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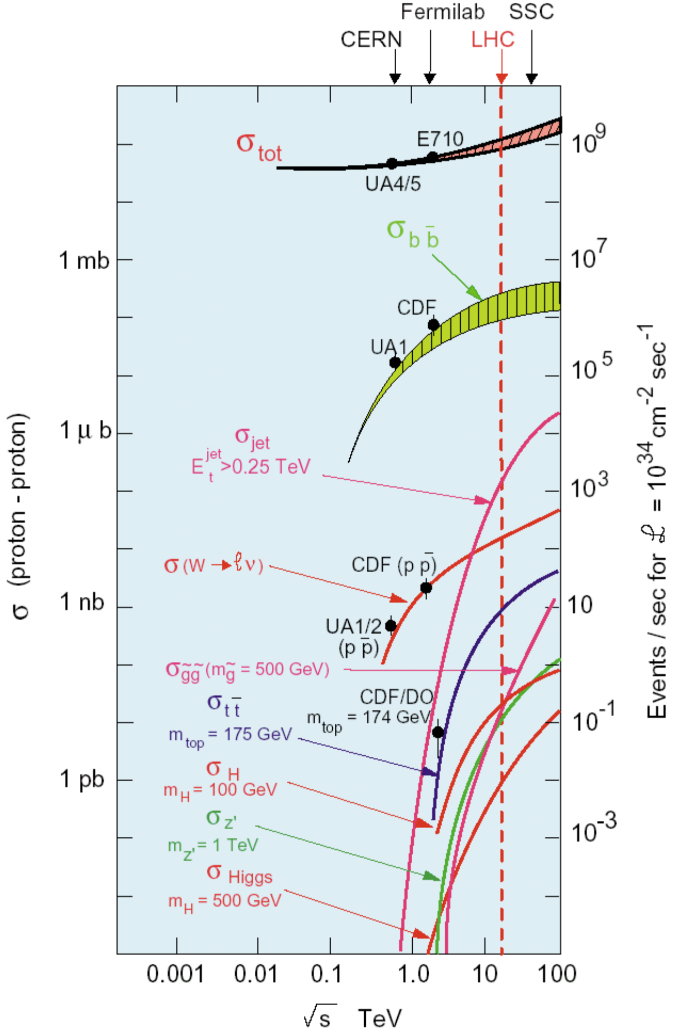
PHYSICS AT THE LHC

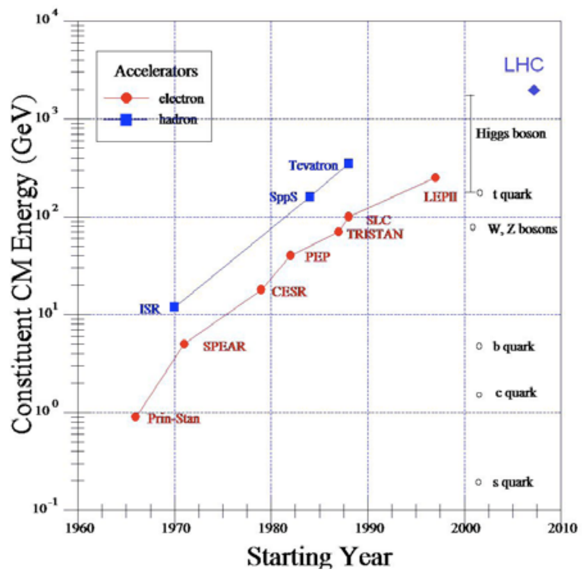
Overview

- The LHC
- The Experiments ATLAS and CMS
- Analysis objects
- Event structure
- Example analysis: the discovery of the Higgs
- Higgs properties and outlook

Why a hadron collider ?

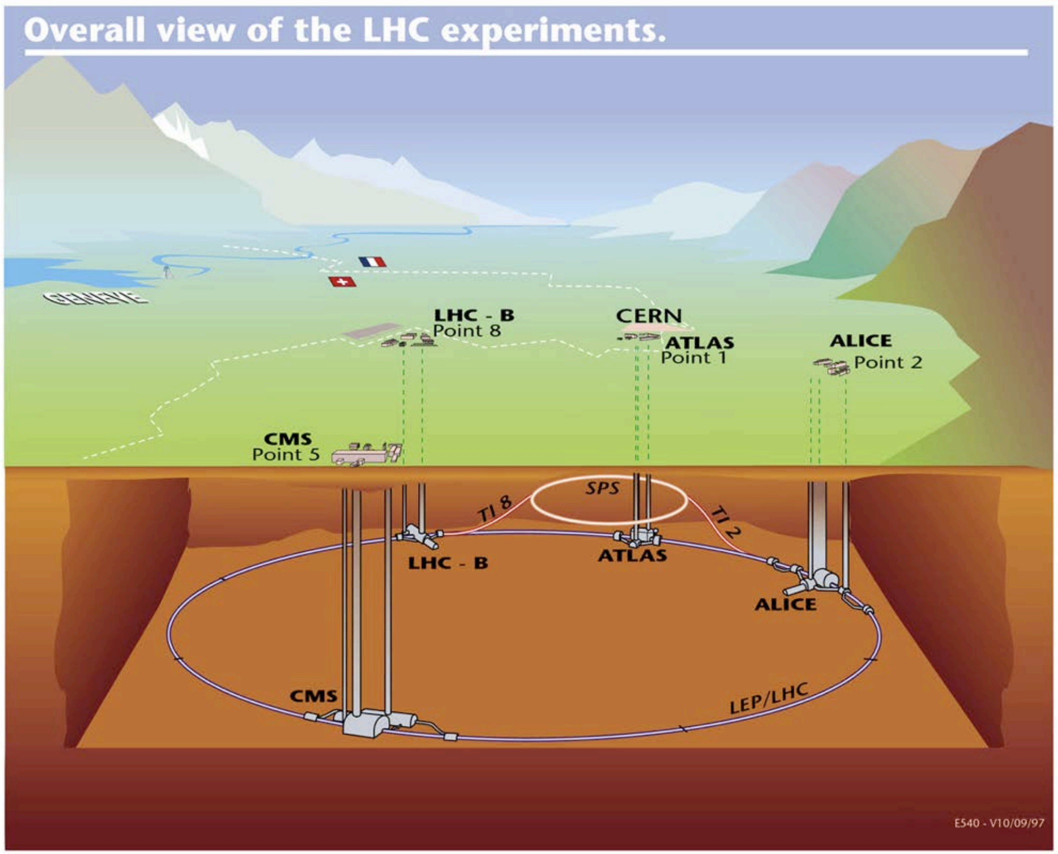


- Hadron machines have the highest energy. They are discovery machines
- Hadron collisions have large cross-sections.

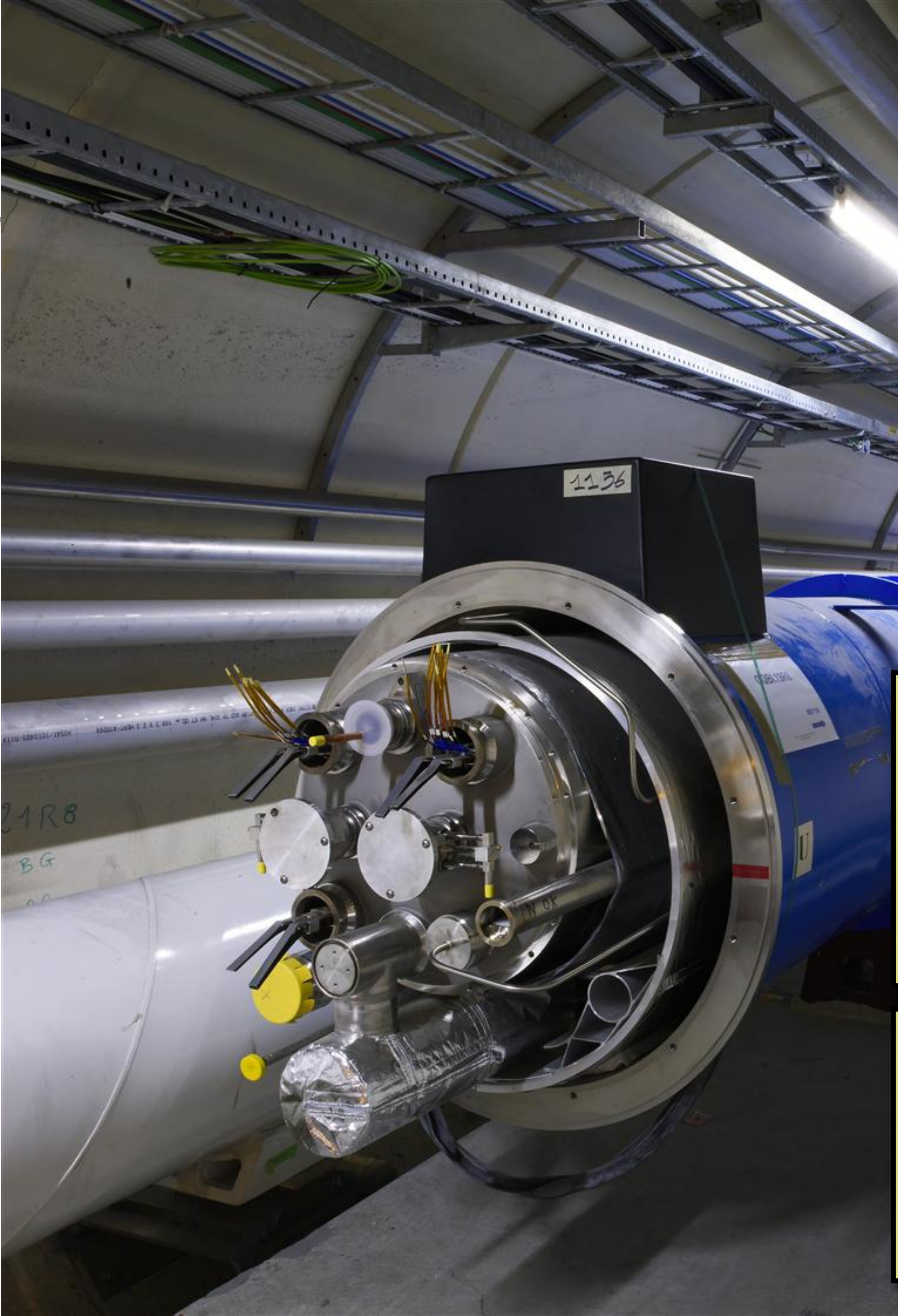


Having to deal with such high energy and high rates, the LHC detectors have to fulfill number of challenging requirements in terms of :
Triggering, data acquisition, radiation tolerance, precision and high detector granularity

The Large Hadron Collider



- 14 TeV proton-proton collisions (now 8 TeV)
- 27 km circumference
- 4 large experiments
- I will focus on CMS and ATLAS
- LHCb: b-physics, CP violation
- ALICE: heavy-ions, quark-gluon plasma, Pb-Pb
- Totem, LHCf,…



Acceleration is 'easy'

High energy: 14 TeV

Energy limited by strength of 1234 dipole magnets, with B= 8.4 T at 1.9 K

→ *Production of heavy particles (few TeV)*

High intensity: $10^{33/34}$ $cm^{-2}s^{-1}$

40 million collisions per second

→ *Look for rare processes*

Cross-section

$$N_{obs} = \int L dt \cdot \varepsilon \cdot \sigma$$

$$L = \frac{f_{rev}\, n_{bunch}\, N_p^2}{4\pi\sigma_x\sigma_y}$$

revolving frequency: f_{rev}=11245.5/s
#bunches: n_{bunch}=2808
#protons / bunch: N_p= 1.15 x 10^{11}
Area of beams: $4\pi\sigma_x\sigma_y$~40 µm

number of observed events

background contamination in the sample

cross section: $\sigma = \dfrac{N_{obs} - N_{bkg}}{\varepsilon \cdot \int \mathcal{L} dt}$

analysis efficiency

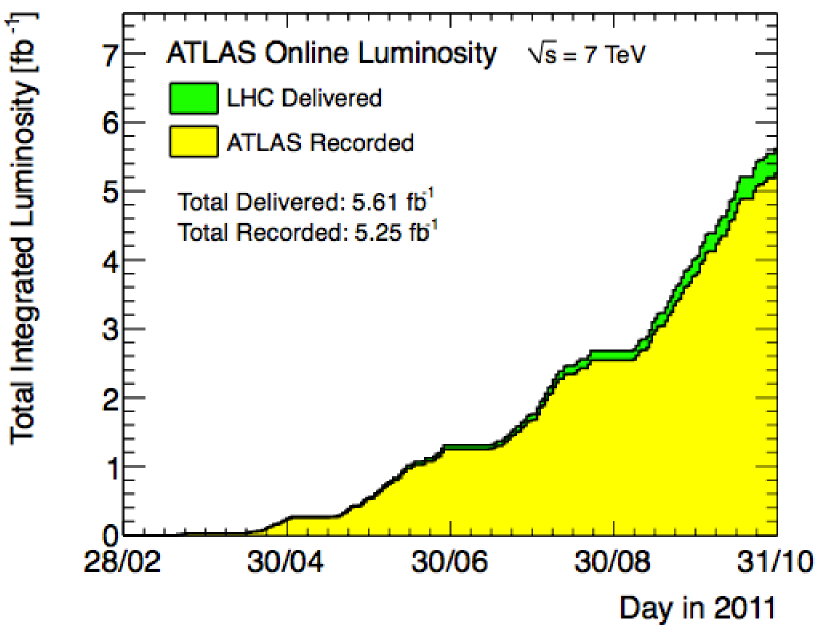
$\varepsilon = \varepsilon_{tr} \cdot \varepsilon_{reco} \cdot \varepsilon_{ID} \cdot \varepsilon_{sel}$

luminosity delivered by LHC

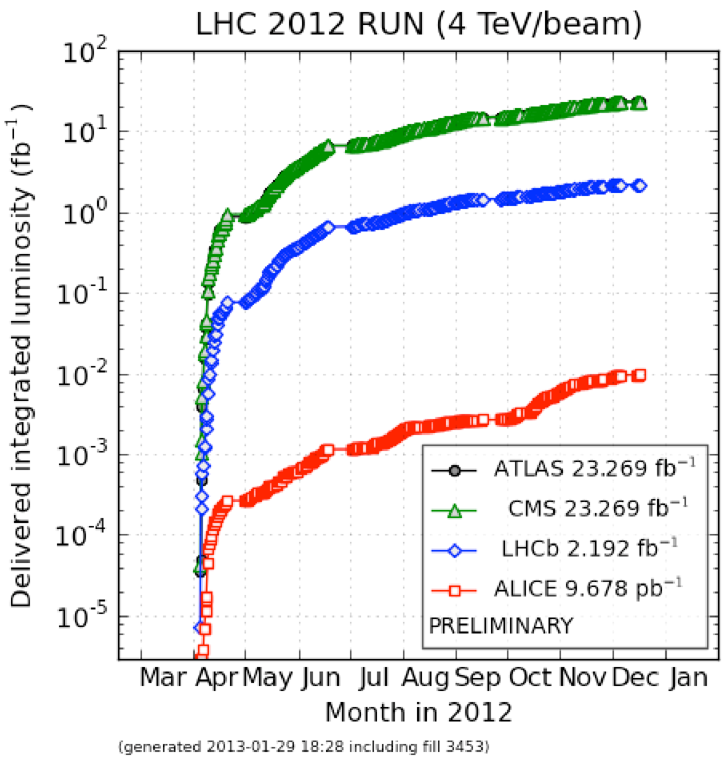
Number of observed events proportional to luminosity and analysis efficiency.

$$1 \text{ barn} = 10^{-28}\text{ m}^2 = 10^{-24}\text{ cm}^2$$

Luminosity



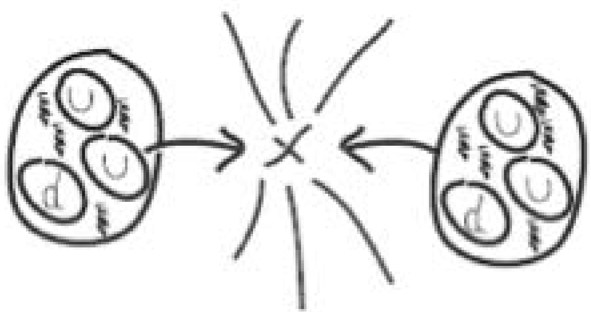
ATLAS Online Luminosity √s = 7 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 5.61 fb-1
Total Recorded: 5.25 fb-1
Total Integrated Luminosity [fb-1]
28/02
30/04
30/06
30/08
31/10
Day in 2011



LHC 2012 RUN (4 TeV/beam)
Delivered integrated luminosity (fb-1)
ATLAS 23.269 fb-1
CMS 23.269 fb-1
LHCb 2.192 fb-1
ALICE 9.678 pb-1
PRELIMINARY
Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan
Month in 2012
(generated 2013-01-29 18:28 including fill 3453)

Collider kinematics

Protons (and antiprotons) are formed by quarks (uud) kept together by gluons



The energy of each beam is carried by the proton constituents, and it is not the entire proton which collides, but one of his constituents

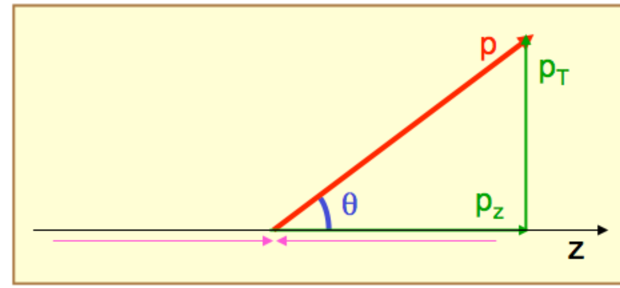
Ecoll < 2Eb

Pros: with a single energy possible to scan different processes at different energies

Cons: the energy available for the collision is lower than the accelerator energy

Coordinates

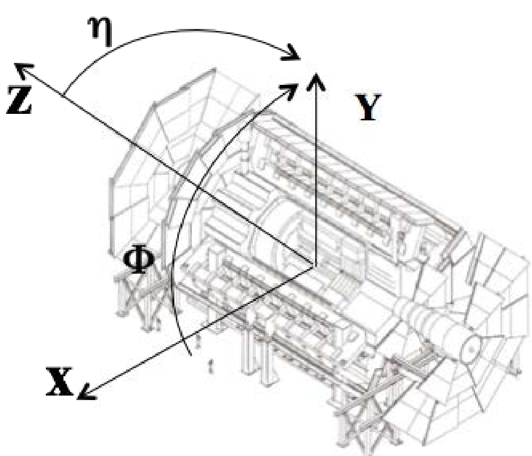
•As a consequence of the collision kinematic, the visible p_Z is not known only the con-servation of the transverse momentum p_T can be used.



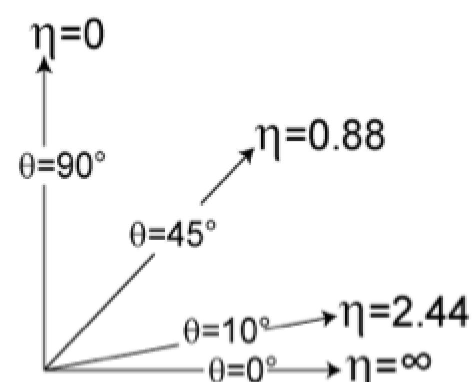
•Polar angle ϑ is not Lorentz invariant

•Rapidity y is Lorentz invariant:

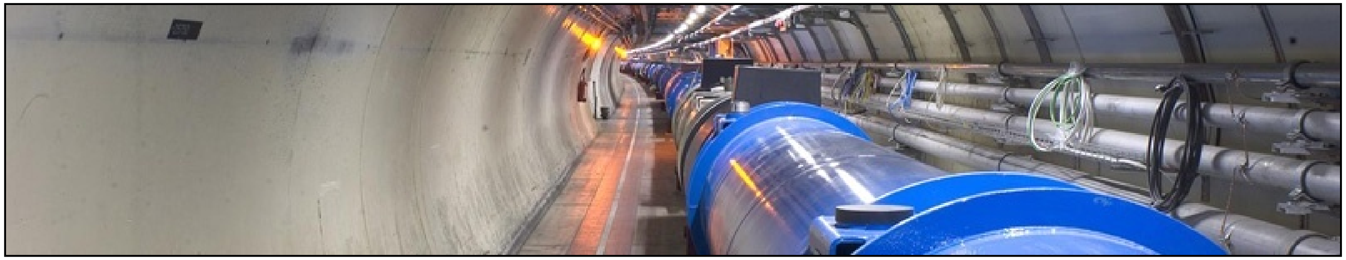
$$y = \frac{1}{2}\ln\frac{E + p_Z}{E - p_Z} \approx \eta = -\ln\left(\tan\frac{\vartheta}{2}\right)$$

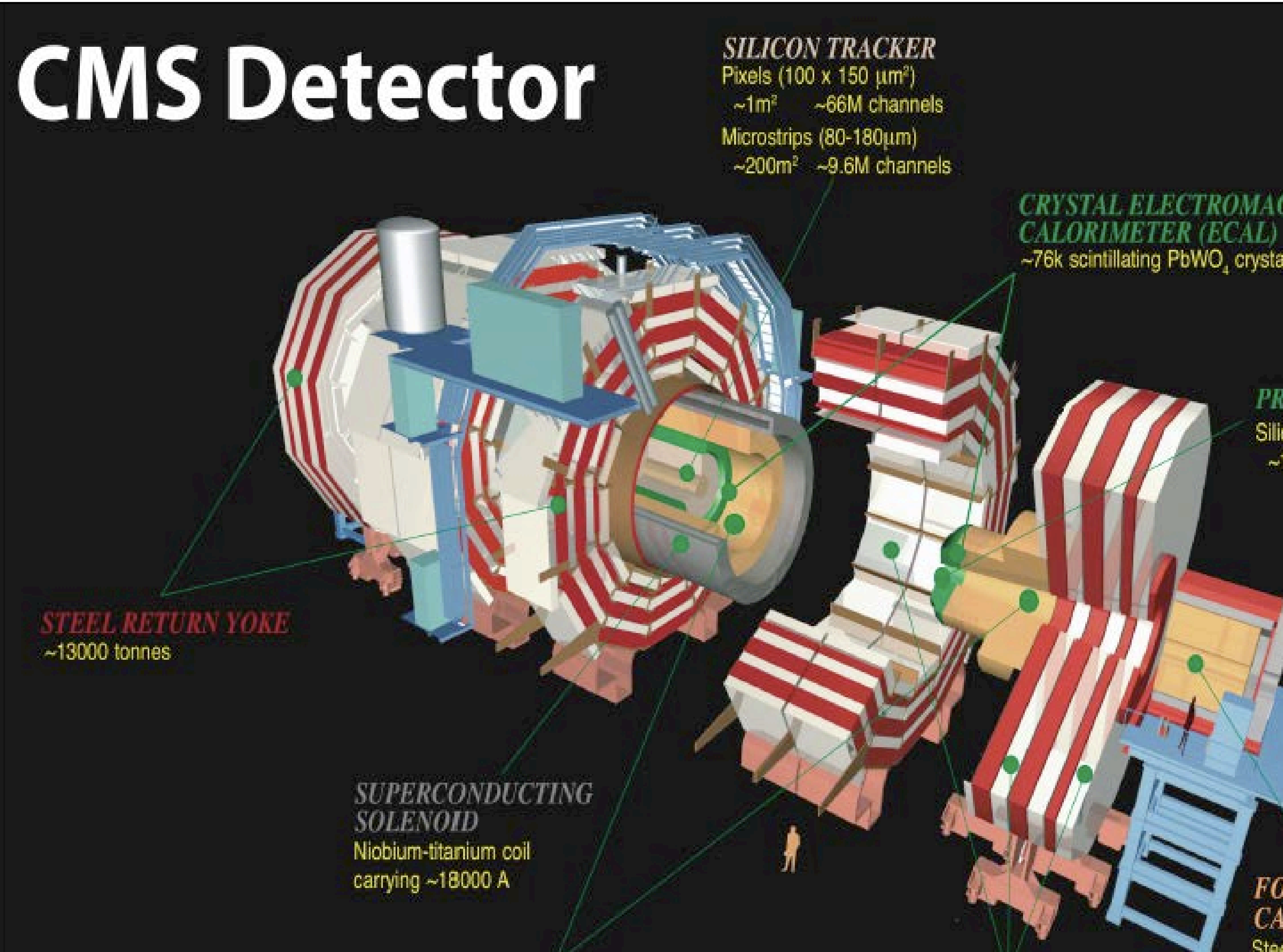


rapidity ≈ pseudorapidity (|)
in massless approximation



The experiments



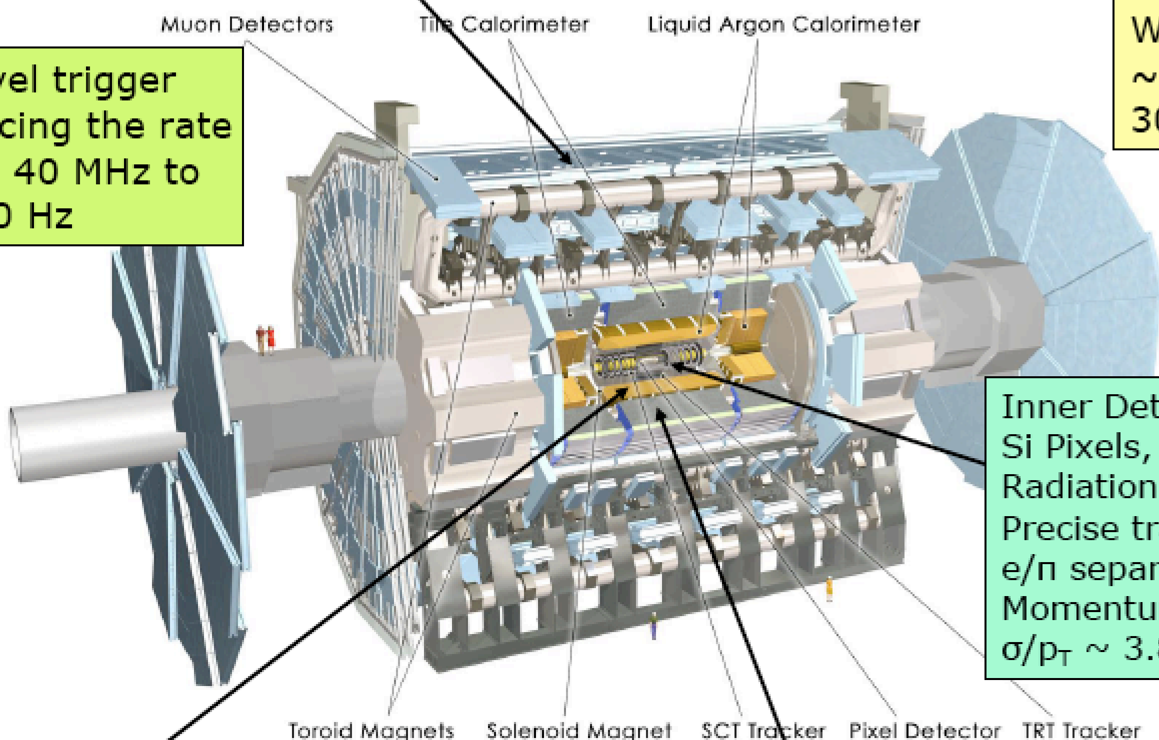

CMS Detector
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels
CRYSTAL ELECTROMAG
CALORIMETER (ECAL)
~76k scintillating PbWO₄ crysta
STEEL RETURN YOKE
~13000 tonnes
SUPERCONDUCTING
SOLENOID
Niobium-titanium coil
carrying ~18000 A

Atlas

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to $E_\mu \sim 1$ TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
$\sim 10^8$ electronic channels
3000 km of cables

3-level trigger reducing the rate from 40 MHz to ~200 Hz



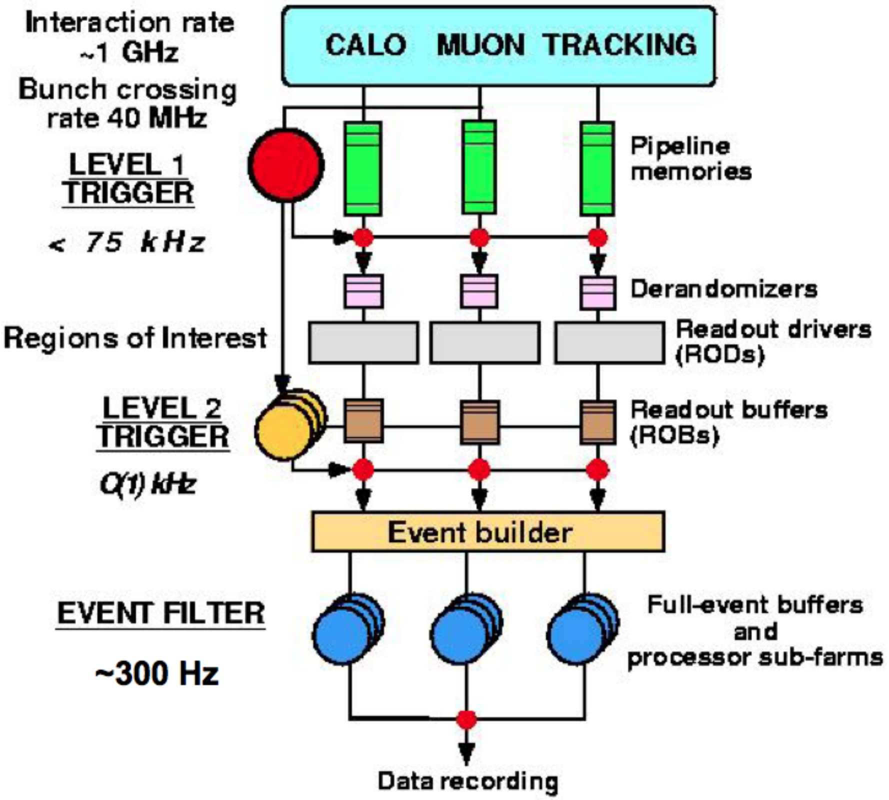
Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T\,(\mathrm{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

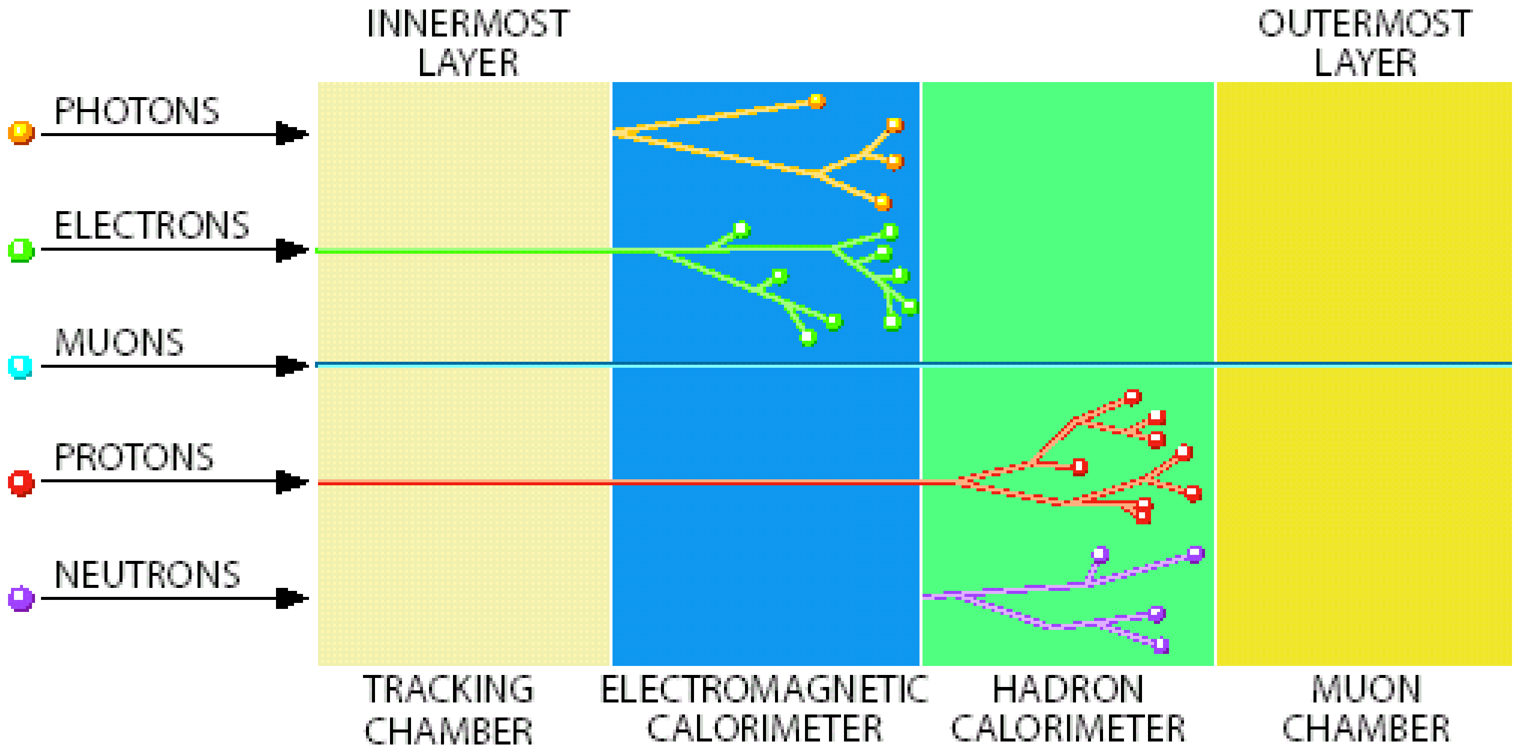
Trigger System

- Level-1:
  - Implemented in hardware
  - Muon + Calo based
  - coarse granularity
  - e/γ, μ, π, τ, jet candidate selection
  - Define regions of interest (ROIs)
- Level-2:
  - Implemented in software
  - Seeded by level-1 ROIs, full granularity
  - Inner Detector – Calo track matching
- Event Filter:
  - Implemented in software
  - Offline-like algorithms for physics signatures
  - Refine LV2 decision
  - Full event building



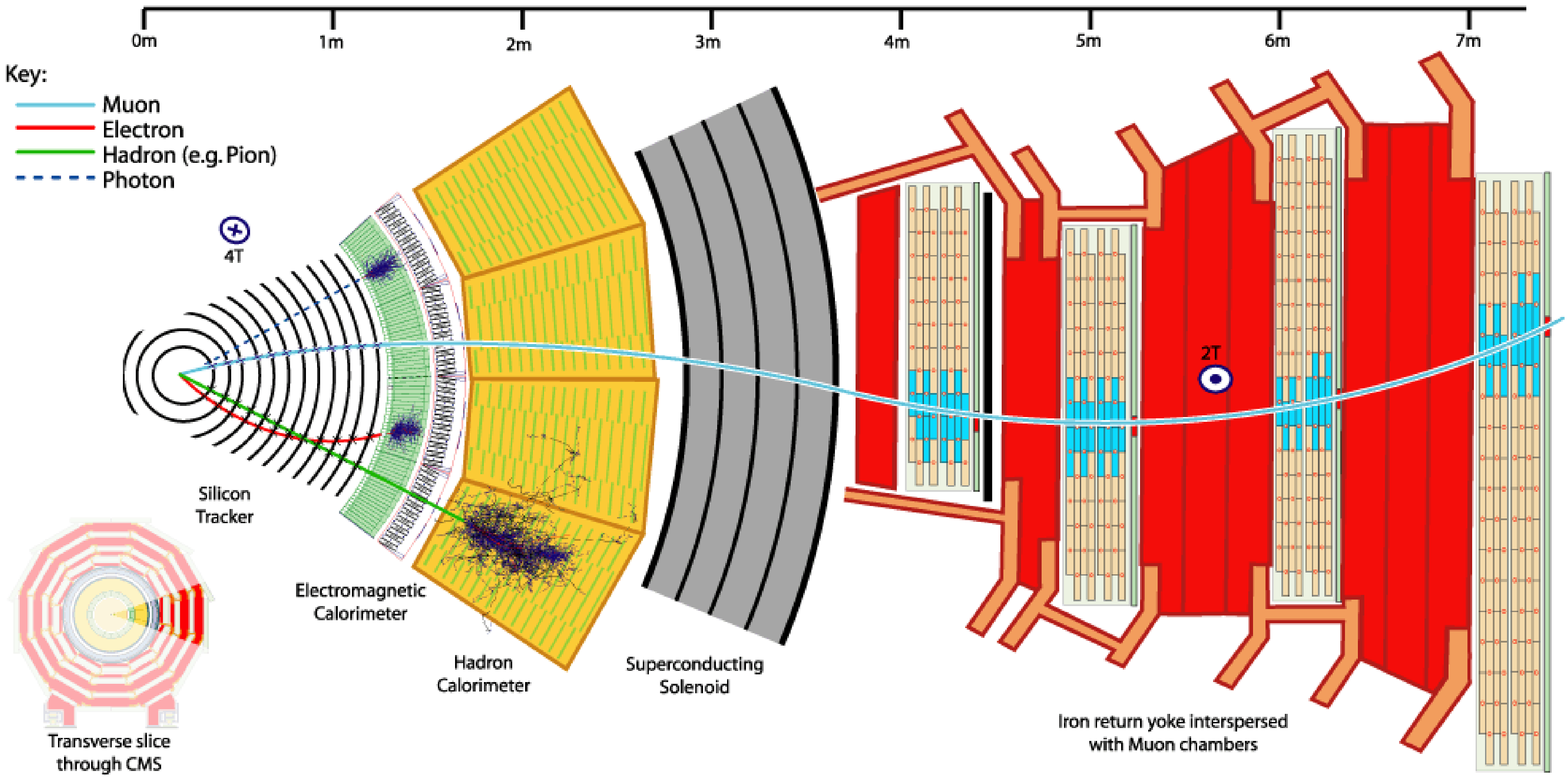
- Collisions 40MHz
- LV1 max 75kHz
- To disk ~300 Hz

Collider Detectors *101*



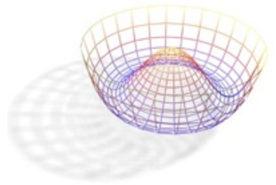
$E^2 = p^2 + m^2$; For high energy particle $m << E \Rightarrow E \sim p$

Analysis objects



υ: nothing

Analysis objects



Electrons:

- Electroweak or conversion: quite rare
- Energy deposition in the ECAL
- Track pointing to cluster
- Some shape information
- Isolation: track & energy
- Min p_T of few GeV

Photons:

- Energy deposition in ECAL
- No pointing track
- Converted γ to electrons
- Shape information

Taus:

- EW, but difficult
- 1-3 hadronic tracks
- Isolated

Muons:

- Electroweak
- Track in muon system
- Stand-alone or combined with track in ID
- Track in ID tagged by muon segment
- Calorimeter muons
- Isolation
- Min p_T of few GeV

Jets:

- Cluster of object coming from q or g
- 4-many tracks, mostly pions
- Energy in calos E & hadronic
- Min p_T of 20-30 GeV
- b-tagging (ε 50%, fake 0.2%)

Missing E_T:

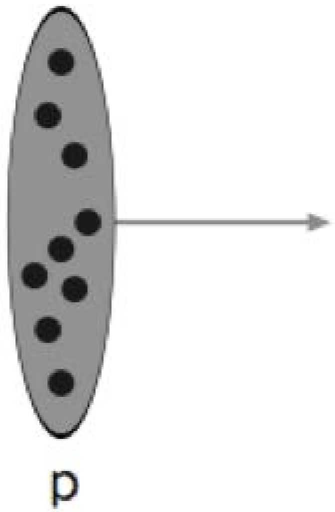
- Negative energy sum
- From neutrinos

Event structure

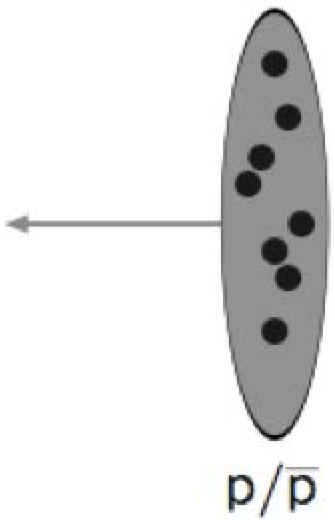
We will introduce some of the concepts when protons interact, like:

- The hard process
- Radiation: ISR/FSR
- Underlying event
- Minimum bias
- Parton density functions

Event structure: PDF’s



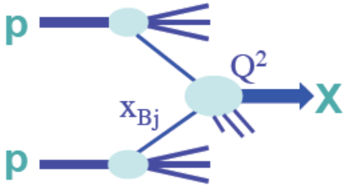
Initially two beam particles are coming in towards each other. Normally each particle is characterized by a set of parton distributions, which defines the partonic substructure in terms of flavour composition and energy sharing.This determines the energy of the interacting partons (x1, x2)



$$\sigma(p(P_1) + p(P_2) \to Y) = \int_0^1 dx_1 \int_0^1 dx_2 \sum_f f_f(x_1) f_{\bar{f}}(x_2) \cdot \sigma(q_f(x_1 P) + \bar{q}_f(x_2 P) \to Y)$$

Incoming beam: parton densities
Described by PDF’s

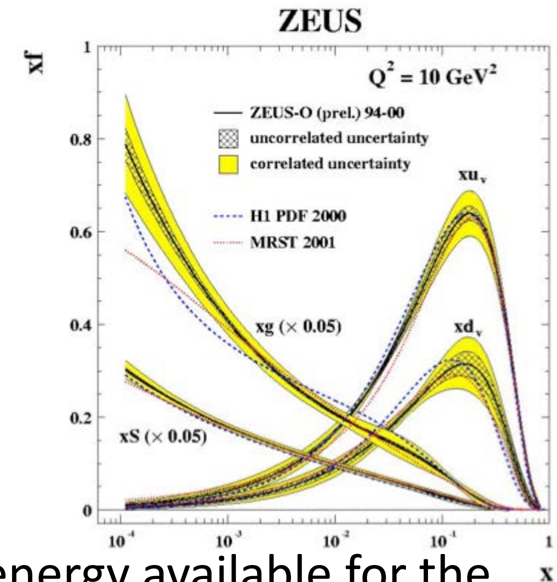
partonic x-section:
phase space* matrix element

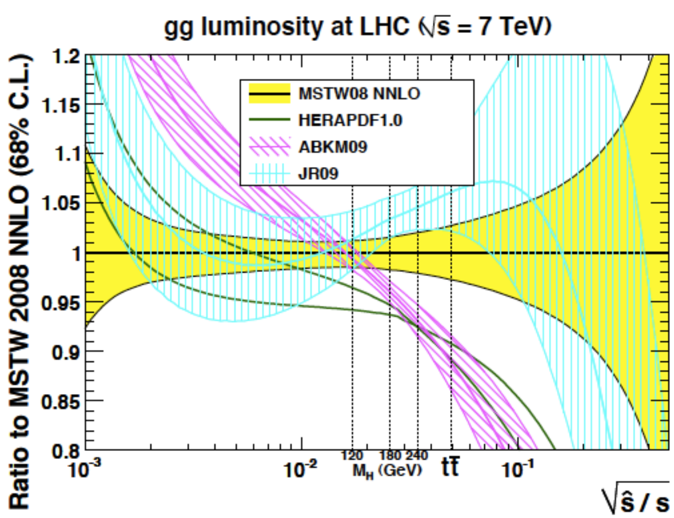


PDF’s

Describe energy distribution of partons inside proton. There are several PDF’s parametrizations, determined by the data from ep experiments at Hera or from Tevatron or fixed target.

u-and d-quarks dominate at large x, while gluons dominate at low x.





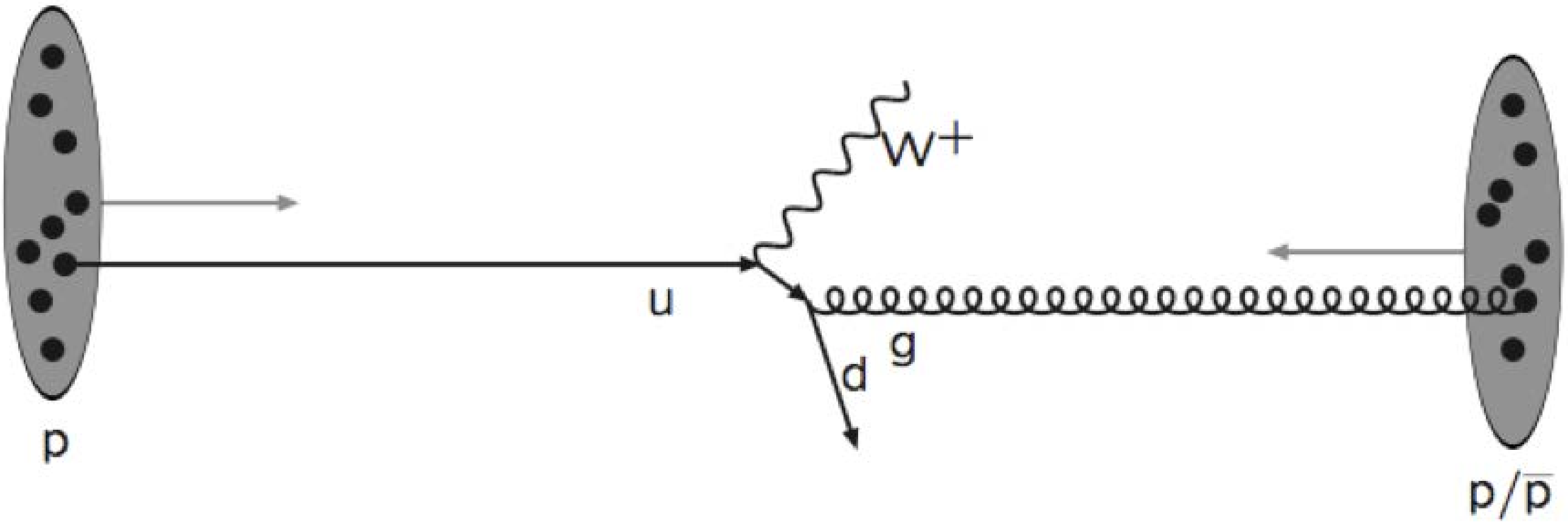
Large uncertainties

The effective energy available for the interaction is:

$$\sqrt{\hat{s}} = \sqrt{x_a x_b s} \approx x\sqrt{s}$$

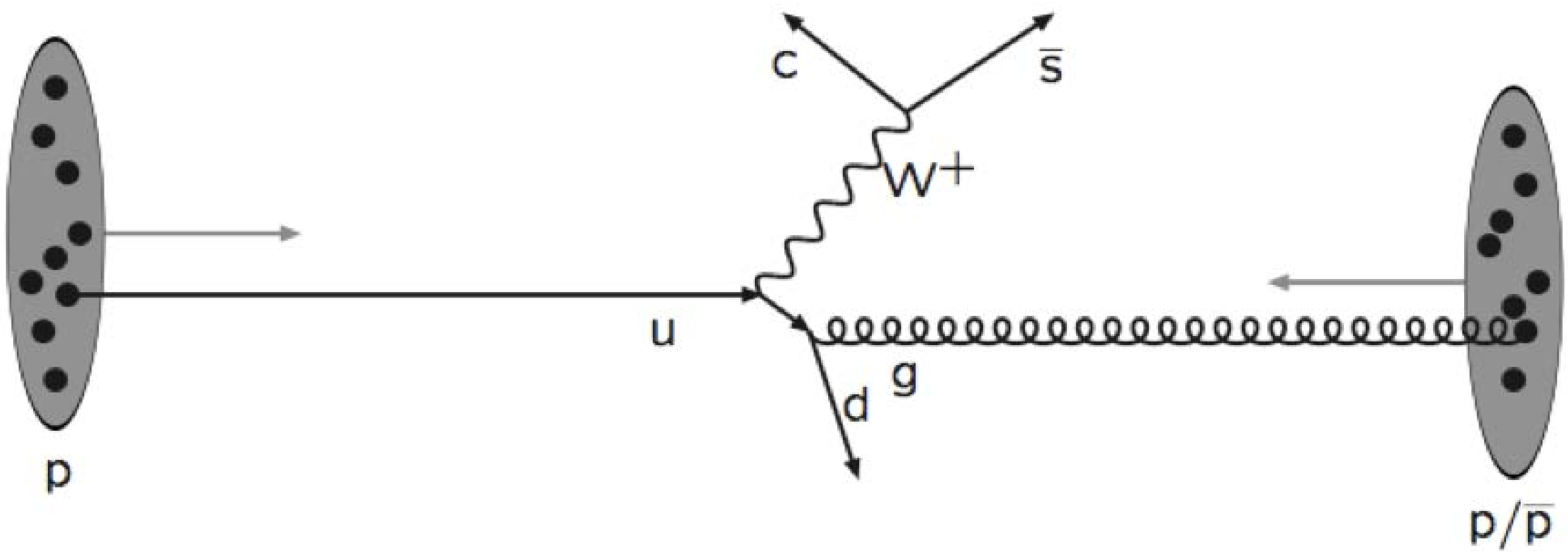
to produce particles with high masses (M_X $\sqrt{\hat{s}}$ large x are needed.

Event structure: hard process



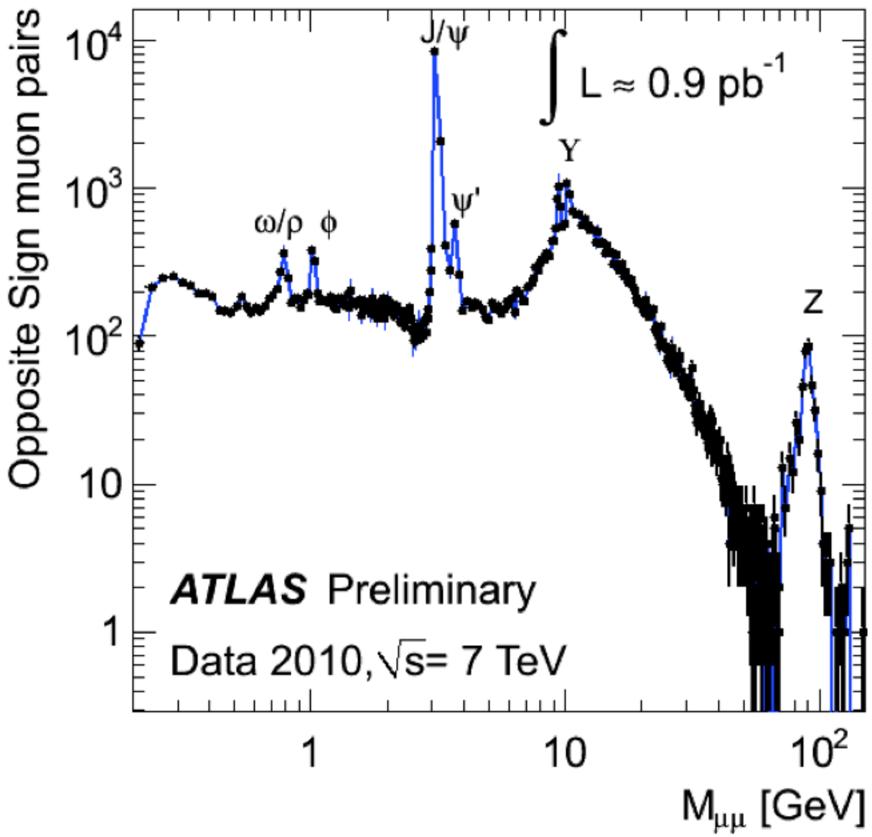
One incoming parton from each of the protons enters the hard process, where then a number of outgoing particles are produced. It is the nature of this process that determines the main characteristics of the event. This is described by a Matrix Element.

An event: Resonances



The hard process may produce a set of short-lived resonances, like the Z0/W± gauge bosons.

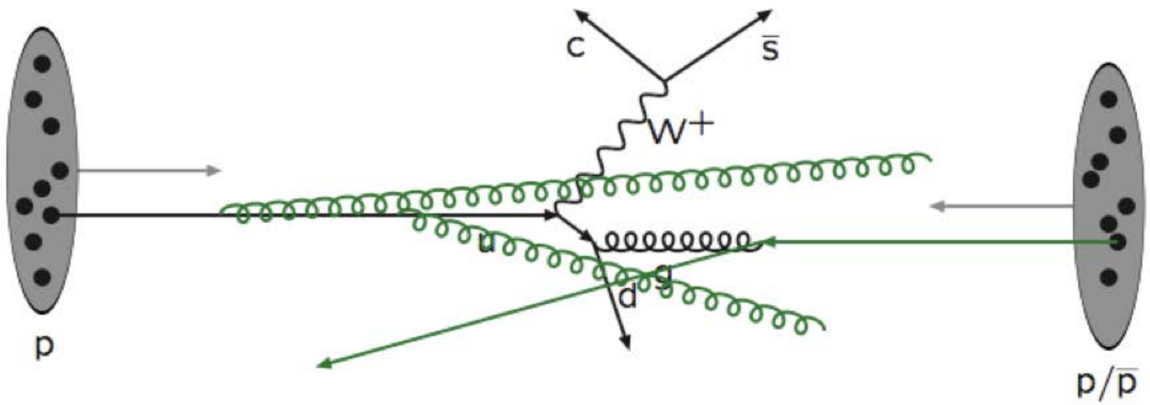
Resonances



Resonances are your friend:

- Well known mass
- Important cross-check for detector performance, esp lepton momentum/energy

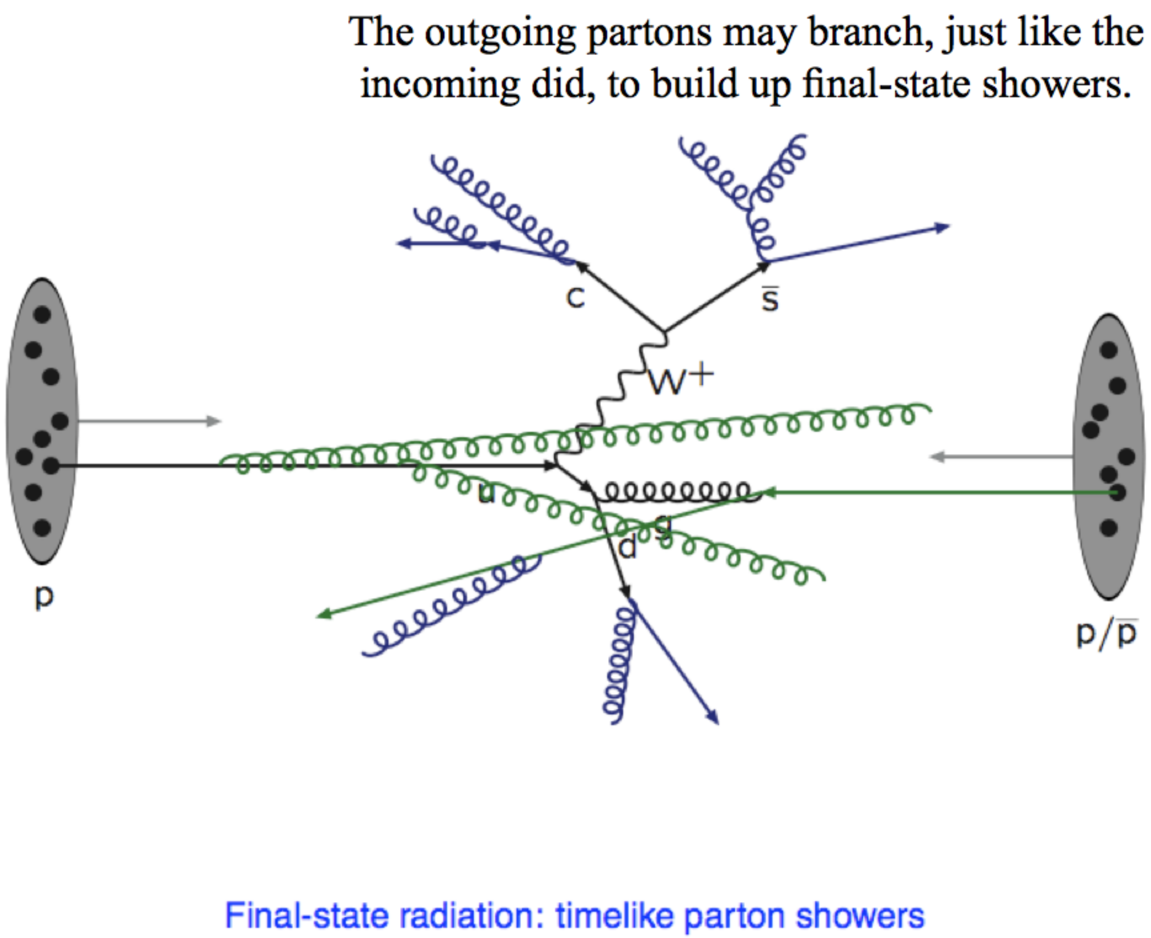
An event: Initial State Radiation



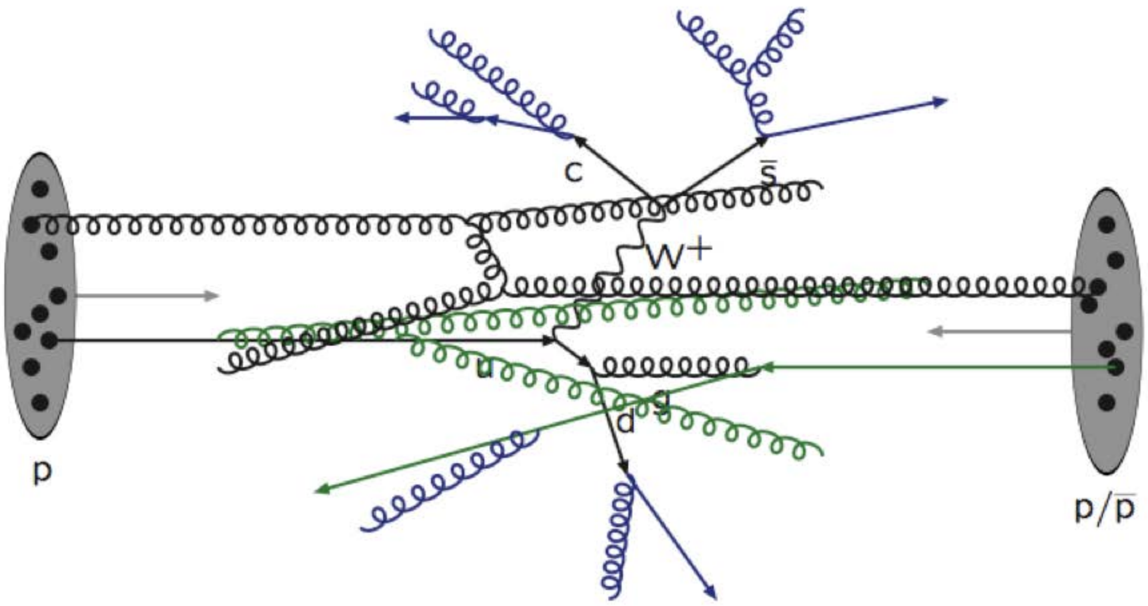
One shower initiator parton from each beam may start-off a sequence of branchings, such as q → qg, which build up an initial-state shower.

Initial-state radiation: spacelike parton showers

An event: Final State Radiation

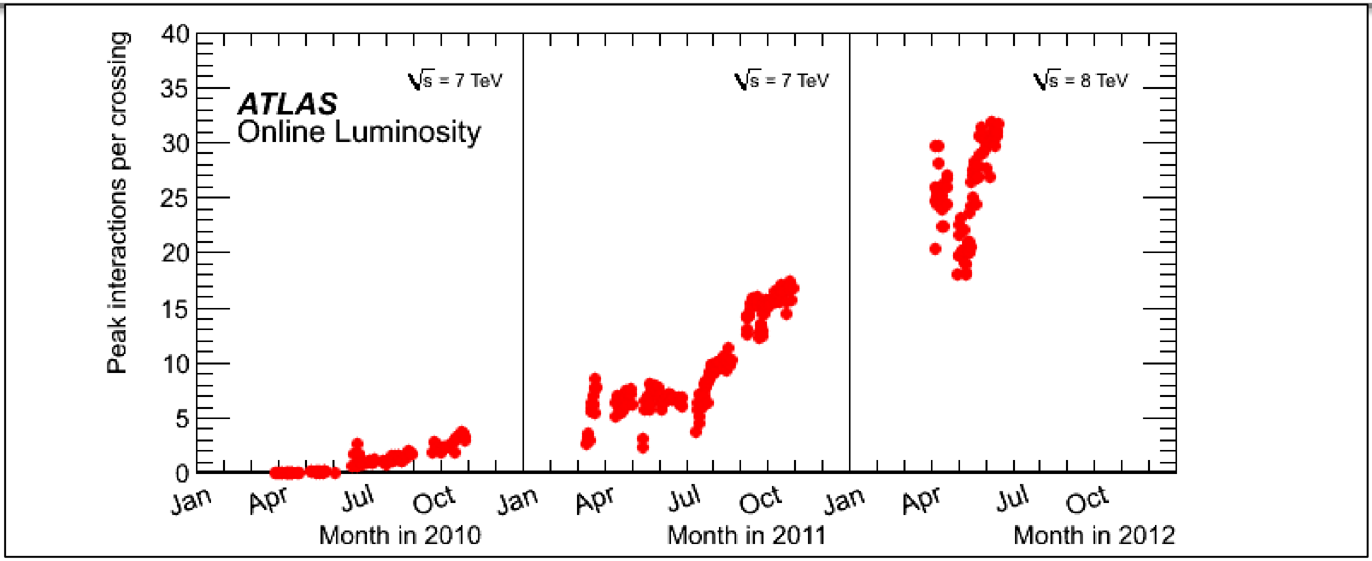


An event: Pile-up

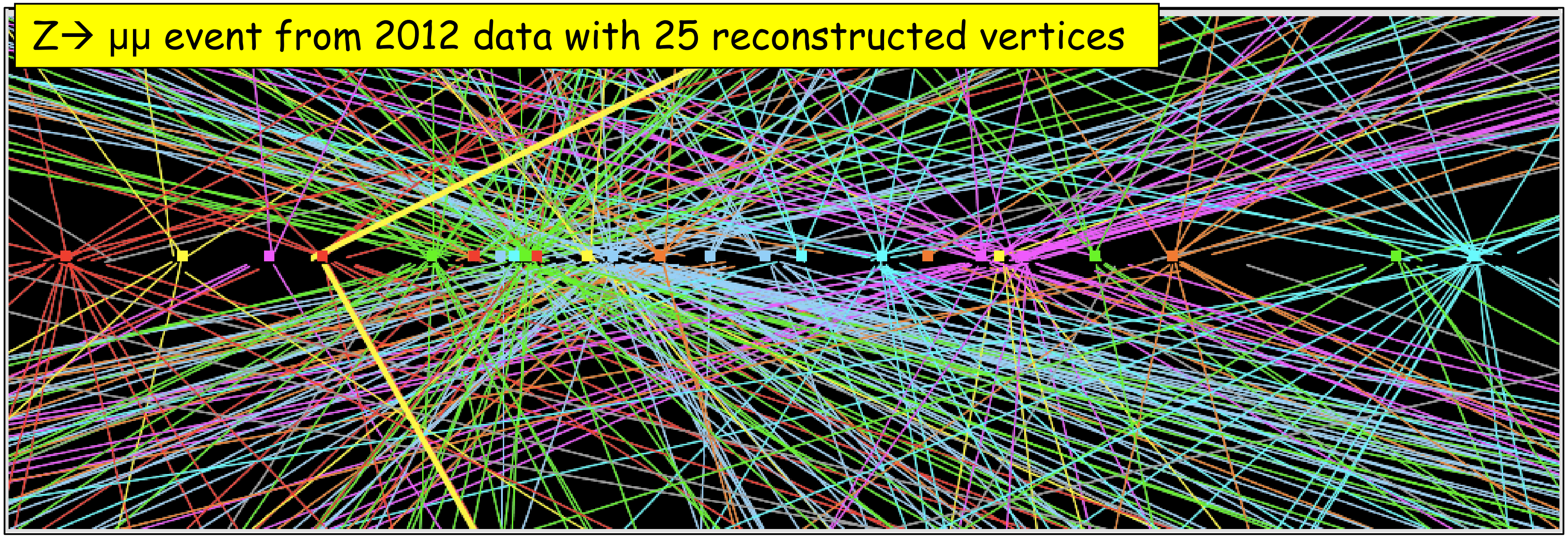


In addition to the hard process considered above, further semi-hard interactions may occur between the other partons of two incoming hadrons.

Pile-up

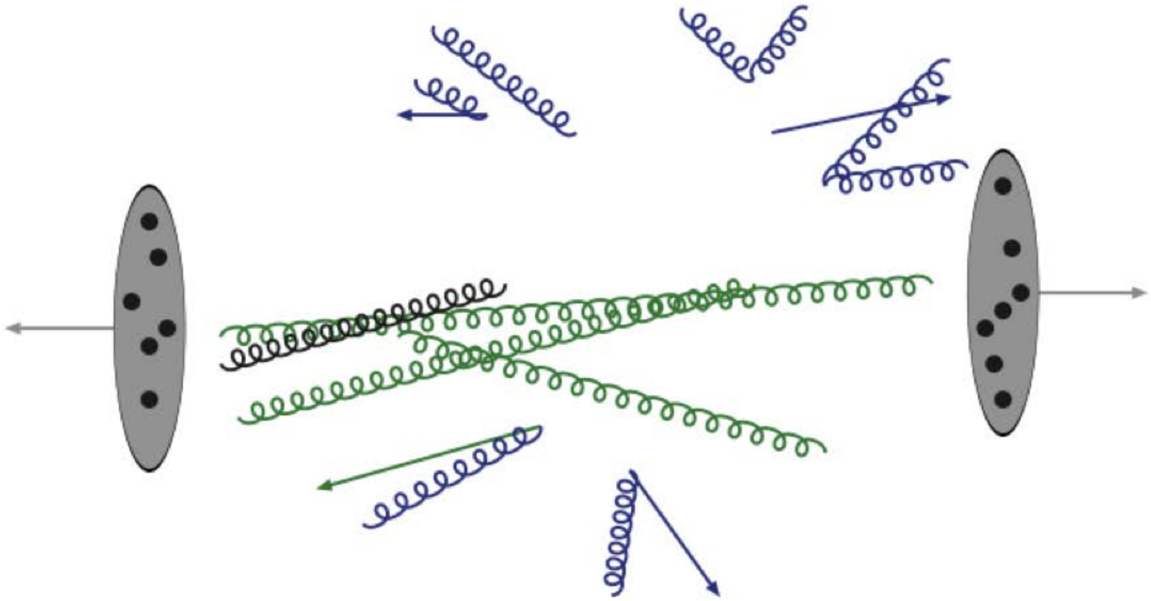


Peak interactions per crossing
40
35
30
25
20
15
10
5
0
ATLAS
Online Luminosity
√s = 7 TeV
√s = 7 TeV
√s = 8 TeV
Jan
Apr
Jul
Oct
Jan
Apr
Jul
Oct
Jan
Apr
Jul
Oct
Month in 2010
Month in 2011
Month in 2012



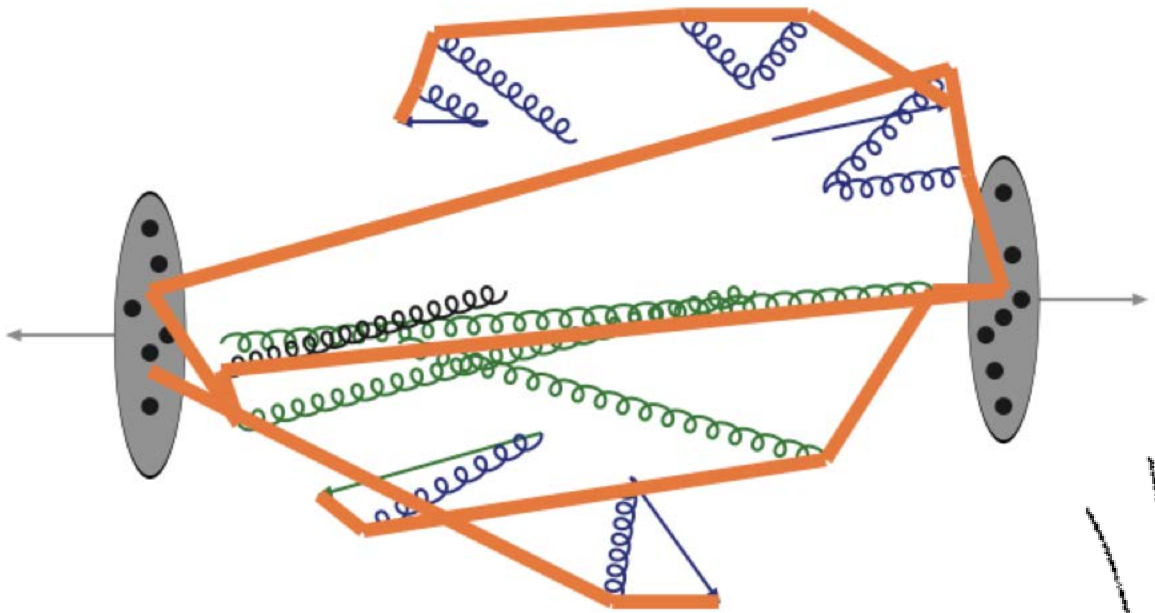
Z→ μμ event from 2012 data with 25 reconstructed vertices

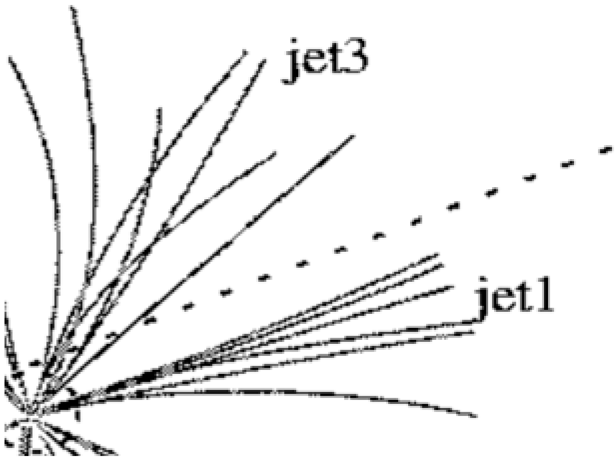
An event: underlying event (min-bias)



- Proton remnants (in most cases coloured!) interact: Underlying event, consist of low pT objects.
- There are events without a hard collision (dependent on pT cutoff) , those are called minimum bias events

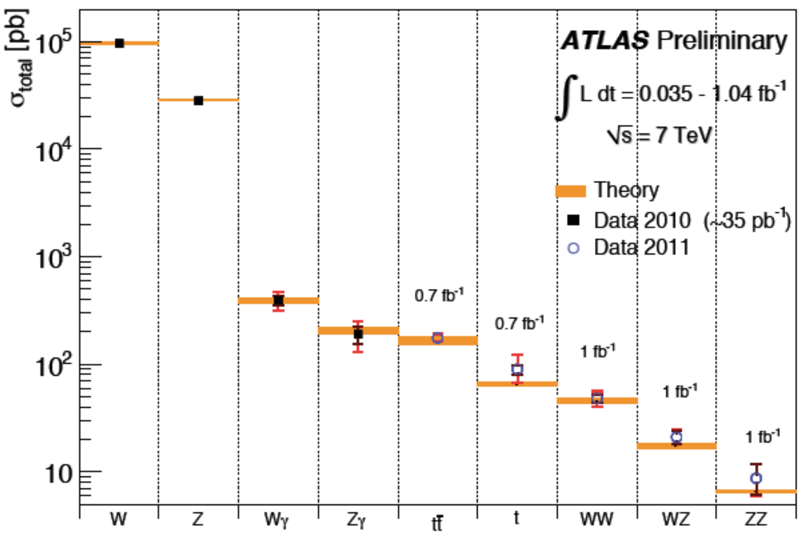
An event: hadronization



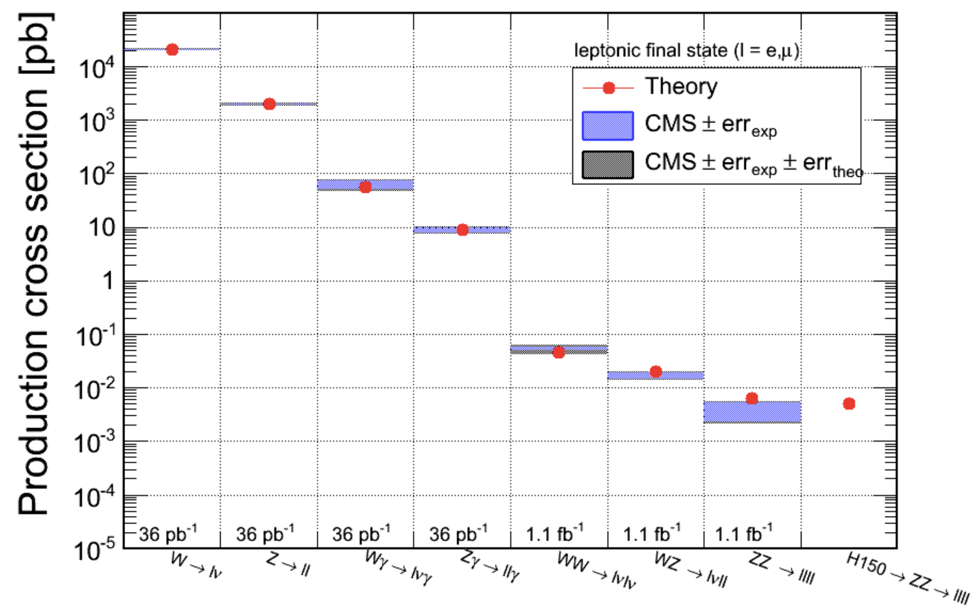


The result of the hadronization is that quark and gluons are not observed as free particles but as Hadrons, and actually in the detector as jets of particles in a narrow cone

Rediscovery of SM



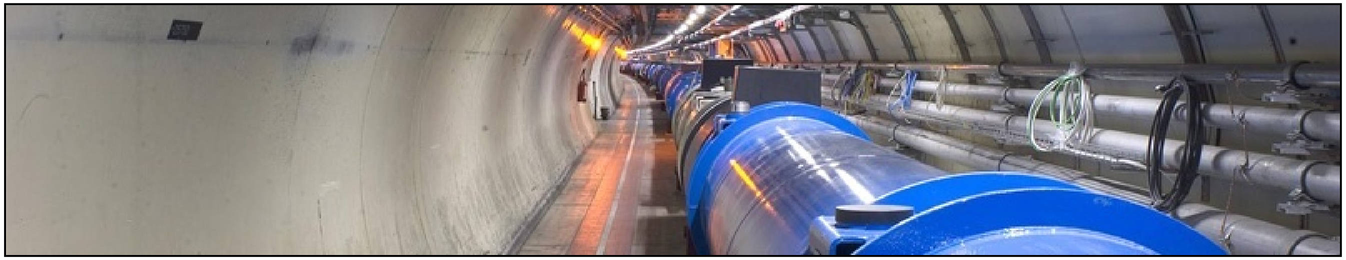
Early 2011: 1fb^{-1}



W/Z processes

- Consistent with SM
- Background for Higgs search
- Important calibration tool

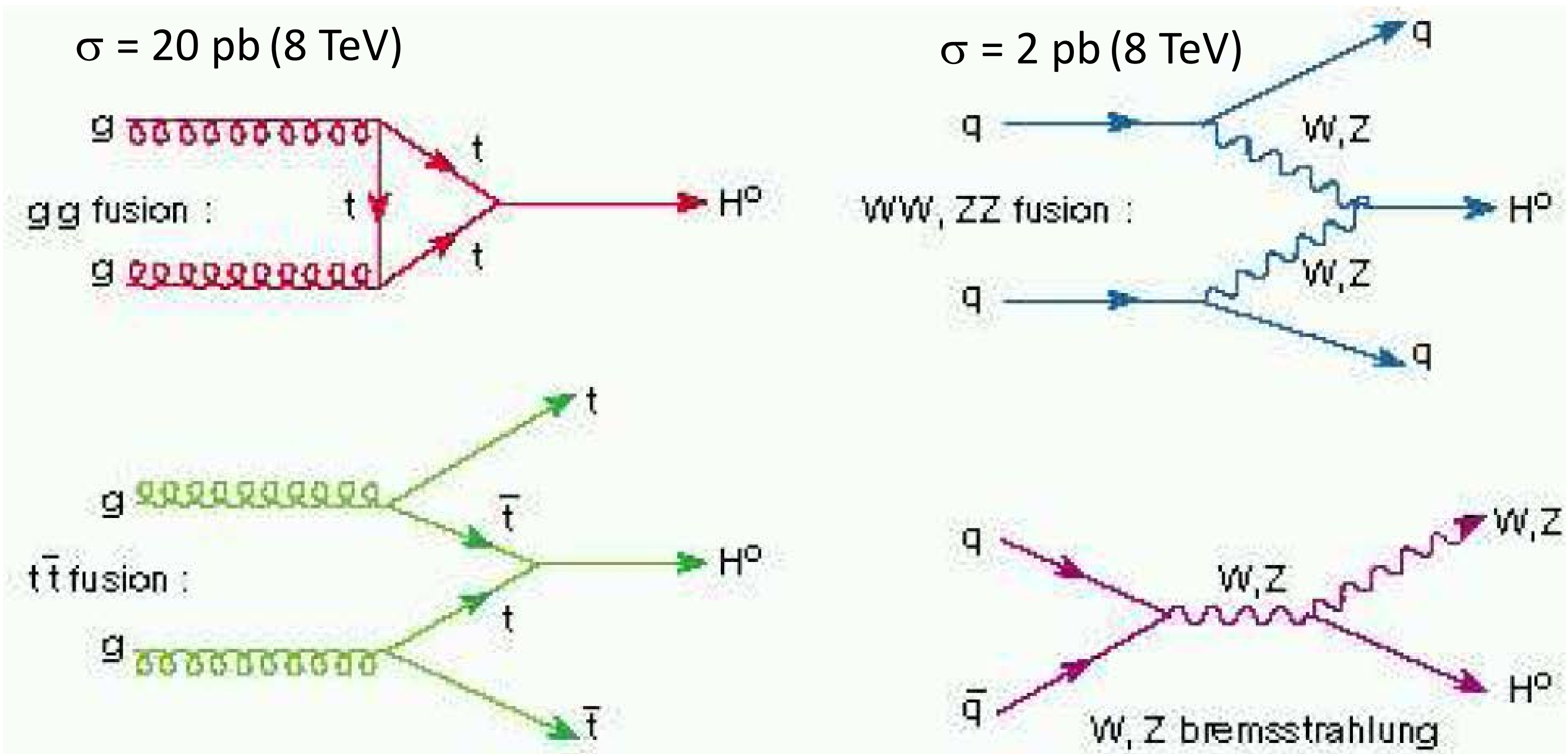
The discovery of the Higgs boson



Higgs production at the LHC

σ = 20 pb (8 TeV)

σ = 2 pb (8 TeV)



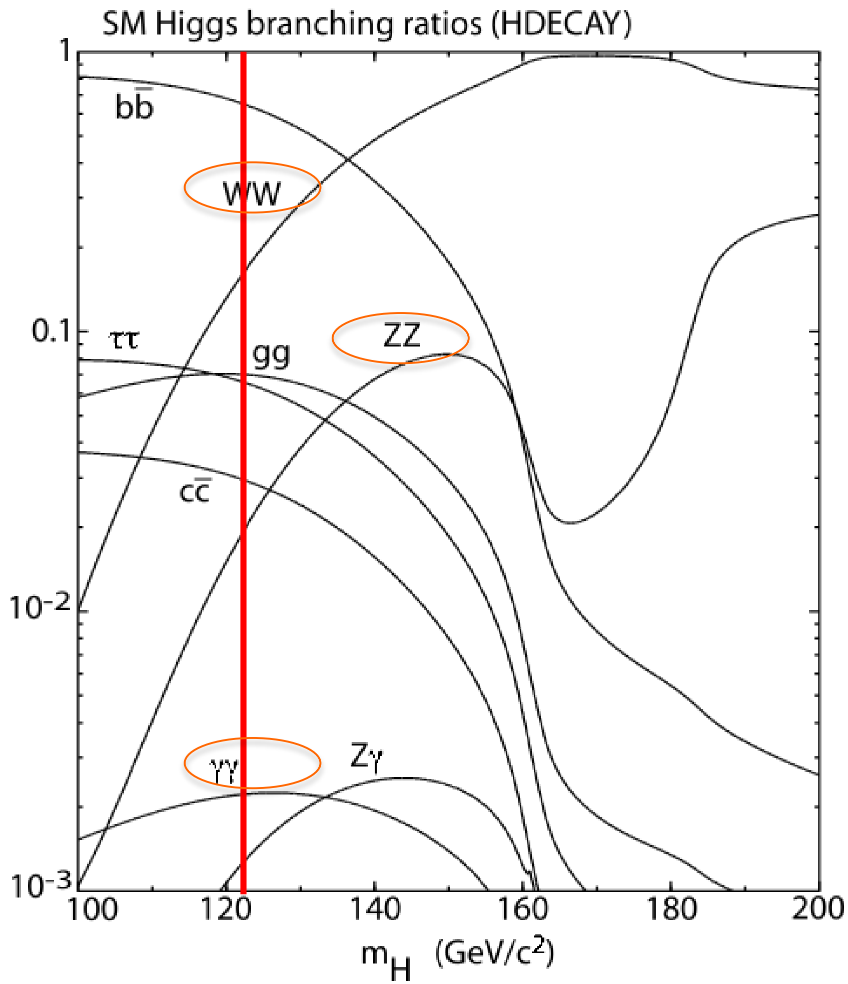
σ = 0.13 pb (8 TeV)

σ = 1 pb (8 TeV)

1 fb^{-1}: 23 kHiggs

1

SM Higgs Decay Modes



- At low m_h, mostly bb, ττ, but also cc and gg can be important.
- At large m_h, H➔VV
- h➔gg, h➔γγ, h➔Zγ generated at one loop, but due to heavy particles in loop ➔relevant contributions

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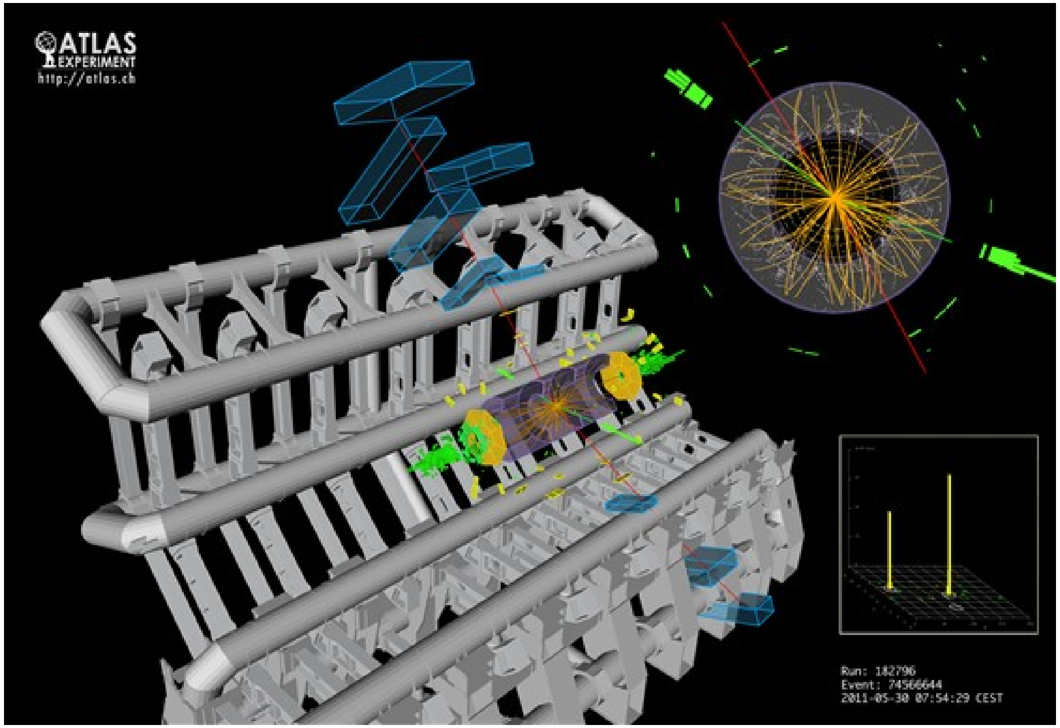
H → ZZ

- Very rare process, especially with both Z particles decaying to leptons (Br 3 x 10^{-5})
  - but very clean, and with good mass resolution



Selection and backgrounds

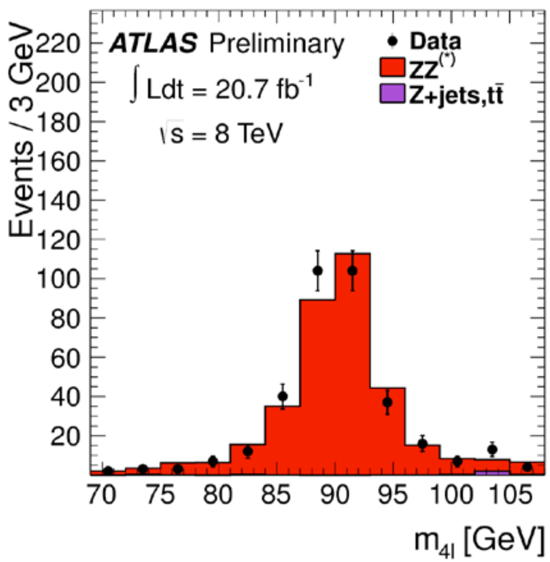
Selection: 4 leptons, matching, PT (20, 20, 7, 7 GeV), isolated

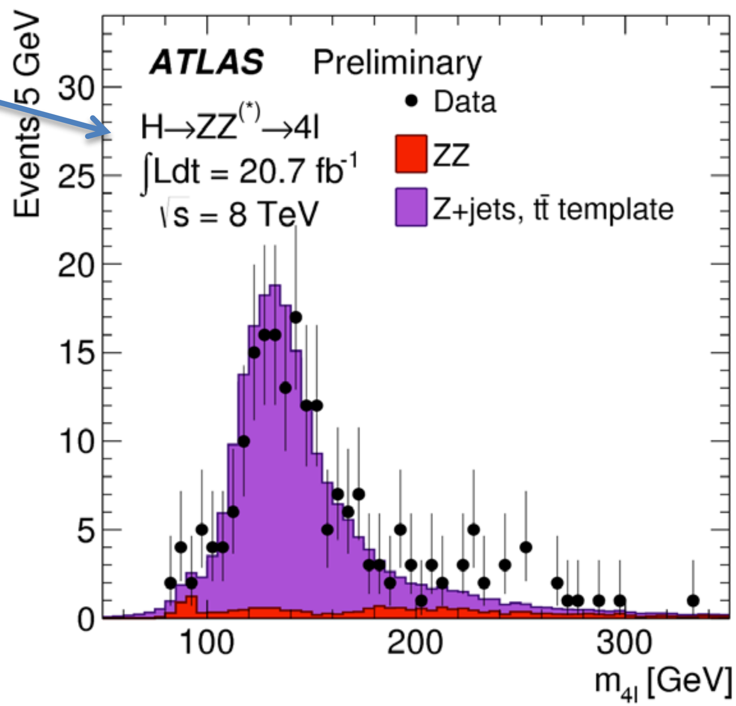
Backgrounds:

•Real ZZ: irreducible but peak at higher mass

•Z + jets, study in data with control plots (reverse lepton isolation

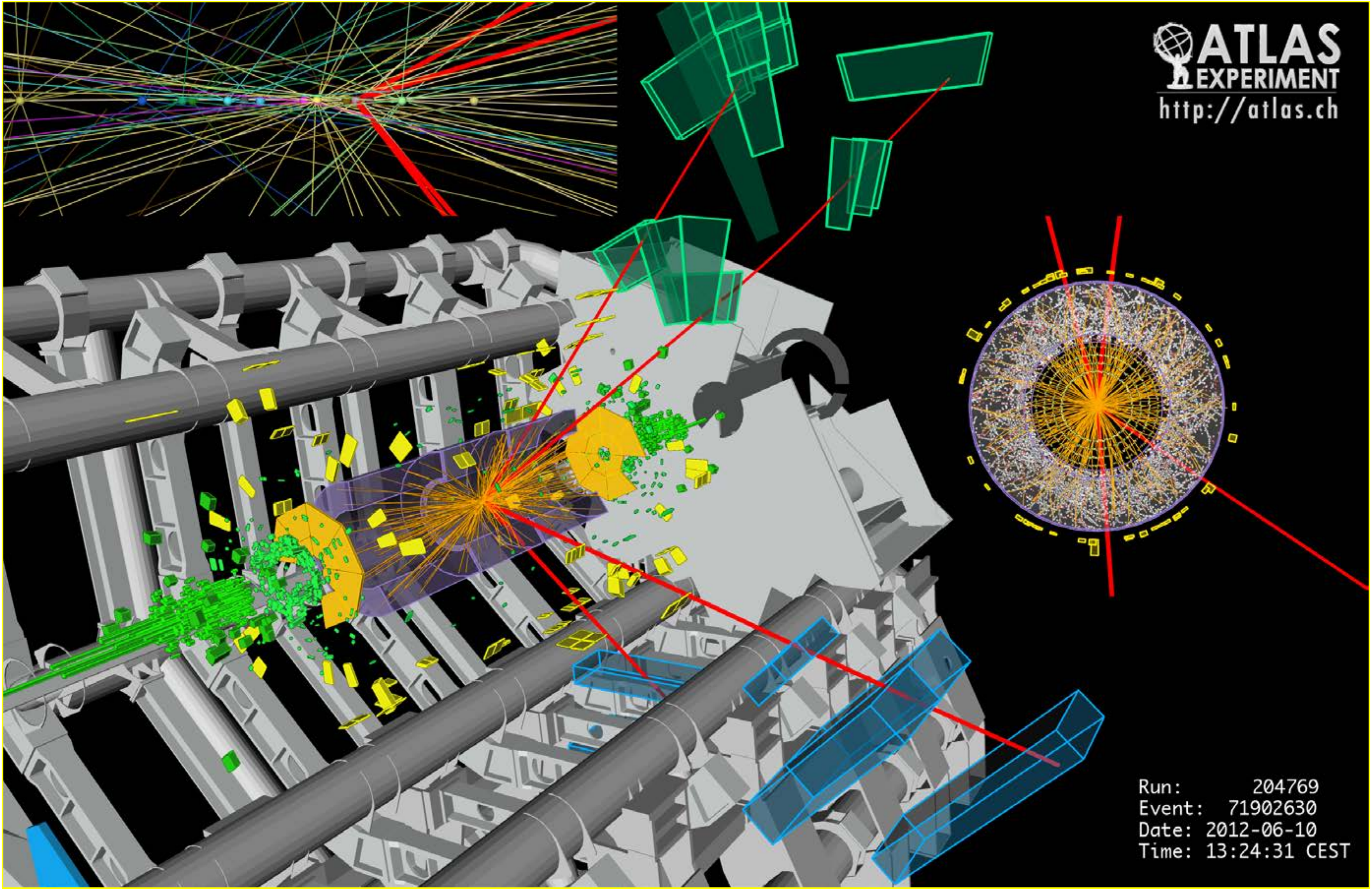
•Z→4 leptons, no real background, but useful to study efficiencies



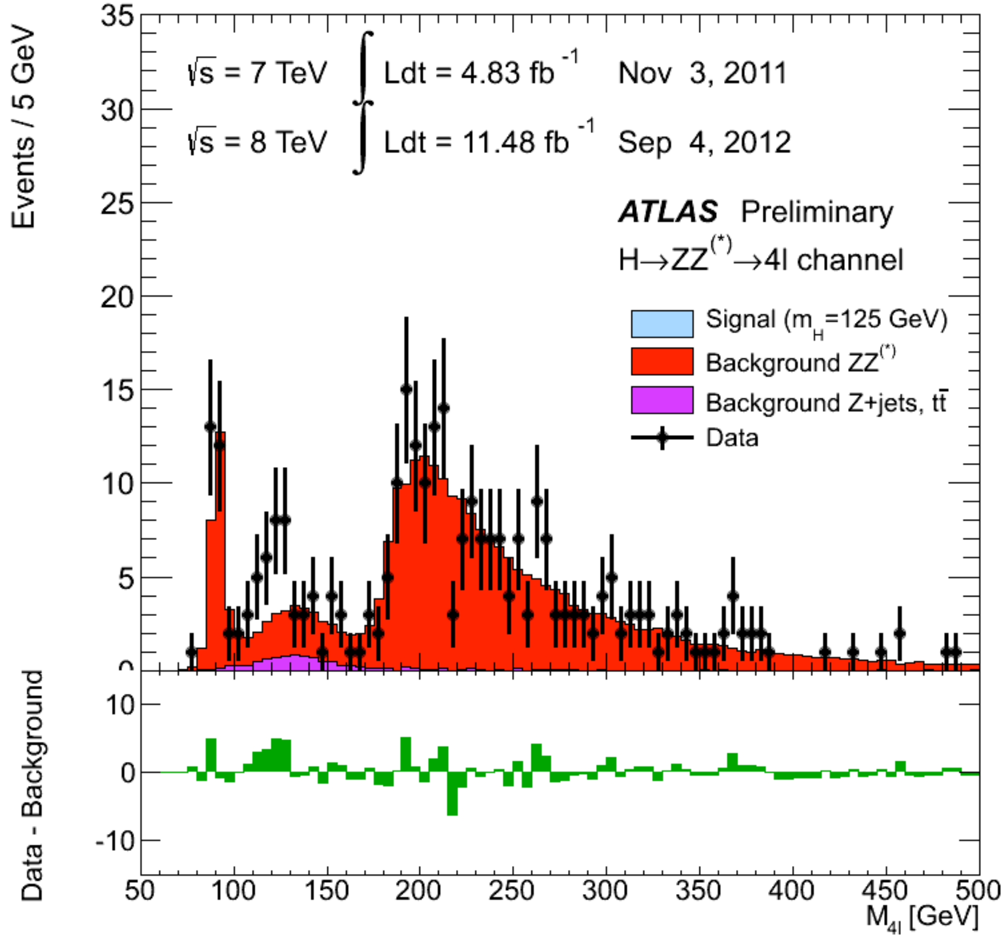


4μ candidate with $m_{4\mu}$= 125.1 GeV

p_T (muons)= 36.1, 47.5, 26.4, 71 .7GeV m_{12}= 86.3 GeV, m_{34}= 31.6 GeV
15 reconstructed vertices

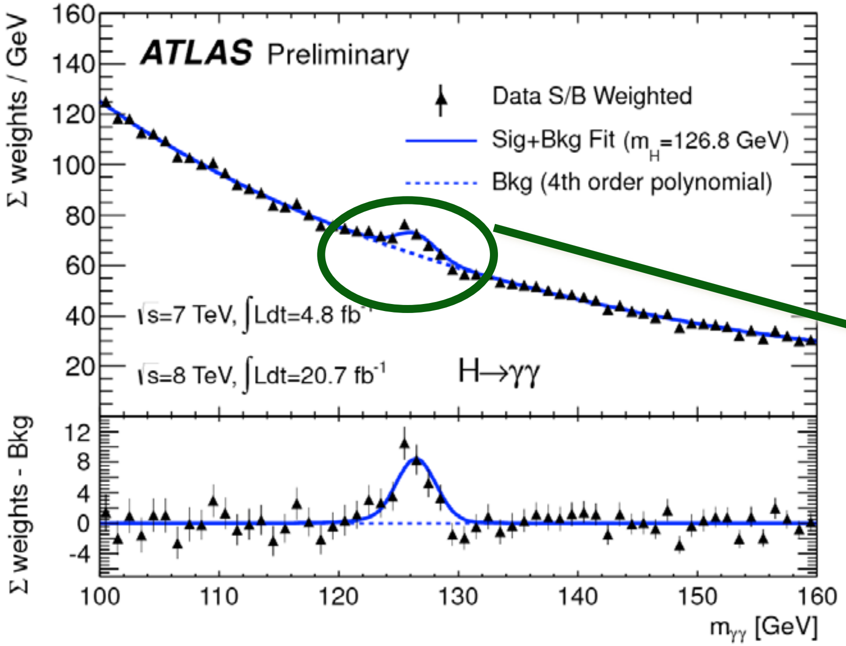


History of the Signal



H → γγ

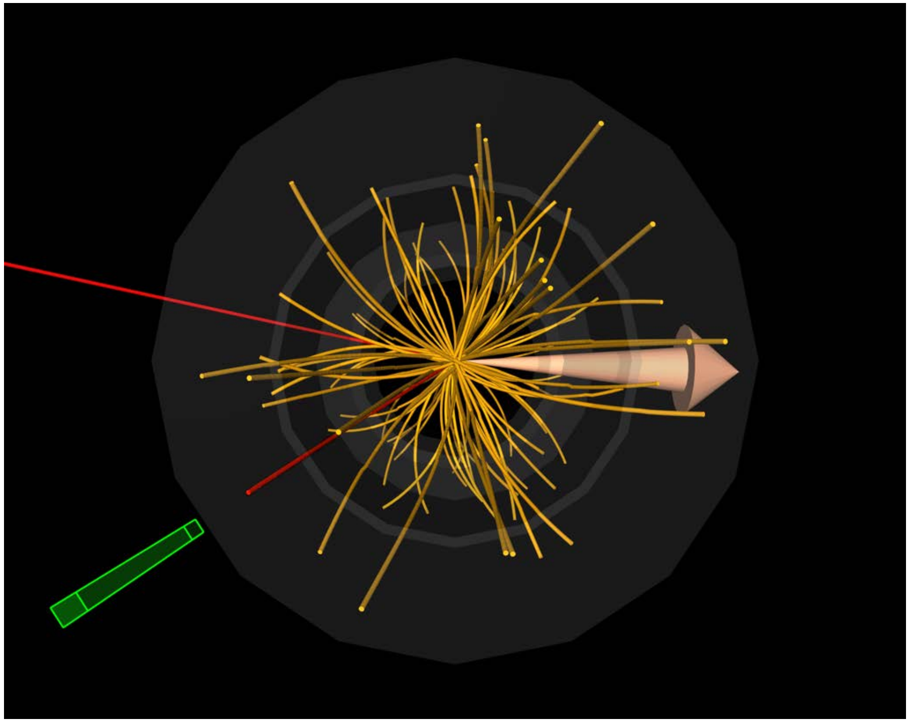
- Requires excellent discrimination between single high-energy photons from hadrons
  - but offers good energy resolution



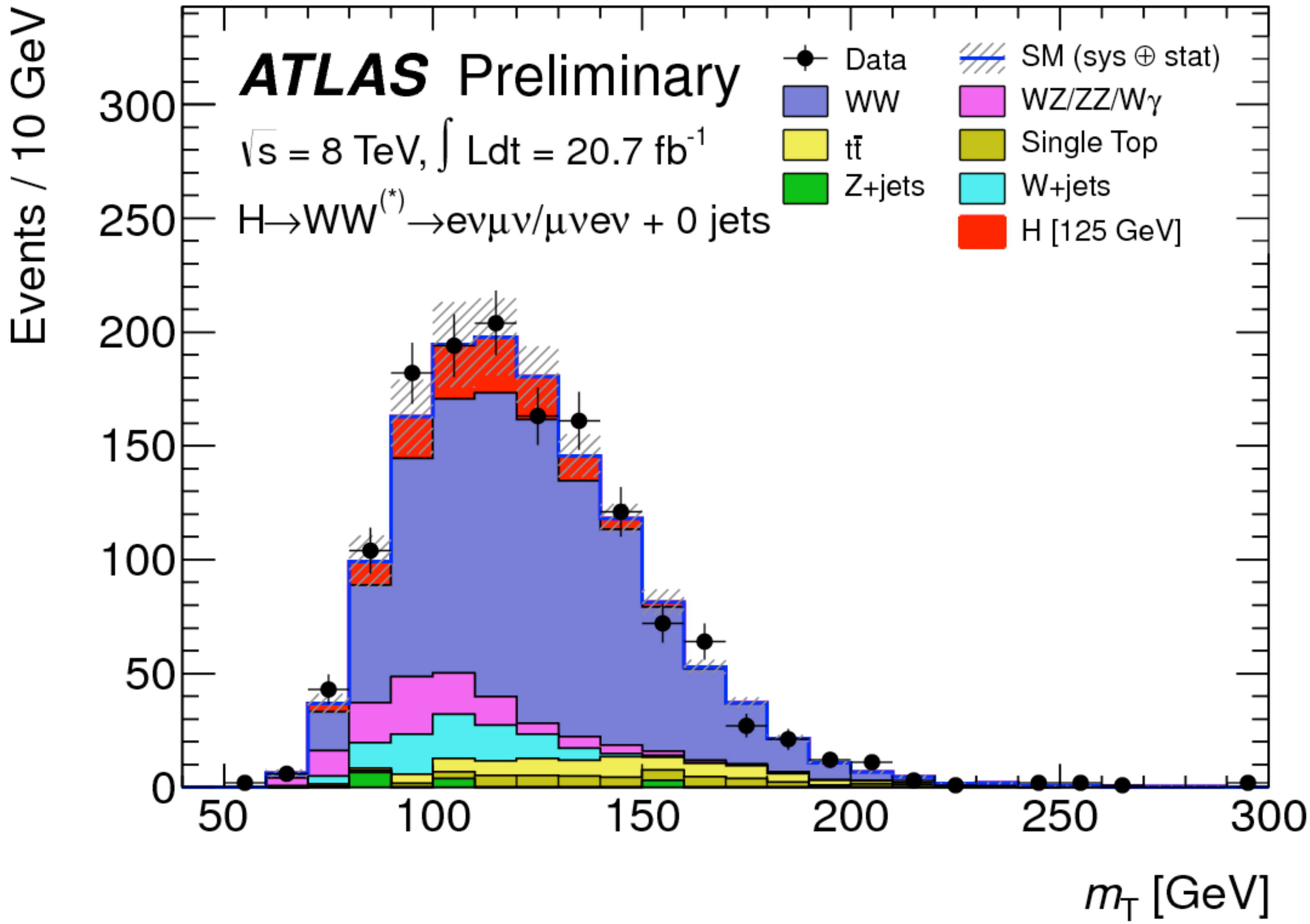
Looking for small excess on top of large (but smooth) background

$H \rightarrow W^+W^-$

- Relatively large event rate, but leptonic W boson decays lead to unobserved neutrinos
  - cannot reconstruct mass of a WW system



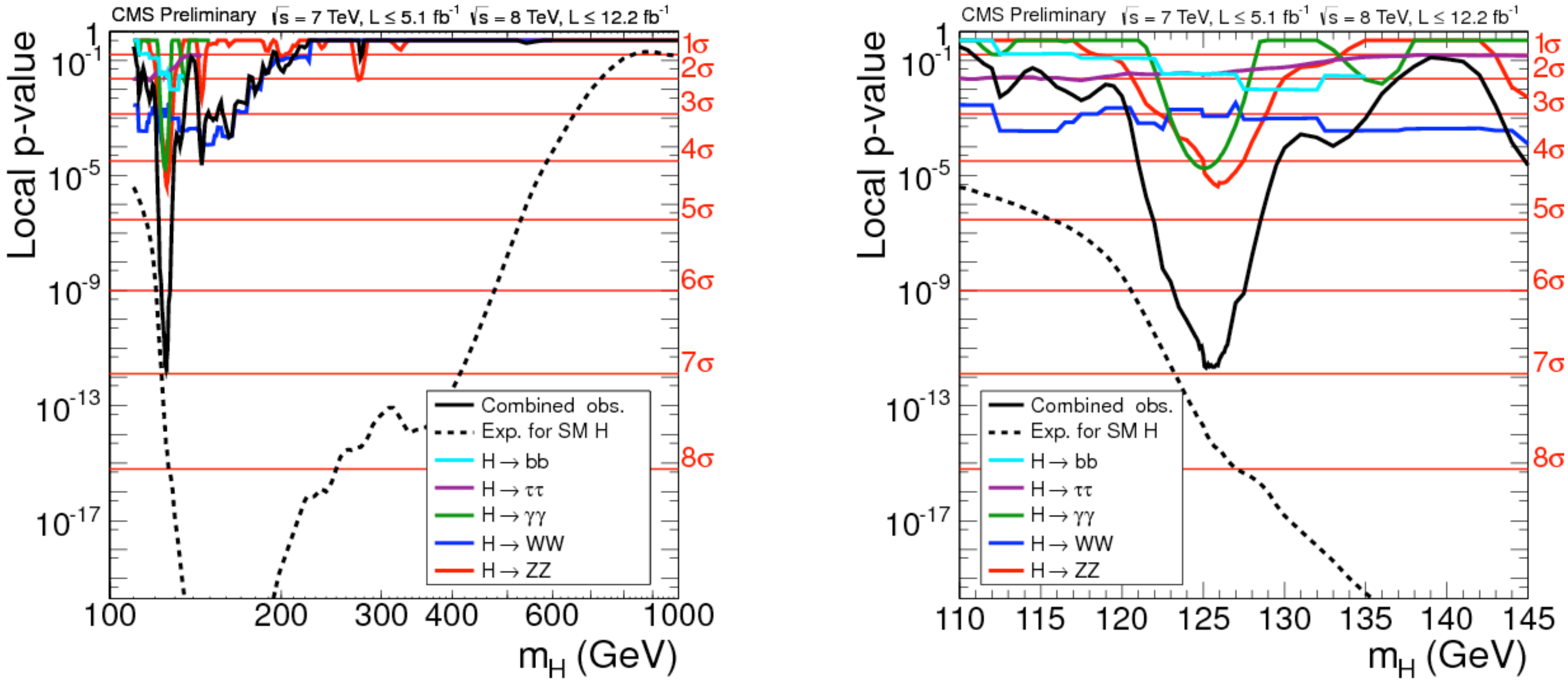
$H \rightarrow W^+W^-$



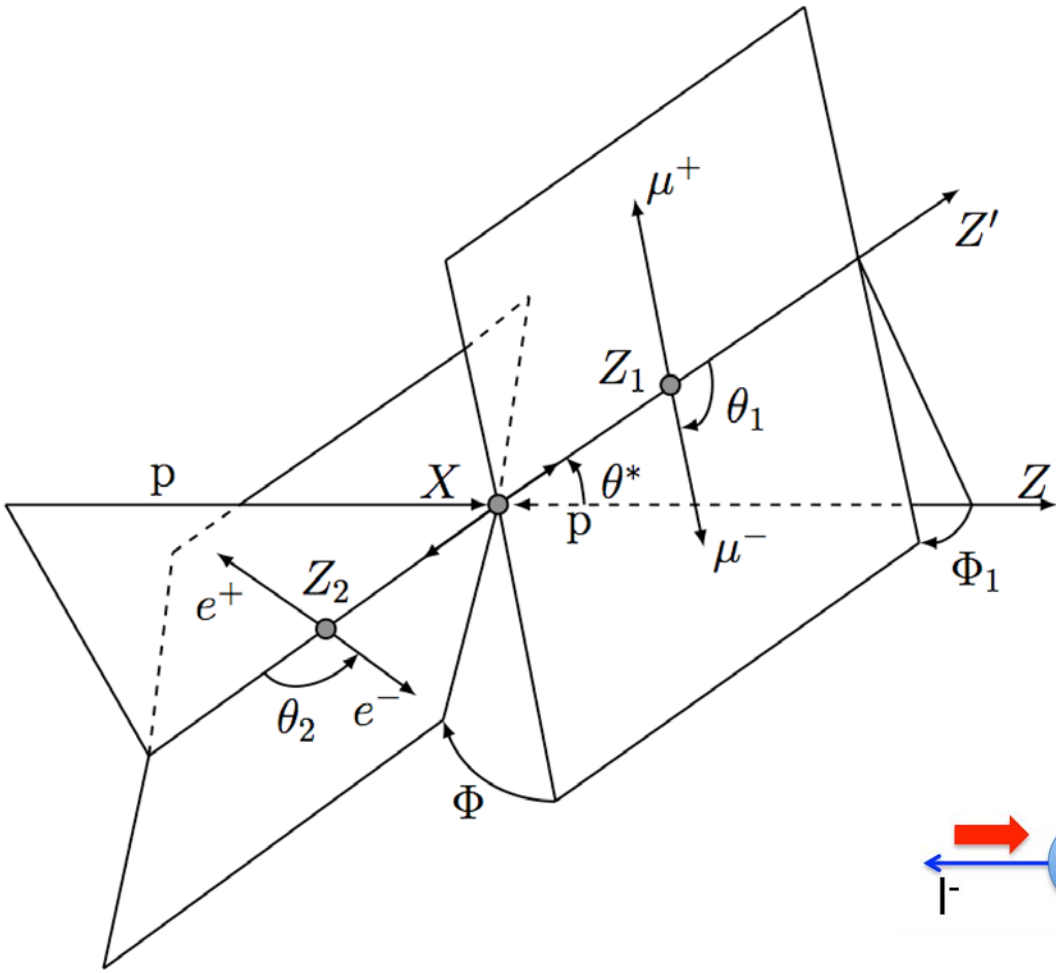
LHC discovery approach

- Use frequentist statistics formalism to construct statements with precisely defined meanings
  - **P-value of Null hypothesis**: probability that nature without Higgs would give observed result, ***or more extreme***.
  - **Probability defined as fraction of future repeated experiments**
  - Note that statements is restricted to P(data|hypo)
  - You can also formulate P(hypo|data), e.g. “probability that Higgs exists given LHC data”, but such statements cannot be formulated without using P(hypo) as ingredient (what is your belief in the Higgs boson prior to the experiment). It is difficult to sell this as ‘objective summary’ of your data.
- Note that the ‘or more extreme’ entails a substantial amount of fine print, can mean e.g.
  1. Or more extreme ‘at a given value of m_H’
  2. Or more extreme ‘for any m_H’?
  3. Or more extreme ‘for any m_H that is reasonably allowed’

Combining it all



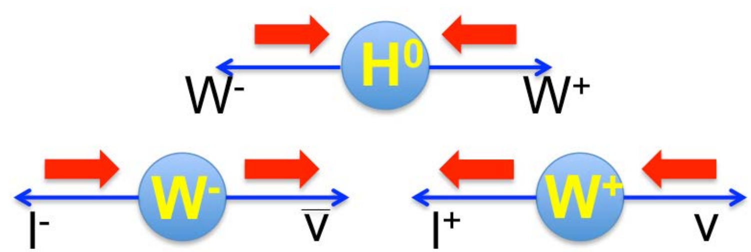
Spin and parity measurement



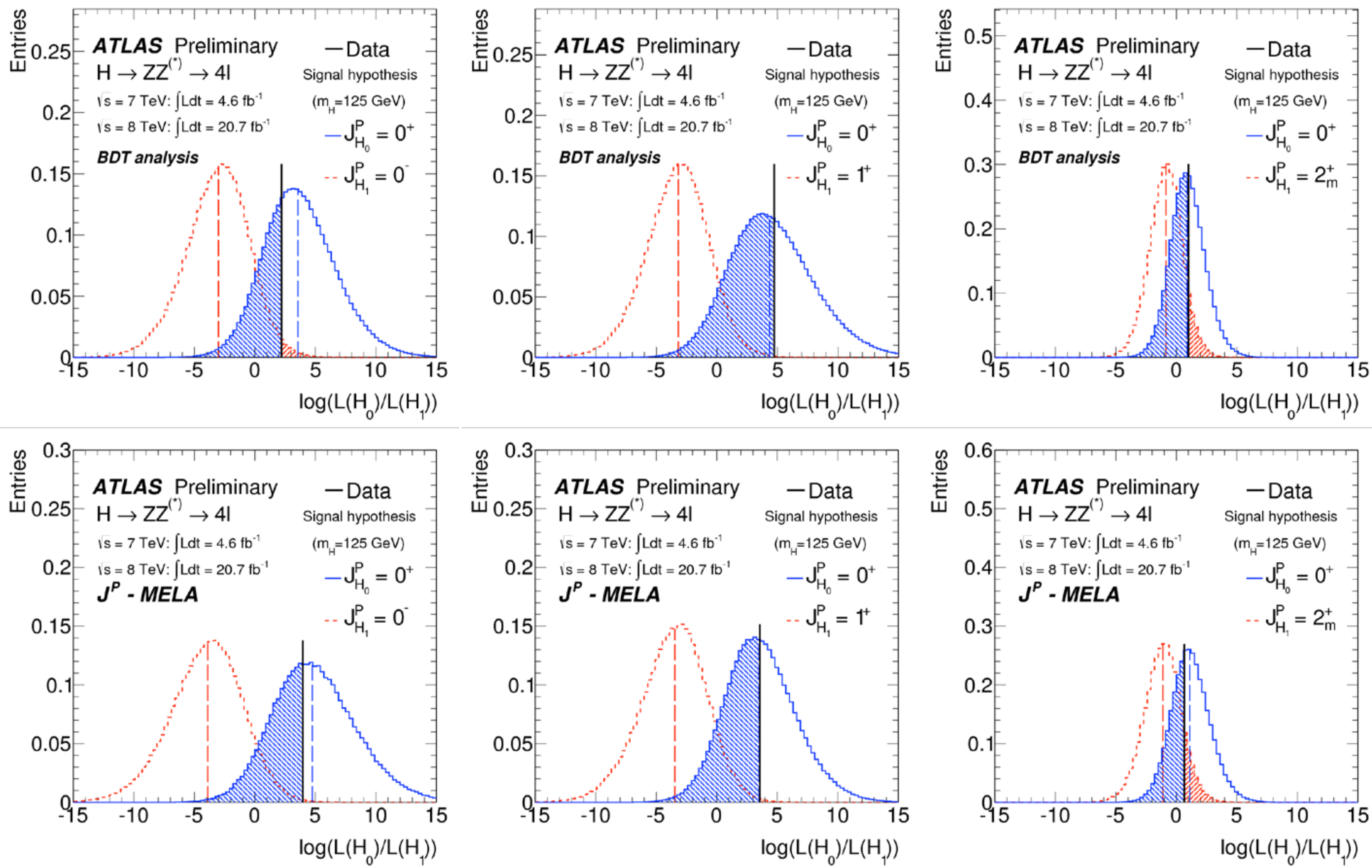
SM Higgs is spin 0 and positive parity

Decay angles are sensitive to the spin and parity of the Higgs boson

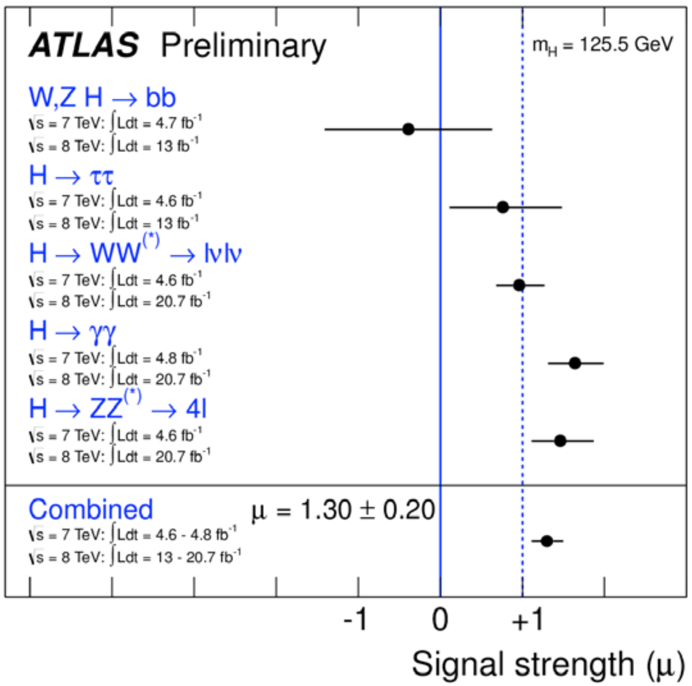
These are input to a multivariate analysis (BDT or NN)

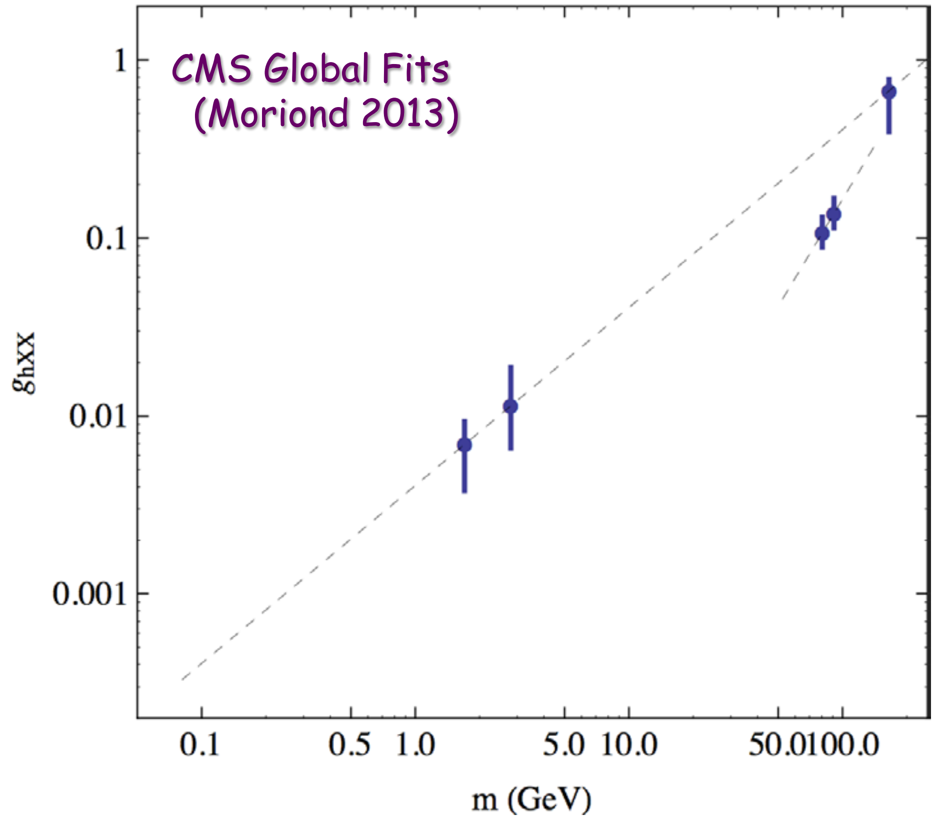


Spin-CP results (ZZ)



Coupling measurements





Outlook and conclusions

Conclusions

- The LHC is a spectacular success
- Higgs is just one of many topics
- We have found a Higgs boson with a mass of 125 GeV

Outlook

- 2013-2014: shutdown
- 2015+:13 TeV run, 10x more data
- Beginning of Higgs precision phyiscs.