QCD at ATLAS: measurements, models, and implications

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Contents

Outline

The intention is to present a selection of QCD results from the first "proper year" of ATLAS activity.

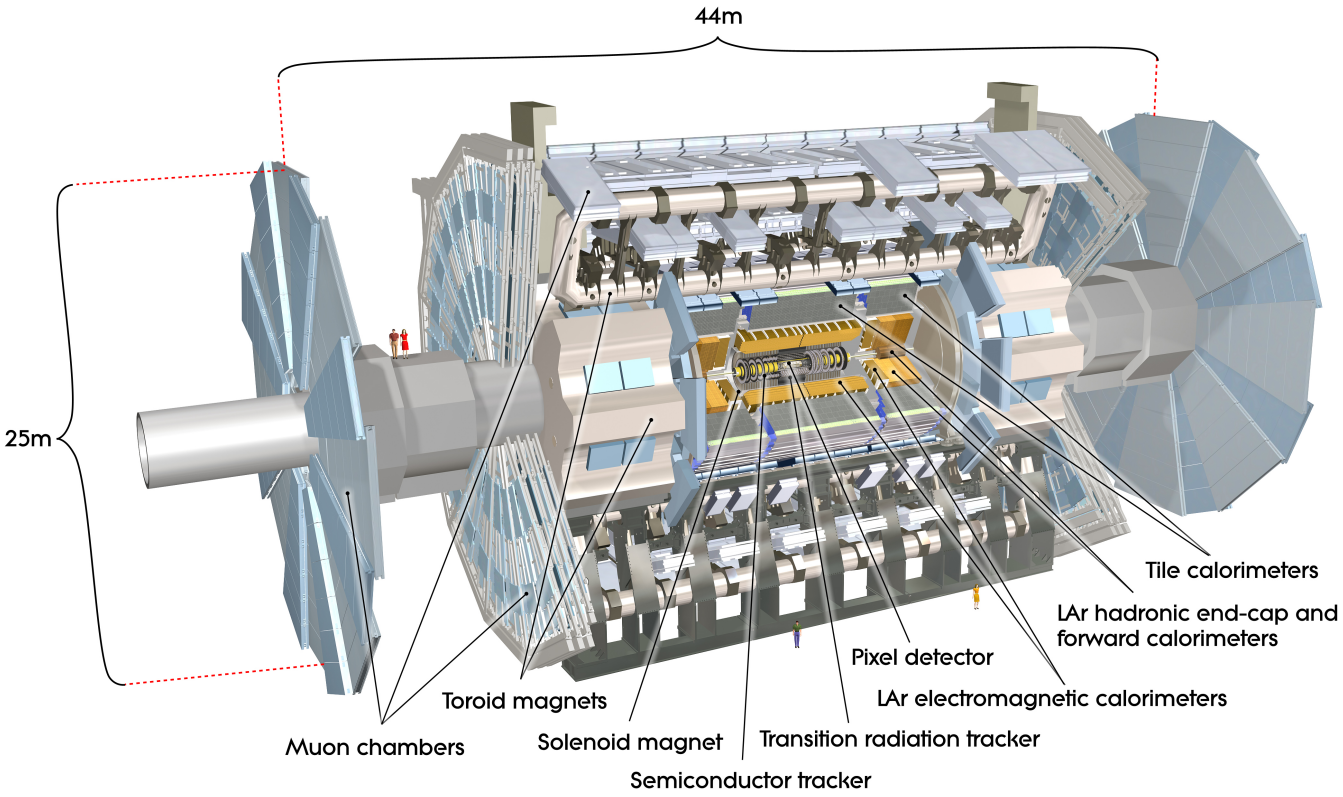
This ranges from very inclusive measurements at 900 GeV to never-seen-before 1 TeV jets – quite a range! Given the scope of the school, I will mainly focus on soft aspects: MPI and intra-jet observables. I will try to avoid too much overlap with CMS (but hey, I'm first...)

My bias is also towards interpretation in terms of Monte Carlo models. Again, hopefully this will provide a distinct perspective rather than duplication!

Not enough room for all sorts of interesting things: in particular, total inelastic cross-section measurement, diffraction-enhanced minimum bias, and heavy ion jet quenching have been elided.

Introduction to ATLAS and MC models

The ATLAS detector

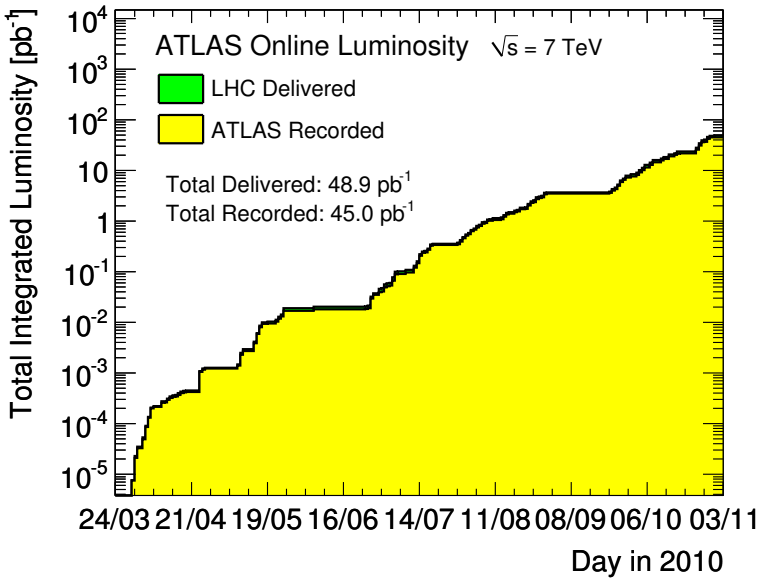


Complementary to CMS in particular: ECAL and mag field configs.

For QCD, LHCb and ALICE have some specific advantages over the GPDs – particle ID, no B field $\Rightarrow$ low track p_T cut. . . but much patchier acceptance.

LHC and ATLAS performance in 2010

All the soft QCD studies I will show are based on low pile-up 2010 data:



ATLAS Detector Status

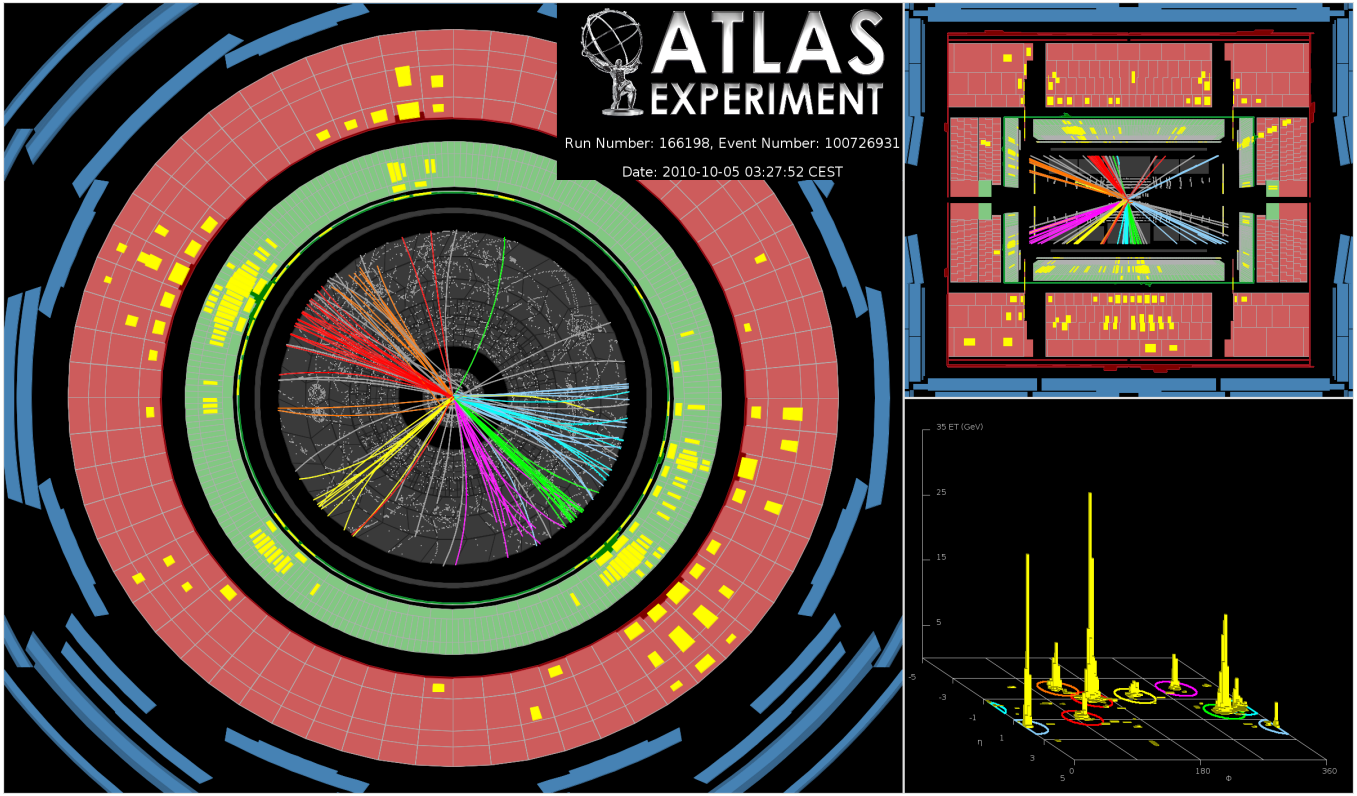
Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	96.9%
SCT Silicon Strips	6.3 M	99.1%
TRT Transition Radiation Tracker	350 k	97.5%
LAr EM Calorimeter	170 k	99.5%
Tile calorimeter	9800	97.9%
Hadronic endcap LAr calorimeter	5600	99.6%
Forward LAr calorimeter	3500	99.8%
LVL1 Calo trigger	7160	99.9%
LVL1 Muon RPC trigger	370 k	99.5%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.8%
CSC Cathode Strip Chambers	31 k	98.5%
RPC Barrel Muon Chambers	370 k	97.0%
TGC Endcap Muon Chambers	320 k	98.4%

Sustained exp increase in luminosity. ATLAS efficiency of 93.6%.

$48\,\mathrm{pb}^{-1}$ collected in all of 2010 – in 2011, already $860\,\mathrm{pb}^{-1}$ since Feb!

An 8 jet event!

Soft physics is still important here for calibration



Modelling of QCD at the LHC

The LHC was not built to study QCD! That's just an interesting side-effect. For the most part, new physics searches want a good *model* of QCD effect for understanding of backgrounds.

This is certainly the case for MPI-driven physics: parameterisations are acceptable. The very flexible PYTHIA model is very successful in this respect: QCD-motivated rather than first-principles.

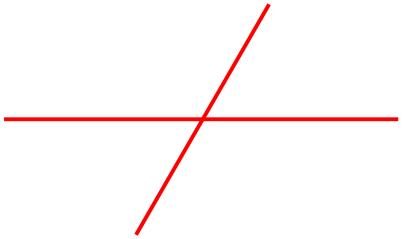
For harder QCD: intra-jet and inter-jet features definitely need as much predictive QCD content as possible. Intra-jet structure dominated by pQCD parton showers (Pythia, Herwig, Sherpa). Inter-jet is traditionally $2 \to 2$ ME + PS: being rapidly replaced for LHC by NLO + multijet ME/PS merging. Interim: K-factor reweighting of PYTHIA to NLOJET++.

Diffractive modelling remains largely ignored: PHOJET (but not useful in general processes), POMPYT model in Pythia 8. PY6 model far too soft.

Since all data is interpreted and used in an MC context, first a quick overview of model contents...

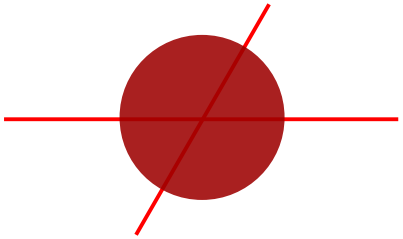
MC generator anatomy

Matrix element



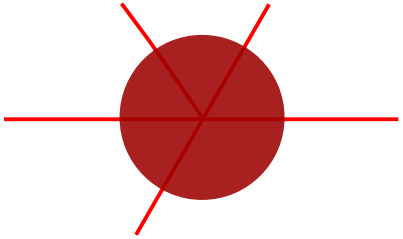
MC generator anatomy

Matrix element



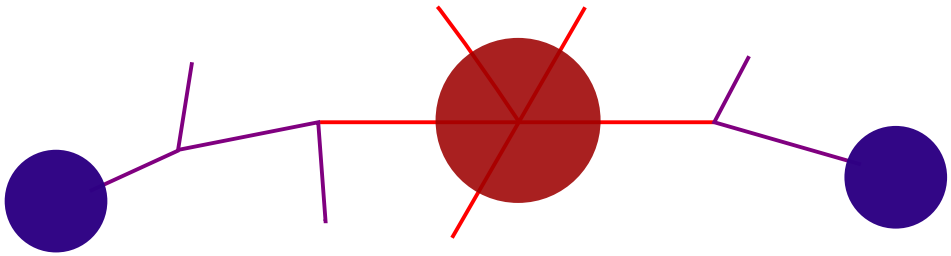
MC generator anatomy

Matrix element



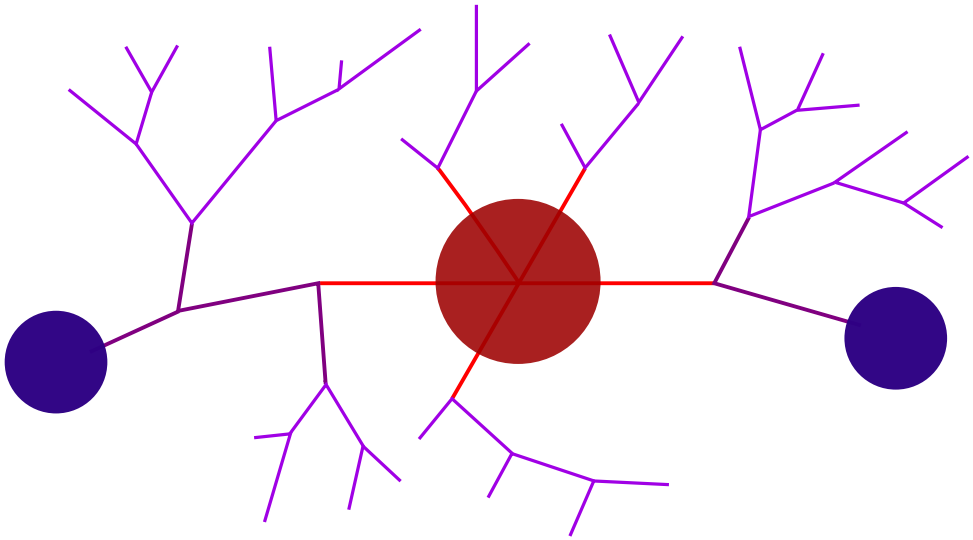
MC generator anatomy

ISR / spacelike shower



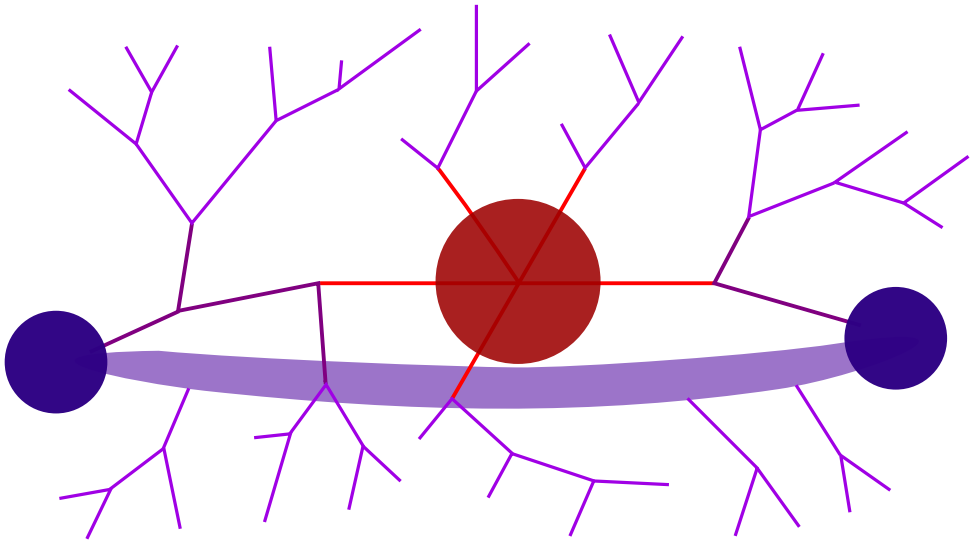
MC generator anatomy

FSR / timelike shower



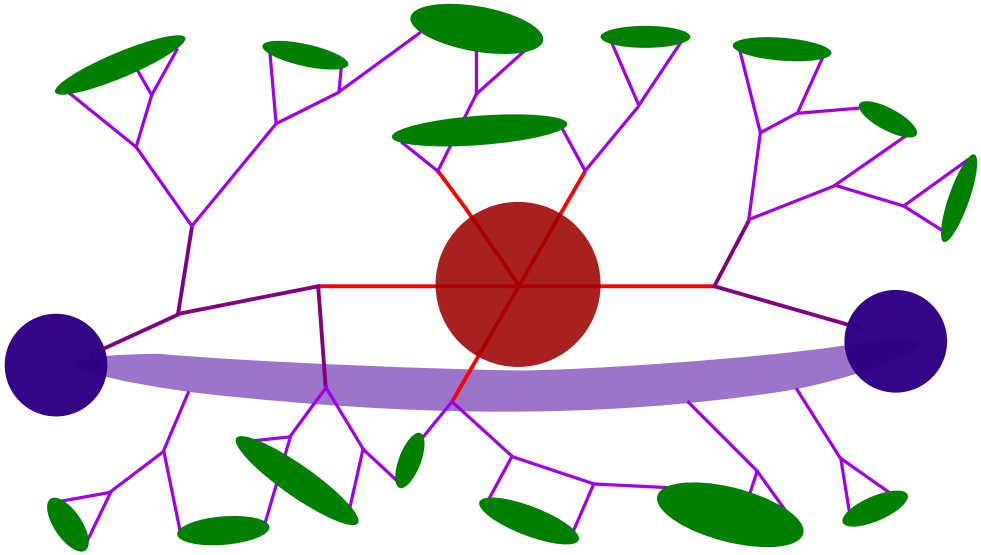
MC generator anatomy

Underlying event / BBR



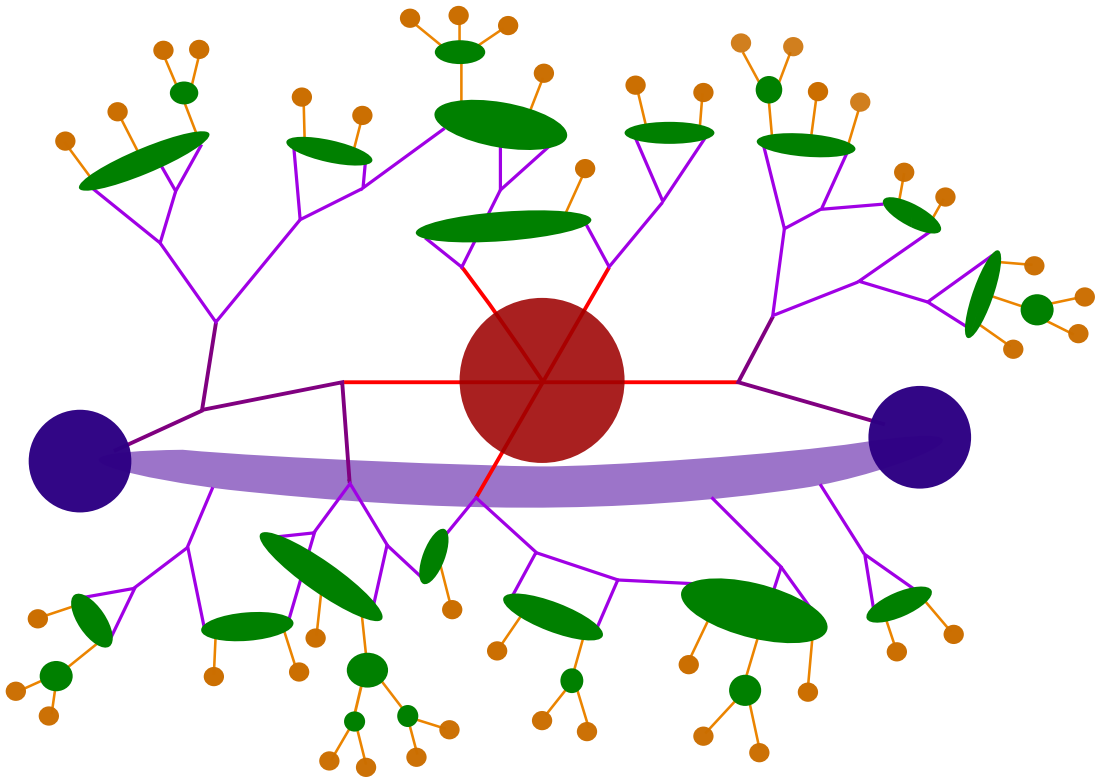
MC generator anatomy

Hadronisation



MC generator anatomy

Decays



MC generator families

Shower/hadronisation generators (SHGs) are historically defined by two things: shower model and hadronisation model (duh).

Showers need colour coherence: angular ordering (HERWIG/Herwig) or scale-ordered with angular vetoing (PYTHIA/Pythia). Or Sherpa: now using a *dipole shower*.

Hadr. models are either string (Pythia) or cluster (Herwig & Sherpa). Two different asymptotes of long-range QCD: pheno relevance in both cases needs concessions $\Rightarrow$ parameters!

More recently, two new discriminating factors, closer to the matrix element: NLO (mainly via POWHEG) and multi-leg LO (and sometimes both – MENLOPS). Merging with shower needs care due to double-counting, but is a solved problem.

Tuning of event generators

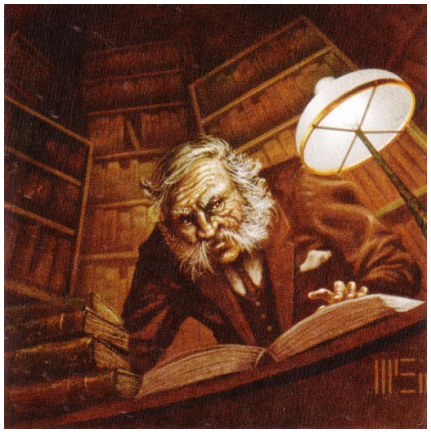
So, which bits of the generators can we tune and tweak – all of them?

- **Matrix elements:** NO! But scale variations for systematics with (POWHEG) NLO. Diffractive mass etc. in Pythia/Phojet?
- **Hadronisation:** oodles of params for flavour and several for kinematics, including b and c quark frag functions.
- **Showers:** yes, with care, in some generators. But usually just the cutoff scale and some wiggle room in the definition/eval scale of α_s. Good modelling is key on the relevant observables. PYTHIA gives all sorts of ugly tuning handles, mainly in having 5 different Λ_{QCD}s!
- **MPI:** YES! Trick is to give it as *little* room as possible: tune everything else first.
- **Decays:** nope.

The tools of the tuning trade: Rivet and Professor

- **Rivet** is an MC analysis toolkit, with various computational tricks to allow efficient and physically meaningful calculation of observables from the MC HepMC event record. Any event generator which can output HepMC can be analysed in Rivet. 100+ analyses built in (LEP, Tevatron, HERA, ...), and more arriving from the LHC experiments (although more active input would still be nice!) Data mainly taken semi-automatically from HepData.

- **Professor** is a semi-automated system for parameterising expensive calculations, such as computation of high-stats MC observables. Relies on trivial parallelisability to sample a parameter space, uses SVD to fit a polynomial to each bin of each observable ⇒ interactive MC generator / numerically optimised params. Param correlations are built in. "PDF-like" errors.



ATLAS MC tuning strategy

ATLAS has an active MC tuning group, making use of Rivet and Professor. Developing Rivet analyses is a semi-standard part of any ATLAS SM analysis' progress through the approval chain.

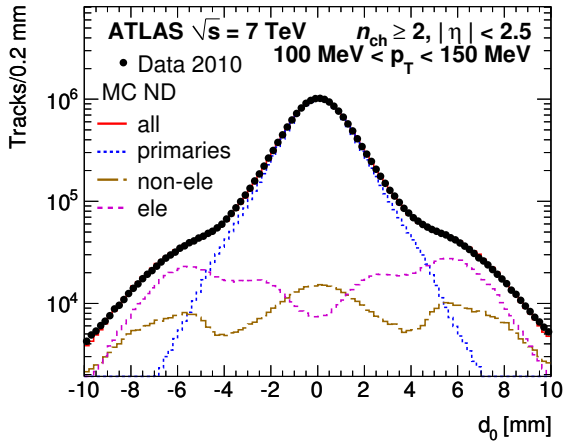
Some general idioms worked out by trial and error to minimise iteration and false steps.

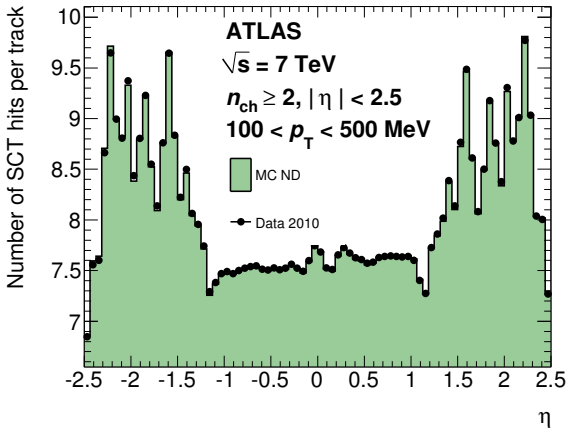
- Use as much data as possible – multiple energies, different colliders and detectors. Weight fits to favour the data you *need* to describe. Iterate weights (how?!?) if the model is not omnipotent!
- Avoid data your model has no chance of describing (e.g. multijets in PYTHIA, diffraction-dominated regimes, etc.)
- Factorise the parameters into tuning blocks
- Tune first at e^+e^- to cleanly constrain hadr and FSR.
- Then with a solid base, tune to hadron collider hard QCD: CAREFUL! Prefer shower effects to ME.
- Then MPI: models are sufficiently unpredictive that we need to get everything else right first!
- The step yet untaken: re-tuning to flavour physics at hadron colliders. Strangeness puzzle?

Soft QCD at ATLAS: minimum bias

Minimum bias measurement

- "MB" measurements from ATLAS made at 900 GeV, 2.36 TeV, and 7 TeV.
- "Min bias" in this sense is defined by activation of the two MBTS trigger detectors, plus at least one track within the analysis acceptance: avoid awkward "zero bin" issues!
- Using central tracker only, so only charged particles seen, and $|\eta| < 2.5$
- Unfolding of detector effects by Bayesian iterative unfolding using multiple MC priors (PYTHIA and PHOJET)



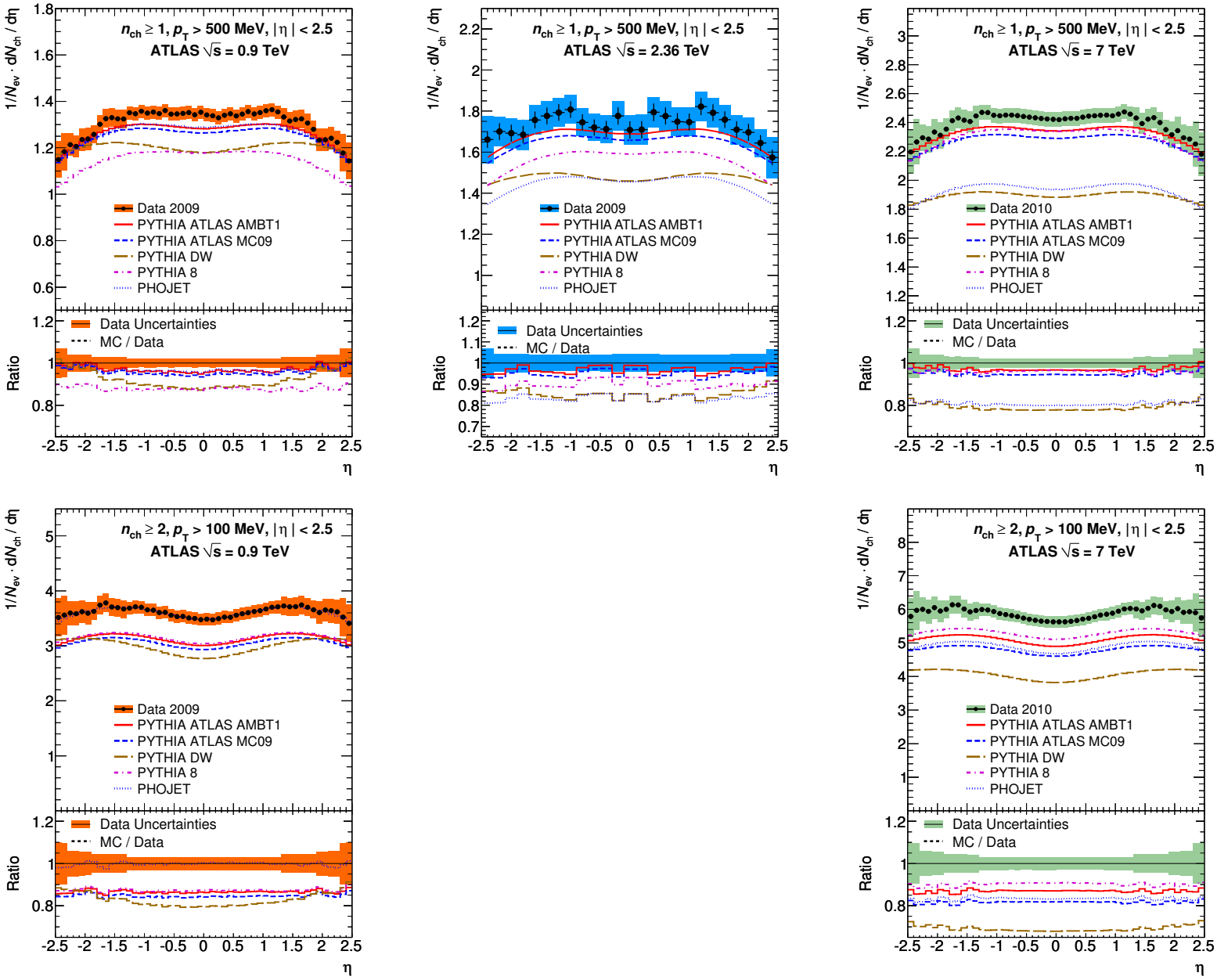


7 TeV event in the ATLAS central tracker, showing MBTS

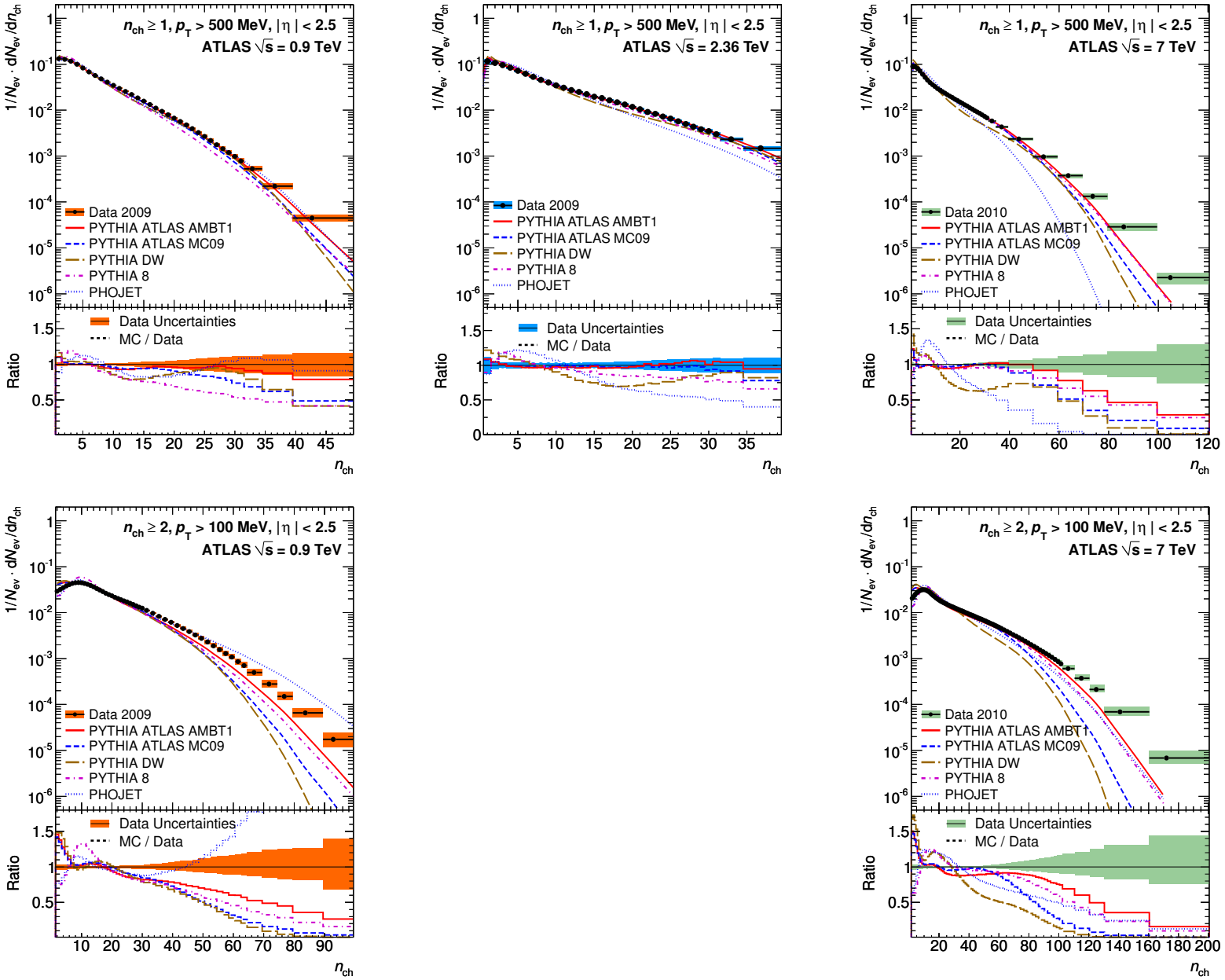
Minimum bias – measurement "philosophy"

- Emphasis on plotting what we measure, and can correct for detector effects!
- ATLAS really pushed the approach to define observables within defined final state cuts, rather than traditional "NSD" approach (as taken by the first CMS & ALICE analyses.) Everyone in agreement now(?)
- "NSD" involves "correcting" measured observables by subtraction of PYTHIA's *naïve* SD model component. But that's the worst-modelled part of PYTHIA!
- We prefer to define a range of $|\eta|$ (< 2.5), a low track p_T cut (> 100, 500, or 2500 MeV), and *a low cut on* $N_{ch} > 1, 2, 6, 20$.
- This way the data remains valid and useful as models change and improve.
- "Common phase space" plots for comparison to CMS and LHCb.

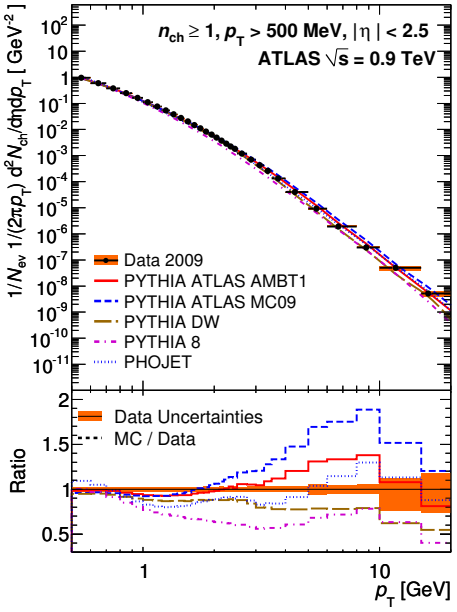
Minimum bias – $dN_{ch}/d\eta$

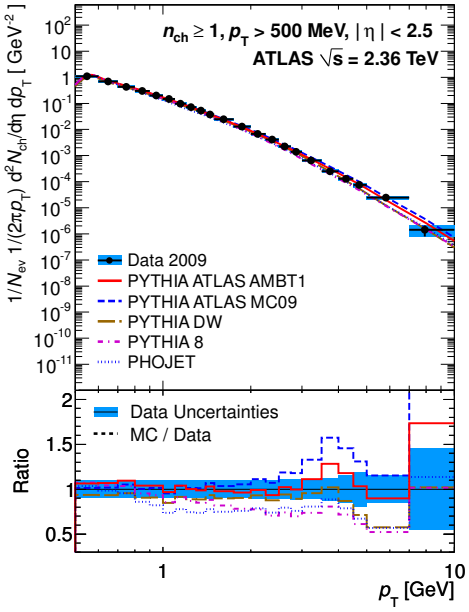


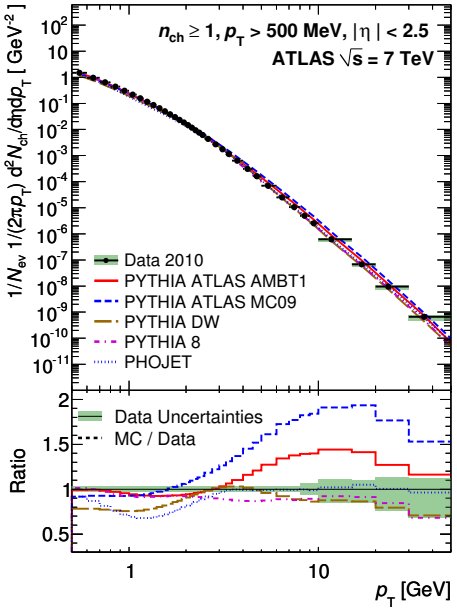
Minimum bias – N_{ch}

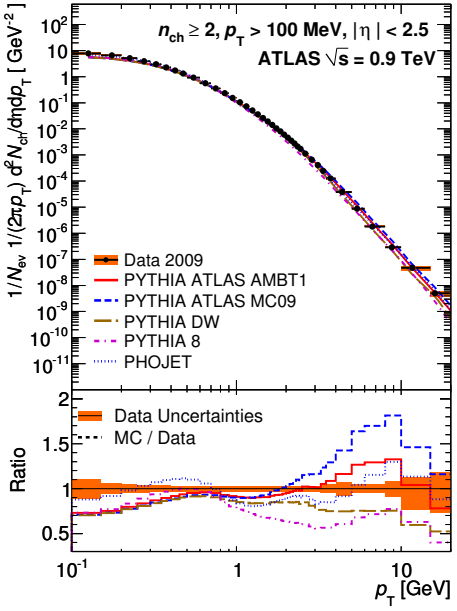


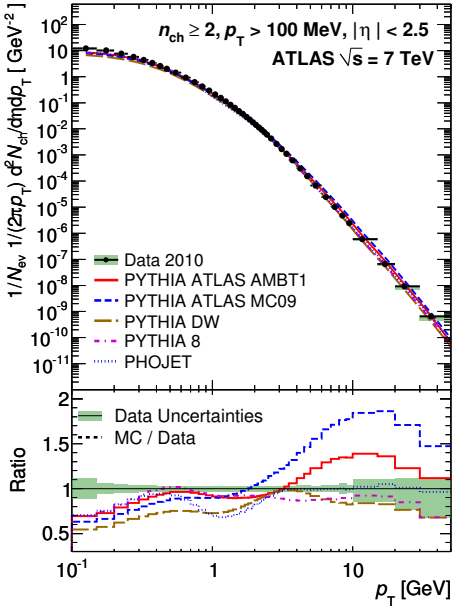
Minimum bias – p_T



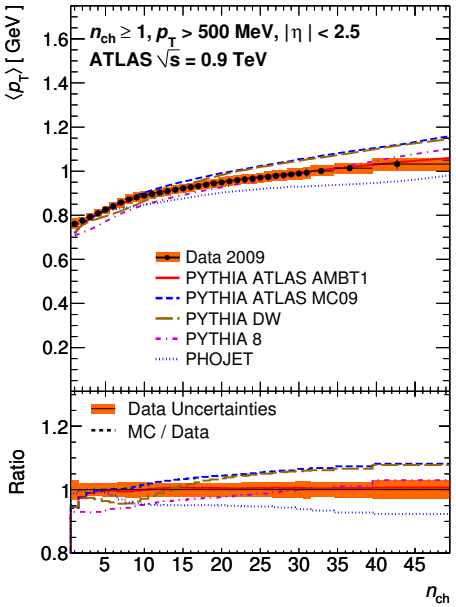


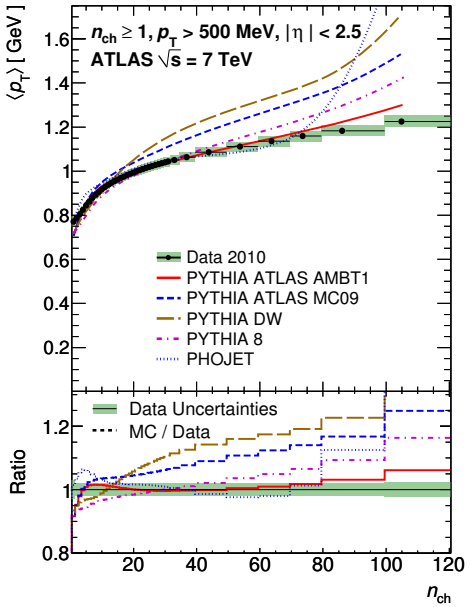


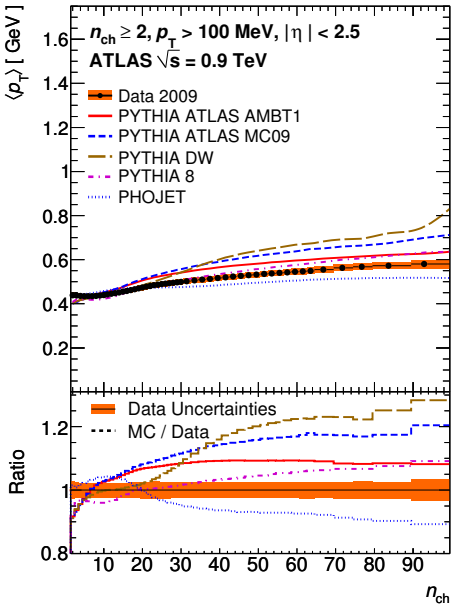


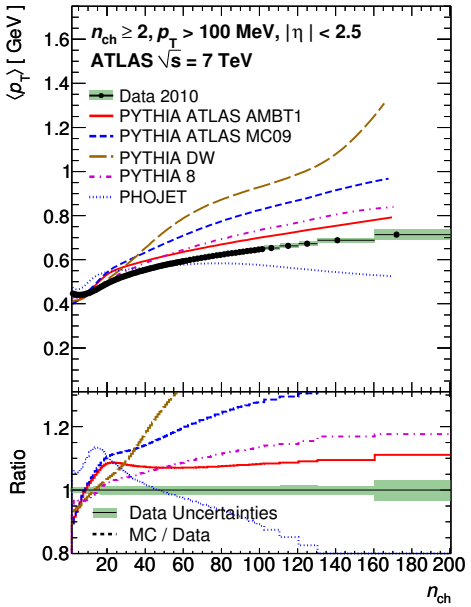


Minimum bias – $\langle p_T \rangle$ vs. N_{ch}

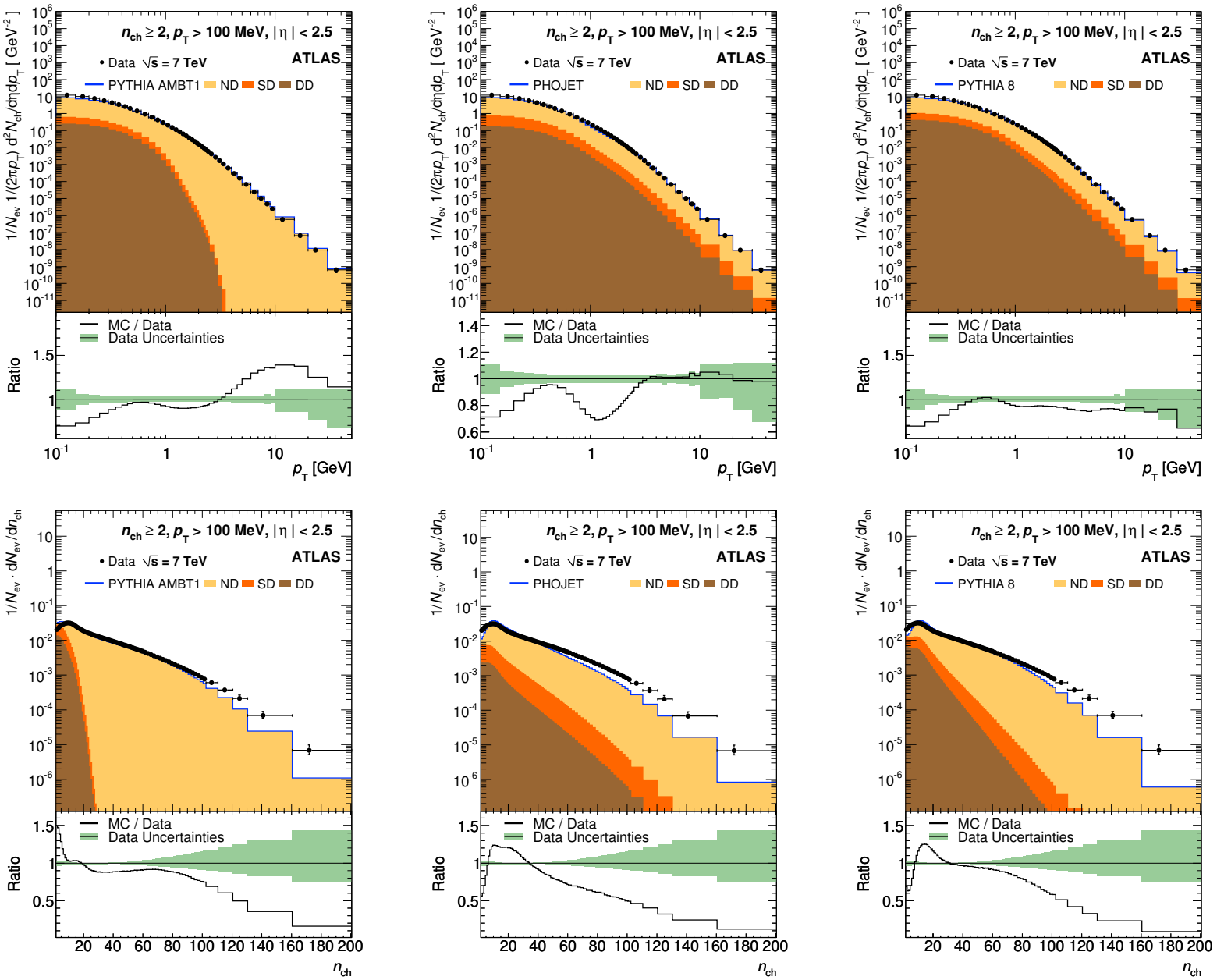








Diffraction in min bias observables



MC models of soft QCD

UE/MB models in MC generators are based on several things:

- Multiple parton interactions (in a classical eikonal approximation)
- Regularised cross-section ($gg \to 2$ QCD naïvely diverges for low p_T, in both cross-section and PDF)
- Hadronic transverse matter distribution
- (Colour topology rearrangement between all scattered partons)

Implemented in PYTHIA, JIMMY, Herwig++, Pythia 8, Sherpa, PHOJET, EPOS, (more?)

MPI models are the least predictive part of MC event generators! However, the simple model works surprisingly well for both MB and UE. Universality assumptions are being challenged by LHC data, though.

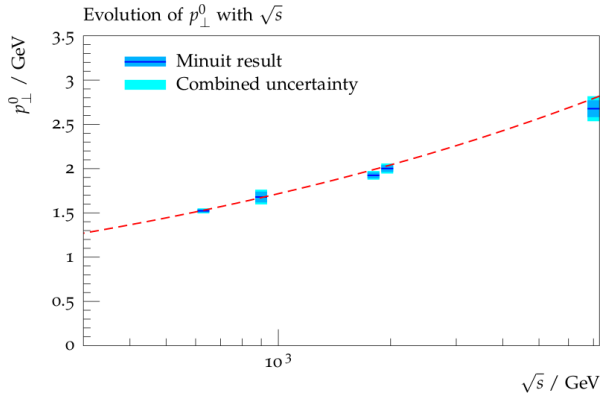
Tuning of MPI models

PYTHIA and Pythia 8 have essentially the same MPI model and params: parameterised transverse matter distribution, plus eikonal MPI scattering pert. regularised by $1/p_T^2 \to p_T^2/(p_T^2 + p_{T0}^2)^2$ ansatz.

p_{T0} parameterised:

$$p_{T0}(\sqrt{s}) = p_{T0}(\sqrt{s_0}) \left(\frac{\sqrt{s}}{\sqrt{s_0}} \right)^e$$

$\sqrt{s_0}$ is usually set to 1800 GeV w.l.o.g.



Schulz/Skands arXiv:1103.3649.

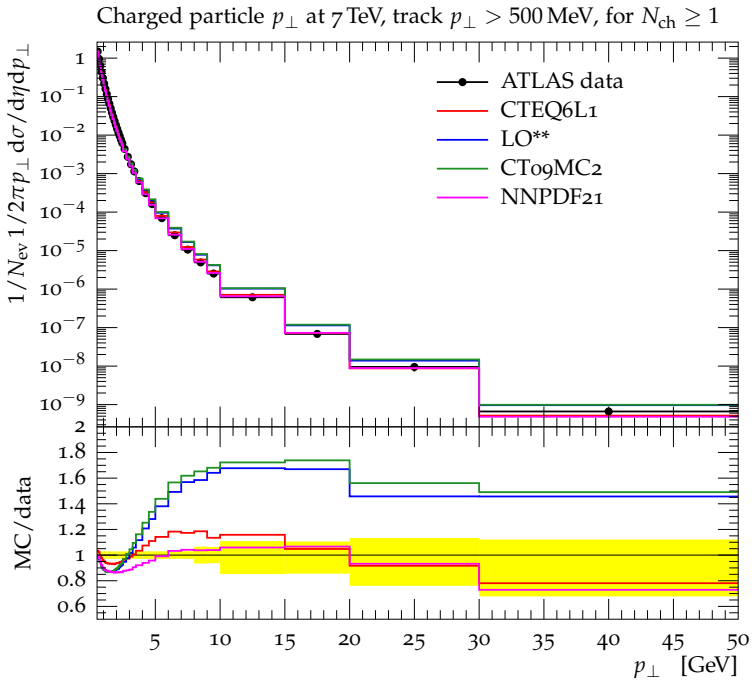
Also colour reconnection: probabilistic reassignment of disfavoured colour topologies. In total: $p_{T0}(\sqrt{s_0})$, e, 2 $\times$ CR params, 2 $\times$ matter dbn params = 7 params if decoupling from shower assumed safe. Interleaving with shower(s) complicates derivation of e.g. non-pert correction factors for NLO fixed order generators.

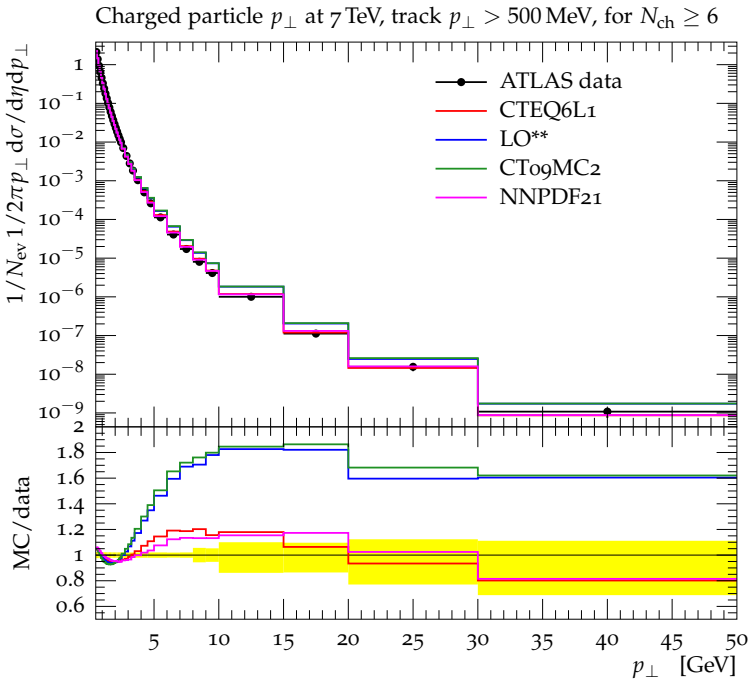
JIMMY, Sherpa, and Herwig++ models similar to the above. However, no ansaetz for energy evolution or low-p_T extension. H++ low-p_T by connection to DL elastic slope. And fewer parameters: only 1 for matter dbn, no CR.

PDF effects in MB tuning

Automation of PYTHIA tuning means we can tune equivalently for a *lot* of PDFs!

Some strange features being seen in min bias p_T spectrum for some PDFs – particularly mLO ones:



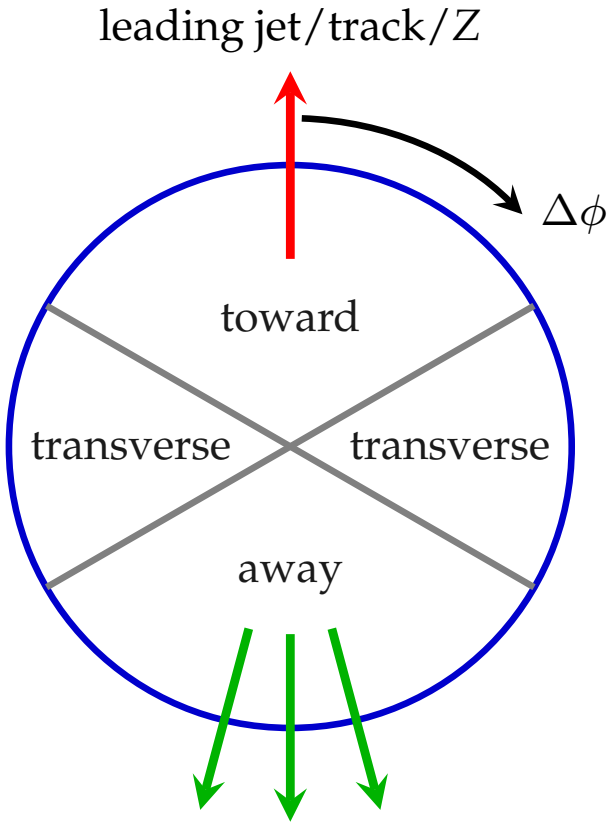


Soft associated QCD at ATLAS: underlying event

The underlying event

There is no underlying event – there is only "event"! "UE observables" are designed to require a hard scattering process, and to study its effect on associated soft physics.

- Simplest is to align an event with the momentum flow of the hard scatter, and then look perpendicular to that: define three azimuthal regions, toward, transverse, and away.
- Towards region contains hardest jet/EW boson/etc., away contains balance QCD, and transverse should be UE. (NB. In DY, *towards* is most interesting for UE)
- Plot evolution of UE characteristics (multiplicity, $\sum p_T$, etc.) with hard process characteristics ($p_\perp^{\text{lead}}$, η_{lead}, etc.)



Underlying event analysis topology

More thoughts about the UE

UE exposes the myth of a distinct division between min bias and hard physics – process-independence? Models seemed to do pretty well at CDF. UE is (apparently) relatively diffraction-insensitive

Irreducible QCD background for all hard processes: no vertexing cut will remove it. Correction to jet energies – similar effect to pile-up in forward calorimeters where there is no tracking to help with vertex ID. Dynamic jet area trimming?

Rick mentioned strangeness rates with the Z1/Z2 tunes: ATLAS doesn't have identified hadron rates and p_T spectra results yet, so the ALICE data are very interesting for us. "Q2" and "pT" shower names don't tell the whole story, and notably the p_T shower was never tuned to LEP data: does a LEP tuning improve the LHC data description?

ATLAS UE measurements

We so-far use the leading track rather than leading jet for event orientation – only a useful strategy for a short $p_\perp^{\text{lead}}$ reach ($< 20\,\text{GeV}$) but fewer systematics.

Min bias triggered events, but require one track within tracker acceptance of $|\eta| < 2.5$ with $p_T > 1\,\text{GeV}$. Measured at both 900 GeV (limited stats) and at 7 TeV: different energies important for MPI model tuning. Track p_T cuts of 100 and 500 MeV.

Also a leading cluster UE analysis with the same cuts on the calo clusters. First UE measurement to measure the neutral component of the soft scattering, also at 900 and 7000 GeV. Measurement difficulty is in directly assigning a cluster-to-particle interpretation which can be replicated at MC truth level: it works in this analysis only because the calo cell occupancies are sufficiently low that a particle = cluster approx. is valid.

Leading jet UE analysis is well-underway – for leading jets above 20 GeV.

ATLAS UE measurements: detector correction

Correct the tracks/clusters back to primary charged particle level, in a two-stage procedure:

1. First manually reweight for event efficiencies:
   - from data: MBTS eff, vertexing eff
   - from MC: lead track reconstruction eff

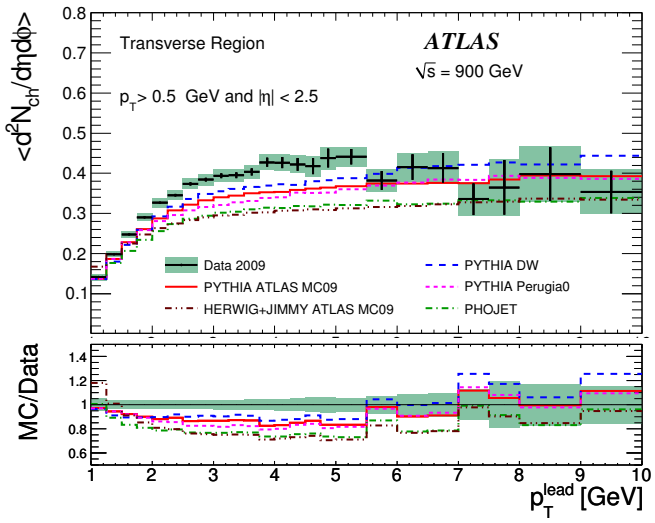
   and for each reconstructed track using MC:
   - tracking efficiencies as function of η and pT
   - track rate corrections from secondaries and fake tracks
2. Then the remaining 5%–10% correction was done bin-by-bin using primarily the PYTHIA MC09 tune, with unfolding systematic errors of $\sim 2\%$ from symmetrised PHOJET deviation. NB. Not a full bin-matrix inversion: bin migration systematic.

Extra systematics: a conservative migration systematic obtained assuming all migrations from lowest $p_{\perp}^{\mathrm{lead}}$ bin (biggest difference), $\Delta\phi$ reorientation, track reco χ^2 cut, and material uncertainties. Total systematic of 4.5% for lowest $p_{\perp}^{\mathrm{lead}}$ bins, increasing to 8% (6.5%) at high $p_{\perp}^{\mathrm{lead}}$ for 7 TeV (900 GeV) analyses respectively.

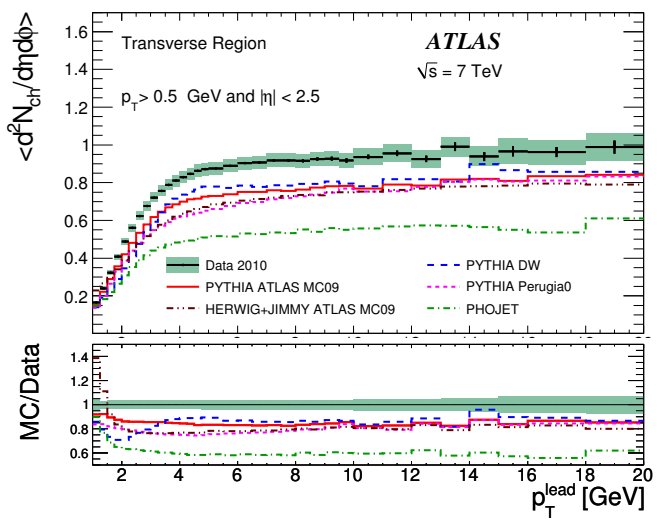
ATLAS underlying event results

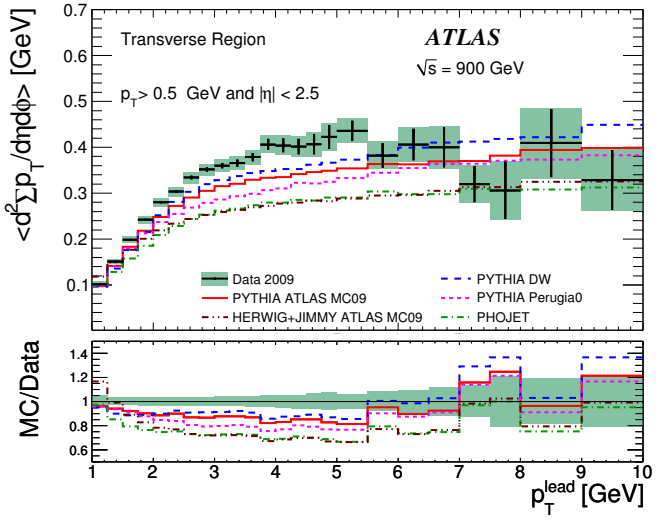
Leading charged track N_{ch} and $\sum p_T$, $p_T > 500$ MeV (arXiv:1012.0791)

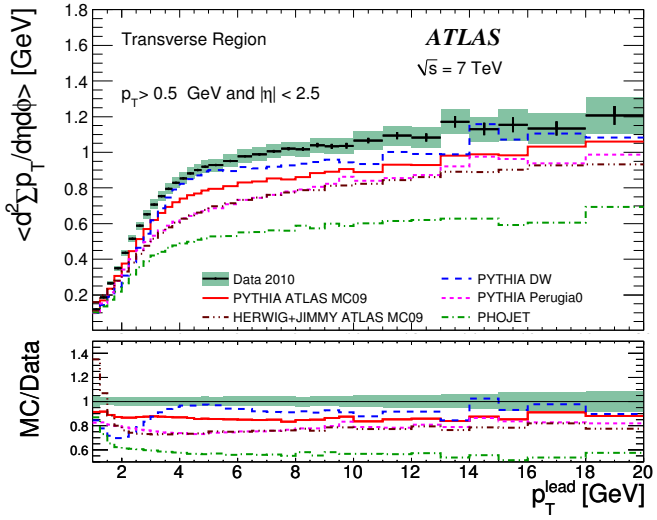
900 GeV



7 TeV



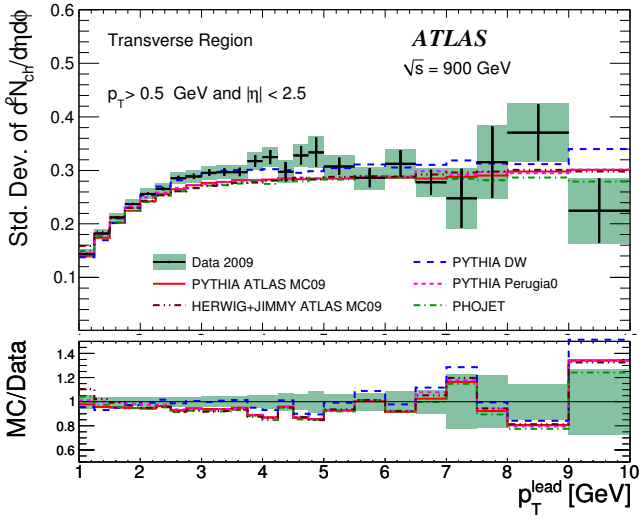




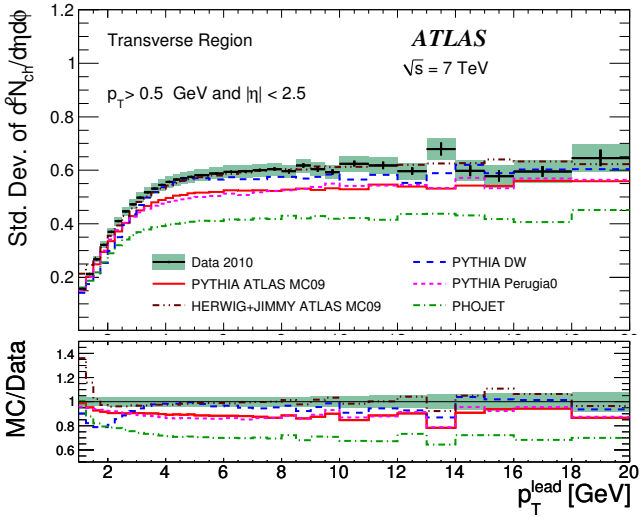
ATLAS underlying event results

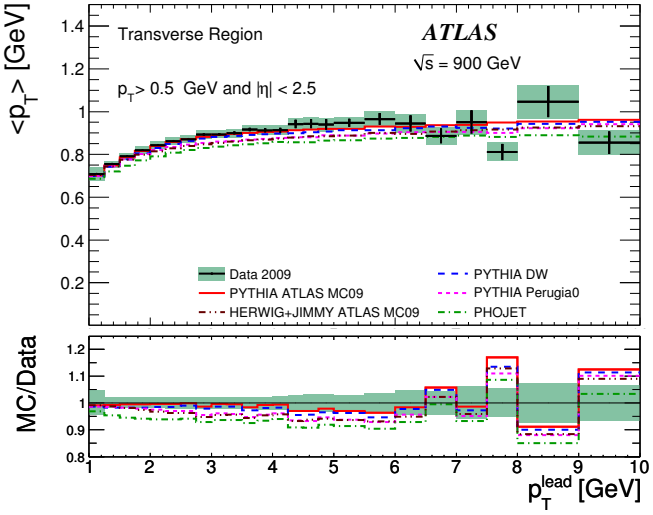
Leading charged track $\sigma(N_{\mathrm{ch}})$ and $\langle p_T \rangle$, $p_T > 500$ MeV (arXiv:1012.0791)

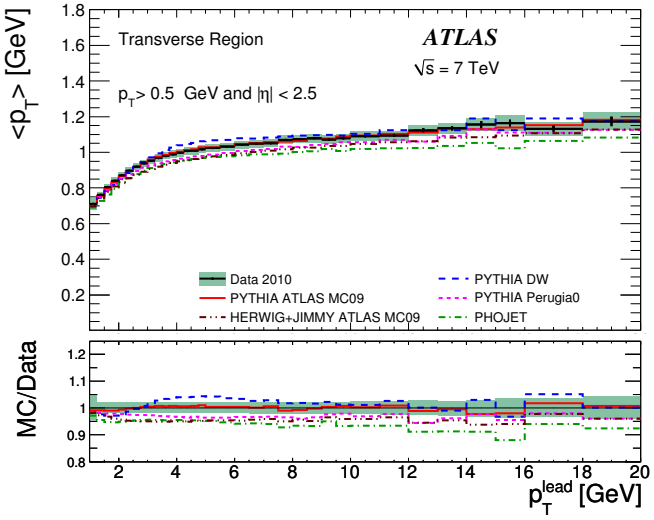
900 GeV



7 TeV



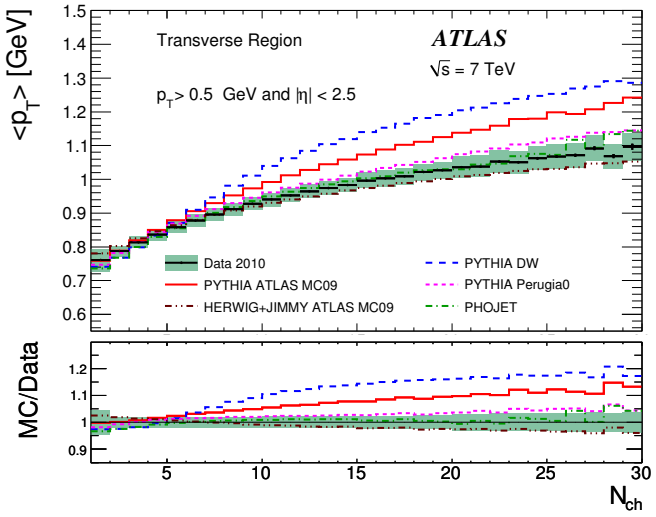


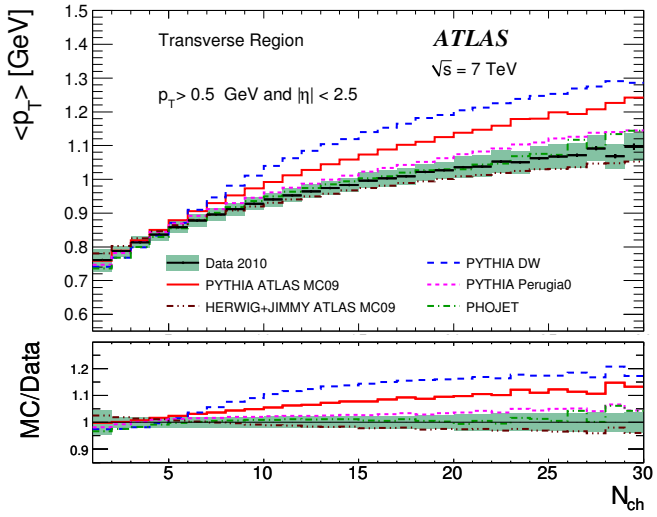


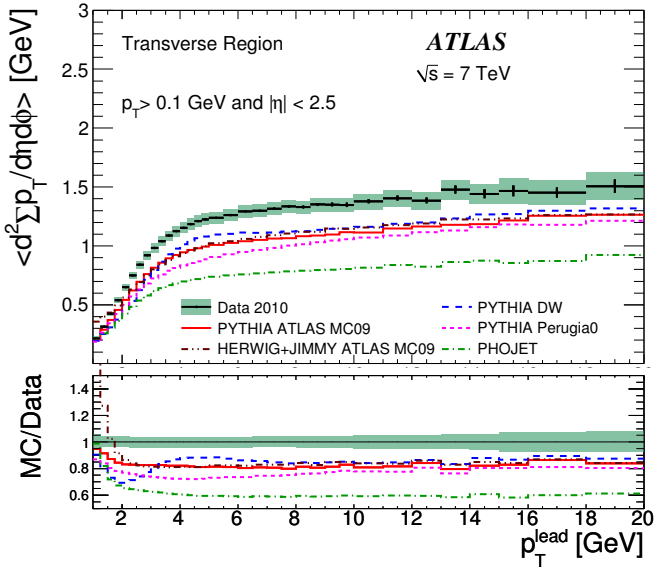
ATLAS underlying event results

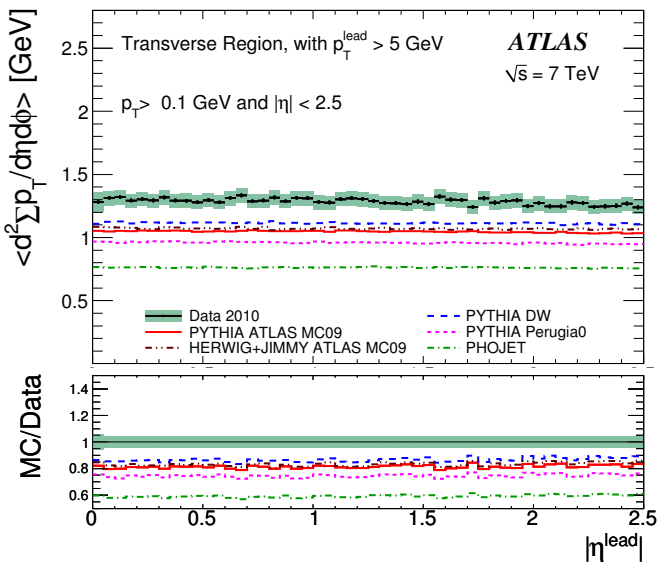
Leading charged track $\langle p_T \rangle$ vs. N_{ch} ($p_T > 500$ MeV) and $\sum p_T$ vs. p_T^{lead} & η^{lead} ($p_T > 100$ MeV)

7 TeV (arXiv:1012.0791)





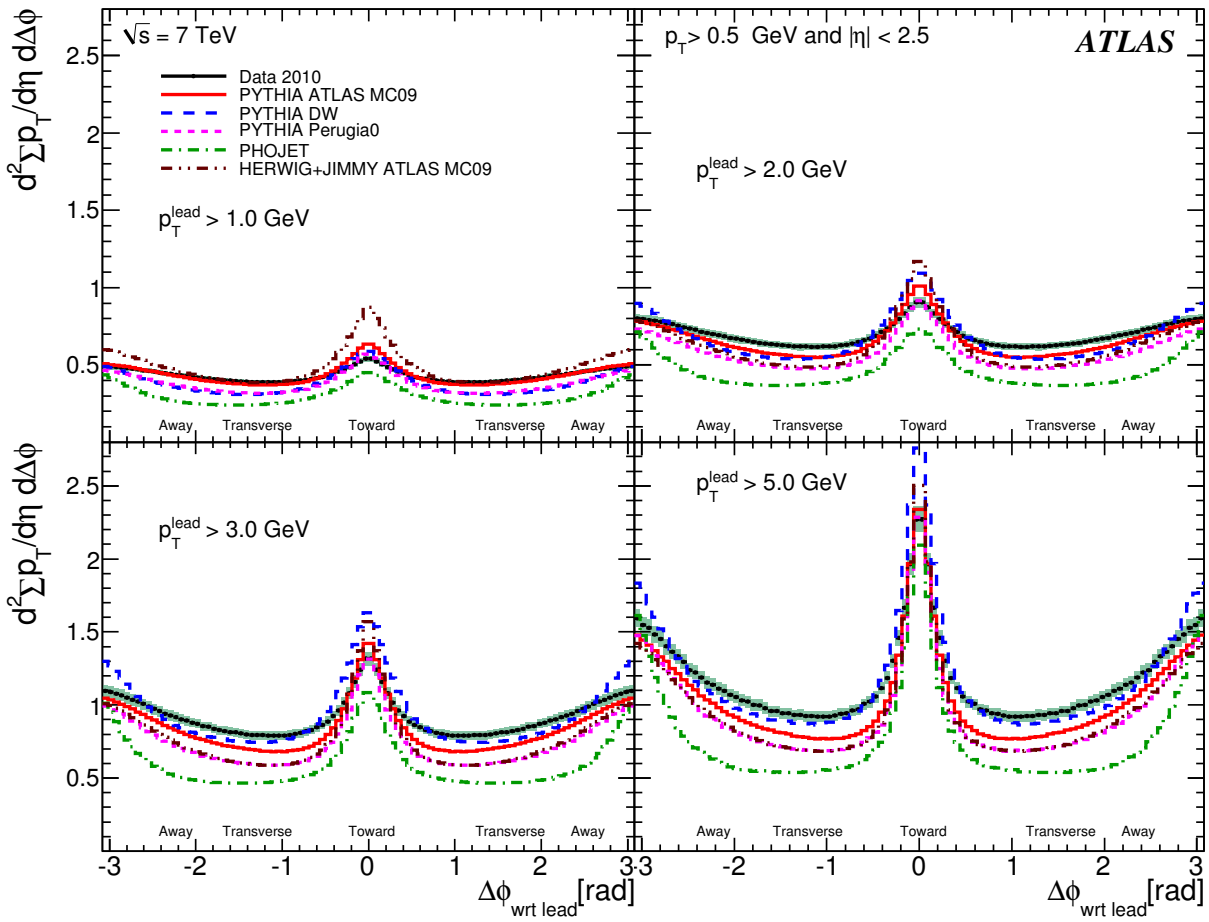




ATLAS underlying event results

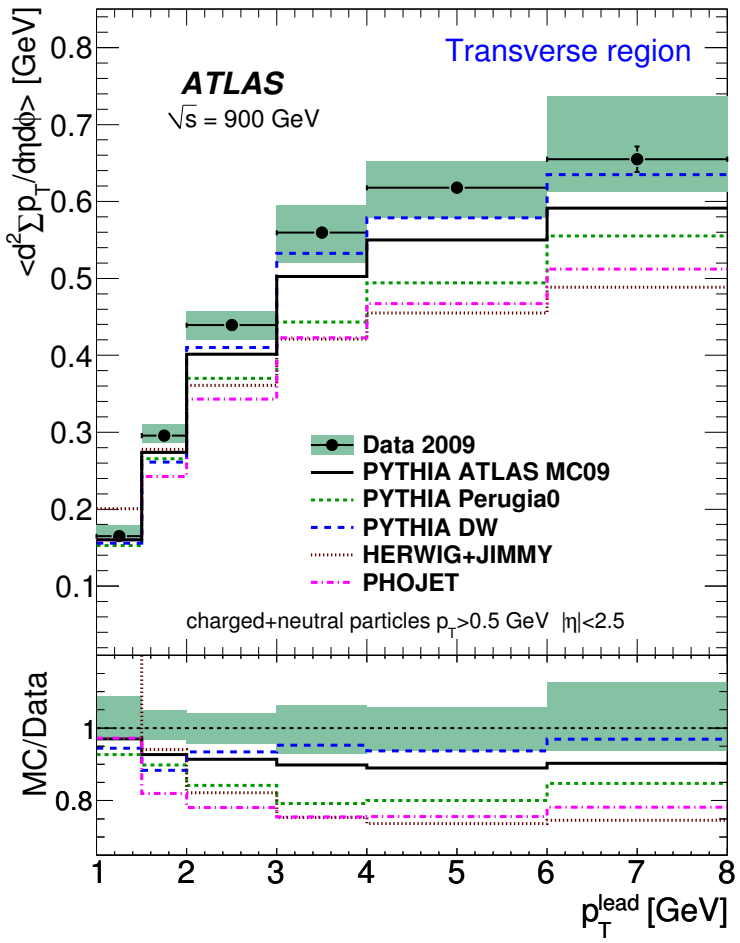
Leading charged track $\sum p_T(|\Delta\phi|)$, $p_T > 500$ MeV (arXiv:1012.0791)

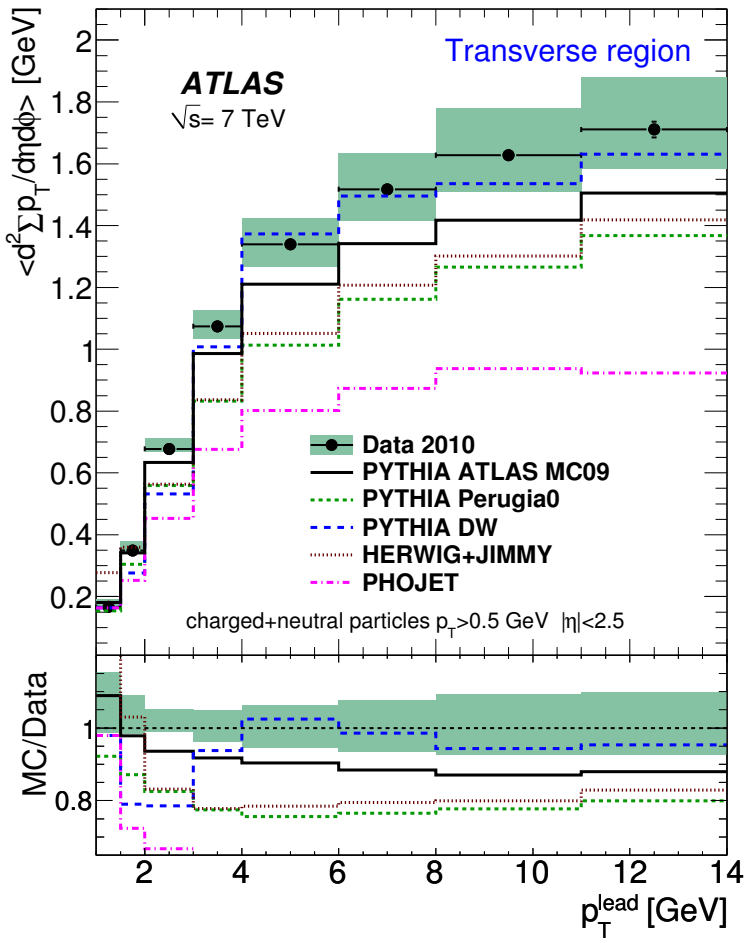
7 TeV



ATLAS underlying event results

Leading calo cluster $\sum p_T$ (arXiv:1103.1816)





ATLAS MC tuning for UE

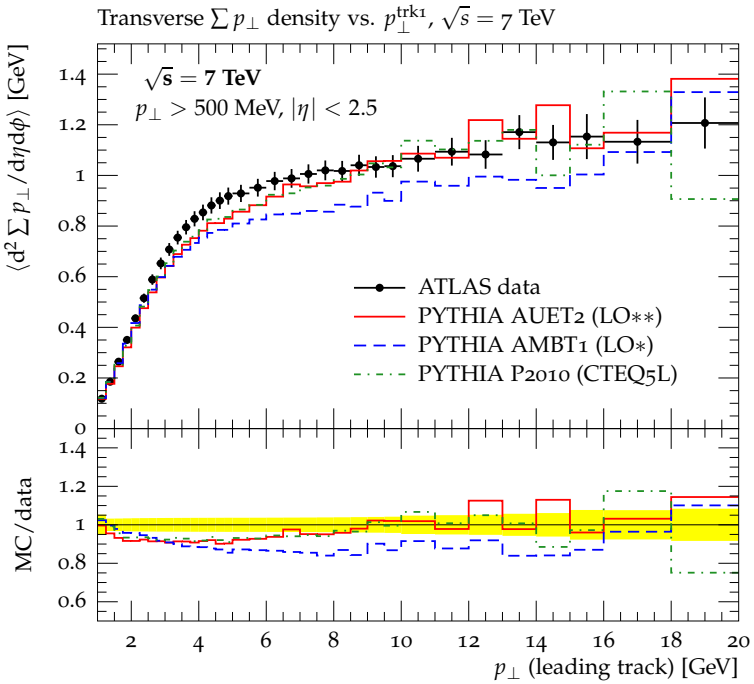
MC event modelling needed both for experimental understanding of QCD, V+jets, etc. as backgrounds to new physics, and to allow highest-tech theory/data comparisons.

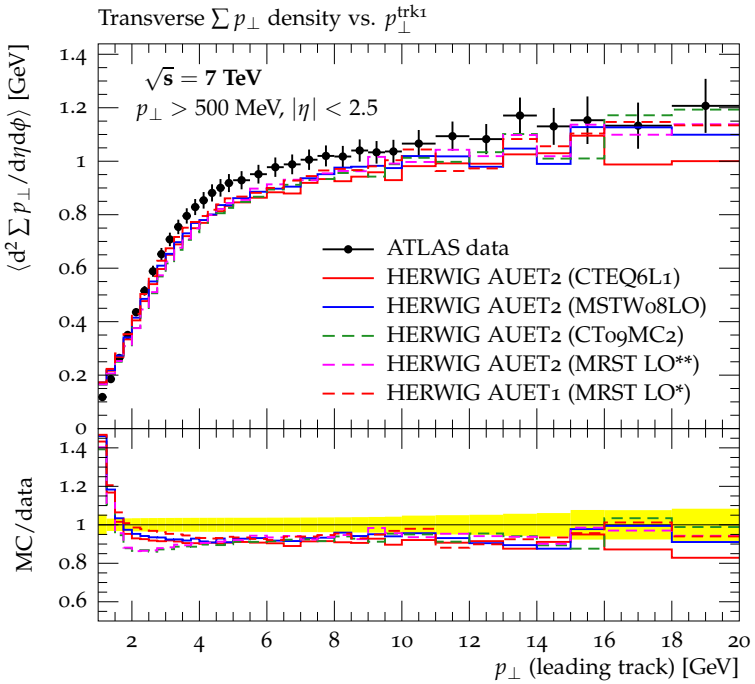
Tuning PYTHIA again with Rivet/Professor, using all ATLAS UE data *and* the Tevatron Run I and Run II data used for pre-LHC tunings. Important features are colour reconnection strength – used to balance N_{ch} and $\sum p_T$ activities – and the energy evolution of MPI p_T cutoff.

Most recent tunes (ATLAS AUET2 and Perugia 2010) attempt to tune jet shapes as well as MPI: problems with simultaneous profile ramp/plateau description, resolving MB/UE, and resolving LHC vs. CDF Run II leading jets UE. FSR/hadr fully tuned to give excellent description of LEP multiplicities, event shapes, diff. jet rates...

New tunes: AMBT1 (PYTHIA), AUET1 (JIMMY), AUET2 (PYTHIA and JIMMY), AUET2b (PYTHIA with different shower config: not yet released). Also Rick's Z1, Z2, etc. in CMS.

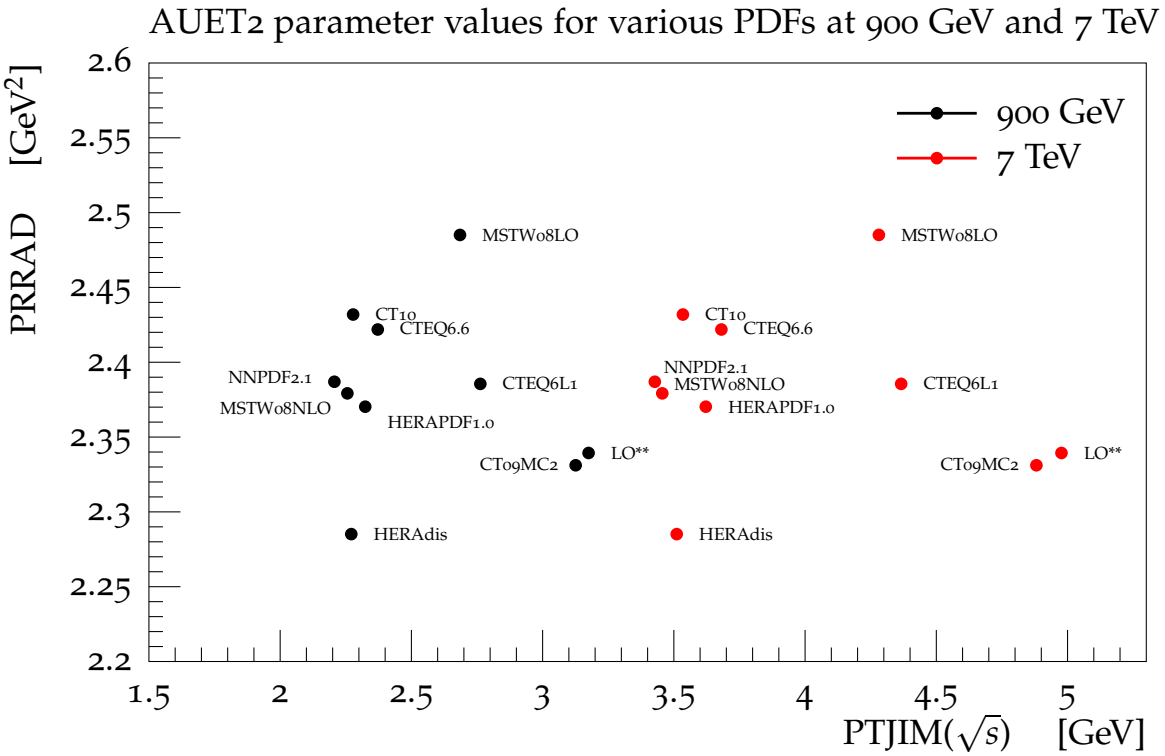
New ATLAS PYTHIA and HERWIG/JIMMY tunes





Note AUET2 LO** undershoot of UE turn-over shape. New PYTHIA AUET2b tunes also nearly complete: will be shown at PDF4LHC at the start of July.

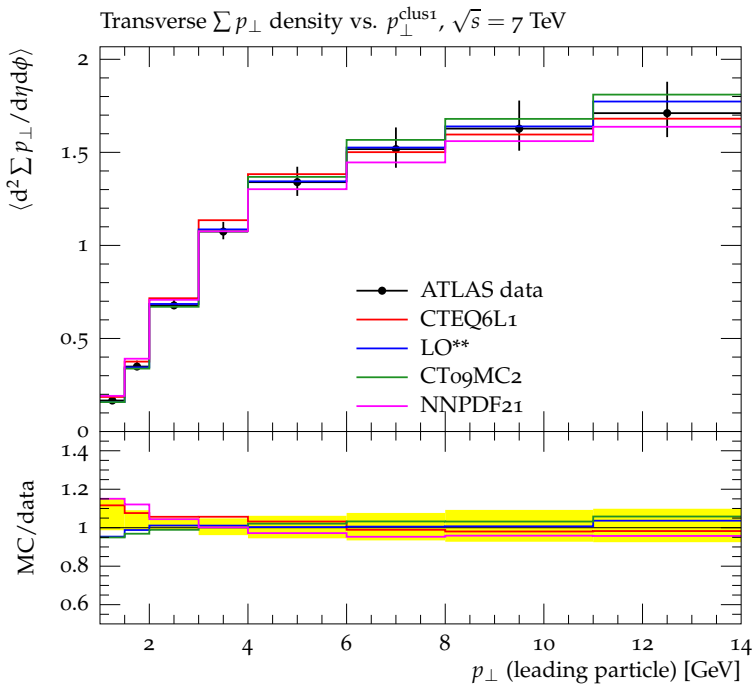
PDF effects on UE tune parameters

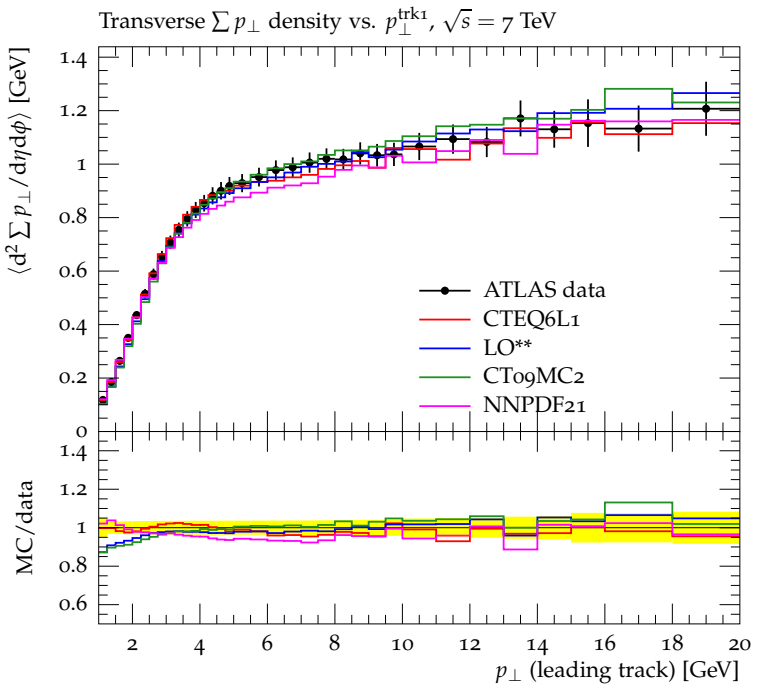


This plot shows the scatter of HERWIG/JIMMY's two real MPI parameters at two energies, using the PYTHIA energy evolution ansatz in the fit. Note the grouping in PTJIM (MPI p_T cutoff) by PDF type.

PDF effects in UE tuning

Look at PYTHIA tuning with lots of PDFs again, this time for a UE tune (unlike with CDF data, we couldn't get a tune that described ATLAS MB and UE nicely at the same time – also seen with Pythia 8. Colour reconn. seems to be different between the two event types.)





Again, mLO PDFs very distinct from "normal" LO and NLO PDFs, in particular they strongly differ in the soft "min bias" region and the std dev profile, implying a harder MPI p_T spectrum, cf. min bias.

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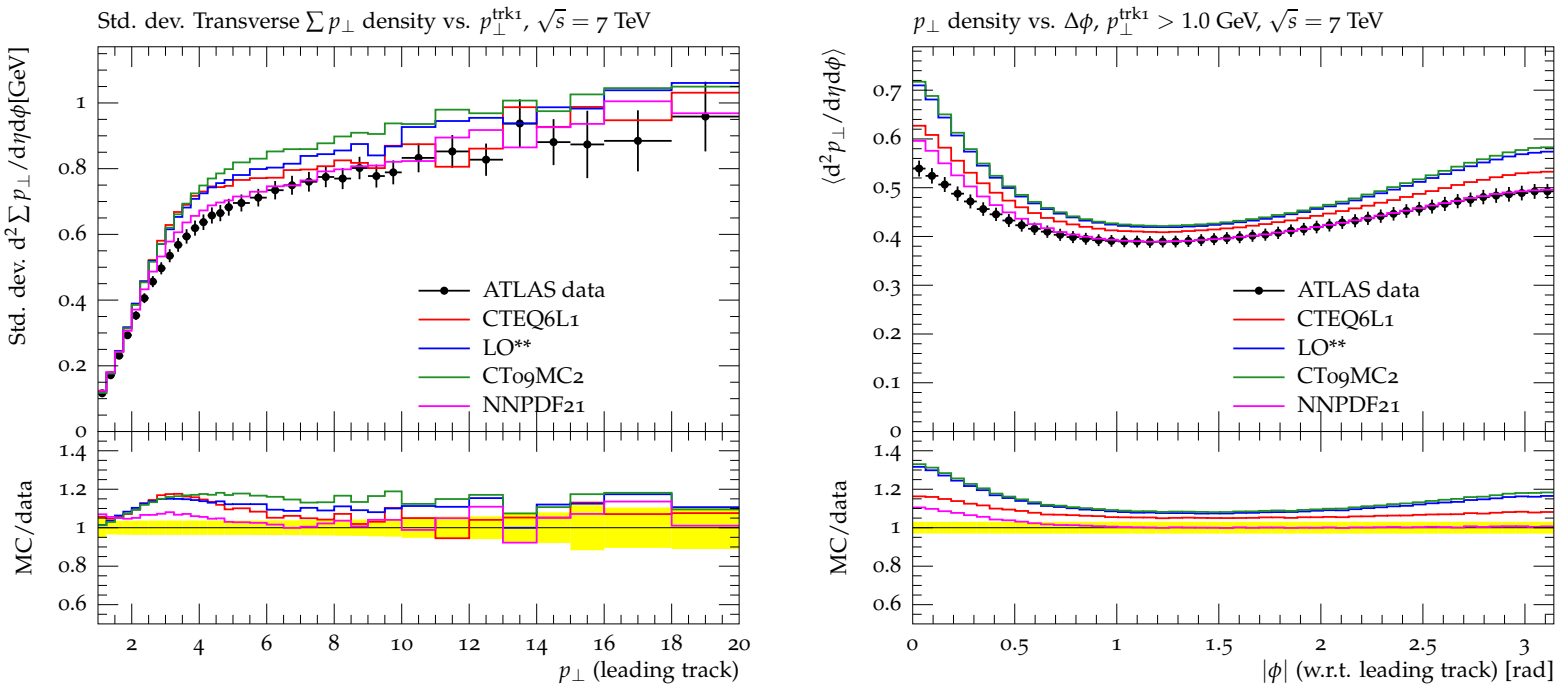

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Conclusions

Summary (ATLAS)

Soft QCD at the LHC is predominantly modelled by shower/hadron/MPI event general purpose MC event generator codes. Shower modelling is well-defined pQCD, hadronisation and MPI are certainly not: much more *models* than *theories*! Also used to obtain scaling factors for fixed-order calcs.

ATLAS has measured many soft QCD observables using the low-pile-up 2010 data, most obviously minimum bias (tracks) and underlying event (tracks and clusters).

Work is well underway on extensions such as lead jet and Drell-Yan UE, fwd E_T flow and UE, double parton scattering, and identified particles, esp. K & Λ.

Also semi-hard QCD tests such as jet substructure and small angle dijet balance corrections, jet veto studies, and heavy ion physics.

Emphasis on model-independent analysis strategies ensure that these measurements will continue to be useful.

Summary (MC models & tuning)

Tuning studies based on all the available data from Tevatron and ATLAS:

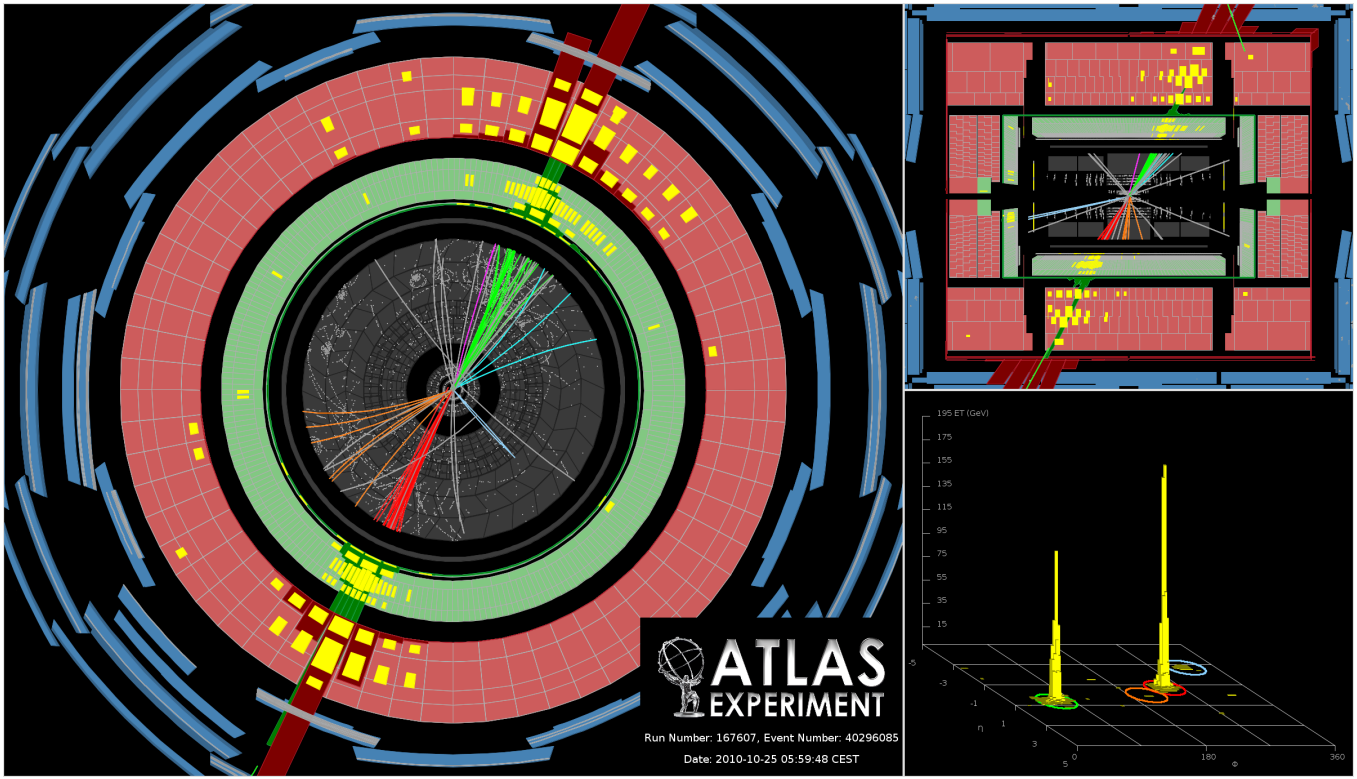
- New PYTHIA, HERWIG/JIMMY, Pythia 8 tunes describe ATLAS data well. New Herwig++ and Sherpa author tunes, too. PDF effects.
- However, description of all datasets by the PYTHIA (most "flexible") model has evaded us so far: ATLAS minimum bias has $\sim 10\%$ lower MPI than ATLAS UE. Track and cluster UE are consistent. PYTHIA energy evolution describes much CDF UE data well, but not the min bias triggers, and not the Run II leading jet UE.
- ATLAS UE tunes describe CDF min bias $\langle p_T \rangle$ vs. N_{ch} correlation better than ATLAS MB tunes! JIMMY model has gone as far as it can with AUET1, AUET2.
- Side-effect of tuning technology: more sophisticated systematics

The devil is in the (simultaneous) details – my feeling is that the MPI models are starting to crack under pressure – but maybe we just need to understand PDFs better... **More questions than answers! New models? "Tune killing." Watch this space.**

Semi-soft QCD

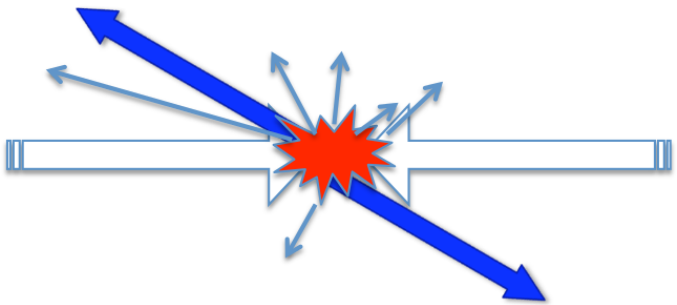
Highest-mass ATLAS dijet system: $M_{12} = 3.8$ TeV

There is still soft physics at work here!

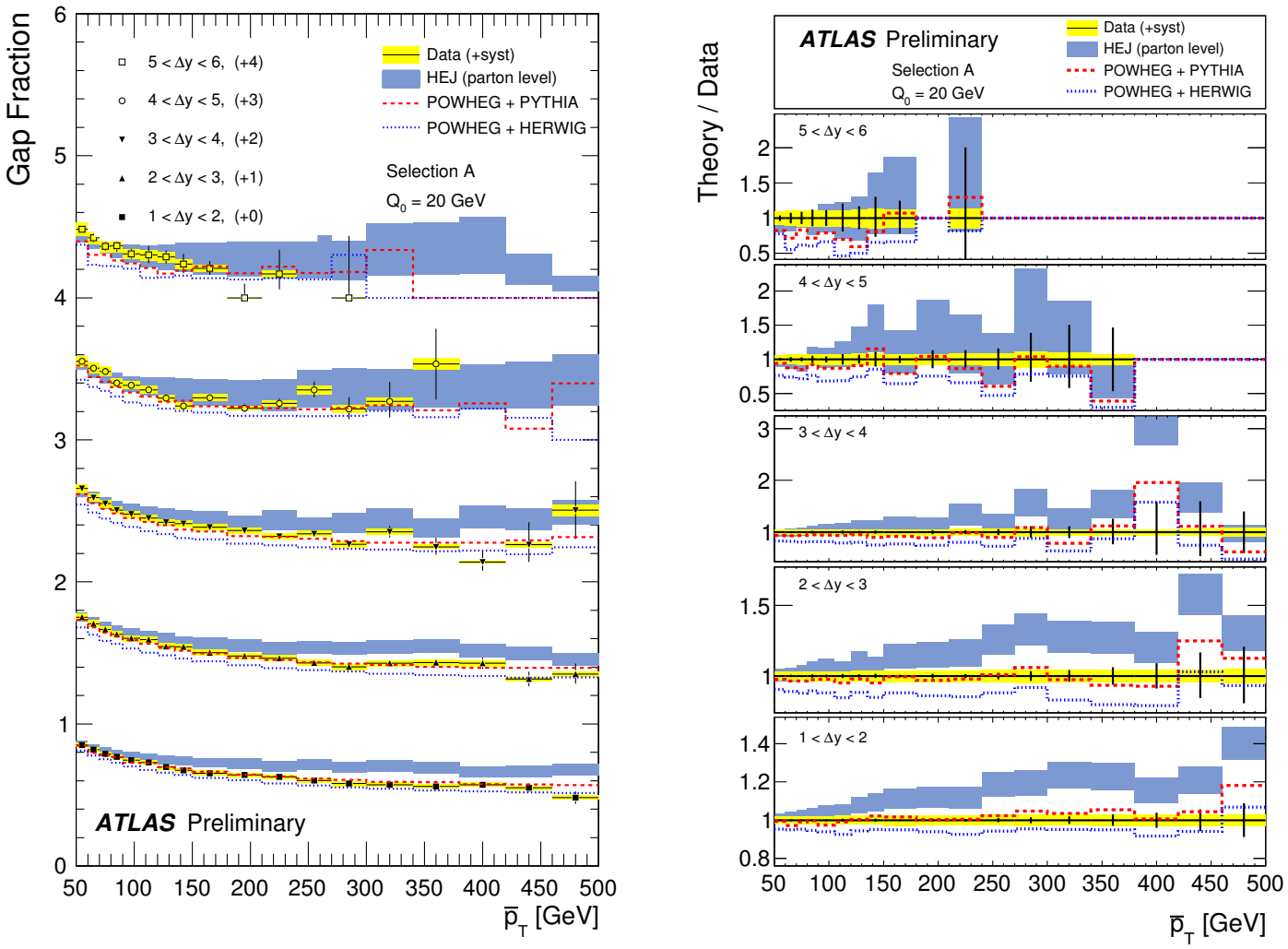


Rapidity gap and dijet veto

- Dijet veto preliminary analysis studies the fraction of events with a rapidity gap of size Δy between two hard forward jets.
- Two selections applied, where A) boundary jets are the two hardest jets in the event, B) boundary jets are the two most separated jets in the event. For various jet p_T cuts. ATLAS-CONF-2011-038
- Driven largely by interest in backgrounds and rapidity gaps for central excusive Higgs production (cf. FP420 project). Sensitive to UE effects, rapidity evolution logarithms missing from most generators (except HEJ), etc.

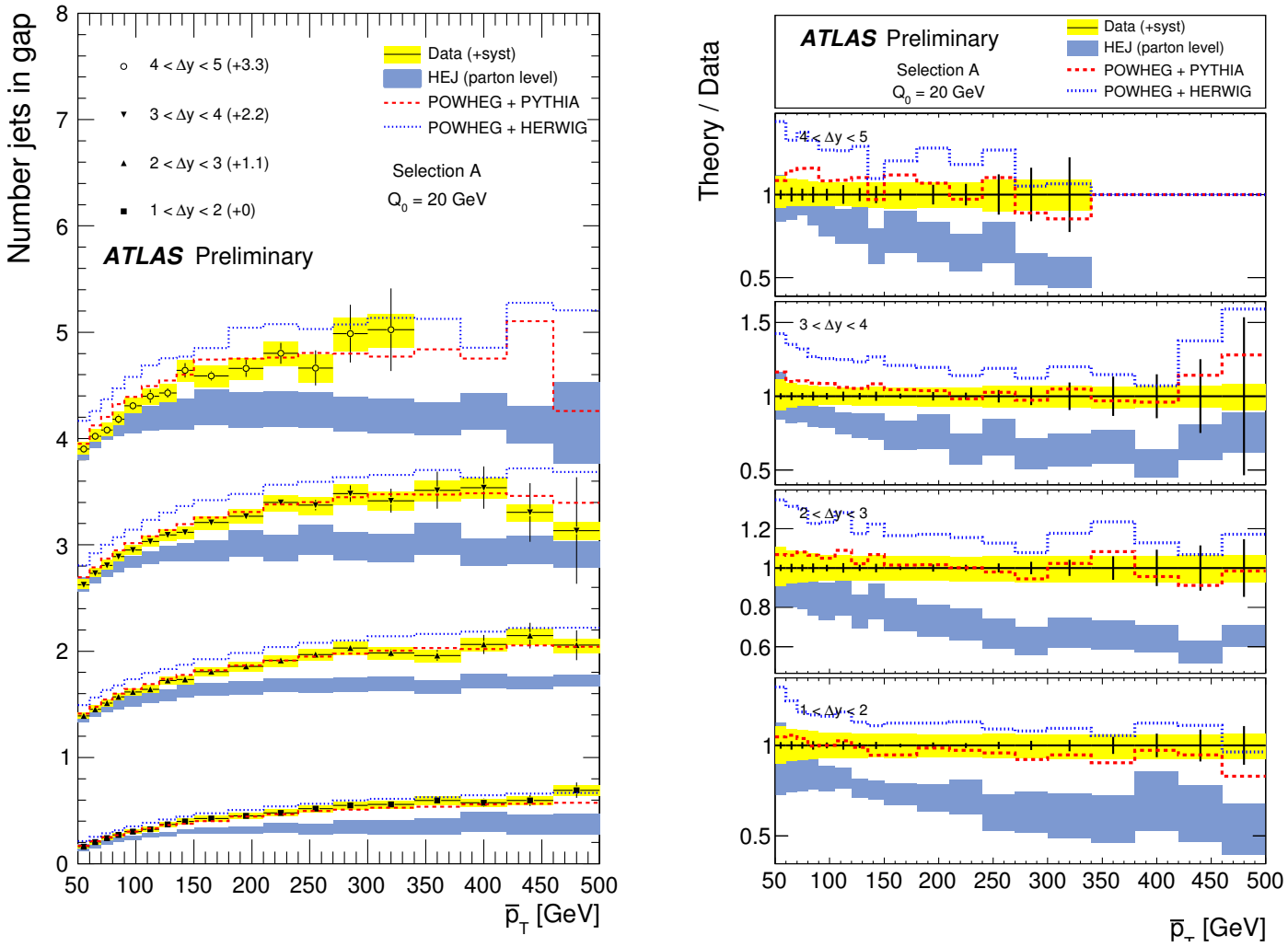


Rapidity gap and dijet veto: jet fraction



Does HEJ do better, or does it just have bigger displayed systematic errors? HERWIG seems to be in trouble.

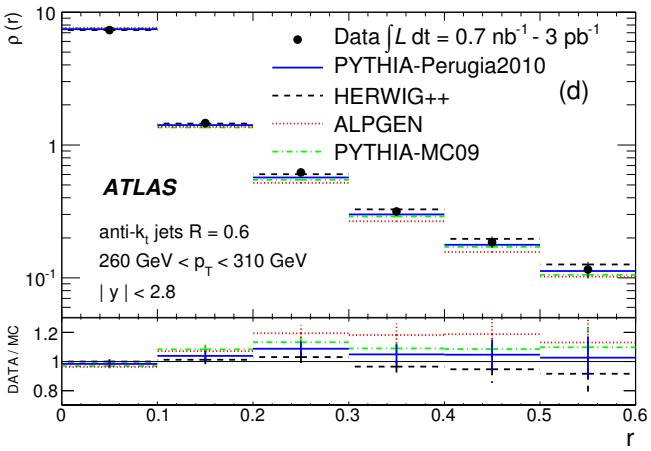
Rapidity gap and dijet veto: # jets in gap

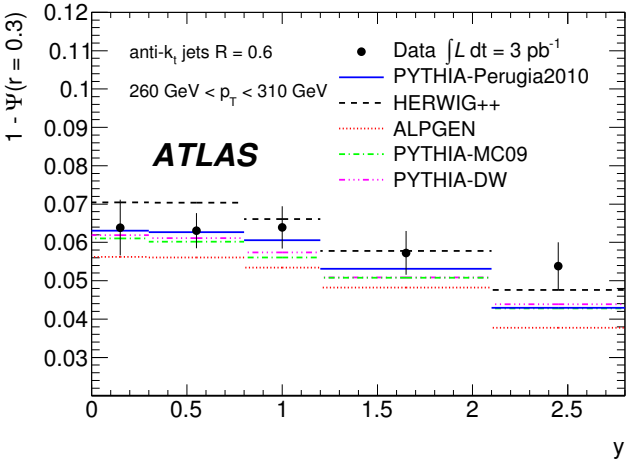


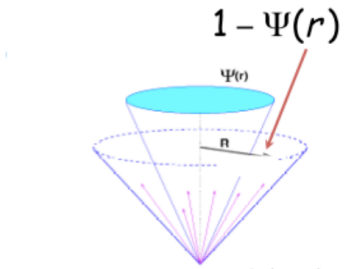
HEJ not doing well at predicting the number of jets in the gap.
PYTHIA really doing surprisingly well!

Jet shapes

Study the amount of p_T in annuli around jet centroids, binned in jet y and p_T. See the usual result, that jet become more collimated with increasing p_T. How well is this modelled by parton shower MCs?





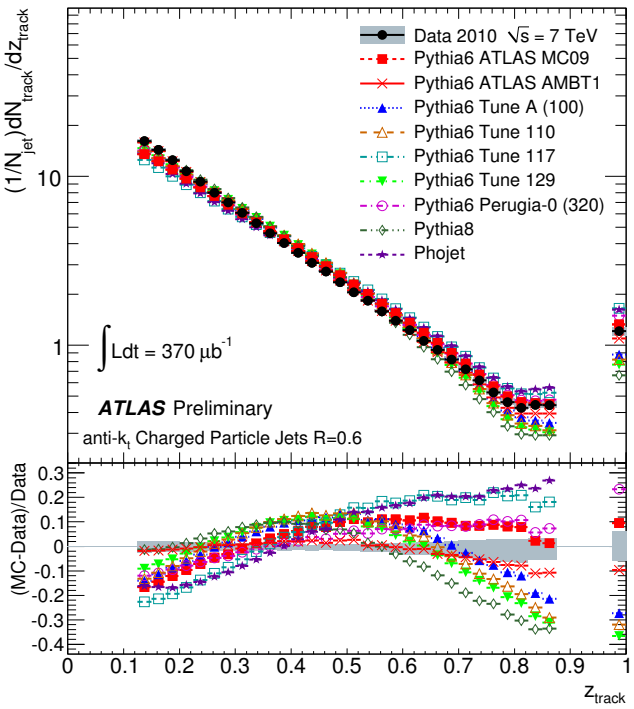


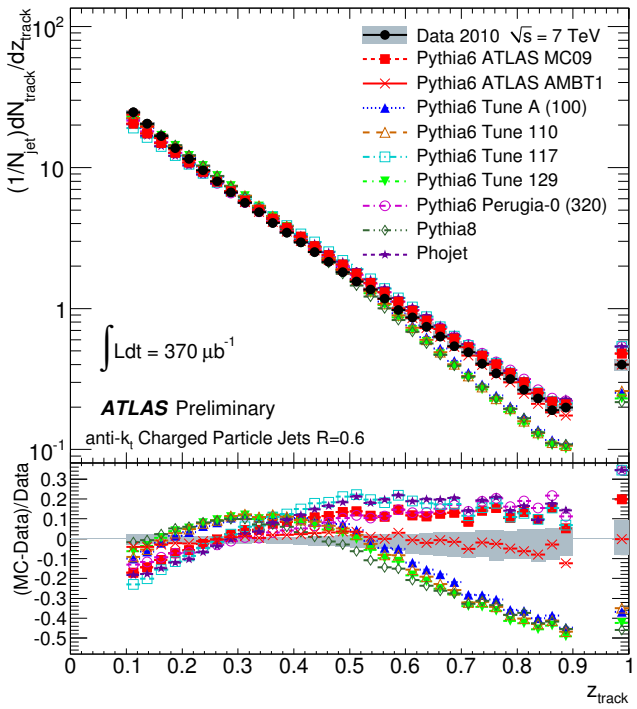
$$\Psi(r) = \frac{1}{N_{jets}} \Sigma_{jets} \frac{P_T(0,r)}{P_T^{jet}(0,R)}$$

AlpGen is screwing up leading log accuracy of the HERWIG parton shower! Similar seen for AlpGen+PYTHIA.

Consistency needed between ME and shower α_s – new AlpGen release expected, for use with PYTHIA Perugia 2011 setup. Constraint agreements like this are also good for tuners' sanity!

Track-jet fragmentation

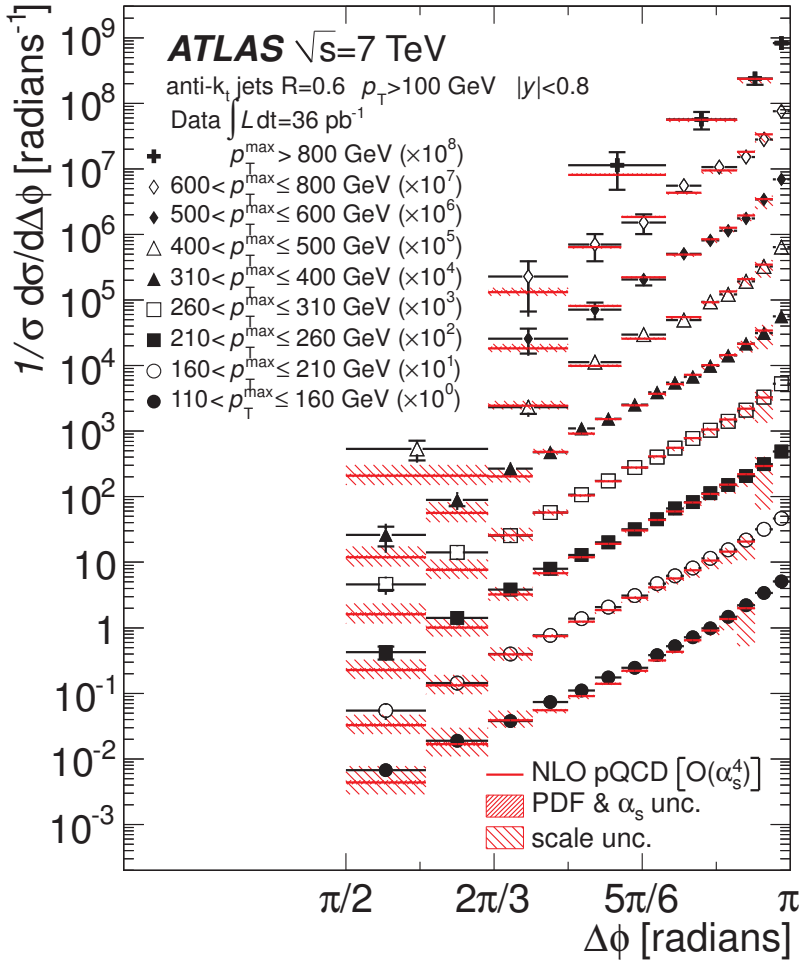




Longitudinal fragmentation function $z_i = p_{\text{jet}} \cdot p_{i \in \text{jet}} / p_{\text{jet}}^2 = p_{||}^i / p_{\text{jet}}$ is sensitive to α_s in FSR from ISR stub emissions. Tension with transverse jet shapes in shower tuning.

Dijet azimuthal decorrelation ($\Delta\phi_{12}$)

- Interaction with MPI modelling of UE etc. cf. Tune A vs. Tune DW.
- Still important in tuning – but we're now careful to try not to ask PYTHIA to describe unambiguously > 2 jet configurations.
- Tune shower to this *before* tuning MPI.



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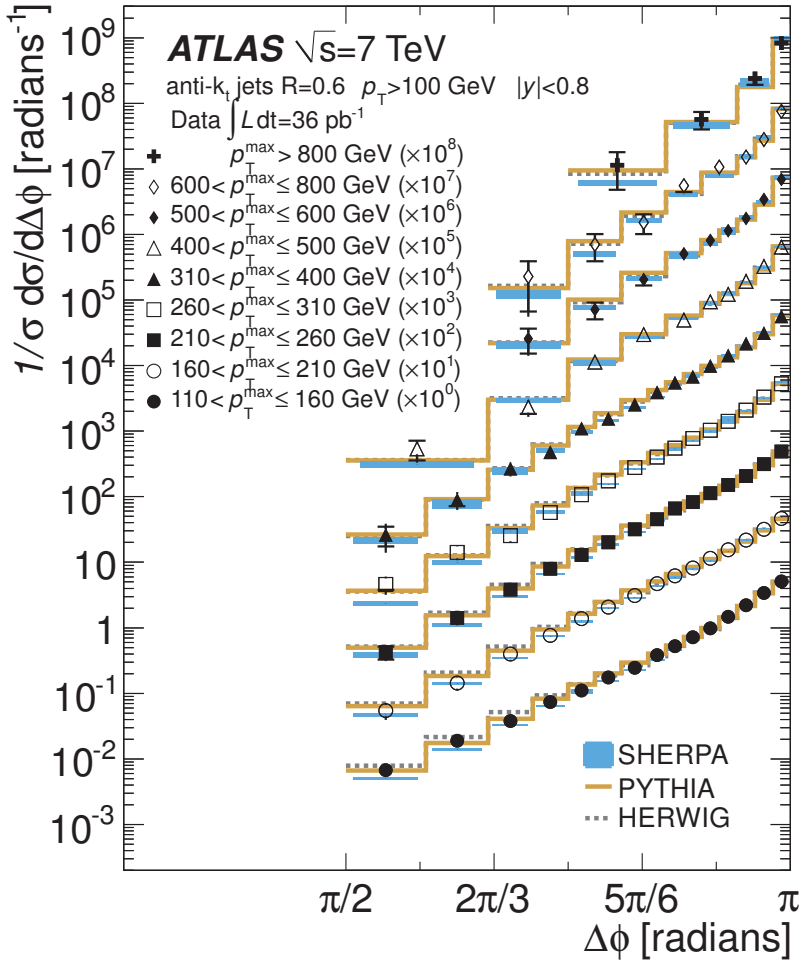

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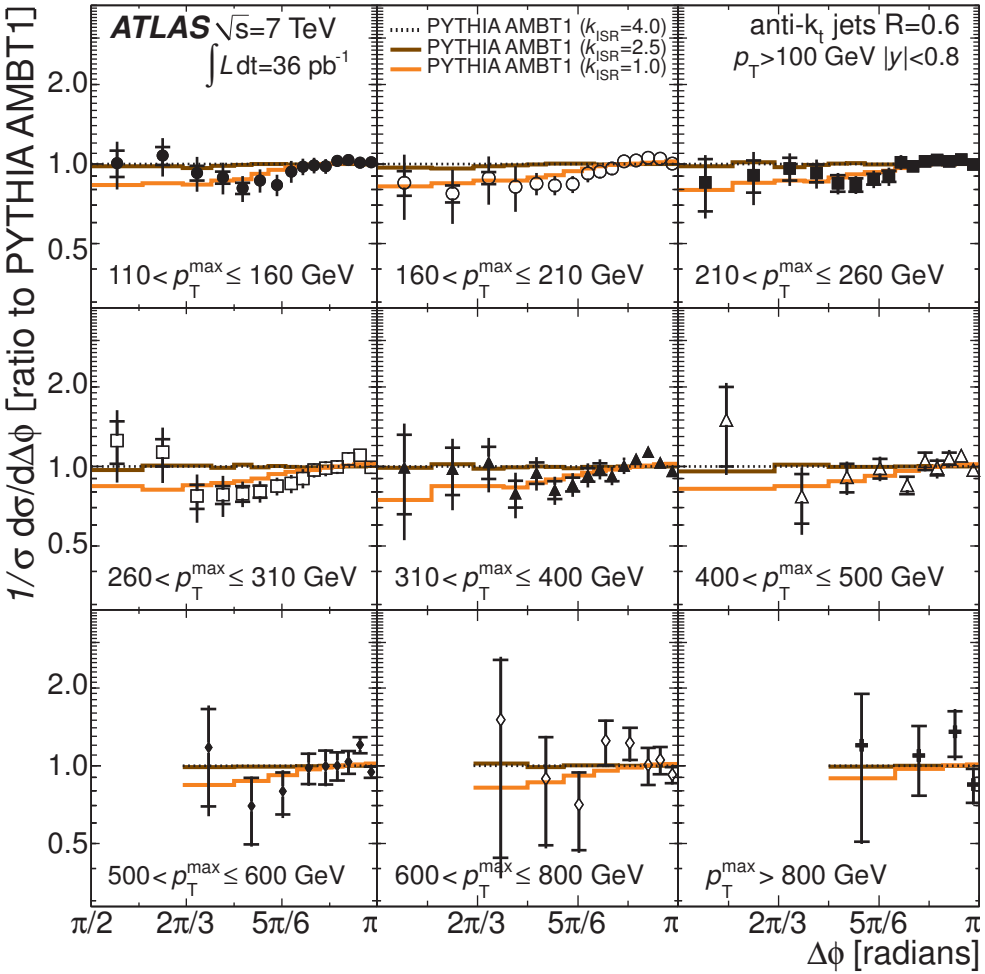

PYTHIA k_{ISR} = PARP(67) result: p_T-ordered shower favours lower boost factors – maybe even < 1. CMS study with Q^2-shower wanted *larger* K_{ISR}! Different logs in shower: no contradiction.