The Future of Particle Physics

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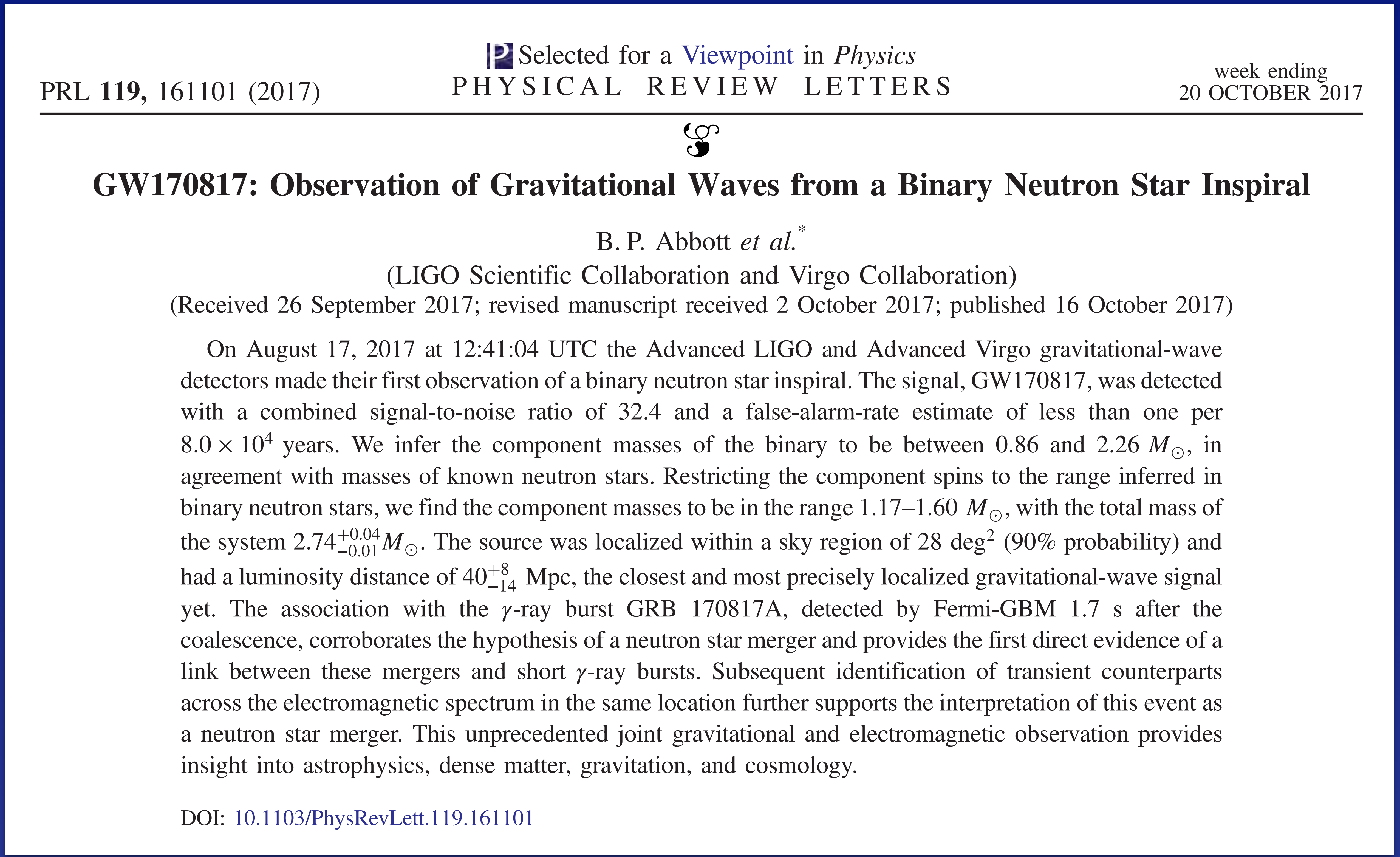
?

Physikalisches Kolloquium · Universität Heidelberg · 20.X.2017

Three Cheers for Multimessenger Astronomy!



PRL **119,** 161101 (2017) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

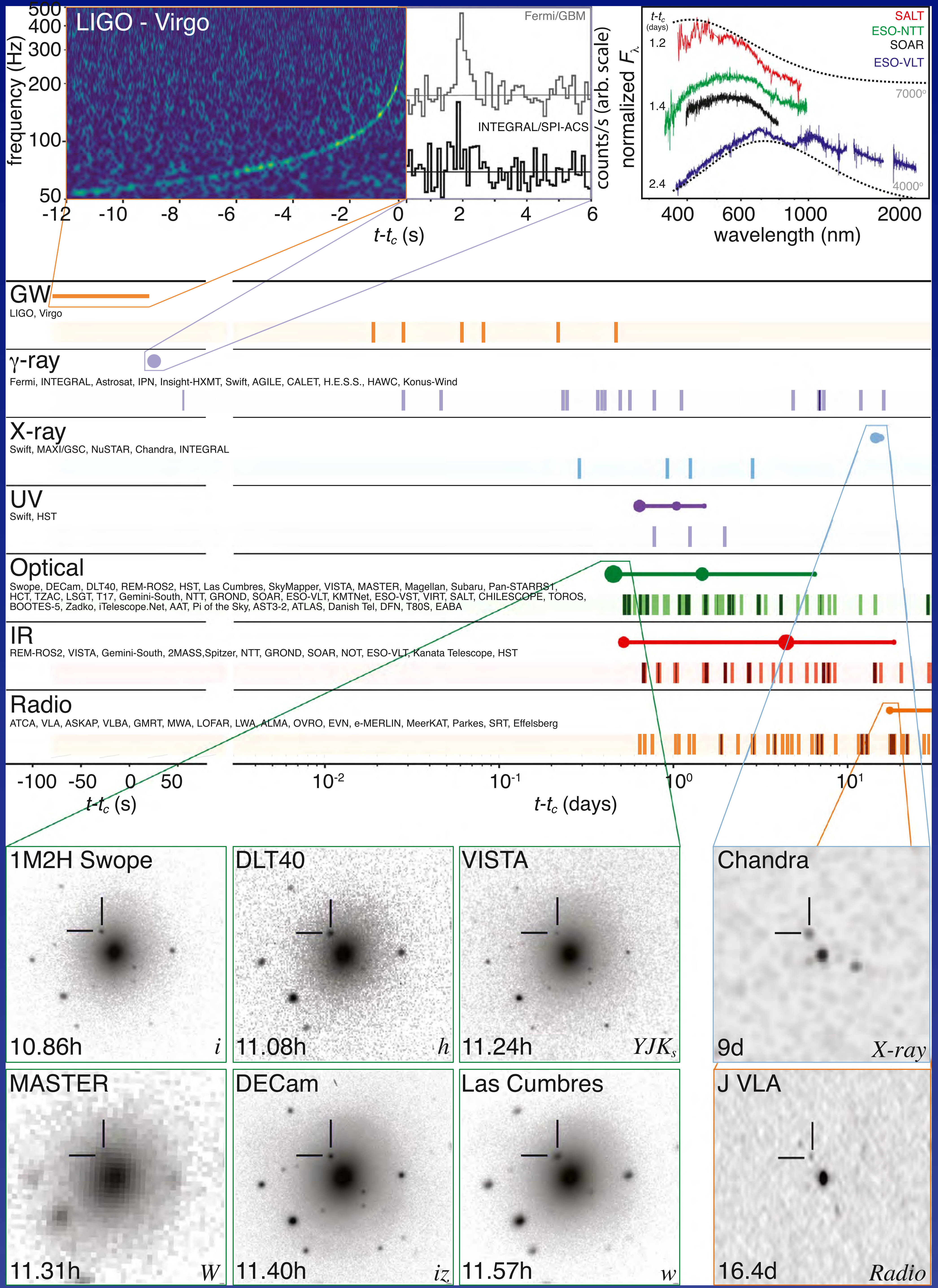
B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

DOI: 10.1103/PhysRevLett.119.161101



GW + prompt short GRB, EM transients: test gravity theories, H_0 determination, heavy-element production (no UHE CRs, ν)


Fermilab's Greatest Hits @DPF2017

50 years ago: How little we knew

Problems of High-Energy Physics (NAL Design Report, January 1968)

We would like to have answers to many questions. Among them are the following:

Which, if any, of the particles that have so far been discovered, is, in fact, elementary, and is there any validity in the concept of "elementary" particles?

What new particles can be made at energies that have not yet been reached? Is there some set of building blocks that is still more fundamental than the neutron and the proton?

Is there a law that correctly predicts the existence and nature of all the particles, and if so, what is that law?

Will the characteristics of some of the very short-lived particles appear to be different when they are produced at such higher velocities that they no longer spend their entire lives within the strong influence of the particle from which they are produced?

Do new symmetries appear or old ones disappear for high momentum-transfer events?

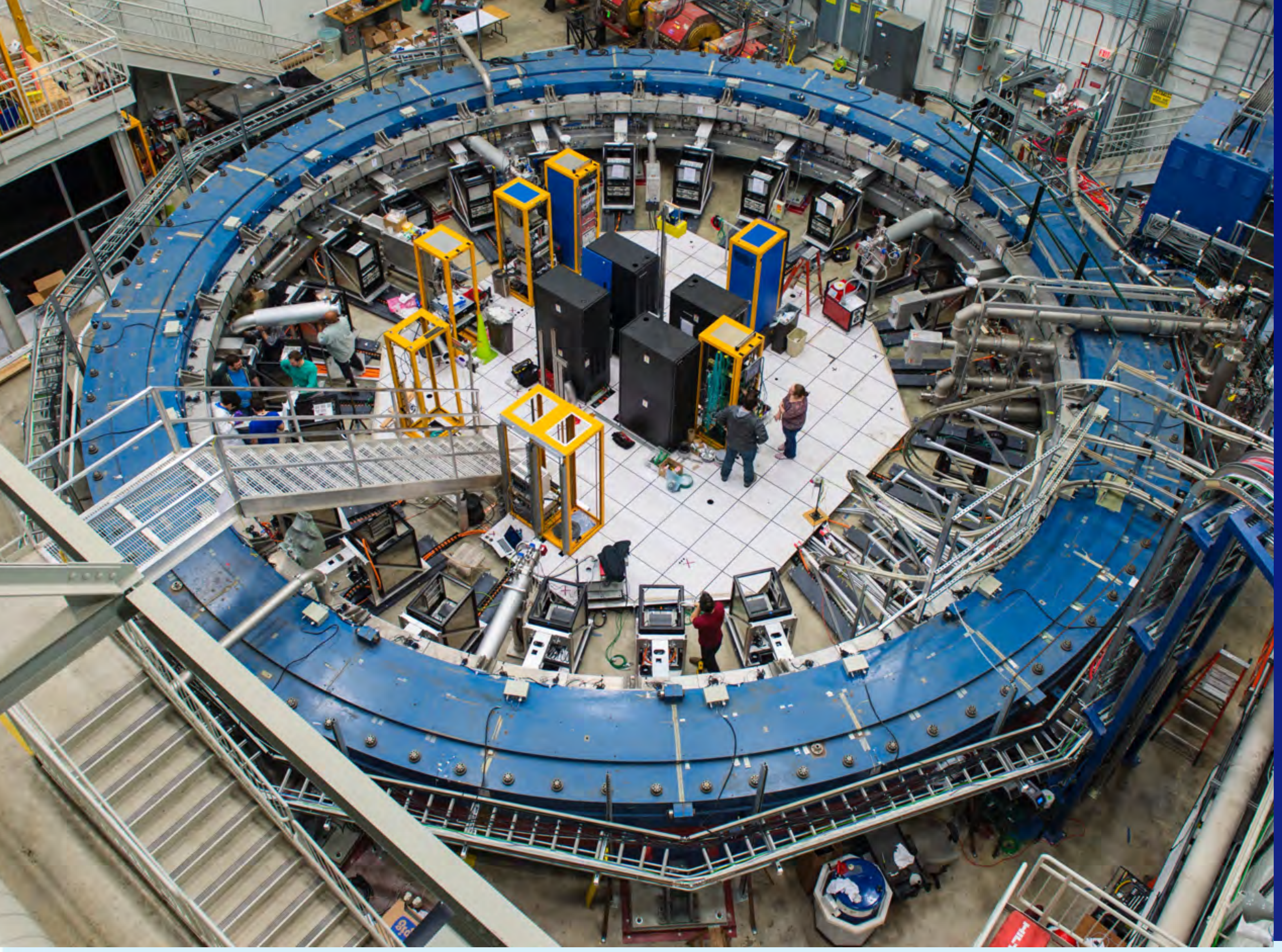
What is the connection, if any, of electromagnetism and strong interactions?

Do the laws of electromagnetic radiation, which are now known to hold over an enormous range of lengths and frequencies, continue to hold in the wavelength domain characteristic of the subnuclear particles?

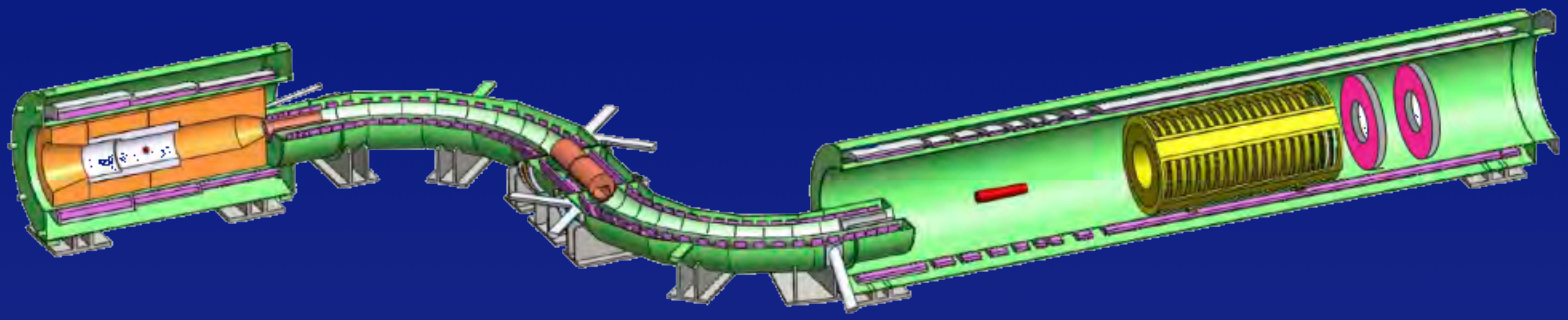
What is the connection between the weak interaction that is associated with the massless neutrino and the strong one that acts between neutron and proton?

Is there some new particle underlying the action of the "weak" forces, just as, in the case of the nuclear force, there are mesons, and, in the case of the electromagnetic force, there are photons? If there is not, why not?

In more technical terms: Is local field theory valid? A failure in locality may imply a failure in our concept of space. What are the fields relevant to a correct local field theory? What are the form factors of the particles? What exactly is the explanation of the electromagnetic mass difference? Do "weak" interactions become strong at sufficiently small distances? Is the Pomeranchuk theorem true? Do the total cross sections become constant at high energy? Will new symmetries appear, or old ones disappear, at higher energy?



Next for Fermilab: CMS, g–2, μ2e, DUNE, astroparticle

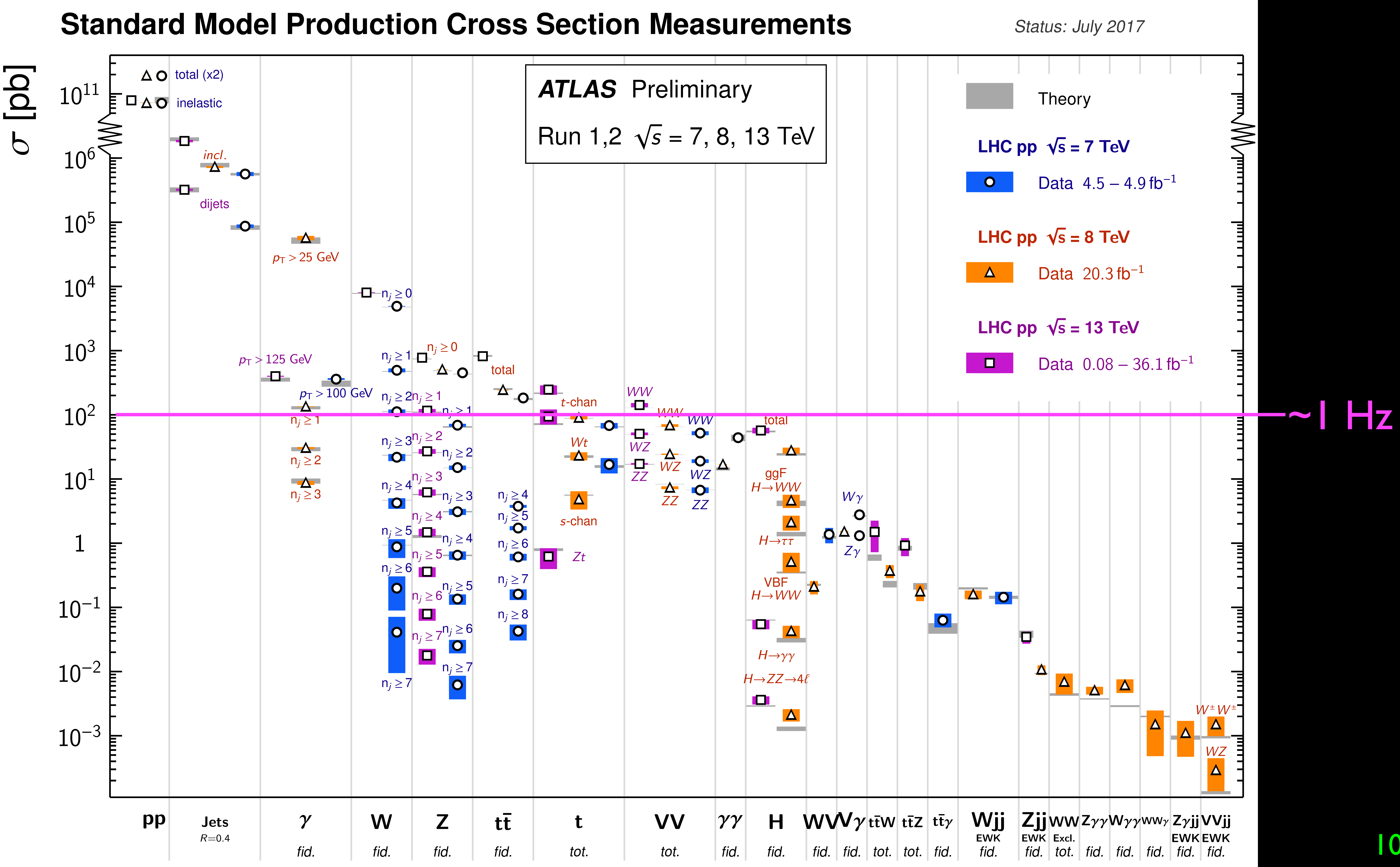


DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Large Hadron Collider

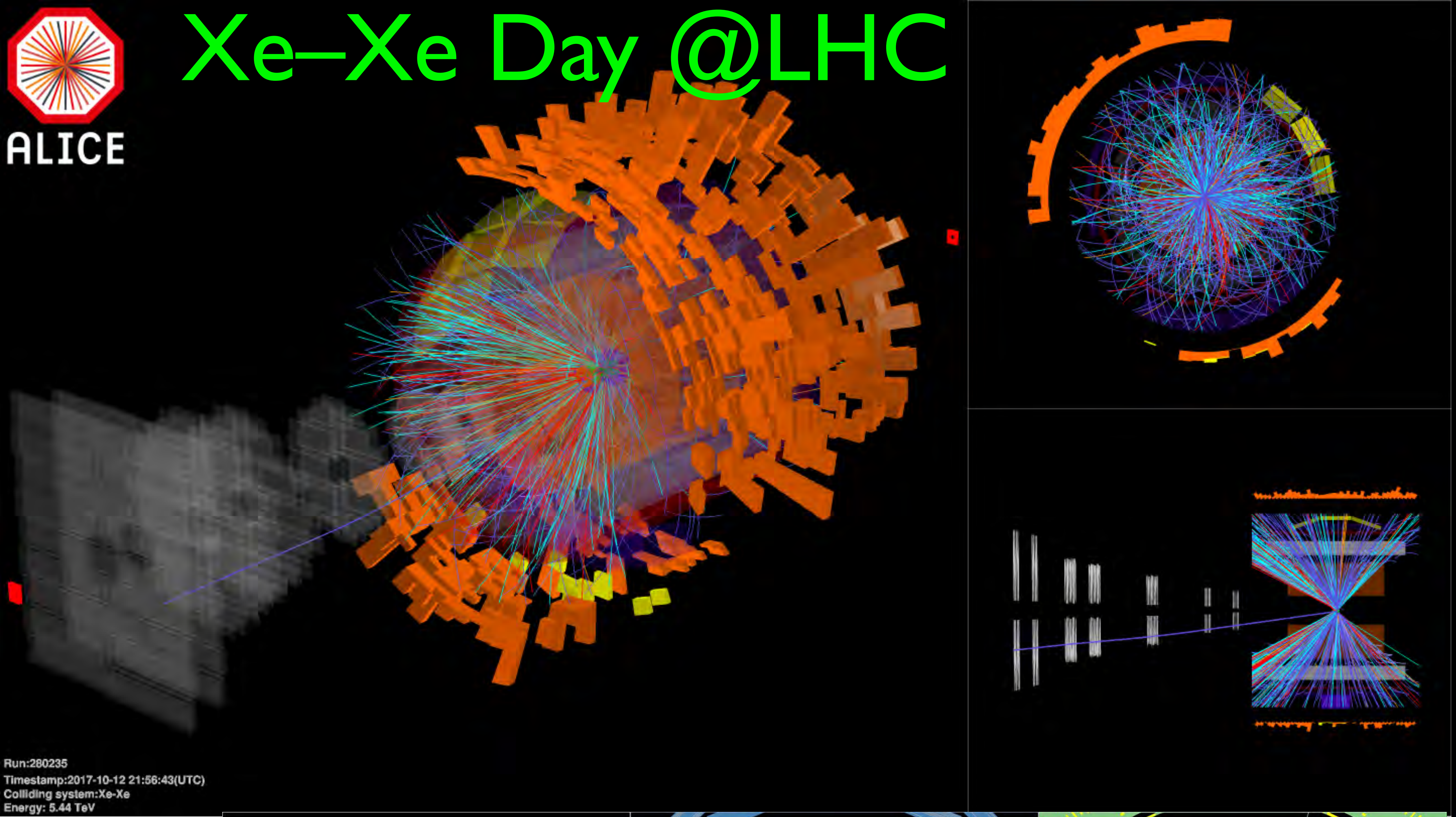
Very-High-Rate Experiments

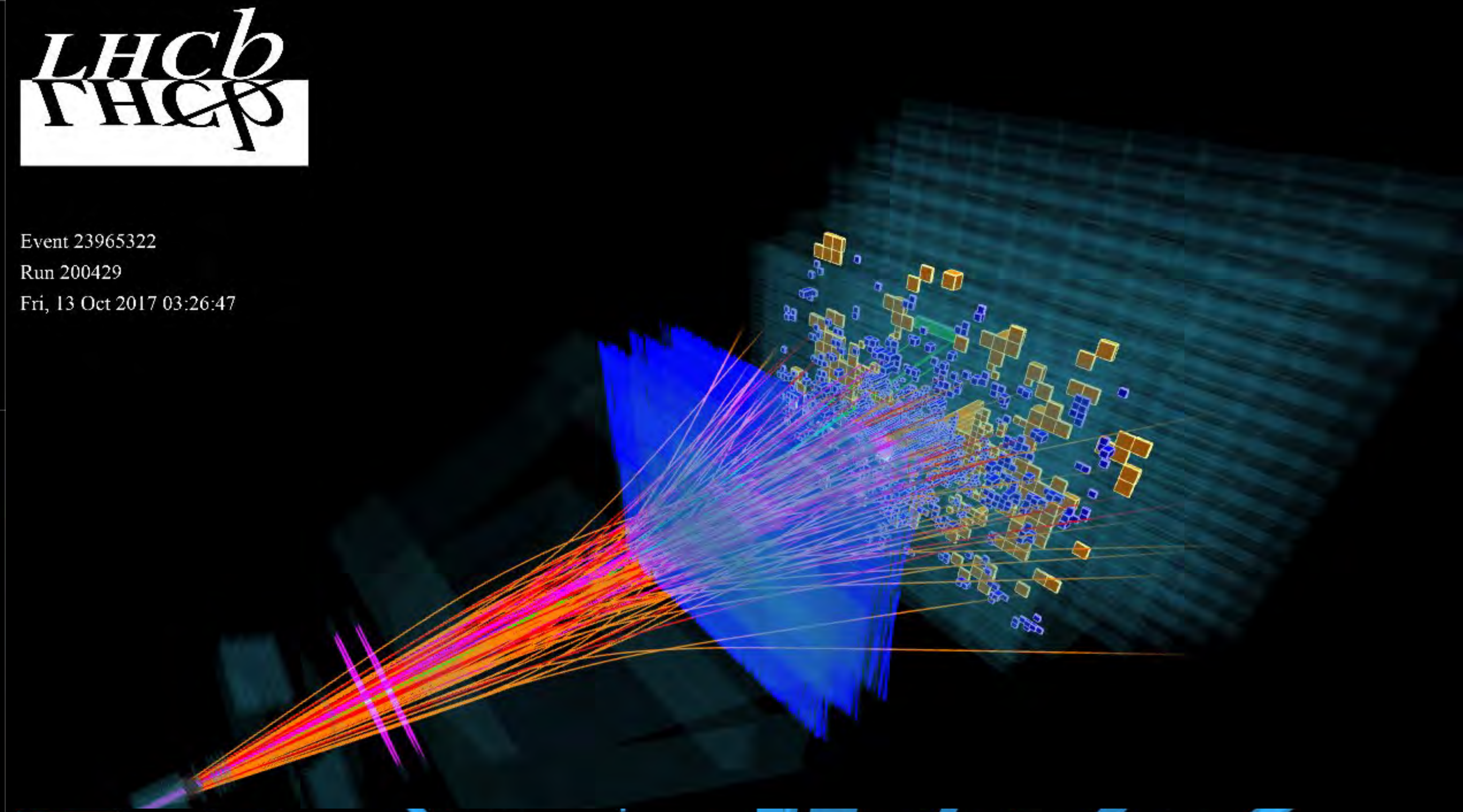
ATLAS

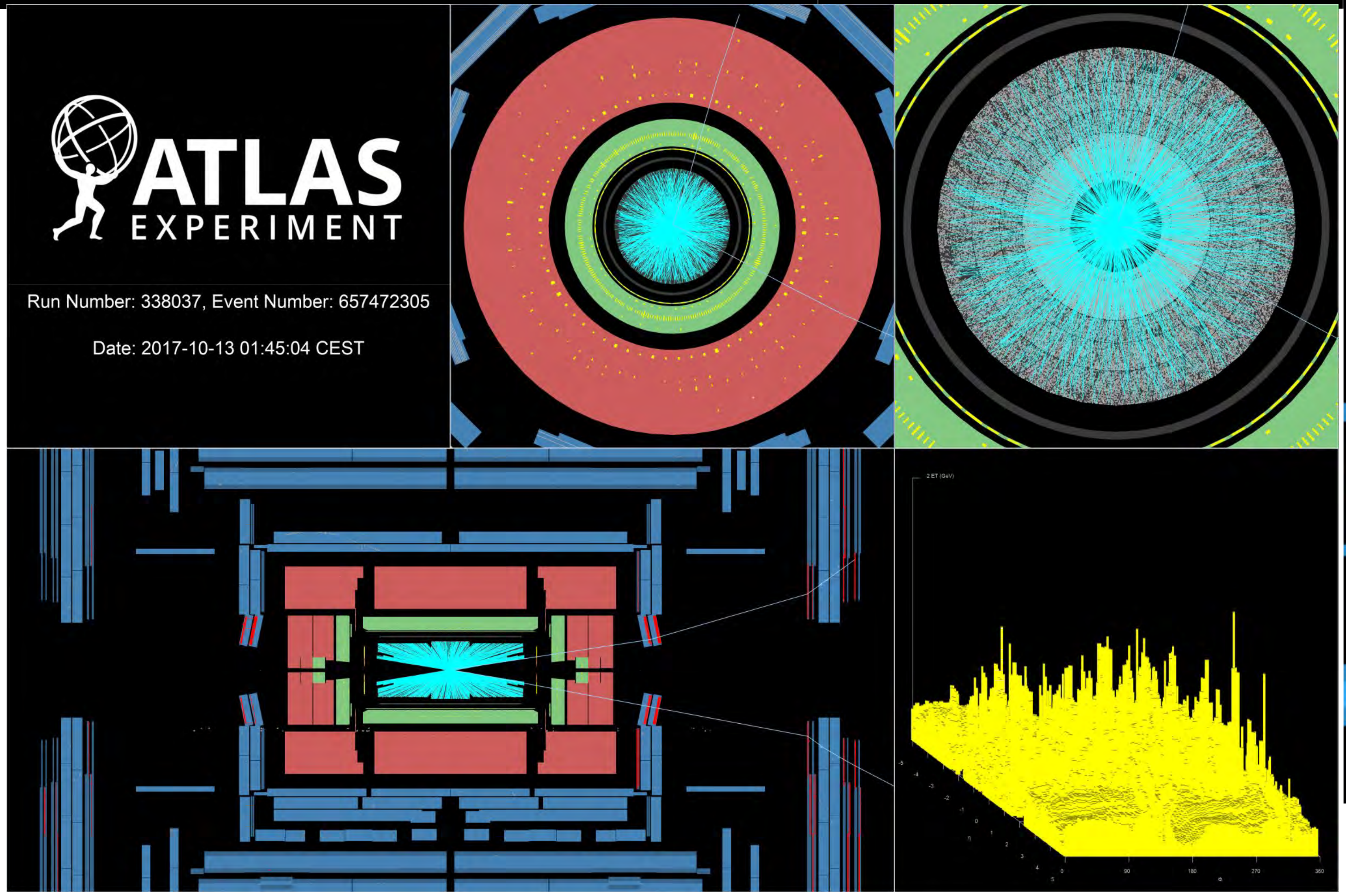


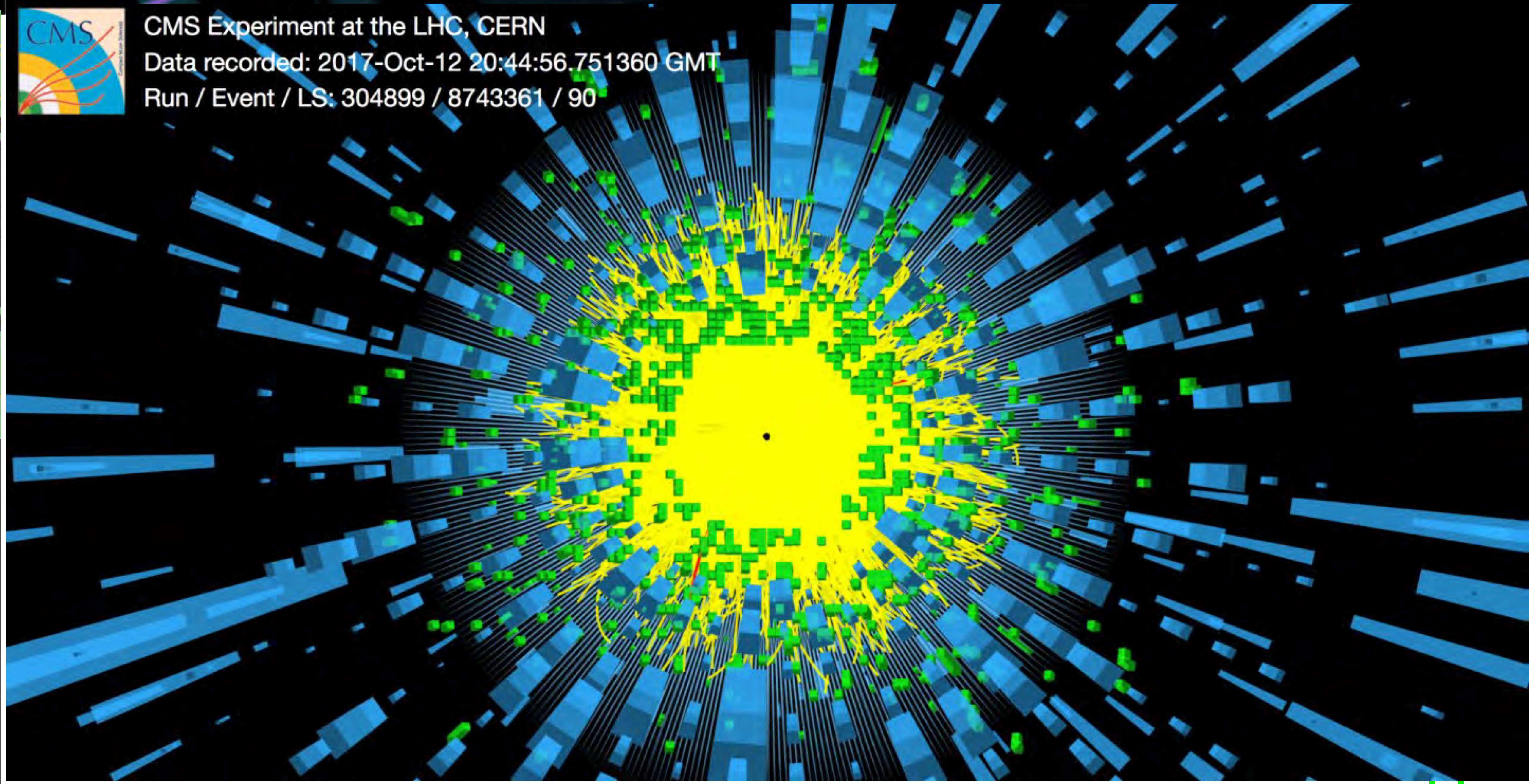
Standard Model Production Cross Section Measurements
Status: July 2017
ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.9 fb⁻¹
LHC pp √s = 8 TeV
Data 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 0.08 – 36.1 fb⁻¹
σ [pb]
~1 Hz
pp
Jets R=0.4
γ fid.
W fid.
Z fid.
tt̄ fid.
t tot.
VV tot.
γγ fid.
H fid.

Xe–Xe Day @LHC


ALICE
Run:280235
Timestamp:2017-10-12 21:56:43(UTC)
Colliding system:Xe-Xe
Energy: 5.44 TeV


LHCb
Event 23965322
Run 200429
Fri, 13 Oct 2017 03:26:47


ATLAS
EXPERIMENT
Run Number: 338037, Event Number: 657472305
Date: 2017-10-13 01:45:04 CEST


CMS
CMS Experiment at the LHC, CERN
Data recorded: 2017-Oct-12 20:44:56.751360 GMT
Run / Event / LS: 304899 / 8743361 / 90

To-do / wish list for particle physics & friends, from 2005

In a decade or two, we can hope to . . .

Understand electroweak symmetry breaking
Observe the Higgs boson
Measure neutrino masses and mixings
Establish Majorana neutrinos ($\beta\beta_{0\nu}$)
Thoroughly study CP violation in B decay
Exploit rare decays (K, D, . . .)
Observe n EDM, pursue e^- EDM
Use top as a tool
Observe new phases of matter
Understand hadron structure quantitatively
Uncover QCD's full implications
Observe proton decay
Understand the baryon excess
Catalogue matter & energy of universe
Measure dark energy equation of state
Search for new macroscopic forces
Determine GUT symmetry

Detect neutrinos from the universe
Learn how to quantize gravity
Learn why empty space is nearly weightless
Test the inflation hypothesis
Understand discrete symmetry violation
Resolve the hierarchy problem
Discover new gauge forces
Directly detect dark-matter particles
Explore extra spatial dimensions
Understand origin of large-scale structure
Observe gravitational radiation
Solve the strong CP problem
Learn whether supersymmetry is TeV-scale
Seek TeV dynamical symmetry breaking
Search for new strong dynamics
Explain the highest-energy cosmic rays
Formulate problem of identity

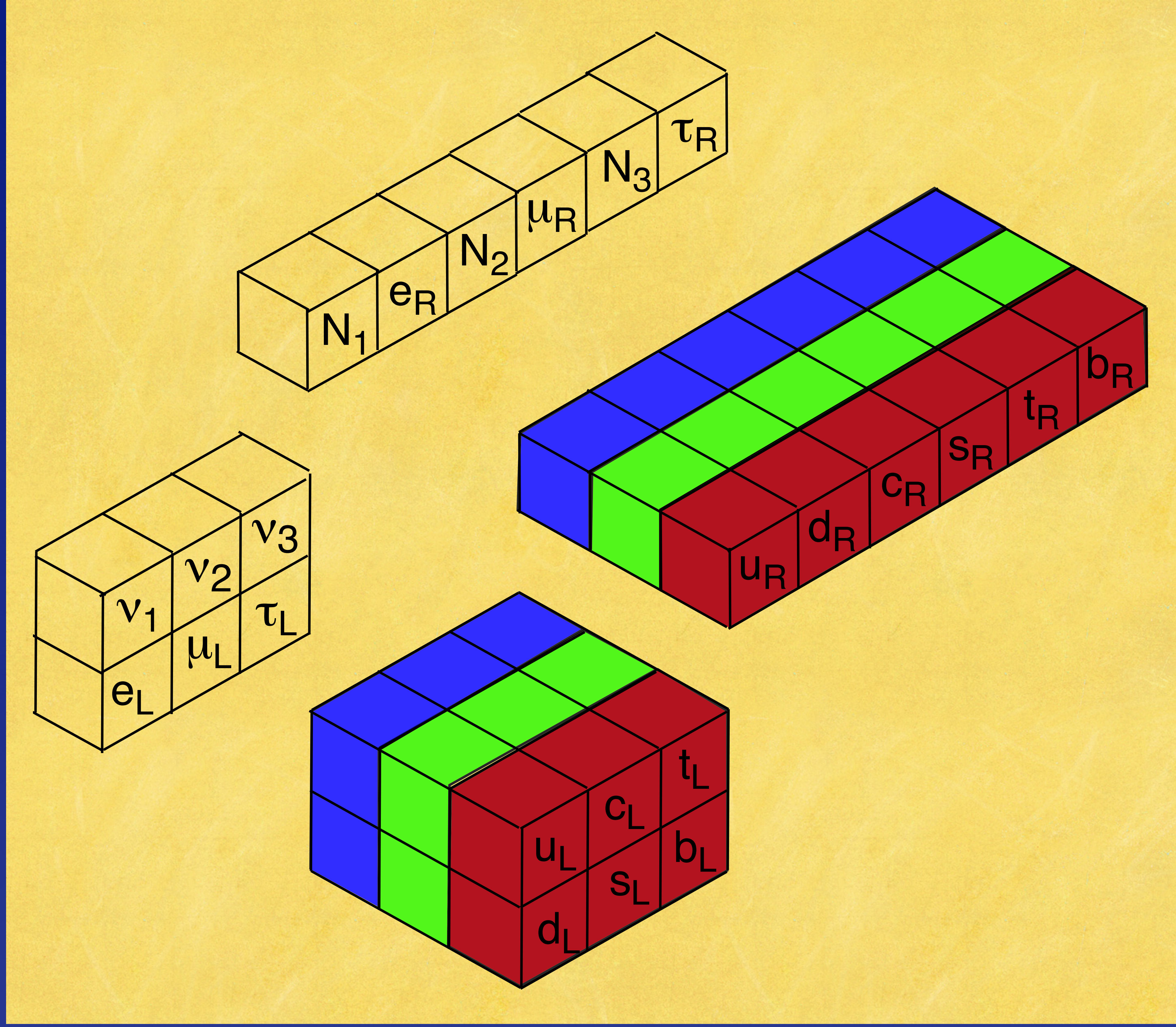
. . .

. . . learn the right questions to ask

. . . and rewrite the textbooks!

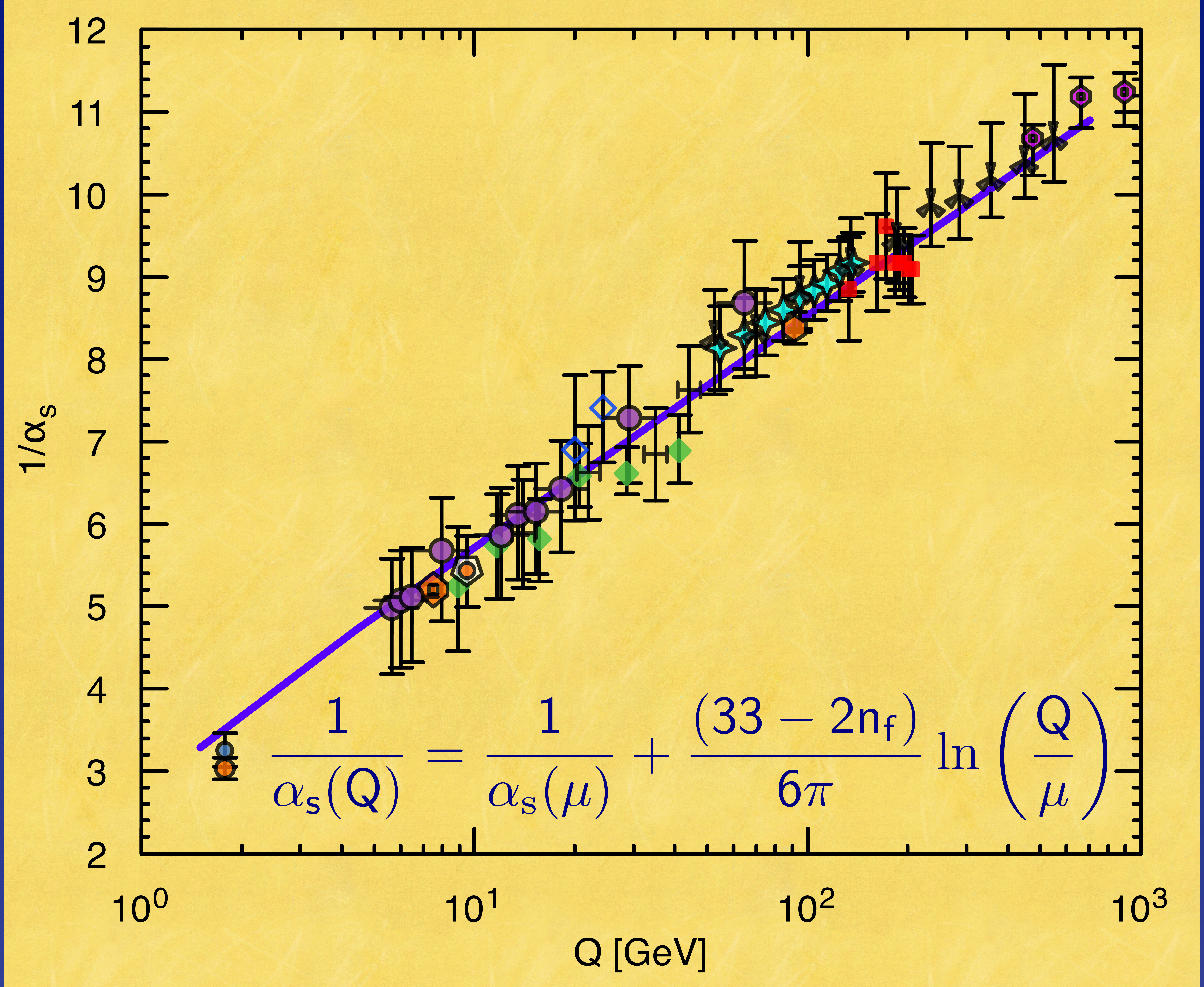
Before LHC

Two then-new Laws of Nature + pointlike *quarks* & *leptons*



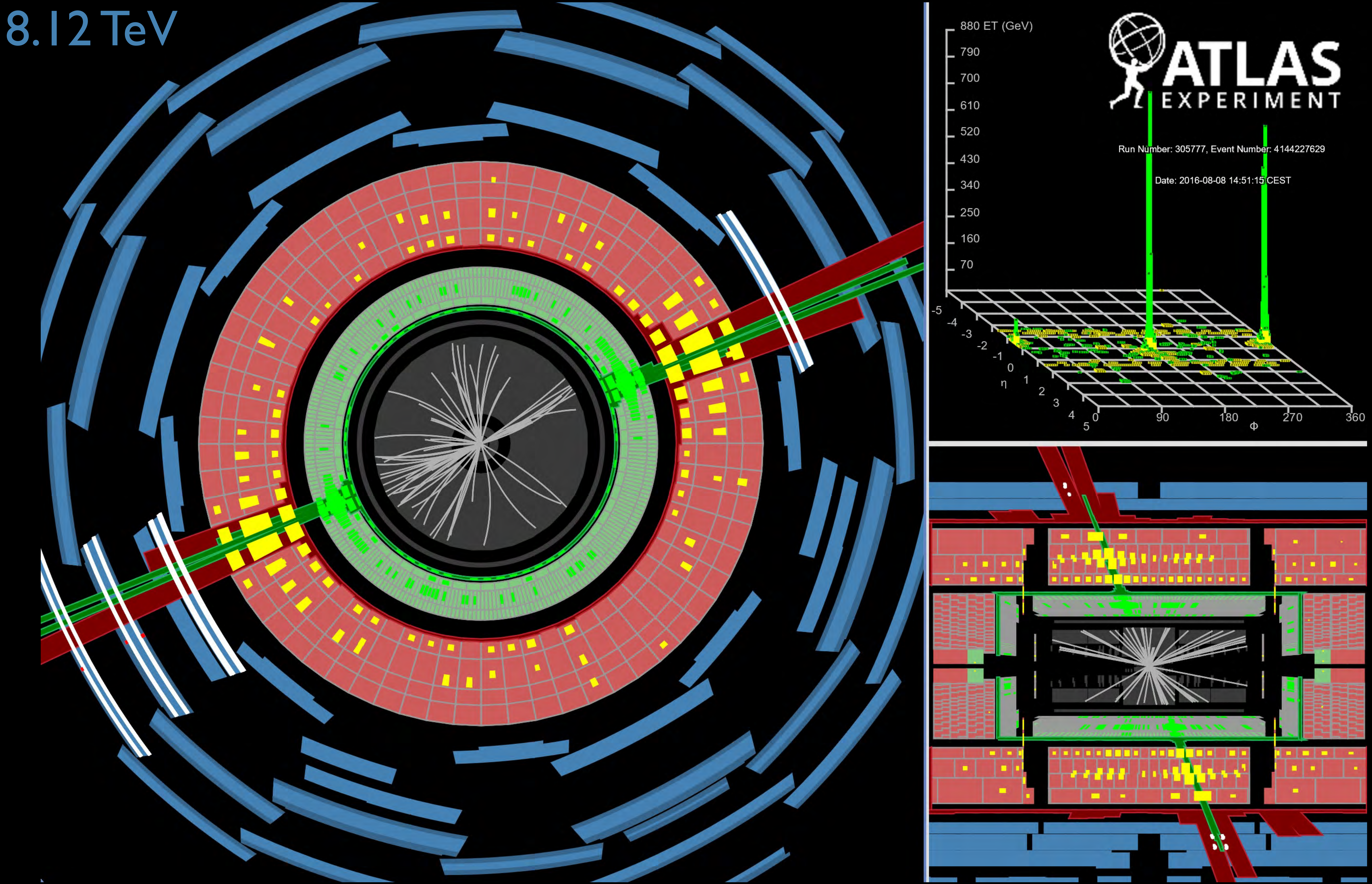
Interactions: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries

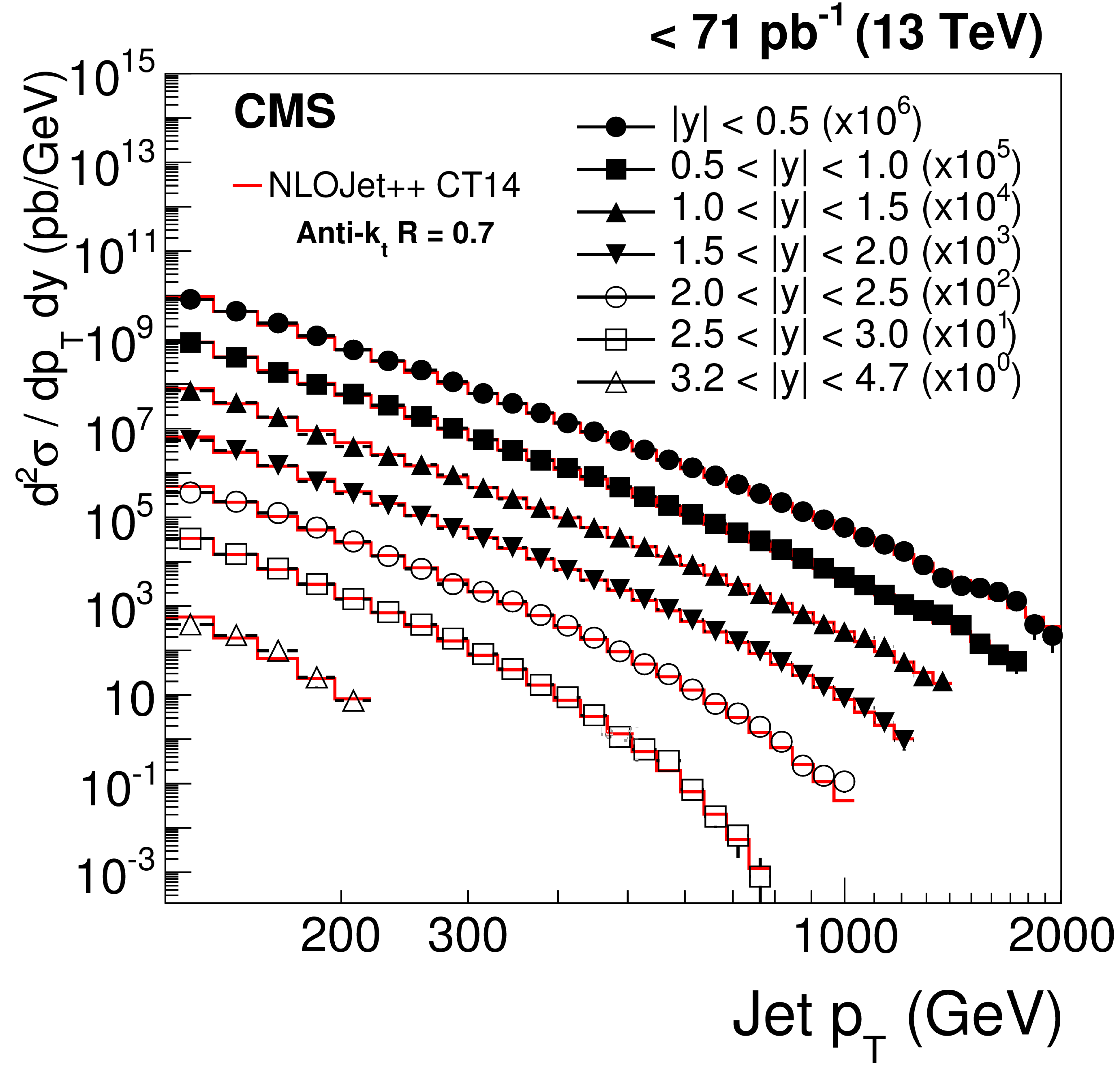
Antiscreening evolution of the strong coupling "constant"



The World's Most Powerful Microscopes

nanonanophysics




< 71 pb-1 (13 TeV)
CMS
NLOJet++ CT14
Anti-kt R = 0.7
|y| < 0.5 (x10^6)
0.5 < |y| < 1.0 (x10^5)
1.0 < |y| < 1.5 (x10^4)
1.5 < |y| < 2.0 (x10^3)
2.0 < |y| < 2.5 (x10^2)
2.5 < |y| < 3.0 (x10^1)
3.2 < |y| < 4.7 (x10^0)
d2σ / dpT dy (pb/GeV)
Jet pT (GeV)
200
300
1000
2000

sum of parts

rest energy

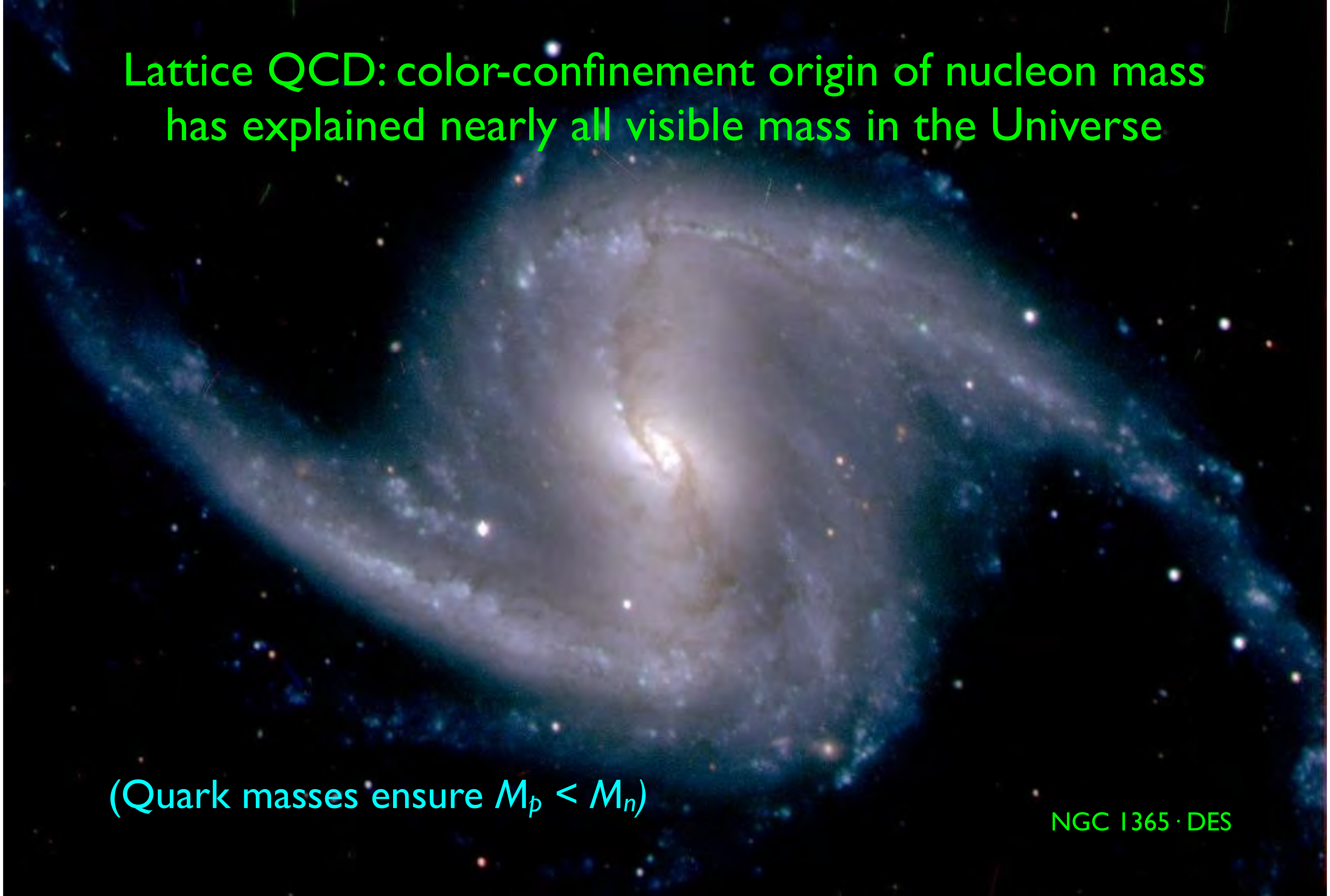
Nucleon mass (~940 MeV): exemplar of $m = E_0/c^2$

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: color-confinement origin of nucleon mass has explained nearly all visible mass in the Universe



(Quark masses ensure $M_p < M_n$)

NGC 1365 · DES

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?

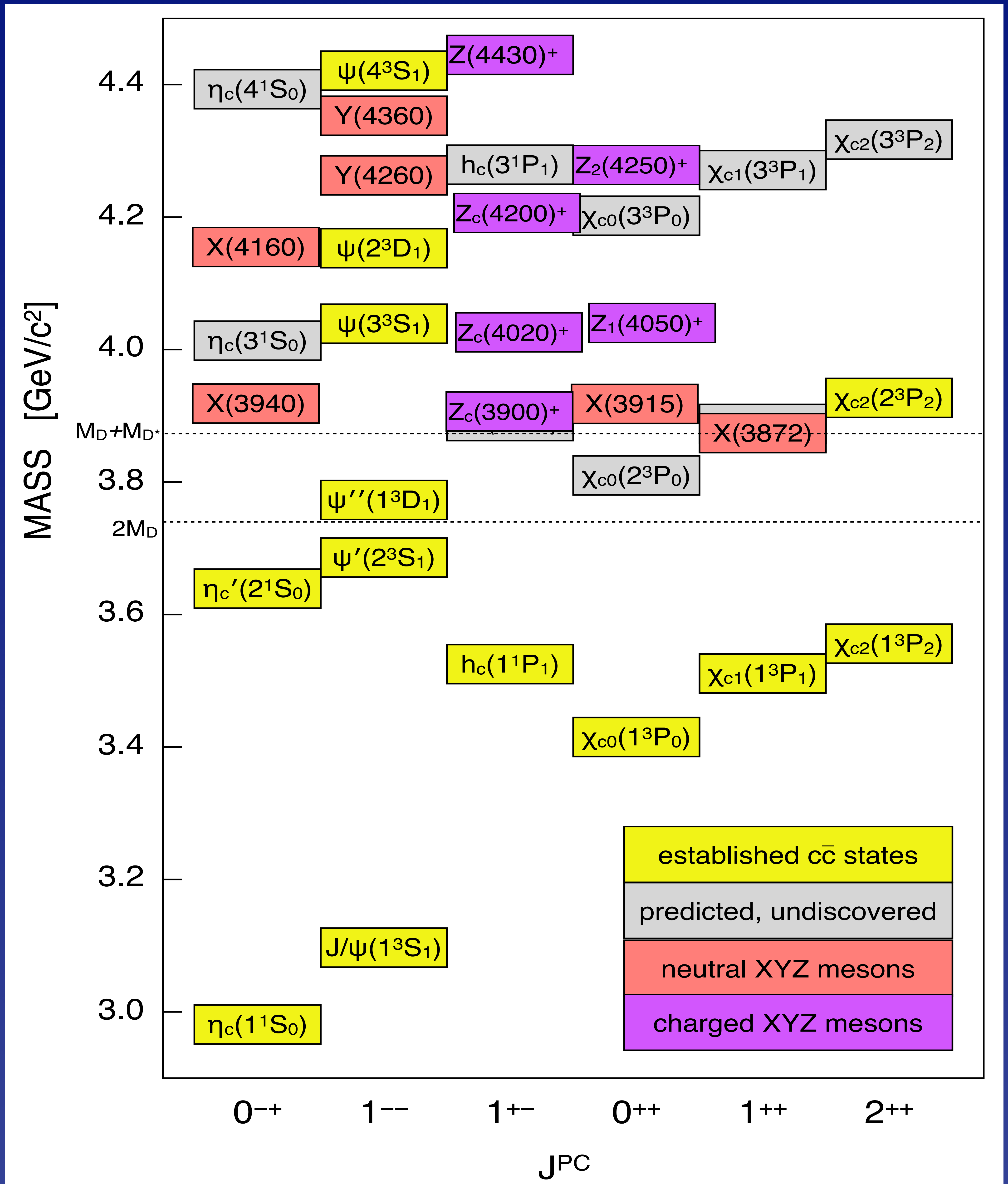
High density of few-GeV partons … thermalization?

Long-range correlations in y?

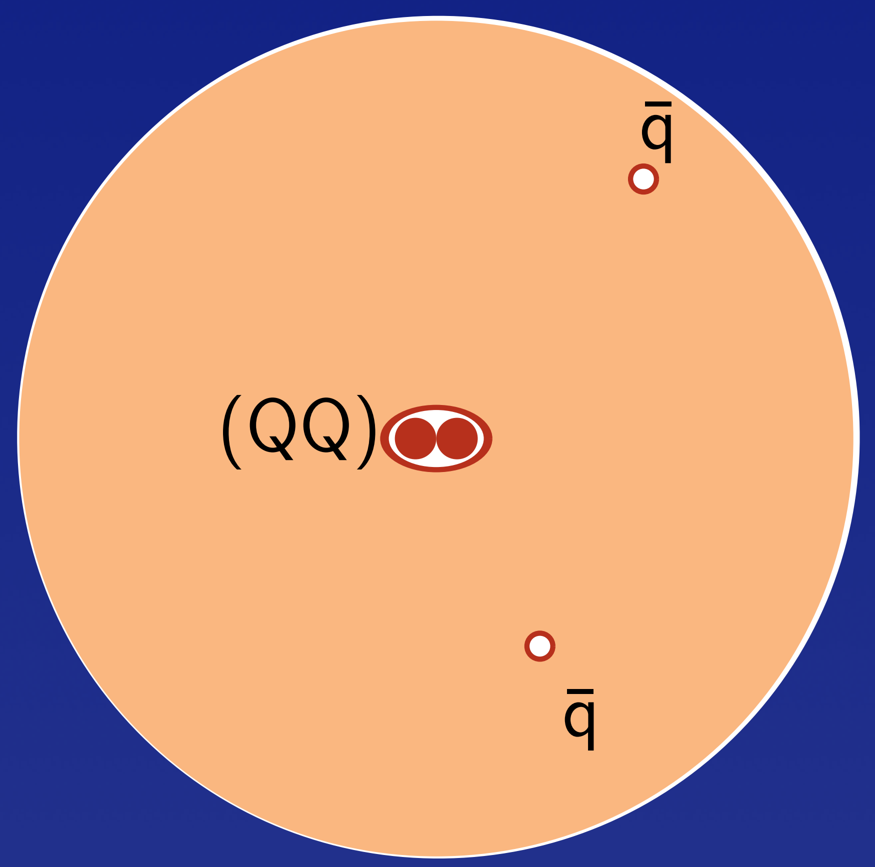
Unusual event structures …

Look at events in informative coordinates.
More is to be learned from the river of events than from a few specimens!

New spectroscopy of quarkonium–associated states

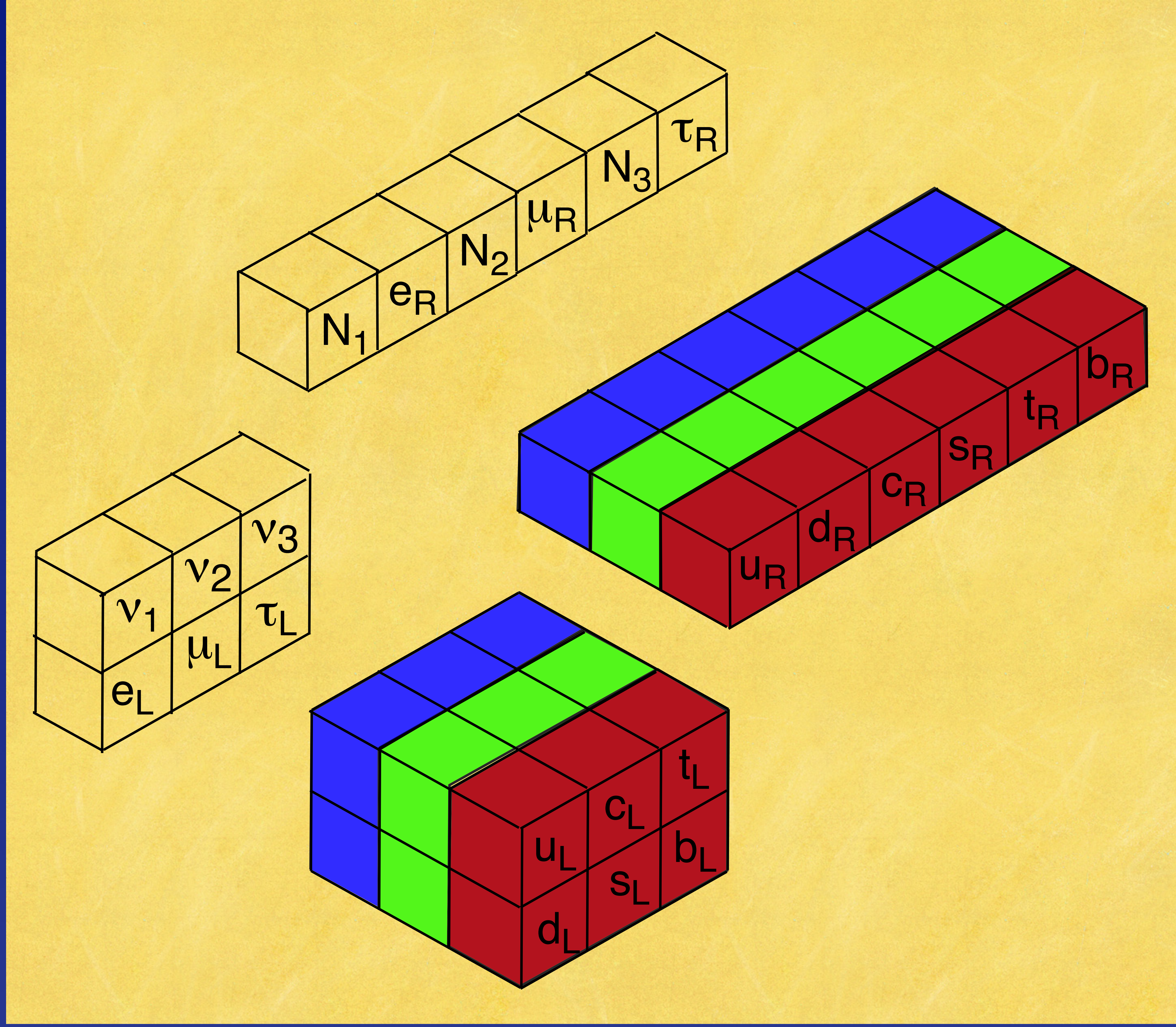


Stable doubly heavy tetraquark mesons



Eichten & CQ, PRL

Electroweak Symmetry Breaking



$U(1)_{EM}$

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

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,

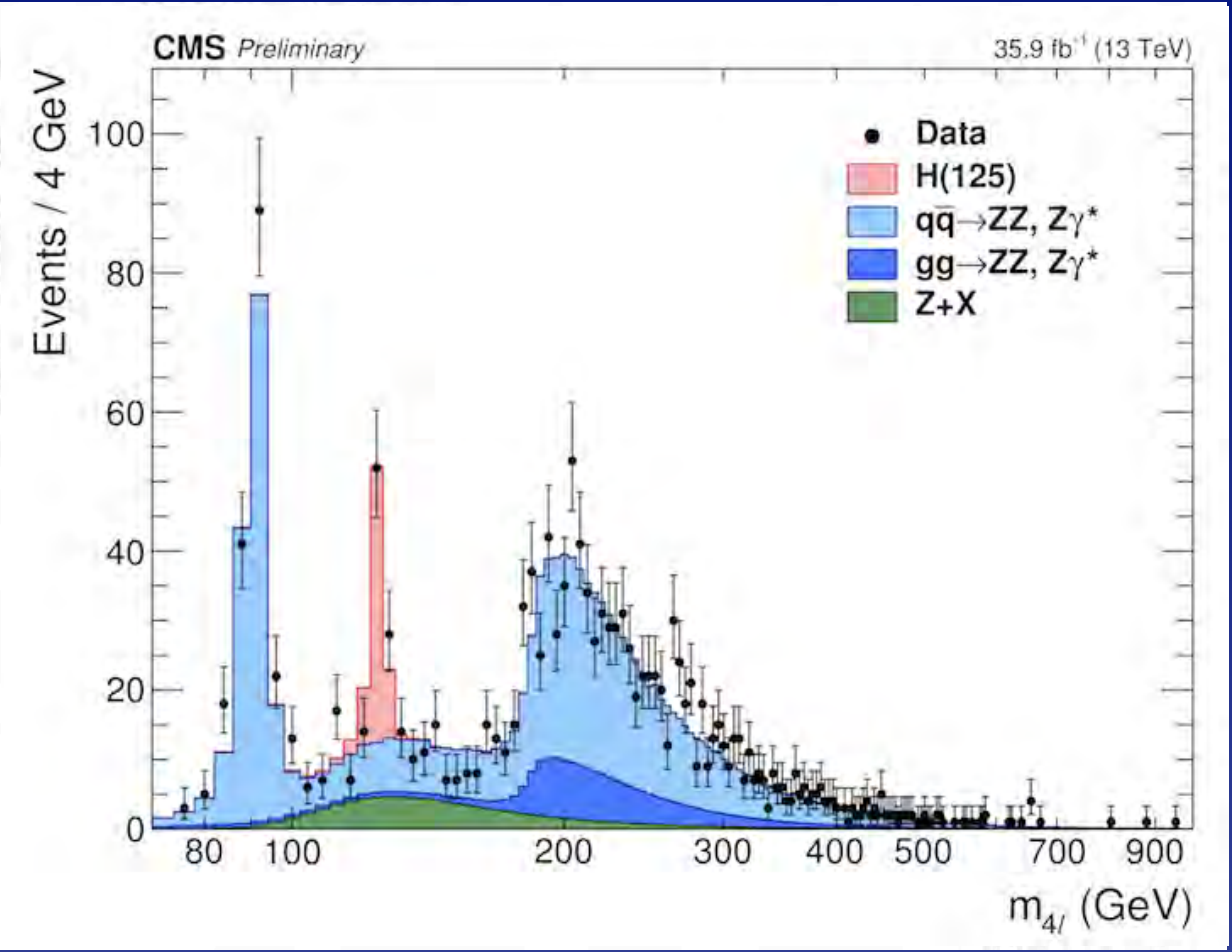
provided $\boxed{M_H \le (8\pi\sqrt{2}/3G_F)^{1/2} \approx 1\text{ TeV}}$

If bound is respected, perturbation theory is everywhere" reliable

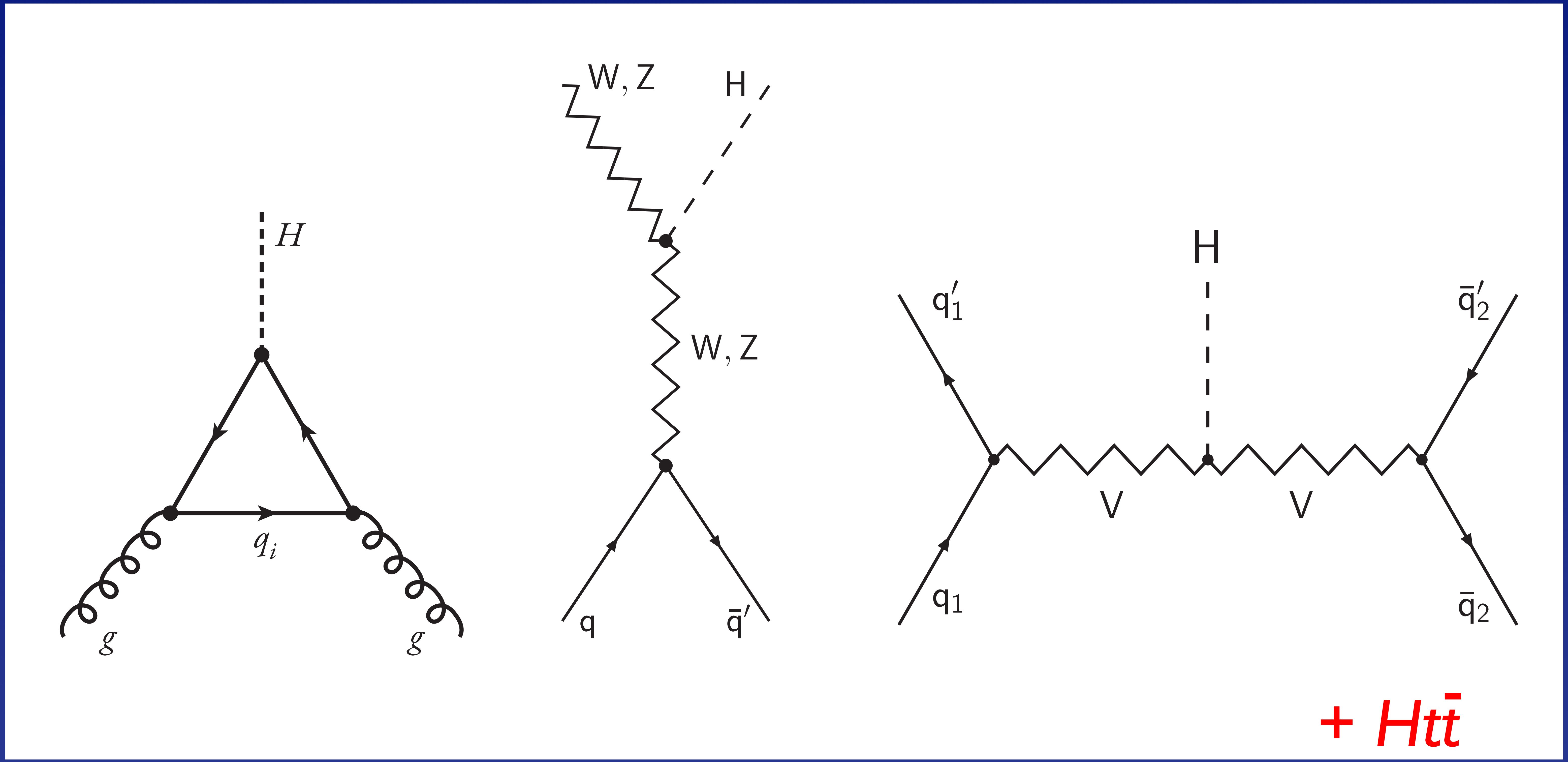
If not, weak interactions among $W^{\pm}$, Z, H become strong on 1-TeV scale

New phenomena are to be found around 1 TeV

Evolution of CMS 4-lepton Signal

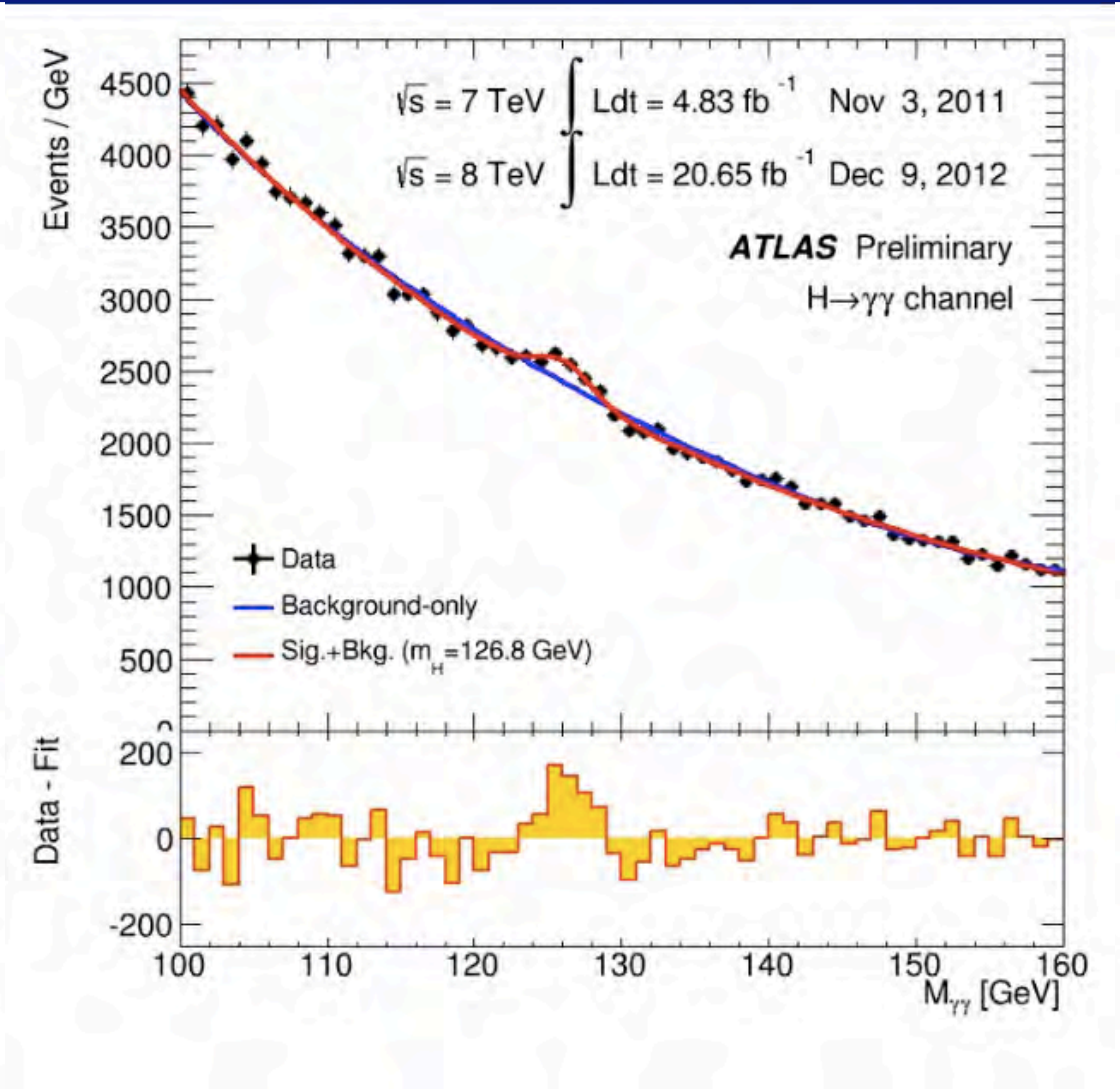


LHC can study Higgs boson in many channels



$\gamma\gamma$, WW^*, ZZ^*, $\tau^+\tau^-$, b pairs, …

Evolution of ATLAS γγ Signal



What the LHC has told us about H so far

Evidence is developing as it would for
a "standard-model" Higgs boson

Unstable neutral particle near 125 GeV

$M_H = 125.09 \pm 0.24$ GeV

decays to $\gamma\gamma$, W^+W^-, ZZ

dominantly spin-parity 0^+

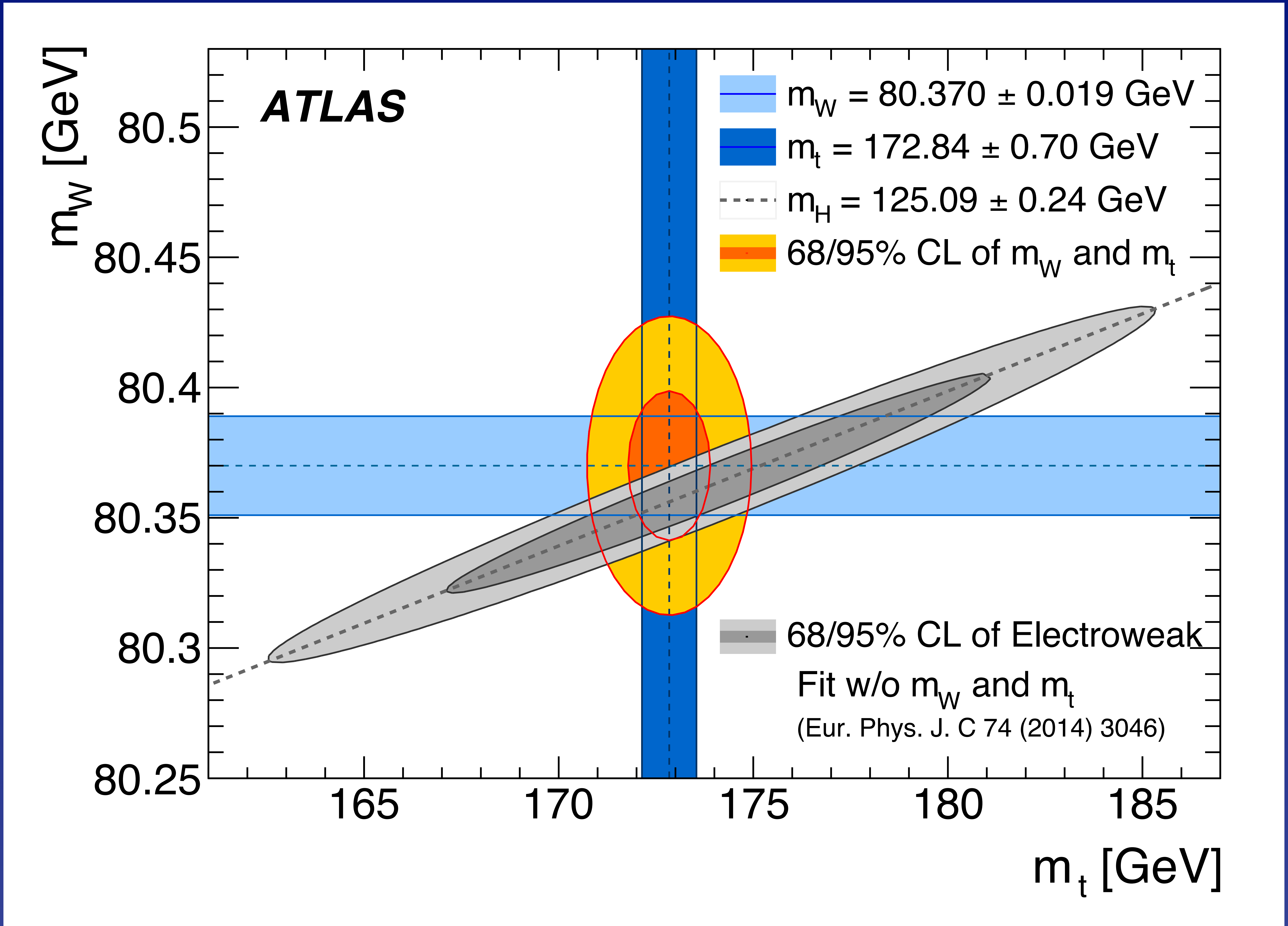
evidence for $\tau^+\tau^-$, $b\bar{b}$, $t\bar{t}$; $\mu^+\mu^-$ limited

Only third-generation fermions tested

Motivates HL-LHC,
electron–positron Higgs factory

$Hf\bar{f}$ couplings
not universal

Quantum corrections test electroweak theory



Why does discovering the agent matter?

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

Electron and quarks would have no mass via Higgs

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, …

… no template for life.

arXiv:0901.3958

What we expect of the standard-model Higgs sector

Hide electroweak symmetry

Give masses to *W*, *Z*, *H*

Regulate Higgs-Goldstone scattering

Motivates VLHC

Account for quark masses, mixings

Account for charged-lepton masses

ΦBSM

A role in neutrino masses?

Fully accounts for EWSB (*W*, *Z* couplings)?

Couples to fermions?

t from production, $Ht\bar{t}$

need direct observation for b, τ

Accounts for fermion masses?

Fermion couplings ∝ masses?

Are there others?

Quantum numbers? ($J^P = 0^+$)

SM branching fractions to gauge bosons?

Decays to new particles?

All production modes as expected?

Implications of $M_H \approx 125$ GeV?

Any sign of new strong dynamics?

More new physics on the TeV scale?

WIMP dark matter

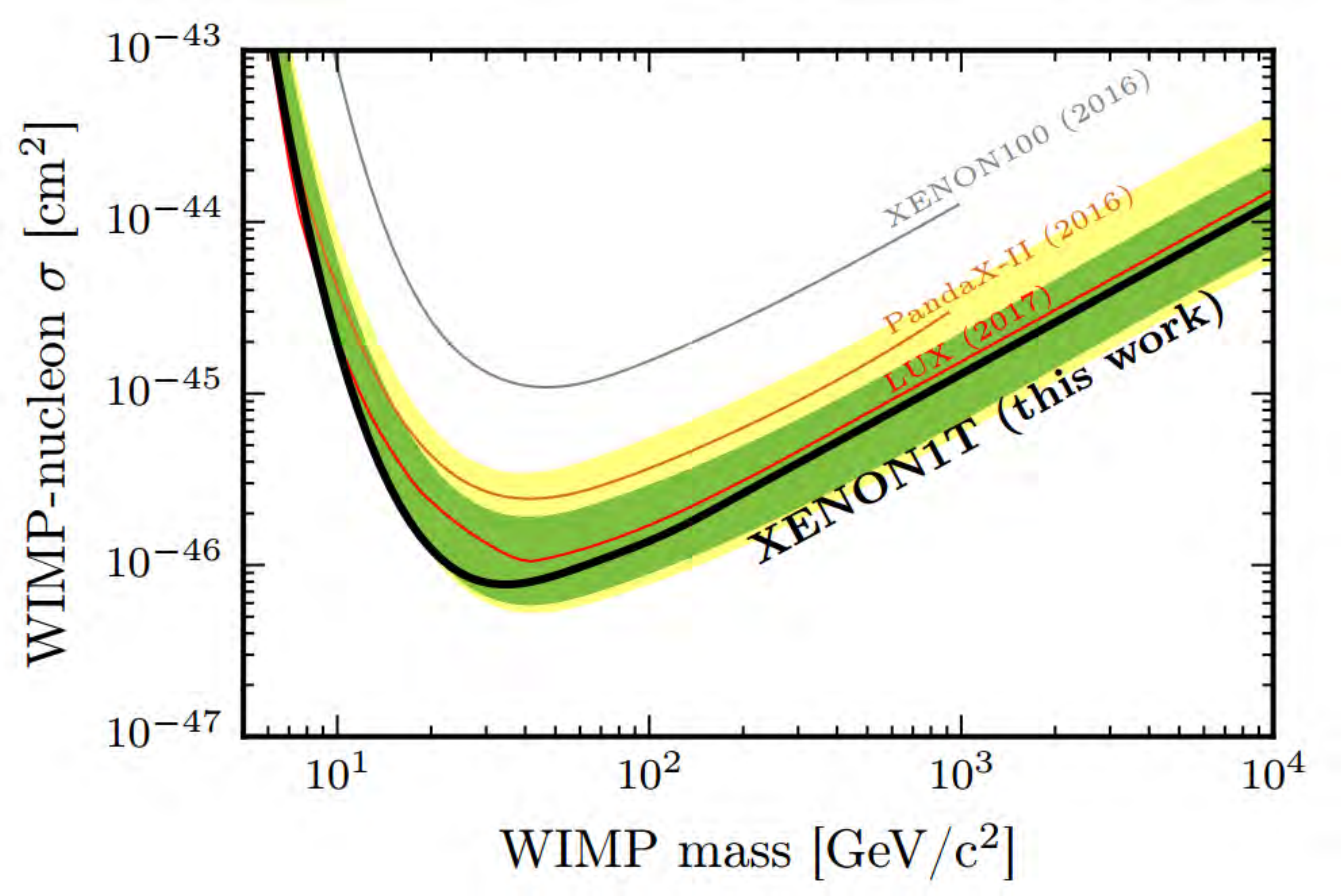
"Naturalness"

Hierarchy problem: EW scale ≪ Planck scale

Vacuum energy problem

Clues to origin of EWSB

Direct searches for WIMP dark matter



Supersymmetry could respond to many SM problems,
but (as we currently understand it) it is
largely unprincipled!

R-parity (overkill for proton stability)
gives dark-matter candidate
μ problem (getting TeV scale right)
Taming flavor-changing neutral currents
All these are added by hand!

Very promising: search in EW production modes
reexamine squark + EWino, too.

How have we misunderstood the hierarchy problem?

If other physical scales are present, there is something to understand

We originally sought once-and-done remedies, such as supersymmetry or technicolor

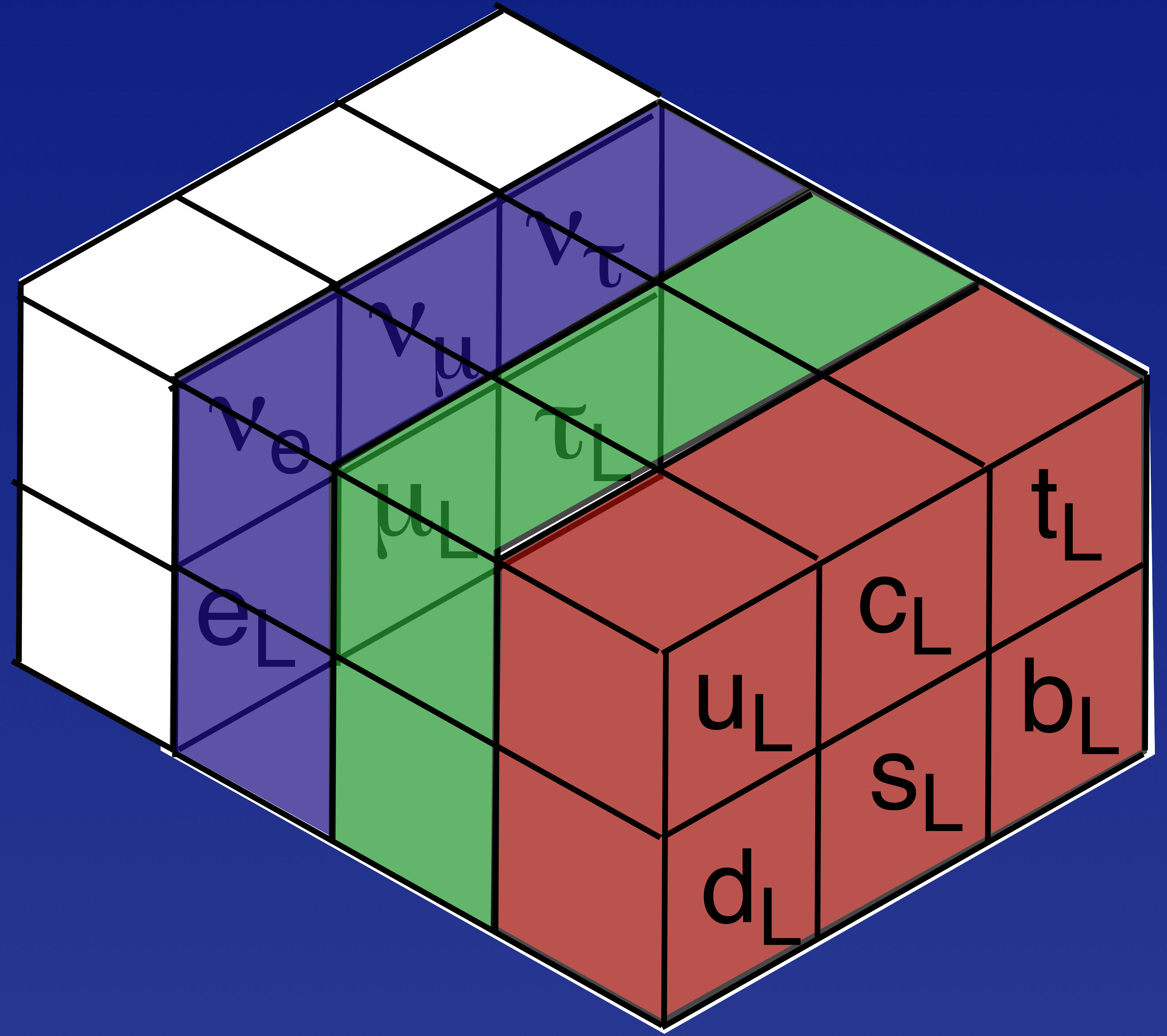
Go in steps, or reframe the problem?

The unreasonable effectiveness of the standard model

arXiv:09053187 arXiv:1503.01756 arXiv:1507.02977

A Unified Theory?

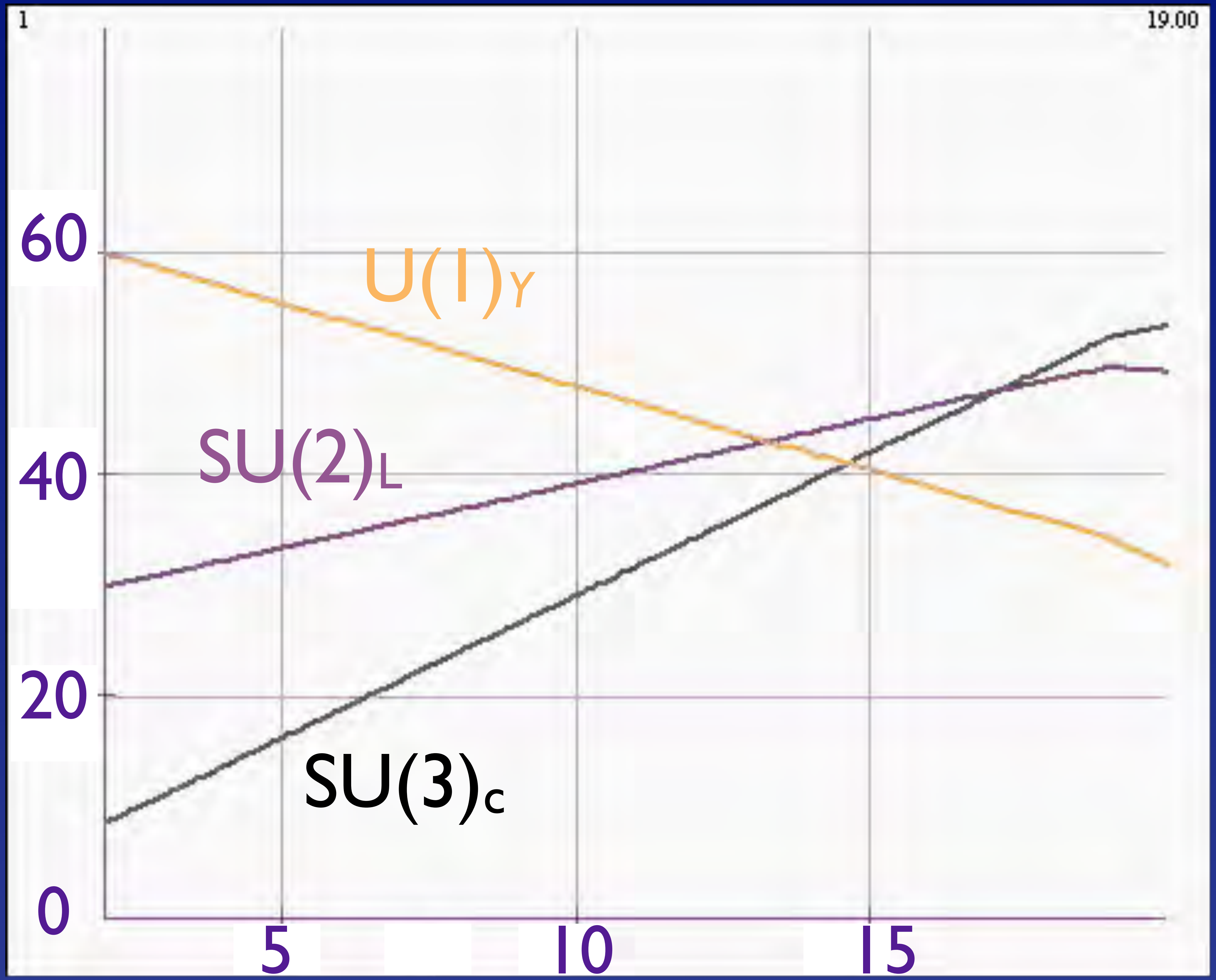
Why are atoms so remarkably neutral?



Coupling constant unification?

Extended quark–lepton families:
proton decay! n–$\bar{n}$ oscillations

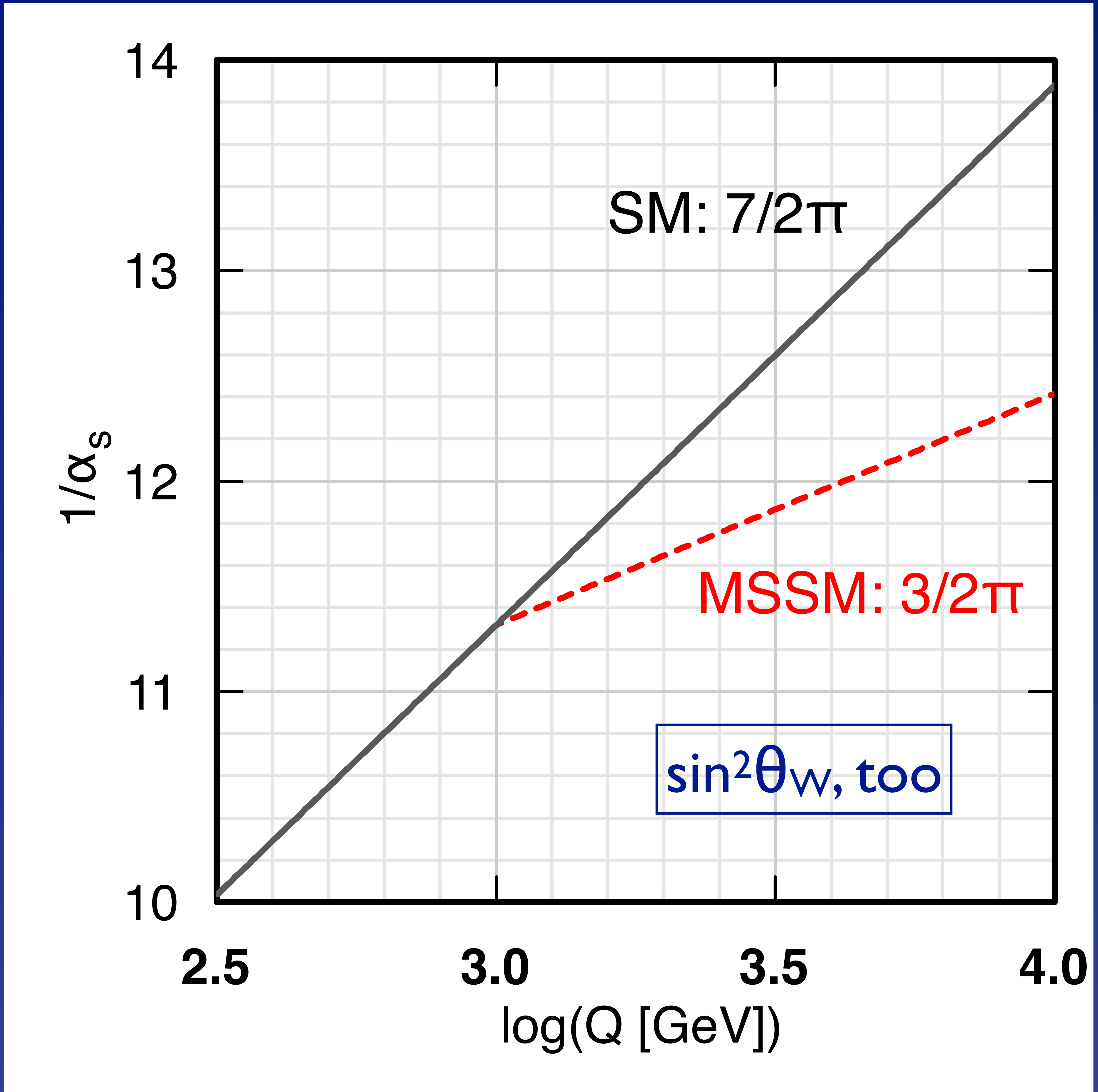
Unification of Forces?



$1/\alpha$

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

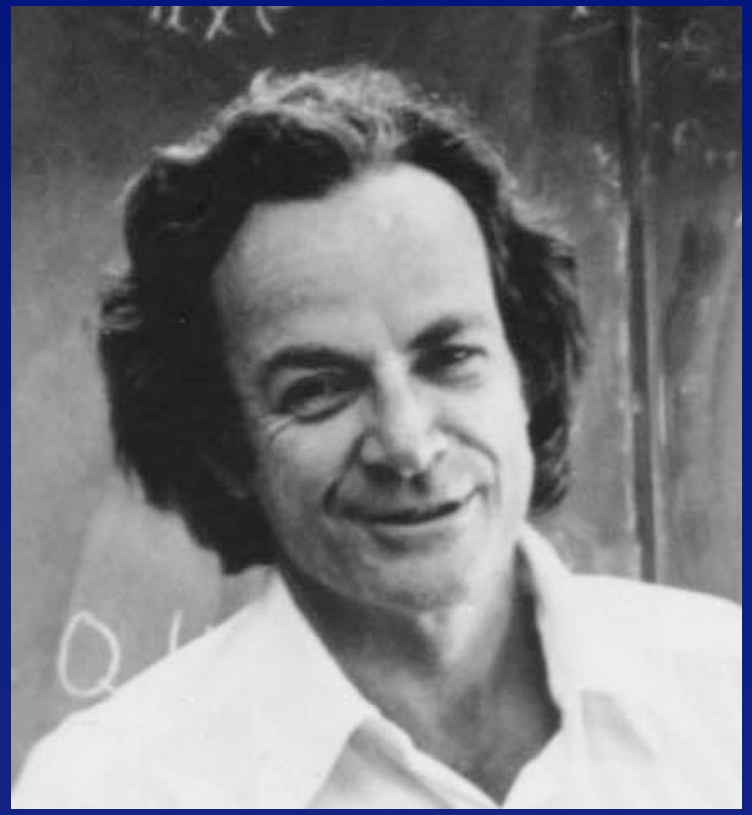
Might (HE-)LHC (or 100-TeV) see change in evolution?



Parameters of the Standard Model

3	coupling parameters $\alpha_s, \alpha_{\text{em}}, \sin^2\theta_W$
2	parameters of the Higgs potential
1	vacuum phase (QCD)
6	quark masses
3	quark mixing angles
1	CP-violating phase
3	charged-lepton masses
3	neutrino masses
3	leptonic mixing angles
1	leptonic CP-violating phase $(+$ Majorana $\ldots)$
26^{+}	arbitrary parameters

Flavor physics may be where we see, or diagnose, the break in the SM.



Why does the muon weigh?

gauge symmetry allows

$$\zeta_e\left[(\bar{e}_L\Phi)e_R + \bar{e}_R(\Phi^\dagger e_L)\right] \rightsquigarrow m_e = \zeta_e v/\sqrt{2}$$

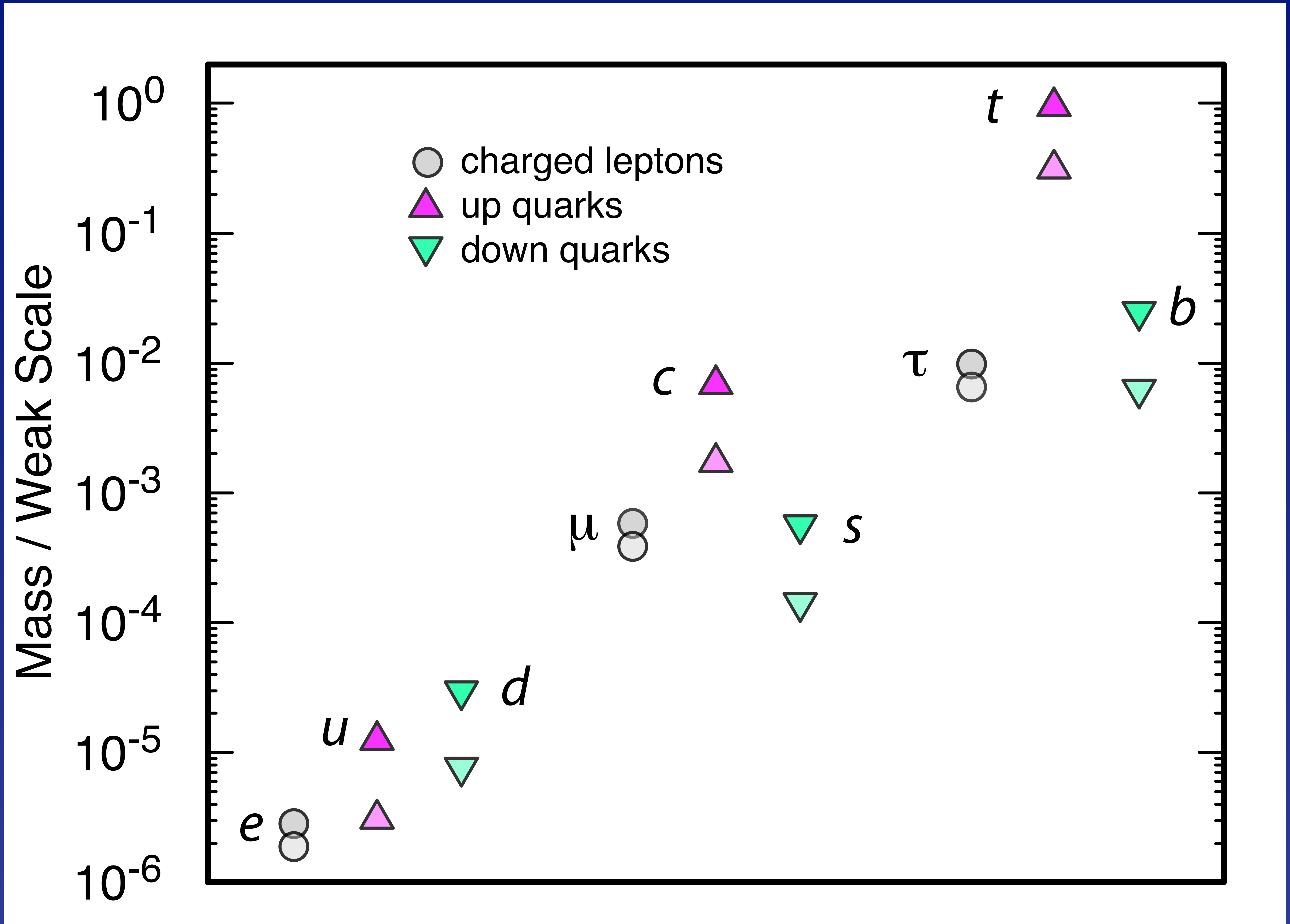
after spontaneous symmetry breaking

What does the muon weigh?

ζ_e : picked to give right mass, not predicted

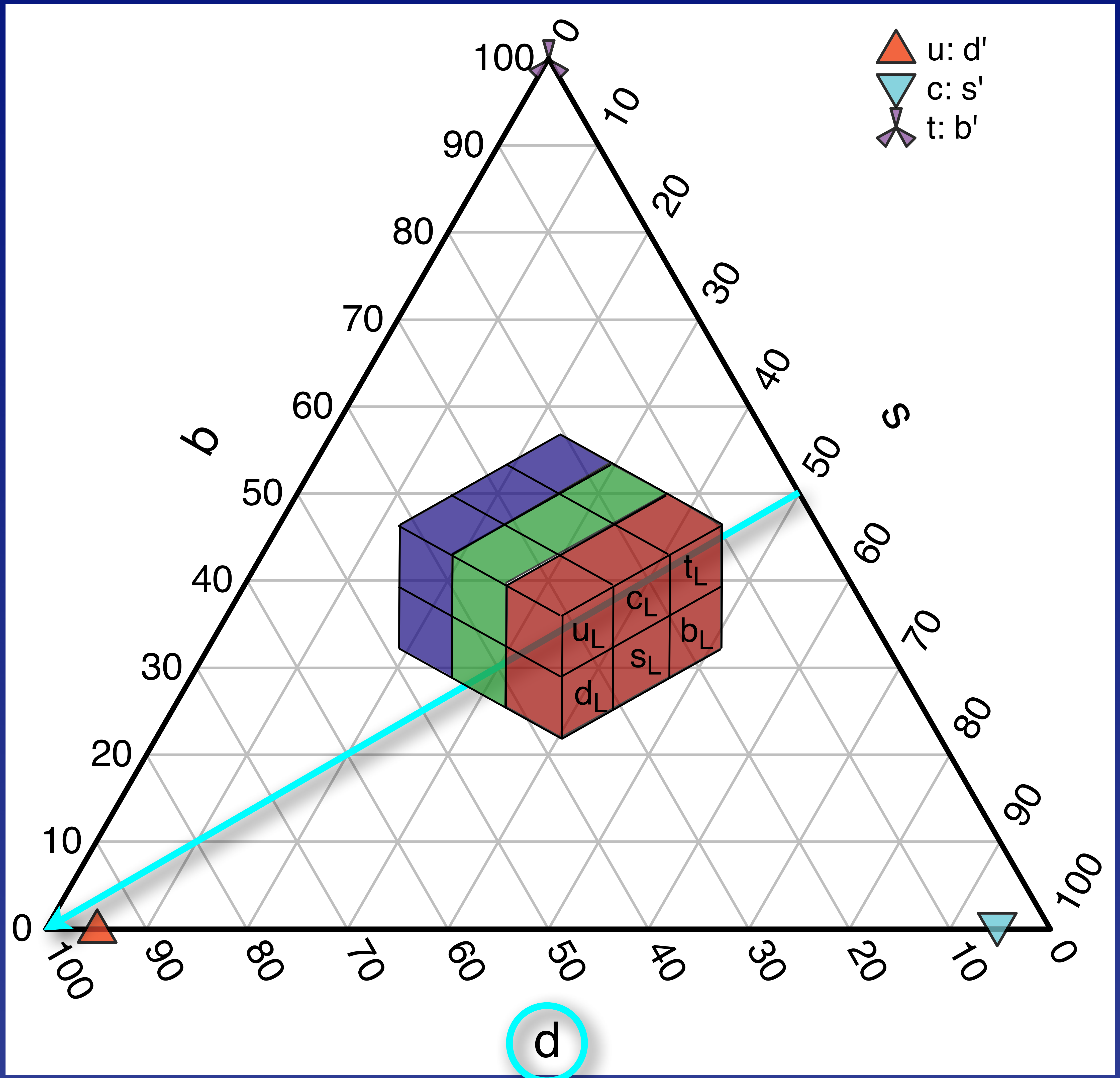
fermion mass implies physics beyond the standard model

Charged Fermion Masses

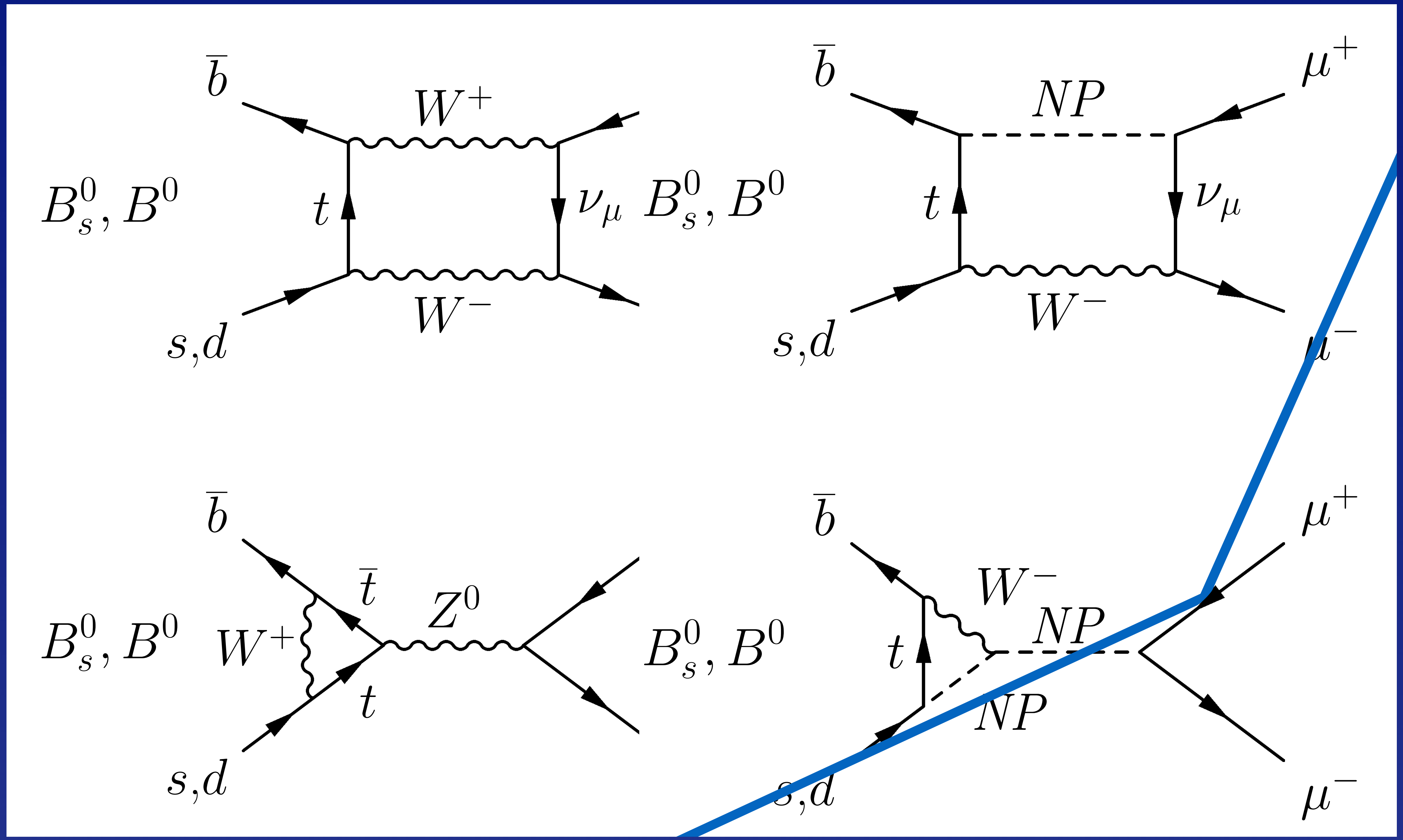


Running mass $m(m)$ … $m(U)$

Quark family patterns: *generations*

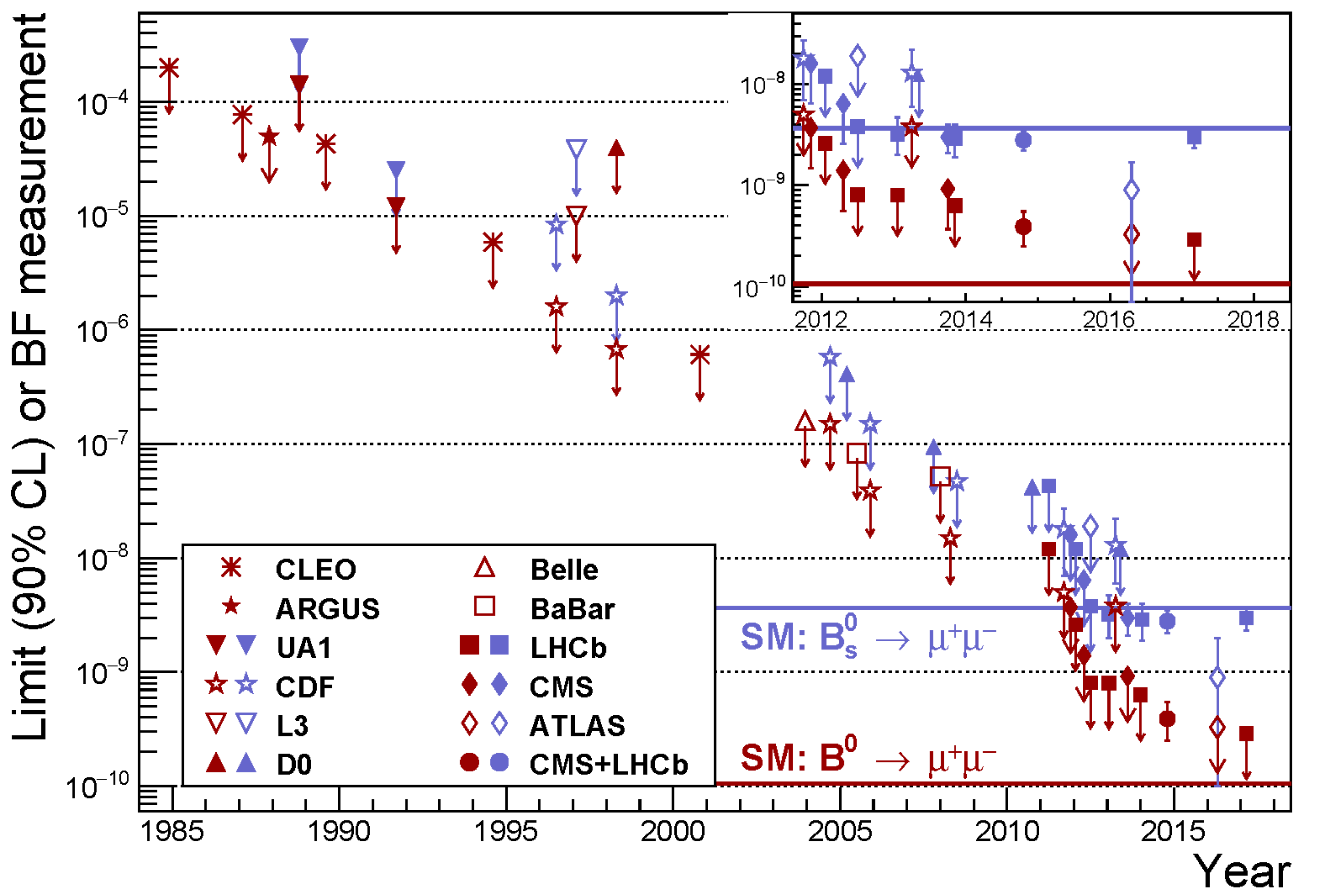


Rare Processes: Flavor-changing neutral currents



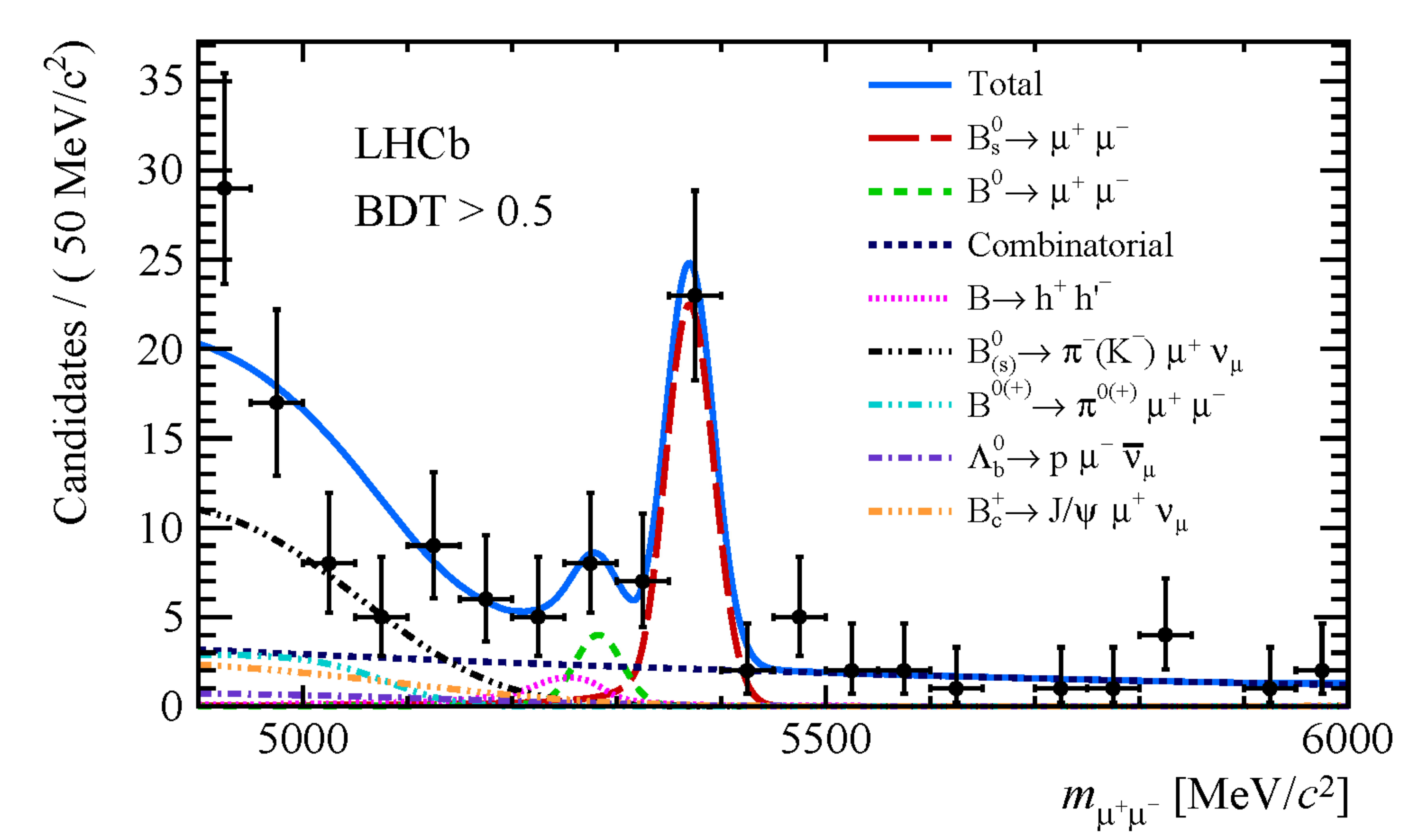
$$\mathrm{SM:\ BR}(\mathrm{B_s} \to \mu^+\mu^-) = (3.65 \pm 0.30) \times 10^{-9}$$

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



Limit (90% CL) or BF measurement
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
1985
1990
1995
2000
2005
2010
2015
Year
2012
2014
2016
2018
CLEO
ARGUS
UA1
CDF
L3
D0
Belle
BaBar
LHCb
CMS
ATLAS
CMS+LHCb
SM: $B^0_s \to \mu^+\mu^-$
SM: $B^0 \to \mu^+\mu^-$

$(\mathrm{B}^0, \mathrm{B_s}) \to \mu^+\mu^-$

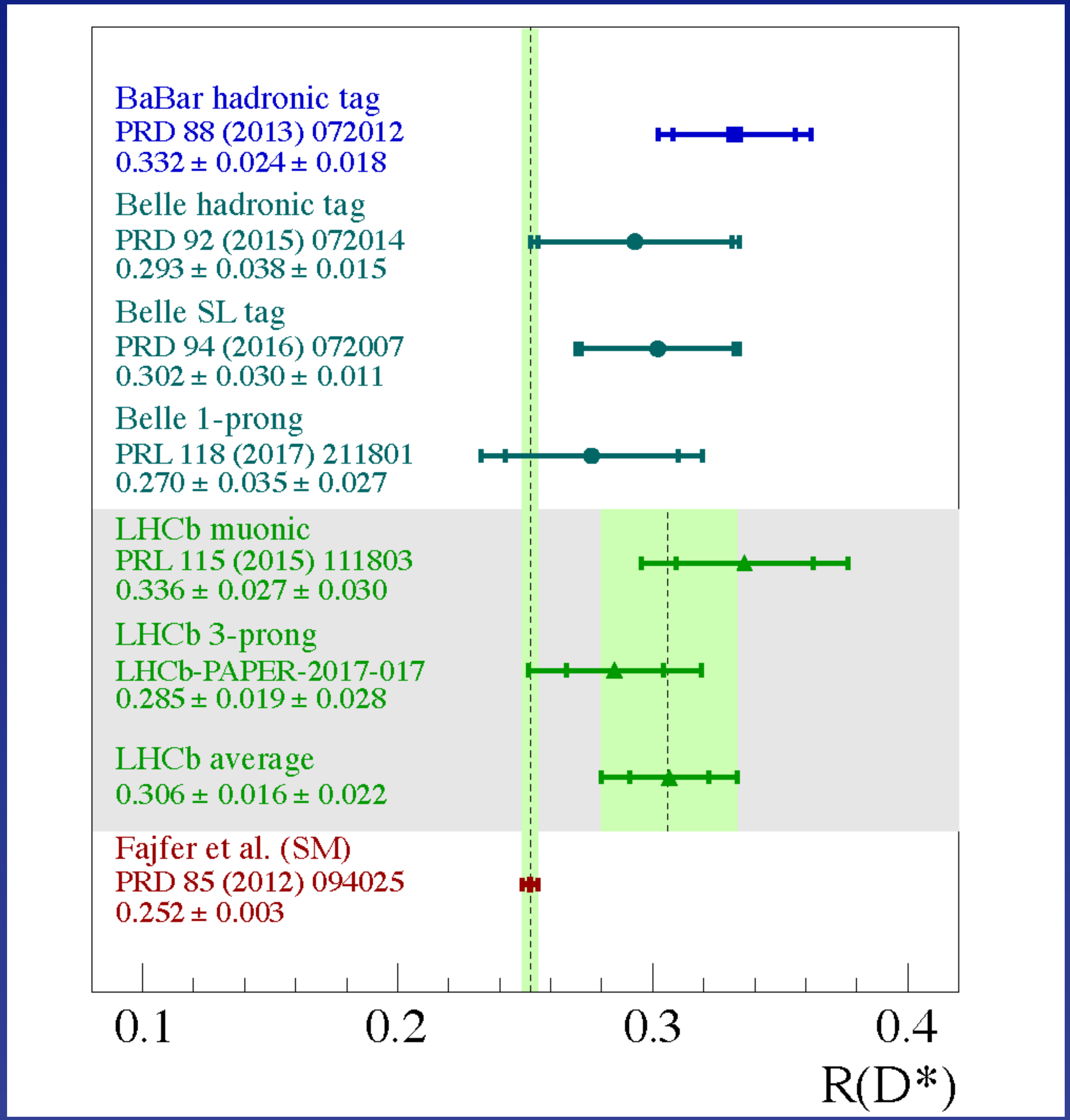


LHCb: $\mathrm{BR}(\mathrm{B_s} \to \mu^+\mu^-) = (3.0^{+0.7}_{-0.6}) \times 10^{-9}$

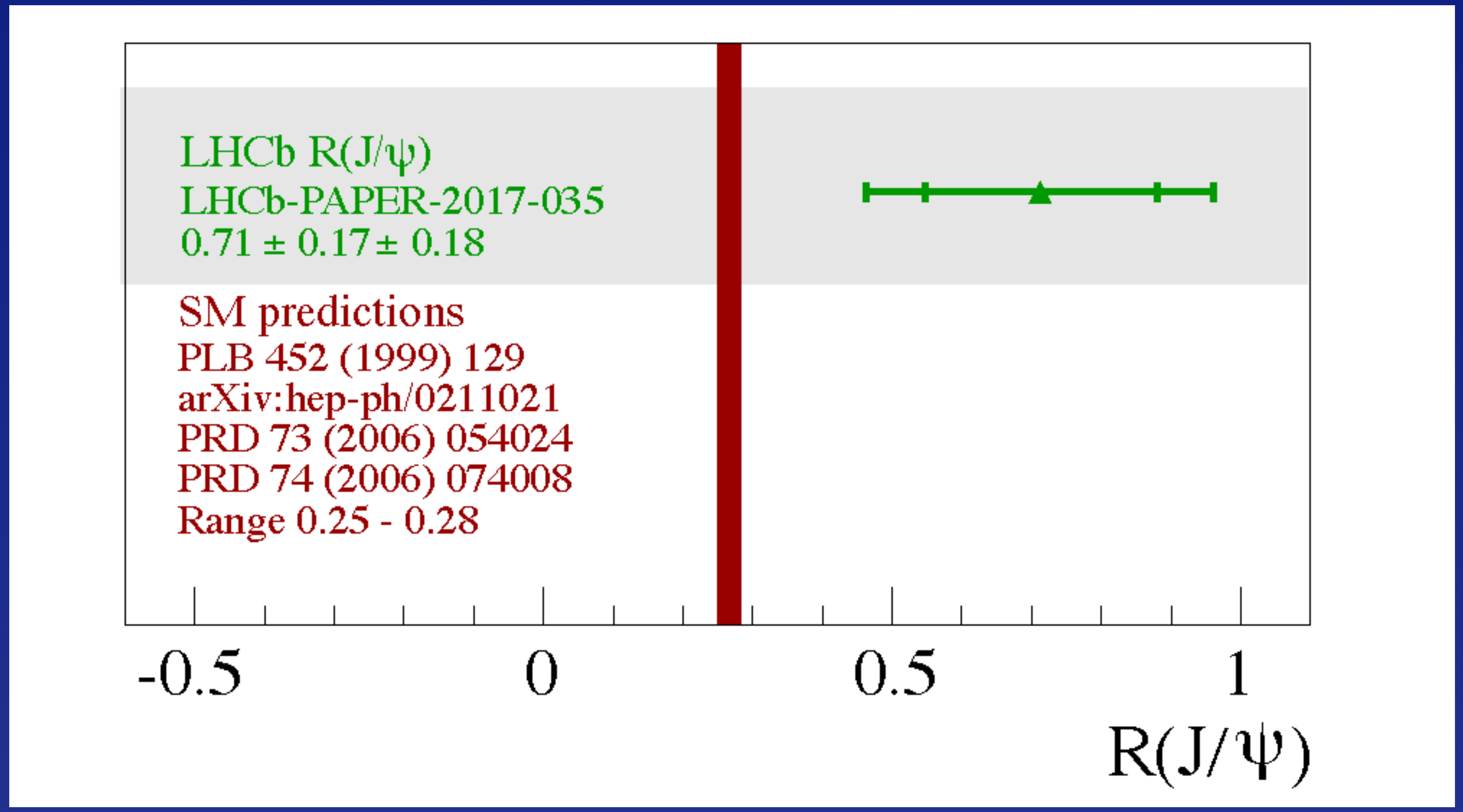
Flavor anomalies

LHC*b* sees several hints of flavor nonuniversality

$B^0 \to D^{*-} \tau^+ \nu_\tau$ / $B^0 \to D^{*-} \mu^+ \nu_\mu$



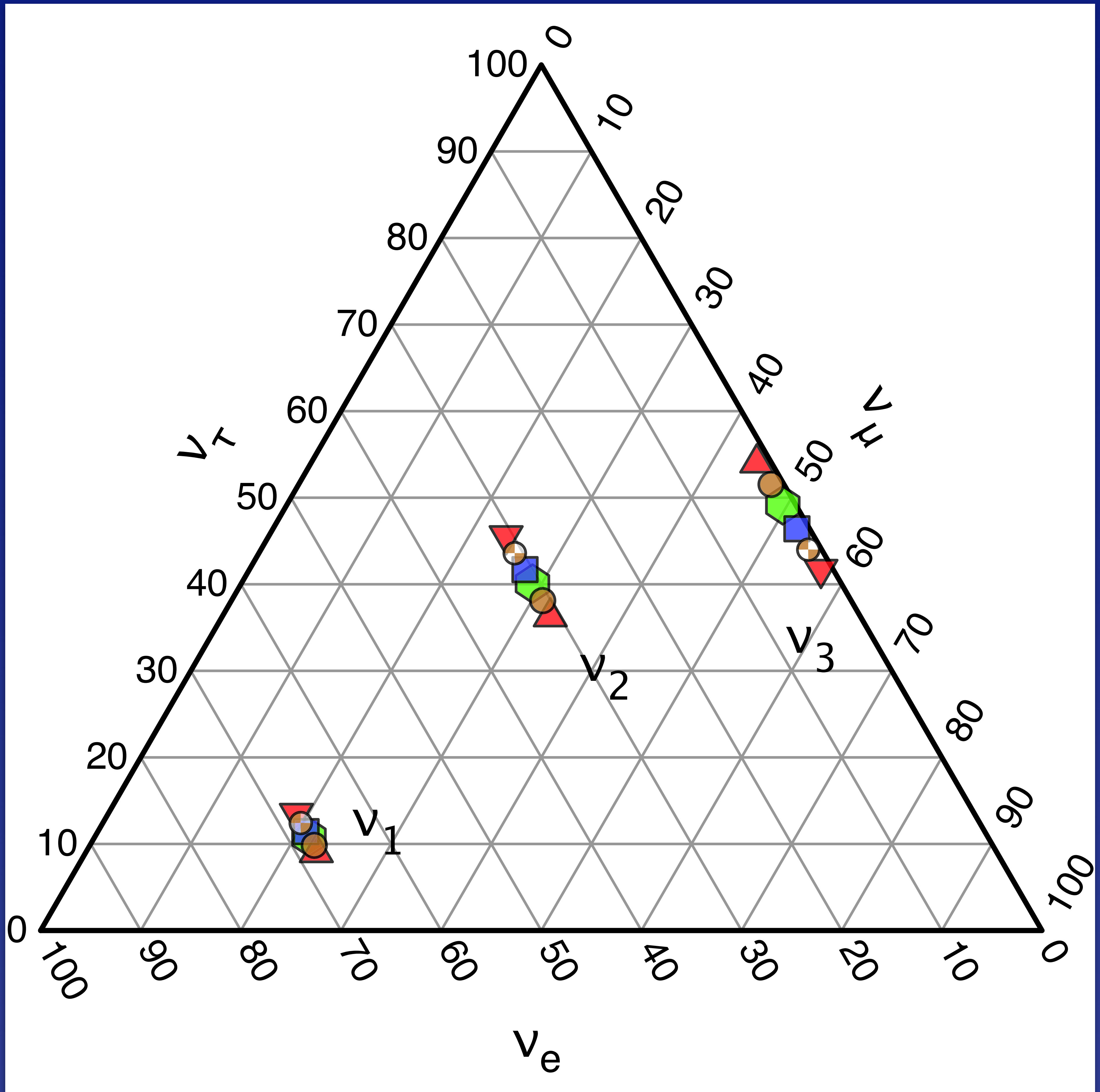
$B_c^+ \to J/\psi \tau^+ \nu_\tau$ / $B_c^+ \to J/\psi \mu^+ \nu_\mu$



Too many τ; other evidence for excess $\mu^+\mu^-$ / e^+e^-

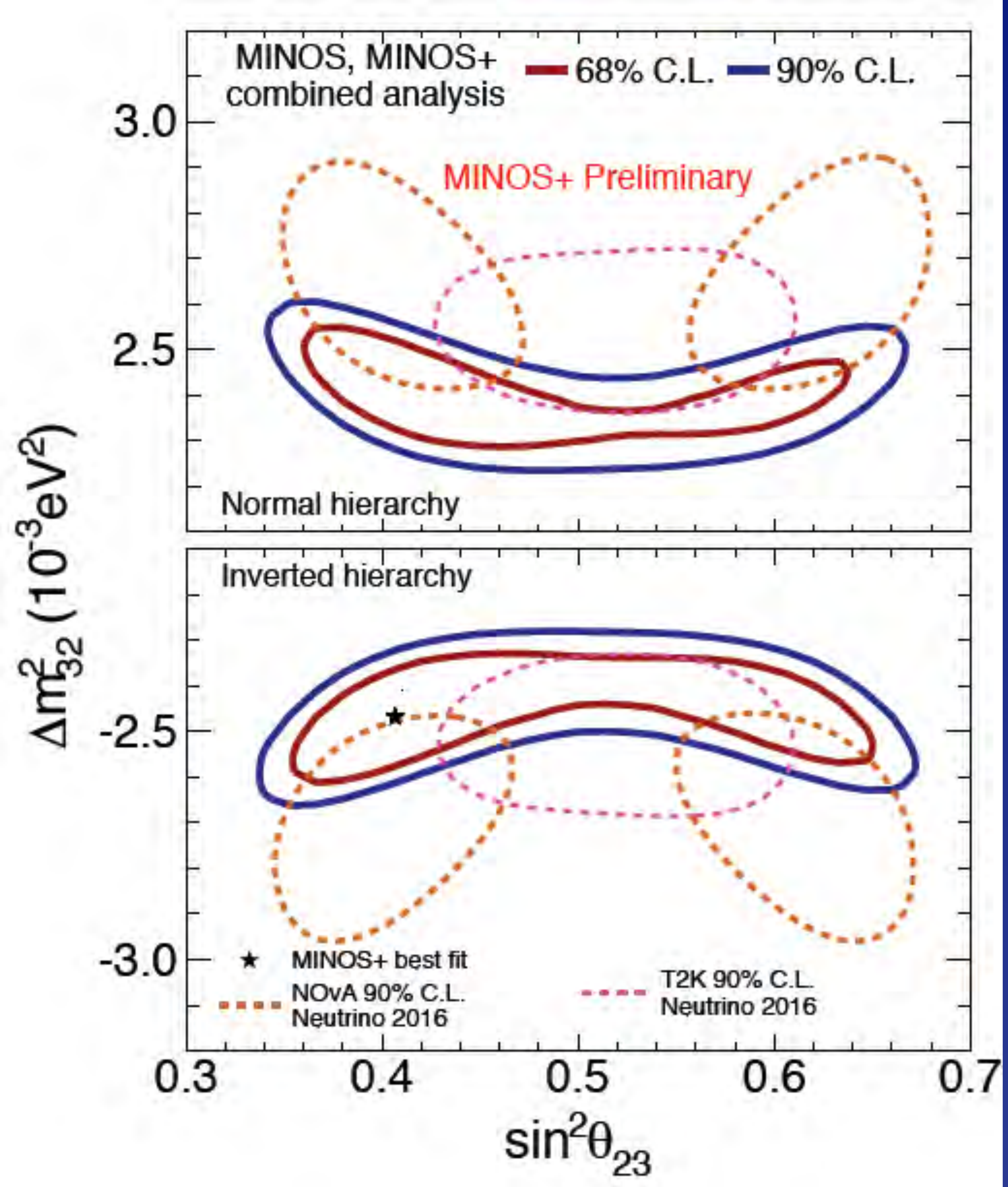
Some outstanding questions in ν physics

What is the composition of ν_3?



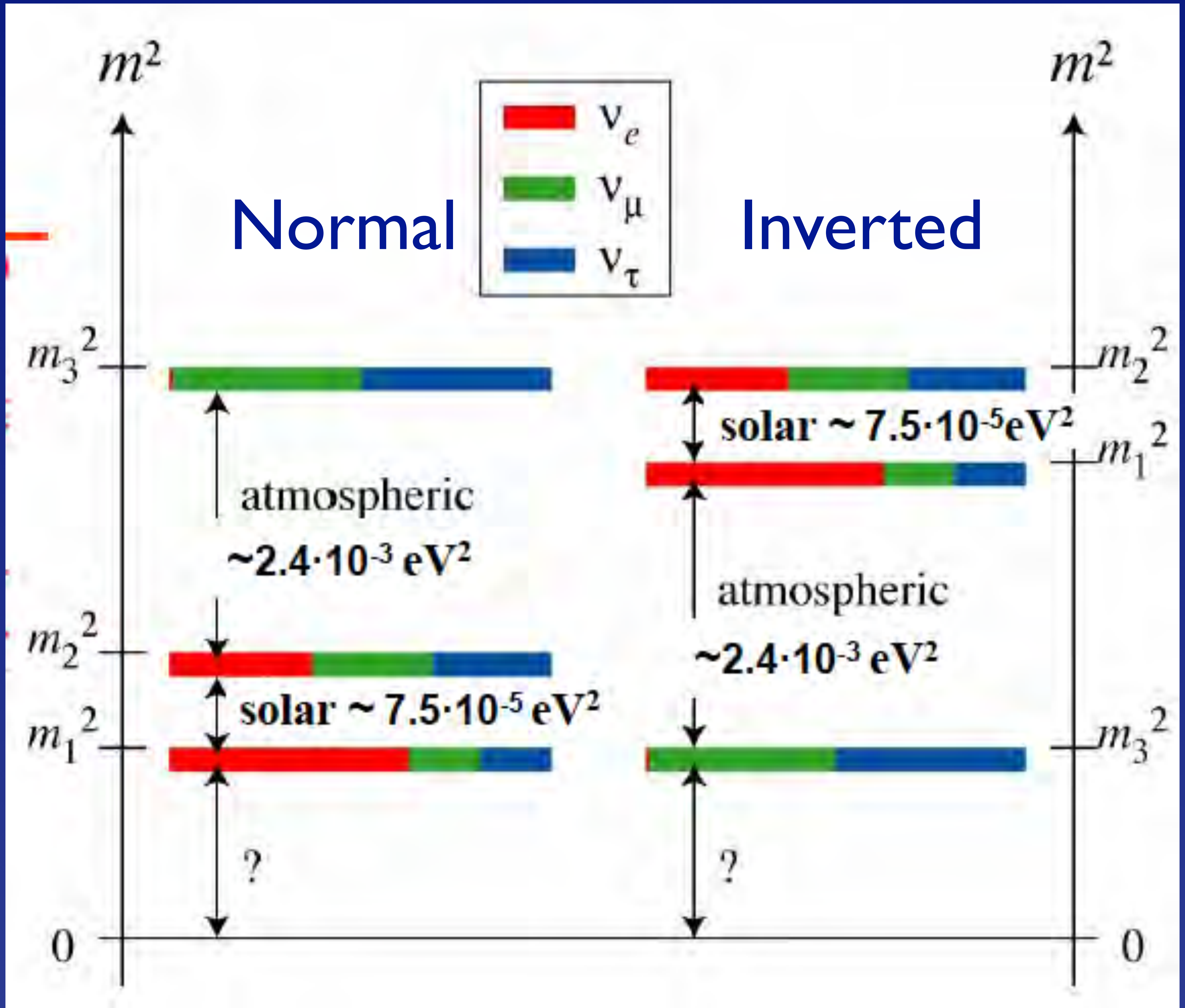
Before most-recent experiments

Some outstanding questions in ν physics
What is the composition of ν_3?



T2K favors maximal mixing, NOνA nonmaximal

Some outstanding questions in ν physics



NOνA, T2K ν_e appearance *begin to hint* normal hierarchy

Some outstanding questions in ν physics

CP Violation?

T2K disfavors $0 < \delta < \pi$ at 90% CL

NOνA shows some sensitivity

Are neutrinos Majorana particles?

Search for $(Z,A) \rightarrow (Z+2,A) + ee$: $\beta\beta_{0\nu}$

Do 3 light neutrinos suffice?

Are there light sterile ν?

Short baseline ν experiments test for light steriles

Might neutrinos decay?

Can we detect the cosmic ν background?

Tabletop precision experiments

Electric dipole moment d_e: CP/T violation

$|d_e| < 8.7 \times 10^{-29}$ e · cm

ACME Collaboration, ThO

$|d_e| < 1.3 \times 10^{-28}$ e · cm

NIST, trapped $^{180}Hf^{19}F^{+}$

(SM phases: $d_e < 10^{-38}$ e · cm)

Tabletop precision experiments

(Anti)proton magnetic moments: CPT test

$$\mu_{\bar{p}} = -\,2.792\,847\,344\,1(42)\ \mu_N$$

vs.

$$\mu_p = +\,2.792\,847\,350\,(9)\ \mu_N$$

BASE Collaboration @CERN Antiproton Decelerator

Accelerator and magnet R&D

HE-LHC (x2 in energy) requires ~15 T magnets:

NbTi → Nb_3Sn …

Nuclear & particle physics consider e(p,A)

electron positron, circular or linear Higgs factory

high-energy lepton collider

More attention to neutrino factory

?

Issues for the Future *(Starting now!)*

1. *There is a Higgs boson!* Might there be several?
2. Does the Higgs boson regulate *WW* scattering?
3. Is the Higgs boson elementary or composite? How does it interact with itself? What triggers EWSB?
4. 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?*
5. Are there new flavor symmetries that give insights into fermion masses and mixings?
6. What stabilizes the Higgs-boson mass below 1 TeV?

Issues for the Future (Now!)

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

Issues for the Future (Now!)

12. What are the dark matters? Any flavor structure?
13. 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?
14. Is EWSB related to gravity through extra spacetime dimensions?
15. What resolves the vacuum energy problem?
16. (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!)

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? Do they speak to the TeV, unification, Planck scale, …?
21. Could our laws of nature be environmental?

22. How are we prisoners of conventional thinking?