Low-energy QCD at the high-energy frontier

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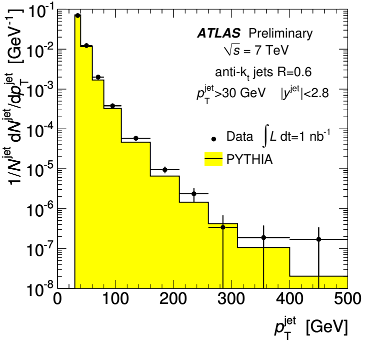
Soft QCD at a hard collider

- The LHC is the highest-energy particle collider ever made – built to directly produce new particles at the TeV scale.
- But the dominant interactions are still overwhelmingly soft!
- Usually dismiss this stuff as "just min bias" – but that means it's collective QCD interactions of whole nucleon systems. A theory nightmare!
- In these early days of running we want to understand it as well as we can: as a background and for pure interest.



This talk will be ATLAS-dominated: sorry! But it's not all *that* unfair.

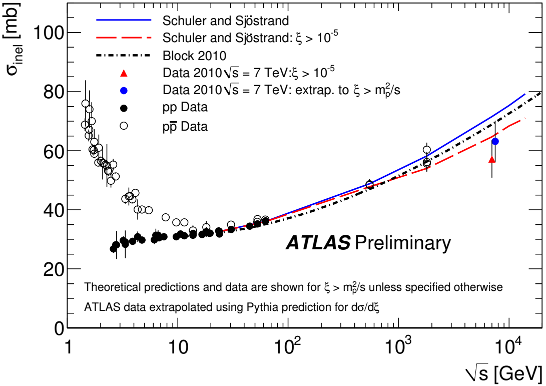
Multiple parton interactions (MPI)

Number of parton interactions connected to the ratio of parton–parton cross-sections $\hat{\sigma}$ and total p–p cross-section, σ.

QCD total cross-section evolves with $\sqrt{s}$, e.g. 1992 Donnachie–Landshoff parameterisation, from S-matrix analyticity:

$$\sigma^{pp}_{\mathrm{tot}}(s) \gtrsim 21.7\,\mathrm{mb} \cdot (s/\mathrm{GeV}^2)^{0.0808} \to \sigma_{\mathrm{tot}}(14\,\mathrm{TeV}) = 101\text{–}164\,\mathrm{mb}$$

New ATLAS measurement of σ_{inel} evolution to 7 TeV:



Minimum bias vs. "underlying event"

Soft QCD is interesting because it's not just a single-parton interaction: instead we have multiple, correlated interactions. Correlations are non-perturbatively generated.

Minimum bias is purely soft MPI; underlying event (UE) is soft QCD in the presence of a hard scattering, such as hard QCD, EW boson production…or Higgs production/new physics! UE = "partial bias". There is no sharp distinction.

TeV-scale new physics searches are mostly designed to be pretty insensitive to soft QCD, but it's still important to describe the QCD structure of the events as well as possible. UE could be important for e.g. analyses based on jet-structure.

MC models of soft QCD

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

- Multiple parton interactions (in an eikonal approximation formalism)
- 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)
- Black magic!

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

MPI models are the least predictive part of MC event generators! Lots of non-perturbative QCD, but very dynamic so lattice/semi-analytic methods don't work (even if they were tractable on MC event CPU timescales)

MC models are the place where theory meets experiment – close interaction.

More MC model details

Many variations: basic PYTHIA model is the most used/familiar:

- Ansatz: apply a $\hat{p}_\perp$ cutoff, $\hat{p}_\perp^0$, below which scatterings are vetoed or their cross-sections are suppressed. PYTHIA uses special "soft-scattering" matrix elements below the $\hat{p}_\perp^0$ cutoff.
- Another ansatz: assume that $\hat{p}_\perp^0$ evolves with energy with a power law "inspired" by the original Donnachie–Landshoff pomeron fit:

$$\hat{p}_\perp^0(\sqrt{s}) = \hat{p}_\perp^0(\sqrt{s_0}) \cdot \left(\frac{s}{s_0}\right)^{e/2}$$

  $\hat{p}_\perp^0(\sqrt{s_0})$ and e are user-configurable parameters. Usually set $\sqrt{s_0} = 1800\,\mathrm{GeV}$. DL pomeron $e \sim 0.16$.
- Finally, a configurable nucleon hadronic mass distribution in impact parameter space. PYTHIA has several variants, the most-used being a 2-parameter double-Gaussian.

Tuning the PYTHIA and JIMMY MPI models

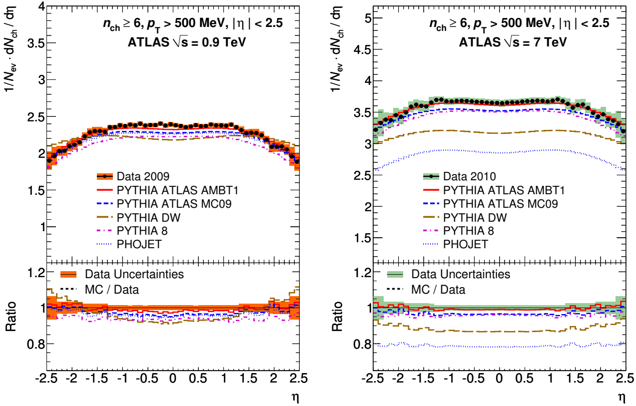
Need to fit pheno parameters of asymptotic MPI models to describe data. Model tuning is best done as the final stage of a wider tune. The first stages constrain hadronisation (flavour + kinematics), and initial/final-state parton showers: leave as little room as possible for the MPI to exceed its mandate.

ATLAS has driven tuning of the Fortran PYTHIA and HERWIG/JIMMY generators to LHC data: new set of tunes for each generator, using early ATLAS data: diffractive-reduced MB data with $N_{\mathrm{ch}} \geq 6$, ATLAS UE (limited stats) + CDF MB & UE data.

Tuning done using the *Rivet* analysis system to produce data at lots of points in the tuning parameter space, then parameterisation of the observables is done with the *Professor* tool to find optimal parameters.

Minimum bias and PYTHIA AMBT1

Minimum bias data from ATLAS covering quite inclusive charged particle observables using the central tracker. Mainly with a track cut of $p_T > 500\,\mathrm{MeV}$, but also at $100\,\mathrm{MeV}$: a challenge for the models. Various phase spaces, such as diffraction-suppressing N_{ch} cuts.



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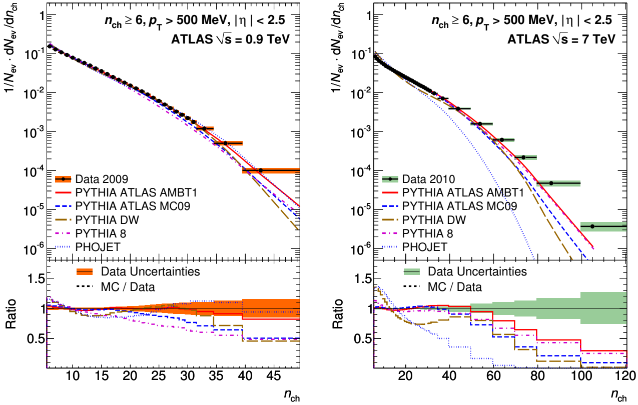

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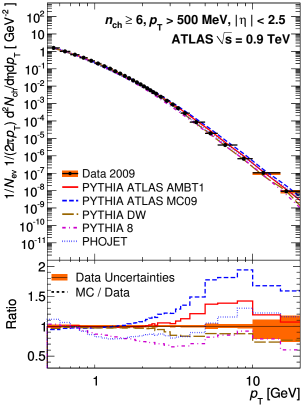

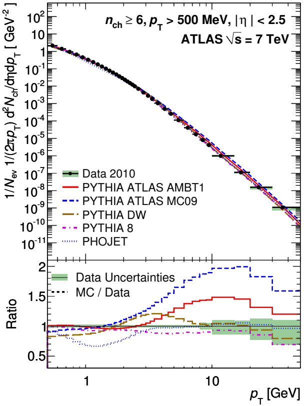

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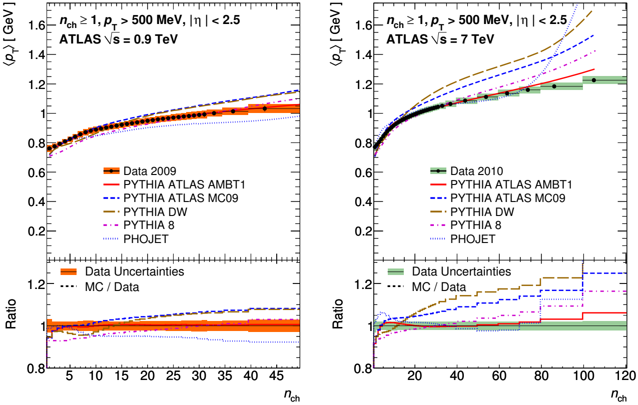

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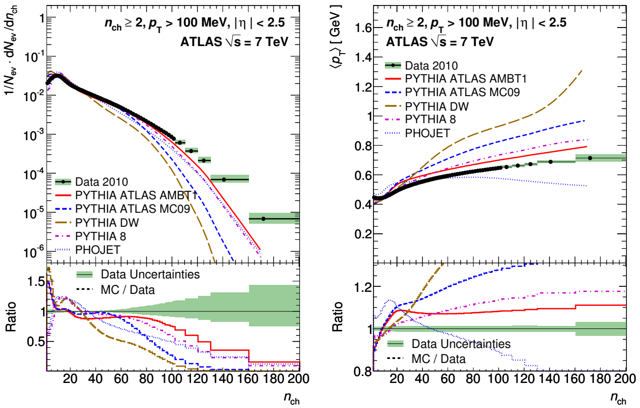
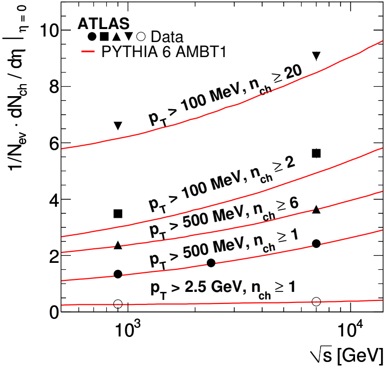


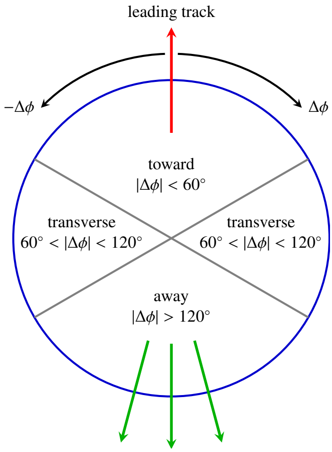
Minimum bias and PYTHIA AMBT1

AMBT1 is a min bias dominated tune of PYTHIA MPI: massive improvement in data description by MC. Since then, PYTHIA tuning has moved on to describing hard jets, and then revisiting MB and UE with more data and observables.



UE observables

- Underlying event observables are designed to require a hard scattering process, but to minimise its effect.
- 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.)



ATLAS UE measurements

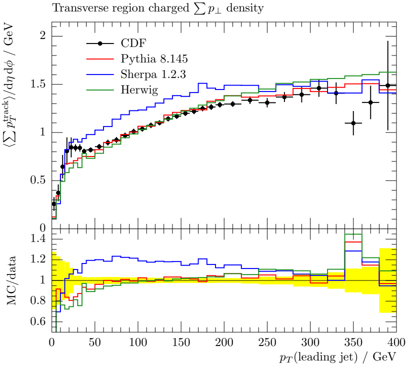
We use the leading track rather than leading jet for event orientation – only a useful strategy for a short $p_\perp^{\text{lead}}$ reach (< 20 GeV) but fewer systematics. A good plan: CMS are still unfolding and ATLAS JES is not yet well-understood below ~ 30 GeV!

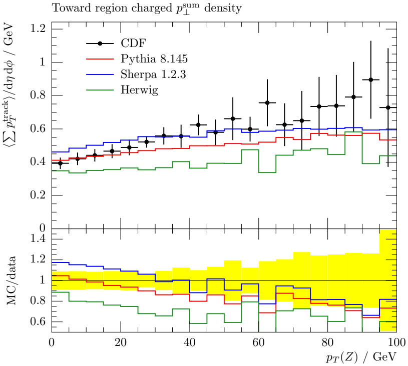
Min bias triggered events, but require one track within tracker acceptance of $|\eta| < 2.5$ with $p_T > 1$ GeV. Measured at both 900 GeV (limited stats) and at 7 TeV: different energies important for MPI model tuning. Track p_T cuts of 100 and 500 MeV.

Correction back to particle level (as for min bias) – lots of reweighting to account for track and vertex efficiency functions, bin migrations, fakes and secondaries, MC input systematics, detector material. Direct input for signal MC tunings of MPI etc..

Previous UE observations

First UE measurements were made by CDF in 2001: $p\bar{p}$ at 1800 GeV. Since then, several more CDF studies: transverse cones in 2004, and Drell-Yan and high-stats leading calo jet versions in 2008.



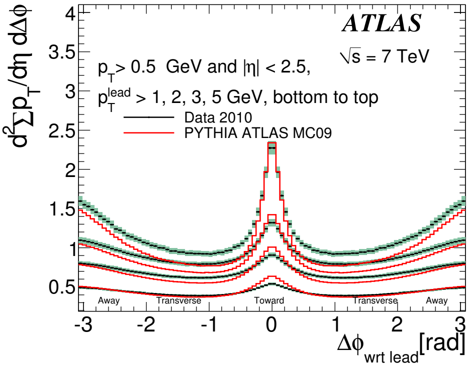


These have all been used in recent years for MC tuning. Little diffractive process effect means it is a clean observable: most MC diffractive models are not great!

$\Delta\phi$ distribution

$\sum p_T$ in $\Delta\phi$ relative to leading track, at 7 TeV

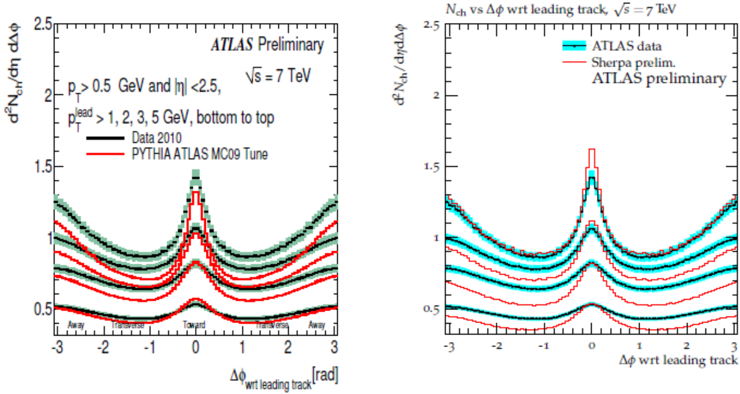
- Leading track at $\Delta\phi = 0$ has been removed, plot is $+/-$ symmetrized.
- Various cuts on track p_T shown.
- Note emergence of leading and balance jet structure; transverse region is depleted of jet activity.
- MC description of $\Delta\phi$ is pretty bad for higher $p_\perp^{\text{lead}}$



PYTHIA vs. Sherpa description of $\Delta\phi$ data

UE at LHC 7000 GeV – included in tuning

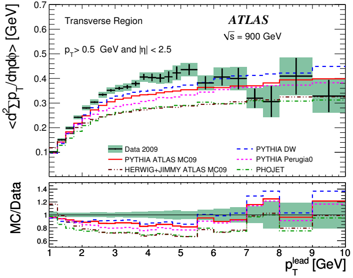
ATLAS-CONF-2010-081 – left plot taken from ATLAS note

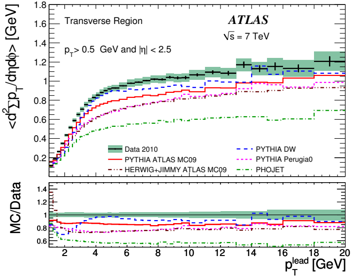


(from Hendrik Hoeth, Nov 2010 ATLAS MC meeting / MPI@LHC)

ATLAS UE measurements

$\sum p_T$, transverse region, 900 GeV and 7 TeV

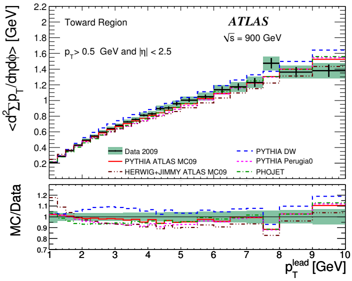


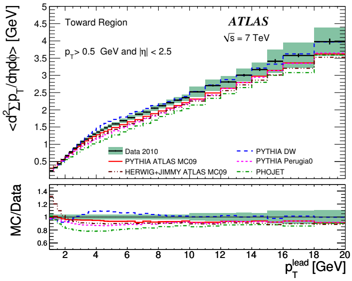


Variety of different MC predictions! PHOJET totally uncompetitive for UE (and not generally useful, anyway).

ATLAS UE measurements: results

$\sum p_T$, towards region, 900 GeV and 7 TeV

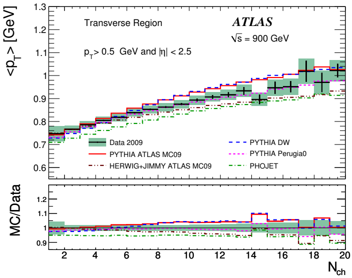


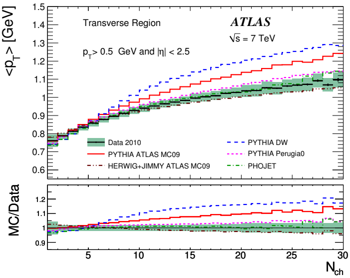


Mostly perturbative hard process, so well-described by MC.

ATLAS UE measurements: results

$\langle p_T \rangle$ vs. n_{ch}, transverse region, 7 TeV, 500 MeV track p_T cut



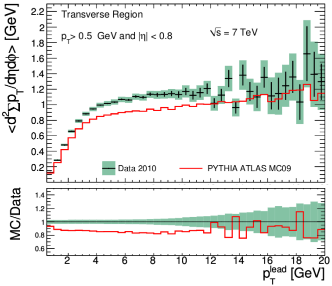


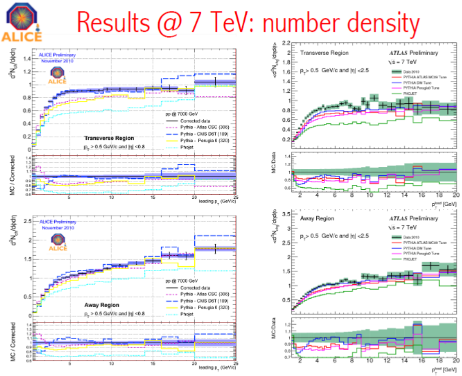
Strongly influenced by tuning of colour reconnection models: variety of MC model predictions. JIMMY surprisingly good!

LHC common UE observables

Restrict to $|\eta| < 0.8$, $p_T > 500\,\mathrm{MeV}$ for LPCC inter-LHC experiment comparisons:

ATLAS $\sum p_T$ with common cuts (see LPCC MB/UE workshop Mon/Tues this week!):





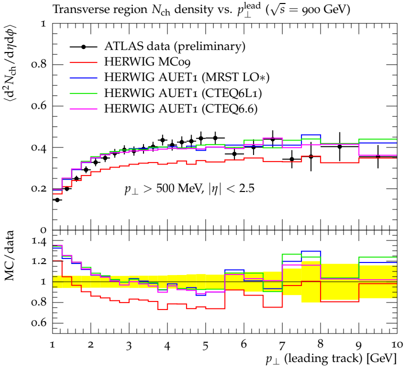
Good agreement ALICE/ATLAS

Informal comparison to ALICE looked good at MPI@LHC! (from Sara Vallejo, MPI@LHC)

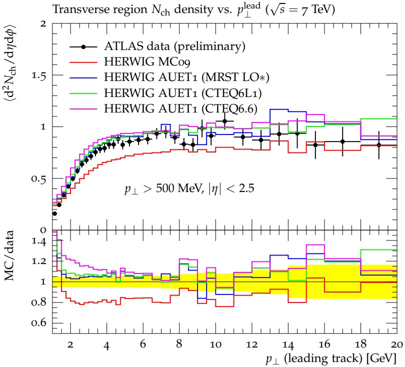
HERWIG+JIMMY AUET1 vs. ATLAS UE

JIMMY model is only valid for secondary scattering in the presence of a hard interaction: special UE-only tunes to several PDFs. Manual version of PYTHIA $\sqrt{s}$ evolution.

900 GeV



7 TeV



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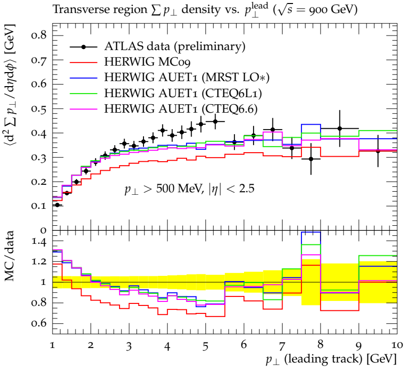

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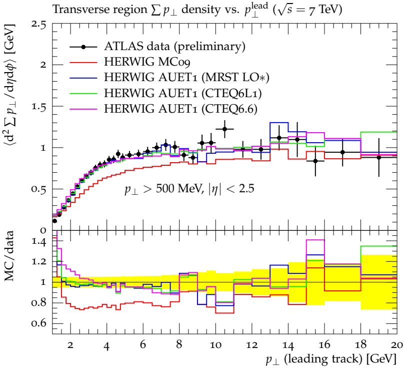

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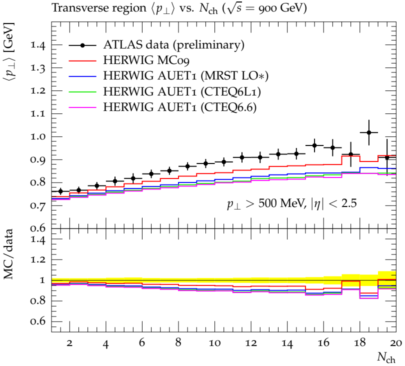
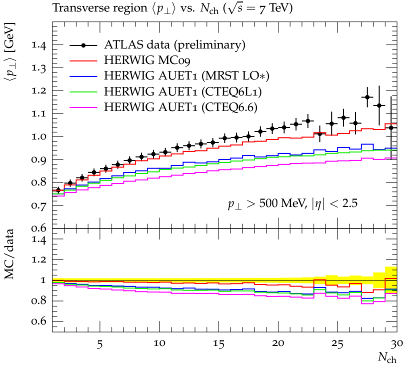
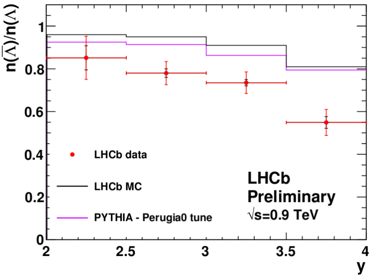
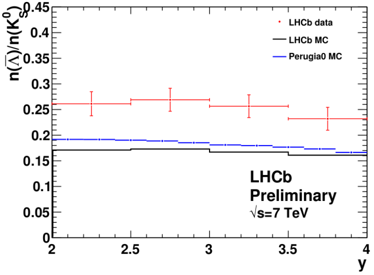




Strangeness!





ALICE and LHCb – deficient MC models. Requires a really comprehensive retune of PYTHIA (and newer C++ generators) from LEP via Tevatron to LHC to understand what's going on: happening in ATLAS.

Summary

- Collective excitations of protons are being constrained through MC models using the first year of LHC data.
- Total inel. cross-section, min bias (= pile-up), and underlying event particle and energy-momentum flow has been constrained – super-high precision, full-data version nearing completion. See almost whole particle spectrum with low-p_T tracking.
- Baryon number, strangeness, forward regions, neutral particle flow, correlations all being constrained by data *nearly* released: only 1 year in and we're already entering a new era of precision soft QCD!
- More UE measurements underway: in jets, W and Z events, using jet structure techniques for jet cleaning heuristics.
- The interesting and still mysterious places are the awkward tails of min bias, particularly forward regions and high multiplicity (cf. CMS' "near-side ridge" effect). Hard to measure, but could be very rewarding.
- Everything is a tail of min bias eventually! ;-)

Backup slides

Specific MC model details

- **PYTHIA (and Pythia 8)** also have a complex interleaving of parton shower and MPI scattering evolution, and a dynamic (and very tweakable) colour string reconnection/reconfiguration mechanism.
- **HERWIG/JIMMY** has a variant on the basic model with no energy evolution, no colour reconnection, and no purely soft scattering ("min bias")
- **Herwig++** has an extension of the JIMMY model, with soft scattering introduced in a more theoretically motivated way than PYTHIA (connection to elastic scattering and total cross-section). The immediate next release will also have pre-hadron cluster reorganisation, cf. PYTHIA's colour string reconnection.
- **PHOJET/EPOS** have a more "pomerony" soft of model, but with a lot of similar stuff like the eikonal multiple scattering bit.
- **Sherpa** currently has pretty much the basic model above, with very simple colour reconnection. But totally new KMR-based model in development for 2.0.