Antideuteron Production in the EPOS Event Generator

Tanguy Pierog

Karlsruhe Institute of Technology, Institut für Kernphysik, Karlsruhe, Germany

K. Werner, Iu. Karpenko, G. Sophys, Subatech, Nantes, France
B. Guiot, FSMT University, Valparaiso, Chile
M. Stefaniak, Warsaw University of Technology, Warsaw, Poland

Karlsruhe Institute of Technology

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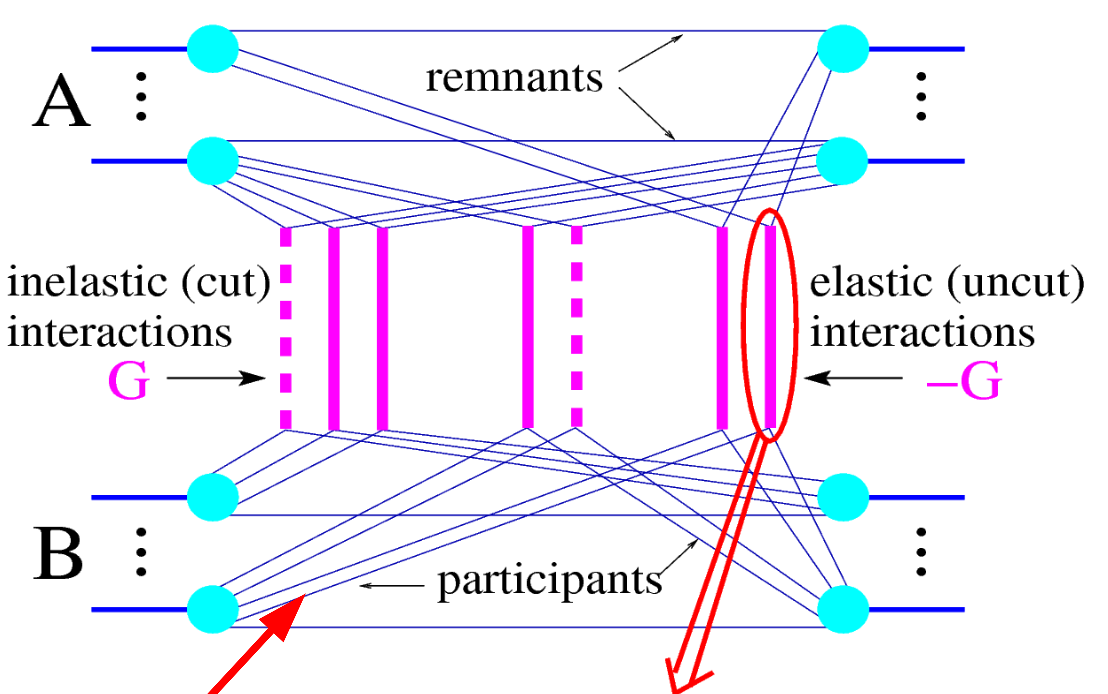
Outline

- **EPOS Basic principles**
- **Core Hadronization**
  - Antideuteron production
- **Uncertainties**
  - Link to air showers and LHC
- **Summary**

New input from LHC which could help to reproduce EAS data consistently but solution still under study. Possible consequences on antideuteron production.

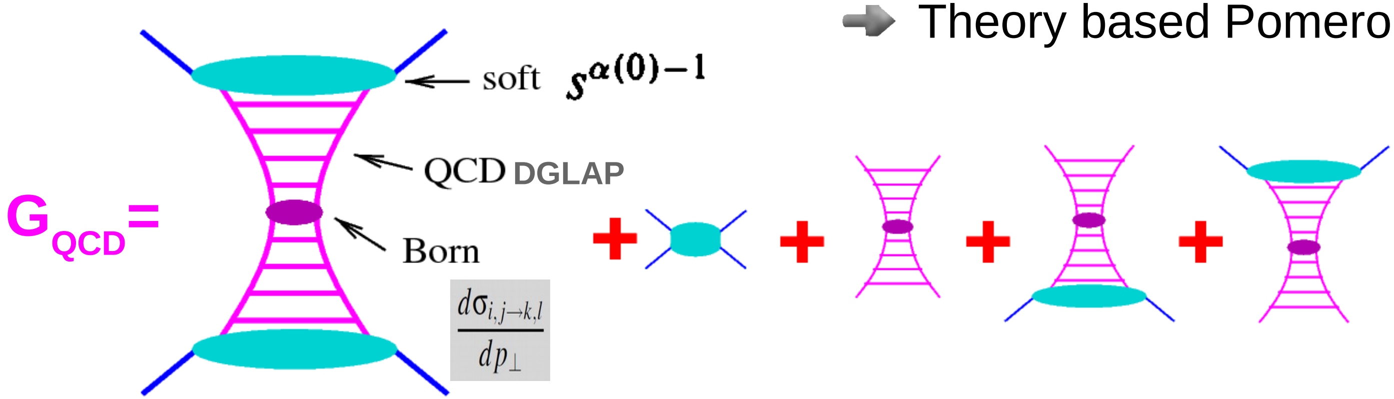
Parton-Based Gribov-Regge Theory



Energy sharing at the cross section level

- Energy shared between cut and uncut diagrams (Pomeron)
- Reduced number of elementary interactions
- Generalization to (h)A-B
- Particle production from momentum fraction matrix (Markov chain metropolis)
- Theory based Pomeron definition

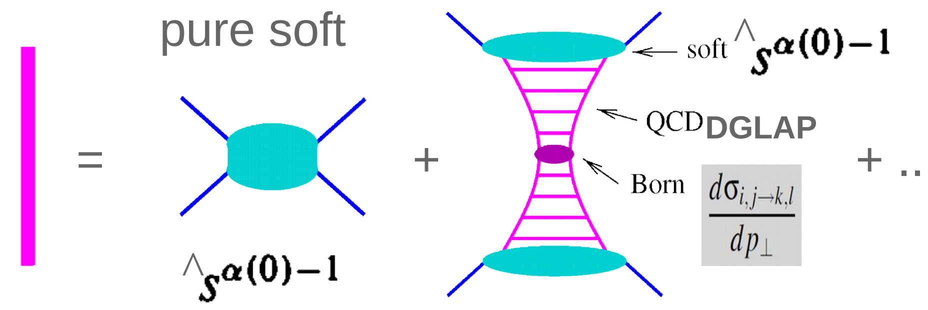
Pomeron momentum fraction x^- (x^+ for projectile)



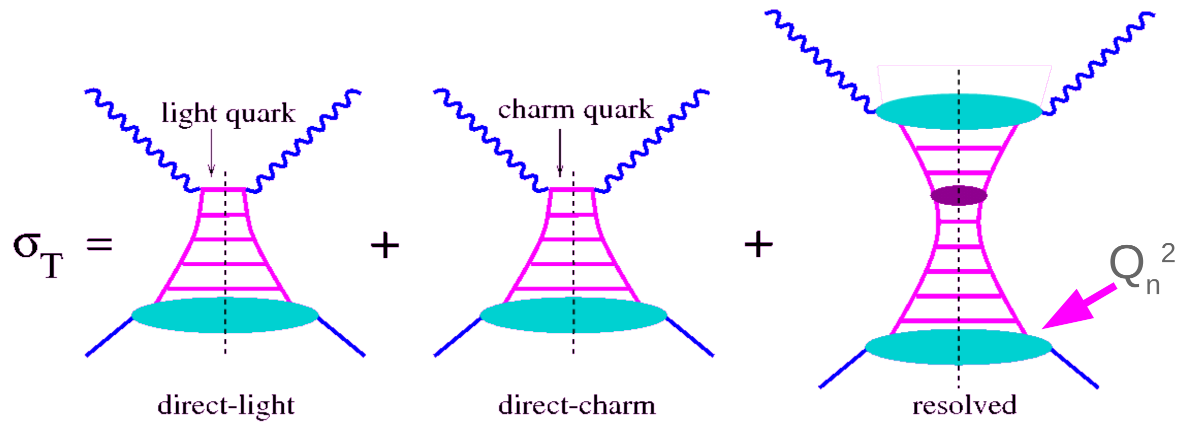
Parton-based Gribov-Regge Theory, H. J. Drescher, M. Hladik, S. Ostapchenko, T.Pierog, and K. Werner, Phys. Rept. 350 (2001) 93-289;

EPOS : Pomeron Definition

Semi-hard Pomeron : $G_{QCD}=$
$(\hat{s}=x^{+}x^{-}s)$

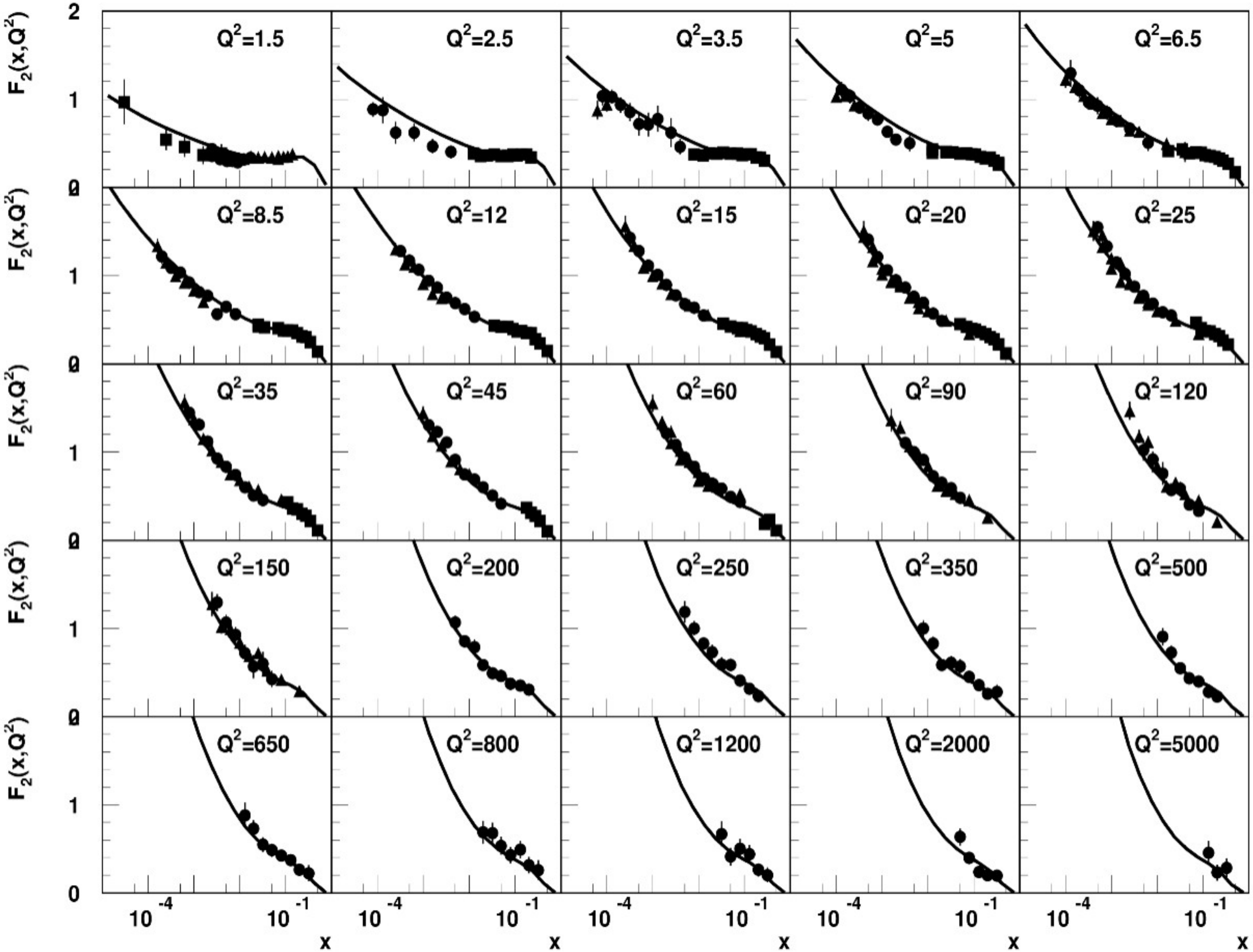


Test of semi-hard Pomeron with DIS: (Parton Distribution Function from HERA)

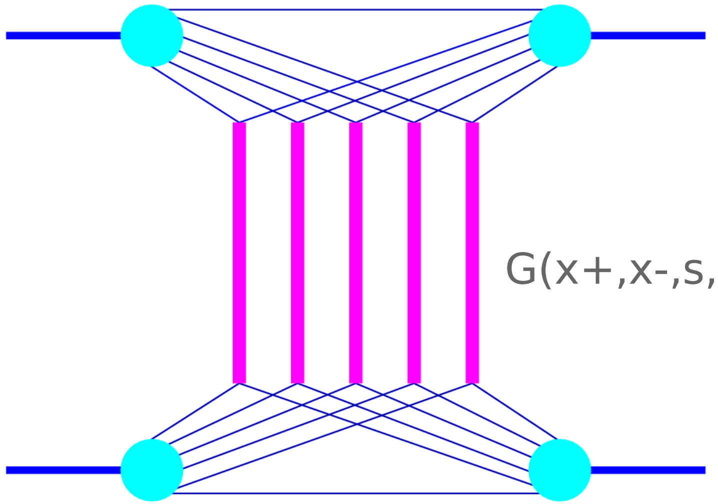


- Theory based Pomeron definion
  - pQCD based (DGLAP and Born)
    - large increase at small x (without saturation)
  - External pdf only for valence quark
  - Minimum non-perturbative scale Q_n^2=2 GeV^2 with soft pre-evolution $s^{\alpha(0)-1}$
  - F2 from HERA used to fix parameters for sea quarks and gluons below Q_n^2

EPOS Parton Distribution Function Q_n^2=2 GeV²



Cross Section Calculation : EPOS



- Gribov-Regge but with energy sharing at parton level (Parton Based Gribov Regge Theory)
- amplitude parameters fixed from QCD and pp cross section (semi-hard Pomeron)
- cross section calculation take into account interference term

$$\boxed{\sigma_{\mathrm{ine}}(s) \quad = \quad \int d^2b\,(1 - \Phi_{\mathrm{pp}}(1,1,s,b))}$$

$$\Phi_{\mathrm{pp}}\left(x^+, x^-, s, b\right) \quad = \quad \sum_{l=0}^{\infty} \int dx_1^+ dx_1^- \ldots dx_l^+ dx_l^- \left\{ \frac{1}{l!} \prod_{\lambda=1}^{l} -G(x_\lambda^+, x_\lambda^-, s, b) \right\}$$
$$\times \quad F_{\mathrm{proj}}\left(x^+ - \sum x_\lambda^+\right) F_{\mathrm{targ}}\left(x^- - \sum x_\lambda^-\right).$$

can not use complex diagram with energy sharing:
non linear effects taken into account as correction of single amplitude G

EPOS – non-linear effects

Well known problem with pQCD based Pomerons

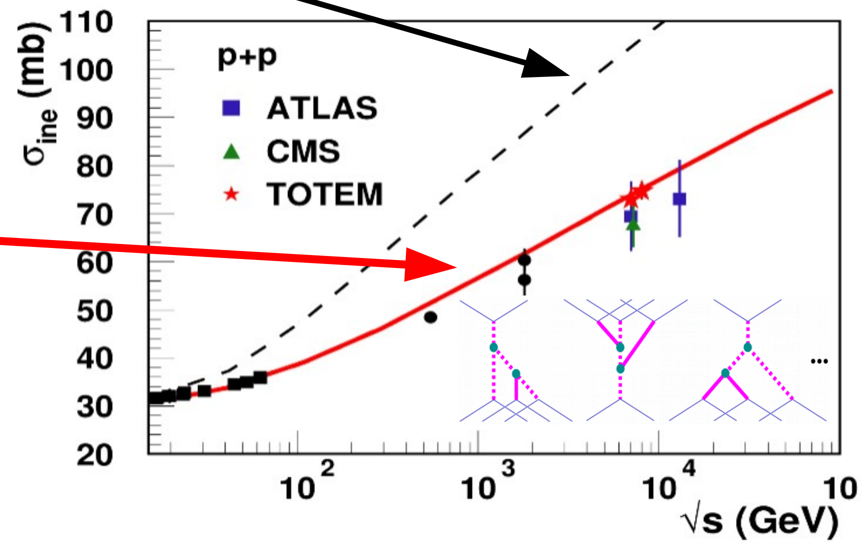
- total cross-section too high : MPI required
  - in EPOS <Pomerons> fixed by b-dep of Pomeron amplitude (slope)
- effective coupling introduced to mimic effect of enhanced diagrams and reduce cross-section (screening effect) to get cross-section AND multiplicity right in p-p, p-A and AA
  - Amplitude G_{eff} no longer fit to G_{QCD}

No effective coupling

$$G_{QCD} \sim (x_1 x_2)^{\beta}$$

With effective coupling

$$G_{eff} \sim x_1^{\beta} x_2^{\beta-\varepsilon}$$



Parametrization

$$\varepsilon_S = a_S\, \beta_S\, Z(\mathrm{s,b,A})$$

$$\varepsilon_H = a_H\, \beta_H\, Z(\mathrm{s,b,A})$$

Particle Production in EPOS

m number of exchanged elementary interaction per event fixed from elastic amplitude taking into account energy sharing :

- m cut Pomerons from :

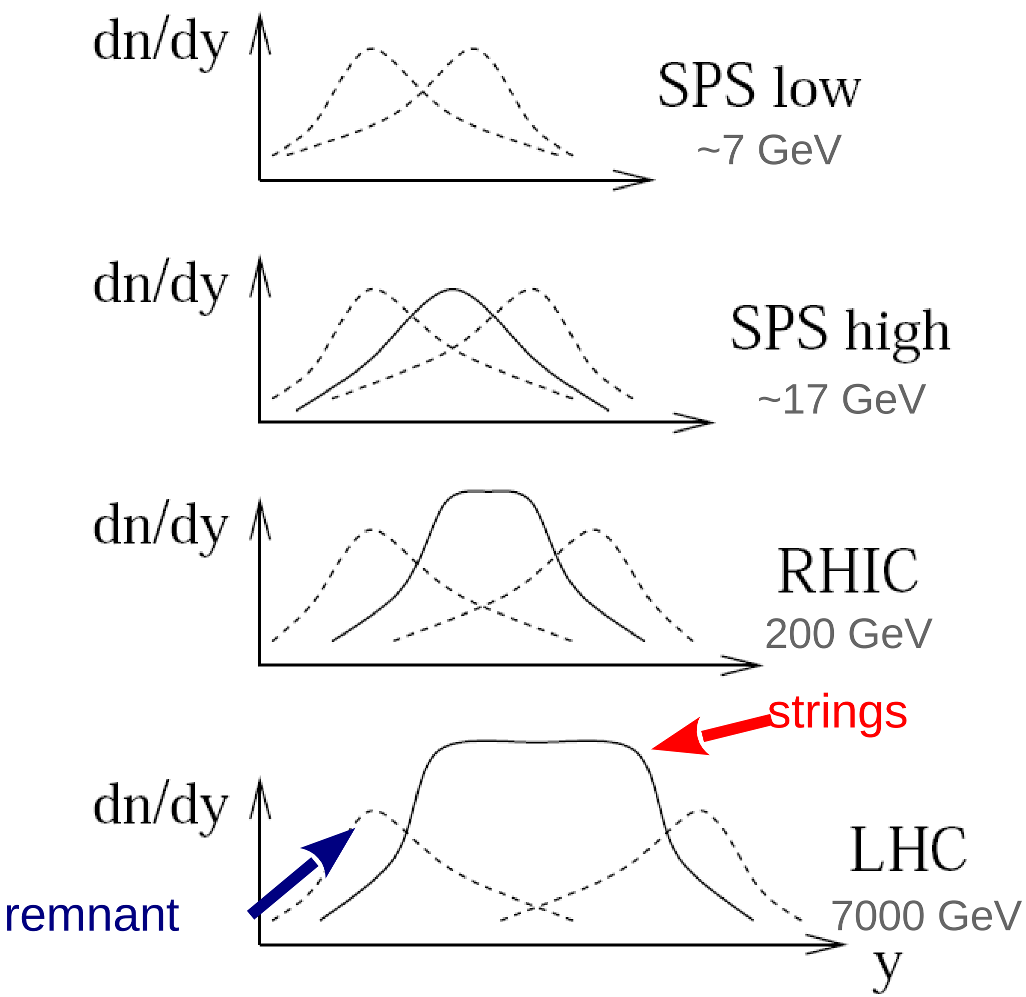
$$\Omega_{AB}^{(s,b)}(m,X^+,X^-) = \prod_{k=1}^{AB}\left\{\frac{1}{m_k!}\prod_{\mu=1}^{m_k} G(x_{k,\mu}^+,x_{k,\mu}^-,s,b_k)\right\}\ \Phi_{AB}\left(x^{\mathrm{proj}},x^{\mathrm{targ}},s,b\right)$$

  - m and X fixed together by a complex Metropolis (Markov chain)
- 2m “kinky” strings formed from the m elementary interactions
  - energy conservation : energy fraction of the 2m strings given by X
- consistent scheme : energy sharing reduce the probability to have large m

Consistent treatment of cross section and particle production:
number AND distribution of cut Pomerons depend on cross section

Remnants

Forward particles mainly from projectile remnant

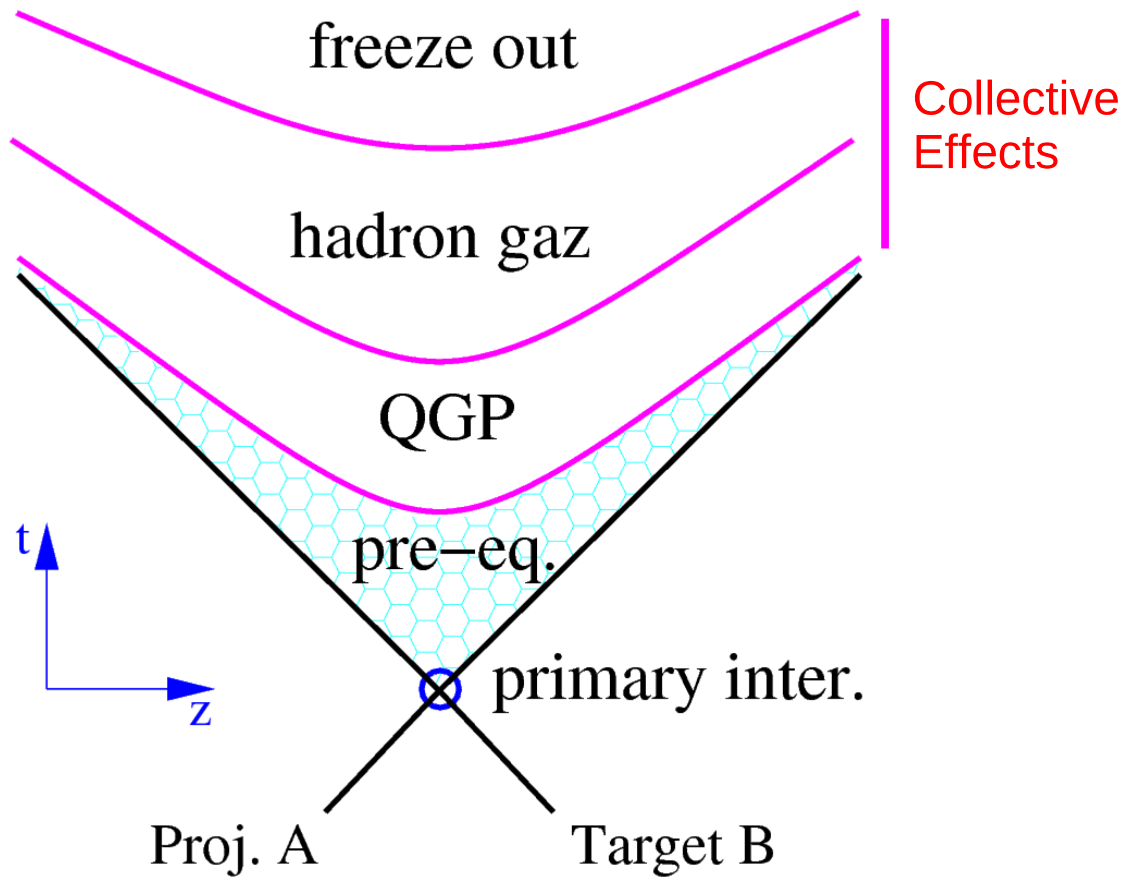


Forward hadronization from remnant :

- At very low energy only particles from remnants
- At low energy (fixed target experiments) (SPS) strong mixing
- At intermediate energy (RHIC) mainly string contribution at mid-rapidity with tail of remnants.
- At high energy (LHC) only strings at mid-rapidity (baryon free)

Remnant considered as universal object : same behavior at low or high energy

High Energy Hadronic Interactions

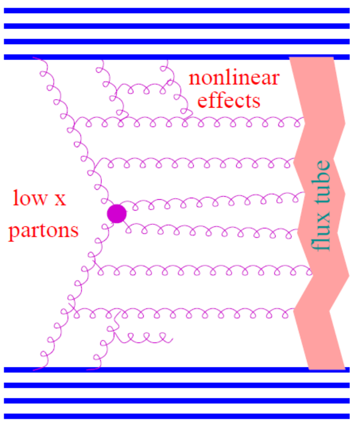


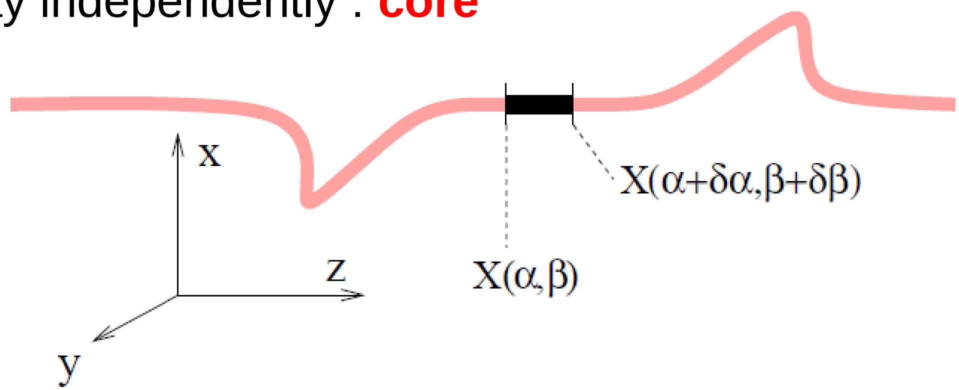
For a complete description of LHC pp data (from minimum-bias to high multiplicity), same process chain as for heavy ion needed.

High Density Core Formation

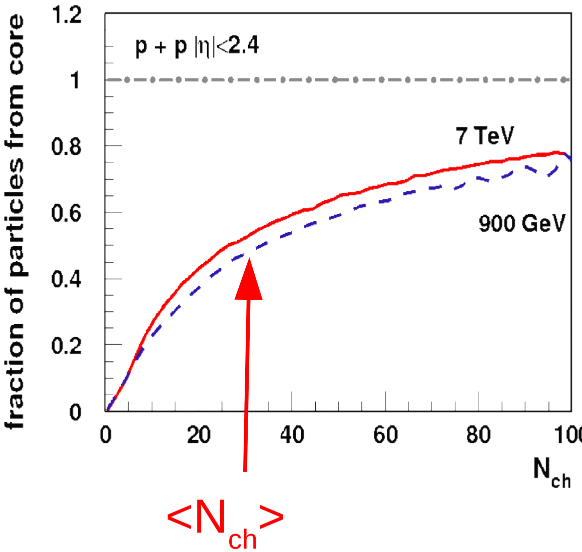
Heavy ion collisions or high energy proton-proton scattering:

- the usual procedure has to be modified, since the density of strings will be so high that they cannot possibly decay independently : **core**

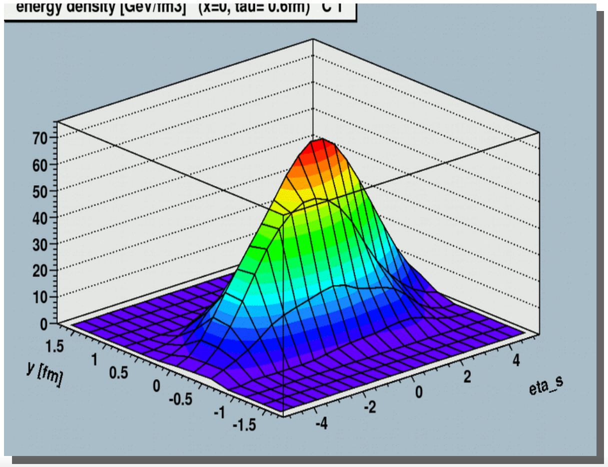




- Each string split into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space

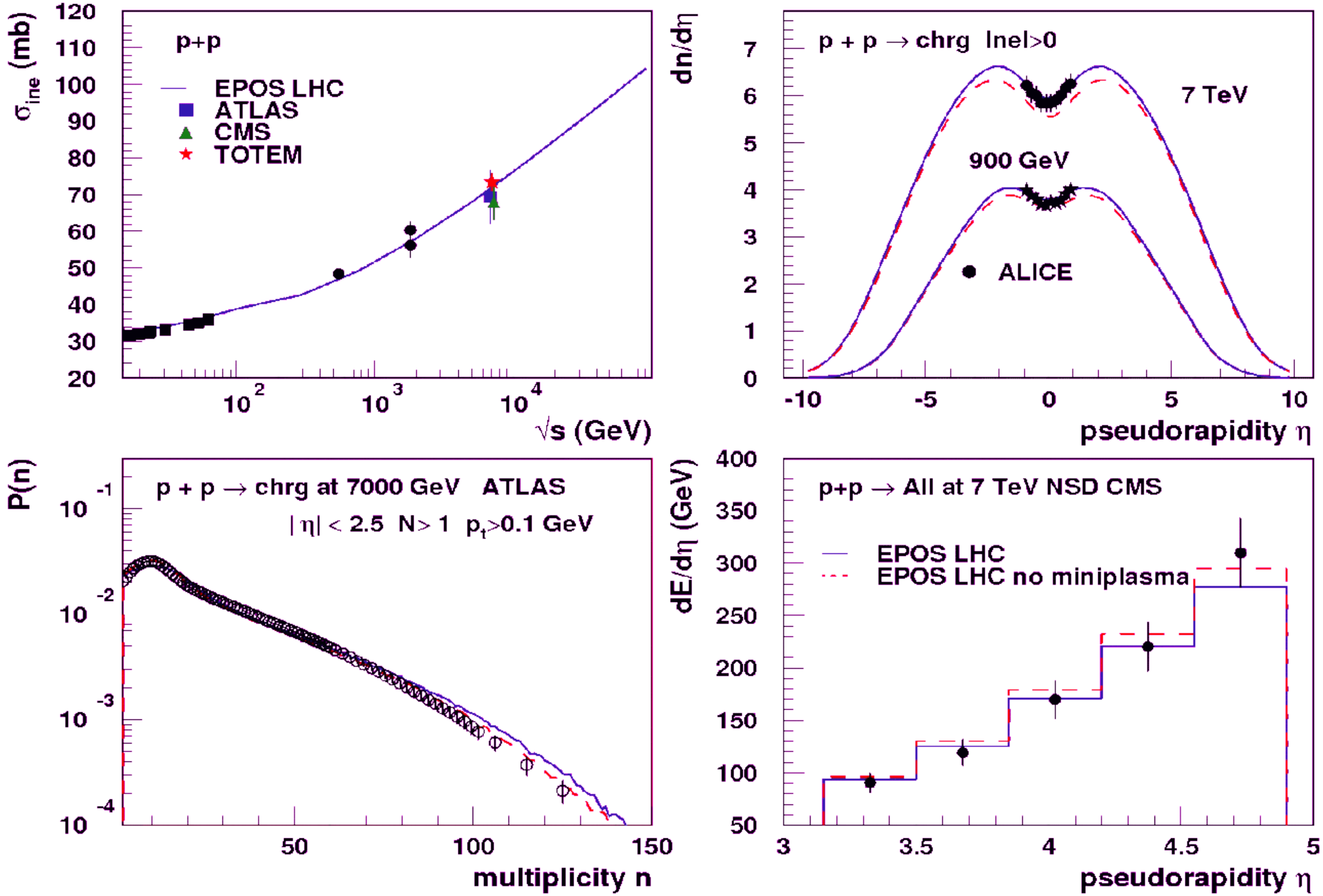


- If energy density from segments high enough
  - segments fused into core
    - full 3D+1 hydro evolution
    - lattice QCD EoS
- If low density (corona)
  - segments remain hadrons
    - string fragmentation



EPOS LHC

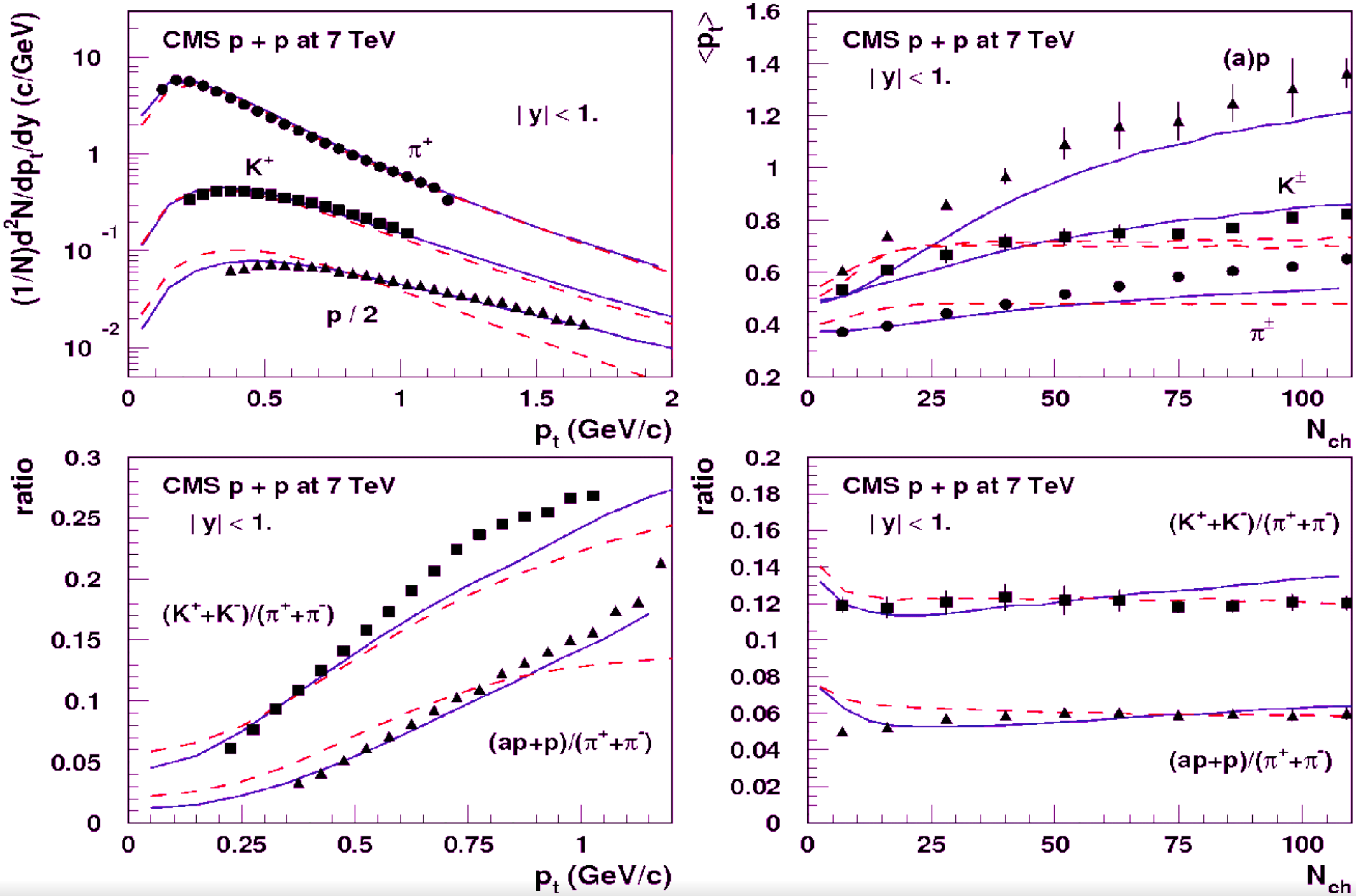
Effective flow treatment



EPOS LHC

Detailed description can be achieved

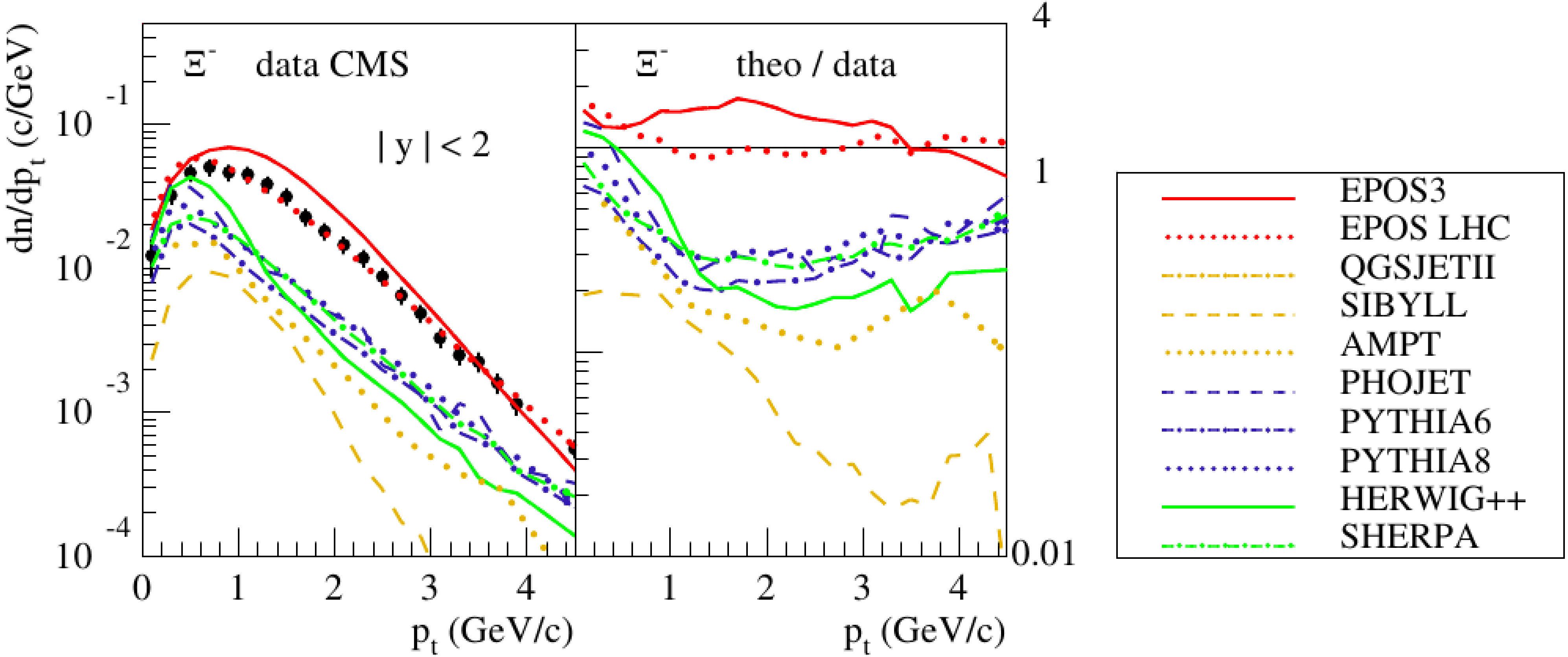
- identified spectra
- p_t behavior driven by collective effects (statistical hadronization + flow)



EPOS LHC

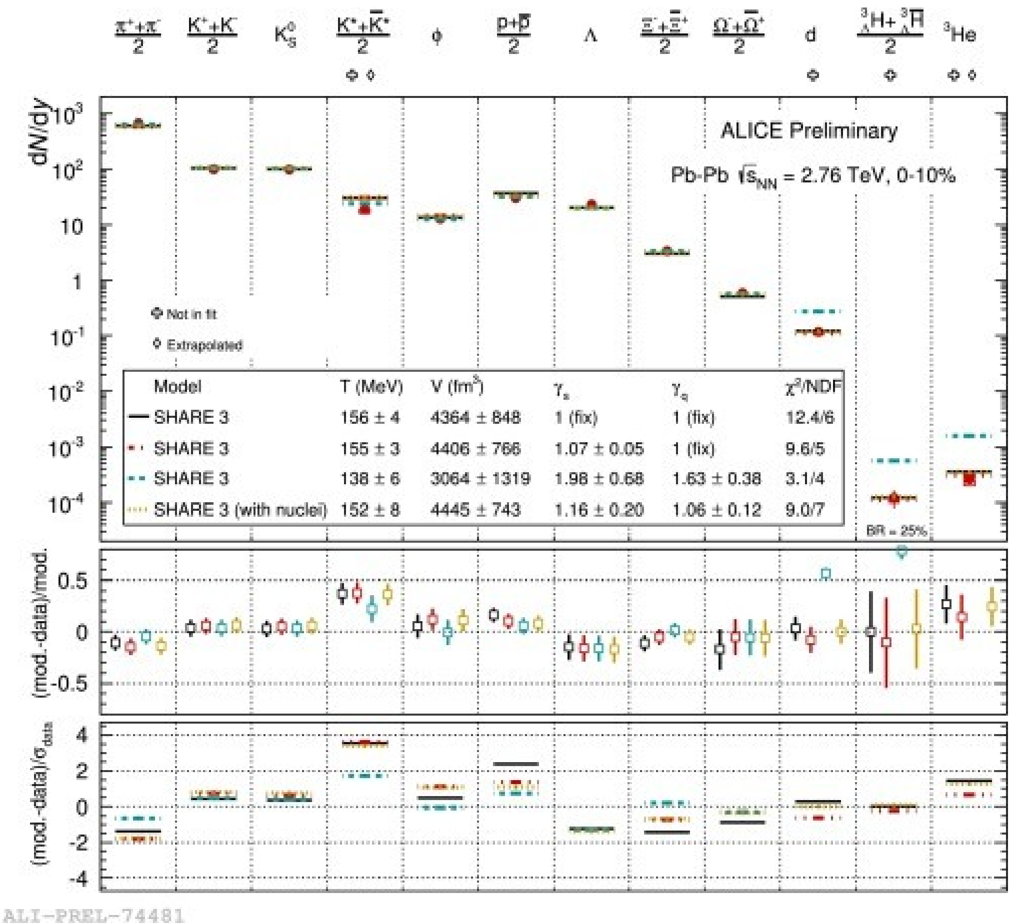
Detailed description can be achieved

- identified spectra
- p_t behavior driven by collective effects (statistical hadronization + flow)
  - large effect for multi-strange baryons (yield AND <p_t>)
  - effect on antideuteron ?



Antideuteron Production in EPOS

- **EPOS has 2 types of hadronization**
  - ➔ Corona (low density) : standard string hadronization without light (anti-)nucleus
  - ➔ Core (high density) : collective (thermal) hadronization
- **Thermal hadronization**
  - ➔ Good description of light (anti-)nuclei production in heavy ion collisions
  - ➔ Parameters fixed by other type of particles
  - ➔ No need for coalescence
- **Energy/system/centrality evolution fixed by core/corona ratio**
  - ➔ Source of different coalescence momentum



Cosmic Ray Analysis from Extended Air Showers

- **EAS simulations necessary to study high energy cosmic rays**
  - complex problem: identification of the primary particle from the secondaries

- **Hadronic models are the key ingredient !**
  - follow the standard model (QCD)
    - but mostly non-perturbative regime (phenomenology needed)
  - main source of uncertainties
  - Very good test of models (full phase space)
- **Which model for CR ? (alphabetical order)**
  - **DPMJETIII.17-1** by S. Roesler, A. Fedynitch, R. Engel and J. Ranft
  - **EPOS** (1.99/**LHC**/3) (from VENUS/NEXUS before) by H.J. Drescher, F. Liu, T. Pierog and K.Werner.
  - **QGSJET** (01/II-03/**II-04**/III) by S. Ostapchenko (starting with N. Kalmykov)
  - **Sibyll** (2.1/**2.3c**) by E-J Ahn, R. Engel, R.S. Fletcher, T.K. Gaisser, P. Lipari, F. Riehn, T. Stanev

Muons in Air Showers

- **Many muon measurement available from air showers**
  - Auger, EAS-MSU, KASCADE-Grande, IceCube/IceTop, HiRes-MIA, NEMOD/DECOR, SUGAR, TA, Yukutsk
- **Working group (WHISP) created to compile all results together. Analysis led and presented on behalf of all collaborations by H. Dembinski at UHECR 2018 :** **H. Dembinski** (LHCb, Germany),

L. Cazon (Auger, Portugal), **R. Conceicao** (AUGER, Portugal), **F. Riehn** (Auger, Portugal), **T. Pierog** (Auger, Germany),

Y. Zhezher (TA, Russia), **G. Thomson** (TA, USA) , **S. Troitsky** (TA, Russia), **R. Takeishi** (TA, USA),

T. Sako (LHCf & TA, Japan), **Y. Itow** (LHCf, Japan),

J. Gonzales (IceTop, USA), **D. Soldin** (IceCube, USA),

J.C. Arteaga (KASCADE-Grande, Mexico),

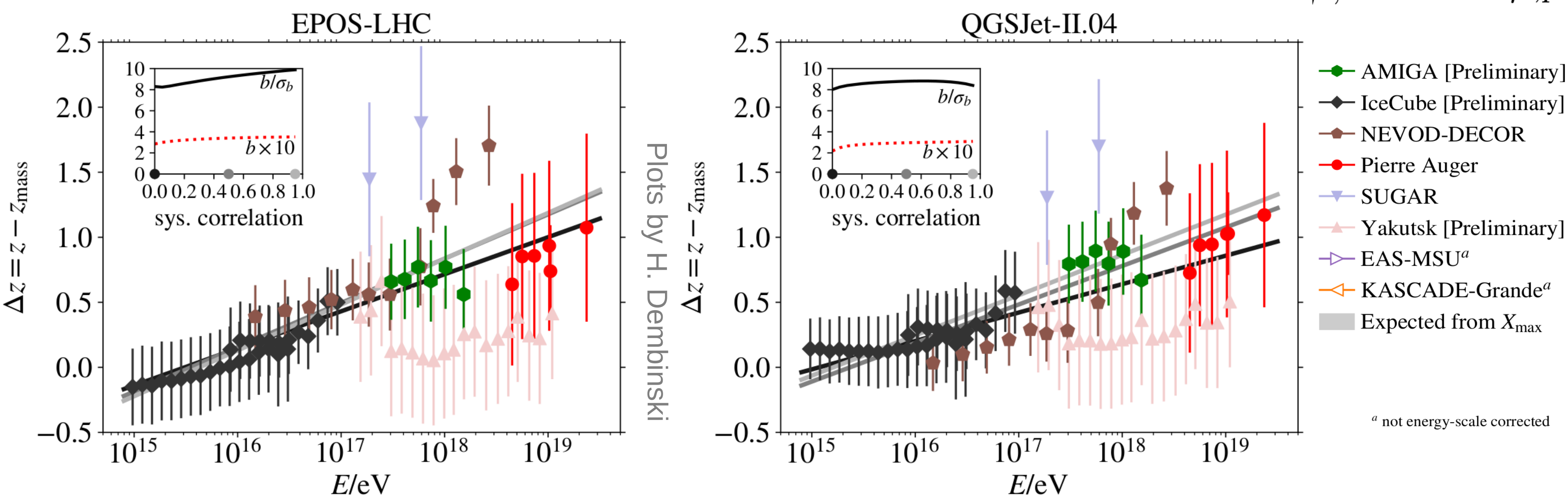
I. Yashin (NEMOD/DECOR, Russia). **E. Zadeba** (NEMOD/DECOR, Russia)

N. Kalmykov (EAS-MSU, Russia) **and I.S. Karpikov** (EAS-MSU, Russia)

Global Behavior

- **Clear muon excess in data compared to simulation**
  - Different energy evolution between data and simulations
    - Significant non-zero slope (>8σ)

$$z = \frac{\ln N_\mu^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}{\ln N_{\mu,\mathrm{Fe}}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}$$

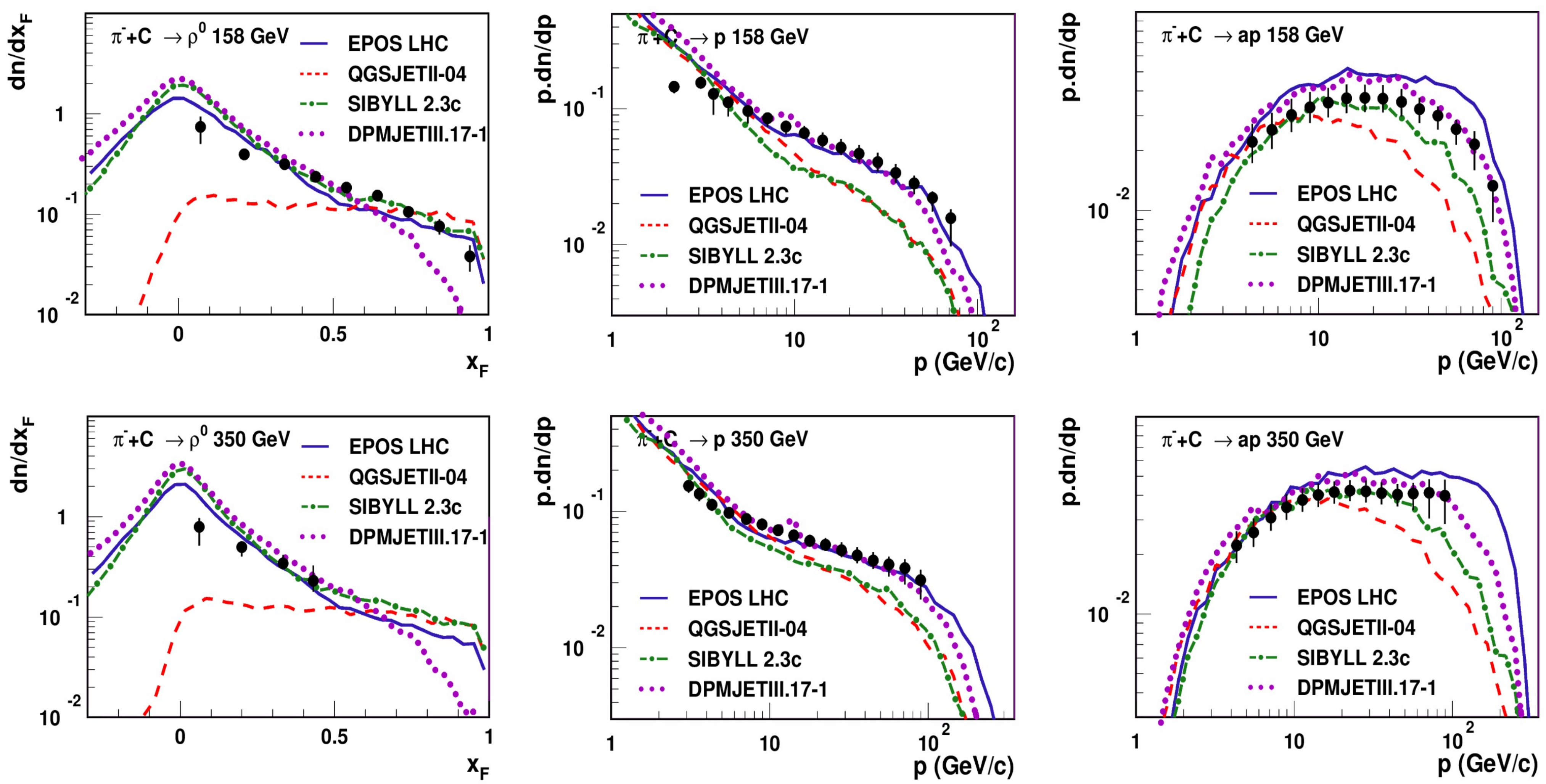


- **Different energy or mass scale cannot change the slope**
  - Different property of hadronic interactions at least above 10^{16} eV

NA61 Pion-Carbon Data

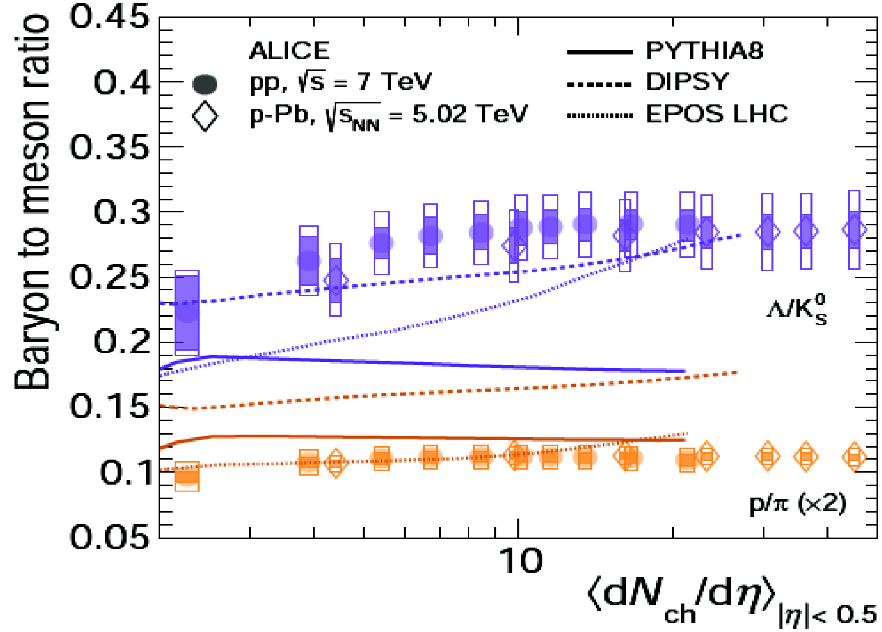
New data from NA61 : wrong old data interpretation

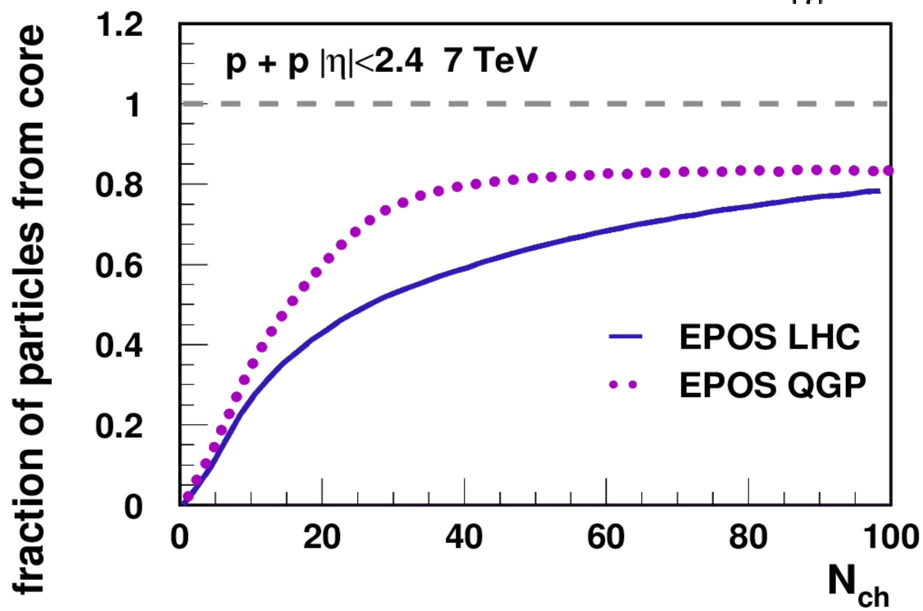
- ➡ over production of forward anti-baryons in EPOS LHC : problems in air showers
- ➡ Implication for anti-proton flux ?



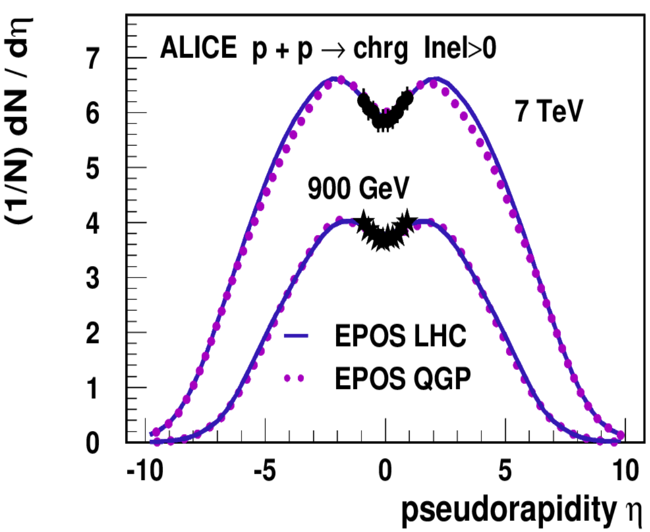
Modified EPOS with Extended Core

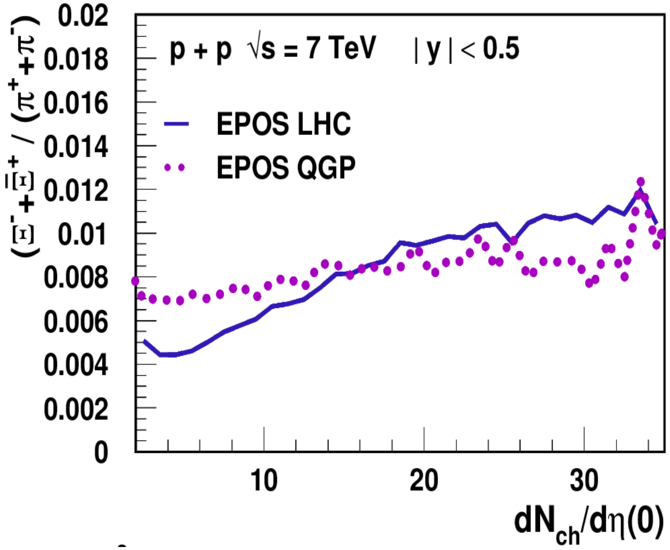
- **Core in EPOS LHC appear too late**
  - Recent publication show the evolution of chemical composition as a function of multiplicity
  - Large amount of (multi)strange baryons produced at lower multiplicity than predicted by EPOS LHC
- **Create a new version EPOS "QGP" with more collective hadronization**
  - Core created at lower energy density
  - More remnant hadronized with collective hadronization
  - Collective hadronization using grand canonical ensemble instead of microcanonical (closer to statistical decay)

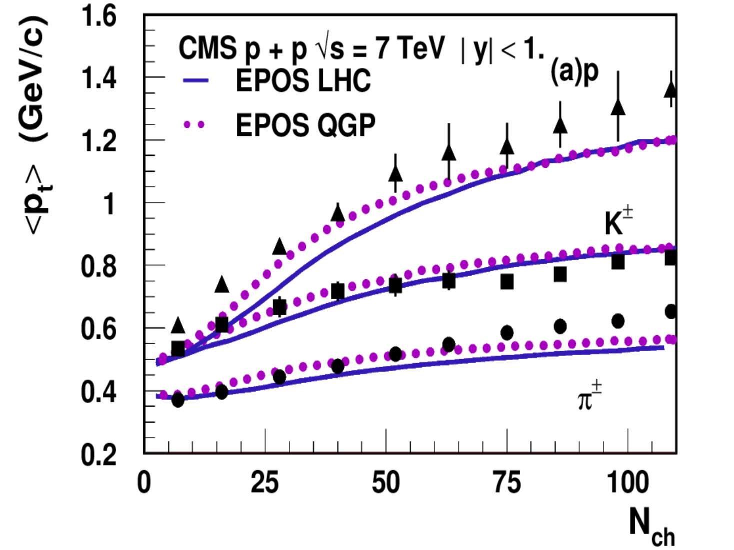


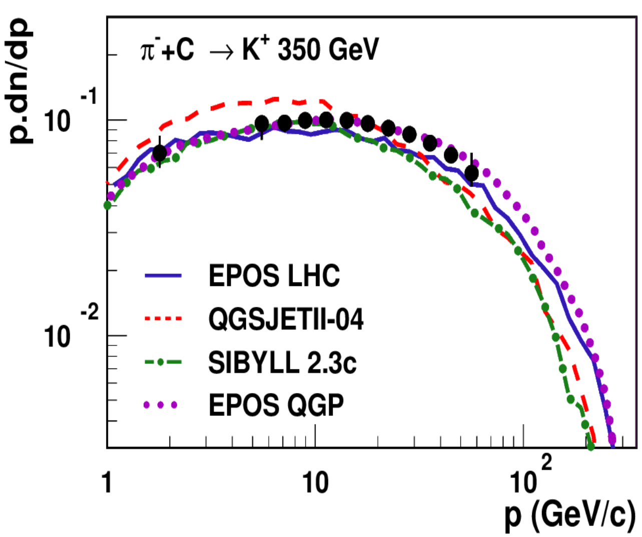


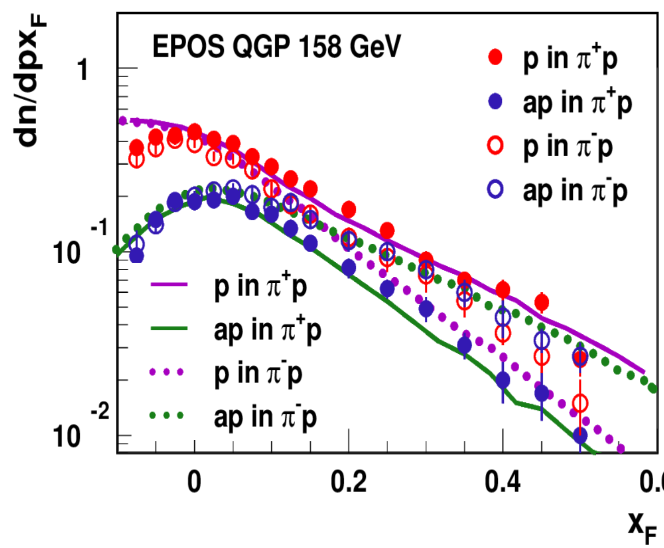
Preliminary Version with Minimum Constraints

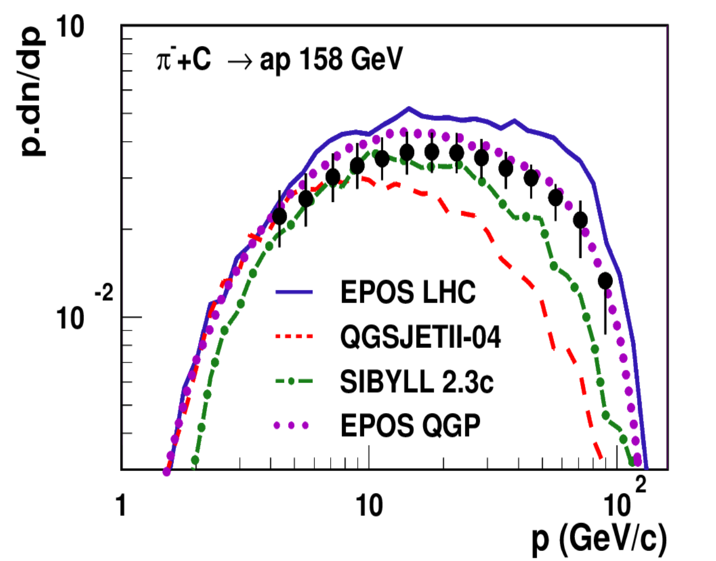








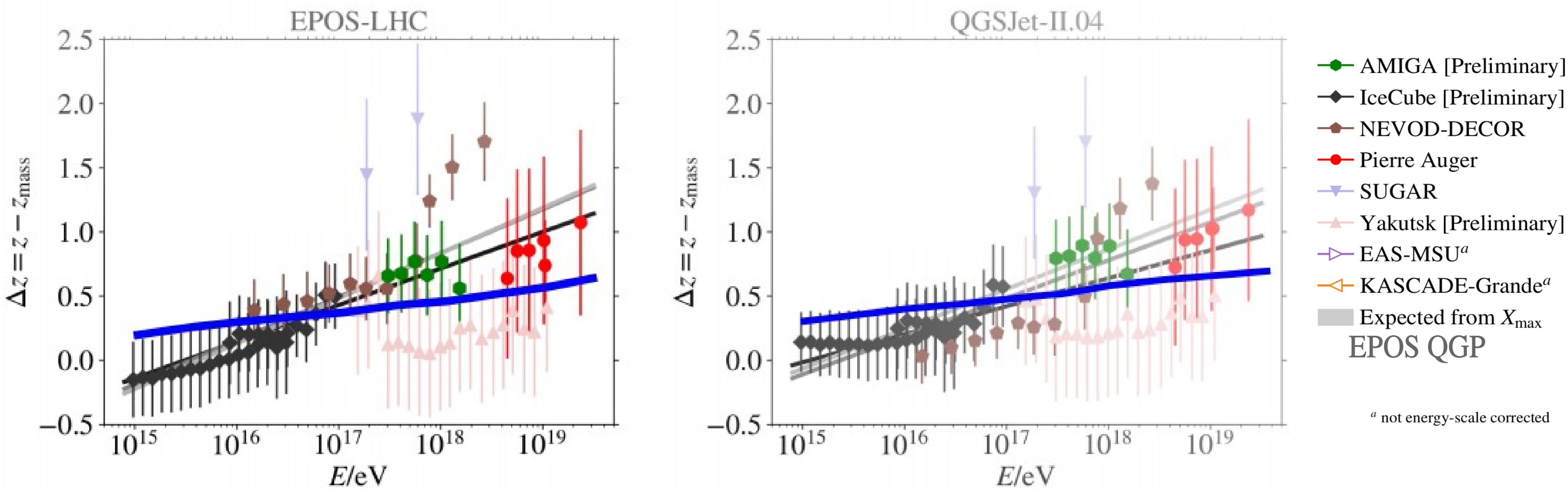




Comparison with Data

- **Collective hadronization gives a result compatible with data**
  - Still different energy evolution between data and simulations
    - Significance to be tested

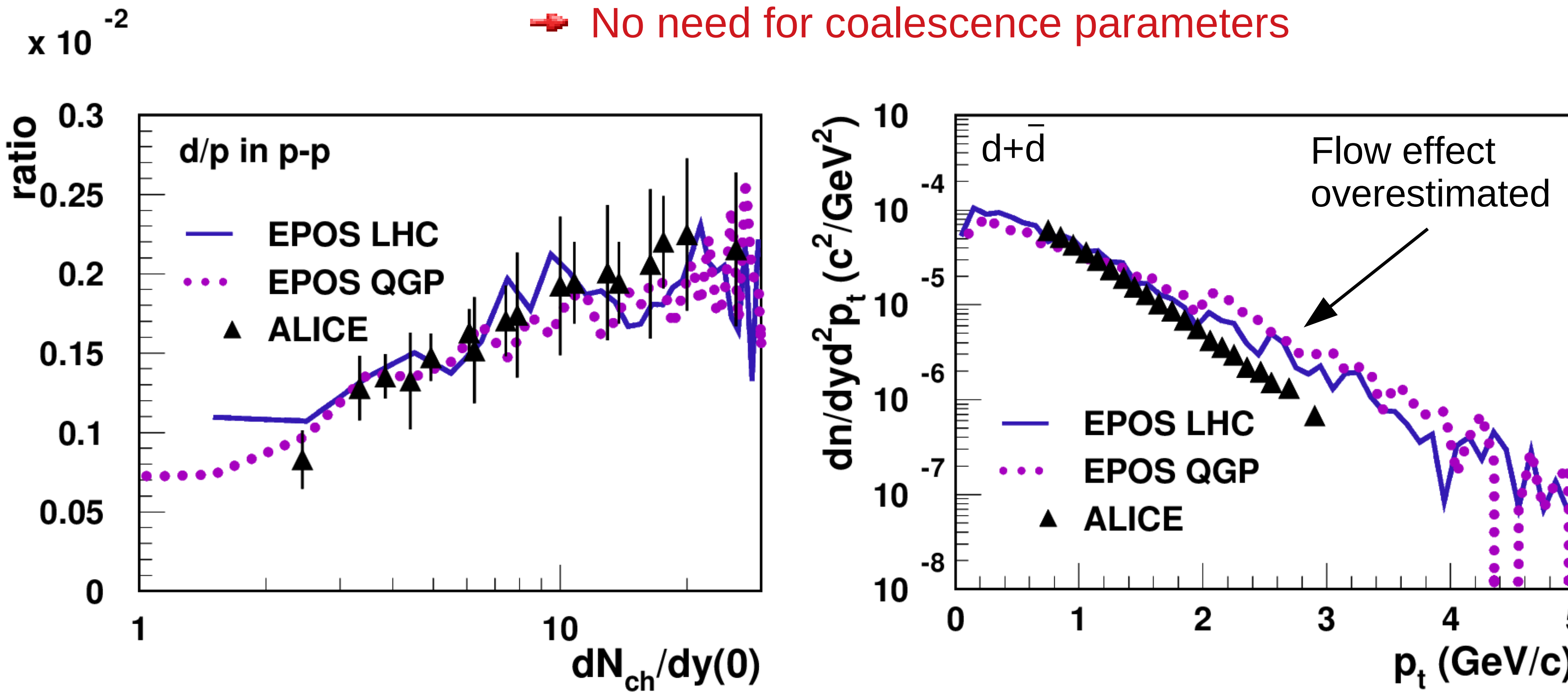
$$z = \frac{\ln N_{\mu}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}{\ln N_{\mu,\mathrm{Fe}}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}$$



- **Probably tension at low energy (too many muons)**
  - Ideally a larger slope would be needed … what kind of hadronization possible ?
  - QGP with large chemical potential (Anchordoqui et al.) ?

Effect on Antideuteron

- **Core easier to produce (lower energy density)**
  - Core effect start at lower center of mass energy than EPOS LHC
  - Effect can be checked with more data (RHIC, HERA, SPS)
- **Once the core/corona fixed, light (anti-)nuclei production yield fixed by thermal model**
  - No need for coalescence parameters



Effect on Antideuteron

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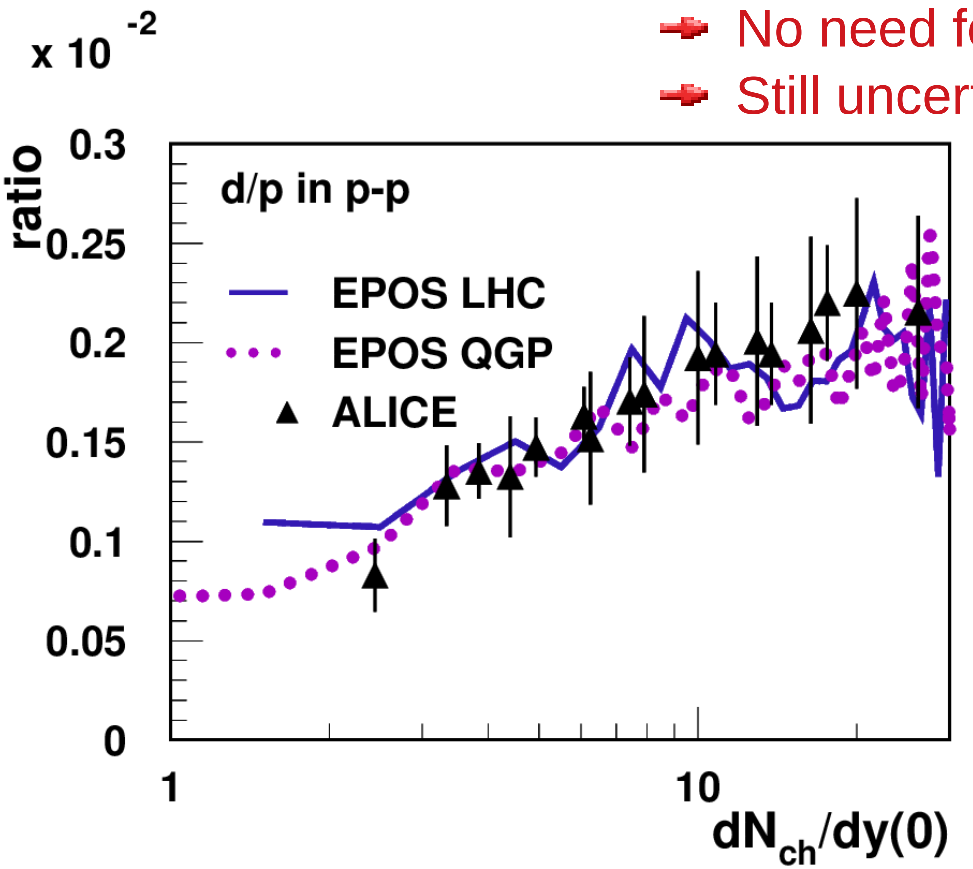
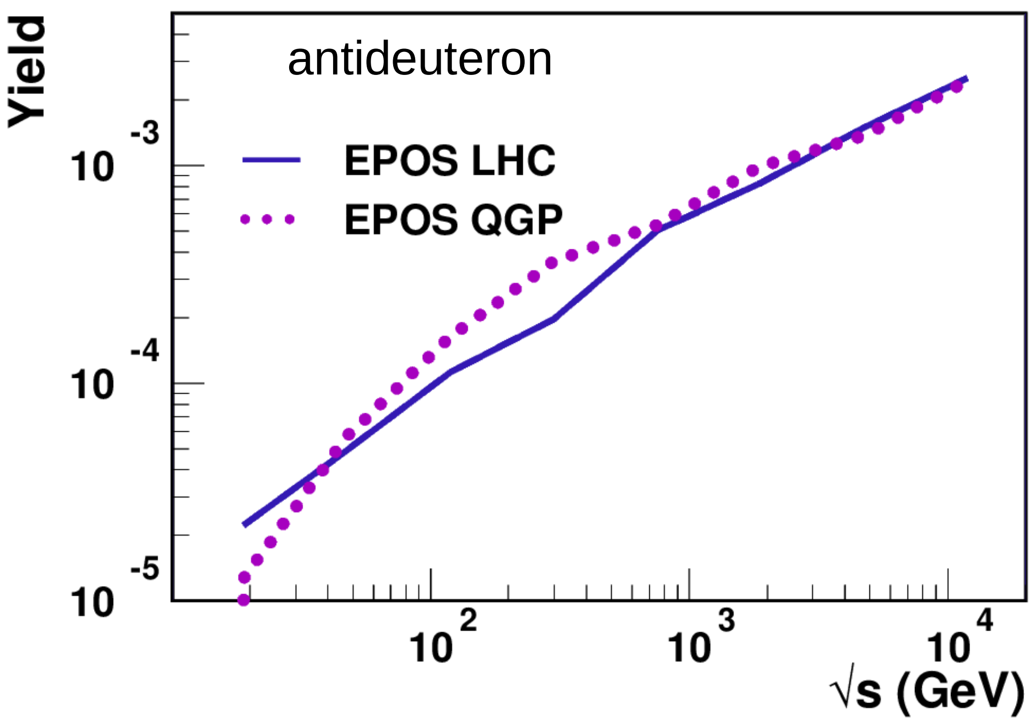
  - Effect can be checked with more data (RHIC, HERA, SPS)
- **Once the core/corona fixed, light (anti-)nuclei production yield fixed by thermal model**
  - No need for coalescence parameters
  - Still uncertainty on the core/corona ratio to be fixed





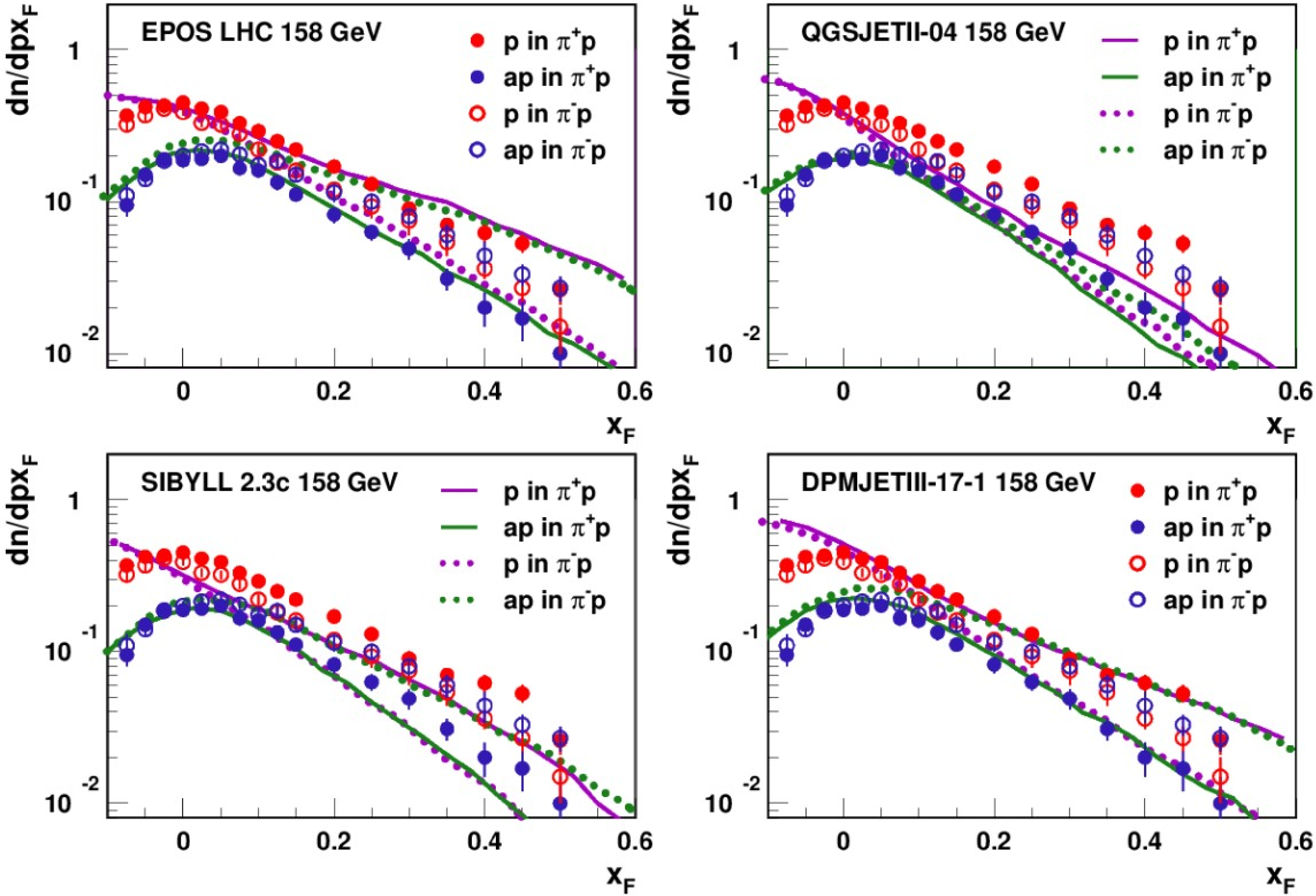
Summary

New input from LHC which could help to reproduce EAS data consistently but solution still under study. Possible consequences on antideuteron production.

- **In EPOS LHC, antideuteron can be produced directly**
  - ➡ No need for coalescence model and results compatible with ALICE data
- **WHISP working group clearly established a muon production deficit in air shower simulations.**
  - ➡ Exact scale not known (dependent on energy and mass)
  - ➡ Large change needed in hadronization
  - ➡ Different type of hadronization (extended range for QGP ?)
- **Possible to approach data but energy slope at the lower limit (preliminary)**
  - ➡ Same effect will increase the light (anti-)nuclei production
  - ➡ Increase of core increase the production of antideuteron
- **More study to constrain the model and include nuclei production in EPOS 3**

Baryons in Pion Interactions

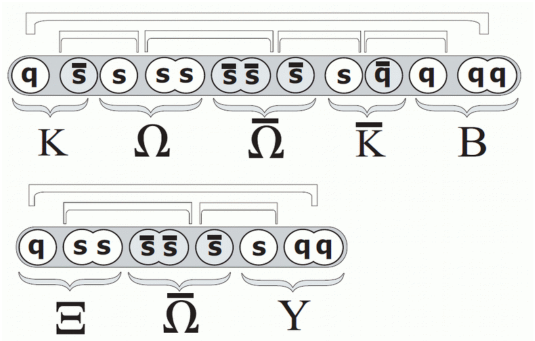
Data from NA49 (Gabor Veres PhD) : full picture



Baryons and Remnants

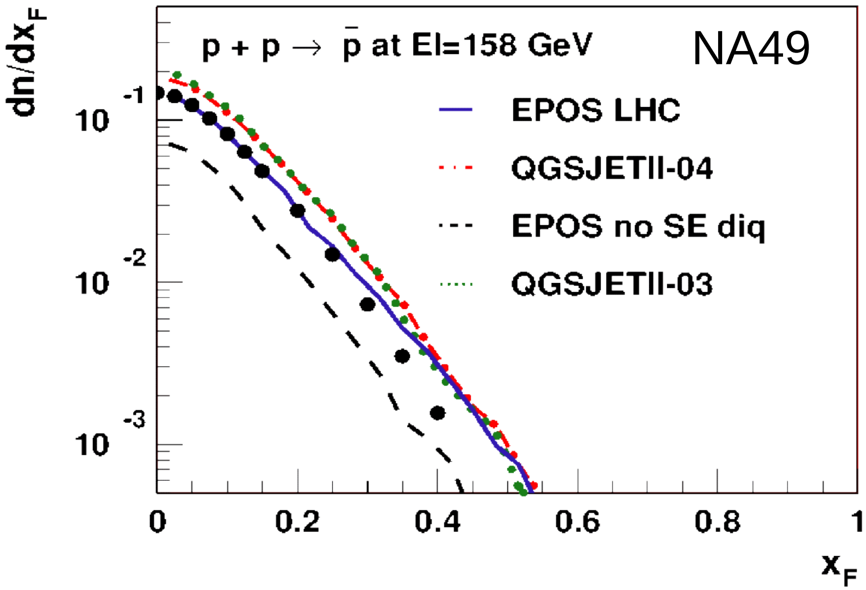
Parton ladder string ends :

- Problem of multi-strange baryons at low energy (Bleicher et al., Phys.Rev.Lett.88:202501,2002)
  - 2 strings approach :
    - $\bar{\Omega}$ / Ω always > 1
    - But data < 1 (Na49)



- EPOS
  - No “first string” with valence quarks : all strings equivalent
  - Wide range of excited remnants (hadronization via light resonance decay, string fragmentation or heavy quark-bag statistical decay)
    - Ω / Ω always < 1

Forward Baryons (low energy)



- Large differences between models
- Need a new remnant approach for a complete description (EPOS)
- Problems even at low energy
- No measurement at high energy !

Without remnant, string fragmentation has to be changed for baryon production