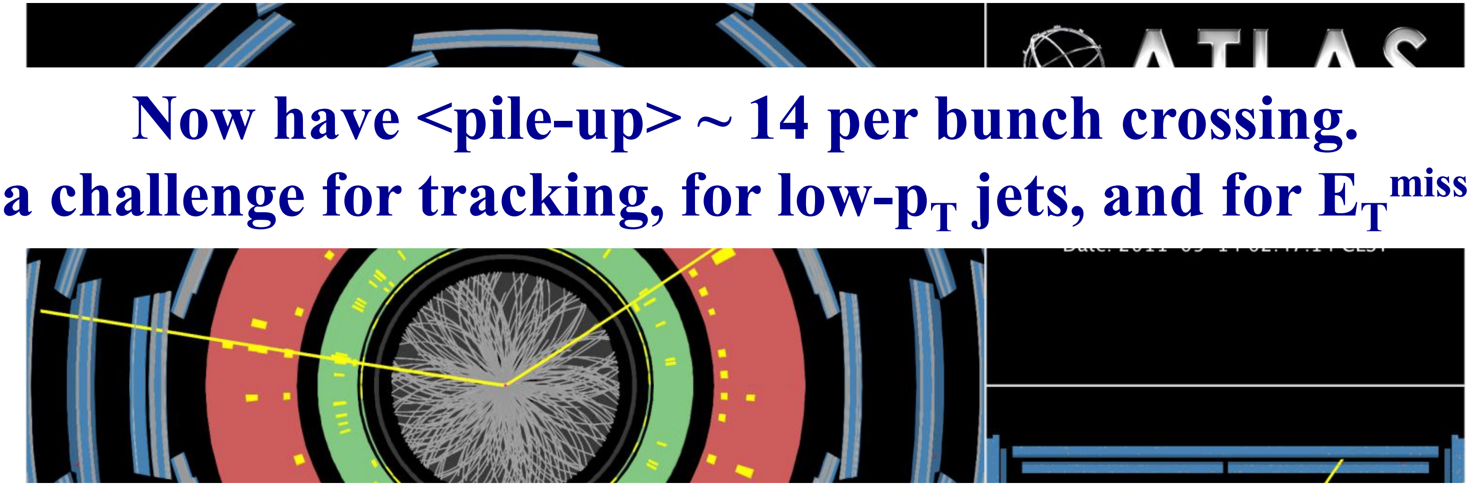
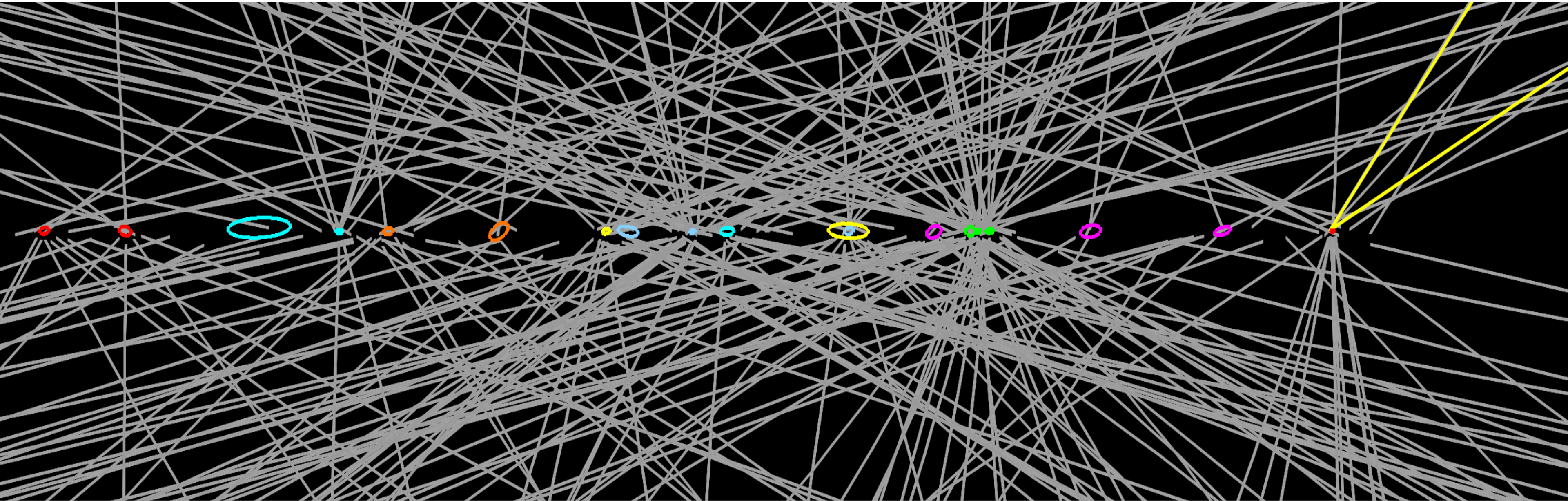
# Outlook on physics at the LHC as viewed by an experimentalist



**Now have <pile-up> ~ 14 per bunch crossing.**
**a challenge for tracking, for low-$p_T$ jets, and for $E_T^{miss}$!**

**Example of Z → μμ decay with 20 reconstructed vertices**
**Total scale along z is ~ ± 15 cm, $p_T$ threshold for track reco is 0.4 GeV**
**(ellipses have size of 20σ for visibility)**



# Experimental particle physics: 1976 to 2010

✦ Today we are able to ask questions we were not able to formulate 25-30 years ago when I was a student:

- ✓ What is dark matter? How is it distributed in universe?
- ✓ What is the nature of dark energy?
- ✓ Is our understanding of general relativity correct at all scales?
- ✓ Will quantum mechanics fail at very short distances, in conscious systems, elsewhere?
- ✓ Origin of CP violation, of baryons, what about the proton lifetime?
- ✓ Role of string theory? Duality?

✦ Some of these questions might well lead me towards astrophysics or astro-particle physics today if I would become a young student again!

✦ The more we progress, the longer will be the gap in time between the reformulation of fundamental questions in our understanding of the universe and its complexity? This gap is already ~ equal to the useful professional lifetime of a human being? This poses real problems.

# Endless loop of experimental physicist: measure, simulate, talk to theorists …

**Observations** (measurements: build detectors)

- An apple falls from a tree
- There are four forces + matter particles

**Models** (simulations)

- $F = GmM/R^2$
- Standard Model

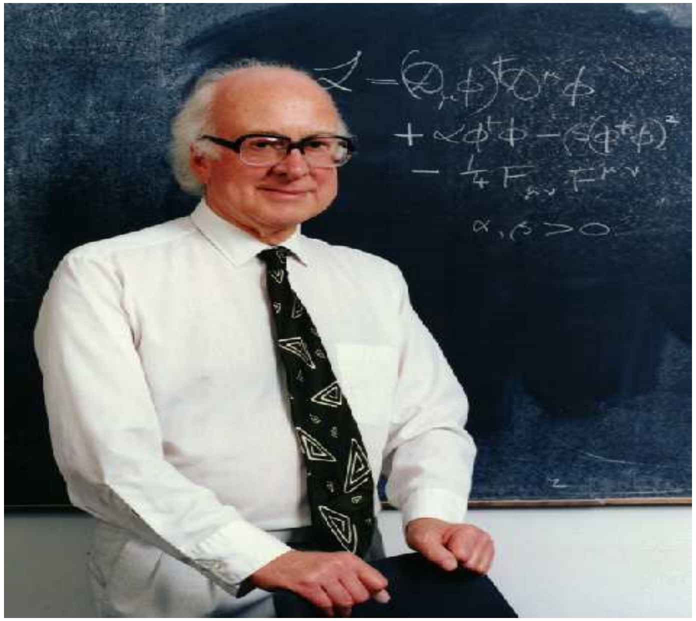
**Predictions** (theories, ideas)

- Position of planets in the sky
- Higgs boson, supersymmetric particles

# What about the Higgs boson?

Higgs boson has been with us for many decades as:

1. a theoretical concept,
2. a scalar field linked to the vacuum,
3. the dark corner
   of the Standard Model,
4. an incarnation of the Communist Party, since it controls the masses (L. Alvarez-Gaumé in lectures for CERN summer school in Alushta),
5. a painful part of the first chapter
   of our Ph. D. thesis

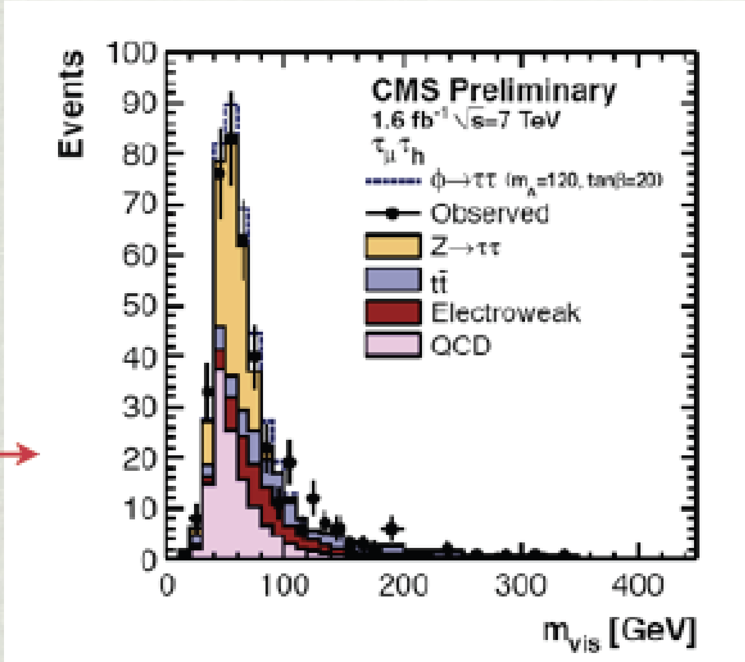


P.W. Higgs, Phys. Lett. 12 (1964) 132

# e wiggly limit curves!

).

an the potential signal in the distributions
cannot be analysed optimally with only ~ 5 fb$^{-1}$.



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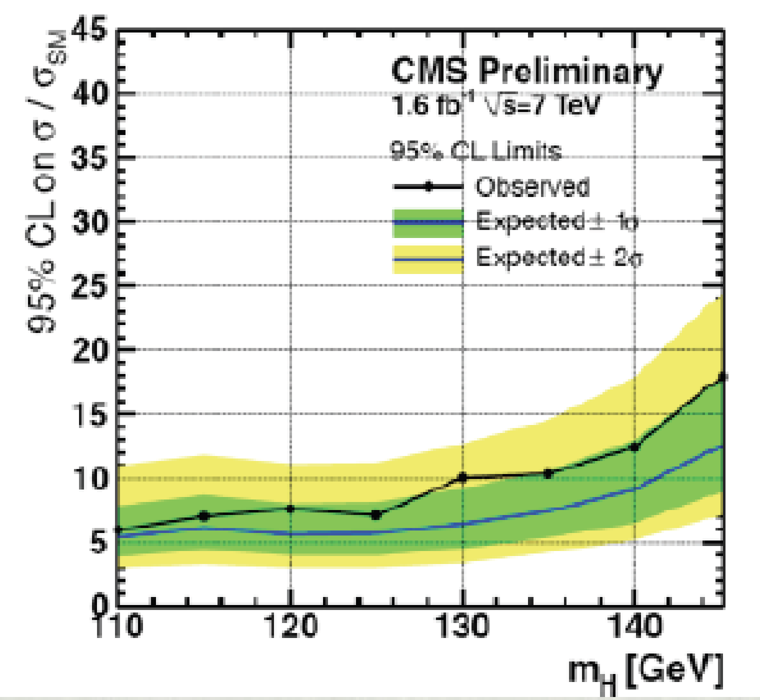
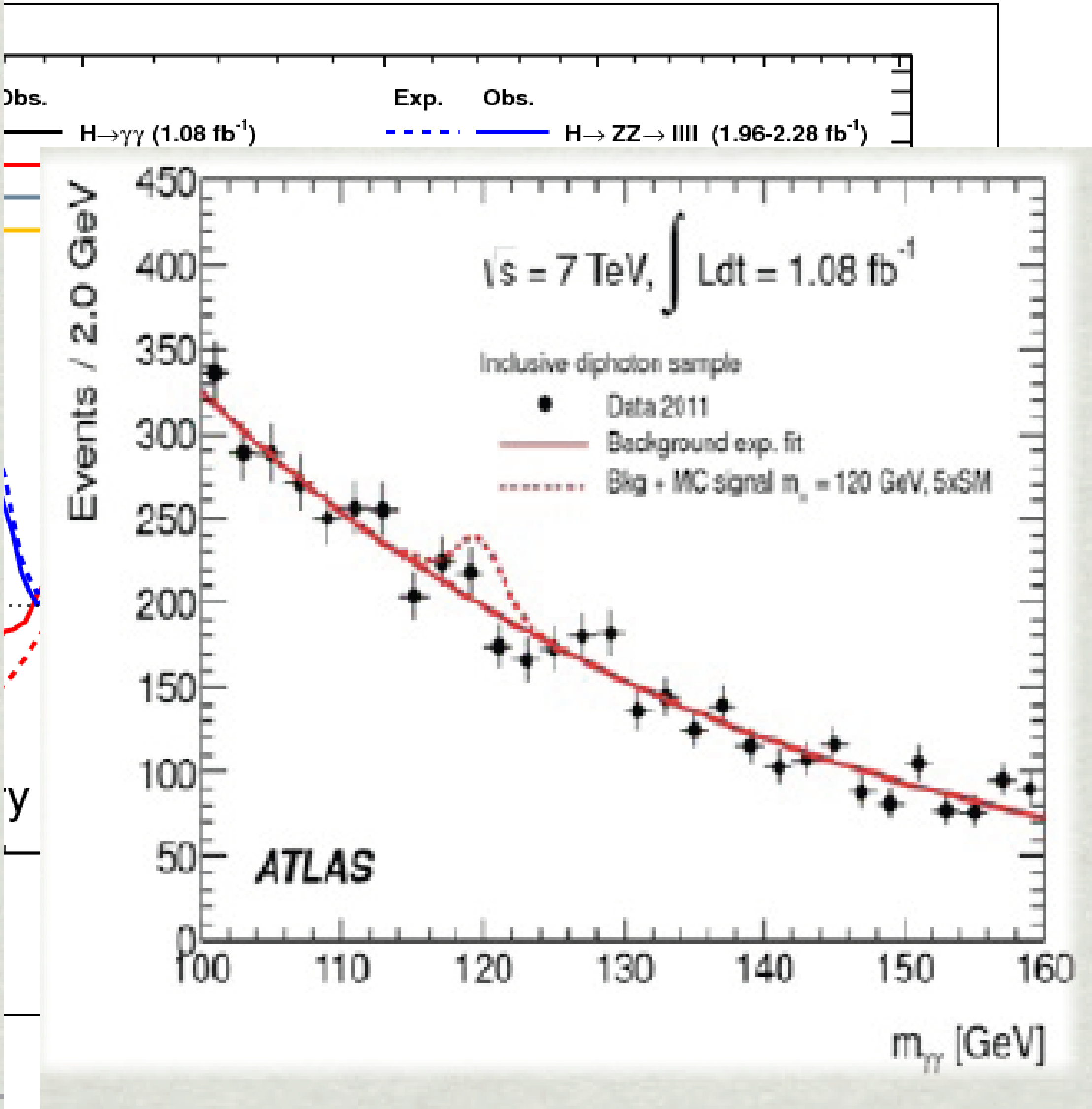




# The zoo of elementary particles in the Standard Model

Three families of matter particles

**Where will the Higgs boson fit in? Probably as a type of killer whale too.**

**Masses are in MeV or millions of electron-volts.**

**The weights of the animals are proportional to the weights of the corresponding particles.**

# Outlook on physics at the LHC as viewed by an experimentalist

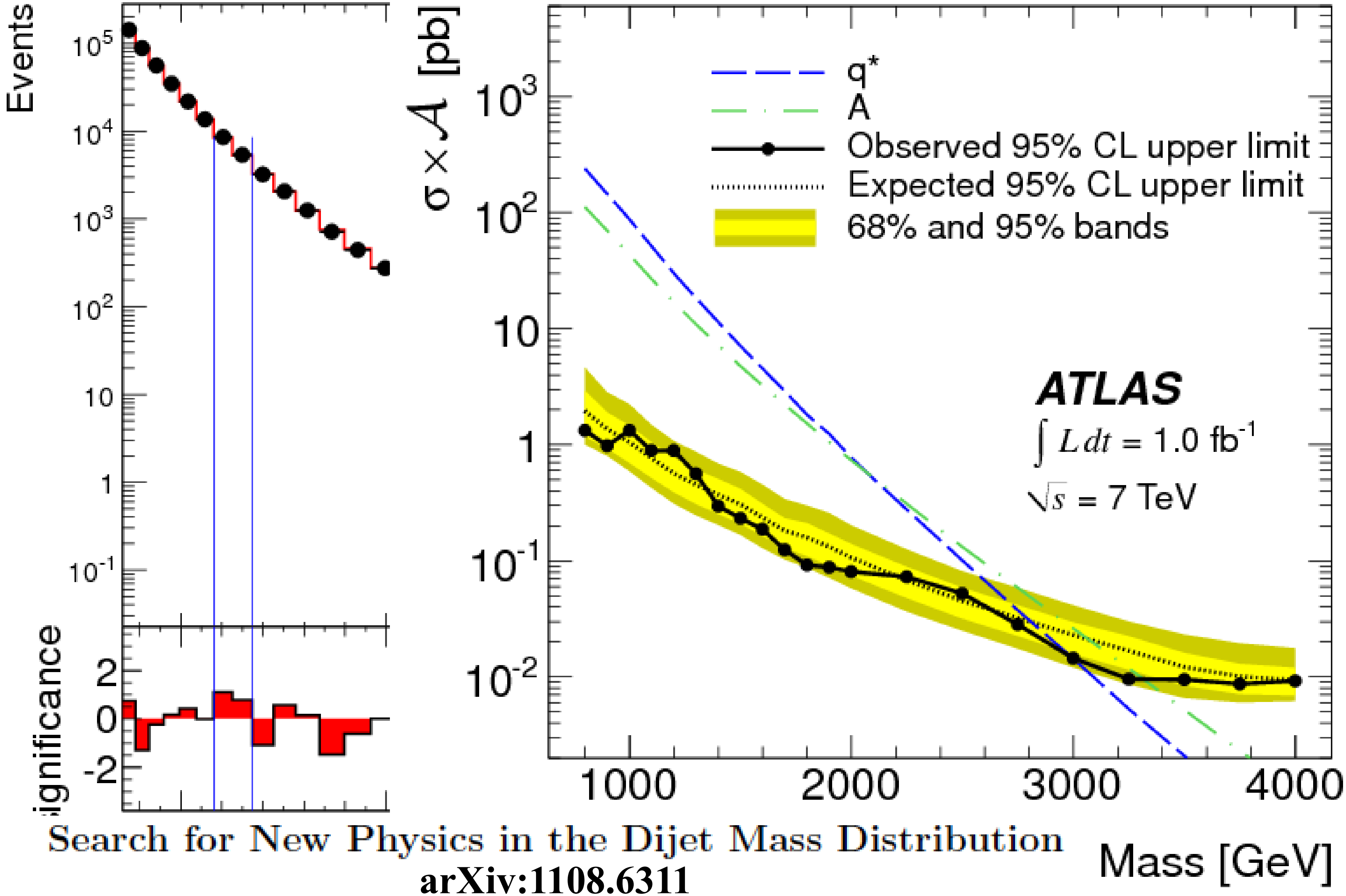
## Where are we compared to where we expected to be?

1) Machine energy is a factor two lower than design:
   Does not matter much for early physics: results are astonishing to people like me who did not work on LEP nor on Tevatron!
   - Matters a lot for searches at the edge of phase space: many have stated their sadness at absence of new physics at the ~ TeV scale.
   - WW scattering at the TeV scale will certainly require 14 TeV.
   - Measuring the Higgs self-coupling will require SLHC if not more.

   But aren't we behaving like spoiled brats?
   Who seriously expected that LHC would overtake Tevatron and even B-factories so quickly, especially in the Higgs sector and even in certain precision measurements (LHCb recent results, W/Z, diboson and top-quark cross-sections from ATLAS/CMS)?

# Is 7 TeV enough?

# Now have covered a lot of phase space for many signatures



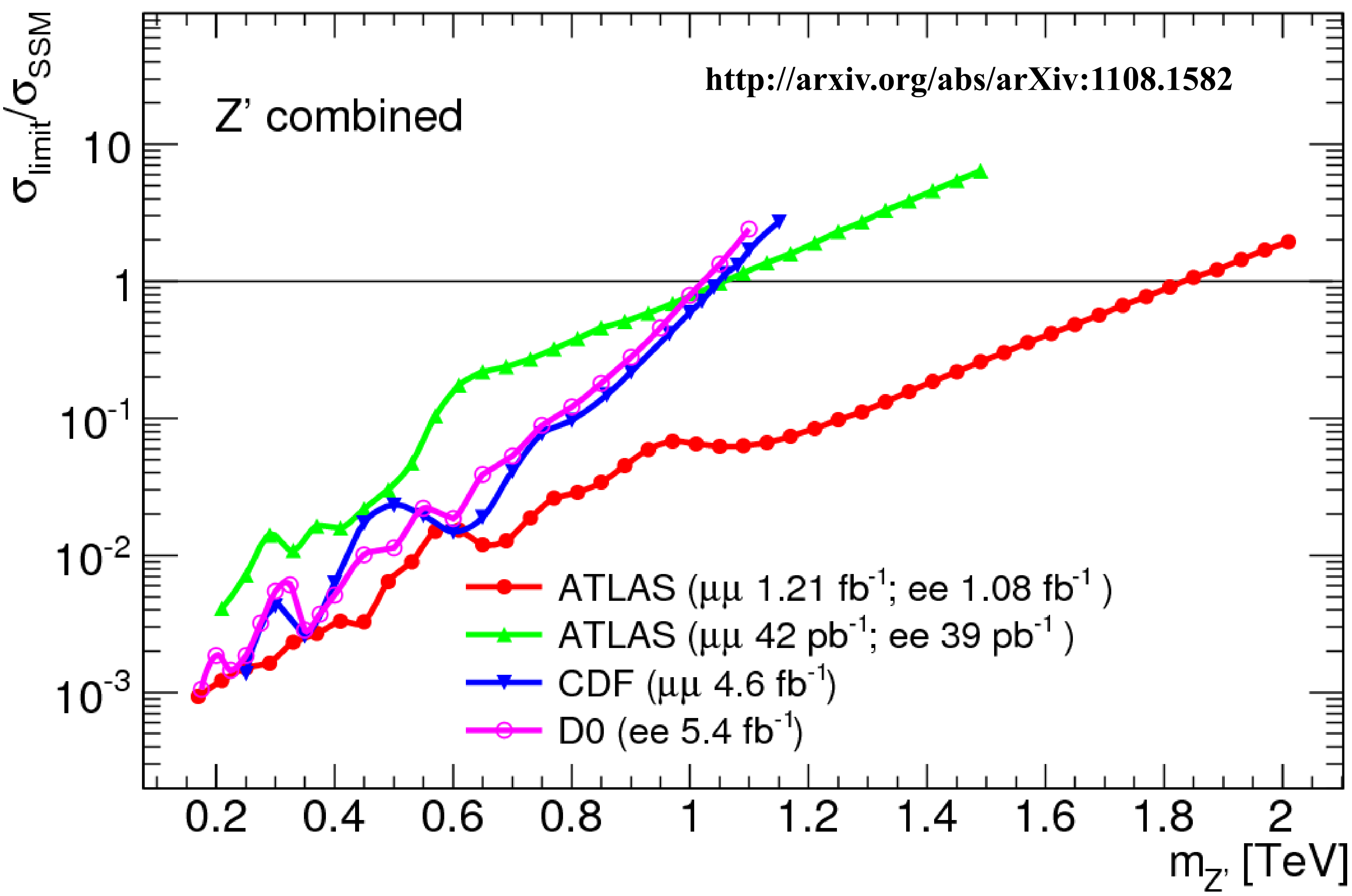
Search for New Physics in the Dijet Mass Distribution

**arXiv:1108.6311**

# Is 7 TeV enough?

## Now have covered a lot of phase space for many signatures

Search for dilepton resonances in $pp$ collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector



http://arxiv.org/abs/arXiv:1108.1582

# Outlook on physics at the LHC as viewed by an experimentalist

## Where are we compared to where we expected to be?

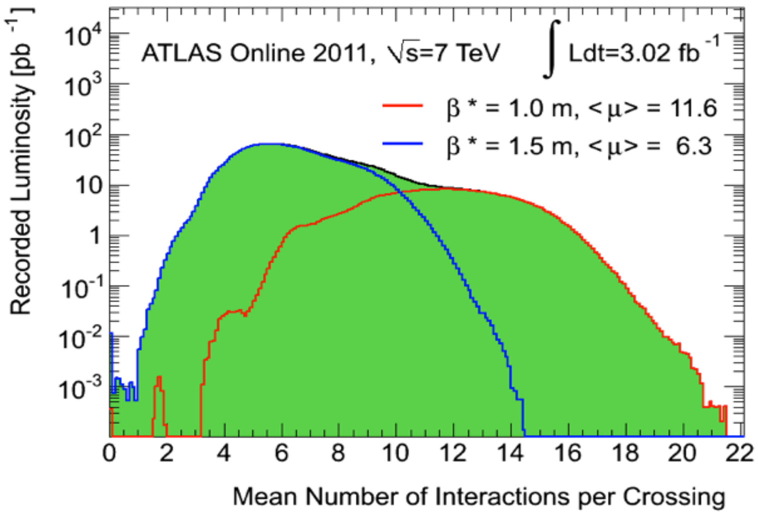
2) Instantaneous luminosity is getting close to design luminosity!
This has been a key point in overtaking Tevatron in the Higgs sector.
This has a price!
→ Higher trigger thresholds, already cutting to some extent into the early physics program
→ Performance degradation for tracking, low-$p_T$ jets, $E_T^{miss}$ resolution, and identification of hadronic τ-decays
→ Difficult data processing and analysis environment when the data taken until a month or so ago becomes so quickly "obsolete"
The more insidious problem is the lack of time (and effort!) to understand and improve basic performance and differences between data and simulation, and even complex analyses!

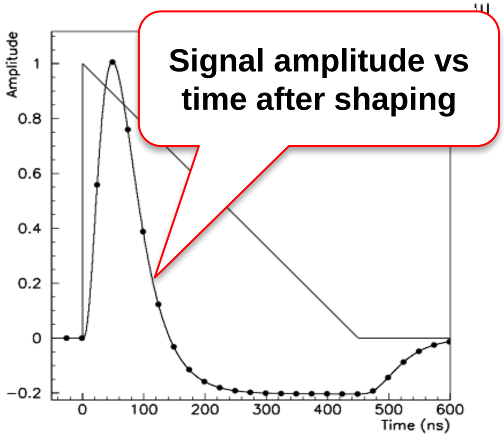
# ATLAS trigger: preserve perf. and physics!

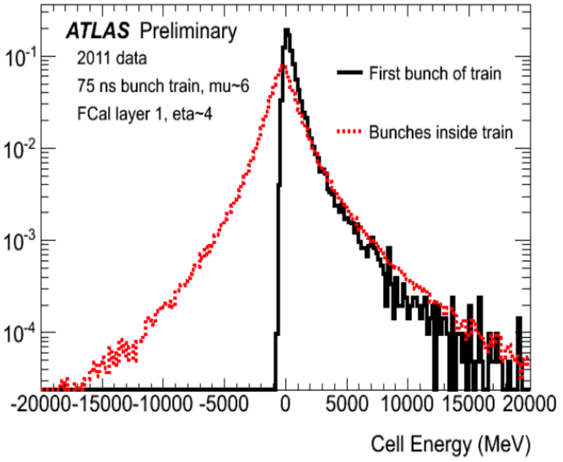
## Difficult e.g. to keep inclusive single lepton trigger at ~ 20 GeV!

| Trigger objects | Offline Selection ($p_T$ thresholds) | Trigger Selection | | L1 Rate (kHz) at 3 $10^{33}$ | EF Rate (Hz) at 3 $10^{33}$ |
|---|---|---|---|---|---|
| | | L1 | EF | | |
| Single leptons | Single muon > 20 GeV | 11 GeV | 18 GeV | 8 | 100 |
| | Single electron > 25 GeV | 16 GeV | 22 GeV | 9 | 55 |
| Two leptons | 2 muons > 4 GeV | 11 GeV | 15,10 GeV | 6 | 5 |
| | 2 electrons, > 15 GeV | 2x10 GeV | 2x12 GeV | 2 | 1.3 |
| | 2 $\tau \rightarrow$ h > 45, 30 GeV | 15,11 GeV | 29,20 GeV | 7.5 | 15 |
| Two photons | 2 photons, > 25 GeV | 2x12 GeV | 2x20 GeV | 3.5 | 5 |
| $E_T^{miss}$ | $E_T^{miss}$ > 170 GeV | 50 GeV | 70 GeV | 0.6 | 5 |
| Multi-jets | 5 jets, > 55 GeV | 5x10 GeV | 5x30 GeV | 0.2 | 9 |
| Single jet plus $E_T^{miss}$ | Jet $p_T$ > 130 GeV & $E_T^{miss}$ > 140 GeV | 50 GeV & 35 GeV | 75 GeV & 55 GeV | 0.8 | 18 |
| Total rate (peak) | | | | 55 kHz | 550 Hz |

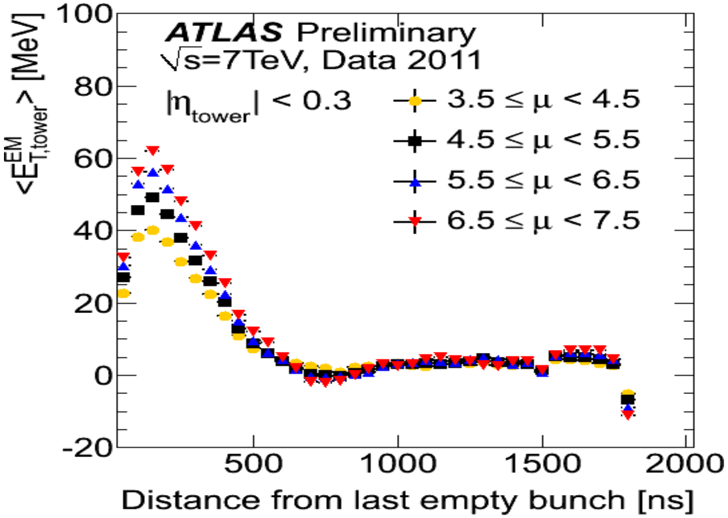
# ATLAS reconstruction: impact of pile-up




Signal amplitude vs time after shaping



- Do not expect a significant impact on tracking, nor muons, nor even electrons and photons
- But sizable impact on jets (+$E_T^{miss}$) and $\tau$
- LAr drift-time is ~ 500 ns and out-of-time bunches have impact on measurement. Bipolar pulse shaping designed so that <ET> ~ 0 for 25 ns bunch-spacing and uniform intensity per BX



- Optimal performance will require correction per cell type in η-bins and as a function of luminosity to set average measured $E_T$ to ~ 0
- At the moment, introduce increased jet energy scale uncertainty for low-$p_T$ jets (at maximum 7% for jets in forward calo)

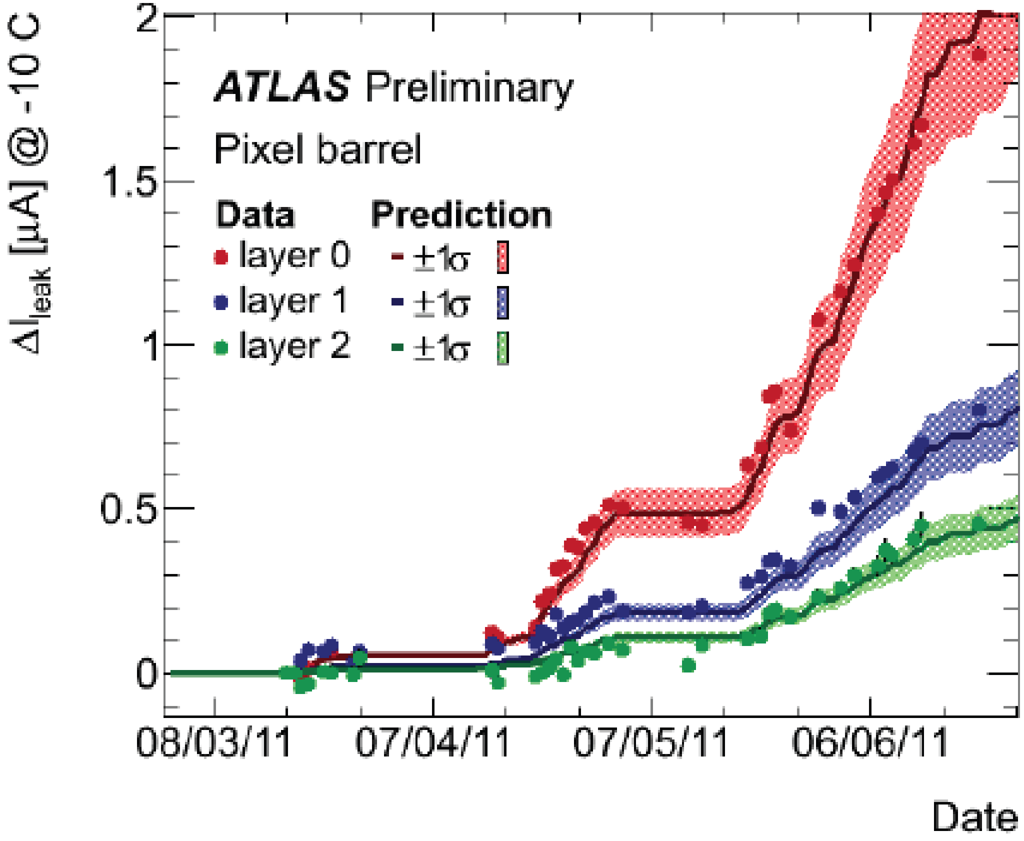
# Outlook on physics at the LHC as viewed by an experimentalist

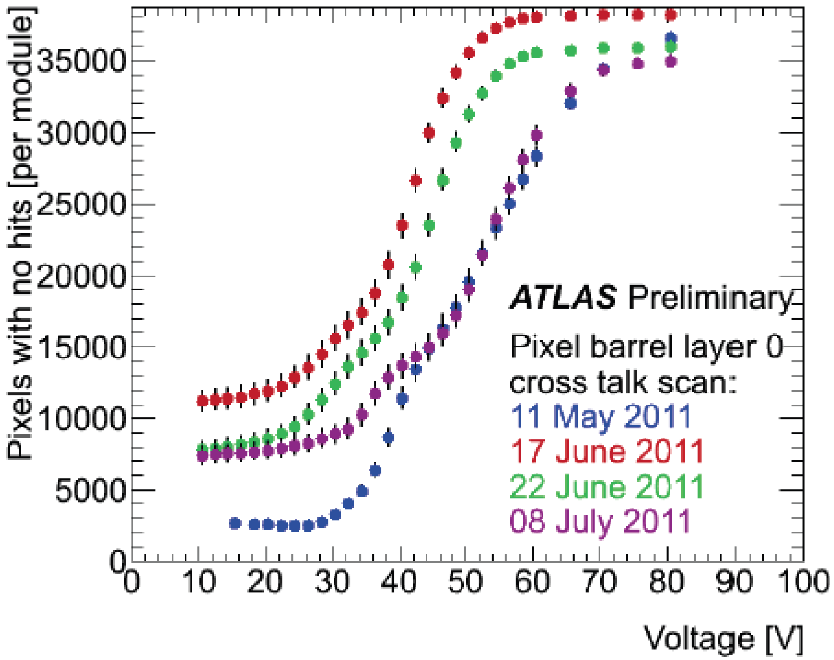
## Where are we compared to where we expected to be?

3) Integrated luminosity per year is 5-20 (?) fb$^{-1}$ for 2011-2012
This is now approaching "interesting" values for the survival of the detectors: remember that LHC electronics (experiments for sure and even machine!) need to be radiation tolerant at the very least and radiation hard near the beams.
But we must remember that this only the very beginning! Type inversion in the silicon detectors will probably only occur in the innermost layers during 2012, after which there will be a long "annealing" period in 2013-2014.
This is a somewhat strange situation:
- by 2017, we will most likely still have fully operational tracking and vertexing detectors in ATLAS and CMS
- upgrade plans for these detectors are constantly adapting to the rapidly evolving situation

# Instrument should not be forgotten!

## Pixel detectors now see radiation damage from beam … and annealing without beam!





## Interlude: a plea to not forget where we started from

# Physics Nobel Prizes for Instrumentation

1927: C.T.R. Wilson, Cloud Chamber
1939: E. O. Lawrence, Cyclotron & Discoveries
1948: P.M.S. Blacket, Cloud Chamber & Discoveries
1950: C. Powell, Photographic Method & Discoveries
1954: Walter Bothe, Coincidence method & Discoveries
1960: Donald Glaser, Bubble Chamber
1968: L. Alvarez, Hydrogen Bubble Chamber & Discoveries
1992: Georges Charpak, Multi-Wire Proportional Chamber

# Detector Physics and Simulation

Precise knowledge of the processes leading to signals in particle detectors is necessary.

The reason is that modern detectors are nowadays working close to the limits of theoretically achievable measurement accuracy and, in certain cases, of operation and survival – even in large systems.

Thanks to the huge available computing power, detectors can be simulated to within 5-10% of reality, based on a very precise description of:

a) the fundamental physics processes at the microscopic level (atomic and nuclear cross-sections)
b) the signal processing (electronics and readout),
c) the detector geometry (tens of millions of volumes)

For the first time, this procedure has been followed for the LHC detectors: the first physics results show that it has paid off!

# History of Energy Loss Calculations: dE/dx

**1915: Niels Bohr, classical formula, Nobel prize 1922.**
**1930: Non-relativistic formula found by Hans Bethe**
**1932: Relativistic formula by Hans Bethe**

Bethe's calculation is leading order in perturbation theory, thus only $z^2$ terms are included.

Additional corrections:

$z^3$ corrections calculated by Barkas-Andersen

$z^4$ correction calculated by Felix Bloch (Nobel prize 1952, for nuclear magnetic resonance). Although the formula is called Bethe-Bloch formula the $z^4$ term is usually not included.

Shell corrections: atomic electrons are not stationary

Density corrections: by Enrico Fermi (Nobel prize 1938, for discovery of nuclear reaction induced by slow neutrons).

Hans Bethe
1906-2005

**Born in Strasbourg, emigrated to US in 1933. Professor at Cornell U. Nobel prize 1967 for theory of nuclear processes in stars.**

# Particle Detector Simulation

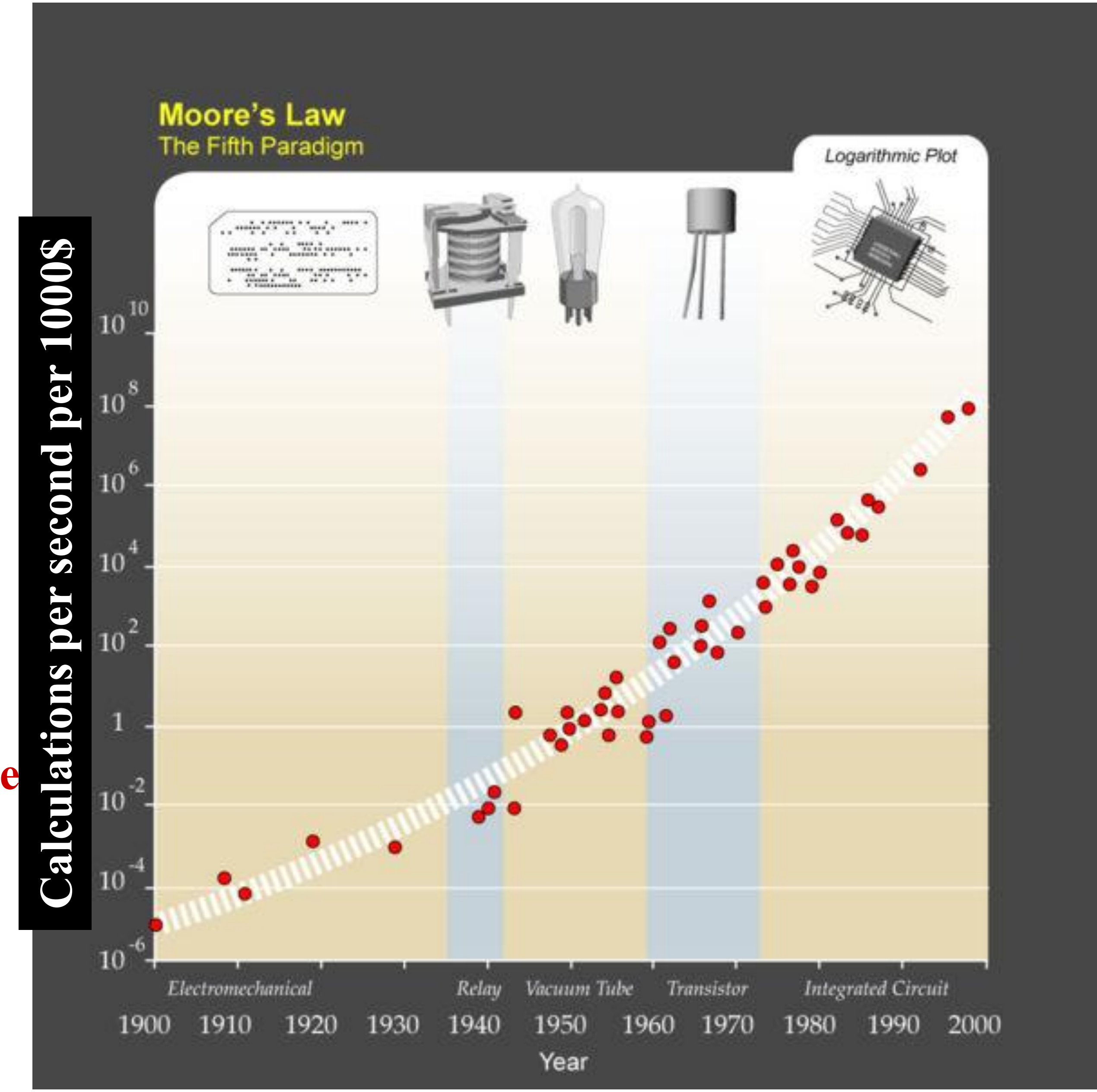
## I) C. Moore's Law:

Computing power doubles every 18 months.

## II) Modern World's Law:

The use of the human brain for solving a problem is inversely proportional to the available computing power.

Design and construction of LHC detectors has taken advantage of Moore's law (it would most likely not have been possible without it) but has also been the result of the combined power of human brains and modern computers.



Knowing the basics of particle detectors is essential!!

# Outlook on physics at the LHC as viewed by an experimentalist

## Where are we compared to where we expected to be?

4) Detectors are operating marvelously well

- Data-taking efficiency is well above 90%
- Data quality is in general above 95%
- Performance is close to design
- Simulation and data agree remarkably well!

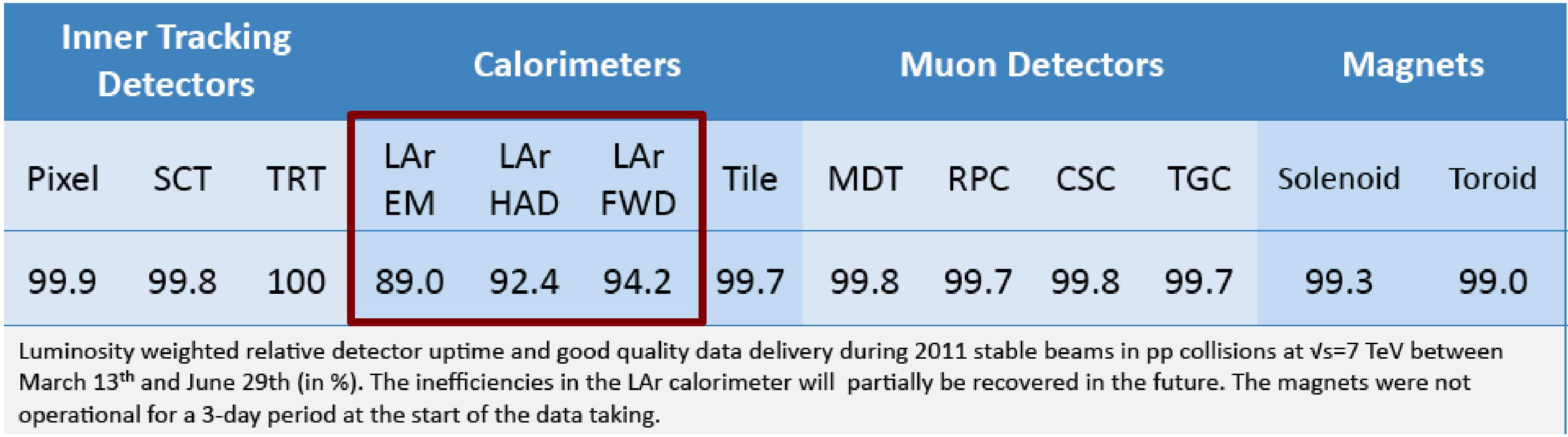
By now, few remember that in 1989, the community was very uncertain about having any functional tracking in the LHC detectors.

It is nor for free that the above detector performance has been achieved! Young experimental physicists today must be frustrated: it's a bit like in church, you have to "believe" that there is a detector spitting out the byte-stream processed at Tier-0.

Achieving the ultimate detector performance is still a long way ahead of us, and the rewards will be commensurate to the effort!

# ATLAS data quality: improve data quality → physics

**Tier0 processing**

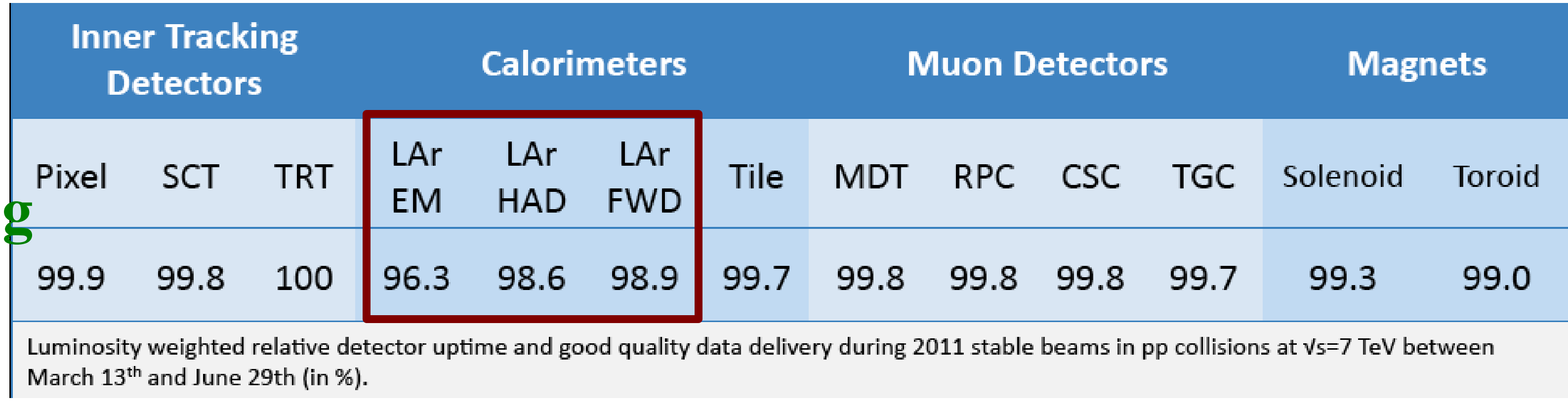


| Inner Tracking Detectors | | | Calorimeters | | | | Muon Detectors | | | | Magnets | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pixel | SCT | TRT | LAr EM | LAr HAD | LAr FWD | Tile | MDT | RPC | CSC | TGC | Solenoid | Toroid |
| 99.9 | 99.8 | 100 | 89.0 | 92.4 | 94.2 | 99.7 | 99.8 | 99.7 | 99.8 | 99.7 | 99.3 | 99.0 |

Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at $\sqrt{s}=7$ TeV between March 13th and June 29th (in %). The inefficiencies in the LAr calorimeter will partially be recovered in the future. The magnets were not operational for a 3-day period at the start of the data taking.

- **Data quality close to 100% for all sub-detectors apart from LAr calorimeter in Tier0 processing**
- **Origin of lower data LAr quality is mostly noise bursts (and HV trips)**

**Reprocessing**



| Inner Tracking Detectors | | | Calorimeters | | | | Muon Detectors | | | | Magnets | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pixel | SCT | TRT | LAr EM | LAr HAD | LAr FWD | Tile | MDT | RPC | CSC | TGC | Solenoid | Toroid |
| 99.9 | 99.8 | 100 | 96.3 | 98.6 | 98.9 | 99.7 | 99.8 | 99.8 | 99.8 | 99.7 | 99.3 | 99.0 |

Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at $\sqrt{s}=7$ TeV between March 13th and June 29th (in %).

- **In reprocessing, event by event flagging of noise bursts was used**
- **Gain back about 7% of the data for physics analyses (now also at Tier-0)**

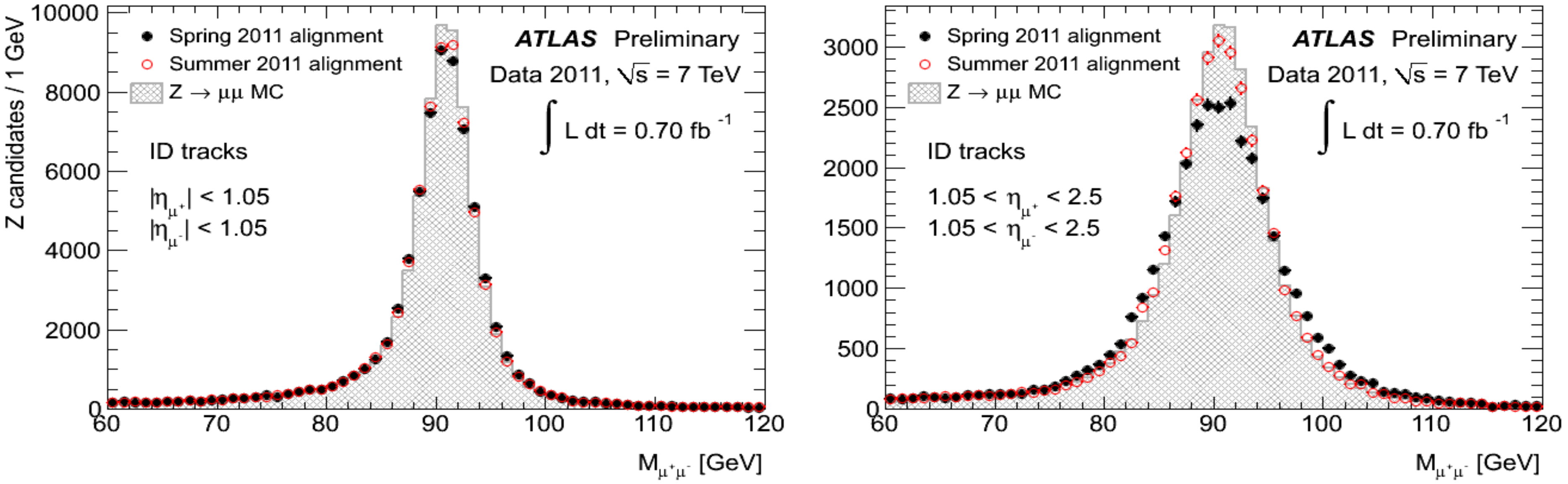
# ATLAS alignment and calibration: inner detector

- Unfortunately, alignment work for “light-weight” inner detector does not stop at minimising residuals
- Need to eliminate distortions which affect track parameters, especially impact parameter and momentum measurements (residuals are insensitive to a number of these possible distortions). Use E/p measurement for electrons and apply to muons!
- This has led to large improvement on $Z$ to $\mu\mu$ experimental resolution, a factor three in end-caps (much weaker initial constraints from cosmics)

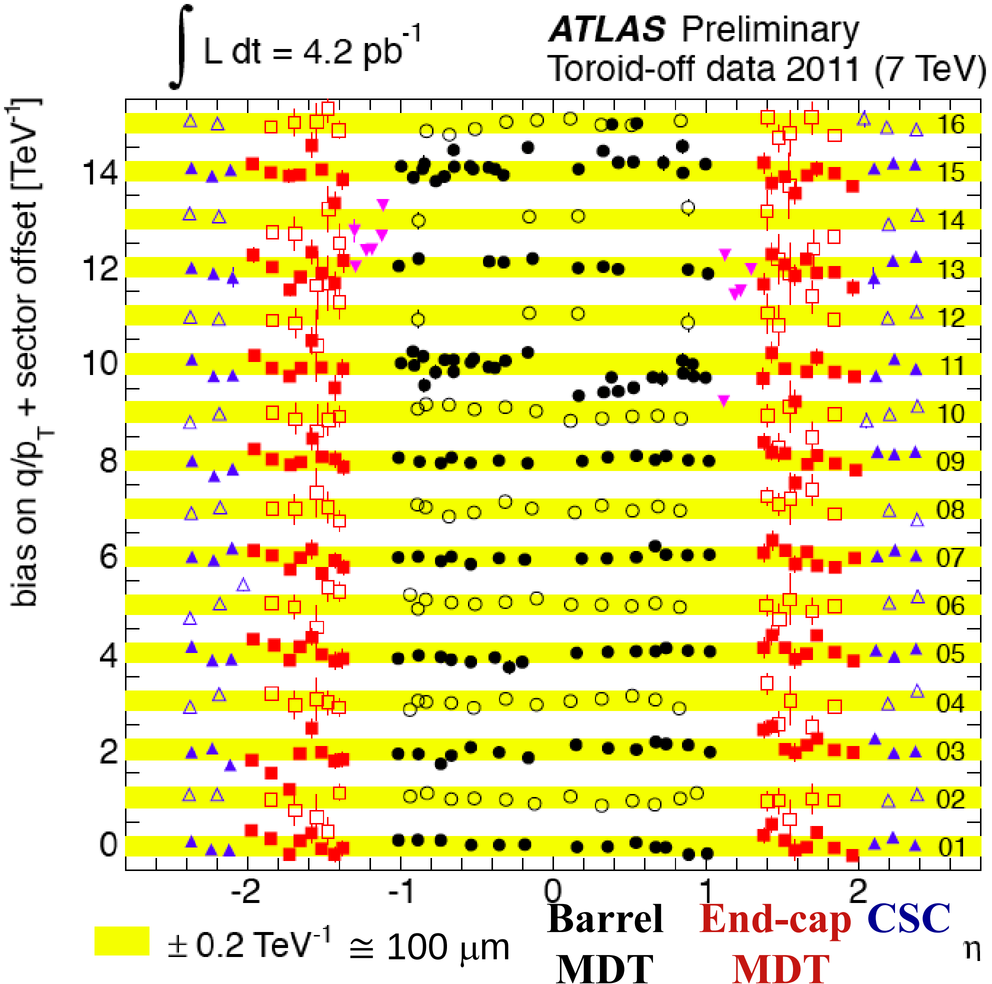
Exp. resolution expected from MC (GeV)

Additional contribution to exp. resolution from data (to be added quadratically)

| $Z$ to $\mu\mu$ in ID only (250k events) | Ideal | Only residuals used in minim. | Add E/p constraint from $e^+$ vs $e^-$ |
|---|---|---|---|
| Both $\mu$ in barrel ID | 1.60 | 0.98 ± 0.01 | 0.71 ± 0.01 |
| Both $\mu$ in same end-cap ID | 3.42 | 3.03 ± 0.03 | 1.16 ± 0.01 |



# ATLAS alignment and calibration: muon spectrometer



- **Main difficulty in ~ 10’000 m$^3$ of muon spectrometer system is to achieve design performance in terms of stand-alone resolution, i.e. 10% at 1 TeV over $|\eta| < 2.7$**

- **Combination of optical alignment and of tracks taken with toroid field off and solenoid on (4.2 pb$^{-1}$ in spring 2011) has resulted in major improvements in end-caps where constraints from cosmics were statistically much weaker than in barrel**

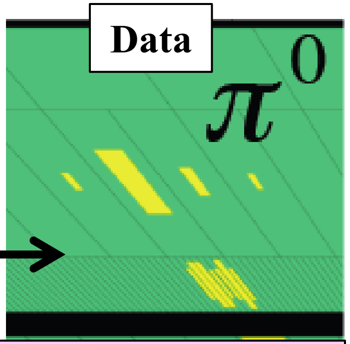
- **Recent reprocessing has yielded a factor more than two improvement for CSC chambers at high $|\eta|$.**

- **All chambers now within < ± 100 μm**

- **Curvature bias expressed in units of TeV$^{-1}$ is shown as a function of η and for each ϕ sector above.**
- **Table displays averages per η-region**

| Detector region | $\sigma_{\mathrm{ali}}$ |
|---|---|
| Barrel | $0.130 \pm 0.005 \pm 0.050\ \mathrm{TeV}^{-1}$ |
| MDT end-caps | $0.174 \pm 0.008 \pm 0.050\ \mathrm{TeV}^{-1}$ |
| CSC end-caps | $0.146 \pm 0.009 \pm 0.050\ \mathrm{TeV}^{-1}$ |

# Photon measurements: physics and commissioning of H to γγ search

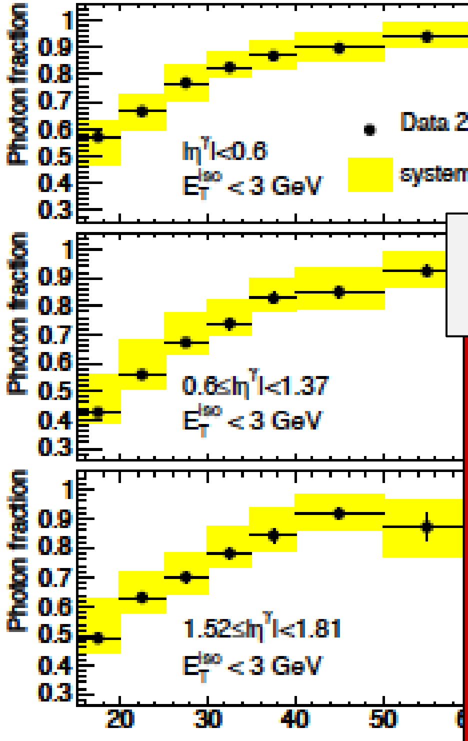


Potentially huge background from jets fragmenting into a single hard $\pi^0$

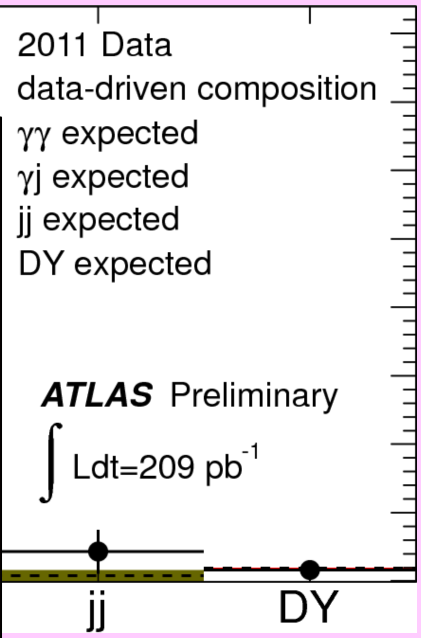
**Photon purity versus ET:**
- around 70-80% in H to γγ range (25-40 GeV)
- above 90% at high $E_T$

Determined choice of fine lateral segmentation (4 mm strips) of the first compartment of ATLAS

R ~ O(8000)

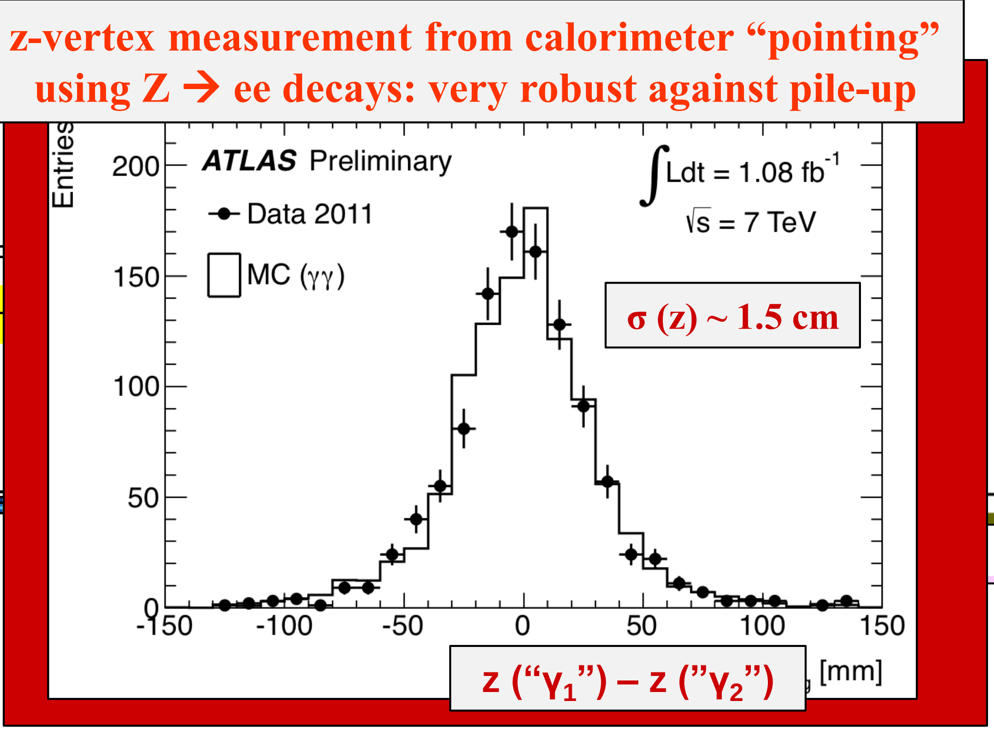


γγ, γj, jj backgrounds estimated from data using control samples → γj + jj << γγ irreducible



with data.

z-vertex measurement from calorimeter "pointing" using Z → ee decays: very robust against pile-up

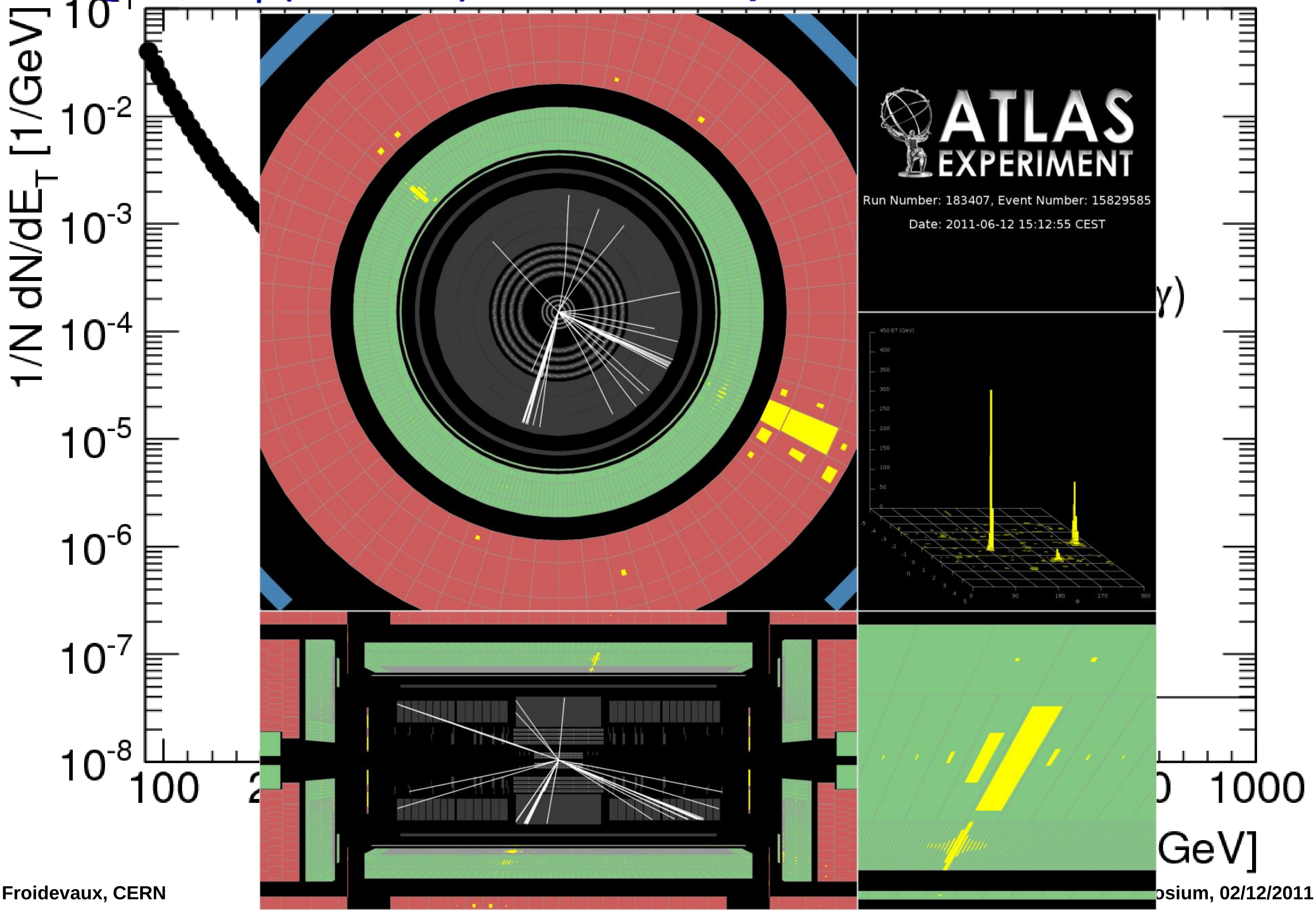


σ (z) ~ 1.5 cm

z ("$\gamma_1$") – z ("$\gamma_2$")

# Photon measurements: reach also TeV scale by now!

## Highest $E_T$ (960 GeV) unconverted photon observed to-date

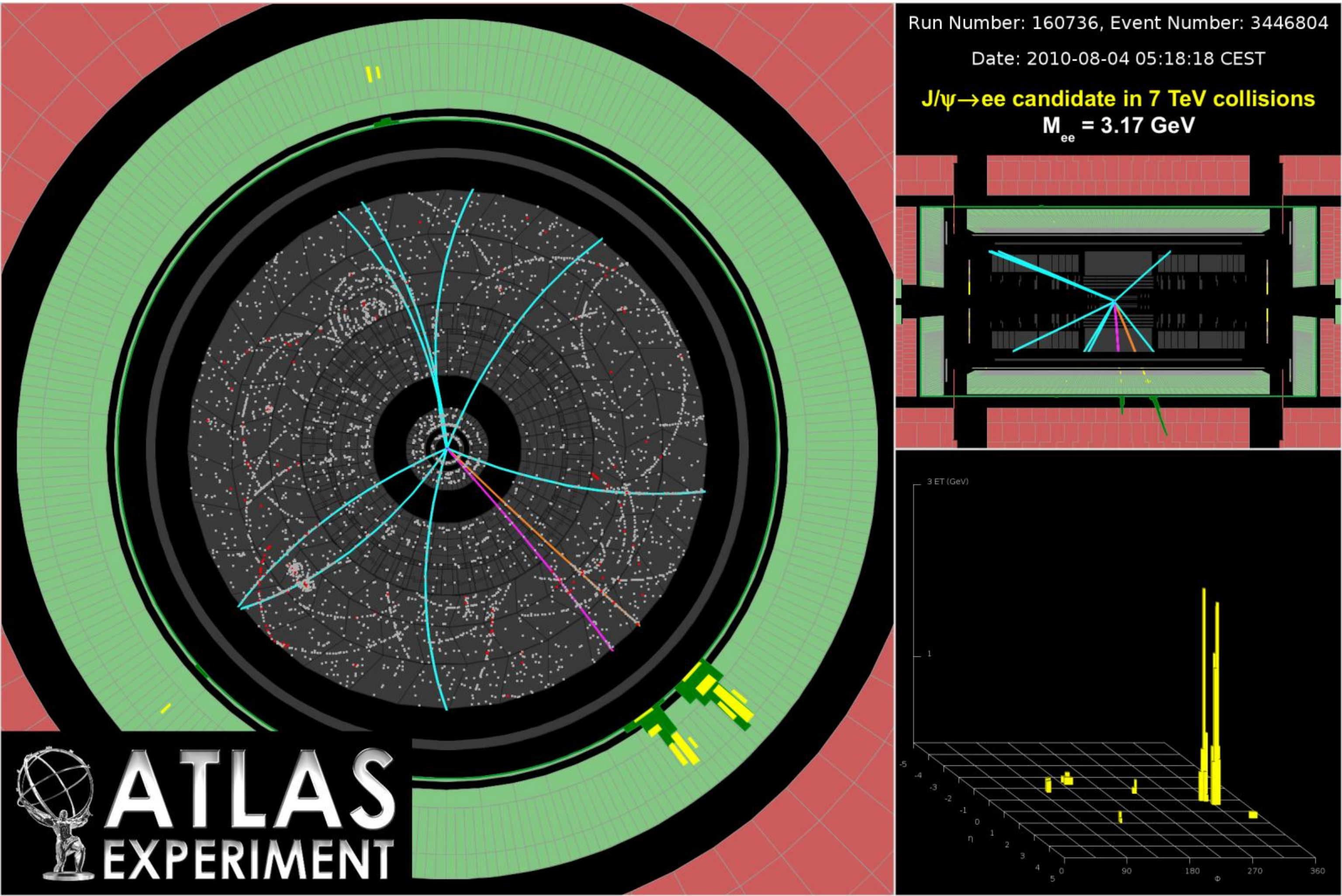


Run Number: 183407, Event Number: 15829585

Date: 2011-06-12 15:12:55 CEST

# Electrons from J/ψ decay

- Thanks to TRT, ATLAS has a J/ψ tag-and-probe trigger even at 3 $10^{33}$ luminosity. This is crucial to understand low-$p_T$ electrons for e.g. H to 4e
- J/ψ → ee events are also important for the understanding of the EM calorimeter performance (extraction of resolution, intercalibration, etc)



# Electrons from J/ψ decay and H to ZZ decays

**Crucial experimental aspects:**

**High lepton acceptance, reconstruction and identification efficiency down to lowest $p_T$**

**Present analysis: $p_T^{1,2,3,4} > 20,20,7,7$ GeV**

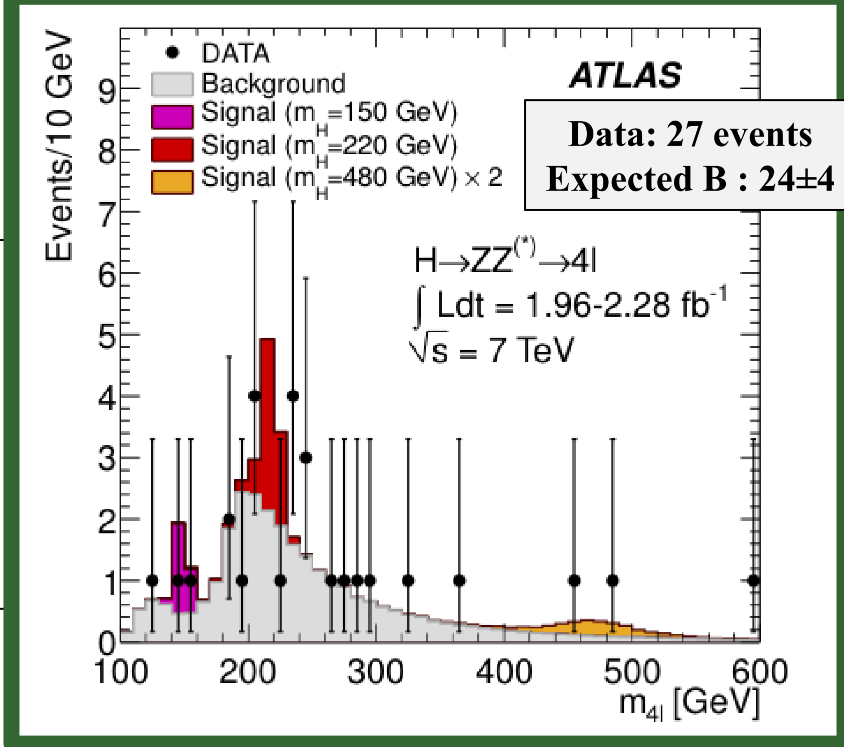
**Need also good mass resolution**

**(presently 1.9 GeV for H→ 4μ for $m_H$=130 GeV)**

**Lepton efficiency from J/ψ → ll, W →lν, Z→ ll data samples**

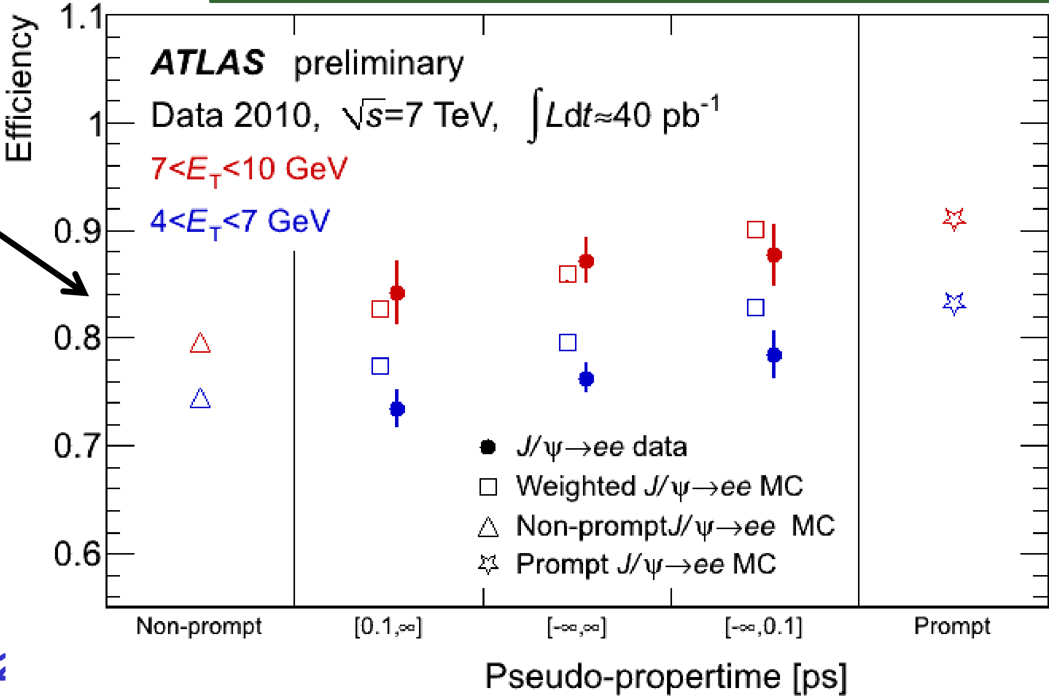
**J/ψ sample contains both prompt and non-prompt J/ψ → ee decays**

**Difficult analysis requiring very performant trigger and good control of backgrounds**



**Data: 27 events**

**Expected B : 24±4**



# Outlook on physics at the LHC as viewed by an experimentalist

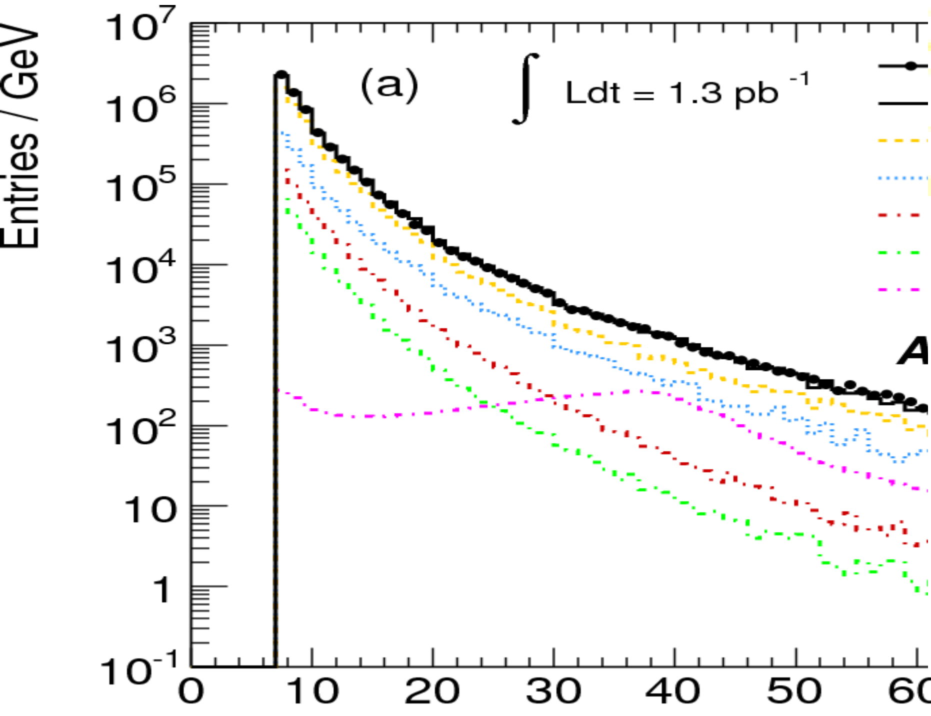
## Where are we compared to where we expected to be?

5) **SM physics is in its early infancy at the LHC**
**This is the aspect most striking to me after two years of data-taking:**
**- many 2010 analyses (less than 1% of the total dataset) are still ongoing. I personally find this absolutely normal: a difficult and complex measurement is not done in two months! Human brains have not improved their clocking cycle with Moore's law, perhaps they have actually slowed down by relying ever more on CPU capacity of modern computing.**
**A number of these analyses are even unique because they rely on data without pile-up!**
**- despite this (from 1-10% of data really used for precision measurements), we see already now that the combination of LHC machine * modern detectors (ok expensive also) * state-of-the-art MC generators will lead not only to precision EW measurements at the LHC but also to precision QCD measurements!**

**This is something few of the people my age were brought up to believe!**
**There remain a number of strong believers in $e^+e^-$ machines for precision measurements of the top mass, the Higgs couplings, etc, of course.**

# Inclusive electrons at the LHC: a real challenge!

**To improve the efficiency for electrons from heavy flavour, but above all to preserve best discriminating variables to measure the composition of the background before rejecting it, apply less stringent identification cuts leading to an expected signal contribution of ~ 10% for $E_T$ < 20 GeV**



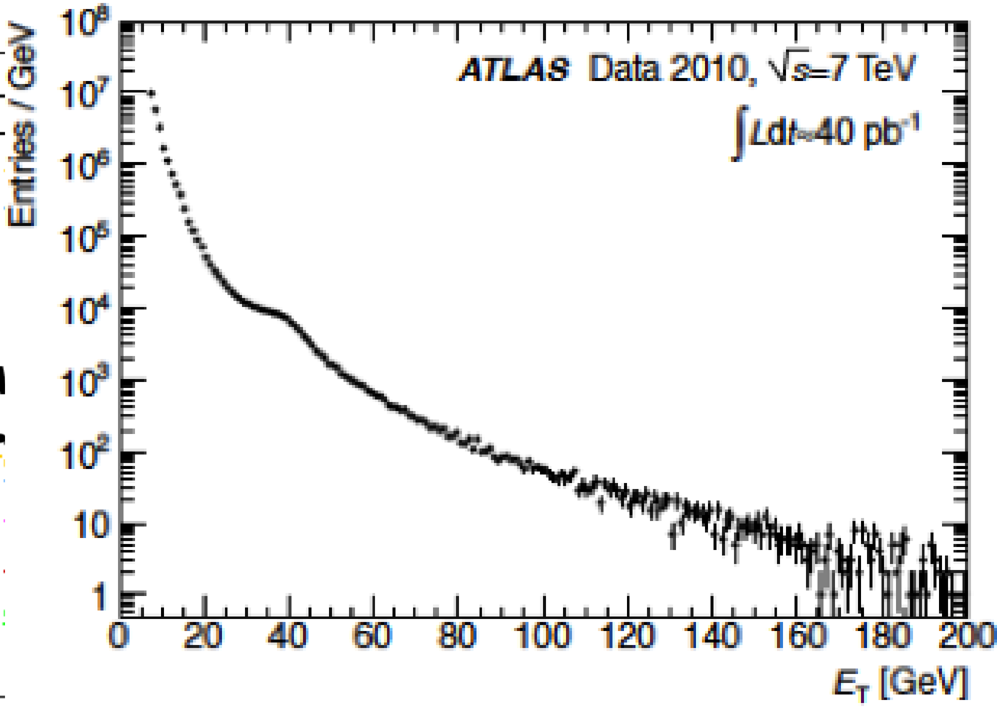


Figure 1: *(a) Distribution of cluster transverse energ dates. The simulation uses* PYTHIA *with the W and to their NNLO total cross-sections and the heavy-fla components then normalised to the total expectatio* $p_T$ *< 18 GeV are rescaled to 1.3* $pb^{-1}$ *from lower*

**If one selects single electrons after applying the tightest selection criteria to reduce the background from hadrons (initially dominant) and photon conversions, inclusive electron spectrum at low $p_T$ is ~ 50% pure and Jacobean peak from W → eν decays is clearly visible.**

# Inclusive leptons at the LHC: final result

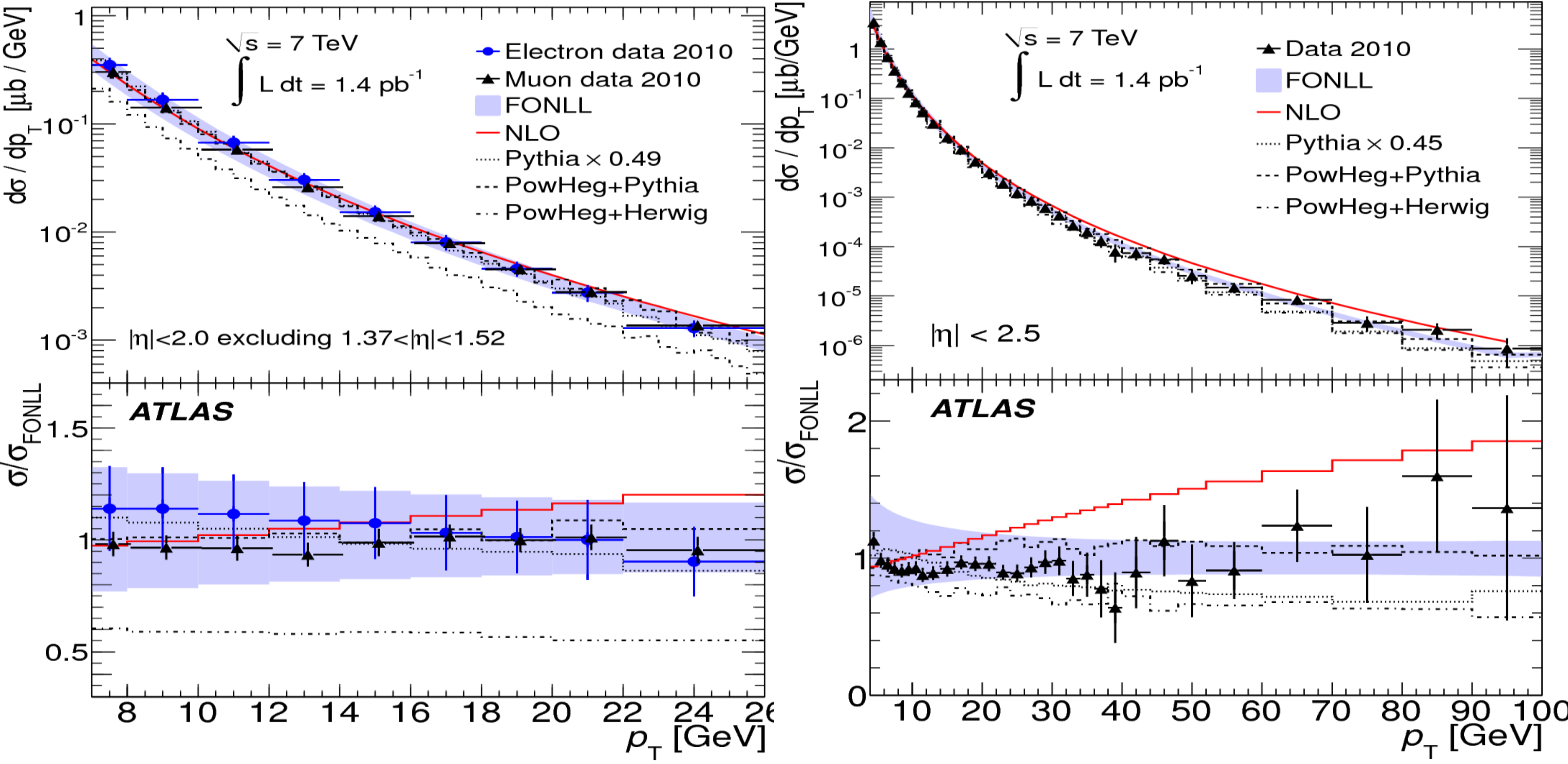


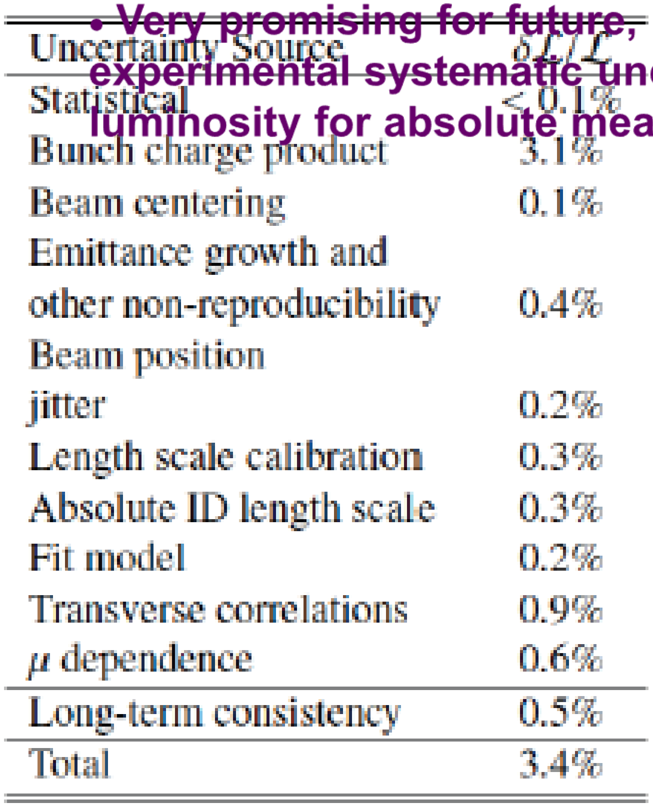
*Figure 4: (Left) Electron and muon differential cross-sections as a function of the charged lepton transverse momentum for $|\eta| < 2.0$ excluding the $1.37 < |\eta| < 1.52$ region. (Right) Muon differential cross-section as a function of the muon transverse momentum for $|\eta| < 2.5$. The ratio of the measured cross-section and the other predicted cross-sections to the FONLL calculation is given in the bottom of each plot. The* `PYTHIA` *(LO) cross-sections are normalised to the data in order to compare the shape of the spectra.*

# SM physics: W/Z differential measurements

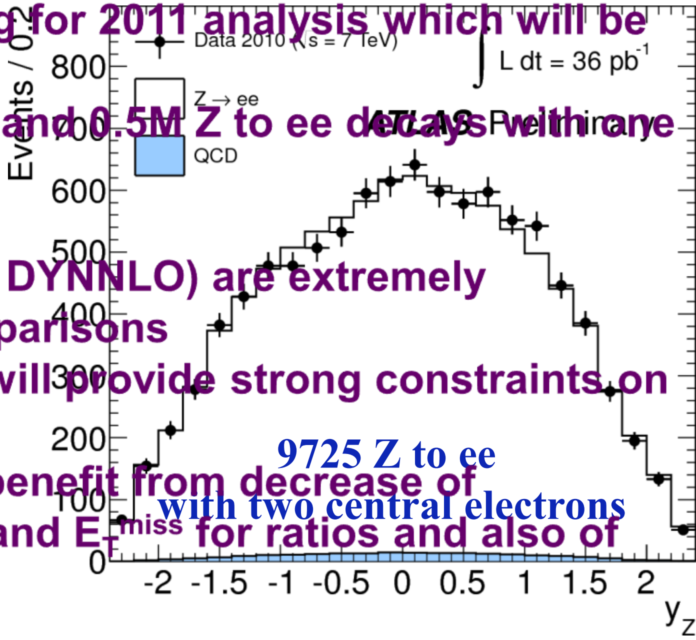
- Submitted for publication for 2010 data: excellent training for 2011 analysis which will be a precision test of theoretical predictions.

For 3 fb$^{-1}$, expect ~ 20M W to l$\nu$ decays, 1.7M Z to ll decays, and 0.5M Z to ee decays with one forward electron ($2.5 < |\eta| < 4.9$)

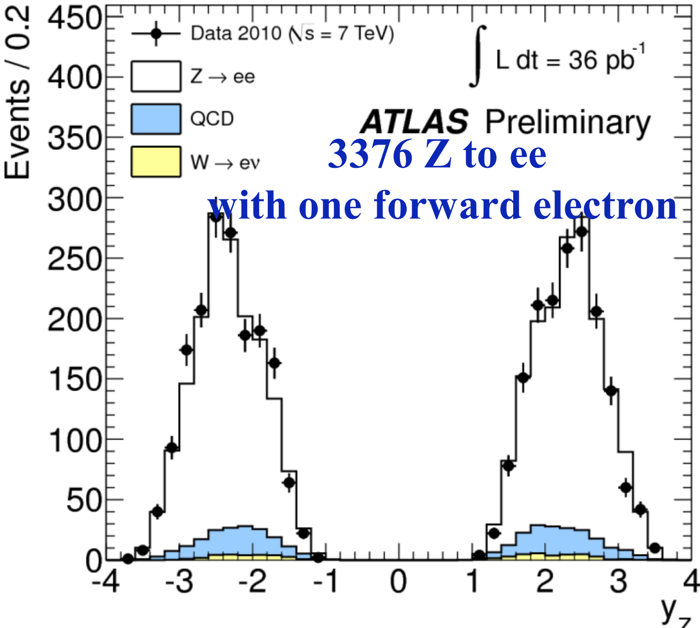
- A certain number of interesting lessons learned already:
  - NNLO tools to predict fiducial cross-sections (FEWZ, DYNNLO) are extremely powerful and provide the means for more precise comparisons
  - Full set of differential distributions for W$^+$, W$^-$, and Z will provide strong constraints on theoretical predictions and in particular on pdfs
  - Very promising for future, but measurements would benefit from decrease of experimental systematic uncertainties on efficiencies and $E_T^{miss}$ for ratios and also of luminosity for absolute measurements



| Uncertainty Source | $\delta\mathcal{L}/\mathcal{L}$ |
|---|---|
| Statistical | < 0.1% |
| Bunch charge product | 3.1% |
| Beam centering | 0.1% |
| Emittance growth and other non-reproducibility | 0.4% |
| Beam position jitter | 0.2% |
| Length scale calibration | 0.3% |
| Absolute ID length scale | 0.3% |
| Fit model | 0.2% |
| Transverse correlations | 0.9% |
| $\mu$ dependence | 0.6% |
| Long-term consistency | 0.5% |
| Total | 3.4% |



9725 Z to ee with two central electrons



3376 Z to ee with one forward electron

# SM physics: W/Z differential measurements

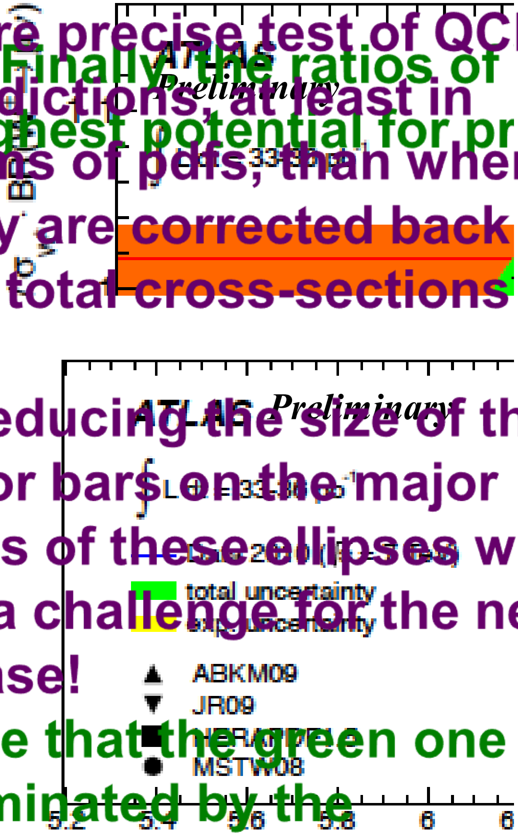
- Fiducial measurements provide a new more precise test of QCD predictions, at least in terms of pdfs, than when they are corrected back to the total cross-sections

Already now,

the PDG average

- Finally, the ratios of

highest potential for pr



- Reducing the size of the error bars on the major axes of these ellipses will be a challenge for the next phase!

Note that the green one is dominated by the uncertainty on the luminosity measurement.

FIG. 19. *Measured and predicted fiduci uncertainty (inner yellow band) of the m green band) includes the statistical unce of the ABKM, JR and MSTW predictio correlations are derived from the eigenve set.*

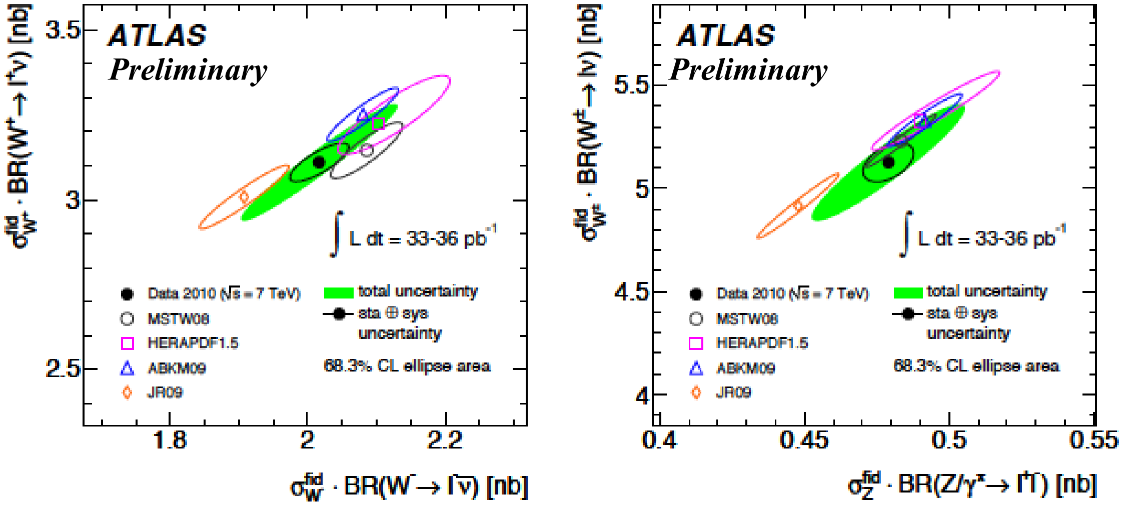


FIG. 15. *Measured and predicted fiducial cross sections times leptonic branching ratios, $\sigma_{W^+}$ vs. $\sigma_{W^-}$ (left) and $(\sigma_{W^+} + \sigma_{W^-})$ vs. $\sigma_{Z/\gamma^*}$ (right). The ellipses illustrate the 68 % CL coverage for total uncertainties (full green) and excluding the luminosity uncertainty (open black). The uncertainties of the theoretical predictions are the PDF uncertainties only.*

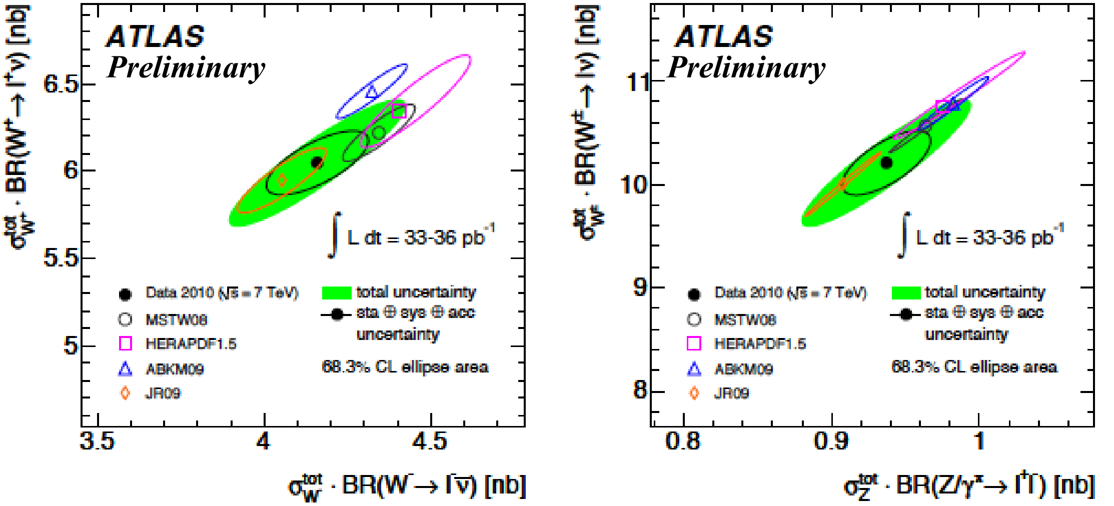


FIG. 16. *Measured and predicted total cross sections times leptonic branching ratios: $\sigma_{W^+}$ vs. $\sigma_{W^-}$ (left) and $(\sigma_{W^+} + \sigma_{W^-})$ vs. $\sigma_{Z/\gamma^*}$ (right). The ellipses illustrate the 68 % CL coverage for total uncertainties (full green) and excluding the luminosity uncertainty (open black). The uncertainties of the theoretical predictions are the PDF uncertainties only.*

# SM physics: measurement of $p_T^Z$ and $p_T^W$

- Already a quite precise measurement for $p_T^W$, with the hadronic recoil calibrated in terms of data to MC differences using the Z → ll decays
- Longer-term goal is a high-precision measurement of $m_W$

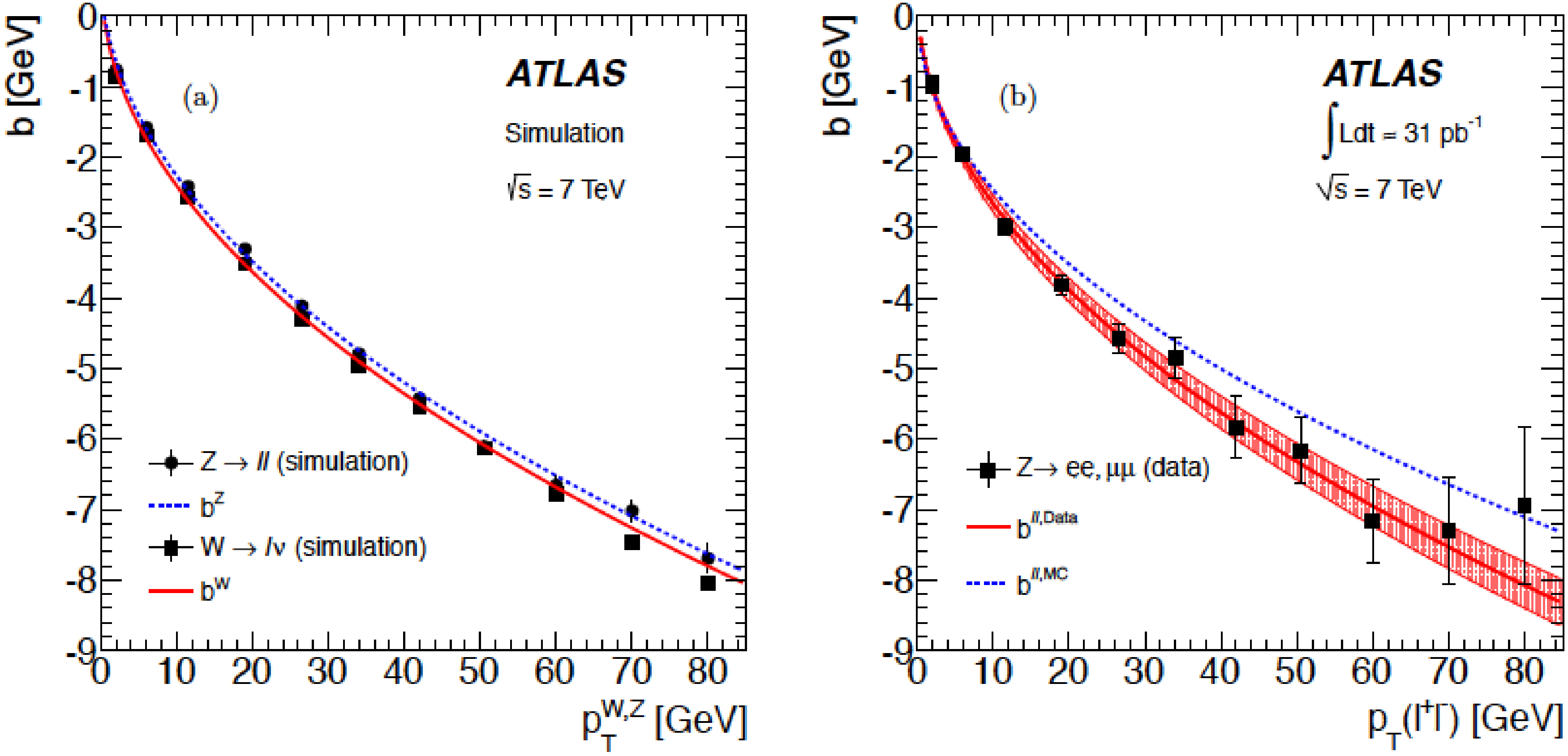
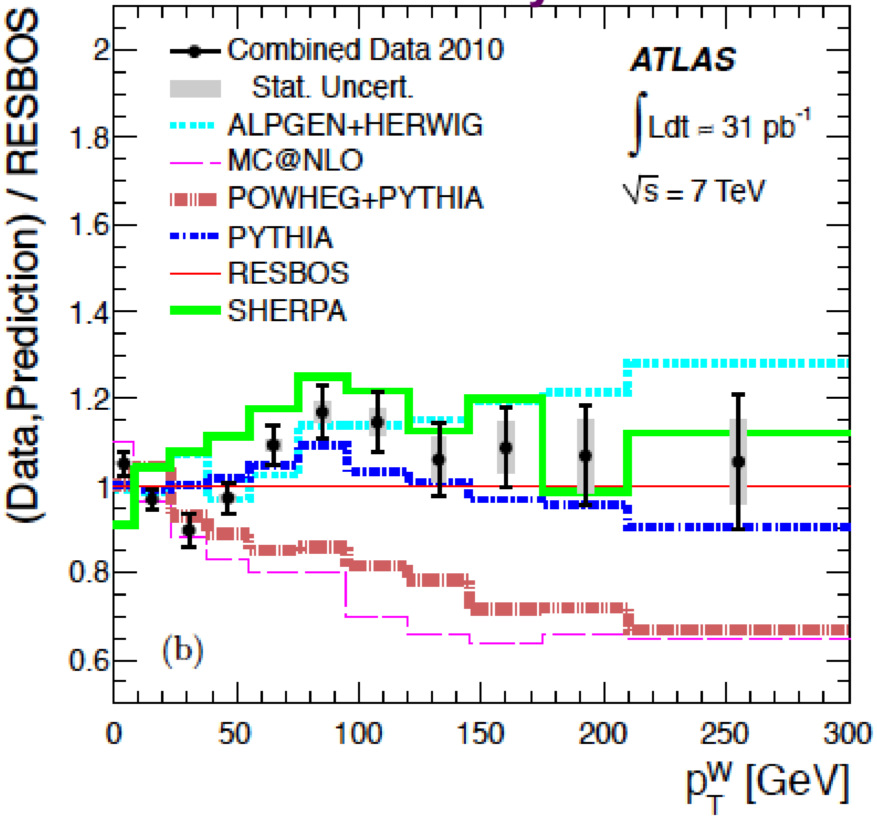


FIG. 2. **(a)** Parametrization of the recoil bias as a function of the vector boson transverse momentum, $b(p_T^{W,Z})$, in $W$ simulation (solid squares, solid line) and $Z$ simulation (solid circles, dashed line). **(b)** Parametrization of the recoil bias as a function of the reconstructed lepton pair transverse momentum, $b(p_T^{\ell\ell})$, in $Z$ simulation (dashed line) and data (solid squares, shaded band). The shaded band shows the uncertainty on the fit.

# SM physics: measurement of $p_T^Z$ and $p_T^W$

- Already a quite precise measurement for $p_T^W$, with the unfolded fiducial distribution showing shape differences wrt certain models
- As shown bottom right, the Z → ll and W → lν shapes agree perhaps better with each other than with any model



Ratio of the combined measurement and various predictions to the RESBOS prediction for the normalized differential cross section, using the O(alpha_s) and O(alpha_s^2) predictions from ALPGEN+HERWIG, MC@NLO, POWHEG+PYTHIA, PYTHIA, and SHERPA. The statistical uncertainties on the predicted distributions are negligible compared to the uncertainty on the measurement and are not shown.

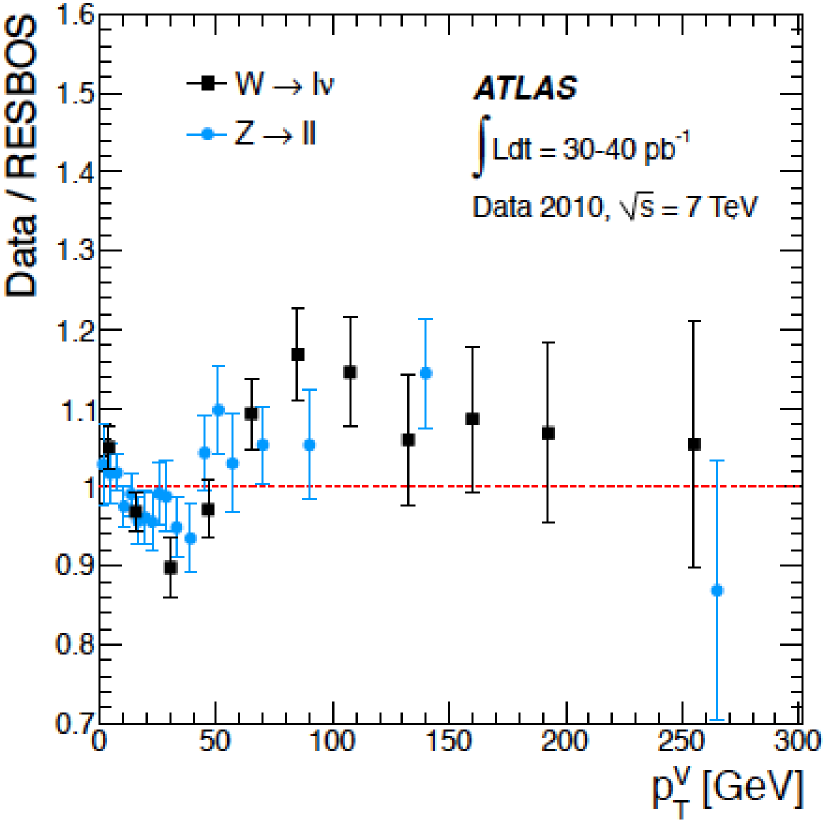


FIG. 8. The ratio of $(1/\sigma_{\rm fid})(d\sigma_{\rm fid}/dp_T^W)$ as measured in the combined electron and muon data to the RESBOS prediction, overlaid with the ratio of $(1/\sigma_{\rm fid})(d\sigma_{\rm fid}/dp_T^Z)$ measured as described in Ref. [2] to the RESBOS prediction.

# SUSY searches

## Where are we compared to where we expected to be?

6) **SUSY searches or how to work at the boundary between theory and experiment?**
**SUSY limits: how are they built? what are the uncertainties? are ATLAS and CMS comparable?**
**What is bad practice for theorists who wish to compare their favourite model to ATLAS/CMS results?**
**What is good practice?**
**How to improve this situation? What about simplified models?**

# SUSY searches: progress on understanding of SM background

**Example: 0 lepton+ jets + ETmiss analysis, using $m_{eff}$ = ETmiss + $H_T$**

## QCD background

≥ 3-jet events with

$E_T^{miss} > 130$ GeV, $p_T^{j1} > 130$ GeV,

$p_T^{j} > 40$ GeV and with

min[$\Delta\phi(p_T^j$,ETmiss)] < 0.2

## Top-pair background

≥ 3-jet events as on left,

but with one b-jet and

one lepton with

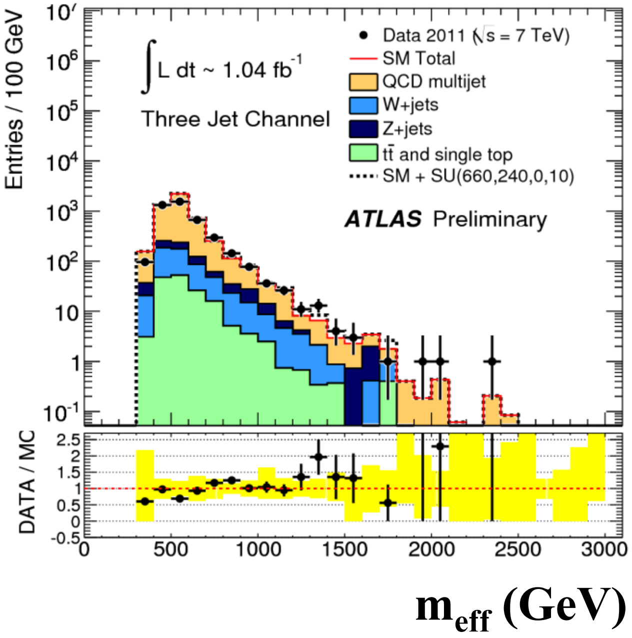
$30 < m_T^{l\nu} < 100$ GeV

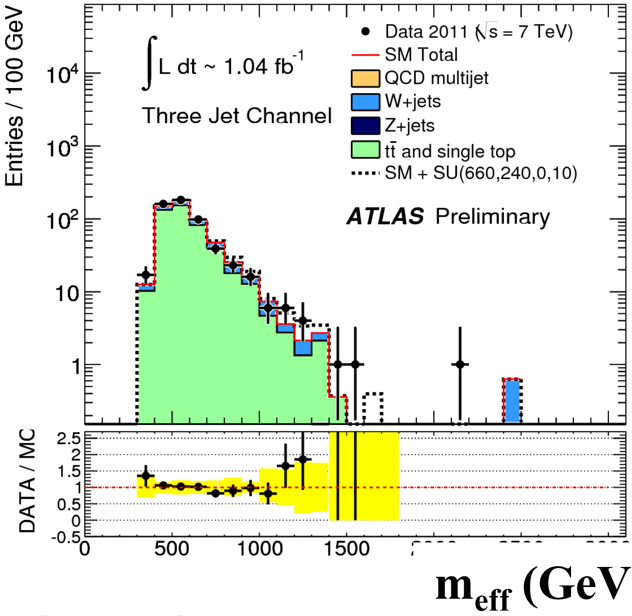
## Z(->vv) background

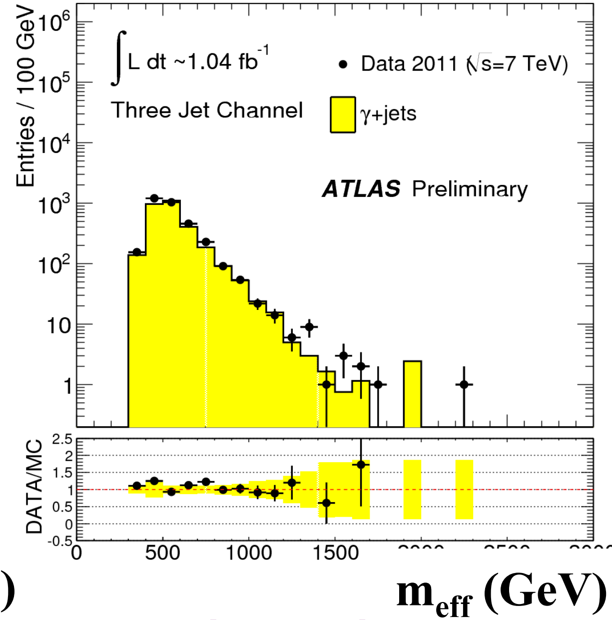
Mimic by replacing

Z → νν by high-$p_T$

photon or Z → ll







**Yellow band in ratio plots shows that agreement is good between data and MC**

# SUSY searches: progress on understanding of SM background

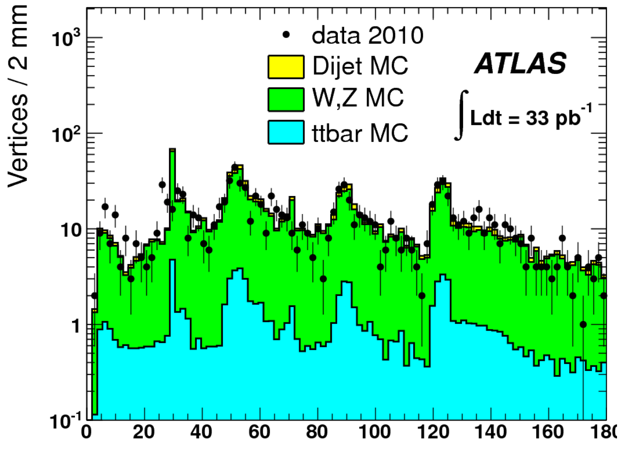
## Other examples: stranger SUSY partners!

## Depend on good understanding of detector performance

**Long-lived neutralino:**

**decay to two jets,**

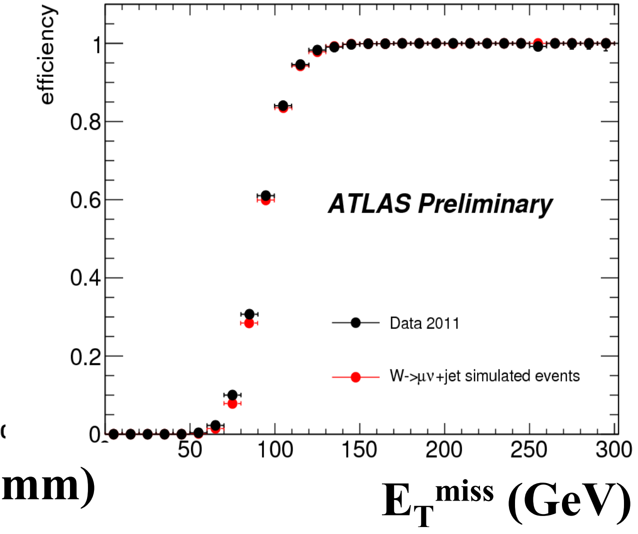
**displaced vertex with high track multiplicity (tracking, vertex reco.)**



**Radius of displaced vertex (mm)**

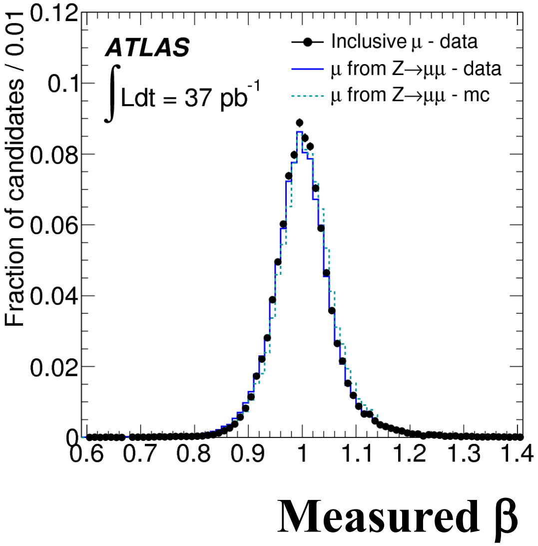
**Monojets:**

**efficiency of $E_T^{miss}$ turn-on curve for trigger**



**Long-lived isolated slepton:**

**timing of muon spectrometer**



# SUSY searches: quick overview of results

Excellent performance of $E_T^{miss}$ measurements even with high pile-up

Most sensitive channel for squarks/gluinos: jets + $E_T^{miss}$ (no leptons)

Some have been heard to say: SUSY will be dead if $m_{stop}$ > 1 TeV!

$E_T^{miss}$ spectrum in data for events with a lepton pair with $m_{ll} \sim m_Z$ well described (over 5

a real challenge for the LHC and its experiments!

Note: d

a

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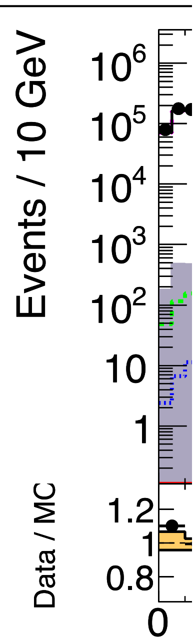
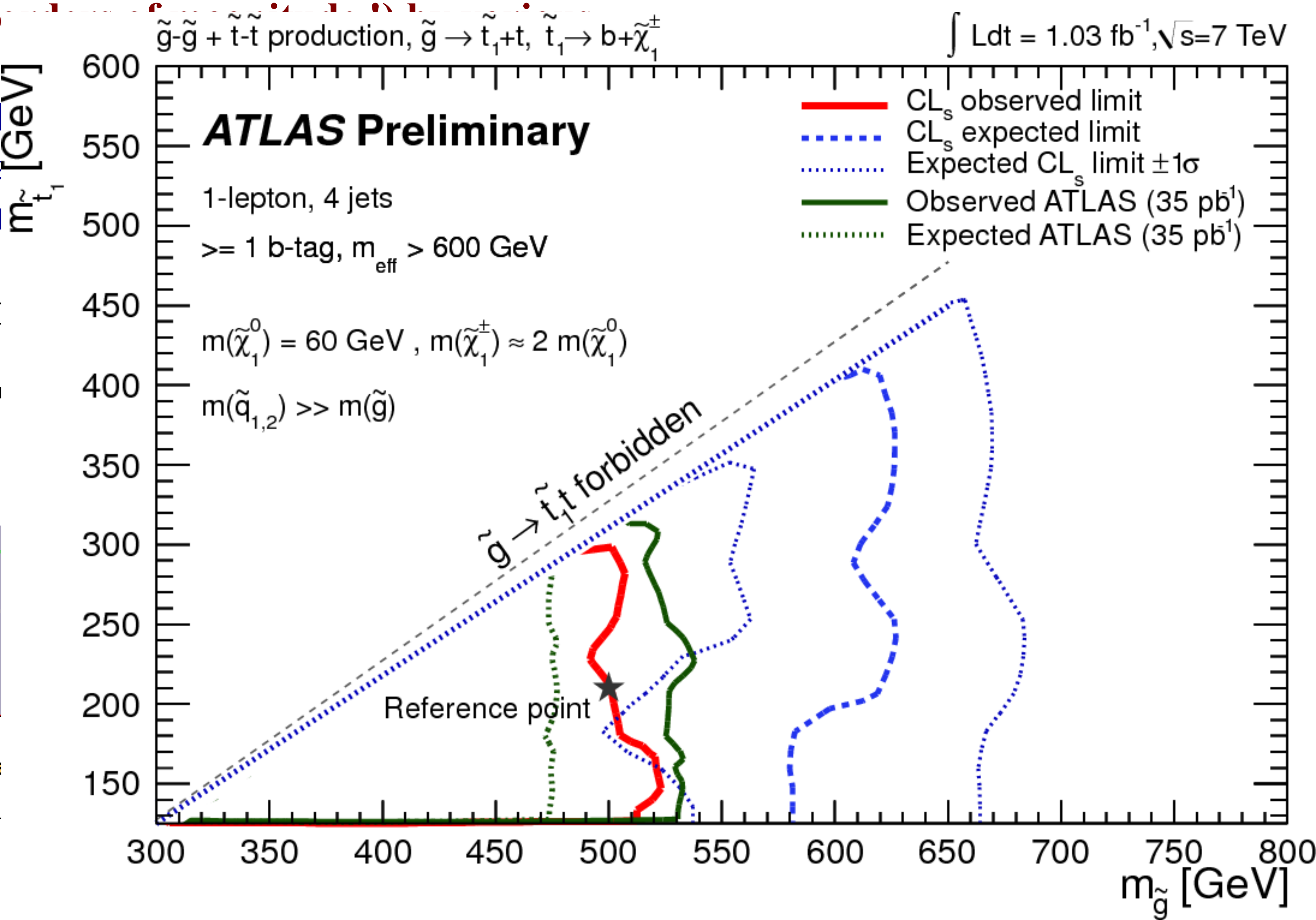
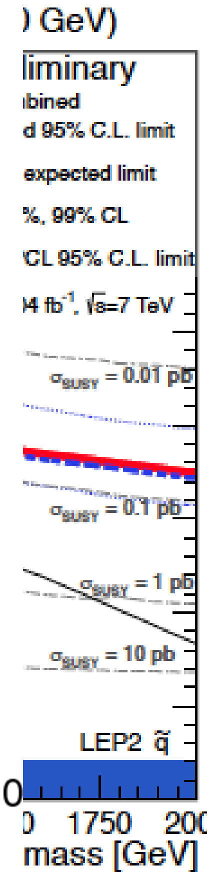
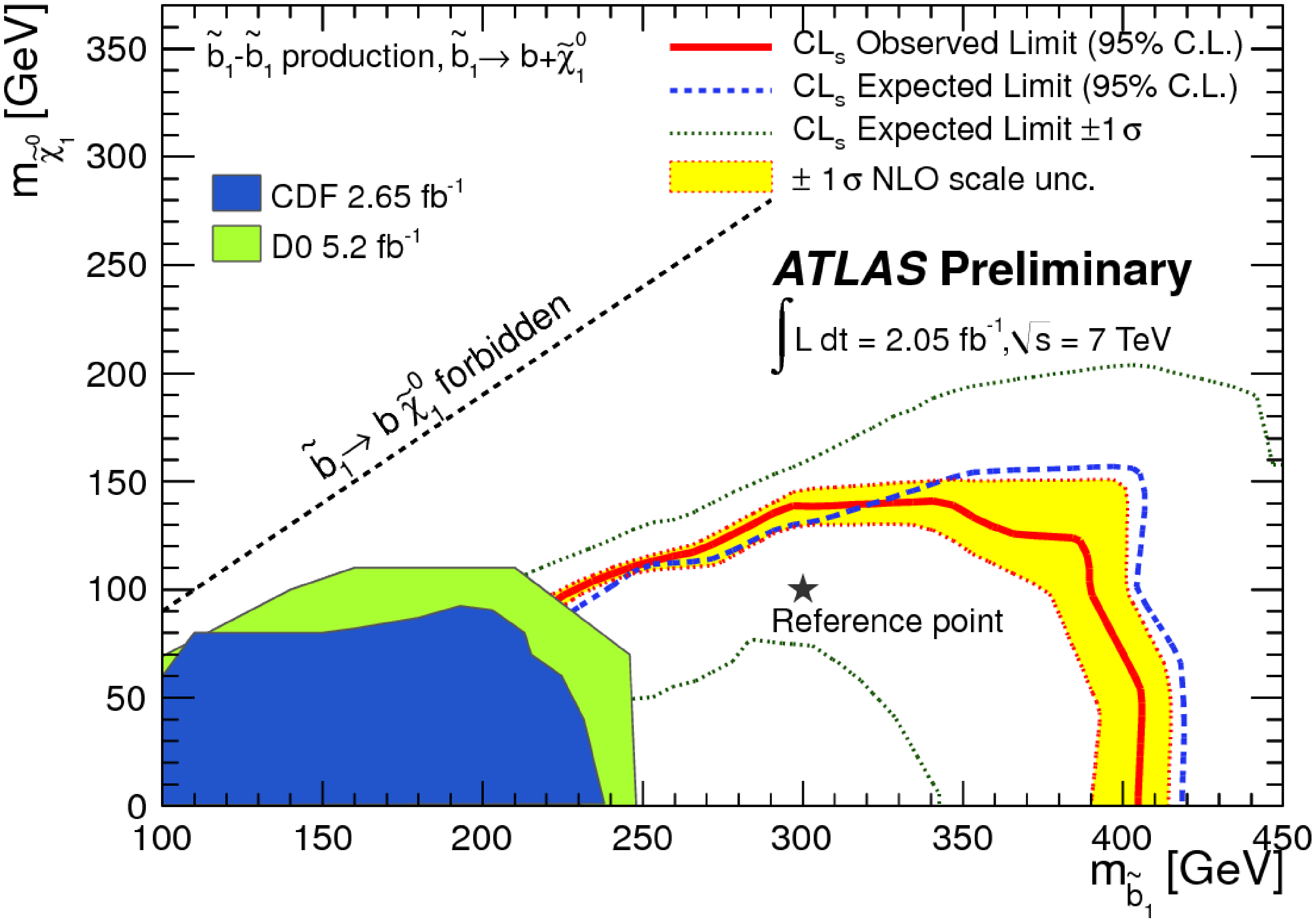






# SUSY searches: comparisons to theory

- **Theoretical uncertainties: why include them in the limits?**



# SUSY searches: comparisons to theory

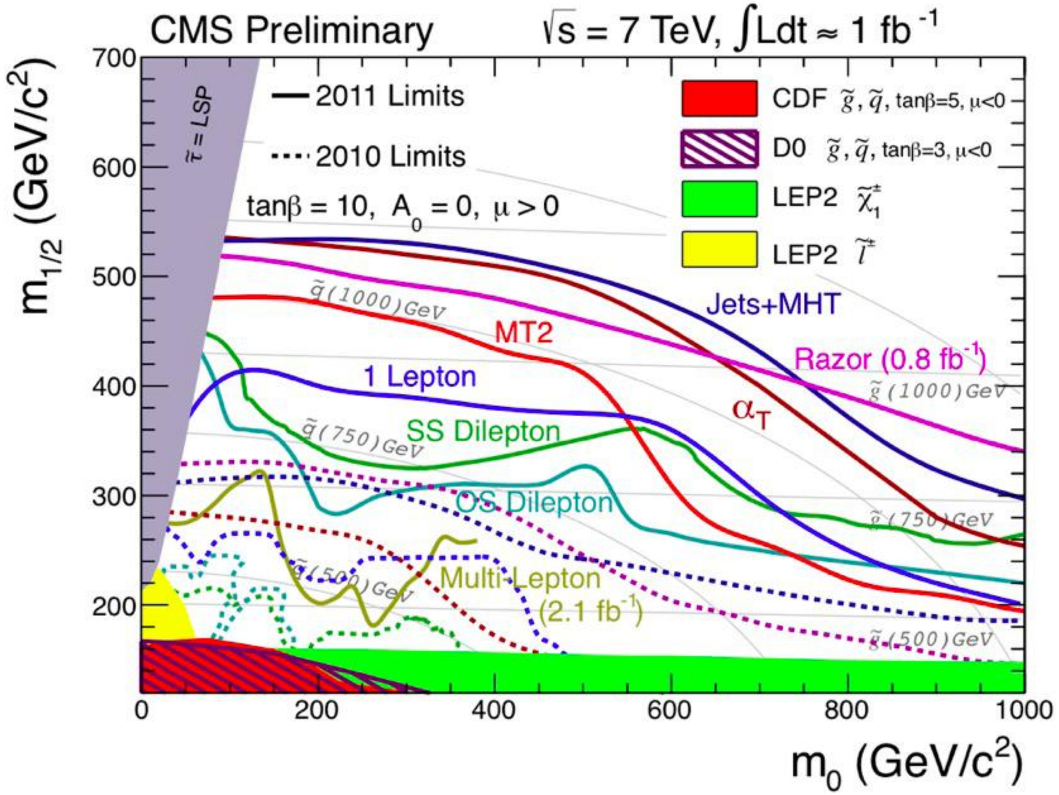
- Theoretical uncertainties: why include them in the limits?
- If one thinks about it, there is really no reason to do this!

As an experimentalist, I want to publish a result which does not have to be recomputed each time a new (NLO+NLL) calculation is made available

But there is also a deeper reason: there are many more theoretical uncertainties than meet the eye at first glance:

- SUSY breaking mechanism itself
- RGE solving (or predicting the mass spectrum): ATLAS uses ISAJET and CMS SOFTSUSY
- Treatment of ISR near kinematic boundaries
- Factorisation scale μ
- PDFs
- Gaussian nuisance parameters??

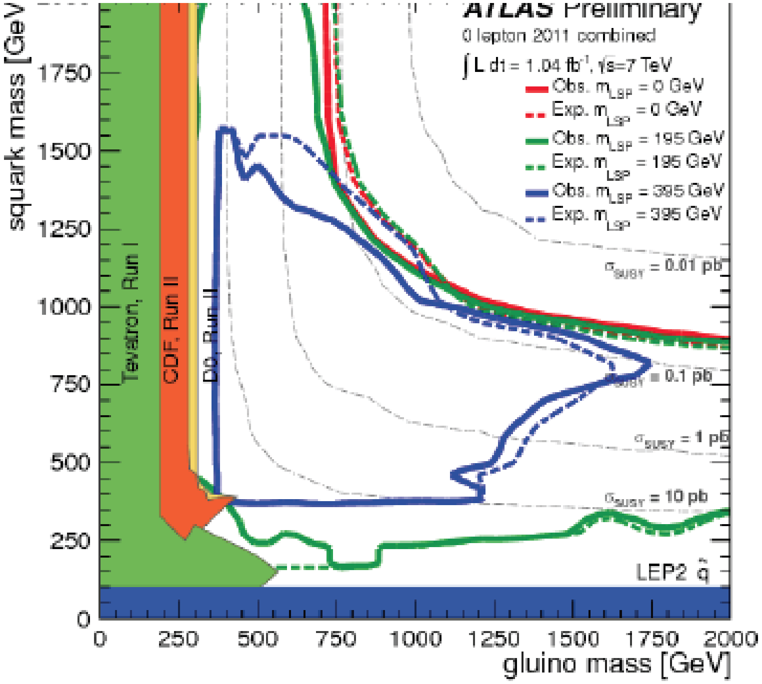
So the most important thing is to state clearly what has been done.



D. Froidevaux, CERN

# SUSY searches: comparisons to theory

- Theoretical uncertainties: why include them in the limits?
- What about the simplified models? They help to explore the strengths and weaknesses of our analyses
- But, they can only be indicative since they assume 100% BR into one exclusive final state
- In addition, analysis using such models is risky: the main background to exclusive SUSY final states is SUSY itself. So beware in particular contamination of control regions by SUSY signal from other processes not considered in analysis.



red: r

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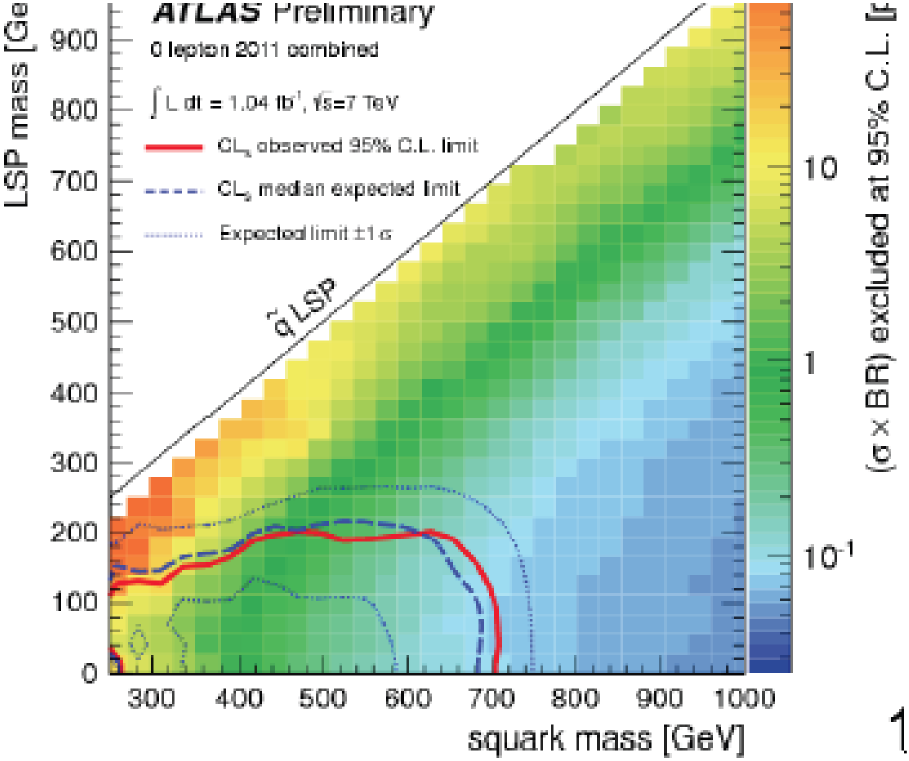
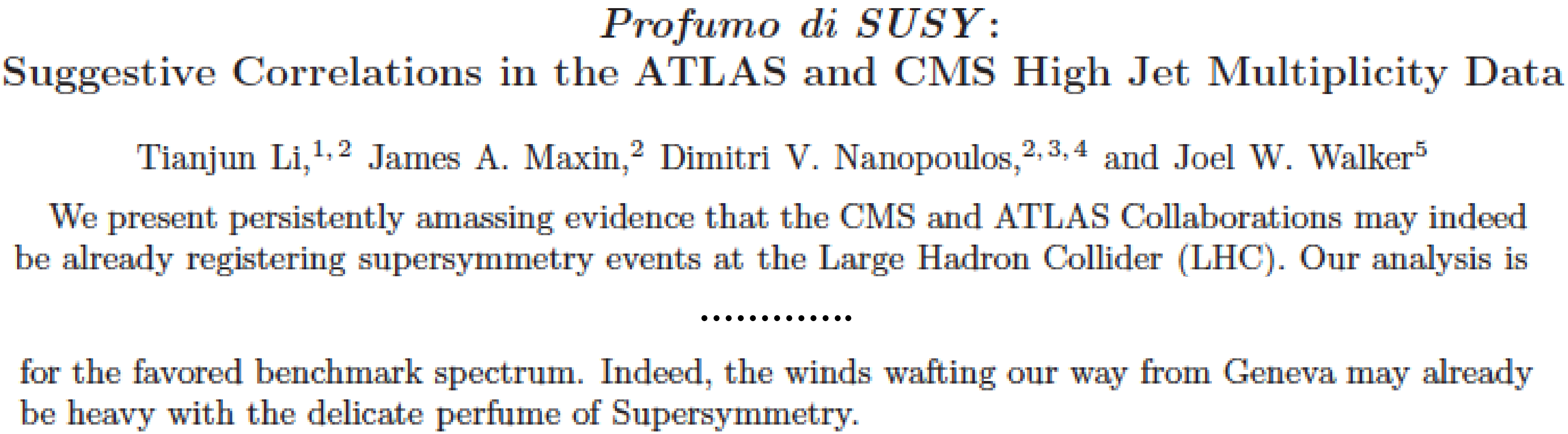
blue:



# SUSY searches: comparisons to theory

- **What is bad practice from theorists? To reinterpret data without having the required tools at hand.**
- **Take eg [http://arxiv.org/abs/1111.4204](http://arxiv.org/abs/1111.4204)**



*Profumo di SUSY*:
Suggestive Correlations in the ATLAS and CMS High Jet Multiplicity Data

Tianjun Li,[1,2] James A. Maxin,[2] Dimitri V. Nanopoulos,[2,3,4] and Joel W. Walker[5]

We present persistently amassing evidence that the CMS and ATLAS Collaborations may indeed be already registering supersymmetry events at the Large Hadron Collider (LHC). Our analysis is

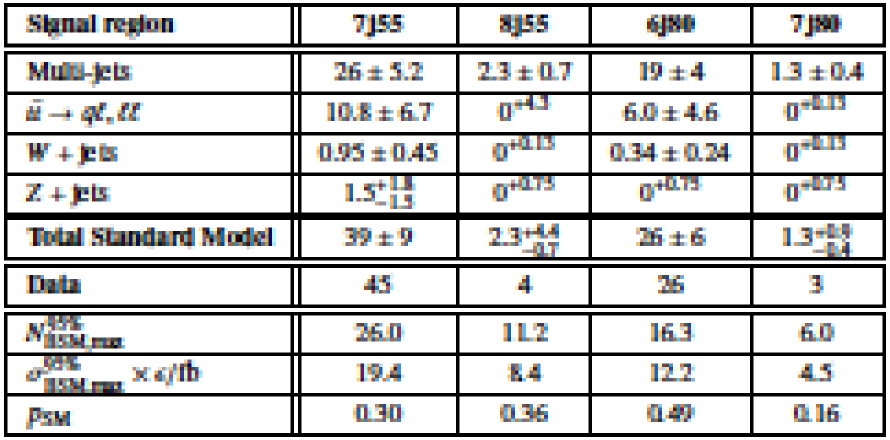
…………

for the favored benchmark spectrum. Indeed, the winds wafting our way from Geneva may already be heavy with the delicate perfume of Supersymmetry.

**The analyses of multijet+$E_T^{miss}$ data in CMS and ATLAS are over-interpreted to announce that these results favour a flipped SU(5) SUSY model which has certain attractive features but which is totally unsupported by any data so far (in my opinion).**

# SUSY searches: comparisons to theory

- What does the ATLAS multijet+ETmiss paper state?
- Look at http://arxiv.org/abs/1110.2299
- The data are compatible with SM in all the signal regions
- Therefore one can infer the limits shown in the plot



| Signal region | 7j55 | 8j55 | 6j80 | 7j80 |
|---|---|---|---|---|
| Multi-jets | $26 \pm 5.2$ | $2.3 \pm 0.7$ | $19 \pm 4$ | $1.3 \pm 0.4$ |
| $t\bar{t} \to q\ell, \ell\ell$ | $10.8 \pm 6.7$ | $0^{+4.3}$ | $6.0 \pm 4.6$ | $0^{+0.15}$ |
| $W$ + jets | $0.95 \pm 0.45$ | $0^{+0.15}$ | $0.34 \pm 0.24$ | $0^{+0.15}$ |
| $Z$ + jets | $1.5^{+1.8}_{-1.5}$ | $0^{+0.75}$ | $0^{+0.75}$ | $0^{+0.75}$ |
| Total Standard Model | $39 \pm 9$ | $2.3^{+4.4}_{-0.7}$ | $26 \pm 6$ | $1.3^{+0.9}_{-0.4}$ |
| Data | 45 | 4 | 26 | 3 |
| $N^{95\%}_{\mathrm{BSM,max}}$ | 26.0 | 11.2 | 16.3 | 6.0 |
| $\sigma^{95\%}_{\mathrm{BSM,max}} \times \epsilon$/fb | 19.4 | 8.4 | 12.2 | 4.5 |
| $p_{\mathrm{SM}}$ | 0.30 | 0.36 | 0.49 | 0.16 |

Table 2: Results for each of the four signal regions for 1.34 fb$^{-1}$. The expected number of Standard Model events are given for each of the following sources: multi-jet (including fully hadronic $t\bar{t}$), semi- and fully-leptonic top combined, and $W$ and $Z$ bosons (separately) in association with jets, as well as the total Standard Model expectation. Where small event counts in control regions have not made it possible to determine a central value for the expectation, an asymmetric bound is given instead. The number of observed events is also shown. The final three rows show the statistical quantities described in the text.

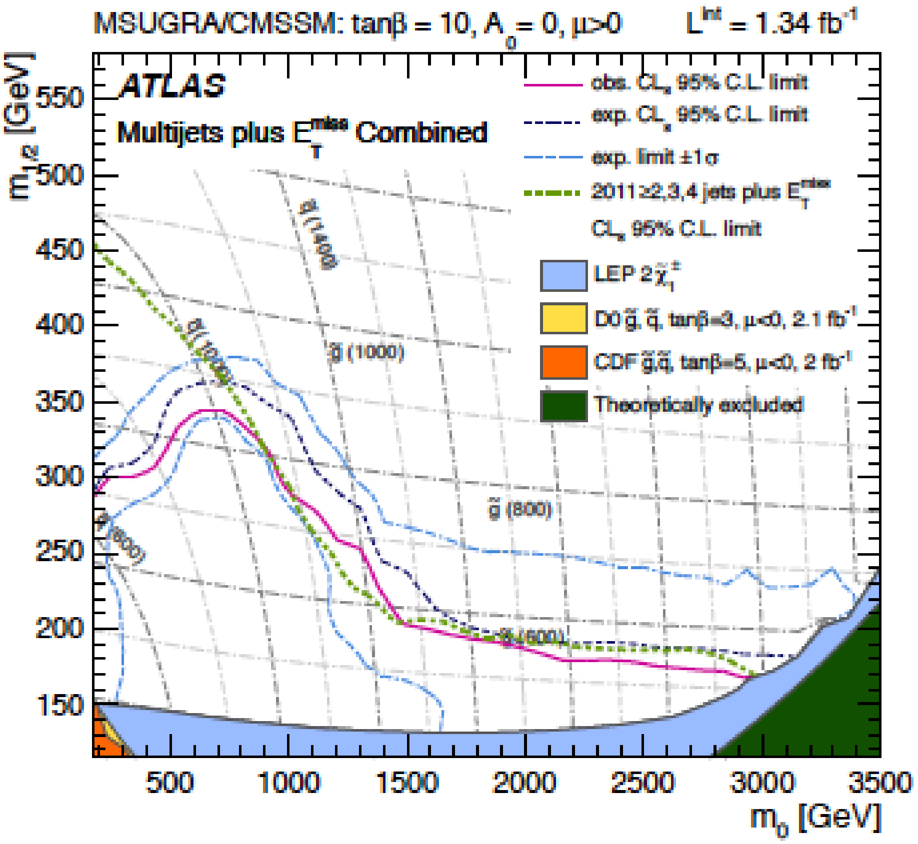
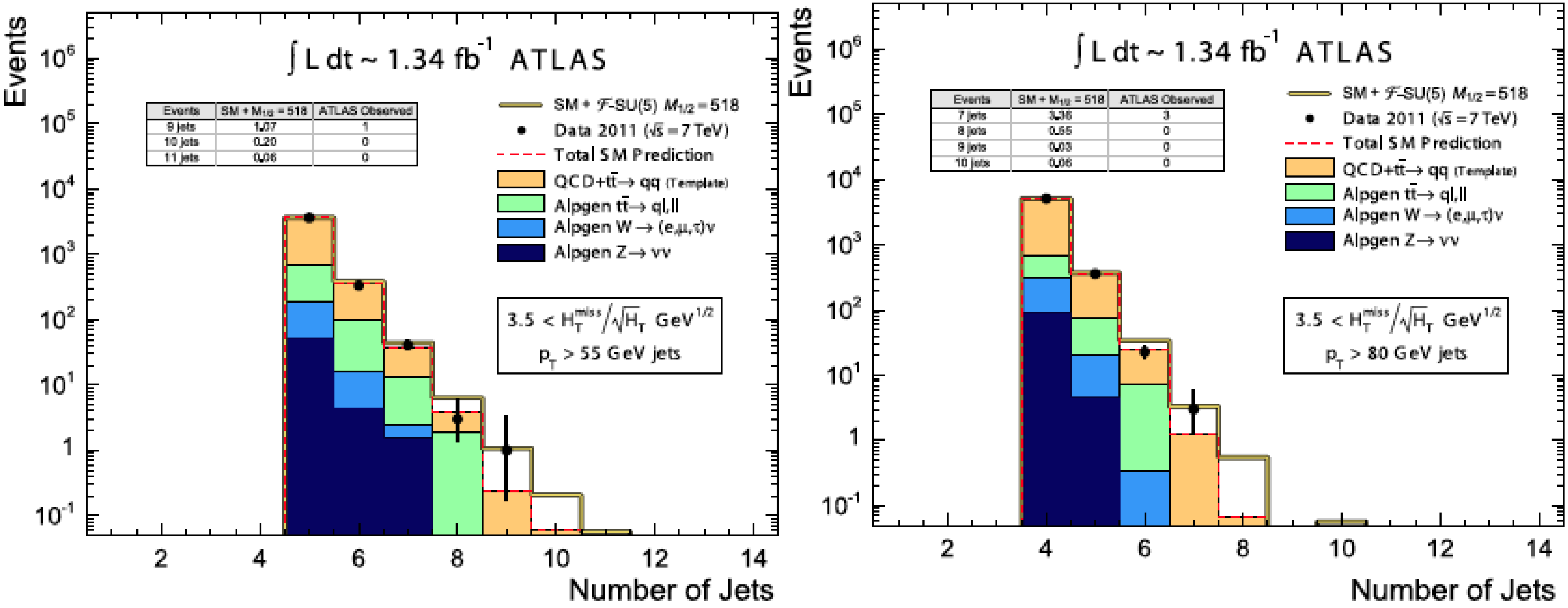


Figure 5: Combined exclusion bounds in the tan $\beta$ = 10, $A_0 = 0, \mu > 0$ slice of the MSUGRA/CMSSM space. Gluinos with masses below 520 GeV, and gluinos with masses below 680 GeV under the assumption that $m_{\mathrm{squark}} = 2 \times m_{\mathrm{gluino}}$ are excluded at the 95% confidence level. Limits from individual SRs can be found elsewhere [36]. Recent limits from ATLAS [5], as well as previous limits from D0 and CDF [37] and LEP [38] are also shown.

# SUSY searches: comparisons to theory

- **What does this paper attempt to do? It first adds a theory distribution on top of the published data without knowing the differential acceptances, and then it extrapolates the result from 1.34 fb$^{-1}$ to 5 fb$^{-1}$ without any statistical treatment!**



| Events | SM + $M_{1/2}$ = 518 | ATLAS Observed |
|---|---|---|
| 9 jets | 1.07 | 1 |
| 10 jets | 0.20 | 0 |
| 11 jets | 0.06 | 0 |

| Events | SM + $M_{1/2}$ = 518 | ATLAS Observed |
|---|---|---|
| 7 jets | 3.36 | 3 |
| 8 jets | 0.65 | 0 |
| 9 jets | 0.03 | 0 |
| 10 jets | 0.06 | 0 |

FIG. 2: The ATLAS signal and background statistics for $H_T^{\rm miss}/\sqrt{H_T} \geq 3.5$ for 1.34 $fb^{-1}$ of integrated luminosity at $\sqrt{s} = 7$ TeV, as presented in [6], are reprinted with an overlay consisting of a Monte Carlo collider-detector simulation of the No-Scale $\mathcal{F}$-$SU(5)$ model benchmark $M_{1/2}$=518 GeV for $p_T > 55$ GeV (left) and $p_T > 80$ GeV (right). The plot counts events per jet multiplicity. The Monte Carlo overlay consists of the $\mathcal{F}$-$SU(5)$ supersymmetry signal plus the Standard Model background, thus permitting a direct visual evaluation against the ATLAS observed data points.

5 $fb^{-1}$ for $p_T > 80$ GeV and $H_T^{\rm miss}/\sqrt{}$

Number of Jets

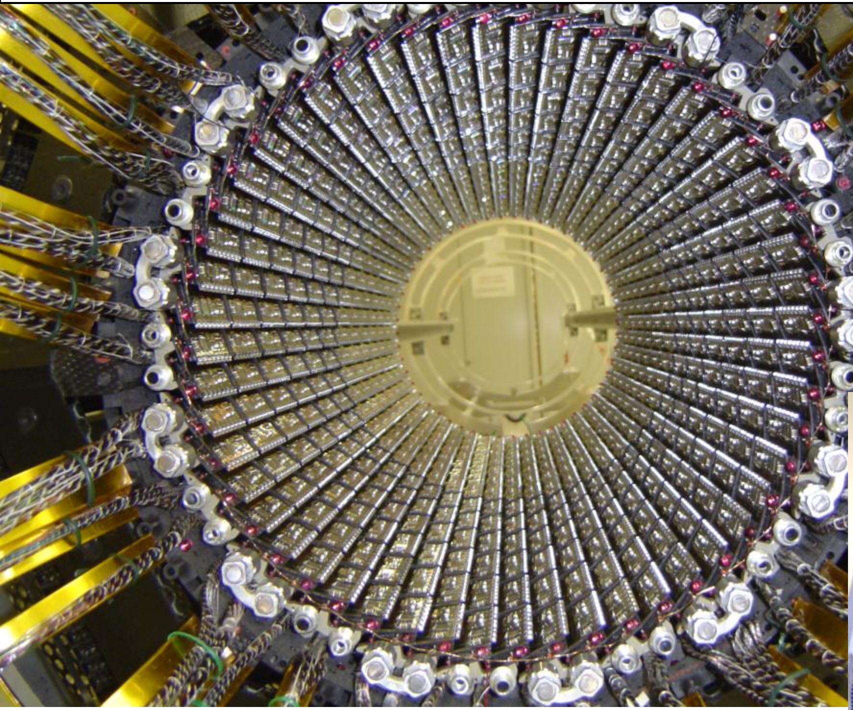
# SUSY searches: comparisons to theory

- More interestingly then, what is good practice from both theorists and experimentalists? To talk together and to make sure with time that we all speak the same language and that data meets theory in a clear field.
- This is actually very difficult for searches, unlike the precision measurements discussed in the earlier slides: the reason is that unfolding the experimental effects to publish fiducial cross-section limits is almost impossible in the case of SUSY and that there are too many possible signatures and model parameters as soon as one goes away from pure SUGRA. But we should certainly try for e.g. monojets.
- Take eg http://arxiv.org/pdf/1110.6926 and http://arxiv.org/pdf/1110.6444 as good examples of working together between theory and experiment (many others!)
- At the very minimum, the experiments will have to publish in HEPDATA the following information for a specific signature based on experimental (not truth!) observables passing certain selection cuts in a certain region of SUSY parameter space:

- the number of SM background events expected and the number of observed events with the p-value for a background-only hypothesis
- the total experimental systematic uncertainty on the number of observed events
- the efficiencies and acceptances for each signal sub-process of interest
- the cross-sections used for each signal sub-process of interest
- the theoretical uncertainties assumed (hopefully not included in the limit setting!)

# We must remain humble!
# Remember that tracking at the LHC is a risky business!

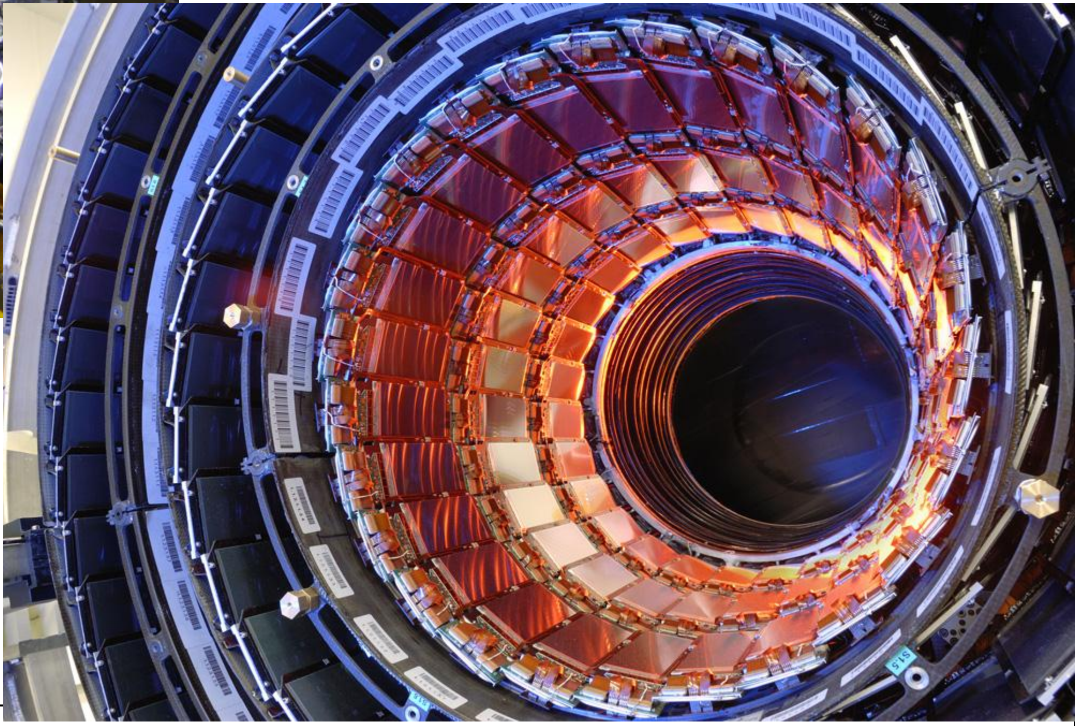
## ATLAS pixels, September 2006



- All modules and services integrated and tested
- 80 million channels !
- 10%-scale system test with cosmics done at CERN
- Inst. in ATLAS: June 2007

## CMS silicon strips

- 200 $m^2$ Si, 9.6 million channels
- 99.8% fully operational
- Signal/noise ~ 25/1
- 20% cosmics test under way
- Inst. in CMS: August 2007



CMS Tracker Inner Barrel, November 2006

# What next?

Should one fear that experimental particle physics is an endangered species with its gigantic scale and long time-scales?

- The front-wave part of this field is becoming too big for easy continuity between the generations. I have been working on LHC for 25 years already. Most of the analysis will be done by young students and postdocs who have only a vague idea what the 7000 tonnes of ATLAS is made of. More importantly, fewer and fewer people remember for example that initially most of the community did not believe tracking detectors would work at all at the LHC.
- The stakes are very high: one cannot afford unsuccessful experiments (shots in the dark) of large size, one cannot anymore approve the next machine before the current one has yielded some results and hopefully a path to follow
- Theory has not been challenged nor nourished by new experimental evidence for too long (in front-line high-energy physics, because neutrino oscillations are of course the single but major counter-example!

# What next?

This is why the challenge of the LHC and its experiments is so exhilarating! A major fraction of the future of our discipline hangs on the physics which will be harvested at this new energy frontier.
How ordinary or extraordinary will this harvest be? Only nature knows. No promises, no crystal ball …

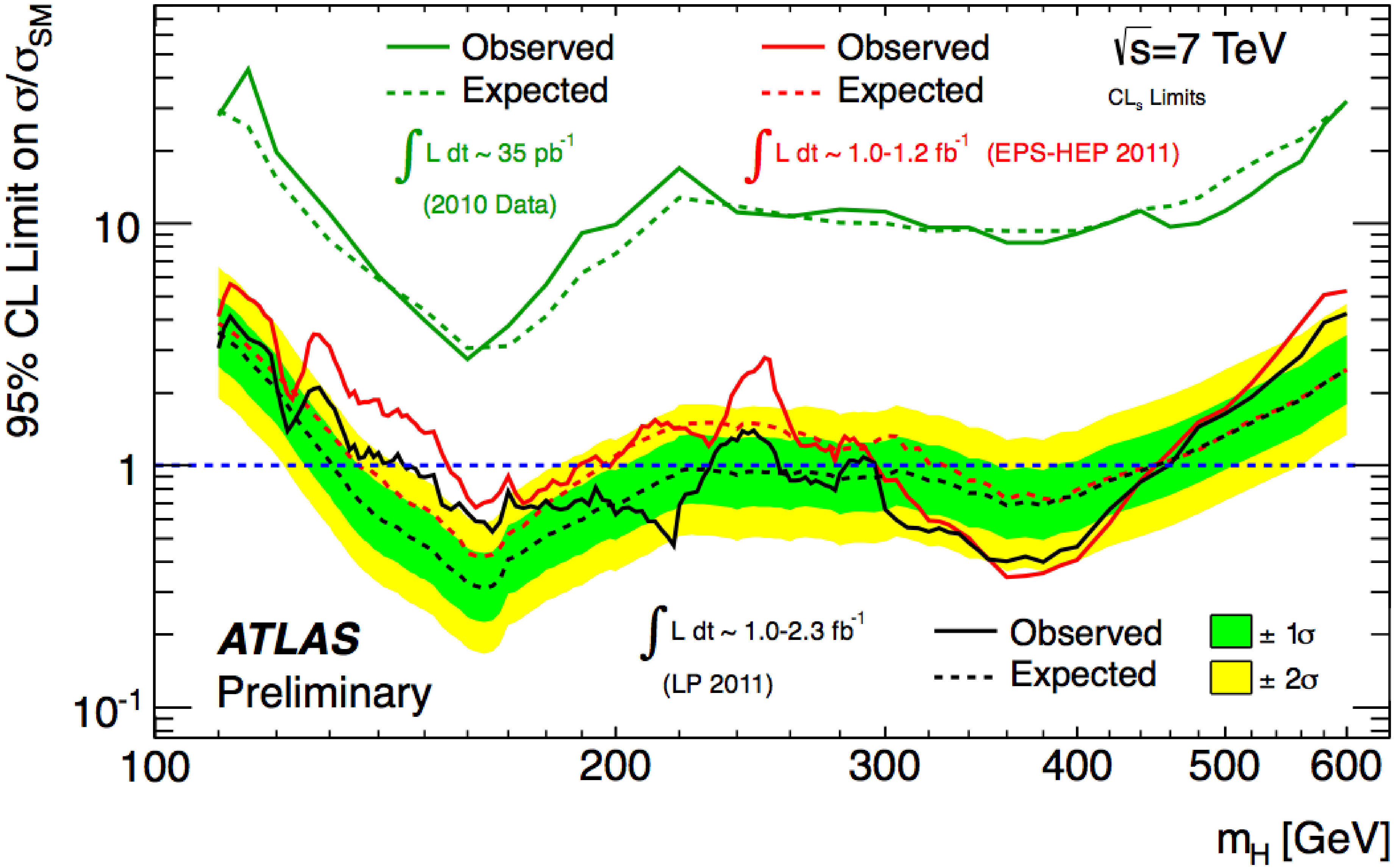
The large instruments built for the LHC by huge international collaborations are now operational and delivering a wide variety of exploratory and precision physics results. They are the end product of extraordinary technological challenges: their solution has been possible only thanks to the progress realised world-wide in extremely diverse areas. But the first and foremost motivation in all of this is our desire to understand better our universe.

Many thanks to all my colleagues who helped me with this talk!

# Back-up slides

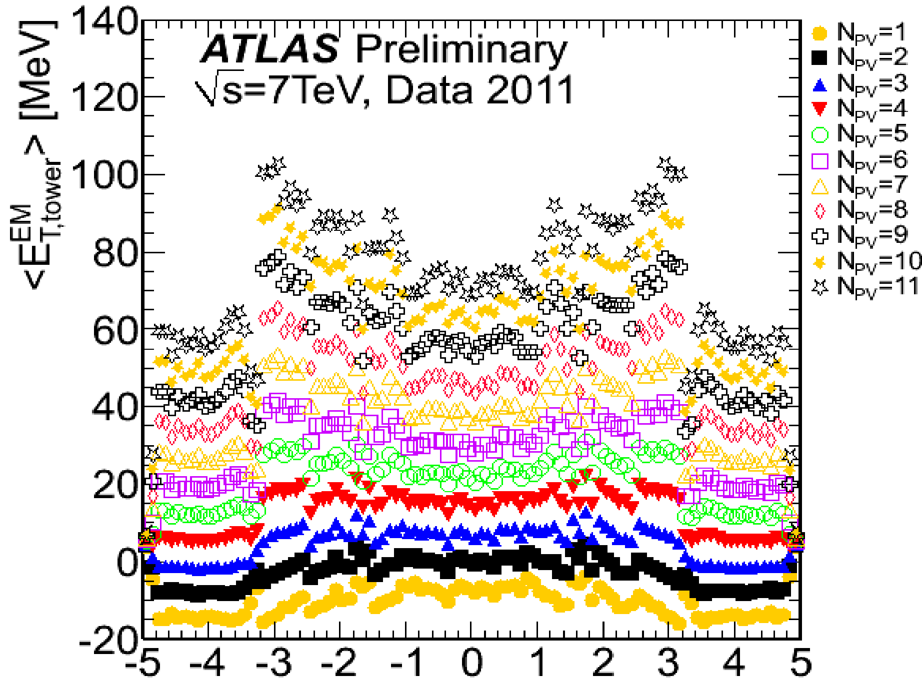
# ATLAS status report: what about the hunt for the Higgs boson?

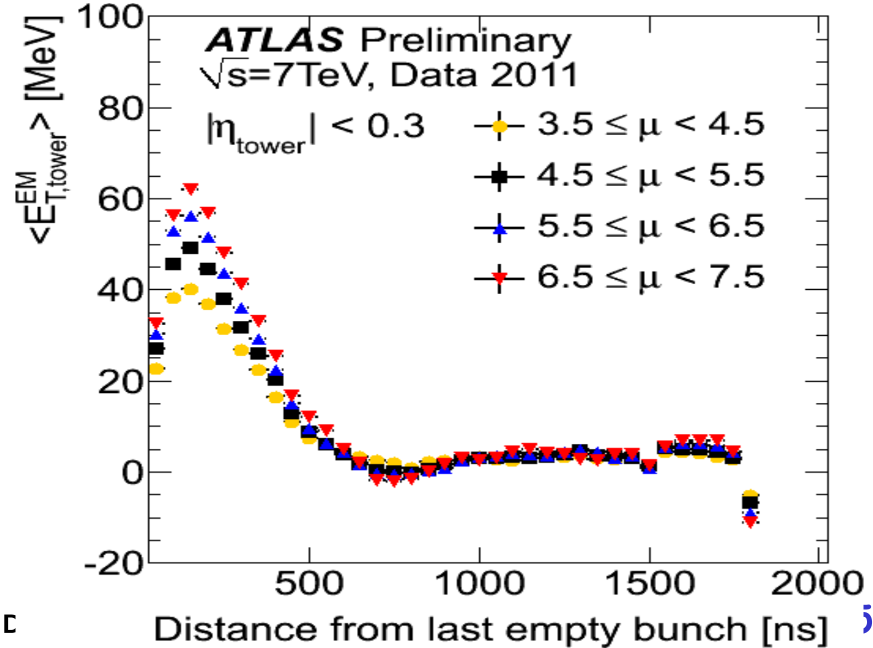
## Search for the Higgs boson: huge progress over 2011. More to come.

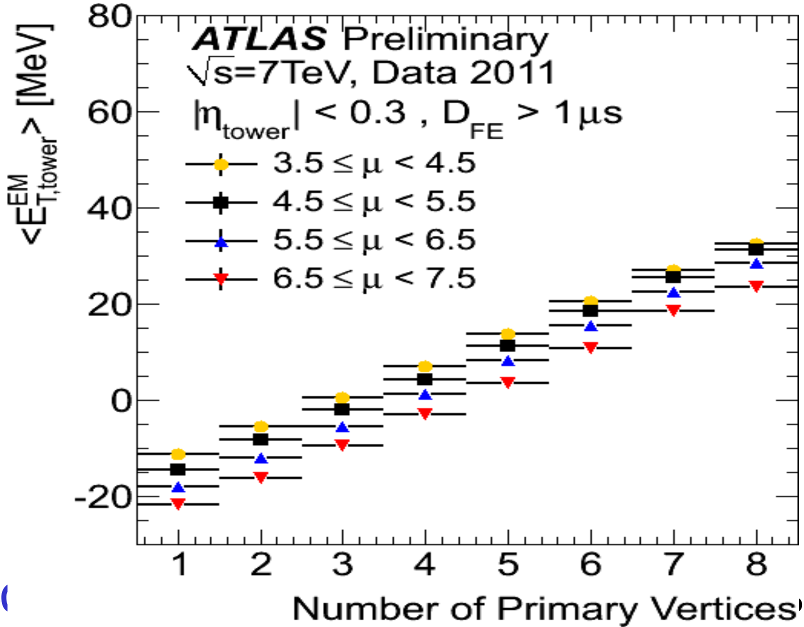


# ATLAS reconstruction: impact of pile-up

- Effective noise per cell/tower increases as pile-up increases (many towers in a jet!)
- Optimal performance will require correction per cell type in η-bins and as a function of luminosity to set average measured $E_T$ to ~ 0
- At the moment, introduce increased jet energy scale uncertainty for low-$p_T$ jets (at maximum 7% for jets in forward calo)

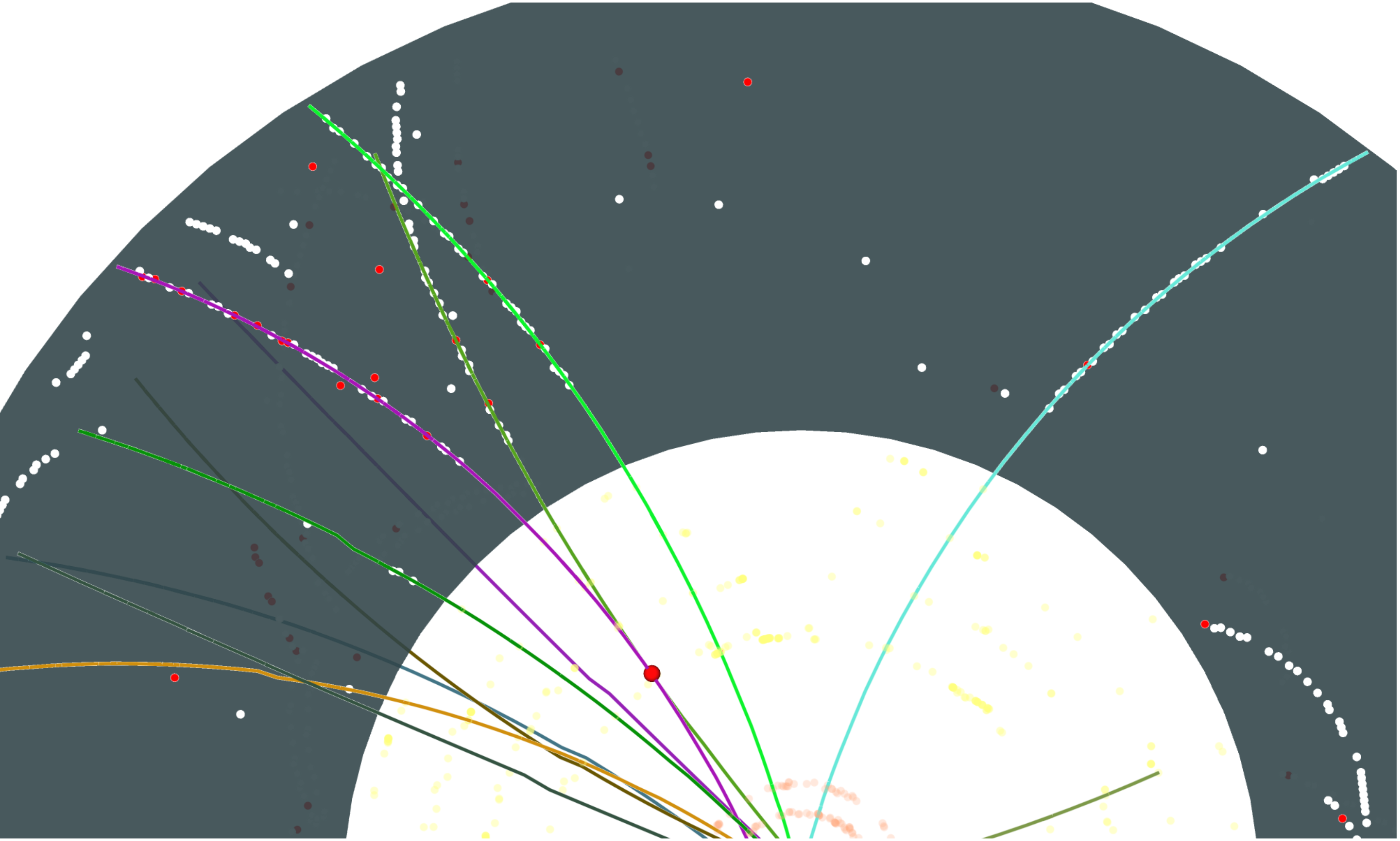






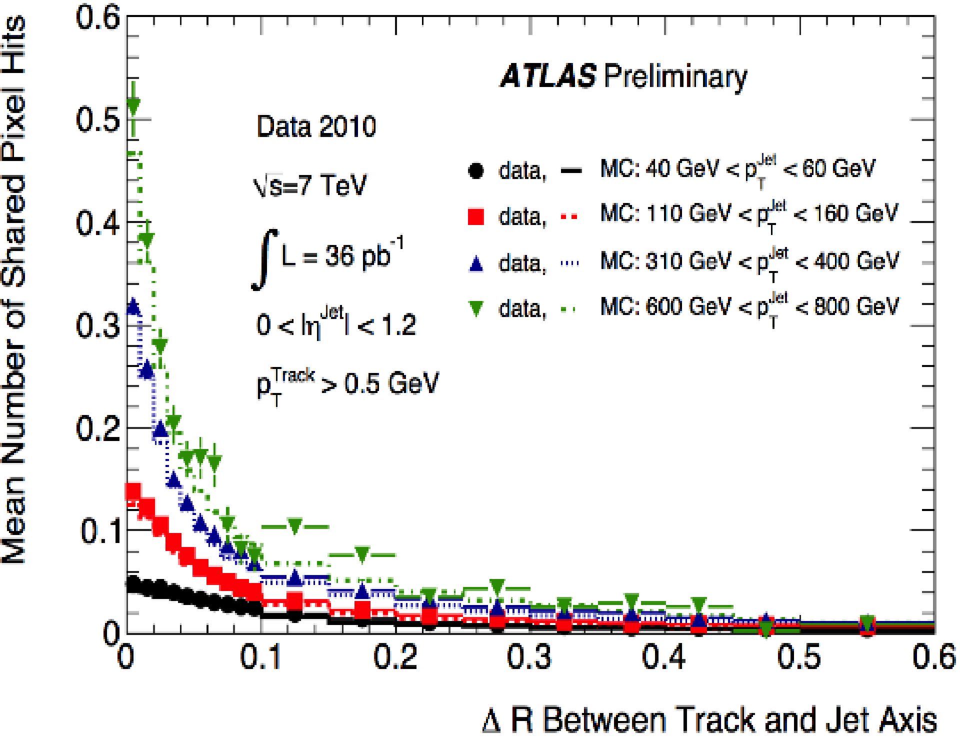
# Electrons from photon conversions

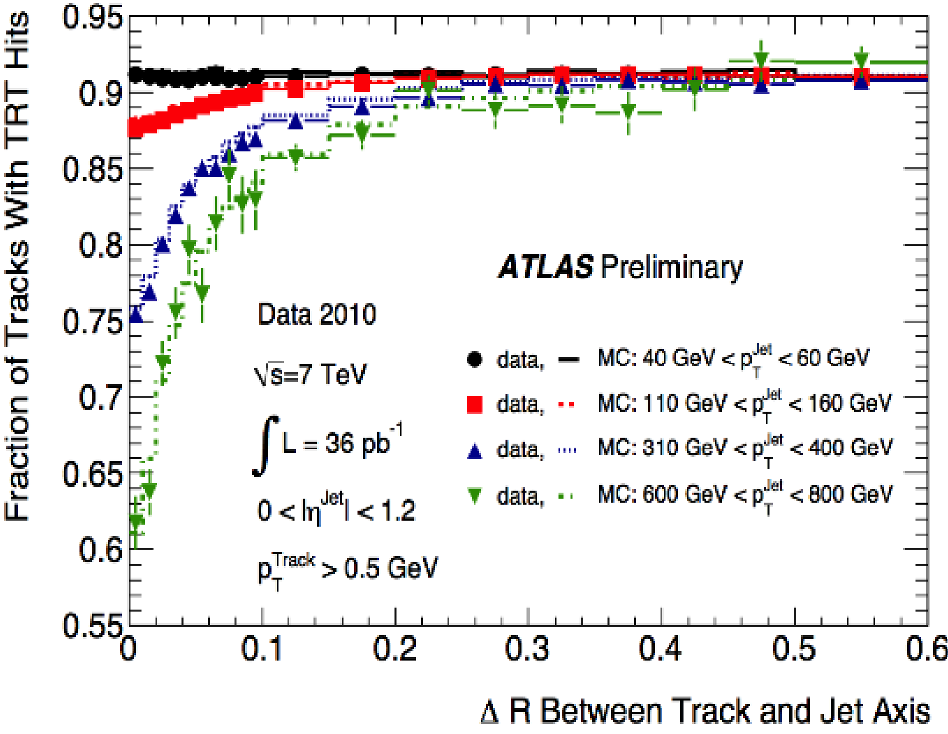
- TRT very powerful to track secondaries and then identify which ones are conversions. A few beautiful examples shown here for the pleasure of the eye.



# Tracking in jets: a step towards measuring jet fragmentation

- Even though jet fragmentation properties have been measured precisely at LEP at and near the Z pole, there is room for constraining the various models in terms of the parameters specific to hadron collider physics and over a much wider kinematic range than at LEP
- Need first to establish the tracking performance inside jets, and in particular as a function of the distance of the track to the jet axis and of the jet $p_T$
- Since end August, improved pixel clustering commissioned and operational at Tier-0 for bulk reconstruction (should result in decrease of number of shared pixel hits by a factor of ~ 4 near the axis of high-$p_T$ jets).





# Jet fragmentation measurements: a step towards improved JES?

- **Precise fragmentation function measurements now available and in good agreement with eg Pythia6 for 25 < $p_T^{jet}$ < 500 GeV.**
- **None of the current generators nor tunes agree well with all the transverse measurements ($p_T^{rel}$, wrt to jet axis, is shown below on the right) within their uncertainties.**
- **Large difference between HERWIG++ and Pythia dominates JES uncertainty at high $E_T$**

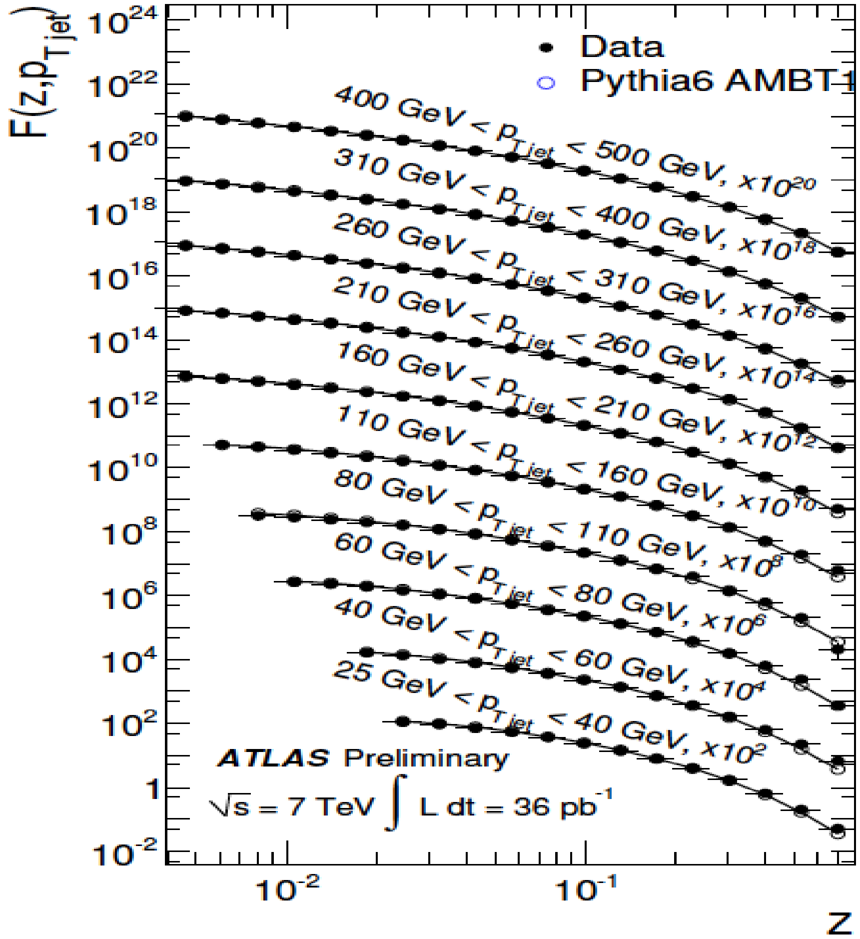


Fig. 5. Distributions of $F(z)$ in bins of $p_{T\,jet}$. The filled circles show unfolded data and the open circles and accompanying lines are the predictions from AMBT1 Pythia.

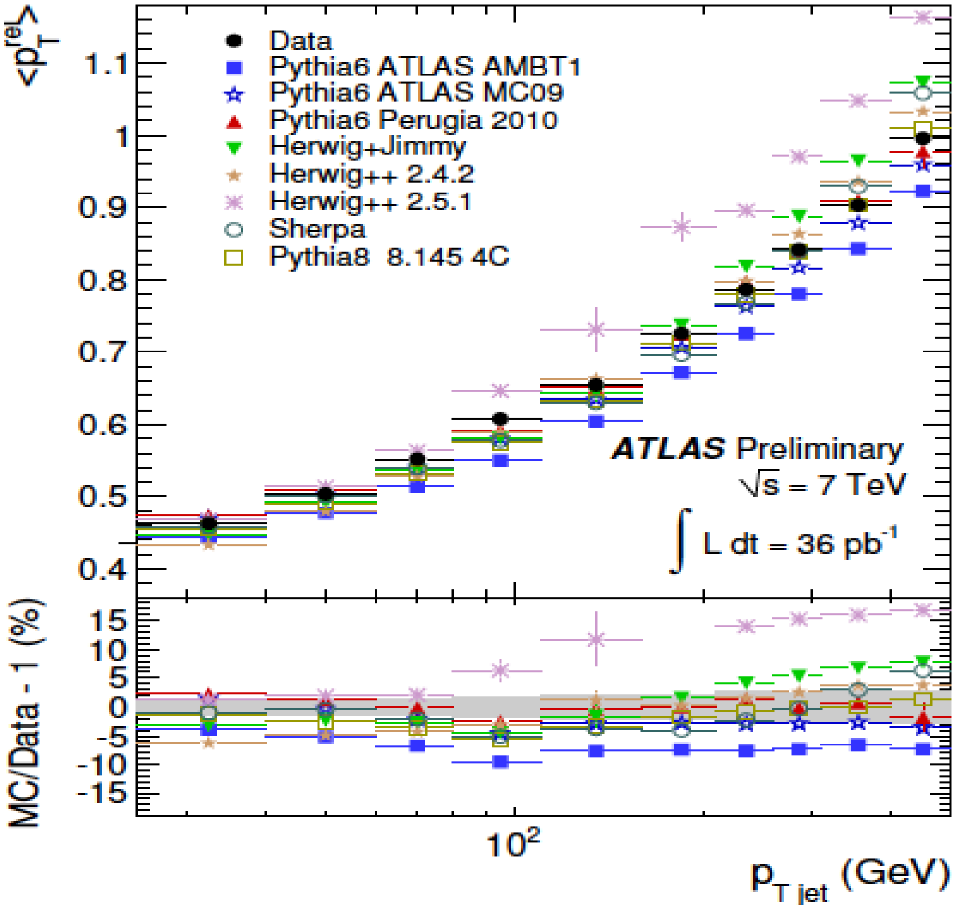


Fig. 14. Comparison of the measured value of the average value of $p_T^{rel}$ as a function of $p_{T\,jet}$ with various Monte Carlo expectations.

# SM physics: W/Z differential measurements

- **Differential distributions indicate that probing pdfs will perhaps be best achieved by using separately measurements for $W^+$, $W^-$ and Z as inputs to the fits**

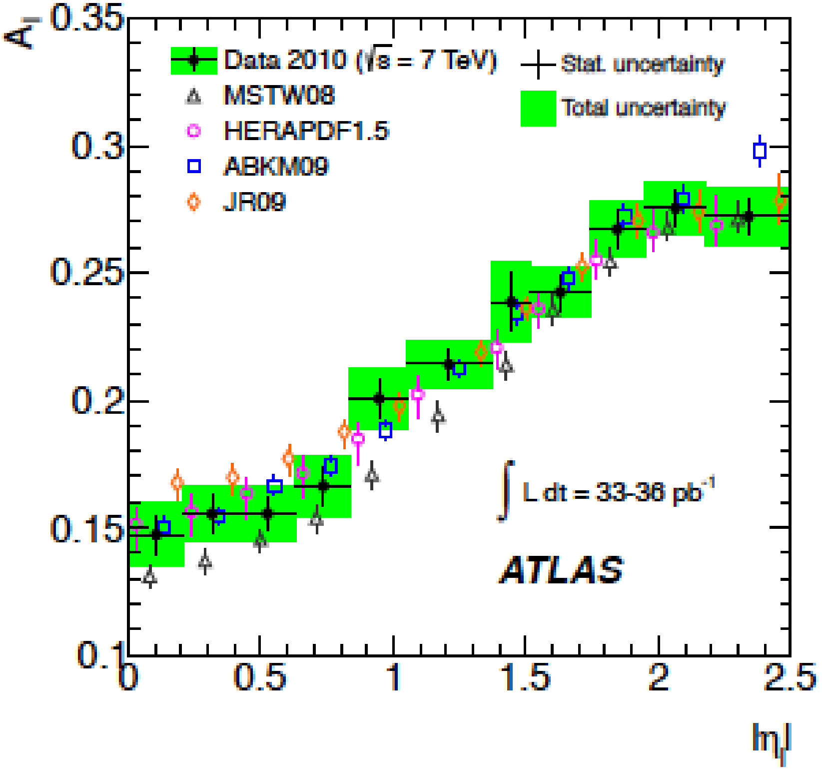
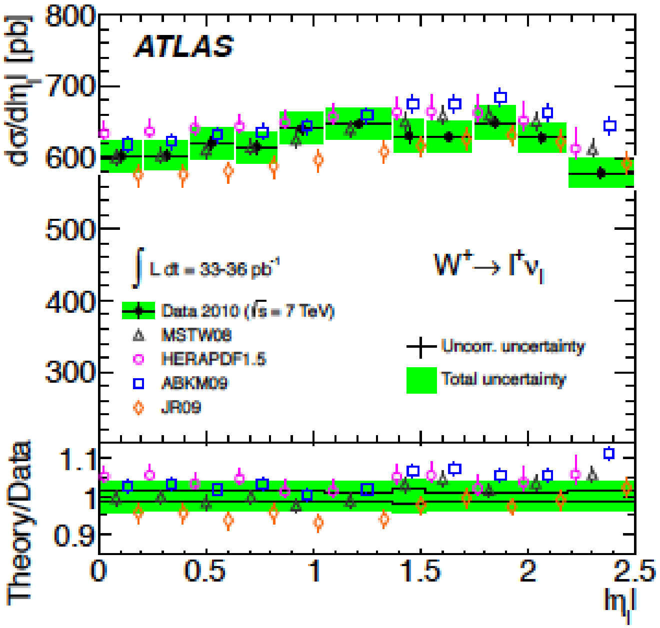
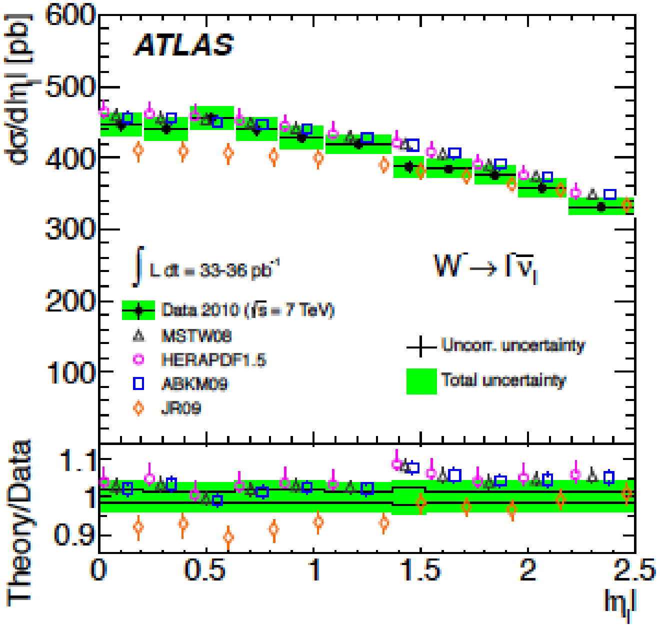


FIG. 14. *Measured W charge asymmetry as a function of lepton pseudorapidity* $|\eta_l|$ *compared with theoretical predictions calculated to NNLO. The kinematic requirements are* $p_{T,\ell} > 20$ GeV, $p_{T,\nu} > 25$ GeV *and* $m_T > 40$ GeV. *Theoretical points are displaced for clarity within each bin.*

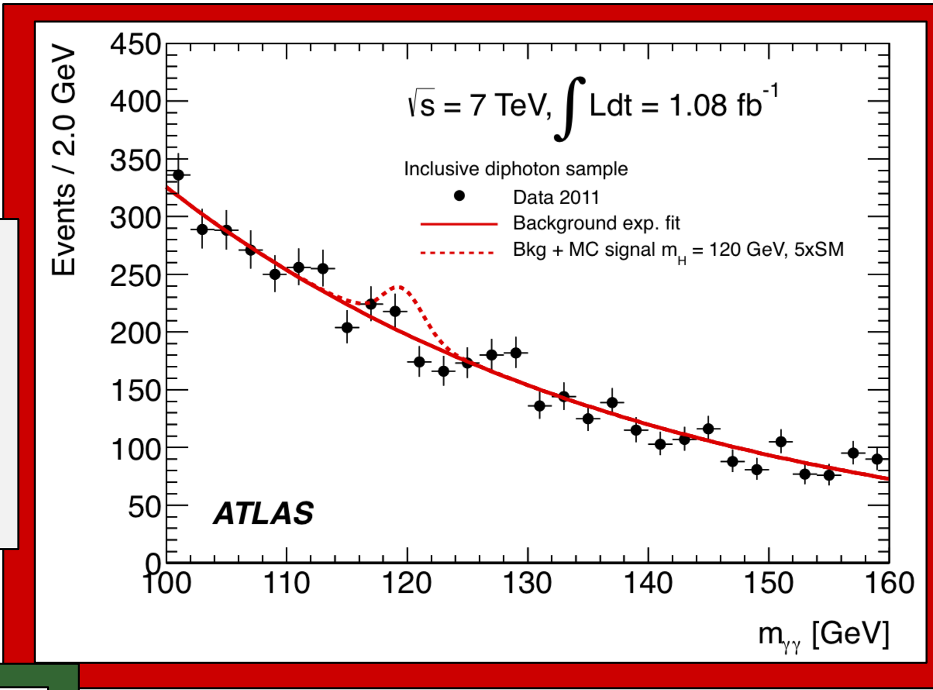


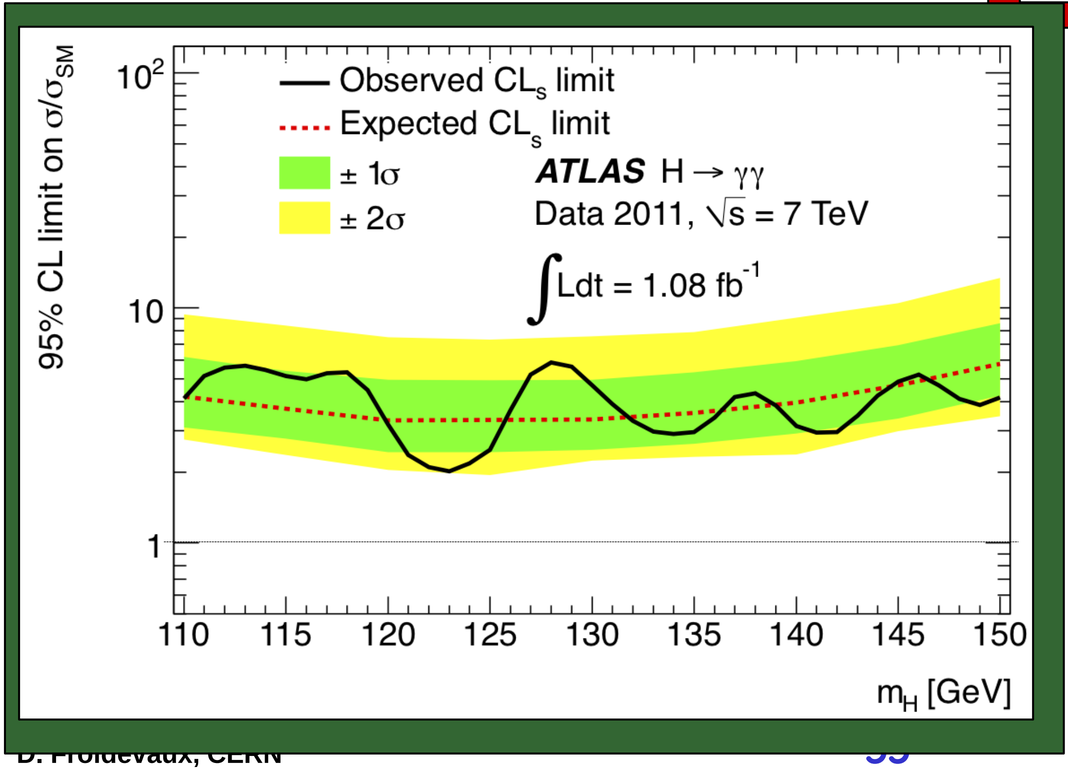


# H → γγ

**114 < $m_H$ ≤ 150 GeV**

**Signature is two high-$p_T$ photons**
**($E_T$ ($\gamma_1$, $\gamma_2$) > 40, 25 GeV)**
**σ ~ 40 fb**
**15 signal events expected in 1 $fb^{-1}$**
**after all selections**
**Main background: γγ continuum; S/B ~ 0.02**





**Crucial experimental aspects:**
**excellent γγ mass resolution to observe narrow signal peak above irreducible γγ background**
**($\sigma_{\gamma\gamma}$ ~ 1.7 GeV $m_H$=120 GeV)**
**powerful γ/jet separation to suppress γj and jj background with jet → $\pi^0$ faking single γ**

# Prospects for Higgs-boson searches

**More data:**

- ~ 4-5 $\text{fb}^{-1}$ by end of 2011 and > 10 $\text{fb}^{-1}$ by end of 2012

**Refine understanding of detector performance:**

- Alignment, calibration, comparison with simulation
- Better performance, smaller systematic uncertainties and higher efficiency for rare channels

**More precise measurements of SM processes**

- Additional constraints on MC generators

**More sophisticated analyses:**

- Multivariate techniques and additional discriminating variables ($p_T$, angular distributions)
- Exclusive channels (e.g. VBF channels)
- Higher statistics leading to sharper observables (e.g. H to $\tau\tau$ mass reconstruction for non back-to-back $\tau$-pairs)