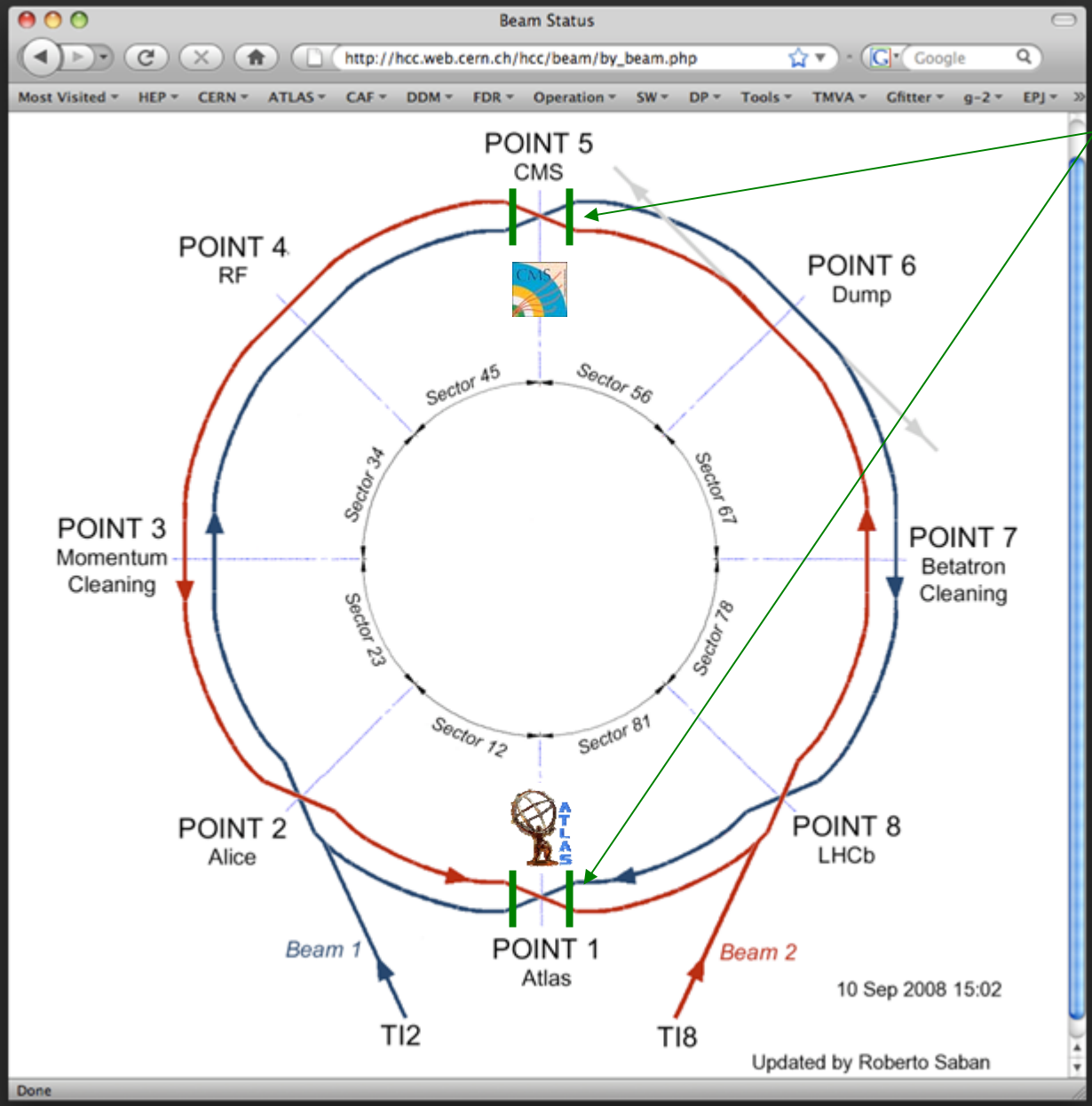
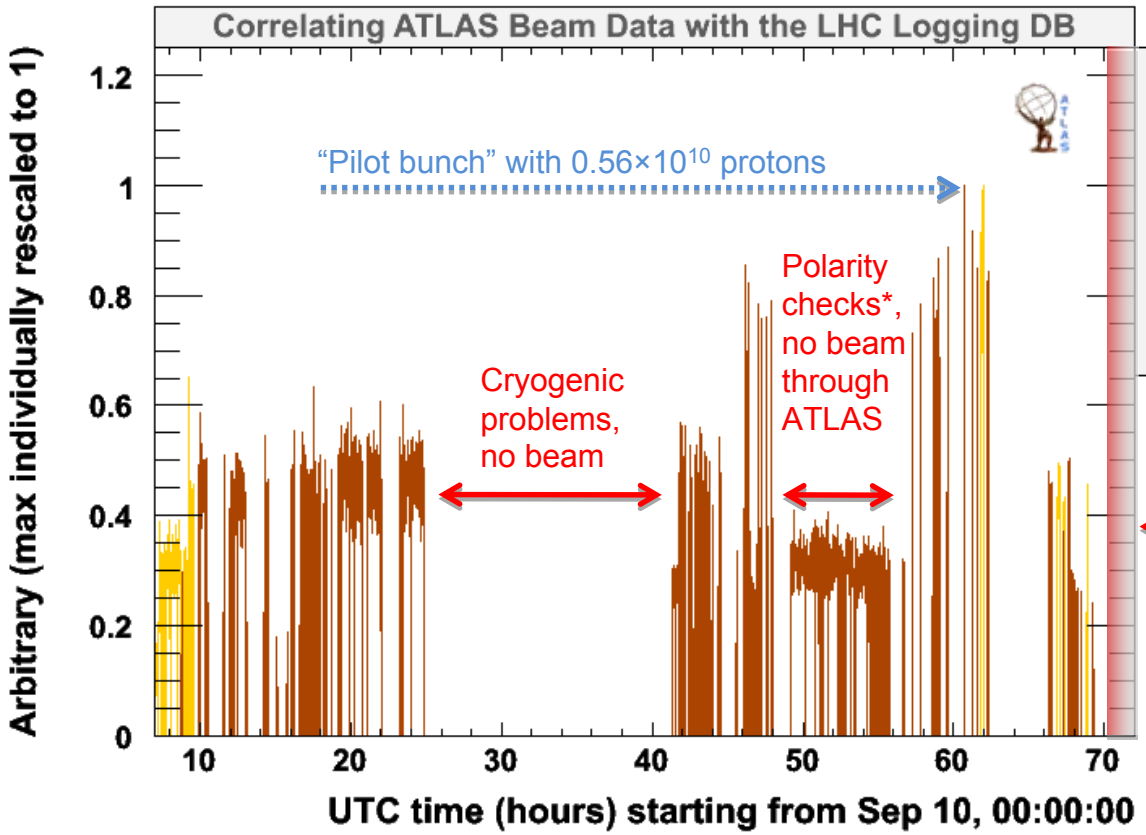
What happened ?



±140m before the detectors are collimators in both LHC beam lines, which – when closed – stop the beam

Sep 10 – 13: Beam History

- Beam injections into LHC through transfer lines TI2 (beam-1) and TI8 (beam-2)



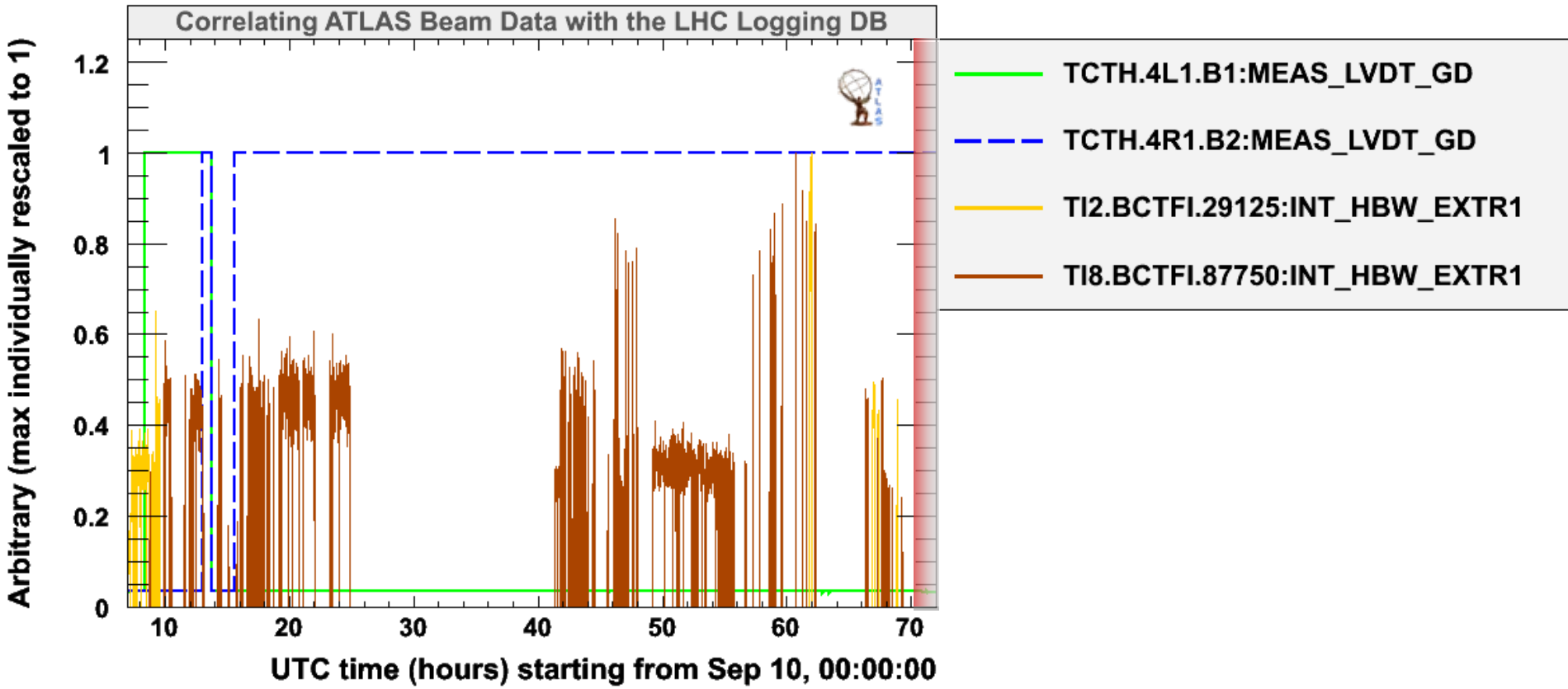
Followed by electrical failure with helium leak a week later.

Restart planned for Oct 2009

* Polarity checking scans verify multipole field order, type and polarity of the superconducting LHC magnets

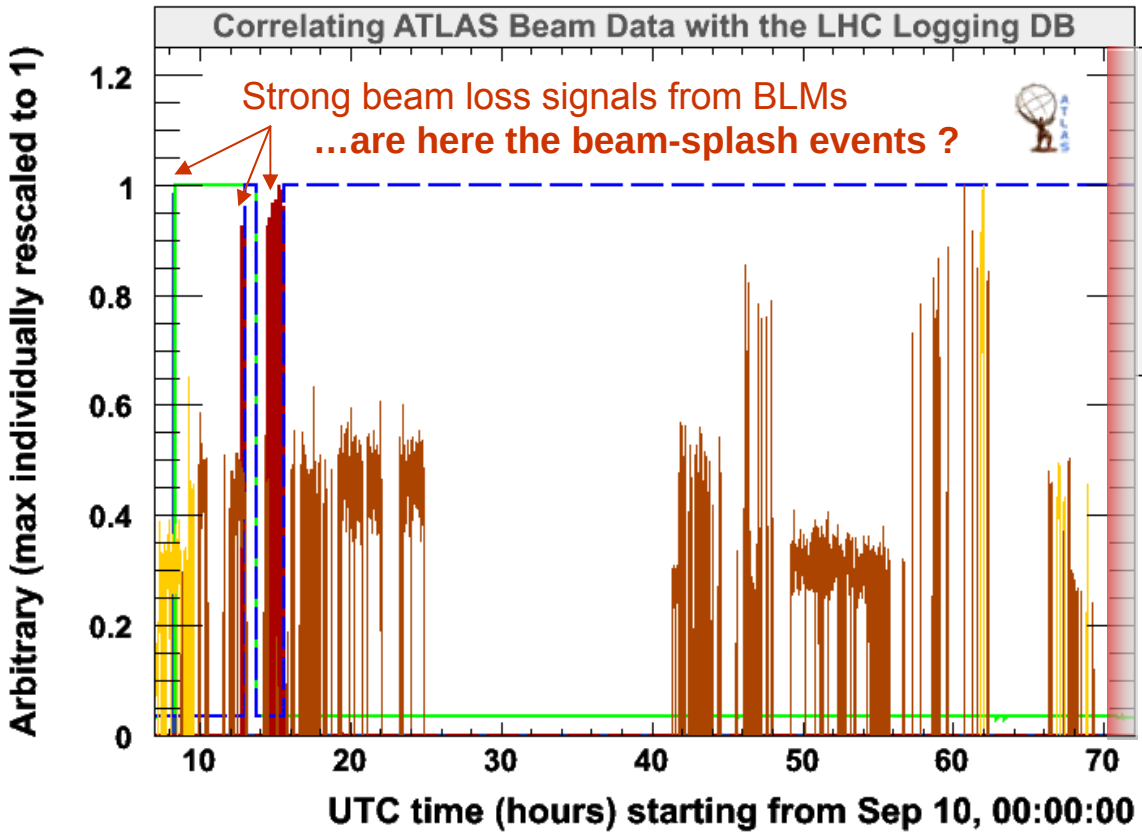
Sep 10 – 13: Beam History

- Collimator positions before ATLAS: ‘1’ = open, ‘0’ = closed (stops beam)



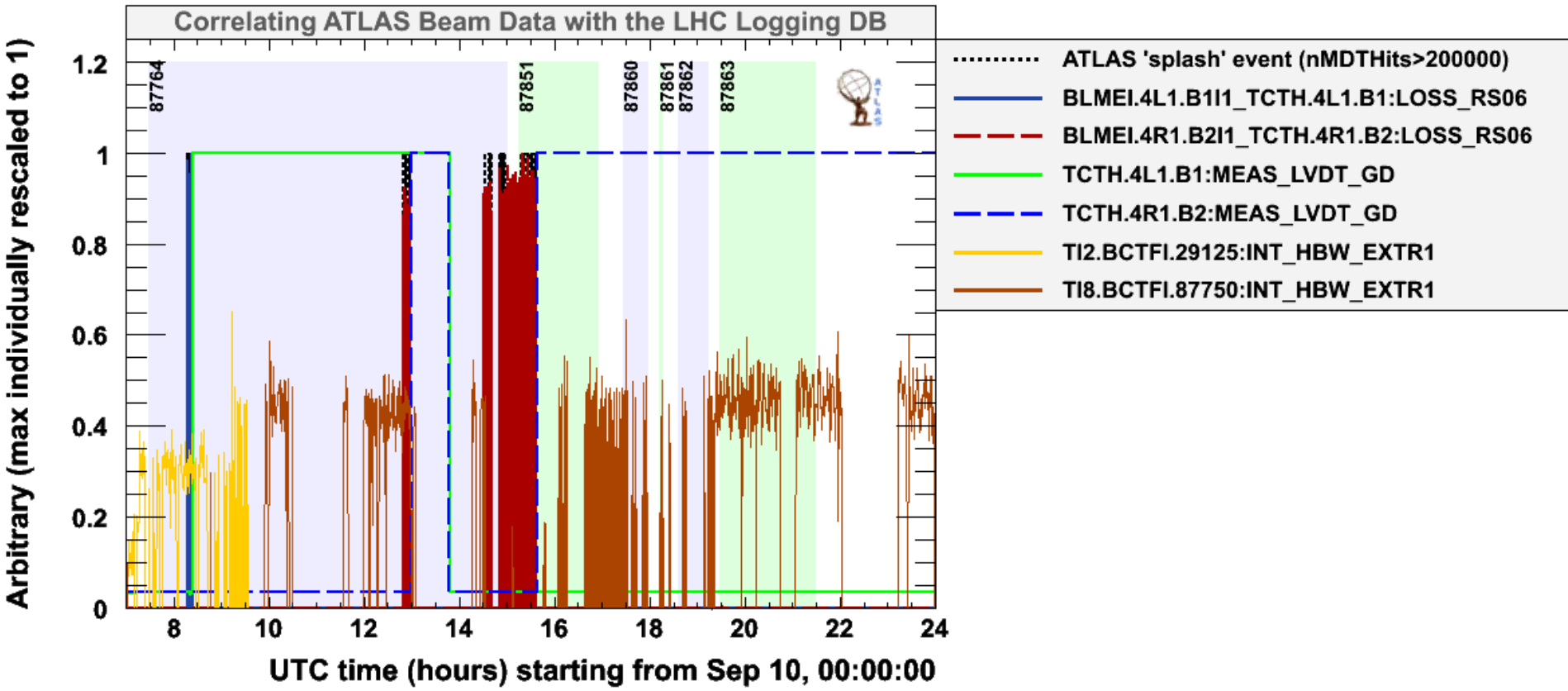
Sep 10 – 13: Beam History

- Collimator positions before ATLAS: ‘1’ = open, ‘0’ = closed (stops beam)



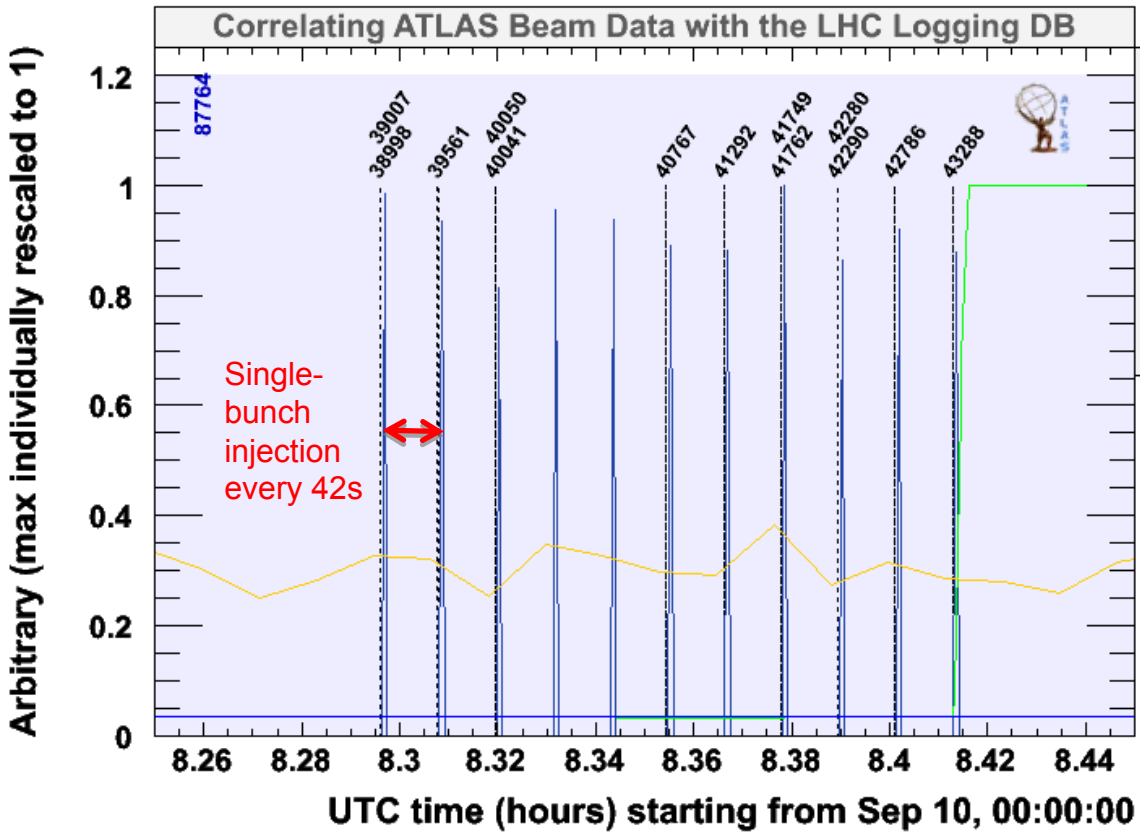
Sep 10 – 13: Beam History

- Indeed, for ATLAS there were 3 ‘splash’ phases during Sep 10 → let’s zoom…



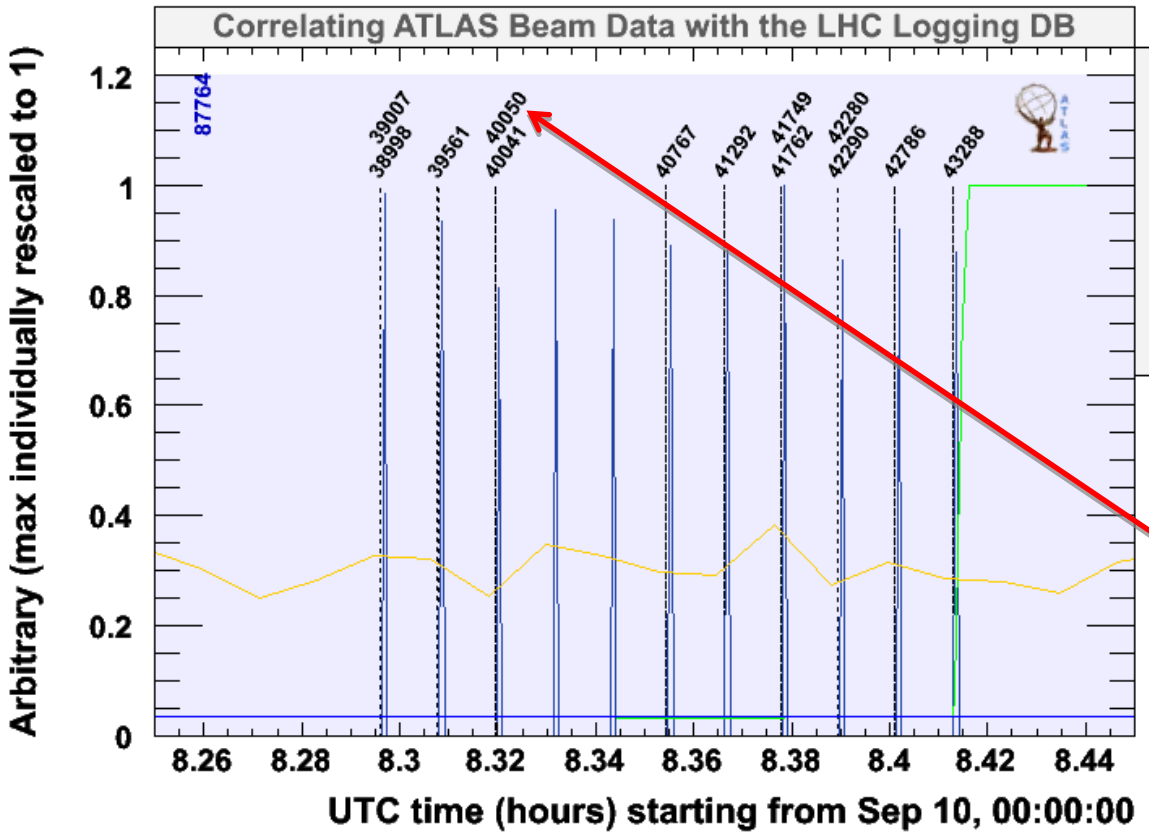
Sep 10 – 13: Beam History

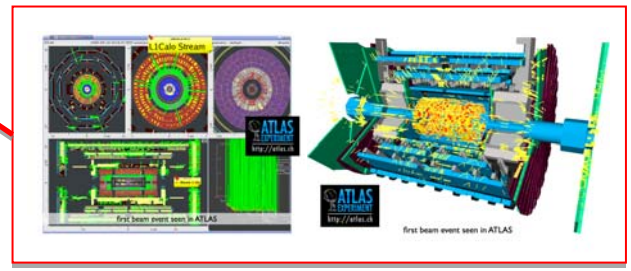
- And zoom even more, into the 1st splash (beam 1) on Sep 10



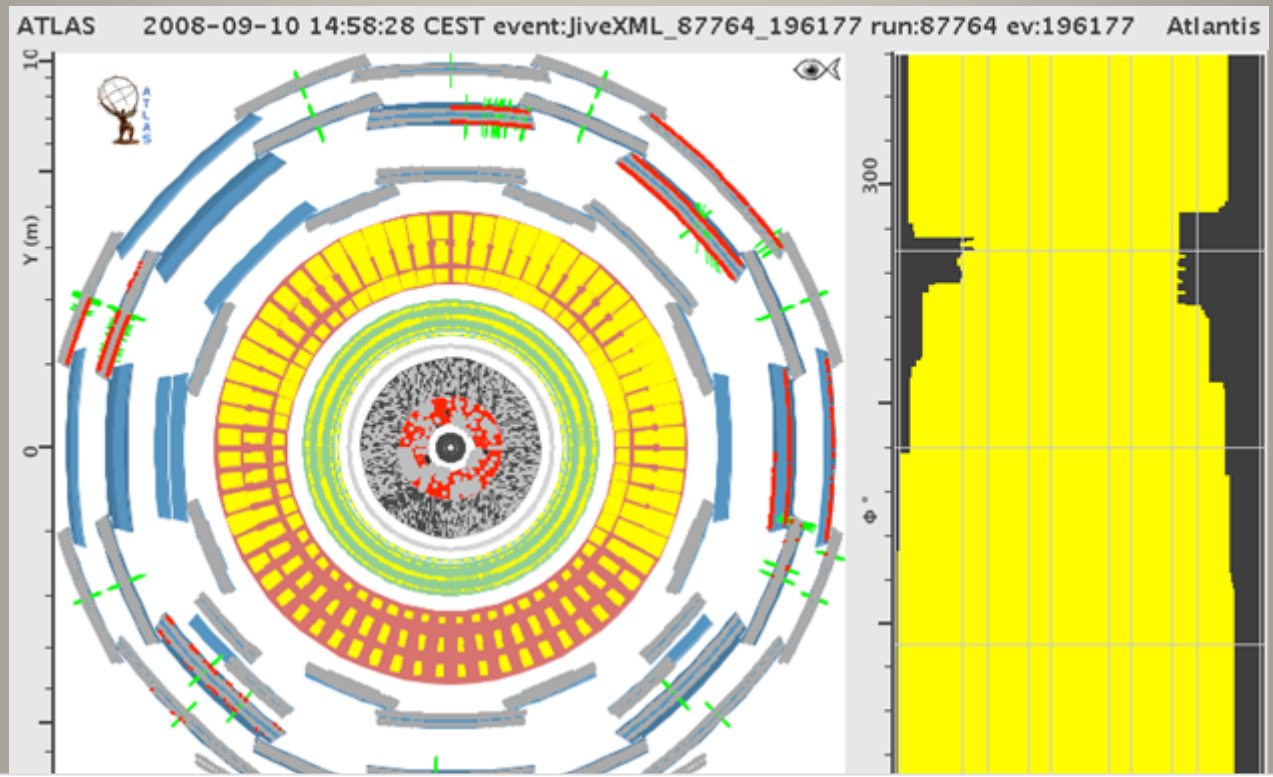
Sep 10 – 13: Beam History

- We can correlate in time the LHC splashes with ATLAS recorded events !





"First beam event seen in ATLAS"
(not quite !)



ATLAS has recorded about 70 splash events from a total of ~100 produced

Apart from being spectacular, they have been used in various ways to:

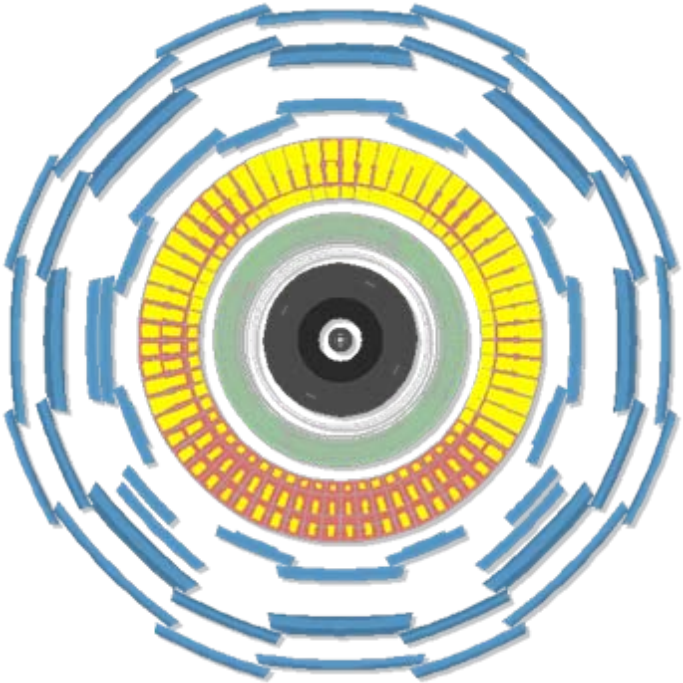
- Time-in the detector components (incl. trigger) with the bunch crossing signal
- Correlate position and energy response of various detector systems

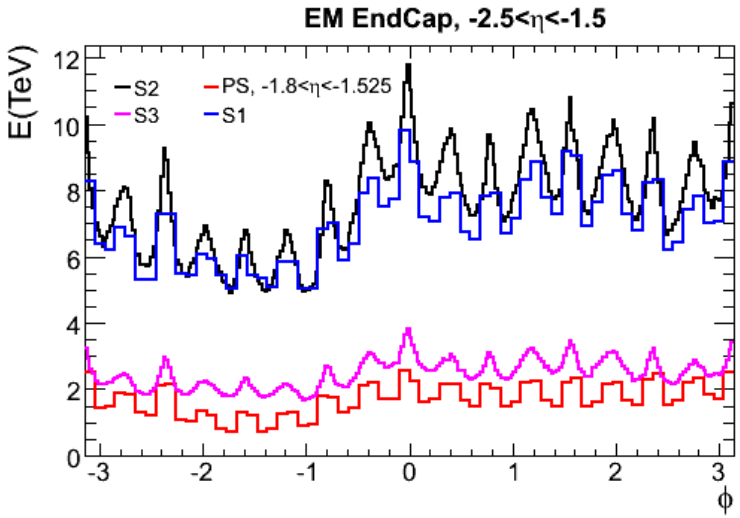
The detectors have also recorded “beam-halo” events, originating from single protons leaving the beam pipe and creating secondary muons

Absorption of collimator “splashes” in toroid and feet structures

Runs 87764, Sep 10, 2008

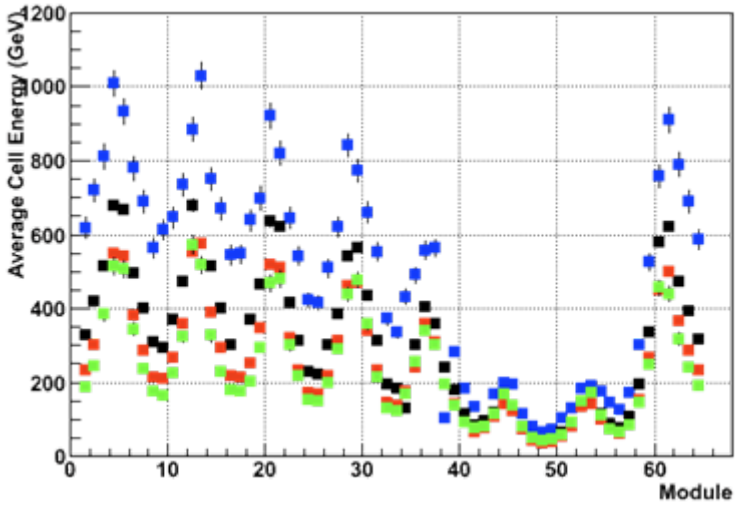
Collimator “Splash” event in Tile calorimeter





“Splash” events in LAr, energy integrated over η<0 in middle layer

About 100 TeV total deposited LAr energy found in such an event



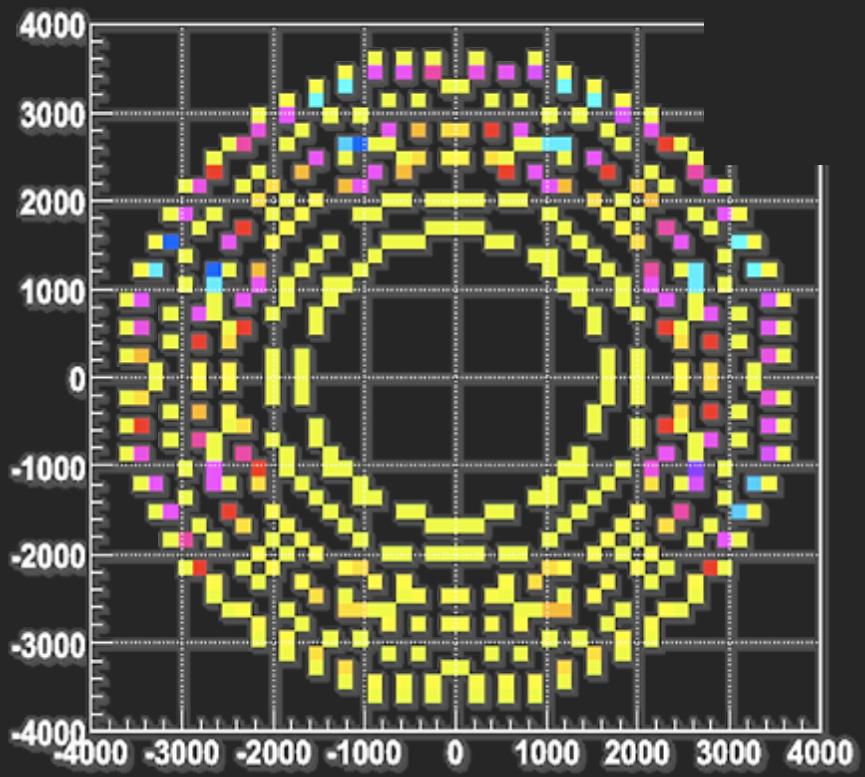
“Splash” events in Tile, integrated over η

Events with >1000 TeV total deposited Tile energy found!

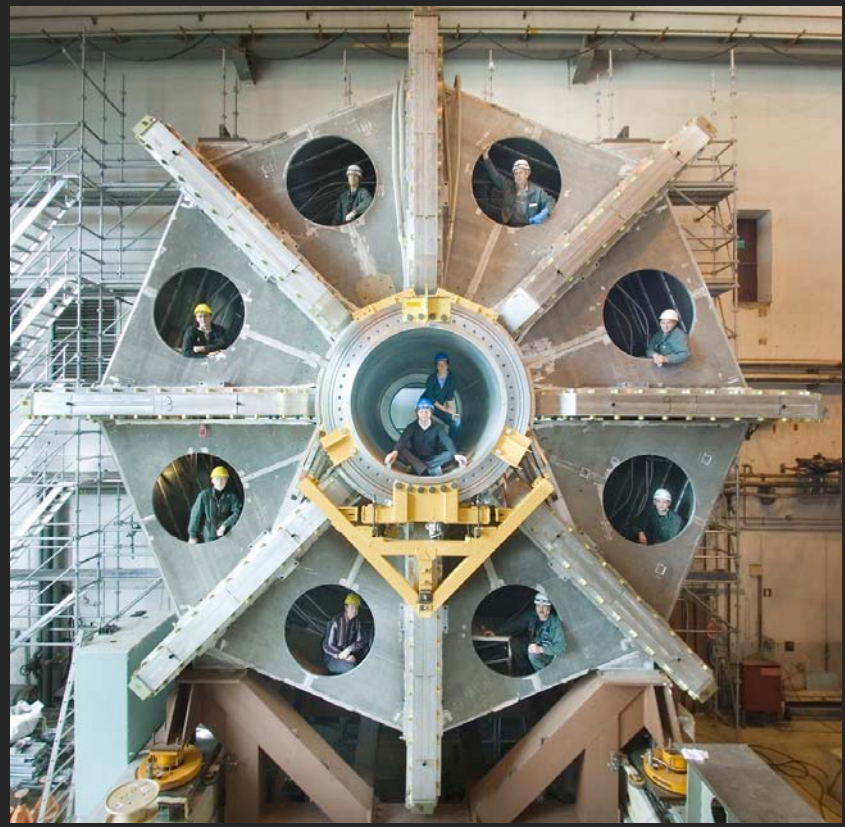
Absorption of collimator “splashes” in toroid and feet structures & shielding

Runs 87764, Sep 10, 2008

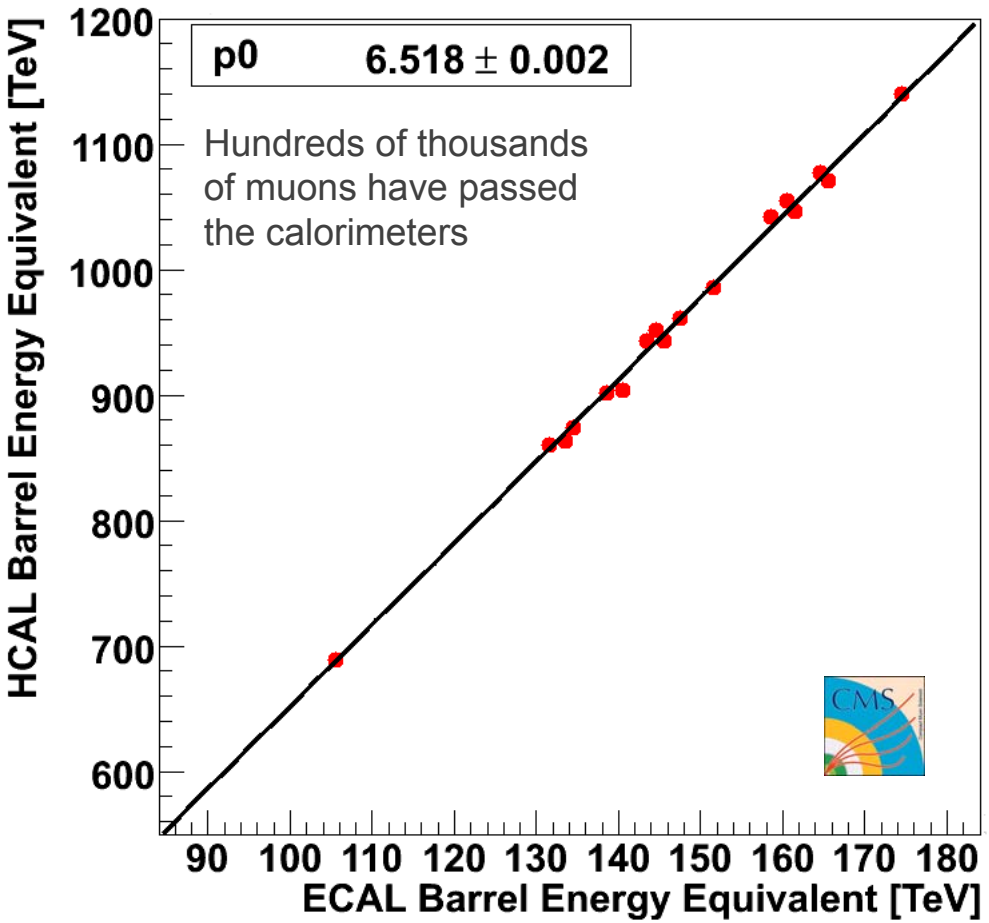
Tile calorimeter longitudinally integrated energy deposition
(different from yellow means larger energy)



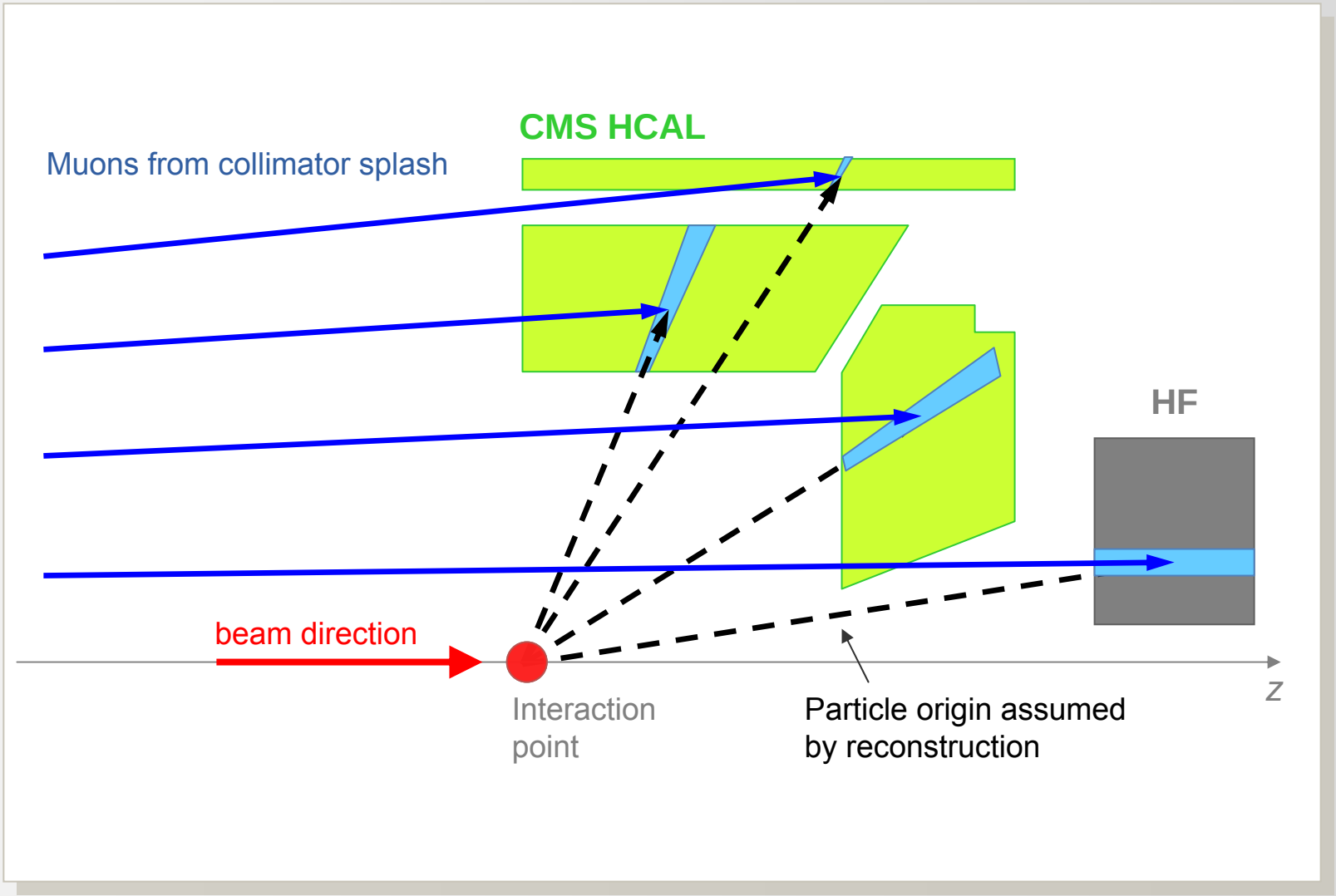
Endcap toroid



HCAL versus ECAL energy correlation in “splash” events in **CMS**

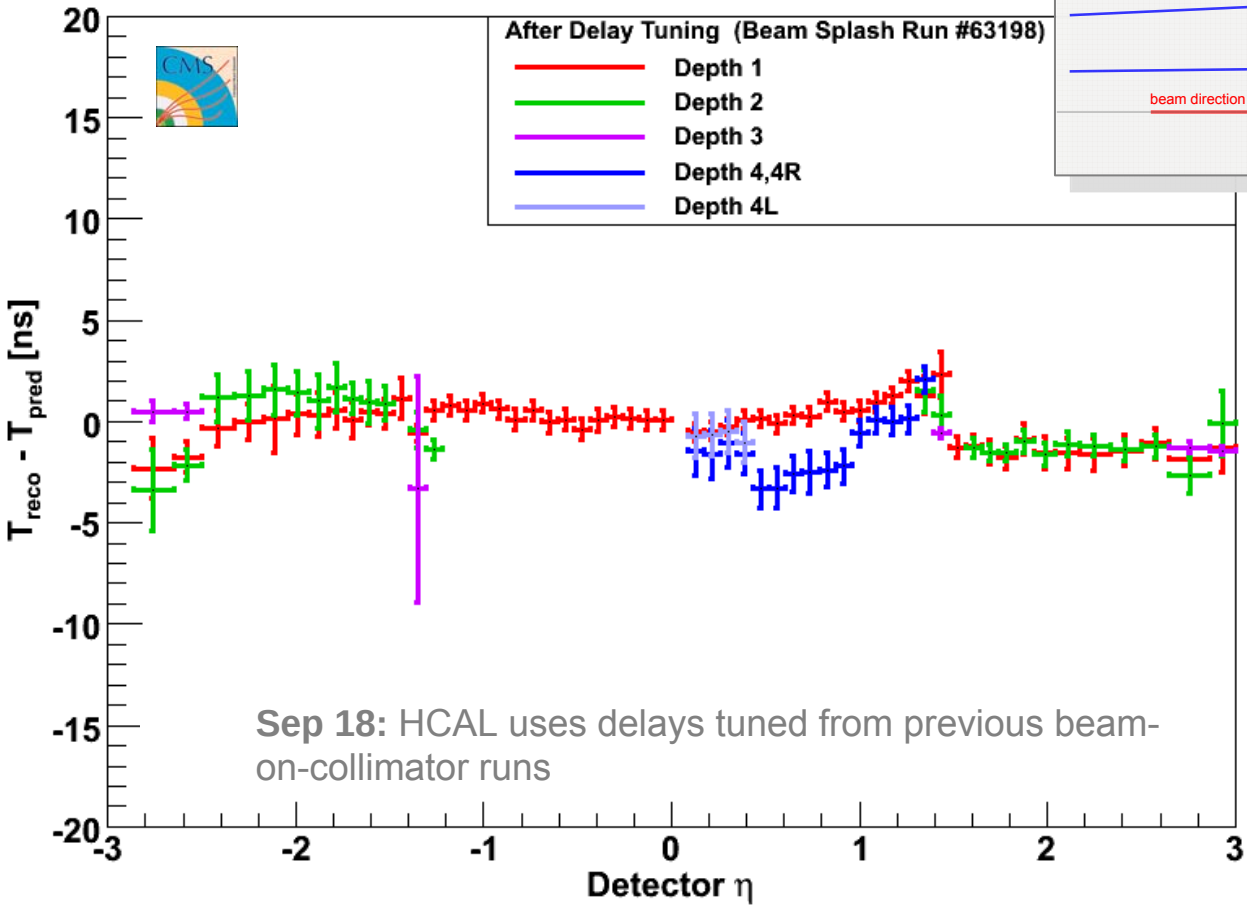


Time synchronisation of **CMS HCAL** in “splash” events

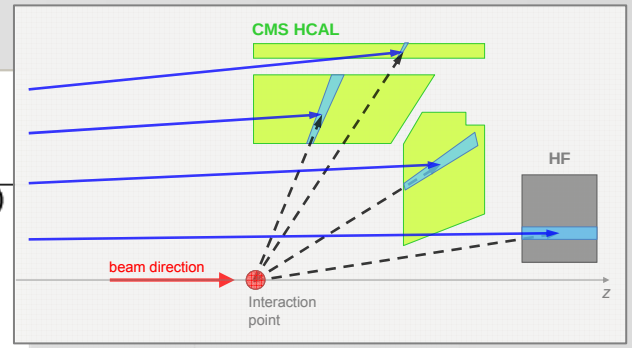


Time synchronisation of **CMS HCAL** in "splash" events

Difference between predicted and mean pulse arrival time

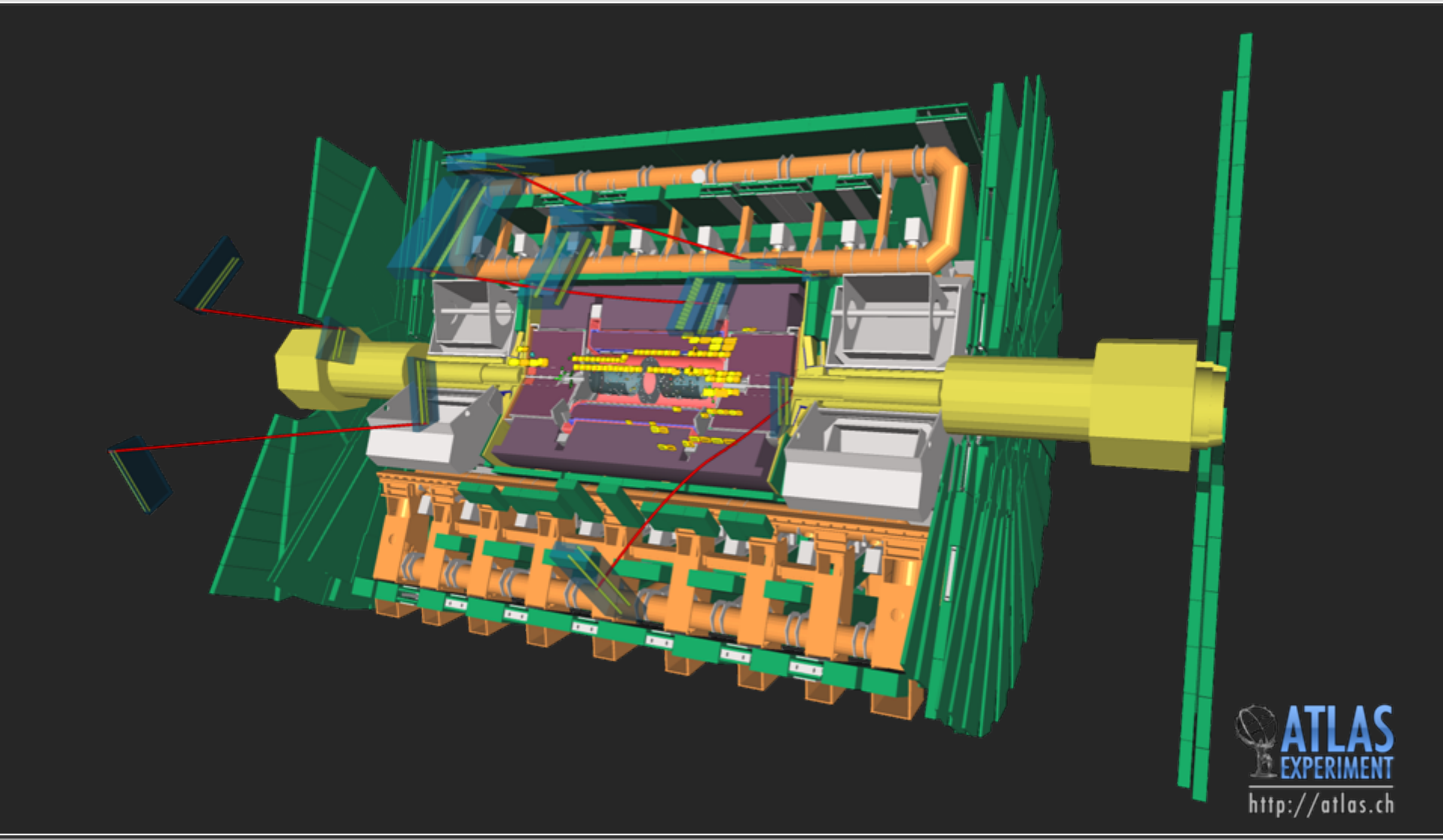


Sep 18: HCAL uses delays tuned from previous beam-on-collimator runs

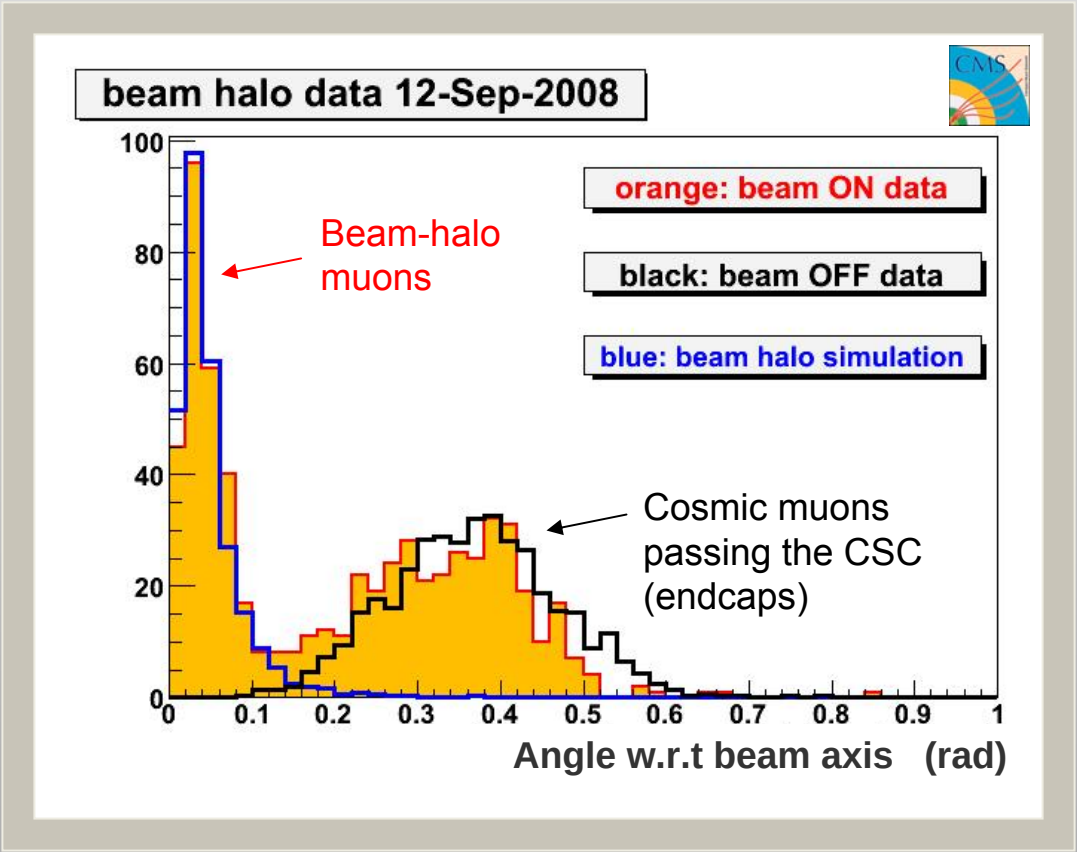


“Beam-halo” muon in **ATLAS**

Runs 87863, Event 1450, Sep 10, 2008

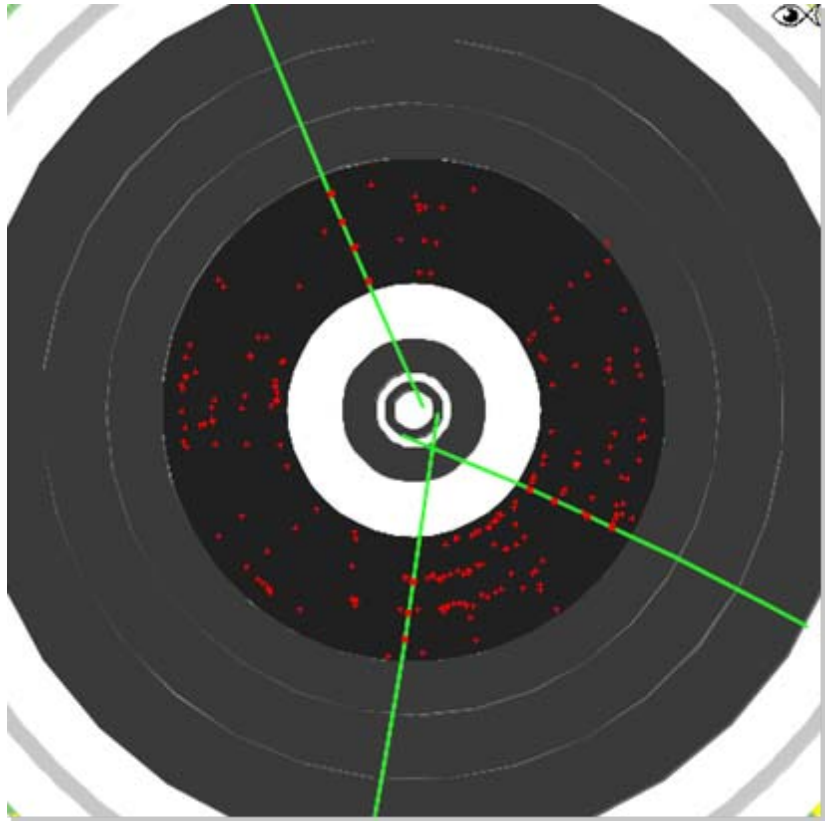


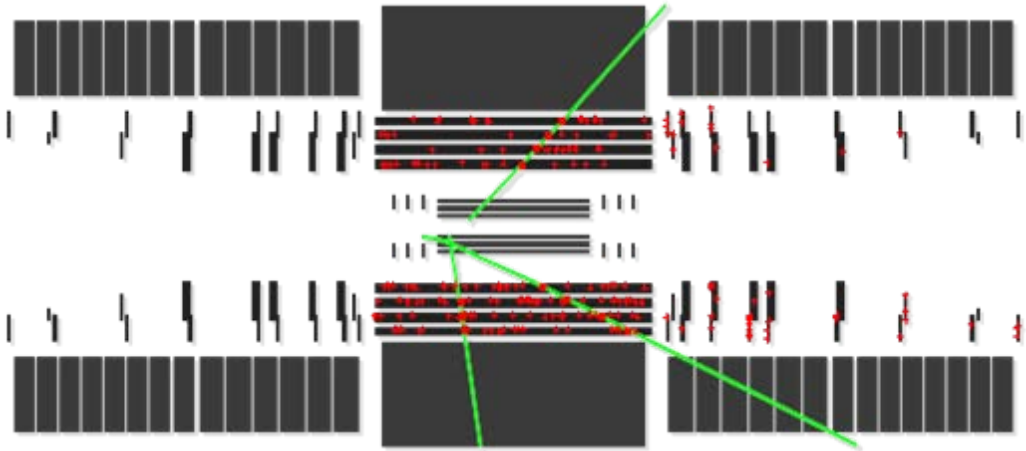
“Beam-halo” versus cosmic ray muons in **CMS**



Beam gas/wall event ?

(only SCT powered)

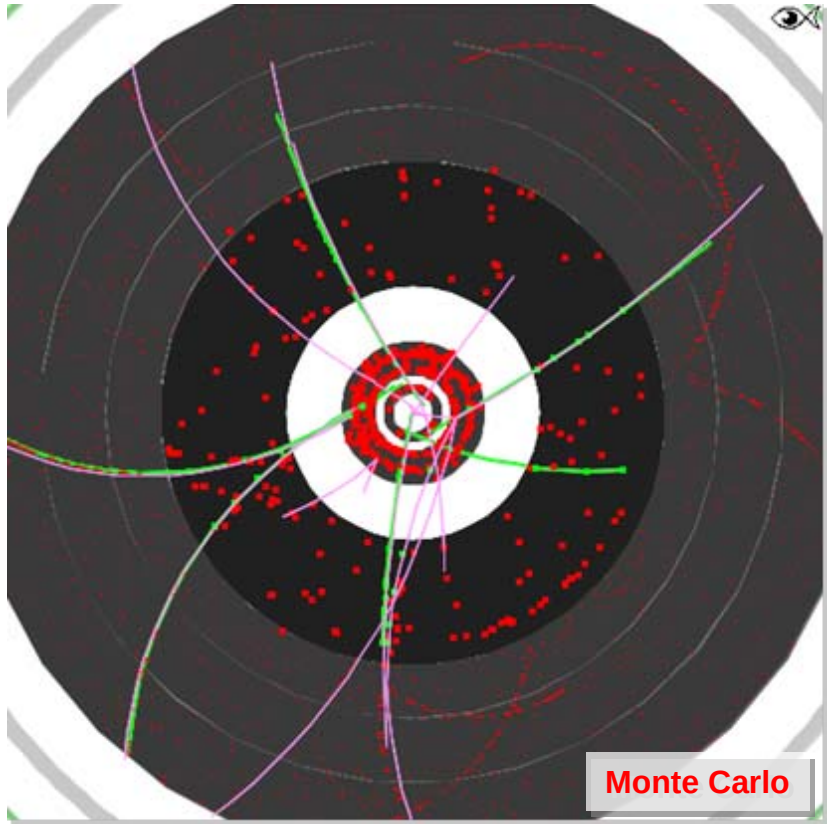


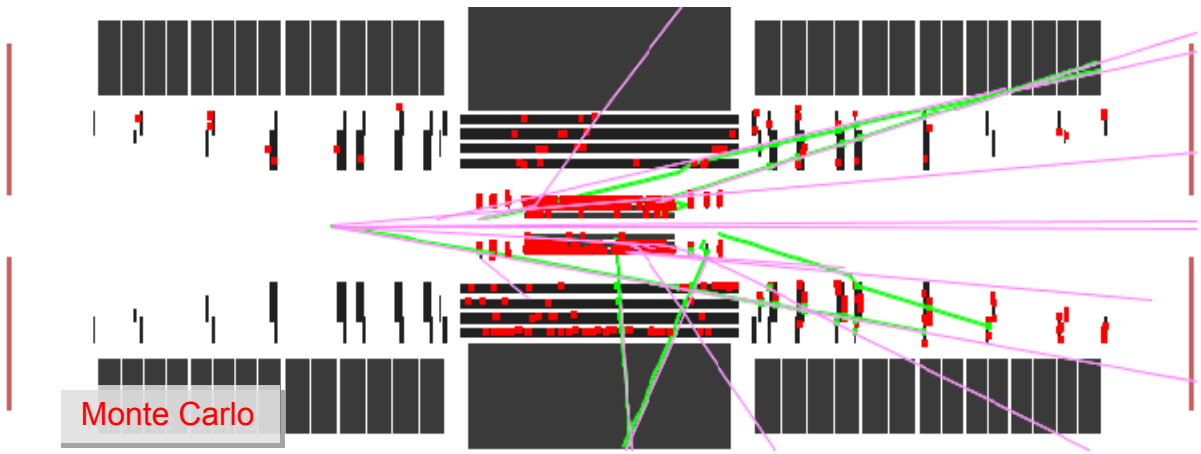


Runs 88153,
Event 12060,
Sep 12, 2008

How a beam gas event should look like

Very rare events due to excellent vacuum in beam pipe





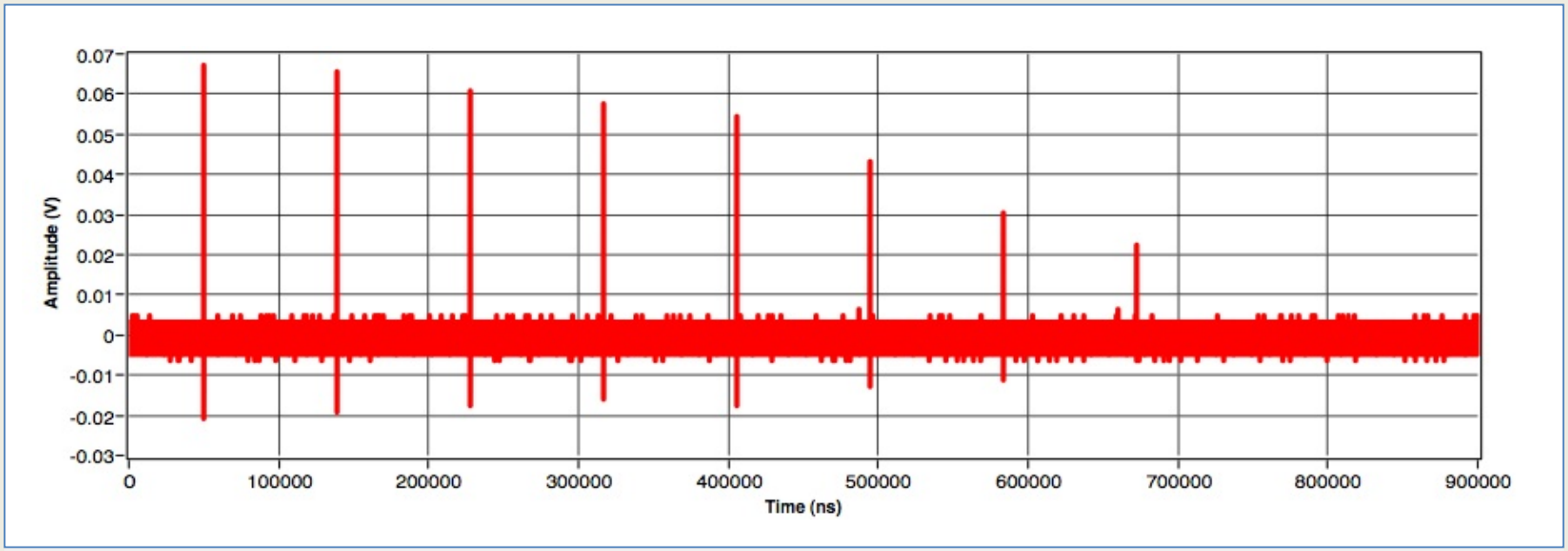
MC & Geant4 detector simulation

Beam pickup signals

Run 87863, Sep 10, 2008

ATLAS Logbook (ELOG): 10.09.08, 20:04

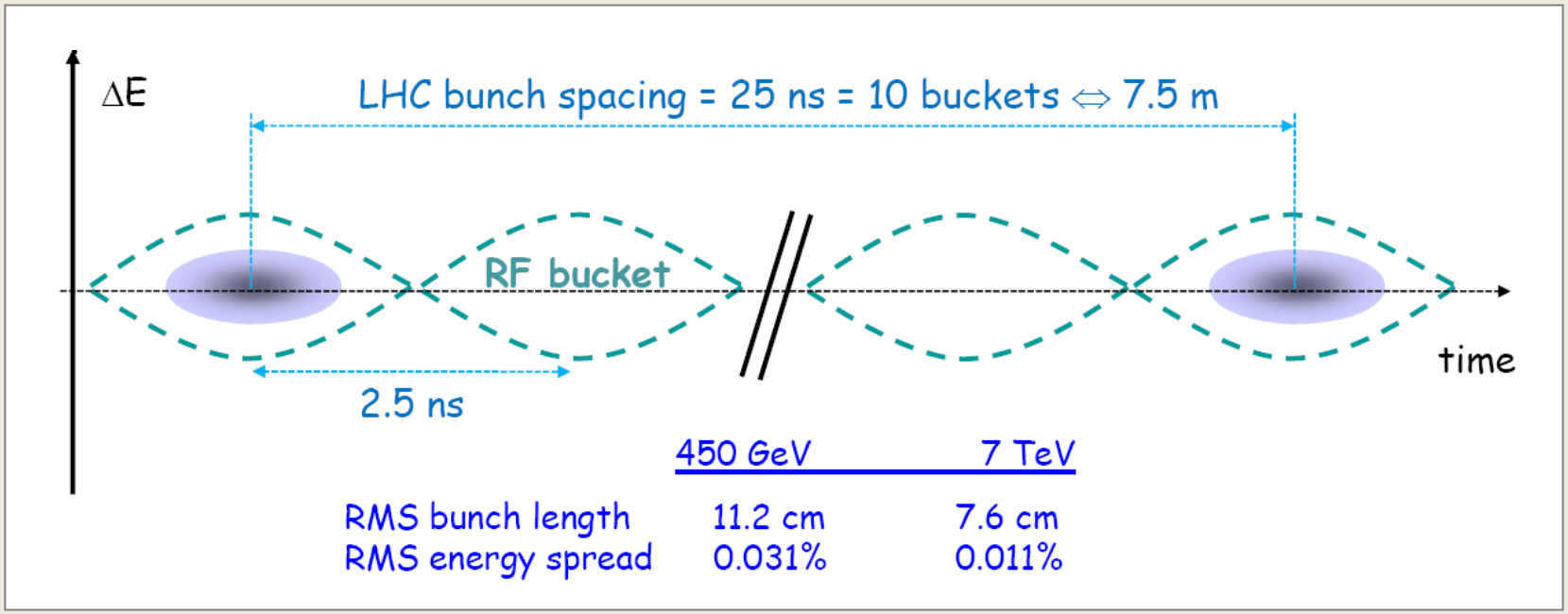
Right before the LHC Page 1 reported 9 full turns, the BPTX system saw the pilot bunch pass by ATLAS 8 times, see […] plot. It's not clear whether the deteriorating pulse amplitude is caused by the bunch actually disintegrating (since it's not locked in by the RF system yet) or if it's because the beam is shaved off against the collimator to give us several sprays of particles. Regardless, it's impressive work by our machine friends.



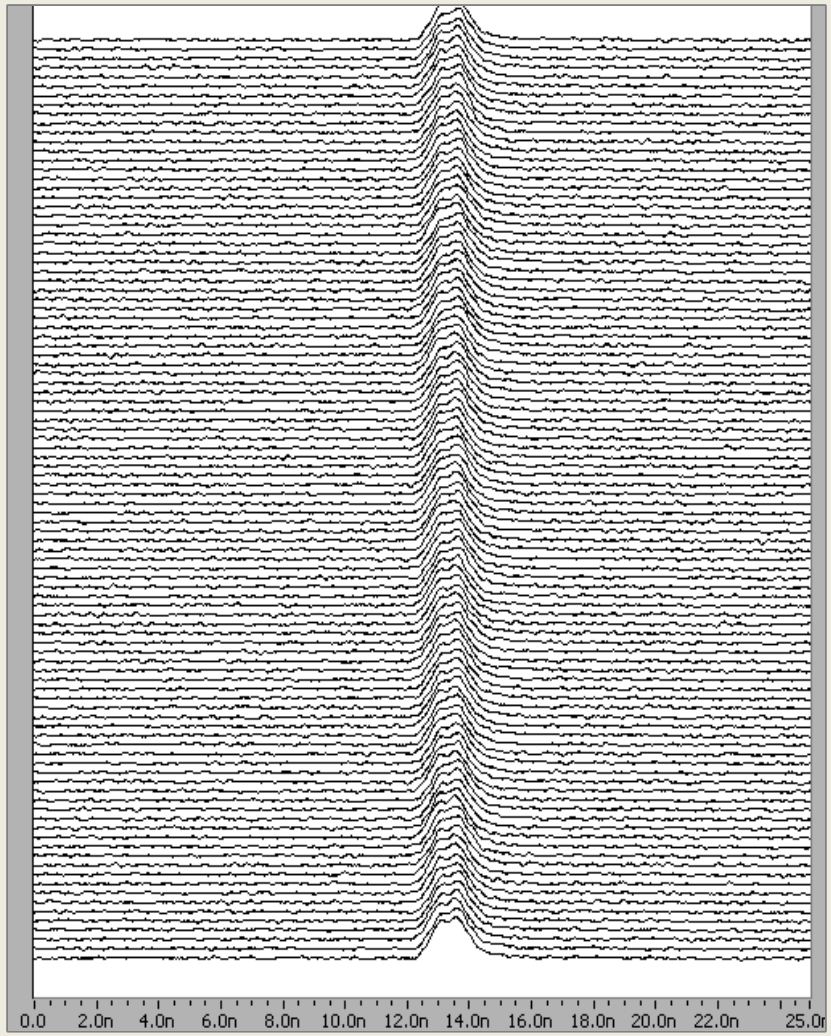
Debunching in non-radio-frequency (RF) captured beam in the **LHC**

When a bunch (filled proton packet) is injected from the SPS via the transfer lines into the LHC it decays after several turns if it is not trapped inside a radio-frequency voltage defining the bunch structure.

The LHC has a 400 MHz = 2.5ns bucket structure …



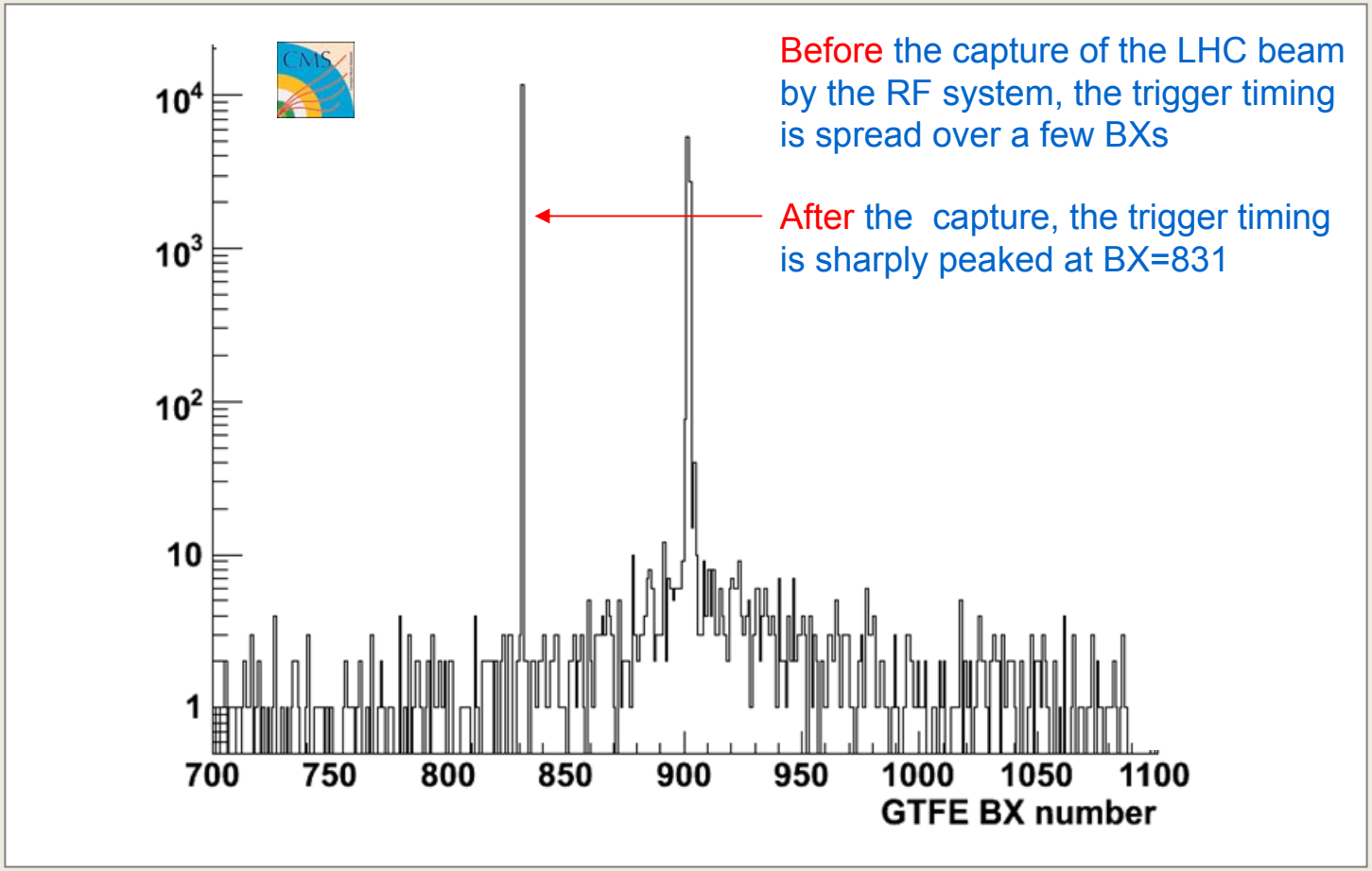
Radio-frequency capture of bunch in **LHC**



Capture with optimal injection phasing, correct reference

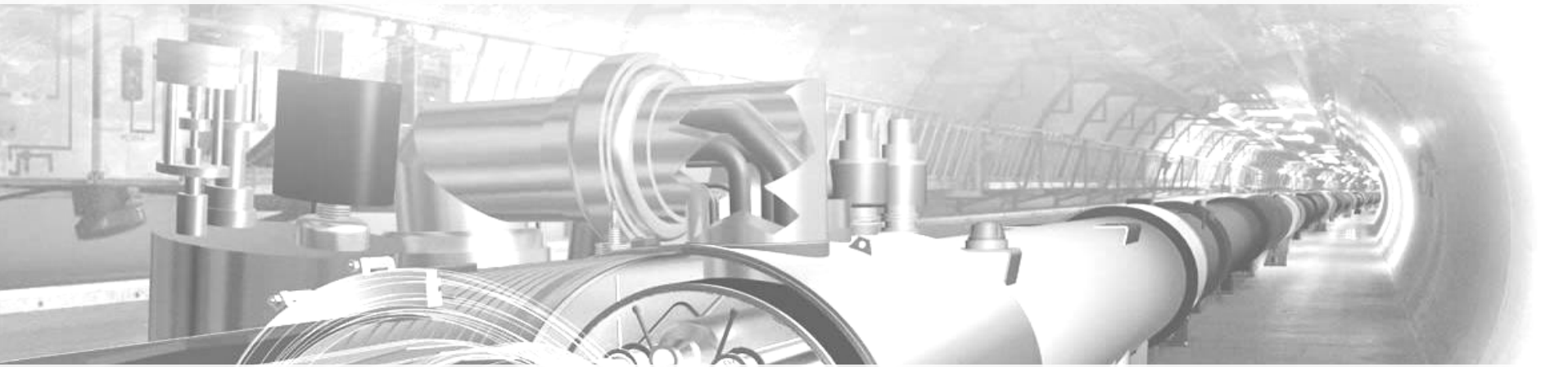
Beam debunching measured by **CMS**

Triggered events versus bunch crossing (BX) number



and tomorrow …

Early Physics at the LHC



Recall: 1 $pb^{-1} = 10^{36}\ cm^{-2}$

1 second at $L = 10^{31}\ cm^{-2}s^{-1} \rightarrow \int L dt = 10^{-5}\ pb^{-1}$

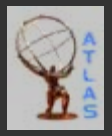
1 10h running day at $L = 10^{31}\ cm^{-2}s^{-1} \rightarrow \int L dt = 0.36\ pb^{-1}$

The LHC Physics Programme

1. Mass
   - Search for the Higgs Boson
2. Electroweak unification
   - Precision measurements (M_W, m_{top}) and tests of the Standard Model
3. Hierarchy in the TeV domain
   - Search for Supersymmetry, Extra dimensions, Higgs composites, …
4. Flavour
   - *B* mixing, rare decays and *CP* violation as tests of the Standard Model

The LHC Physics Programme

… is reflected in ATLAS and CMS physics organisation



Combined Performance Groups:

- e/gamma
- Jets / Missing E_T
- Tau
- Muons
- Flavour tagging

Analysis Groups:

- Standard Model
- Luminosity
- *B* Physics
- Top
- Higgs
- SUSY
- Exotics
- Heavy Ions
- Monte Carlo

Physics Objects Groups:

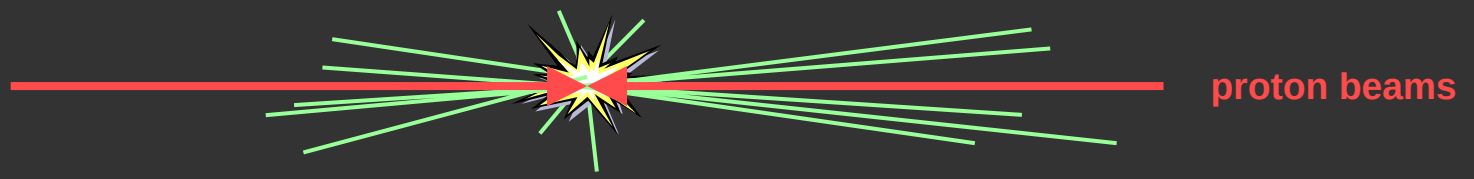
- e/gamma
- Jets / Missing E_T
- Particle Flow / Tau
- Muons
- *B*-tagging and Vertexing

Analysis Groups:

- QCD
- Electroweak
- Diffraction and forward physics
- *B* Physics
- Top
- Higgs
- SUSY
- Exotica
- Heavy Ions
- Generator Tools

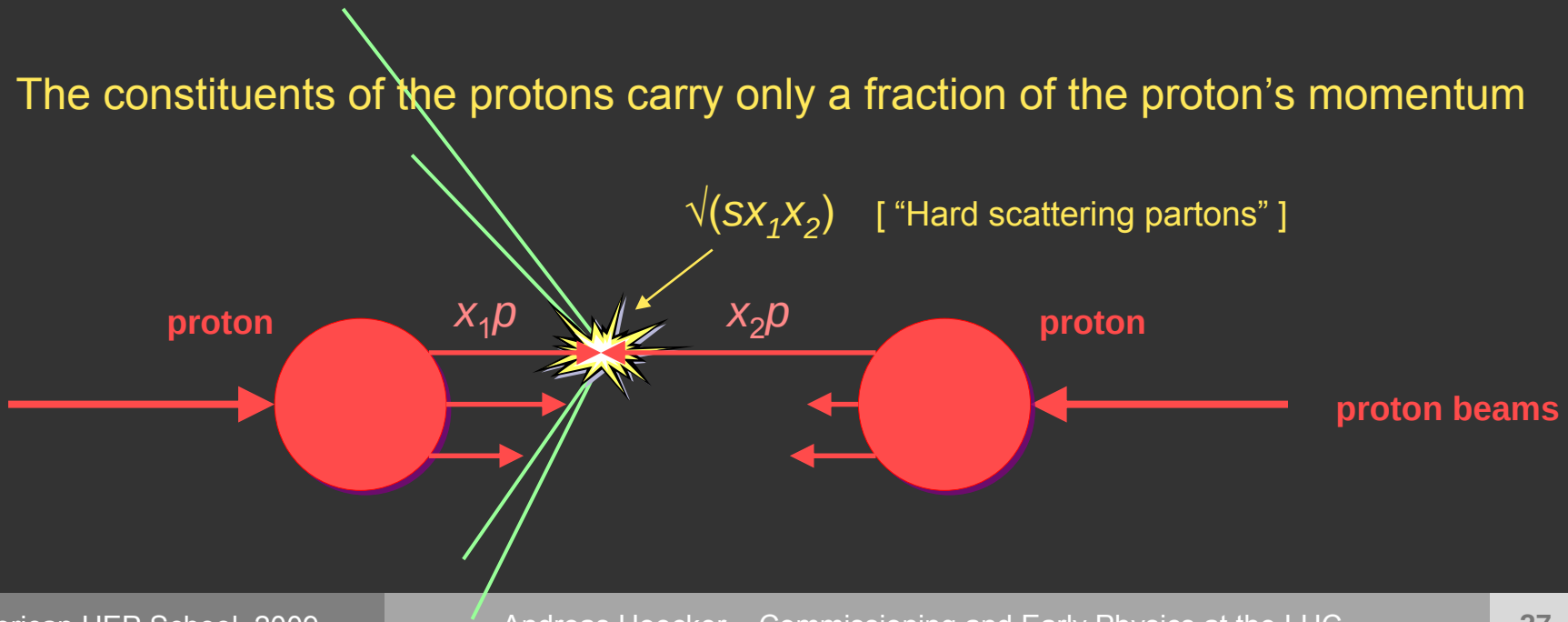
Proton-Proton Collisions are Complex

- Most events are due to interactions at large distance between protons
  - Large longitudinal, but small transverse momentum: $\langle p_T \rangle$ = 0.5 GeV



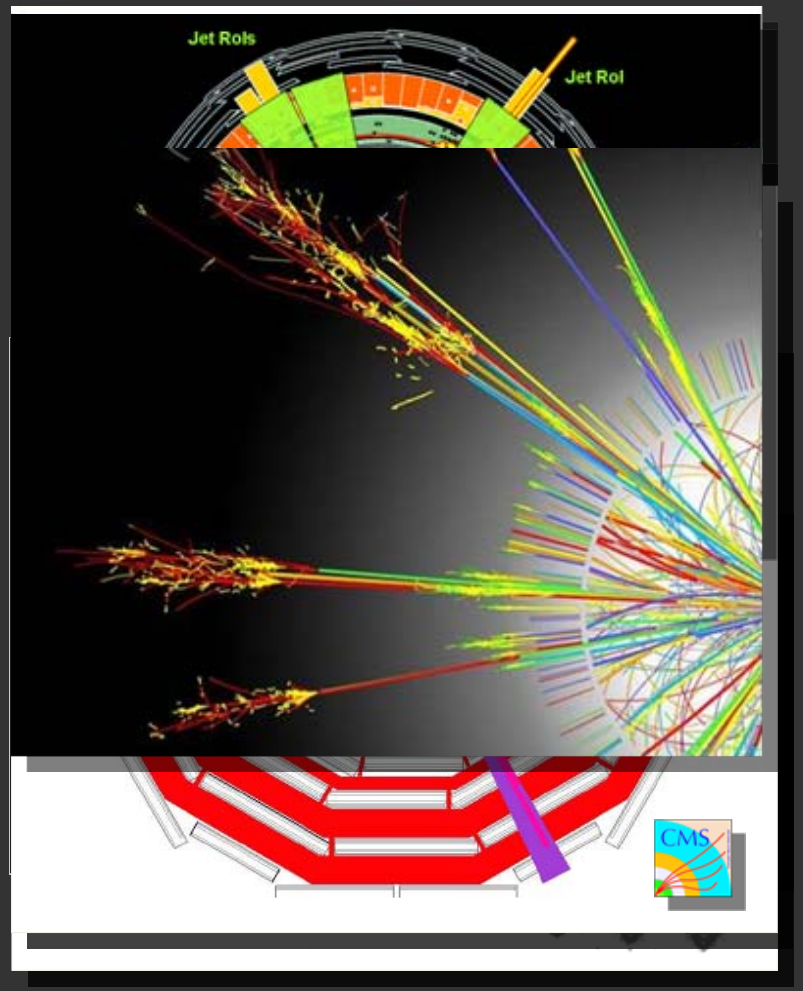
"Minimum bias events"

  - The constituents of the protons carry only a fraction of the proton's momentum



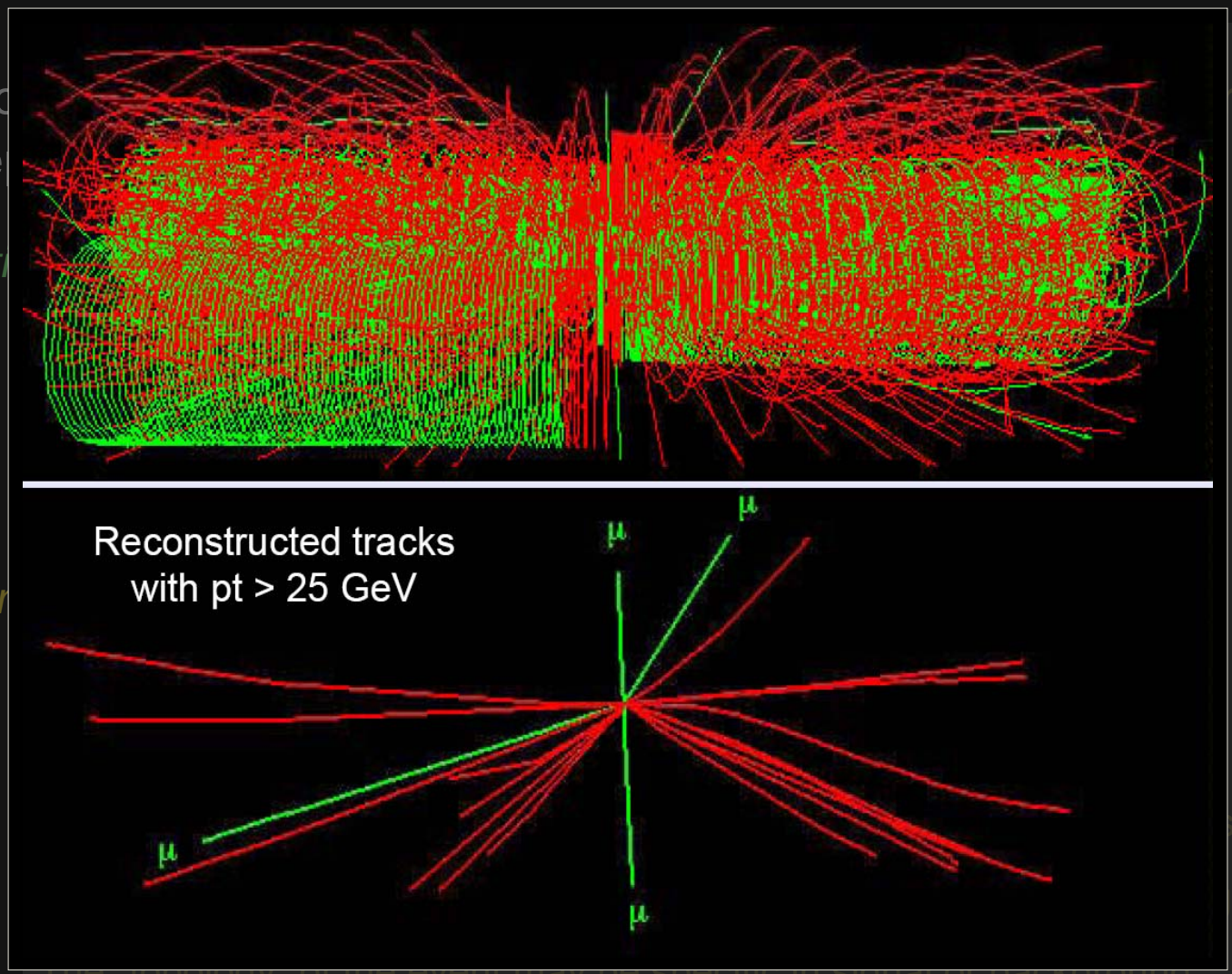
Event Reconstruction – Basic

- Trigger an event and readout detector
- Reconstruct tracks in inner detector
- Reconstruct tracks in muon system
- Reconstruct electromagnetic clusters
- Reconstruct hadronic clusters and jets
- Reconstruct missing transverse energy
- Identify particles and objects: muon, electron, photon, tau, jet, *q*-flavour



Event Reconstruction – Cleaning

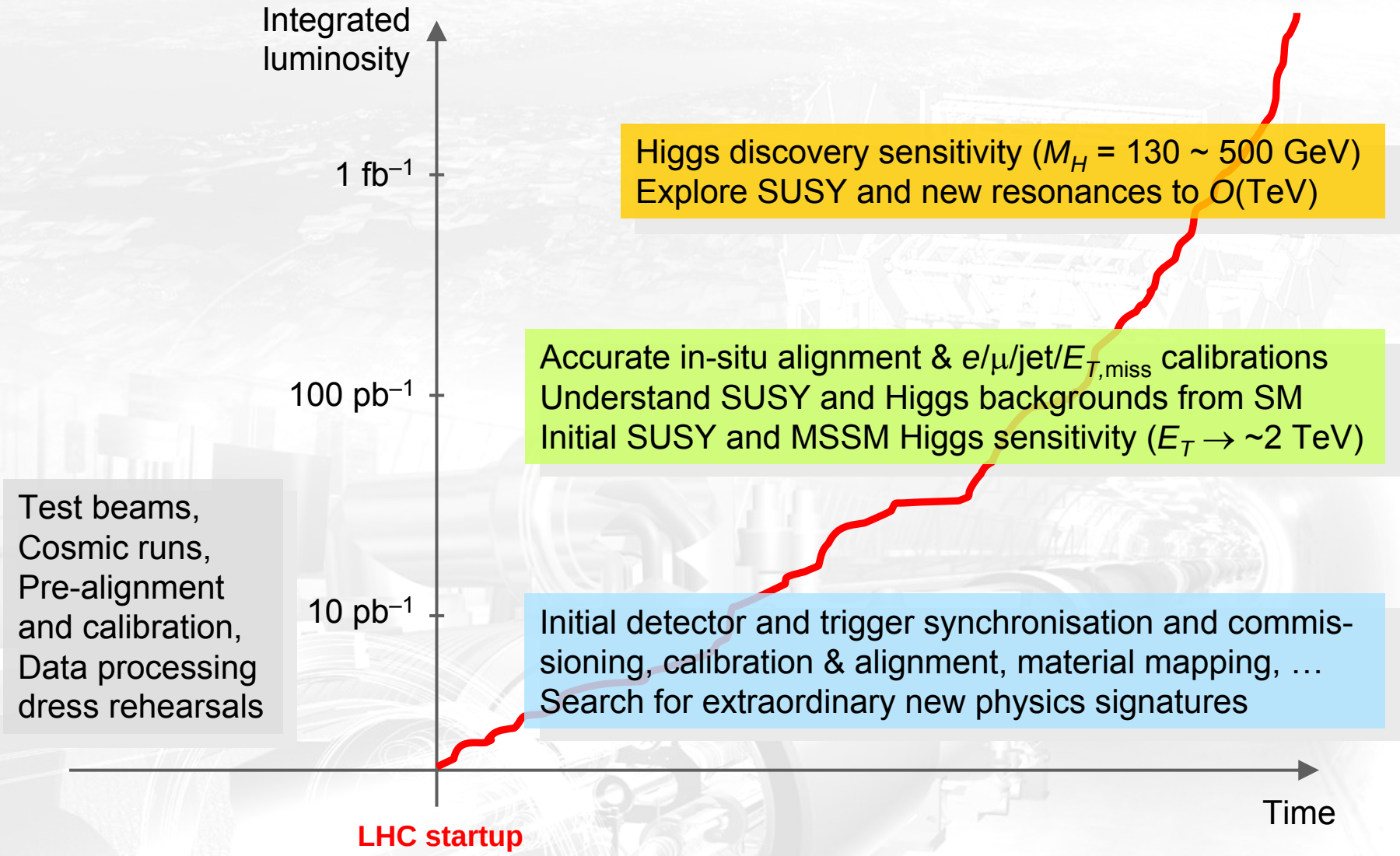
- Backgro… …operties, both de…
  - *Parti…*
    - …
    - …
    - …
  - *Ever…*
    - …
    - …
    - …
    - …
    - …
    - The "topology" of the event may be specific in signal or background



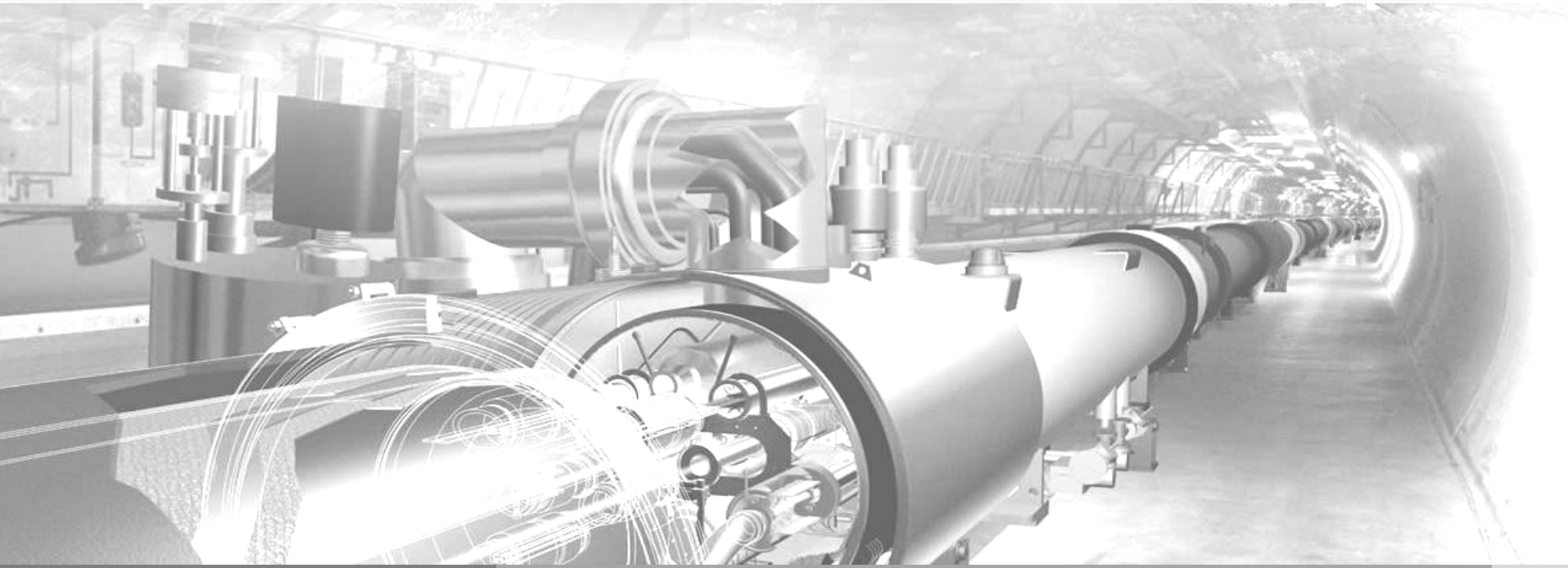
Event Reconstruction – Topological

- The physics analysis drives the topological reconstruction of an event:
  - *Inclusive analyses count events with leptons, γ, jets or missing E_T – examples*
    - QCD : select events with high-energetic (or many) jets
    - QCD / EW : select events with leptons or photons in final state
    - SUSY : select events with large missing E_T (with or without leptons)
  - *Exclusive analyses kinematically combine reconstructed objects – examples*
    - $W \to \mu\nu$: identify muon and approximate W mass with $m_T(\mu$, missing $E_T)$
    - $tt \to (be\nu)(bqq)$: identify electron and 2 b-jets, and compute top mass as $m(b,qq)$
    - $H \to \gamma\gamma$: identify 2 photons and compute mass: $m^2 = 2E_{\gamma 1}E_{\gamma 2}(1 - \cos\theta_{\gamma\gamma})$
    - $H \to e^+e^-\mu^+\mu^-$: identify $2e$ and 2μ and compute mass
    - $G_{RS} \to e^+e^-$: identify 2 electrons and compute mass
- Combine all available information via *multivariate* statistical techniques

Remember …the Roadmap



Physics Commissioning



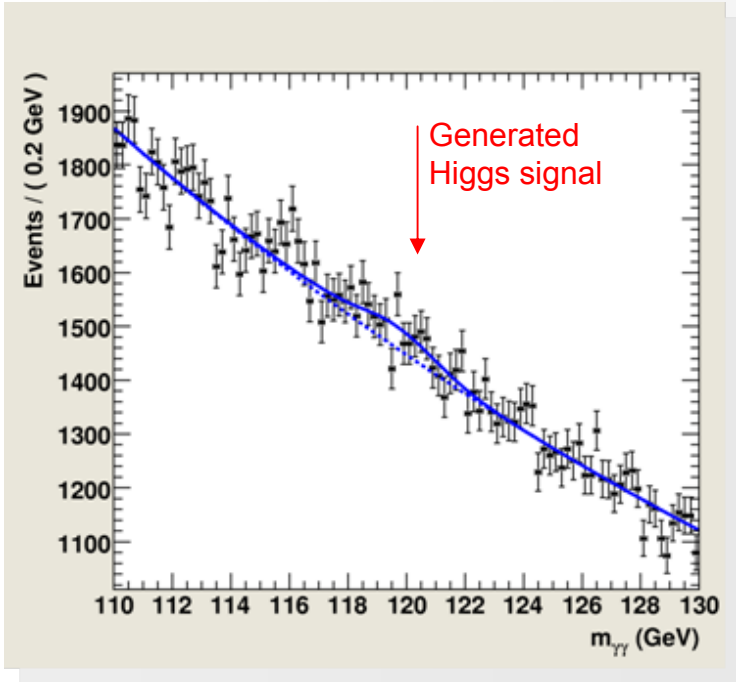
“In-situ” Calibration of EM Calorimeter

- Main goal: reduce constant term to design goal, *i.e.*, below ~0.7% ($H \to \gamma\gamma$, *eeee*)
- Back-on-the-envelope test for effect of constant term on Higgs discovery(*)

Example for 20 fb^{-1} :
690 $H \to \gamma\gamma$ and
~170,000 background in
[110, 150] mass window

Default in ATLAS simulation

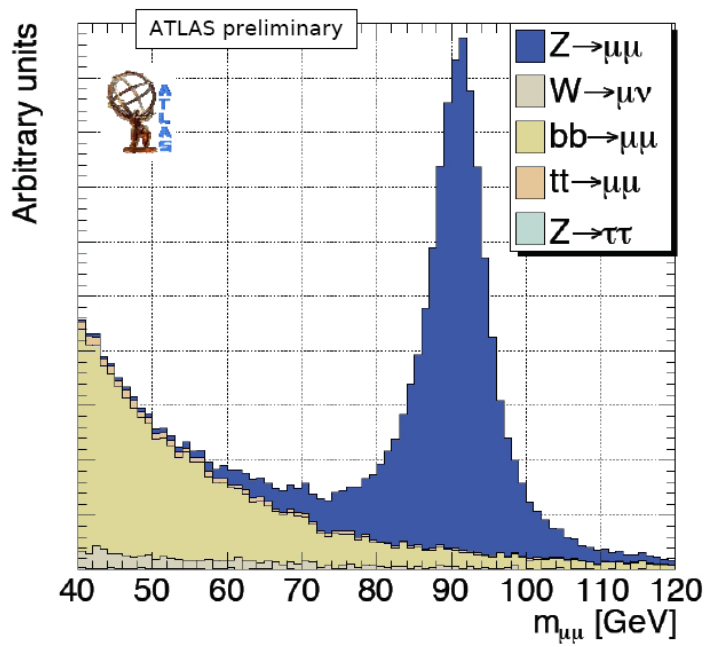
Constant term	Signal significance
0.7%	2.9 σ
1.0 %	2.4 σ
2.0 %	1.8 σ

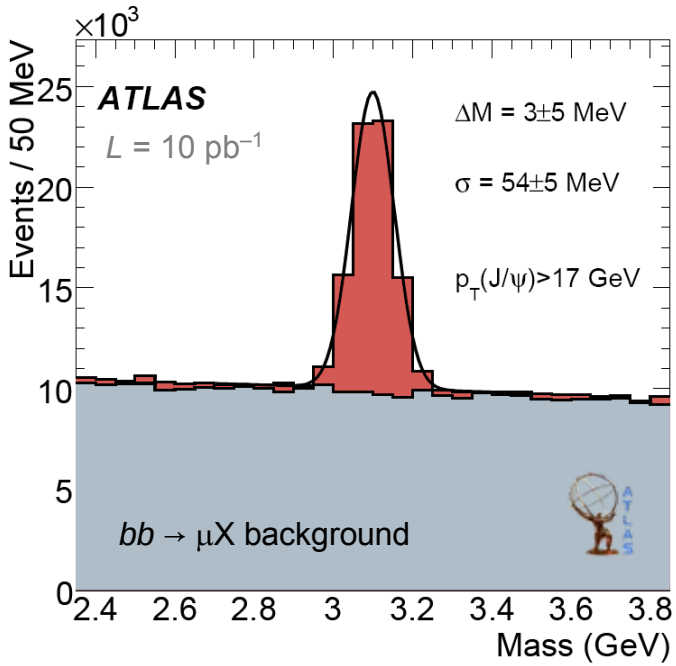


(*) Note that this test uses the simplest possible $H \to \gamma\gamma$ analysis approach: a more sophisticated fit using more discriminating variables and detector-specific “categories” boosts the fit performance significantly.

“In-situ” Calibration of EM Calorimeter

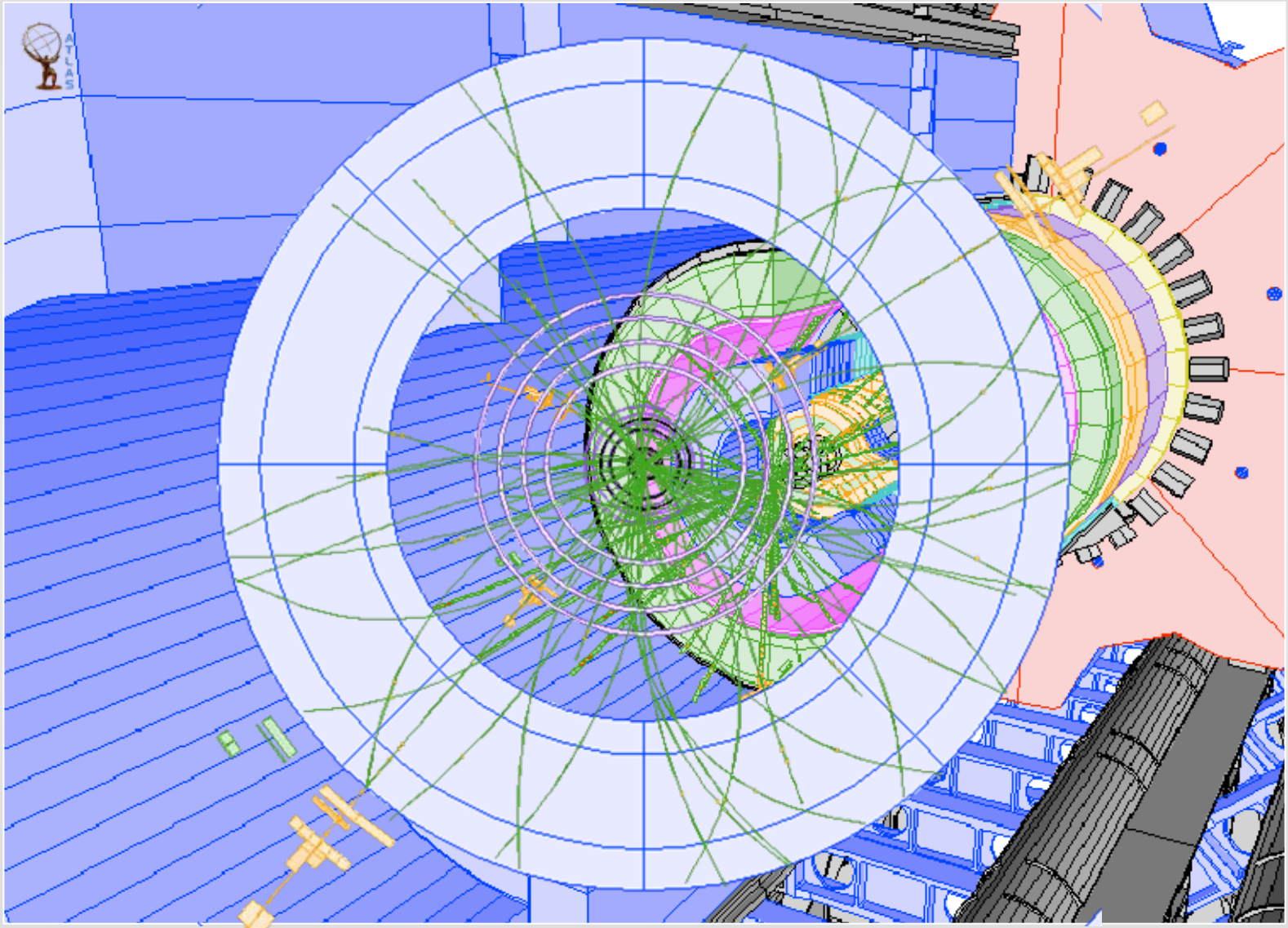
- Methods using physics events are:
  - $Z \rightarrow ee$ events (Z has 2.5 GeV width, but peak value known from LEP to 0.0023% !)
  - $W \rightarrow e\nu$, once tracker is understood one can intercalibrate with E/p
  - Other resonances: J/ψ, Υ, π^0, η, …





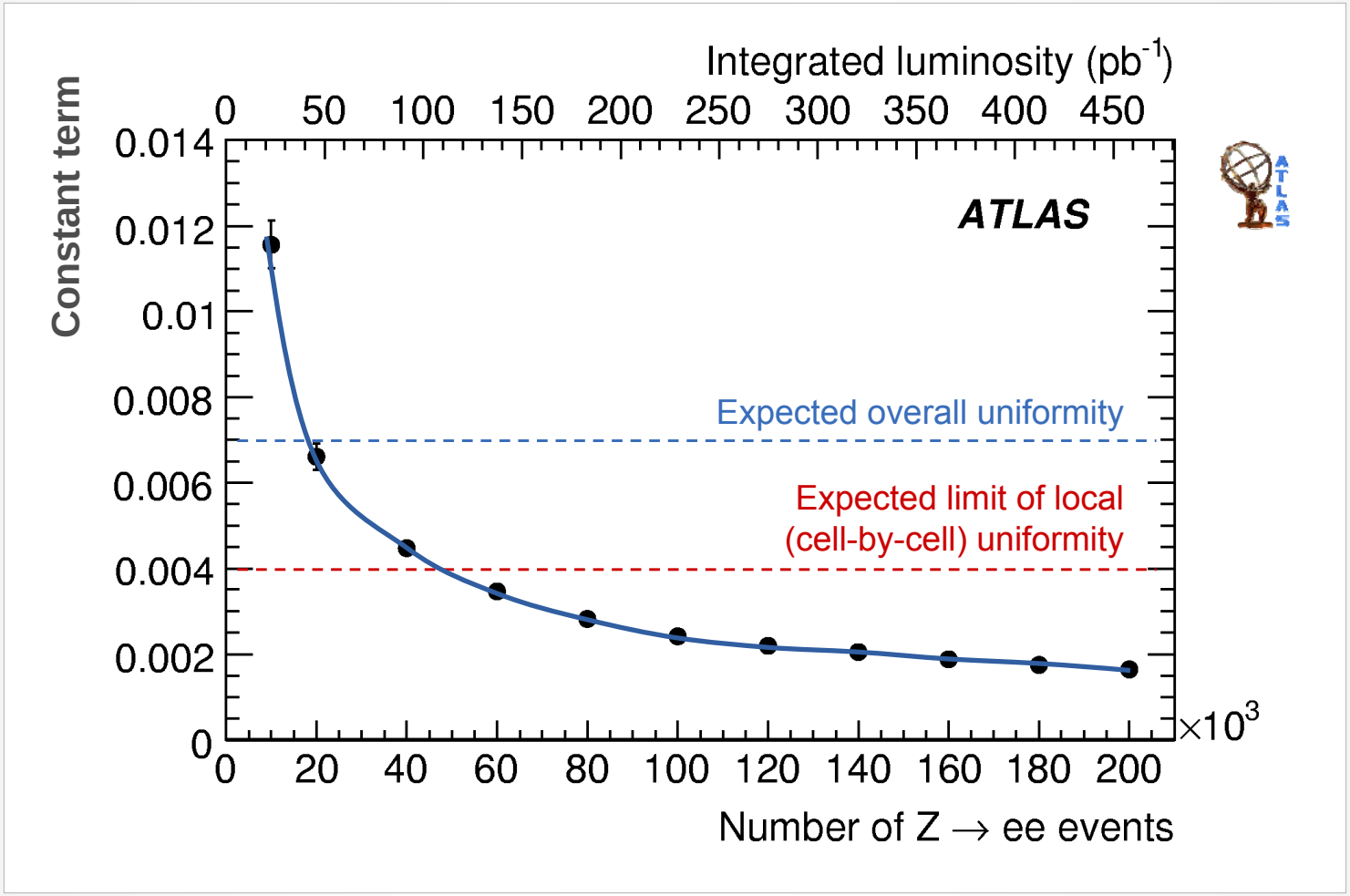
Simulated $Z \to ee$ event in **ATLAS**

Expect 10,000 of these events in first 10 pb^{-1} (and 10 times more $W \to e\nu$) recorded



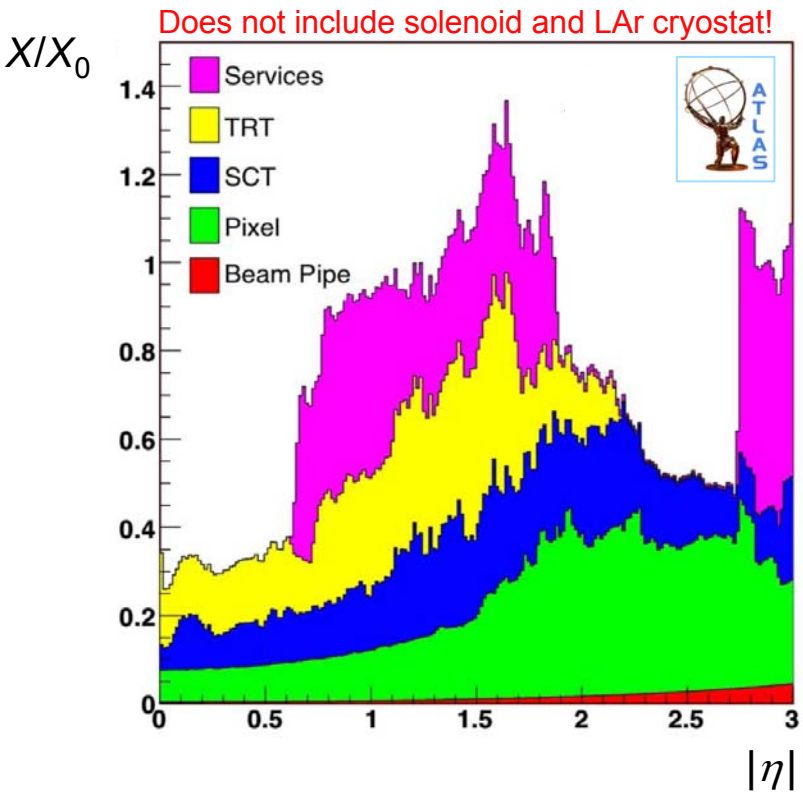
“In-situ” Calibration of EM Calorimeter

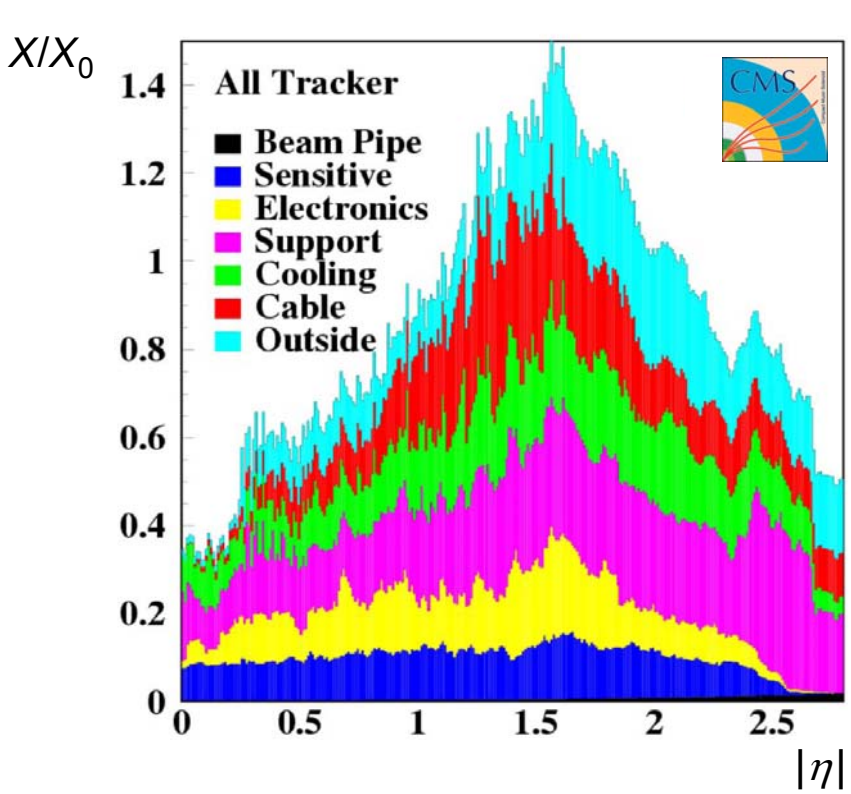
- Expected statistical yield for $Z \rightarrow ee$ intercalibration (14 TeV)



Material in Inner Detector

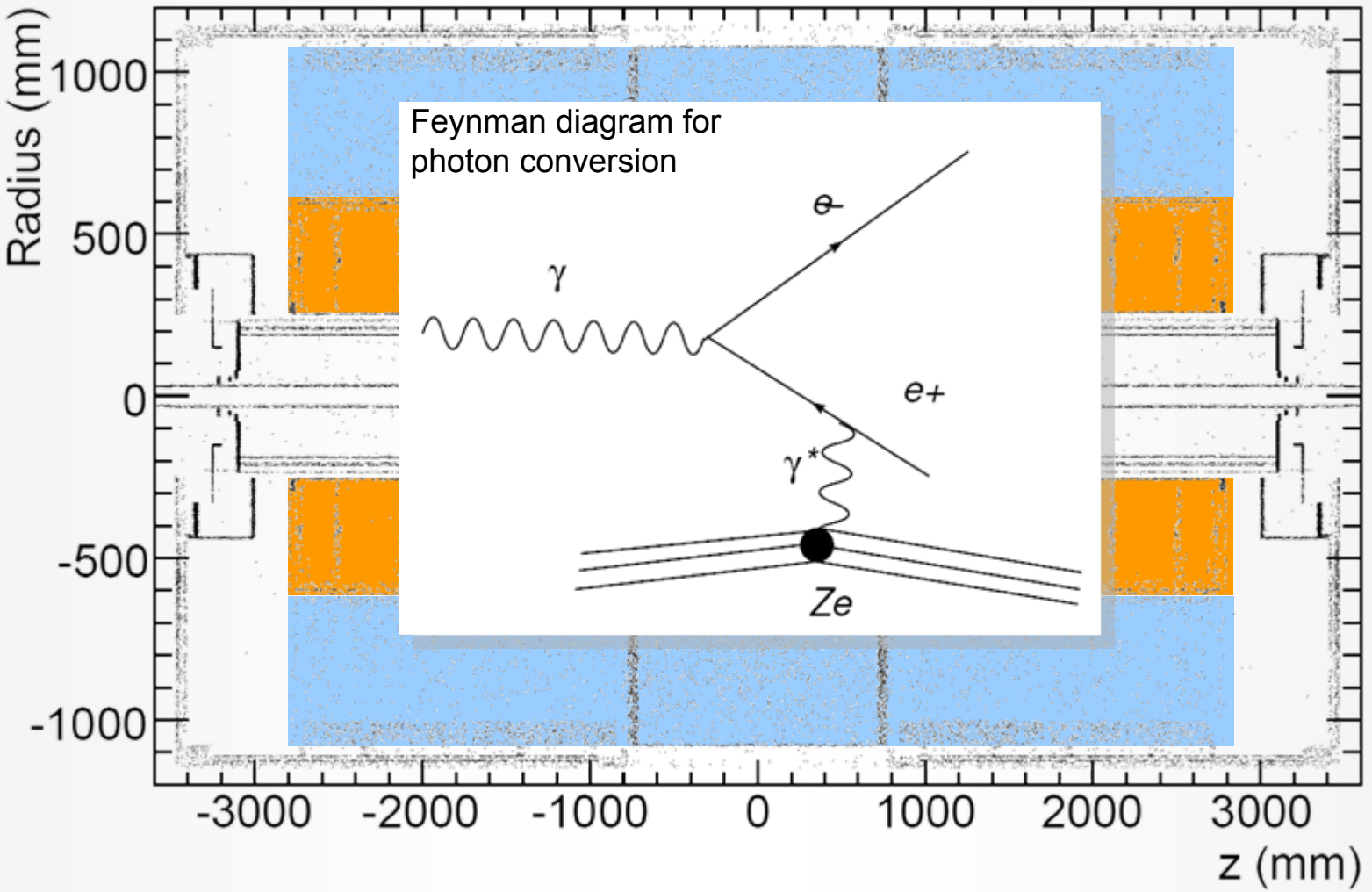
Radiation length for the ATLAS and CMS inner trackers





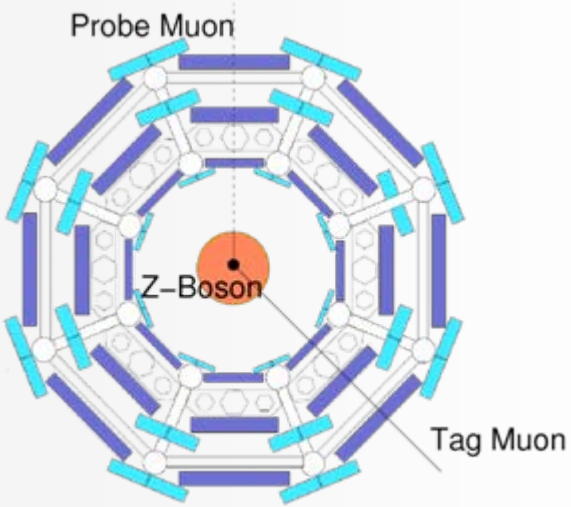
- **Excellent knowledge of inner tracker material is mandatory for precise simulation**

Material Mapping With $\gamma \rightarrow e^+e^-$ Conversions



“Tag and Probe” Method

- Method to determine efficiencies for particle identification and trigger selections



Example: MS reconstruction efficiency with $Z \rightarrow \mu\mu$

Tag muon:
- event triggered by tag muon
- isolated ID-MS muon with $p_T > 20$ GeV

Probe muon (unbiased wrt. tag selection):
- require inner detector track
- $m(\mu\mu) \sim M_Z$ (91 GeV)
- Count how often the probe muon has been reconstructed in the muon spectrometer

With sufficient statistics the efficiency can be evaluated in bins of p_T, η ,ϕ

Usually, the result has to be corrected for combinatorial background under the Z peak

The Tag and Probe Method is very flexible, many versions of the same idea exist

Consider measured sample of N events: apply tag and probe criteria, where tag is tighter than probe

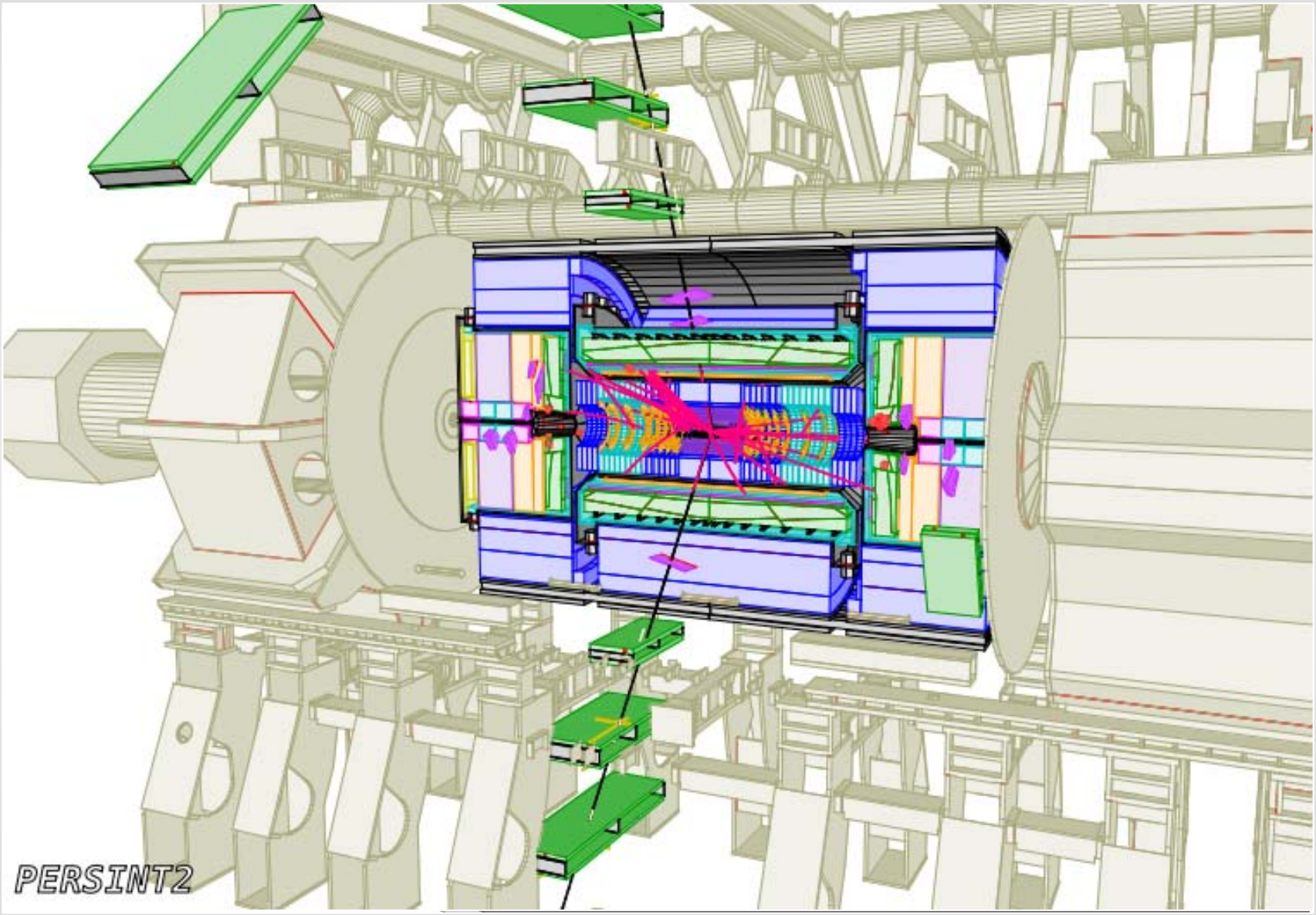
N_{TT} events have both muons tagged

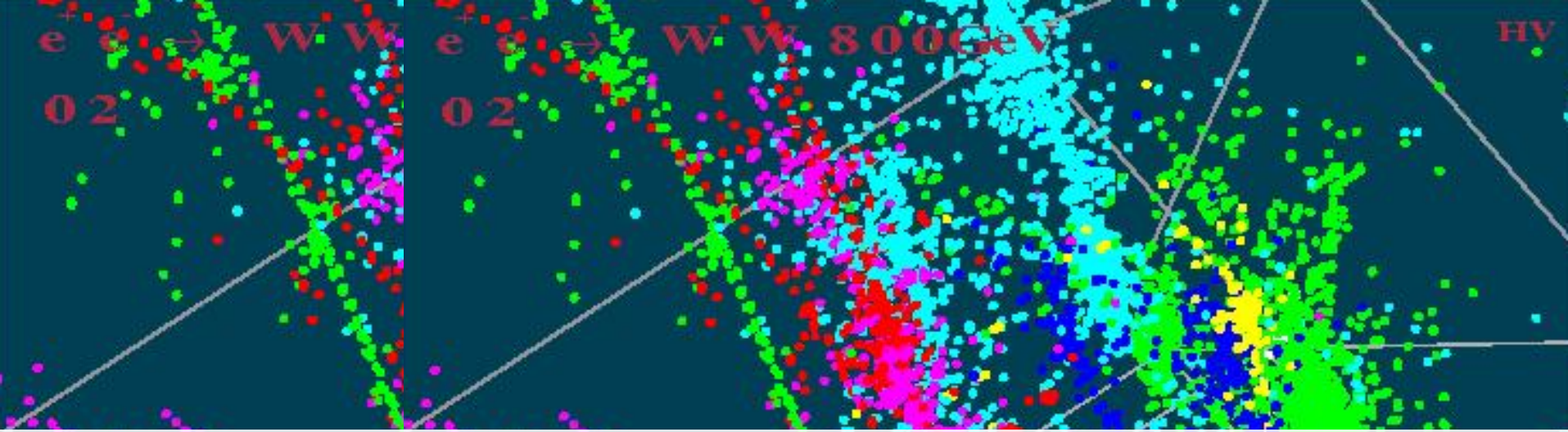
N_{TP} events have one tag and one probe muon

$$\left.\begin{aligned} N_{TT} &= \varepsilon_T^2 \cdot N \\ N_{TP} &= 2\varepsilon_T \cdot \varepsilon_P \cdot N \end{aligned}\right\} \Rightarrow \varepsilon_P = \frac{N_{TP}}{2\sqrt{N \cdot N_{TT}}}$$

Simulated $Z \rightarrow \mu\mu$ event in **ATLAS**

Expect 10,000 of these events in first 10 pb^{-1} (and 10 times more $W \rightarrow e\nu$) recorded

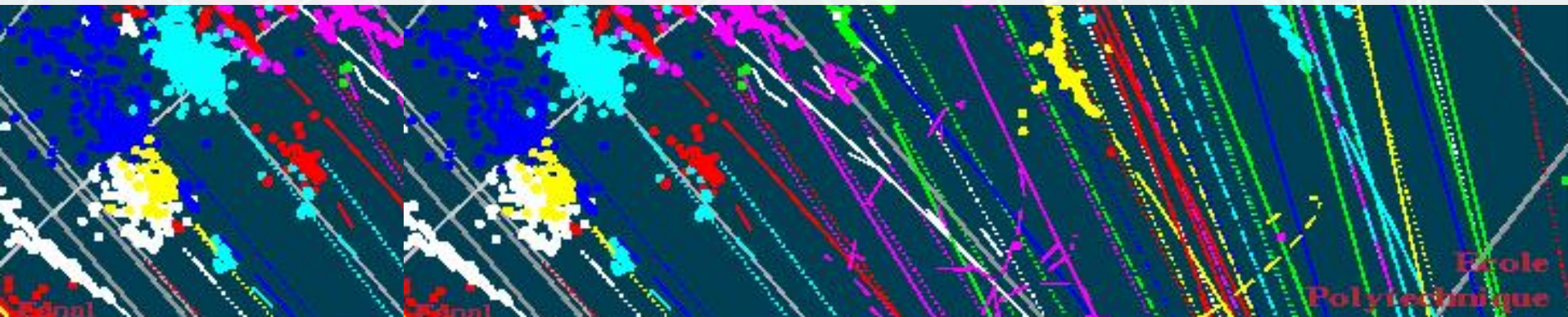




Jet Calibration

Precise absolute knowledge of the jet energy scale (JES) is required for many measurements. Typically a calibration of better than 1% is required for the measurement of the top quark mass, but also for SUSY signatures.

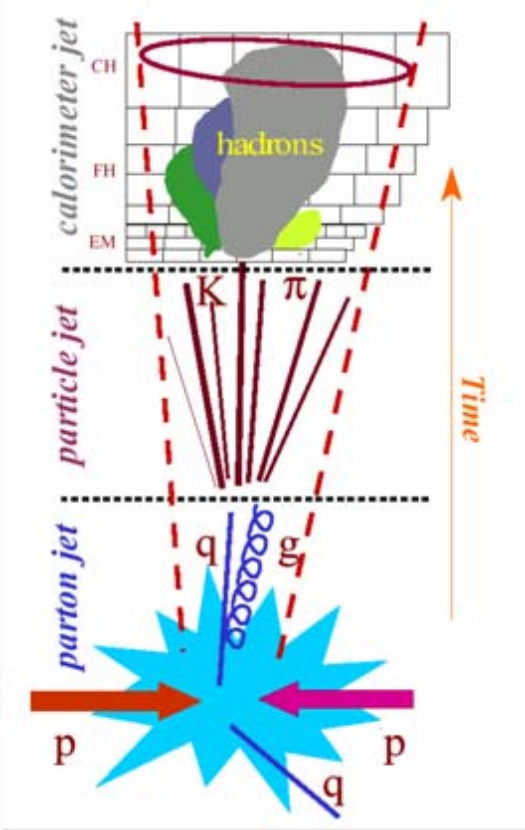
Jets are complicated objects, and their reconstruction involves a large number of corrections and calibrations. Only a brief overview is given here…



Jet Energy Reconstruction and Calibration

- Jet energy reconstruction and calibration can be divided in 4 steps

1. Calorimeter tower/cluster reconstruction
2. Jet making (cone 0.4/0.7, k_T, other "Jet Algorithms")
3. Jet calibration from calorimeter to particle scale
4. Jet calibration from particle scale to the parton scale



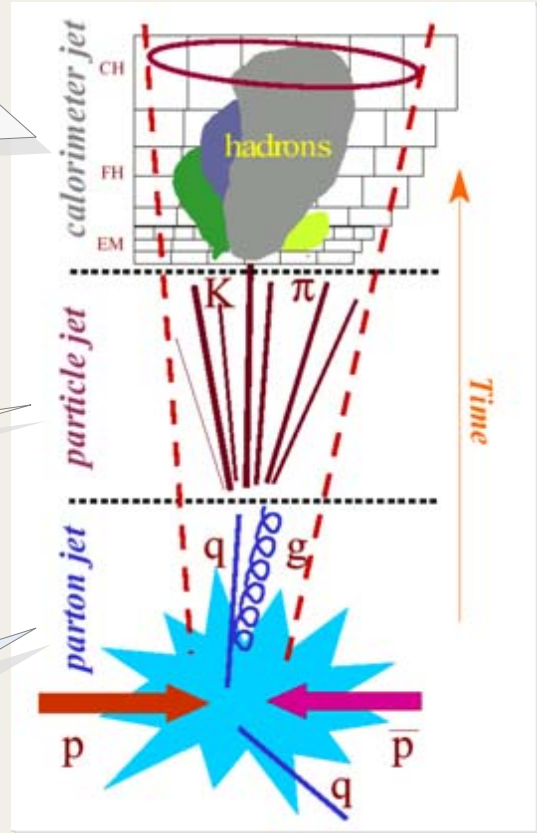
- Approaches:
  - Global jet calibration (uses MC)
    - jet inputs are EM-scale clusters, matched in *E* to truth particle jet for bins of *E*, η → *hadronic scale*
  - Local hadron calibration (uses MC)
    - calibrate clusters independent of jet algorithm making an assumption on their EM or non EM nature. Then make jets out of calibrated clusters → *hadronic scale*
  - In-situ calibration of hadronic scale (uses data)
    - match hadron to parton level using physics processes

Jet energy scale: contributions to the jet signal

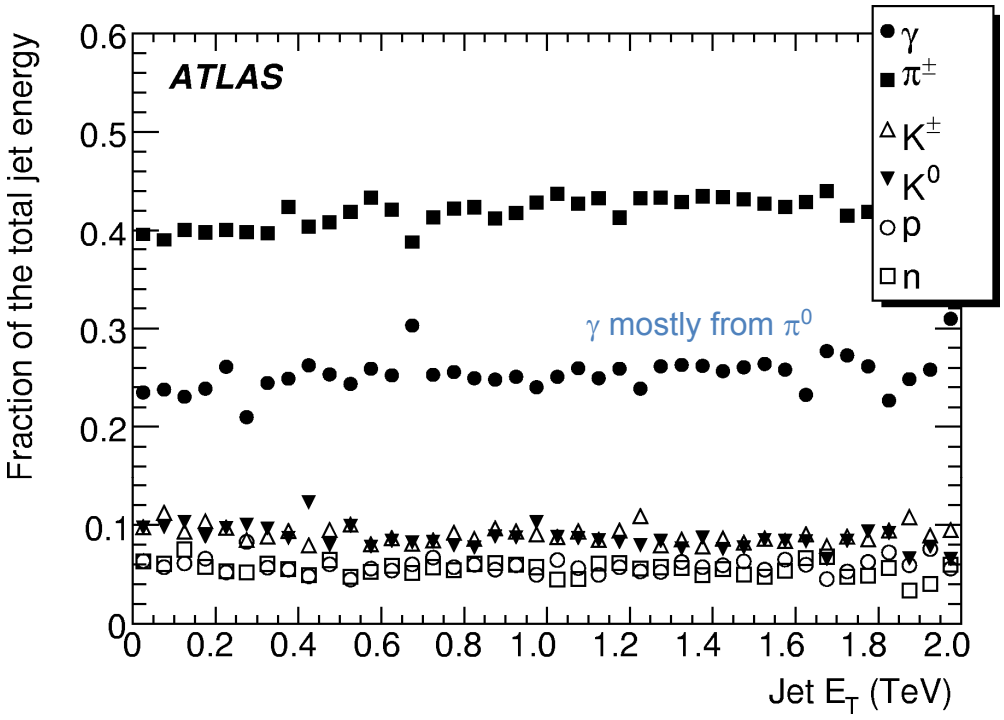
Longitudinal energy leakage
Detector signal inefficiencies (dead channels, HV…)
Pile-up noise
Electronic noise
Calo signal definition (clustering, noise suppression ,…)
Dead material losses (front, cracks, transitions…)
Detector response characteristics ($e/h \neq 1$)
Jet reconstruction algorithm efficiency

Jet reconstruction algorithm efficiency
Added tracks from in-time (same trigger) pile-up event
Added tracks from underlying event
Lost soft tracks due to magnetic field

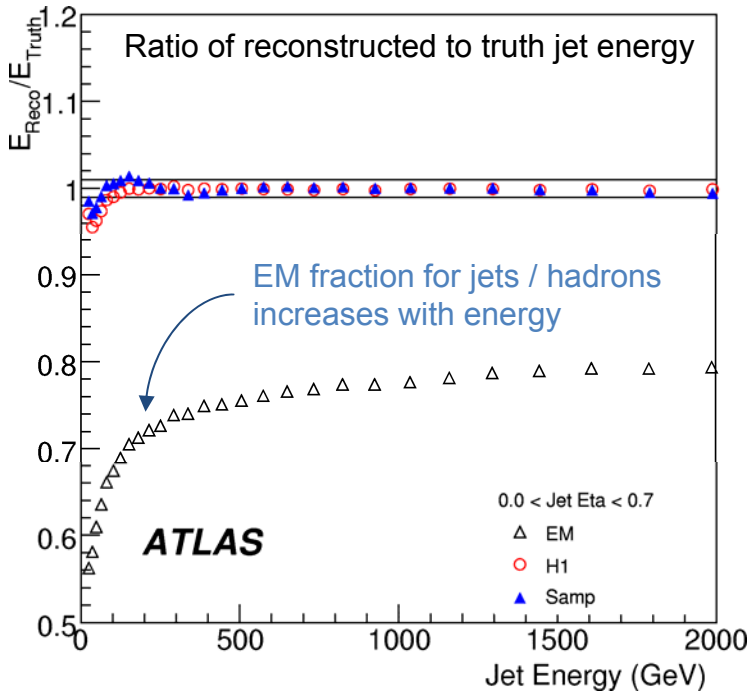
Physics reaction of interest (parton level)



Jet energy scale: particle contributions and linearity



Fractional energy carried by different particle types as a function of the jet energy.

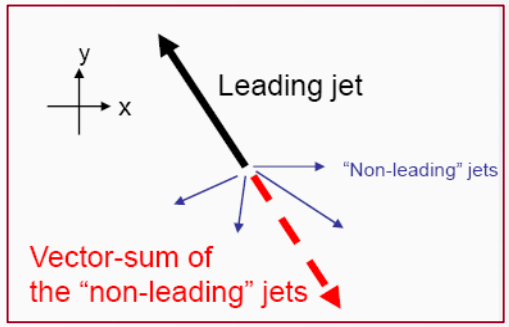


Jet energy linearity as a function of jet energy. The points are for jets reconstructed at the electromagnetic scale (EM), for the global weighting scheme described here (Samp) and for the H1-style calibration described in the previous Section. The jets have a cone radius of $R_{cone} = 0 \triangleright 7$.

In-situ Jet Calibration – Approaches

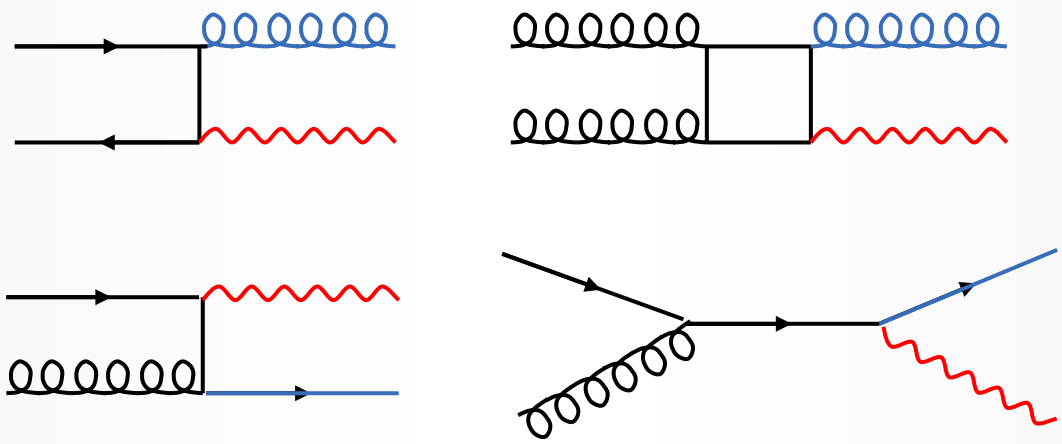
- Ultimate goal is reconstruction of initial parton momentum via physics events:
  - Verify hadronic scale with
    - E/p of isolated pions from minimum bias events and τ decays
    - Via energy flow using ϕ symmetry
  - Transverse balance in γ ($Z \rightarrow \ell\ell$) + jets events ($\sigma_{\gamma\text{-jet}} \sim 180$ nb)
    - Assumes EM calibration done
    - Potential biases from underlying events and pileup
  - QCD di/multi-jet events for η, ϕ intercalibration
    - For multi jets: choose leading jet for E_T, η, ϕ "calibration"
    - Balance with vector sum of other, softer jets
    - Huge statistics (di-jet = 100–5000 $\times$ γ–jet) , but systematic effect form soft jets
  - Absolute calibration from $W \rightarrow$ jet + jet decays for clean W from top decays
    - For soft jets (< 200 GeV) only
    - W jets colourless, different from QCD jets

Sketch for multi-jet calibration



In-situ Jet Calibration – Selected Results

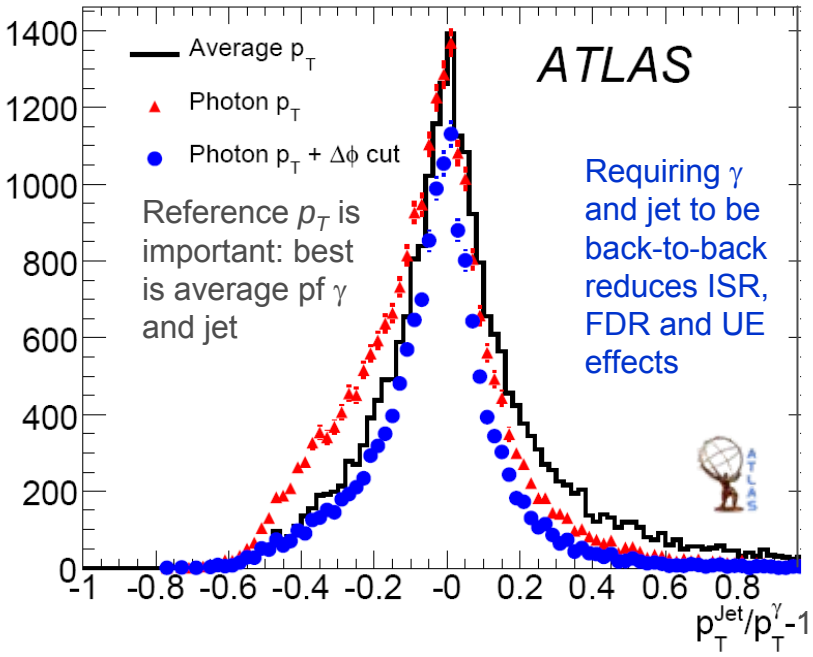
- Example γ–jet balance: use as reference average of γ and jet p_T

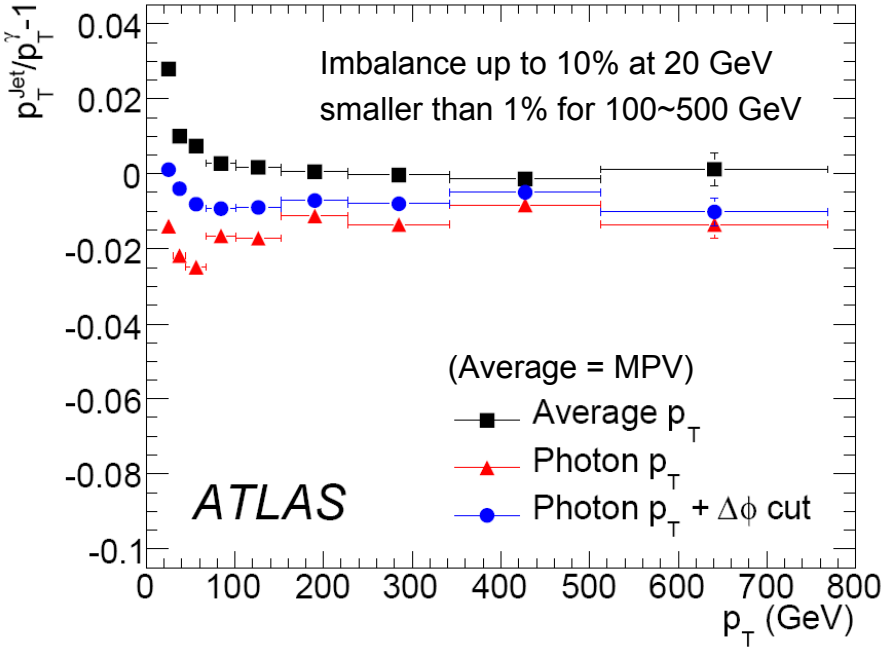


Leading γ–jet Feynman diagrams

In-situ Jet Calibration – Selected Results

- Example: γ–jet balance for absolute jet energy scale (JES) calibration





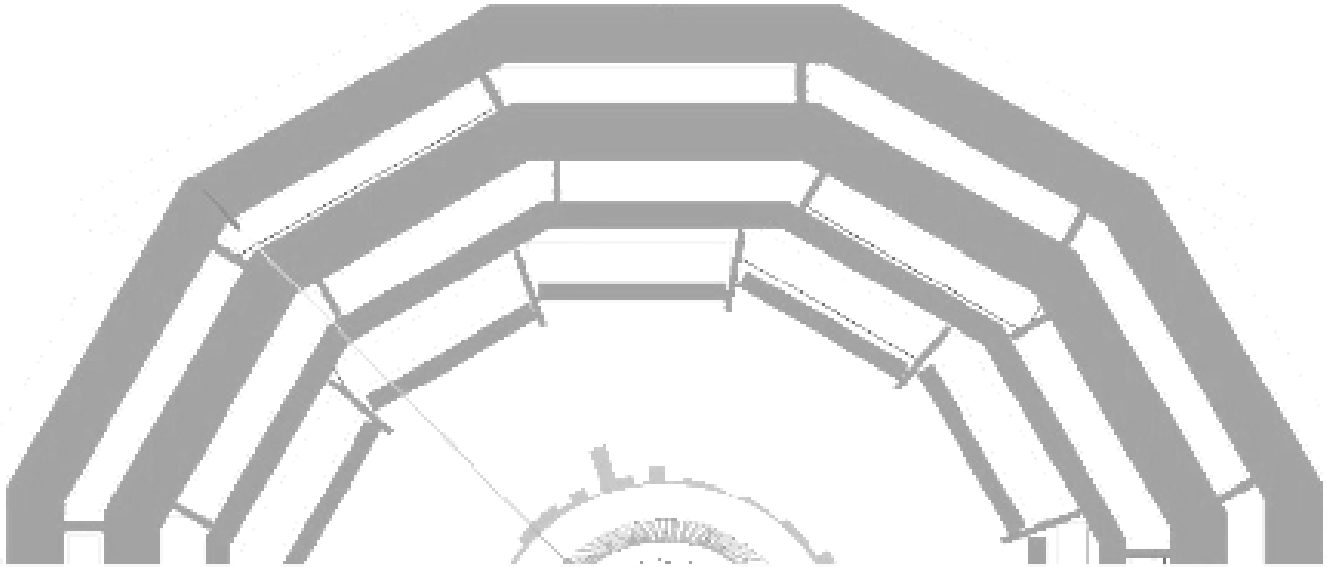
- Careful MC studies needed to disentangle the effects contributing to the imbalance
- Statistical yield: jet calibration of better than 1% for $p_T < 200$ GeV with 10 pb^{-1}

In-situ Jet Calibration – Selected Results

- Multi-jet balance method (> 2 jets) for jet intercalibration

Conclusions:

- Use di/multi-jet balancing for precise intercalibration and γ–jet for absolute JES calibration up to 500 GeV
- Detailed MC studies needed to control systematics below 100 GeV
- Above 500 GeV, no measurements are available, also no test beam results for particles at such energy. Multi-jet balancing should allow few % JES accuracy with 1 fb^{-1} integrated luminosity



Excellent (scale, linearity, resolution) reconstruction of missing transverse energy (MET) is essential for the ATLAS and CMS physics programme

- Large MET is predicted in many new physics scenarios, notably SUSY
- MET is ingredient to precision measurements, such as semileptonic top reconstruction, $H \rightarrow \tau\tau$, and W mass

MET is particularly sensitive to systematic effects in detector and reconstruction: understanding MET in data is one of the primary physics commissioning challenges

MET Reconstruction

- Simplest method: cell-based MET reconstruction (ATLAS procedure)

$$\not{E}_T = \sqrt{\not{E}_x^2 + \not{E}_y^2}$$

$$\not{E}_{x,y} = \not{E}_{x,y}^{\text{Calo}} + \not{E}_{x,y}^{\text{Cryo}} + \not{E}_{x,y}^{\text{Muon}}$$

  - Calorimeter term (calibrated at hadronic *E* scale – EM scale would underestimate MET)

$$\not{E}_{x,y}^{\text{Calo}} = -\sum_{\text{EM \& Had cells}} E_{x,y}$$

  - "Cryostat" term corrects for energy loss in cryostats between EM and Had calorimeters

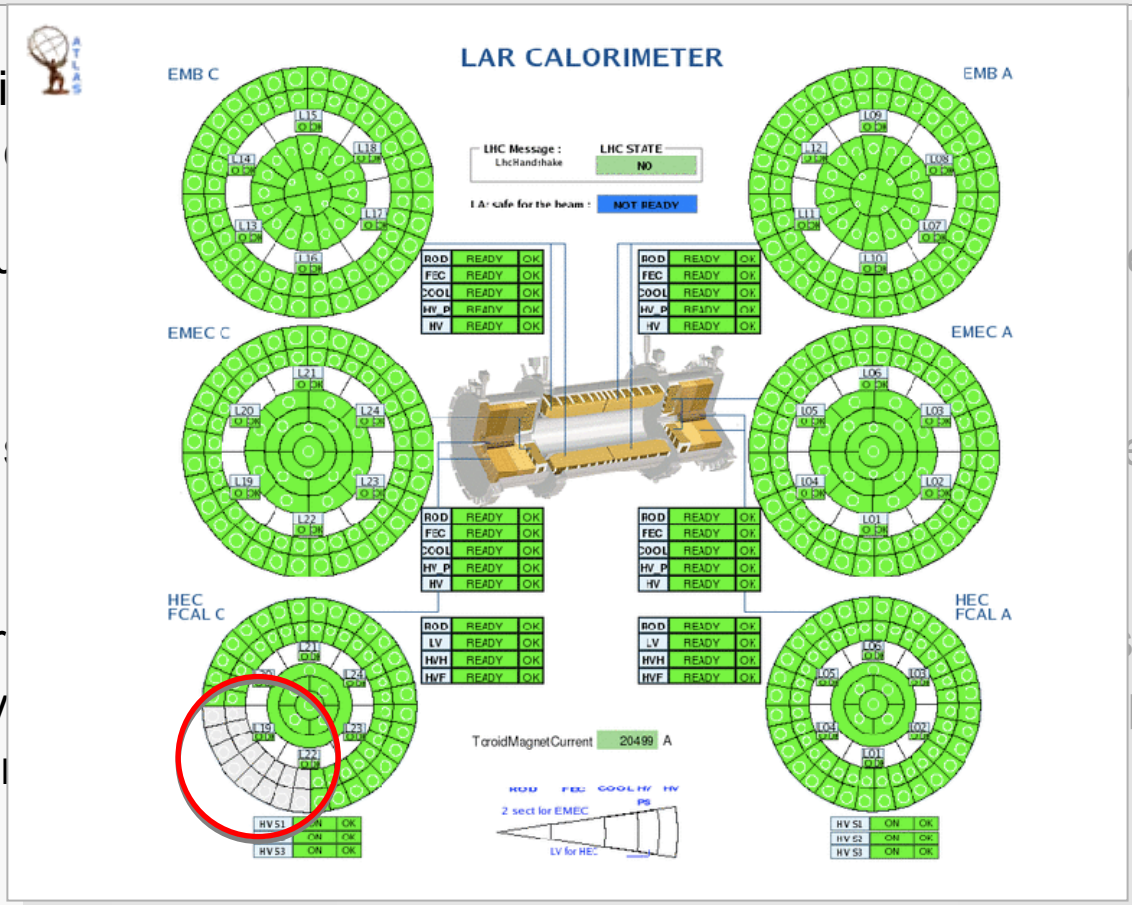
$$\not{E}_{x,y}^{\text{Cryo}} = -\sum_{\text{Jets}} w^{\text{Cryo}} \cdot E_{\text{Jet around cryo}-x,y}$$

  - Muon term uses muon momenta for $|\eta| < 2.7$ (muon spectrometer acceptance)

$$\not{E}_{x,y}^{\text{Muon}} = -\sum_{\text{Muons}} E_{x,y}$$

MET Reconstruction

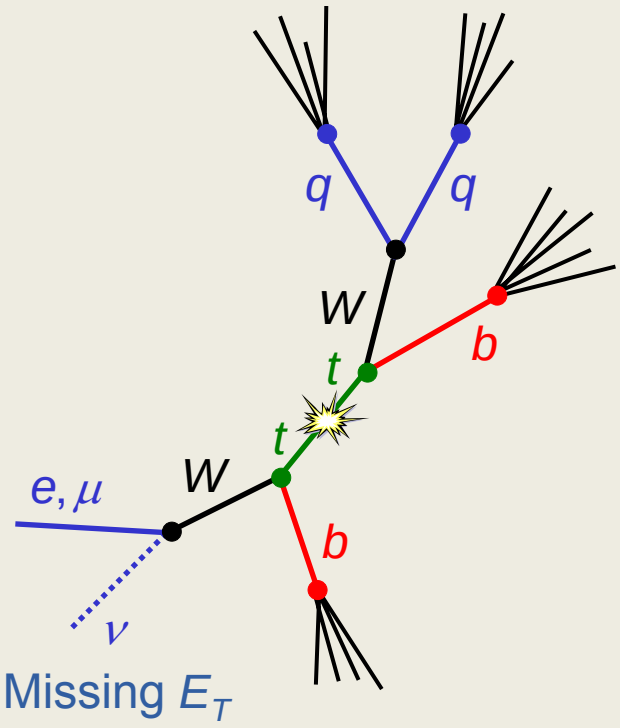
- Contributi … hardware, reconstru…
- MET is du… ew particles ?)
- MET is al… effects
- Moreover … reconstruction: dead and noisy … > 2.7) pile-up(*), backgrou… more effects …

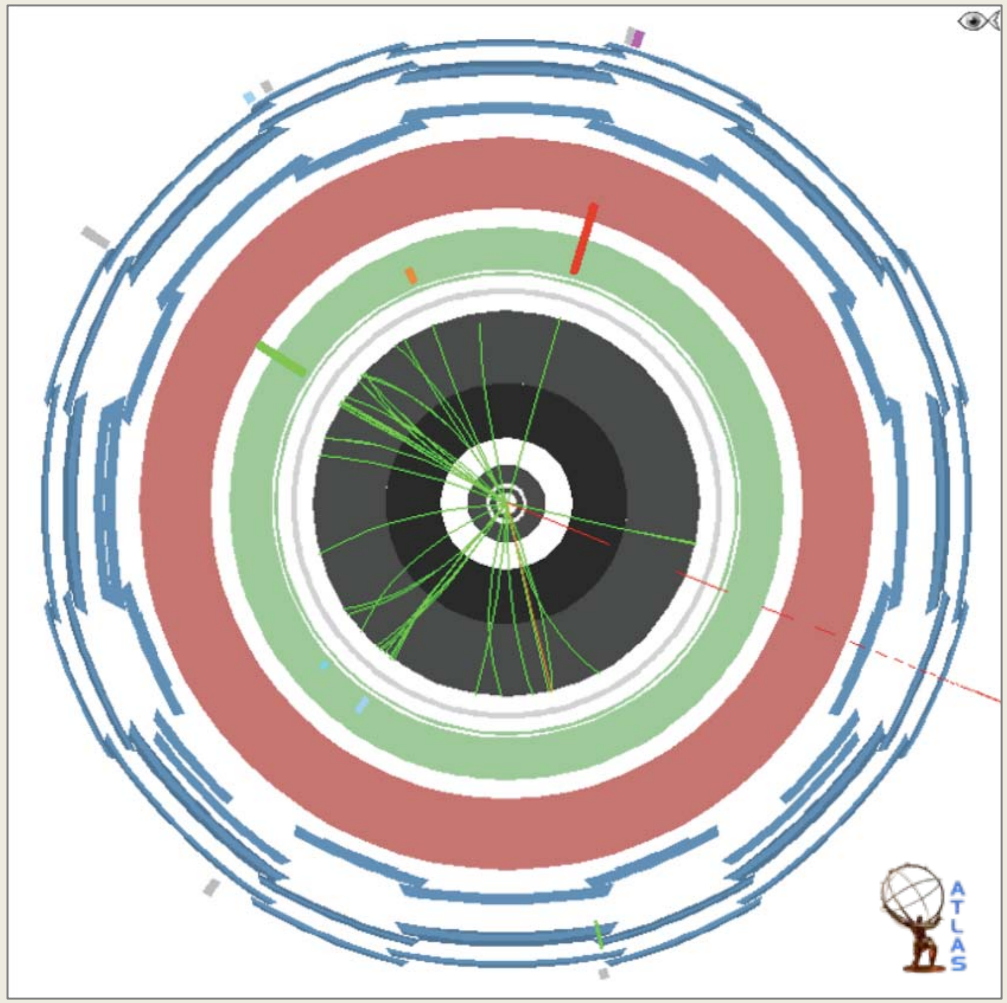


- Reduction of fake MET is crucial to increase sensitivity to true MET
  - Best possible jet energy absolute scale and resolution
  - Thorough classification (data quality!) and simulation of detector problems

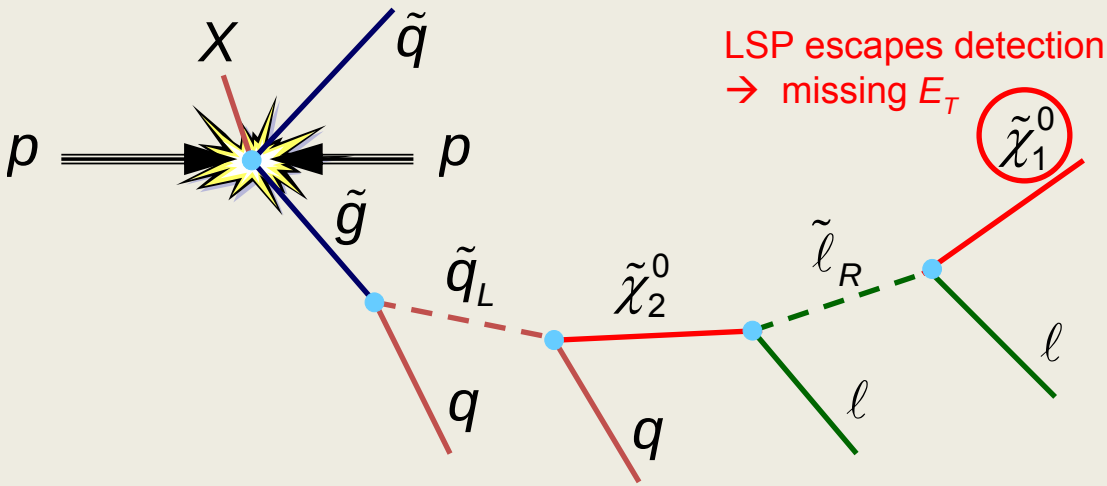
(*)All plots shown here are without pile-up. Earlier studies suggest a MET deterioration due to pile-up at 10^{34} $cm^{-2}s^{-1}$ by up to factor 2

True MET is generated by neutrinos in a $pp \rightarrow tt + X$ event

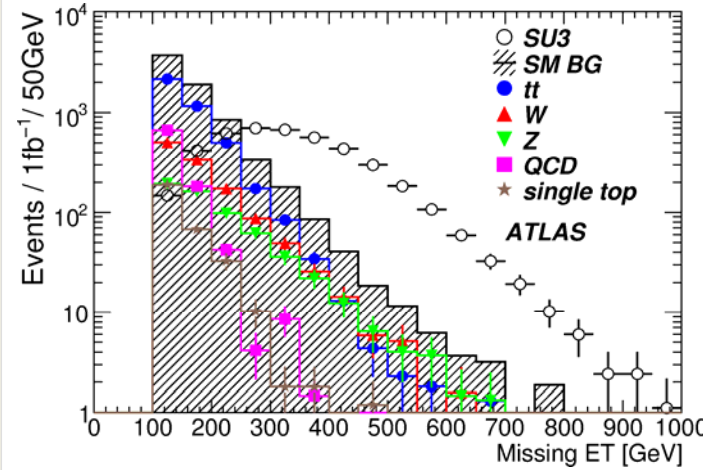




True MET would be generated by stable neutralinos in SUSY

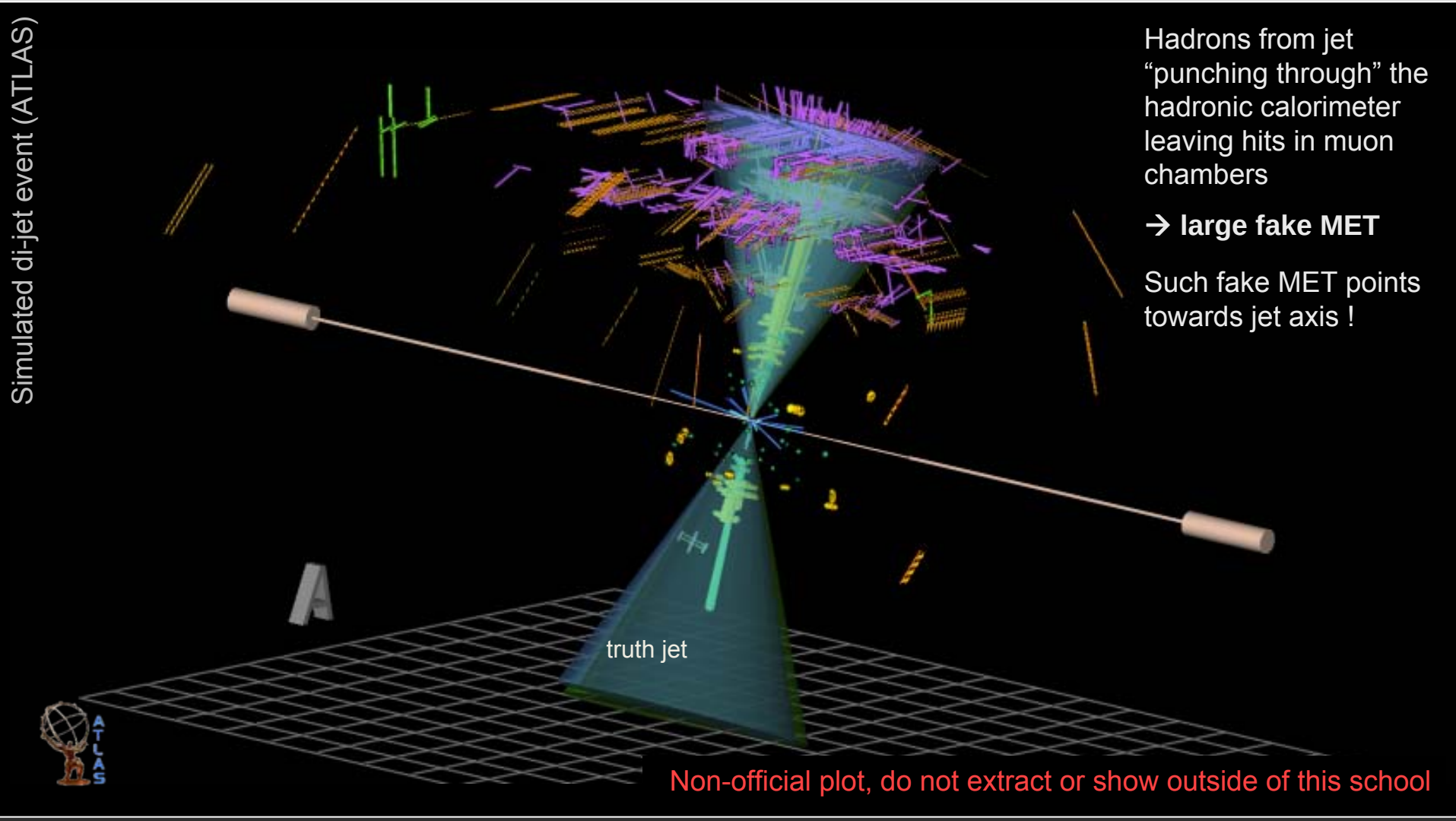


"Typical" SUSY decay chain at the LHC – assuming R-parity conservation

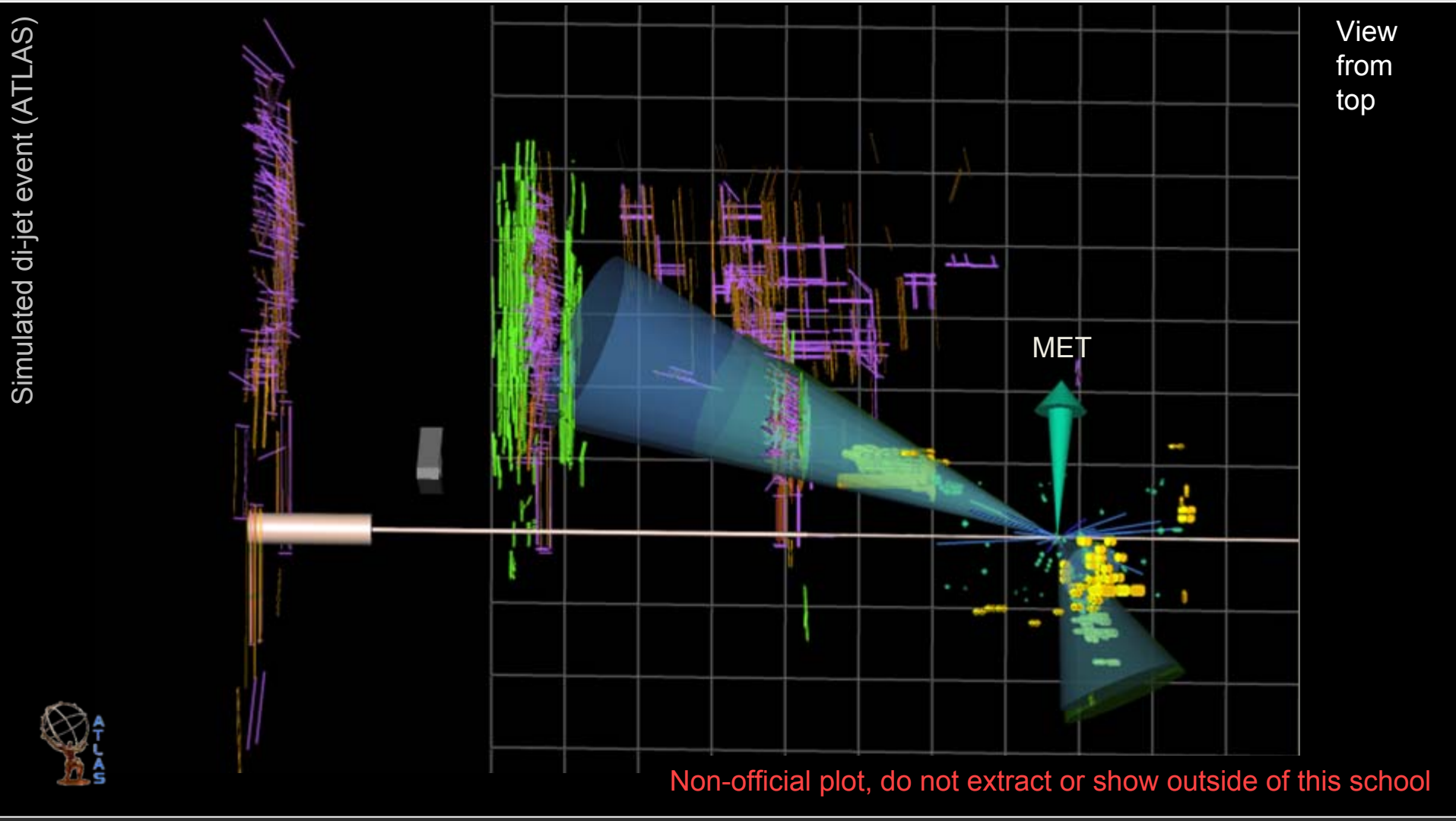


Distribution of MET in SUSY and background events

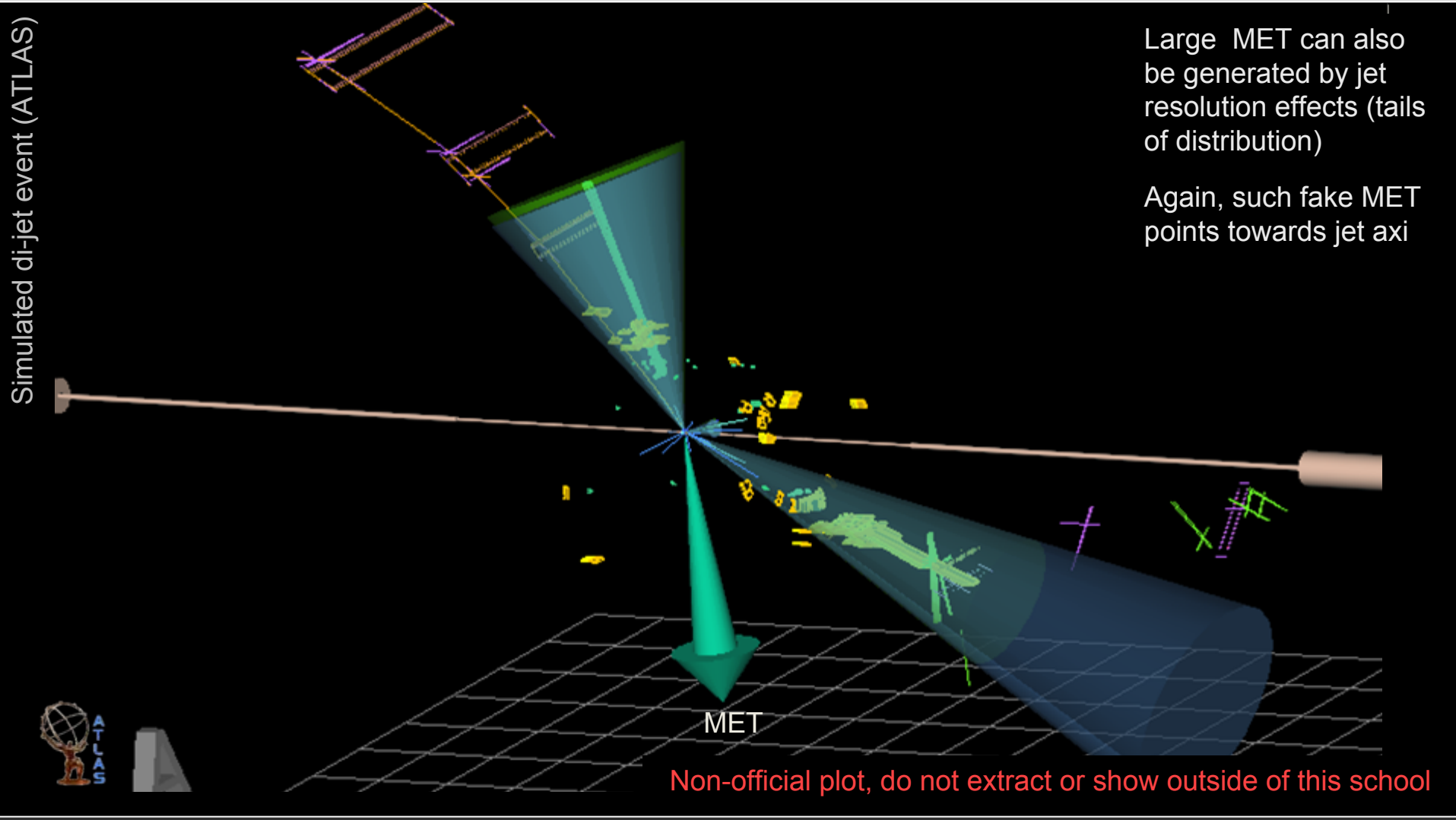
Fake MET can be generated by “punch-through” events



Fake MET can be generated by “punch-through” events



Fake MET can be generated by resolution effects



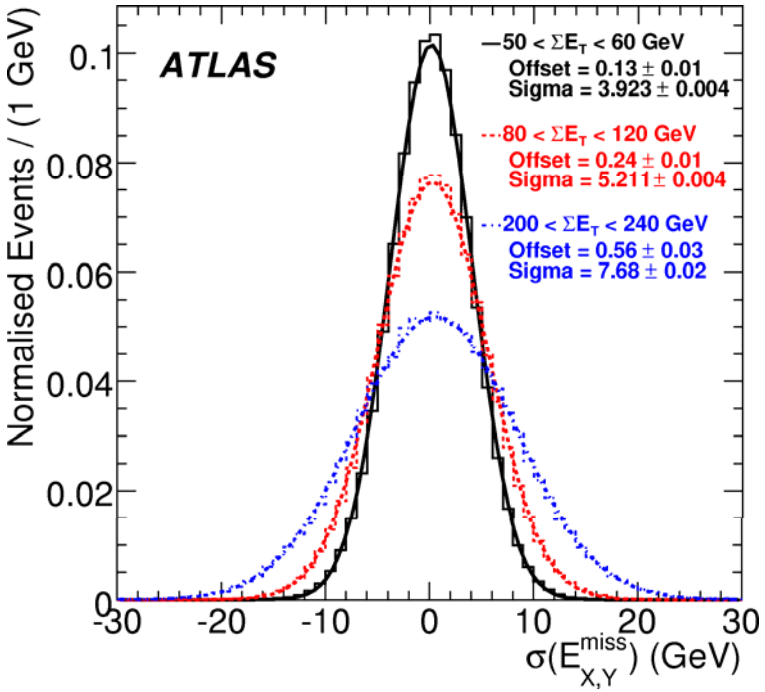
MET in Early Data

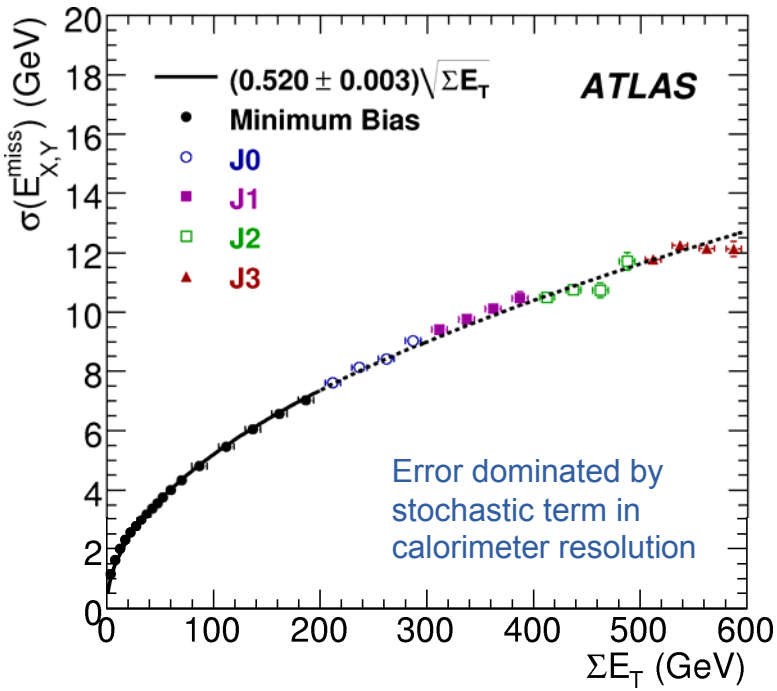
- Fake MET in soft QCD ("minimum bias") events

  Useful for early commissioning thanks to large statistics (however clean sample required)

  ⟨MET⟩ = 4.3 GeV: True MET ~ 0.06 GeV

  Fake MET mainly from calorimeter energy resolution (82%) and acceptance (18%)



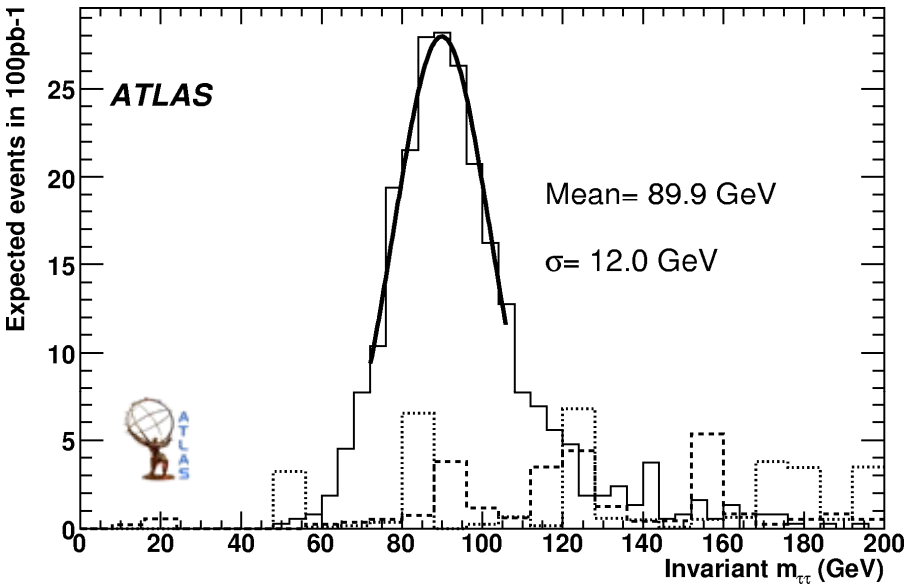


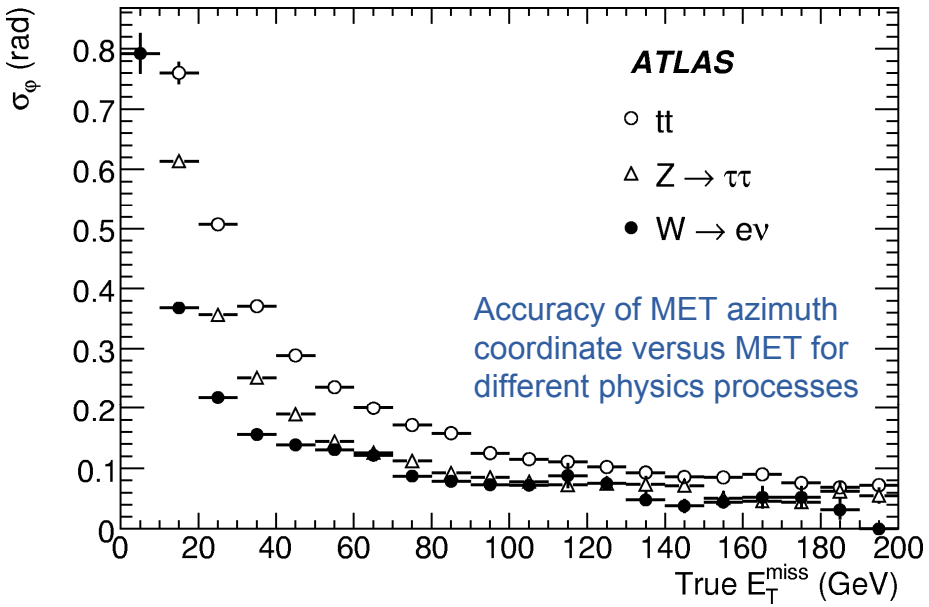
MET in Early Data

- Measure true MET in $Z \to \tau\tau \to \ell\nu\nu\, h\nu$ events (select ~200 events in 100 pb^{-1}, lepton trigger)

  Reconstruct $m(\tau\tau)$ assuming τ decay products collinear with τ in laboratory frame (OK, since strong boost)

  Then: $m^2(\tau\tau) \approx 2(E_h + E_{\nu(h)})(E_\ell + E_{\nu(\ell)})(1 - \cos\theta_{\ell h})$, and the ν energies are approximated with MET





Early Physics with ATLAS and CMS…

Experimental phases:

- Build detector, get beam
- Commission the trigger system – long process: L1/L2/EF, many trigger signatures
- Understand, align and calibrate the detector systems
- Understand the performance for physics objects: e, γ, μ, τ, jets, MET, *b*-flavour tagging
- **Establish signals for, and measure rates and spectra of, simple objects**
- **Only then can we expect any reliable observation of, or limits on, new physics**

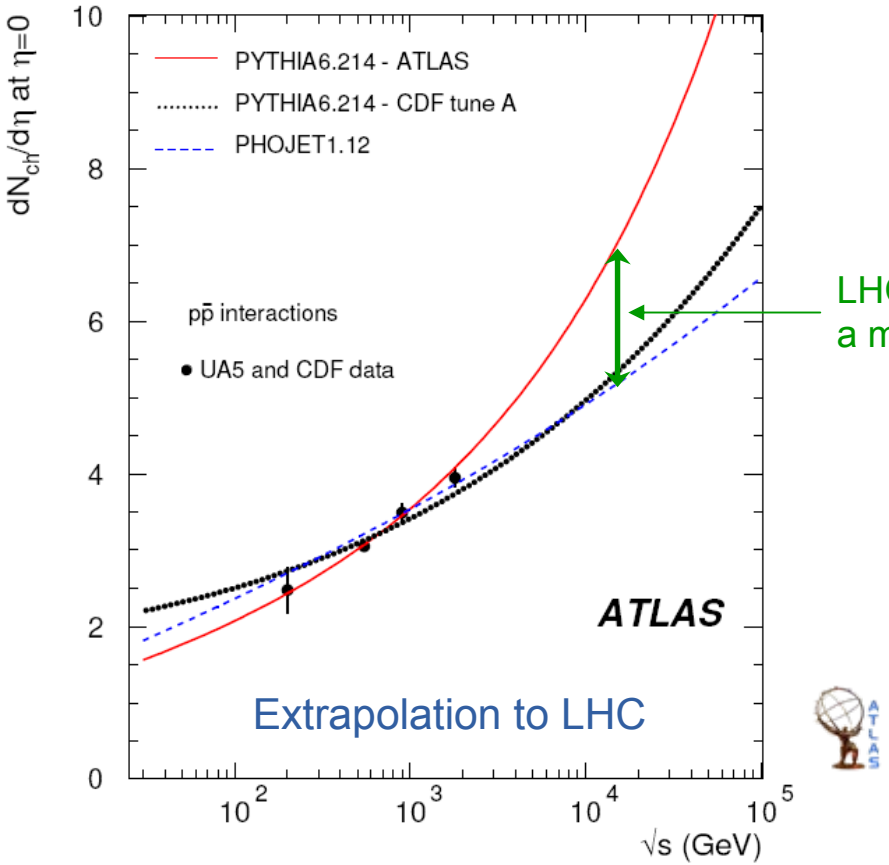
Use mostly ATLAS studies (apologies to CMS!) from new "Physics and performance book" – results from CMS very similar

Minimum Bias (Inelastic scattering)

- Early measurements – need alignment, efficiency and material, to be understood

MinB events allow to characterise the soft-part of the underlying event in high-p_T collisions in terms of η, p_T, multiplicity of particles. A first rough, but important test of the extrapolation of QCD to LHC energies. Finally, measure backgrounds for events with pile-up. Extrapolation to low p_T will be a challenge.

Central charged particle density for non-single diffractive inelastic events as a function of energy



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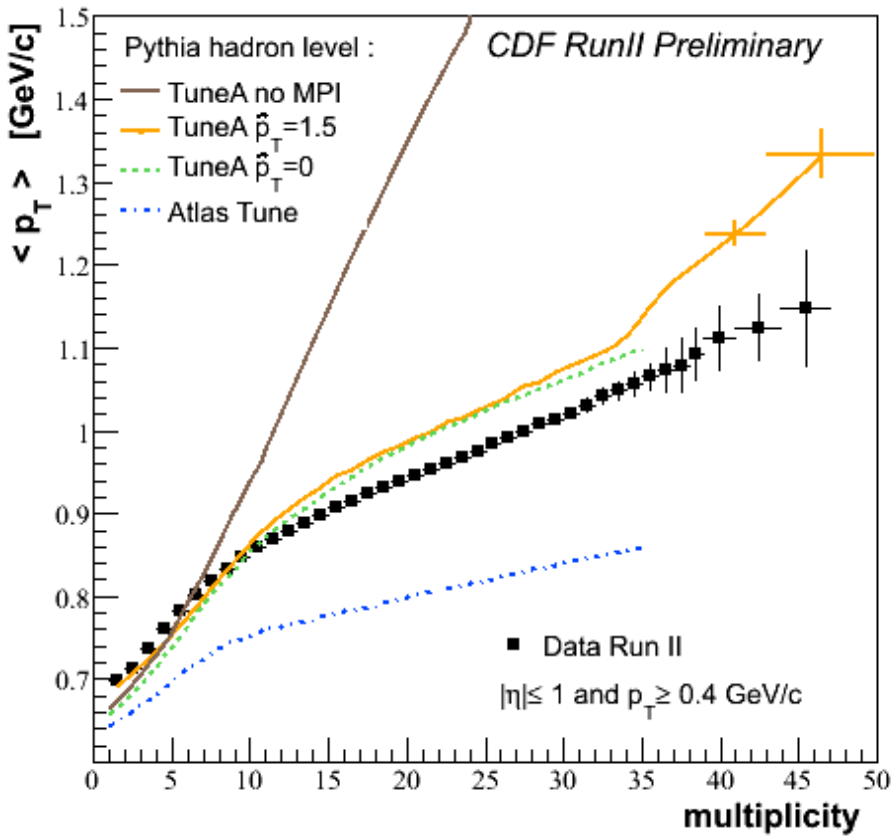
Correlation between average track momentum and track multiplicity

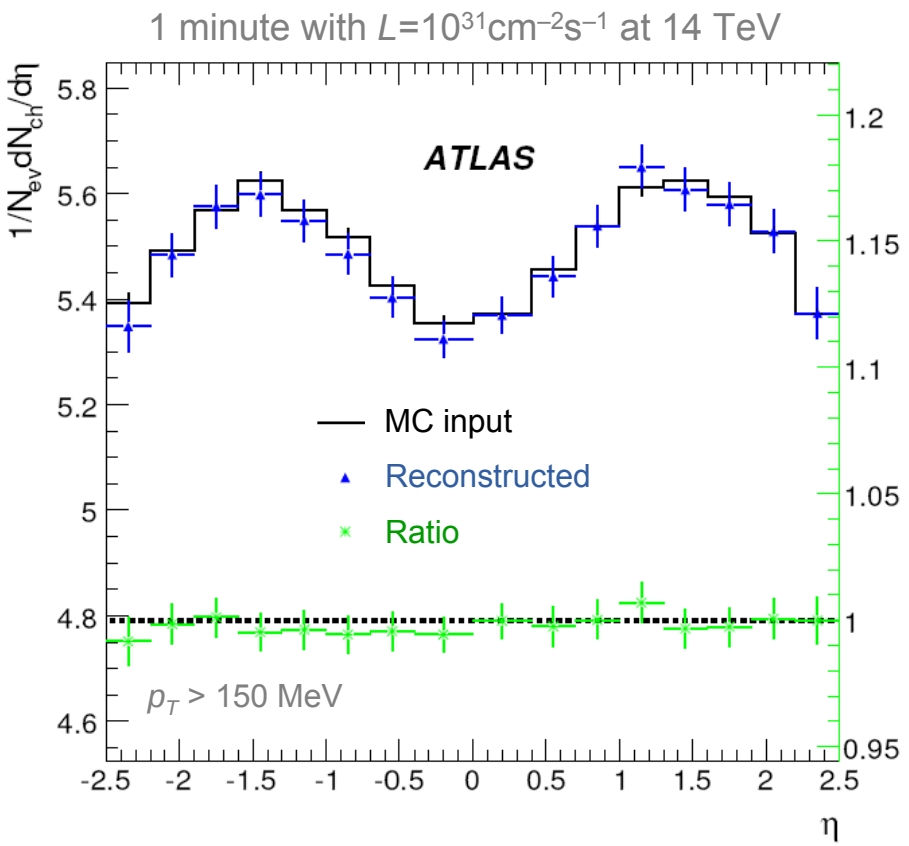
Minimum bias events are useful for early Monte Carlo generator tuning

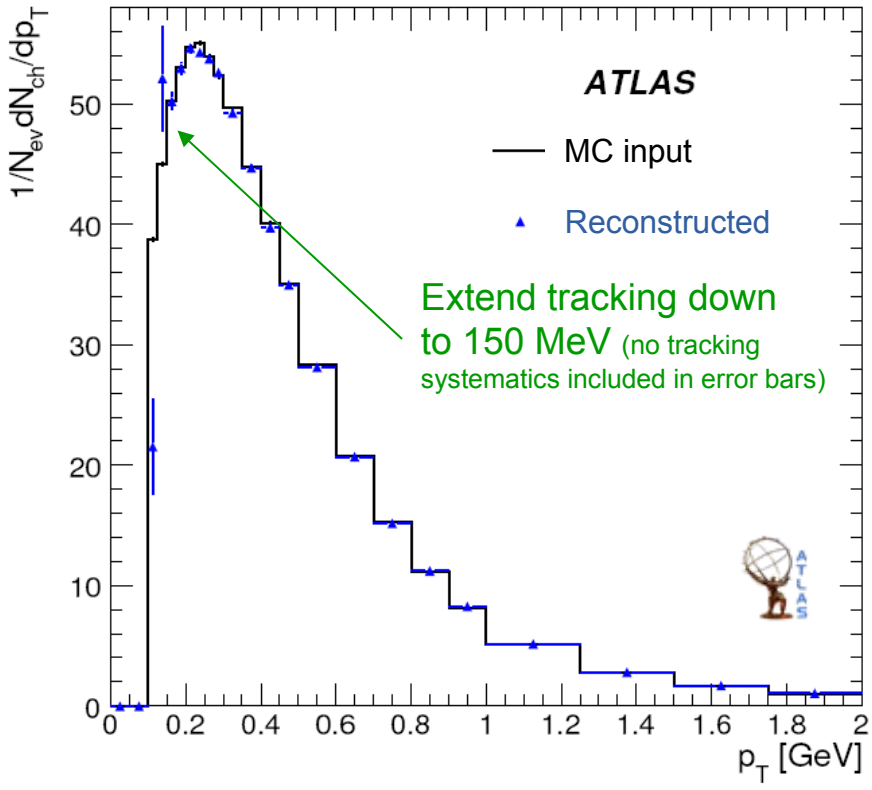


Minimum Bias (Inelastic scattering)

- Early measurements – need alignment, efficiency and material, to be understood

Particle density in minimum bias events versus pseudorapidity (left) and p_T (right)

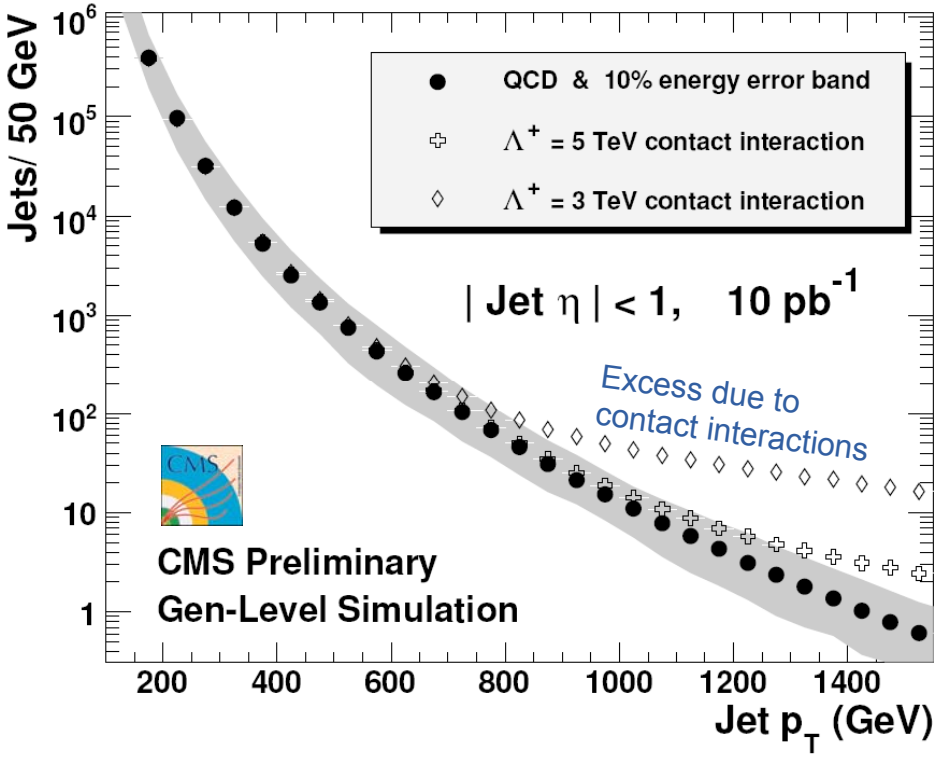


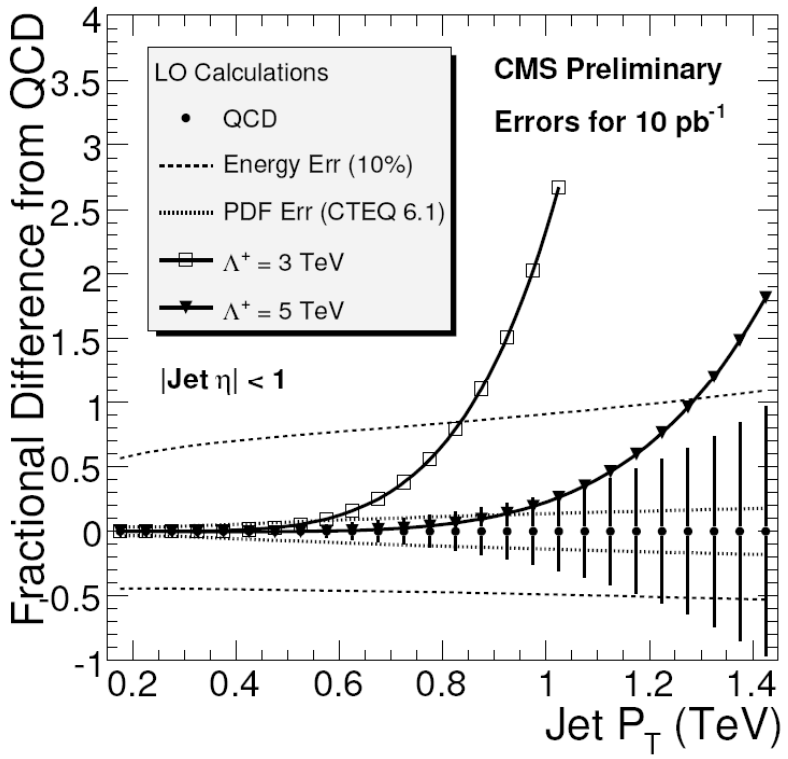


QCD Jets and New Physics

- Huge cross-sections – rapidly probe QCD and new physics above Tevatron scales

  Study of sensitivity to **contact interactions** from di-jet p_T spectrum – can reach 3 TeV scale with 10 pb^{-1}
  Systematic errors dominate over statistical and PDF errors
  However, requires good understanding of jet resolution and proton structure (PDF) at LHC scale



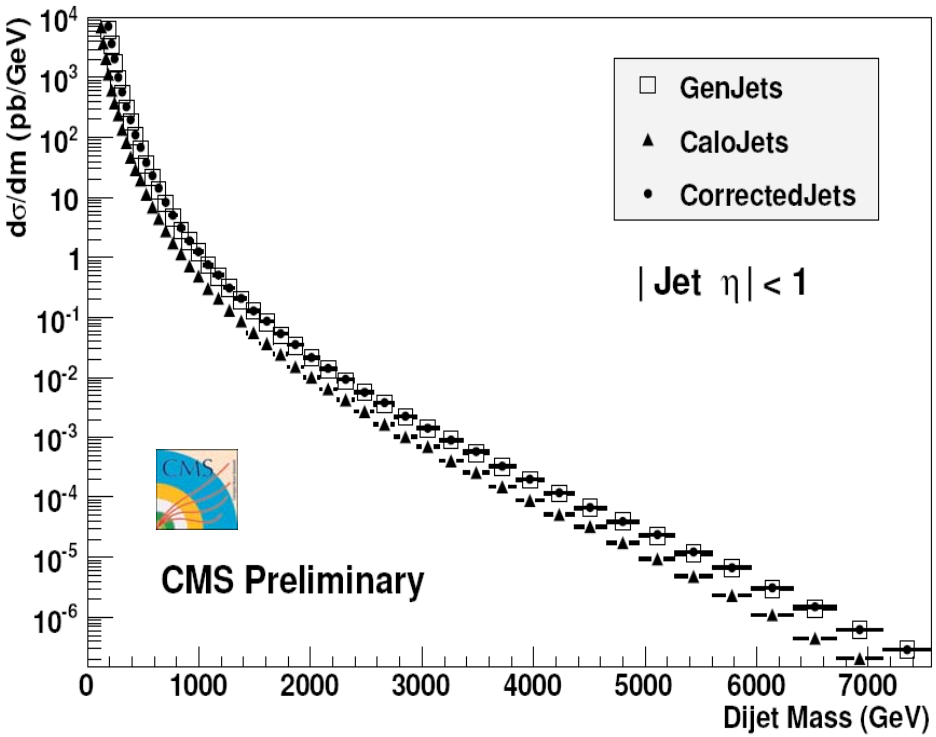


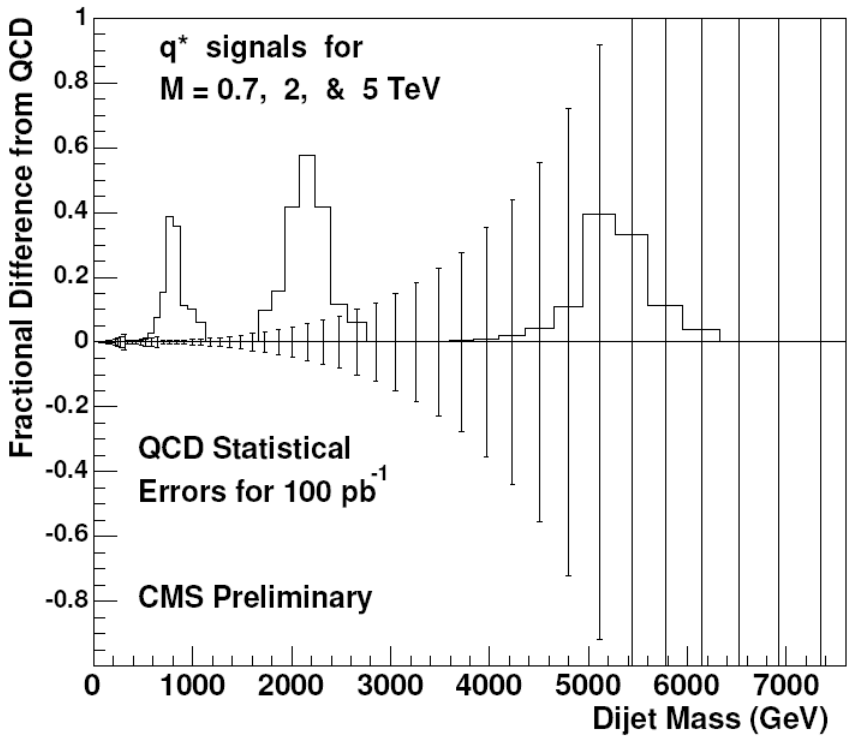
Contact interactions and systematic uncertainties in jet cross section for 10 pb^{-1}

QCD Jets and New Physics

- Huge cross-sections – rapidly probe QCD at a scale above Tevatron

  Search for d-jet resonances, *e.g.*, from heavy *Z'* decays produced by strong interaction
  Discovery of, *e.g.*, excited quarks with 2 TeV mass possible with 100 pb^{-1}



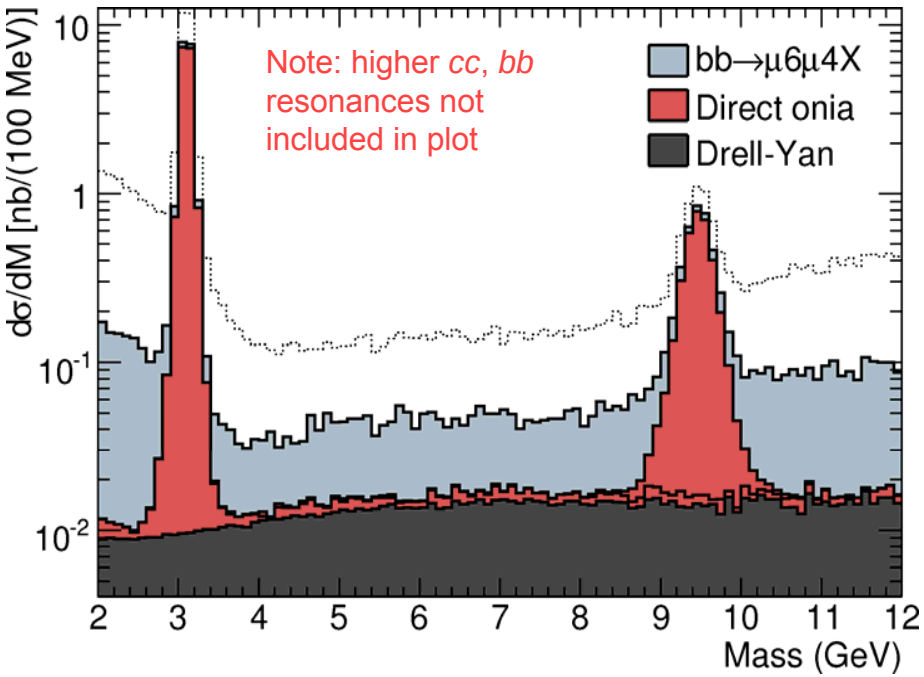


Left: di-jets from QCD. Right: di-jet resonances compared to QCD for 100 pb^{-1}

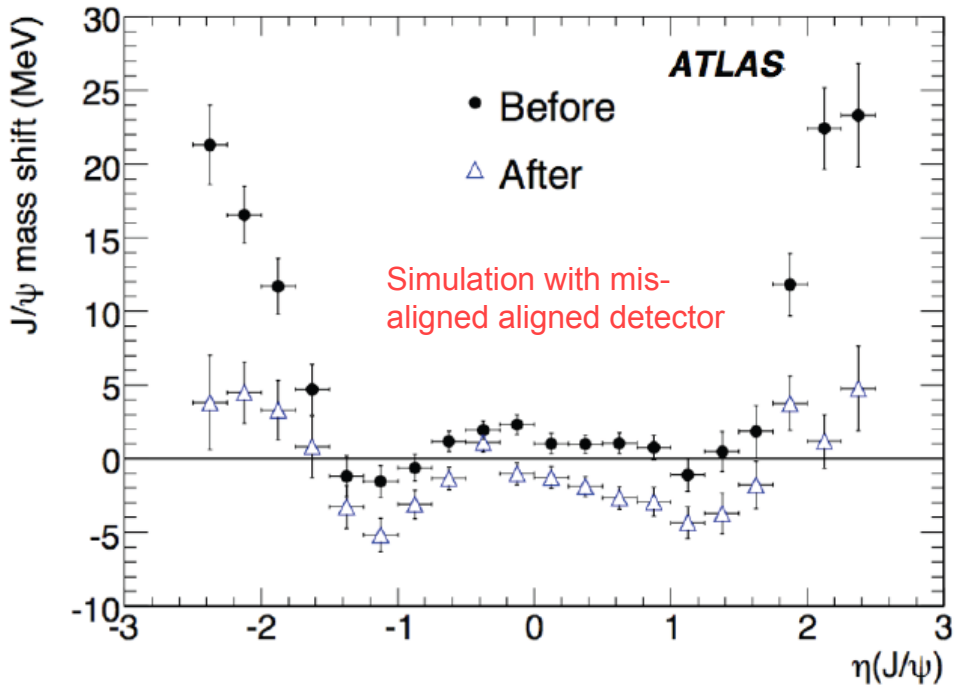
Quarkonia Physics

- Quarkonia – J/ψ, ψ', Υ, Υ', … – are excellent sources for early commissioning, but also for early physics measurements, e.g., prompt versus non-prompt production via J/ψ lifetime, ratios of cross sections, polarisation, …

J/ψ and Υ production – differential cross section



Alignment tests – may discover "weak modes"

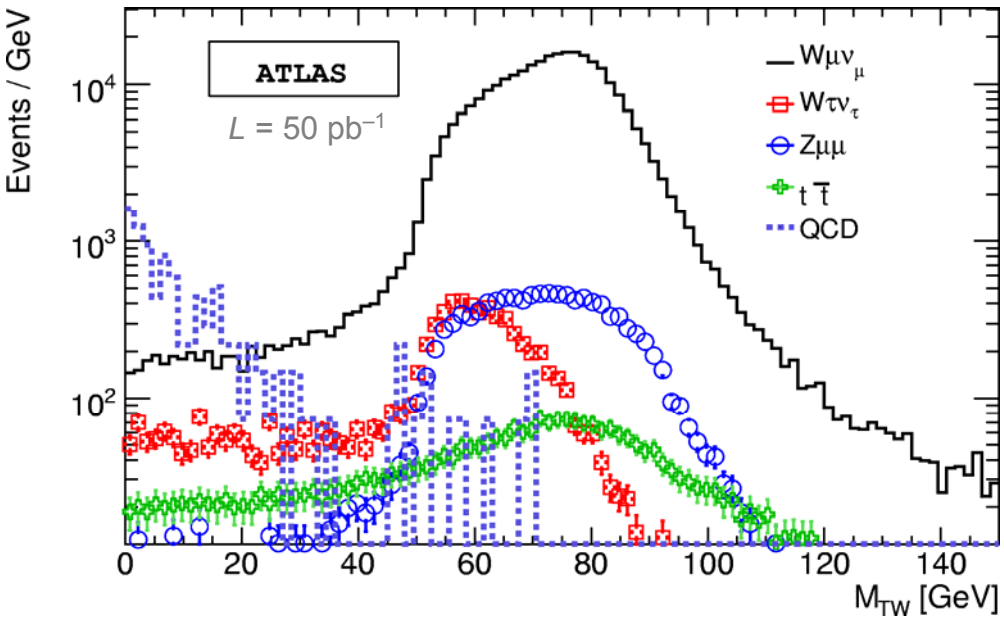


W and *Z* Cross Section

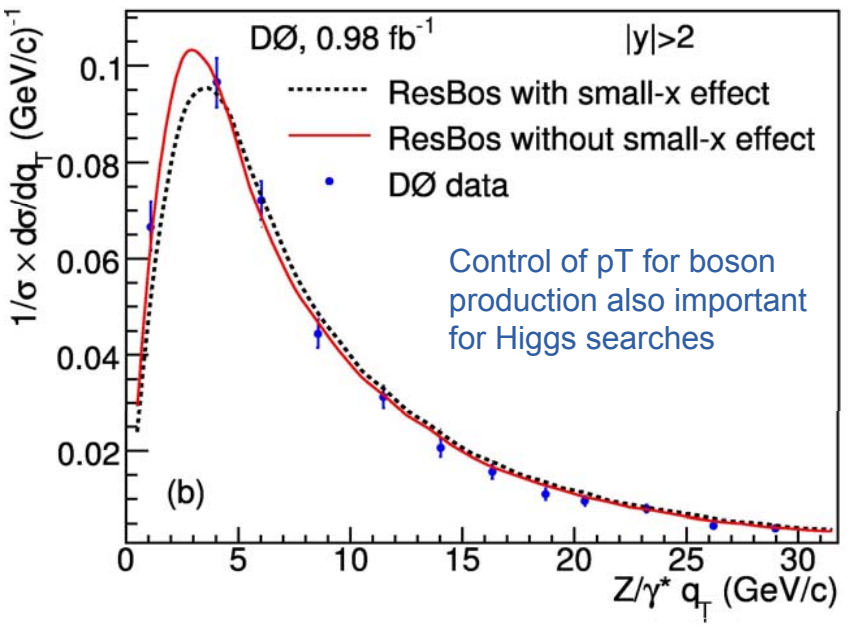
- $pp \to Z,W + X$ has large cross section allowing for data-driven cross-section measurements with early data (10–50 pb^{-1} shown)

  Z production most important for in-situ calibration (we've learned that already)
  Z and *W* + jets are sensitive probes to higher order QCD calculations

W transverse mass distribution and backgrounds



p_T of *Z* measured by D0 (Tevatron)

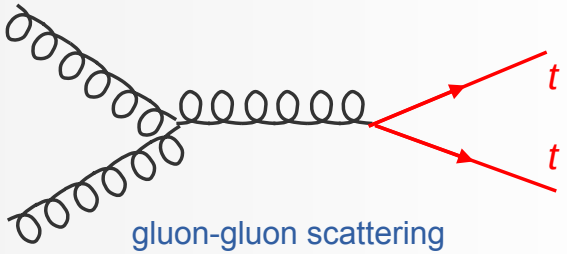


Top Physics

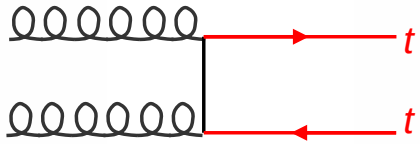
- ~100 times larger cross section at LHC (~830 pb) compared to Tevatron

Excellent channel for data-driven commissioning and calibration, notably *b*-tagging and jet energy
Significant single top production: ~300 pb (electroweak process, involves *W*), factor of ~100 over Tevatron

Leading order *tt-bar* production diagrams



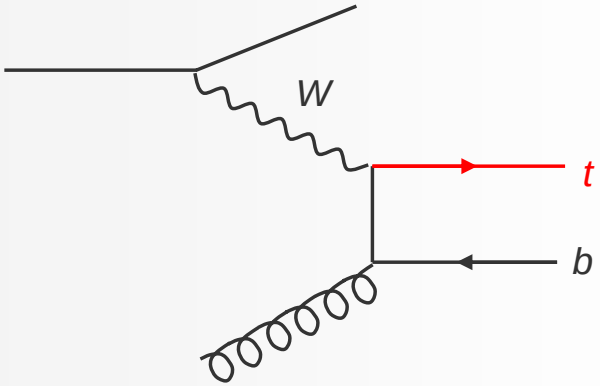
gluon-gluon scattering



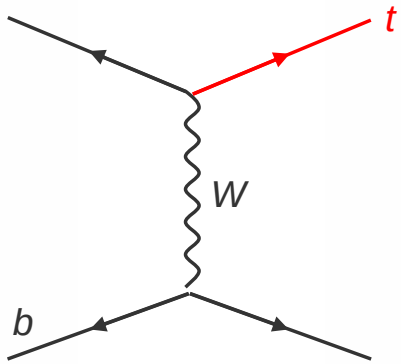
gluon-gluon scattering

quark-antiquark annihilation

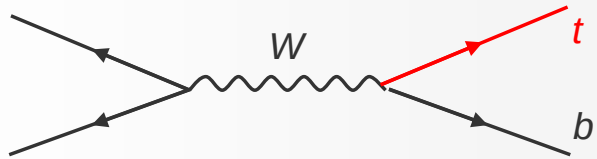
Leading electroweak single top production diagrams [Not shown: associated production of *t* + *W*]



W –gluon fusion (t-channel)



W exchange (t-channel)

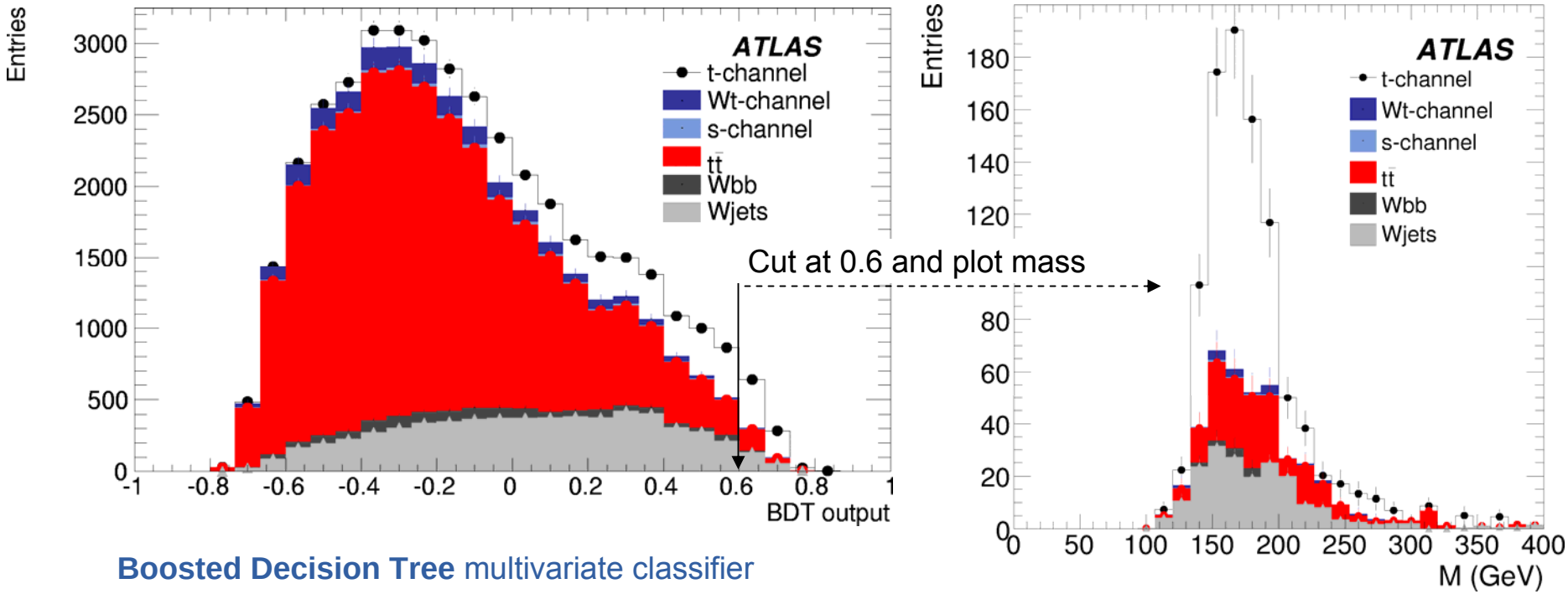


quark-antiquark annihilation
(s-channel, smaller cross section)

Electroweak ("Single") Top Production

- Electroweak top production 40% of t-pair cross section (just observed at Tevatron)

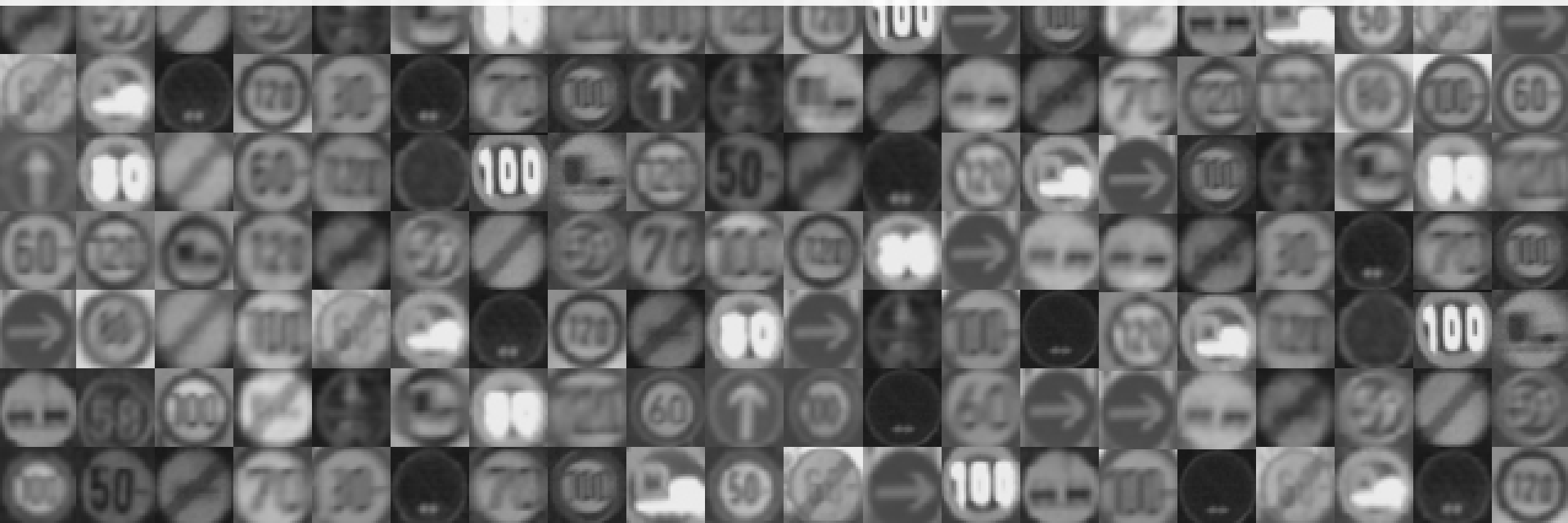
  Sensitive to new physics, *e.g.*, charged 2HDM Higgs replacing W in weak propagator
  Various production processes and final state topologies.
  Most promising: t-channel. Measure t-channel cross-section to ~10% accuracy with 10 fb^{-1}



Boosted Decision Tree multivariate classifier

Interlude

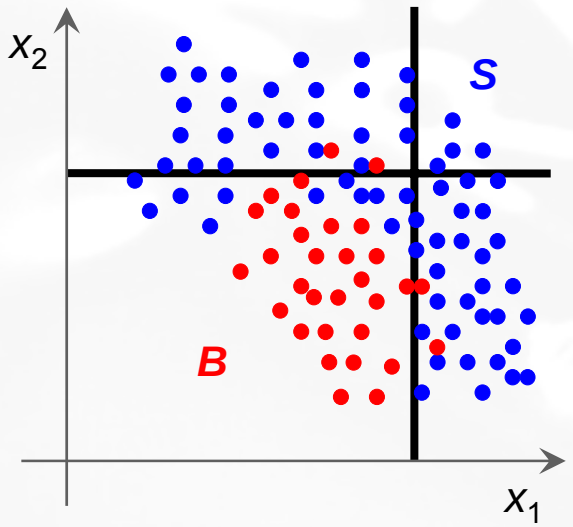
Multivariate Classification



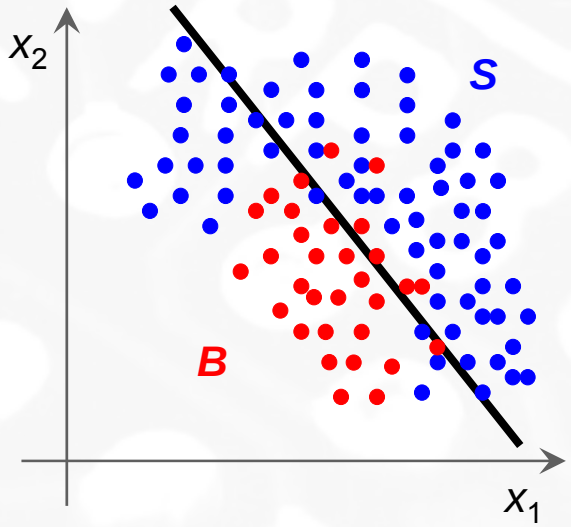
Multivariate Event Classification

- Suppose data sample with two types of events: *Signal, Background*
  - We have found discriminating input variables x_1, x_2, …
  - What decision boundary should we use to select events of type *Signal* ?

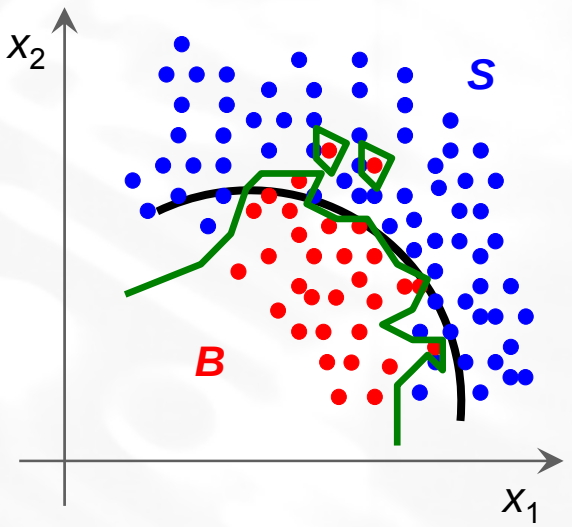
Rectangular cuts?



A linear boundary?



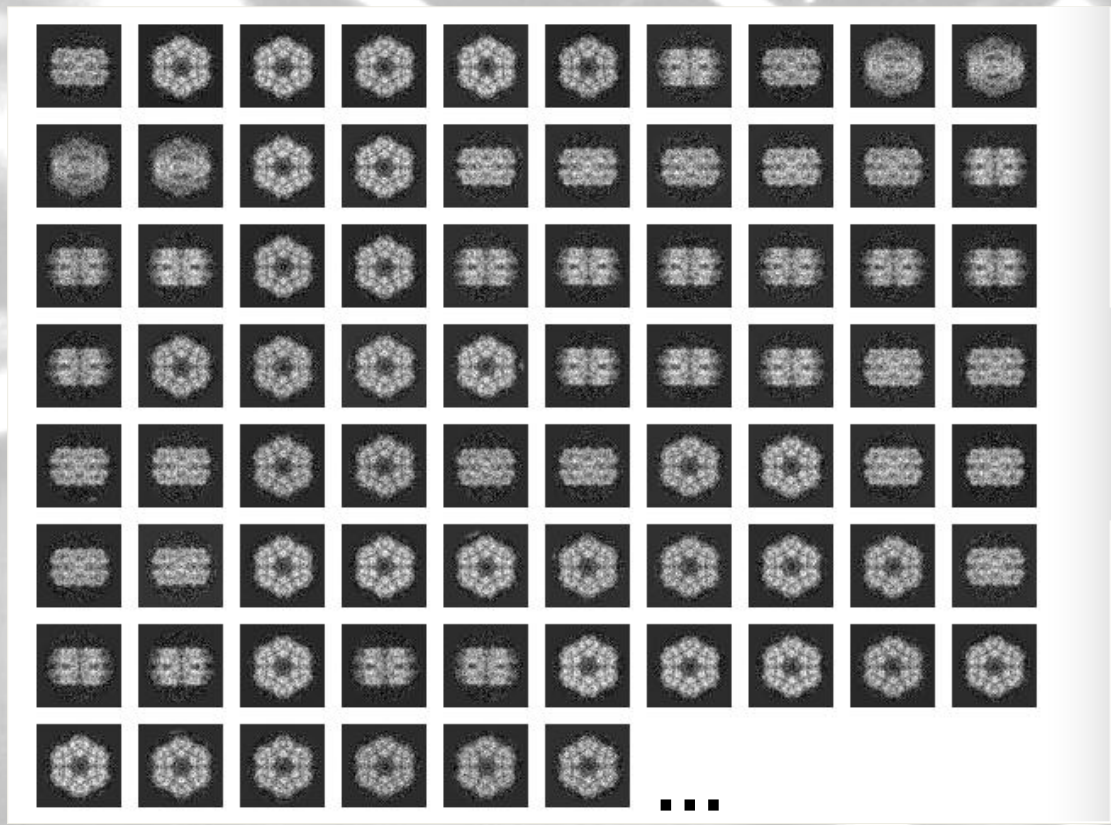
A nonlinear one?



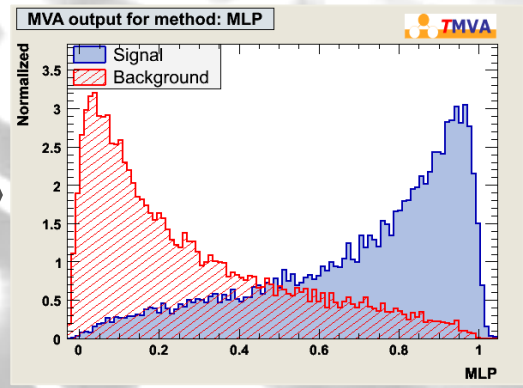
- How can we decide this in an optimal way ? → Let the machine learn it !

Multivariate Event Classification

- Multivariate classification condenses multi-variable input information in a single scalar output variable. Many, very different approaches exist !
  - It is a $R^n \rightarrow R$ regression problem; classification is in fact a *discretised regression*



$y(B) \rightarrow 0, y(S) \rightarrow 1$

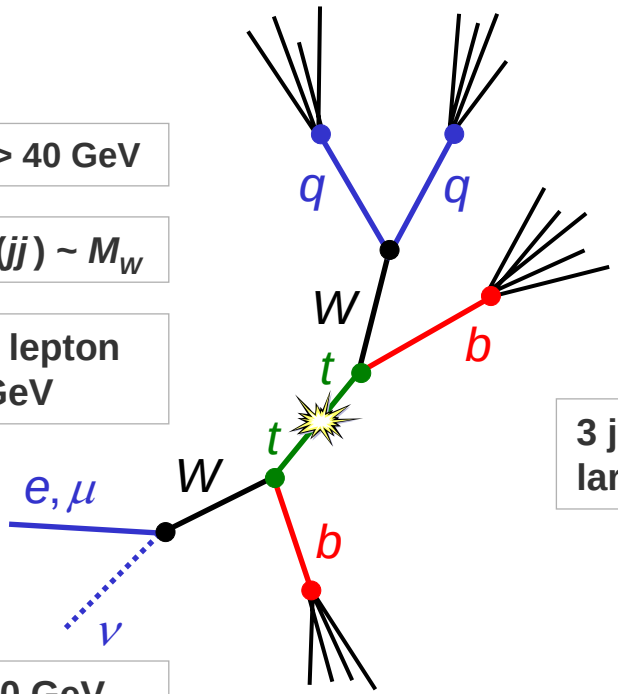


Top Physics

- ~100 times larger cross section at LHC (~830 pb) compared to Tevatron

  Excellent channel for data-driven commissioning and calibration, notably b-tagging and jet energy
  Significant single top production: ~300 pb (electroweak process, involves *W*), factor of ~100 over Tevatron

$\sigma_{tt} \approx 250$ pb for $tt \rightarrow bW\,bW \rightarrow b\lambda\nu\,bjj$



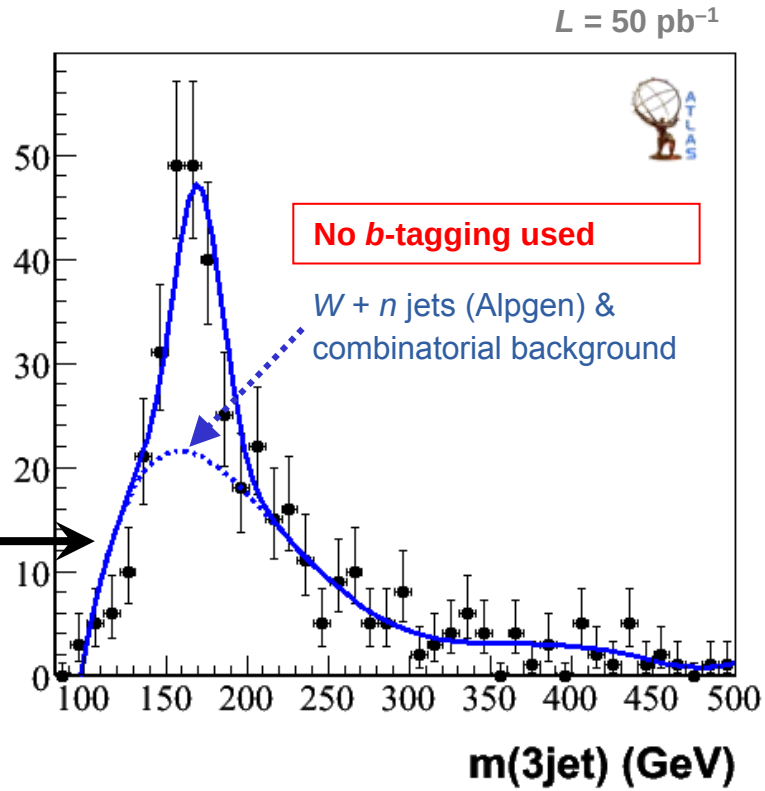
4 jets p_T> 40 GeV

2 jets $M(jj) \sim M_W$

Isolated lepton p_T> 20 GeV

MET > 20 GeV

3 jets with largest $\sum p_T$



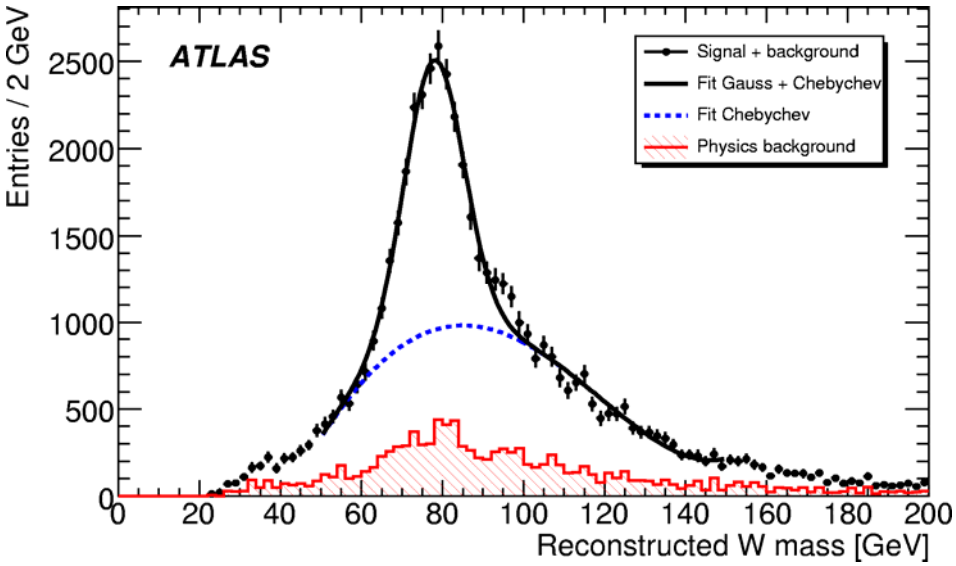
Top Physics

- ~100 times larger cross section at LHC (~830 pb) compared to Tevatron

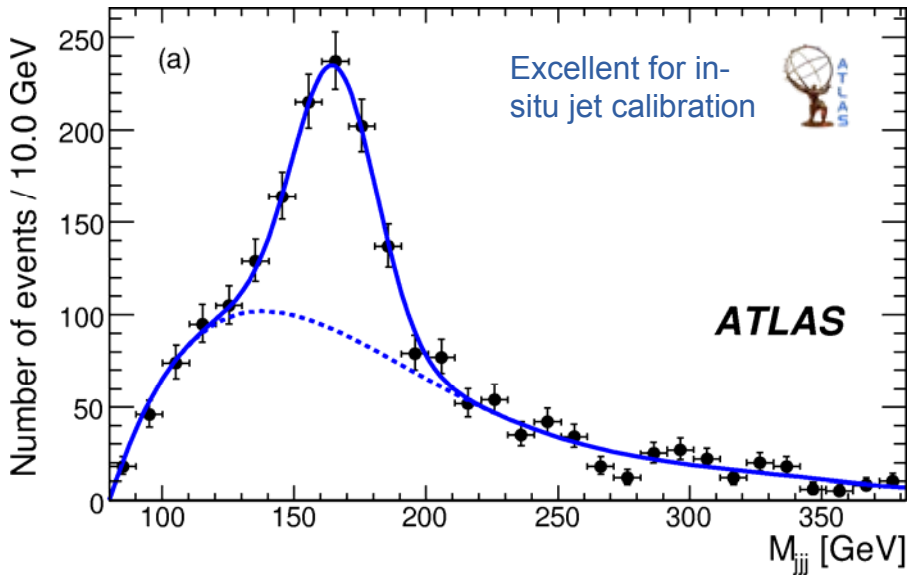
  100 pb^{-1} of data should allow to measure the *t*-pair production cross section to 3% statistical and 5% systematic error (dominated by luminosity uncertainty). Best final state: both *W* decay to leptons

  → Probe of new physics !

Fitted top signal for 1 fb^{-1}



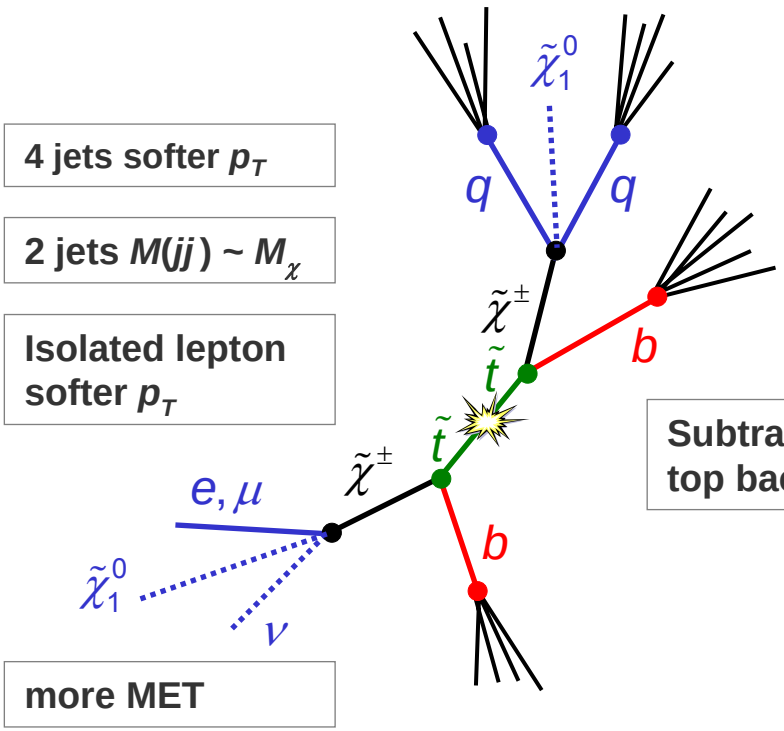
Fitted $W \rightarrow qq$ mass in top decays



Top Physics – *Be Ready for Surprises*

- Example: SUSY with very light stop (m_{stop} ~ 137 GeV < m_{top})
- Final state similar to t-pair production, but more MET and softer lepton, jets

$\sigma_{st\,st} \approx 412$ pb for $st\,st \rightarrow b\chi\,b\chi \rightarrow b\chi^0\lambda\nu\,b\chi^0 jj$



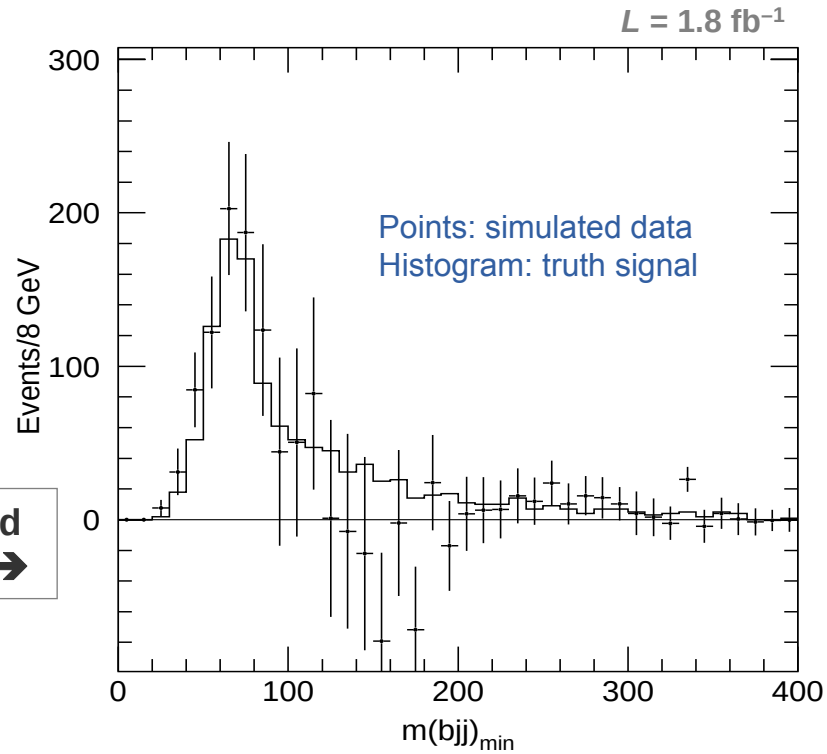
4 jets softer p_T

2 jets $M(jj) \sim M_\chi$

Isolated lepton softer p_T

more MET

Subtract expected top background ➔

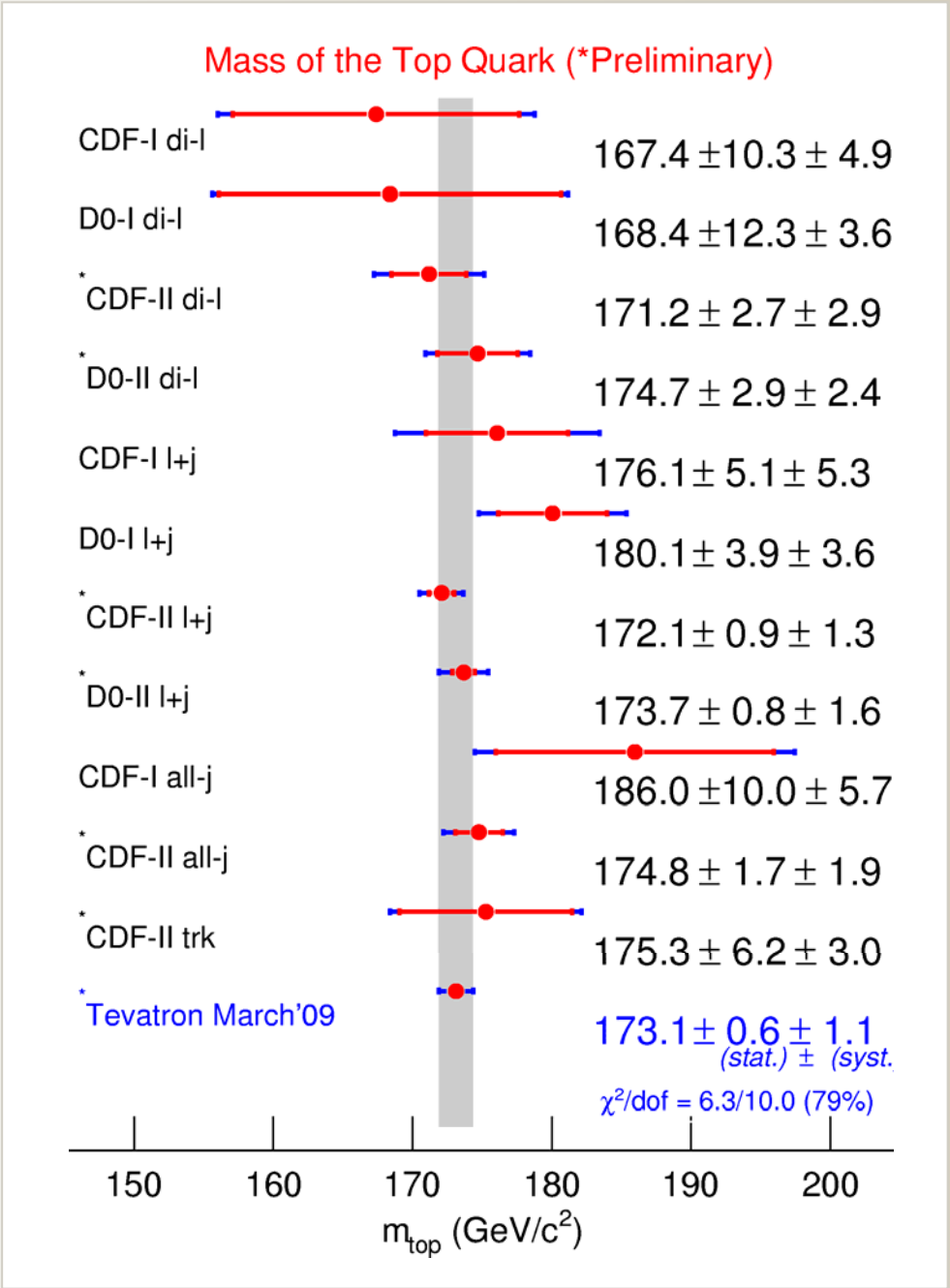


New *m*(top) result from Tevatron (Moriond EW'09)

… hard to beat at LHC.

Important input to global electroweak fit predicting Higgs mass, and to new physics predictions (SUSY)

Goal for LHC: ~1.0 GeV

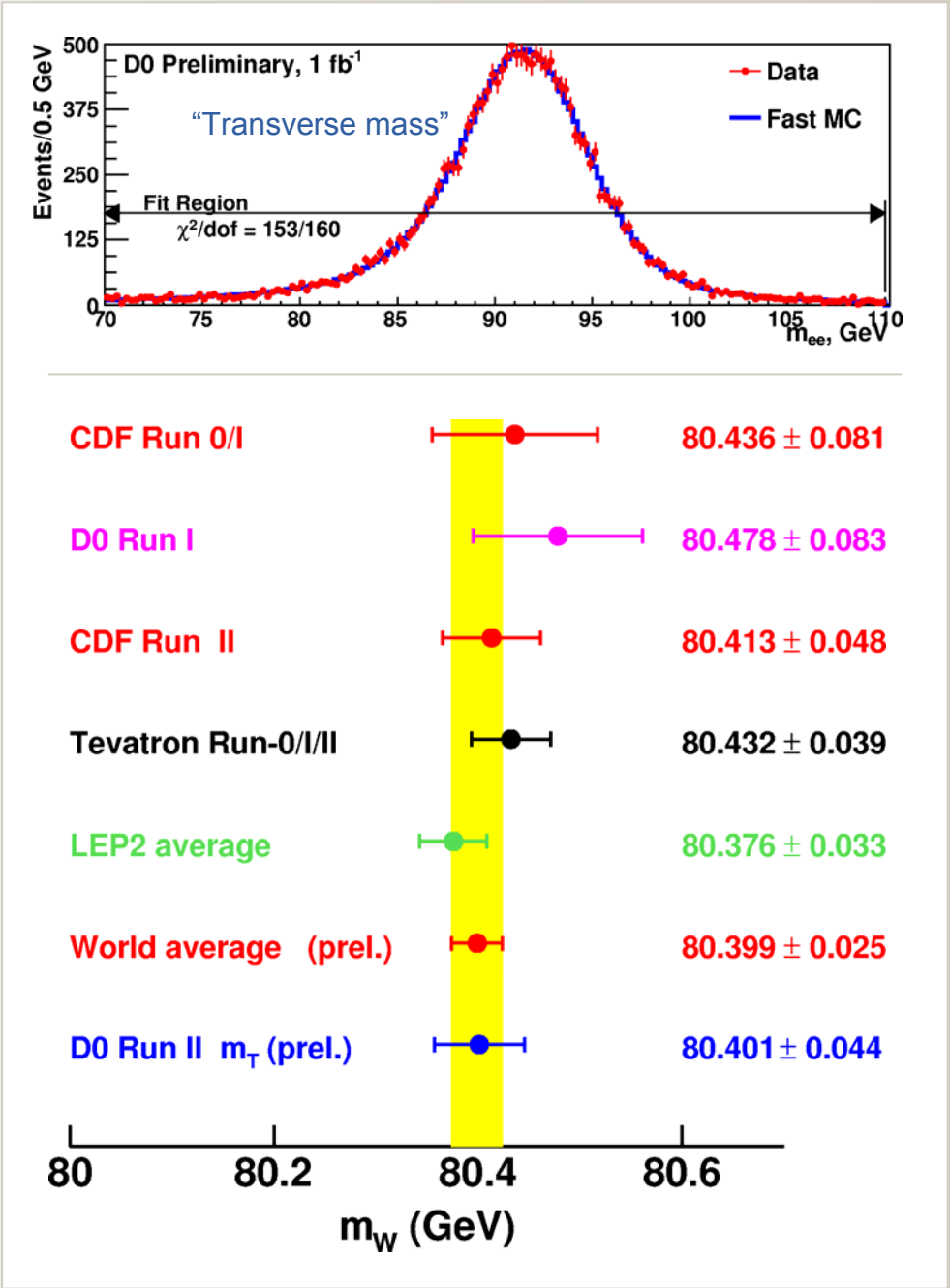


Also, new *m*(W) result from Tevatron (Moriond EW'09)

… should be beaten at LHC.

Important input to global electroweak fit predicting Higgs mass

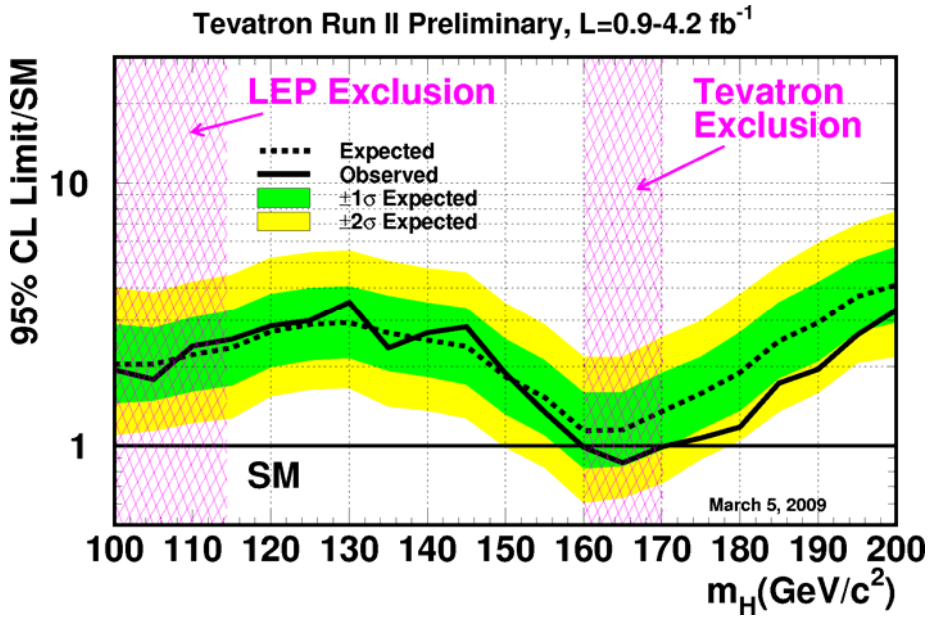
Goal for LHC: 15 MeV (conservative), maybe even down to 7 MeV ?



Also, new results on direct Higgs search from Tevatron (Moriond EW'09)

… easy to beat at LHC ;-)

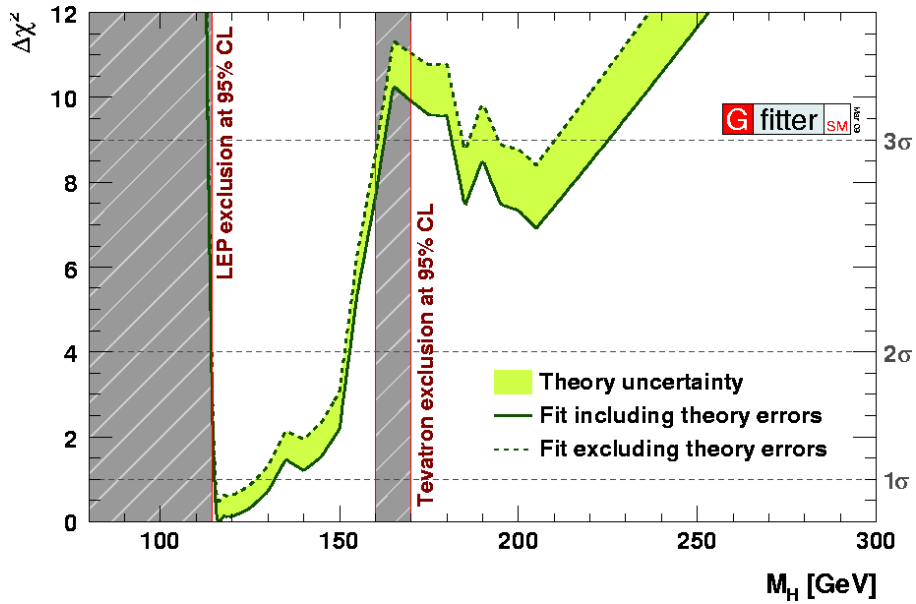
Another important input to, and comparison for, global electroweak fit …



Here the new result from the global electroweak fit:

95% CL bounds:

- without direct searches:
  $42 < M_H < 158$ GeV
- including direct searches
  $114 < M_H < 153$ GeV



Standard Model Higgs production (and decay) at the LHC

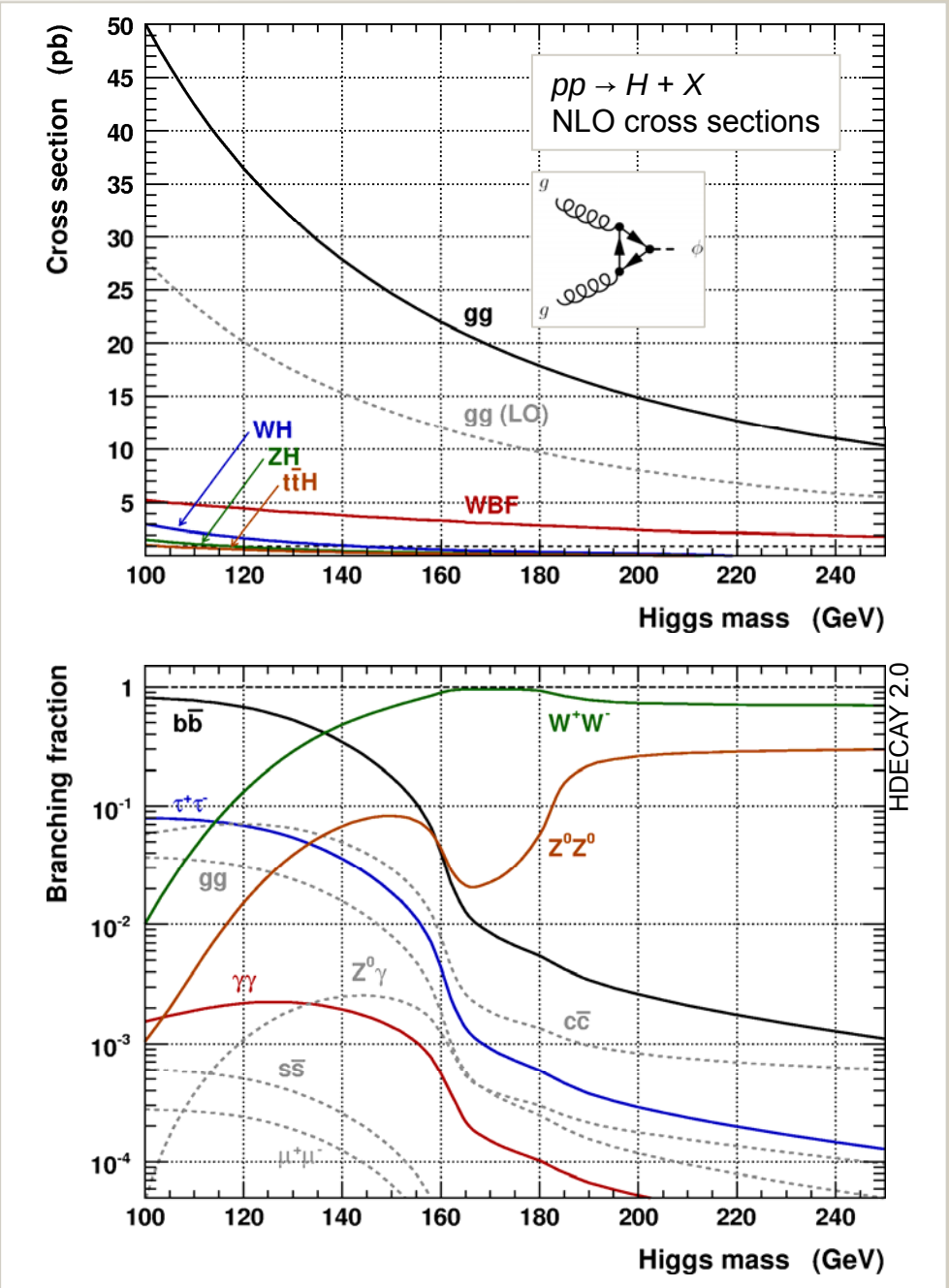
Very different search strategies depending on the Higgs mass hypothesis

Golden search modes:

$H \to \gamma\gamma$: rare, but clean

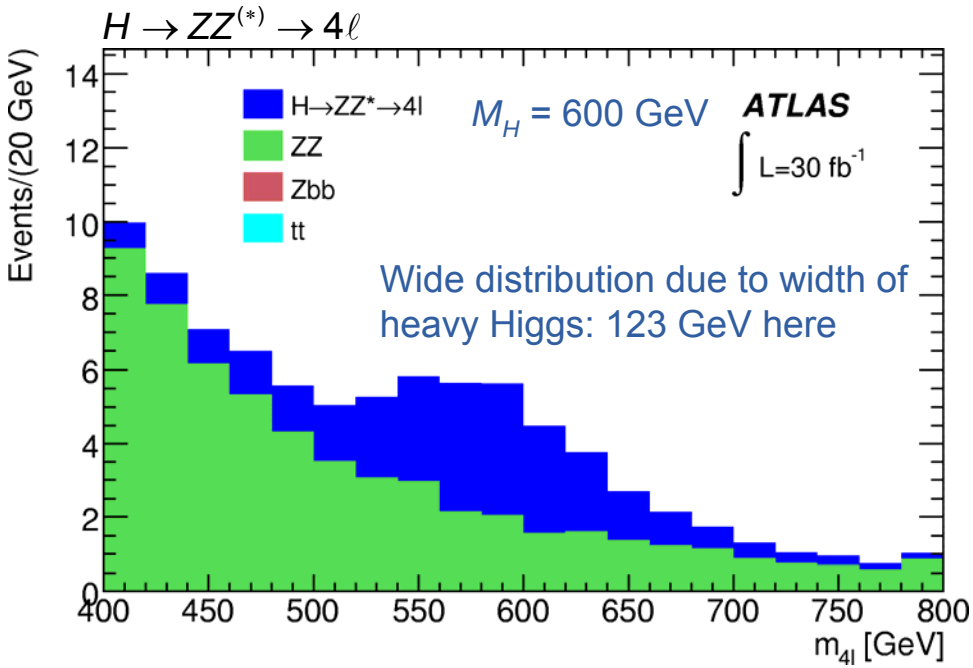
$H \to WW^{(*)}$: abundant, but not clean

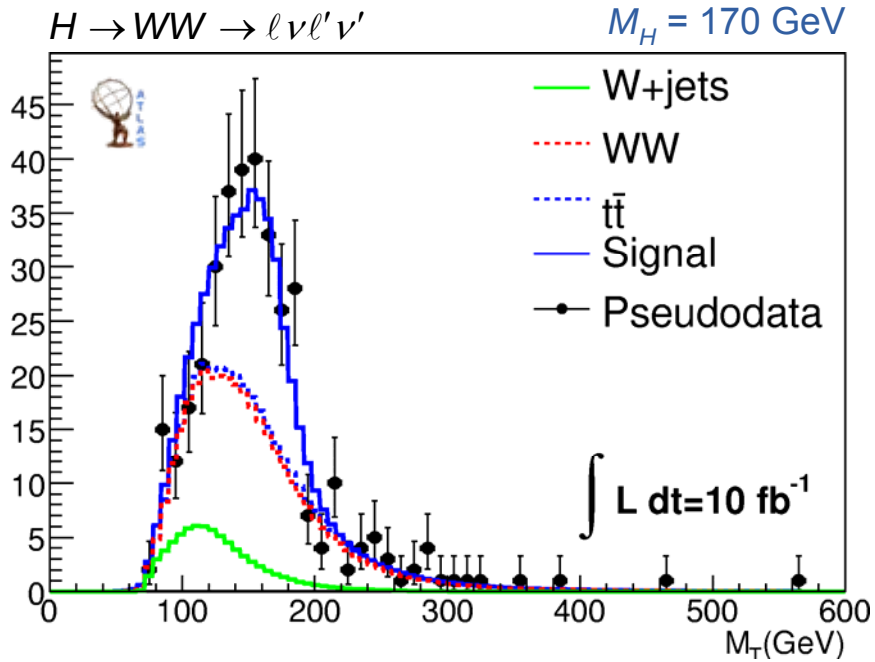
$H \to ZZ^{(*)}$: sizable branching fraction, and clean



Standard Model Higgs Search

- Observation Higgs needs fb^{-1} and not pb^{-1} integrated luminosity!
- Not a priority topic for early physics, however need to be ready for surprises. Also: background studies and comparisons with MC can be done early on





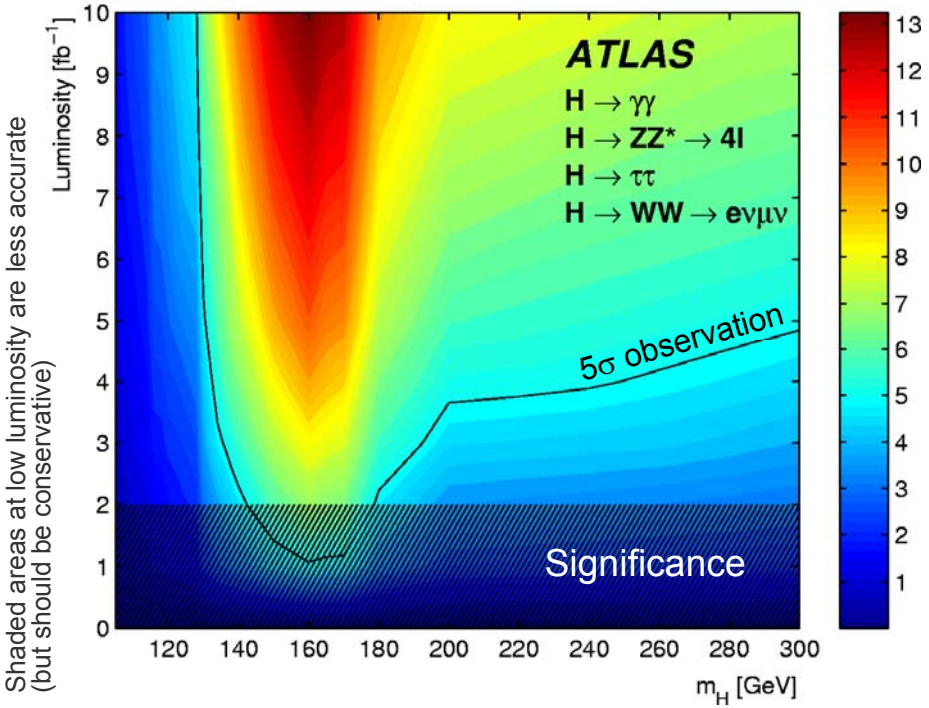
Best result with multivariate approach

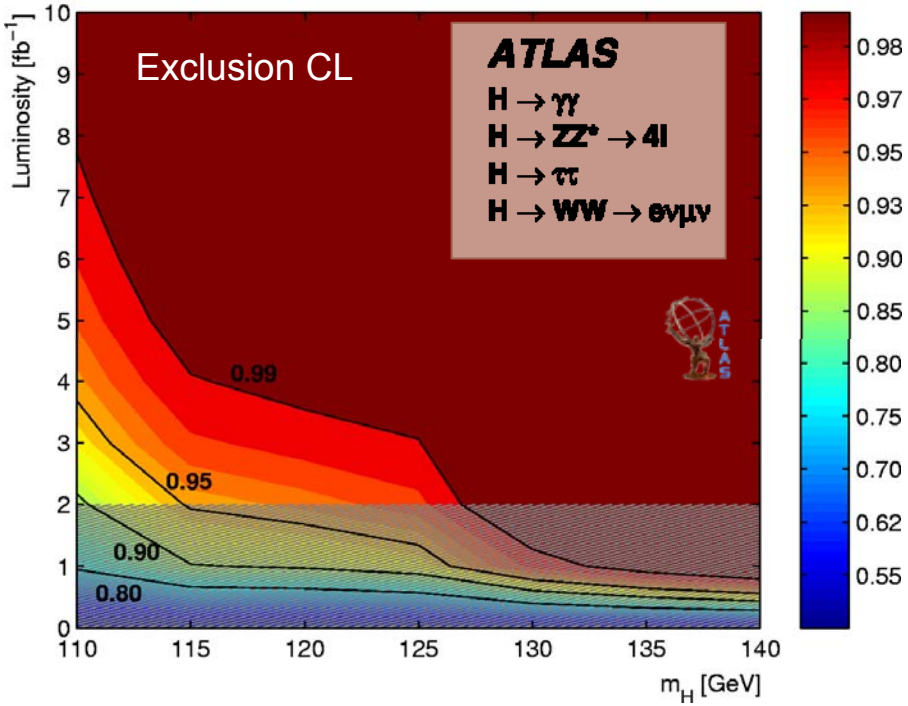
Standard Model Higgs Search

- Apart from background studies, the preparations for Higgs search include

  Look for $ZZ \to 4\ell$, $WW \to 2\ell 2\nu$; understand prompt photon signal; understand τ from $Z \to \tau\tau$; study b-tagging

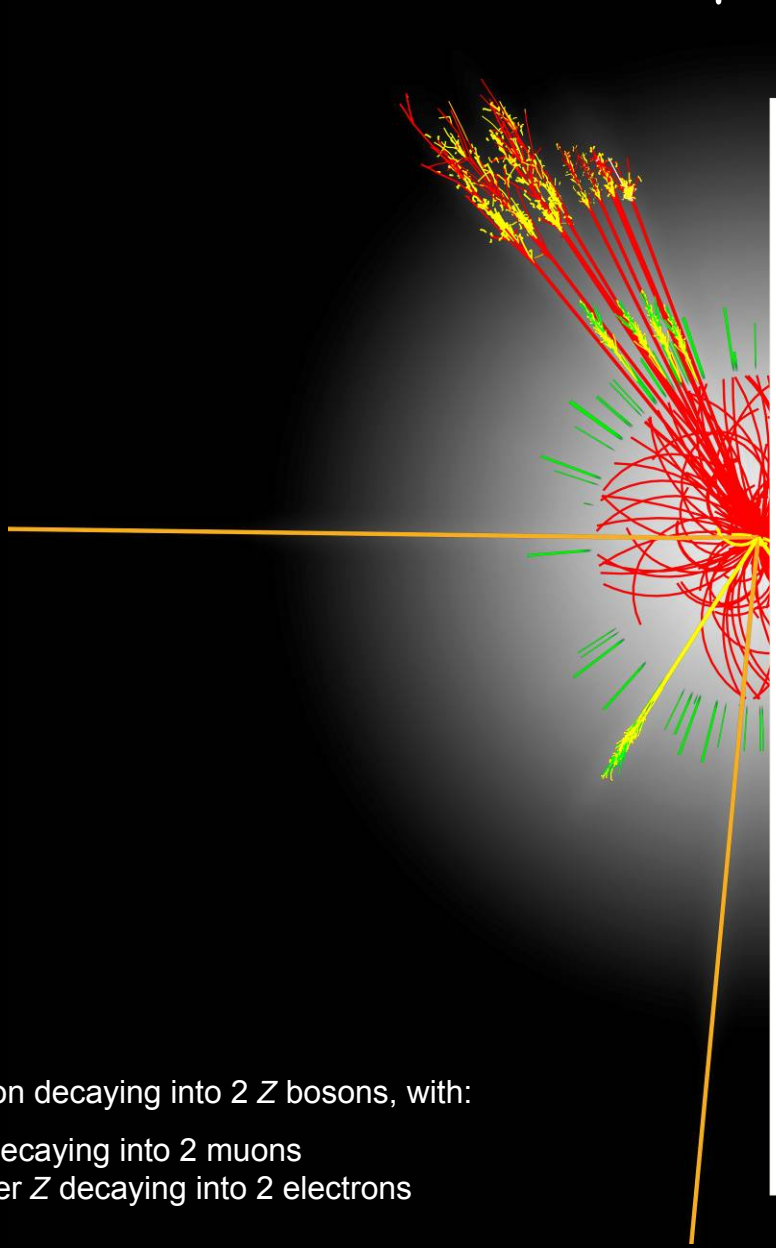
- Expected discovery (left) and exclusion reach (right)

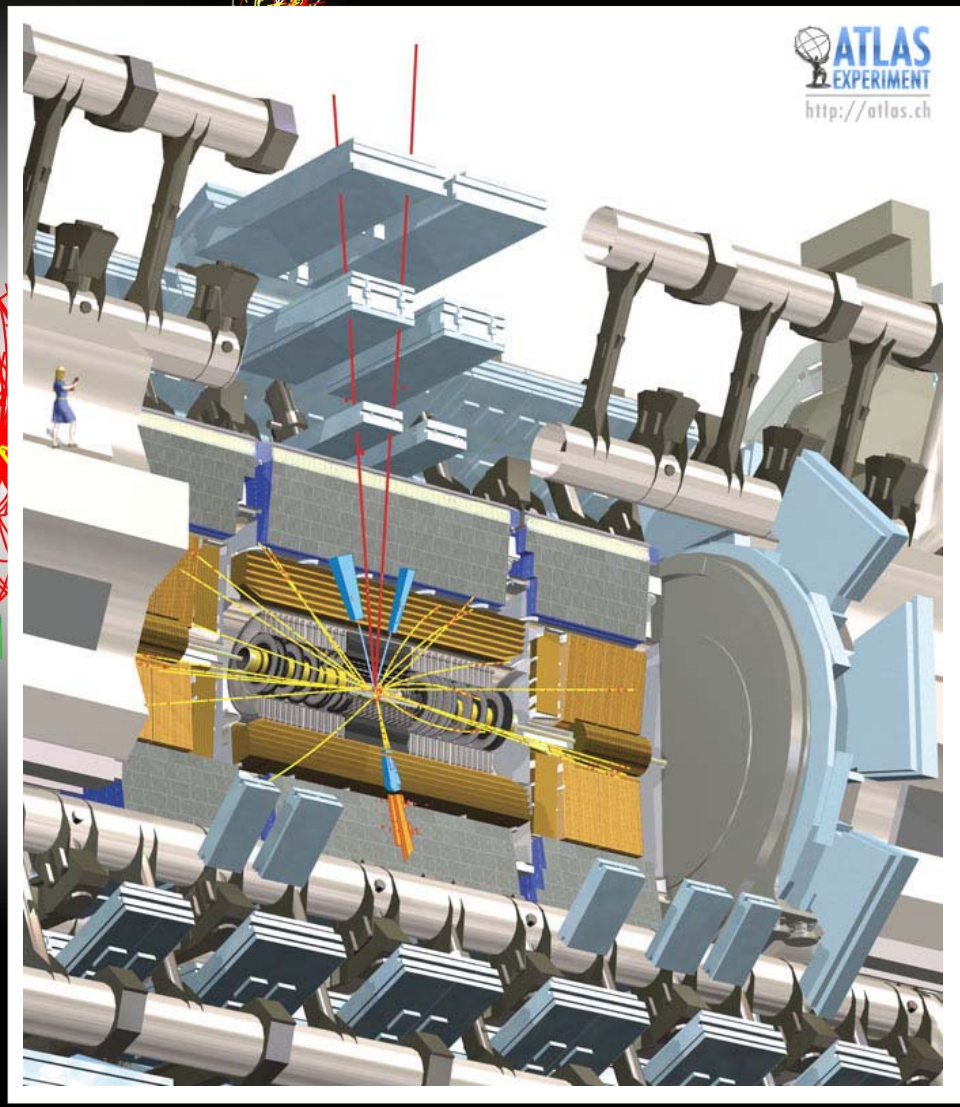




With 1 fb^{-1} could barely discover Higgs with 150 ~ 170 GeV, end exclude Higgs > ~127 GeV

Simulation of a $H \rightarrow ZZ^{(*)} \rightarrow 2e2\mu$ event in ATLAS





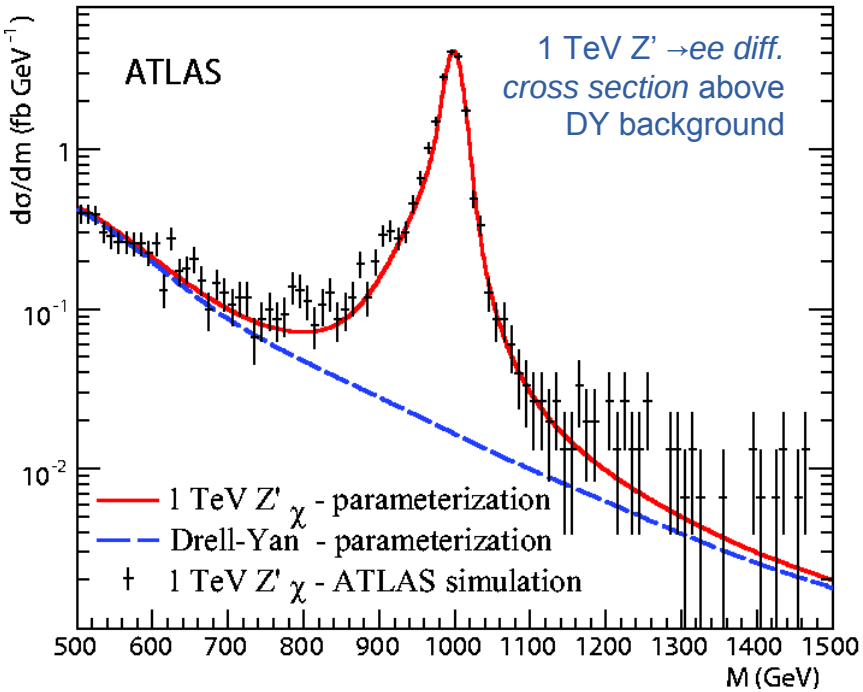
Higgs boson decaying into 2 *Z* bosons, with:

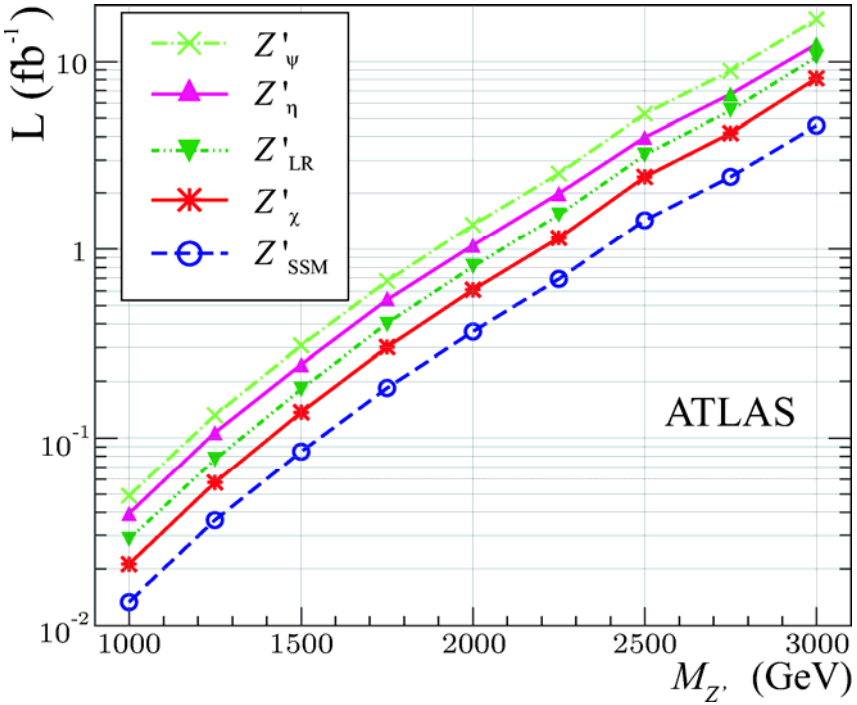
- One *Z* decaying into 2 muons
- The other *Z* decaying into 2 electrons

New Physics in Early Data – *Z'* or *W'* ?

- Search for heavy di-lepton resonances among the first new physics searches

  Ultimate calorimeter performance not required – however good alignment required in muon channel
  Backgrounds from Drell-Yan processes can be determined from data
  With 100 pb^{-1} large enough signal for discovery up to $m(Z',W')$ ~ 1.5 TeV (14 TeV) [ultimate reach: ~5 TeV]

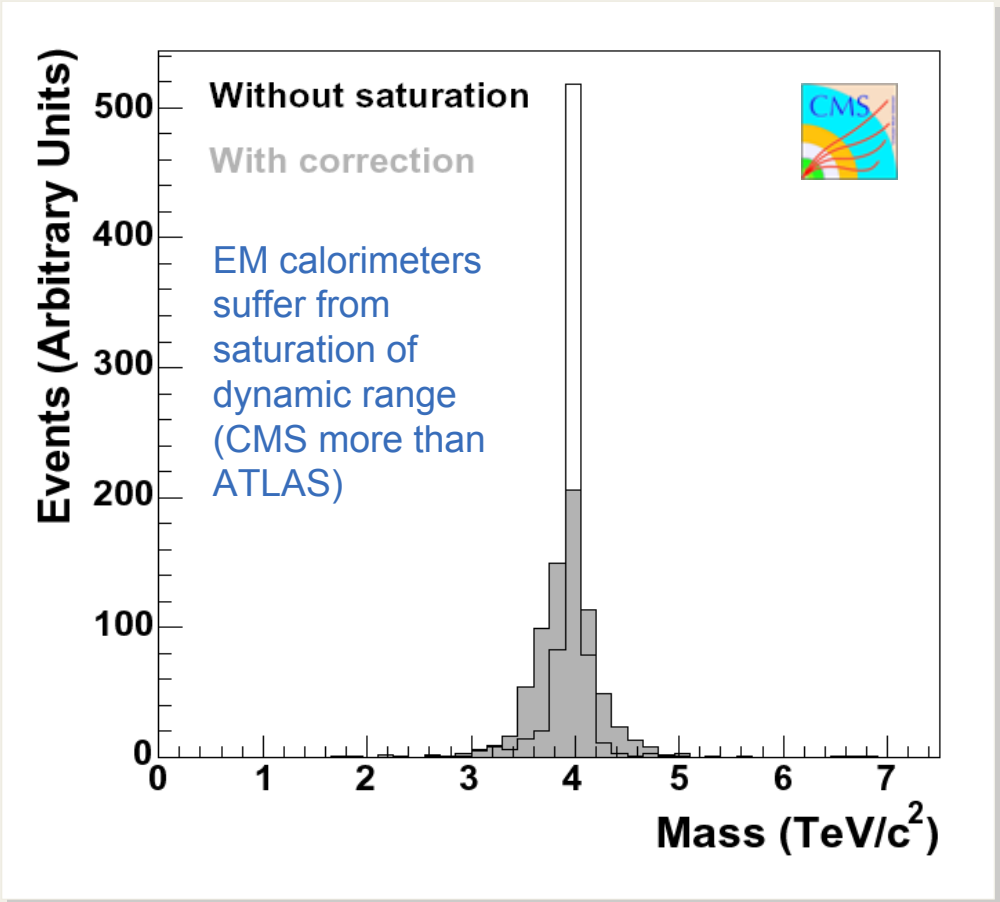




Dynamic Range of EM Energy Reconstruction

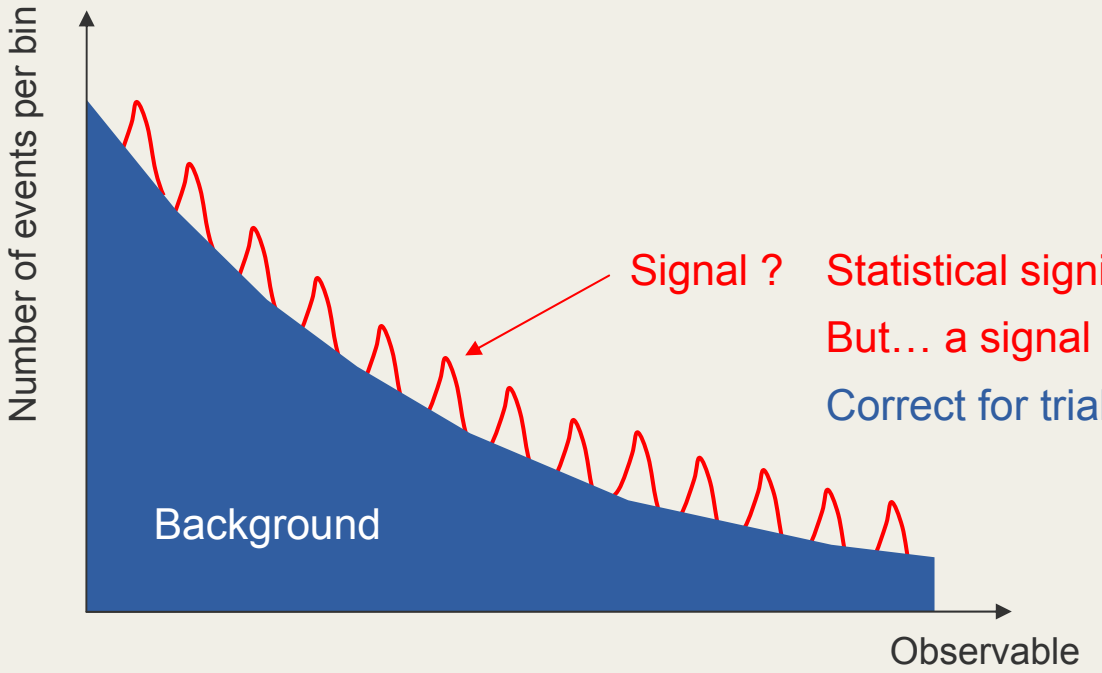
Need to reconstruct electrons from lowest (*B* and charm physics) to highest (new resonances) energy scale…

Example: Randall-Sundrum Graviton decaying to e^+e^-



Note: width of KK gravitons smaller than experimental resolution

Caution with statistical “look-elsewhere” effect (trial factor)



Statistical significance: p-value = 3.0σ (5.0σ)?

But… a signal could appear anywhere !

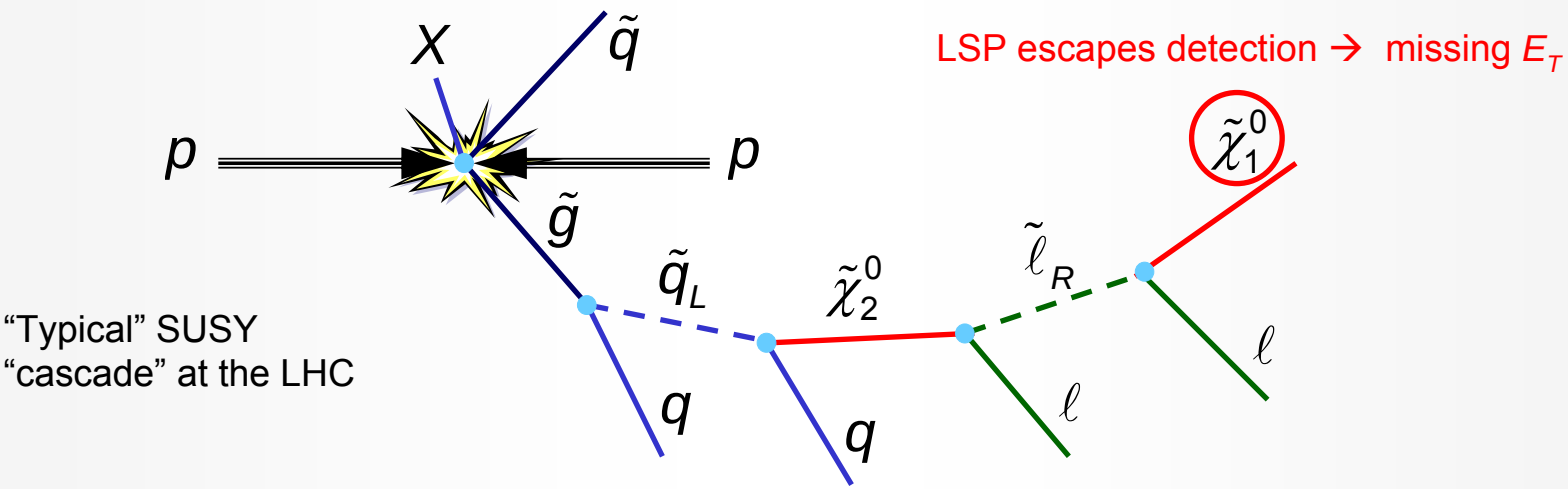
Correct for trial factor: p-value = 2.1σ (4.5σ)

(assuming 13 trials)

In practice more complicated → use toy Monte Carlo simulation to evaluate corrected p-value

Searches for Supersymmetry

- Conserved ***R*-parity** requires existence of a **lightest stable SUSY particle (LSP)** → **WIMP** (LSP signature just as heavy neutrino)
- The LSP is typically found to be a spin-½ **neutralino**, a linear combination of gauginos (in much of the SUSY parameter space the neutralino is a mixture of photino and zino); it could also be a gravitino
- With *R*-parity: **SUSY** production in **pairs** only → **requires energy 2×SUSY mass** !

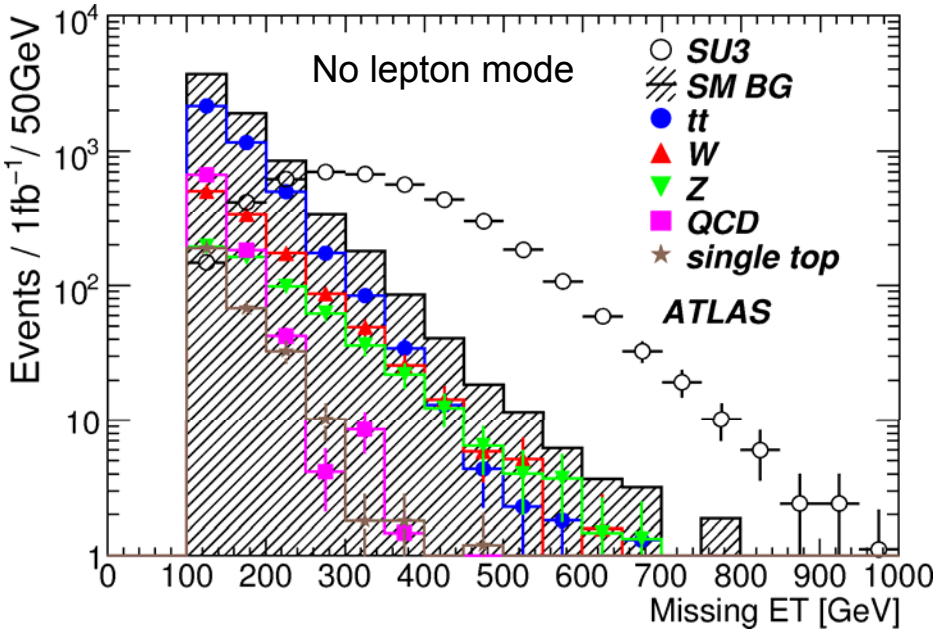


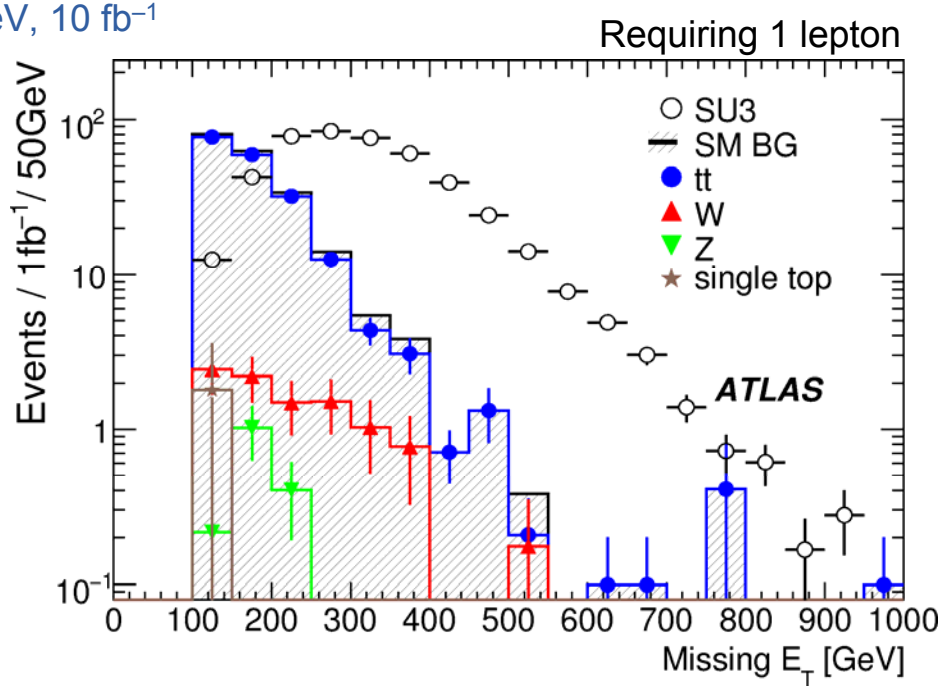
Searches for Supersymmetry

- *R*-parity conserving SUSY has clear signature… with the right mass it could be discovered early

  With 100 pb^{-1} signal could show up – with 10 pb^{-1} it would be marginal → problem: show it's real !
  Need to control backgrounds from data (cannot trust Monte Carlo prediction)

Plots for mSUGRA with m_0=100 GeV, $m_{1/2}$=300 GeV, 10 fb^{-1}

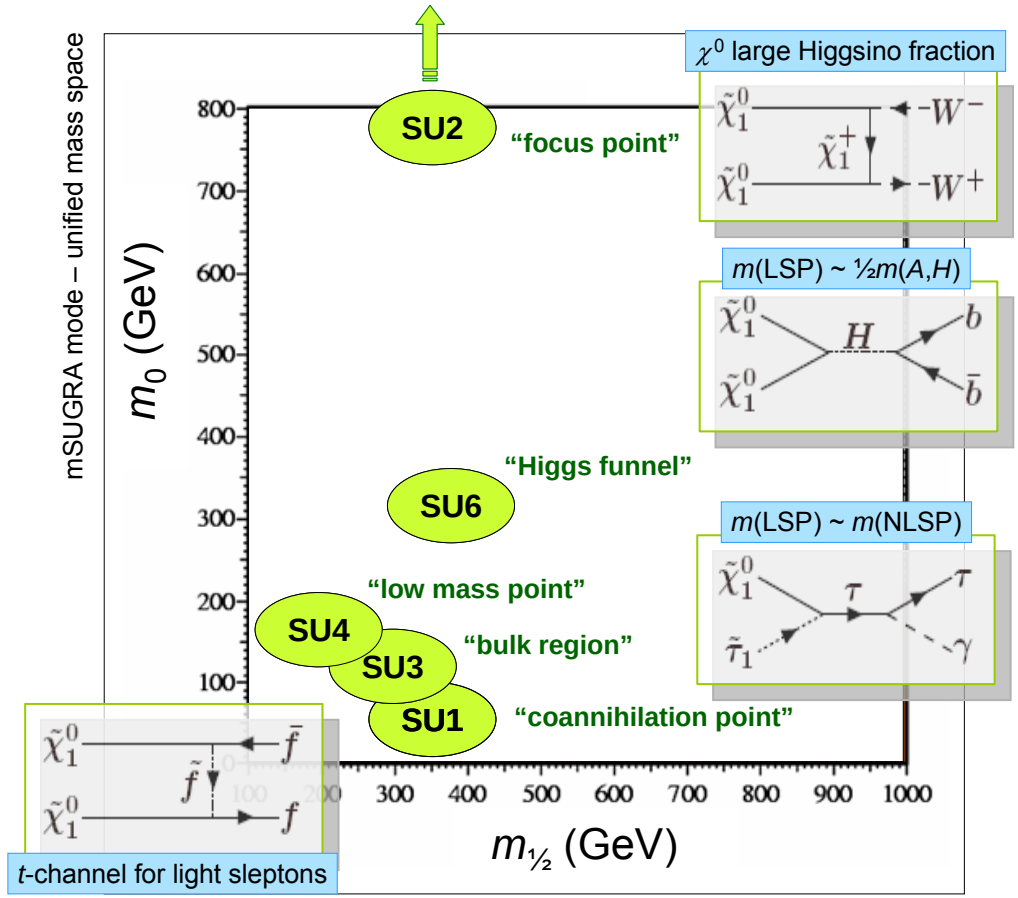




Excellent understanding of jet and MET scale and resolution necessary ! – include other variables

SUSY – inclusive search analysis in practice:

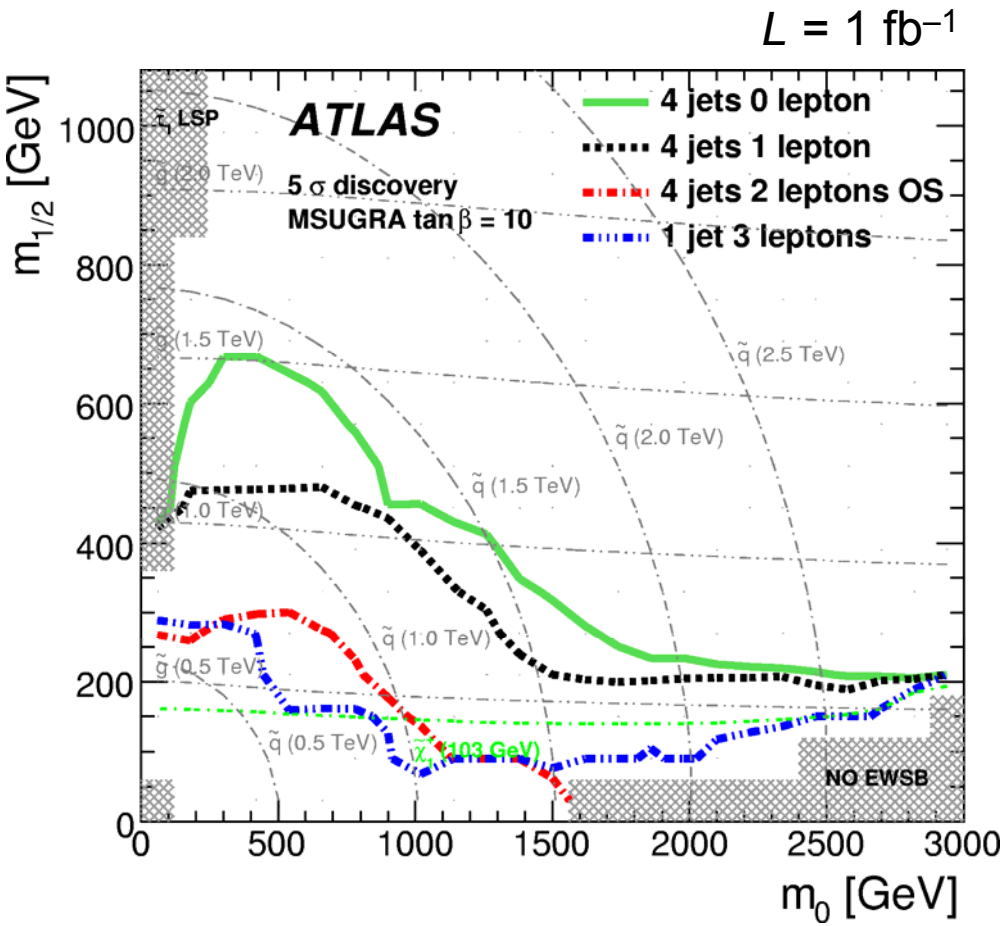
1. Define MSSM characteristic benchmark points
   (often mSUGRA, GMSB, AMSB)
   (The benchmark points are fully simulated, fast simulation extrapolates between them)



Since mSUGRA has only 5 parameters, it is predictive and already highly constrained from direct and indirect accelerator-based searches, and from cosmology

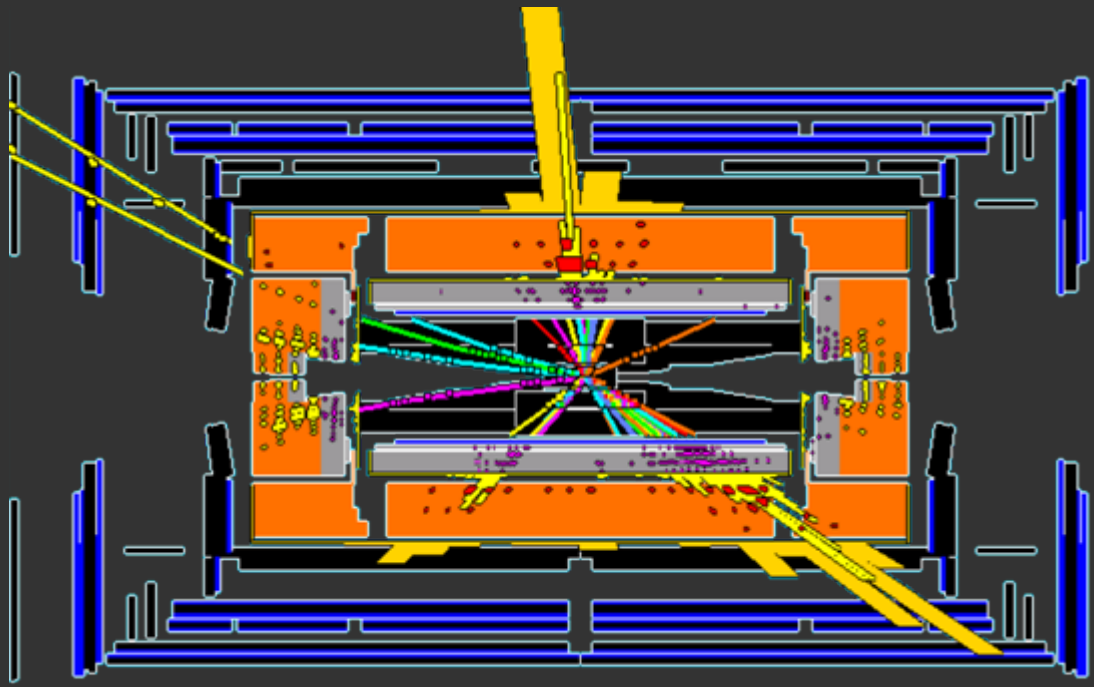
SUSY – inclusive search analysis in practice:

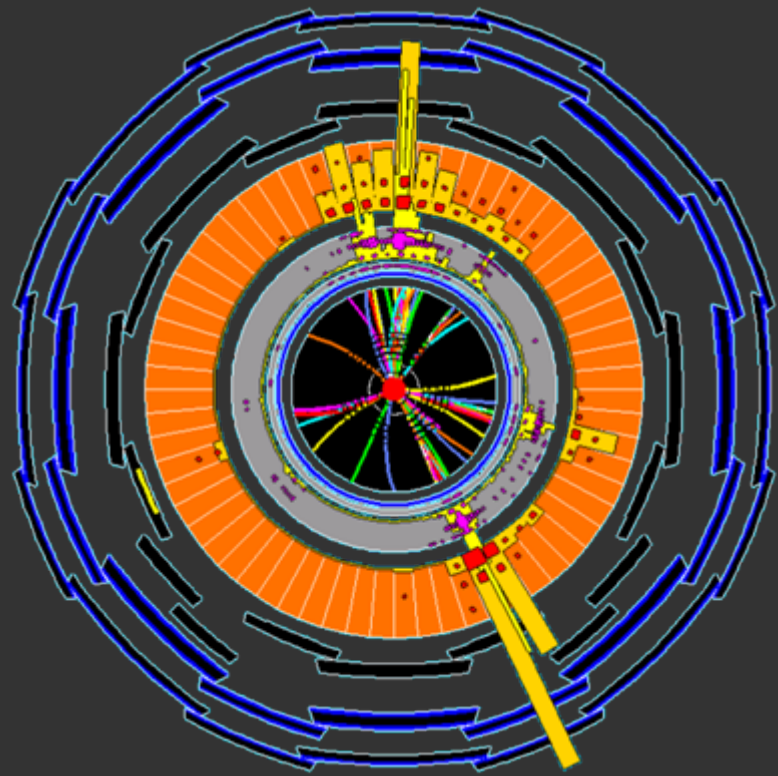
1. Define MSSM characteristic benchmark points (often mSUGRA, GMSB, AMSB)
   (The benchmark points are fully simulated, fast simulation extrapolates between them)
1. Find discriminating variables (MET, scalar event mass, transverse mass, "sphericity", …)
2. Optimise analysis cuts, or use multivariate analysis, for good sensitivity in all points
   (Several analyses are possible, but must account for trial factor)
3. Determine background in signal region by using approximately orthogonal variables (cut on one, probe distribution of other).
   (May use more sophisticated fit techniques.)
4. Determine number of events in signal region and compare to expected backgrounds
5. Systematic studies
6. Compute signal significance or exclusion



Reach for squark & gluino masses using 4-jets + 0-lepton mode:	0.1 fb^{-1}	→	M ~ 750 GeV
	1 fb^{-1}	→	M ~ 1350 GeV
	10 fb^{-1}	→	M ~ 1800 GeV

Simulation of a Supersymmetry event in ATLAS





Pair of SUSY particles decaying via:

- Six particle jets
- Two muons with opposite charges (visible in the side view going to the left, but not in the end view because they exited the detector in the forward direction
- Large missing transverse energy

SUSY could also break *R*-parity

(the signature could be τ's in final state from $\tilde{\chi}^0 \to \tilde{\tau}\tau$ decays)

Signals due to other phenomena could look like SUSY

Proceed SUSY search as model-independently as possible

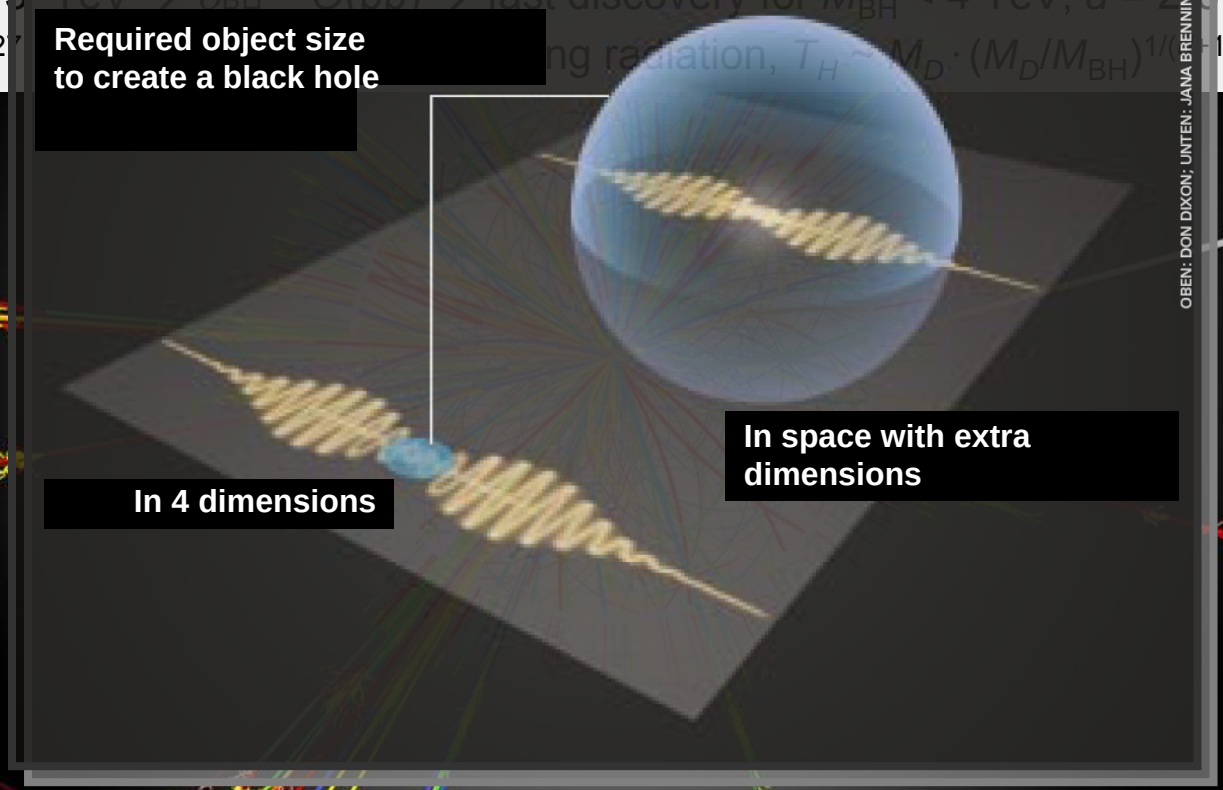
Check for anomalies: γ's, τ's, strange *t*'s

And … if we are allowed to enter Trans-Planck scales, that is, Gravity in *extra dimensions* is strong, we may produce **Black Holes**

Artist's portrayal of the IC 10 X-1 system: the black hole lies at the upper left and its companion star is on the right

Strong gravity in extra dimensions could allow black hole production at the LHC

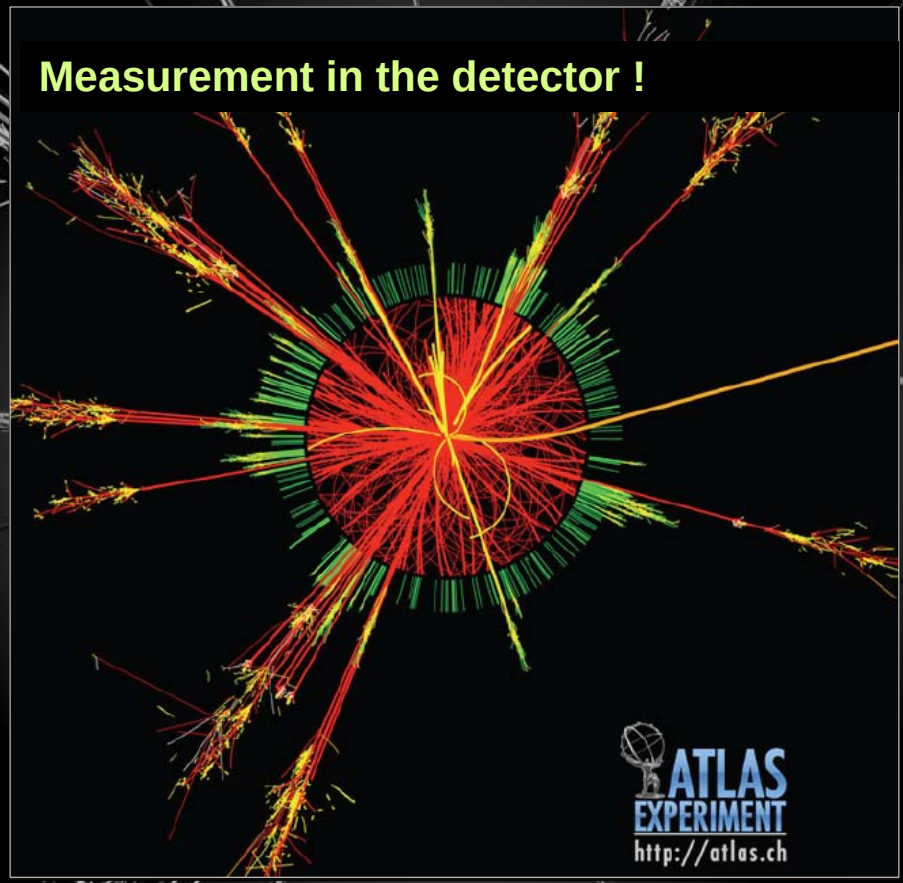
- An object becomes a black hole if it is smaller than Schwarzschild radius: $r = 2GM/c^2$
- In *extra 4+d dimensions*: $r = 2G^{(4+d)}M_D/c^2$
- Cross section: $\sigma_{BH} \sim \pi r^2$
- With $M_D \sim 2$–3 TeV $\Rightarrow \sigma_{BH} \sim O(\text{pb}) \Rightarrow$ fast discovery for $M_{BH} < 4$ TeV, $d = 2$–6
- Fast ($\tau \sim 10^{-27}$ s) decay by Hawking radiation, $T_H \sim M_D \cdot (M_D/M_{BH})^{1/(d+1)}$



Simulated micro black hole in ATLAS detector

Black hole universally and spherically evaporating into leptons, photons and jets in ATLAS. Final state multiplicity increases with M_{BH}

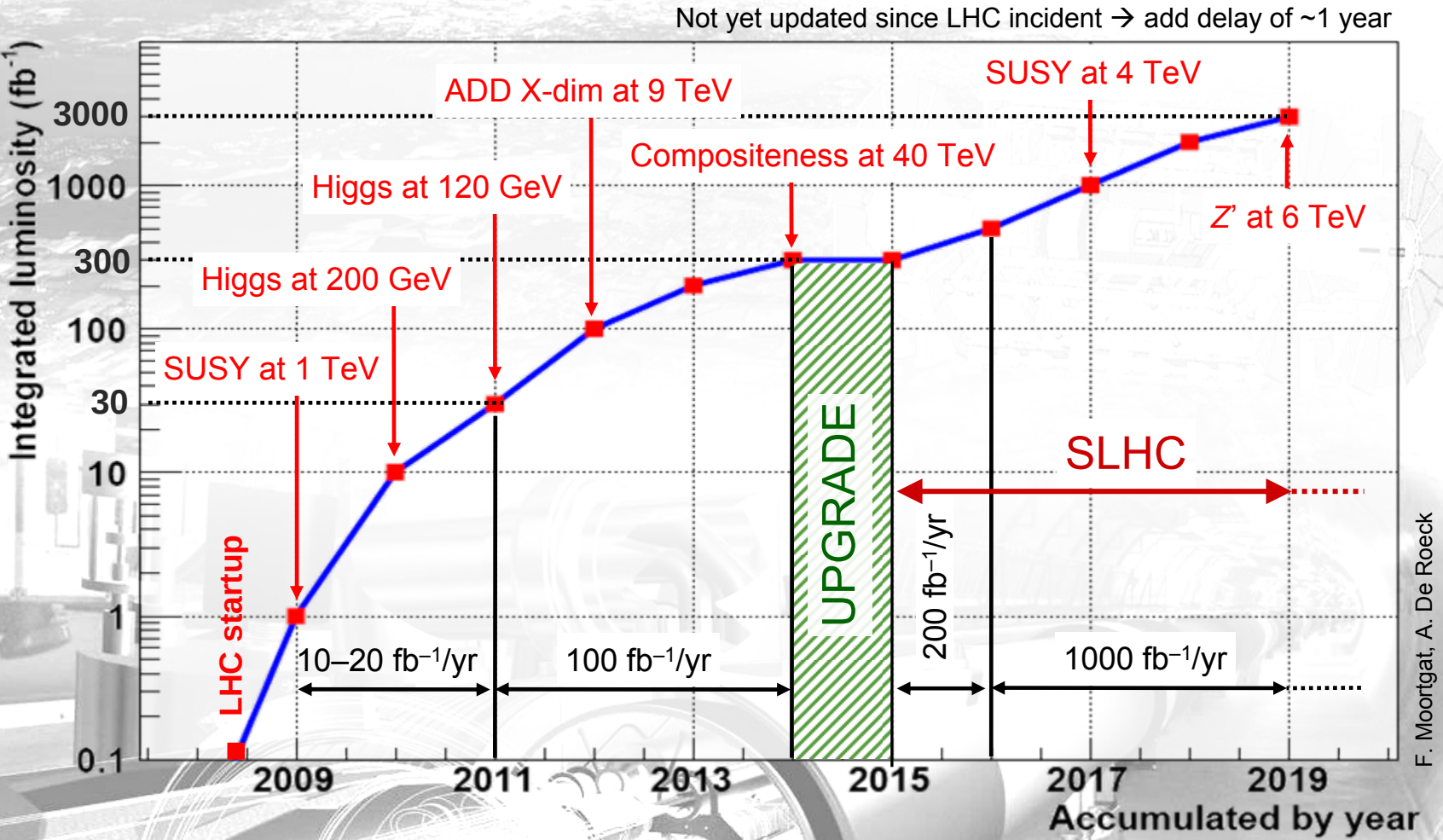
Life Cycle of a 10 TeV Micro Black Hole



Source: Spektrum der Wissenschaft Sep 2005

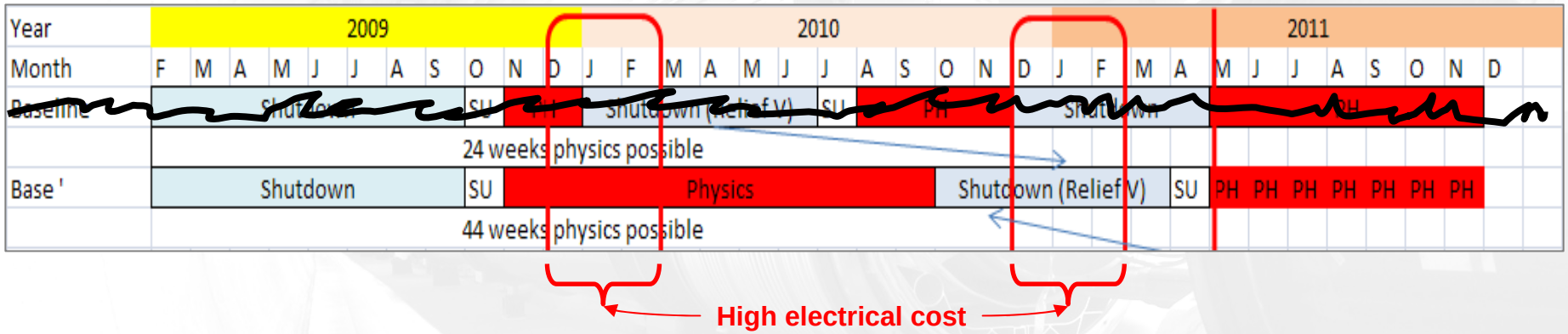
Outlook to the Future

Last Slide: The LHC Programme in a Nutshell



LHC Schedule

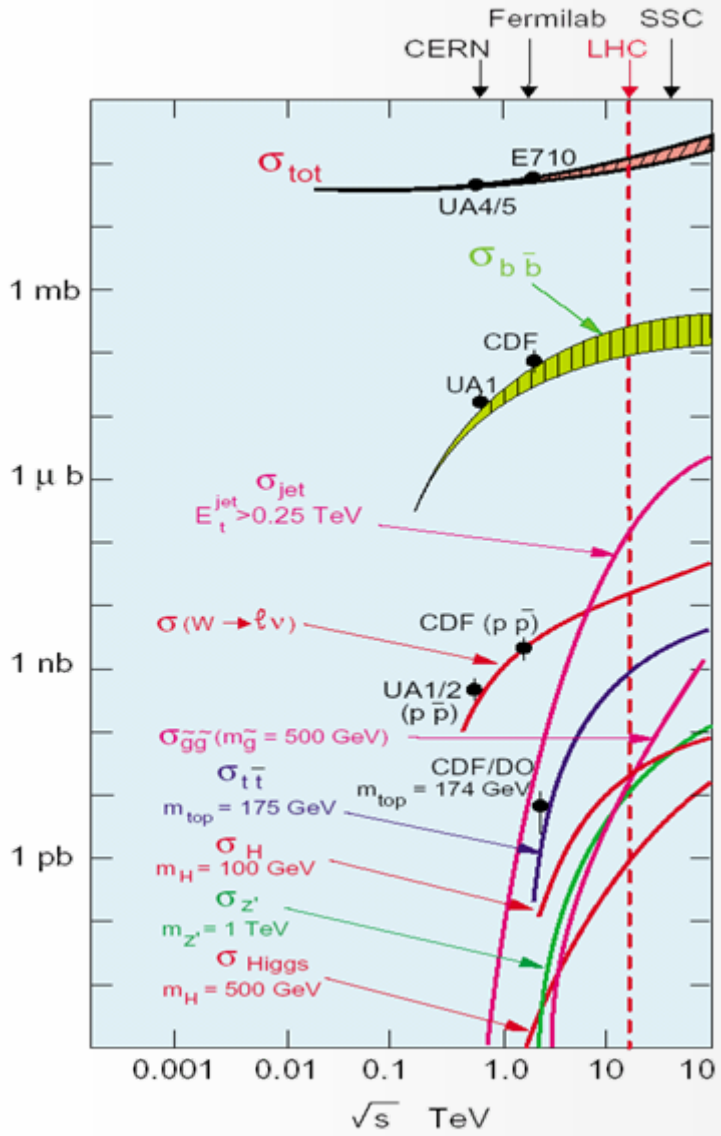
- LHC Workshop in Chamonix, Feb 2009, decided about 2009/10 schedule
  http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=45433



- Fortunately (for the experiments) plan “Base’” was chosen, gaining 20 weeks of physics in the Winter months. Downside: ~8 MCHF additional electricity bill
- Center-of-mass energy in 2009 and 2010 limited to **10 TeV**
- Estimated integrated luminosity (up to 300 days physics possible till end of 2010 shutdown)
  - 100 pb^{-1} first 100 days of operation
  - 200 pb^{-1} next 100 days of operation

10 TeV versus 14 TeV

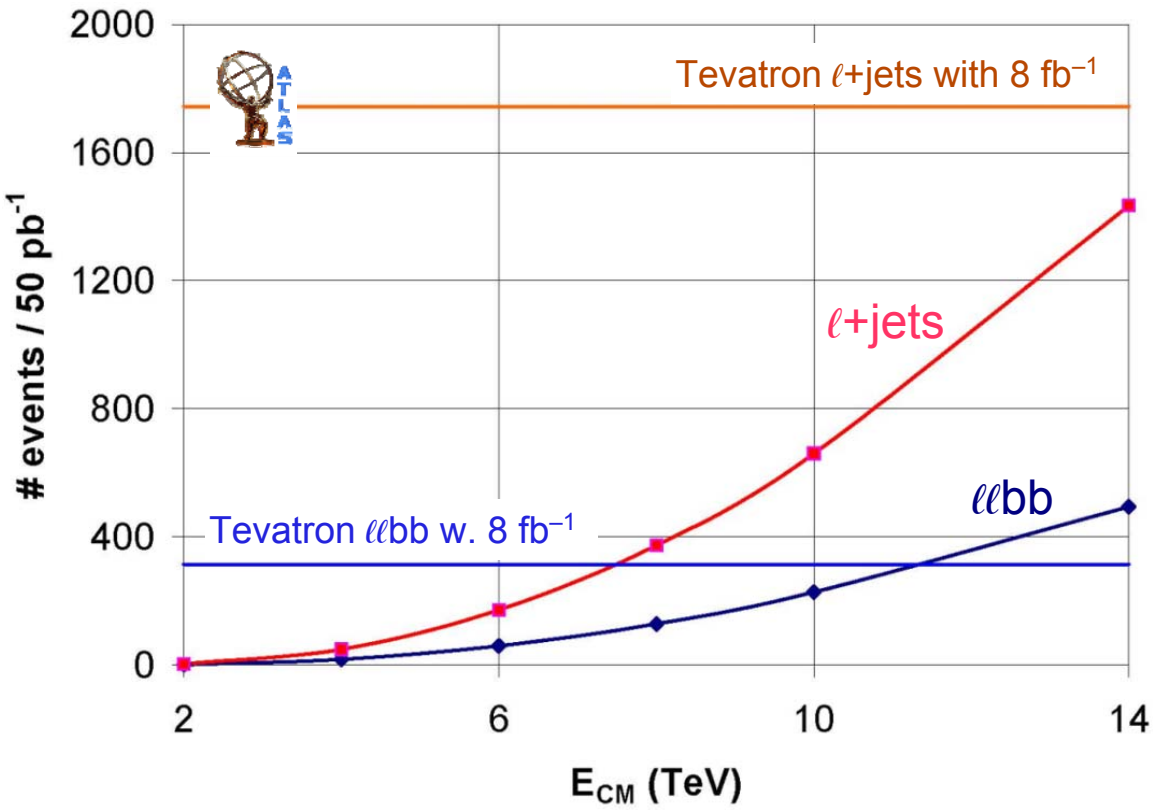
- Many new physics phenomena at the LHC involve heavy particles requiring high-energetic parton collisions → either large proton energy or large E_{parton} fraction
- Thus, at reduced proton energy it is still possible to create similarly heavy particles, but with a much lower cross section
- Rough rule of thumb for int. luminosity needed for discovery: $L(E_1) \sim (E_2/E_1)^2 \, L(E_2)$
- Before coming to commissioning and physics analysis with beam, which will be mainly based on studies at 14 TeV CM energy, a few **indicative** plots illustrating the discovery reach for various LHC energies



10 TeV versus 14 TeV: *Top quark*

- Background in new physics searches → must measure total cross section

~50 pb^{-1} at 14 TeV would match full Tevatron sample



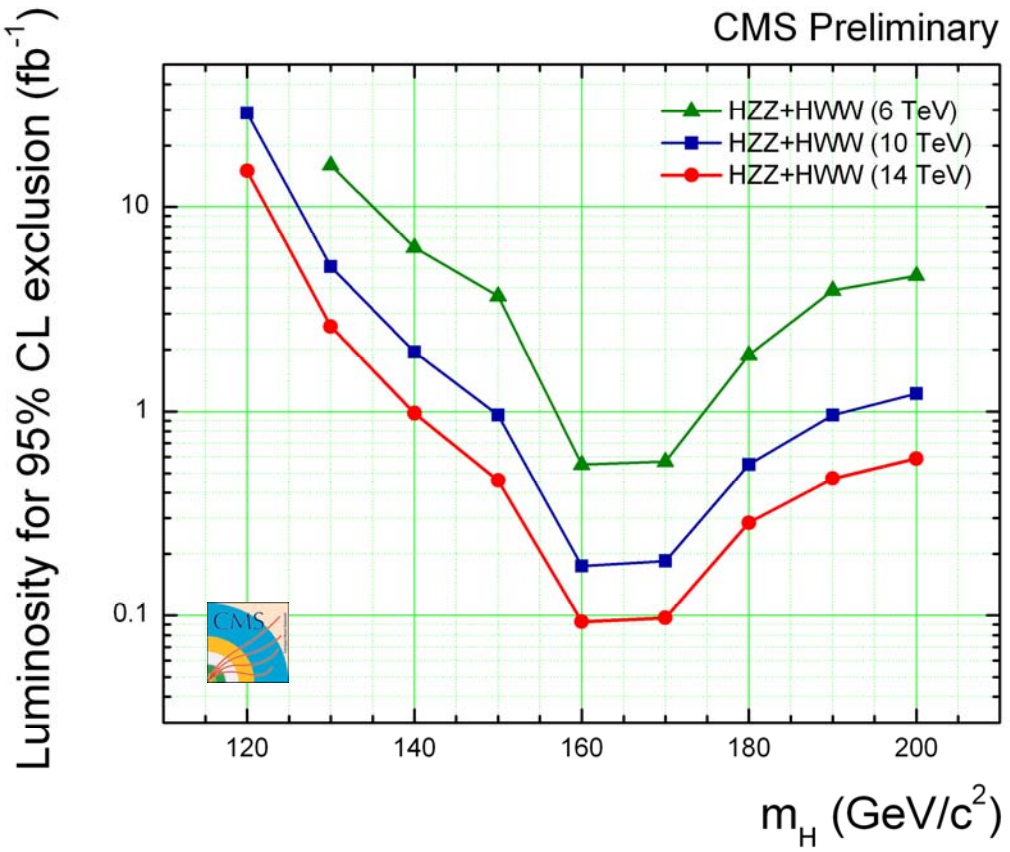
Catch up with Tevatron at E_{CM} = 10 TeV, with 100 pb^{-1}

Results indicative only !

10 TeV versus 14 TeV: *Higgs*

- Higgs exclusion for 3 CM energies. A 5σ discovery at M_H=160 GeV needs ~1 fb^{-1}

Combined $H \rightarrow WW, ZZ$



95% exclusion for M_H = 160 GeV	
CM energy [TeV]	Lumi. needed [pb^{-1}]
14	100
10	200
6	600

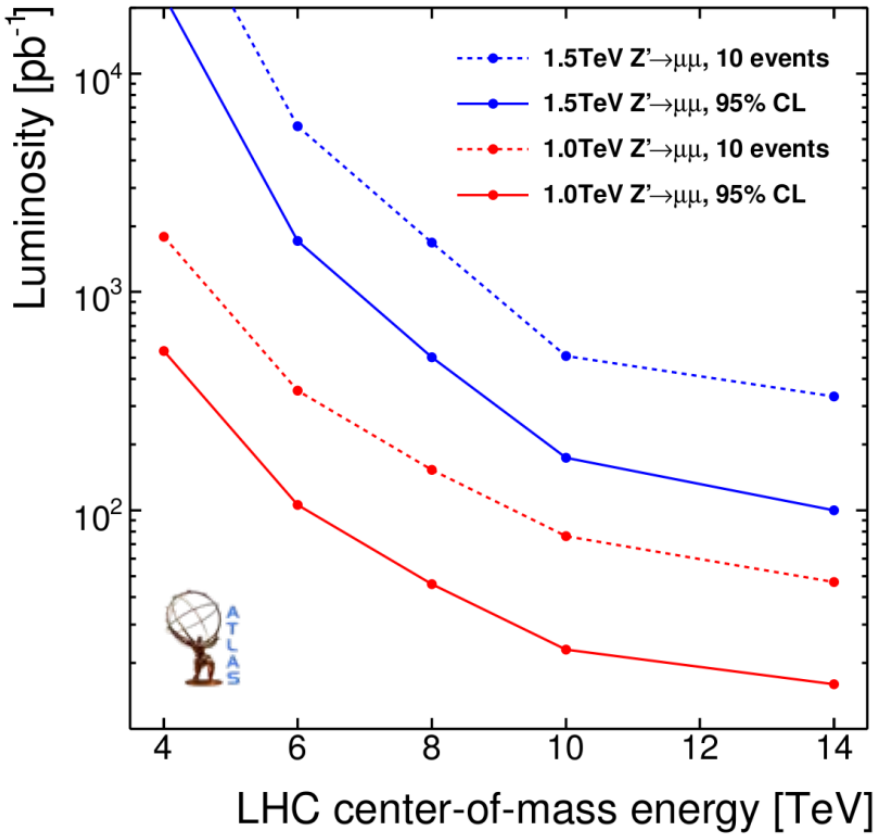
To challenge Tevatron with E_{CM} = 10 TeV, we need ~200 pb^{-1}

Results indicative only !

10 TeV versus 14 TeV: *Z'*

- Heavy *Z* partner: *Z'* (current Tevatron limit: $M_{Z'} > 1$ TeV)

Z' → *ee*, $\mu\mu$ with very clean experimental signature



95% exclusion for $M_{Z'}$ = 1 TeV	
CM energy [TeV]	Lumi. needed [pb^{-1}]
14	13
10	30
6	110

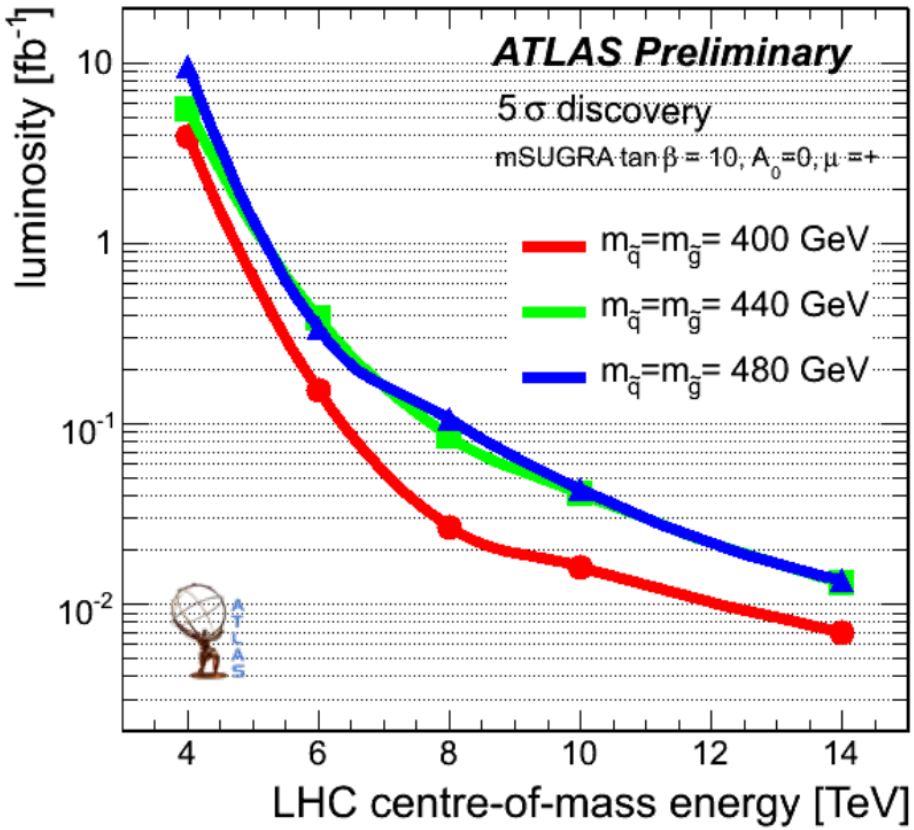
5σ discovery possible at E_{CM} = 10 TeV, with ~100 pb^{-1}

Results indicative only !

10 TeV versus 14 TeV: *SUSY*

- Inclusive SUSY search (current Tevatron limit: $M_{g,q} > 380$ GeV)

Lepton + jets + missing E_T channel (startup compromise: reasonably clean & powerful)



5σ discovery beyond Tevatron limits at E_{CM} = 10 TeV, with ~15 pb^{-1}

Results indicative only !

That’s it !
Thanks.