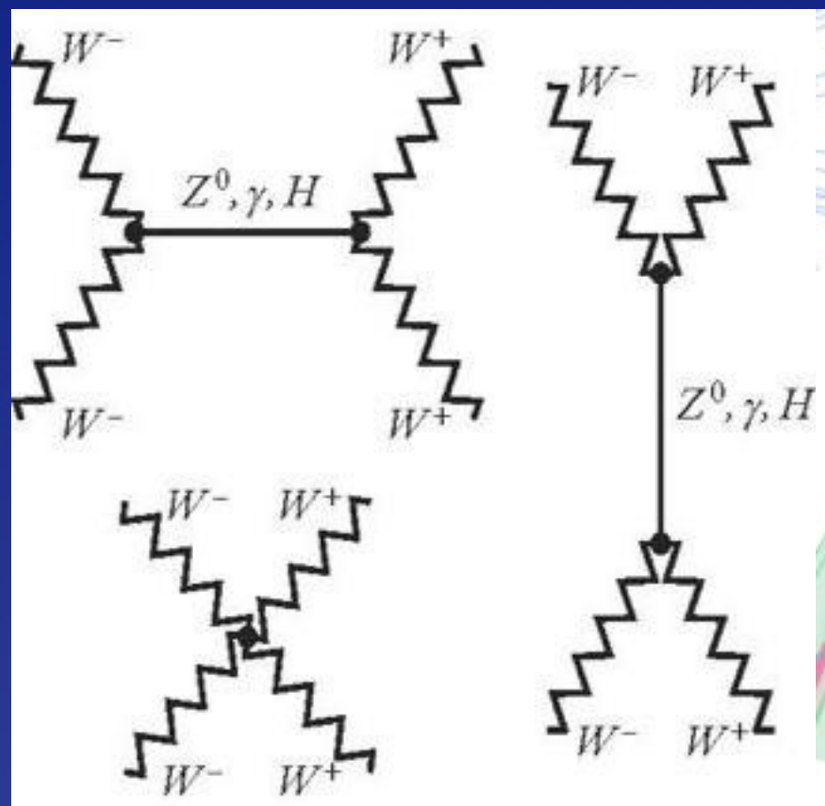
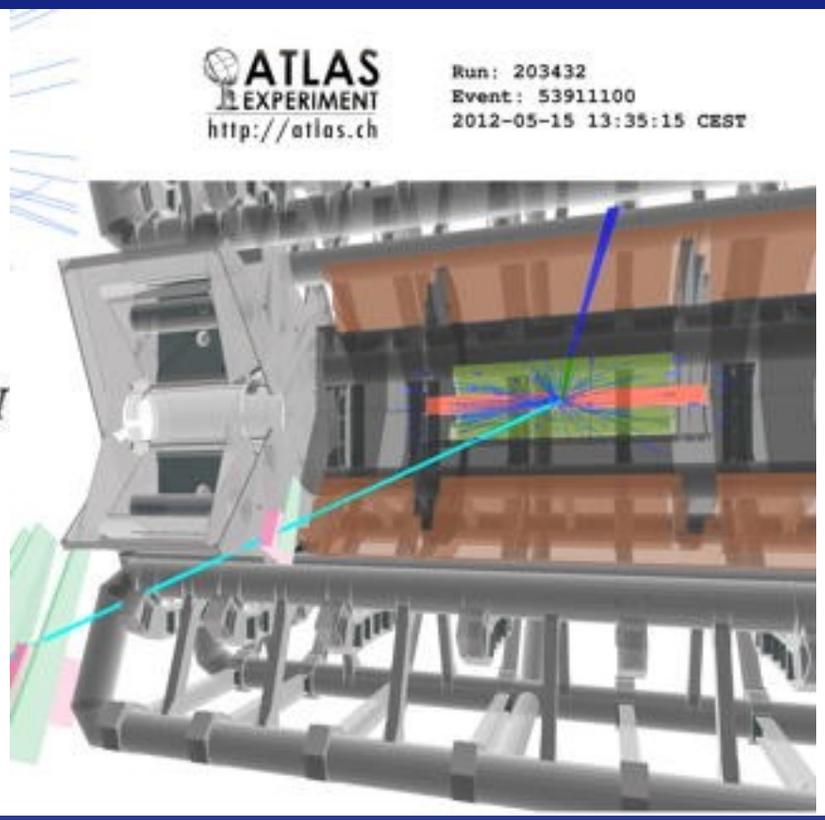
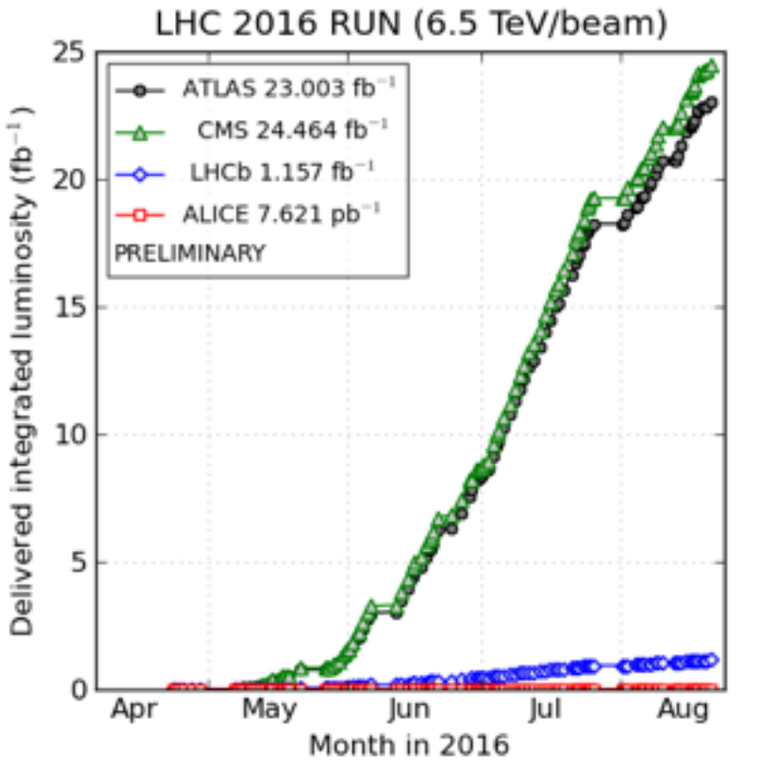
# Impressions of MBI 2016

Chris Quigg
*Fermi National Accelerator Laboratory*




Multi-Boson Interactions 2016 · Madison · 26 August 2016

# Uli Baur

Appreciation

*You people are maniacs!*

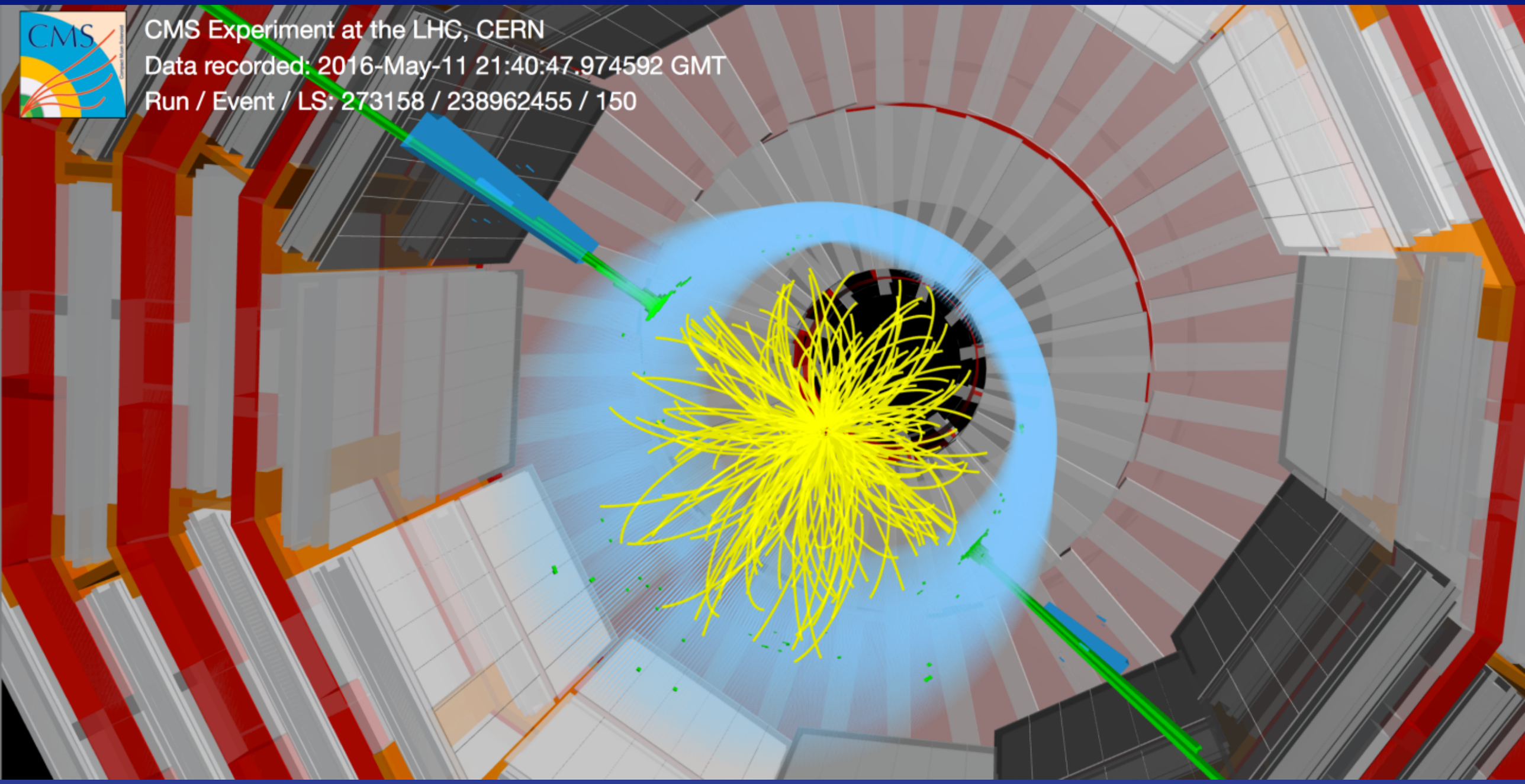
Impressive inventions on all sides

Exemplary dialogue between theory & experiment

Apply elsewhere tools developed here

Integrate MBI with our entire program

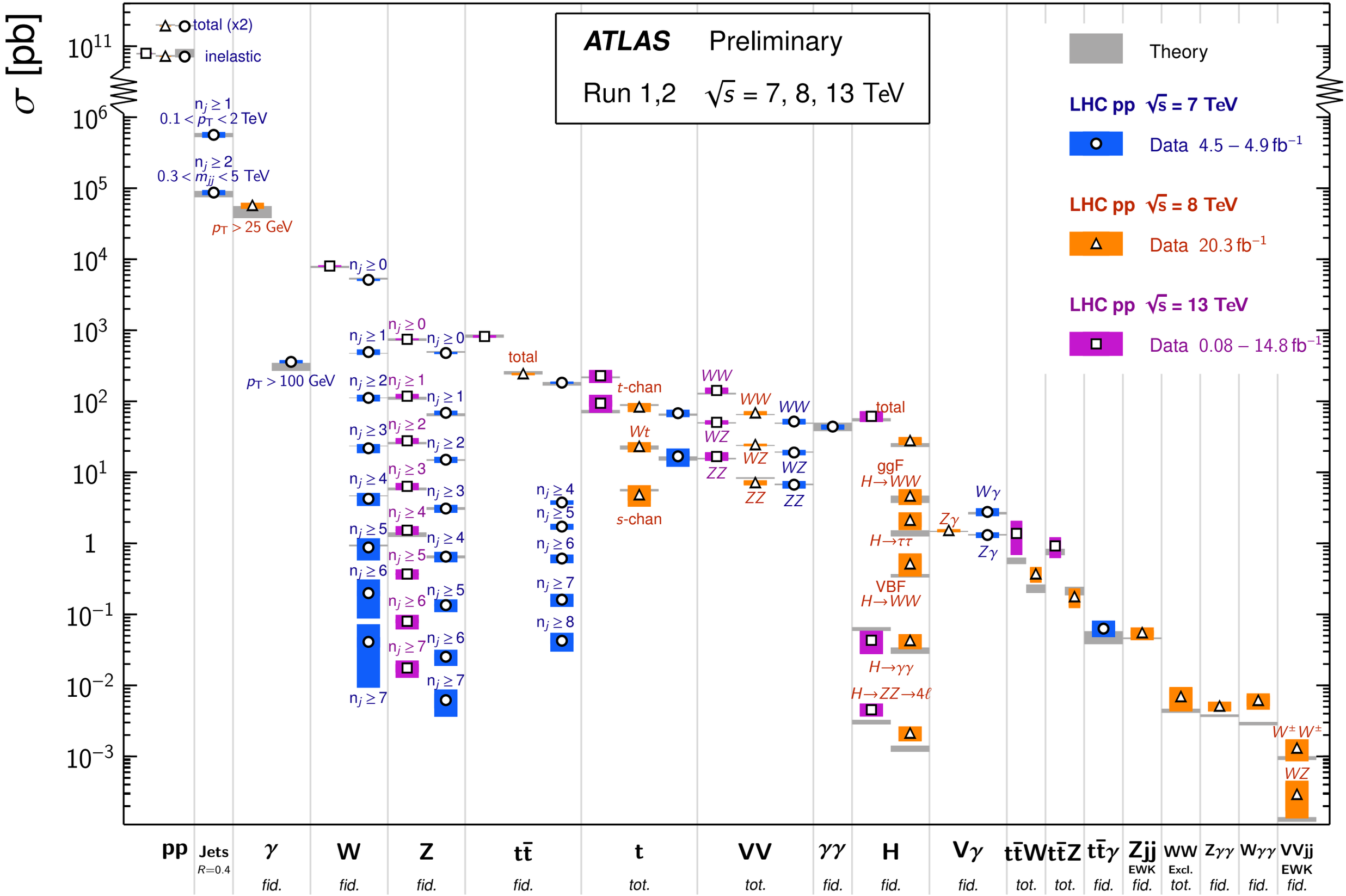
# LHC + detectors: the world's most powerful microscope




Dijet mass ≈ 7.7 TeV

# Standard Model Production Cross Section Measurements

*Status: August 2016*



July 2016

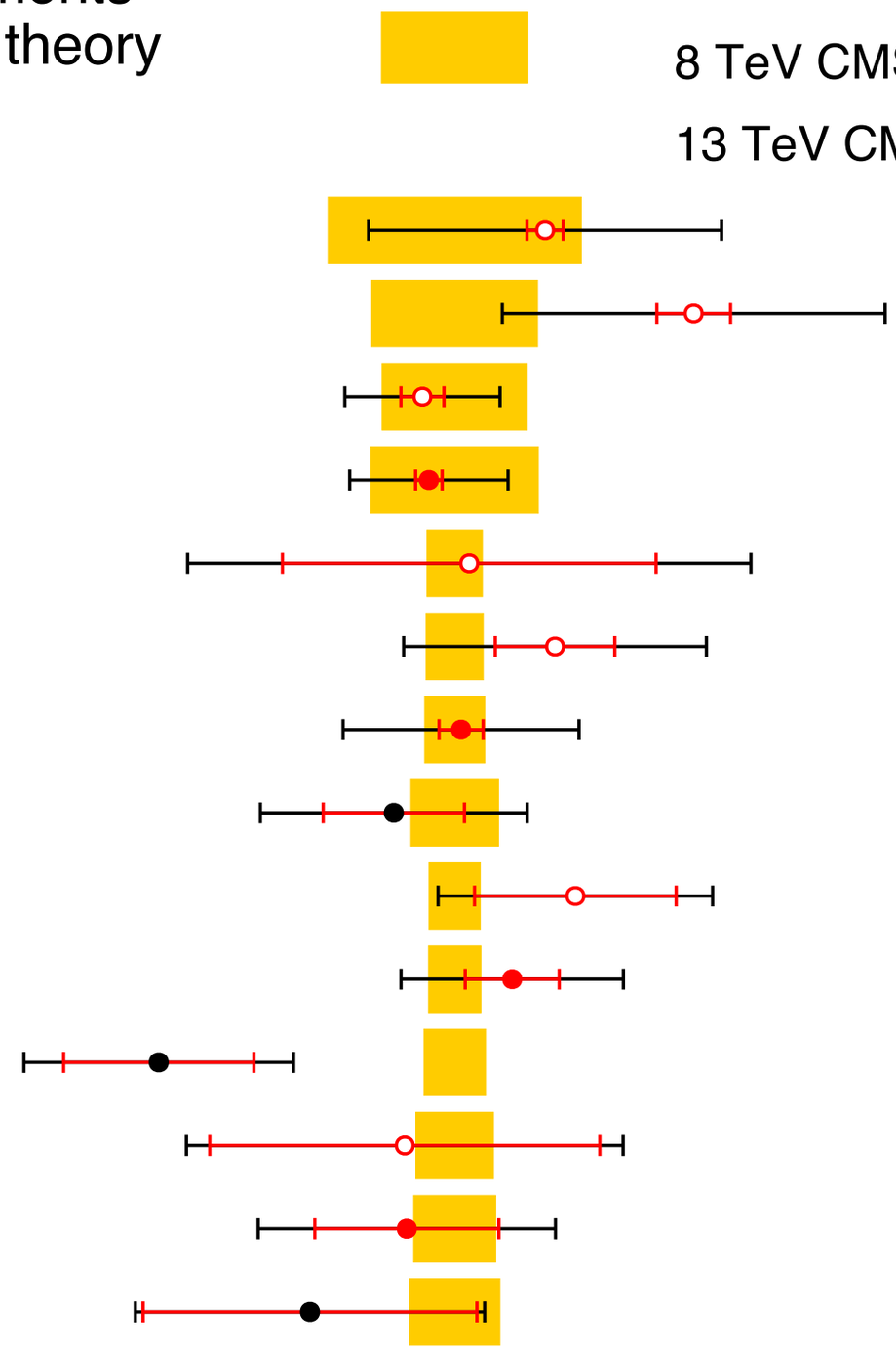
CMS Preliminary

CMS measurements
vs. NNLO (NLO) theory

7 TeV CMS measurement (stat,stat+sys)

8 TeV CMS measurement (stat,stat+sys)

13 TeV CMS measurement (stat,stat+sys)



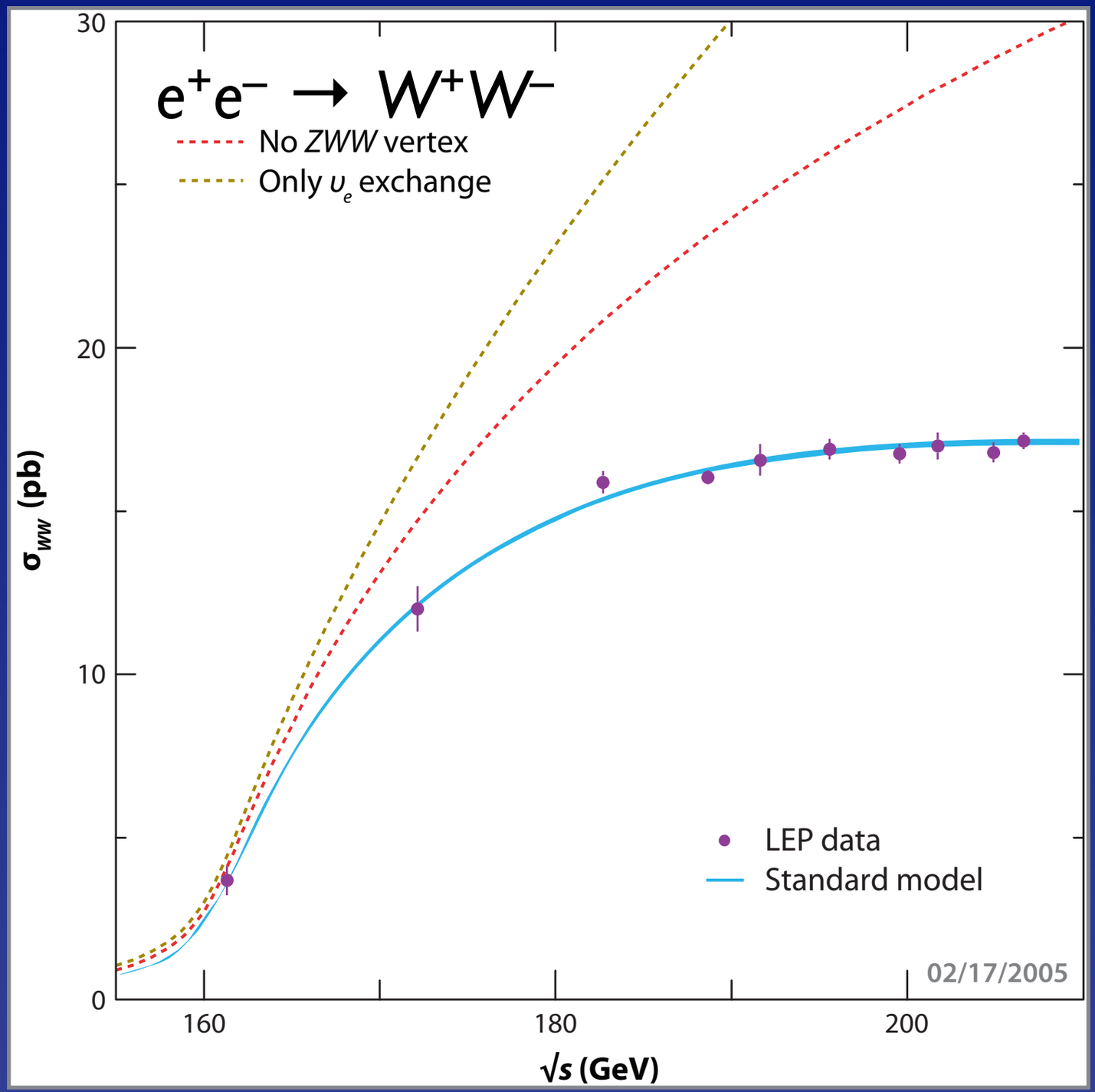
| | | |
|---|---|---|
| $\gamma\gamma$ | $1.06 \pm 0.01 \pm 0.12$ | $5.0\ fb^{-1}$ |
| $W\gamma$, (NLO th.) | $1.16 \pm 0.03 \pm 0.13$ | $5.0\ fb^{-1}$ |
| $Z\gamma$, (NLO th.) | $0.98 \pm 0.01 \pm 0.05$ | $5.0\ fb^{-1}$ |
| $Z\gamma$, (NLO th.) | $0.98 \pm 0.01 \pm 0.05$ | $19.5\ fb^{-1}$ |
| WW+WZ | $1.01 \pm 0.13 \pm 0.14$ | $4.9\ fb^{-1}$ |
| WW | $1.07 \pm 0.04 \pm 0.09$ | $4.9\ fb^{-1}$ |
| WW | $1.00 \pm 0.02 \pm 0.08$ | $19.4\ fb^{-1}$ |
| WW | $0.96 \pm 0.05 \pm 0.08$ | $2.3\ fb^{-1}$ |
| WZ | $1.08 \pm 0.07 \pm 0.06$ | $4.9\ fb^{-1}$ |
| WZ | $1.04 \pm 0.03 \pm 0.07$ | $19.6\ fb^{-1}$ |
| WZ | $0.80 \pm 0.06 \pm 0.07$ | $2.3\ fb^{-1}$ |
| ZZ | $0.97 \pm 0.13 \pm 0.07$ | $4.9\ fb^{-1}$ |
| ZZ | $0.97 \pm 0.06 \pm 0.08$ | $19.6\ fb^{-1}$ |
| ZZ, (NNLO th.) | $0.90 \pm 0.11 \pm 0.04$ | $2.6\ fb^{-1}$ |

0.5 1 1.5 2

All results at:
http://cern.ch/go/pNj7

Production Cross Section Ratio: $\sigma_{exp} / \sigma_{theo}$

# Multiboson interactions revealed secret symmetry



# The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

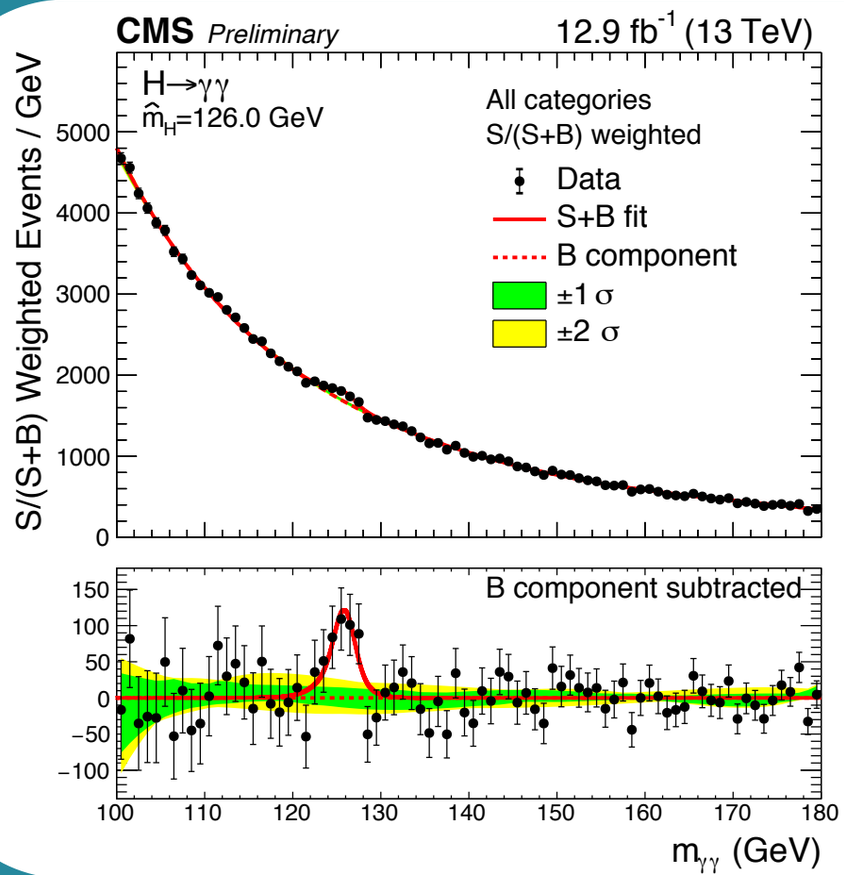
Thought experiment: *conditional upper bound*

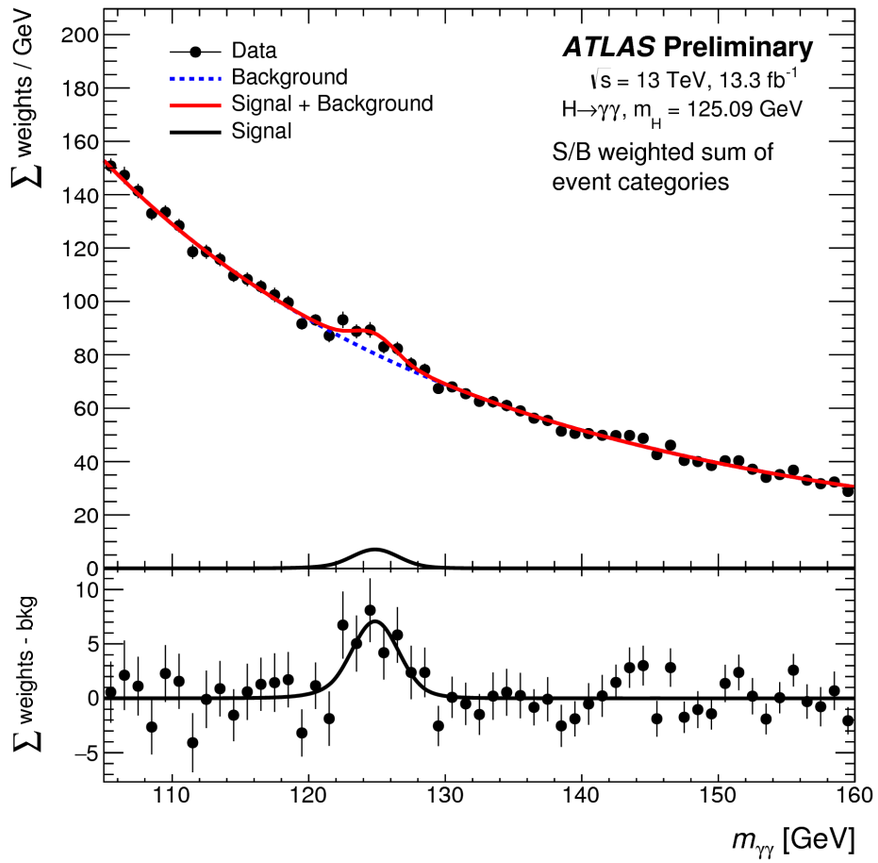
$W^+W^-$, $ZZ$, $HH$, $HZ$ satisfy s-wave unitarity,

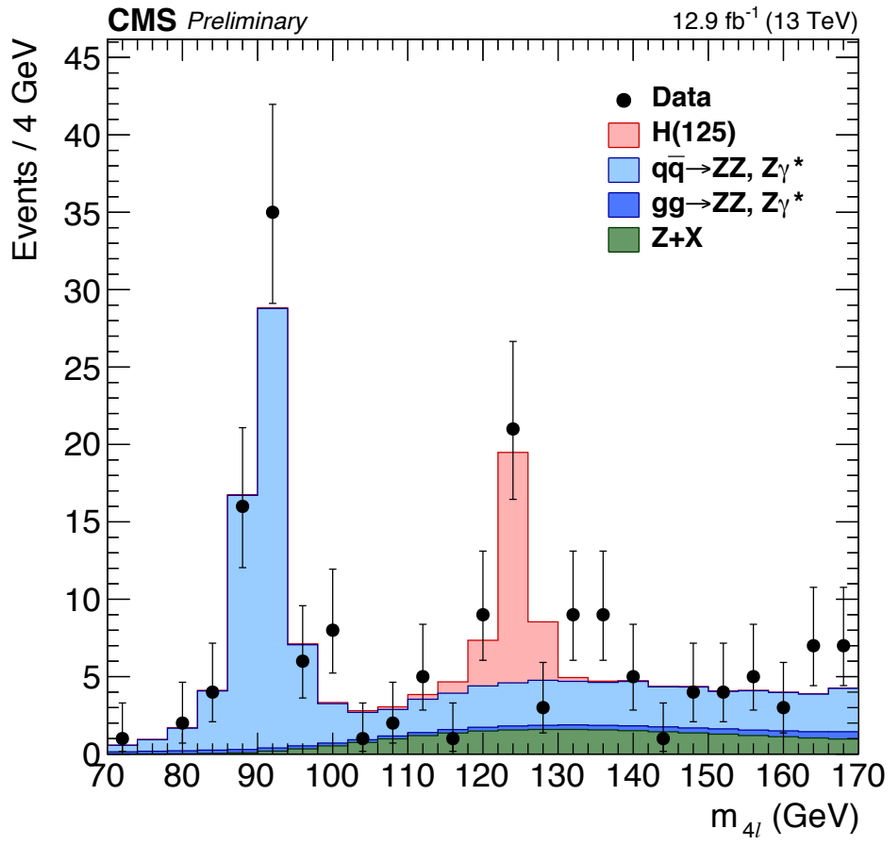
provided $\boxed{M_H \leq (8\pi\sqrt{2}/3G_F)^{1/2} \approx 1\ \text{TeV}}$

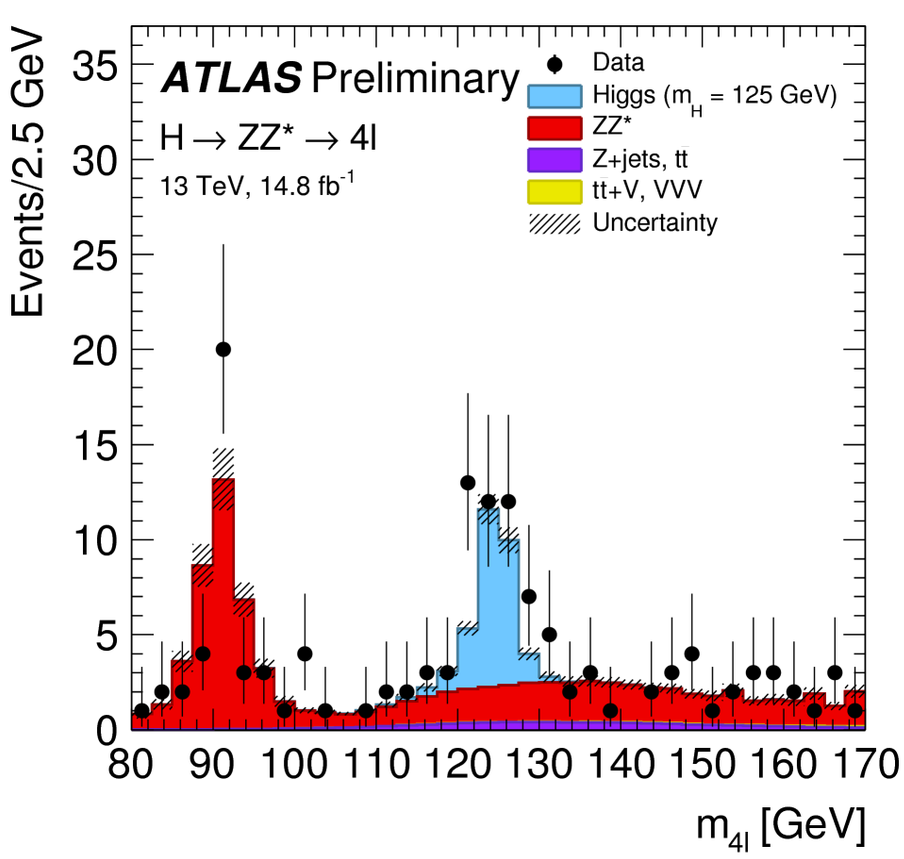
- If bound is respected, perturbation theory is "everywhere" reliable
- If not, weak interactions among $W^{\pm}$, $Z$, $H$ become strong on 1-TeV scale

*New phenomena are to be found around 1 TeV*




Florencia Canelli, ICHEP 2016

# Summary of evidence from LHC Run 1

Evidence is developing as it would for
a "standard-model" Higgs boson

Unstable neutral particle near 125 GeV

$M_H = 125.09 \pm 0.24$ GeV

decays to $\gamma\gamma$, $W^+W^-$, $ZZ$

dominantly spin-parity $0^+$

evidence for $\tau^+\tau^-$, $b\bar{b}$; $t\bar{t}$

*only third-generation fermions tested*

What we expect of the standard-model Higgs sector

Hide electroweak symmetry

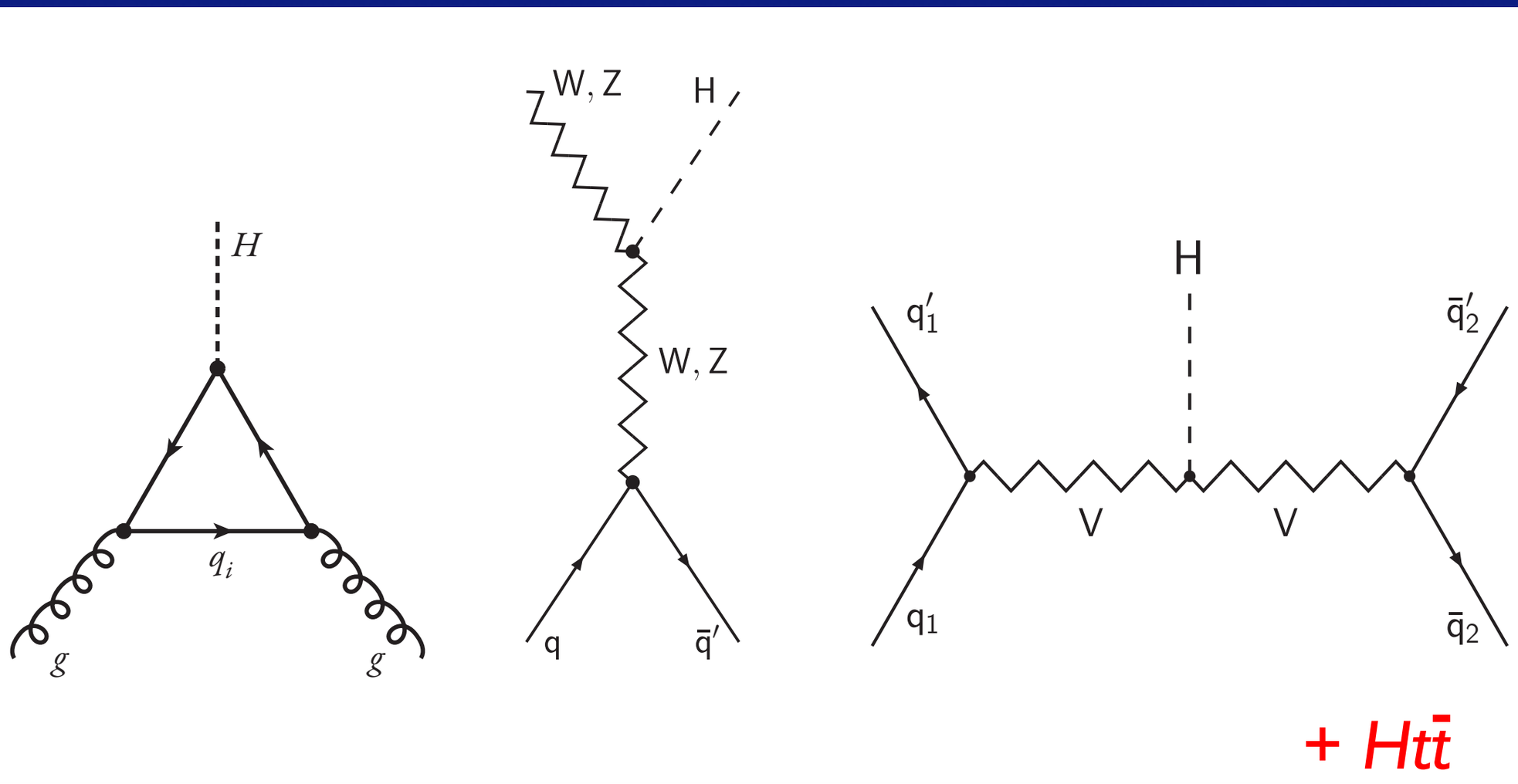
Give masses to *W*, *Z*, *H*

Regulate Higgs-Goldstone scattering

Account for quark masses, mixings } ΦBSM

Account for charged-lepton masses }

# LHC can study Higgs boson in many channels




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

Fully accounts for EWSB ($W, Z$ couplings)?

Couples to fermions?

*t from production,*

*need direct observation for b,* τ

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 $M_H \approx$ 125 GeV?

Any sign of new strong dynamics?

# What is a proton?

At high energy: an unseparated, broadband beam
of quarks, antiquarks, and gauge bosons (primarily gluons),
and perhaps other constituents, yet unknown.

## >40 years of an amazingly robust idealization: Renormalization-group–improved Parton Model

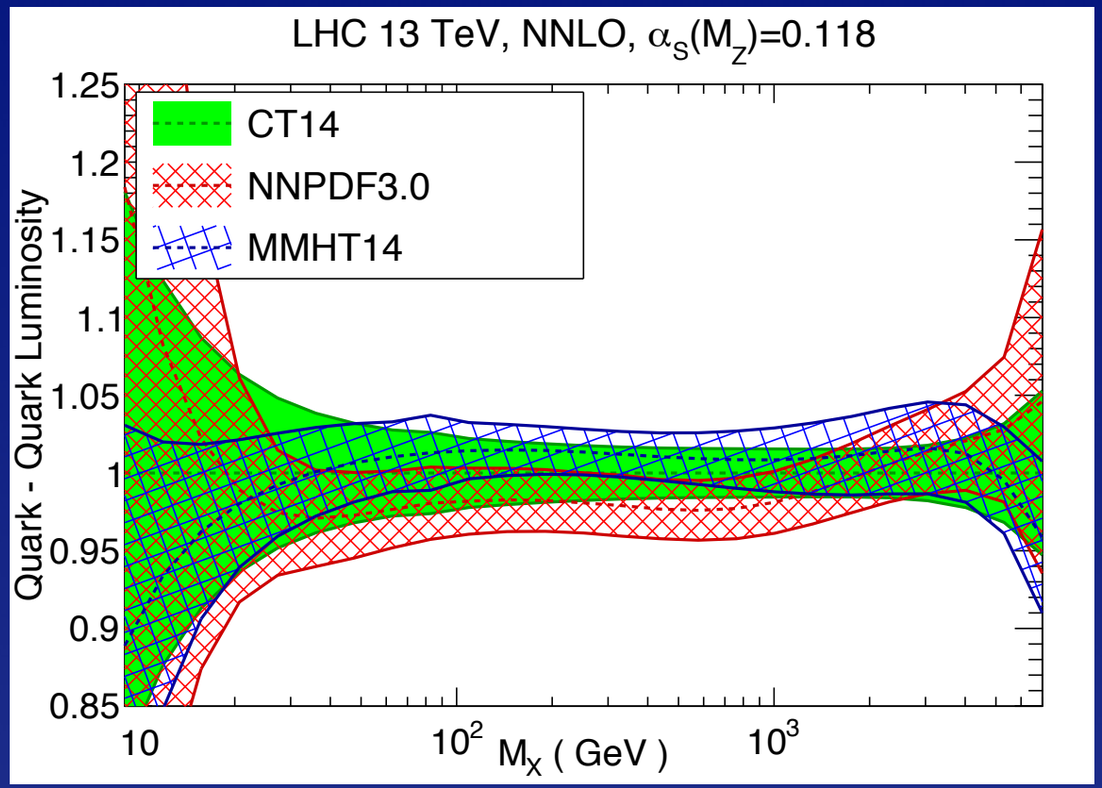
Factorization theorem +
One-dimensional parton distributions,
no correlations among the partons

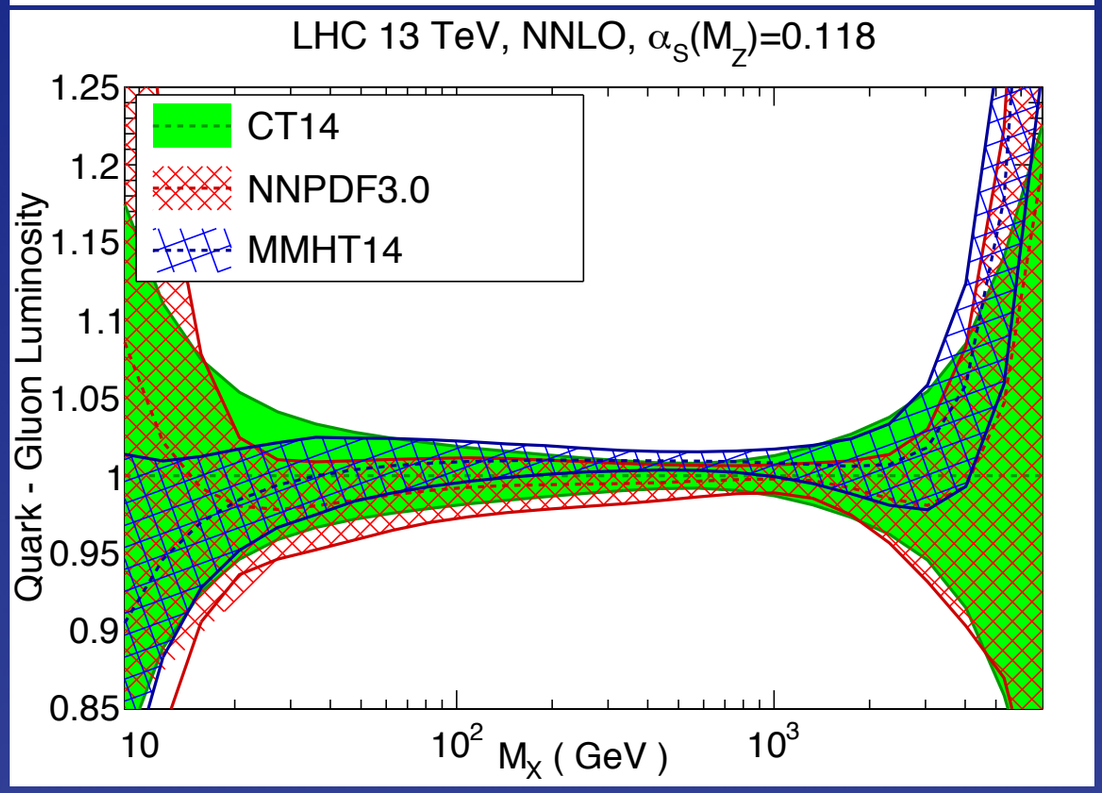
# What is a proton?

Confronting measurements with higher-order calculations has led to the development of highly refined parton distributions that describe a plethora of phenomena over a vast kinematic range and begin to exhibit reliable uncertainty estimates.

This is a remarkable achievement,
the work of many hands,
a testament to creativity and perseverance.

# Improving knowledge of parton luminosities (Huston)



# What is a proton?

The one-dimensional idealization is overcome
by the development of
generalized parton distributions
and transverse-momentum distributions

Studies of elastic and total cross sections at LHC
should lead to improved impact-parameter descriptions
of the stuff in a proton.

*A lively conversation should ensue!*

# What is a proton?

We need to relax approximations made long ago, for lack of data, such as the universality of sea-quark distributions.

$$u_{\rm s}(x) = \bar{u}_{\rm s}(x) = d_{\rm s}(x) = \bar{d}_{\rm s}(x) = \kappa s(x) = \kappa \bar{s}(x)$$

Gluon splitting enforces $q_{\rm s}(x) = \bar{q}_{\rm s}(x)$

Low-scale, nonperturbative processes may not.

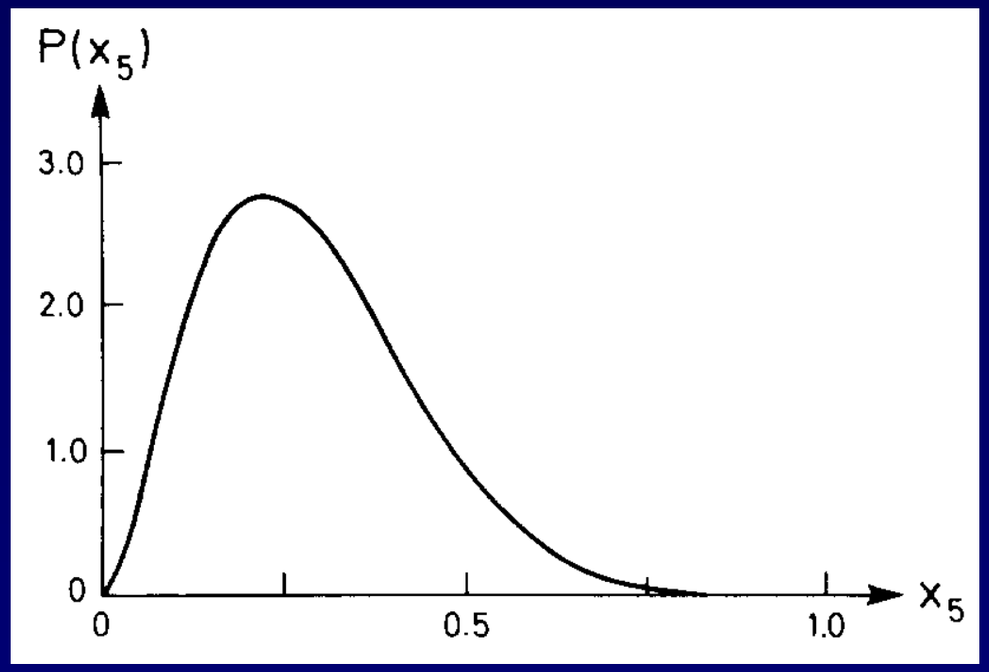
*Increased attention to photon PDFs*

# Intrinsic charm of the proton (some hints)

Brodsky et al., *Phys. Lett.* **93B**, 451 (1980)

Assertion: all constituents move with a common velocity

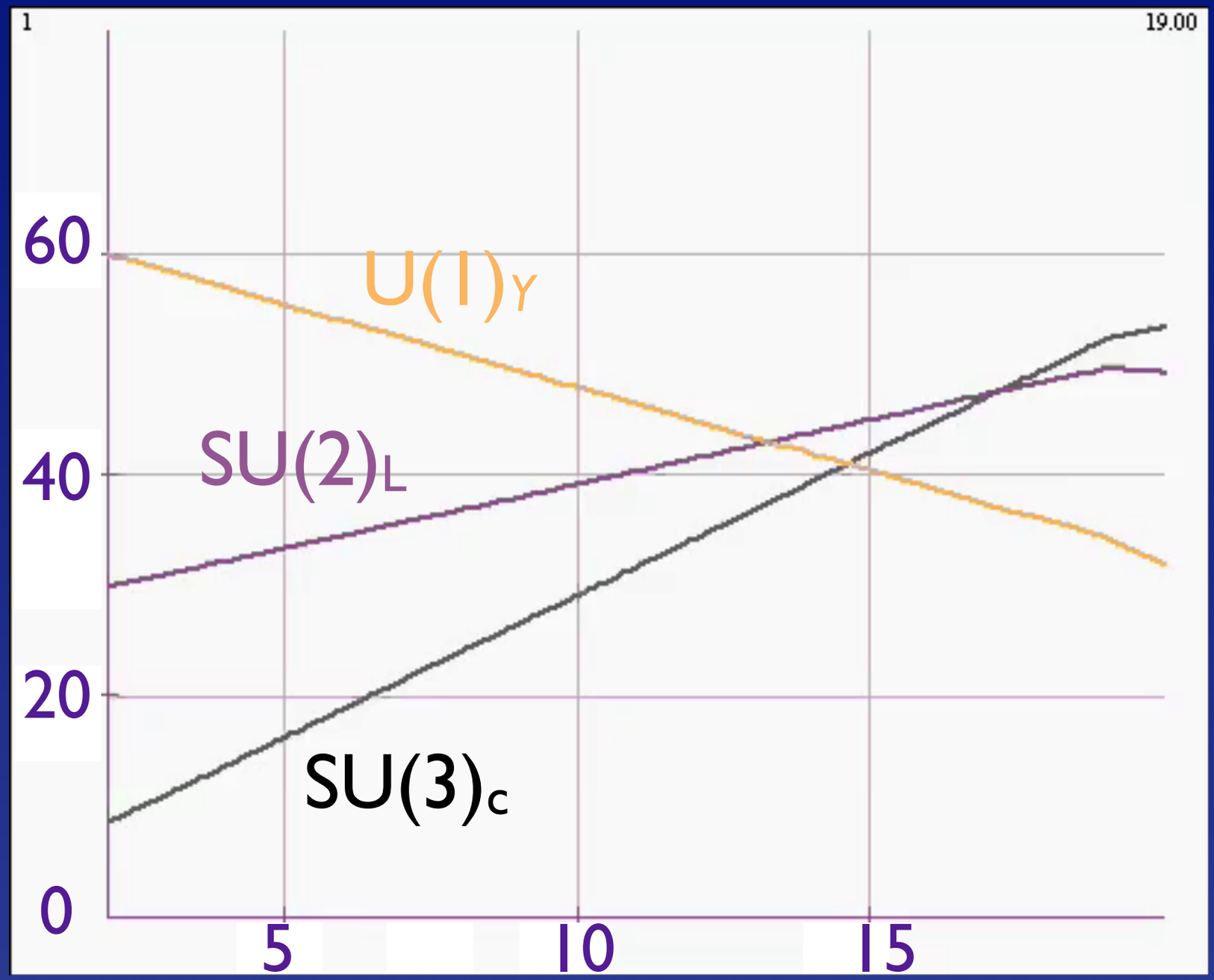
$\therefore$ in a $uudc\bar{c}$ Fock state, $c$ quarks populate large $x$



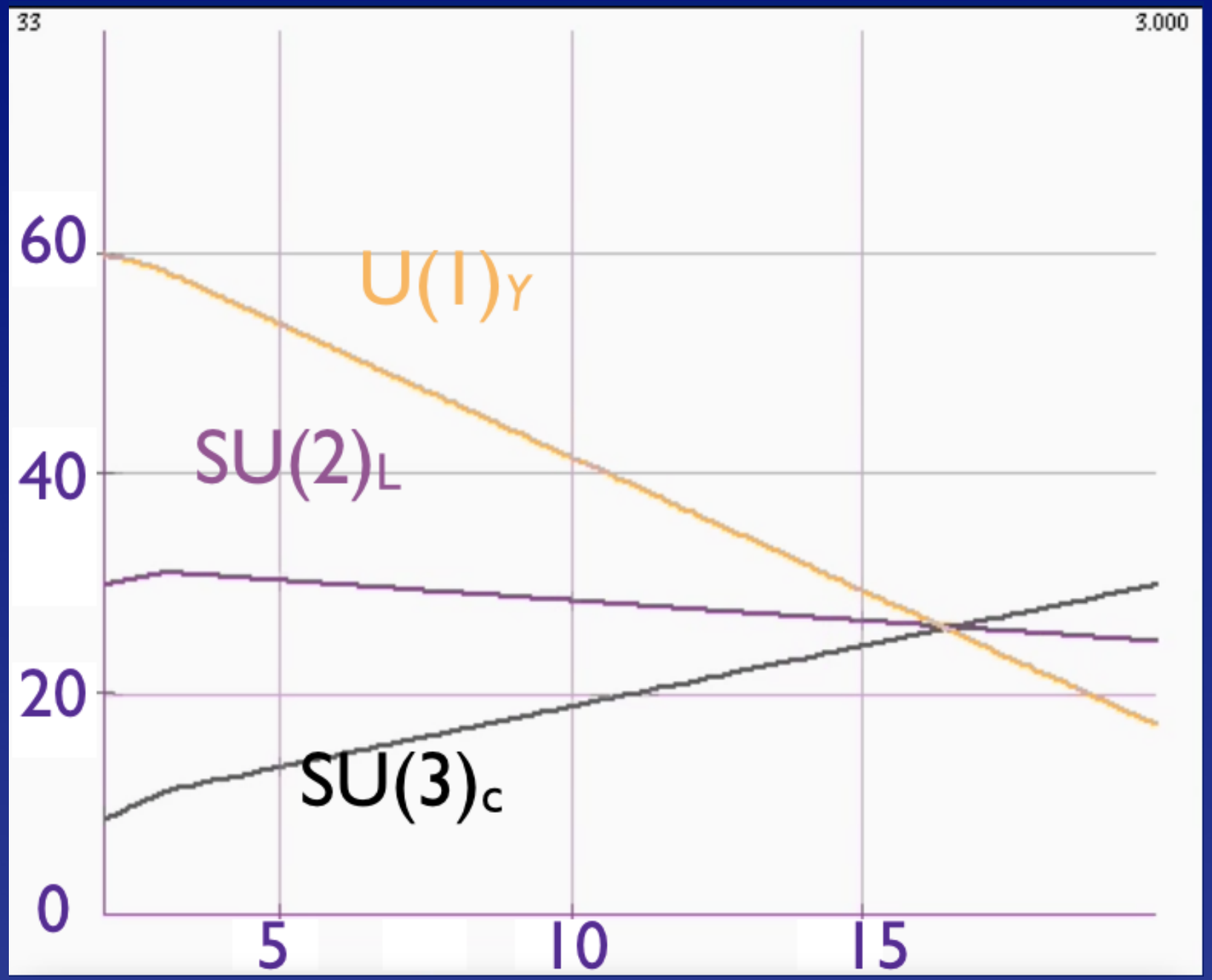

Implications for LHC$b$ $J/\psi p$ cryptopentaquarks $P_c(4380), P_c(4450)$?

Along with the particle spectrum,
multiboson interactions influence
coupling-constant evolution

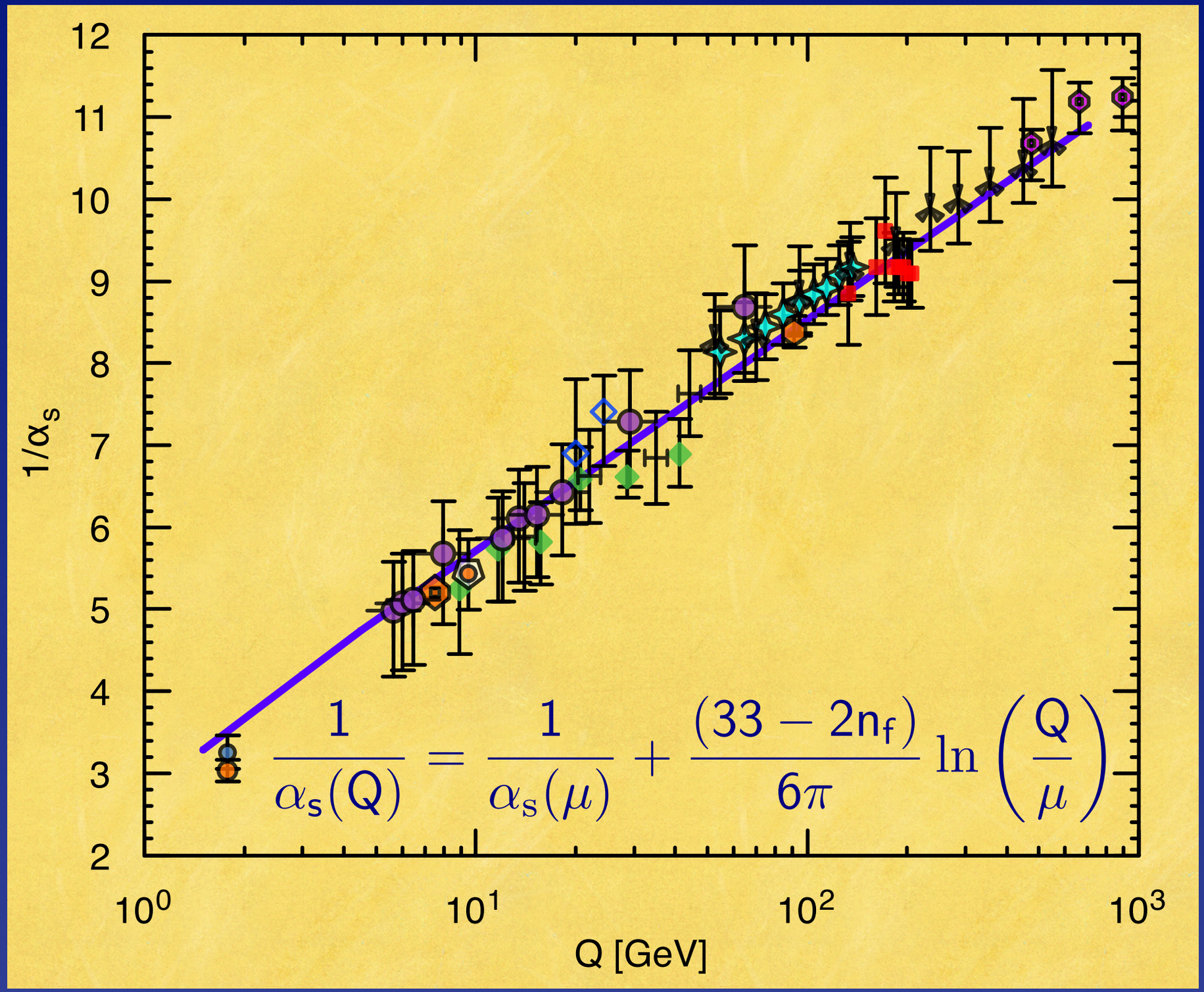
# Unification of Forces?



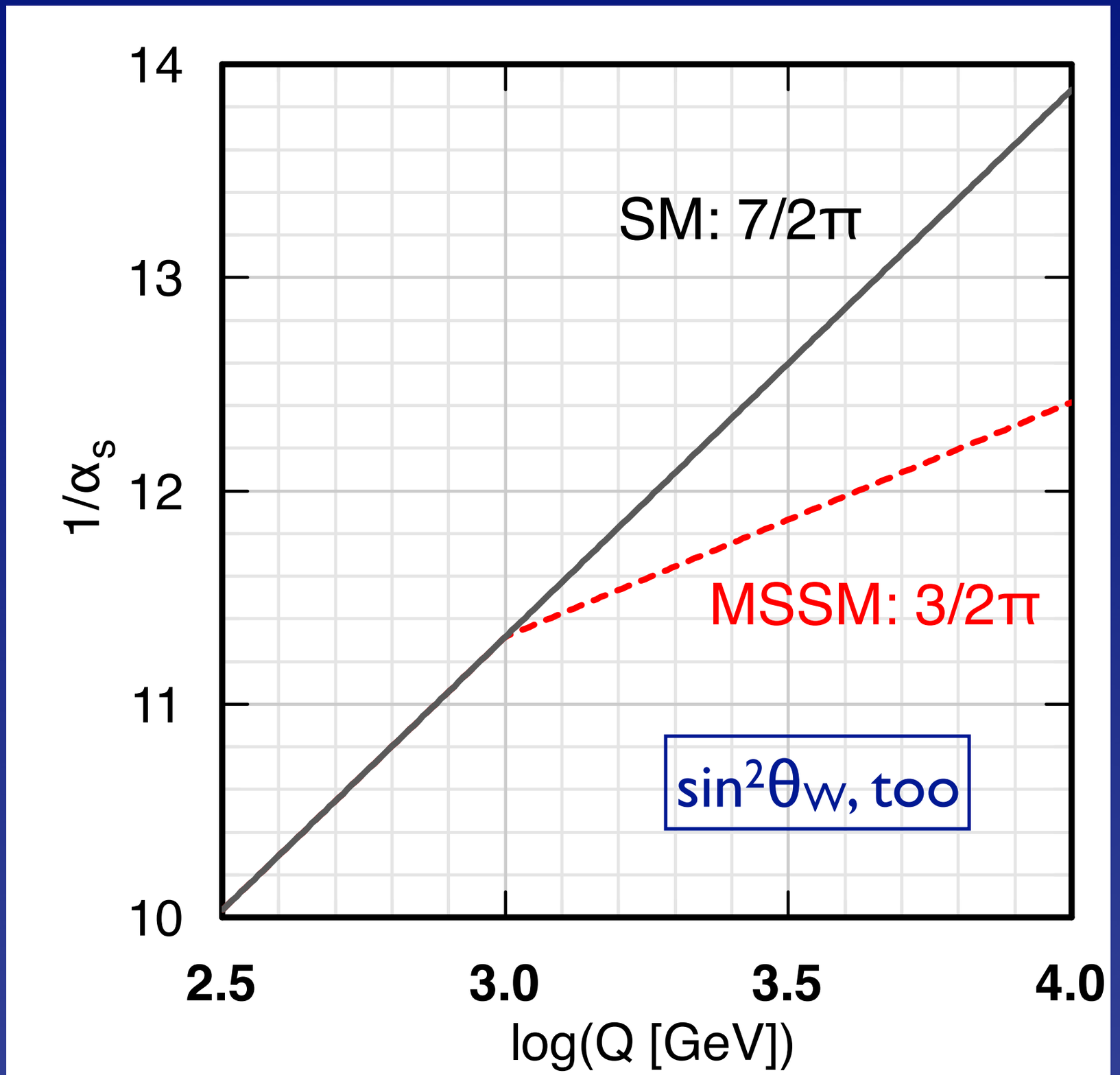
# Unification of Forces?



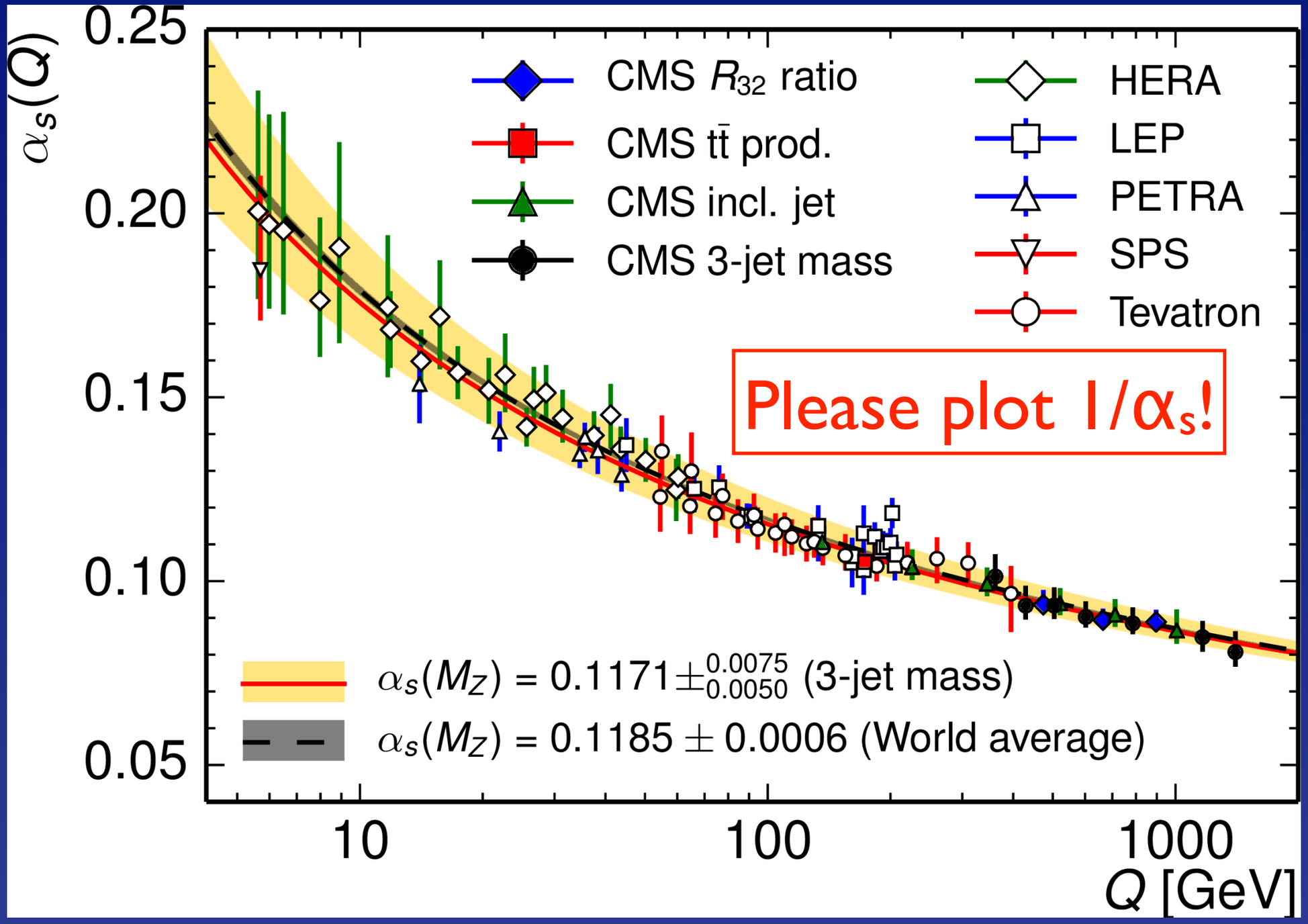
# Antiscreening evolution of the strong coupling "constant"



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



# Exploratory estimates by CMS & ATLAS




*Best processes? Z+ jets? How isolate $\alpha_s(Q)$?*

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,
no sign of large electric dipole moments (*n*, e)

# *The unreasonable effectiveness of the standard model*

arXiv:09053187 arXiv:1503.01756 arXiv:1507.02977

*What are the most likely manifestations of nonstandard MBI?*

*HZZ, HWW* couplings smaller than SM values
[*H*(125) is not the only source of *W, Z* masses]

Diboson resonances or excess σ(*VV*)

*Highlights importance of $V_L V_L$ scattering*

$e^+e^-$: Petcov & Jones, 1979
$p^{\pm}p$: Cahn & Dawson, 1984

Challenge: Can we measure the energy dependence of $V_L V_L$ scattering well enough to constrain *HVV* couplings beyond what we already can infer from *H* decay?

How far can we go in Run 2 / HL-LHC / HE-LHC / …?

Gauge symmetry implies low-energy amplitudes $a_{IJ}$

$a_{00} \sim G_{FS}/8\pi\sqrt{2}$ : attractive

$a_{11} \sim G_{FS}/48\pi\sqrt{2}$ : attractive

$a_{00} \sim -G_{FS}/16\pi\sqrt{2}$ : repulsive

## To unitarize, or not to unitarize …

Nature does,  often by driving a resonance
We do not have a unique prescription
*Different* ℞ *lead to qualitatively different results*

## Report what you measure

Once a deviation is discovered,
useful parametrizations will materialize,
and it may make sense to standardize

CQ, "Gauge Boson Dynamics" (1991)

More new physics on the TeV scale?

WIMP dark matter

Naturalness

Hierarchy problem

How have we misunderstood
the hierarchy problem?

*If other physical scales are present,*
*there is something to understand*

We originally sought once-and-done remedies,
such as supersymmetry or technicolor

*Go in steps, or reframe the problem?*

# Issues for the Future *(Starting now!)*

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

# Issues for the Future (Now!)

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

# Issues for the Future (Now!)

12. What are the dark matters? Any flavor structure?
13. 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?
14. Is EWSB related to gravity through extra spacetime dimensions?
15. What resolves the vacuum energy problem?
16. (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!)

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

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21. Could our laws of nature be environmental?

22. How are we prisoners of conventional thinking?

*Hearty thanks to our Organizers*

Matthew Herndon (UW Madison, Chair)

Sridhara Dasu (UW Madison)

Wesley Smith (US Madison)

John Campbell (FNAL)

Sally Dawson (BNL)

Lindsey Gray (FNAL)

Christophe Grojean (DESY)

Tao Han (U Pittsburgh)

Barbara Jager (JGU)

Michael Kobel (TU Dresden)

Sabine Lammers (Indiana U)

Hong Ma (BNL)

Yurii Maravin (KSU)

Marc-André Pleier (BNL)

Jurgen Reuter (DESY)

Junjie Zhu (U Michigan)


YOU ARE IN A CONSTANT STATE OF DISCOVERY