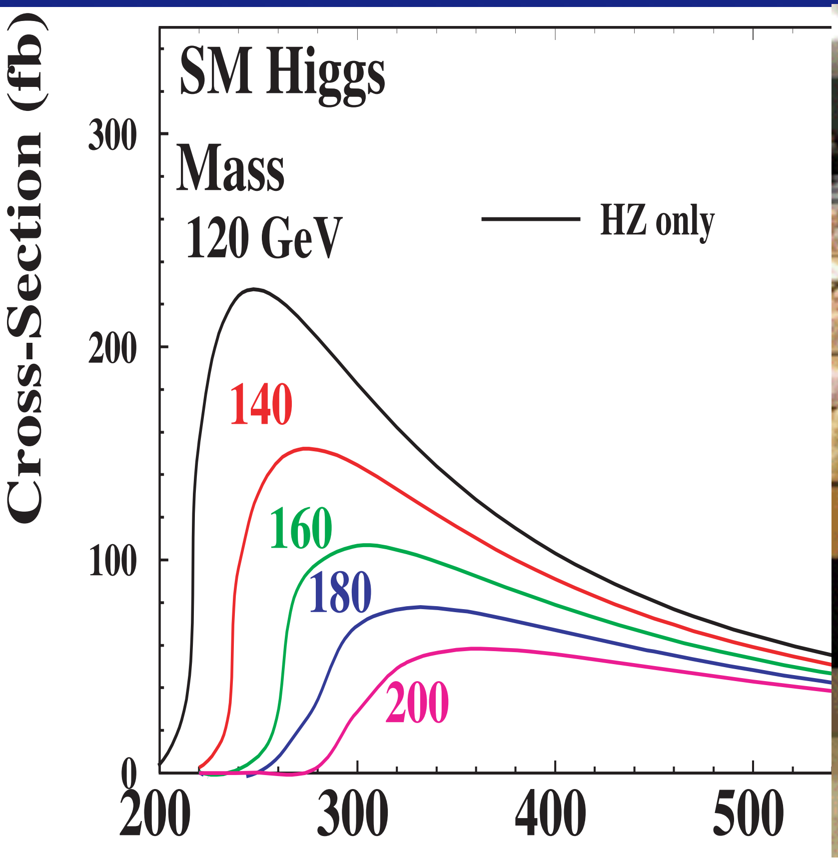
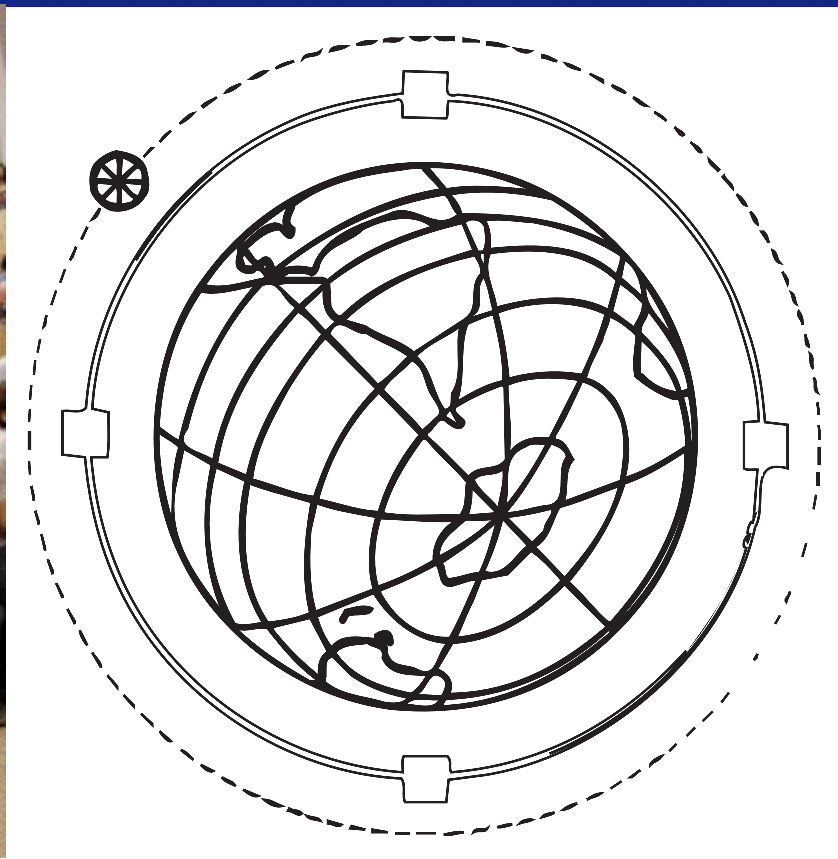
Perspectives at the Energy Frontier

Chris Quigg

Fermi National Accelerator Laboratory





Future of High Energy Physics · HKUST IAS · 19 January 2015


To the end of an era
of physics
The discovery of the Higgs
To Chris
from Jochen
You were right
XII
APOSTELHOEVE
NEDERLANDSE WIJN

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

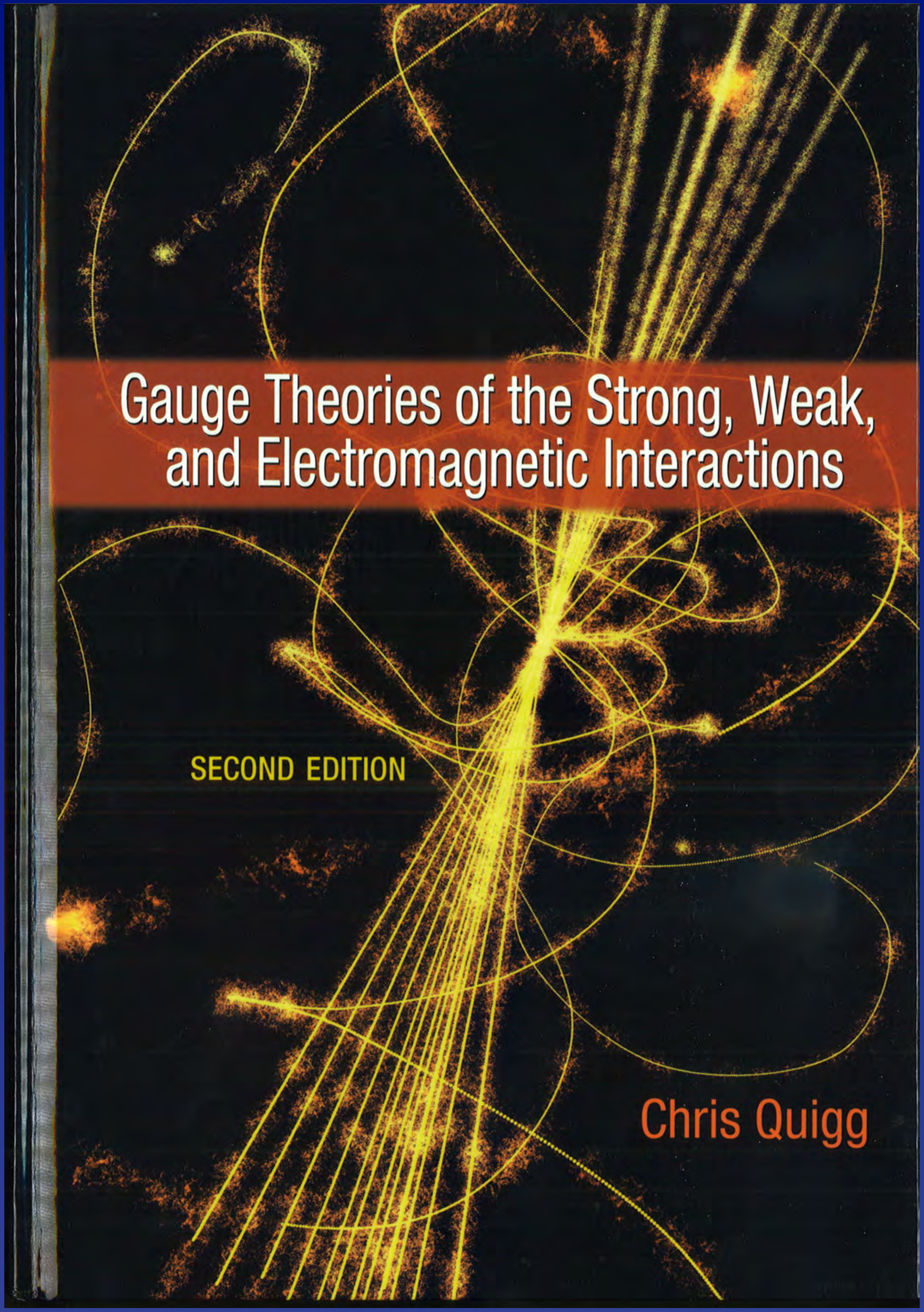
Surprise?: QCD would hide EW symmetry, give tiny masses to *W*, *Z*

Massless electron: atoms lose integrity

No atoms means no chemistry, no stable composite structures like liquids, solids, …

… no template for life.

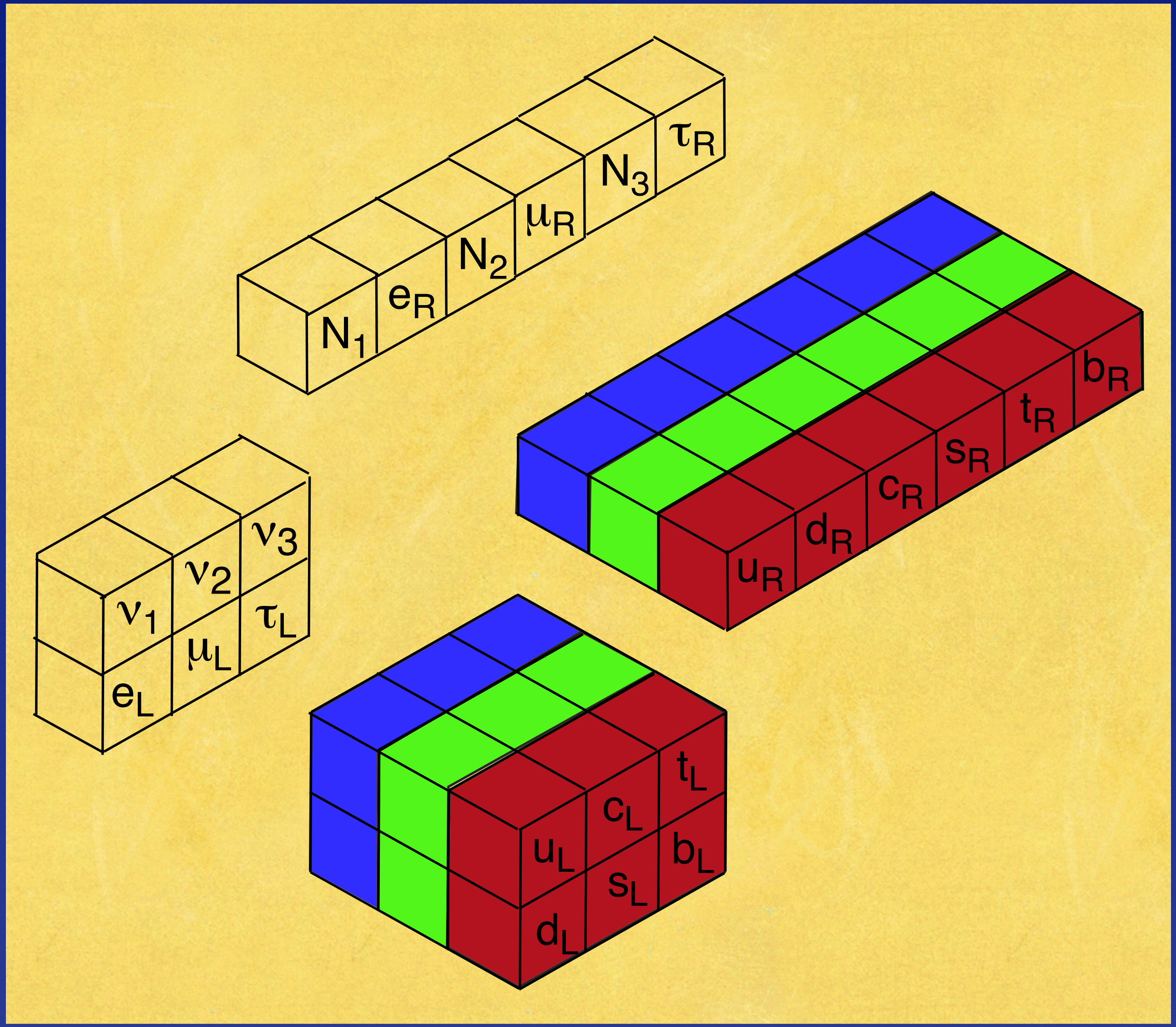
arXiv:0901.3958


Gauge Theories of the Strong, Weak, and Electromagnetic Interactions
SECOND EDITION
Chris Quigg

Before LHC

Two New Laws of Nature +

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



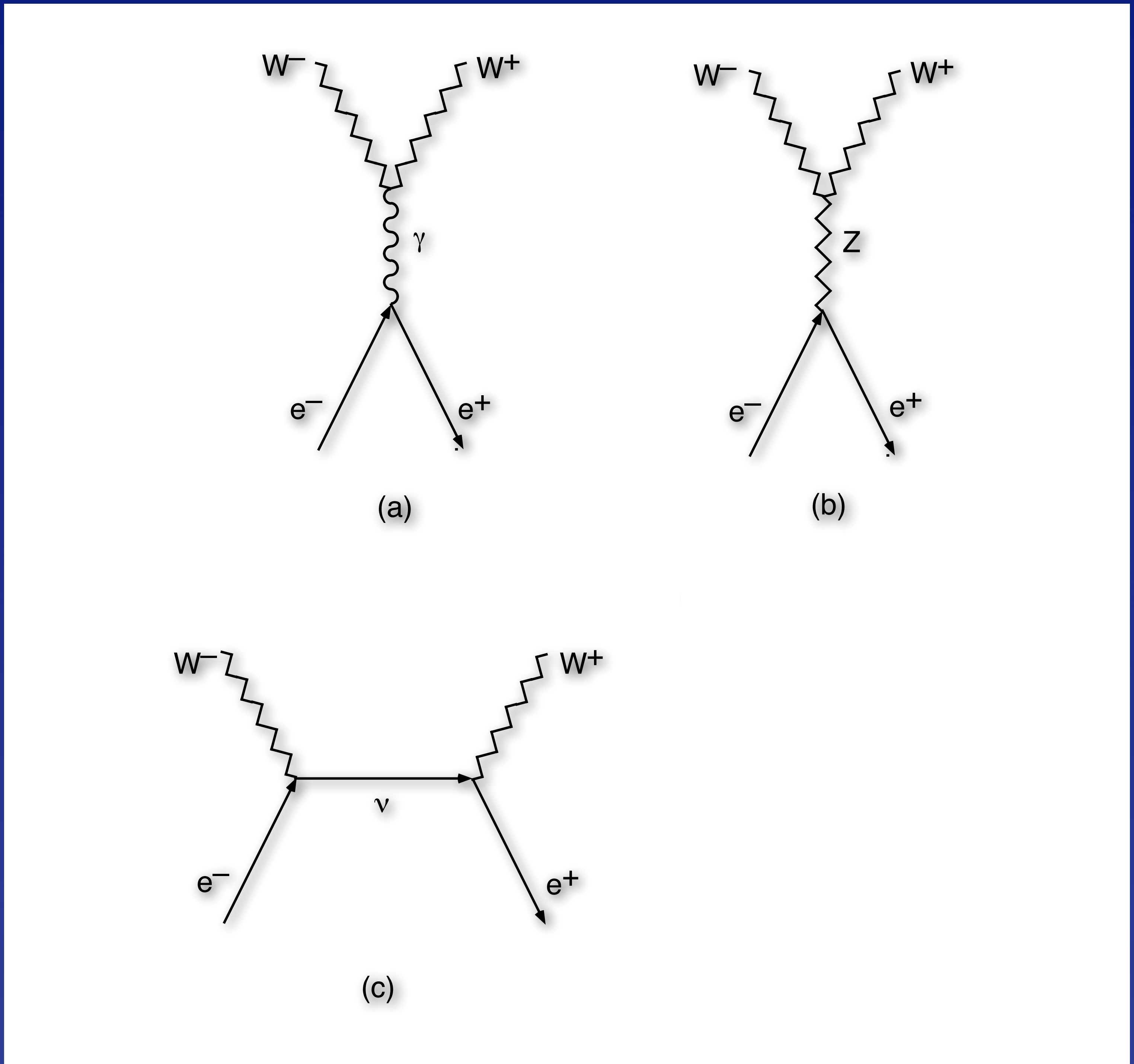
$U(1)_{EM}$

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

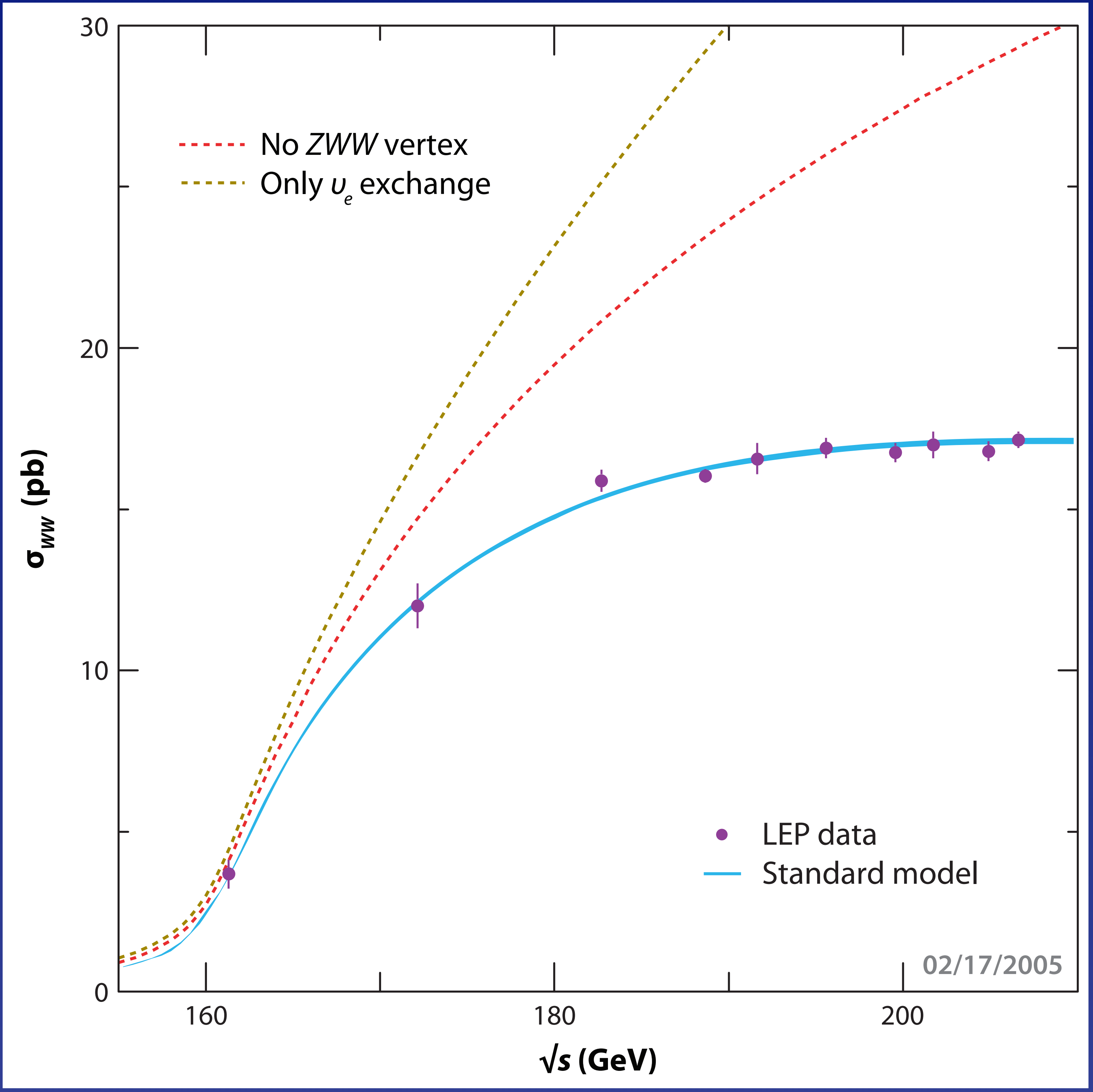
A hitherto unknown agent hides electroweak symmetry

- ✳ 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

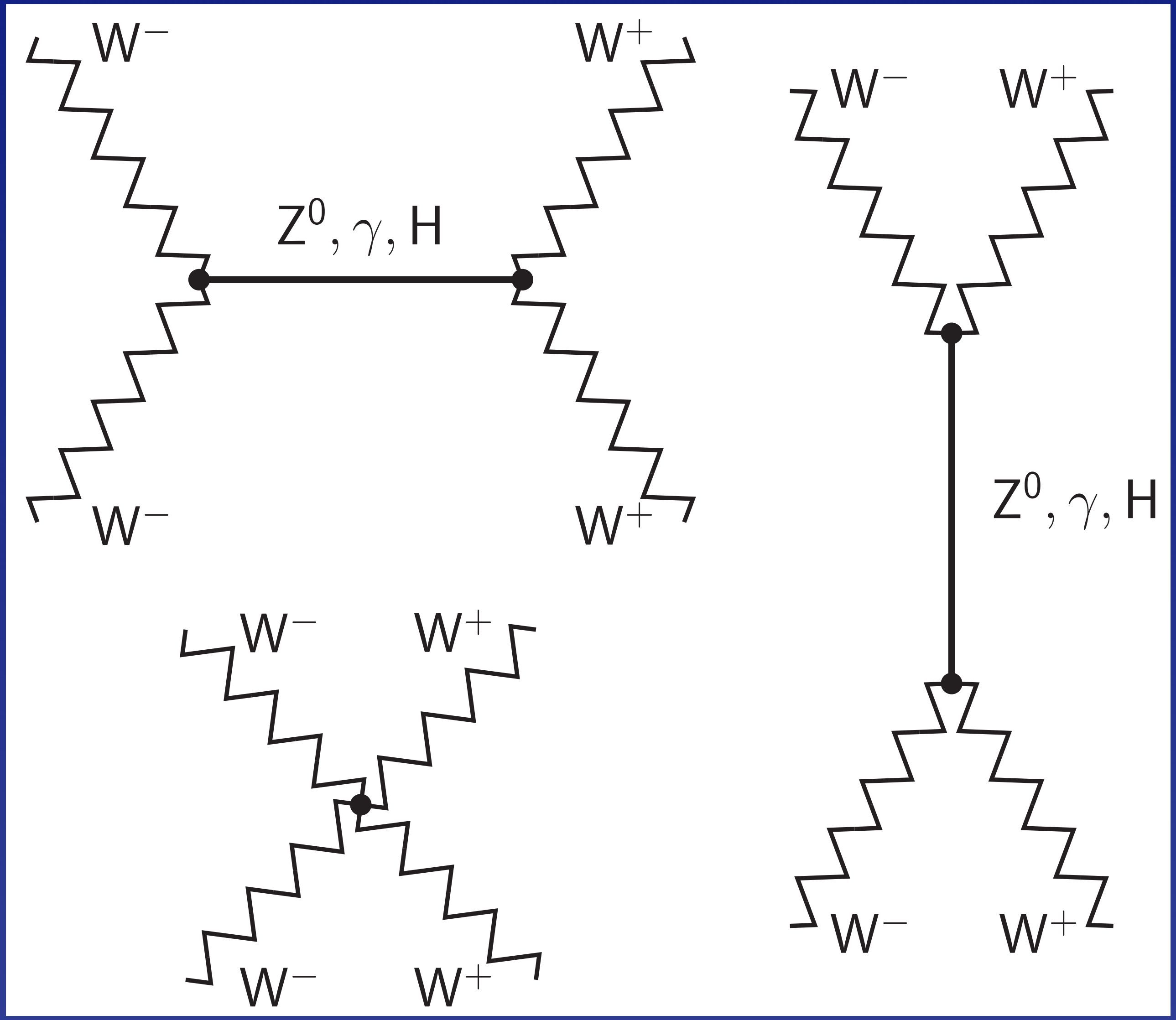
Gauge symmetry (group-theory structure) tested in $e^+e^- \to W^+W^-$



Electroweak symmetry validated at LEP



Standard-model Higgs boson hides electroweak symmetry, gives masses to $W^{\pm}$ and Z^0, ensures good high-energy behavior.



Something must do this job

Origin of fermion mass?

By decree, Weinberg & Salam add interactions between fermions and scalars that give rise to quark and lepton masses.

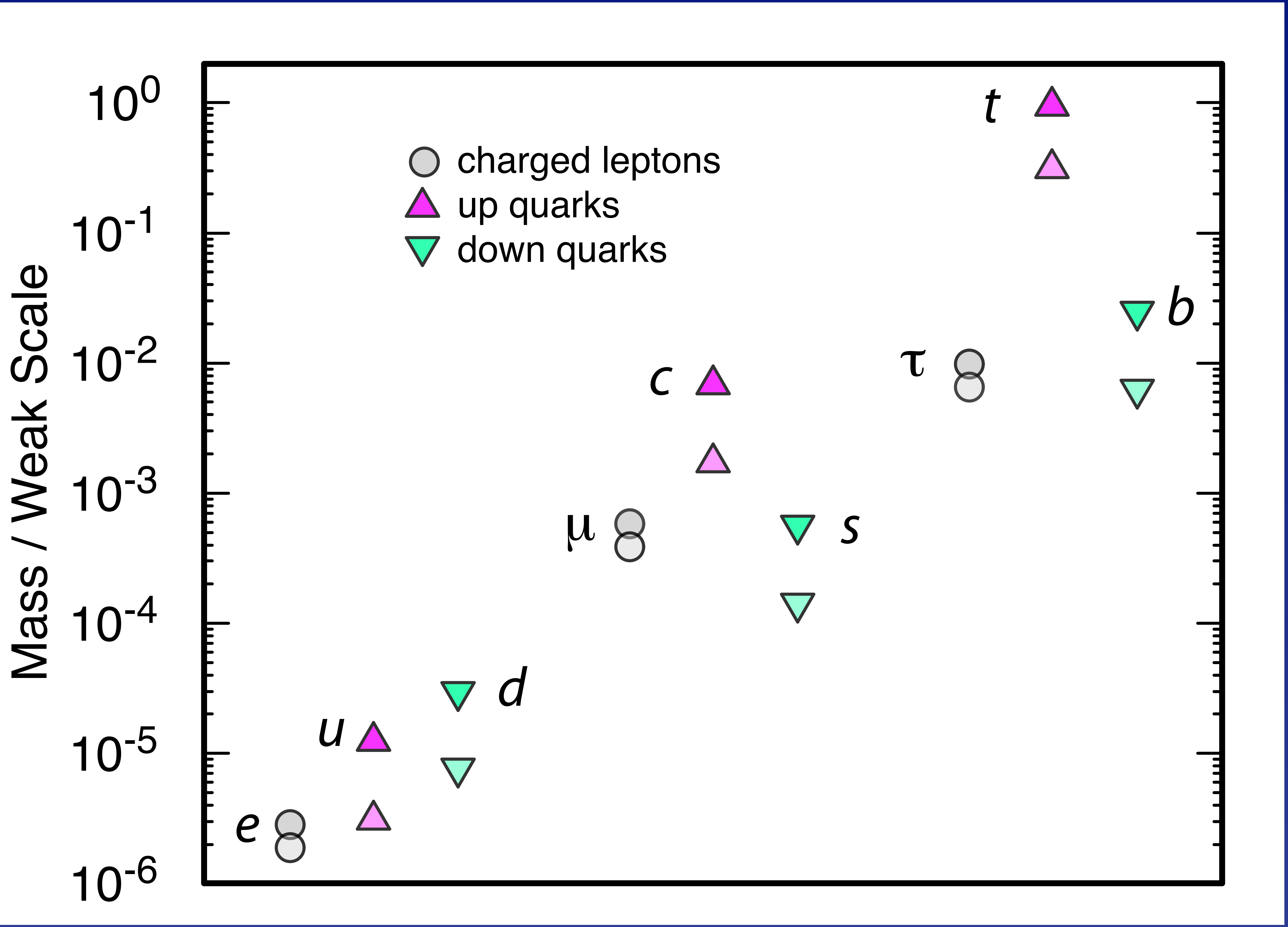
$$\zeta_e\left[(\overline{e_{\mathsf{L}}}\Phi)e_{\mathsf{R}} + \overline{e_{\mathsf{R}}}(\Phi^\dagger e_{\mathsf{L}})\right] \rightsquigarrow m_e = \zeta_e v/\sqrt{2}$$

ζ_e picked to give right mass, not predicted

fermion mass implies physics beyond standard model

Highly economical, but is it true?

Fermion Masses



Running mass *m*(*m*) … *m*(*U*)

The Higgs field is not molasses

Viscosity resists motion

Mass resists acceleration

We do not know what sets the Yukawa couplings,
nor the scale on which they are set.

Unanswered Questions in the Electroweak Theory

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0163-8998/09/1123-0505$20.00

Key Words

electroweak symmetry breaking, Higgs boson, 1-TeV scale, Large Hadron Collider (LHC), hierarchy problem, extensions to the Standard Model

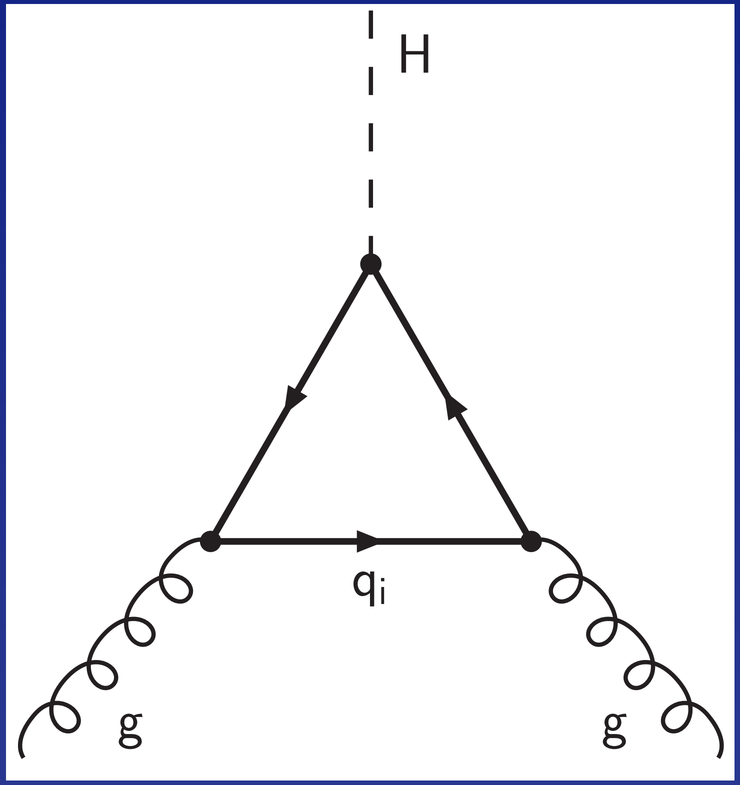
Abstract

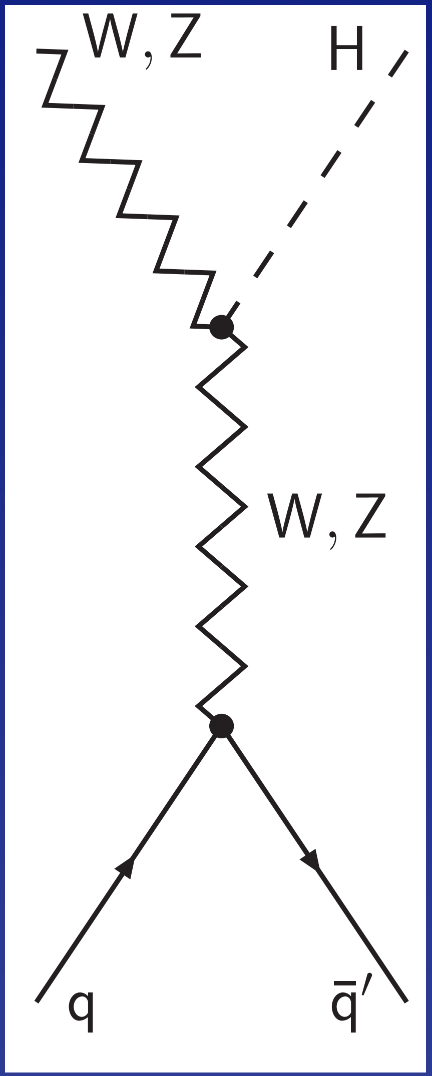
This article is devoted to the status of the electroweak theory on the eve of experimentation at CERN's Large Hadron Collider (LHC). A compact summary of the logic and structure of the electroweak theory precedes an examination of what experimental tests have established so far. The outstanding unconfirmed prediction is the existence of the Higgs boson, a weakly interacting spin-zero agent of electroweak symmetry breaking and the giver of mass to the weak gauge bosons, the quarks, and the leptons. General arguments imply that the Higgs boson or other new physics is required on the 1-TeV energy scale.

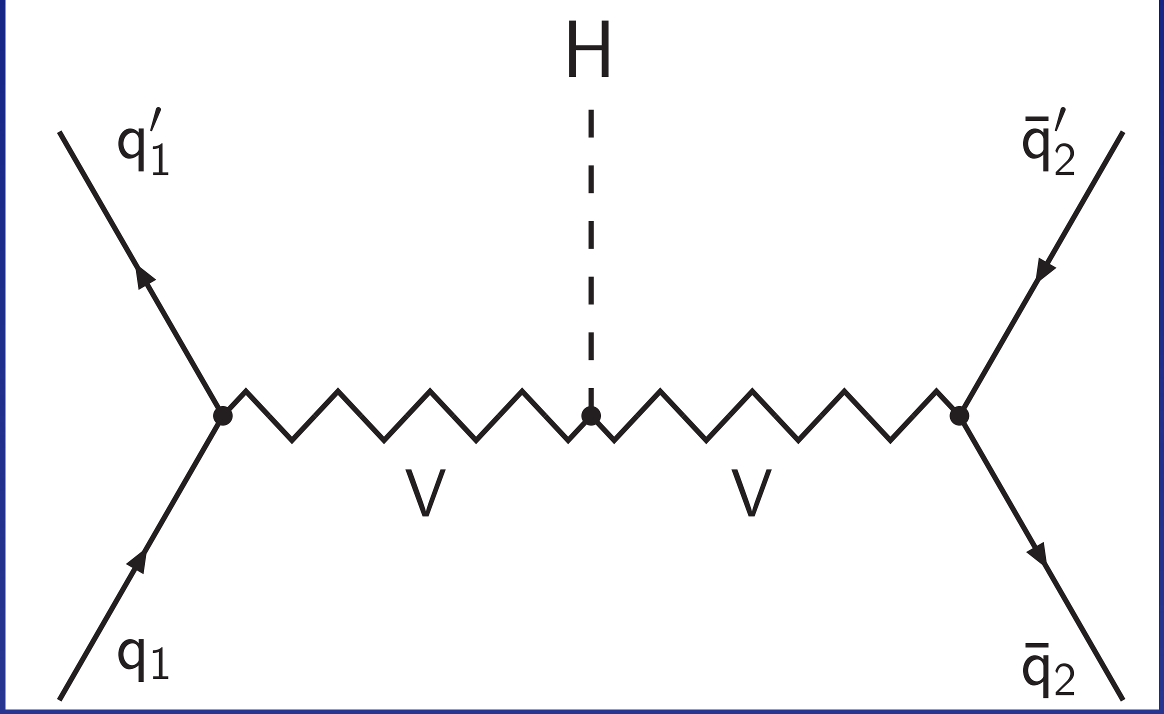
Even if a "standard" Higgs boson is found, new physics will be implicated by many questions about the physical world that the Standard Model cannot answer. Some puzzles and possible resolutions are recalled. The LHC moves experiments squarely into the 1-TeV scale, where answers to important outstanding questions will be found.

LHC affords multiple looks at the new boson

≥ 3 production mechanisms, ≥ 5 decay channels

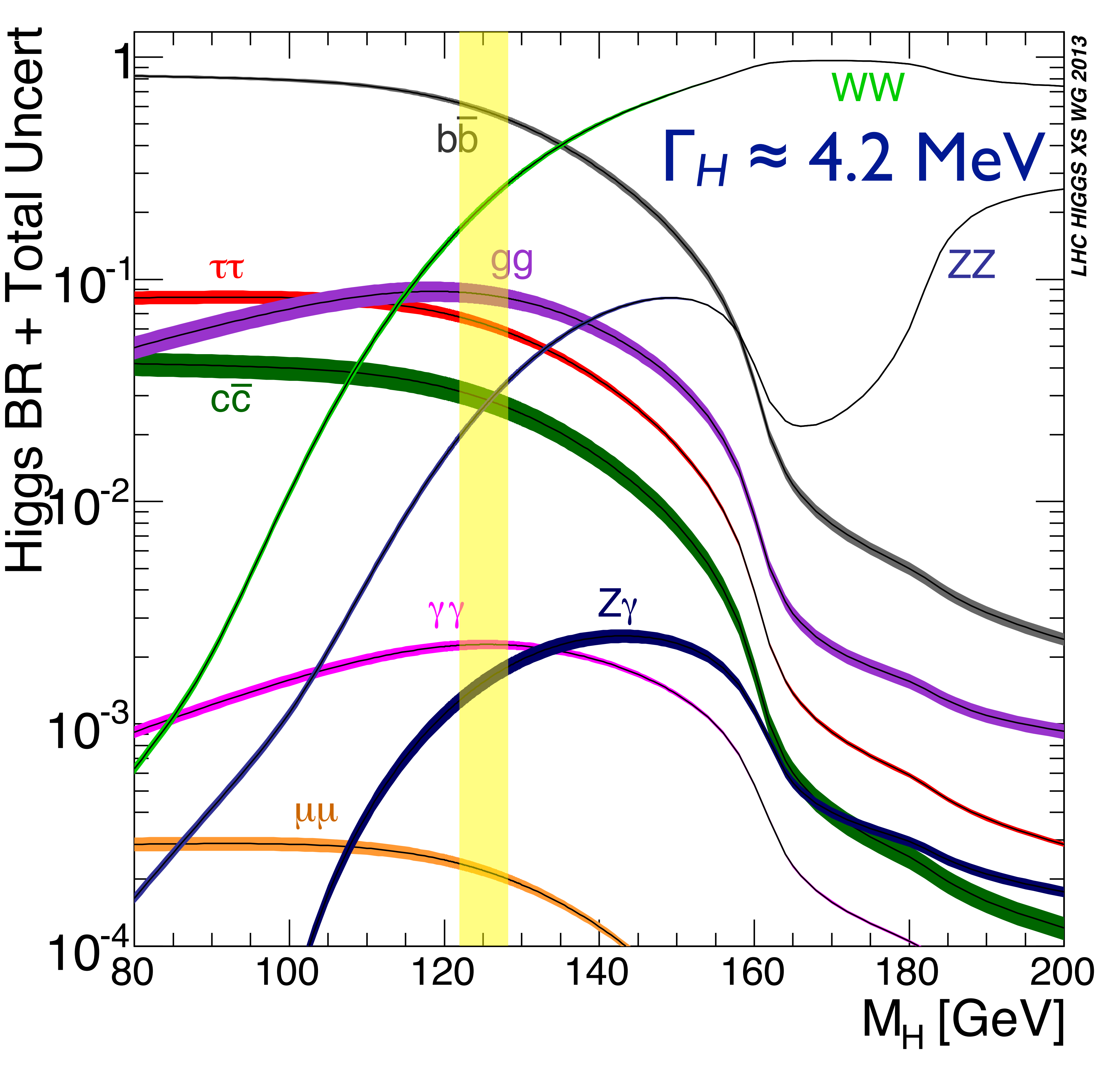




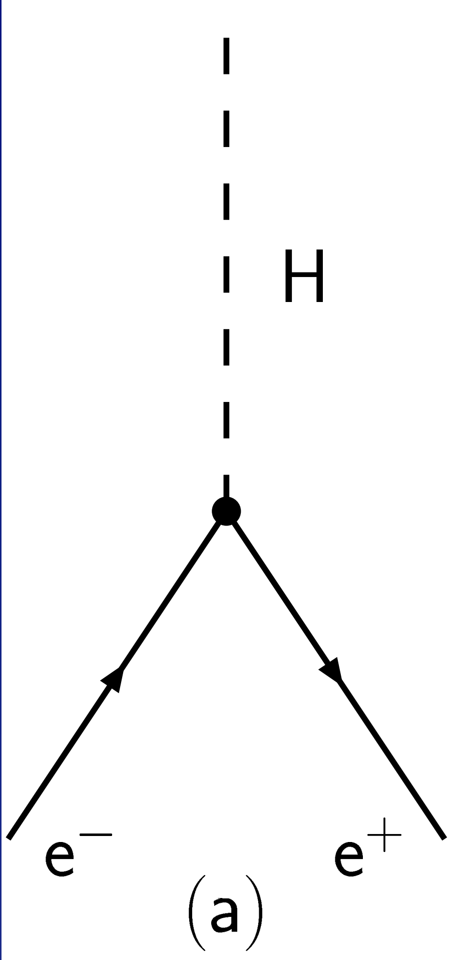


$\gamma\gamma$, ZZ^*, WW^*, b pairs, $\tau^+\tau^-$

Standard-Model Higgs-Boson Branching Fractions



Fully accounts for EWSB (W, Z couplings)?
Couples to fermions?
Top from production,
need direct observation for b, τ
Accounts for some or all fermion masses?
Fermion couplings $\propto$ masses?
Are there others?
Quantum numbers?
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?



s-channel formation?

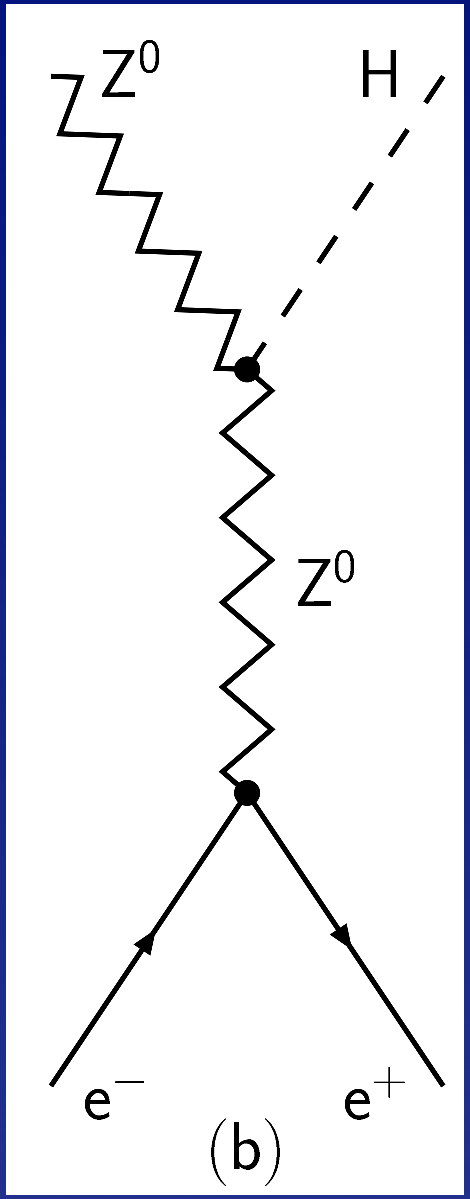
$$\sigma_{\rm peak}(e^+e^- \to H) = \frac{4\pi}{M_H^2} \cdot \frac{\Gamma(H \to e^+e^-)}{\Gamma(H \to \text{all})}$$

$$= 4.89 \times 10^{-31}\ \text{cm}^2 \left[\frac{100\ \text{GeV}}{M_H}\right]^2 \cdot \frac{\Gamma(H \to e^+e^-)}{\Gamma(H \to \text{all})}$$

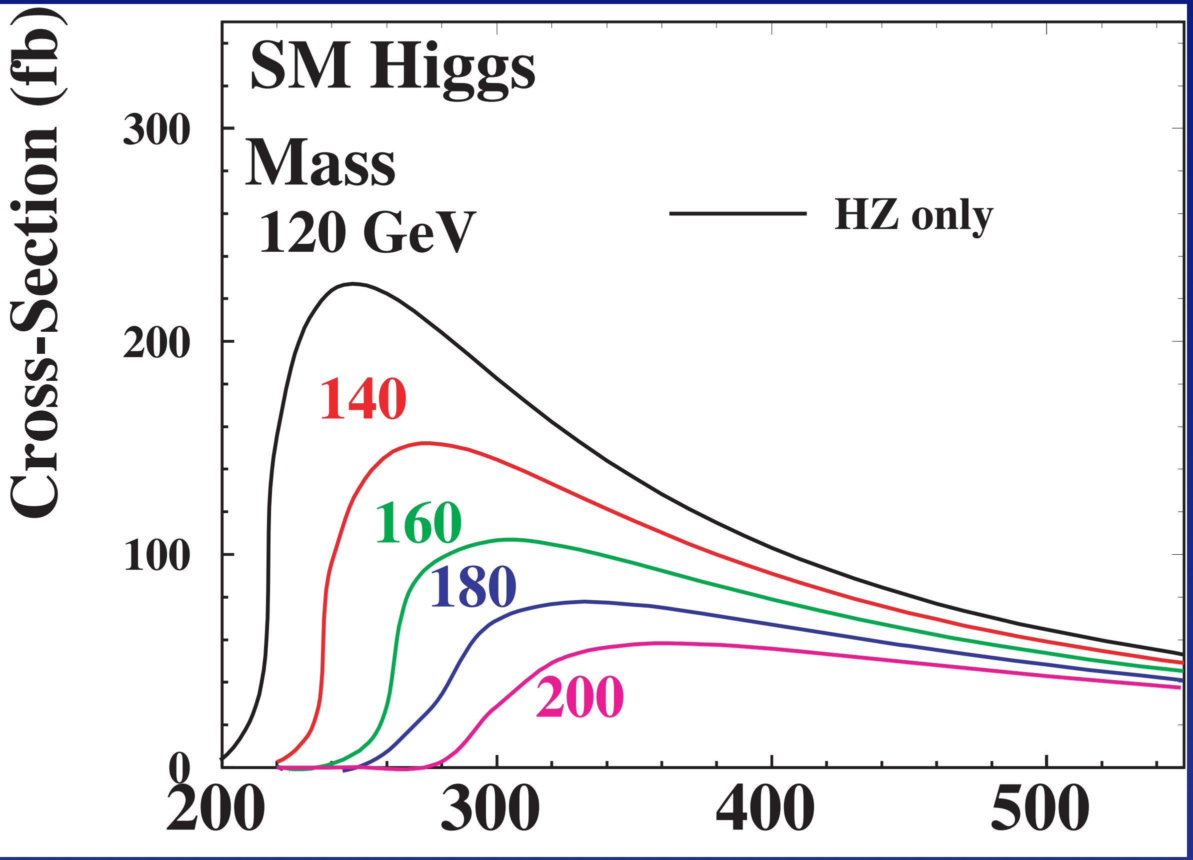
$$\approx 1.5 \times 10^{-39}\ \text{cm}^2$$

$$\approx 5 \times 10^{-9}$$

$$\sigma_{\rm peak}(\mu^+\mu^- \to H) \approx 6.4 \times 10^{-35}\ \text{cm}^2$$



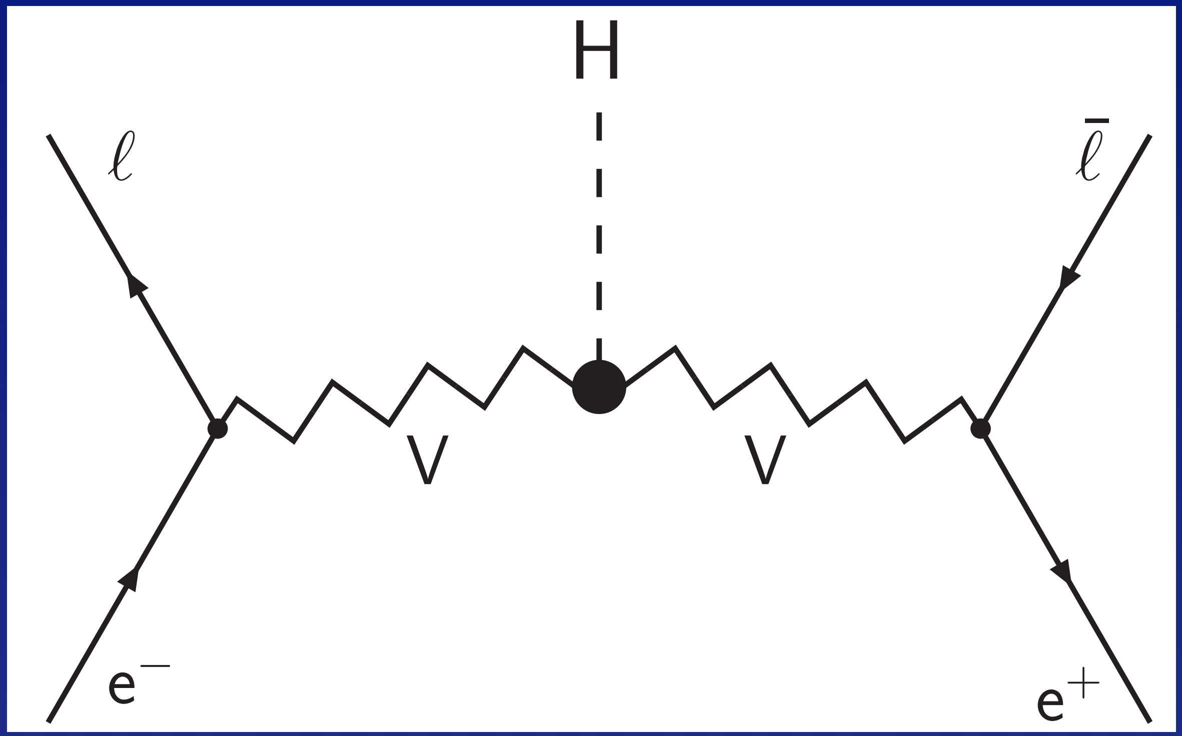
Higgsstrahlung

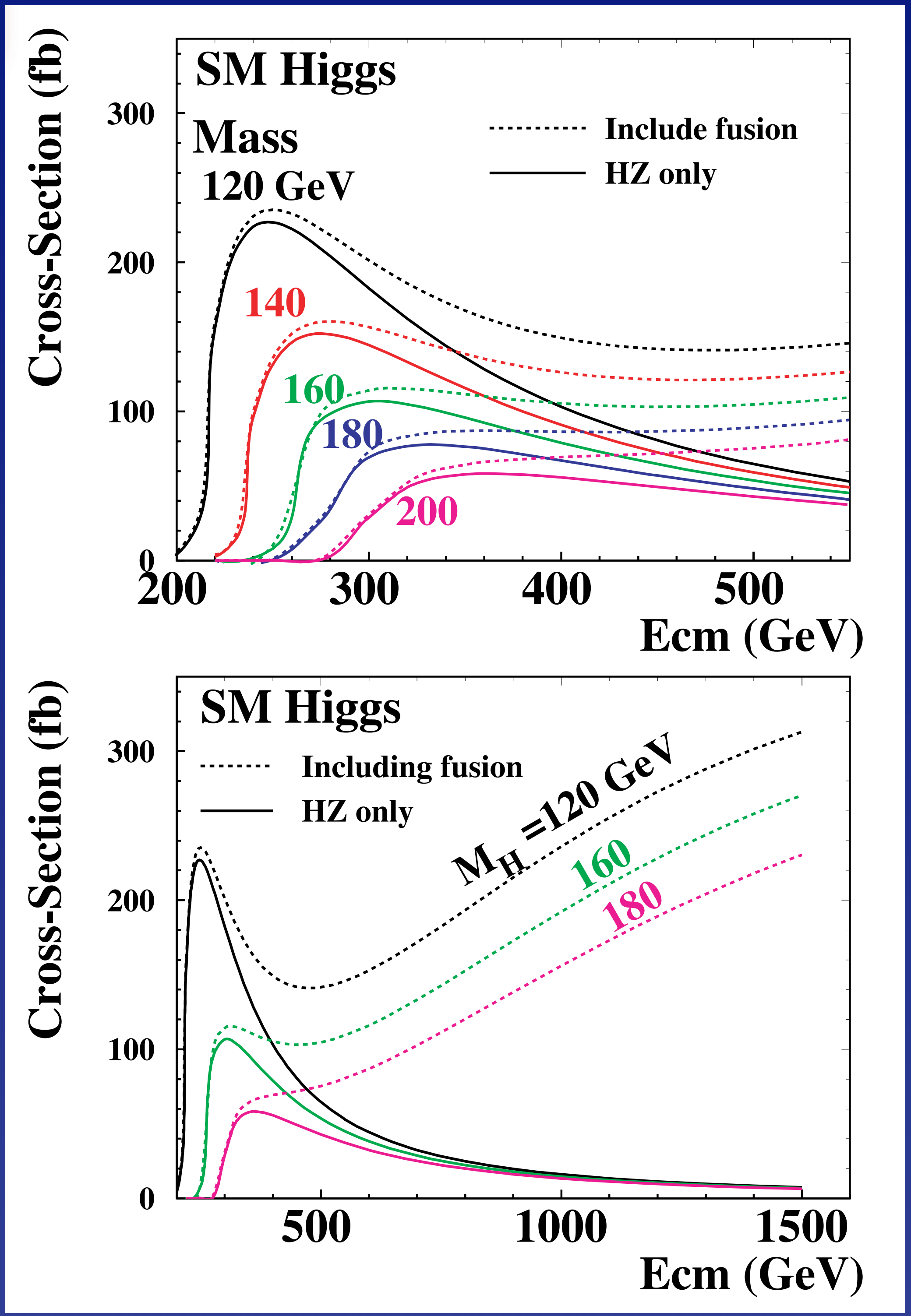


$$\sigma(e^+e^- \to HZ) = \frac{\pi\alpha^2}{24}\left(\frac{2K}{\sqrt{s}}\right)\frac{(K^2+3M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\,\frac{(1-4x_{\rm W}+8x_{\rm W}^2)}{x_{\rm W}^2(1-x_{\rm W})^2}$$

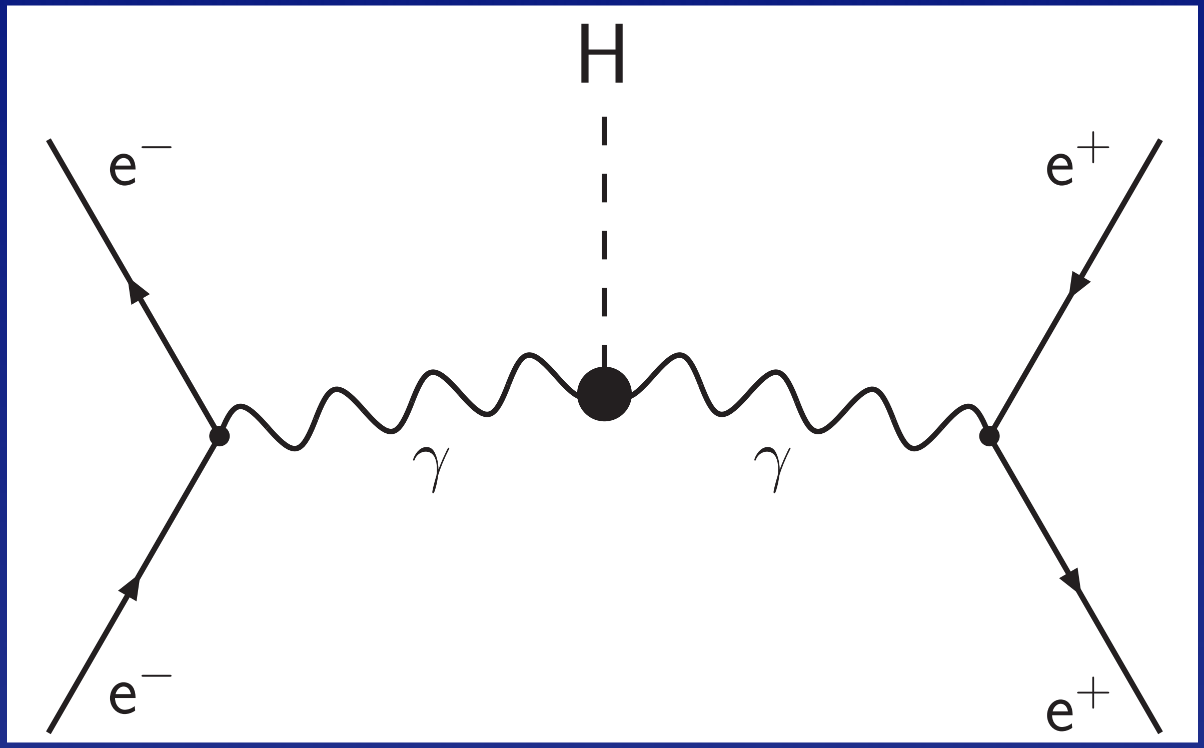
$$x_{\rm W} = \sin^2\theta_{\rm W}; \quad K = \text{c.m. momentum}$$

Vector Boson Fusion





Photon–Photon Collisions



$$\sigma(E) = 16\alpha^2 \frac{\Gamma(H^0 \to \gamma\gamma)}{M_H^3}(2J+1)\ln^2\left(\frac{E}{m_e}\right) f\left(\frac{M_H}{2E}\right)$$

↳ γγ Collider

Important measurements at any moment depend on what is already known

SM-like or very nonstandard

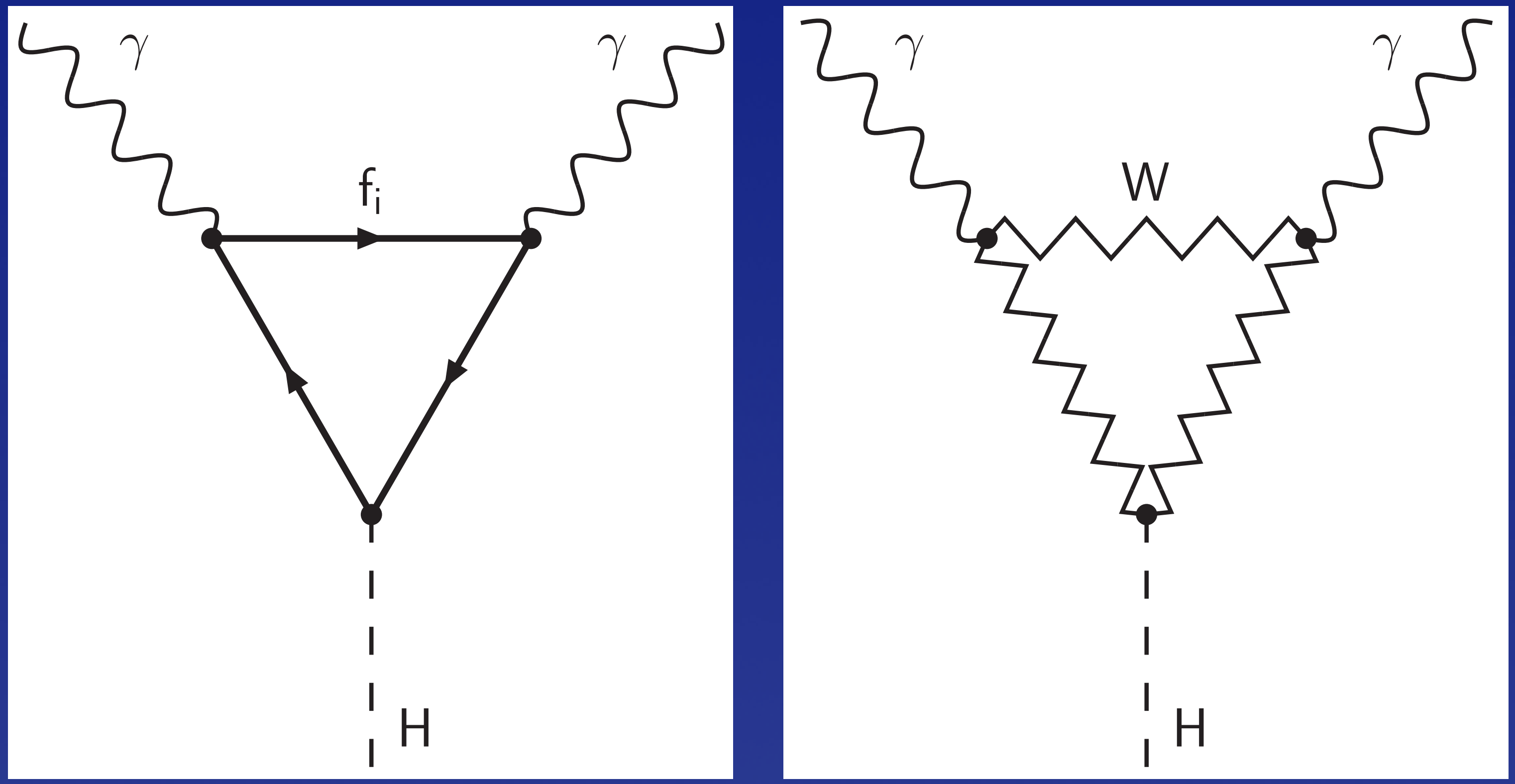
Discovery of another "Higgs-like object"

Direct evidence for or against new degrees of freedom

Examples of non-standard behavior

Spin ≠ 0

deviant γγ branching fraction



↳ New particles in loops (not too heavy)

Examples of non-standard behavior

Suppression of *WW*, *ZZ* modes
Acid test for low-scale technicolor:
Higgs impostor, η_T(125 GeV)
+ higher mass (180 GeV?) companion

Eichten, Lane, Martin arXiv:1210.5462

Not a favorable scenario for a Higgs factory!

Examples of non-standard behavior

"Higgs" is not a simple Breit-Wigner,
or does not account for all of EWSB

Premium on measuring Γ_H
(perhaps 1 GeV),
seeking remaining contribution,
scanning spectral density

van der Bij, arXiv:1204.3435

Snowmass 2013 Higgs Working Group

Table 1-13. *Expected relative precisions on the signal strengths of different Higgs decay final states as well as the 95% CL upper limit on the Higgs branching ratio to the invisible decay from the ZH search estimated by ATLAS and CMS. The ranges are not comparable between ATLAS and CMS. For ATLAS, they correspond to the cases with and without theoretical uncertainties while for CMS they represent two scenarios of systematic uncertainties.*

$\int \mathcal{L}dt$ (fb^{-1})	Higgs decay final state							
	$\gamma\gamma$	WW^*	ZZ^*	$b\bar{b}$	$\tau\tau$	$\mu\mu$	$Z\gamma$	$\mathrm{BR}_{\mathrm{inv}}$
ATLAS								
300	$9-14\%$	$8-13\%$	$6-12\%$	N/A	$16-22\%$	$38-39\%$	$145-147\%$	$< 23-32\%$
3000	$4-10\%$	$5-9\%$	$4-10\%$	N/A	$12-19\%$	$12-15\%$	$54-57\%$	$< 8-16\%$
CMS								
300	$6-12\%$	$6-11\%$	$7-11\%$	$11-14\%$	$8-14\%$	$40-42\%$	$62-62\%$	$< 17-28\%$
3000	$4-8\%$	$4-7\%$	$4-7\%$	$5-7\%$	$5-8\%$	$14-20\%$	$20-24\%$	$< 6-17\%$

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Table 1-16. *Uncertainties on coupling scaling factors as determined in a completely model-independent fit for different e^+e^- facilities. Precisions reported in a given column include in the fit all measurements at lower energies at the same facility, and note that the model independence requires the measurement of the recoil HZ process at lower energies. ‡ILC luminosity upgrade assumes an extended running period on top of the low luminosity program and cannot be directly compared to TLEP and CLIC numbers without accounting for the additional running period. ILC numbers include a 0.5% theory uncertainty. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.*

Facility	ILC			ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	< 0.9%	< 0.9%	0.4%	0.19%	< 0.19%			

Requirements for a shopper's guide

Clearly stated assumptions

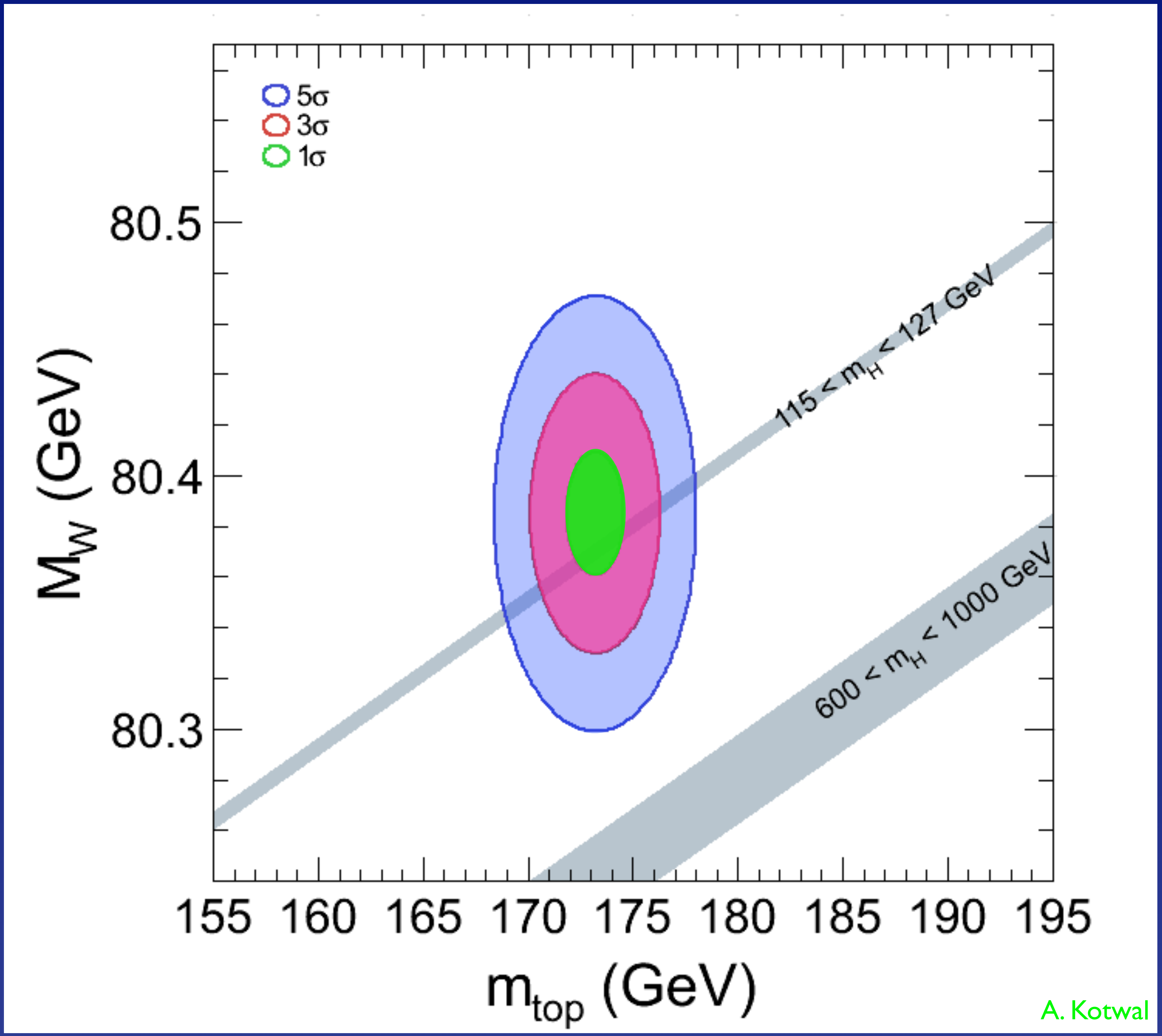
Documented uncertainty estimates

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)

Collateral Measurements: M_W, m_t?



Will it be important to improve on Tevatron + LHC?

As you elaborate machine concepts …

Important not to narrow the physics vision
by pretending we know the answer

Couplings

Distributions

Mass / width

Searches in the Higgs sector

Searches beyond the Higgs sector

Other parameters: M_W, m_t

Back to Z^0?

Toward the next *pp* collider

Explore

Search

Measure

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?

Is it the standard-model Higgs boson?

Do not get ahead of the evidence!

How well must we know its properties?

Couples to fermions beyond 3rd generation?

Can we show H gives rise to m_e?

$H \to VV$ couplings: WW scattering vs E?

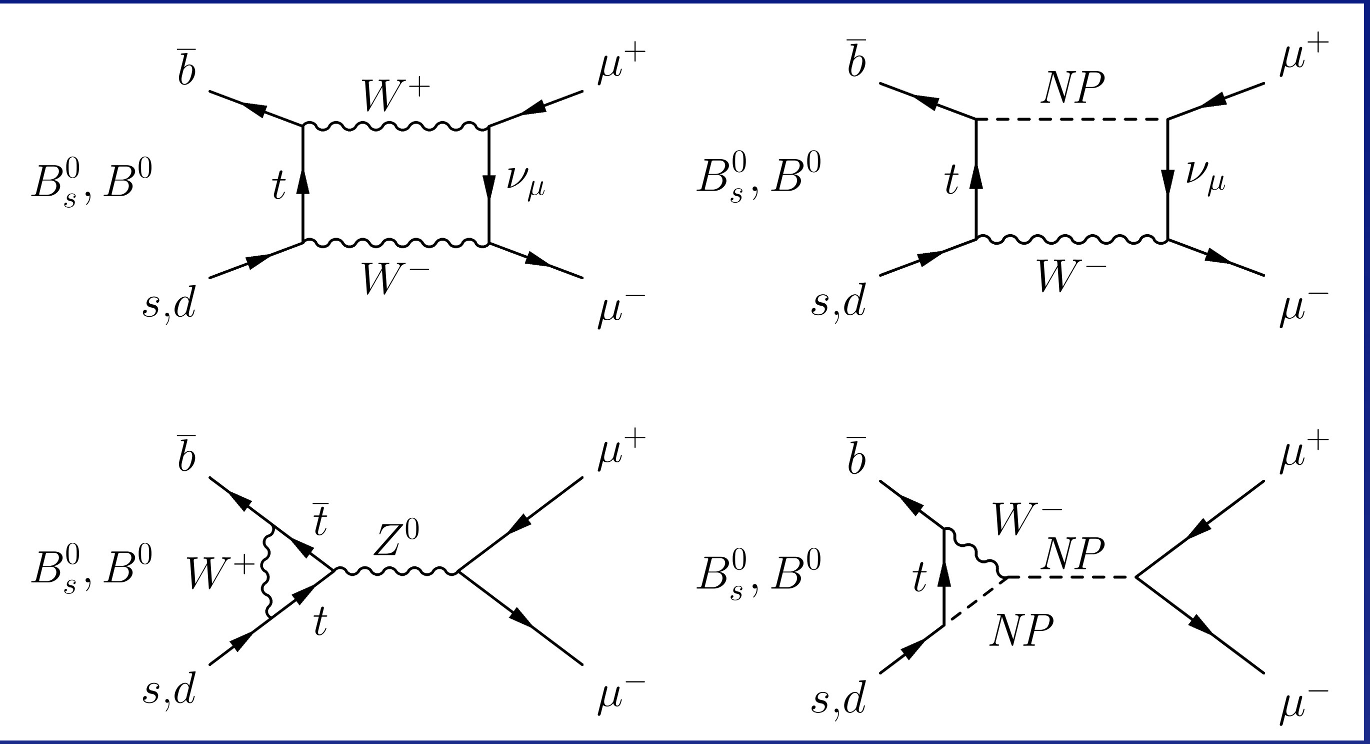
Puzzle #1: Expect *New Physics* on TeV scale
to stabilize Higgs mass, solve hierarchy problem,
but no sign of flavor-changing neutral currents.
Minimal flavor violation a name, not yet an answer

Great interest in searches for
forbidden or suppressed processes

Puzzle #2: Expect *New Physics* on TeV scale
to stabilize Higgs mass, solve hierarchy problem,
but no quantitative failures of EW theory

arXiv:0905.3187

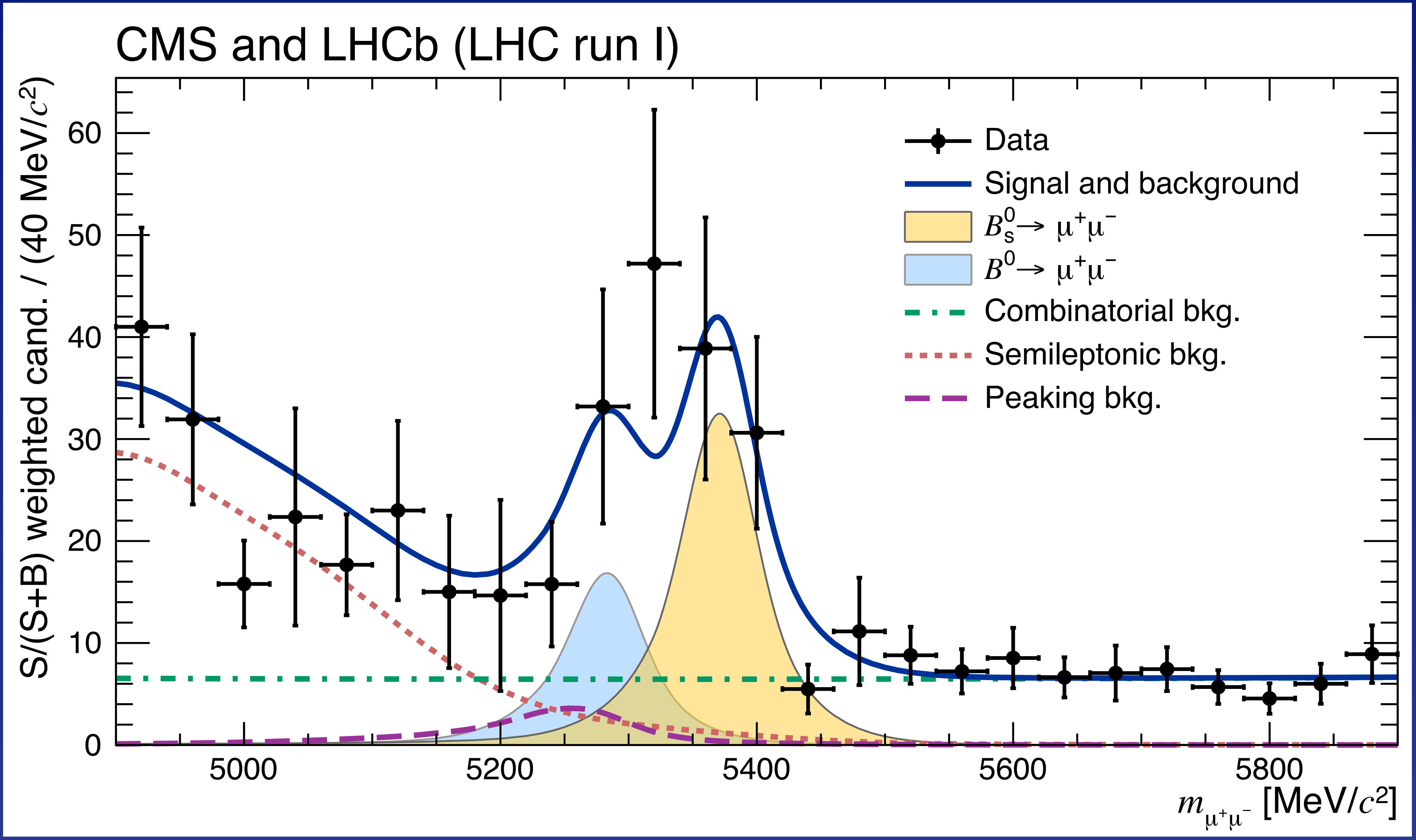
Rare Processes: Flavor-changing neutral currents



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

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

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



≈ SM rate

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

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

1983-1984 was also a charmed time

Neutral currents

Parity violation in ed

c, τ, *b* discoveries

W, *Z* discovery

Importance of TeV scale recognized

Tevatron (SC synchrotron) operated

Supersymmetry invented

SSC conceived, parameters not fixed

The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: *identify a tipping point*

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

Very primitive tools:
No suitable pdfs

Detectors limited to 10^{32}?
No SVX

SUSY σ computed
for $p^{\pm}p$ and e^+e^-

Potential of VBF recognized

1984:

Supercollider physics

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Eichten *et al.* summarize the motivation for exploring the 1-TeV ($=10^{12}$ eV) energy scale in elementary particle interactions and explore the capabilities of proton-(anti)proton colliders with beam energies between 1 and 50 TeV. The authors calculate the production rates and characteristics for a number of conventional processes, and discuss their intrinsic physics interest as well as their role as backgrounds to more exotic phenomena. The authors review the theoretical motivation and expected signatures for several new phenomena which may occur on the 1-TeV scale. Their results provide a reference point for the choice of machine parameters and for experiment design.

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I. INTRODUCTION

The physics of elementary particles has undergone a remarkable development during the past decade. A host of new experimental results made accessible by a new generation of particle accelerators and the accompanying rapid convergence of theoretical ideas have brought to the subject a new coherence. Our current outlook has been shaped by the identification of quarks and leptons as fundamental constituents of matter and by the gauge theory synthesis of the fundamental interactions.[1] These developments represent an important simplification of

[1]For expositions of the current paradigm, see the textbooks by Okun (1981), Perkins (1982), Aitchison and Hey (1982), Leader and Predazzi (1982), Quigg (1983), and Halzen and Martin (1984) and the summer school proceedings edited by Gaillard and Stora (1983).

Explicit calculations + Parton luminosities

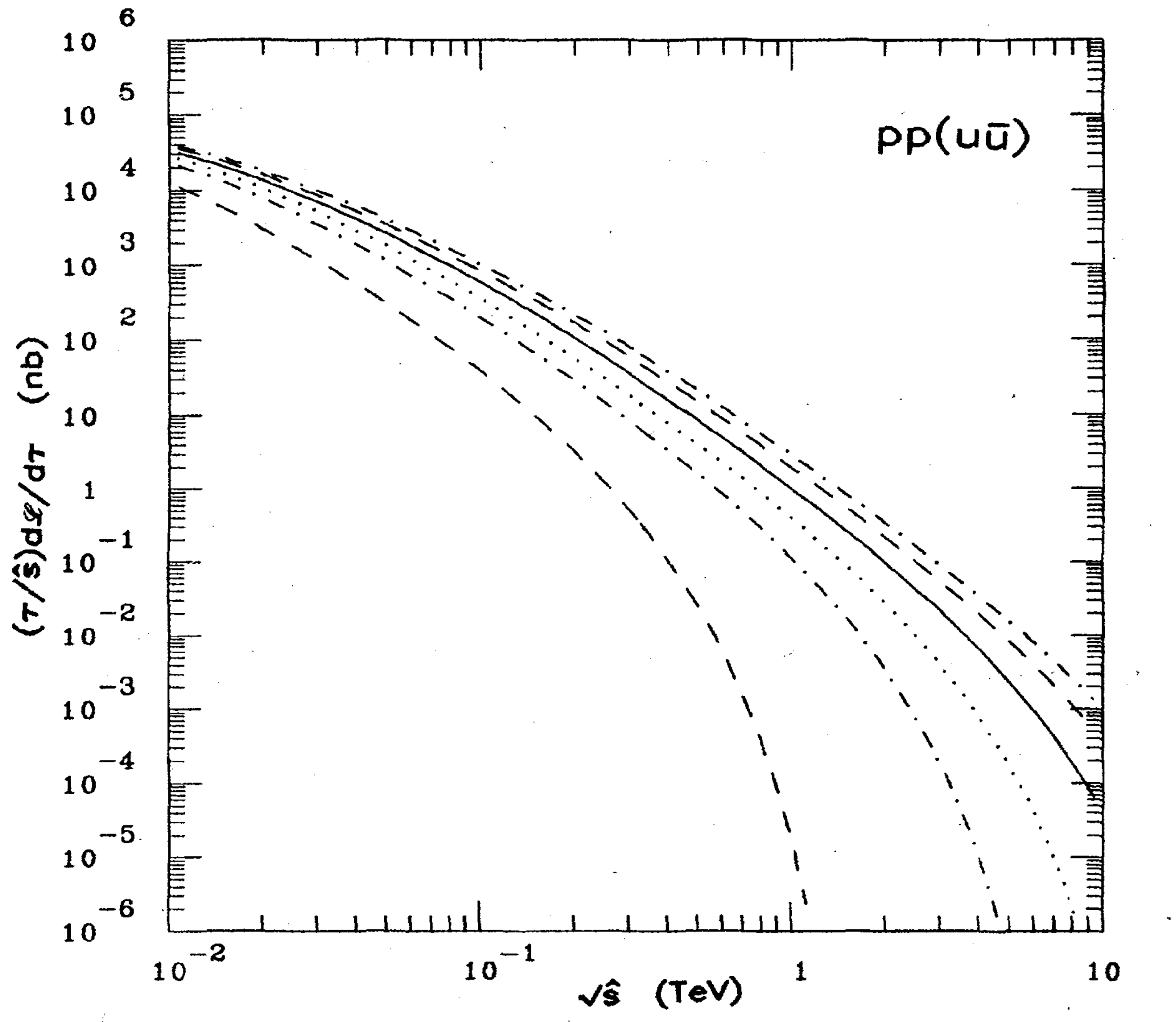


FIG. 40. Quantity $(\tau/\hat{s})d\mathscr{L}/d\tau$ for $u\bar{u}$ interactions in proton-proton collisions.

$\sqrt{s}$ = 2, 10, 20, 40, 70, 100 TeV

Parton luminosities

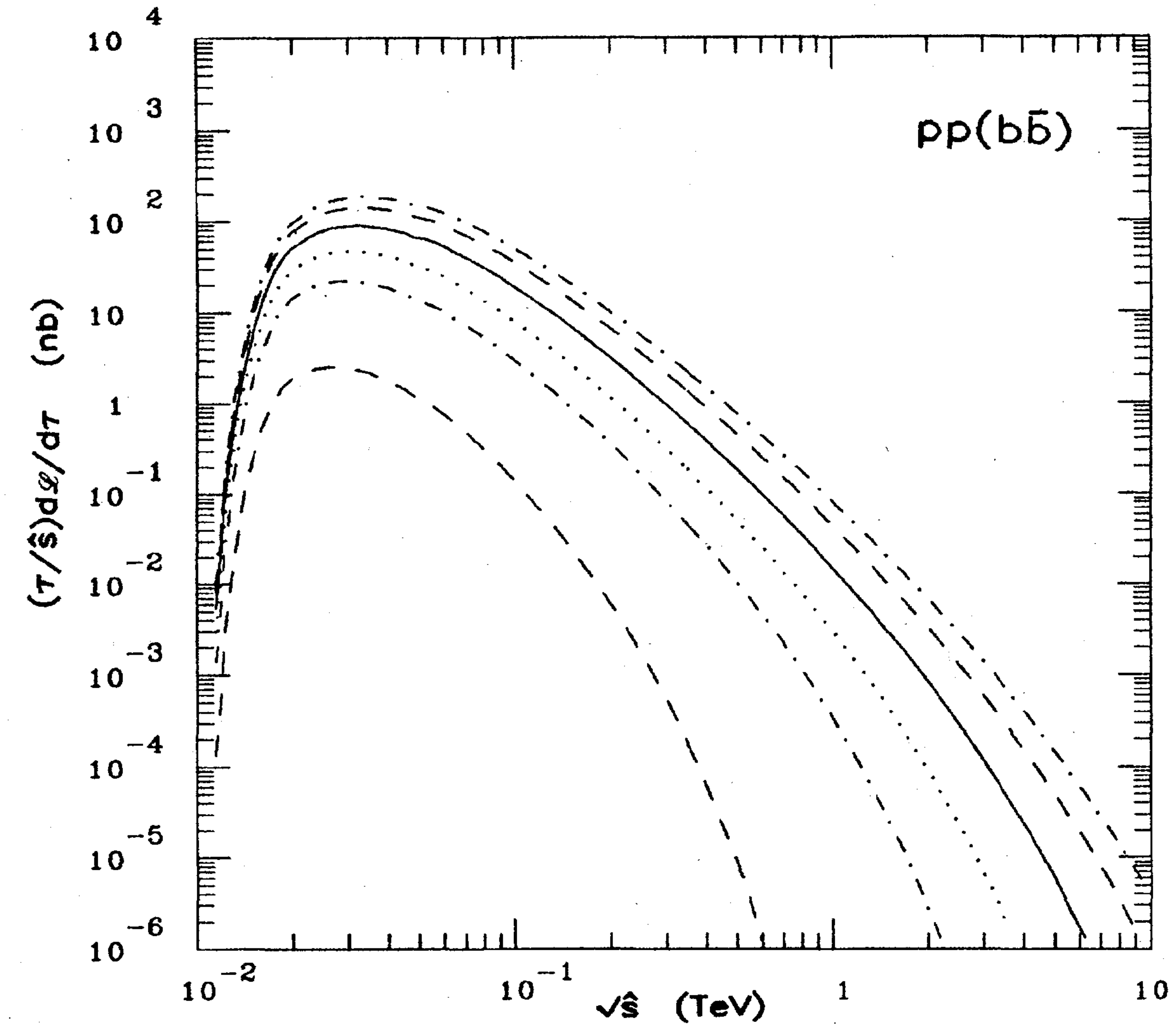


FIG. 49. Quantity $(\tau/\hat{s})d\mathcal{L}/d\tau$ for $b\bar{b}$ interactions in proton-proton collisions.

$\sqrt{s}$ = 2, 10, 20, 40, 70, 100 TeV

Parton luminosity contours

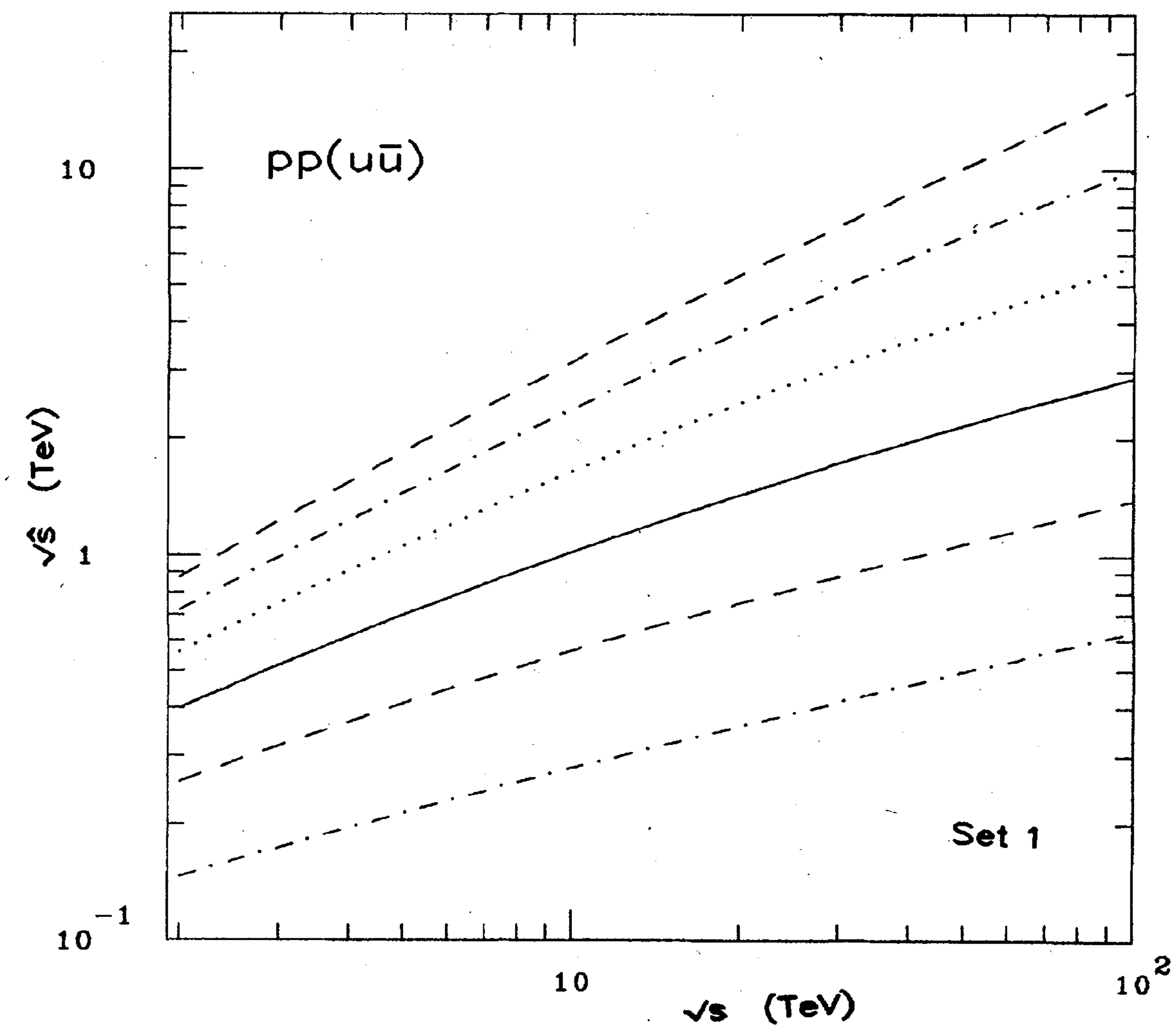


FIG. 64. Contours of $(\tau/\hat{s})d\mathscr{L}/d\tau$ for $u\bar{u}$ interactions in pp collisions according to the parton distributions of Set 1. Lines correspond to 10^4, 10^3, 10^2, 10, 1, and 0.1 pb.

Parton luminosity ratios

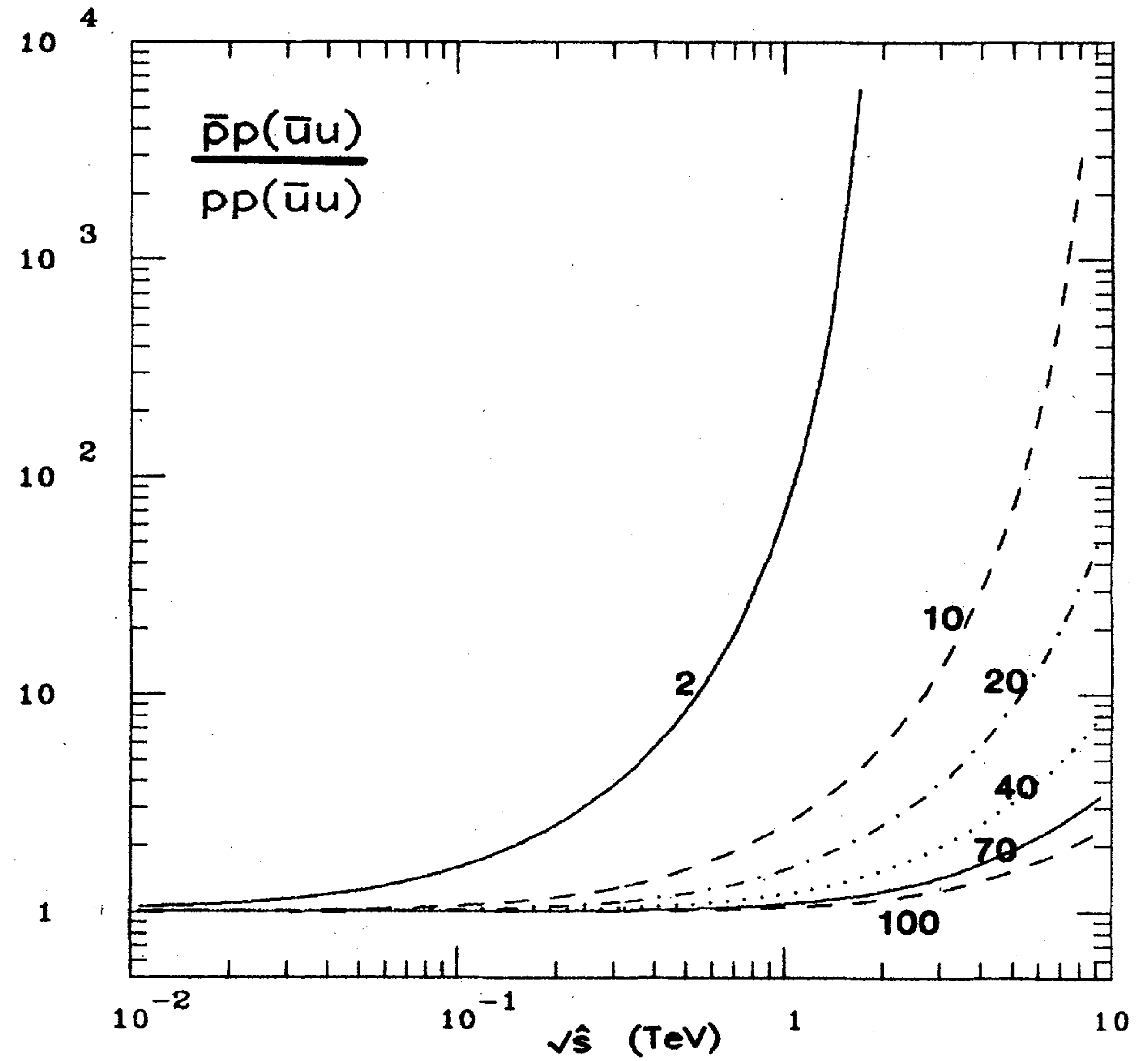


FIG. 57. Ratio of $(\tau/\hat{s})d\mathscr{L}/d\tau$ for $u\bar{u}$ interactions in $\bar{p}p$ and pp collisions, according to the parton distributions of Set 2. Collider energies $\sqrt{s}$ are given in TeV.

Discovery reach: 2 jets

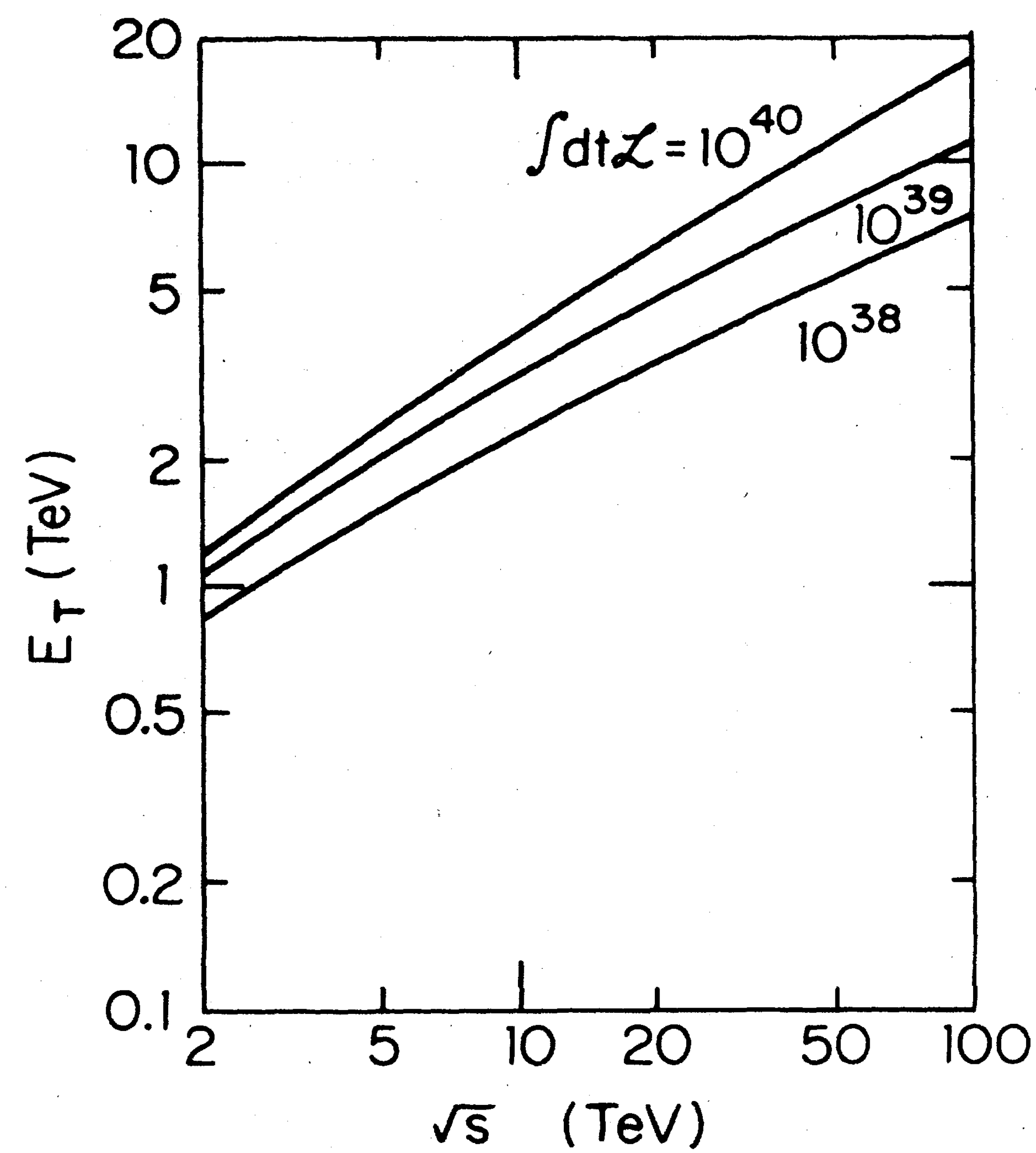
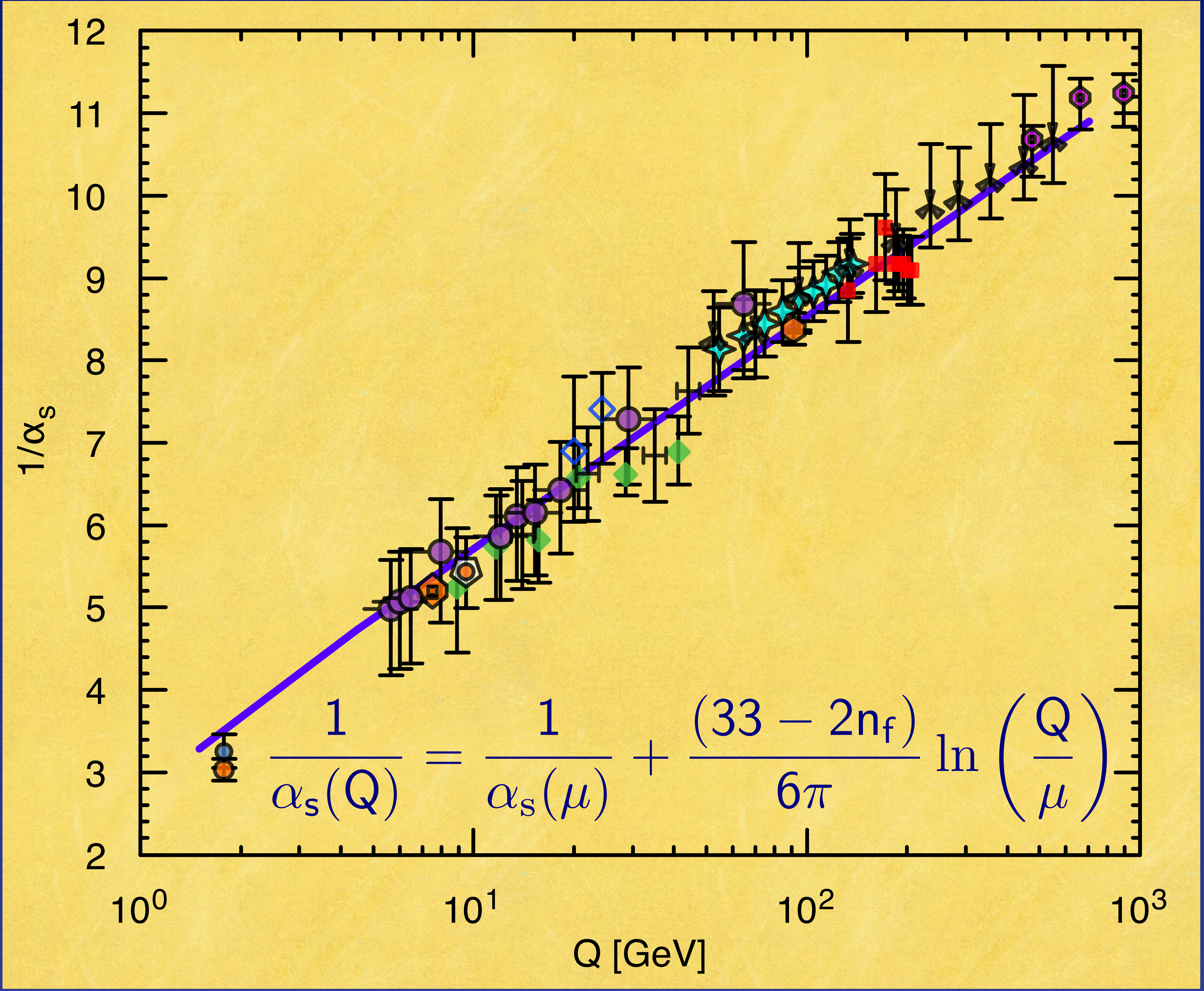


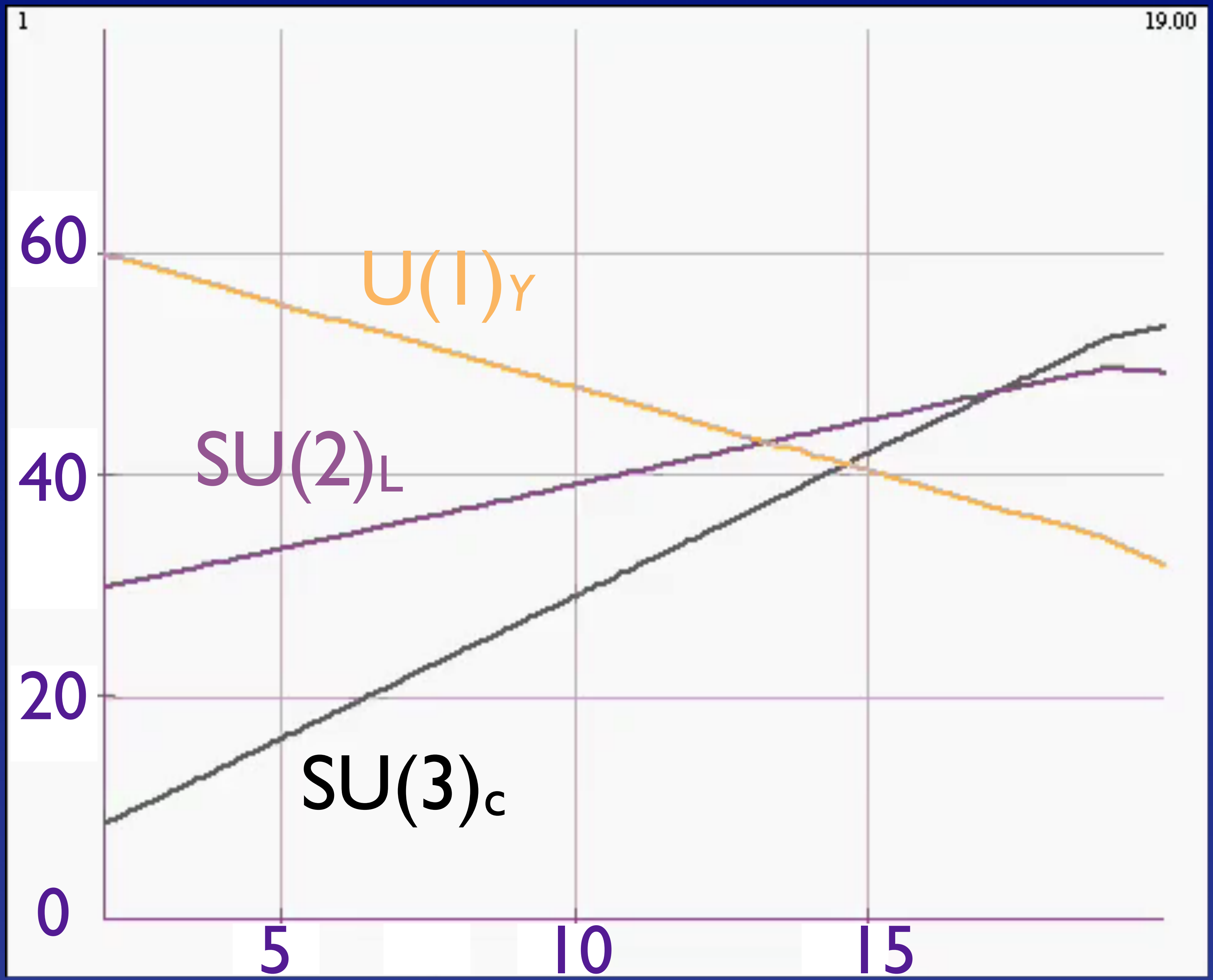
FIG. 104. Discovery reach of hadron colliders for the observation of two-jet events, according to the parton distributions of Set 2, for integrated luminosities of 10^{38}, 10^{39}, and 10^{40} cm^{-2}.

Evolution of the strong coupling "constant"



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

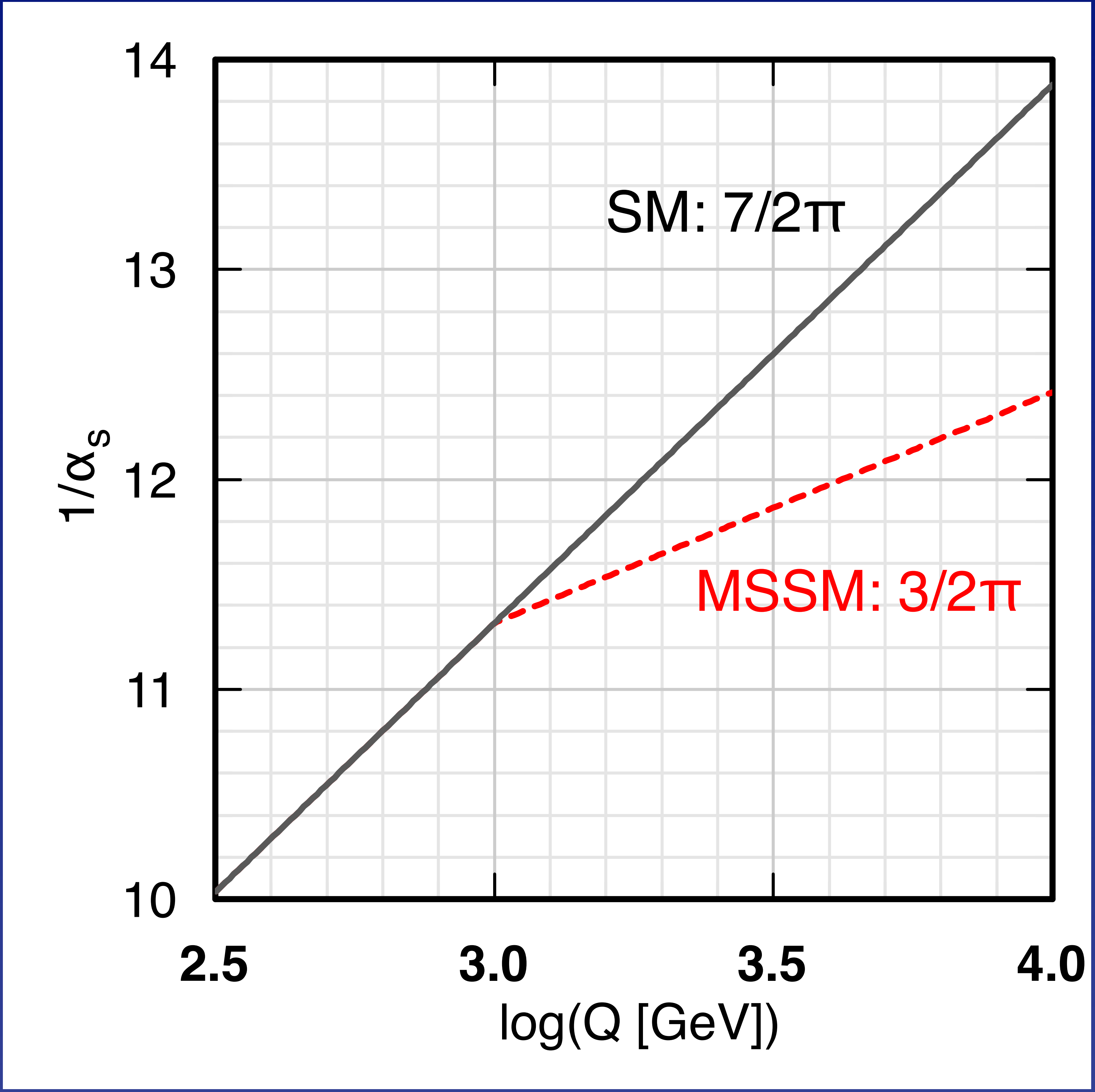
Unification of Forces?



$$1/\alpha$$

$$\log_{10}\left(\frac{E}{1\ \mathrm{GeV}}\right)$$

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



Develop examples that will stretch detector capabilities

The ability to tag and measure heavy quarks and tau leptons would significantly enhance the incisiveness of many searches.

Imagine special-purpose detectors

Explore a range of collider energies; investigate Luminosity / Energy tradeoffs

Develop tools that enable others to extend the work

No general relationship for E vs $\mathscr{L}$

●There is no general relationship that governs energy-luminosity tradeoffs, but a few rules of thumb are useful for orientation.

(i) For a number of processes, and for 10 TeV $\lesssim \sqrt{s} \lesssim 40$ TeV with $\int dt\, \mathscr{L} \gtrsim 10^{38}\ \mathrm{cm}^{-2}$, a factor-of-10 increase in luminosity is roughly equivalent to a factor-of-2 increase in the c.m. energy. Processes for which this rule holds are those for which we deemed background unimportant, so that the discovery criterion was some number of events produced. Examples include the production of massive quark pairs or additional intermediate bosons, and signals for compositeness in high-$p_\perp$ jets or high-mass dileptons.

(ii) At fixed c.m. energy, physics reach increases much more rapidly with increasing luminosity below $\int dt\, \mathscr{L} = 10^{38}\ \mathrm{cm}^{-2}$ than it does above this value. This is easily understood from the shape of the parton luminosity curves, which fall more and more steeply as $\tau = \hat{s}/s$ increases.

(iii) Near 40 TeV and above, a tenfold increase in luminosity generally corresponds to more than a factor-of-2 increase in c.m. energy. For central production of both low-mass and high-mass particles, this again can be understood from the shapes of the parton-parton luminosities $(\tau/\hat{s})d\mathscr{L}/d\tau$ as functions of s and τ.

(iv) Finally, of course, no increase in luminosity can compensate for c.m. energy below the threshold for a new phenomenon.

Starting point matters for scaling $\mathscr{L}$ with E

Hard processes, minimal background:
HL-LHC $\rightsquigarrow$ 2.5 x 10^{36} cm^{-2} s^{-1} @ 100 TeV
40 TeV, 10^{33} $\rightsquigarrow$ 2.5 x 10^{34} cm^{-2} s^{-1}

Cost, performance, technical risk tradeoffs for collider and detectors

Better to start with physics goals than machismo

It is premature to develop the scientific case for the “100-TeV” collider,

but the right time to explore possibilities.

What we do for “100-TeV” can enhance what we achieve with LHC

LHC might point to an energy landmark

?