Confronting Theory with Experiment at the LHC

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Introduction

- Standard Model: a theory of interactions

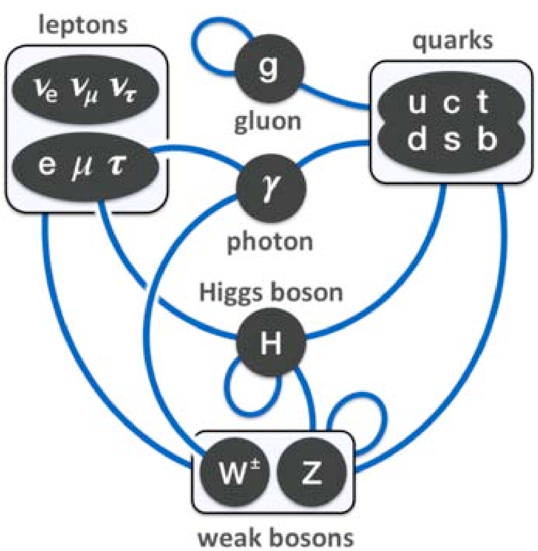
  -Gauge symmetry SU(3)xSU(2)xU(1) based on quantum field theory
  -Properties of fermions are inputs
  -Properties of interaction bosons in terms of couplings, propagations, masses are linked

➢ **Measuring a few parameters allows us to predict the rest, then measure and compare with expectation**

➢ **It's remarkably successful:**

-Predictions verified to be correct at sometimes incredible levels of precision

-After ~30 years, still no serious cracks!

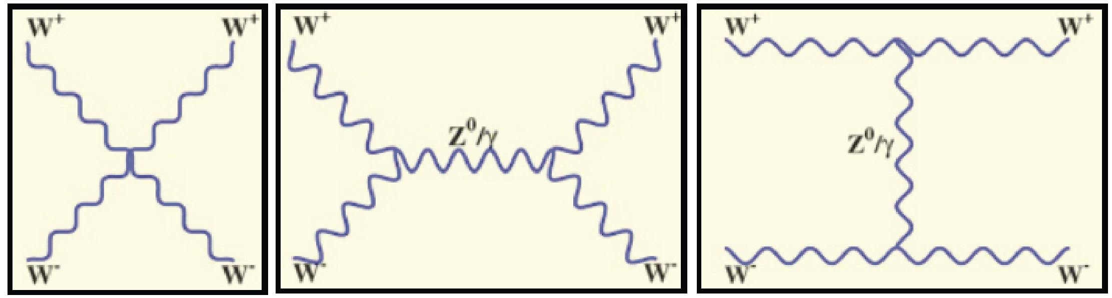


EW symmetry (SU(2)xU(1)) breaking & mass generation

$F_{\mu\nu}F^{\mu\nu}$-term contains self couplings between gauge bosons.

∴ WW ➛ WW possible; cross section:

$$\sigma_{W_L W_L} \sim E_{cm}^2$$



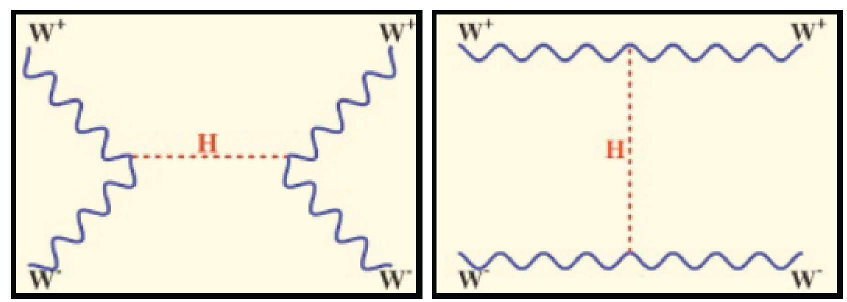
massive gauge bosons: 2 transverse d.o.f. + 1 longitudinal d.o.f.
massless gauge bosons: 2 transverse d.o.f.

$W_L W_L$ scattering probability becomes larger than unity for $E_{cm} > 1.2$ TeV ...
Violation of unitarity if force remains weak at this scale ...

To restore unitary it needs some scalar boson "H" with

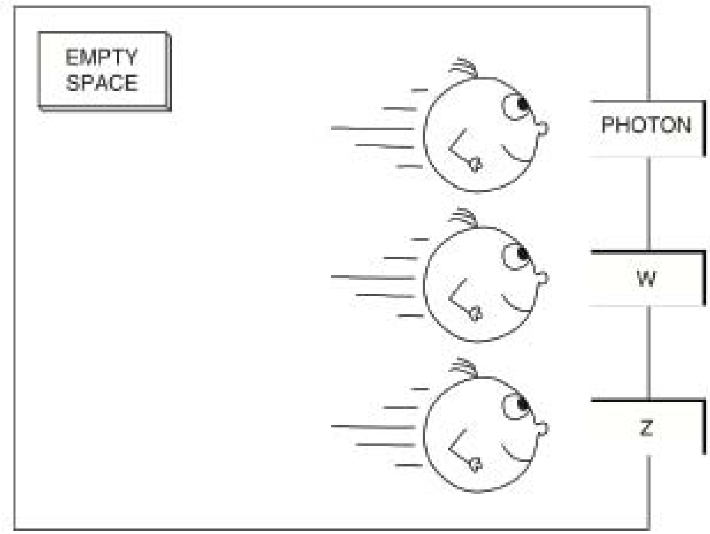
$$\left.\begin{array}{ll} g_{HWW} & \sim M_W \\ g_{Hff} & \sim m_f \\ M_H & < 1\ \text{TeV} \end{array}\right\} \quad \sigma \to \text{const}$$

for large energies

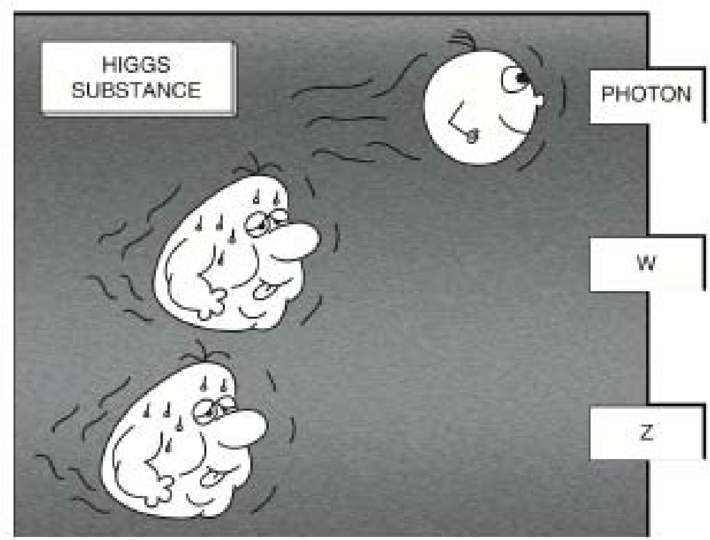


EW symmetry breaking (SU(2)xU(1)) & mass generation

Higgs field fills space with uniform distribution of EW charge



Longitudinal polarization isn't present for on-shell massless particles.



Waves with new degree of freedom i.e. longitudinal components are generated!!

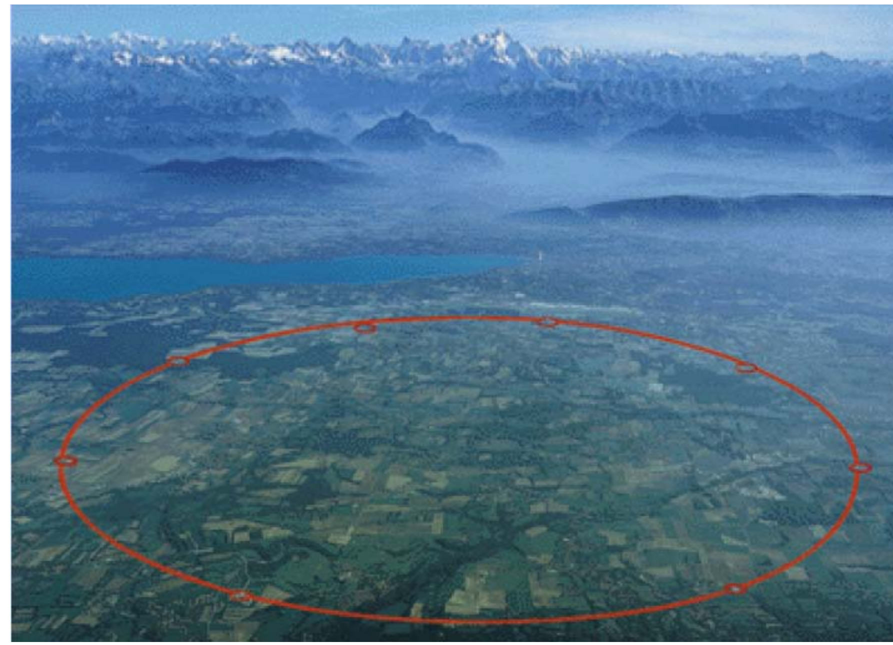
Tool:

- to find the Higgs→By Dr. A. Mohammadi
- to measure the polarization of the W,Z-bosons
- Test all aspects of the SM
- Search for BSM if any!

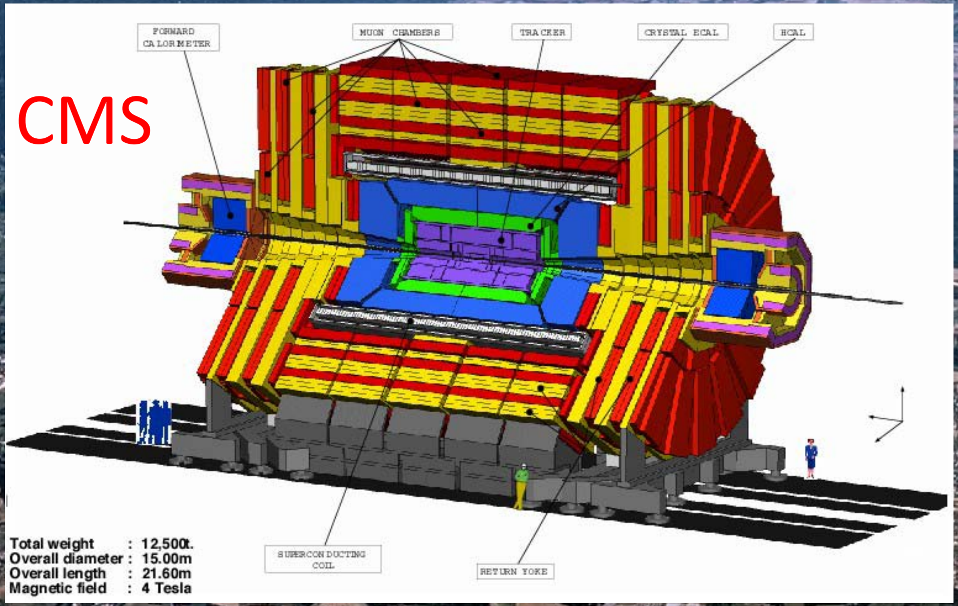
The Large Hadron Collider (LHC) at CERN

- Proton-proton collider in the former LEP tunnel at CERN (Geneva)

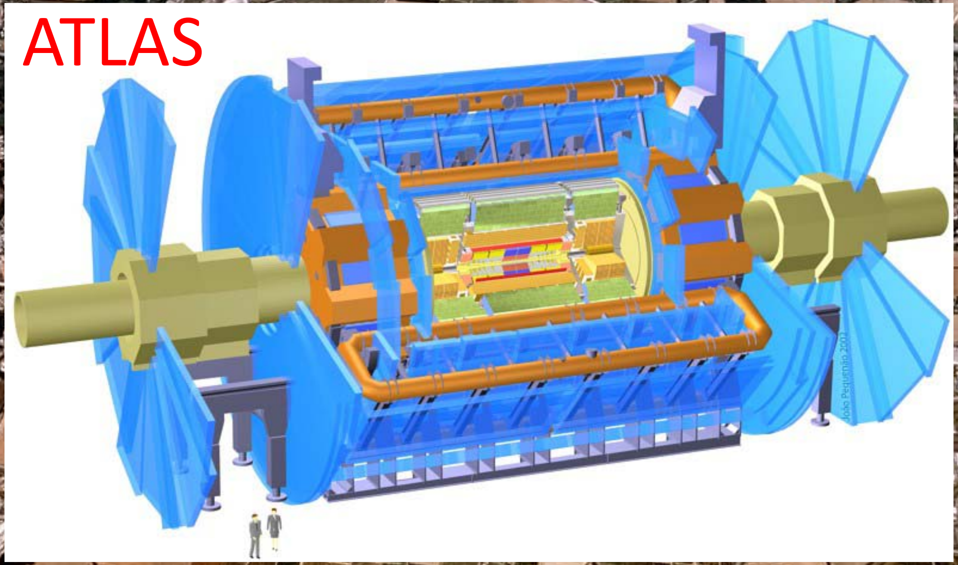
- Highest ever energy per collision
  7,8,13,14,33 TeV in the pp-system
- Conditions as 10^{-13} – 10^{-14} s after the Big Bang
- 4 experiments:
  ATLAS
  CMS
  LHC-B specialised on b-physics
  ALICE specialised for heavy ion collisons



The Large Hadron Collider LHC

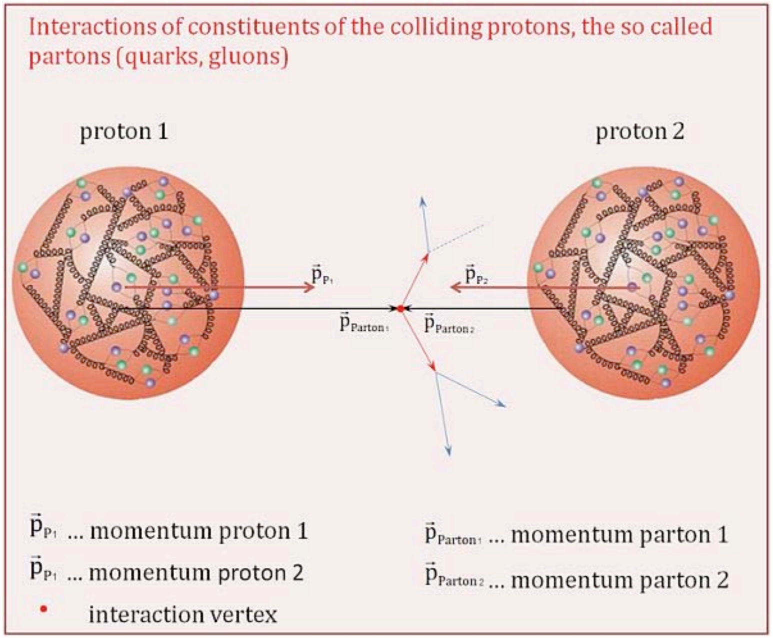


LHCb

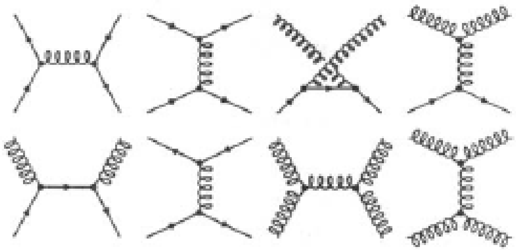


ALICE

Physics at Proton Colliders



- Protons are composite, complex objects
  - partonic substructure
  - quarks and gluons
- Interesting hard scattering processes
  quark-(anti)quark
  quark-gluon
  gluon-gluon



- Proton beam can be seen as beam of quarks and gluons with a wide band of energies
- The proton constituents (partons) carry only a fraction $0 \leq x \leq 1$ of the proton momentum

Cross Section of Various SM Processes

⇒ Low luminosity phase

$10^{33}/cm^2/s = 1/nb/s$

approximately

- 10^8 pp interactions
- 10^6 bb events
- 200 W-bosons
- 50 Z-bosons
- 1 tt-pair

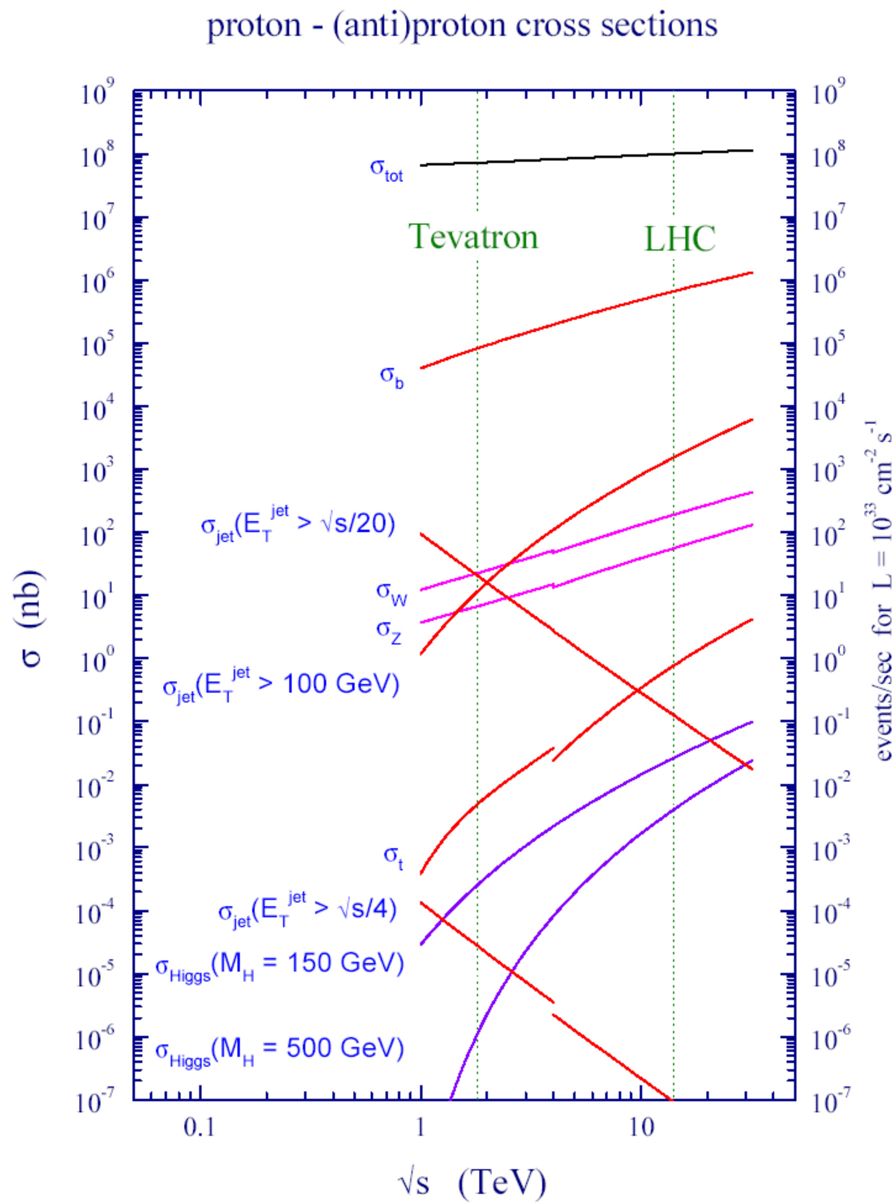
will be produced per second and

- 1 light Higgs

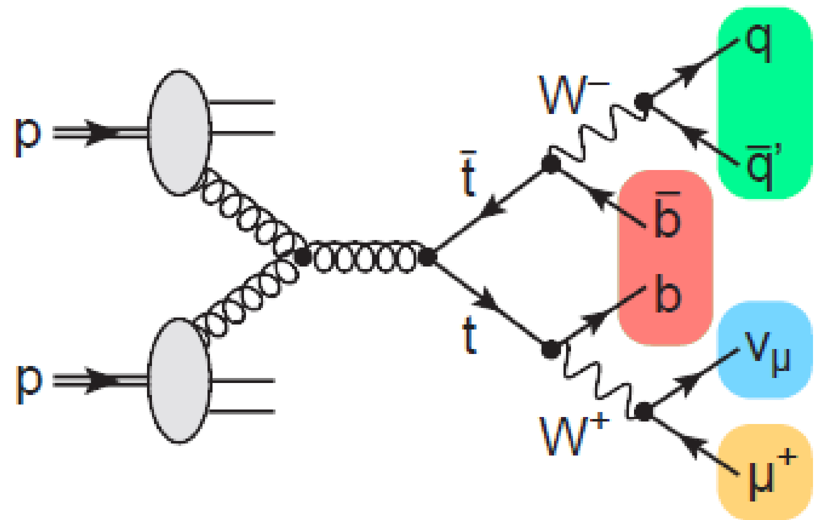
per minute!

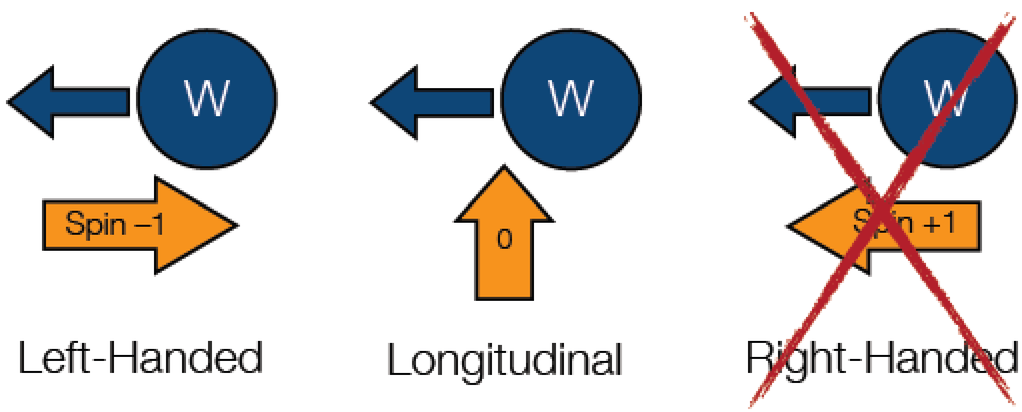
The LHC is a b, W, Z, top, Higgs, … factory!

The problem is to detect the events!



W-polarization measurement





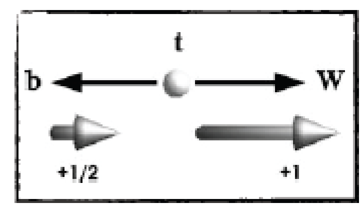
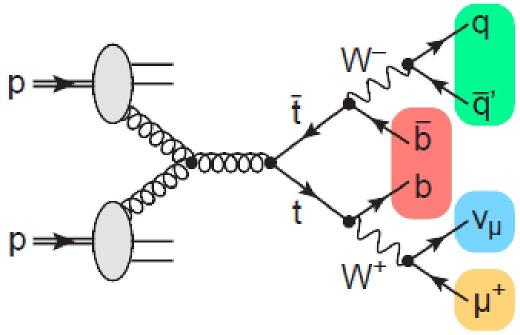


Illustration that the top mass cannot decay into a right-handed W-boson

$$\mathcal{L}^{W}_{\rm int} = -{}^{g}/\sqrt{2}\ \mathbf{W}^{+}_{\mu}\ \bar{b}_L \gamma^{\mu} t_L$$

W-polarization measurement

$$\frac{d\sigma}{d\cos\theta^*} \sim \underbrace{\frac{3}{8}(1-\cos\theta^*)^2 F_{LH}}_{\text{left-handed}} + \underbrace{\frac{3}{4}(1-\cos^2\theta^*) F_{long}}_{\text{longitudinal}} + \underbrace{\frac{3}{8}(1+\cos\theta^*)^2 F_{RH}}_{\text{right-handed}}$$



SM prediction for helicity fractions [LO, $m_b = 0$]:

$$F_{LH} = \frac{2m_W^2}{m_t^2 + 2m_W^2} \approx 0.3 \qquad F_{long} = \frac{m_t^2}{m_t^2 + 2m_W^2} \approx 0.7 \qquad F_{RH} \approx 0$$

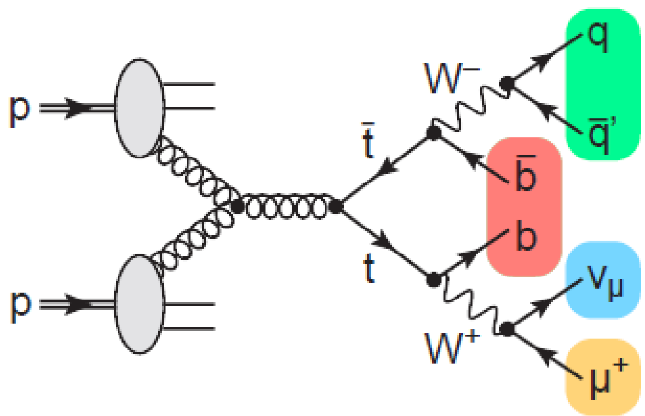
Physical picture:

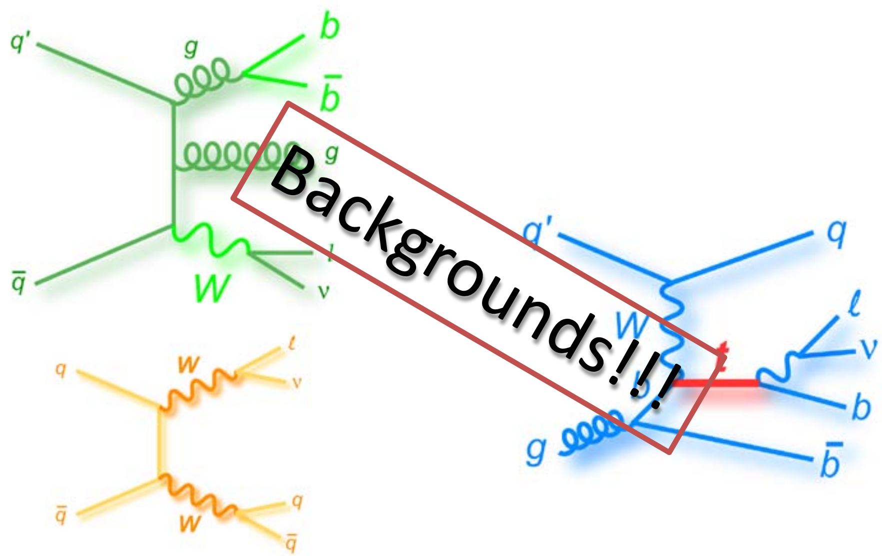
Top quark: large mass ➛ large Higgs (Yukawa) coupling

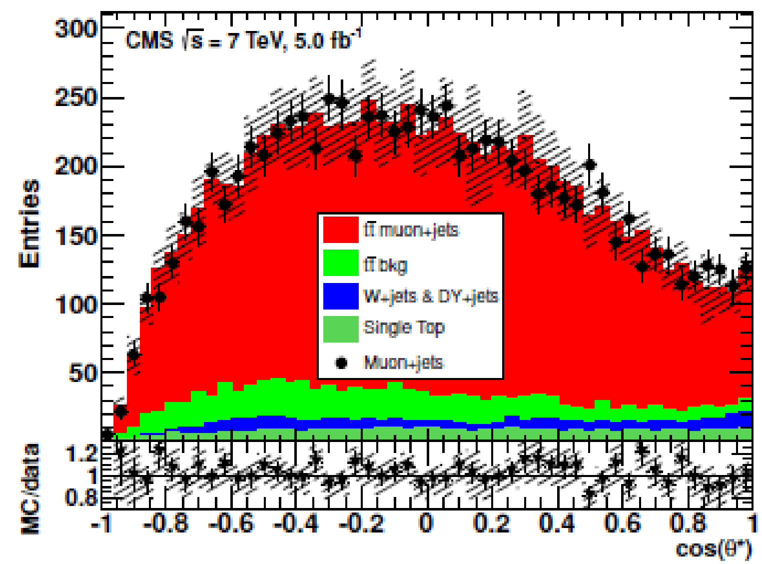
Longitudinal d.o.f. of W bosons generated by Higgs mechanism
Thus: top quark prefers to couple to longitudinal W ...

[see later]

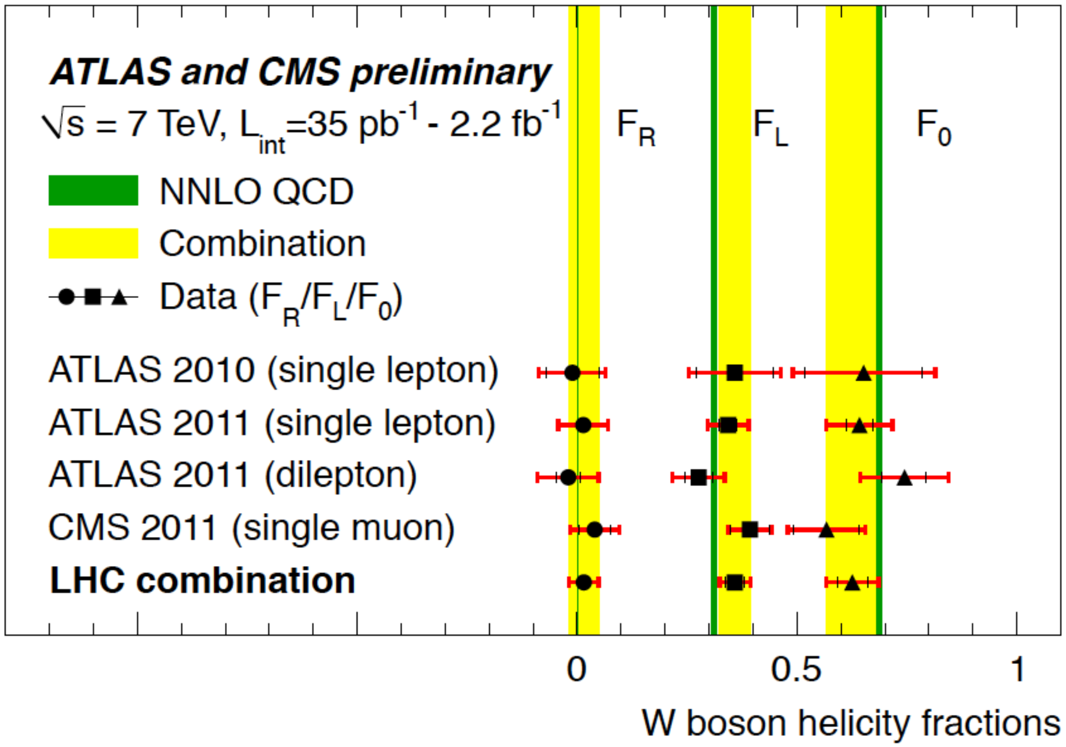
W-polarization measurement







W-polarization measurement



$$F_L = 0.288 \pm 0.035(\text{stat}) \pm 0.040(\text{syst})$$

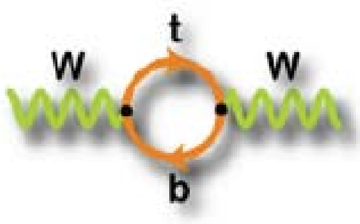
$$F_0 = 0.698 \pm 0.057(\text{stat}) \pm 0.063(\text{syst})$$

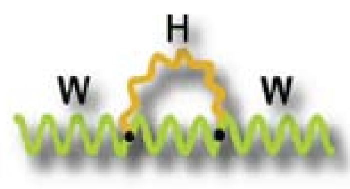
CMS PAS TOP-12-015 CMS-PAS-TOP-12-020 CMS-PAS-TOP-12-025

W-boson mass: TH vs. EXP importance of quantum corrections

SM is a quantum theory. The vacuum is a busy place!

Particle-antiparticle pairs can be produced out of nothing, borrowing an energy E for a time t: $E\,t \approx \hbar$





1-loop correction: $M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F Sin^2\theta_W}(1+\Delta r)$

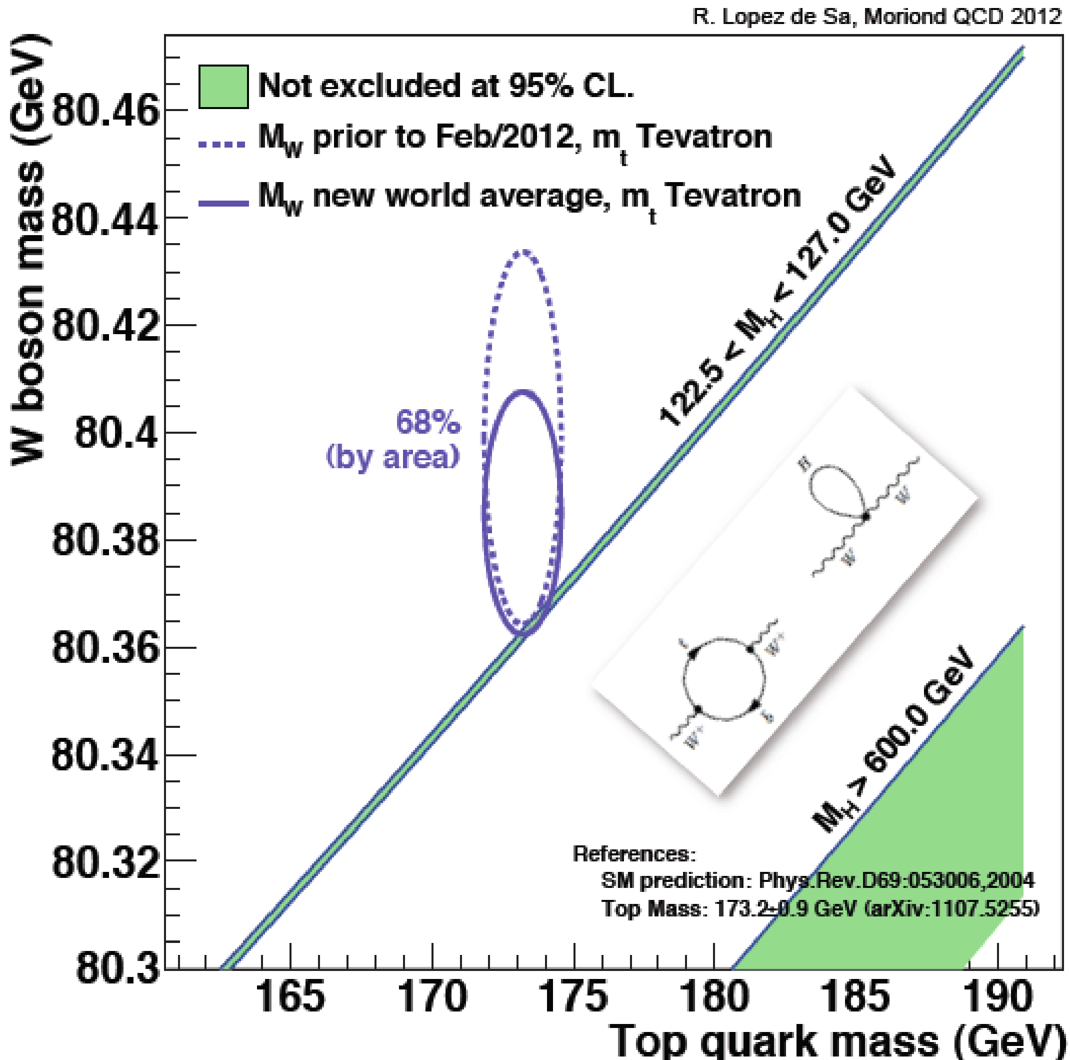
$\Delta r_t \sim m_t^2$

$\Delta r_{Higgs} \sim \ln(m_H^2)$

1 GeV change of m_{top} leads to ~10 GeV change of m_{Higgs}

Discovery at : m_H = 125.6 ± 0.4 (stat.) ± 0.2 (syst.) GeV

m_W-m_{top} plane



The observation of the physical Higgs boson with m_H well consistent with the (indirect) prediction of the e.w. precision tests is a great success of the SM.

$$m_H = 99^{+28}_{-23}\ \mathrm{GeV}$$

direct $m_h \neq$ indirect m_h

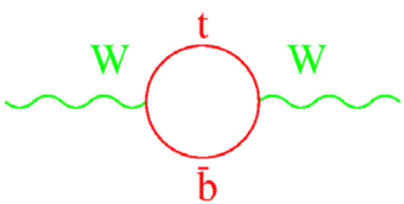
unambiguous indication

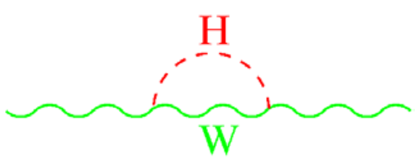
NP close to the TeV scale

+/- 1 GeV in top mass→ +/- 10 GeV in Higgs mass

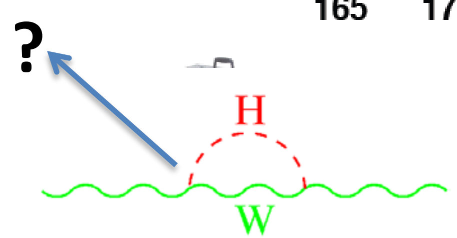
m_W-m_{top} plane

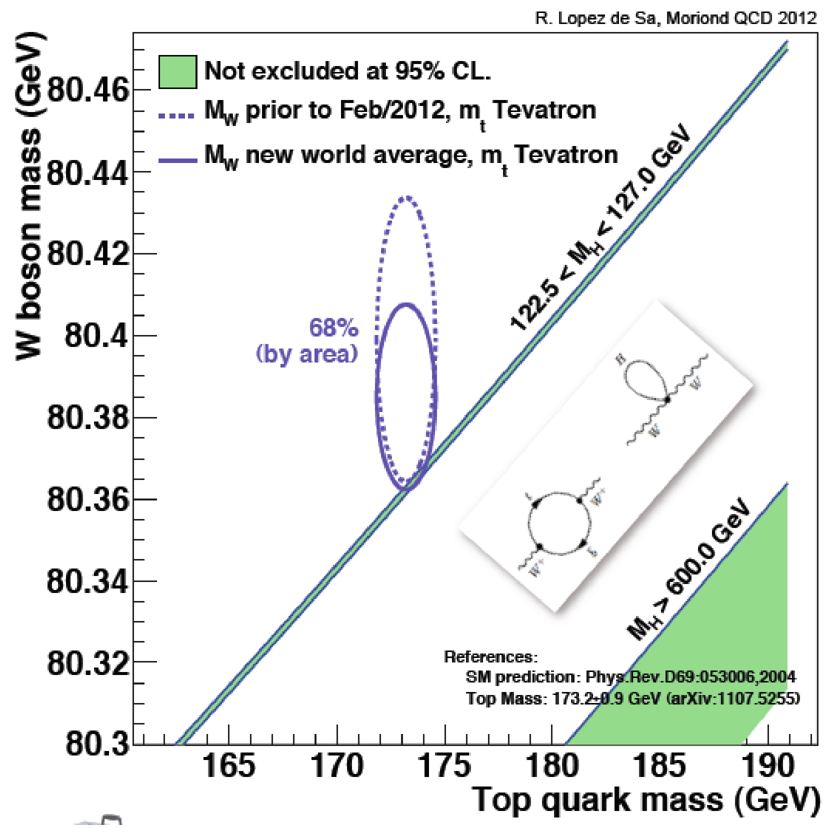
Precise Measurement is NEEDED!



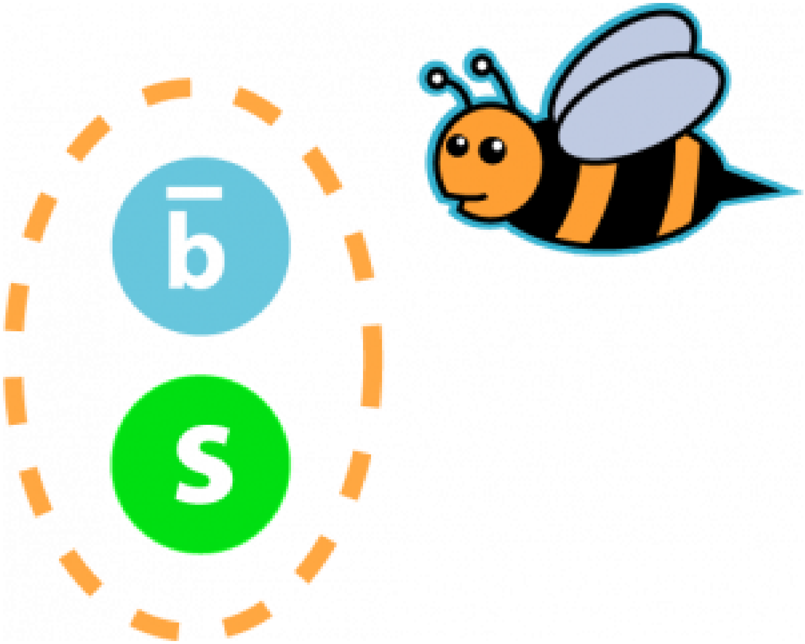


OR





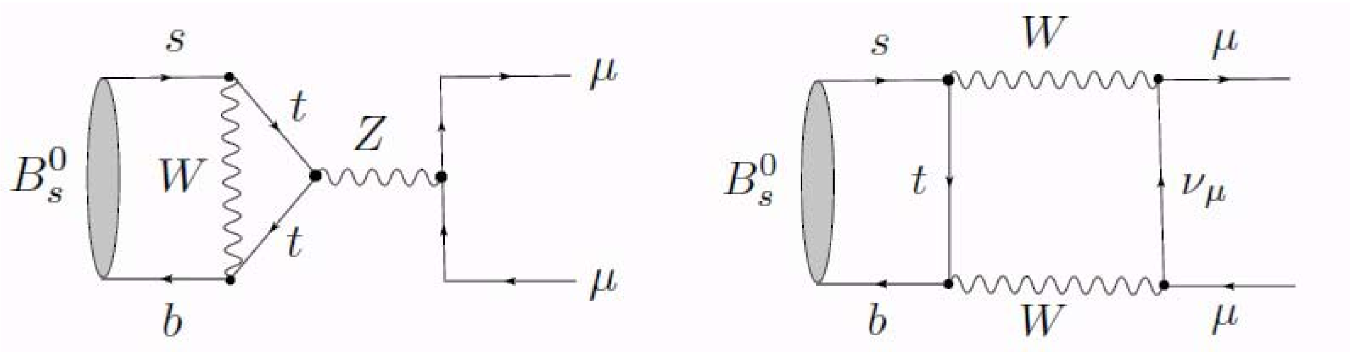
Rare B^0_s-Meson Decay to di-muon



The Rare Decay $B_s^0 \rightarrow \mu^+ + \mu^-$

◆ 10^6 bb events per second!!!

❖ **Decays highly suppressed in SM *forbidden*** at tree level
❖ $B^0 \rightarrow \mu^+ + \mu^-$ transition only through *Penguin* diagrams
❖ Suppressed by factors of $(m_\mu/m_B)^2$



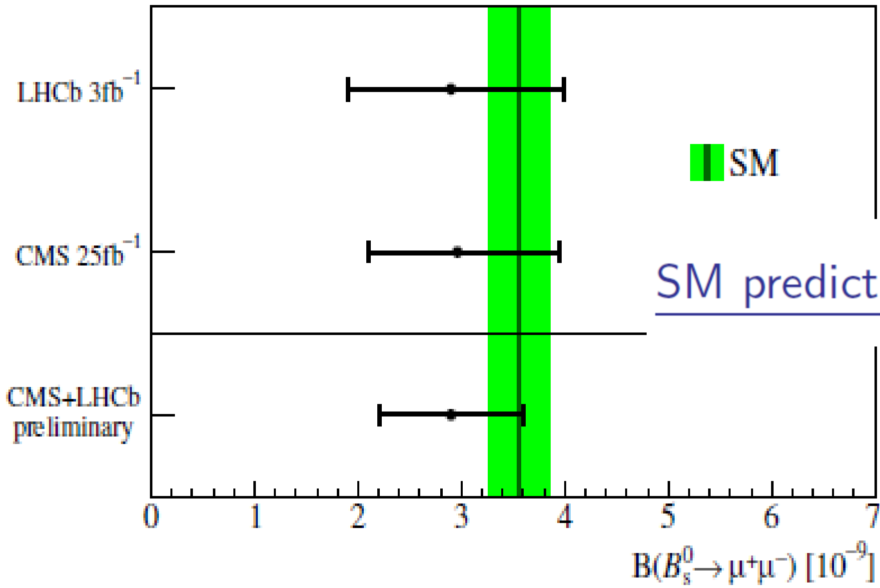
[De Bruyn et al. PRL 109, 041801]; [A. Buras et al. arXiv:1303.3820]

SM prediction: $\mathrm{BR}(B_s \rightarrow \mu^+\mu^-) = (3.6 \pm 0.4) \times 10^{-9}$

Significance

An excess of B_0→dimuon events with respect to background is observed with a significance of 4.3 standard deviations.

Expected	Observed
4.8σ	**4.3σ (p-value = 9.8×10^{-6})**



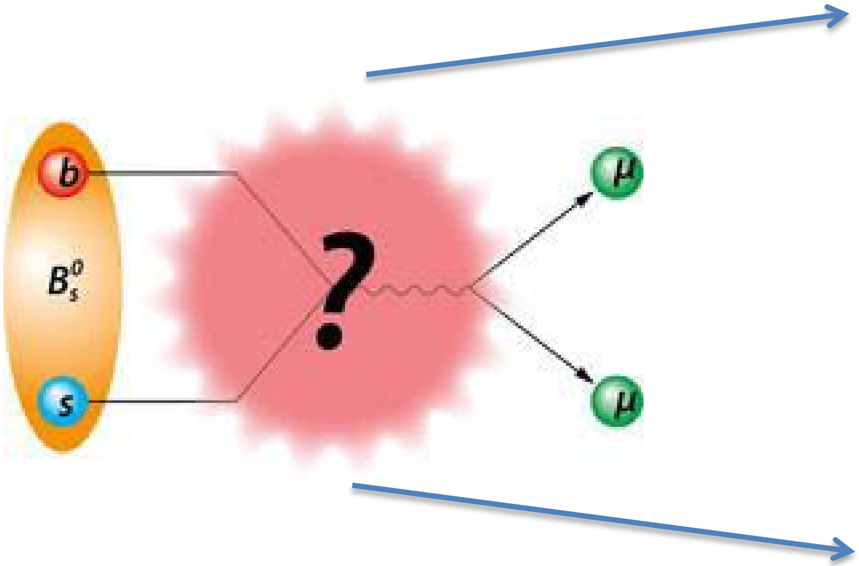
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$

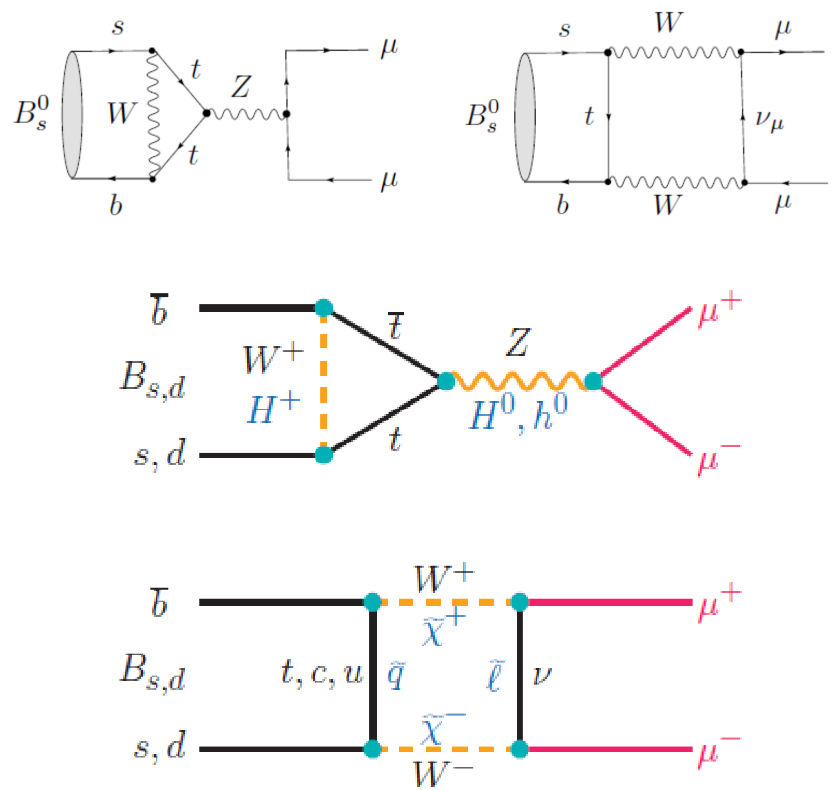
SM prediction: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.6 \pm 0.4) \times 10^{-9}$

Test of SM with high precision: 10^{-9}

CMS PAS BPH-13-007

Sensitivity to new physics BSM





- ▷ $\mathcal{B} \sim (\tan\beta)^6$ in MSSM
- ▷ $\mathcal{B} \sim (\tan\beta)^4,\ m_{H^+}$ in 2HDM

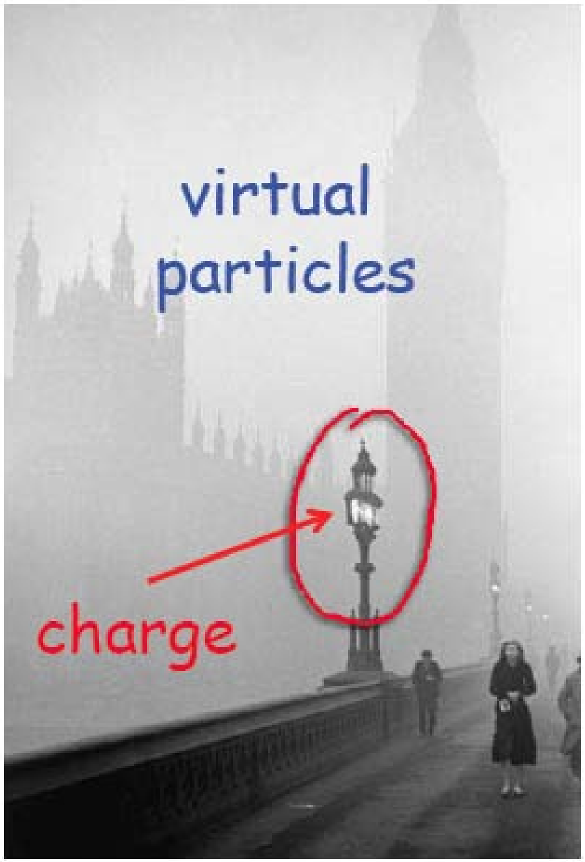
arXiv:1205.1845

Strong limits on new MSSM, ED, fourth Generation, ... parameters

Strong Coupling Constant Measurement: α_s

Strong Coupling Constant

Classical physics: force depends on distance
Quantum physics: charge depends on distance



A strange phenomenon

QED:
virtual particles screen the charge
→charge gets weaker as we move away even stranger

QCD:
virtual particles anti-screen the charge→ charge gets stronger as we move away

Coupling constant is not a "constant"

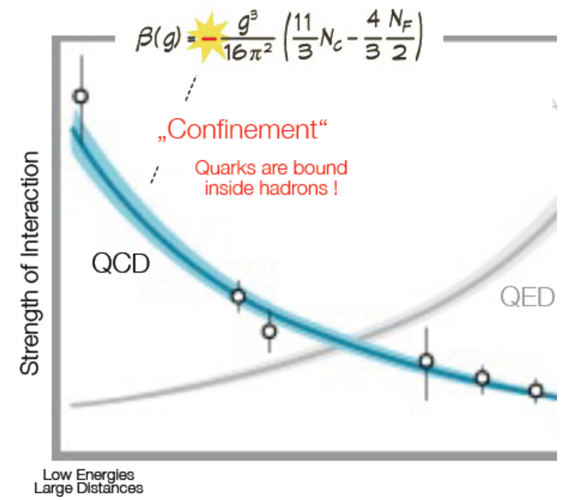
Verification of running of α_s and
test of QCD at the smallest distance scale

- α_s = 0.118 at m_Z
- $\alpha_s \approx$ 0.082 at 4 TeV (QCD expectation)

Strong Coupling Measurement

-Runs with Q^2, accounts for vacuum polarization

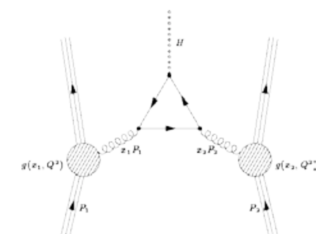
$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{[1 + (\alpha_s(\mu^2)\frac{(33-2n_f)}{12\pi})ln(Q^2/\mu^2)]}$$



$-\alpha_s(Q^2) \rightarrow 0$, as $Q \rightarrow \infty$, $r \rightarrow 0$

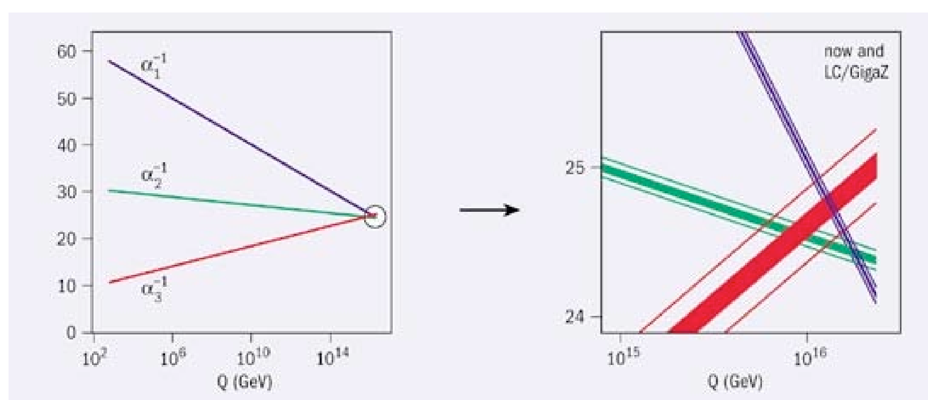
Coupling very weak → partons are essentially free

In addition to its running, precise measurement is important:



-Higgs,… Productions

-Forces Unification



Multijet ratios for α_s measurements

- **Ratios of inclusive cross-sections for event with ≥ 3 jets and ≥ 2 jets:**

– Sensitive to the value of α_s

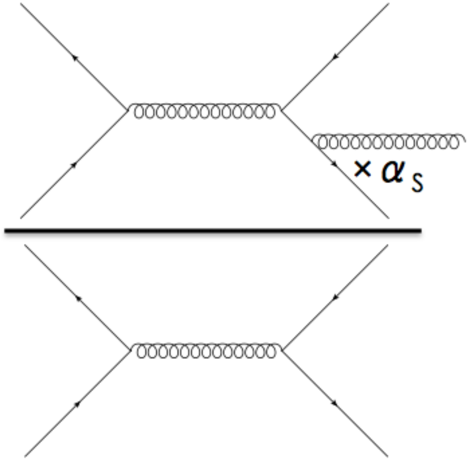
– Cancellation of systematic uncertainties (luminosity, PDFs, etc) for more precise test of QCD

$$R_{3/2}(p_{\mathrm{T}}^{\mathrm{lead}}) = \frac{d\sigma_{N_{\mathrm{jet}}\geq 3}}{dp_{\mathrm{T}}^{\mathrm{lead}}} \Bigg/ \frac{d\sigma_{N_{\mathrm{jet}}\geq 2}}{dp_{\mathrm{T}}^{\mathrm{lead}}} \sim \alpha_s$$

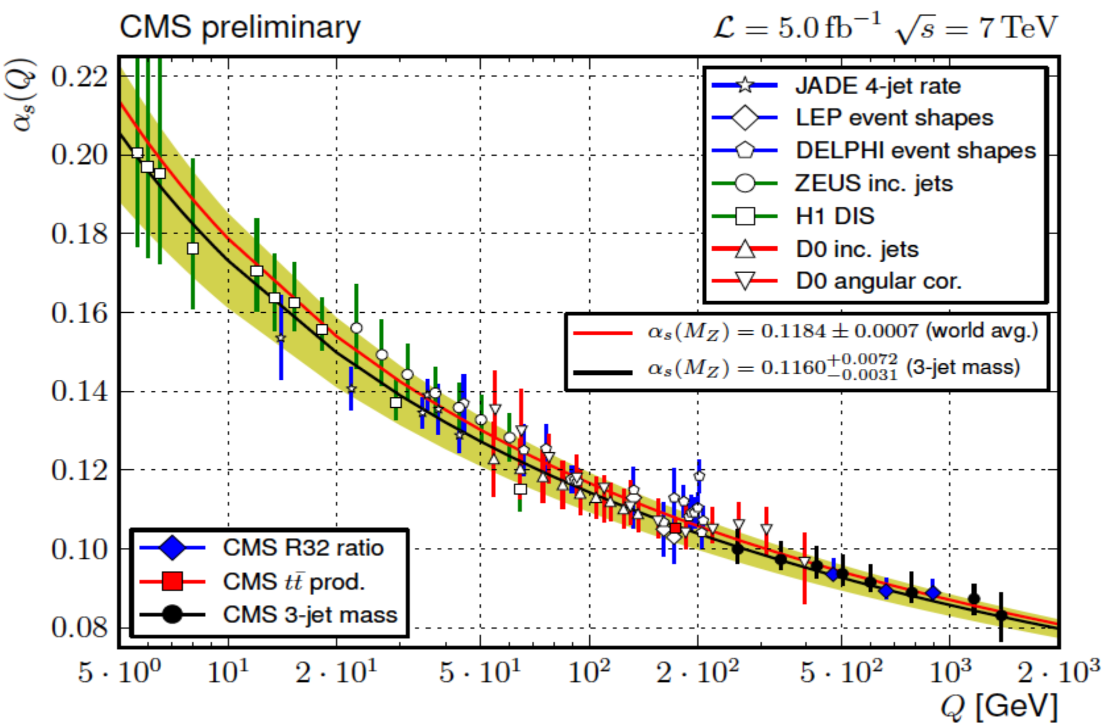
"Probability that a 2-jet event has a third jet"

- Cross-section can be measured relative to various quantities, typically jet transverse momenta

– Collision energy at LHC means running of the coupling can be tested at new scales



Multijet ratios for α_s measurements: Running of Coupling Constant



QCD, as a theory, is a good description of strong interactions

One universal coupling is sufficient to describe the strong interaction

CMS-PAS-SMP-12-027

0.02 fm **0.002 fm** **0.0002 fm**

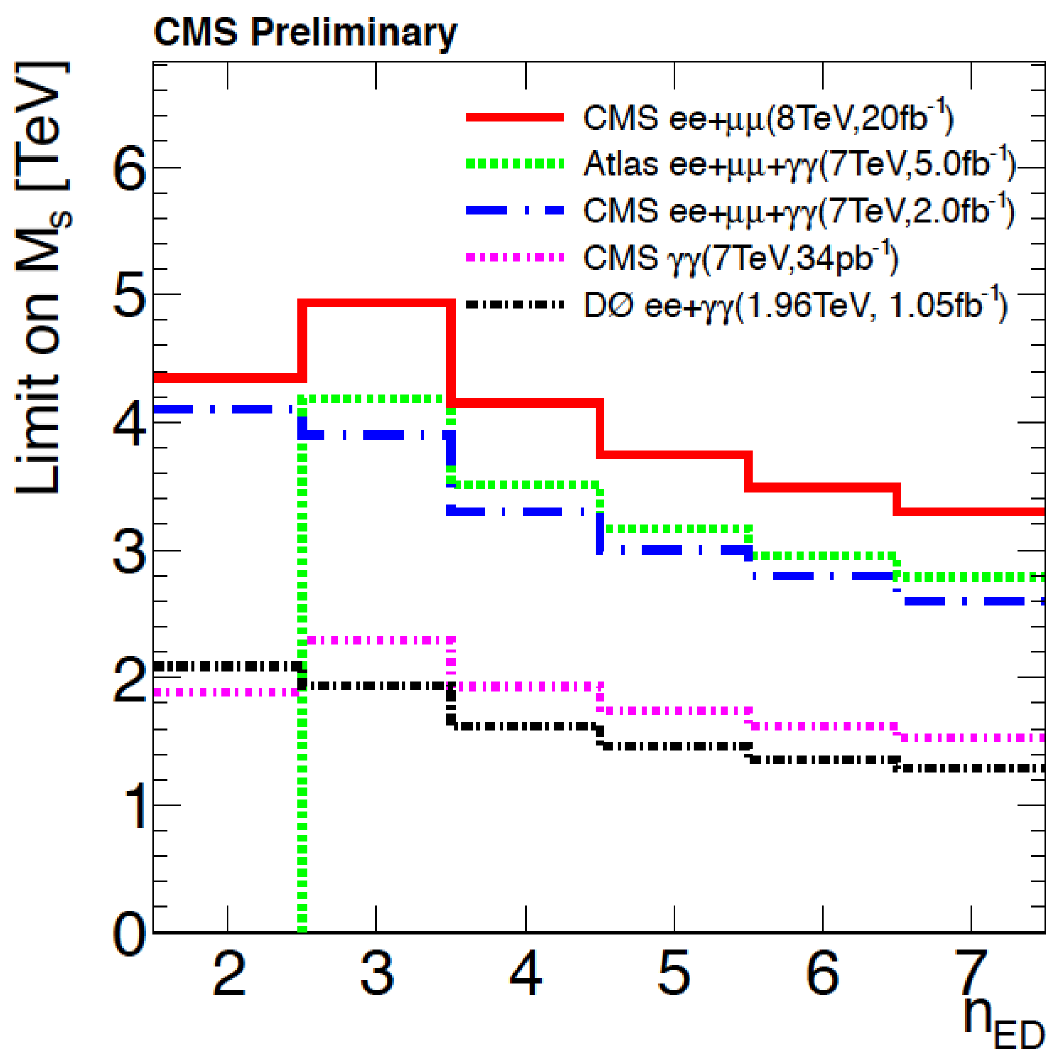
$$\alpha_S(M_Z) = 0.1160 \pm^{0.0025}_{0.0023} \text{ (exp, PDF, NP)} \pm^{0.0068}_{0.0021} \text{ (scale)}$$

All LHC-era results are consistent with the current world average from the Particle Data Group:

$$\alpha_s(M_Z) = 0.1184 +/- 0.0007$$

Beyond Standard Models

Large Extra Dimensions:

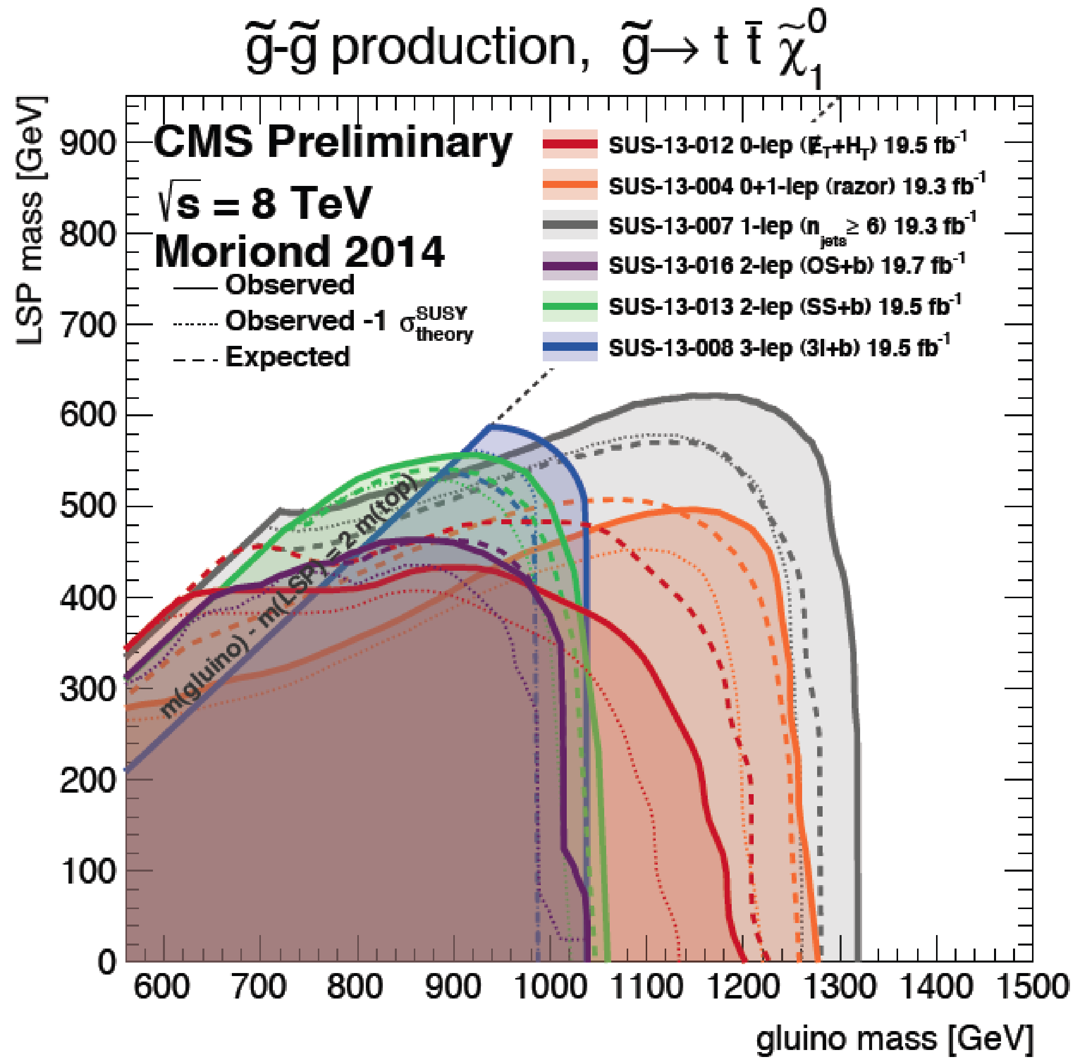


CMS-PAS-EXO-12-031

CMS-PAS-EXO-12-027

Beyond Standard Models

Supersymmetry:



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS


THANKS!