# Standard Model probing at the LHC

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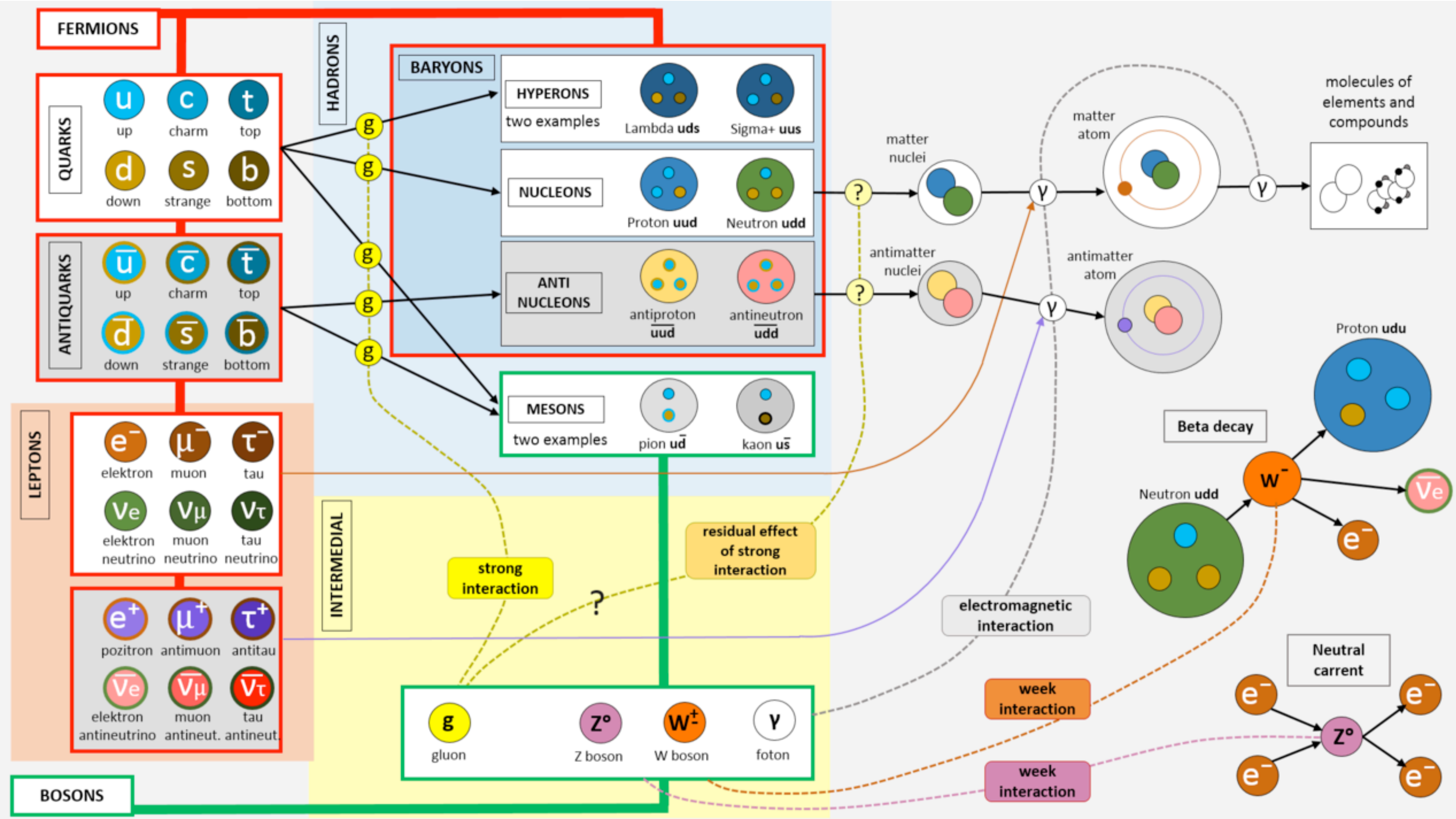
# The Standard Model

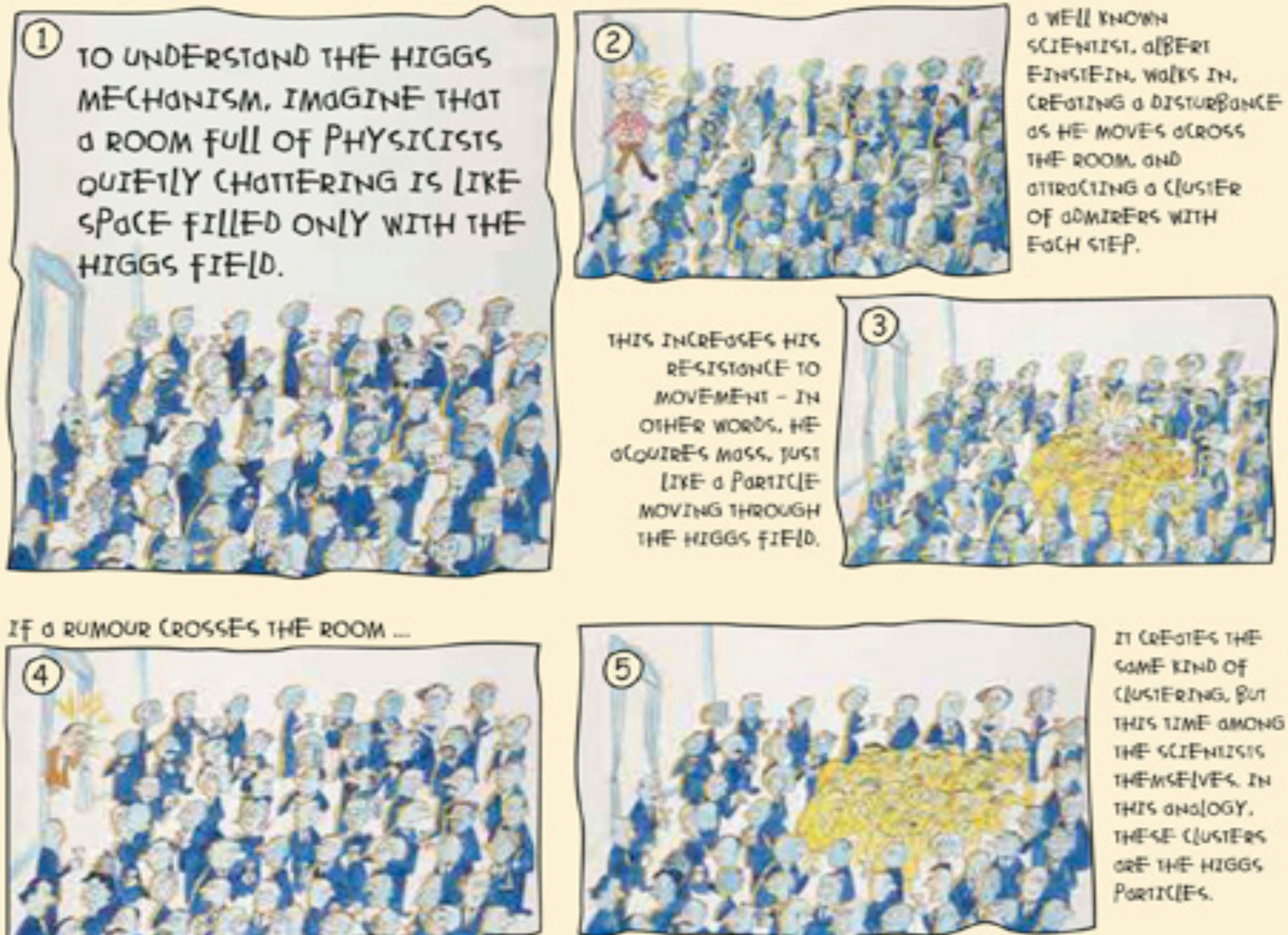


# STANDARD MODEL OF ELEMENTARY PARTICLES


**04/07/2012**

the Higgs boson has been found !

# THE HIGGS MECHANISM



# Looking for the Higgs: Large Hadron Collider

The LHC project started at the initiative (and with the daring!!) of C. Rubbia

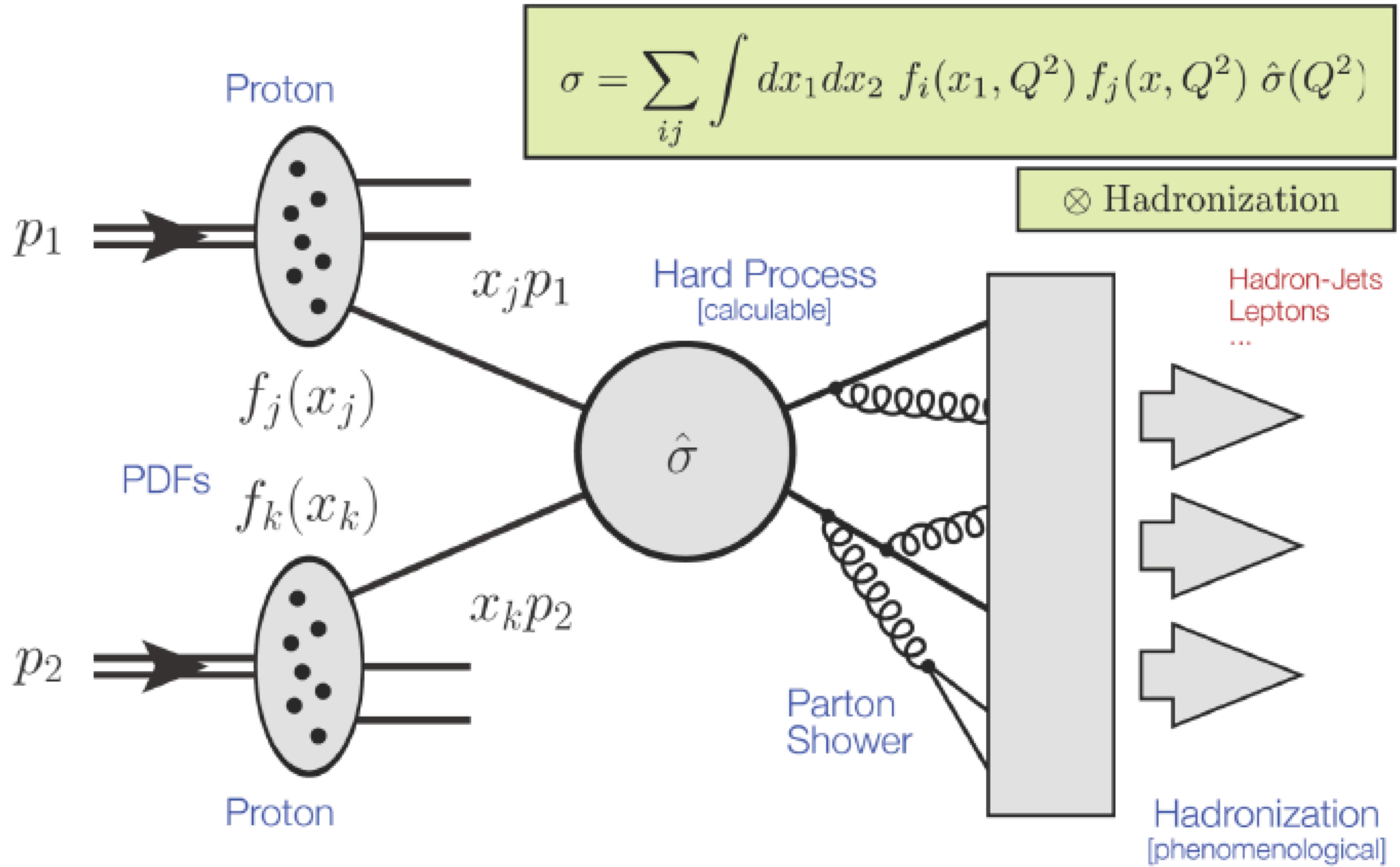
The Aachen Conference in October 1990 marked the start-up, since then work on the collider and magnets, various detector designs and understanding physics issues went on without let-up

➡ Scientific-diplomatic trips in 1990/91/92 to Japan, India, Russia, USA, Canada etc

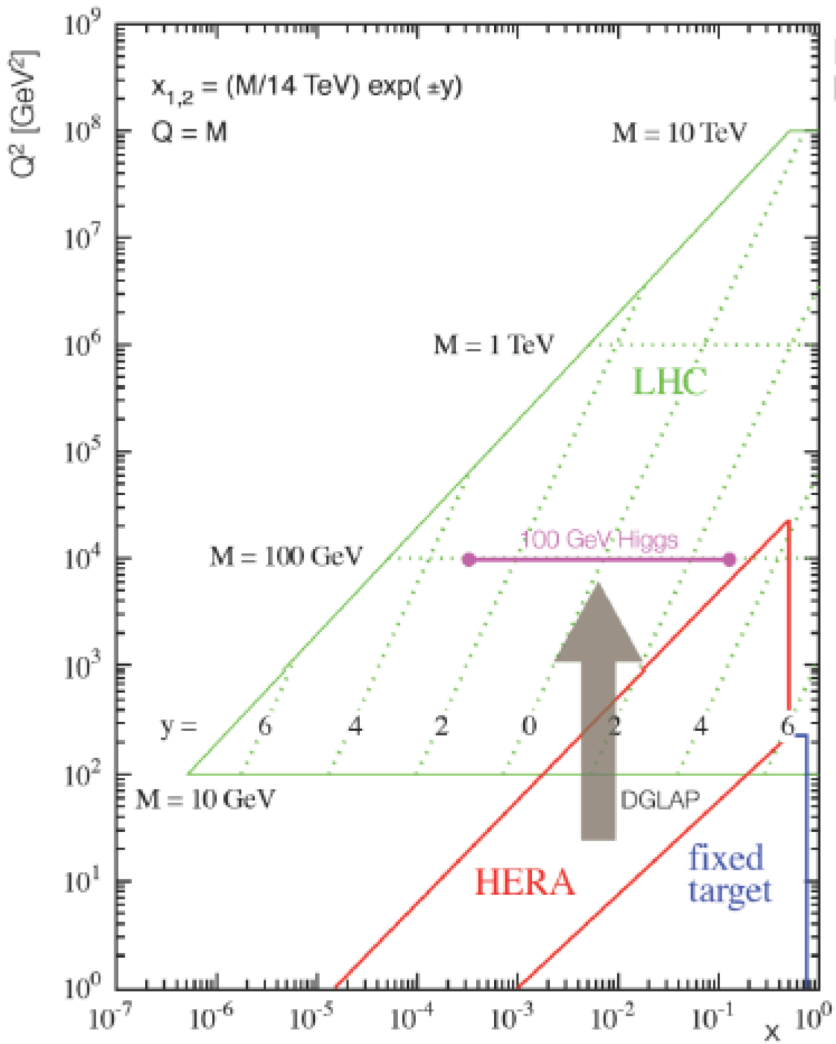
LHC vs SSC: Rubbia's arguments: savings!

- existing LEP tunnel ~1 GCHF
- existing infrastructure at CERN (PS. SPS, etc) ~ 1 GCHF
- "two-in-one" scheme for dipoles saves ~ half the cost of magnet ~ 0.7 to 1 GCHF
  thus overall LHC cost ~ 3 GCHF
- will be ready by 1998 - 2000 !!

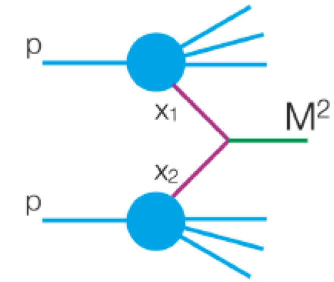
# Proton-proton scattering @ LHC



# Particle production @ LHC




LHC parton kinematics




pp → $X_M$ + remnants

$X_M$: particle with mass M
e.g. Higgs

$$M^2 = x_1 x_2 \cdot s$$

i.e. to produce a particle with mass M at LHC energies ($\sqrt{s}$ = 14 TeV)

$\langle x \rangle = \sqrt{x_1 x_2} = M/\sqrt{s}$
[$x_1 = x_2$: mid-rapidity]

LHC needs:

Knowledge of parton densities
Extrapolation over orders of magnitudes

# From Partons to Jets

From partons to
color neutral hadrons:

Fragmentation:

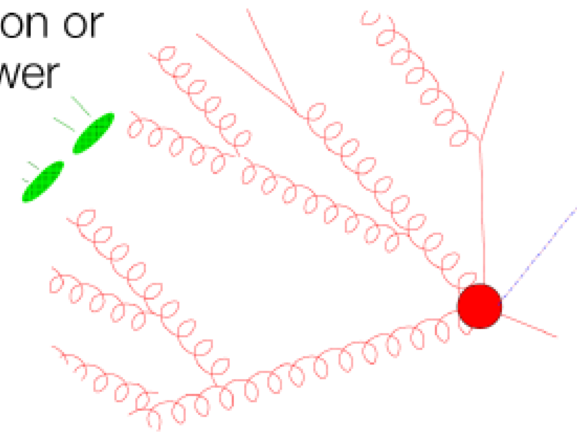
Parton splitting into other partons
[QCD: re-summation of leading-logs]
["Parton shower"]

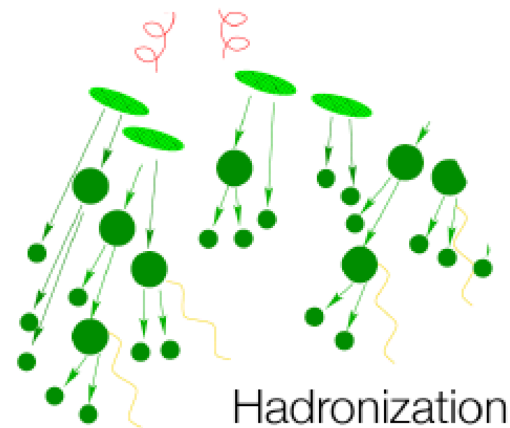
Hadronization:

Parton shower forms hadrons
[non-perturbative, only models]

Decay of unstable hadrons
[perturbative QCD, electroweak theory]

Fragmentation or
Parton Shower





Hadronization &
Decays

# Cross section & luminosity

**Number of observed events**

just count …

**Background**

measured from data or calculated from theory

$$\sigma = \frac{N^{\mathrm{obs}} - N^{\mathrm{bkg}}}{\int \mathcal{L}\, \mathrm{d}t \cdot \varepsilon}$$

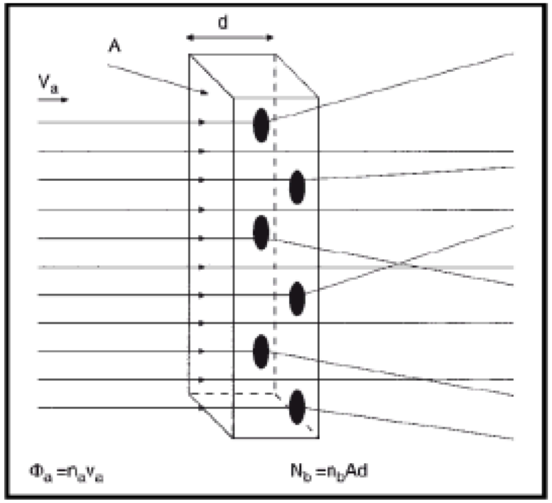
**Luminosity**

determined by accelerator, triggers, …

**Efficiency**

many factors, optimized by experimentalist

# Cross section & luminosity




$$\Phi_a = \frac{\dot{N}_a}{A} = n_a v_a$$

$\Phi_a$ : flux
$n_a$ : density of particle beam
$v_a$ : velocity of beam particles

$$\dot{N} = \Phi_a \cdot N_b \cdot \sigma_b$$

$\dot{N}$ : reaction rate
$N_b$ : target particles within beam area
$\sigma_a$ : effective area of single scattering center

$$L = \Phi_a \cdot N_b$$

L : luminosity

$$\dot{N} = L \cdot \sigma$$

$$N = \sigma \cdot \underbrace{\int L\, dt}_{\text{integrated luminosity}} \qquad \sigma = N/L$$

Collider experiment:

$$\Phi_a = \frac{\dot{N}_a}{A} = \frac{N_a \cdot n \cdot v/U}{A} = \frac{N_a \cdot n \cdot f}{A}$$

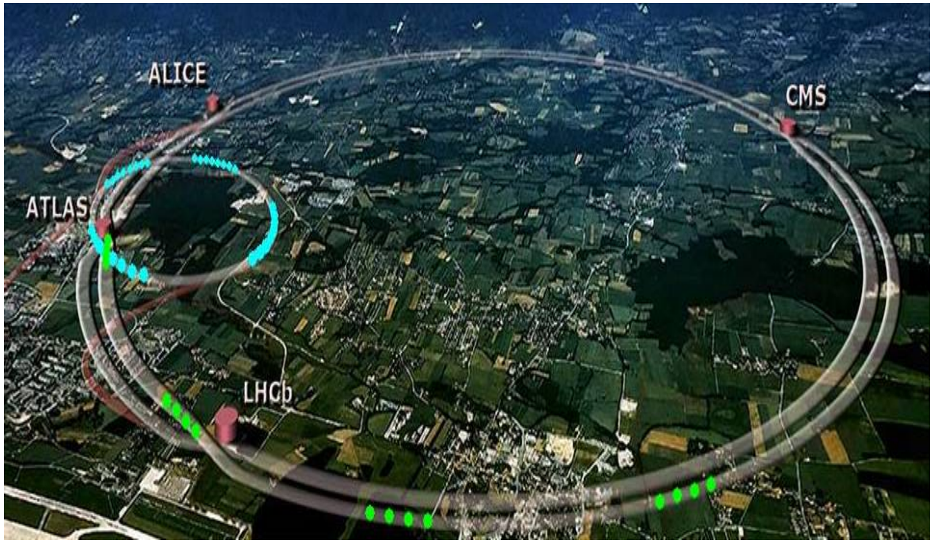
$$L = f\frac{nN_aN_b}{A} = f\frac{nN_aN_b}{4\pi\sigma_x\sigma_y}$$

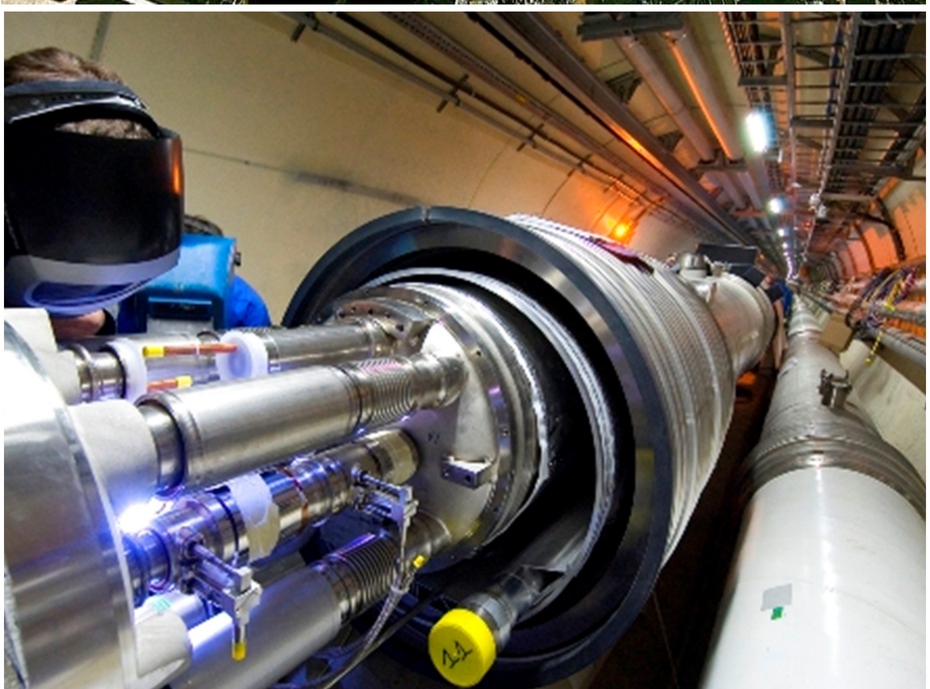
LHC:

| | | |
|---|---|---|
| $N_x$ | ~ | $10^{11}$ |
| A | ~ | .0005 $mm^2$ |
| n | ~ | 2800 |
| $f$ | ~ | 11 kHz |
| L | ~ | $10^{34}$ $cm^{-2}$ $s^{-1}$ |

$N_a$ : number of particles per bunch (beam A)
$N_b$ : number of particles per bunch (beam B)
U : circumference of ring
n : number of bunches per beam
v : velocity of beam particles
$f$ : revolution frequency
A : beam cross-section
$\sigma_x$ : standard deviation of beam profile in x
$\sigma_y$ : standard deviation of beam profile in y

# The LHC machine



| | |
|---|---|
| Circumference (km) | 26.7 |
| Number of superconducting Dipoles | 1232 |
| Length of Dipole (m) | 14.3 |
| Dipole Field Strength (Tesla) | 8.4 |
| Operating Temperature (K) | 1.9 |
| Current in dipole sc coils (A) | 13000 |
| Beam Intensity (A) | 0.5 |
| Beam Stored Energy (MJoules) | 362 |
| Number of particles per bunch | $1.15 \times 10^{11}$ |
| Number of bunches per beam | 2808 |
| Crossing angle (μrad) | 285 |
| Bunch length (cm) | 7.55 |
| Norm transverse emittance (μm rad) | 3.75 |
| Beta function at IP 1,2,5,8 (m) | 0.55,10,0.55,10 |

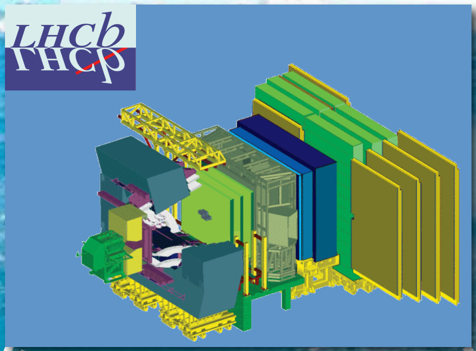
$$L = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \varepsilon_n \beta *} F$$

$N_b$ = number of proton per bunch
$n_b$ = number of bunches

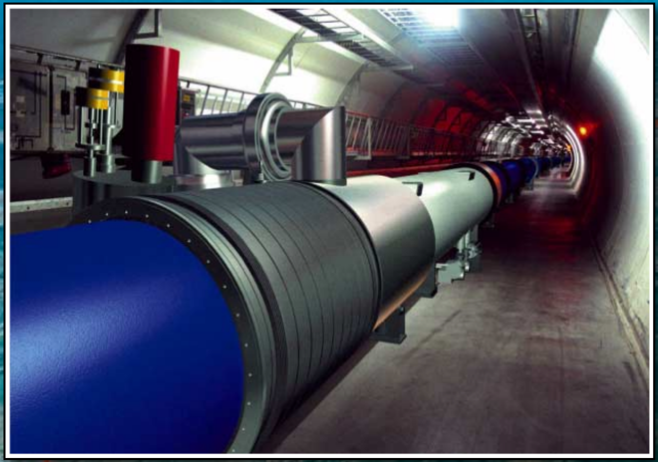
$f_{rev}$ = rotation frequency (~ 11Hz)
F = crossing angle factor

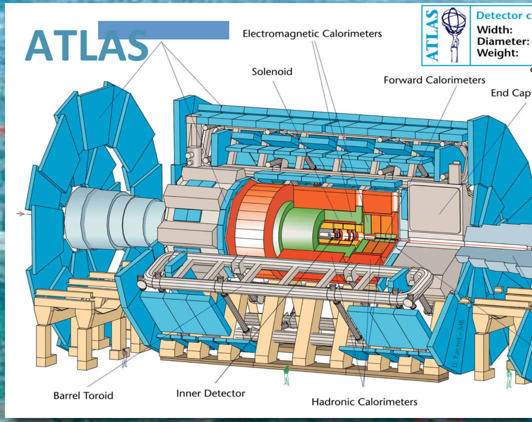
Rms transverse beam size $= \sqrt{\varepsilon \beta / \gamma}$
$\varepsilon_n$ = renorm. transverse emittance
$\beta*$ = optics at beam crossing (m)
$\gamma_r$ = relativistic factor

pp, B-Physics,
CP Violation

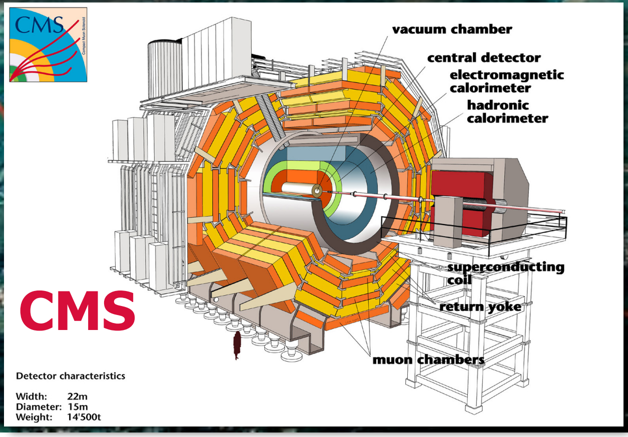



LHC : 27 km long
100m underground

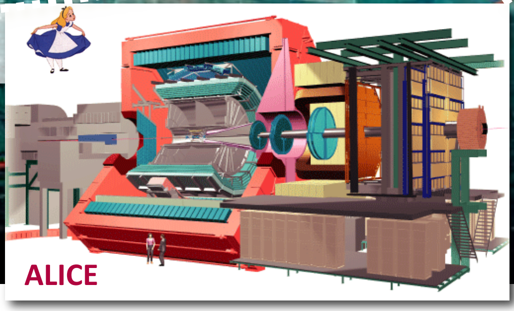




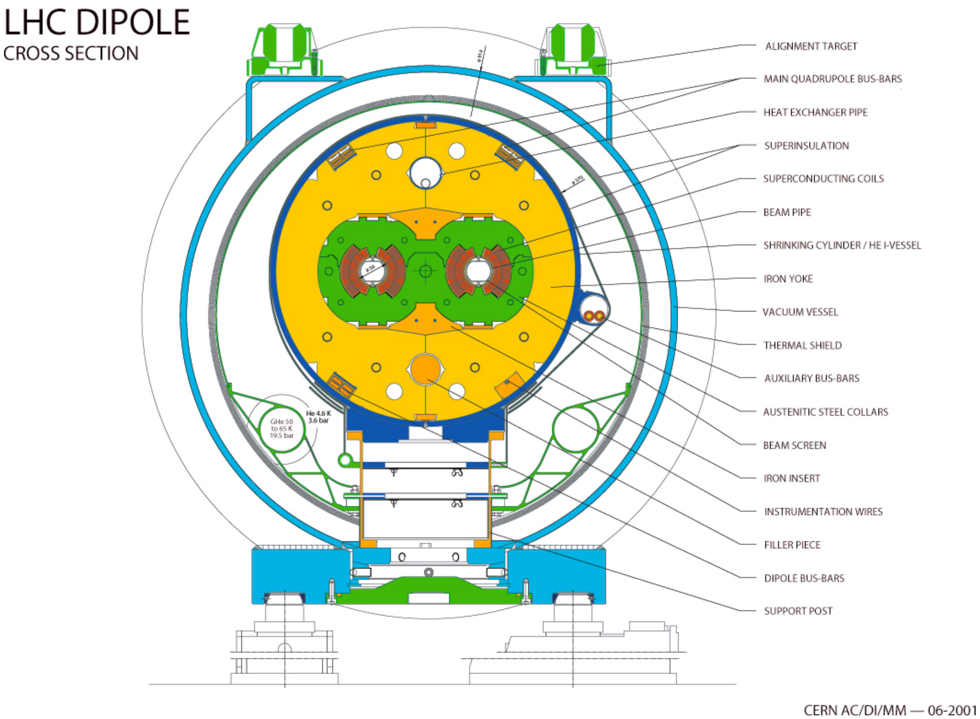

General Purpose,
pp, heavy ions




Heavy ions, pp



# LHC Magnets




9300 Superconducting Magnets
1232 Dipoles (15m), 448 Main Quads, 6618 Correctors.
Operating temperature: 1.9° K
26.7 km tunnel

# LHC magnets

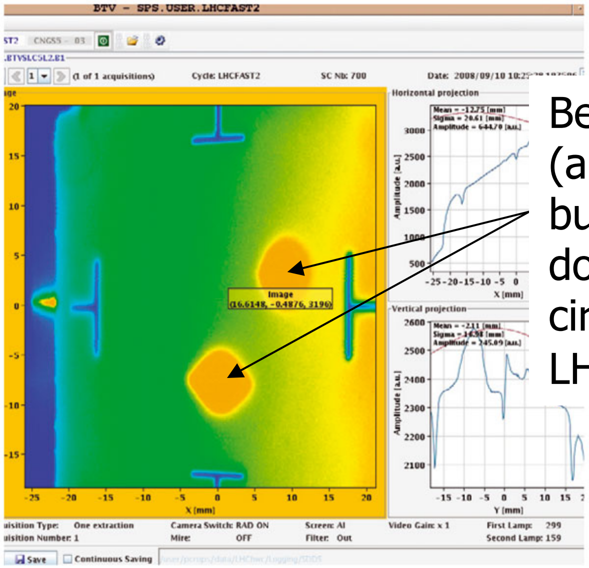

Lowering one of the 1232
15m long dipoles 100m down into the LHC
There are another 8000 magnets of different types as well
1st magnet lowered in March 2005

*The last dipole magnet makes its descent towards its final destination in the LHC tunnel.*

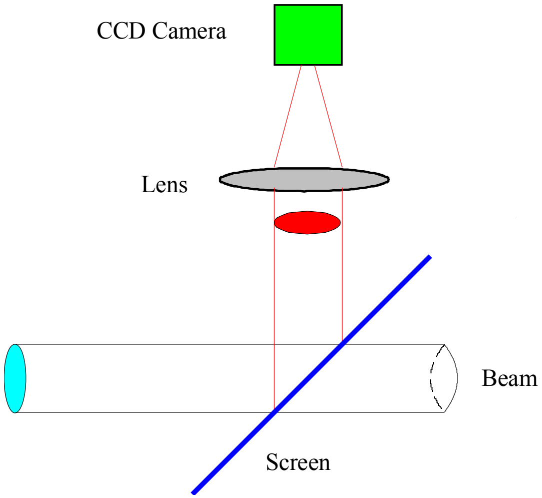
18 | CERN

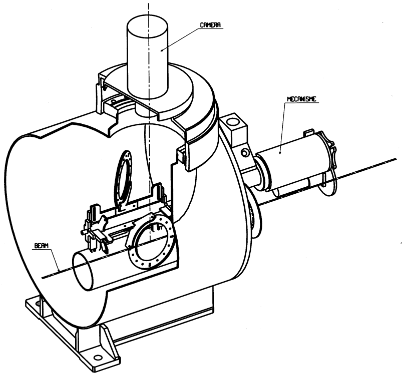
# First beams around the LHC

Joyous faces on **10 Sep 2008** at 10.23



Beam (a single proton bunch) enters and does a complete circle around the LHC ring

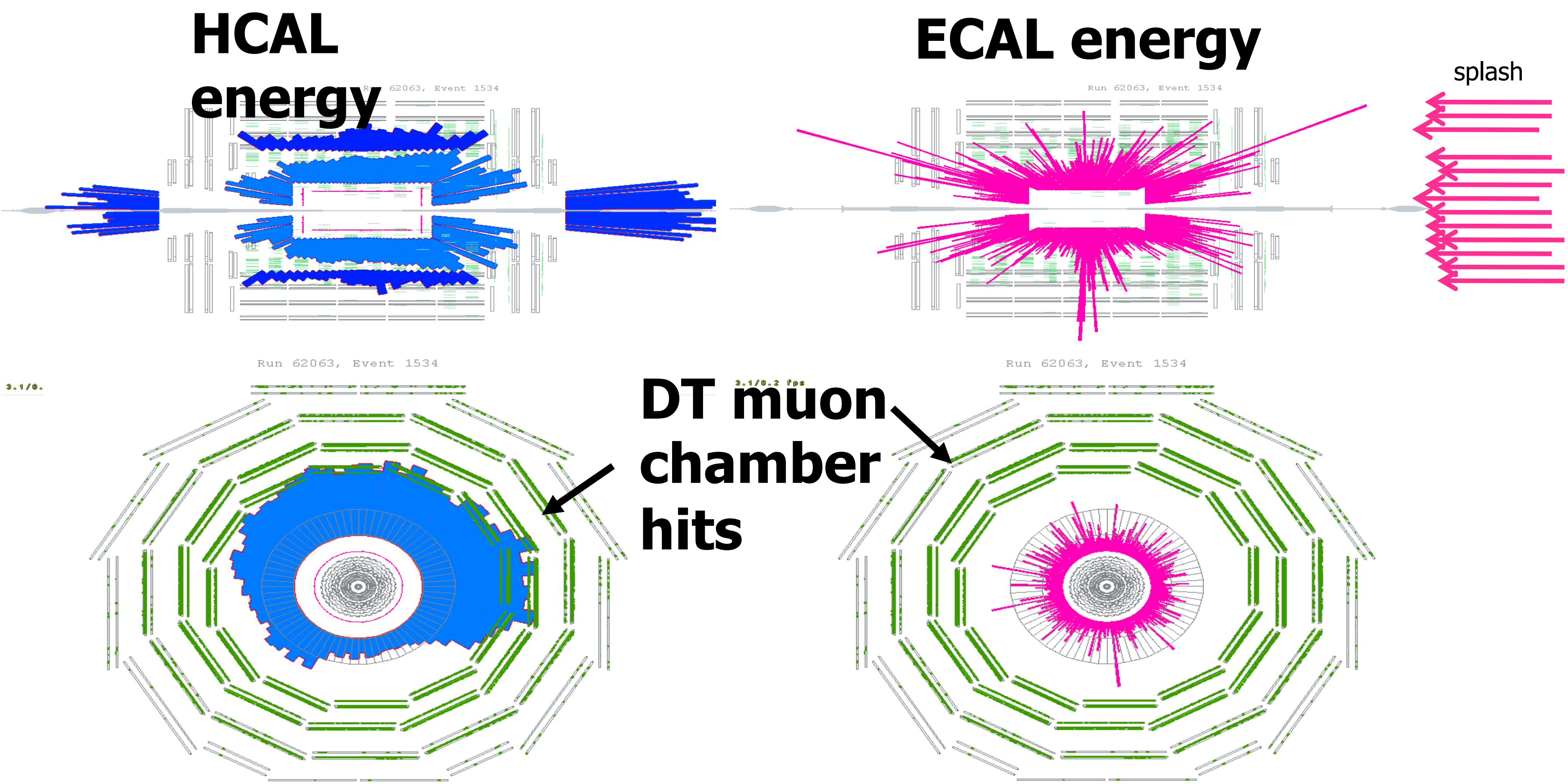


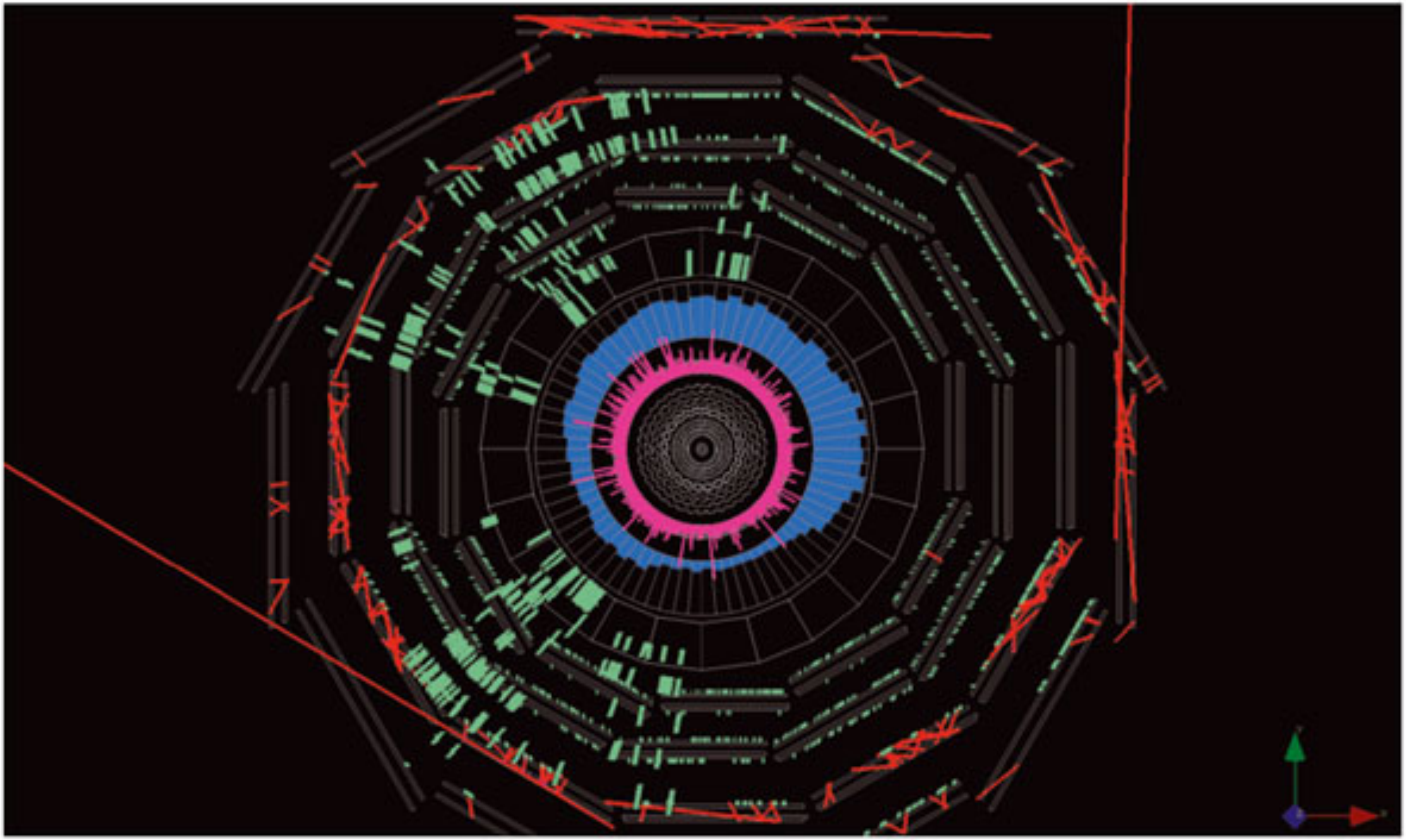
Fluorescent screen to detect the beam – like that in a CRT television

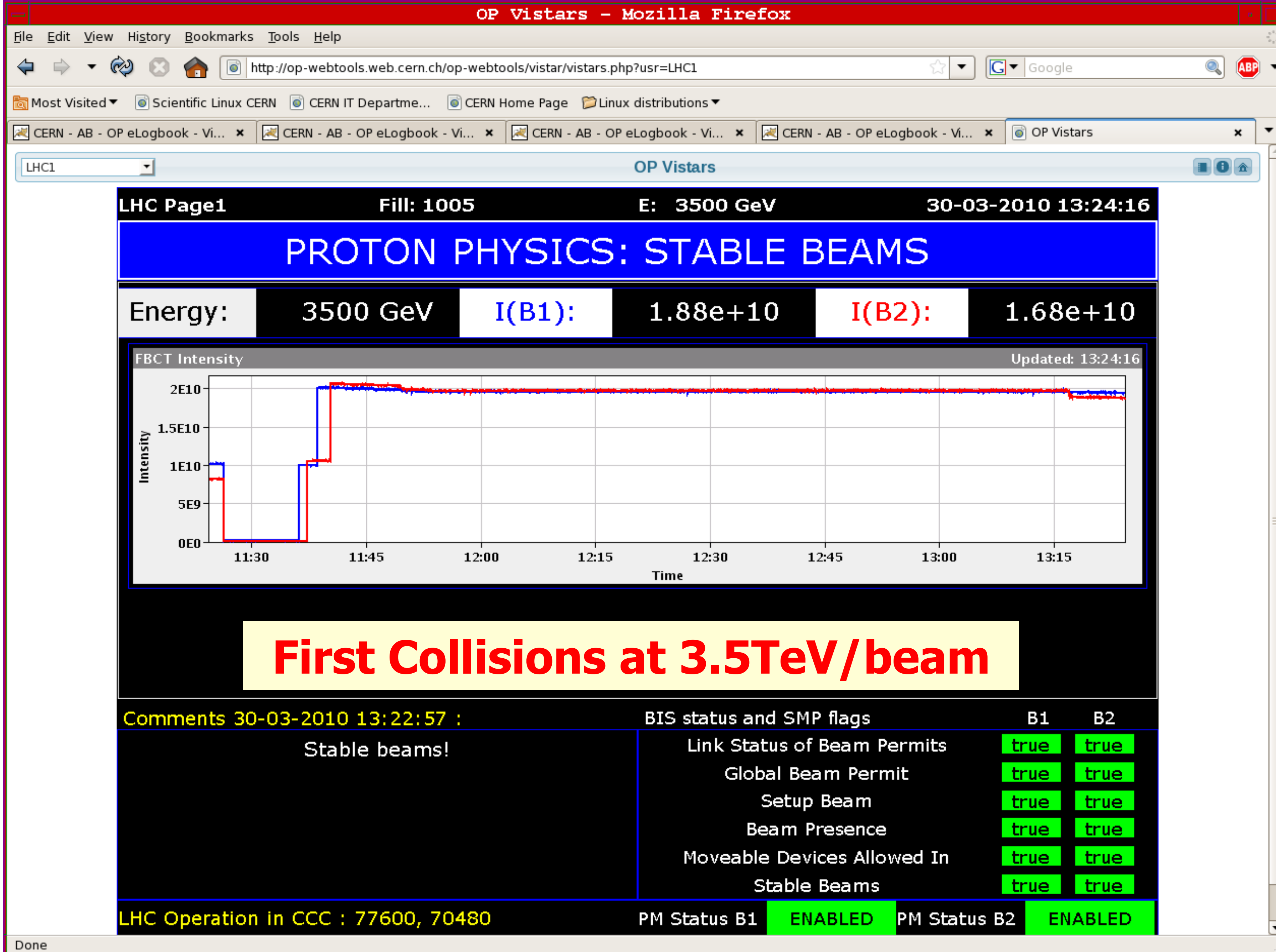
# Beam splashes at CMS

- $10^9$ protons at 450 GeV dumped on collimator 150 m upstream of the CMS experiment. ECAL total energy: 150-250 TeV



# First beams around the LHC in CMS




OP Vistars - Mozilla Firefox
http://op-webtools.web.cern.ch/op-webtools/vistar/vistars.php?usr=LHC1
OP Vistars
LHC Page1
Fill: 1005
E: 3500 GeV
30-03-2010 13:24:16
PROTON PHYSICS: STABLE BEAMS
Energy:
3500 GeV
I(B1):
1.88e+10
I(B2):
1.68e+10
FBCT Intensity
Updated: 13:24:16
Intensity
Time
First Collisions at 3.5TeV/beam
Comments 30-03-2010 13:22:57 :
Stable beams!
BIS status and SMP flags
B1
B2
Link Status of Beam Permits
Global Beam Permit
Setup Beam
Beam Presence
Moveable Devices Allowed In
Stable Beams
true
LHC Operation in CCC : 77600, 70480
PM Status B1
ENABLED
PM Status B2
ENABLED

# Basic principles of the detectors

Need "general-purpose" experiments covering as much of the solid angle as possible ("4$\pi$") since we don't know how New Physics will manifest itself

→ detectors must be able to detect as many particles and signatures as possible: e, $\mu$, $\tau$, $\nu$, $\gamma$, jets, b-quarks, ....

Momentum / charge of tracks and secondary vertices (e.g. from b-quark decays) are measured in central tracker (Silicon layers).

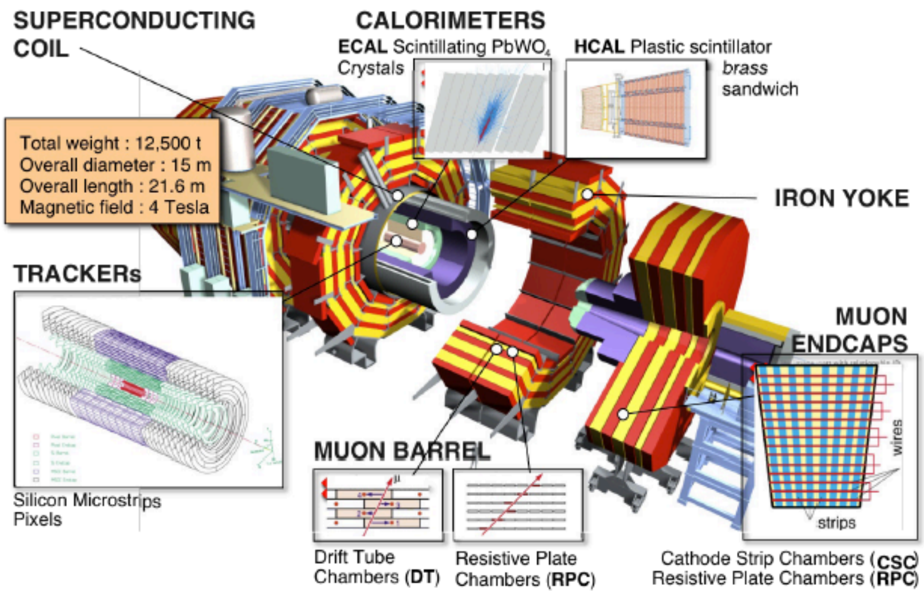
Energy and positions of electrons and photons measured in electromagnetic calorimeters (+central tracker).

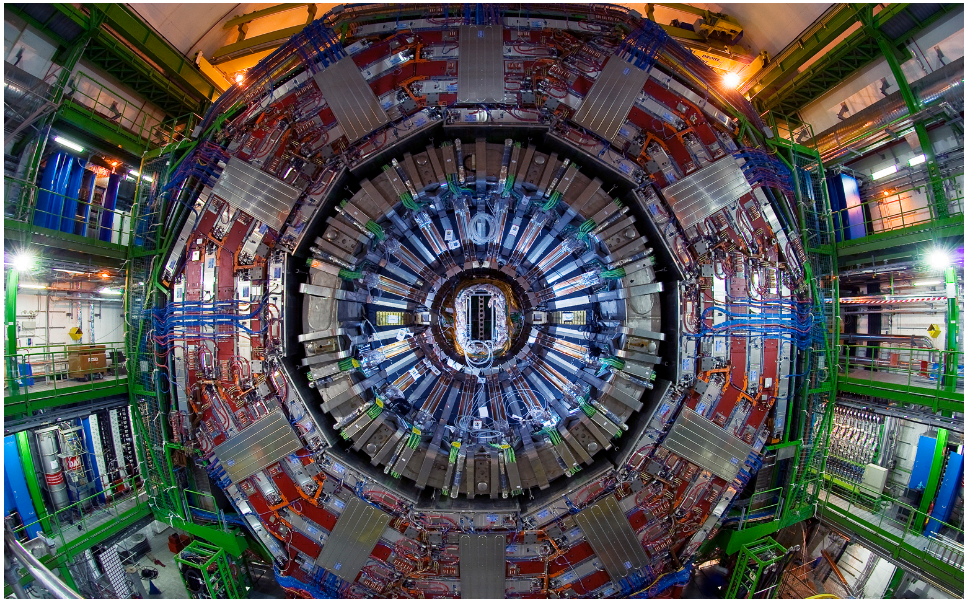
Energy and position of hadrons and jets measured mainly in hadronic calorimeters (+central tracker for charged hadrons).

Muons identified and momentum measured in external muon spectrometer (+central tracker).

Neutrinos "detected and measured" through measurement of missing transverse energy (**$ET^{miss}$**) in calorimeters (+central tracker).

# CMS in a nutshell



$|\eta|<2.5$ : *Tracker*

$\sigma/p_T \approx 10^{-4} p_T \oplus 0.005$

$|\eta|<4.9$ : *EM Calorimeter*

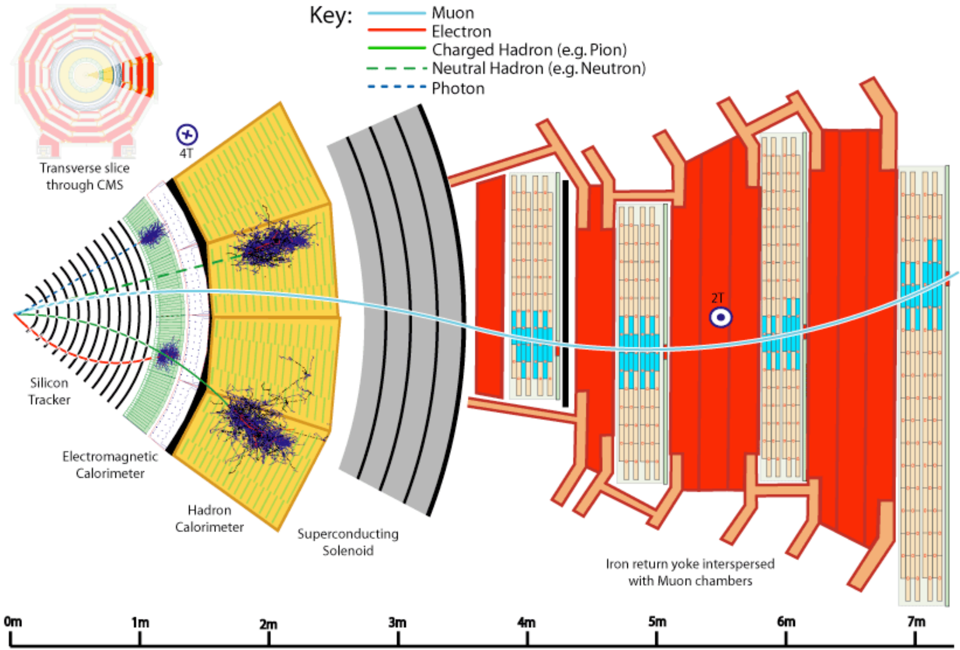
$\sigma/E \approx 0.03/\sqrt{E} + 0.003$

$|\eta|<4.9$ : *HAD Calorimeter*

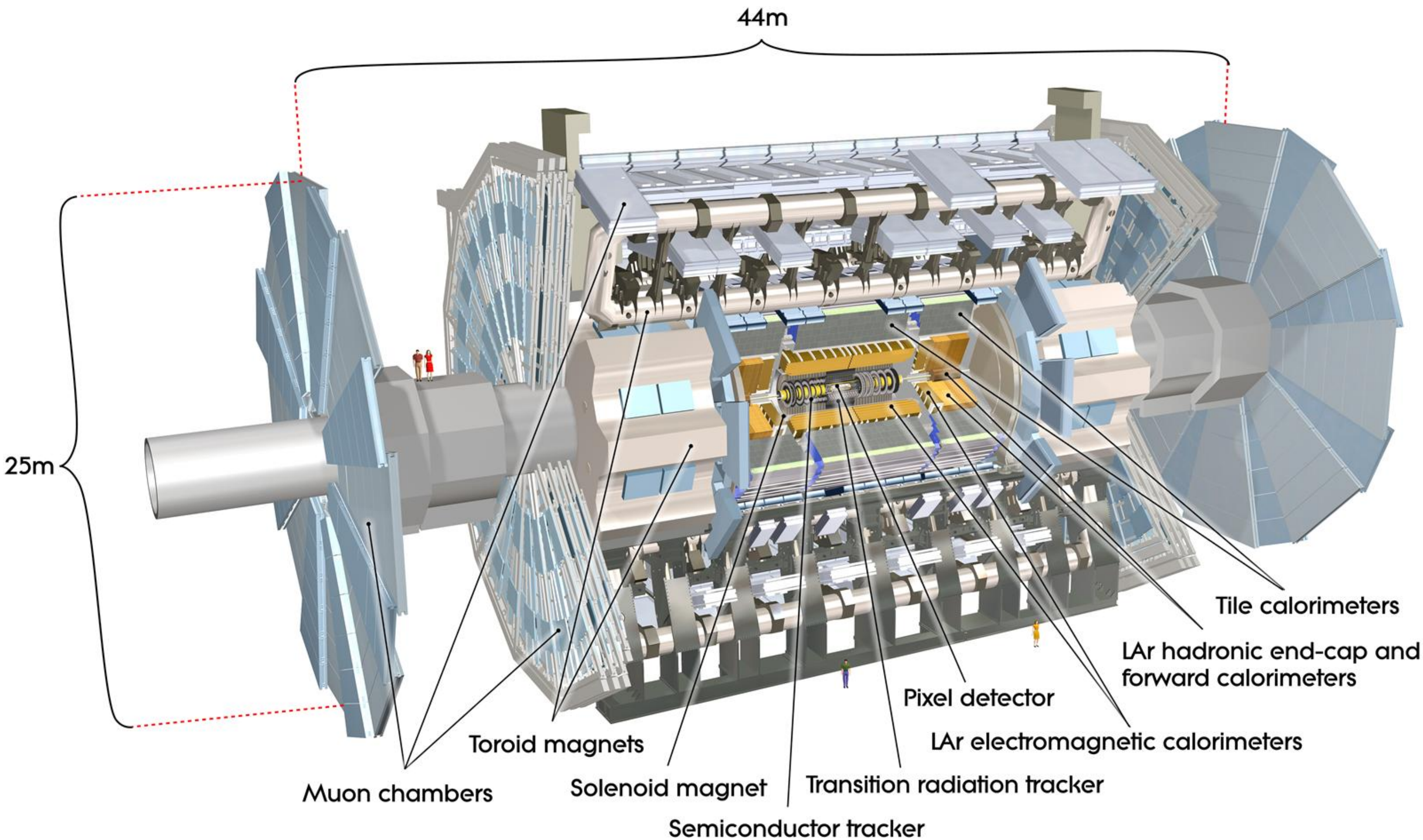
$\sigma/E \approx 1.0/\sqrt{E} + 0.05$

$|\eta|<2.4$ : *Muon spectrometer*

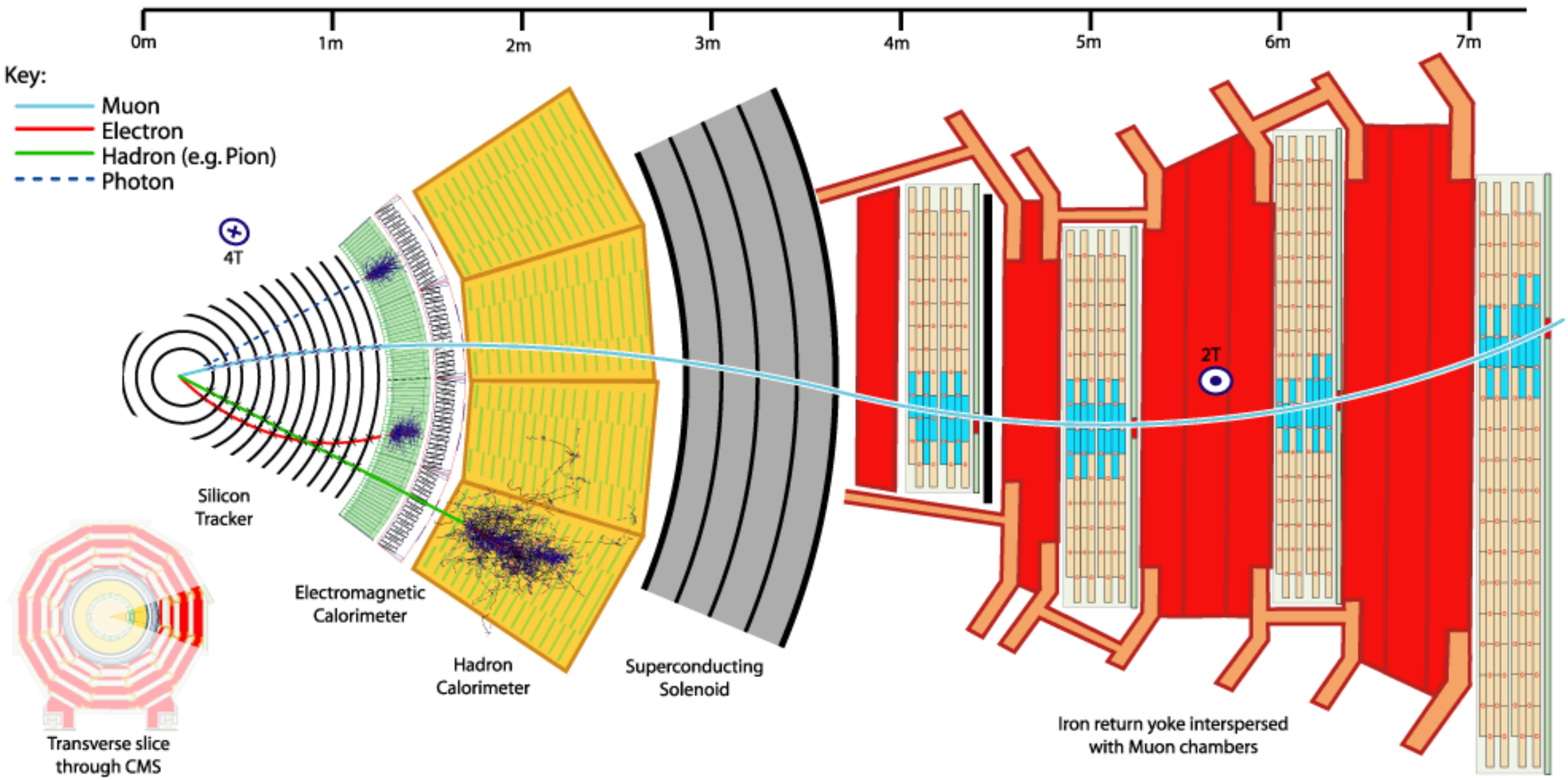
$\sigma/p_T \approx 0.10$ *(1TeV muons)*



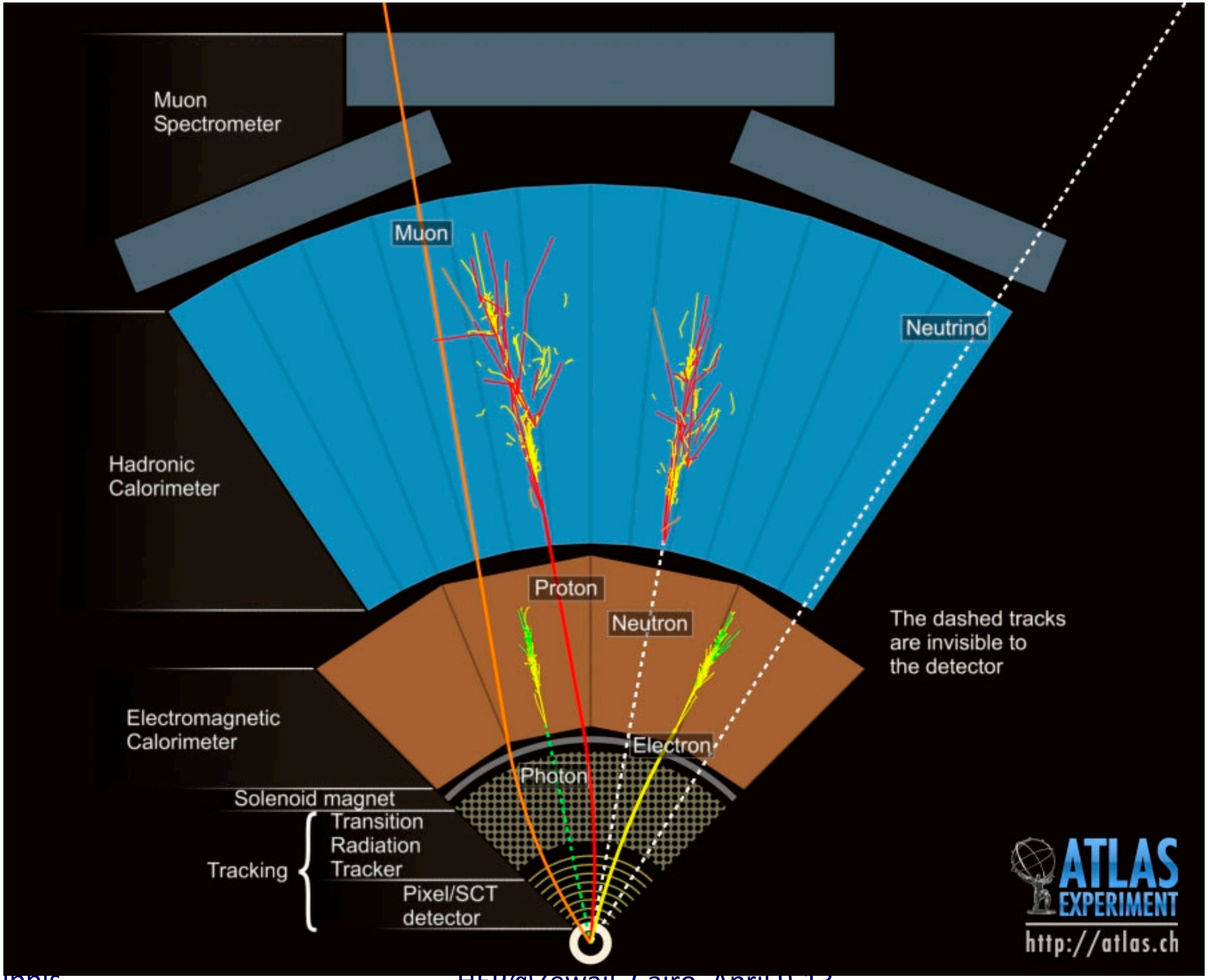
# ATLAS in a nutshell



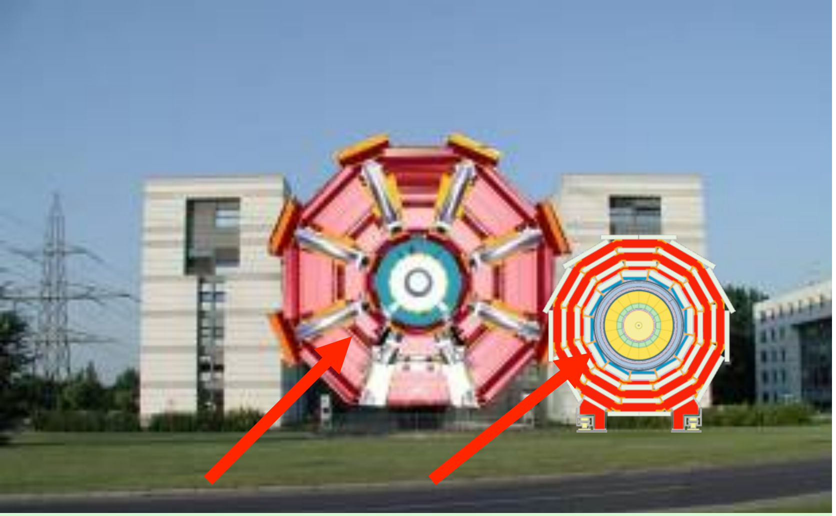
# Particles as seen in CMS



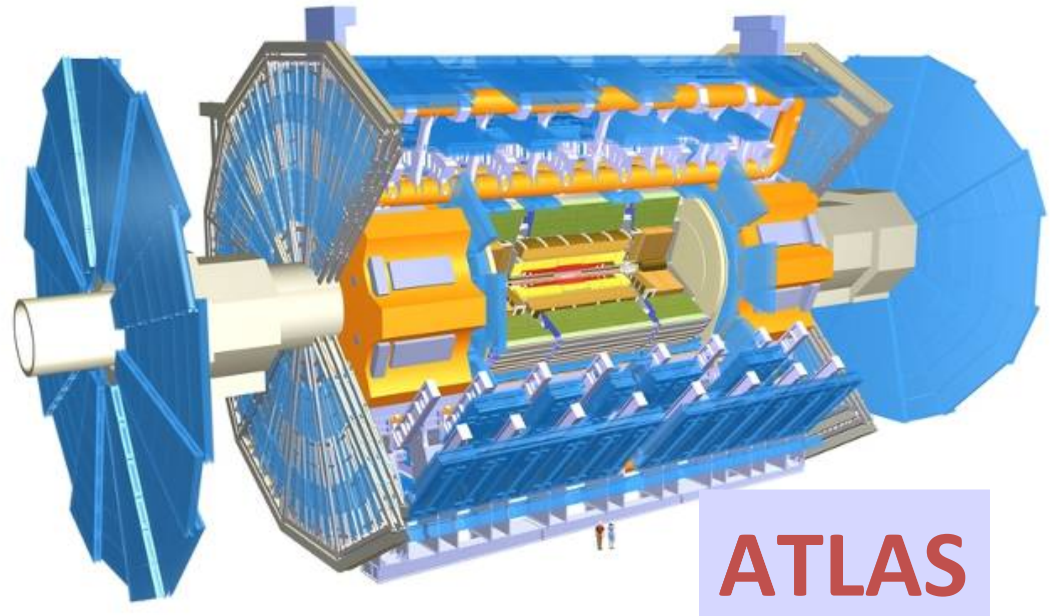
# Particles as seen in ATLAS

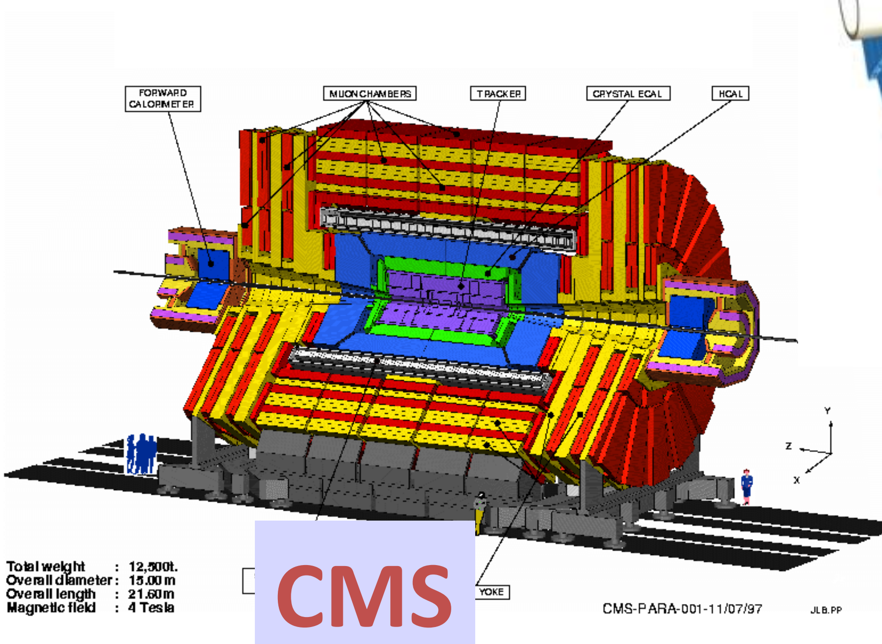


# How big are ATLAS and CMS?



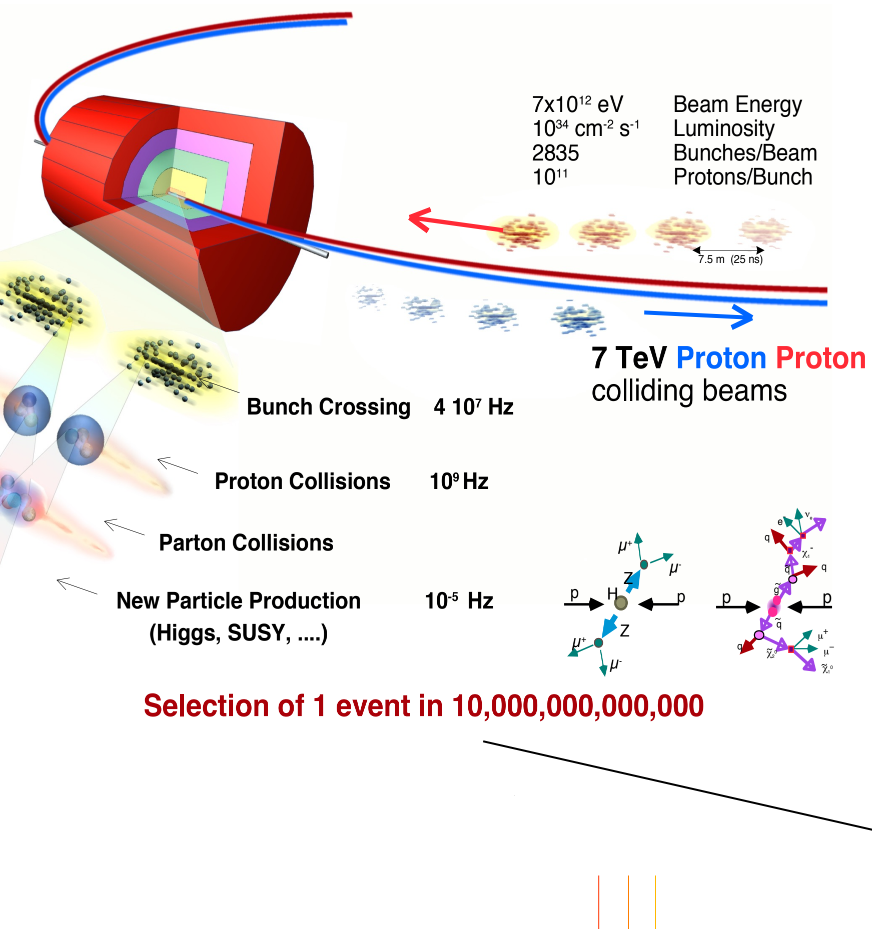
ATLAS/CMS and a 5 floor building

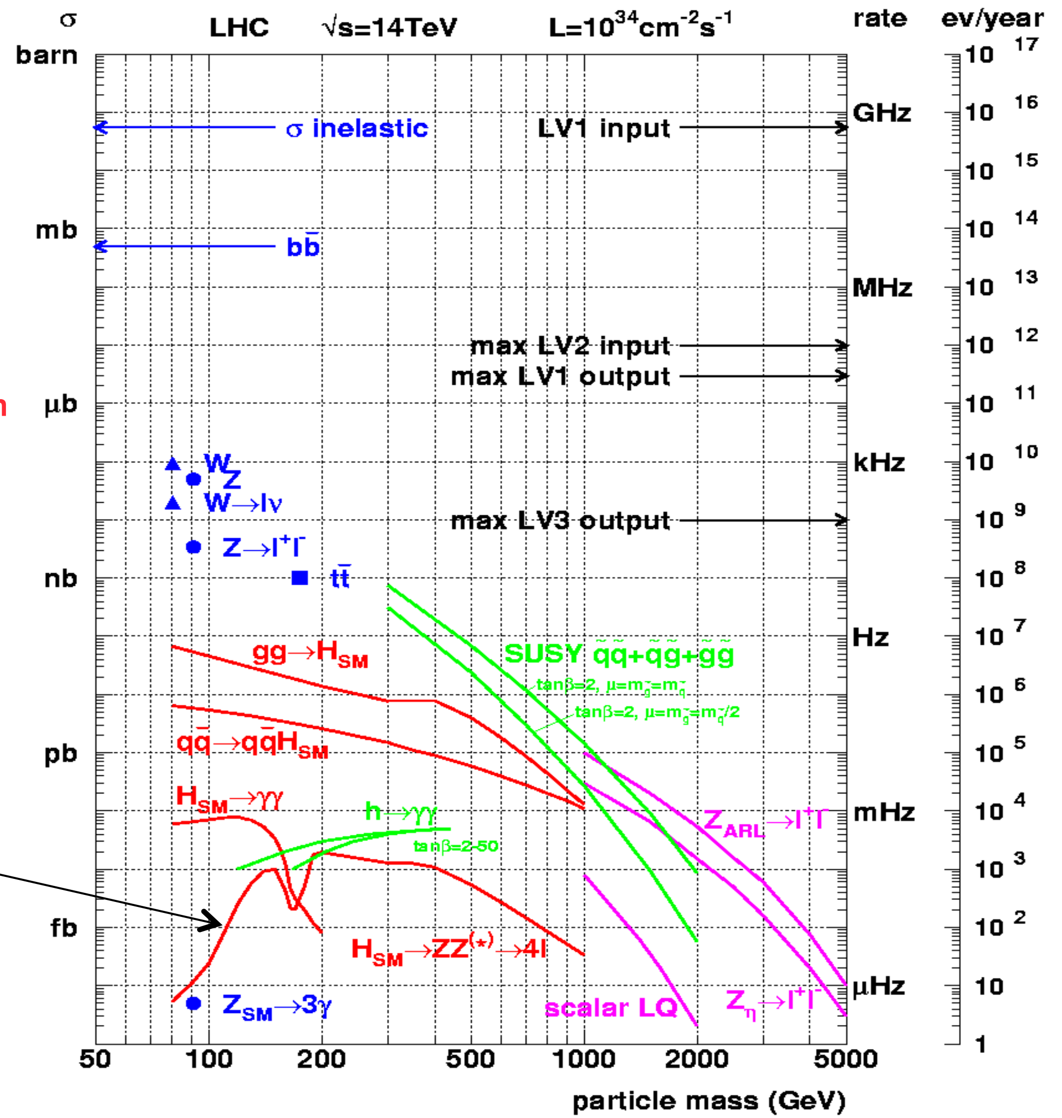


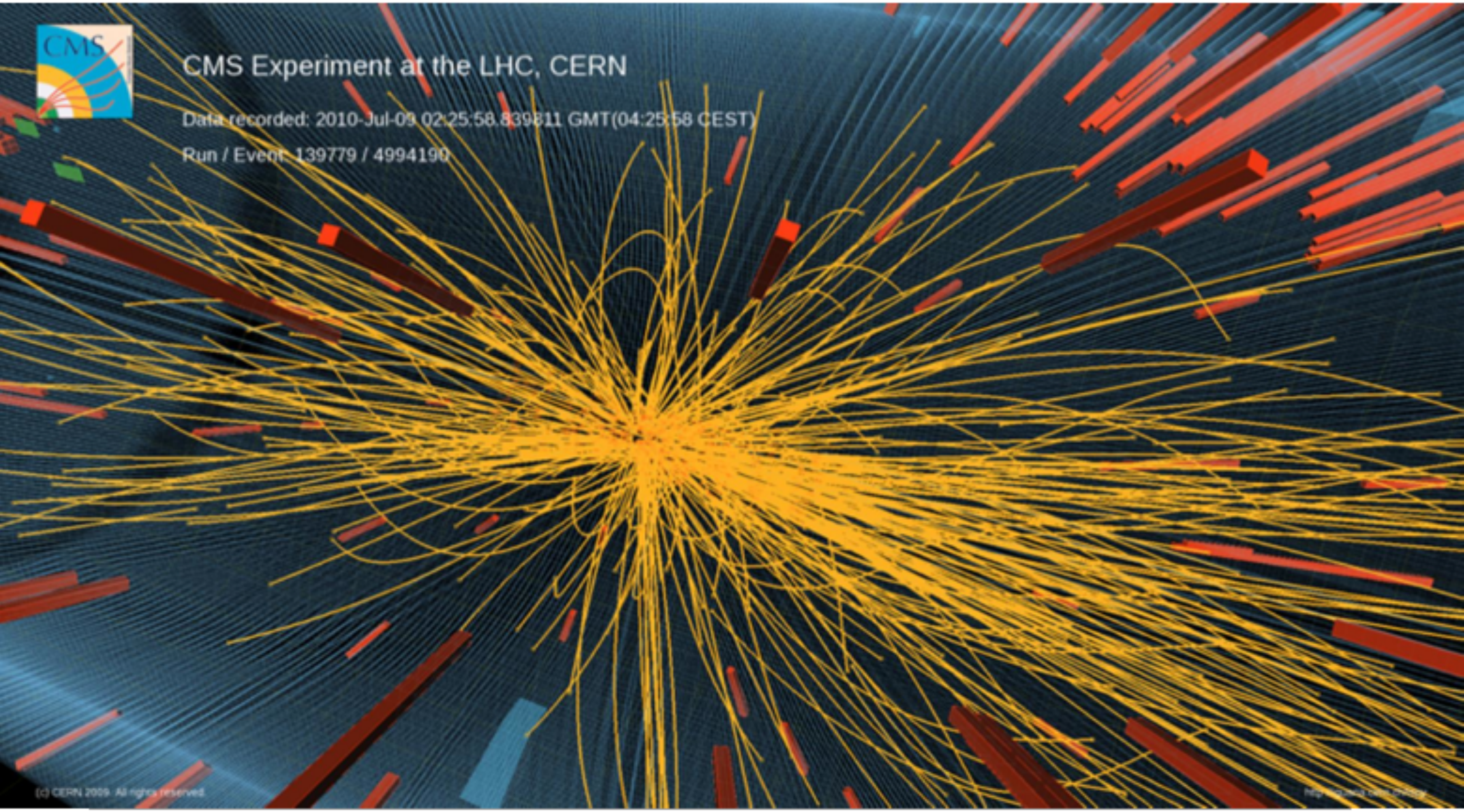

| | ATLAS | CMS |
|---|---|---|
| Weight (tons) | 7000 | 12500 |
| Diameter | 22 m | 15 m |
| Lenght | 46 m | 22 m |
| Magnetic field | 2 T | 4 T |

# Proton-proton collisions at LHC



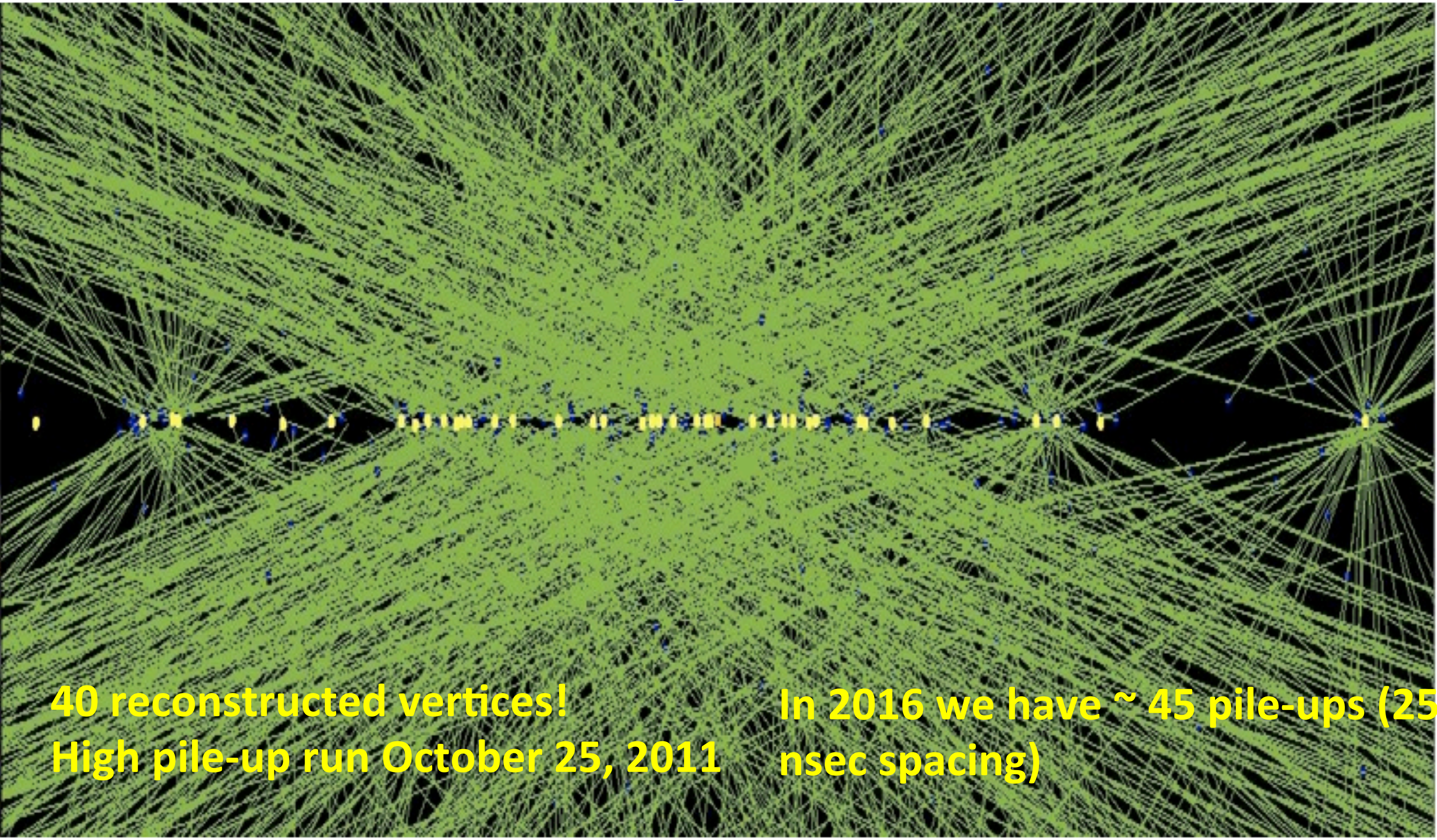



# A typical pp collision at the LHC



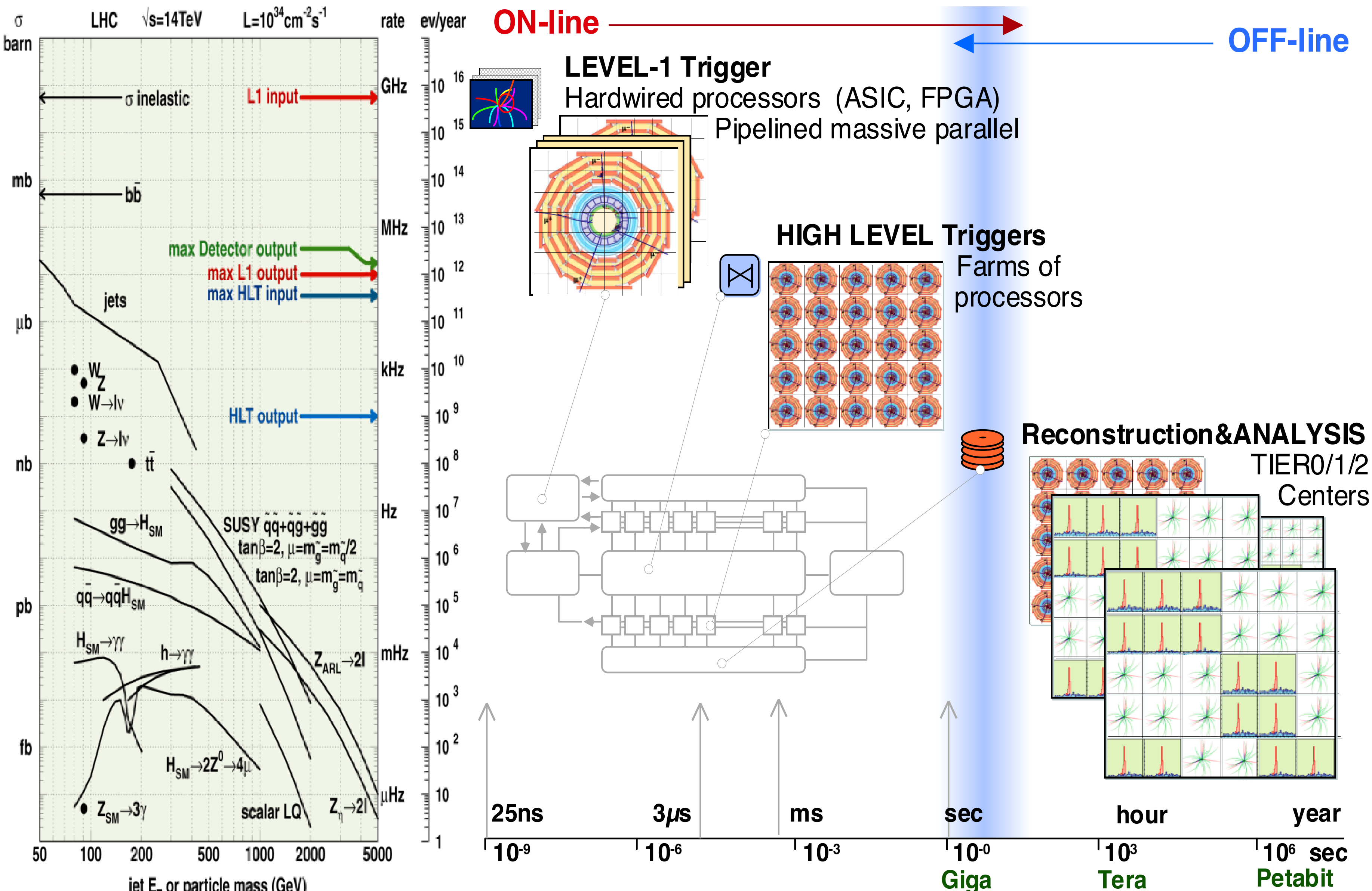

Expected Higgs boson production rate is less than one in a billion pp colisions!

# Pile-up events




In HL-LHC phase ( ~$5x10^{34}cm^{-2}s^{-1}$)we expect to go to ~150 pile-ups per crossing!

# Event selection stages



## SM Physics

# MB, jets, W, Z, top, Higgs

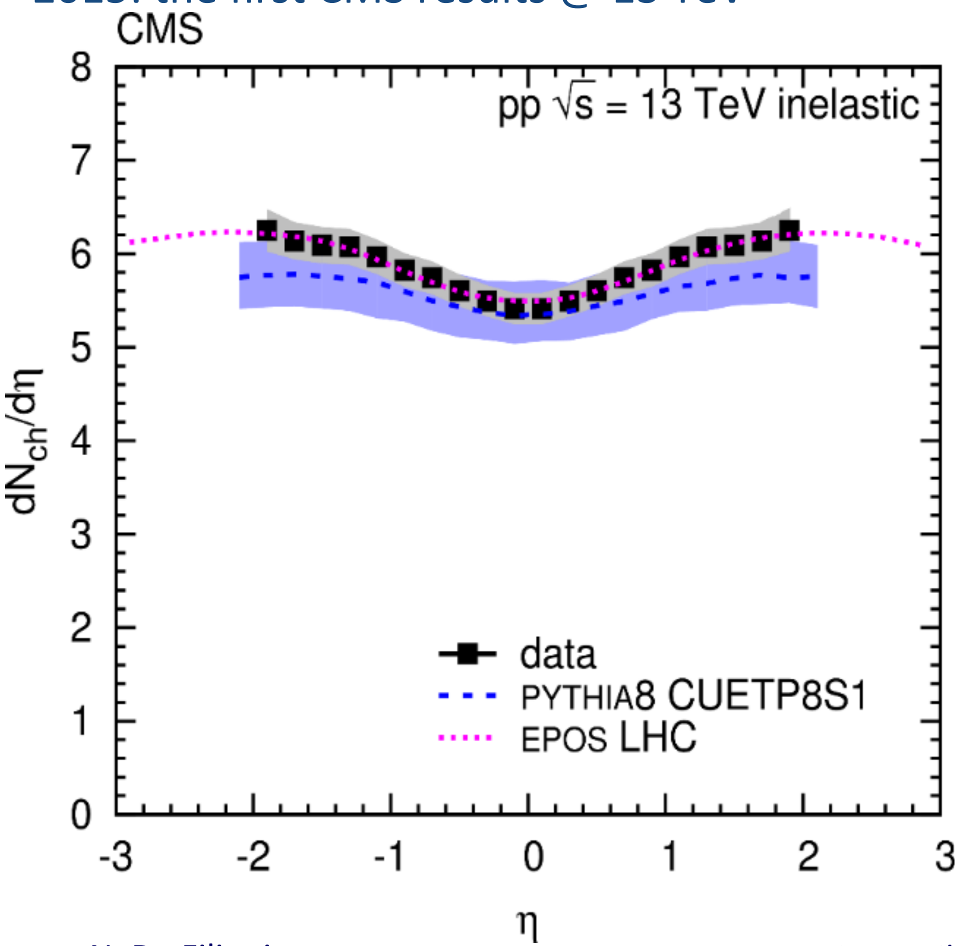
# Inelastic pp collision: charged multiplicity

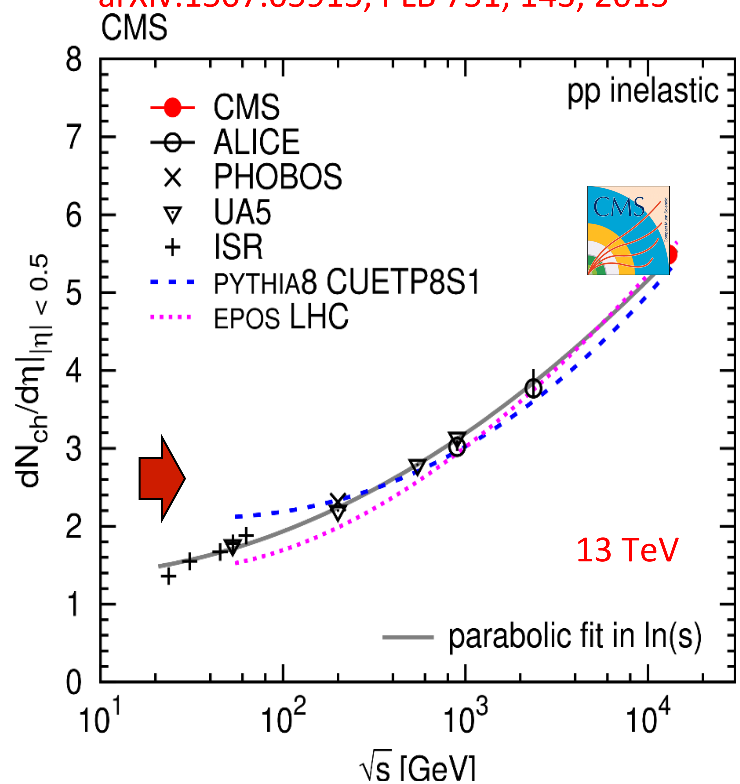
**Particle density in minimum bias events**

- Soft QCD (PT threshold on tracks: 50 MeV)

2009: the first CMS results @ 0.9-2.36 TeV
2010: the first CMS results @ 7 TeV
2015: the first CMS results @ 13 TeV

arXiv:1507.05915, PLB 751, 143, 2015



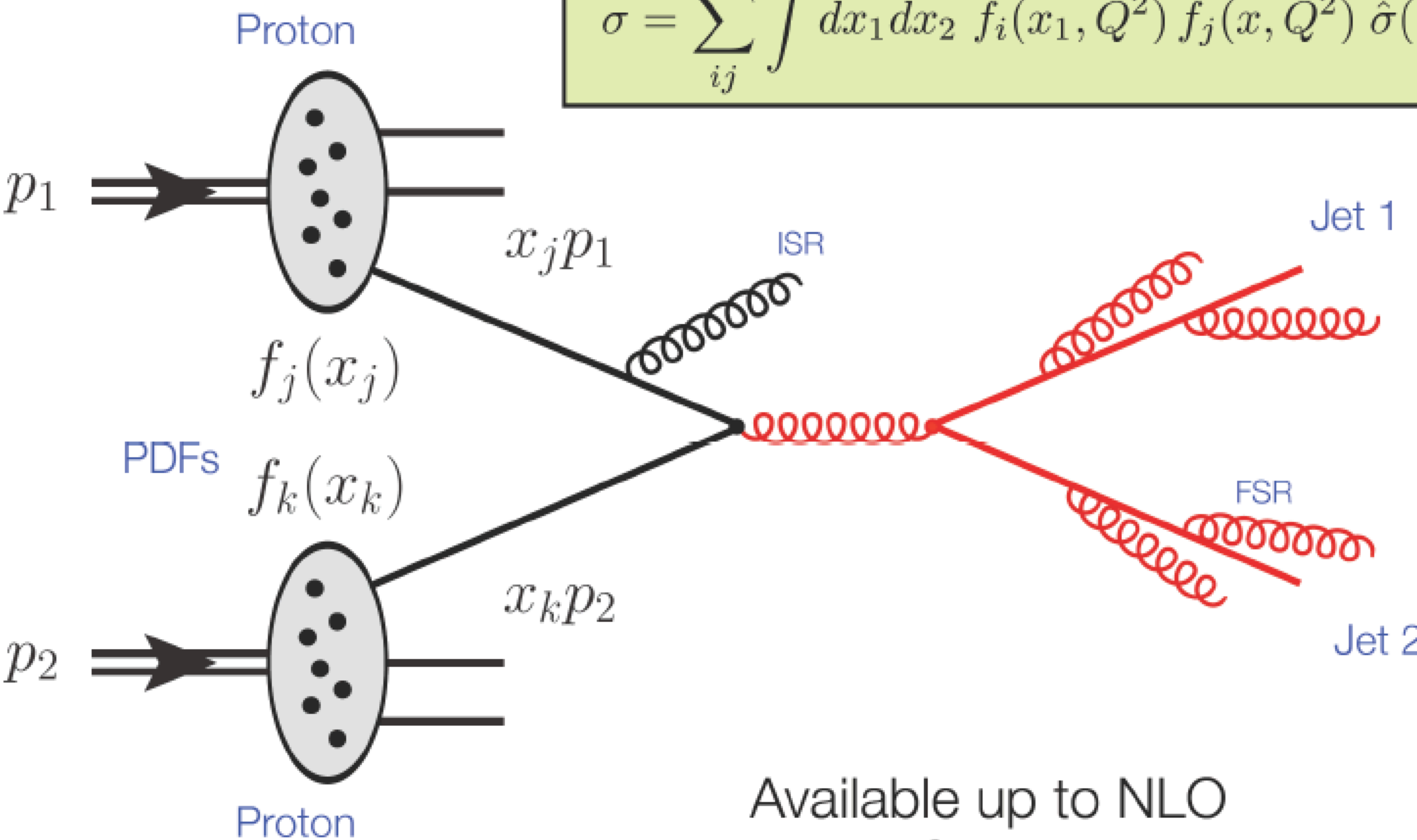




**In the central region, the measured dNch/dη distribution is consistent with predictions of the PYTHIA8 (with the CMS underlying event tunes CUETP8S1 and CUETP8M1) and EPOS LHC (LHC tune) event generators**

**recheck the Monte-Carlo tunes**

# Jet production @ LHC

$$\sigma = \sum_{ij} \int dx_1 dx_2 \; f_i(x_1, Q^2)\, f_j(x, Q^2)\, \hat{\sigma}(Q^2)$$



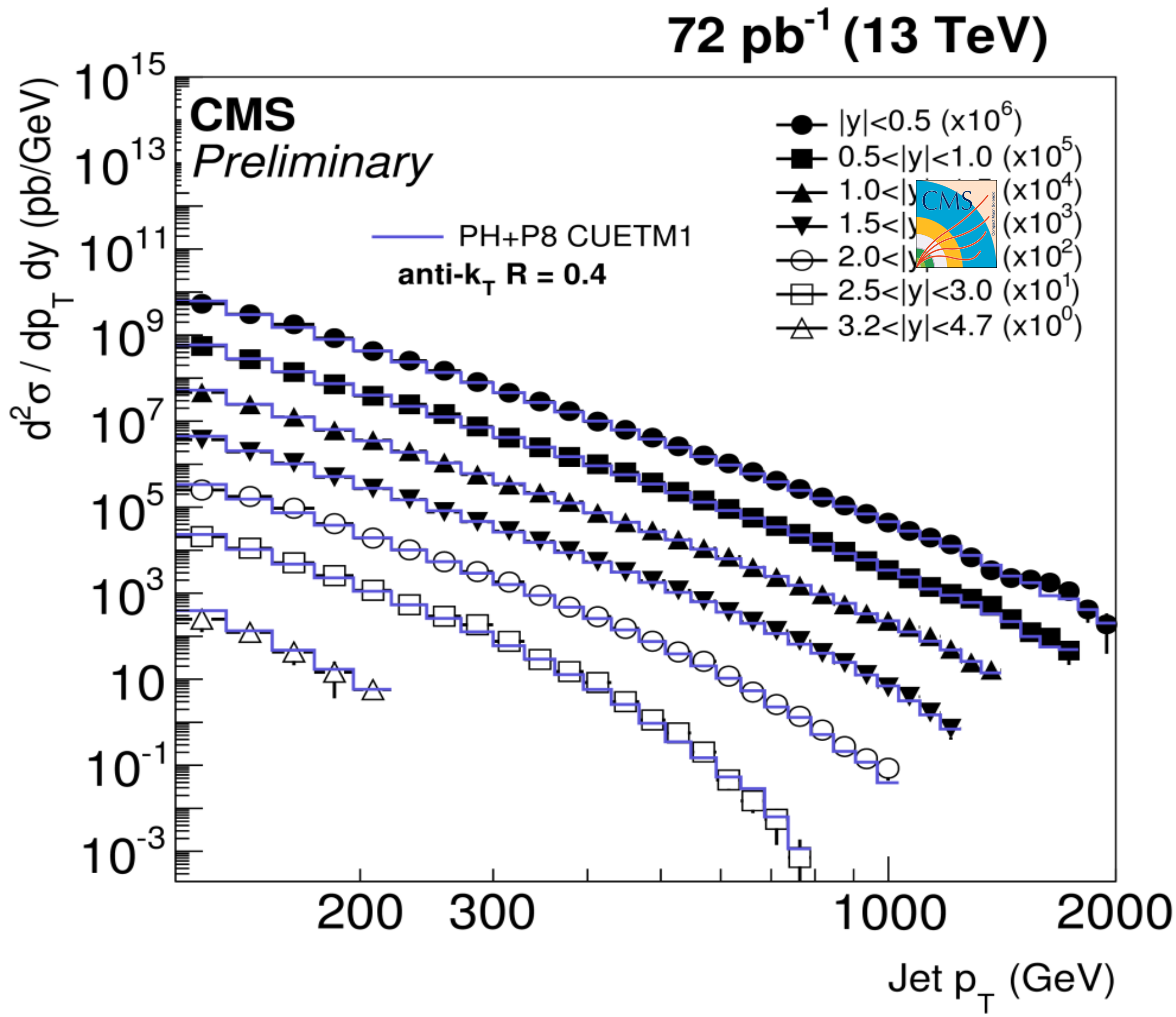

Available up to NLO

First NNLO calculations becoming available ...

# QCD: Inclusive jet cross section

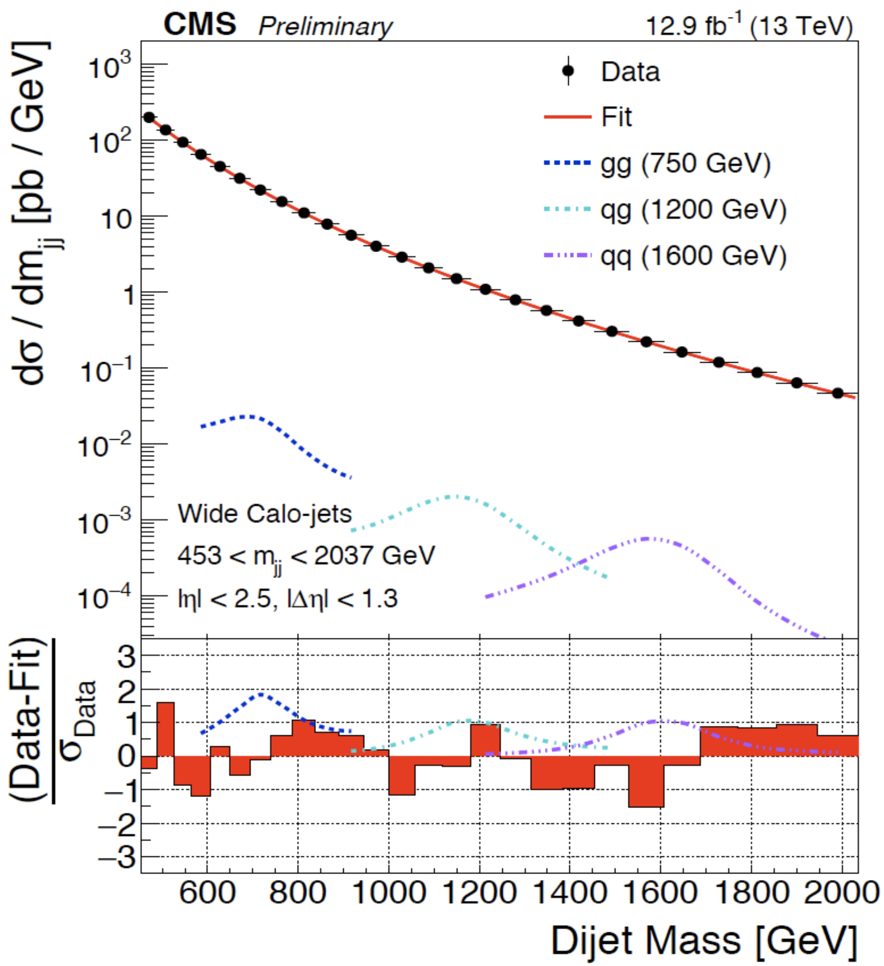
- Cross section is huge (~ Tevatron x 100)
- **Very good agreement with NLO QCD over nine orders of magnitude**
- PT extending from 20 GeV to 2 TeV
- Main uncertainty: Jet Energy Scale (3-4%)

CMS-PAS-SMP-15-007

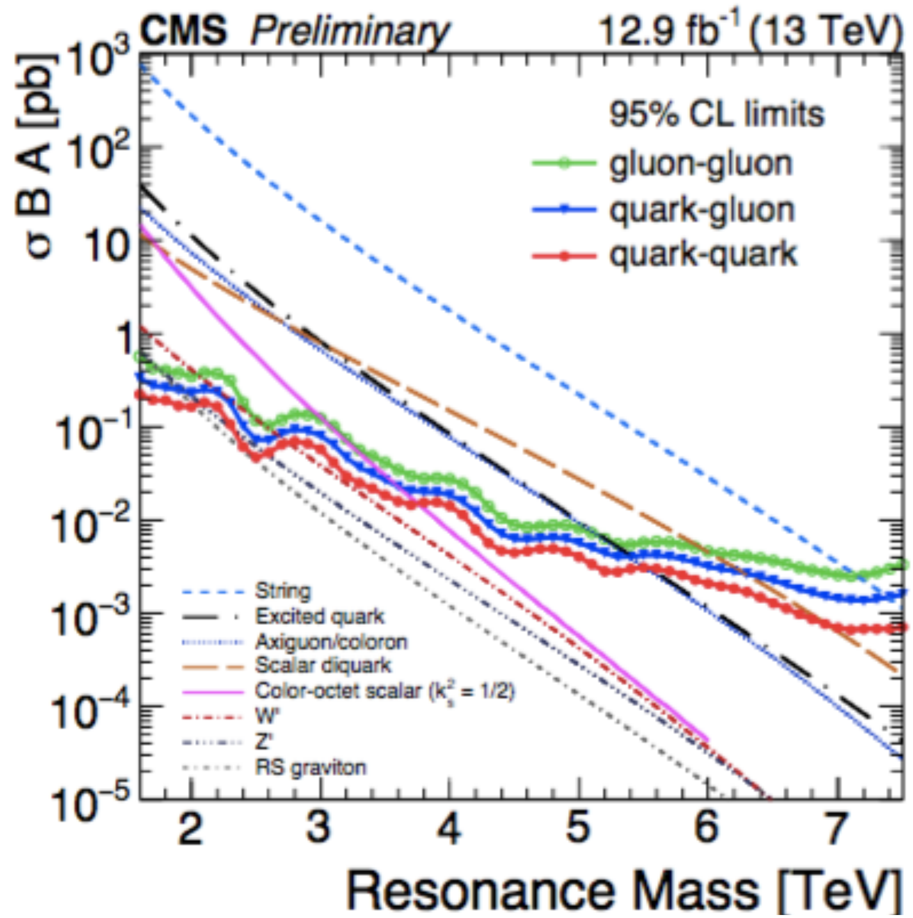


# QCD: Di-jet cross section

Low mass Analysis



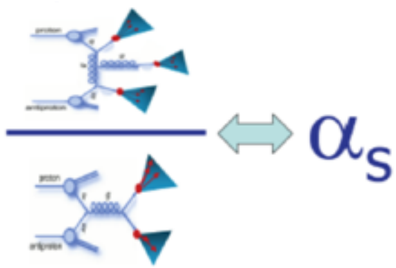

High mass Analysis




STRING resonances excluded up to 7.4 TeV

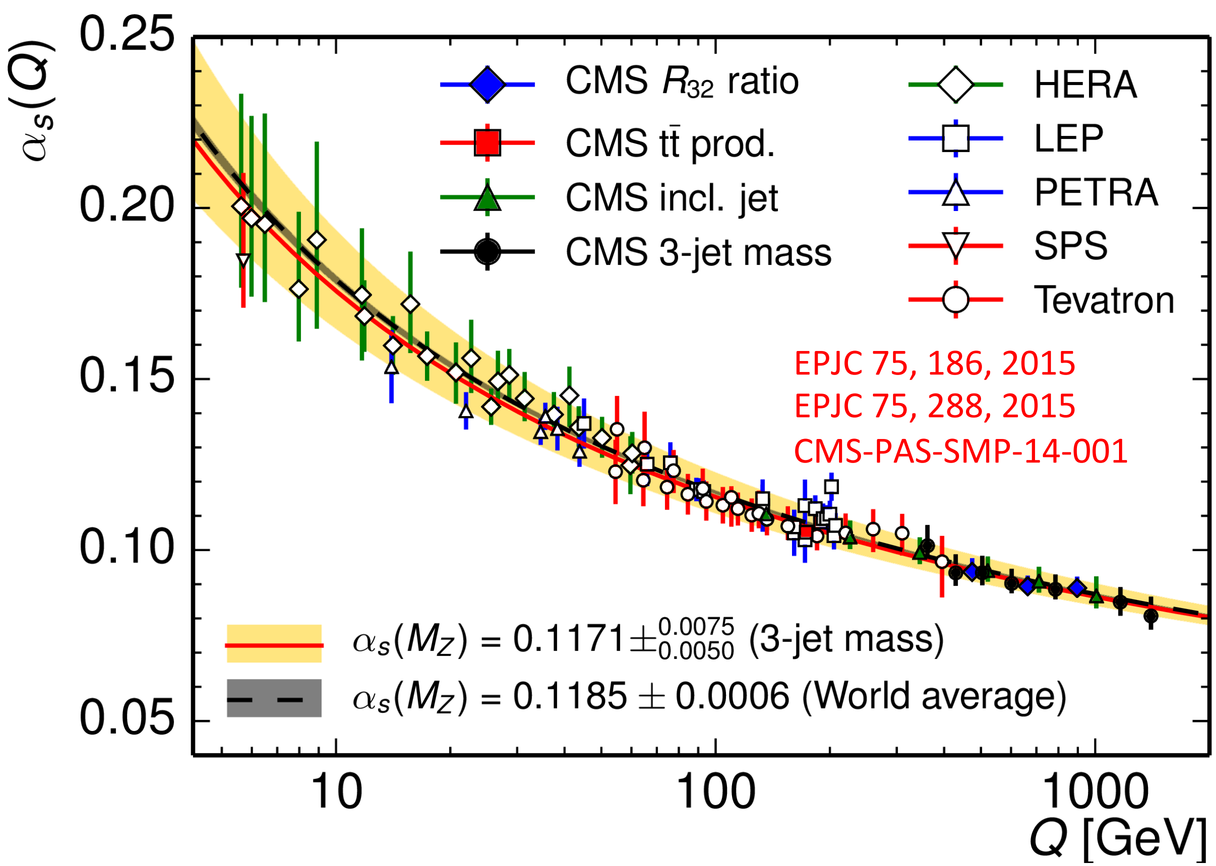
# QCD: Measurements of $\alpha_S$

Ratio of 3-jets of 2-jets, 3-jet mass & inclusive jets x-sections constrain αs (NLO only) up to so-far unprobed scales Q ~ 1.4 TeV




$$R_{32} = \frac{d\sigma_{3+}/dp_{\mathrm{T}}}{d\sigma_{2+}/dp_{\mathrm{T}}} \propto \alpha_s(Q)$$

$$Q = \langle p_{\mathrm{T}1,2} \rangle = \frac{p_{\mathrm{T}1} + p_{\mathrm{T}2}}{2}$$

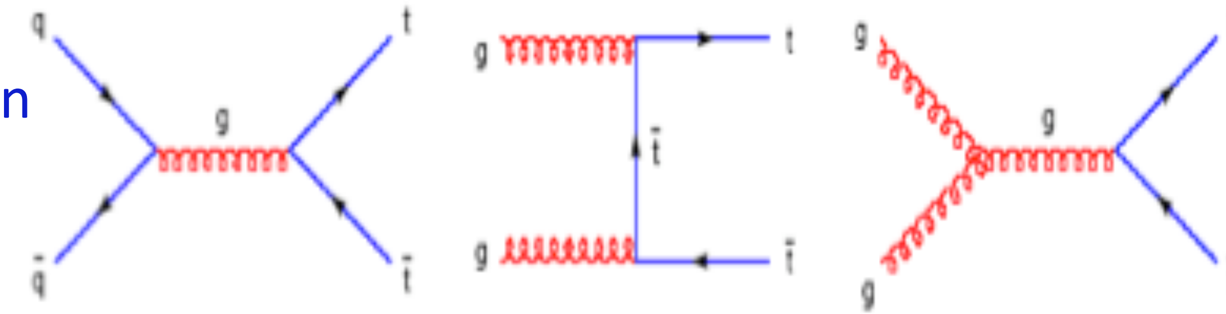



Test of QCD asymptotic freedom in SM

# Top at the LHC, production and decays

## for ex. top → lepton + jets final states

tt-bar production diagrams, some….

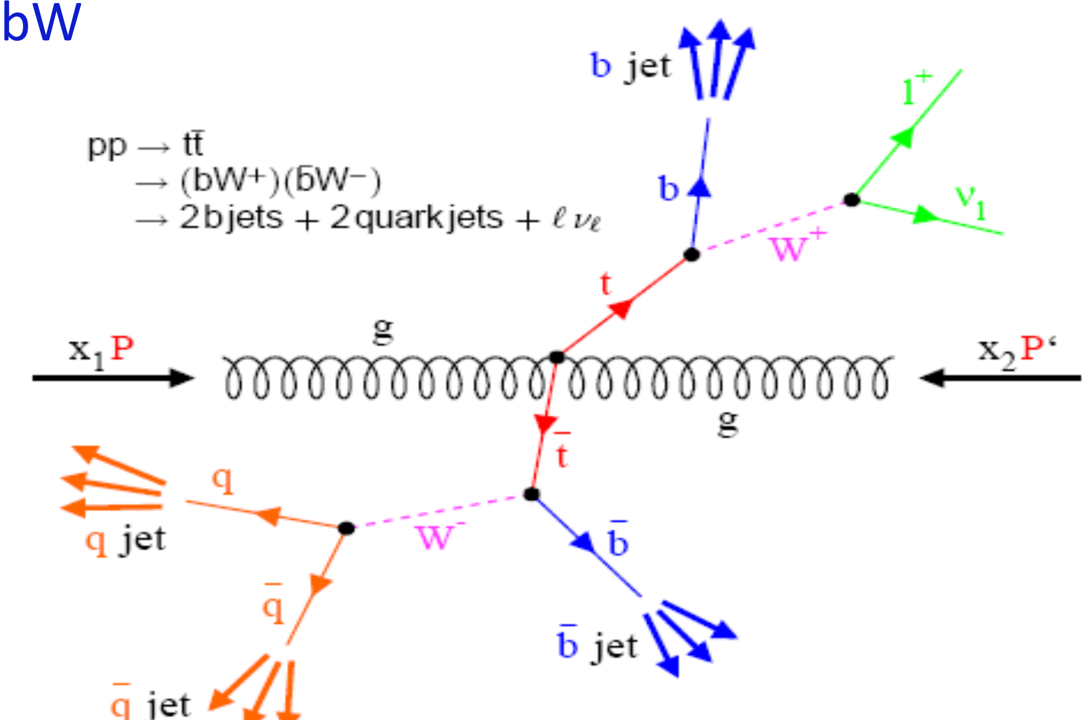



+…..

Top decay in the SM: t → bW

tt-bar event decay topology in «sigle lepton mode »:

$t\bar{t} \rightarrow bWbW \rightarrow bl\nu bqq$




N. De Filippis

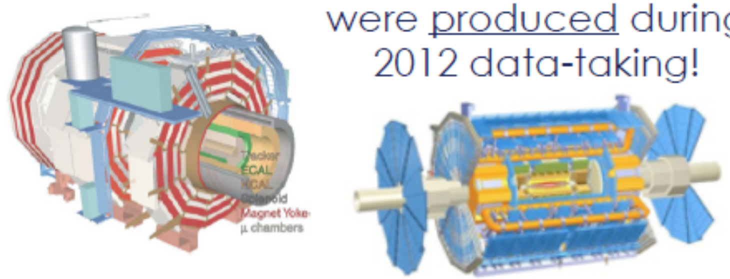
# LHC is a "top" factory

**Era of Precision Top Quark Measurements**

At peak instantaneous luminosities @ **ATLAS** & **CMS:**

~**2** top pairs/sec (per experiment)

~**1** single top/sec




were produced during 2012 data-taking!

Overall from **both** experiments combined:

~**4M** top quarks produced in 2011 (**√s = 7 TeV**)

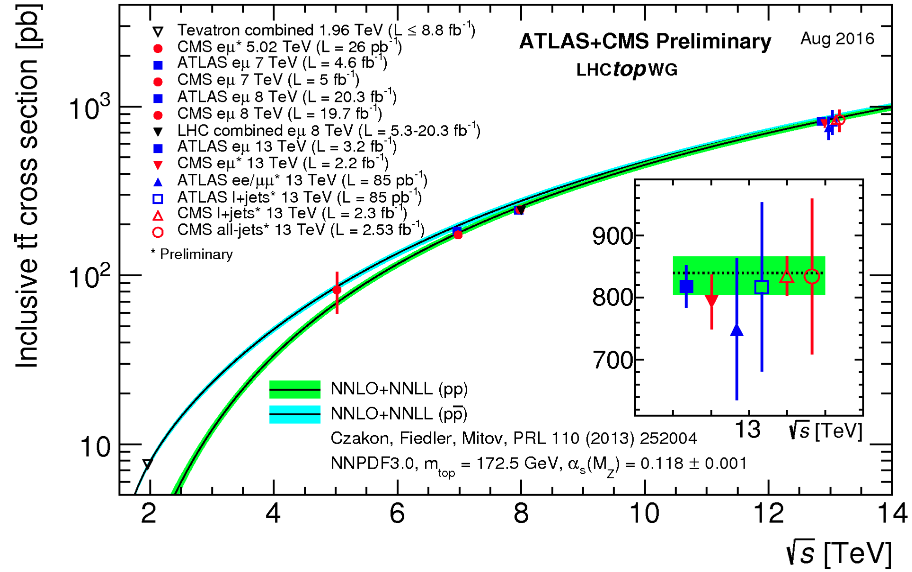
~**24M** top quarks produced in 2012 (**√s = 8 TeV**)

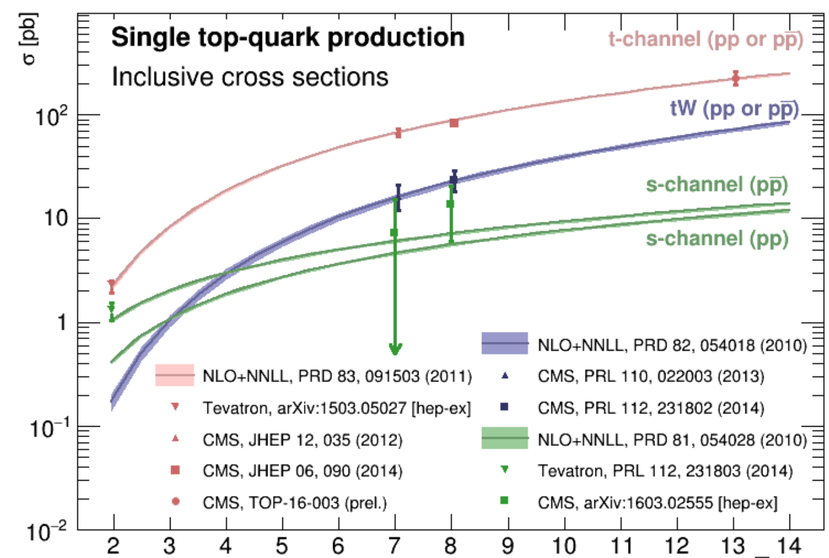
~**13M** top quarks produced in 2015 (**√s = 13 TeV**)

Cross-section values taken from:

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SingleTopRefXsec

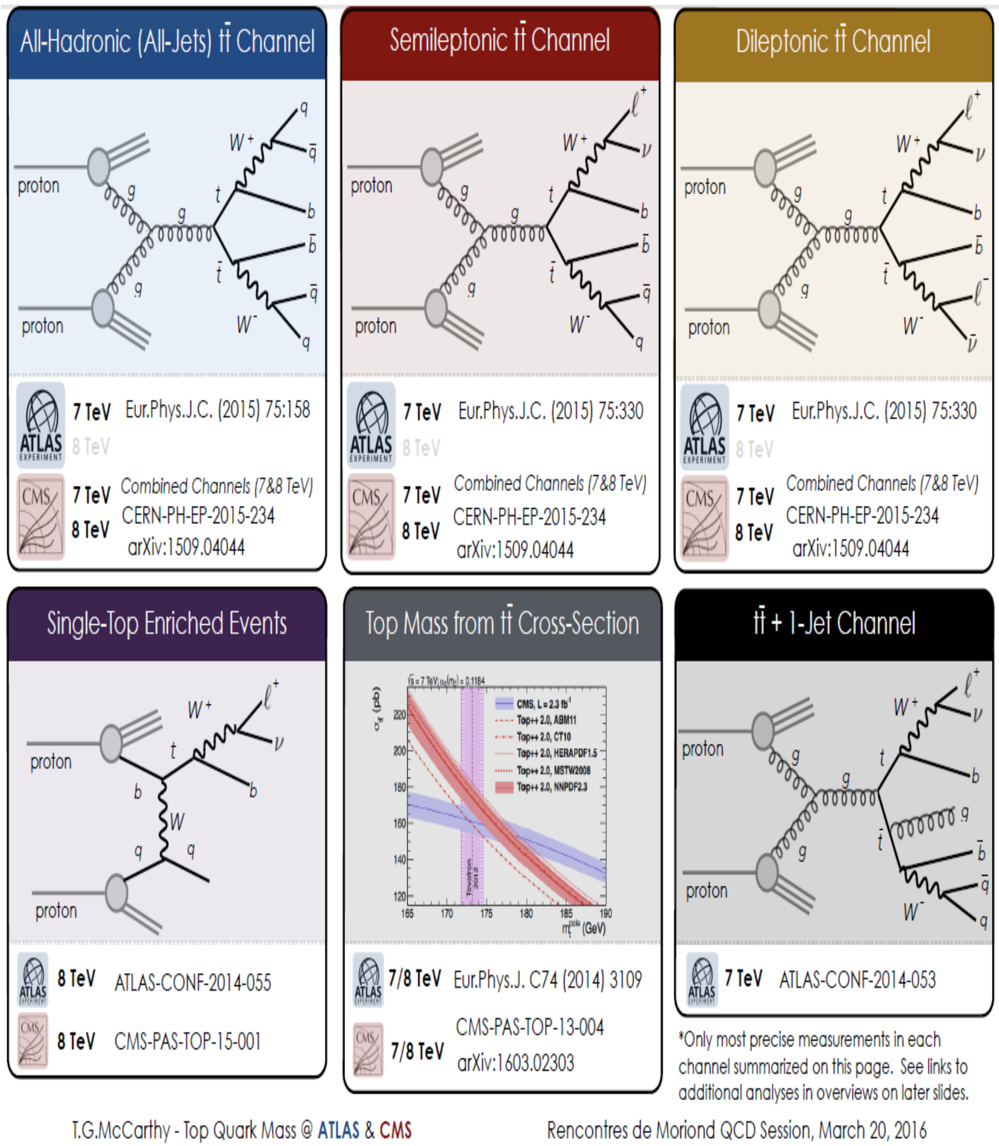
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO

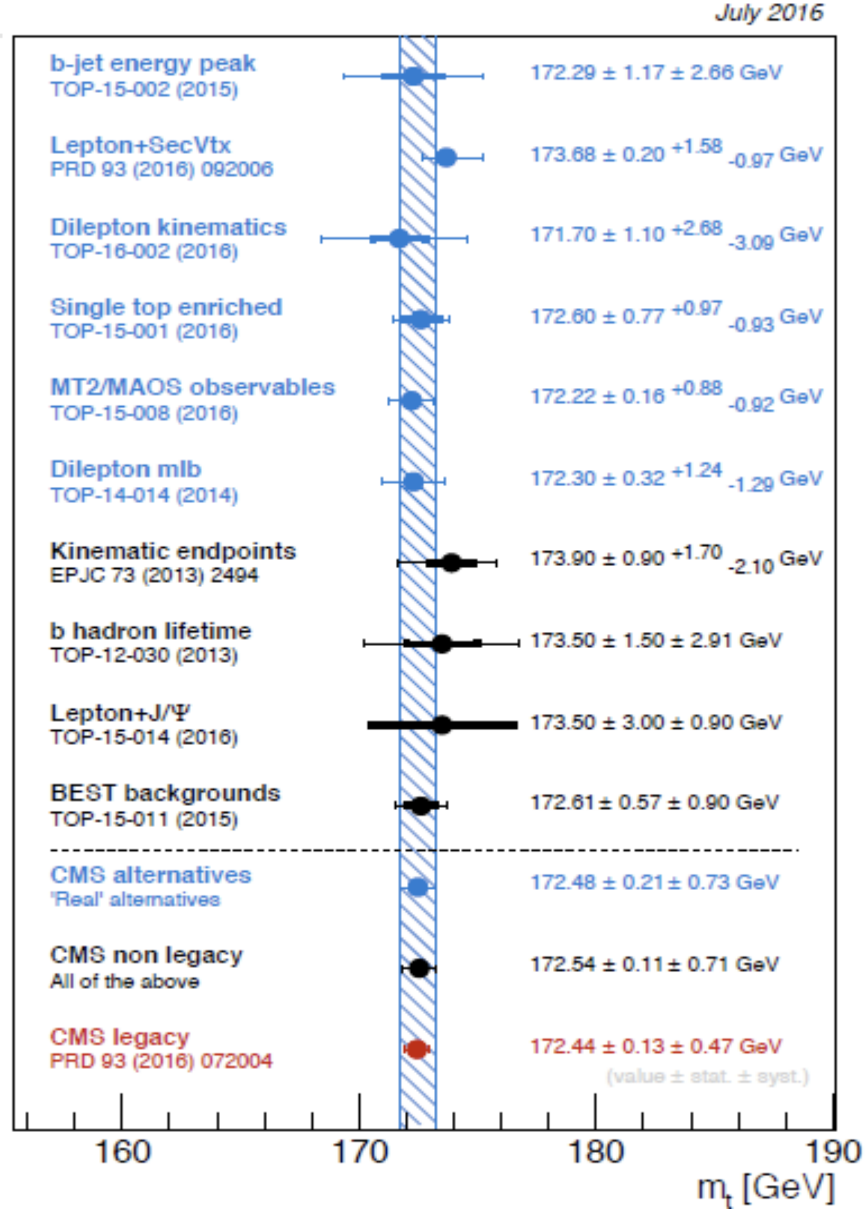



LHC and Tevatron results consistent and in agreement with NNLO+NNLL over a large range of center-of-mass energies

# Mass of “top”: CMS results

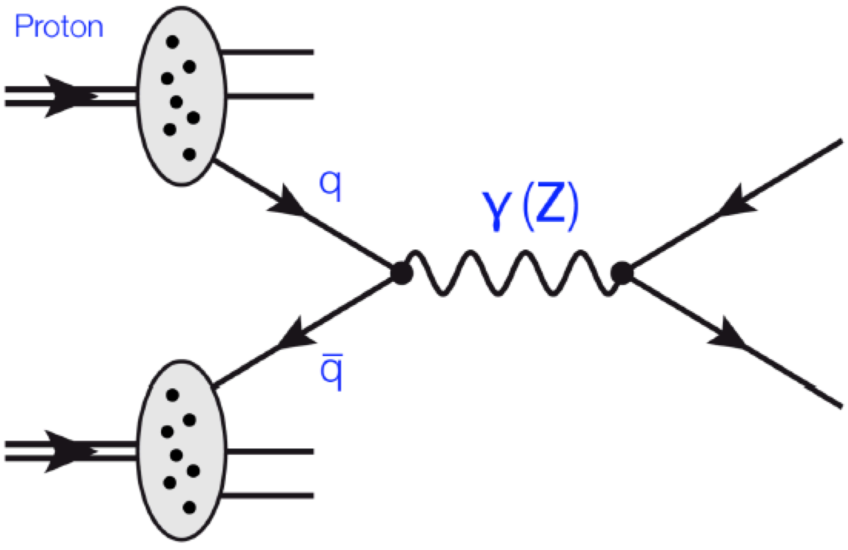


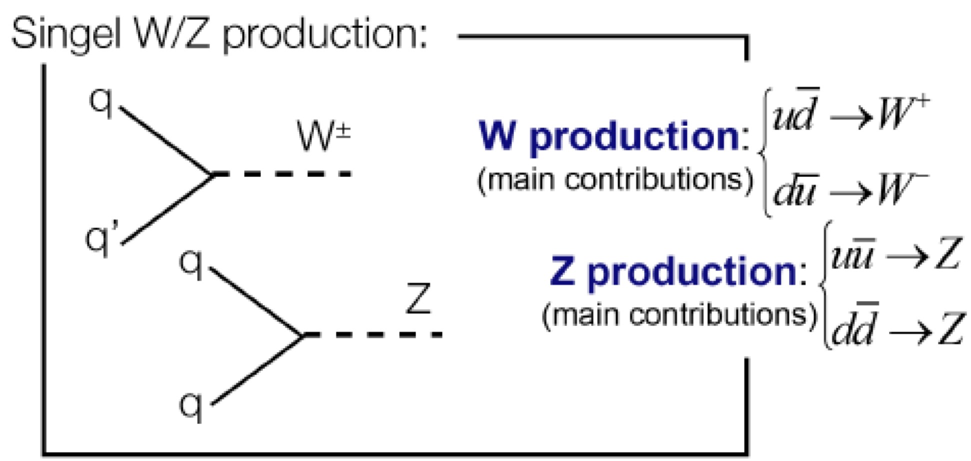




We have the best mass measurementin the world (by combining the best analyses per channel), TOP-14-022, Phys. Rev. D 93, 072004 (2016)

# EWK Processes: W and Z production

## Drell-Yan process

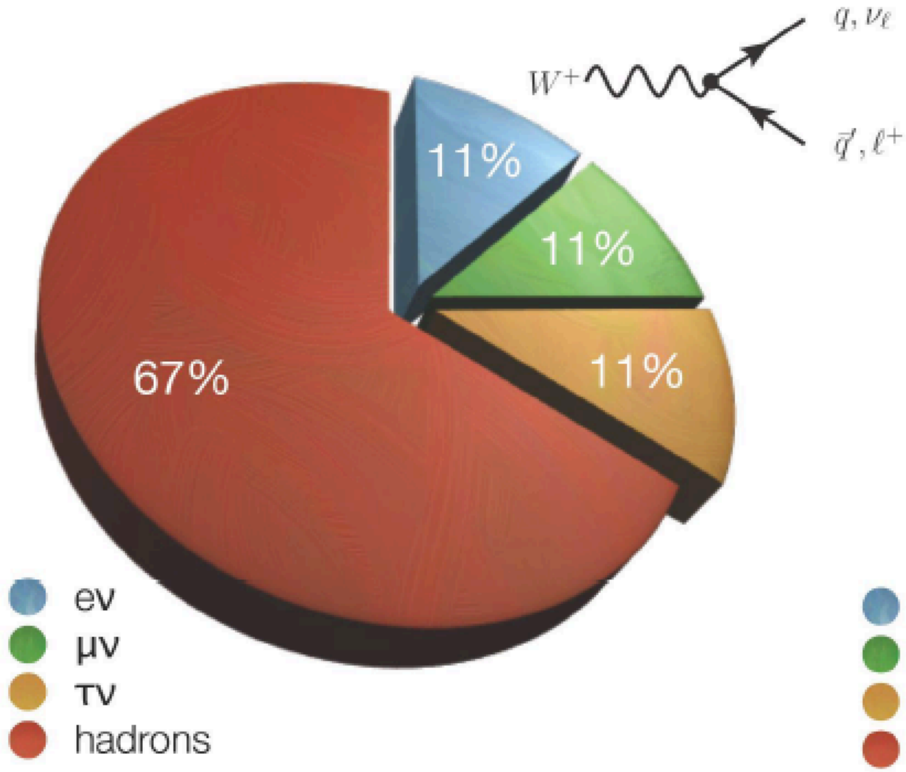


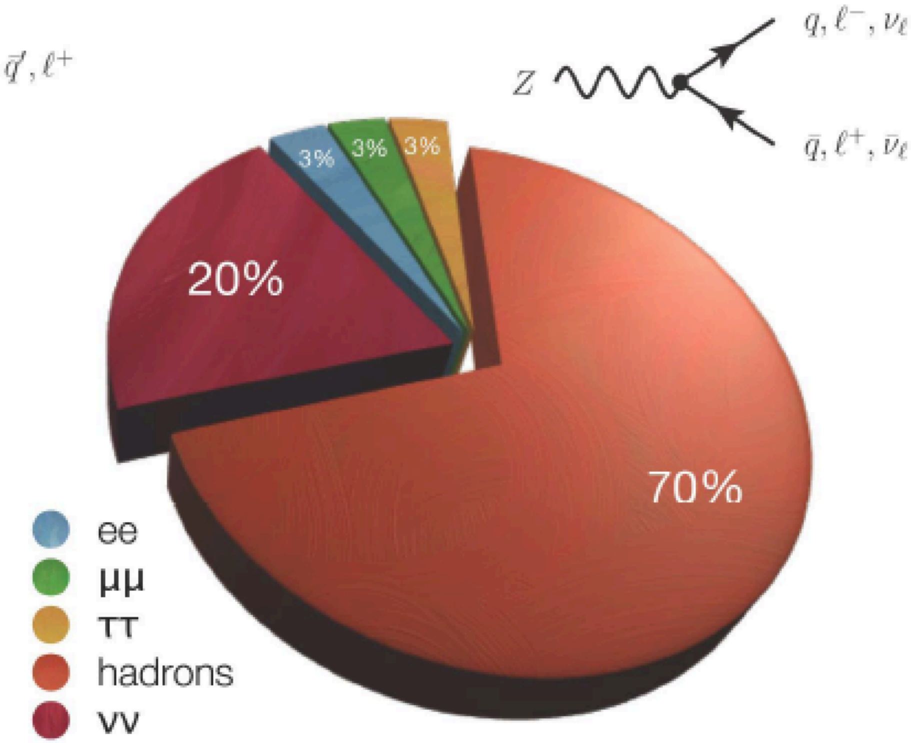




High rate at the LHC

- ✓ provides statistic to study inclusive and differential distributions
- ✓ Good understanding of the detectors allow for precision measurements
- ✓ Test p-QCD and PDF in different regimes
- ✓ Developments and testing of new MC generators and techniques

# W and Z decay



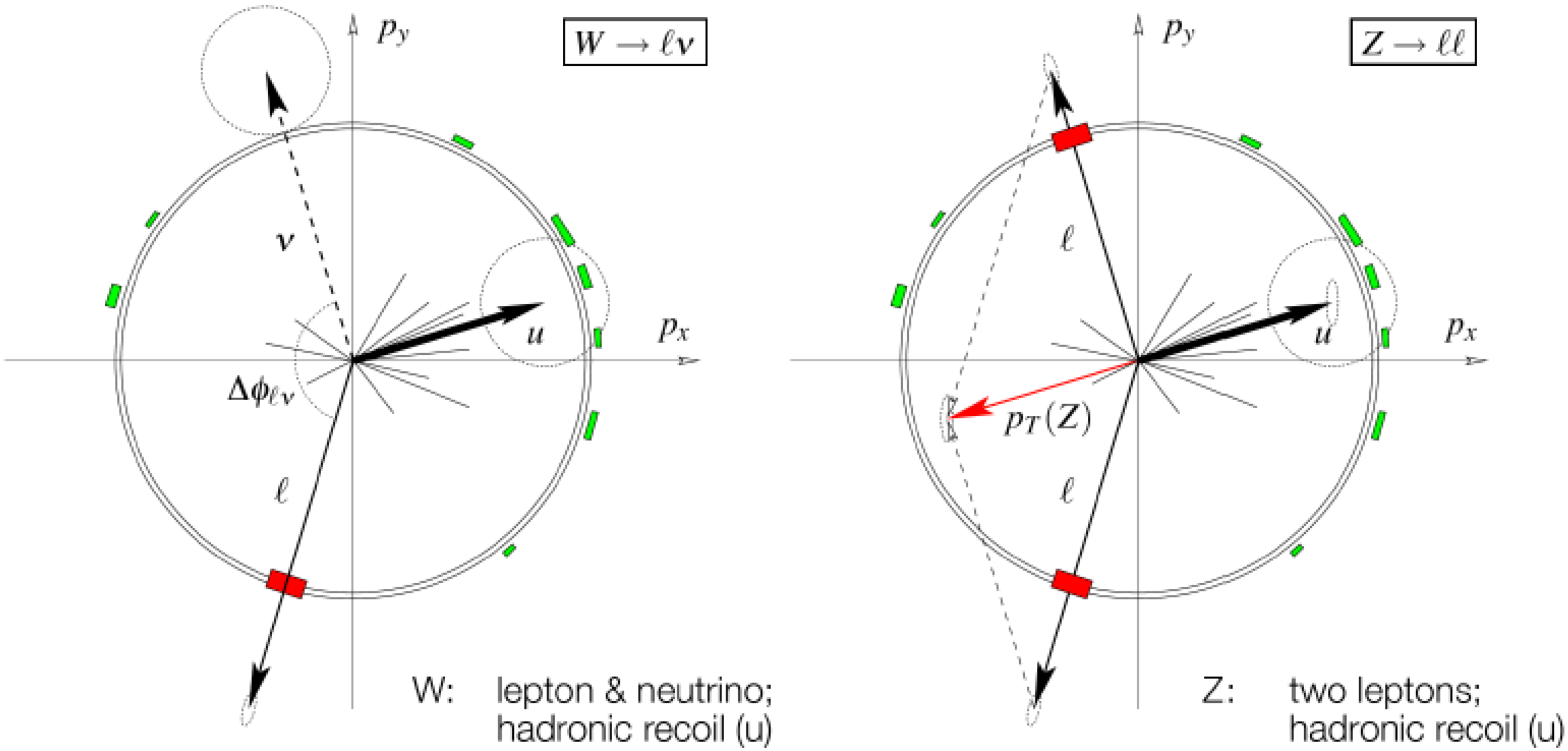




Leptonic decays (e/μ): very clean, but small(ish) branching fractions

Hadronic decays: two-jet final states; large QCD dijet background

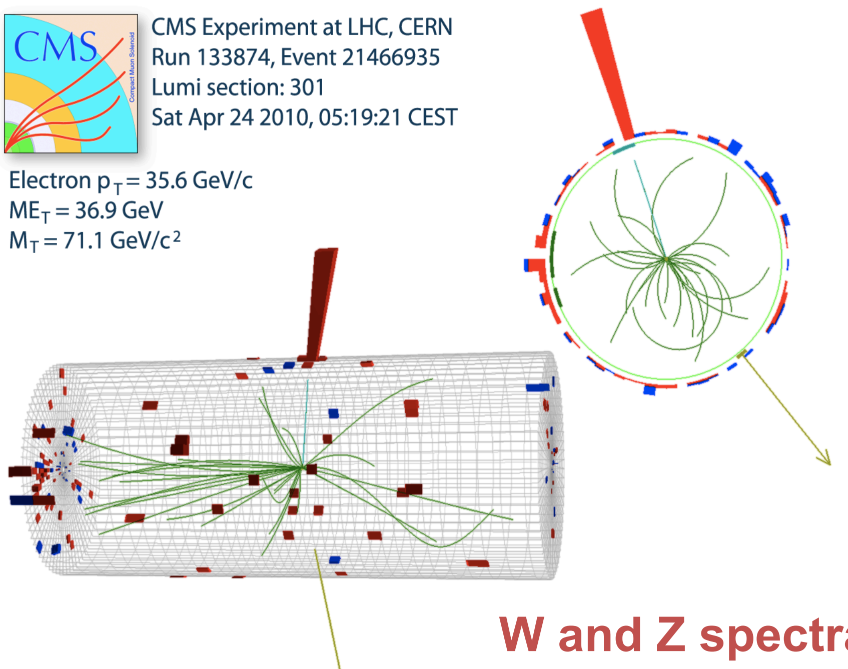
Tau decays: somewhere in between…

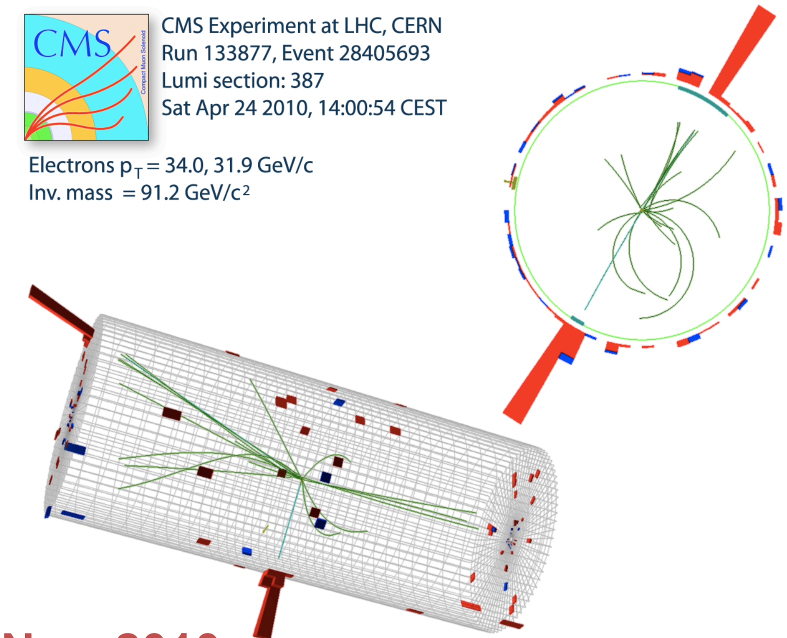
# W and Z signatures



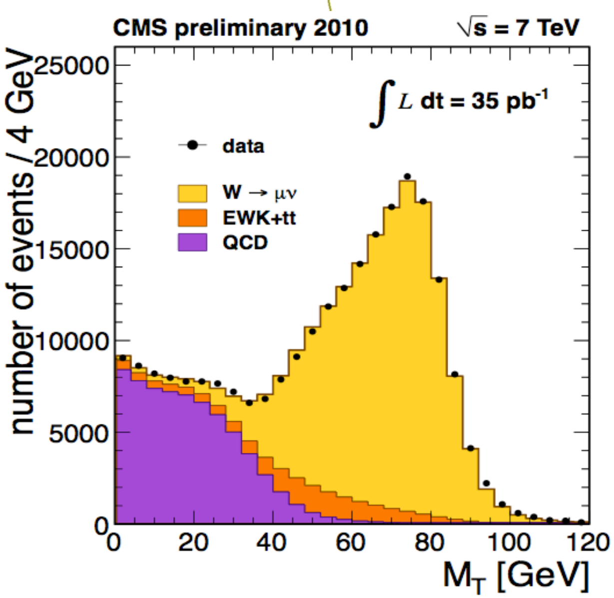

Additional hadronic activity ➛ recoil, not as clean as $e^+e^-$
Precision measurements: only leptonic decays

# First W → eν and Z → e⁺e⁻ events in LHC, April 2010



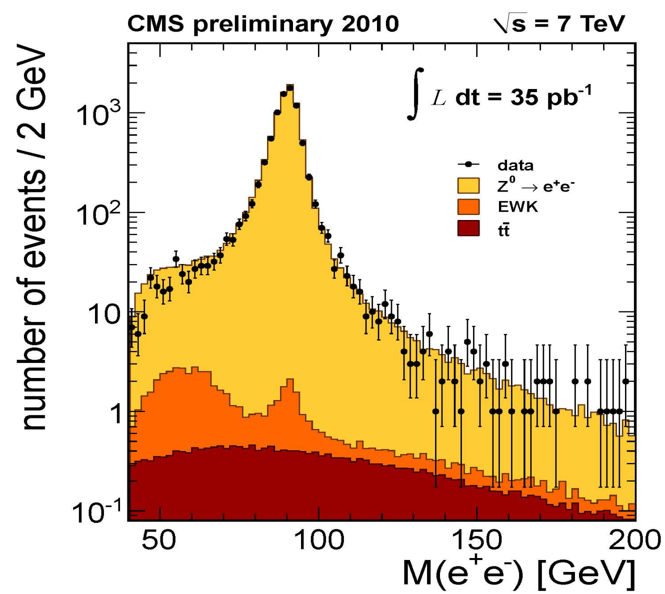




## W and Z spectra in CMS, Nov. 2010

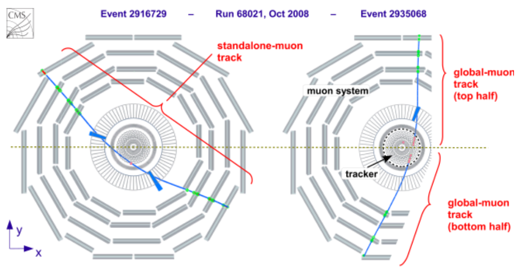


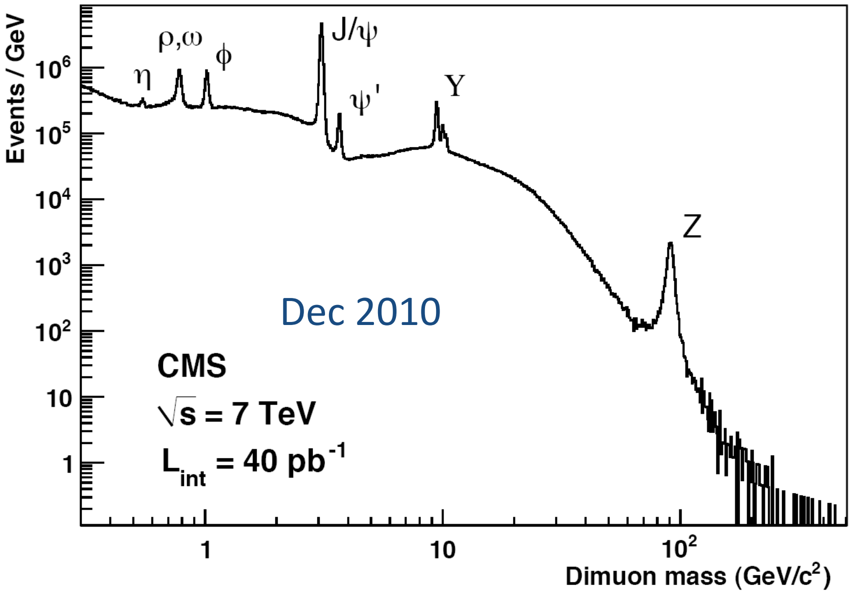

By end-2012 we had ~150.000.000 W and ~15.000.000 Z decaying leptonically!!

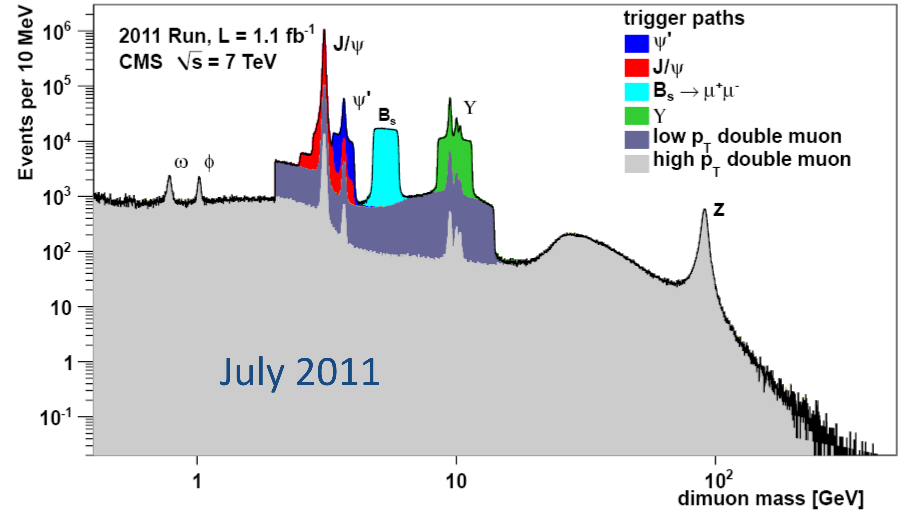
$$M_T = \sqrt{2E_T^{\mu}E_T^{miss}(1-\cos\Delta\phi_{e,miss}}$$

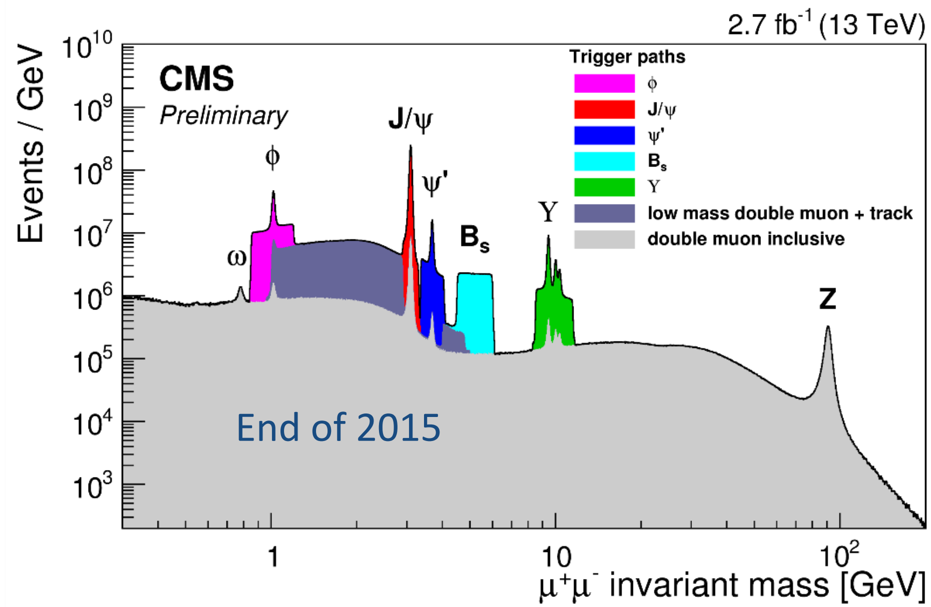


# Di-muon resonances



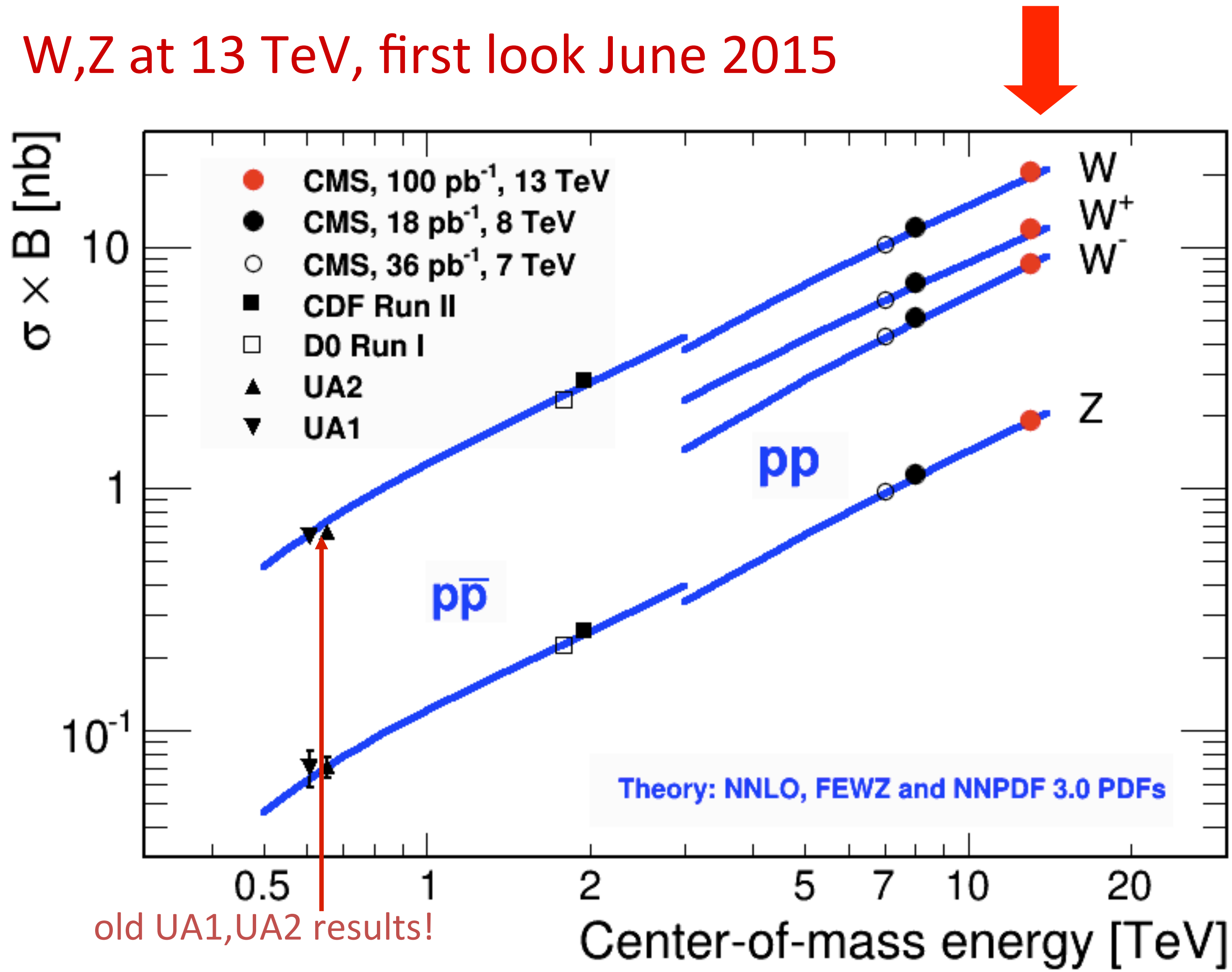




CMS shows a excellent performance to detect different signals

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

# W and Z production cross section

W,Z at 13 TeV, first look June 2015




old UA1,UA2 results!

# W+/W- charge asymmetry

NNLO cross sections:
scale uncertainties very small

W rapidity: asymmetry
[sensitivity to PDFs]

$$A_W(y) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy}$$

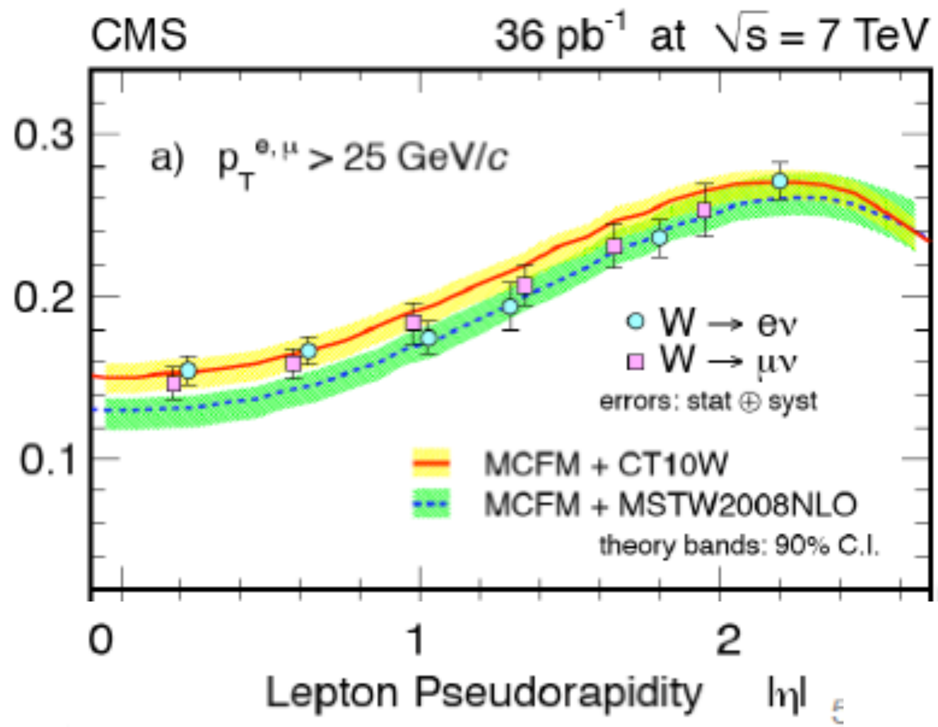
Proton-Proton Collider:

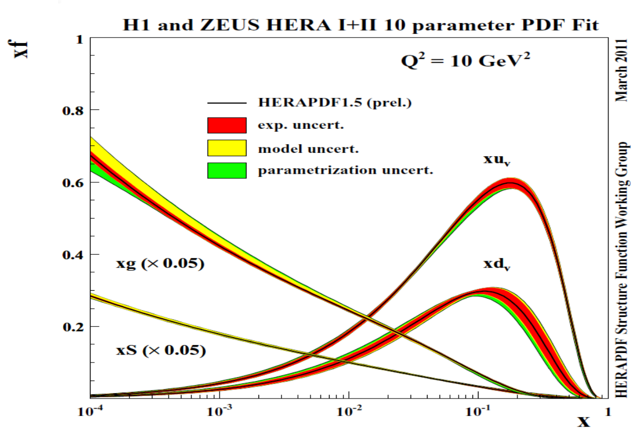
symmetry around y=0 ...

PDFs:

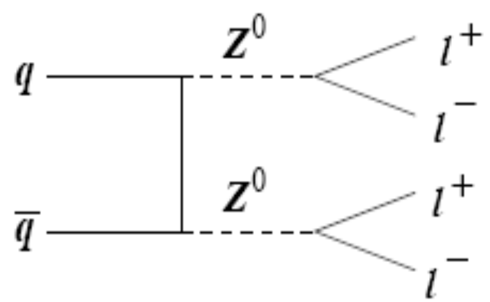
u(x) > d(x) for large x ...
more $W^+$ at positive rapidity

d/u ratio < 1 ...
always more $W^+$ than $W^-$

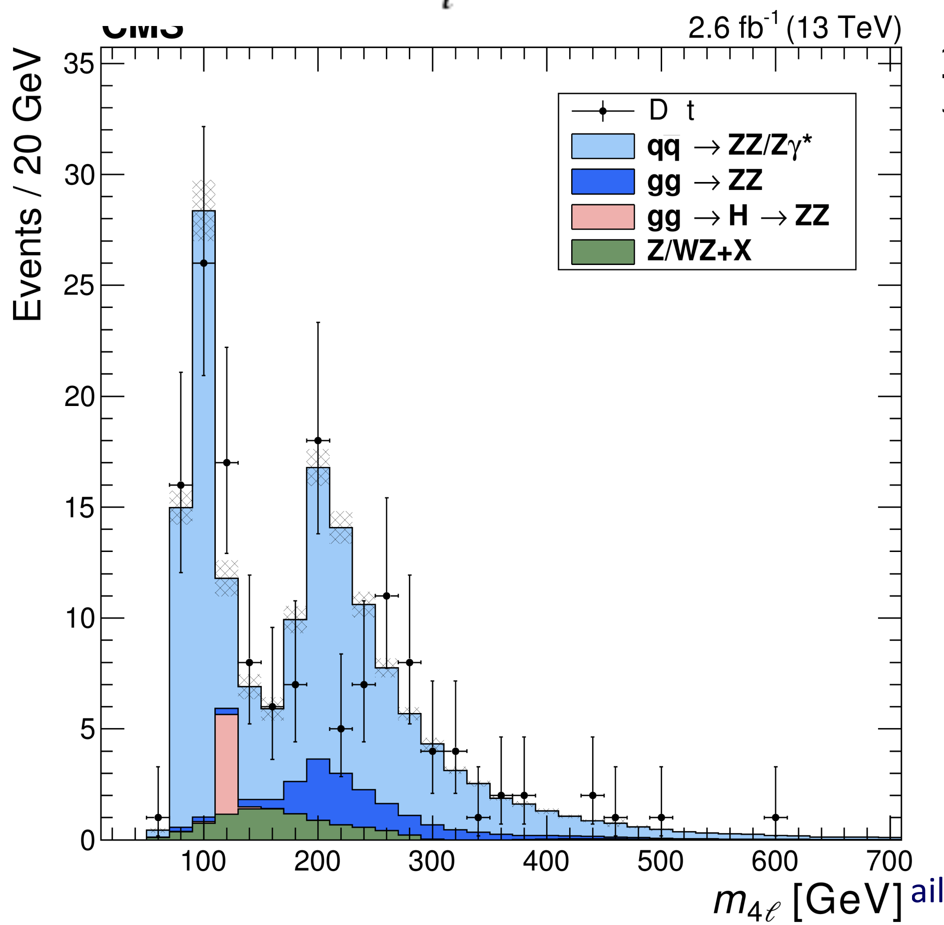


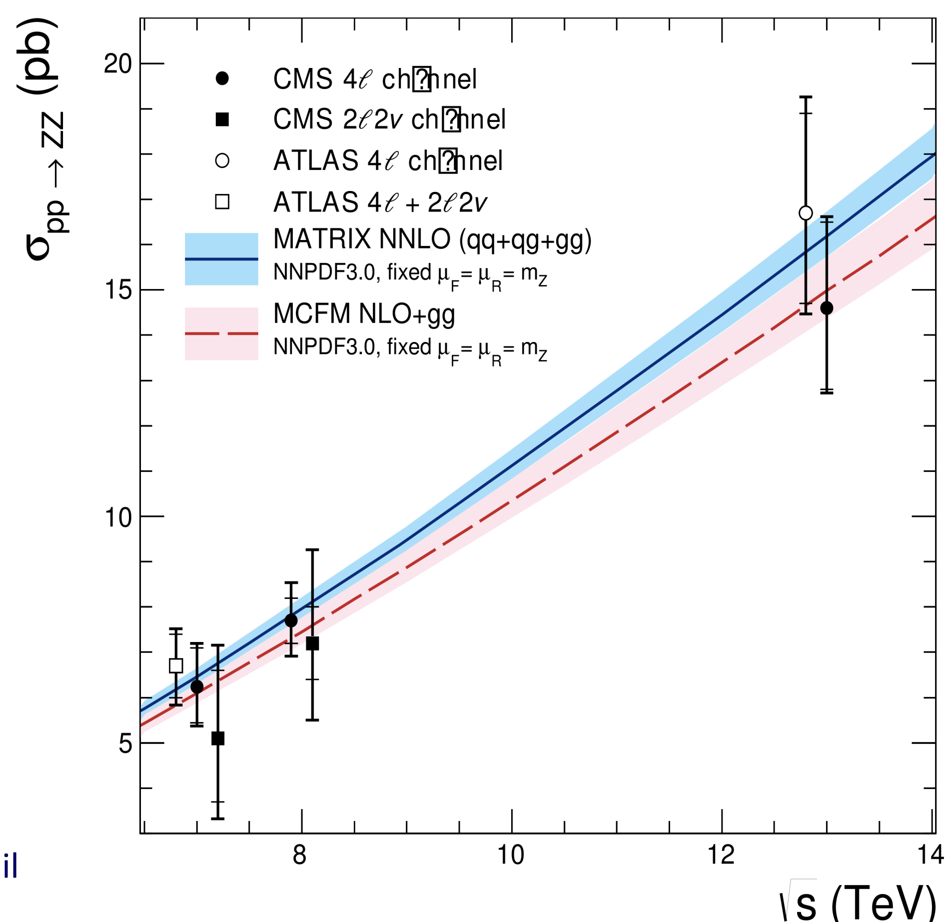



# EWK di-bosons: ZZ → 4l, 13 TeV, CMS,



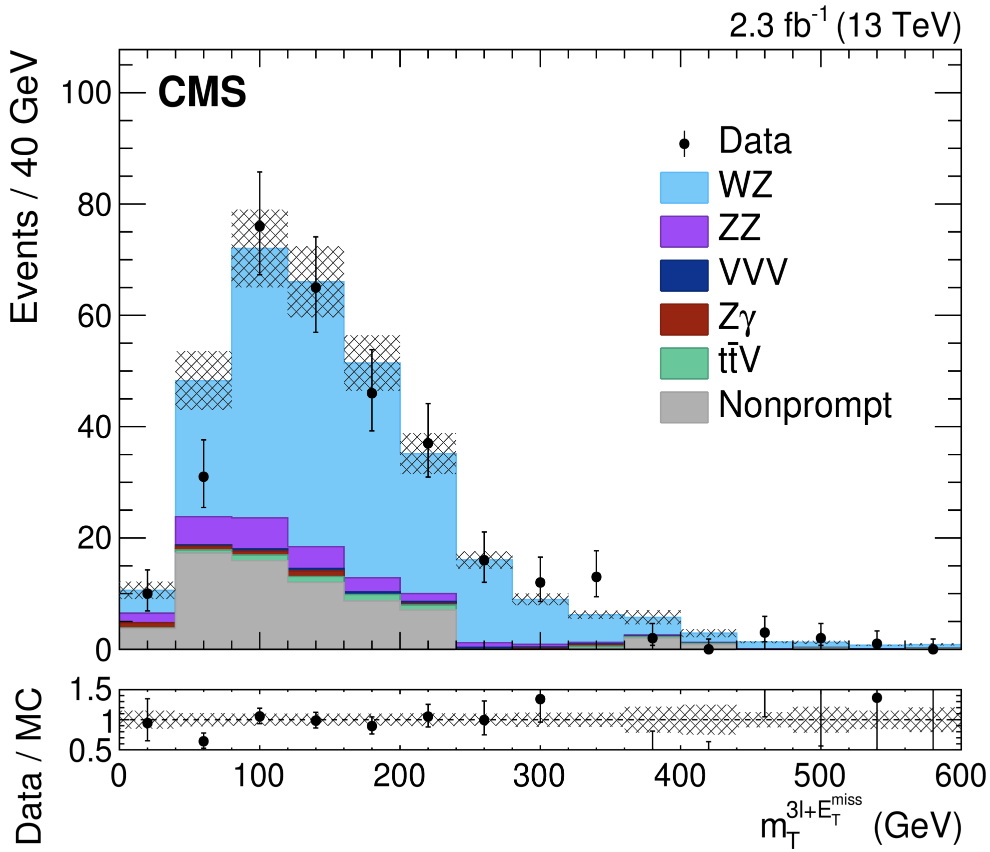

**Measurement of ZZ→ lll'l'**
**CMS, 2.6fb$^{-1}$, 13 TeV**
$\sigma(ZZ) = 14.6^{+1.9}_{-1.8}(st)^{+0.5}_{-0.3}(sy)\pm0.2(th)\pm0.4(lu)$ pb
NNLO: $15.0^{+0.7}_{-0.6}\pm0.2$ pb
~14% precision, statistically limited



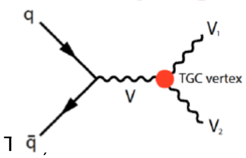
# EWK di-bosons: WZ→ 3l, 13 TeV, CMS,

**Measurement of WZ→ lνl'l'**
**CMS, 2.3fb$^{-1}$, 13 TeV**
**$\sigma(WZ) = 39.9 \pm 3.2(stat)^{+2.9}_{-3.1}(syst) \pm 0.4(theo) \pm 1.3(lumi)$ pb**
**NNLO: $50.0^{+1.1}_{-1.0}$ pb**

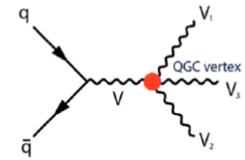


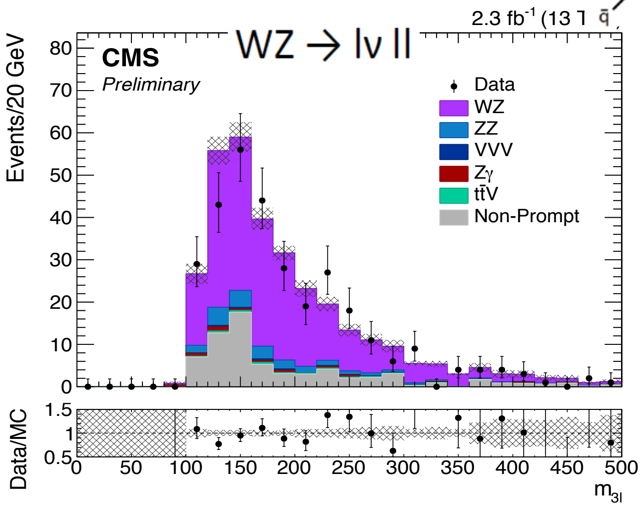
# EWK Processes: Multi-bosons

Triple gauge couplings
(di-boson production)

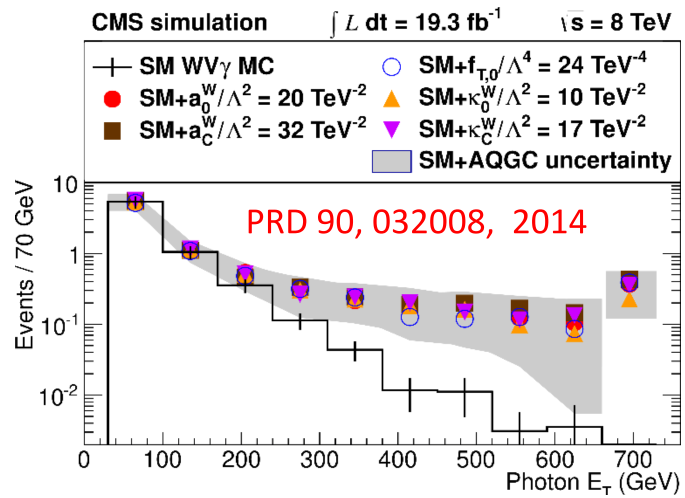


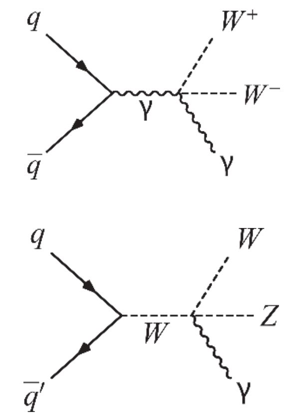

Quartic gauge couplings
(tri-boson production)

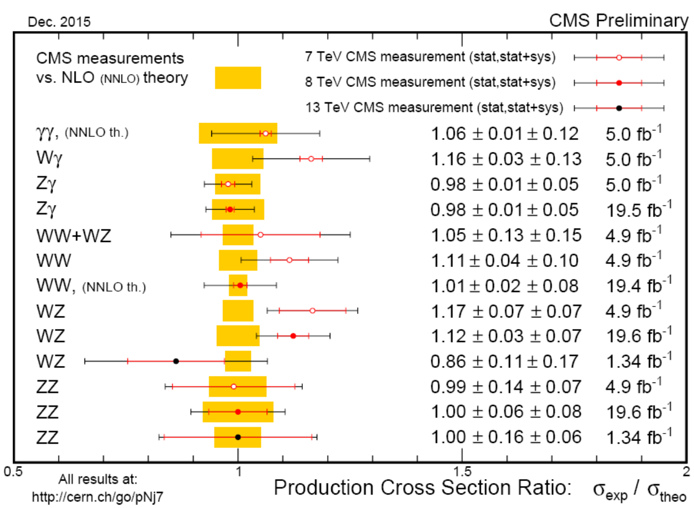


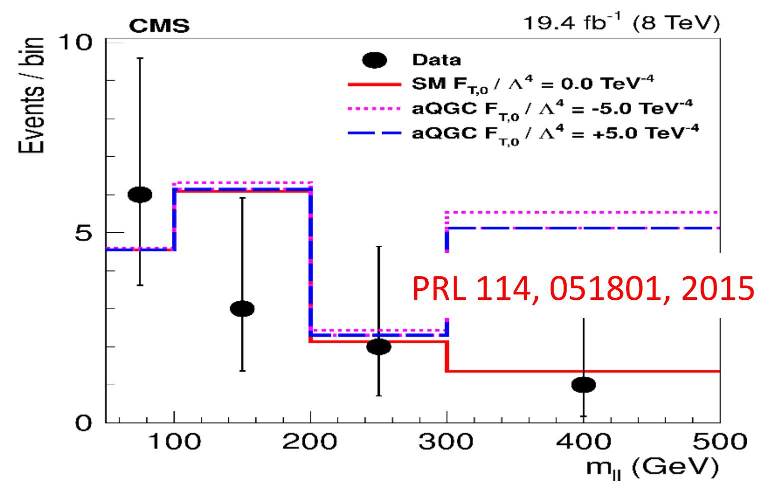



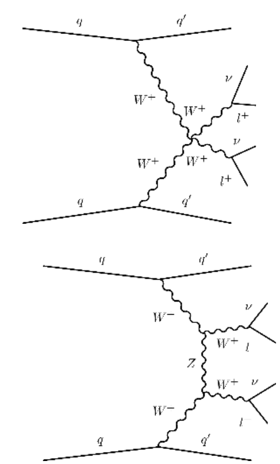

CMS-PAS-SMP-16-002





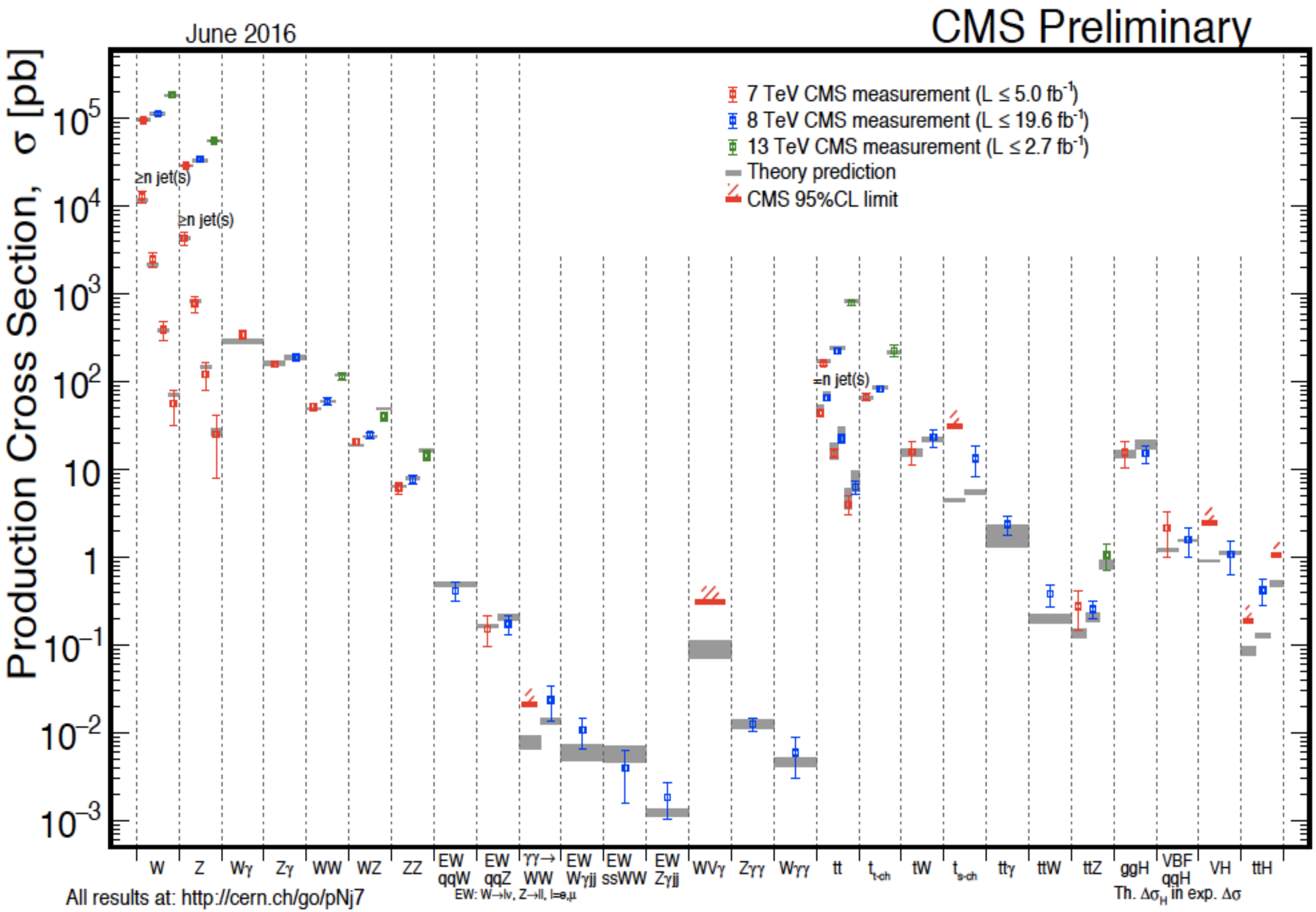



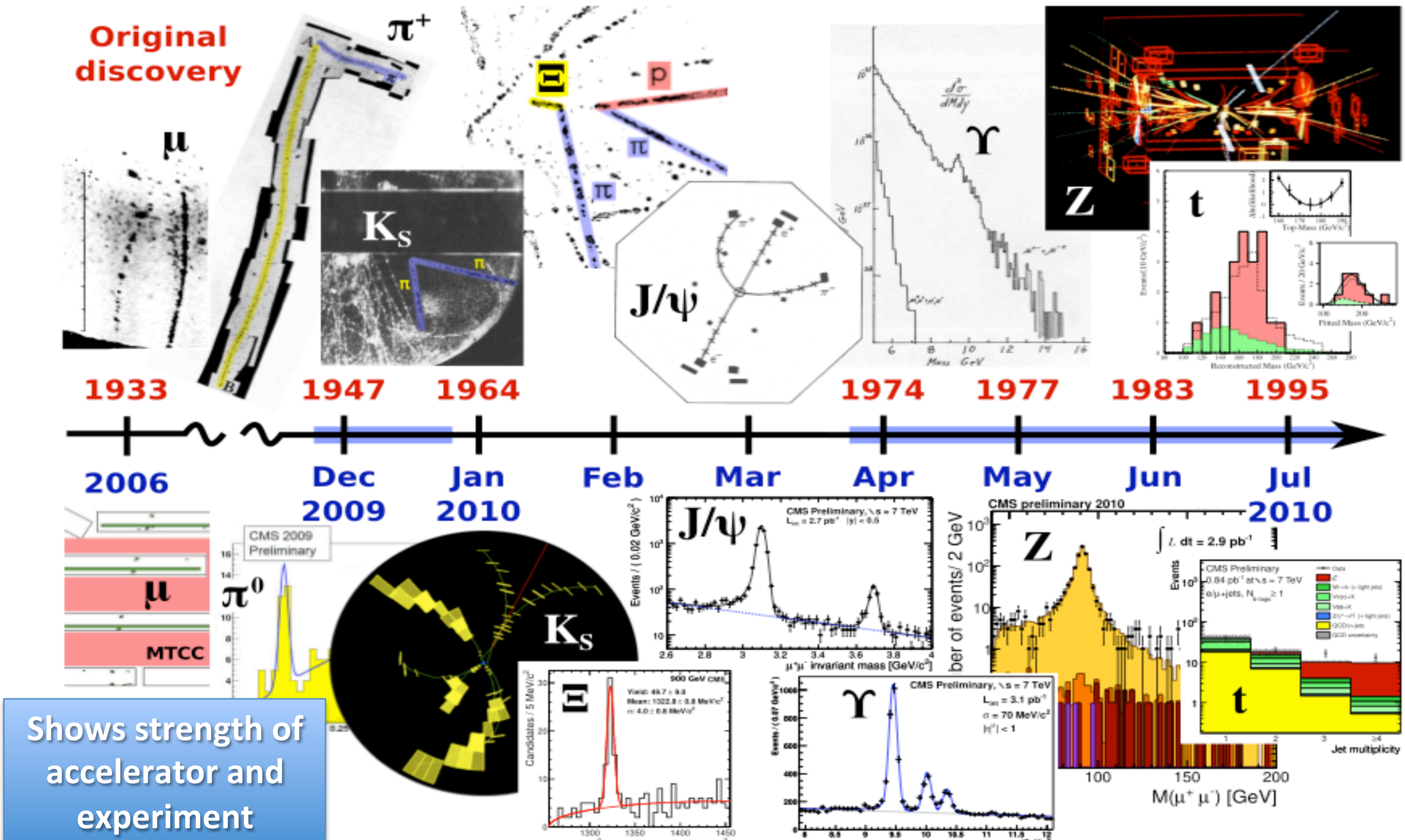
**Contributions from aTGC and aQGC are not observed**

# EWK Summary (7-13 TeV)

SM remains to be strong: good agreement between data and theory

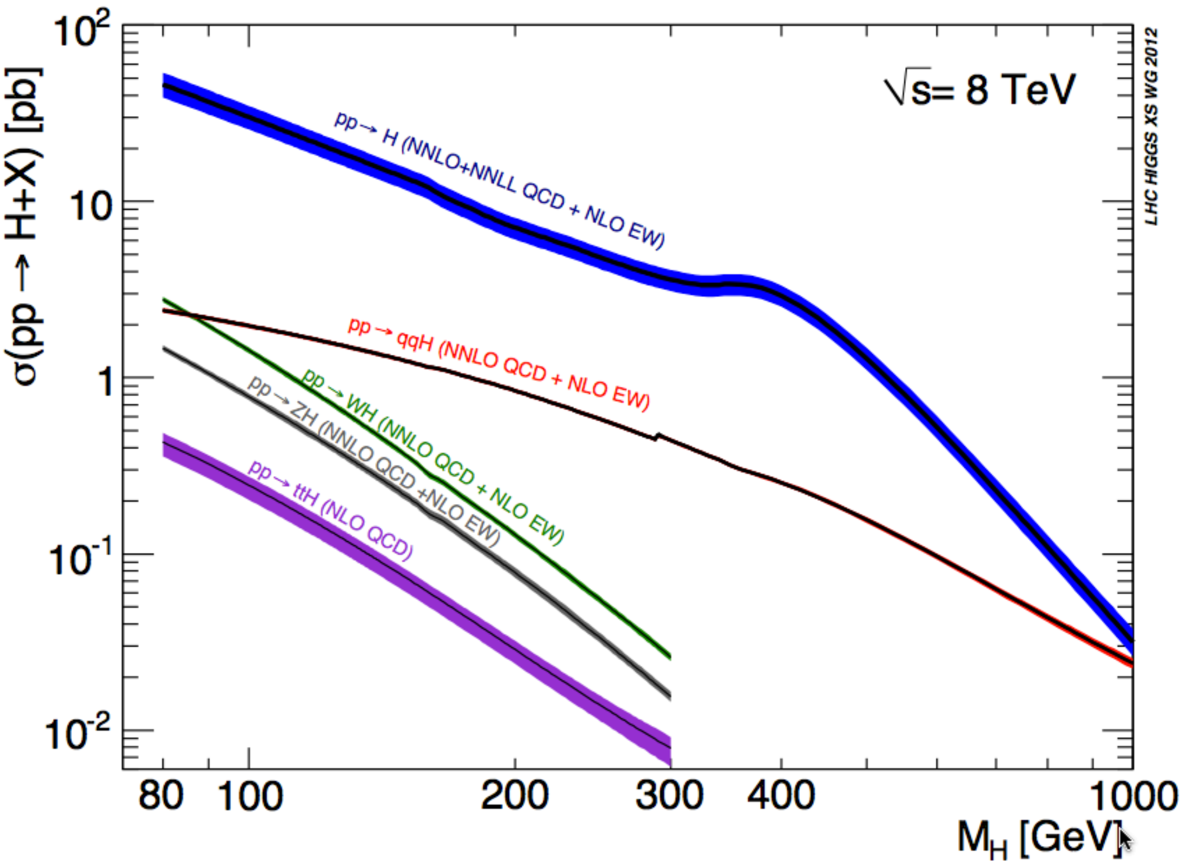


# CMS "re-discovers" the Standard Model in Particle Physics



# Higgs discovery

# SM Higgs production at LHC

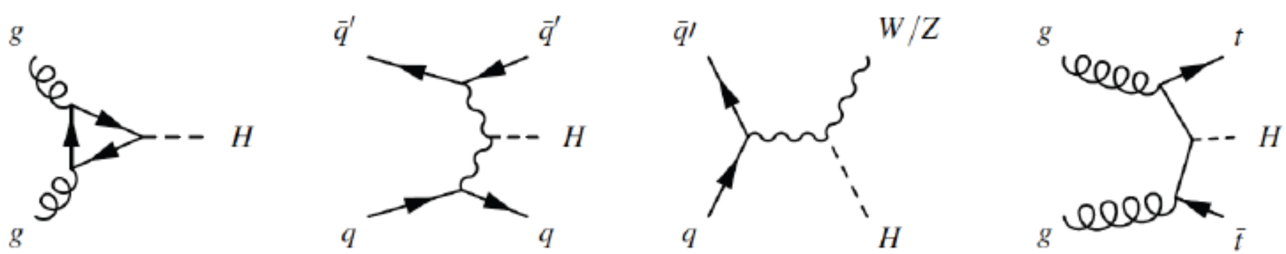



Gluon-gluon fusion:

→ radiative corrections at:

- NLO QCD
- NNLO QCD
- NNLL QCD
- NLO EW

| | $K_{NNLO/NLO}$ ($K_{NLO/LO}$) | Scale | PDF+$a_s$ | Total error |
|---|---|---|---|---|
| ggF | +25% (+100%) | +12% -7% | ±8% | +20 -15% |
| VBF | <1% (+5-10%) | ±1% | ±4% | ±5% |
| WH/ ZH | +2-6% (+30%) | ±1% | ±4% | ±5% |
| ttH | - (+5-20%) | +4% -10% | ±8% | +12 -18% |



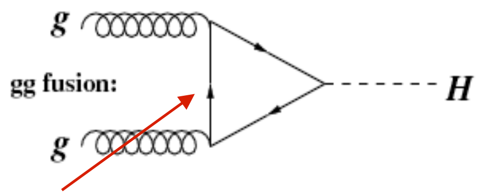

(a) $gg \to H$ (b) VBF (c) $VH$ (d) $t\bar{t}H$

**LHC Higgs Xsection WG**

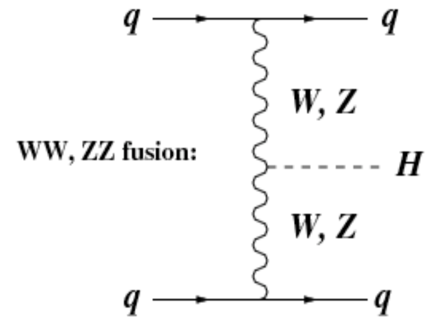
# Higgs production mechanisms and decay modes

@120 GeV

87.4 %

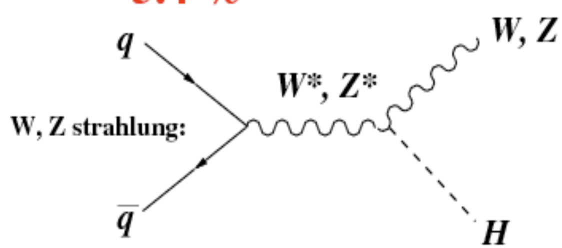



6.7 %

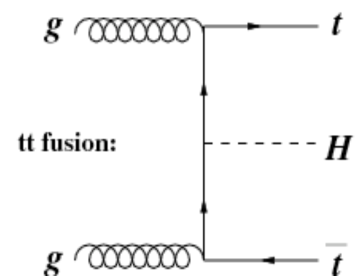


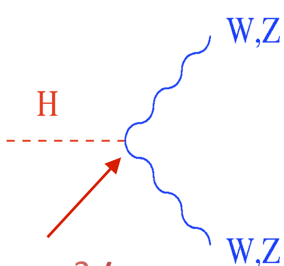

indirect coupling to gg, top in the loop

5.4 %



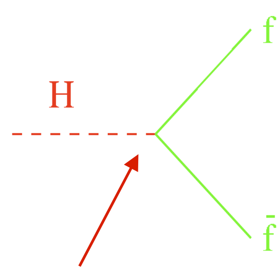

0.5 %



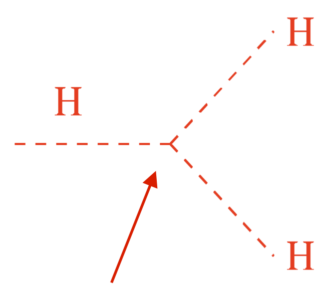




$g_{HVV} = 2m_V^2/v$

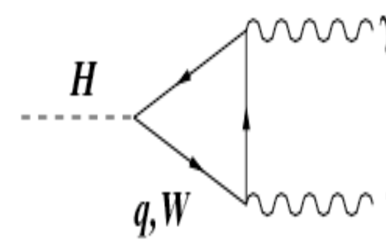
$g_{HWW} = g\ m_W$




$g_{Hff} = m_f/v$

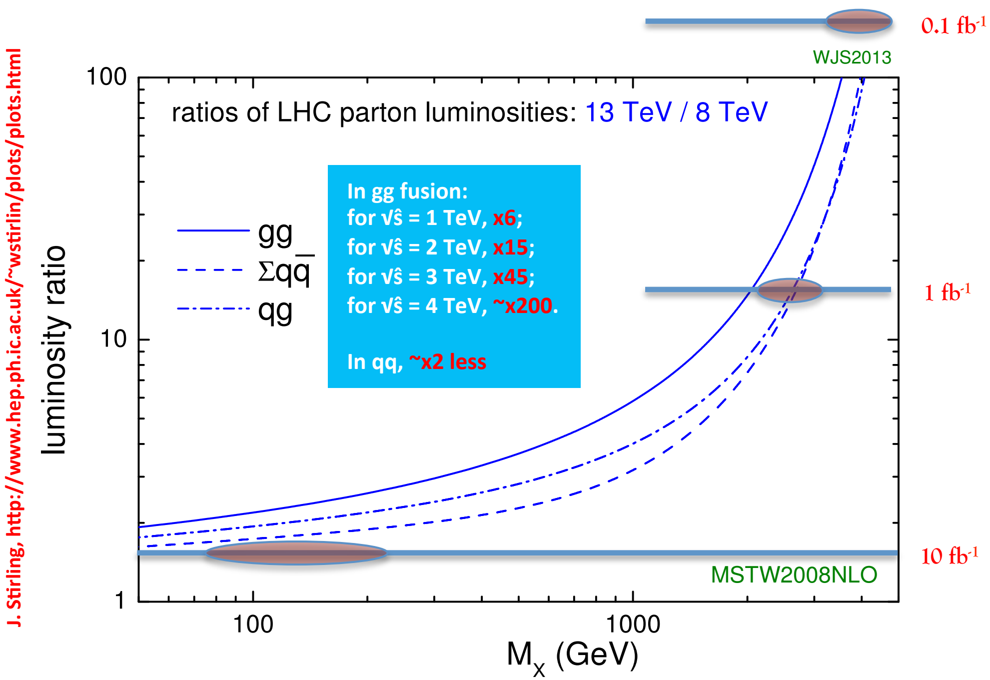



$g_{HHH} = 3m_H^2/v$

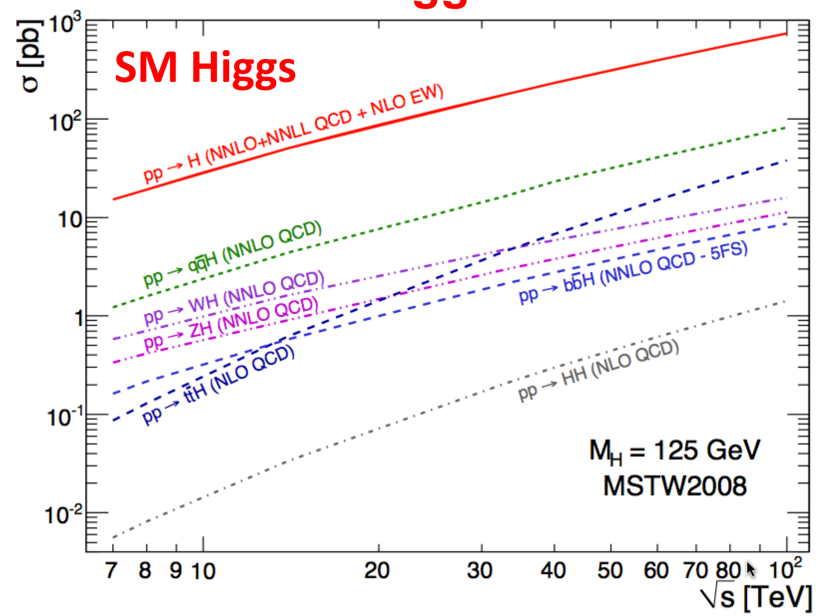


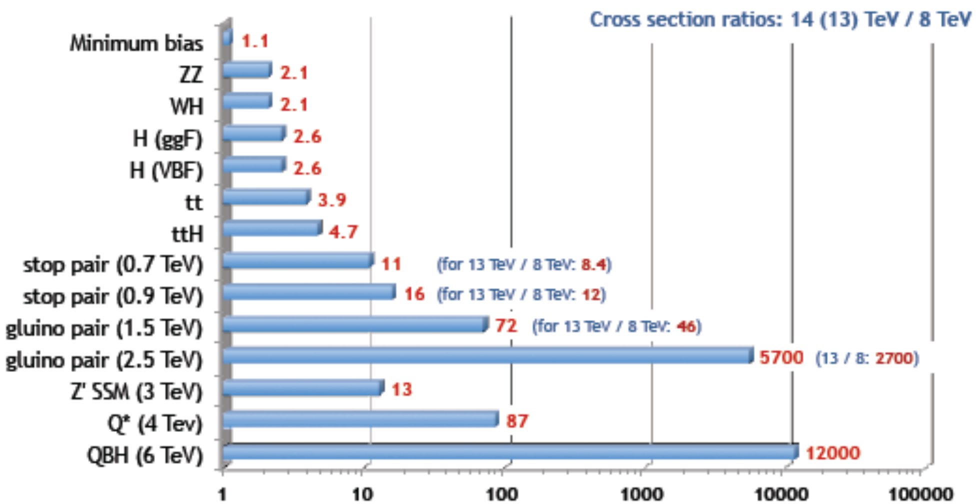

indirect coupling to γγ

# 8 TeV → 13 TeV: What does it change ?



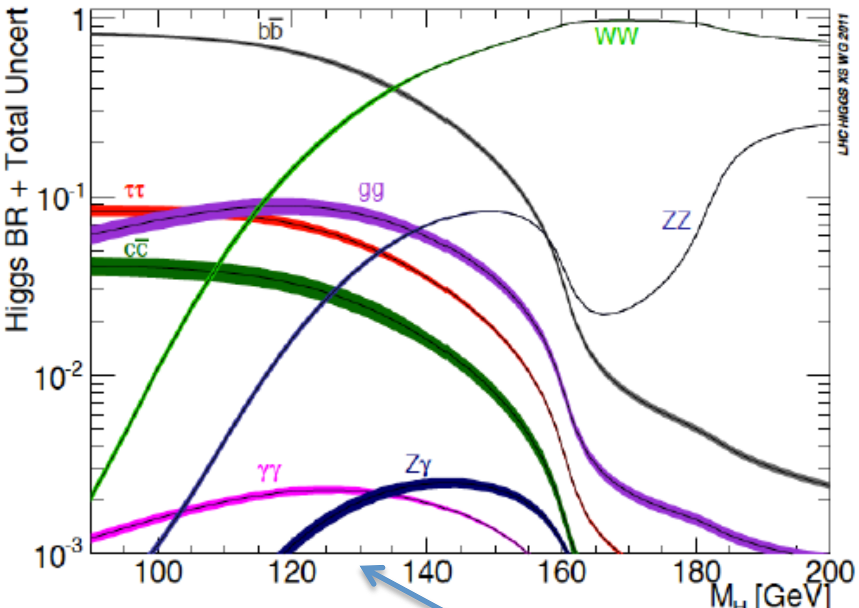

LHC Higgs Xsection WG

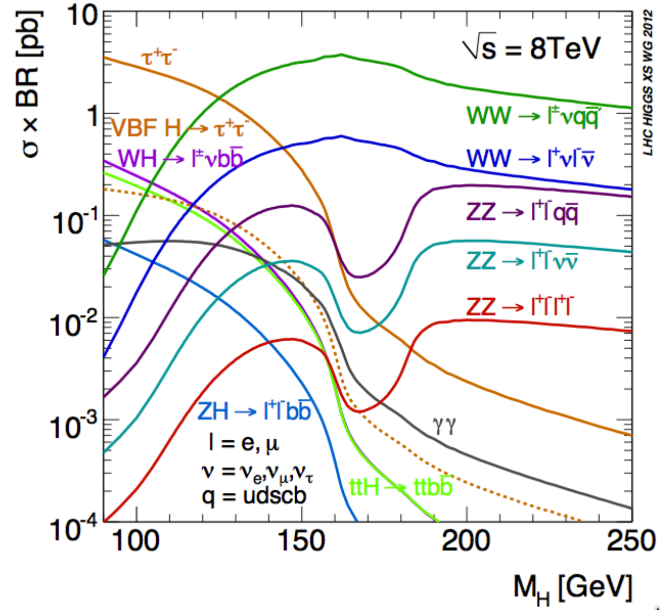


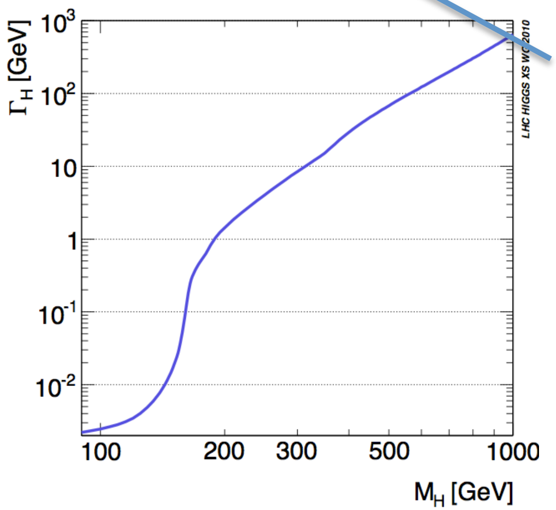




- SM Higgs is light, so the gluon fusion cross section doesn't get that much boost (x2, 19.1 → 43.6 pb)
- **Background cross sections increase too**

# Higgs decay channels



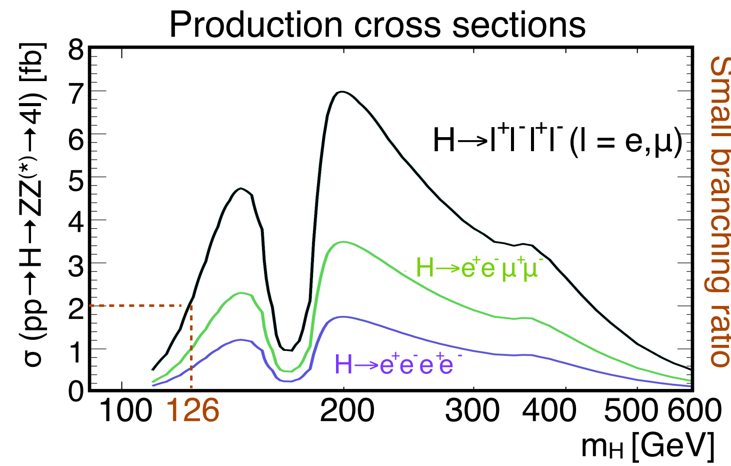

At $m_H$ =125 GeV:

- H(bb) ≈ 57%
- H(WW) ≈ 22%
- H(ττ) ≈ 6.2%
- H(ZZ) ≈ 2.8%
- H(γγ) ≈ 0.23%

| Channel | $m_H$ resolution |
|---|---|
| $H \to \gamma\gamma$ | 1–2% |
| $H \to \tau\tau \to e\tau_h/\mu\tau_h/e\mu + X$ | 20% |
| $H \to \tau\tau \to \mu\mu + X$ | 20% |
| $WH \to e\mu\tau_h/\mu\mu\tau_h + \nu$'s | 20% |
| $(W/Z)H \to (e\nu/\mu\nu/ee/\mu\mu/\nu\nu$ | 10% |
| $H \to WW^* \to 2\ell 2\nu$ | 20% |
| $WH \to W(WW^*) \to 3\ell 3\nu$ | 20% |
| $H \to ZZ^{(*)} \to 4\ell$ | 1–2% |
| $H \to ZZ^{(*)} \to 2\ell 2q$ | 3% 3% |
| $H \to ZZ \to 2\ell 2\tau$ | 10–15% |
| $H \to ZZ \to 2\ell 2\nu$ | 7% |

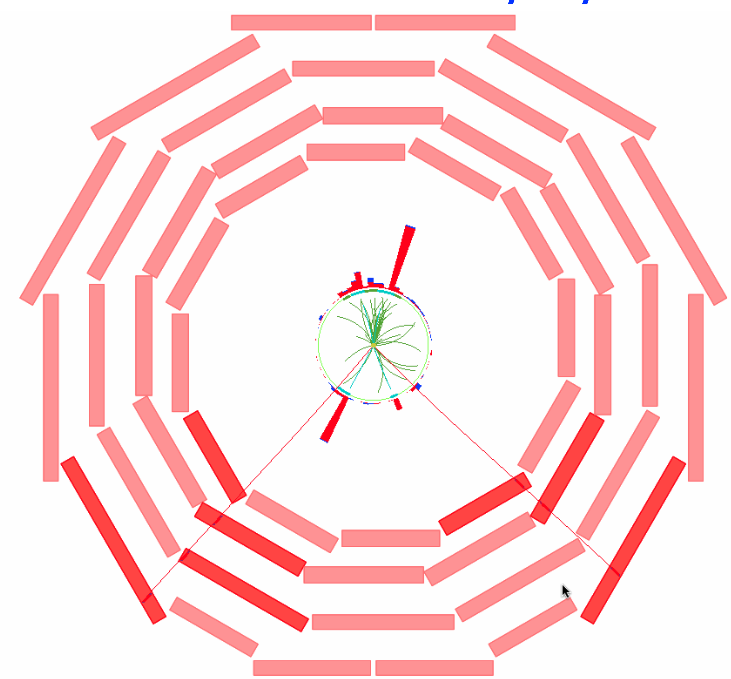
# H→ZZ→4l in a nutshell

- Signatures: **4e, 4μ and 2e2μ** final state
  - clean but extremely demanding channel for requiring the **highest possible efficiencies (lepton Reco/ID/Isolation)**.
  - s x BR small ≈ few fb



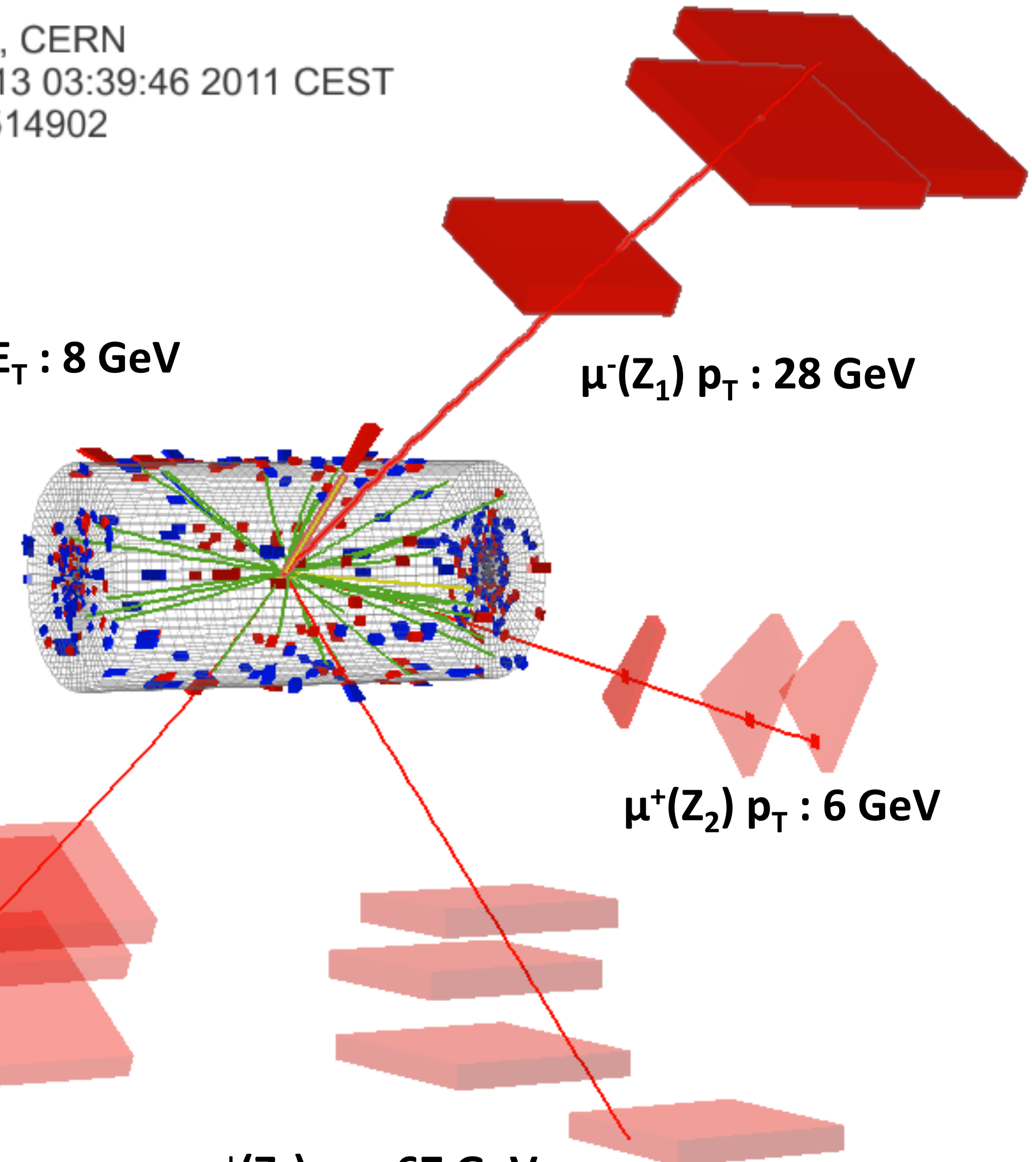

- Backgrounds:
  - Irreducible: ZZ*
  - Reducible: Zbb, tt+jets, Z+light jets, WZ+jets

H → ZZ* → e+e- μ+μ-



- Sensitivity: $115 < m_H <$ **1000** GeV
- Selection strategy:
  - triggering on double leptons
  - applying reco, id and isolation of leptons
  - recovery of FSR photons
  - use of impact parameter
  - $m_Z$ and $m_{Z*}$ constraint
  - kinematical discriminant / scalarity of the Higg

CMS Experiment at LHC, CERN
Data recorded: Thu Oct 13 03:39:46 2011 CEST
Run/Event: 178421 / 87514902
Lumi section: 86

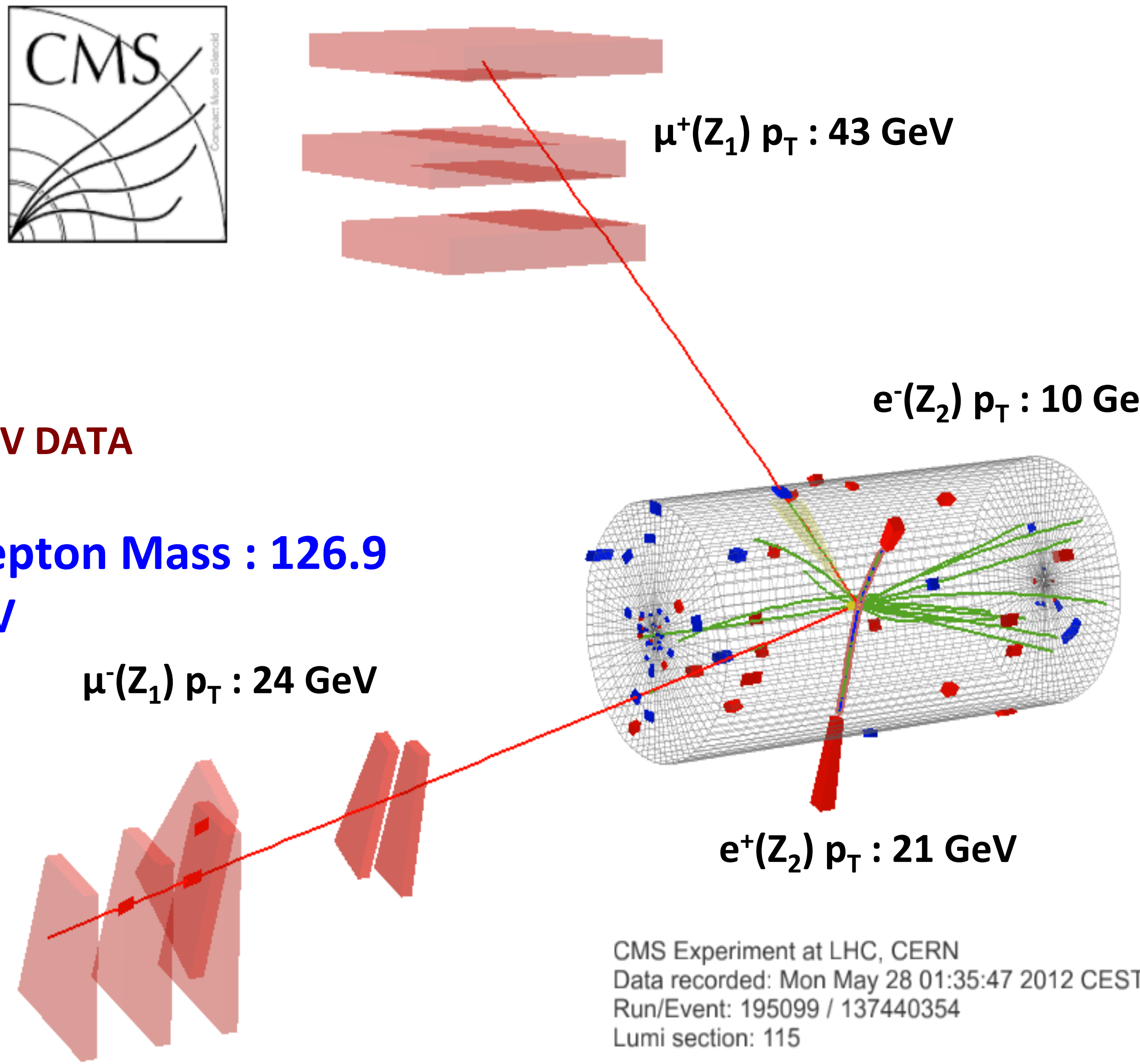



**7 TeV DATA**

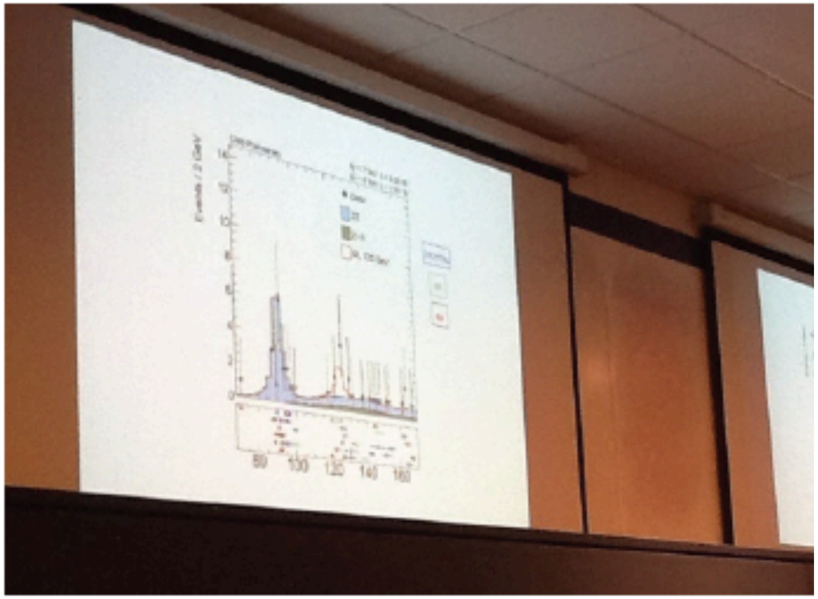
**4μ+γ Mass : 126.1 GeV**

**8 TeV DATA**

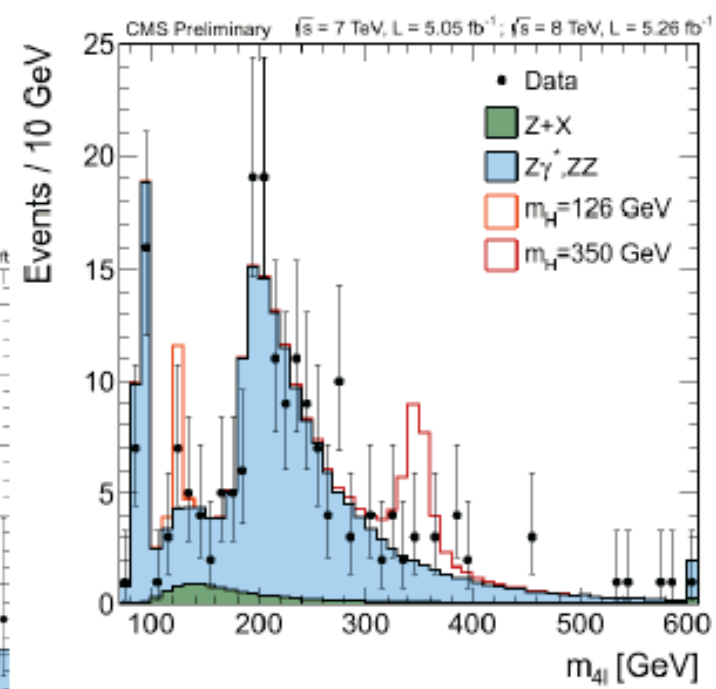
**4-lepton Mass : 126.9 GeV**

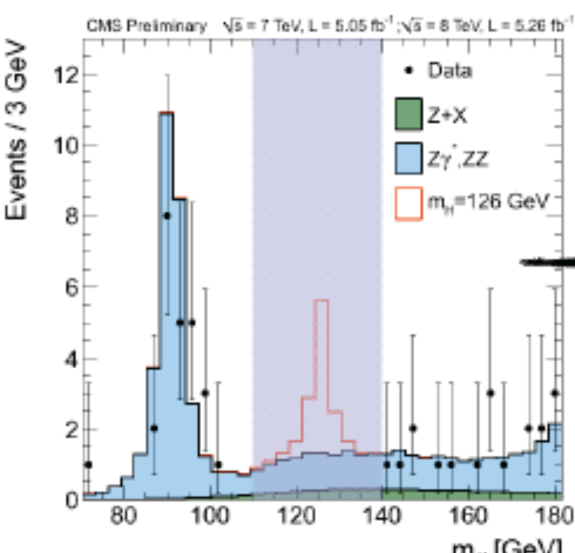


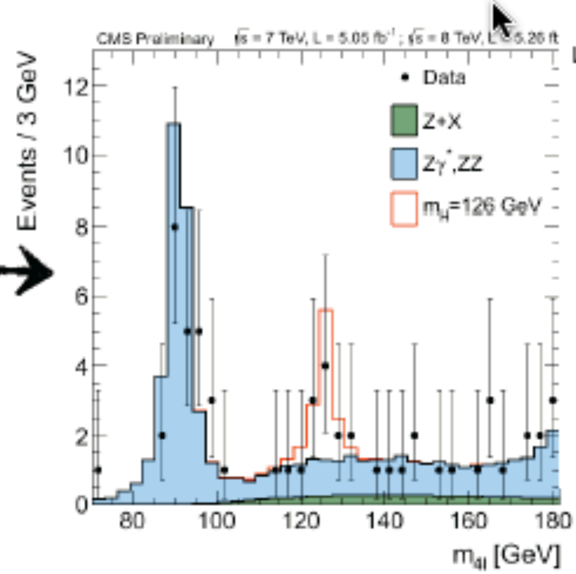
# June 2012:



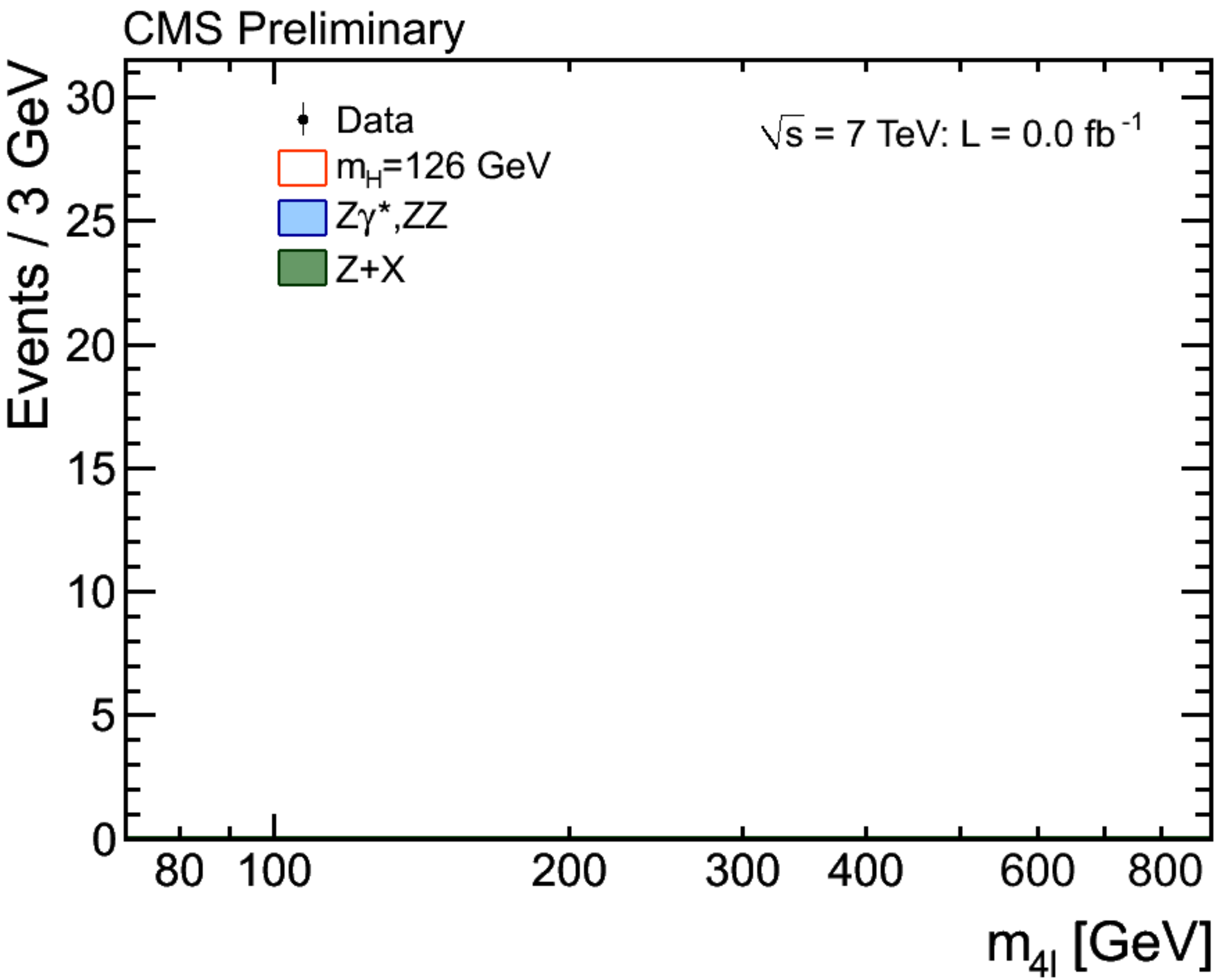
14/6/2012: Approval of **H→ZZ→4l** analysis



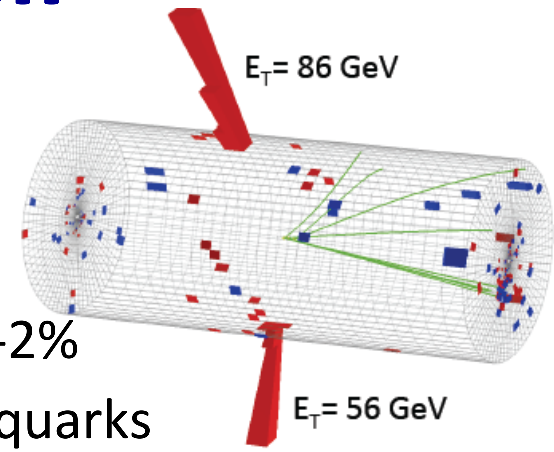



# 4-lepton mass: H→ZZ→4l, July 4 2012



# H→γγ in a nutshell




**Important channel** for Higgs with $110 < m_H < 140$ GeV

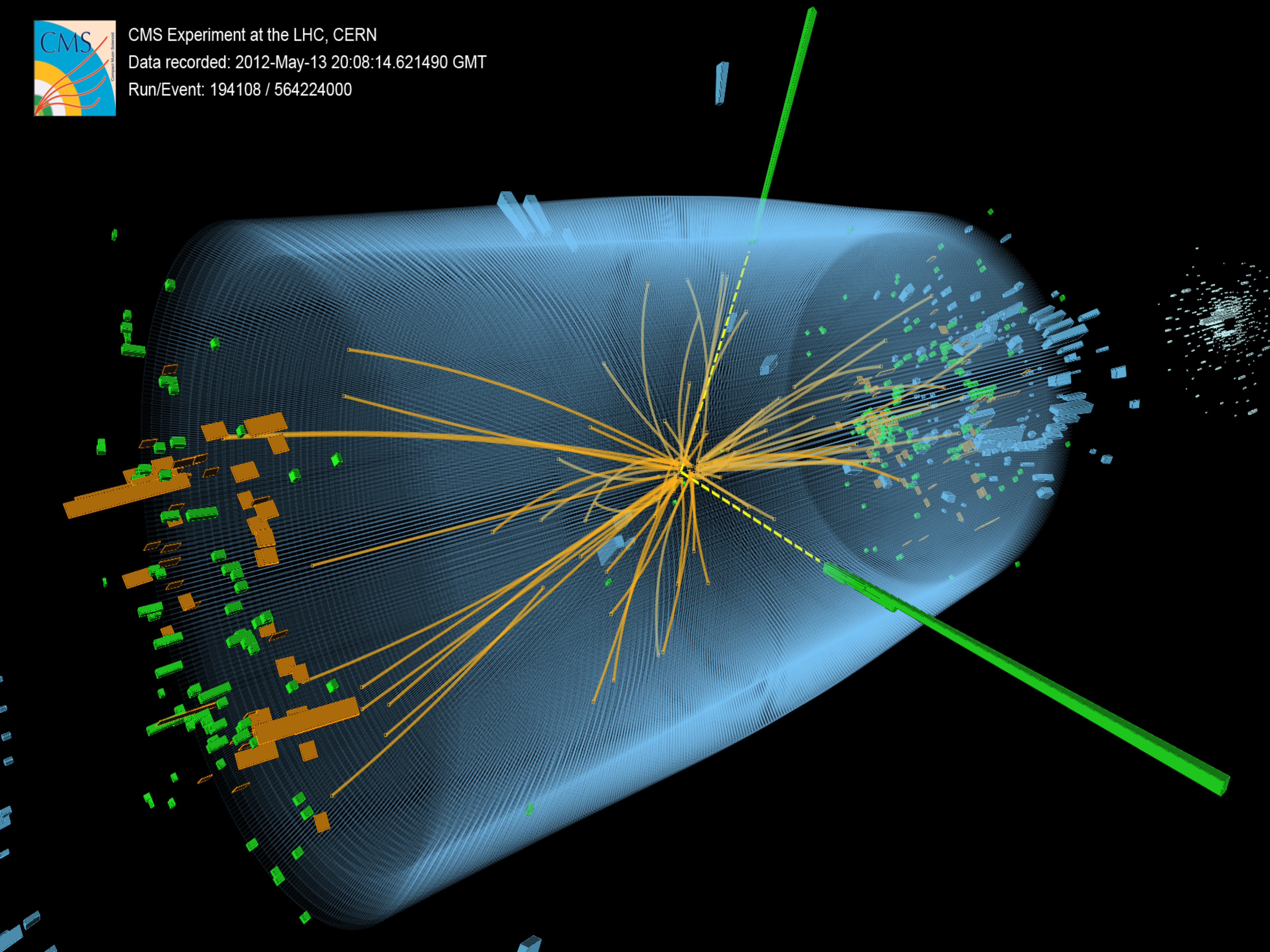
- clear signature of two isolated high $E_T$ photons
- small B.R. (0.2%)
- narrow mass peak with very good mass resolution 1-2%
- **VBF** channels has two additional jets from outgoing quarks
- Associate production: WH with W->lν

**Background:**

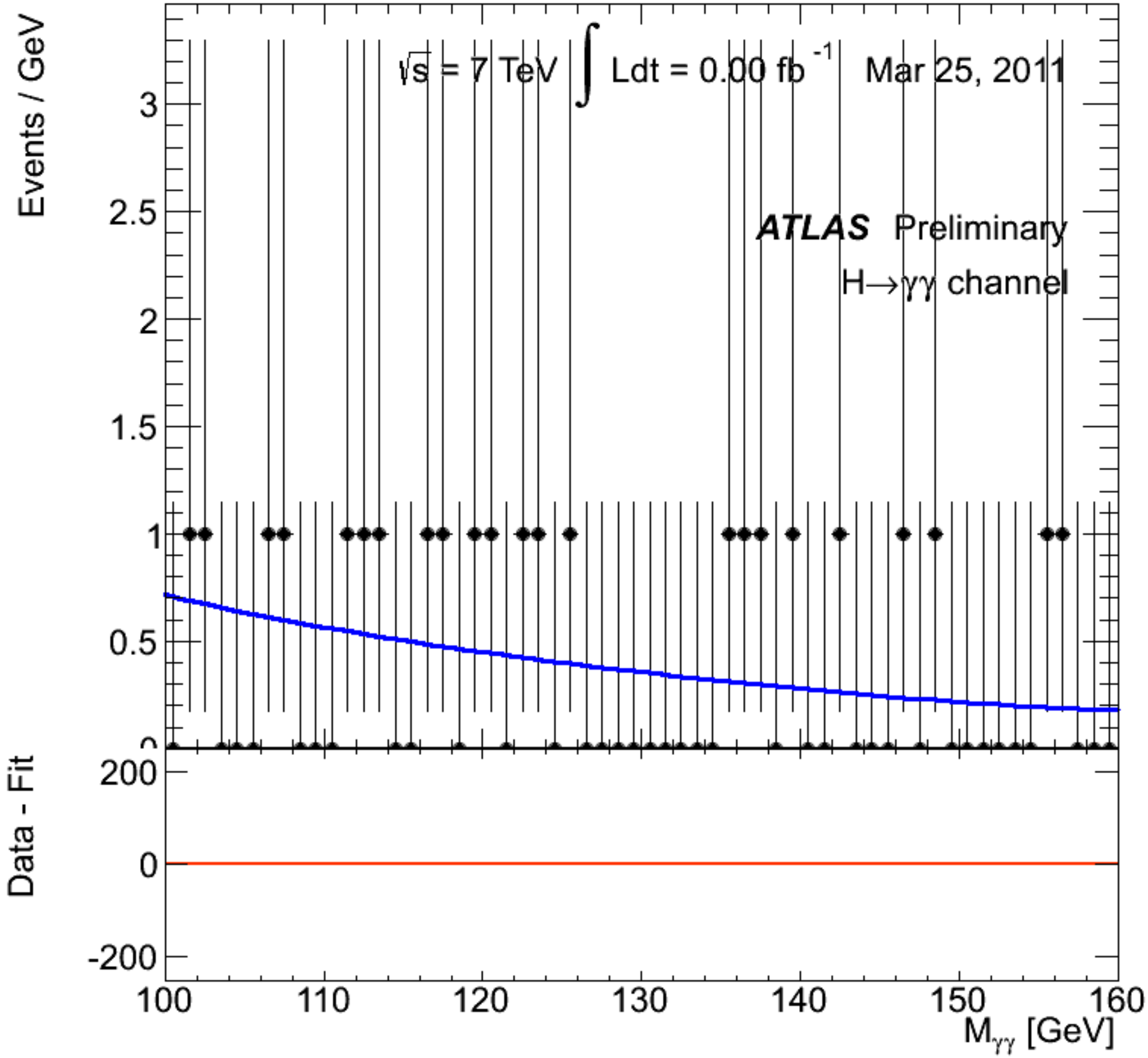
- irreducible : γγ→γγ, qqbar, qg→γγ from QCD
- reducible: pp → γ+jets (1 prompt γ + 1 fake γ)
  pp → jets (2 fake γ), fake γ from $\pi^0 \to \gamma\gamma$

**Analysis strategy based on:**

- trigger (double photon HLT)
- vertex ID via MVA, photon reconstruction, ID and isolation via MVA
- categories of events based on the γ shower shape ($R_9$) to optimize s/b
- look for a peak with MVA techniques and cut-based


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

# Di-photon mass: H→γγ, July 4 2012



# October 8 2013: Nobel prize

## Nobel Prizes and Laureates

Physics Prizes | 2013

▼ About the Nobel Prize in Physics 2013

- Summary
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- Press Release
- Advanced Information
- Popular Information
- Greetings

▶ François Englert

▶ Peter Higgs

All Nobel Prizes in Physics

All Nobel Prizes in 2013

**The Nobel Prize in Physics 2013**
François Englert, Peter Higgs

## The Nobel Prize in Physics 2013

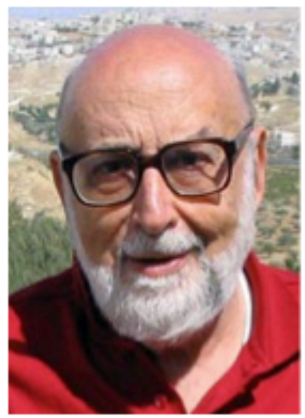


Photo: Pnicolet via Wikimedia Commons

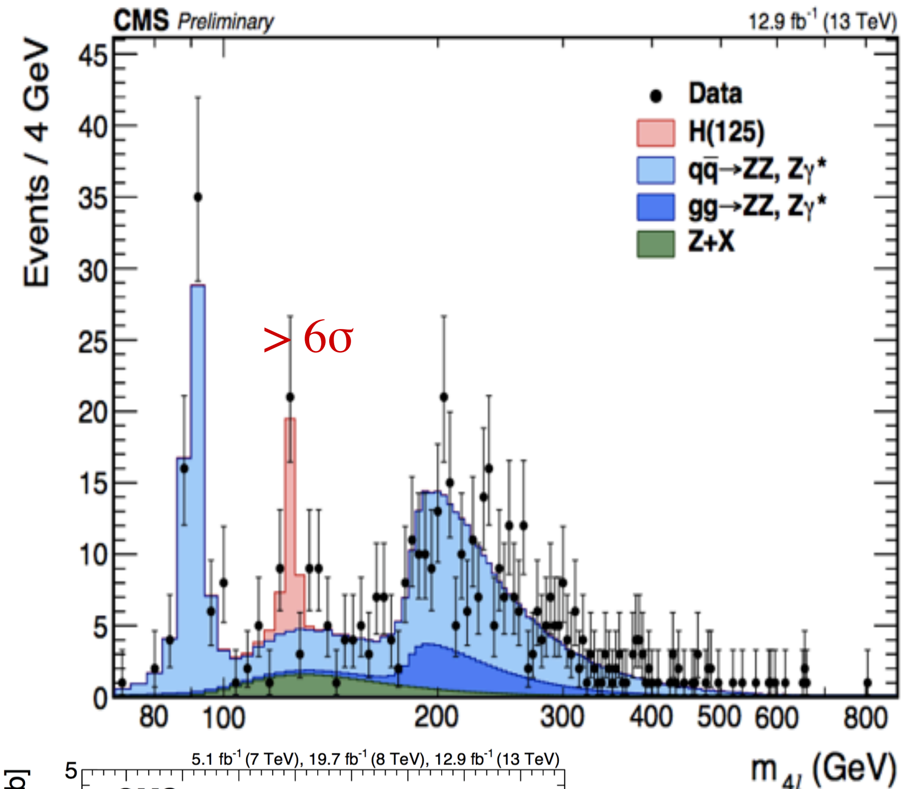
**François Englert**

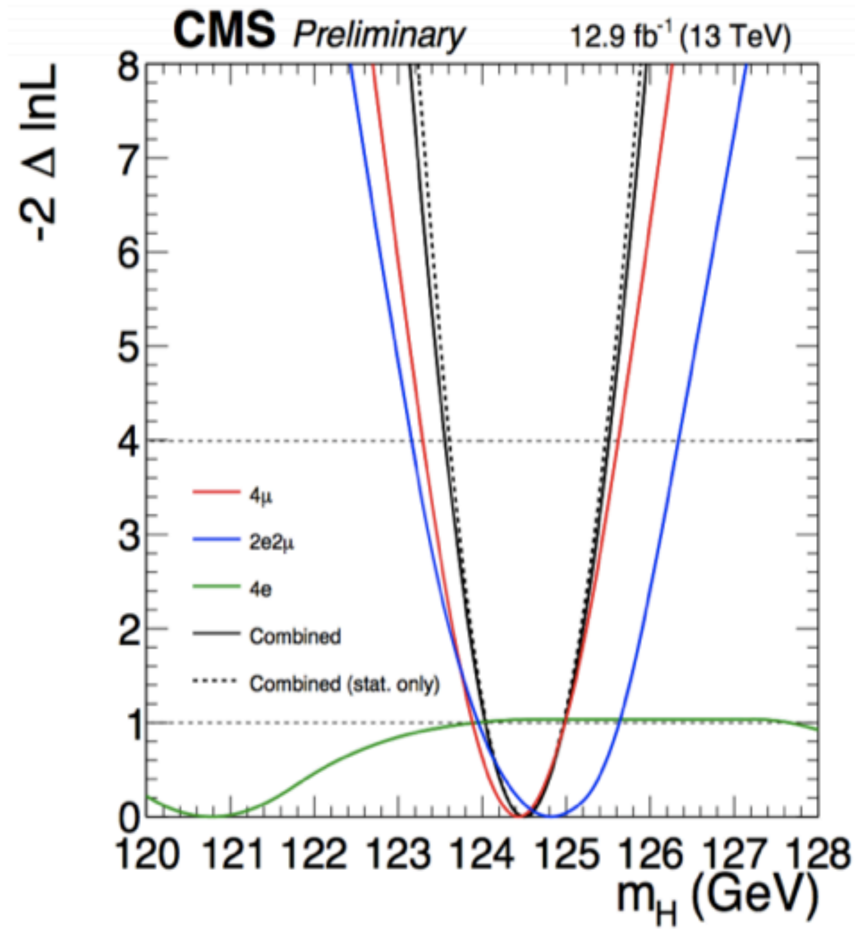
Photo: G-M Greuel via Wikimedia Commons

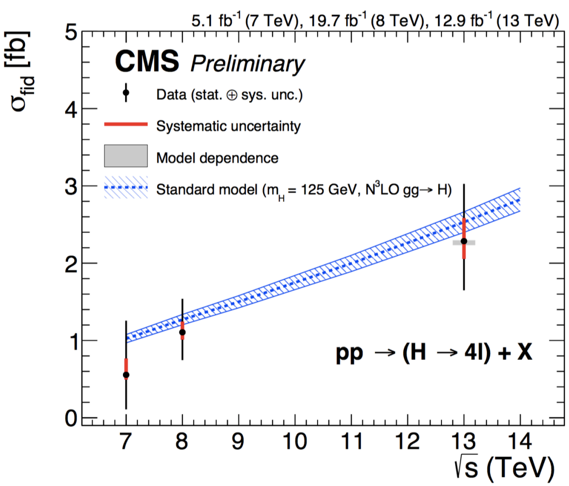
**Peter W. Higgs**

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

# H → 4 leptons, Sept-15th 2016, CMS, 13 fb$^{-1}$



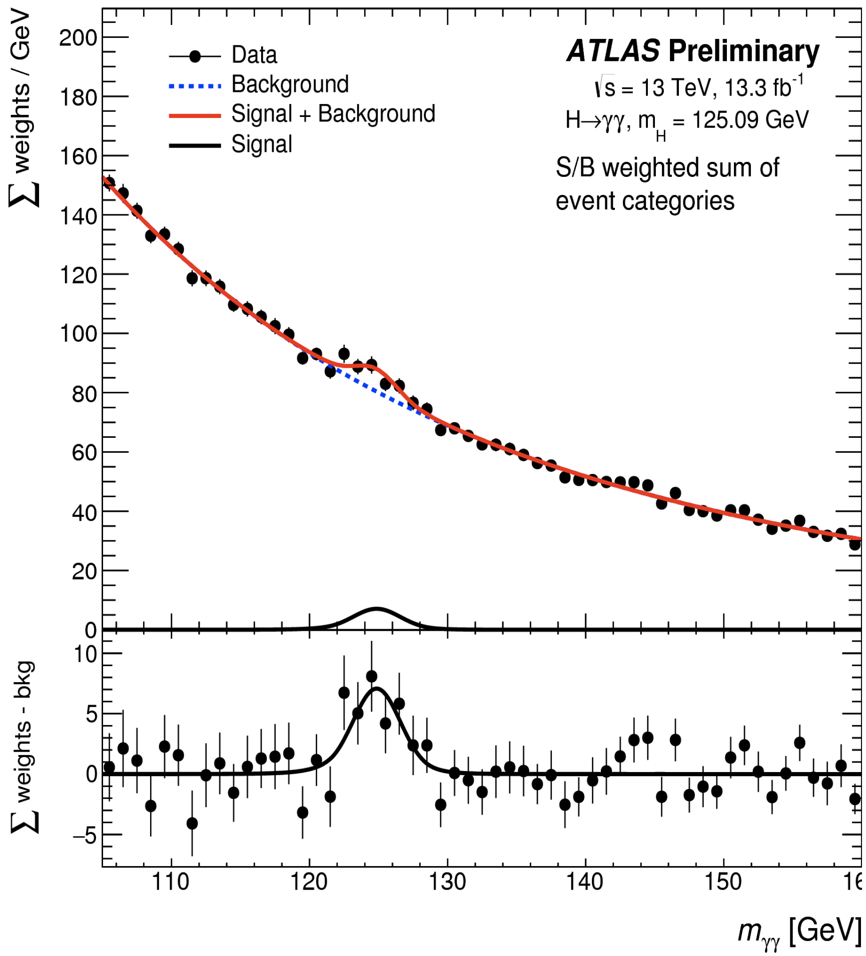



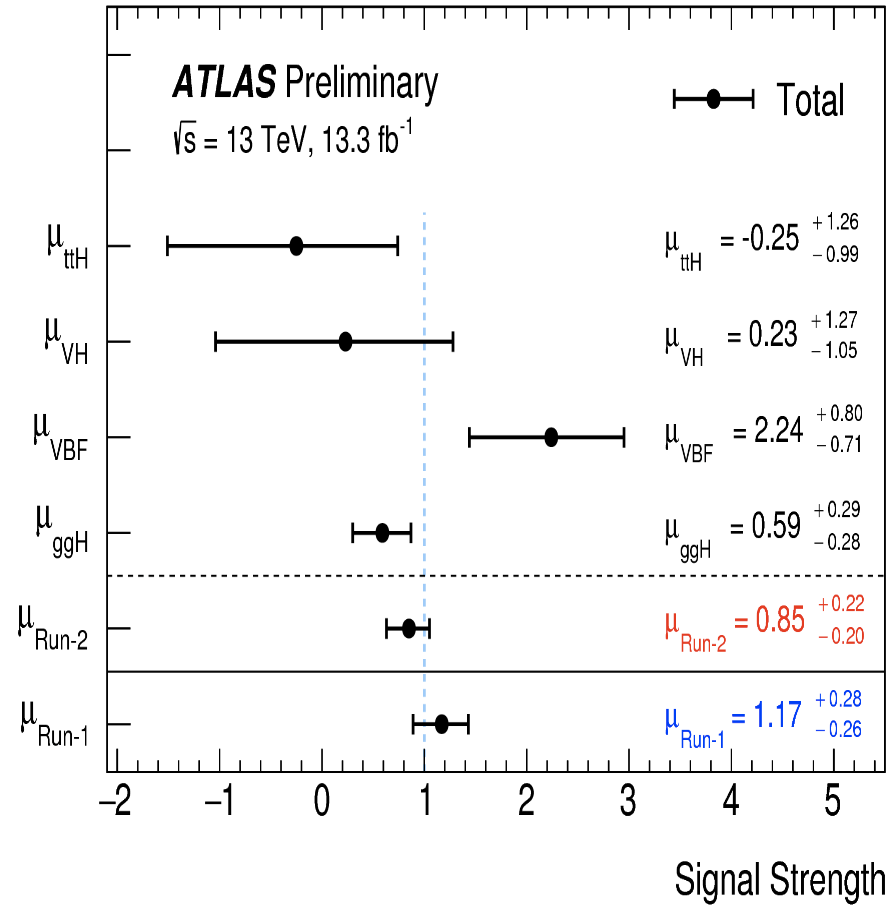




$$m_H = 124.50^{+0.48}_{-0.46}\ \text{GeV} = 124.50^{+0.47}_{-0.45}(\text{stat.})^{+0.13}_{-0.11}(\text{sys.})\ \text{GeV}$$

$$\mu = \sigma/\sigma_{SM} = 0.99^{+0.33}_{-0.26}$$

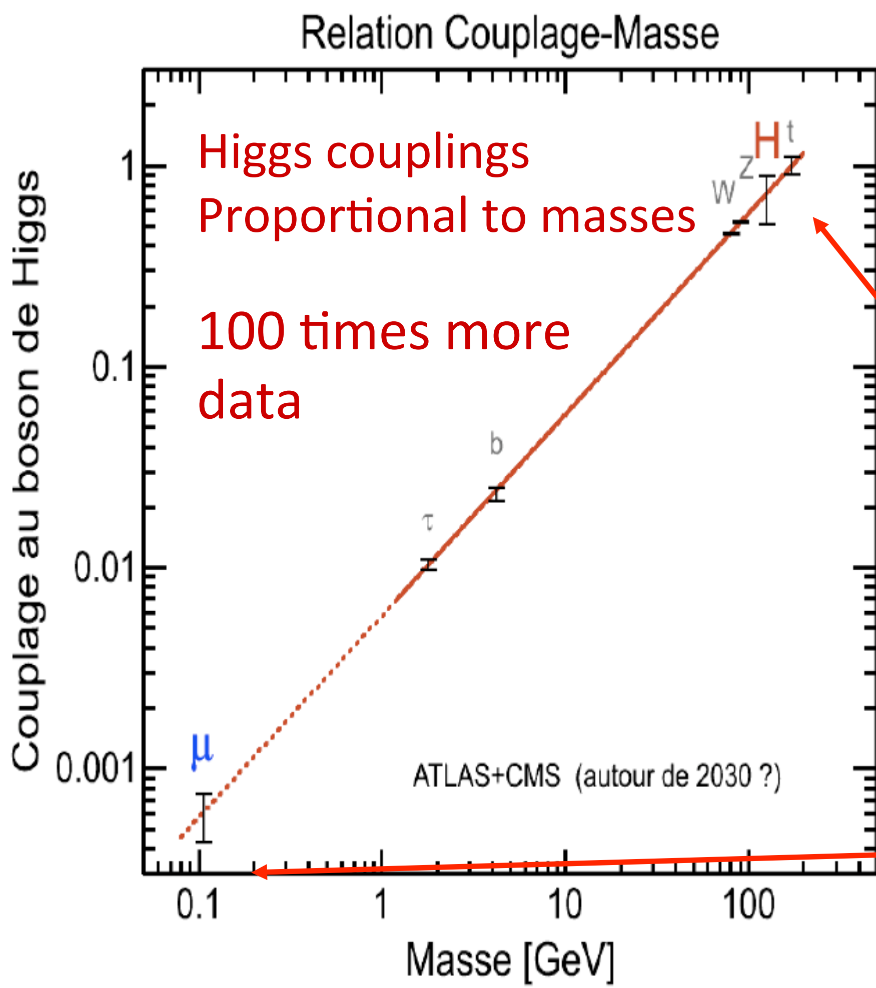
# $H \rightarrow \gamma\gamma$, 13 TeV, 13fb$^{-1}$, ATLAS, August 2016




| 13 TeV | Fiducial σ (fb) | SM prediction (fb) |
|---|---|---|
| ATLAS (13.3 fb$^{-1}$) | 43.2±14.9(stat)±4.9(syst) | 62.8+3.4-4.4 (N3LO+XH) |

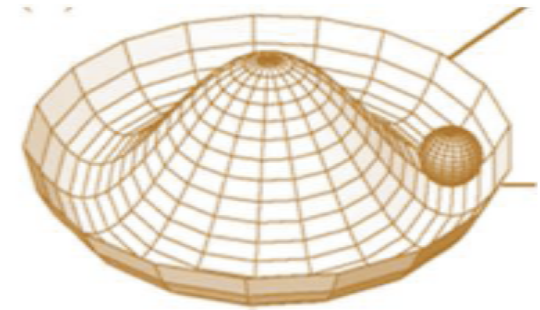
# Higgs couplings - future up to HL-LHC and 3000fb$^{-1}$




$g_{Hff} = m_f/v$

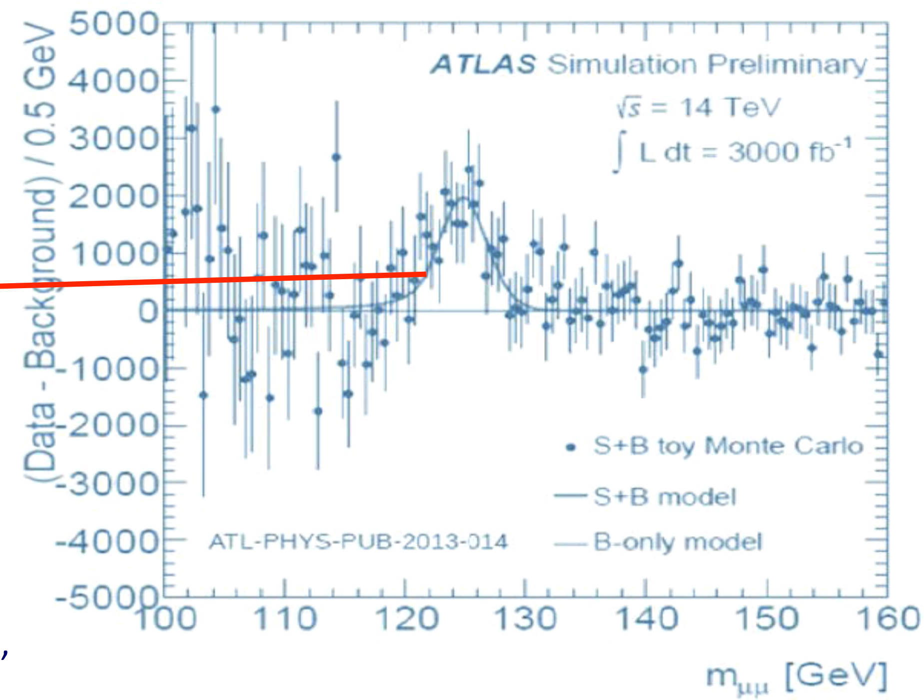
$g_{HHH} = 3m_H^2/v$

$g_{HVV} = 2m_V^2/v$



$v = (-\mu^2/\lambda)$ = 246 Γες

Higgs self-coupling and Higgs potential

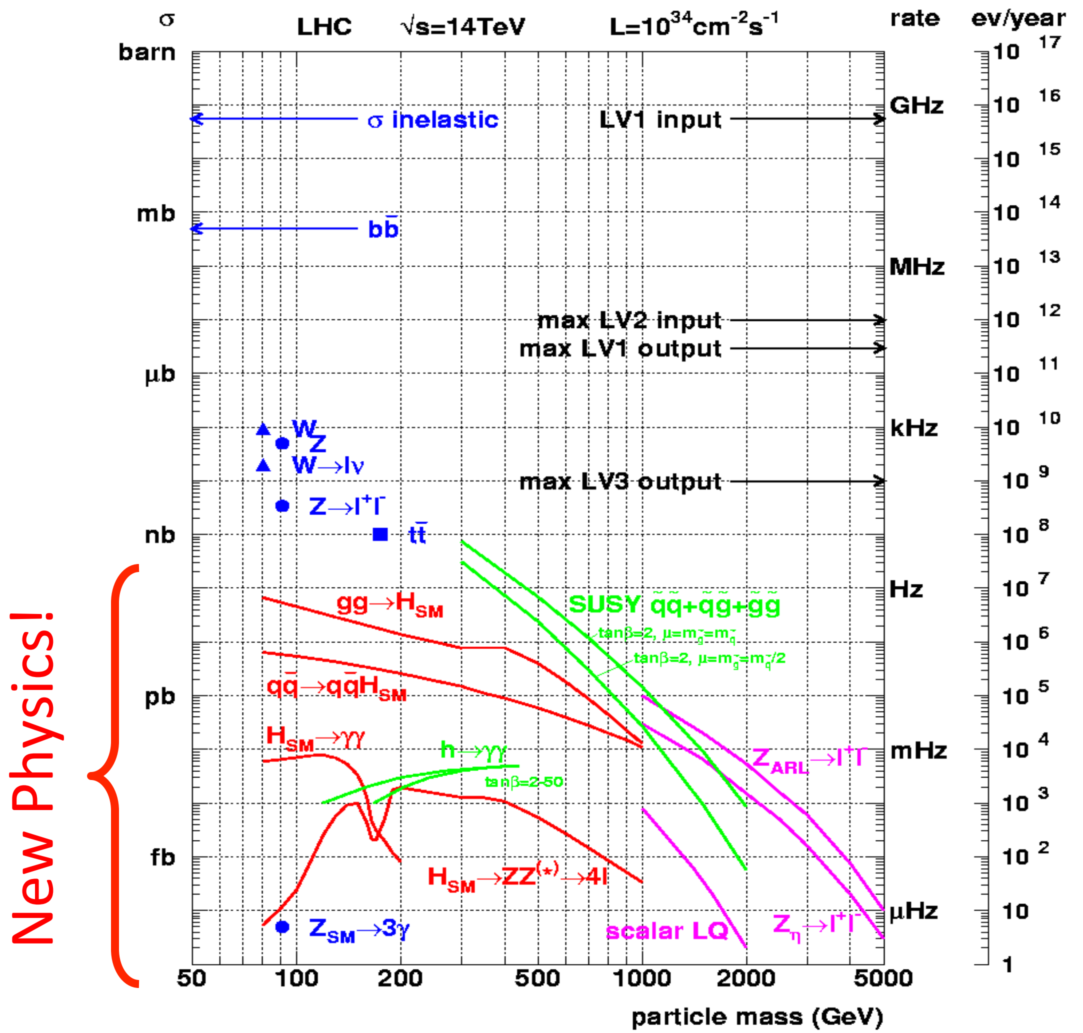



With 3000fb$^{-1}$ data at 13 TeV (by ~ 2025) couplings to 8 particles, including coupling to muons

# Is the SM enough? Open questions

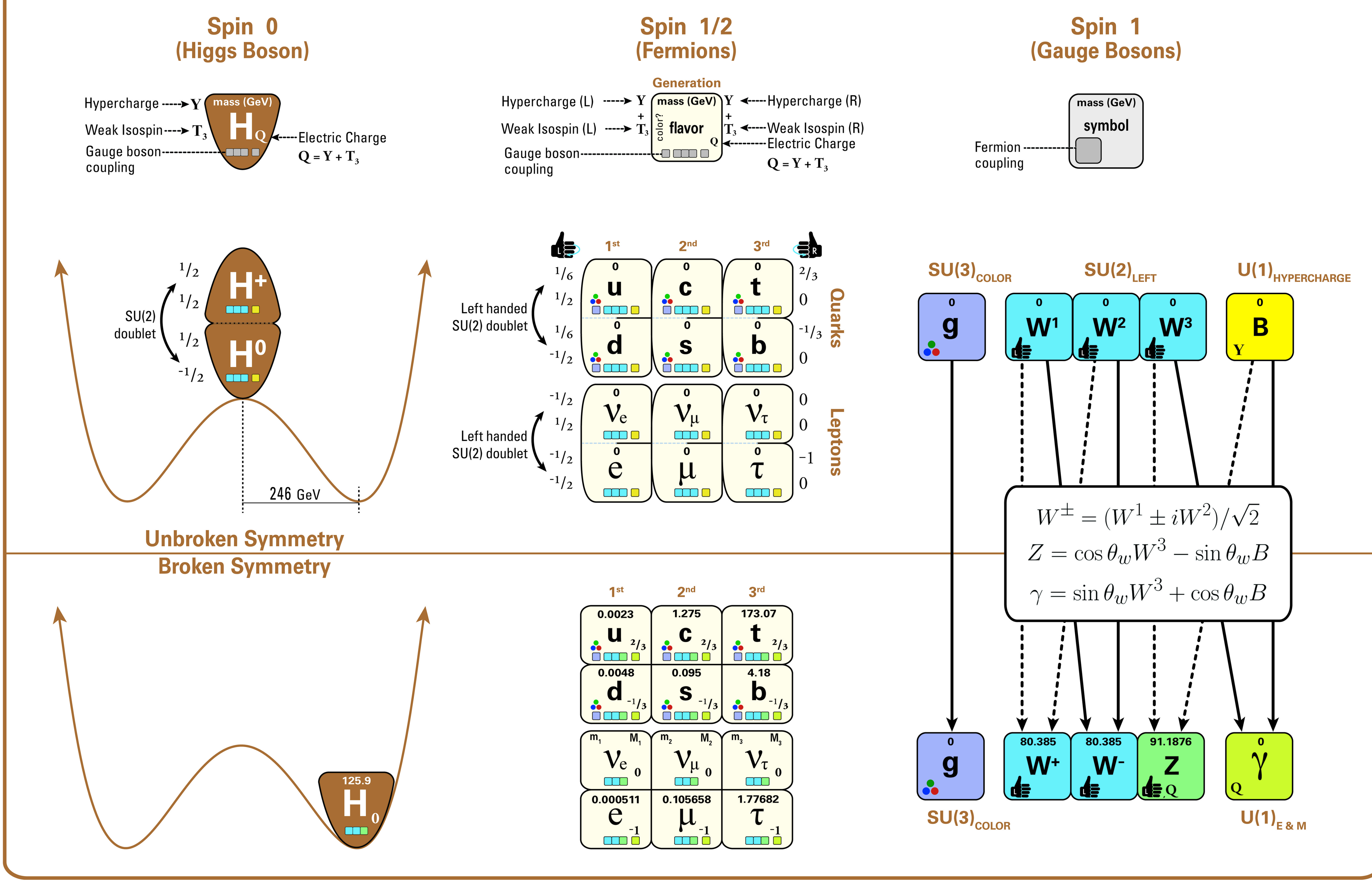
- Is the Higgs mechanism to generate weak boson and fermions masses real ?
- How to solve the problem of the hierarchy between the EWK scale and the GUT or Planck scale ?
- Are the electroweak and strong forces unified at some GUT scale
- Is the SUSY realized in nature ? Do the SUSY particles exist ? Can they explain the dark matter ?
- Do extra dimensions exist?
- ....etc..

LHC can provide some answers



# Backup

# The Standard Model of Particle Physics



# The Standard Model Lagrangian

$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c^2_w} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - \\
Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
\tfrac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s^2_w (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - \\
2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - g\alpha_h M \left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8} g^2 \alpha_h \left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2\right) - gMW^+_\mu W^-_\mu H - \\
\tfrac{1}{2} g \tfrac{M}{c^2_w} Z^0_\mu Z^0_\mu H - \tfrac{1}{2} ig \left(W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)\right) + \\
\tfrac{1}{2} g \left(W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W^-_\mu (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)\right) + \tfrac{1}{2} g \tfrac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
M \left(\tfrac{1}{c_w} Z^0_\mu \partial_\mu \phi^0 + W^+_\mu \partial_\mu \phi^- + W^-_\mu \partial_\mu \phi^+\right) - ig \tfrac{s^2_w}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + igs_w M A_\mu (W^+_\mu \phi^- - \\
W^-_\mu \phi^+) - ig \tfrac{1-2c^2_w}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
\tfrac{1}{4} g^2 W^+_\mu W^-_\mu \left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8} g^2 \tfrac{1}{c^2_w} Z^0_\mu Z^0_\mu \left(H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2 \phi^+\phi^-\right) - \\
\tfrac{1}{2} g^2 \tfrac{s^2_w}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \tfrac{1}{2} ig^2 \tfrac{s^2_w}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) + \tfrac{1}{2} ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w} (2c^2_w - 1) Z^0_\mu A_\mu \phi^+ \phi^- - g^2 s^2_w A_\mu A_\mu \phi^+ \phi^- + \\
\tfrac{1}{2} ig_s \lambda^a_{ij} (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu - \bar{e}^\lambda (\gamma\partial + m^\lambda_e) e^\lambda - \bar{\nu}^\lambda (\gamma\partial + m^\lambda_\nu) \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m^\lambda_u) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + m^\lambda_d) d^\lambda_j + \\
igs_w A_\mu \left(-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j)\right) + \tfrac{ig}{4c_w} Z^0_\mu \{(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s^2_w - \\
1 - \gamma^5) e^\lambda) + (\bar{d}^\lambda_j \gamma^\mu (\tfrac{4}{3} s^2_w - 1 - \gamma^5) d^\lambda_j) + (\bar{u}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3} s^2_w + \gamma^5) u^\lambda_j)\} + \\
\tfrac{ig}{2\sqrt{2}} W^+_\mu \left((\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) U^{lep}{}_{\lambda\kappa} e^\kappa) + (\bar{u}^\lambda_j \gamma^\mu (1+\gamma^5) C_{\lambda\kappa} d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}} W^-_\mu \left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda} \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda} \gamma^\mu (1+\gamma^5) u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^+ \left(-m^\kappa_e (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1-\gamma^5) e^\kappa) + m^\lambda_\nu (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1+\gamma^5) e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^- \left(m^\lambda_e (\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa} (1+\gamma^5) \nu^\kappa) - m^\kappa_\nu (\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa} (1-\gamma^5) \nu^\kappa\right) - \tfrac{g}{2} \tfrac{m^\lambda_\nu}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
\tfrac{g}{2} \tfrac{m^\lambda_e}{M} H (\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2} \tfrac{m^\lambda_\nu}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \tfrac{ig}{2} \tfrac{m^\lambda_e}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \tfrac{1}{4} \bar{\nu}_\lambda M^R_{\lambda\kappa} (1-\gamma_5) \hat{\nu}_\kappa - \\
\tfrac{1}{4} \overline{\bar{\nu}_\lambda M^R_{\lambda\kappa} (1-\gamma_5) \hat{\nu}_\kappa} + \tfrac{ig}{2M\sqrt{2}} \phi^+ \left(-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1-\gamma^5) d^\kappa_j) + m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1+\gamma^5) d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^- \left(m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1+\gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1-\gamma^5) u^\kappa_j\right) - \tfrac{g}{2} \tfrac{m^\lambda_u}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2} \tfrac{m^\lambda_d}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \\
\tfrac{ig}{2} \tfrac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \tfrac{ig}{2} \tfrac{m^\lambda_d}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j)
\end{gathered}
$$