Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH)

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Monte Carlo event generation for pp collisions, phenomenological models and tuning.

WE Heraeus Physics School,
QCD - Old Challenges and New Opportunities,
27.09.2017

Bad Honnef, September 2017

Outline

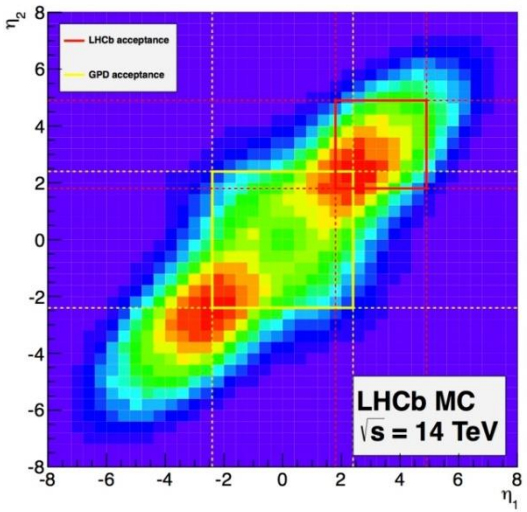
- The LHCb experiment;
- The parton model and the string fragmentation model;
- Generation steps of PYTHIA;
- Brief description of the Gribov-Regge model and the cosmic ray models EPOS, QGSJET and SIBYLL which are based on it.

- Sample generation for comparative study of the generators taking as reference LHCb data.
- Results for:
  - Energy flow;
  - Prompt charged particle distributions;
  - Prompt charged hadron ratios;
  - Prompt V^0 ratios;
  - Strange particle distributions.
- Conclusions.

The LHCb Experiment

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

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

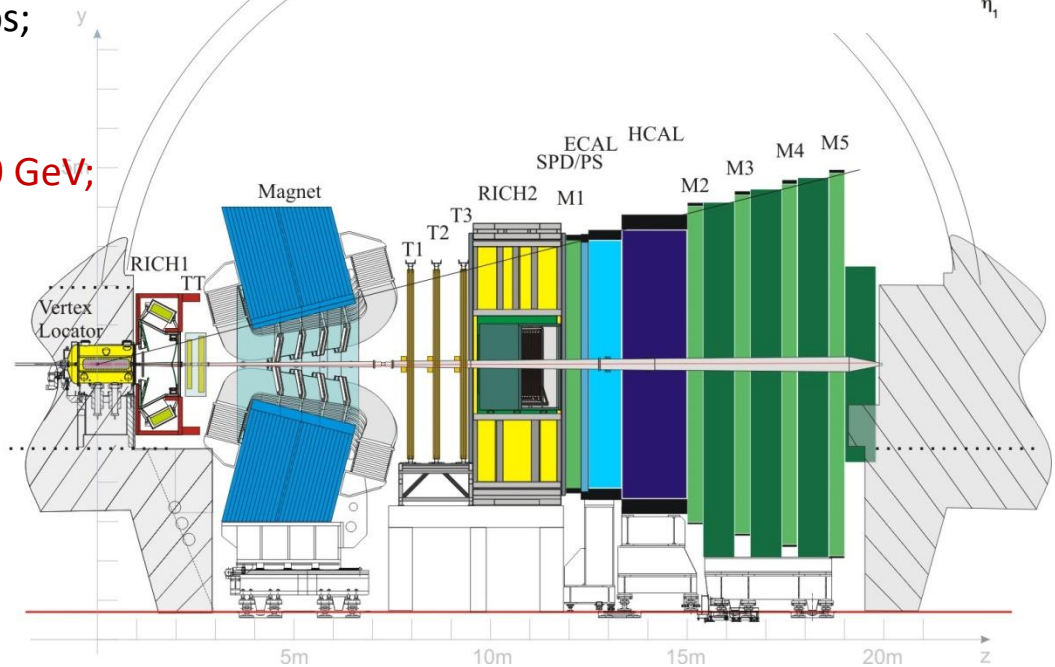


Tracking:

- VErtex LOcator (VELO) – Si microstrips;
- 4 Tm magnet;
- Silicon Tracker, TT + IT (T1-T3) – microstrips;
- Outer Tracker, OT (T1-T3) – drift tubes.
  - Good tracking efficiency;
  - 0.5% - 1% momentum res. up to 200 GeV;
  - $(15 + 29/p_T)\ \mu m$ PV resolution.

PID:

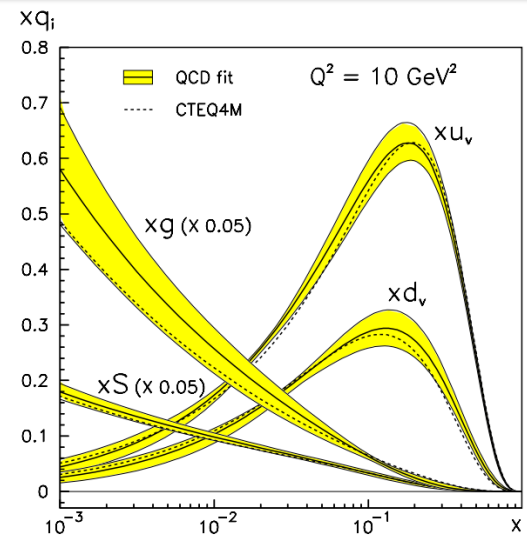
- RICH1 – low energy region;
- RICH2 – high energy region;
- Calorimeters: SPD/PS, ECAL, HCAL;
- Muon system: M1-M5.



Parton level and hadronization

The Parton Model basics:

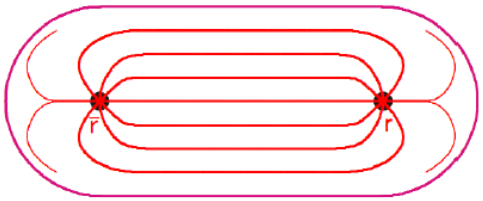
- DIS experiments at SLAC in the 1960's ($lp \to X$) → Scattering off point-like particles → Partons (Feynman, 1969).
- A hadron is a collection of partons with its mom. split between them.
- σ_h is obtained by incoherent summing over the partonic σ's.
- The parton distribution function (PDF) – mom. distribution of partons.
- The nucleon structure function: $F_2(x) = \sum_i e_i^2 x f_i(x)$;
- Bjorken scaling: Scattering off point-like particles.



https://www.nikhef.nl/~h24/qcdcourse/section-8.pdf

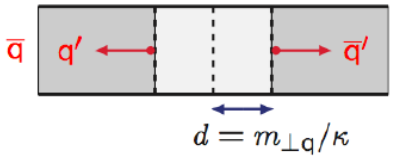
Hadronization: string fragmentation model.

Also cluster fragmentation, indep. fragm. etc.

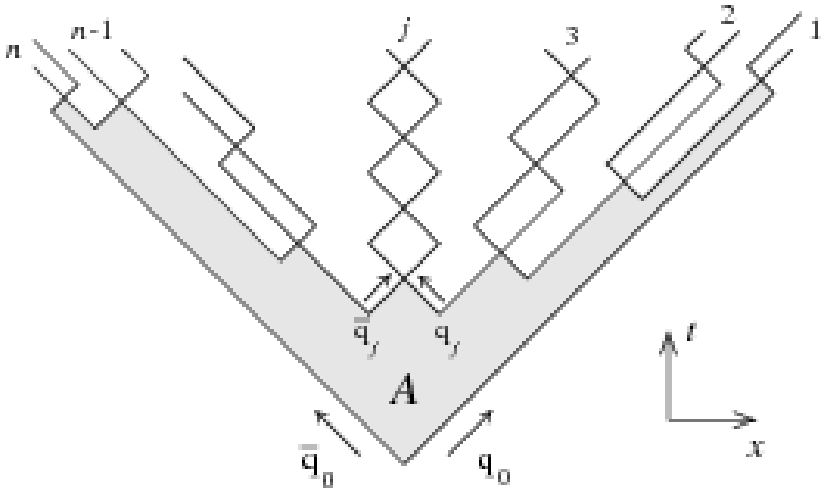


Field lines compressed to tubelike regions: **strings**!
Linear confinement:
$V(r) \approx \kappa r$, $\kappa \approx 1$ GeV/fm
Lorentz invariant.

String breaking by tunneling:
$\mathcal{P} \propto \exp(-\pi m_{\perp q}^2/\kappa)$
with adjacent pairs forming mesons (and baryons).



Taken from T. Sjöstrand presentation



https://inspirehep.net/record/475420/files/figures_lunddecay.png

PYTHIA generation steps

All HEP generators have more or less the same steps.

1. PDF – Parton distribution functions → interaction cross-sections.
2. Initial State Radiation, ISR

→ parton branching on hard process ingoing partons;

3. Hard process – interaction between the most energetic partons. Can be:

- Hard QCD (eg. $qg \rightarrow qg$, at large Q) – perturbative QCD;
- Soft QCD (at low Q) – non-perturbative QCD;
  - diffraction, elastic scattering, minimum bias;
- Heavy flavor production ($gg \rightarrow t\bar{t}$) etc.

4. Final State Radiation, FSR

→ parton branching on hard process outgoing partons;

5. Multiple Parton Interactions, MPI

→ interactions between the other partons;

6. Beam Remnants, BR

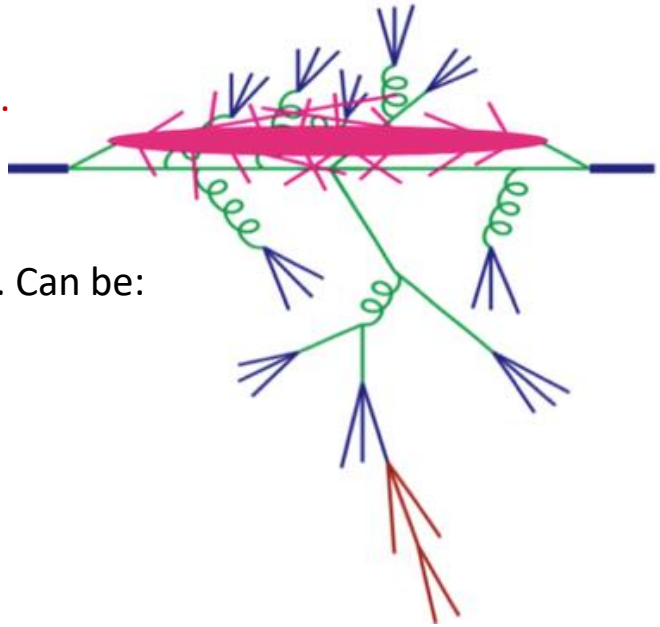
→ left behind after shower initiator is taken out.

7. Hadronization

→ String fragmentation.

8. Decay.

See arXiv:hep-ph/0603175v2



1. Hard process
2. Parton shower
3. Hadronization
4. Underlying event
5. Unstable particle decays

M. H. Seymour and M. Marx, "Monte Carlo event generators".

Cosmic rays MC

Gribov-Regge Model

- Hard process with $x \ll 1 \rightarrow semihard\ process \rightarrow$ $\sigma \sim$ hadron size $\rightarrow$ similar to soft processes.
- But small transverse distances $\rightarrow$ amplitudes calculated with pQCD.
- Parametrically small α_s and two main parameters:
  - $R \sim 1\ GeV^{-1}$, effective transverse dim., determined by mean p_T of partons;
  - $\Lambda \sim 100\ MeV$, the infrared pole, which determines $\alpha_s(q^2)$.
- The model tries to describe soft processes using pQCD. Pro:
  - Characteristic p_T of partons in the hadron wavefunction are of the order $\sim m_\rho^2$;
  - R in strong interactions are determined by values of the order $\sim 1/m_\rho$;
  - R in multiperipheral models with constant total σ are also determined by m_ρ.

Cosmic rays MC generators:

- based on the Gribov-Regge model;
- hadronization through string frag.;
- latest versions tuned to central LHC data.

SIBYLL

See arXiv:0906.4113

- Minijet model, similar to Dual parton model.

EPOS

See arXiv:1306.0121v2

- Takes into account energy cons. in σ calc.;
- Good remnant treatment;
- Core-corona model (unique);
- Effects not present in other models;
- The core – high density of string segments
  - collective hadronization;
- Corona – low density of string segments.

QGSJET

See arXiv:hep-ph/0412332v1

- Quark-Gluon String Model.

Samples and observables

CRMC package (Default, w/ LHC tunes):

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

PYTHIA 8.186 (Default, 4C tune).
PYTHIA 8.219 (Default, Monash 2013).

Energy flow:

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

Data taken 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.
http://hepdata.cedar.ac.uk/view/p8694

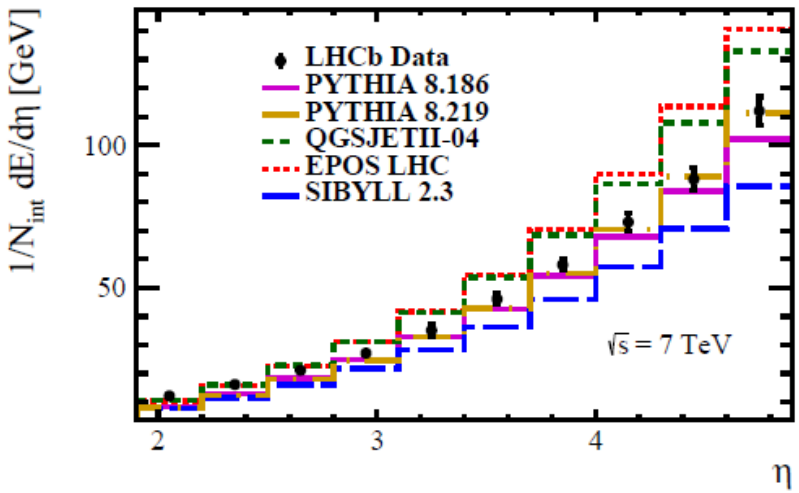
Samples:

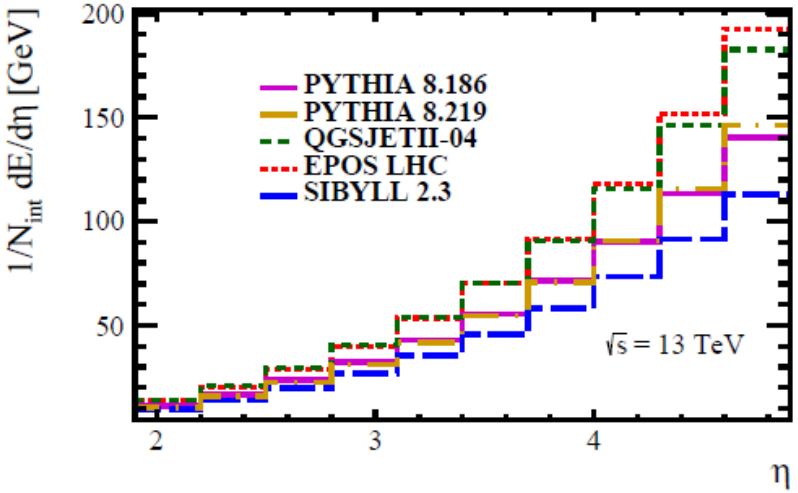
- 10^7 minbias events w/ default settings @ 7 & 13 TeV;
- LHCb fiducial phasespace: $\sim 2 \leq \eta \leq 5, p_{ch} \geq 2\ GeV$;
- Stable particle definition: $nominal\ c\tau \geq 3000\ mm$;
- Promptness cut: $prodvertex \leq 0.2\ mm$.

Observables:

- Energy flow:
  - Charged stable particles which escape a sphere with a radius of $0.2\ mm$ around the PV.
- Prompt charged-particle distributions:
  - p_T, η, multiplicity.
- Prompt charged-hadron ratios:
  - p/K, p/π, K/π etc.
- Prompt V^0 ratios:
  - $\bar{\Lambda}/\Lambda$, $\bar{\Lambda}/K_S^0$.
- Strange particle distributions:
  - p_T, η for Λ, K.

Energy flow

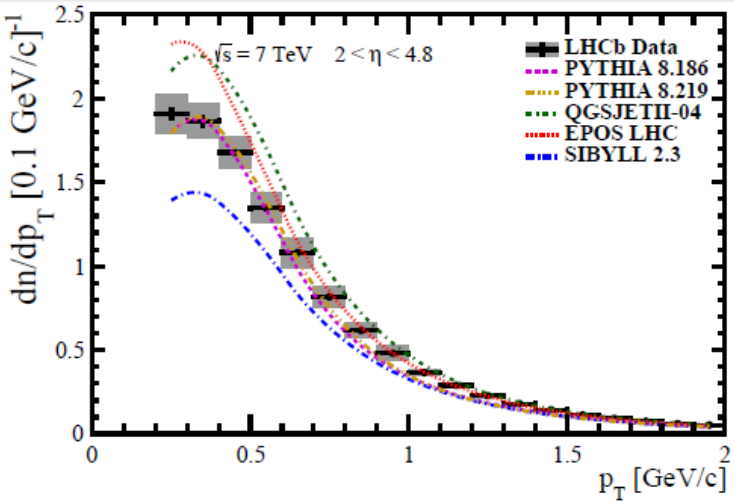


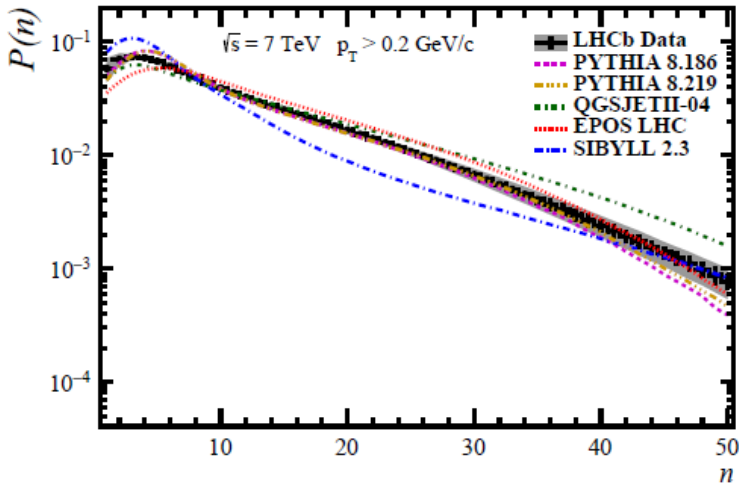


$1.9 \leq \eta \leq 4.9$, $\Delta\eta = 0.3$, $2 \leq p_{ch} \leq 1000\ GeV$

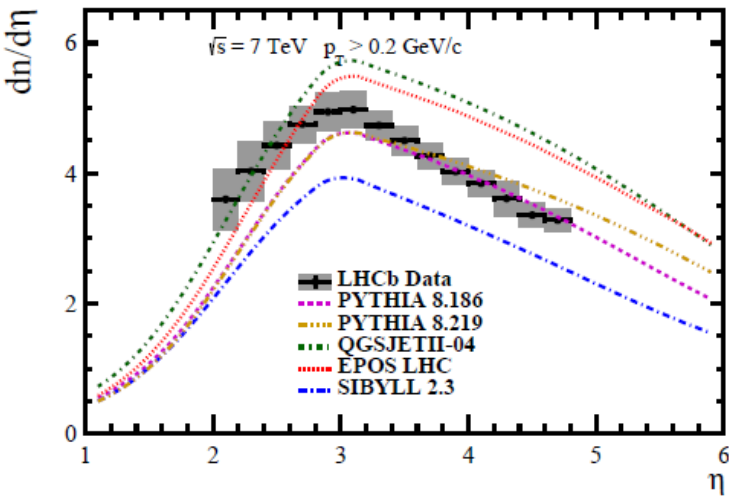
- All models have the same trend;
- PYTHIA:
  - Better description for $\eta > 2.5$;
  - No major difference between versions;
- EPOS, QGSJET:
  - Better for $\eta < 2.5 \rightarrow$ tuning with central data;
  - Increasing overestimation with η.
- Expected increase in energy flow @ 13 TeV compared to7 TeV;

Prompt charged-particle distributions





Scaled with the number of visible events (with minimum one charged particle in the kinematical region of $2 < \eta < 4.8$, $p > 2$ GeV/c and $p_T > 0.2$ GeV/c).



PYTHIA – Better description for:

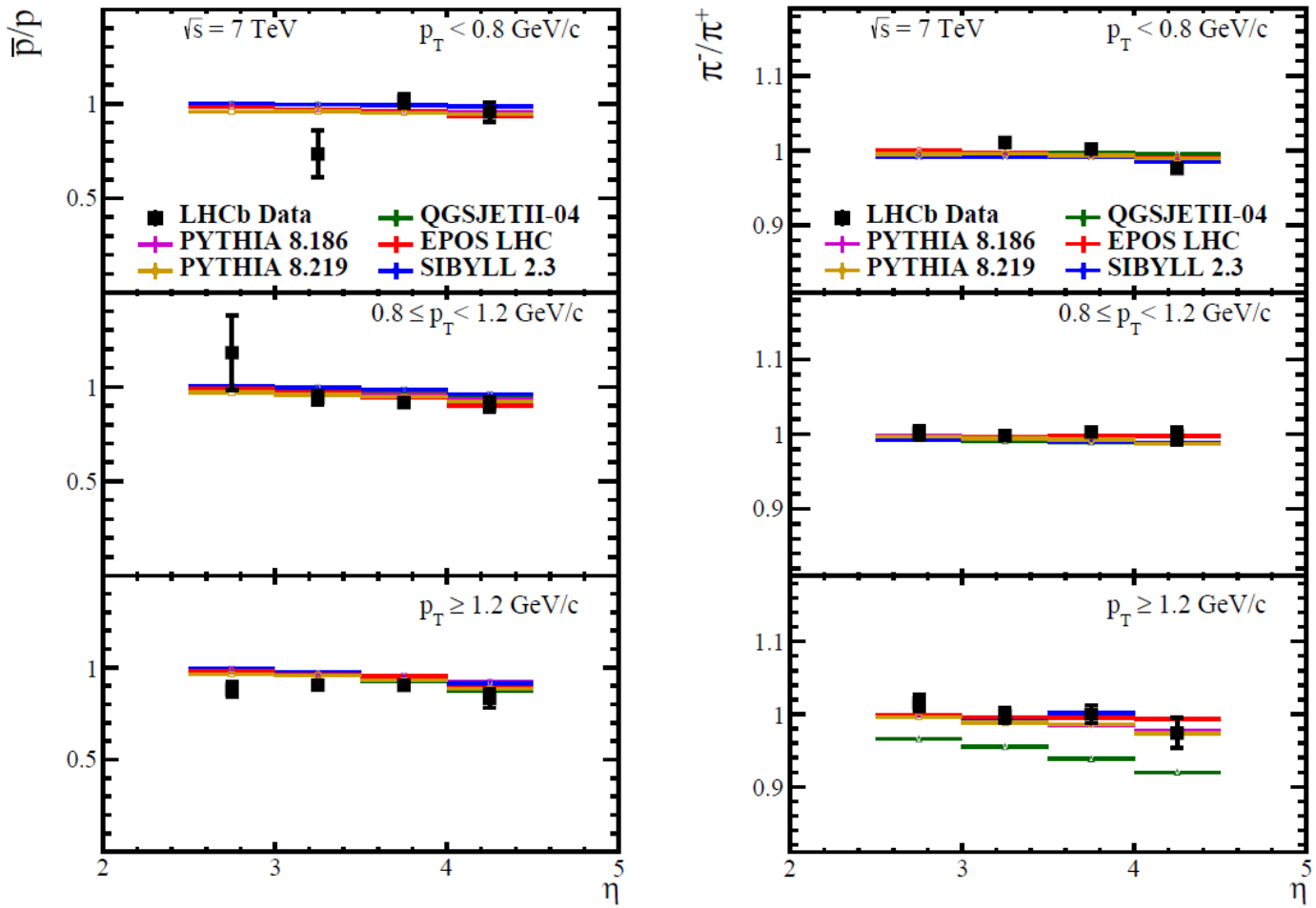
- low p_T region;
- low-medium multiplicities ($n \sim 10 - 30$);
- high η region ($\eta > 3$);

EPOS, QGSJET – Good for:

- high p_T region;
- high multiplicities ($n \sim 10 - 30$);
- low η region ($\eta < 3$) → tuning with central data;

See:
inspirehep.net/record/1352304/files/v2_0681.pdf
https://arxiv.org/pdf/1306.0121v1.pdf

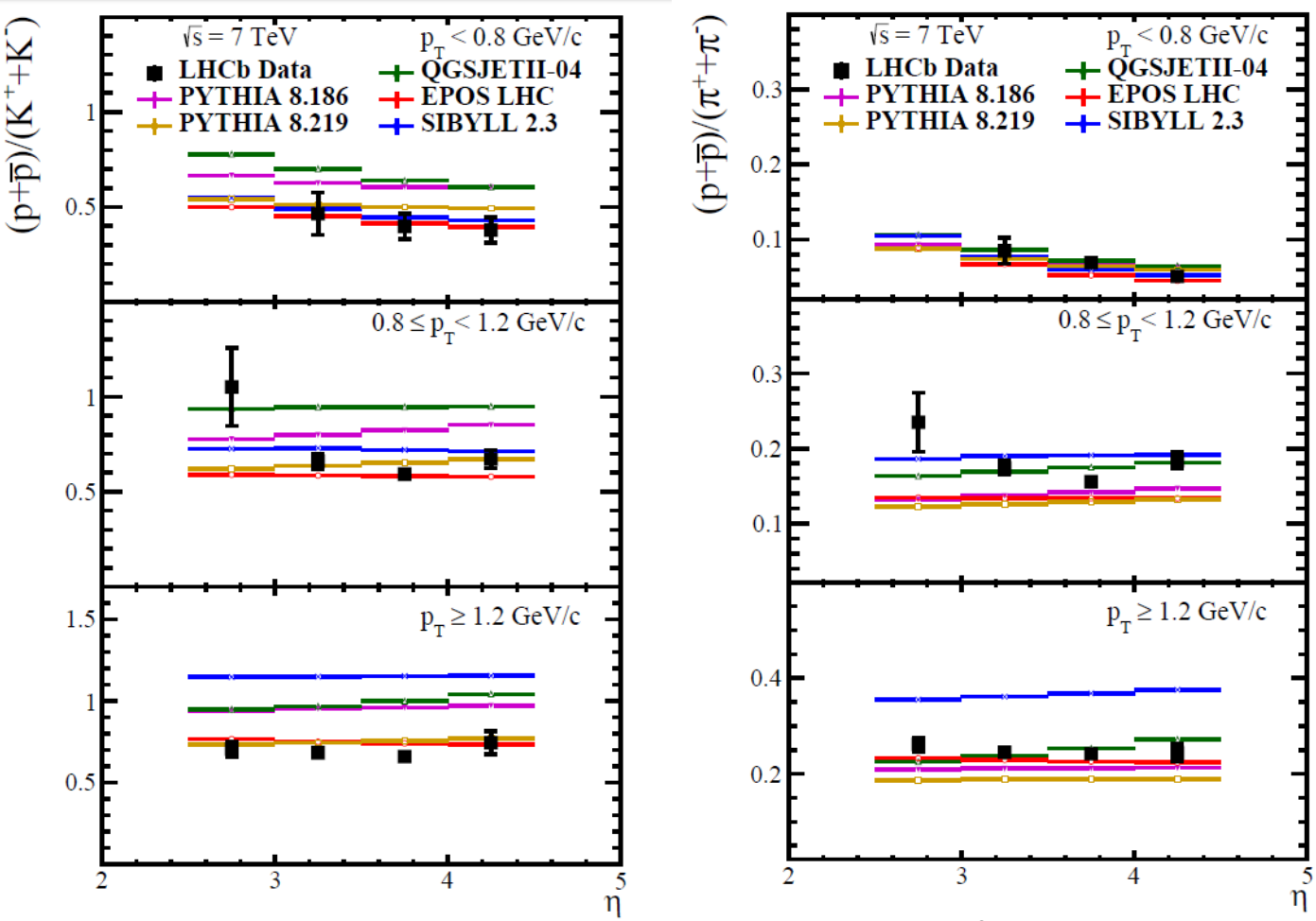
Prompt charged-hadron ratios



$\bar{p}/p$: All models have the same trend of apparent decrease towards the beam. Relatively good description.

π^-/π^+: Good description with the exception of QGSJET at high p_T.

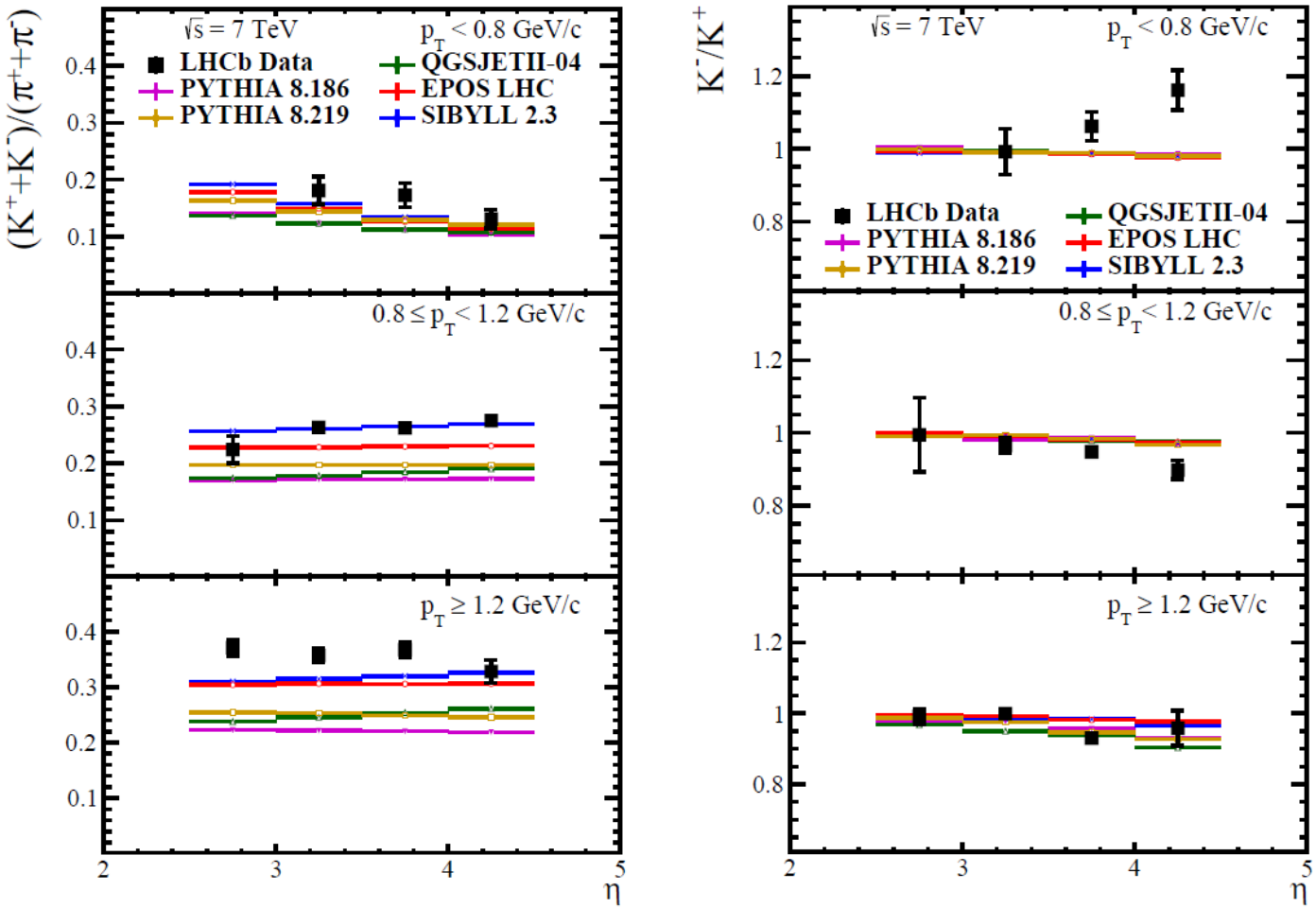
Prompt charged-hadron ratios



p/K : All models have the same trend at low p_T. Good description for PYTHIA 8.2 and EPOS and also SIBYLL at low-medium p_T. Good baryon number transport for EPOS from remnant treatment.

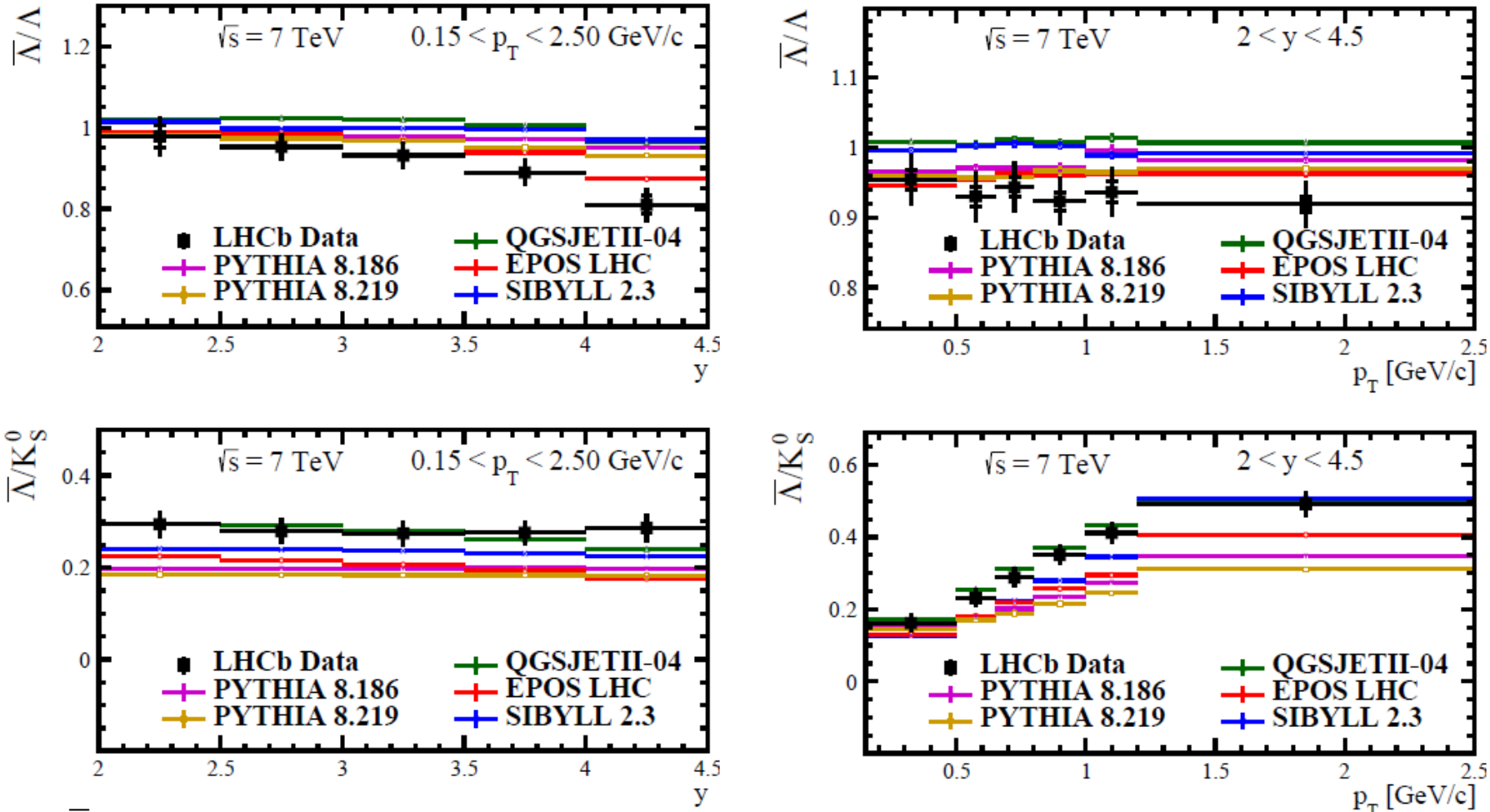
p/π : Good description for all models at low p_T. Better description for EPOS at high p_T.

Prompt charged-hadron ratios



K/π : All models have the same trend at low p_T. Better description for SIBYLL, but also EPOS.
K^-/K^+ : Same trend for all models. Relatively good description at medium-high p_T.

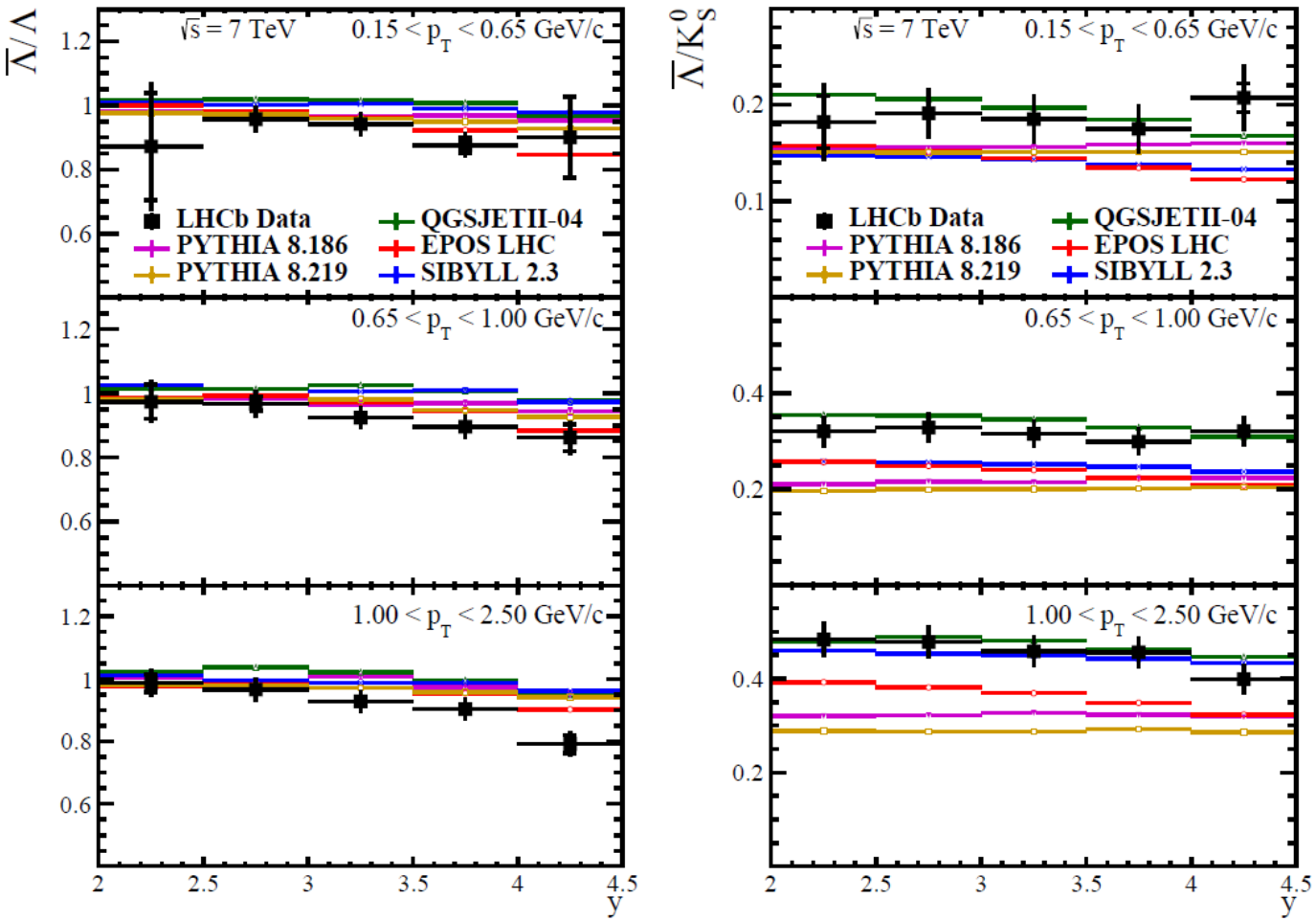
Prompt V^0 ratios



$\overline{\Lambda}/\Lambda$: All models have the same trend of decrease towards the beam. Better description for EPOS, but also PYTHIA.

$\overline{\Lambda}/K_S^0$: Same trend for all models. Good description for QGSJET and SIBYLL.

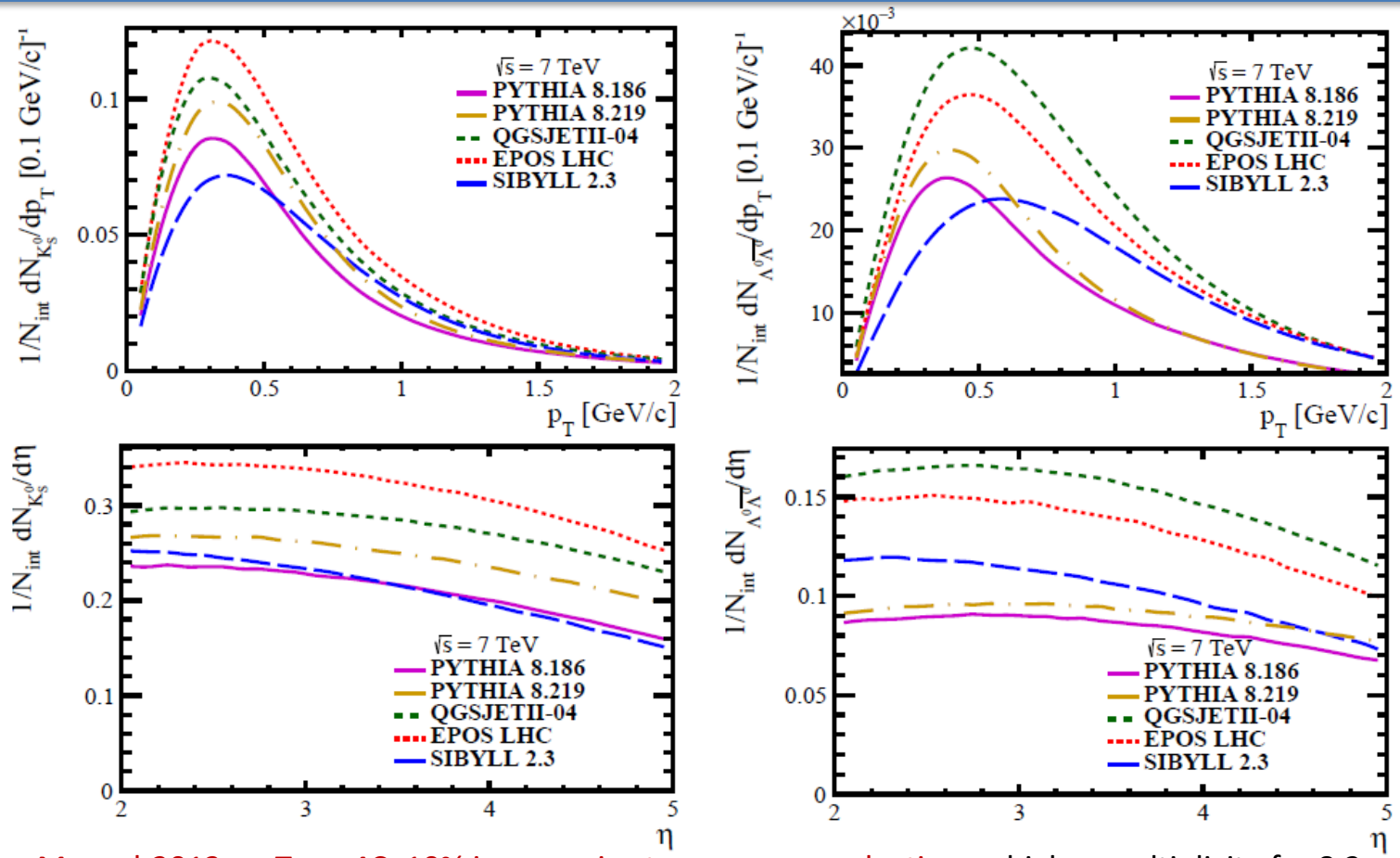
Prompt V^0 ratios



$\overline{\Lambda}/\Lambda$: All models have the same trend of decrease towards the beam. Better description for EPOS, but also PYTHIA.

$\overline{\Lambda}/K_S^0$: Same trend for all models. Good description for QGSJET and SIBYLL (high p_T).

Strange particle distributions



- PYTHIA – Monash2013 vs. Tune 4C: 10% increase in strangeness production → higher multiplicity for 8.2.
- EPOS (tuned with CMS data) – Very good agreement with CMS data for p_T (see: arxiv.org/pdf/1306.0121v1.pdf), while PYTHIA underestimates the data, explaining the lower multiplicity.
- For η: QGSJET tuned with ATLAS data (see inspirehep.net/record/1352304/files/v2_0681.pdf), but slightly underestimates the data for K_S^0, while EPOS overestimates the data and the other way around for Λ.

Conclusions

- 10^7 minbias events generated using default settings @ 7 TeV & 13 TeV (backup slides);
- Only prompt particles in the forward region (LHCb acceptance);
- The observables studied are:
  - Energy flow;
  - Prompt charged-particle distributions;
  - Prompt charged-hadron ratios;
  - Prompt V^0 ratios;
  - Strange particle distributions.
- No model offers a globally perfect description, but some are better than others concerning the description of different observables. For example:
  - PYTHIA for energy flow;
  - EPOS for ratios involving baryons strange particle distributions;
  - QGSJET for $\overline{\Lambda}/K_S^0$.
- Most differences are explainable by tuning, but also some by assumptions of the models:
  - Between PYTHIA versions in strangeness production → Monash 2013 vs. 4C;
  - The core effects for EPOS (affects strageness production).

Still work in progress.

References

http://physik.uibk.ac.at/hephy/Hess/more/VFHess.gif
http://astroparticle.uchicago.edu/siteold/sciam1.jpg
http://moriond.in2p3.fr/J05/trans/sunday/engel1.pdf
http://images.iop.org/objects/phw/news/7/10/13/cascade.jpg
http://s2.quickmeme.com/img/fc/fc485d49a8ceacf0a8d546b6a56d5c0b9640a2f68eccbe81755a4eebae0701a1.jpg
http://slice.seriouseats.com/images/20081203-original-cosmic-rays.jpg
http://www.frontline.in/static/html/fl2610/images/20090522261008505.jpg
https://inspirehep.net/record/475420/files/figures_lunddecay.png
http://home.thep.lu.se/~torbjorn/pythia81html/Welcome.html
http://www.scholarpedia.org/article/Parton_shower_Monte_Carlo_event_generators
https://home.cern/about/accelerators
http://cern-accelerators-optics.web.cern.ch/cern-accelerators-optics/PSnew_2.jpg
https://inspirehep.net/record/1256328/files/Rapidity.png
http://design-guidelines.web.cern.ch/badge-logo
http://lhcb.web.cern.ch/lhcb/speakersbureau/html/Material_for_Presentations.html
B. Andersson, G. Gustafson, G. Ingelman și T. Sjöstrand. Parton fragmentation and string dynamics. Physics Reports 97, 1983.
T. Sjöstrand, Soft QCD (and PYTHIA), ATLAS SM Workshop, Annecy, 4th February 2015.
http://home.thep.lu.se/~torbjorn/ppp2011/lec7.pdf
http://pdg.lbl.gov/2015/reviews/rpp2015-rev-cosmic-rays.pdf
http://moriond.in2p3.fr/J05/trans/sunday/engel1.pdf
https://arxiv.org/pdf/0801.4376v1.pdf
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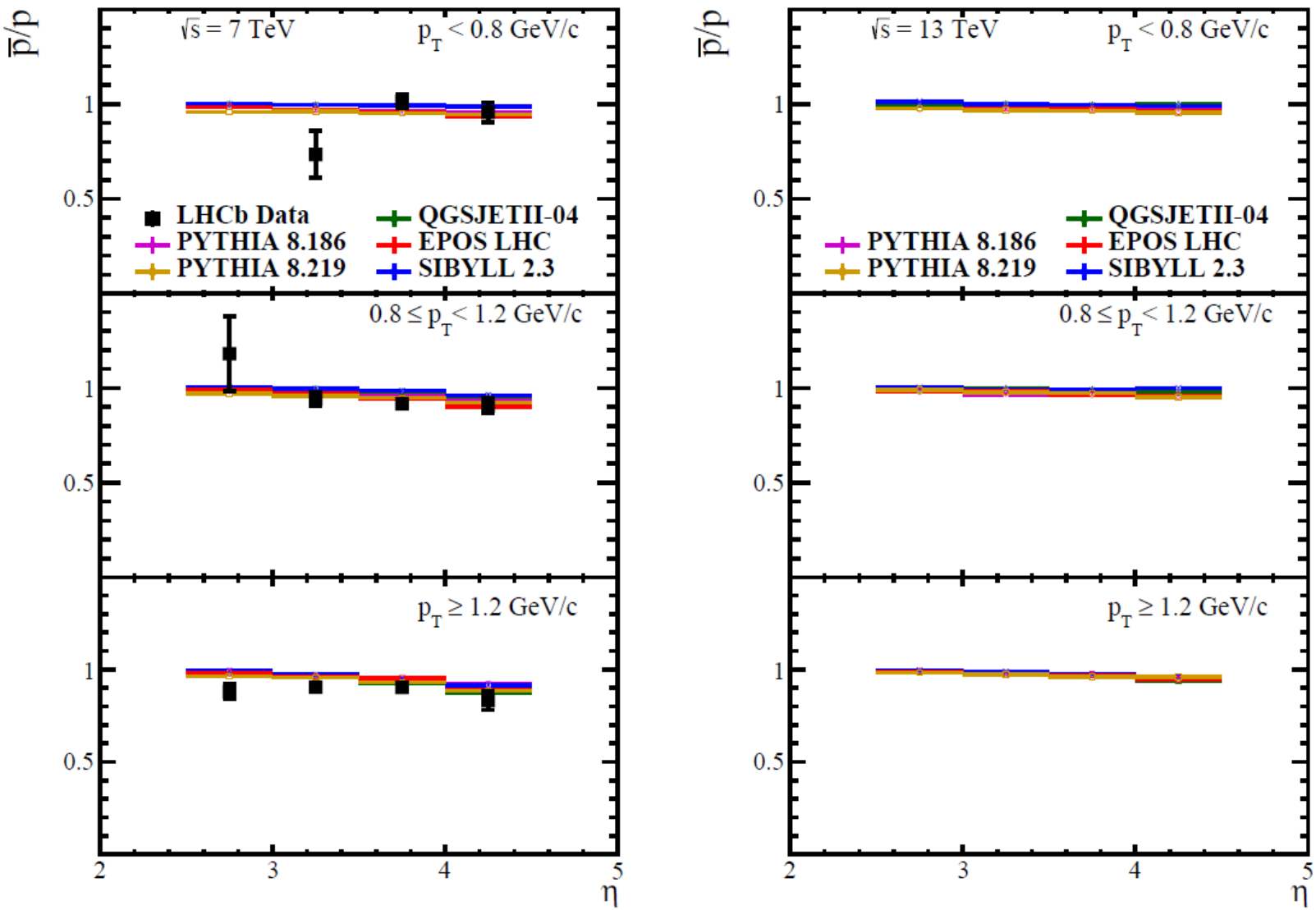
https://arxiv.org/pdf/hep-ph/0603175v2.pdf
http://icecube.wisc.edu/~tmontaruli/801/lect14.pdf
http://www.hep.shef.ac.uk/edaw/PHY206/Site/2012_course_files/phy206rlec7.pdf
https://arxiv.org/pdf/0906.4113.pdf
https://arxiv.org/pdf/1212.4755v3.pdf

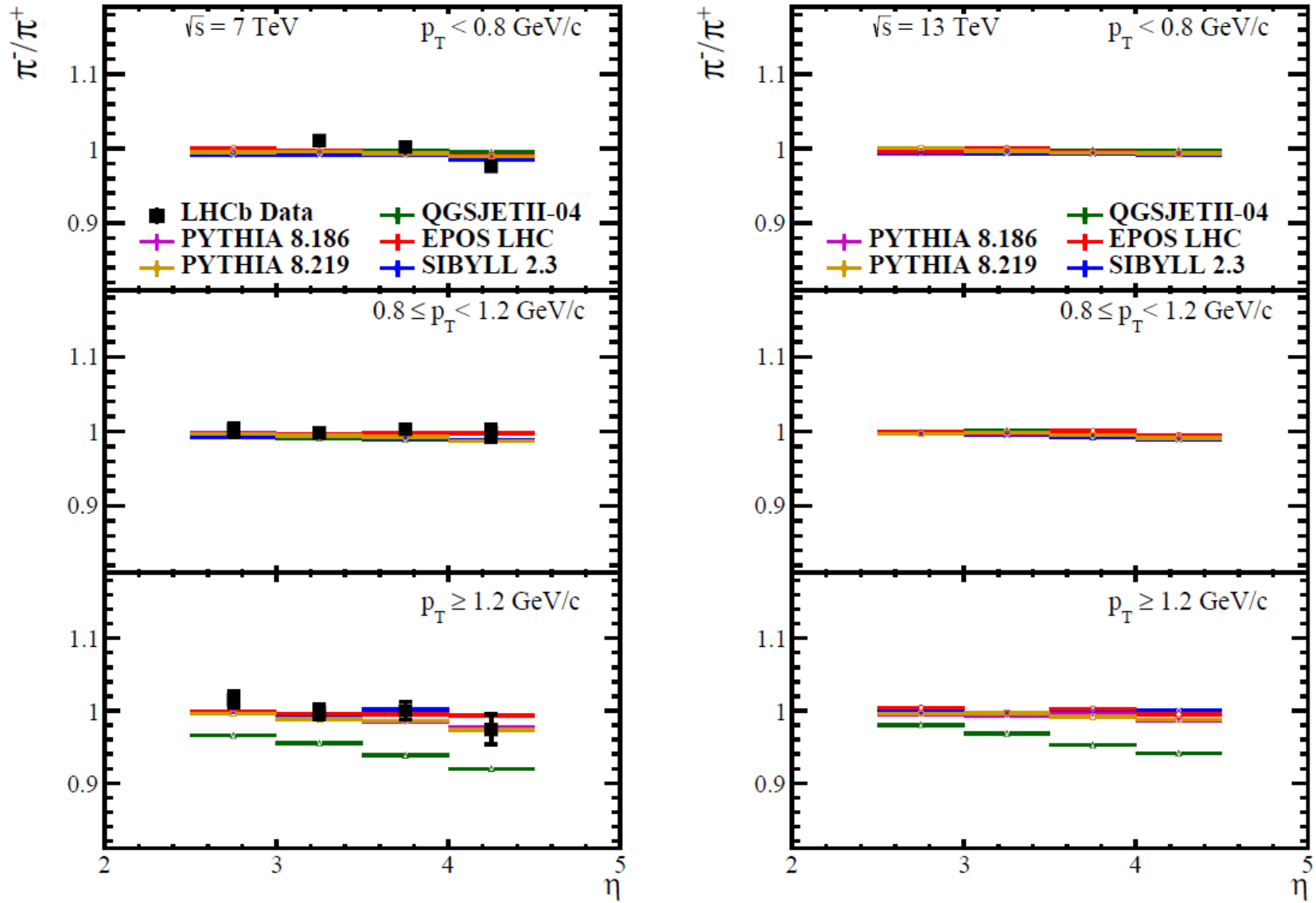
Backup

Prompt charged-hadron ratios



Good baryon number transport in EPOS LHC due to good beam remnant treatment.

Prompt charged-hadron ratios



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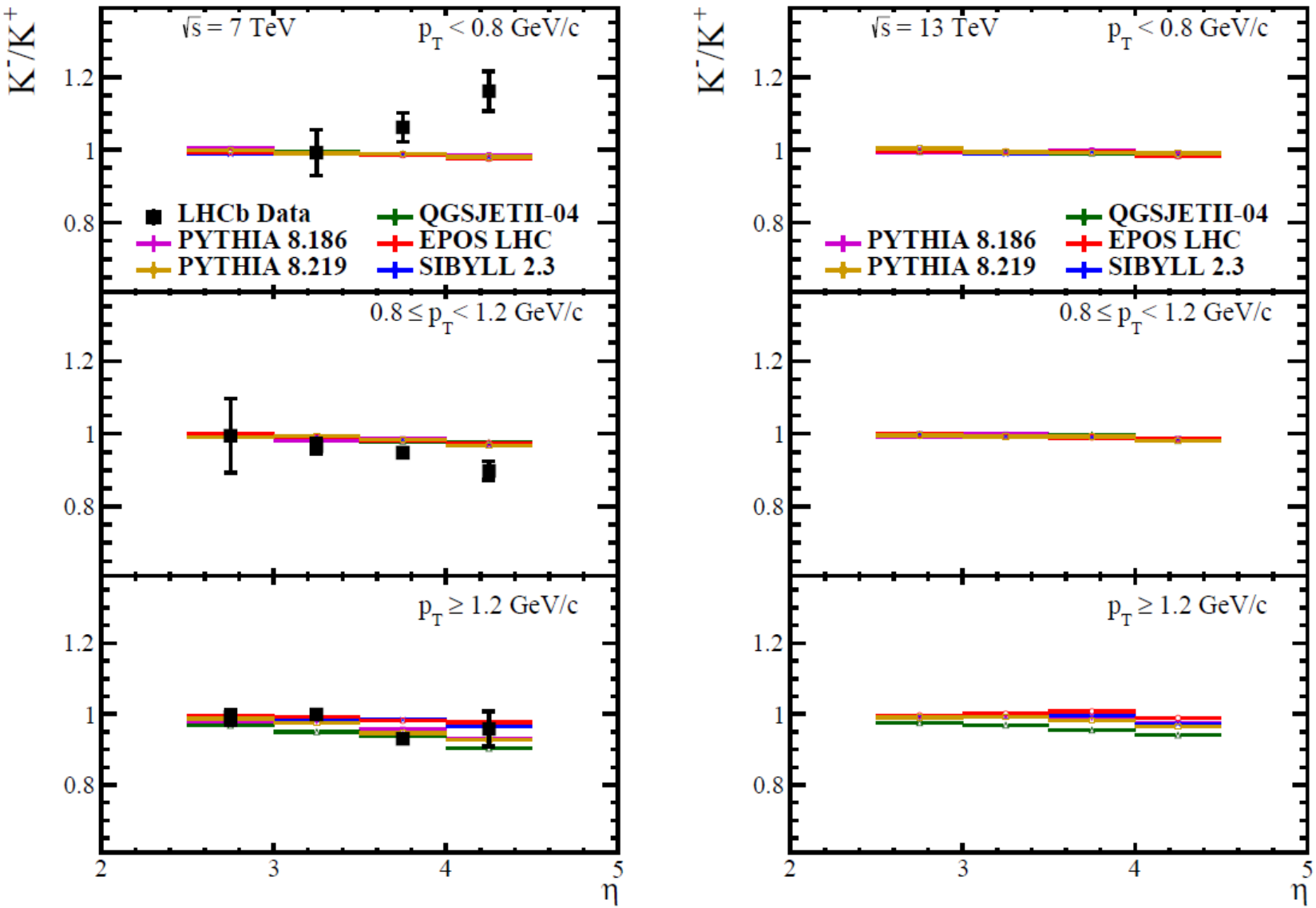

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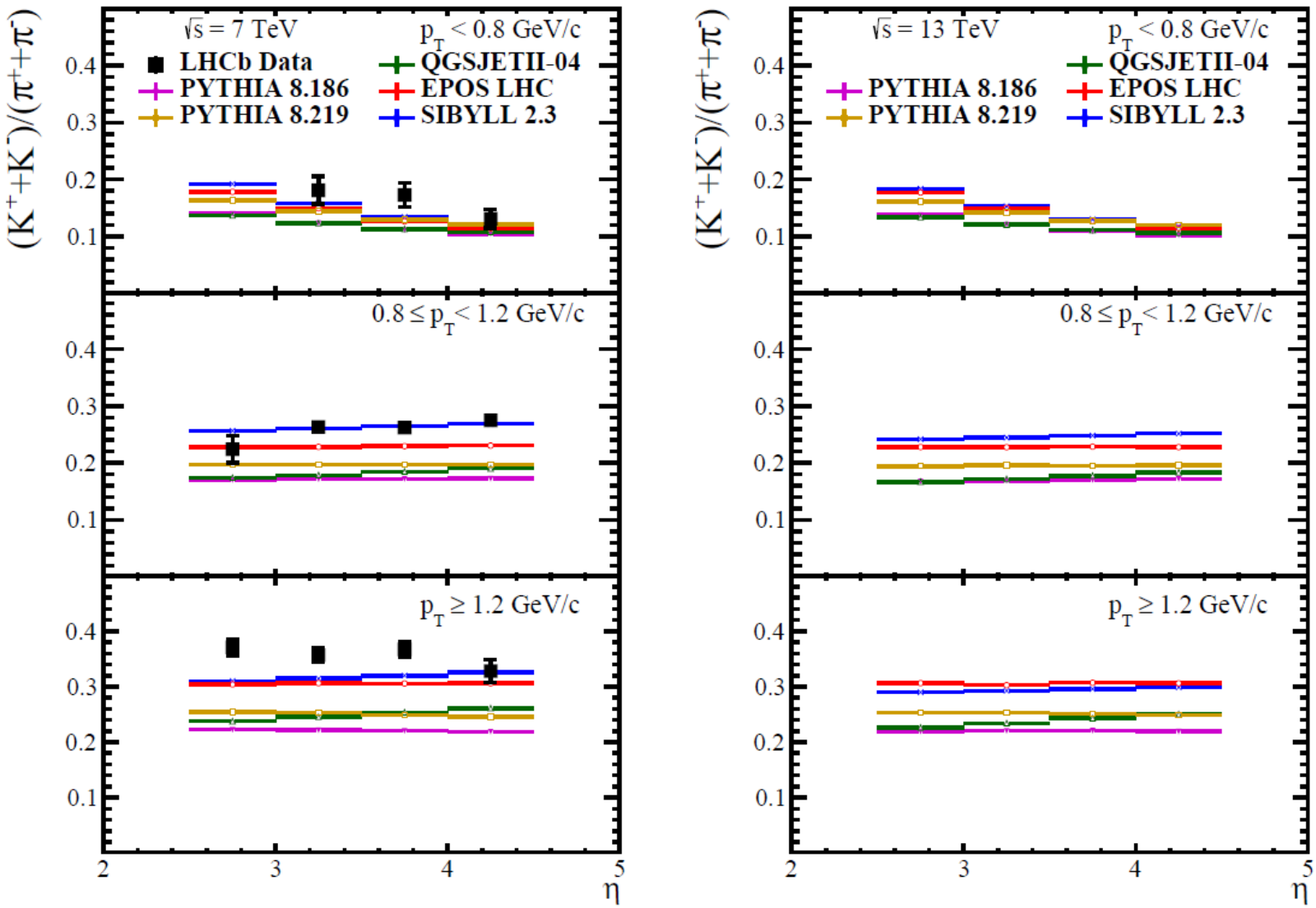
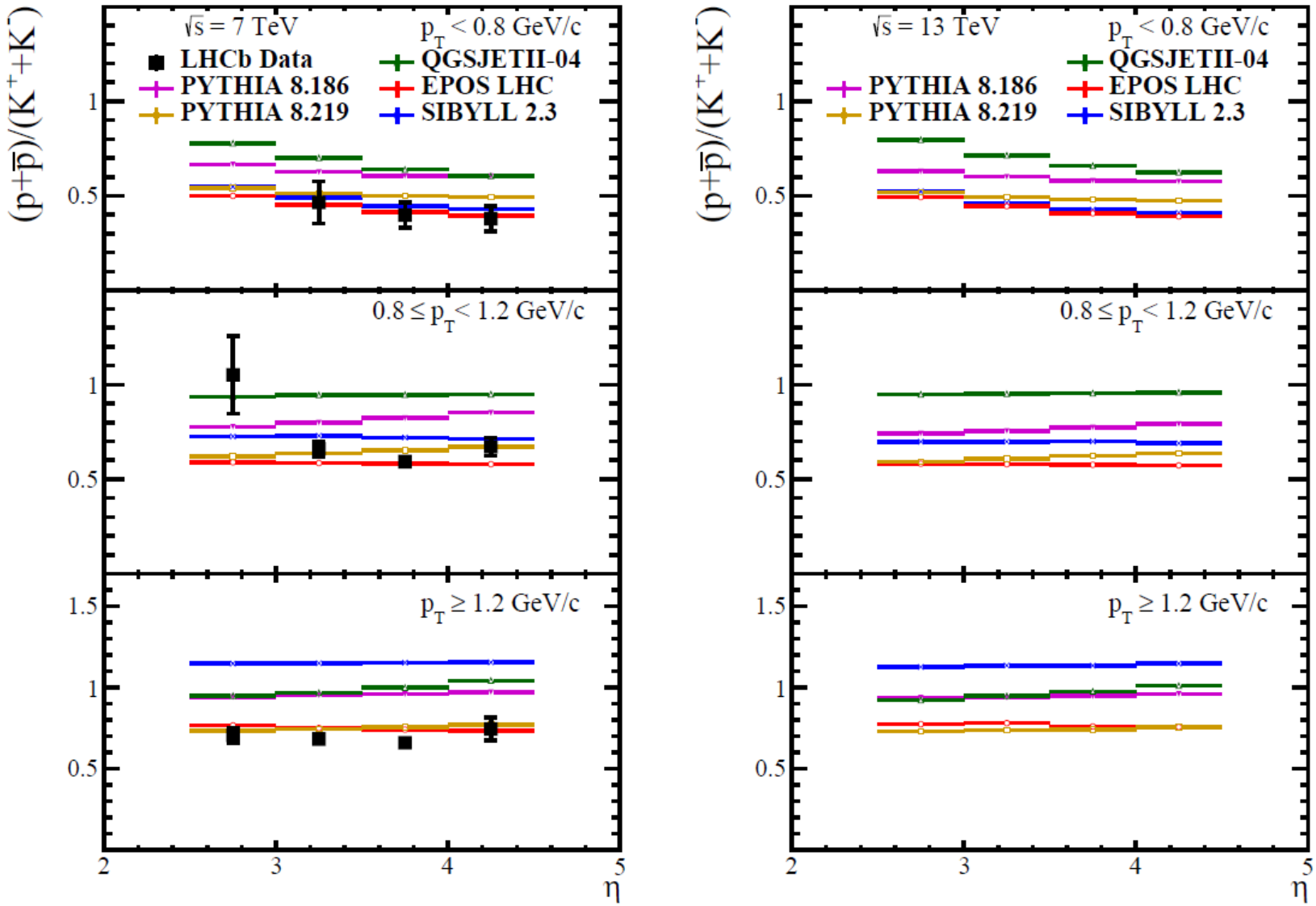


Prompt charged-hadron ratios



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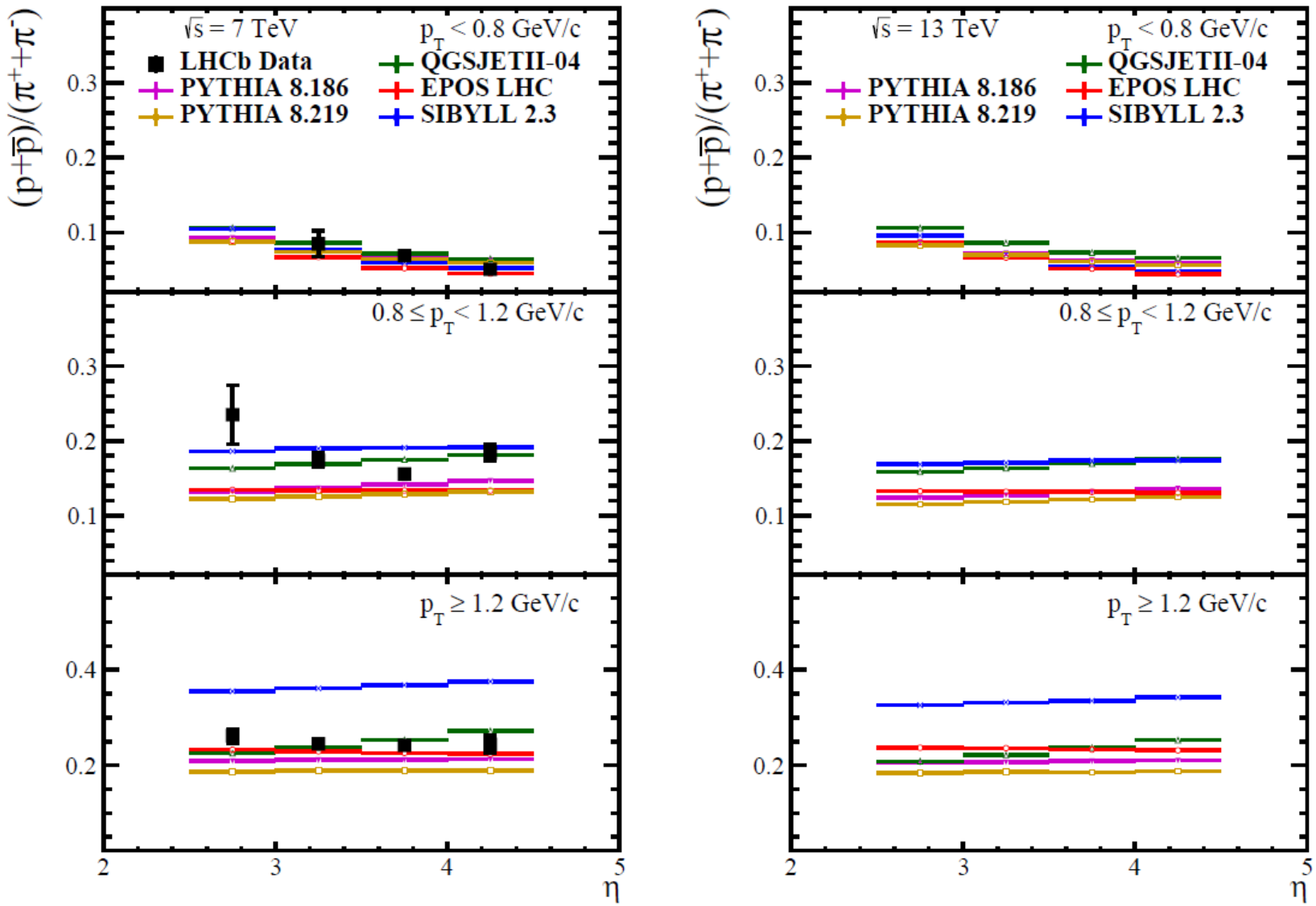
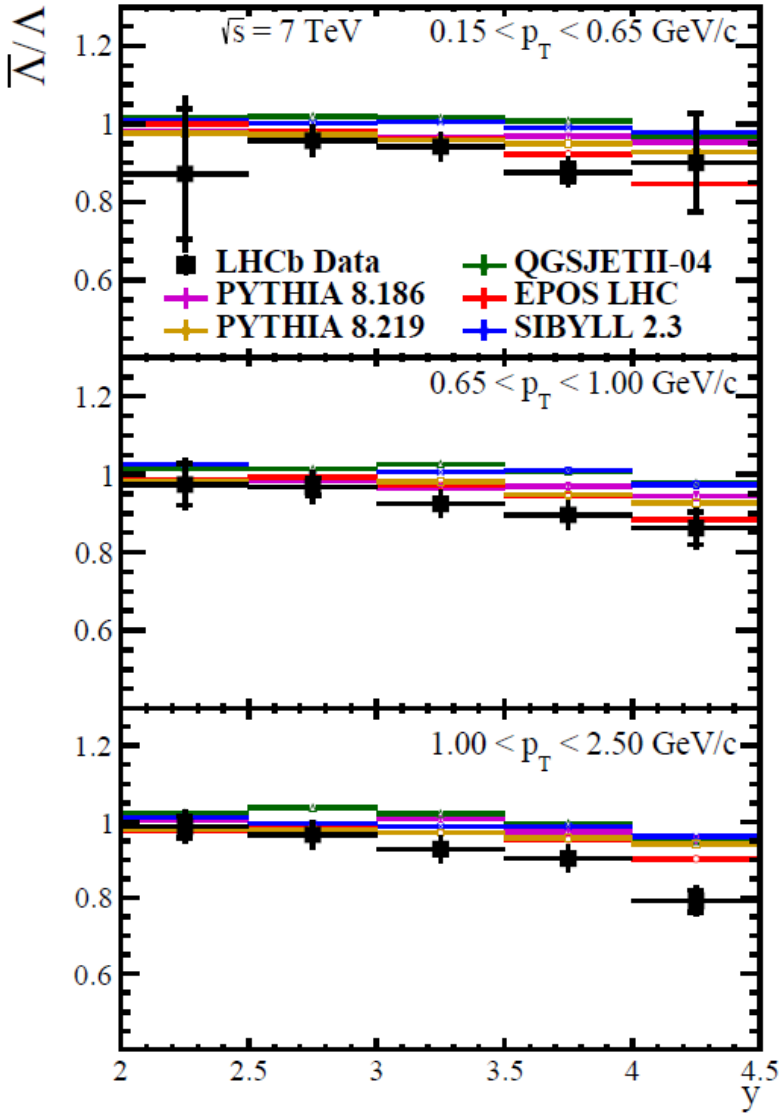
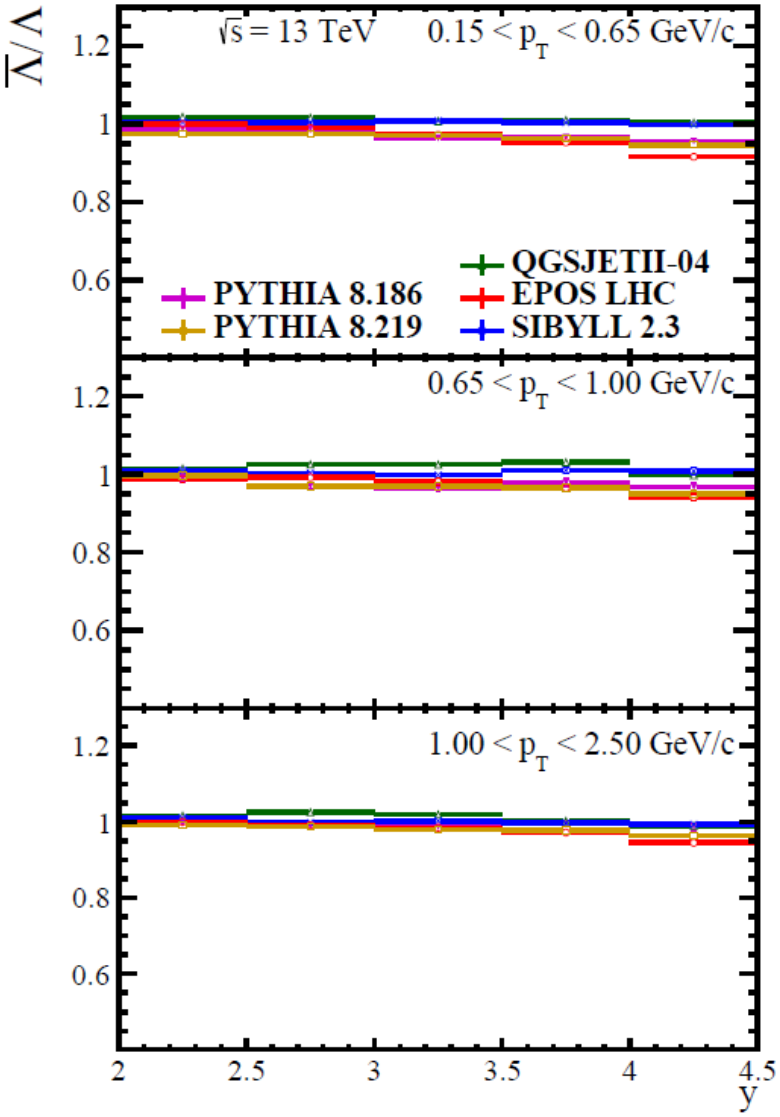


Prompt V^0 ratios





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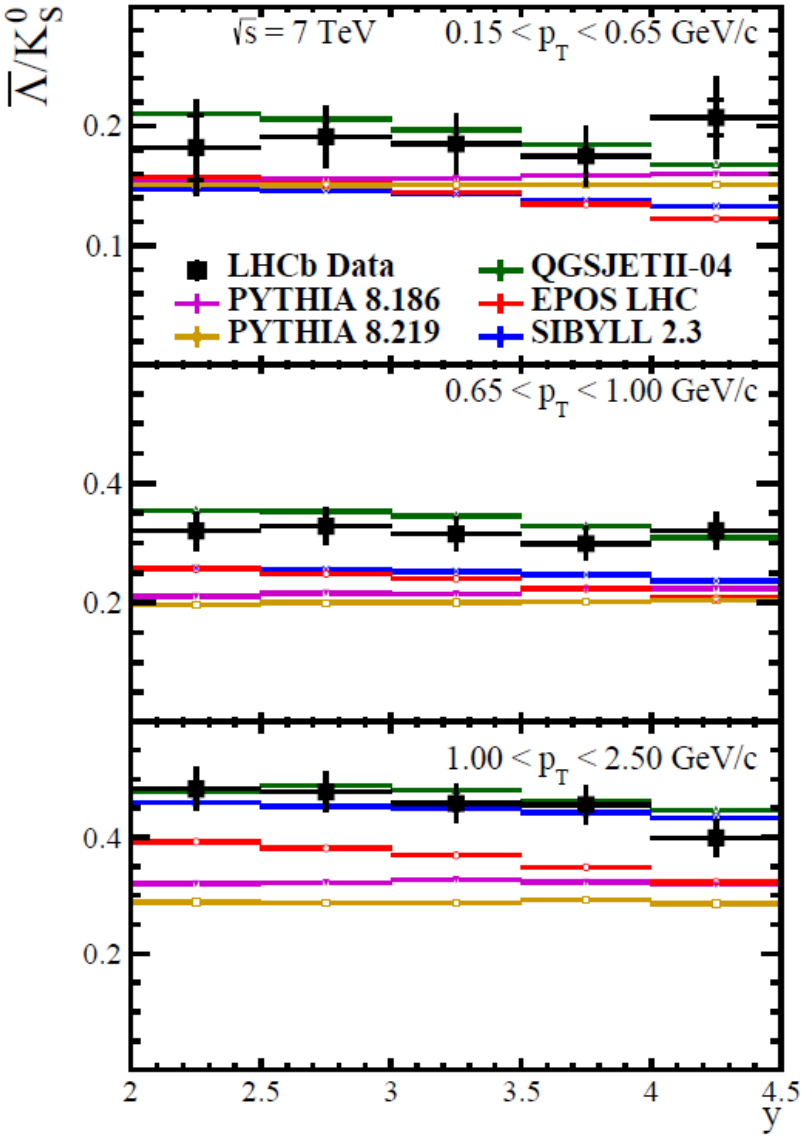

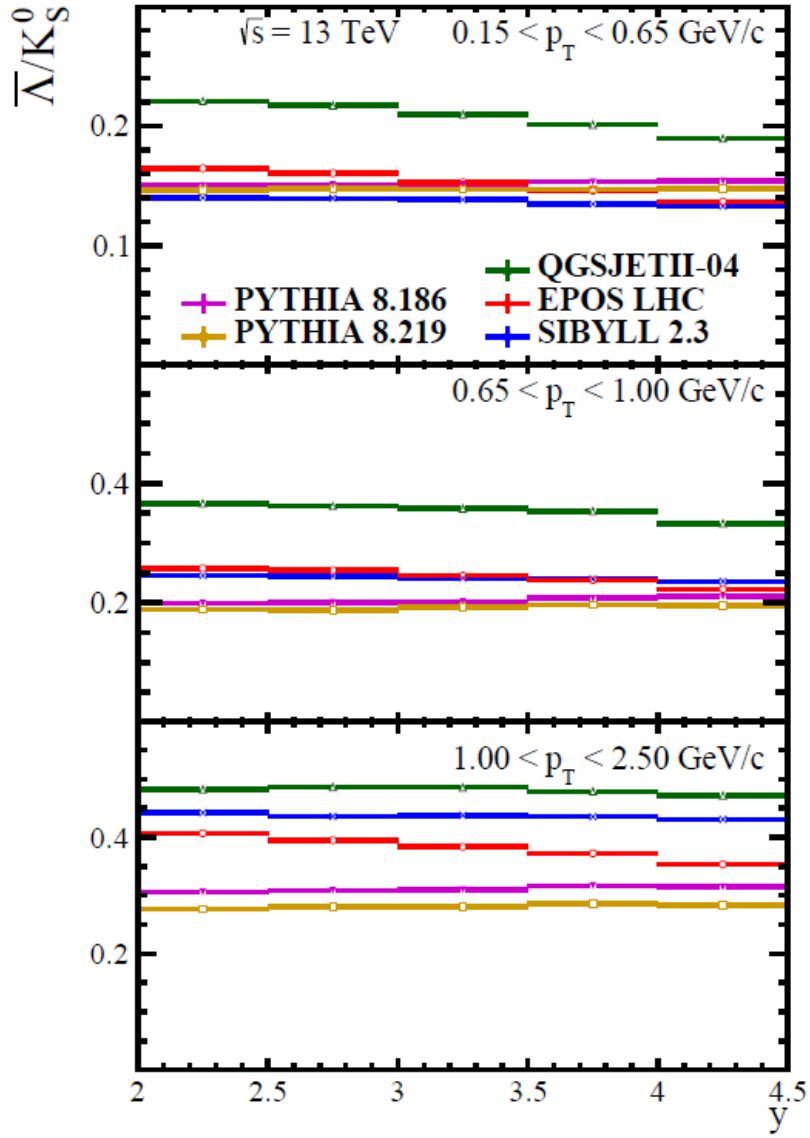

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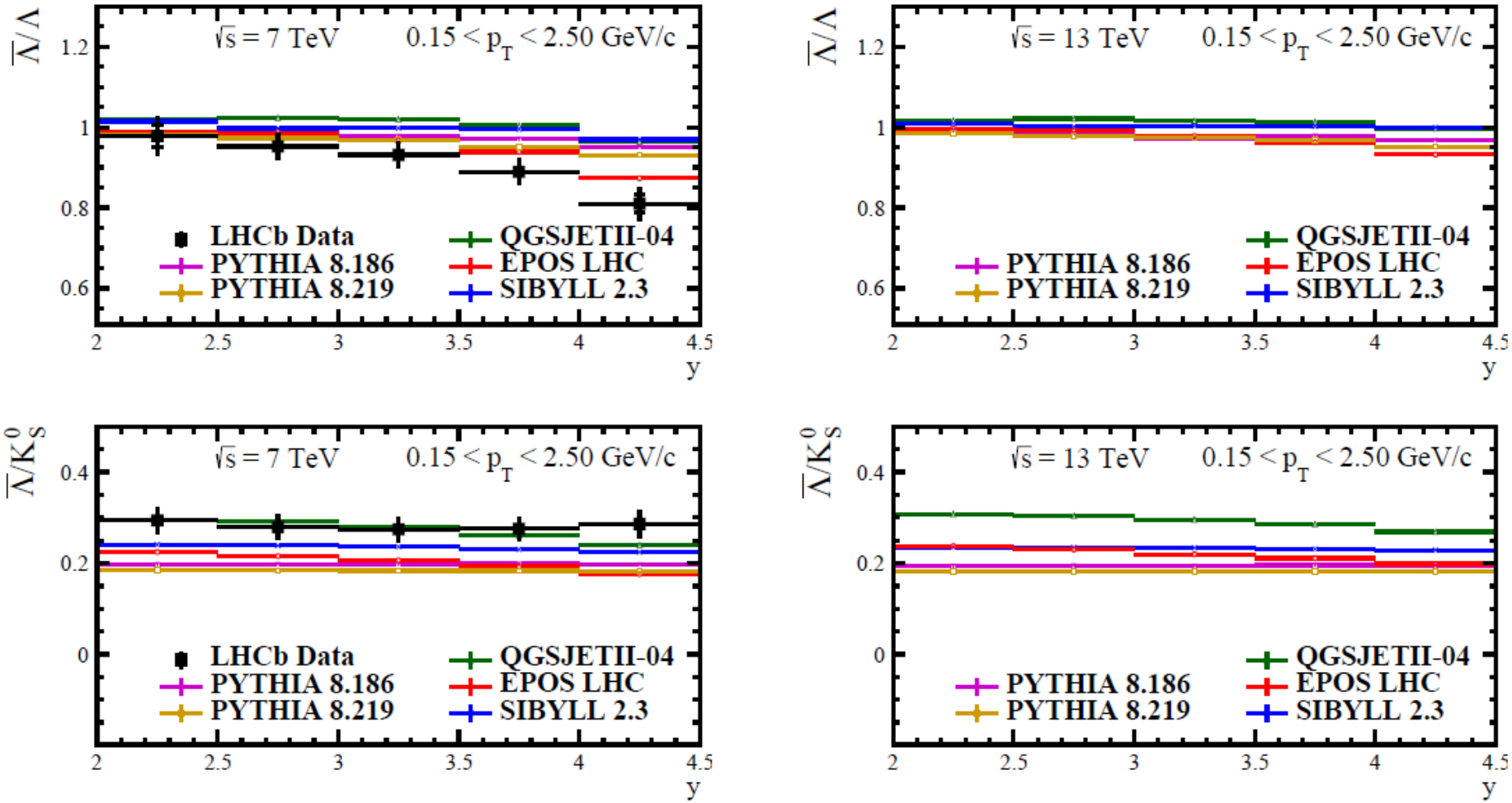

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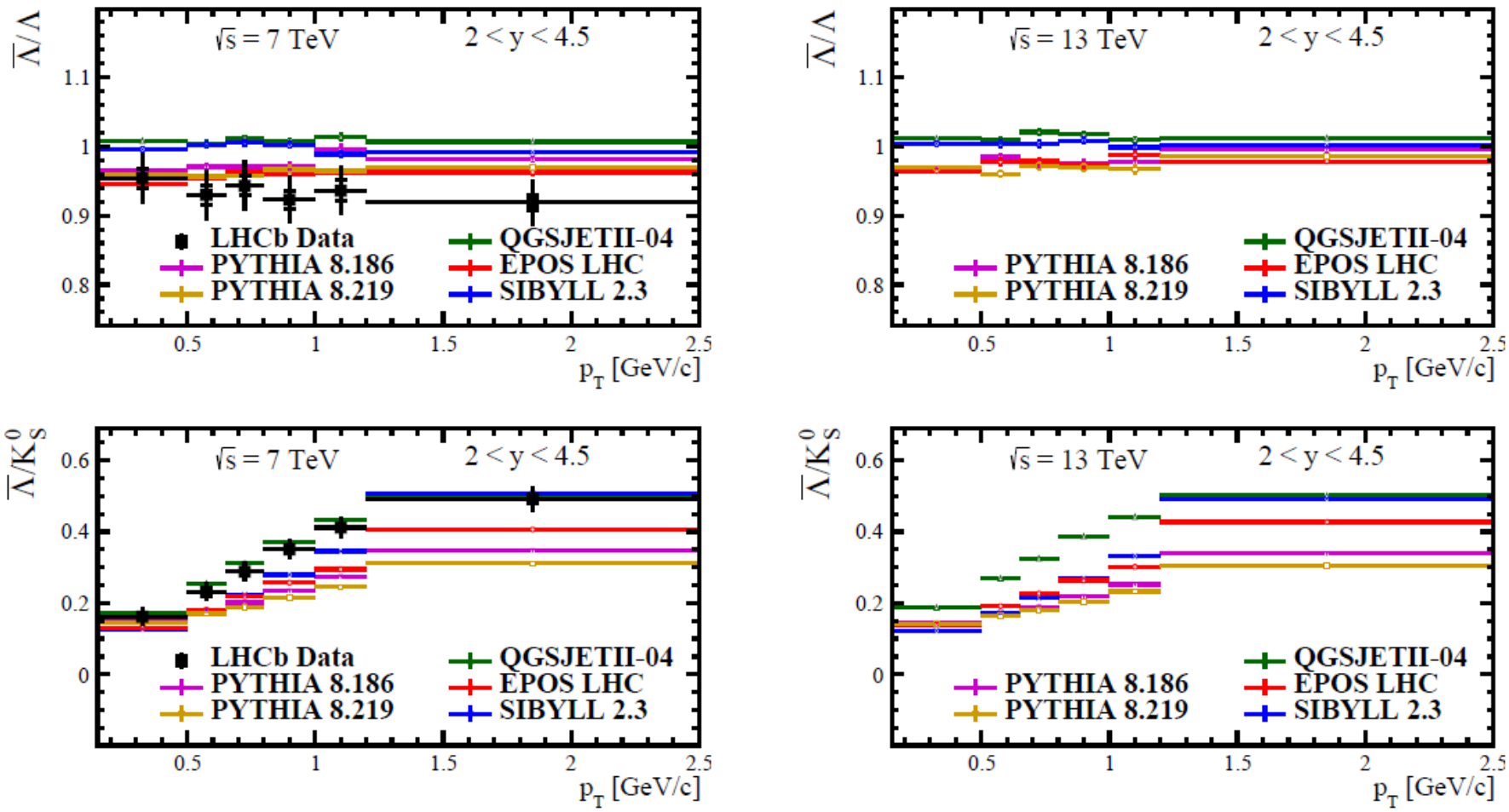
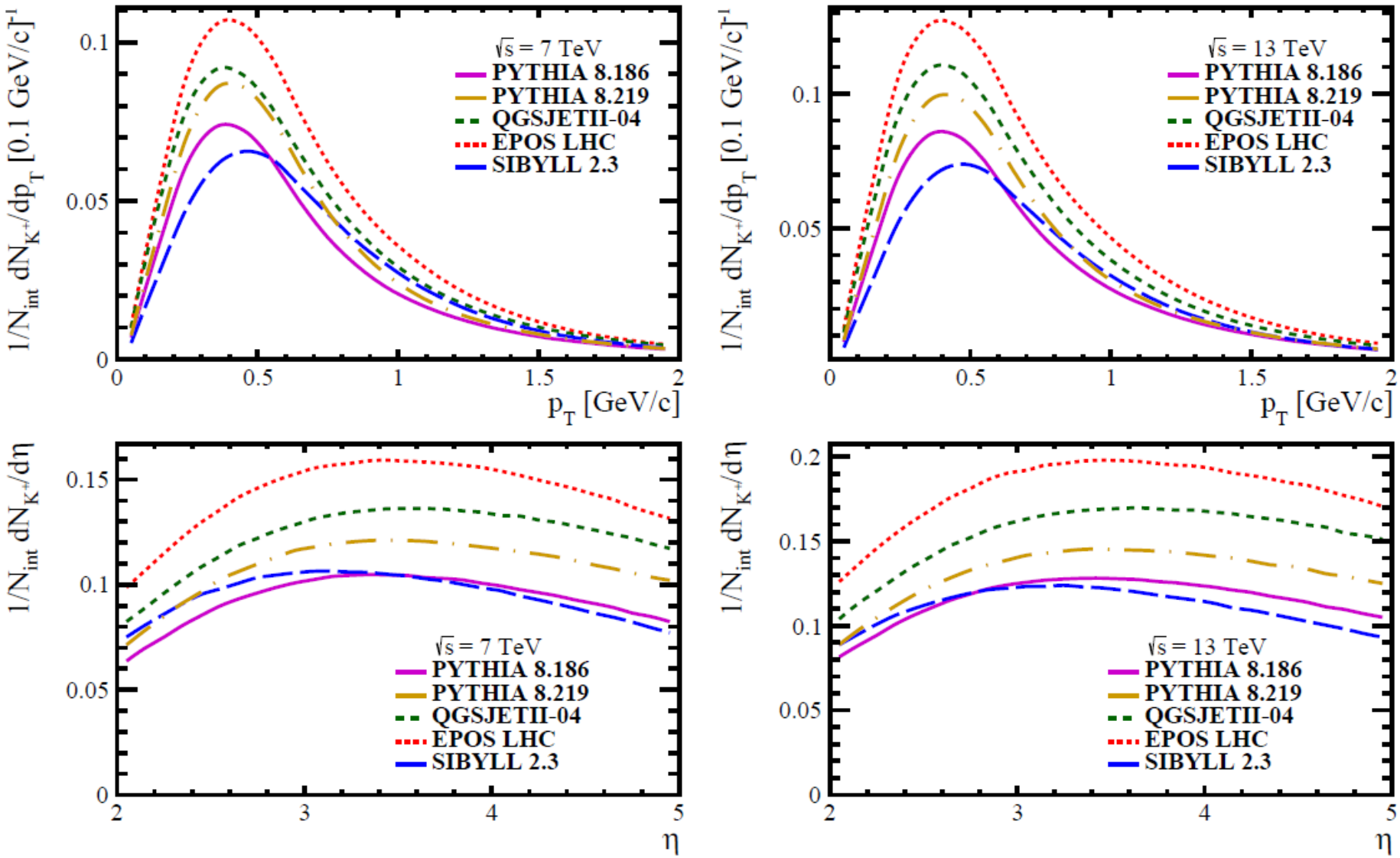


Strange particle distributions



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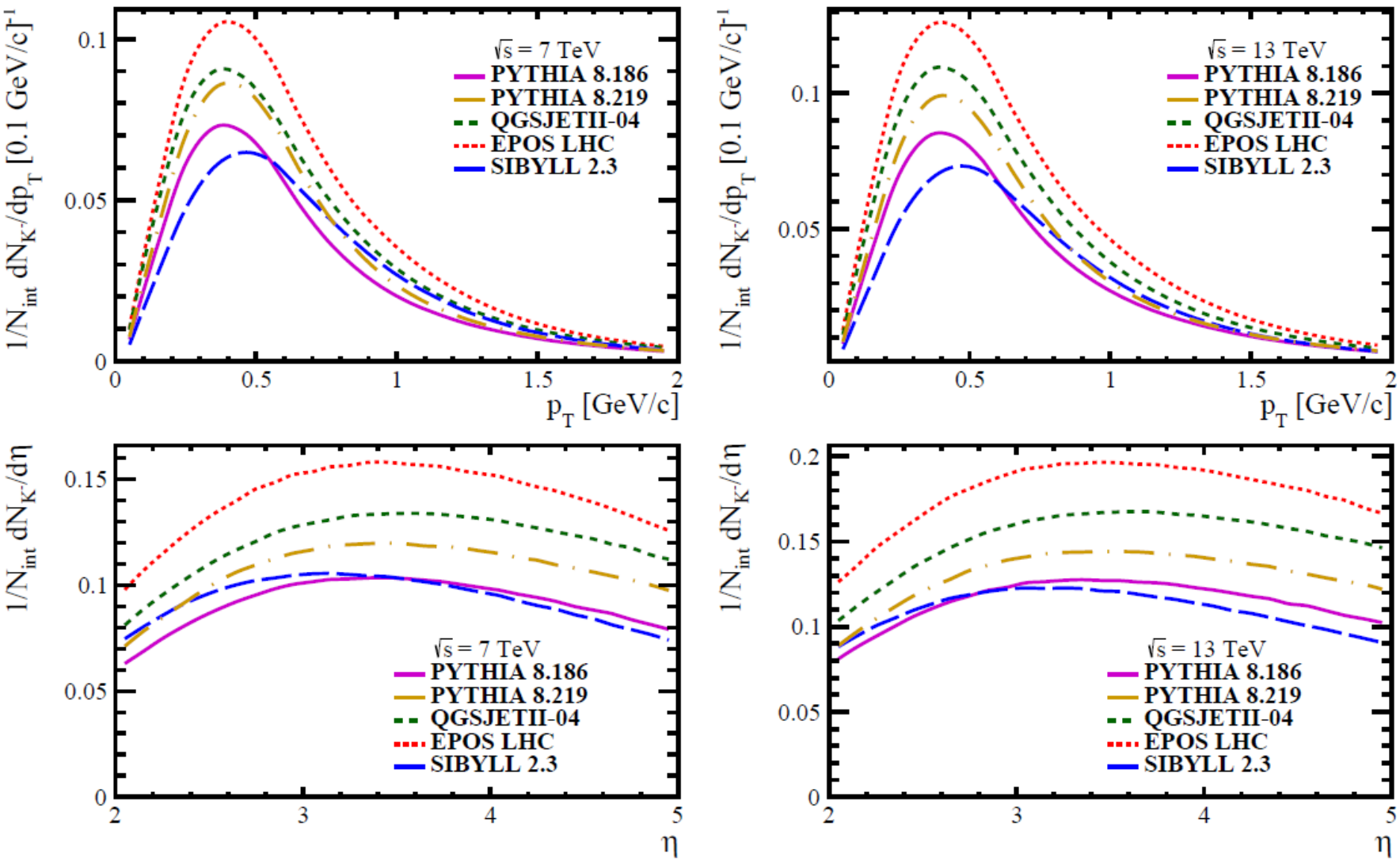
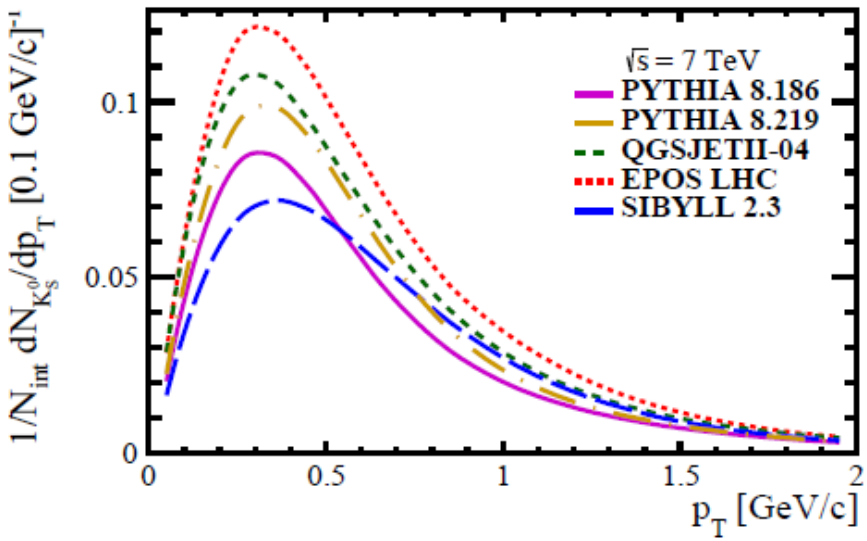
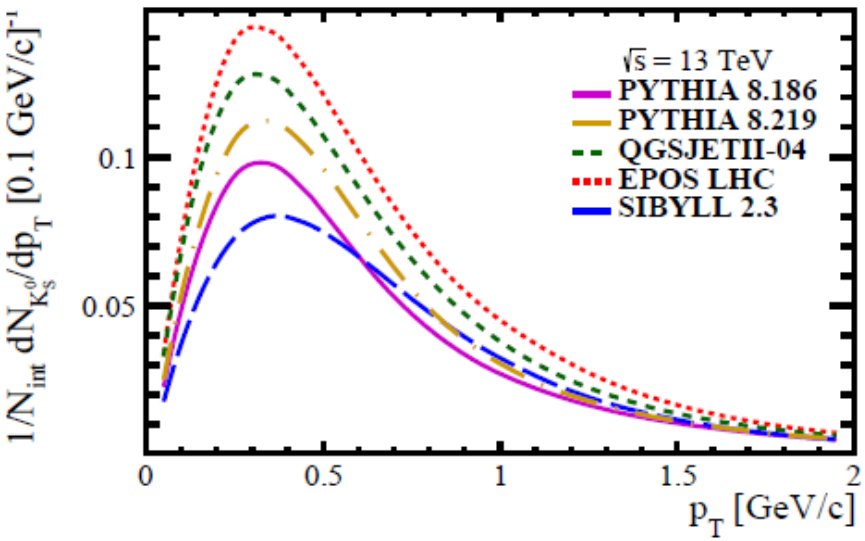
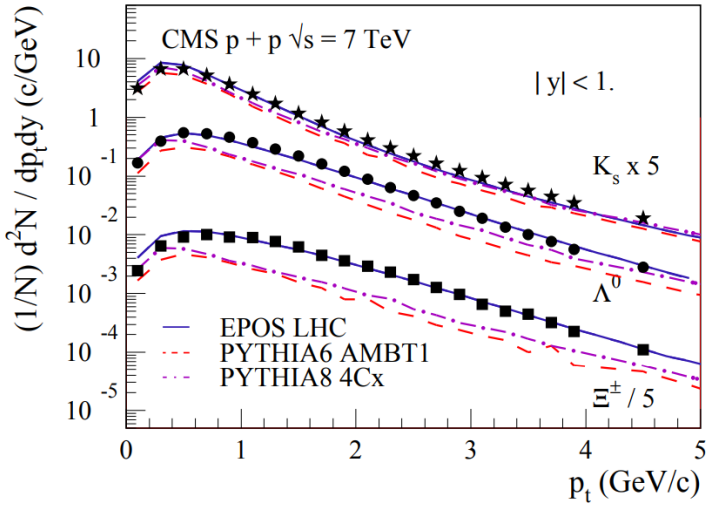


Strange particle distributions



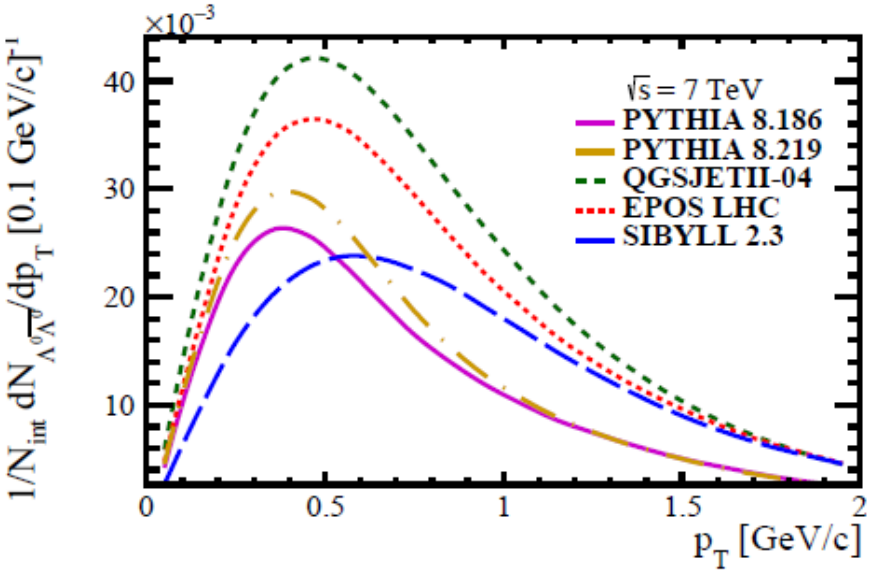


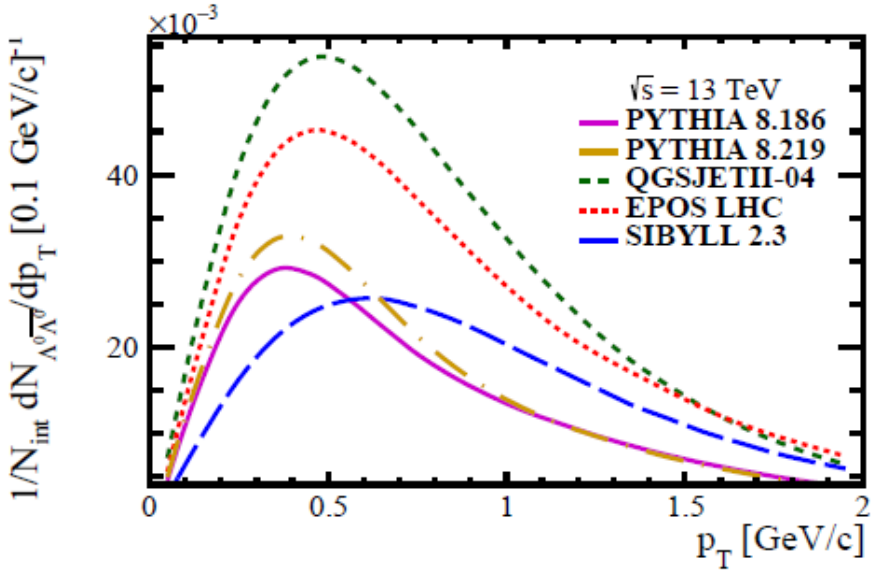


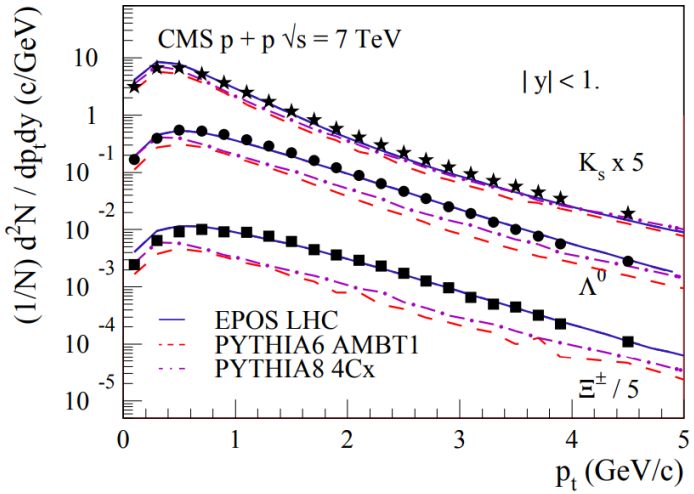
Monash2013 vs. Tune 4C: 10% increase in strangeness production

https://arxiv.org/pdf/1306.0121v1.pdf

Strange particle distributions







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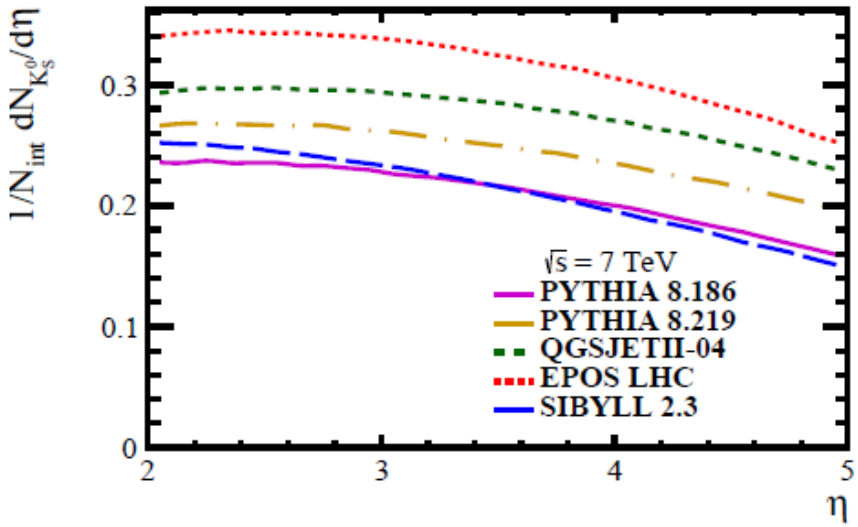
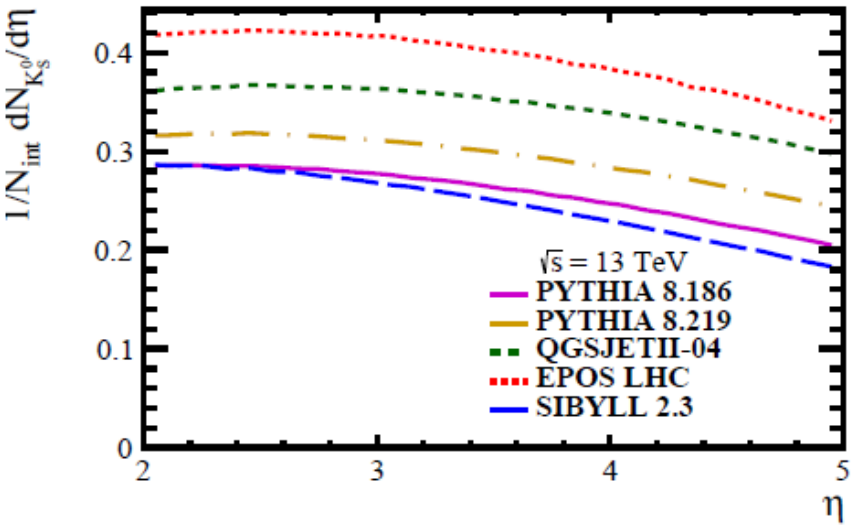
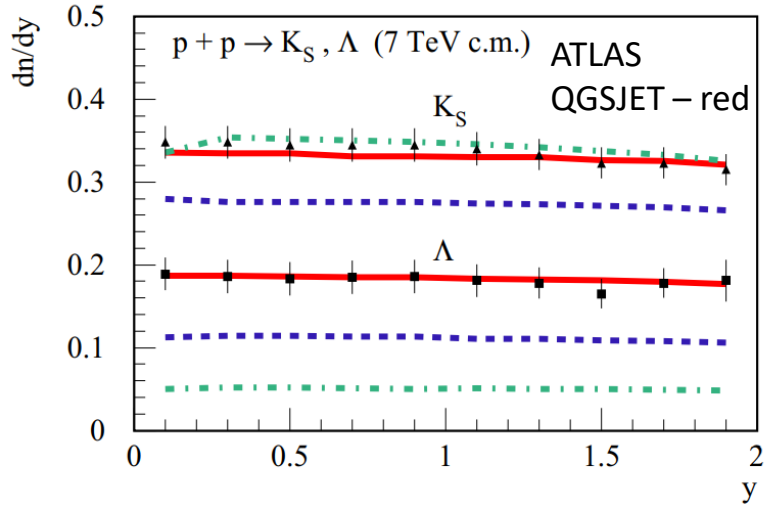
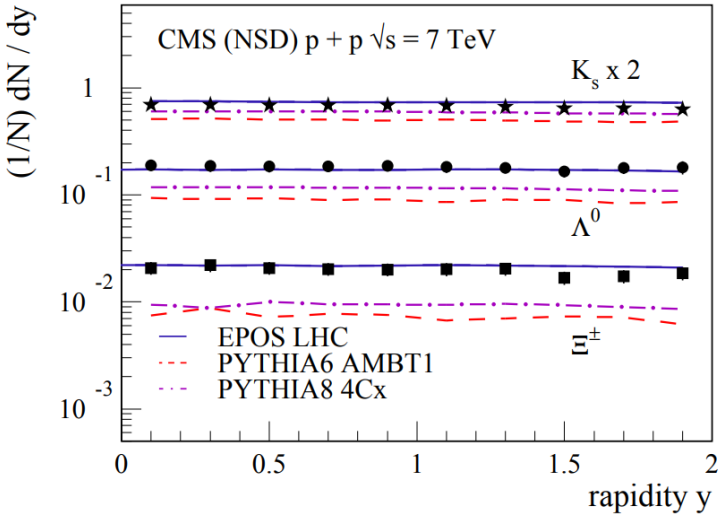
Strange particle distributions









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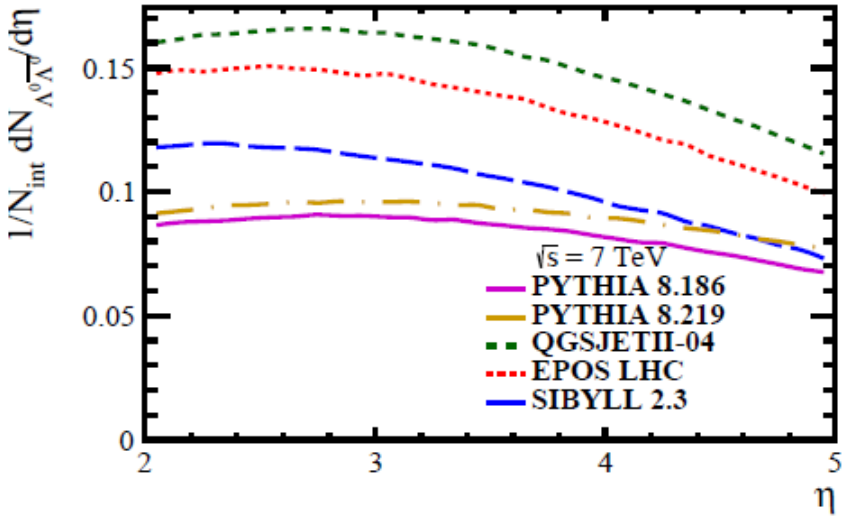
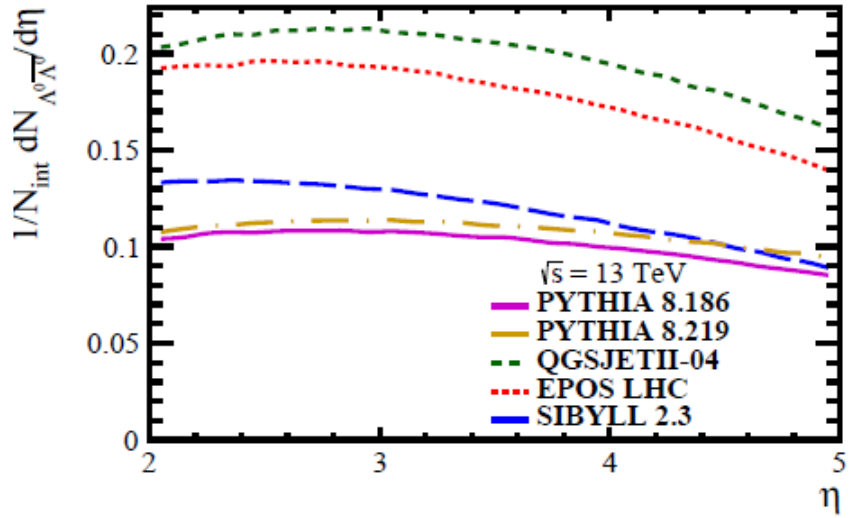
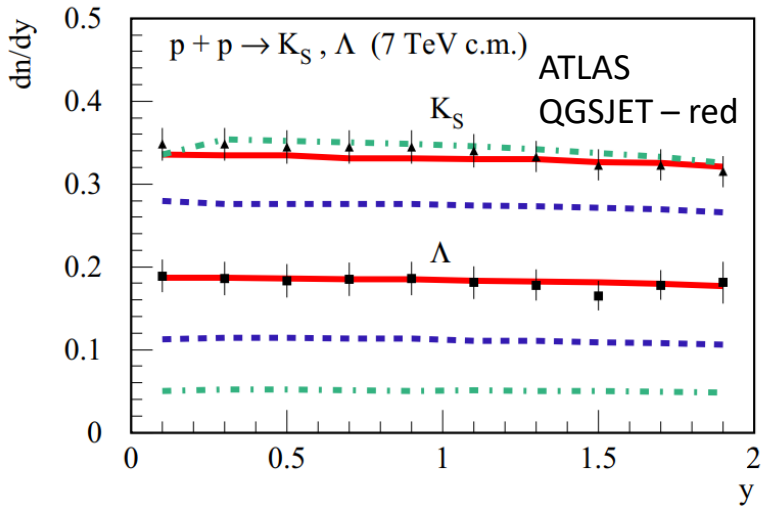
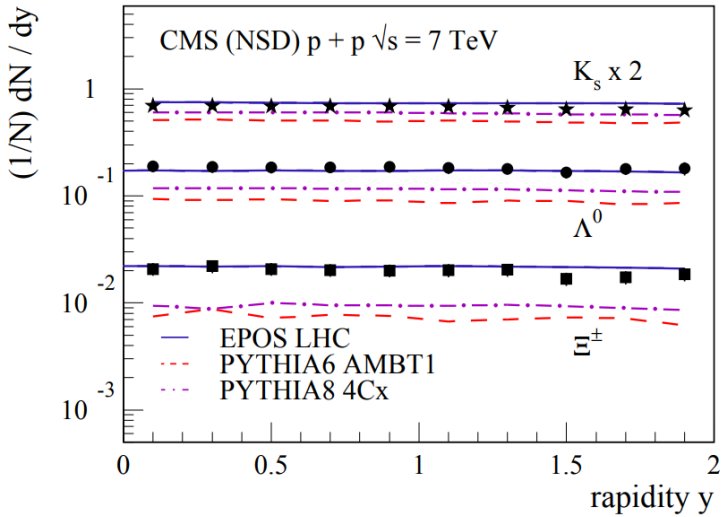
Strange particle distributions









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