“Monte Carlo simulations in measurements and searches done with the ATLAS detector”

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On behalf of the ATLAS collaboration

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Introduction:

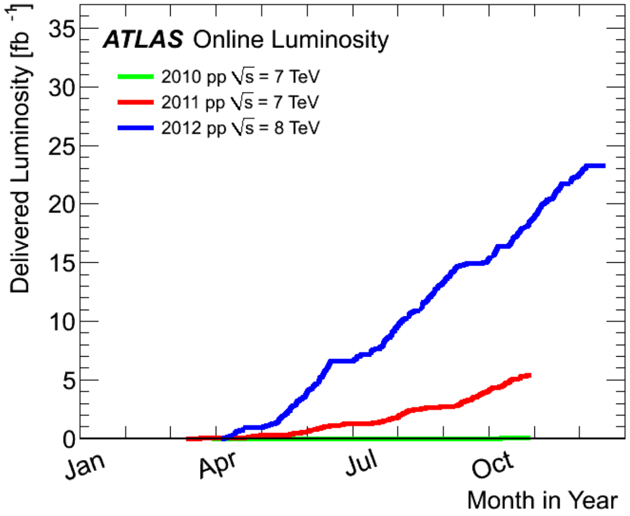
The ATLAS detector at the LHC
(status and prospects)

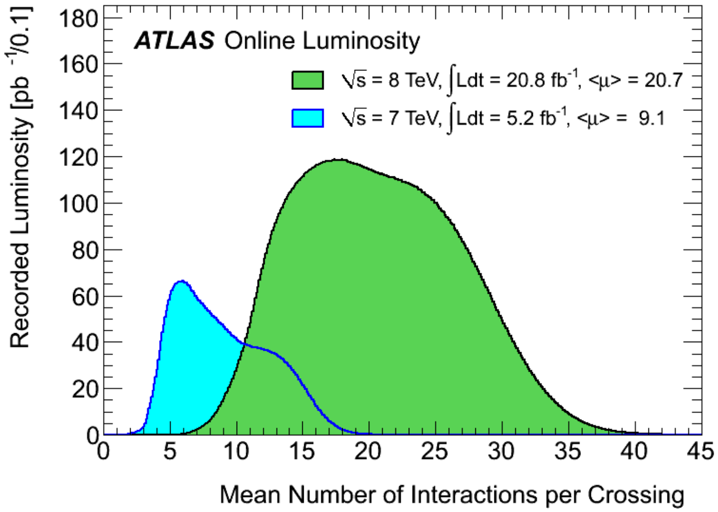
The ATLAS detector in a nutshell

- Two independent Magnetic Fields
  - Inner Detector → Ultra thin solenoid (2T homogeneous field)
  - Muons → Air Core Toroid (stand alone measurement 10% resolution @ 1 TeV)
- High Granularity Calorimeters
  - Sampling LAr → Good γ angle resolution
    - Drives H → $\gamma\gamma$ mass resolution
  - Tile → Very good jet measurement
  - Hermetic (up to |eta| < 5)
- Particle Identification (various level of fake rejection)
  - Shower shapes, track matching
  - Separation of jet/electrons and pion/photons
  - Secondary vertices (heavy flavor)
- Three level trigger (dedicated L1 muon chambers)
  - Reduce the event rate (~1 GHz) to affordable values for the storage (200 Hz)

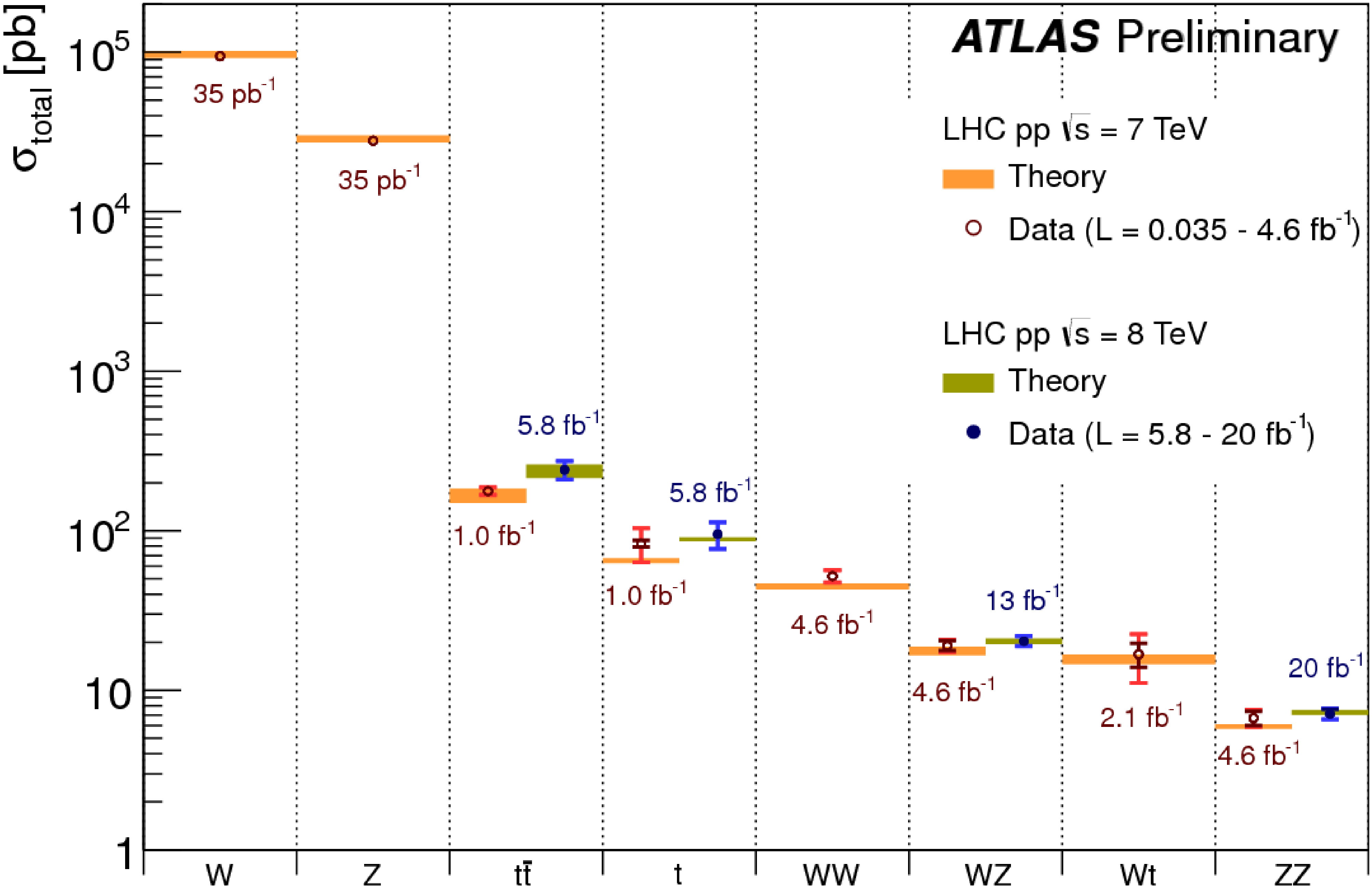
ATLAS Run 1

- 2010, √s=7 TeV, 36/pb
- 2011, √s=7 TeV
  - Peak luminosity 3.65x10^{33} $cm^{-2}s^{-1}$
  - Peak of 140/pb of data per day
  - Integrated luminosity 5.62/fb
  - 50 ns bunch spacing
  - Pile up - collisions/bunch crossing <μ>=6.3 (11.6) before (after) September
- 2012, √s = 8 TeV
  - Peak luminosity 7.73x10^{33} $cm^{-2}s^{-1}$
  - Integrated luminosity 23/fb
  - Data taking eff. 93%, good quality 95%
  - Pile up - <μ>=20
  - Total : ~5 billion events, ~25 fb-1
  - 120 PB data and MC on disk!

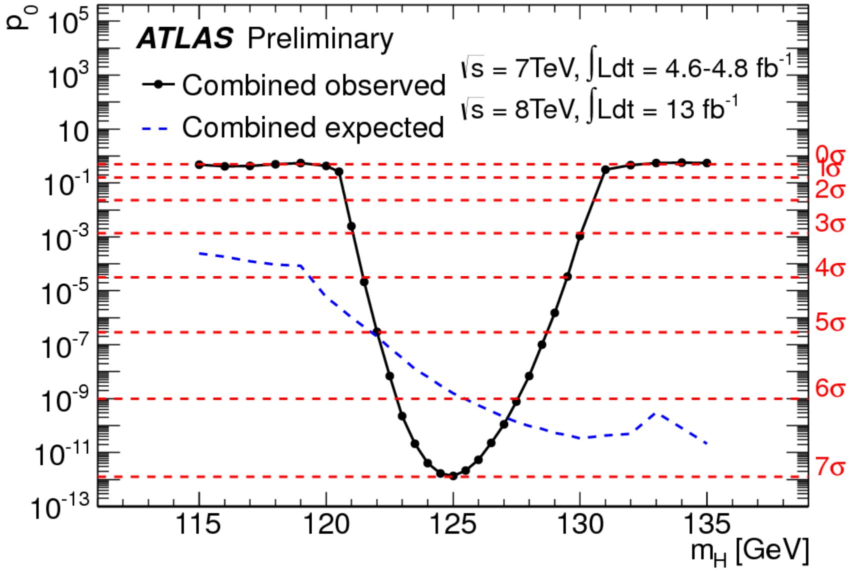


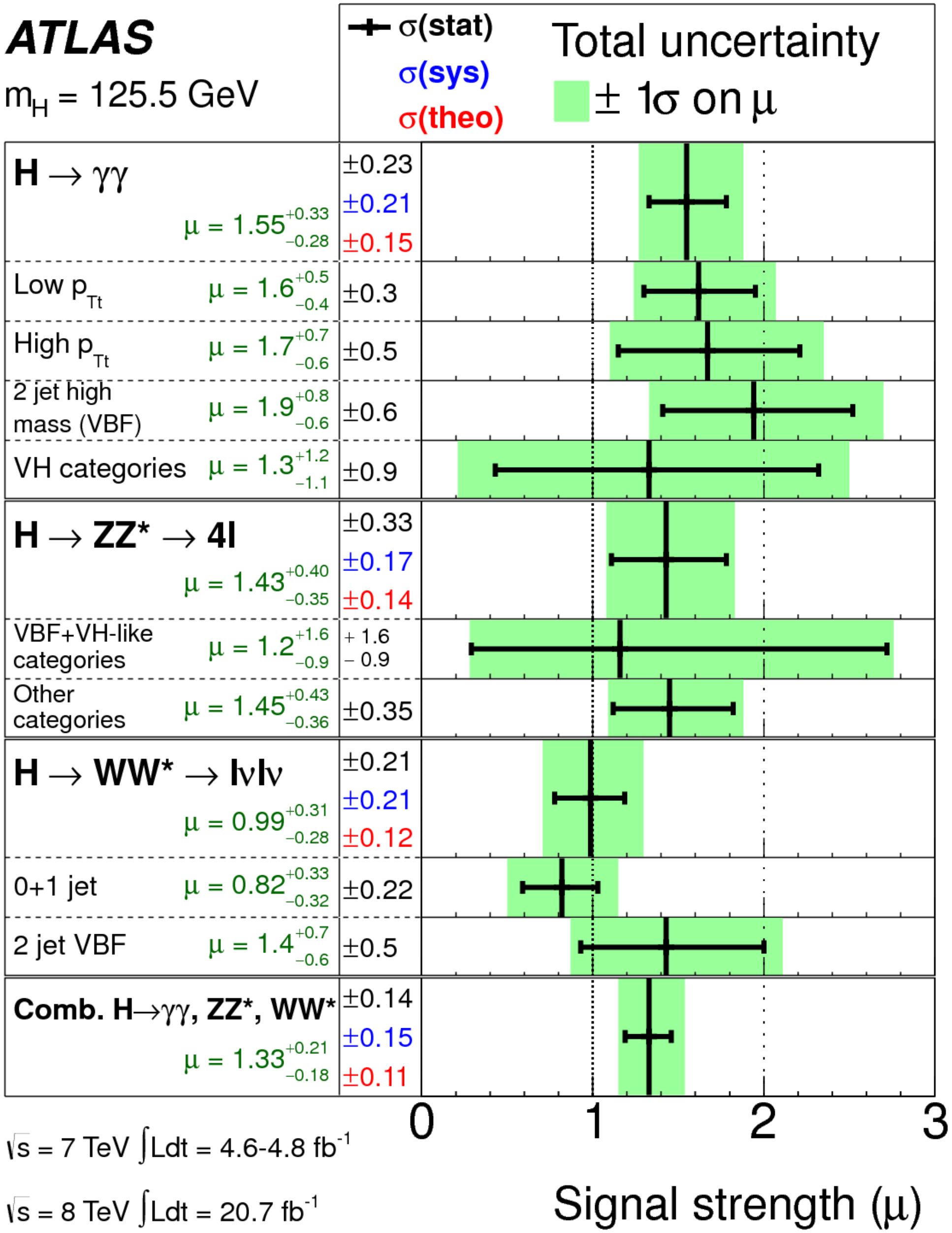


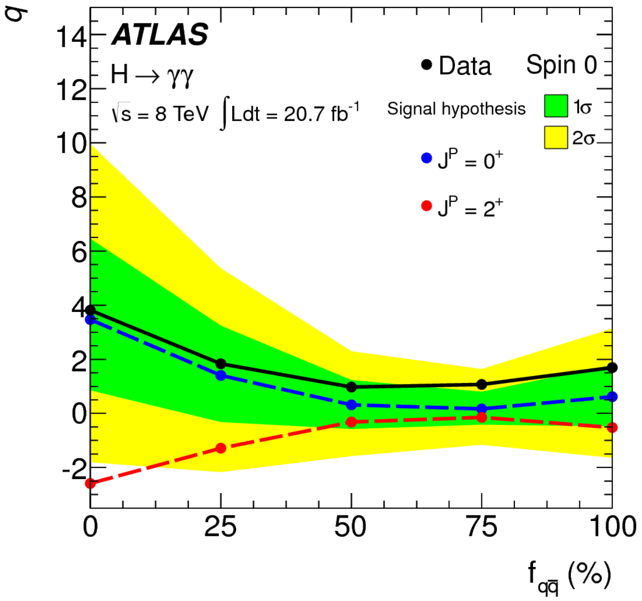
SM physics from a ATLAS perspective



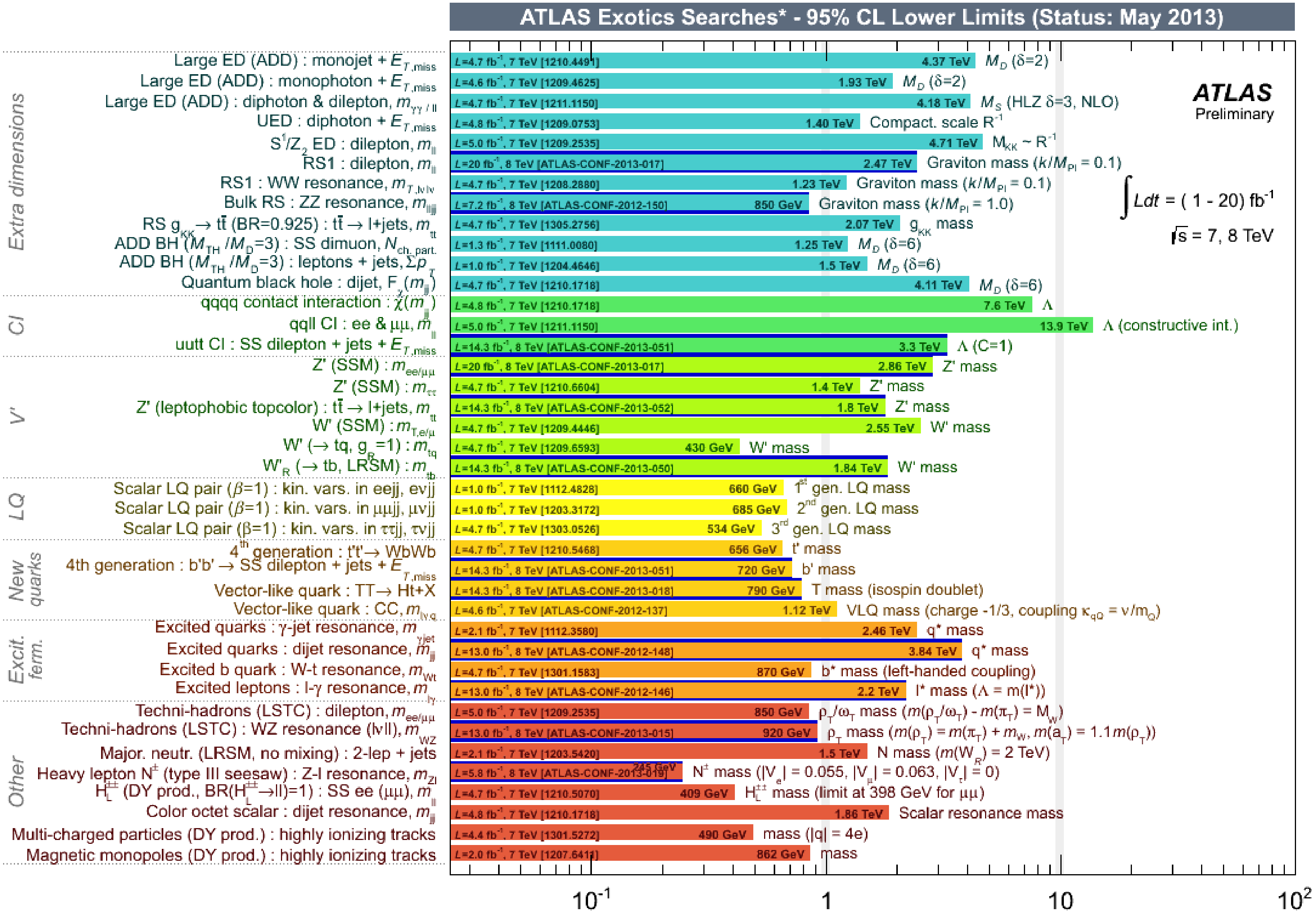
Higgs


ATLAS Preliminary
Combined observed
Combined expected
√s = 7TeV, ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8TeV, ∫Ldt = 13 fb⁻¹
p₀
10⁵
10³
10
10⁻¹
10⁻³
10⁻⁵
10⁻⁷
10⁻⁹
10⁻¹¹
10⁻¹³
0σ
1σ
2σ
3σ
4σ
5σ
6σ
7σ
115
120
125
130
135
m_H [GeV]


ATLAS
m_H = 125.5 GeV
σ(stat)
σ(sys)
σ(theo)
Total uncertainty
± 1σ on μ
H → γγ
μ = 1.55 +0.33 −0.28
±0.23
±0.21
±0.15
Low p_Tt
μ = 1.6 +0.5 −0.4
±0.3
High p_Tt
μ = 1.7 +0.7 −0.6
±0.5
2 jet high mass (VBF)
μ = 1.9 +0.8 −0.6
±0.6
VH categories
μ = 1.3 +1.2 −1.1
±0.9
H → ZZ* → 4l
μ = 1.43 +0.40 −0.35
±0.33
±0.17
±0.14
VBF+VH-like categories
μ = 1.2 +1.6 −0.9
+ 1.6
− 0.9
Other categories
μ = 1.45 +0.43 −0.36
±0.35
H → WW* → lνlν
μ = 0.99 +0.31 −0.28
±0.21
±0.21
±0.12
0+1 jet
μ = 0.82 +0.33 −0.32
±0.22
2 jet VBF
μ = 1.4 +0.7 −0.6
±0.5
Comb. H→γγ, ZZ*, WW*
μ = 1.33 +0.21 −0.18
±0.14
±0.15
±0.11
0
1
2
3
√s = 7 TeV ∫Ldt = 4.6-4.8 fb⁻¹
√s = 8 TeV ∫Ldt = 20.7 fb⁻¹
Signal strength (μ)


ATLAS
H → γγ
√s = 8 TeV ∫Ldt = 20.7 fb⁻¹
Data
Spin 0
Signal hypothesis
1σ
2σ
J^P = 0⁺
J^P = 2⁺
q
14
12
10
8
6
4
2
0
-2
0
25
50
75
100
f_qq̄ (%)

Exotics

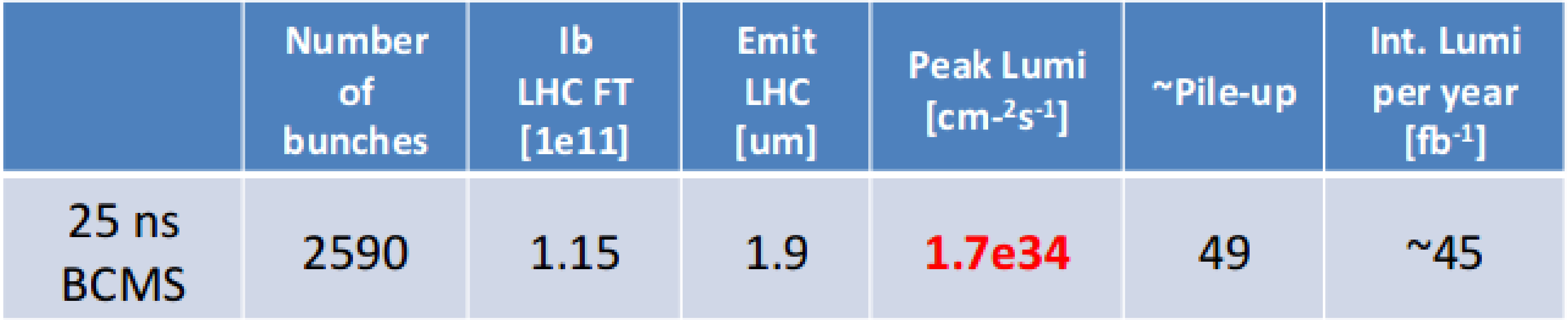


*Only a selection of the available mass limits on new states or phenomena shown

LHC Run 2

- Beam energy: starting with 13 TeV (6.5+6.5)
  - May be reach quickly 14 TeV
- Luminosity (Integrated)
  - The plan is to accumulate ~70-100 / fb per year (three years of run)
- Luminosity (Instantaneous)
  - Less interesting for theorists, but really important for the experiment
    - Trigger, pileup, etc...
    - Reference value (1.7e34) could be enhanced up to 4.e34

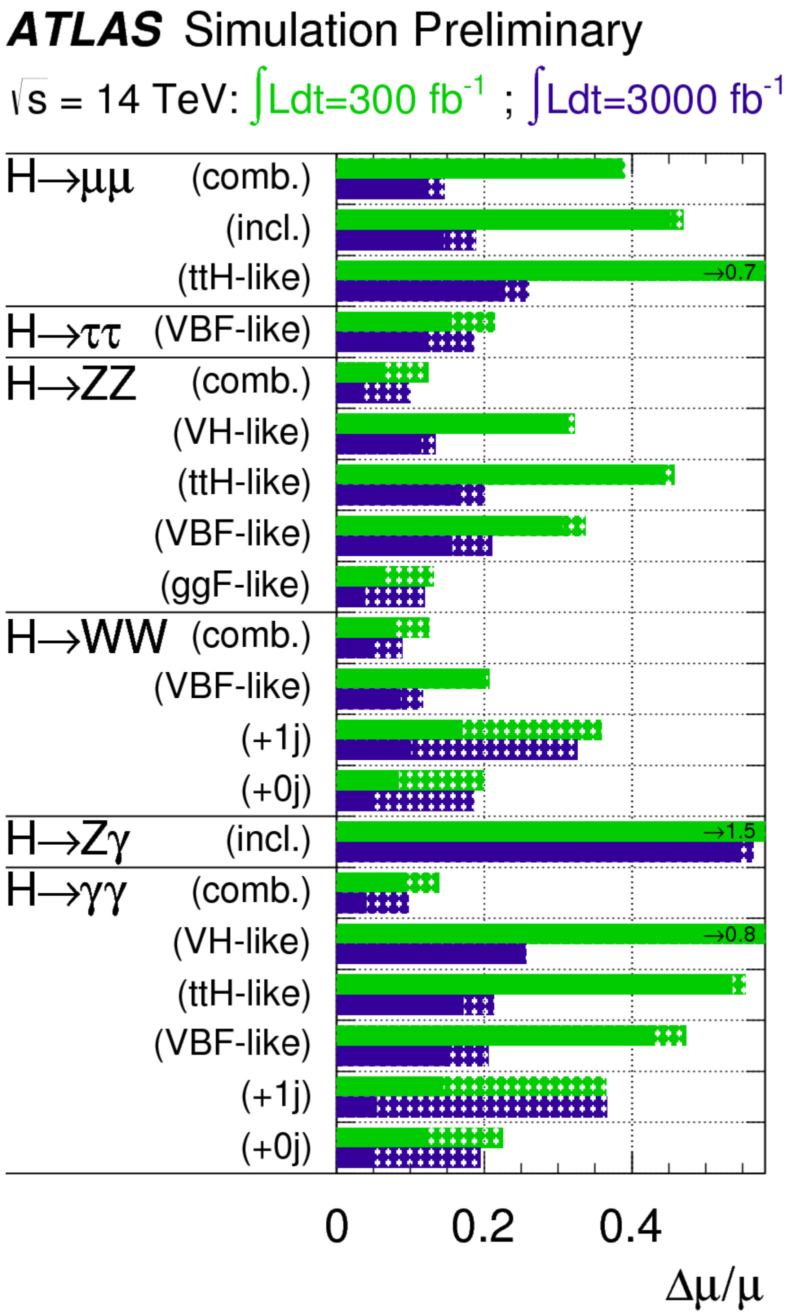
Total cross-sections and pile-up behavior have to be extrapolated from models (until we can measure them)



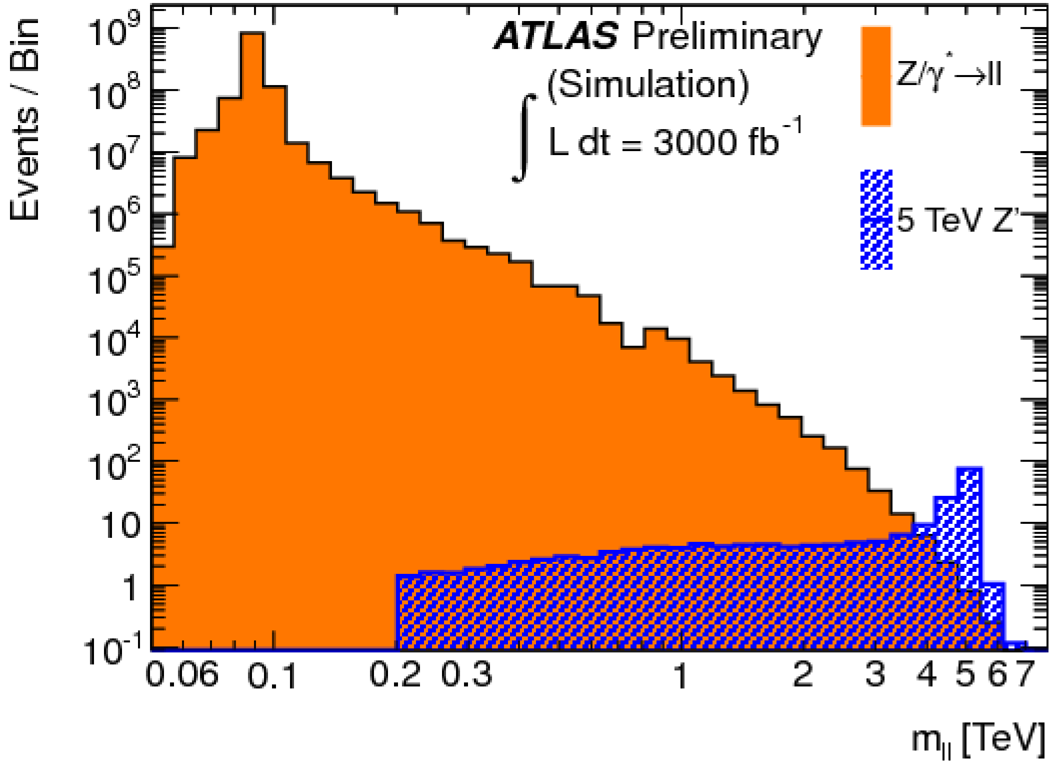
	Number of bunches	Ib LHC FT [1e11]	Emit LHC [um]	Peak Lumi [$cm^{-2}s^{-1}$]	~Pile-up	Int. Lumi per year [fb^{-1}]
25 ns BCMS	2590	1.15	1.9	**1.7e34**	49	~45

For a more detailed report see:W. Herr, “*Performance reach of LHC after LS1*“ (**Chamonix 2012**)

Physics prospects at high luminosity



arXiv:1307.7292 [hep-ex]



- Uncertainty on the Higgs signal strength ~20% with 3000/fb
- Sensitivity to heavy Z bosons up to ~5 TeV

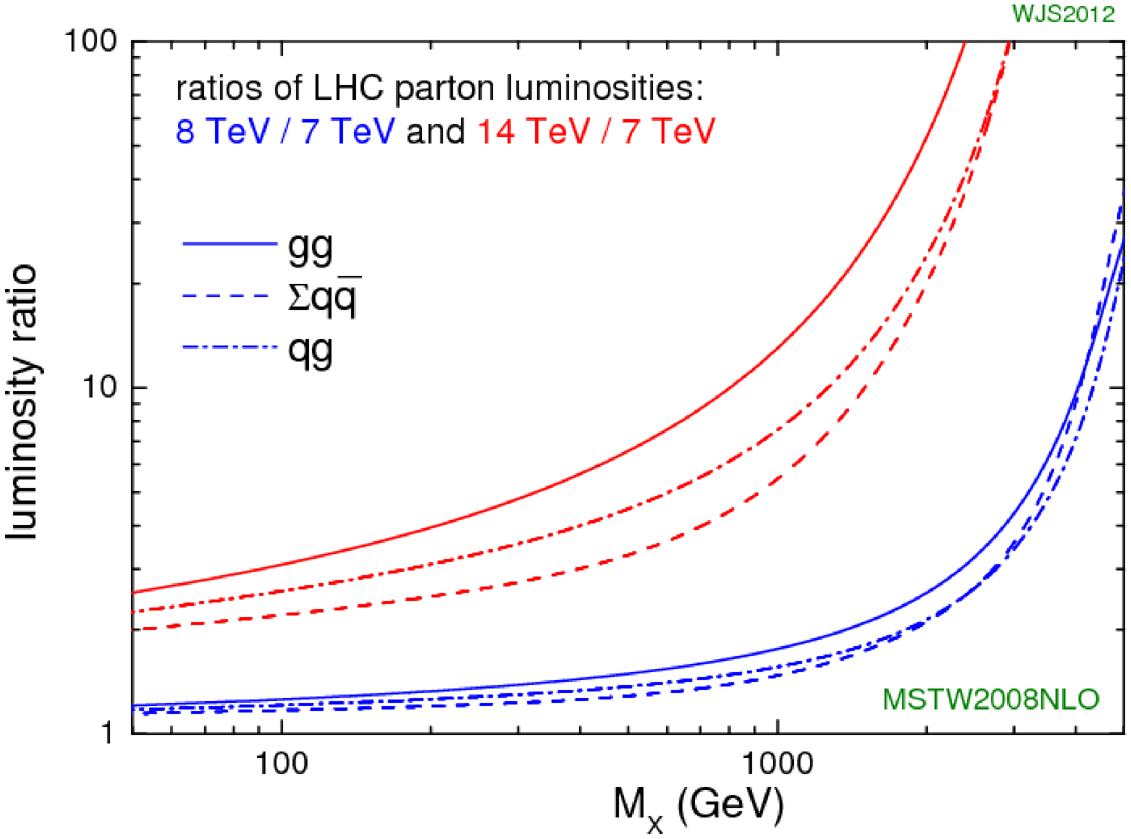
Physics prospects at 14 TeV

Enhancement (14 TeV / 7 TeV)

- Factor 100 for objects of mass 2.5-3 TeV
- Factor 10 for masses around 1 TeV
- Factor 3 for 100 GeV objects (2 if consider cme 13 TeV)

Improvement in PDFs is one of the things that will help the run 2 physics output

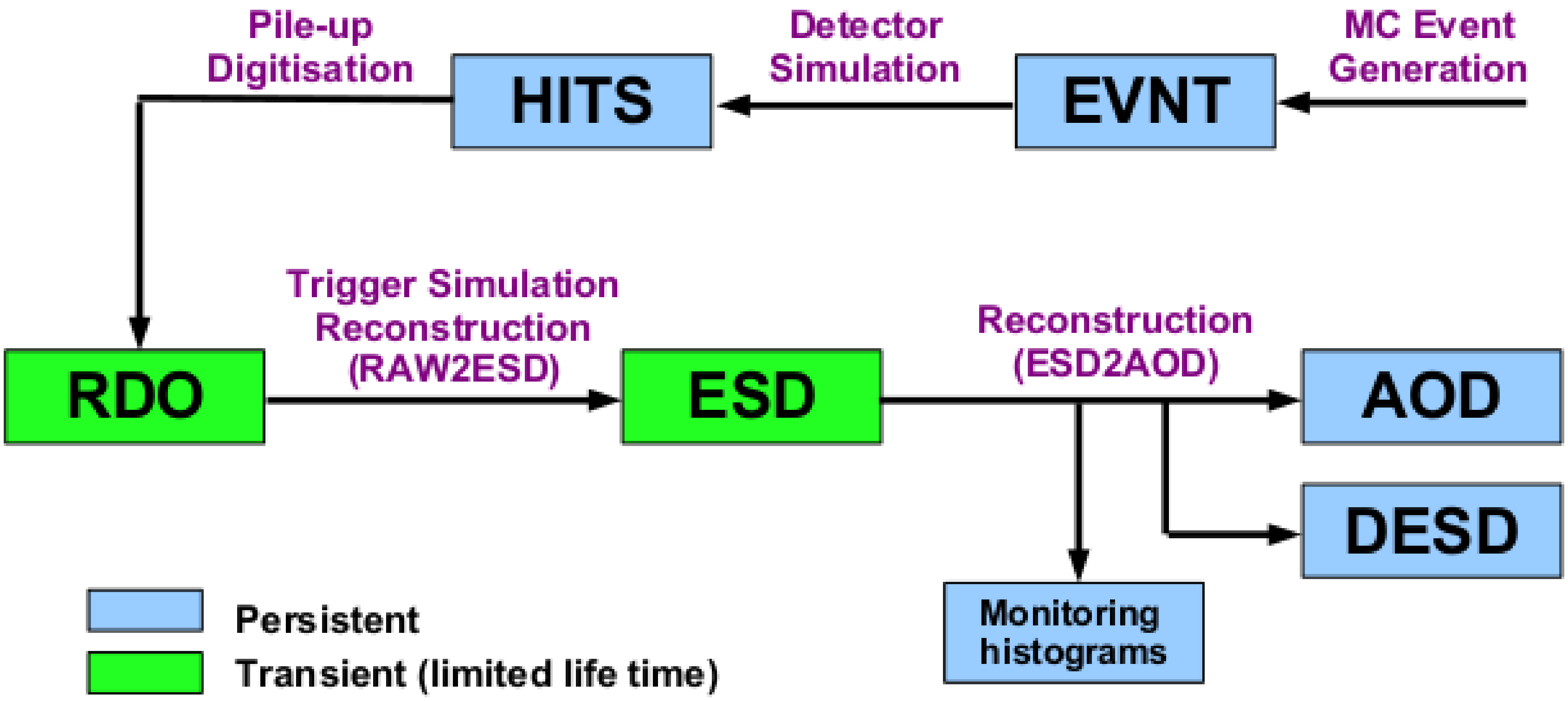
CMS-NOTE-13-002



MC Production in ATLAS

MC Production: state of the art

ATLAS Monte Carlo Simulation Flow



MC Event Generation

EVNT

Detector Simulation

HITS

Pile-up Digitisation

RDO

Trigger Simulation Reconstruction (RAW2ESD)

ESD

Reconstruction (ESD2AOD)

AOD

DESD

Monitoring histograms

🟦 Persistent

🟩 Transient (limited life time)

For a more detailed report see:
W. Ehrenfeld, “*Challenges in the ATLAS Monte Carlo Production during Run 1 and beyond*“ (**CHEP2013**)

Event Generation

~30 MC generators used in ATLAS

- Framework-integrated generators / Stand-alone generators
- Choice of generator driven by
  - Availability of the requested physics process
  - Performance in describing data
  - Traditionally used by a certain physics group
  - Expertise in the experiment

Event generation work flow

- Single step (Pythia6/8, Herwig(++), Sherpa)
- Two-step generation: parton level generator usually coupled via LHEF files to framework generator for hadronisation (Pythia(6/8), Herwig(++))
  - default configuration: external, pre-made 4-vectors uploaded to the grid
  - on-the-fly configuration: run external generator before hadronisation in the same job

Event Generation performance

Many different samples

- 50 different generator combination in mc12 campaign
- ~34 thousand different samples produced in mc12 campaign

job characteristics

- 5000 events per job
- running time per job varies from
  - a few minutes for simple final states/hadronisation of external 4-vectors
  - hours or days for complex final states or low filter efficiencies

performance improvements:

- on-the-fly generator setups: avoid storing 4-vector input files on the grid
  - simplifies job submission and helps reduce the risk of mistakes due to book-keeping errors or lack of documentation
- use pre-made integration files (Sherpa, Alpgen, MadGraph): reduce running time

Produced MC Events

- mc11: 2.4 x 10^9 full and 2.1 x 10^9 fast simulation events
  - mc11a: 0.8 x 10^9 events
  - mc11b: 1.0 x 10^9 events (super seeds mc11a)
  - mc11c: 4.8 x 10^9 events (super seeds mc11b) → total: 4.8 x 10^9 events

- mc12: 3.8 x 10^9 full and 3.0 x 10^9 fast simulation events
  - mc12a: 5.9 x 10^9 events
  - mc12b: 0.5 x 10^9 events
  - mc12c: 0.2 x 10^9 events → total: 6.6 x 10^9 events

→ total of 6.2 x 10^9 full and 5.1 x 10^9 fast simulation events

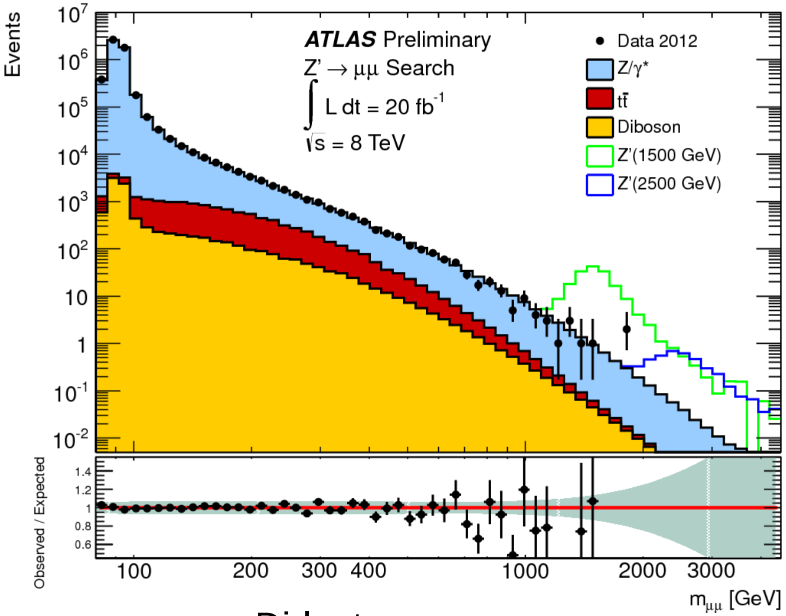
- Verification of MC generators /Physics validation
  - Normally quite expensive for the experiment to switch to a new generator version

Signal and background models

Signal models and backgrounds

A lot of different models

- Signal samples (Physics beyond the SM)
    - Benchmark models widely used: they allow comparison between experiments and with previous results (effective models, sometimes driven by experimental needs)
    - Availability of other models allow re-interpretation of results (lot of interactions with theorists)
- SM processes
    - Need very good understanding
        - Explore the full phase space (e.g. high-mass DY + jets for Leptoquarks)
    - Often discrepancies treated as scaling factors
    - Data-driven techniques very important (e. g. QCD background, W recoil modeling)



Di-lepton resonances:

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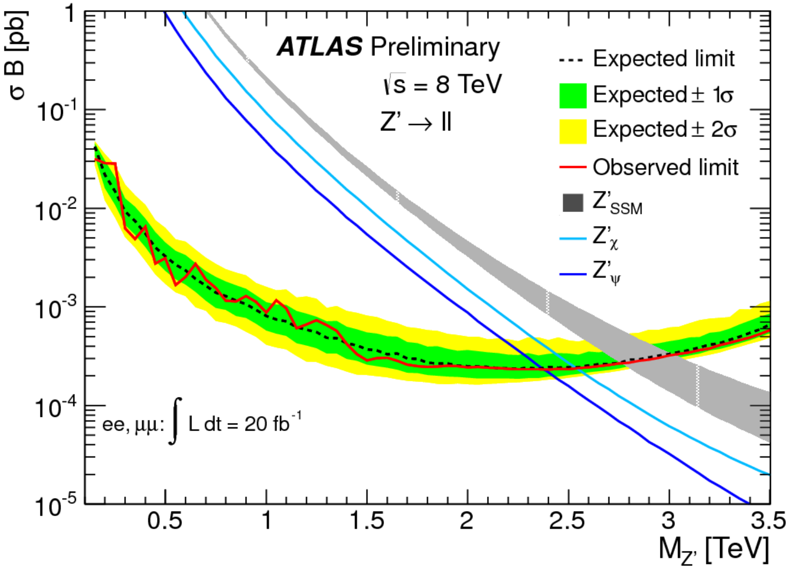


Constrain predictions with data

How to treat data/MC discrepancies?

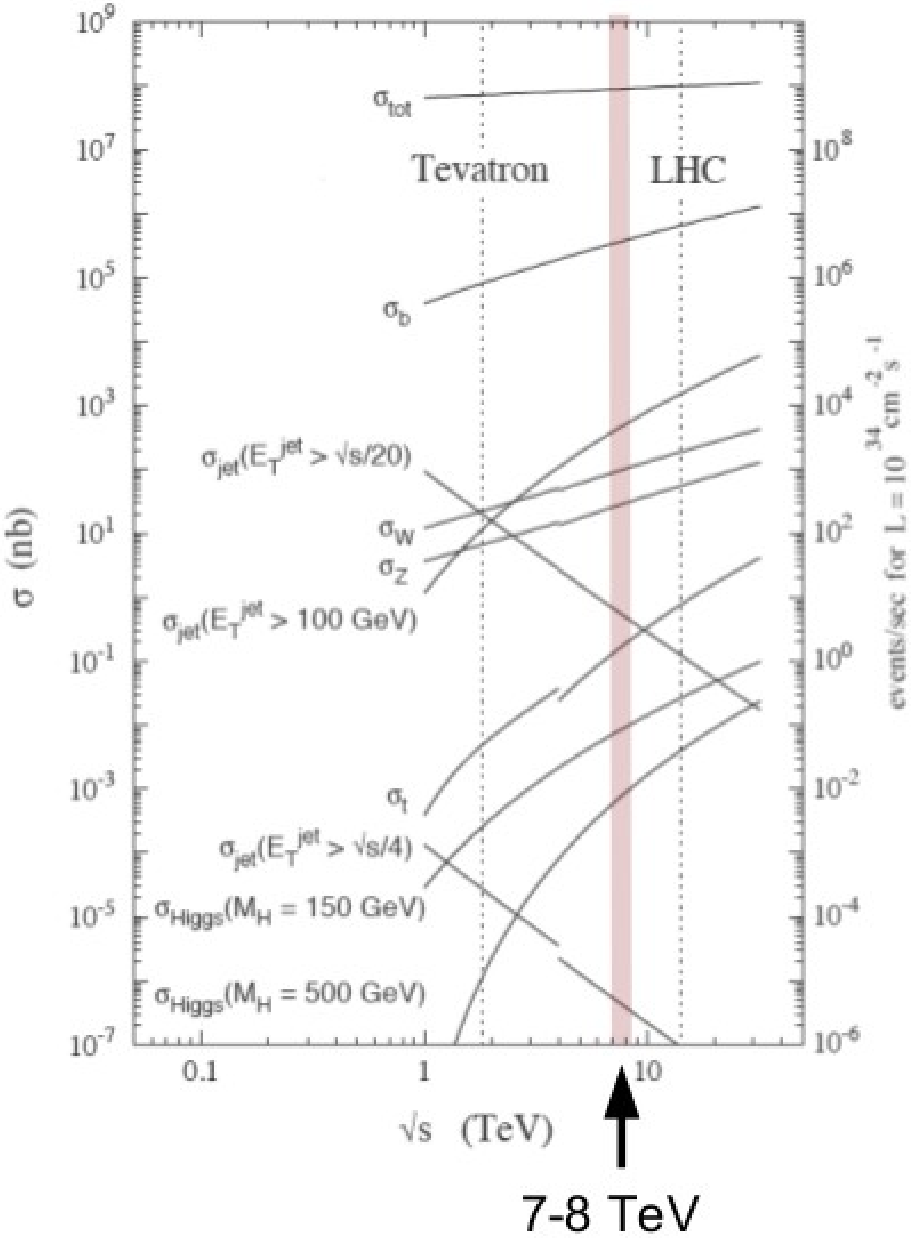
- Use control regions to check (standard candles very useful in this case)
  - Need a bit of care (the control region for one analysis could be the signal region of another one: these kind of interplay are not taken into account normally)
- In many cases (mostly searches) assign a scale factor: constrains the cross section
  - Not always the “healthiest” solution, but mostly effective
  - Doesn't apply very well to cross-section measurements
  - Even worst when analysis are aiming for differential measurement
- Decouple detector/simulation effects from pure physics effects
  - W-mass, top-mass measurements use template fits

What can we do better?

- A lot of efforts in tuning → we should profit of the shutdown to get more results on this
- Features of MC generators need to be well known and documented
  - We have scope to improve the matching of ME generators to showers

QCD backgrounds

- Total inelastic cross section very large
  - O(100 mb)
  - 10^7-10^9 larger than W/Z and top
  - 10^10 times SM-Higgs
- Average pileup: 20.7 events
  - Max 40 events/ bunch crossing
- Limited MC statistics
  - Impossible to produce as much simulated events as expected in data
- Suppress by physics signatures
  - Low mis-identification probability
  - Very difficult to extrapolate results



7-8 TeV

Suppress and estimate QCD processes

- Most non-QCD analyses are designed to suppress QCD with non QCD signatures:
    - Use Leptons, Missing ET, photons
    - QCD contribution described by cocktail of MC predictions plus data driven approach:
        - Experimental description of “Fakes”

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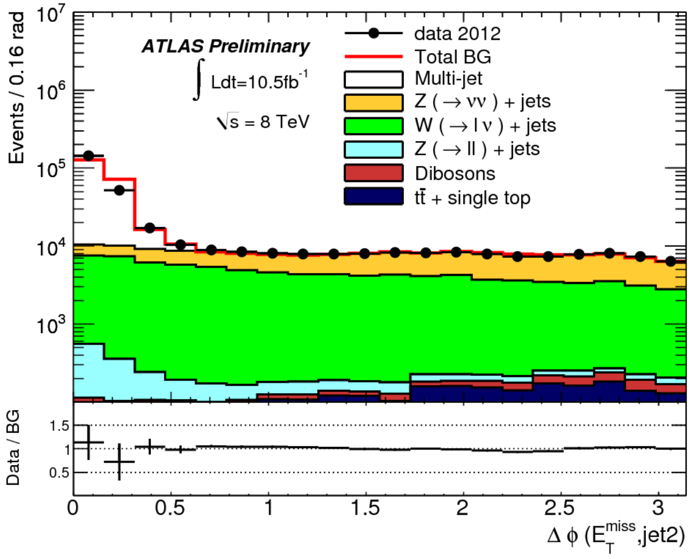

- All hadronic searches use different methods:
    - Bump hunting
    - Data driven extrapolations from side band
    - Theoretical predictions (templates for shape, not normalization)
    - Top background from (N)NLO calculation

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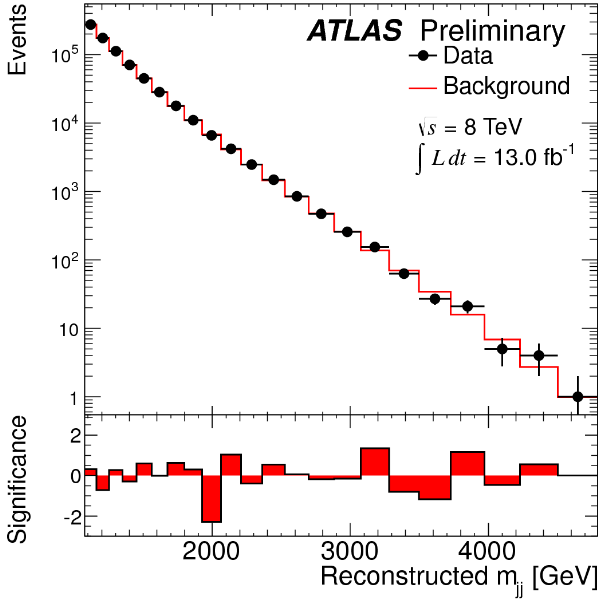

Top as QCD background

- Top-pair and single top cross section often taken from NNLO calculation
    - Full uncertainty from scale,fragmentation, hadronisation, PDF
- Try to constrain top modelling from data:
    - Rapidity gap fraction (ISR/FSR)
    - Jet shapes
    - N-Jet spectrum
- Possible handling: comparing data with one and two b-tags
- Searches are very often sensitive to tails of ttbar Monte Carlo:
    - High mass tails
    - HT tails
    - Large MET tails

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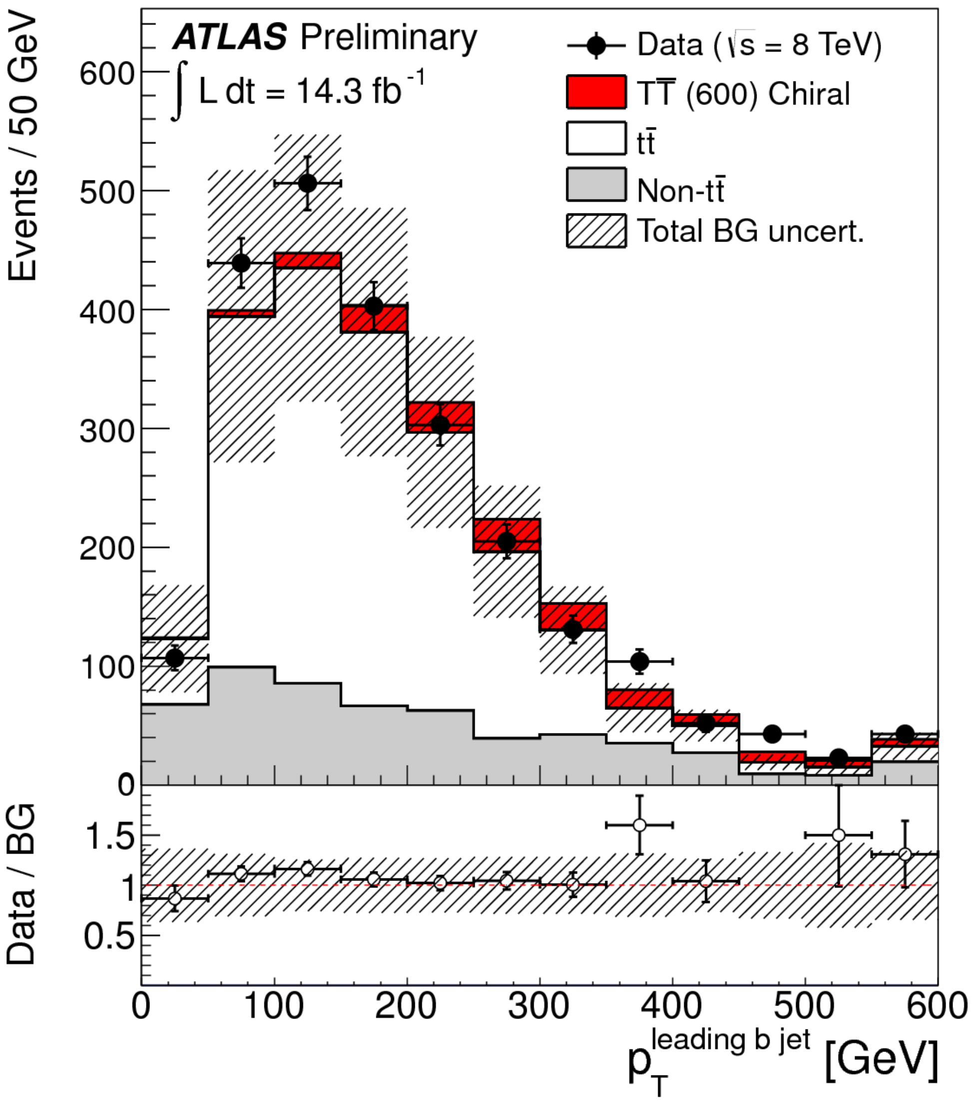
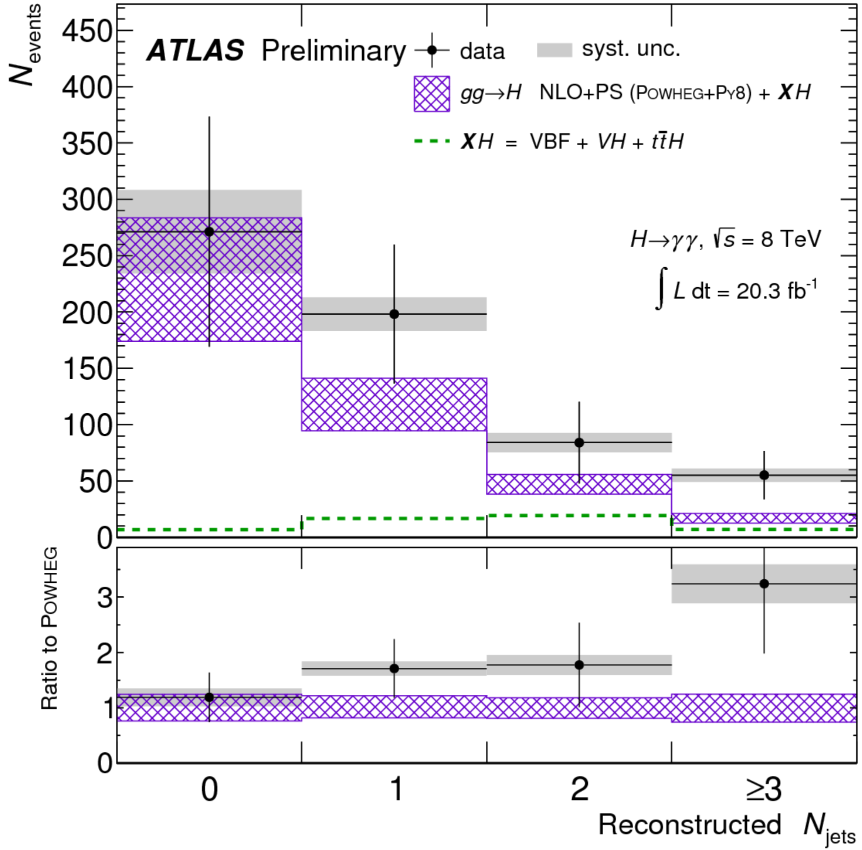


Differential measurements (H → γγ)

Higgs area of precision measurement started:

- Most analyses in bins of fixed number of jets
- Many analyses using multivariate methods, need to describe correctly distribution in exclusive jet bins
- Need calculations of of H+0,1,2 jets plus VBF-jet
- Start to constrain by measurements



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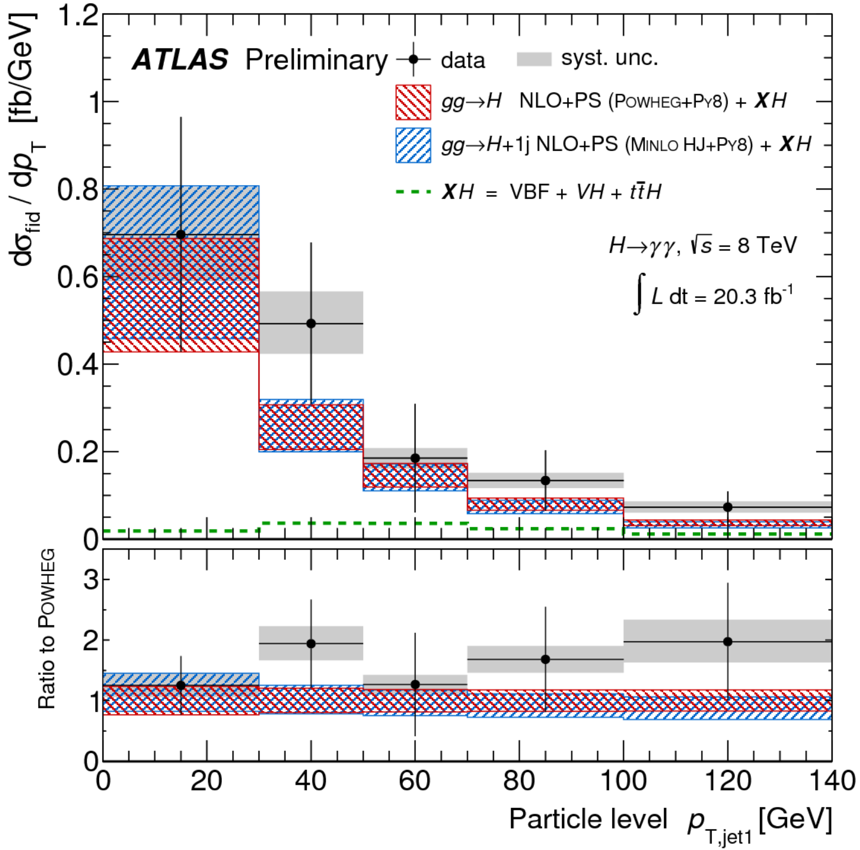


Tuning

Soft QCD

- The high-p_T jet production is calculated by convolving
  - the matrix elements for the scattering of two initial-state partons
  - with the corresponding parton distribution functions (PDF)
- To predict the momentum spectrum of final particles
  - additional effects must be considered (which vary with the momentum transfer of the hard parton scattering)
    - The outgoing partons fragment into jets of hadrons
    - The beam remnants also hadronize and the spectator partons in the proton can also interact → multiple parton interactions (MPI)
    - QCD radiation from the initial- and final-state partons occurs, leading to additional jets and to an increase in the ambient energy
- Some of these processes take place at an energy scale where the QCD coupling constant is large and perturbation theory cannot be used
  - They must therefore be described using QCD-motivated phenomenological models
  - These models contain a number of free parameters with values that must be obtained by fitting to experimental data

ATLAS MC tuning system

A Brief History of Tuning

- Historically most effort has been devoted to tuning (Fortan) Pythia6, even at LEP/CDF.
- ATLAS did tune (Fortran) Herwig+Jimmy(which adds MPI), and now (C++) Pythia8.
- (C++) Herwig++, Sherpa has so far been tuned by authors.

Hadronization and FSR: LEP

ISR and MPI: Hadron colliders

Automated tuning tool (Rivet/Professor):

- ATLAS has been one of the earliest adopters and keen supporter and developer of it
- Essentially generate lot of samples covering the parameter space. Interpolate the generator response, get the best fit by minimization (and burn a lot of CPU!)

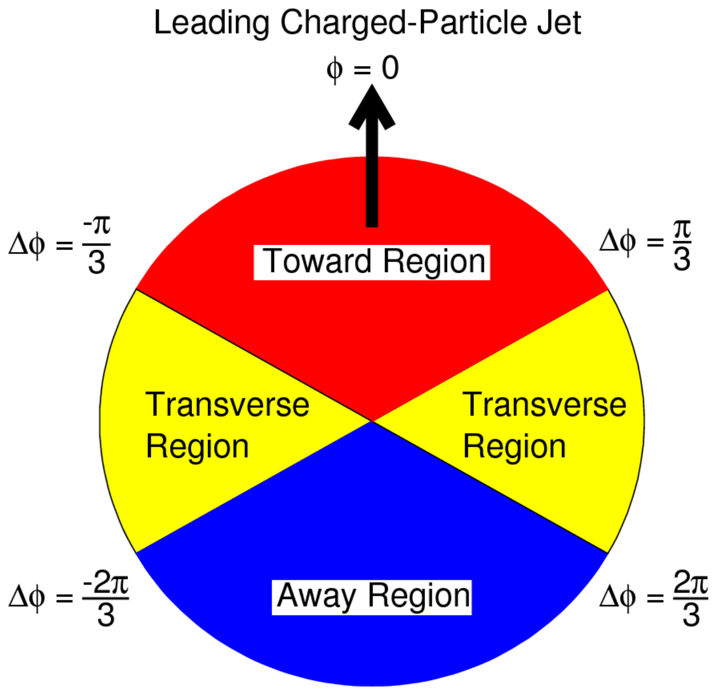
Tuning: Minimum Bias and Underlying Event

MB and UE

- Event Generators are at their least predictive when dealing with soft, non-perturbative QCD effects
- MPI most obviously seen in Minimum Bias (MB) and Underlying Event (UE) observables
  - MB dominated by purely soft-QCD scattering
  - UE is the soft-QCD component of the event → irreducible background in events with an identified hard scattering
  - Also efforts in tuning diffractive processes → Improve description of forward ET flow
- Typical observation
  - Observed QCD jet rates exceed the total hadronic interaction cross-section
    - More of the incoming hadrons are interacting than just the single hard scattering
  - Phenomenological modeling: $\mathbf{p_{\perp}^{min}}$ most prominent MPI tuning parameter
    - It determines the ad-hoc regularization of the low-pT jet cross-section
    - The higher its value, the lower the level of MPI activity

UE: definition and observables

- UE: any hadronic activity not associated with the jets or leptons produced in the hard scattering process
  - Color fields connect all the strongly interacting partons in the proton-proton event
    - no unambiguous assignment of particles to the hard scattering partons or UE is possible
  - Use regions "depleted of QCD activity (coming from the hard interaction)"
    - Far from the direction of the products of the hard scatter
    - In the direction of the Z boson



- Construct observables from tracks/clusters in the UE-enriched region
  - N_{ch}, Σp_T, $<p_T>$
  - These are then shown as a function of the leading object (e.g. jet) p_T

UE and MB tuning

Performed on Pythya8

- Long term replacement of Phythia6 (which has been tuned as well)
- Used for various soft QCD simulations
  - MPI samples, pileup, etc...

Tuning parameters for MPI

- Cutoff parameter for MPI (MultipleInteractions:pT0Ref → PARP(82))
- Power of the energy rescaling for the cutoff (MultipleInteractions:ecmPow → PARP(90)
- Color reconnection probability (BeamRemnants::ReconnectRangs → PARP(76) and PARP(78)
- Constant term for the width of the gaussian matter function (MultipleInteractions:a1)

PDF sets

- LO: CTEQ6L1, MSTW08LO, NNPDF21LO
- Modified LO: MRST2007 (LO*), MRSTMCal (LO**)
- NLO: CTEQ6.6, CT10, NNPDF21NLO, MSTW08NLO

Pythia8 → Pythia6
Parameters not
exactly mapped 1:1

UE and MB tuning: data and selection

Soft QCD measurements

- $\sqrt{s}$=900 GeV and $\sqrt{s}$=7 TeV used for tuning

Only LHC data (no Tevatron)

- With this choice of parameters was not possible to find a common tune for three different CM energies

Minimum Bias

- Used various different requirements on p_T and N_{ch}

Underlying Event

- Used a leading track / leading cluster

Higher weight in tuning

- $\sqrt{s}$=7 TeV and p_T>500MeV

Starting point: 4C-like parameter configuration

- Discrete MPI model more like 4Cx, due to x-dependent hadronic matter distribution

UE and MB tuning: results

- A minimum bias tune (A2) was performed for LO PDFs
- UE tune (AU2) for various type of PDFs (LO, MLO, NLO)

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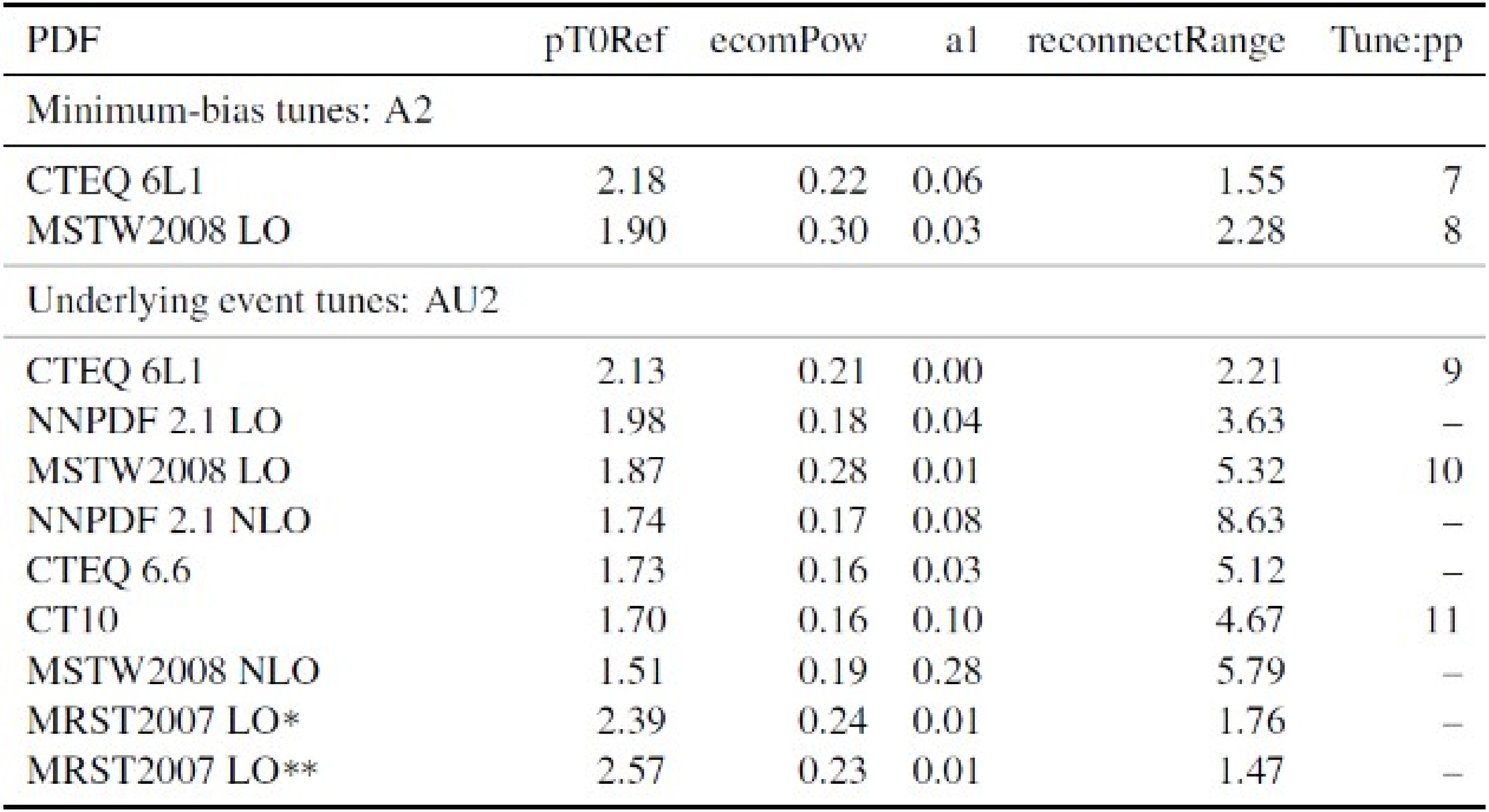
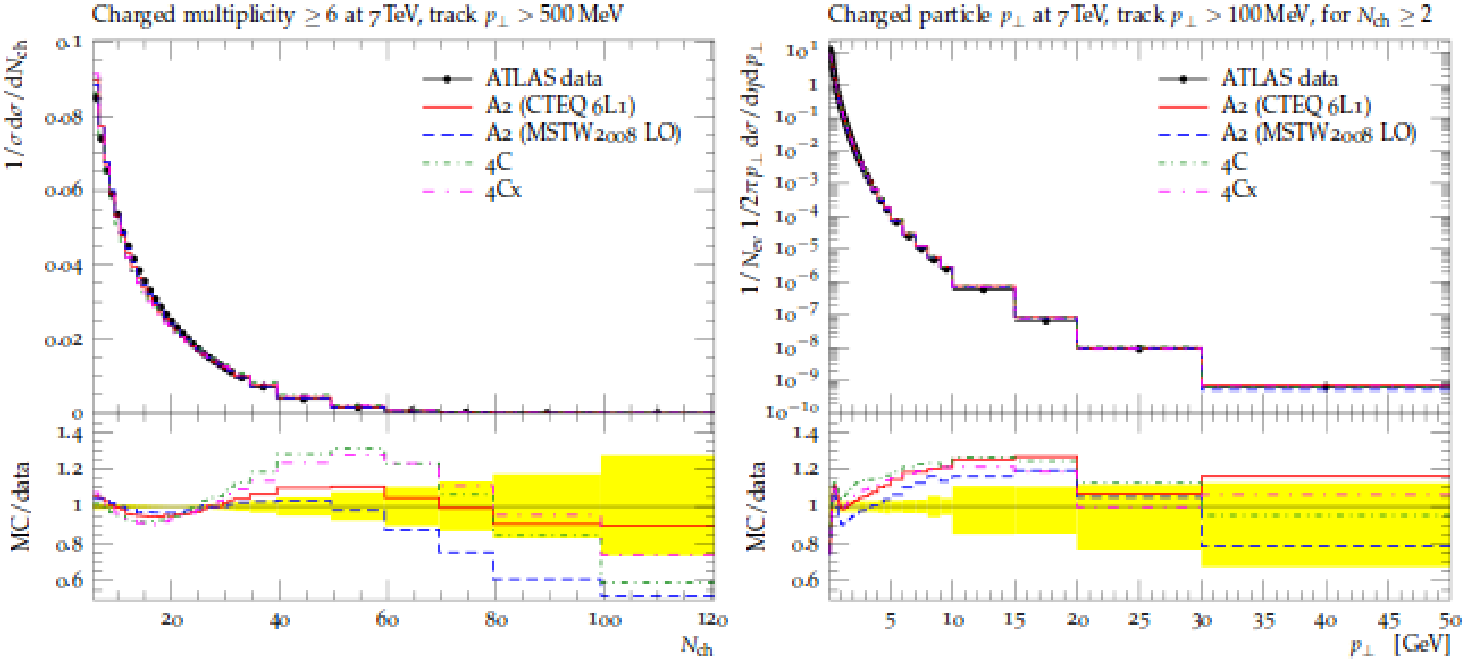


PDF	pT0Ref	ecomPow	a1	reconnectRange	Tune:pp
Minimum-bias tunes: A2					
CTEQ 6L1	2.18	0.22	0.06	1.55	7
MSTW2008 LO	1.90	0.30	0.03	2.28	8
Underlying event tunes: AU2					
CTEQ 6L1	2.13	0.21	0.00	2.21	9
NNPDF 2.1 LO	1.98	0.18	0.04	3.63	–
MSTW2008 LO	1.87	0.28	0.01	5.32	10
NNPDF 2.1 NLO	1.74	0.17	0.08	8.63	–
CTEQ 6.6	1.73	0.16	0.03	5.12	–
CT10	1.70	0.16	0.10	4.67	11
MSTW2008 NLO	1.51	0.19	0.28	5.79	–
MRST2007 LO*	2.39	0.24	0.01	1.76	–
MRST2007 LO**	2.57	0.23	0.01	1.47	–

UE and MB tuning: results (2)

MB



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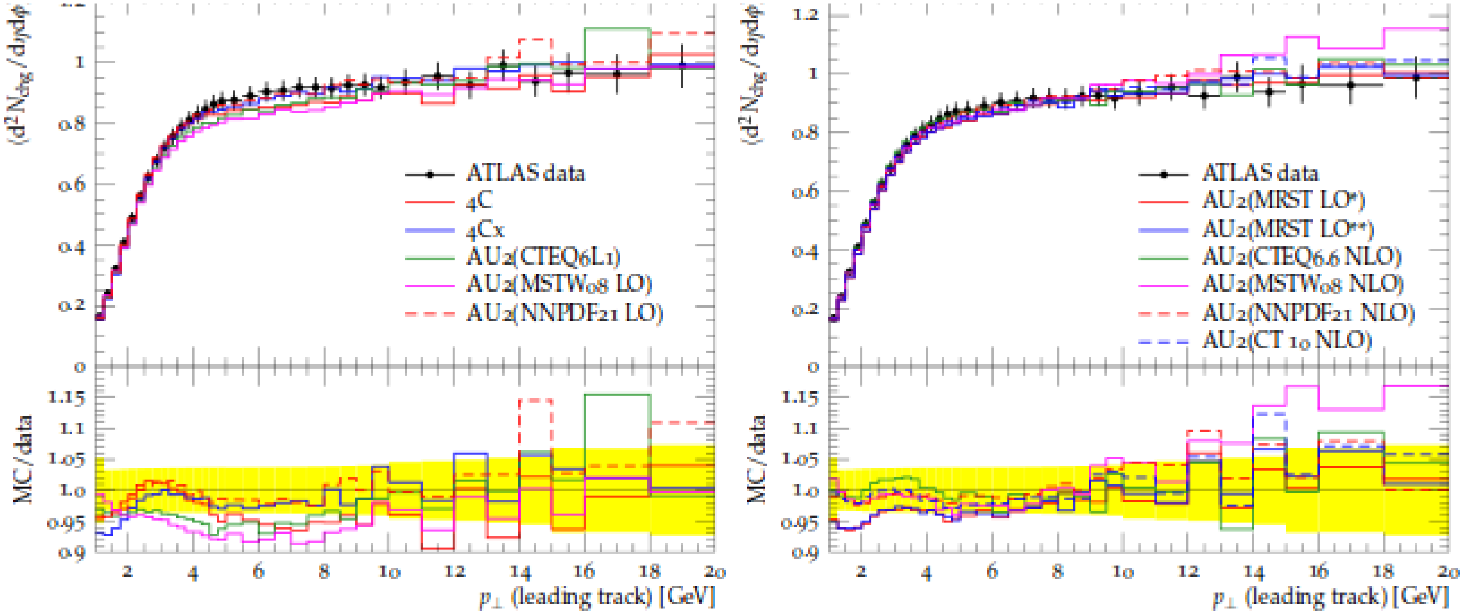
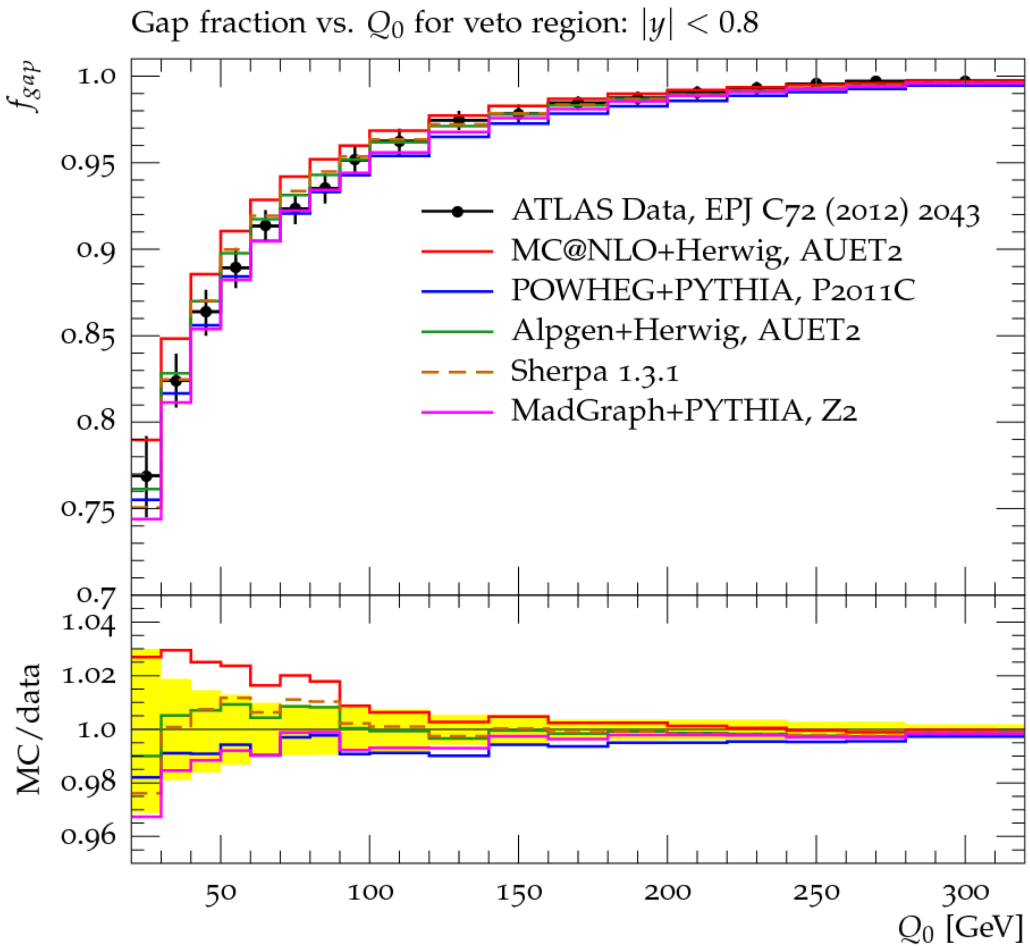
UE



Tuning: rapidity gap fraction in ttbar events

Ttbar: Rapidity gap fraction

- Measure fraction of top events (di-lepton channel) without additional jets with $p_T > Q_0$ within the rapidity range



Gap fraction vs. Q_0 for veto region: $|y| < 0.8$

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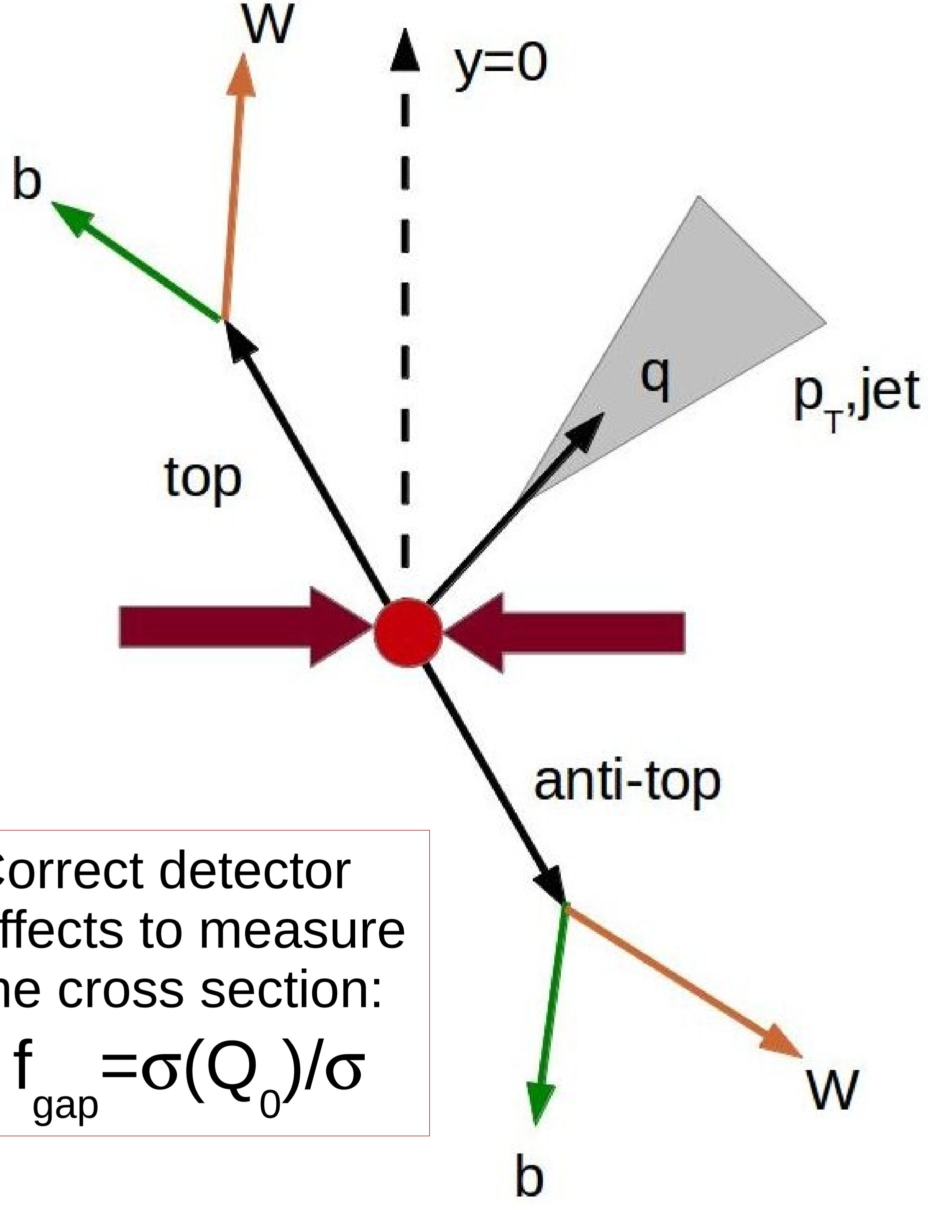
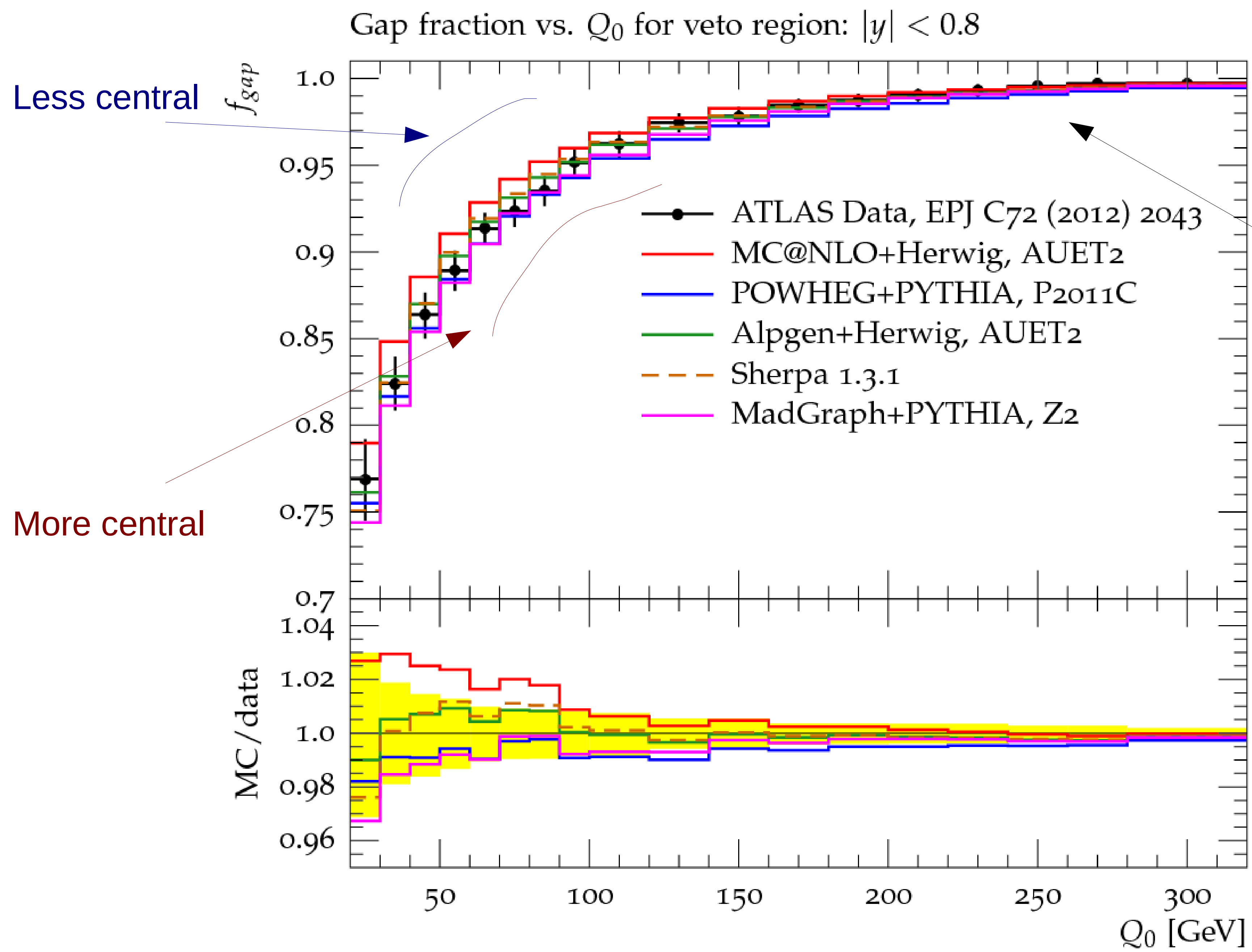


Correct detector effects to measure the cross section:

$$f_{gap} = \sigma(Q_0)/\sigma$$

Rapidity gap fraction: Interpretation



Less central

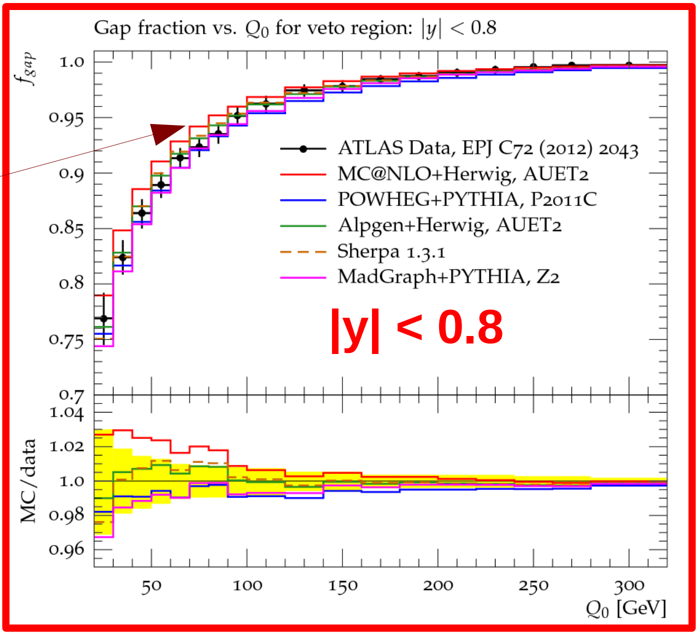
More central

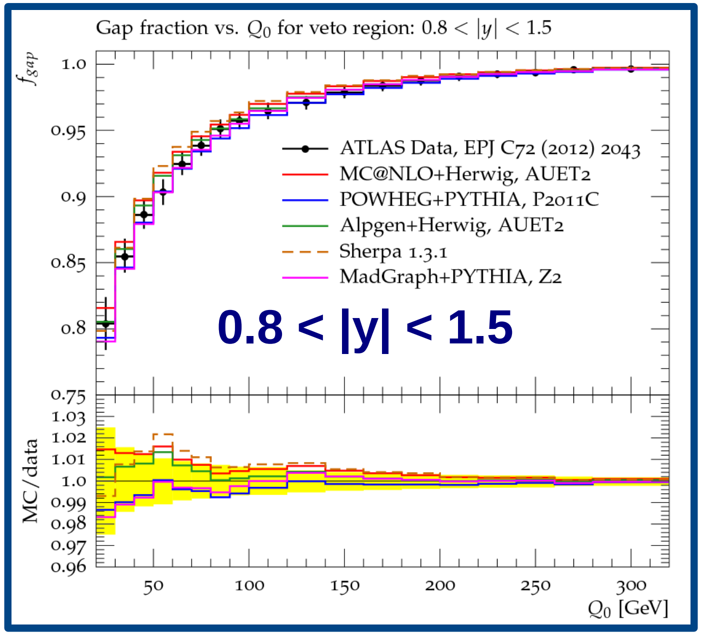
As the p_T cut increases, the fraction tends to 1

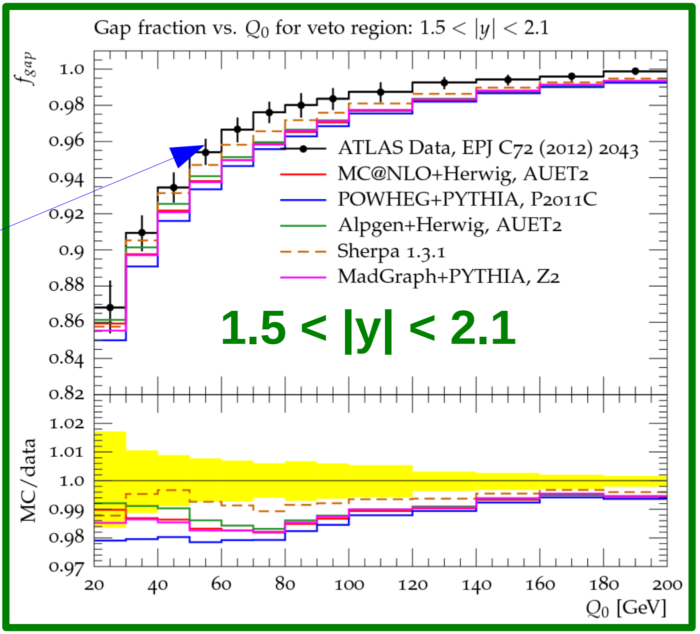
Rapidity gap fraction: Results

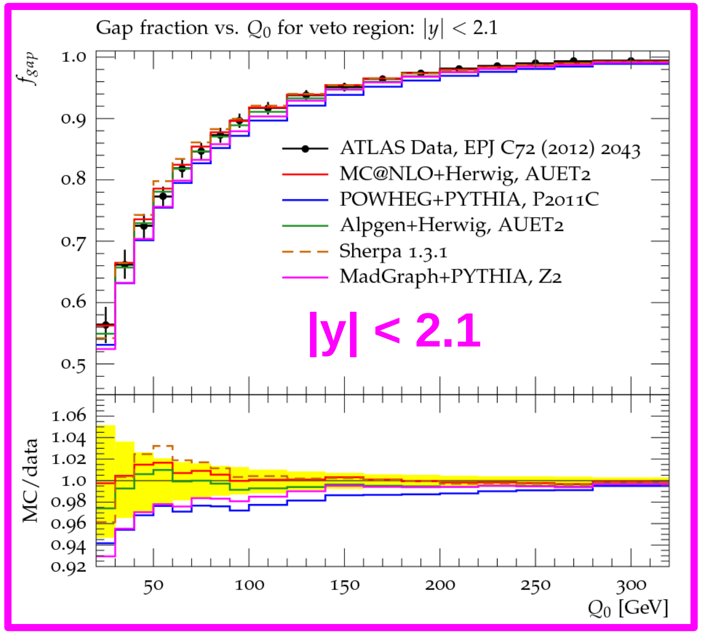
MC@NLO produces fewer central jets

All MC generators produce too much activity

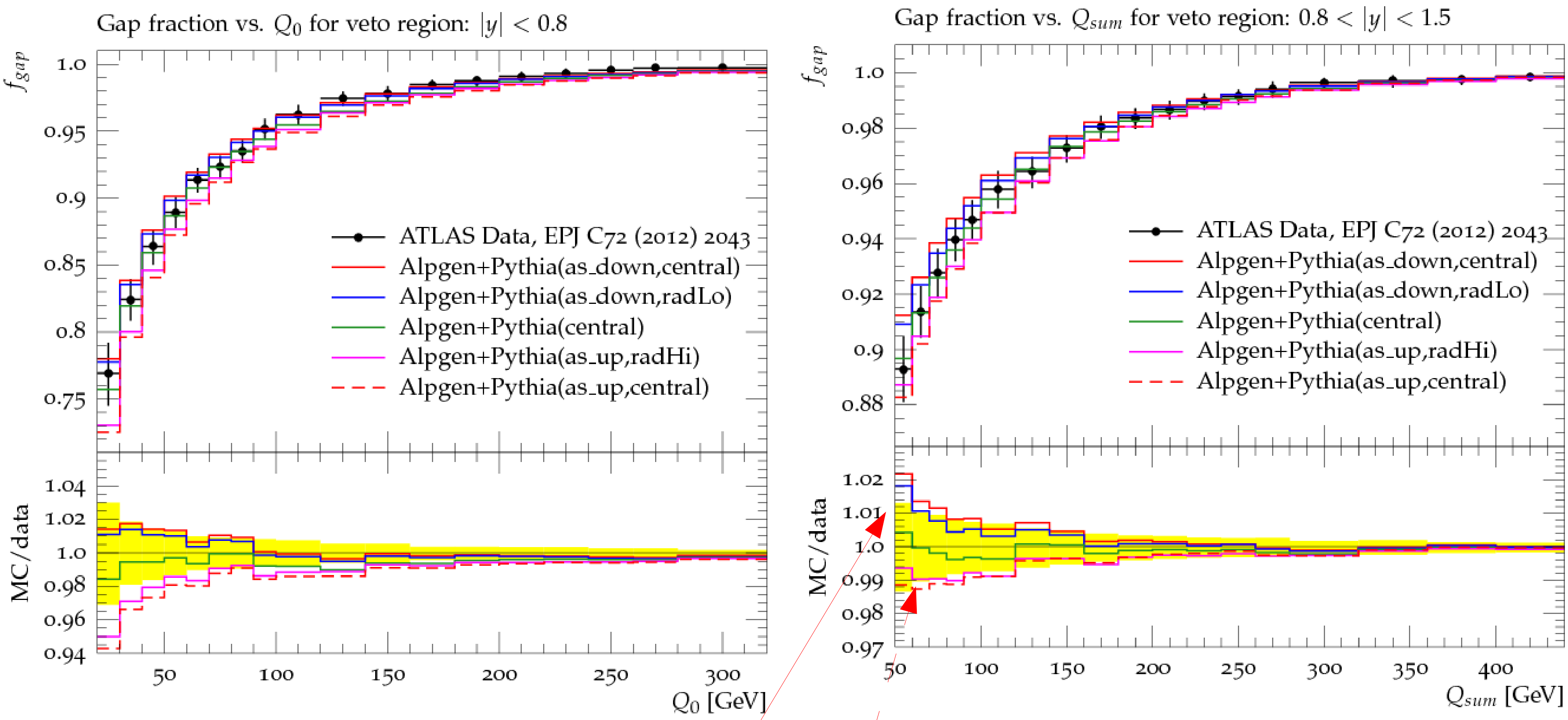








Rapidity gap fraction: Effect of α_s



The measurement constrains the ISR

ttbar is a very important process: ATLAS task force dedicated to improving its description in terms of matching, α_s, PDFs, etc.

Tuning: observables sensitive to Z-p_T

Tunes to observables sensitive to Z-p_T

"Example ATLAS tunes of PYTHIA8, PYTHIA6 and POWHEG to an observable sensitive to Z boson transverse momentum"

ATL-PHYS-PUB-2013-017

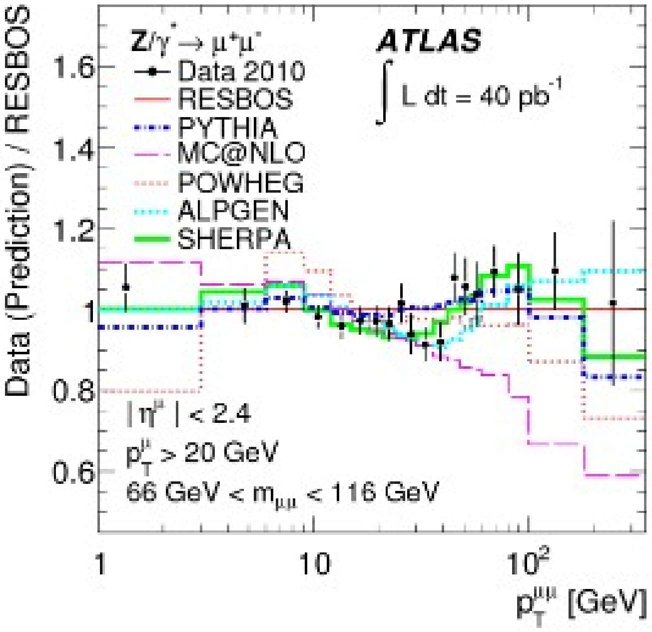
- New tunes to improve the Monte Carlo description of vector boson production
- 4 MC generators:
  PYTHIA8, POWHEG+PYTHIA8, PYTHIA6, POWHEG+PYTHIA6
- Professor tune to Z ϕ^*_η → leptons angular correlation observable sensitive to Z p_T, validation against a large variety of related observables from Tevatron and LHC
- New methodology in POWHEG+PYTHIA8 configuration settings

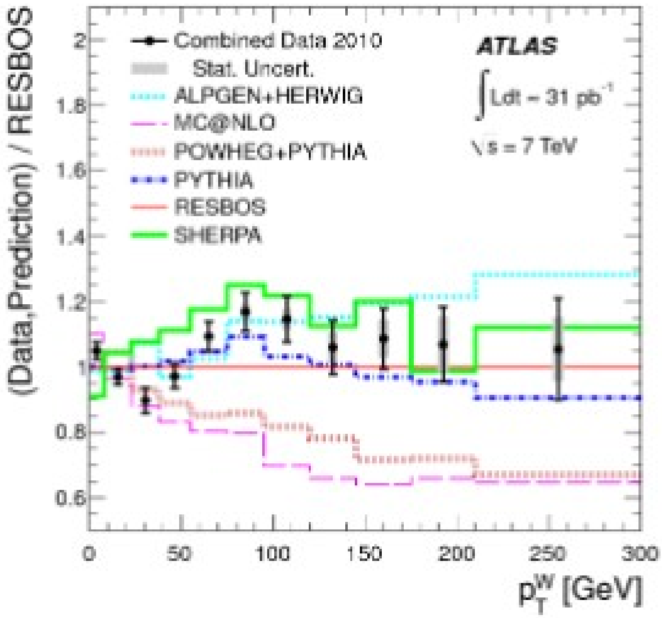
- PoWHEG and Pythia were tuned together

- α_s in the shower matched to that used in PoWHEG (not by default the case)

Z-p_T tuning: Motivation

- Z p_T spectrum provides insight into
  - ISR QCD radiation in the parton shower models
  - Proton remnants recoil → intrinsic k_T
- $Z \rightarrow l^+l^-$, ($l = e, \mu$) provides a clean signature, no QCD FSR, precise measurement down to low pt recoil ~2 GeV
- Improve the modelling of low p_T vector boson
  - → Affects acceptance of lepton p_T cuts in W, Z measurements
  - Crucial for W mass measurement
  - Important for W, Z inclusive cross sections for constraining the PDFs

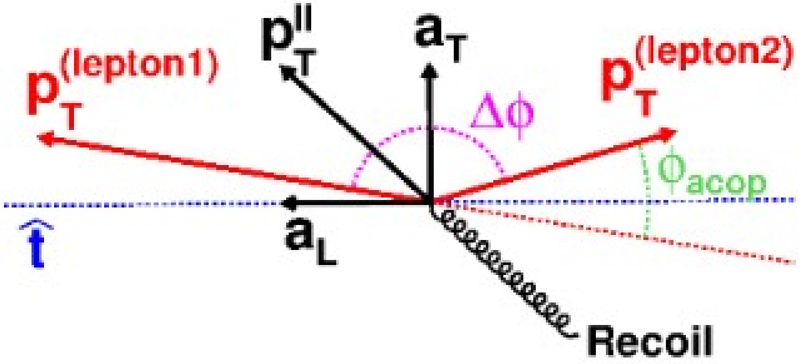




First Z p_T tunes: Rick Field's Tunes AW, DW

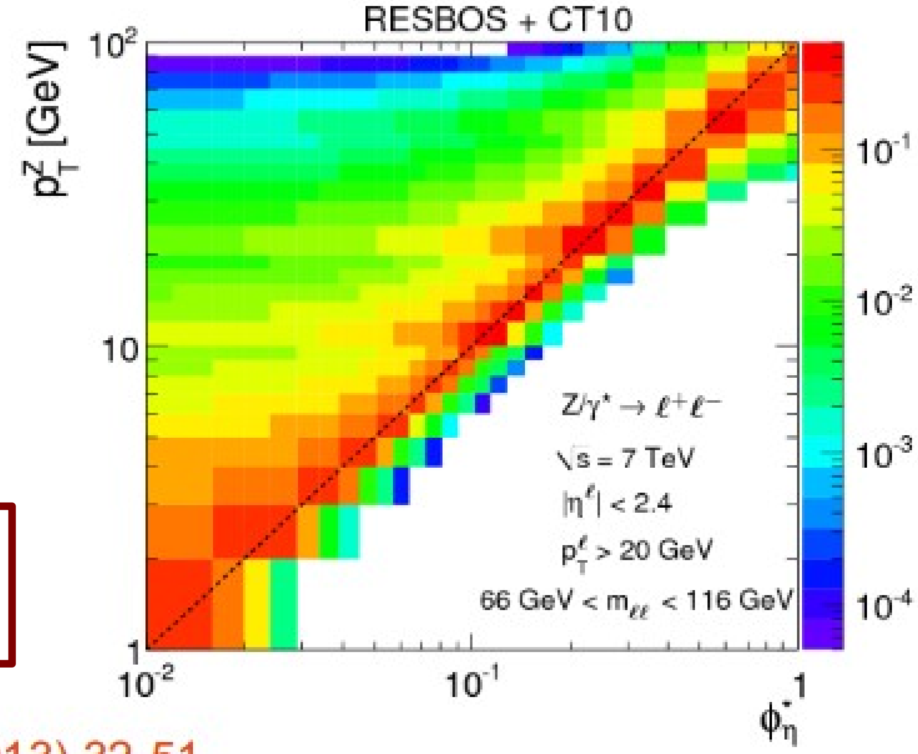
Pythia6

Z-p_T tuning: the ϕ^*_η observable



$$\phi^*_\eta = \tan(\phi_{acop}/2)\,\sin(\theta^*_\eta)$$

- Z ϕ^*_η is strongly correlated to Z p_T
  → $\phi^*_\eta \sim p_T^Z / M_{ll}$
- Ideal for probing the low Z p_T region
- ATLAS Z ϕ^*_η 2011 data is more sensitive to tuning parameters than ATLAS Z p_T 2010 data
- Situation may change if Z p_T data gets more precise



Phys. Lett. B 720 (2013) 32-51

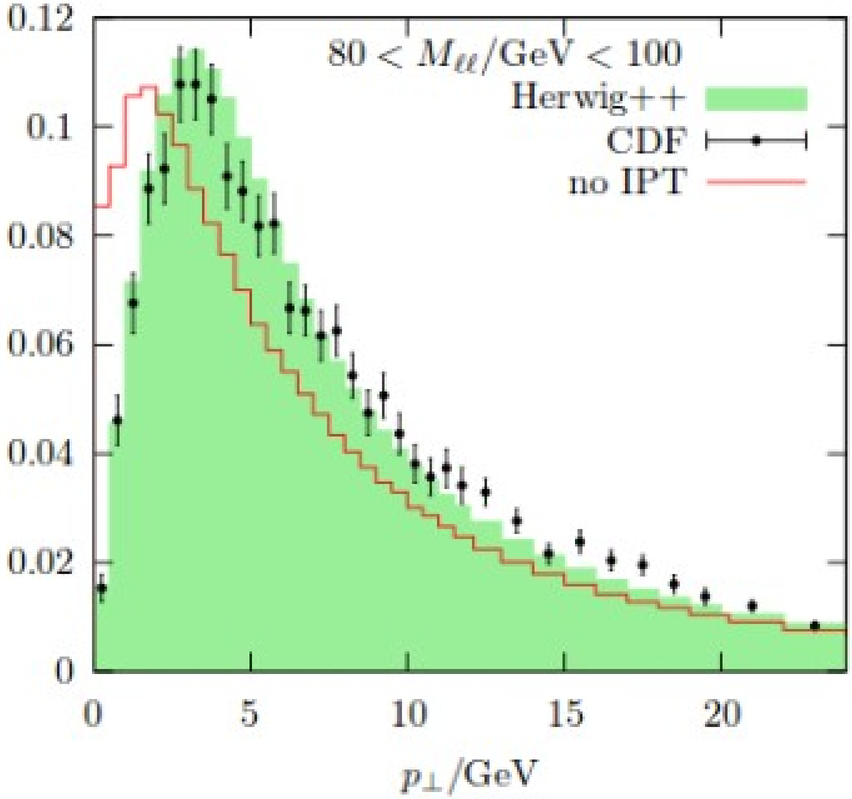
Z-p_T tuning: Monte Carlo parameters

- Parton remnants
  - Intrinsic (or primordial) k_T

- Initial state radiation (ISR) shower and matrix element (ME)
  - ISR cut-off
  - NLO ME real radiation cut-off
  - ISR α_s scale factor on evolution scale
  - ISR $\alpha_s(M_Z)$

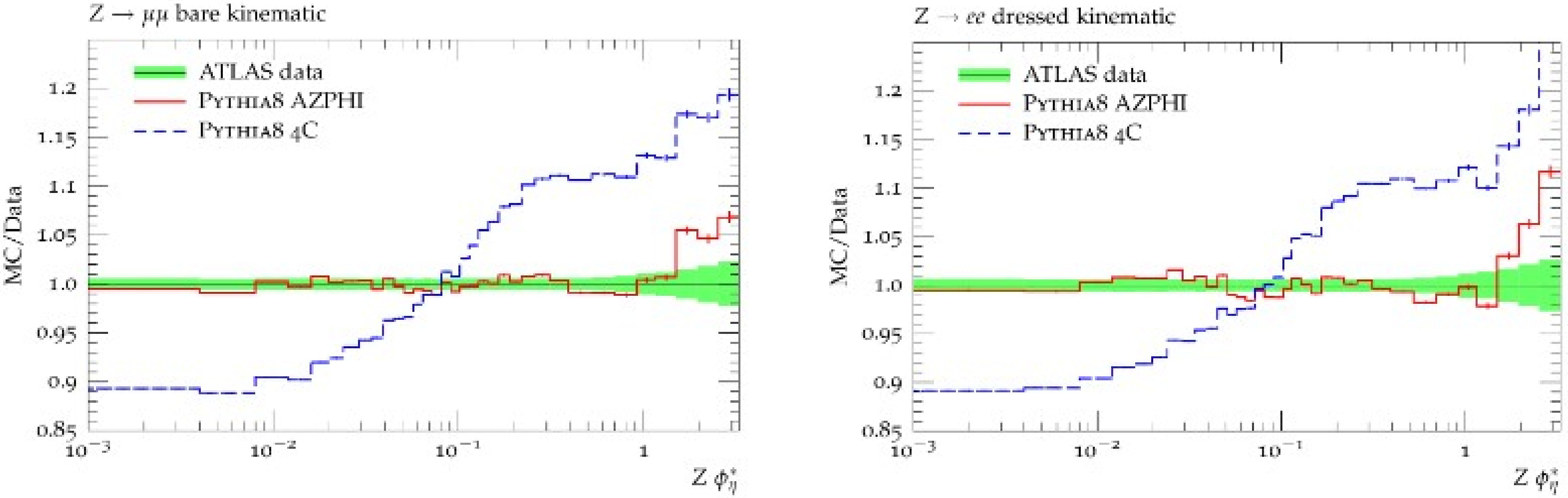
- multi-parton interaction (MPI)
  - MPI cut-off

Effect of switching off intrinsic k_T in HERWIG++



JHEP 0806:001,2008

Z-p_T tuning: PoWHEG + Pythia results



Parameter	Pythia8 setting	Variation range	AZPHI	4C
Primordial kt	BeamRemnants:primordialKThard	1.0 – 2.5	1.73	2.0
ISR $\alpha_s(M_Z)$	SpaceShower:alphaSvalue	0.120 – 0.140	0.124	0.137
ISR cut-off	SpaceShower:pT0Ref	0.5 – 2.5	0.63	2.0
MPI cut-off	MultipartonInteractions:pT0Ref	1.5 – 2.5	2.22	2.085

Matching (ME - PS)

LO vs NLO

- The LO parton shower generators cannot predict the radiation of one or more hard jets (among other things), but do well in soft collinear regime
- Use NLO matrix elements to improve description of the hardest jet
- LO matrix elements with higher legs to improve description of many hard jets
- Combine all these?

Matching issue

- E.g. Z+ 2jets
  - PS: Z+1 jet + shower
  - Multileg: Z+2 jets; then shower from each leg

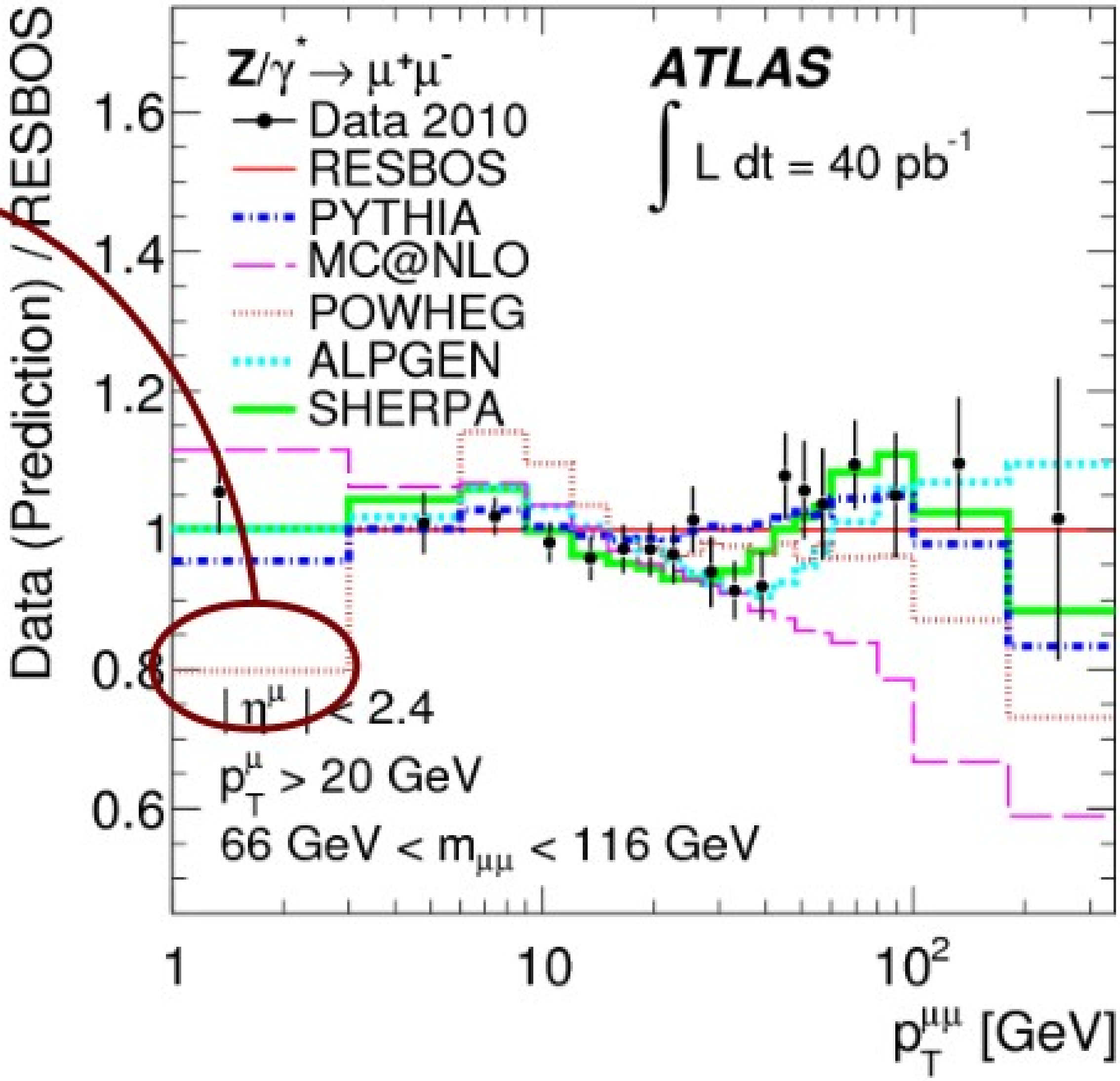
Double counting!

PoWHEG provides a scale (SCALUP) that is an indication of where the shower should take over from the perturbative calculation

- What should be this scale?
- Imperfection in transition region

POWHEG+PYTHIA: low Z-p_T mis-modeling

- POWHEG+PYTHIA6 underestimates the data at very low Z p_T ~2 GeV
- Same issue for POWHEG+PYTHIA8
- A simple tune of intrinsics k_T and ISR parameters does not bring the MC to the data

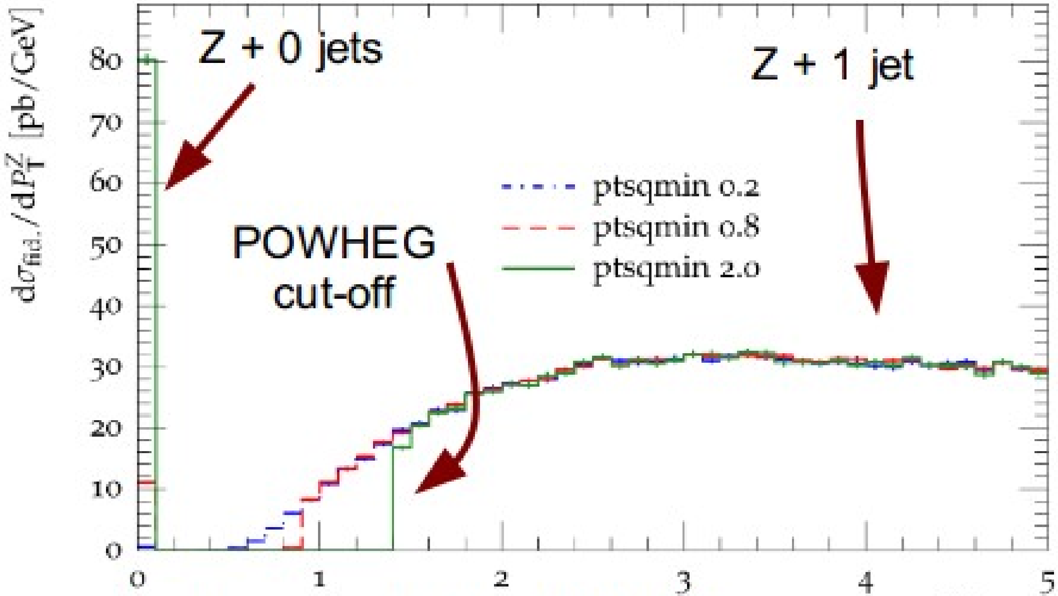


Improve the tuning using the matching ME-PS parameter → ptsqmin (next slide)

Matching POWHEG+PYTHIA: ptsqmin

→ Essential to understand the interplay between POWHEG NLO ME and PYTHIA PS

- POWHEG generates inclusive Z events at NLO, including the first emission of QCD radiation.
- The cut-off for the minimum p_T of the first emission is implemented as a steerable parameter "*ptsqmin*"



Events generated by POWHEG

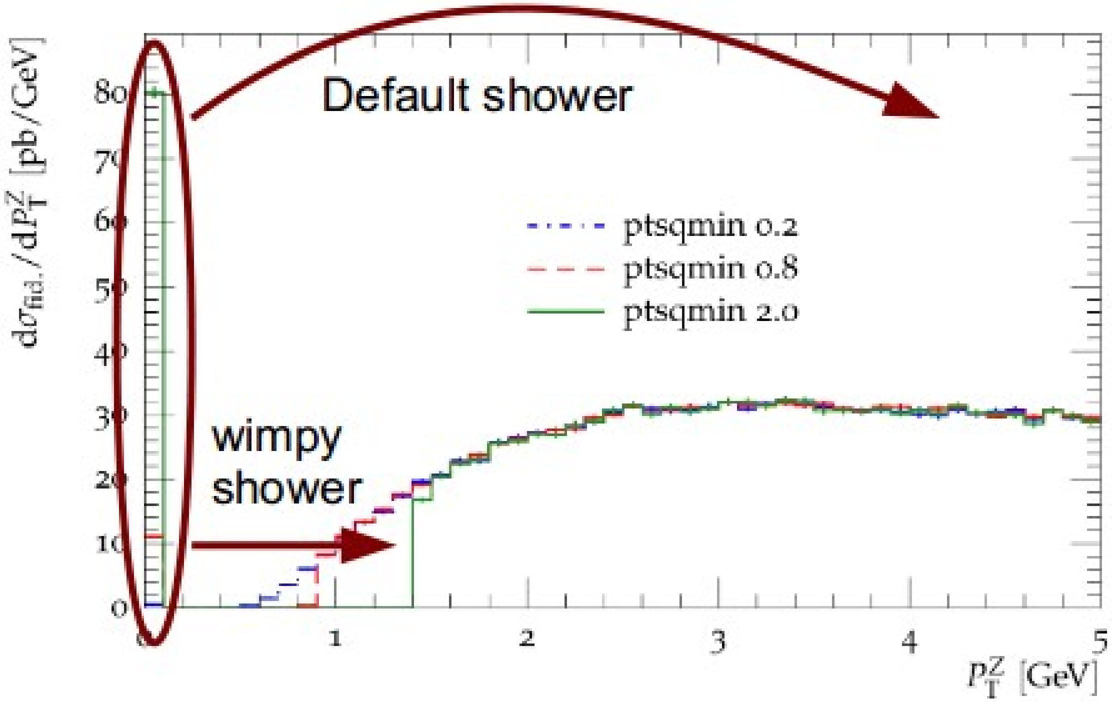
In POWHEG:

- Below the cut-off, Z + 0 jets events are generated with Z p_T = 0 GeV
- For higher values of the cut-off, more events are generated with Z p_T = 0 GeV

Z-p_T determined only by the shower MC (and non-zero at the end!)

Matching POWHEG+PYTHIA ISR shower

- Default PYTHIA8 setup ISR shower setting:
  PYTHIA8 shower the Z + 0 jet events up to the kinematic limit
  → no events below the POWHEG cut-off
  → very low Z p_T mismodeling
- “wimpy” ISR shower setting:
  Z + 0 jets are showered up to the POWHEG cut-off (ptsqmin)
  and fill the space below the POWHEG cut-off

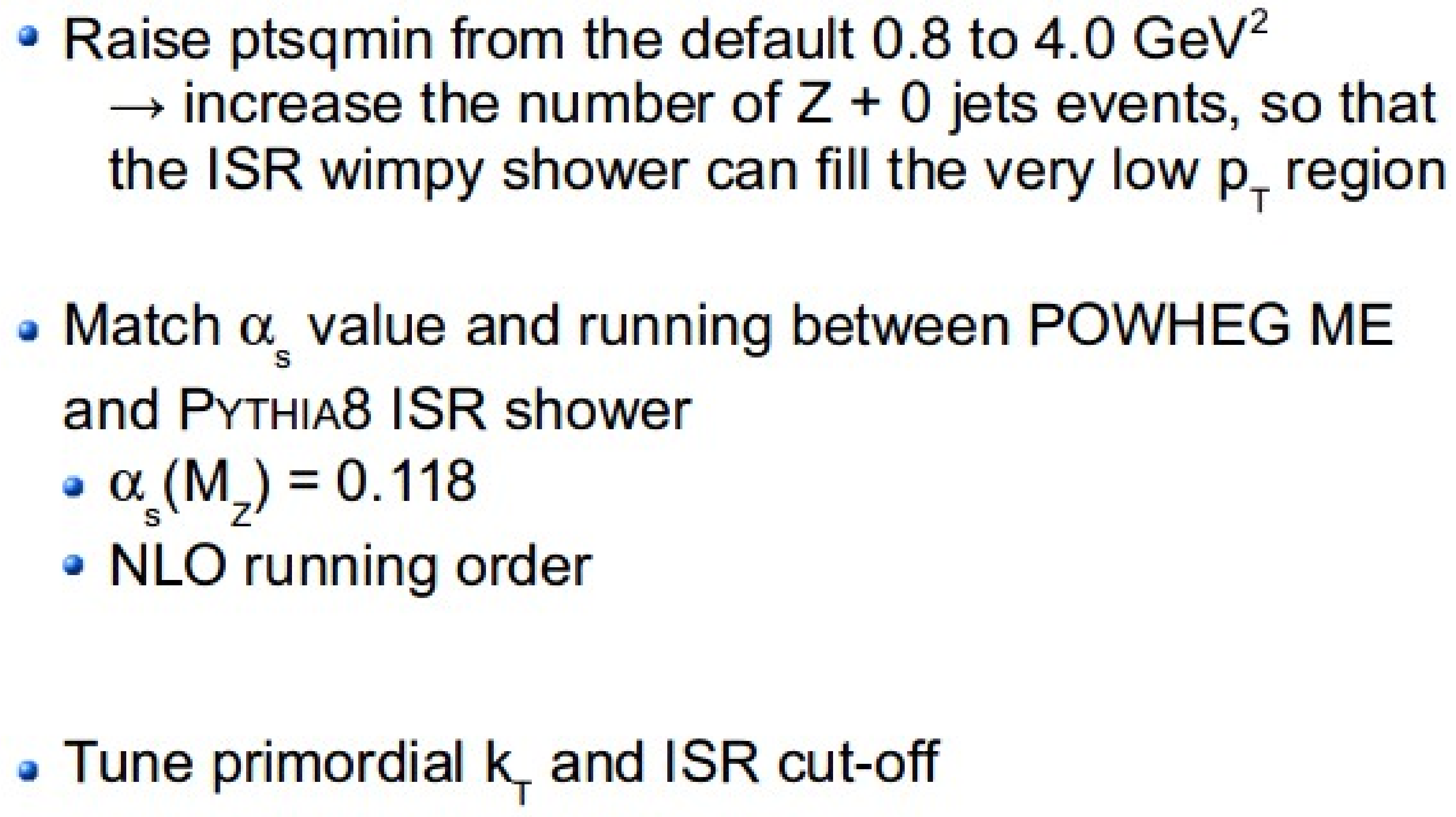


In POWHEG 1-jet events:

-) Pythia does not shower up to the kinematic limit

-) it showers only up to the SCALUP value

POWHEG+PYTHIA8: Configuration

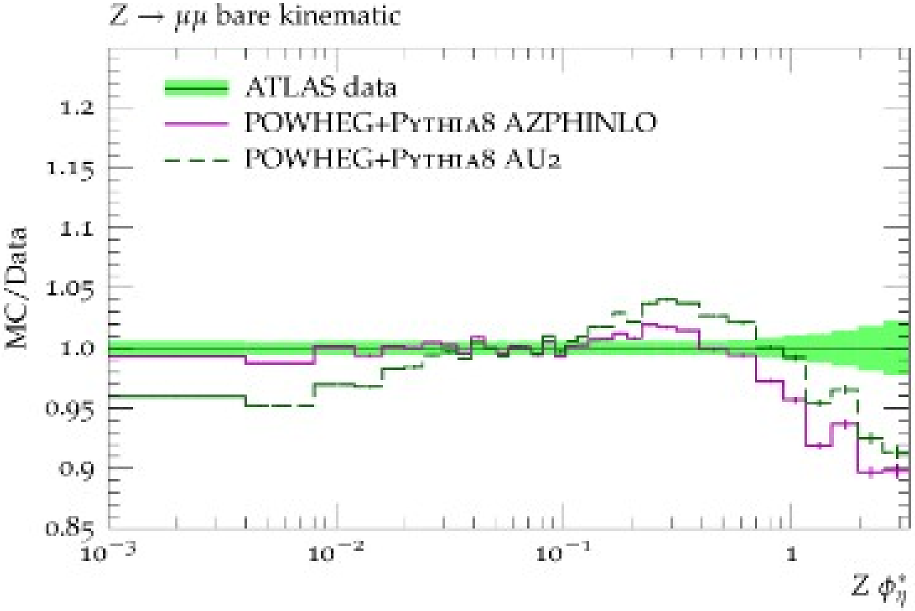


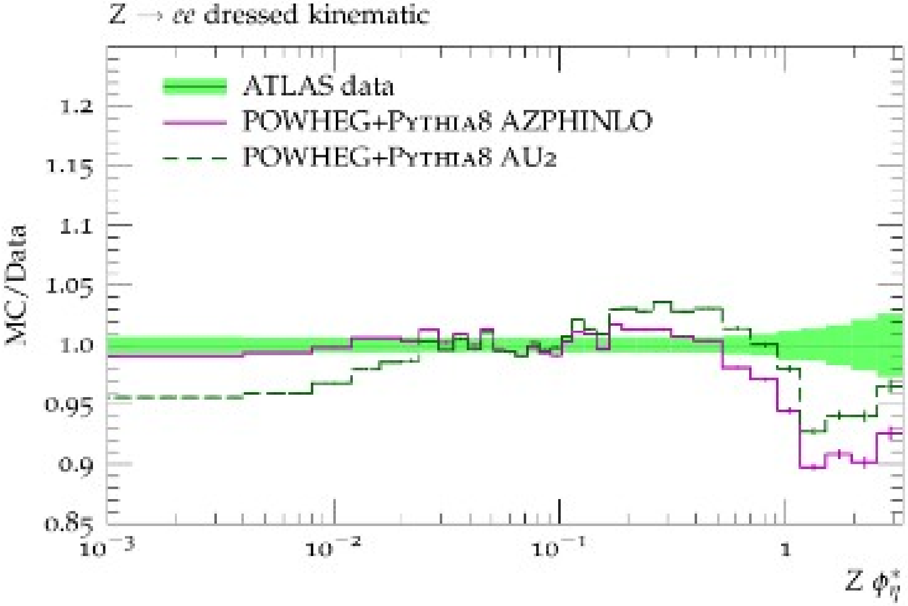
- Raise ptsqmin from the default 0.8 to 4.0 GeV^2
  → increase the number of Z + 0 jets events, so that
  the ISR wimpy shower can fill the very low p_T region

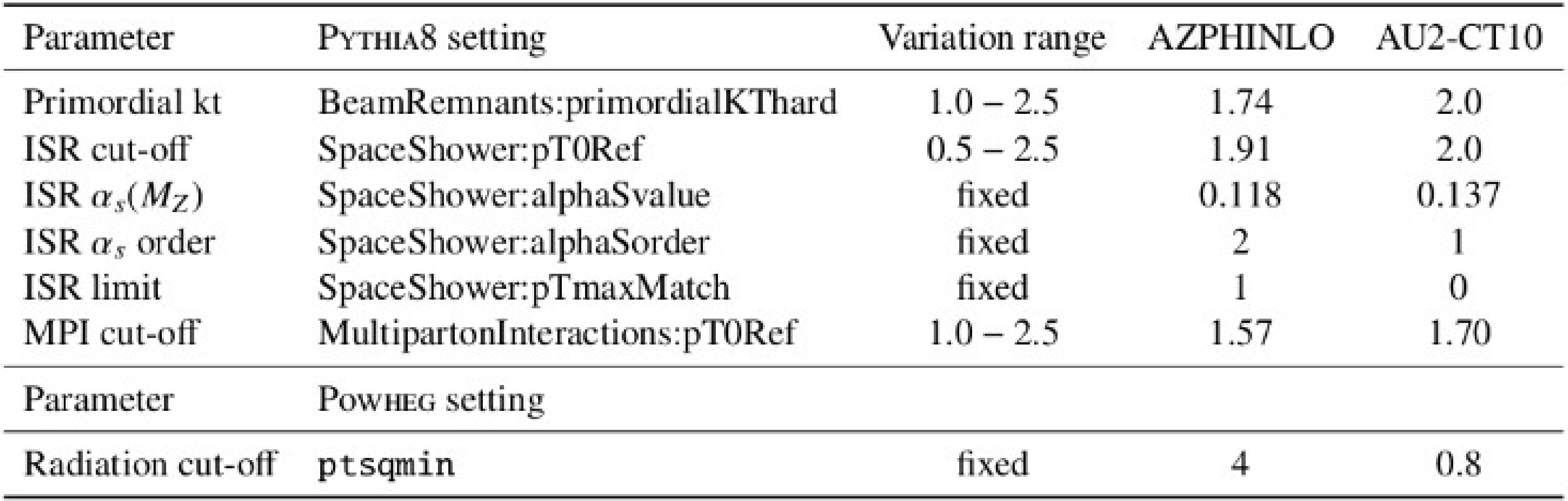
- Match α_s value and running between POWHEG ME and PYTHIA8 ISR shower
  - $\alpha_s(M_Z) = 0.118$
  - NLO running order

- Tune primordial k_T and ISR cut-off

POWHEG+PYTHIA8: Tuning and results

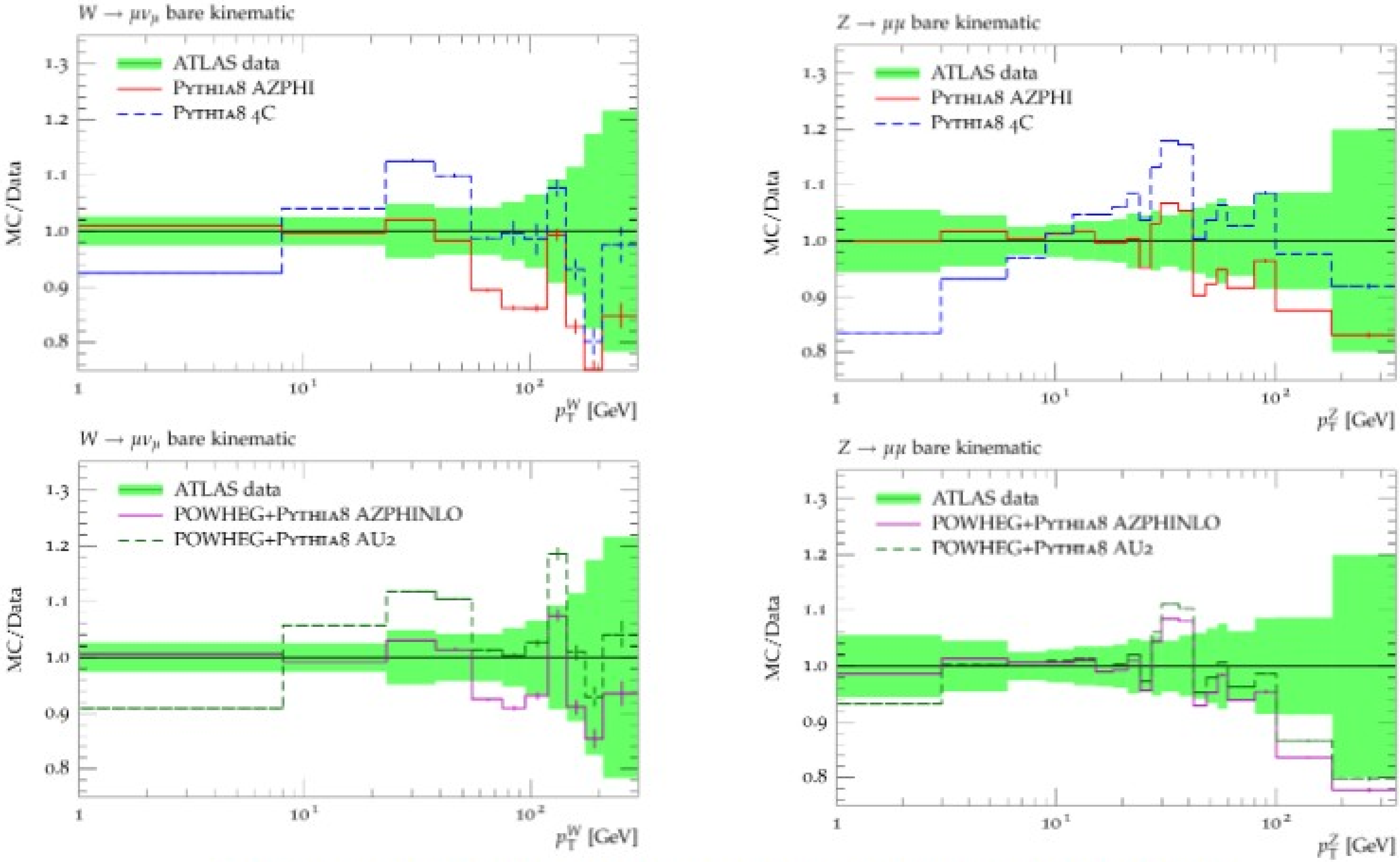






Parameter	PYTHIA8 setting	Variation range	AZPHINLO	AU2-CT10
Primordial kt	BeamRemnants:primordialKThard	1.0 – 2.5	1.74	2.0
ISR cut-off	SpaceShower:pT0Ref	0.5 – 2.5	1.91	2.0
ISR $\alpha_s(M_Z)$	SpaceShower:alphaSvalue	fixed	0.118	0.137
ISR α_s order	SpaceShower:alphaSorder	fixed	2	1
ISR limit	SpaceShower:pTmaxMatch	fixed	1	0
MPI cut-off	MultipartonInteractions:pT0Ref	1.0 – 2.5	1.57	1.70
Parameter	**POWHEG setting**			
Radiation cut-off	`ptsqmin`	fixed	4	0.8

ATLAS W, Z-p_T after tuning



- Tune validation against other sensitive observables
- Tuning results consistent with W p_T, Z p_T observables

Other issues

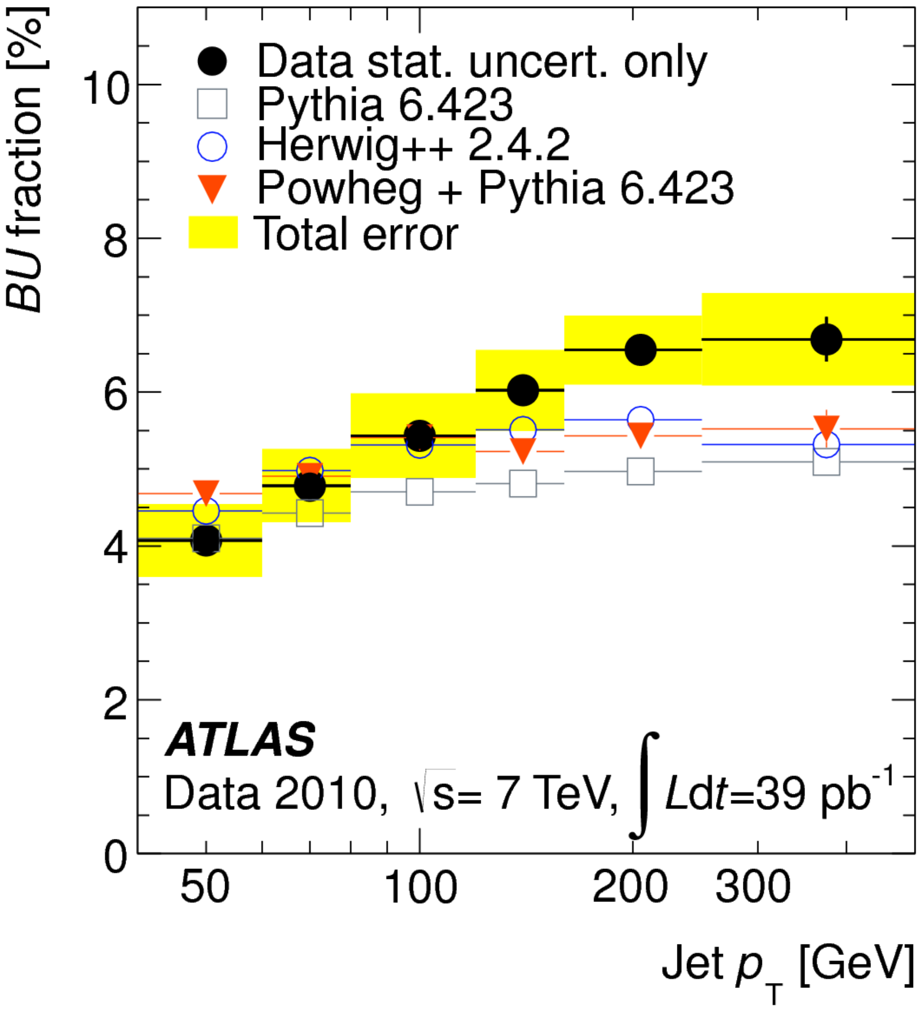
Heavy Flavor

- HF modeling could be a very important issue for run 2 physics output
  - Needed by many searches/measurements (very good handle for background suppression)
  - Overlap removal for b/c produced in ME and PS
    - Some generators have internal tool (Sherpa)
    - In other cases developed by us (not clean, but works)
  - Branching fractions can be different for different generators
    - working on unified tool (EvtGen)

ATLAS task-force in place to study HF issues

HF production from showers not well constrained / modeled

Eur. Phys. J. C (2013) 73:2301



The Devil is in the details

Heavy flavor and generator features

- Studied HF content (at hadron-level) for different Alpgen and Sherpa samples
- Too many HF in Sherpa NLO (massless treatment)
- Big difference in treatment of massless c-quarks in Alpgen and Sherpa
- In the massive treatment (massive b- and c-quarks) very similar results for Alpgen and Sherpa

Tau polarisation

- p_T of tau decay products (excluding neutrinos) harder when no tau polarisation considered

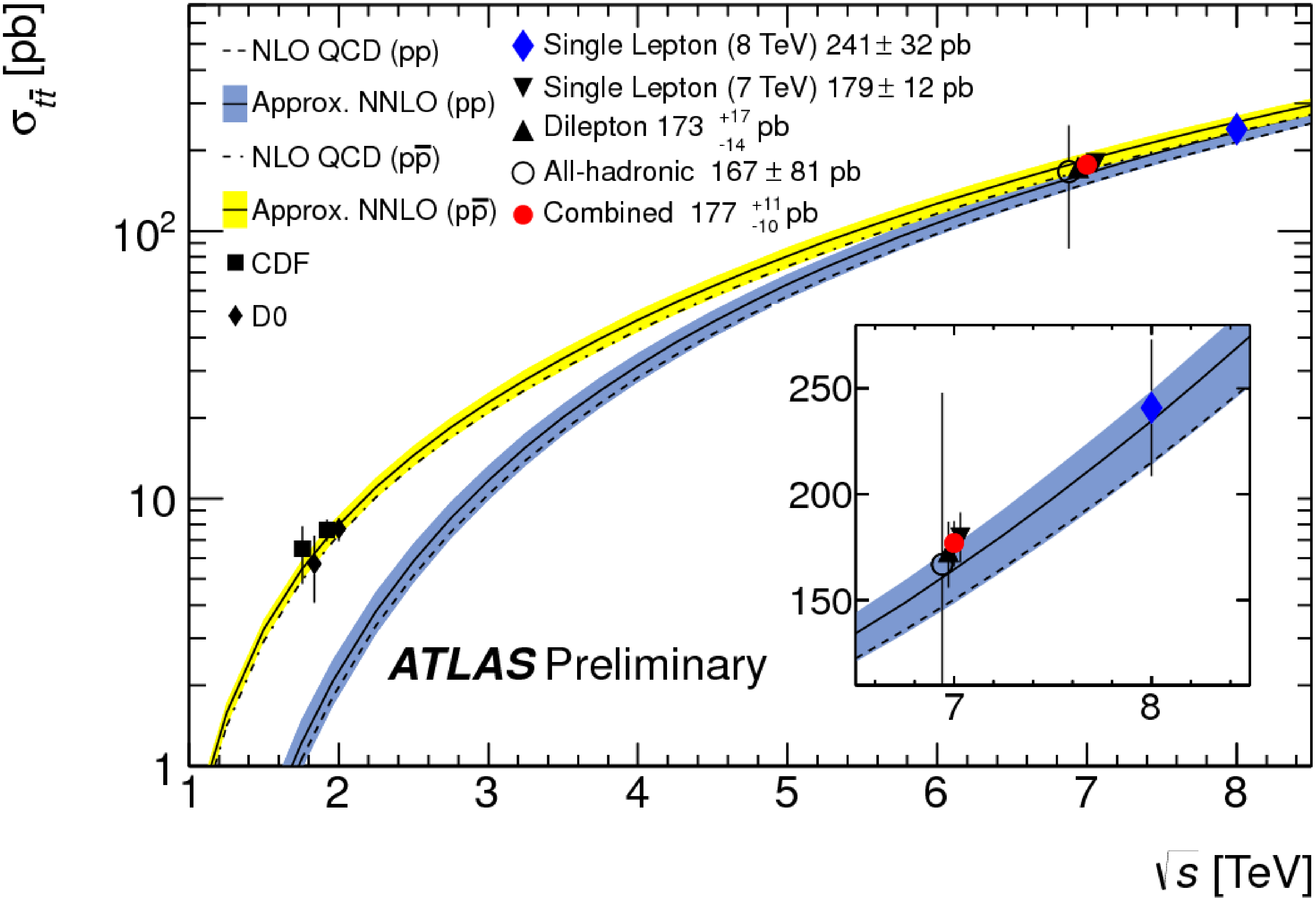
Conclusion

- With the Run2 we will have completely new data (a new LHC era starting)
- A lot of efforts needed to provide proper MC estimates for signal and backgrounds at 13 (14) TeV
- The experiments did put a lot of effort in tuning and understanding data/MC discrepancies
  - Some times very basic handling (scaling, re-weighting)
    - Mostly satisfactory, but not always 100% correct
- Need to take advantage of the full available dataset
  - Already 1000 Z+5 jets events
  - Very nice tools for MC generators comparison and tuning (Rivet/Professor)
  - More and more accuracy needed: Higgs analyses going differential
- MC production is a very expensive and time-consuming activity:
  - We have to ensure that everything is correct from the start (MC generator level)
    - A lot of issues under observation, especially in top and Higgs physics
- Unprecedented effort in simulation technologies
  - Together with the physics results, for sure, one of the big achievement of the LHC

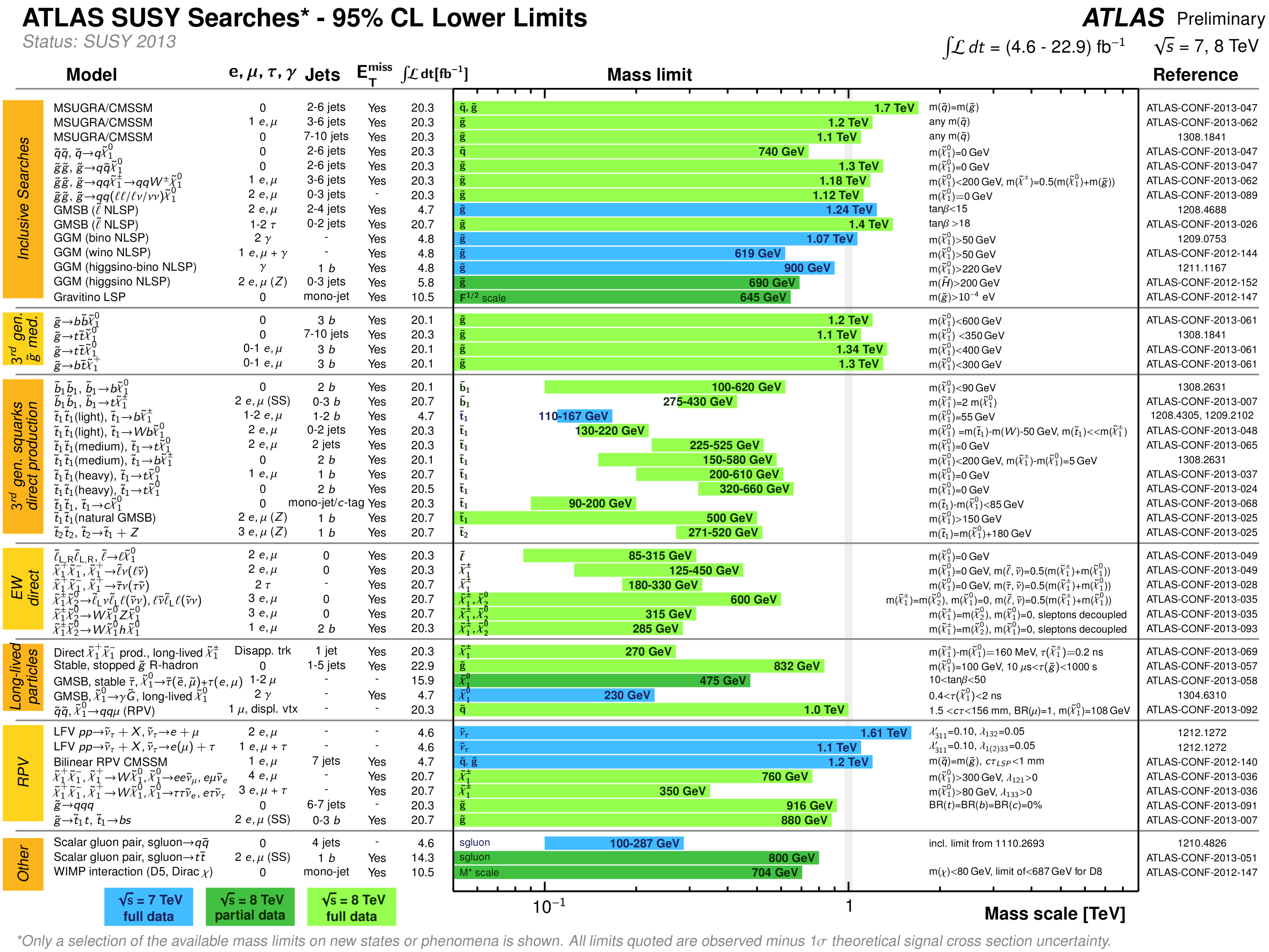
Many thanks for your attention!

Extra material

Top


$\sigma_{t\bar{t}}$ [pb]
- - NLO QCD (pp)
Approx. NNLO (pp)
- · NLO QCD (p$\bar{p}$)
Approx. NNLO (p$\bar{p}$)
CDF
D0
Single Lepton (8 TeV) 241 ± 32 pb
Single Lepton (7 TeV) 179 ± 12 pb
Dilepton 173 $^{+17}_{-14}$ pb
All-hadronic 167 ± 81 pb
Combined 177 $^{+11}_{-10}$ pb
10^2
10
1
1
2
3
4
5
6
7
8
250
200
150
7
8
ATLAS Preliminary
$\sqrt{s}$ [TeV]

SUSY



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int\mathcal{L}\,dt$ = (4.6 - 22.9) fb^{-1} $\sqrt{s}$ = 7, 8 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$		Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	tanβ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$	1.07 TeV	m($\tilde{\chi}_1^0$)>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$	619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	m($\tilde{H}$)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	m($\tilde{g}$)>10^{-4} eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	m($\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	ATLAS-CONF-2013-061
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	275-430 GeV	m($\tilde{\chi}_1^\pm$)=2 m($\tilde{\chi}_1^0$)	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-220 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^\pm$)	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$	225-525 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-200 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$	500 GeV	m($\tilde{\chi}_1^0$)>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$	271-520 GeV	m($\tilde{t}_1$)=m($\tilde{\chi}_1^0$)+180 GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$	85-315 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	125-450 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	180-330 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	600 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	315 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	285 GeV	m($\tilde{\chi}_1^\pm$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	270 GeV	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^\pm$)=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <cτ<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e + \mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$	1.2 TeV	m($\tilde{q}$)=m($\tilde{g}$), cτ_{LSP}<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu$, $e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	760 GeV	m($\tilde{\chi}_1^0$)>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e$, $e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$	350 GeV	m($\tilde{\chi}_1^0$)>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e, μ (SS)	1 b	Yes	14.3	sgluon	800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

$\sqrt{s}$ = 7 TeV full data

$\sqrt{s}$ = 8 TeV partial data

$\sqrt{s}$ = 8 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

MC Production: Simulation

G4 full simulation (335 s /event):

- every stable particle is tracked through the ATLAS geometry
- the list of possible interactions is defined by the physics list: QGSP_BERT as default
- one event takes ~5 minutes → major simulation time spent in calorimeters

G4 full simulation with Frozen Showers (FS) in calorimeters: 25% speed up in mc12 (250 s /event)

- showers are tracked down to very low energy by G4 → stop showering at a threshold and substitute each end particle by a pre-made list of energy deposits
- frozen showers in the forward calorimeters as default in mc11/mc12 including upgrade production

AtlFast-II (AF-II): factor 10 speed up in mc12 (20 s /event)

- parametrise all particles except muons in the calorimeters
    - do not simulate particles except muons in the calorimeter
    - parametrise non-simulated particles before the digitisation step

Integrated Simulation Framework (ISF)

- better integration of full and fast simulation based on sub-detectors and particles

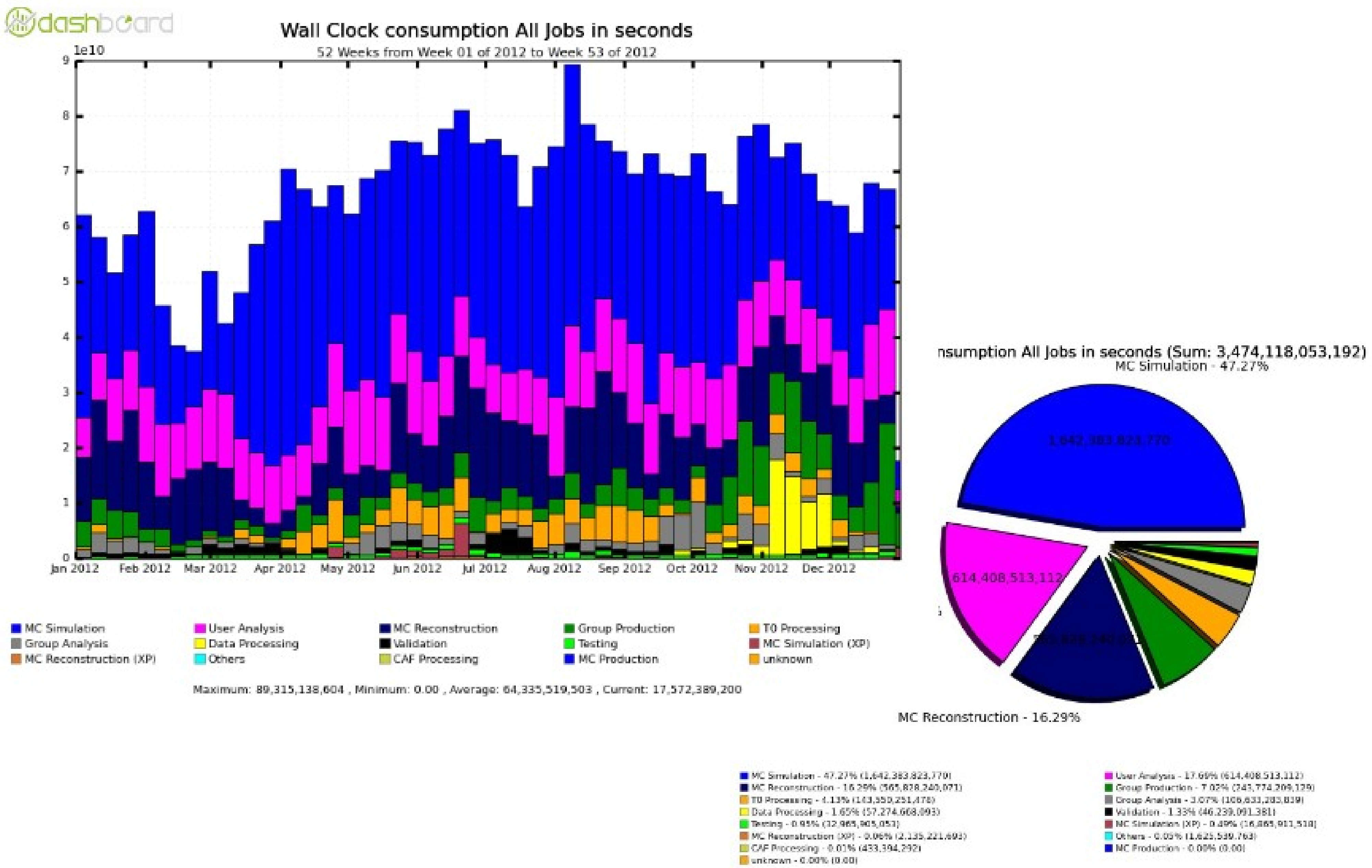
MC Production: Digitisation

- Simulate detector readout
- Simulate pile-up contributions (multiple pp interactions on top of hard scatter event)
- Overlay a number of pre-simulated minimum bias events on each signal event
  - <μ> average number of additional pp collisions
  - fixed <μ> (for performance studies)
  - pre-defined <μ> profile (default for physics samples)
    - sample given <μ> profile over 5000 events
      - small samples should be multiple of 5000 events
  - <μ> re-scaling of MC pile up
    - accounts for the fact that the models of forward particle production are not as well constrained as for central production
- Minimum bias pile-up samples
  - separate into low-Q and high-Q (Q=35GeV) samples to allows for frequent re-use of low-Q events per job and limit re-use of within one sample

MC Production: Campaigns

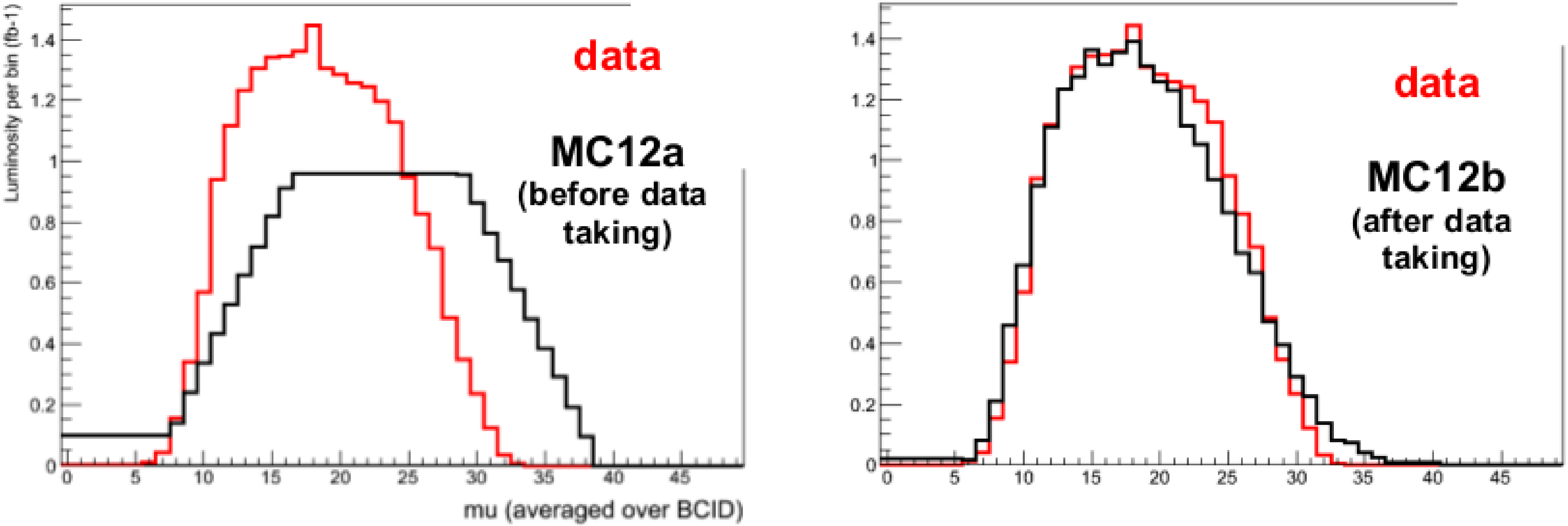
- MC production campaigns correspond to data taking periods with same conditions
  - centre-of-mass energy, detector configuration, conditions, …
- Major MC production campaigns
  - mc11: simulation configuration for 7 TeV in 2011
    - mc11a: digitisation+reconstruction configuration with Pythia 8 pile-up sample, estimated beam spot and pile-up profile based on three run periods
    - mc11b: same as mc11a with updated pile-up profile/conditions based on four run periods and two trigger menus
    - mc11c: same as mc11b with Pythia 6 pile-up sample
  - mc12: simulation configuration for 8 TeV in 2012
    - mc12a: digitisation+reconstruction configuration with Pythia 8 pile-up sample, estimated pile-up profile and beam spot based on 2011 data
    - mc12b: same as mc12a with beam spot and pile-up profile from data
    - mc12c: improved geometry description for precision measurements: simulation based on mc12 and digitisation+reconstruction based on mc12b
- Pythia 8 pile up sample in MC12 is much better description of data than the one in MC11 due to improved tune that uses LHC data as input

MC Production: Grid Resources in 2012



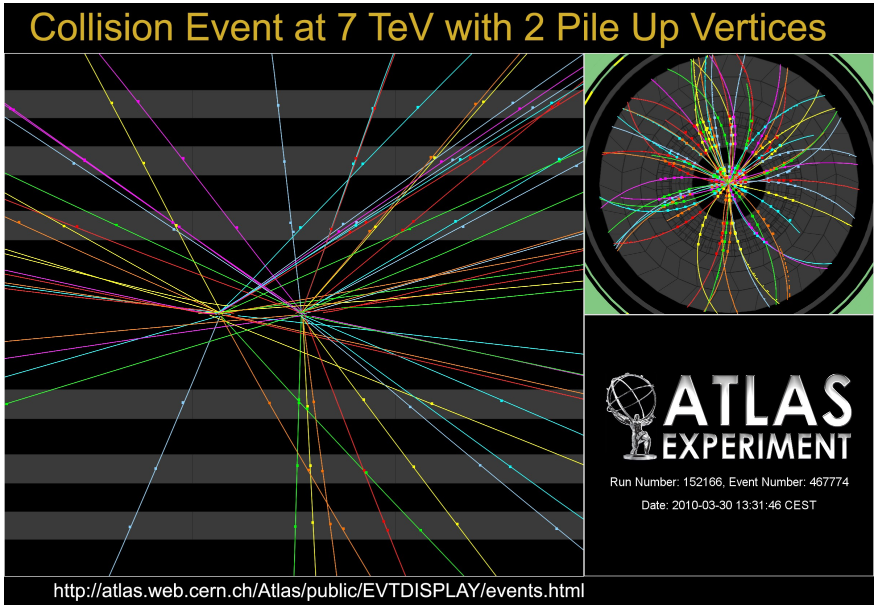
MC Production: Pileup simulation

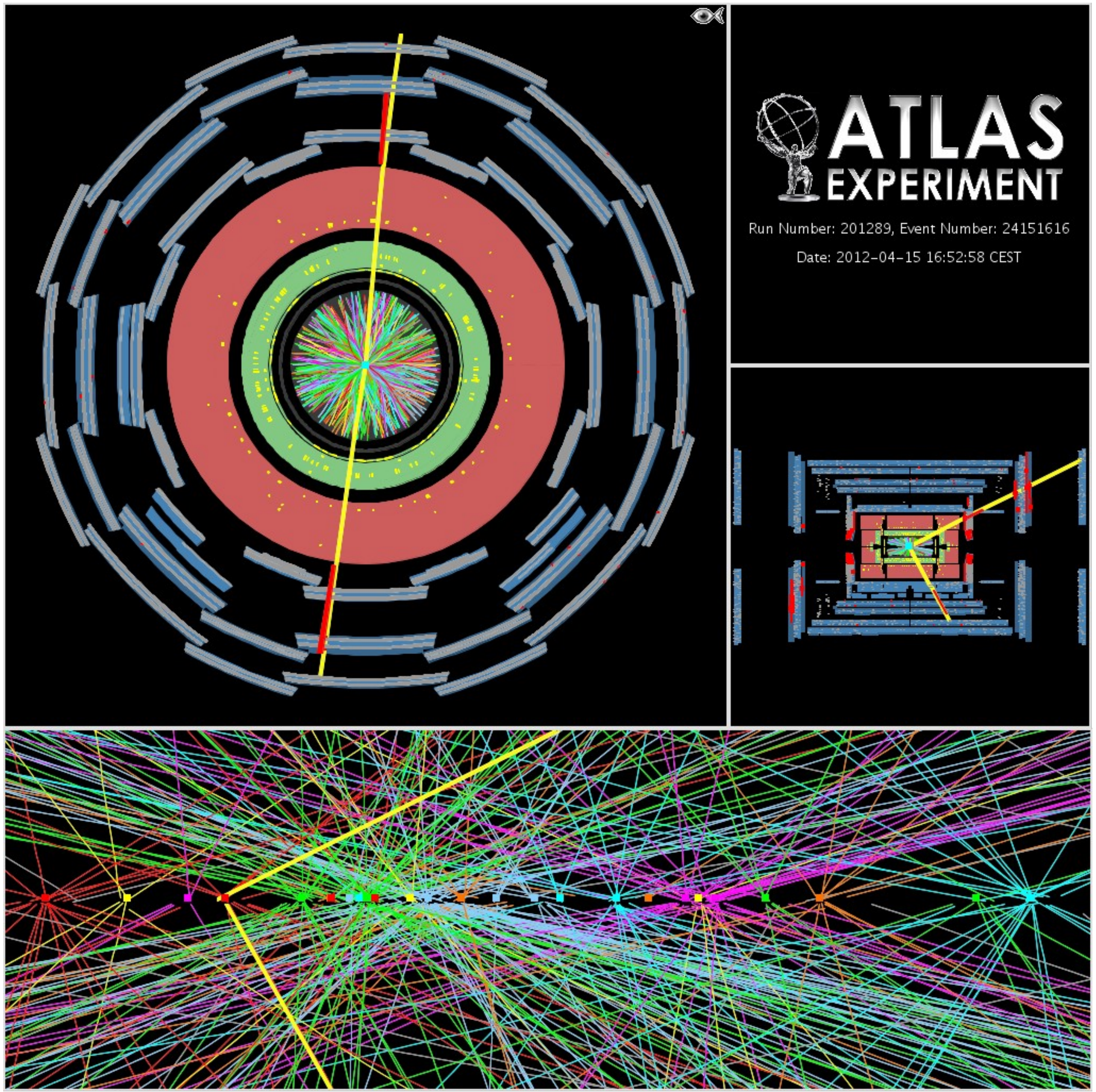
- pile-up profile in MC matched to observed distribution in data if possible



- mc12 pile-up sample configuration
  - <μ> profile samples from 0 to 40, with a mean of <μ>=20
  - 10M low/high-Q (1.5/4.8 TB = 6.3 TB) → 5000/500 events per file
  - 500 events per job: one signal file, 5 low/high-Q files → 4.8 GB of input files per job (100 events per job: one signal file, 1 low/high-Q file → 1.1 GB of input files per job)
  - distribute minimum bias pile-up sample to T1 and larger T2 sites → 0.3-0.4 PB total

Event displays: pile-up





Leptons and MET in QCD events

Prompt (signal) muons and electrons are isolated

- Leptons from heavy flavor decay in jets show activity in a cone around them
- Leptons in jets have a non-zero probability of passing the isolation cut
    - Matrix method mostly used to estimate their contribute (FAKES)

Jets can be mis-identified as electrons or photons

- Very low probability, but very large cross-section
- In the case of $H \rightarrow \gamma\gamma$
    - a fit to the data used as background prediction

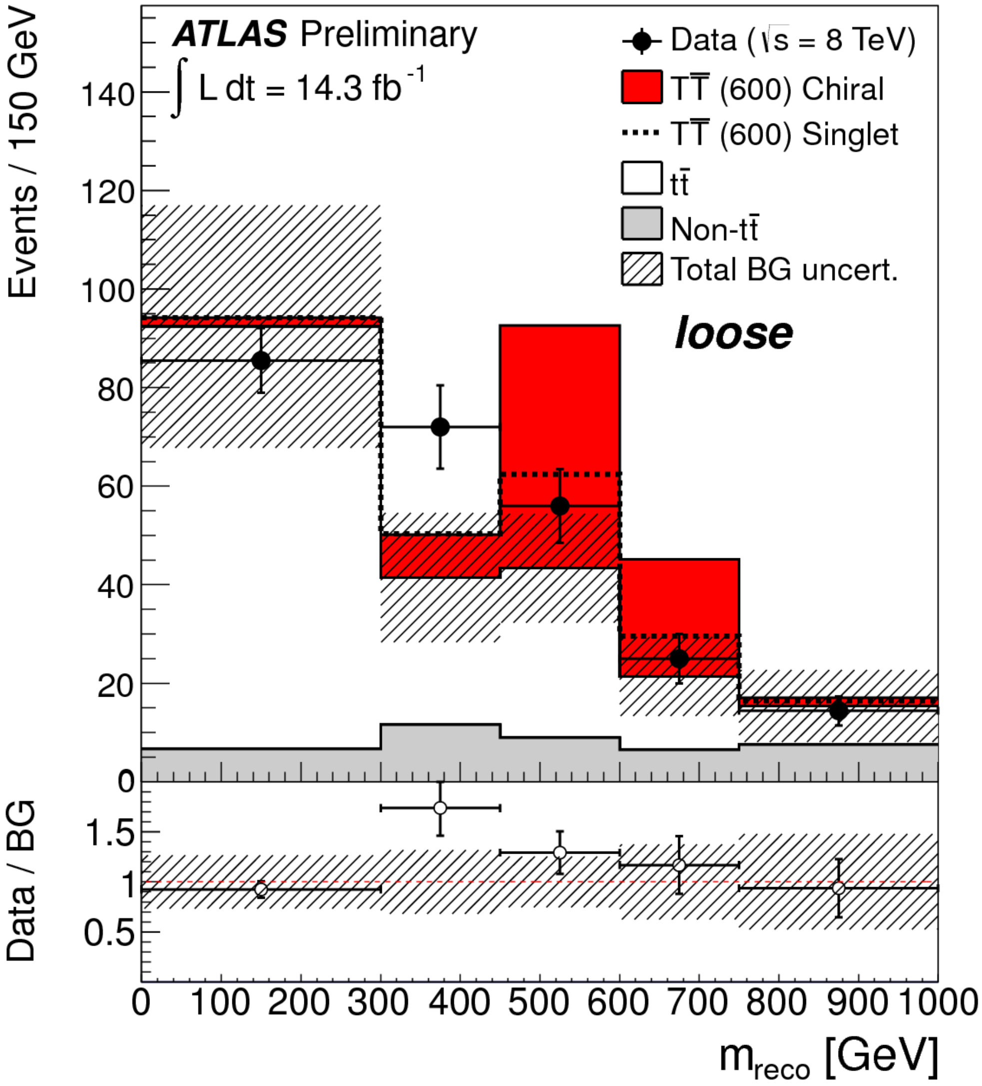
Fake MET due to poorly-measured jets/ jets escaping the detector

- Mostly in the direction of one jet
- Strongly influenced by the pile-up interactions
- In addition, contribute (real MET form heavy flavor decay)

Top as QCD background: tails

- Searches are very often sensitive to tails of ttbar Monte Carlo:
  - High mass tails
  - HT tails
  - Large MET tails
- Often new developments on NLO:
  - Off-shell tops (single-top Wt has only one “off-shell”)
  - ttZ, ttW
  - ttbb, ttcc (see also ttH)

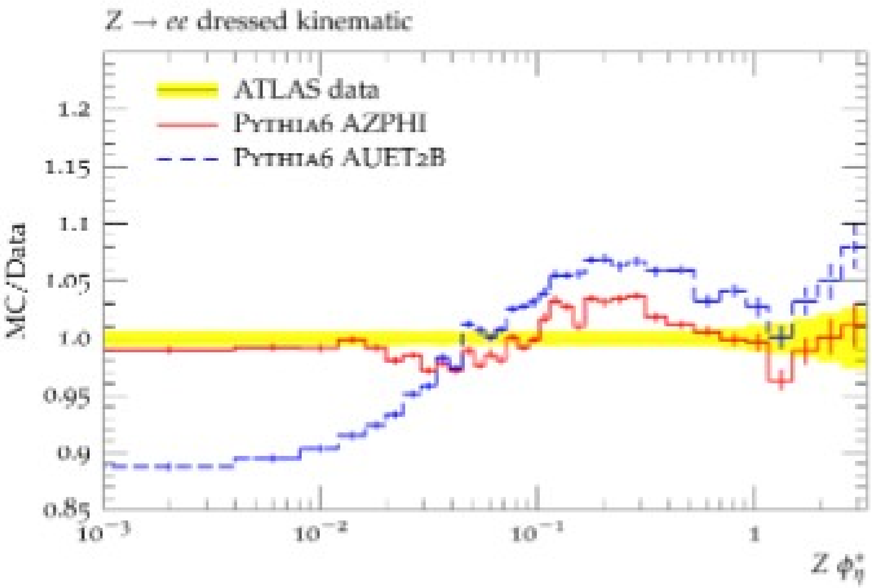
ATLAS-CONF-2013-060

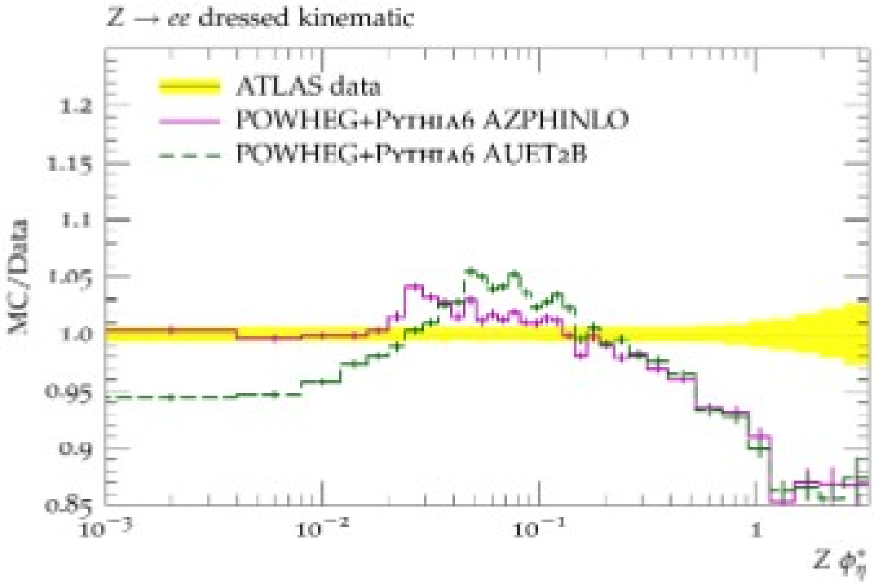


Z-p_T Tune: PYTHIA6 and POWHEG+PYTHIA6

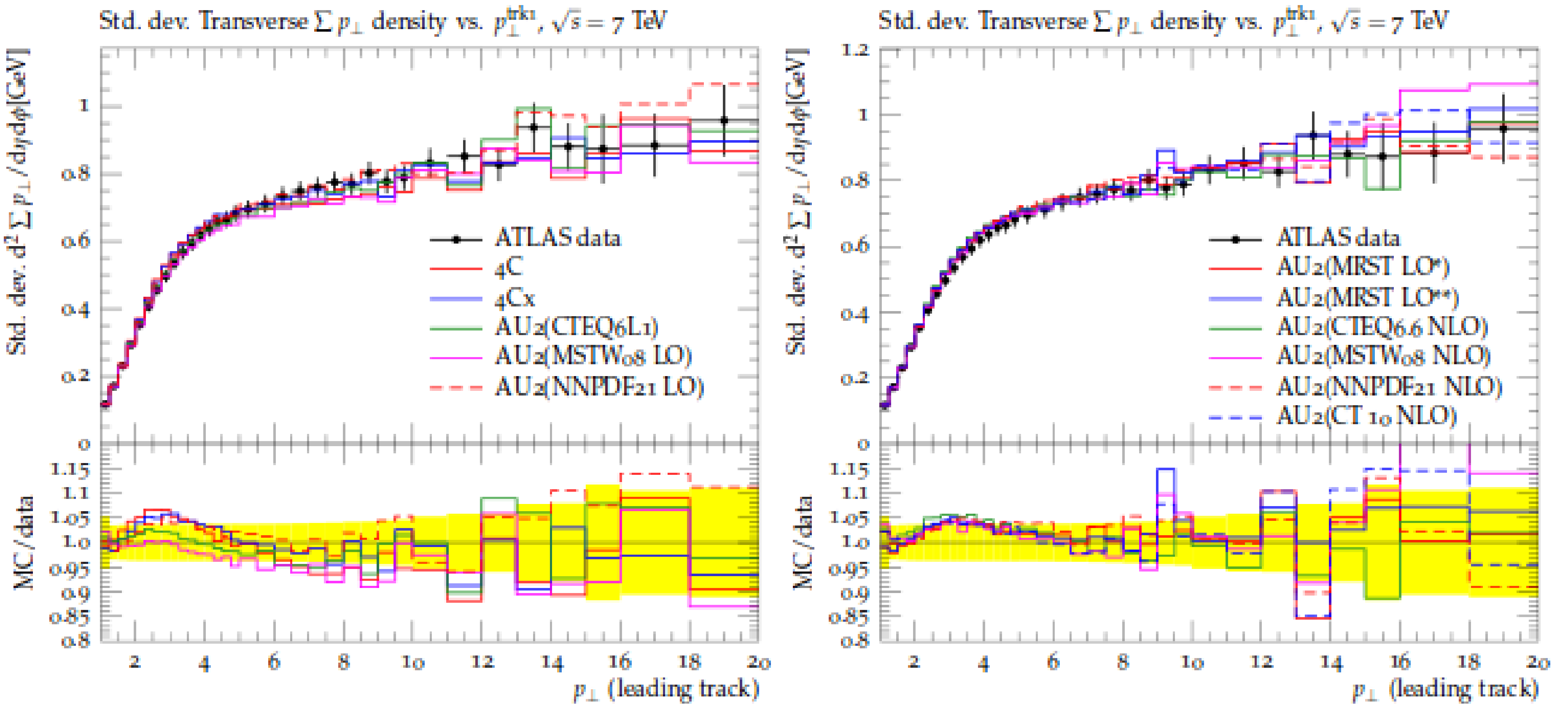
Tuning performed also with PYTHIA6 and POWHEG+PYTHIA6 with some differences

- In PYTHIA6 $\alpha_s(M_Z)$ is not tuned, the default value of Λ_{QCD} already gives reasonable results
- In POWHEG+PYTHIA6 the wimpy shower mode does not effectively limit the shower to *ptsqmin*





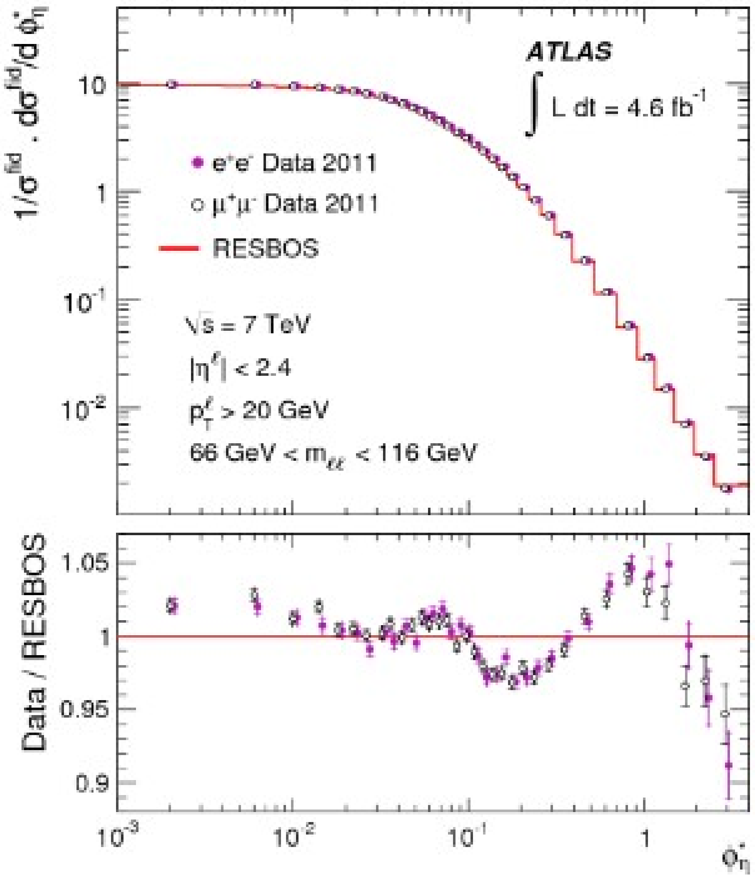
Pythia8 tuning: UE results (2)

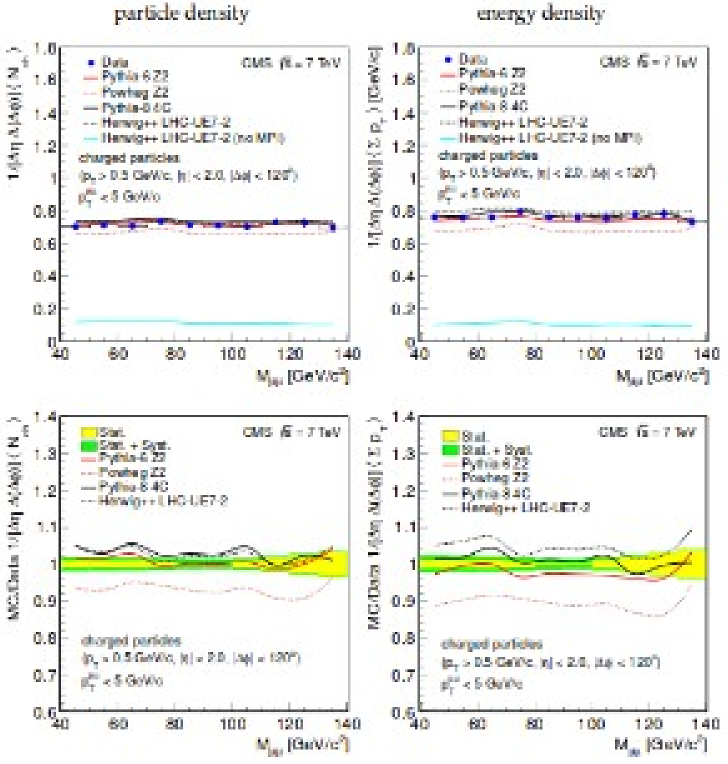


ATL-PHYS-PUB-2011-009

Z-p_T tuning: Strategy and input data

- Tuning based on Professor and Rivet
- Tune ISR and intrinsic k_T to ATLAS Z ϕ^*_η measurement
- Focus on the low Z p_T region:
  Z $\phi^*_\eta < 0.29 \rightarrow$ Z $p_T < 26$ GeV
- Validation against ATLAS W p_T, Z p_T and D0 Z p_T, Z ϕ^*_η





Eur. Phys. J.
C72 (2012) 2080

- Adjust MPI by retuning to CMS Z UE data (only for PYTHIA8 and POWHEG+PYTHIA8)
- Baseline tunes: 4C (PYTHIA8), AU2-CT10 (POWHEG+PYTHIA8), AUET2B (PYTHIA6, POWHEG+PYTHIA6)