I would like to know …

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?

Nikhef Colloquium · 20 April 2018

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?

(2005) In a decade or two, we can hope to …

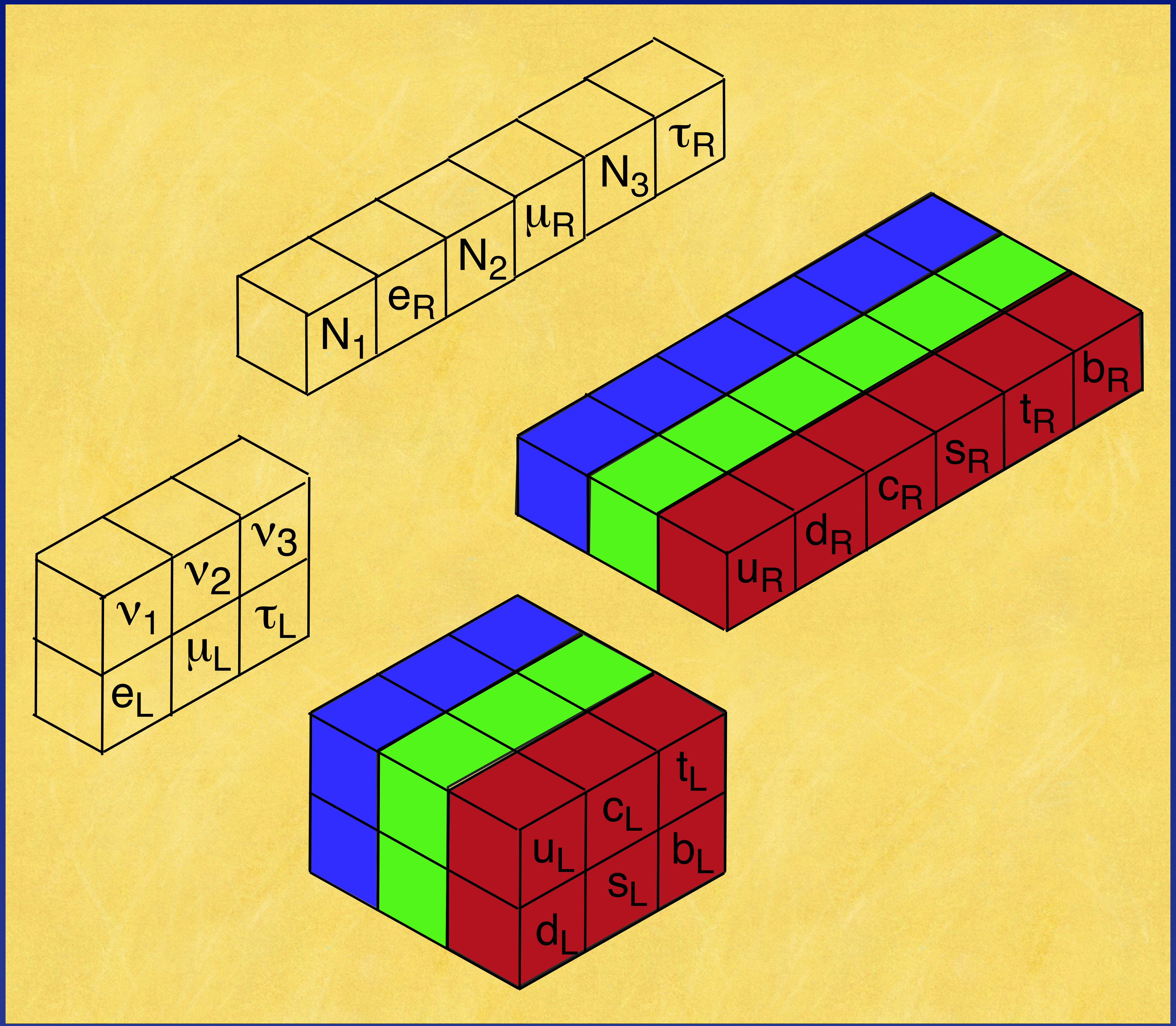
Understand electroweak symmetry breaking
Observe the Higgs boson
Measure neutrino masses and mixings
Establish neutrinos as Majorana particles
Thoroughly explore CP violation in *B* decays
Exploit rare decays (*K*, *D*, …)
Observe neutron's EDM, pursue electron's
Use top quark as a tool
Observe new phases of matter
Understand hadron structure quantitatively
Uncover the full implications of QCD
Observe proton decay
Understand the baryon excess
Catalogue matter and energy of the universe
Measure dark energy equation of state
Search for new macroscopic forces
Determine the unifying symmetry

Detect neutrinos from the universe
Learn how to quantize gravity
Learn why empty space is nearly massless
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 the origin of large-scale structure
Observe gravitational radiation
Solve the strong CP problem
Learn whether supersymmetry is TeV-scale
Seek TeV-scale dynamical symmetry breaking
Search for new strong dynamics
Explain the highest-energy cosmic rays
Formulate the problem of identity

Before LHC

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

We do not know what the Universe at large is made of.



Mendele'ev did not know of the noble gases.

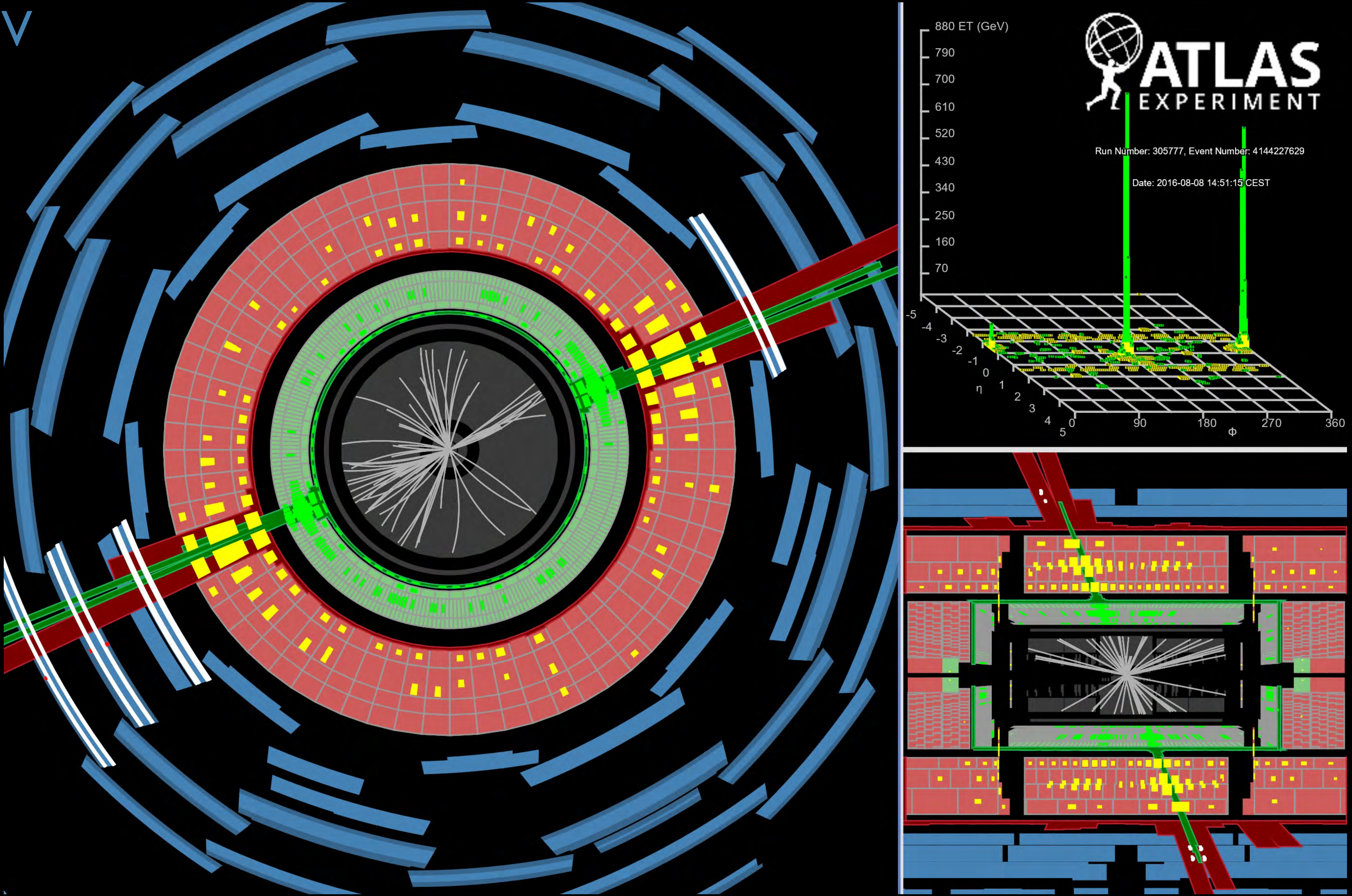
Interactions: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries

8 gluons

The World's Most Powerful Microscopes

nanonanophysics

8.12 TeV



Quantum Chromodynamics: QCD

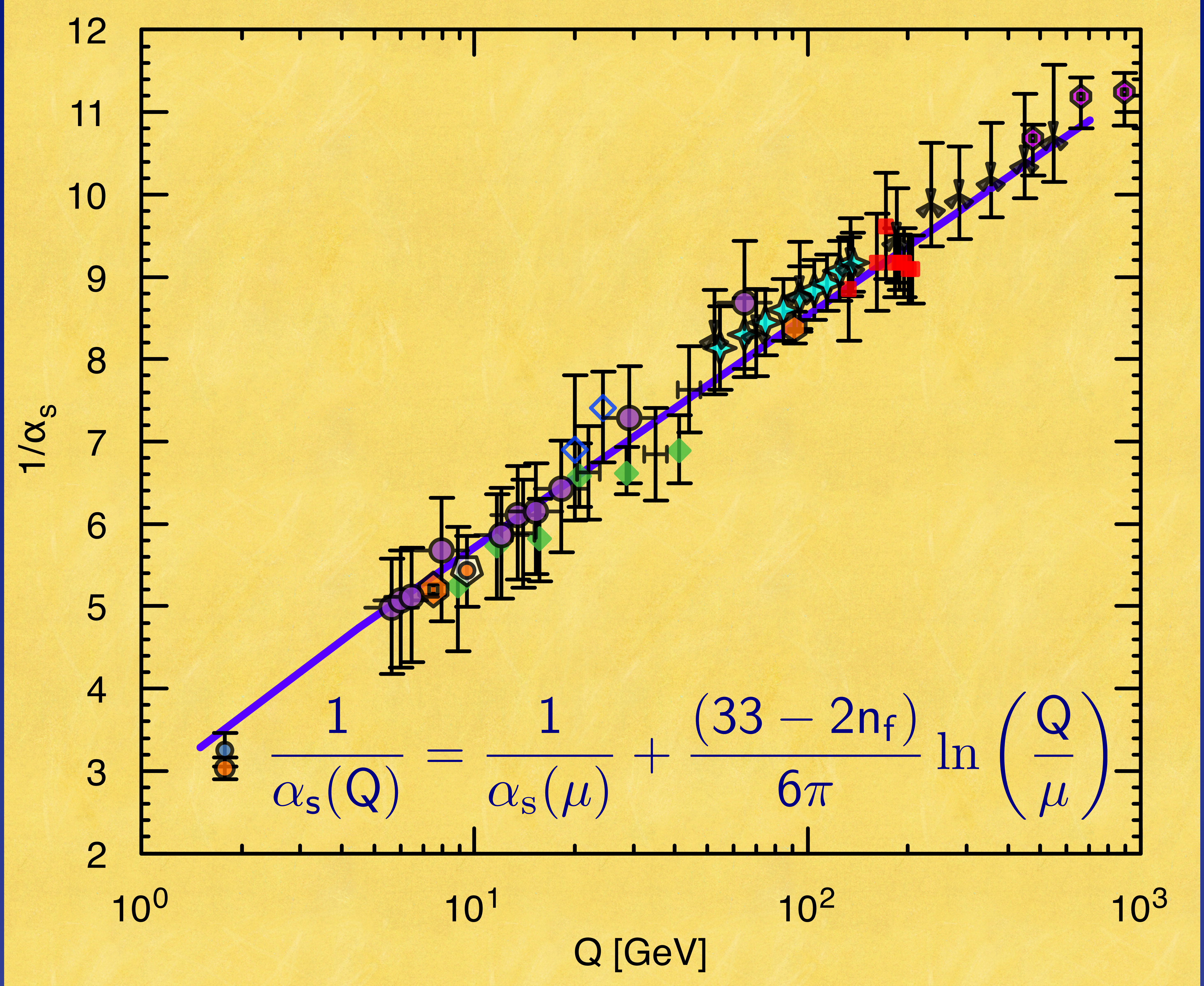
Dynamical basis for quark model

Gluons (vector force particles) mediate interactions among the quarks and themselves experience strong interactions.

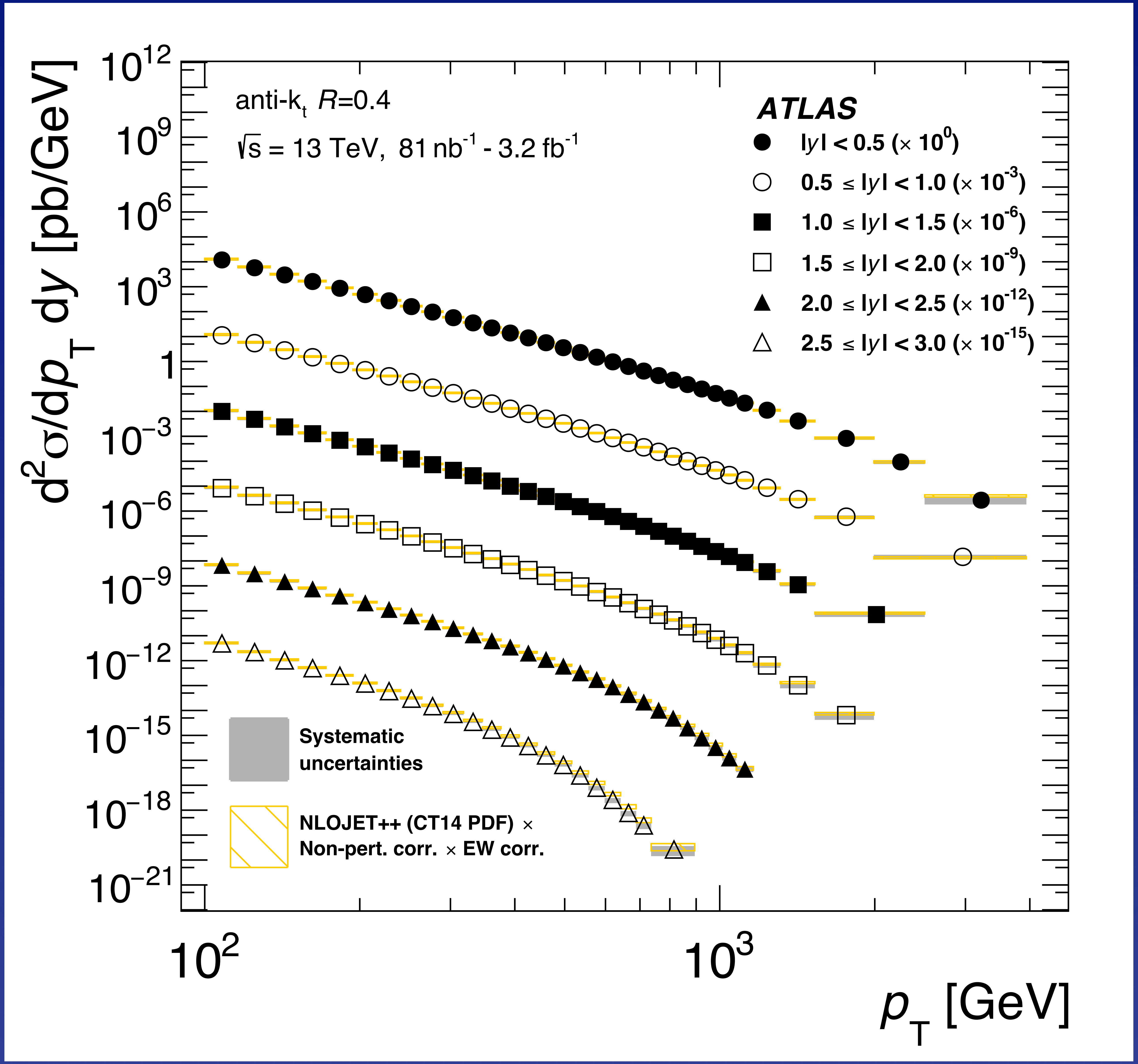
Contrast *photons* of QED, which mediate interactions among charged particles, not among themselves.

Quark, gluon interactions ⇛ nuclear forces

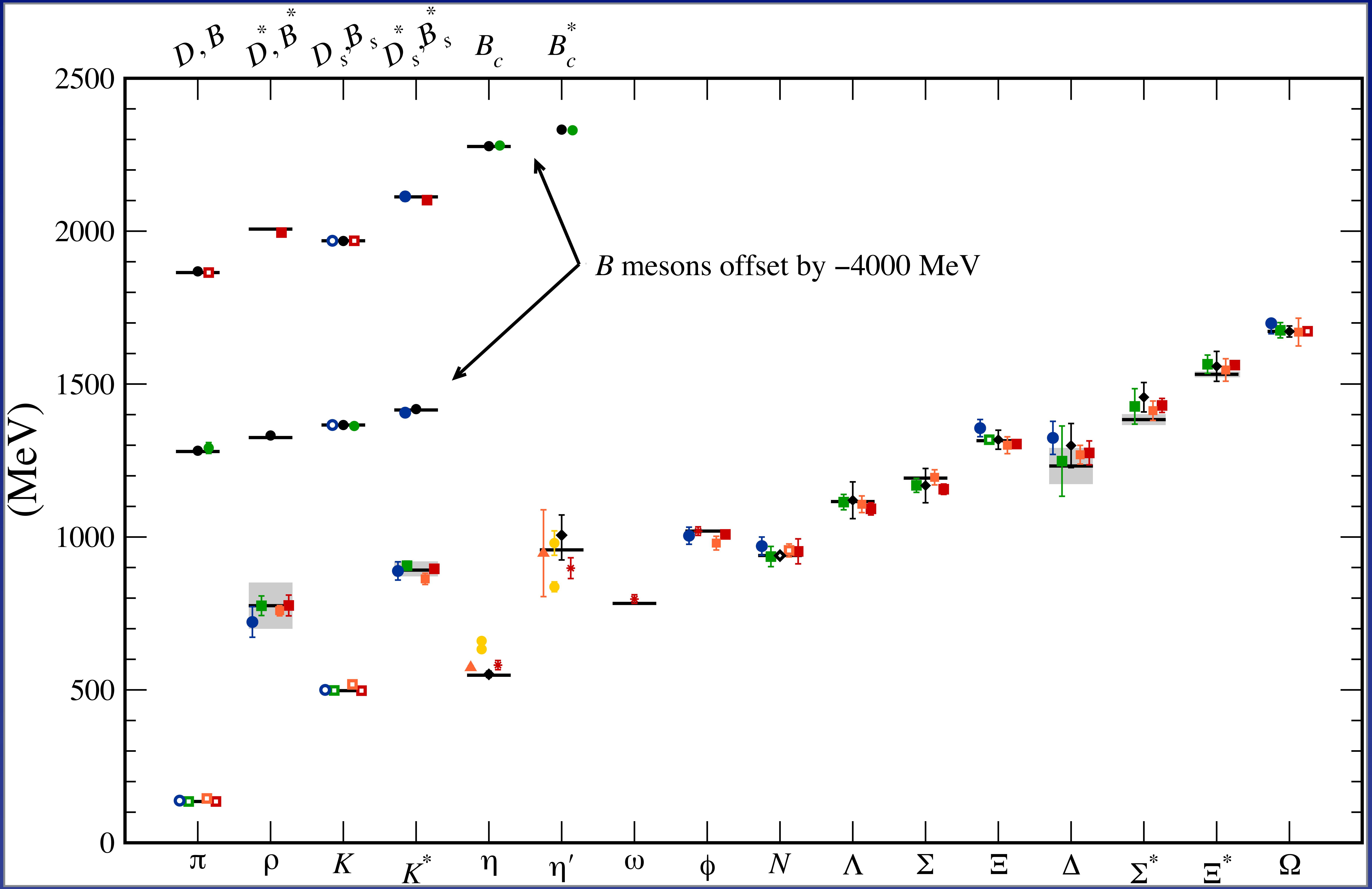
Antiscreening evolution of the strong coupling



Jet production: success of perturbative QCD



Hadron masses from (nonperturbative) lattice QCD



Kronfeld, update of arXiv:1203.1204

sum of parts

rest energy

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

up and down quarks contribute few %

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

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 – *massive gluon partners?*

*modulo Strong CP Problem

New phenomena within QCD?

Multiple production beyond diffraction + short-range order?

High density of few-GeV partons … thermalization?

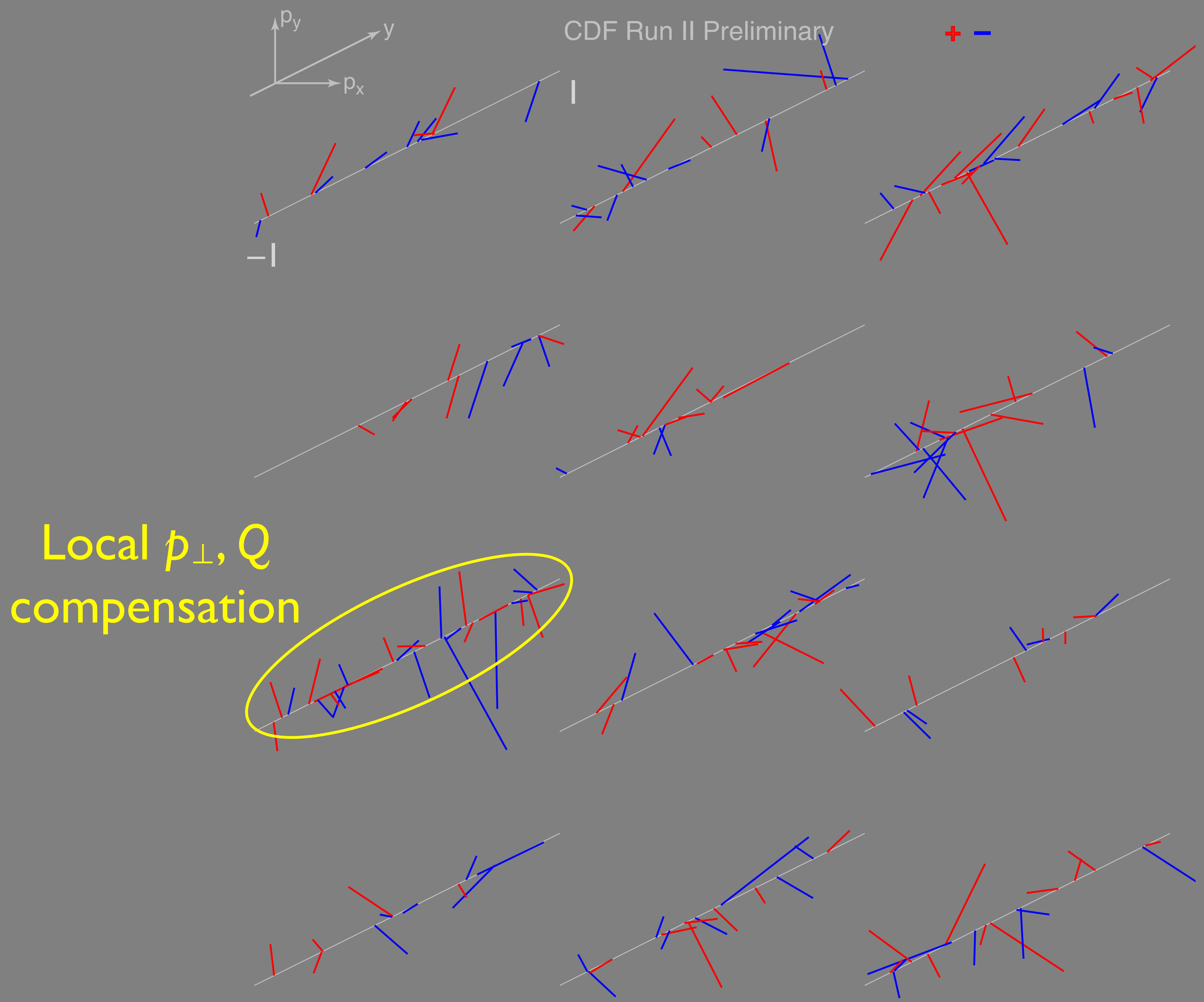
Long-range correlations in y (or η)?

Unusual event structures …

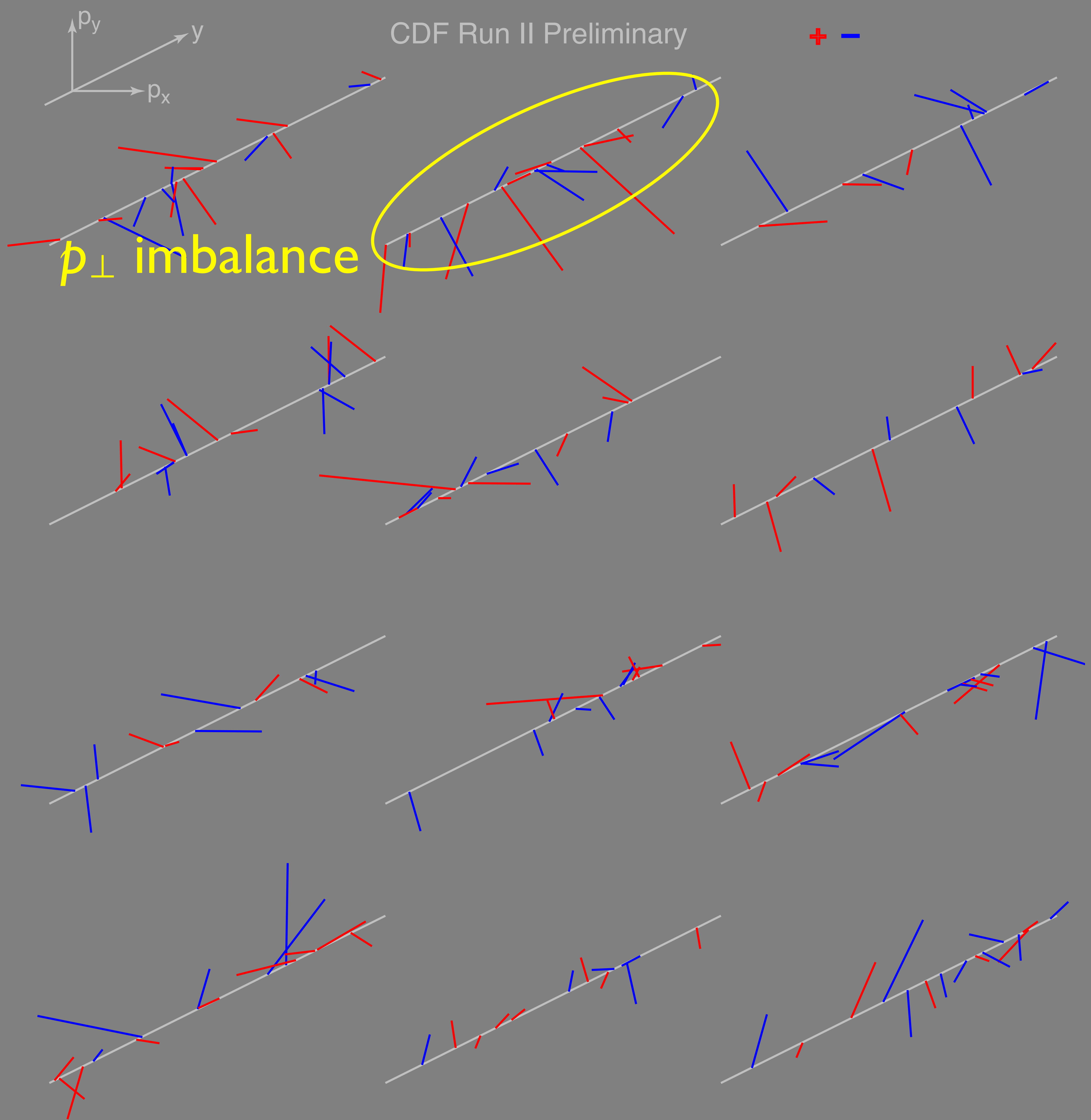
Look at events in informative coordinates.

More is to be learned from the river of events than from a few specimens!

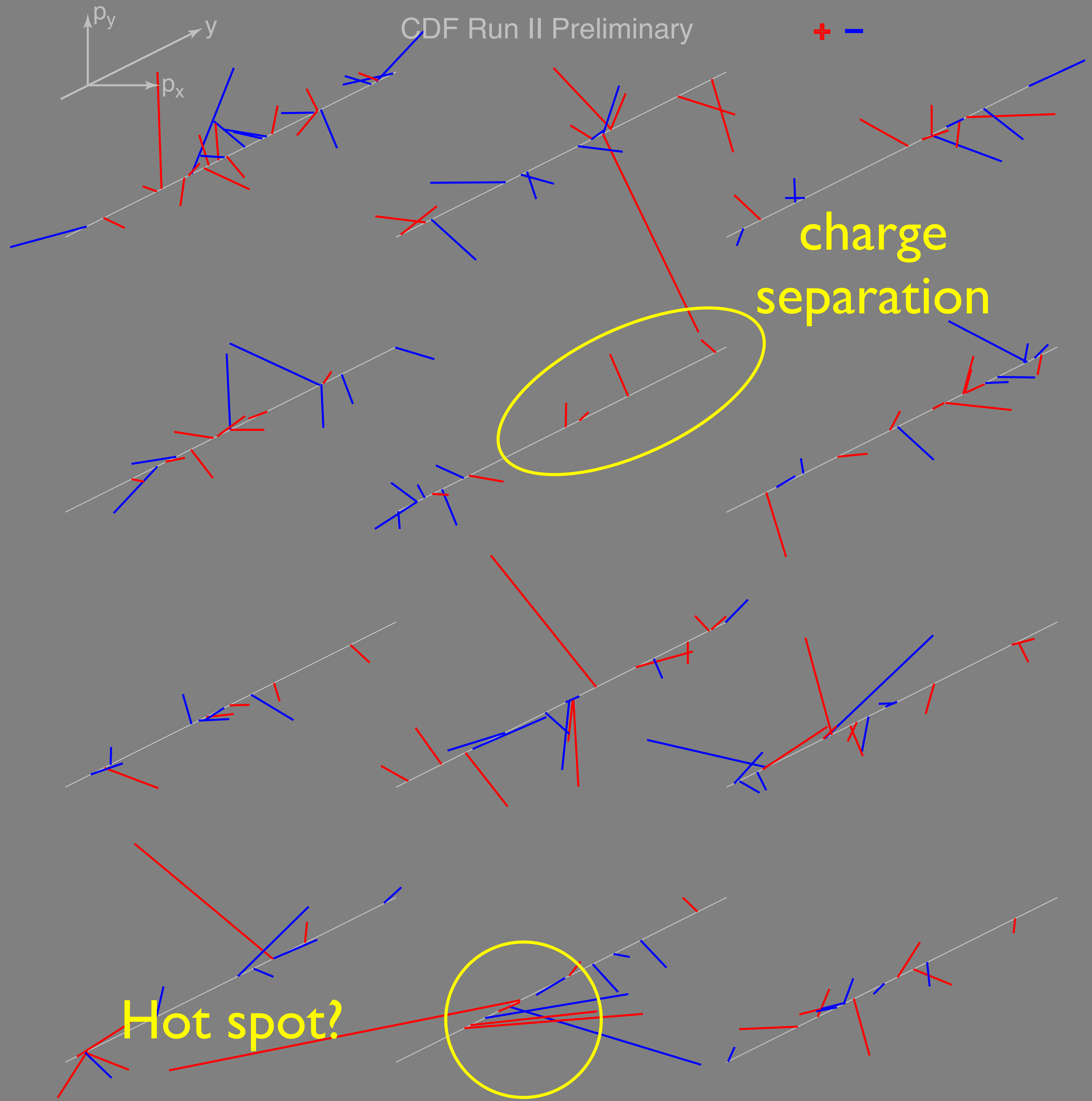
Learning to See at the Large Hadron Collider, 1001.2025



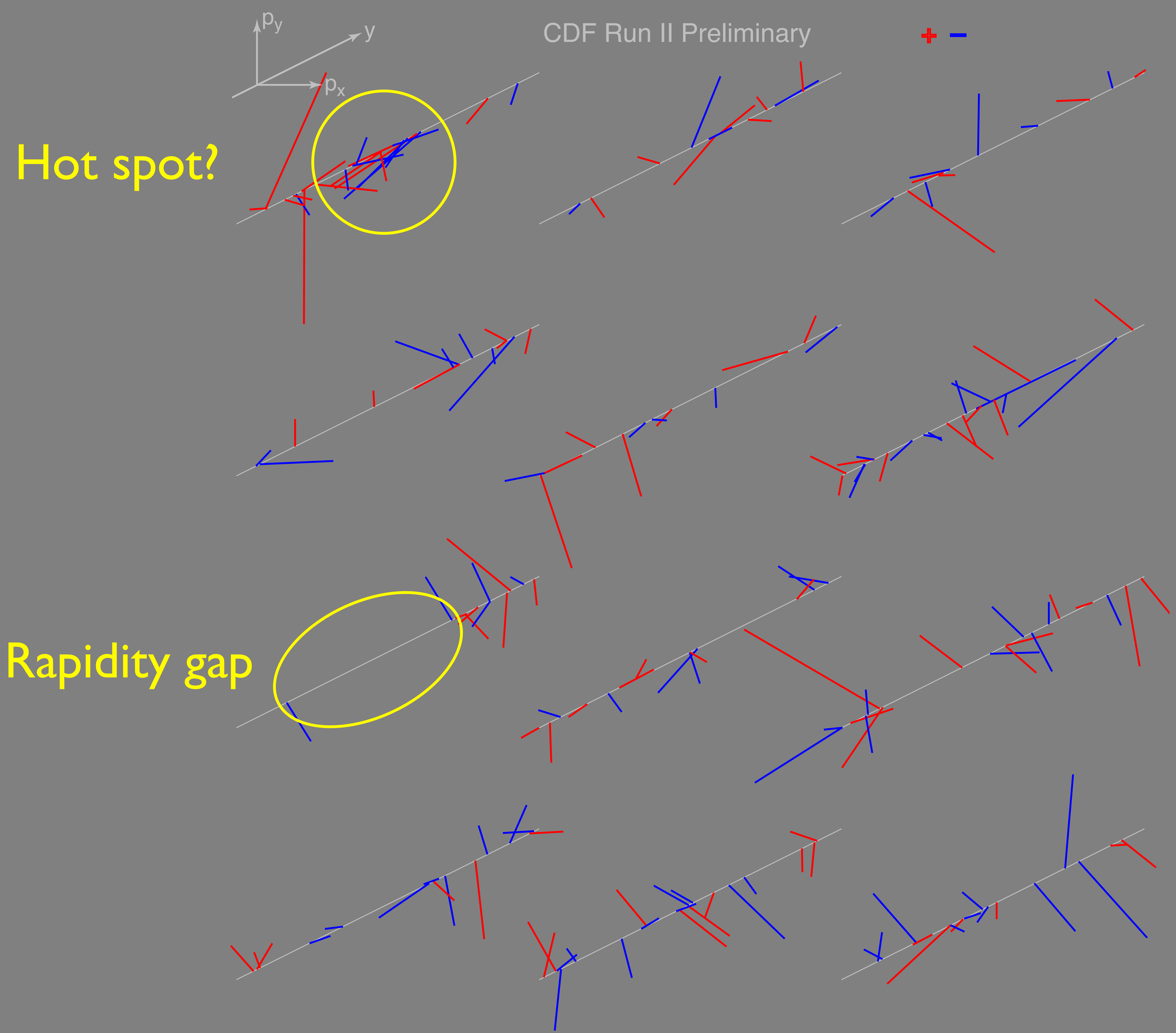
p_y
y
p_x
CDF Run II Preliminary
+ −
1
−1
Local $p_\perp$, Q
compensation



p_y
y
p_x
CDF Run II Preliminary
+ −
$p_\perp$ imbalance



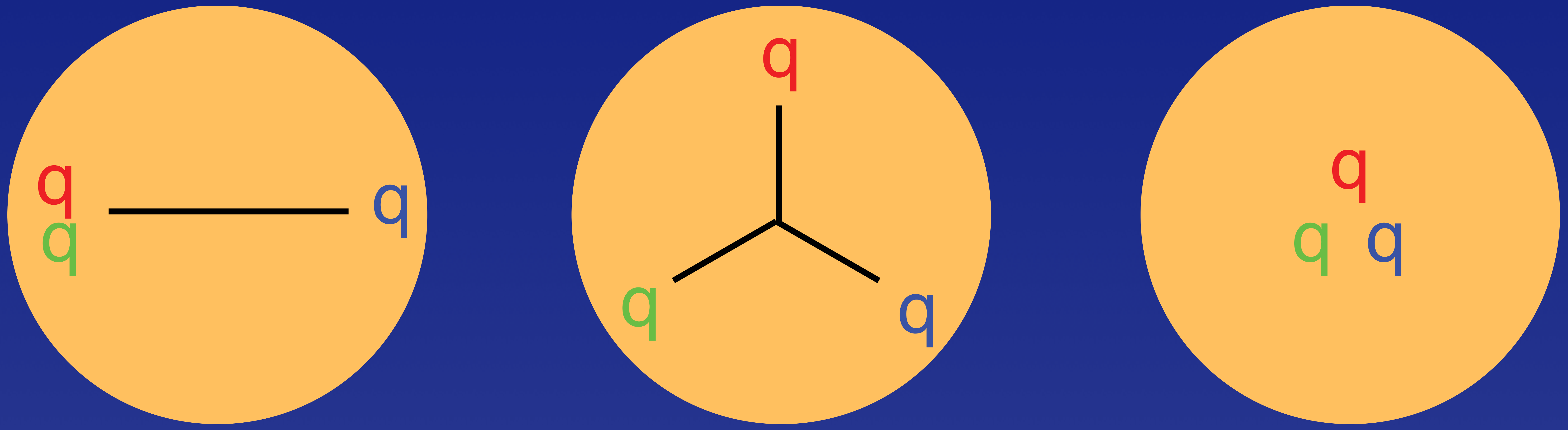
CDF Run II Preliminary
+ −
p_y
y
p_x
charge separation
Hot spot?



CDF Run II Preliminary
+ −
p_y
y
p_x
Hot spot?
Rapidity gap

Correlations among the partons?

A proton knows it is a proton.
Single-spin asymmetries imply correlations.
What else?



Bjorken (2010)

Can we distinguish different configurations?
Interplay with multiple-parton interactions?

Machine learning opportunities?

ATLAS

What is a proton?

At high energy: an unseparated, broadband beam
of quarks, antiquarks, and gauge bosons (primarily gluons),
and perhaps other constituents, yet unknown.

↳50 years of an amazingly robust idealization:
Renormalization-group–improved Parton Model
with one-dimensional parton distributions

Questions: intrinsic heavy flavors, saturation at small *x*

development of generalized parton distributions
and transverse-momentum distributions

What is a proton?

Quasistatic properties: interesting on their own,
have implications for interpretation of
dark matter searches: WIMP–*N* interactions

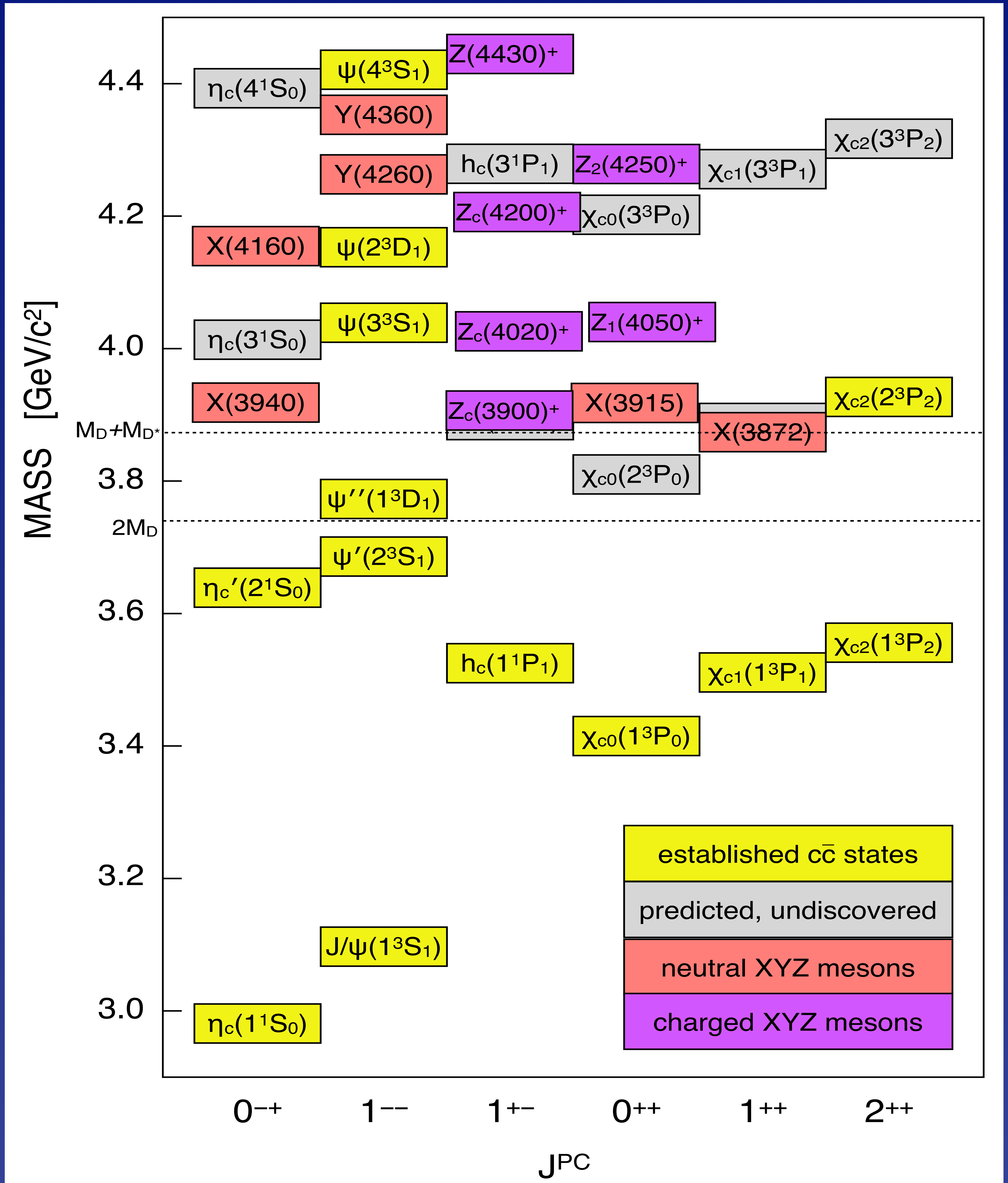
How does *H* interact with nucleon?

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

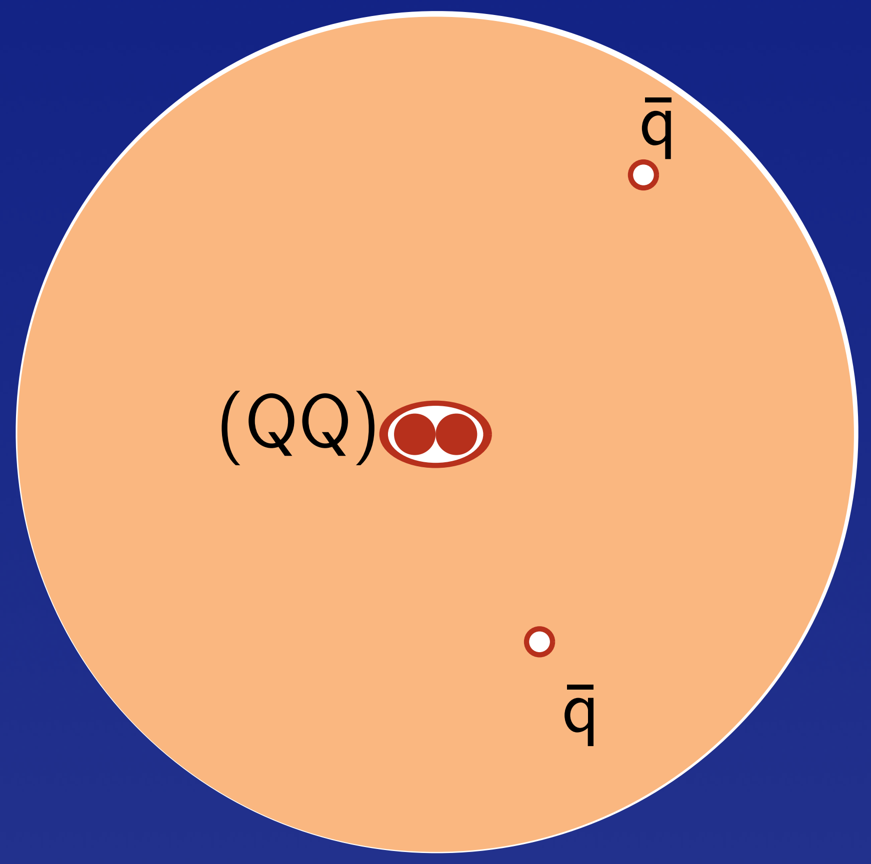
Muon-storage-ring Neutrino Factory could deliver
10^{20} ν per year for on-campus experiments

Polarized target? H/D target? Active target?
What would constitute the ideal experiment(s)?

New spectroscopy of quarkonium–associated states



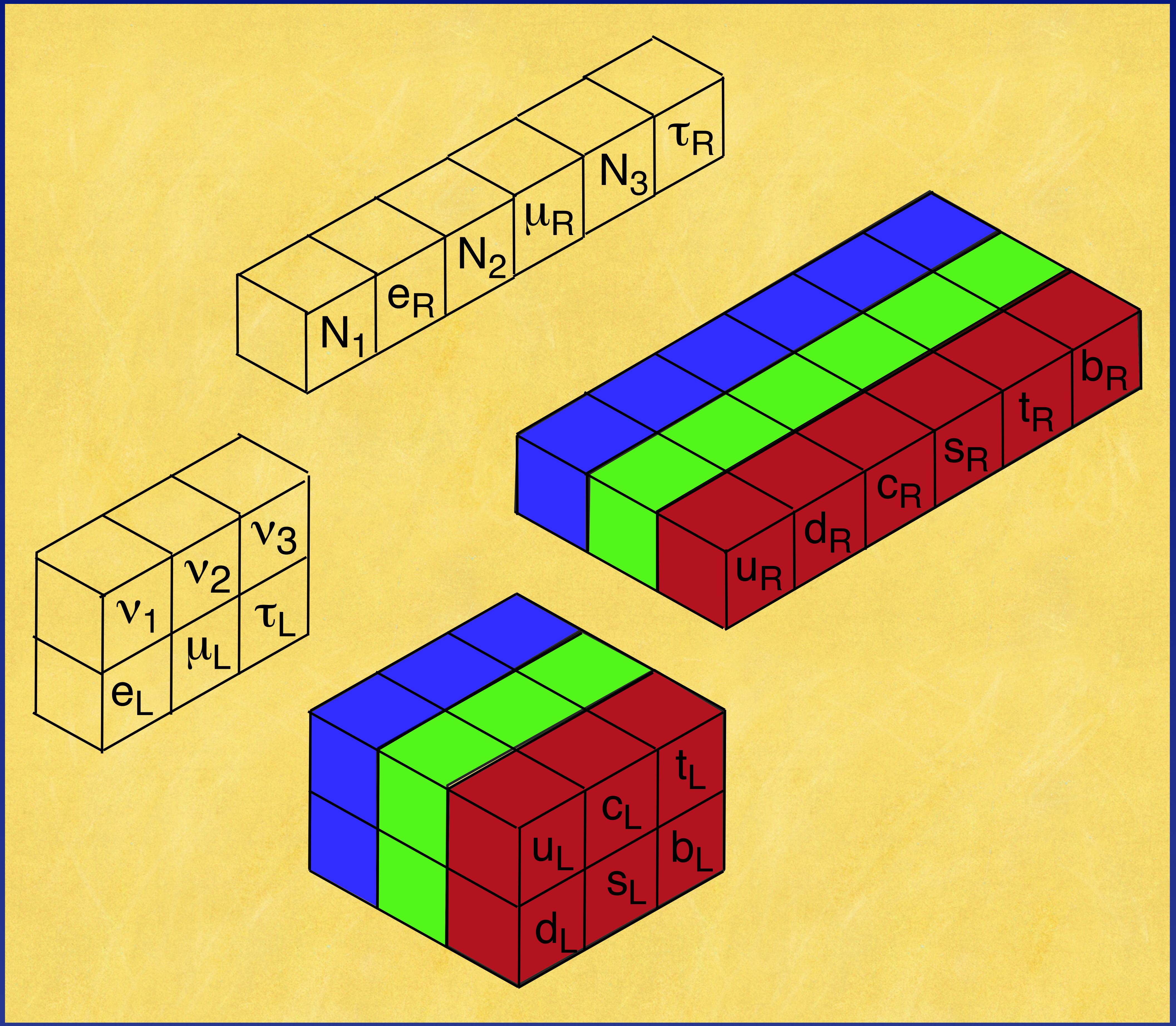
Stable doubly heavy tetraquark mesons



Eichten & CQ (PRL)

What body plans beyond qqq, $\bar{q}q$?

Electroweak Symmetry Breaking



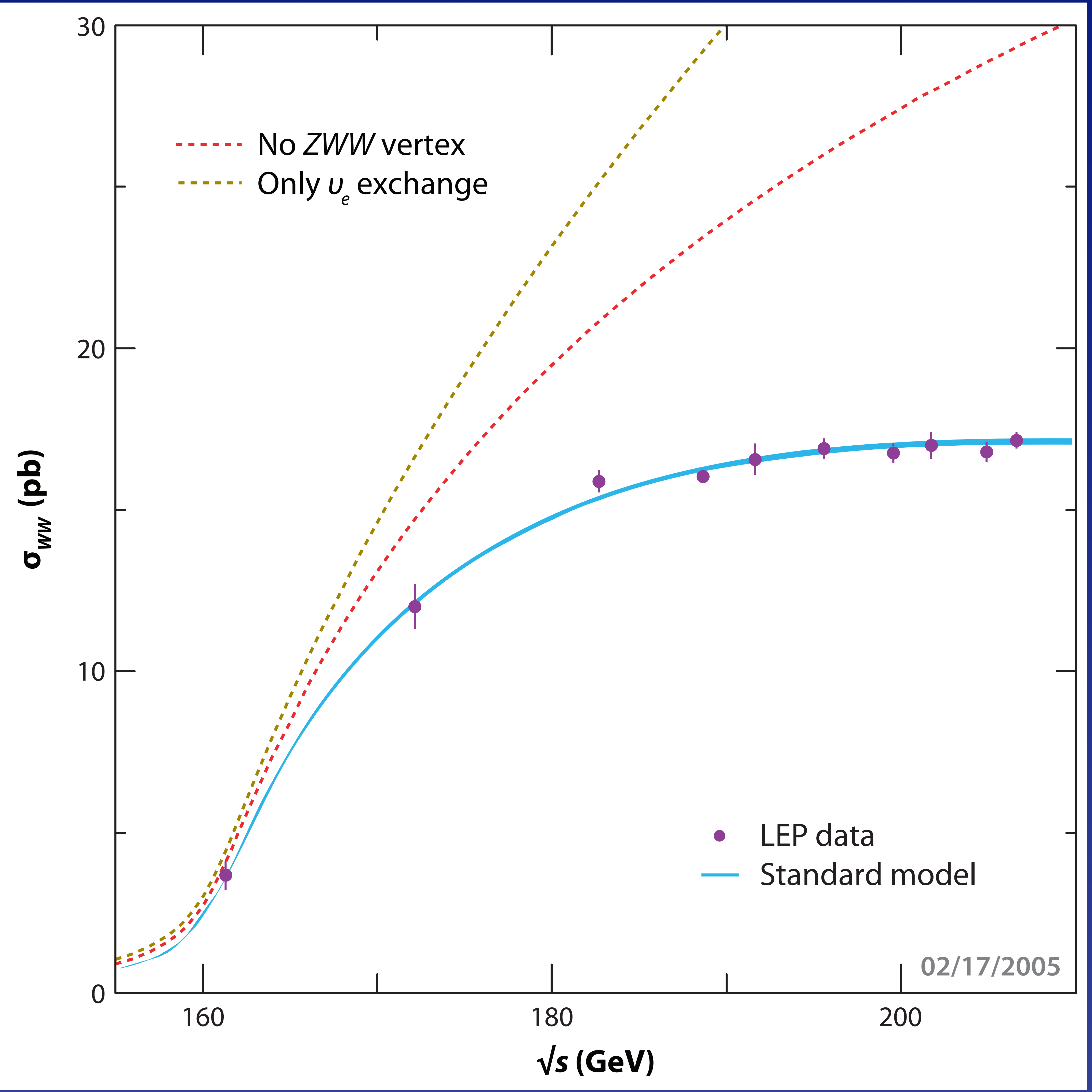
$U(1)_{EM}$

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

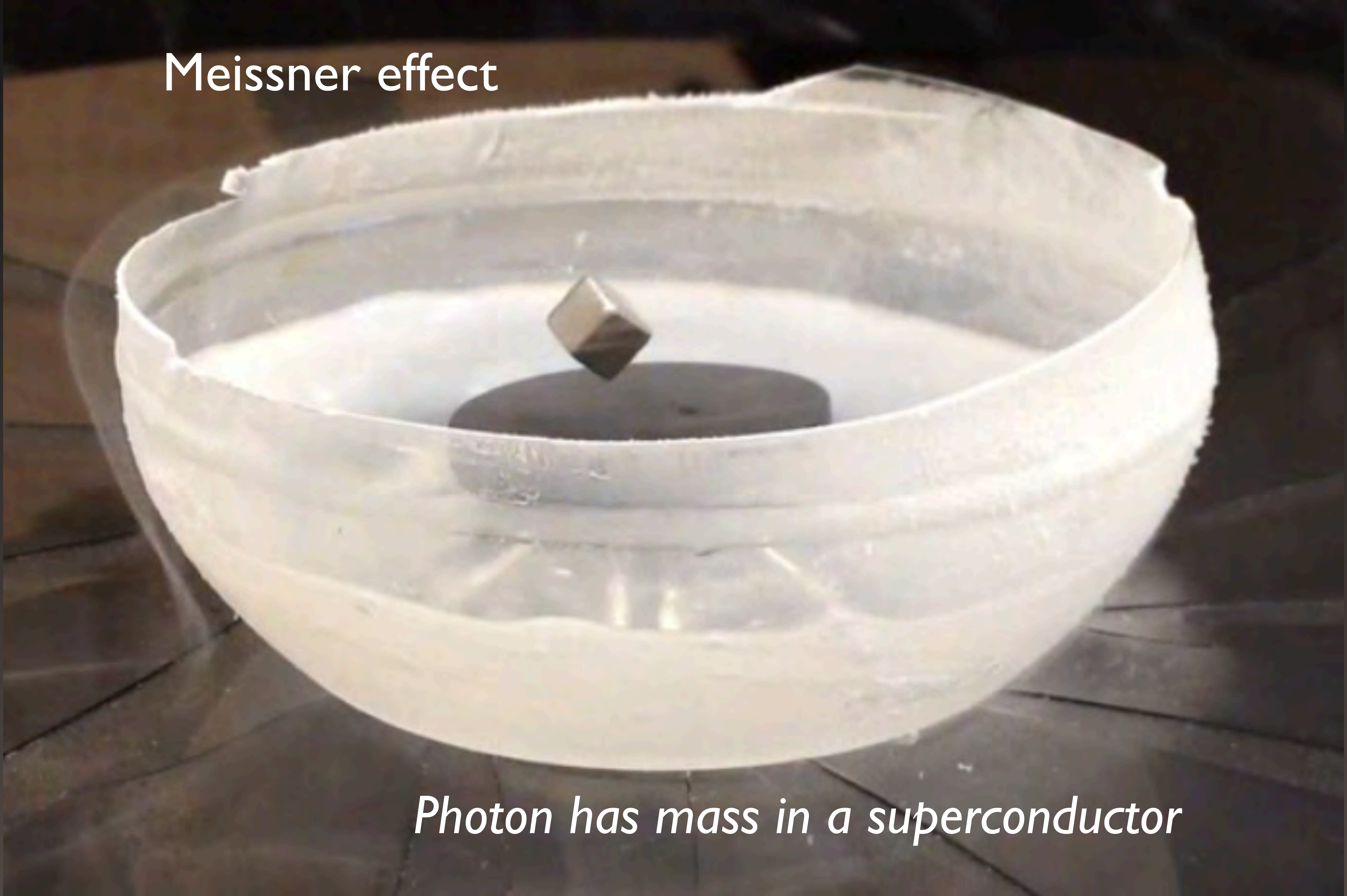
8 gluons $W^{\pm} \cdot Z^0 \cdot \gamma$

Gauge symmetry (group-theory structure) tested in

$$e^+e^- \rightarrow W^+W^-$$



Meissner effect



Photon has mass in a superconductor

Simplest example: Abelian Higgs model

= Ginzburg–Landau in relativistic notation

Yields massive photon
+
a massive scalar particle
"Higgs boson"

No mention of weak interactions in 1964 papers.

No question of origin of fermion masses
(not an issue for Yang–Mills theory or QED).

An *a priori* unknown agent hides electroweak symmetry

A force of a new character, based on interactions of an elementary scalar

OR

A new gauge force, perhaps acting on undiscovered constituents

OR

A residual force that emerges from strong dynamics among electroweak gauge bosons

OR

An echo of extra spacetime dimensions

OR

. . .

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

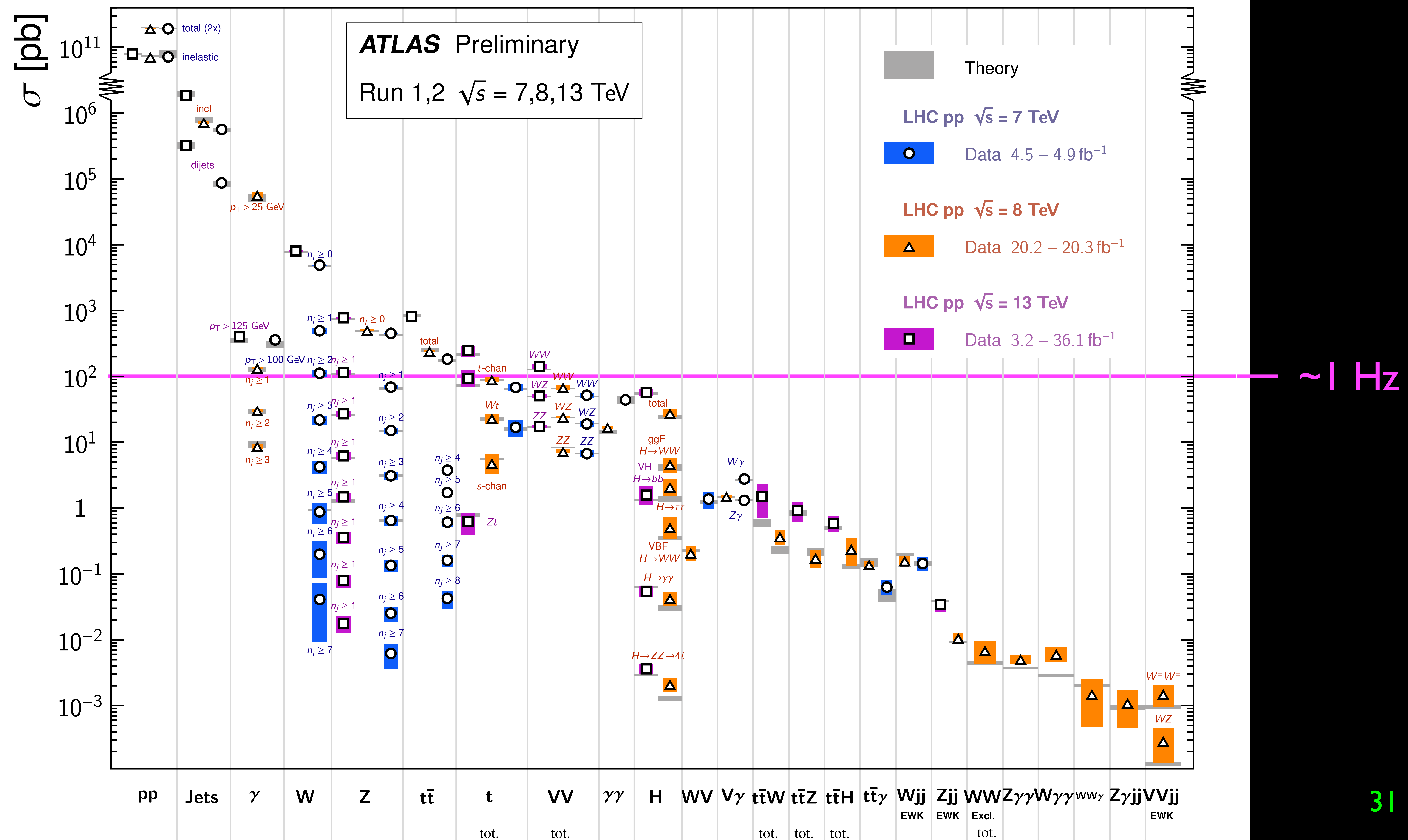
If not, weak interactions among $W^\pm$, Z, H become strong on 1-TeV scale

New phenomena are to be found around 1 TeV

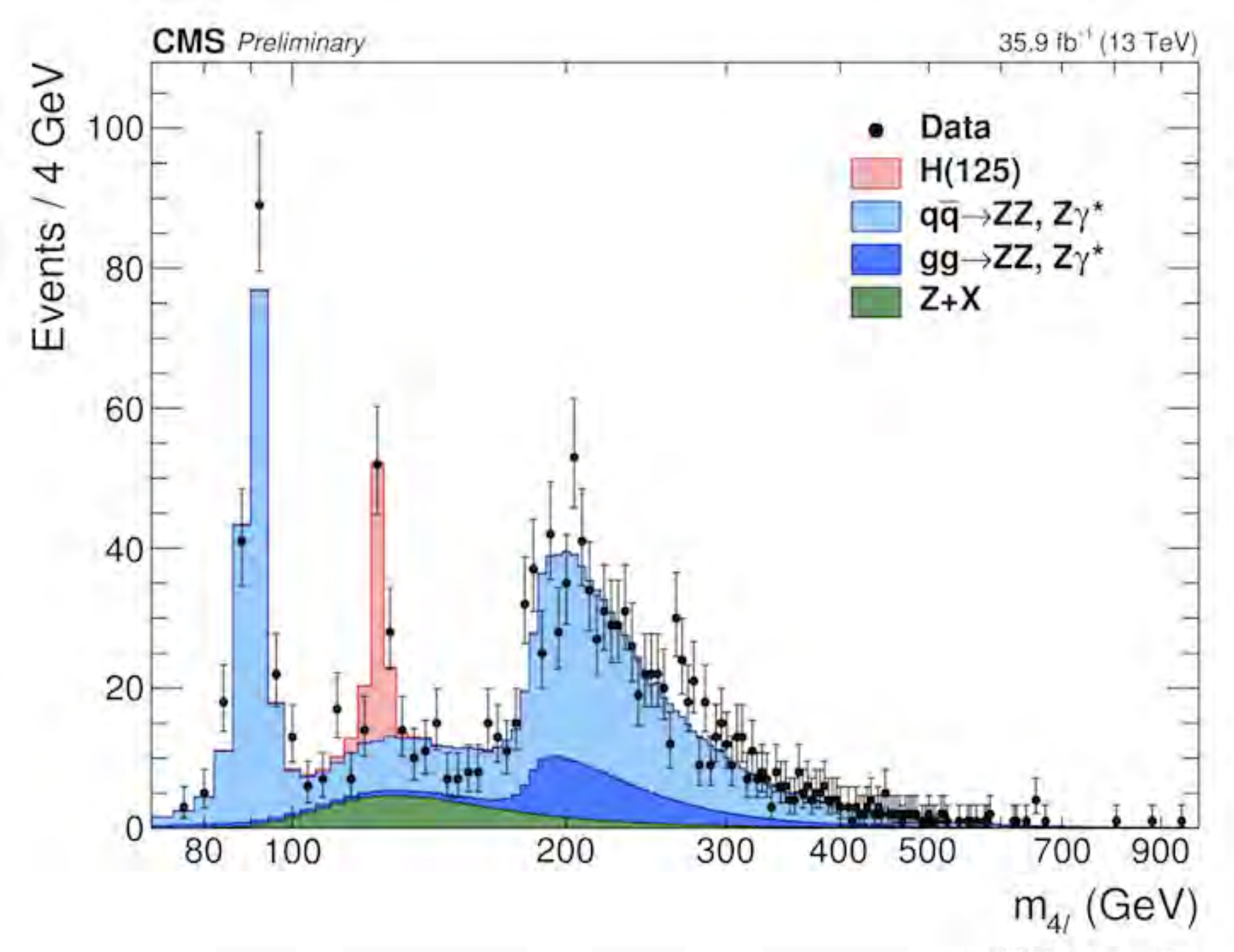

Large Hadron Collider
CMS
LHCb
ALICE
ATLAS

Standard Model Production Cross Section Measurements

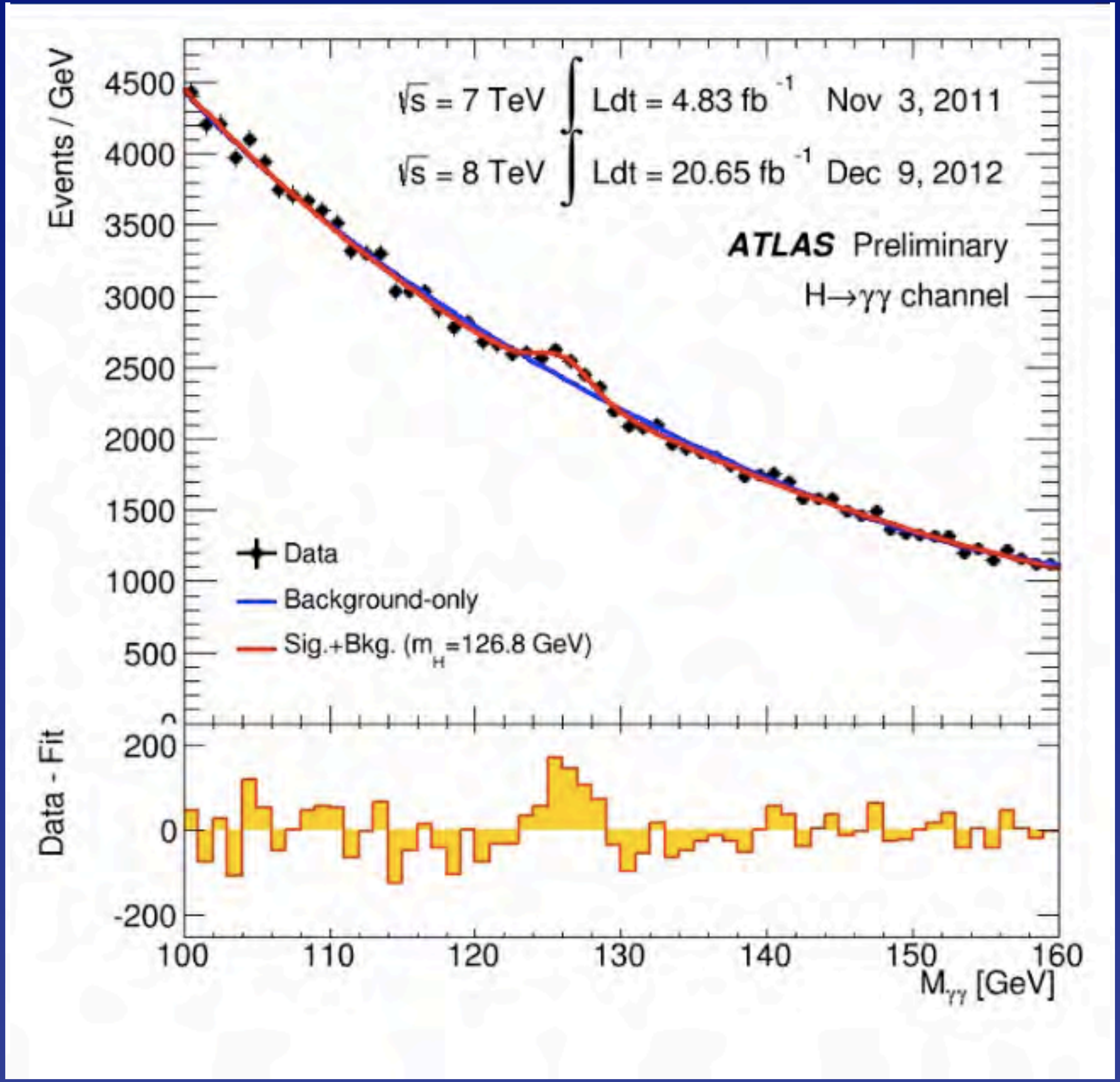
Status: March 2018



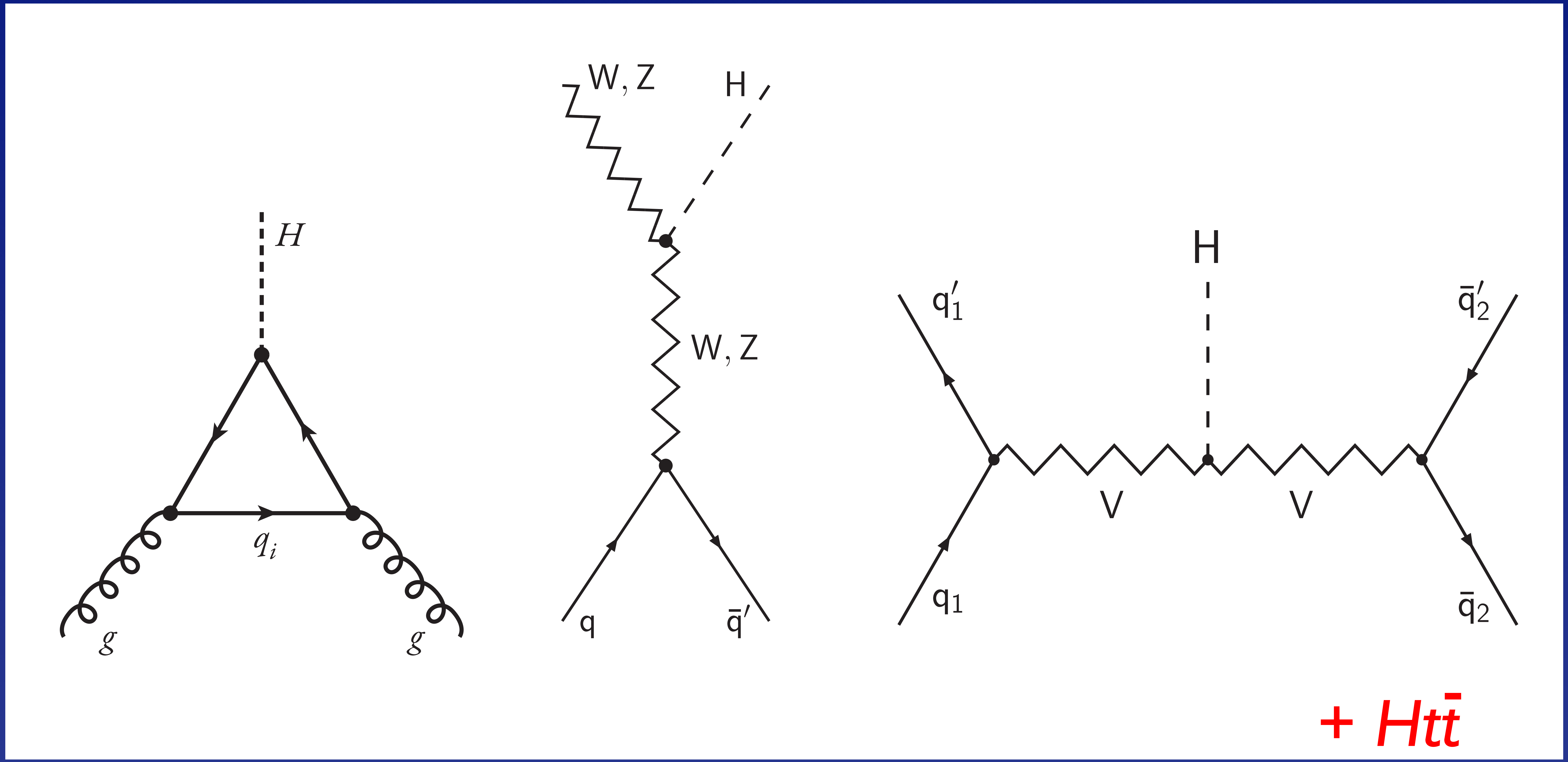
Evolution of CMS 4-lepton Signal



Evolution of ATLAS γγ Signal



LHC can study Higgs boson in many channels



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

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

Motivates HL-LHC,
electron–positron Higgs factory

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

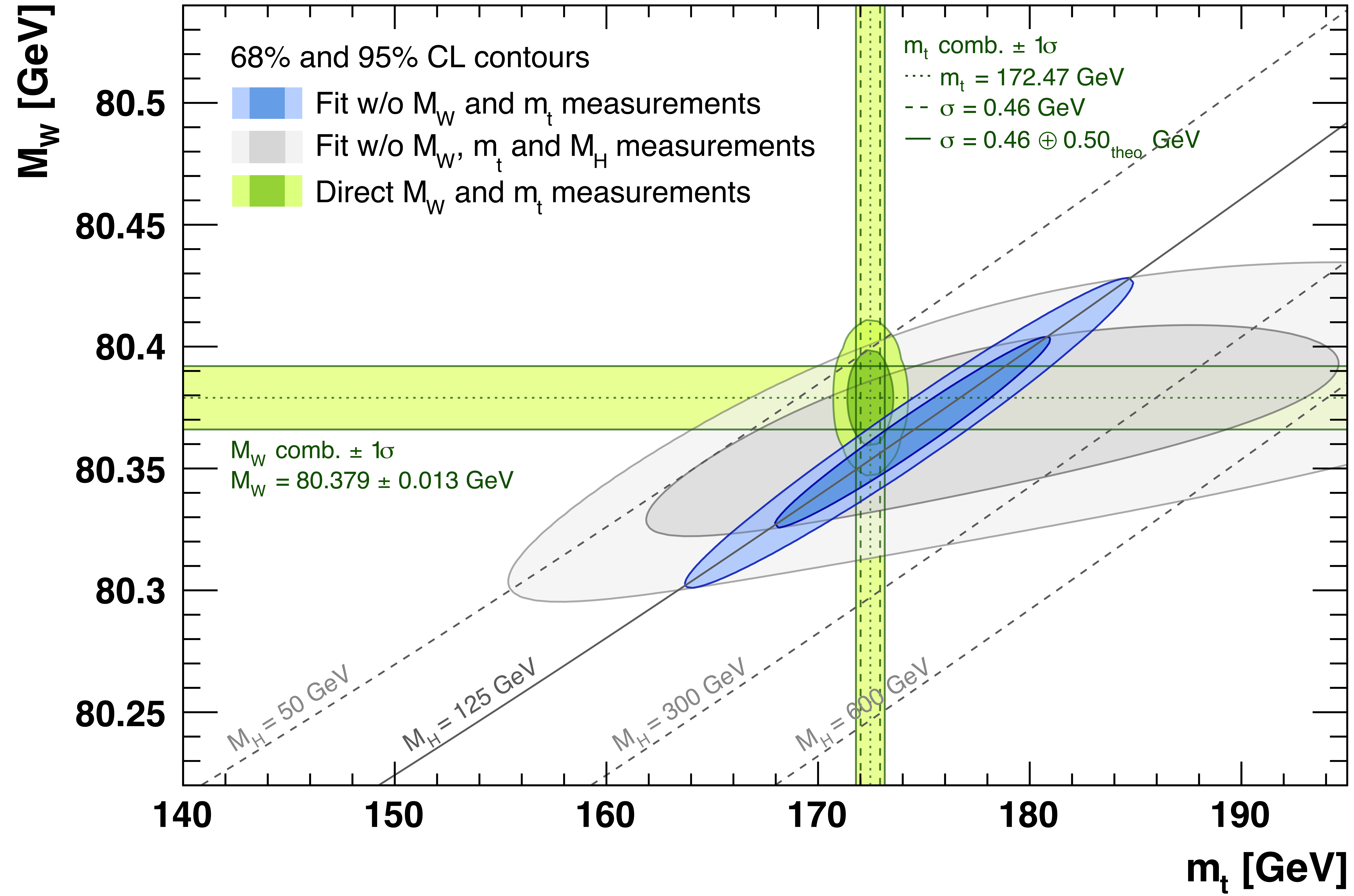
dominantly spin-parity 0^+

$Hf\bar{f}$ couplings
not universal

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

Only third-generation fermions tested

Quantum corrections test electroweak theory



GfitterGroup, March 2018

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

H

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

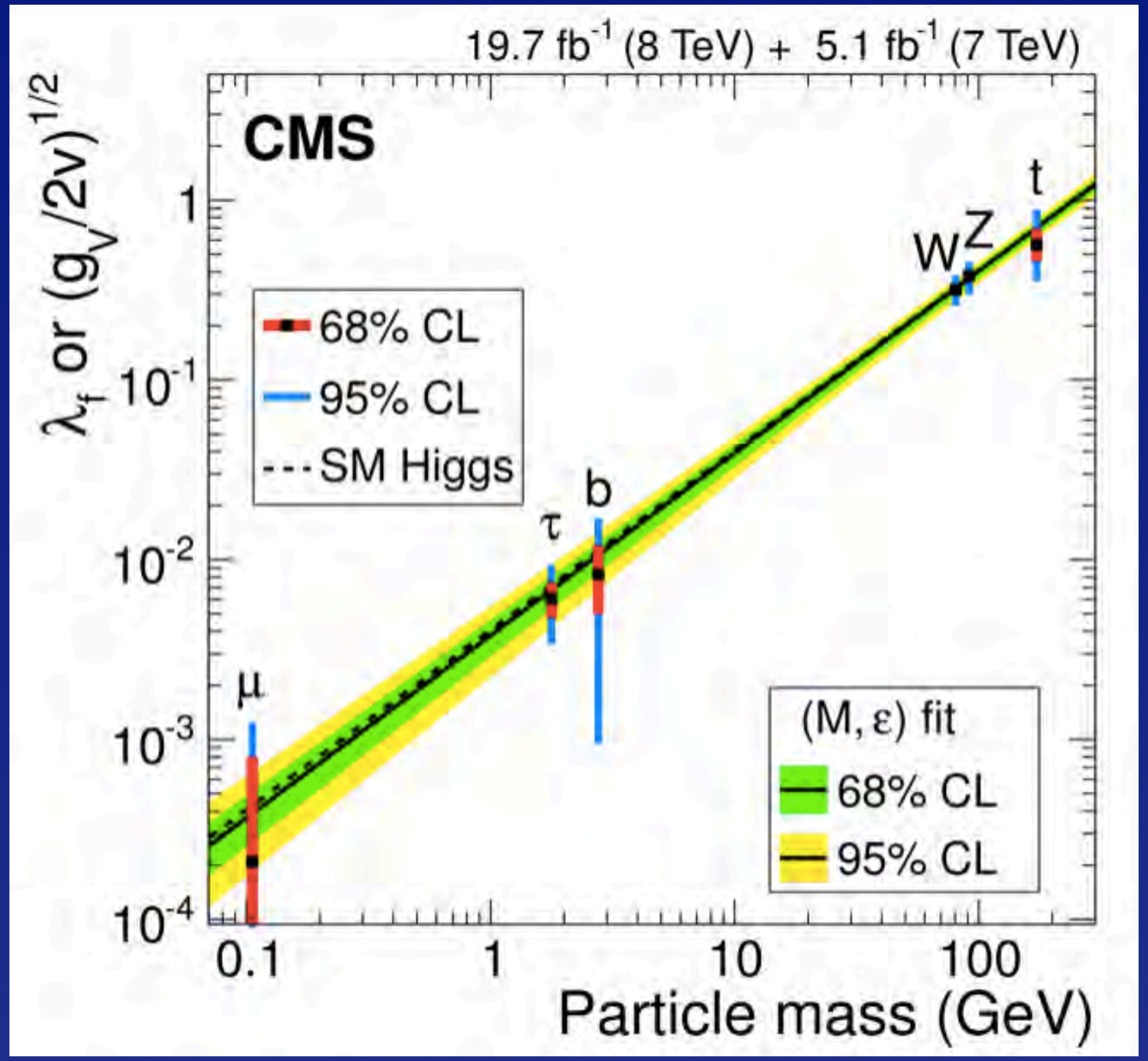
Couples to fermions?

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?

What we expect of the standard-model Higgs sector

Hide electroweak symmetry

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

Motivates VLHC

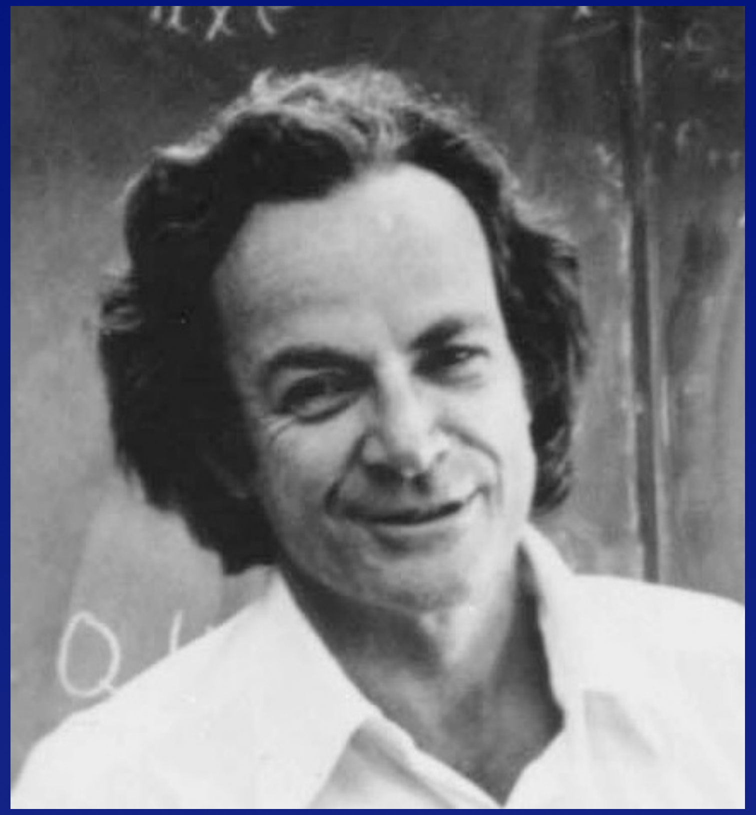
Regulate Higgs-Goldstone scattering

Account for quark masses, mixings

Account for charged-lepton masses

} ΦBSM

A role in neutrino masses? / A portal to hidden sectors?



Why does the muon weigh?

gauge symmetry allows

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

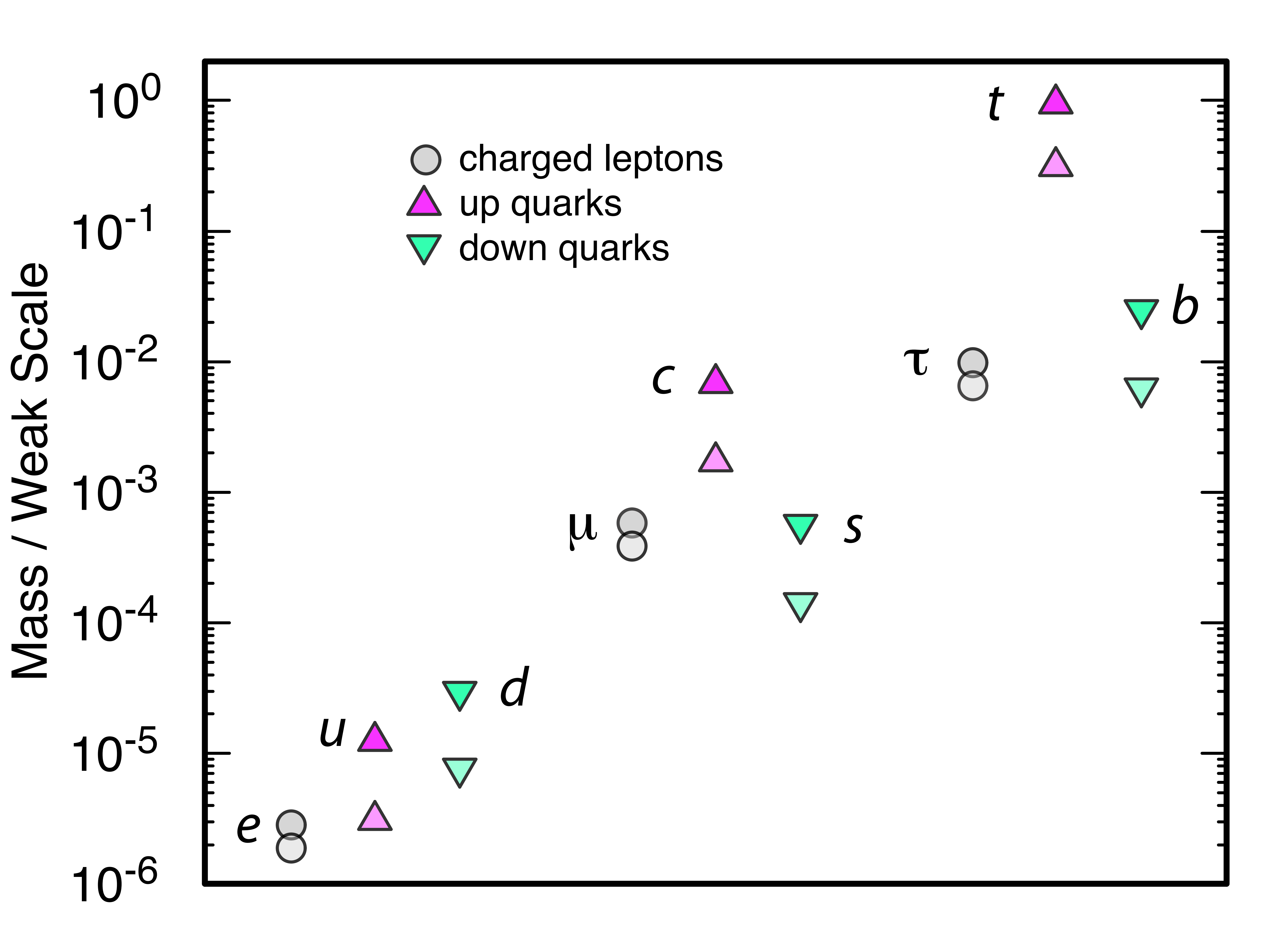
after spontaneous symmetry breaking

What does the muon weigh?

ζ_e : picked to give right mass, not predicted

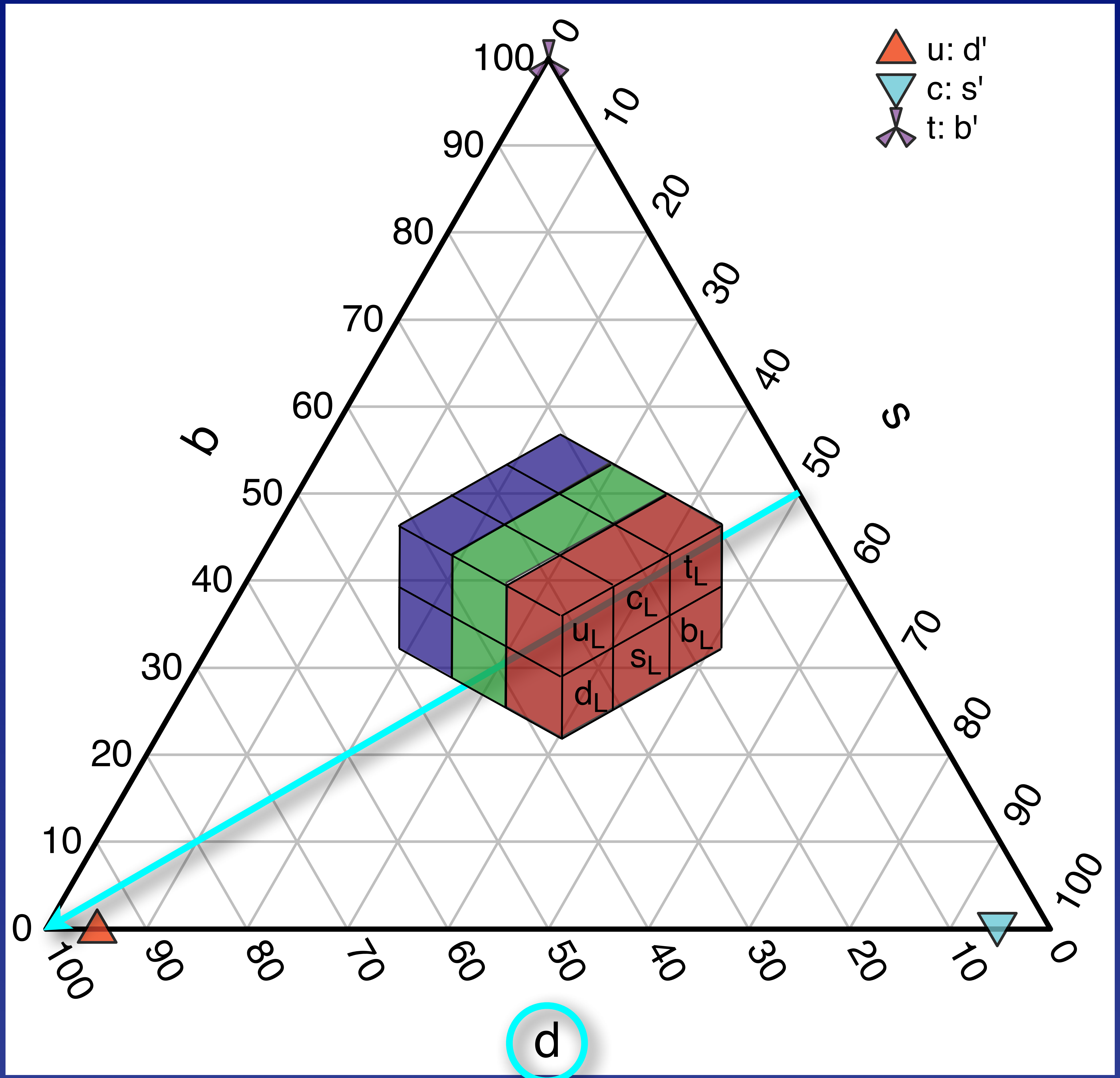
fermion mass implies physics beyond the standard model

Charged Fermion Masses



Running mass $m(m)$ … $m(U)$

Quark family patterns: *generations*

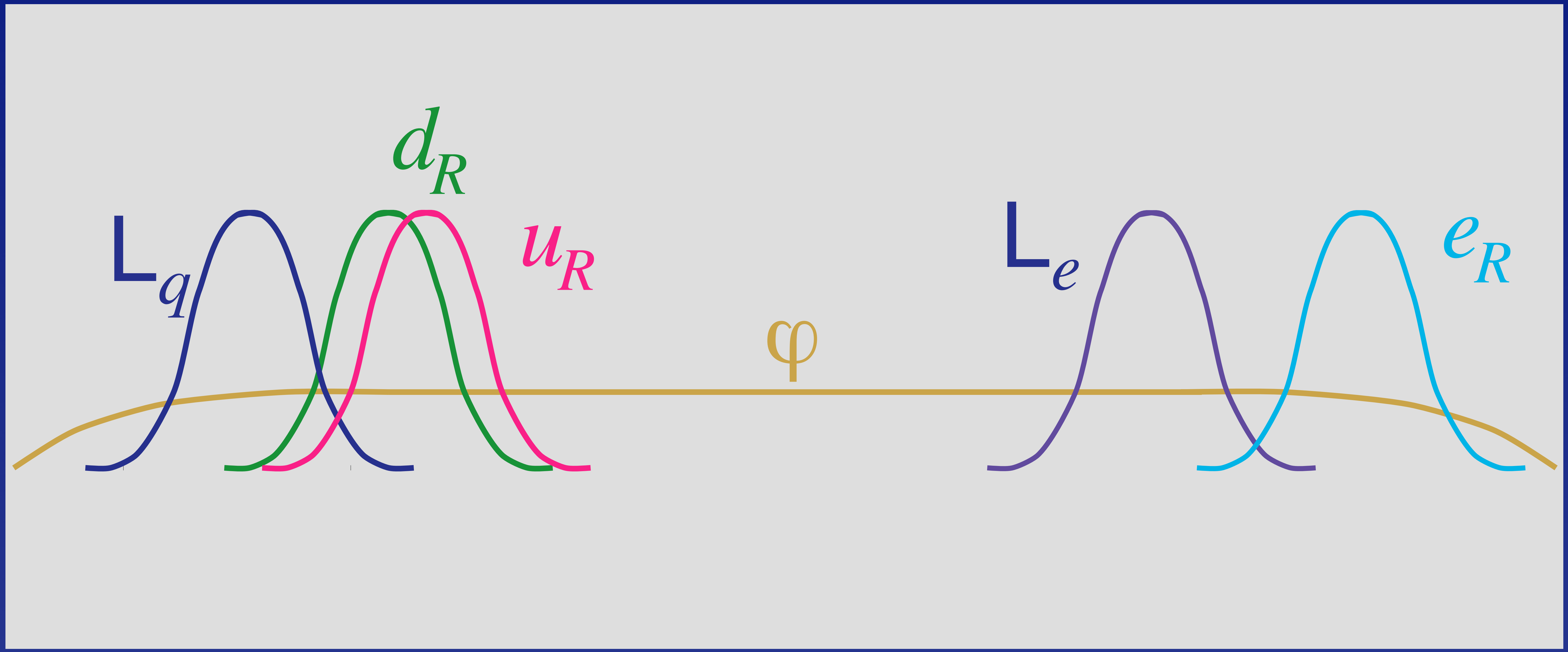


Veltman: Higgs boson knows something we don't know!

0 … 1 … ∞

How might ratios far from unity arise?

Could extra dimensions explain the range of fermion masses?



Arkani-Hamed & Schmaltz (2000)

Fermions ride separate tracks in 5th dimension

Small offsets in x_4: exponential differences in masses

Will the fermion masses and mixings reveal symmetries or dynamics or principles?

Some questions now seem to us the wrong questions:
Kepler's obsession – Why six planets in those orbits?

Landscape interpretation as environmental parameters

Might still hope to find equivalent of Kepler's Laws!

The Problem of Identity

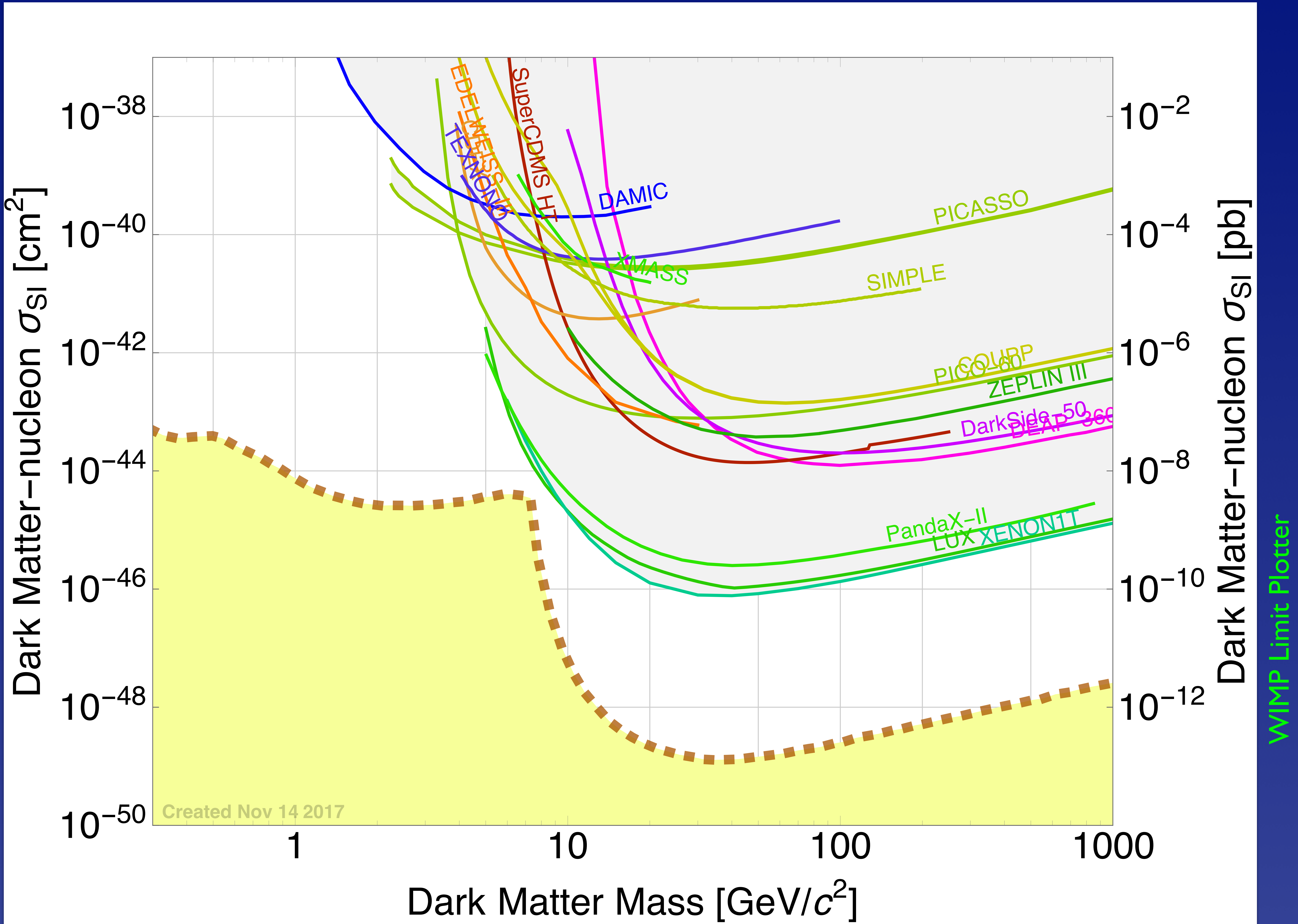
What makes a top quark a top quark,
an electron an electron, a neutrino a neutrino?

Why three families?

Neutrino oscillations give us another take.
Clue to matter excess in the universe?

Might new kinds of matter unlock the pattern?

Direct searches for WIMP dark matter



More new physics on the TeV scale?

Production of WIMP dark matter

"Naturalness"

Hierarchy problem: EW scale $\ll$ Unification or Planck scale

Vacuum energy problem

Clues to origin of EWSB

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?

Hierarchy Problem – a second look

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Nuclear Physics B (Proc. Suppl.) 140 (2005) 3–19

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The Origins of Lattice Gauge Theory

K.G. Wilson

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The final blunder was a claim that scalar elementary particles were unlikely to occur in elementary particle physics at currently measurable energies unless they were associated with some kind of broken symmetry [23]. The claim was that, otherwise, their masses were likely to be far higher than could be detected. The claim was that it would be unnatural for such particles to have masses small enough to be detectable soon. But this claim makes no sense when one becomes familiar with the history of physics. There have been a number of cases where numbers arose that were unexpectedly small or large. An early example was the very large distance to the nearest star as compared to the distance to the Sun, as needed by Copernicus, because otherwise the nearest stars would have exhibited measurable parallax as the Earth moved around the Sun. Within elementary particle physics, one has unexpectedly large ratios of masses, such as the large ratio of the muon mass to the electron mass. There is also the very small value of the weak coupling constant. In the time since my paper was written, another set of unexpectedly small masses was discovered: the neutrino masses. There is also the riddle of dark energy in cosmology, with its implication of possibly an extremely small value for the cosmological constant in Einstein's theory of general relativity.

This blunder was potentially more serious, if it caused any subsequent researchers to dismiss possibilities for very large or very small values for parameters that now must be taken seriously. But I

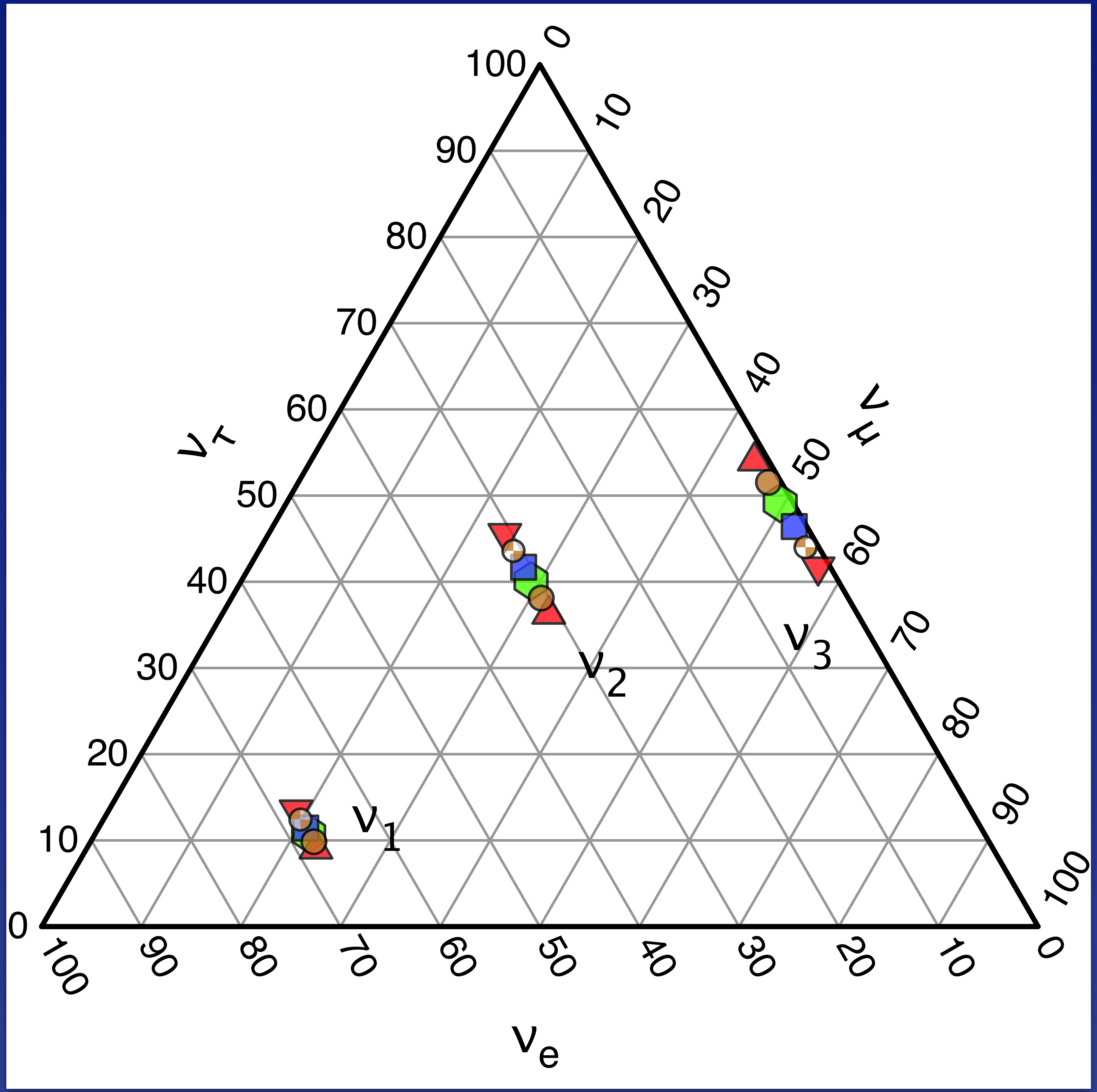
Parameters of the Standard Model

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 . . .)
26^+	arbitrary parameters

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

Some outstanding questions in ν physics

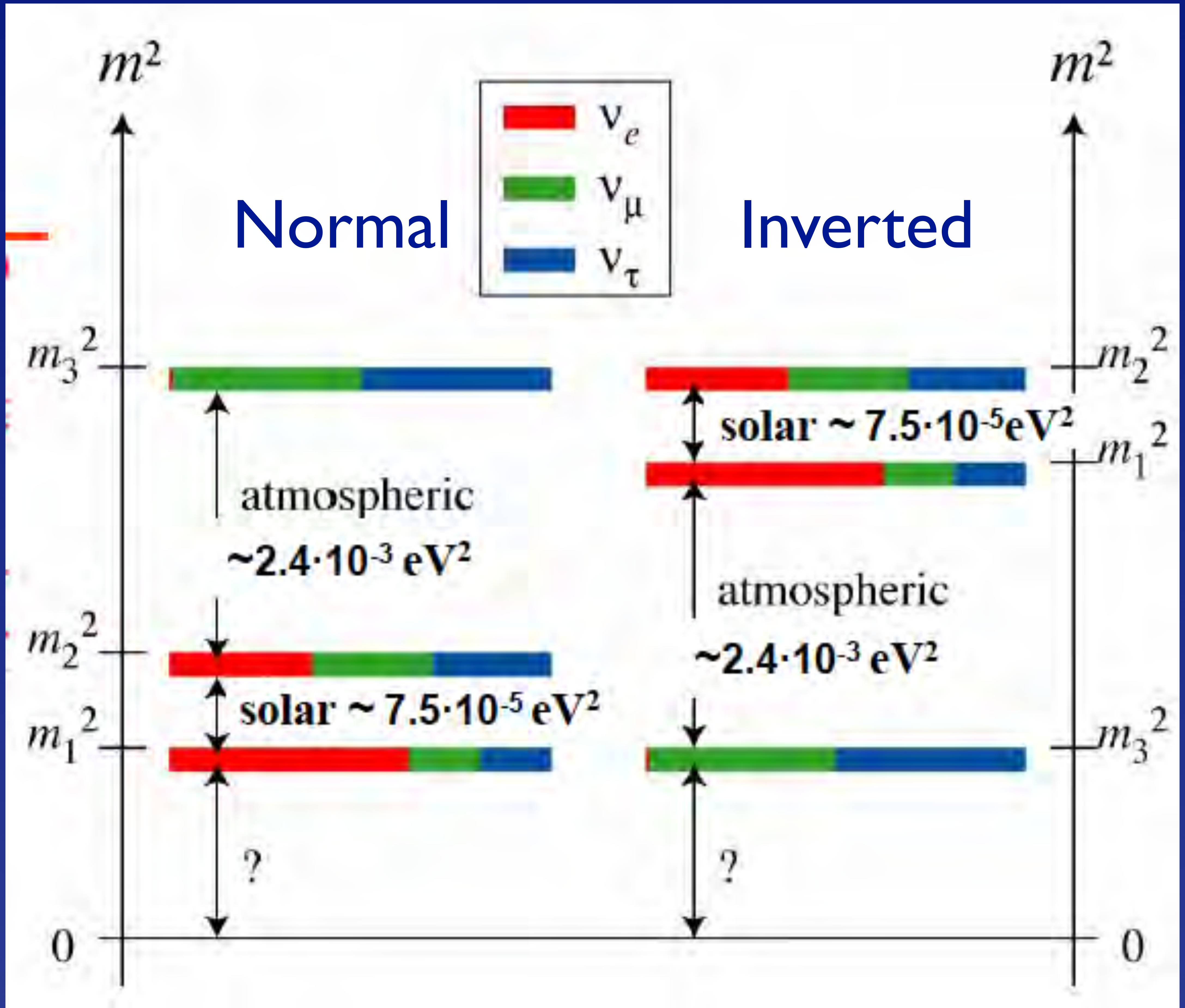
What is the composition of ν_3?



Before most-recent experiments

Some outstanding questions in ν physics

Absolute scale of neutrino masses?



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

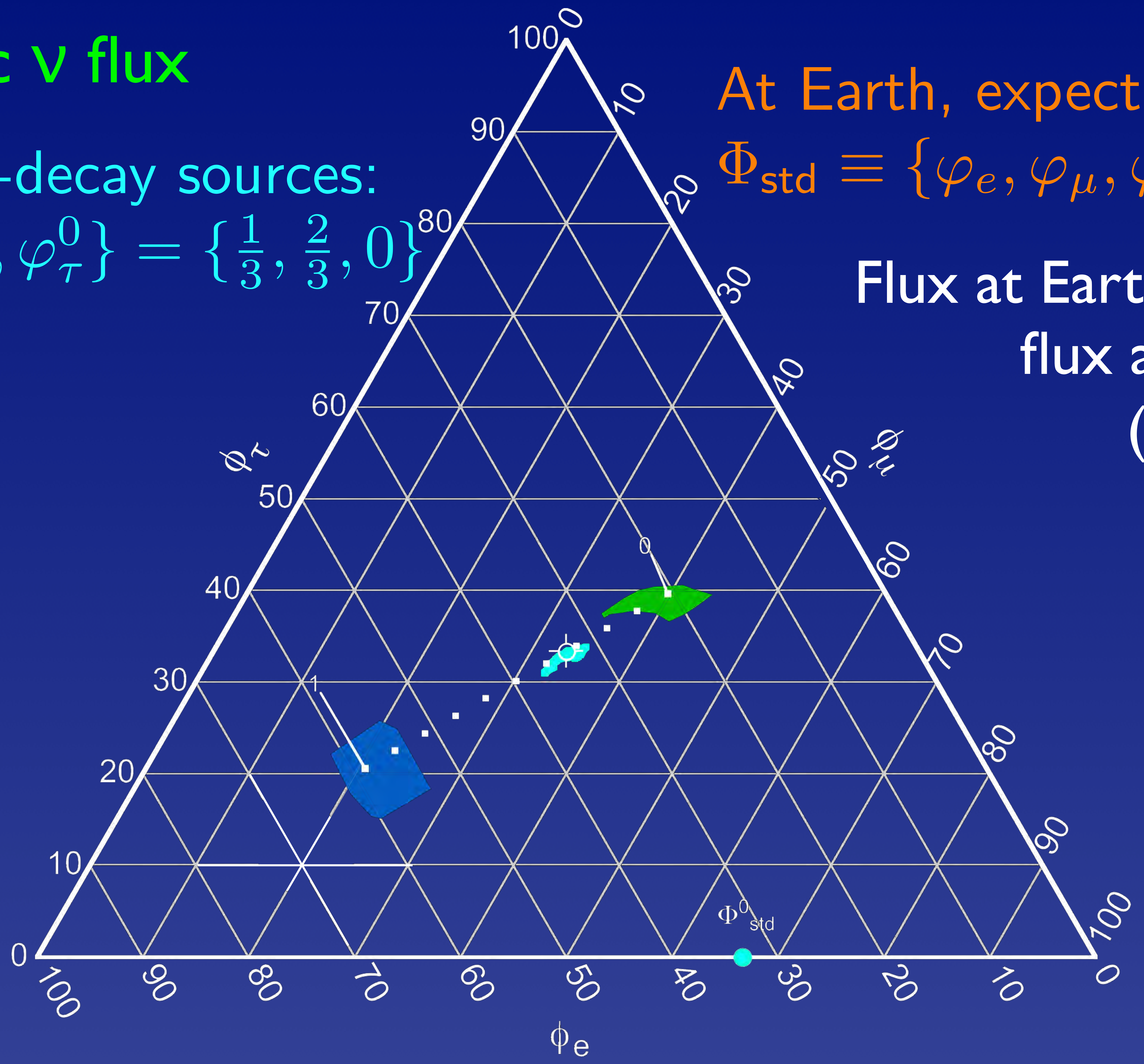
How can we detect the cosmic ν background?

$\nu_i, \bar{\nu}_i$ number density now: 56/cm^3, $\propto (1+z)^3$ $T_{\nu 0} = 1.945$ K $= 1.697 \times 10^{-4}$ eV; $T_\nu \propto (1+z)$

Cosmic ν flux

Conventional π-decay sources:

$\Phi^0_{\rm std} \equiv \{\varphi^0_e, \varphi^0_\mu, \varphi^0_\tau\} = \{\frac{1}{3}, \frac{2}{3}, 0\}$



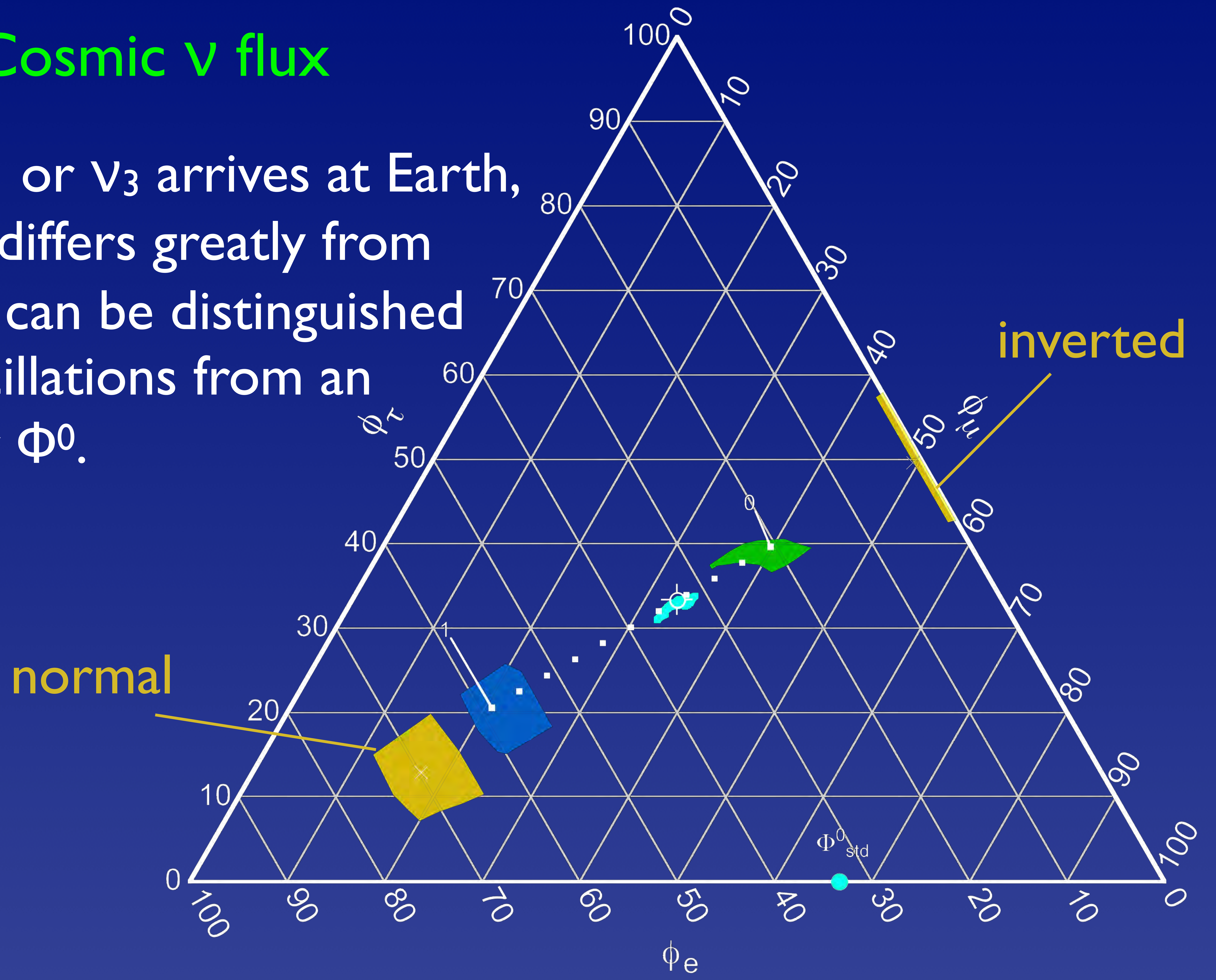
At Earth, expect:

$\Phi_{\rm std} \equiv \{\varphi_e, \varphi_\mu, \varphi_\tau\} = \{\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\}$

Flux at Earth reveals flux at source (stable ν)

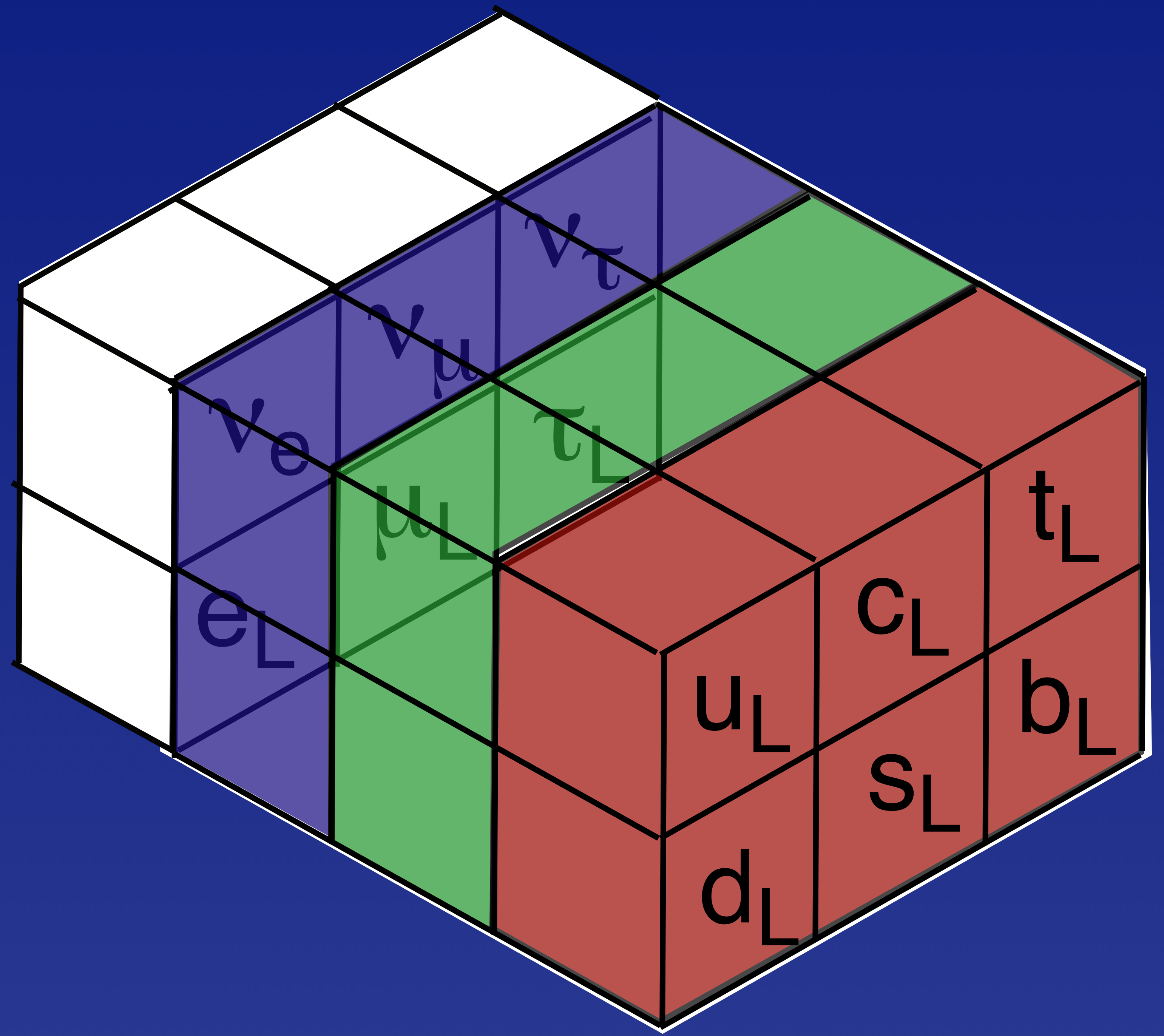
Cosmic ν flux

If only ν_1 or ν_3 arrives at Earth, $\Phi_{observed}$ differs greatly from Φ_{std}, and can be distinguished from oscillations from an arbitrary Φ^0.



A Unified Theory?

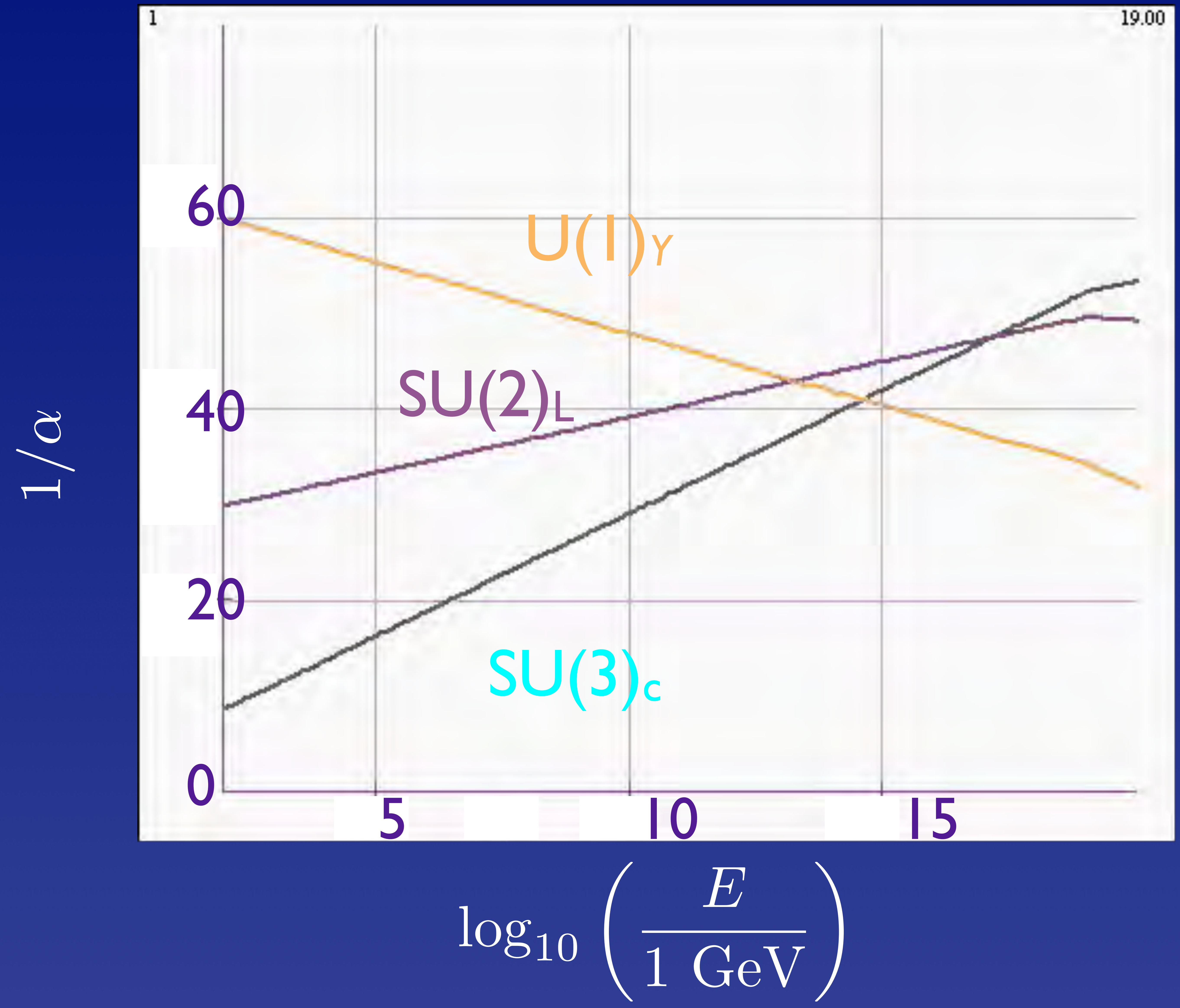
Why are atoms so remarkably neutral?



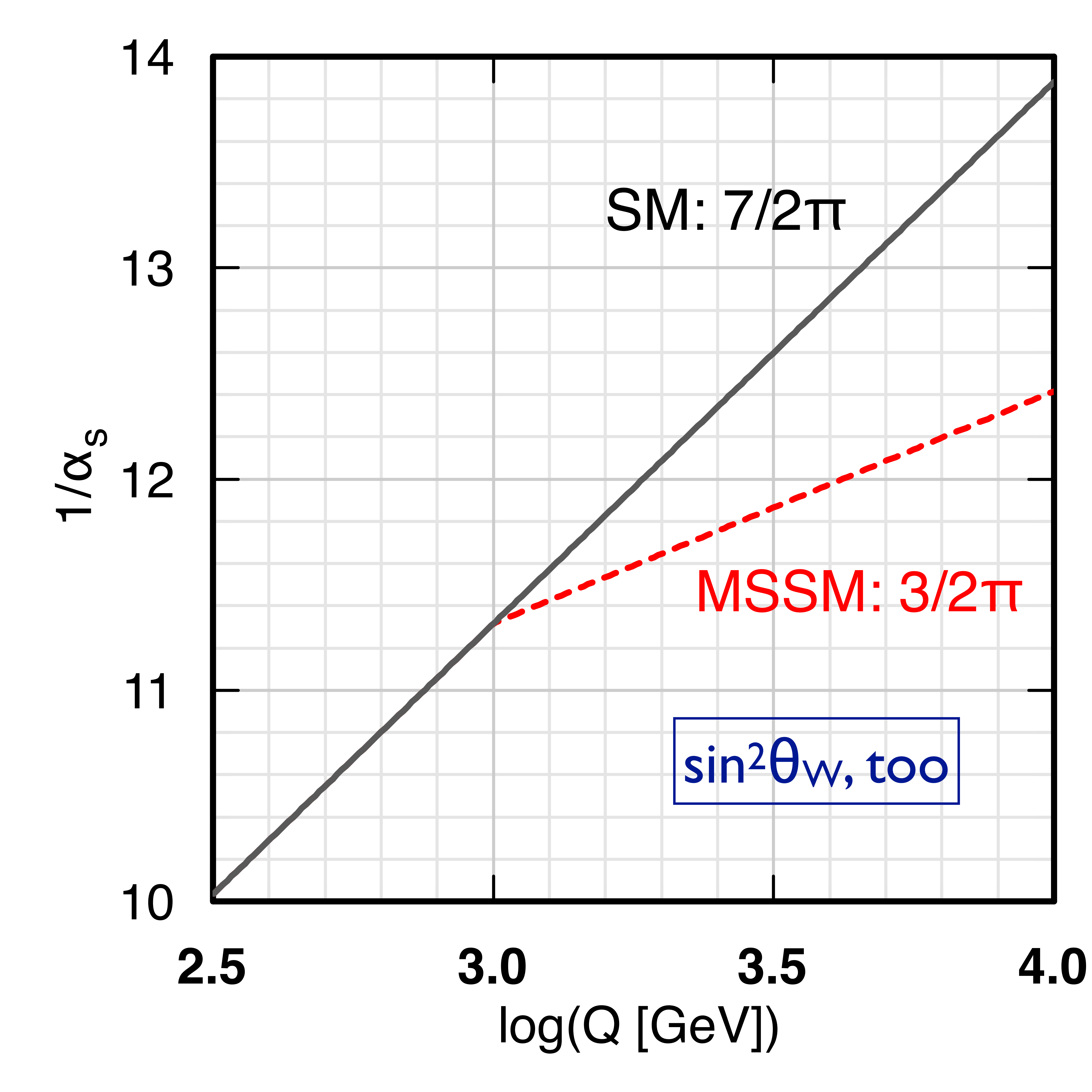
Coupling constant unification?

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

Unification of Forces?



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



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.

$\mu_p = +\,2.792\ 847\ 344\ 62\ (82)\ \mu_N$

BASE Collaboration @CERN Antiproton Decelerator

A few more questions in closing

Where are flavor-changing neutral currents?

Is charged-current universality exact?

Can we find evidence for charged-lepton flavor violation?

Can we find right-handed charged-current interactions?

Can we detect $H \to c\bar{c}$?

Can we observe axions / dark photons / … ?

Might we be misreading the evidence about dark matter?

Can we observe electric dipole moments of μ, *p*?

What is the order of the electroweak phase transition?

Can we probe dark energy in laboratory experiments?

What are best uses of a fully instrumented beam dump?

Exercise 1. How should we respond if:

(a) The DAMA "seasonal variation" cannot be explained away?

(b) The LHC Higgs signal strength settles at $\mu = 1.17 \pm 0.03$? Or if $Ht\bar{t}$ remains high?

(c) The LHC*b* flavor anomalies persist?

(d) The muon (g–2) anomaly strengthens?

(e) WIMP dark matter searches reach the neutrino floor?

Exercise 2. Sketch five "small-scale" (you define) experiments with the potential to change our thinking about particle physics or related fields.

Exercise 3. How would you assess the scientific potential (in view of cost and schedule) of

(a) The High-Luminosity LHC?
(b) The High-Energy LHC?
(c) A 100-TeV *pp* Collider (FCC-hh)?
(d) A 250-GeV ILC?
(e) A circular Higgs factory (FCC-ee or CEPC)?
(f) A 380-GeV CLIC?
(g) LHeC / FCC-eh? (or an *e*–ion collider)
(h) A muon-storage-ring neutrino factory?
(i) A multi-TeV muon collider?
(j) *The instrument of your dreams?*