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Monte Carlo event generator predictions for forward physics in $\sqrt{s} = 7$ TeV proton-proton collisions

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Outline

- LHCb experiment
- Models
- Generators

→ Brief description of the models and of the generators based on them: PYTHIA, EPOS, QGSJET and SIBYLL.

- Samples and observables – Sample generation, observables used and analysis methods for the study of the generators taking as reference LHCb and TOTEM data.

- Charged energy flow
- Prompt charged particle distributions
- Prompt charged hadron ratios
- Prompt V^0 ratios

← Results for these observables.

- Conclusions.

LHCb Experiment

LHCb (*L*arge *H*adron *C*ollider - *b*eauty)

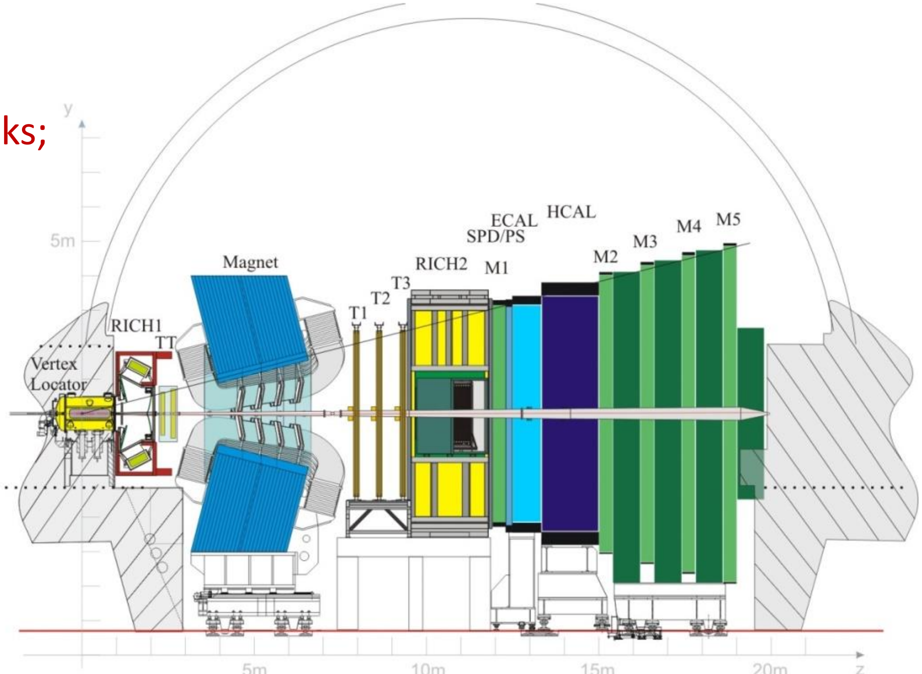
- Single-arm fully instrumented forward spectrometer $2 < \eta < 5$;
- Study of *b* and *c* hadron decays → Standard Model precision tests;
- Search for New physics beyond the Standard Model.

Tracking:

- VErtex LOcator (VELO) – Si microstrips;
- 4 Tm warm magnet;
- Silicon Tracker, TT + IT (T1-T3) – microstrips;
- Outer Tracker, OT (T1-T3) – drift tubes.
- $\sim$96% track reconstruction efficiency for long tracks;
- 0.5% - 1% momentum res. up to 200 GeV;
- $(15 + 29/p_T$ [GeV]) μm IP resolution.

PID:

- RICH1 – $\sim$ 1-60 GeV;
- RICH2 – $\sim$ 15-100 GeV;
- Kaon ID prob. of $\sim$ 95% with 5% $\pi \to K$ mis-id;
- Calorimeters: SPD/PS, ECAL, HCAL;
- Muon system: M1-M5.



The generators

Regge Field Theory (RFT): Effective field theory - interactions proceed via Pomerons (colourless).

QGSJET – based on quark-gluon string model.

- Pomerons – non-perturbative gluon pair exchange.
- Nucleons – quark-diquark systems
- Quark from first nucleon exchanges a soft gluon with the diquark from the second and viceversa.
- 2 quark-gluon strings which fragment.
- Soft and semihard Pomeron contributions.
- Non-linear effects at high energies from Pomeron-Pomeron interactions.

SIBYLL:

- dual-parton model for soft processes (similar to quark-gluon string model)
- minijet model for hard processes
- Lund string fragmentation for hadronization.

- Used for CR and HI collisons (+EPOS).

PYTHIA – parton based:

- Used for collider physics.
- Based on QCD.
- Main event can be: elastic and diffractive (using Pomerons), soft and hard QCD processes. electroweak, heavy flavour production etc.
- Parton Showers (ISR and FSR).
- Multiparton interactions (MPI) and beam remnants (BR).
- Lund string fragmentation model.
- Extensions for AA collisions exist.

EPOS: Parton-based Gribov-Regge theory.

- Hydrodynamic models for AA and pp.
- Soft, hard ($Q^2 <,> Q_0^2 \sim 1\ \mathrm{GeV}^2$) and semihard (sea partons with $x \ll 1$) Pomerons.
- Good remnant treatment.
- Both cross section and particle production calculations take into account energy cons.
- Core-corona model: core – region with high density of strings (collective hadronization).

Samples and observables

Generators:

- with default settings.
- all with LHC tunes (in central rapidity).

- PYTHIA 8.186 (4C tune).
- PYTHIA 8.219 (Monash 2013 tune).

From CRMC (Cosmic Ray Monte Carlo) package:

- EPOS LHC;
- QGSJETII-04;
- SIBYLL 2.3.

Measurements from:

R. Aaij *et al.*, Eur. Phys. J. C (2013) 73:2421.
R. Aaij *et al.*, Eur. Phys. J. C 72 (2012) 2168.
R. Aaij *et al.*, JHEP 1108 (2011) 034.
R. Aaij *et al.*, Eur. Phys. J. C (2014) 74:2888.
R. Aaij *et al.*, Eur. Phys. J. C (2012) 72: 1947.
G. Antchev *et al.*, EPL, 98 (2012) 31002.

Samples:

- 10^7 minbias events @ 7 TeV;
- LHCb phase-space: $\sim 2 \leq \eta \leq 5, p_{ch} \geq 2\ GeV$;
- Stable particle definition: $c\tau \geq 3000\ mm$;
- Promptness cut: $prodvertex \leq 0.2\ mm$.

Observables:

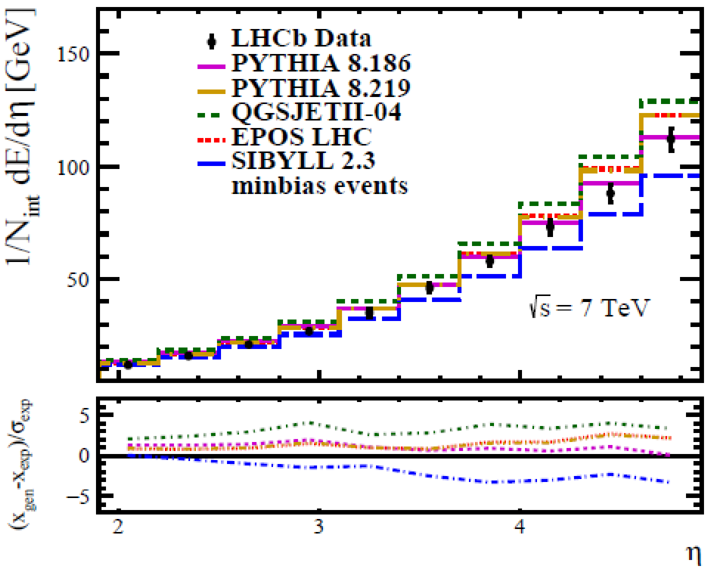
- Charged energy flow:

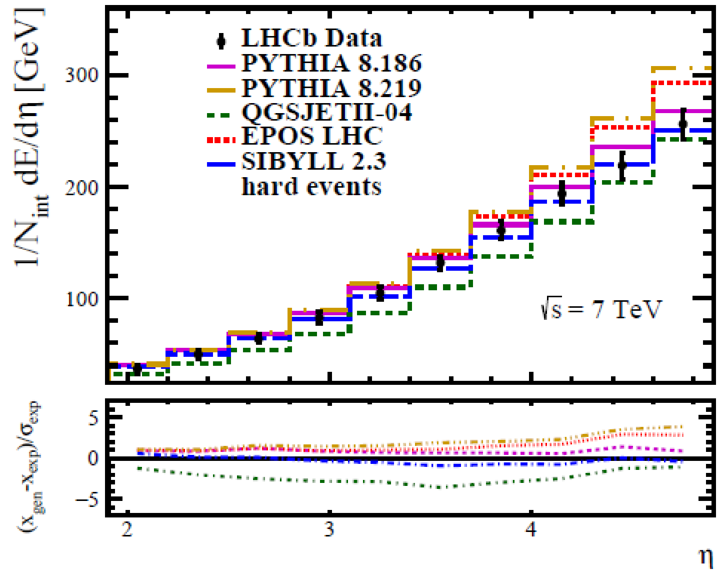
$$\frac{1}{N_{int}} \frac{dE_{ch}}{d\eta} = \frac{1}{\Delta\eta} \left(\frac{1}{N_{int}} \sum_{i=1}^{N_{part,\eta}} E_{i,\eta} \right)$$

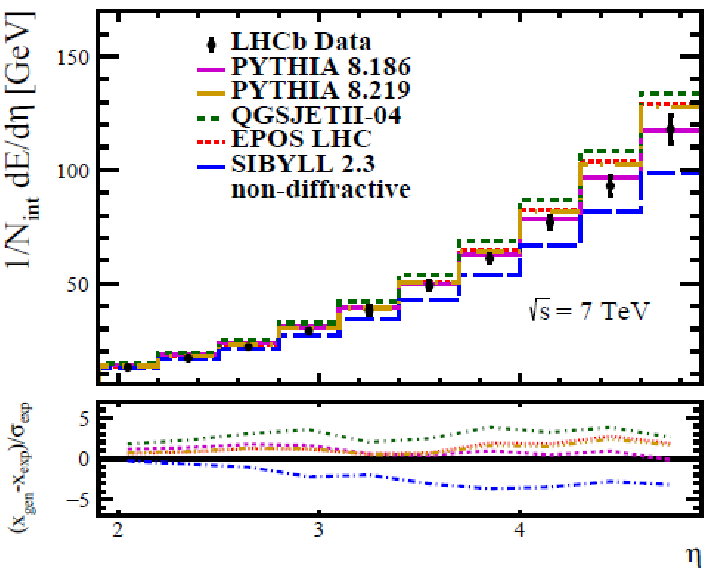
  - Charged stable particles (p, K, π, e, μ).

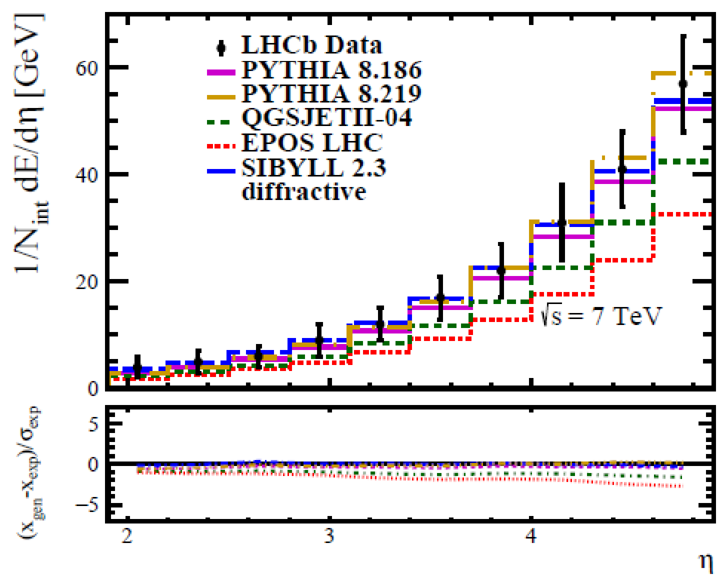
- Prompt charged-particle distributions:
  - p_T, η, multiplicity.
- Prompt charged-hadron ratios:
  - p/K, p/π, K/π etc.
- Prompt V^0 ratios:
  - $\overline{\Lambda}/\Lambda$, $\overline{\Lambda}/K_S^0$.

Charged energy flow









Charged energy flow

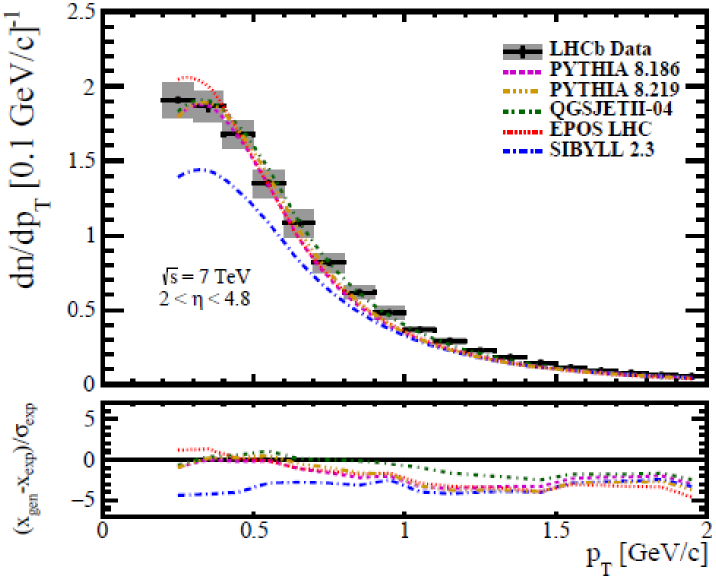
Event class definitions:

- Minimum bias: $n_{ch} > 0$ in $1.9 \leq \eta \leq 4.9$
- Hard: $n_{ch} > 0$ with $p_T \geq 3$ GeV/c in $1.9 \leq \eta \leq 4.9$
- Non-diffractive enriched: $n_{ch} > 0$ in $-3.5 \leq \eta \leq 1.5$
- Diffractive enriched: $n_{ch} = 0$ in $-3.5 \leq \eta \leq 1.5$

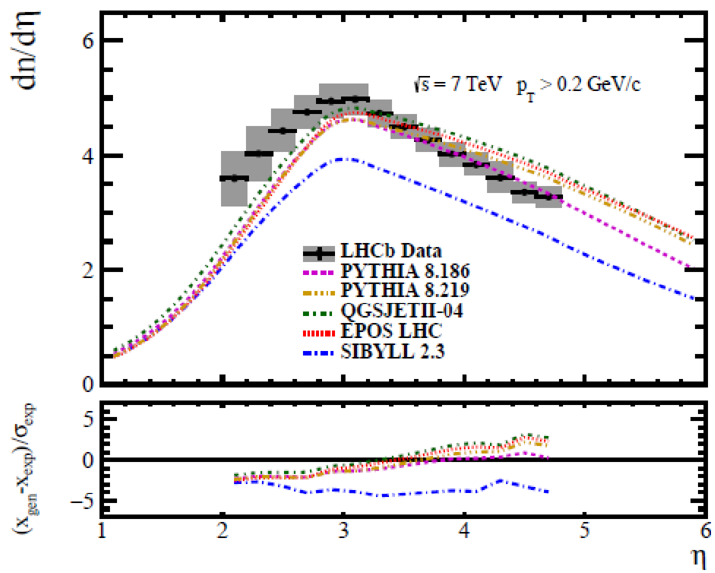
Results:

- Shapes are reasonably well described.
- PYTHIA 8.186 has the best description overall.
- PYTHIA 8.219 – good description for diffractive events, but worse than 8.1 for the rest. Similar to 8.1 in the central region, but overestimating in the forward region – Effect of extrapolation in forward or increase in strangeness production from Monash 2013 tune.
- EPOS LHC is similar to PYTHIA 8.219 (and close to PYTHIA 8.186 values) except for diffractive events where it underestimates.
- QGSJETII-04 overestimates the charged energy flow for minbias and underestimates for hard events. Except for the diffractive events, the differences are significant at 5σ level.
- SIBYLL 2.3 has the best prediction for hard events and is on par with PYTHIA 8.1 for diffractive events, but largely underestimates the soft process component.

Prompt charged-particle distributions

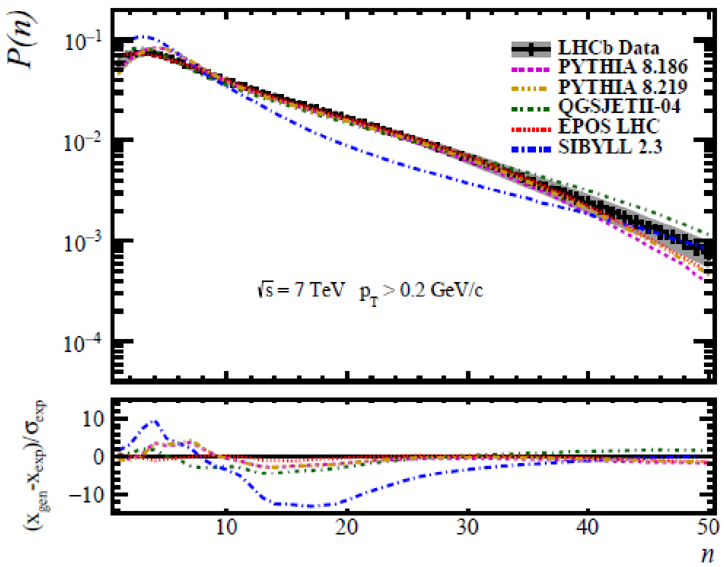


- p_T - All shapes approach the experimental one, but differences in abs. values are large, esp. in the harder part.
- QGSJET is closest to the measurements.
- PYTHIA and QGSJET are similar in shape.
- No major difference between PYTHIA versions.
- PYTHIA and EPOS similar in $0.5 \leq p_T \leq 1.5$ GeV/c.
- SIBYLL - deviations are significant.

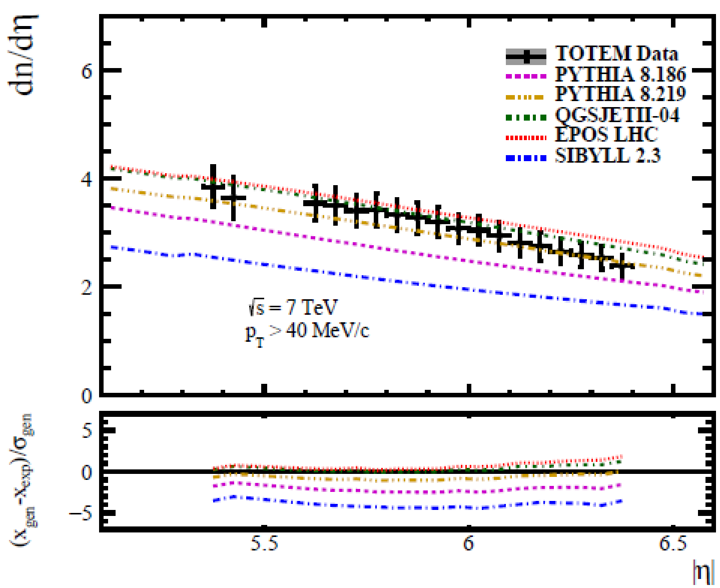


- η - All predictions cluster in the central region – Tuning.
- QGSJET, EPOS and PYTHIA 8.2 underestimate below η = 3.5 and overestimate in the forward region (where they also remain clustered together).
- PYTHIA 8.1 also underestimates the measurements in the central region, but the prediction in the forward region seems to be reasonably good.
- SIBYLL largely underestimates across the whole range.

Prompt charged-particle distributions

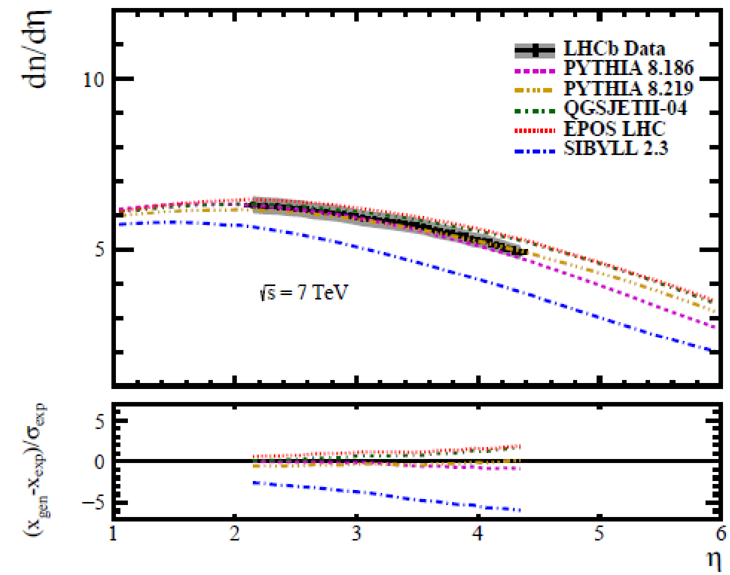


- All except SIBYLL describe the measurements well.
- EPOS is closest to the measurements.
- EPOS and PYTHIA cluster together in the mid-high region.
- For low values EPOS is better than PYTHIA.
- QGSJET underestimates the measurements in $n_{ch} = 5 - 20$ and overestimates them in the high multiplicity region.
- SIBYLL has wrong shape – heavily favouring low multiplicities, but getting closer at high values.
- Similar polarizing effect can be seen for the other generators, but at a much lower level.

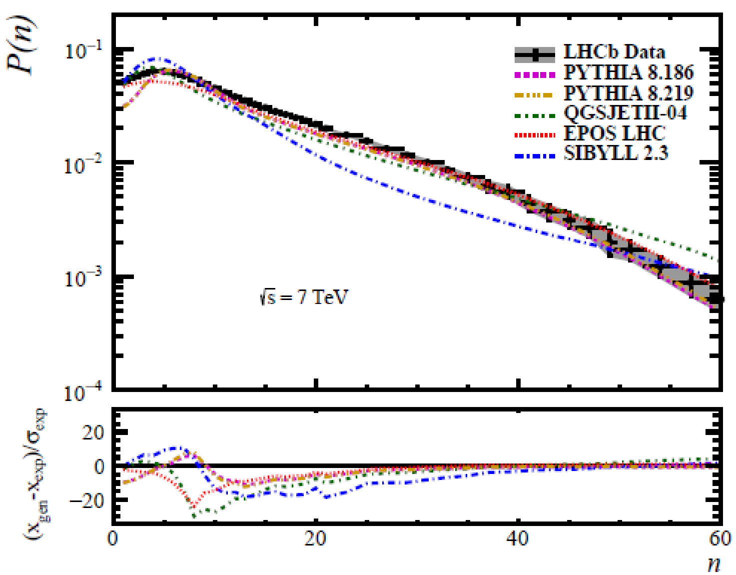


- QGSJET, EPOS and PYTHIA 8.219 descriptions are very good.
- All shapes agree well with the experimental one.

Prompt charged-particle distributions

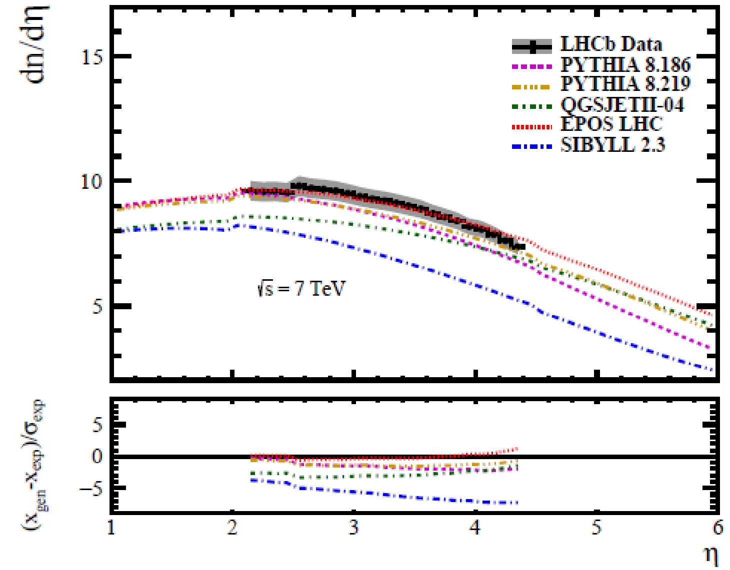


- Best described by PYTHIA 8.1.
- PYTHIA 8.2 is close, too.
- QGSJET and EPOS diverge in the forward region – similar to previous plot.
- SIBYLL is significantly different.
- All except SIBYLL cluster in the central region.



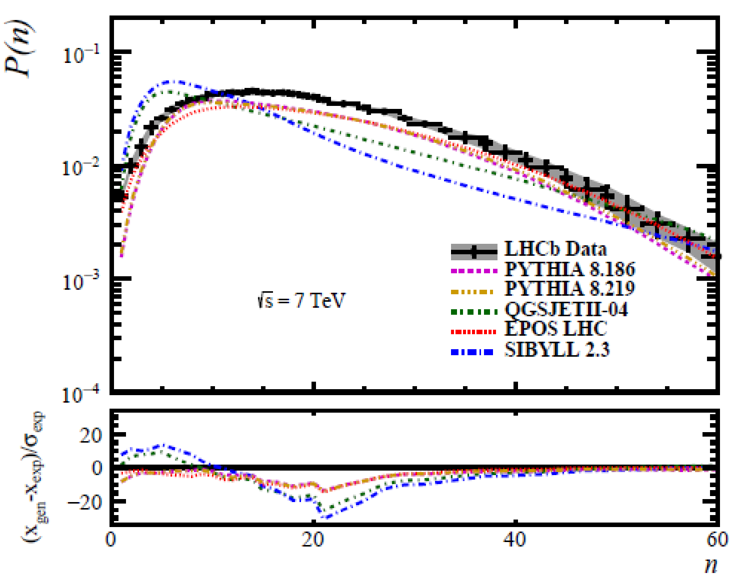
- Not well described by any of the generators.
- EPOS and PYTHIA are better at higher values – as in the previous plot.
- QGSJET and SIBYLL differ significantly from measurements.
- Favouring of very low multiplicities.

Prompt charged-particle distributions



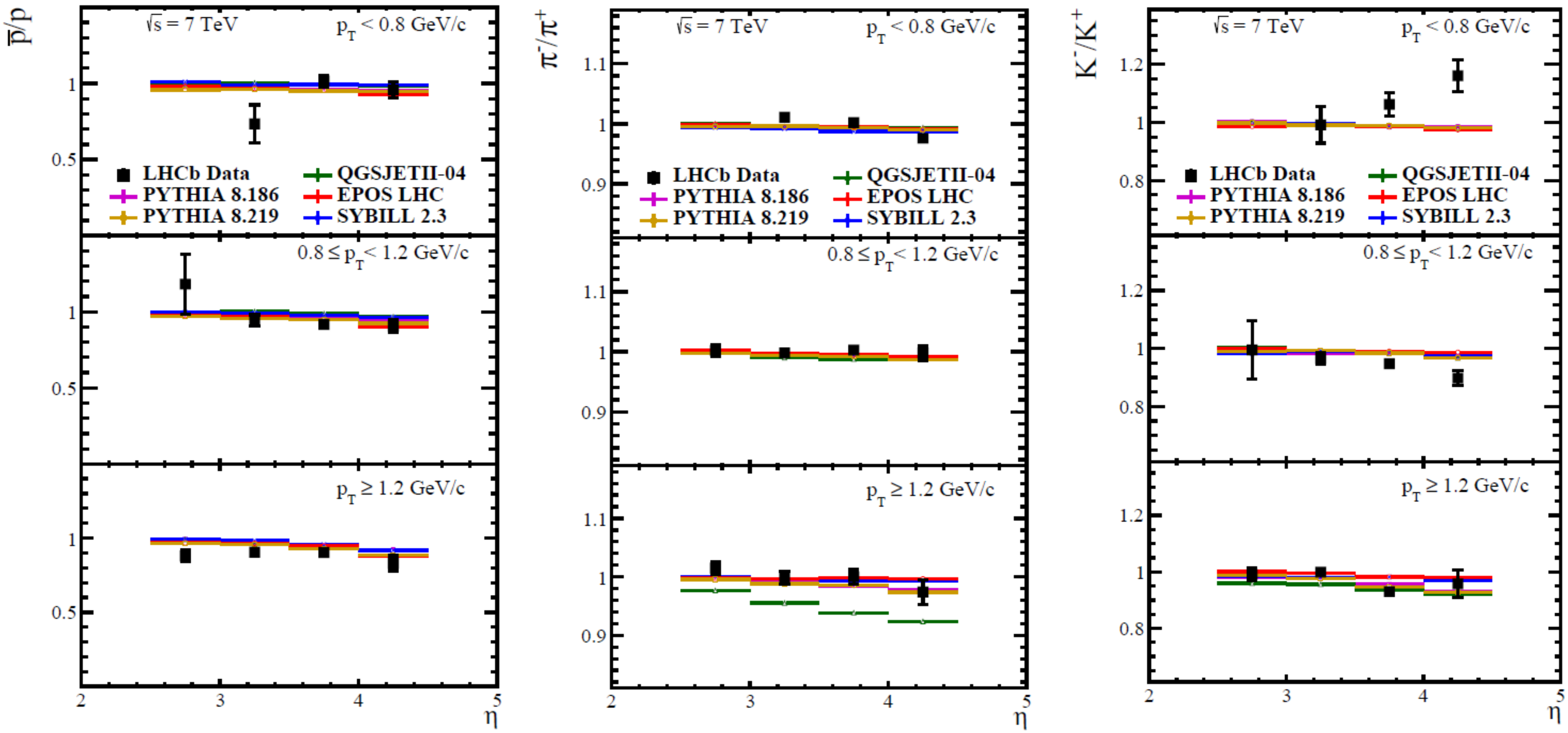
Hard events with $n_{ch} > 0$ with $p_T \geq 1$ GeV/c

- Relatively good agreement for EPOS and PYTHIA.
- SIBYLL and QGSJET are similar in the central region, but diverge in the forward region and are both far from the measured values.



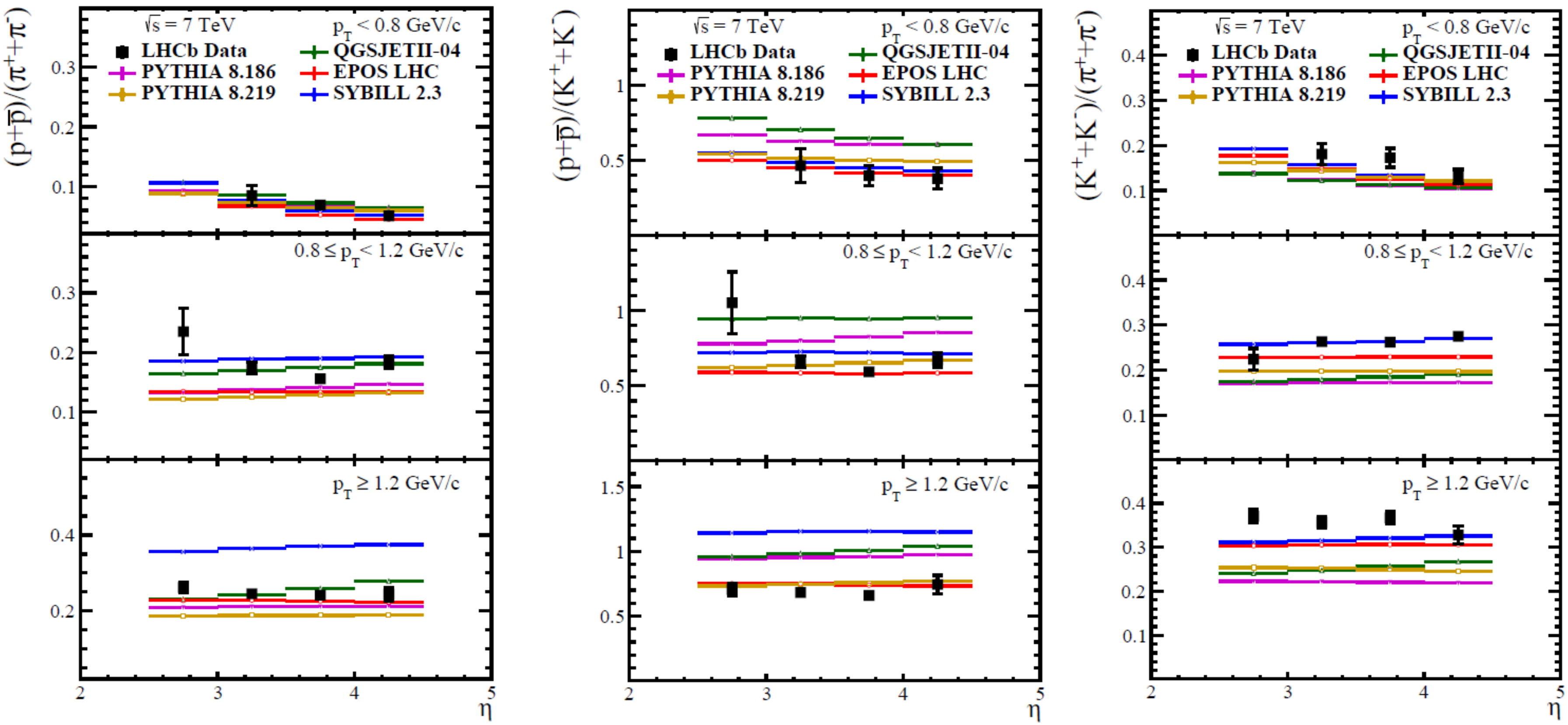
- As in the previous multiplicity plot, EPOS and PYTHIA are better at higher values.
- Favouring of very low multiplicities.

Prompt charged-hadron ratios



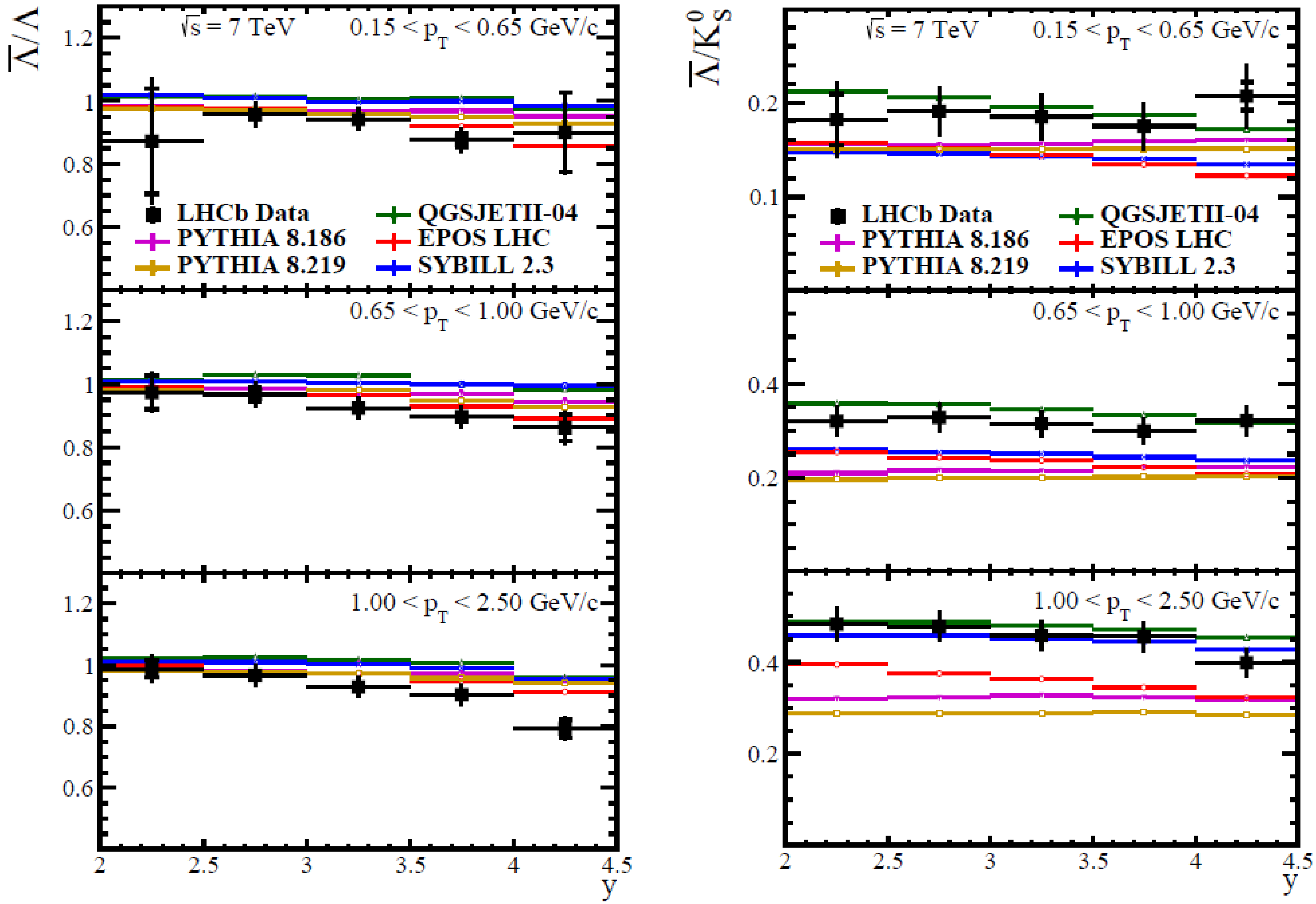
- $\bar{p}/p$ – Reasonably well described by all with apparent decrease towards the beamline.
- π^-/π^+ – Also well described by all, except QGSJET at high p_T.
- K^-/K^+ – Reasonably well described by all.

Prompt charged-hadron ratios



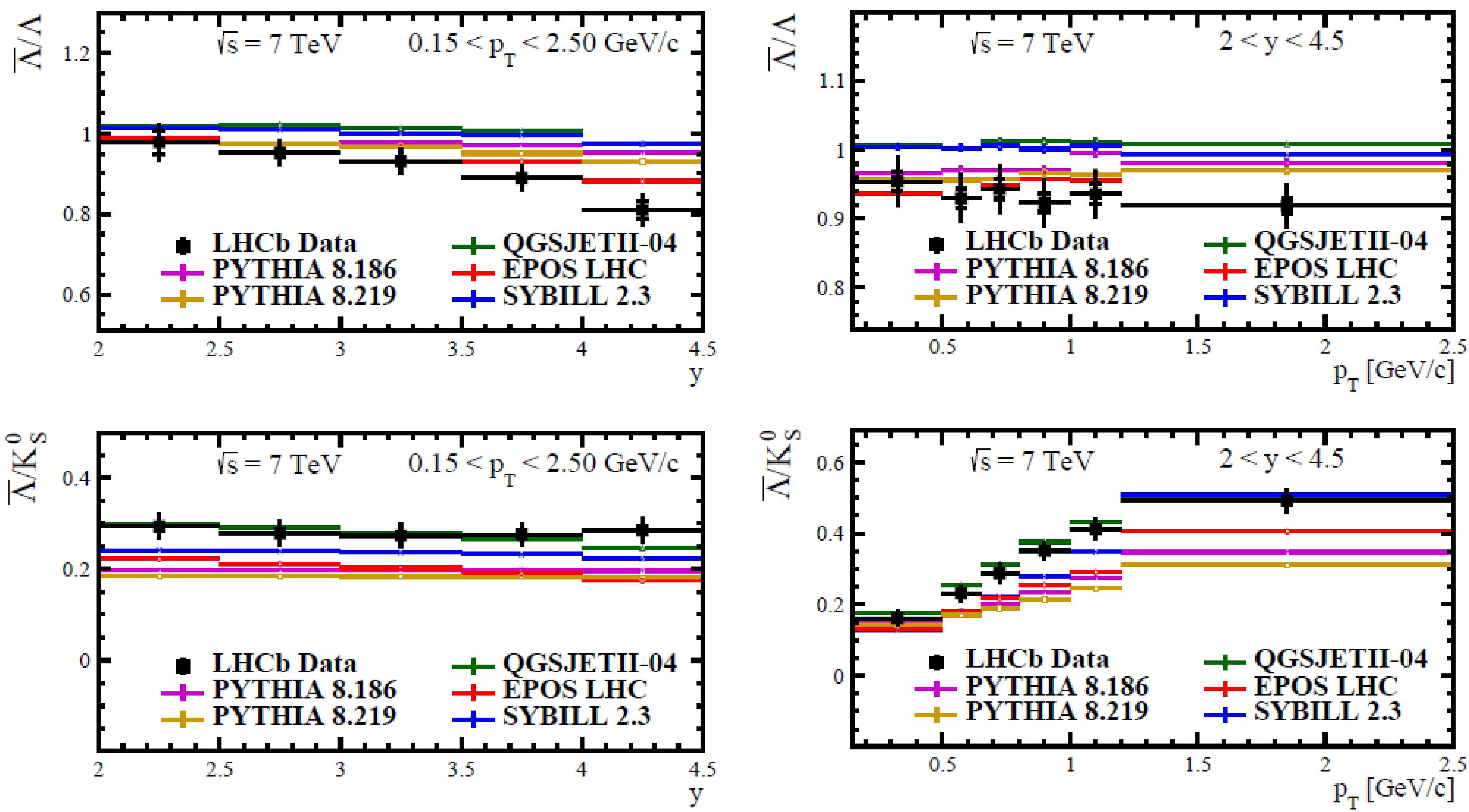
- p/π – Reasonably well described by all at low p_T. For high and middle p_T ranges the closest are EPOS, PYTHIA 8.1 and QGSJET.
- p/K – Best described by EPOS and PYTHIA 8.2.
- K/π – Closest prediction seems to be the one of SIBYLL followed by EPOS, yet all generators fail to describe this ratio.

Prompt V^0 ratios



- $\overline{\Lambda}/\Lambda$ – best described by EPOS (good baryon transport from remnant treatment).
- $\overline{\Lambda}/K_S^0$ – best described by QGSJET and SIBYLL (at high p_T).

Prompt V^0 ratios



- $\overline{\Lambda}/\Lambda$ – best described by EPOS (good baryon transport from remnant treatment).
- $\overline{\Lambda}/K_S^0$ – best described by QGSJET and SIBYLL (at high p_T).

Conclusions

- No model offers a globally perfect description.
- Charged energy flow – global event observable:
  - Reasonably well described by all generators, at least the shape.
  - The best prediction is the one of PYTHIA 8.186.
- EPOS and PYTHIA are similar – both based on the parton model.
- QGSJET seems to overestimate particle production from soft processes and at the same time to favour hard processes. Shares similarities with EPOS and SIBYLL, reflecting the use of Regge Field Theory.
- The shapes of the multiplicity distributions are generally well reproduced. EPOS and PYTHIA seem to be better, especially in the case of hard processes.
  - Similar behaviour of favouring very soft and hard processes.
- SIBYLL – notably good for energy flow for hard and diffractive events and some particle ratios.
  - Also good shape for charged particle densities.
  - Large underestimation of the soft component.
  - Generally good predictions for hard processes – minijet model.
- EPOS has the best baryon number tranport mechanism and PYTHIA's one is similar.
- QGSJET is best for $\overline{\Lambda}/K_s^0$ and also good for proton-pion ratio – good quark-diquark ratio.
- The modelling of the soft processes is still open to improvement and a forward tuning of the generators is required to improve precision in this rapidity range.