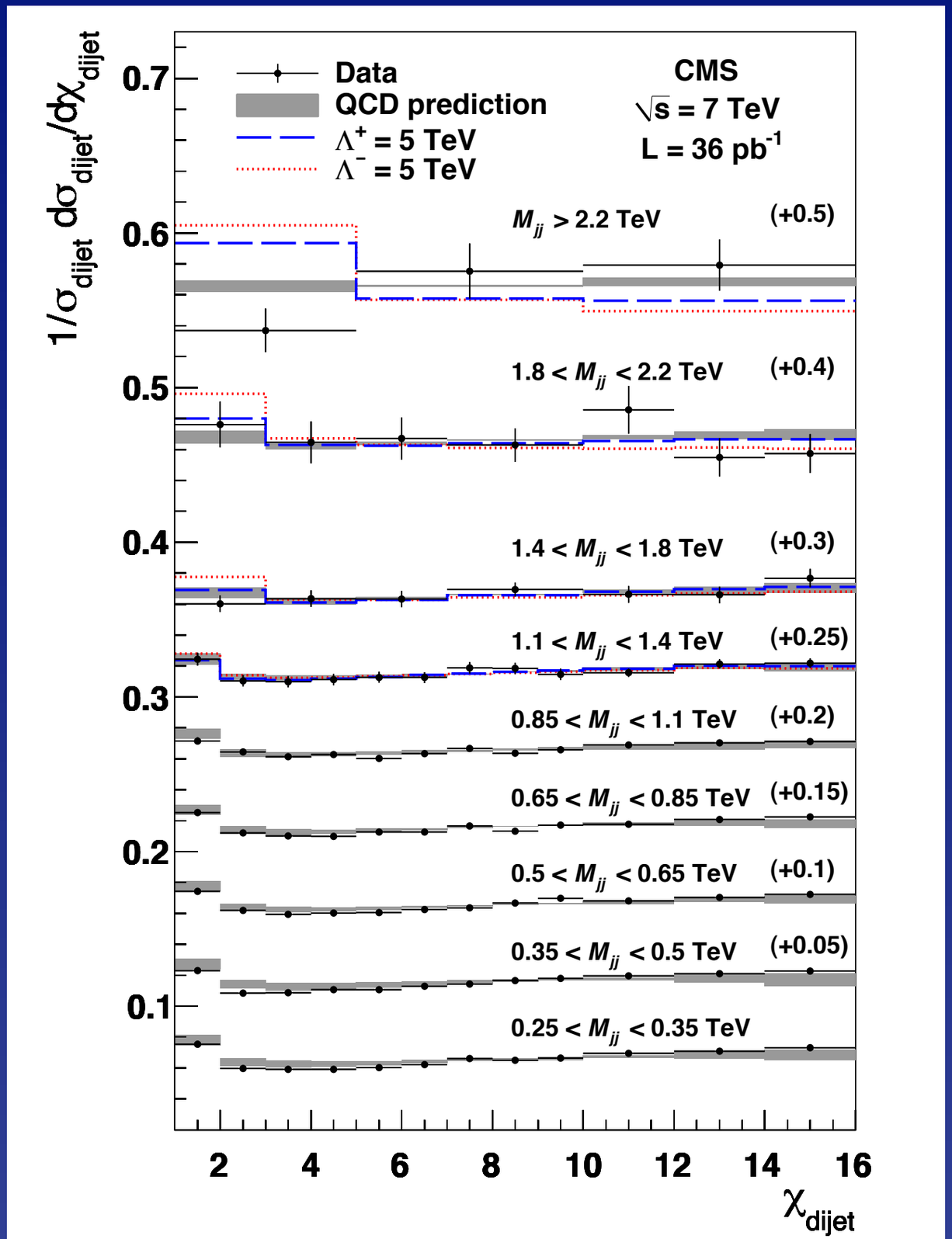
nanonanophysics



Transverse momenta: 1.8 TeV + 1.8 TeV · *Dijet mass:* 4 TeV

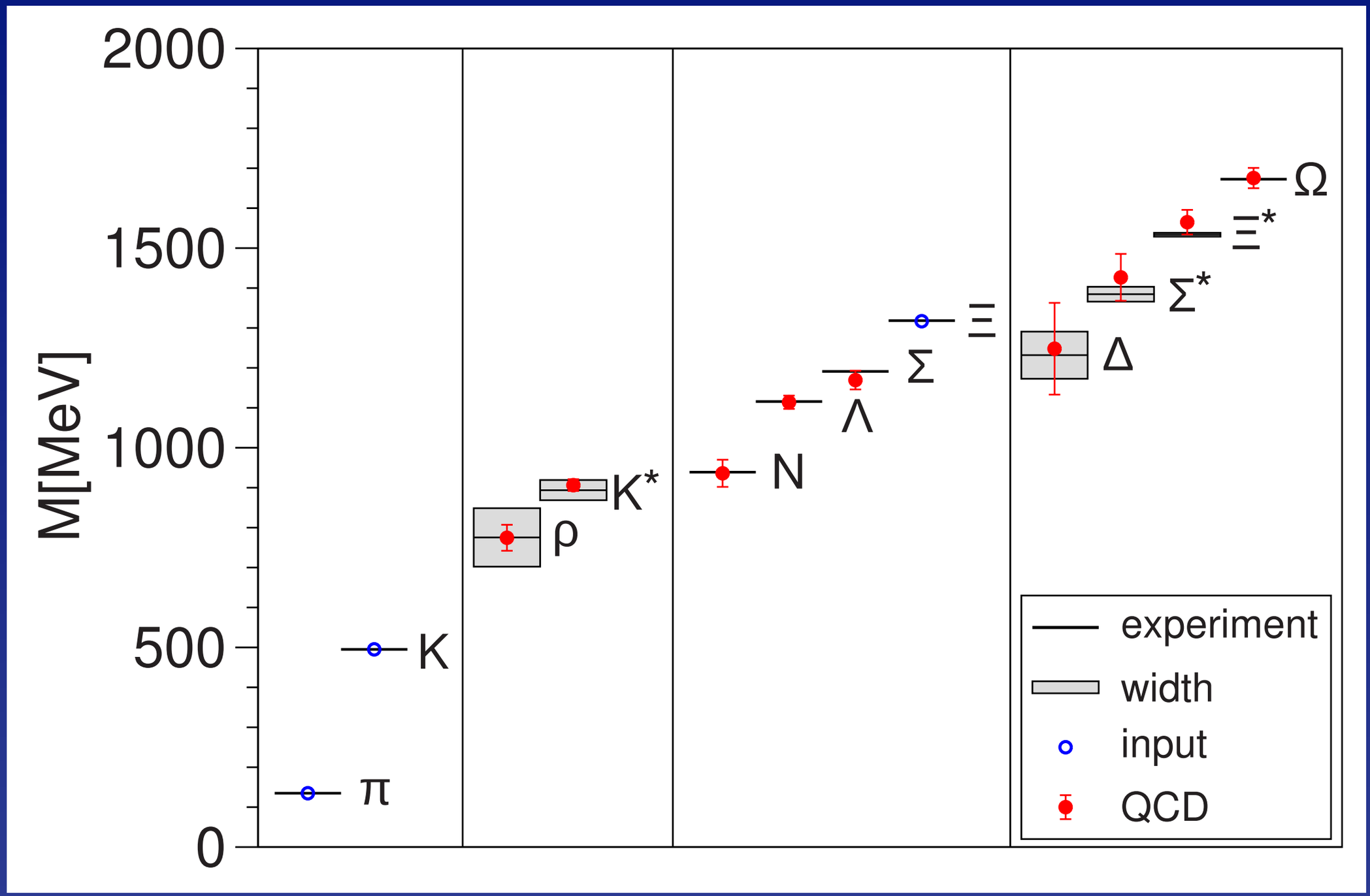
Rutherford scattering test for quark compositeness

$$\frac{d\sigma}{d\cos\theta^*} \propto \frac{1}{\sin^4(\theta^*/2)} \rightsquigarrow \frac{d\sigma}{d\chi} \propto 1$$



$$\chi \equiv \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

Light hadron spectrum with dynamical fermions



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 …

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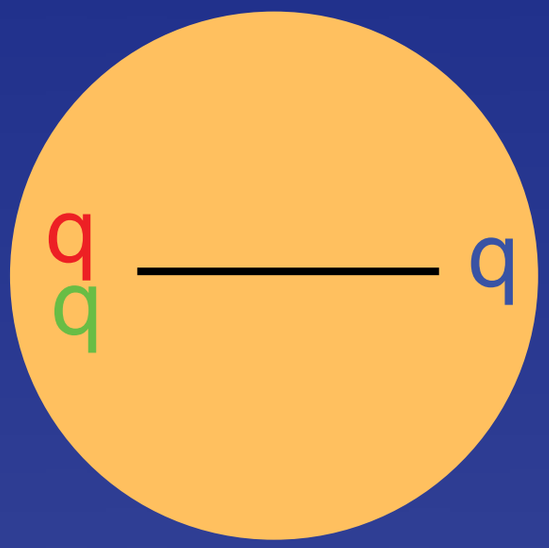
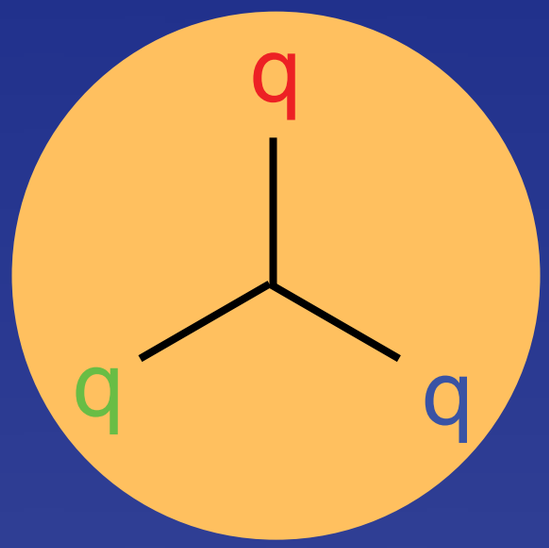
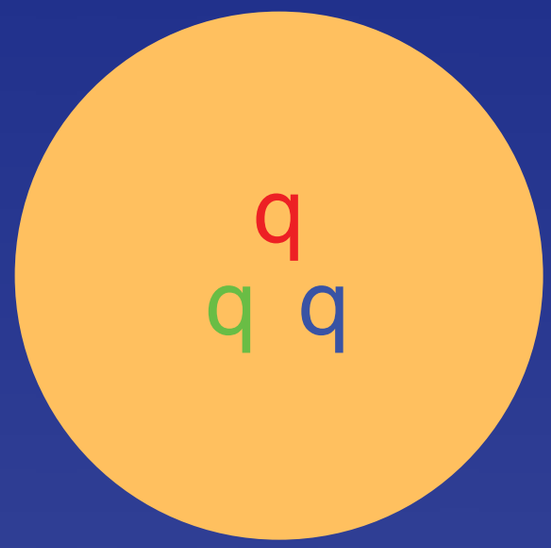
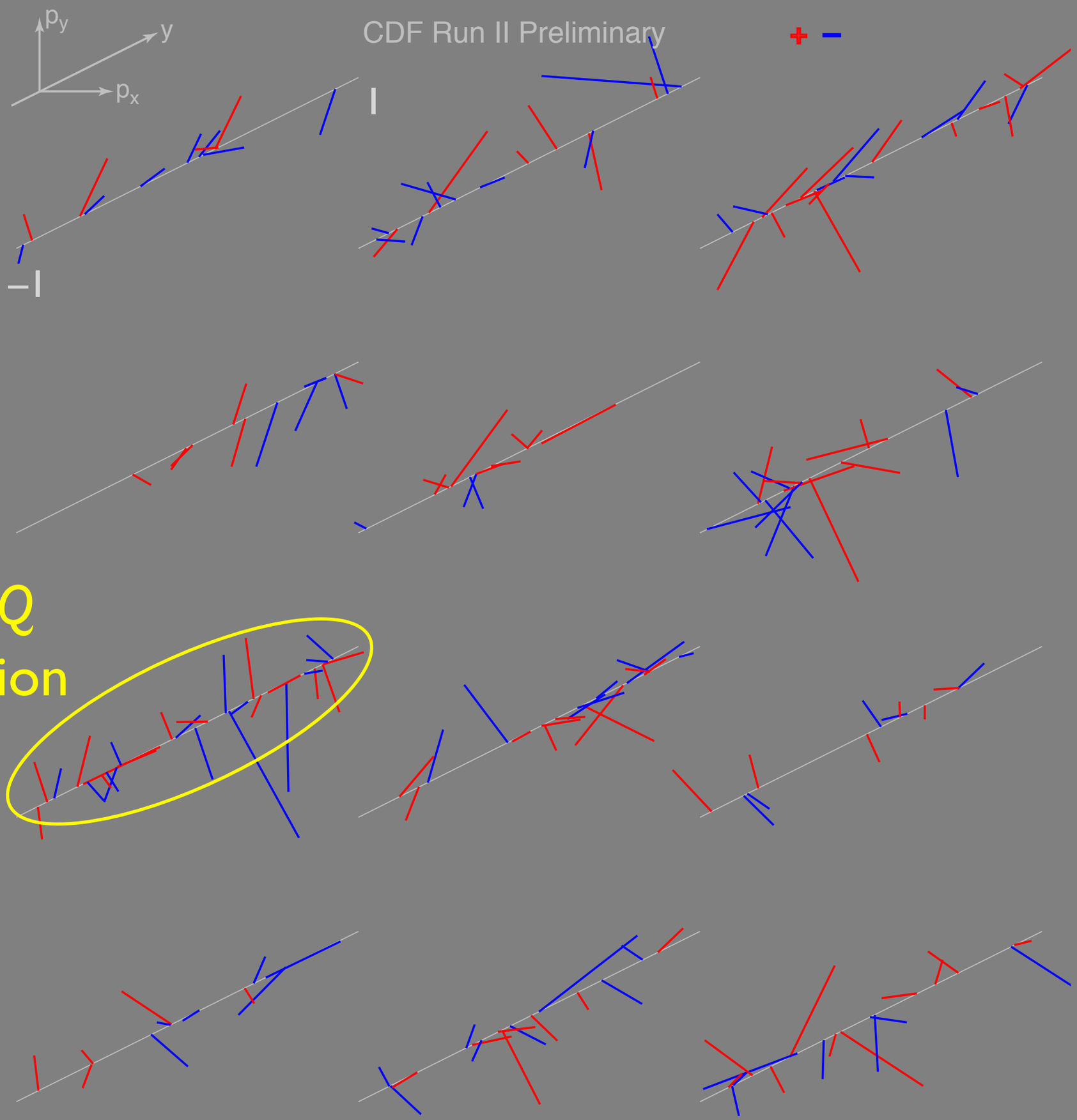




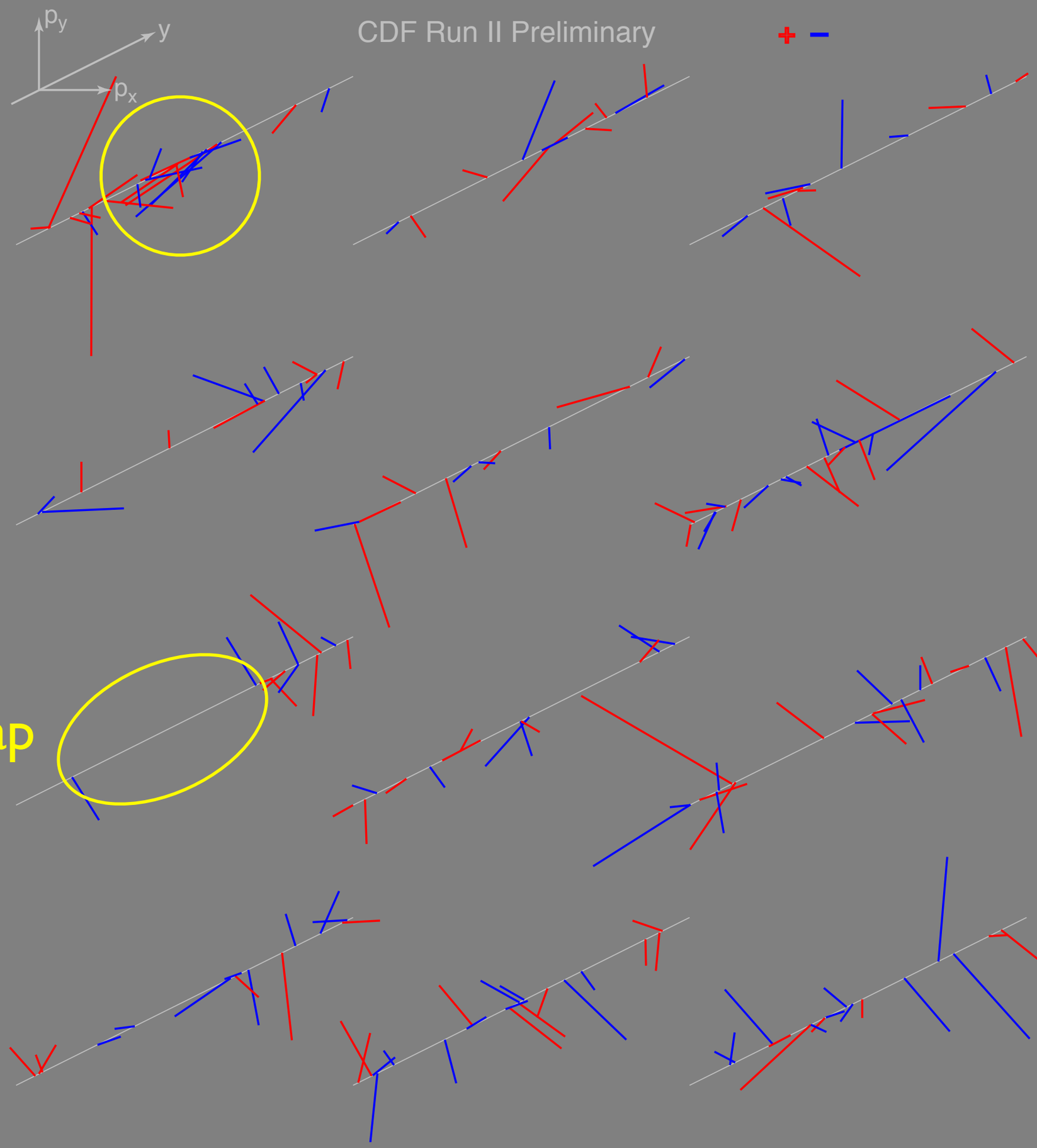


Bjorken (2010)

Local $p_\perp$, Q compensation

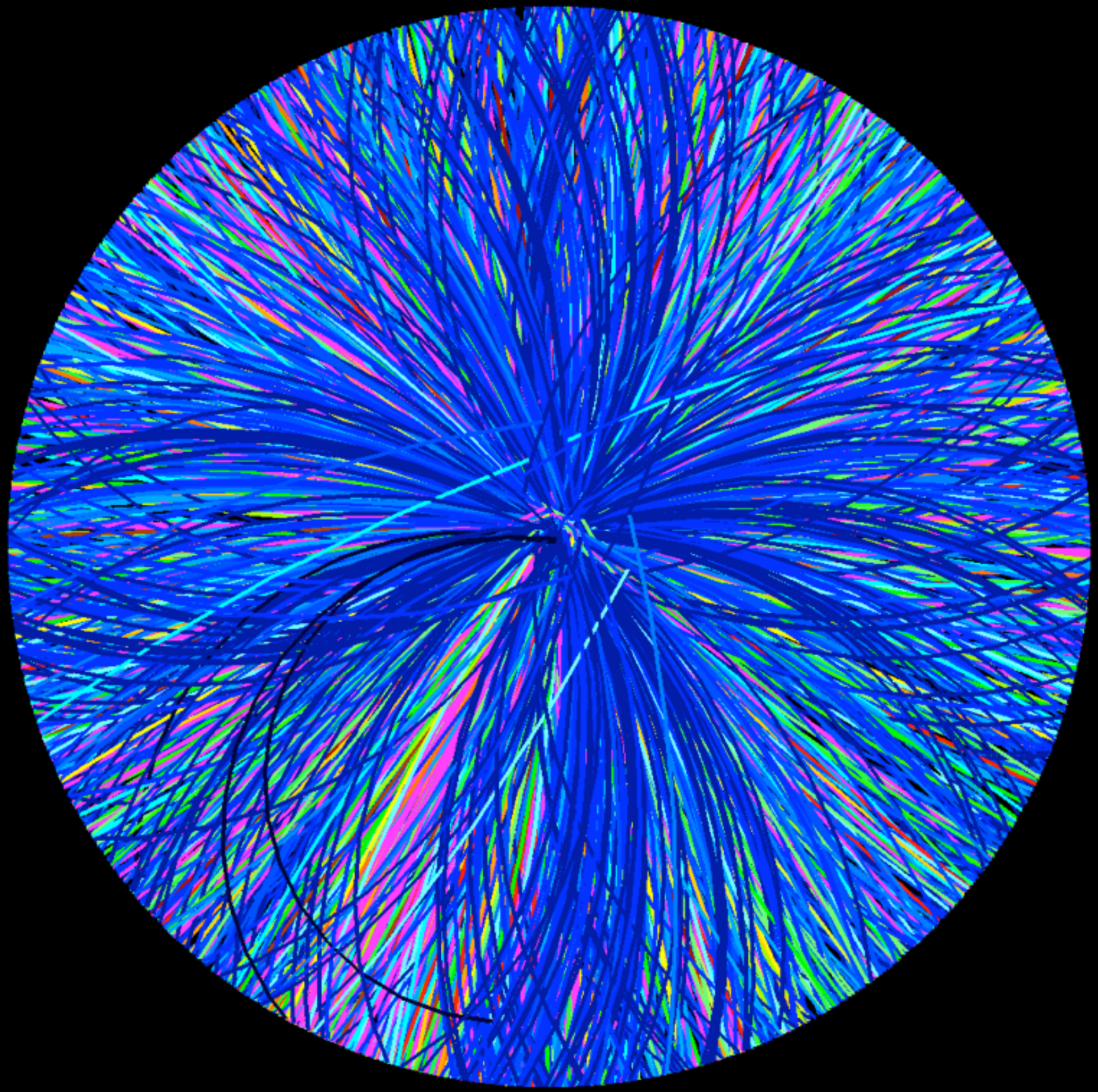


Hot spot?

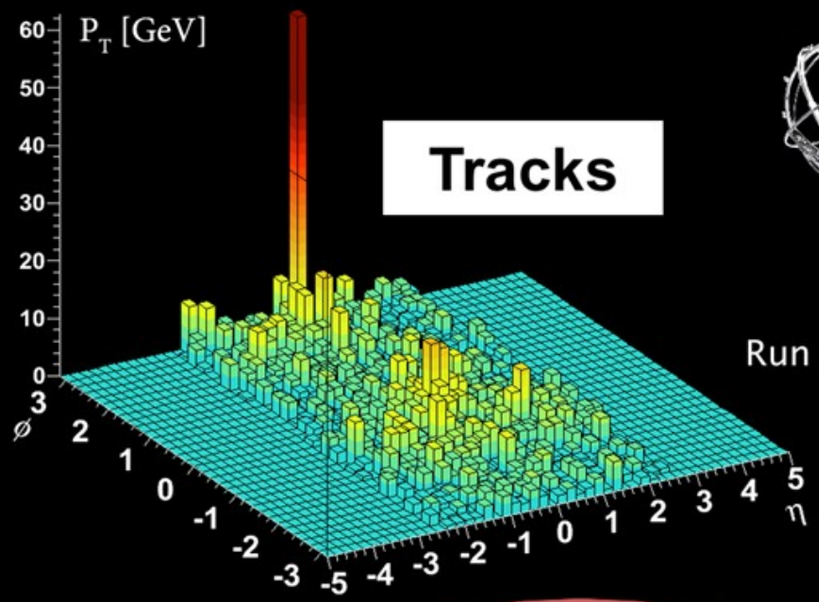


Rapidity gap

New Era of Heavy-Ion Physics



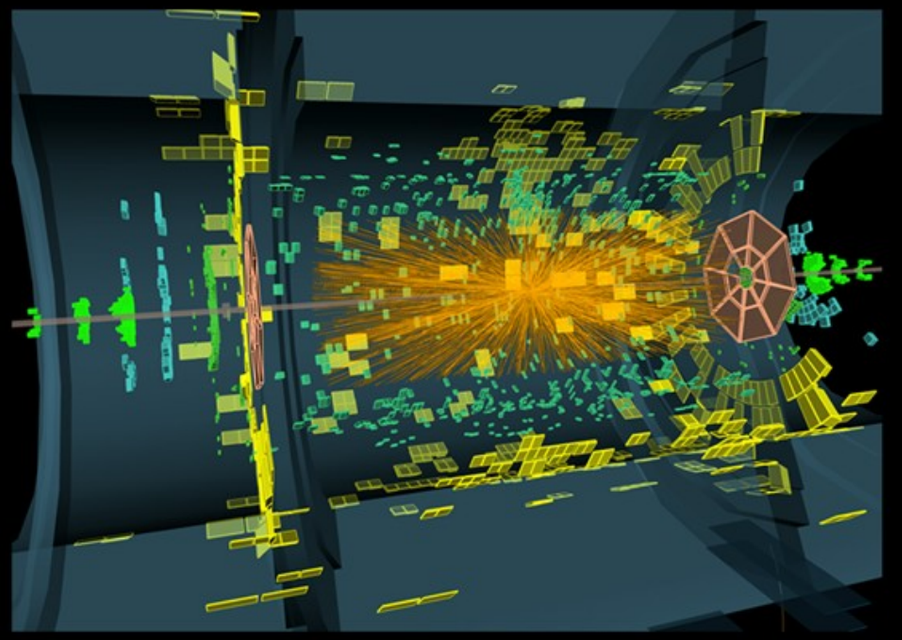
ALICE: Pb-Pb Collisions at 287 TeV

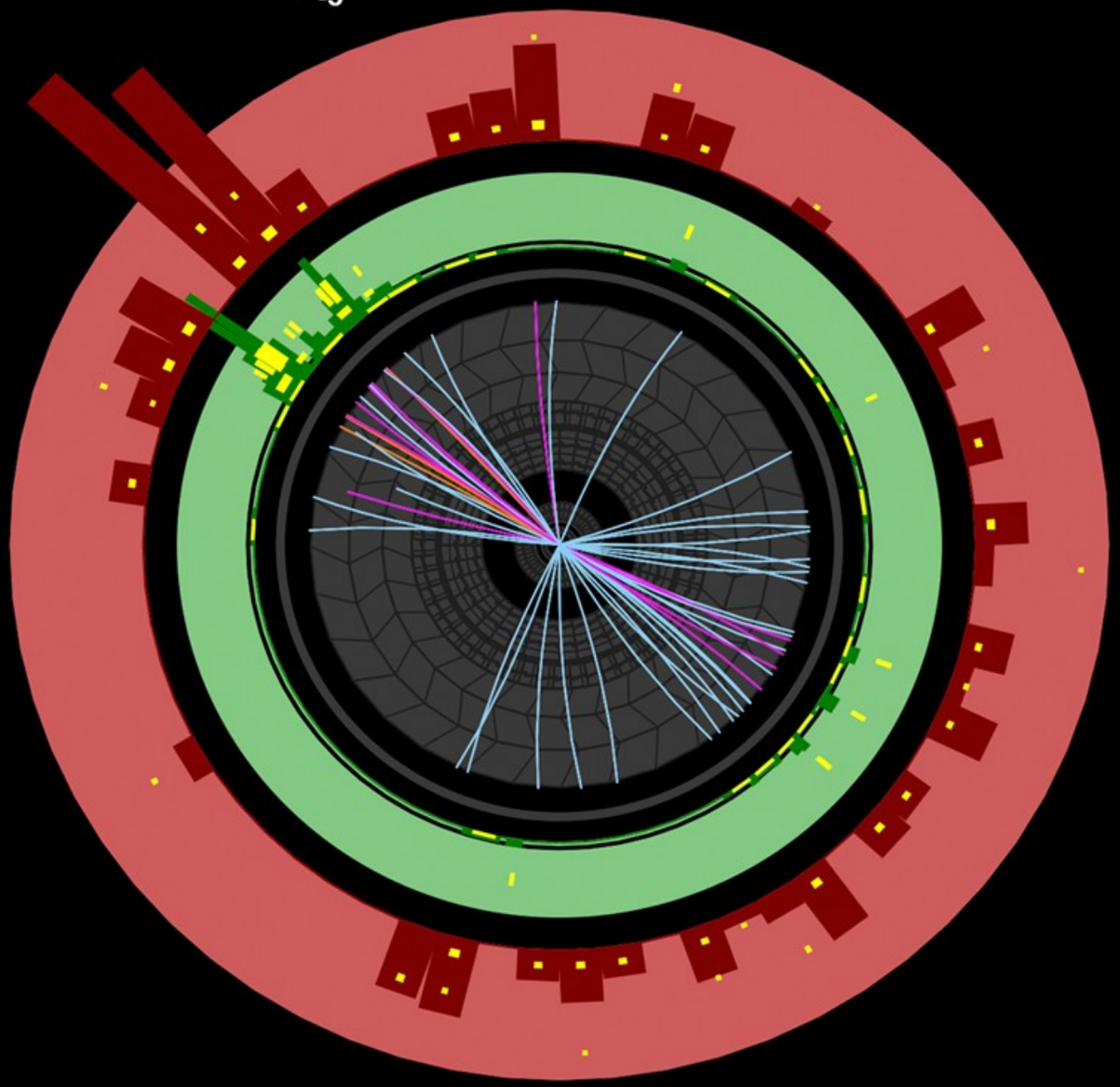


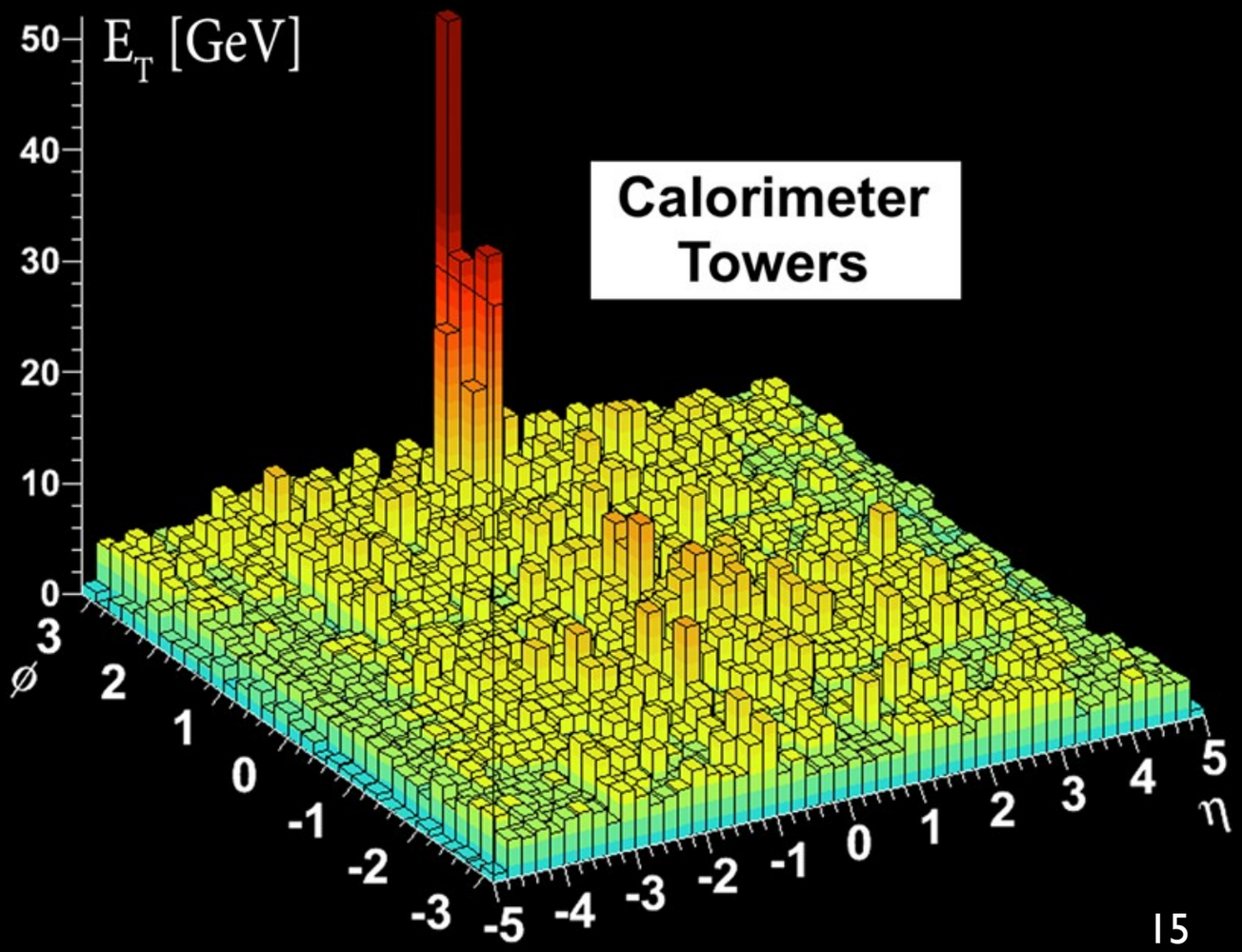
ATLAS EXPERIMENT

Run Number: 169045, Event Number: 1914004

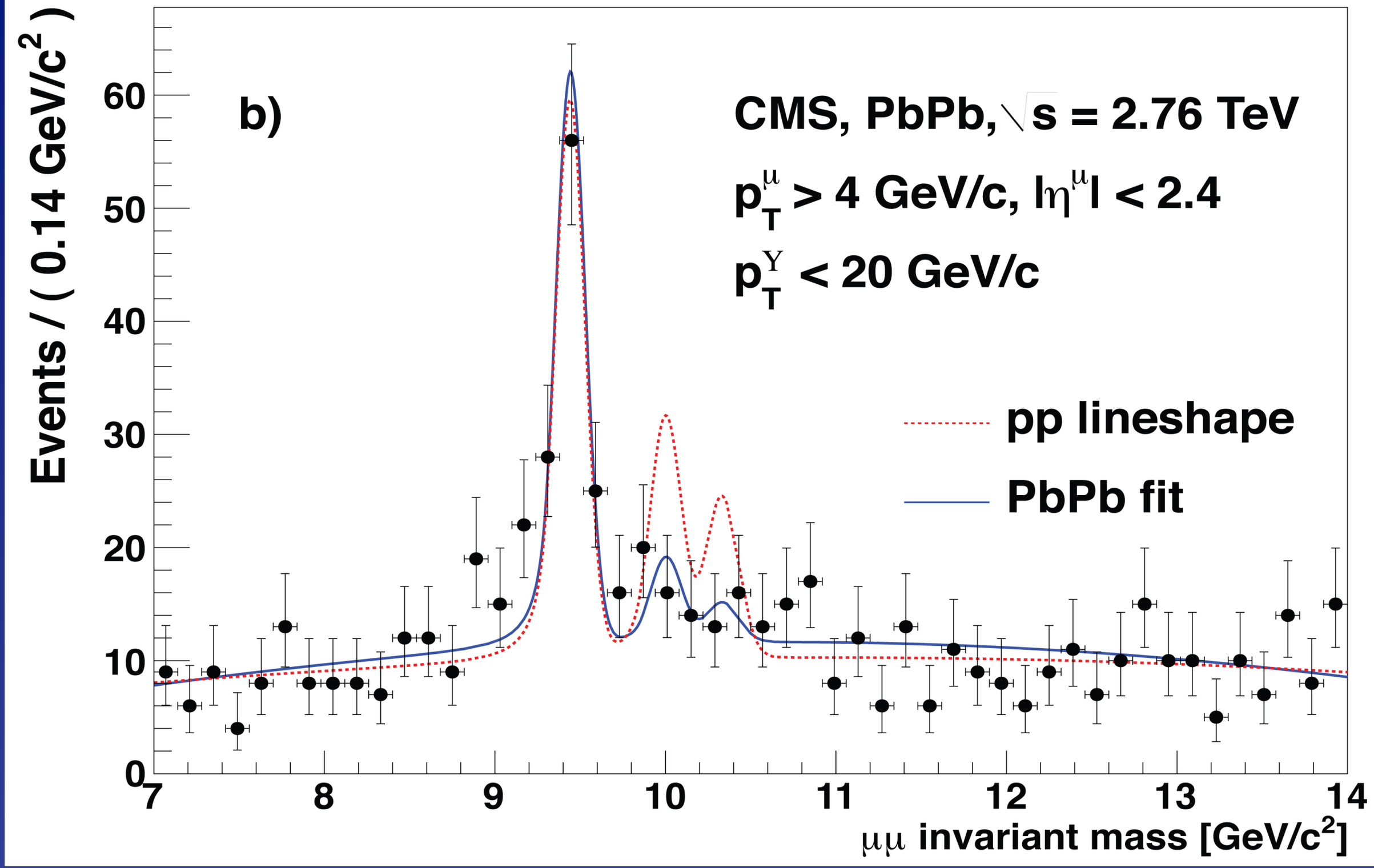
Date: 2010-11-12 04:11:44 CET







CMS suggestion of quarkonium melting



Electroweak Theory

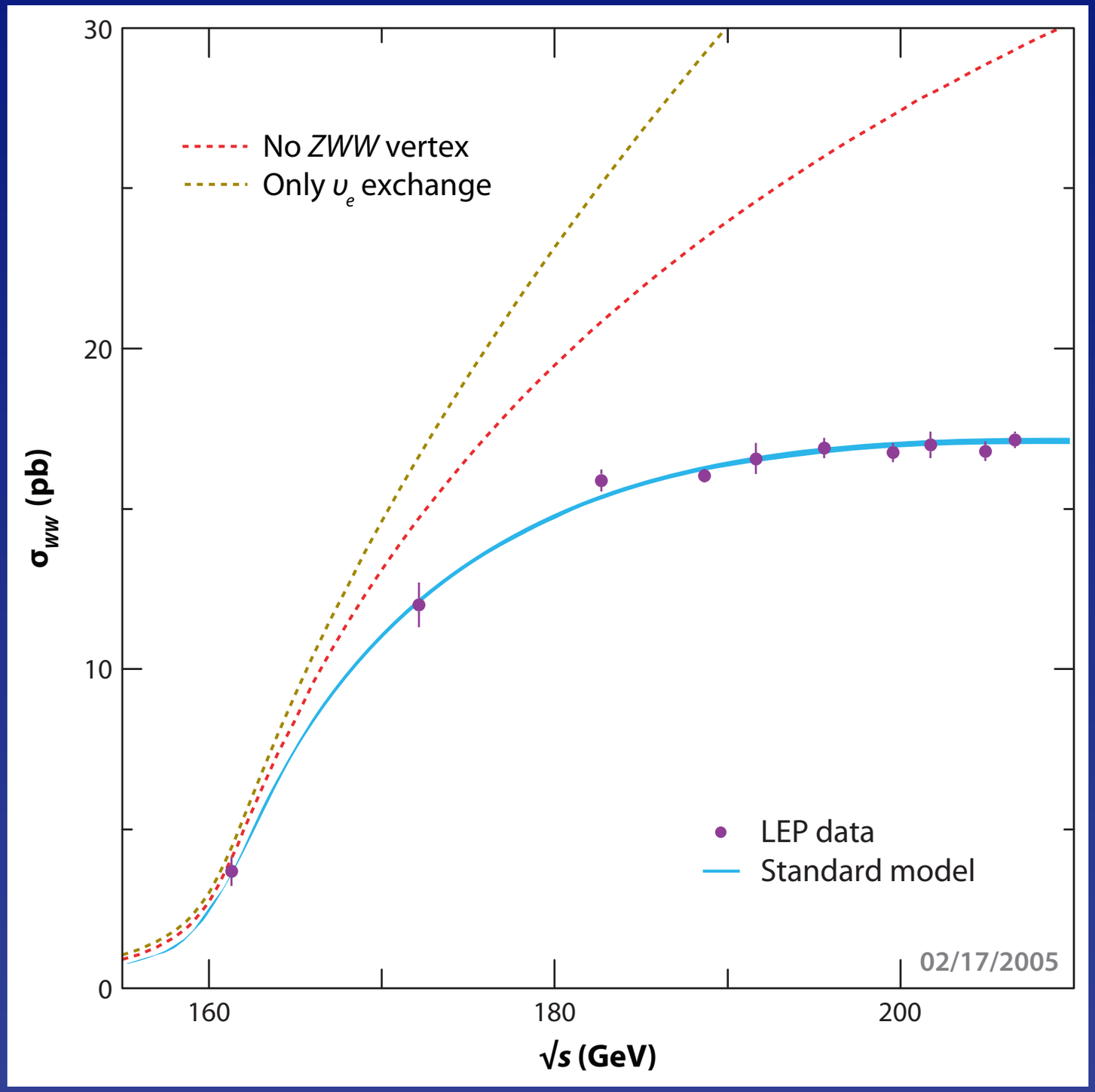
To good approximation …
3-generation V–A
GIM suppresses FCNC
CKM quark-mixing matrix describes CPV

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

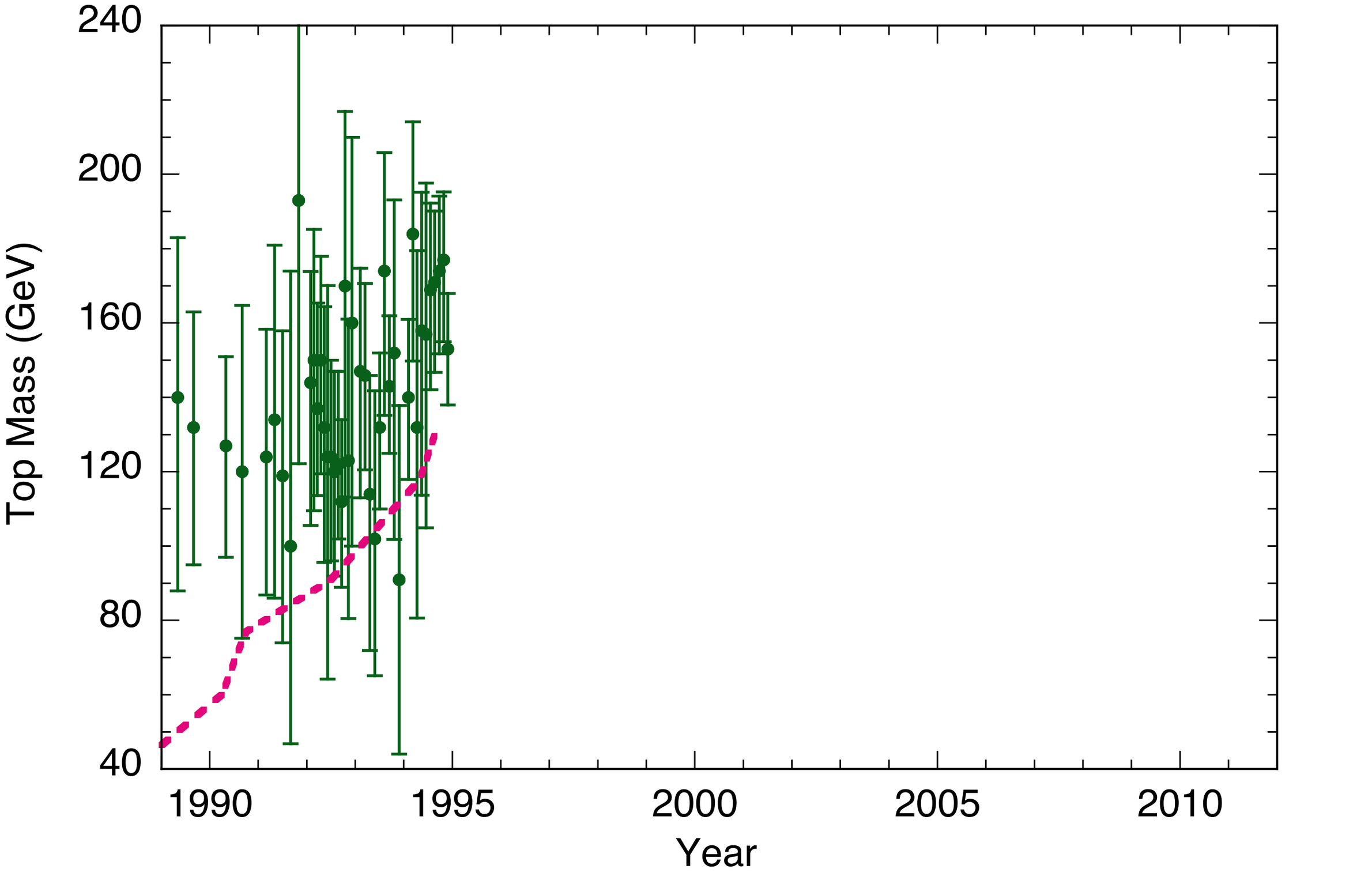
Tested as quantum field theory at per-mille level

Gauge symmetry (group-theory structure) tested in

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



Electroweak theory anticipates discoveries



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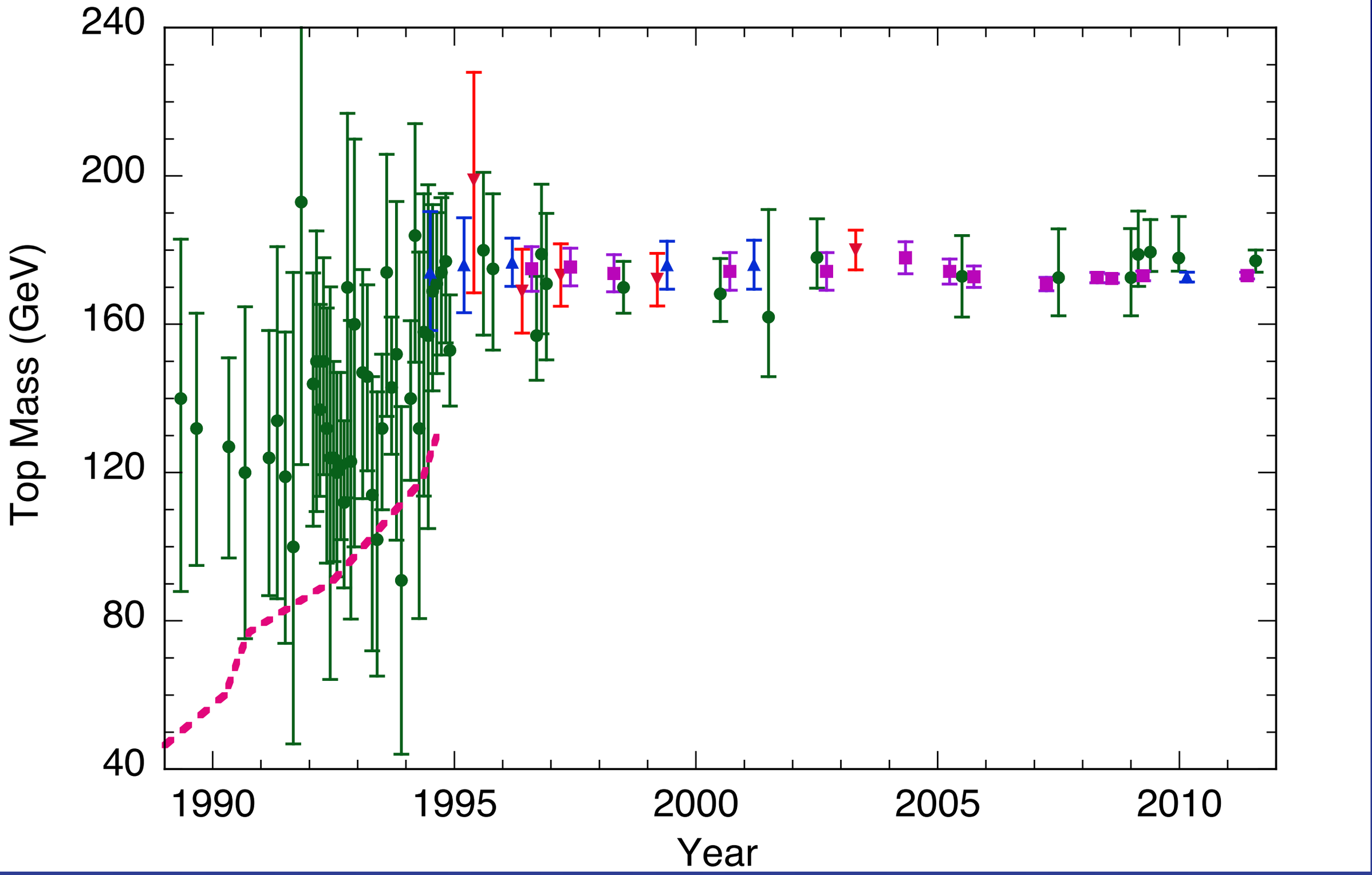


Several persistent tensions in flavor sector

New physics in *B* mixing?

4th generation?

Supersymmetry?
Extra dimensions?
… ?

$|V_{ub}|$ comparisons

Latest combined fit to data,lattice $B \to \pi \ell \nu$ $(2.95 \pm 0.31) \times 10^{-3}$

Inclusive, PDG2010 average: $b \to u \ell \nu$ $(4.37 \pm 0.39) \times 10^{-3}$

$\Big\} 2.7\sigma$

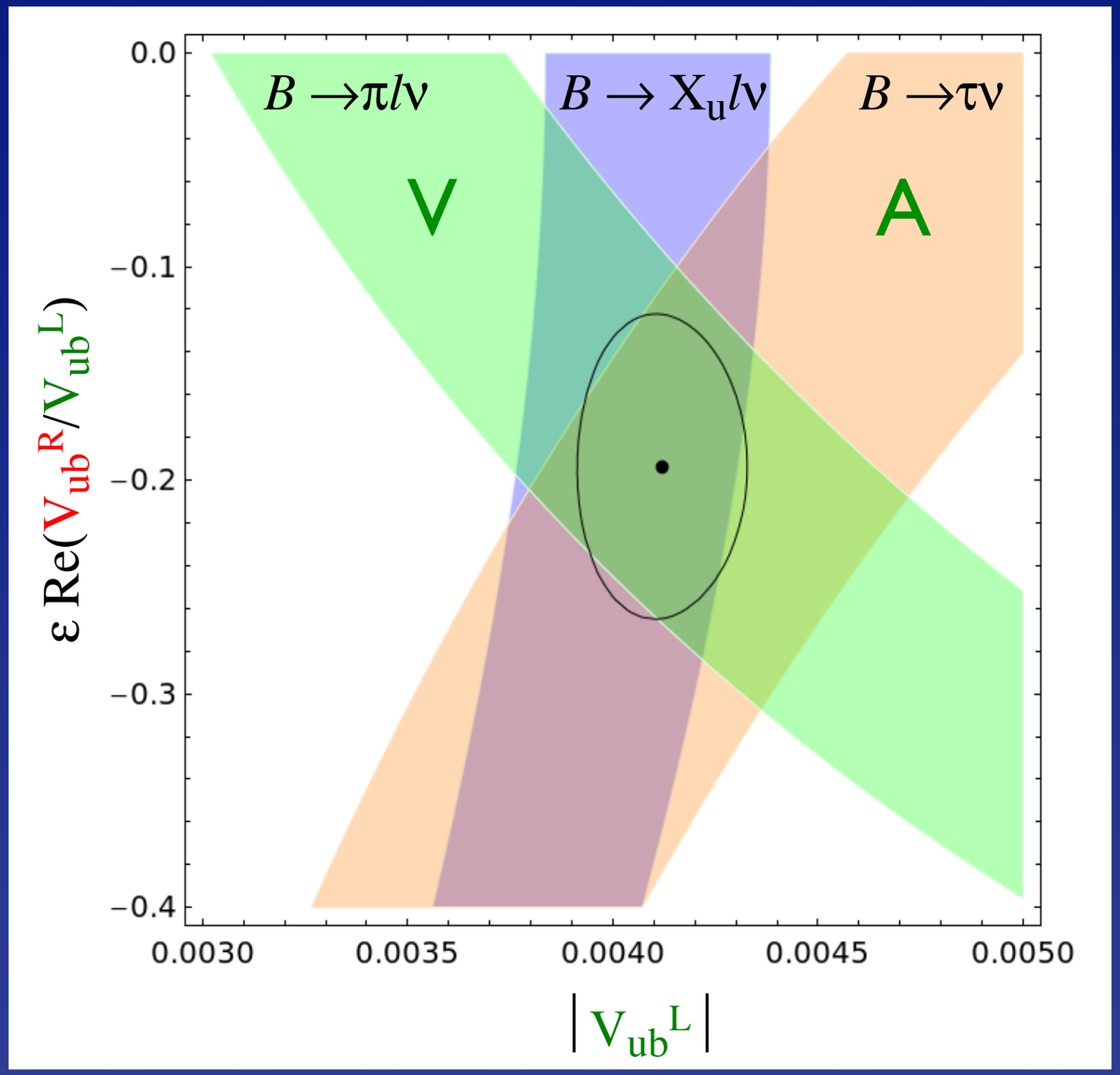
Difference is a problem and perhaps should be identified as an unattributed uncertainty

- work of multiple experiments, multiple theoretical groups.
- exclusive result relies on non-perturbative normalization input
- inclusive result uses m_b, non-perturbative extrapolations and perturbative corrections

Predictions from CKM fits:

UTFit	**3.48±0.16**	**(ICHEP 2008)**
CKMFitter	**$3.51 \pm {}^{0.15}_{0.16}$**	**(Beauty 2009)**

Resolution by RH current?



Buras/Gemmler/Isidori 1007.1993

An unknown *agent provocateur* 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?

The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: *conditional upper bound*

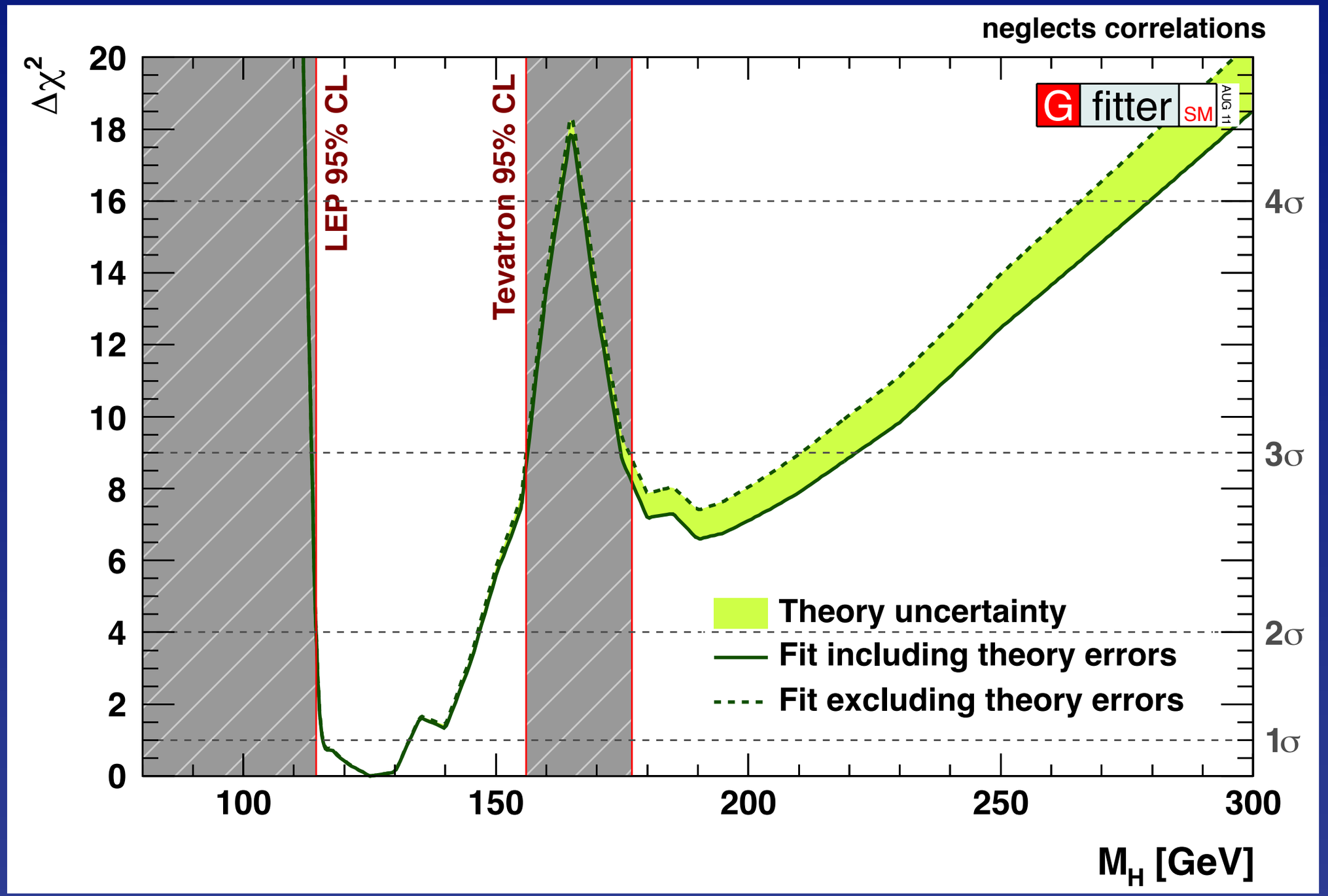
W^+W^-, ZZ, HH, HZ satisfy s-wave unitarity,

provided $\boxed{M_H \leq (8\pi\sqrt{2}/3G_F)^{1/2} \approx 1\ \text{TeV}}$

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

New phenomena are to be found around 1 TeV

Where the SM Higgs boson should be



Outside standard model, heavy Higgs allowed, even natural

We *do not know* that the agent of electroweak symmetry breaking gives mass to fermions.

We *do not know* what determines fermion masses and mixings.

Why will 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

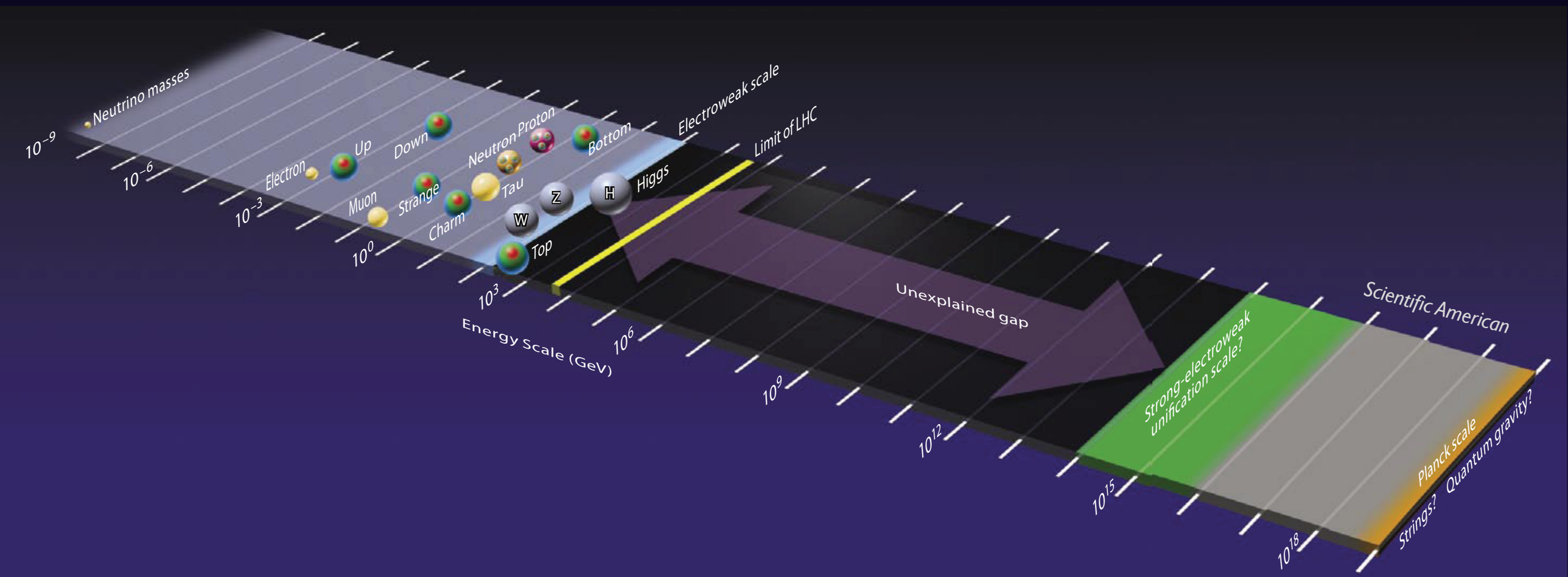
Massless electron: atoms lose integrity

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

arXiv:0901.3958

Does M_H < 1 TeV make sense?

The peril of quantum corrections



The unreasonable effectiveness of the standard model

Puzzle #1: Expect *New Physics* on TeV scale
to stabilize Higgs mass, solve hierarchy problem,
but no sign of flavor-changing neutral currents.
Minimal flavor violation a name, not yet an answer

Great interest in searches for
forbidden or suppressed processes

Puzzle #2: Expect *New Physics* on TeV scale
to stabilize Higgs mass, solve hierarchy problem,
but no quantitative failures of EW theory

arXiv:0907.3187

No departures
from established physics
have turned up in early running

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from established physics
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Supersymmetry is hiding very effectively

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 ** Jon Ansjon A.Tseytlin D.S.Berman Kingsley Lee	Peter Orland Petrov FADDEEV G. 't Hooft *) G.C. Rossi P.H. Damgaard E. Lirits is I. Klebanov M.A. 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.

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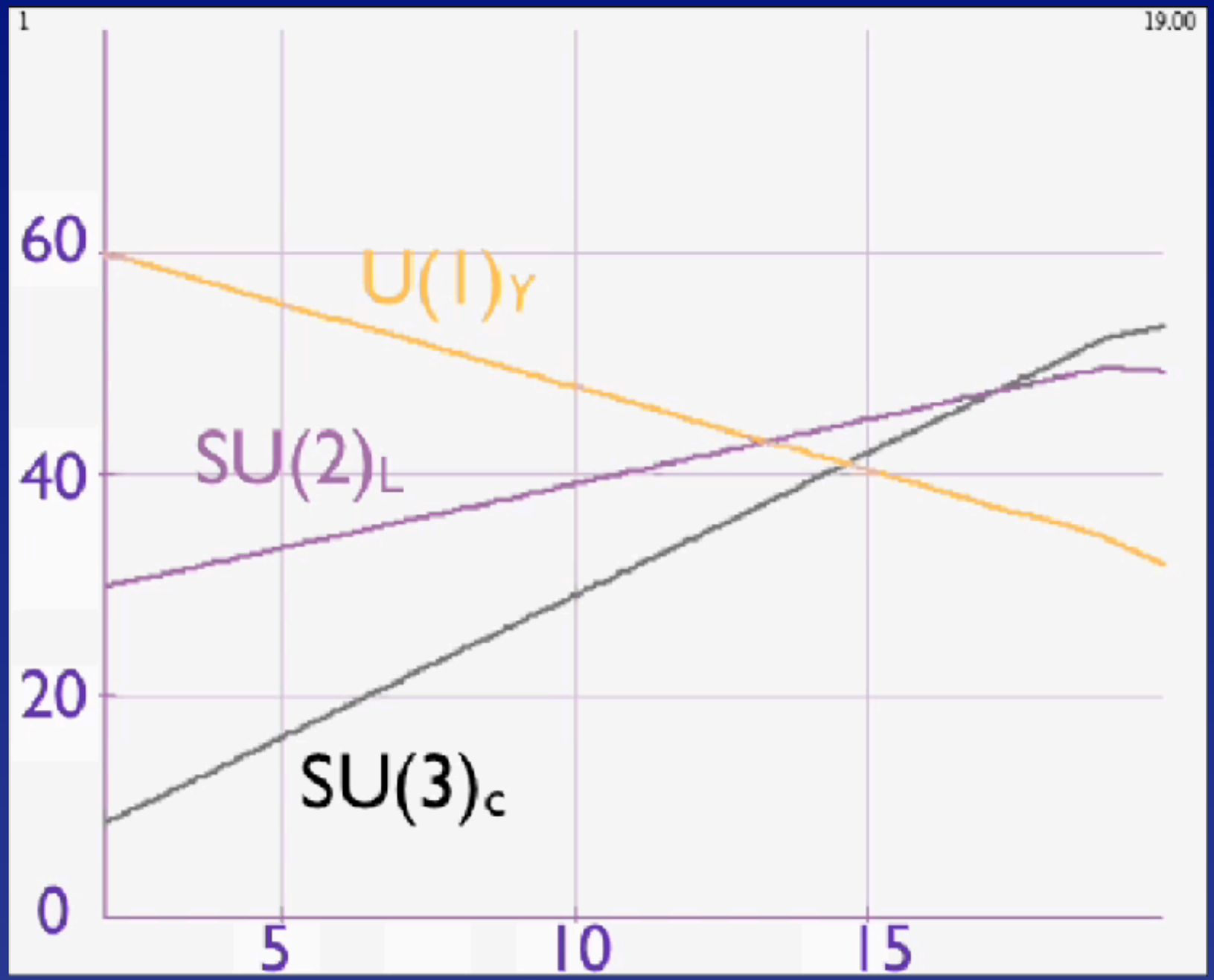
Unification of Forces?



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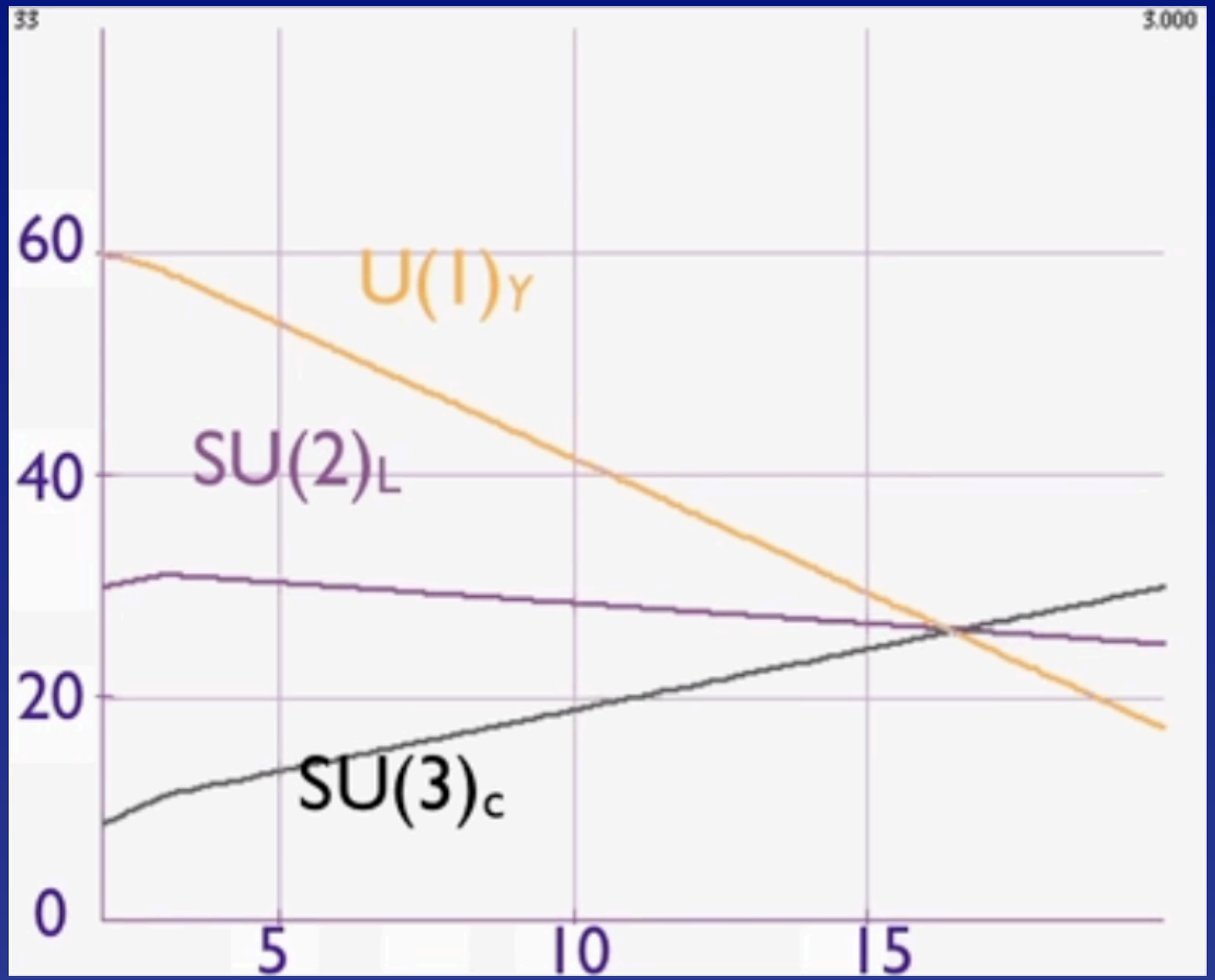
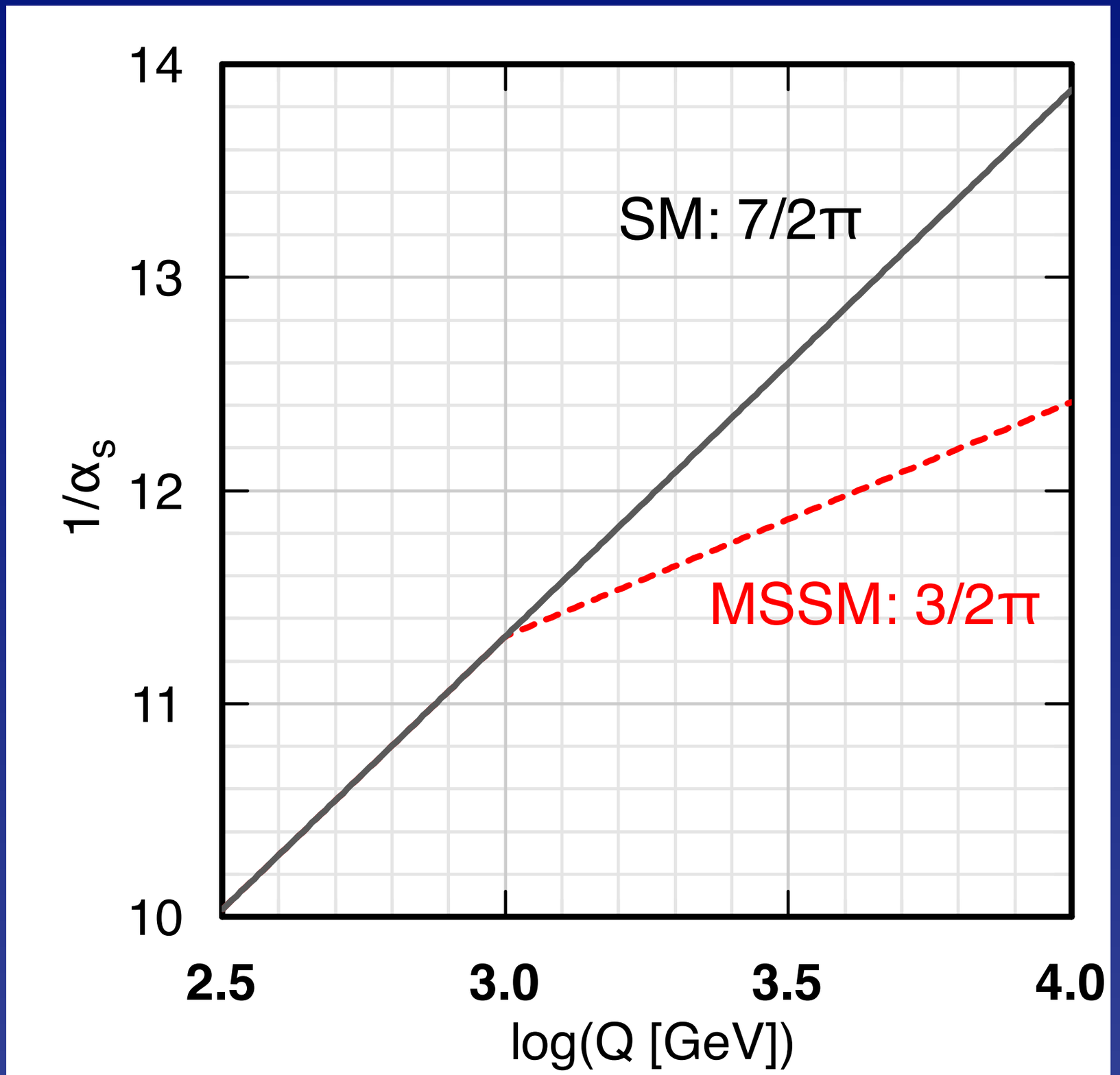


$1/\alpha$

$$\log_{10}\left(\frac{E}{1\ \mathrm{GeV}}\right)$$

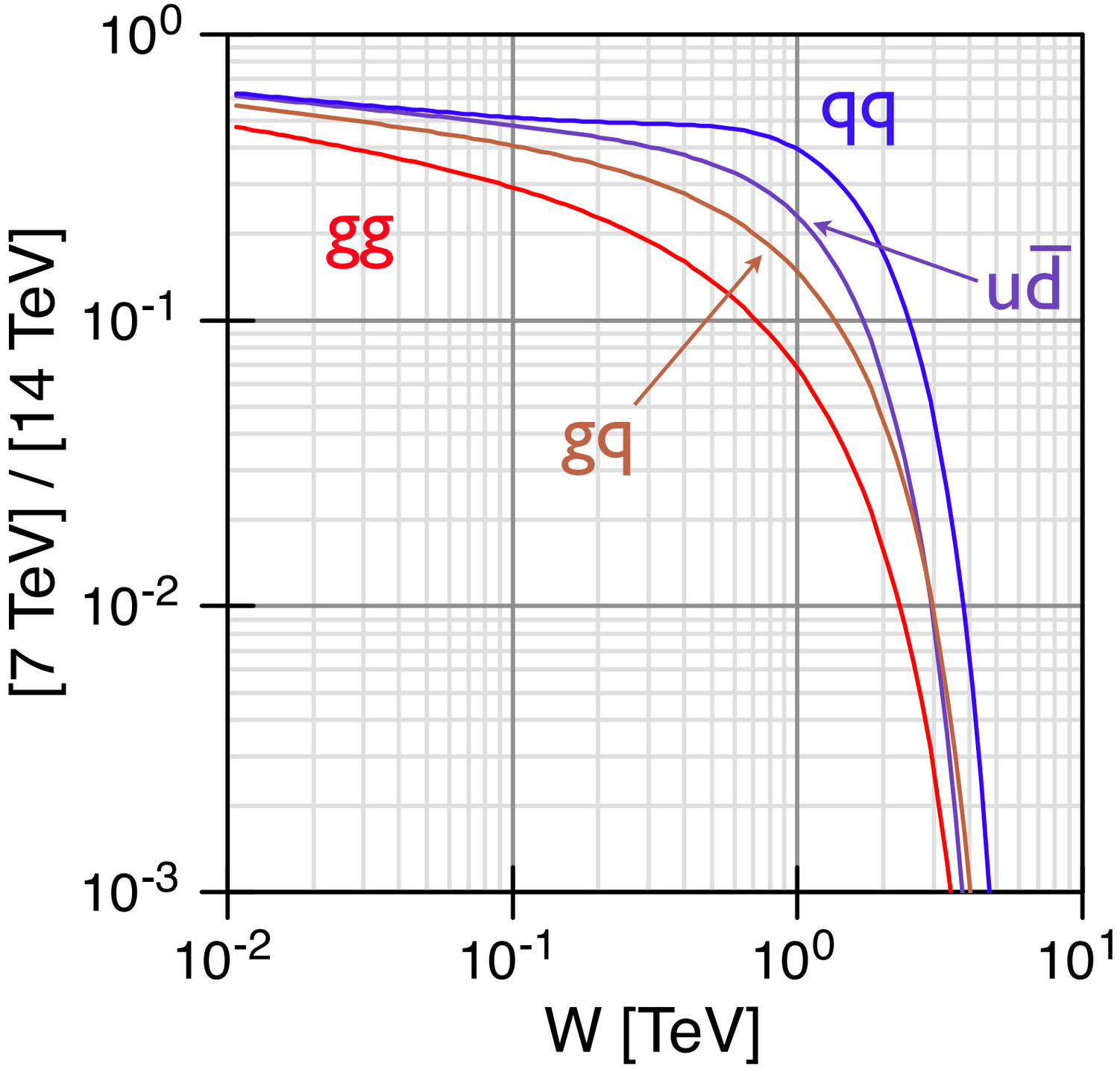
Might LHC see the change in evolution?



Wonderful progress …
… but miles to go:

Beam energy x 2
Luminosity x 100

Ratios of Parton Luminosities



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?

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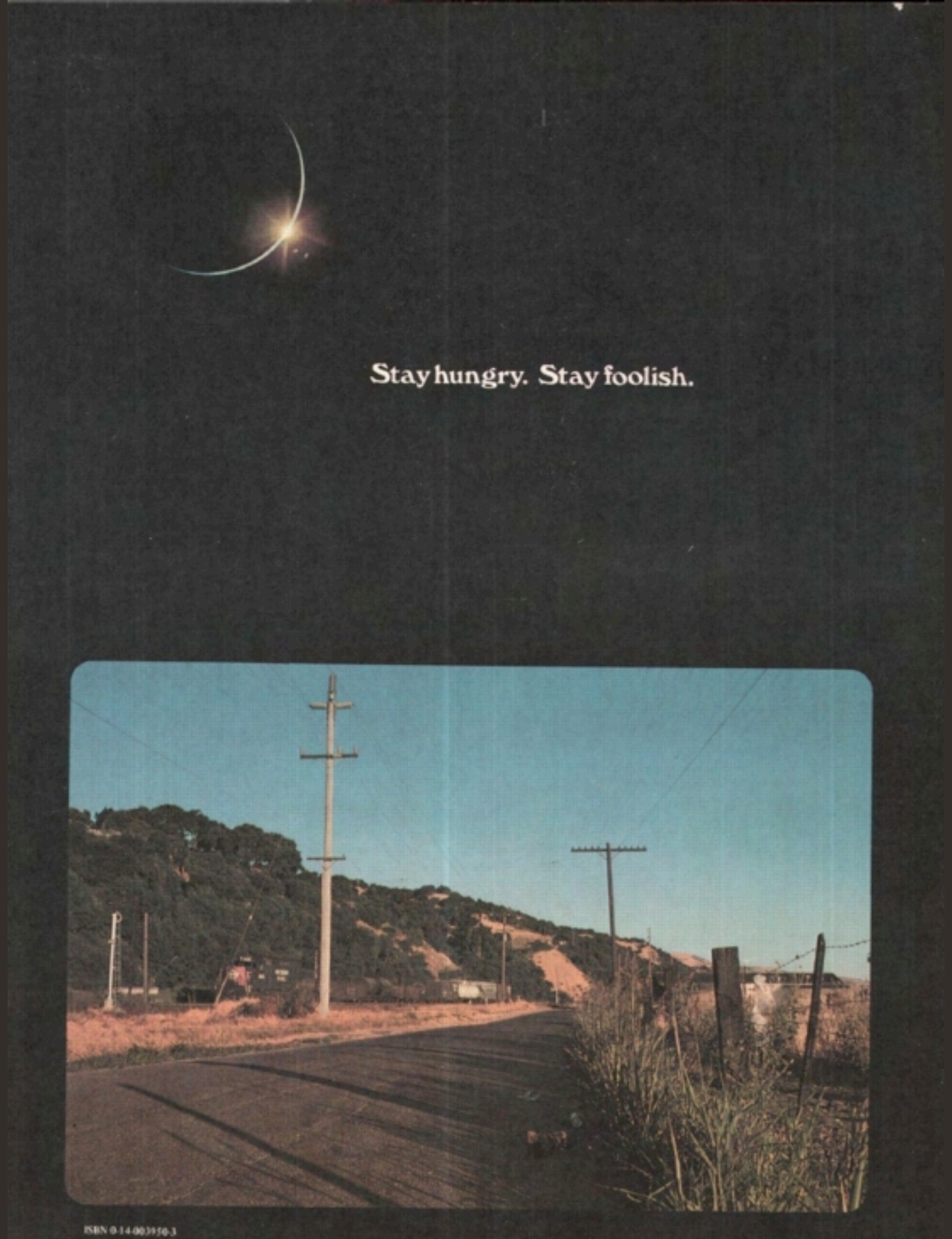
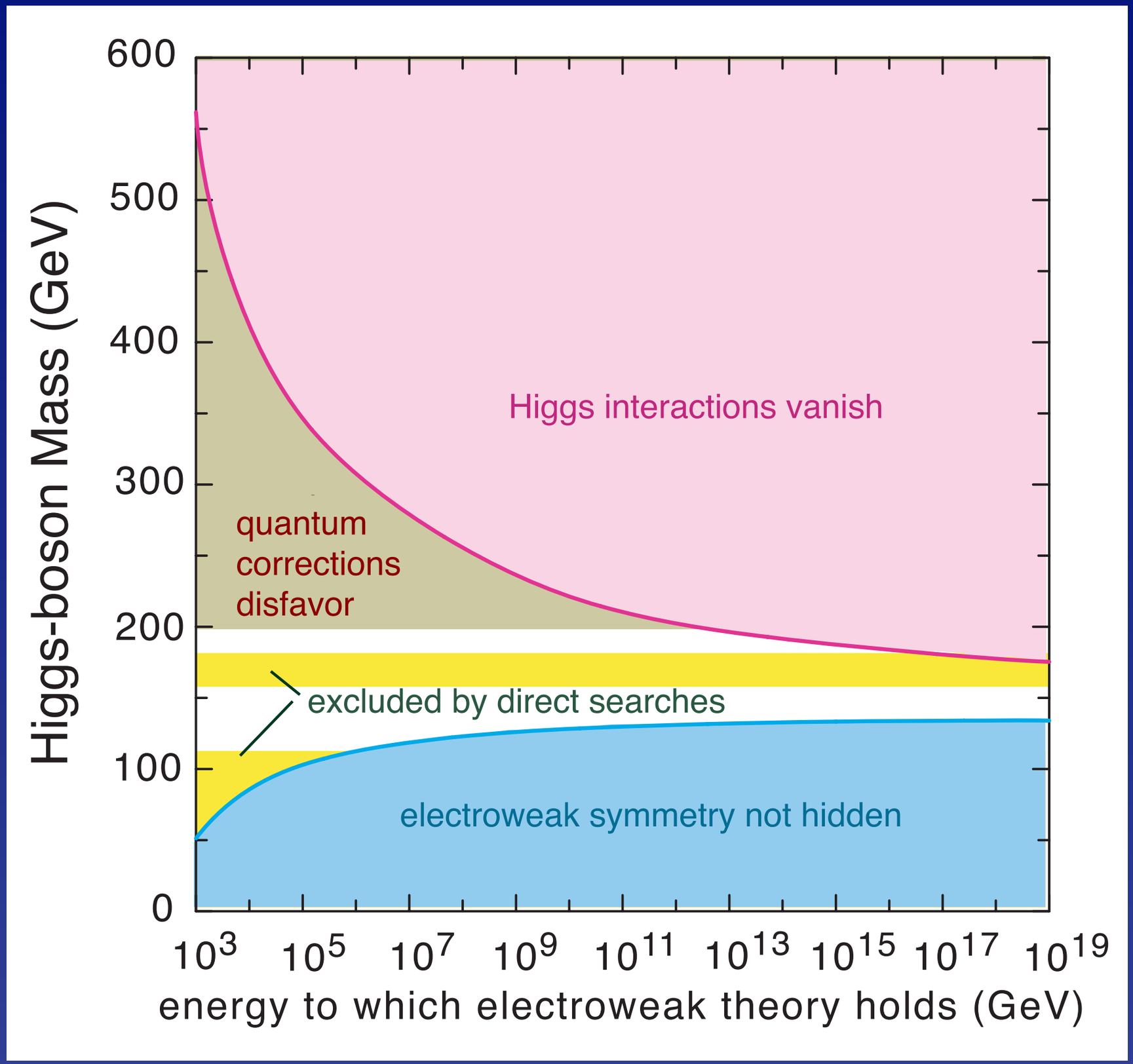
21. How are we prisoners of conventional thinking?



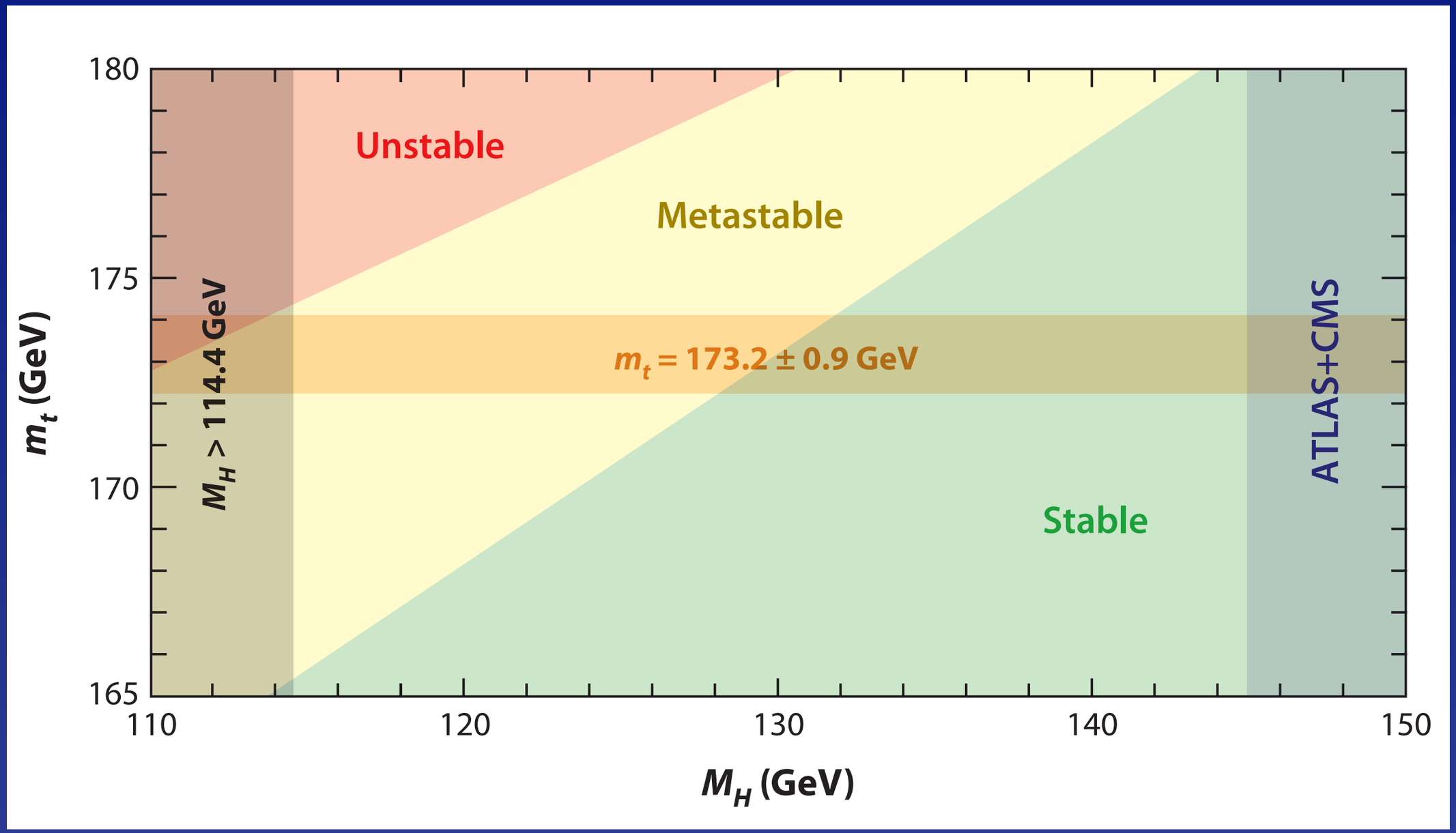
ISBN 0-14-003950-3

Stewart Brand, *The Whole Earth Catalog* (197

Where EW Theory Breaks Down



Might we live in a metastable vacuum?



$$\text{SM: BR}(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$

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

$$\text{LHCb: BR}(B_s \to \mu^+\mu^-) < 1.5 \times 10^{-8}$$