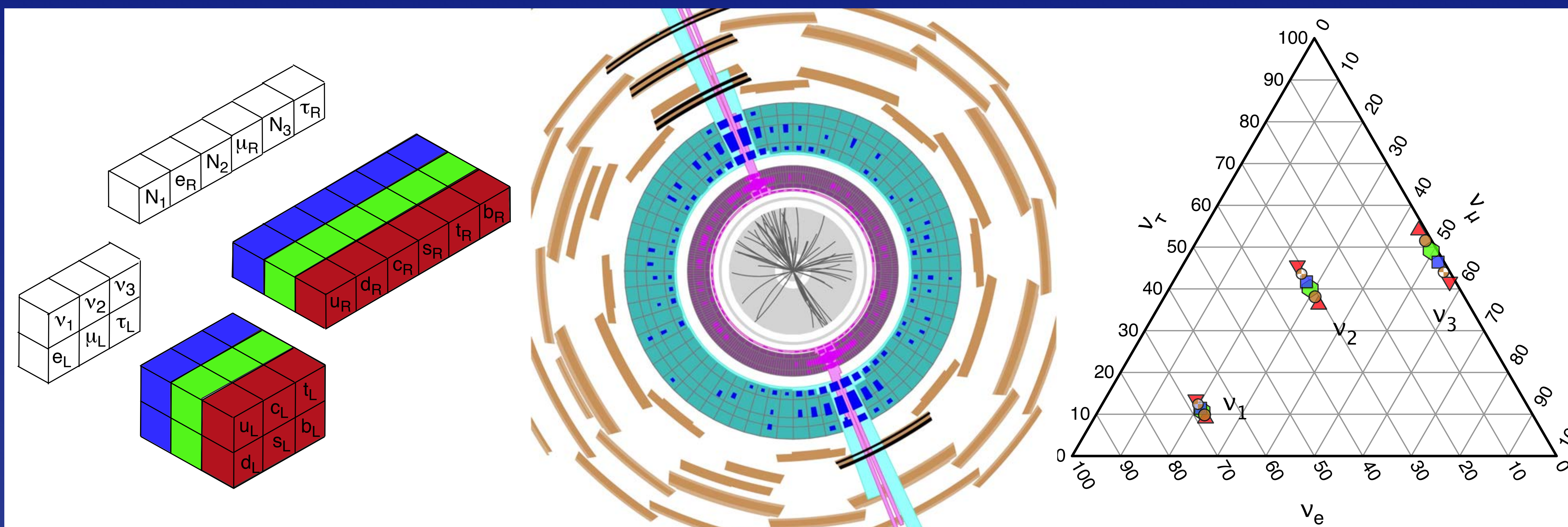
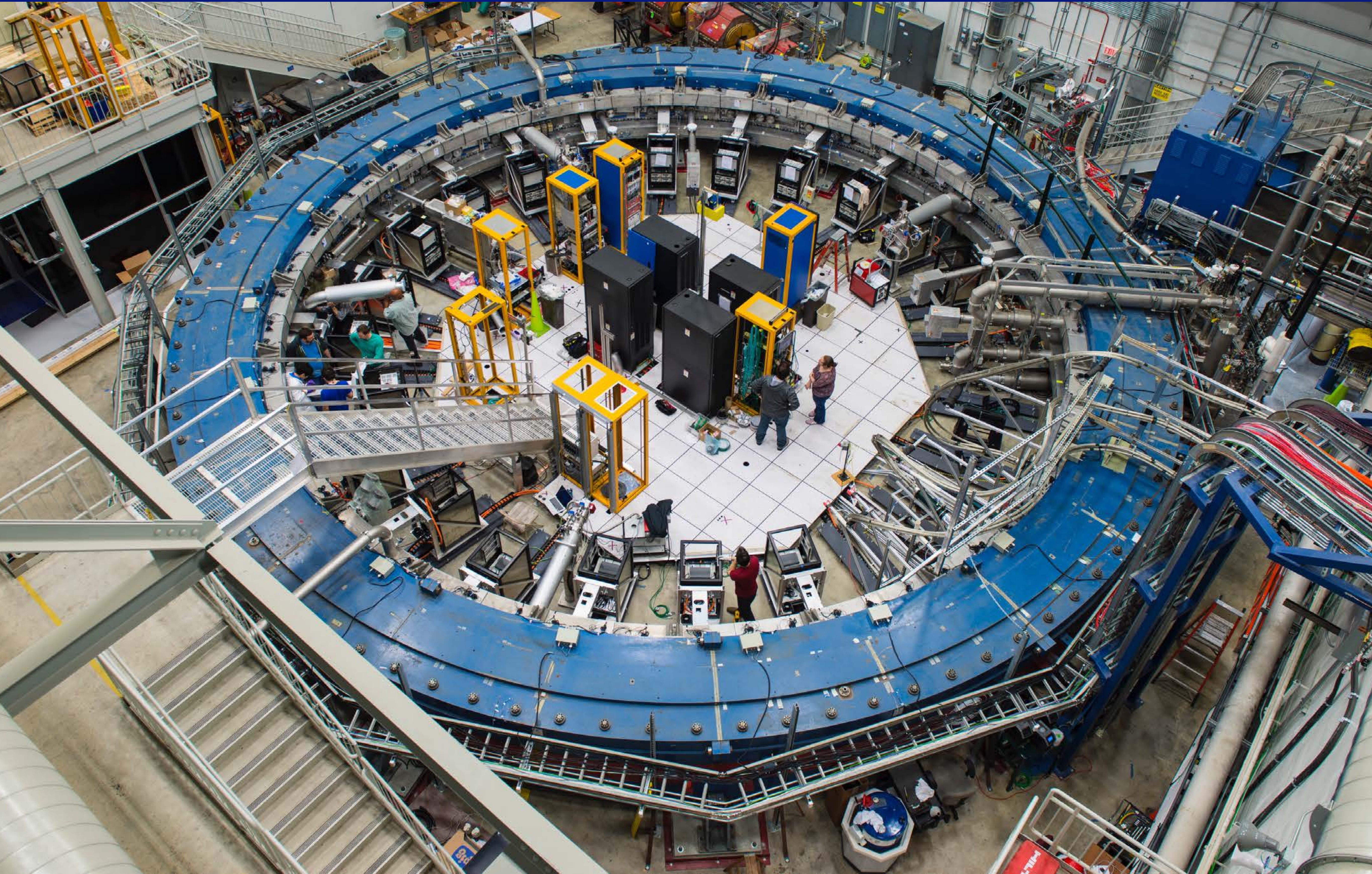
Perspectives & Prospects for Particle Physics

Chris Quigg
Fermi National Accelerator Laboratory



CAP Annual Congress · Queen's University · 1 June 2017

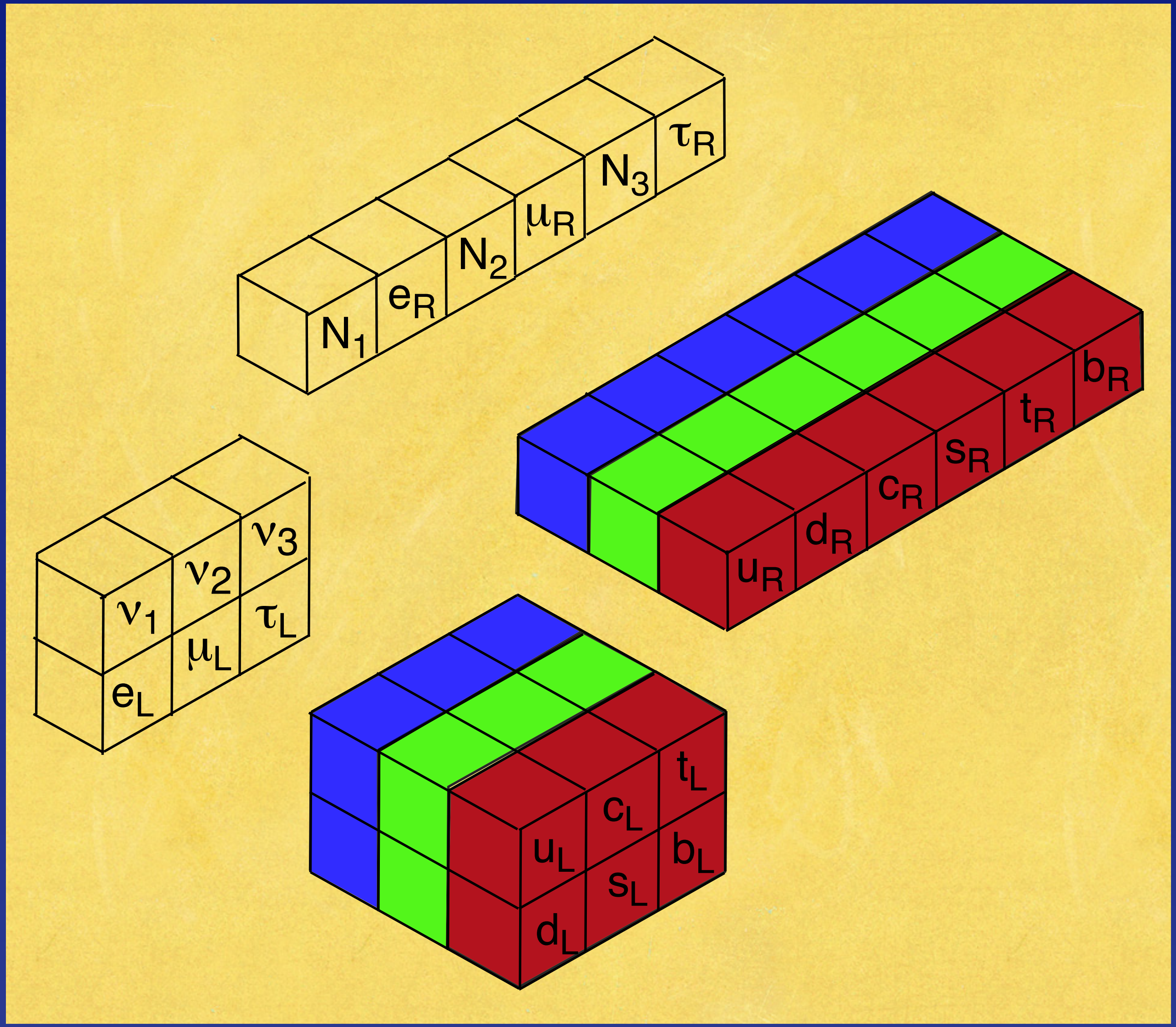
Yesterday: circulating muons in the g–2 ring at Fermilab



Before LHC

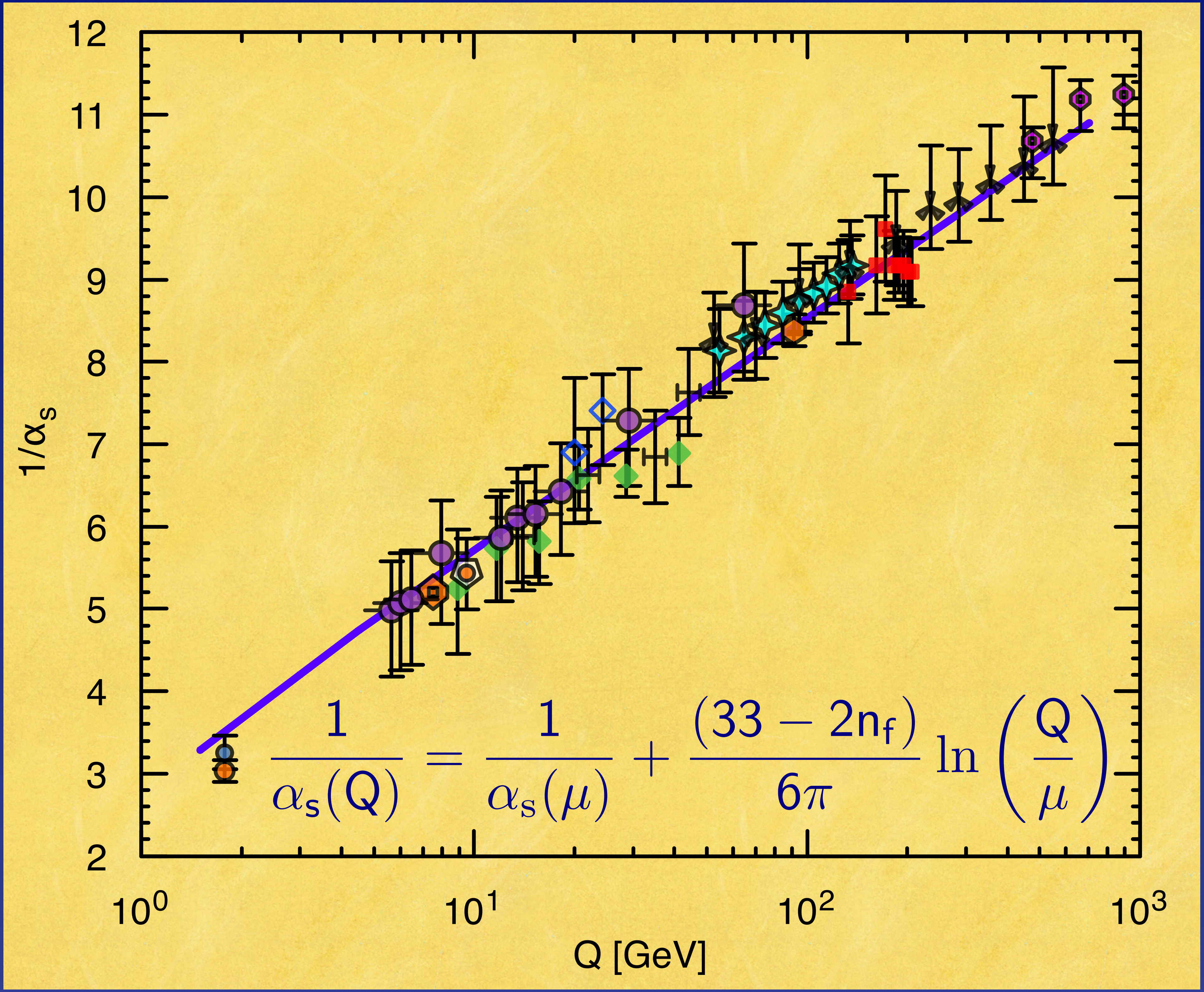
Two New Laws of Nature +

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



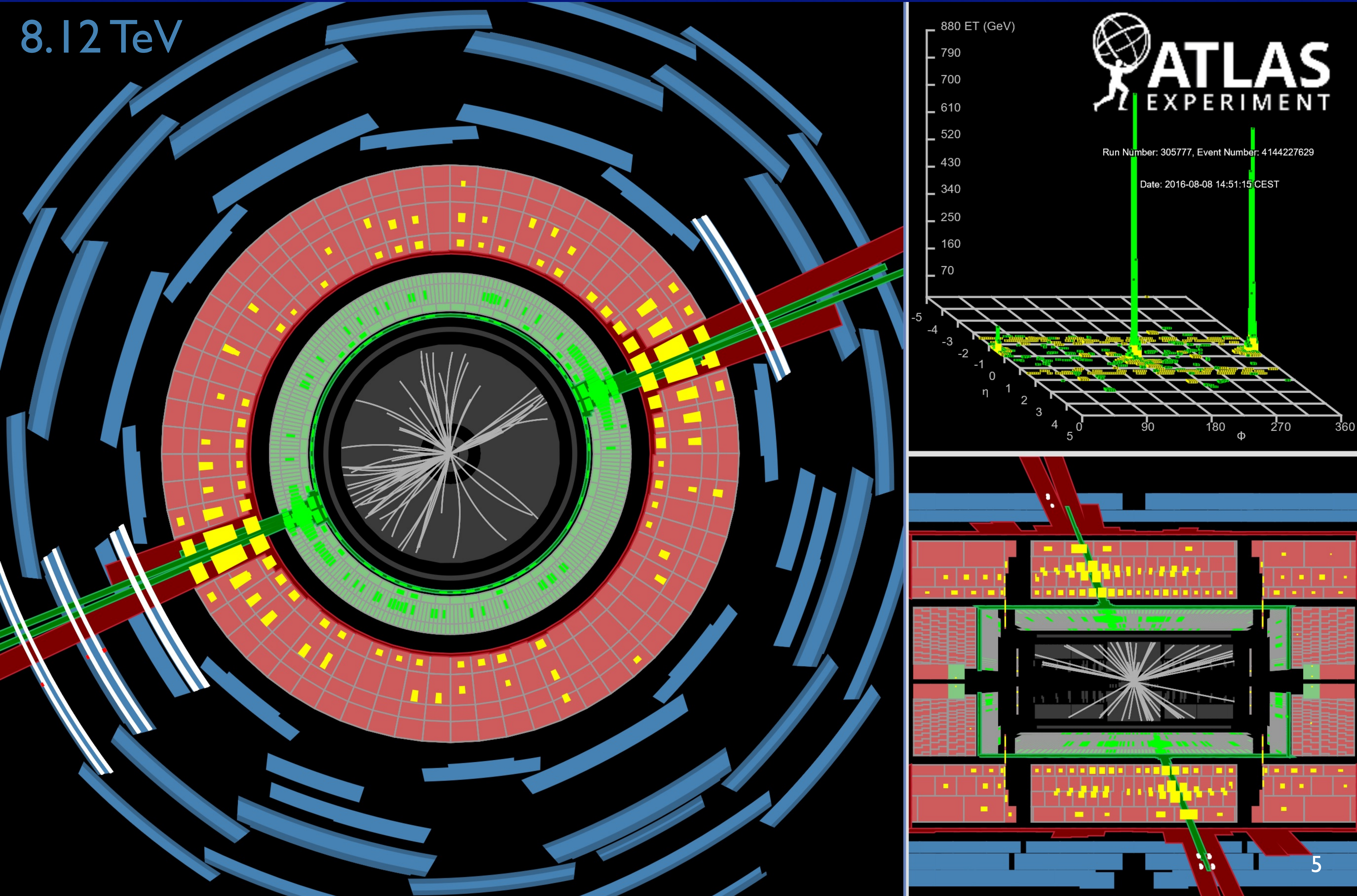
Interactions: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries

Antiscreening evolution of the strong coupling “constant”



The World's Most Powerful Microscopes

nanonanophysics



sum of parts

rest energy

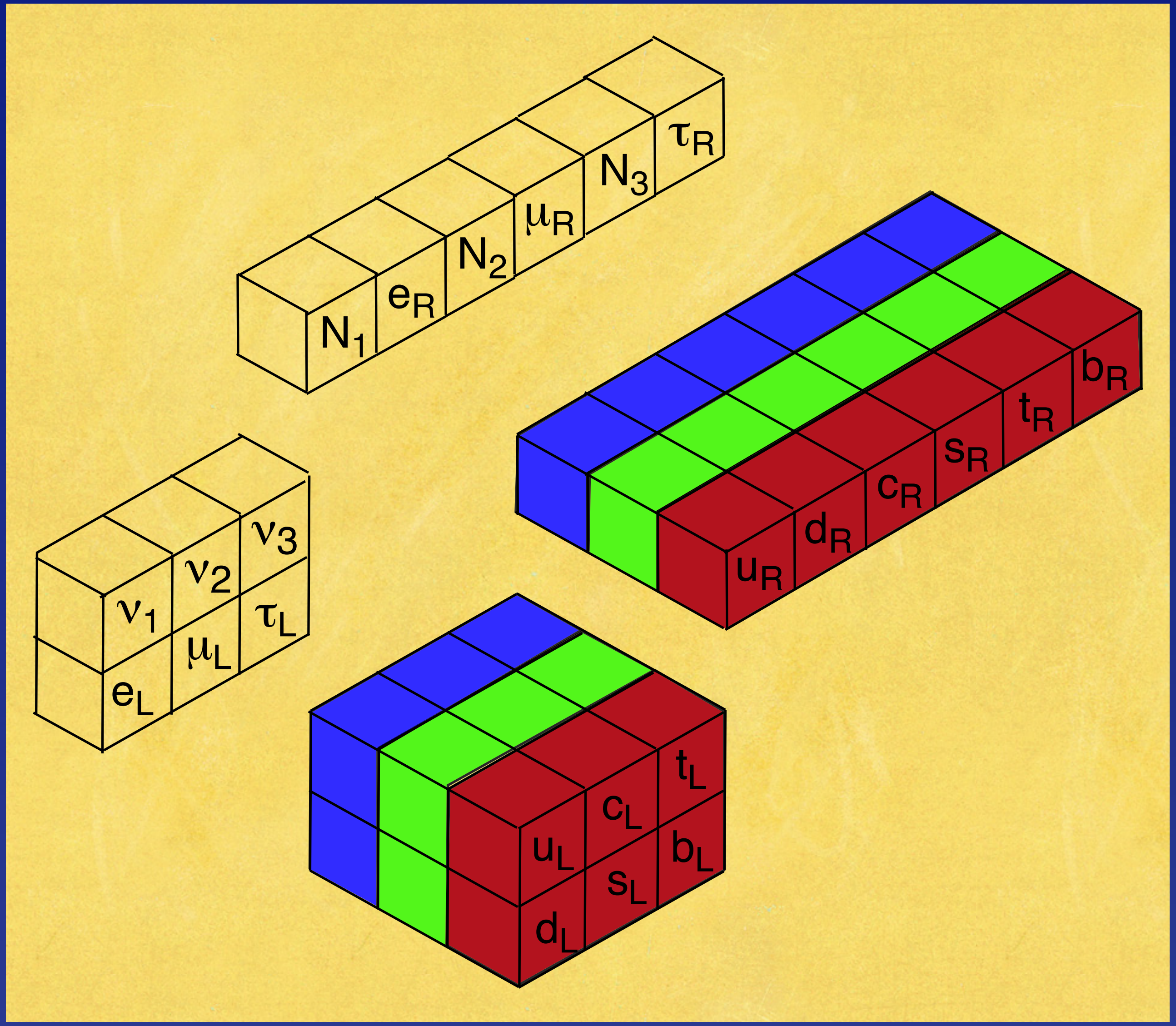
Nucleon mass: exemplar of $m = E_0/c^2$

up and down quarks contribute few %

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

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

Electroweak Symmetry Breaking



$U(1)_{EM}$

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

The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: *conditional upper bound*

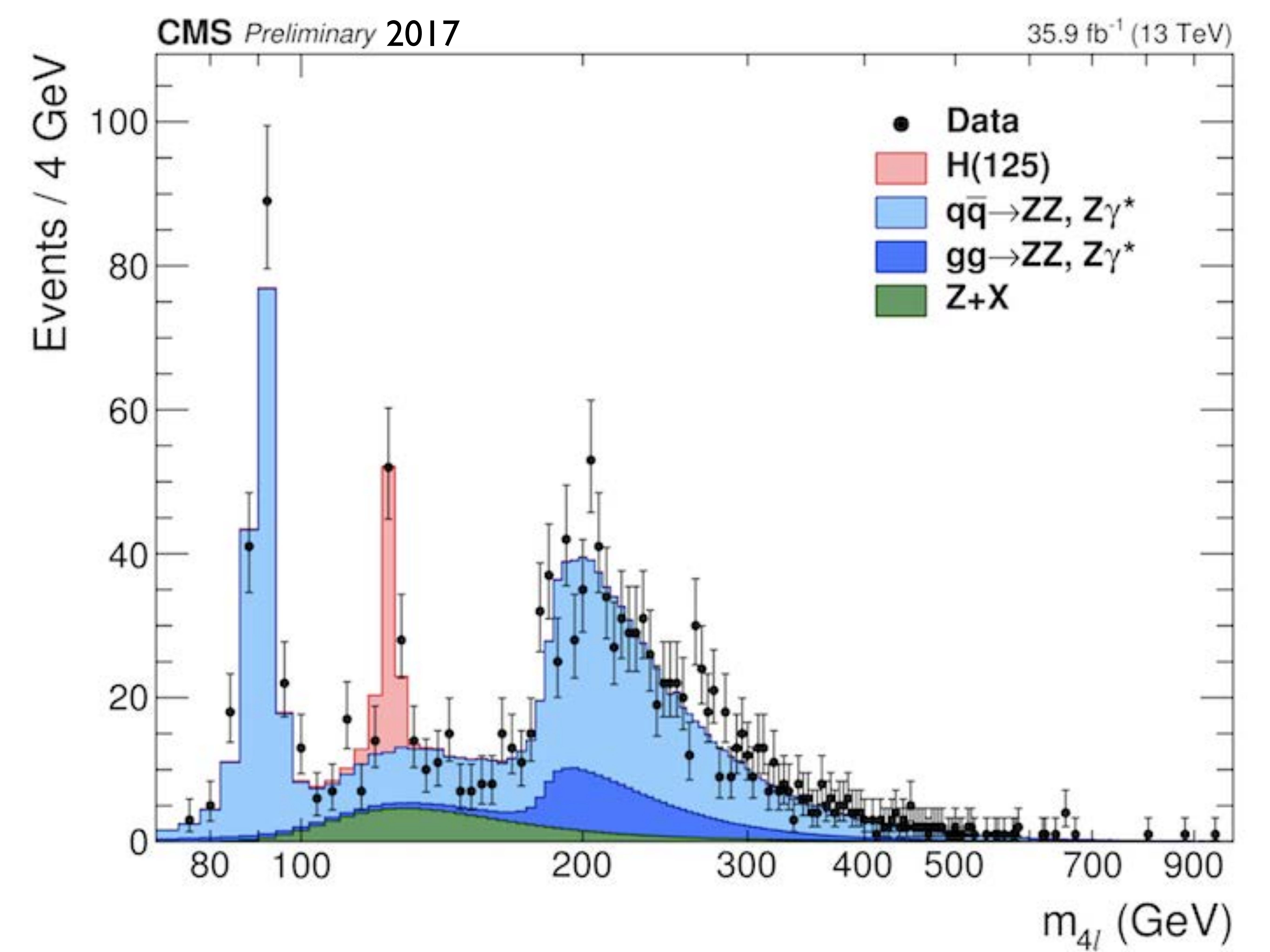
W^+W^-, ZZ, HH, HZ satisfy s-wave unitarity,

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

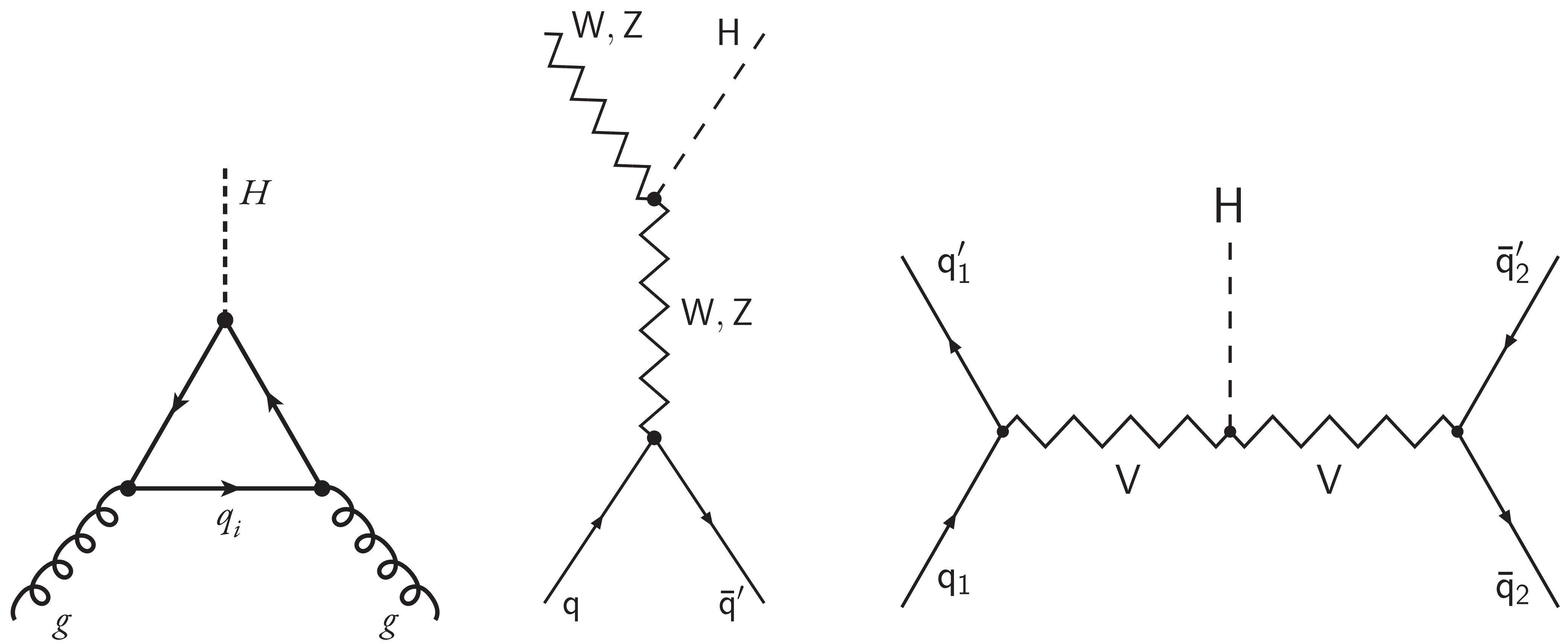
- If bound is respected, perturbation theory is "everywhere" reliable
- If not, weak interactions among $W^\pm$, Z, H become strong on 1-TeV scale

New phenomena are to be found around 1 TeV

Large Hadron Collider

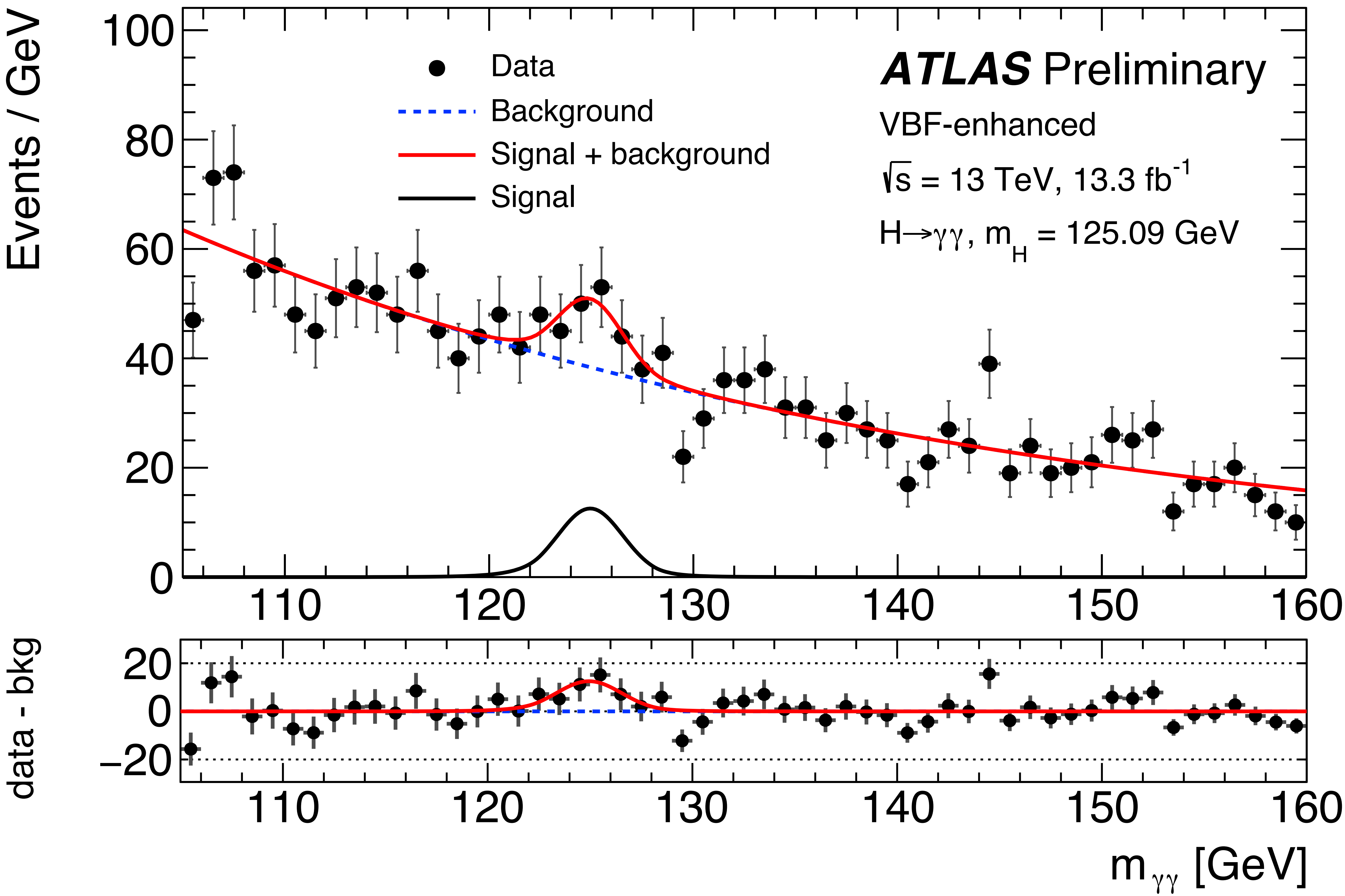

CMS Preliminary 2017
35.9 fb-1 (13 TeV)
Events / 4 GeV
Data
H(125)
qq̄→ZZ, Zγ*
gg→ZZ, Zγ*
Z+X
0
20
40
60
80
100
80
100
200
300
400
500
700
900
m4l (GeV)

LHC can study Higgs boson in many channels



+ $Ht\bar{t}$

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



Events / GeV
Data
Background
Signal + background
Signal
ATLAS Preliminary
VBF-enhanced
√s = 13 TeV, 13.3 fb-1
H→γγ, mH = 125.09 GeV
data - bkg
mγγ [GeV]

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^+

$Hf\bar{f}$ couplings
not universal

evidence for $\tau^+\tau^-$, $b\bar{b}$, $t\bar{t}$; $\mu^+\mu^-$ limited
Only third-generation fermions tested

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

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

Account for quark masses, mixings } ΦBSM

Account for charged-lepton 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 $\propto$ masses?

Are there others?

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

SM branching fractions to gauge bosons?

Decays to new particles?

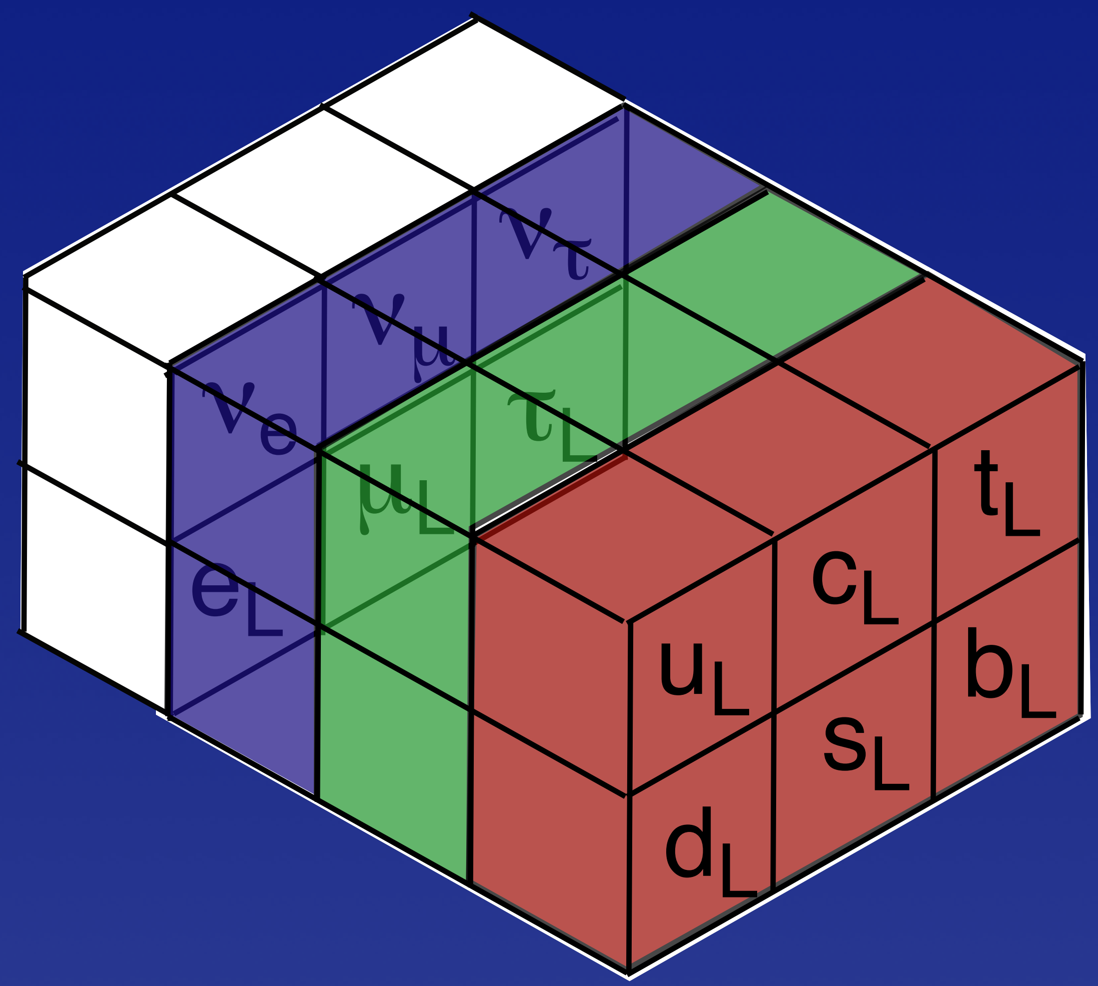
All production modes as expected?

Implications of $M_H \approx 125$ GeV?

Any sign of new strong dynamics?

A Unified Theory?

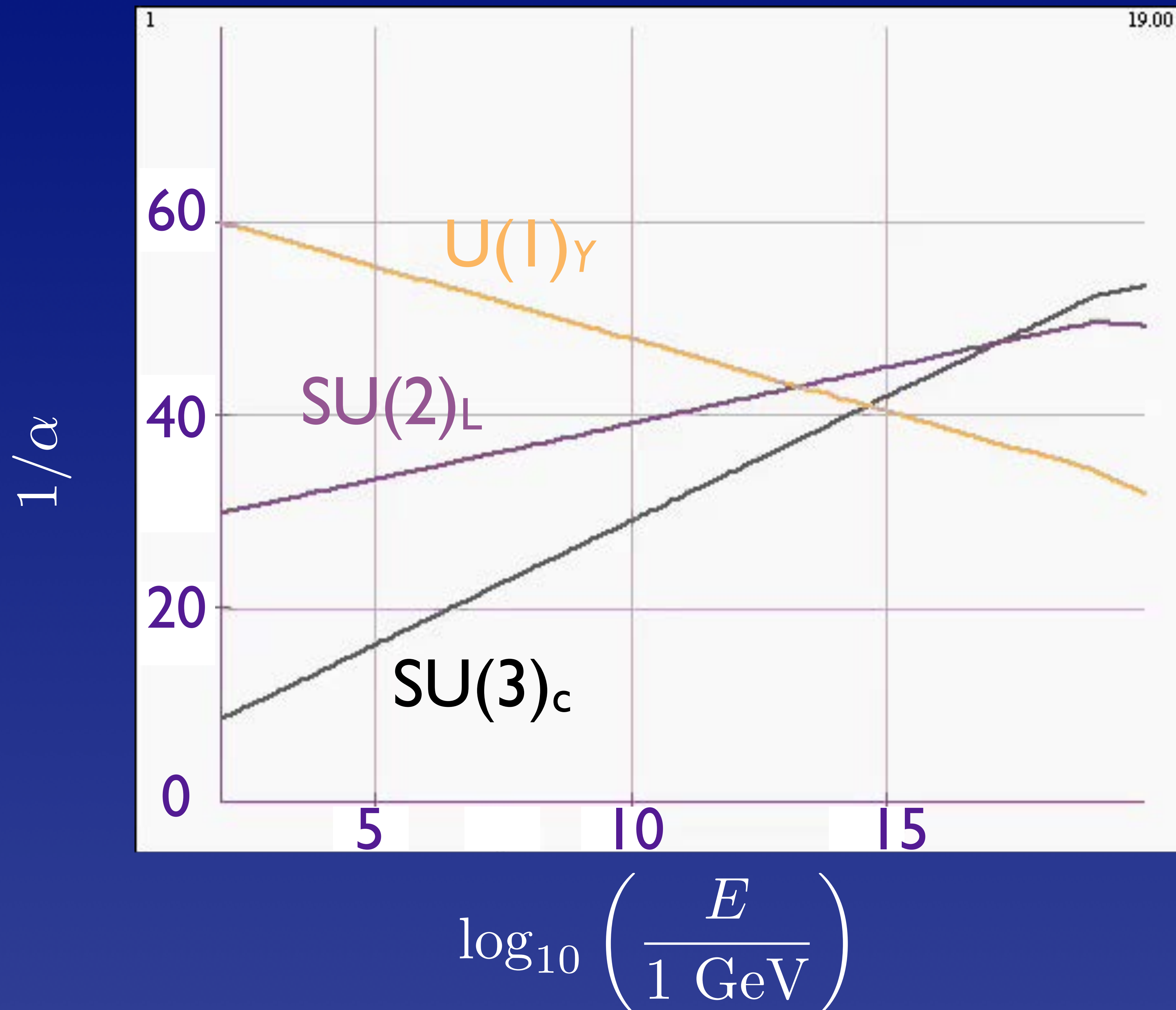
Why are atoms so remarkably neutral?



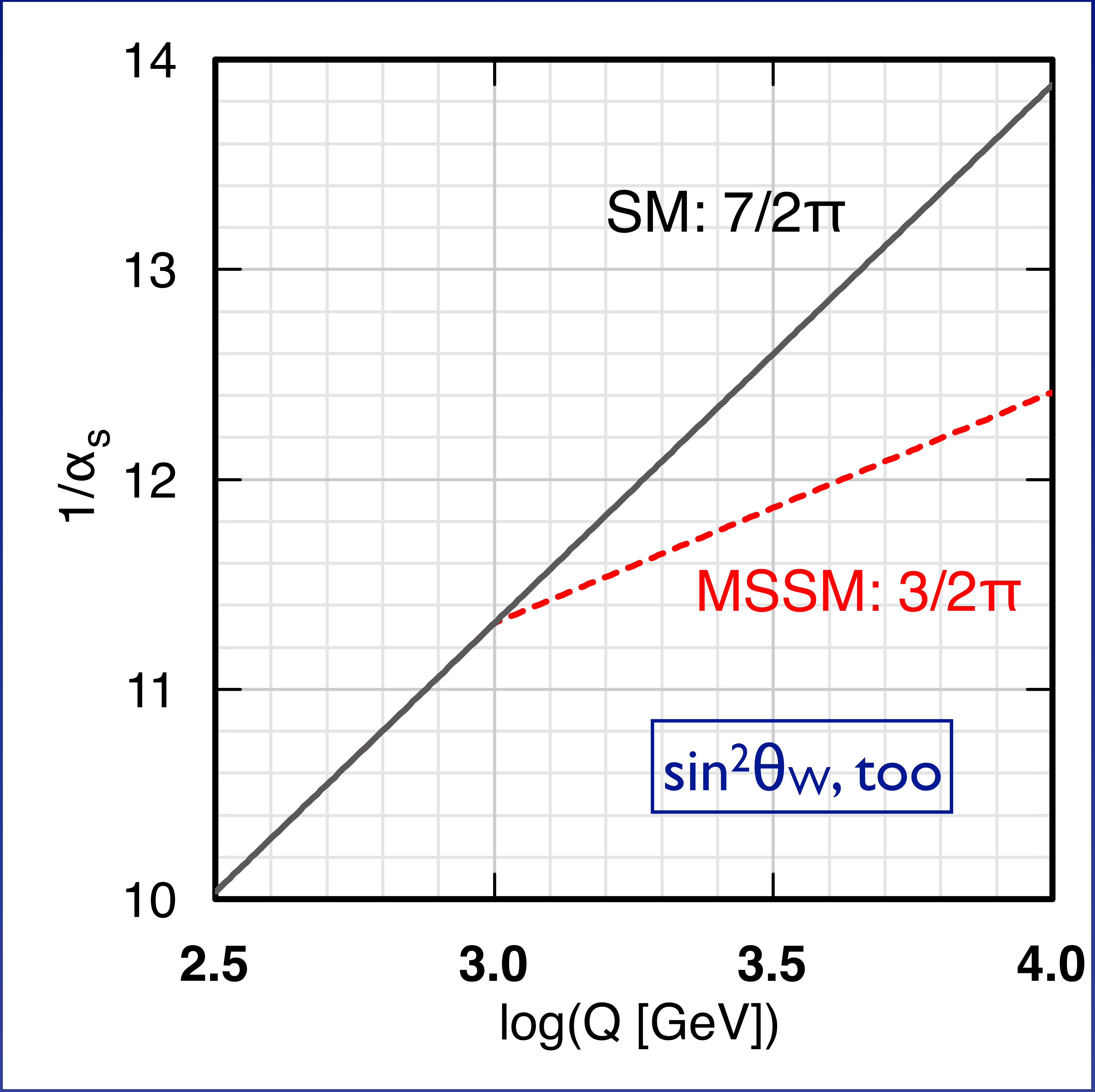
Coupling constant unification?

Extended quark–lepton families:
proton decay!

Unification of Forces?



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



More new physics on the TeV scale?

WIMP dark matter

Naturalness

Hierarchy problem: EW scale $\ll$ Planck scale

Vacuum energy problem

Clues to origin of EWSB

SUSY 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.

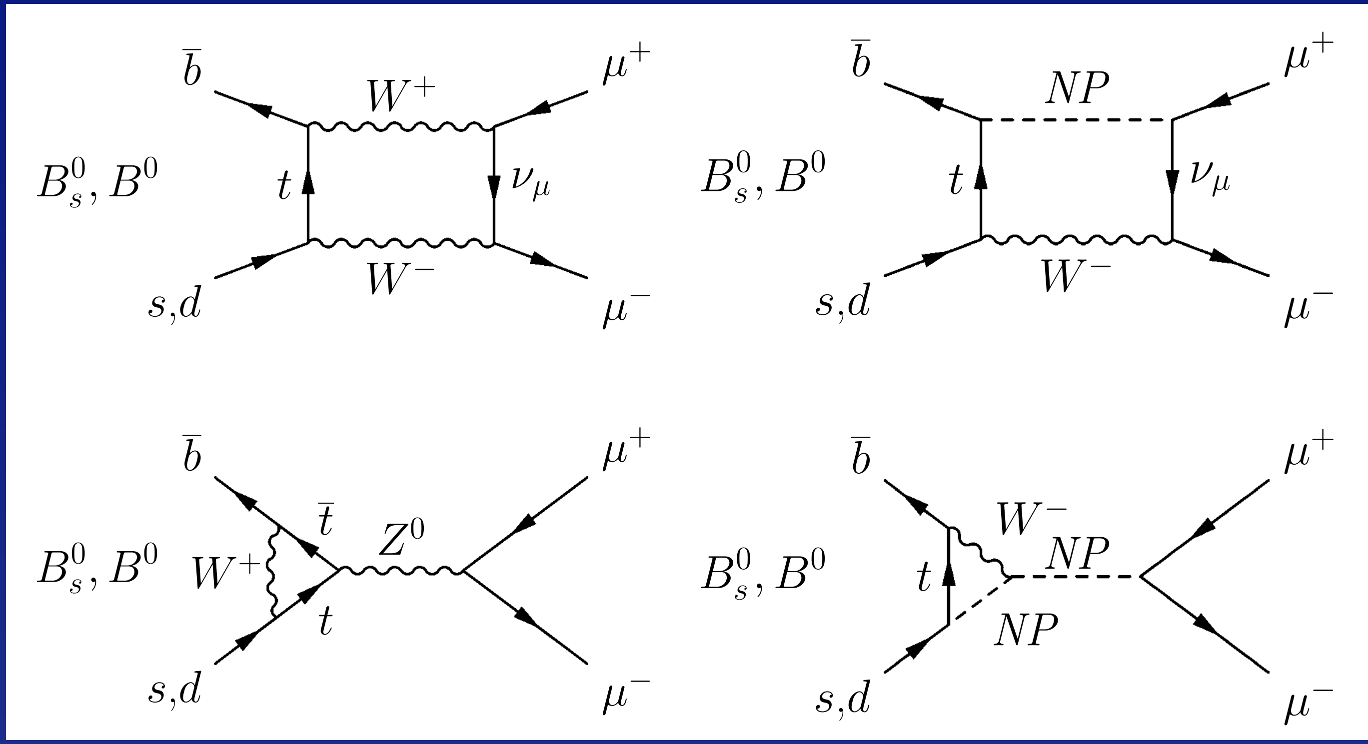
How have we misunderstood the hierarchy problem?

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?

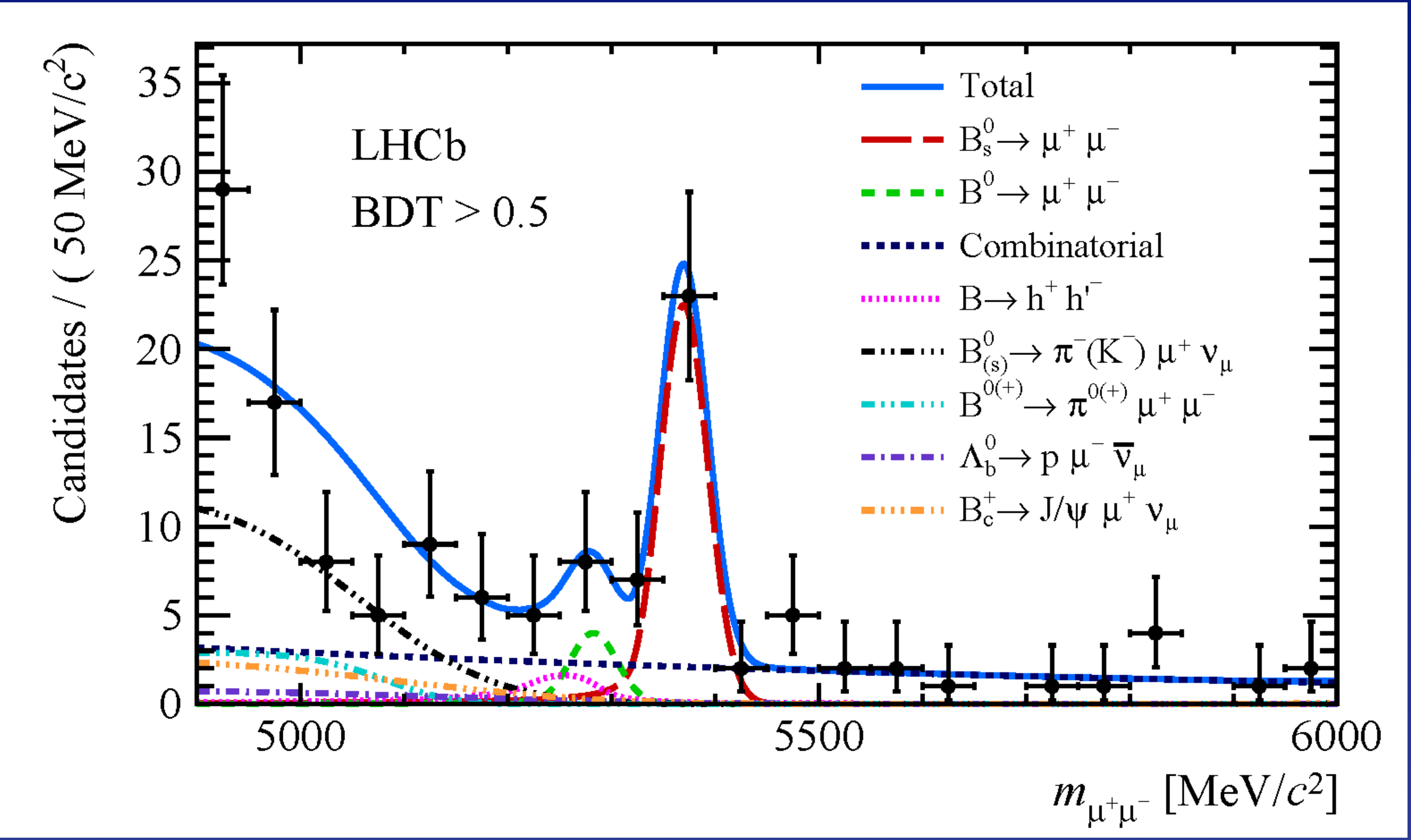
Rare Processes: Flavor-changing neutral currents



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

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

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

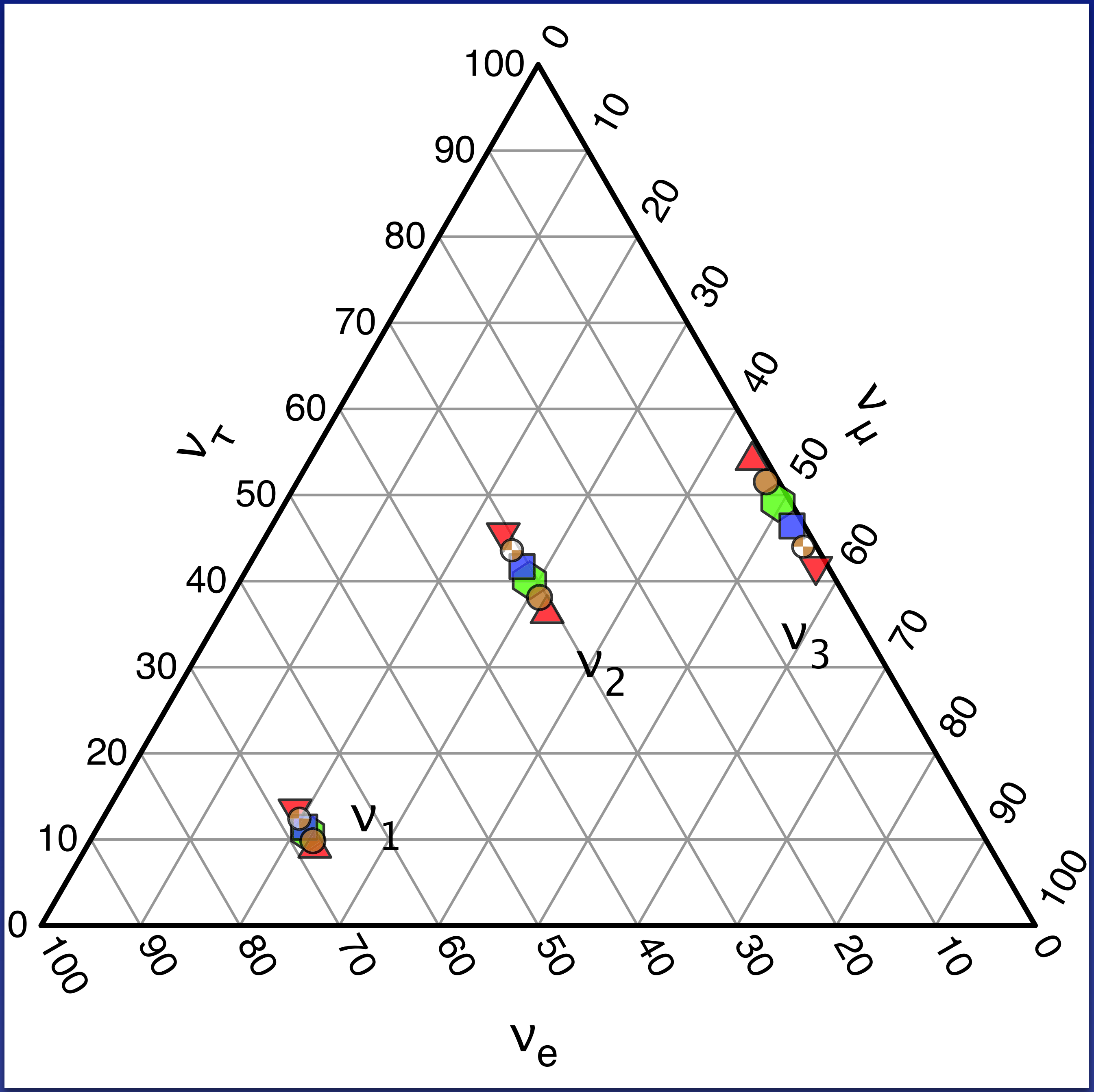


LHCb: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.0^{+0.7}_{-0.6}) \times 10^{-9}$

The unreasonable effectiveness of the standard model

arXiv:09053187 arXiv:1503.01756 arXiv:1507.02977

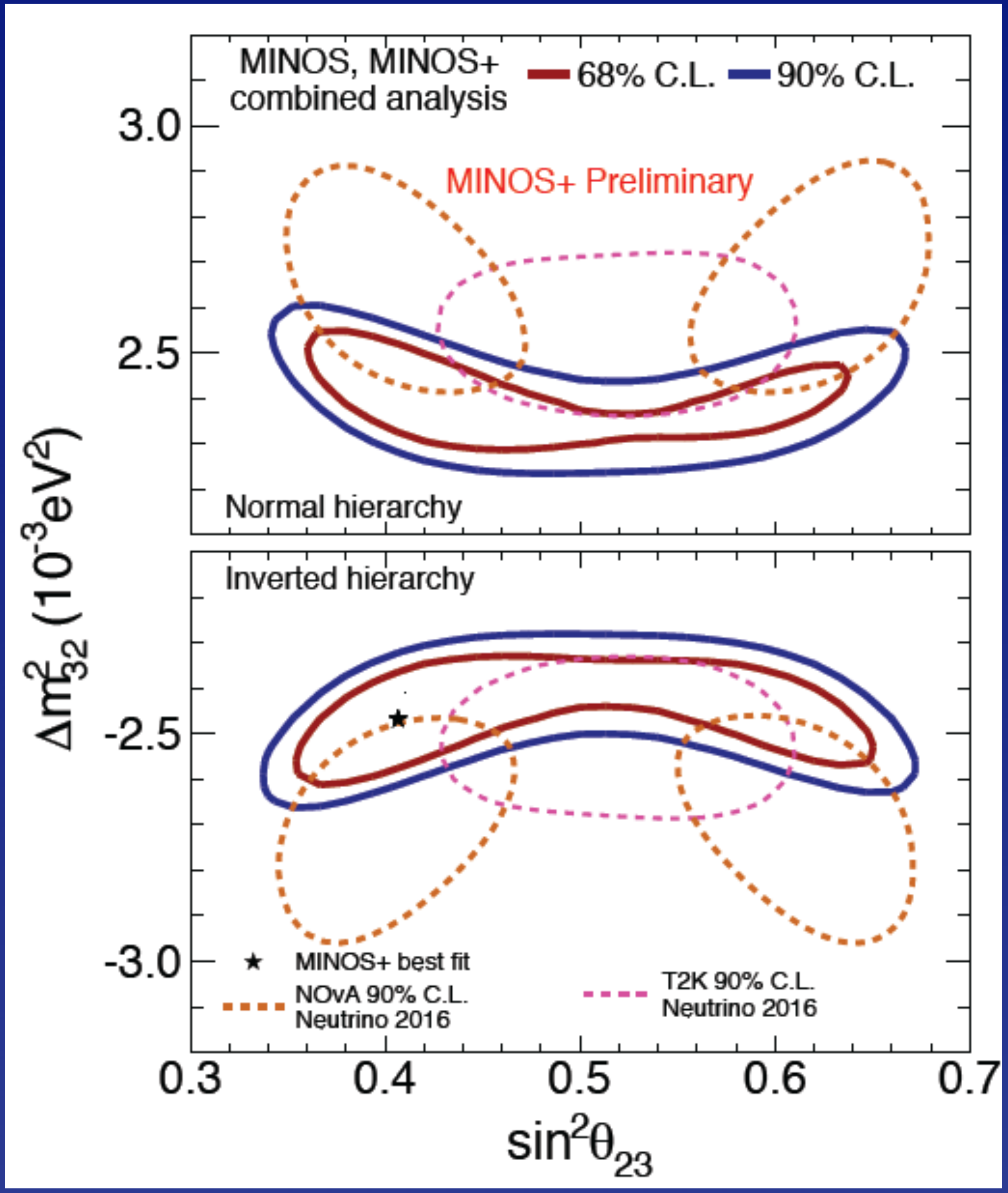
Some outstanding questions in ν physics
What is the composition of ν_3?



Before recent experiments

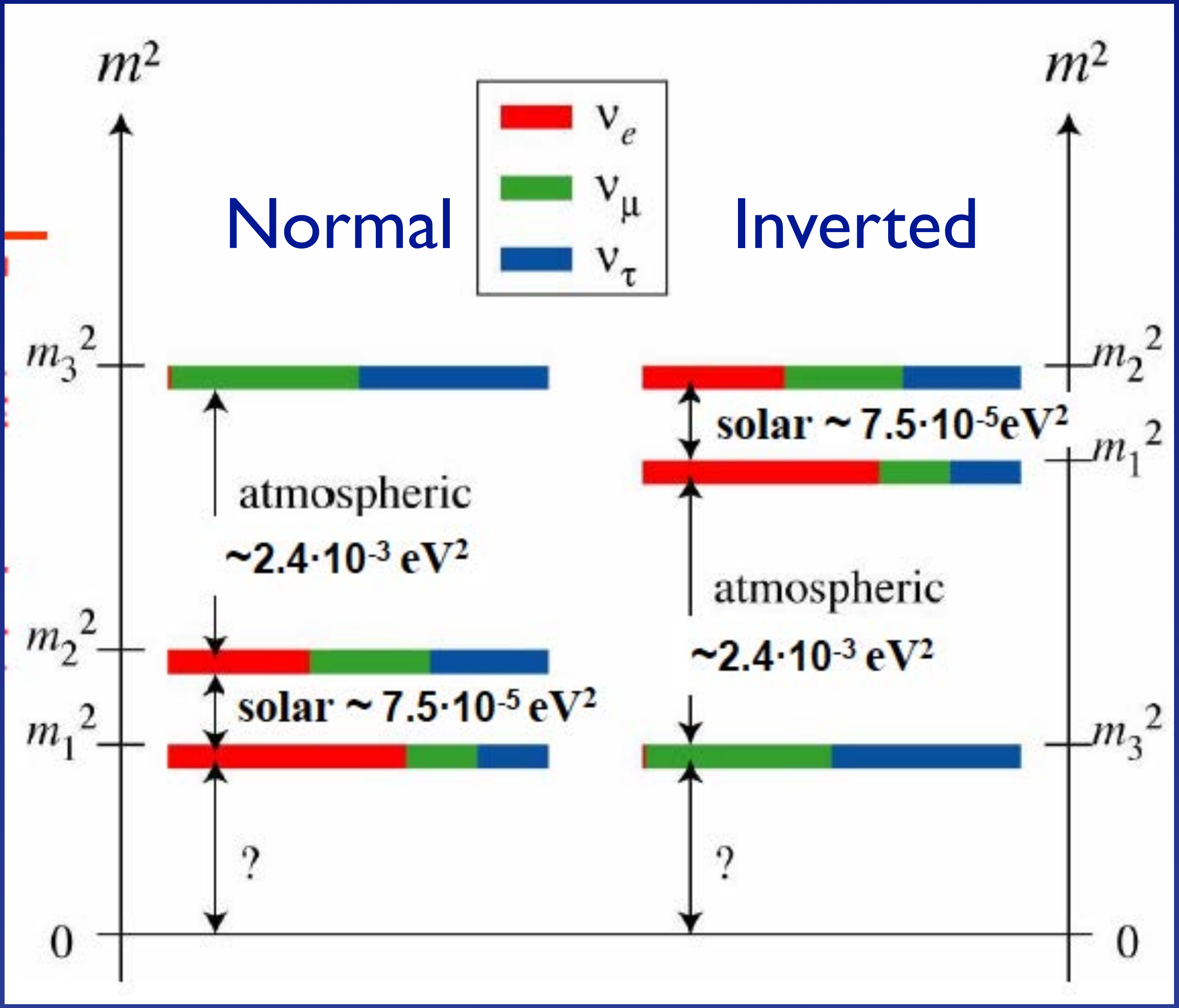
Some outstanding questions in ν physics

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

?

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?

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!