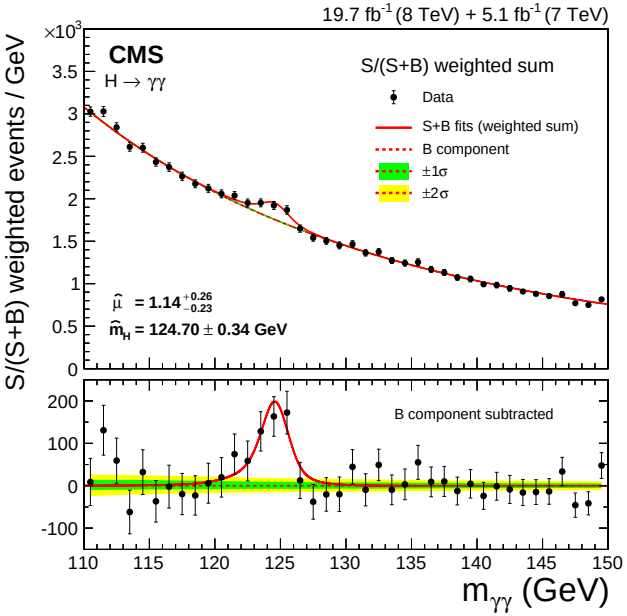
Large Hadron Collider Physics: The Next Generation

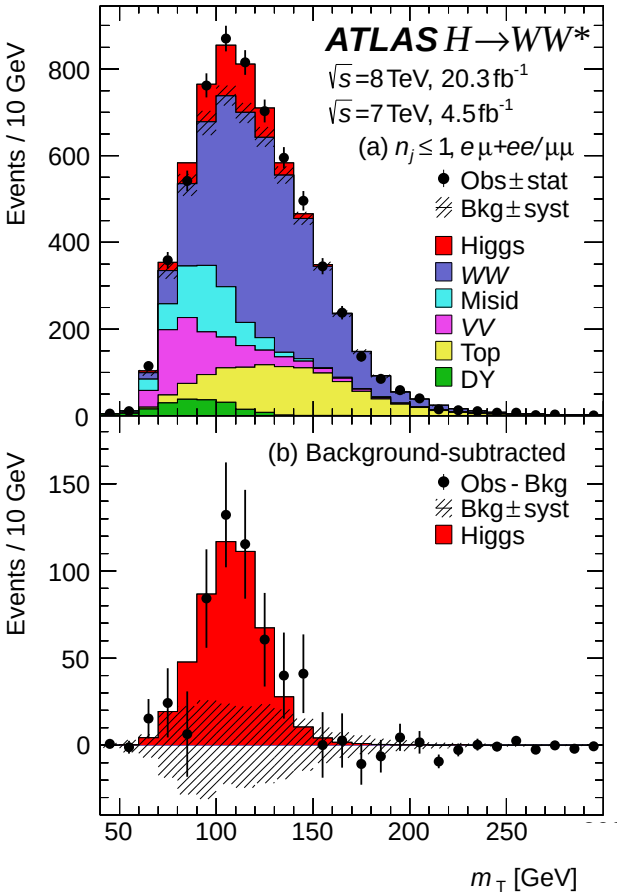
Lecture 3

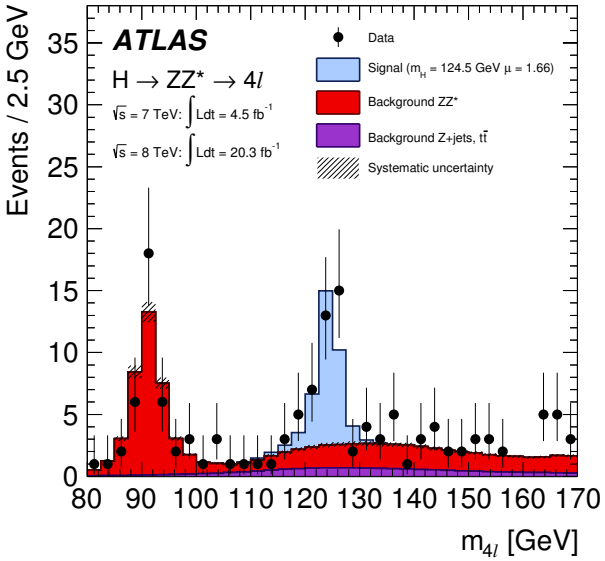
Chris Quigg

Fermilab & LPTENS

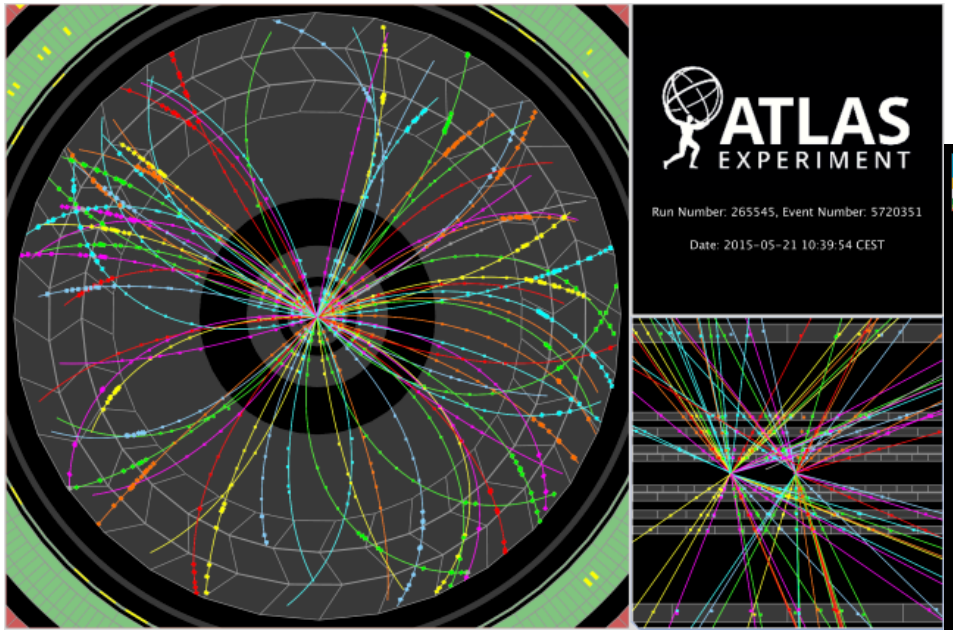
Summary of Higgs discovery modes

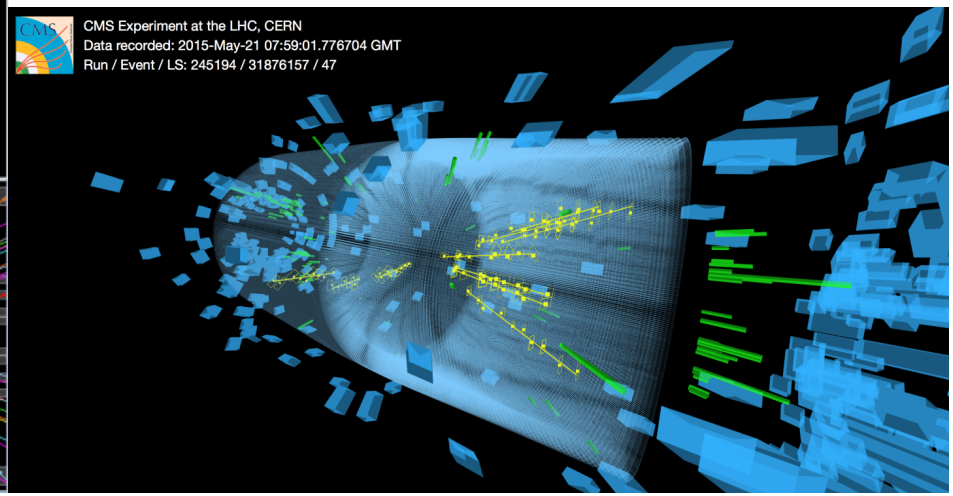


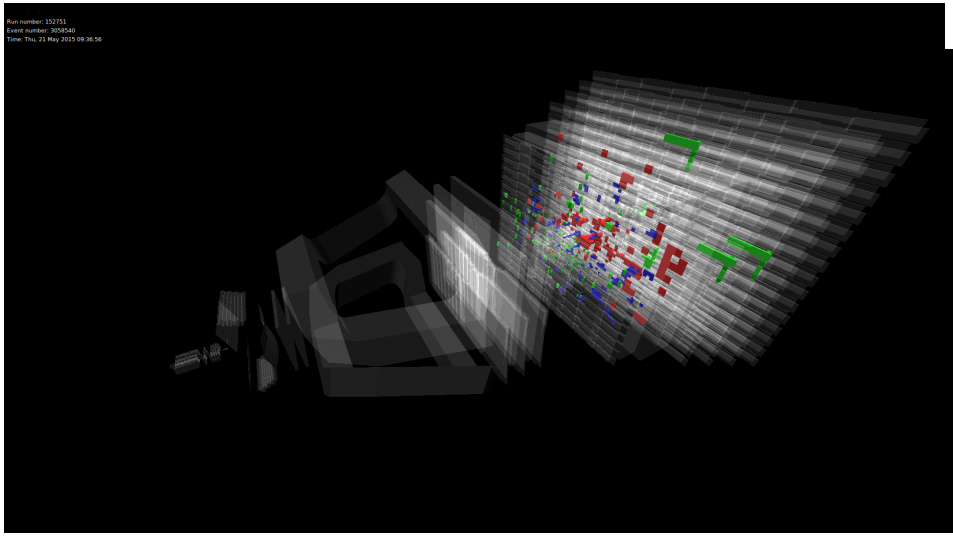


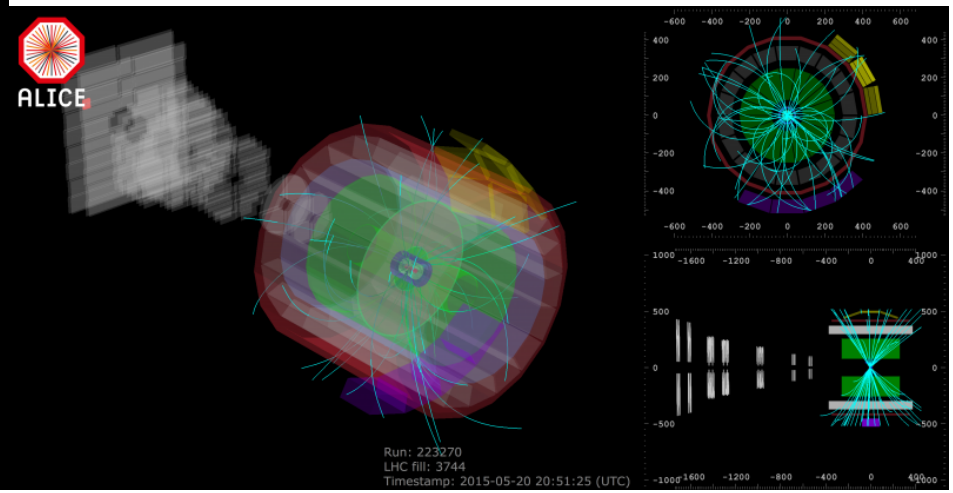


13-TeV Test Collisions (ca. 21.05.2015)









Why Electroweak Symmetry Breaking Matters

What would the world be like, without a (Higgs) mechanism to hide electroweak symmetry and give masses to the quarks and leptons?

(No EWSB agent at $v \approx 246$ GeV)

Consider effects of all SM interactions!

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

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, ...

Modified Standard Model: No Higgs Sector

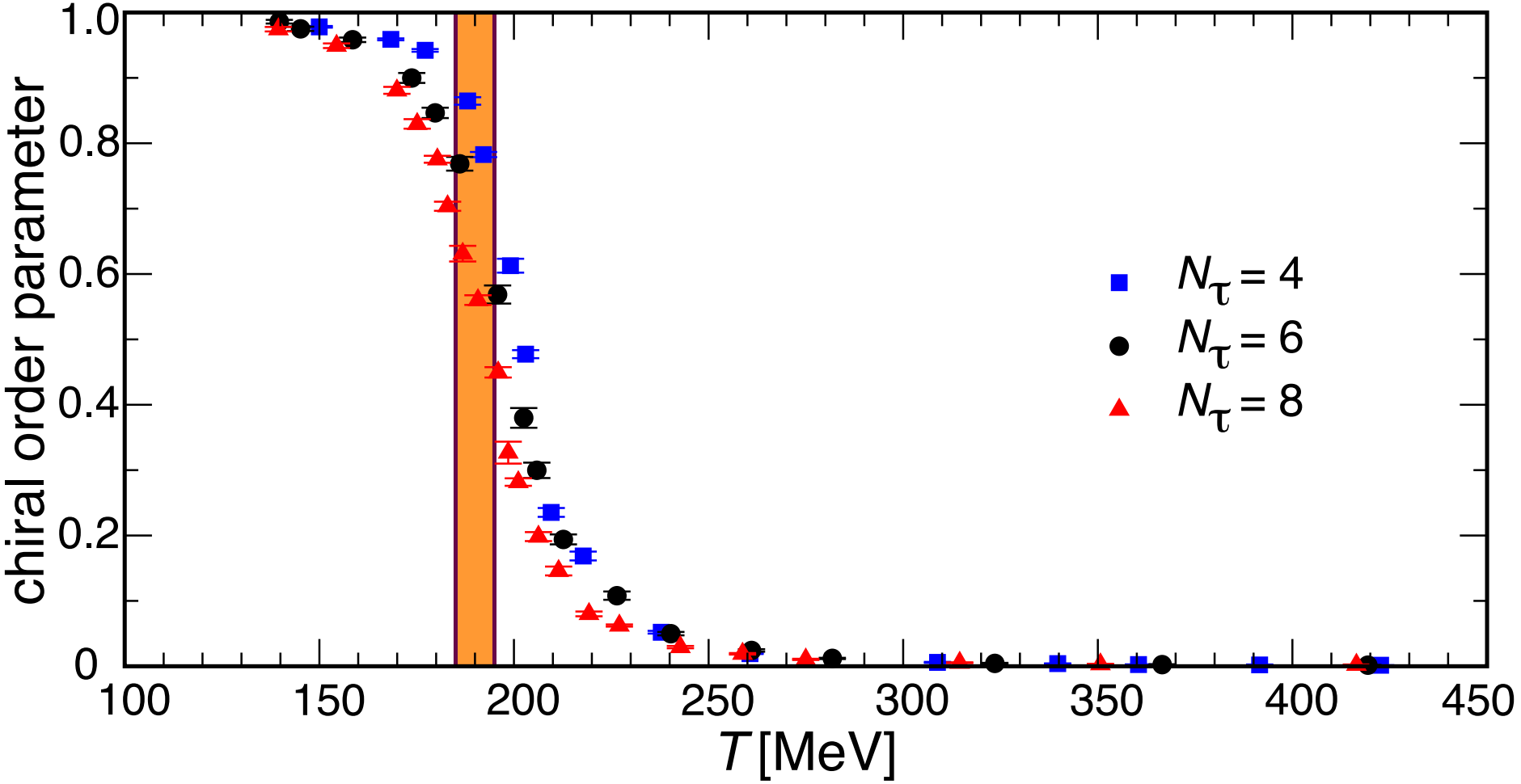
With massless (u, d) quarks,
QCD has exact $\mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{SU}(2)_\mathrm{R}$ chiral symmetry.

At an energy scale $\sim \Lambda_\mathrm{QCD}$, strong interactions become strong, fermion condensates $\langle \bar{q} q \rangle$ appear, and

$$\mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{SU}(2)_\mathrm{R} \to \mathrm{SU}(2)_\mathrm{V}$$

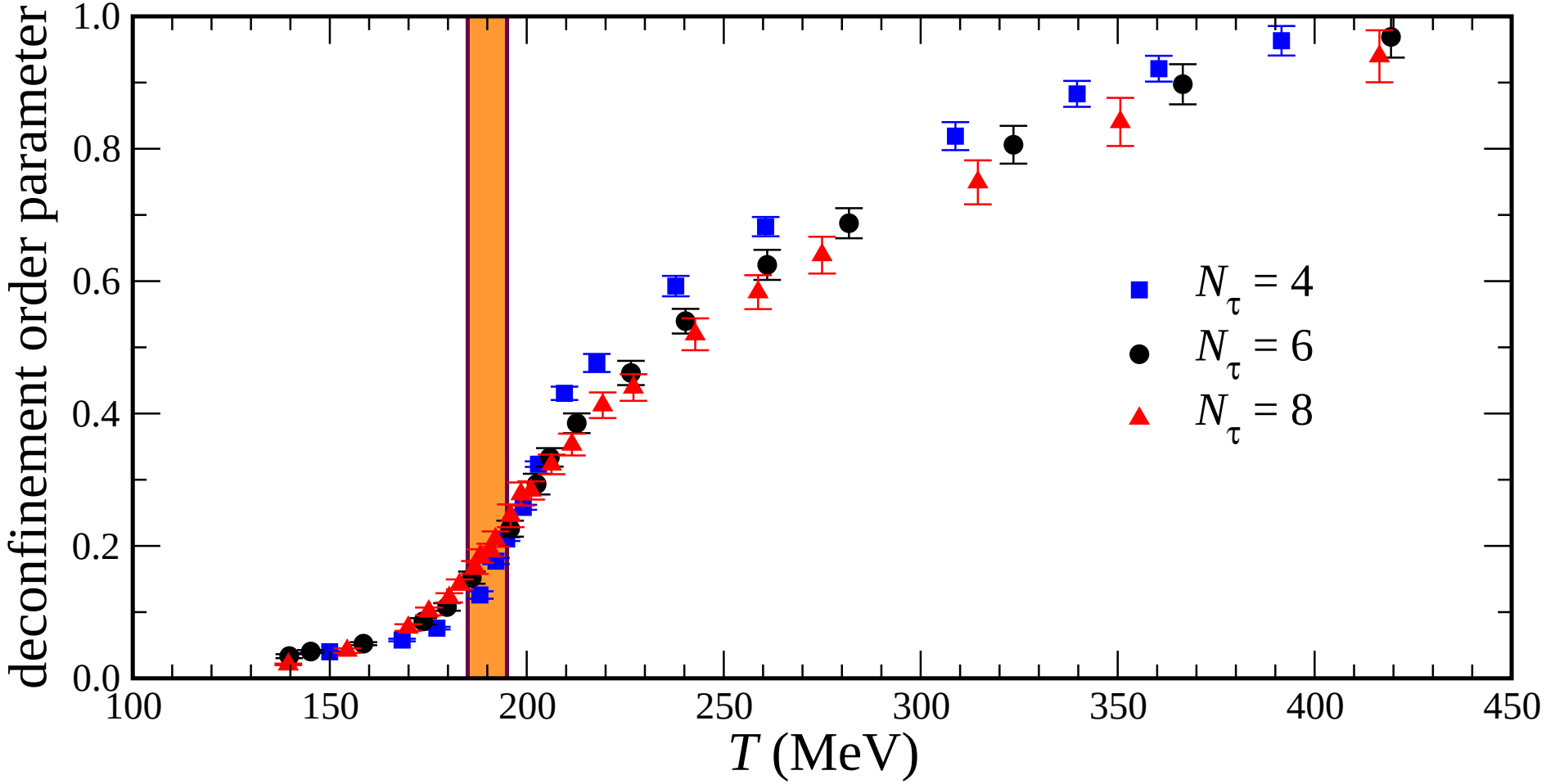
$\rightsquigarrow$ 3 Goldstone bosons, one for each broken generator:
3 massless pions (Nambu)

Chiral Symmetry Breaking on the Lattice



Weise lecture for review and lattice QCD references

Deconfinement on the Lattice



A. Polyakov, *Phys. Lett.* **B72,** 477 (1978)

Fermion condensate . . .

links left-handed, right-handed fermions

$$\langle \bar{q} q \rangle = \langle \bar{q}_{\mathrm{R}} q_{\mathrm{L}} + \bar{q}_{\mathrm{L}} q_{\mathrm{R}} \rangle$$

$$1 = \tfrac{1}{2}(1 + \gamma_5) + \tfrac{1}{2}(1 - \gamma_5)$$

$$\mathrm{Q}^a_{\mathrm{L}} = \begin{pmatrix} u^a \\ d^a \end{pmatrix}_{\mathrm{L}} \qquad u^a_{\mathrm{R}} \quad d^a_{\mathrm{R}}$$

$$(\mathrm{SU}(3)_{\mathrm{c}}, \mathrm{SU}(2)_{\mathrm{L}})_Y\colon\ (\mathbf{3}, \mathbf{2})_{1/3} \qquad (\mathbf{3}, \mathbf{1})_{4/3} \quad (\mathbf{3}, \mathbf{1})_{-2/3}$$

transforms as $\mathrm{SU}(2)_{\mathrm{L}}$ doublet with $|Y| = 1$

Induced breaking of $\mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{U}(1)_Y \to \mathrm{U}(1)_\mathrm{em}$

Broken generators: 3 axial currents; couplings to π: $\bar{f}_\pi$

Turn on $\mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{U}(1)_Y$*:*

Weak bosons couple to axial currents, acquire mass $\sim g\bar{f}_\pi$

$$g \approx 0.65,\ g' \approx 0.34,\ f_\pi = 92.4\ \mathrm{MeV} \rightsquigarrow \bar{f}_\pi \approx 87\ \mathrm{MeV}$$

$$\mathcal{M}^2 = \begin{pmatrix} g^2 & 0 & 0 & 0 \\ 0 & g^2 & 0 & 0 \\ 0 & 0 & g^2 & gg' \\ 0 & 0 & gg' & g'^2 \end{pmatrix} \frac{\bar{f}_\pi^2}{4} \qquad (w_1, w_2, w_3, \mathcal{A})$$

same structure as standard EW theory

Induced breaking of $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$

Diagonalize:

$$\begin{aligned} \overline{M}_W^2 &= g^2 \bar{f}_\pi^2/4 \\ \overline{M}_Z^2 &= (g^2 + g'^2)\bar{f}_\pi^2/4 \\ \overline{M}_A^2 &= 0 \end{aligned}$$

$$\overline{M}_Z^2/\overline{M}_W^2 = (g^2 + g'^2)/g^2 = 1/\cos^2\theta_W$$

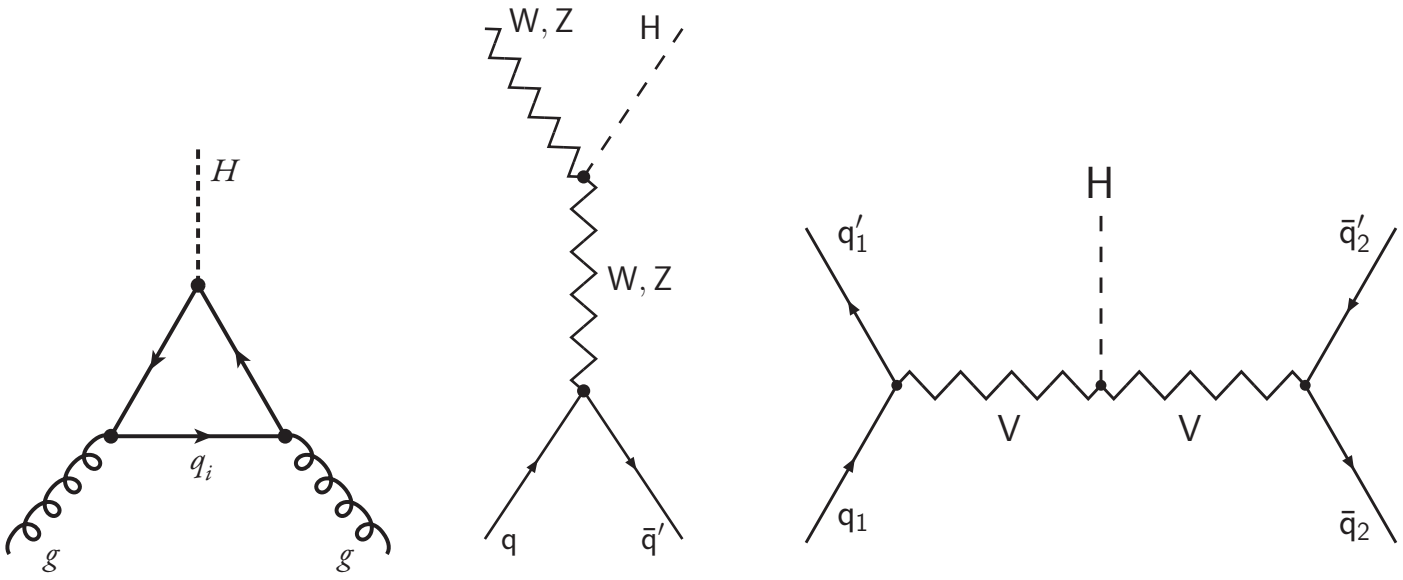
NGBs become longitudinal components of weak bosons.

$$\boxed{\overline{M}_W \approx 28 \text{ MeV} \qquad \overline{M}_Z \approx 32 \text{ MeV}}$$

$$(M_W \approx 80 \text{ GeV} \qquad M_Z \approx 91 \text{ GeV})$$

LHC: Multiple looks at the new boson

Now: 3 production mechanisms, $\geq$ 5 decay modes



$\gamma\gamma, WW^*, ZZ^*, b\bar{b}, \tau^+\tau^-, Z\gamma(?)$

Higgs-Boson Questions for ATLAS and CMS

Fully accounts for EWSB (W, Z couplings)?

SM branching fractions to gauge bosons?

Are there others? Charged partners?

Couples to fermions?

Top from production, direct evidence for $b\bar{b}, \tau^+\tau^-$

Accounts for fermion masses? Yukawas $\propto$ masses?

Couples beyond third generation? $\mu^+\mu^-$ next?

Quantum numbers? $J^{PC} = 0^{++}$; admixtures?

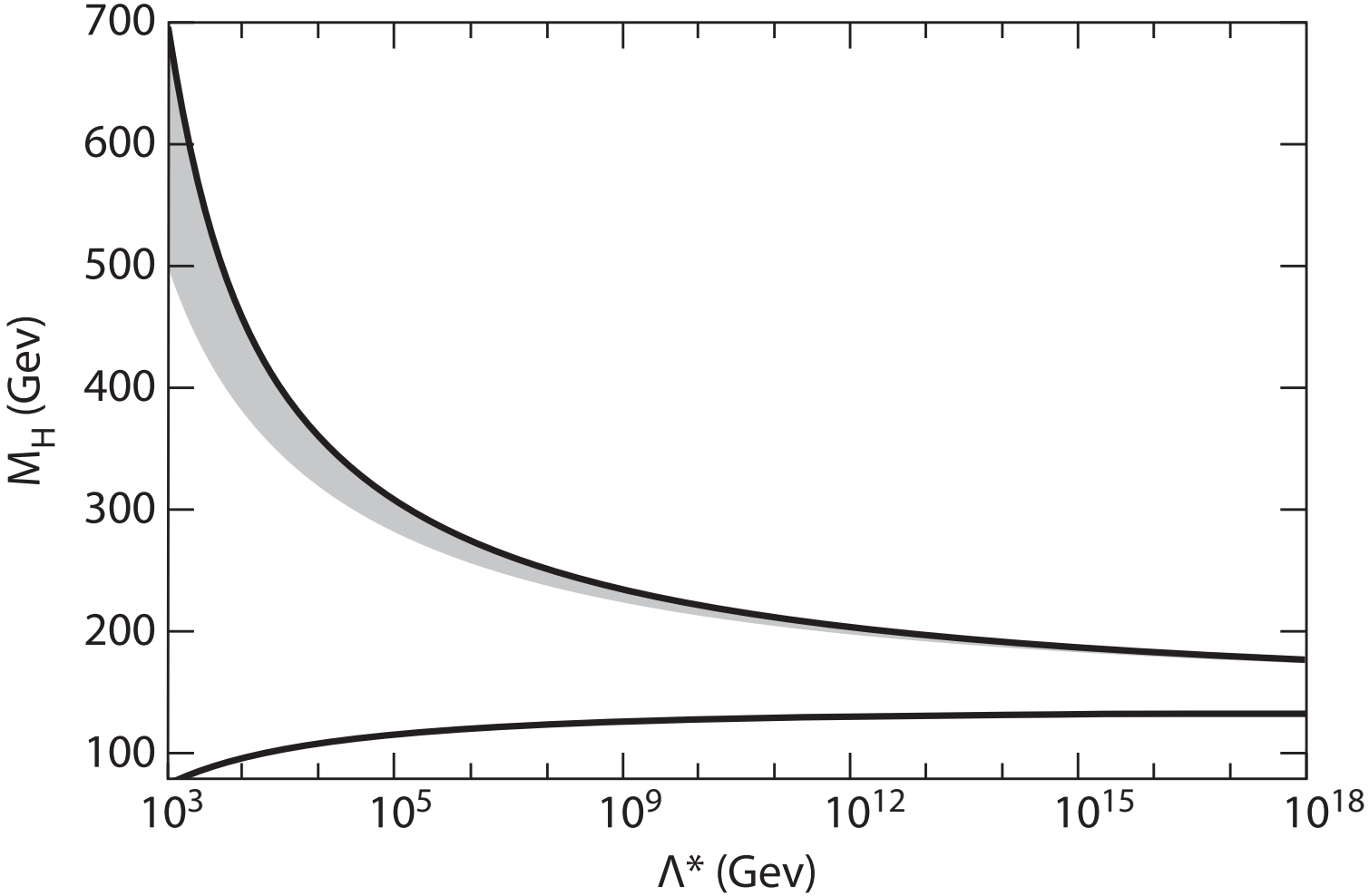
All production modes as expected? $Ht\bar{t}$ next?

Implications of $M_H \approx 125$ GeV?

Any sign of new strong dynamics?

Decays to new particles? via new forces?

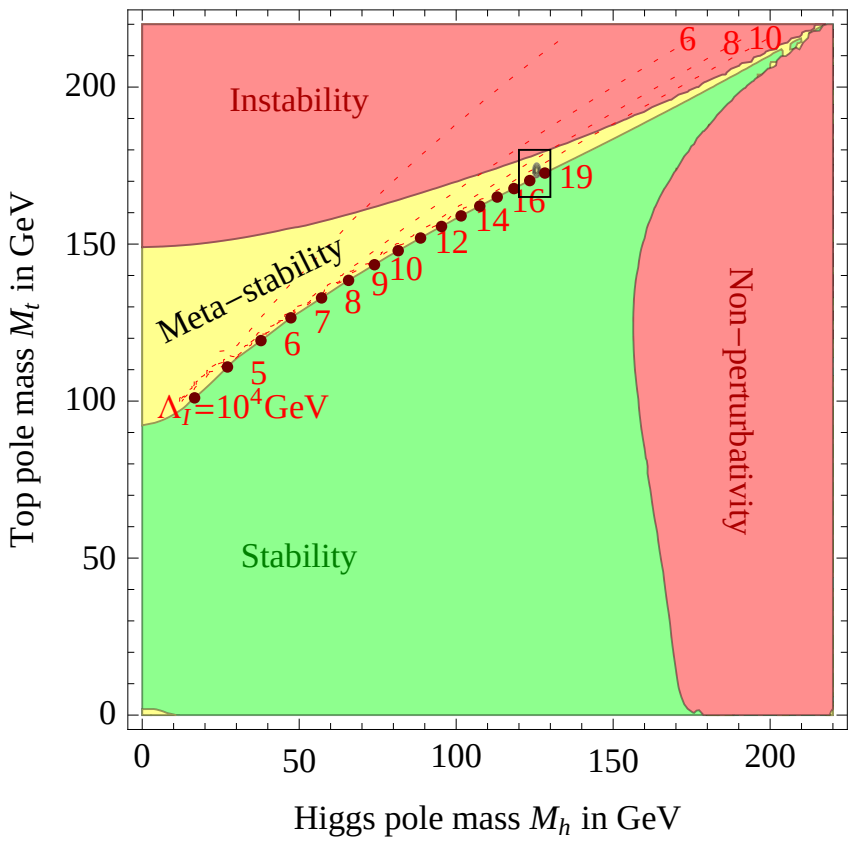
Could the electroweak theory hold up to M_{Planck}?

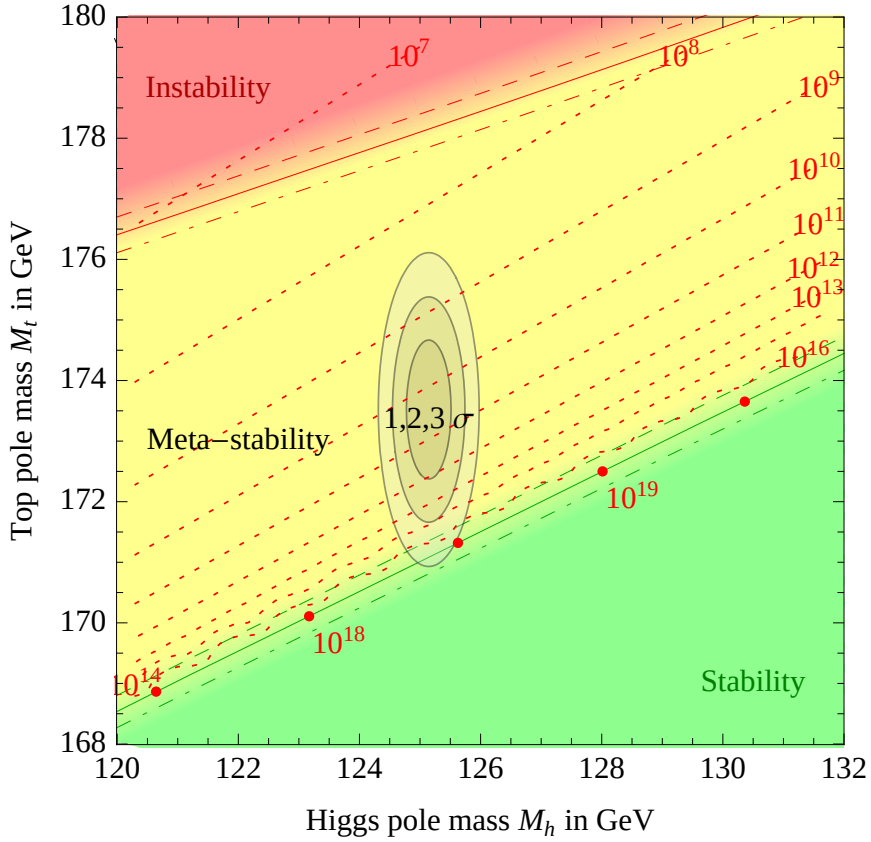


Would require 134 GeV $\lesssim M_H \lesssim$ 177 GeV

Living on Borrowed Time?

In standard EW theory, we may live in a false vacuum in which both M_H and m_t have near-critical values



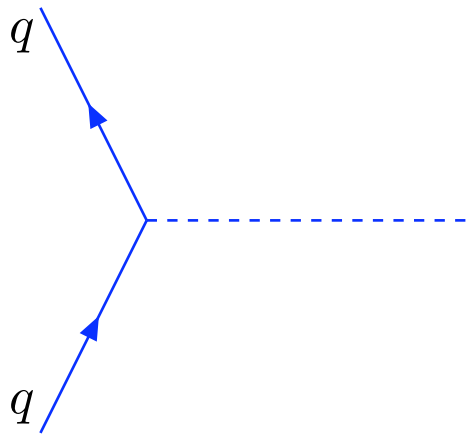


Why is empty space so nearly massless?

Natural to neglect gravity in particle physics . . .

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

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



$$G \qquad \sim \frac{E}{M_{\text{Planck}}}$$

300 years after Newton: Why is gravity weak?

But gravity is not always negligible . . .

The vacuum energy problem

$$\text{Higgs potential } V(\varphi^\dagger\varphi) = \mu^2(\varphi^\dagger\varphi) + |\lambda|\,(\varphi^\dagger\varphi)^2$$

At the minimum,

$$V(\langle\varphi^\dagger\varphi\rangle_0) = \frac{\mu^2 v^2}{4} = -\frac{|\lambda|\,v^4}{4} < 0.$$

$$\text{Identify } M_H^2 = -2\mu^2$$

$V \neq 0$ contributes position-independent vacuum energy density

$$\boxed{\varrho_H \equiv \frac{M_H^2 v^2}{8} \approx 1.2 \times 10^8 \text{ GeV}^4} \quad \approx 10^{24} \text{ g cm}^{-3}$$

$$\varrho_{\text{critical}} = \frac{3H^2}{8\pi G_{\text{N}}} \approx 10^{-29} \text{ g cm}^{-3}$$

Standard-model shortcomings

- No explanation of Higgs potential
- No prediction for M_H
- Doesn't predict fermion masses & mixings
- M_H unstable to quantum corrections
- No explanation of charge quantization
- Doesn't account for three generations
- Vacuum energy problem
- Beyond scope: dark matter, matter asymmetry, etc.

$\rightsquigarrow$ imagine more complete, predictive extensions

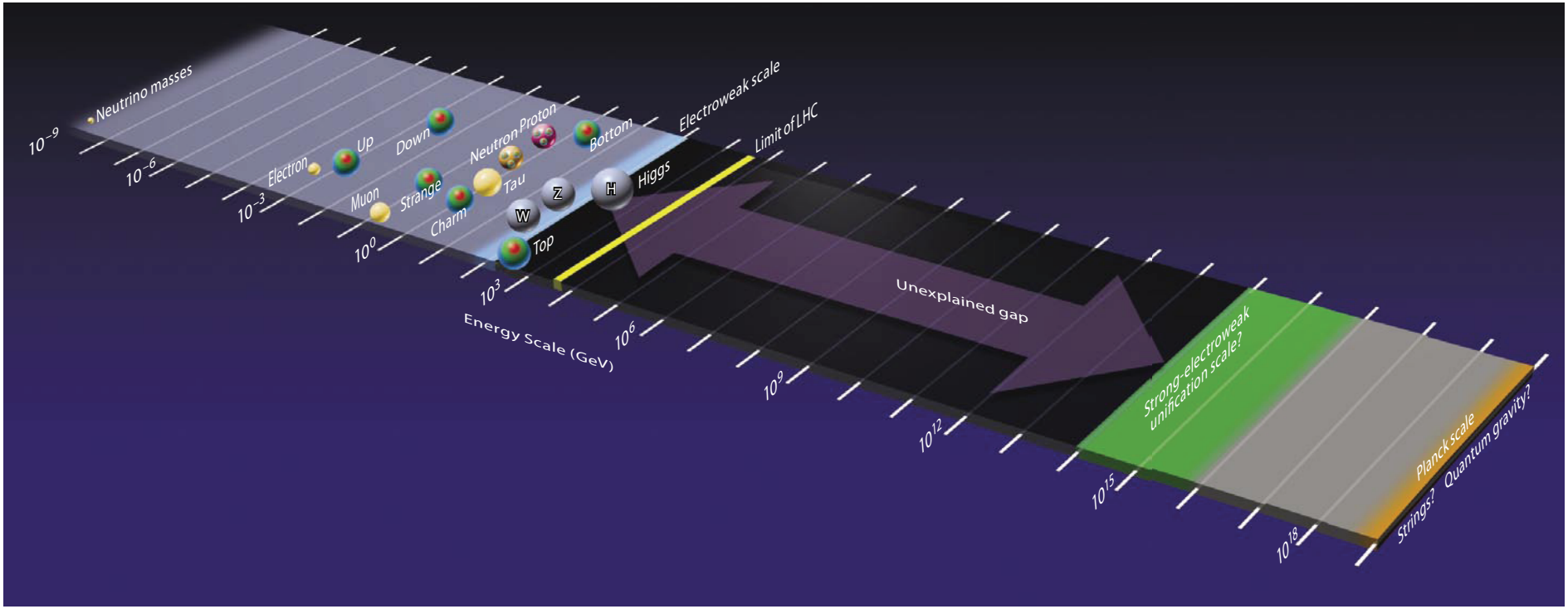
Beyond the Standard Model
More physics on the TeV scale?

Partial-wave unitarity analysis of WW scattering argues for new physics on the TeV scale.
In SM: a Higgs boson or strongly interacting gauge sector
In general, something new on the TeV scale

At the level of suggestion, rather than theorem ...

- The hierarchy problem: if light H, new physics implicated on the TeV scale
- WIMPs as dark matter: reproduce relic density for masses $0.1-1$ TeV

The Hierarchy Problem



How to keep the distant scales from mixing in the face of quantum corrections? *OR*

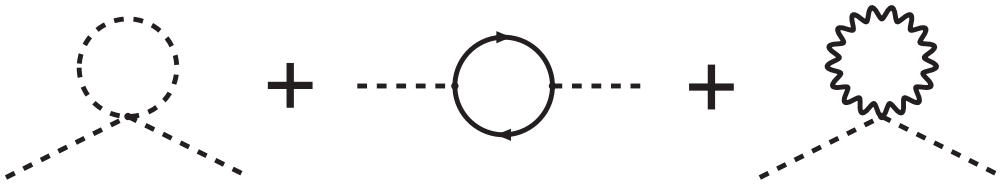
How to stabilize the mass of the Higgs boson on the electroweak scale? *OR*

Why is the electroweak scale small?

The Hierarchy Problem

Evolution of the Higgs-boson mass

$$M_H^2(p^2) = M_H^2(\Lambda^2) +$$



quantum corrections from particles with $J = 0, \frac{1}{2}, 1$

Potential divergences:

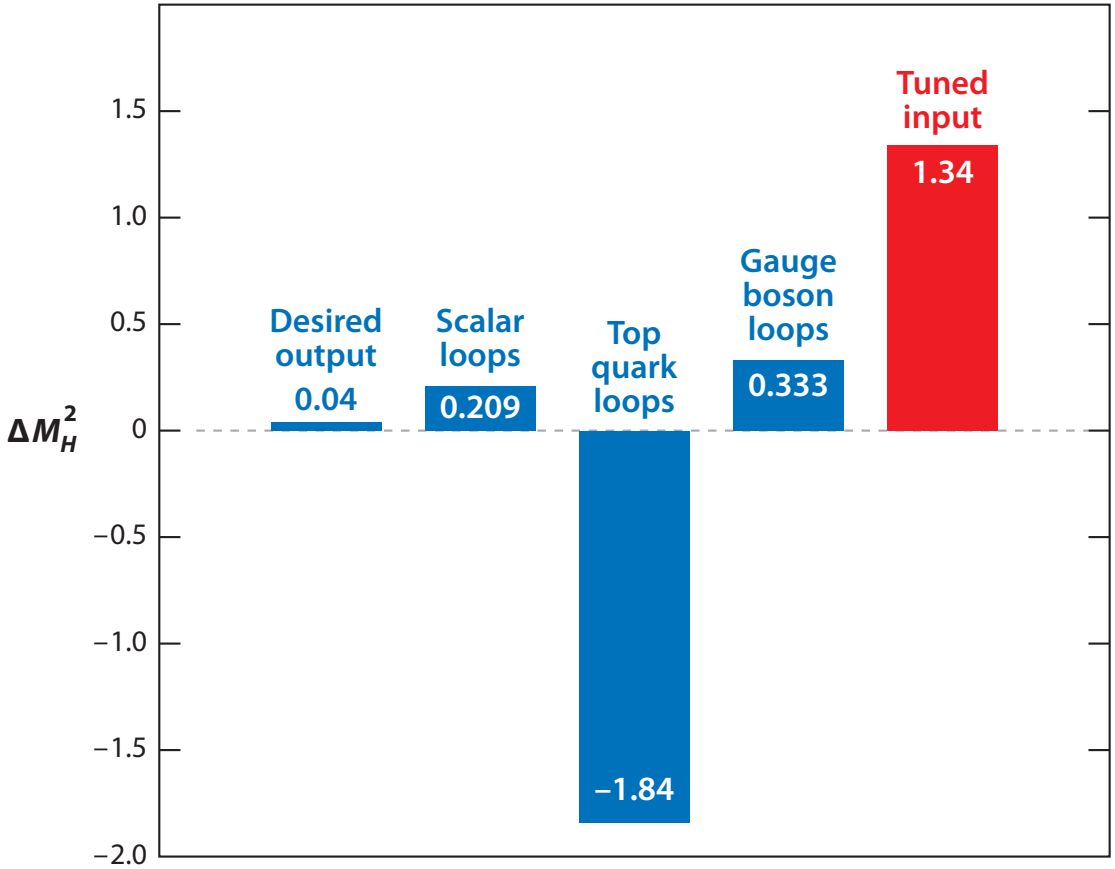
$$M_H^2(p^2) = M_H^2(\Lambda^2) + \mathcal{C} g^2 \int_{p^2}^{\Lambda^2} dk^2 + \cdots \ ,$$

Λ: naturally large, $\sim M_{\text{Planck}}$ or $\sim U \approx 10^{15-16}$ GeV

How to control quantum corrections?

A Delicate Balance . . . even for $\Lambda = 5$ TeV

$$\delta M_H^2 = \frac{G_F \Lambda^2}{4\pi^2\sqrt{2}}(6M_W^2 + 3M_Z^2 + M_H^2 - 12m_t^2)$$



Light Higgs + no new physics: "LEP Paradox"

The Hierarchy Problem

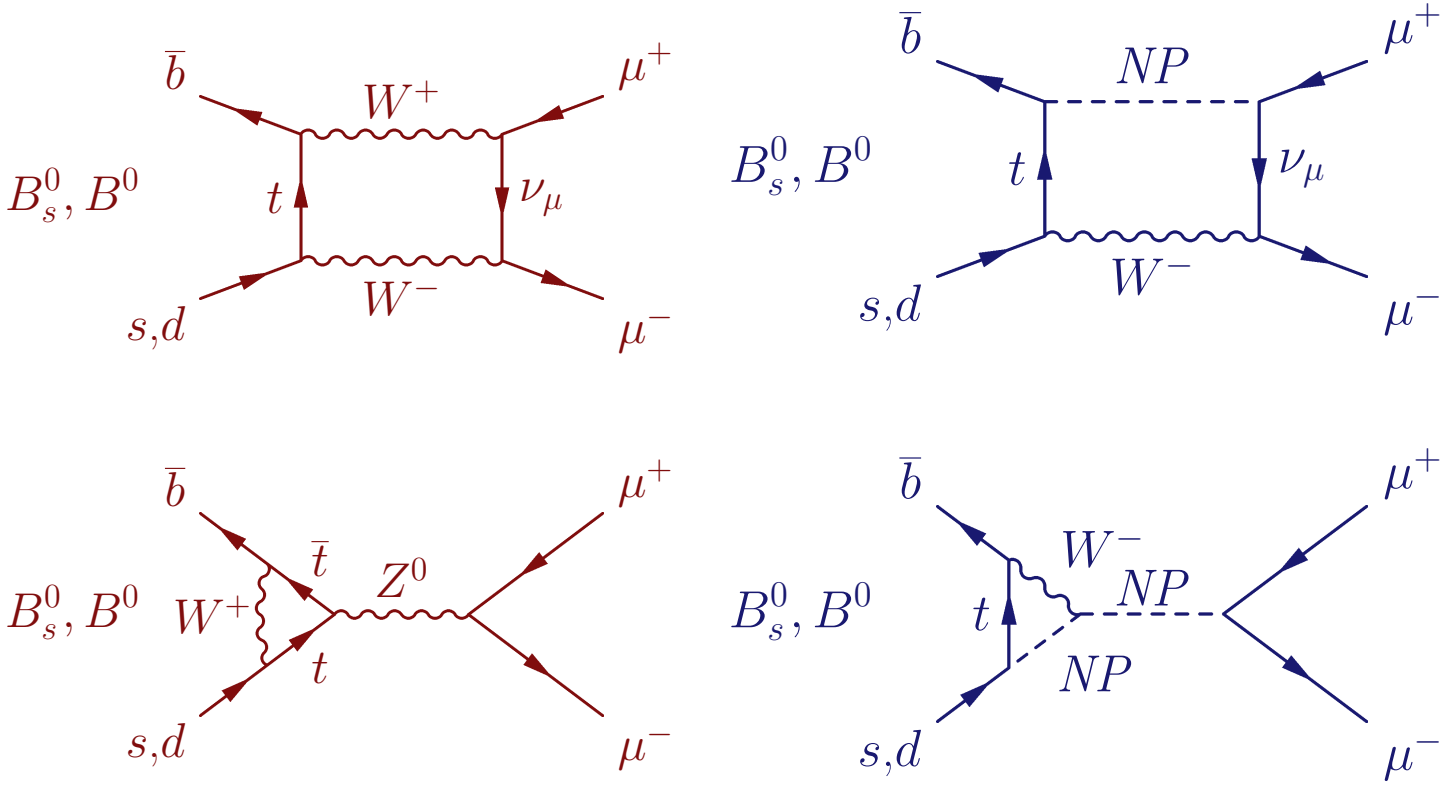
Possible paths

1. Fine tuning
2. A new symmetry (supersymmetry)
   fermion, boson loops contribute with opposite sign
3. Composite "Higgs boson" (technicolor . . .)
   form factor damps integrand
4. Low-scale gravity (shortens range of integration)
5. Little Higgs models, etc.

All but #1 require new physics near the TeV scale

#2 – #4 *could be* "once and done"

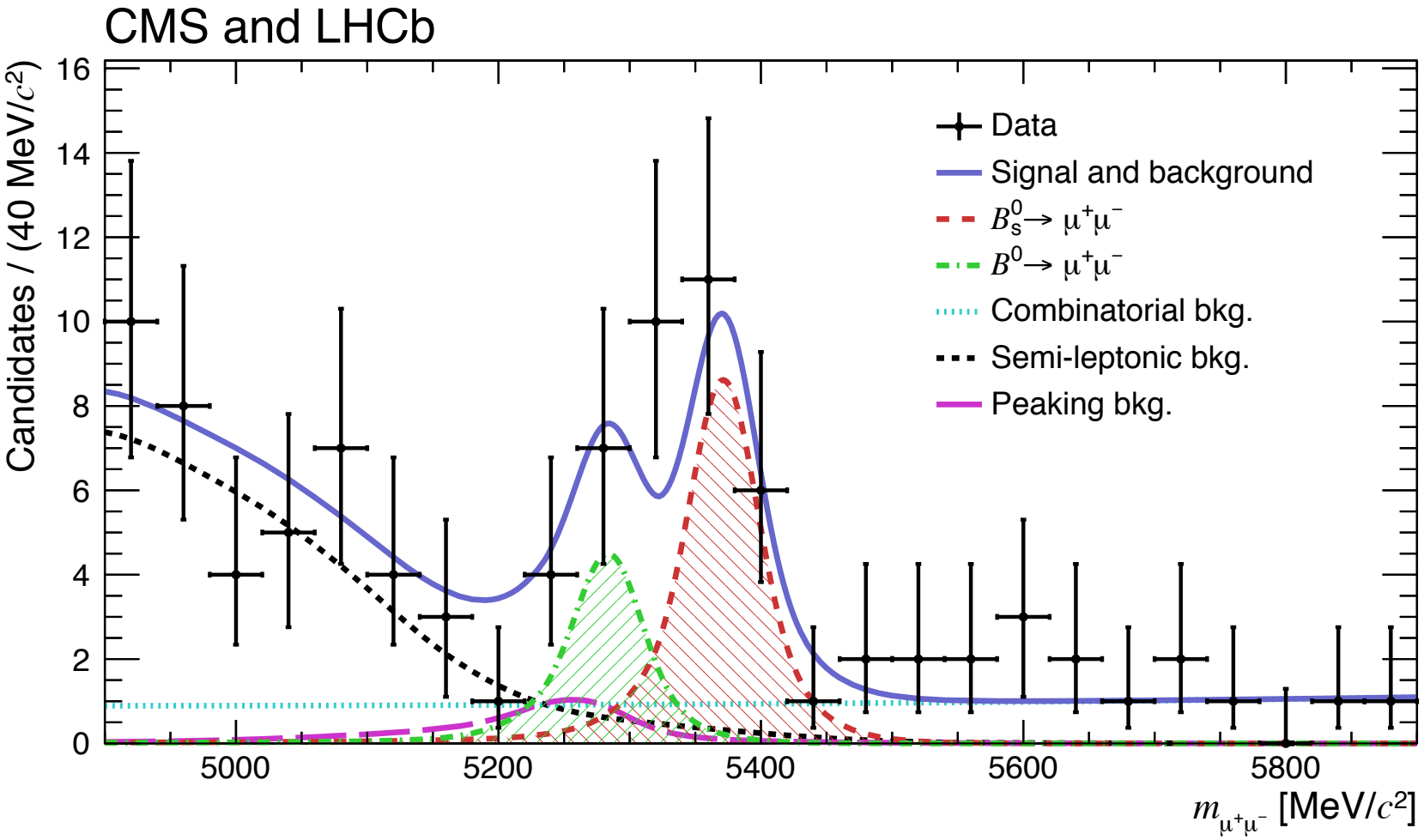
Rare Processes: Flavor-Changing Neutral Currents



Standard model: $\mathrm{BR}(B_s \to \mu^+\mu^-) = 3.56 \pm 0.30 \times 10^{-9}$

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

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



CMS + LHCb: $\mathrm{BR}(B_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$

Electron Electric Dipole Moment d_e

Standard-model phases: $d_e < 10^{-38}\ e \cdot \mathrm{cm}$

ACME Collaboration, ThO

$$\boxed{d_e < 8.7 \times 10^{-29}\ e \cdot \mathrm{cm}}$$

$12\times$ improvement!

So Where Is the New Physics?

The unreasonable effectiveness of the Standard Model

More Electroweak Questions for the LHC

- What is the agent that hides electroweak symmetry?
- Is the "Higgs boson" elementary or composite? How does the Higgs boson interact with itself? What triggers electroweak symmetry breaking?
- New physics in pattern of Higgs-boson decays?
- Will (unexpected or rare) decays of H reveal new kinds of matter?
- What would discovery of > 1 Higgs boson imply?
- What stabilizes M_H below 1 TeV?
- How can a light H coexist with absence of new phenomena?
- Is EWSB related to gravity via extra dimensions?

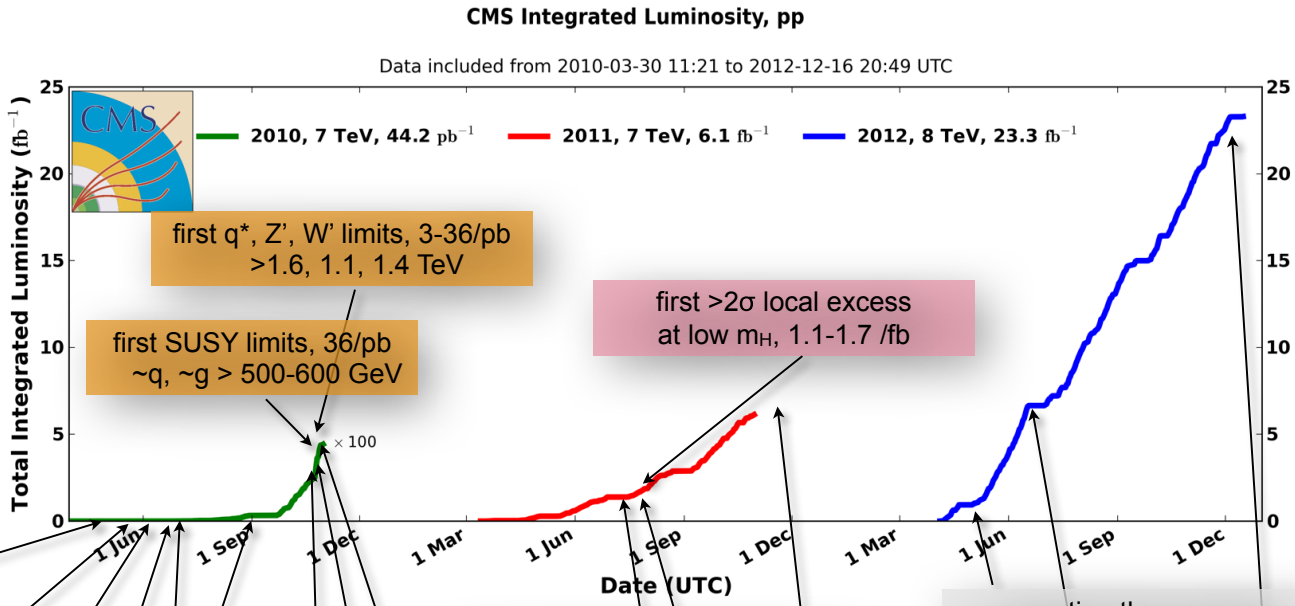
More Electroweak Questions for the LHC^{bis}

- Is EWSB emergent, connected with strong dynamics?
- If new strong dynamics, how can we diagnose? What takes place of H?
- 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?
- Does the different behavior of left-handed and right-handed fermions with respect to charged-current weak interactions reflect a fundamental asymmetry in the laws of nature?

More Electroweak Questions for the LHC^{ter}

- What will be the next symmetry recognized in Nature? Is Nature supersymmetric? Is the electroweak theory part of some larger edifice?
- Are there additional generations of quarks and leptons?
- What resolves the vacuum energy problem?
- What lessons does electroweak symmetry breaking hold for unified theories of the strong, weak, and electromagnetic interactions?

LHC physics is not just about the Higgs boson . . .



first q*, Z', W' limits, 3-36/pb >1.6, 1.1, 1.4 TeV

first SUSY limits, 36/pb ~q, ~g > 500-600 GeV

first >2σ local excess at low m_H, 1.1-1.7 /fb

repeating the program at 8 TeV

first MinBias / UE studies, particle multiplicities

first top xsec, 3/pb δ ~ 40%

first ZZ xsec, 1.1 /fb δ ~ 40%

a new boson is announced, 5 /fb

first incl. b x-section, 8/nb δ ~ 15 %

first single top xsec, t-chan., 36/pb δ ~ 36%

going more differential, e.g. Z/W + j,b,c

first incl. jet x-section, PF jets 60/nb δ ~ 20-30%

first m_{top}, 36/pb Δ ~ 6.5 GeV

first significant limit on $B_s \to \mu\mu$, BR<1.9x10^{-8}

first incl. W/Z x-sections, 200/nb δ ~ 4-6%, +11% lumi

first WW xsec, 36/pb δ ~ 40% first limit on HWW

first particle discovered by CMS: Ξ_b

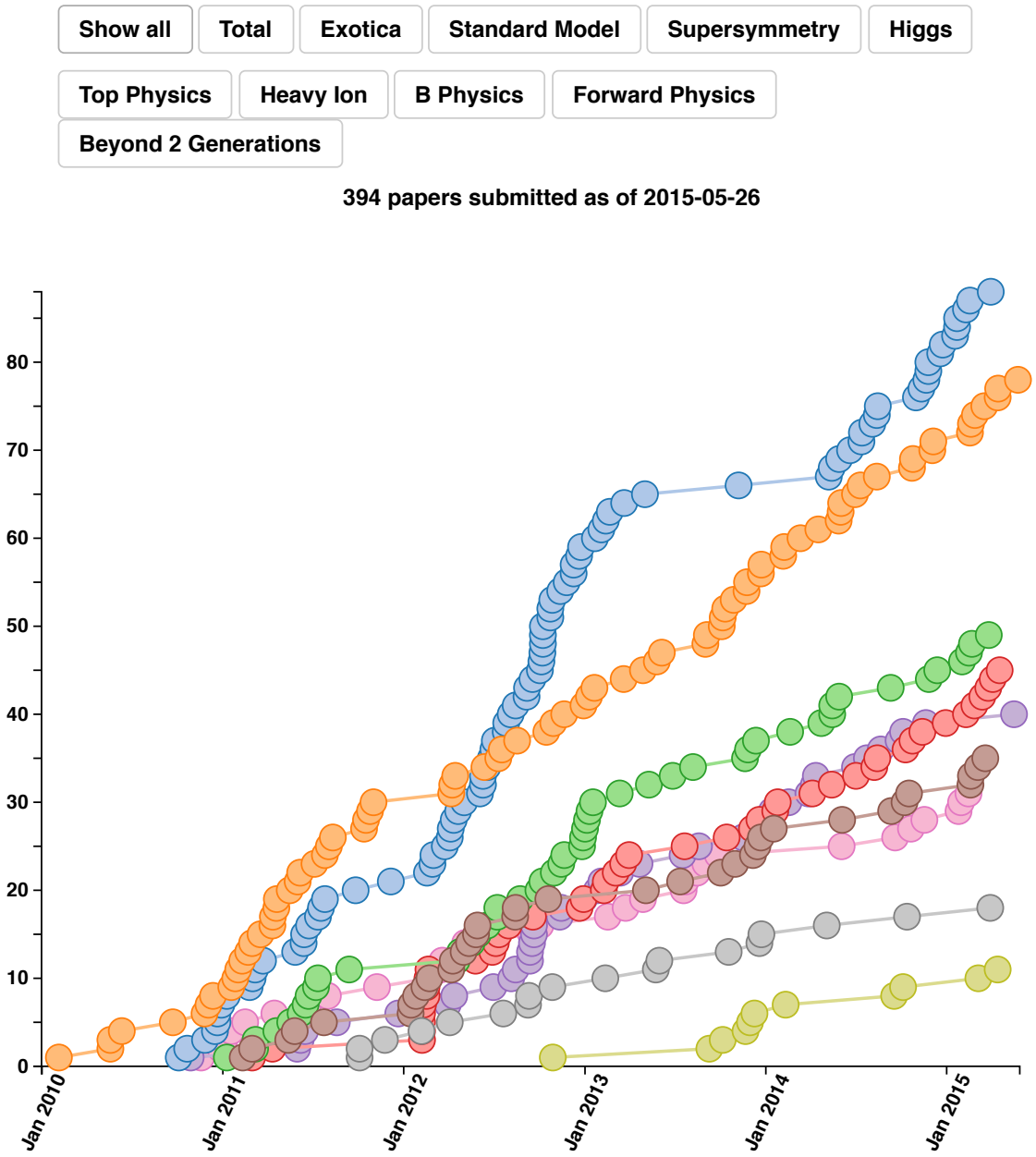
first incl. J/Ψ x-section, 100/nb δ ~ 20%

BSM searches continue, limits pushed

first spin parity analysis of the boson, 17 /fb

δ .. relative uncert Δ .. absolute uncert.

CMS Physics Timeline



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
Superpartners / color $\mathbf{6}, \mathbf{8}$ quarks

Quark compositeness

Larger color symmetry containing QCD
$\mathrm{SU}(3)_{\mathrm{L}} \otimes \mathrm{SU}(3)_{\mathrm{R}} \to \mathrm{SU}(3)_{\mathrm{c}} \rightsquigarrow$ (axigluons)

New phenomena within QCD?

Multiple production beyond diffraction+short-range order?

High density of few-GeV partons . . . thermalization?

Long-range correlations in y?

Unusual event structures . . .

"Dead cone" for radiation from heavy quarks

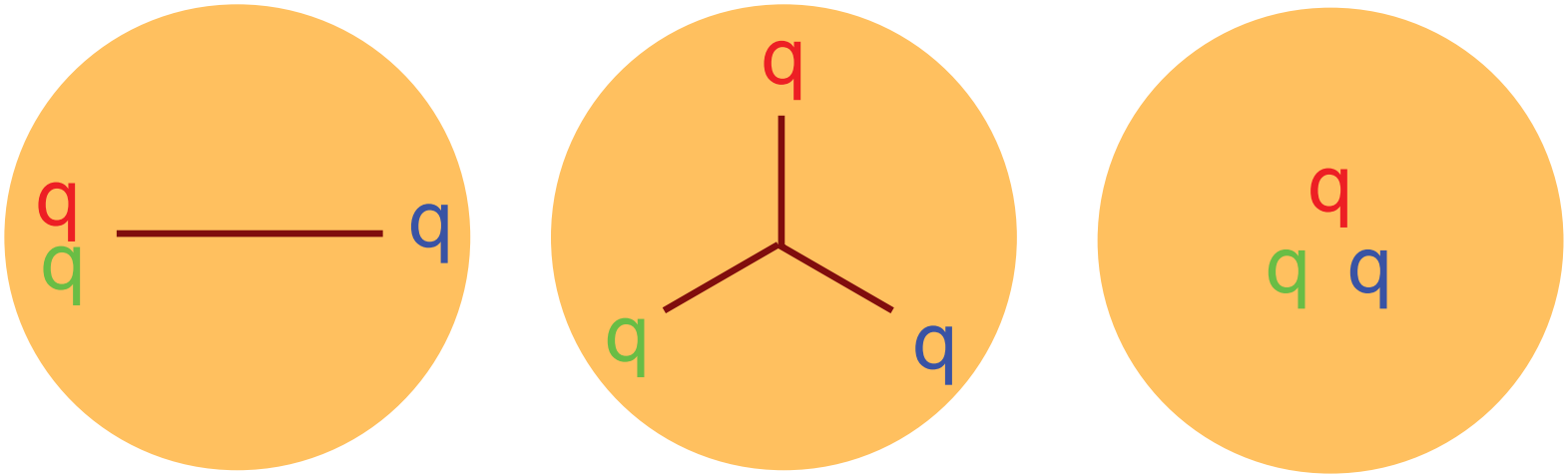
Look at events in informative coordinates.

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

Correlations among the partons?

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

Bjorken speculates . . .



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

Some targets for LHC Run 2

- Search for new force carriers:
  "Not unexpected" — W' (RH?), Z'

Additional W Bosons

W' with standard couplings
Mass $m > 2.900 \times 10^3$ GeV, CL = 95% (pp direct search)
W_R (Right-handed W Boson)
Mass $m > 715$ GeV, CL = 90% (electroweak fit)

Additional Z Bosons

$Z'_{\rm SM}$ with standard couplings
Mass $m > 2.590 \times 10^3$ GeV, CL = 95% (pp direct search)
Mass $m > 1.500 \times 10^3$ GeV, CL = 95% (electroweak fit)
Z_{LR} of $SU(2)_L \times SU(2)_R \times U(1)$ (with $g_L = g_R$)
Mass $m > 630$ GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m > 1162$ GeV, CL = 95% (electroweak fit)
Z_χ of $SO(10) \rightarrow SU(5) \times U(1)_\chi$ (with $g_\chi = e/\cos\theta_W$)
Mass $m > 1.970 \times 10^3$ GeV, CL = 95% (pp direct search)
Mass $m > 1.141 \times 10^3$ GeV, CL = 95% (electroweak fit)
Z_ψ of $E_6 \rightarrow SO(10) \times U(1)_\psi$ (with $g_\psi = e/\cos\theta_W$)
Mass $m > 2.260 \times 10^3$ GeV, CL = 95% (pp direct search)

Integrated Luminosity [fb^{-1}]	300	3000
95% CL exclusion limit (ATLAS)	6.5 TeV	7.8 TeV
5σ discovery limit (CMS)	5.1 TeV	6.2 TeV

Some targets for LHC Run 2

- Search for new force carriers (continued):
  "Imagined" — Axigluons $SU(3)_L \otimes SU(3)_R \to SU(3)_c$
  — Colorons (new strong dynamics)
  — Leptoquarks
  — KK Gravitons
  "Why not?" — Dijet or Diquark resonances
- Extend the search for quark and lepton compositeness: contact term alters σ, changes angular distribution
- Search for superpartners
  Plausible to push $m_{\tilde{t}} \to 1$ TeV, $m_{\tilde{g}} \to 1.5$ TeV
  backgrounds a concern, limits always have evasions
  Don't forget global search for colored objects: $\alpha_s(Q^2)$

Status of Superpartner Searches

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	1405.7875
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{G})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^\pm)=2\, m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-210 GeV	$m(\tilde{\chi}_1^0)$ =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^\pm$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$ 215-530 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$ 260-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}_1^0)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 140-465 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 100-350 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1407.0350
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$ 285 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$ 270 GeV	$m(\tilde{\chi}_1^\pm)$-$m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.35 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 750 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^\pm)$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$ 450 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^\pm)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon 350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

Looking toward higher energies . . .

Future Circular Collider Studies

FCC-*hh*: $\sqrt{s} = 100$ TeV *pp* collider,

ultimate $\mathcal{L} \approx 2 \times 10^{35}$ cm^{-2} s^{-1}

For now, we have no well-defined science target

If $\sqrt{s} = 100$ TeV fixed, what should $\mathcal{L}$ be?

Simplest argument: hard-scattering $\sigma \propto 1/s$

so scale HL-LHC parameters for "comparable reach"

$\rightsquigarrow \mathcal{L}(100 \text{ TeV}) \approx 50\mathcal{L}(14 \text{ TeV}) > 10^{36}$ cm^{-2} s^{-1}

scaling violations in PDFs raise the requirement

But LHC compensated limited $\sqrt{s}$ (fixed size of LEP tunnel) by aggressive $\mathcal{L}$; $\sqrt{s} - \mathcal{L}$ optimization could differ

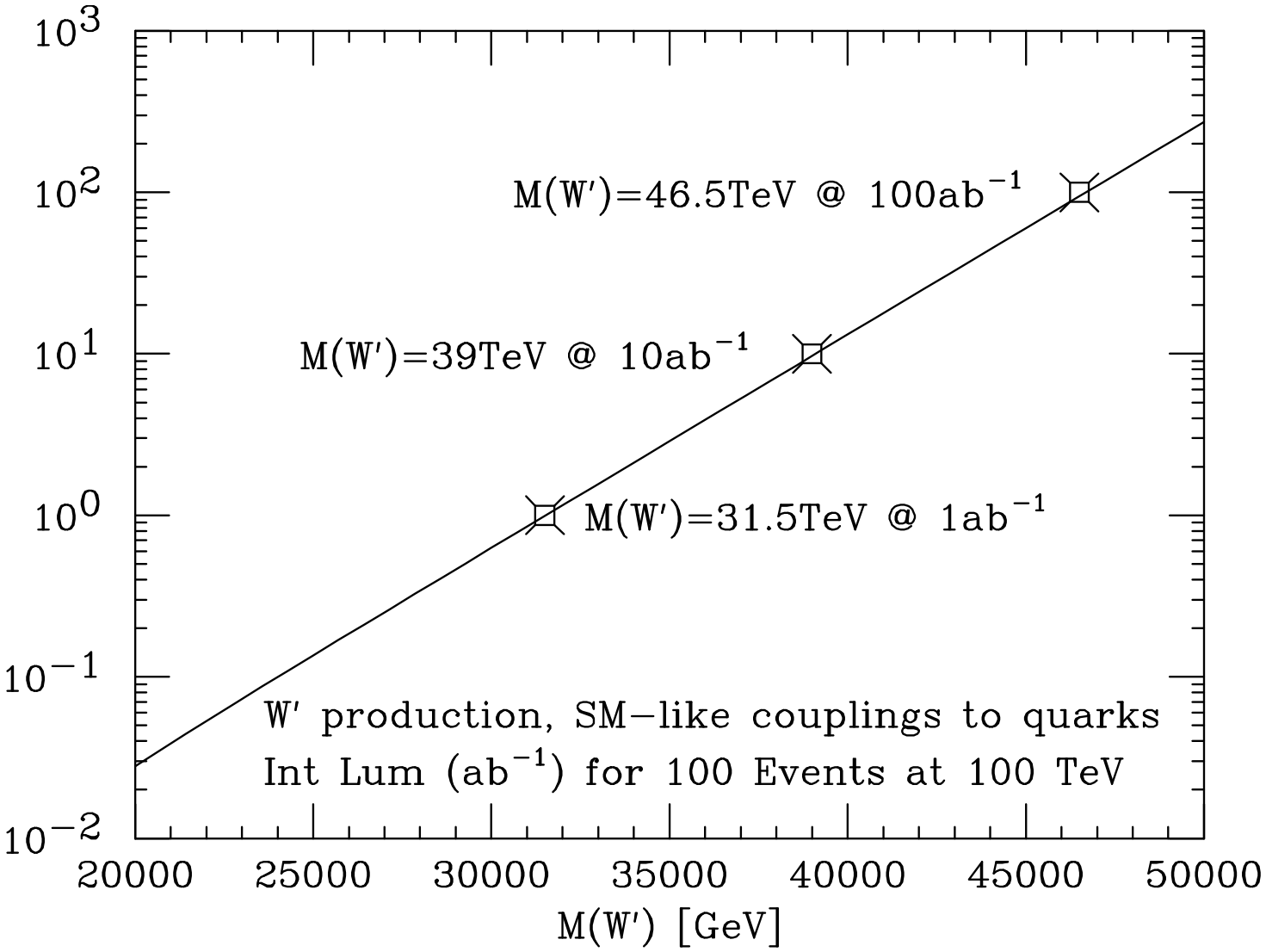
How to think about Luminosity Goals

Initial $\mathcal{L}$ of a new hadron collider should be sufficient to surpass the LHC exploration potential very quickly.

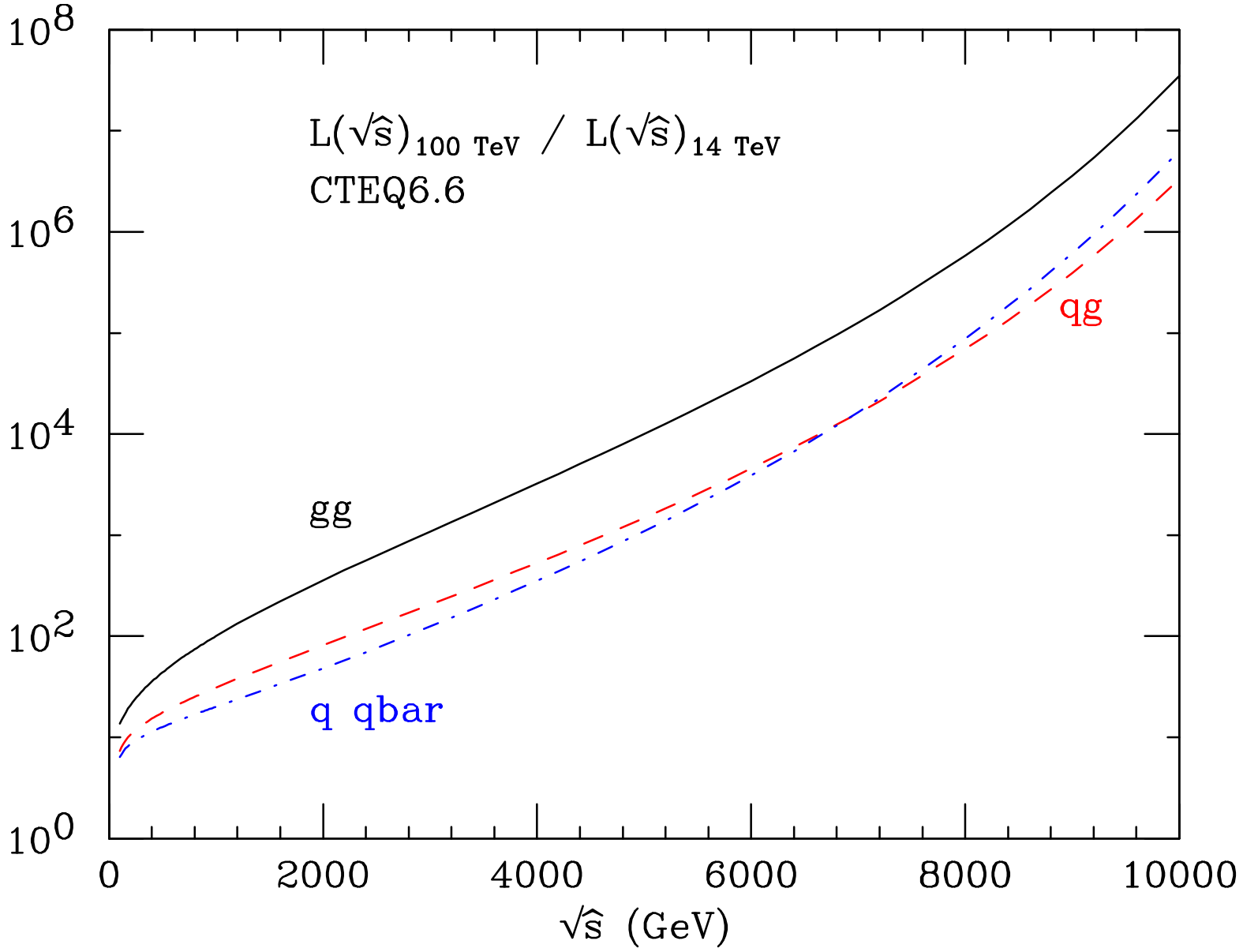
Four considerations:

1. The search for new phenomena, inaccessible to the LHC, at high mass scales.
2. Increased sensitivity to rare or high-background processes at mass scales well below kinematic limit.
3. Increased precision for studies of new particles accessible to the LHC.
4. Incisive studies of the Higgs boson, both in the domain of precision and in the exploration of new phenomena.

Search for W' at $\sqrt{s} = 100$ TeV



FCC would be a "factory" for LHC Discoveries



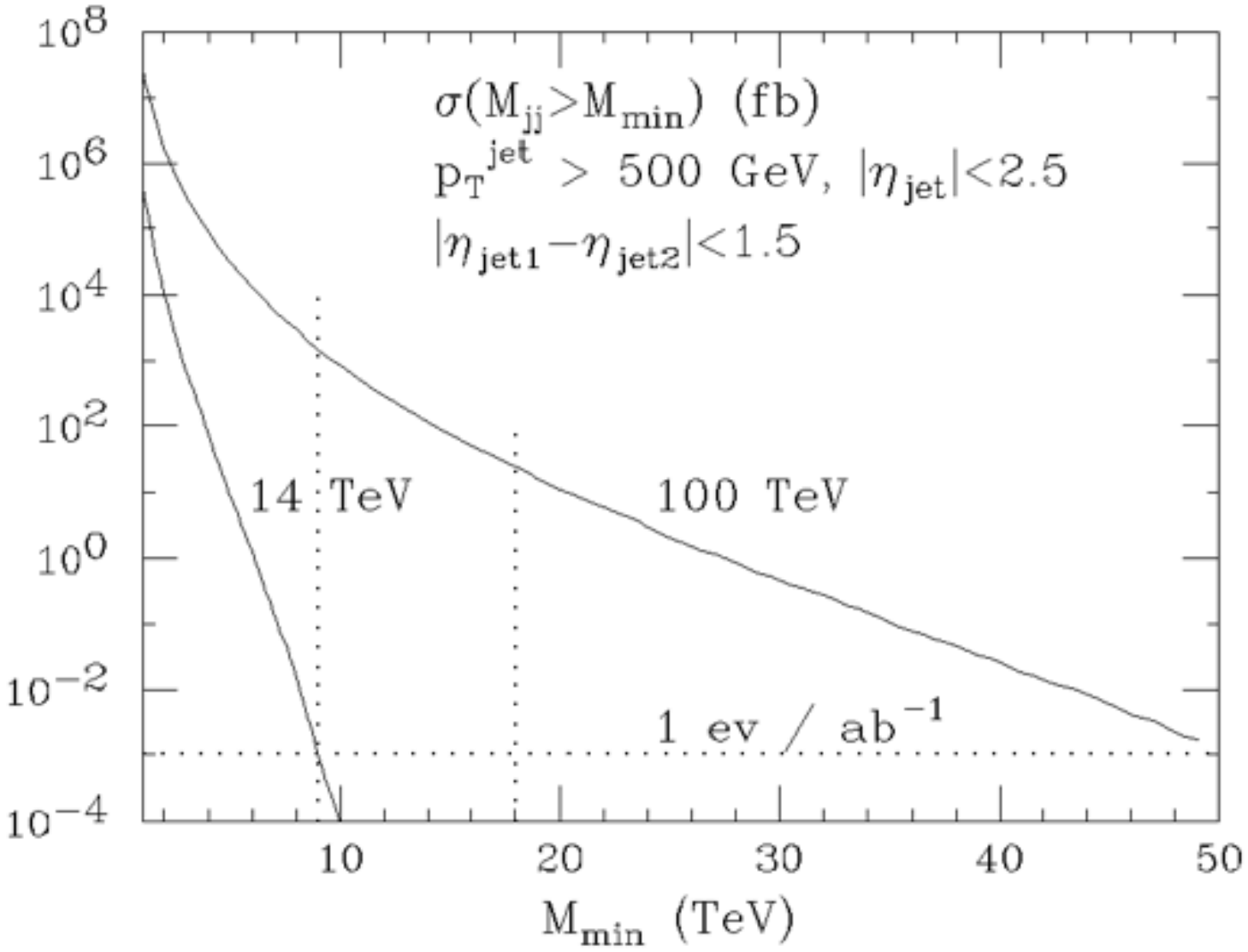
Precision Higgs Studies: Prospects

$$\sigma(\sqrt{s} = 100 \text{ TeV})/\sigma(\sqrt{s} = 14 \text{ TeV})$$

$gg \to H$	$q\bar{q} \to WH$	$q\bar{q} \to WH$	$qq \to qqH$	$gg/q\bar{q} \to t\bar{t}H$	$gg \to HH$
14.7	9.7	12.5	18.6	61	42

Preliminary: 5% measurement of HHH at 30 ab^{-1}, $HH \to \gamma\gamma b\bar{b}$

Sensitivity to high-mass dijets



LHC sensitivity reached at 1 pb^{-1} = 1 day at 10^{32} cm^{-2} s^{-1}

The LHC and Beyond

Focus over next decade on LHC and HL-LHC ...

... but look over the horizon

What science targets can we set?

$\sqrt{s} - \mathcal{L}$ optimization is multifaceted

$\int \mathcal{L} dt \approx 10 - 20$ ab^{-1} ($\mathcal{L} \approx 2 \times 10^{35}$ cm^{-2} s^{-1}) would extend discovery reach at high $\sqrt{\hat{s}}$, enable high-statistics studies of $H +$ new physics discovered at (HL)-LHC.

Even $\mathcal{L} \approx 10^{32}$ cm^{-2} s^{-1} can greatly extend the discovery reach over LHC, or to enhance the precision in the measurement of discoveries made at the HL-LHC.

Merci, à la prochaine !