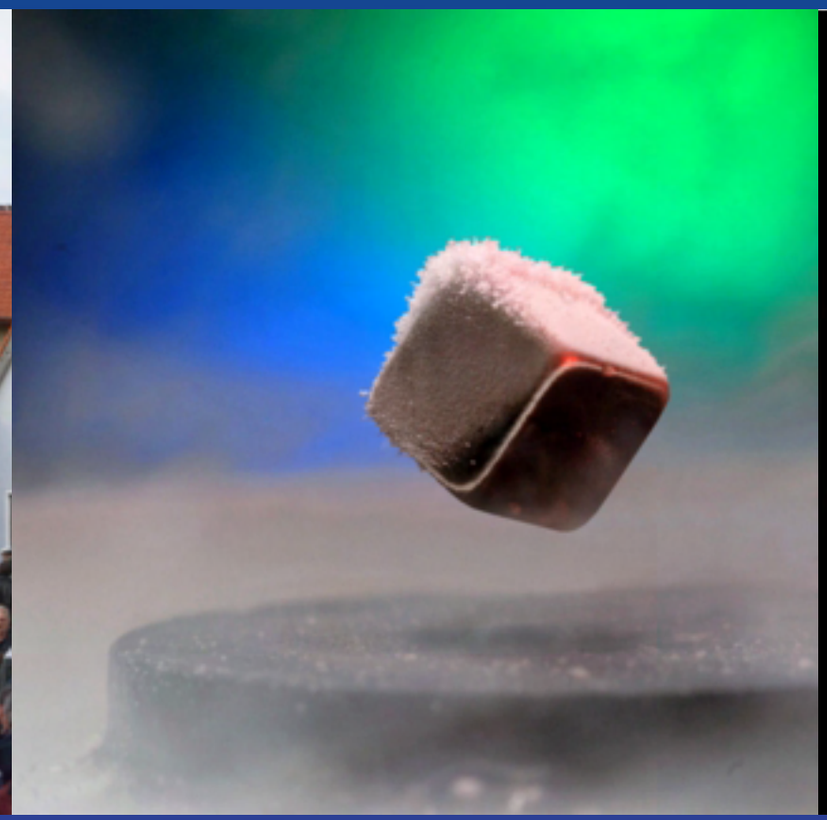
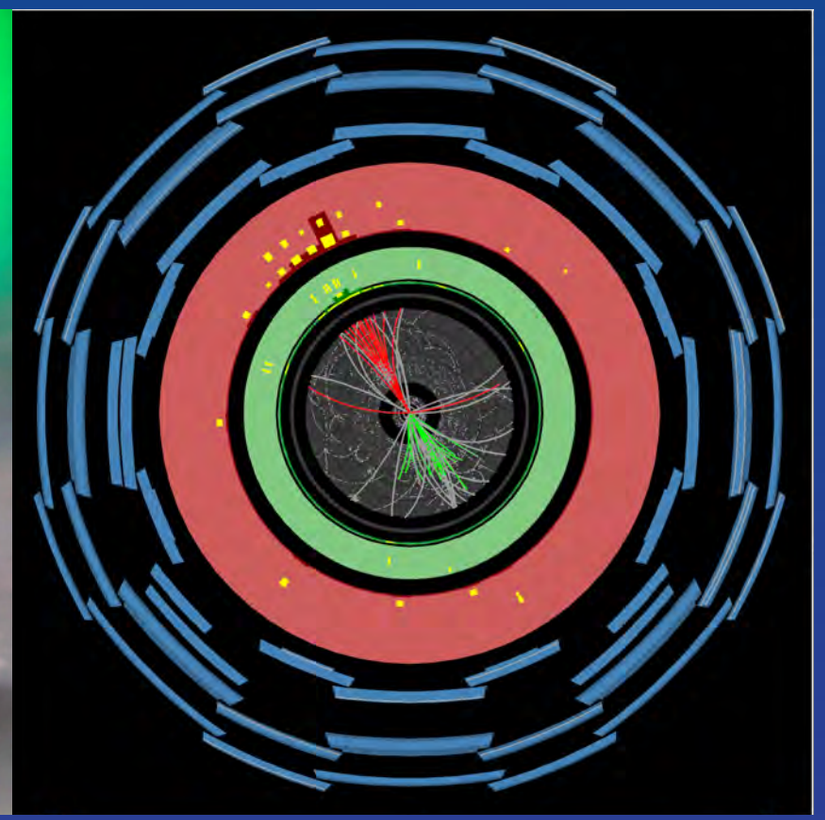
The Coming Revolutions in Particle Physics

Chris Quigg
Fermi National Accelerator Laboratory

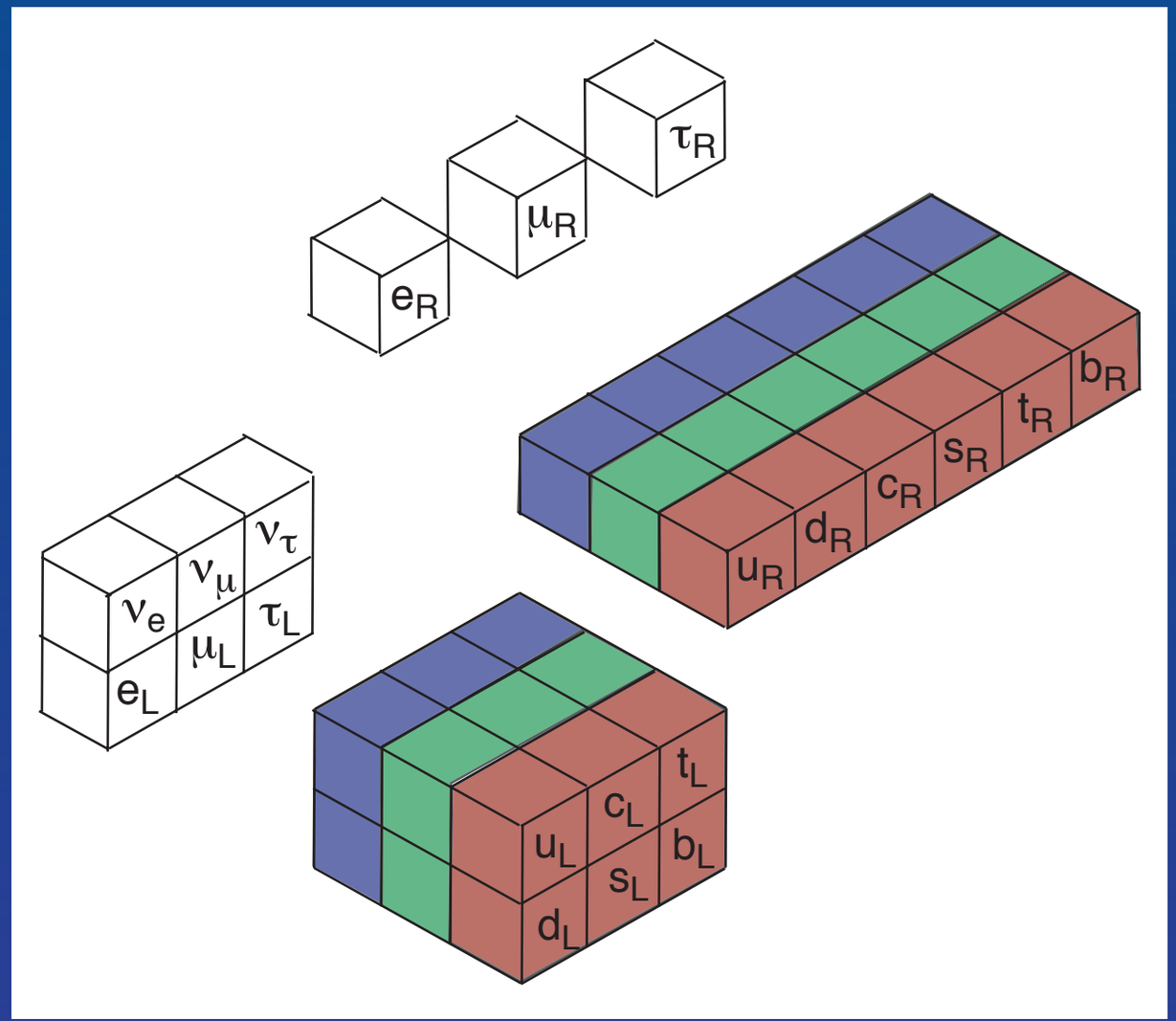




Arizona State Colloquium · 2 December 2010

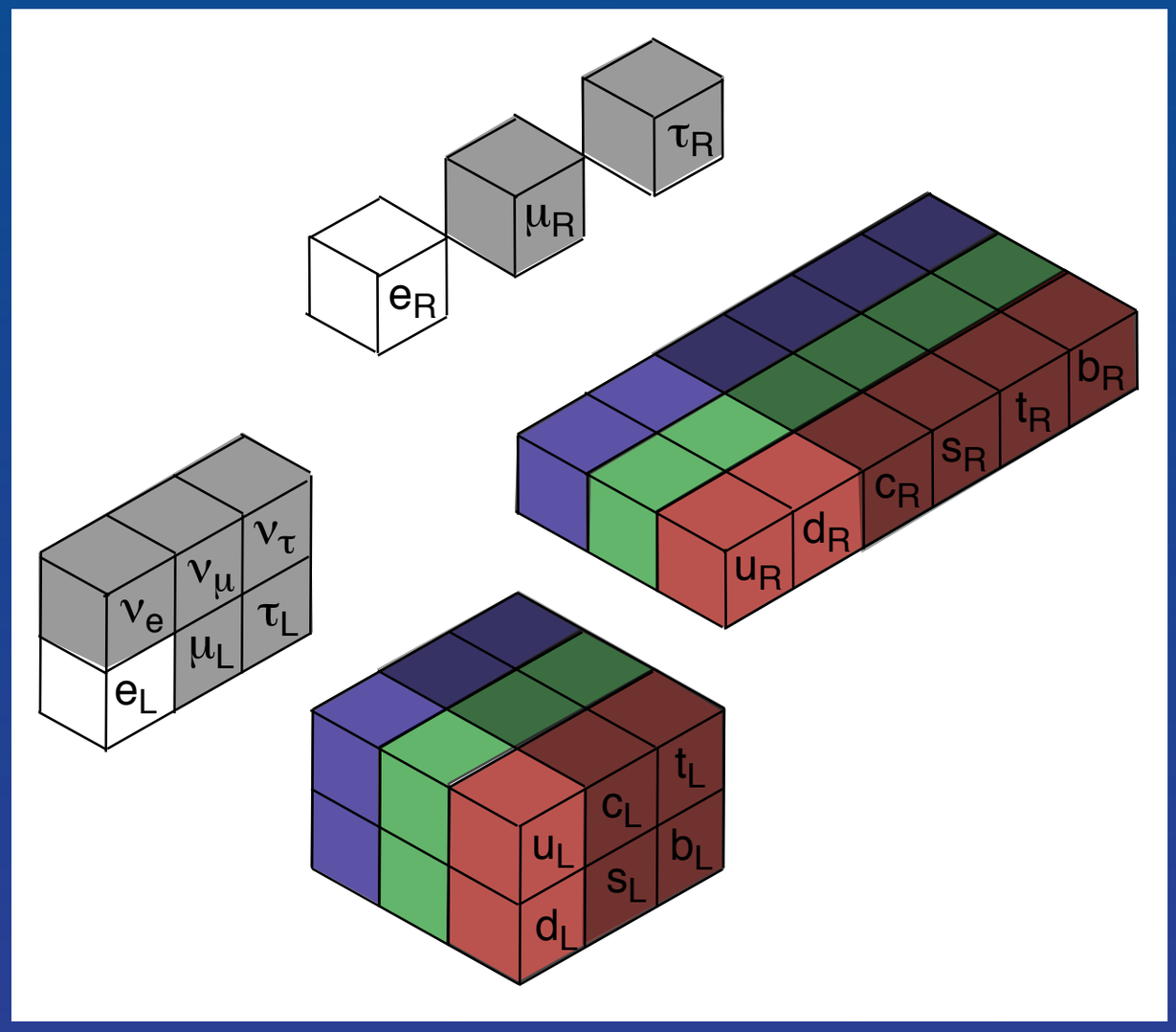
Our Picture of Matter (revolution just past)

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



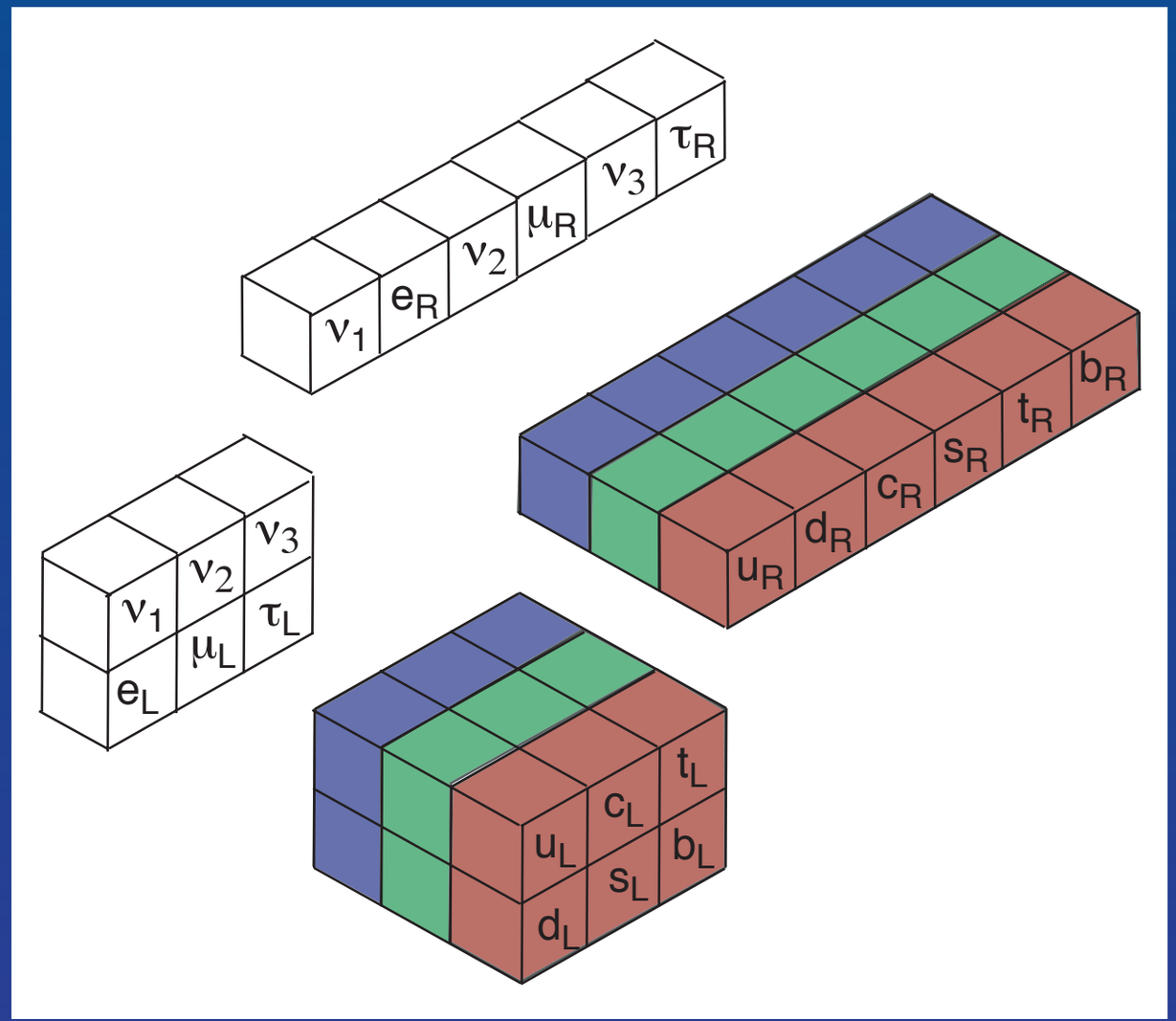
Our Picture of Matter (revolution just past)

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



Our Picture of Matter (revolution just past)

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



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

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

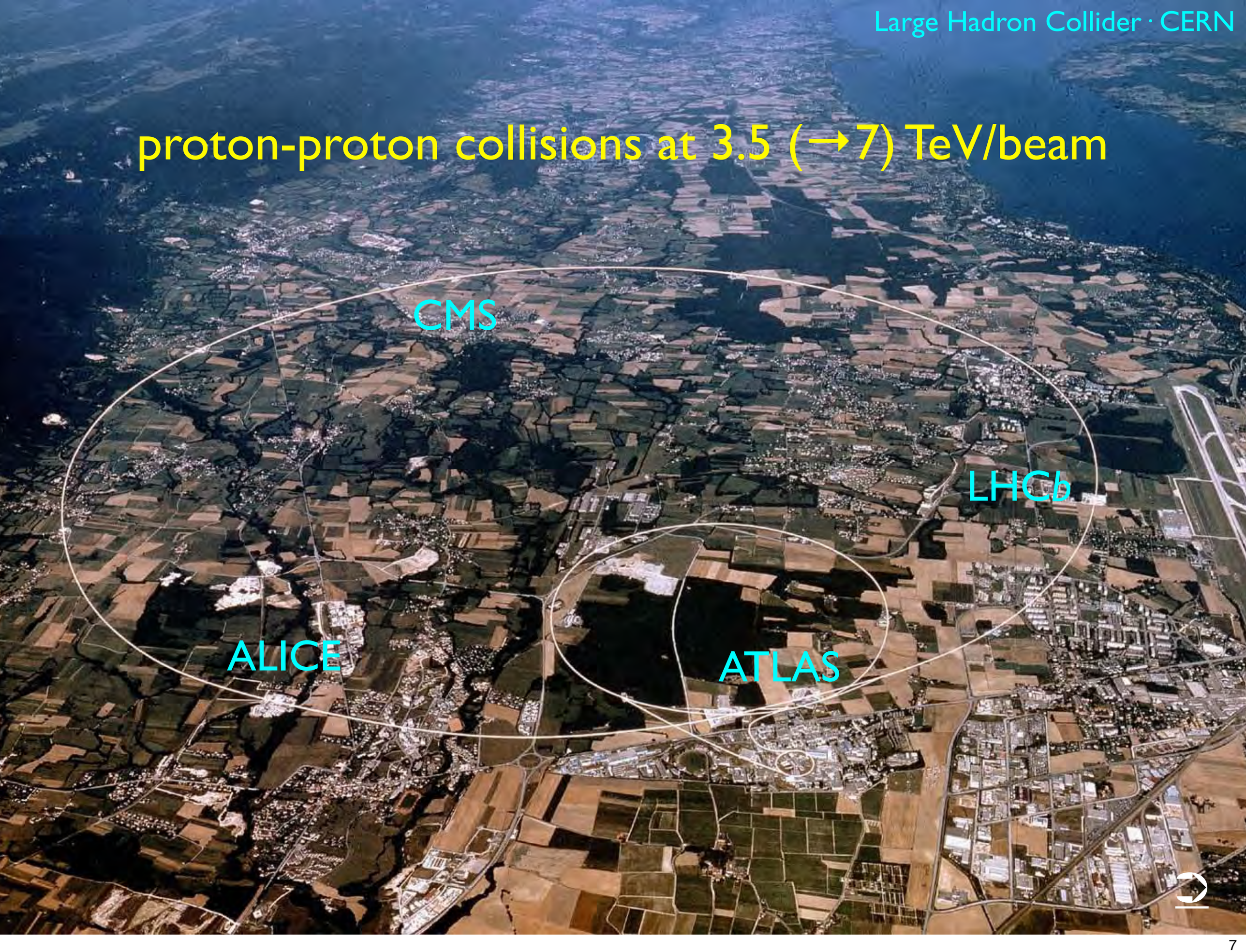
The world's most powerful microscopes … home to *nanonanophysicists!*

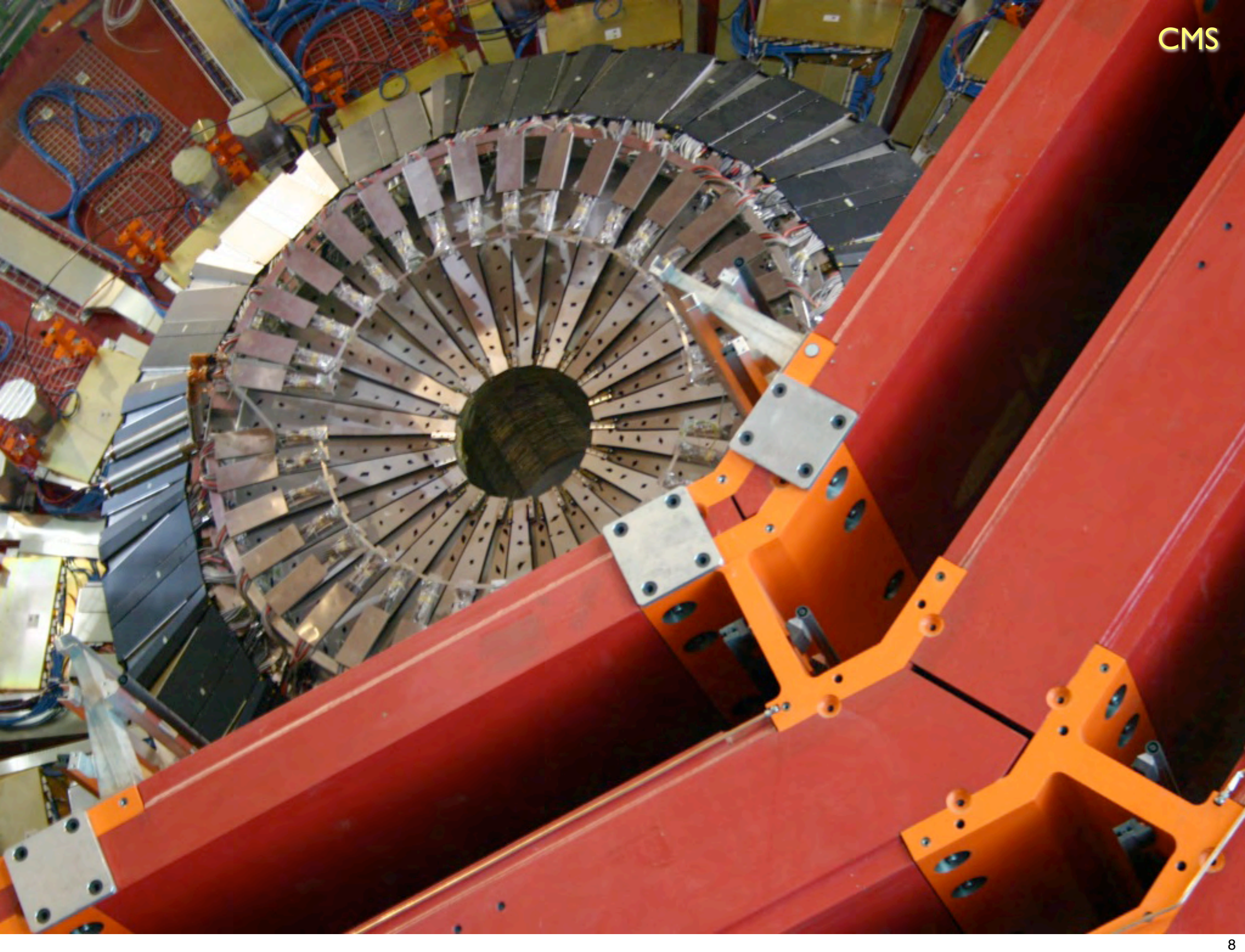
Tevatron collider at Fermilab
protons on antiprotons at 1+1 TeV
speed of light: c ≈ 10^9 km/h
speed of protons: c – 495 km/h

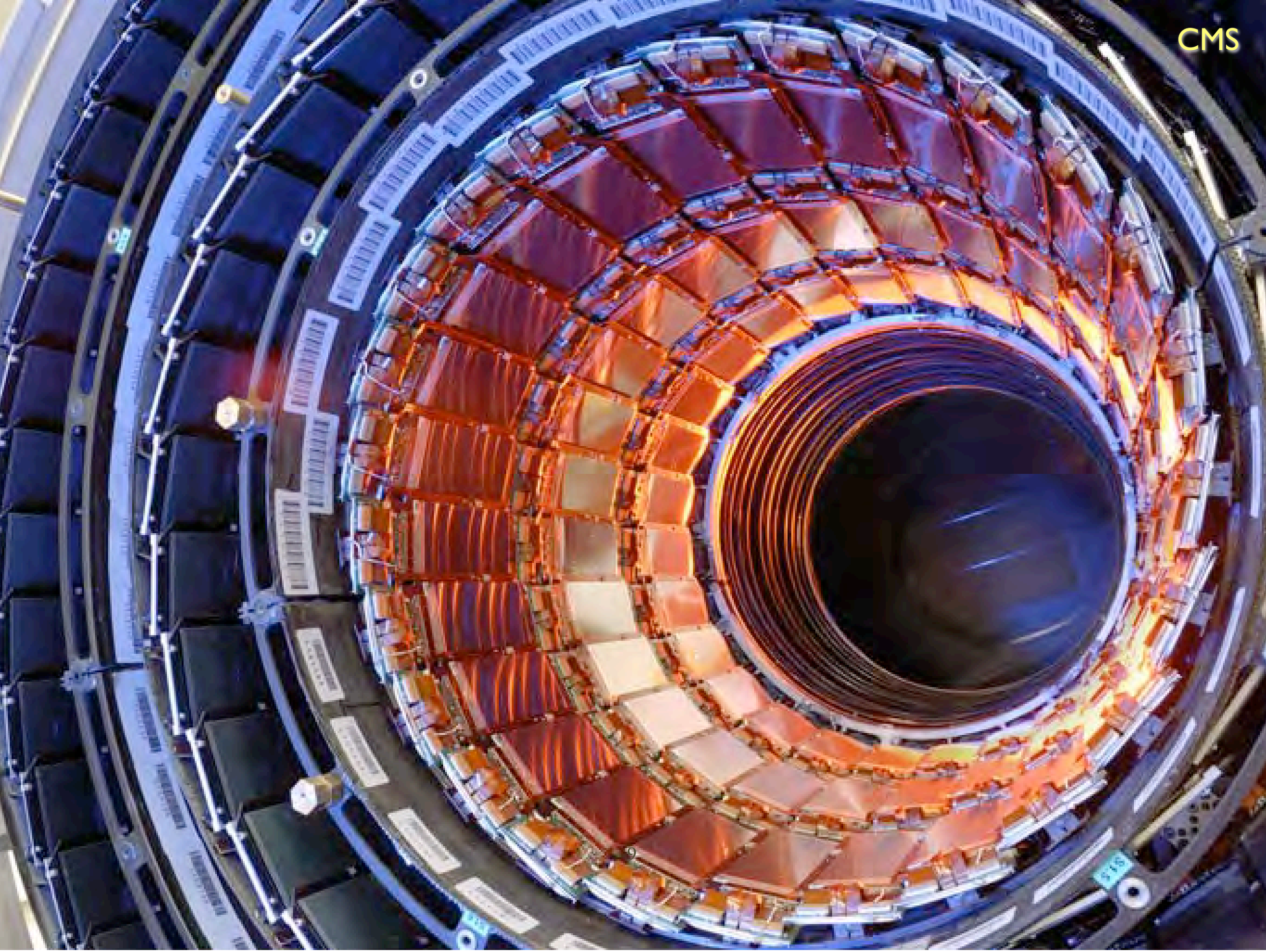
Large Hadron Collider at CERN
protons on protons at 3.5+3.5 TeV
speed of protons: c – 39 km/h
soon: c – 10 km/h

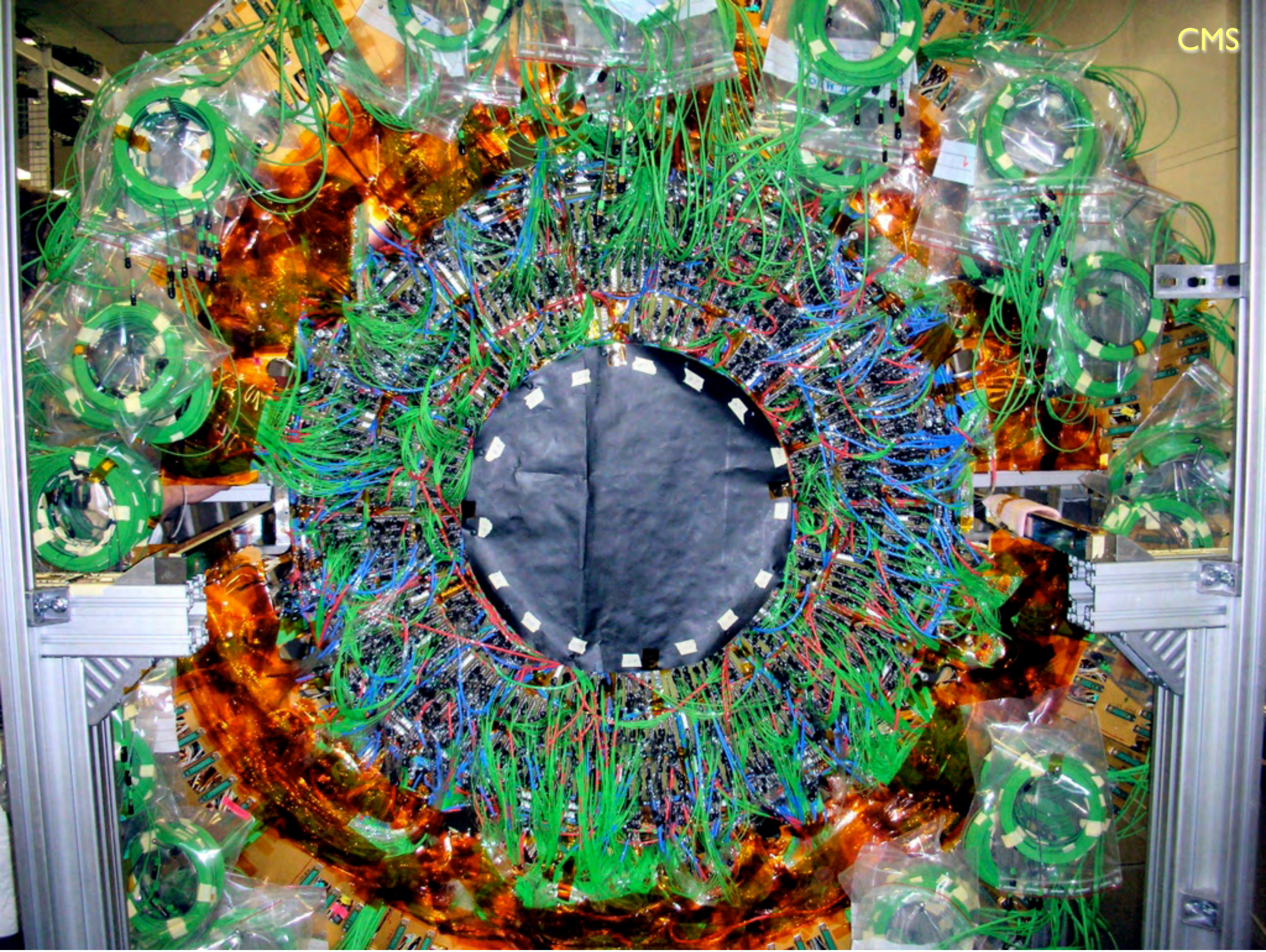
>10 million collisions per second

proton-proton collisions at 3.5 (→7) TeV/beam

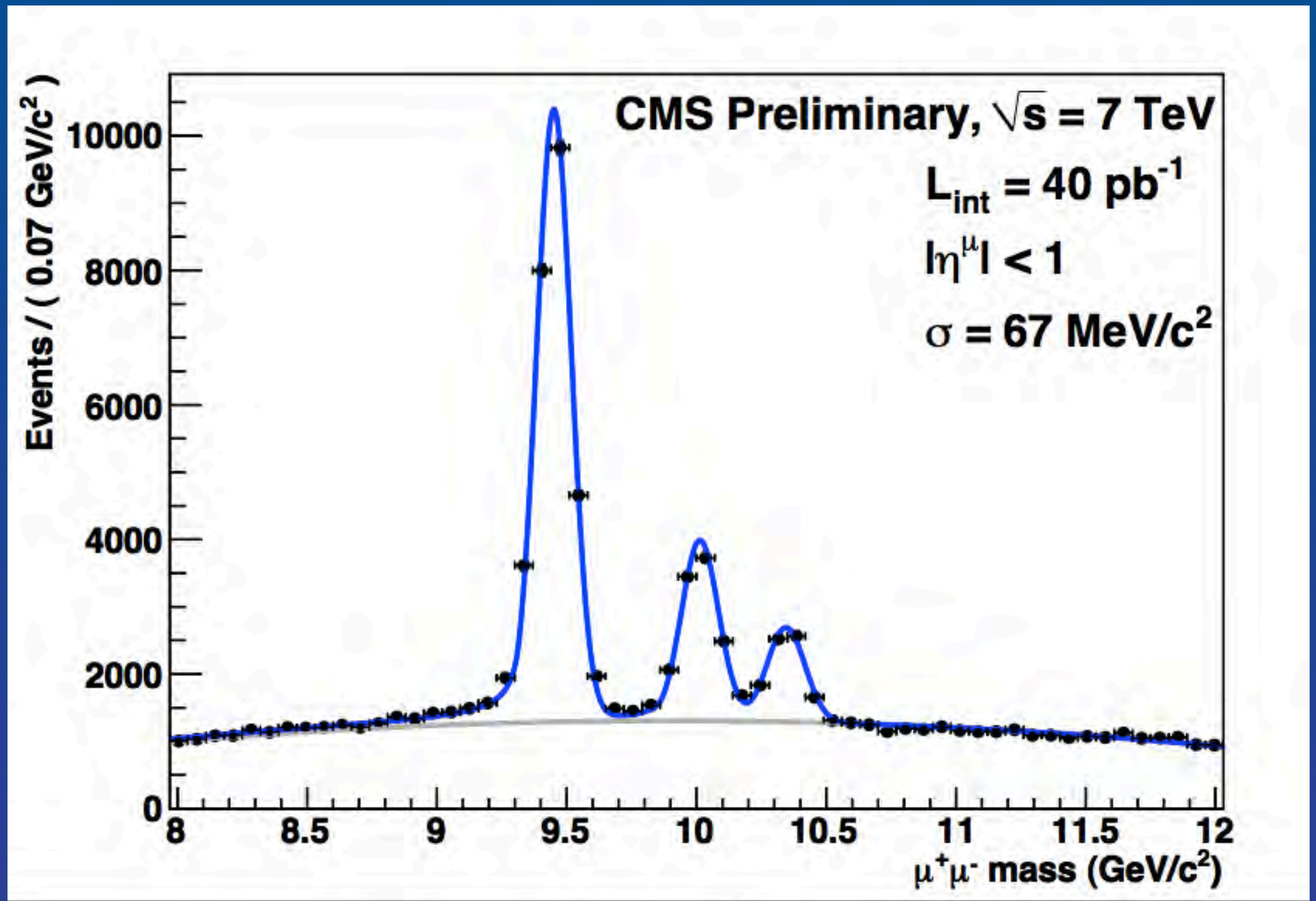


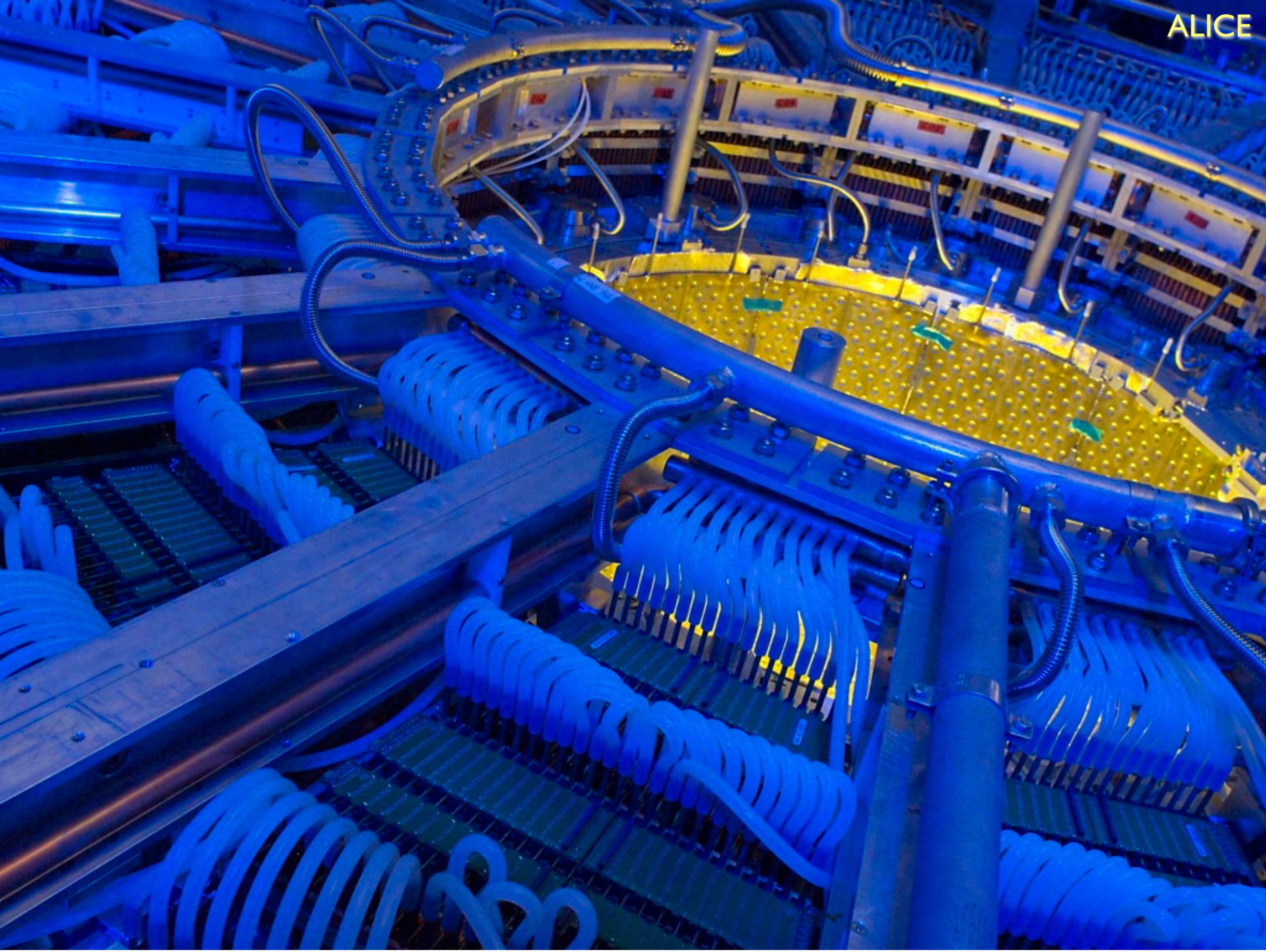

CMS


CMS

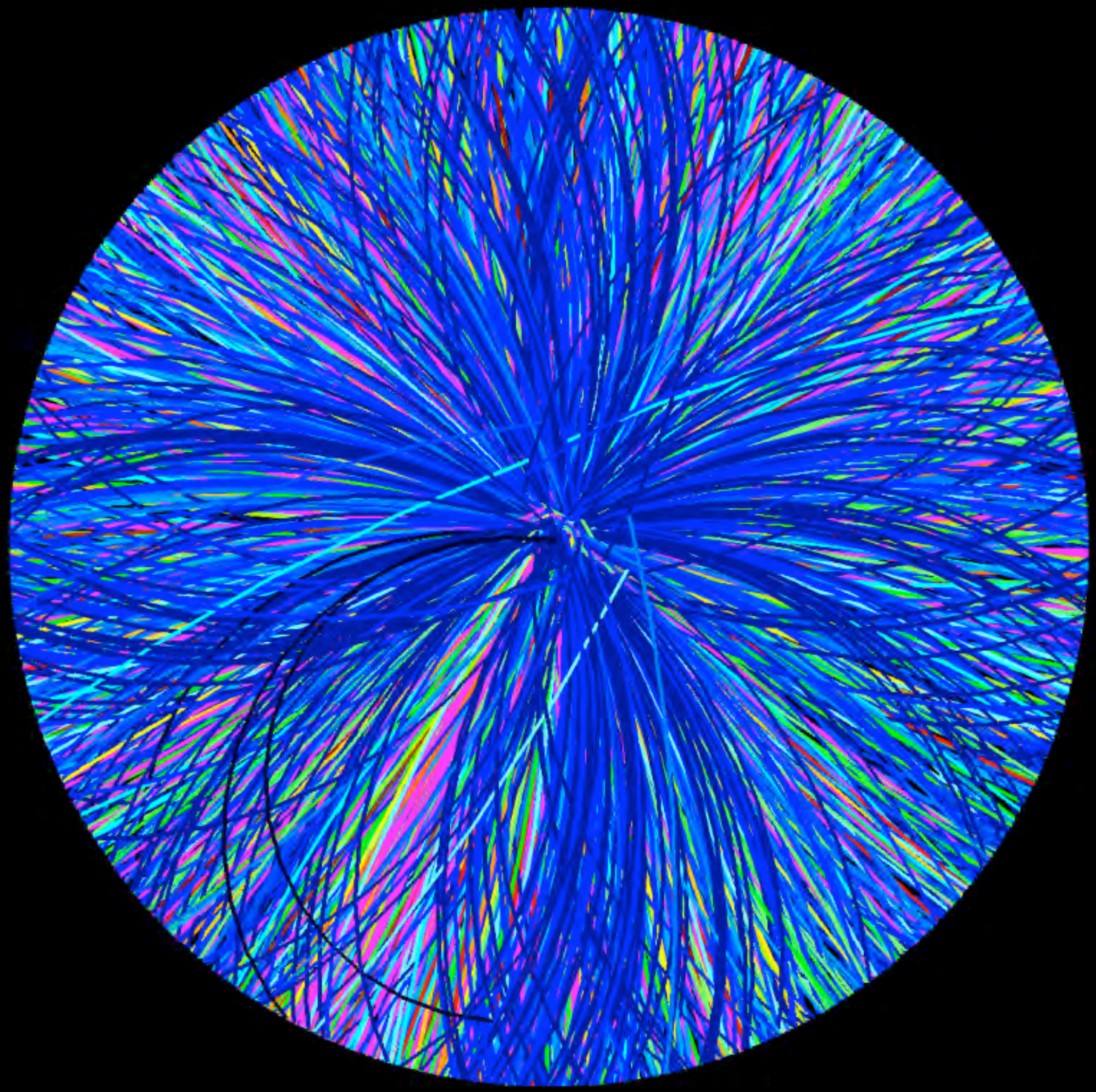

CMS

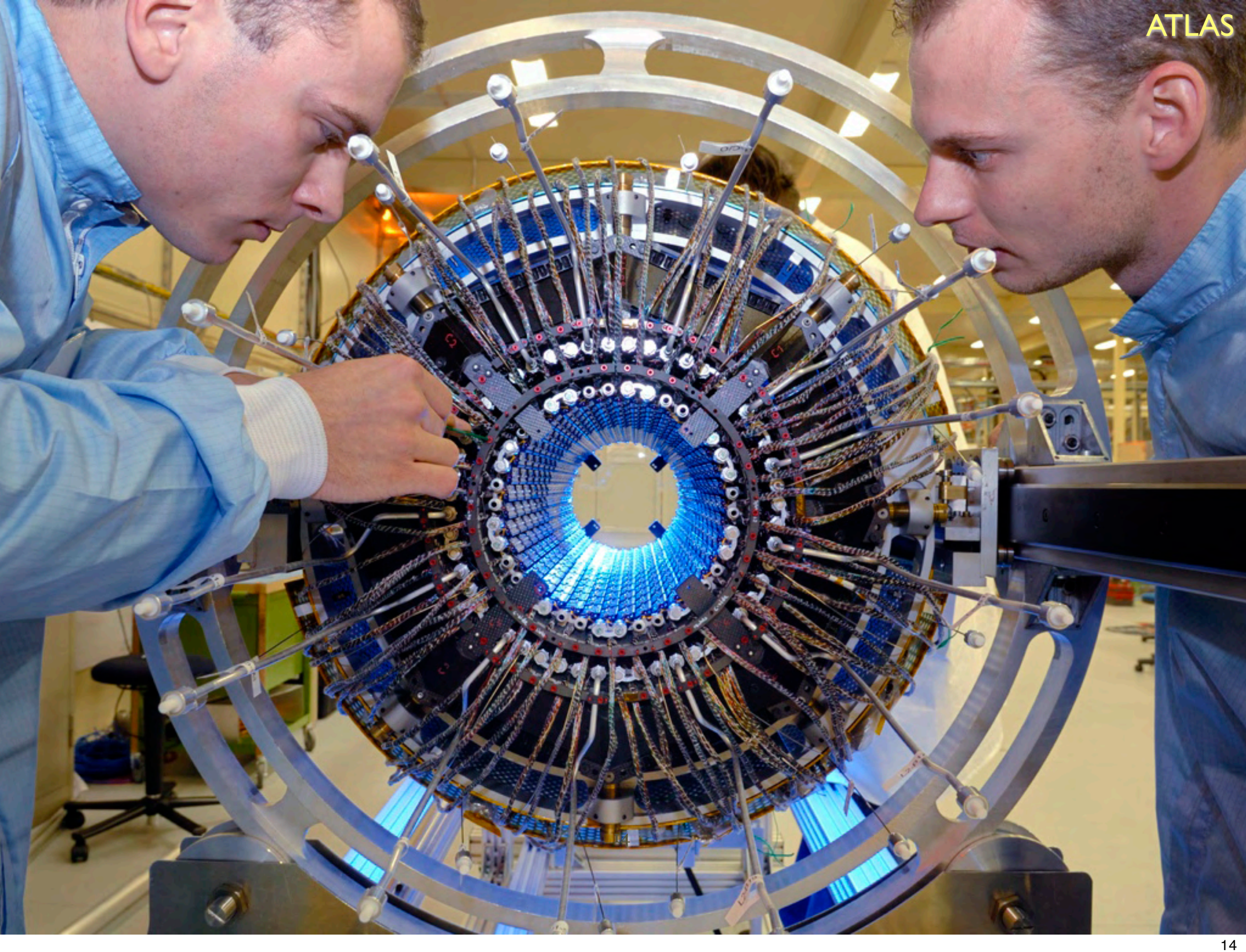
ϒ Spectrum

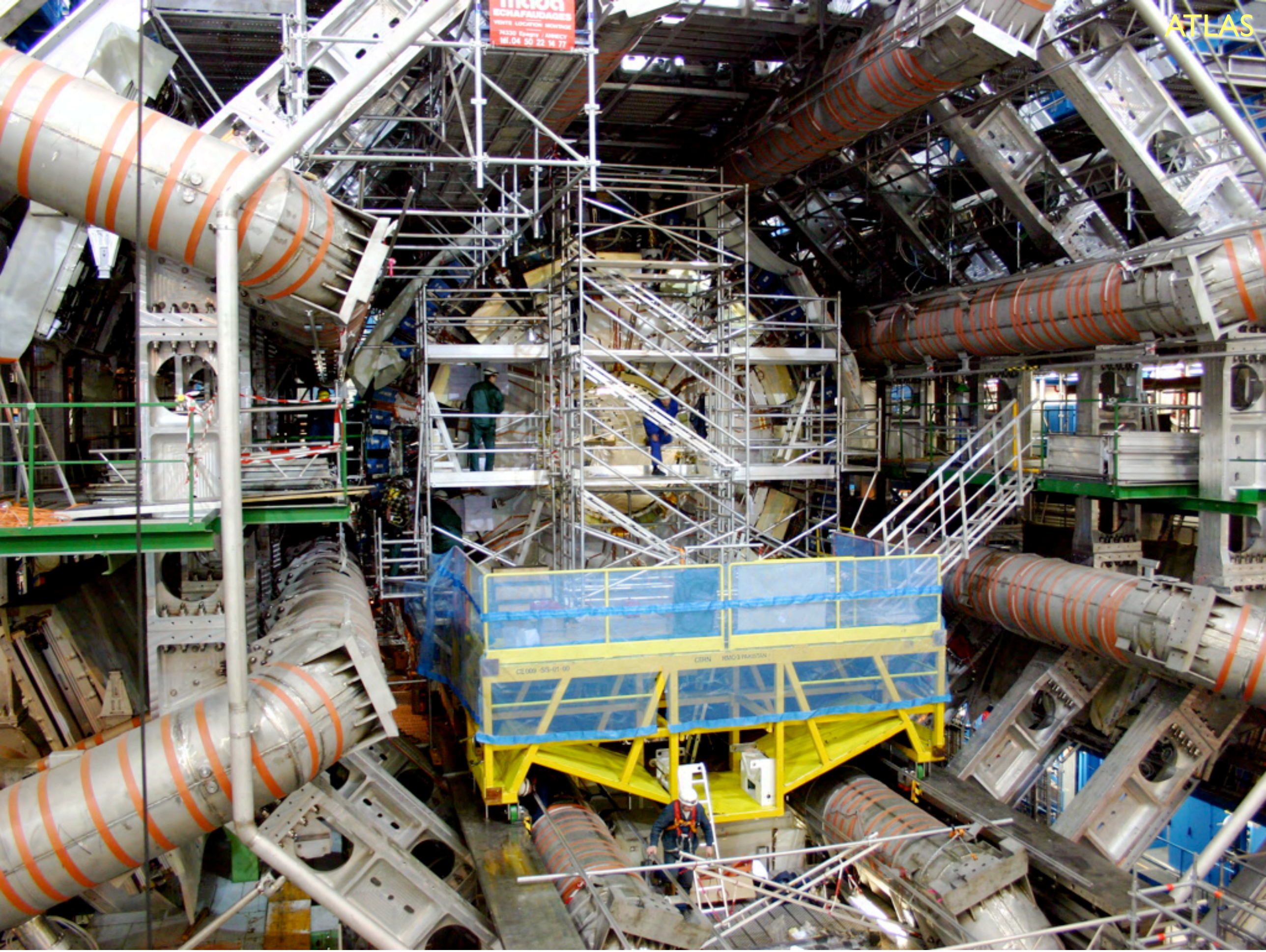

CMS Preliminary, √s = 7 TeV
L_int = 40 pb^-1
|η^μ| < 1
σ = 67 MeV/c^2
Events / (0.07 GeV/c^2)
10000
8000
6000
4000
2000
0
8
8.5
9
9.5
10
10.5
11
11.5
12
μ^+μ^- mass (GeV/c^2)

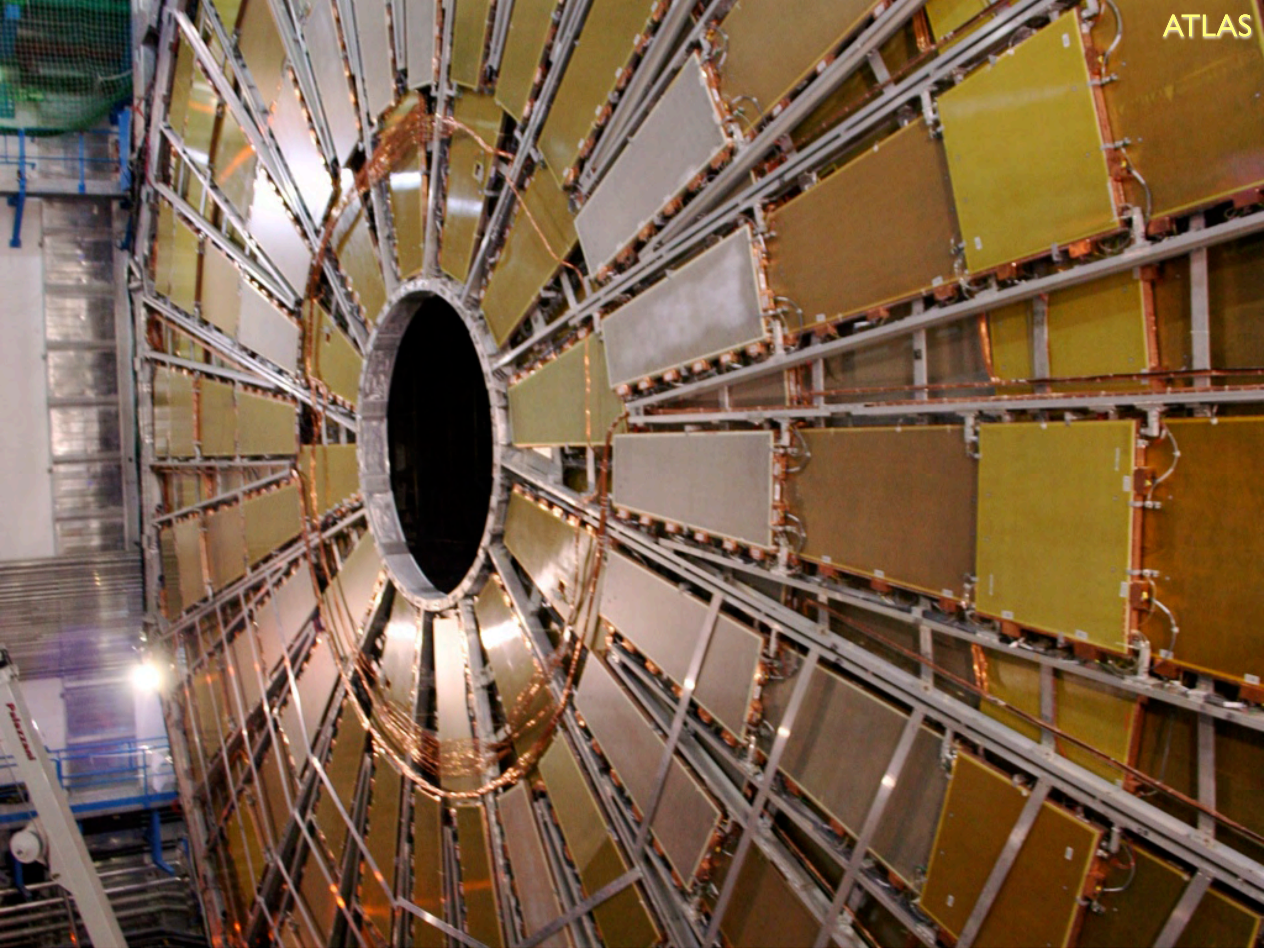

ALICE

ALICE Experiment: Pb-Pb Collisions at 287 TeV



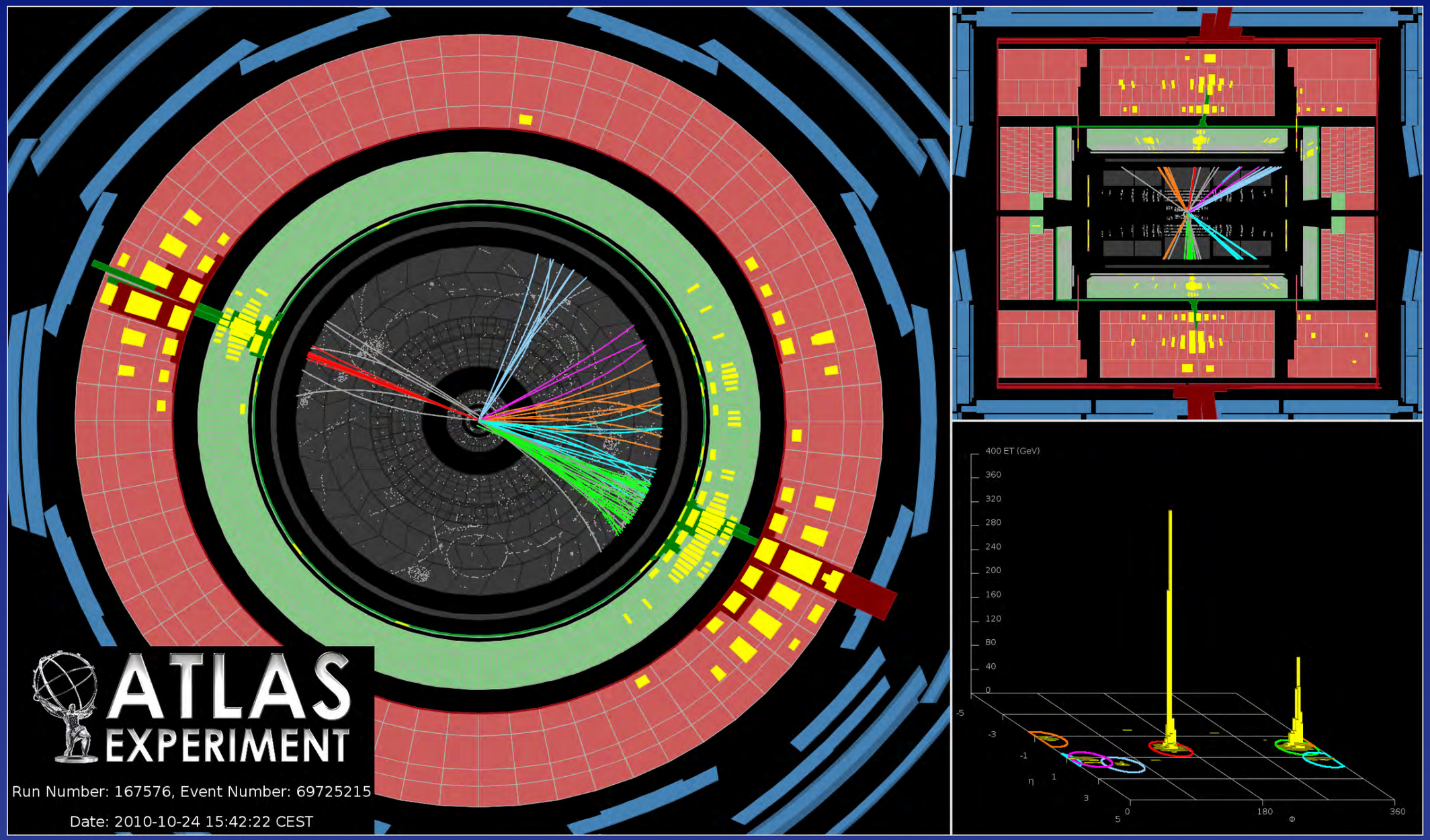

ATLAS


ATLAS


ATLAS

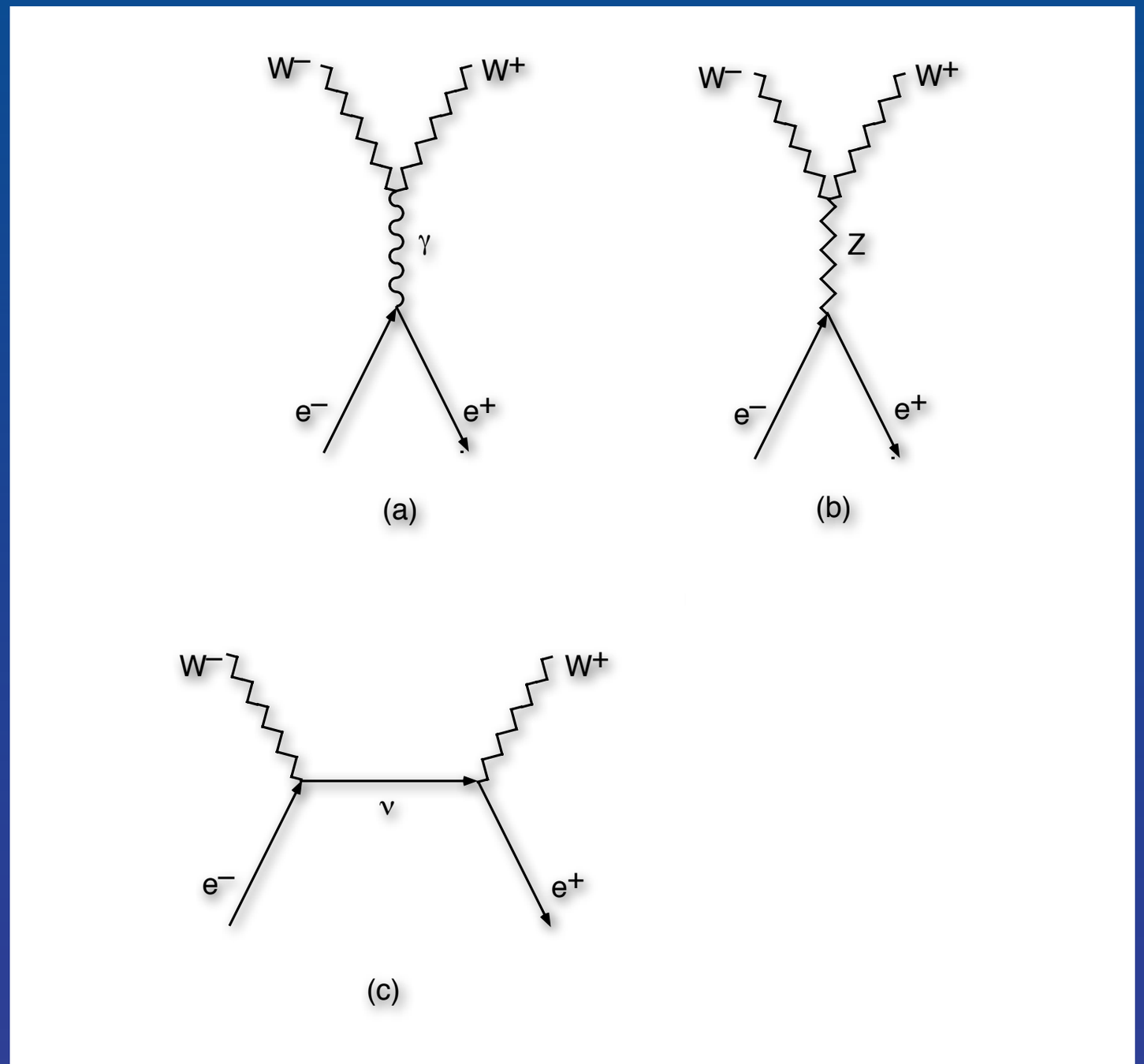
The World's Most Powerful Microscopes

nanonanophysics

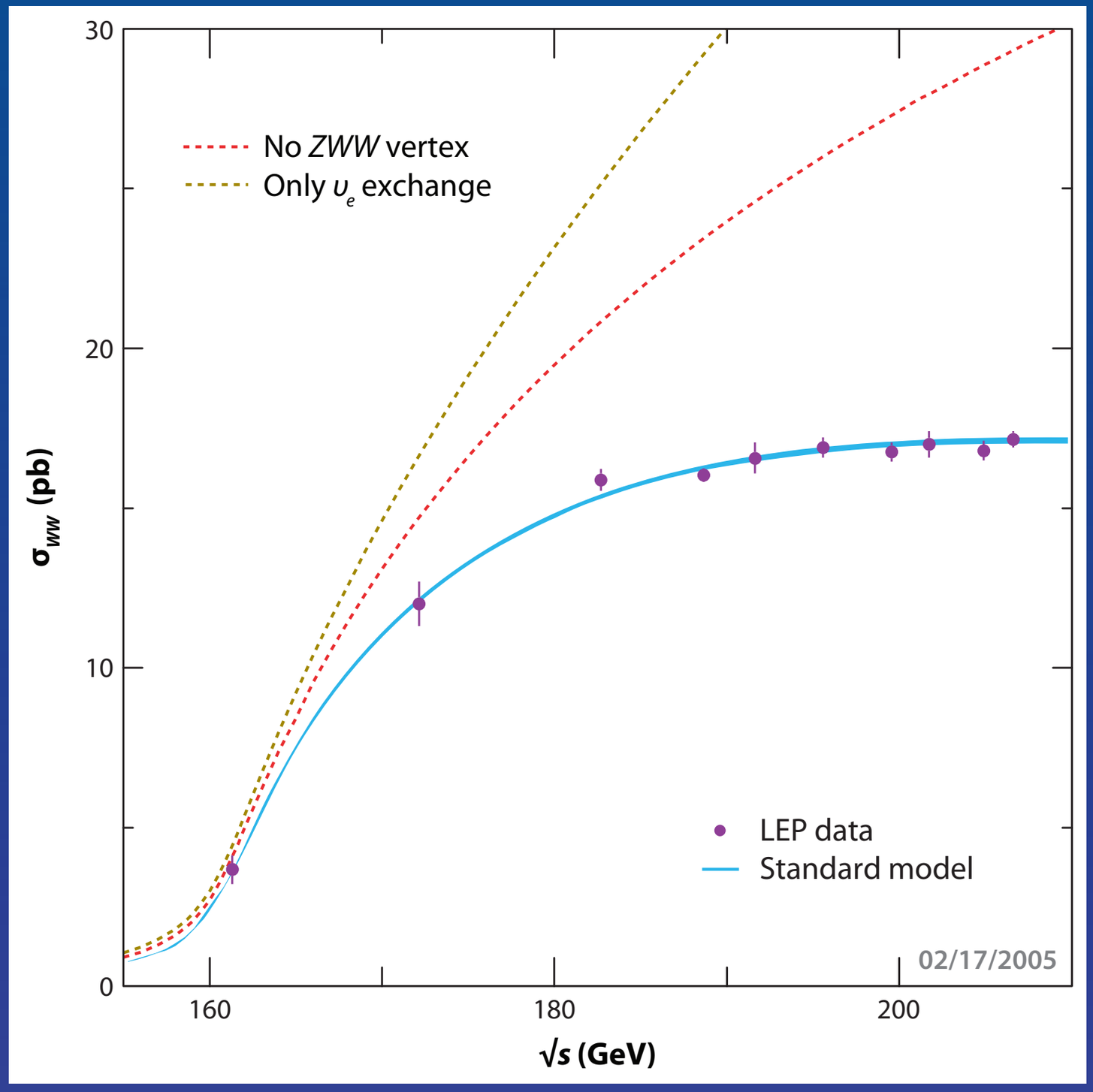


Transverse momenta: 1.3 TeV + 1.2 TeV

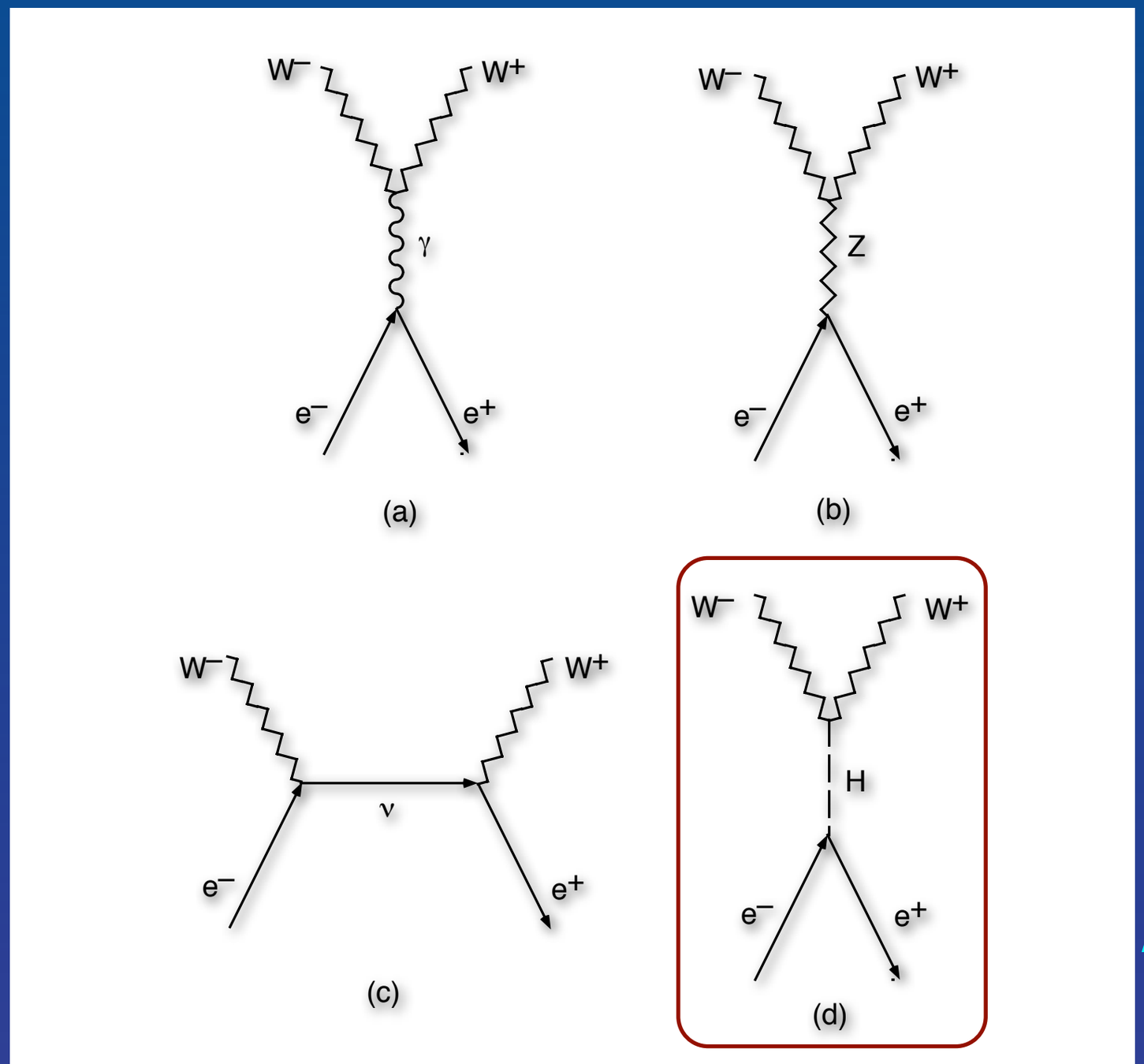
Gauge symmetry (group-theory structure) tested in $e^+e^- \to W^+W^-$



Gauge symmetry (group-theory structure) tested in $e^+e^- \to W^+W^-$



Gauge symmetry (group-theory structure) tested in $e^+e^- \to W^+W^-$

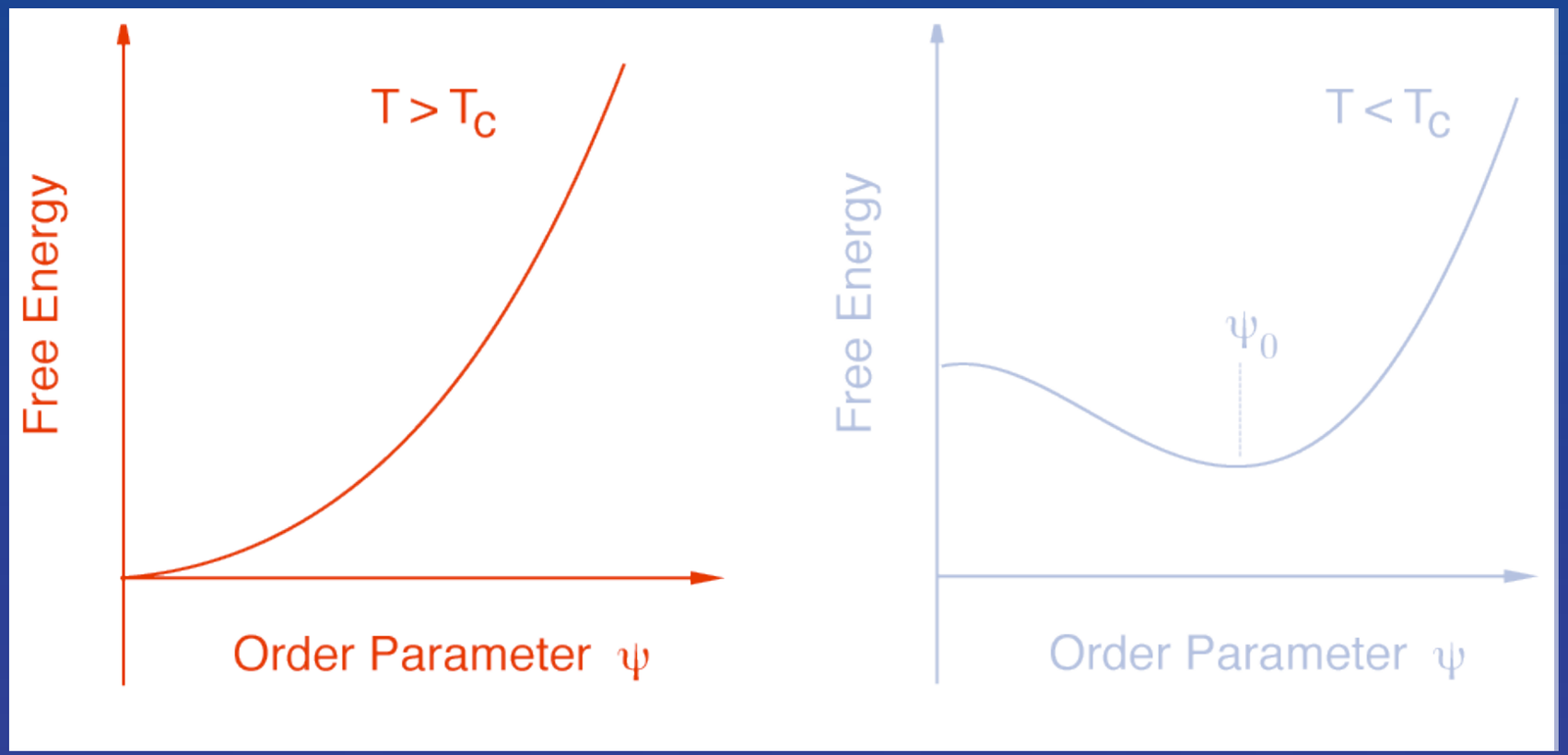


Massive weak bosons: Higgs boson

Meissner effect

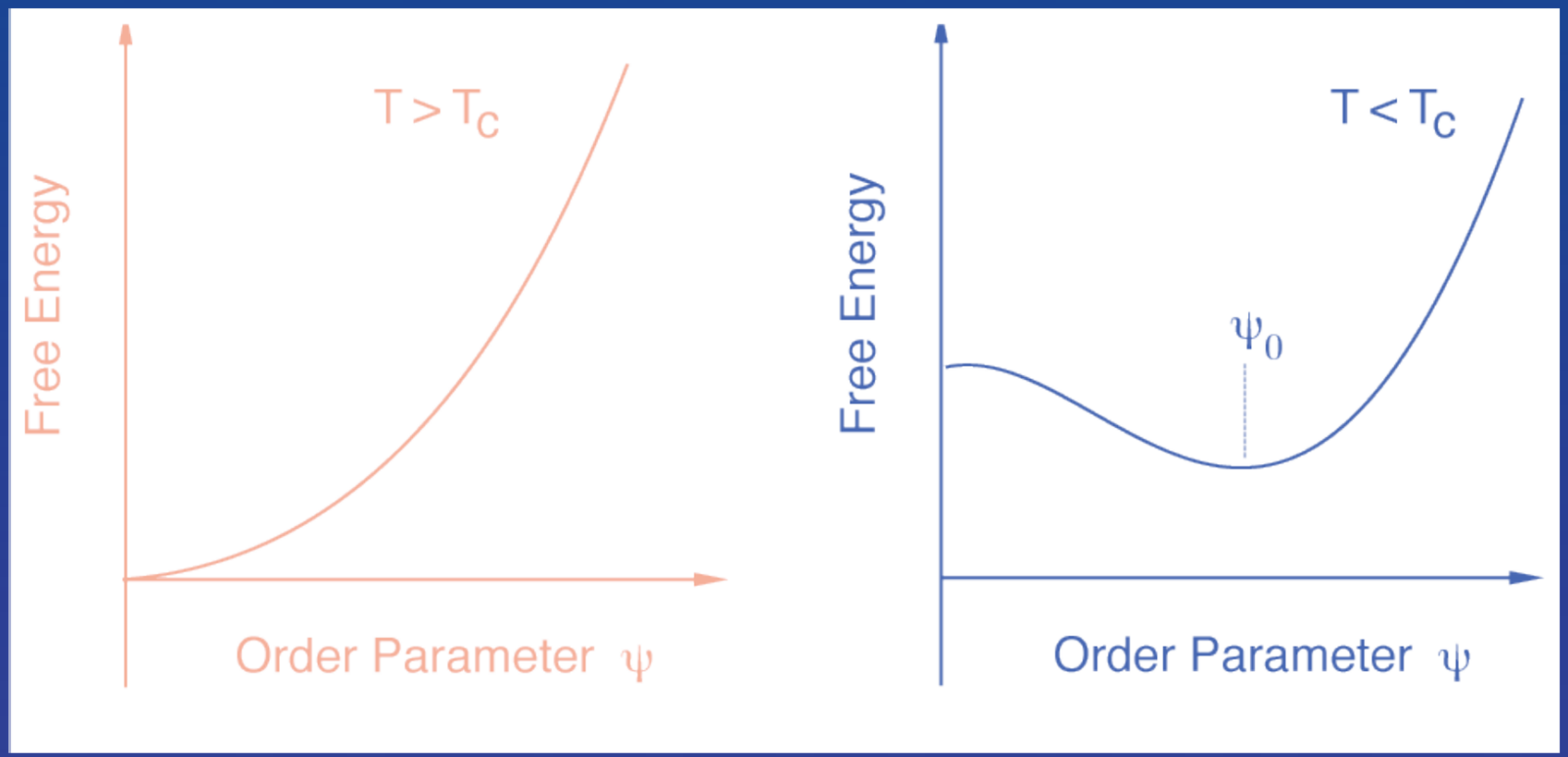
The agent of electroweak symmetry breaking represents a novel fundamental interaction at an energy of a few hundred GeV …

We do not know the nature of the new force.



The agent of electroweak symmetry breaking represents a novel fundamental interaction at an energy of a few hundred GeV …

We do not know the nature of the new force.



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,

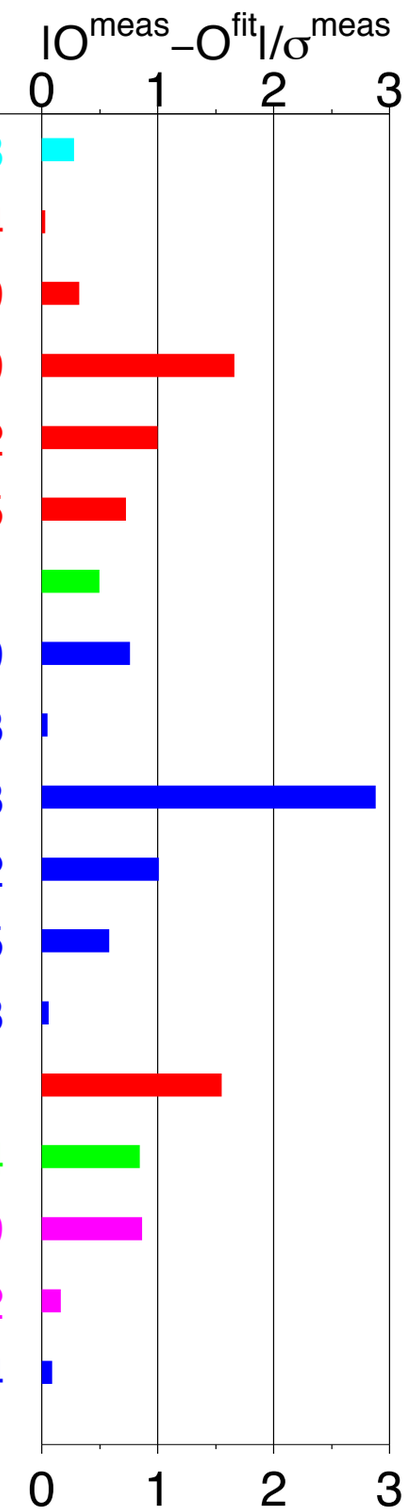
provided $\boxed{M_H \leq (8\pi\sqrt{2}/3G_F)^{1/2} \approx 1 \text{ TeV}}$

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

New phenomena are to be found around 1 TeV

Precision Measurements Test the Theory …

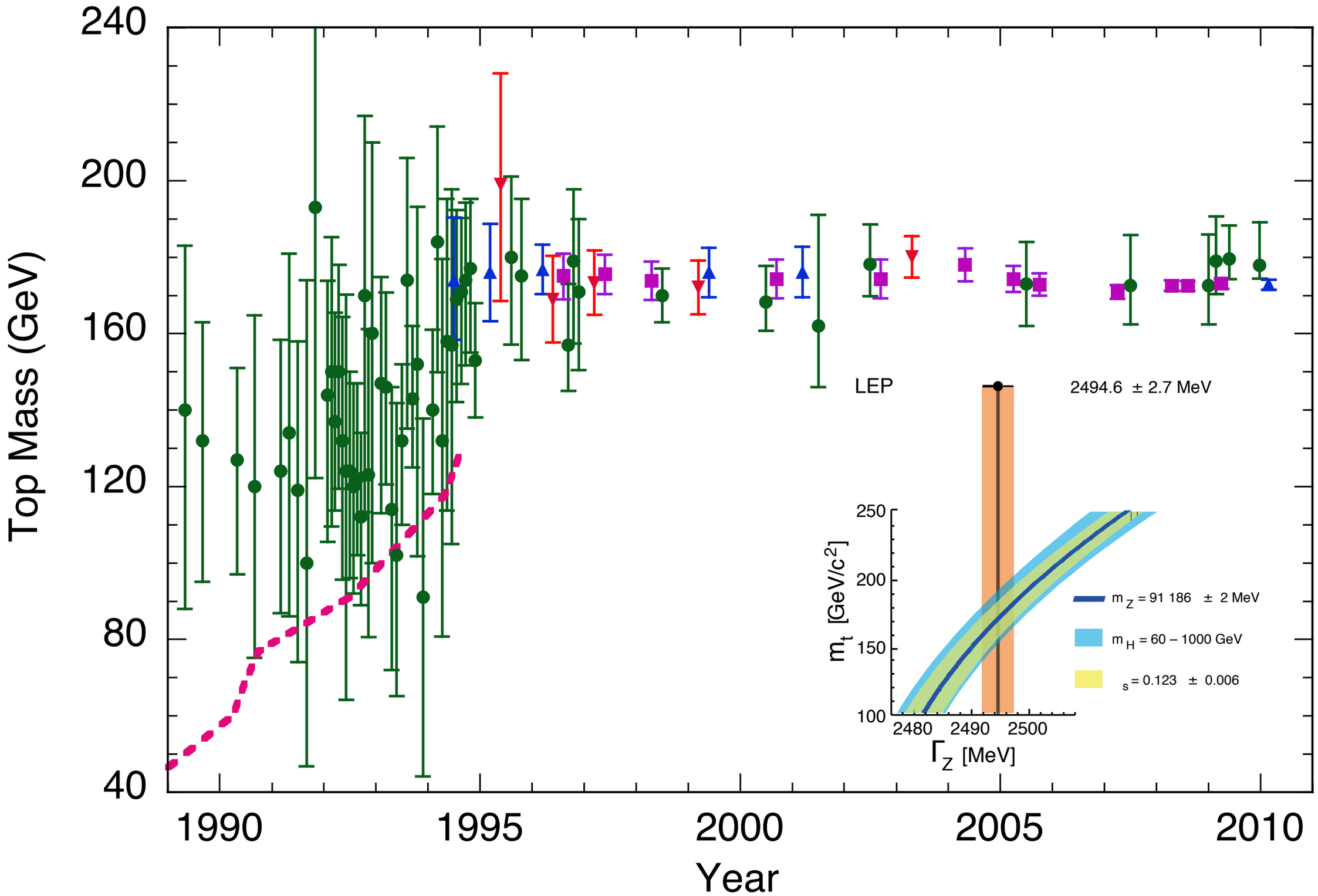
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4



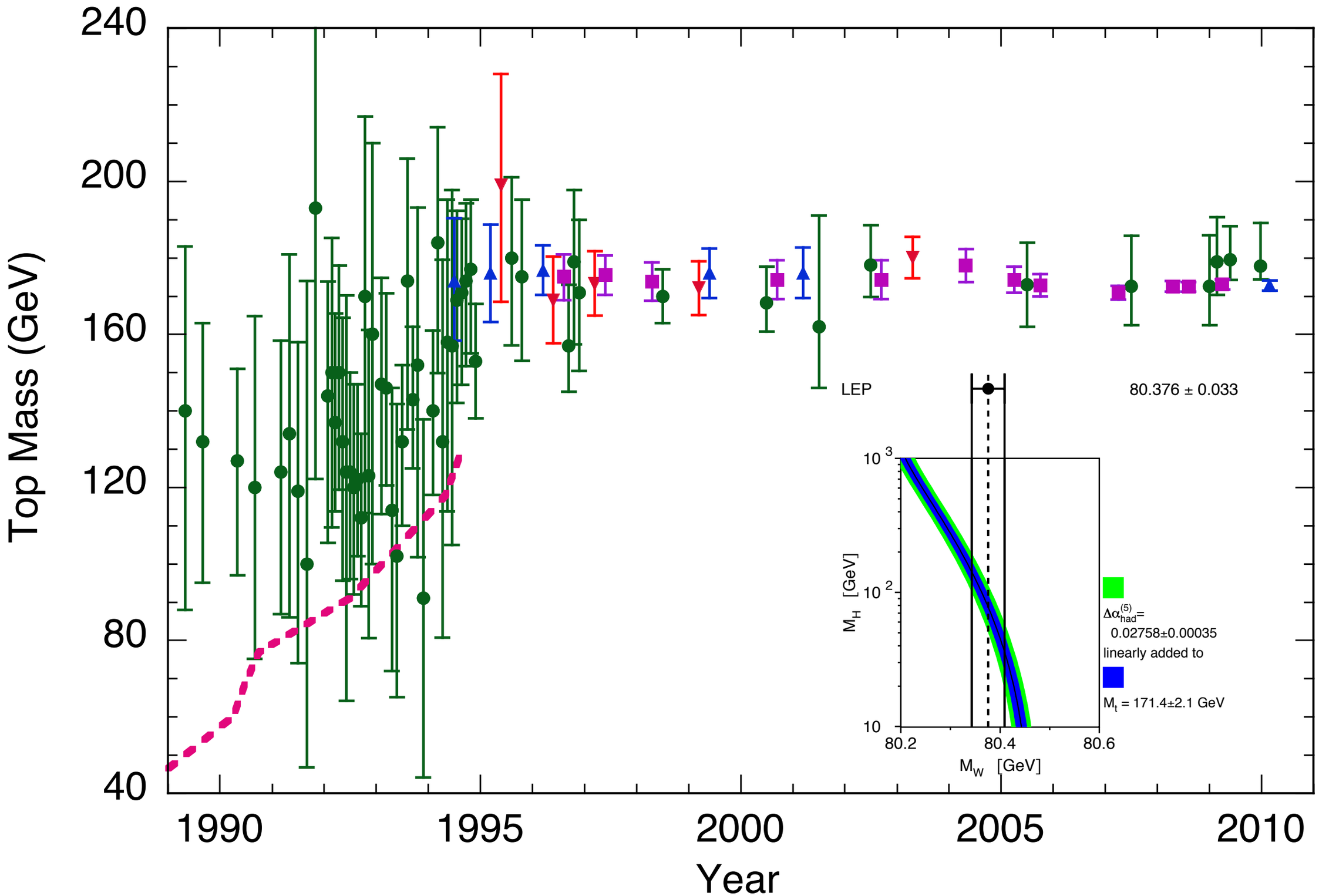
July 2010

LEP EWWG

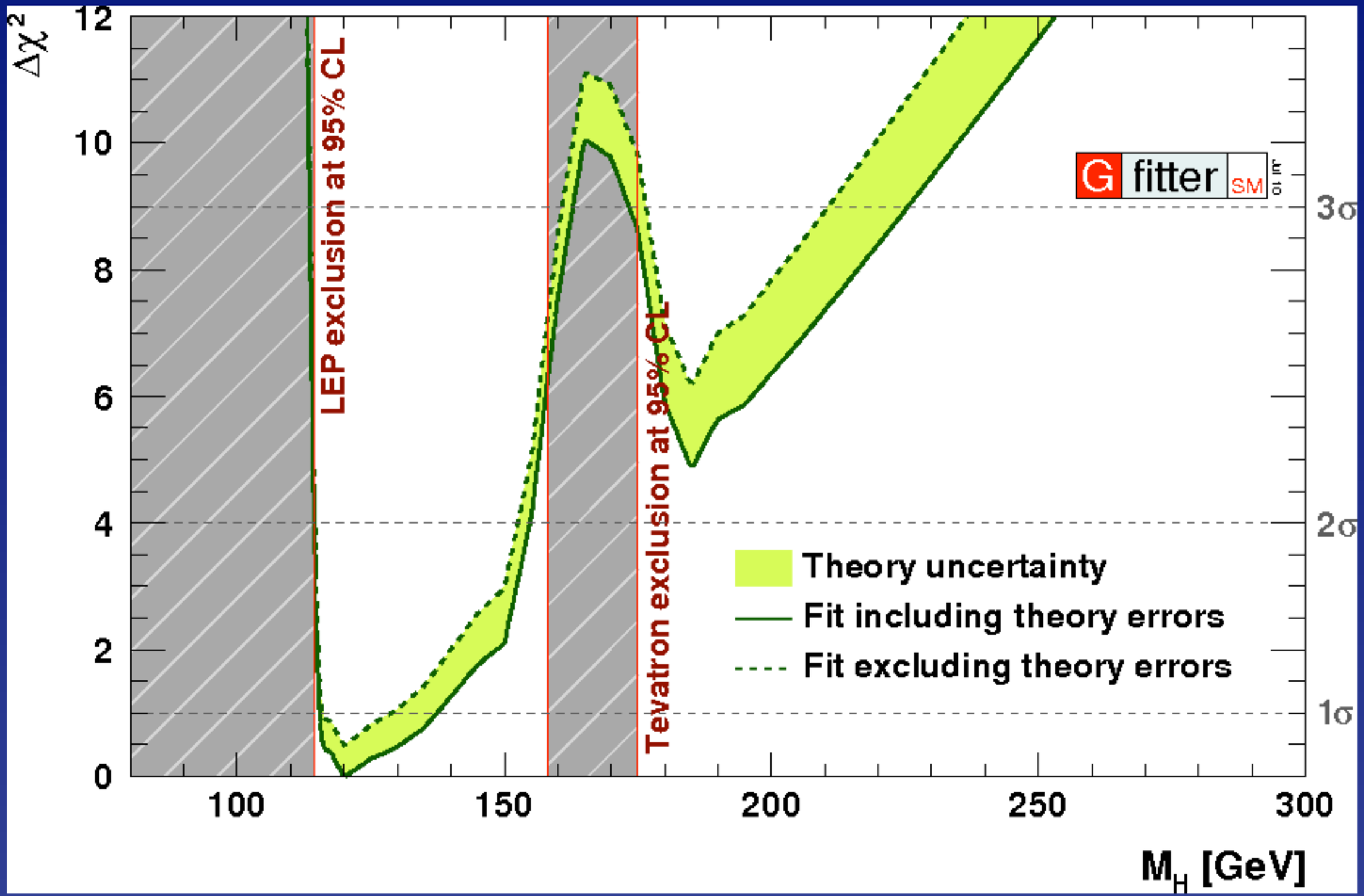
… and determine unknown parameters



… and determine unknown parameters



Where the (standard) Higgs boson might be



What is the nature of the mysterious new force that 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

Which path has Nature taken?

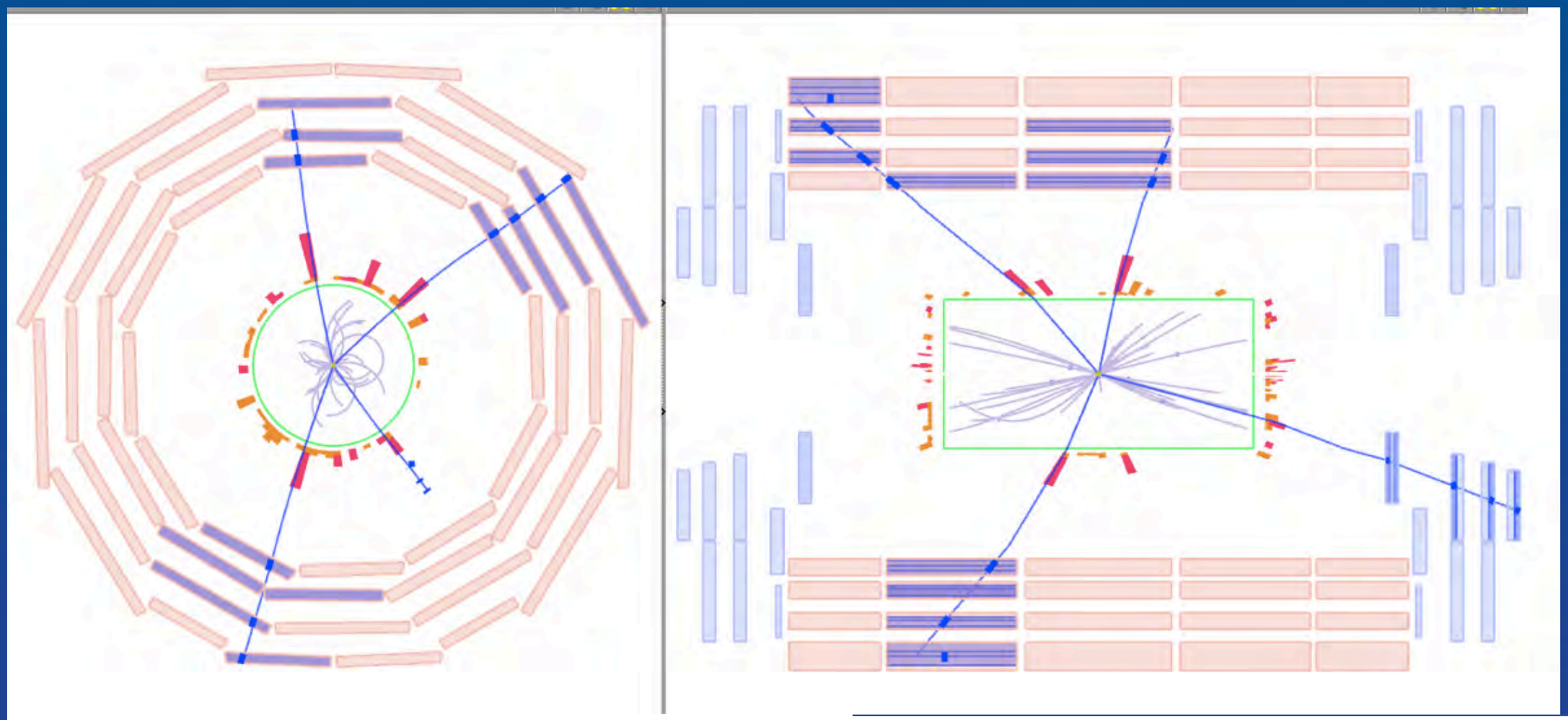
Essential step toward understanding the new force that shapes our world:

Find the Higgs boson and explore its properties.

- ✳ Is it there? How many?
- ✳ Verify quantum numbers (spin, parity, …)
- ✳ Does *H* generate mass for gauge bosons and for fermions?
- ✳ How does *H* interact with itself?

Finding the Higgs boson starts a new adventure!

How a heavy Higgs boson would appear



CMS event: 7-TeV pp

Invariant Masses

$\mu_0 + \mu_1$: 92.15 GeV (total(Z) p_T 26.5 GeV, ϕ -3.03),
$\mu_2 + \mu_3$: 92.24 GeV (total(Z) p_T 29.4 GeV, ϕ +.06),
$\mu_0 + \mu_2$: 70.12 GeV (total p_T 27 GeV),
$\mu_3 + \mu_1$: 83.1 GeV (total p_T 26.1 GeV).

Invariant Mass of 4μ: 201 GeV

Why will it matter?

Understanding the everyday …

Why atoms?

Why chemistry?

Why stable structures?

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, …

… character of the physical world would be profoundly changed

arXiv:0901.3958

Revolution: The Meaning of Identity

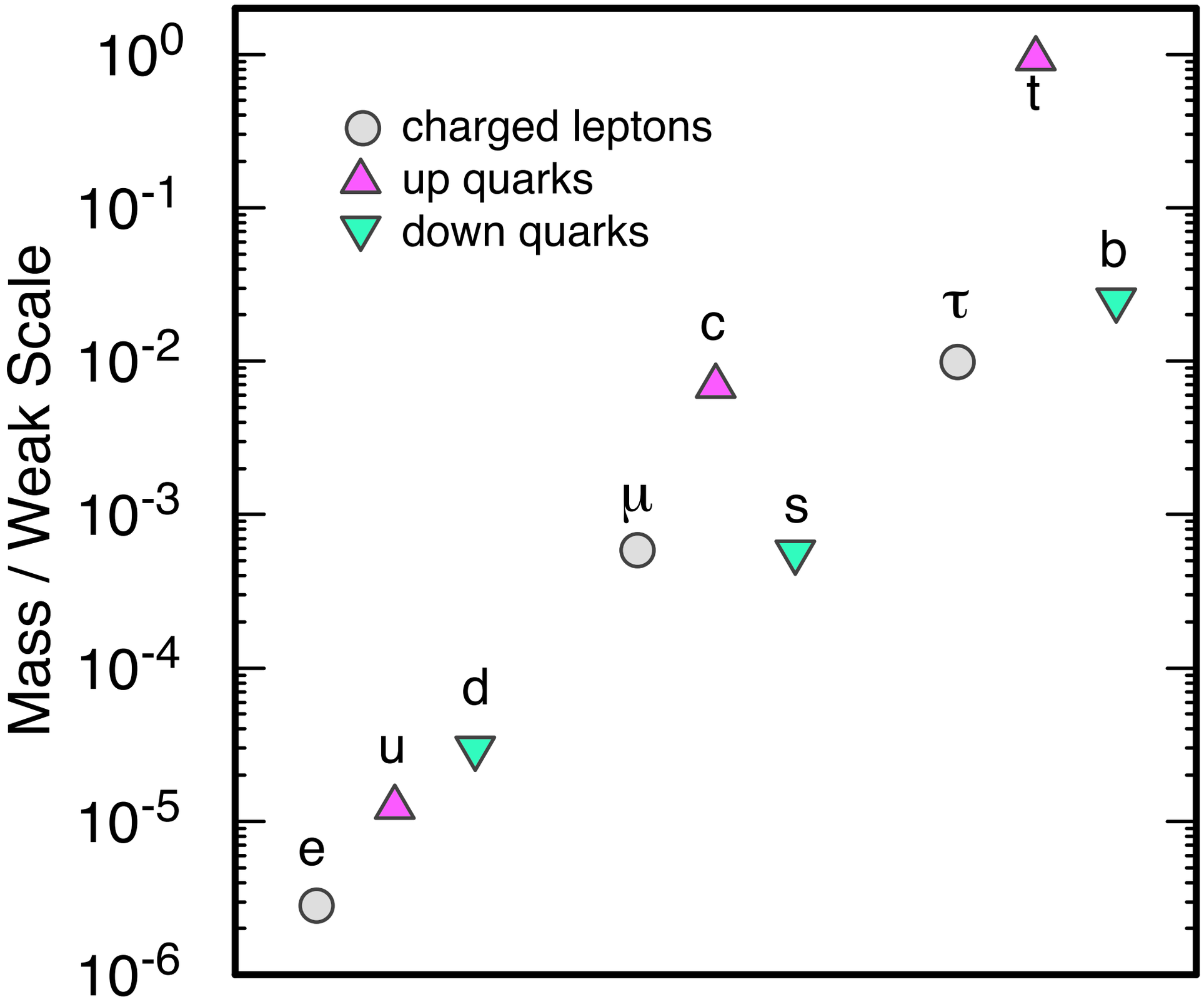
What makes a top quark a top quark,
an electron an electron, a neutrino a neutrino?

What sets masses and mixings of quarks and leptons?
All fermions masses and mixings mean new physics!

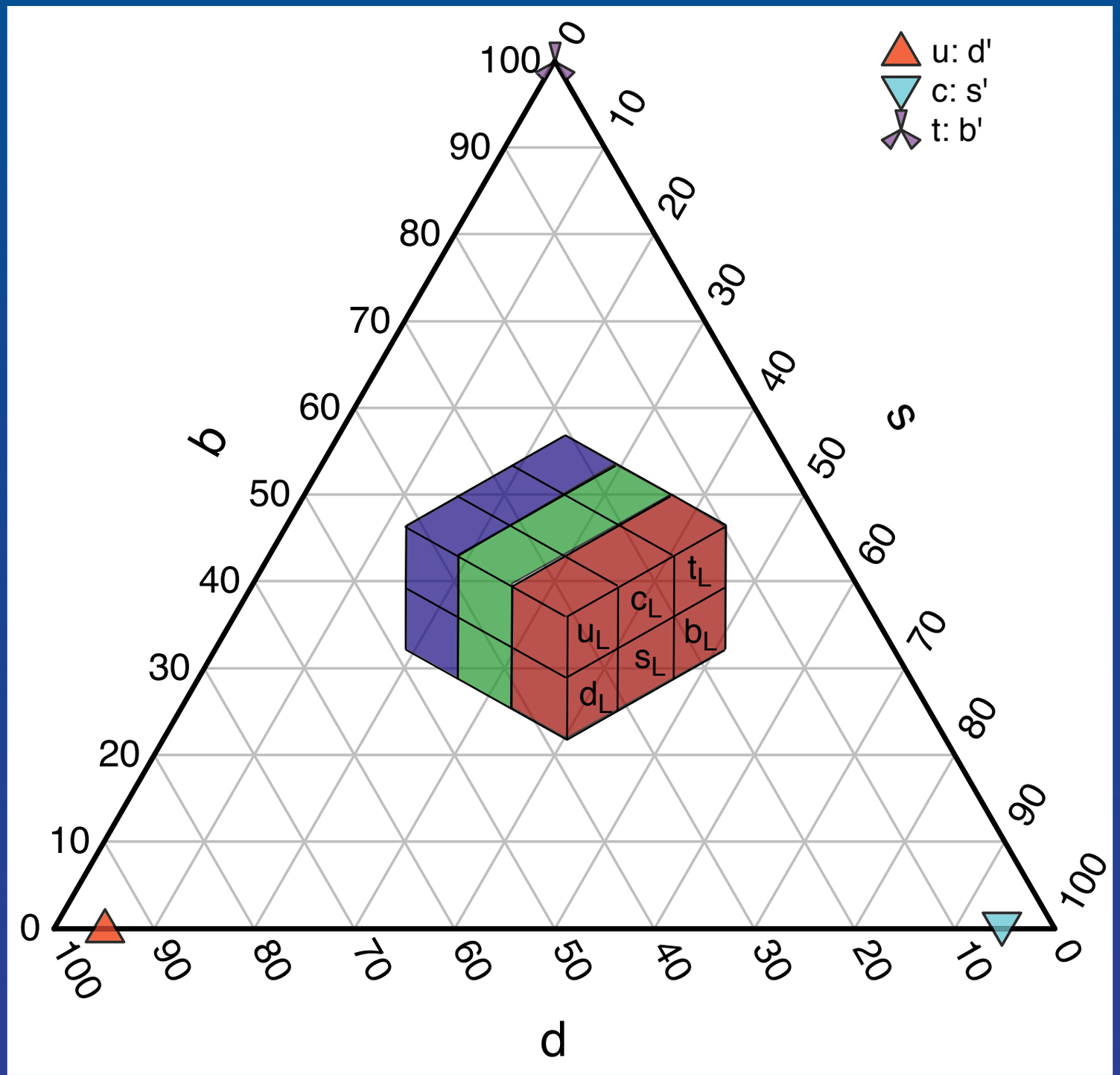
What is CP violation trying to tell us?

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

Might new kinds of matter unlock the pattern?

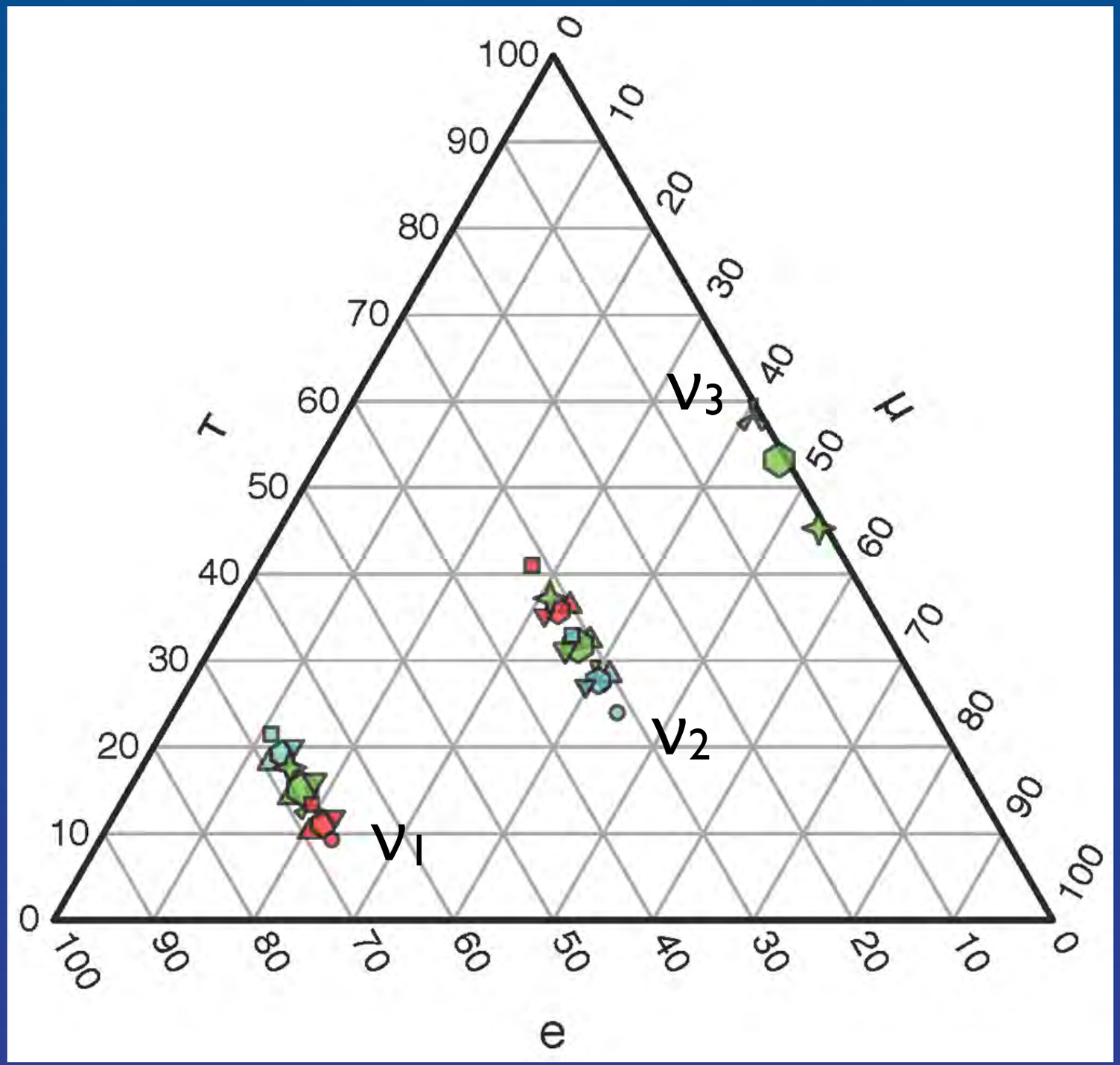

charged leptons
up quarks
down quarks
Mass / Weak Scale
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
t
b
τ
c
μ
s
d
u
e

Quark family patterns: *generations*

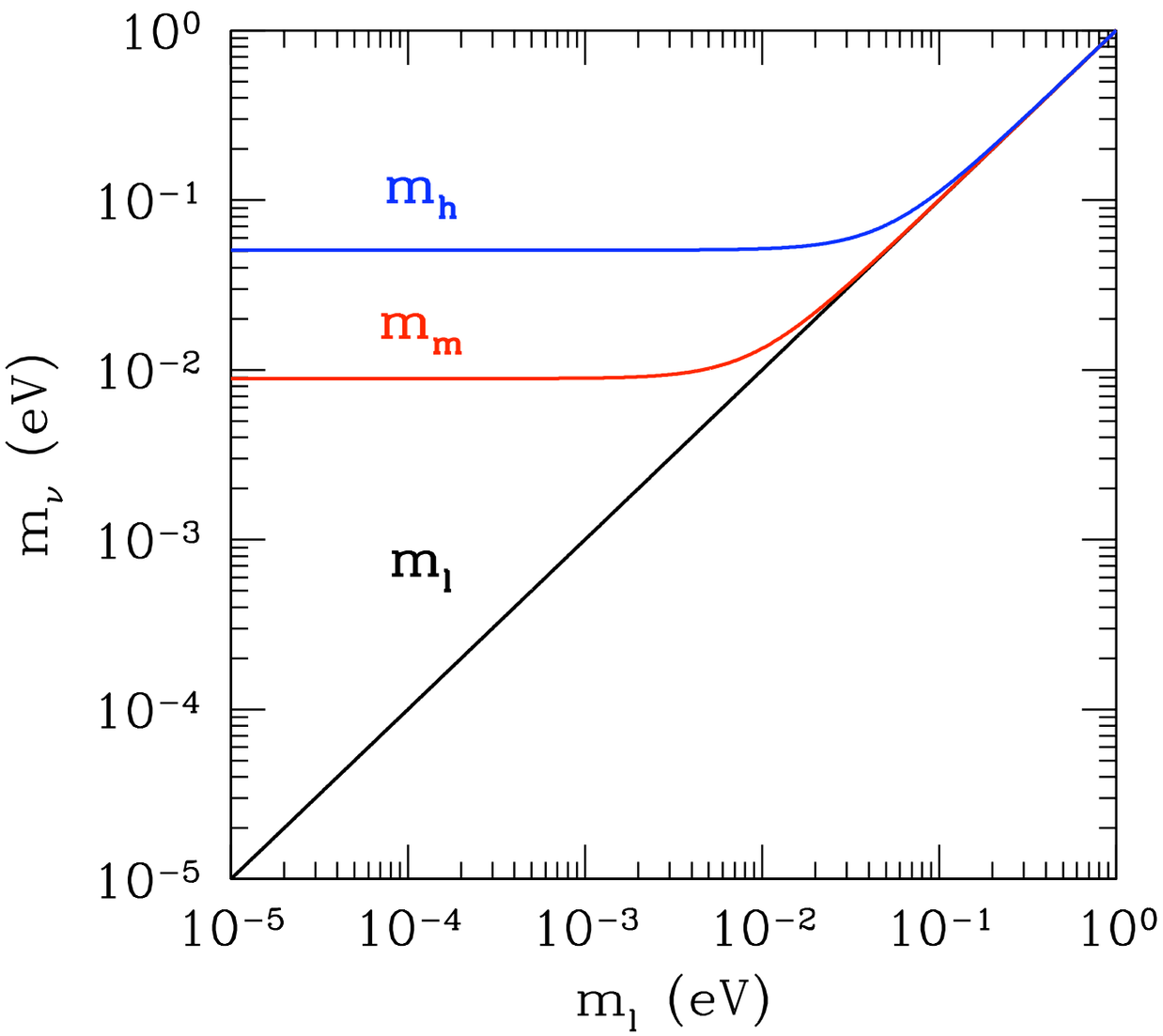


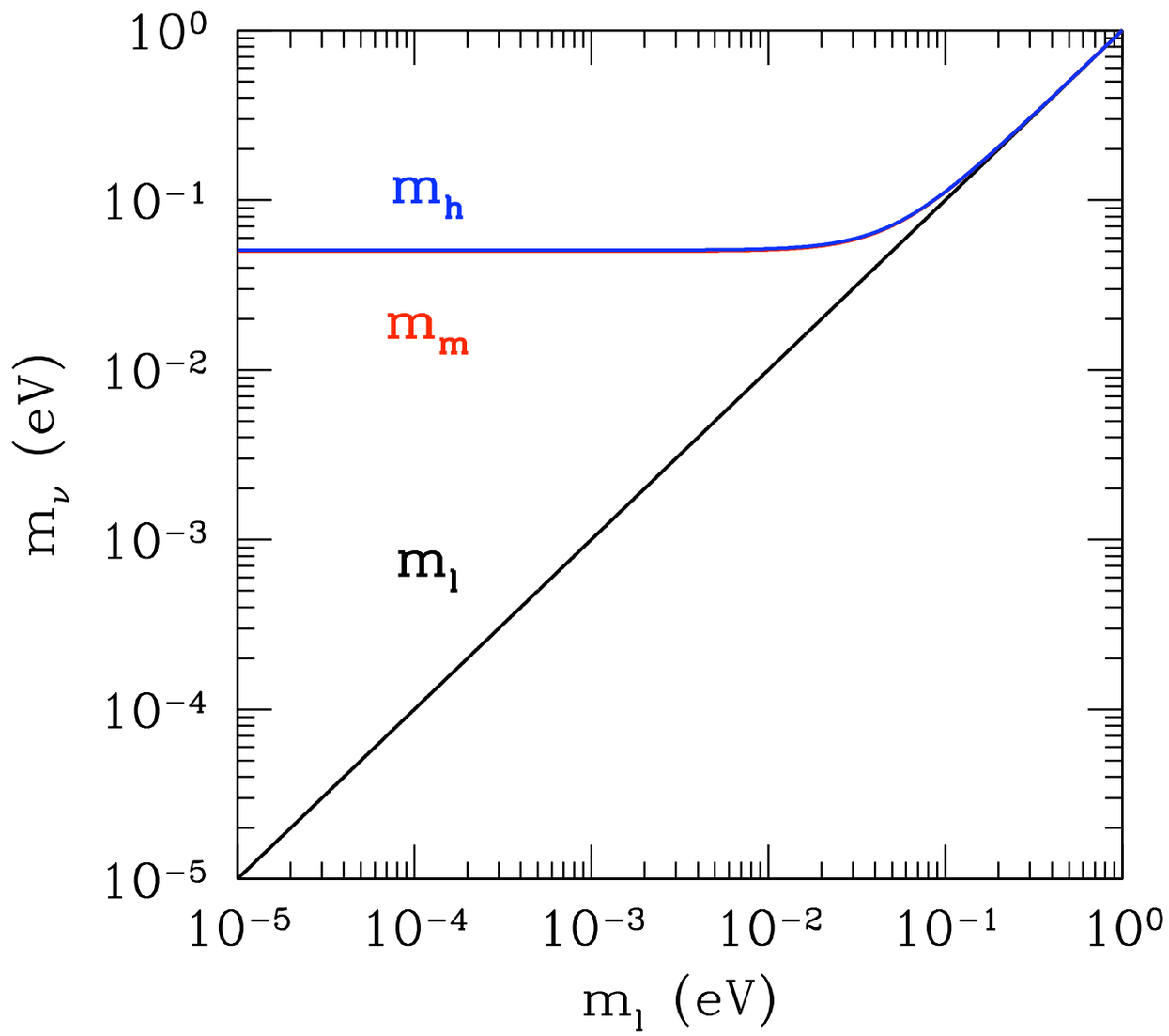
Veltman: Higgs boson knows something we don't know!

Neutrino family patterns



Neutrino Masses



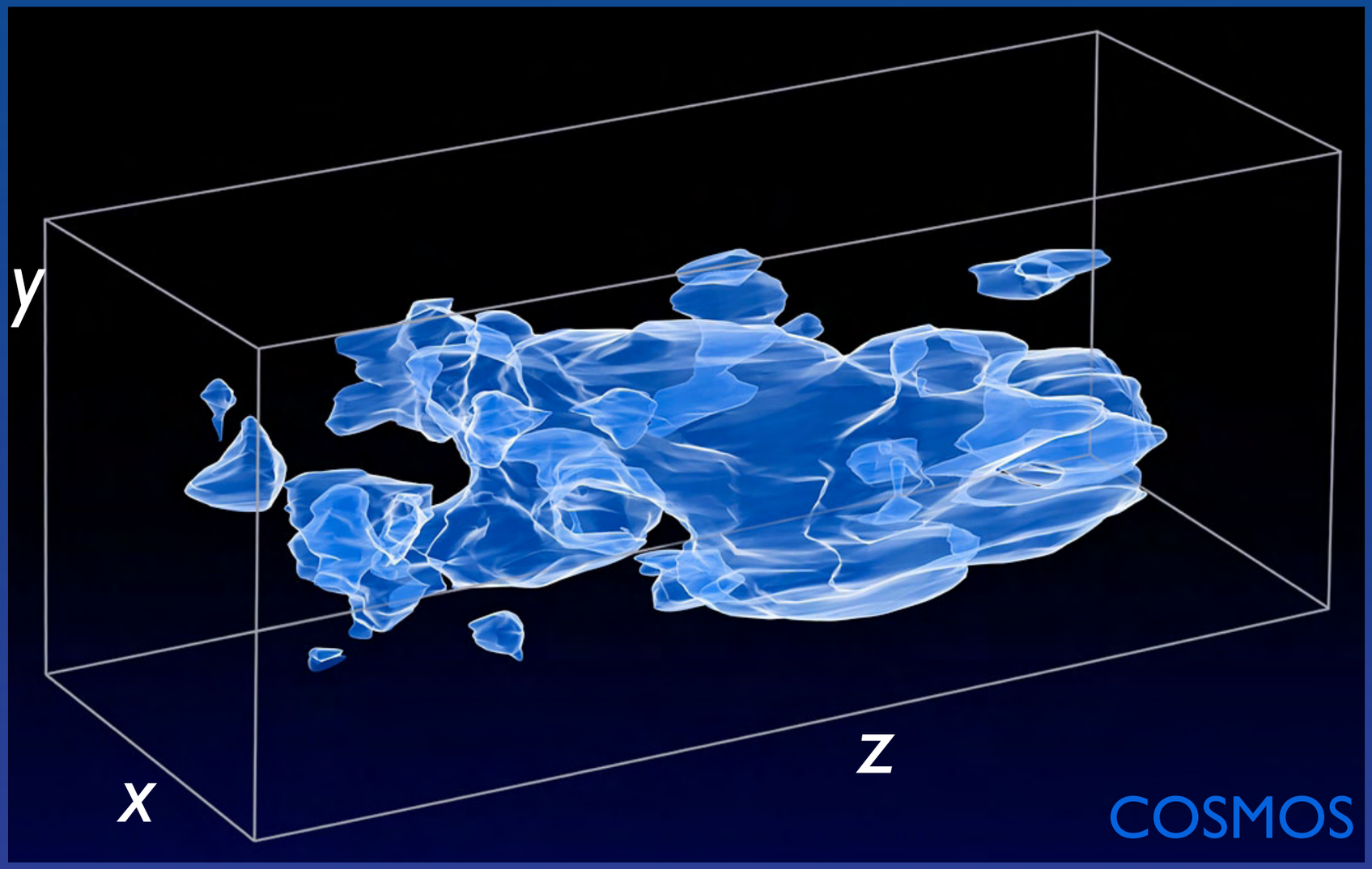


KATRIN aims at 0.2 eV

$^3\mathrm{H} \rightarrow {}^3\mathrm{He}\, e^- \bar{\nu}$

More New Physics on the TeV Scale?

If dark matter interacts weakly …



… its likely mass is 0.1 to 1 TeV

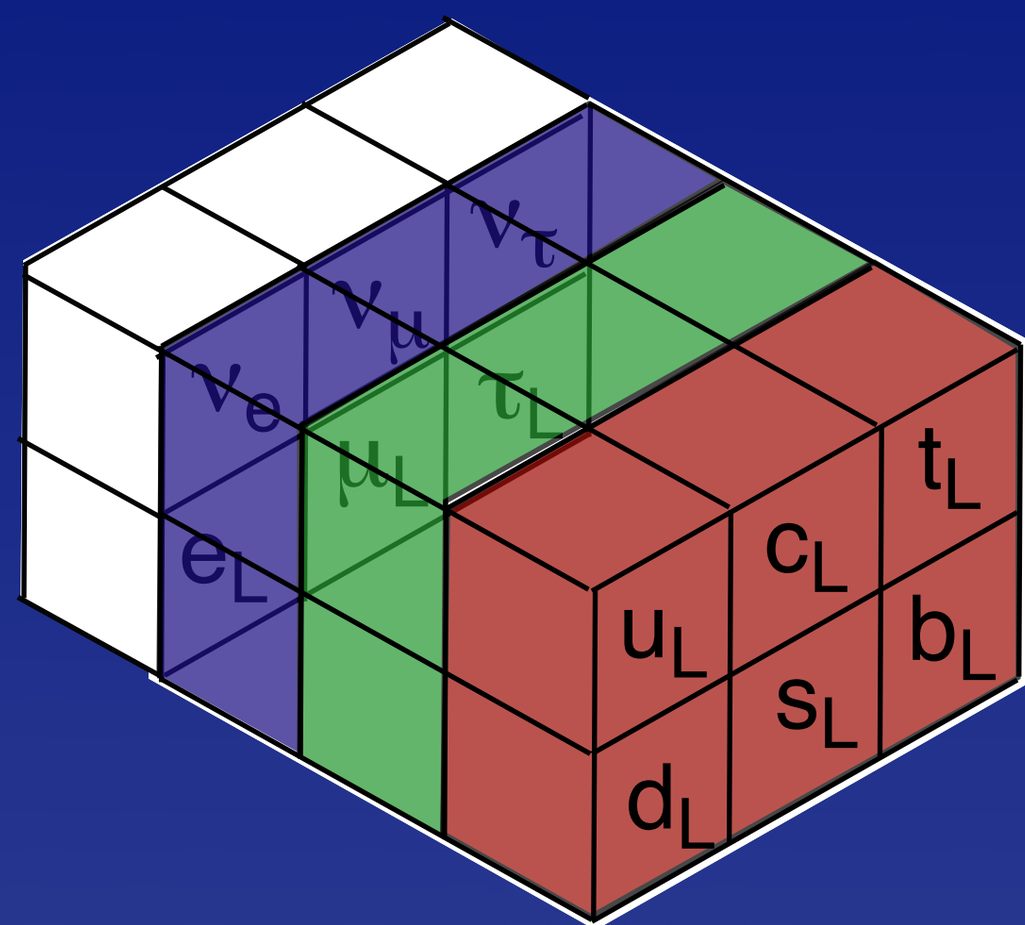
Many extensions to EW theory entail dark matter candidates

Example: *Supersymmetry* (fermion-boson symmetry)

$h\ H\ A$ $H^{\pm}$	$u\ d\ e\ \nu$	g $W^{\pm}\ Z^0\ \gamma$
$\tilde{u}\ \tilde{d}\ \tilde{e}\ \tilde{\nu}$	$\tilde{g}\ \tilde{\chi}^{\pm}_{1,2}\ \tilde{\gamma}$ $\tilde{\chi}^0_{1\ldots4}$	
spin 0	1/2	1

Revolution: The Unity of Quarks & Leptons

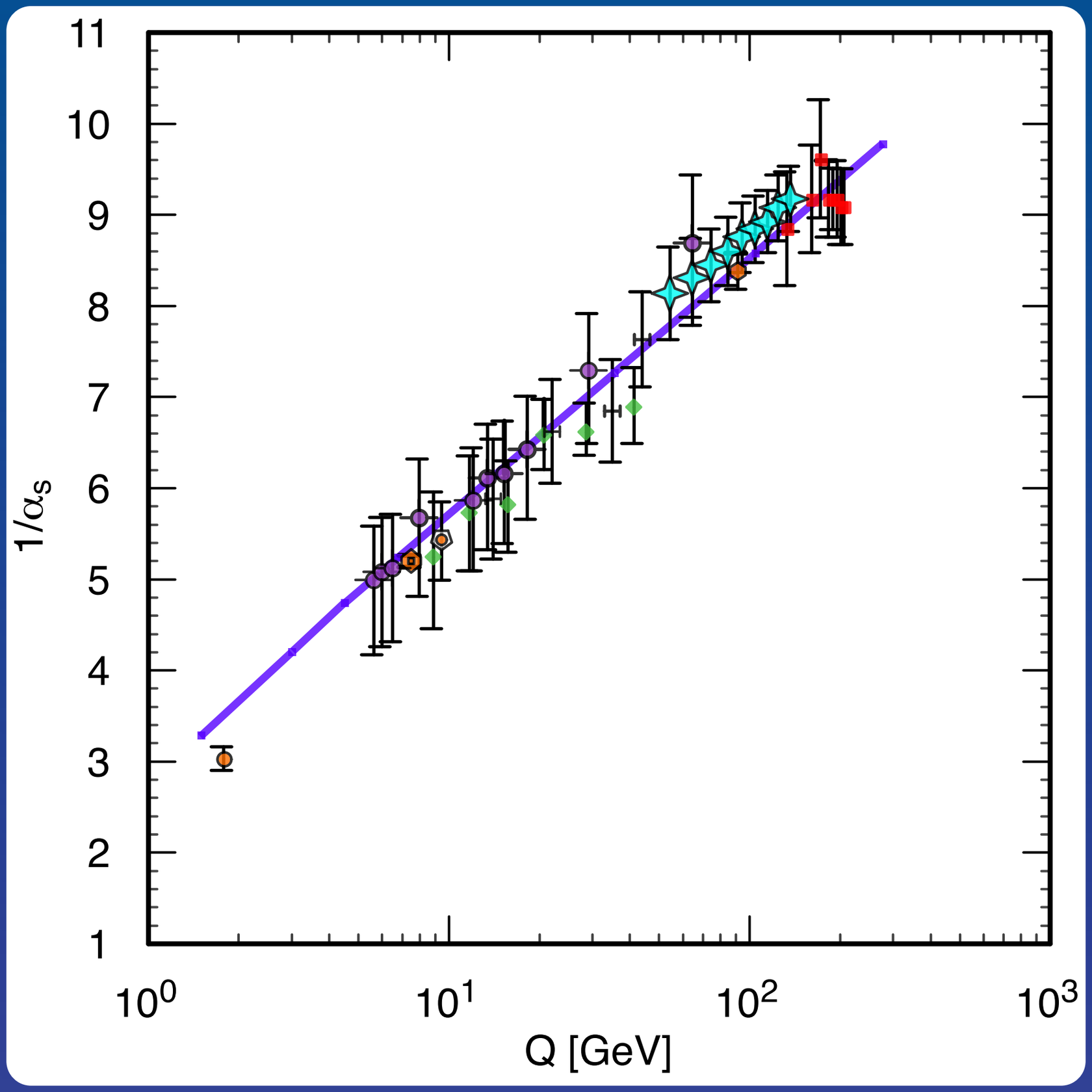
Why are atoms so remarkably neutral?



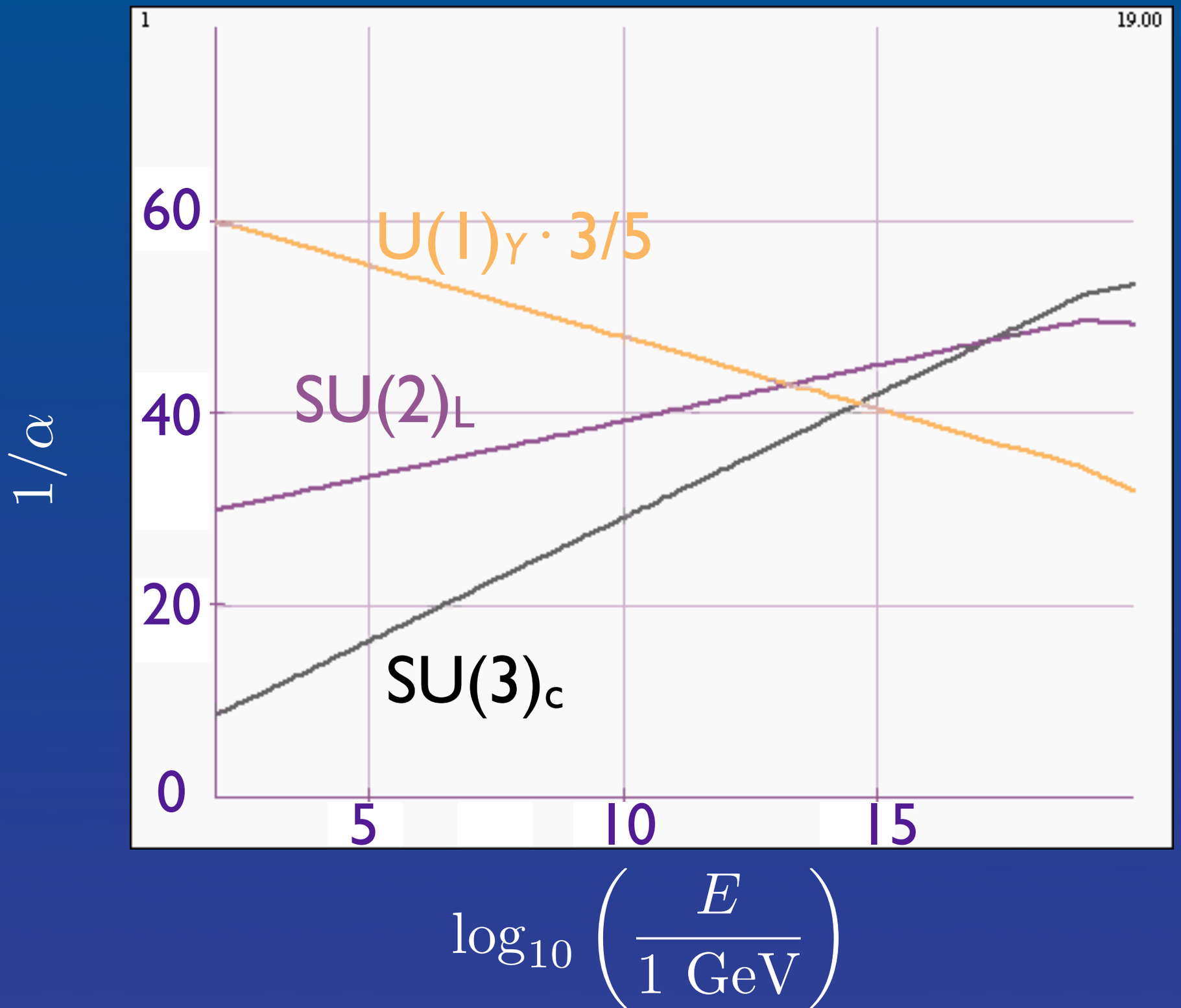
Coupling constant unification?

Extended quark–lepton families:
proton decay!

Evolution of the strong coupling "constant"



Unification of Forces?



An electroweak challenge:

Why is empty space so nearly massless?

Gravitational ep interaction $\approx 10^{-41}$ EM

But gravity is not always negligible …

Higgs field contributes uniform vacuum energy density

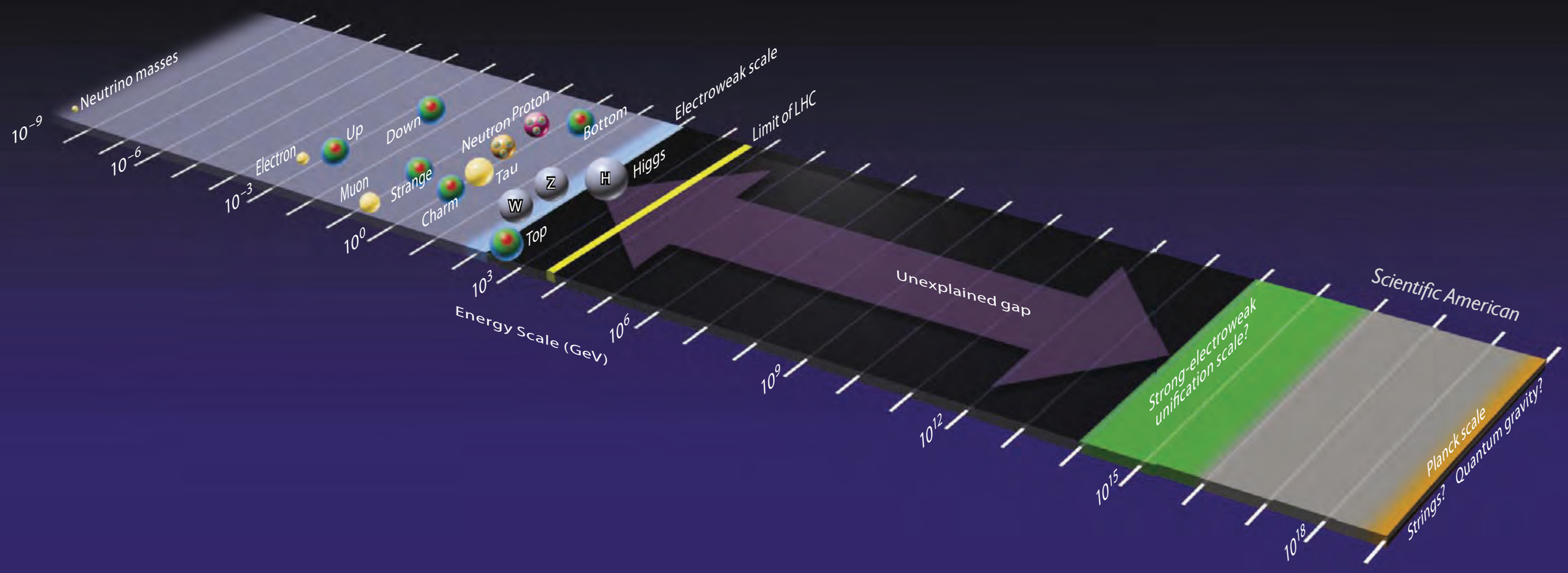
$$\varrho_H \equiv \frac{M_H^2 v^2}{8} \geq 10^8 \text{ GeV}^4 \quad \approx 10^{28} \text{ g/liter}$$

Critical density $\varrho_c \equiv \dfrac{3H_0^2}{8\pi G_{\text{Newton}}} \lesssim 10^{-26}$ g/liter

Another "small" challenge:

Does M_H < 1 TeV make sense?

The peril of quantum corrections



How to separate electroweak, higher scales?

… and address a few outliers, if confirmed

Extend electroweak theory on the 1-TeV scale …

composite Higgs boson

technicolor / topcolor

supersymmetry

…

Ask instead why gravity is so weak

Revolution: A New Conception of Spacetime

Could space be >3-dimensional?

Size and shape of extra dimensions?

J. Lykken

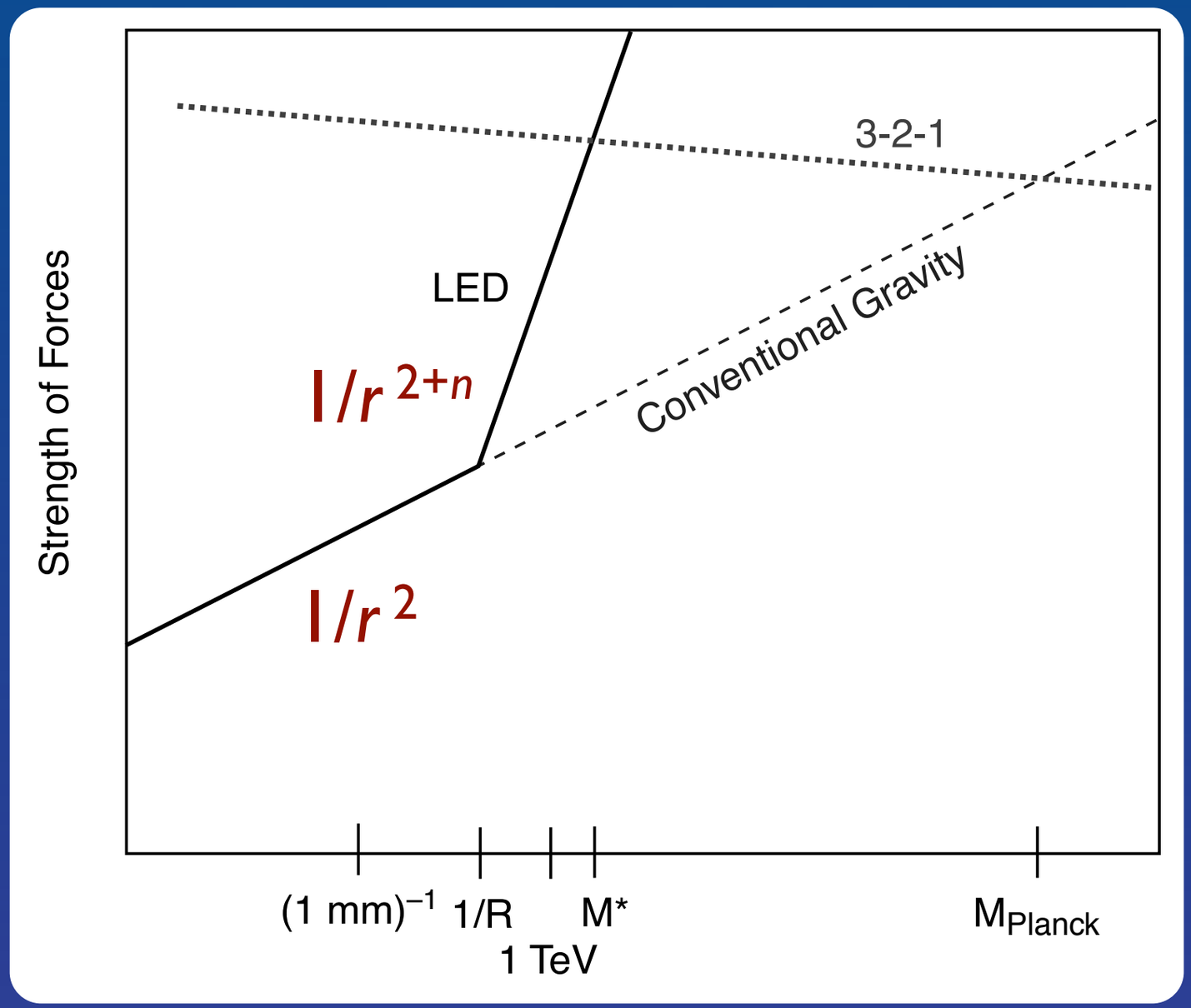
How do extra dimensions influence our world?

How can we map them?

(String theory wants 9 or 10.)

Suppose at scale R … gravity propagates in $4+n$ dimensions

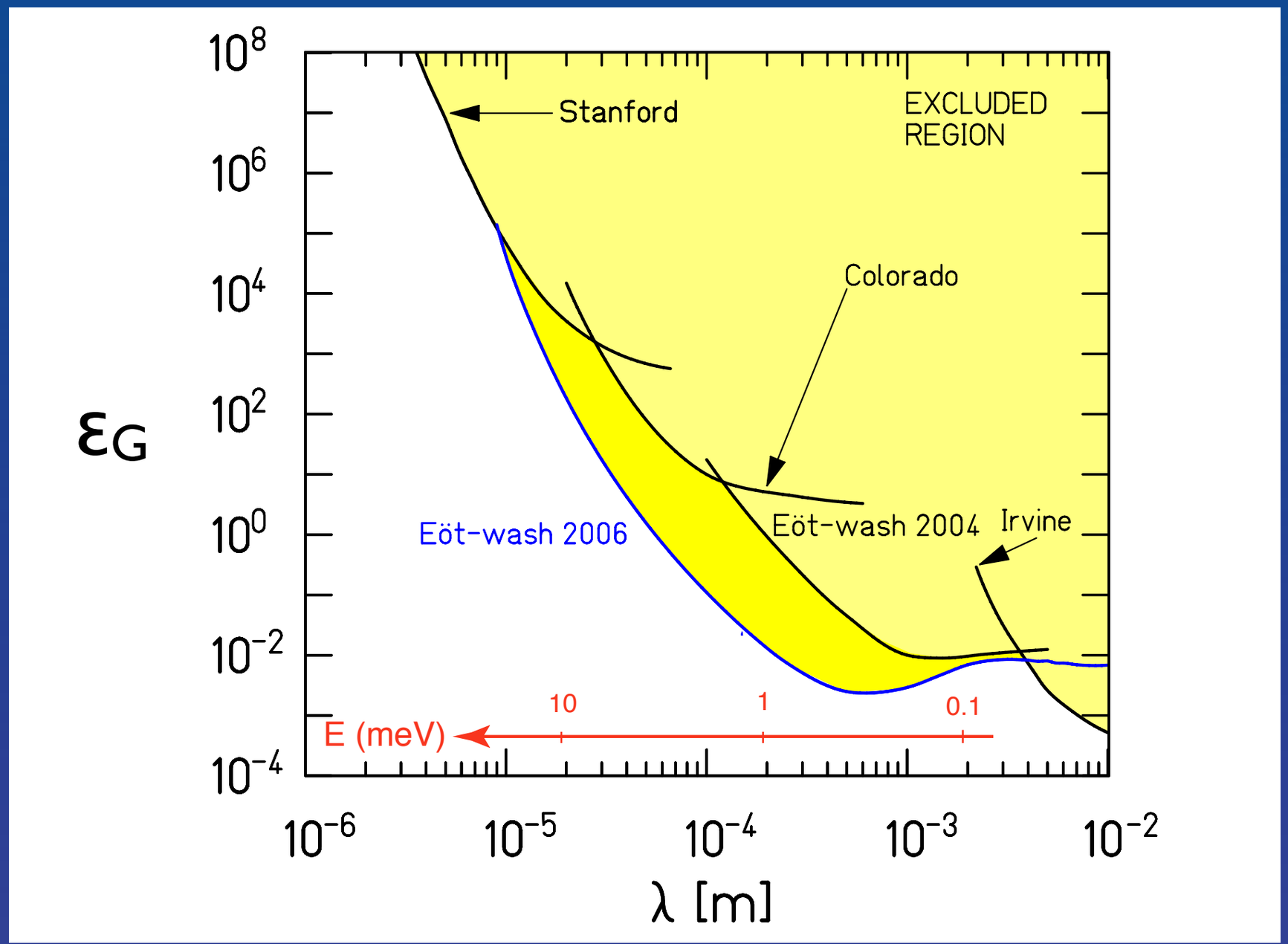
Gauss law: $G_N \sim M^{*-n-2}\ R^{-n}$ M^* : gravity's true scale



M_{Planck} would be a mirage!

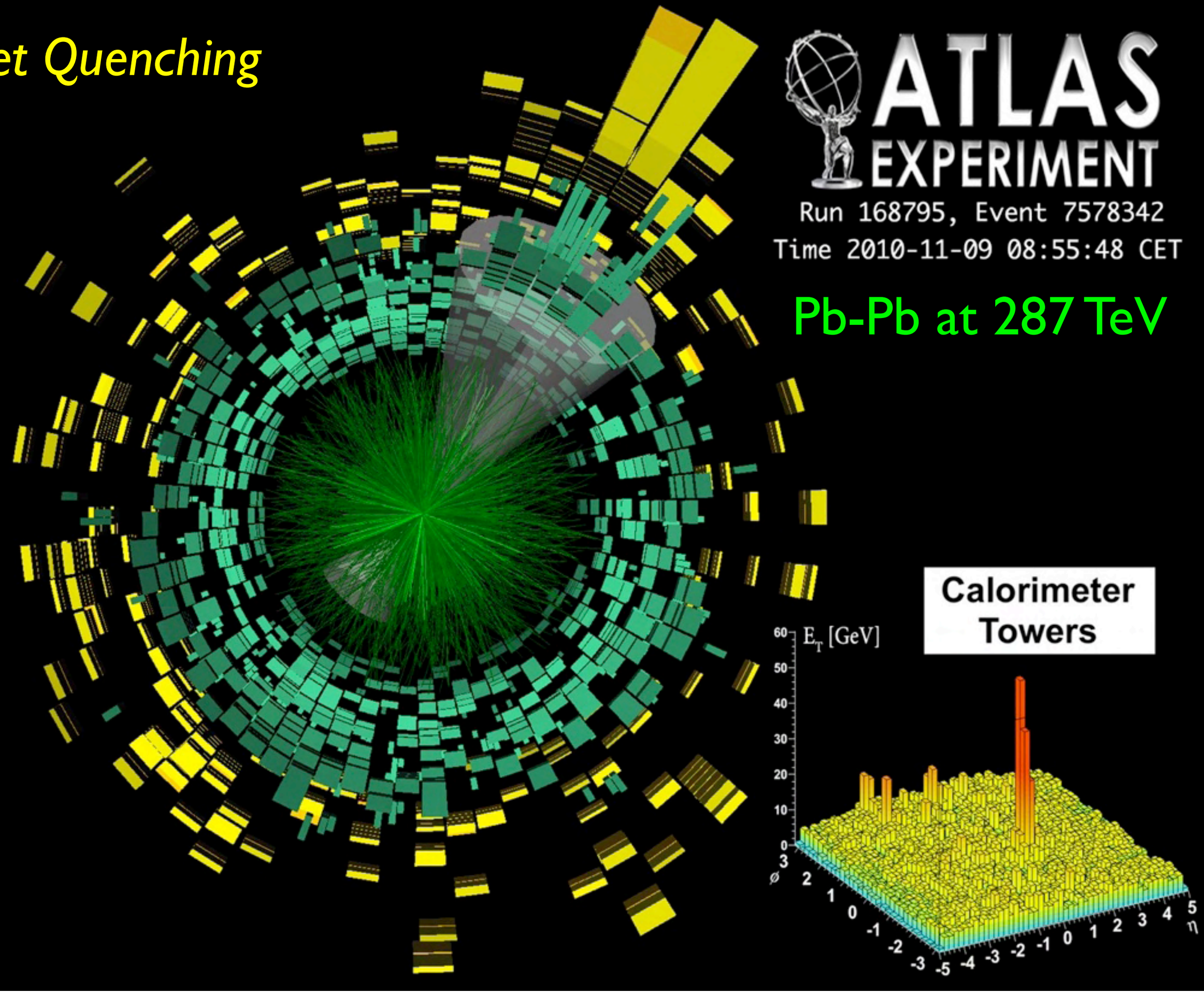
Gravity follows Newtonian force law down to ≲ 1 mm

$$V(r) = -\int dr_1 \int dr_2 \frac{G_{\text{Newton}}\rho(r_1)\rho(r_2)}{r_{12}} \left[1 + \varepsilon_{\text{G}} \exp(-r_{12}/\lambda_{\text{G}})\right]$$



Connections …

arXiv:0905.3187

Scientific American, 2.2008

Jet Quenching