Electroweak Symmetry Breaking: Status and Prospects

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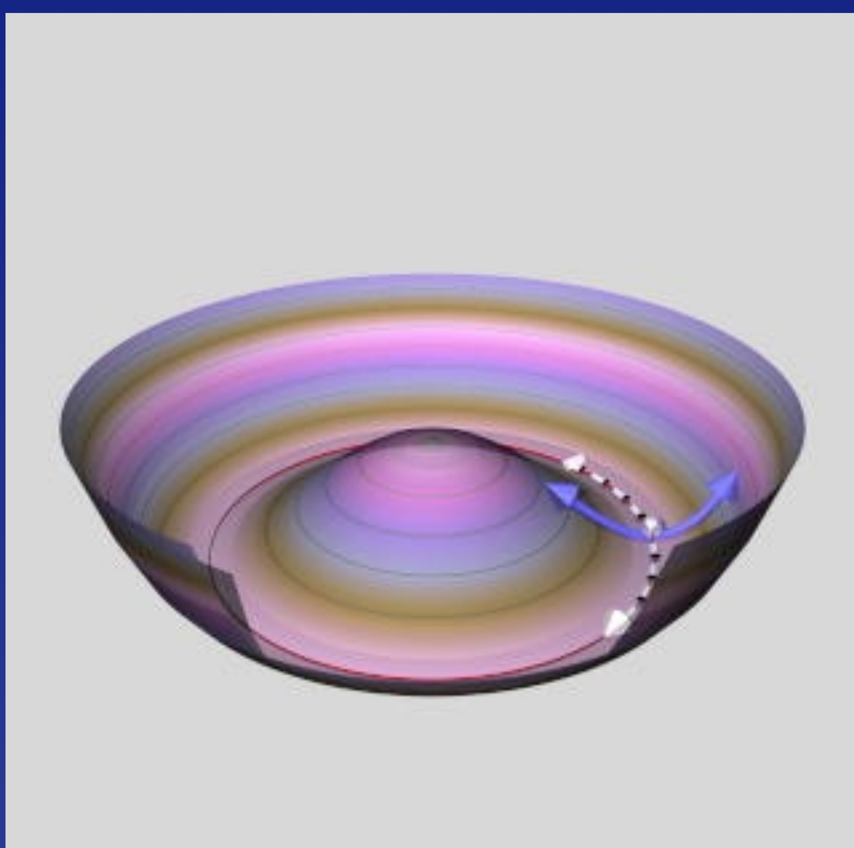
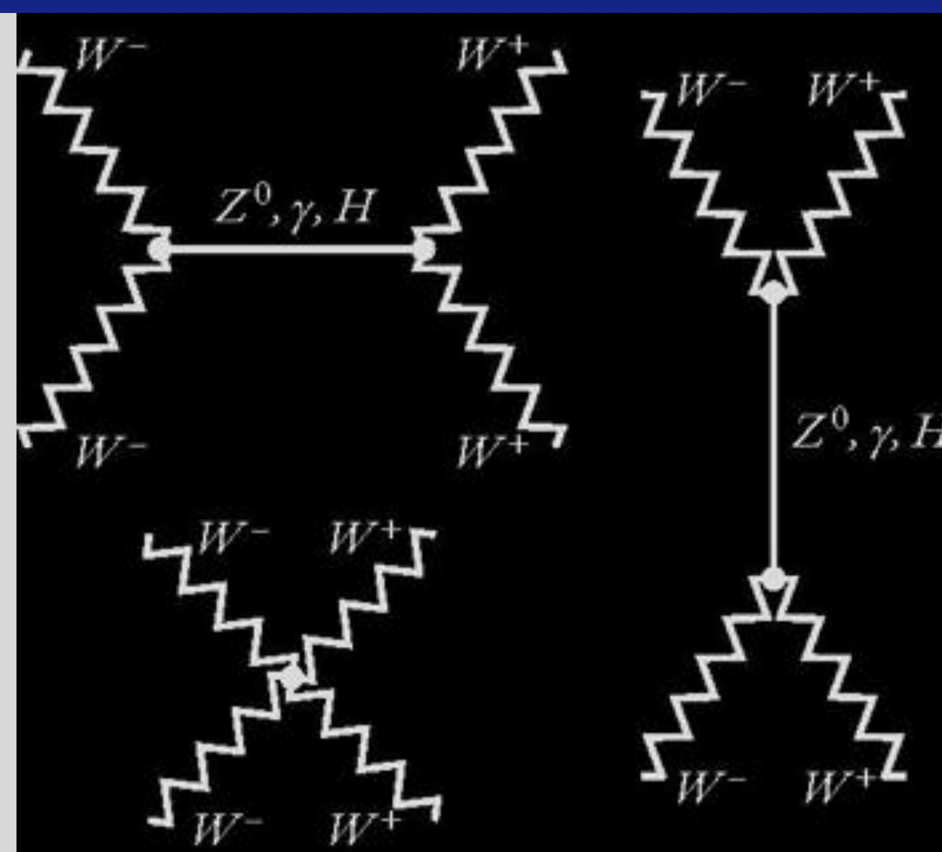


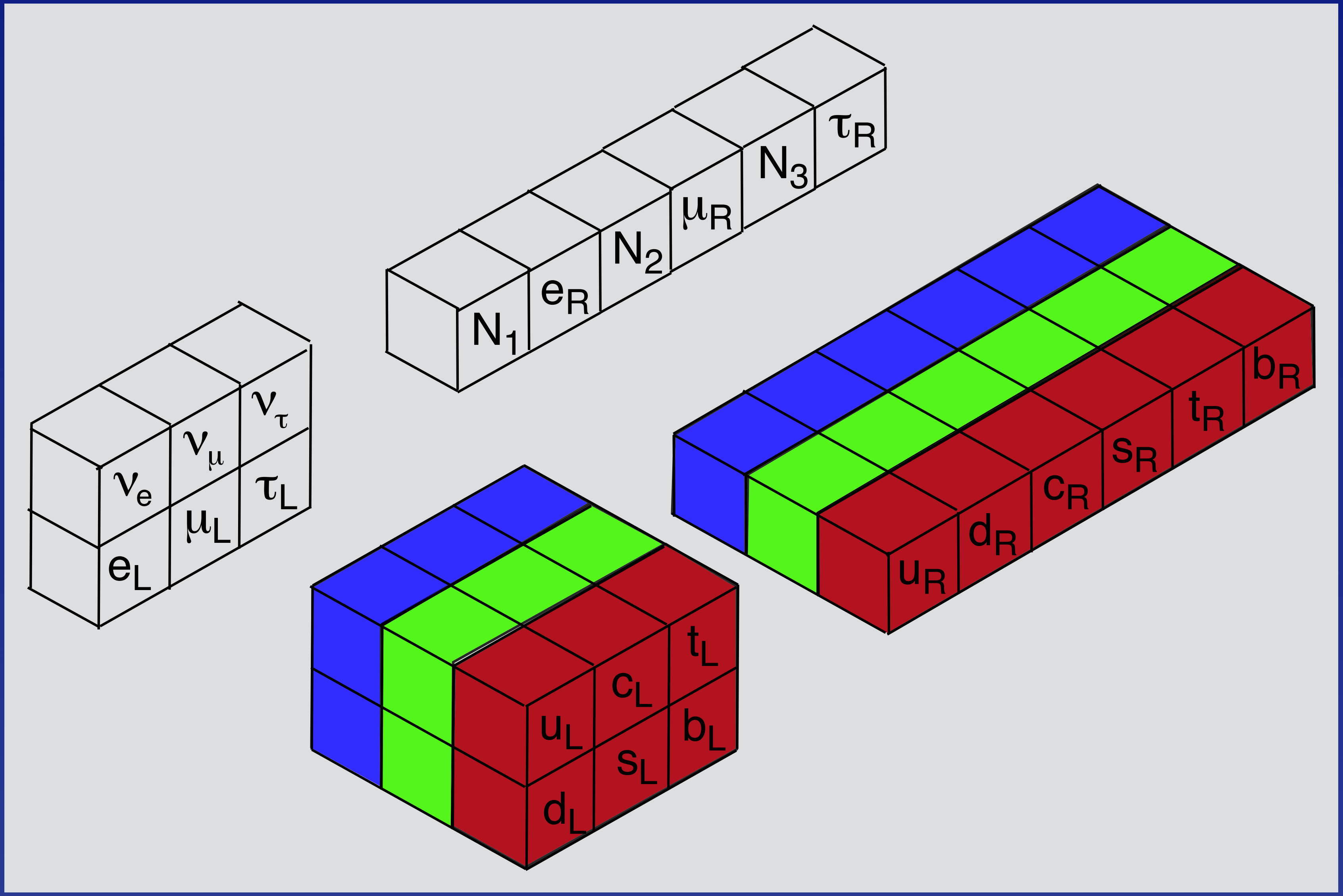


50 Years of Quarks & Color · 11 April 2014

Before LHC

Two New Laws of Nature +

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



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

Quantum Chromodynamics

Asymptotically free theory

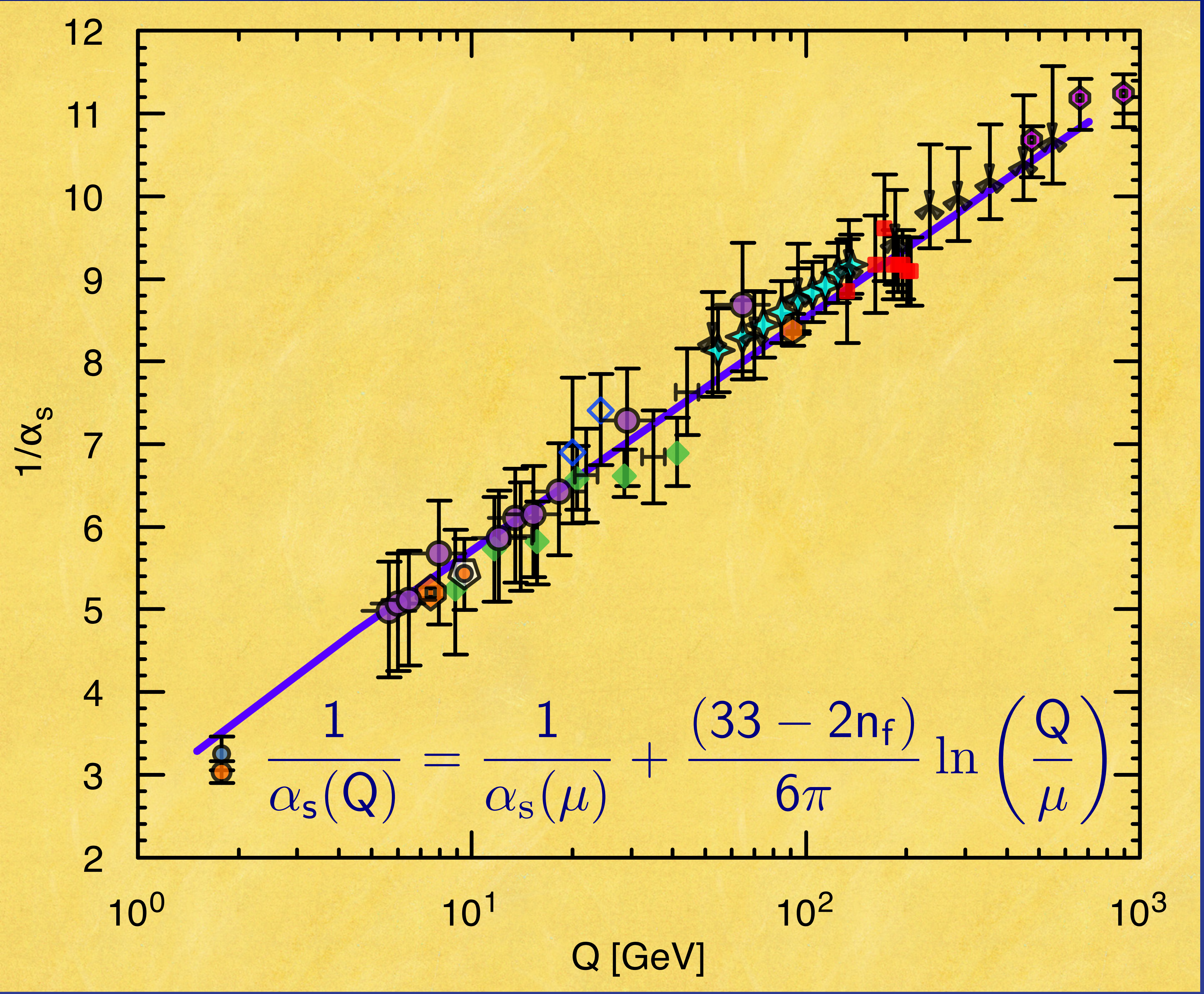
Many successes in perturbation theory to 1 TeV

Growing understanding: nonperturbative regime

Quarks & gluons confined: evidence, no proof

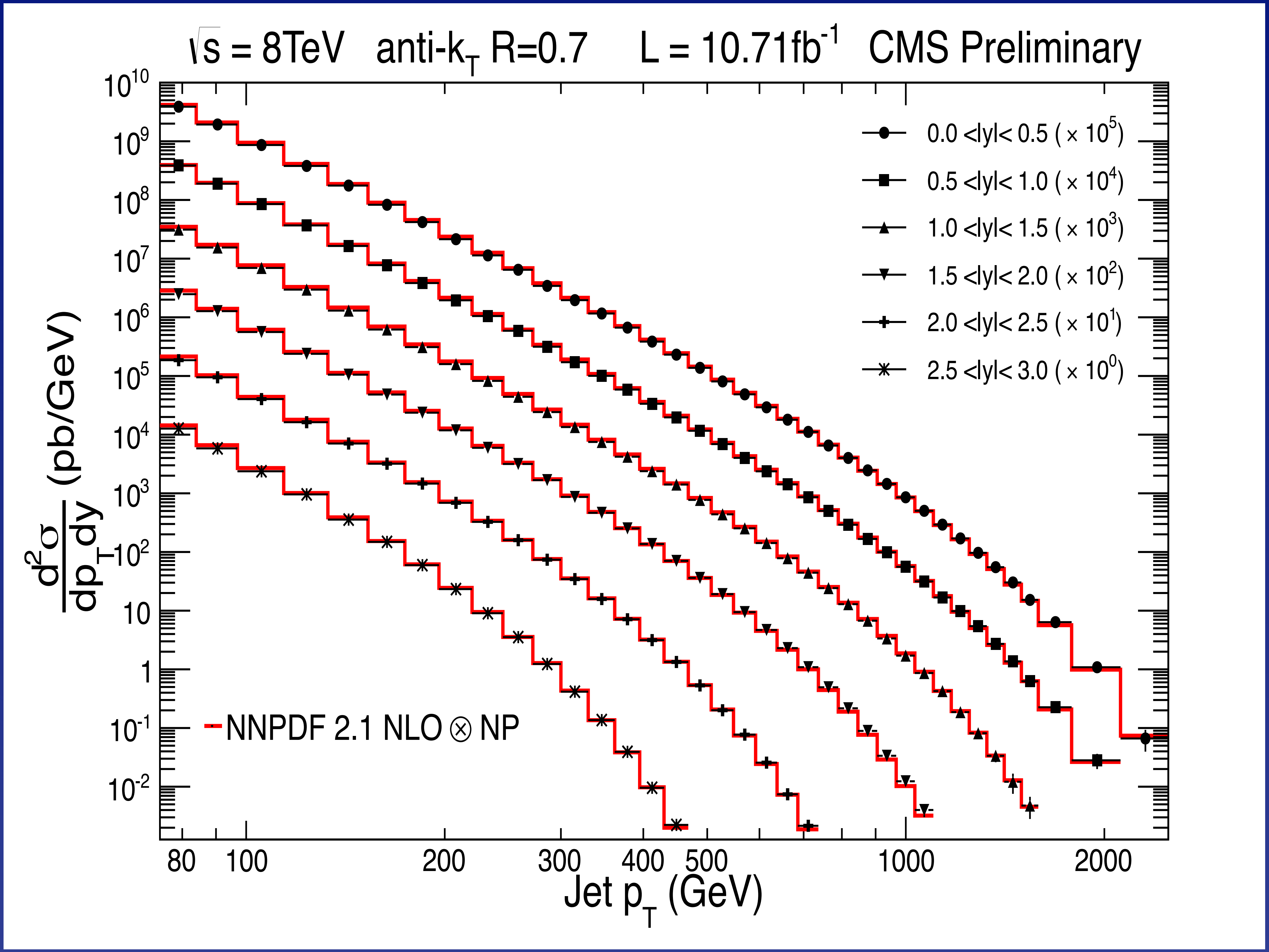
No structural defects, but *strong CP problem*

Evolution of the strong coupling "constant"



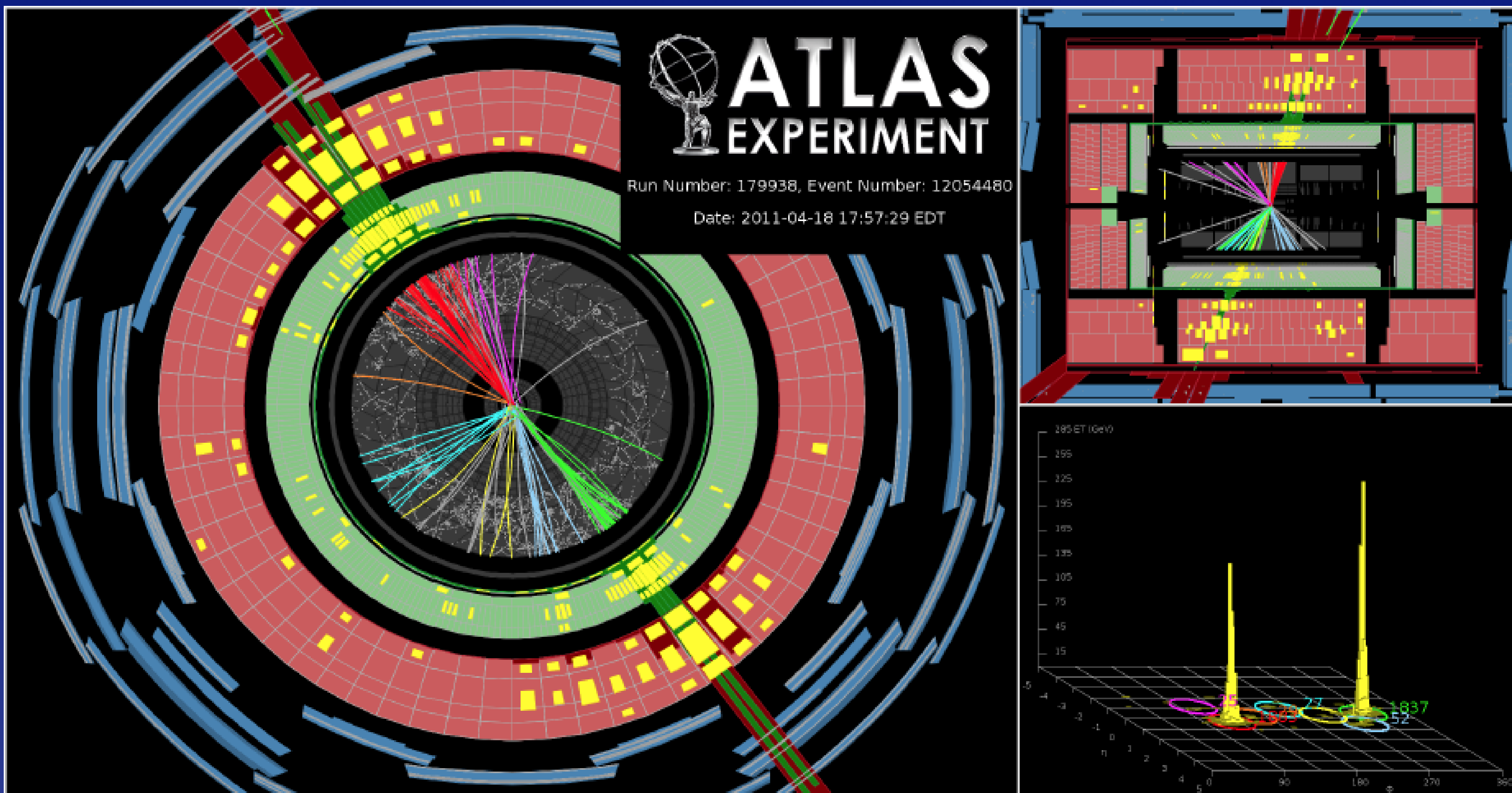
$$\frac{1}{\alpha_s(Q)} = \frac{1}{\alpha_s(\mu)} + \frac{(33 - 2n_f)}{6\pi} \ln\left(\frac{Q}{\mu}\right)$$

Jet Production at LHC



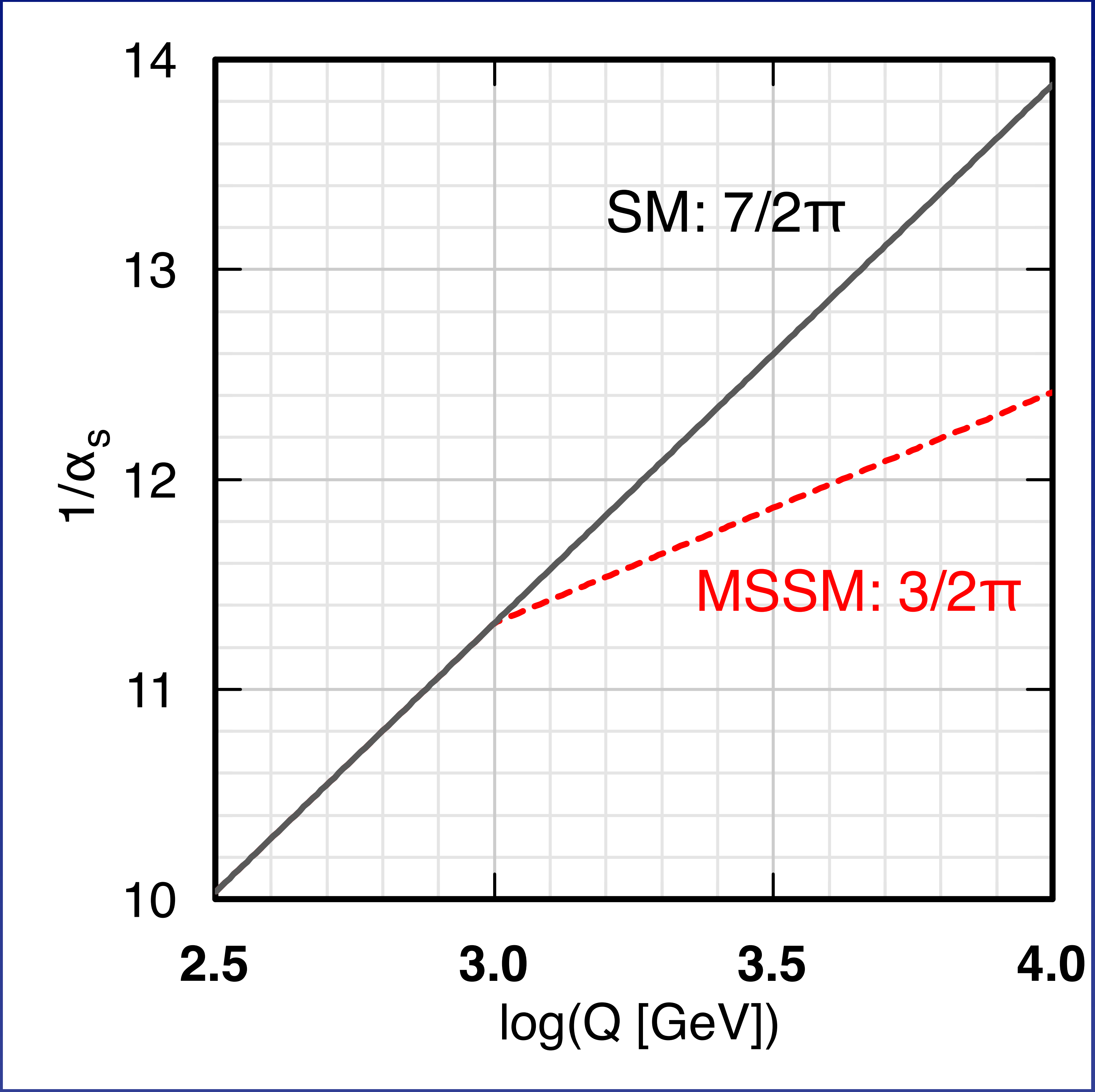
The World's Most Powerful Microscopes

nanonanophysics



Transverse momenta: 1.8 TeV + 1.8 TeV · *Dijet mass:* 4 TeV

Might LHC see a change in evolution?



sum of parts

rest energy

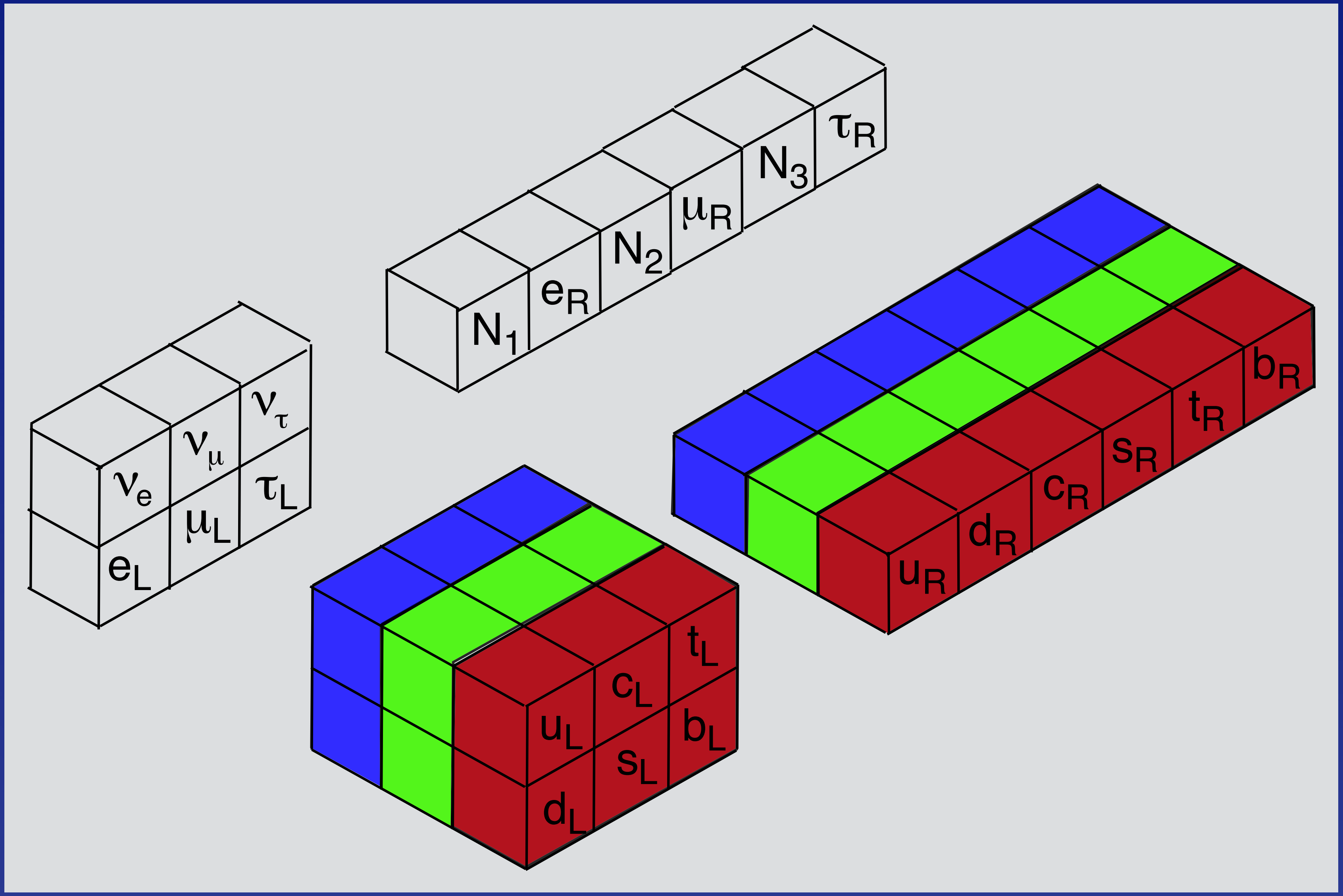
Nucleon mass: exemplar of $m = E_0/c^2$

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

A previously unknown agent hides the 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

Tasks:

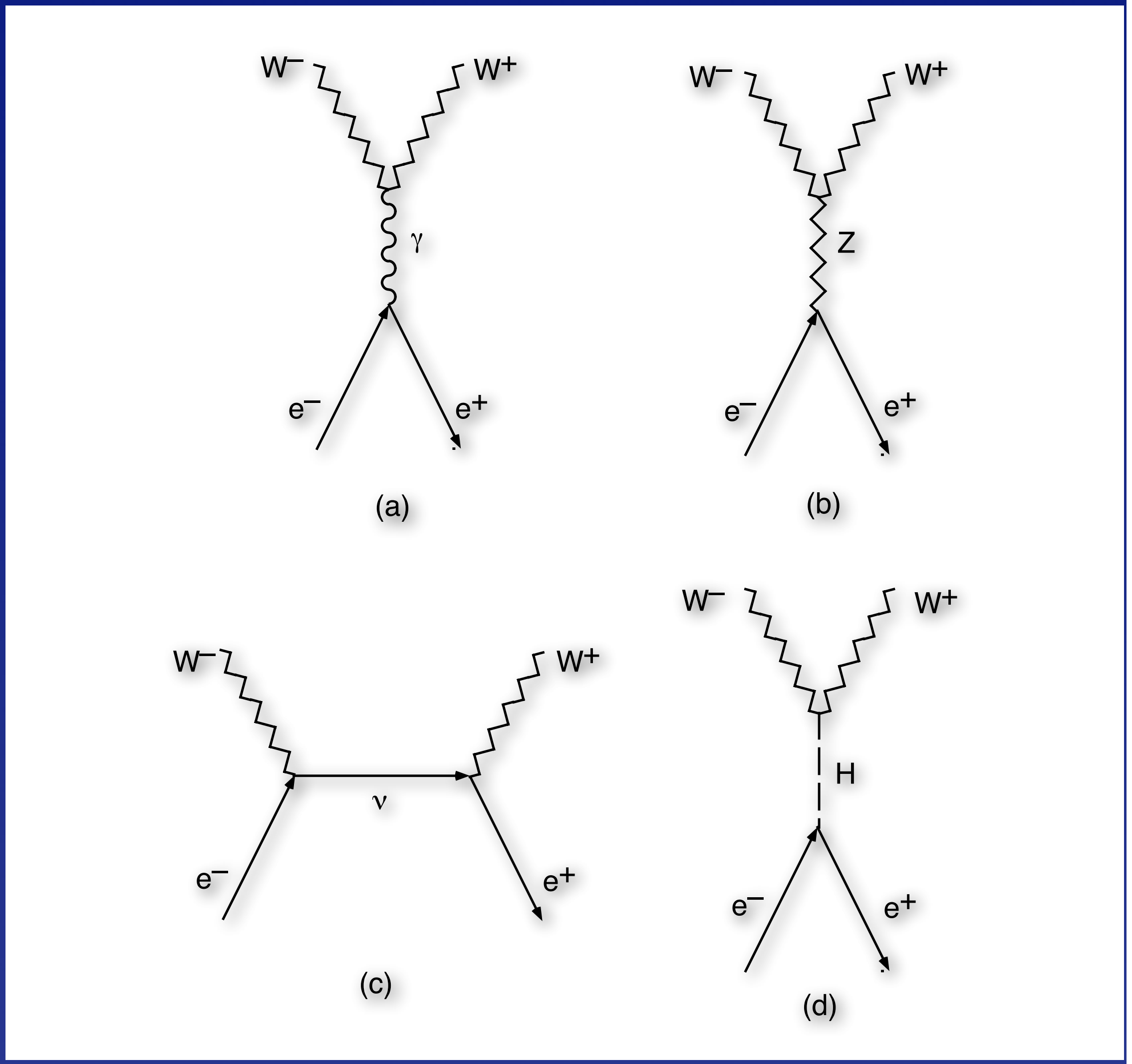
Hide EW symmetry

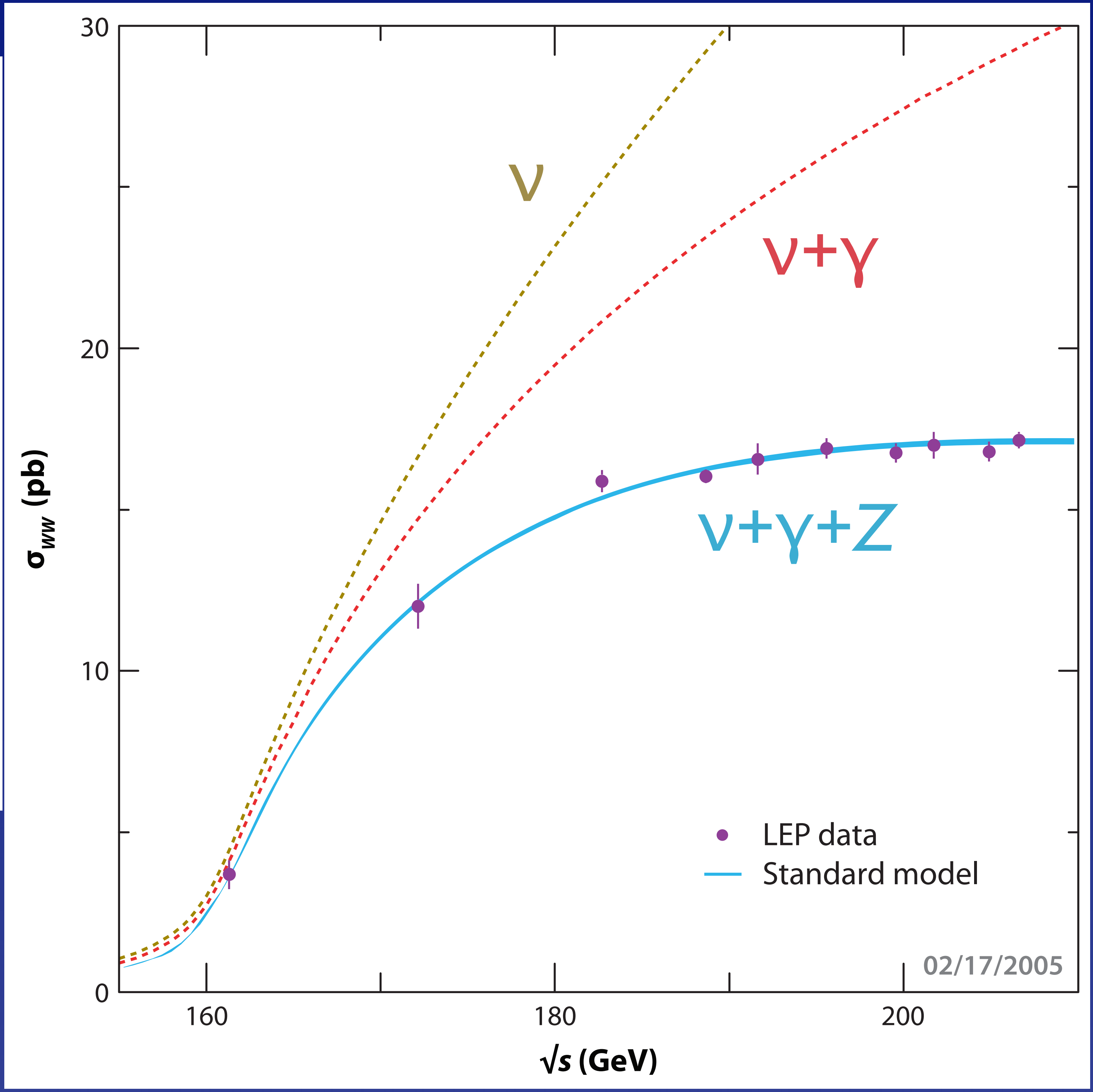
Give masses to W and Z

Give masses to fermions (ν?)

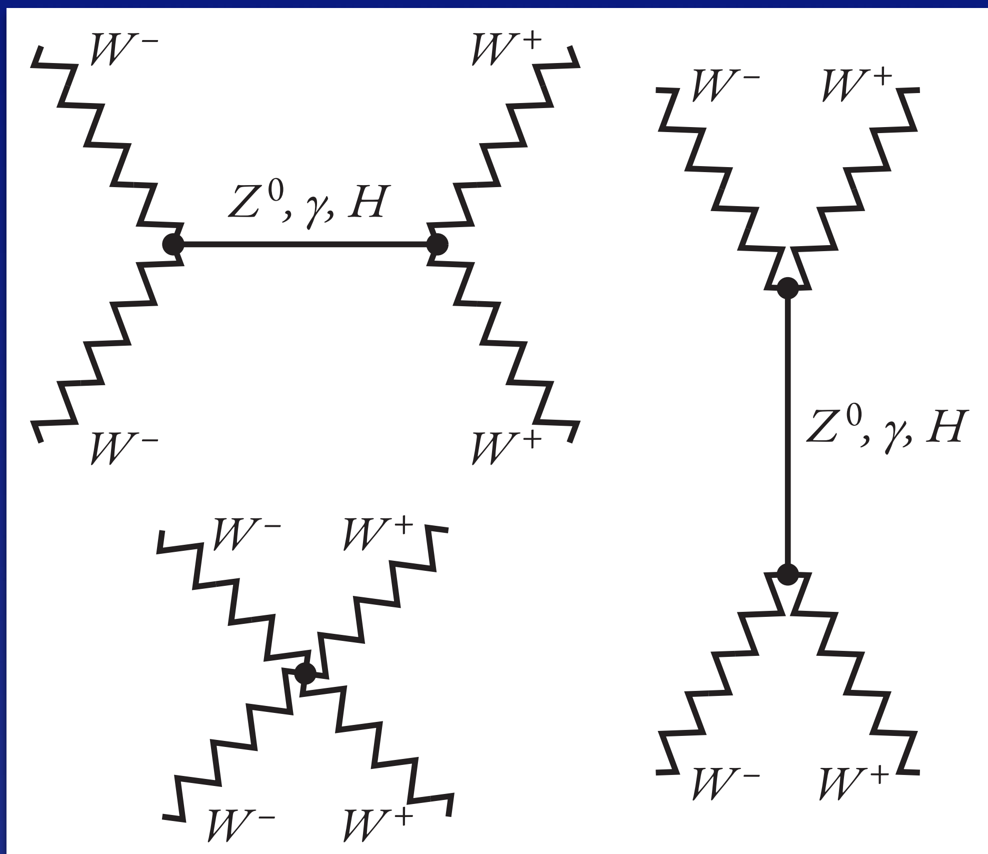
Ensure good high-energy behavior

LEP validated secret SU(2)$_L$⊗U(1)$_Y$ symmetry





Gedankenexperiment: high-energy behavior



$$\mathcal{M}(W_0^+ W_0^- \to W_0^+ W_0^-) = -\sqrt{2} G_F M_H^2 \left[\frac{s}{s - M_H^2} + \frac{t}{t - M_H^2} \right]$$

$$a_0(W_0^+ W_0^- \to W_0^+ W_0^-) \xrightarrow[s \gg M_H^2]{} \frac{-G_F M_H^2}{4\pi\sqrt{2}}$$

The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: *conditional upper bound*

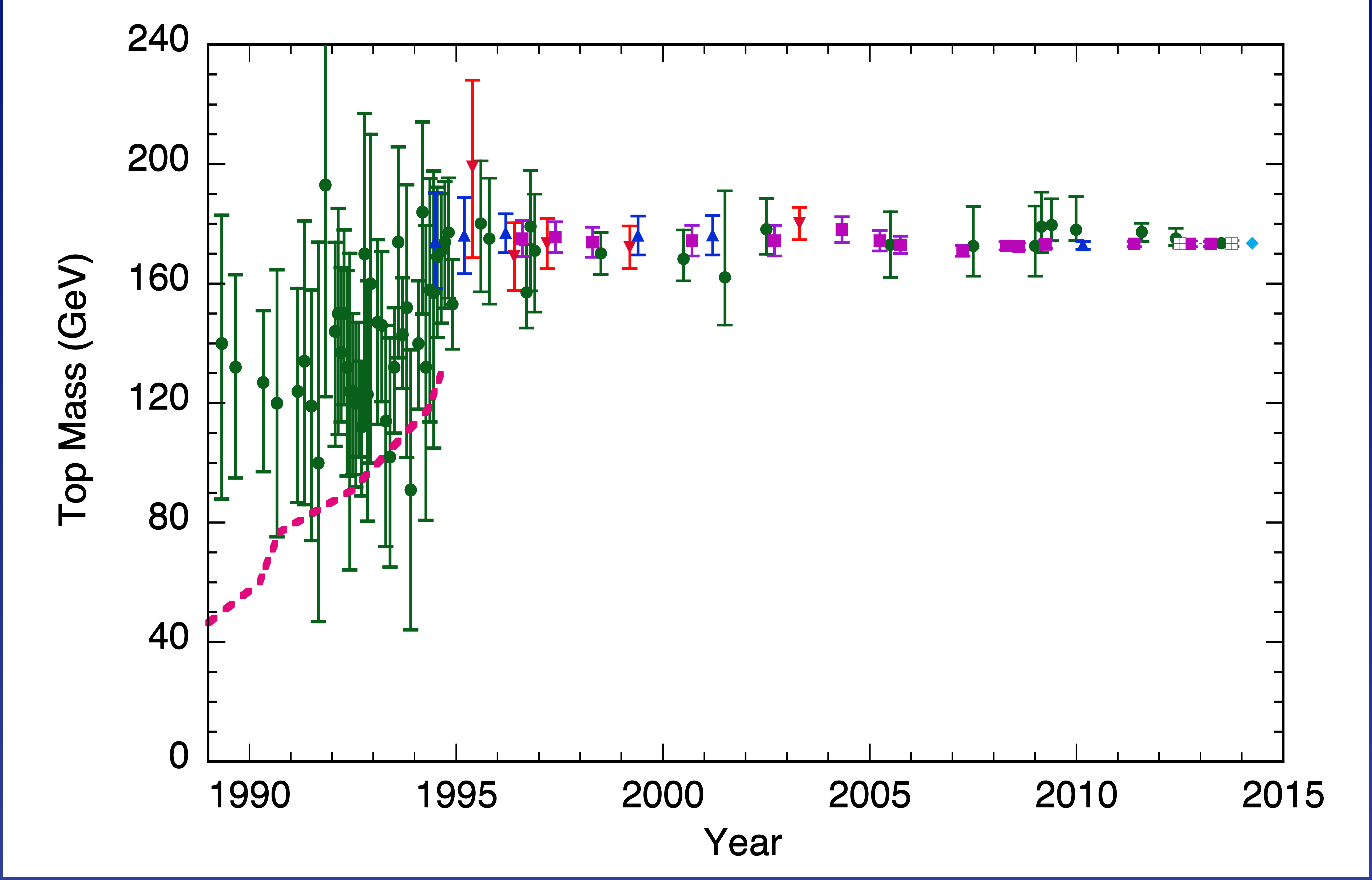
W^+W^-, ZZ, HH, HZ satisfy *s*-wave unitarity,

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

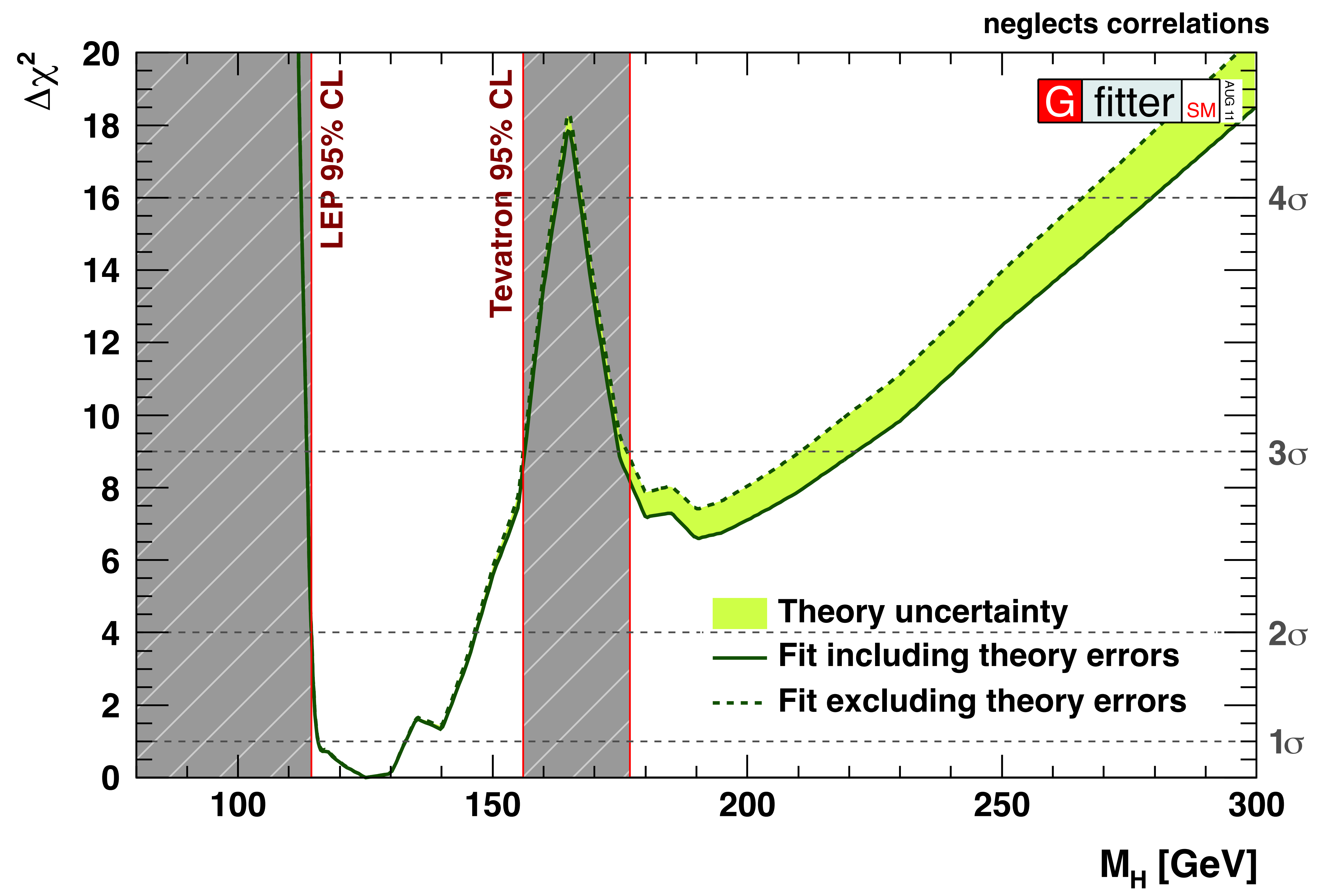
New phenomena are to be found around 1 TeV

Electroweak theory anticipates discoveries



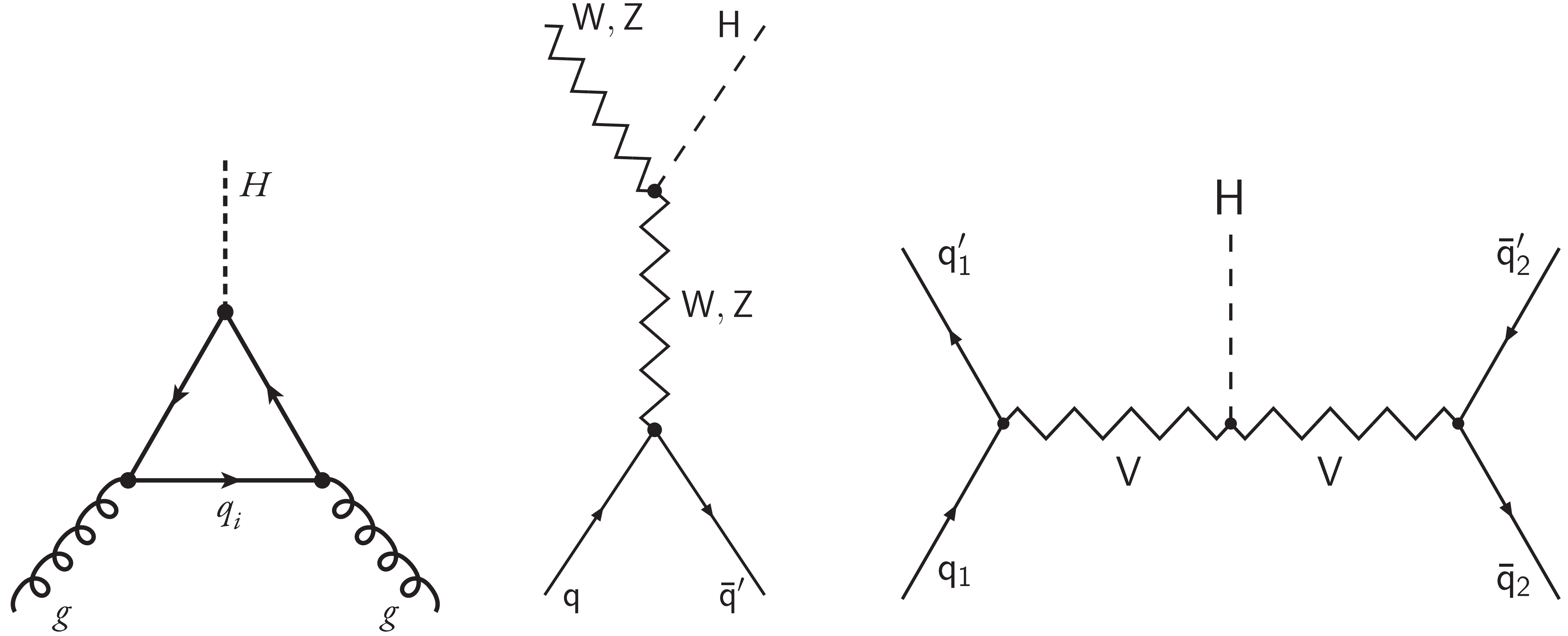
Before

H couplings to *W*, *Z* tested indirectly



BSM: heavy Higgs allowed, even natural

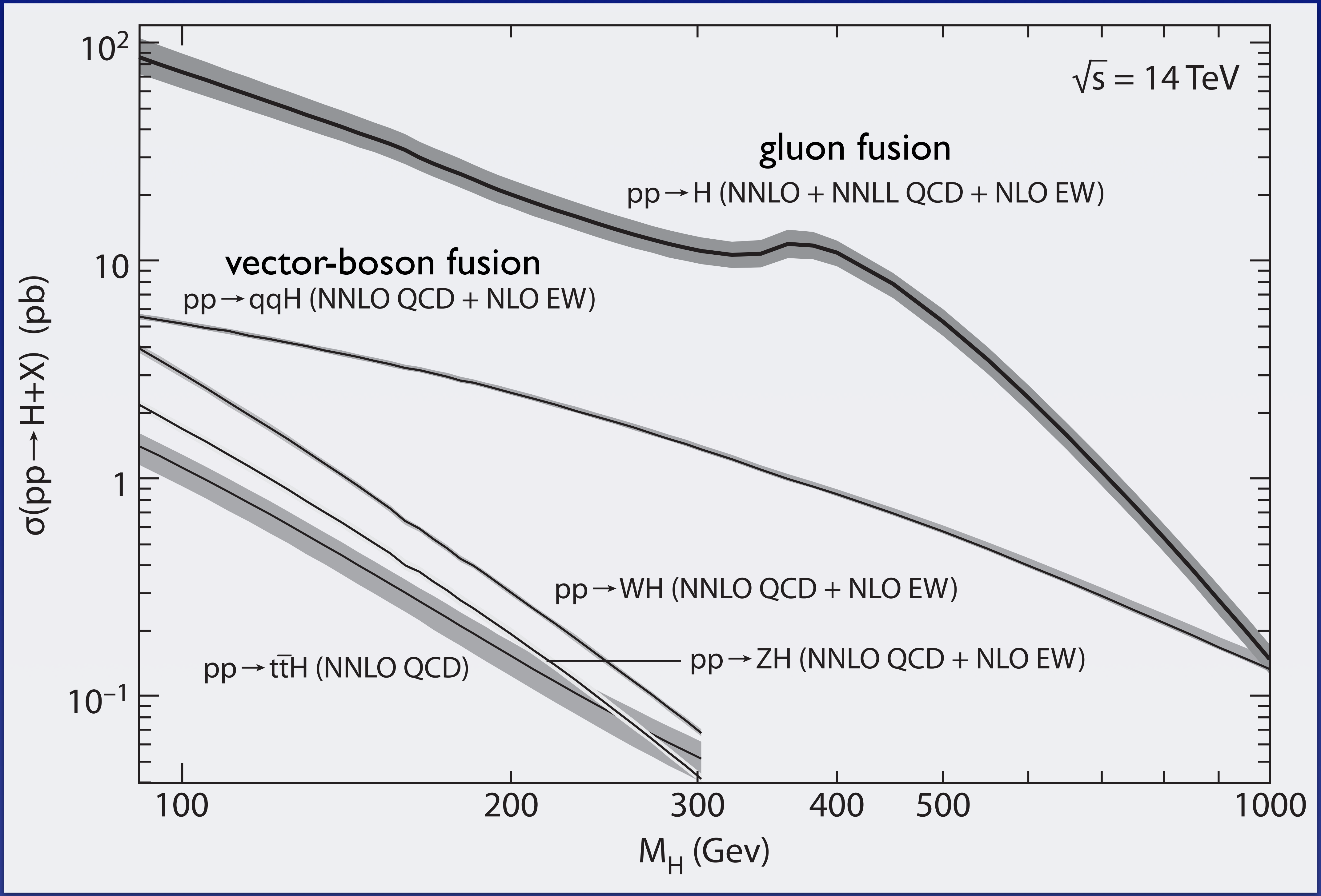
$p^{\pm}p$ colliders search in many channels



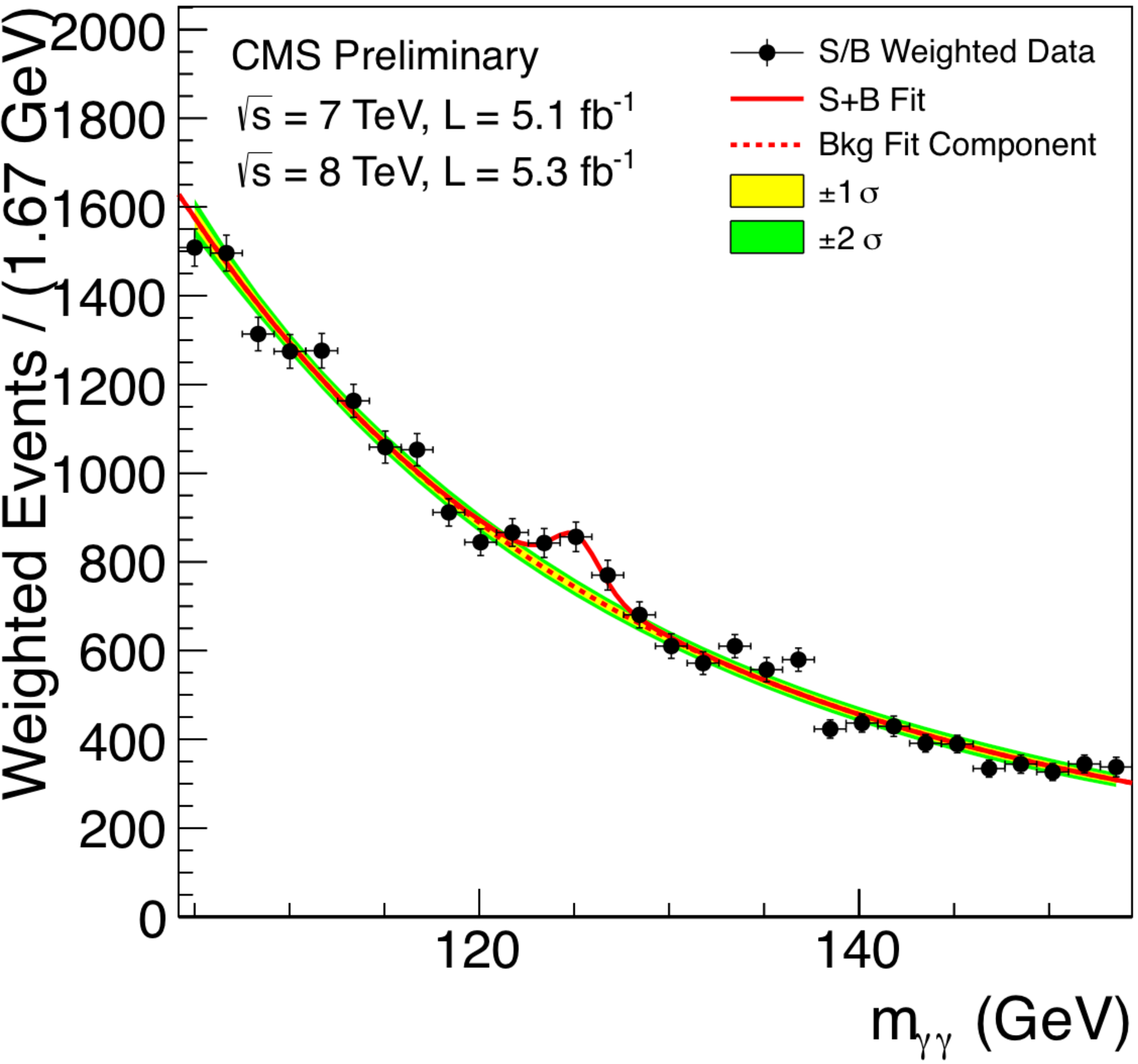
+ $Ht\bar{t}$

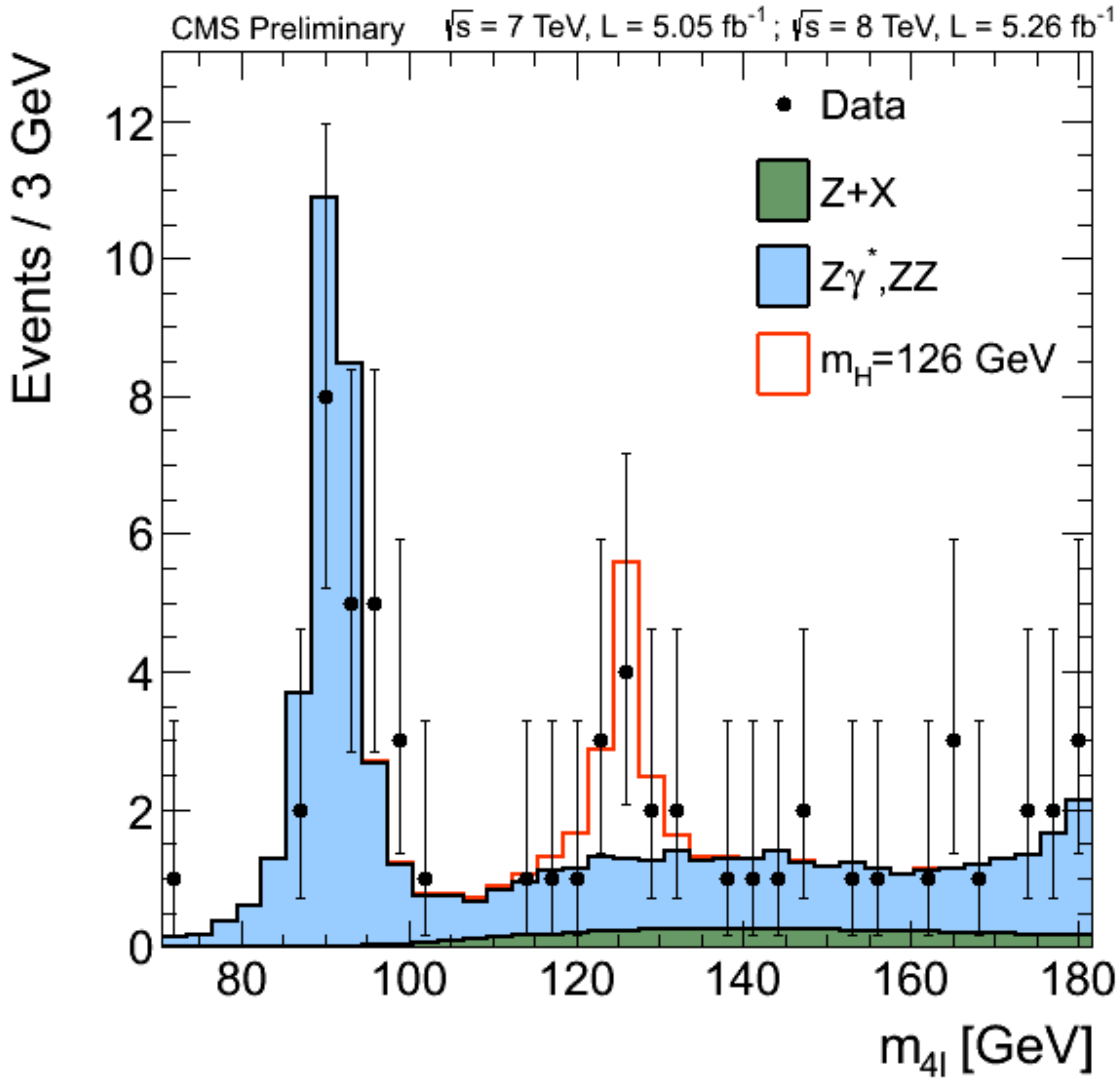
$\gamma\gamma$, WW^*, ZZ^*, γZ, $\tau^+\tau^-$, b pairs, …

Expectations for *H* production

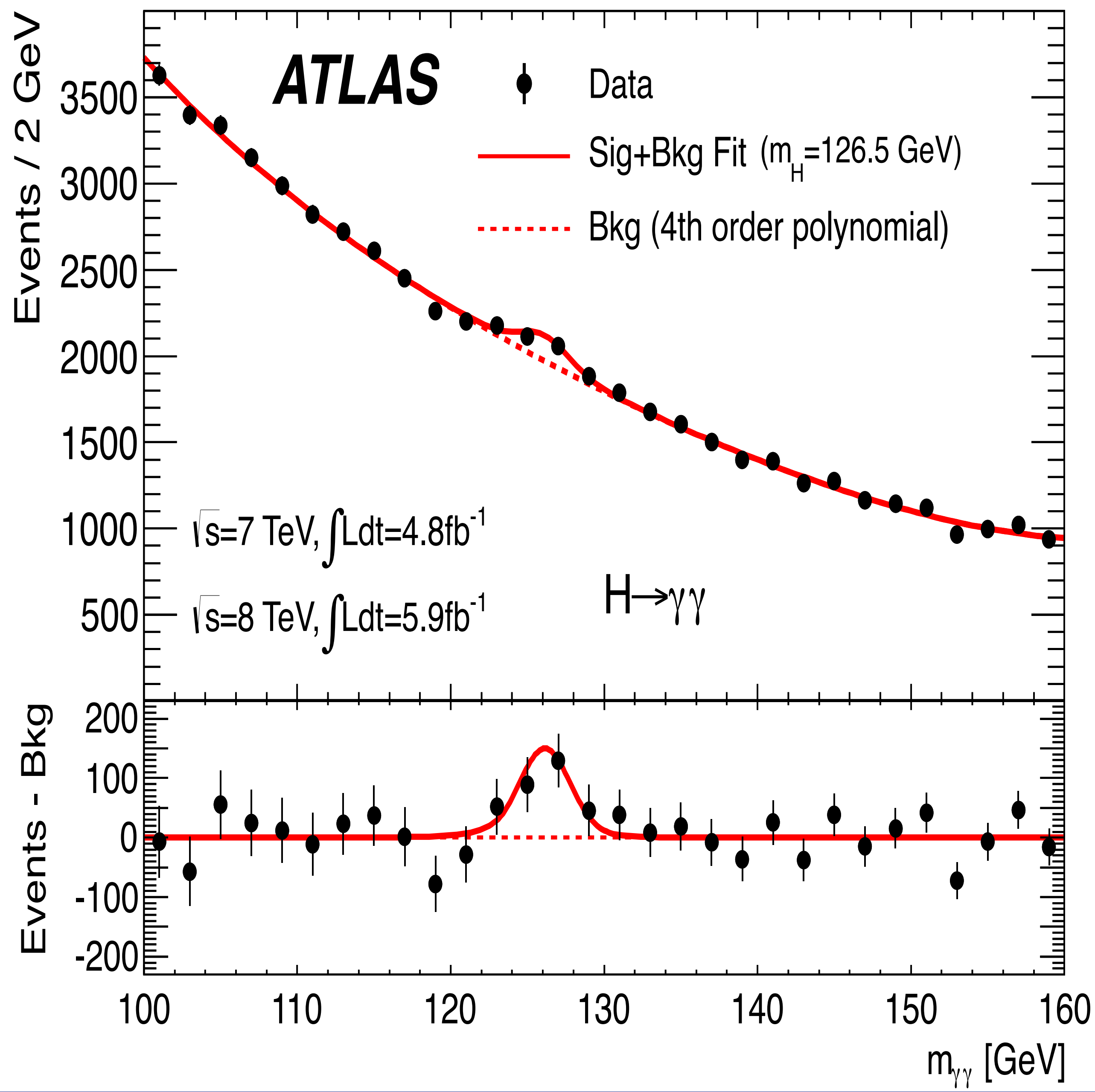


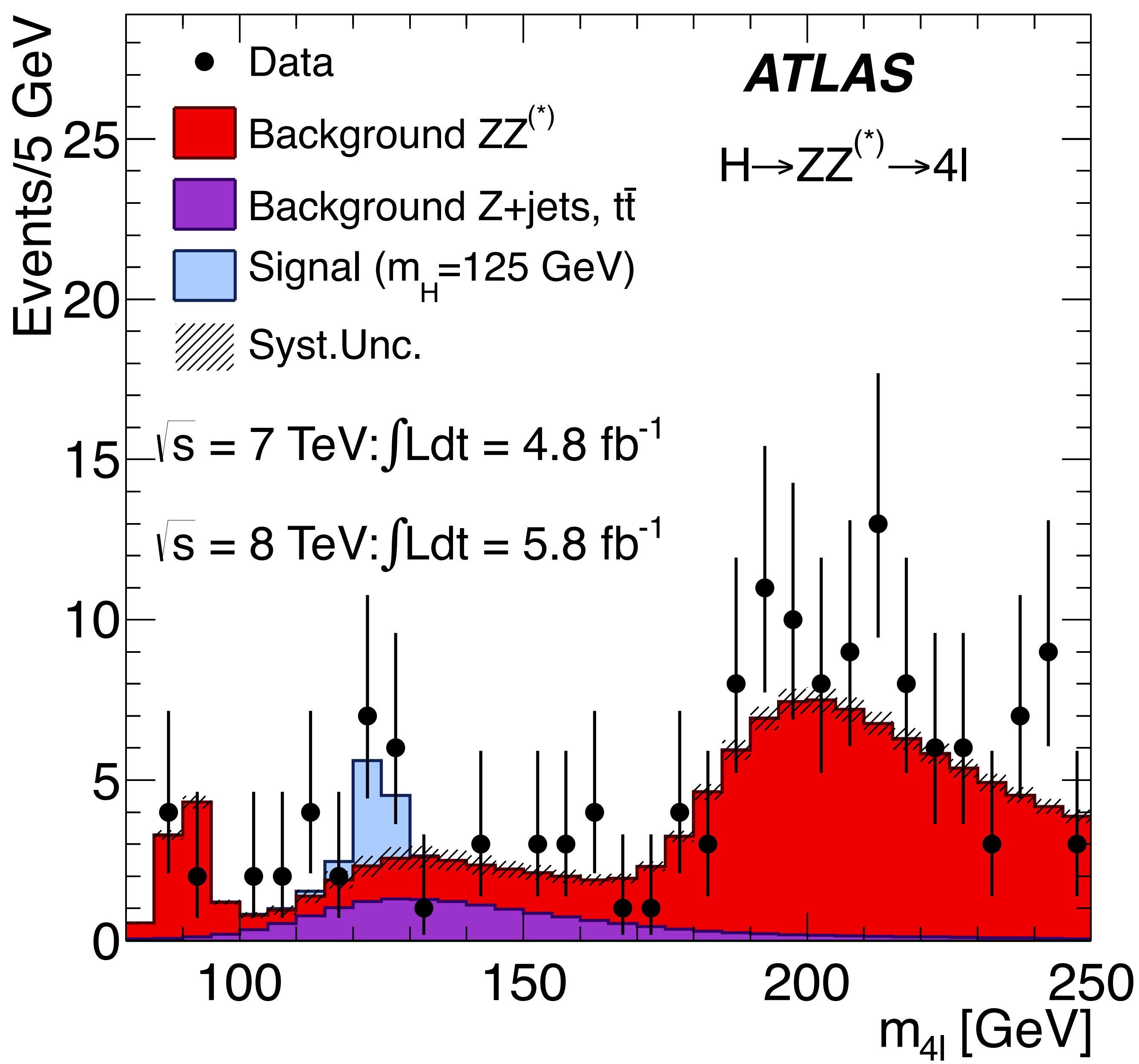
CMS Discovery Plots





ATLAS Discovery Plots





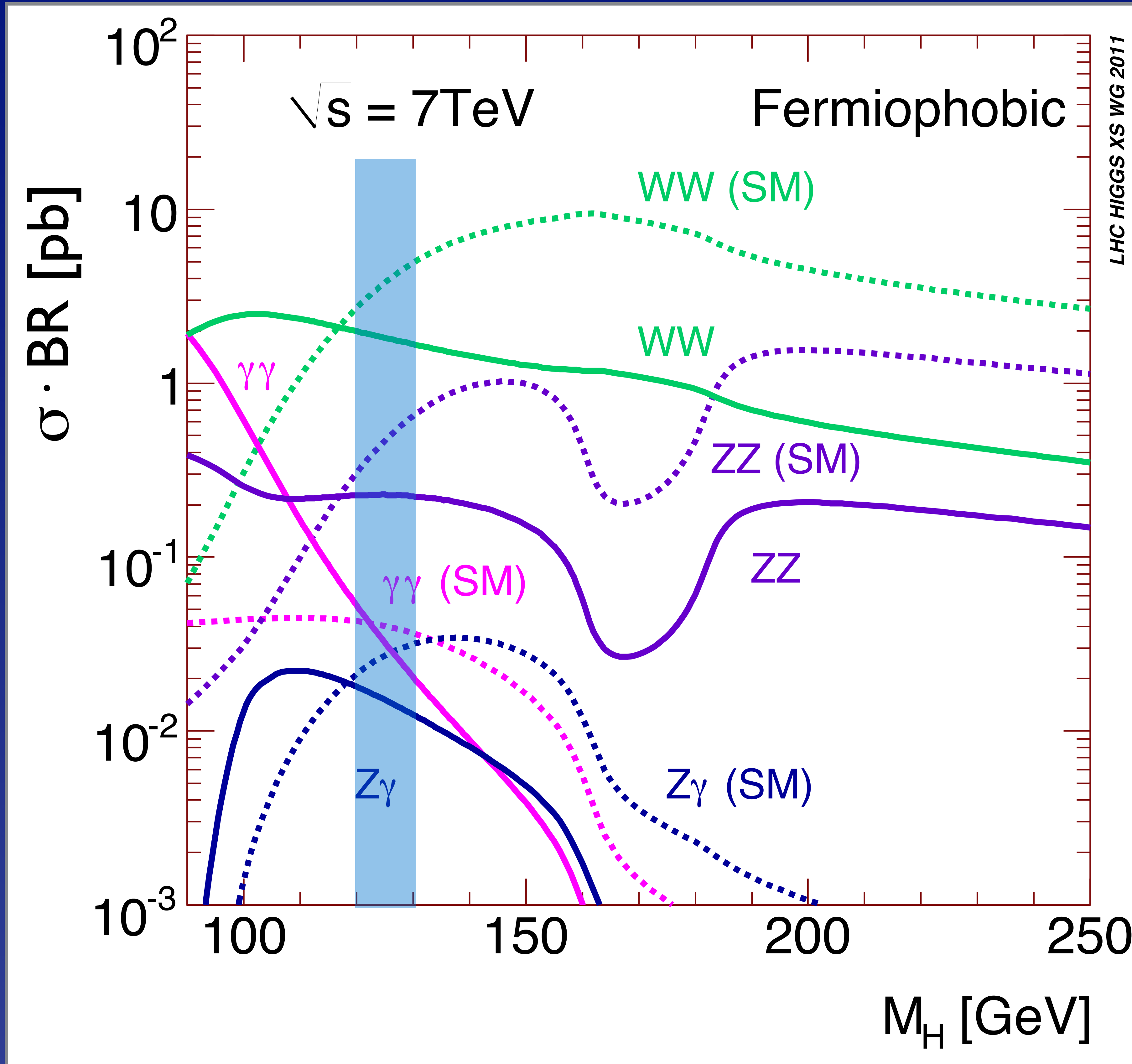
Is it *the* standard-model Higgs boson?

Do not rush ahead of the evidence …

How well must we know its properties?

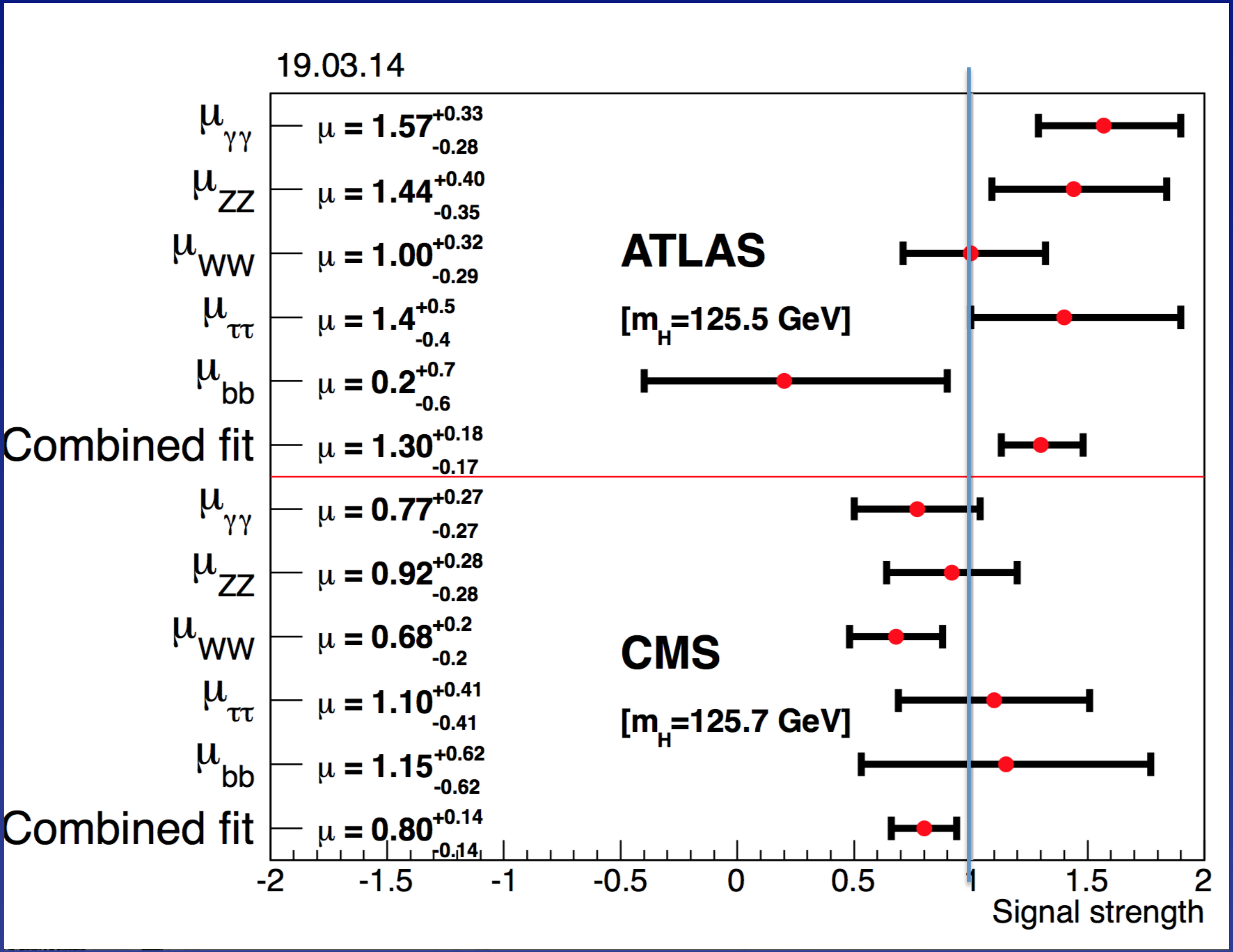
What can we learn?

European Strategy Update · Snowmass 2013



$\sqrt{s}$ = 7TeV
Fermiophobic
LHC HIGGS XS WG 2011
WW (SM)
WW
γγ
ZZ (SM)
ZZ
γγ (SM)
Zγ
Zγ (SM)
σ · BR [pb]
M_H [GeV]
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
100
150
200
250

ATLAS **Signal / Standard Model** CMS



Eilam Gross, Moriond 2014

Fully accounts for EWSB (W, Z couplings)?

Couples to fermions?

Top from production,

direct observation for b, τ

Only 3rd gen. so far

Accounts for fermion masses?

Fermion couplings ∝ masses?

Are there others?

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

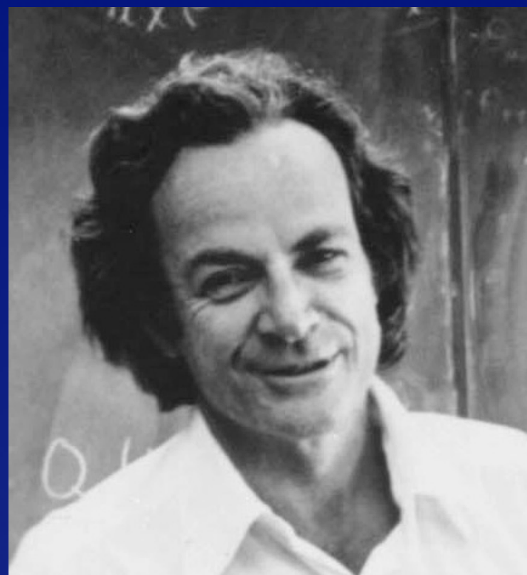
SM branching fractions to gauge bosons?

Decays to new particles?

All production modes as expected?

Implications of $M_H \approx 126$ GeV?

Any sign of new strong dynamics?



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 SSB

What does the muon weigh?

ζ_e : picked to give right mass, not predicted

fermion mass implies physics beyond the standard model

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

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

Wrinkle: 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

How demonstrate origin of m_e?

We live in a metaphorical superconductor

We have found a new space-filling stuff

The Higgs boson is an excitation of the field

Does the stuff weigh too much?

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

An elementary scalar is a *new phenomenon* that poses questions of naturalness and consistency.

EWSB provides a laboratory for unified theories and for other phase transitions in the early universe.

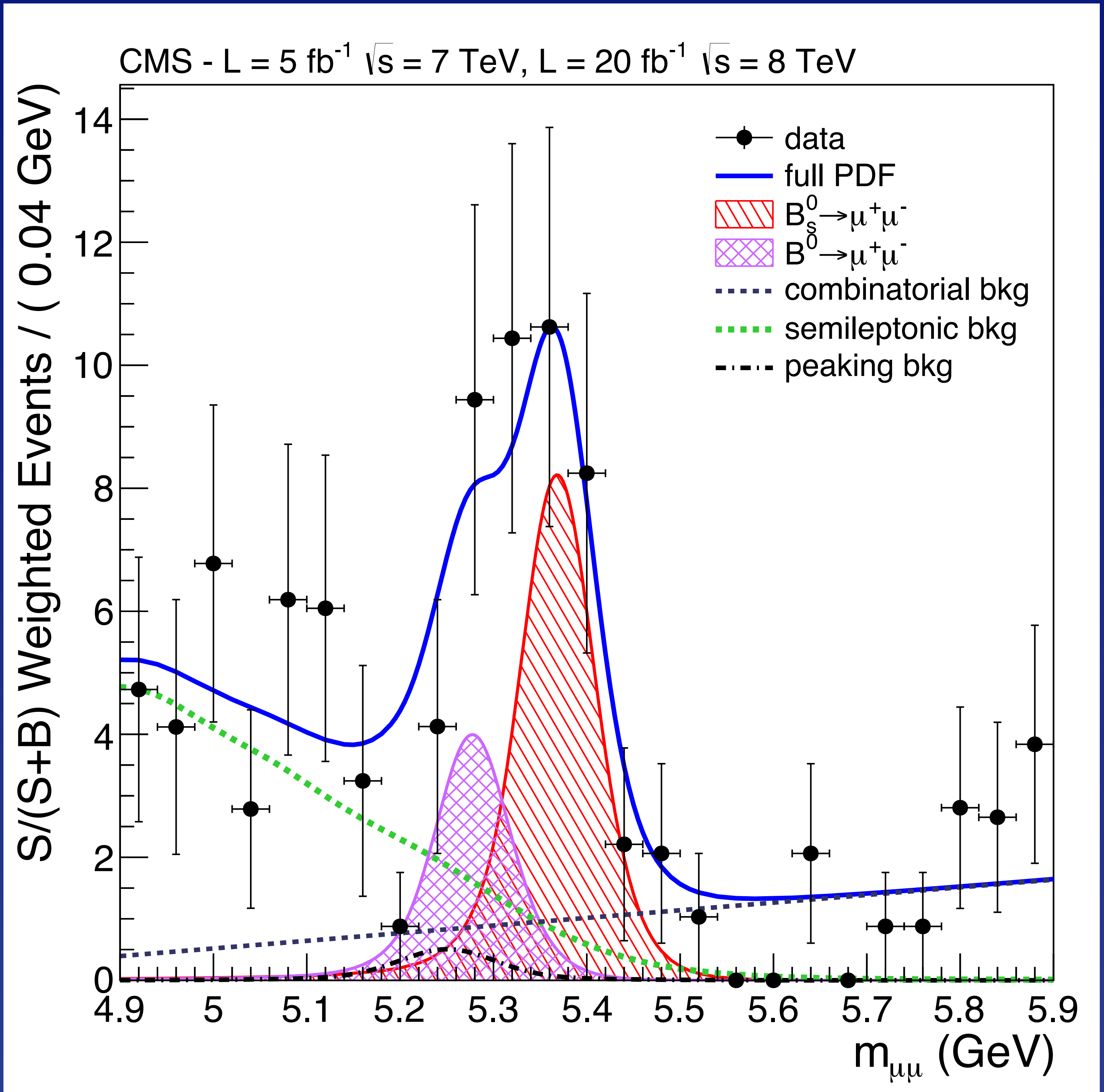
The challenge of vacuum stability; how does M_H arise?

Puzzle #1: Expect New Physics on TeV scale
to stabilize Higgs mass, solve hierarchy problem,
but no quantitative failures of EW theory

Puzzle #2: Expect New Physics on TeV scale
to stabilize Higgs mass, solve hierarchy problem,
but no sign of flavor-changing neutral currents
Minimal flavor violation a name, not yet an answer

Great interest in searches for
forbidden or suppressed processes

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



$\approx$ SM rate

LHCb+ CMS: $BR(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$

Electric dipole moment d_e

$d_e < 8.7 \times 10^{-29}$ e · cm

ACME Collaboration, ThO

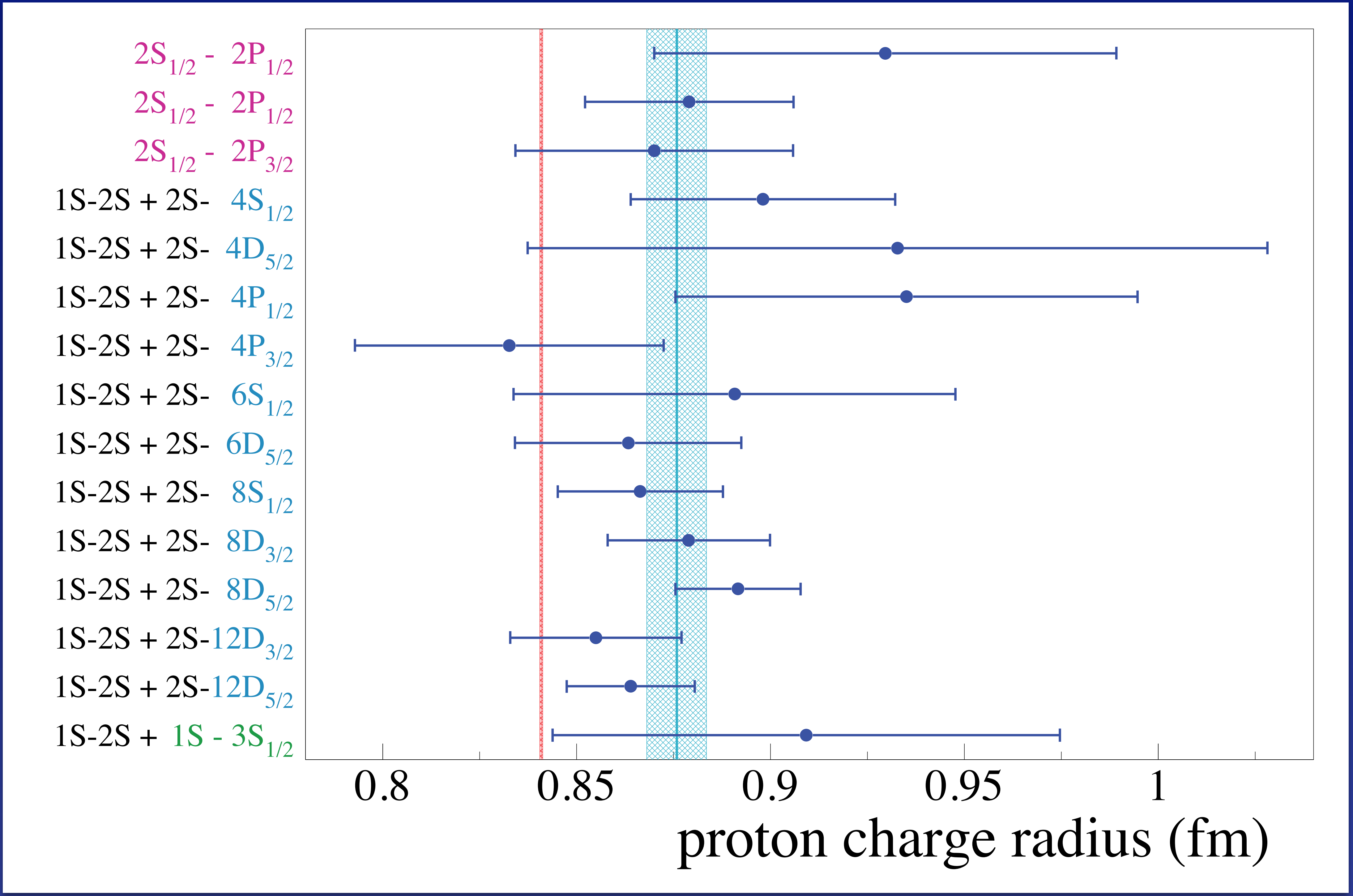
(SM phases: $d_e < 10^{-38}$ e · cm)

The unreasonable effectiveness of the standard model

… but a few clouds (opportunities?)

arXiv:0907.3187

Proton radius puzzle: μ vs *e*



μ: 0.84086±0.00039 fm; e: 0.8758±0.0077 fm

Lepton Anomalous Magnetic Moments

$a_e(\mathrm{QED}) = 1.159\,652\,181\,78\,(77) \times 10^{-3}$

$\underline{a_e(\mathrm{EXP}) = 1.159\,652\,180\,73\,(28) \times 10^{-3}}$

1 05 (82)

$$\delta a_\ell \propto \frac{\alpha}{\pi}\frac{m_\ell^2}{\Lambda^2}$$

$a_\mu(\mathrm{SM}) = 1.165\,918\,02\,(42)\,(26) \times 10^{-3}$

$\underline{a_\mu(\mathrm{EXP}) = 1.165\,920\,89\,(54)\,(33) \times 10^{-3}}$

-2 87 (63) (47)

Standard model omits

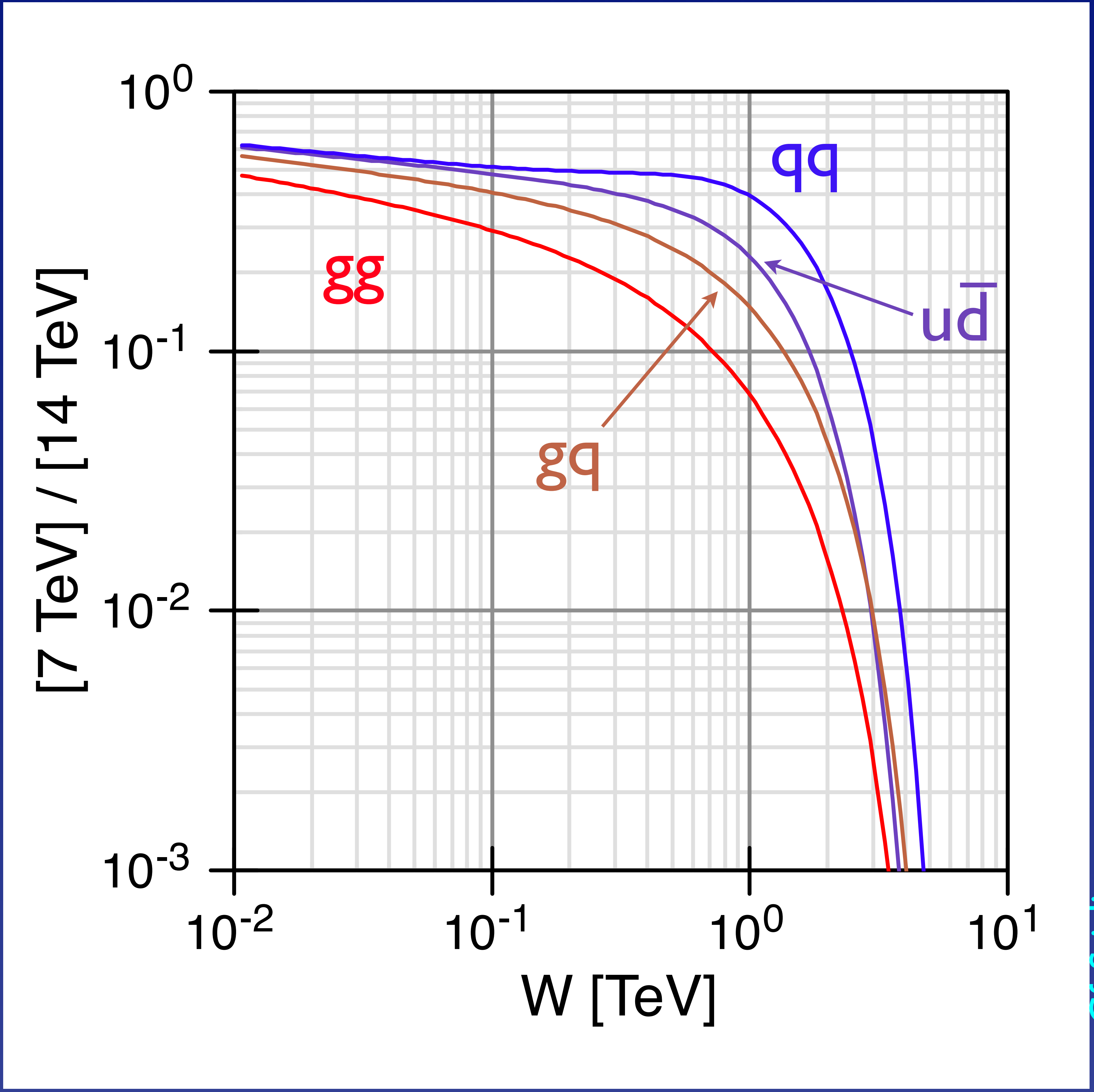
neutrino properties

dark matter

dark energy

baryon asymmetry

LHC Run 2: *Ratios of Parton Luminosities*



Cf. Stirling

Thinking about new machines

International Linear Collider

Circular e^+e^- Higgs Factories

Muon Collider for *H* formation

$\gamma\gamma$ Collider

CLIC (multi-TeV e^+e^-)

Multi-TeV Muon Collider

"100-TeV" VLHC

ep / *eA* Collider

not to neglect

Neutrino Factory

Intense Proton Source …

Important measurements at any moment depend on what is already known

SM-like or very nonstandard

Discovery of another "Higgs-like object"

Direct evidence for or against new degrees of freedom

13-14 TeV LHC will be very telling

Requirements for a shopper's guide

Clearly stated assumptions

Documented uncertainty estimates

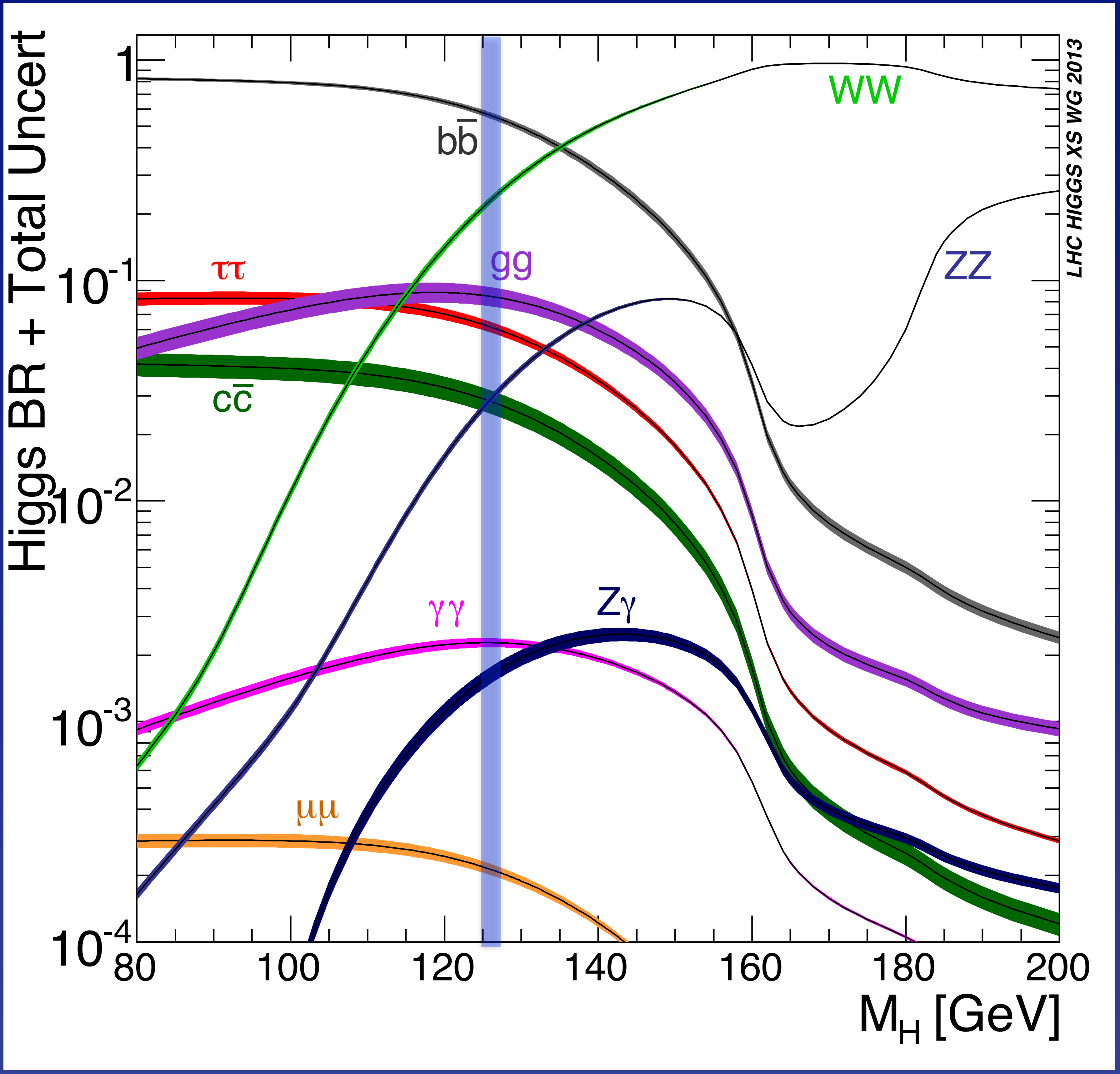
Rich list of observables, including
$\Gamma(\mu\mu)$, M_H, ΔM_H, $\Delta\Gamma_H$, …

Rich list of possible machines

A time dimension (linear scale)

Needs & prospects for theory & parameter improvements

Uncertainties in SM predictions



Uncertainties in SM predictions

	Γ(MeV)	$\Delta\alpha_s$	Δm_b	Δm_c	Theory
$H \rightarrow bb$	2.36	-2.3%	+3.3%	0	+2%
		+2.3%	-3.2%	0	-2%
$H \rightarrow \tau\tau$	.259	0	0	0	+2%
		0	0	0	-2%
$H \rightarrow W^+W^-$	.973	0	0	0	+.5%
		0	0	0	-.5%

LHC Higgs Cross Section WG via S. Dawson

Parametric, theory uncertainties comparable

Improve m_b, α_s

Include two-loop electroweak corrections

Also: improve parton distribution functions

Important not to narrow the physics vision
by pretending we know the answer—or the question!

Couplings

Distributions

Mass / width

Searches in the Higgs sector

Searches beyond the Higgs sector

Other parameters: M_W, m_t

Back to Z^0?

How can precise measurements of Higgs couplings lead us to infer new physics?

We don’t (yet) see how such evidence for new physics can tell us what the new physics is, or on what energy scale it lies. (No standard BSM)

With or without a pointer, high-energy colliders search for new particles and can advance the study of Higgs self-couplings.

Planning can’t neglect opportunities in flavor physics, neutrinos, …

Issues for the Future *(Starting now!)*

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

Issues for the Future (Now!)

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

Issues for the Future (Now!)

11. What are the dark matters? Any flavor structure?

12. 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?

13. Is EWSB related to gravity through extra spacetime dimensions?

14. What resolves the vacuum energy problem?

15. (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!)

16. What explains the baryon asymmetry of the universe? Are there new (CC) CP-violating phases?
17. Are there new flavor-preserving phases? What would observation, or more stringent limits, on electric-dipole moments imply for BSM theories?
18. (How) are quark-flavor dynamics and lepton-flavor dynamics related (beyond the gauge interactions)?
19. At what scale are the neutrino masses set? Do they speak to the TeV scale, unification scale, Planck scale, …?

20. How are we prisoners of conventional thinking?