Experimentation in High Energy Physics

Wei-Ming Yao (LBNL)

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Outline

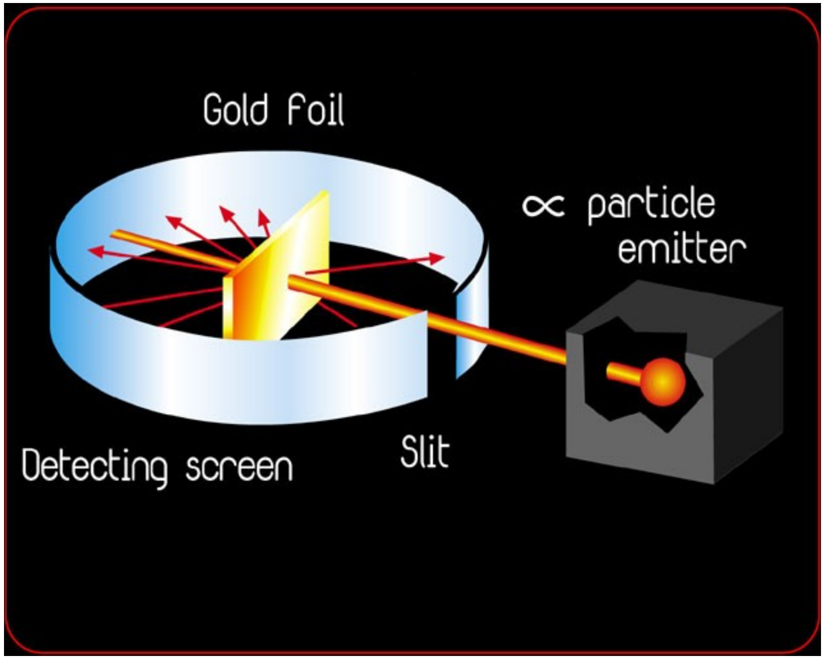
- Part I:
  - Introduction
  - Case for LHC experiments
  - Detectors
  - Experimental challenges
  - Detector performances
- Part II:
  - Re-discovery Standard Module physics
  - Measuring the Higgs boson properties
  - Future Prospects
  - Conclusion

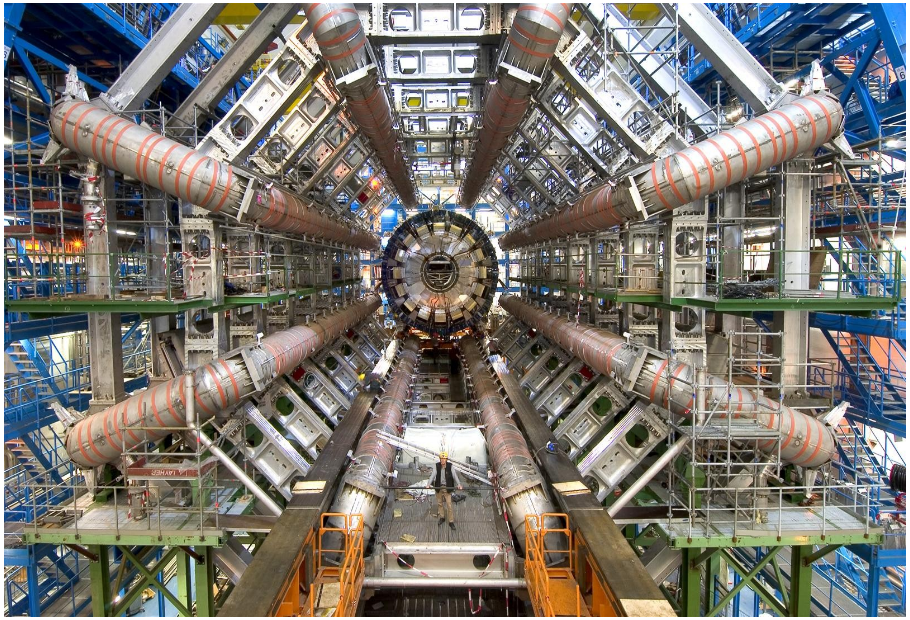
Disclaim

- It would not be possible to cover all aspects of experimentation in high energy physics in two one-hour lectures.
- HEP remains innovative and diverse and I will focus on some basics for the hadron colliders and recent LHC physics results.
- There are many interesting results and talks that can be found at
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
  - http://www.snowmass2013.org/tiki-index.php
  - http://eps-hep2013.eu/
  - http://www-conf.slac.stanford.edu/lp13/
  - http://projects.fnal.gov/hcpss/hcpss12/
- All the errors are mine.

Introduction

- About 100 years ago Ernest Rutherford was experimenting with alpha particles, bombarding gold foils and discovered the nuclear structure of atoms.
- Today's experimentation in high energy physics requires world-wide collaboration by an increasing need of sensitivity to rare phenomena and complicated physics signatures.

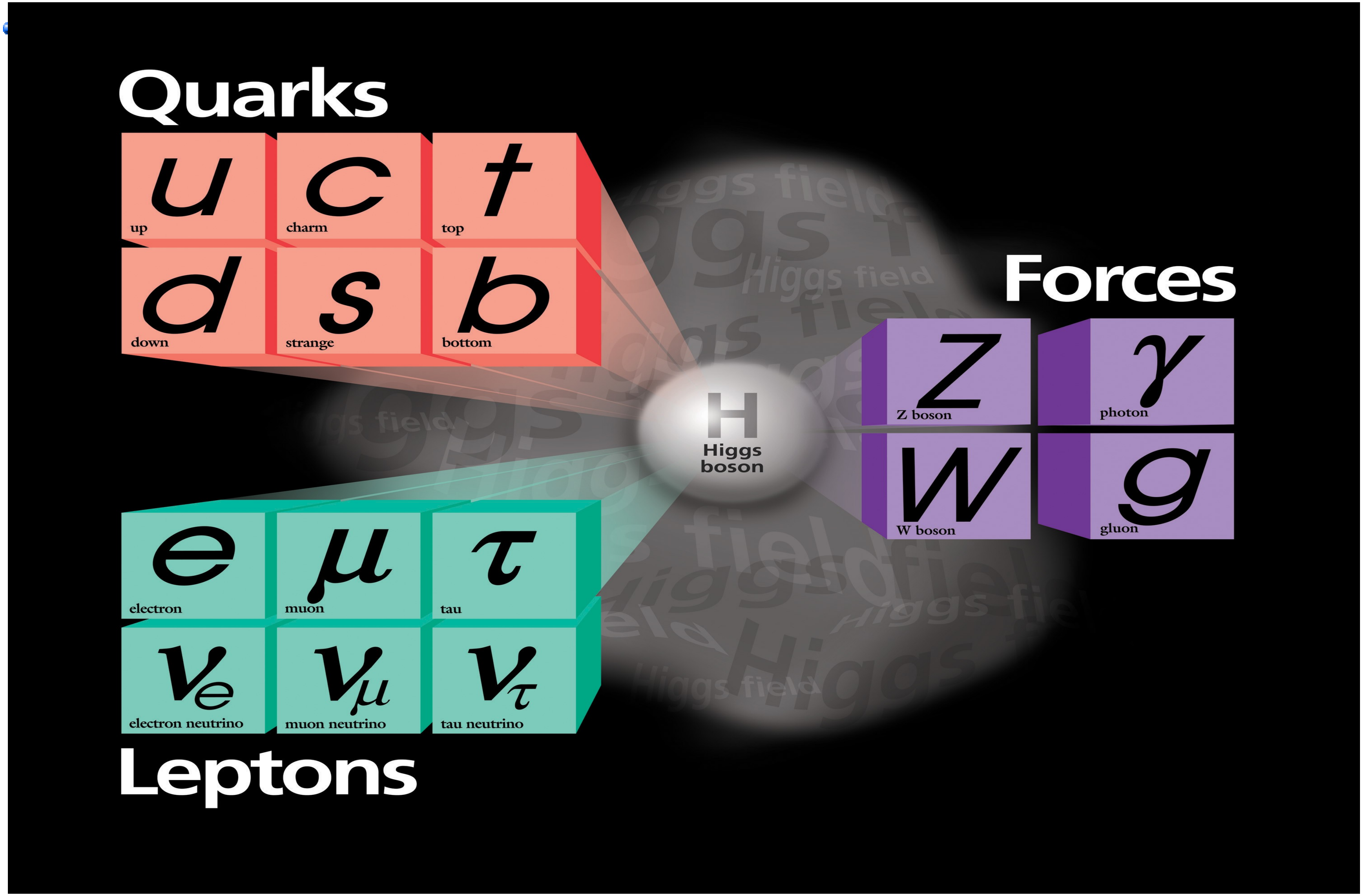




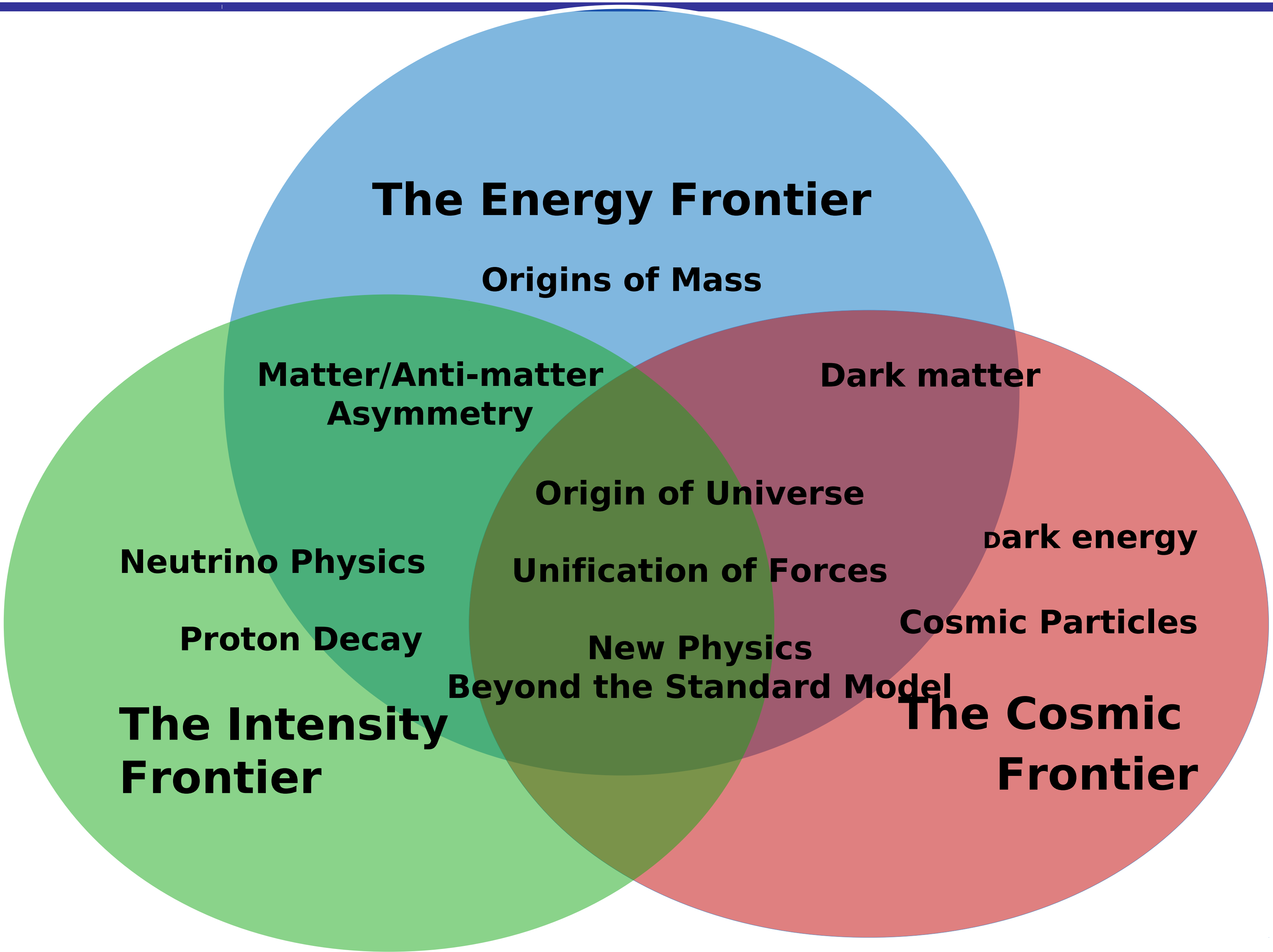
Particle Physics

- Particle physics is the study of the basic elements of matter and the force acting among them. It aims to determine the fundamental laws that control the physical universe.
- Enormous progress made in the last 40 years and the discovery of the Higgs boson last July completes the particle spectrum of the standard model. Now the theory is complete and has been put to the test experimentally with great precision.
- Higgs boson breaks the electroweak symmetry and gives particle mass through the interaction of Higgs field.
- The motivation of physics beyond SM is remaining:
  - It does not account for gravity and unify the forces.
  - It does not describe dark universe(dark matter, energy), nor baryon asymmetry, and flavors of lepton and quarks...

The Standard Model

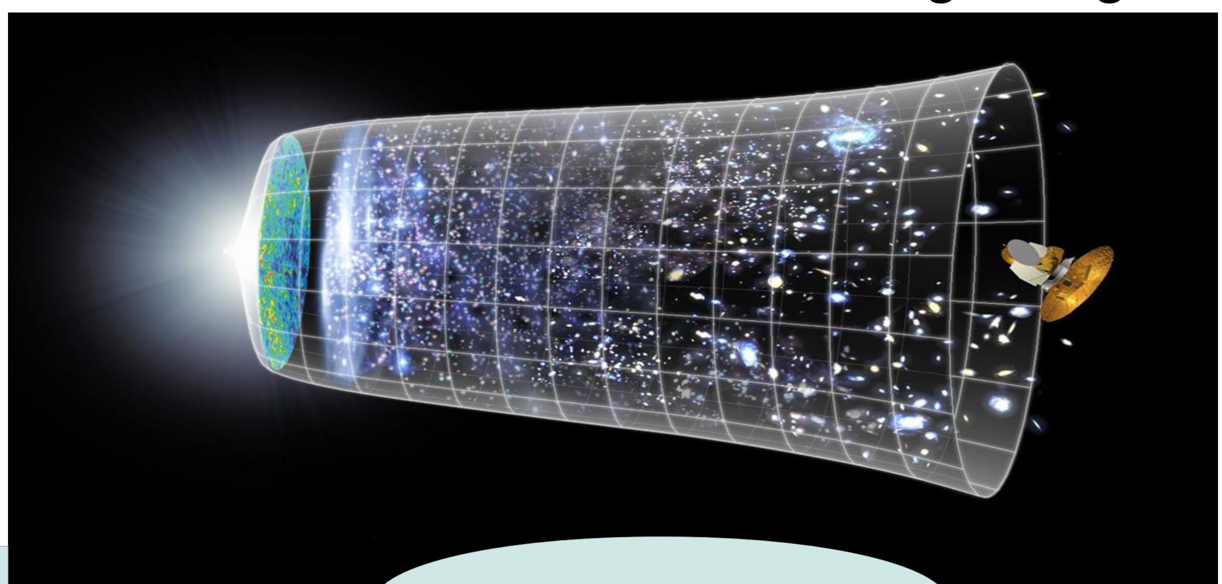


HEP Landscape



The LHC physics case: The Terascale

- The Standard model would fail at high energy without the Higgs particle or other new physics.
- Based on the existing data and general theoretical insights the new physics was expected to manifest at TeV scale.
- Accessible at the LHC for the first time and recreates the conditions one billionth of a second after Big Bang.



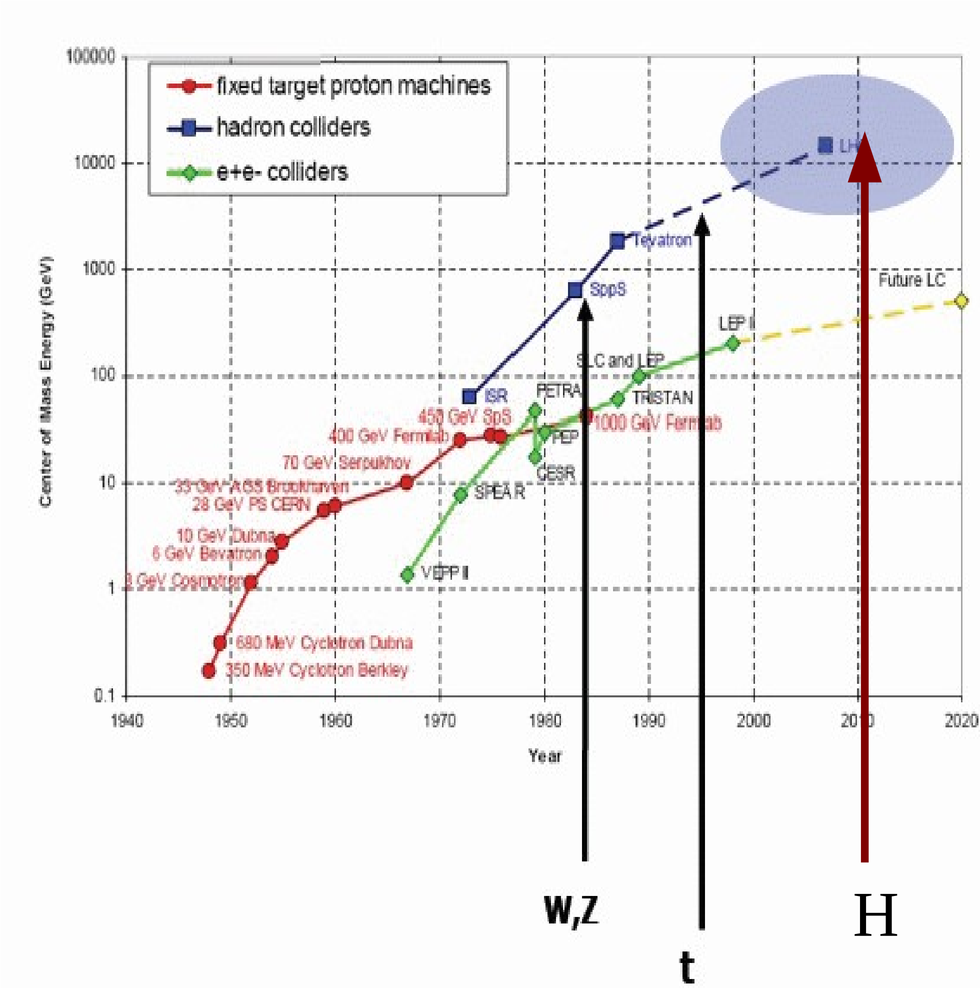
Big Bang

13.7 Billion years

Today

Probing Particles at High Energies

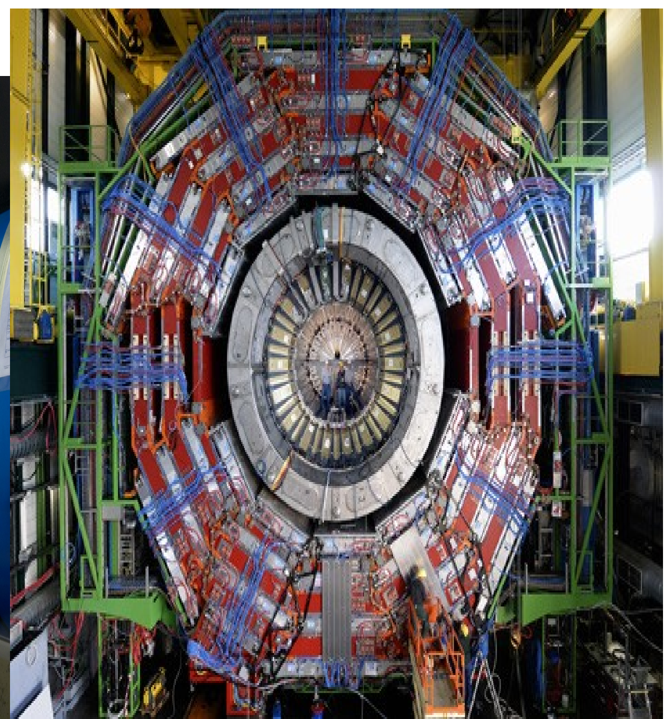
- The accelerator is the basic tool of particle physics,which allows us to create the particle collision that we want to study.
- The kinetic energy of the beam particles is transformed in the mass of particles produced in the collision based on $E=mc^2$.
- Heavy particles need a large accelerator to be created.



Hadron colliders have their advantages when coming to exploration of unknown territory—discovery machines(W,Z,t,H)

What the experiment requires

- Accelerator: accelerating particles to high energies for collisions.
- Detector: gigantic instruments to record the particles produced.
- Computers: to collect, store, distribute, analysis lots of data.
- People: only collaboration of thousands of scientists, engineers, technician staff can design,build, operate such complex machine.
- $$$

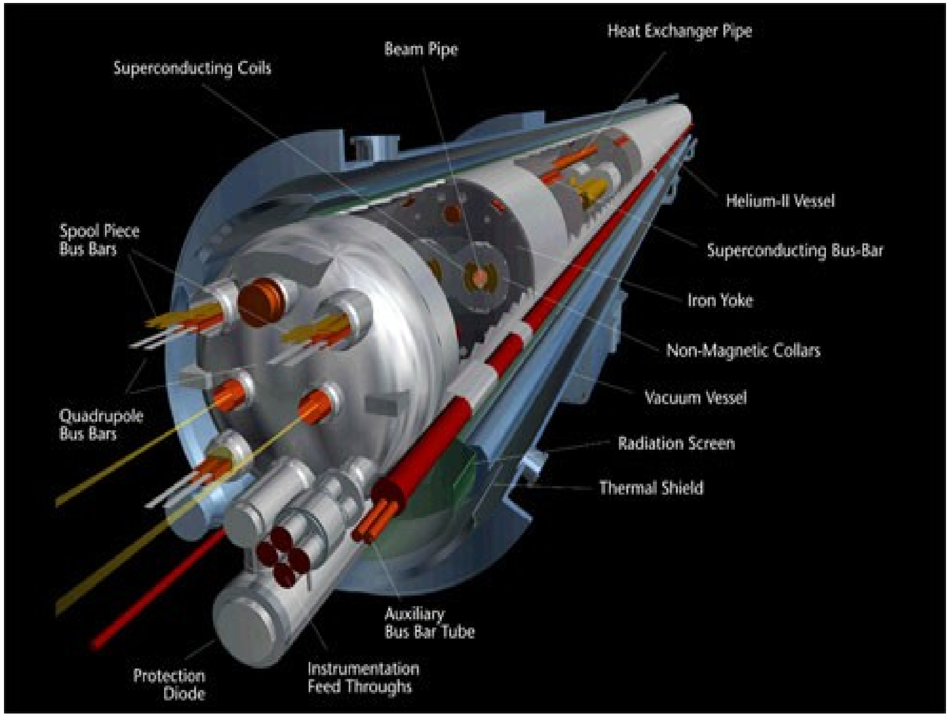




LHC Time lines

- 1993 the SSC was cancelled by US congress
- 1994 the CERN Council approved:
  - Construction of the LHC accelerator, two large detectors (CMS and ATLAS), two smaller ones (ALICE, LHCb)
  - Cost of 10 Billion CHF
- 2000 LEP dismantled, making way for LHC installation.
  - Digging the experimental caverns for ATLAS and CMS
- 2007 LHC largely installed, except fixing some cryogenics problem and repairing faults in some of quadrupoles.
- 2008 Magnets fully cooled down
  - Sept 10th 2008: single beams sent through full 7Km LHC.
  - Sept 19, uncontrolled quench ~100 magnets damaged.
- 2009: pilot run at 900 GeV, follow by collisions at 7TeV

The Large Hadron Collider (LHC) at CERN

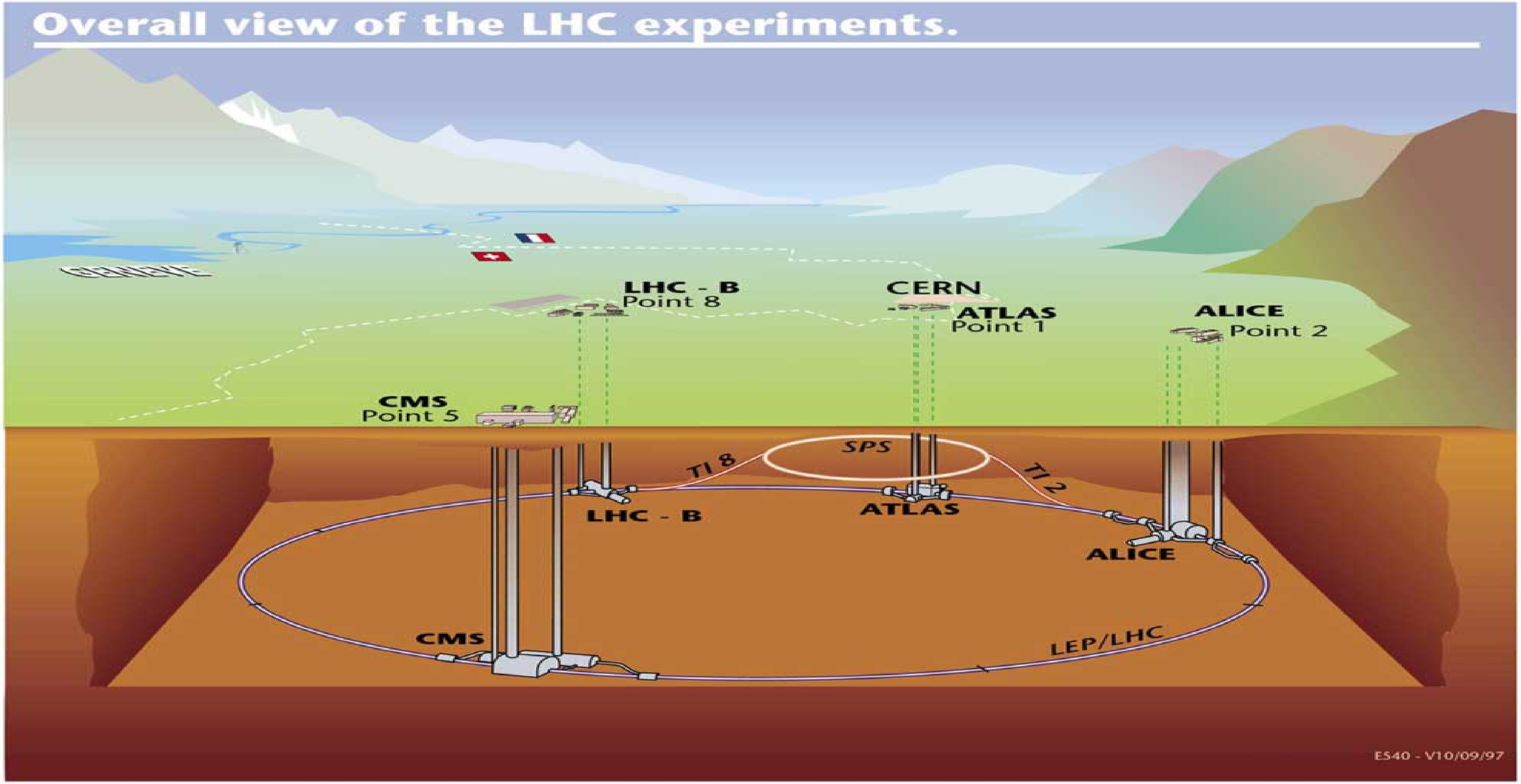
- The most powerful accelerator ever built in particle physics.
- It consists of 27km accelerator ring under 100m below ground. Two proton beams accelerated in opposite directions up to 7TeV.
- Most challenging component of the accelerator: 1232 high-field superconducting dipole magnets ~8.3T, operating at 1.9k.



Accelerator and Experiments

Accelerator and experiments

- Two bunches of counter-circulating protons colliding head-on 40 million times per second or 25 ns for beam crossing.

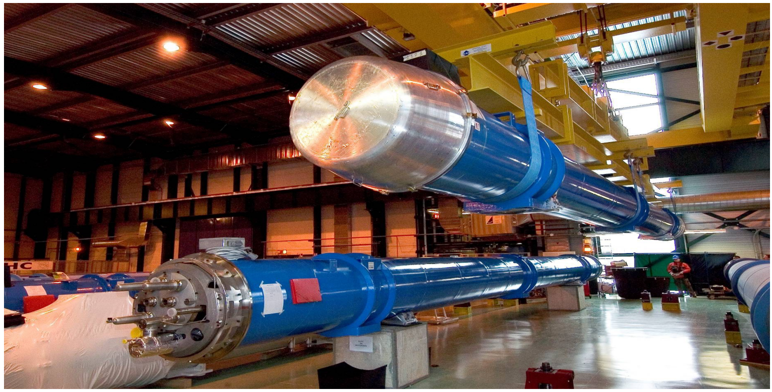


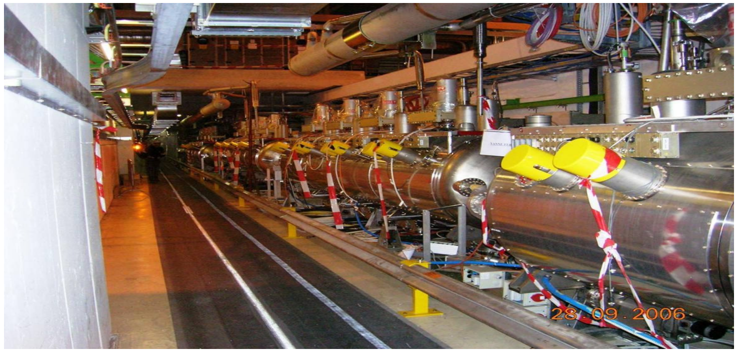
Collider Basics

- Superconducting magnets used to steer, focus beam of particles
  - Dipole create homogeneous field to bend the beam (p=BqR).
  - Quadrupoles and higher order ones used to focus the beam.
- Superconducting radio frequency (RF) cavities are used to accelerate the particle to the higher energy (7TeV).
- Cross-section (σ): the likelihood of interaction between particles
- Luminosity: number of collisions per second per unit of area
  - $L \sim f_n N^2 n_b / A$, where f_n is frequency,N is the number of particles per bunch, n_b is the number of bunches, A is crossing area.
  - Important: $\int L dt$ recorded by experiments over time.
- Detectors are used to trigger and examine the new particles that produced from the collision by L x σ (unit in pb^{-1}, fb^{-1}, ab^{-1}).

Accelerator challenges

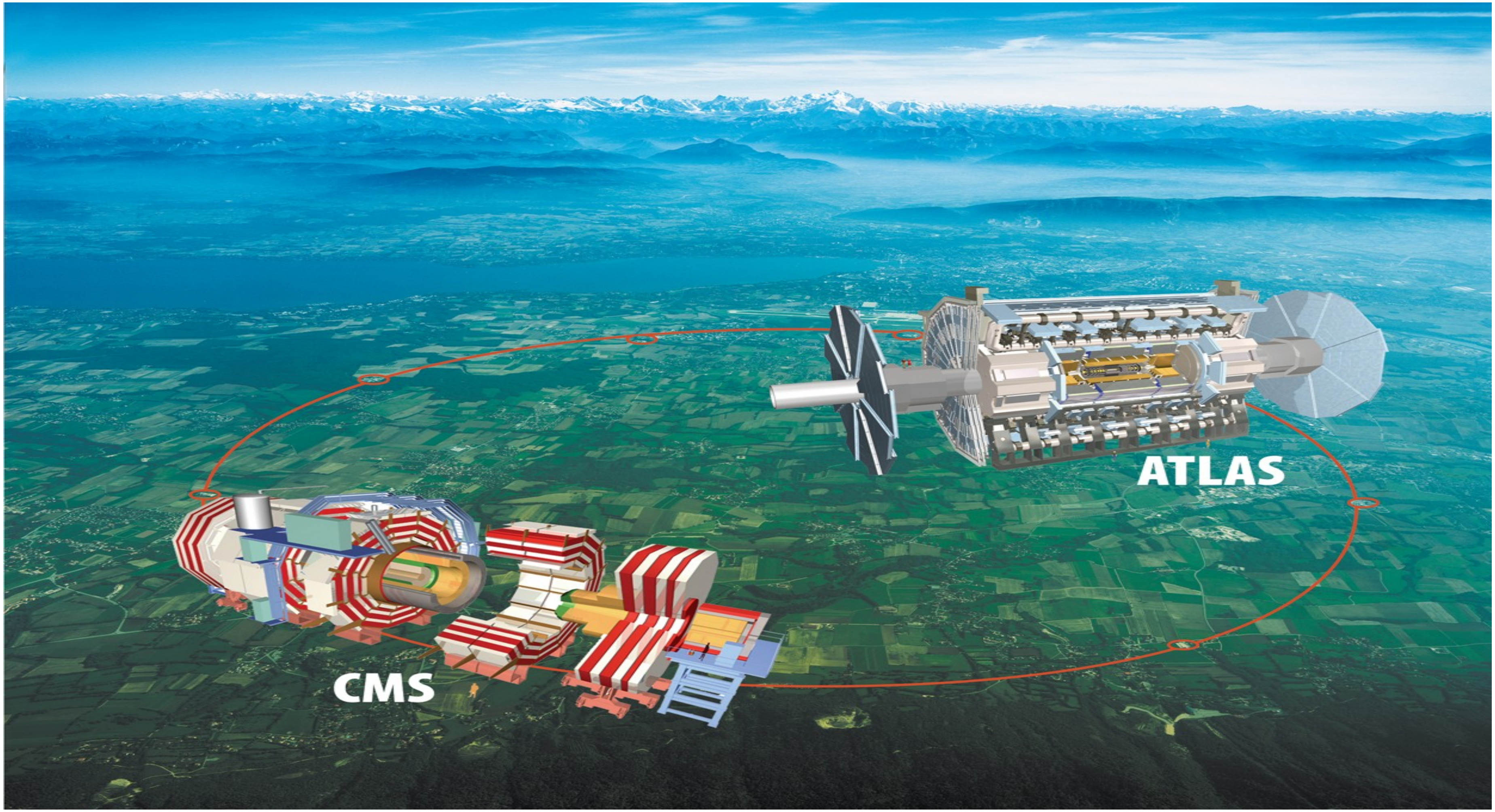
- Superconducting dipoles: 8.3T
- Operating temperature: 1.9K
- Air pressure inside the pipes: 10^{-13} atm
- Stored energy per beam 350 mJour
- Machine with huge size
  - Tunnel 27Km
  - More than 1232 dipoles
  - More than 33k tons of cold mass
  - 100 ton of liquid helium
- LHC power consumption 120 MW
- Relative to Tevatron:
  - Energy: 7 times; Lum: 30 times.





The LHC experiments

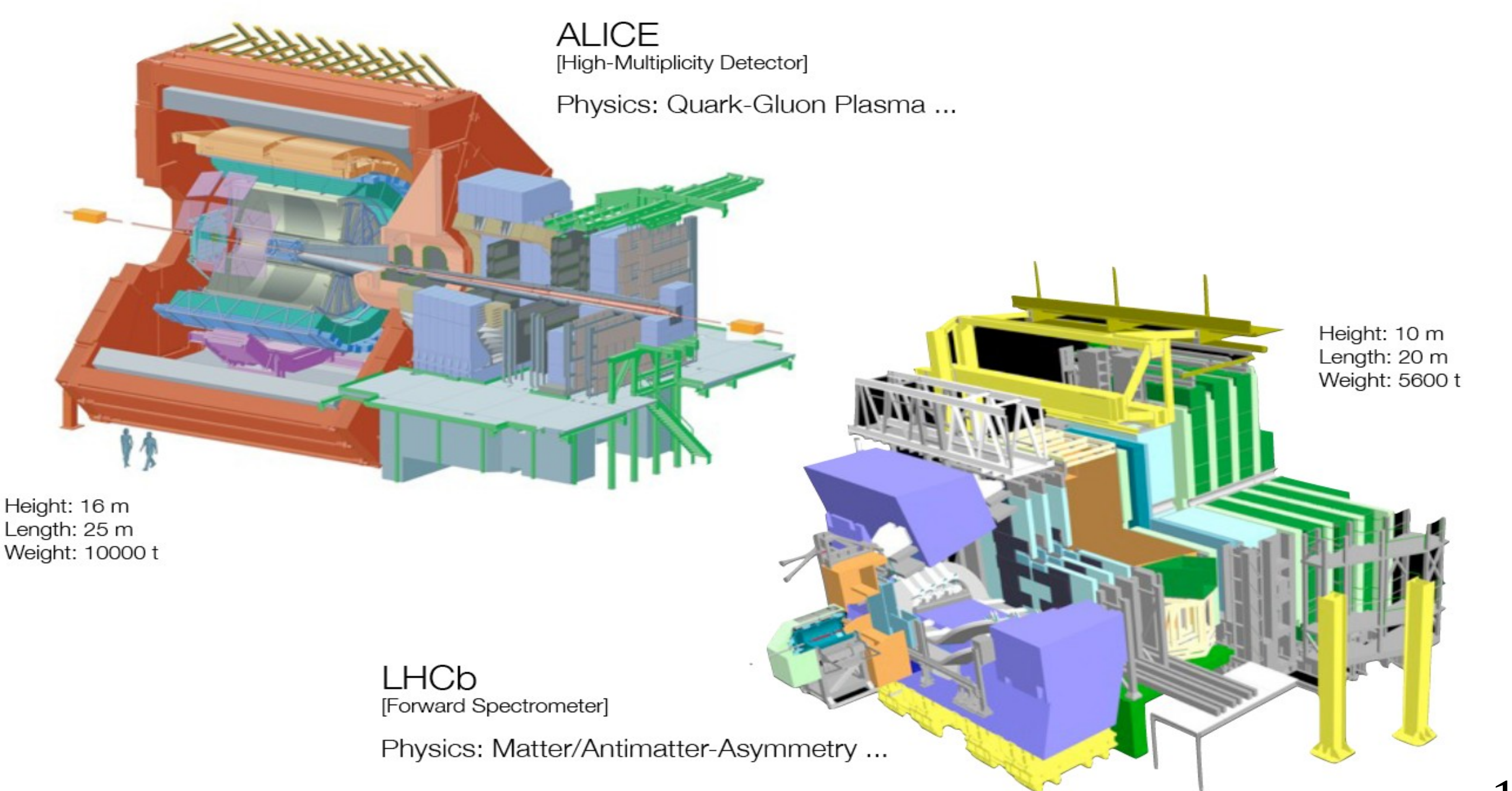
- Two multi-purpose detectors ATLAS and CMS: largest, most complex detectors ever built.



The LHC experiments

- Two dedicated small scale experiments:

ALICE & LHCb

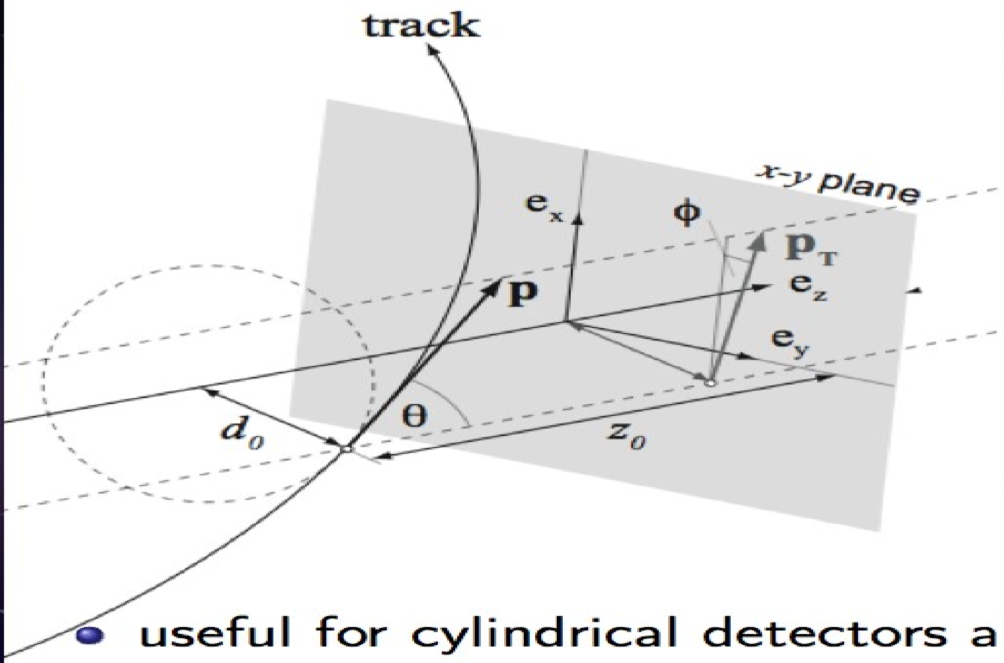


Detectors

- The goal of particle detectors is to determine the particle's creation and decay point, momentum, and the type (mass).
- Detection implies detecting the interaction of particles with matter.
- Design principles:
  - Hermetic, high efficiency covering the full solid angle.
  - Need to distinguish particles with different subsystems.
  - Able to trigger on interesting events without dead time.
  - Detectors need electronic, cable, cooling...as “dead” matter.
- Limitations:
  - Technology difficulty.
  - Space, material, and budget constraints.

Detecting Charged particles

- Most particles will decay into stable charged particles: e, μ, π, k, p, pbar
- They loose energy passing through the detector:
  - Ionization, bremsstrahlung, emission of Cherenkov
- B field is used to bend charged particle,measure momentum(curv)



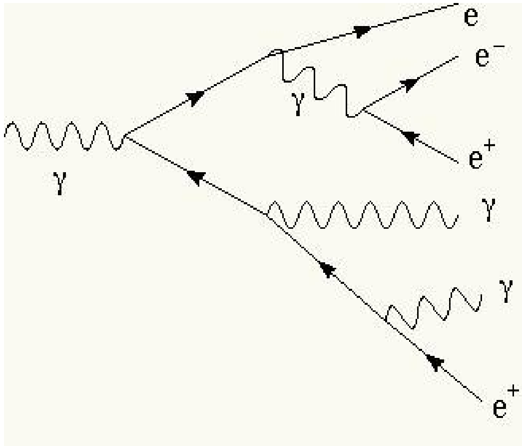
Perigee parameterization:

- d_0 signed distance of closest approach to z axis
- z_0 z of closest approach
- ϕ_0 azimuthal angle at cl. app.
- θ polar angle of track
- q/p charge-signed curvature

- useful for cylindrical detectors and solenoidal B-field (B_z)
- basis for 4-vector parameterization in physics analysis

Detecting neutral particles

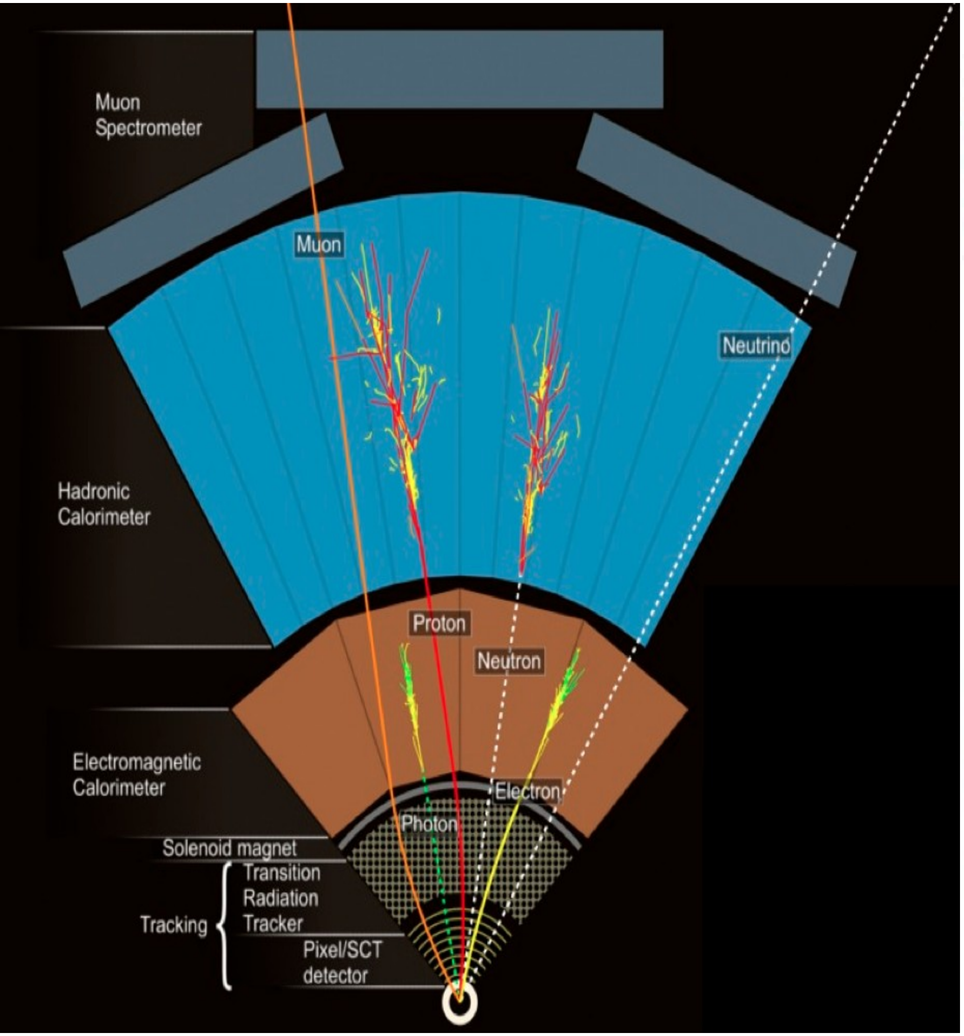
- Most particle will decay into set of stable neutral particles: γ, K_L^0, n, υ
- For photons there's a number of reactions:
  - Photoelectric effect, Compton effect, pair production
  - Lead to full electromagnetic showers in the detectors when combined with similar effects for the electrons

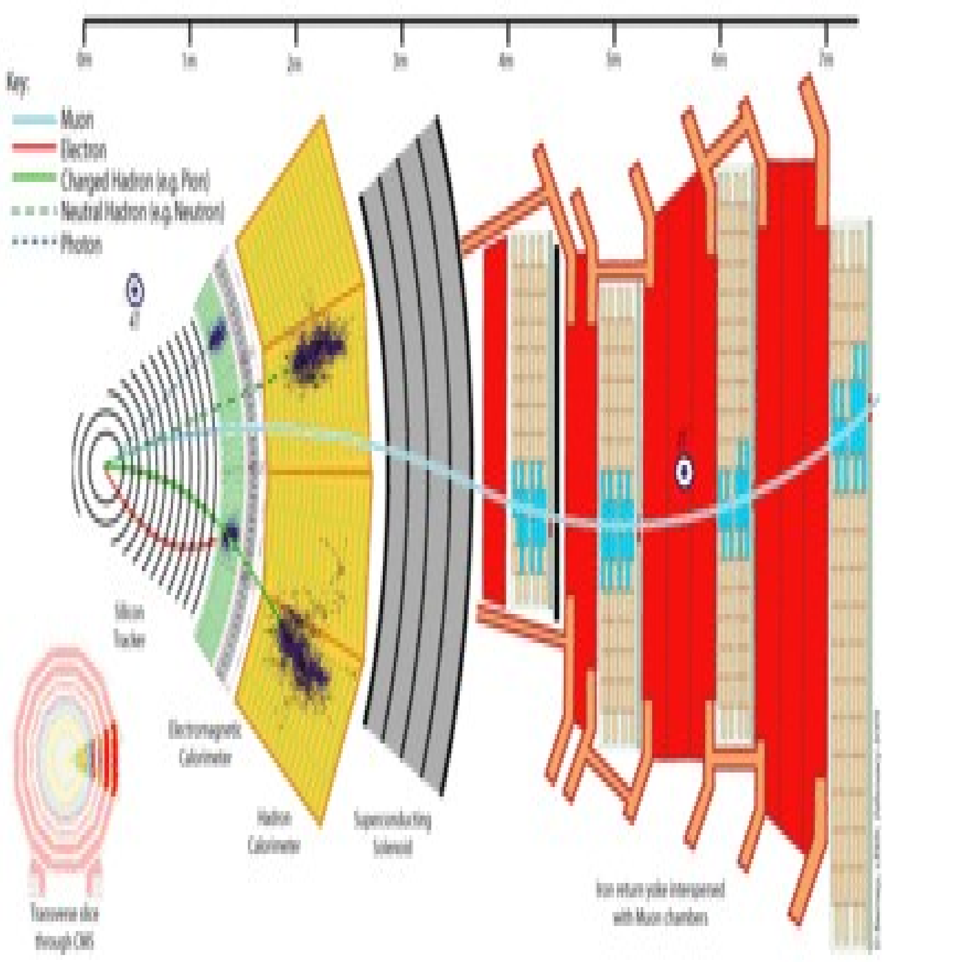


- Other neutrals experience nuclear reactions, depositing their energy in the detector. This is parametrized by the hadronic path length X_0.
- Neutrinos typically do not interact with the detectors and leave a imbalance momentum, or missing Et.

Scheme of particle detection

- ATLAS, CMS built like an onion with layers of trackers,B fields, calorimeters, muons,   to give as much information as possible.



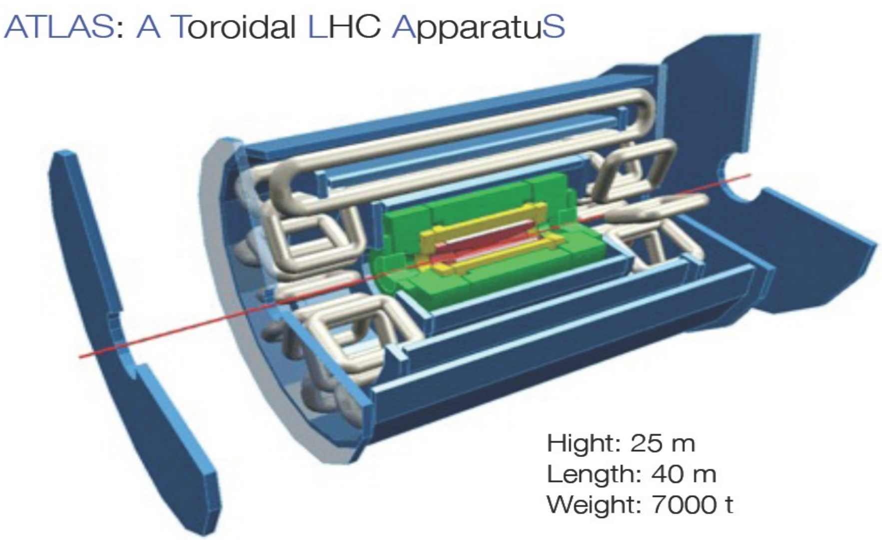


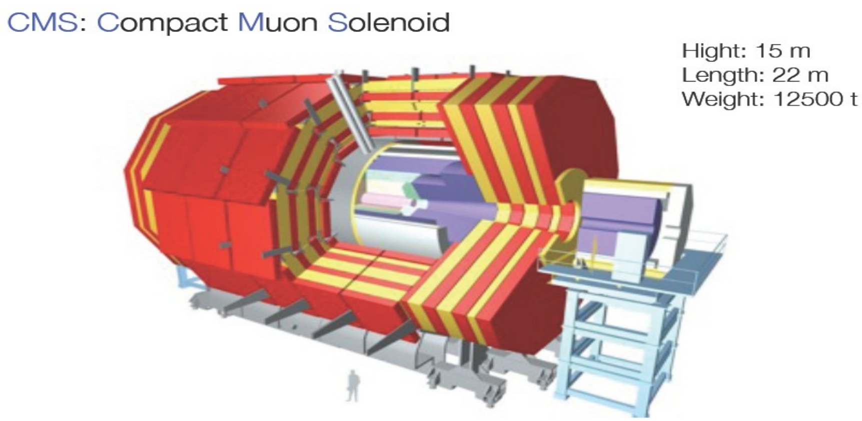
ATLAS and CMS Detectors

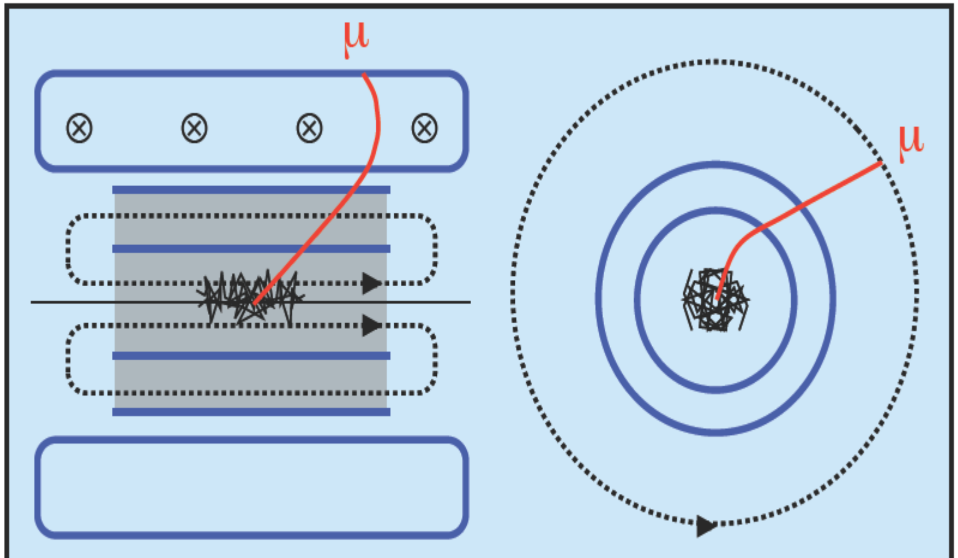
- ATLAS and CMS are two largest general purpose detectors ever built. It involves many people hard work.
- Designed to be sensitive to all aspect of the standard model physics and beyond.
- Required to measure all particles with optimal performance and maximal acceptance under LHC design conditions
  - Cope with harsh machine conditions, high pile up events, and extreme event signatures.
  - Trigger is challenging.
  - Detector huge and consists of many individual systems.
  - Reconstruction, calibration, monitoring all challenging.
  - High complexity of simulating collision events.

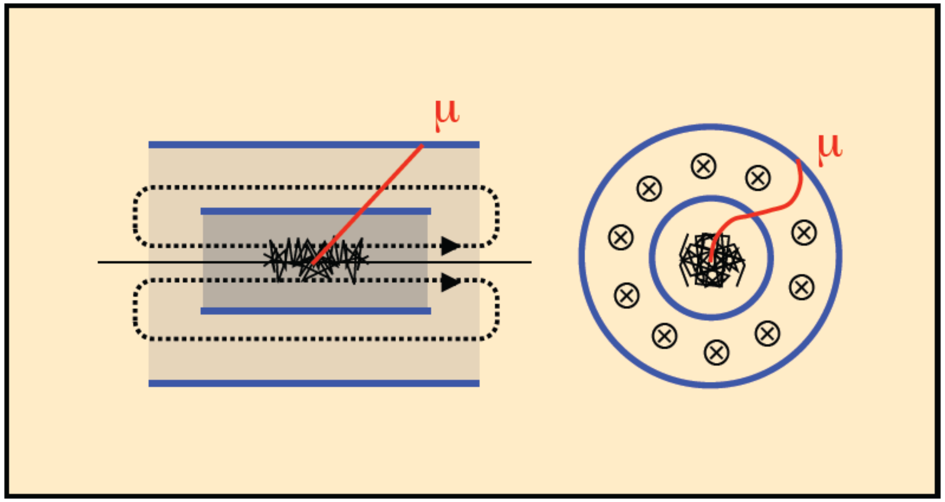
Two different B fields: Toroid vs Solenoid

- Use two very different approaches to the same physics.

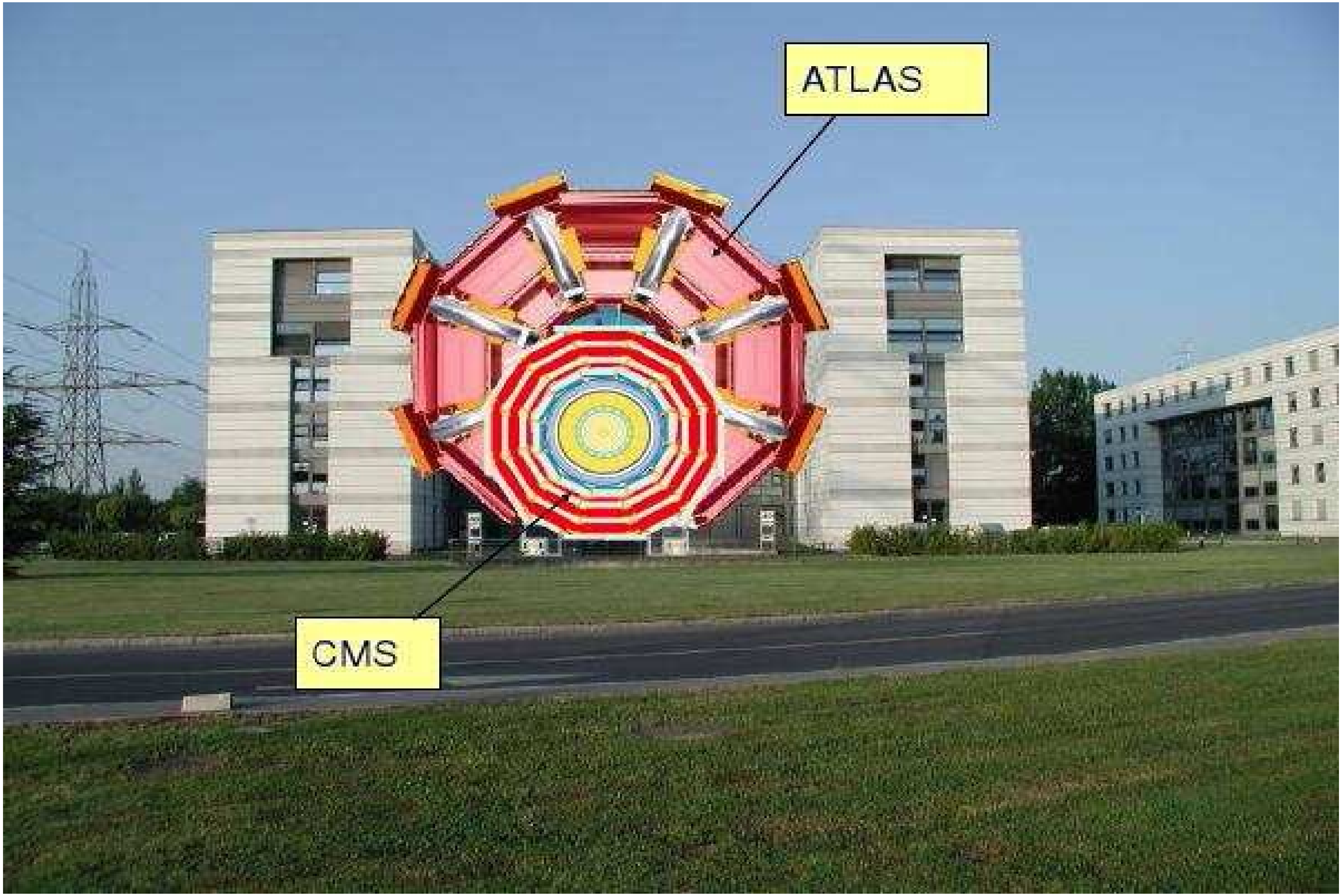








ATLAS and CMS Detectors

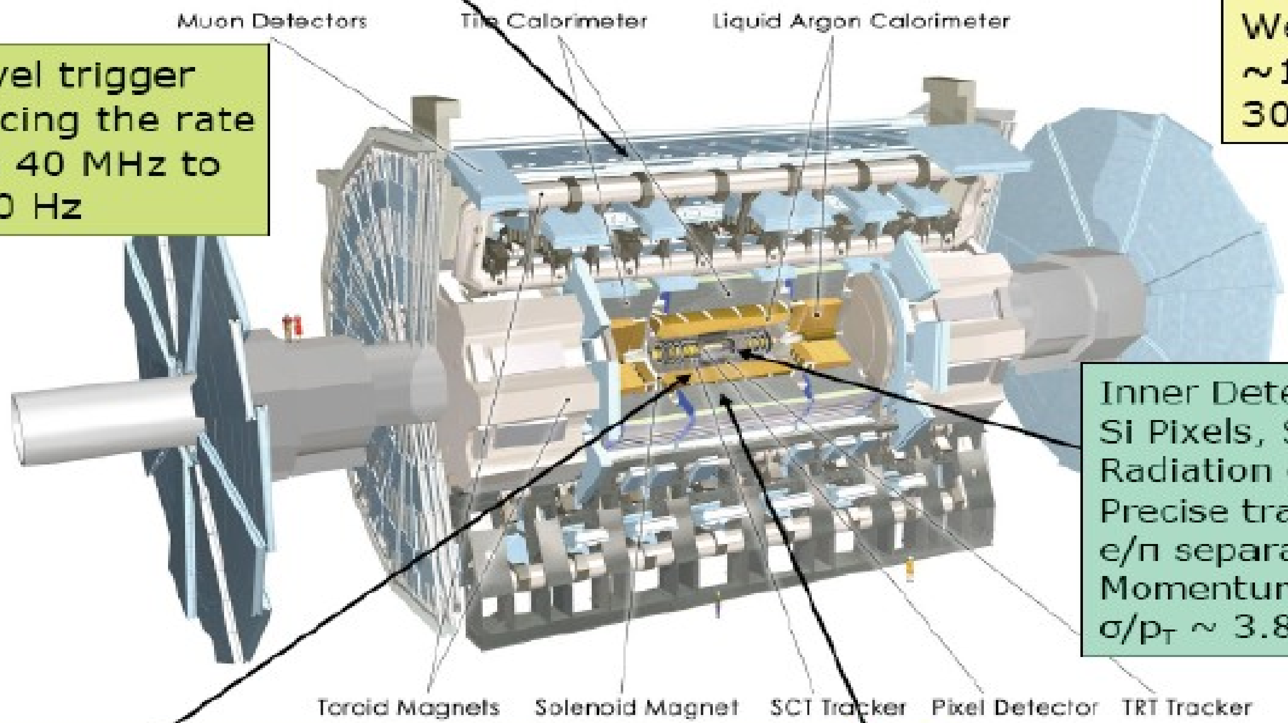


The ATLAS Detector

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
~10^8 electronic channels
3000 km of cables

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

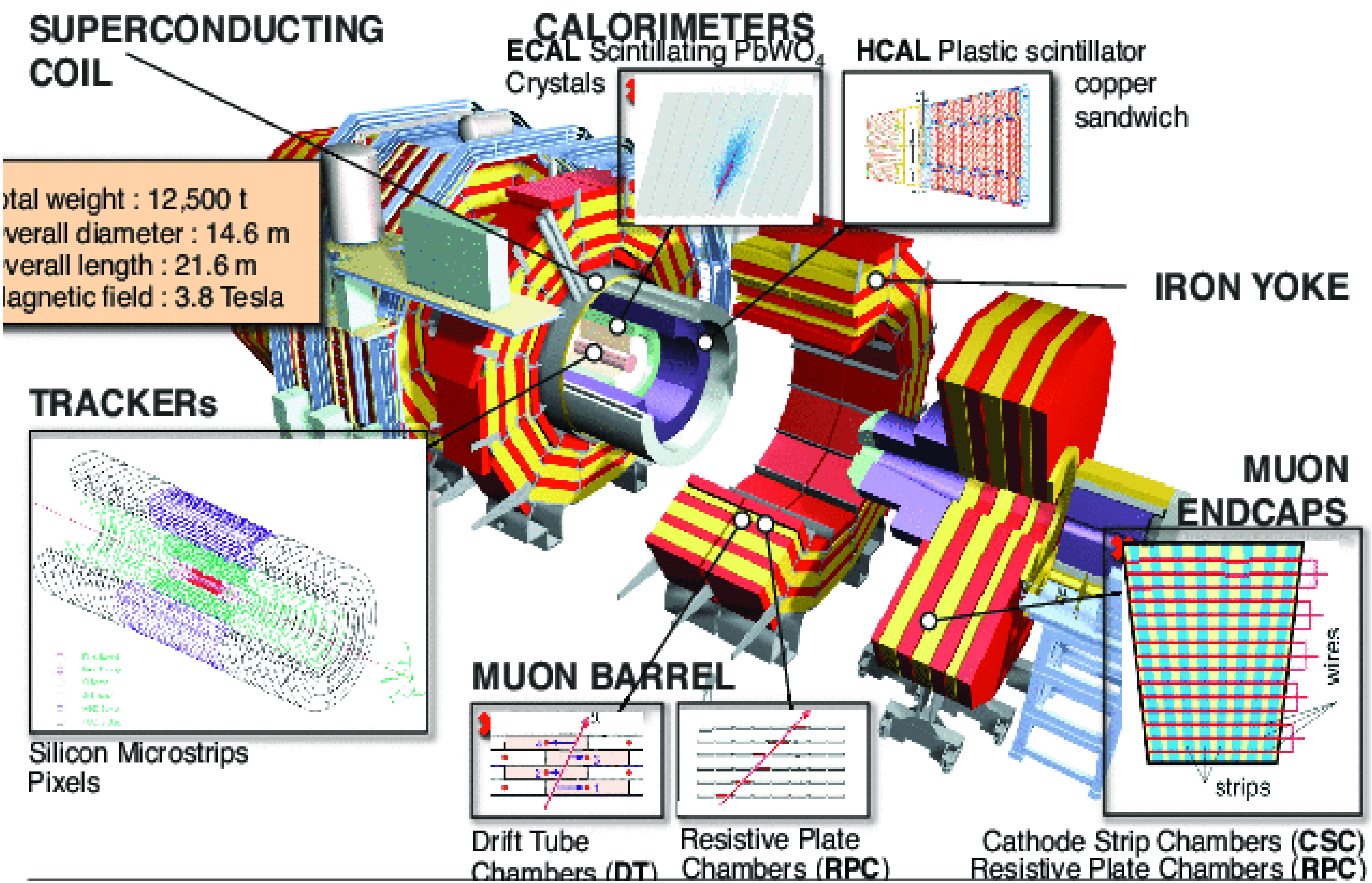


Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing, e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\mathrm{GeV}) \oplus 0.015$

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: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

The Compact Muon Solenoid (CMS)



Large International Collaboration

- ~3000 scientists and engineers (including ~1000 students).
- IHEP is part of ATLAS and CMS collaboration.

ATLAS Main Features

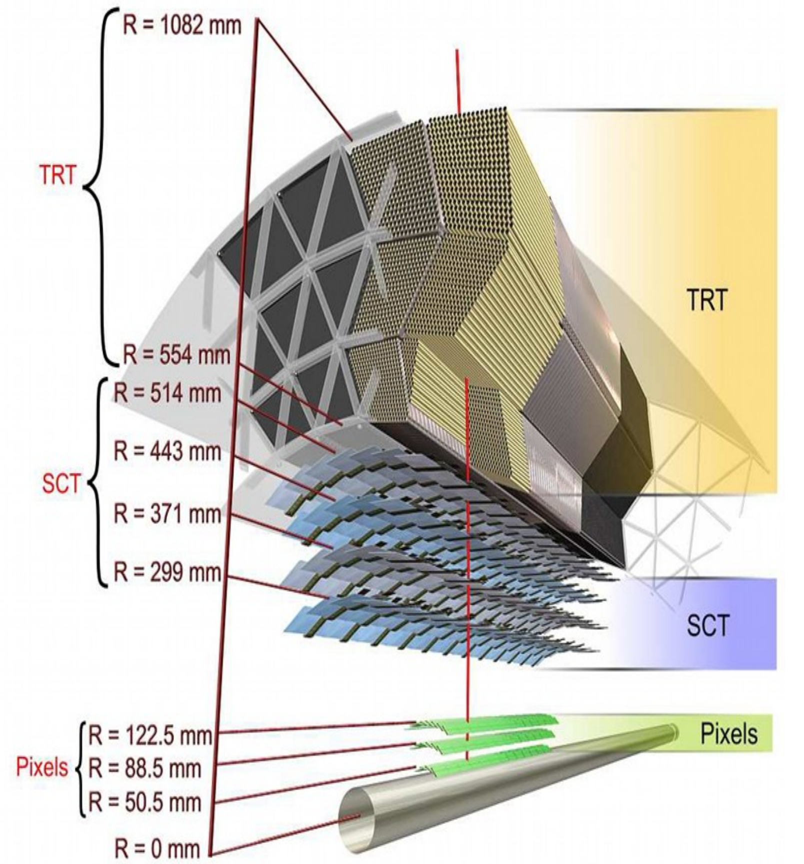
- ATLAS
  - An independent, huge and large coverage system with strong field toroid to identify,measure and trigger muons.
  - A separate and small central solenoid magnet at 2T,just for inner tracker.
  - Calorimeters are in outside of the central solenoid magnet.
  - Able to measure the photon direction in EM.
- Pros:
  - Excellent muon tracking performance without any inner tracker infos, good for triggering
  - Muon tracking in air,no MCS complications
- Cons:
  - Large amount of material in front of the EM calorimeters.

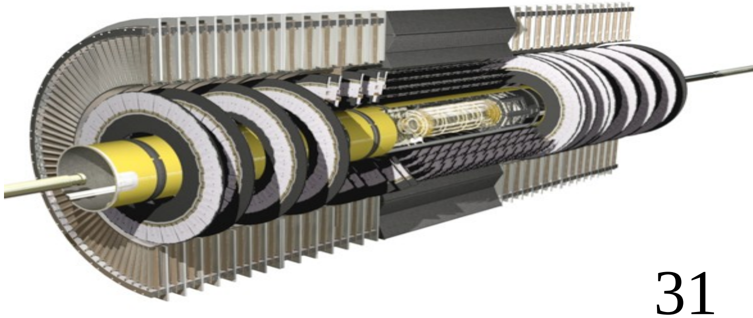
CMS Main Features

- CMS:
  - An integrated and compact system,based on a sole high-field, large volume central solenoid(4T), which contains calorimeters and tracker
  - Muon detection in the solenoid return yoke
  - All silicon highly segmented tracker
- Pros:
  - Excellent inner tracker performance
  - Muon are tracked in the outer muon detector too
  - No extra material in front of EM calorimeter
- Cons:
  - Relatively limited space allowance for calorimeters.
  - Muon tracking in the steel return yoke.

ATLAS Inner Detector

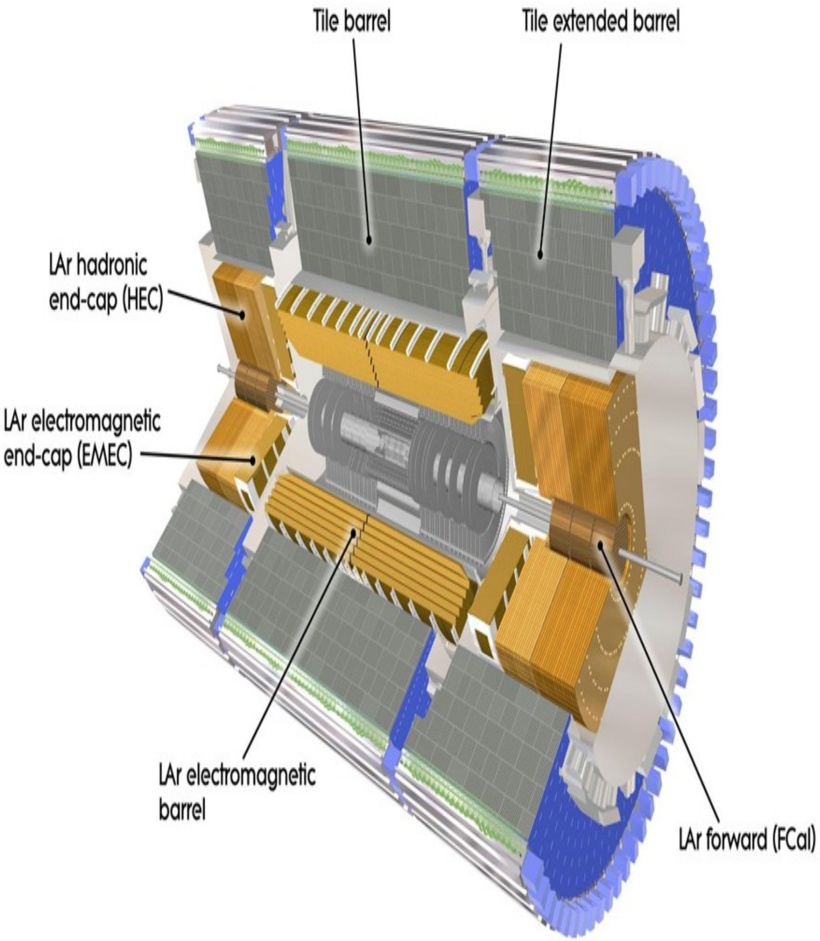
- Pixel:
  - –3 layers with 50x400 um,80M channels.
- SCT:
  - –4 additional double side layers with 80 um spacing
  - –2nd dimension z is from the small angle stereo
- TRT:
  - –298K straw drift tubes detector
  - –Provides rphi, e/π identification
- Systems provide robust 3-D tracking ,precise momentum measurement.





ATLAS Calorimeters

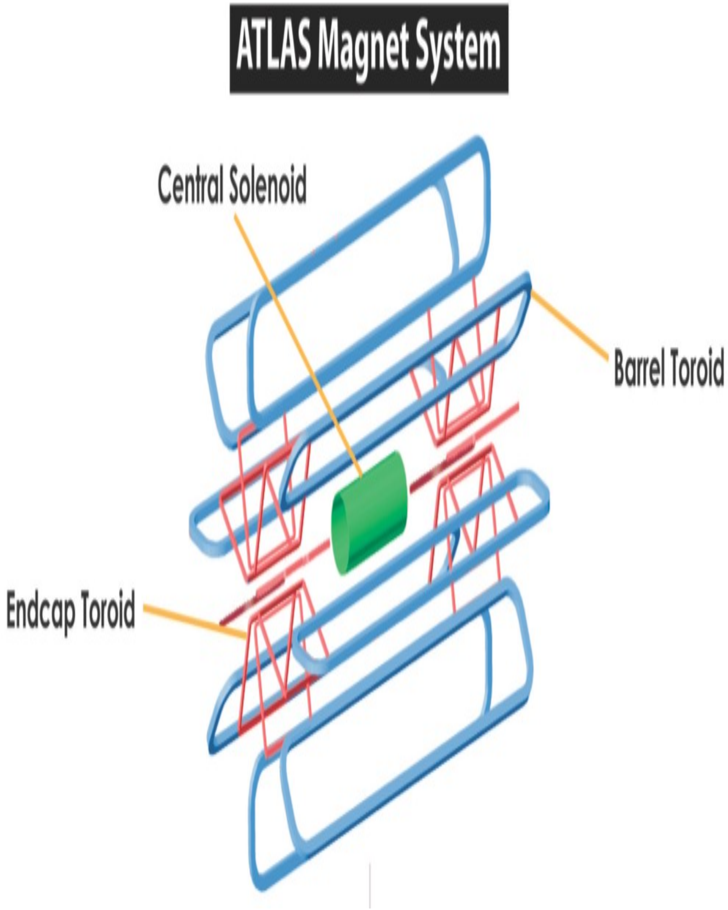
- All calorimeters are sampling calorimeters:
  - LAr EM: pb absorber with liquid argon as active material
  - Tile: steel absorber with scintillating tiles as active material
  - LAr H endcap: Cu absorber with liquid argon
  - LAr forward: Cu and W absorber with liquid argon



- Choice of liquid argon design:
  - Response very linear in E
  - Stability& radiation hardness

ATLAS Magnet System

- Central Solenoid:
  - –5.3m long,2.4m diam.,4.5cm thick
  - –Field strength 2T,current 7.73KA
  - –Field lines parallel to z axis
  - –Homogeneous over Inner Det.
- Toroids:
  - –25.3m long,20m outer diam. Barrel
  - –4T on superconductor,0.5T ave.
  - –20.5kA current,4.7k
  - –Field lines in plane orthogonal to beam axis inhomogeneous field.
- InDet and muon det. have their bending planes orthogonal to each other.



ATLAS Magnet System

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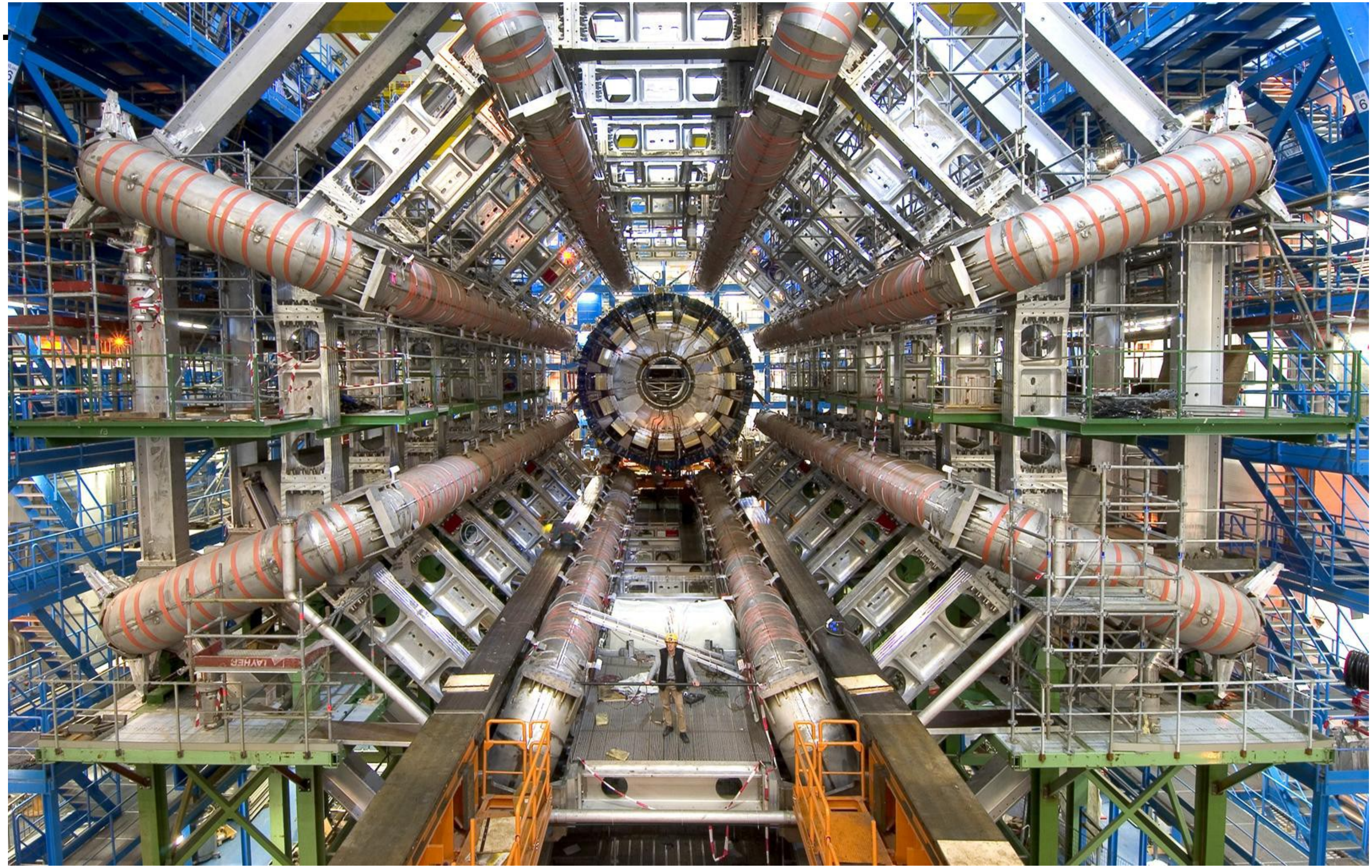
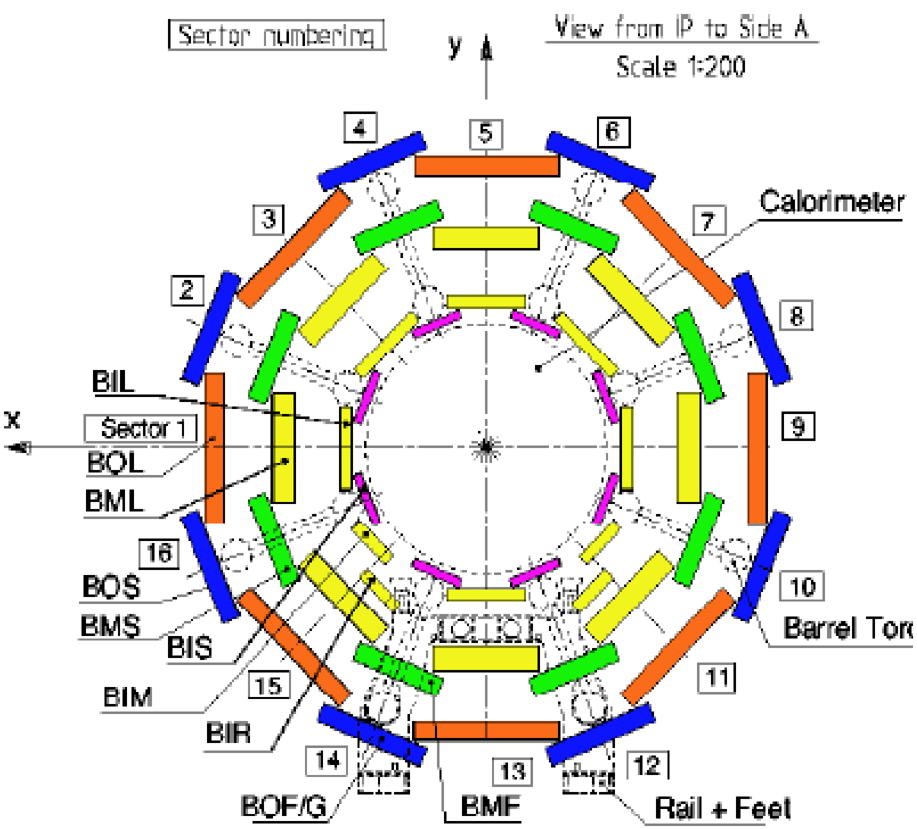
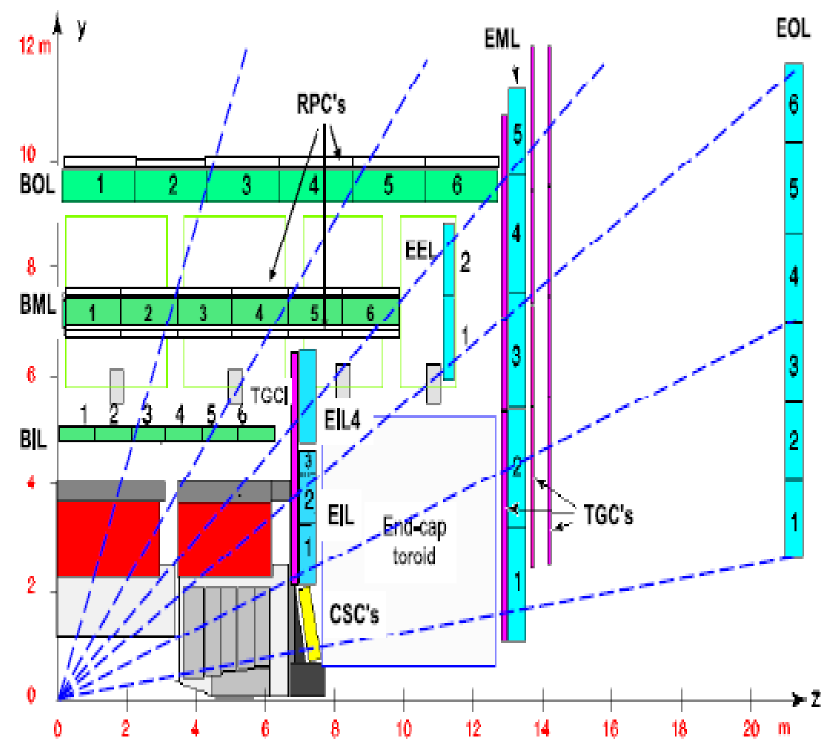


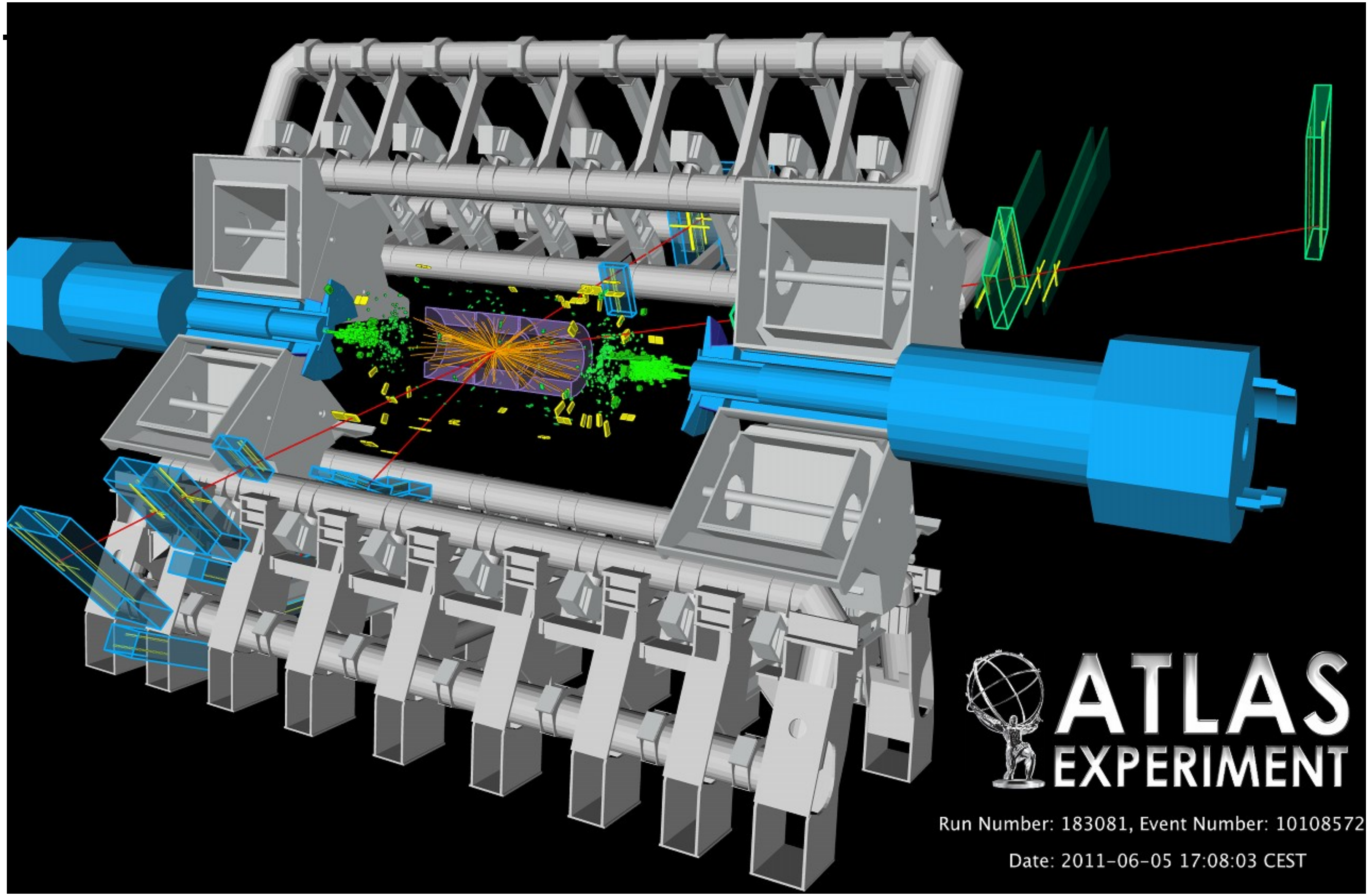
ATLAS Muon Spectrometer

- Consist of many different technologies and chamber geometries:
  - –Monitored Drift Tubes(MDT); Cathode Strip Chambers (CSC) in |η|>2.0; Resistive Plate Chambers (RPC),barrel only; Thin Gap Chambers (TGC), endcap only



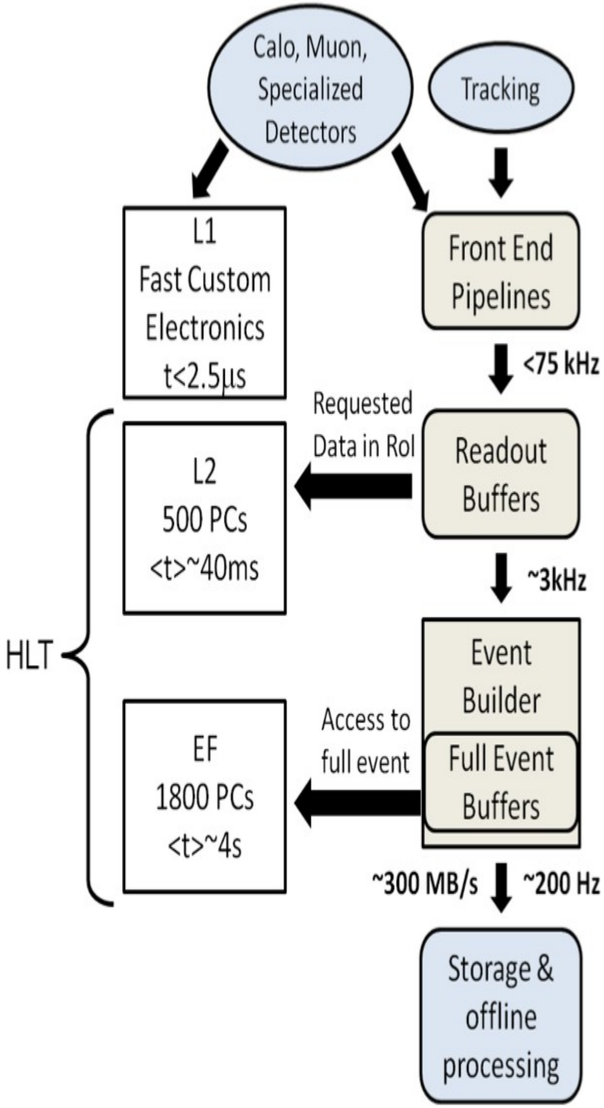


ATLAS Muon Spectrometer



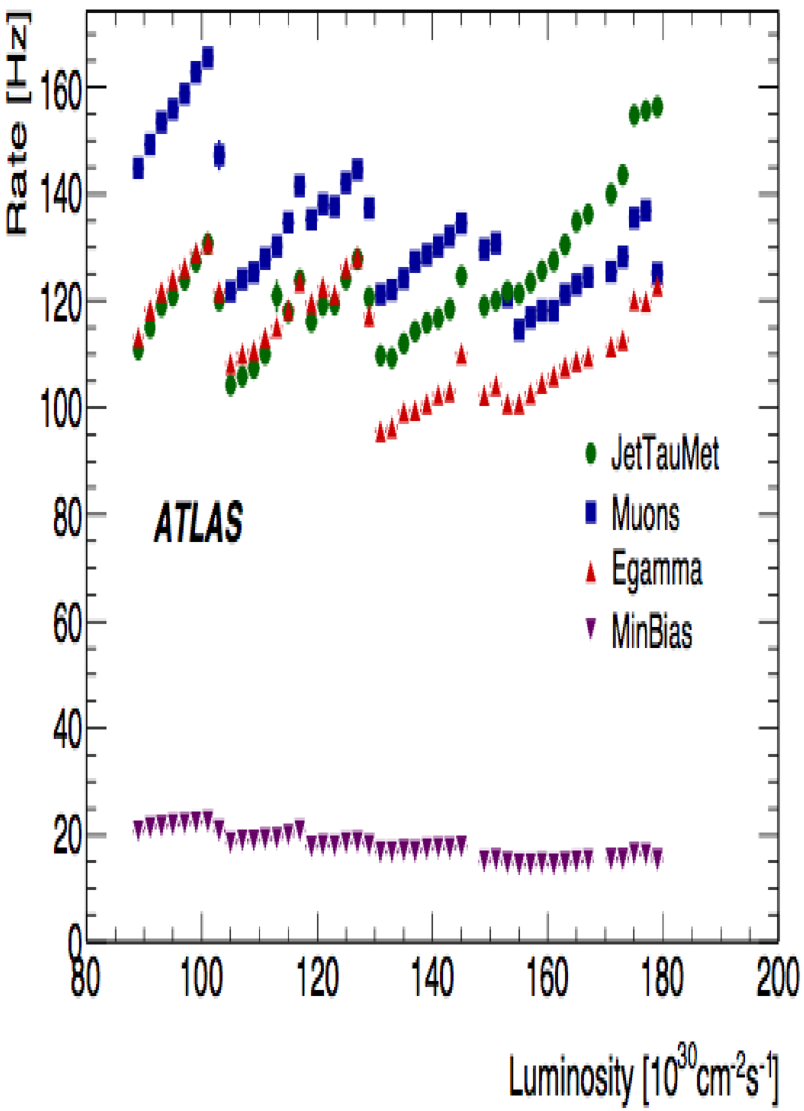
Trigger Strategies

- Both ATLAS and CMS have sophisticated multi-level triggers
- Next level uses more detailed information and has more time to process it
- 1st level is built from dedicated hardware: Calo, muon, specialized detectors.
- Only 200-400Hz can be saved for physics analysis(limited by offline processing power and disk size).
- Time-optimized version of reconstruction algorithms used.
- “Region of Interest”: restricting to region around triggered object.



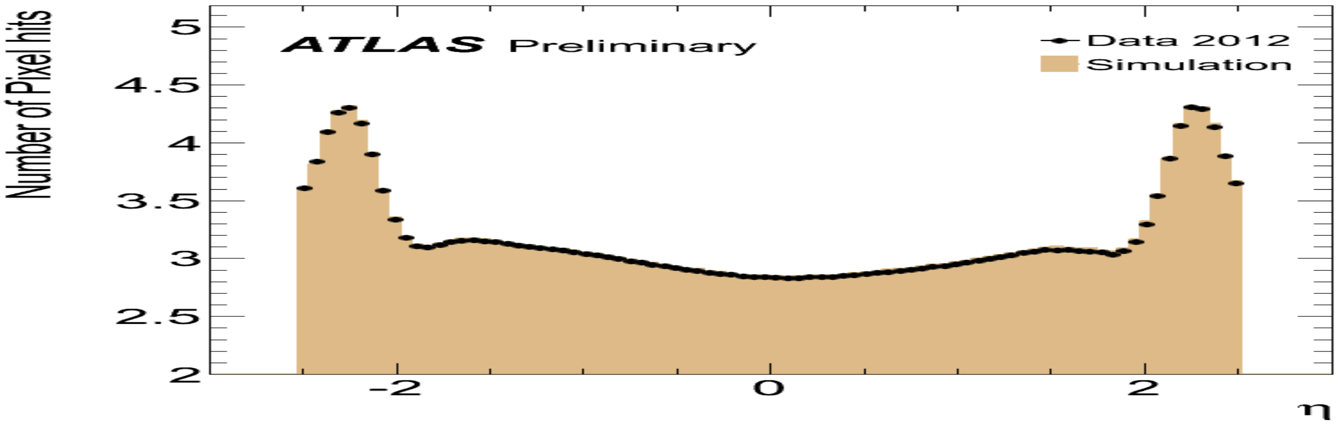
Trigger Performance

- Rate reduction comes at a price:
  - –Pre-scaling: apply arbitrary filter
  - –Kinematic threshold: drop low Pt
  - –Isolation: drop what is more likely background
- LHC regularly increases lumi or changes machine conditions
- Trigger chains are kept decoupled
  - –Minibias/electron/muon/jet
  - –Streams formed
- Each trigger chain has target quota
  - –Reserved 1% for pre-scaled mini -Bias event at high luminosity.



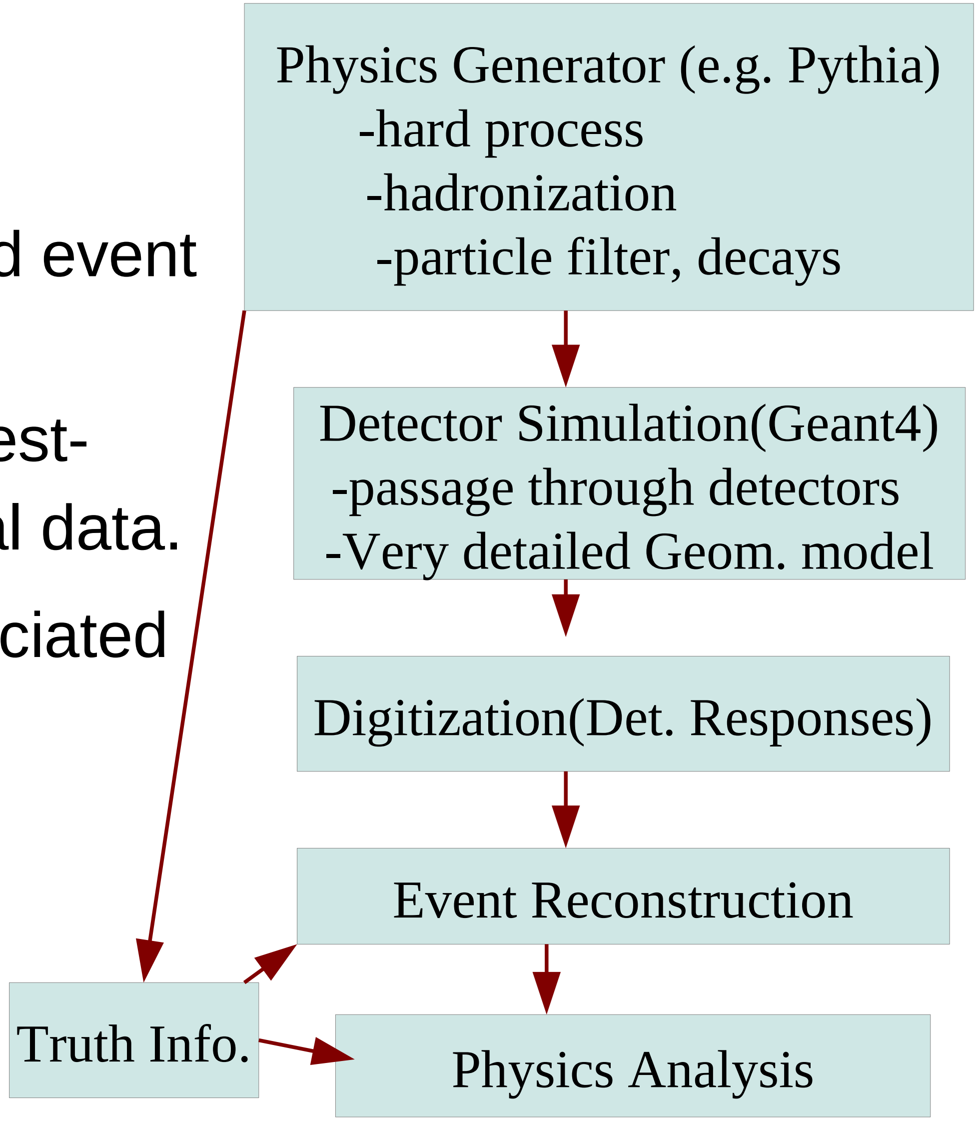
Simulation

- Simulation of collisions is part of the experiment:
  - Conception: decisions about optimal detector design
  - Preparation: setting up reconstruction, physics analysis
  - Data analysis: interpretation of physics results
- Based on Monte-Carlo methods: within given the cross section, phase space, decay lifetimes, and detector resolution the interactions follow random decisions.
- ATLAS and CMS simulation describes their data extremely well.



Event Simulation Chains

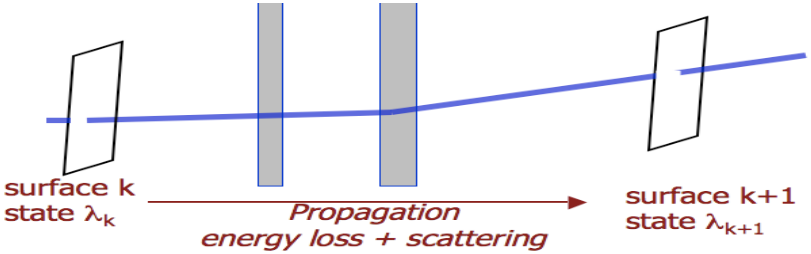
- Simulation chain
  - –Separated in logical steps
  - –Reconstruction of simulated event same as real data
- Detector response tuned with test-beam and calibrated with real data.
- Truth information remains associated
- Simulation is CPU-intensive.
- Other, faster and less accurate simulation exists.



The Grid

- The LHC grid unites computing resources of particle physics institutions around the world, connects 100,000 processors in 34 countries with ultra-high-speed data transfers.

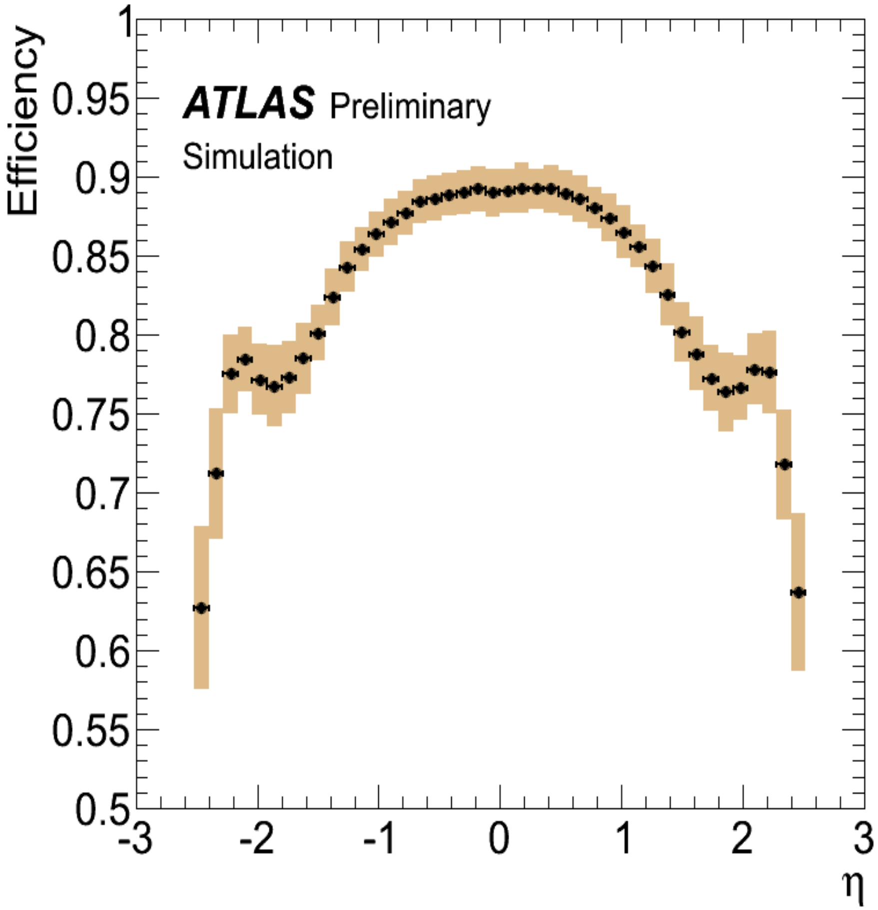
Track Fitting Basic

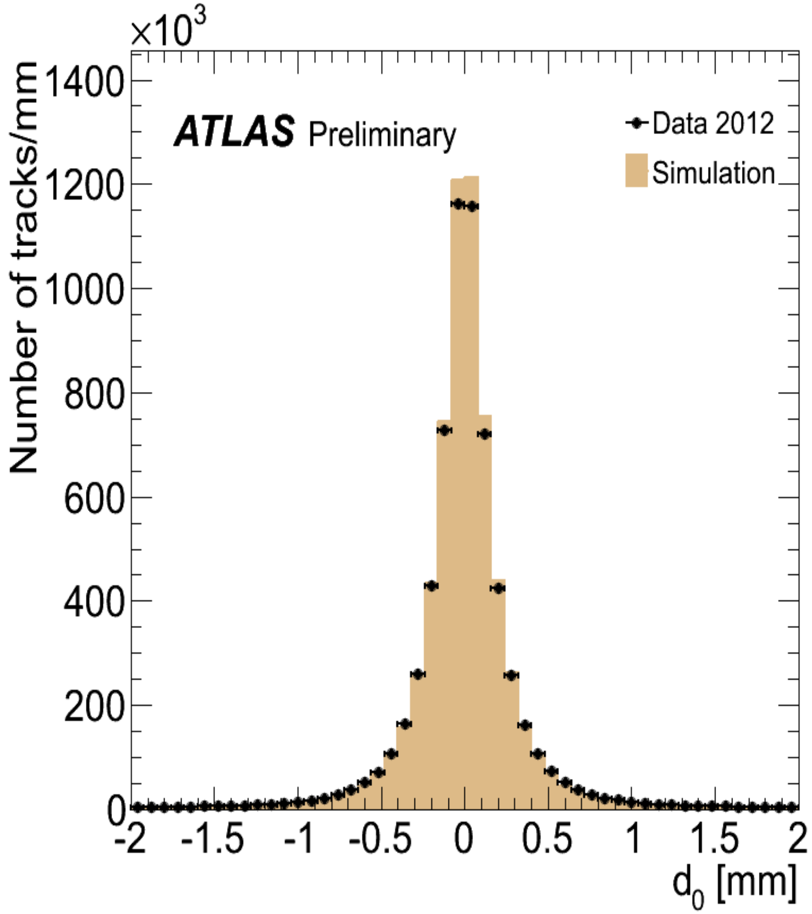


- Measurement constraints:
  - $m_k = h_k(\lambda) + \gamma_k$
  - λ: track parameter
  - h_k:functional dependence of measurement on track parameters.
  - γ_k: noise term,variation within error
- A linear model is applied
  - $h_k(\lambda) = h_k(0) + H_k\lambda$
  - $H_k = dm_k/d\lambda$
- Kalman filters in track fitting
  - Steps through hits and update parameters, progressive way of performing LSE(least squares

Tracking Performance

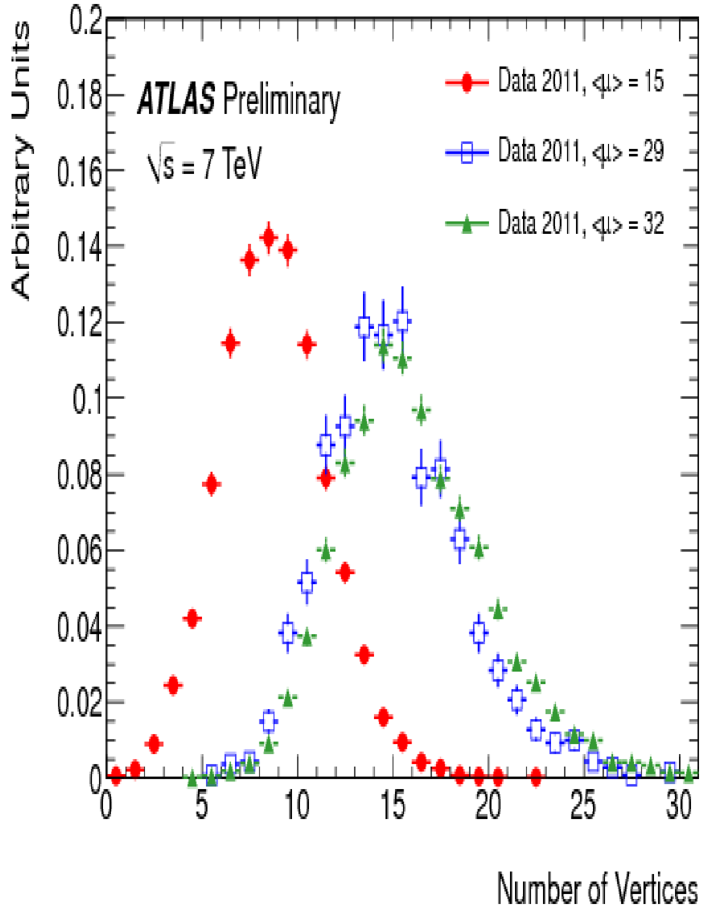
- Tracking efficiency measured from data
- Impact parameter d0 respect to primary vertex.

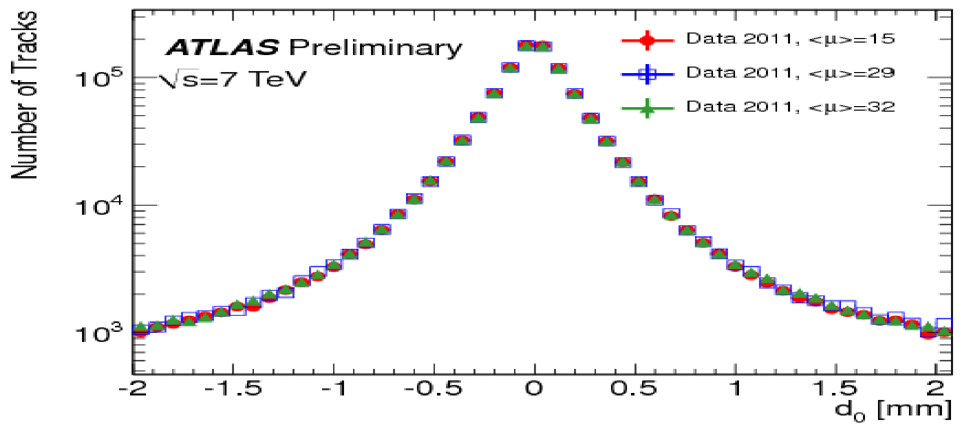


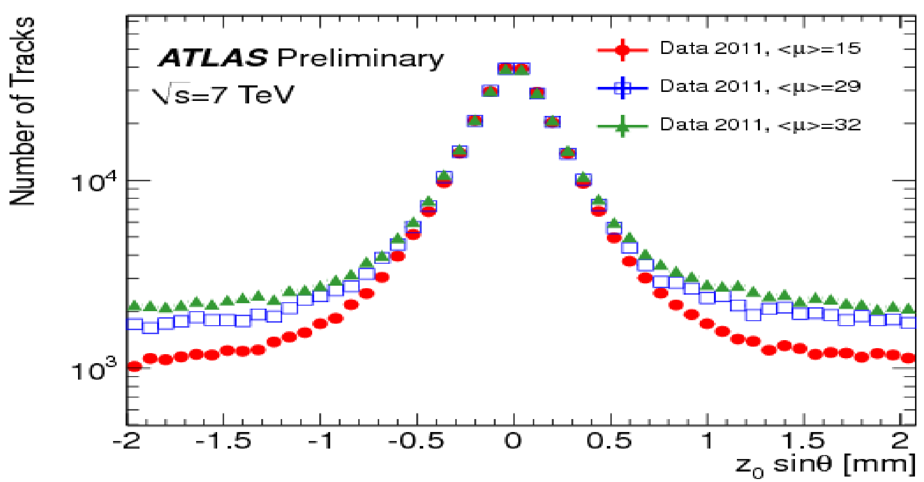


Pileup

- Impact parameter Z0 respect to primary vertex seems sensitive to the number of pileup events.

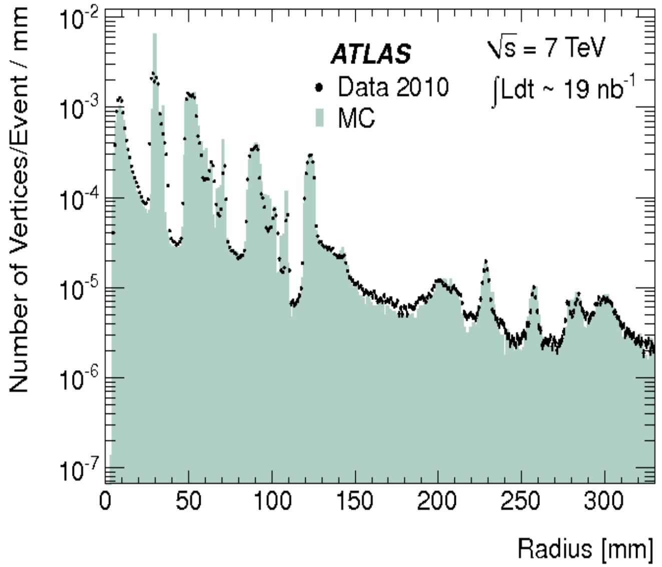


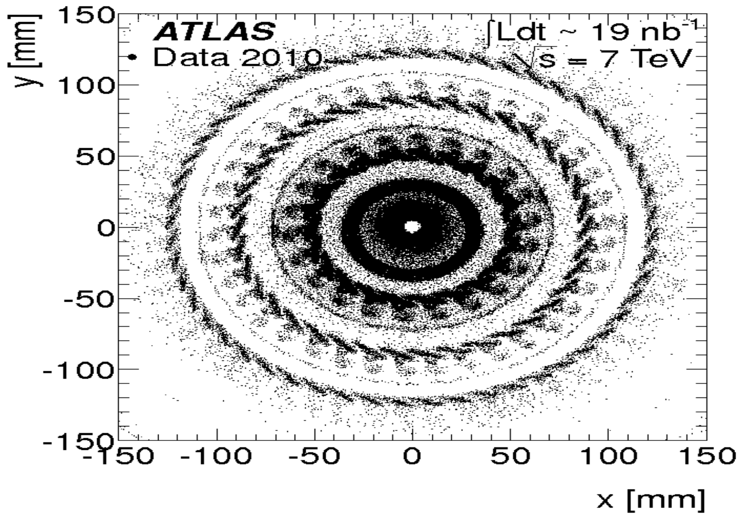


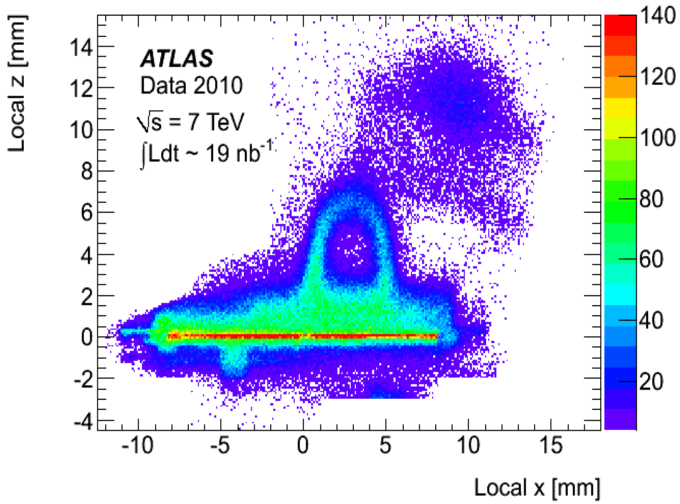


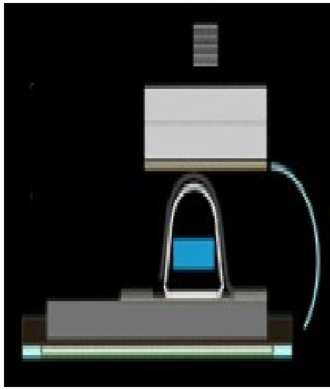
Material Studies

- Interactions in the detector and low mass resonances probe material with high precision
  - γ conversion vertex location
  - Hadronic interaction vertices
  - $k_s \to \pi^+\pi^-$ and $J/\psi \to \mu^+\mu^-$



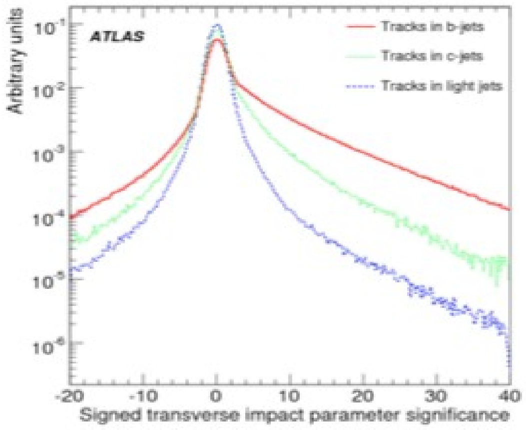




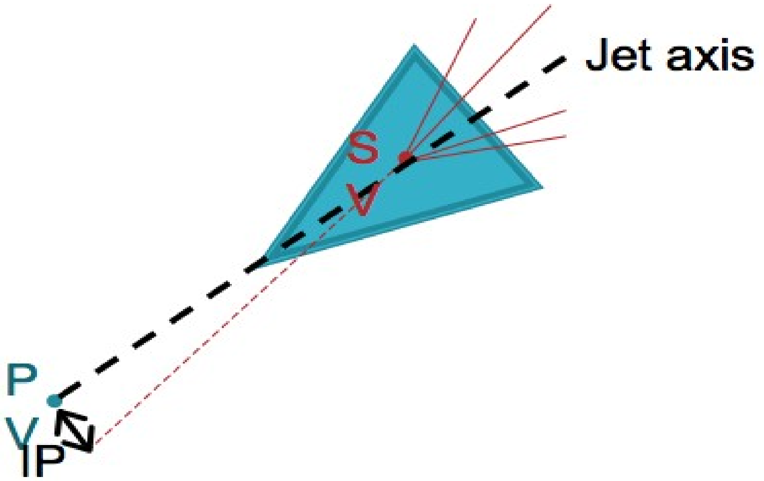


B-Jet Tagging

- Spatial tagging (or life-time tagging):
  - B hadrons have a significant flight path length:
    - E(B) ~ 50 GeV ⇒ L ~ 5 mm
  - Secondary vertex in jets.
  - Tracks with high positive impact parameter.

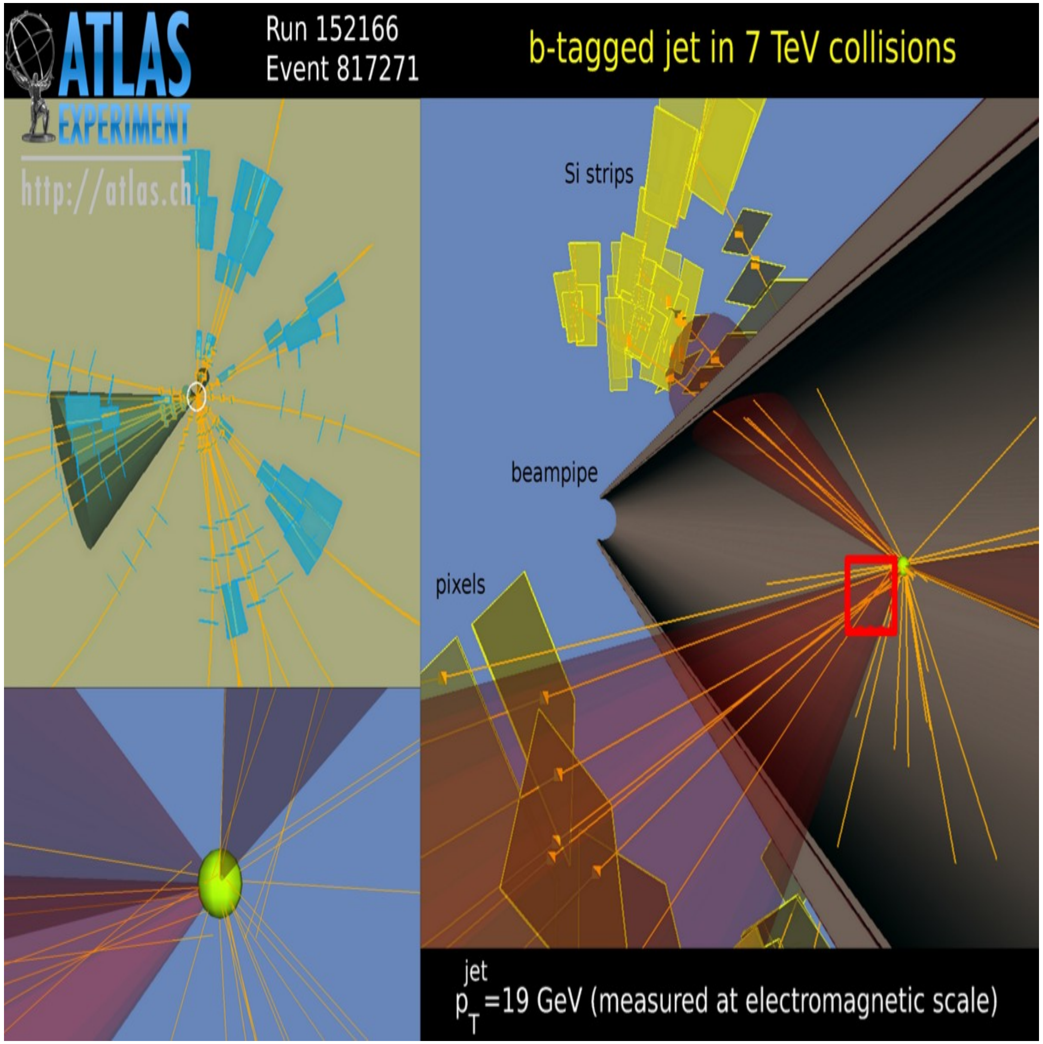


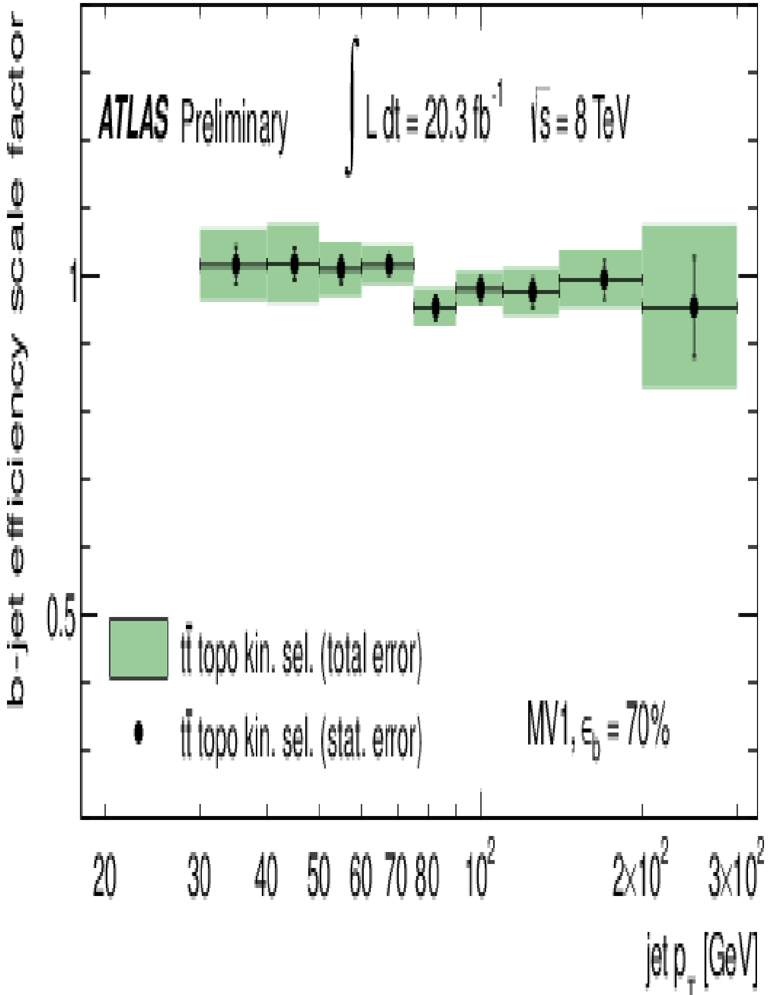
- Soft lepton tagging: Useful to commission other taggers
  - Low pT electron/muon from B/D decay.
  - Efficiency limited by (B/D l) branching ratio.



B-tagged Jet

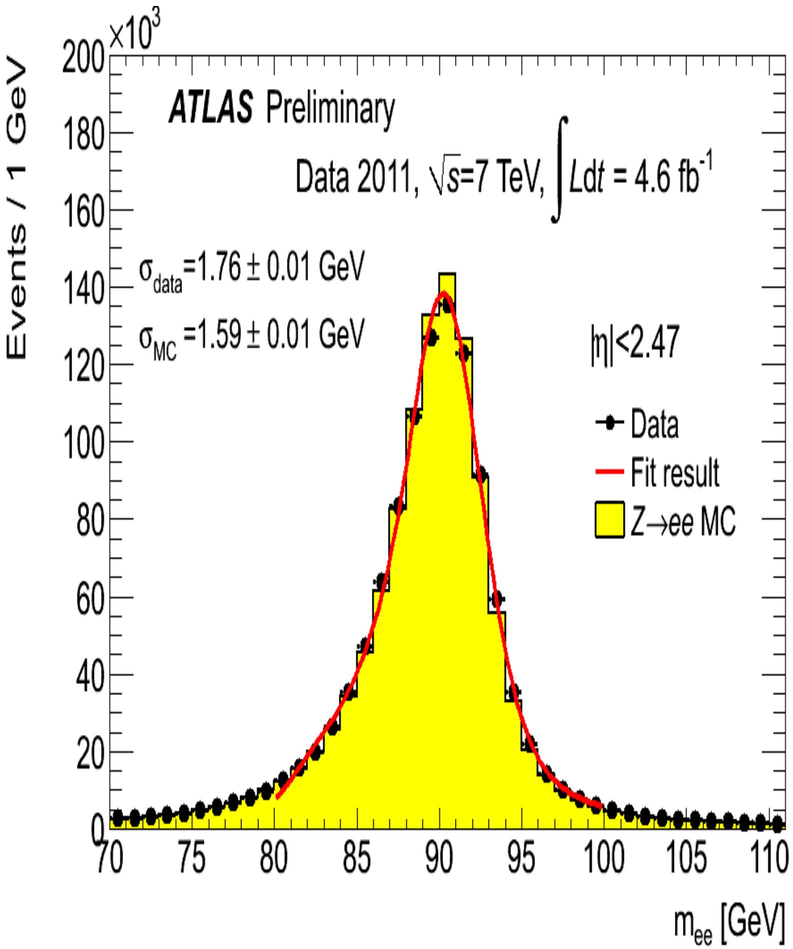
- ...

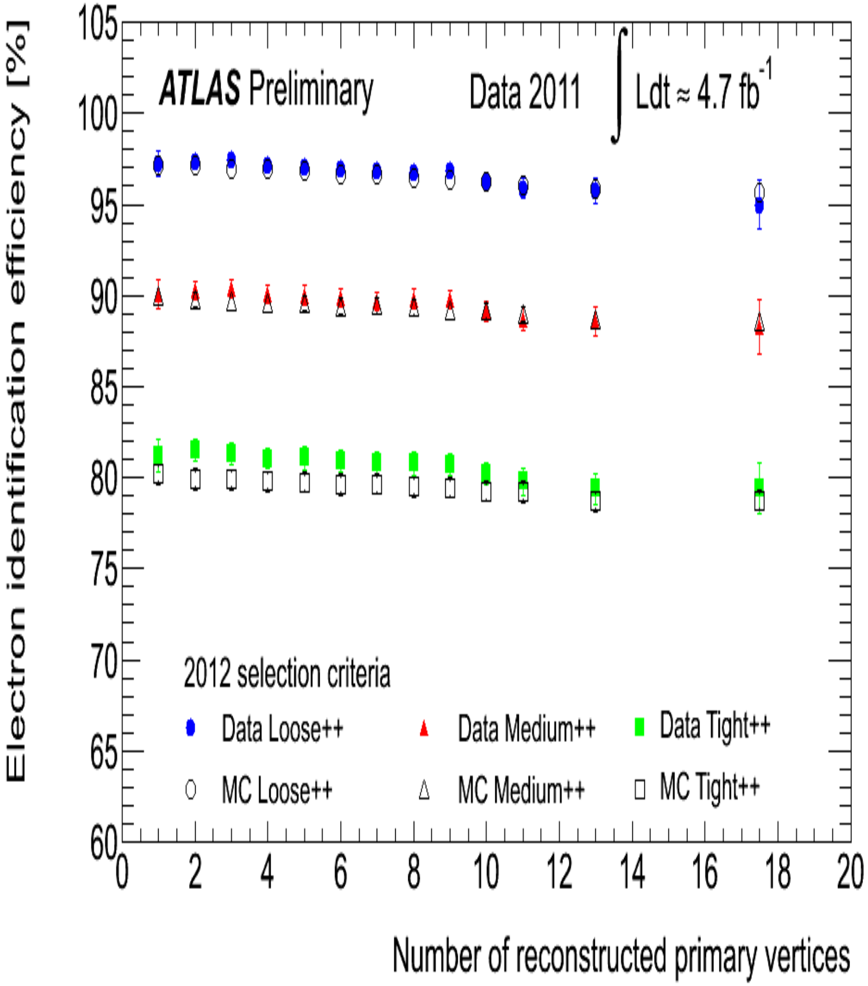

ATLAS
EXPERIMENT
http://atlas.ch
Run 152166
Event 817271
b-tagged jet in 7 TeV collisions
Si strips
beampipe
pixels
jet
p_T =19 GeV (measured at electromagnetic scale)


ATLAS Preliminary
$\int L\,dt = 20.3\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8$ TeV
b-jet efficiency scale factor
1
0.5
$t\bar{t}$ topo kin. sel. (total error)
$t\bar{t}$ topo kin. sel. (stat. error)
MV1, $\epsilon_b = 70\%$
20
30
40
50
60
70
80
10^2
2×10^2
3×10^2
jet p_T [GeV]

Electron Identification Efficiency

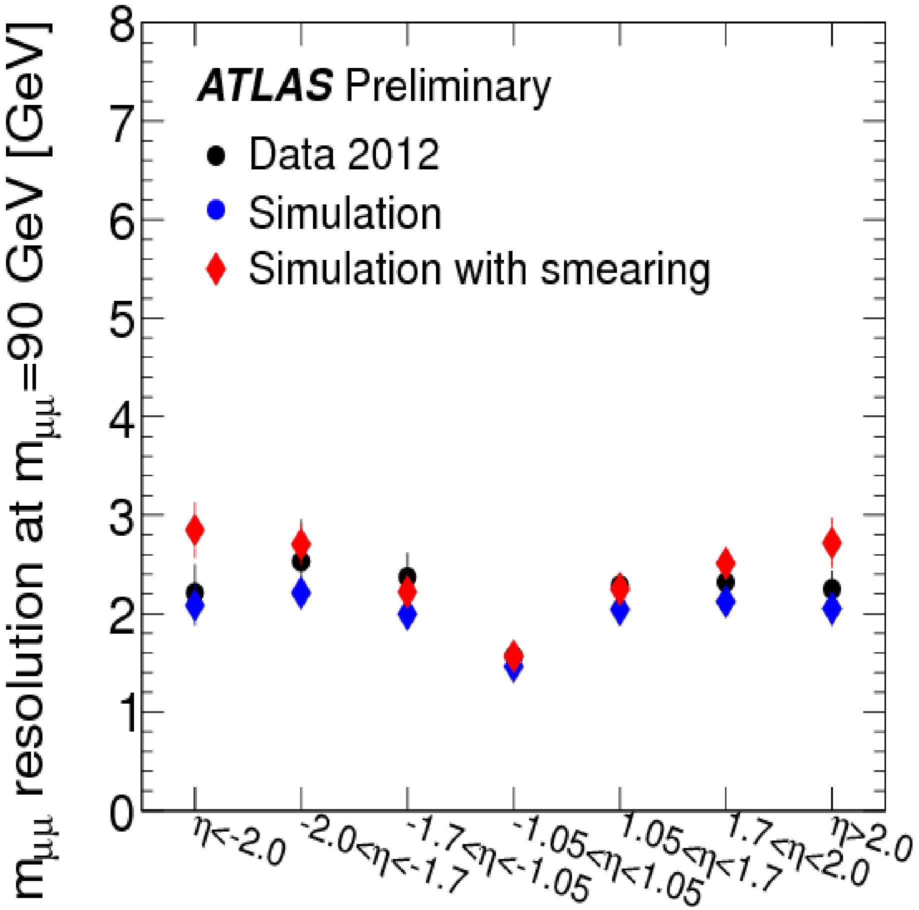
- Measured using tag&Probe with Z→ee.

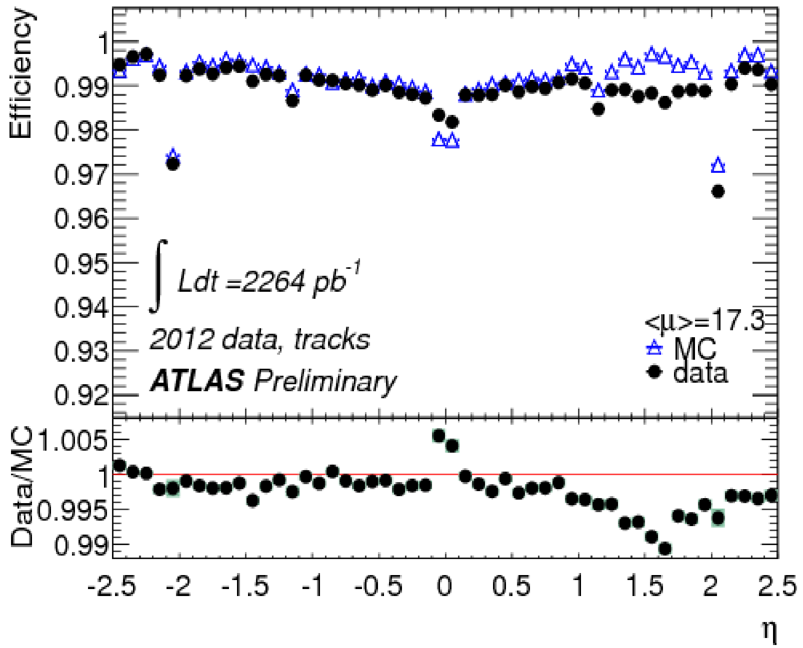




Muon Identification Efficiency

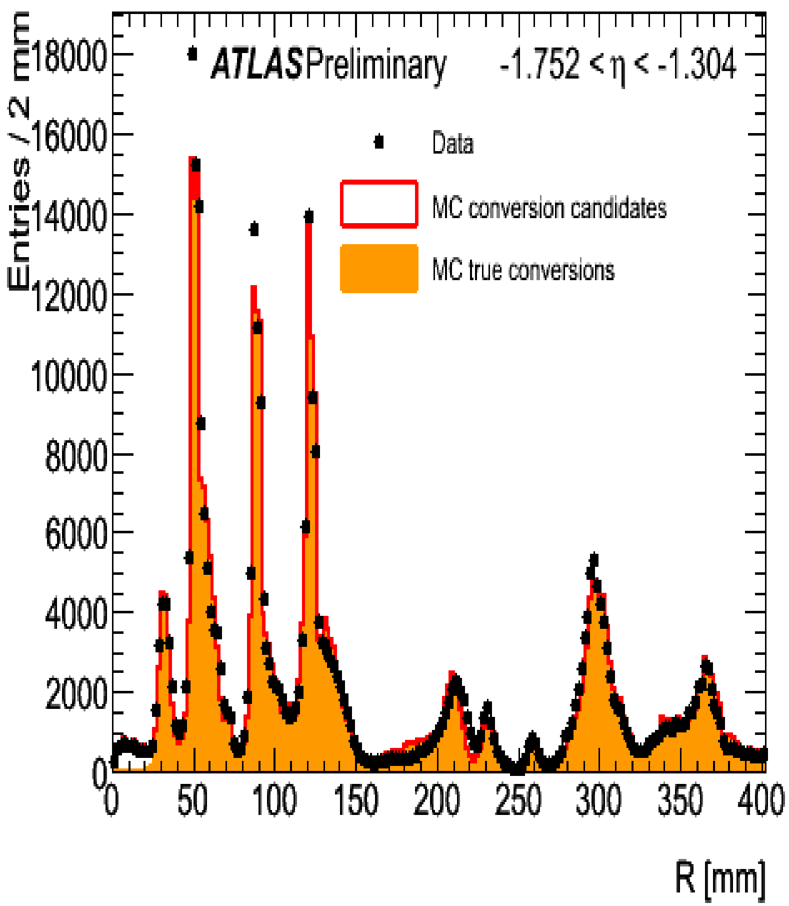
- Measured using tag&probe from $Z \to \mu\mu$ decay

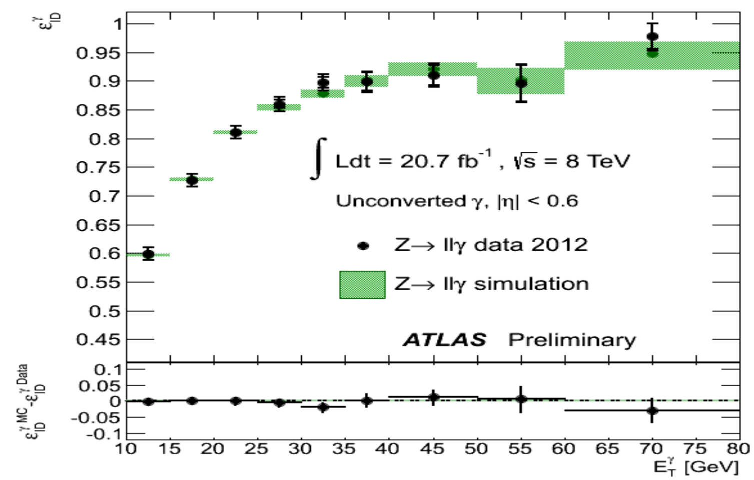


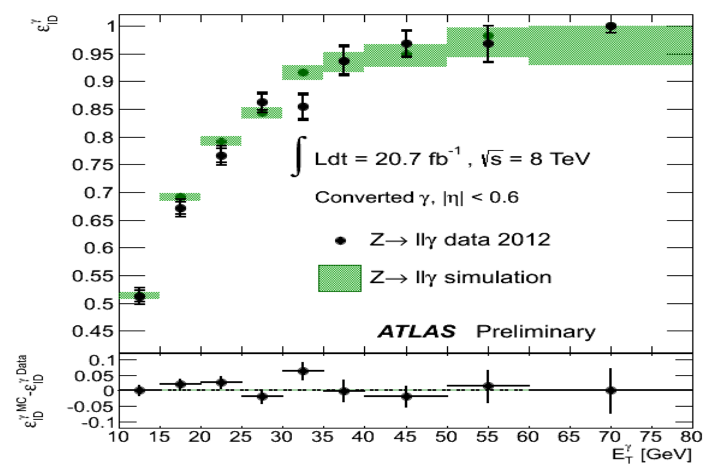


Photon Identification Efficiency

- Conversions are main contributor to inefficiency
  - Studies focus on understanding the material

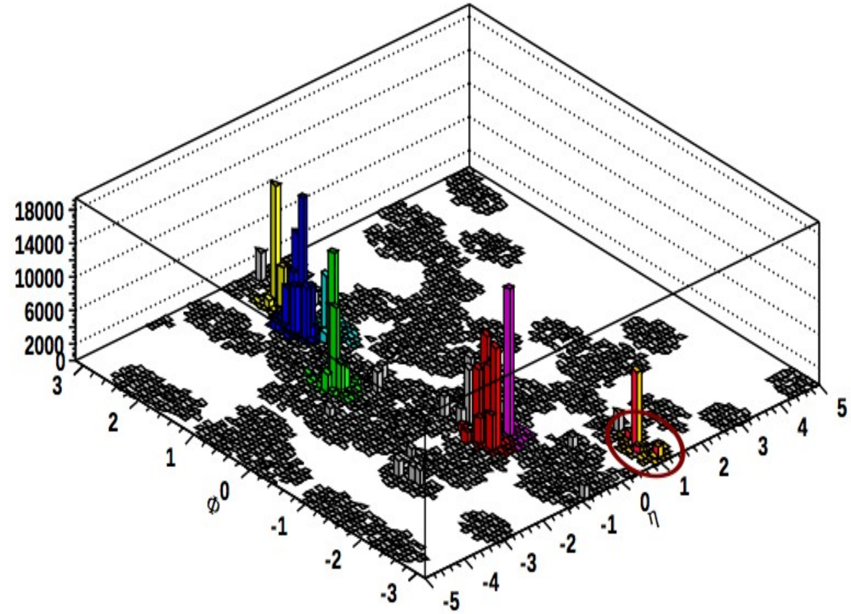


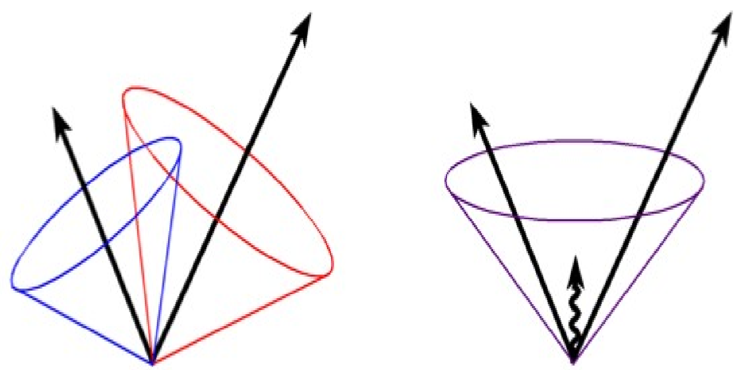




Jets Algorithms

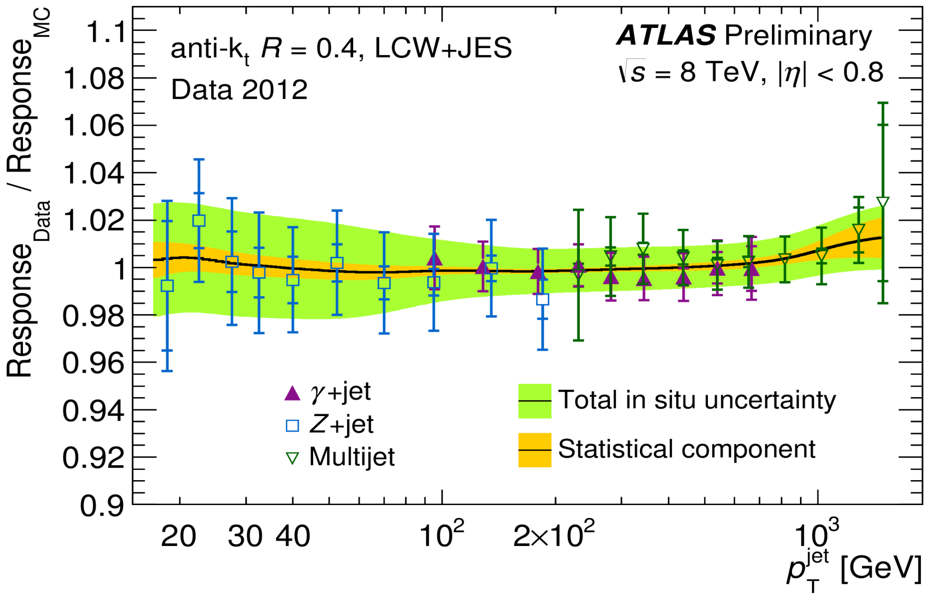
- Measure direction and energy of prompt hadrons from energy deposits in calorimeters.
- Geometrical cone algorithms simple but not infrared safe
- Kt/anti-Kt clustering algorithms
  - Define distance
  - $d_{ij}=\min(Pt_i^k,Pt_j^k)dR_{ij}^2/R$
  - Keep merging two d_{ij} into a new jet until $d_{ij}>d_{ibeam}(Pt_i^k)$
  - k=1:Kt; k=-1: Anti-Kt

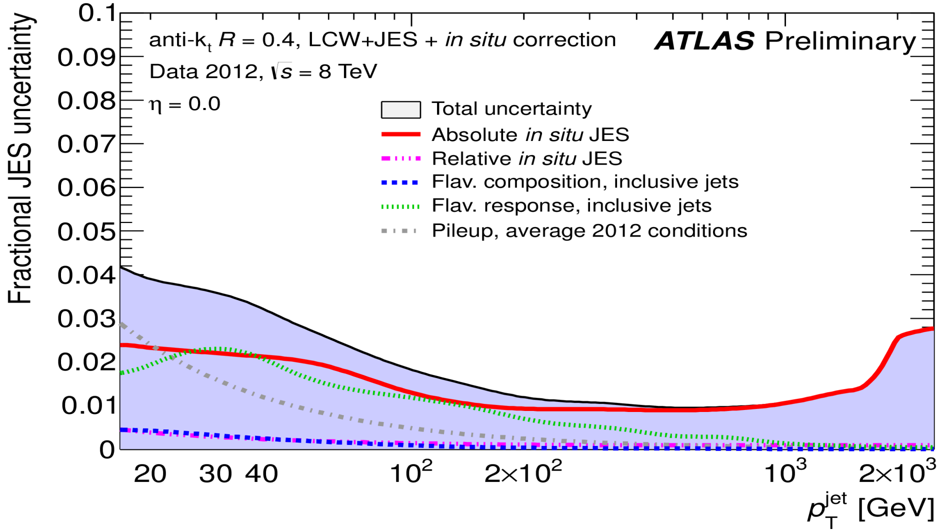




Jet Reconstruction Performance

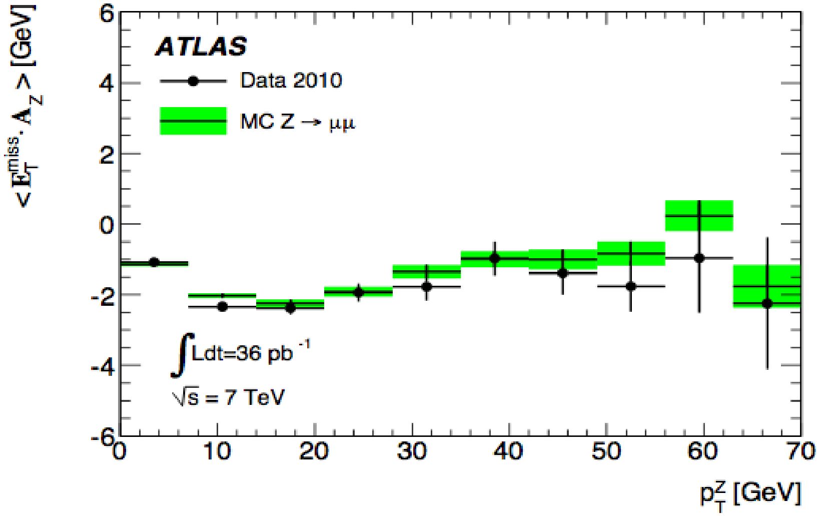
- Mainly energy resolution and reliability of jet energy, the jet energy scale factor(JES).
- Various in-situ methods
  - Di-jet balance
  - Photon-jet balance
  - M_W constrain
- Other effects:
  - Pile-up
  - Out-of-time pile-up

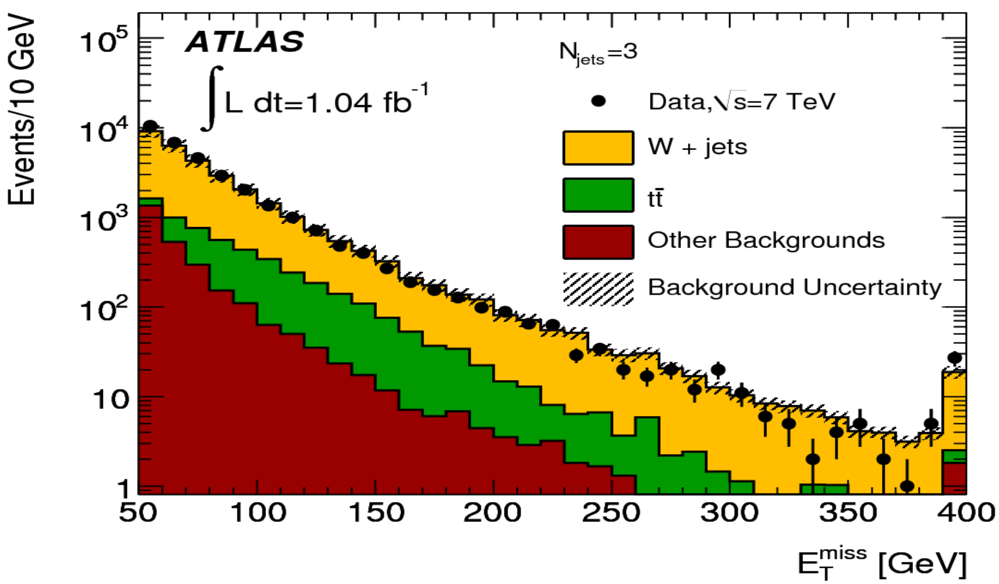




Missing Transverse Energy

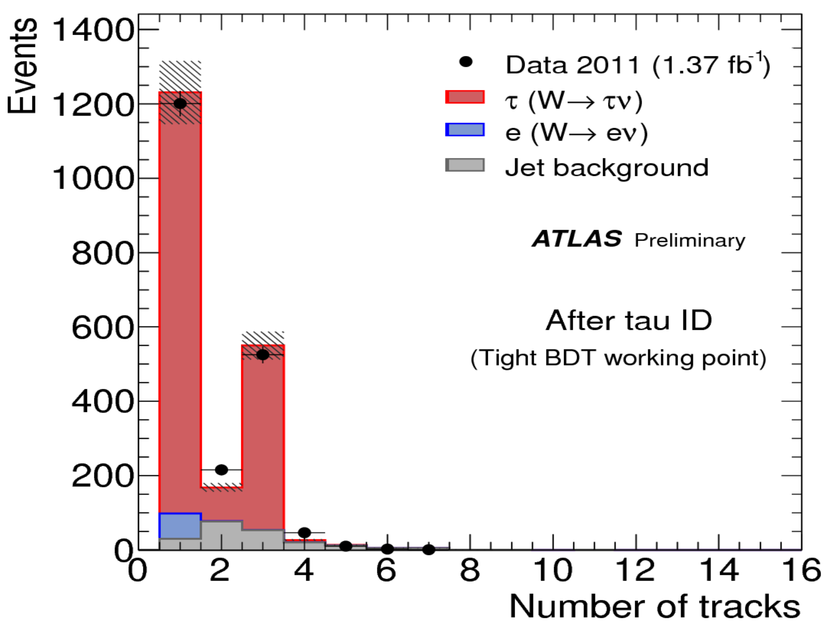
- In hadron collisions, total momentum in transverse is conserved
- Missing Et points to weakly or non-interacting particles
  - Et(miss) = -∑Et
- Simple strategy: sum up calo energy and correcting muon's p
- Best strategy: sum of physics calibrated objets, overlap removal

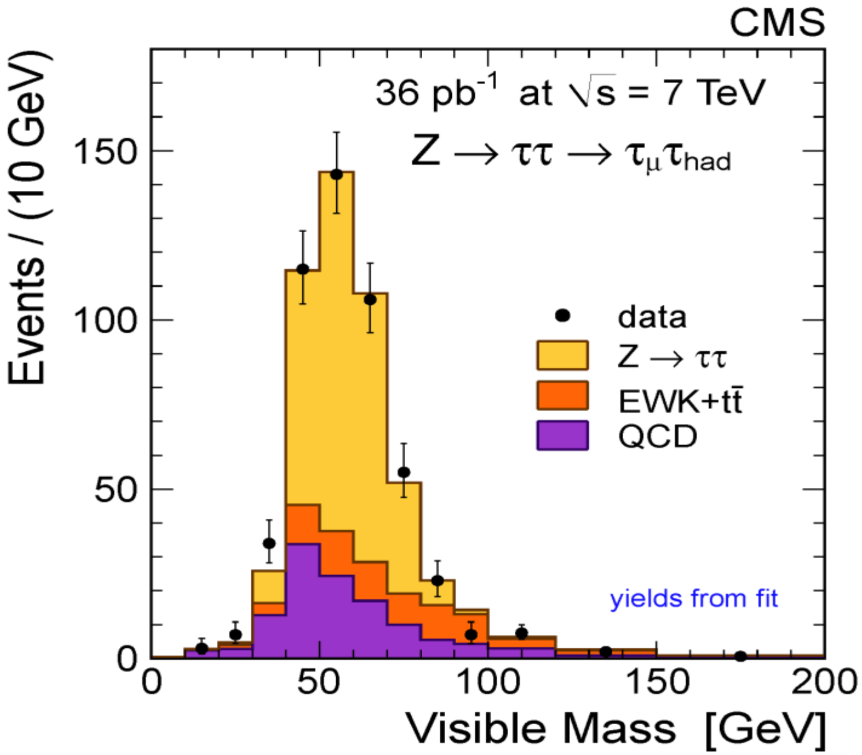




Tau Reconstruction

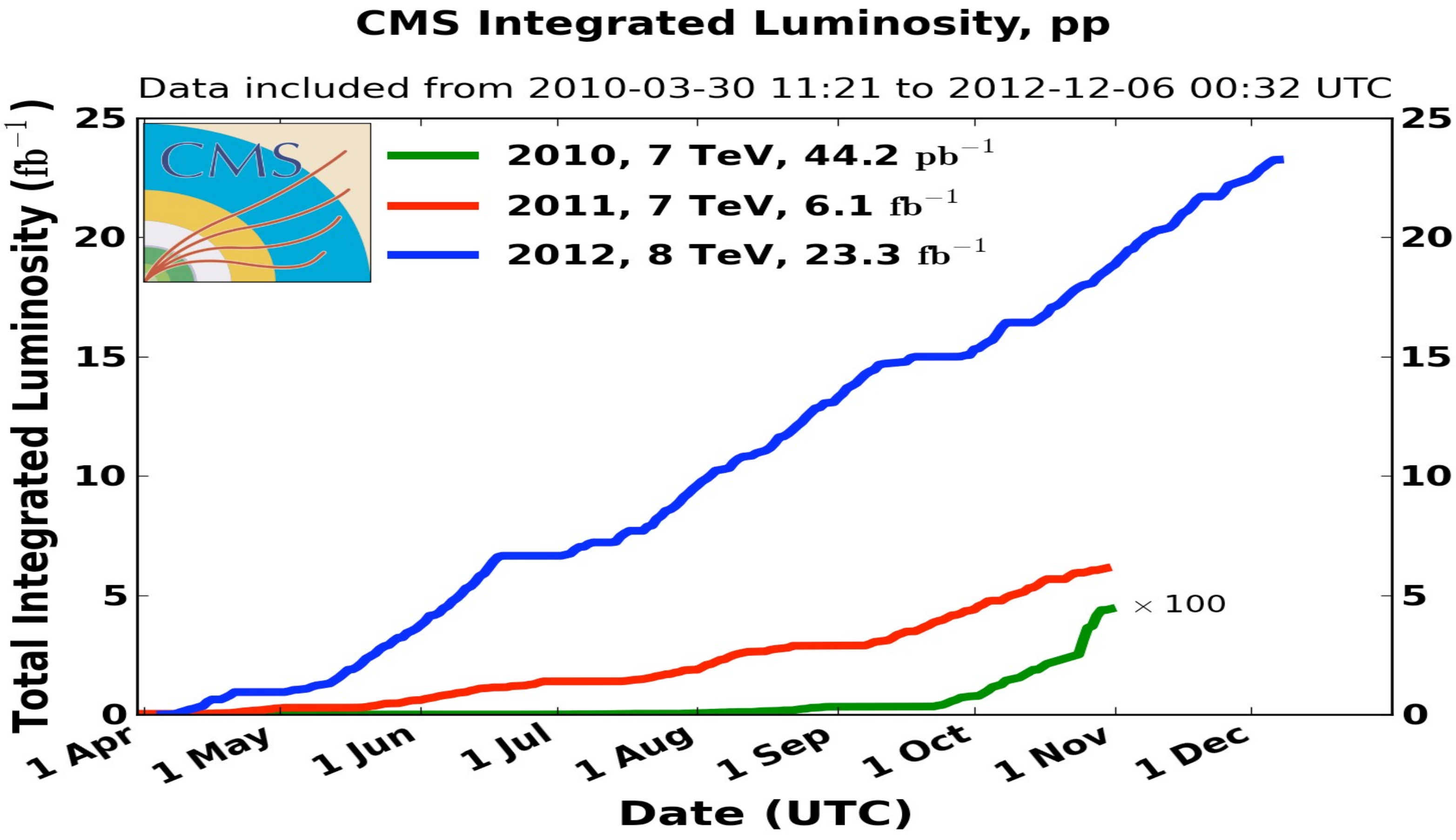
- Track-seeded and Calo-seeded candidate
  - Tracks(Pt>6) or Calo-jet Et>10 GeV as seed
  - Collected tracks(Pt>1) around seed in dR<0.2,0.4
  - Look for large number of identification variables to form set of discriminators.





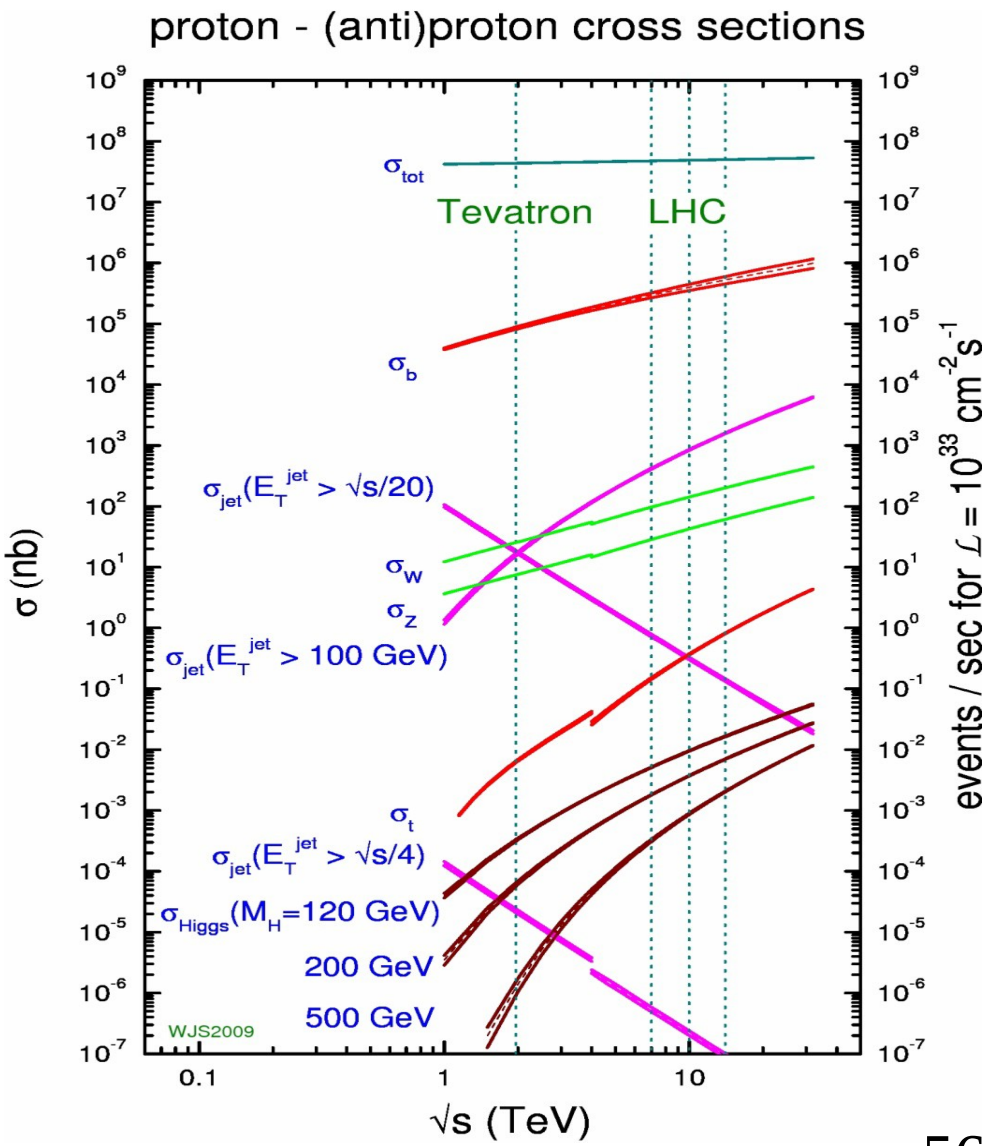
LHC Data Taking over last three years

- Excellent performance over last three years.
- Both ATLAS and CMS have data taking efficiency about 91-95%.
- The achieved record instantaneous luminosity at 7.5×10^{33} $cm^{-2}s^{-1}$



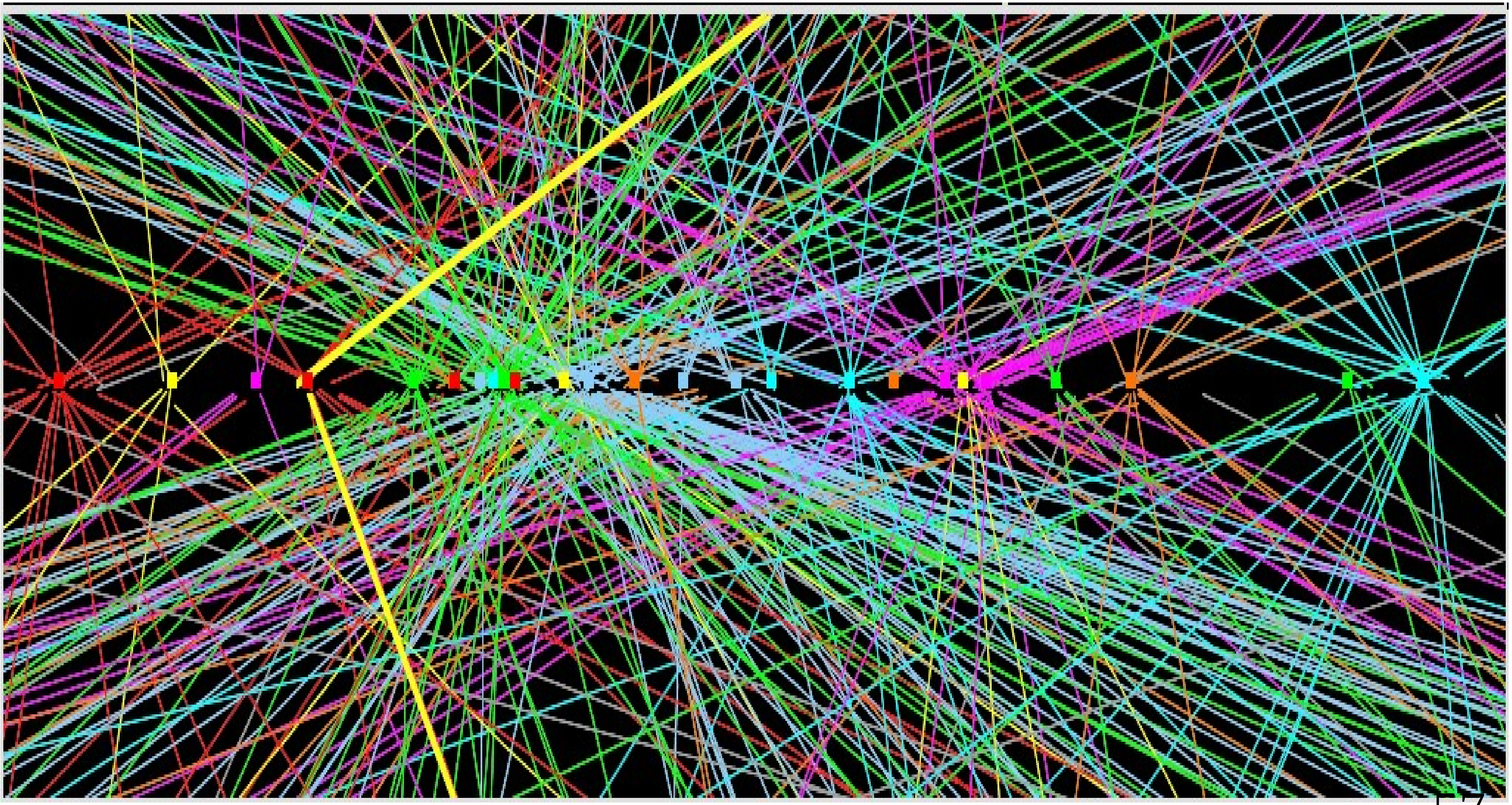
Re-Discovery Standard Model Physics

- Total cross-section ~ 70mb varies slowly with sqrt(s)
- High Pt processes represent only a small fraction of total and are enhanced at high sqrt(s)
- Most interactions are soft and particles in the final state have small Pt.
- There are average 25 pile up events at peak luminosity of 7×10^{33} $cm^{-2}s^{-1}$.



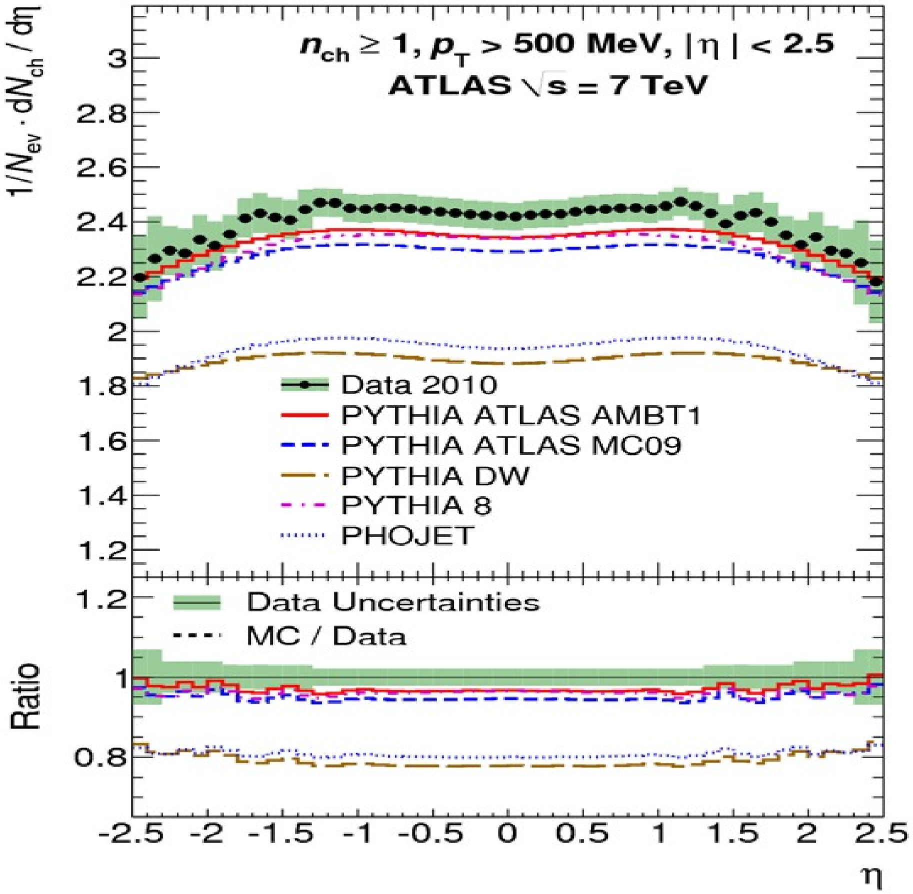
Events with Multiple Interactions

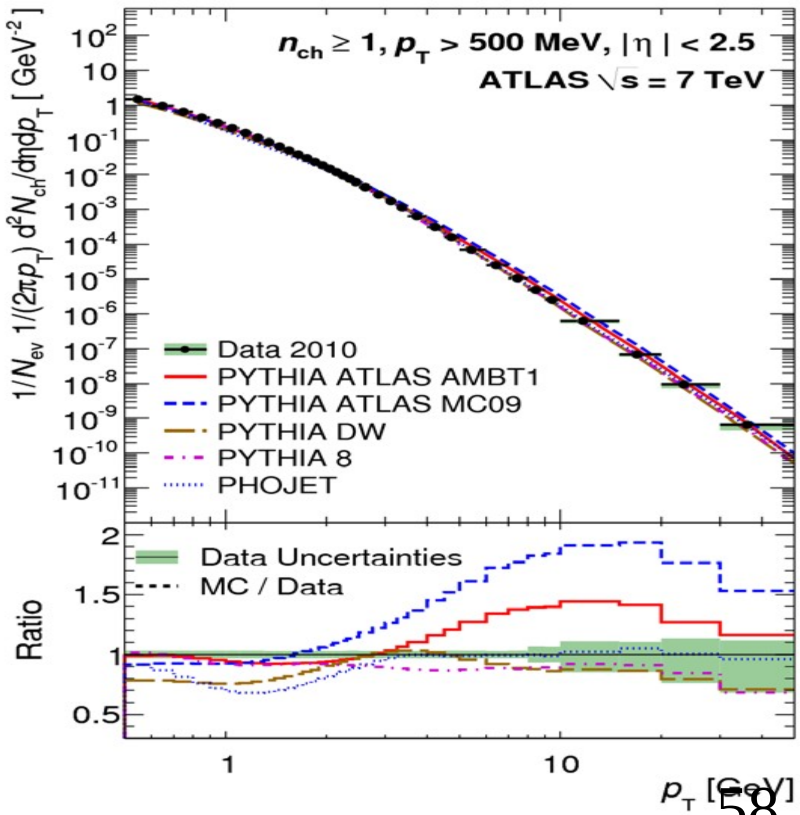
- There are no reliable QCD calculations available for these soft interactions and we have to use data to tune our Monte Carlo



Charged Particle Multiplicities

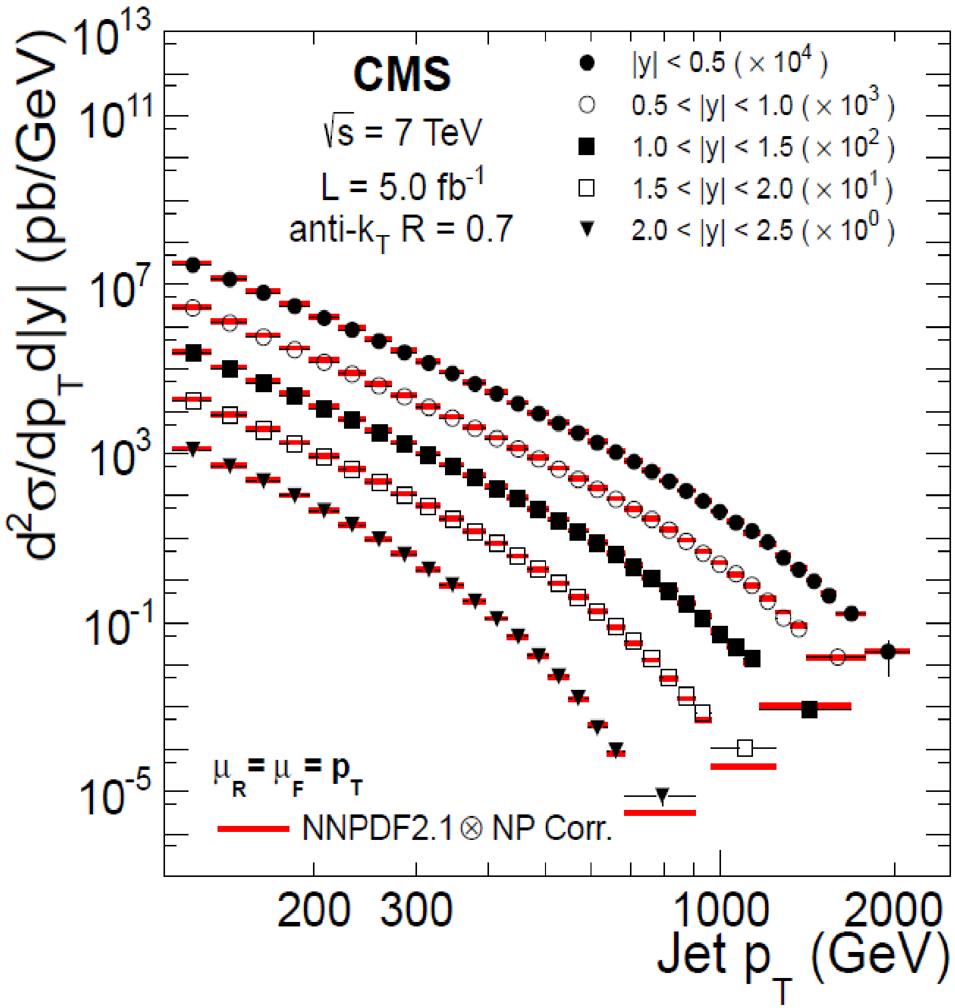
- Charged particle multiplicities at 7 TeV for Pt>500 MeV,nch>=1
- Simple MC model does not fit data well,but MC tuned to data from Tevatron does a reasonable job.

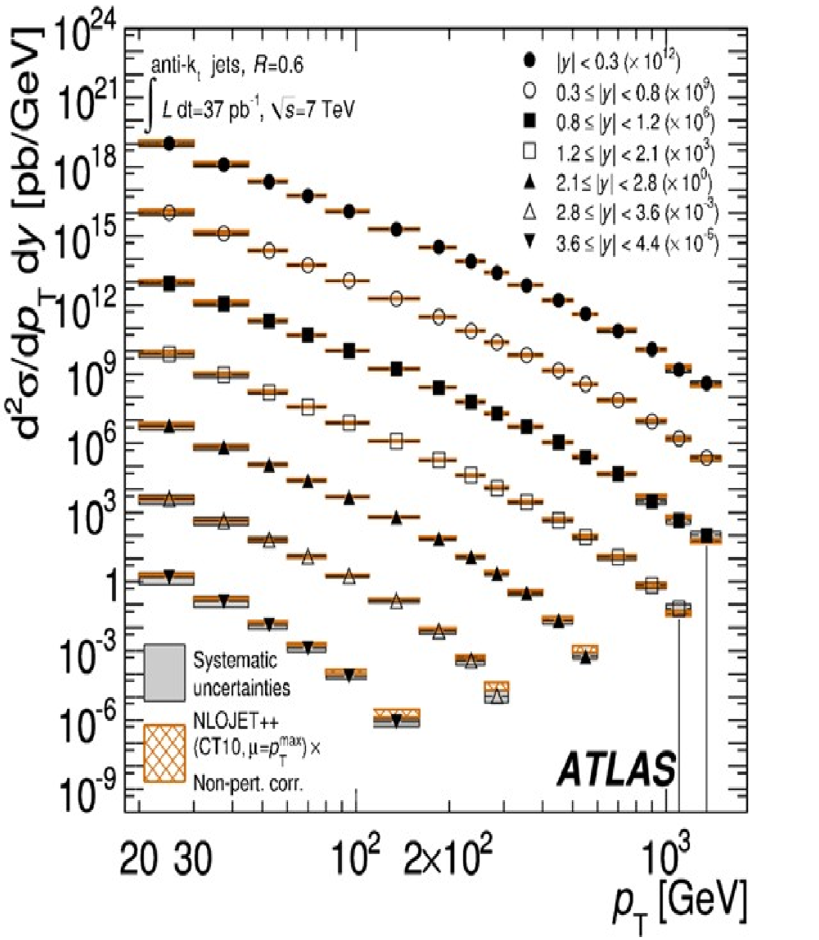




Jets at LHC

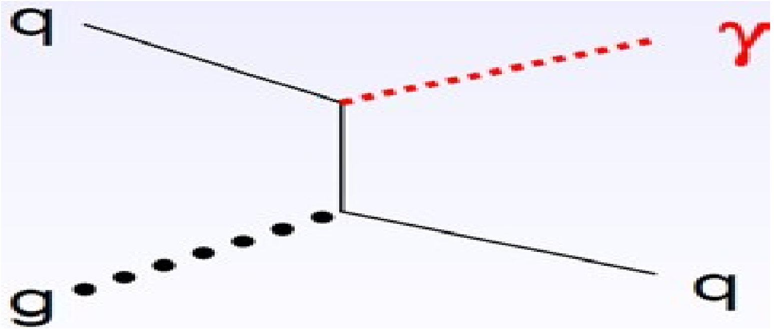
- High Pt jets probe close to the kinematic limit of LHC to test QCD in a new region. Good agreement with NLO QCD predictions.

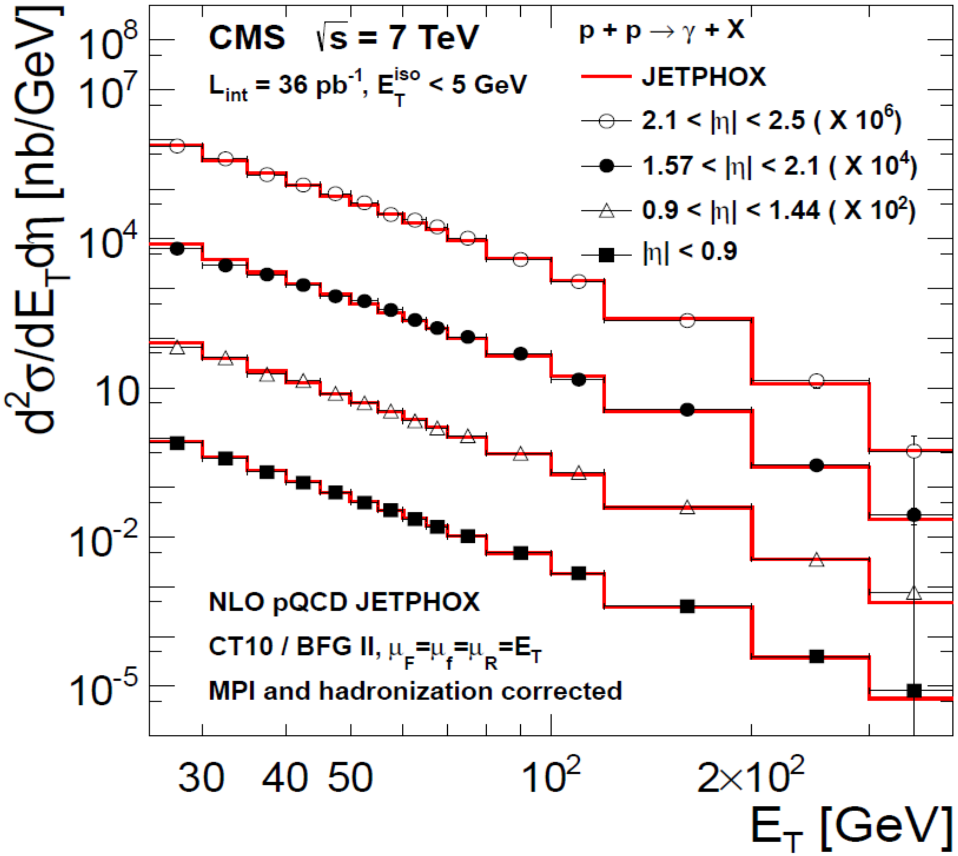


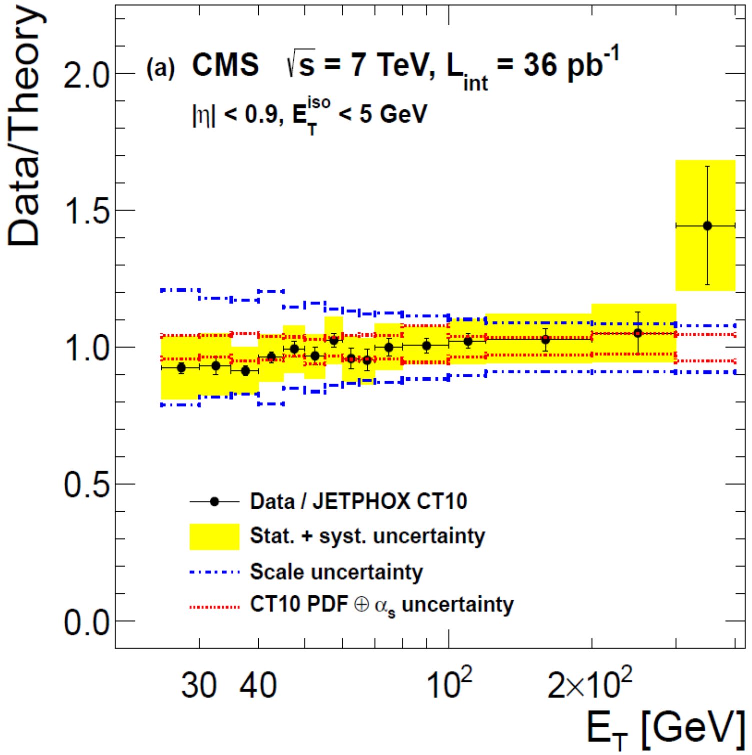


Prompt photon production at LHC

- Isolated prompt photon production
  - Complementary test of pQCD
  - Important background to H→γγ

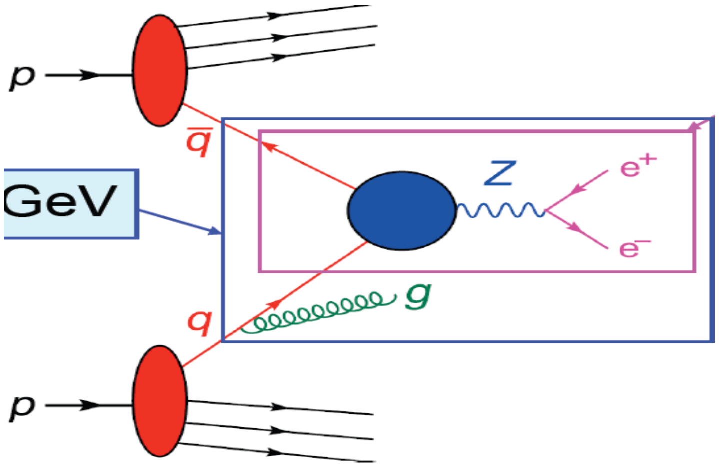


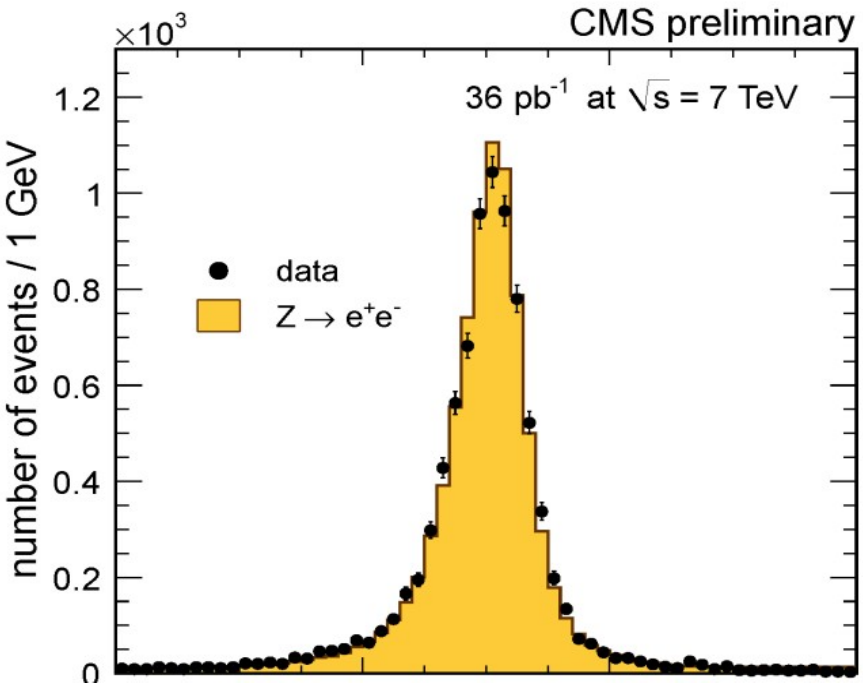


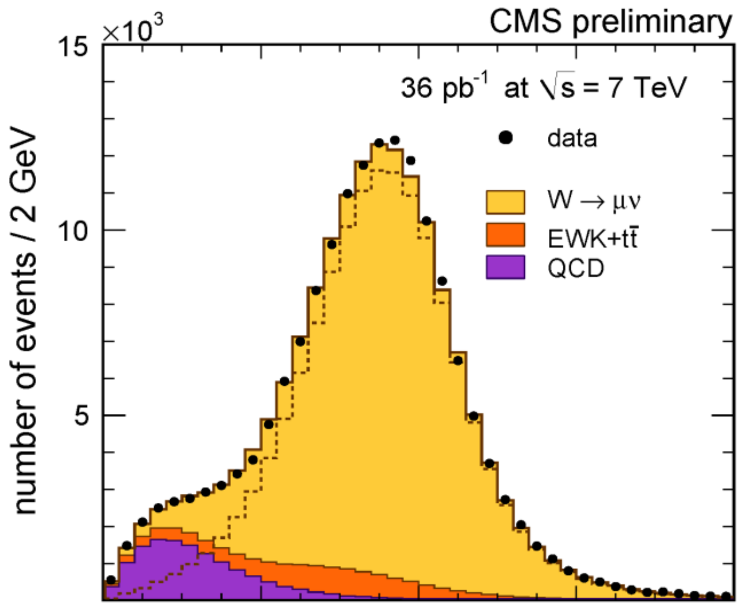


W and Z physics

- Main source of isolated high pt leptons
- Benchmark for lepton performance (eff,scale, resolution)
- Search for new particles via W,Z

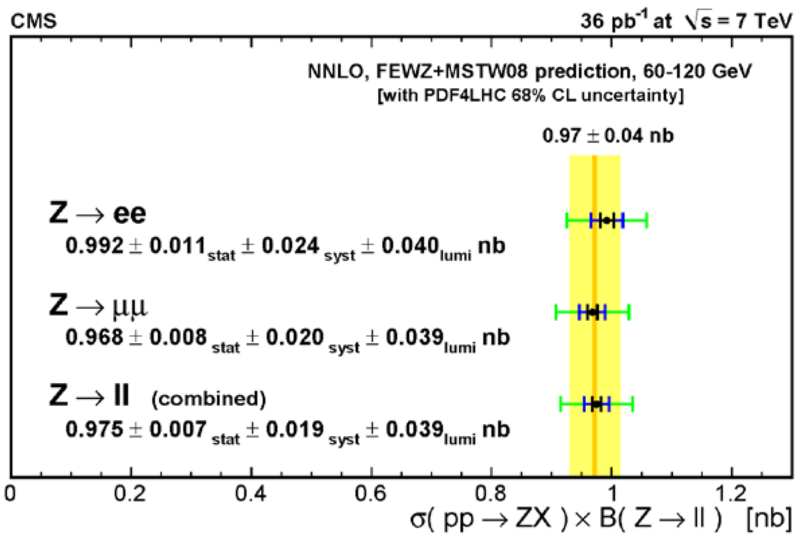


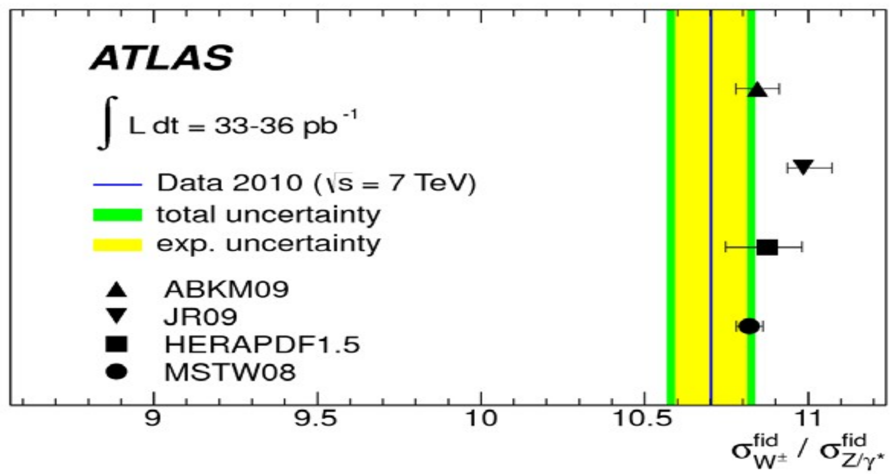


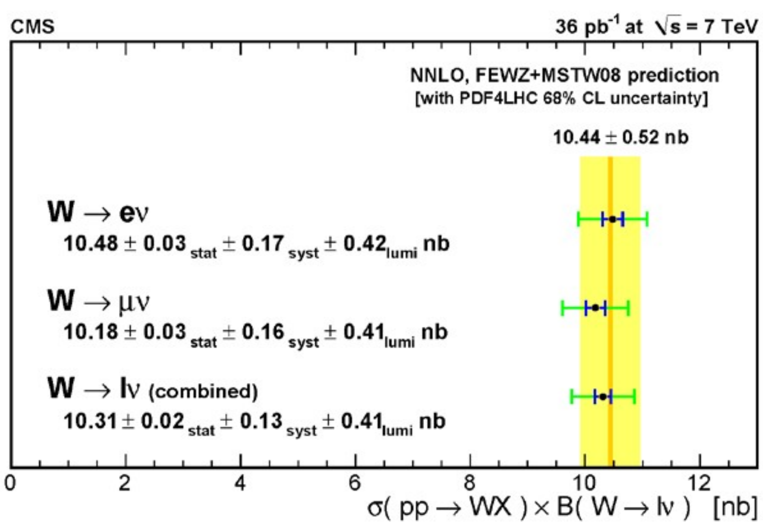


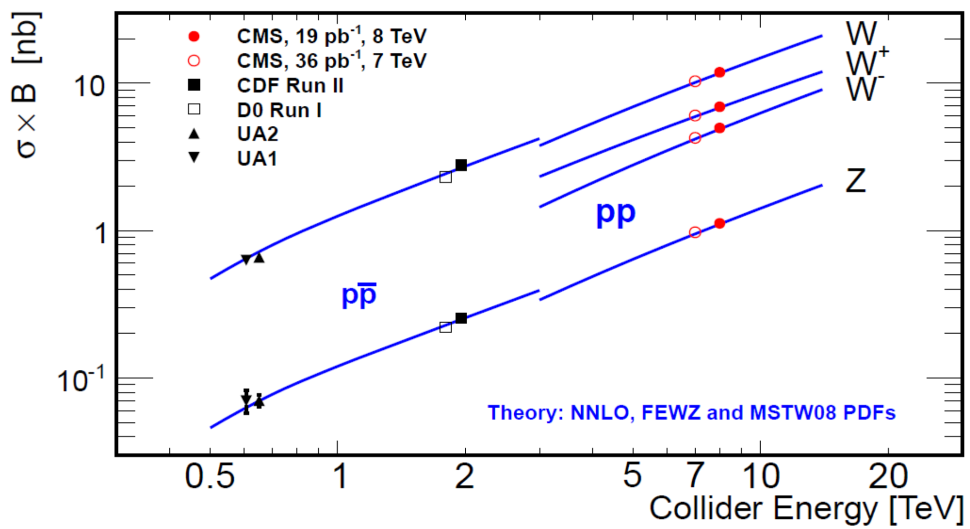
W and Z Inclusive cross section

- Consistent with NNLO predictions.



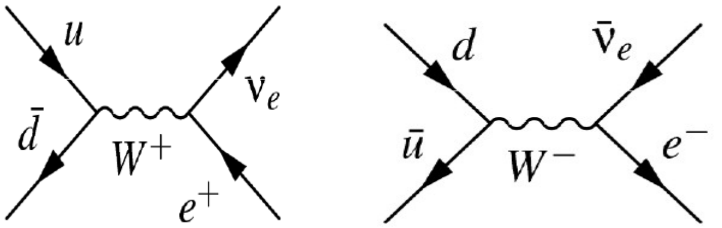


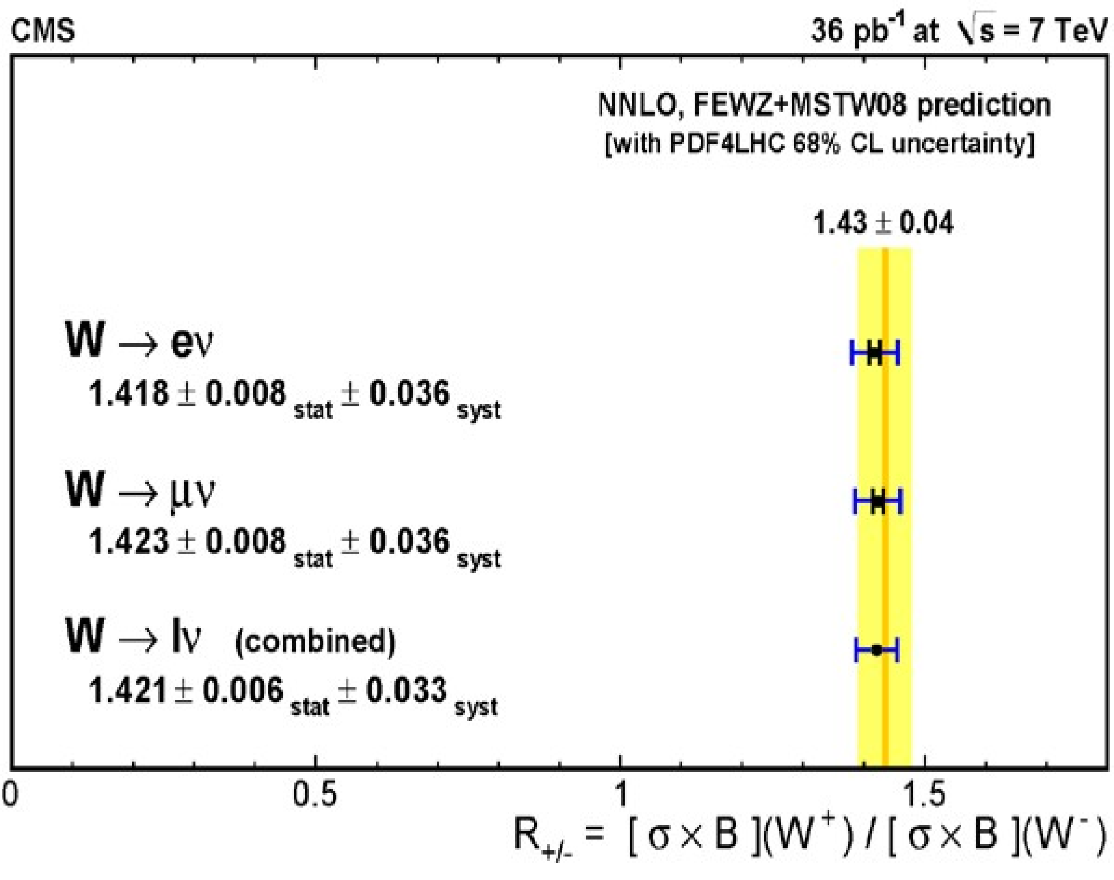


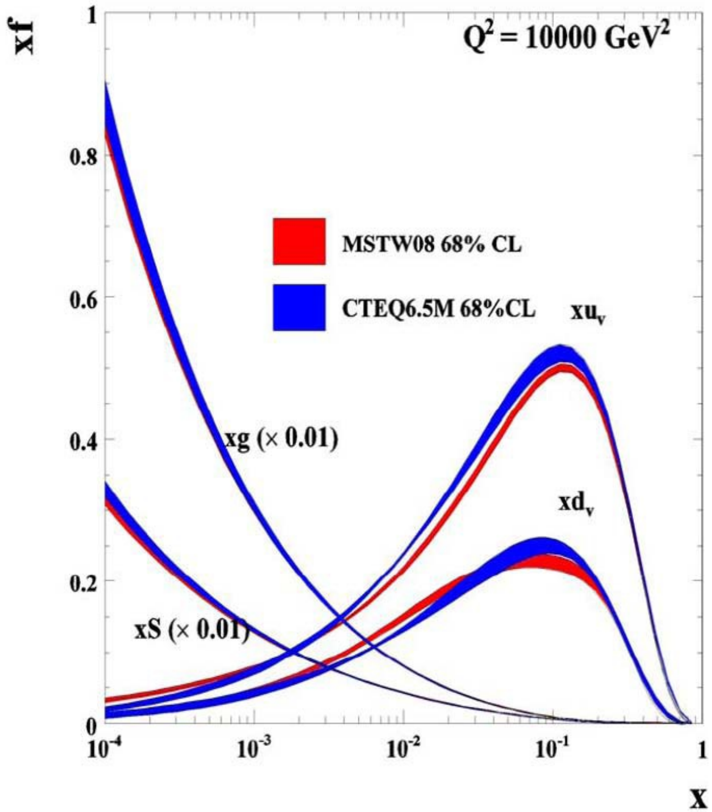


W^+ and W^- cross-section

- pp collisions produce more W+ than W-
- Measurements give ratio of 1.4 for W+ over W-, in good agreement with NNLO

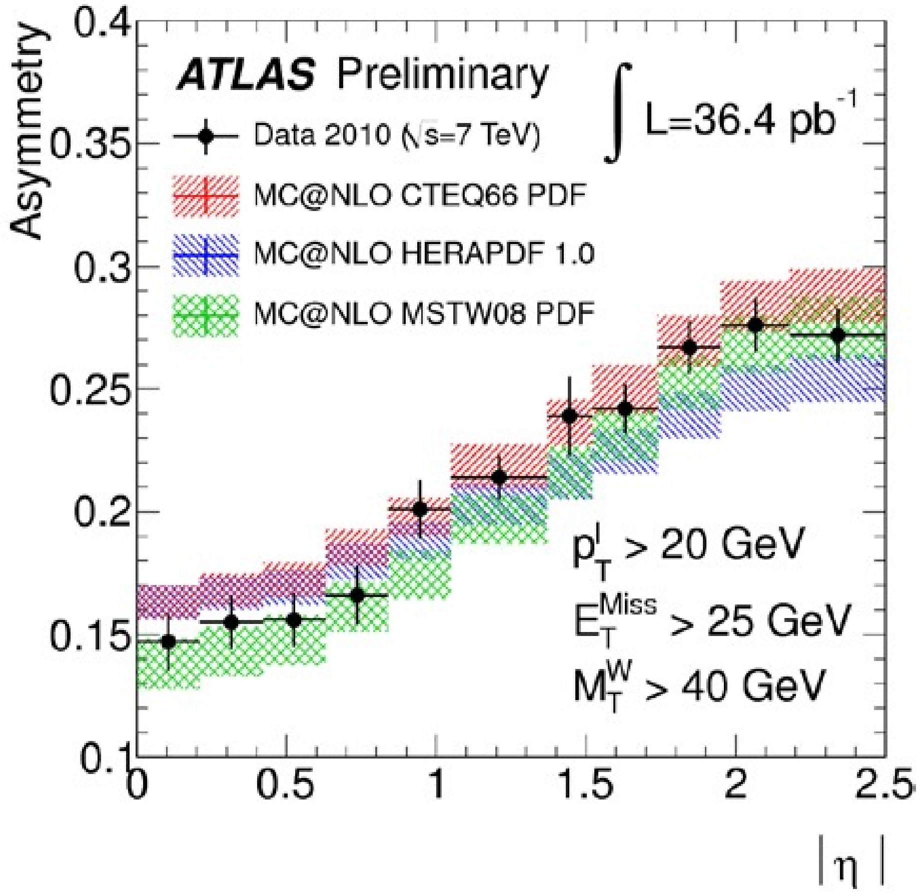


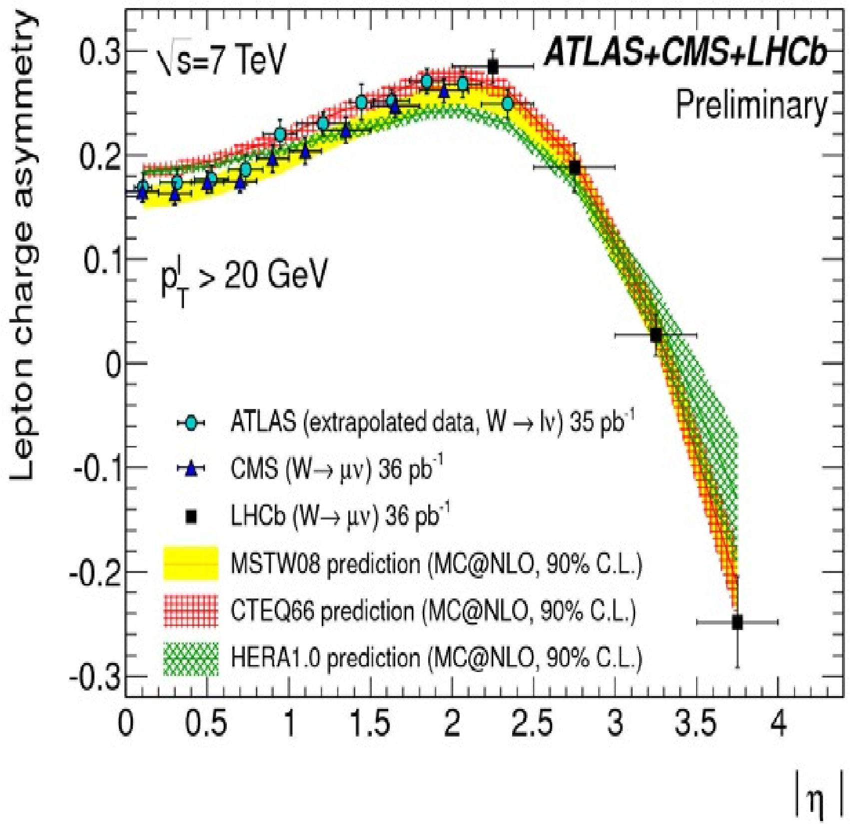




W charge asymmetry

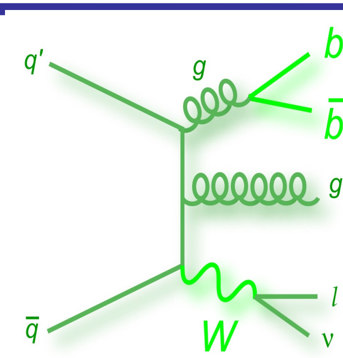
- Cross-section asymmetry depends on momentum fraction x of partons. Rapidity of W is correlated with lep-charge asymmetry.
- Measurements can be used to constrain PDF.

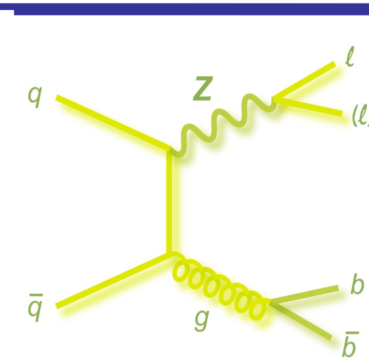


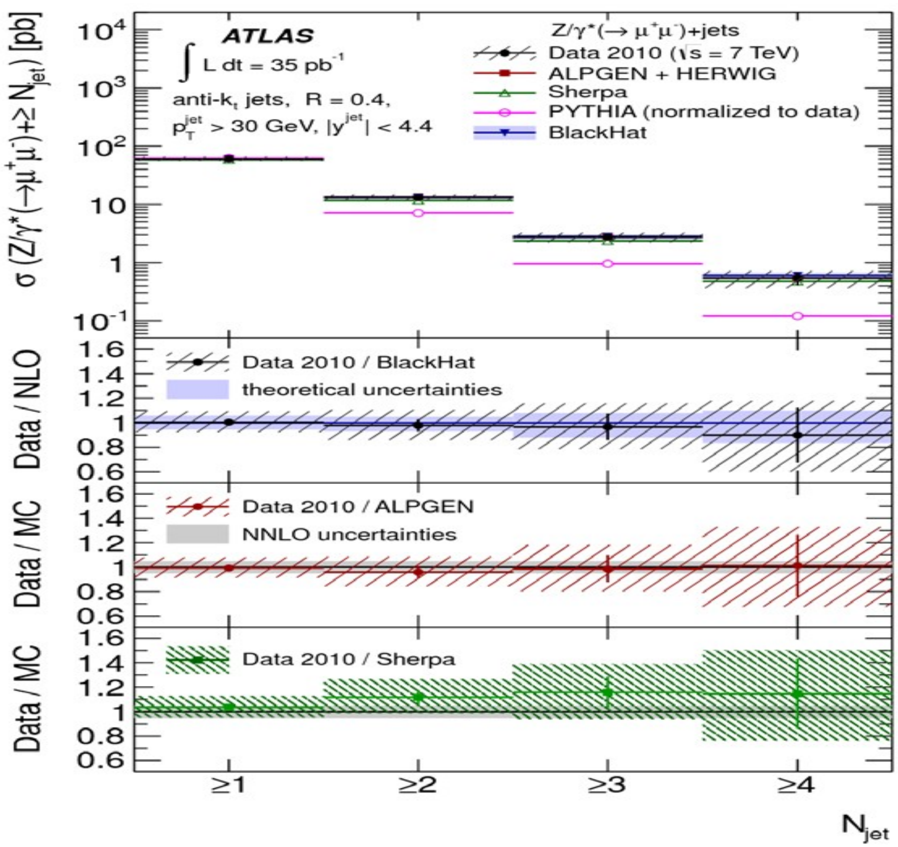


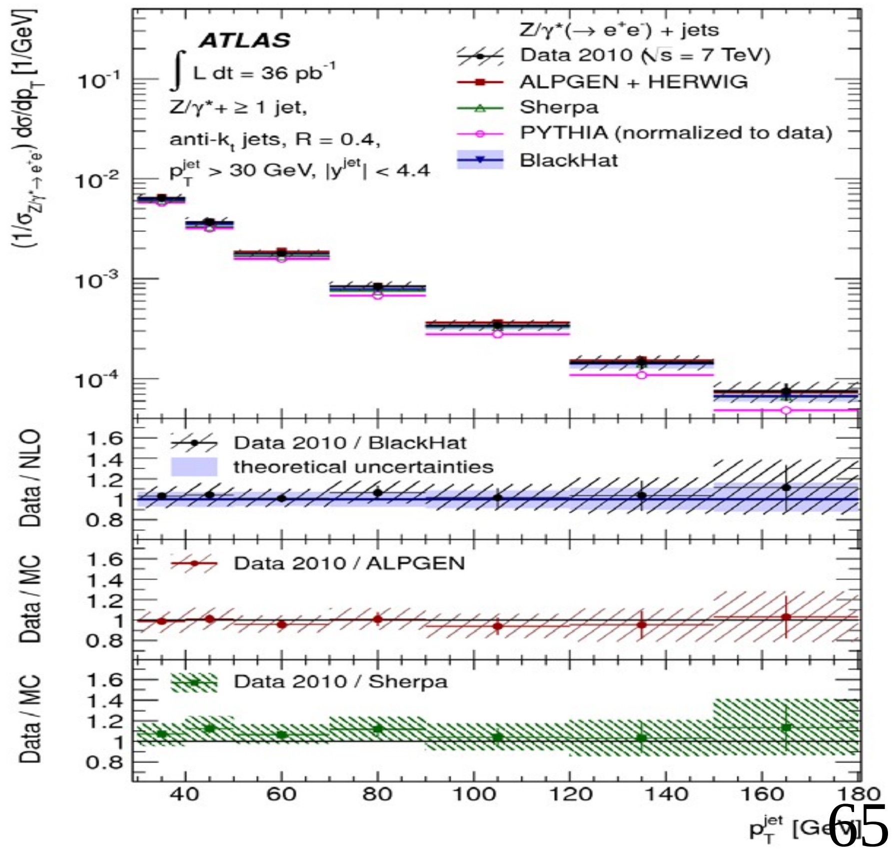
W+jets and Z+jets

- Vector Boson +jets cross section is a stringent test of pQCD
- Significant background for SM and BSM processes



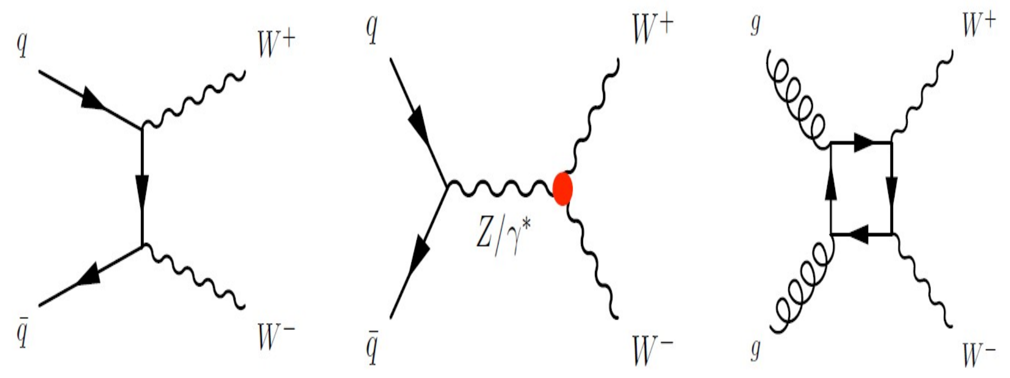


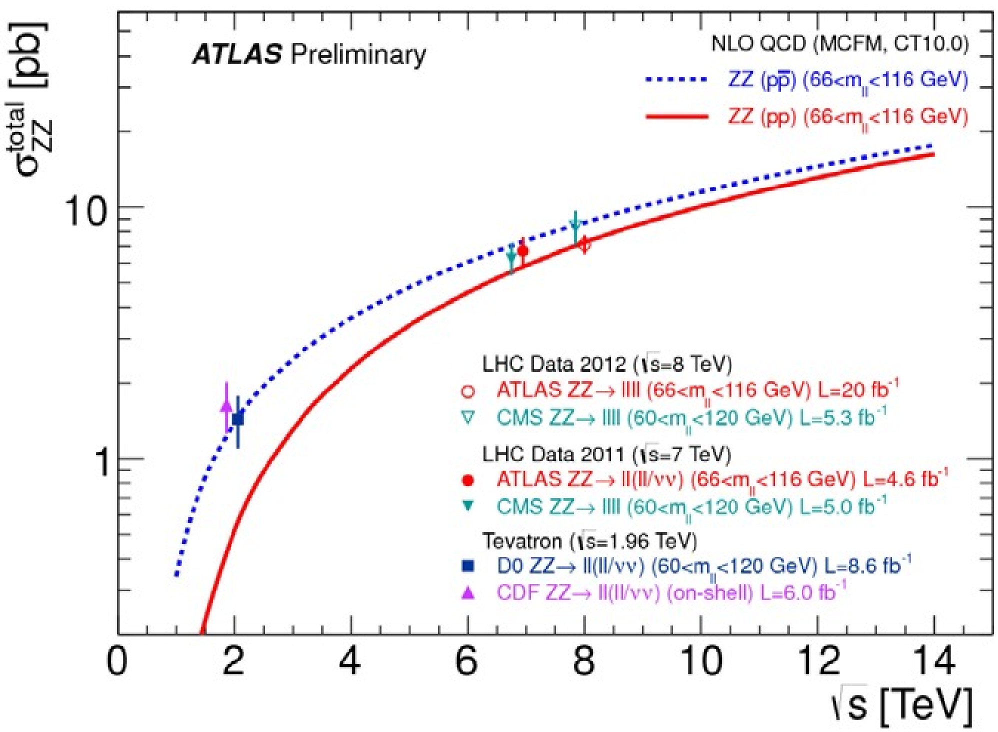


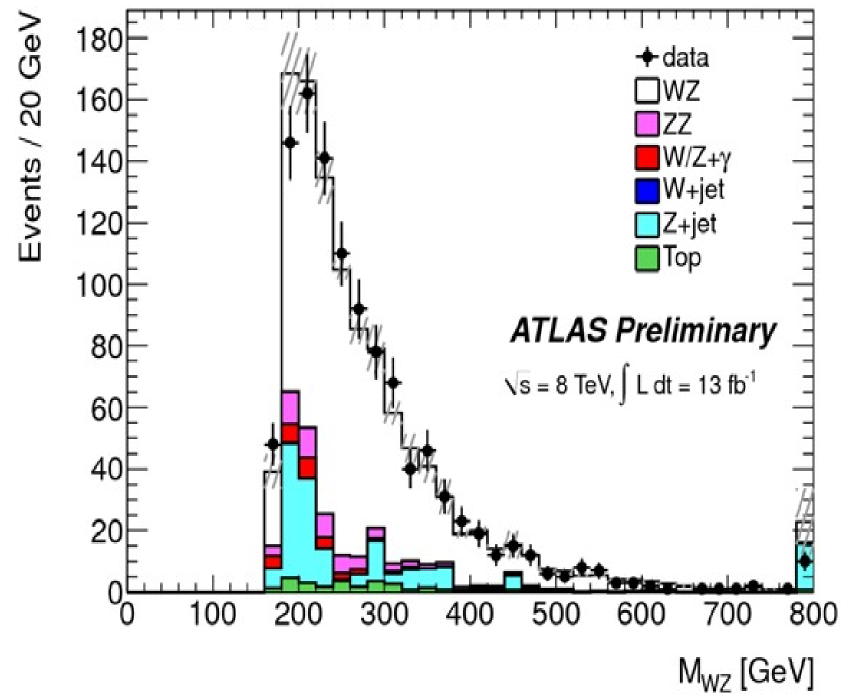


Di-boson: WW, WZ, ZZ

- Test electroweak model
- Sensitive to Triple Gauge couplings
- Dominant backgrounds to H→WW, ZZ searches.

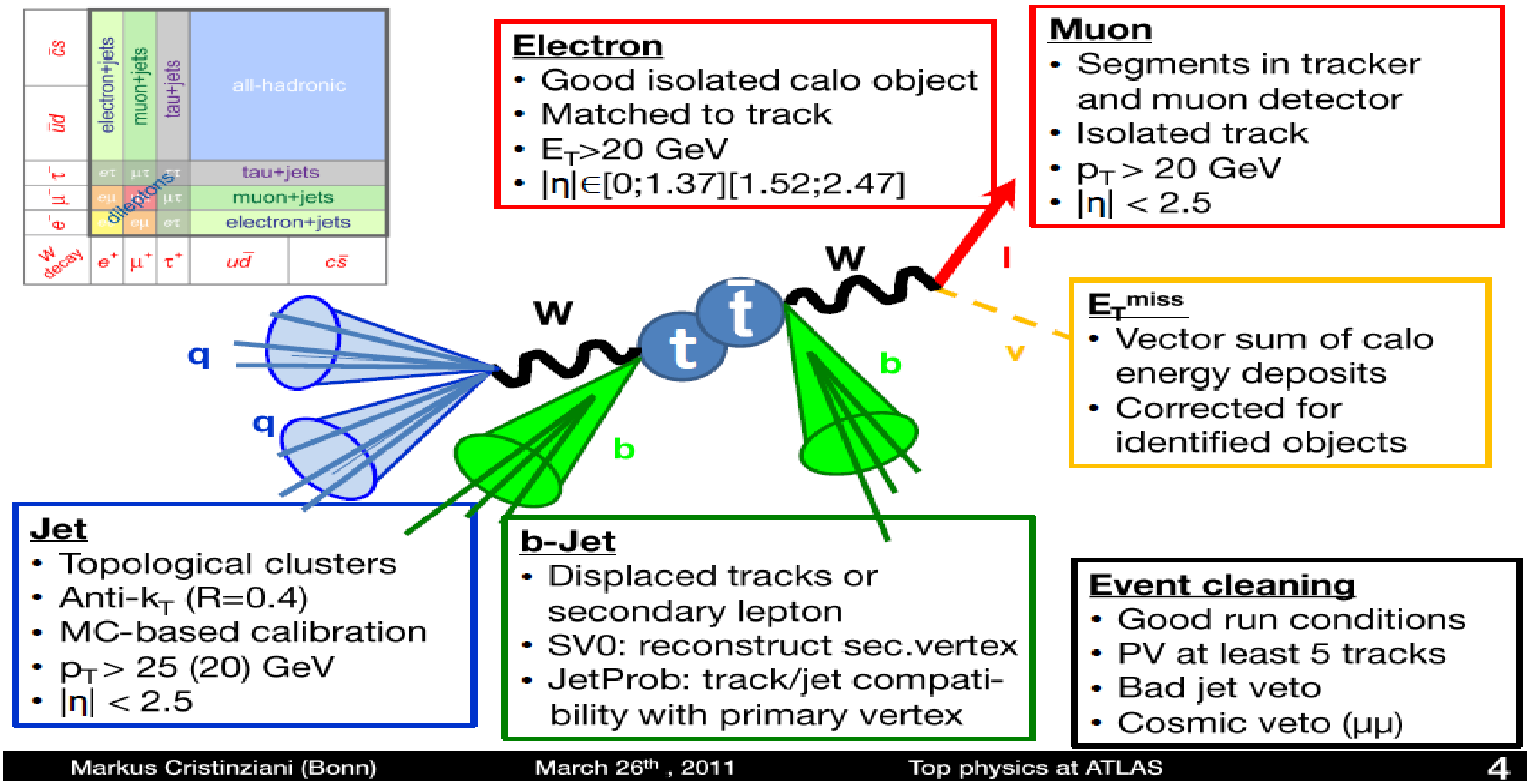






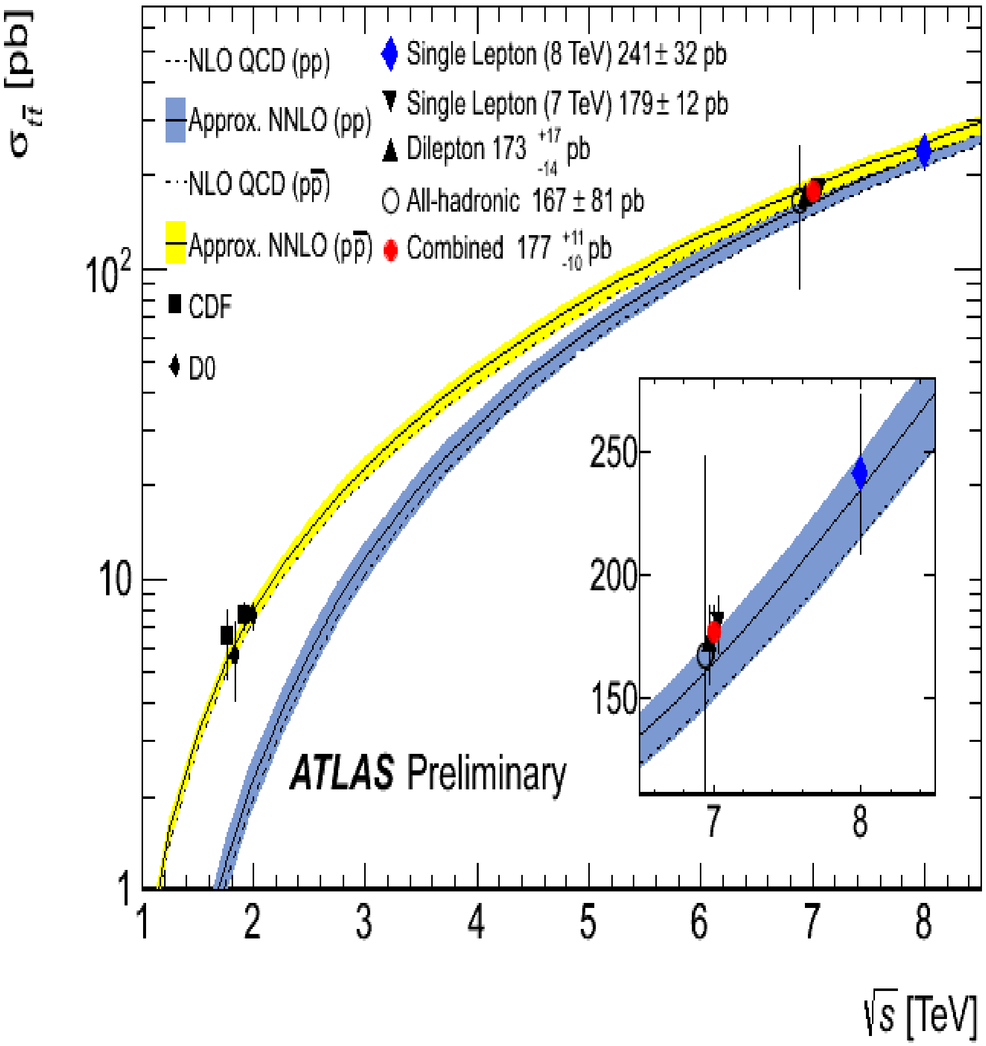
Top production at LHC

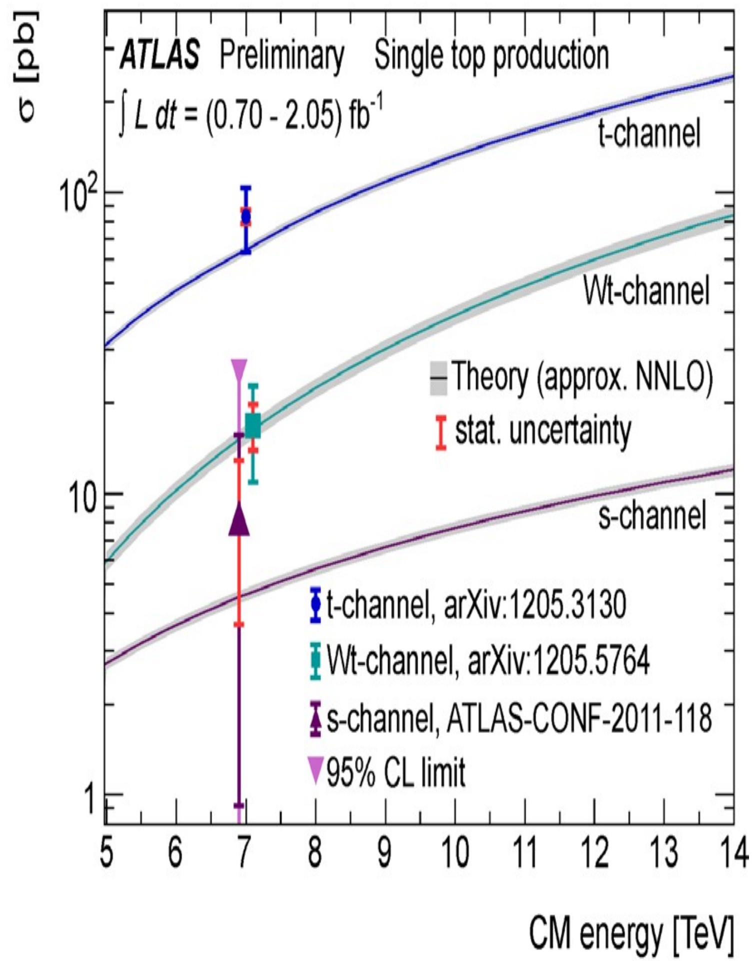
- Discovered by CDF and D0 at the Tevatron in 1995
- Questions about top remain why so heavy,Yukawa coupling,Vtb
- Dominant: pair production via ggF and qq; single t via EW.



Top cross section measurements

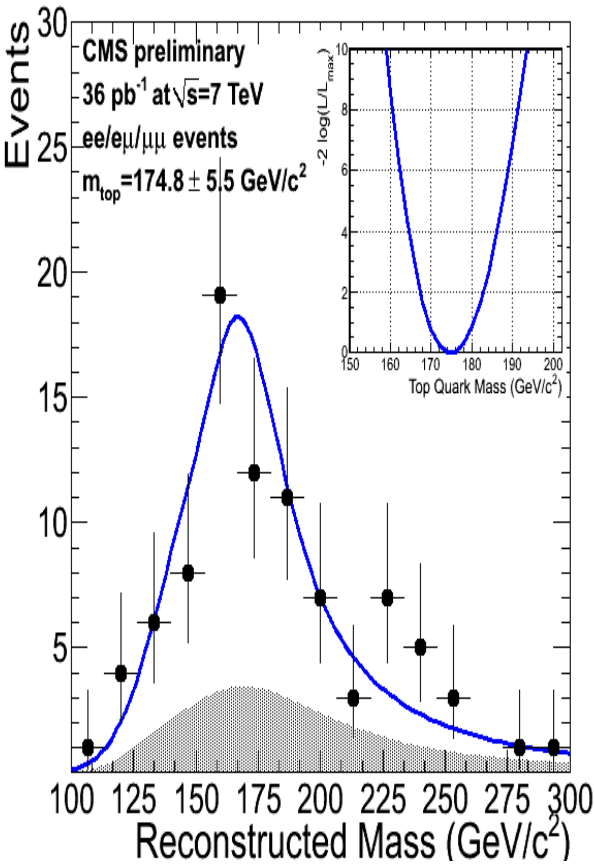
- Provides a stringent test of NNLO and major source of Wb background



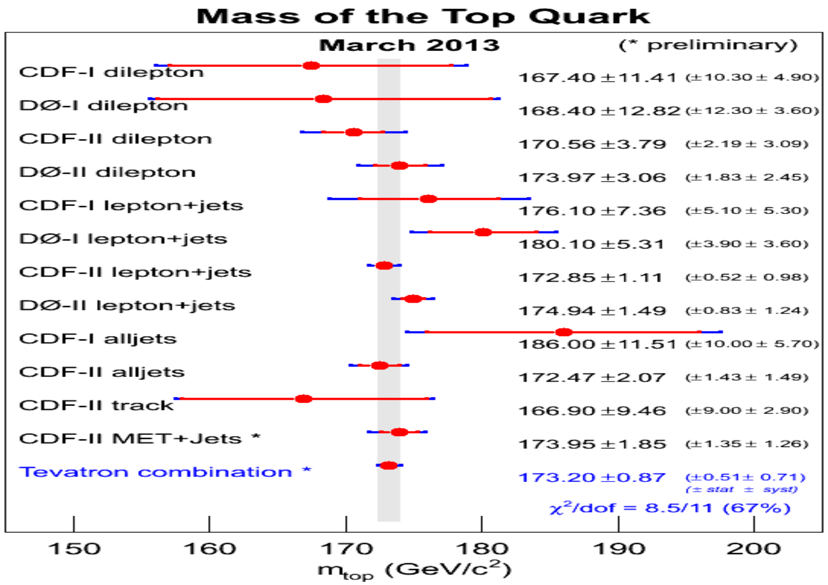


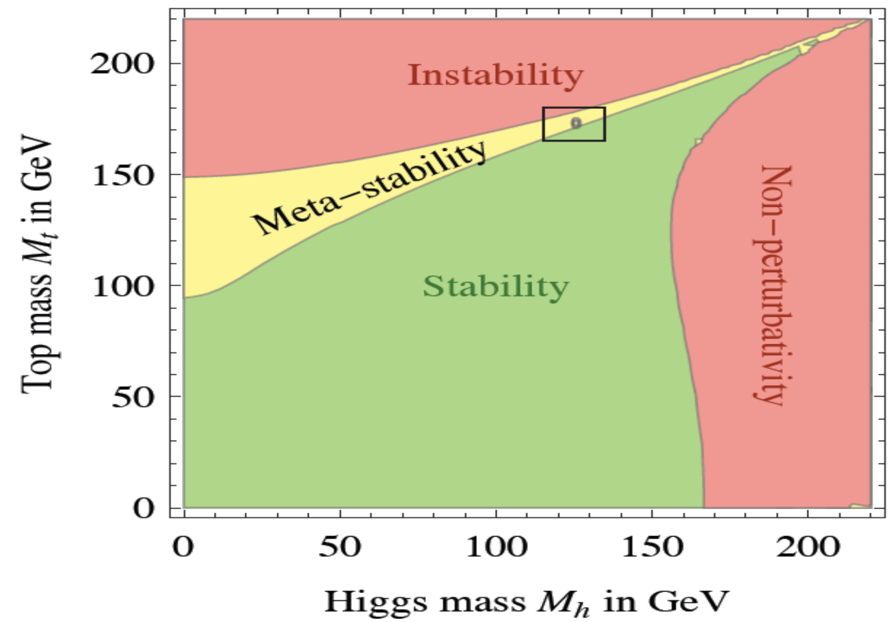
Top mass measurement

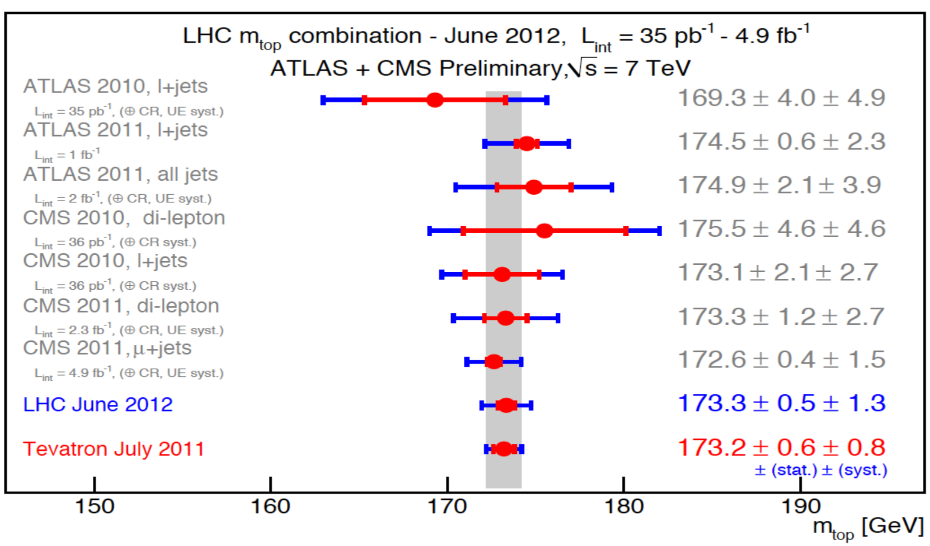
- Mtop is an important parameter of SM
- Provides constrains on the electroweak fit m_H
- General method developed from Tevatron:
  - –Use kinematic fit to constructed set of templates from simulated samples with different mtop.
  - –Use Mw constriant to reduce JES
  - –Likelihood fit to data to extract mtop.
  - –What is measured pole mass or msbar ?
- Measurements are done in both dilepton and lepton +jets channels where both or one of W's decay semileptonicly.

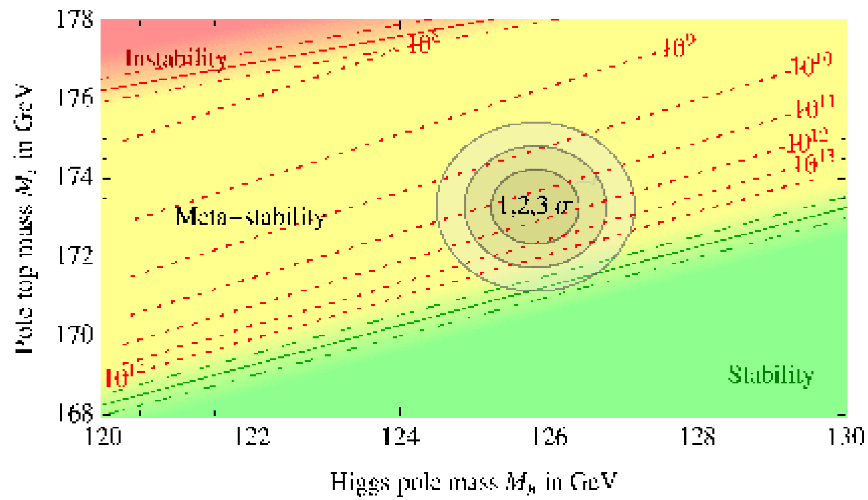


Top Mass and its Implication

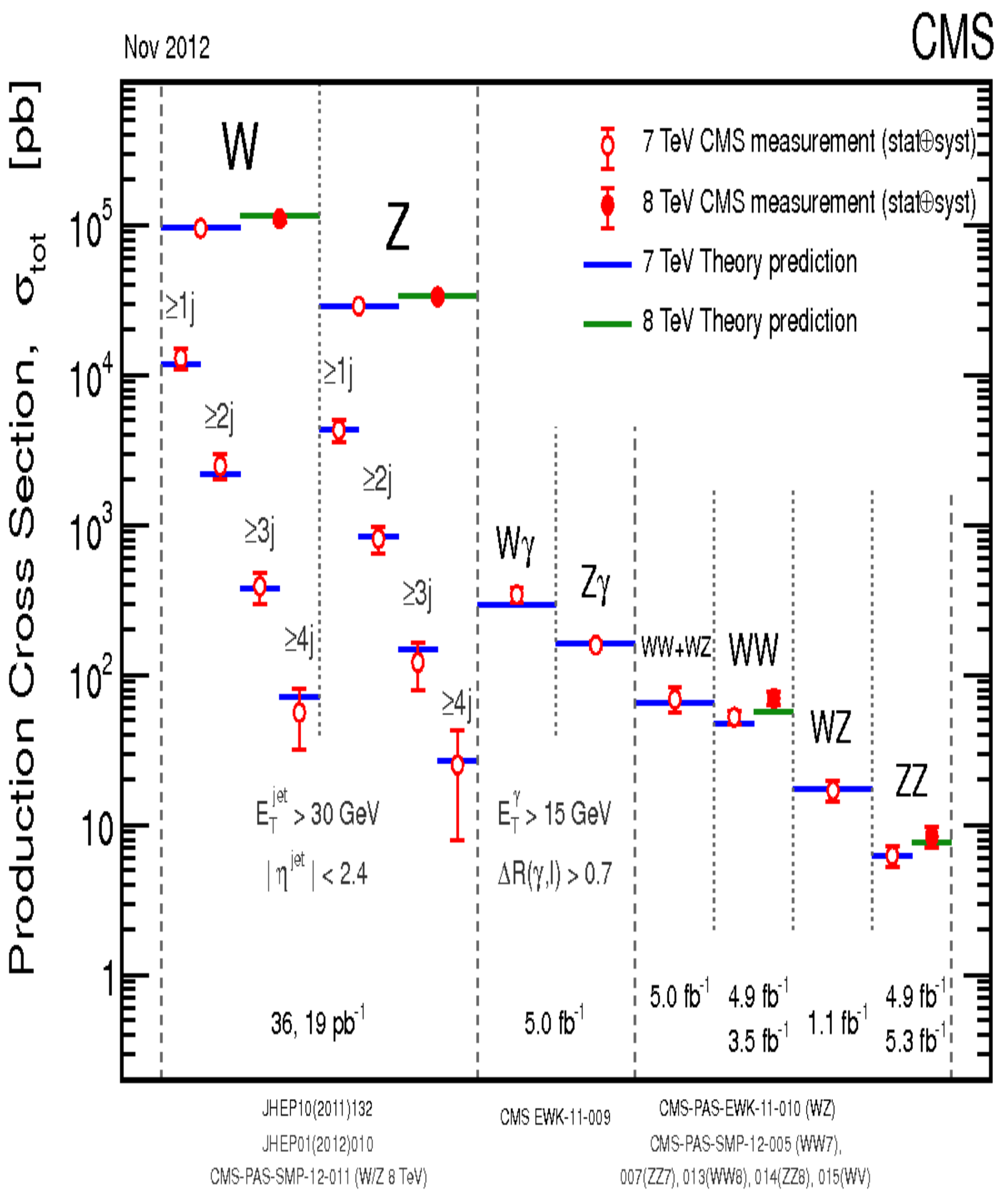


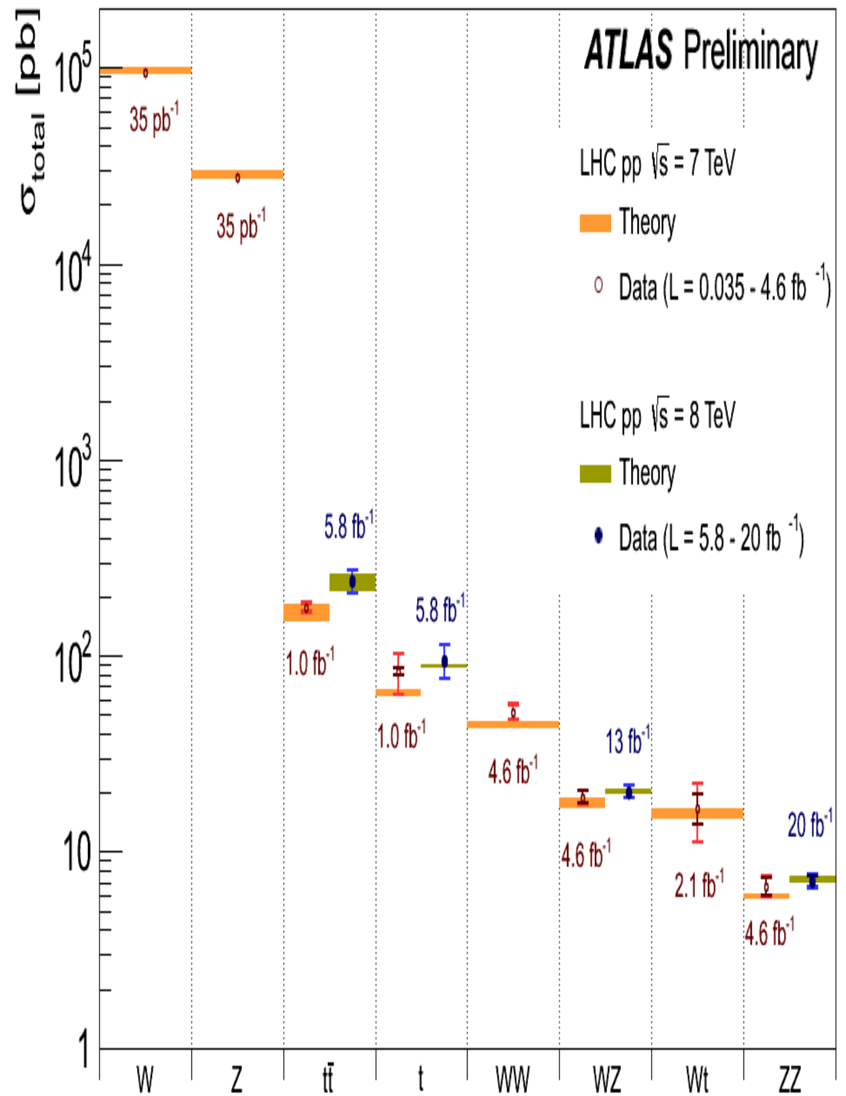






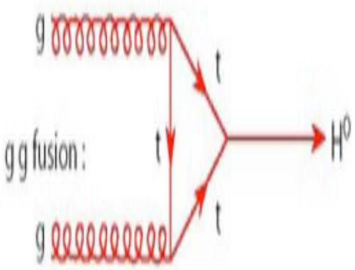
Summary of SM cross-section measurements

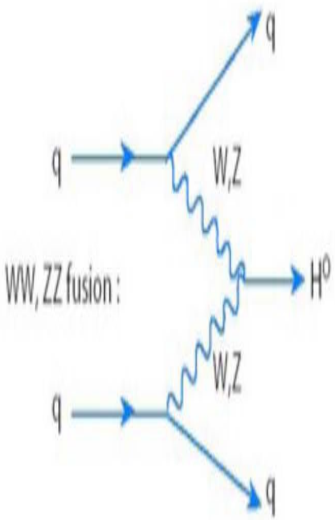


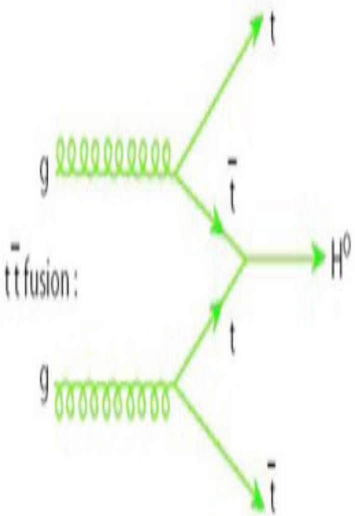


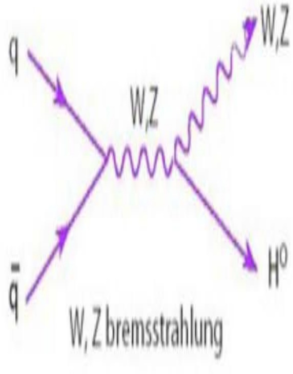
Higgs Production

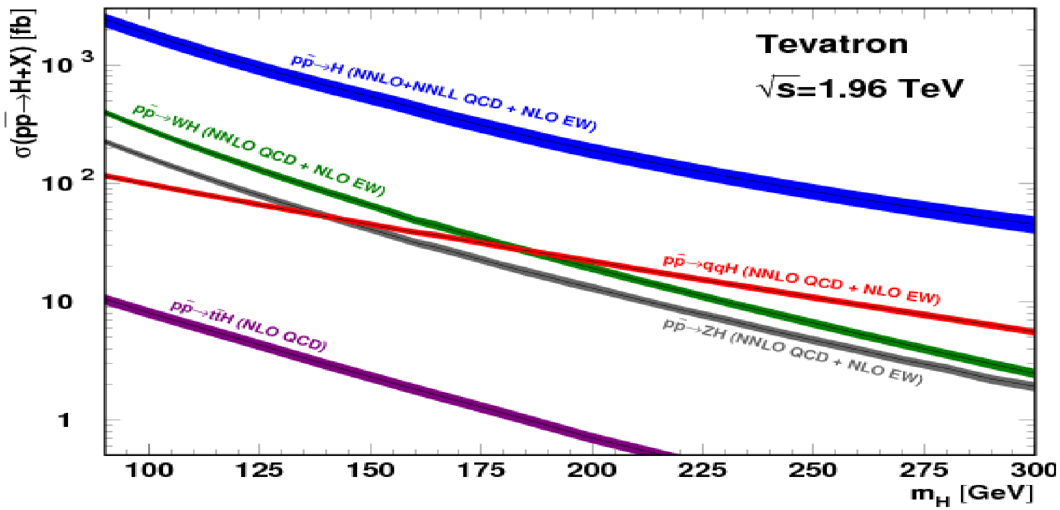
- Higgs predominately produced via ggF at Tevatron and LHC.

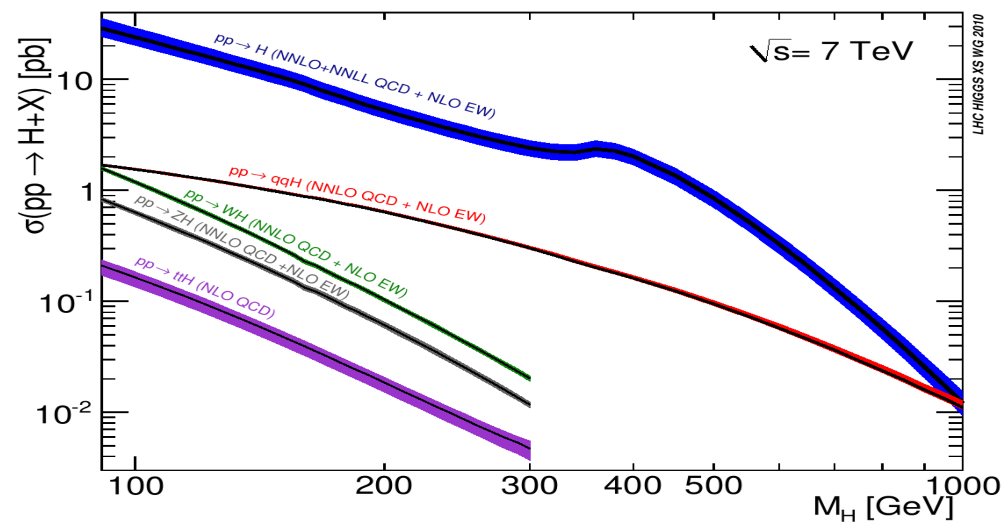






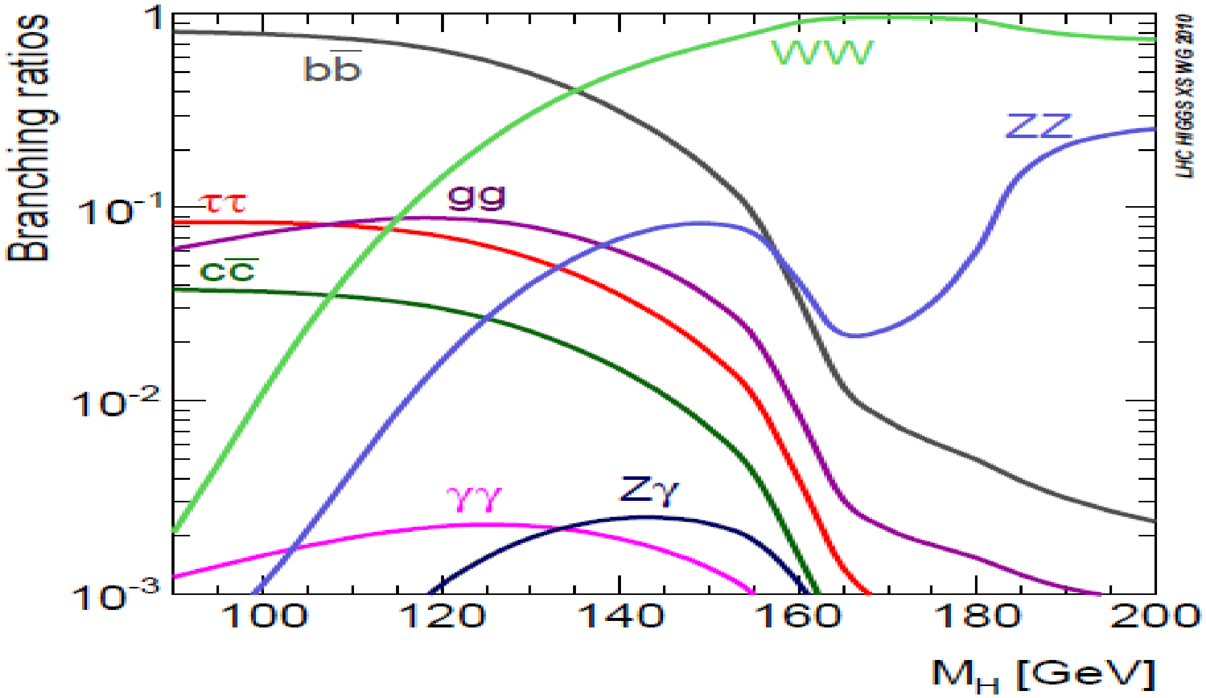






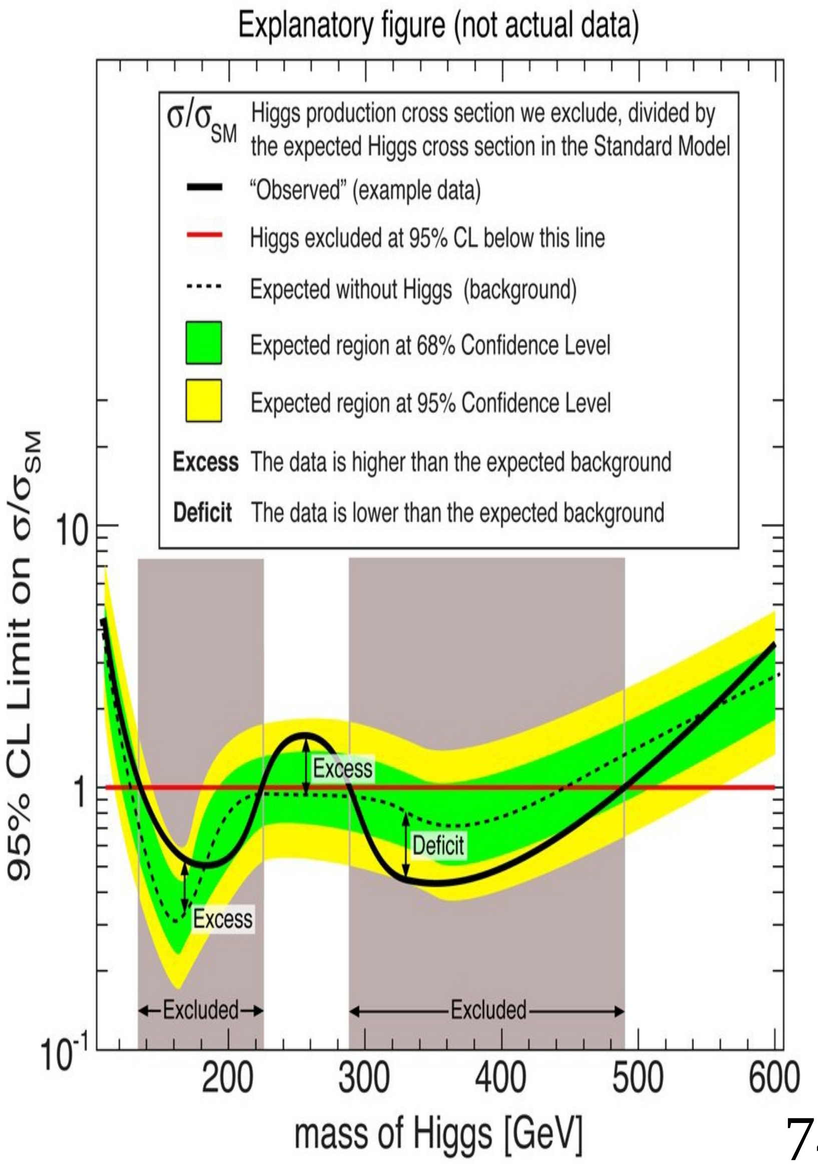
Standard Model Higgs Decays

- Divide into low, intermediate, and high mass regions
- Decay modes change as a function of MH.
- Low mass: dominant decay (bb) is difficult due to QCD:
  - –Tevatron:VH→bb, H→WW
  - –LHC: H→γγ,ZZ,WW.

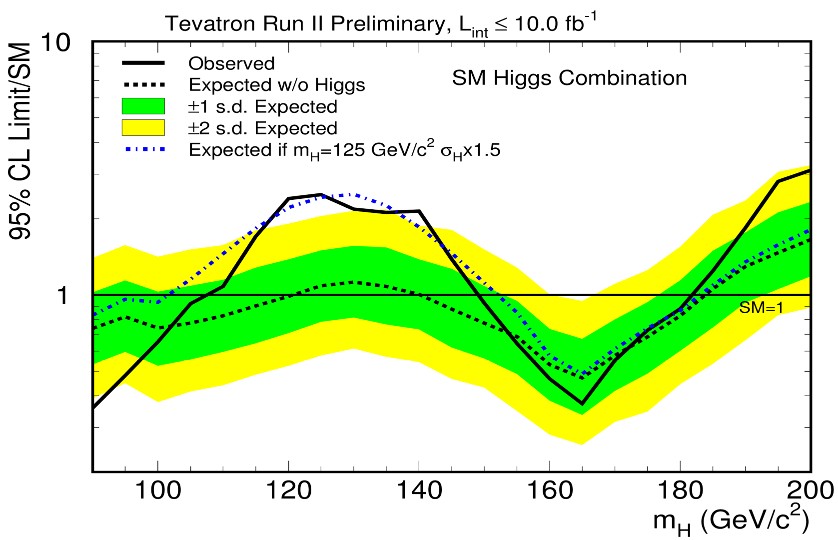


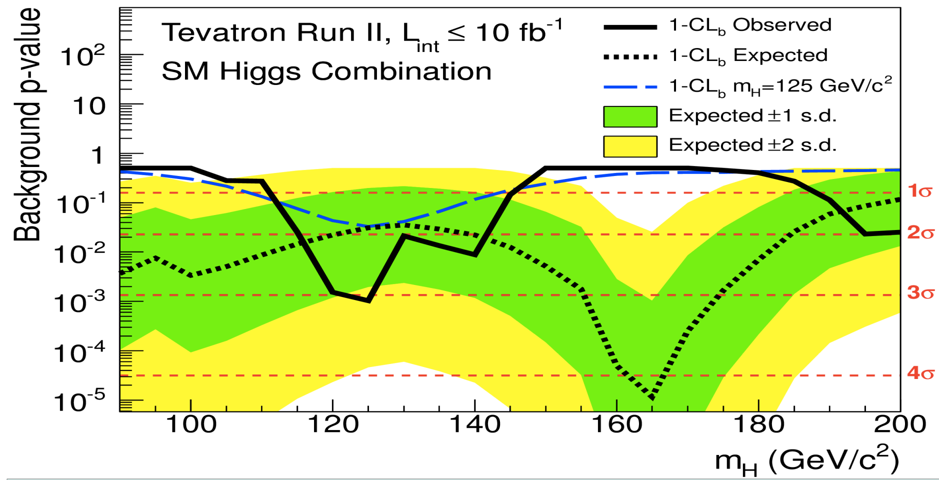
How to interpret limit plot

- SM does not predict M_H, but does predict the production cross section once the mass is known.
- The vertical axis shows the production cross-section excluded at 95% CL, divided by expected cross section in SM for a tested m_H, shown by solid black line.
- The dot back line shown median expected limits without Higgs.
- The green and yellow bands indicate the corresponding 68% and 95% certainty of those values.

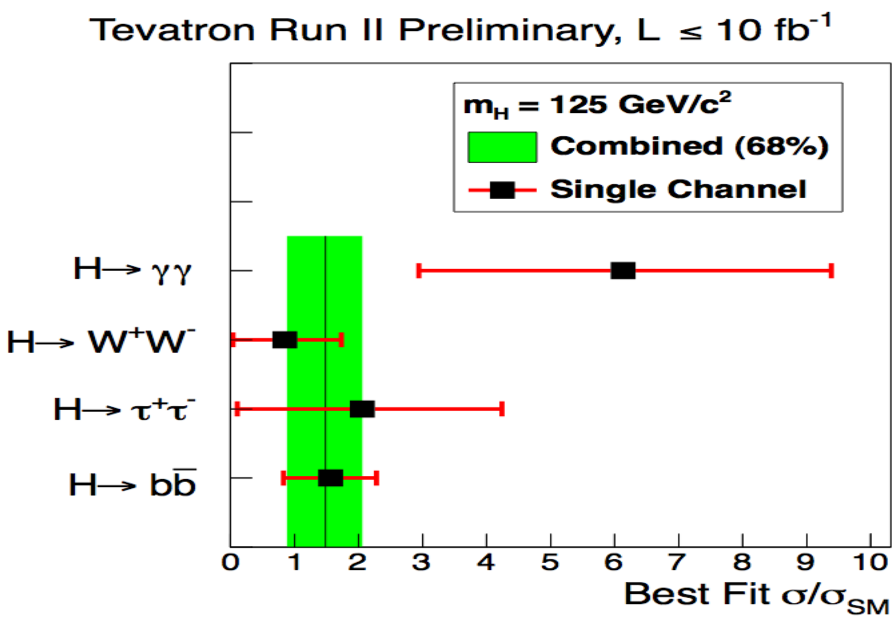


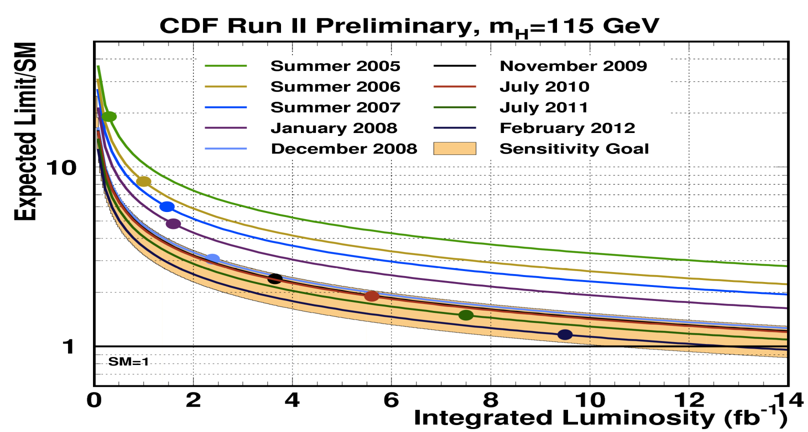
Tevatron Higgs Searches





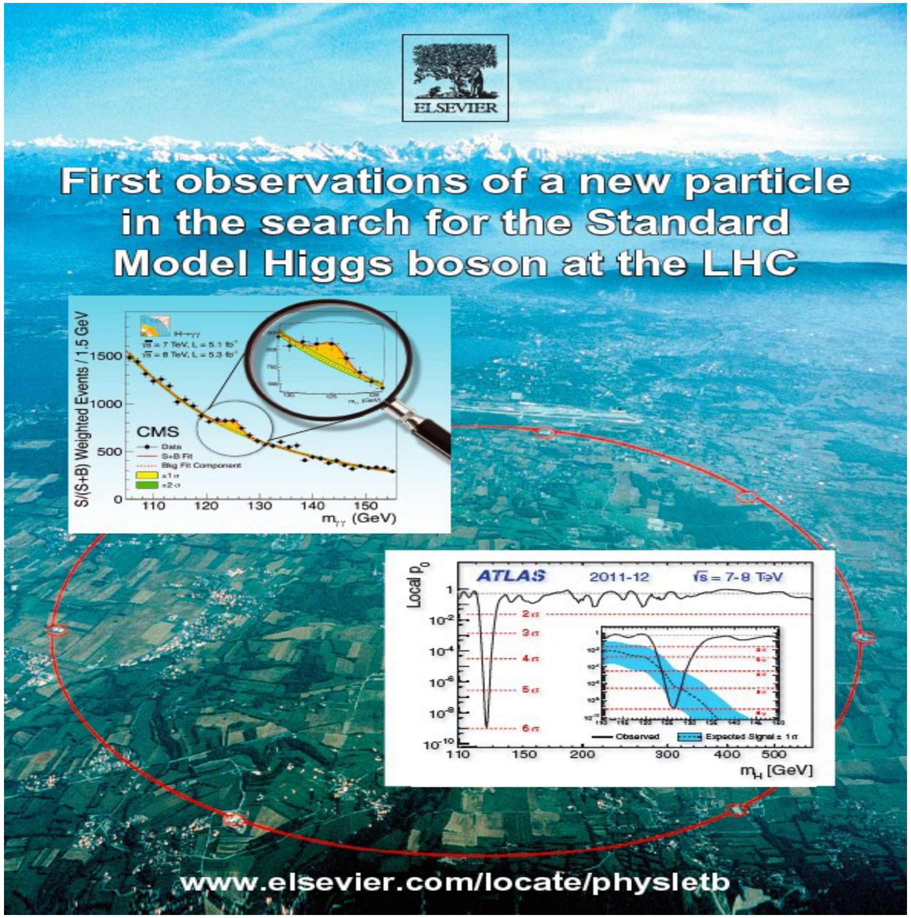
3σ significance @125 GeV, arXiv:1303.6346

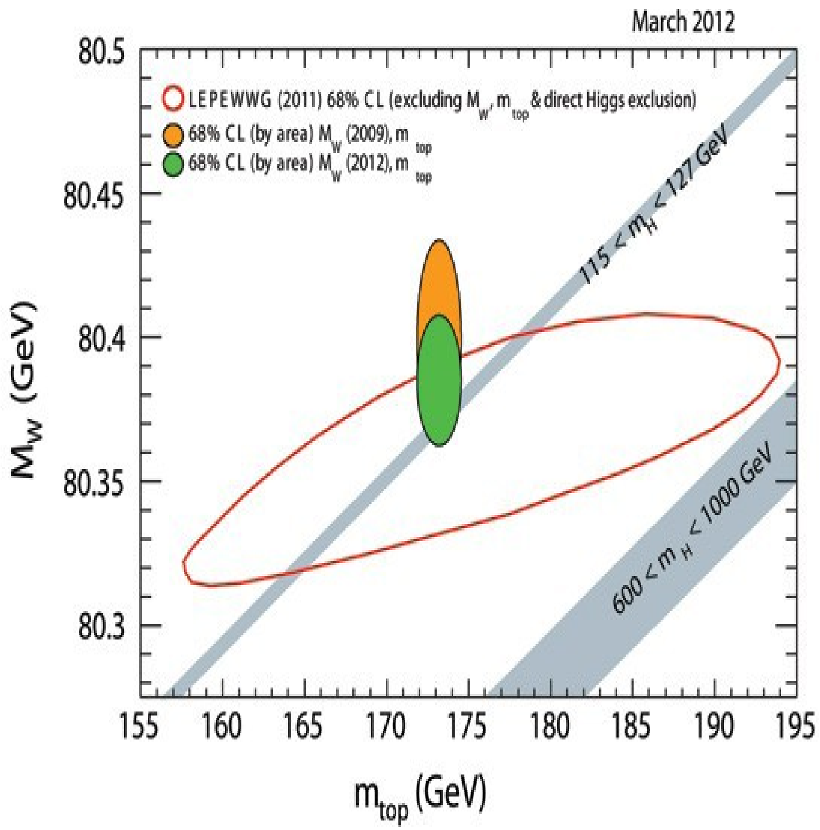




Higgs Discovery at LHC

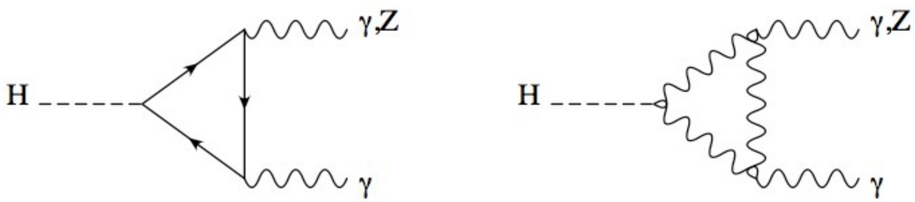
- ATLAS & CMS discovered a new boson at 125 GeV/c^2 last July.
- The results are consistent with the expectation of a Higgs boson.
- Most sensitivity channels are H→ZZ, γγ, WW.





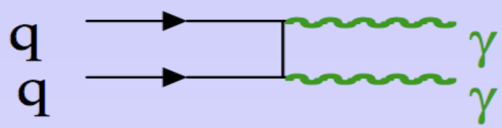
Low mass Higgs: H→γγ

- Low branching ratio, but take advantage of the excellent photon resolution to see a peak above the continuum background.

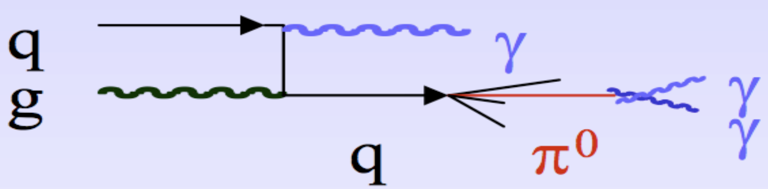


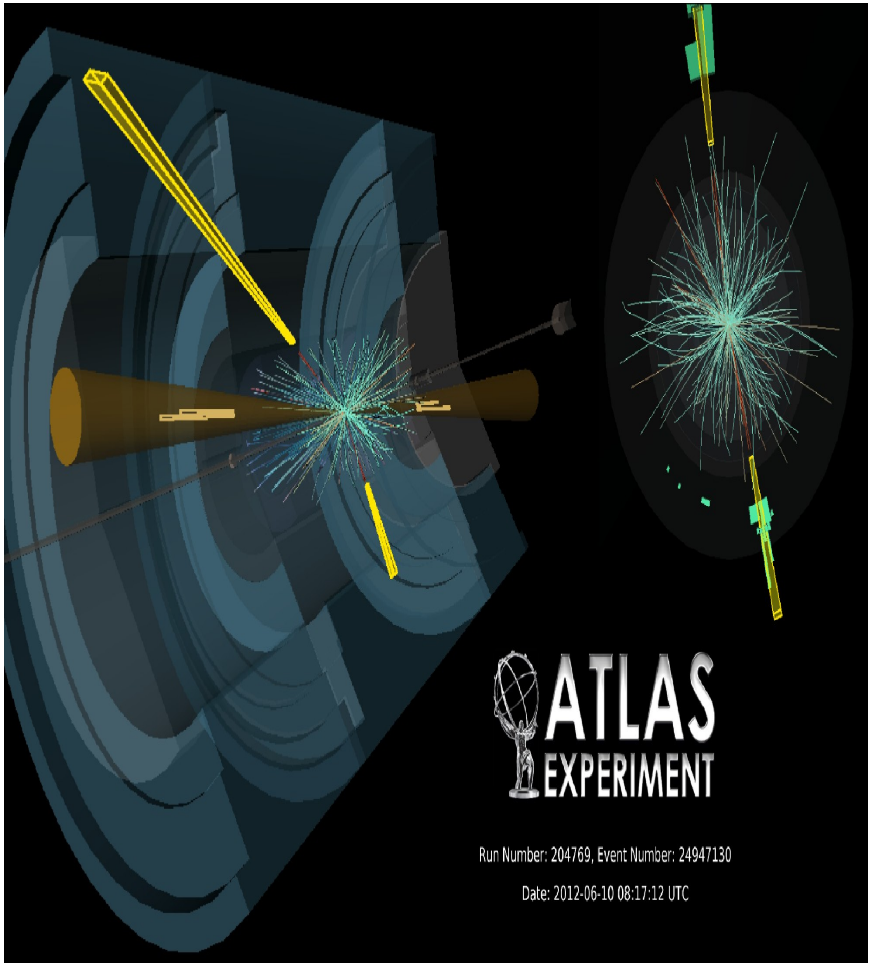
<u>Main backgrounds:</u>

γγ irreducible background

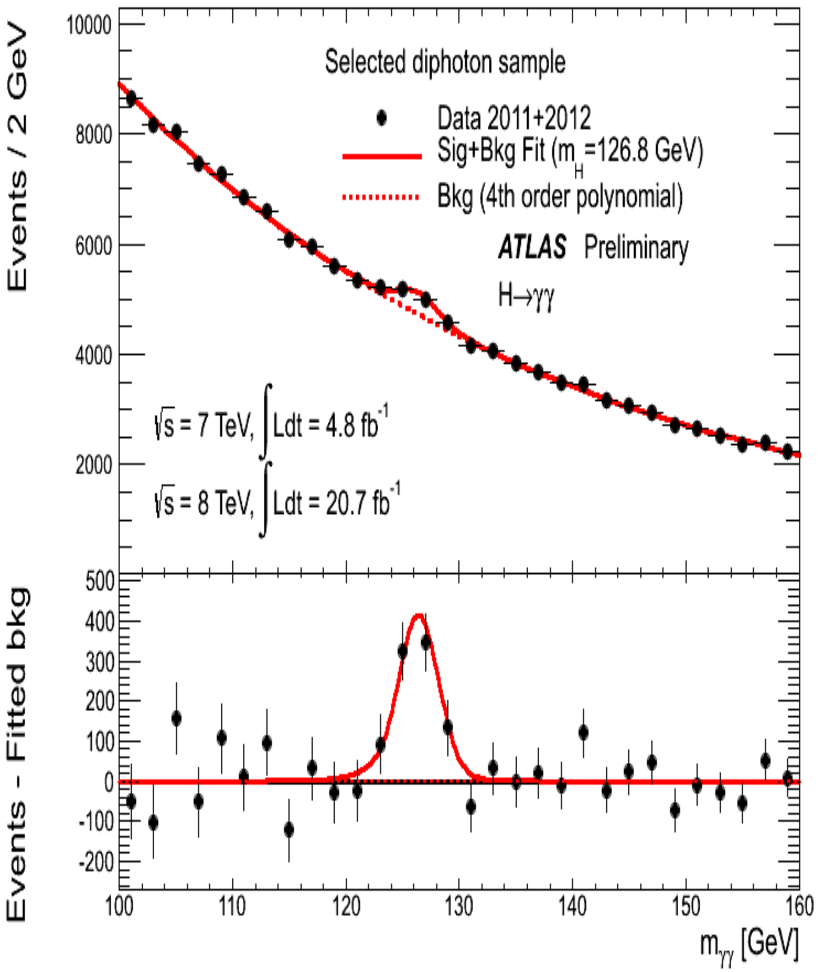


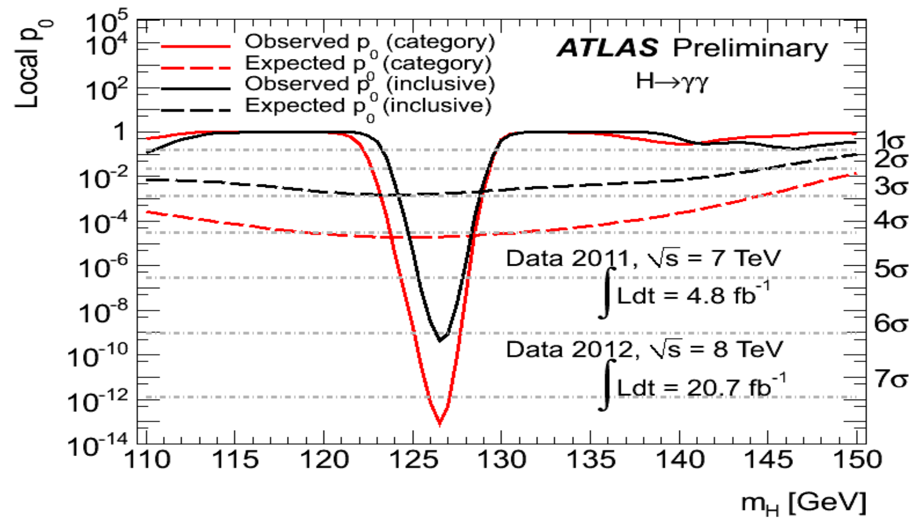
γ-jet and jet-jet (reducible)

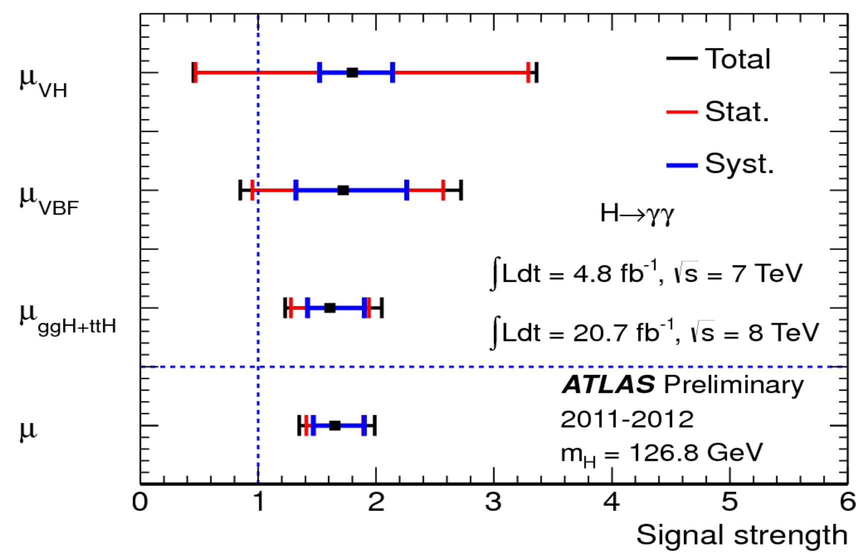




Updated Results on H→γγ (ATLAS)

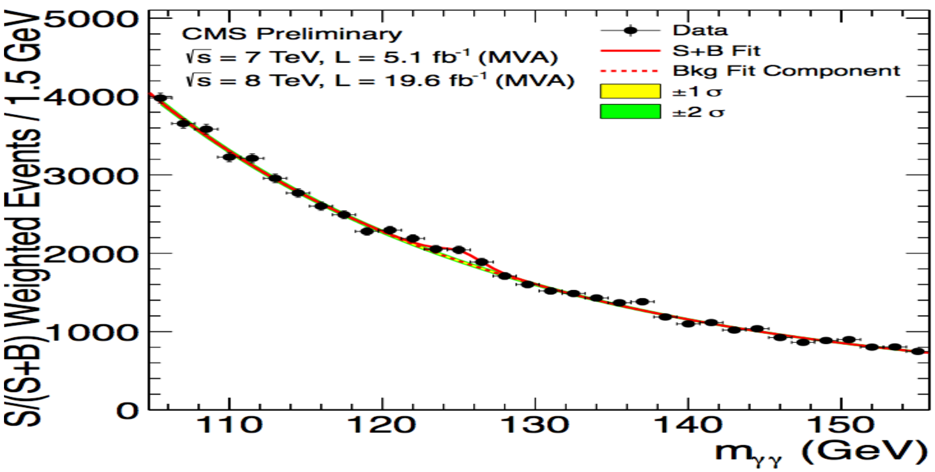


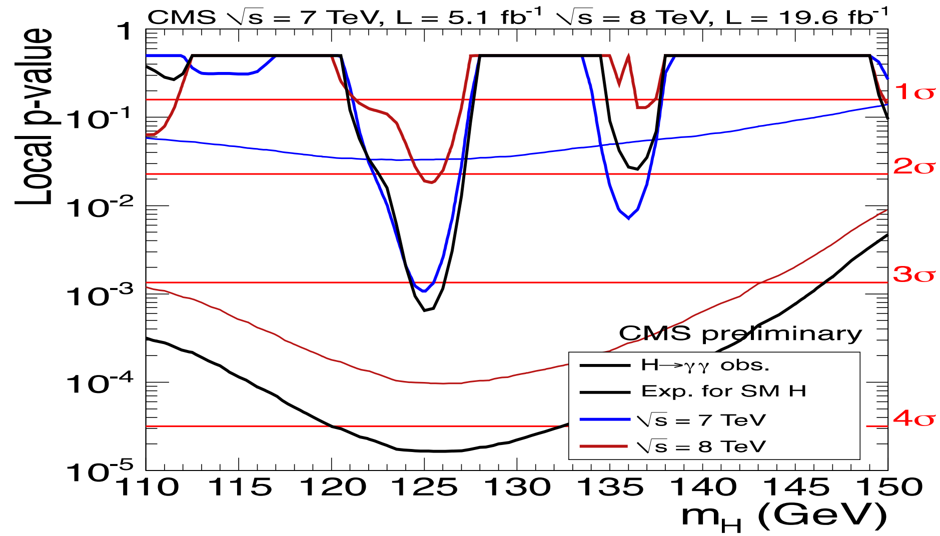


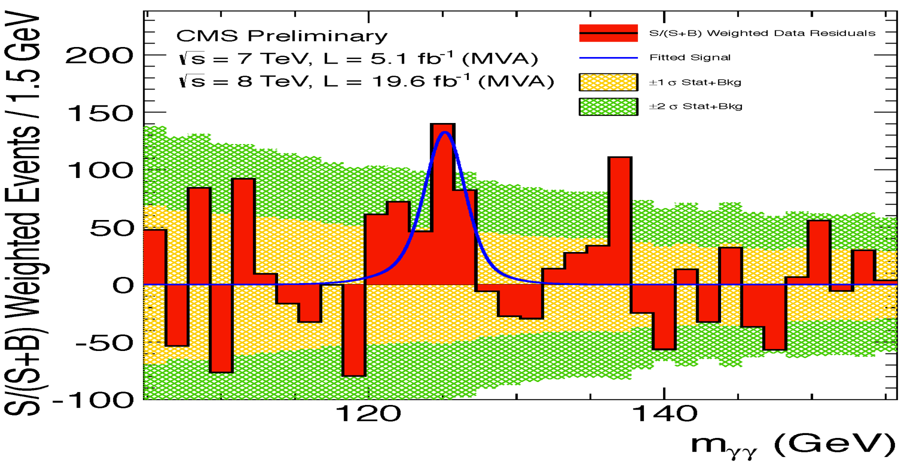


- $\mu = 1.64 \pm 0.34$,
- $M = 126.8 \pm 0.2 \pm 0.7$ GeV/c^2
- Significance@126.8: 7.4σ (4.1σ exp.).

Updated Results on H→γγ (CMS)





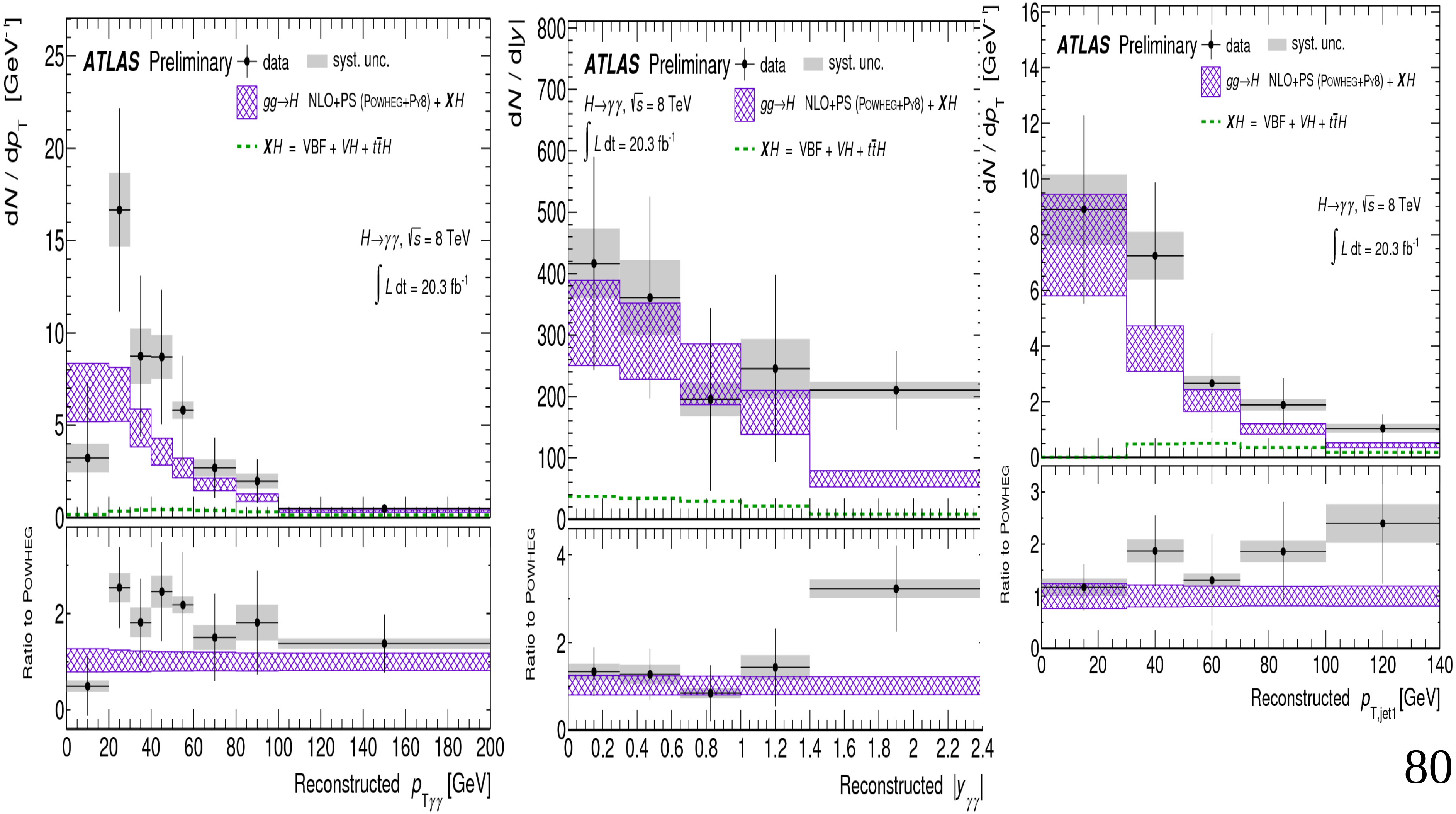


	MVA analysis (at m_H=125 GeV)	cut-based analysis (at m_H=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$

- Improved Ecal calibration, added more exclusive channels.
- μ=0.78+0.28-0.26; M=125.4±0.5±0.6 GeV/c^2
- Significance: MVA 3.2σ (4.2 exp.); Cuts: 3.9σ (3.5exp.).

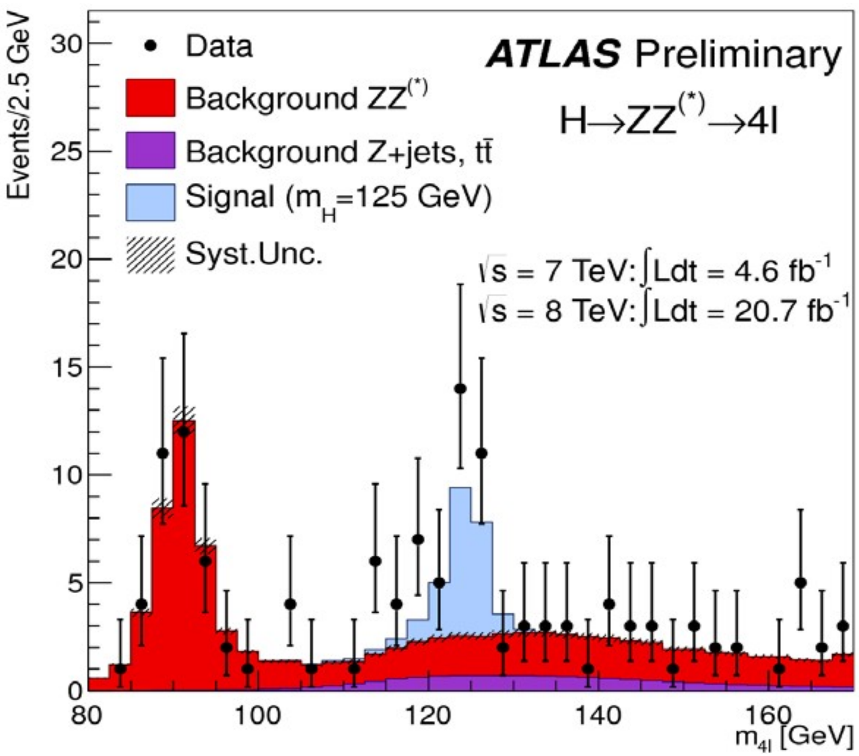
Differential Cross section on H→γγ

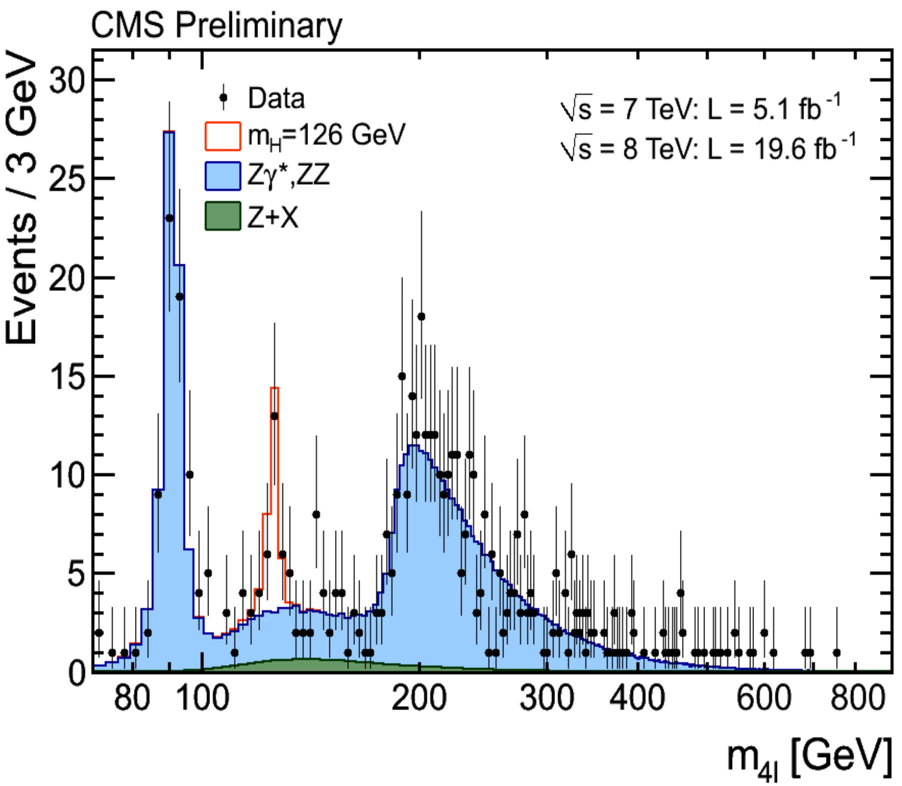
- ATLAS measured the Higgs differential cross section and the results are consist with NLO(POWHEG), NNLO+NNLL(HRes).



Updated Results on H → ZZ* → 4 Leptons

- Multi-lepton signatures are relative easy to observe above the background(ZZ, Zbb,tt)
- H→ZZ*→4l is considered to be the golden model for Higgs search

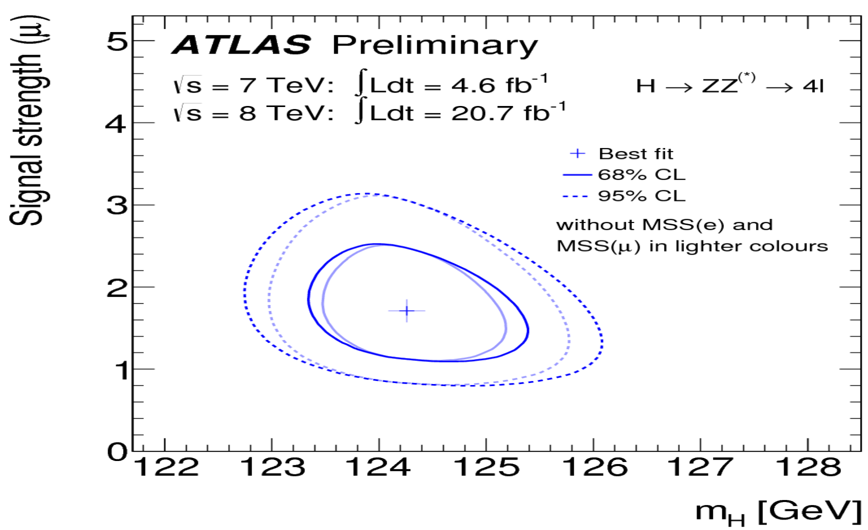


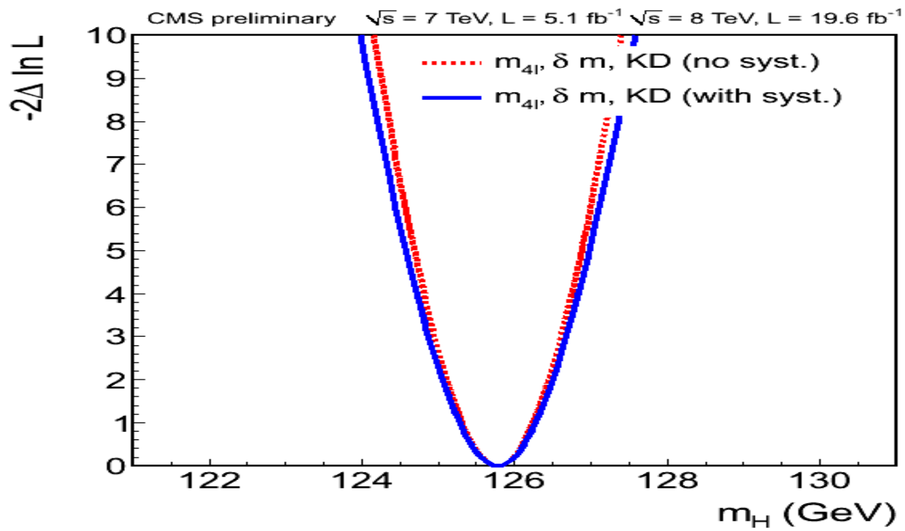


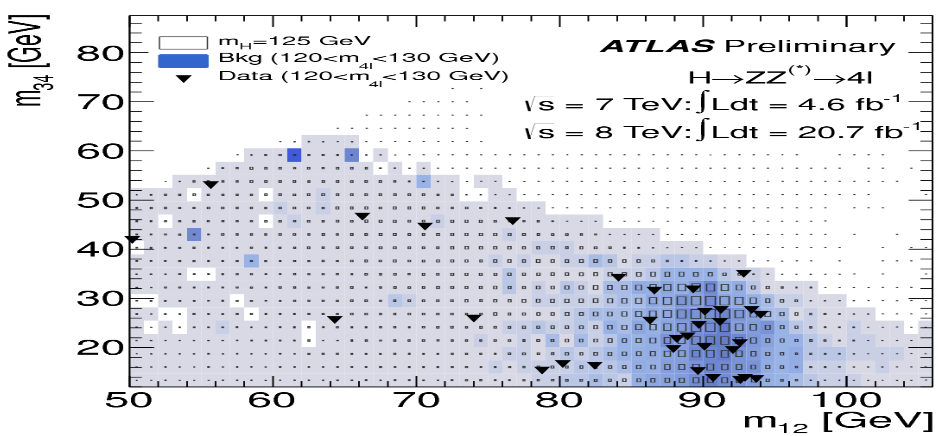
- Significance: ATLAS 6.6σ (4.4σ exp.); CMS 6.7σ (7.2σ exp.)

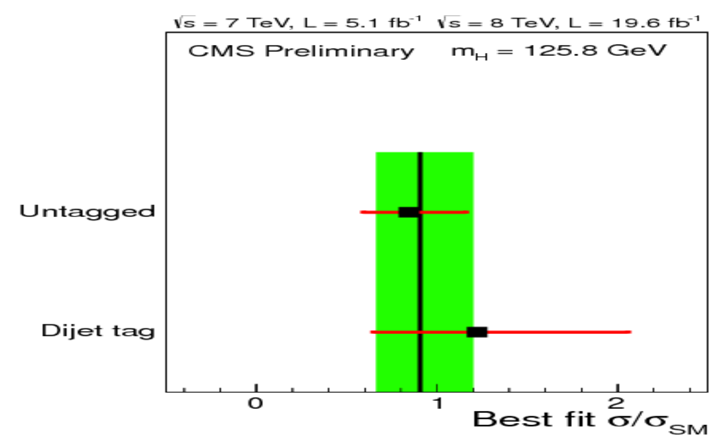
Updated Results on H → 4 Leptons

- ATLAS: M=124.3+0.6-0.5+0.5-0.3 GeV; μ=1.43+0.40-0.35
- CMS: M=125.8+-0.5+-0.2 GeV; μ=0.9+0.30-0.24



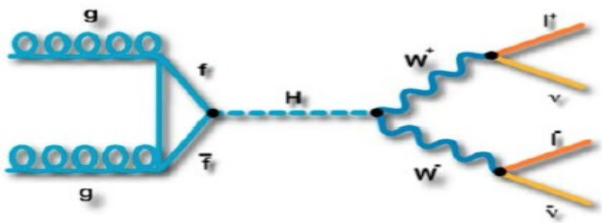






$H \rightarrow WW^* \rightarrow l\nu l\nu$

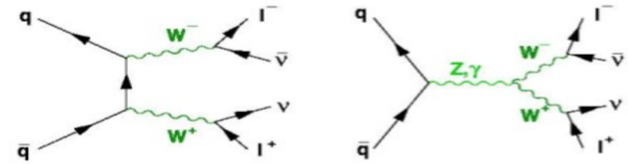
- Signal selections:
  - Two high Pt isolated leptons +missing ET
  - Low invariant mass of two leptons due to a scalar decay
  - There is no mass peak due to missing neutrinos



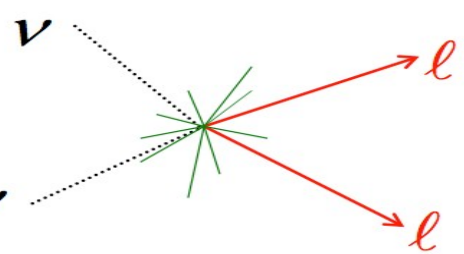
$$\sigma(H \rightarrow WW^* \rightarrow \ell\nu\ell\nu) \approx 0.18 \text{ pb}$$

(m_H=125 GeV)

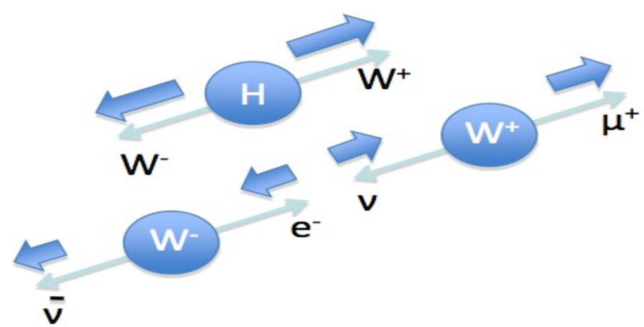
The SM WW is said to be "irreducible"



However, WW from the scalar Higgs is expected to have different kinematics

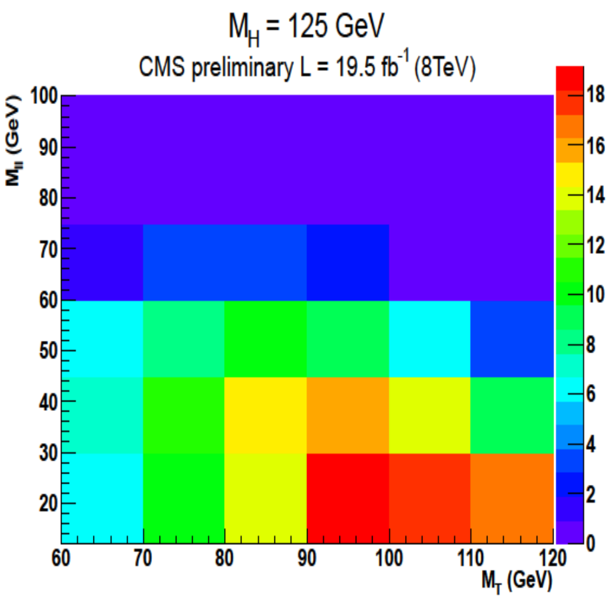


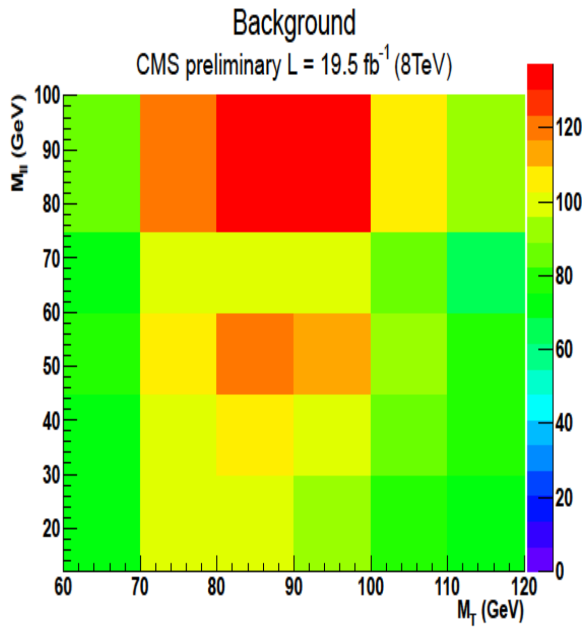
Main background:
WW, W/Z+jets, $t\bar{t}$, ...

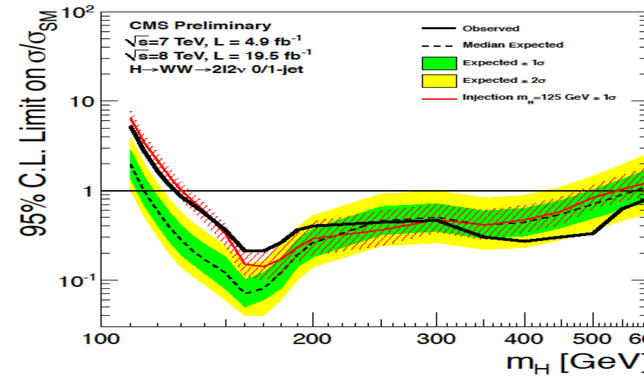


The spin correlation leads to a smaller average opening angle between the two leptons

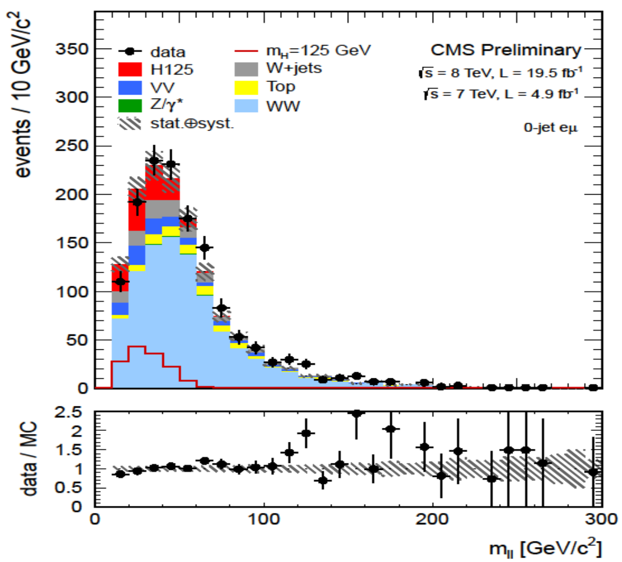
H→WW*→lνlν

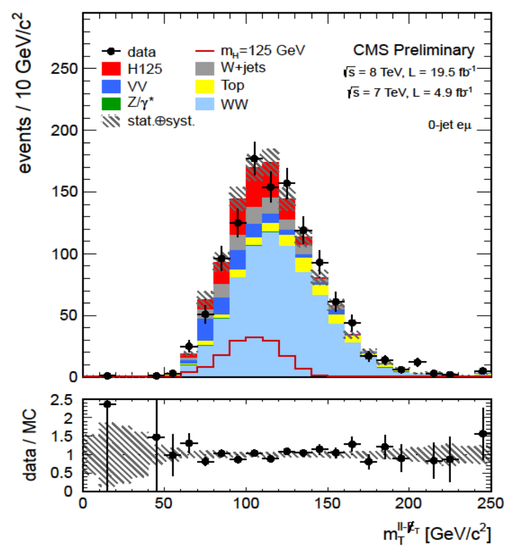


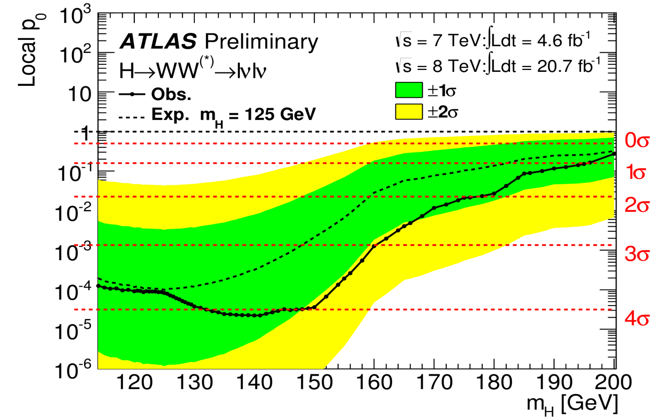




Significance @ 125 GeV: 4.0 σ (5.1 expected) μ=0.76±0.21



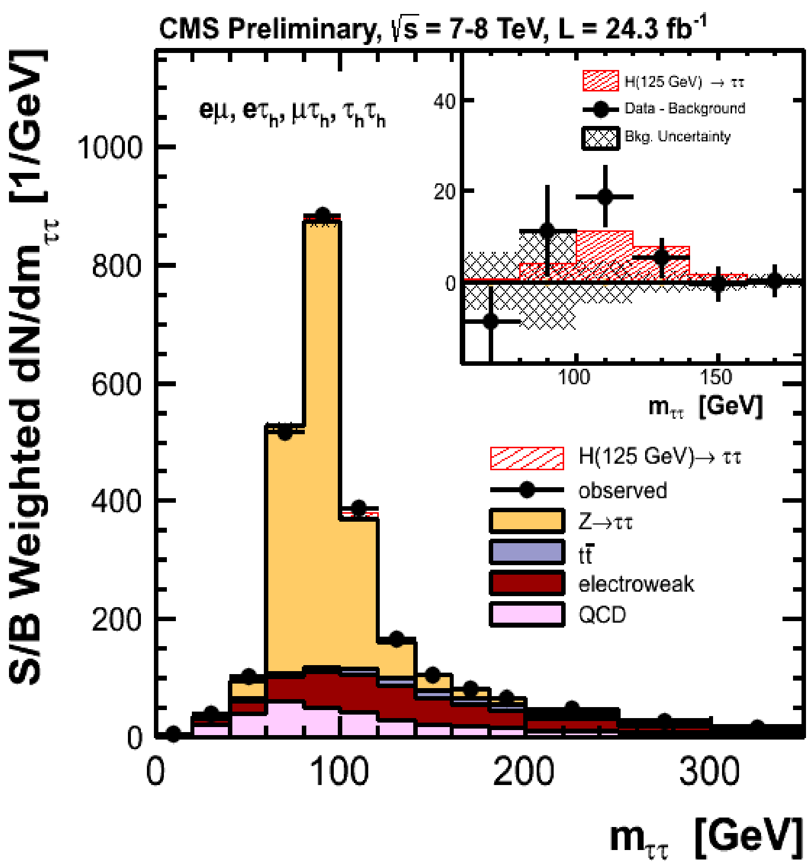


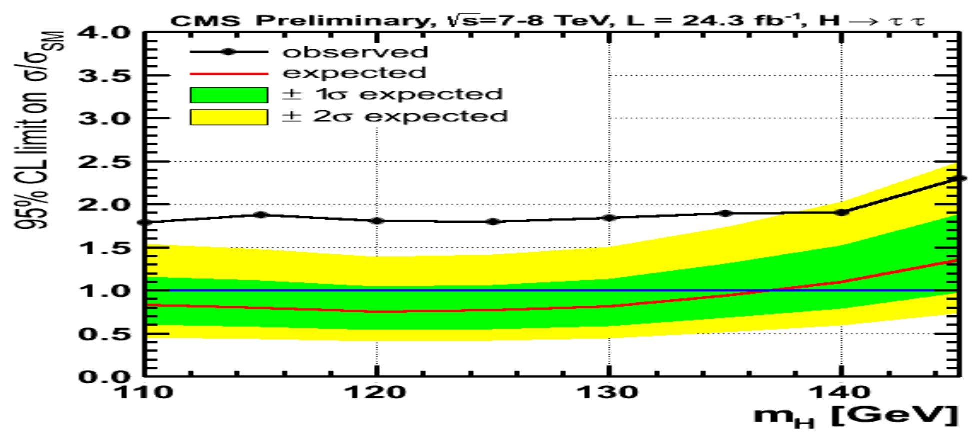


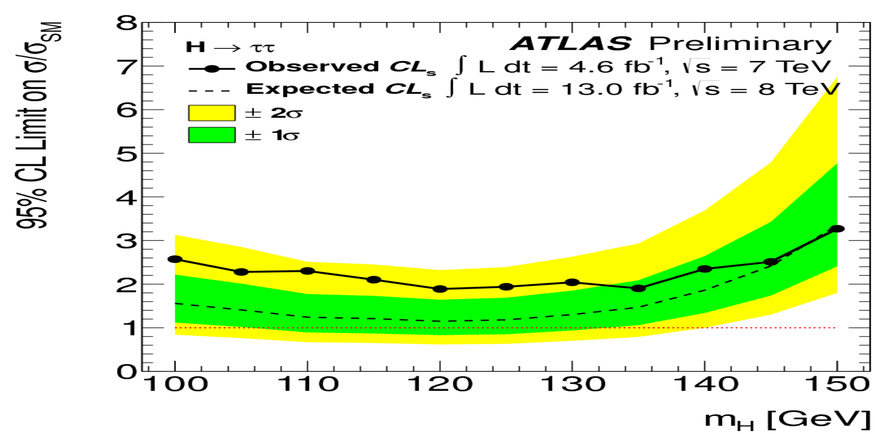
Significance @ 125 GeV: 3.8 σ (3.7 expected) μ=0.83±0.36

$H \to \tau^+\tau^-$

- Divided in five final states (ggH,VH, H → WW → lτx).
- CMS observed excess of 2.9σ(2.6σ exp.),consistent with H(125)
- ATLAS observed excess of 1.1σ (1.7σ exp.)

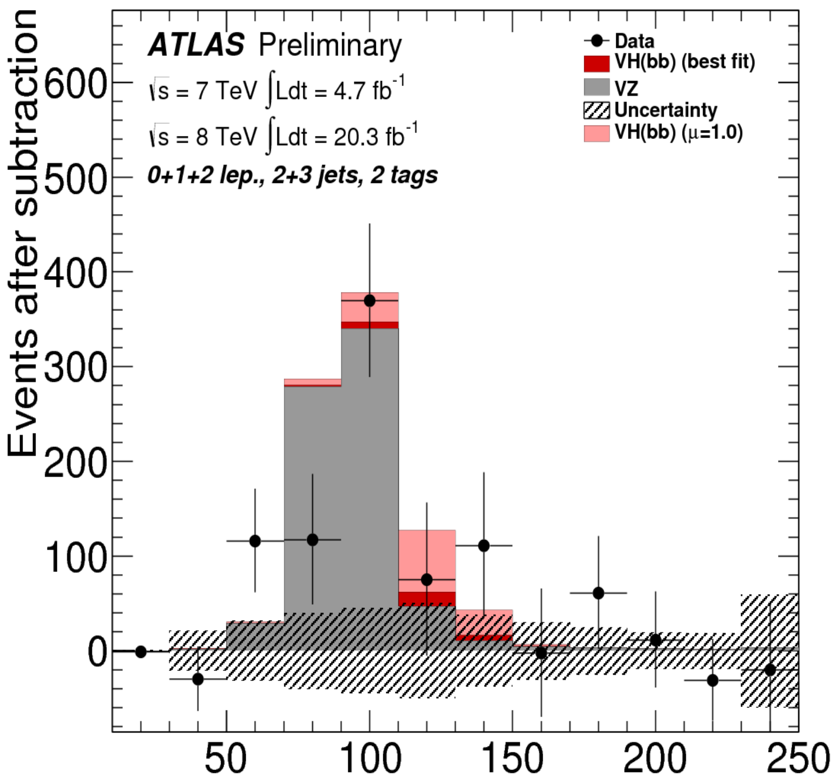




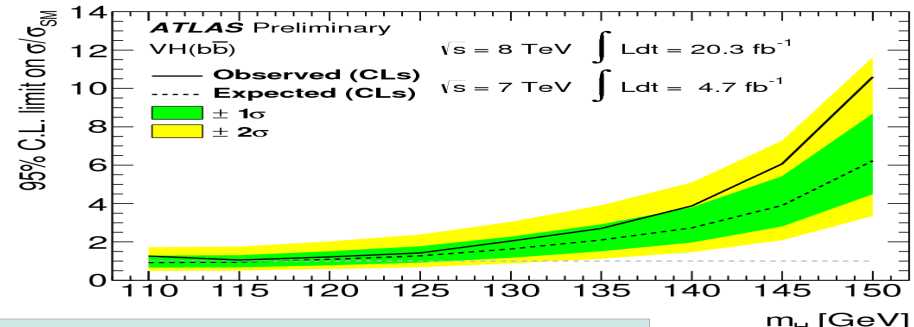


VH→(lν,ll,νν)bb

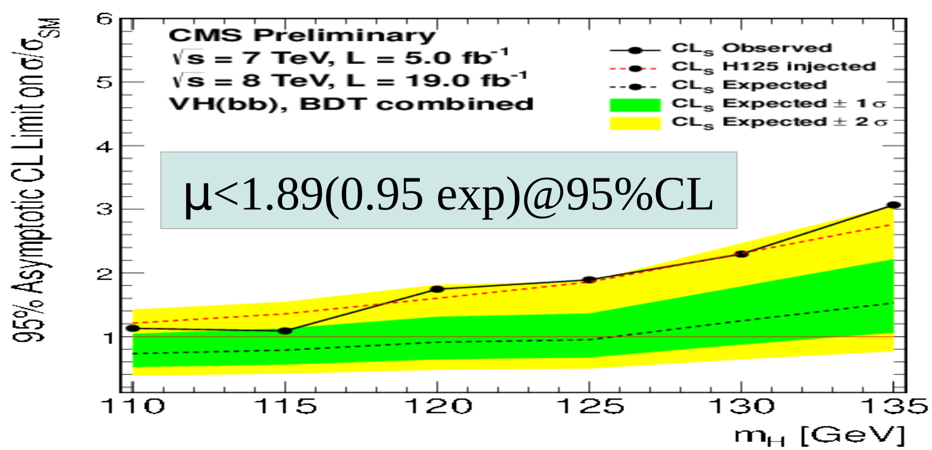
- Search for H→bb in 0, 1, and 2 lepton channels.
- Requiring b-tags and split in bins of Pt(V)
- Validated with VZ cross section measurements (4.8σ)



μ_{VZ}=0.9+-0.2

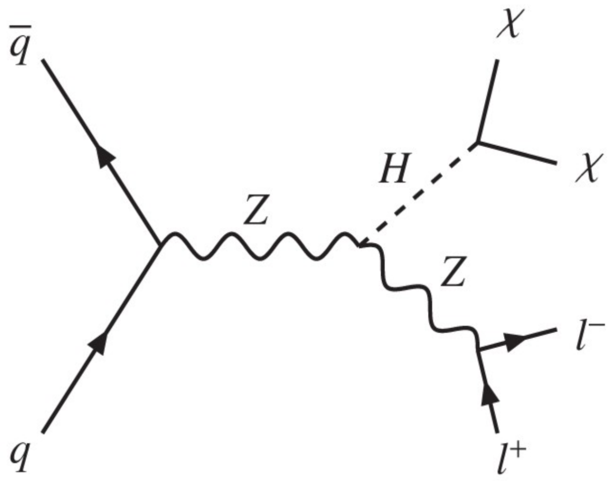


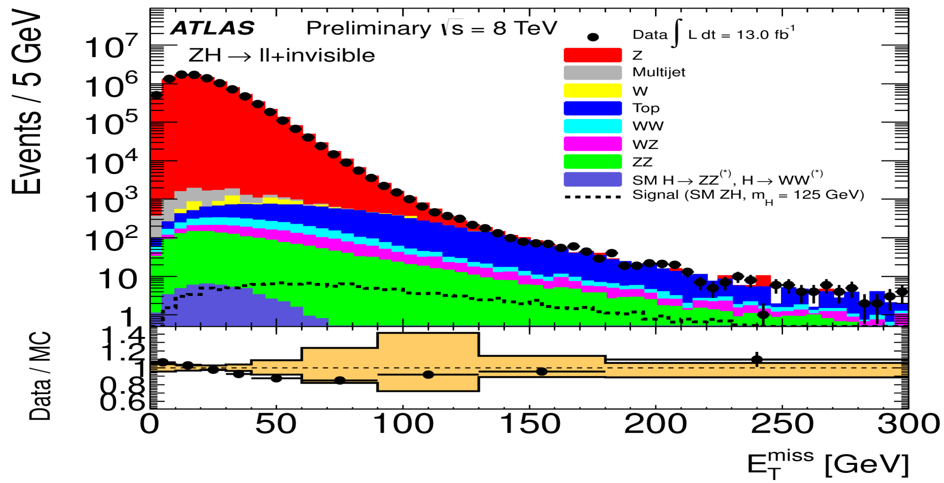
μ_{VH}<1.4(1.3 exp.)@95%CL

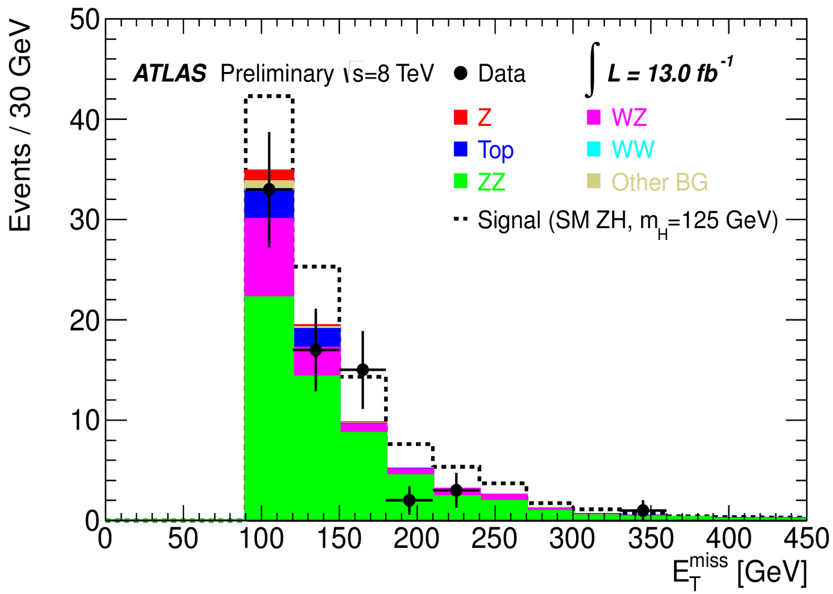


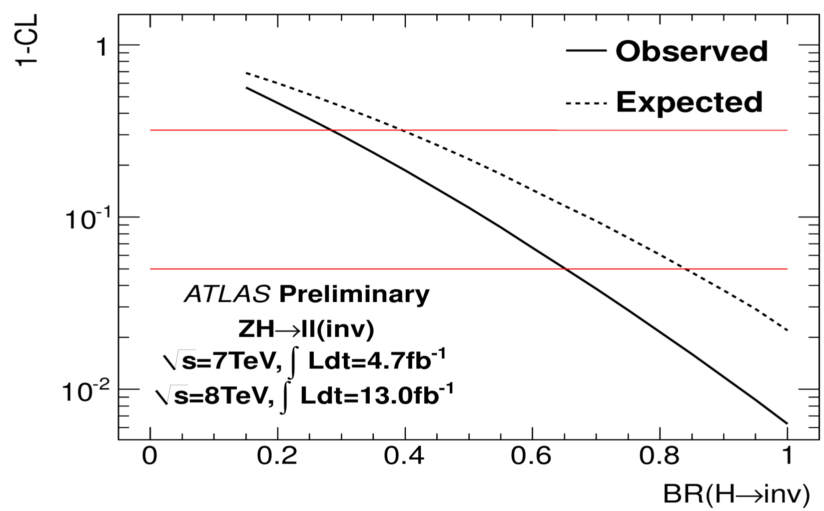
μ<1.89(0.95 exp)@95%CL

H→invisible search (ATLAS)





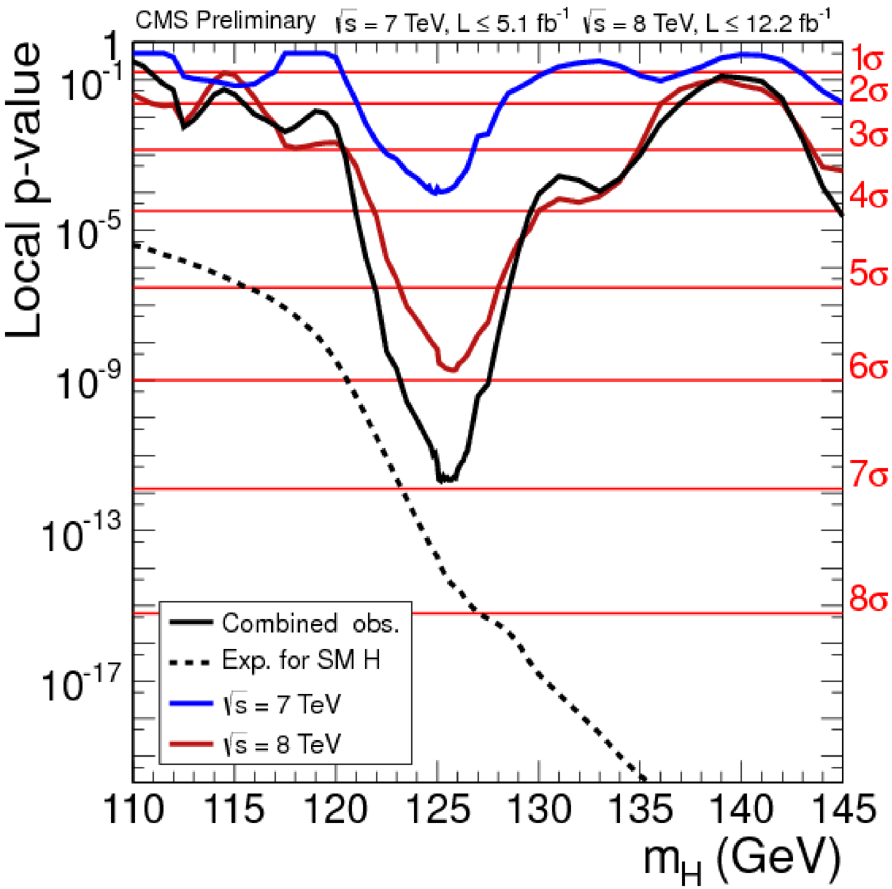


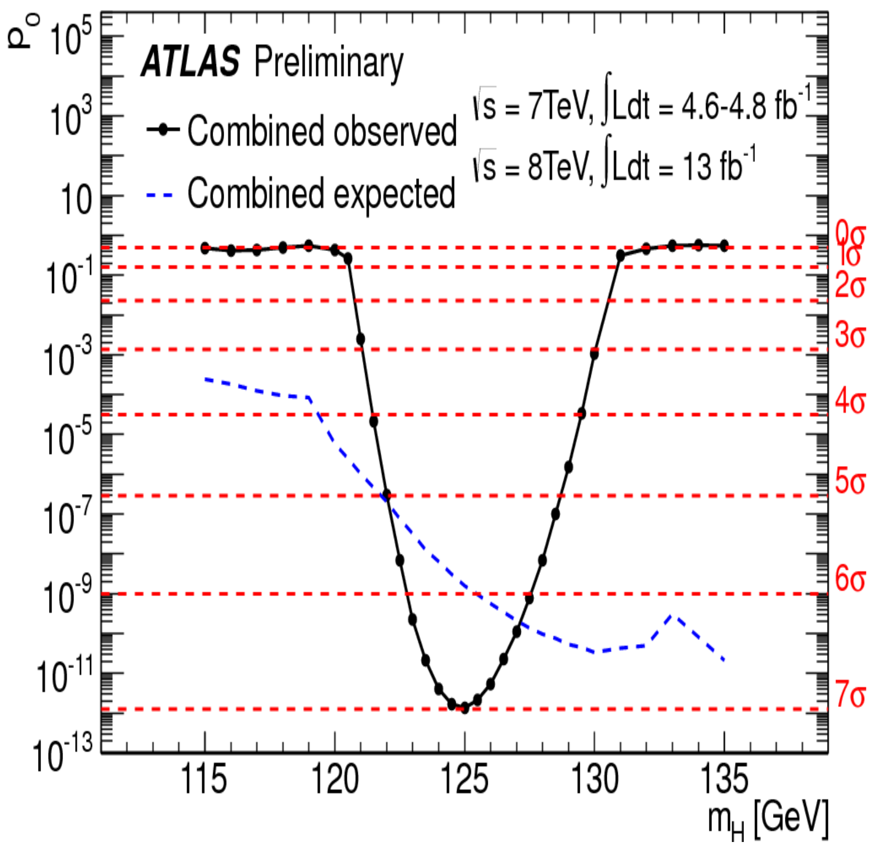


B(H→invisible)<65% @ 95%CL

Local probability (p-value)

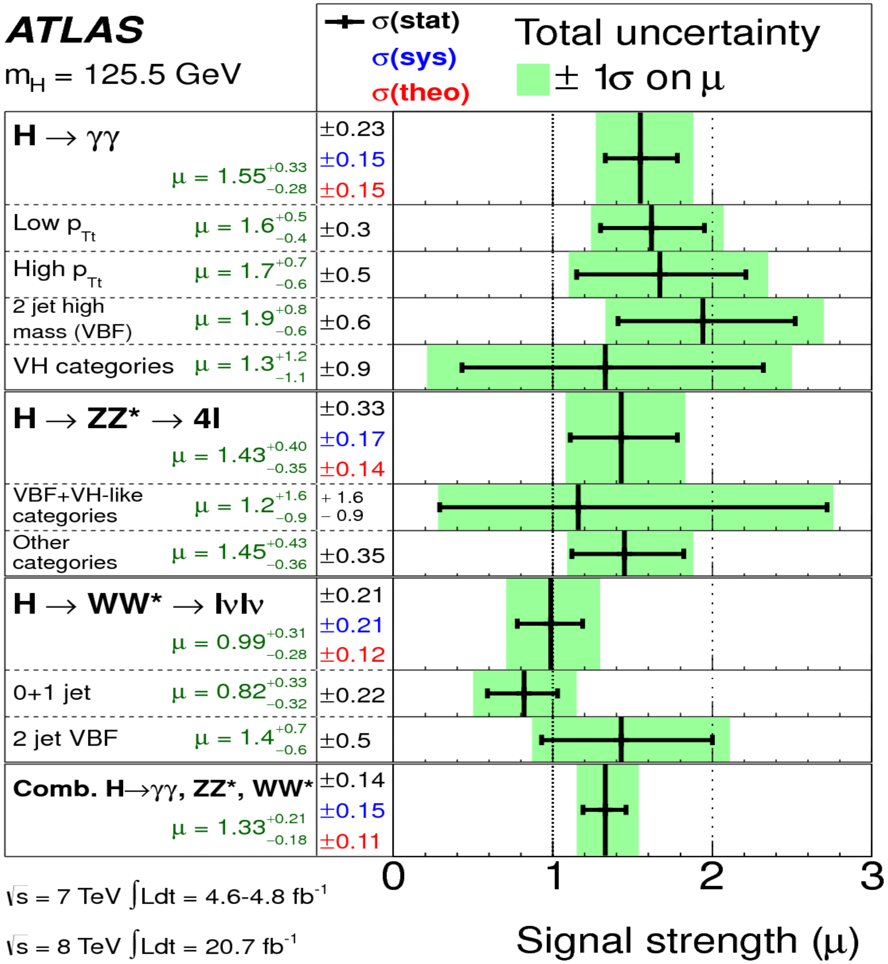
- P-value is the probability that the background can produce a fluctuation greater than or equal to the excess observed in data.
- Consistent with SMHiggs at 125

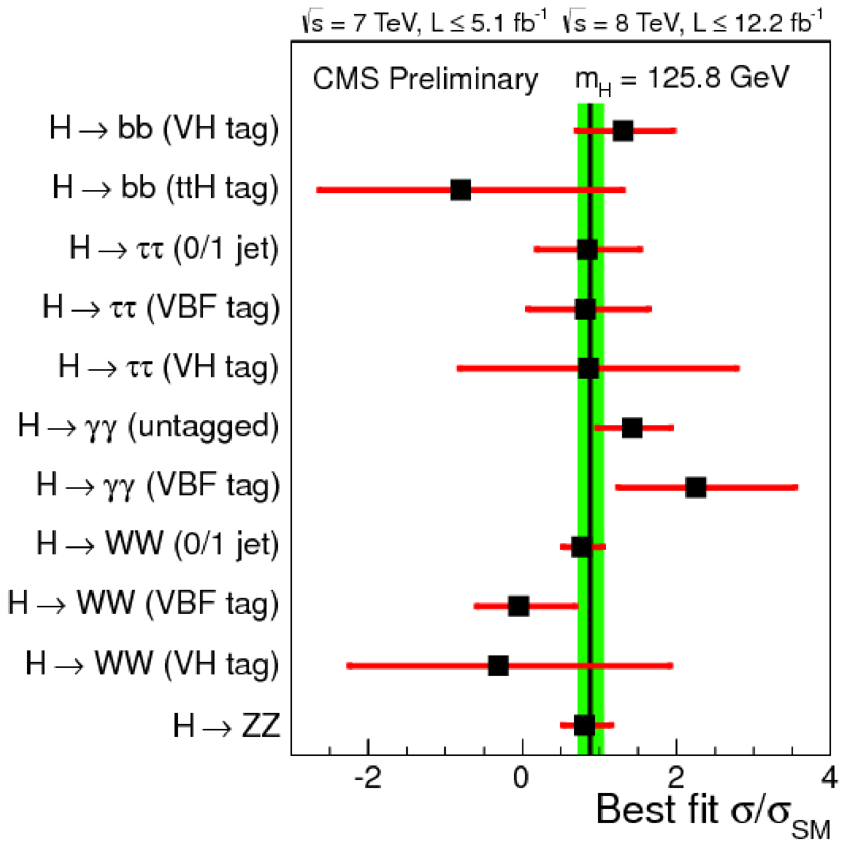




Signal strengths

- Signal strength to test compatibility of different channels
- All channels are consistent with SM

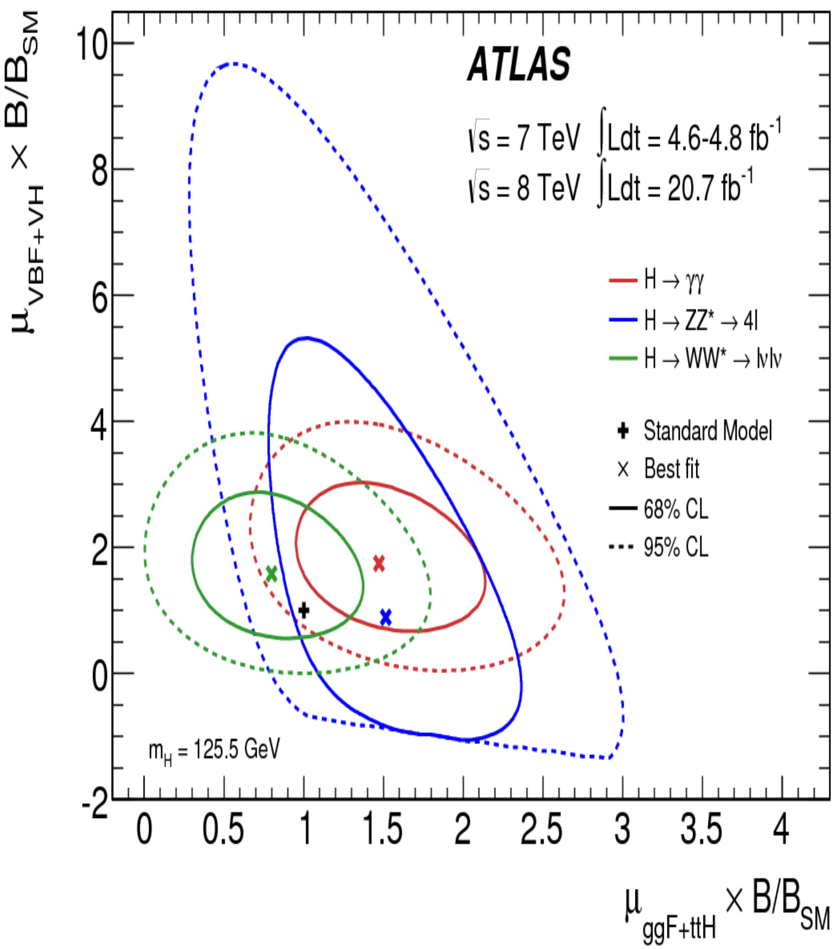


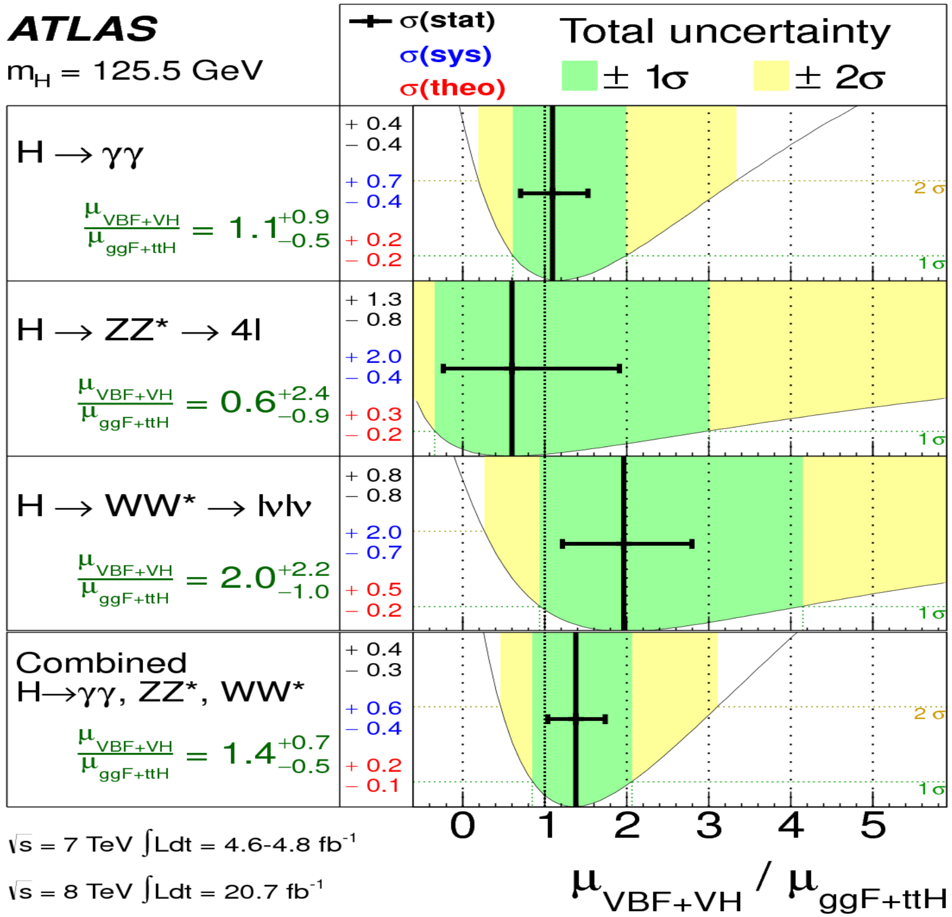


σ/σ_{sm}=0.88+-0.21

Ratio of VBF and ggH

- Test different production processes VBF vs ggH
- Evidence of VBF production at 3.1σ

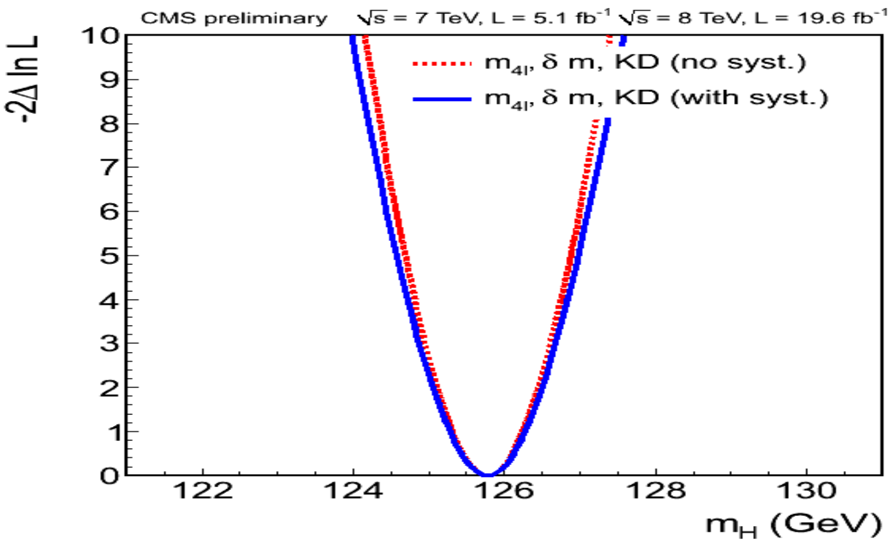




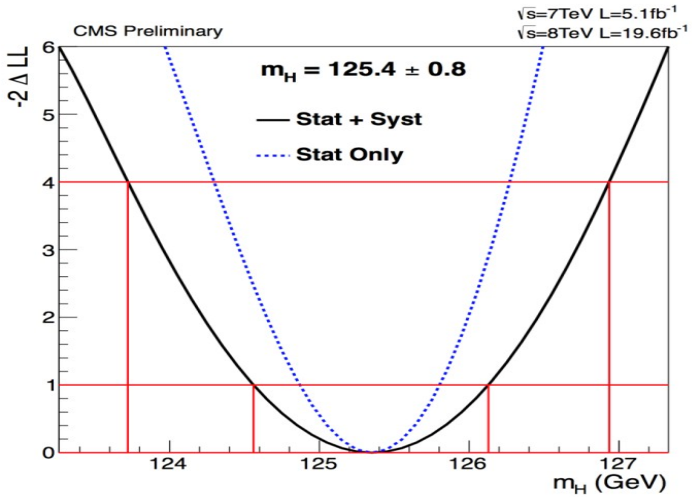
Higgs boson properties

- Now that a Higgs boson has been discovered, want to measure its properties:
  - Mass, width, spin, CP
  - Coupling to other bosons and to ferminos
  - Self-coupling
- Check whether it is a SM Higgs or if it is compatible with theories beyond the SM
  - In principle there could be more than one Higgs boson
  - Continue direct searches for extra Higgs bosons

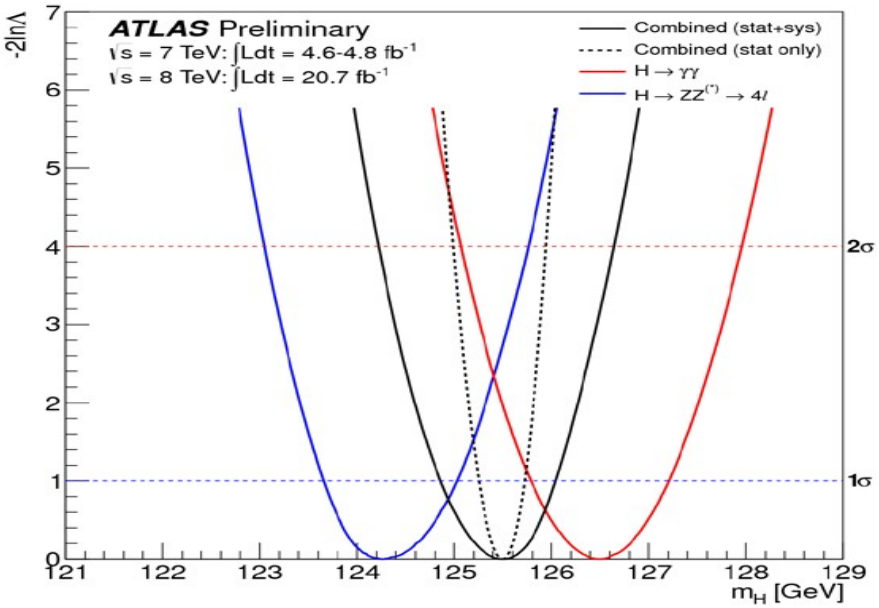
Mass measurements for H→ZZ,γγ



$m_H = 125.8 \pm 0.5$ (stat.) $\pm$ 0.2 (syst.)



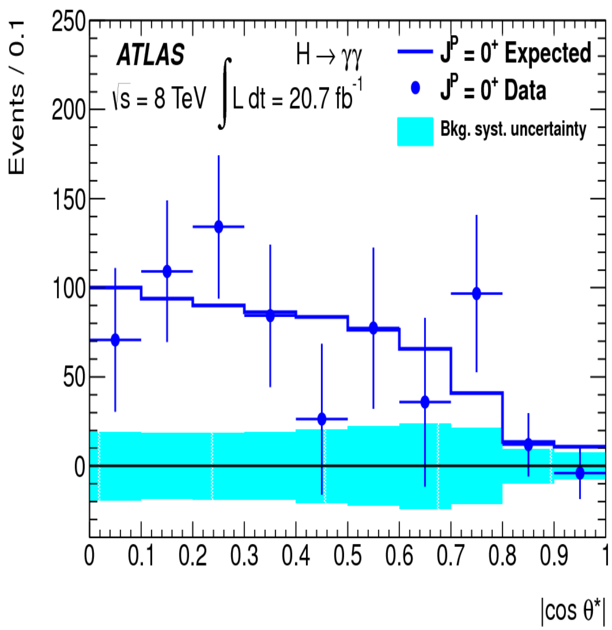
$m_H = 125.4 \pm 0.5$ (stat.) $\pm$ 0.6 (syst.)

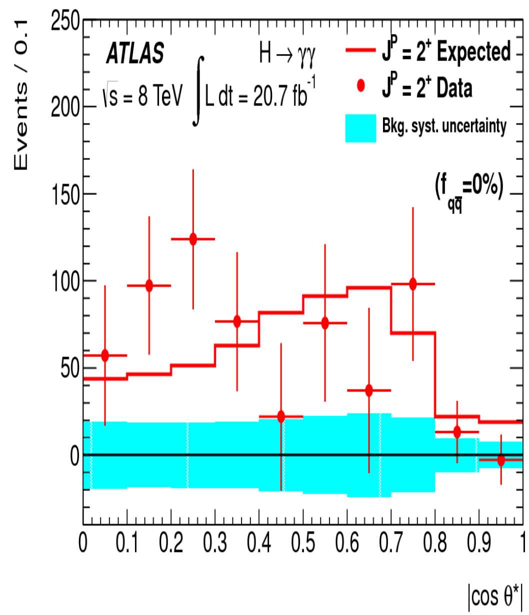


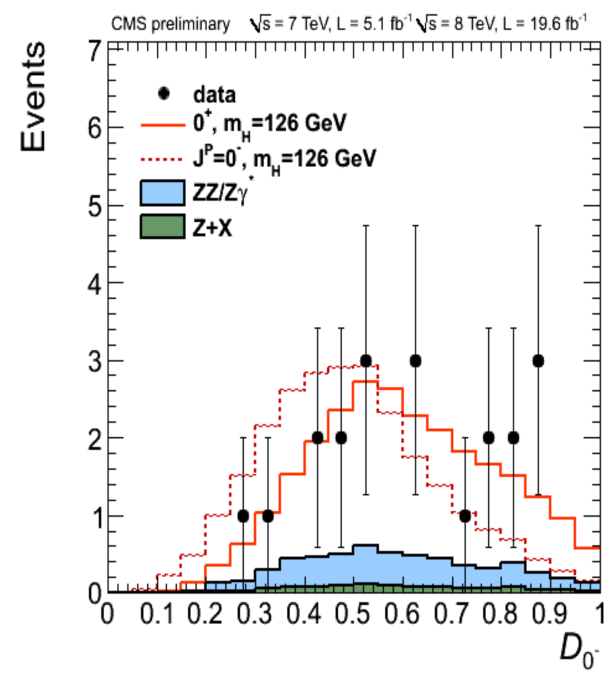
$$m_H = 125.5 \pm 0.2\,(\text{stat})\,^{+0.5}_{-0.6}\,(\text{sys})\ \text{GeV}$$

Spin-Parity Determination

- Use observables that sensitive to Spin and Parity of new boson.
- Several alternative models: 0-, 2+ tested against 0+ hypothesis
- X(J=1)→γγ is not allowed by Laudau-Yang theorem
- H→γγ: cos(θ*) in Collins-Sopper frame sensitive to J.
- H→WW*→lνlν: $\Delta\varphi_{ll}$, M_{ll}... sensitive to J^P
- H→ZZ*→4l: fully reconstruction sensitive to J^P





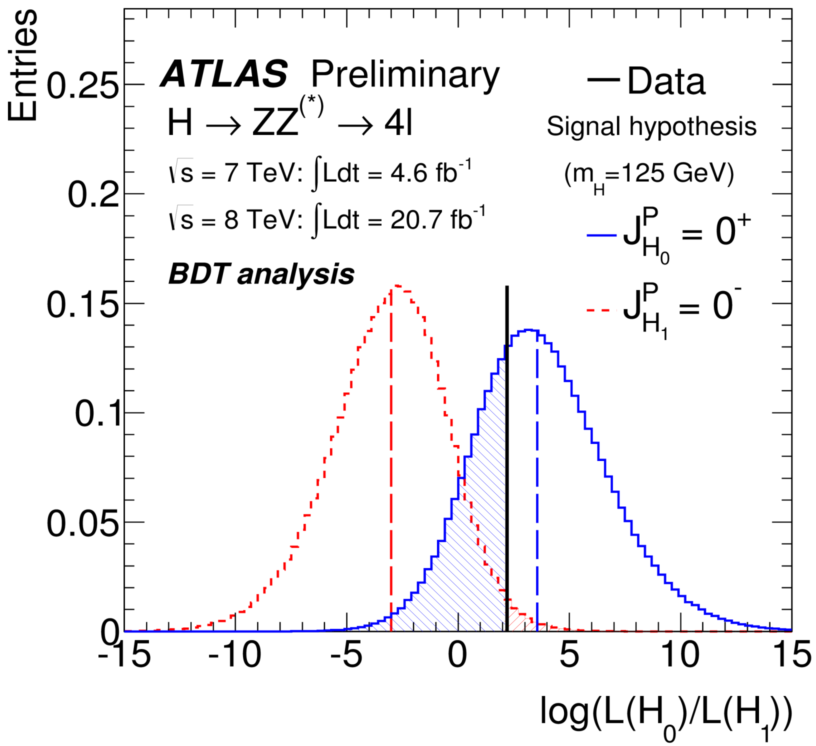


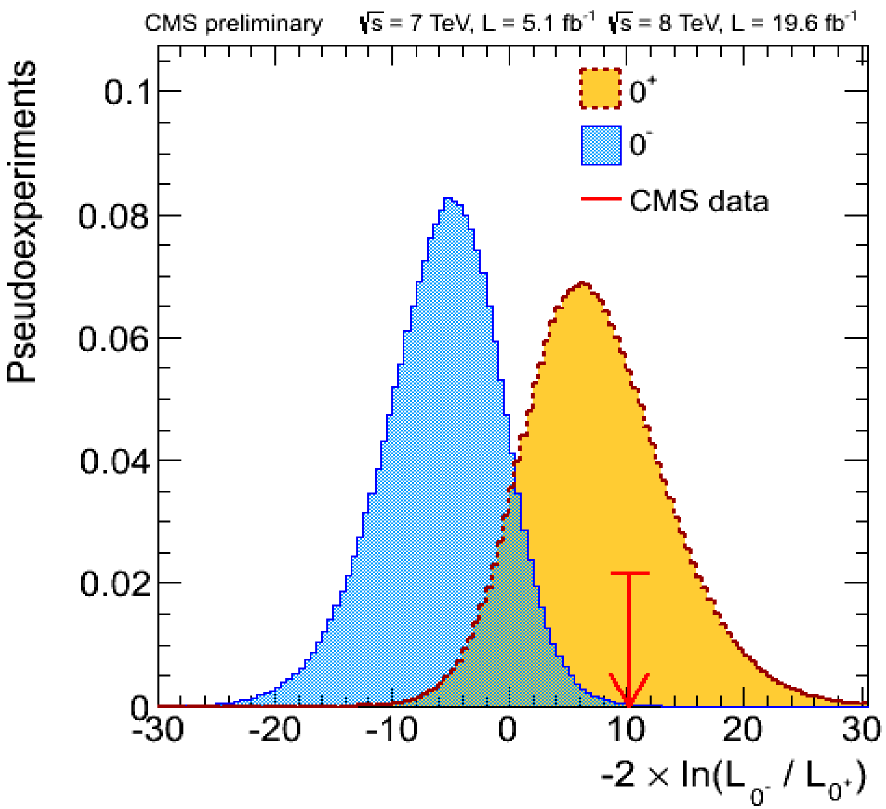
Test 0^+ vs 0^-

- $H \rightarrow ZZ^* \rightarrow 4l$ used for test statistic:

$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\mathrm{alt}}, \hat{\hat{\mu}}_{J^P_{\mathrm{alt}}}, \hat{\hat{\theta}}_{J^P_{\mathrm{alt}}})}$$

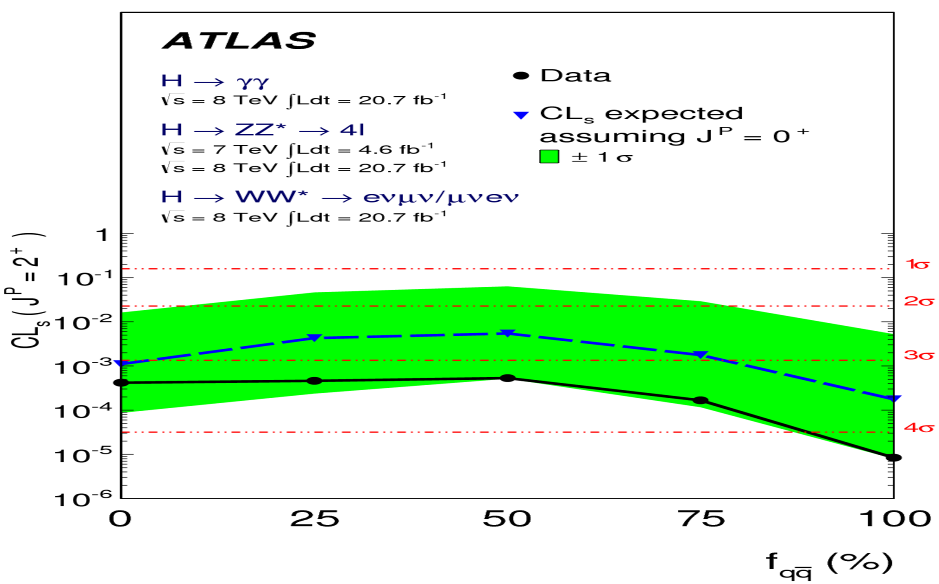
- ATLAS: 0^- excluded@97.8%CL(exp. 99.6%)
- CMS: 0^- excluded@99.8%CL(exp. 99.5%)
- Compatible with SM 0^+

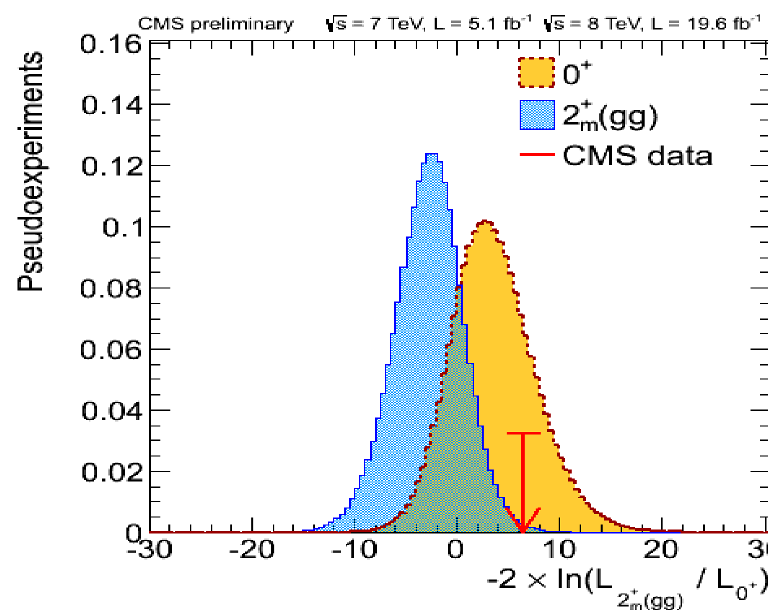




Test 0^+ vs 2^+

- Graviton inspired model with minimal couplings to SM
- It can be produced via gg or qq annihilation (fqq=qq/gg)
- ATLAS: combined H→γγ + ZZ*→4l + WW*→lνlν
  - 2^+(100% qq or gg)excluded >99.9% CL(exp. 99.9%)
- CMS: combined H→ZZ*→4l + WW*→lνlν
  - 2^+(100% gg) excluded at 99.4%(exp 98.8%)

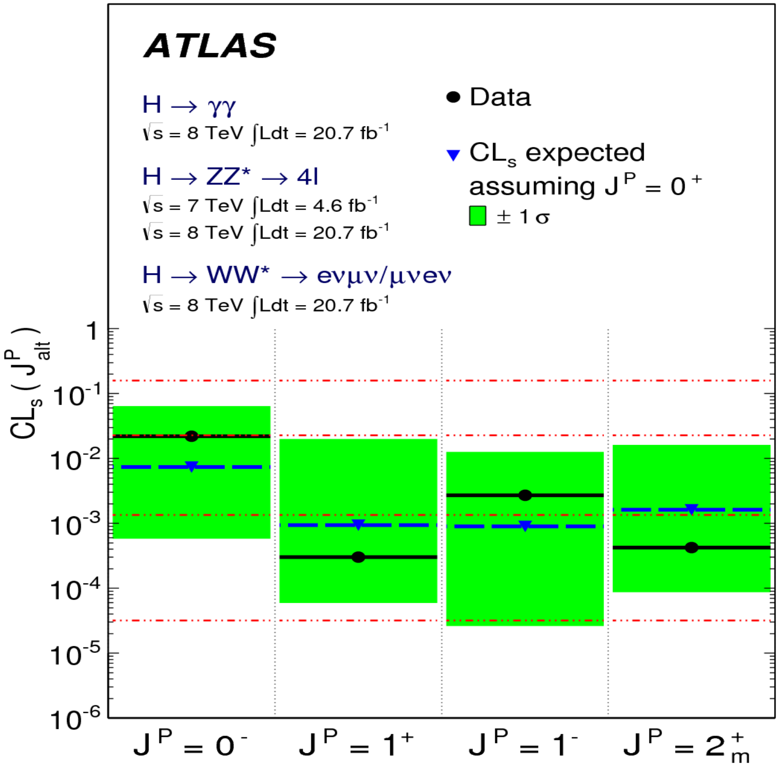




Spin-Parity Summary

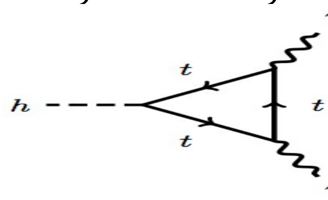
- ATLAS and CMS: strongly favor $J^P=0^+$
- All alternative J^P models tested: excluded @ 95% CL

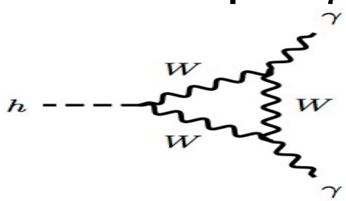
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2_{mgg}^+	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2_{mq\bar{q}}^+$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	>4.0σ	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	>4.0σ	<0.1%



Higgs Coupling

- Studies of the coupling will help to understand what the new particle is and can be parameterized through coupling factors respect to SM.
  - K_f is for Hff fermion coupling
  - K_γ, K_W, K_Z, K_V for Hγγ, HWW*, HZZ*, HVV* boson coupling
- SM loop-level correction:
  - $K_\gamma=|1.28K_W - 0.28K_f|^2$

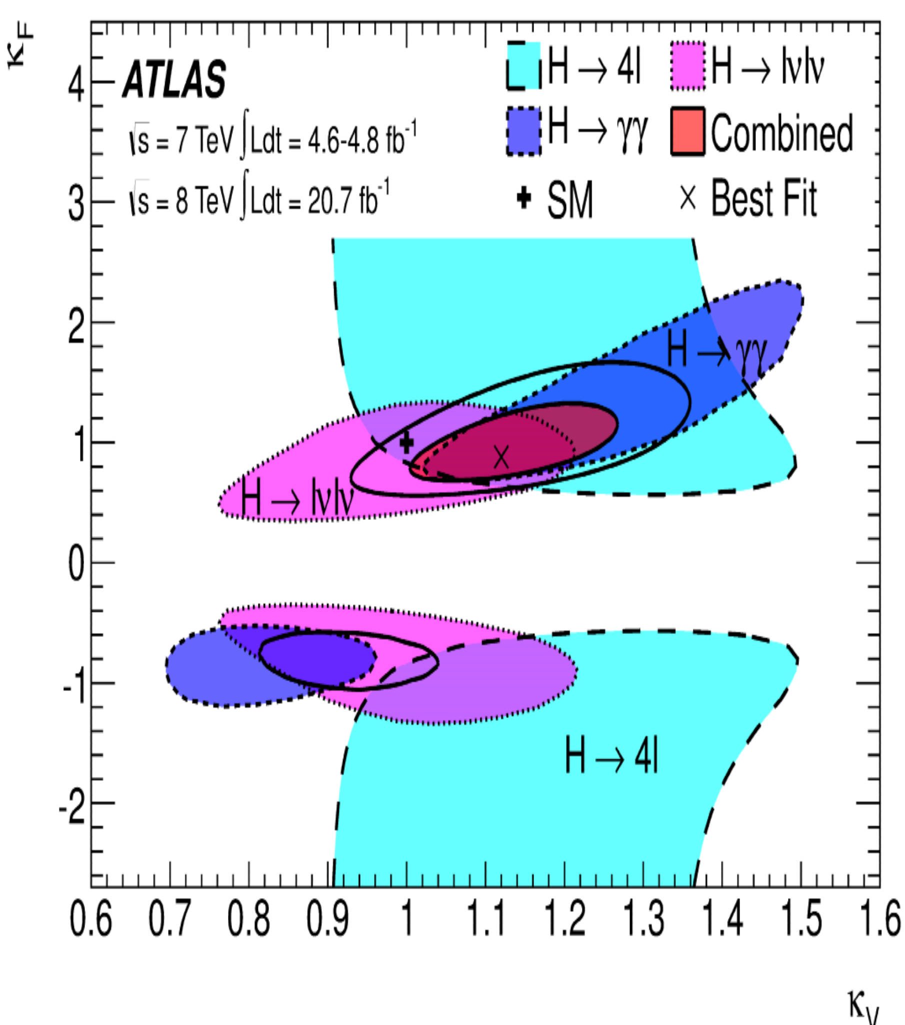


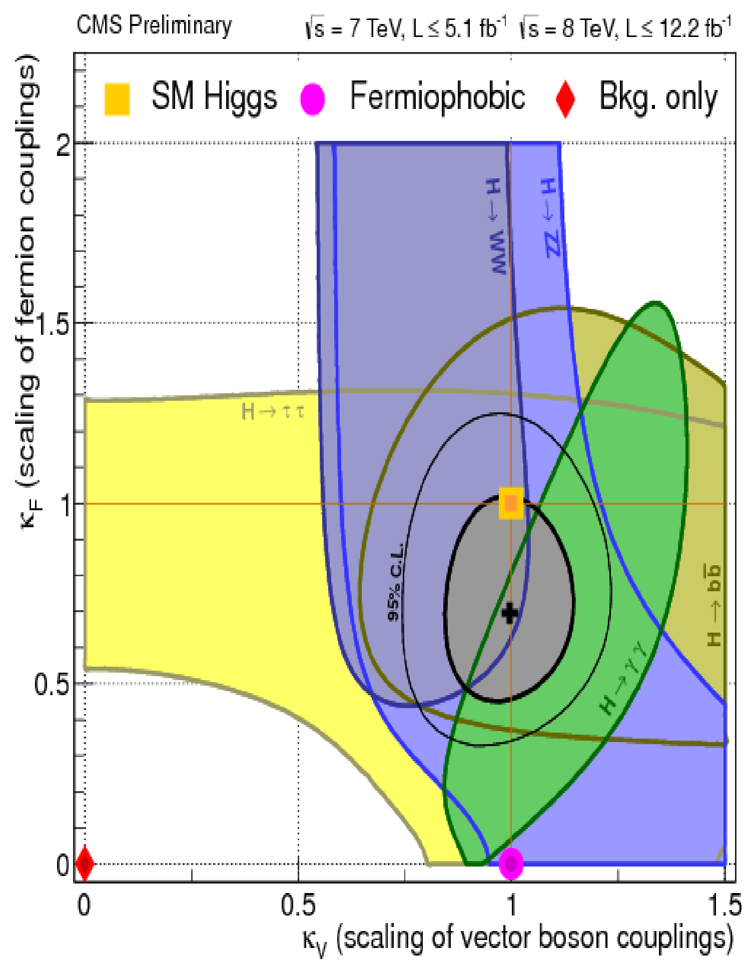


- Follow the procedures of LHC Higgs cross section WG
  - $\sigma \times BR(ii \longrightarrow \mathrm{H} \longrightarrow ff) = \dfrac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$
  - $\mu(ZH\rightarrow Zbb)=\sigma_{ZH} xBR(H\rightarrow bb)/[\sigma_{ZH} xBR(H\rightarrow bb)]_{SM}=(K^2_Z\times K_b^2)/K_H^2$
  - Loop scaling factors K_γ, K_g can be expressed as $K_\gamma(K_W,K_f)$
  - Treated as free parameters to test BSM contributions
  - K_H needs assumptions: ratios, relationships $K_H(K_f,K_W\ldots)$
- All K, μ are consistent with 1 for the SM Higgs boson.

Higgs Coupling

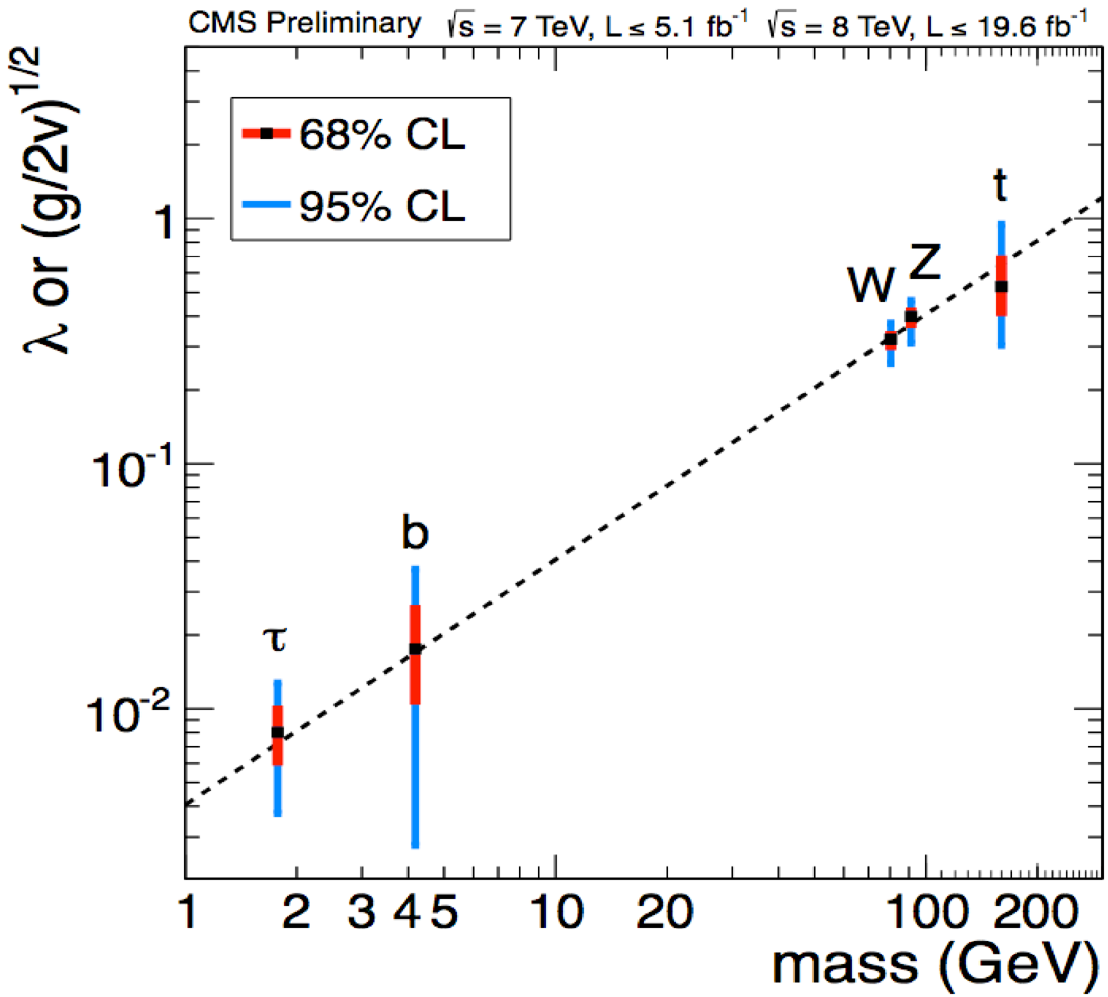
- Results are consistent with SM predictions.





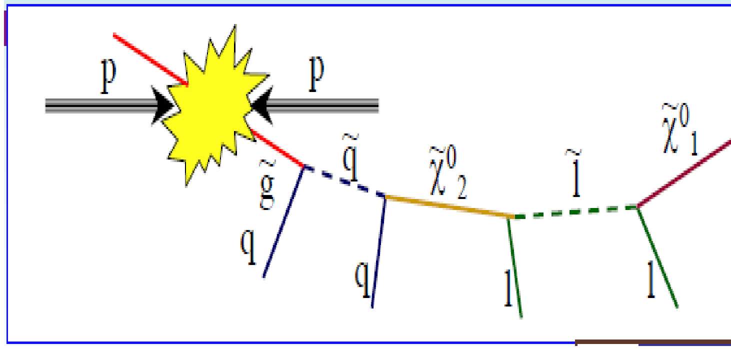
Higgs Coupling vs Mass

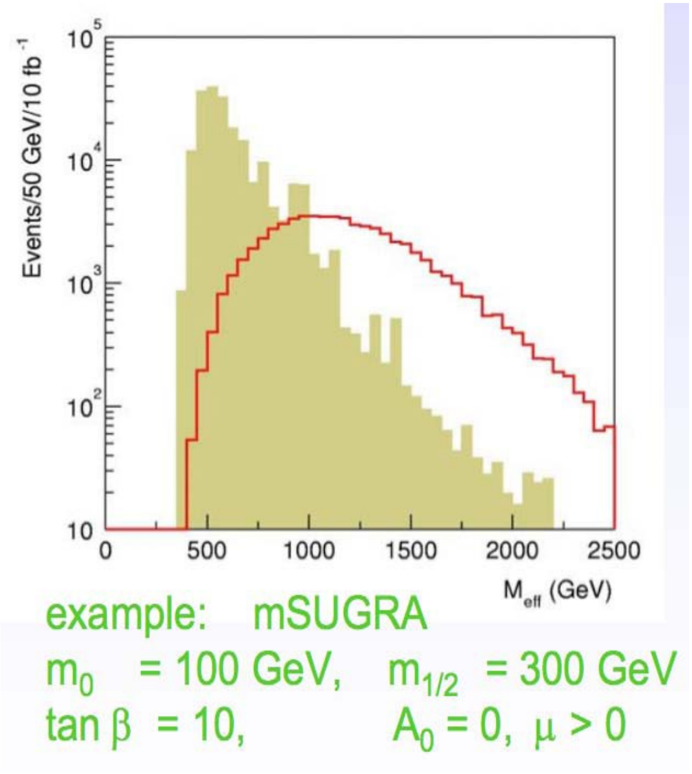
- The coupling seems consistent with the expectation of SM.



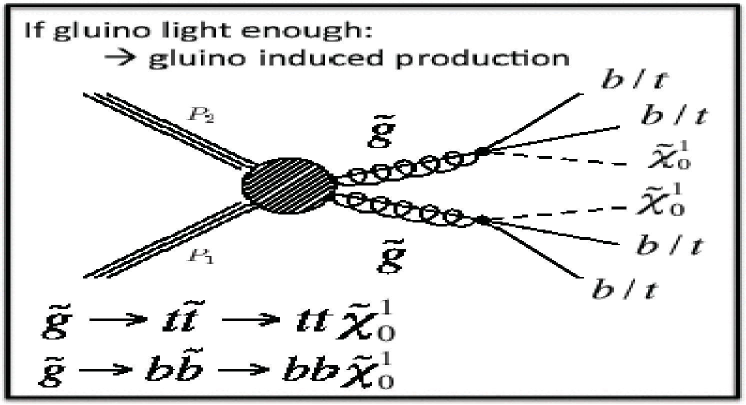
Search for Squark/Gluino Production

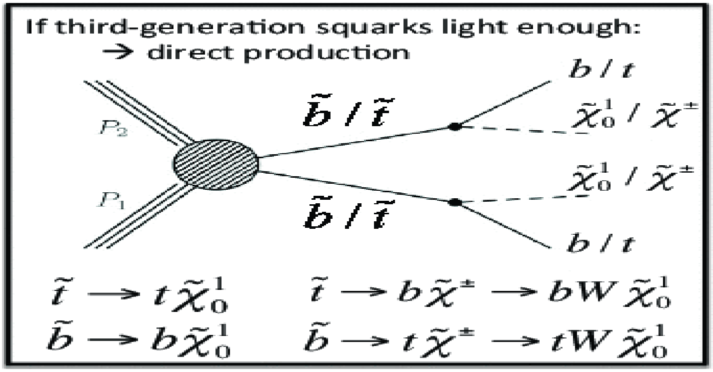
- These particles are strongly produced and thus have cross section similar to QCD at the same mass scale.
- Will produce an experimental signature of multi-jets, leptons, missing Et
- A useful variable is the effective mass
- Use simplified model for guidelines
- Typical selections:
  - Njet>=4, with Et>100,50,50,50
  - 2 leptons with Et>25 GeV
  - Met>100 GeV

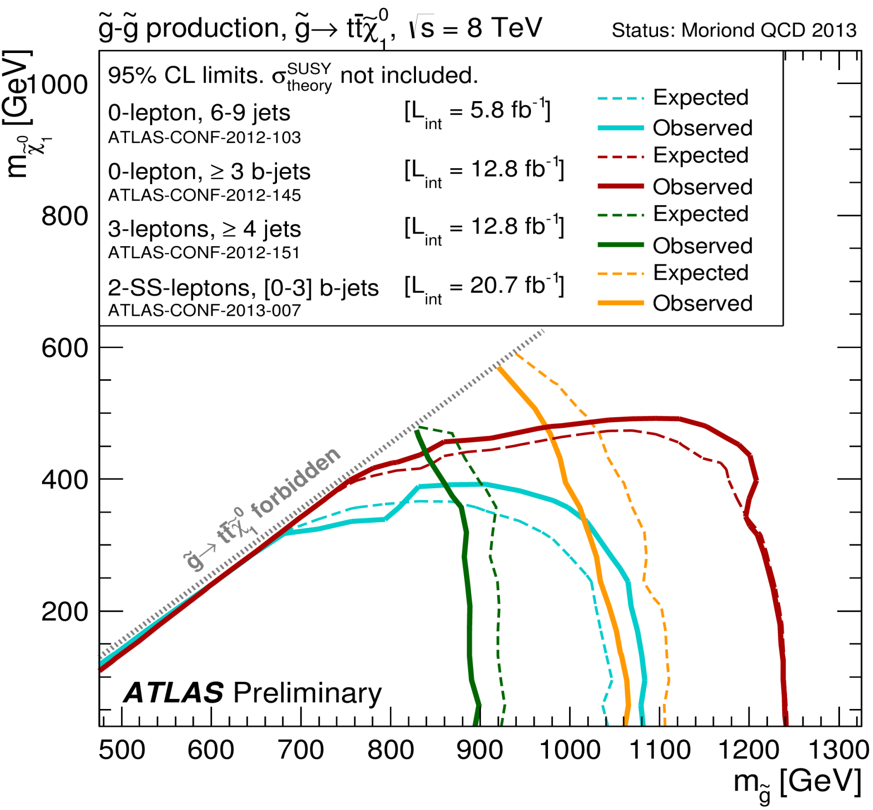


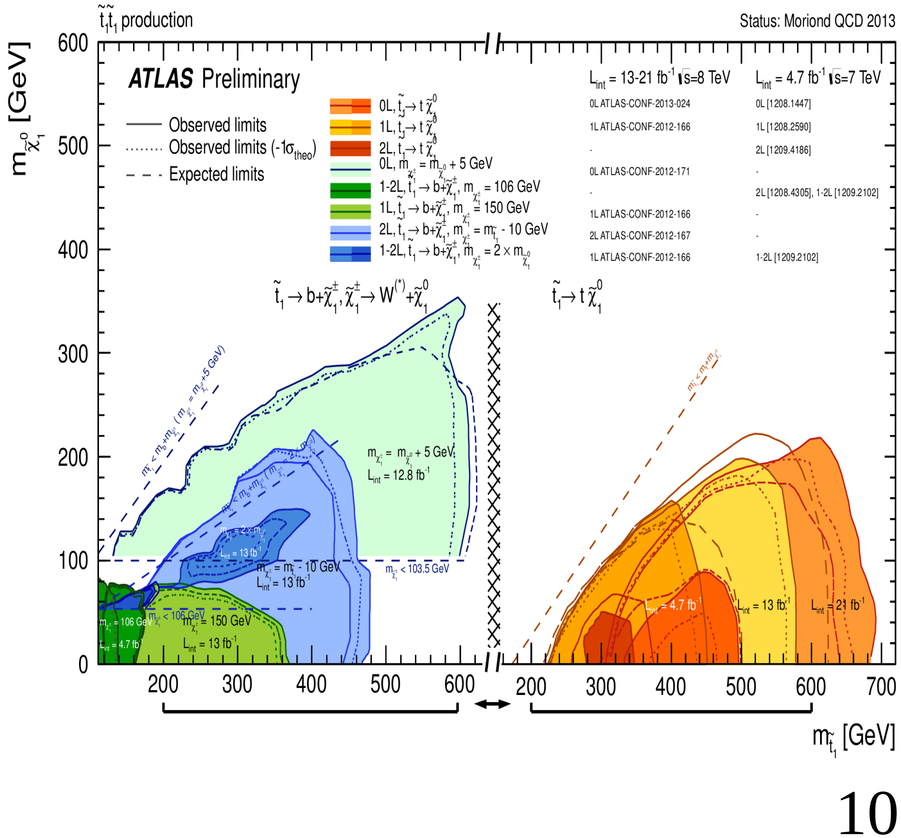


Natural-SUSY searches

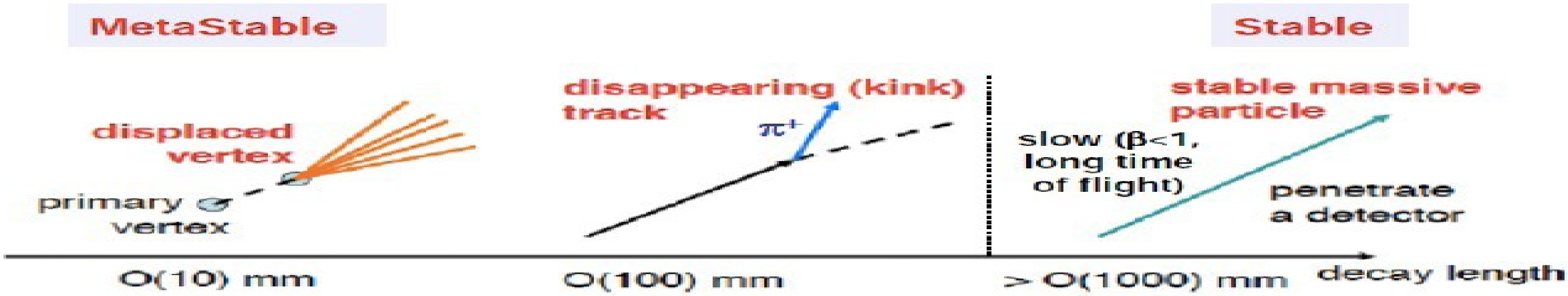




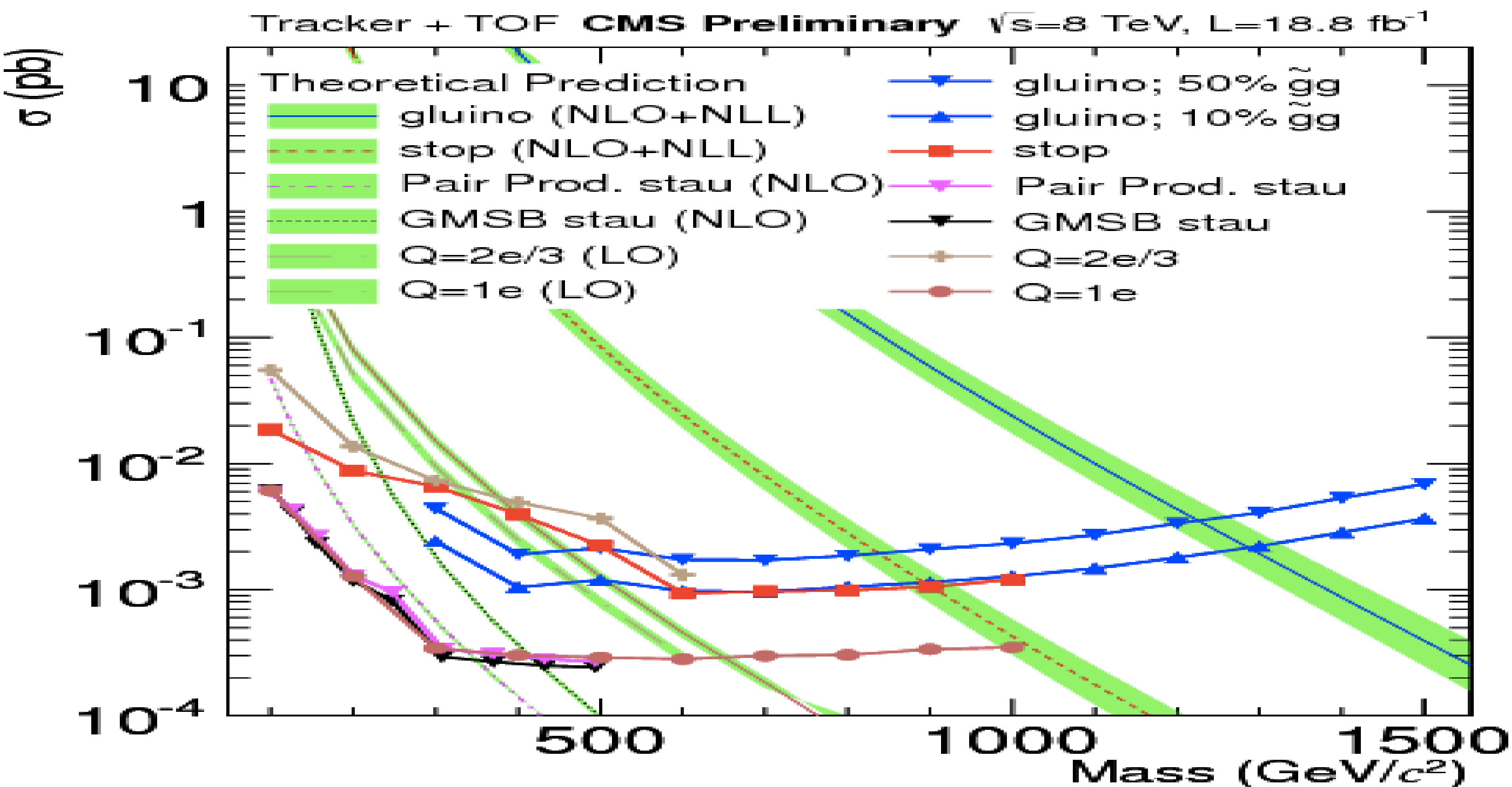




Non-MET SUSY

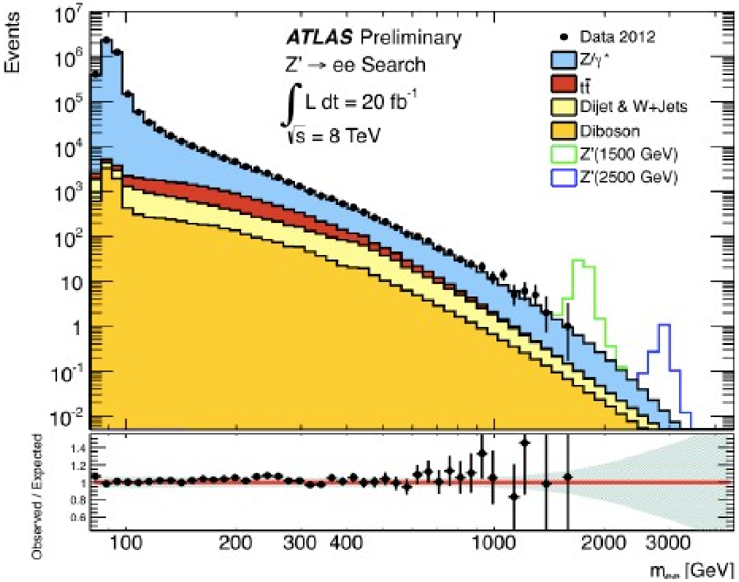


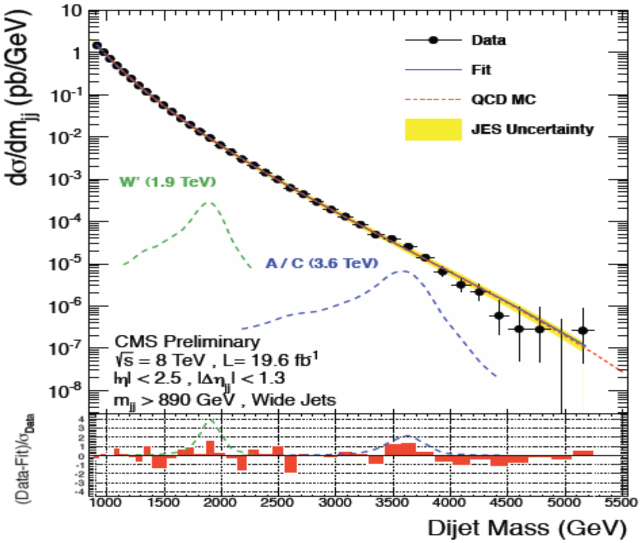
MetaStable
Stable
displaced vertex
primary vertex
disappearing (kink) track
π^+
stable massive particle
slow (β<1, long time of flight)
penetrate a detector
O(10) mm
O(100) mm
> O(1000) mm
decay length

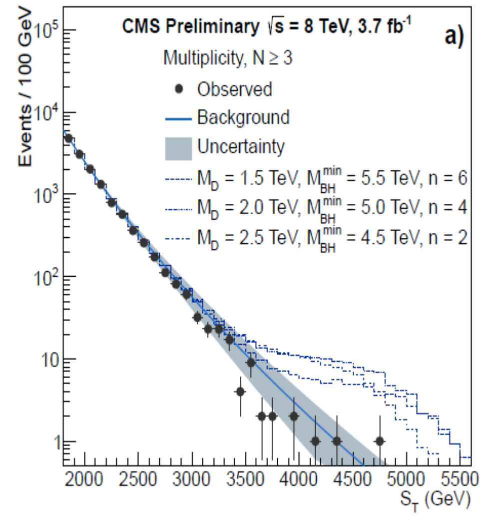


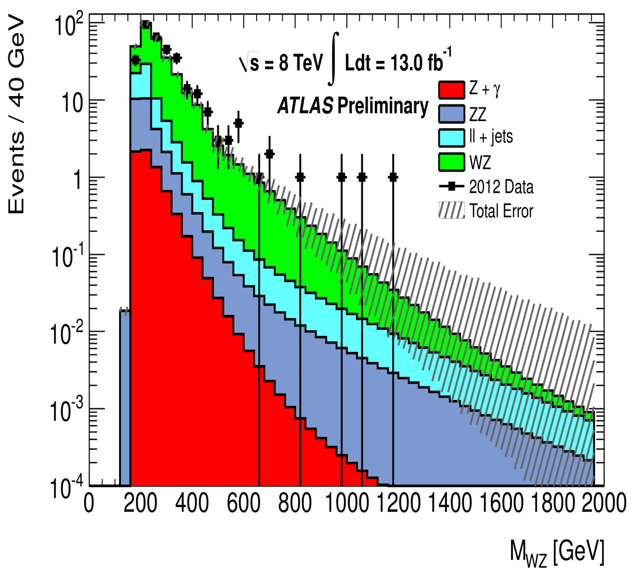
Tracker + TOF CMS Preliminary $\sqrt{s}$=8 TeV, L=18.8 fb^{-1}
σ (pb)
Theoretical Prediction
gluino (NLO+NLL)
stop (NLO+NLL)
Pair Prod. stau (NLO)
GMSB stau (NLO)
Q=2e/3 (LO)
Q=1e (LO)
gluino; 50% $\tilde{g}$g
gluino; 10% $\tilde{g}$g
stop
Pair Prod. stau
GMSB stau
Q=2e/3
Q=1e
Mass (GeV/c^2)

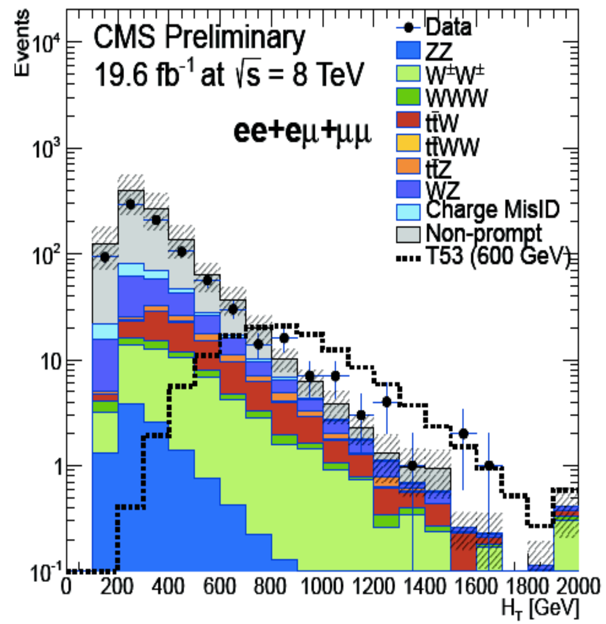
Other Searches

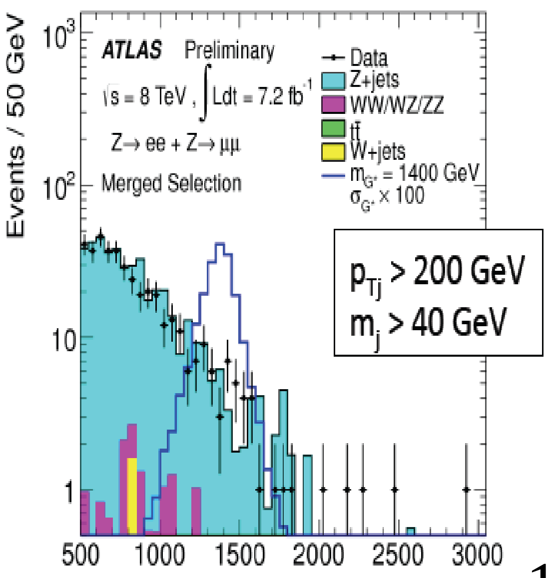




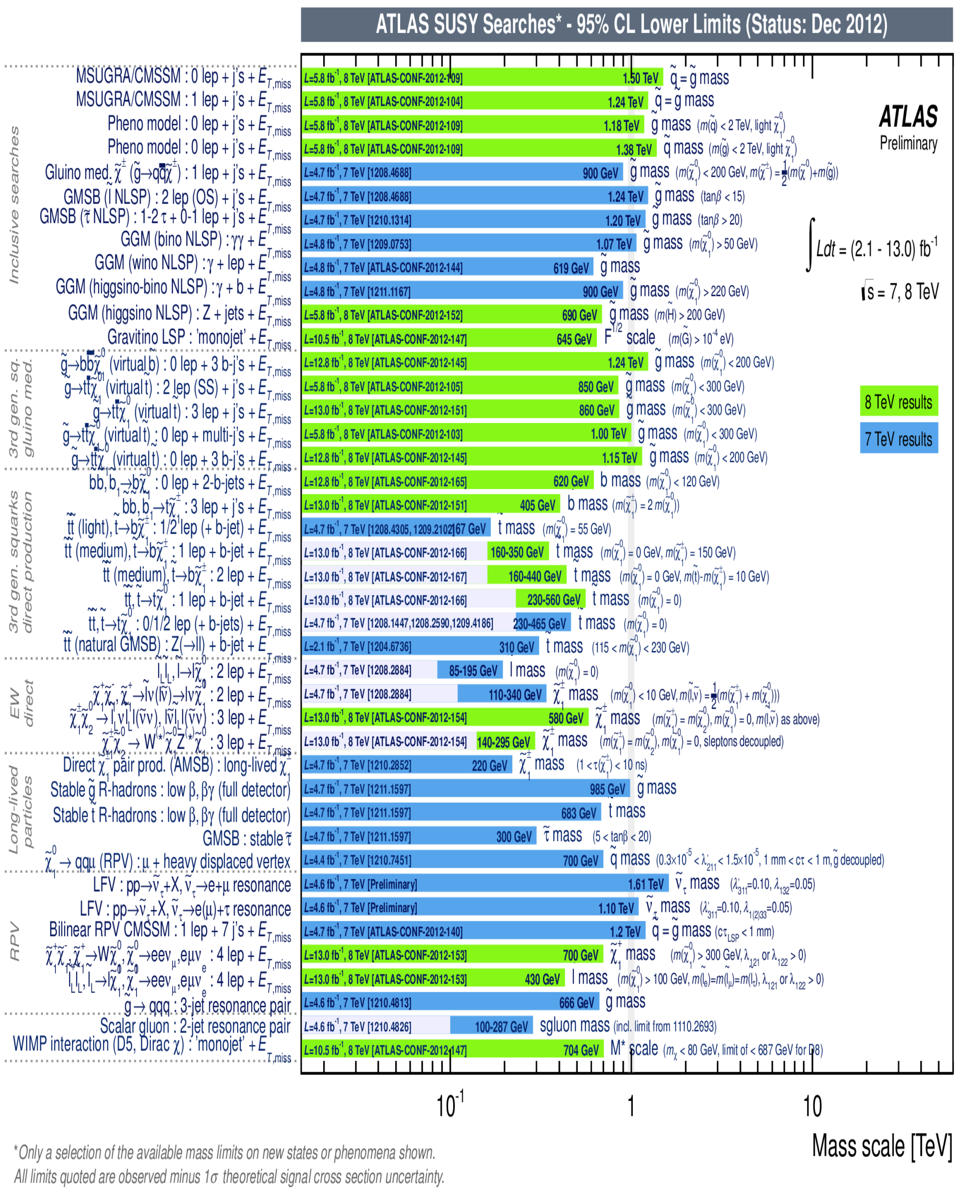


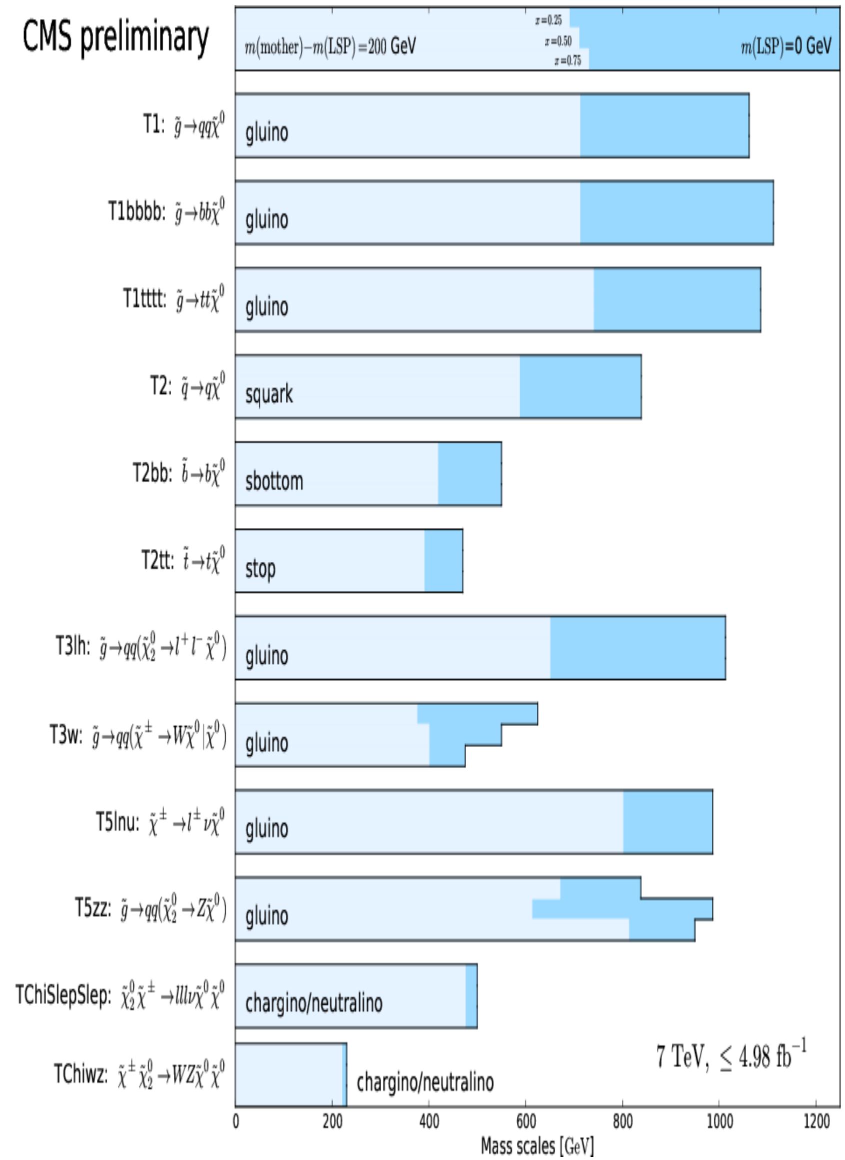




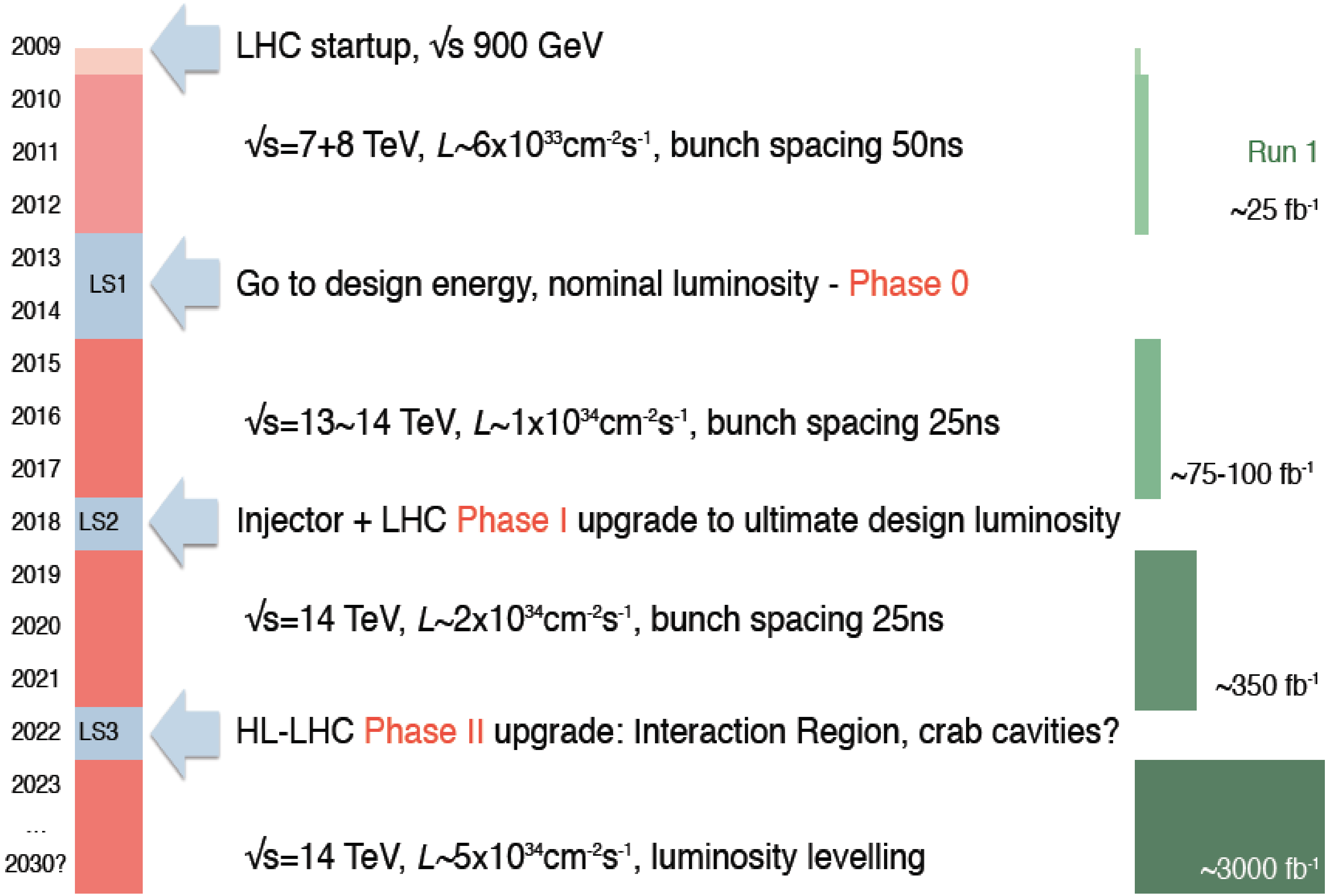


Summary of BSM Searches





LHC Road Map


2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
...
2030?
LS1
LS2
LS3
LHC startup, √s 900 GeV
√s=7+8 TeV, L~6x10³³cm⁻²s⁻¹, bunch spacing 50ns
Go to design energy, nominal luminosity - Phase 0
√s=13~14 TeV, L~1x10³⁴cm⁻²s⁻¹, bunch spacing 25ns
Injector + LHC Phase I upgrade to ultimate design luminosity
√s=14 TeV, L~2x10³⁴cm⁻²s⁻¹, bunch spacing 25ns
HL-LHC Phase II upgrade: Interaction Region, crab cavities?
√s=14 TeV, L~5x10³⁴cm⁻²s⁻¹, luminosity levelling
Run 1
~25 fb⁻¹
~75-100 fb⁻¹
~350 fb⁻¹
~3000 fb⁻¹

e+e- colliders on the horizon

- ILC: Technical Design Report 2013
  - CM Energy: (91/)250-1000 GeV
  - Luminosity: 5×10^{34} $cm^{-2}s^{-1}$
- CLIC: Conceptual Design Report 2013
  - CM Energy: 350-3000 GeV
  - Luminosity: 6×10^{34} $cm^{-2}s^{-1}$
- TLEP:
  - A high performance circular e+e- collider to study the Higgs boson (4th IPAC 2013)
  - CM Energy:91-350 GeV
  - Luminosity: 56×10^{34} $cm^{-2}s^{-1}$
  - Can convert to a pp collider with CM up to 100TeV.

Summary

- With 5 fb-1 at 7TeV and 20 fb-1 at 8 TeV the LHC experiments are already discovered a Higgs boson and making detailed measurements of Standard Model physics.
- These progresses give a solid basis for understanding the detectors and the background to searches for BSM.
- So far, there is nothing new yet!
- With 30 fb-1 at 13-14 TeV in 2015 and beyond we will have
  - Much more detailed understanding of the Higgs
  - Set stringent limits or make discovery for BSM physics
- And we could find something completely unexpected.
- This is just beginning to explore the precision Higgs physics era!