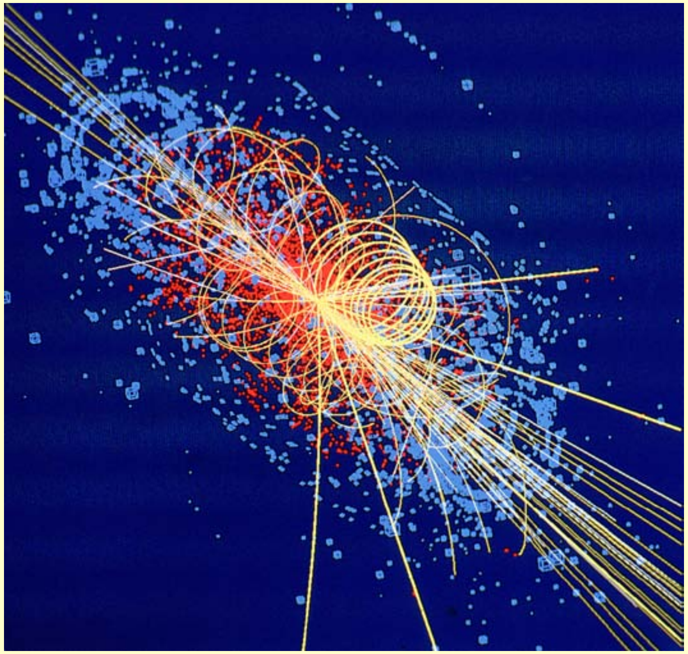
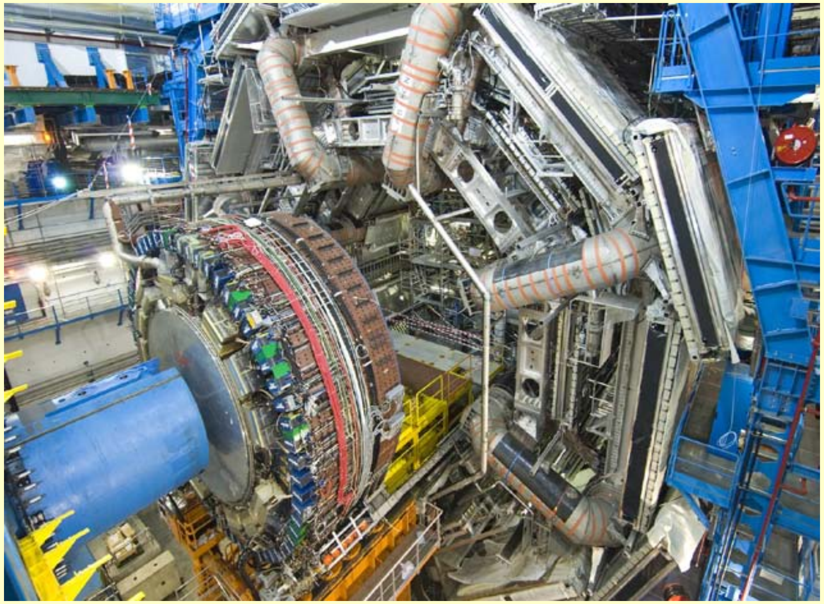
QCD at the LHC
-signals and background for new physics searches-

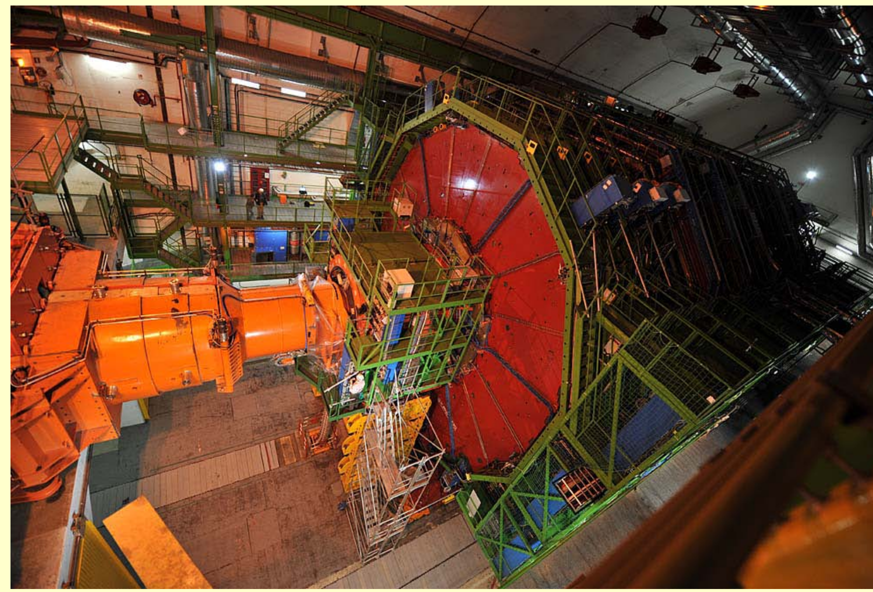


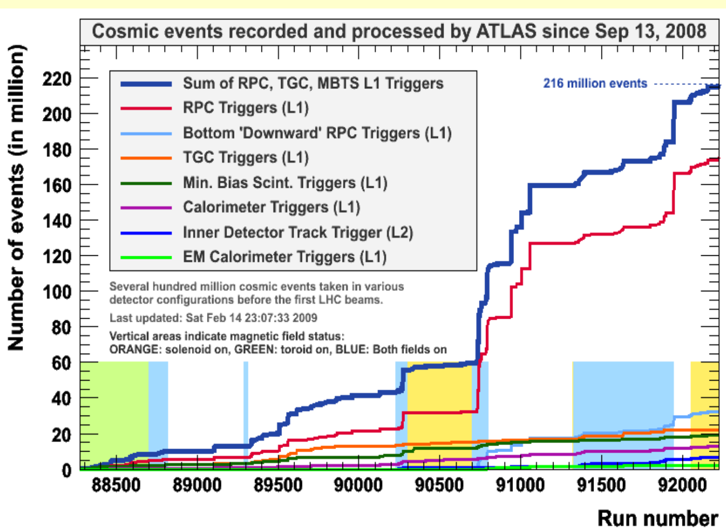
- Introduction
- (Early) QCD measurements
  - Minimum bias events
  - Inclusive jets
  - W/Z (+ jets)
  - Top production
- QCD processes as background in searches for New Physics

Karl Jakobs
Physikalisches Institut
University of Freiburg / Germany

The ATLAS and CMS experiments

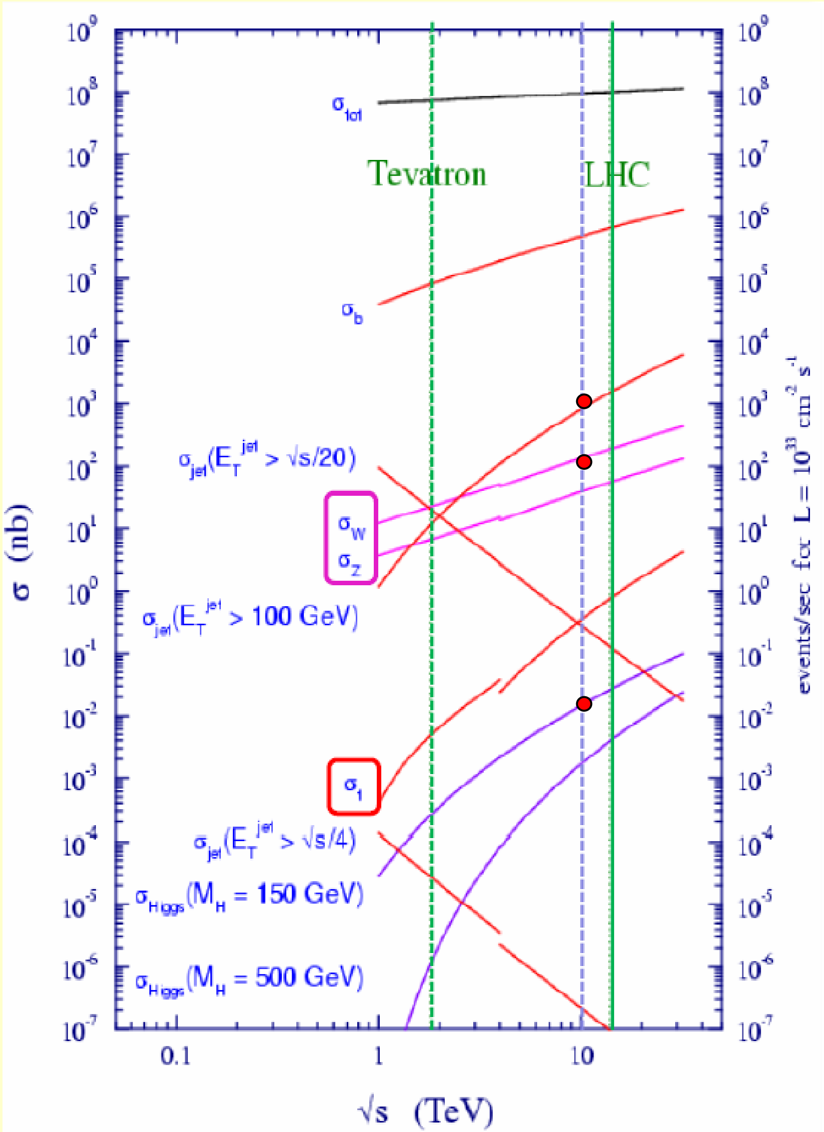


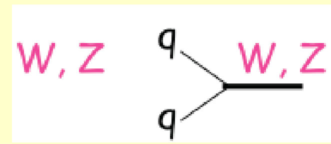


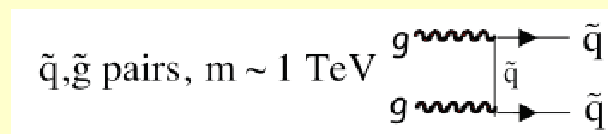


The experiments were ready for collisions in 2008,
….they will be in better shape in 2009.

Cross Sections and Production Rates



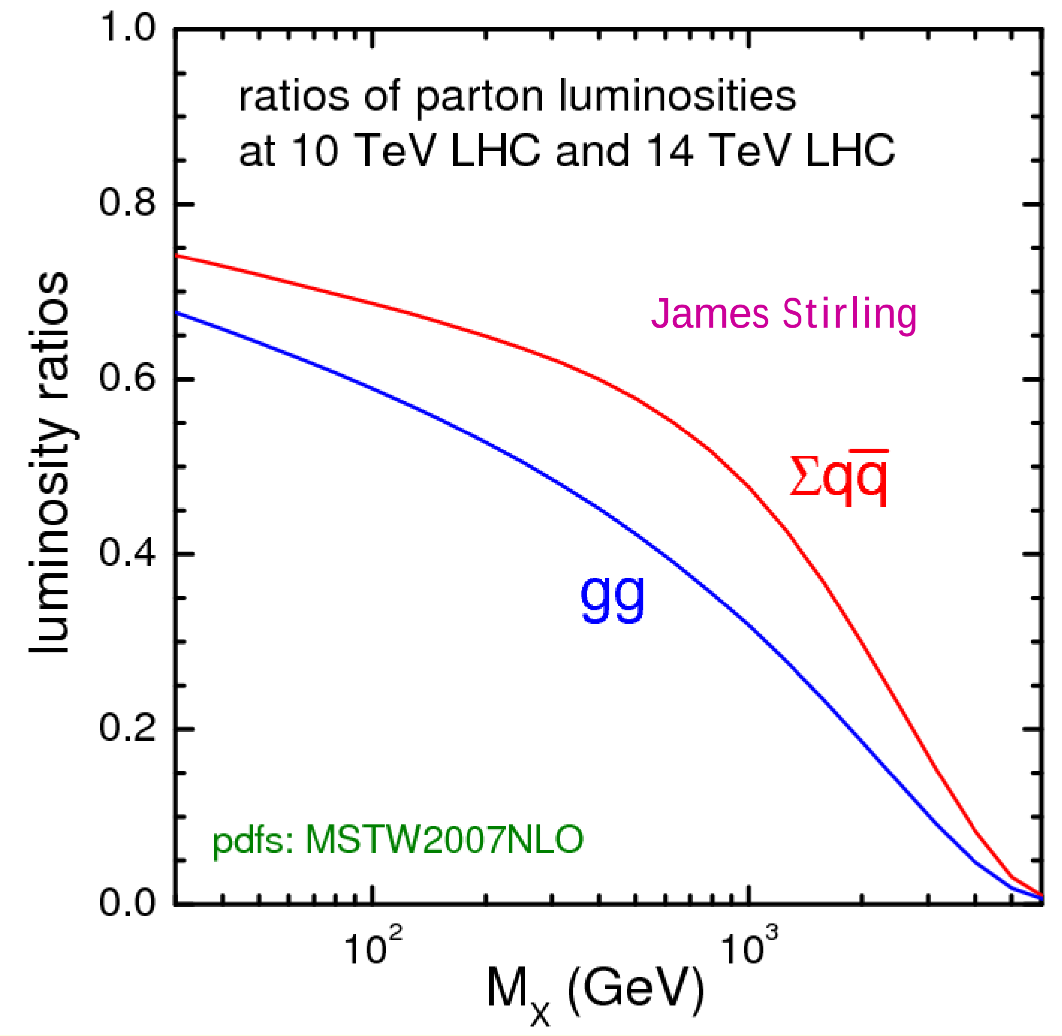




<u>QCD processes at the LHC</u>:

- Large cross sections
- First physics results expected
- Sensitive to new physics
- Background to everything

10 vs 14 TeV ?



- At 10 TeV, more difficult to create high mass objects...
- Below about 200 GeV, this suppression is <50% (process dependent)

	√s [TeV]	Cross section
W-> lν	14	20.5 nb
	10	14.3 nb
Z-> ll	14	2.02 nb
	10	1.35 nb
ttbar	14	833 pb
	10	396 pb

- Above ~2-3 TeV the effect is more marked

14 TeV simulation results will be shown throughout the talk, unless stated otherwise

First goals …. (2009 / early 2010) (?)

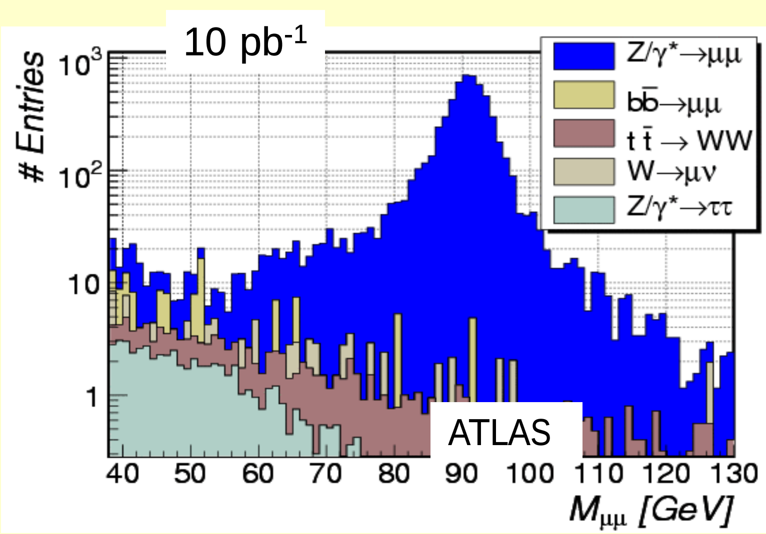
- Understand and calibrate detector and trigger

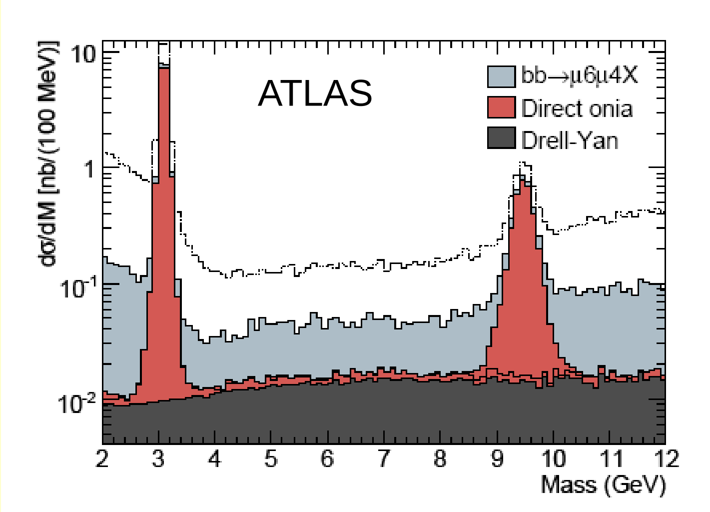
  in situ using well-known physics samples

e.g. - $Z \to ee, \mu\mu$ tracker, calorimeter, muon chambers calibration and alignment

- $tt \to b\ell\nu\ bjj$ 10^3 events / day after cuts at 10^{32} cm^{-2} s^{-1}

  $\to$ b-tag performance

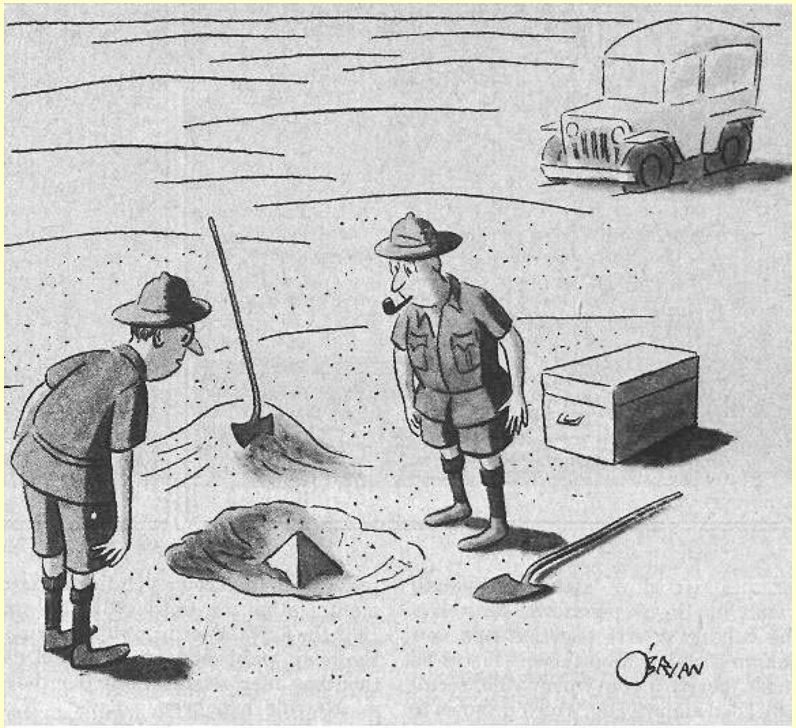




1 pb^{-1}, low p_T muon triggers

......and in parallel.....

....prepare the road for discovery



"This could be the discovery of the century. Depending, of course, on how far down it goes."

- Understand basic SM physics at $\sqrt{s}$ = 10 TeV

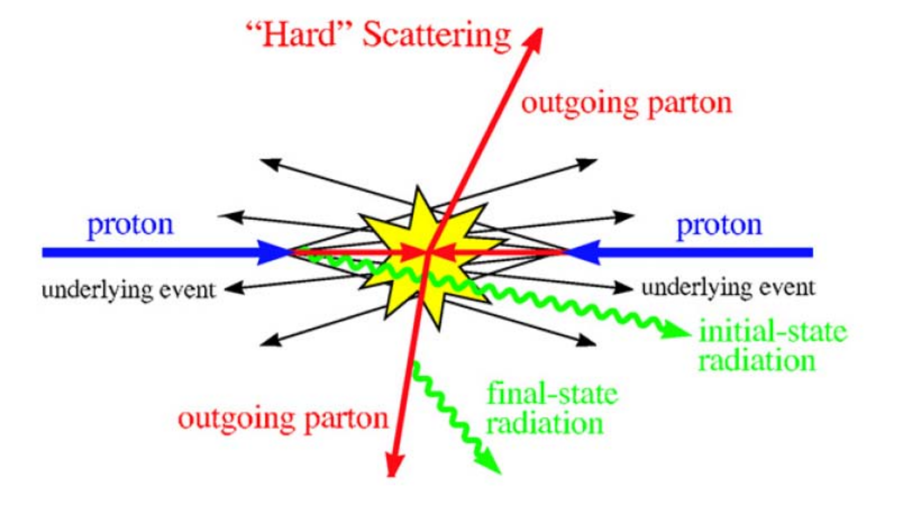
  - First checks of Monte Carlos

    (progress at the Tevatron, but it needs LHC data to get rid of the extrapolation uncertainties)

  - Measure cross-sections for W, Z, tt, QCD jets, and events features (p_T spectra etc.)

    (tt and W/Z+ jets are omnipresent in searches for New Physics)

Study of minimum bias events



… and of the underlying event

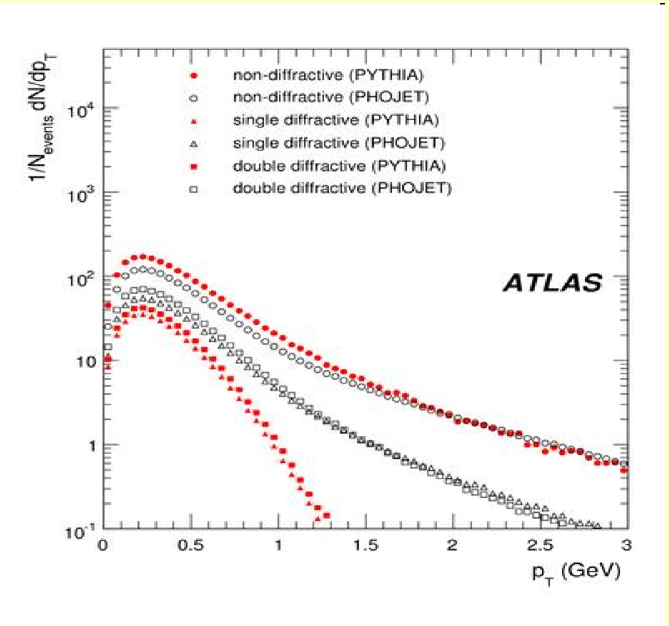
Understanding and modelling of the underlying event and min. bias events is important for:

- Simulation of pileup effects at the LHC
- Understanding of lepton and jet isolation
- Event selections with jet vetos (often low p_T (~ 20 GeV) jet vetos used in searches, e.g. $H \rightarrow WW \rightarrow \ell\nu\, \ell\nu$)
- Calibration of the jet energy scale
- …..

Measurement of properties of minimum bias events

First measurement at the LHC

- Measure charged particle distributions:
  rapidity distribution and p_T-spectrum
- Multiplicity distributions and $\langle p_T \rangle$
- Large uncertainties on model predictions

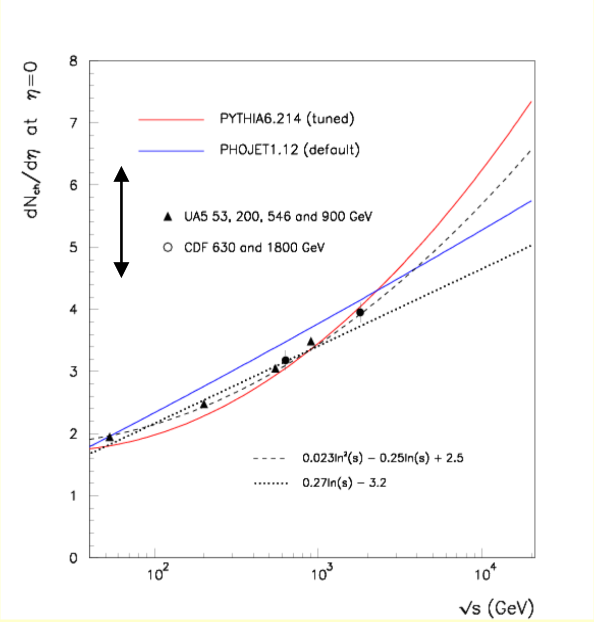


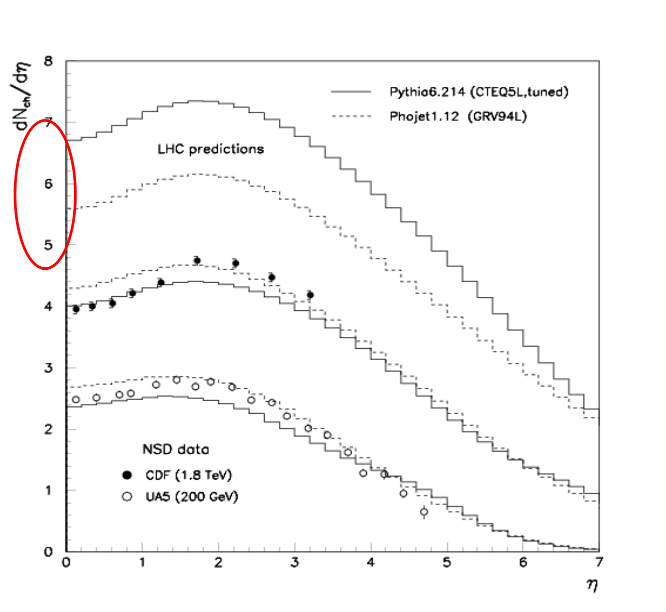
$\langle p_T \rangle$ (η =0): 550 – 640 MeV (15%)

A common definition:

$\sigma_{min.bias} = \sigma_{nd} + \sigma_{dd}$

Non-diffractive and double diffractive part of the inelastic pp cross section

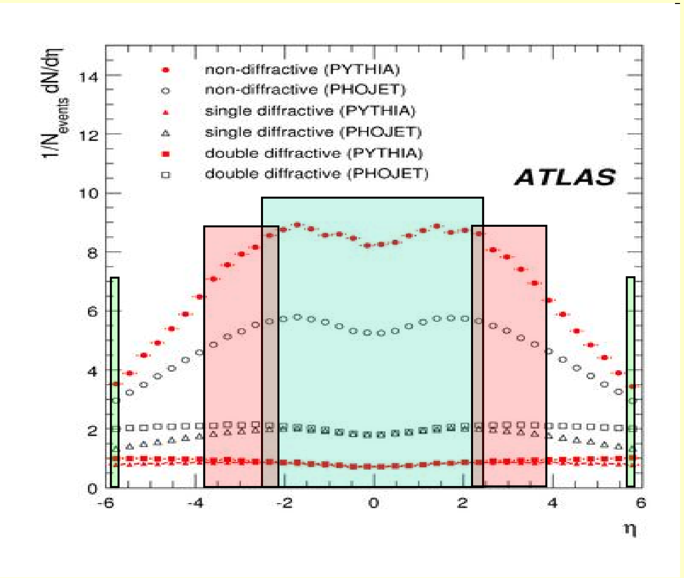




$dN_{ch}/d\eta$ (η=0): 5-7 (~ 33%)

Present experimental preparations / studies

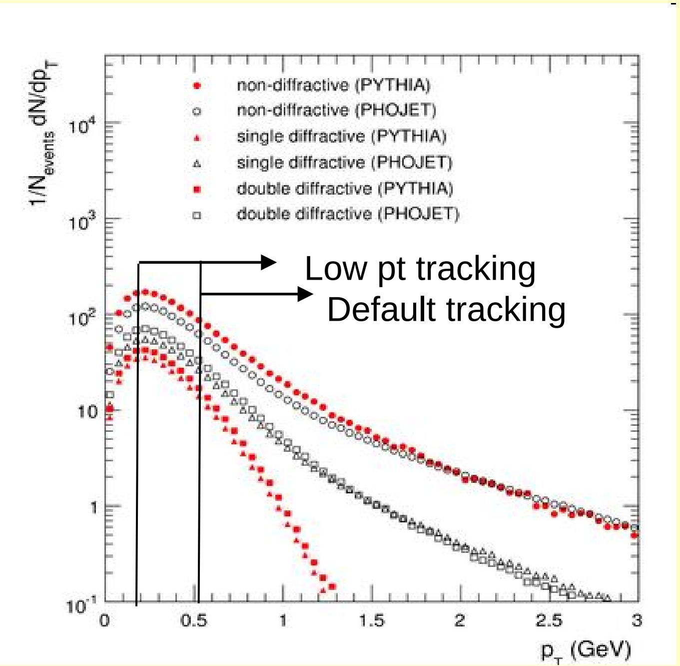
Measurements of minimum bias physics require special **triggers** and **reconstruction**:



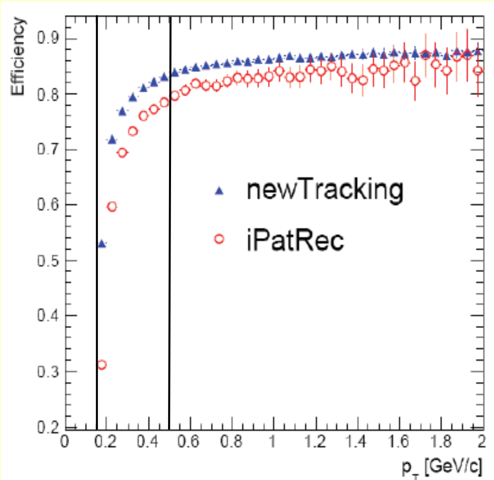
Trigger:
For early running up to ~10^{30} cm^{-2} s^{-1},
number of events/crossing «1

- Inner detector space points and tracks $|\eta|<2.5$
- Trigger scintillators (MBTS) $2.1<|\eta|<3.8$
- LUCID detector $5.6<|\eta|<5.9$
- Zero degree calorimeter (ZDC) $|\eta|>8.3$

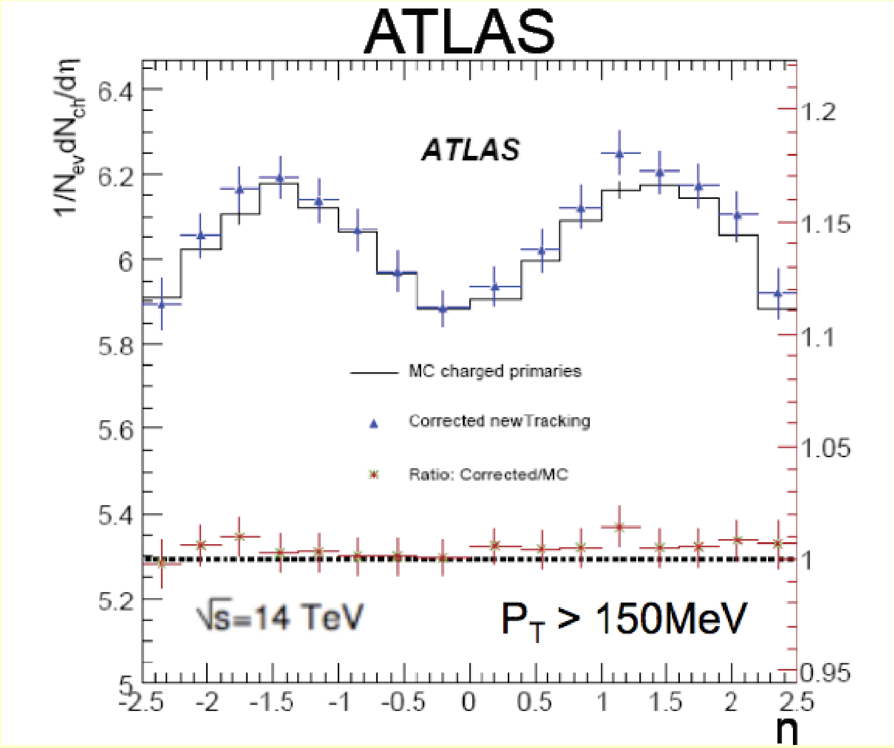
Later, for L = 10^{33}-10^{34} cm^{-2}s^{-1}: use random trigger

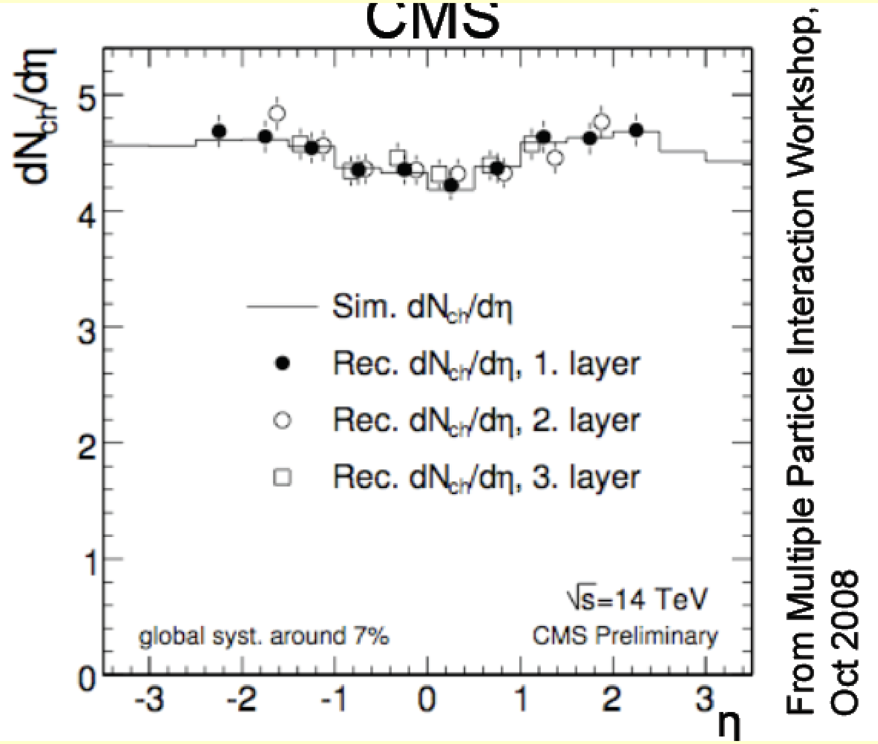


Reconstruction:
Track reconstruction down to very low p_T is required



An ATLAS / CMS comparison





Uses a tracking-based method

Dominant uncertainties from the
Inner Detector misalignment and diffractive cross sections

Goal: total systematic uncertainty ~8%

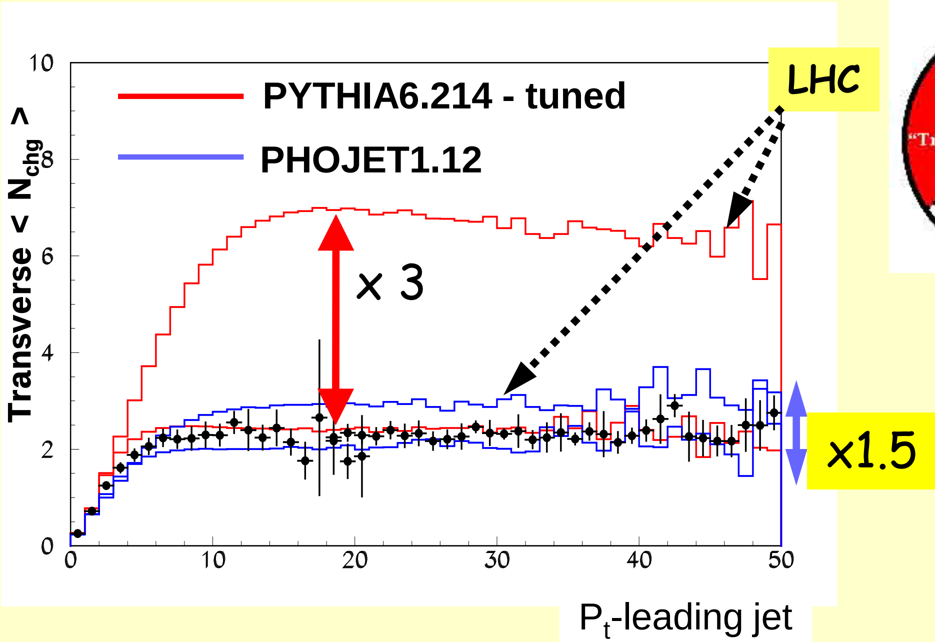
Uses a hit-counting method

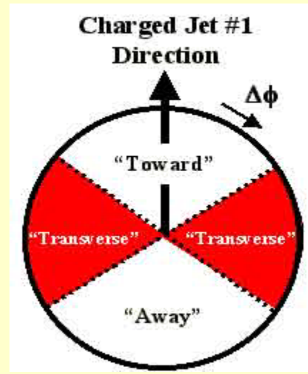
Dominant uncertainties from reconstruction (hit numbers to charged particle conversion functions)

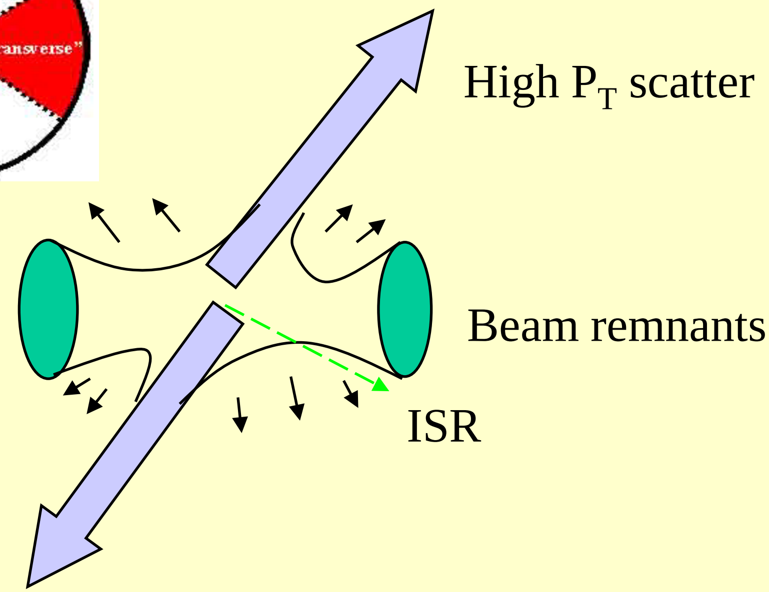
The underlying event

→ talk by Craig Buttar

Average charged particle density in transverse region





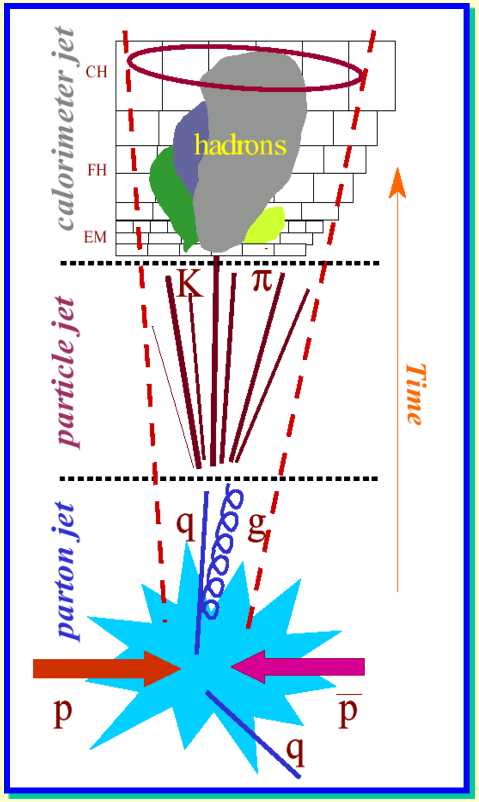


Extrapolation of the underlying event to LHC energies is unknown;

underlying event depends on:
- Multiple interactions
- Radiation
- PDFs
- String formation

- A lot of Monte Carlo tuning is needed;
- Early measurements at the LHC (low p_T jets, but also in W/Z production) will considerably extend our knowledge

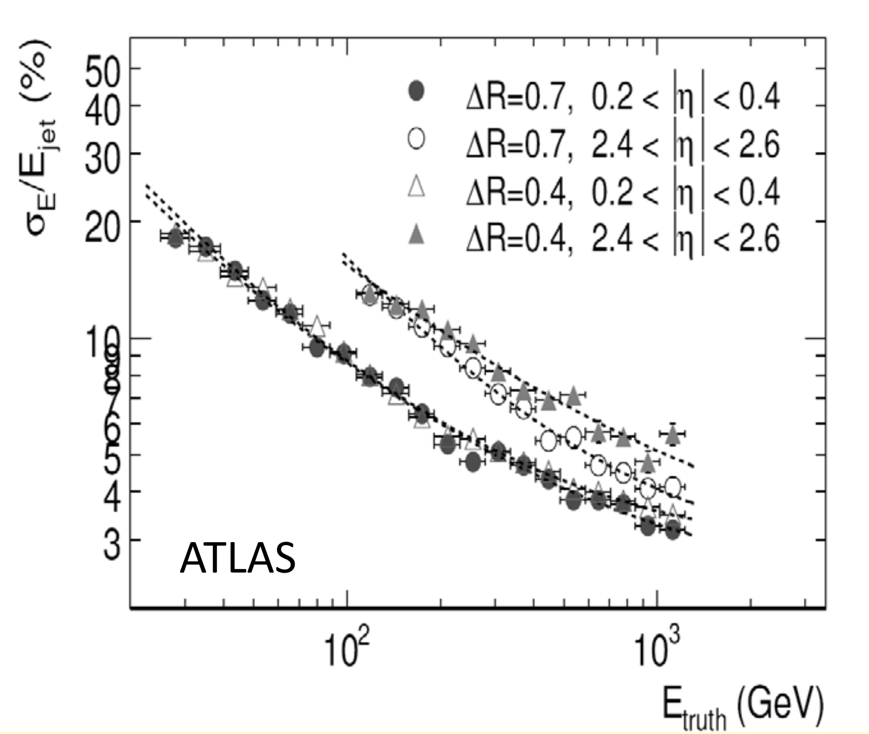
Jet physics



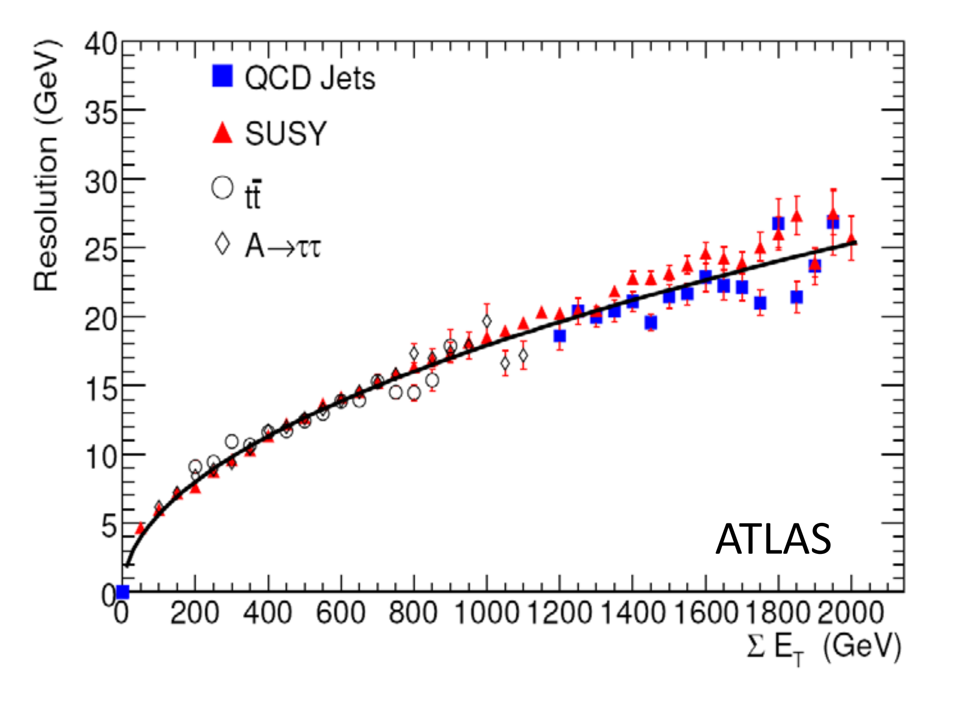
calorimeter jet
CH
FH
EM
hadrons
K
π
particle jet
Time
parton jet
q
g
p
p̄
q

ATLAS jet and E_T^{miss} performance

Jets



E_T miss



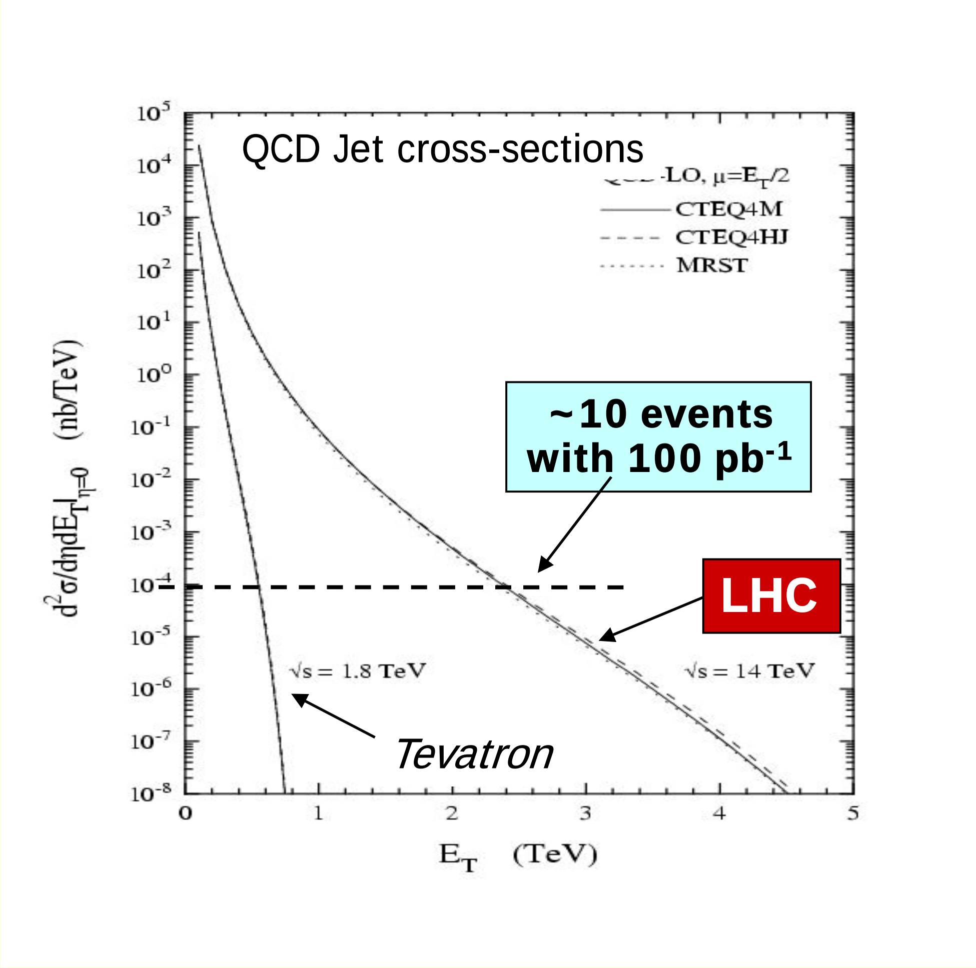
Jet resolution (σ_E / E_{jet}):
O(10-15%) or better at 100 GeV
O(5% or better) at 0.5 TeV.

E_T^{miss} resolution:

$$\sigma = 0.57 \Big/ \sqrt{\sum E_T}$$

Jets from QCD production

- Rapidly probe perturbative QCD in a new energy regime (at a scale above the Tevatron, large cross sections)
- New physics sensitivity at high E_T
  - compositeness
  - new resonances at high mass
- Experimental challenge: understanding of the detector
  - main focus on jet energy scale
  - resolution
- Theory challenge:
  - improved calculations…
  - pdf uncertainties



The jet energy scale

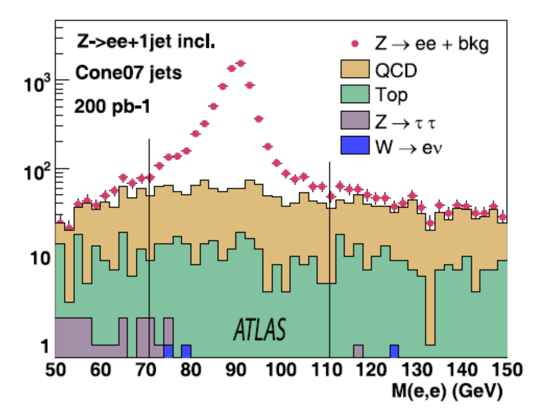
- A good jet-energy scale determination is essential for many QCD measurements
  (arguments similar to Tevatron, but kinematic range (jet p_T) is larger, ~20 GeV – ~3 TeV)

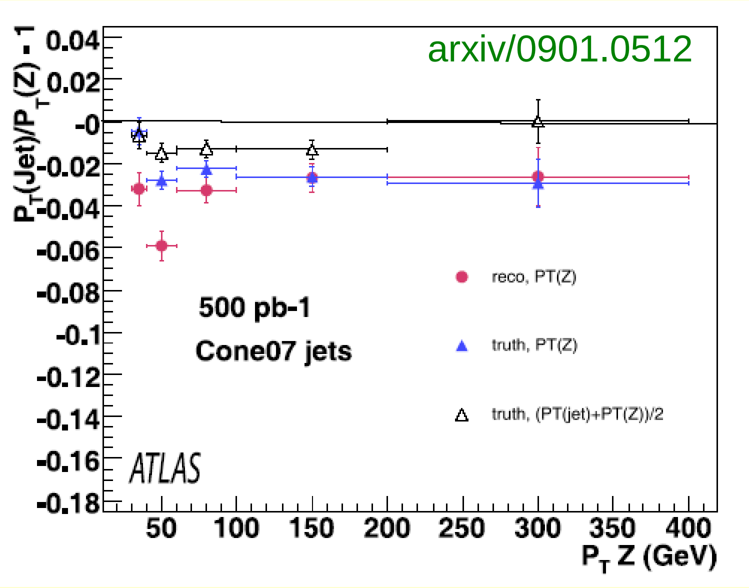
- Propagate knowledge of the em scale to the hadronic scale, but several processes are needed to cover the large p_T range

Measurement process	**Jet p_T range**
Z + jet balance	$20 < p_T < 100 – 200$ GeV
γ + jet balance	$50 < p_T < 500$ GeV (trigger, QCD background)
Multijet balance	500 GeV $< p_T$

Reasonable goal: 5-10% in first runs (1 fb^{-1})
1- 2% long term

Example: Z + jet balance





Stat. precision (500 pb^{-1}): 0.8%
Systematics: 5-10% at low p_T, 1% at high p_T

Sensitivity to New Physics: Contact interactions

- Uncertainties on the absolute jet energy scale result in large effects on the inclusive jet cross section

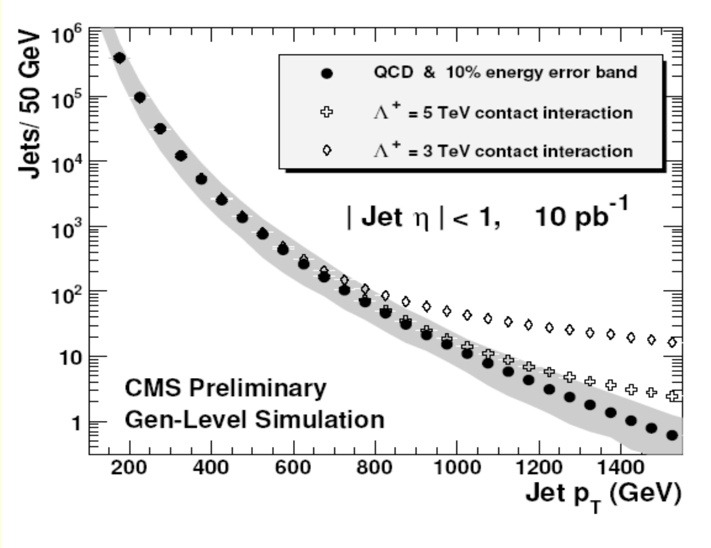
- However: large sensitivity

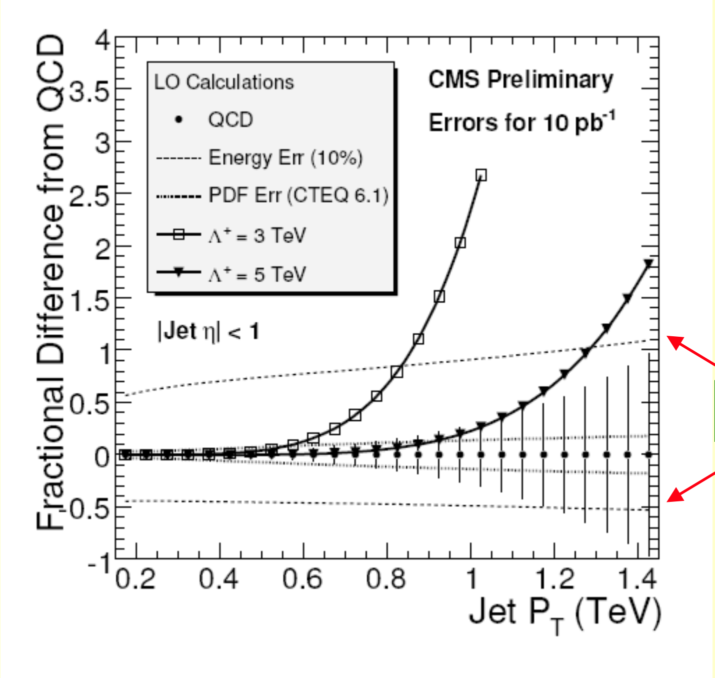
  Even with JES uncertainties expected with early data and an int. luminosity of only 10 pb^{-1} compositeness scales of ~ 3 TeV can be reached

  (close to the present Tevatron reach of Λ > 2.7 TeV)

- Improvements by using:
  - dijet angular distributions or
  - ratios of jet rates in different η regions

  $R = N(|\eta| < 0.5) \;/\; N(0.5<|\eta|<1)$

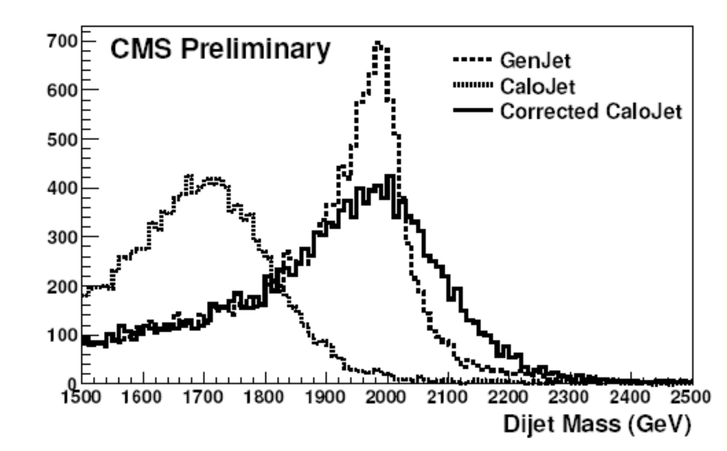


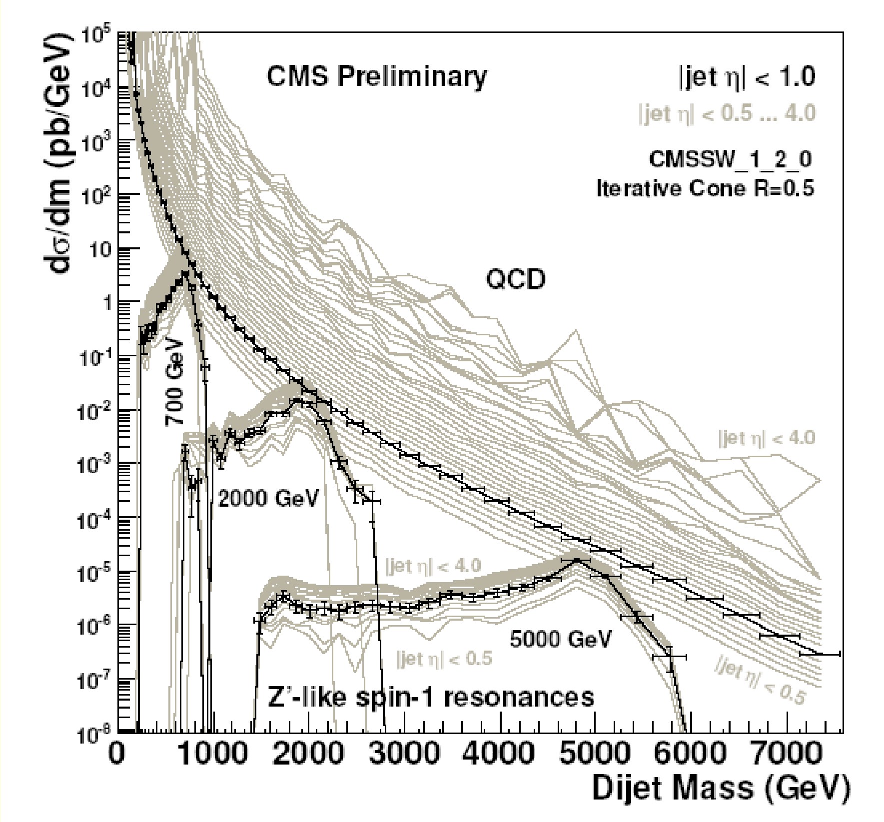


10% JES

Sensitivity to New Physics: Dijet Resonances

- The dijet mass spectrum is also sensitive to new physics
  examples: Excited quarks, Z' models
- Signal-to-background ratio is enhanced in the central region $|\eta| < 1$
- Background from sidebands
- critical exp. issue: dijet mass resolution and mass reconstruction (jet algorithm)



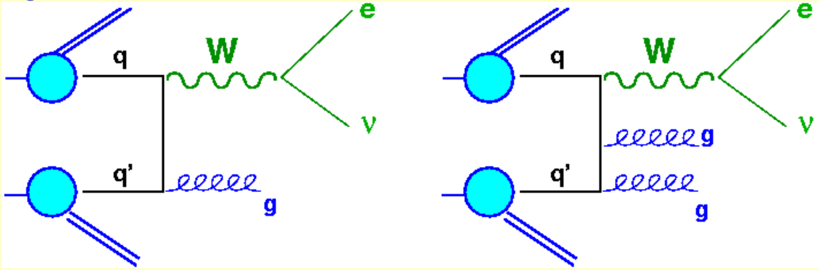


Discovery sensitivity around 2 TeV (Spin-1 Z´ like resonance) for ~200 pb^{-1}

Present Tevatron limits: 320 < m < 740 GeV

QCD aspects in W /Z (+ jet) production

QCD at work



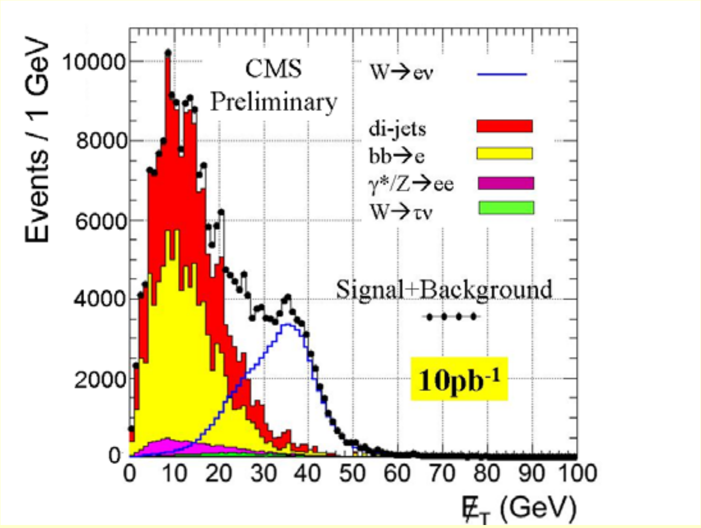
- Important test of NNLO Drell-Yan QCD prediction (what precision can be reached?)
- Test of perturbative QCD in high p_T region (jet multiplicities, p_T spectra,….)
- Tuning and „calibration" of Monte Carlos for background predictions in searches

W and Z cross sections

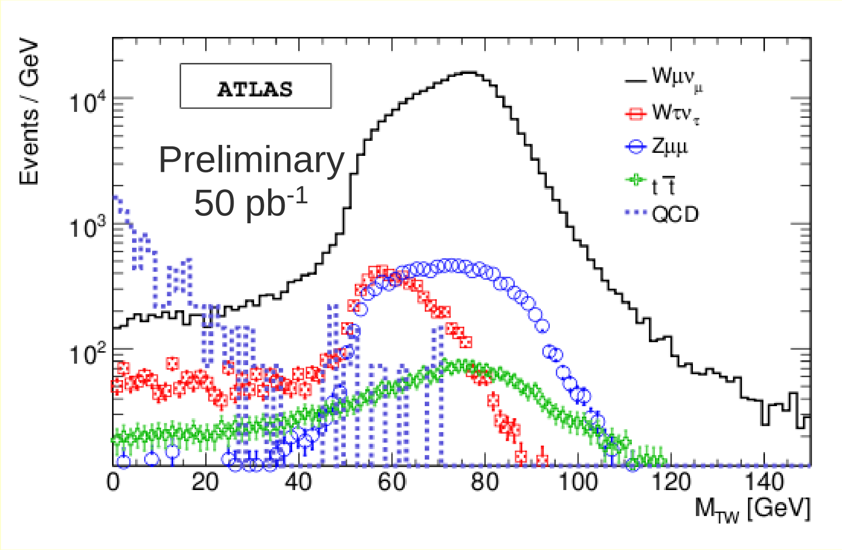
Even with early data (10-50 pb^{-1}), high statistics W and Z samples

→ data-driven cross section measurements

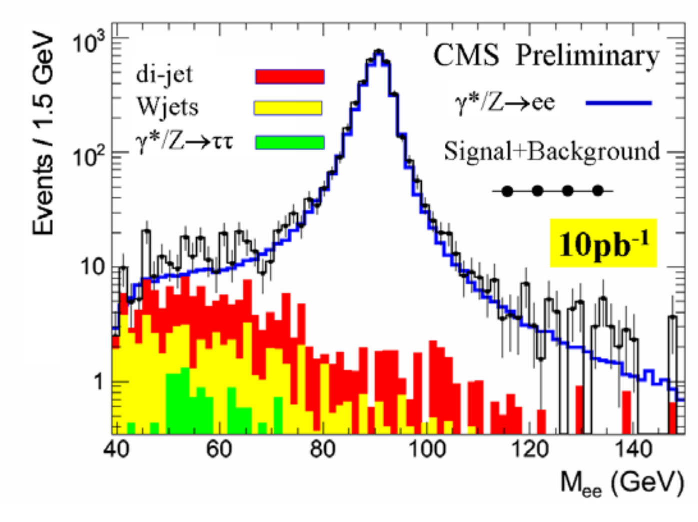
W → e ν



W → μ ν



Z → ee



W and Z Cross-Sections

Present estimated on the achievable precision for the total cross section:

$$\sigma = \frac{N-B}{\mathscr{L}\, A\, \varepsilon}$$

$$\frac{\delta\sigma}{\sigma} = \frac{\delta N \oplus \delta B}{N-B} \oplus \frac{\delta\mathscr{L}}{\mathscr{L}} \oplus \frac{\delta A}{A} \oplus \frac{\delta\varepsilon}{\varepsilon}$$

Estimates of event rates and experimental uncertainties for L = 50 pb^{-1}

Process	$N(\times 10^4)$	$B(\times 10^4)$	$A \times \varepsilon$	$\delta A/A$	$\delta\varepsilon/\varepsilon$
$W \to e\nu$	22.67 ± 0.04	0.61 ± 0.92	0.215	0.023	0.02
$W \to \mu\nu$	30.04 ± 0.05	2.01 ± 0.12	0.273	0.023	0.02
$Z \to ee$	2.71 ± 0.02	0.23 ± 0.04	0.246	0.023	0.03
$Z \to \mu\mu$	2.57 ± 0.02	0.010 ± 0.002	0.254	0.023	0.03

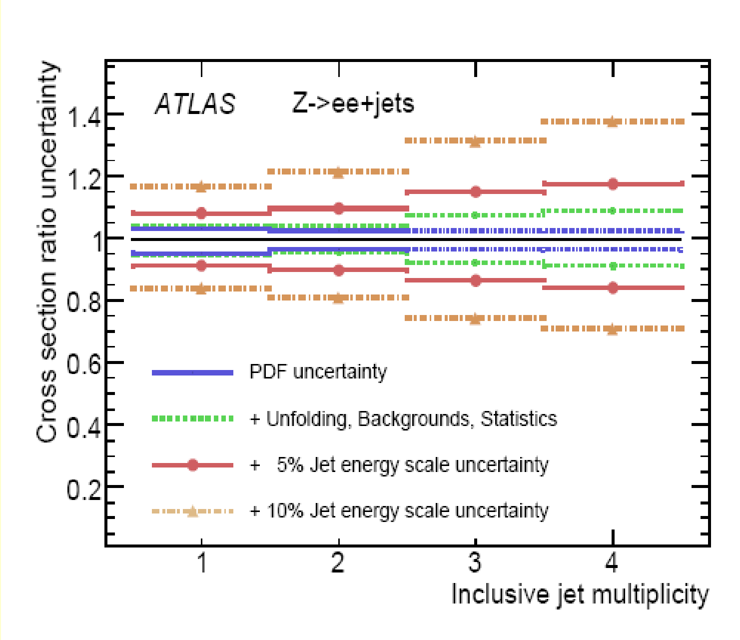
Limited by luminosity error: ~ 5-10% in first year,
Longer term goal ~ 2%

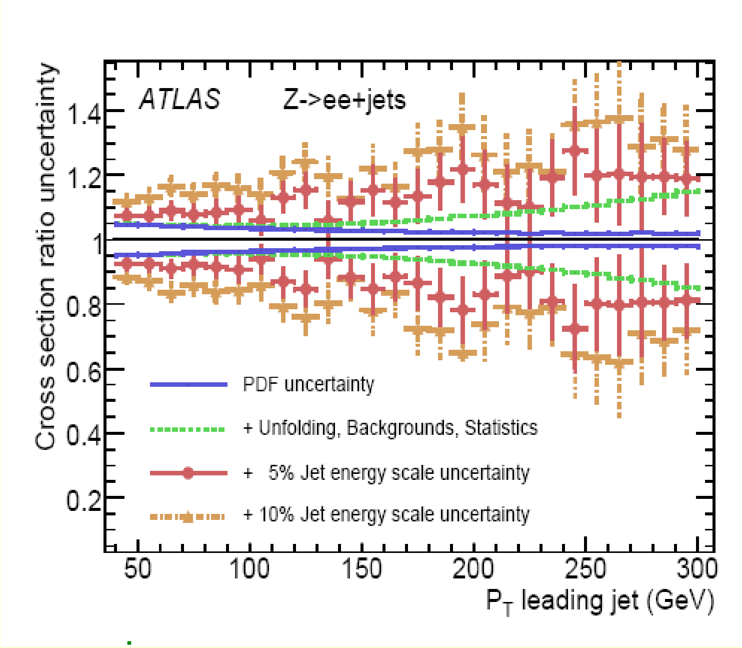
(process might be used later for luminosity measurement)

W/Z + jet cross sections

- Important goal: test of perturbative QCD (higher jet multiplicities, larger p_T)
  Unfolding to particle level (allows for an easier comparison to theory)
  (larger statistics, extend the p_T range and jet multiplicities)

- What precision on cross sections can be reached with 1 fb^{-1} ?



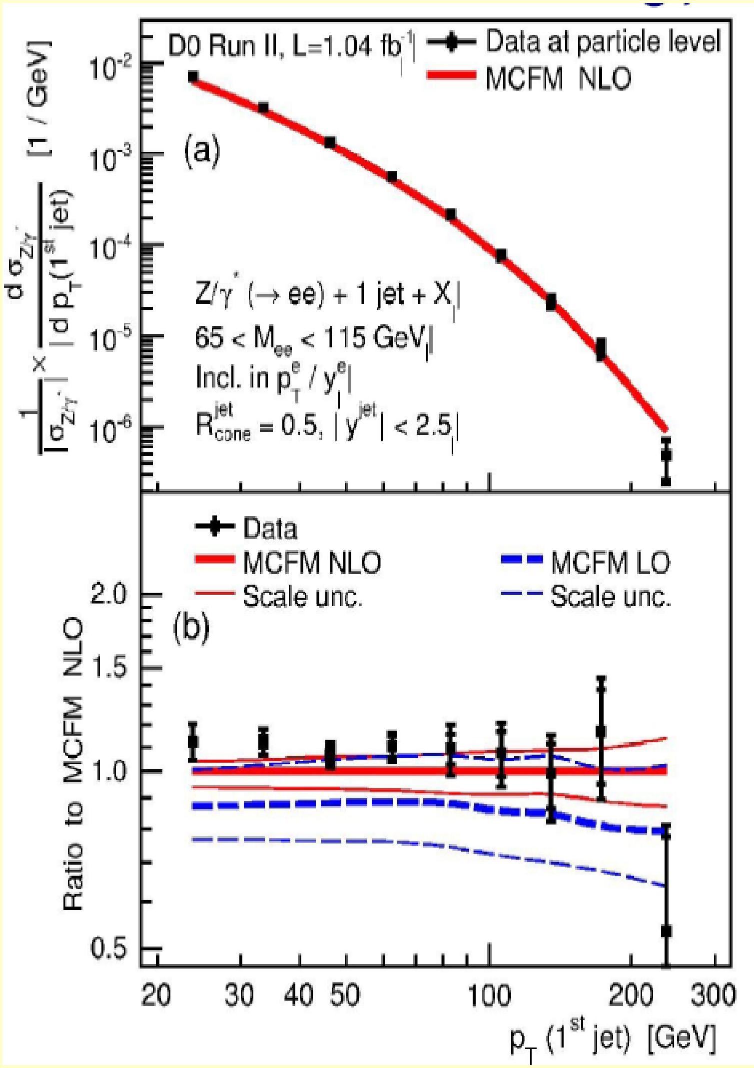


Relative uncertainty on the data – theory comparison

- Again: jet energy scale uncertainty is important;
  Additional uncertainties: backgrounds, unfolding to particle level,….
  Comparison is limited by systematic uncertainties

comparison to the Tevatron

see talk by G. Hasketh

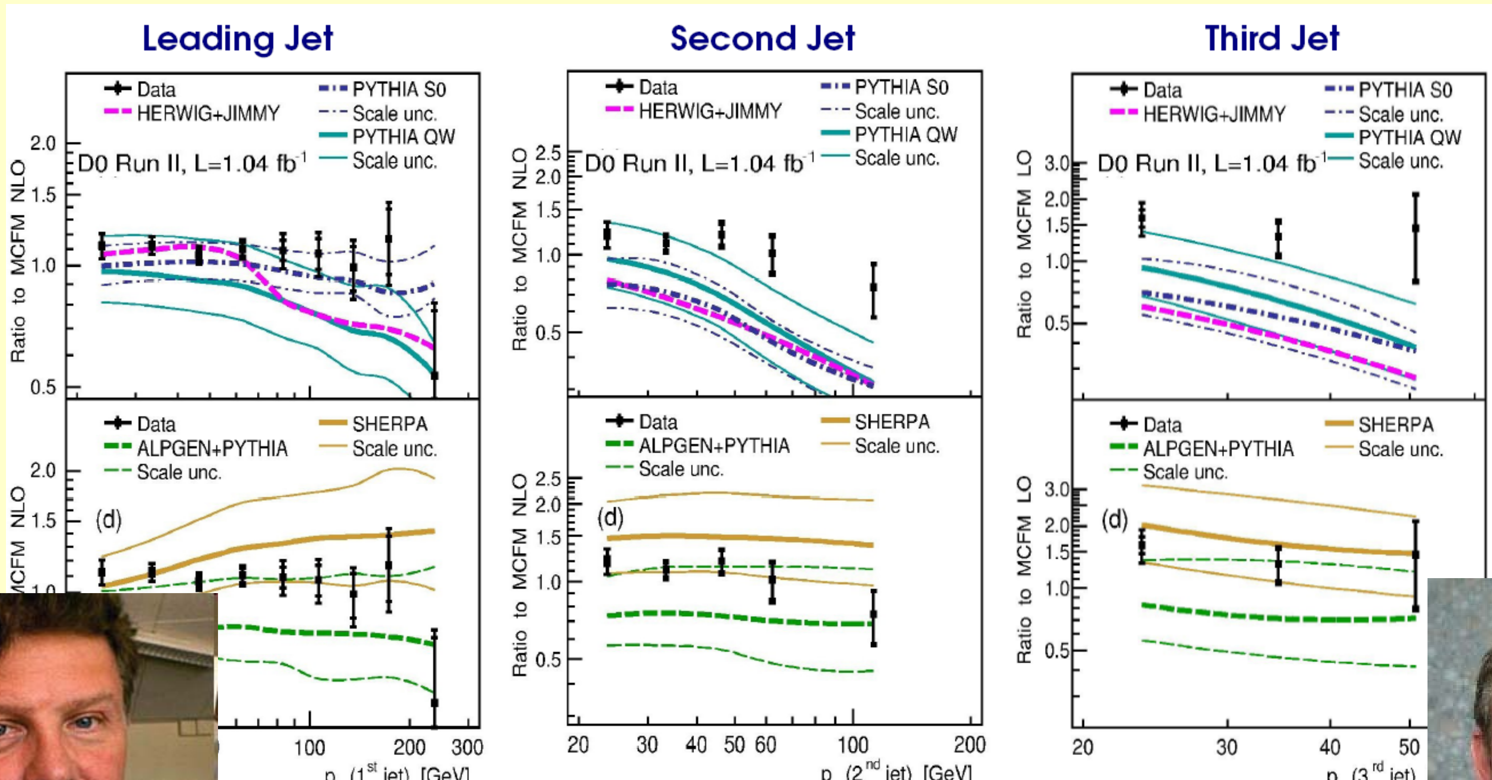


similar situation at the Tevatron:
- comparison is limited by systematics below ~ 100 GeV
- exp. errors at comparable level as theory errors

comparison to Monte Carlos

- Can we tune our Monte Carlos by using these processes ?
  Yes, we can !

- But: Large uncertainties (→ Tevatron results, see talk by G. Hesketh)
  Tree level calculations, NLO parton shower matched calculations would be desirable…

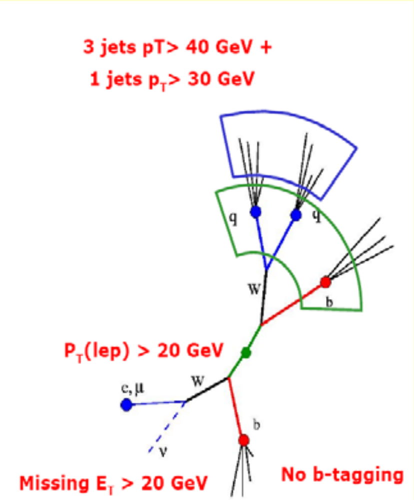


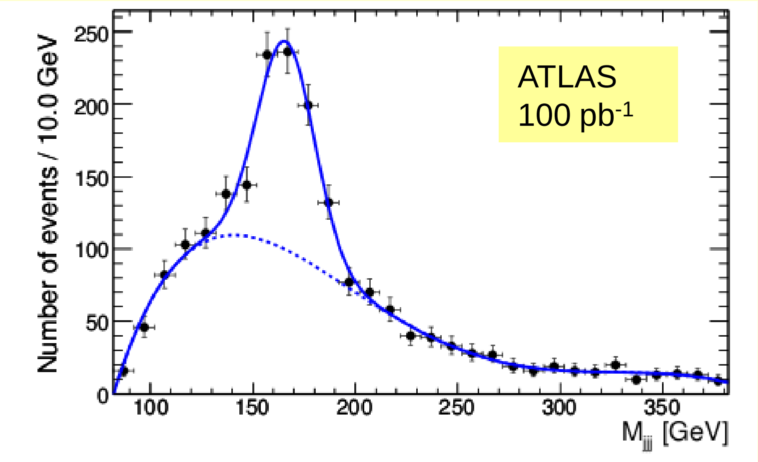
….they might have to try harder

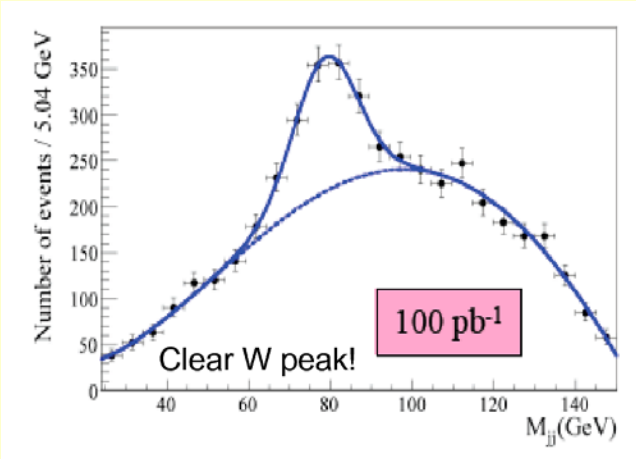
Top cross section in early data

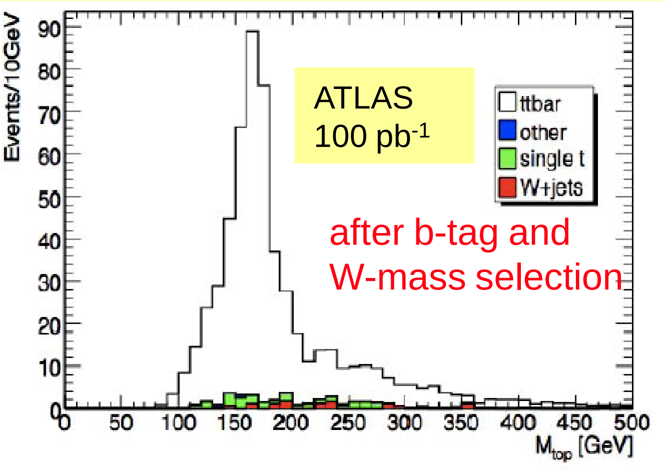
Large cross section: ~ 830 pb at $\sqrt{s}$ = 14 TeV

Reconstructed mass distribution after a simple selection of **tt → Wb Wb → ℓνb qqb** decays:





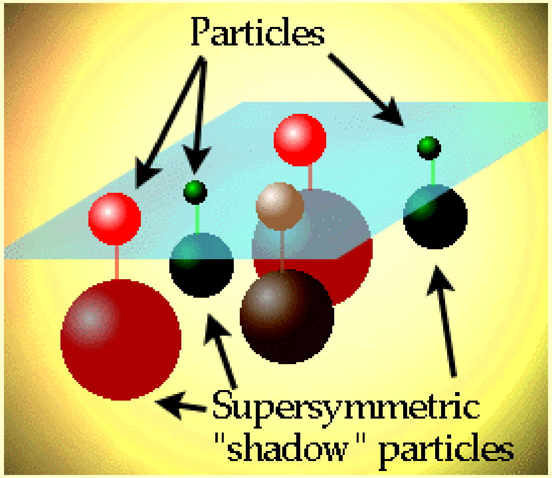




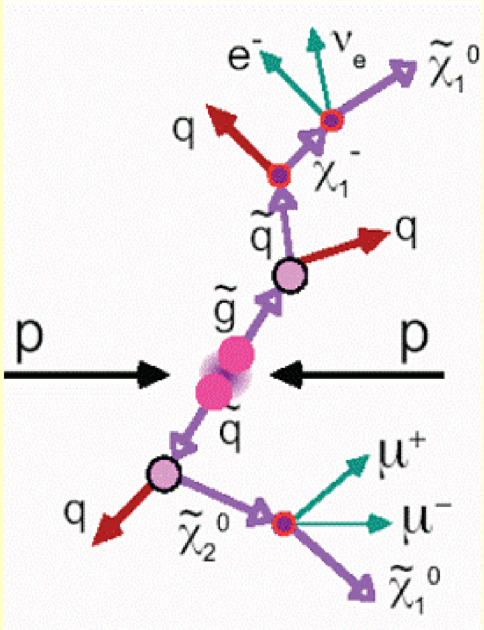
- Cross section measurement (test of perturbative QCD) with data corresponding to 100 pb^{-1} possible with an accuracy of ±10-15%
- Errors are dominated by systematics
(jet energy scale, Monte Carlo modelling (ISR, FSR),…)
- Ultimate reach (100 fb^{-1}): ± 3-5%
(limited by uncertainty on the luminosity)

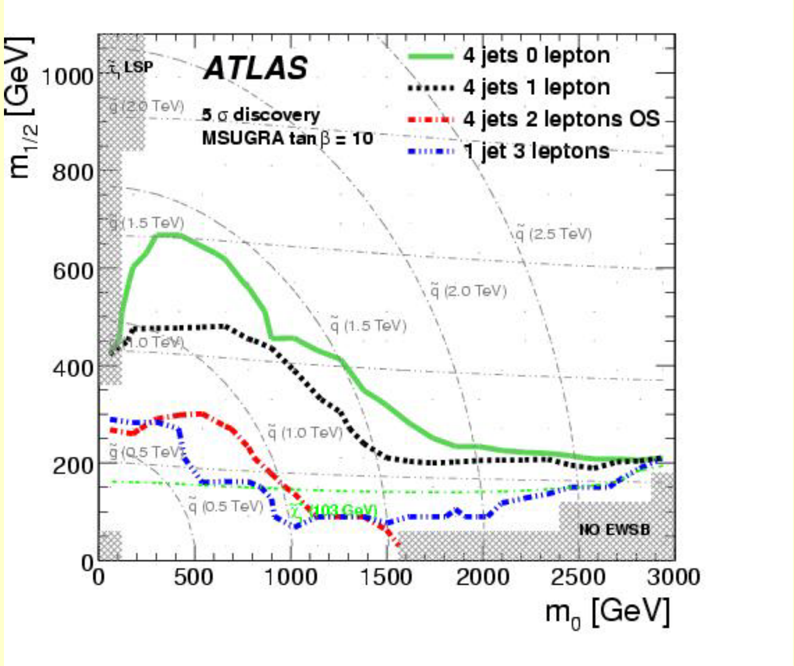
Relevance for

Searches for New Physics



A typical inclusive SUSY search at the LHC:

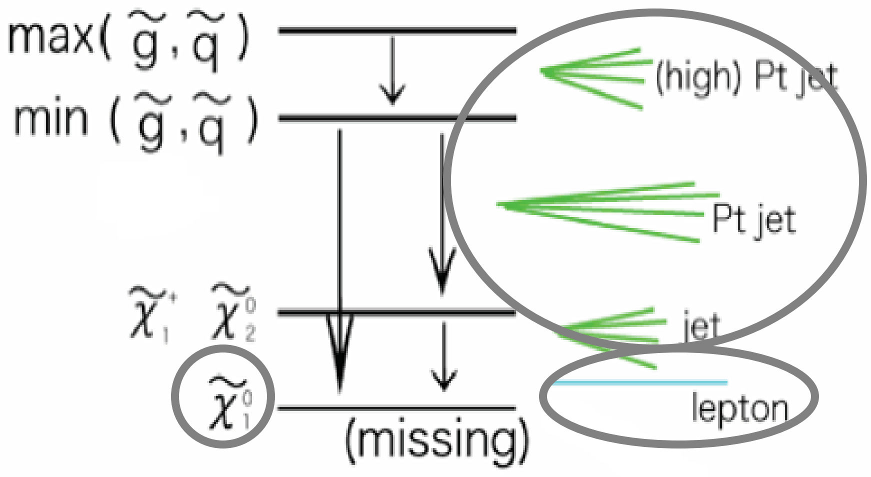




Require: - E_T^{miss}
- High p_T jets
- 0,1,2 leptons
- ….

Main SM backgrounds:
- **tt**
- **W/Z + jets**
- QCD jet production
  (special case, need to be taken from data, instrumental effects likely to contribute to background after final cuts)

SUSY: one lepton mode



Dominant backgrounds:

sample	*x-sec (pb)*
top pair	833
W+jets	10 -10.000
QCD	10.000 -1.000.000.000
Z+jets	10 -1000
SUSY	5 -300

SUSY event selection:

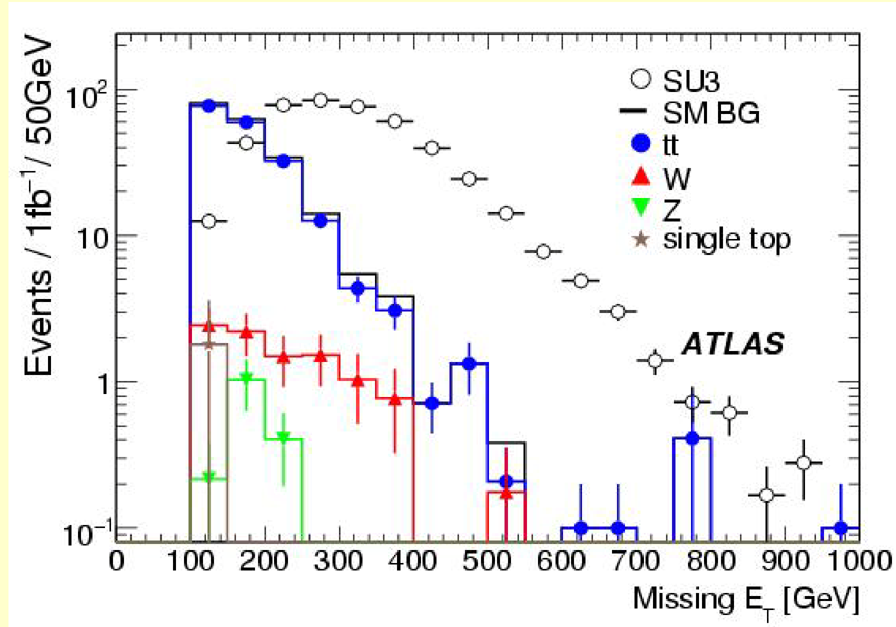
$$1\,jet\ p_T > 100\,GeV$$

$$4\,jets\ p_T > 50\,GeV$$

$$lepton\ \ p_T > 20\,GeV$$

$$2nd\ \ lepton\,veto$$

$$\not{E}_T > 100\,GeV$$



Problem:

- Composition of SM background and shape of background must be known after final selection cuts (i.e. in SUSY phase space region)
- Sometimes data driven methods can be used,
  however: guidance from more reliable Monte Carlos would be important
- In addition: largest background to SUSY is often SUSY

Example of a data-driven background estimate:

- **Control region** = dominated by SM + small contamination SUSY
- **Signal region** = dominated by SUSY + small SM background

Observables:

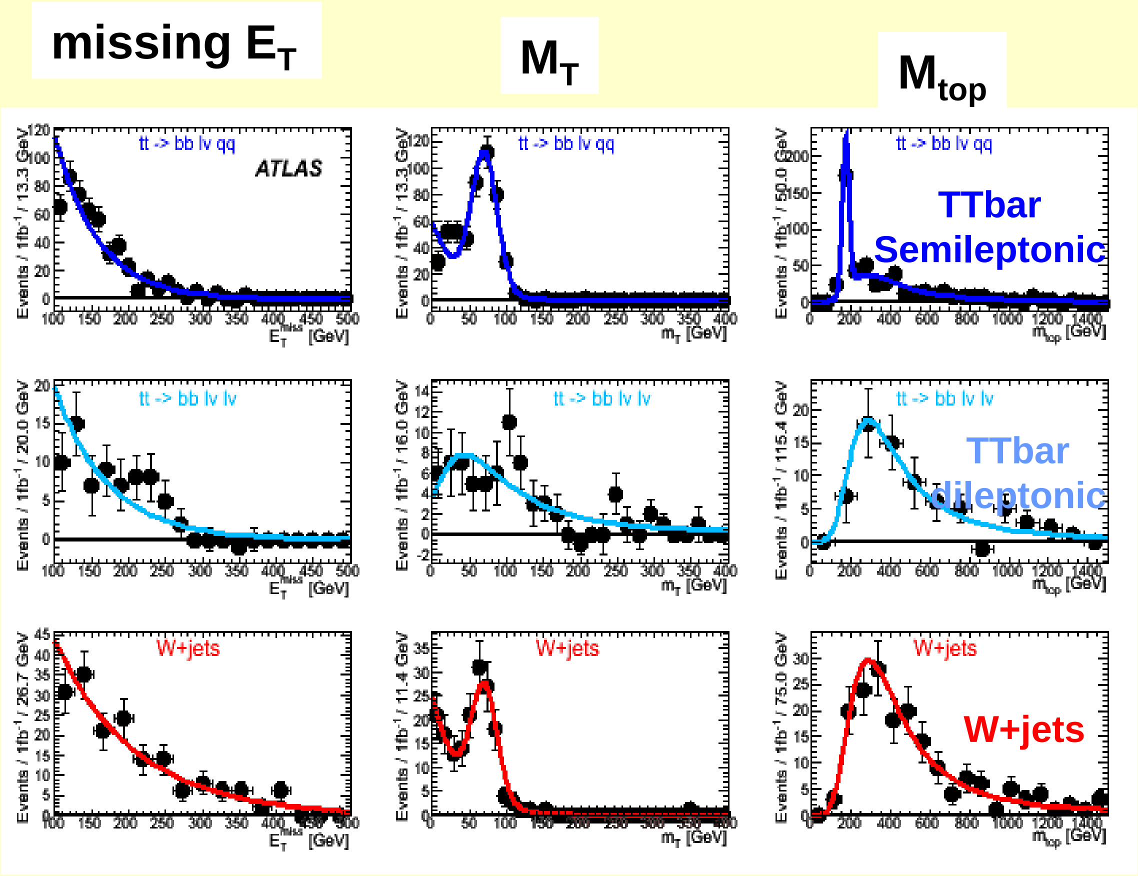
– Missing E_T

– M_T = transverse mass (E_T^{miss} + lepton)
  (get handle on W+jet background)

– M_{top} = invariant mass of 3 jet system with highest sum p_T
  (pin down tt background)

Combined fit method

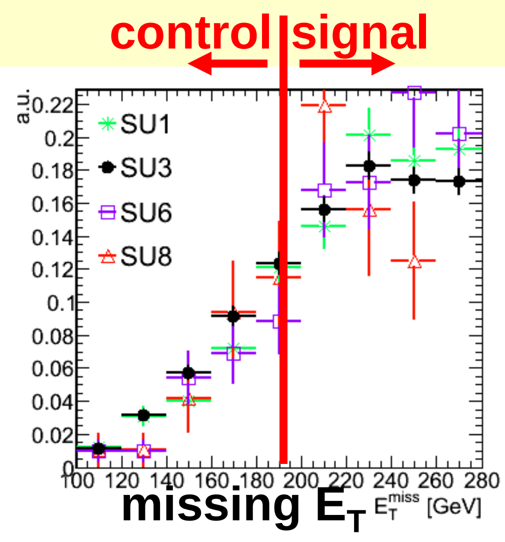
- Construct a 3D model for each background
- Build combined model by simple addition
- Separate three distinct components of background by fitting combined model to data

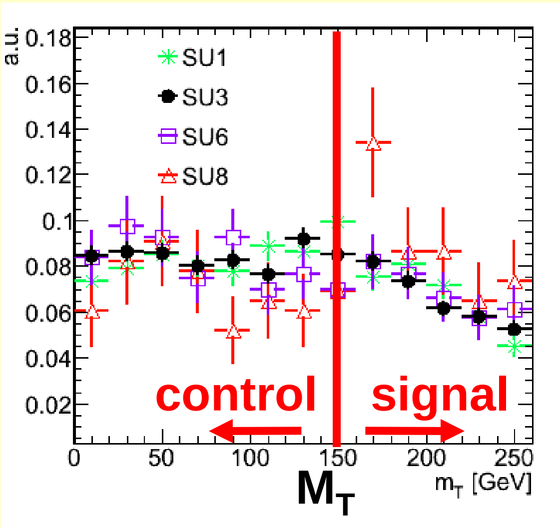


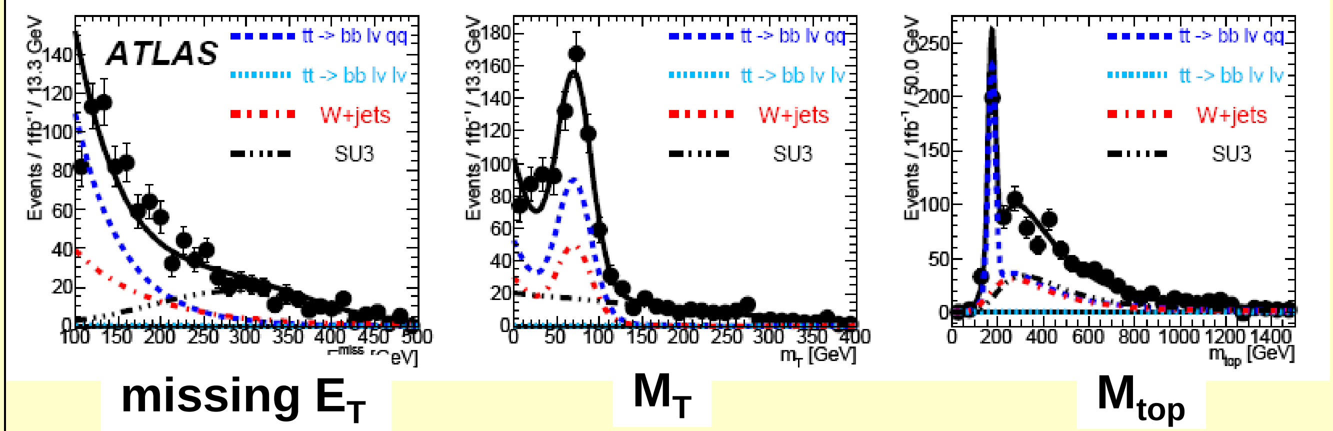
Models (MC inspired) taking physics features into account:
- Top mass peak
- Jacobian W-peak in M_T
- Dileptonic tt different from semileptonic

Combined fit to signal and background shapes

- Need shapes or parametrised shapes for backgrounds
- Need assumptions on SUSY contributions (model dependent)





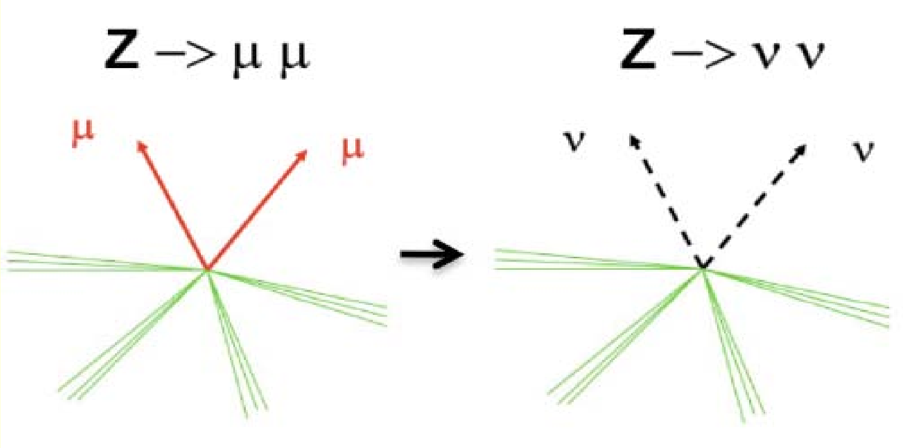


Although data-driven background estimates can be made,

reliable Monte Carlo predictions would help to better constrain and determine the SM physics contributions

…. easier for other backgrounds, e.g. Z+jets

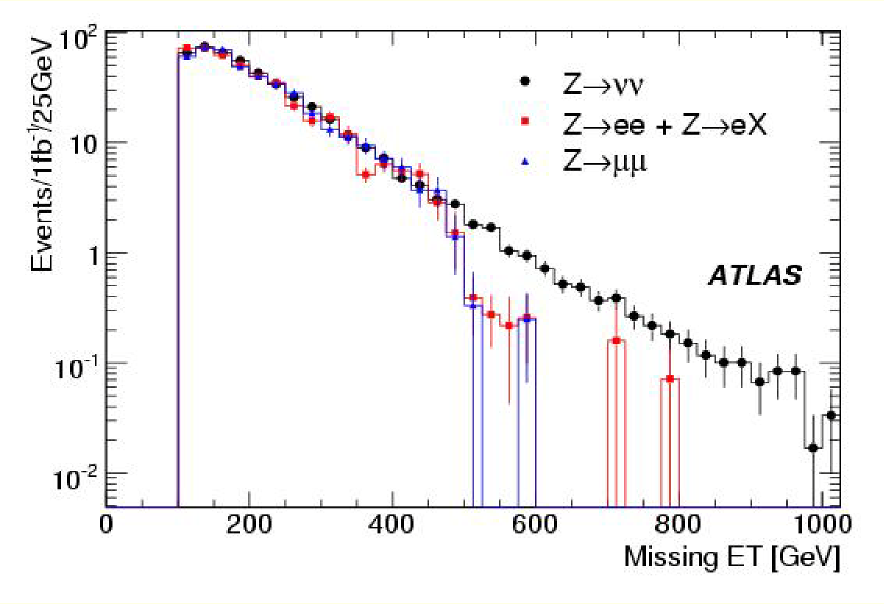
- Z→*νν* and associated jet background
- Use Z→*ll+jets* as control sample with standard selection and:
  - "replace muons by neutrinos"
  - 81 < M (*ll*) <101 GeV
  - missing E_T<30 GeV



$$N_{Z\to\nu\nu}(MET) = N_{Z\to\ell^+\ell^-}(p_T(\ell^+\ell^-)) \times c_{Kin}(p_T(Z)) \times c_{Fidu}(p_T(Z)) \times \frac{Br(Z\to\nu\nu)}{Br(Z\to\ell^+\ell^-)}$$

- Corrections:
  - Kinematic: additional cuts used
  - Fiducial: good lepton detection only for $|\eta| < 2.5$
  - Lepton identification efficiency using tag-and-probe method

- reliable Monte Carlos useful to determine corrections



Conclusions

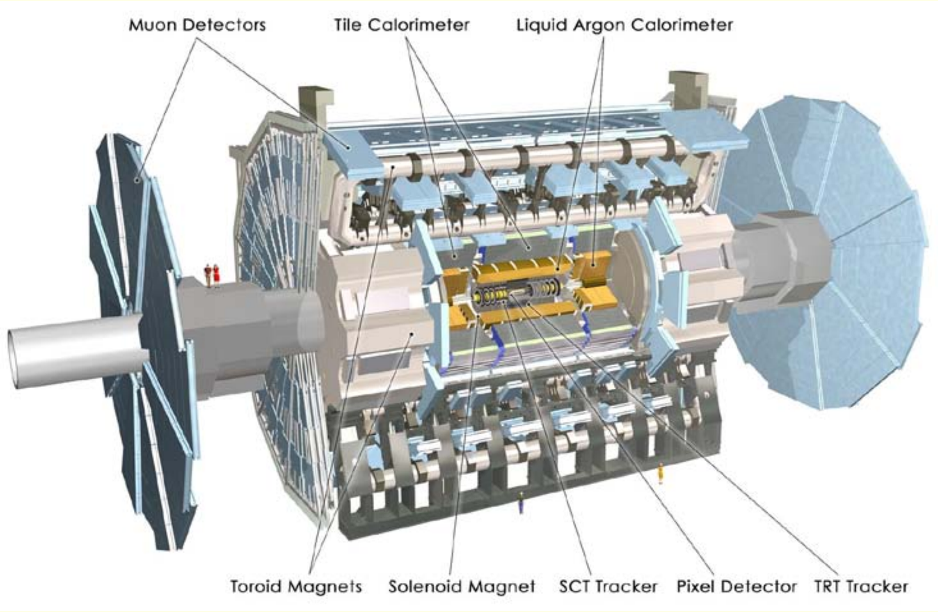
- The LHC experiments are well set up to explore the new energy domain …... and are well prepared for unexpected scenarios

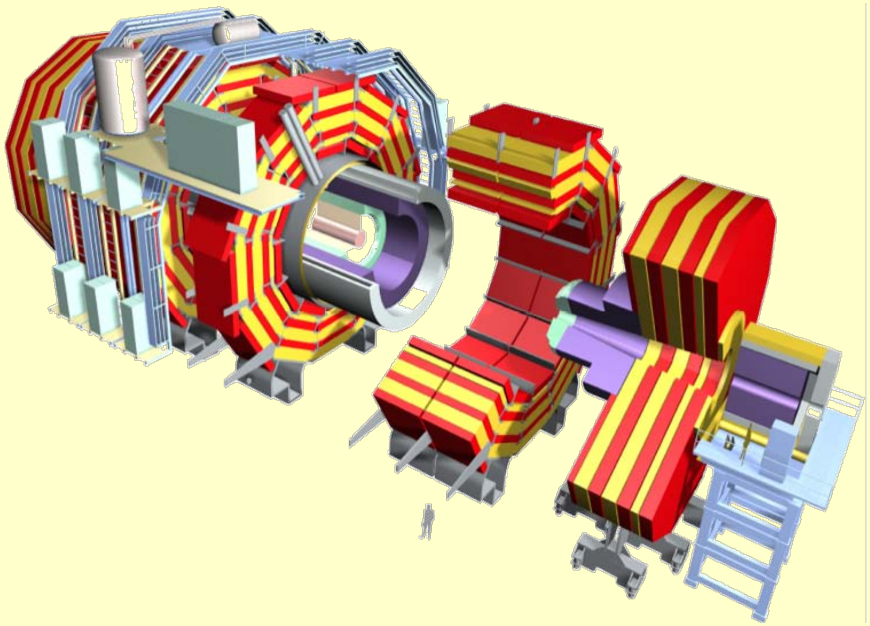
- QCD processes play a key role:
  - in establishing the detector performance (jets, E_T^{miss},…)
  - in tuning Monte Carlo simulations (min. bias, underlying event,…)
  - in tests of the Standard Model (perturbative calculations)
    ↔ searches for deviations and surprises

- QCD processes have to be well understood to obtain more precise background calculations in searches for new physics;
  Although data-driven background estimates can be made, guidance from theory is needed….

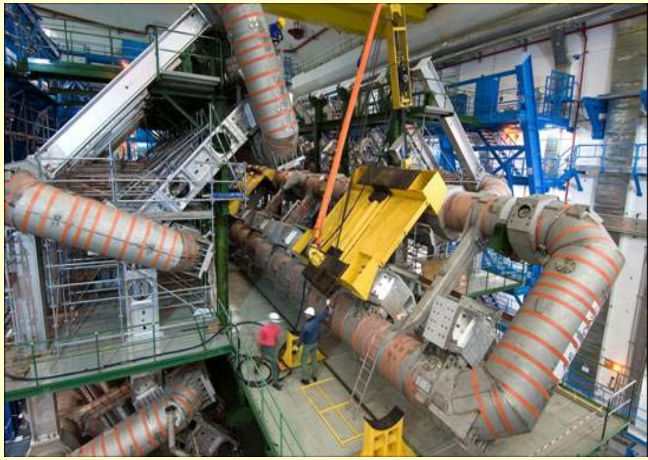
- ATLAS and CMS collaborations are looking forward to exciting years to come

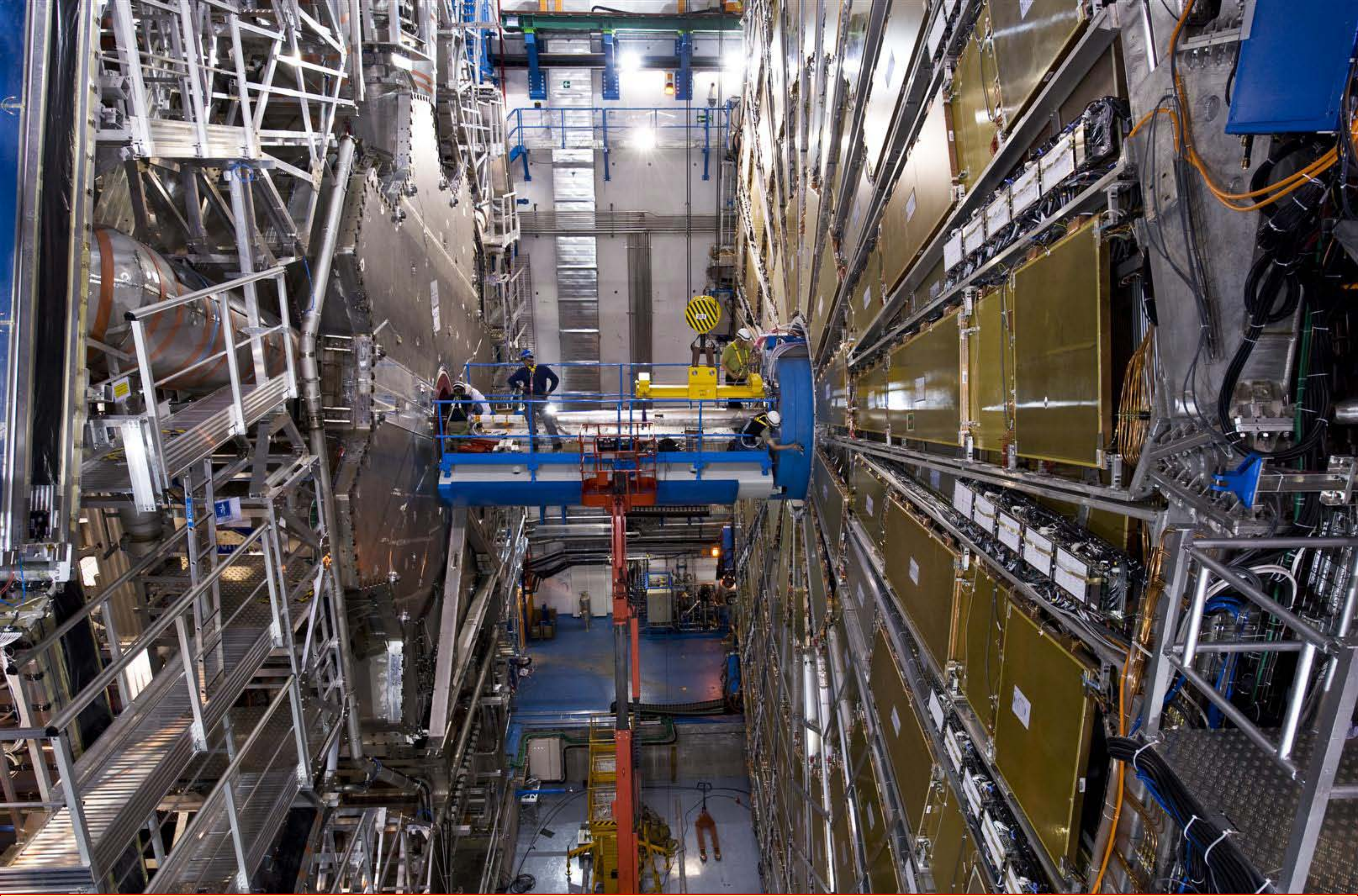
The ATLAS and CMS experiments





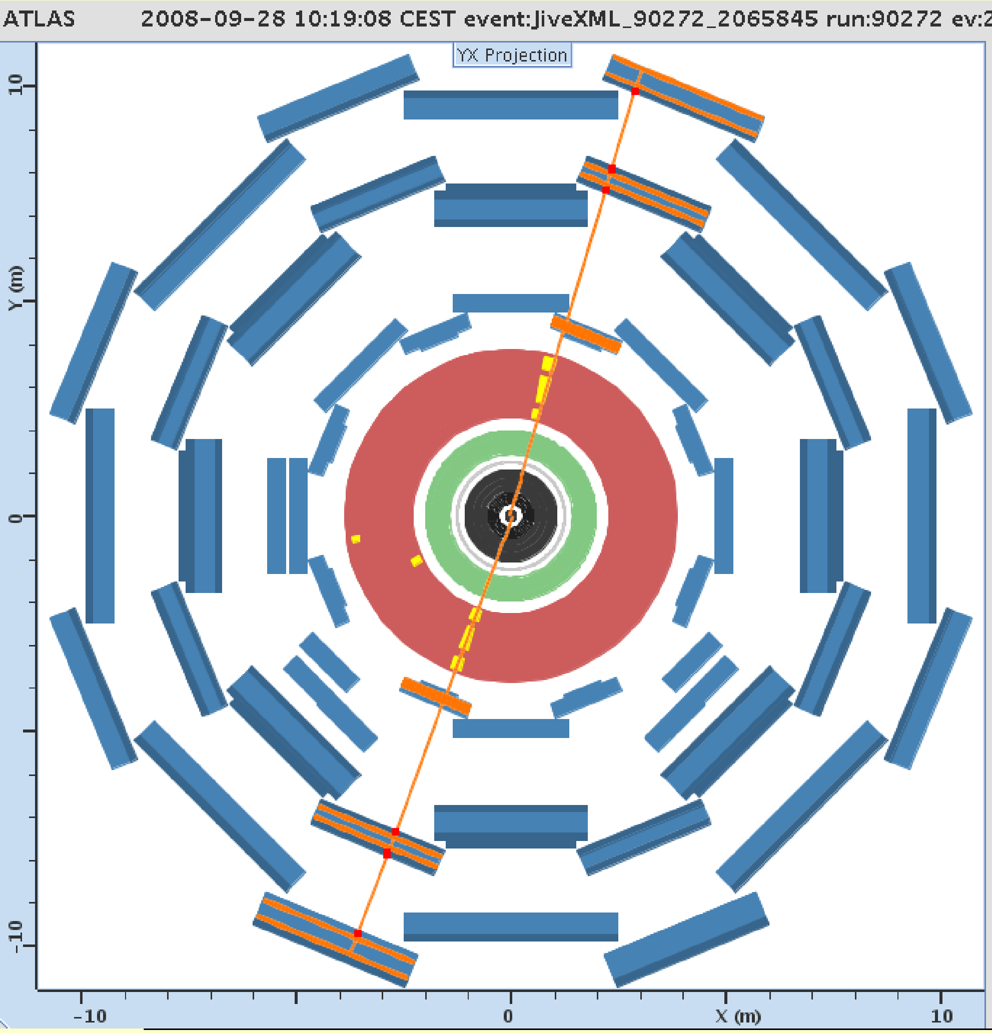
ATLAS Installation

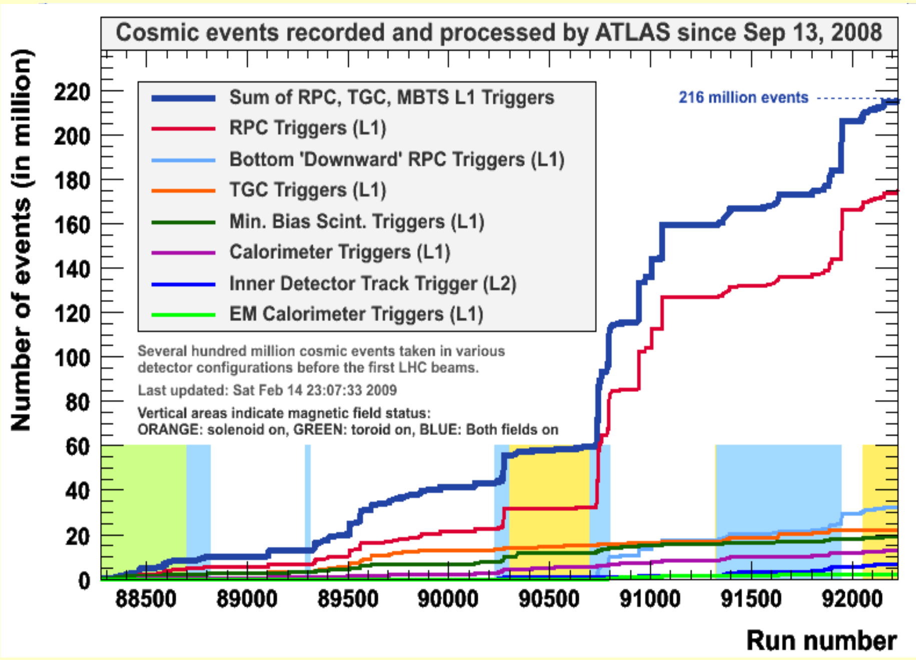




A historical moment:
Closure of the LHC beam pipe ring on 16th June 2008
ATLAS was ready for data taking in August 2008

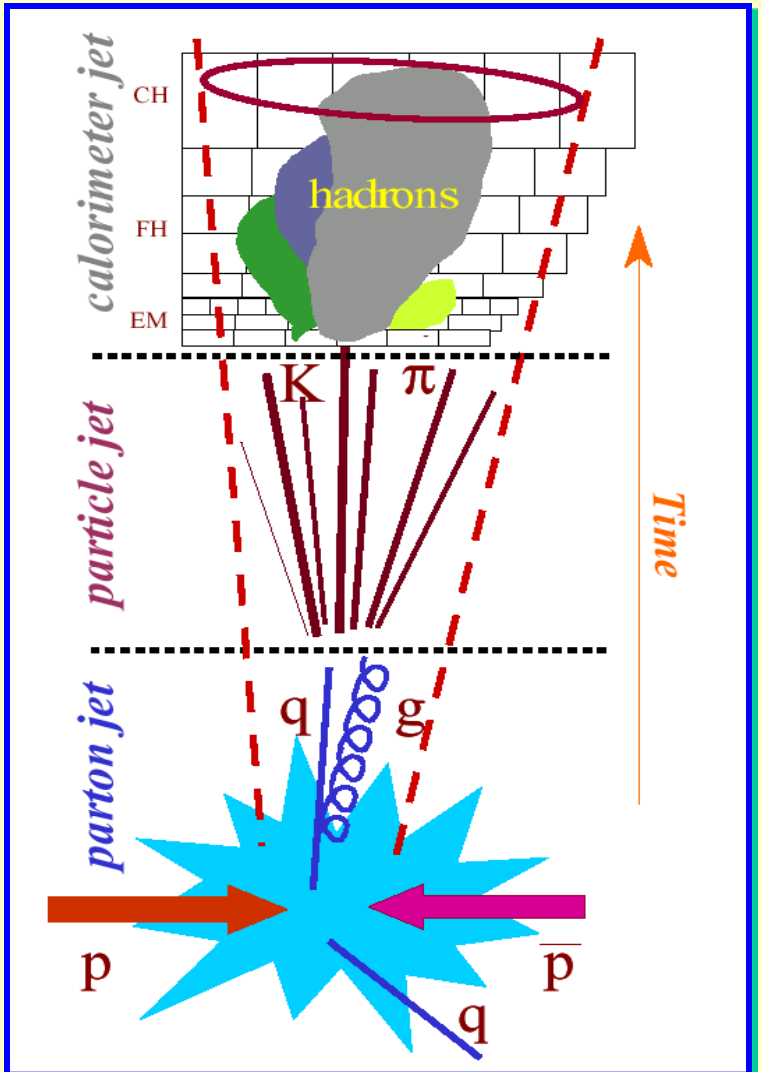
... since LHC accident:
ATLAS commissioning with cosmic rays.....

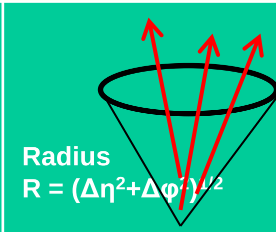
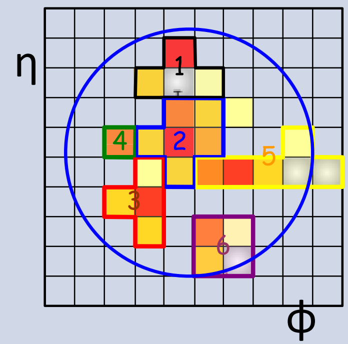




ATLAS was ready for collisions in 2008,
…. we will be in better shape in 2009.

Reminder: Jets



Cone jets		**Maximizes energy inside a cone of (η,φ)** **(R=0.4 or 0.7)**
Cluster		Clusters nearest neighbors (3D clustering in ATLAS)

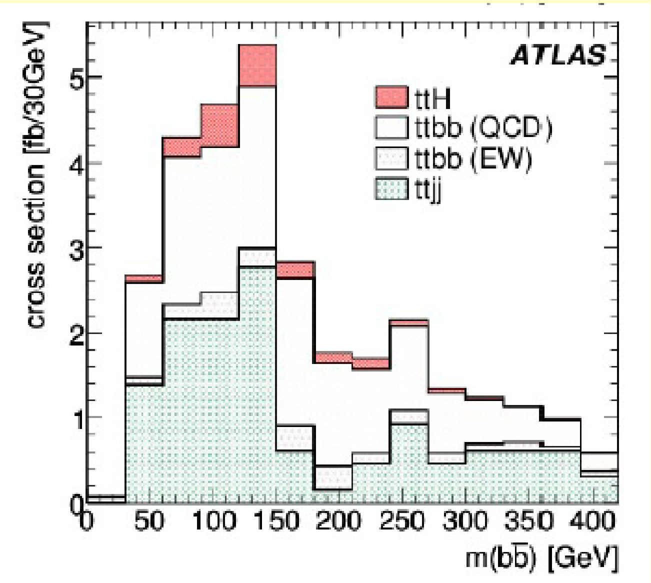
Both cone-jets and cluster-jets used in ATLAS (other algorithms also studied).

$t\bar{t}H \rightarrow t\bar{t}b\bar{b}$

- Complex final states: $H \rightarrow bb$, $t \rightarrow bjj$, $t \rightarrow b\ell\nu$
  $t \rightarrow b\ell\nu$, $t \rightarrow b\ell\nu$
  $t \rightarrow bjj$, $t \rightarrow bjj$

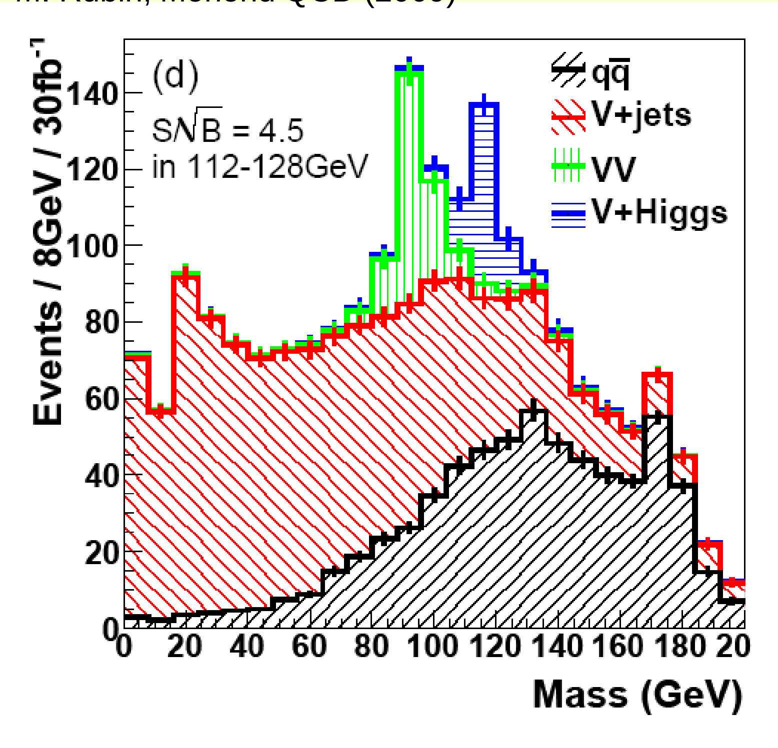
New Idea:
Use highly boosted H-decays in WH / ZH associated production
(J. Butterworth et al.)

- Updated ATLAS and CMS studies:
  matrix element calculations for backgrounds
  → larger backgrounds (ttjj and ttbb)



M (bb) after final cuts, 30 fb^{-1}

M. Rubin, Moriond QCD (2009)



estimated uncertainty on the background reduce drastically the discovery significance

Looks promising, experimental studies with detailed detector simulation are needed for confirmation