The Coming Revolutions in Particle Physics

Chris Quigg
Fermilab / Karlsruhe

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Physics at the Terascale · Aachen · 26.11.2008

Weltbild vor dem Umbruch

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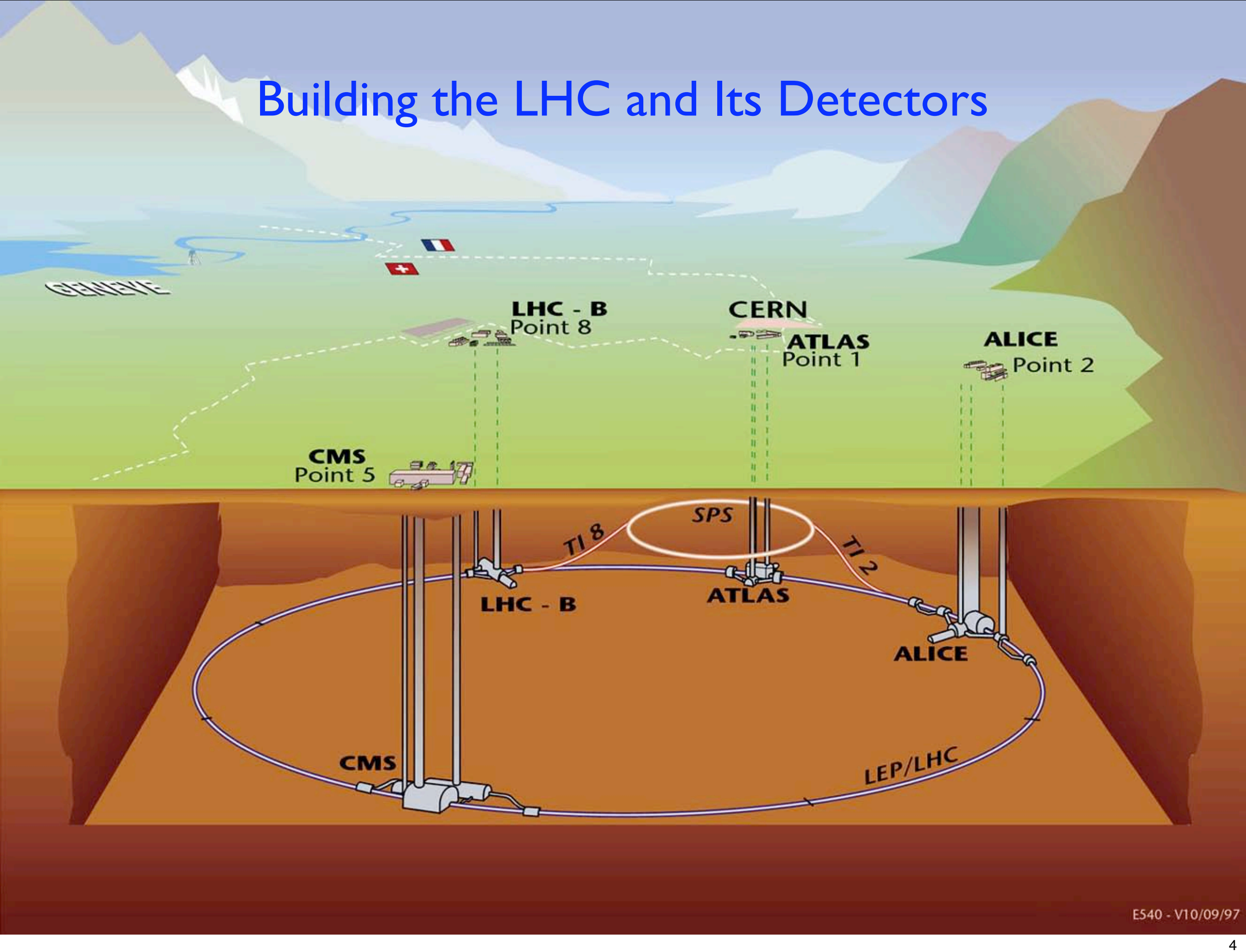
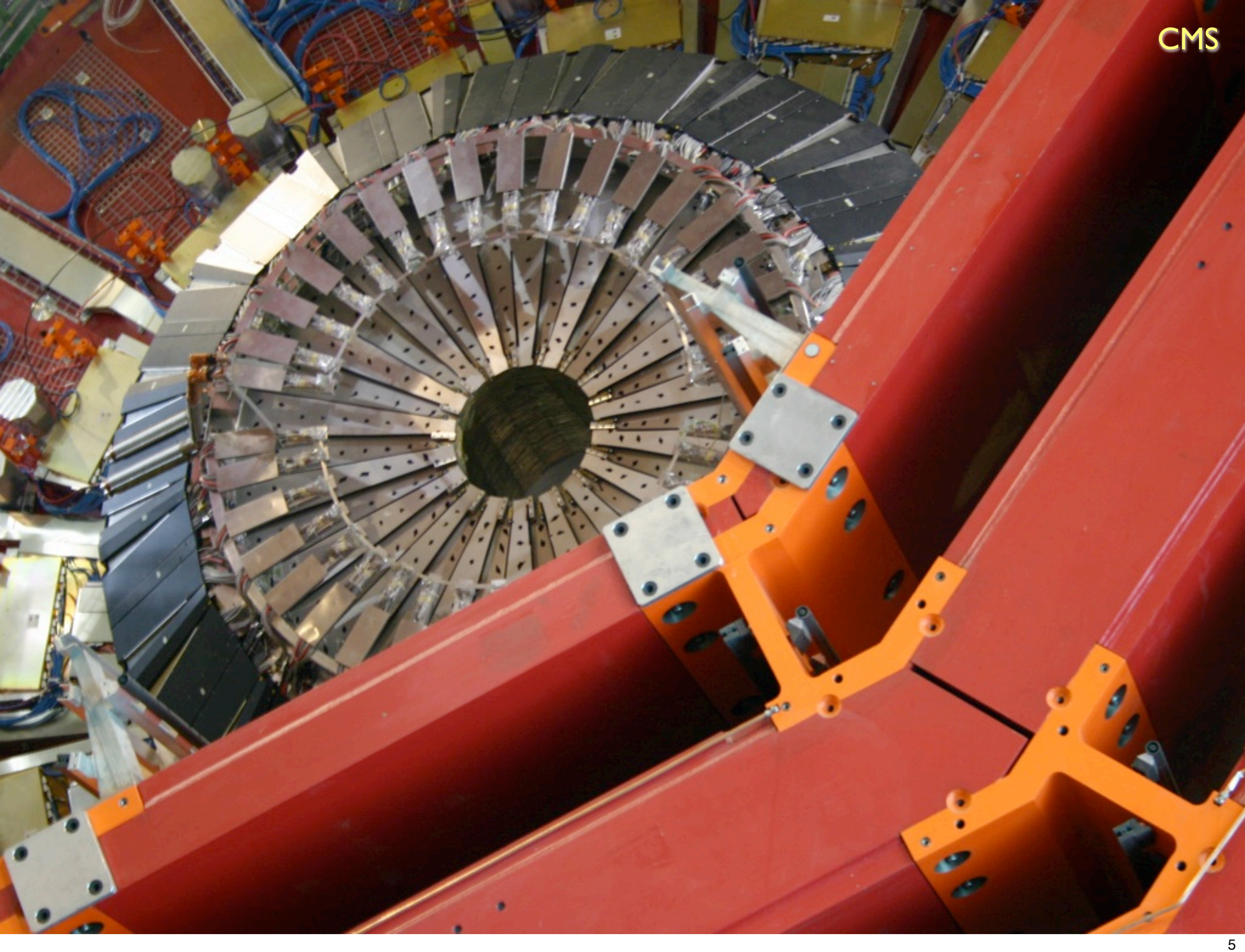
Building the LHC and Its Detectors

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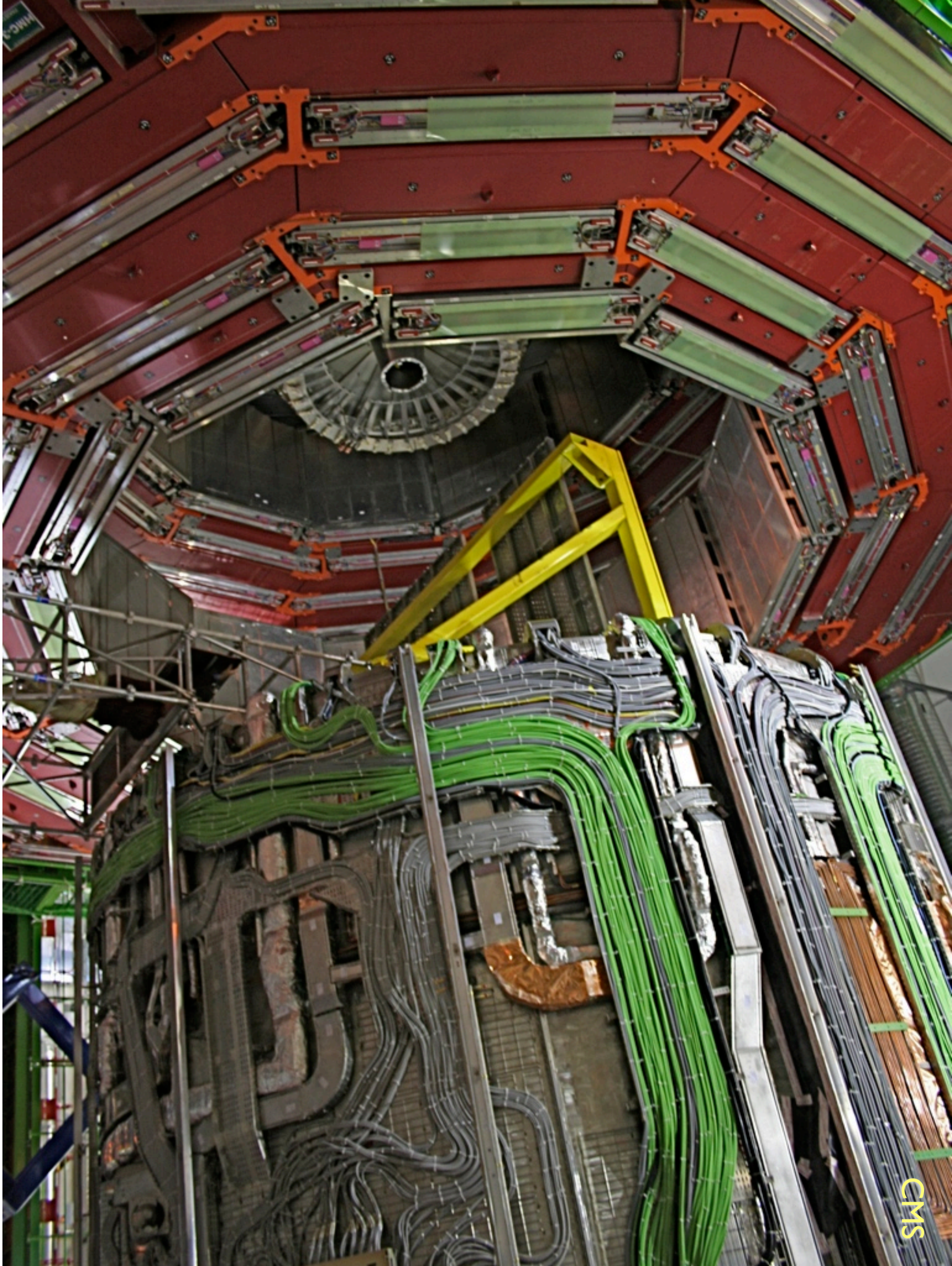
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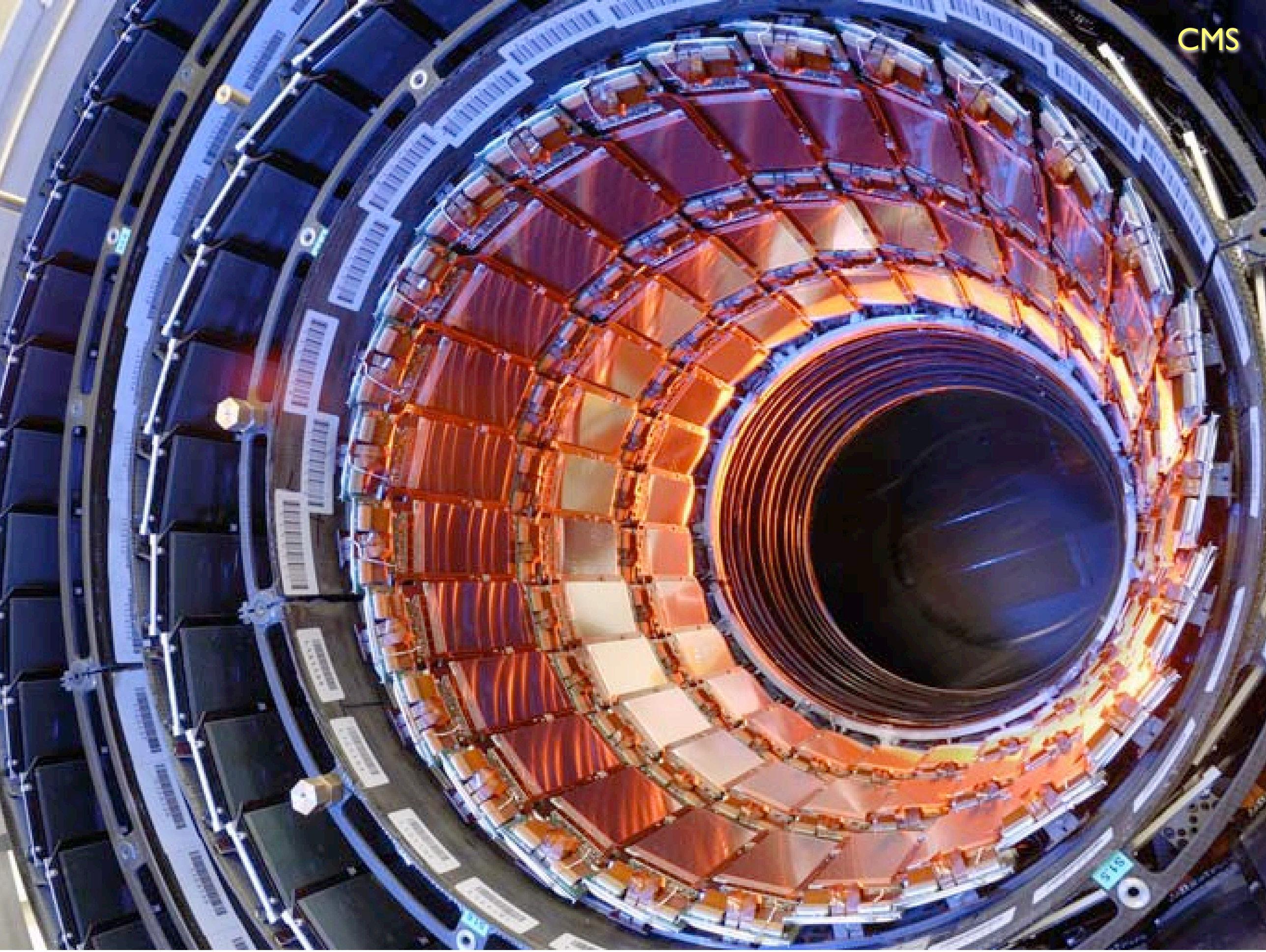
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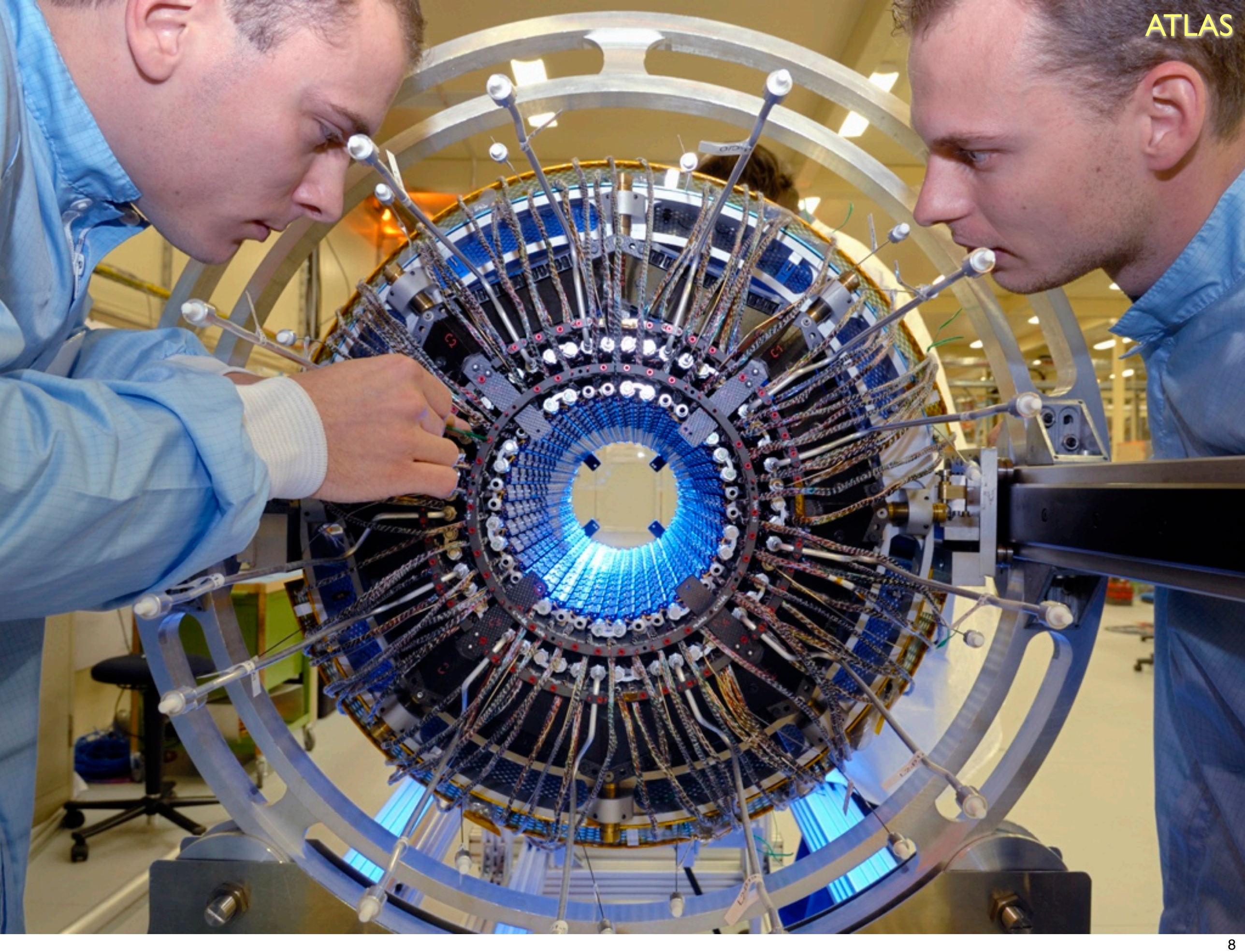
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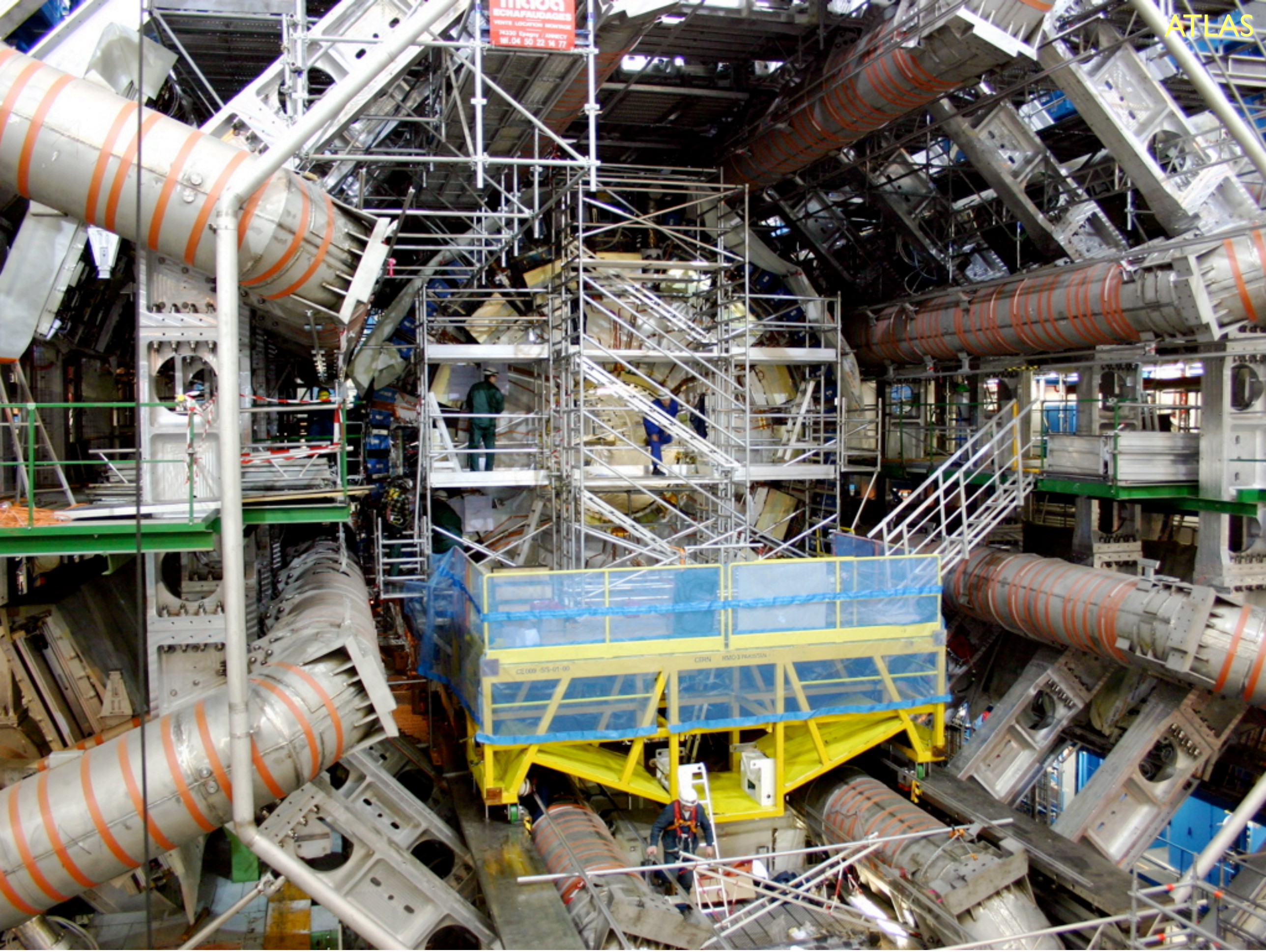
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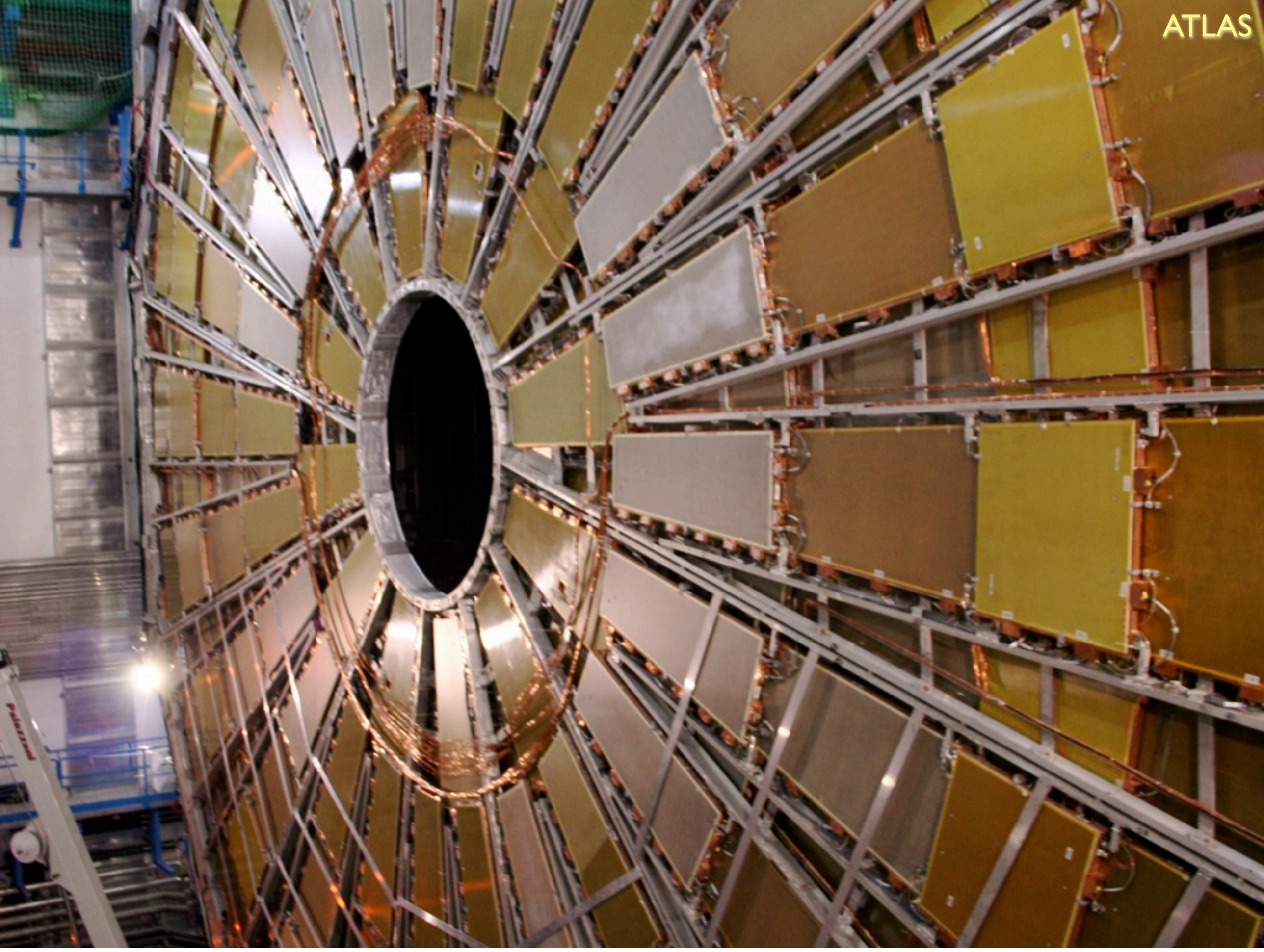
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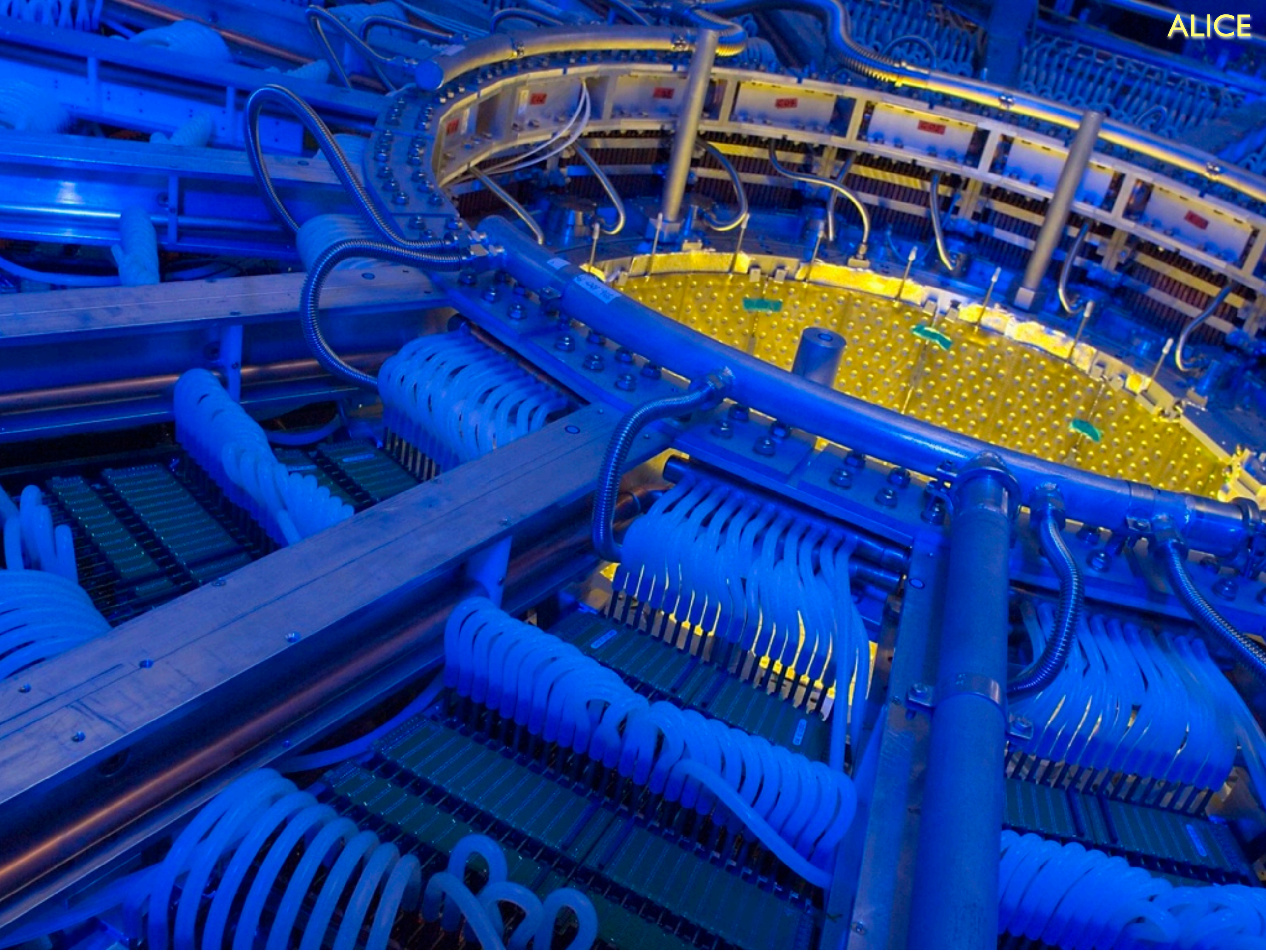

ALICE

ALICE
JIB18

LHCb

LHCb

Building Theoretical Apparatus for the LHC

Signals and backgrounds @ NNLO

Automated evaluation of one-loop amplitudes for NLO, exploiting on-shell methods

Improved parton distribution functions

Parton showers with quantum interference

Elaborating new physics signals, distinctions

Comprehensive event generators

...

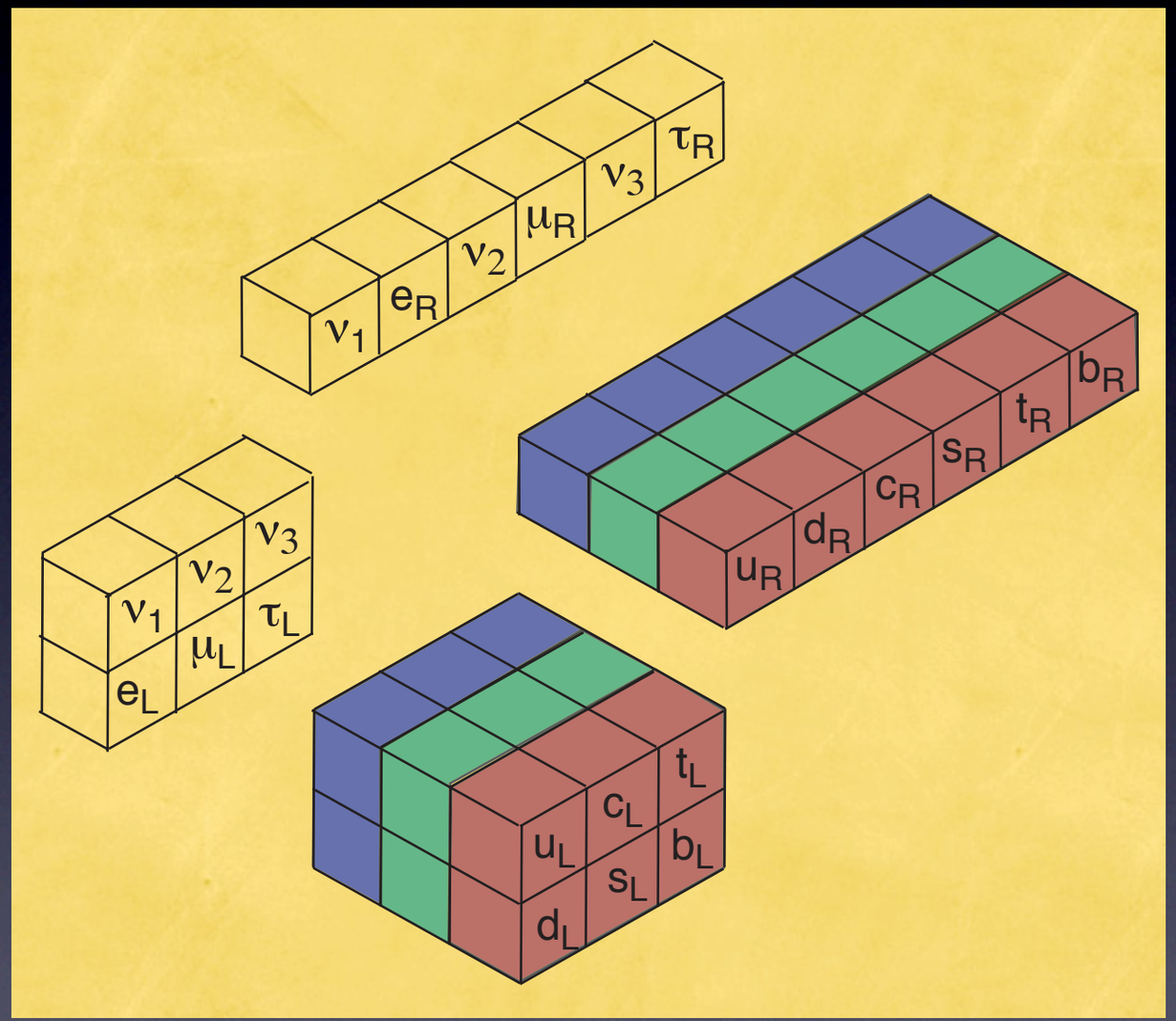
A Decade of Discovery Past

- ▷ Electroweak theory → law of nature [Z, e^+e^-, $\bar{p}p$, νN, $(g-2)_\mu$, ...]
- ▷ Higgs-boson influence observed in the vacuum [EW experiments]
- ▷ Neutrino flavor oscillations: $\nu_\mu \to \nu_\tau$, $\nu_e \to \nu_\mu/\nu_\tau$ [$\nu_\odot$, ν_{atm}]
- ▷ Understanding QCD [heavy flavor, Z^0, $\bar{p}p$, νN, ep, lattice]
- ▷ Discovery of top quark [$\bar{p}p$]
- ▷ Direct CP violation in $K \to \pi\pi$ decay [fixed-target]
- ▷ B-meson decays violate CP [$e^+e^- \to B\bar{B}$]
- ▷ Flat universe dominated by dark matter & energy [SN Ia, CMB, LSS]
- ▷ Detection of ν_τ interactions [fixed-target]
- ▷ Quarks & leptons structureless at TeV scale [mainly colliders]

Connections ...

Our Picture of Matter (the 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

Fermilab

The World's Most Powerful Microscopes

nanonanophysics

Fermilab's Tevatron Collider & Detectors

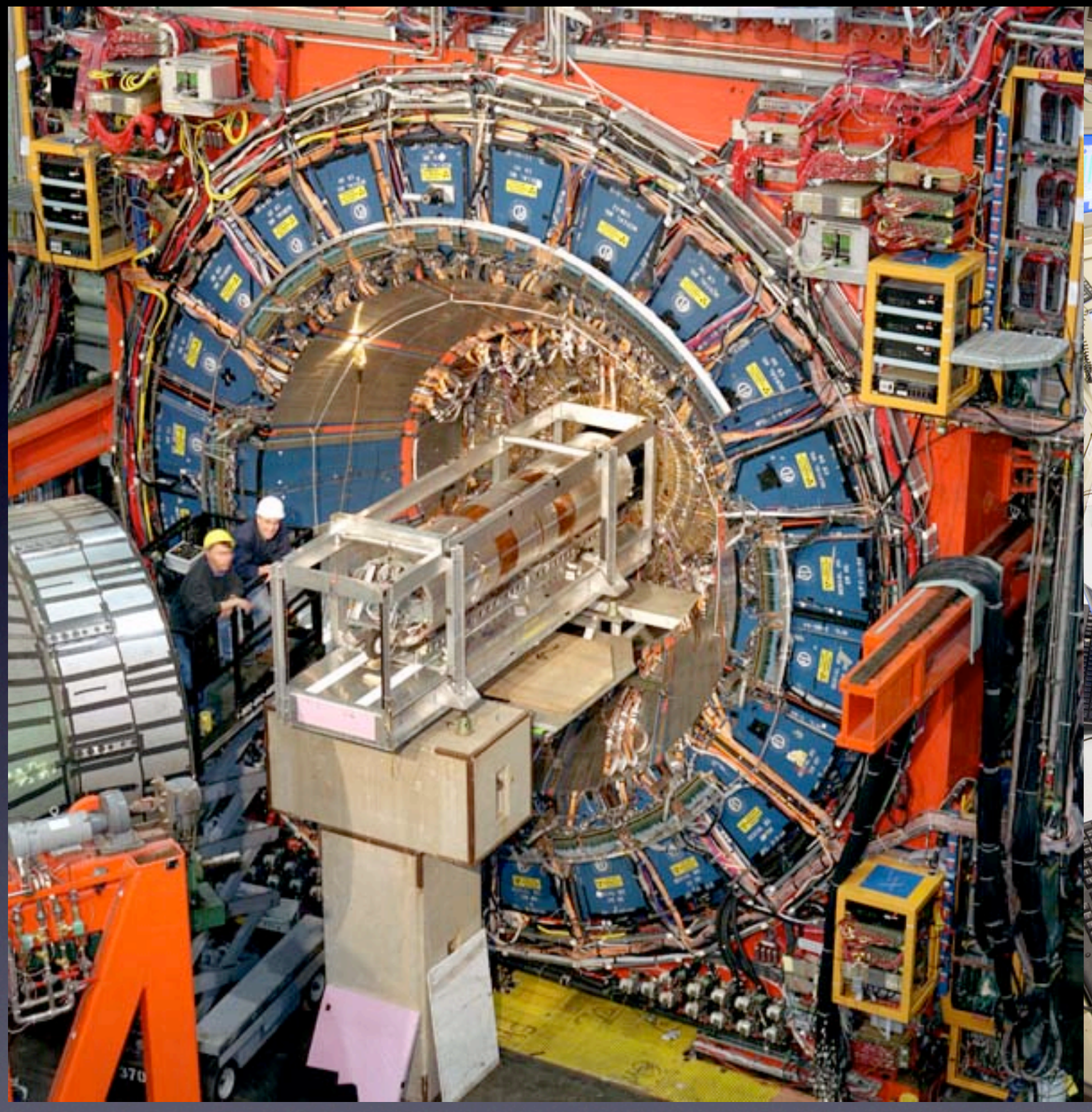
980-GeV protons: $c - 495$ km/h

Protons, antiprotons pass my window 45 000 times / second

...ten million collisions / second

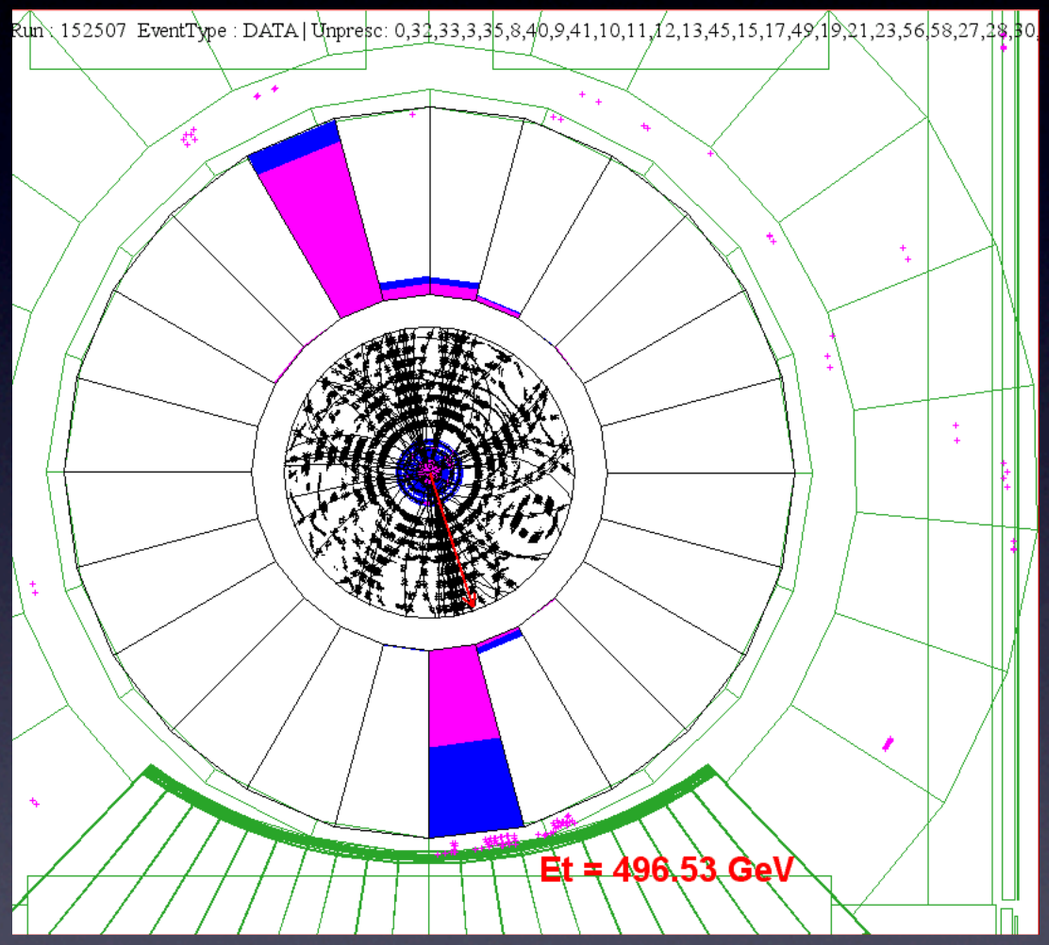
CERN's Large Hadron Collider, 7-TeV protons: $c - 10$ km/h

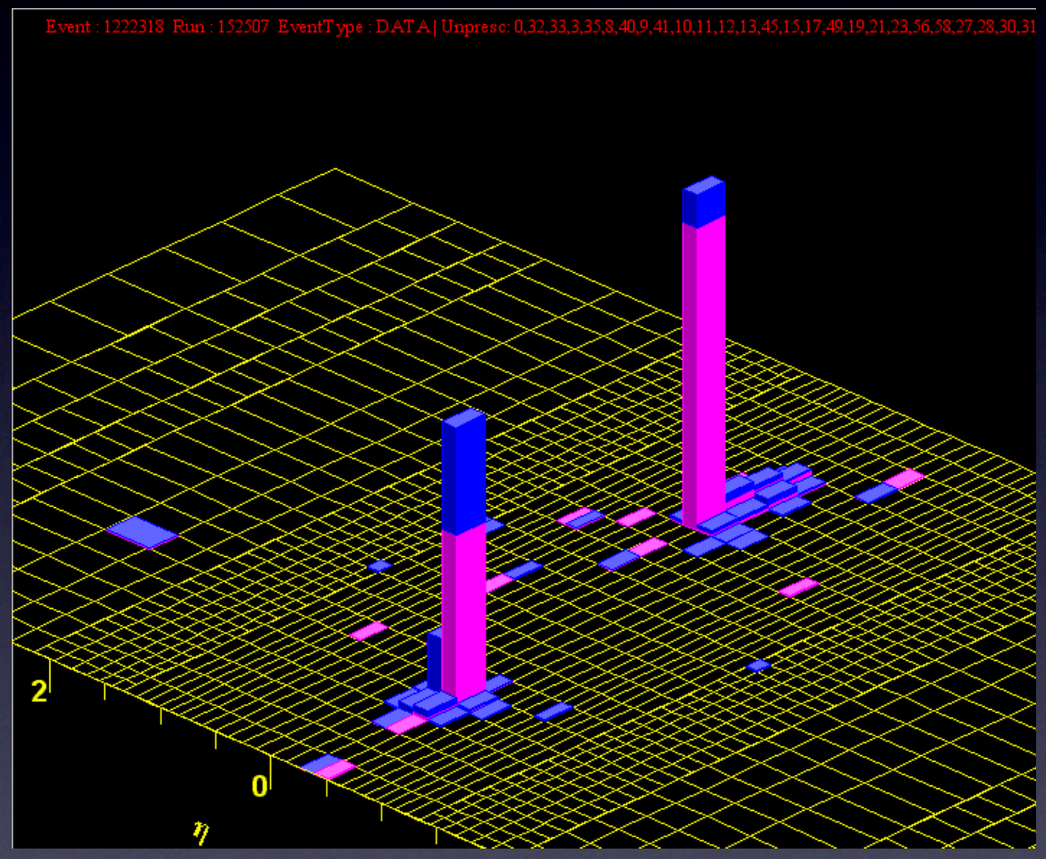
CDF



The World's Most Powerful Microscopes

nanonanophysics

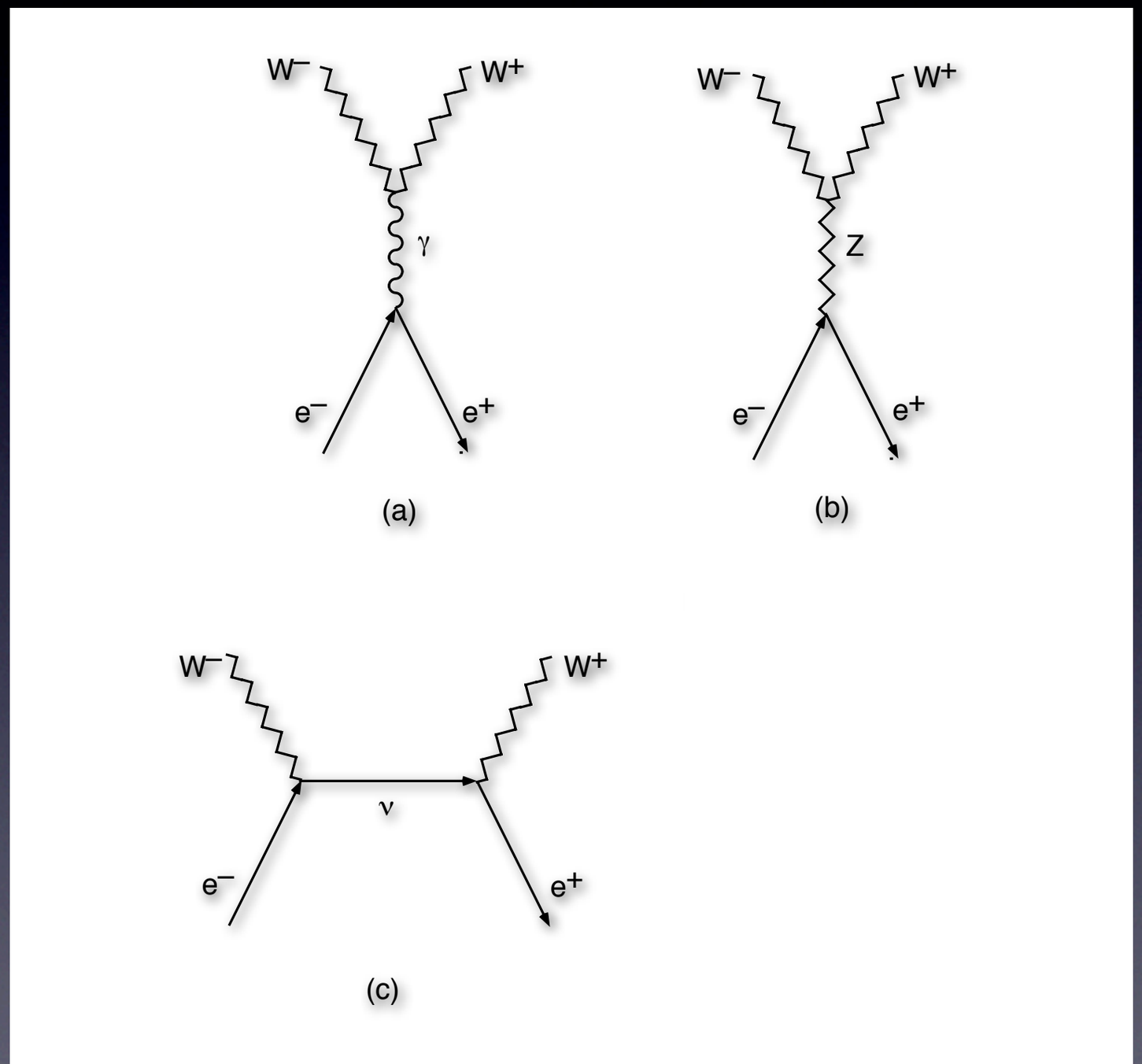




CDF dijet event ($\sqrt{s} = 1.96$ TeV): $E_T = 1.364$ TeV $\boxed{q\bar{q} \to \text{jet} + \text{jet}}$

Gauge symmetry (group-theory structure) tested in

$$e^+e^- \to W^+W^-$$



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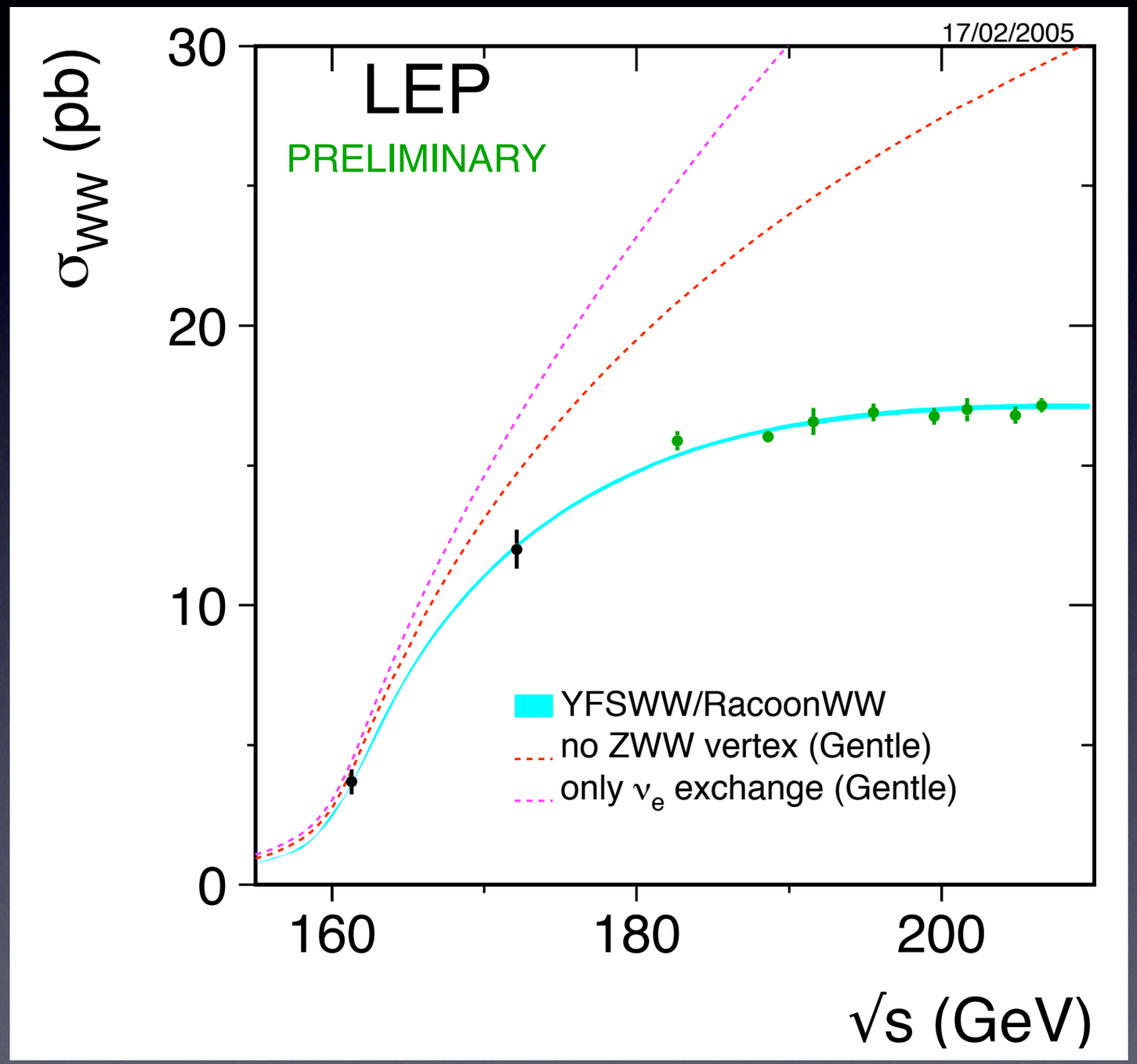

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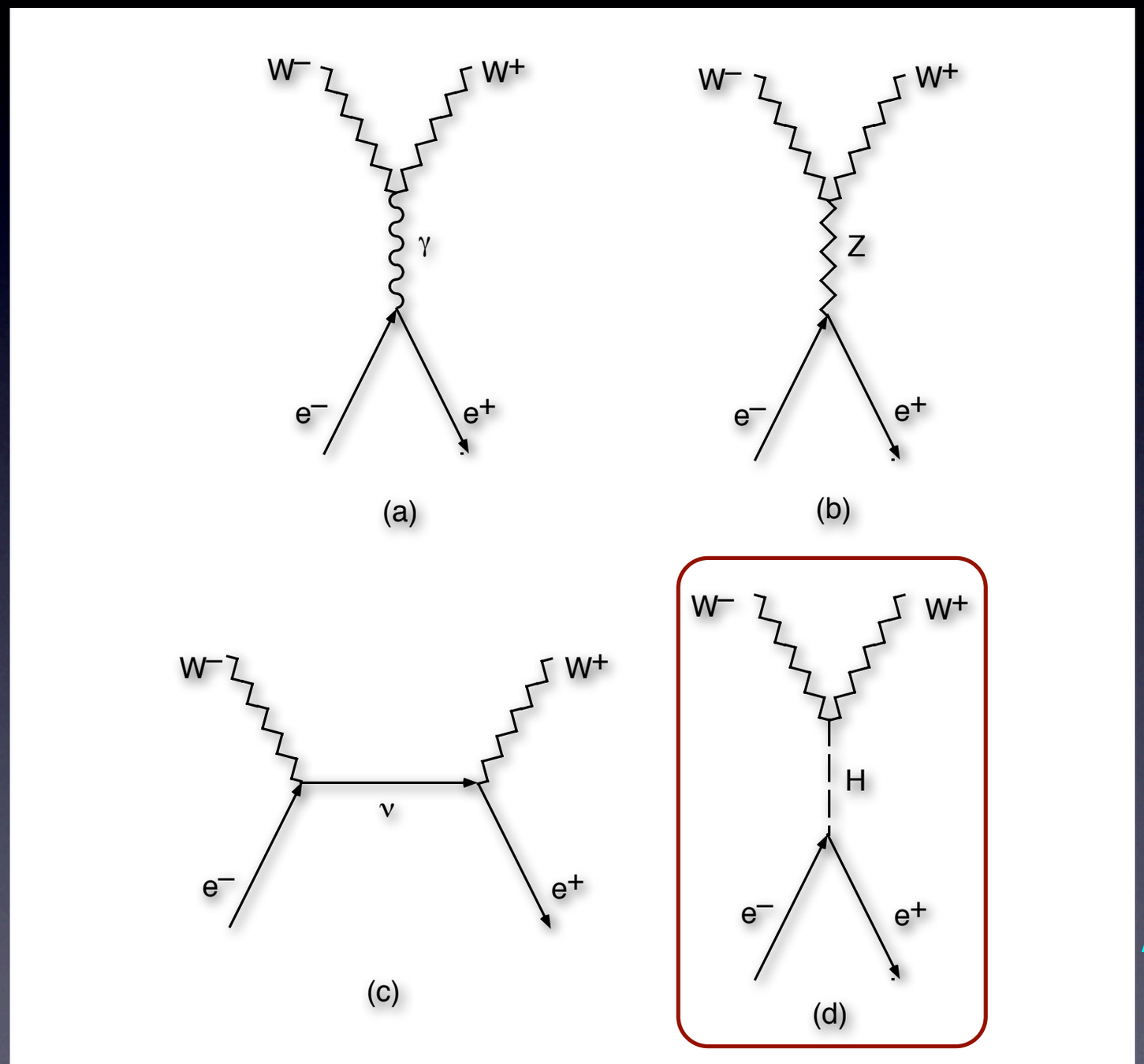
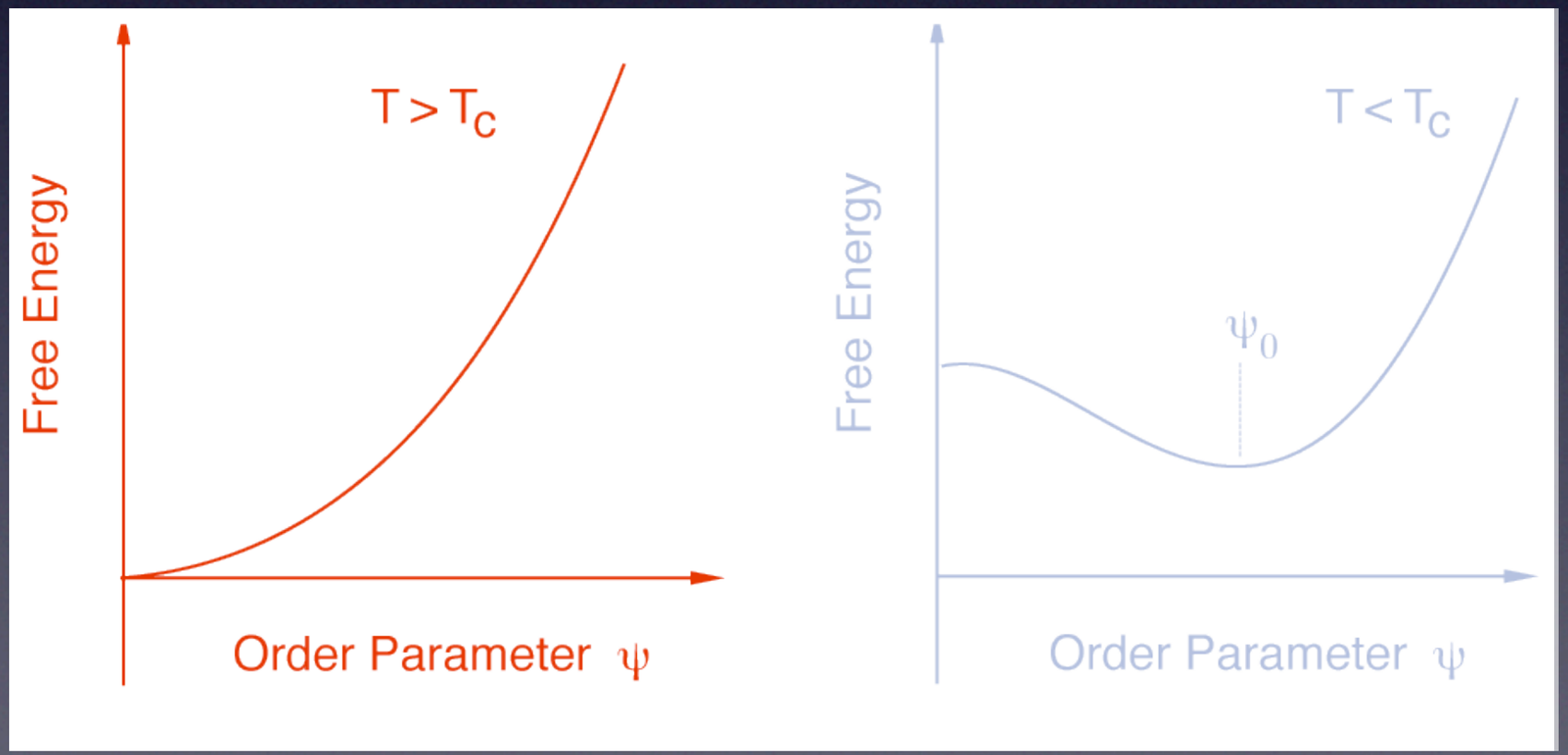


Massive weak bosons: Higgs boson

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.



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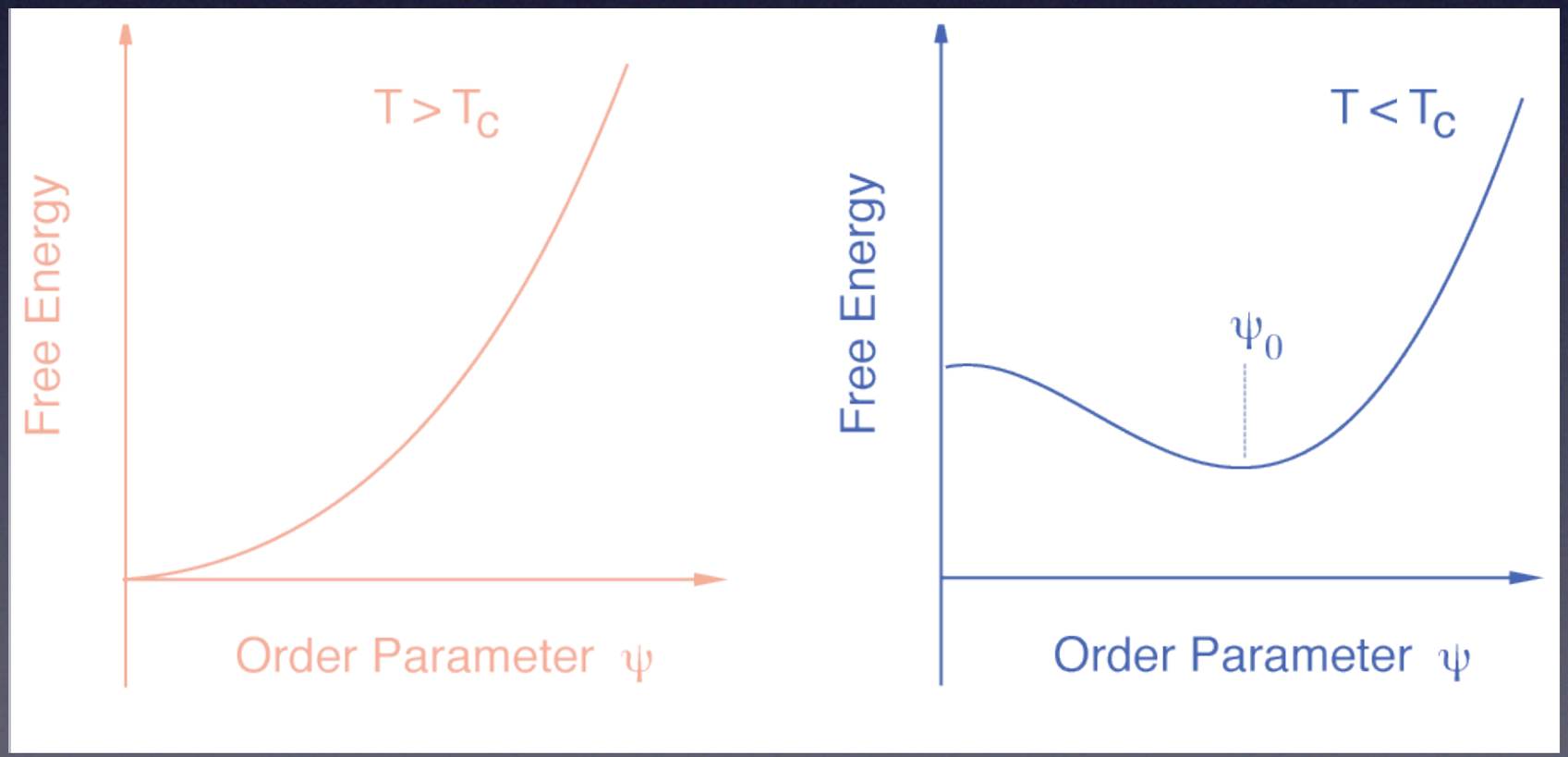


Where to Look: The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: *conditional upper bound*

$W_L^+ W_L^-, Z_L^0 Z_L^0, HH, HZ_L^0$ satisfy *s*-wave unitarity,

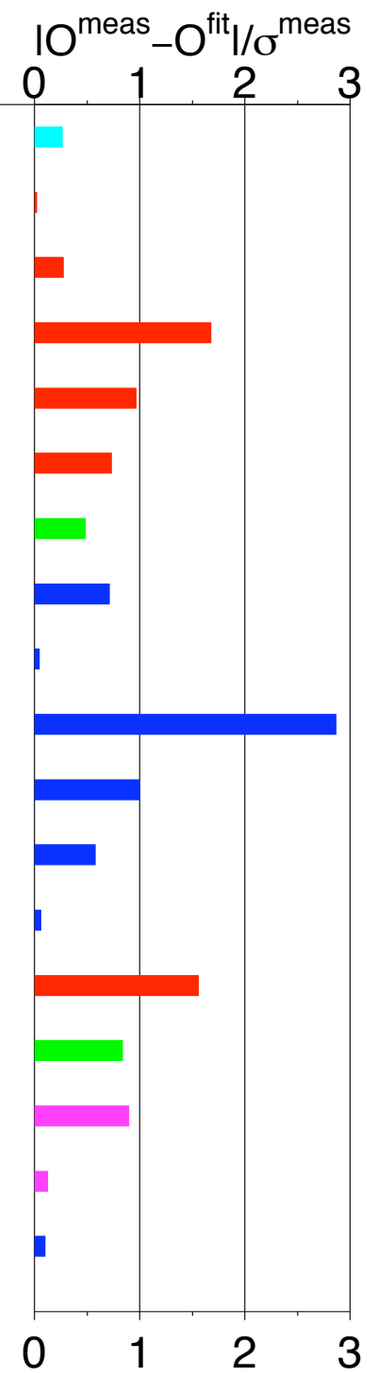
provided $\boxed{M_H \leq \left(8\pi\sqrt{2}/3G_F\right)^{1/2} = 1 \text{ TeV}}$

- 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 …

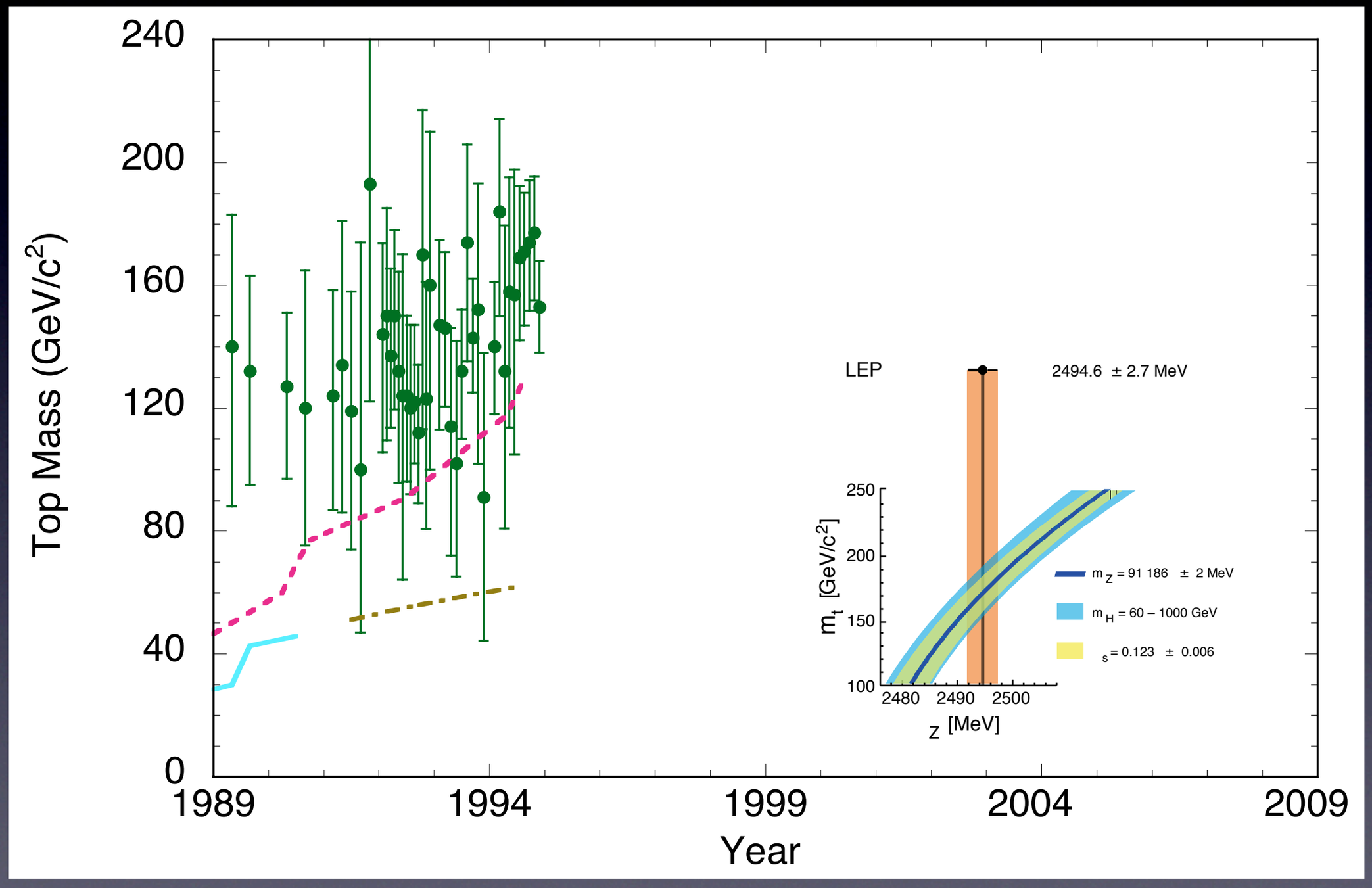
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4958
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01644
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21582
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	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 ± 0.025	80.376
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	172.4 ± 1.2	172.5



July 2008

LEP EWWG

… and determine unknown parameters



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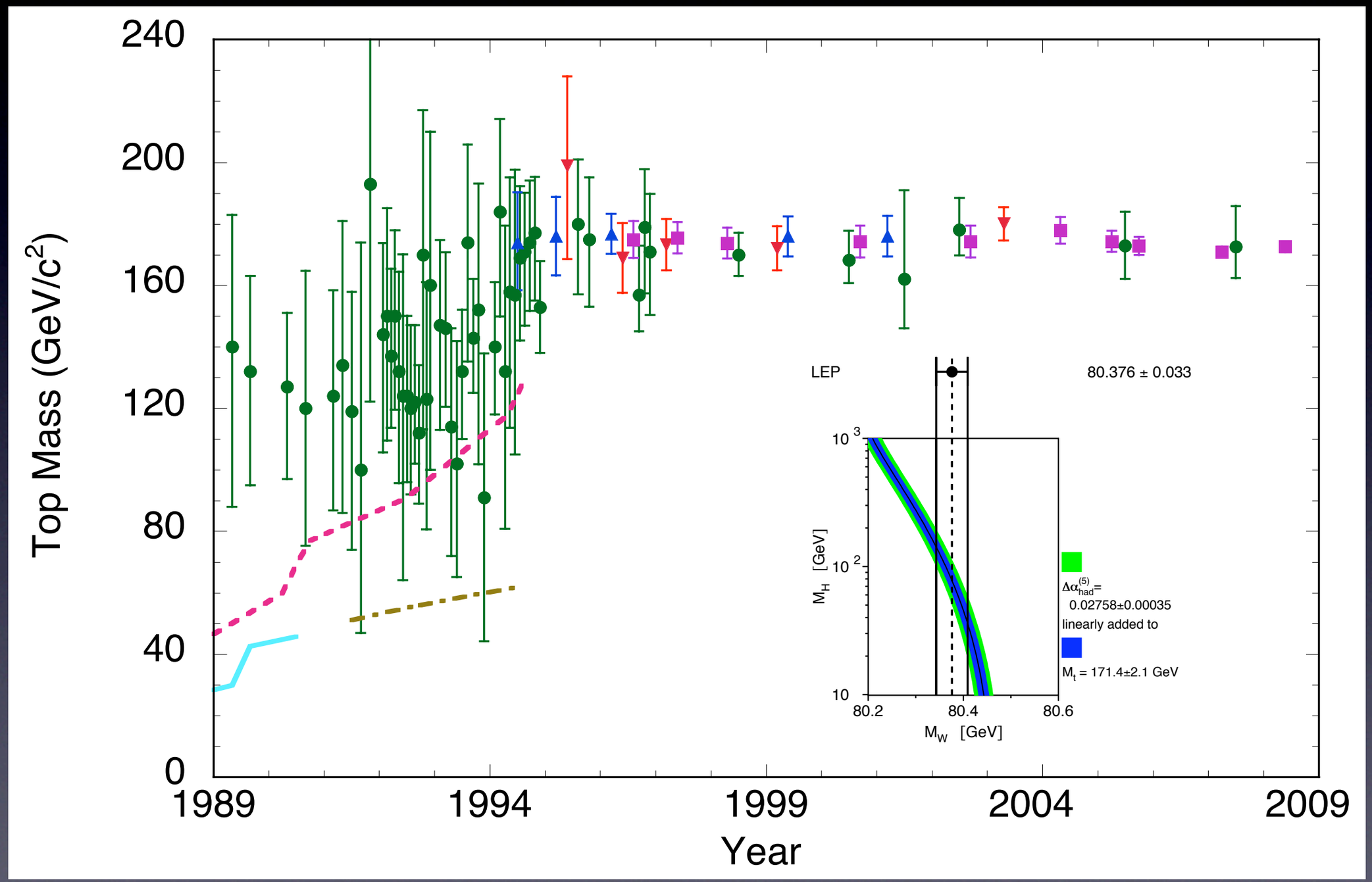
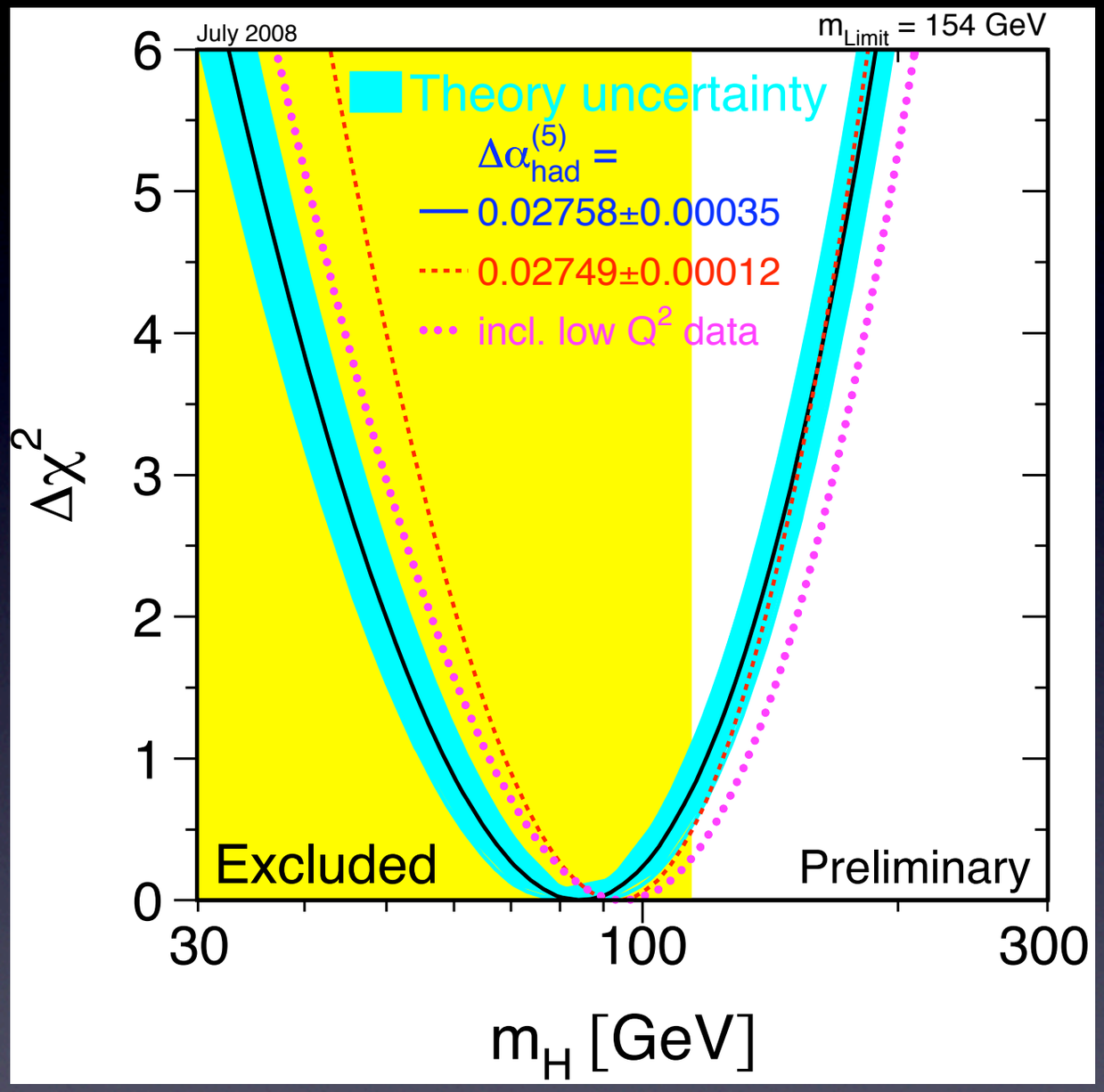
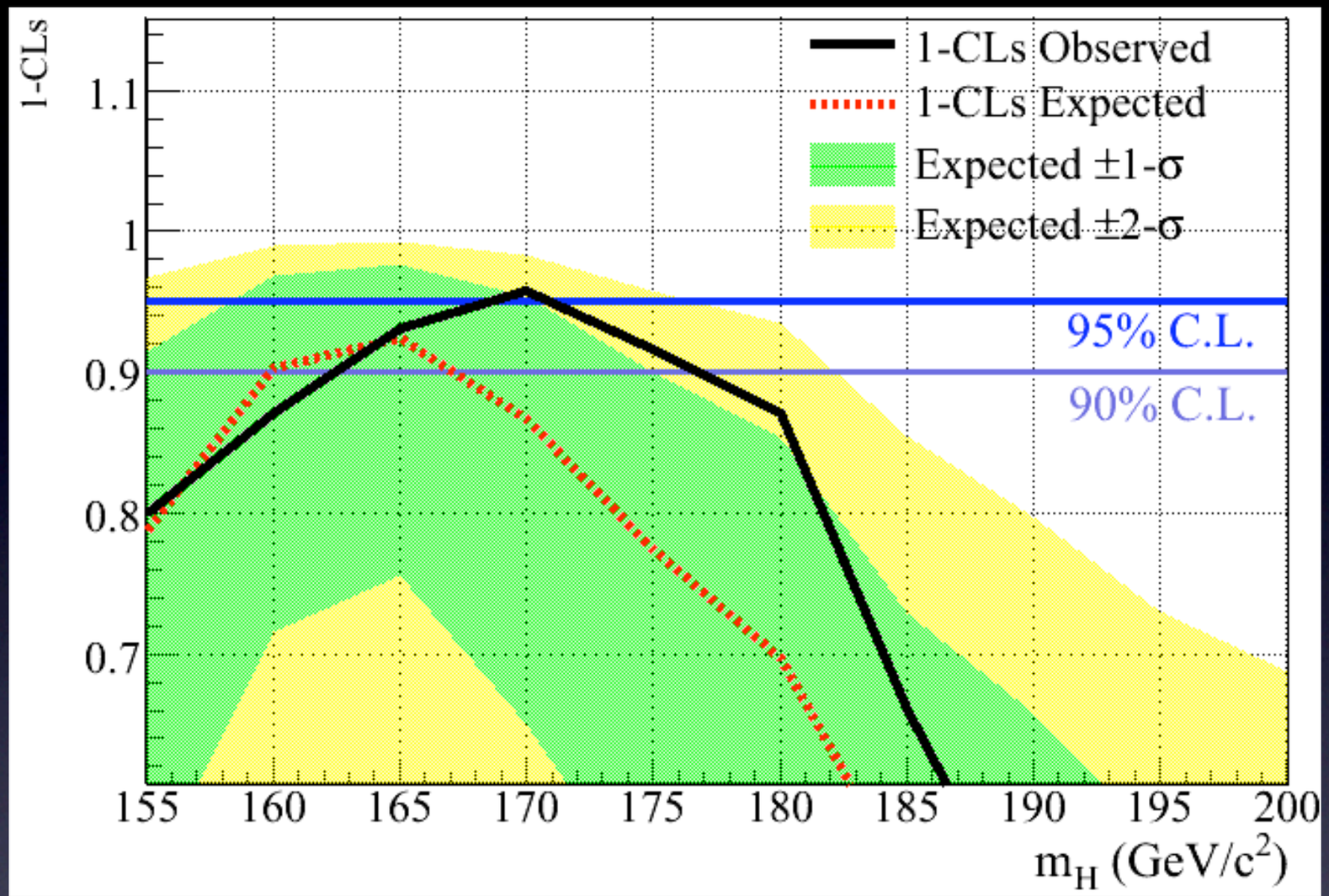


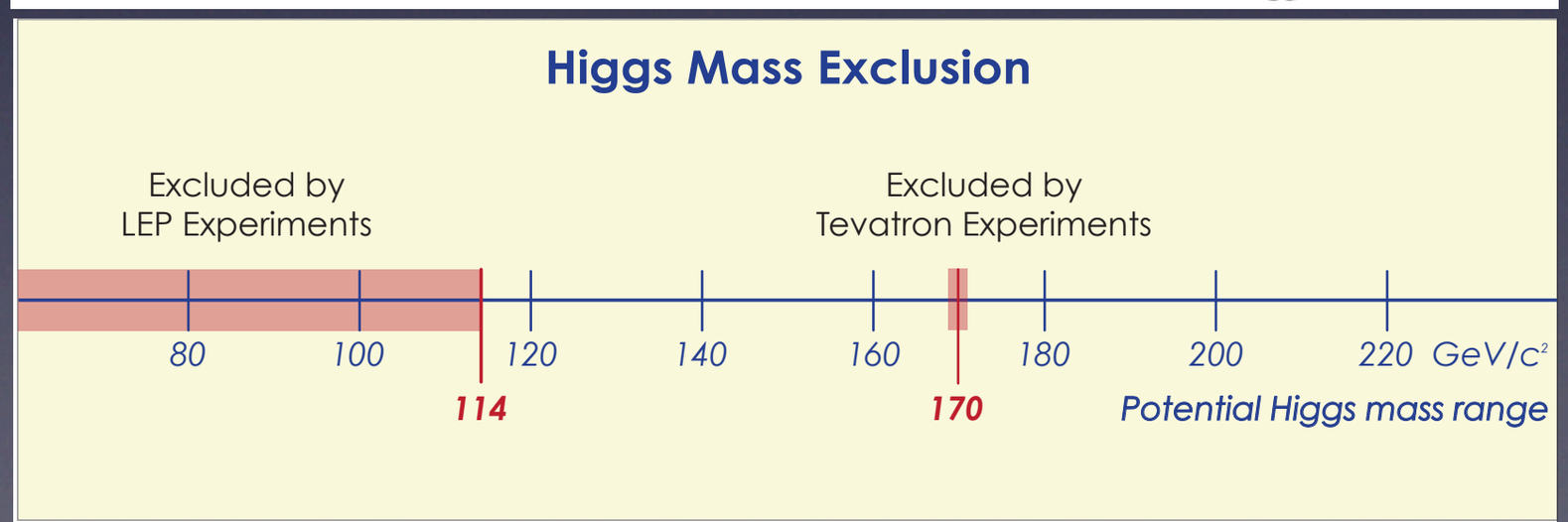
Global fits favor a (light) Higgs boson …



… but only test its coupling to gauge bosons

Tevatron Combined Higgs Exclusion





Understanding the Everyday World

Why are there atoms?

Why chemistry?

Why stable structures?

Imagine a world without a Higgs mechanism

If electroweak symmetry were not hidden …

- Massless quarks and leptons
- QCD confines quarks into color-singlet hadrons
- *Nucleon mass little changed*
- QCD breaks EW symmetry, gives tiny W, Z masses; weak-isospin force doesn't confine
- *p might outweigh n:* rapid β-decay
  $\Rightarrow$ lightest nucleus would be n … no hydrogen atom
- Perhaps light elements from BBN, but ∞ Bohr radius
- No atoms means no chemistry, no stable composite structures like liquids, solids, …

… character of the physical world would be profoundly changed

What is the nature of the mysterious new force that hides electroweak symmetry?

- New kind of force? Higgs field?
- New force from a new symmetry?
- Residual force from strong dynamics?
- 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?

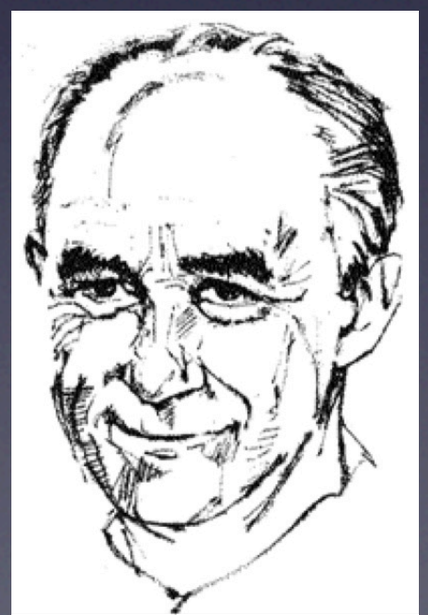
Finding the Higgs boson starts a new adventure!

What the LHC is *not* really for …

1. Find the Higgs boson,
   the Holy Grail of particle physics,
   the source of all mass in the Universe.
2. Celebrate.
3. Then particle physics will be over.

We are not ticking off items on a shopping list …

We are exploring a vast new terrain
… and reaching the Fermi scale



The meaning of identity

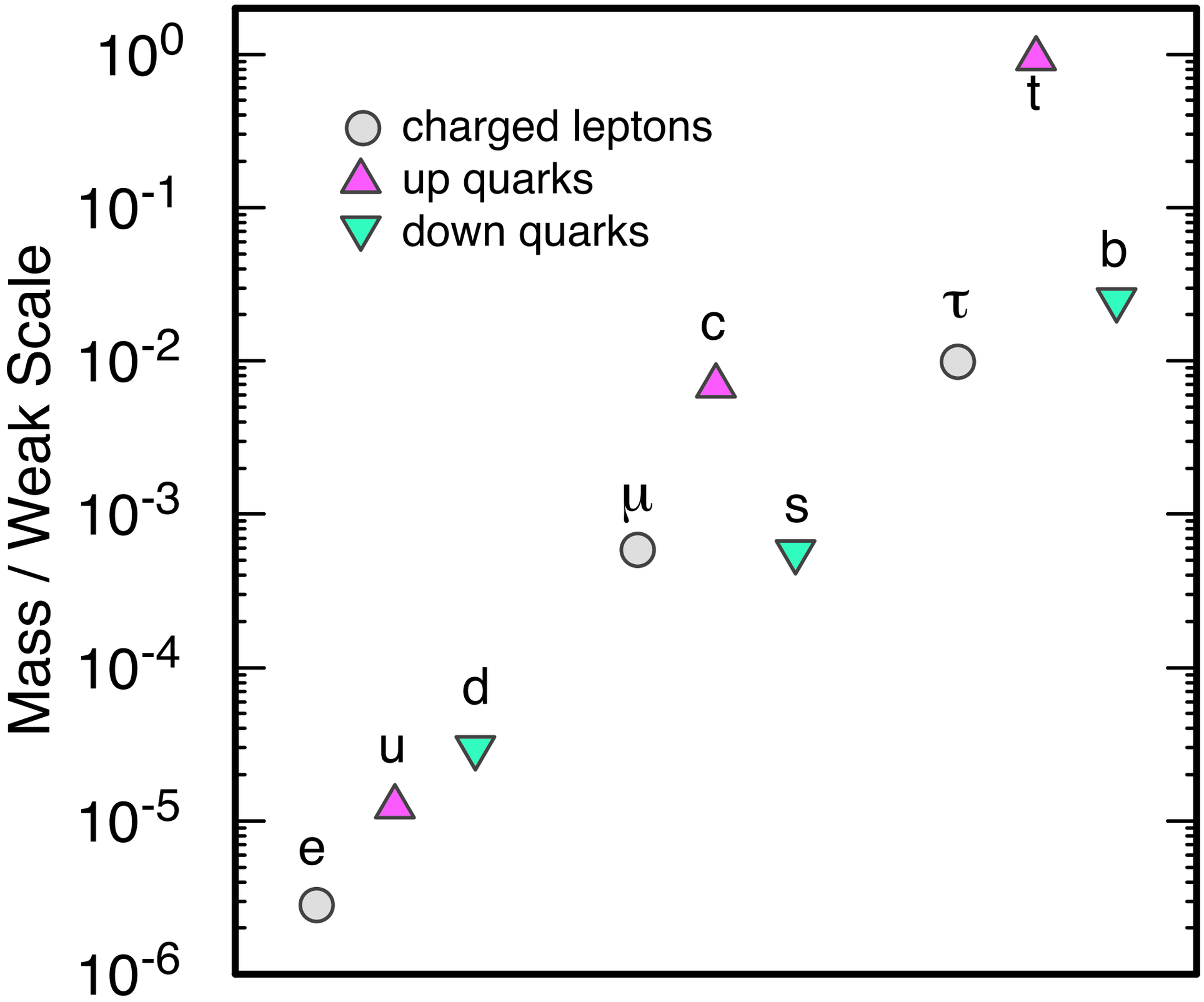
- What makes a top quark a top quark and an electron an electron?
- Slightly different behavior of matter and antimatter (CP violation) means what?
- Neutrino oscillations a new take:
  key to matter excess in Universe?
- New kinds of matter show us pattern?
  dark matter, superpartners, …

Mendele'ev didn't know about noble gases

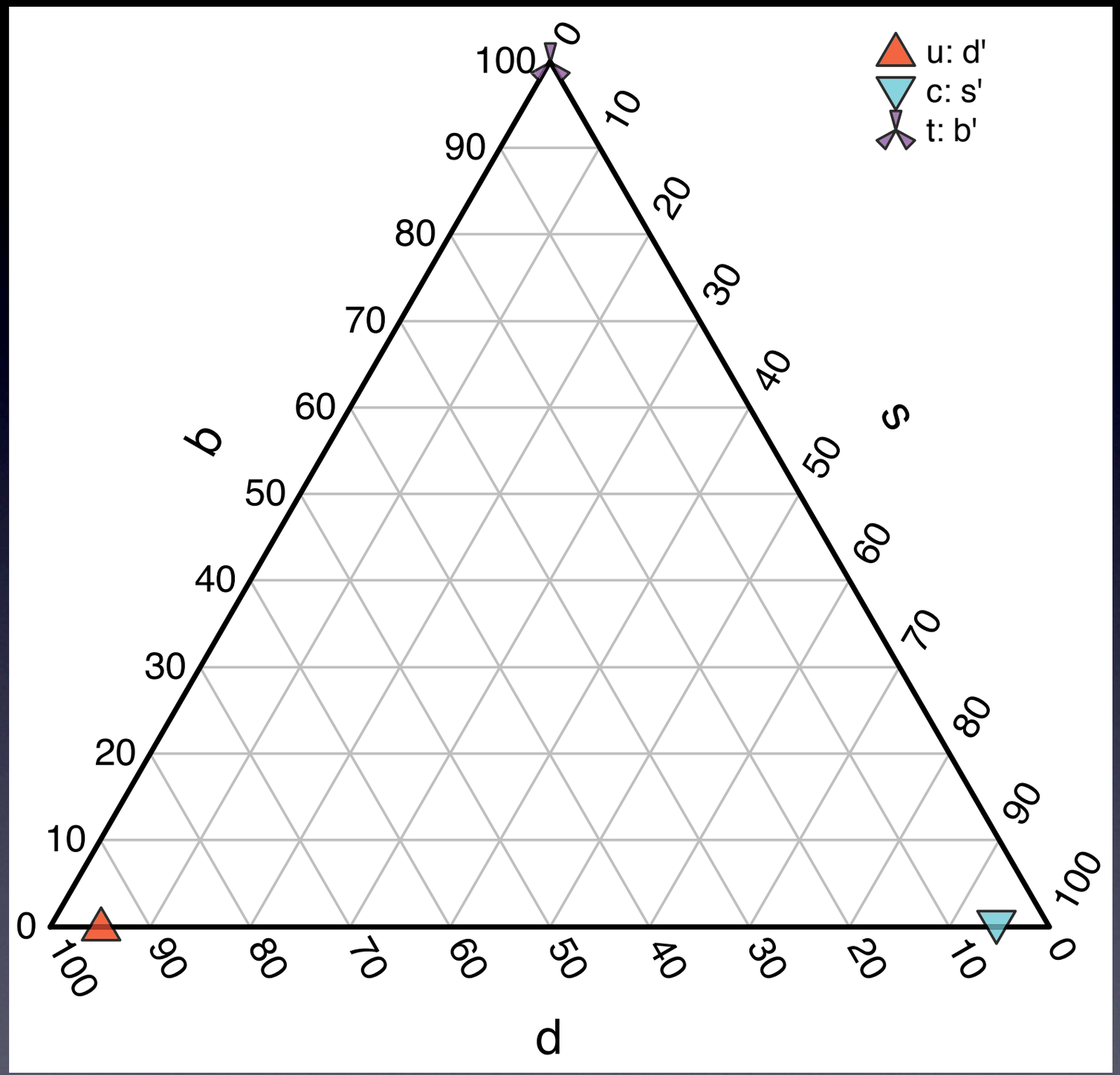
Parameters of the Standard Model

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.

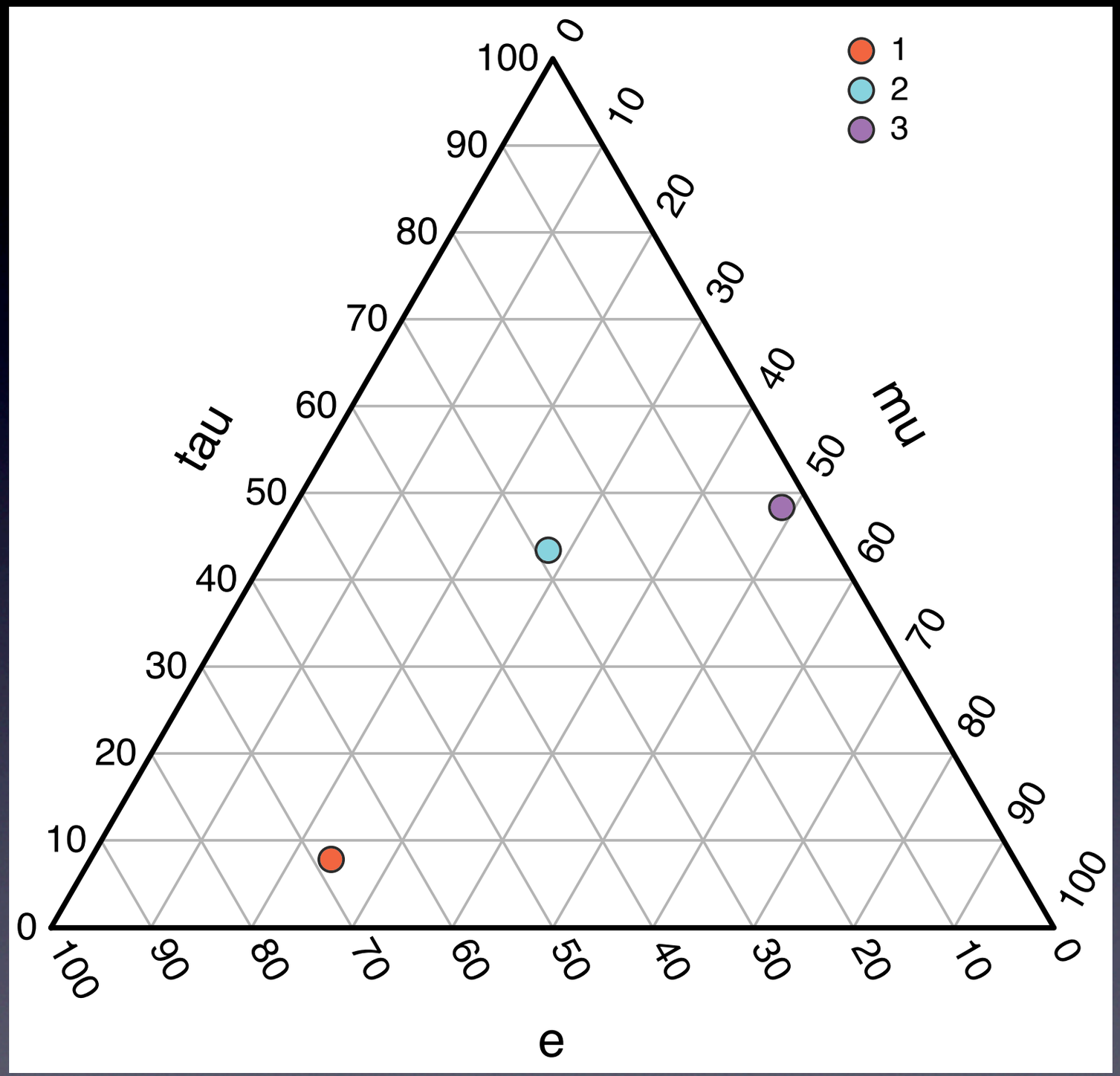

charged leptons
up quarks
down quarks
Mass / Weak Scale
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
t
b
τ
c
μ
s
d
u
e

Quark family patterns: *generations*

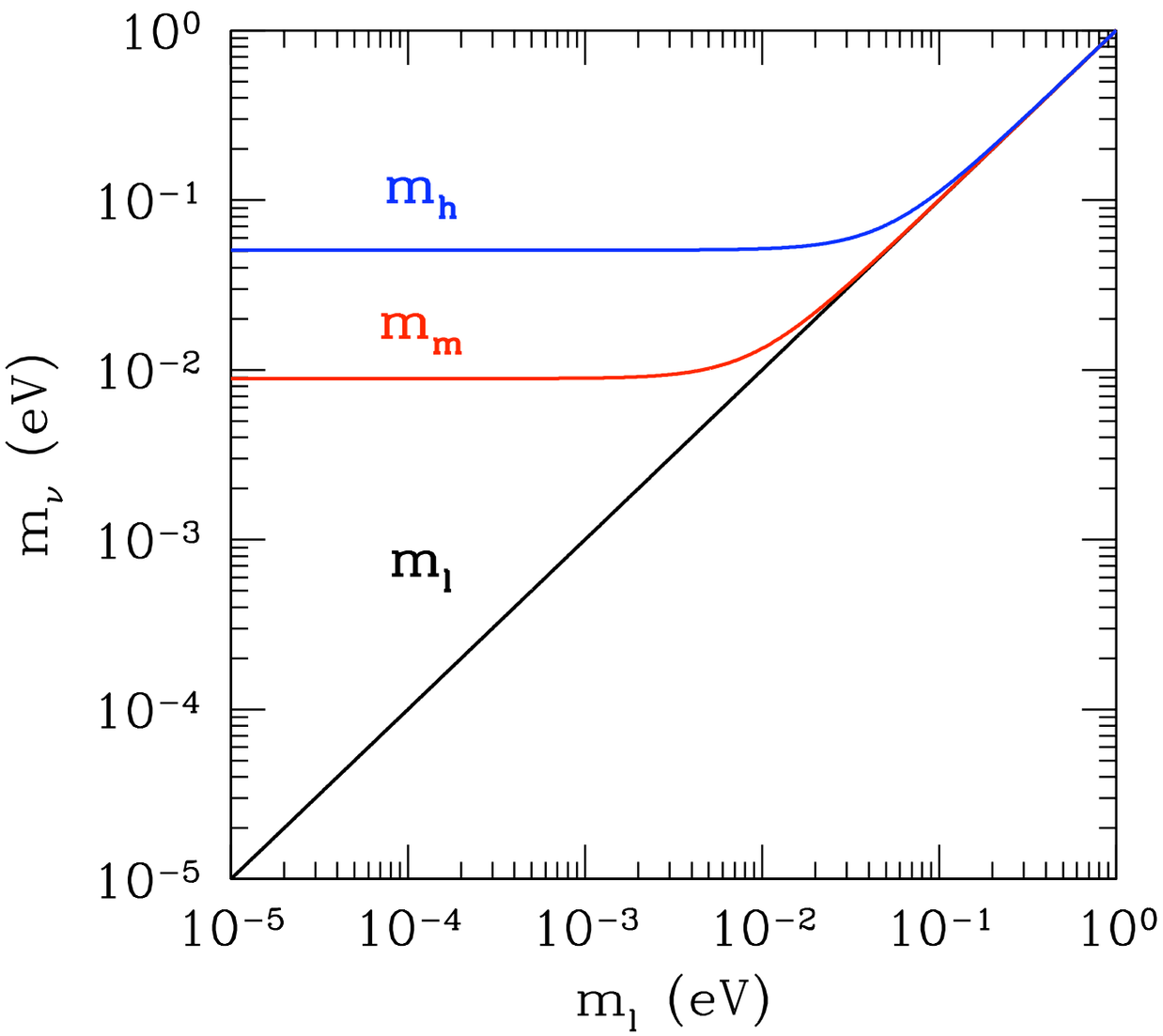


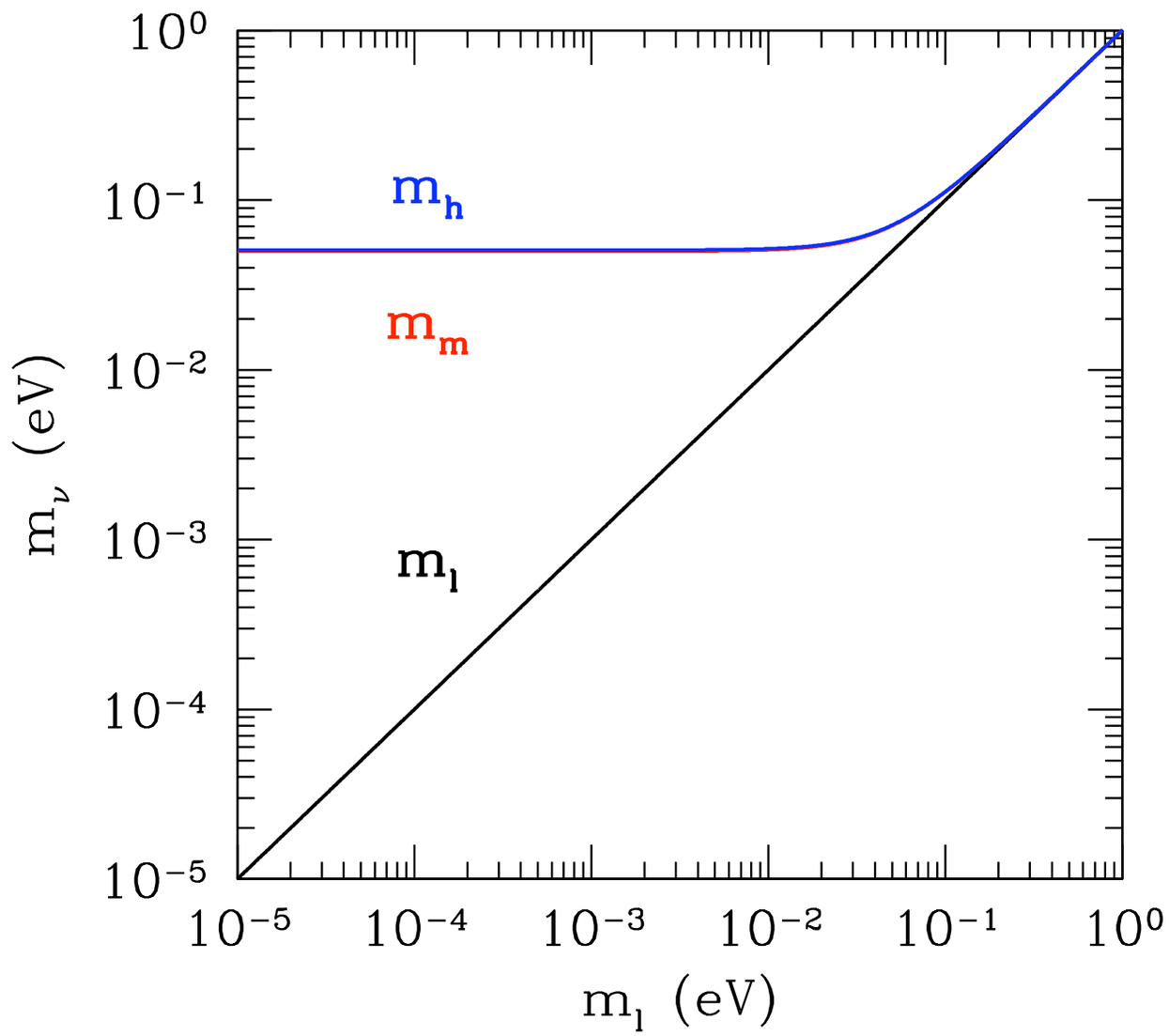
Veltman: Higgs boson knows something we don't know!

Neutrino family patterns (an example)



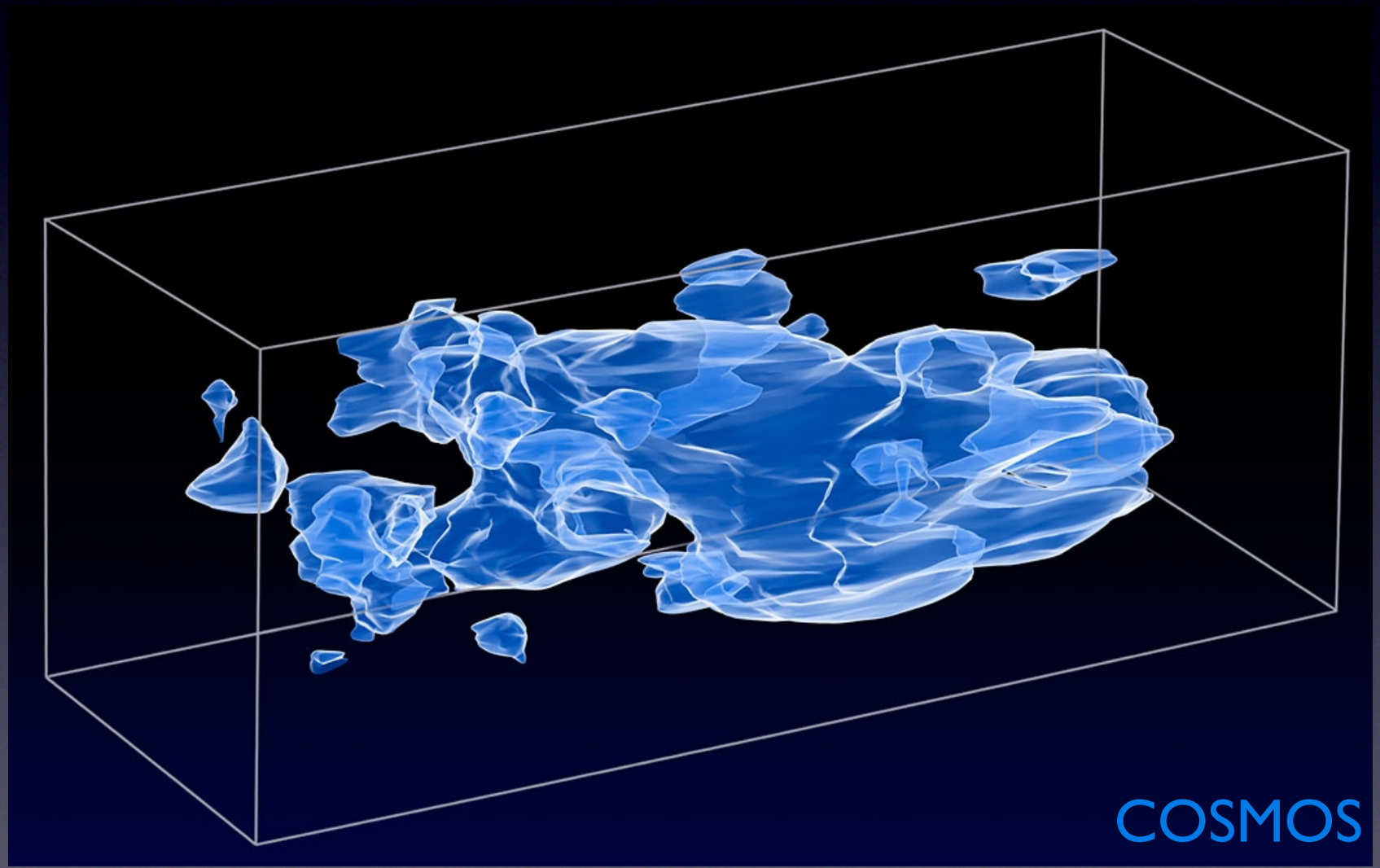
Neutrino Masses





More New Physics on the Fermi Scale?

If dark matter interacts weakly …



… its likely mass is 0.1 to 1 TeV: *Fermi scale*

Many extensions to EW theory entail dark matter candidates

Supersymmetry is highly developed, has several important consequences:

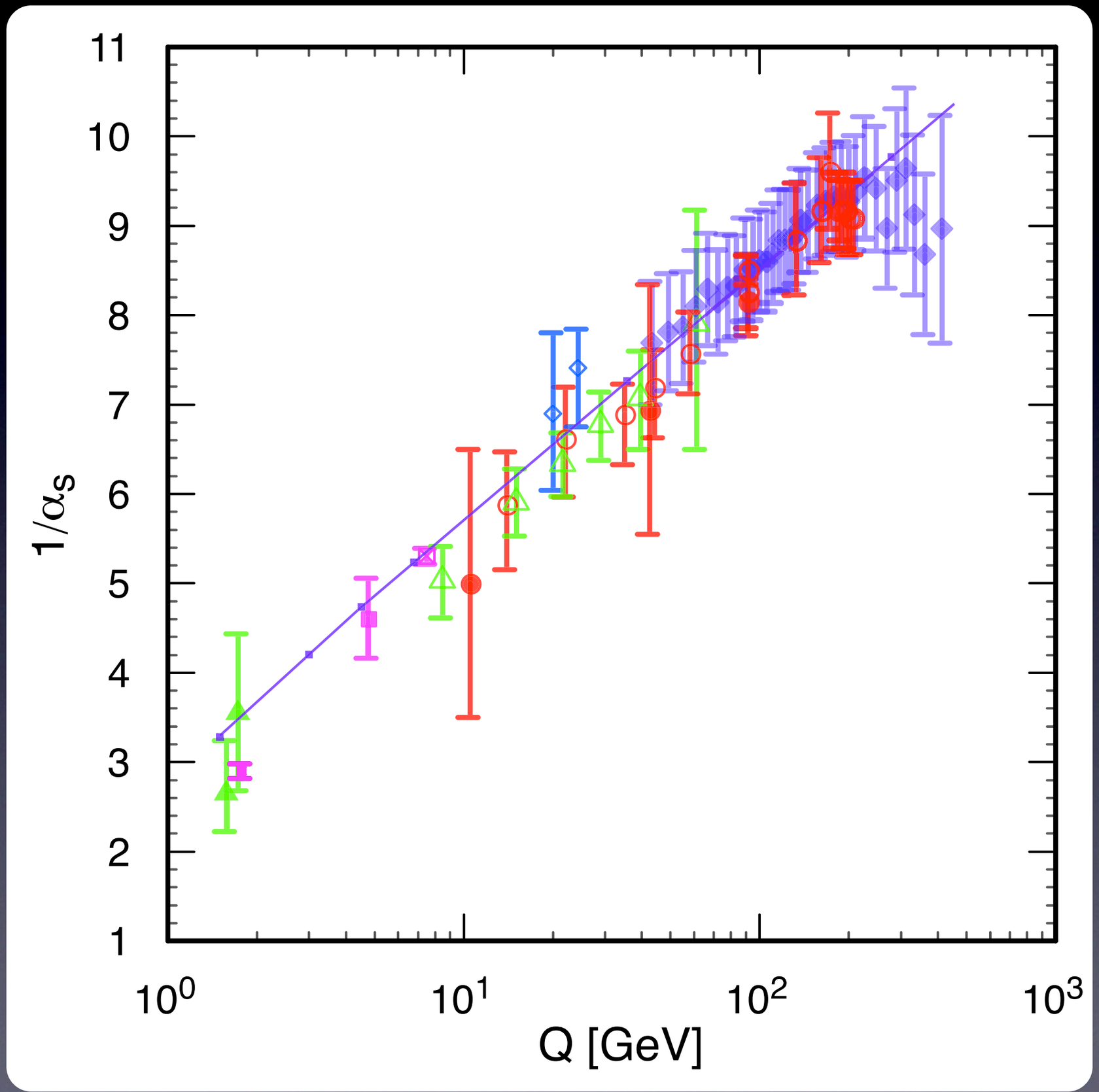
- ✳Predicts that Higgs field condenses, breaking EW symmetry, if top is heavy
- ✳Predicts a light Higgs mass
- ✳Predicts cosmological cold dark matter
- ✳In a unified theory, explains the values of standard-model coupling constants

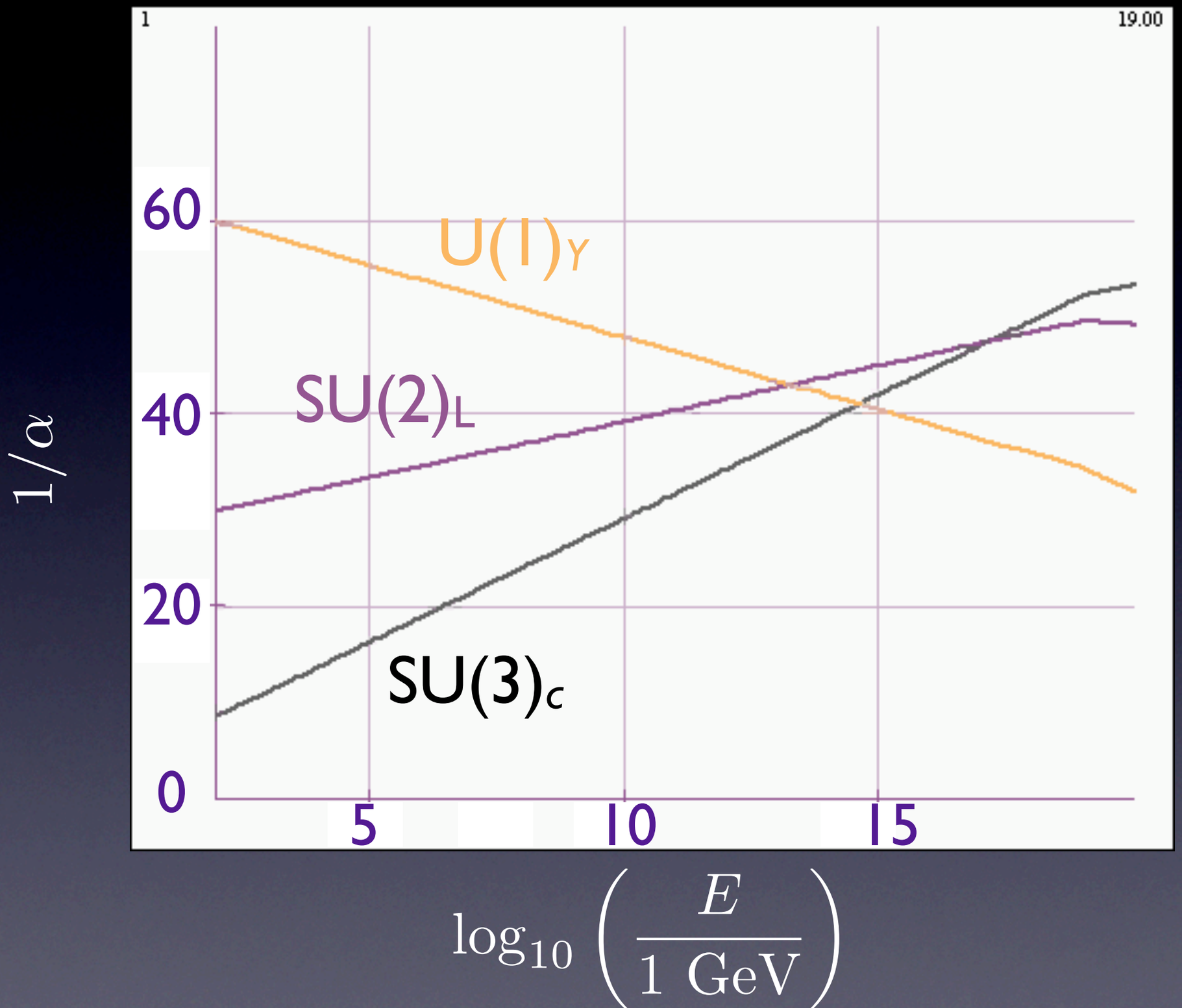
Have we taken too narrow a view of TeV-scale supersymmetry?

The Unity of Quarks & Leptons

- What do quarks and leptons have in common?
- Why are atoms neutral?
- Which quarks with which leptons?
- Extended quark–lepton families: proton decay!

Evolution of the strong coupling "constant"




1
19.00
60
40
20
0
5
10
15
U(1)Y
SU(2)L
SU(3)c
1/α
log10 (E / 1 GeV)

Gravity rejoins Particle Physics rejoins

Natural to neglect gravity in particle physics

two up quarks: gravity/EM ≈ 10^{-41}

$$G_{\text{Newton}} \textit{ small} \iff M_{\text{Planck}} = \left(\frac{\hbar c}{G_{\text{Newton}}}\right)^{\frac{1}{2}} \approx 1.22 \times 10^{19} \text{ GeV } \textit{large}$$

But gravity is not always negligible …

Higgs field contributes uniform vacuum energy density

$$\varrho_H \equiv \frac{M_H^2 v^2}{8} \geq 10^8 \text{ GeV}^4 \quad \approx 10^{24} \text{ g cm}^{-3}$$

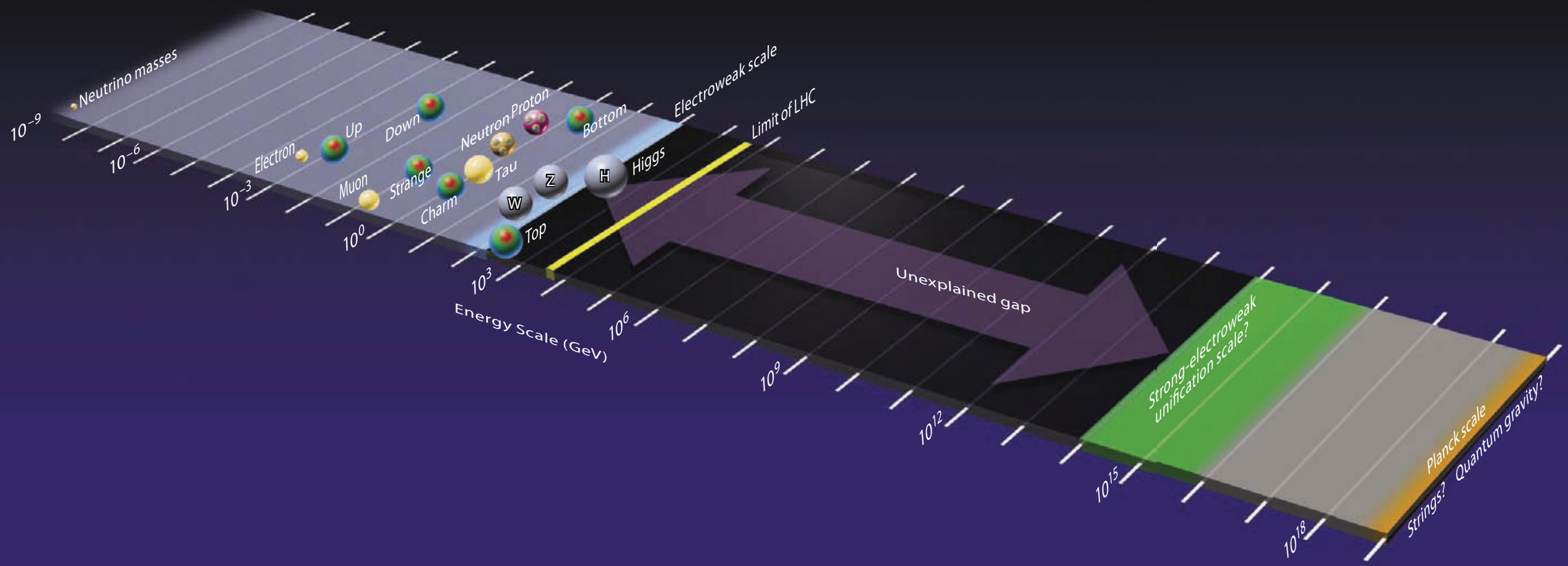
Observed vacuum energy density $\varrho_{\text{vac}} \leq 10^{-46}$ GeV^4

Mismatch by 54 orders of magnitude

How to separate EW, higher scales?

Does M_H < 1 TeV make sense?

The peril of quantum corrections – hierarchy problem



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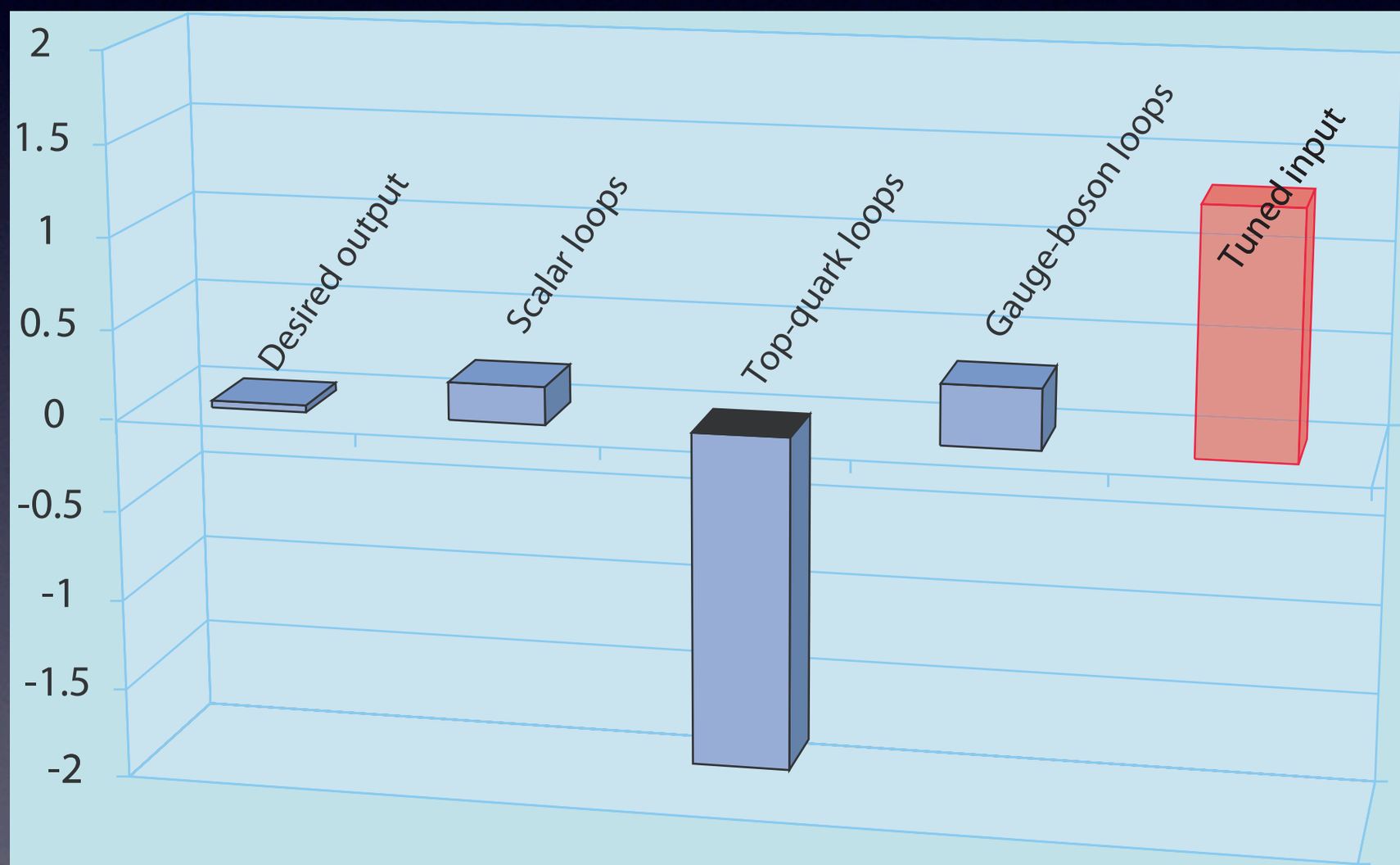


5 TeV

How to separate EW, higher scales?

Traditional: change electroweak theory to understand why M_H, electroweak scale $\ll M_{\text{Planck}}$

To resolve hierarchy problem: extend standard model on the 1-TeV scale …

composite Higgs boson

technicolor / topcolor

supersymmetry

…

$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

Ask instead why gravity is so weak,
why $M_{\text{Planck}} \gg$ electroweak scale

A new conception of spacetime?

Could there be more spatial dimensions than we have perceived?

What is their size? their shape?

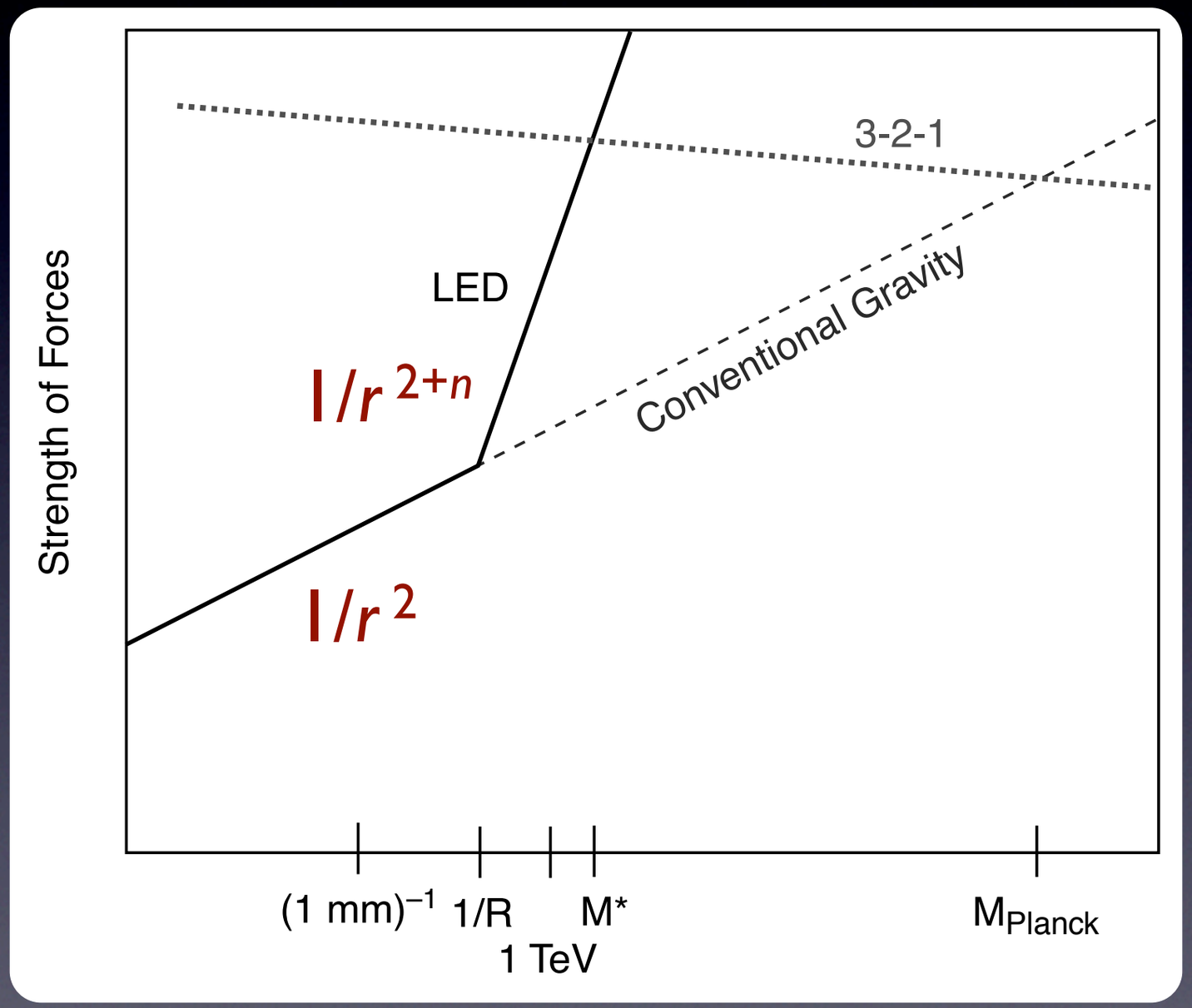
How do they influence the world?

How can we map them?

String theory needs 9 (10)

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

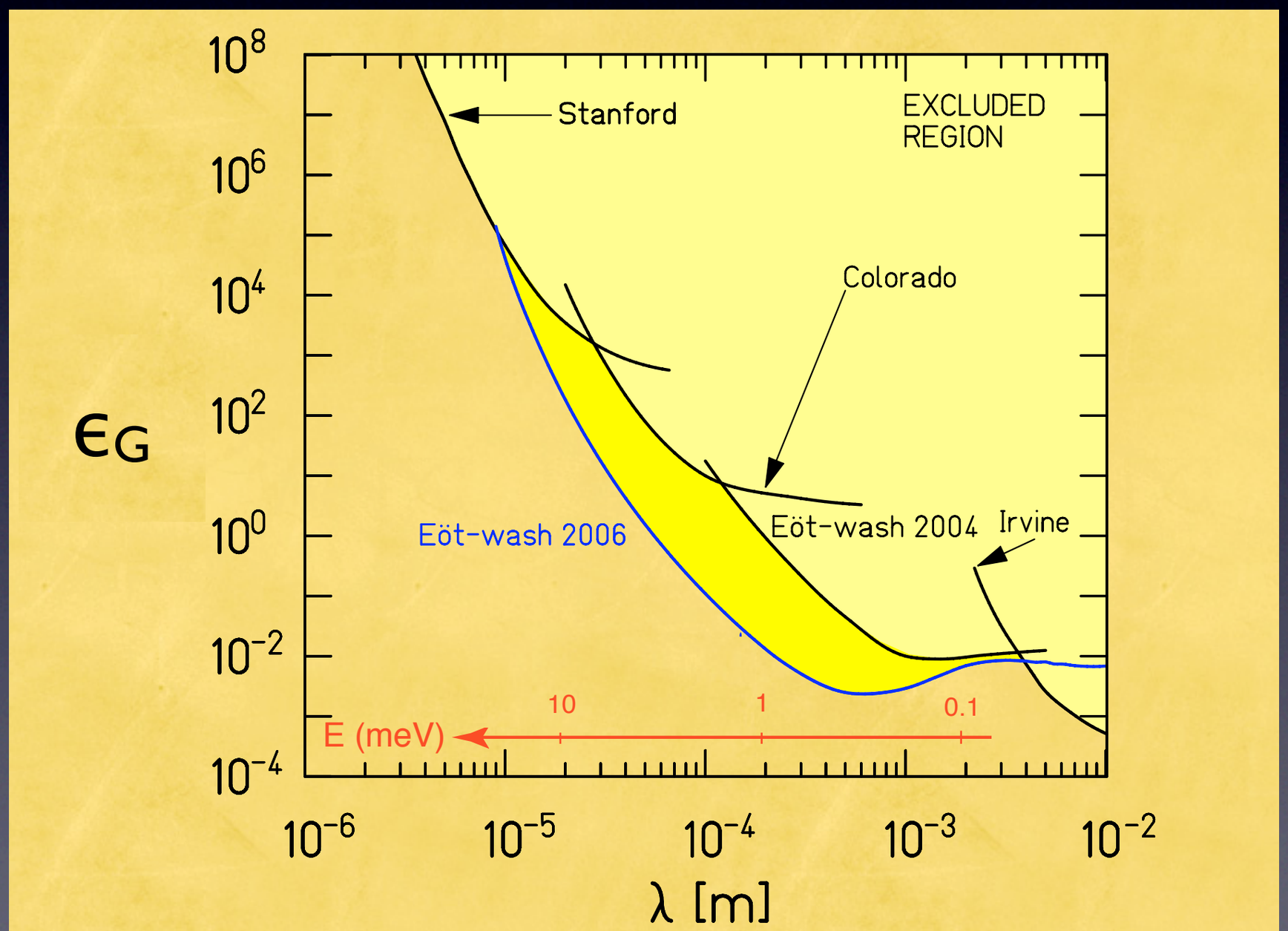
Gauss law: $G_N \sim M^{*-n-2}\ R^{-n}$ M^* : gravity's true scale



M_{Planck} would be a mirage!

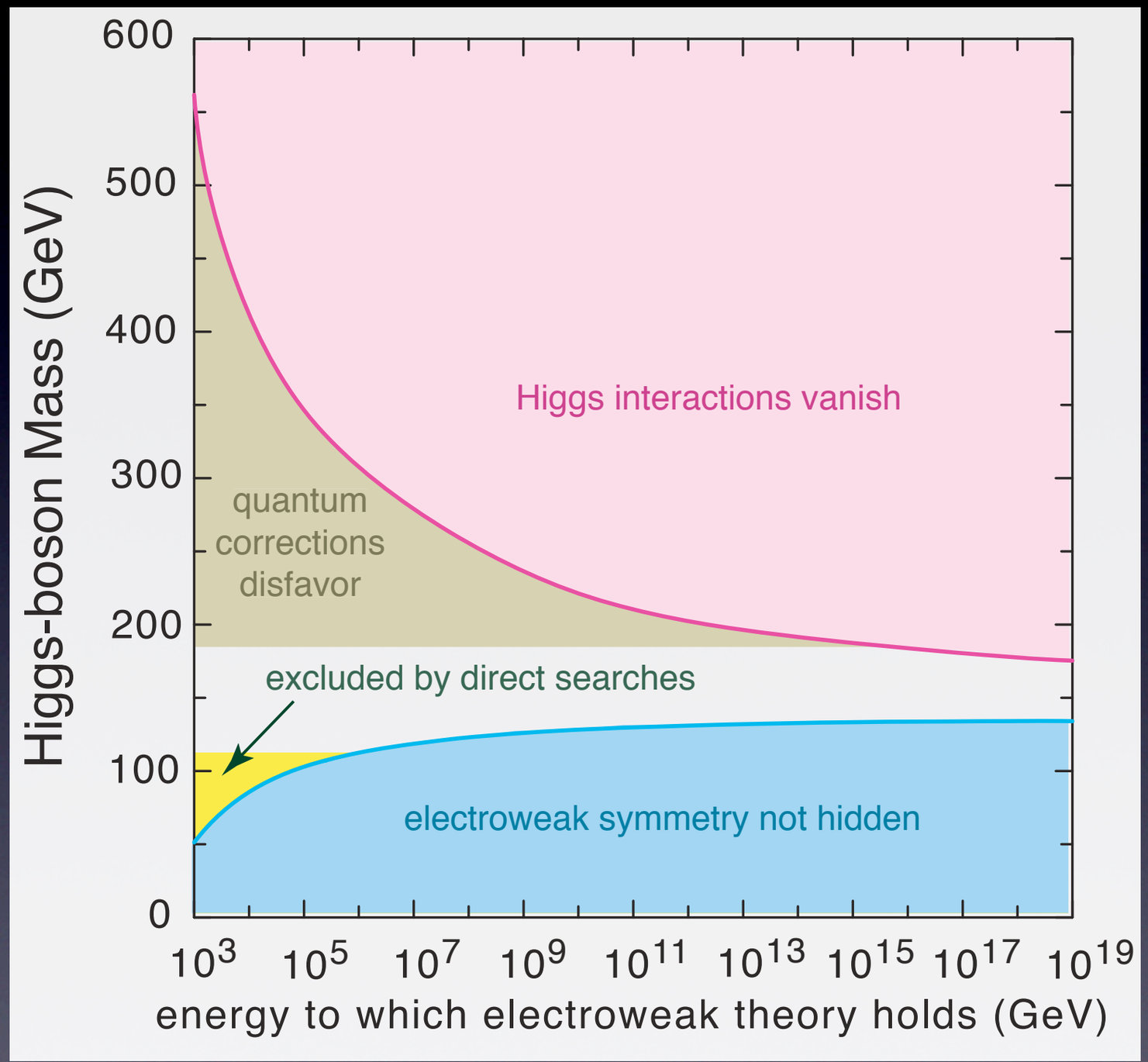
Gravity follows Newtonian force law down to $\lesssim$ 1 mm

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



Connections ...

We think the electroweak theory is incomplete



also hierarchy problem, fermion masses, etc.

QCD could be complete, up to M_{Planck}

… but that doesn't prove it must be

Prepare for surprises!

10. SOME EXPERIMENTS ON MULTIPLE PRODUCTION

KENNETH G. WILSON

Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

Introduction 701
Experiment 1: Partial Cross Sections as a function of Multiplicity . . 715
Experiment 2: Beam Survey from a Hydrogen Target 716
Experiment 3: Factorization in the Single Particle Spectrum . . . 716
Experiment 4: The dk_2/k_2 Law 717
Experiment 5: Search for Double Pomeron Exchange 718
Experiment 6: Correlation Length Experiment 719
Experiment 7: Test of Factorization in Multiperipheral Processes . . 720
Acknowledgements 721
Appendix Short Range Forces and Bounded Transverse Momentum . . 721
References 724

Might we see
unexpected event structure
in early LHC running?

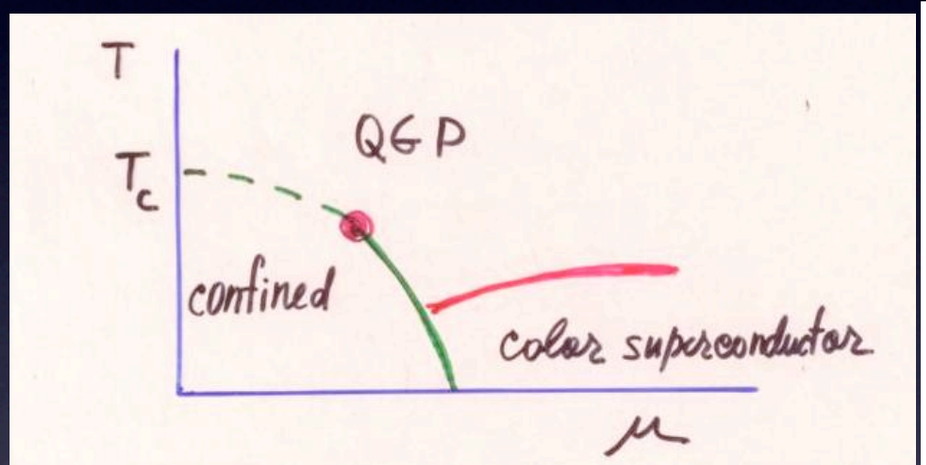
Importance of canonical expectations
for multiplicities, correlations, topologies

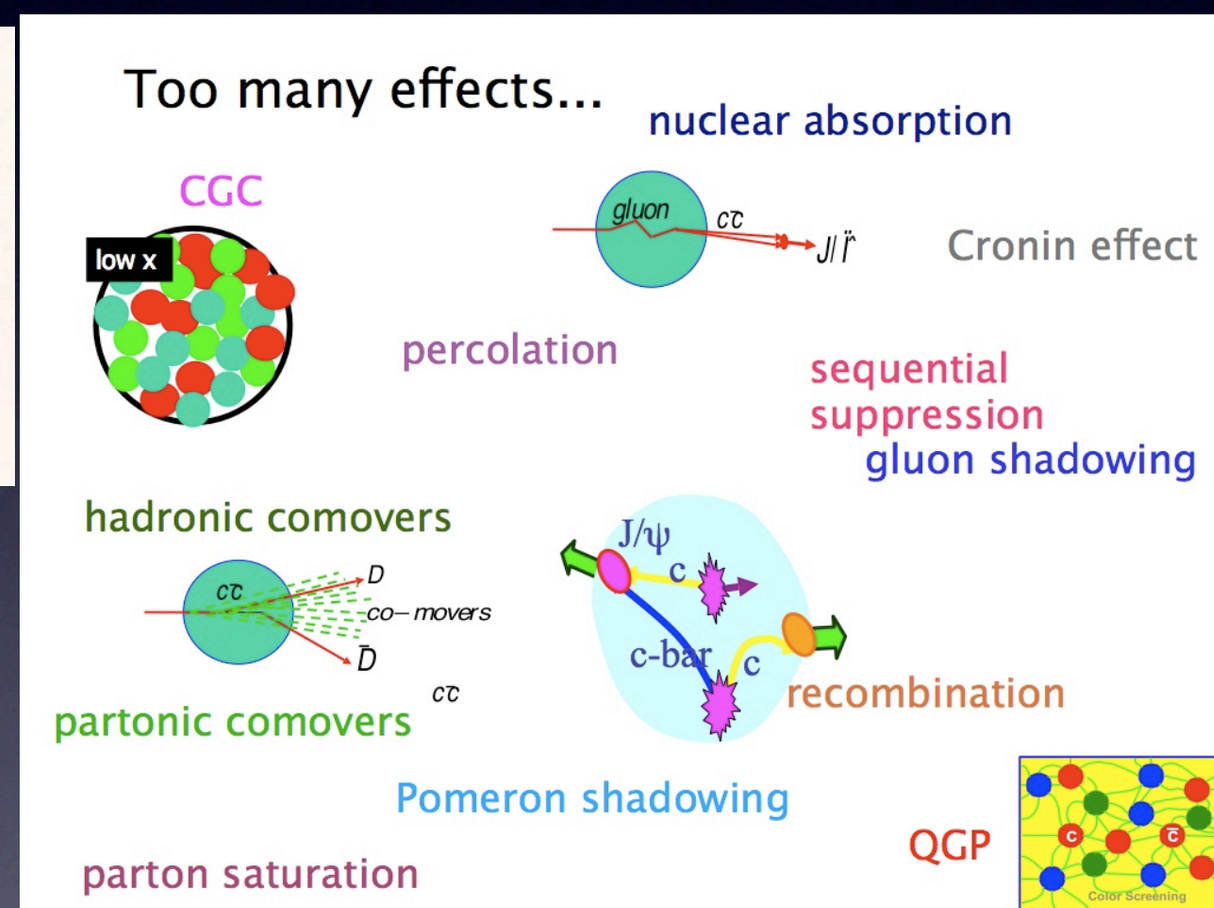
Even without surprises, study of
soft collisions, underlying events
will pay great dividends
in understanding multiple production
and the search for new physics!

New physics within the standard model?

Heavy ion collisions: new realms of QCD

ϵ_{RHIC} = 15 GeV/fm^3, × (3-5) @ LHC

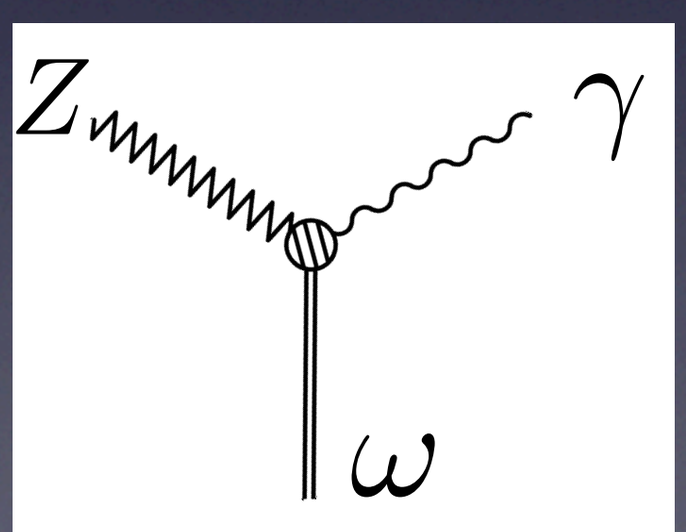




New physics within the standard model?

Searches underway for Wess-Zumino term
NA48, Belle, …

Related: low-energy manifestation of sphaleron
(nonperturbative B violation linked to B-current anomaly)



EW baryogenesis
low-*E* νN signal?
Astrophysical?

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 explore CP violation in *B* decays
Exploit rare decays (*K*, *D*, …)
Observe neutron EDM, pursue electron EDM
Use top 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 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-scale dynamical symmetry breaking
Search for new strong dynamics
Explain the highest-energy cosmic rays
Formulate the problem of identity

… learn the right questions to ask

… and rewrite the textbooks!