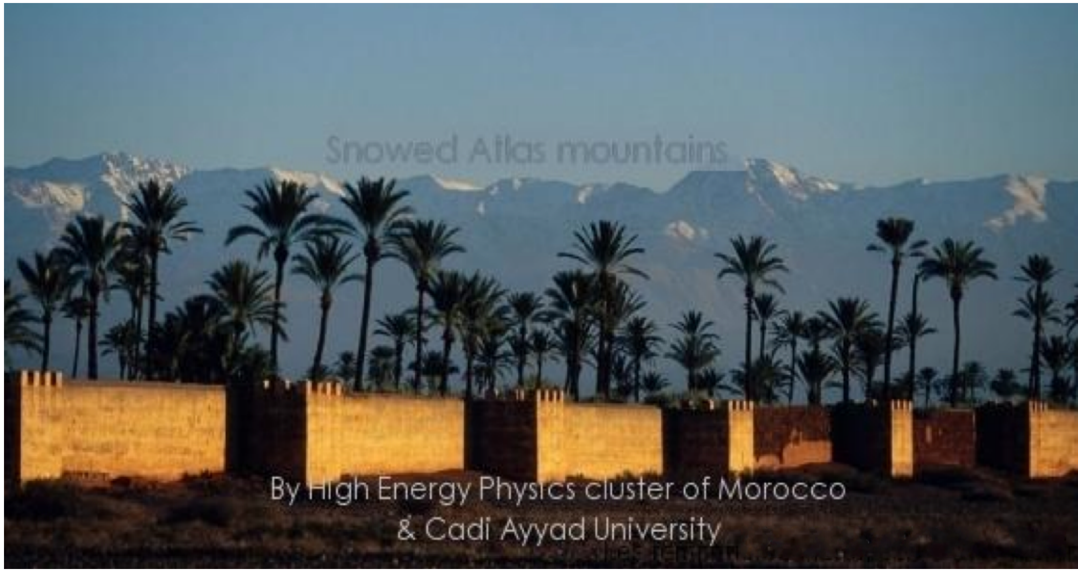
Introduction to ATLAS

- part 1: ATLAS Detector (and LHC)
- **part 2: Physics programme in ATLAS**
- part 3: Event Reconstruction and
  ATLAS Performance
- part 4: Physicists' tools
  analyses in ATLAS

Wolfgang Liebig

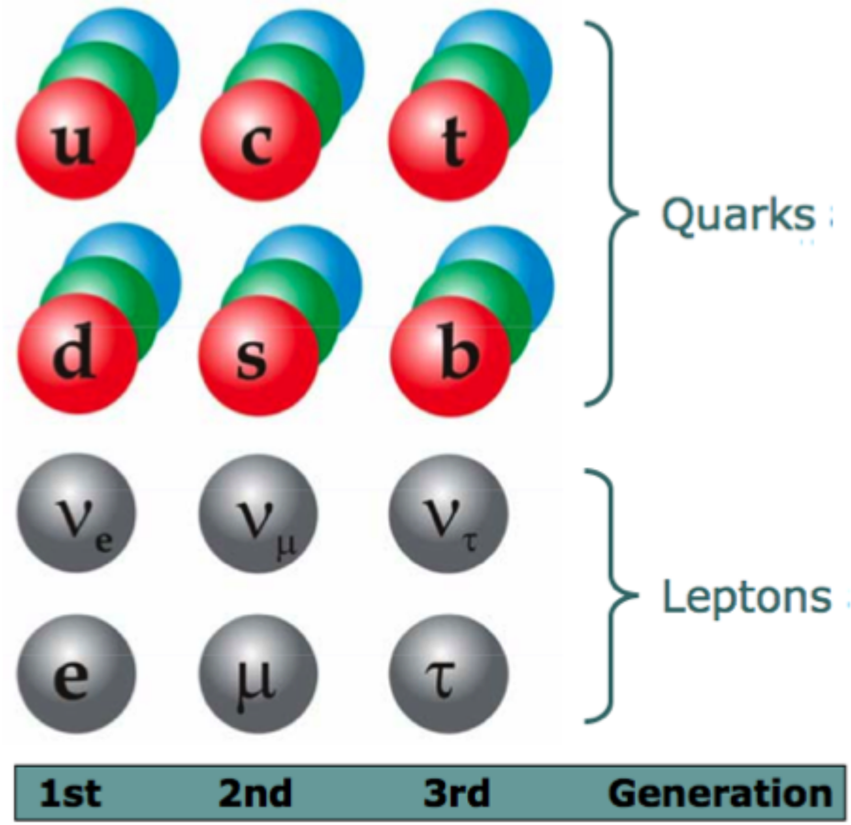
Part 2: Physics at the ATLAS Expt

- The setting: standard model and beyond
- p-p collisions
- Minimum bias and QCD
- Inclusive spectra
- Standard model processes
  - B-physics
  - W and Z bosons
  - top quark physics
- Search for the Higgs boson
- Beyond standard model
  - Supersymmetry
  - Heavy gauge bosons and more
- Pb-Pb collisions = heavy ion physics



The Standard Model: building blocks of matter

- surrounding matter: quarks and leptons
- fermions (spin-$\frac{1}{2}$ particles)
- two additional, heavier generations observed
- quark and lepton masses cover extreme range
  $m_e = 0.000511\,\text{GeV}/c^2$
  $m_\tau = 1.8\,\text{GeV}/c^2$
  $m_{u,d} \approx 0.0005\,\text{GeV}/c^2$
  $m_t = 174\,\text{GeV}/c^2$

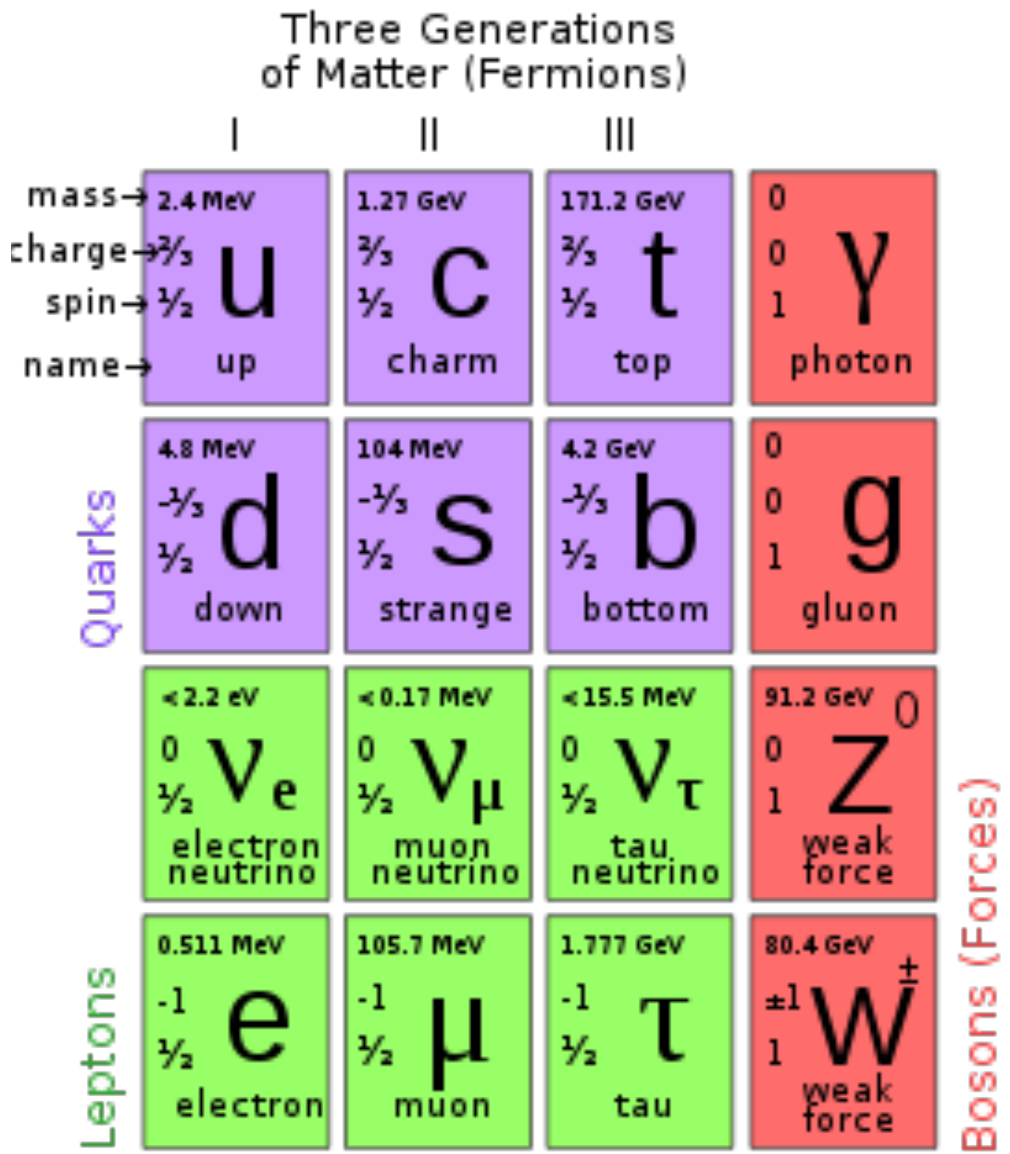


Matter and its Interactions

Observed forces:

- gravitation
- electromagnetic
- weak nuclear force
  (β decay, sun)
- strong nuclear force
  (quarks composing protons)

The Standard Model describes el-mag., weak and strong force as exchange of bosons (spin-1 particles)



The Standard Model: gauge symmetry and forces

under an experimentalist's view

electro-magnetic force

- in quantum field theory described as interaction between charged-particle field and gauge field
- Local $U(1)$ gauge symmetry
- massless photon as force carrier

strong nuclear force

- $SU(3)$ gauge symmetry has the property of asymptotic freedom
  asymptotic freedom = the observed property of quarks to behave as free particles only at very small distance scales
- color charge
- 8 massless force carriers, gluons

What about the weak interaction?

Weak nuclear force

properties unique to weak force:

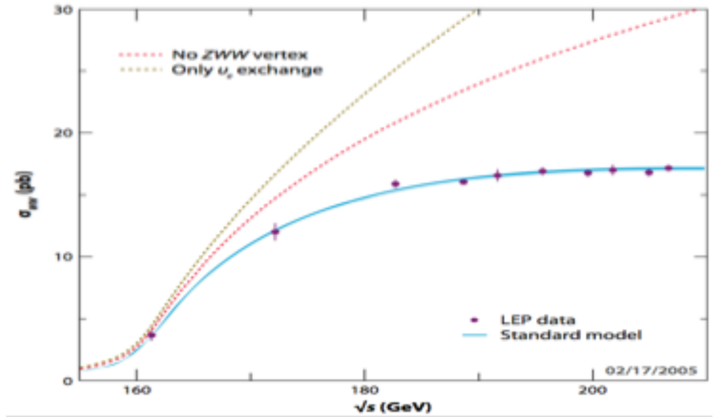
- capable of changing quark flavour
- violates P and CP symmetry
- force carriers must have significant masses to explain short range and low interaction probabilities

The doublet structure of weak states suggests underlying $SU(2)$ symmetry

But: a symmetry group with massive gauge bosons is not gauge invariant!

Glashow, Salam, and Weinberg: unified theory of el-mag. and weak interaction (1968)

- based on local $SU(2)_L \otimes U(1)$ gauge symmetry



- together with a mechanism that breaks the symmetry at low energies and produces massive gauge bosons: the Higgs mechanism.

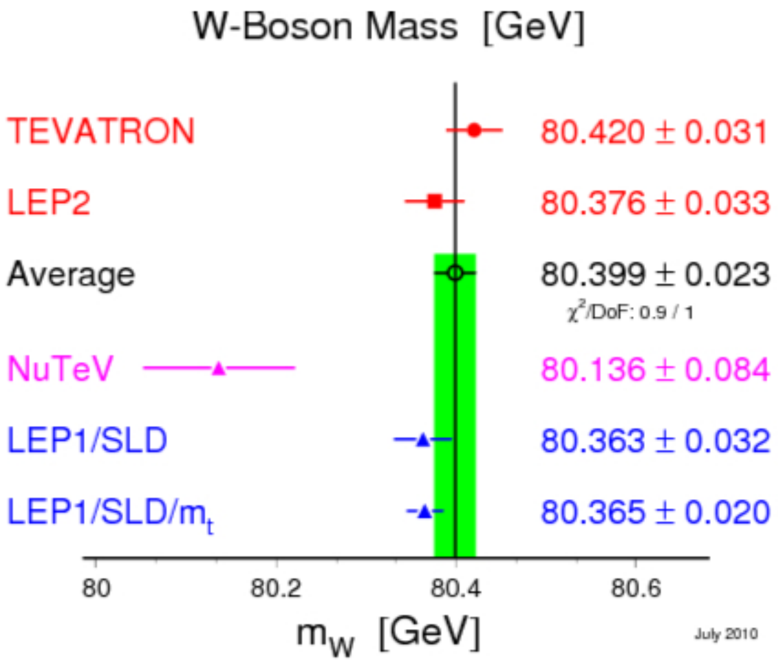
Massive Electroweak Gauge Bosons

After gauge symmetry breaking

$$W^\pm_\mu = \sqrt{2}(W^{(1)}_\mu \pm W^{(2)}_\mu)\,, \qquad m_W^2 = \tfrac{1}{4} g^2 v^2$$
$$Z^0_\mu = \sqrt{g^2+g'^2}(-g'B + gW^{(3)}_\mu)\,, \quad m_Z^2 = \tfrac{1}{4}(g^2+g'^2)v^2$$
$$A_\mu = \sqrt{g^2+g'^2}(gB_\mu + g'W^{(3)}_\mu)\,, \quad m_A^2 = 0 \quad (\text{A} = \text{photon})$$

▷ massive $W^\pm$, Z^0 and massless photon (A).

- EW coupling $g \sin\theta_W = e = g' \cos\theta_W$ (mixing angle $\cos\theta_W = m_W/m_Z$
- Prediction from μ decay
  $\frac{G_F}{\sqrt{2}} = \frac{g^2}{8m_W^2} = \frac{1}{2v^2}$
- Remarkable agreement for m_W
- Higgs also generates masses for fermions but the couplings (Yukawa) are free parameters

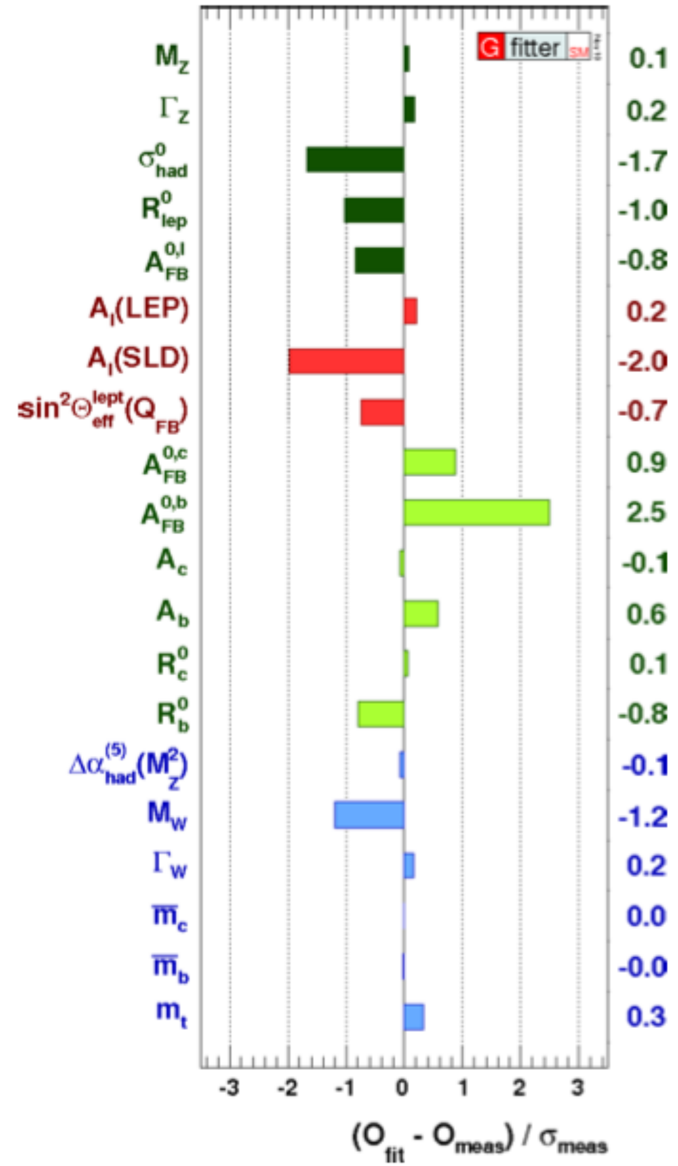


Standard Model Consistency

where do we stand today?

- Standard Model measurements from
  - ▷ e^+e^- colliders (LEP, SLC),
  - ▷ Tevatron,
  - ▷ fixed target experiments
- probed energy range up to $\approx 100\,\text{GeV}$
- Standard Model fit with 20 measurements, 7 free fit parameters
  - ▷ $\chi^2_{\text{min}} = 16.6$, $\text{Prob}(\chi^2_{\text{min}}, 13) = 22\,\%$
  - ▷ plot shows pull values of complete fit
  - ▷ no individual value exceeds 3σ
- Standard Model consistent with all experimental data

no indication for new physics

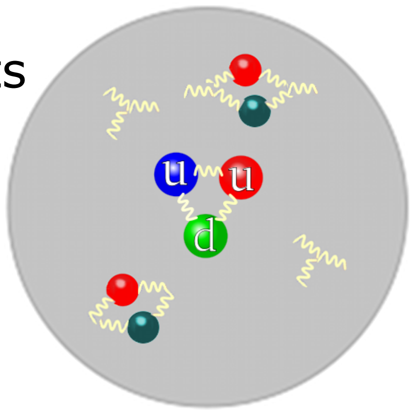


So… why the LHC?

- Today's Standard Model (SM) measurements are consistent without need for new physics. However…
- The mechanism of electro-weak symmetry breaking (EWSB) is not proved, the postulated Higgs boson not yet found
  - LHC was designed and built to **find or exclude** it
  - Searches for the Higgs boson are therefore a main topic of this lecture!
- The Standard Model also has limitations in the extrapolation to very high energies
  - perhaps related to EWSB or simply nature's vast reserves to surprise us
  - LHC expands the energy frontier, may see first evidence for such new physics
  - So **beyond the SM** theories are also part of our lecture
- Let's look at p-p collisions and SM physics first before turning to the search for new particles
  - The ATLAS experiment does it the same: understanding known processes and the detector is prerequisite for solid discovery

Proton Constituents

- Proton constituents
  - valence quarks u,u,d
  - sea quarks and antiquarks
  - gluons



- hard scattering in p–p collisions is
  - q–q or q–gluon scattering
  - q–q annihilation
  - gluon fusion
- centre-of-mass energy is the energy available for producing new particles in elementary processes

- The quarks and gluons carry only a fraction x of the proton momentum

  $0 < x < 1$
- effective centre-of-mass energy:

$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} < \sqrt{s} = 7\,\mathrm{TeV}$$

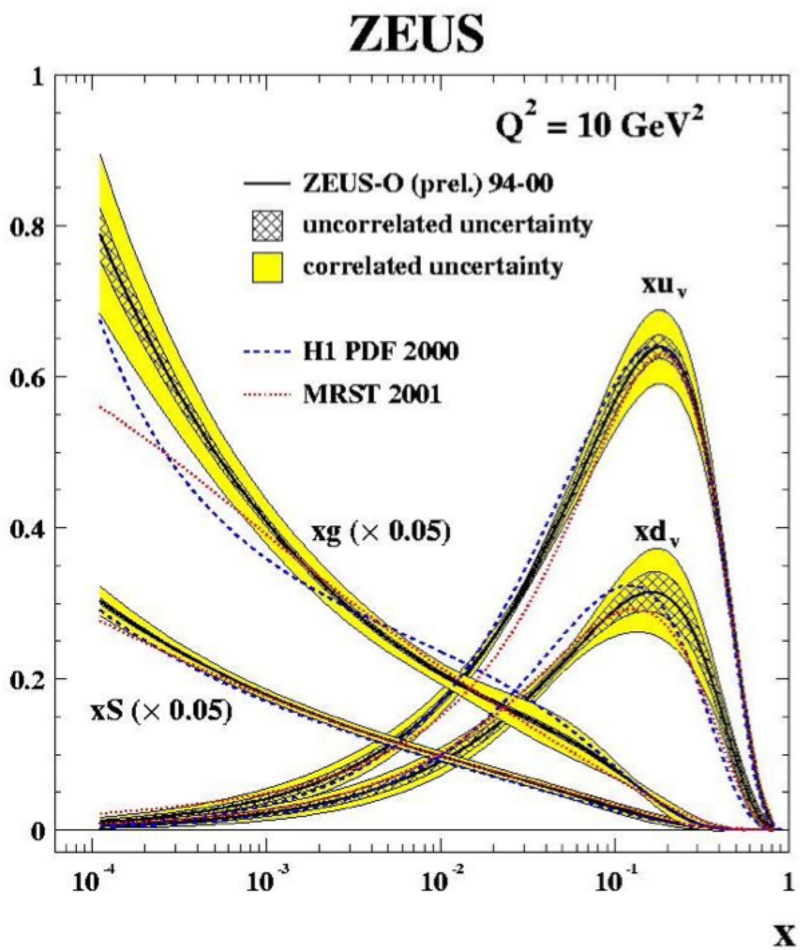
- To produce a particle of mass

  100 GeV –> x=0.014

  2.5 TeV –> x=0.35
- Physics at LHC depends on x-value distributions for quarks and gluons in proton
  - Do we know them?

LHC is... a Gluon Collider!

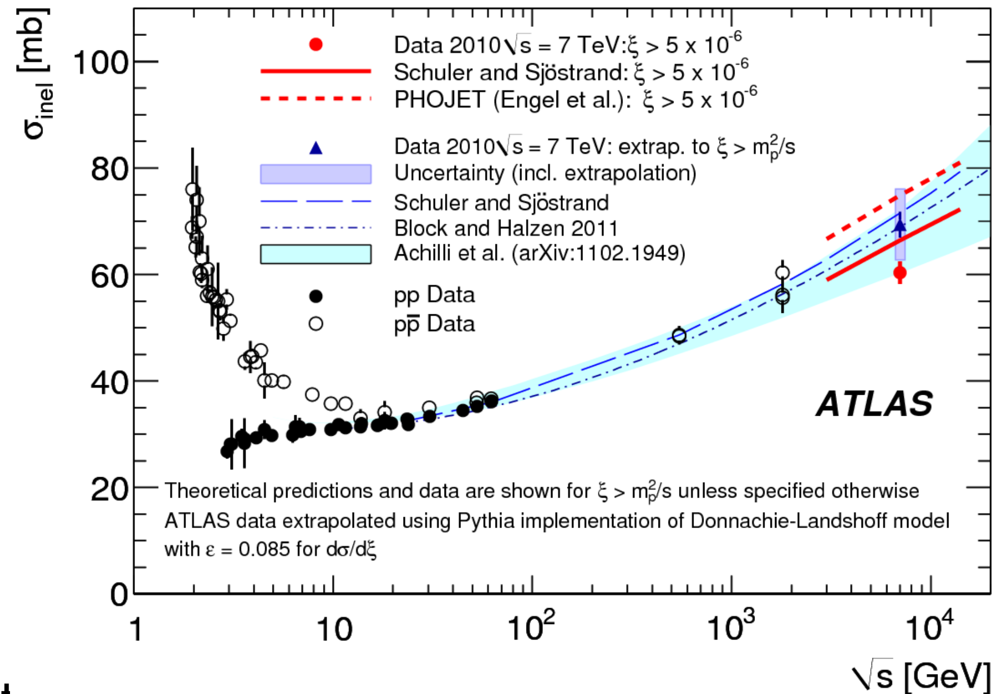
- Parton density functions from HERA e-p collisions

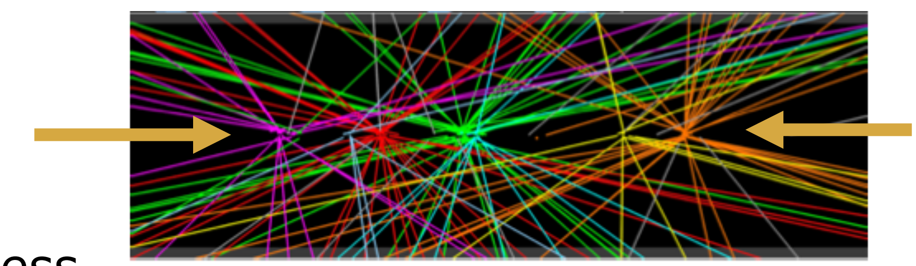


- gluons dominate at small x
- u, d valence quarks peak at large x
  - as we would expect
  - at LHC they do not annihilate in an elementary process! (unlike in proton-antiproton machine)
- LHC is a gluon collider
- gluon PDF has large uncertainties at small x
- measurements of minimum bias and standard model cross-section at LHC needed to improve precision

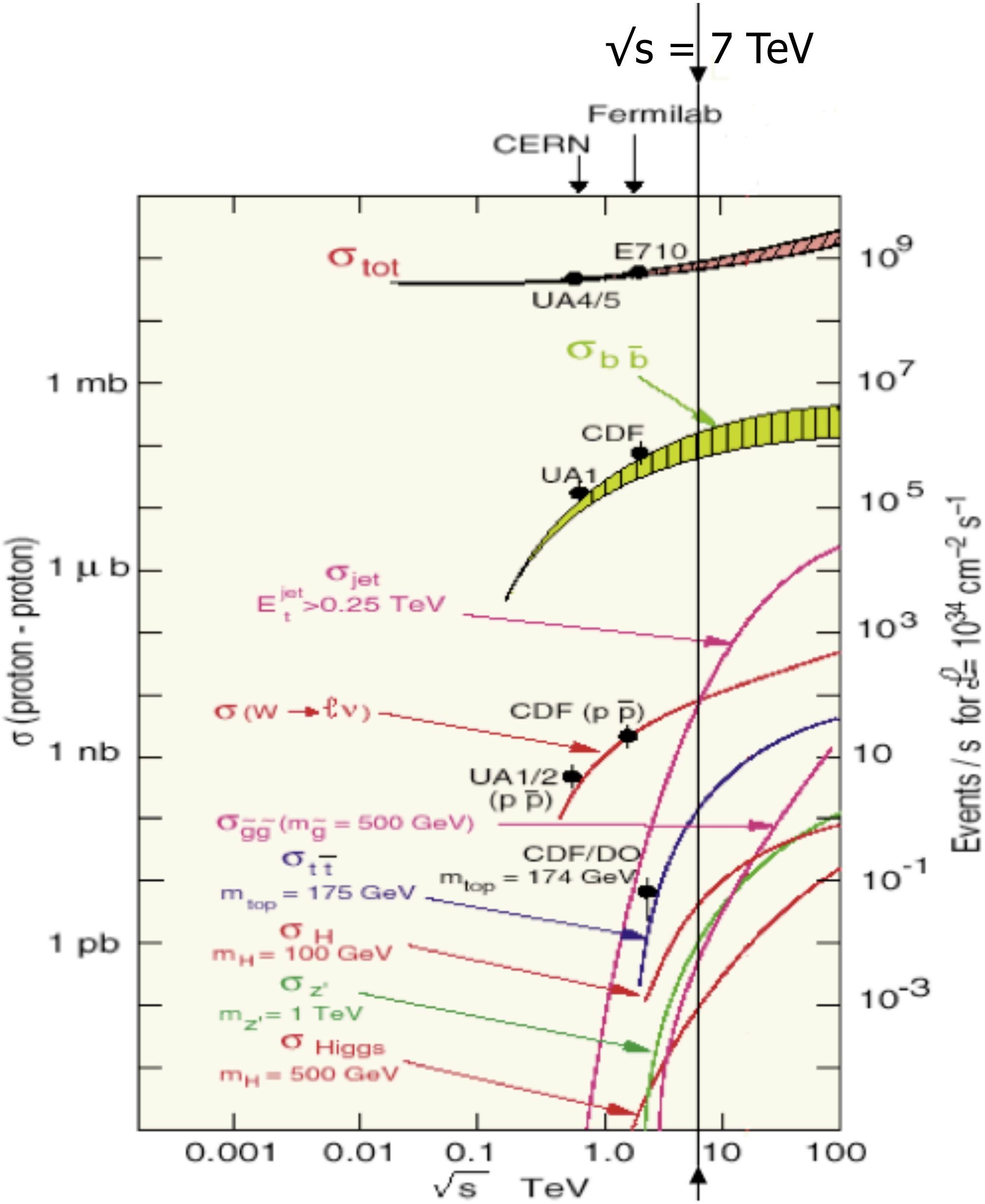
Minimum Bias Events

- are vast majority of collisions
  - small momentum transfer during p–p collision
  - final state particles have small transv. momenta $<p_T>$~400MeV
- uncertainties in extrapolation to LHC energies esp. for
  - total inelastic cross-section
  - charged particle p_T distribution
- ATLAS measurements
- Relevance: while minbias event can not be confused with new particle signatures, they enter all physics analyses as pile-up
- pile-up: protons from same bunch collide and overlay with signal process
  - O(20) simultaneous collisions at high lumi
  - affect jet energies and event kinematics





Production cross-sections



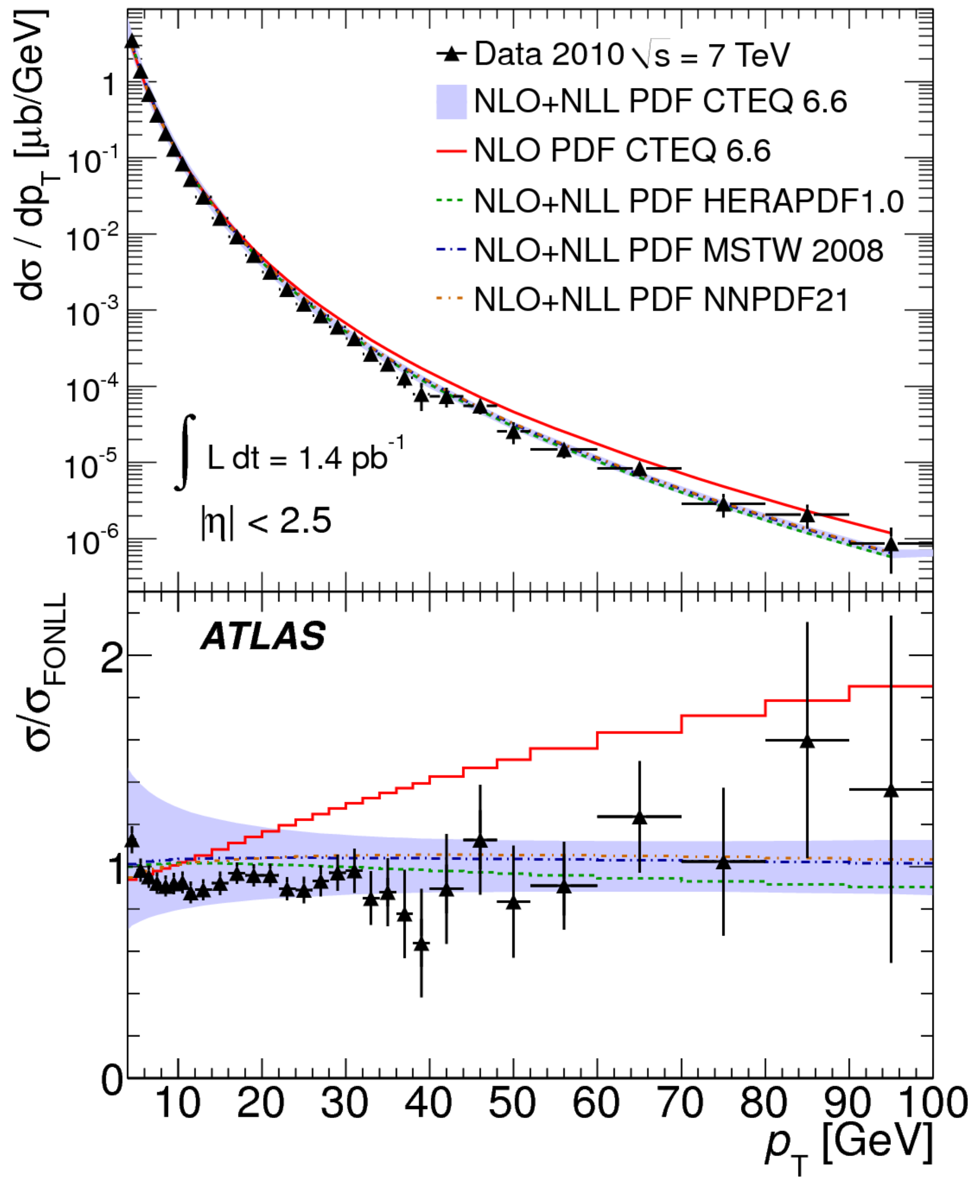
- Event rate = $\sigma \cdot \mathcal{L}$
  - event yield = σ • integrated $\mathcal{L}$
    int. $\mathcal{L}$ expressed in pb^{-1}, fb^{-1}s
    int. $\mathcal{L}$ given on every ATLAS plot
- Large physics cross-section
  - however: the interesting is rare!
- Typical rates for L=10^{34}cm^{-2}s^{-1}, √s = 7 TeV

– inelastic p-p reactions	10^9/s
– bb pairs	10^6/s
– tt pairs	1/s
– W–>ℓν;	100/s
– Z–>ℓℓ	10/s
– Higgs (150GeV)	0.02/s
– gluino, squarks (500 GeV)	0.01/s

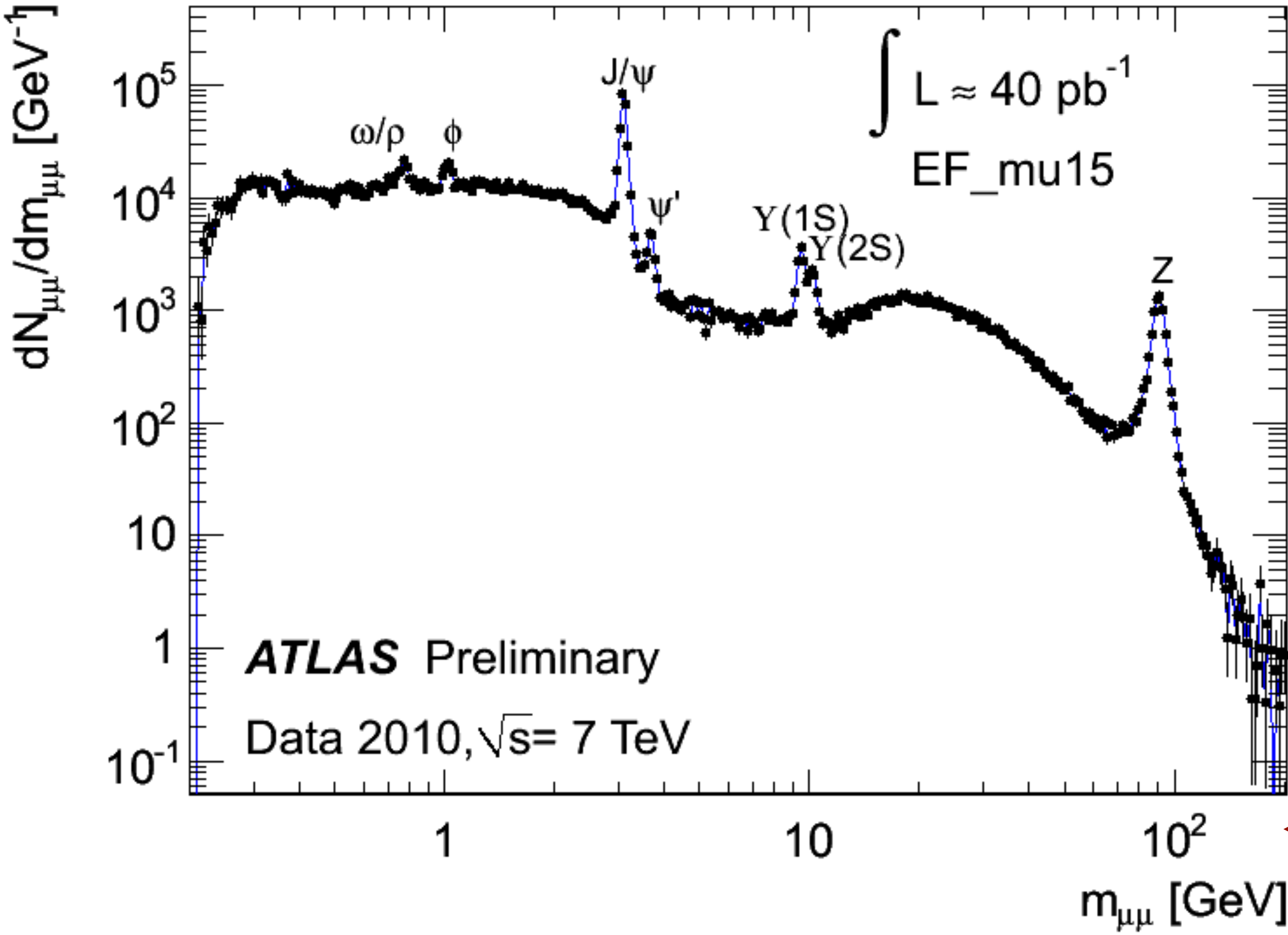
Inclusive Transverse Spectra

- Data analysis usually selects a certain event signature
  - e.g. top or higgs decay to certain final state, see later
  - we need to pay attention not to be blind against the unexpected
- 2010 data were also analysed model-independently, i.e. the “raw” spectrum of muon pT
  - contains muons from pi/K decay, B/D decays, W bosons
  - charged particle p_T distribution
- No unexpected features

Inclusive muon p_T spectrum



Inclusive Muon Pair Spectrum

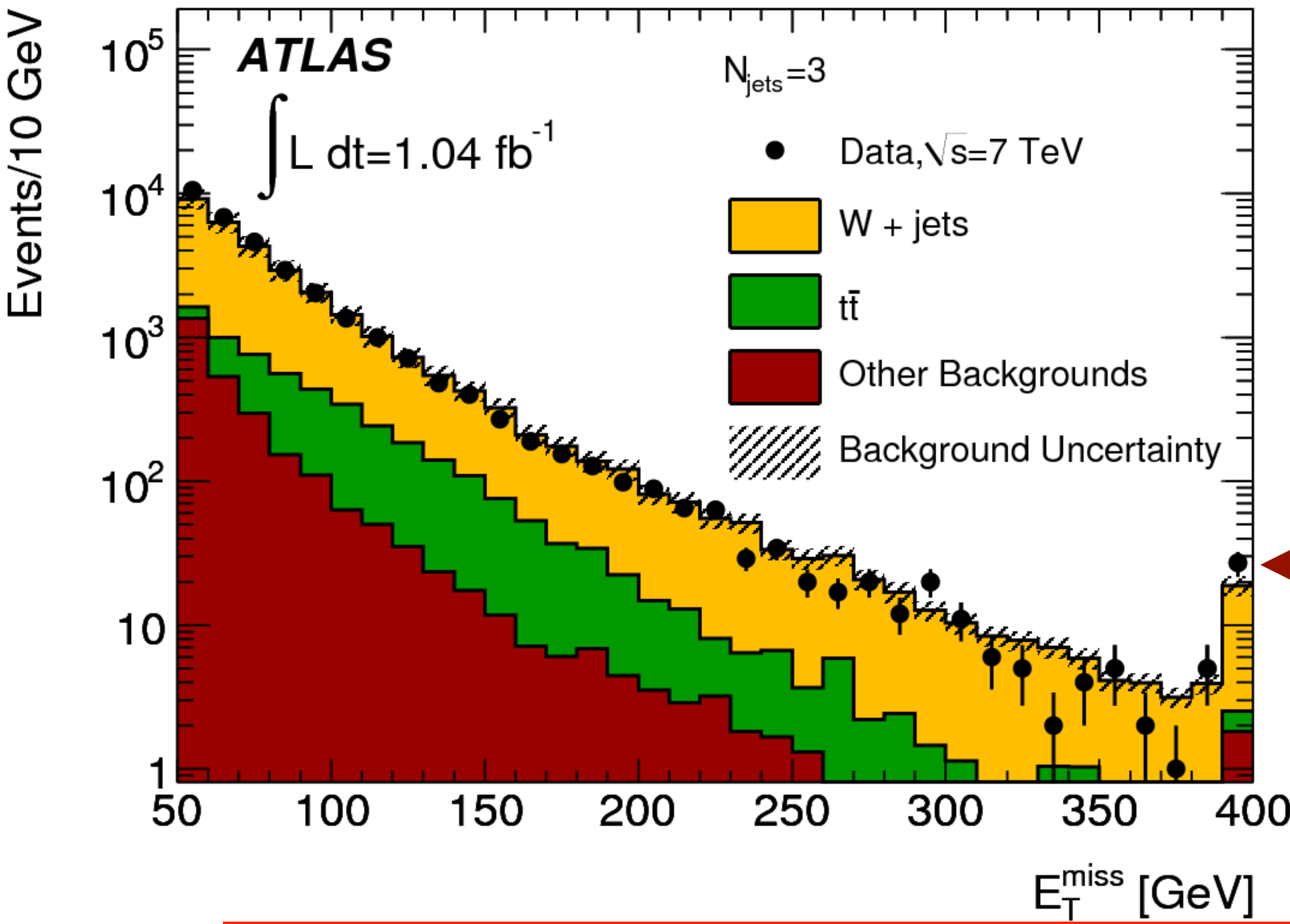


- During 2010 triggers thresholds were raised periodically to follow rising lumi
- modifies slopes in 2-15 GeV region

Log scale!

A delight for the spectroscopist!

Incl. Missing Energy Spectrum



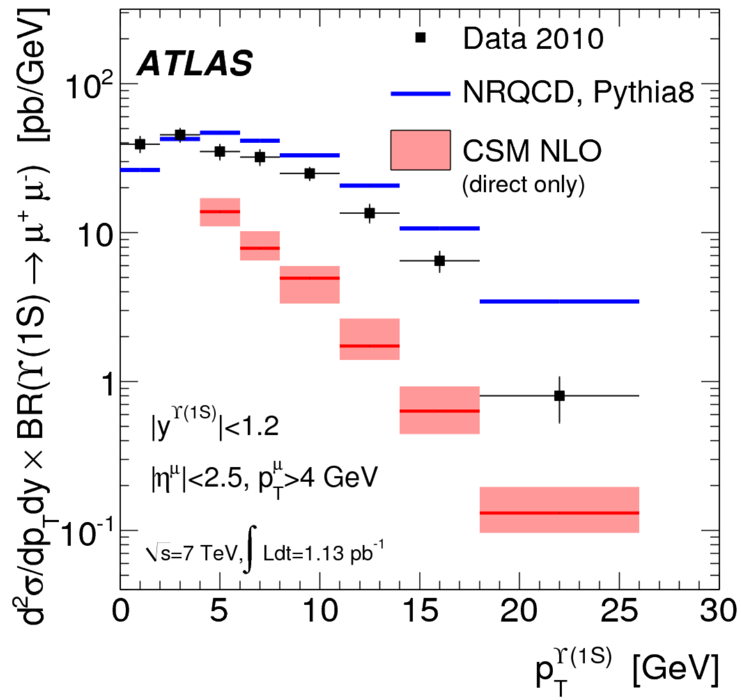
- known undetected energy: neutrinos
- sensitivity to new particles that were produced but don't interact in detector
- no indication for unknown particle

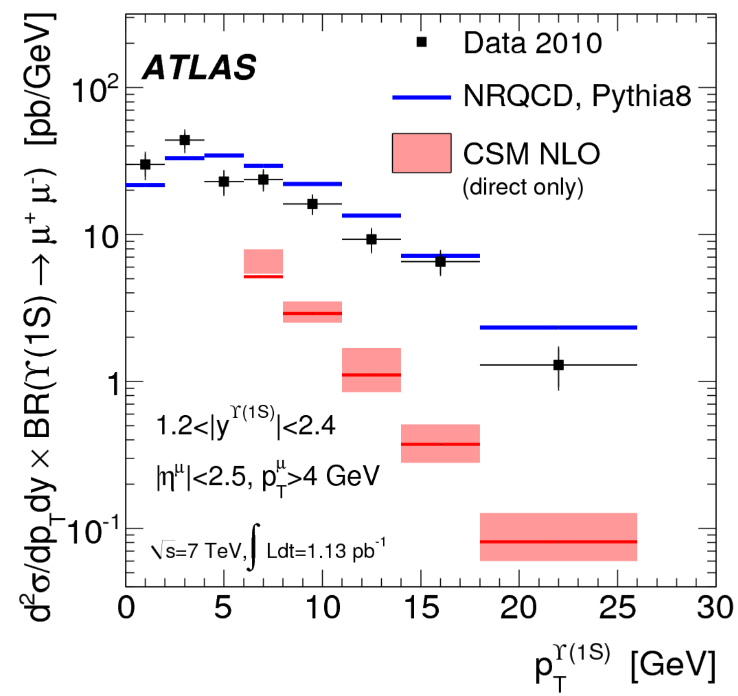
overflow bin

Inclusive spectra:
quick check for obvious presence of new particles before going for dedicated search analyses

B-Physics

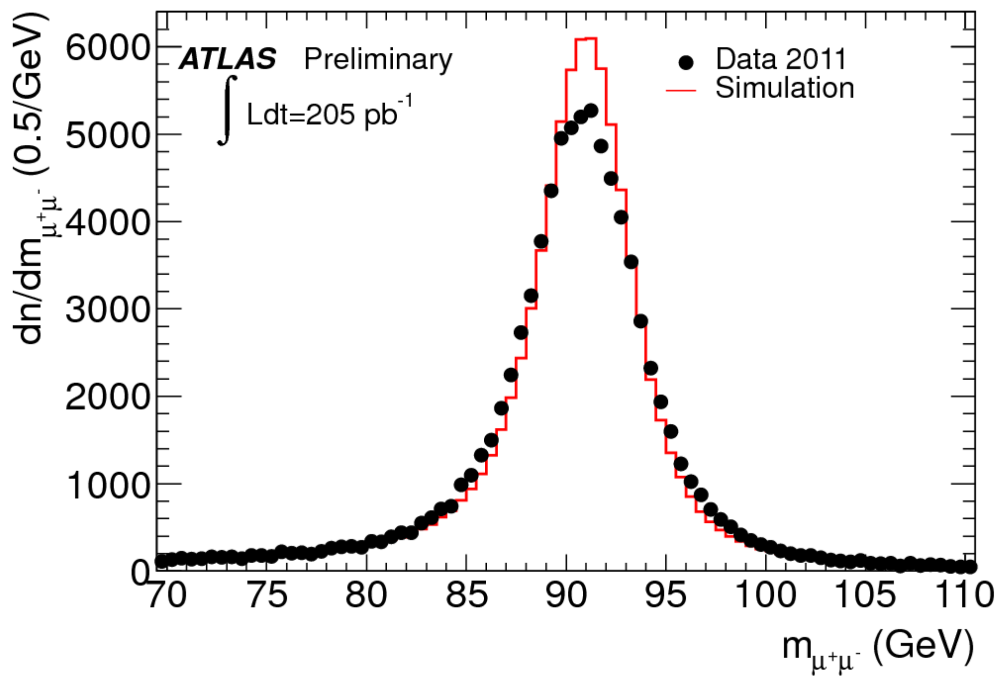
- Identify B-mesons in ATLAS and analyse their properties
- Test C-P violation in with b-quarks, quark mixing matrix (CKM), rare decays
- Complements LHCb: study B hadron production *transverse* to beam
  - LHCb is forward arm: $2 < \eta < 4.5$
- B-physics program begins with observing and quantifying production of known particles
  - J/ψ, Υ, B_0 and B_s, …
  - still large uncertainties in MC generators
- Dilemma: B-Physics is low-energy while trigger thresholds rise with lumi
  - partly recovered by dedicated triggers





Standard Model Physics

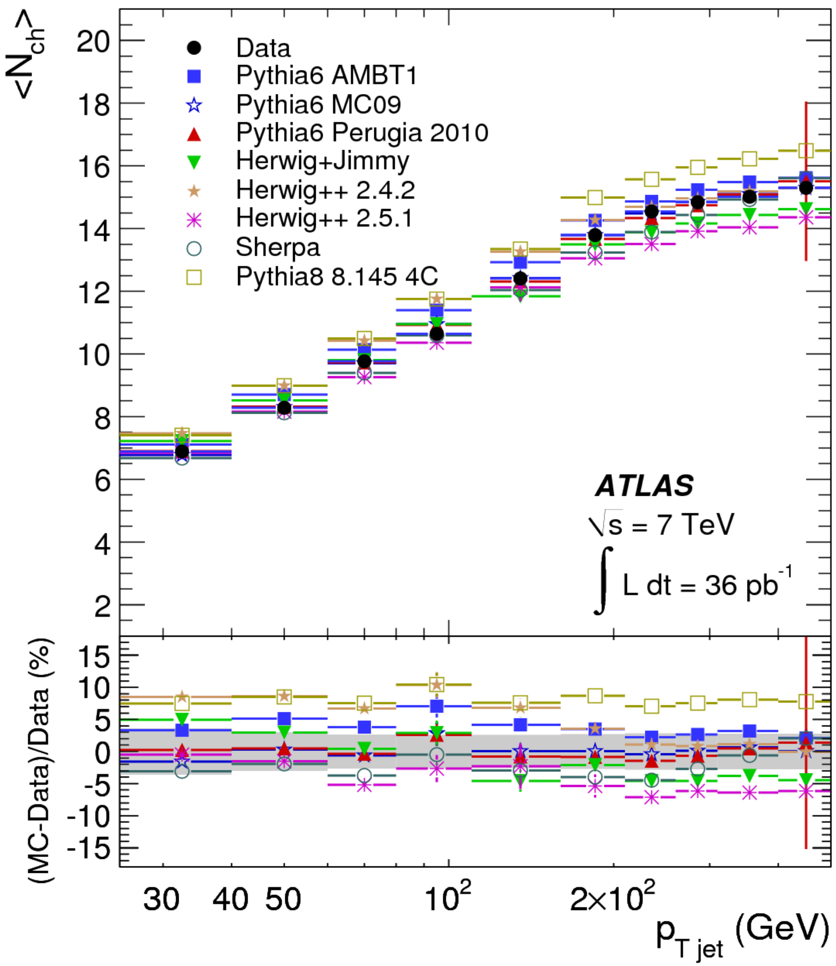
- Minimum bias event properties
  - already discussed on slide 12
- Jet Physics, Photon physics
  - test of higher-order perturbative QCD, fragmentation etc
- Vector bosons:
  - W and Z “rediscovery”
  - W and Z cross sections
  - W and Z with jets
- Multi-boson events: WW, ZZ, ..
  - sensitive to gauge coupling
- W^+/W^- charge asymmetry
- W Mass
- Top physics
  - top is covered by dedicated working group in ATLAS (and CMS)



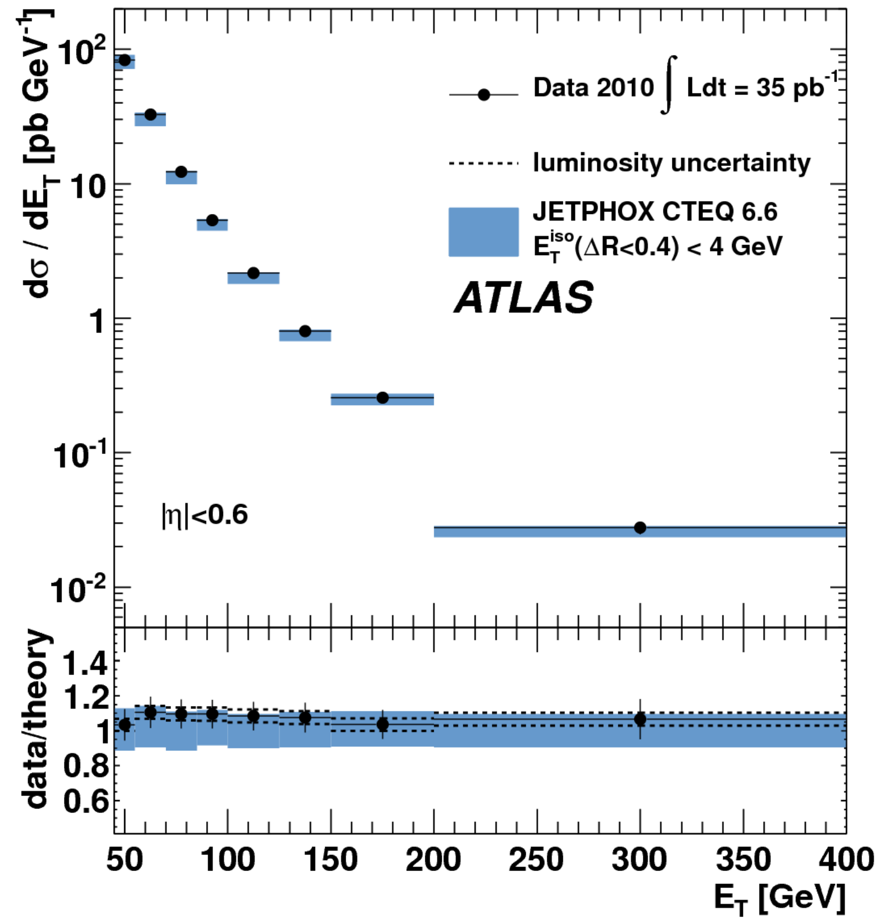
➔ Z is where it should be
➔ O(1M) Z on tape
➔ Residual shape differences from detector resolution (see next lecture!)

Jet and Photon physics

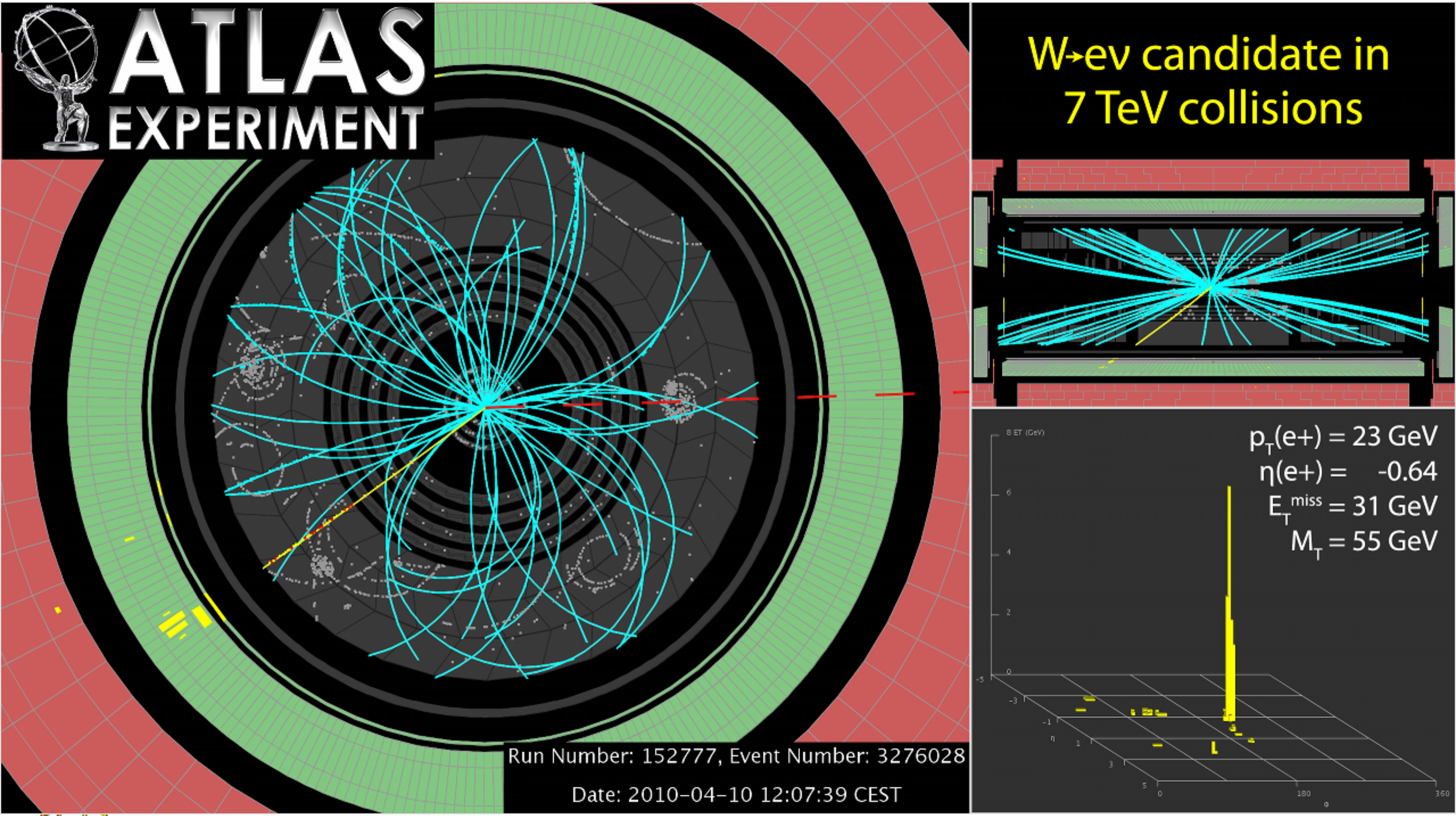
- Fragmentation functions probed by measuring **jet properties**
  - N(charged track), longitudinal and transverse momenta, leading hadron
  - optimization of MC generators



- Perturbative QCD prediction for isolated prompt photons
  - isolated: not in a jet
  - prompt: from the collision process

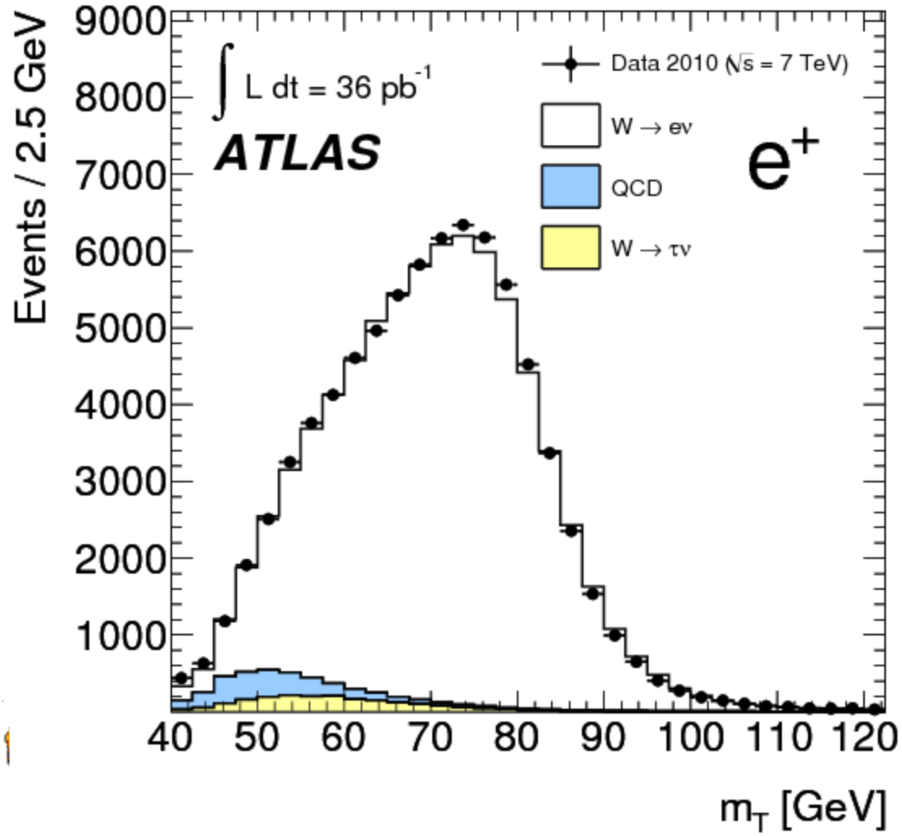


W Decay to e, ν


ATLAS
EXPERIMENT
W→eν candidate in
7 TeV collisions
$p_T(e+)$ = 23 GeV
η(e+) = -0.64
E_T^{miss} = 31 GeV
M_T = 55 GeV
Run Number: 152777, Event Number: 3276028
Date: 2010-04-10 12:07:39 CEST

W Reconstruction at LHC

- W–>$e\nu$, W–>$\mu\nu$ are channels of interest
  (W–>qq->jets drowned in QCD di-jet rate)
- Lepton isolation
  – sum of calorimeter deposits around lepton below a chosen limit
  – or: sum of track p_T below a limit



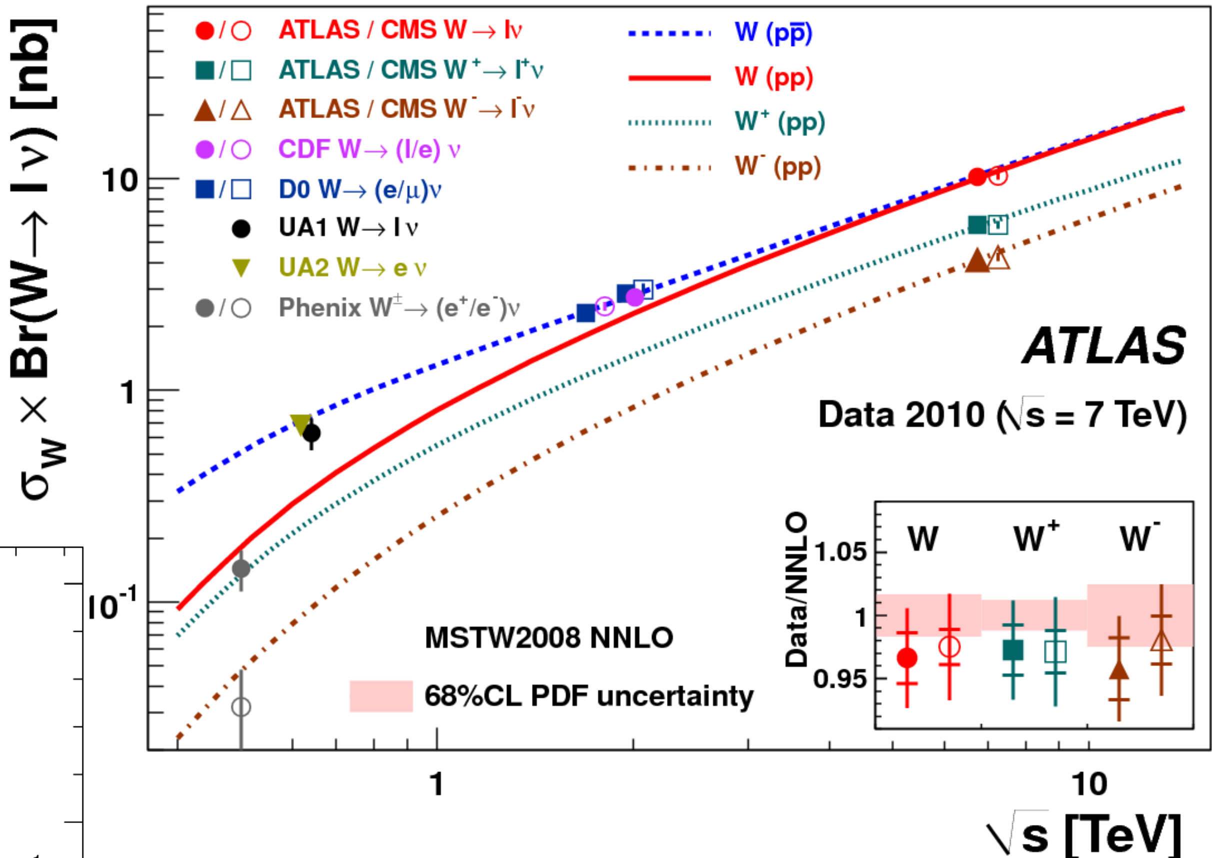
- Missing transverse energy (MET)
  – reflects p_T of neutrino
  – only p_T conserved, $p_{||}$ of neutrino can not be measured
- Thus an exact invariant mass can not be calculated. Instead: transverse mass

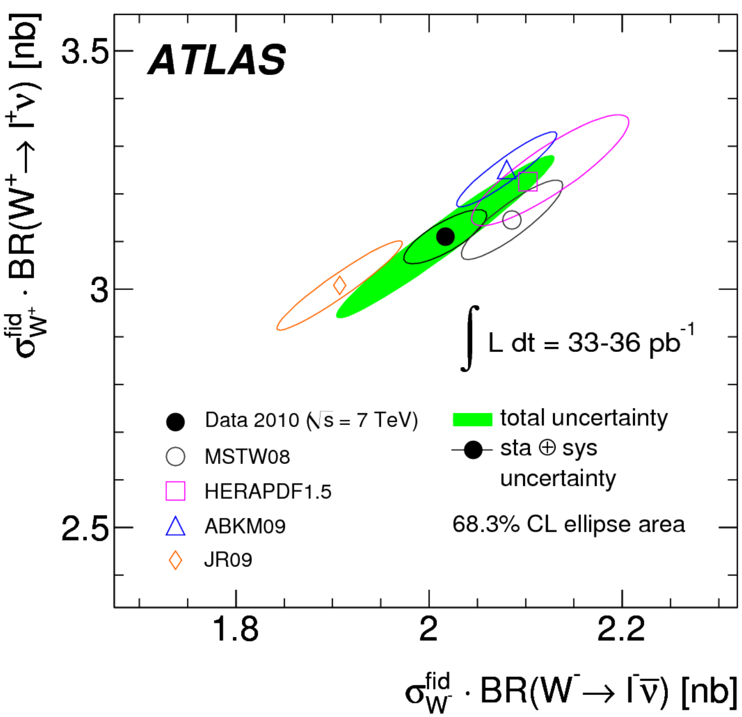
$$m_T^W = \sqrt{2\, p_T^\ell\, p_T^\nu\, (1 - \cos\Delta\phi^{\ell,\nu})}$$

  – cut on transverse mass possible, clean sample

W Production at LHC

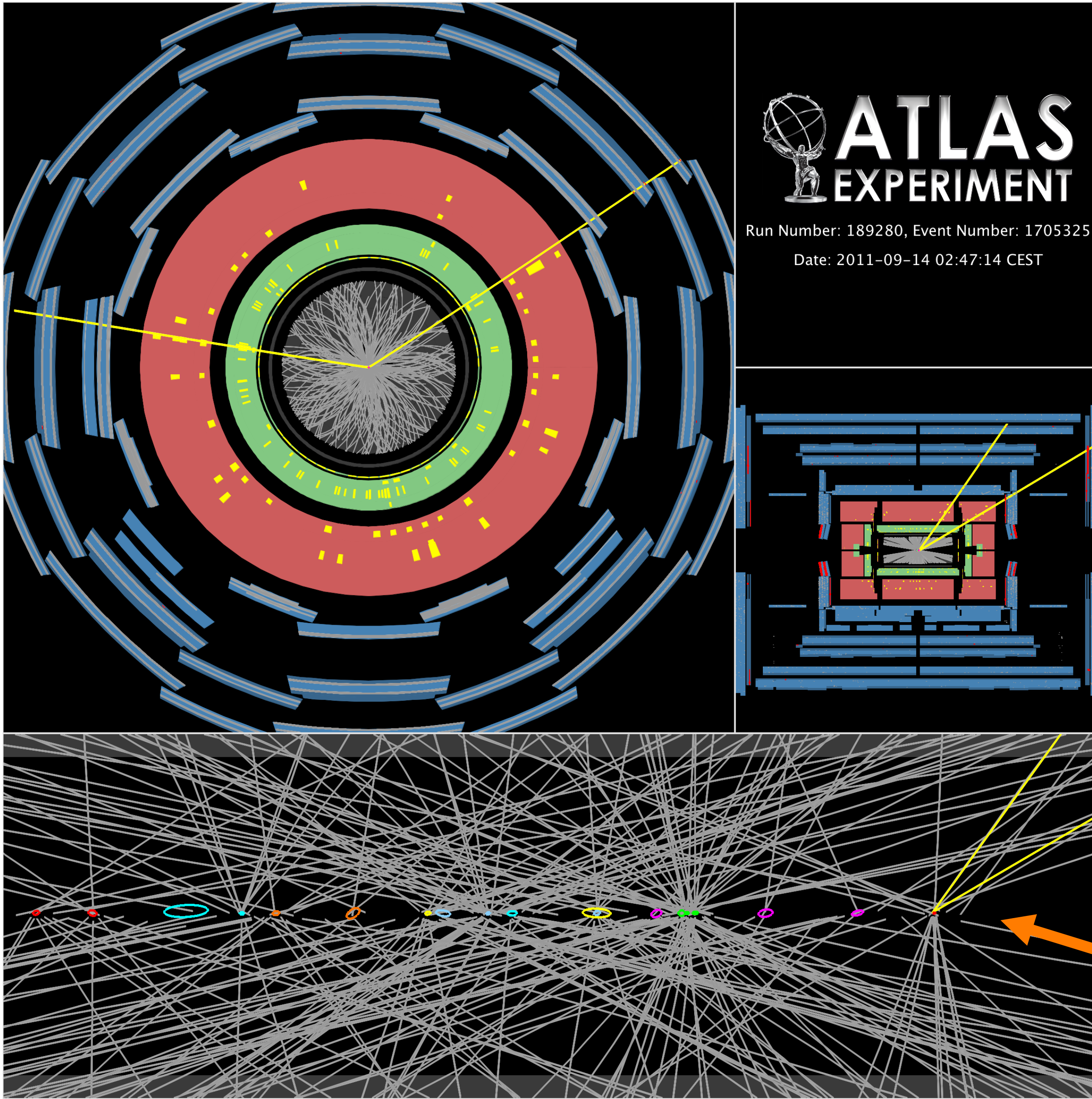
- Cross-section measured by ATLAS
- reasonably well predicted by MC
- cross-section restricted to fiducial region disentangles exper. and theoretical effects





- cross section not charge-symmetric!
- remember: protons contain u,u,d
  u$\bar{d}$ annihilation more probable: W^+

Z–>ℓℓ Signatures

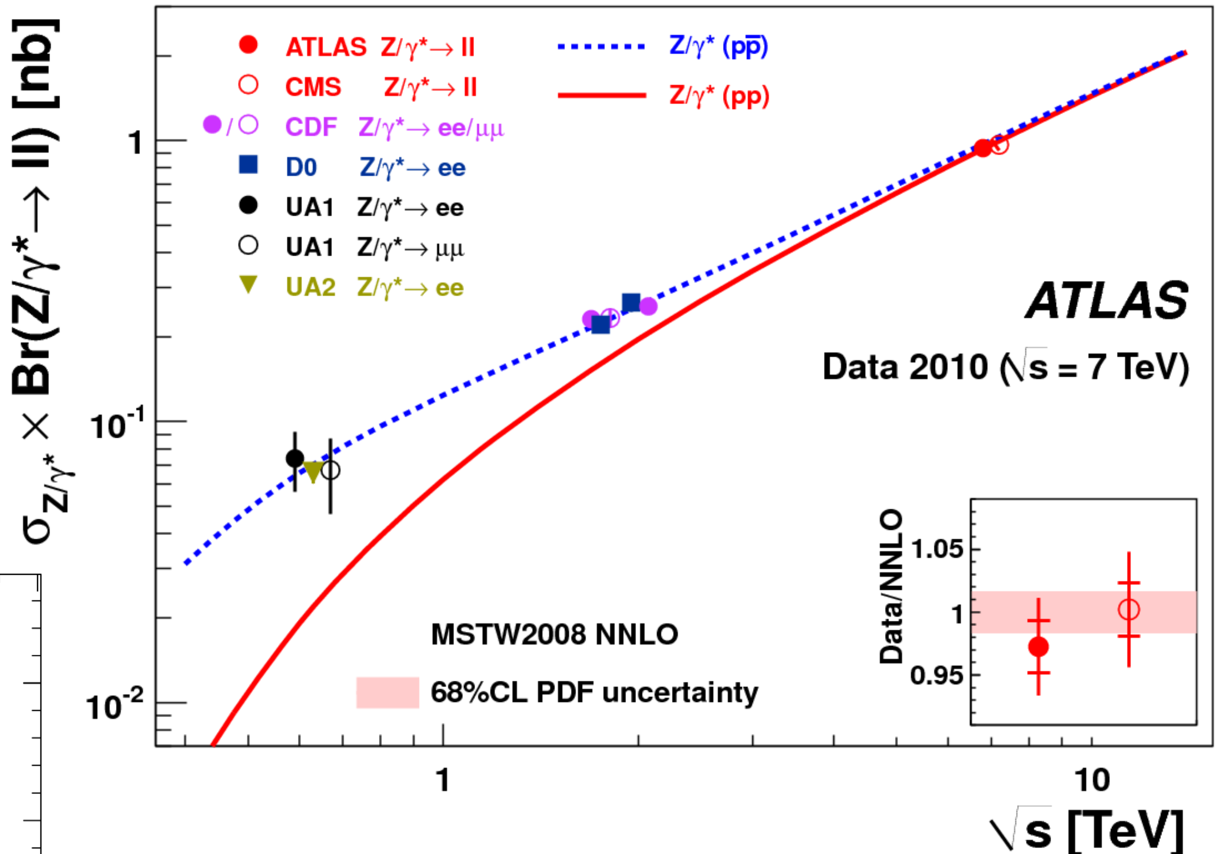


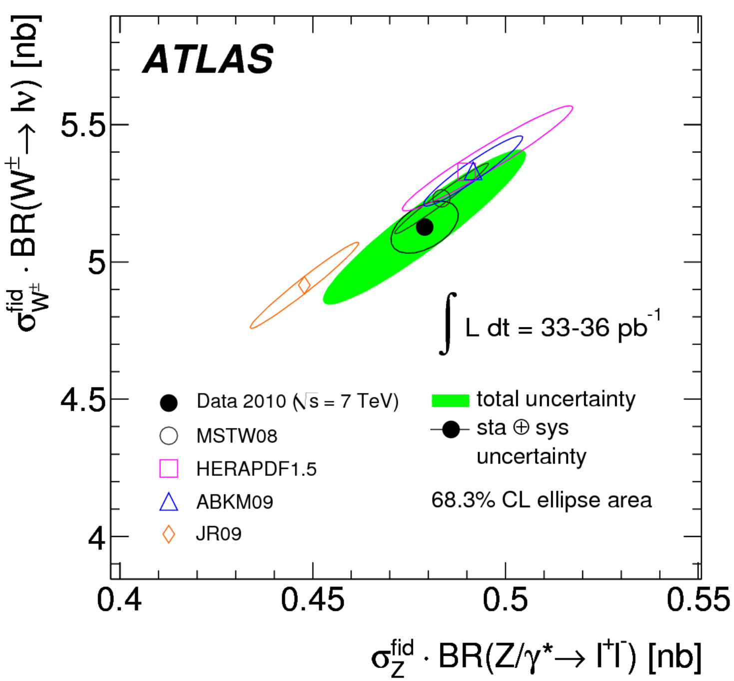
- Two high p_T leptons, isolation
- invariant mass calculated exactly, range typ. 70…110 GeV
- nice example for signal process emerging from 20 pile-up collisions

primary vertex

Z/γ* Production at LHC

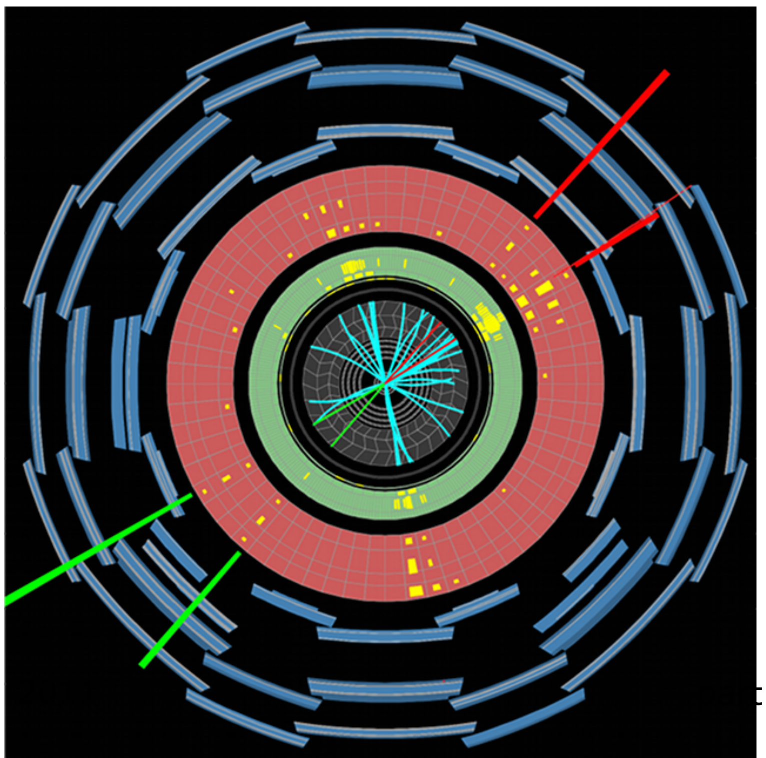
- ~ 10x less than W
- energy dependence

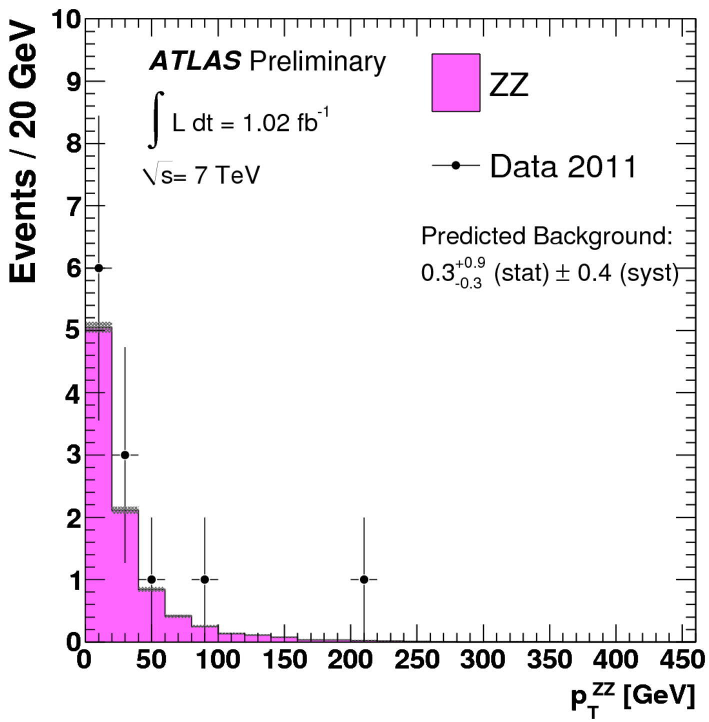




Multibosons

- Studies of WZ, ZZ, WW, Wγ, Zγ events are sensitive to self-coupling of gauge bosons
- Nature of self-couplings predicted by non-Abelian structure of std. model Lagrangian, but heavily constrained
- Powerful test of std model theory but experimentally much less accessible than fermion-boson vertices
  - because colliders collide fermions, not bosons
  - LHC data sample has ample multibosons, background to searches



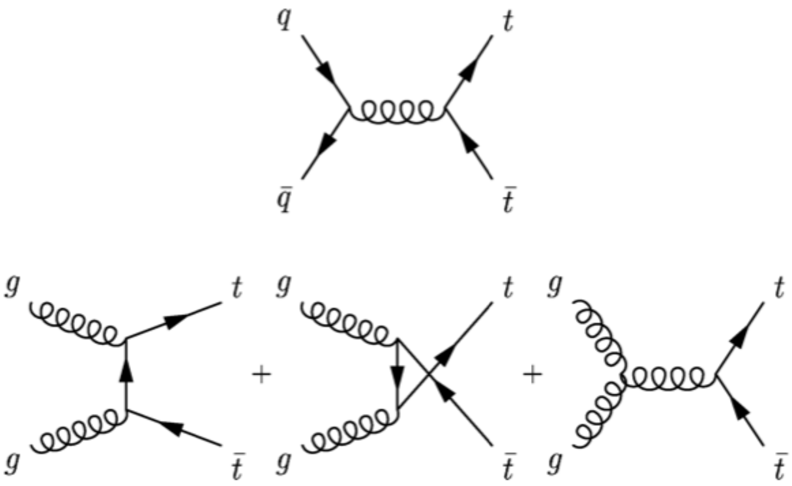


Top Quark Physics

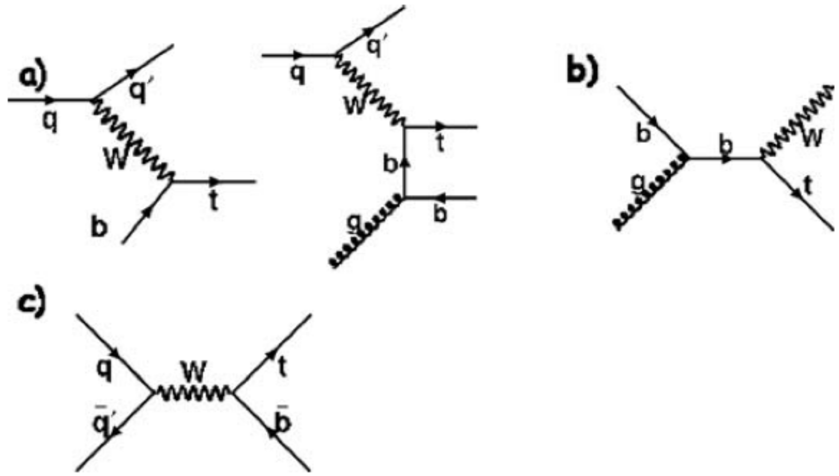
- High mass of t quark makes it special: **m_t=173.2 GeV**
  - comparable to mass of gold atom
  - discovered only in 1995, 18 years after its partner, the b-quark
  - low tt cross section at TeVatron, properties known from small sample
  - decays before hadronisation (due to large phase space for t–>Wb decay)
- It is being produced abundantly at LHC
  - 8 tt pairs per second for design energy and lumi
  - its decay signature produces the entire array of physics objects
    top reconstruction: the strength of ATLAS and CMS
- Top quark also interesting because it is sensitive to new physics related to the electro-weak symmetry breaking
  - dedicated working group to study its properties with high accuracy
    and look for any deviations from standard model

Top Quark Production

top pair production:



electroweak single top production:



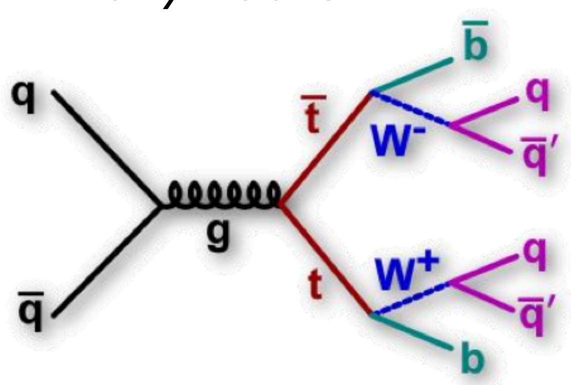
- qq annihilation and gluon fusion
  - gluon fusion dominant channel at LHC (95%)

- qq annihilation and gluon fusion
  - Wg fusion (a)
  - Wt production (b)
  - s-channel (c)

Decay Channels of Top Quark Pairs

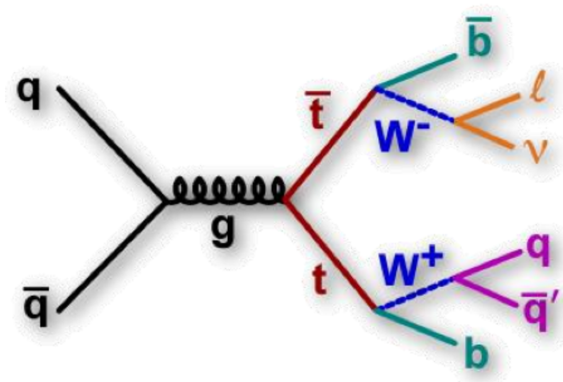
- Branching ratio of t–>Wb ~100%
  - it's the W decay mode that defines the decay channel

"fully hadronic"



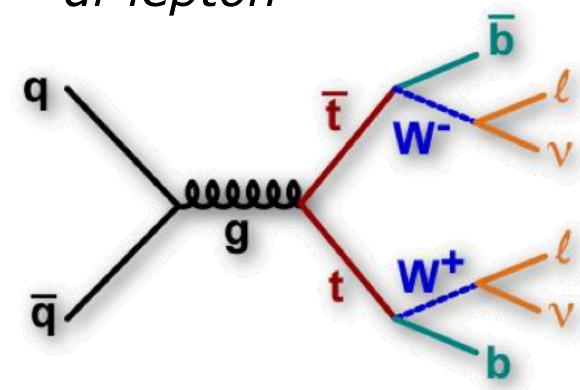
- both W decay to quarks
- ~44% of top quark pairs
- not so useful

"lepton+jets"



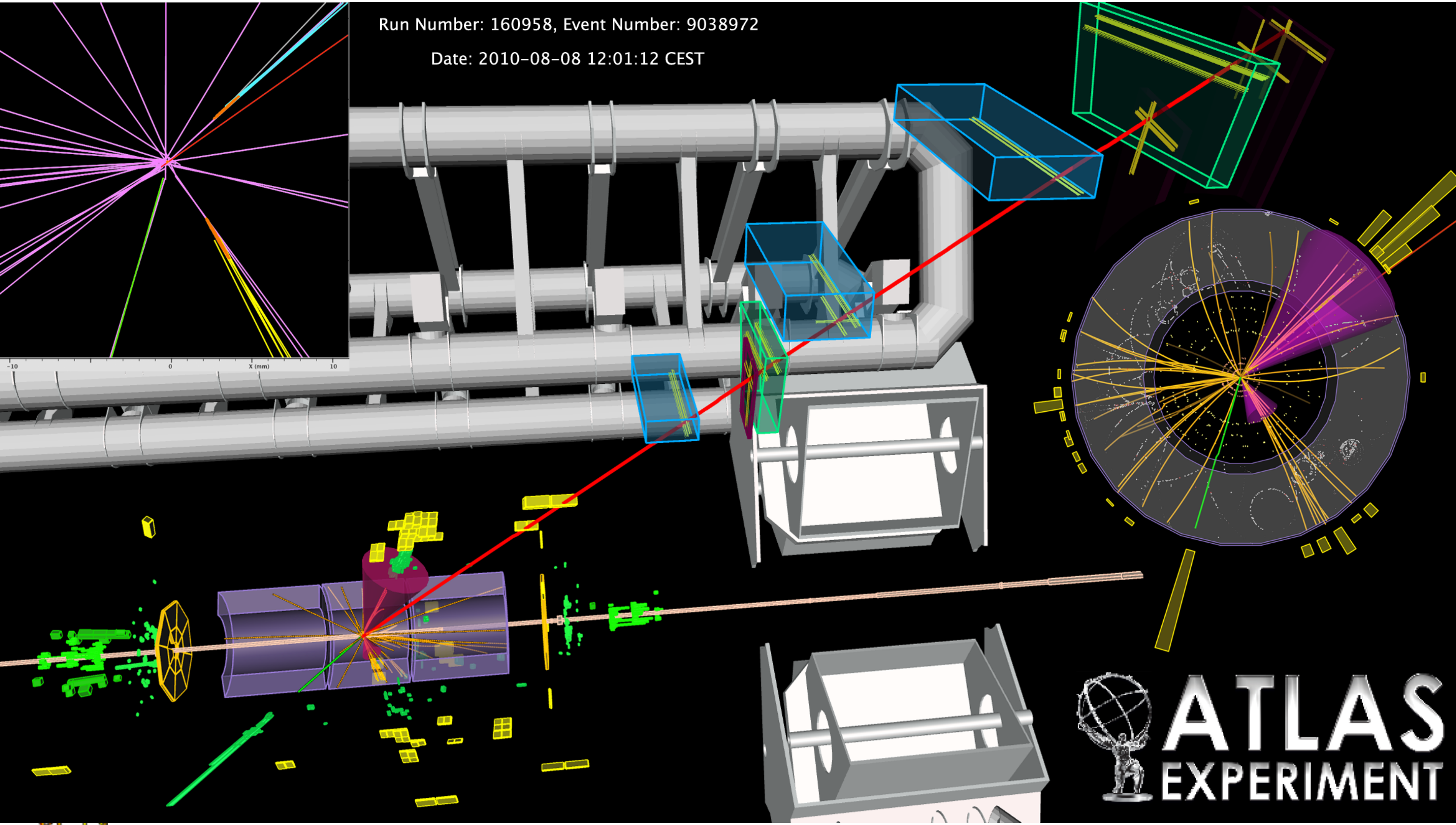
- one W–>$\ell\nu$ decay
- restricted to ℓ=e,μ
- ~30% of top quark pairs

"di-lepton"



- both W decay to $\ell\nu$
- was also restricted to $\ell\ell = ee, e\mu, \mu\mu$
- recently $\ell\ell = \mu\tau$ added
- ~5% of top quark pairs

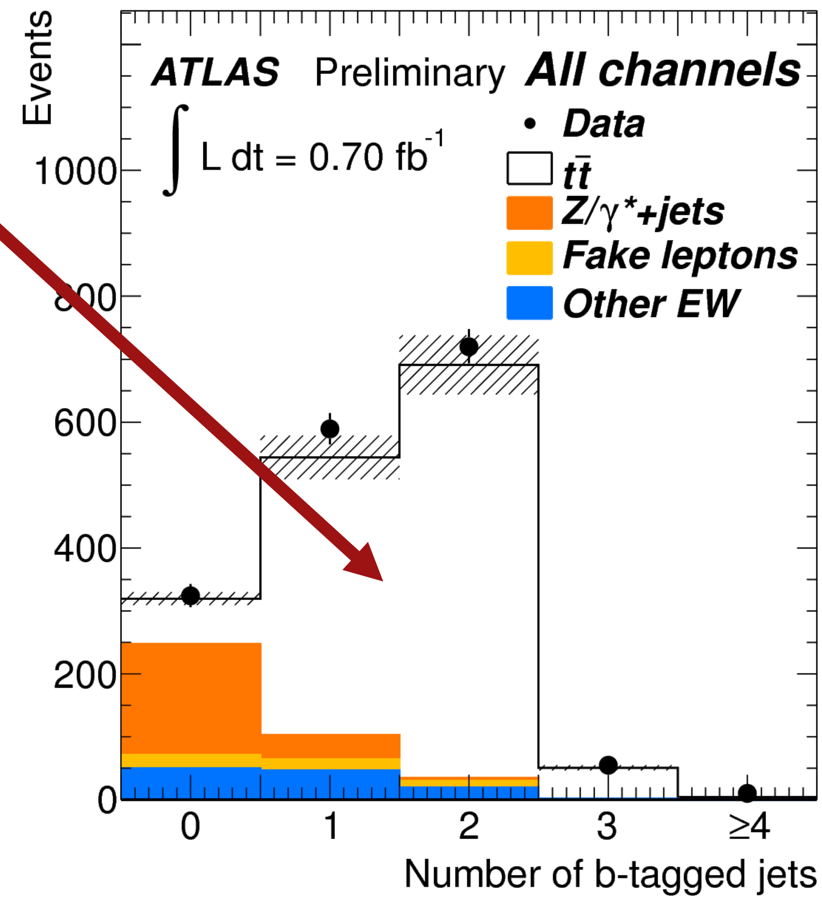
Top Quark Event



Top Quark Analyses

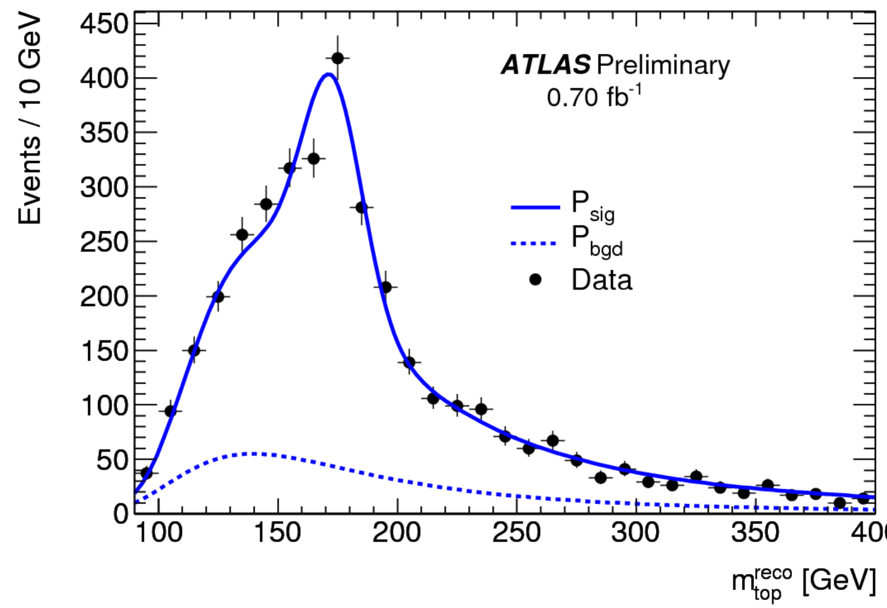
- combined presence of identified final state particles (leptons, b-jets) leads to a **clean event sample** in the lepton+jet and dilepton channels
- pleasant situation: background from std. model processes is low and top is abundantly produced
  LHC is a top factory
- draw-back: abundant top decays are **main background** of many of the much more rare new physics
- Main themes of top physics
  - top mass
  - couplings involving top (cross sections, W polarisation…)
  - precise understanding of cross-section and top reconstruction by ATLAS to reduce uncertainties for top as background

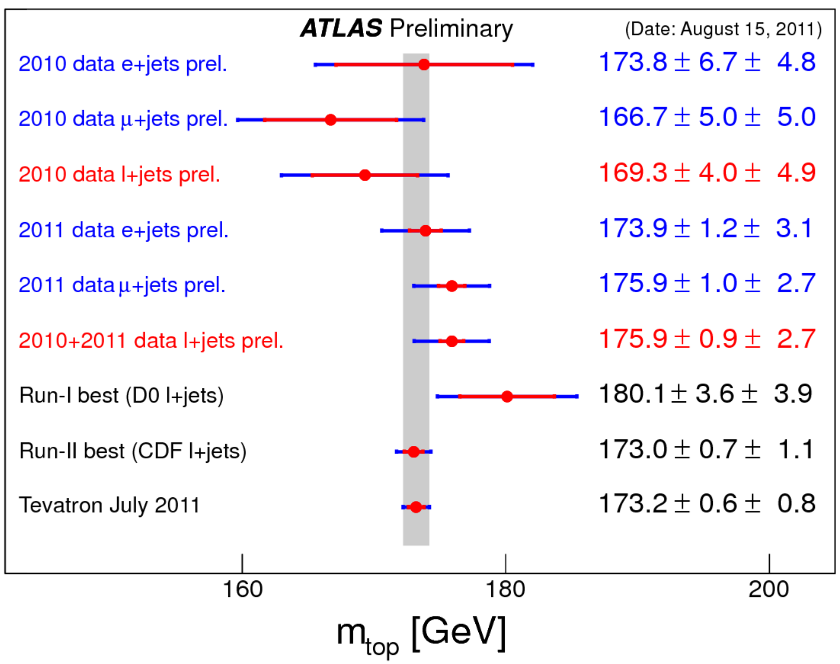
(All dilepton channels)

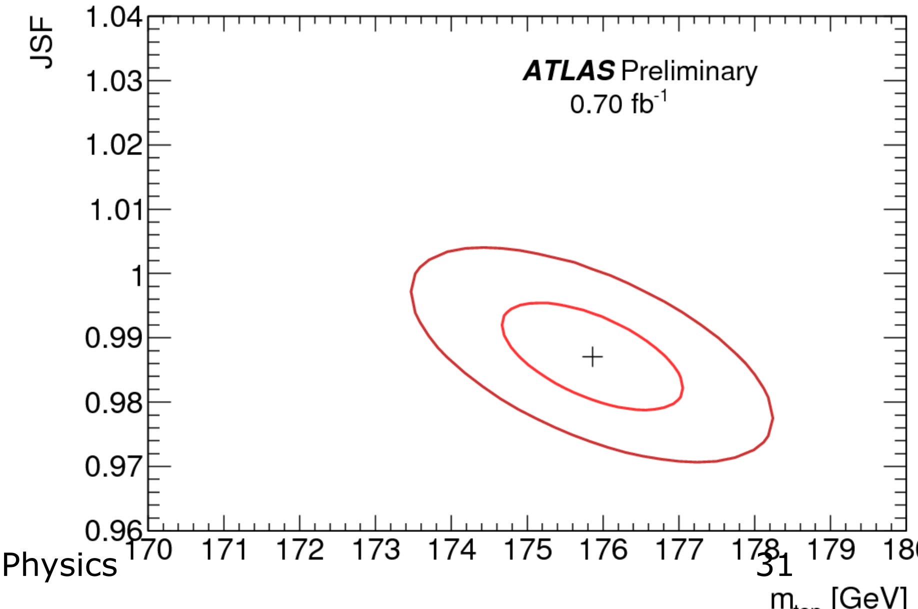


Top Quark Mass

- m_t reconstructed from decay kinematics
- lepton momenta well known but not the jet energy scale
  - this is the dominant syst. Error
  - especially in the initial phase
- Trick: Jet energy Scale Factor (JSF) measured together with top mass
- Systematic error yet dominates

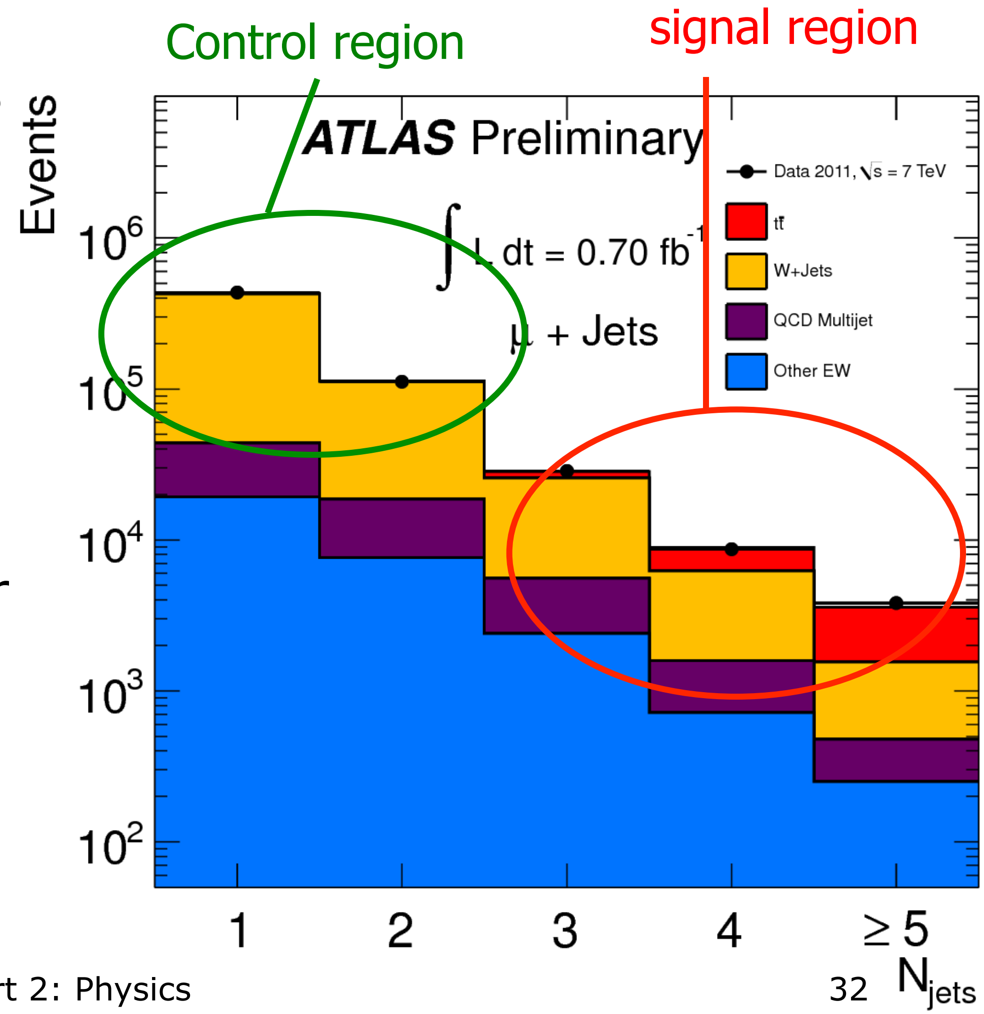






Top Quark Couplings

- the quark mixing matrix contains information on the strength of flavour-changing weak decays
  - matrix element V_{tb}
- top cross section sensitive to V_{tb}
  - tt pairs and single-top
  - example: muon+jet channel in tt
- tt cross-section relative to known std model processes
  - signature of single isolated lepton note well separated from W+jets
  - control and signal regions
- results in agreement with higher order QCD (NNLO) predictions



Measurements and Searches

- Large number of measurements performed (and ongoing!) since the first few weeks of p–p collisions
  - genuine interest
  - std. model as a tool: improve understanding of detector, MC generators and processes which are background to analyses searching for new physics
  - probe consistency of electroweak measurements even tighter
- Mechanism of electroweak symmetry breaking (EWSB) not known
- Higgs boson is postulated as agent of EWSB
  - from electroweak precision data we know it couples to W, Z as expected
  - no evidence yet for Higgs–fermion coupling = not yet observed
  - mass not predicted by theory except m_H<1 TeV in order to function as EWSB agent and make perturbation theory viable above 1 TeV
- If Higgs boson does not exist or m_H>1 TeV the weak interaction among W, Z (and H) becomes strong on the TeV-scale

$\Longrightarrow$ *In both cases new phenomena are to be found around or below 1 TeV, at the LHC and by ATLAS and CMS*

Remark: How to Claim Discovery ?

For a narrow resonance:

- study signal significance

$$S = N_{\text{sig}}/\sqrt{N_{\text{bg}}}$$

- N_{sig} = number of signal events in peak region

  N_{bg} = number of background events in same region

- $S > 5$: Gaussian probability that background fluctuates up by more than 5σ is 10^{-7}

  $\Rightarrow$ discovery!

Parameters to maximise S

- Integrated luminosity, $\int L$

  $N_{\text{sig}}, N_{\text{bg}} \sim \int L$

  $\Rightarrow S \sim \sqrt{\int L}$

- Detector resolution, σ_M

  Peak region becomes smaller with better detector resolution

  Thus less N_{bg} and $S \sim 1/\sqrt{\sigma_M}$

  (for flat background)

Higgs Mass Bounds

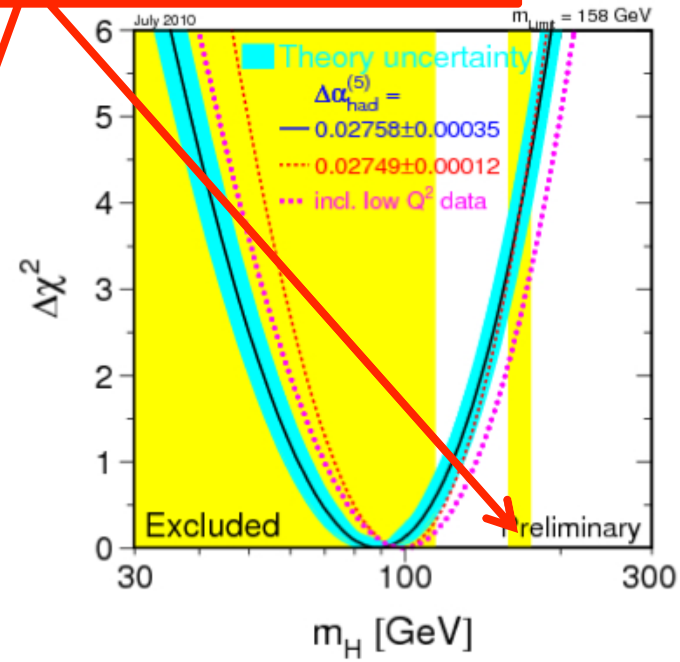
LHC 2011: not yet added!

Theoretical bound

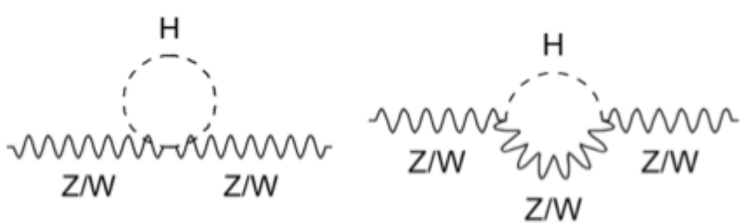
- EW theory does not predict Higgs-boson mass
- except condition to cancel divergence in $W-W$ scattering
  $m_H \leq \sqrt{\frac{8}{3}\pi\sqrt{2}G_F} \sim 1\,\text{TeV}$

Direct searches

- LEP: $m_H > 114.4\,\text{GeV}$ (95% CL)
- Tevatron: $157-173\,\text{GeV}$ excluded



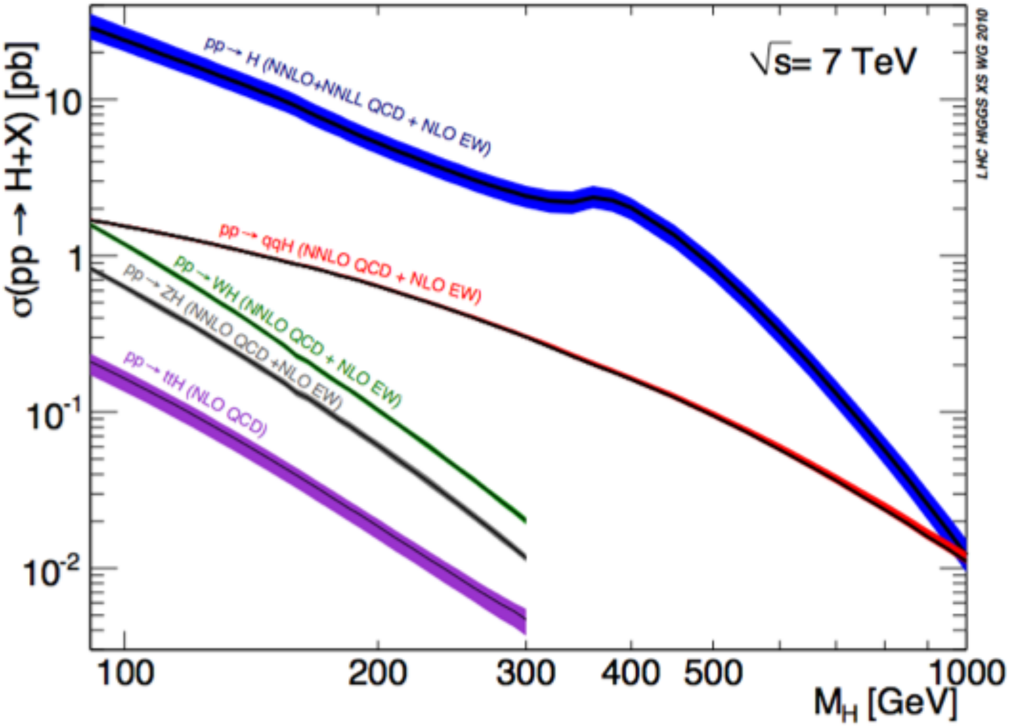
Indirect limits from EW measurements

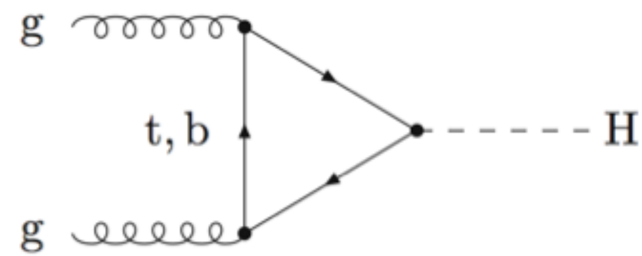


H appears in corrections to SM propagators

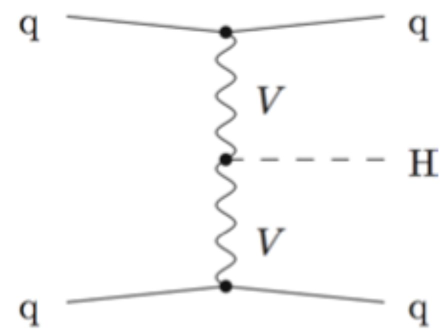
▷ precise measurements of W and t mass constrain m_H

Higgs Boson Production at LHC





gluon fusion

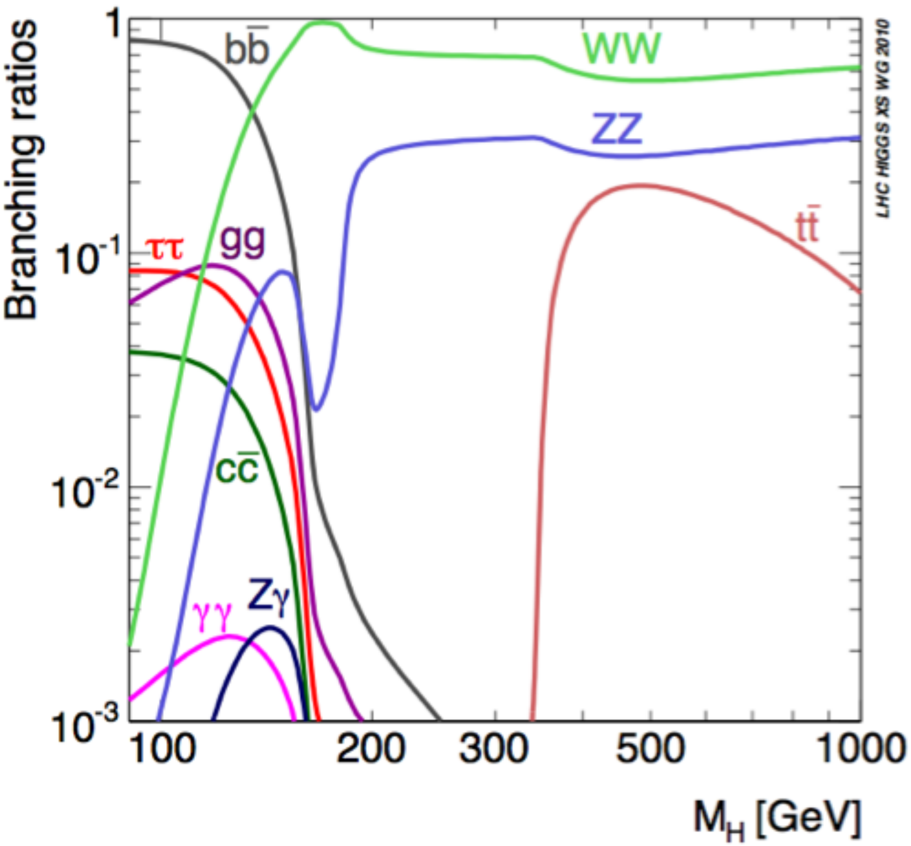


vector boson fusion

(t-channel, $V = Z, W$)

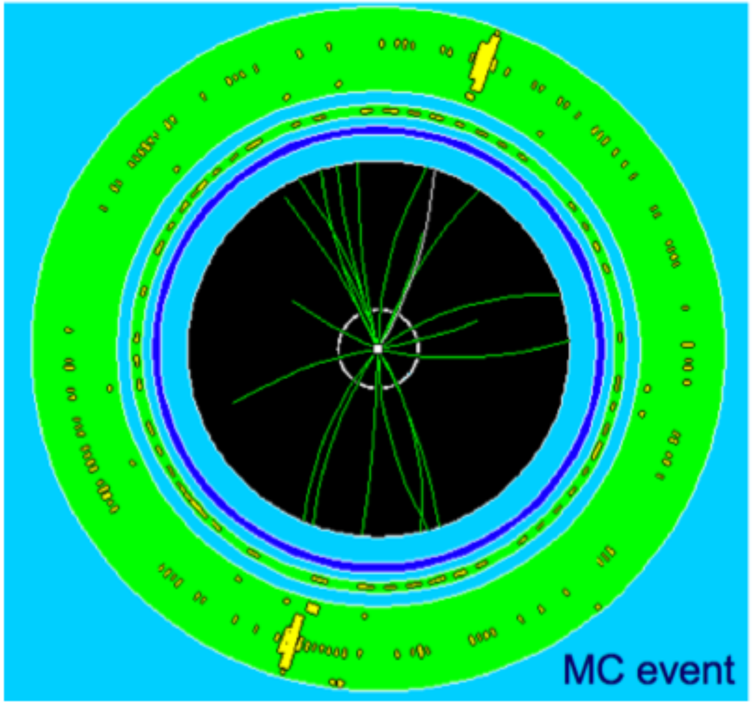
- Gluon fusion is dominant channel for entire M_H range
- Vector boson fusion is second most important production type

Higgs Boson Decays



- at high M_H: visible in lepton final states from $H \to WW$, $H \to ZZ$.
- at low M_H:
  - ▷ photon final state $H \to \gamma\gamma$,
  - ▷ lepton final state $H \to WW^*$
  - ▷ tau final state
- Note: can not separate qq final state from QCD background
- ATLAS & CMS studied main decay channels with 1.08fb^{-1} of 2011
  - two decay channel examples discussed on the next slides
  - previous publication: 40pb^{-1} of 2010
  - now 5fb^{-1} on tape, aim at Dec' 2011 or March 2012

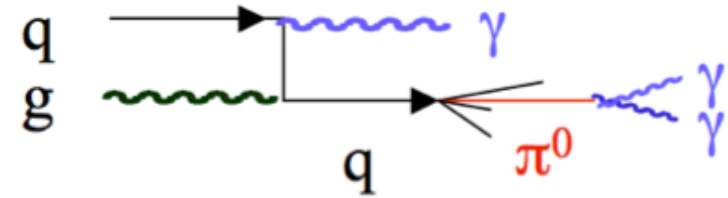
Analysis of Higgs-to-Photon Channel



- select pairs of isolated photons
  $p_T(\gamma_1) > 40$ GeV,
  $p_T(\gamma_2) > 25$ GeV

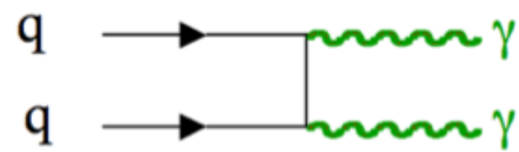
Main backgrounds

- jet misidentified as photon



  ▷ *reducible:*
  discriminate γ against jet

- genuine $qq \rightarrow \gamma\gamma$



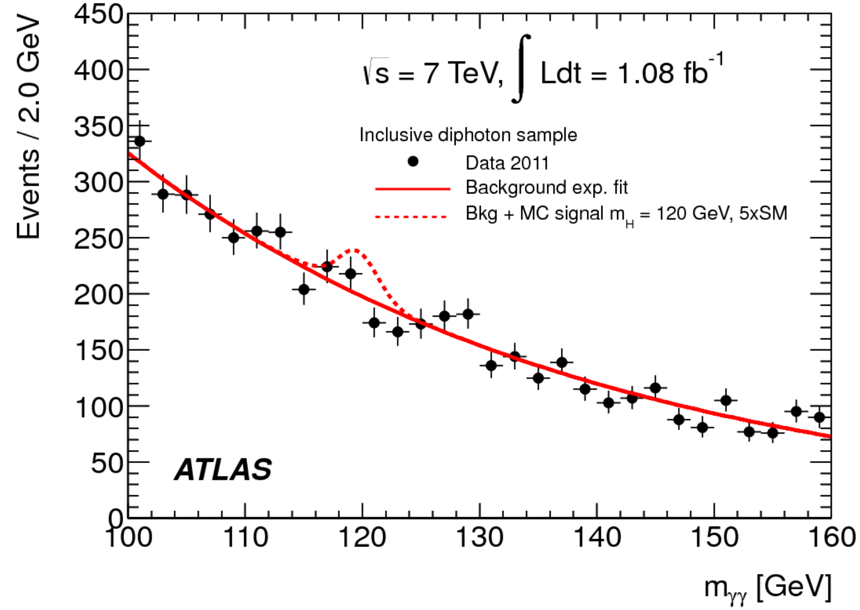
  ▷ *irreducible:* instead optimise reconstruction of $M_{\gamma\gamma}$

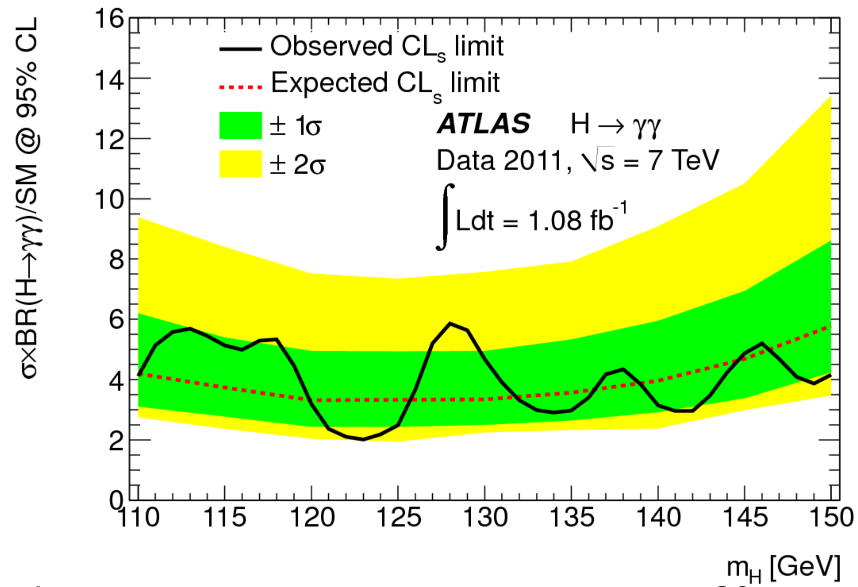
Results in Higgs-to-Photon Channel

- $M_{\gamma\gamma}$ spectrum for 2011 data
  - bin width set accordingly
- expected $M_{\gamma\gamma}$ resol. of ~5 GeV

Interpretation for SM Higgs

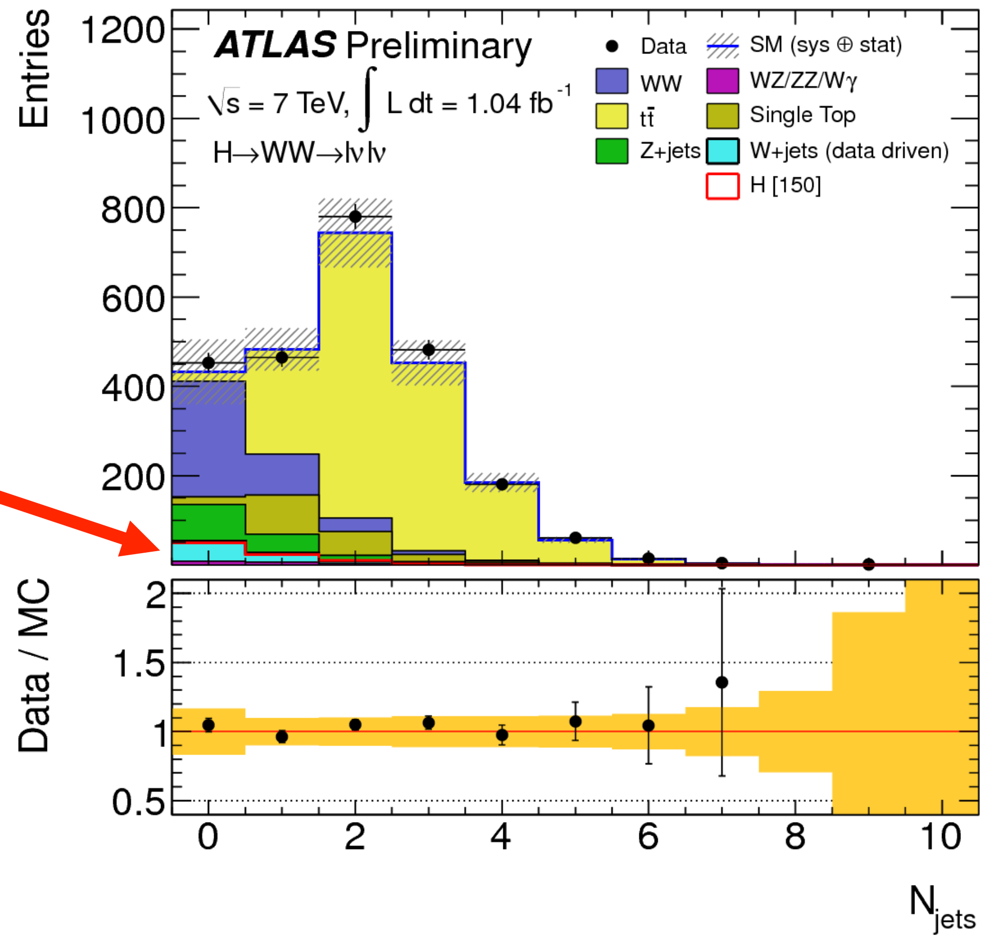
- SM cross-section too small to be visible in 1.1 fb^{-1}
- set limit on $\sigma \times BR(H\rightarrow\gamma\gamma)$ in units of std.model prediction
- 2011 expected limit is for 3-4× enhanced σ/σ_{SM}
  - now better than TeVatron
- Factor ≤ 1.0: SM Higgs excluded for a given mass (or: observe peak!)



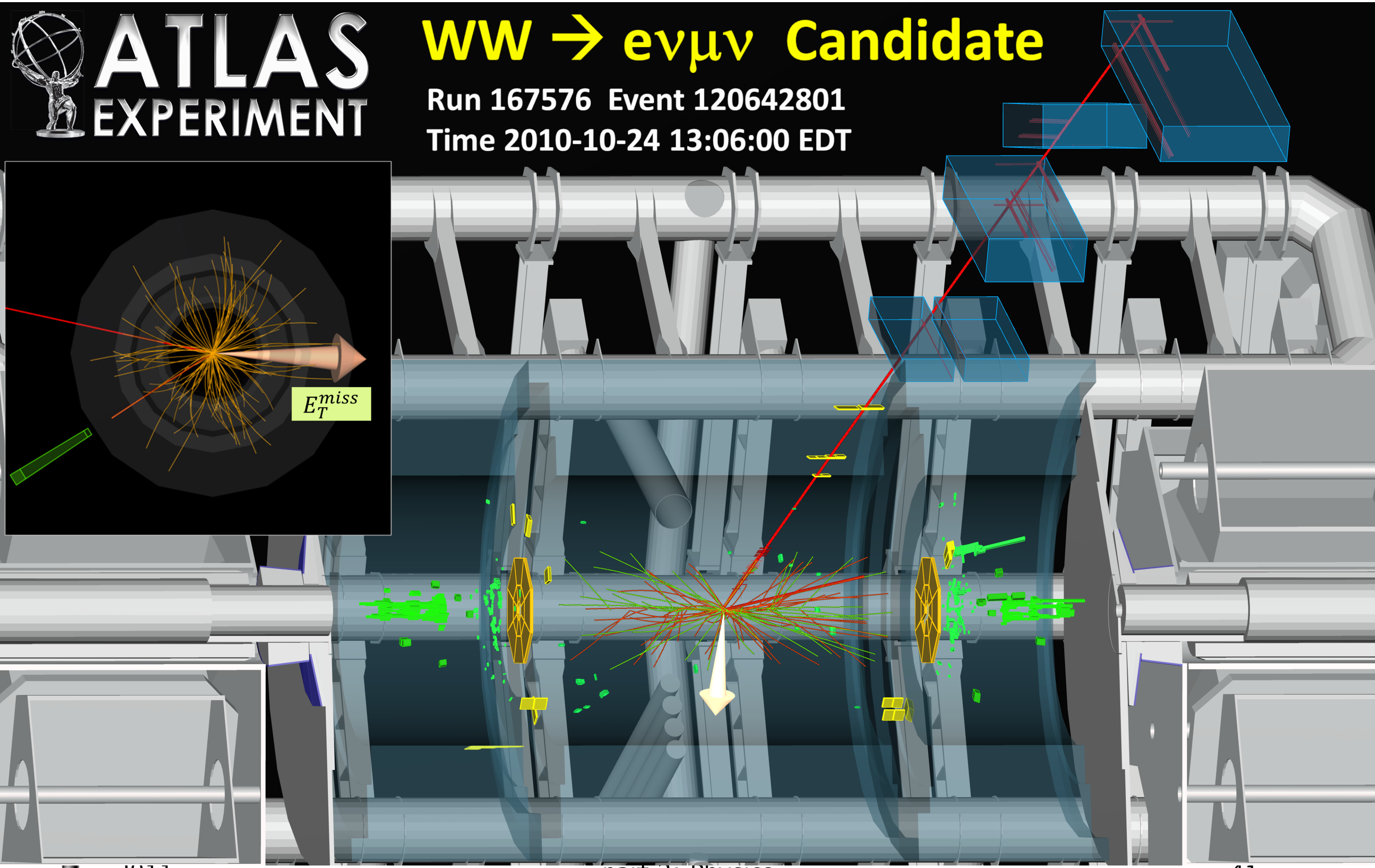


Searches in H->WW Channel

- Decays $H \to WW^{(*)} \to l\nu l\nu$ considered, $l = e, \mu$
- Produced by gluon fusion and vector boson fusion (VBF)
- VBF: presence of additional jets
  - ▷ branch analysis for 0,1,2 jets
  - ▷ better sensitivity
- backgrounds: top, WW, VB+jets
- high BG rejection through event selection using all of ATLAS
  - ▷ di-lepton with ee, $e\mu$, $\mu\mu$
  - ▷ missing transverse energy
  - ▷ veto of tau and b-jets
  - ▷ kinematic event properties



WW->qqenu candidate

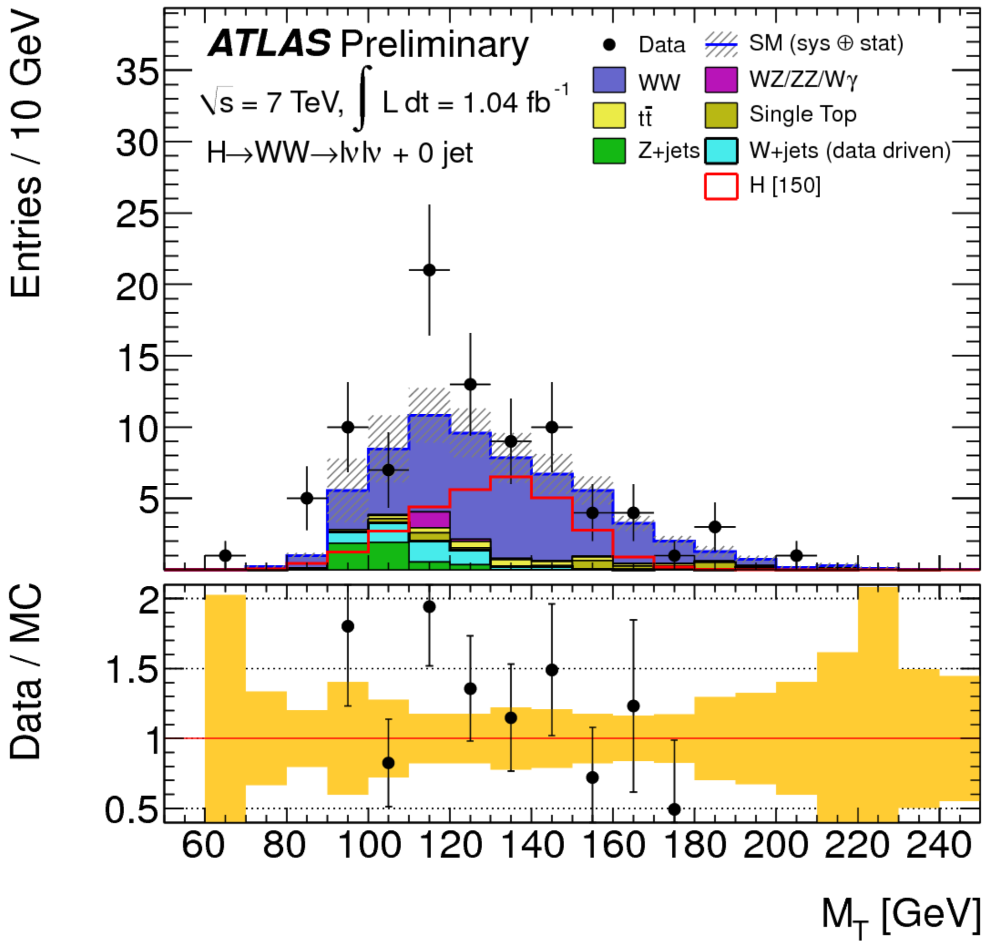


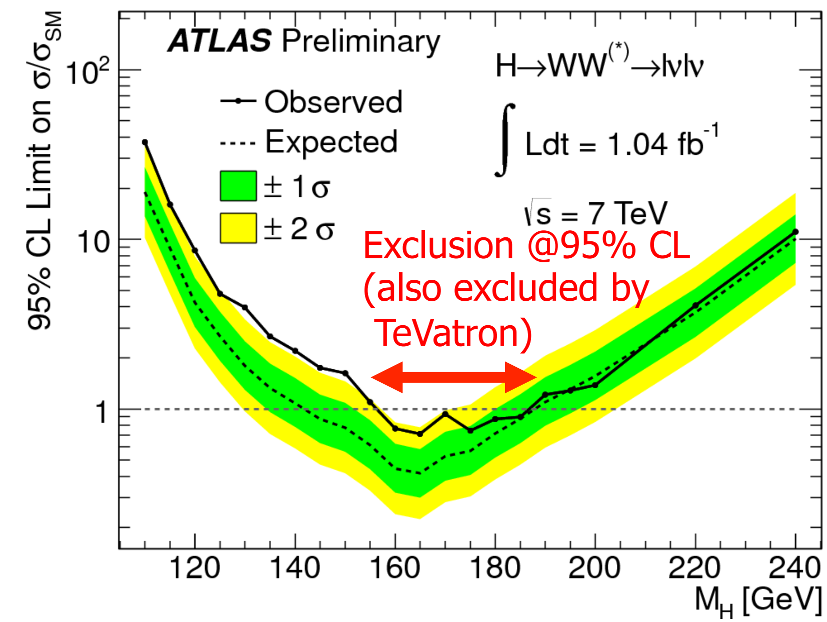
Results in H–>WW Channel

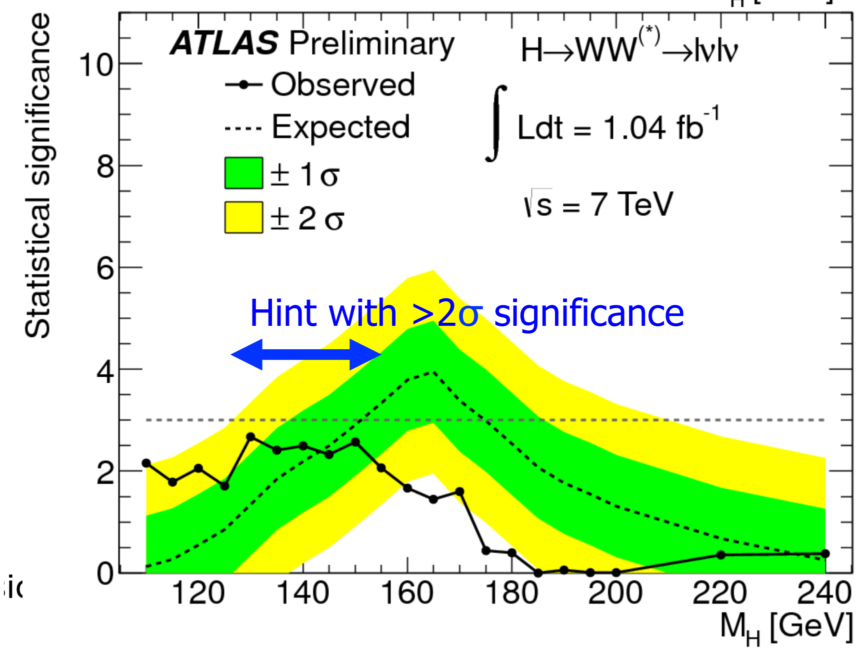
- signal enriched after series of *cuts*

final cut $0.75\, m_H < m_T < m_H$

$$m_T = \sqrt{(E_T^{ll} + E_T^{\text{miss.}})^2 + (\vec{p}_T^{\,ll} + \vec{p}_T^{\,\text{miss.}})^2}$$

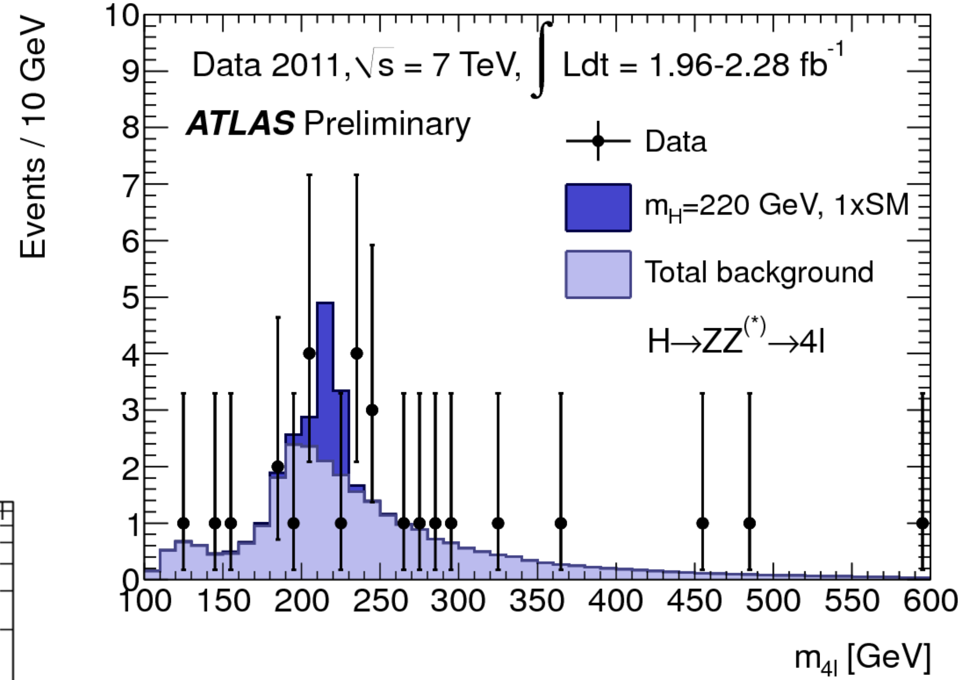


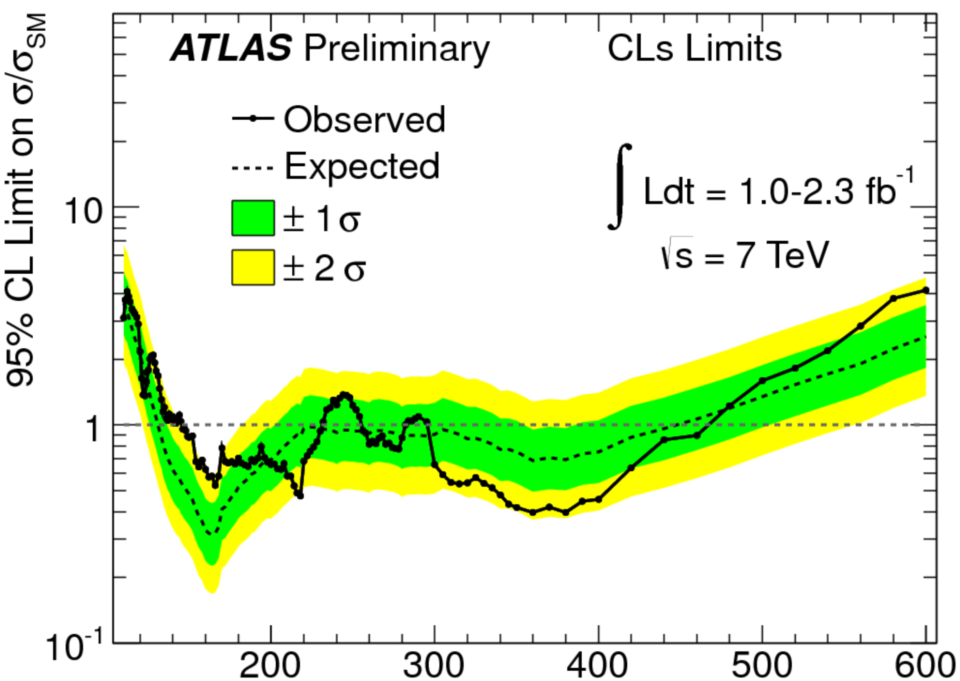




Other Channels/Summary

- More channels being studied to increase combined sensitivity
- best sensitivity at high mH through ZZ–>$\ell\ell\nu\nu$, ZZ–>$\ell\ell$qq
- All channels combined in ATLAS
  - also combination ATLAS–CMS

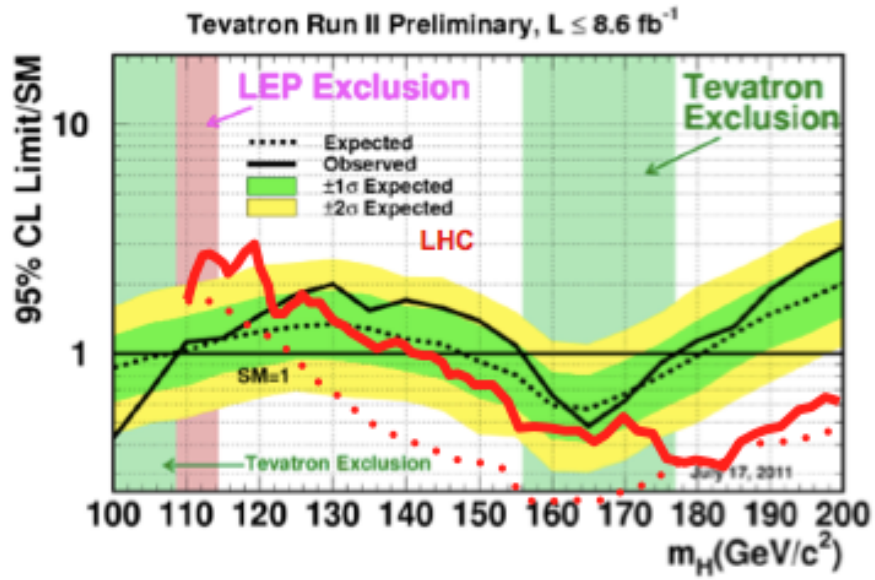


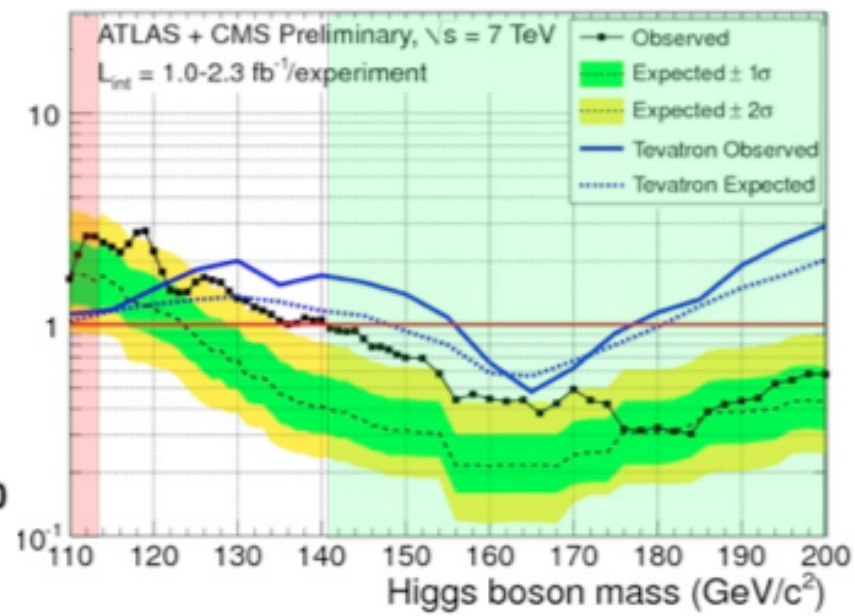


- The air gets thin for the Higgs
- rapid progress!
  - My slides from May '11 were invalid
  - outlook even more interesting
- TeVatron left the game
  - May '11 TeVatron was setting limits

Another Update: HCP Conference

- Nov 18th 2011: ATLAS+CMS combine their limits
- small low-mass band left, in agreement with indirect searches



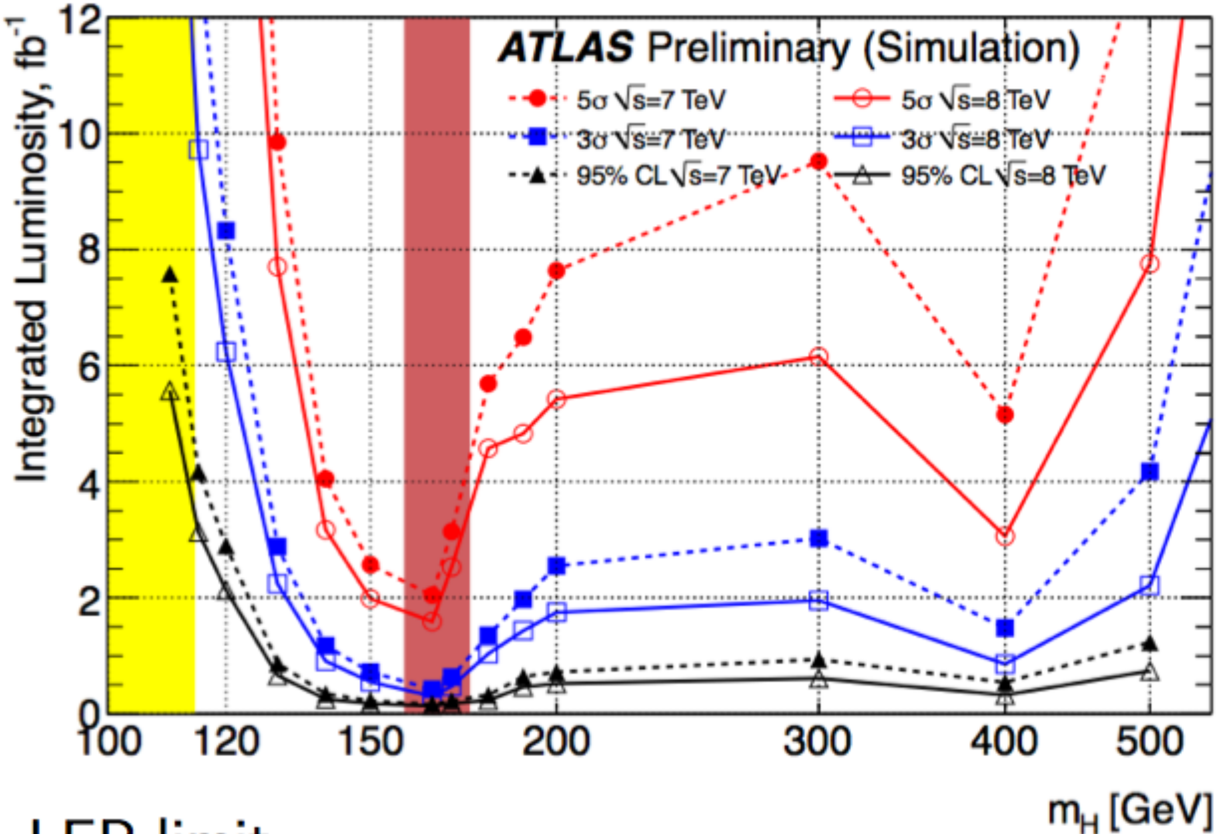


In the non excluded region both colliders show an excess compared to the expectation. Tevatron observed 95% limit is in the 1σ band. LHC excess has a max significance of 1.6σ .

Every discovery starts with the inability to exclude, it is good to see that we have excess compared to expectation !

However here we do not have the clear picture of why do we have this excess. More data (that we have already) will tell us more about the WW excess. And the other channels will become more and more sensitive. **Stay tuned !**

ATLAS Prospects for Higgs Boson Searches



- Most difficult is the low mass region
- with $4/\text{fb}$ at 7 TeV exclude Std.Model Higgs boson down to LEP limit
- evidence or even discovery would be the more exciting option!
- Anticipate:
  - ▷ Analyses still have some room for improvement
  - ▷ ATLAS and CMS will combine their results
  - ▷ Good LHC machine performance

Physics beyond Standard Model

- Particle physics results from LEP, TeVatron and LHC are all well consistent with the standard model
  – no indication yet for new physics

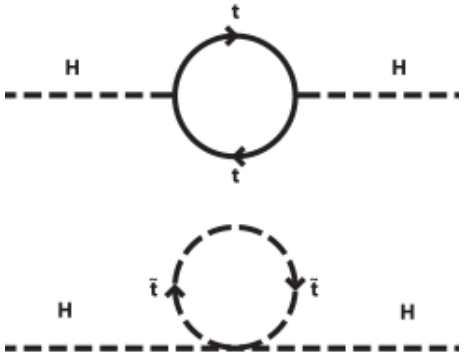
- The situation is different in **astroparticle physics and cosmology**: plenty of evidence for new physics
  – dark matter and dark energy, prevalence of matter over anti-matter, neutrino oscillation/mass, …
  – is this difference a hint in itself?
- From a theoretical perspective there are also motivations for physics beyond the standard model:
- **Unification** of electro-weak with strong force – or even gravitation
- **Hierarchy** or **Naturalness Problem**: finely tuned cancellations in corrections to scalar mass or divergent processes in order to achieve physical predictions at or beyond the electroweak scale

(additional motivations if no < 1 TeV Higgs boson found)

Supersymmetry

- A proposed symmetry between fermions (matter) and bosons (forces), supersymmetry, addresses some of the open questions
  - to every fermion a supersymmetric partner boson associated, and v.v.
  - of course the symmetry is broken at currently accessible energies, proposing that even the lightest partner boson/fermion is heavier than kinematically accessible in today's experiments

- Why is SUSY so popular as extension to std. model?
  - divergent quantum corrections avoided by natural cancellation of contributions from superpartners



  - unification of electroweak and strong coupling
  - lightest supersymmetric particle is dark matter candidate
  - A SuSy extension is a small perturbation of std. model, leaving consistency of electroweak measurements unchanged

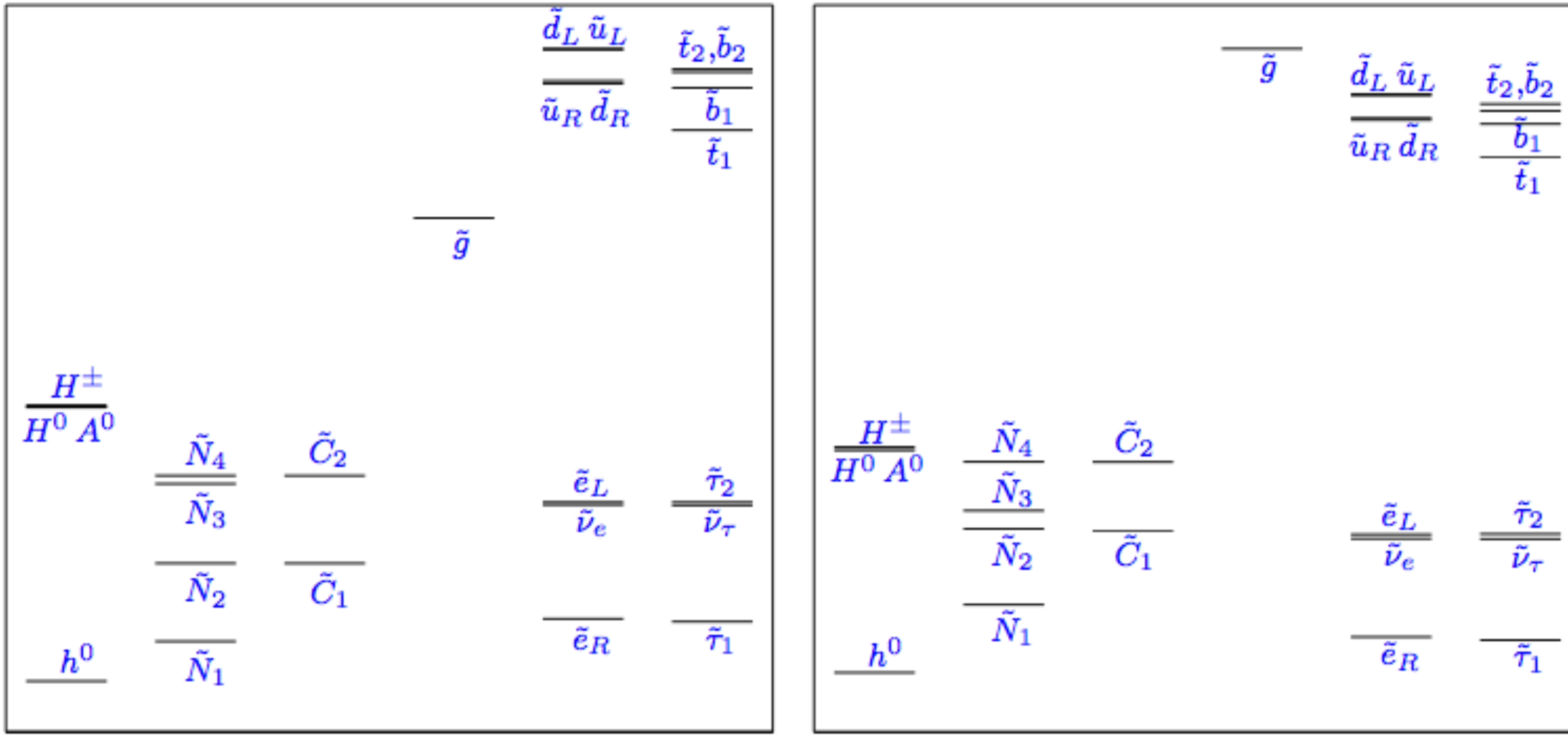
Fundamental Aspects of SUSY

Minimal Supersymmetric Extension of the Std. Model (MSSM)

- Symmetry: for each particle u with spin s there is a SUSY partner ũ with spin diff. Δs=½
- Many new particles predicted, even for the *minimal* SSM
  - quarks ➔ squarks
  - leptons ➔ sleptons
  - $W^{\pm}$ ➔ winos
  - Z ➔ zino
  - γ ➔ photino
  - $H^{\pm}$ ➔ charged higgsino
  - h, H ➔ neutral higgsino
  - g ➔ gluino
  - note: MSSM particle spectrum contains 5 Higgs bosons: h, H, A, $H^{\pm}$

- **R-parity**: multiplicative quantum number
  - R_p=+1 for std model particles
  - R_p=–1 for SUSY partners
- In many SUSY models R-parity is conserved
- As a direct consequence:
  - SUSY particles produced in pairs
  - Lightest SUSY particle is stable
    ➔ cold dark matter candidate
  - Lightest SUSY particle interacts only weakly, like a neutrino
    ➔ shows up in detector as missing E_T

SUSY Spectrum Visualized

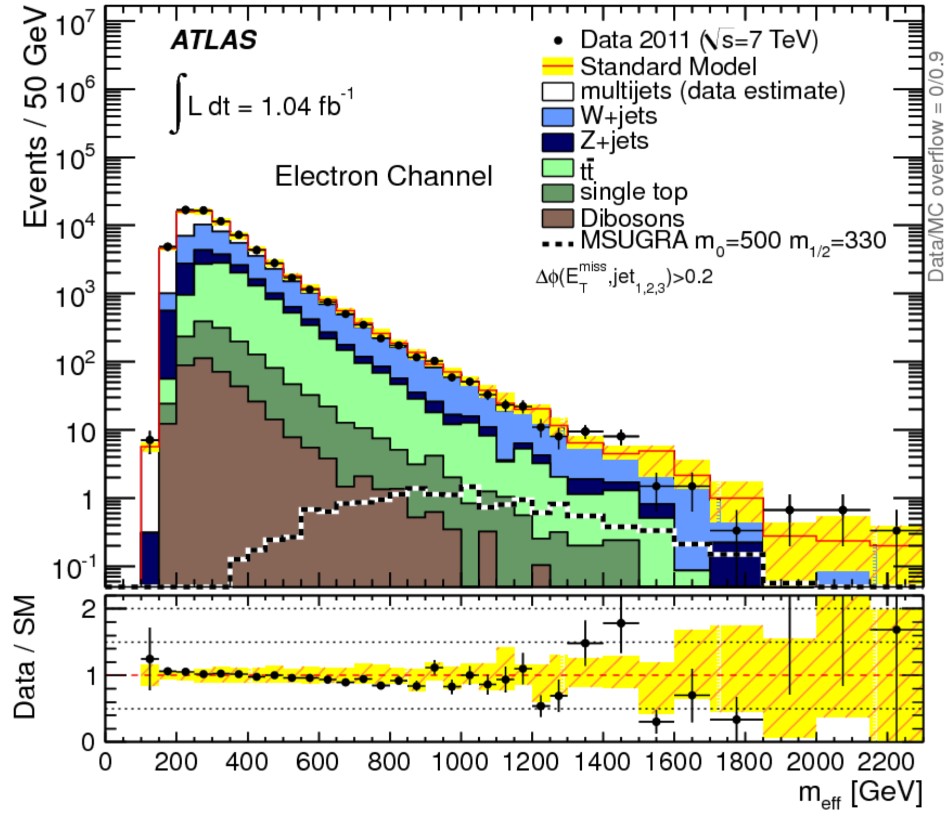


(c) (d)

Figure 8.5: Four sample mass spectra for the undiscovered particles in the MSSM, for (a) MSUGRA with $m_0^2 \ll m_{1/2}^2$, (b) MSUGRA with $m_0^2 \gg m_{1/2}^2$, (c) GMSB with $N_5 = 1$, and (d) GMSB with $N_5 = 3$. Mass scales are not equal for the four cases, and are deliberately omitted. These spectra are presented for entertainment purposes only! No warranty, expressed or implied, guarantees that they look anything like the real world.

SUSY at LHC

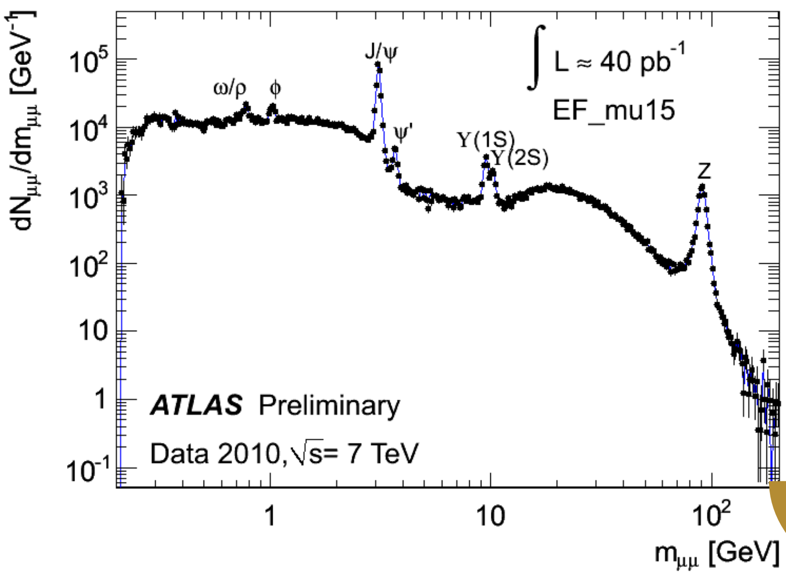
- SUSY particle production @LHC mainly through strong force
  – squark–(anti-)squark pair production, squark–gluino and gluino-gluino pair pr
- Decay to quarks and gluons
  – event signature: jets
- Involving SUSY partner of W,Z
  – the chargino and neutralino
  – their decay can produce leptons
- Lightest SUSY particle (LSP) will escape undetected
  – event signature: Missing E_T
- LHC results structured along number of leptons: 0, 1, 2
  – "Did you read the 1-lepton paper?"
  – largely model-independent analyses
  – number of models and free parameters in SUSY models is high

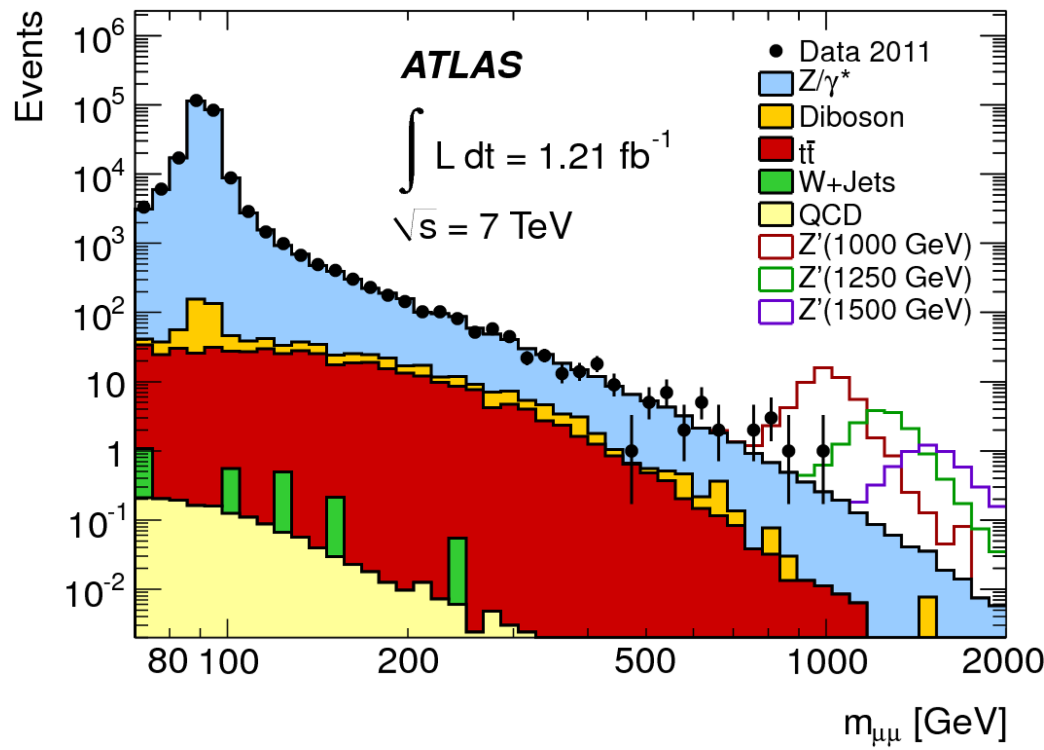


- No deviation yet from Std.Model, excluding range of SUSY prameters
  – parameters are couplings in SUSY contrib's to Lagrangian, scale ratios, mixing…

Z' and W' Searches

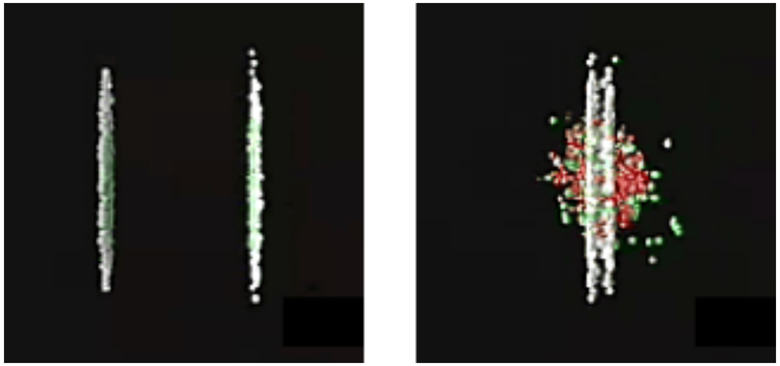
- Many more theories around with predictions accessible at LHC
- one more example: heavy massive gauge bosons decaying to leptons, W'–>$\ell\nu$ or Z' –>$\ell\ell$
- Limits now in multi-TeV range: $m_{Z'}$ > 1.83 Tev (95%CL)
  ~1 TeV from previous colliders



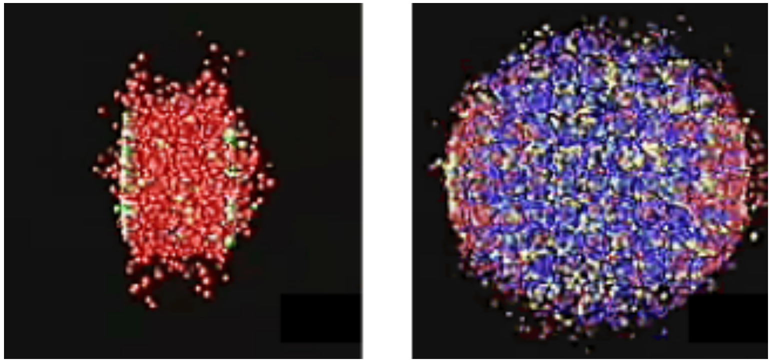


Heavy Ion Physics

- LHC able to collide Pb on Pb
  - accelerate to 3.5 TeV per unit charge
  - 287 TeV beam energy (Z_{Pb}=82)
  - $\sqrt{s}$ =2.76 TeV per nucleon pair
  - compare to RHIC: $\sqrt{s}$ = 0.20 TeV p.n.
- Heavy Ion after proton run in November each year (i.e. now)
- Extreme energy densities create a **quark-gluon-plasma**
  - partons move freely like in hot gas
- ALICE expt. dedicated to Heavy Ion physics – but not exclusively ! excellent results from ATLAS & CMS
  - compared to RHIC profit also from hermeticity
- Found striking differences to particle production in p–p collisions



Pb nuclei colliding head-on



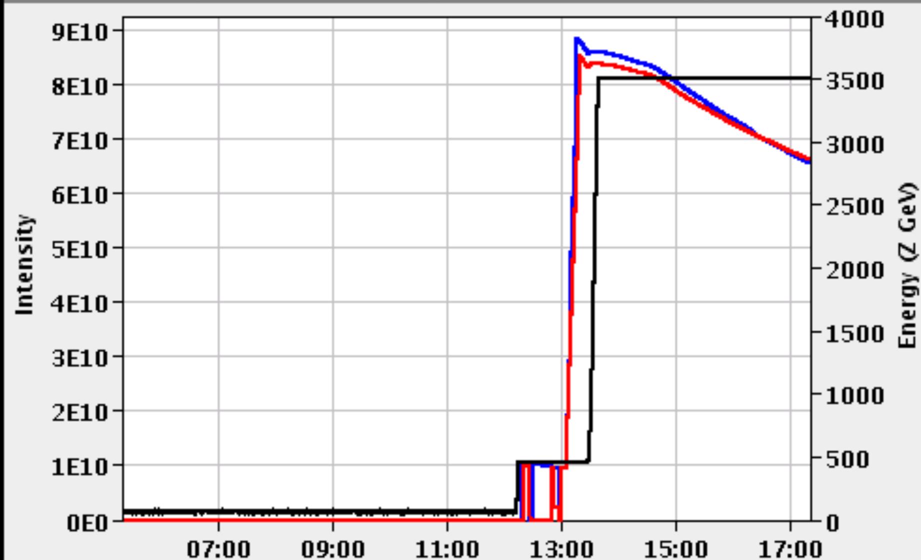
Quark-gluon plasma formed

LHC Page1 | Fill: 2292 | E: 3500 Z GeV | 13-11-2011 17:19:46

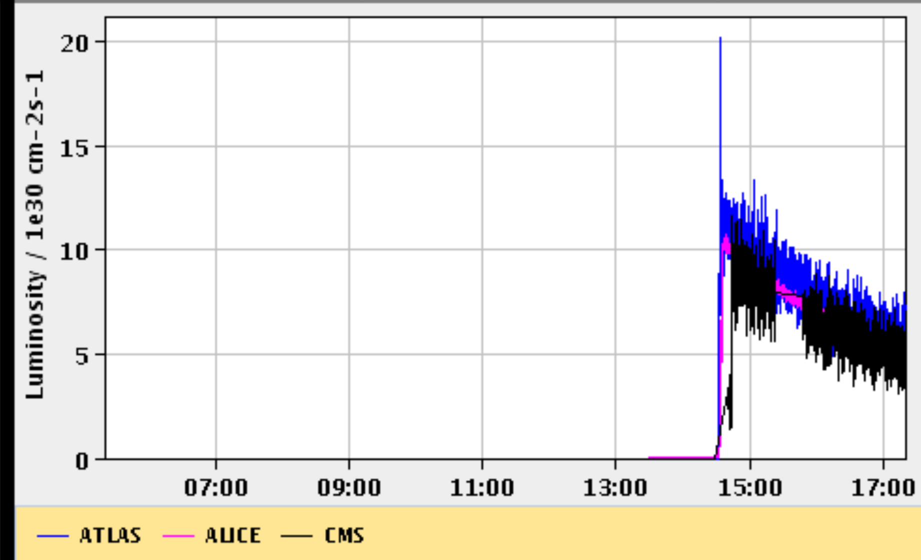
ION PHYSICS: STABLE BEAMS

Energy:	3500 Z GeV	I(B1):	6.76e+10	I(B2):	7.25e+10

FBCT Intensity and Beam Energy Updated: 17:19:45



Instantaneous Luminosity Updated: 17:19:46



Comments 13-11-2011 15:25:11 :

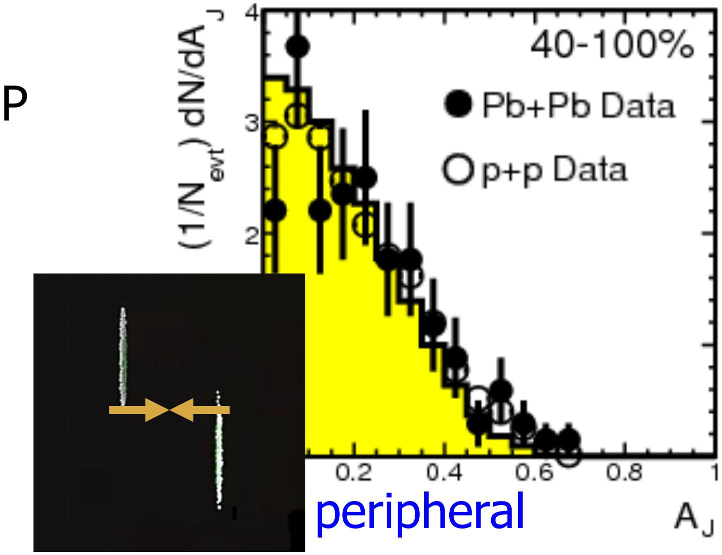
BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: Single_9b_8_8_0_1bpi9inj_IONS

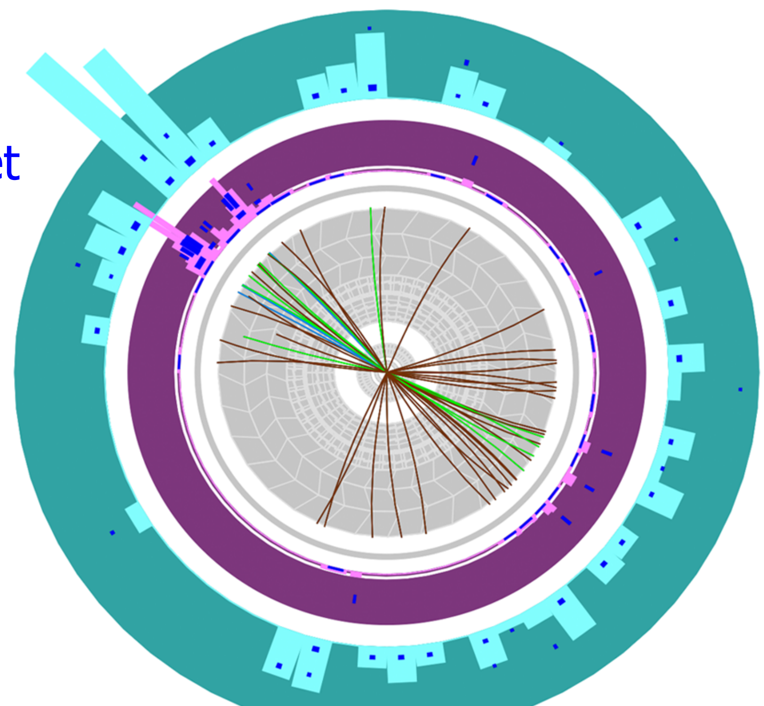
PM Status B1: ENABLED | PM Status B2: ENABLED

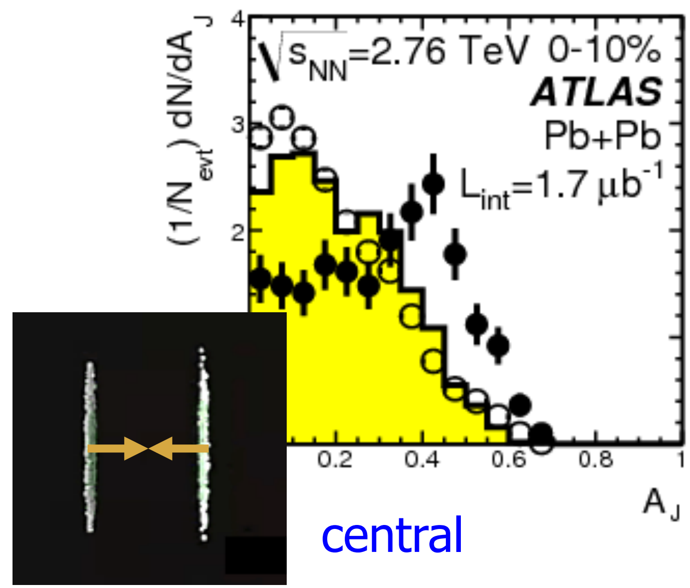
Heavy Ion Physics Highlights (2010)

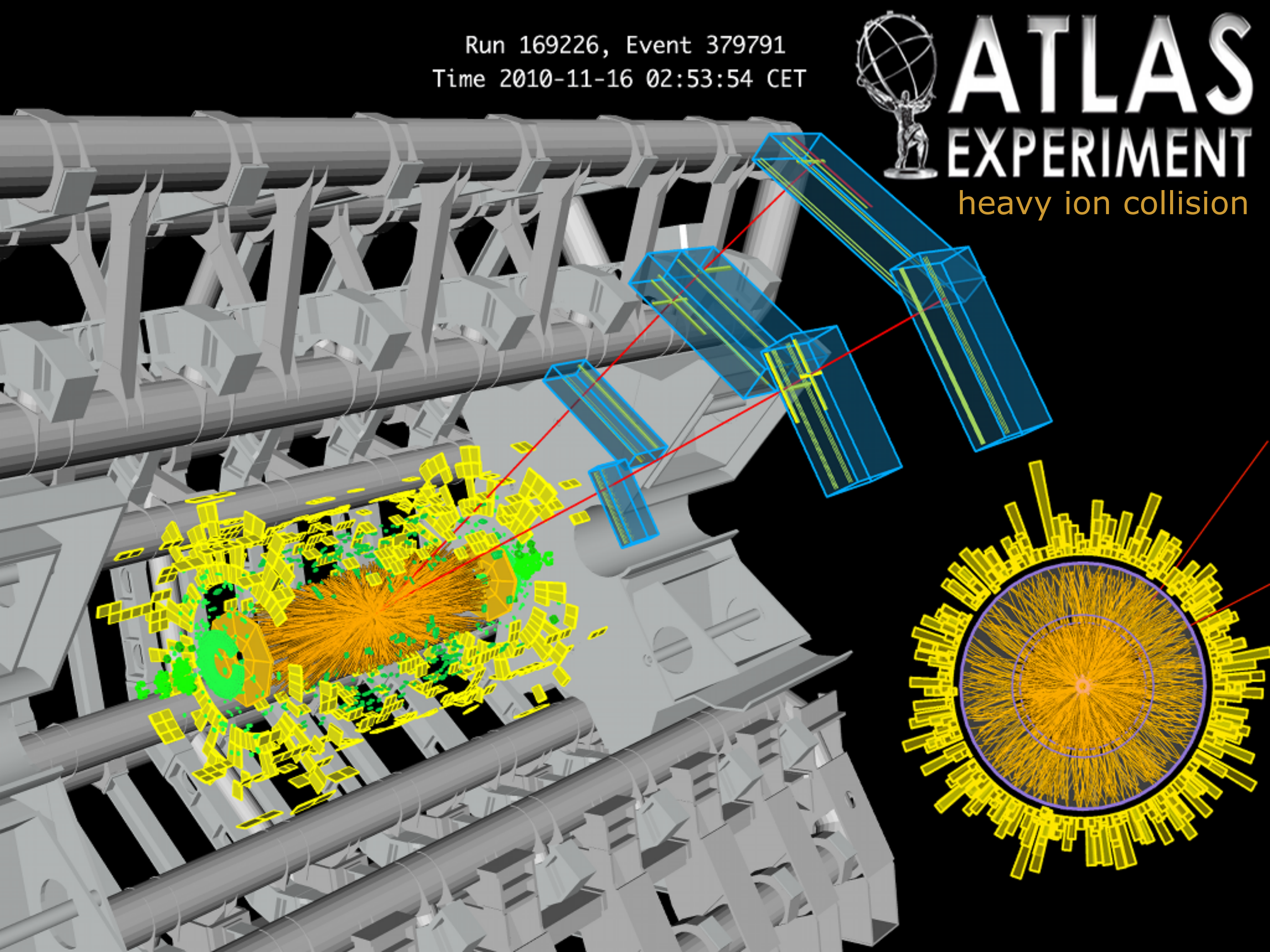
- Centrality of collision: peripheral, like p–p
  head-on, creating QGP
- observe unusually high fraction of mono-jets in central collisions
- interpreted as di-jet where the 2nd jet interacted with the QGP while traversing it
- QGP is opaque to strongly interacting particles



mono-jet

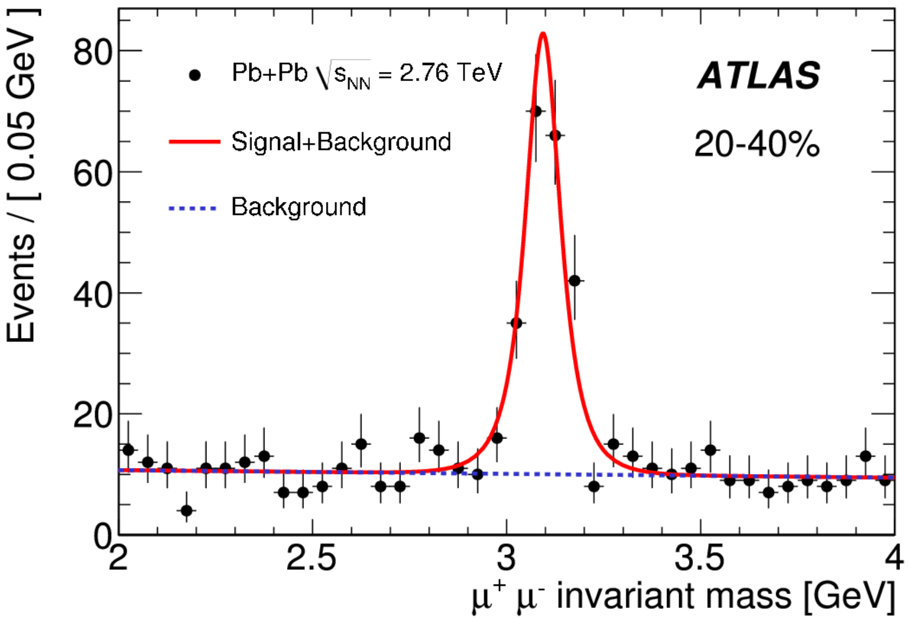


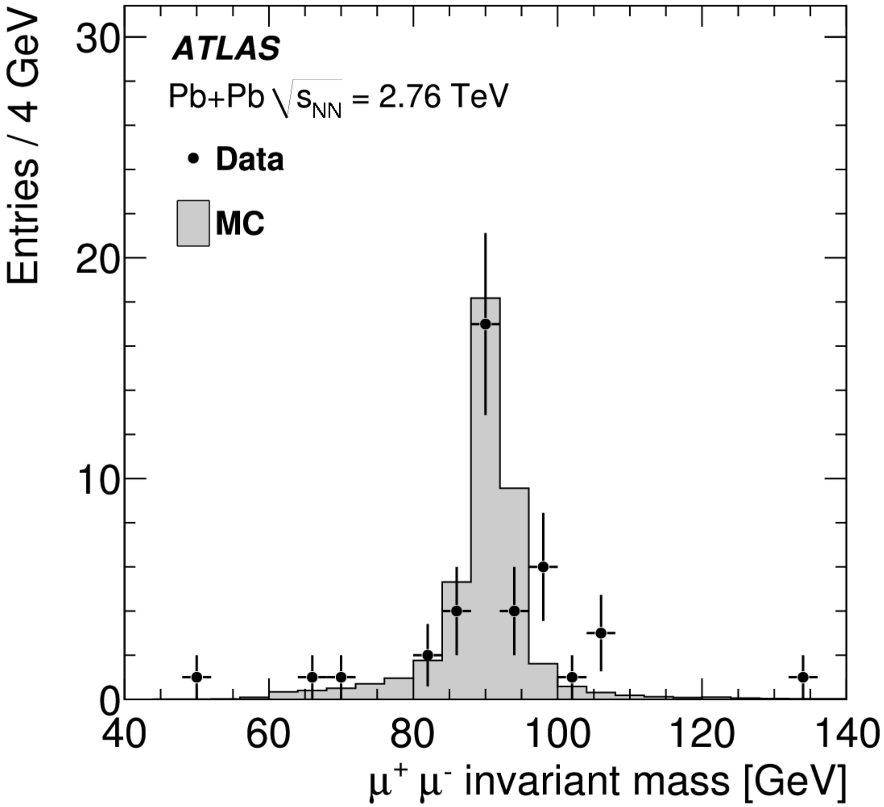




Run 169226, Event 379791
Time 2010-11-16 02:53:54 CET
ATLAS
EXPERIMENT
heavy ion collision

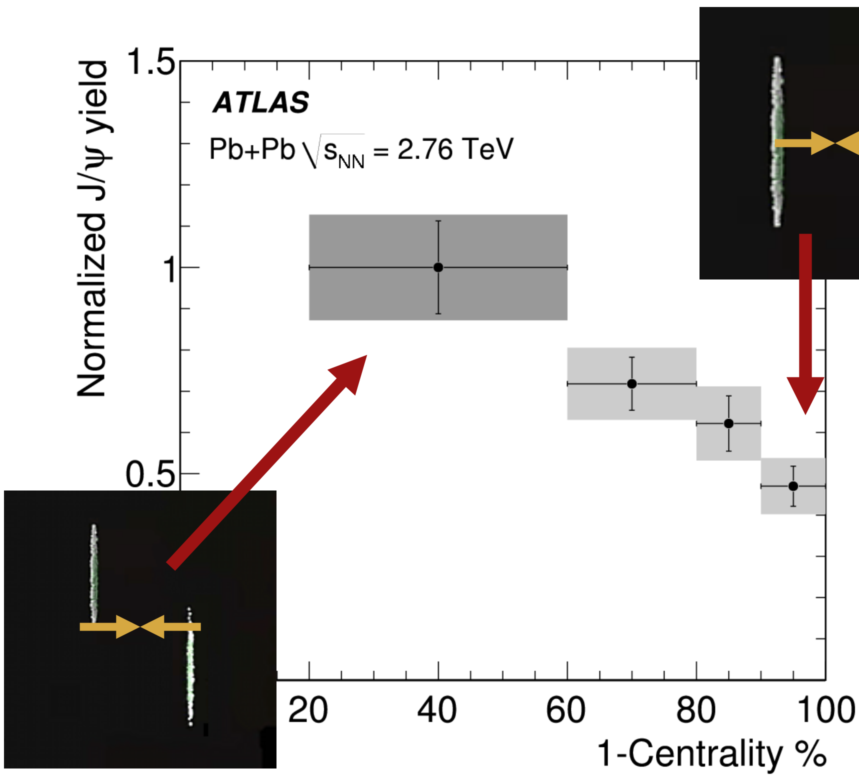
Heavy Ion Physics Highlights

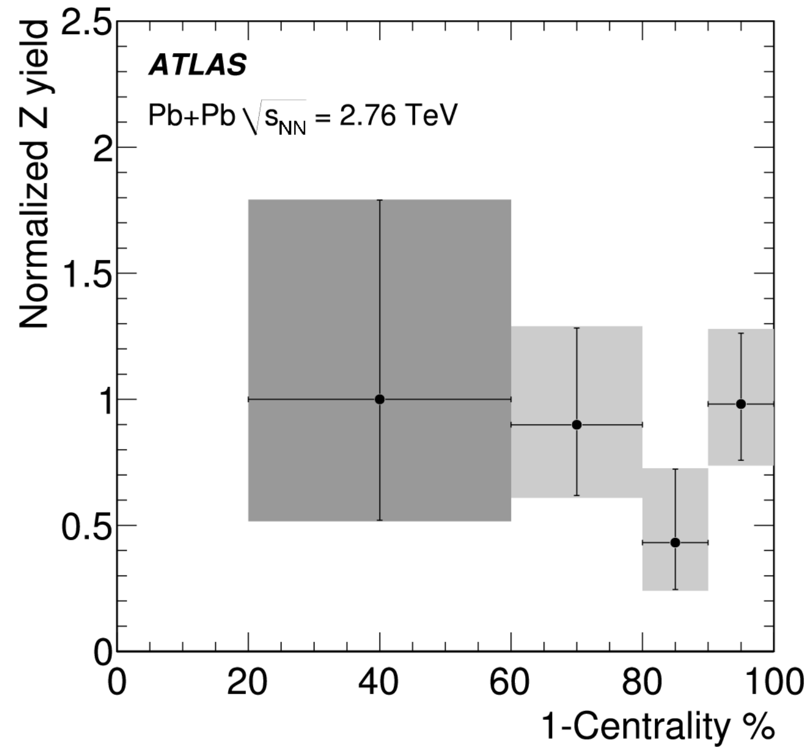




- J/ψ and Z decays observed in Pb–Pb collisions
- Nice achievement for combined muon reconstruction
- Yields were not as high as expected…

J/ψ and Z in Heavy Ion Physics





- Yield of J/Psi scales only poorly with number of colliding nucleons when going to more central collisions
- J/Psi is charmonium: interacts with QGP
- Z does not show this effect – QGP is translucent

Summary

- Discussed key characteristics of p–p collisions at LHC
- Overview of interesting physics studied and probed with LHC, and some physics analyses in ATLAS
  - Many results from last few months and ~1 fb^{-1}

No discovery yet!

- Aim is to understand the big picture
  - Standard Model measurements continue at LHC, and are also relevant as foundation for solid search for new physics
  - Motivation for most interesting new physics candidates, for which hopefully a conclusion can be expected by end of next year
- The given overview could neither go into the details of theoretical models nor into the details of physics analyses
  - there is a lot more to learn, best to pick a dedicated physics topic
- Next lecture will give an overview how to use the detector optimally in physics analysis and the performance aspects of physics analysis
  - last lecture will provide the practical details

Further Reading

Any good book on Standard Model, as well as CERN or national HEP schools

Top physics at Hadron Colliders, A Quadt,
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/InDetTrackingPerformanceApprovedPlots

A Supersummetry Primer, S.P. Martin, arxiv:9709356 [hep-ph] (2011 edition)
http://arxiv.org/abs/hep-ph/9709356

ATLAS conference notes
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES

ATLAS papers
https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Hadron Collider Physics Conference, Paris
http://indico.in2p3.fr/conferenceOtherViews.py?view=cdsagenda&confId=6004