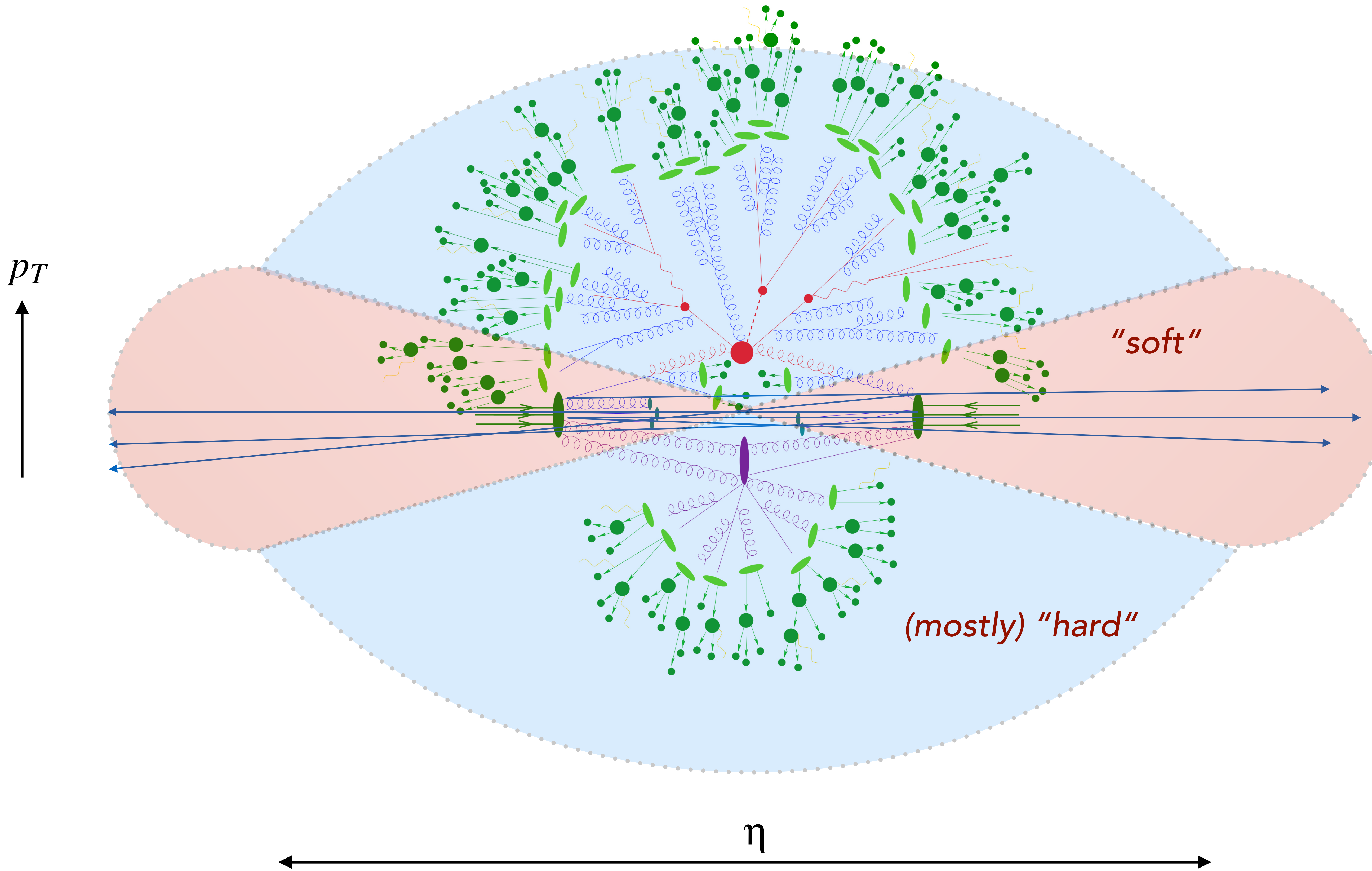
High energy hadronic interaction models bridging accelerators with cosmic ray physics

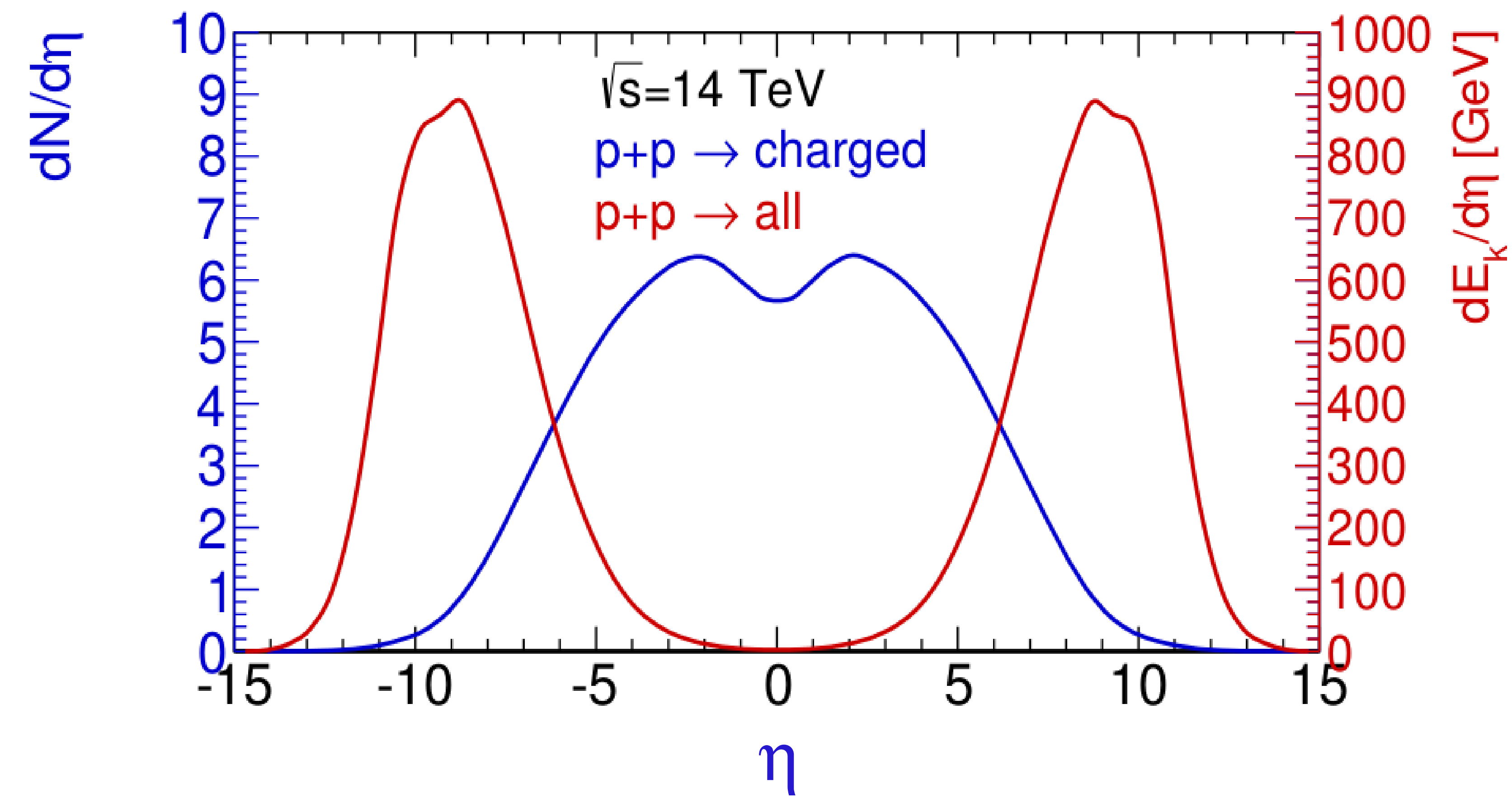
Anatoli Fedynitch

KIT (IKP) & CERN

High energy particle interaction



General properties of particle production



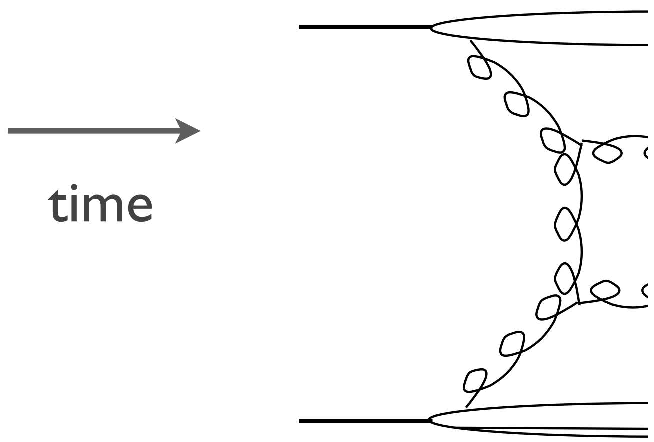
hard (central)

- high particle (number) density
- low energy density
- heavy particles decay into this region
- collider detectors optimized for searches in this region (W, Z, Higgs, SUSY, etc..)

soft (forward)

- low particle density
- high energy density
- products of valence quark interactions
- crucial part for properties of air showers

Why this separation?



Generic diagram of hard scattering

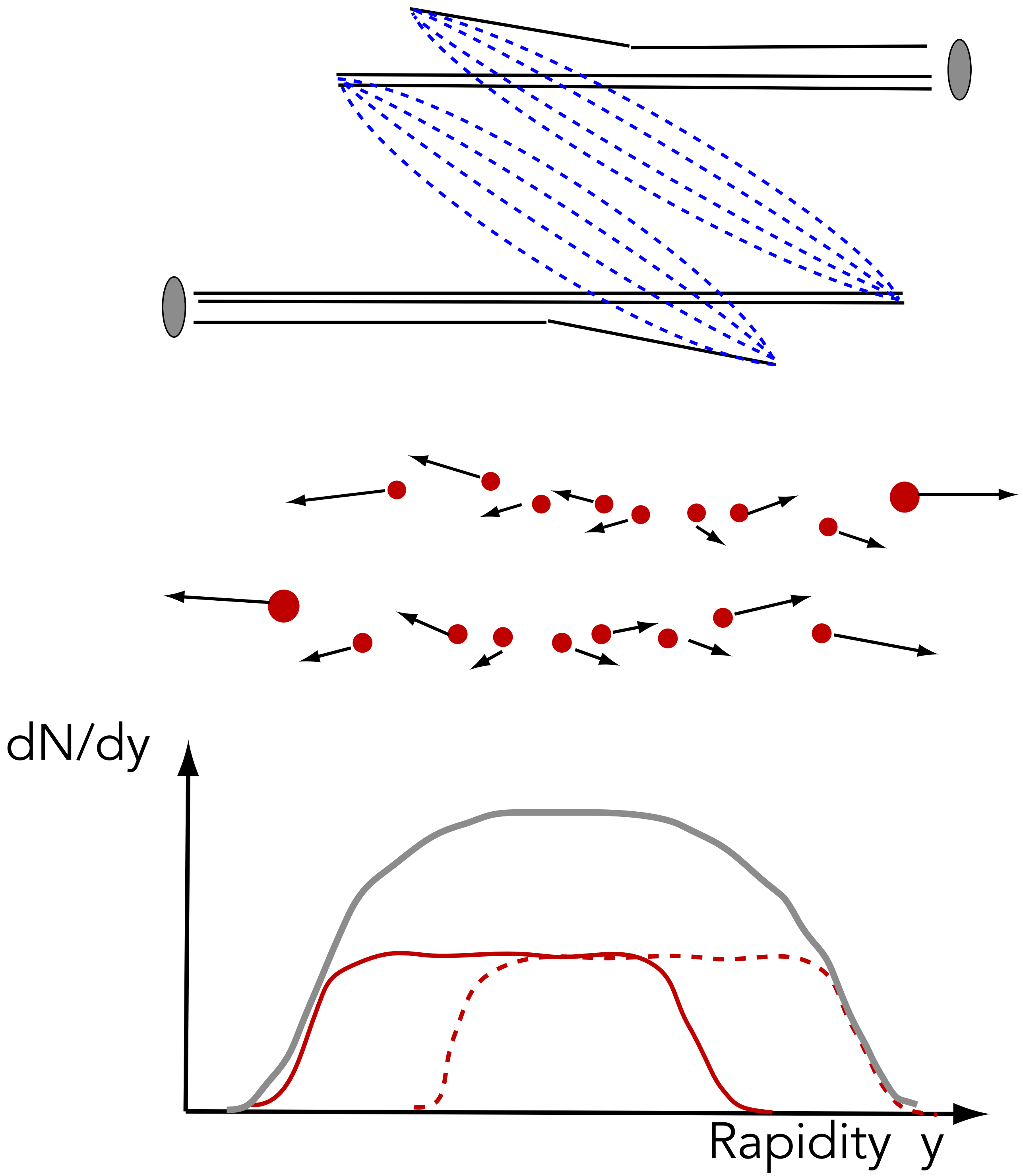
parton momentum fraction

$$\sigma_{QCD} = \sum_{i,j,k,l} \frac{1}{1+\delta_{kl}} \int dx_1\, dx_2 \int_{p_\perp^{\text{cutoff}}} dp_\perp^2\, f_i(x_1,Q^2)\, f_j(x_2,Q^2)\, \frac{d\sigma_{i,j\to k,l}}{dp_\perp}$$

cut-off in transverse momentum, defining perturbative phase-space

- diagrammatical QCD calculations (currently) work only in a perturbative approach due to running coupling constant (pQCD or hard QCD)
- precision of calculation increases with the number of orders included (LO, NLO, NNLO, etc.)
- no calculable theory for non-perturbative regime (soft QCD)
- instead, (Gribov-)Regge Theory is successfully applied
- lattice QCD and other methods (AdS-Stringtheory) are not there (yet)

Predictions of two-string models



(Capella et al., *Physics Reports* 1994)

Two-string models

- Feynman-scaling
- long-range correlations
- leading particle effect
- delayed threshold for baryon pair production

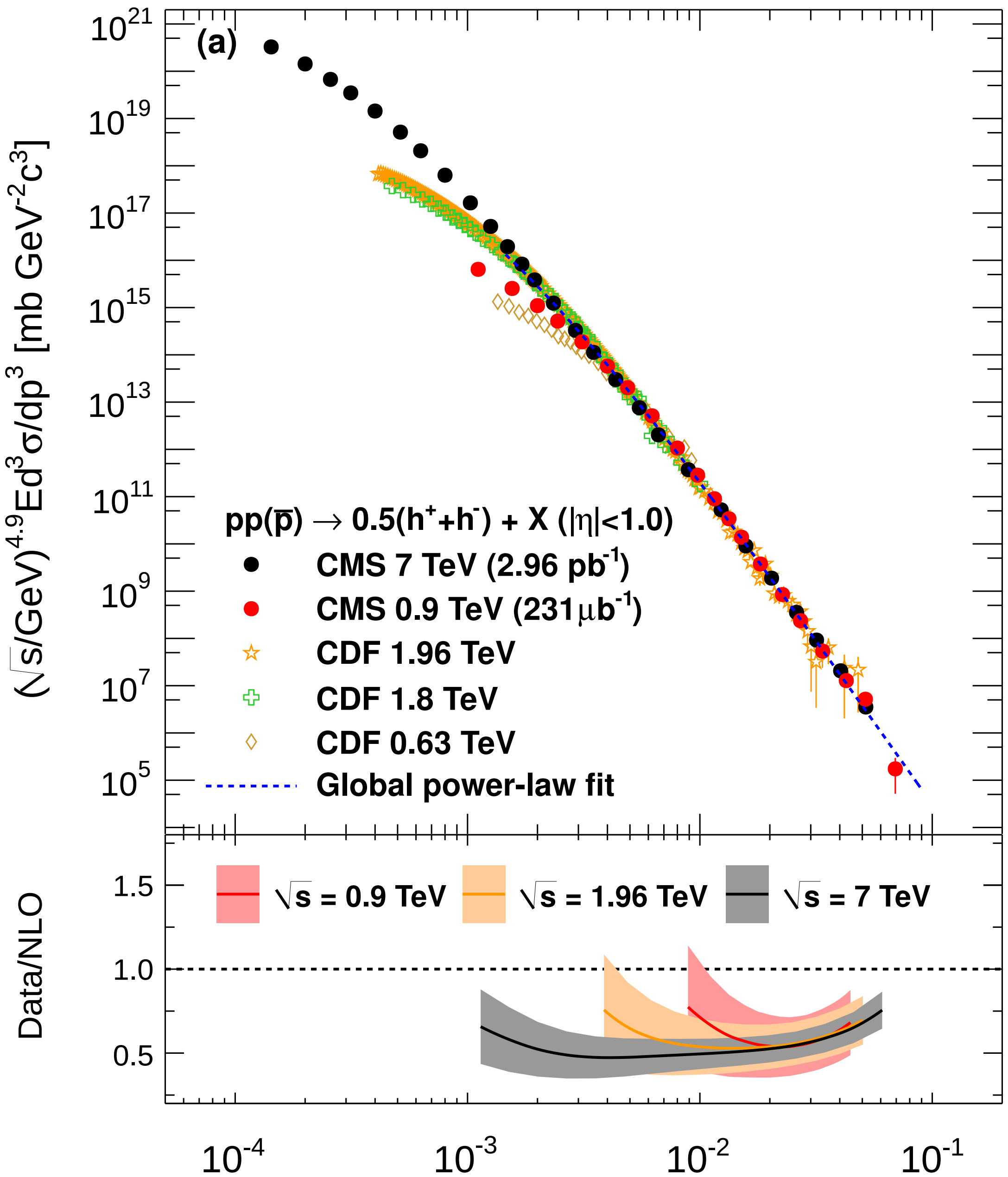
Feynman scaling

$$2E\frac{dN}{d^3p} = \frac{dN}{dy\, d^2p_\perp} \longrightarrow f(x_F, p_\perp)$$

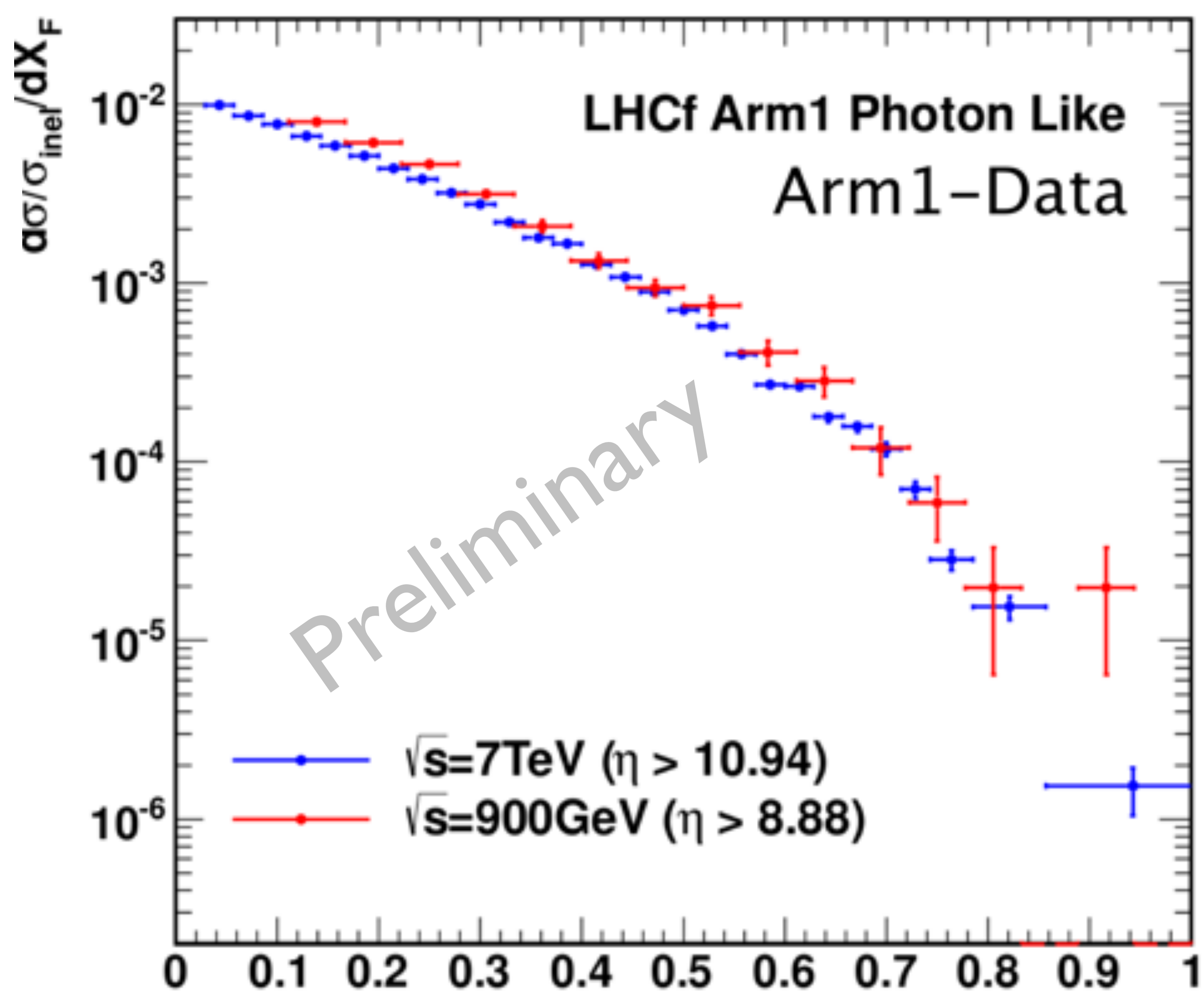
Distribution independent of energy

$$\frac{dN}{dx} \approx \tilde{f}(x) \qquad x = E/E_{\text{prim}}$$

Experimental evidence for scaling



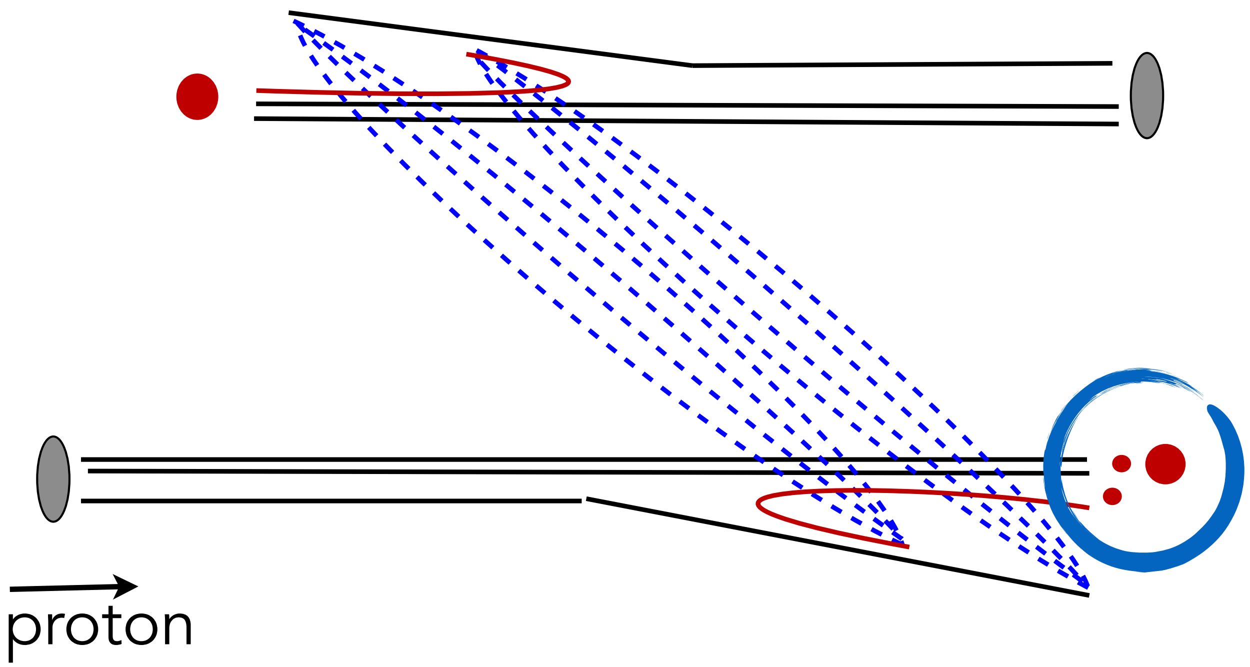
$$x_T = 2\frac{p_T}{\sqrt{s}}$$

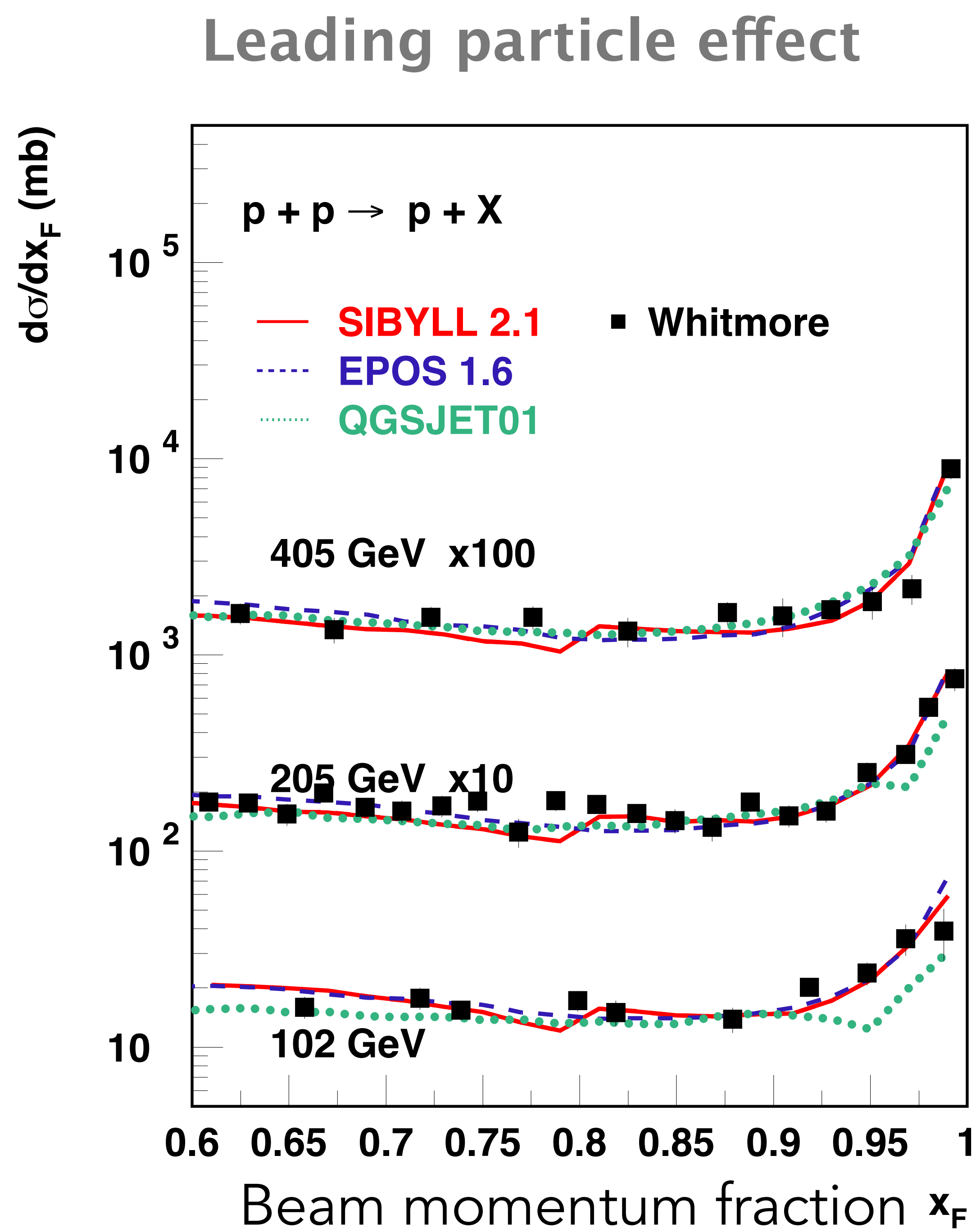


$$x_F = 2\frac{p_L}{\sqrt{s}}$$

CMS Collaboration, Journal of High Energy Physics 08, 086 (2011).

Leading particle effect

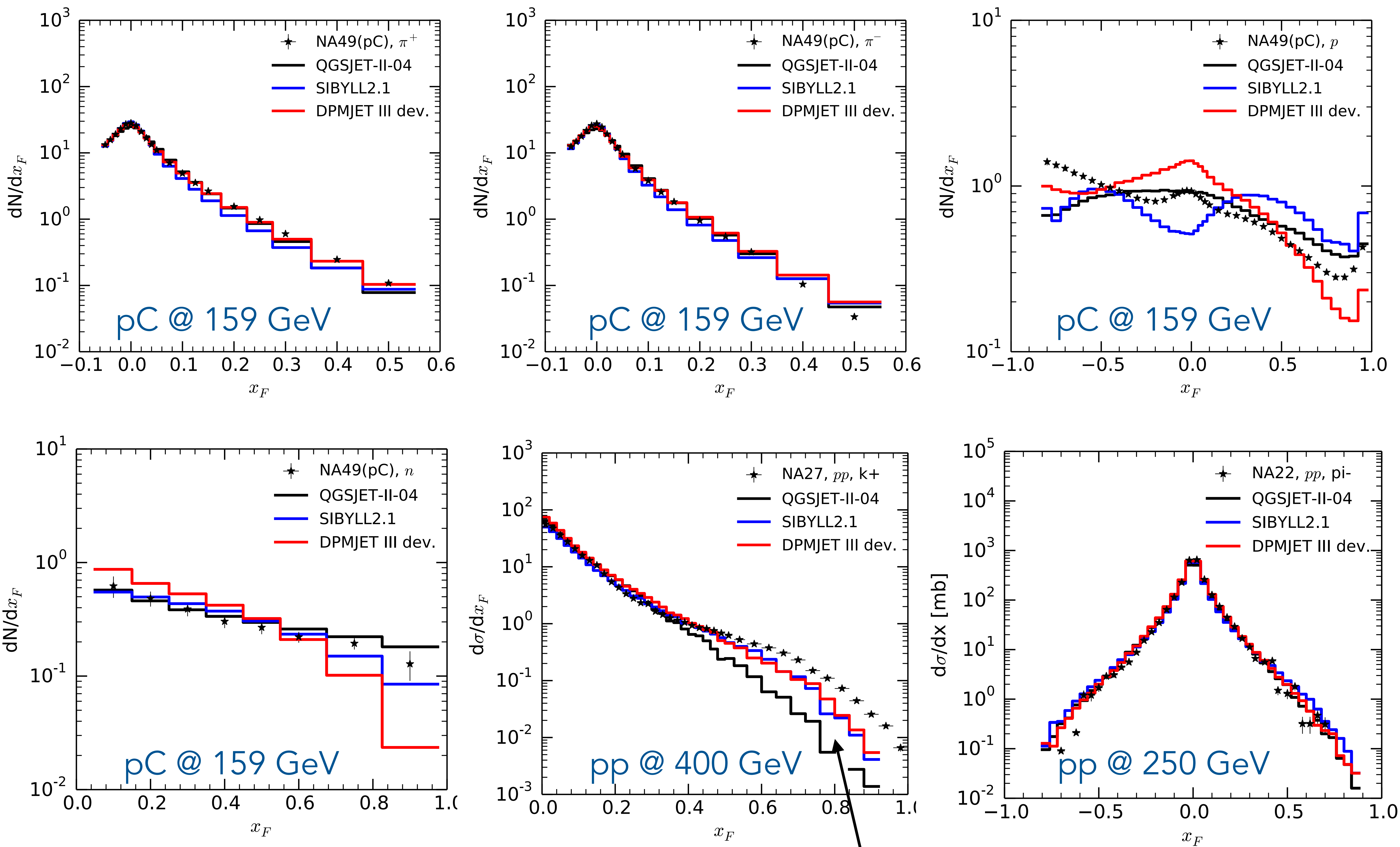




Fluctuations: Generation of sea quark anti-quark pair and leading/excited hadron

In case a pair of strange quarks is raised from the sea - associated production of $p + p \rightarrow \Lambda + K^{+} + X$

Feynman-x distributions at fixed target experiments



associated production with Lambda

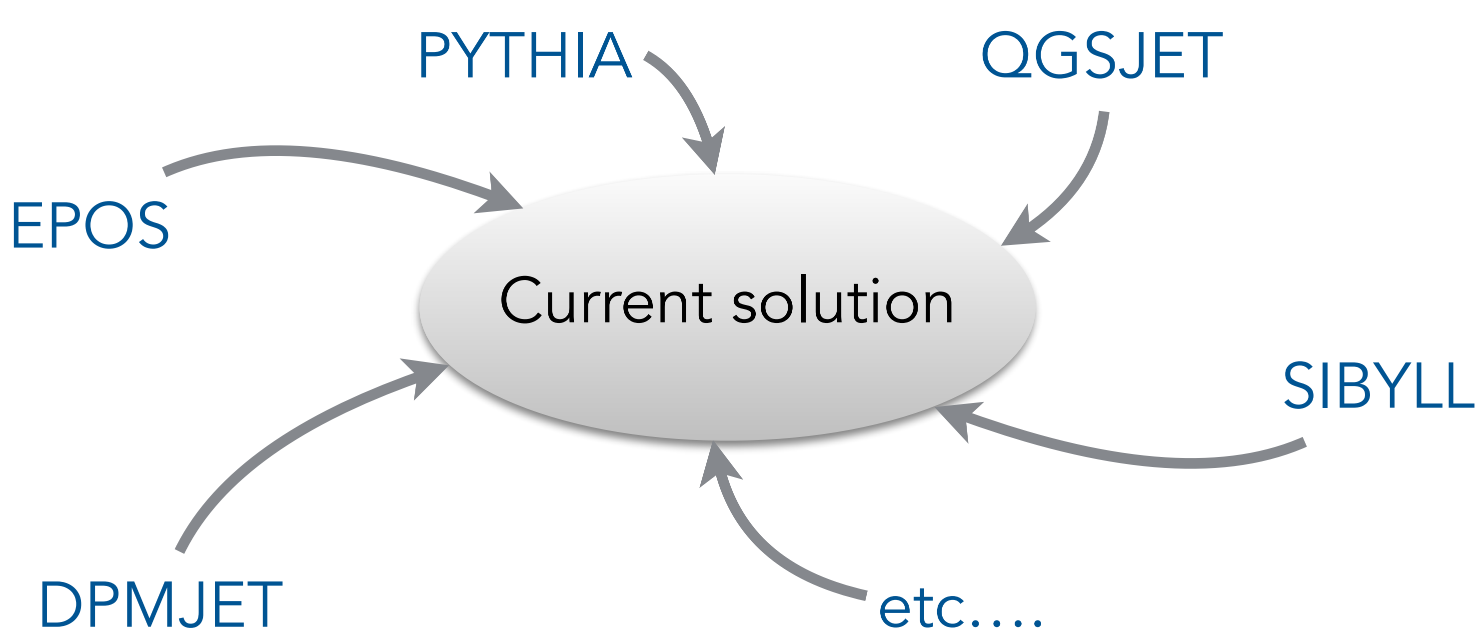
Desired behavior of an interaction model

Requirements

- describe soft and hard physics
- smooth transition between these two regimes
- extrapolation into unknown/-measured phase-space

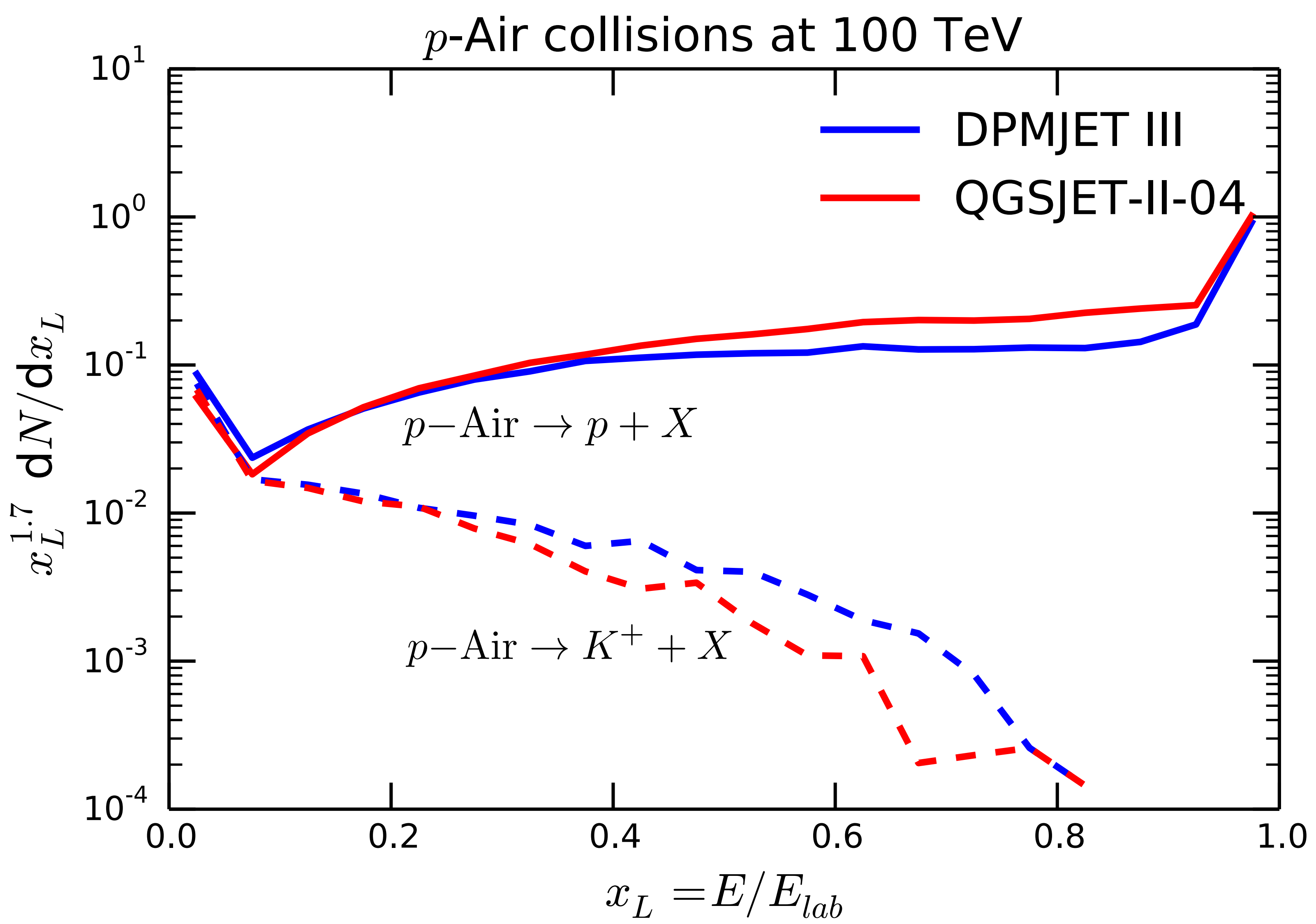
But…

- separation between ‘soft' and ’hard’ not clearly defined
- pQCD minijet cross-section grows faster than $\ln^2 s$
- small-x behavior not well known
- other problems..



Lessons learned from LHC

Spectrum weighted moment (Z-factors)

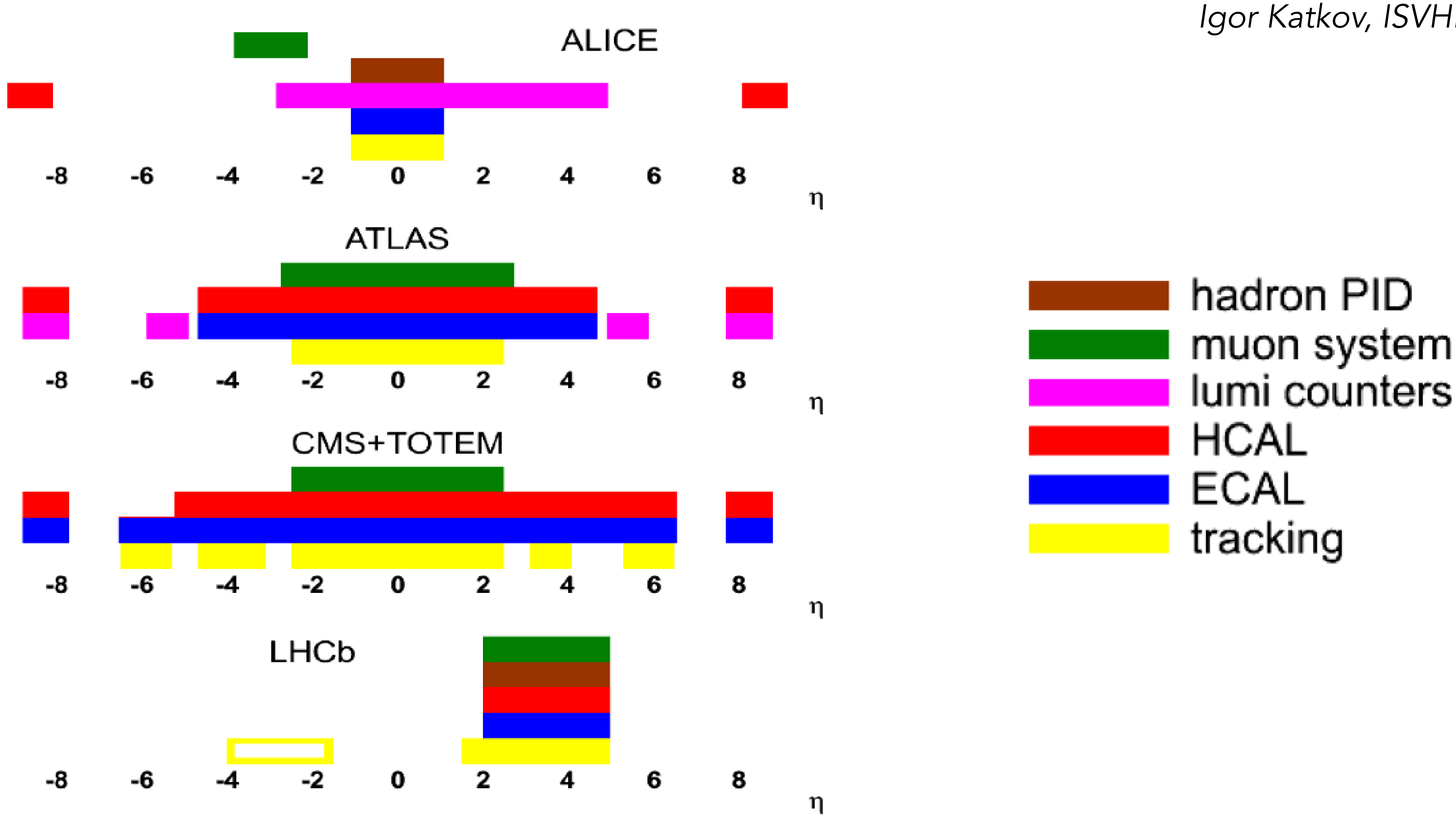


	DPMJET	QGSJet	Ratio
Z_{pp}	0.117	0.154	0.75
Z_{pK^+}	0.0067	0.0056	1.19

$$Z_{kh} = \int_0^1 dx\ x^{\gamma-1} \frac{dn(kA \to hY)}{dx}$$

LHC phase-space coverage

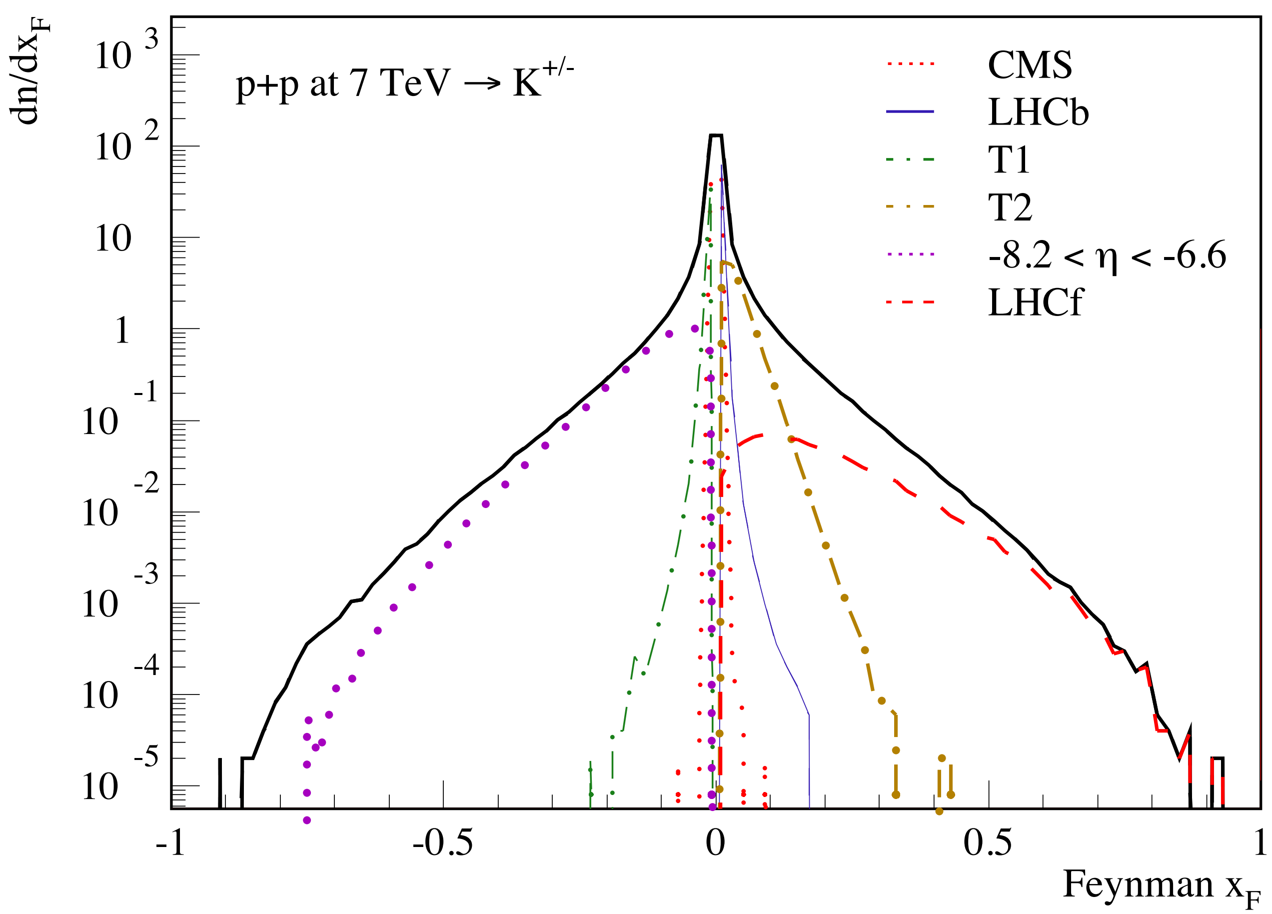
Igor Katkov, ISVHECRI 2014

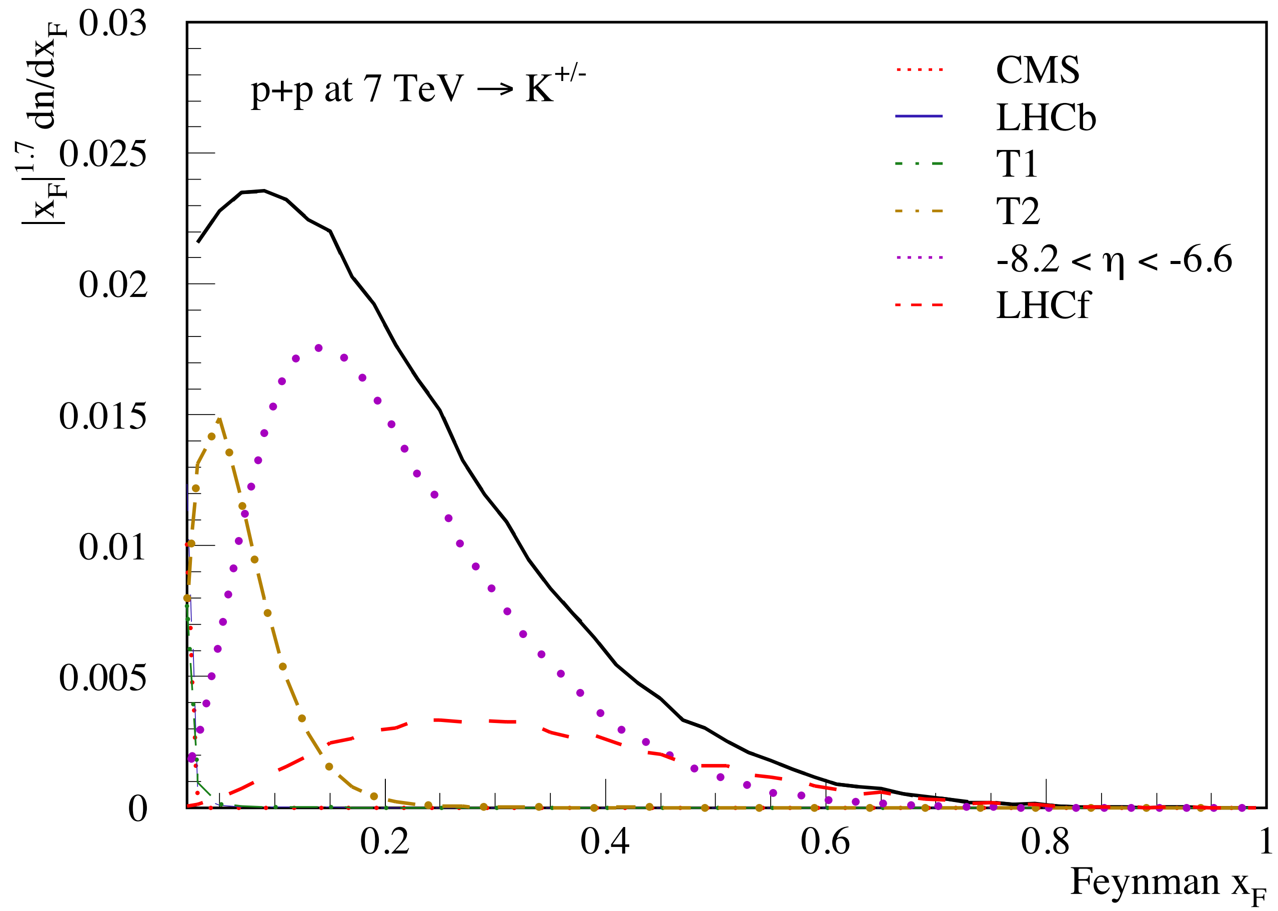


Typical Feynman-x coverage of LHC measurements $x_F \ll 0.1$

How relevant are current LHC measurements for air showers?

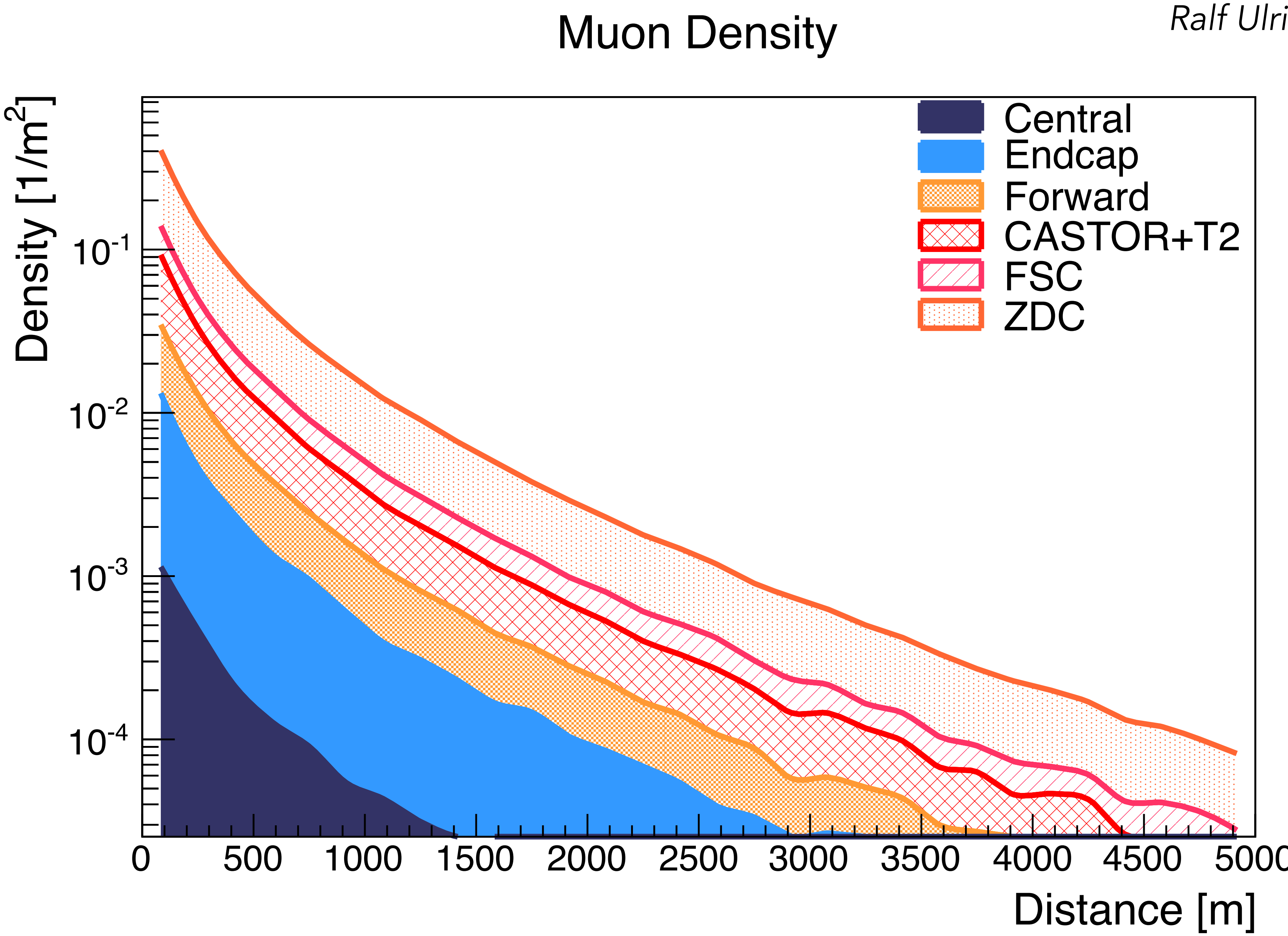
Tanguy Pierog, ISVHECRI 2014





How relevant are current LHC measurements for air showers?

Ralf Ulrich, ISVHECRI 2014

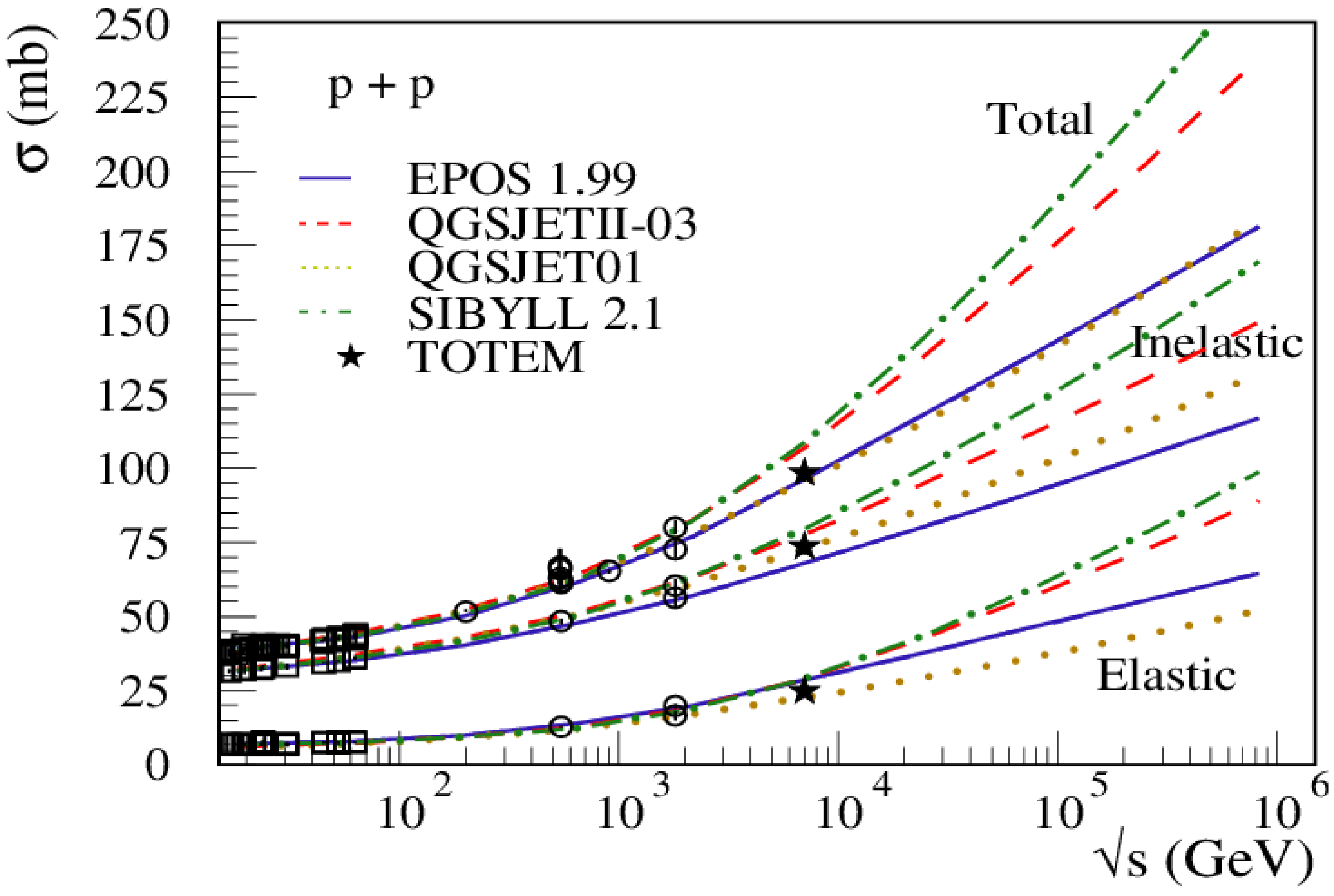


- Air shower models so far only tuned to about 10 % !
- Forward detectors are crucial.

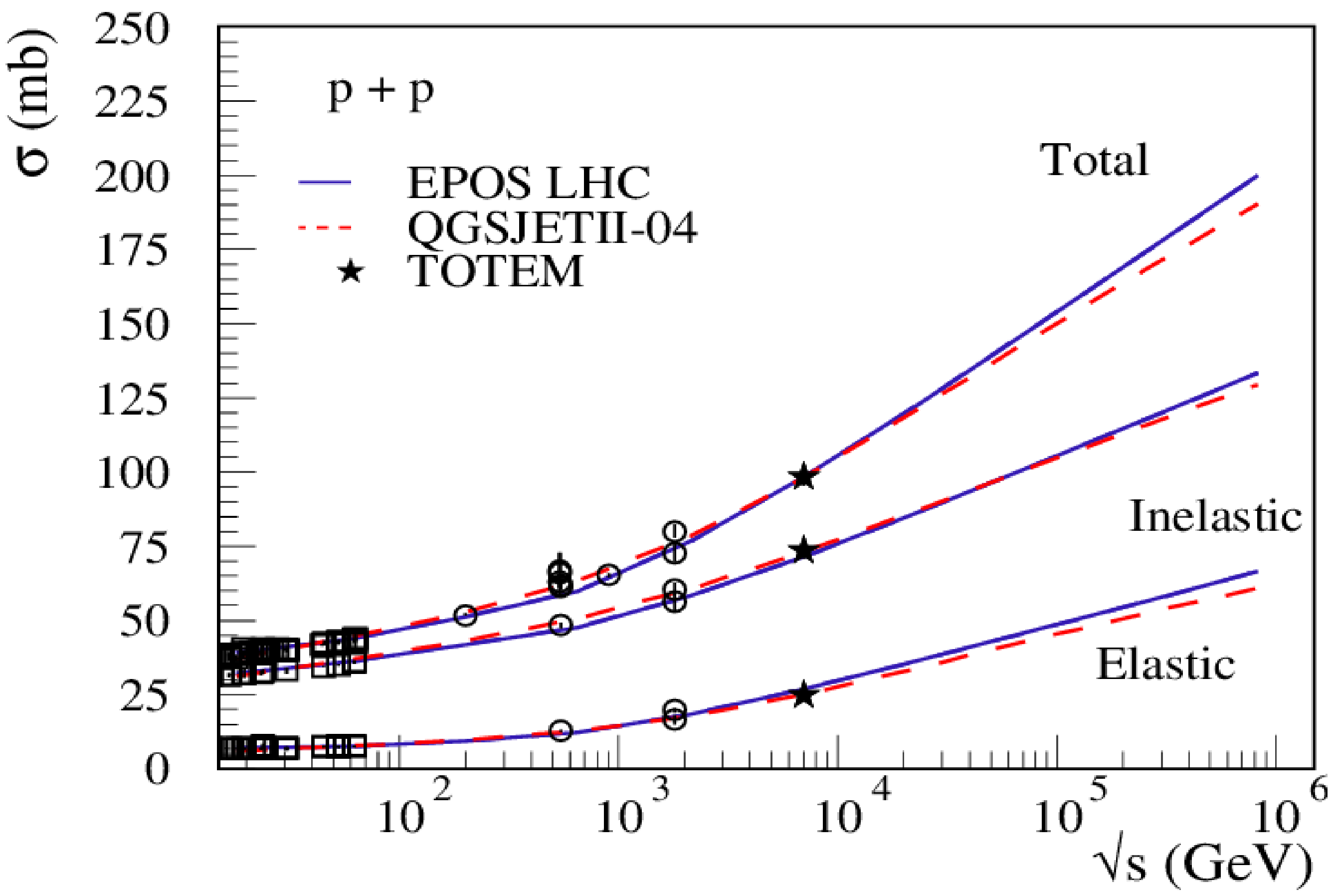
Extrapolation of total pp cross-section

T. Pierog, ISVHECRI 2014

Pre - LHC

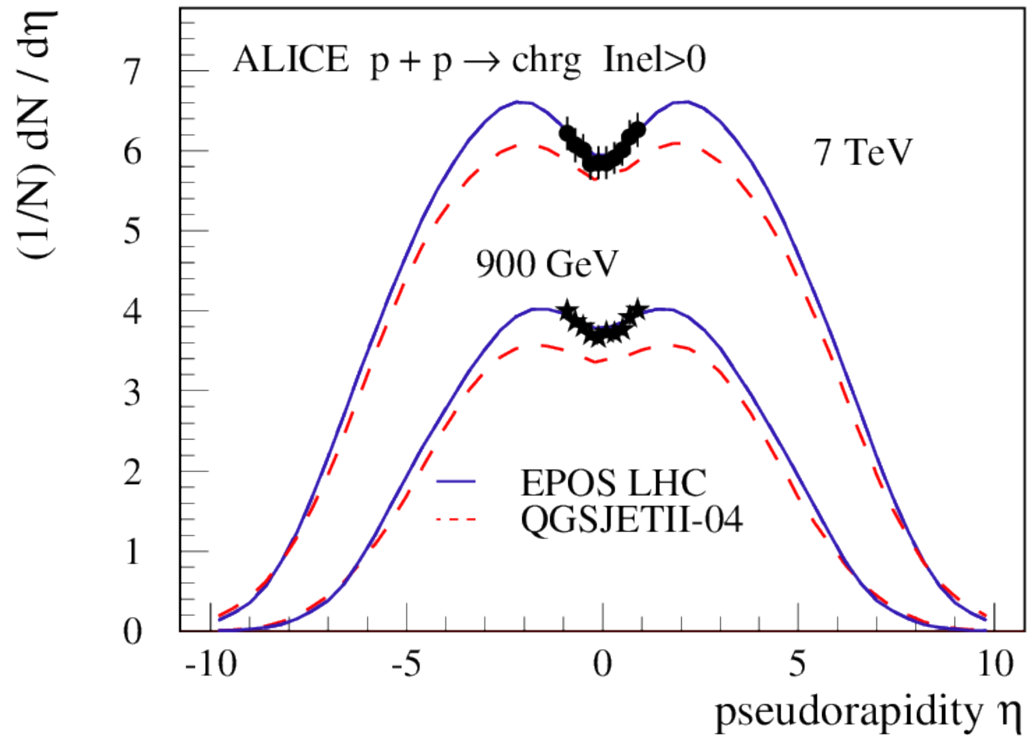


Post - LHC

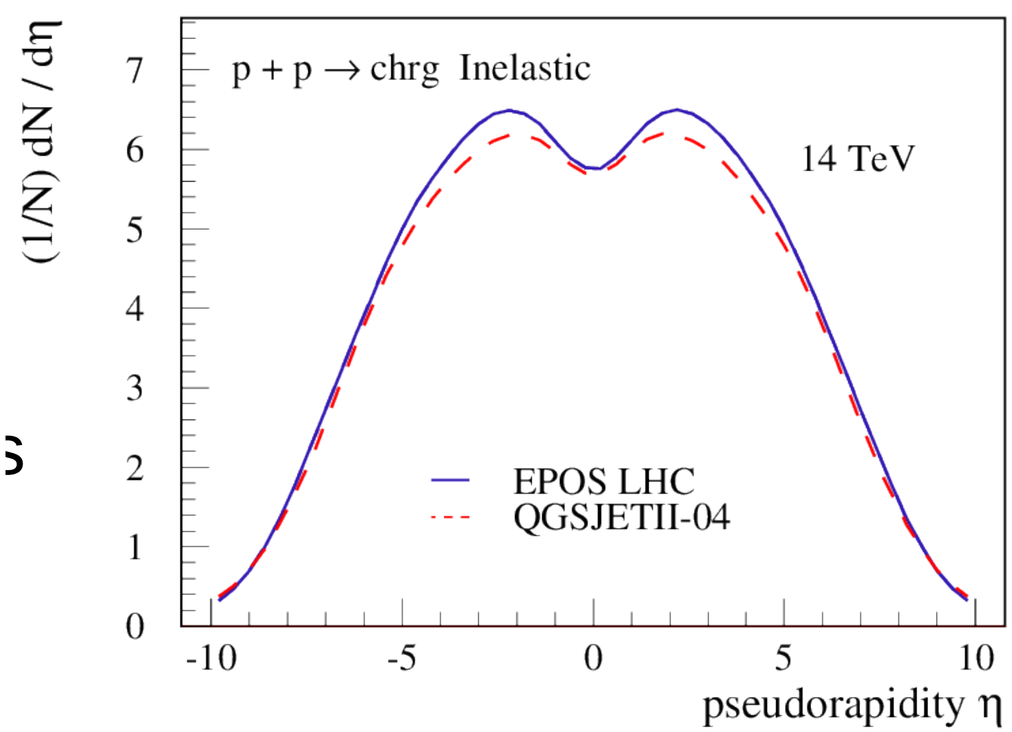


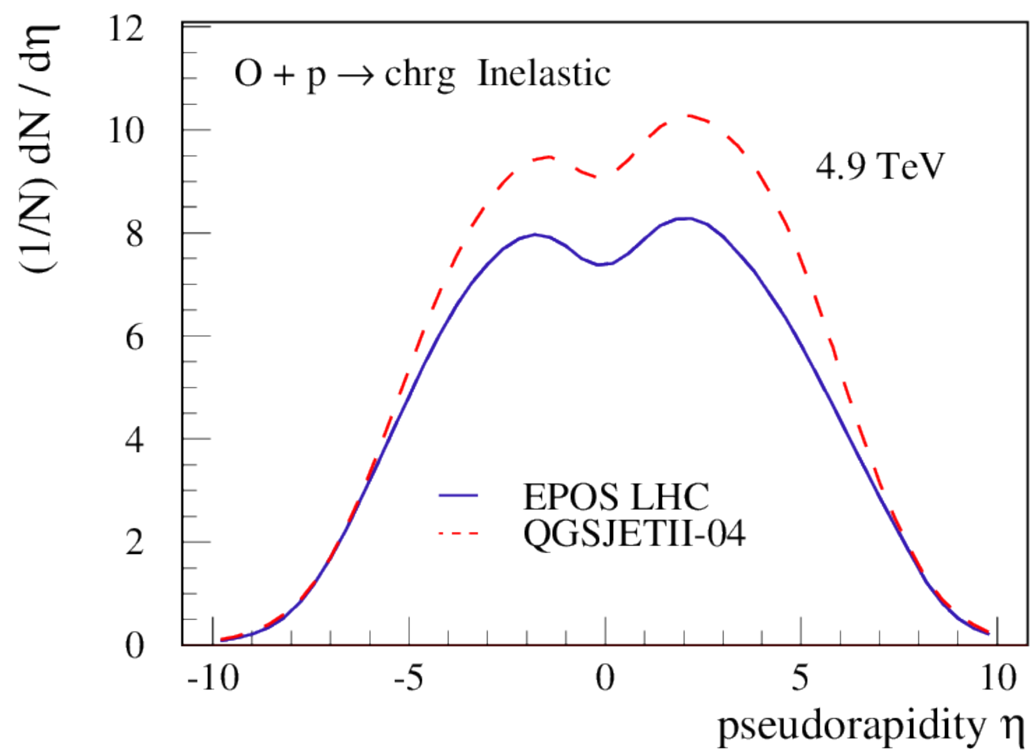
Extrapolation to pA

T. Pierog, ISVHECRI 2014



- Extrapolation in energy after LHC min-bias data is strongly constrained
- Extrapolation from pp to p-air is the bigger problem





Charm in interaction models

Production mechanisms

Contribution from hard scattering

- Largest contribution at high energies
- many NLO calculations available

Non-perturbative component

- di-quark fragments together with charm quark in valence scattering
- leading particle effect (SELEX)
- most relevant contribution for inclusive fluxes of muons and neutrinos

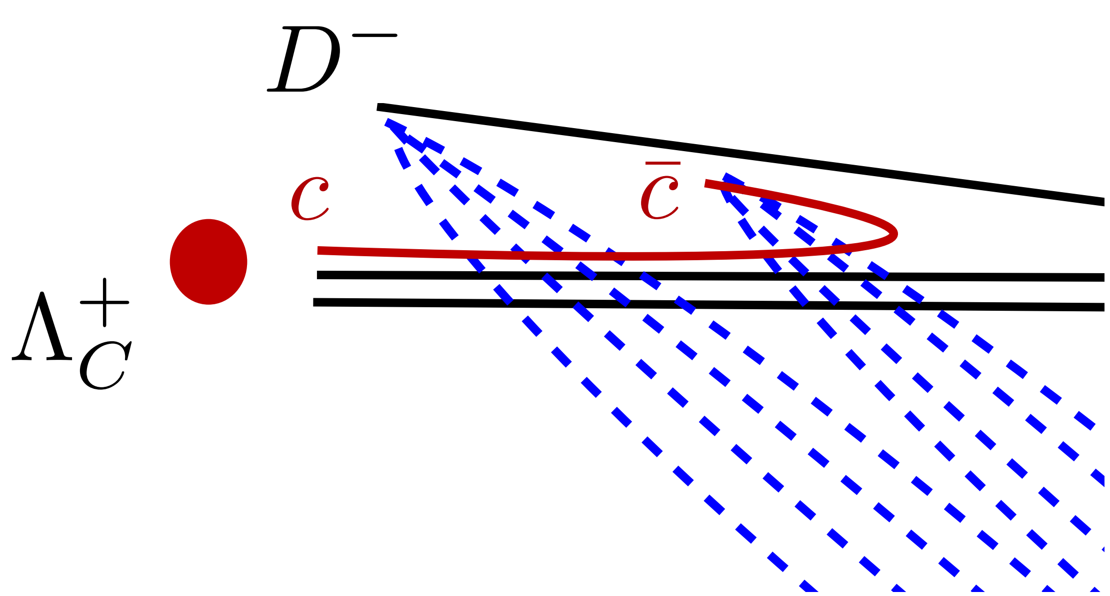
Charm in fragmenation

- usually strongly suppressed u:d:s:c = 1:1:0.3:10^{-11}
- in DPMJET-II.55 enhanced by adding higher probability raising charm from the sea close to string ends

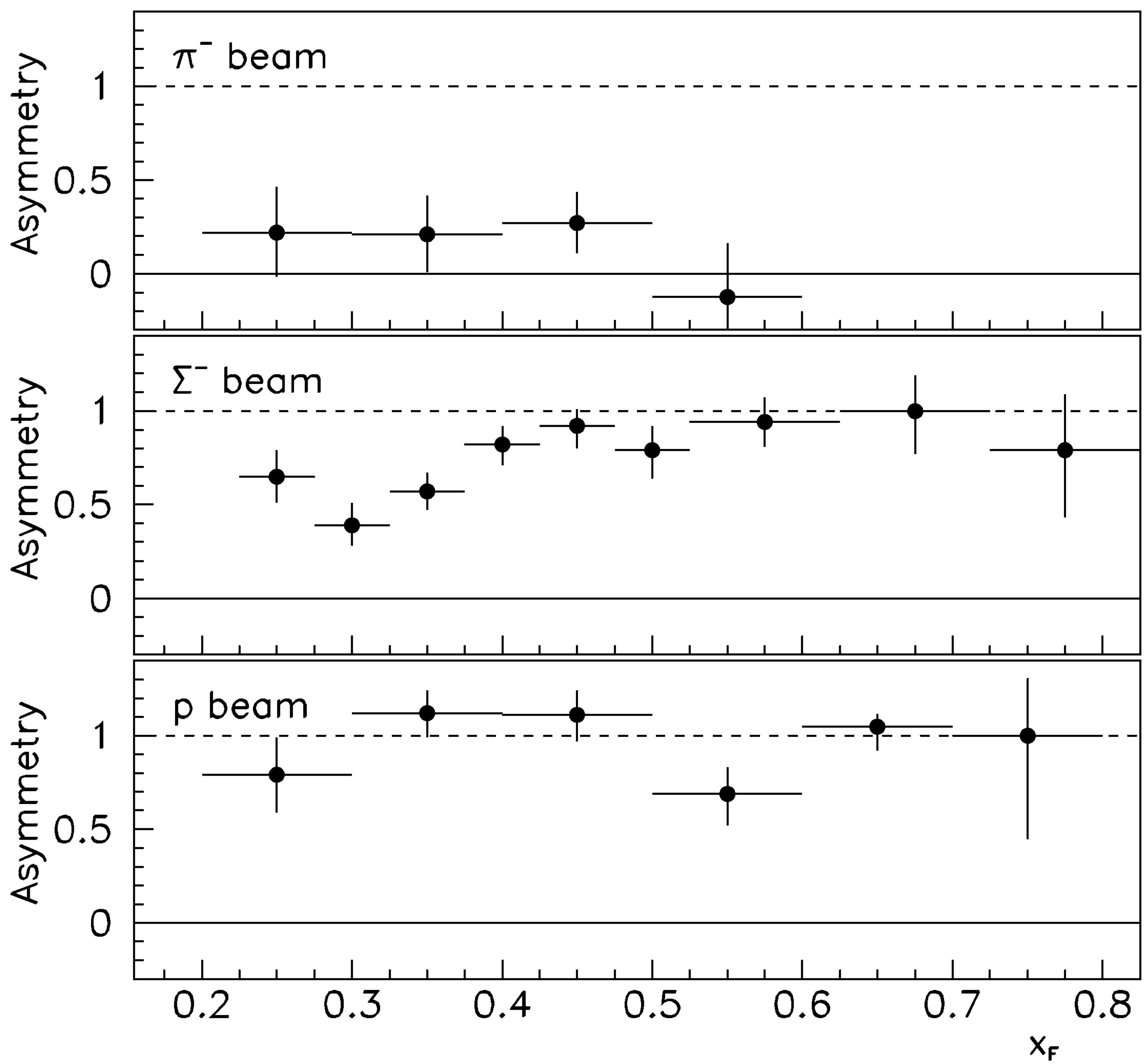
Origin of non-perturbative component

Asymmetry

$$A \equiv \frac{\Lambda_C - \bar{\Lambda}_c}{\Lambda_C + \bar{\Lambda}_c}$$



SELEX Collaboration, F. G. Garcia et al., Physics Letters B 528, 49 (2002).

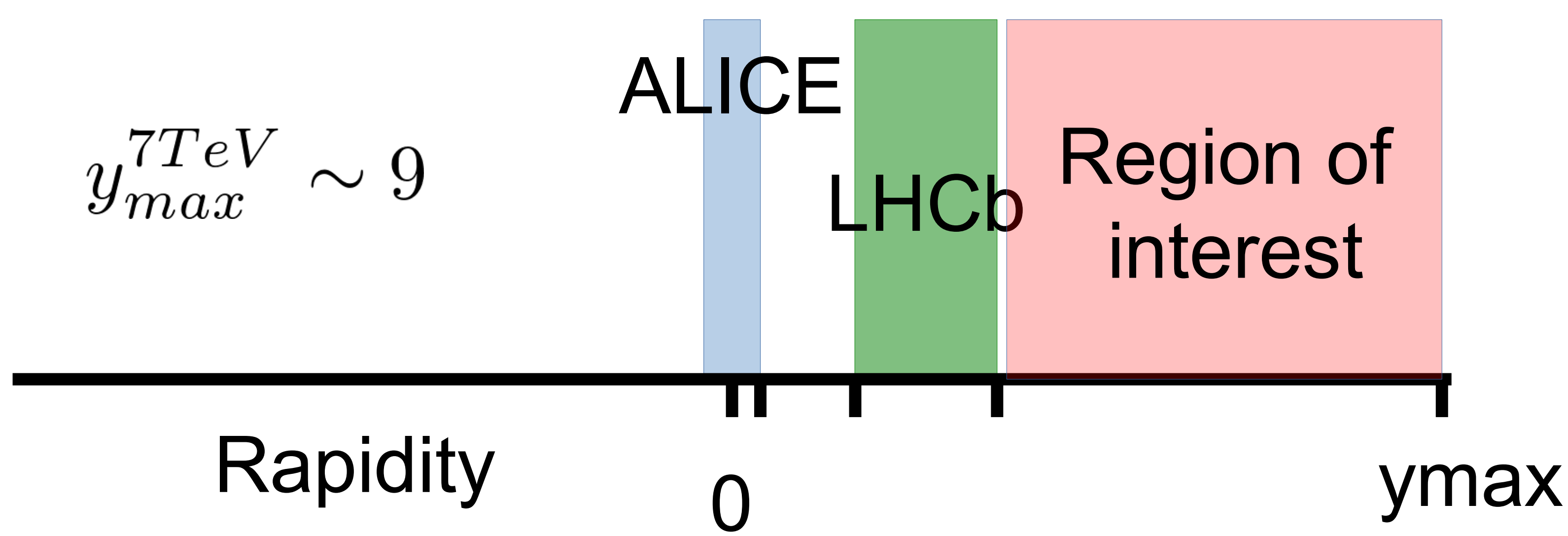


Calibrating model to data

- Low energy: fixed target data
  - Full phase space coverage
  - Mostly non-perturbative
- High energy: collider data
  - Mostly perturbative
  - <u>Limited coverage</u>

$$y = \frac{1}{2} ln\left(\frac{E+p_z}{E-p_z}\right) \leq ln\left(\frac{\sqrt{s}}{m_p}\right)$$

$$y_{max}^{7TeV} \sim 9$$



F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev, ISVHECRI 2014

LHCb phase-space, how limiting is limited?

- 7TeV c.m energy well beyond the knee

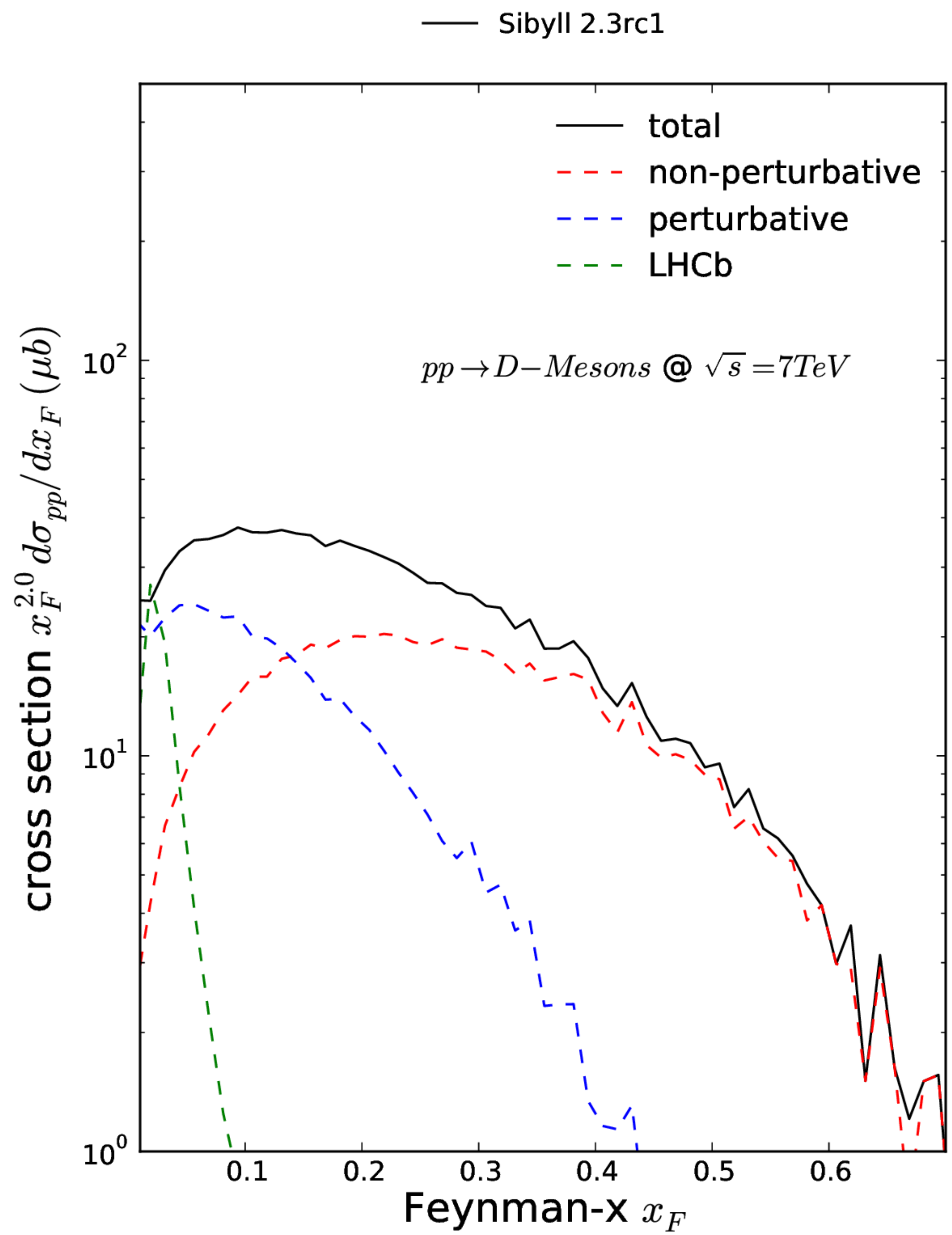
$$\sqrt{s} = 7TeV \rightarrow E_{lab} = 26PeV$$

$$\gamma_{CR} \approx 3$$

- How much does LHCb phasespace contribute to integrated spectrum?

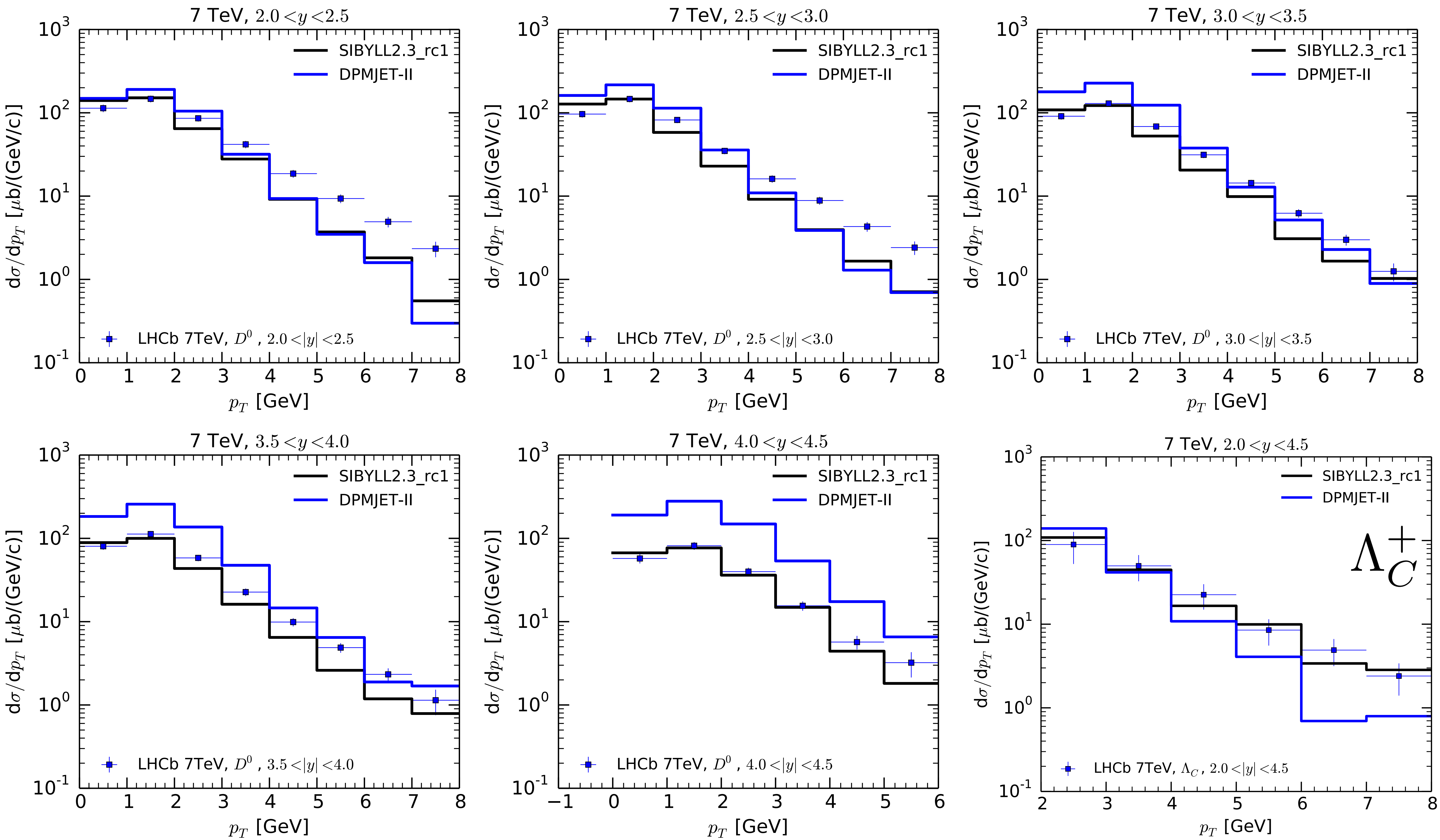
	%
LHCb	7
perturbative	37
Non-perturbative	59

→ LHC data **not** restrictive



F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev, ISVHECRI 2014

LHCb D-mesons and charmed Lambda

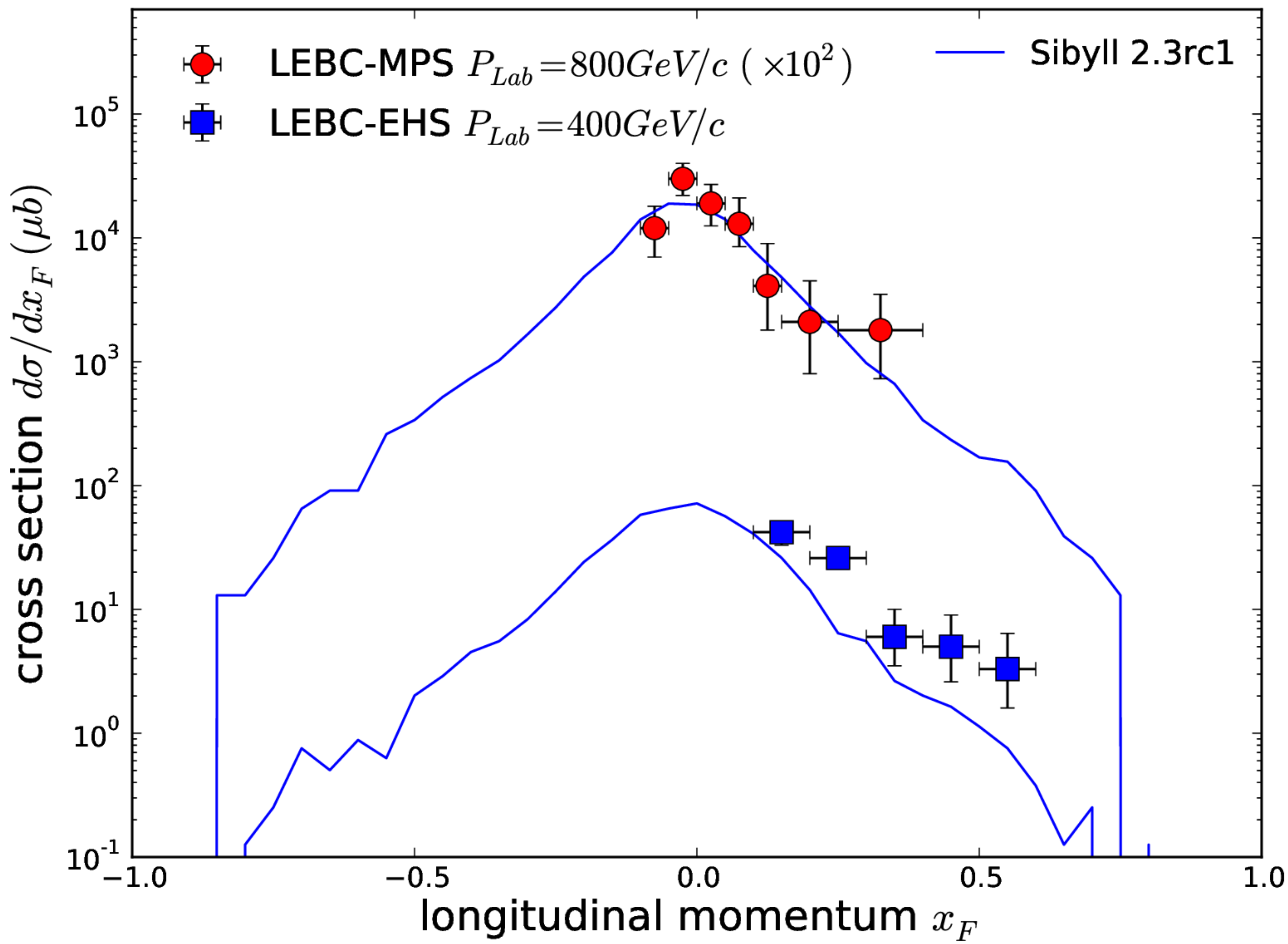


x_F distributions at fixed target experiments

$$\sqrt{s} = 27/39GeV$$

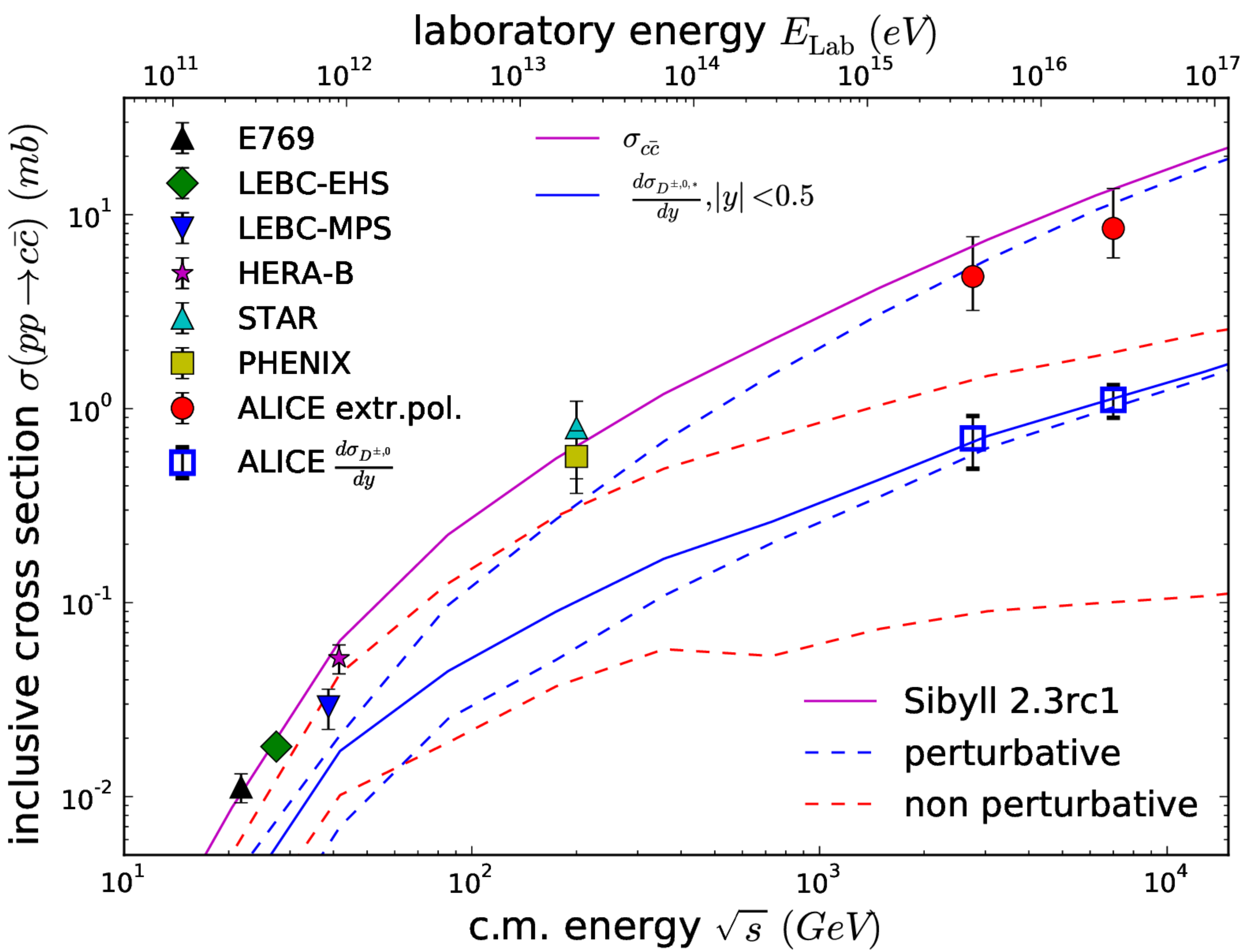
Energy low but full phasespace coverage possible!

$$y_{max}^{39GeV} = 3.7$$



F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev, ISVHECRI 2014

Inclusive charm production



F. Riehn, R. Engel, AF, T. Gaisser, T. Stanev, ISVHECRI 2014

Application to prompt lepton fluxes

Matrix cascade equation

(discretized) coupled cascade equation

for hadron of type h at (grid-) energy Ei:

$$\frac{\mathrm{d}\phi_h(E_i)}{\mathrm{d}X} = -\frac{\phi_h(E_i)}{\lambda_{int}^{(h)}(E_i)} + \sum_{E_k \geq E_i} \sum_k \frac{c_{k\to h}(E_i, E_k)}{\lambda_{int}^{(k)}(E_k)} \phi_k(E_k) - \frac{\phi_h(E_i)}{\lambda_{dec}^{(h)}(E_i, X)} + \sum_{E_k \geq E_i} \sum_k \frac{d_{k\to h}(E_i, E_k)}{\lambda_{dec}^{(k)}(E_k, X)} \phi_k(E_k)$$

More details in

E.J. Ahn, R. Engel, AF, T. Gaisser, F. Riehn, T. Stanev, ICRC 2013 proceedings

R. Engel, AF, T. Gaisser, F. Riehn, T. Stanev, ISVHECRI 2014

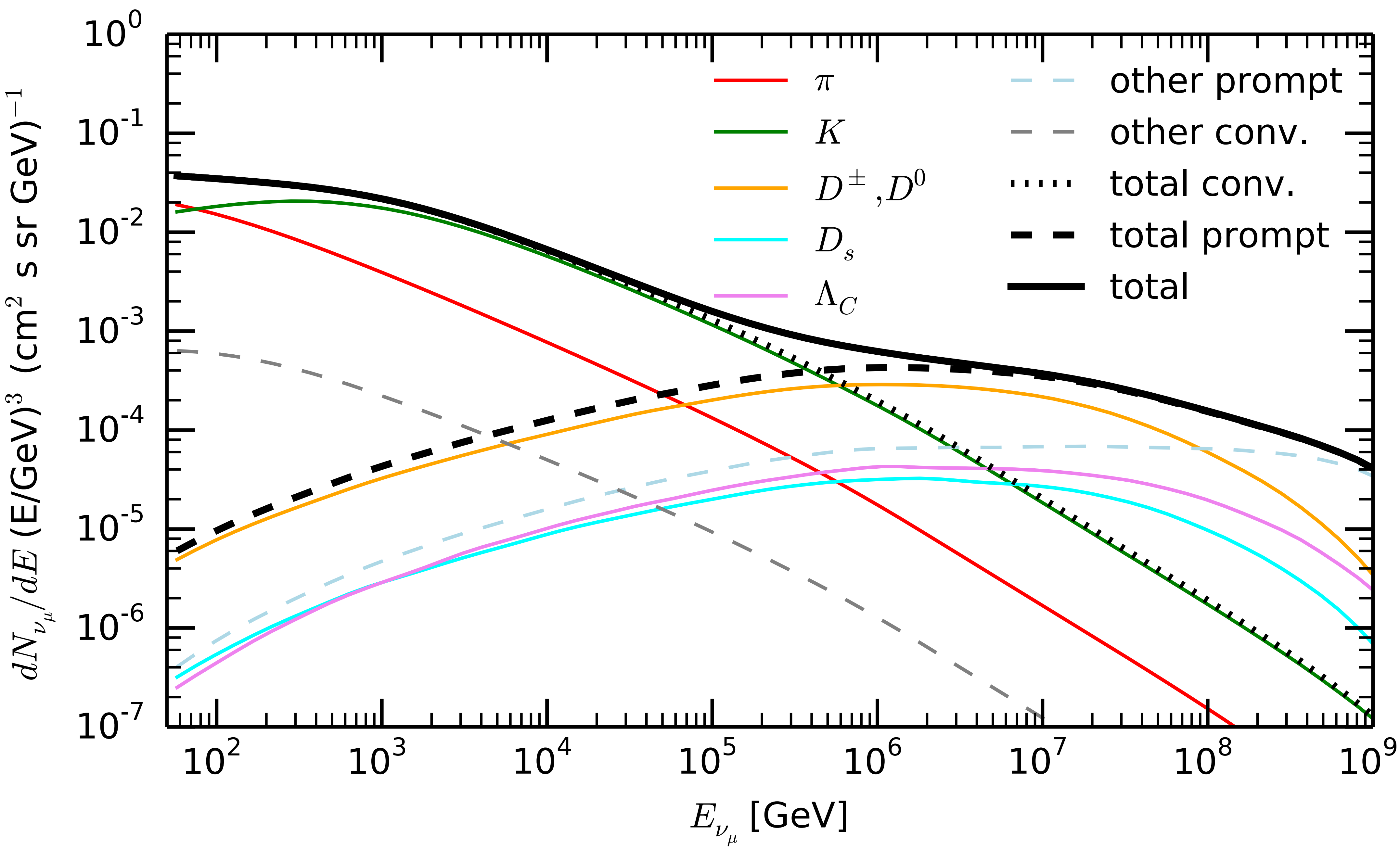
Transformation by distribution of coefficients into matrices

Numerical integration using high performance linear algebra

matrix cascade equation

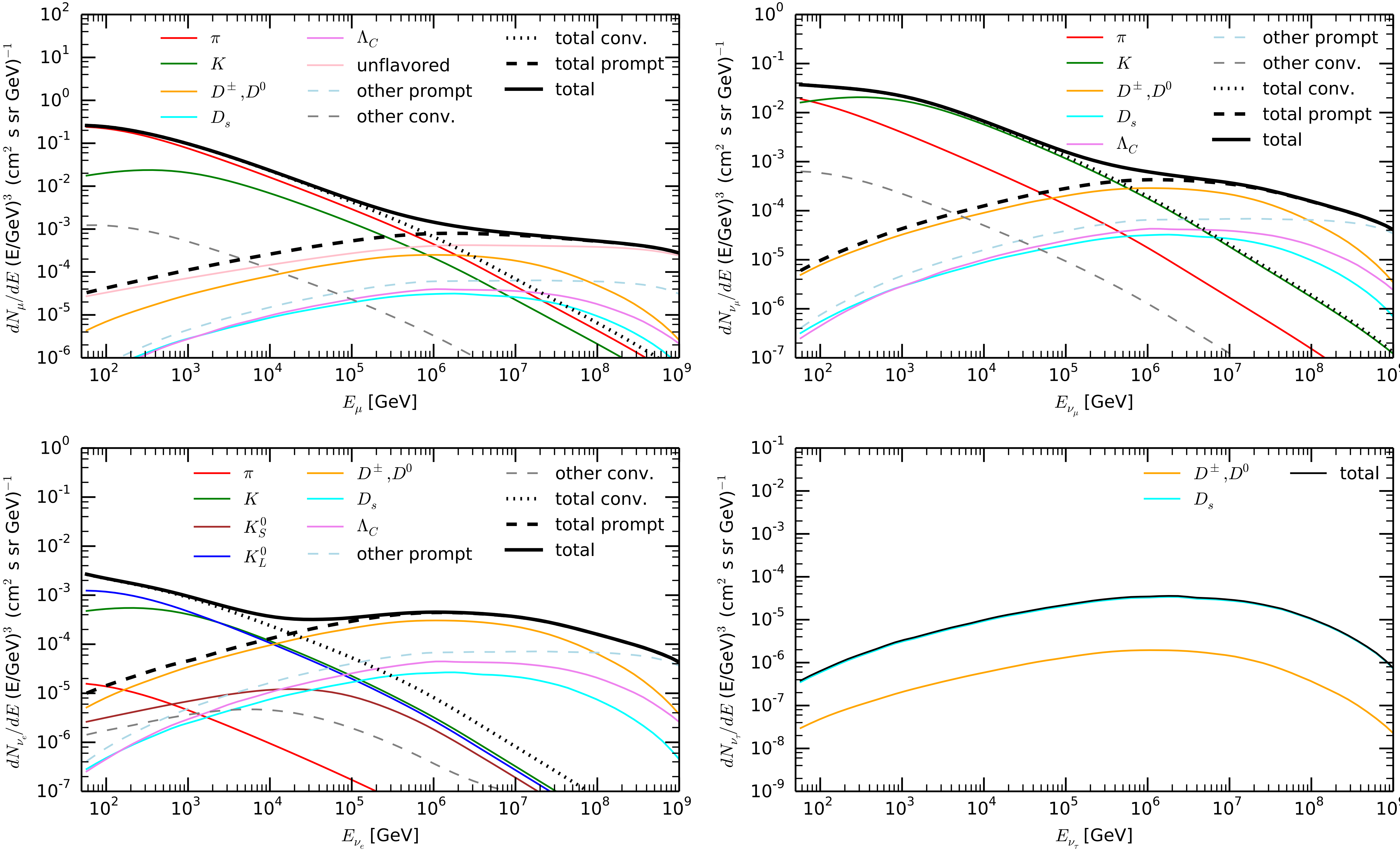
$$\frac{\mathrm{d}\vec{\phi}}{\mathrm{d}X} = \left[(-1 + \mathbf{C} + \mathbf{R})\bar{\Lambda}_{int} + (-1 + \mathbf{D})\bar{\Lambda}_{dec}(X)\right] \vec{\phi}$$

Muon neutrino flux

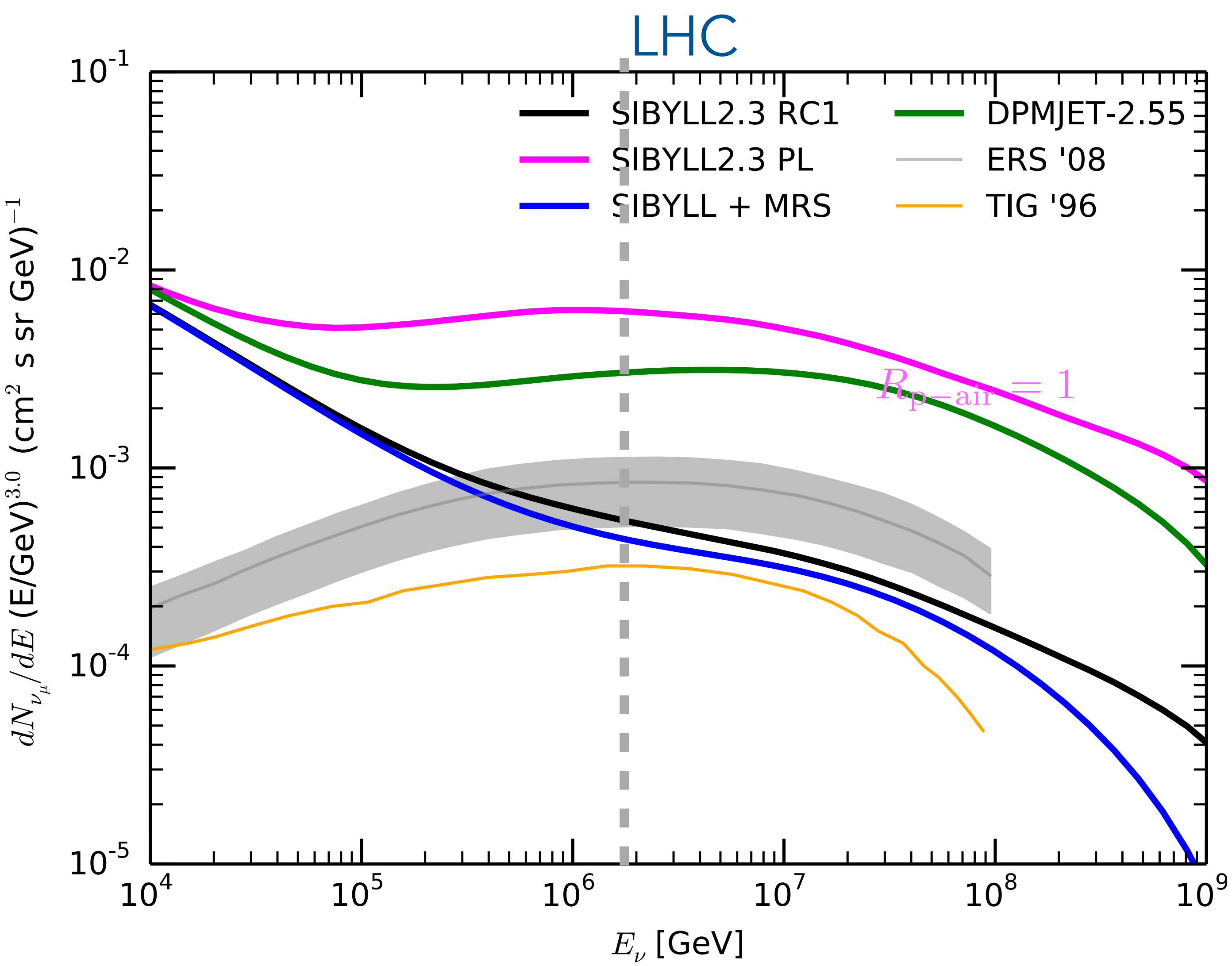


Detailed contribution to atmospheric lepton flux

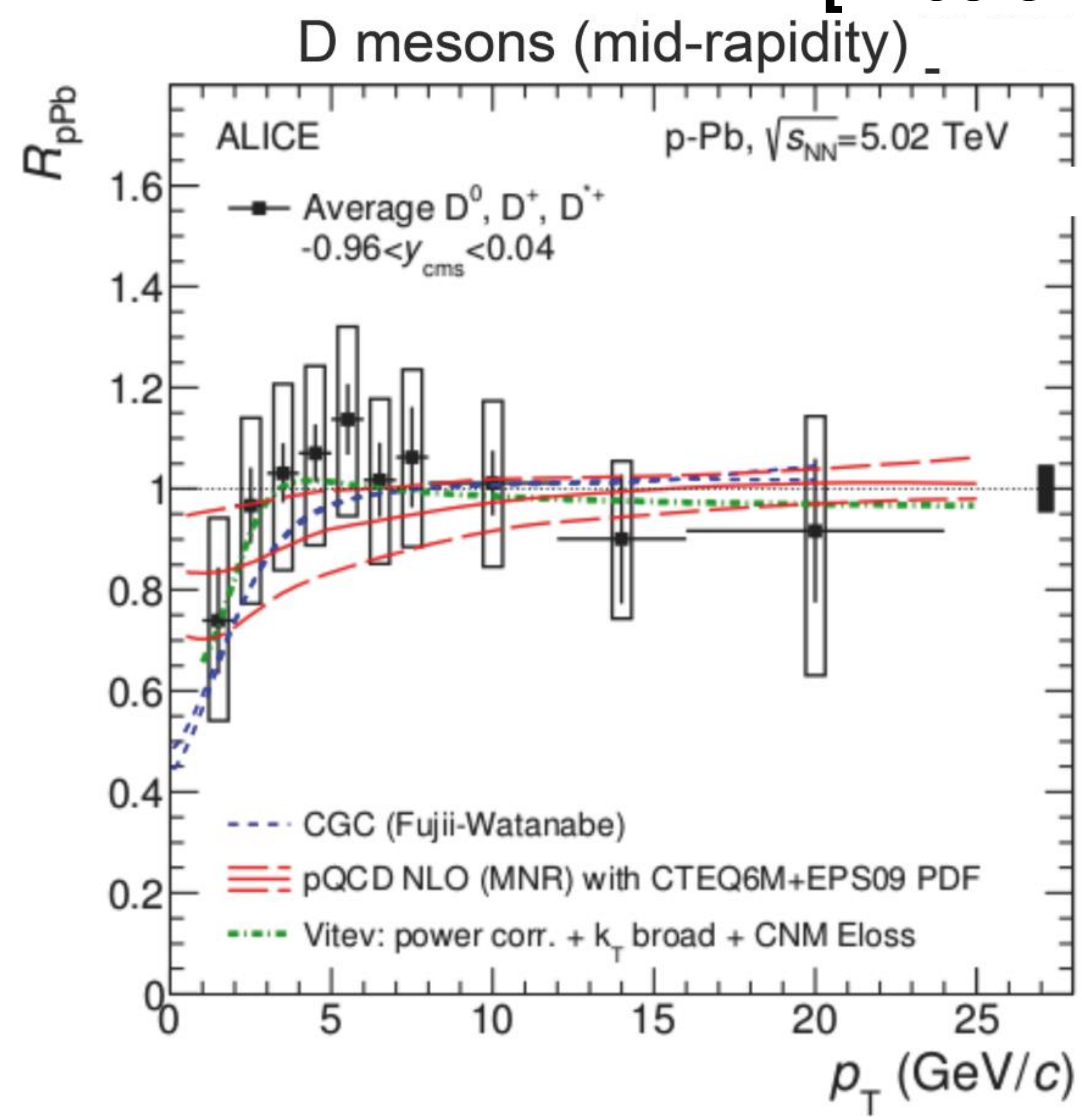
SIBYLL2.3_rc1 atmospheric lepton fluxes, TIG primary flux model.



Uncertainty due to nuclear effects



[1405.3452]



ERS - R. Enberg, M. H. Reno, and I. Sarcevic, Phys. Rev. D 78, 43005 (2008).

TIG - M. Thunman, G. Ingelman, and P. Gondolo, Astroparticle Physics 5, 309 (1996).

Benjamin Dönigus , ISVHECRI 2014

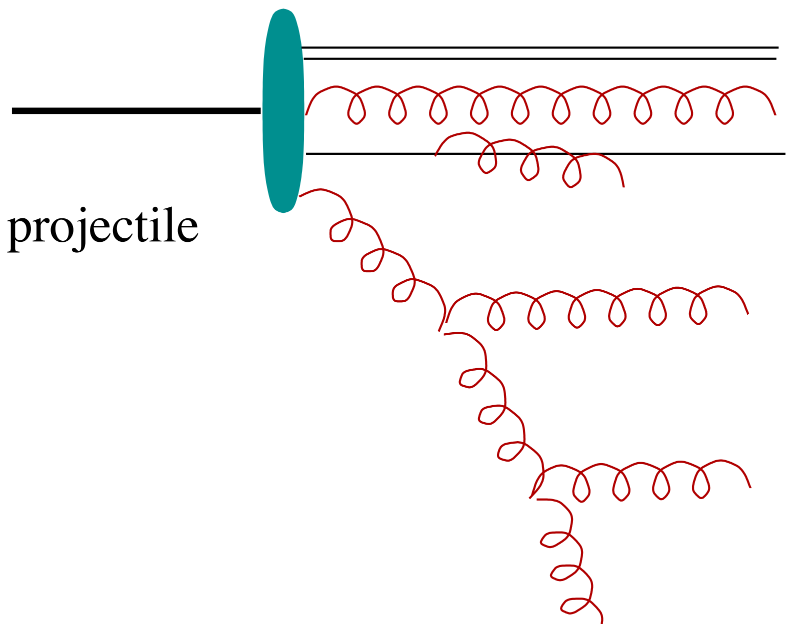
$$R_{pA} = \frac{dN_{pA}/dp_T}{\langle N_{coll}\rangle\, dN_{pp}/dp_T}$$

Summary

- Variety of interaction models due to unsolved questions in theory and experiment
- Calibration of models is based on accelerator data rather than fitting to cosmic ray observations
- LHC data restricted extrapolation behavior of models, although the phase-space of interest for cosmic rays is not well covered
- Progress in modeling charmed particle production in air showers
- Work towards restricting uncertainties on the prompt flux is ongoing
- Uncertainties due to nuclear effects are currently an open question and any type of proton-light nucleus data would help

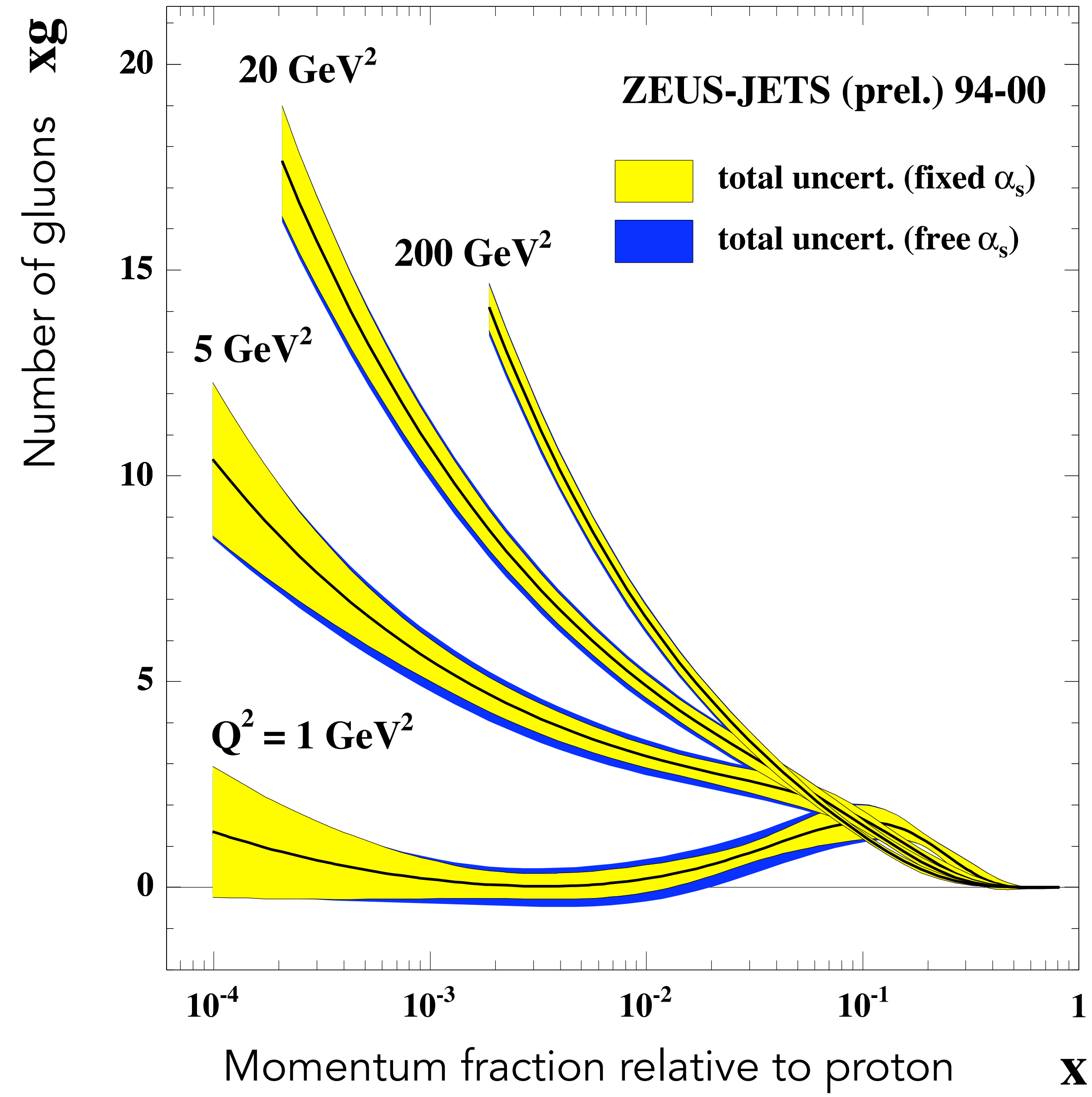
Backup

Momentum fractions



Evolution of parton number given by DGLAP equation (and non-linear versions of it)

HERA data

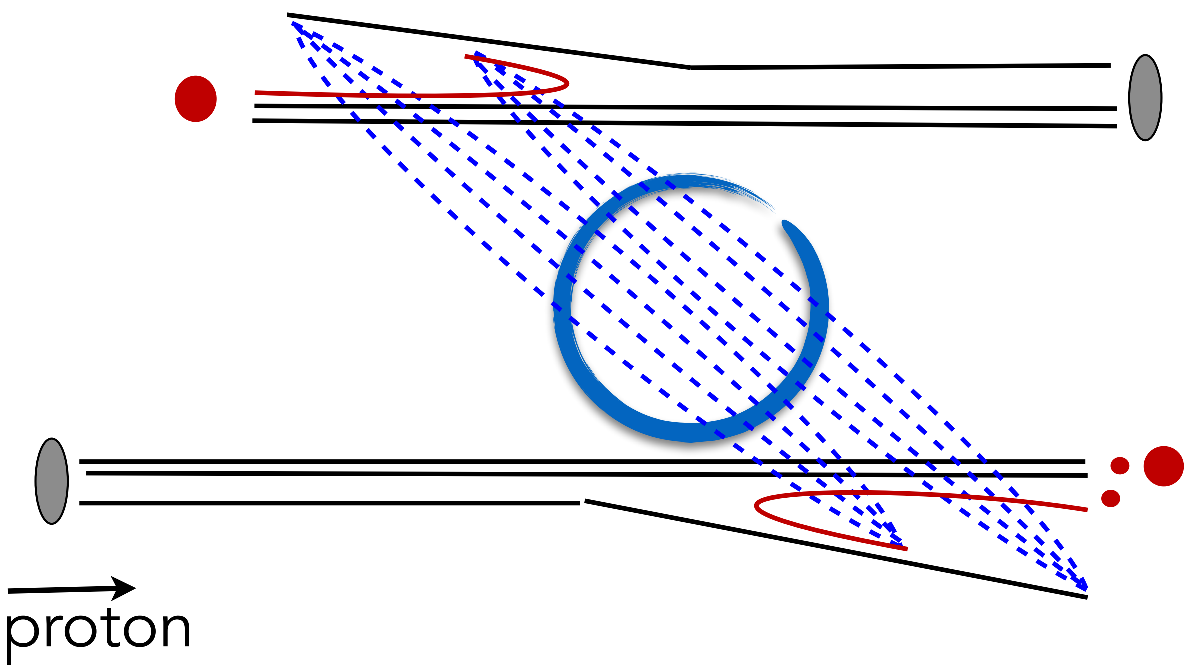


$$\frac{d f_i(x,Q^2)}{d \log Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dy}{y} \sum_j f_j(y,Q^2)\, P_{j\to i}\left(\frac{x}{y}\right)$$

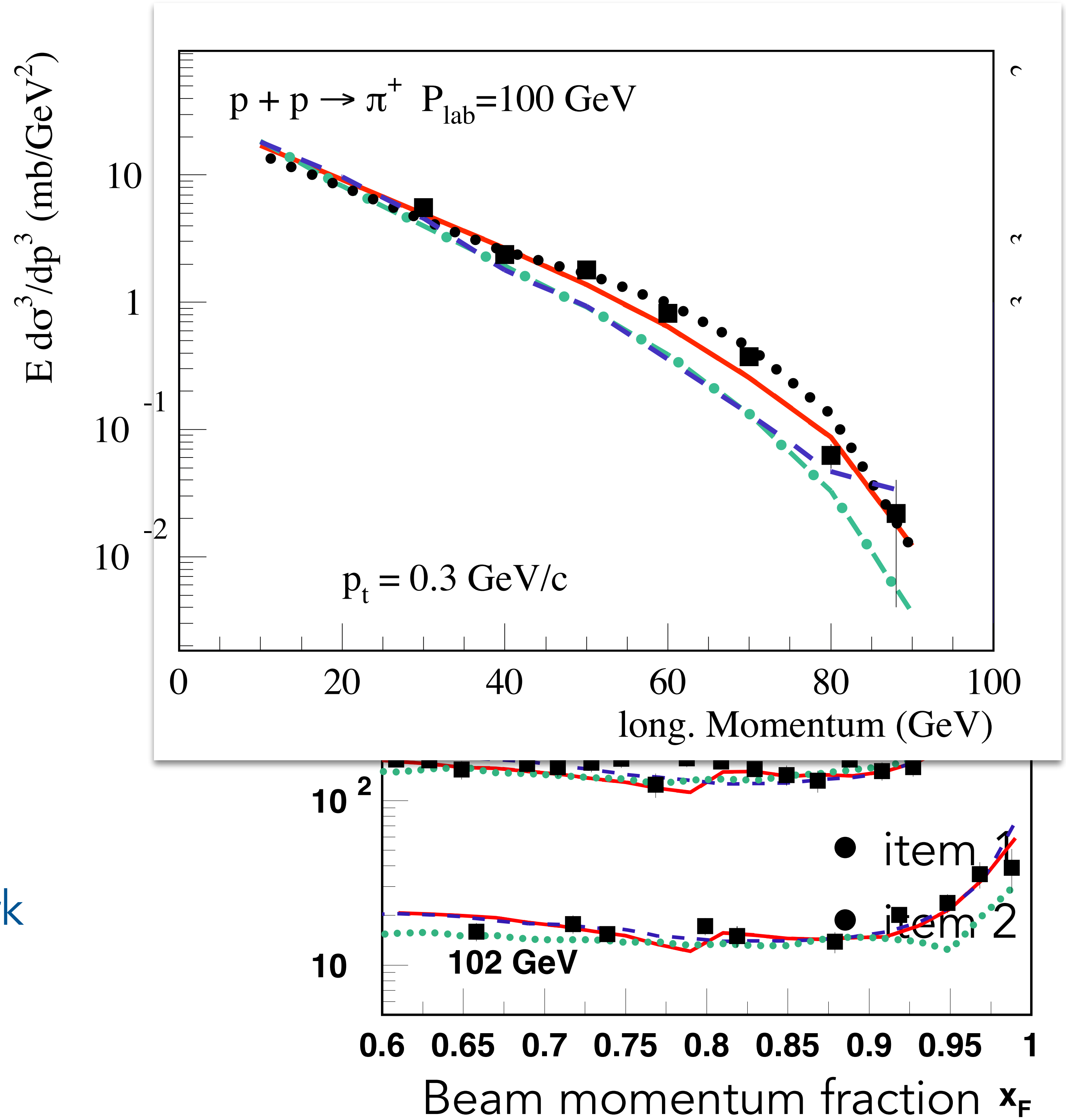
Prediction of perturbative QCD

Particle production spectra (ii)

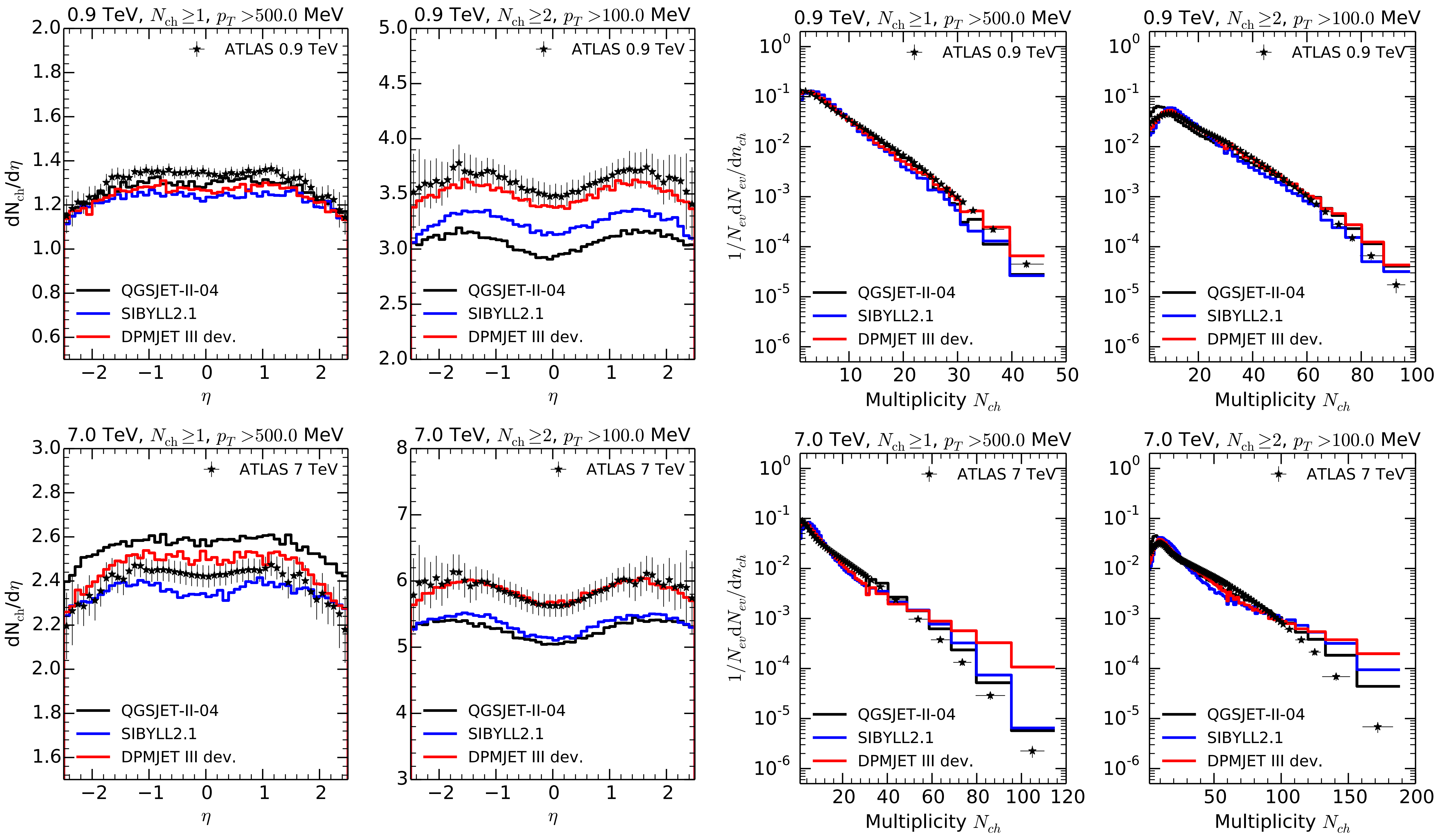
Central particle production



Fluctuations: Generation of sea quark anti-quark pair and leading/excited hadron

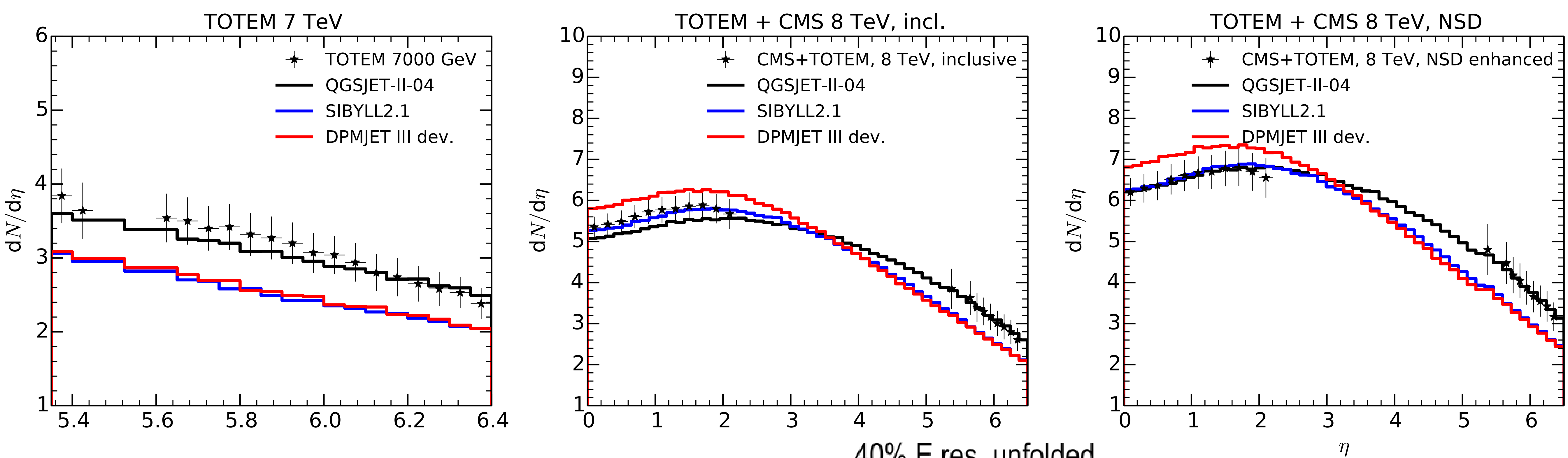


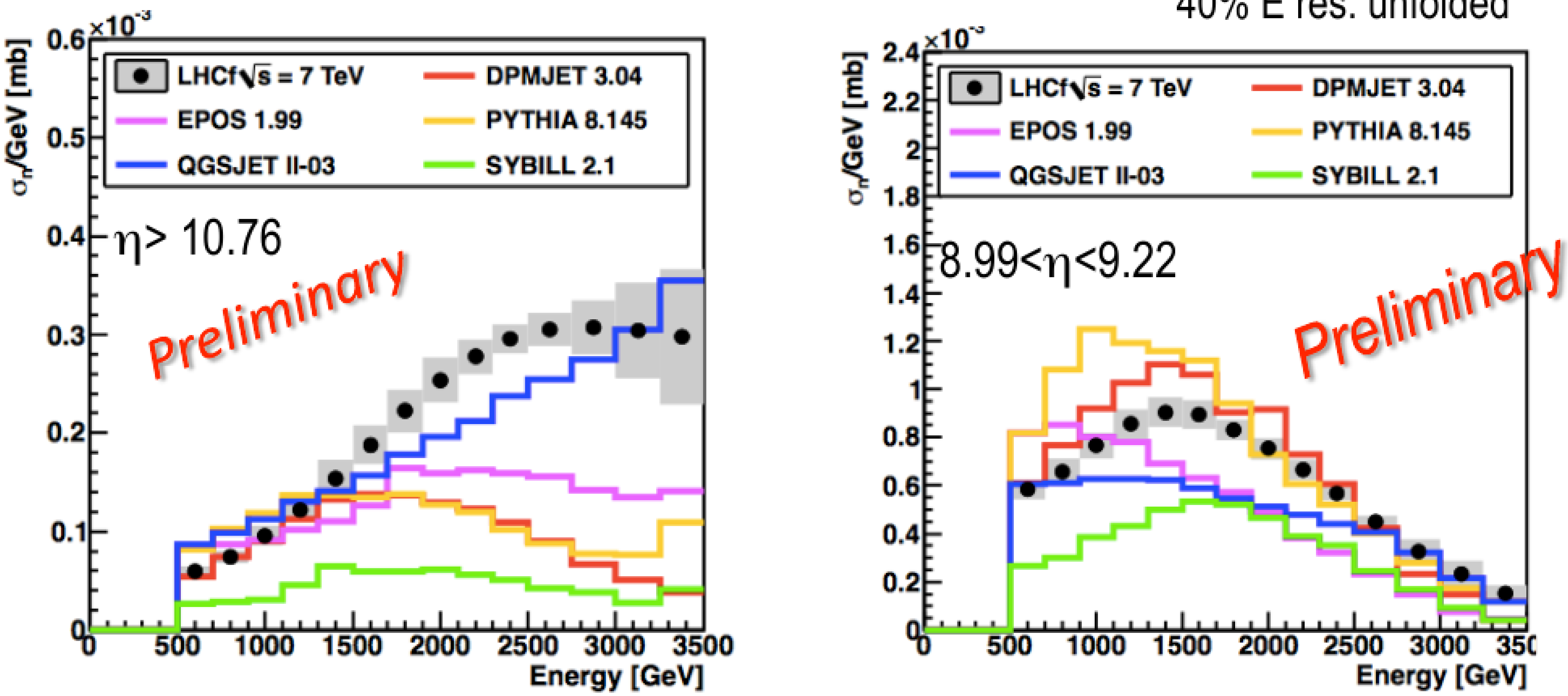
Comparison with ATLAS minimum bias results



ATLAS Collaboration, New J. Phys. 13, 3033 (2011).

LHC forward physics





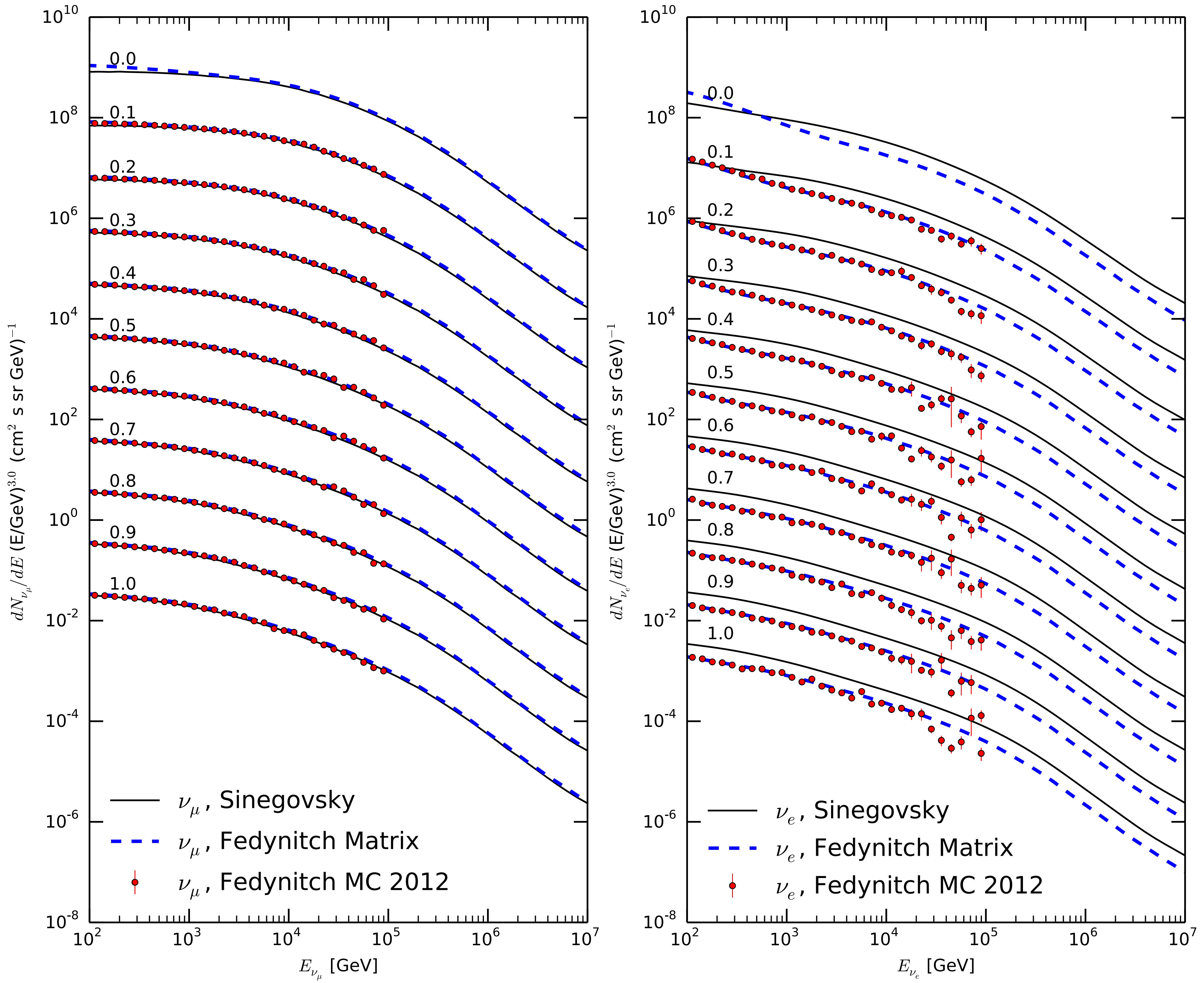
Y. Itow, ISVHECRI 2014

The CMS Collaboration, arXiv:1405.0722, 2014
*The TOTEM Collaboration et al, EPL **98** 31002, 2012*

Comparison with other calculation methods

Comparison for QGSJET-II-03 + H3a. Offset of 10 between lines.

Matrix calculation takes a fraction of time!



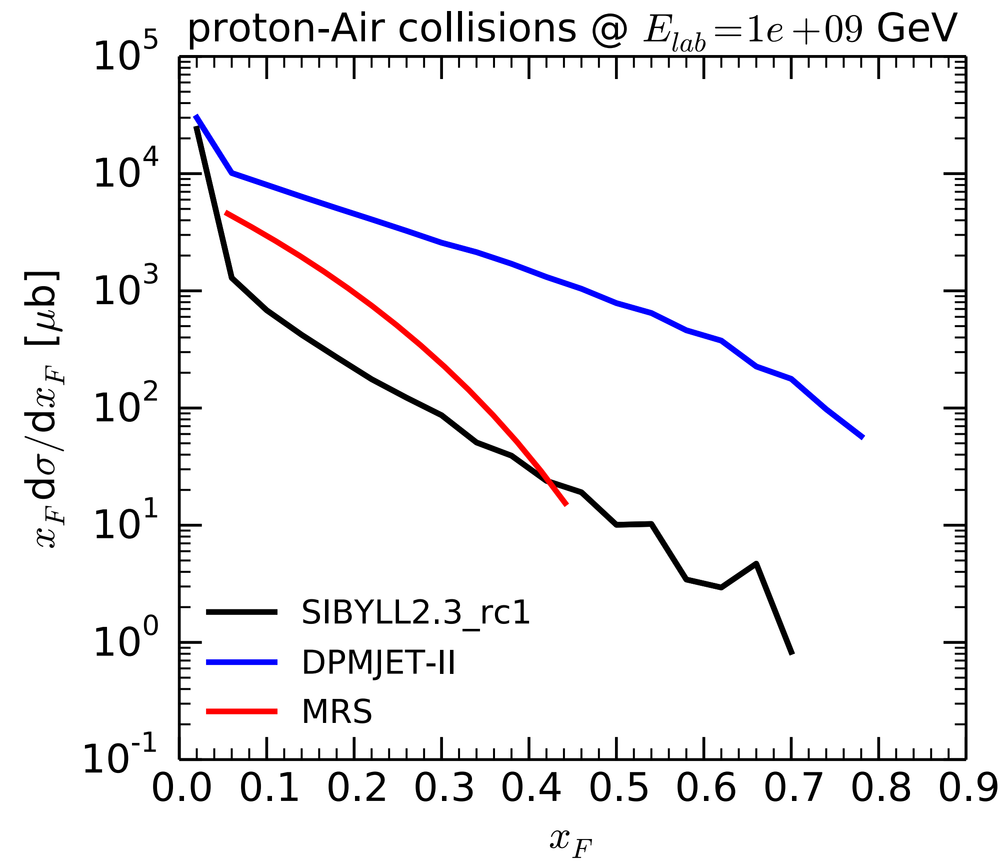
AF, J. Becker Tjus, and P. Desiati, Phys. Rev. D 86, 114024 (2012).

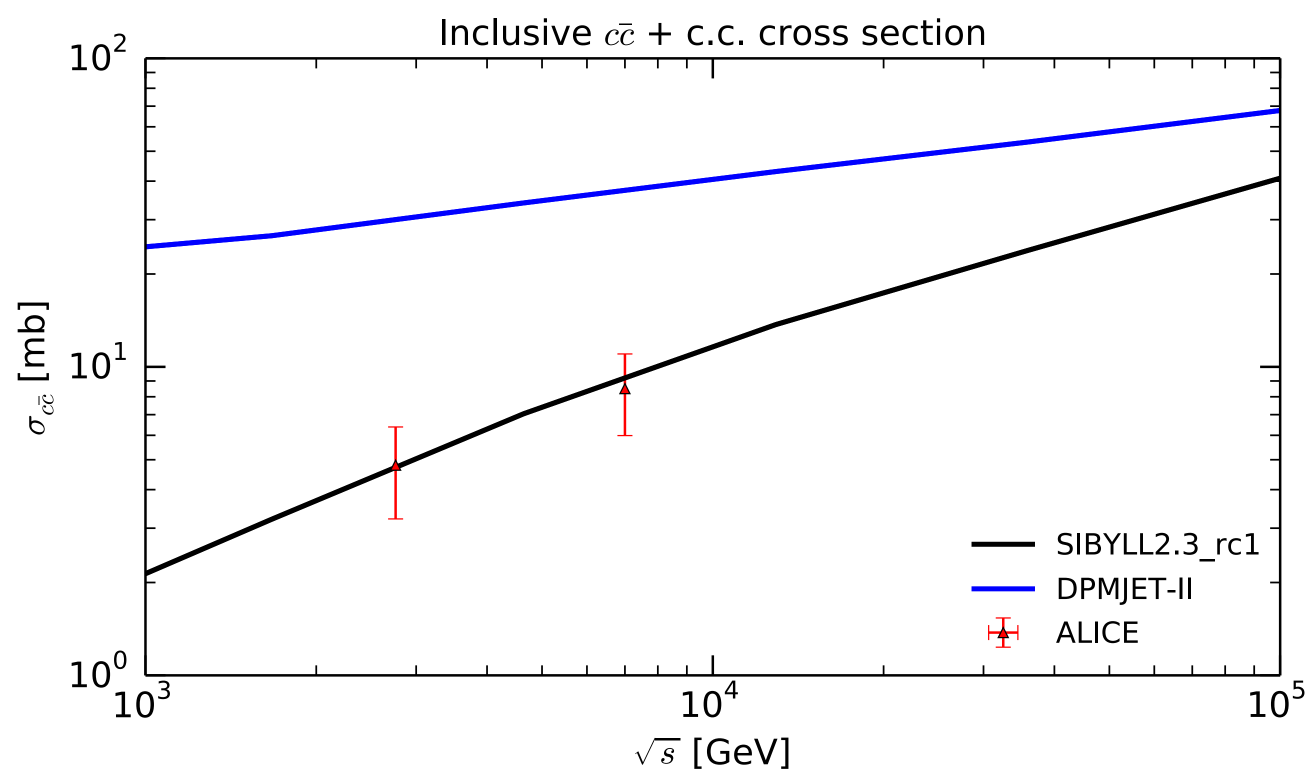
S. I. Sinegovsky, A. A. Kochanov, T. S. Sinegovskaya, A. Misaki, and N. Takahashi, International Journal of Modern Physics A 25, 3733 (2010).

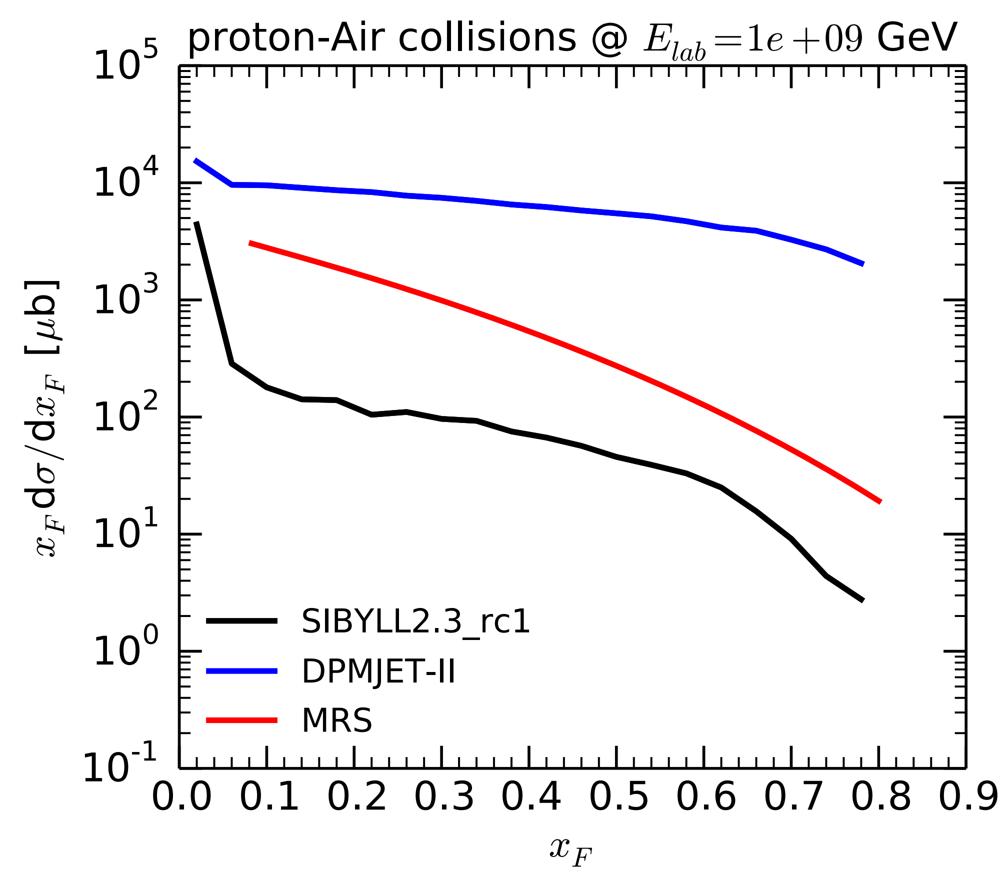
Charm in proton-air interactions

- Additional uncertainties due to extrapolation pp to p-air
- Is the interaction point like?

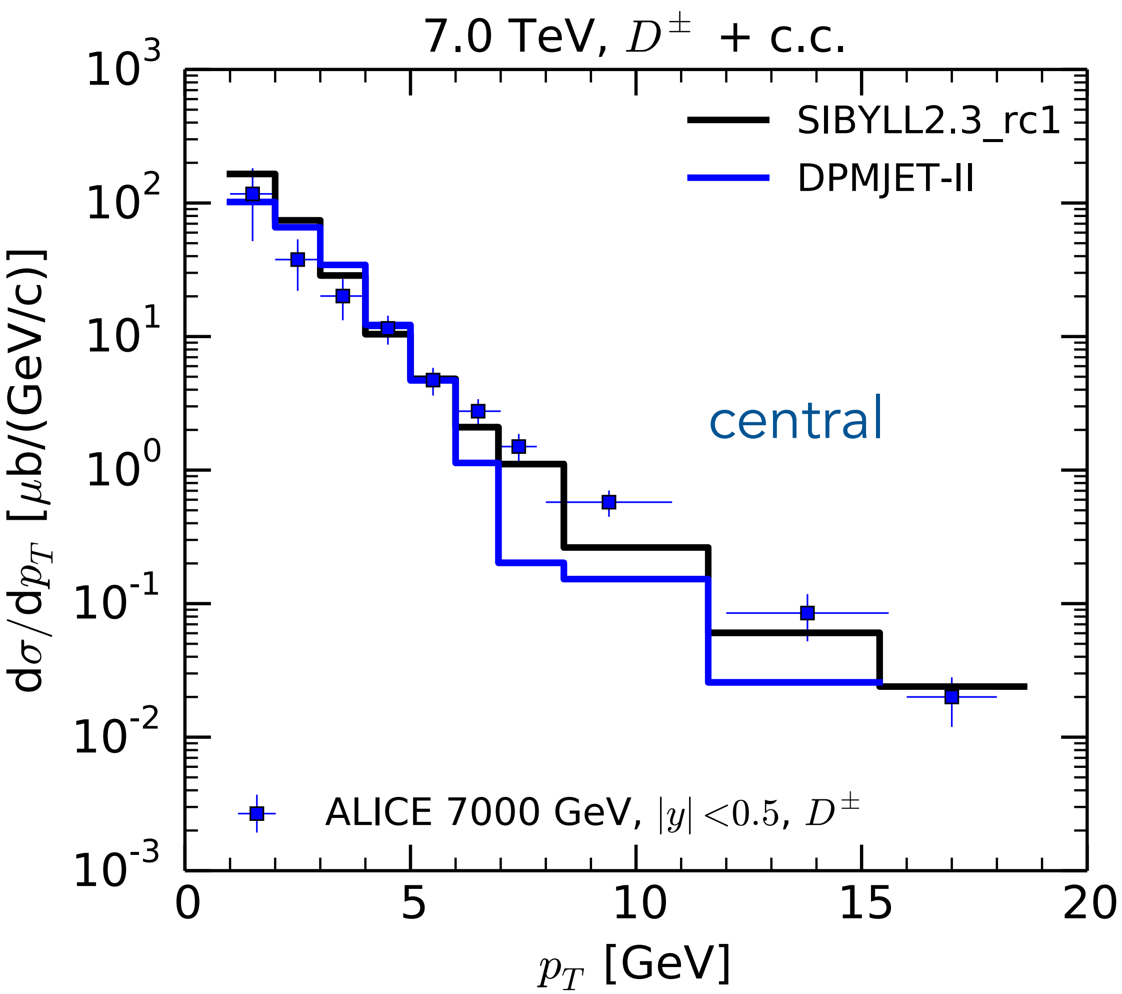
MRS - perturbative QCD + saturation, A. D. Martin, M. G. Ryskin, and A. M. Stasto, Acta Physica Polonica B 34, 3273 (2003).

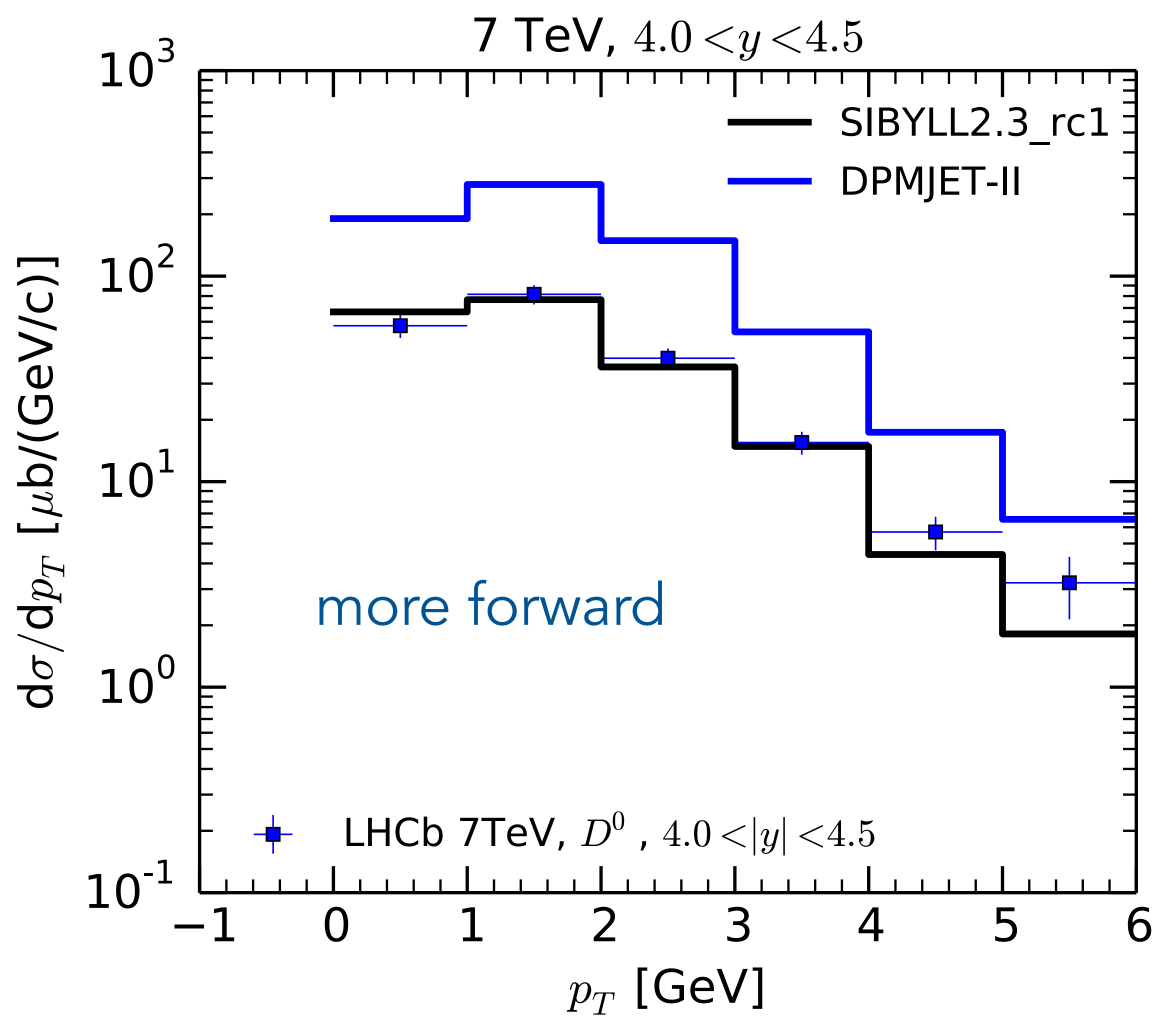






A comment on charm in DPMJET-II





- DPMJET-II is in reasonable agreement with central differential charm distributions at LHC
- In the more forward phase space it consistently overestimates all available measurements

DPMJET-II charm model disfavored by LHC