Performance and future Evolution of EPOS

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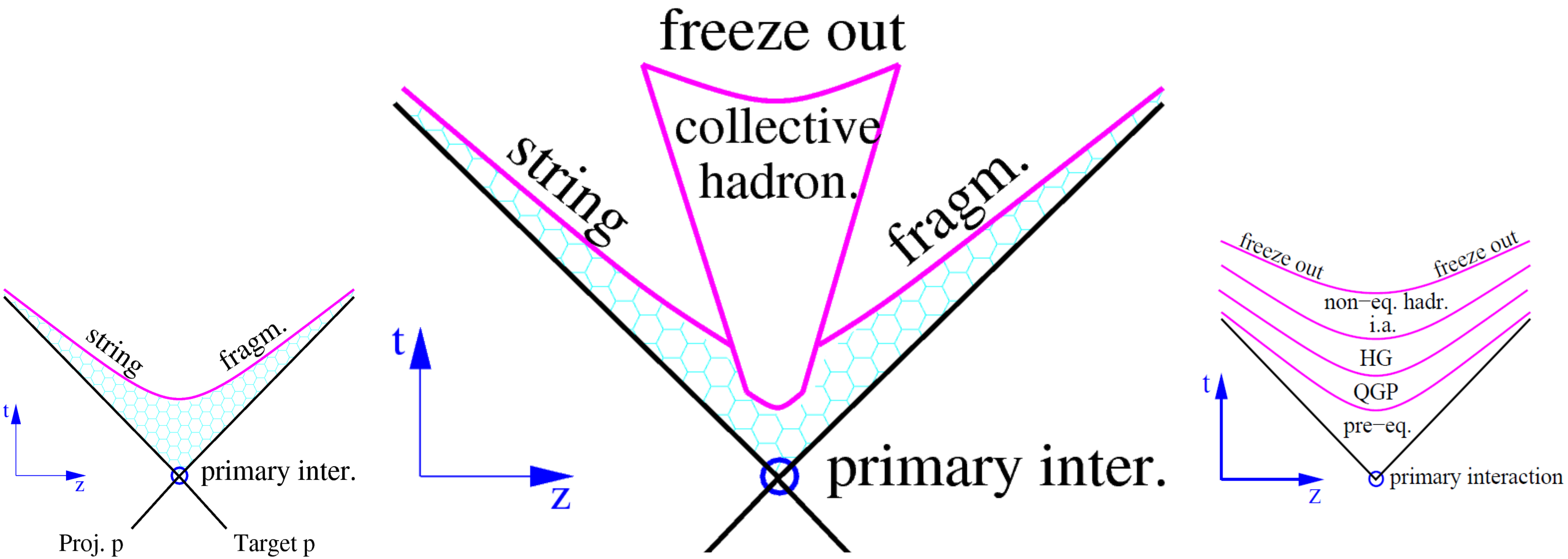
EPOS Scheme

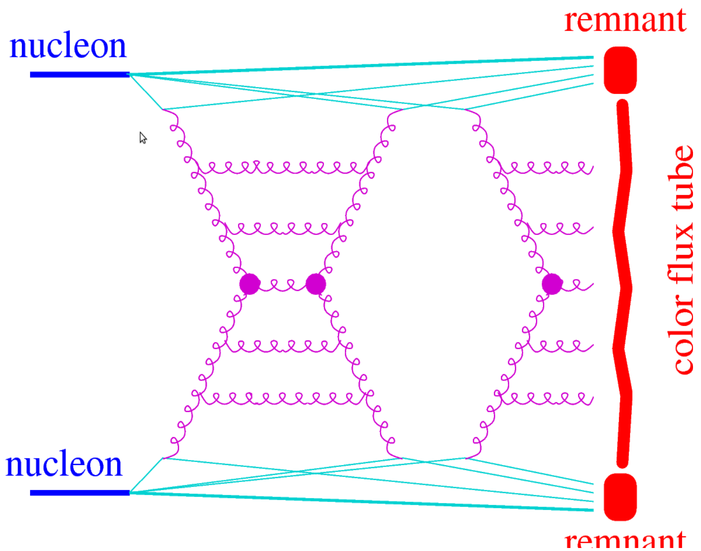


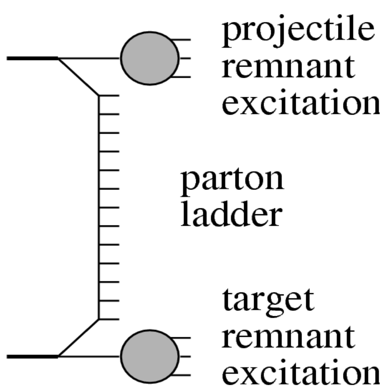
General case valid for all systems :
Collective hadronization if enough particles are produced !

Outline

- **EPOS basic principles**
- **EPOS performances**
  - ➡ accelerator data
  - ➡ cosmic ray (CR) data
- **New developments**
  - ➡ EPOS 3
- **Summary**

The EPOS Model





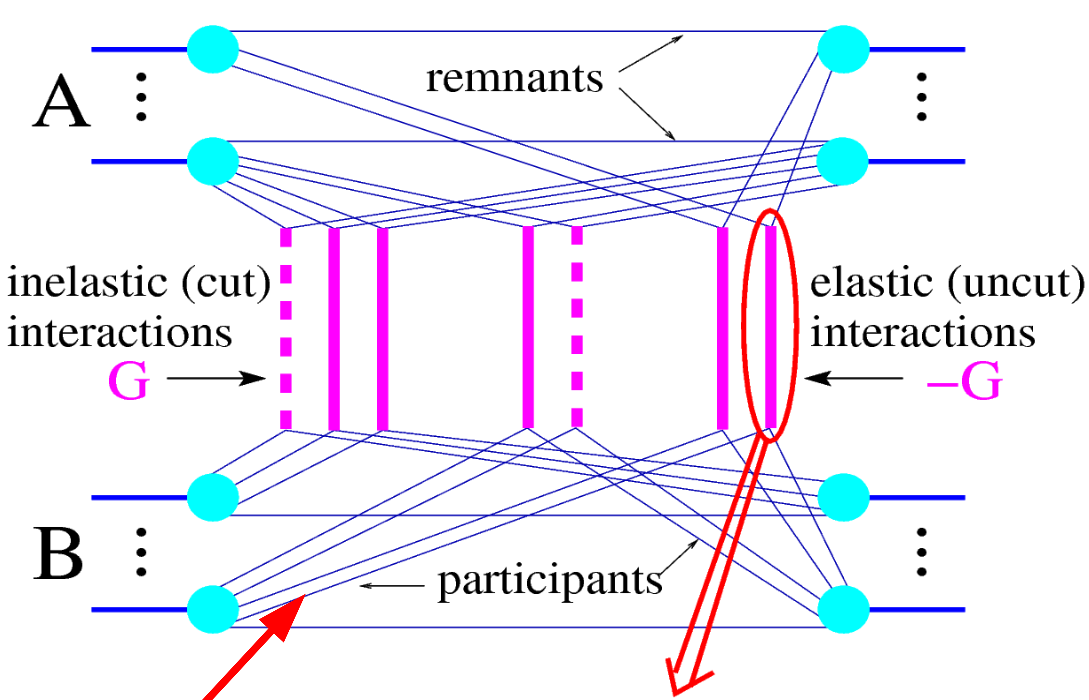
EPOS is a parton model, with many binary parton-parton interactions, each one creating a parton ladder.

- Energy-sharing : for cross section calculation AND particle production
- Parton Multiple scattering
- Outshell remnants
- Screening and shadowing via unitarization and splitting
- Collective effects for dense systems

EPOS can be used for minimum bias hadronic interaction generation (h-p to A-B) from 100 GeV (lab) to 1000 TeV (cms) : used for air shower !

EPOS designed to be used for particle physics experiment analysis (SPS, RHIC, LHC)

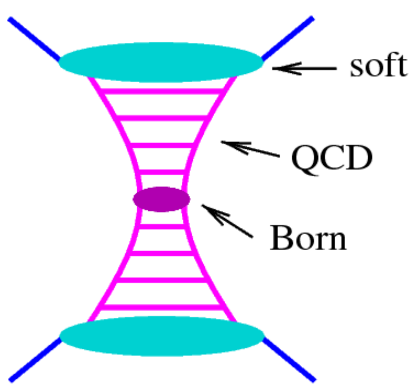
Parton-Based Gribov-Regge Theory

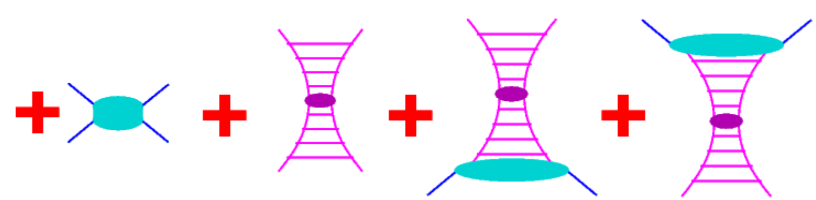


- **Energy sharing at the cross section level**
  - Energy shared between cut and uncut diagrams (Pomeron)
  - Reduced number of elementary interactions
  - Generalization to (h)A-B
  - Particle production from momentum fraction matrix (Markov chain metropolis)

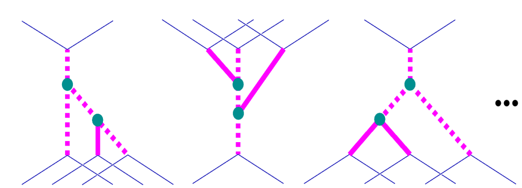
H. J. Drescher et al, Phys. Rept. 350 (2001) 93-289;

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





Non-linear effect (saturation) absorbed in modified vertex functions



EPOS – non-linear effects

Well known problem with pQCD based Pomerons

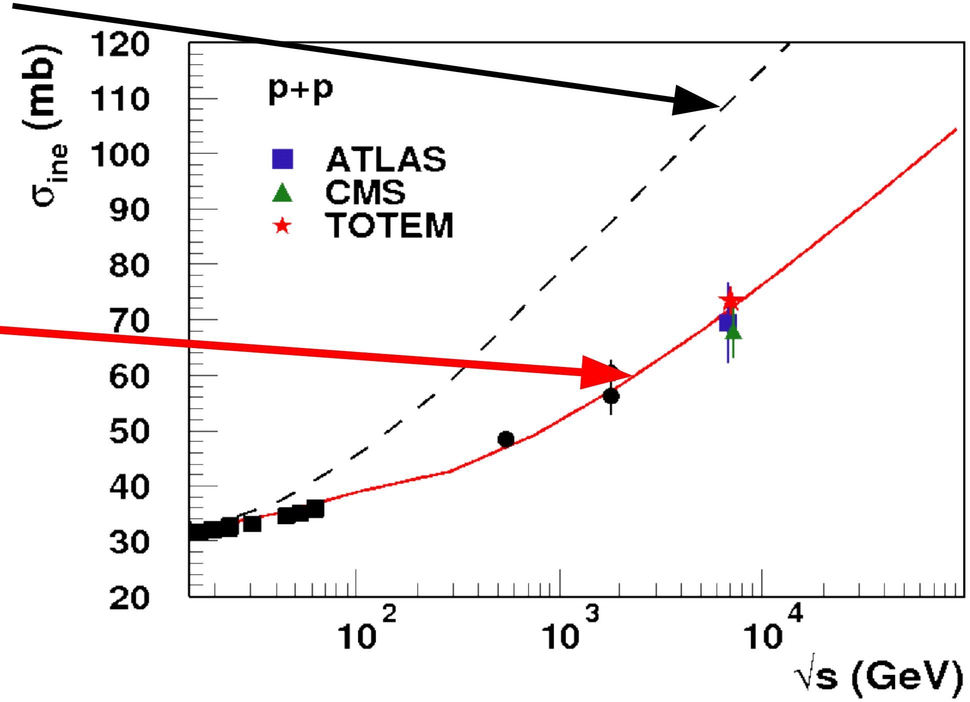
- total cross-section too high : multiple scattering required
  - in EPOS <Pomerons> fixed by b-dep of Pomeron amplitude (slope)
- for historical reason minimum scale Q_0^2 is free but fixed (no energy or b dependence)
- effective coupling introduced to mimic effect of enhanced diagrams and reduce cross-section (screening effect) to get cross-section AND multiplicity right in p-p, p-A and AA.

No effective coupling

$$A_{pom} \sim (x_1 x_2)^{\beta}$$

With effective coupling

$$A_{pom} \sim x_1^{\beta} x_2^{\beta-\varepsilon}$$

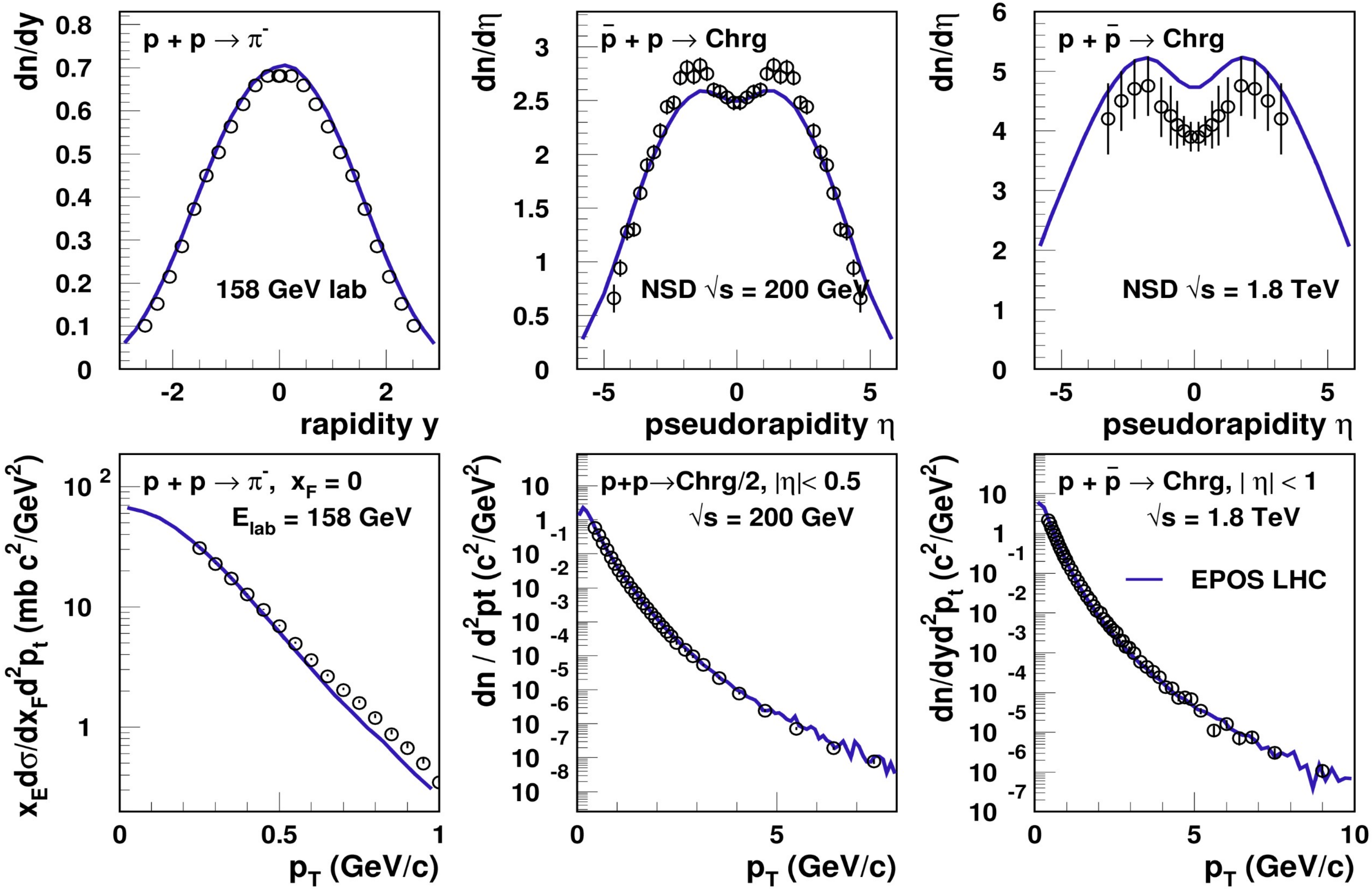


Parametrization

$$\varepsilon_S = a_S\, \beta_S\, Z(s,b,A)$$
$$\varepsilon_H = a_H\, \beta_H\, Z(s,b,A)$$

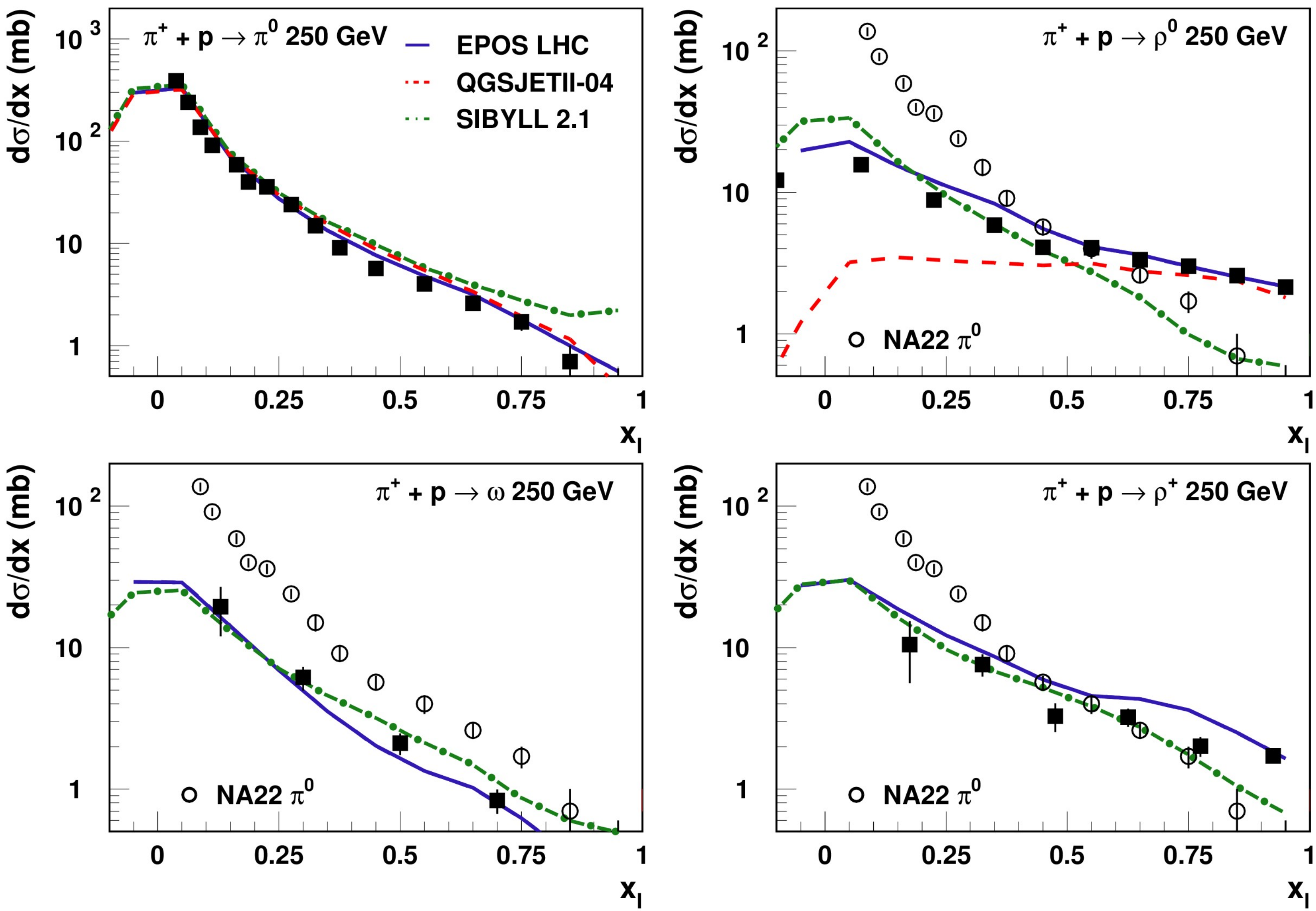
Low Energy Data

Excellent results for soft physics



NA22 π-p Data

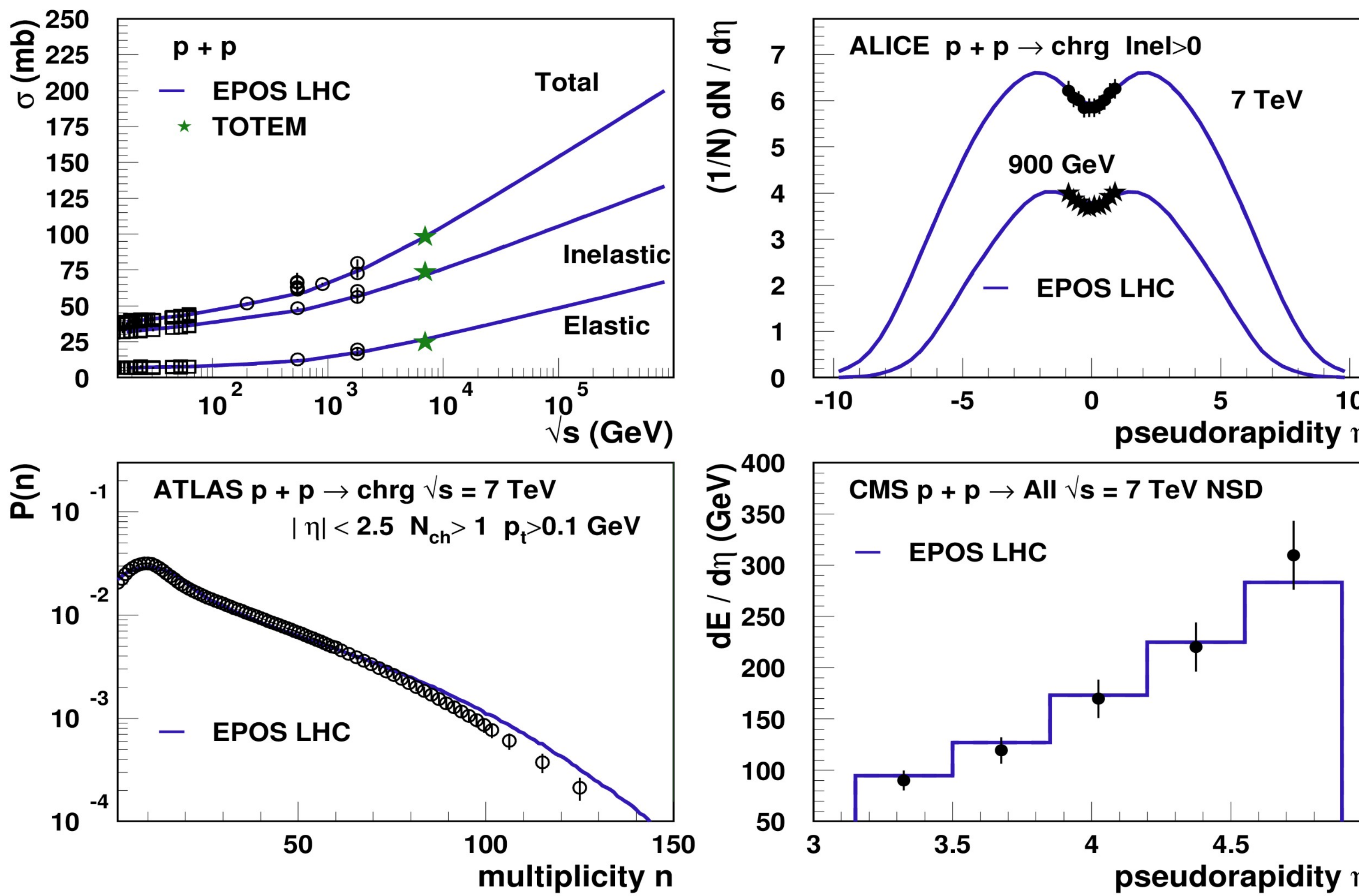
All resonances well described (remnant excitation)



LHC Data

Excellent results for soft physics

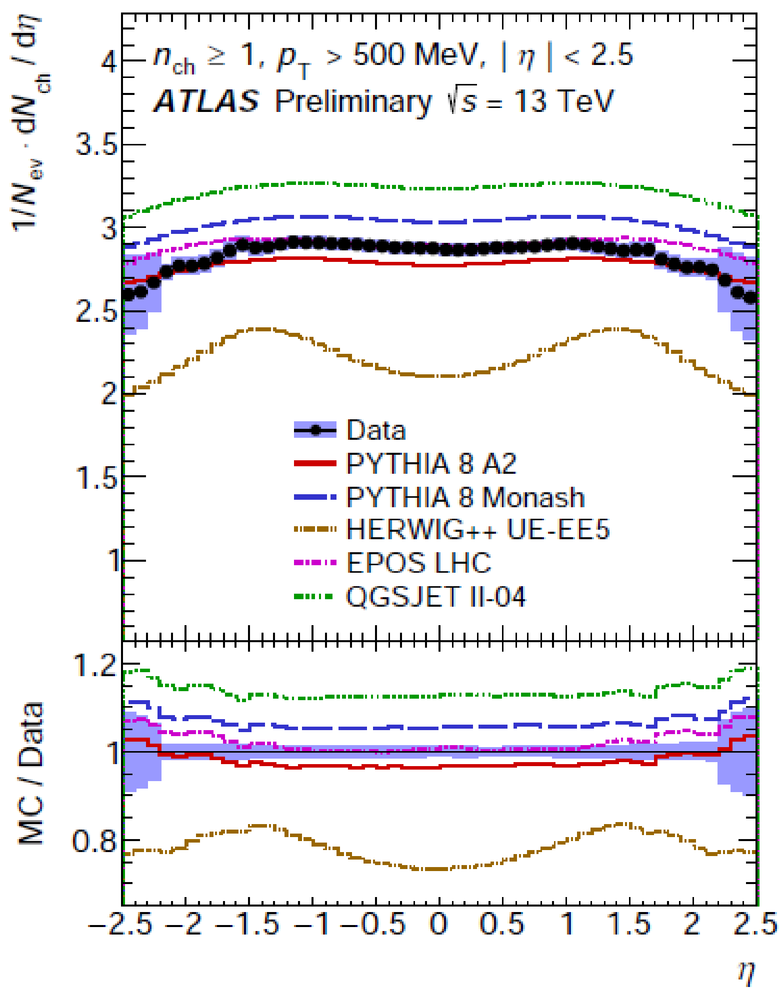
➡ cross-section, multiplicity, pt distributions, identified spectra,energy flow, etc ...

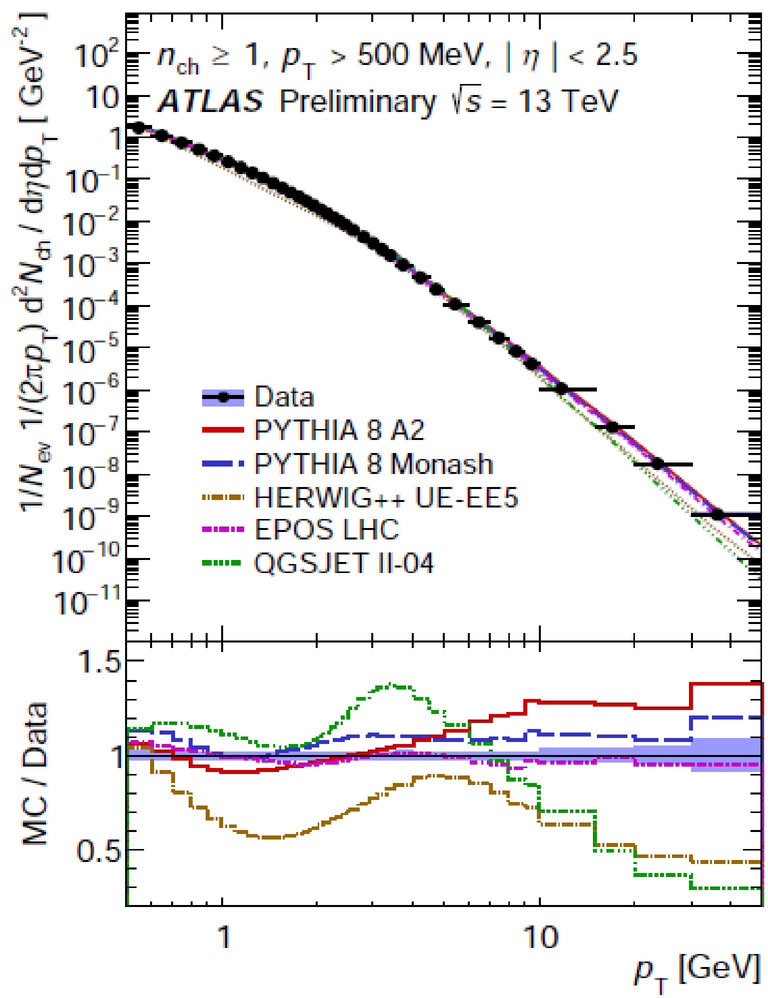


LHC Data

Excellent results for soft physics

- cross-section, multiplicity, pt distributions, identified spectra,energy flow, etc ...
- energy evolution
- best predictions at mid-rapidity

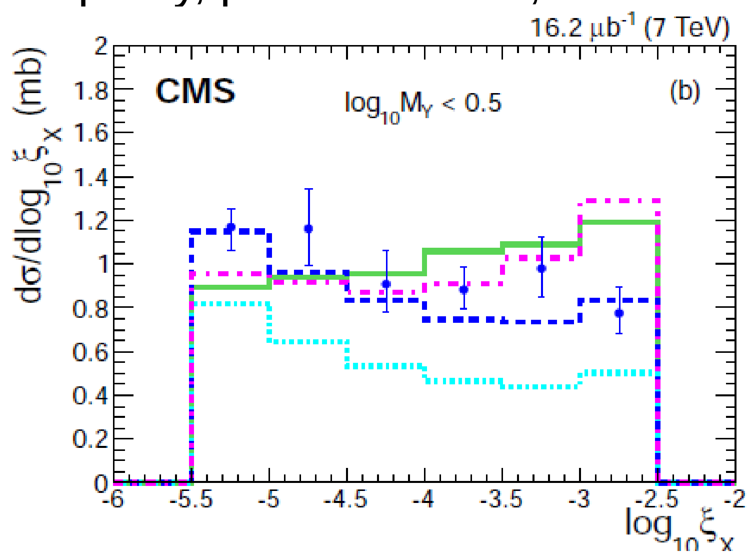


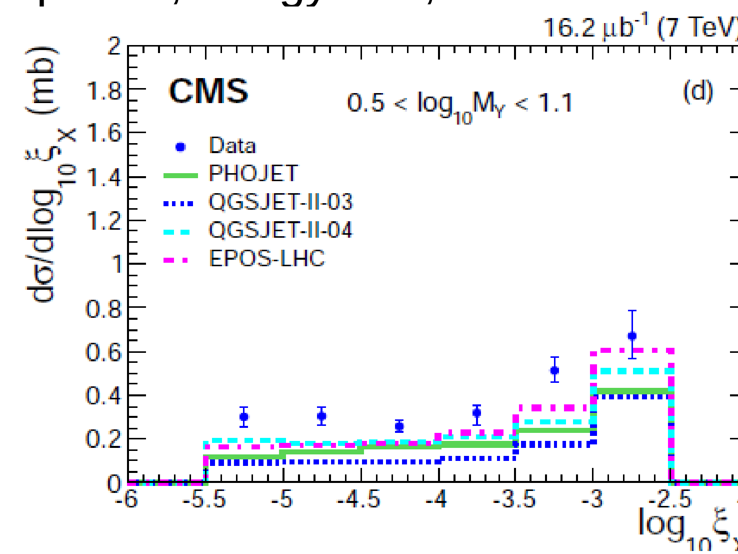


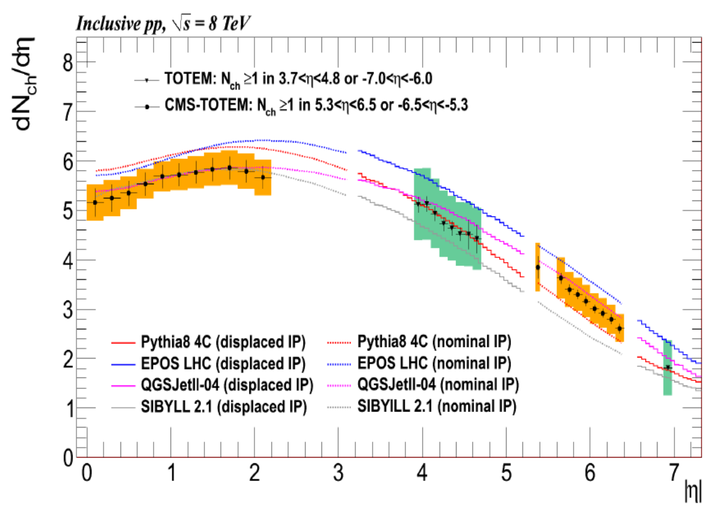
LHC Data

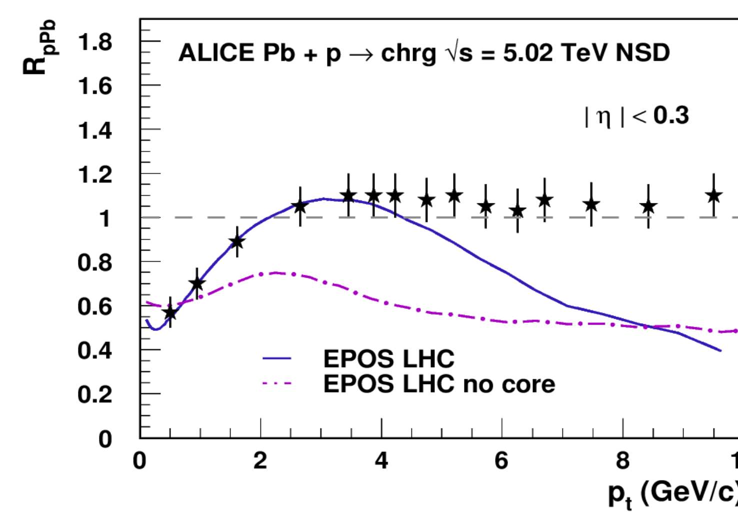
Excellent results for soft physics

- cross-section, multiplicity, pt distributions, identified spectra,energy flow, etc ...
- energy evolution
- best predictions at mid-rapidity
- problem with diffraction
- different results with forward trigger
- problem with high p_t in particular for pA





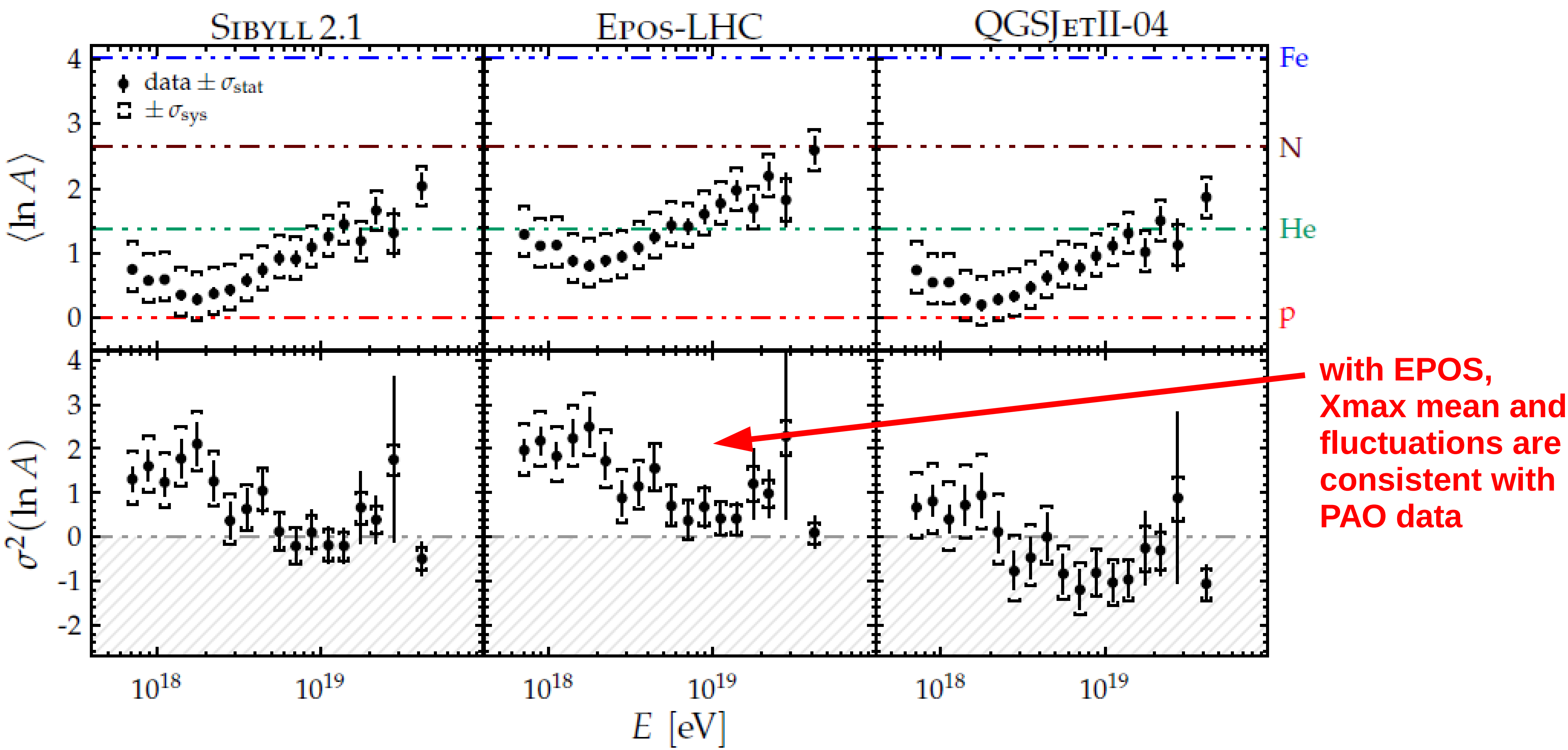




Pierre Auger Observatory: Xmax

Mass evolution

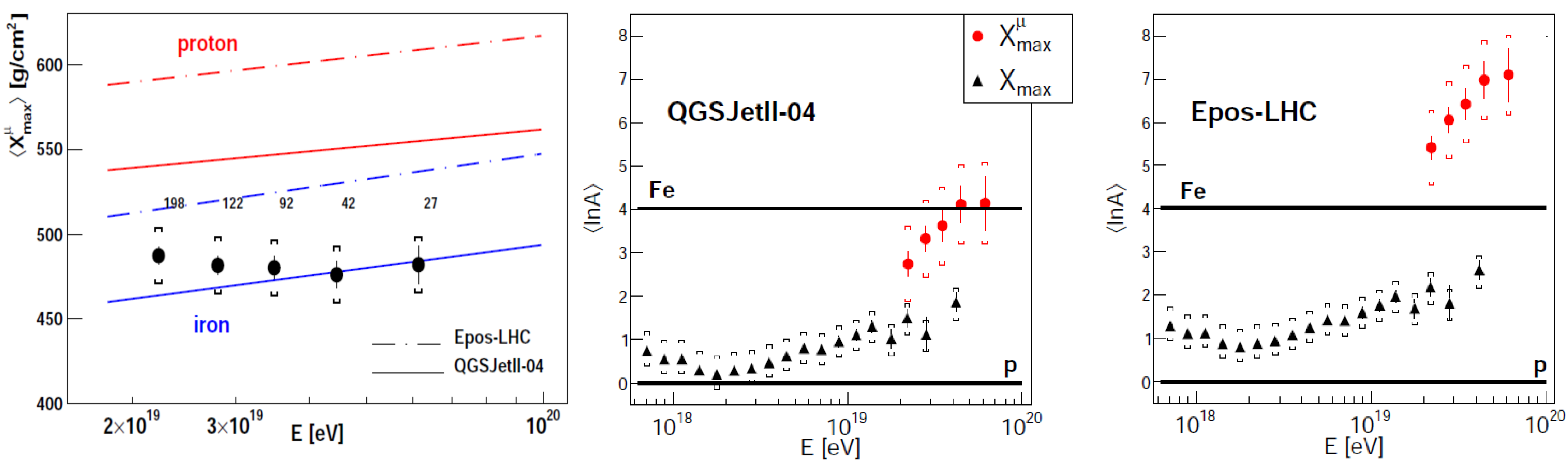
- <lnA> = average (log) mass and σ²(lnA) is the variation of the mass (0=constant mass)
- test consistency of hadronic models (+ tests with muons see other talks)



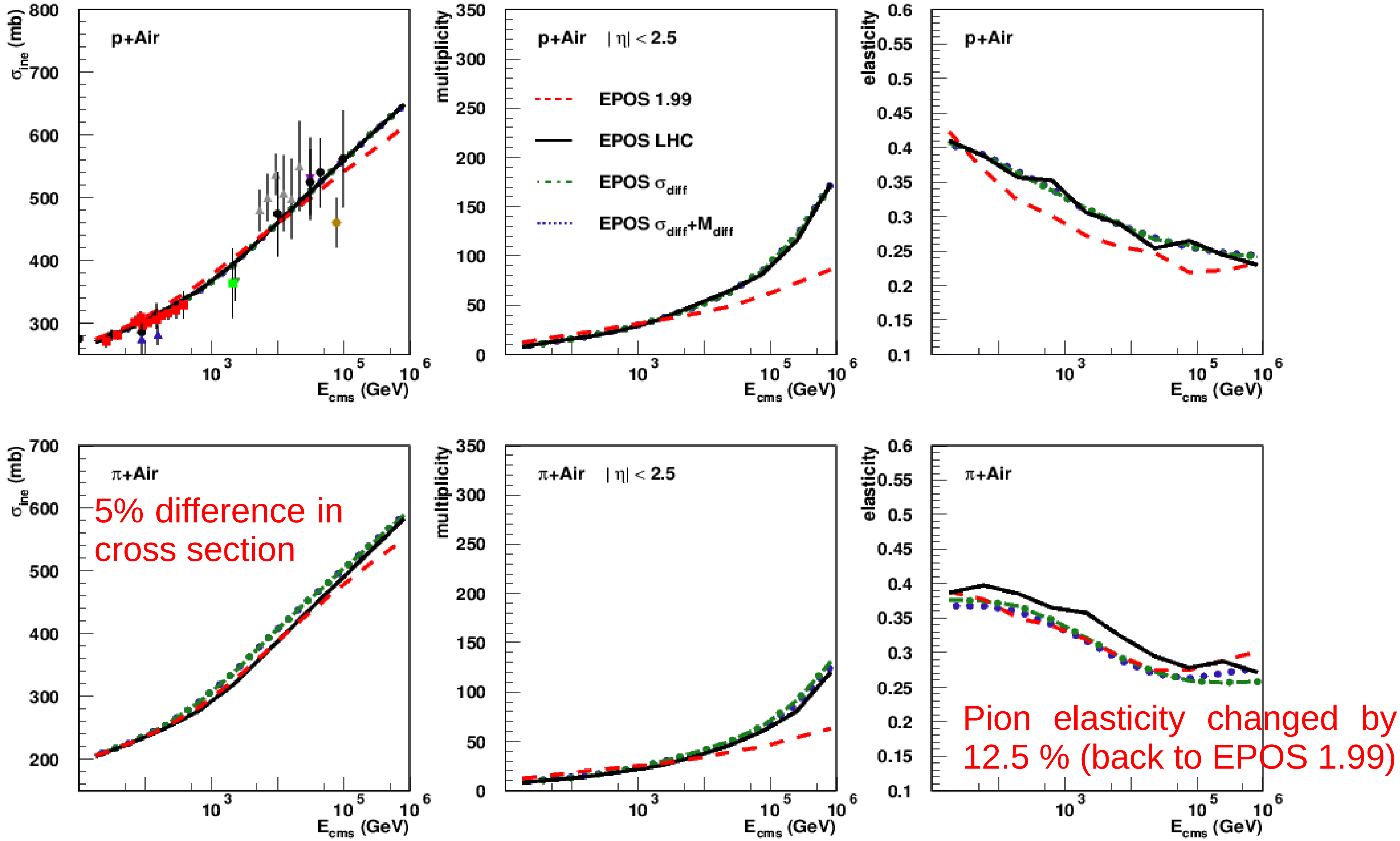
Pierre Auger Observatory: MPD

Measurement of the depth of the maximum muon production

- mass estimator based on muon production: result should be between p and Fe
- should give the same mean logarithmic mass than the one from Xmax for the same model
- problem with EPOS appears after corrections motivated by LHC data
  - lower diffractive mass motivated by rapidity gap cross-section !
  - strong influence of pion diffraction on muon production evolution
  - additional data needed to improve pion diffraction (neutron exchange at LHC ?)

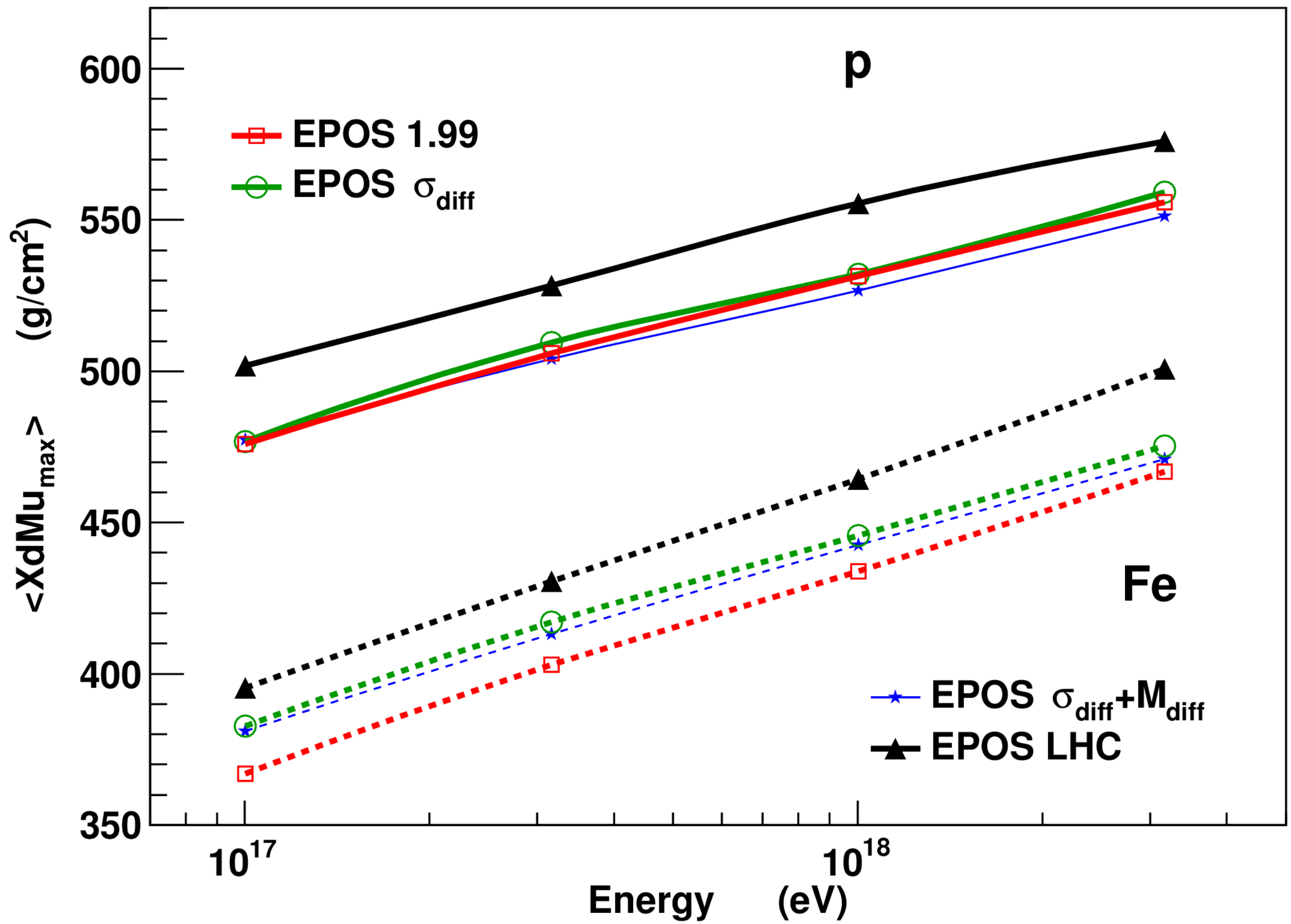


Attempt to change MPD in EPOS



New $\langle X^{\mu}_{max} \rangle$

Not as measured … use EPOS 1.99 as reference ...



-30 g/cm² back to EPOS 1.99

Little influence of diffractive mass

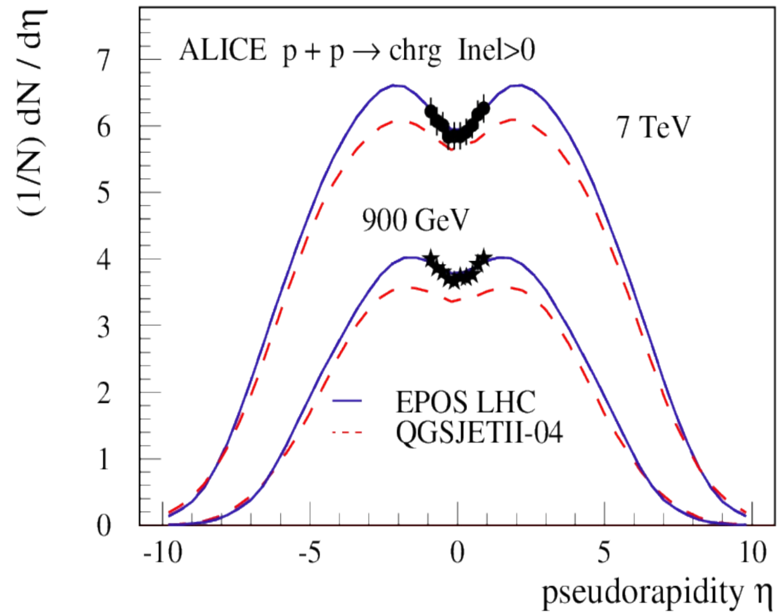
small effect on Xmax (<10 g/cm²)

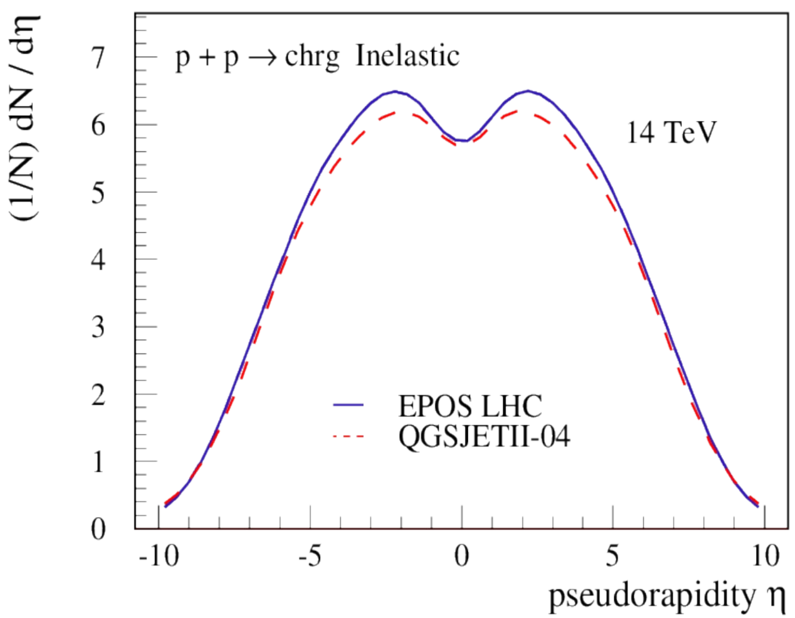
To be confirmed by real MPD simulations...

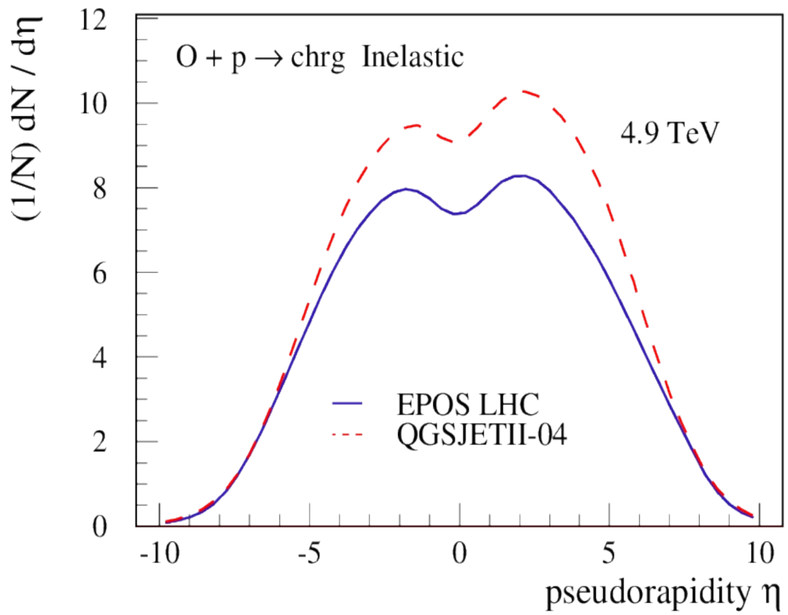
Extrapolation and LHC Results

- **Source of uncertainties : extrapolation**
  - to higher energies
    - strong constraints by current LHC data
  - from p-p to p-Air and pi-Air
    - current main source of uncertainty

- **Needs to better take into account last LHC and NA61 results :**
  - hard scale saturation
  - collective effects in small system
  - detailed diffractive measurements
  - heavy flavors
    - EPOS 3





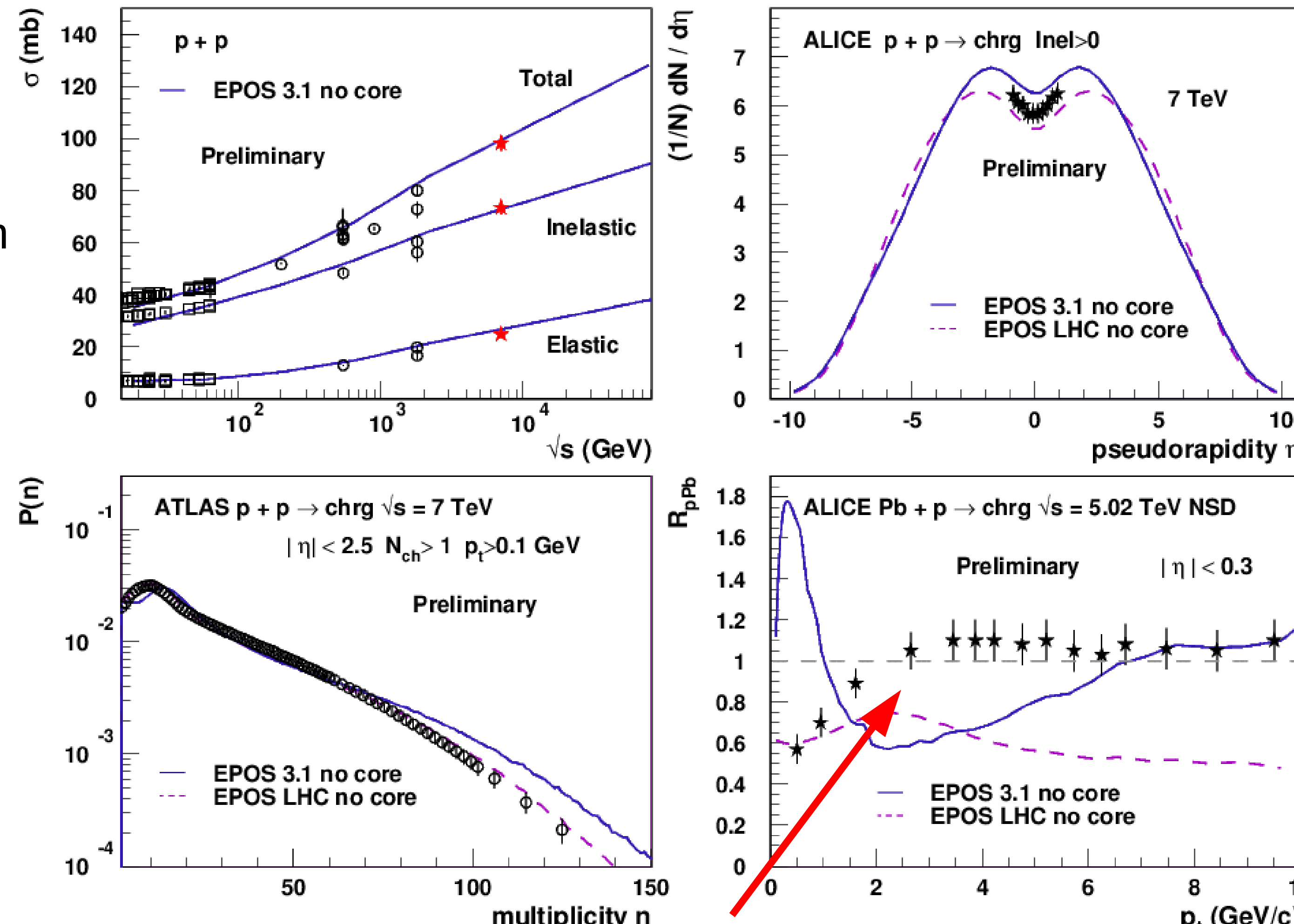


Preliminary Results : Factorization in pA

- **Goal: same excellent results for soft physics**
  - ➜ cross-section, multiplicity, etc ...

- **Problem solved for hard processes**
  - ➜ complete factorization
  - ➜ binary scaling by construction (strong assumption)

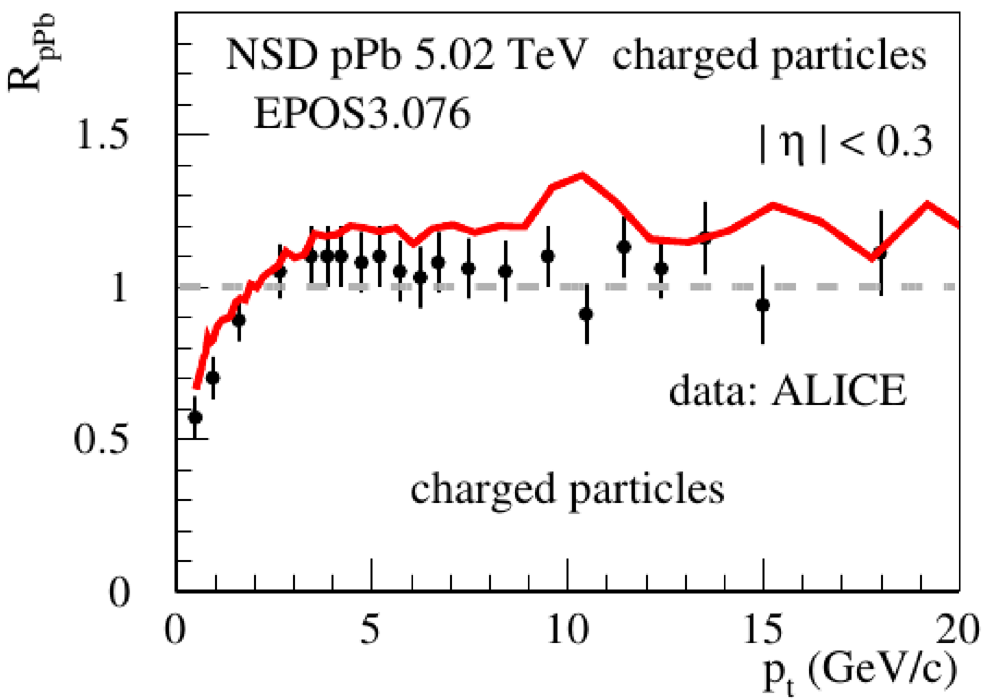
Saturation scale is adapted to get the needed amplitude only low p_t are suppressed: Factorization for hard processes

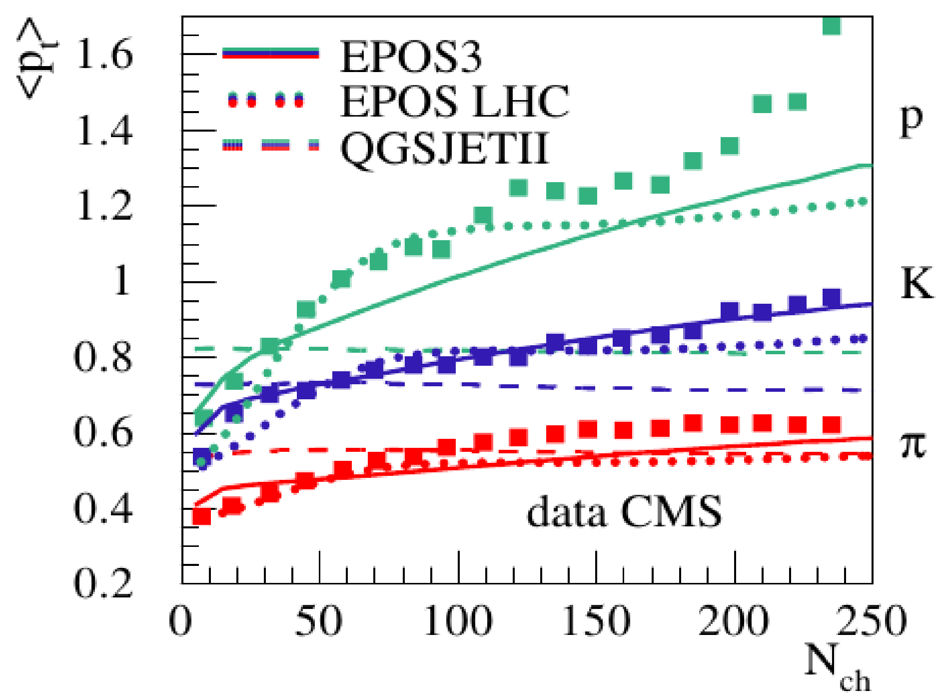


no core = missing flow

EPOS 3 with Full Hydro

- **With Pomeron dependent saturation scale and full 3D hydro**
  - restored binary scaling for high p_t
  - intermediate p_t due to flow
    - mass splitting



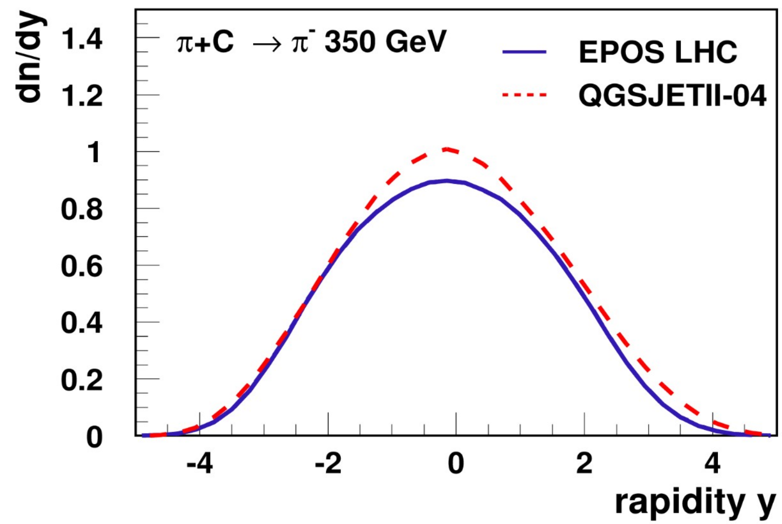


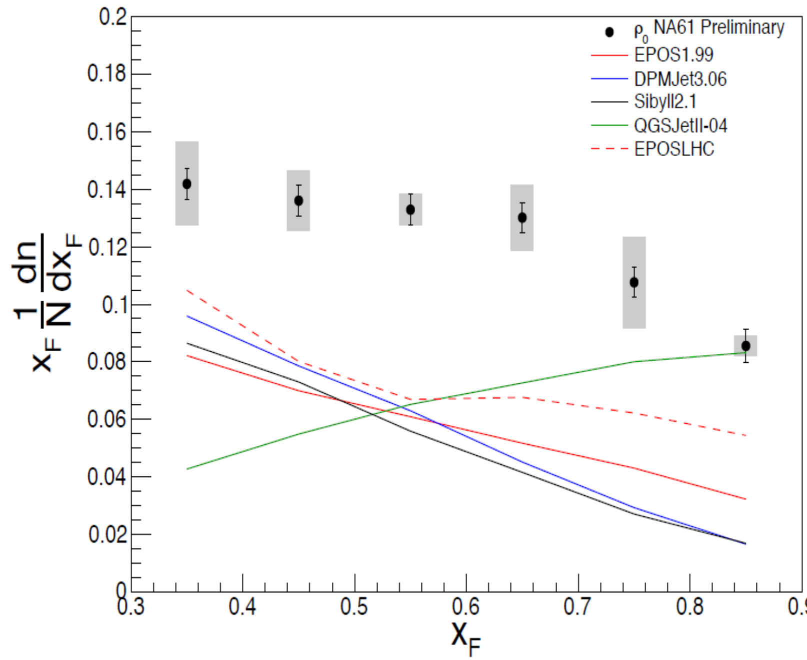
- **For EAS simulations, possibility to use effective flow as in EPOS LHC. Full hydro too slow and not necessary for CR.**

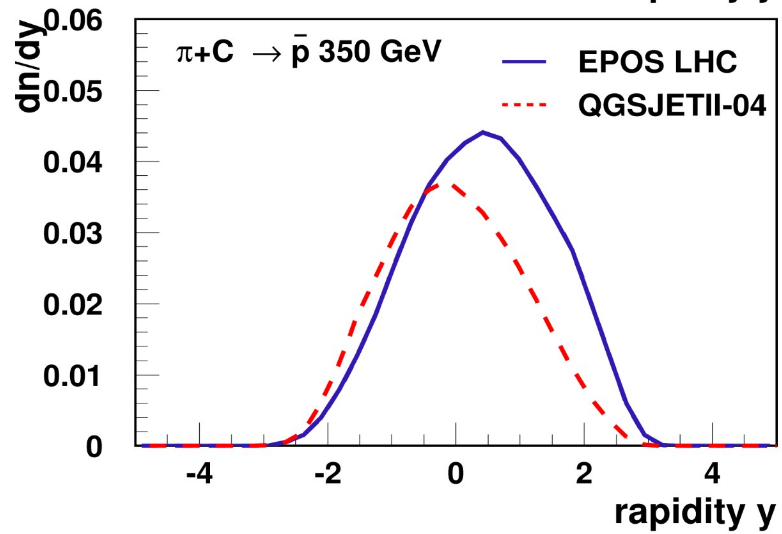
Data for π+C

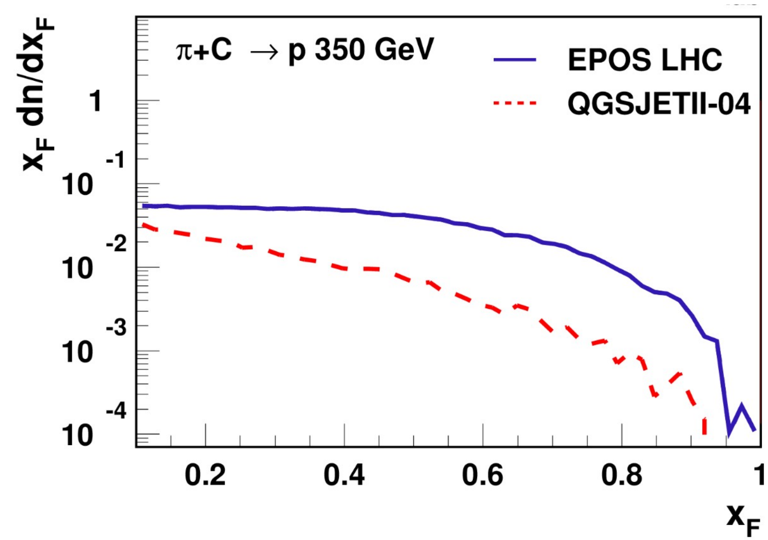
NA61 data are the key to understand muon production

- important for muon production in EAS
- very different behavior for π interactions
- large difference for forward baryon production
- new results on ρ^0 not predicted by models









Summary

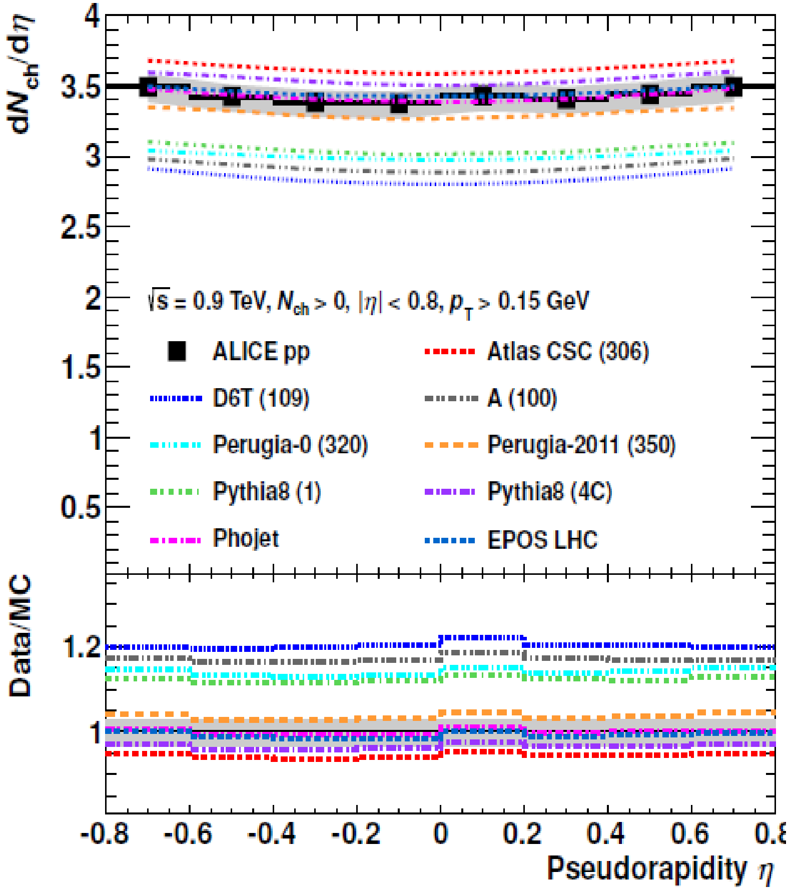
- **EPOS LHC**
  - EPOS is based on pertubative QCD and Gribov-Regge theory with a unique treatment of energy conservation in cross-section calculation, free remnants and collective hadronization in case of high density core formation
  - early LHC tune of EPOS 1.99, only minor changes
  - very nice description of most of particle distributions at mid-rapidity and p_t<5GeV/c
  - problem at high p_t (in particular for pA) and new data on diffraction not well reproduced
  - best description of PAO data with the exception of MPD which are very sensitive to pion interactions

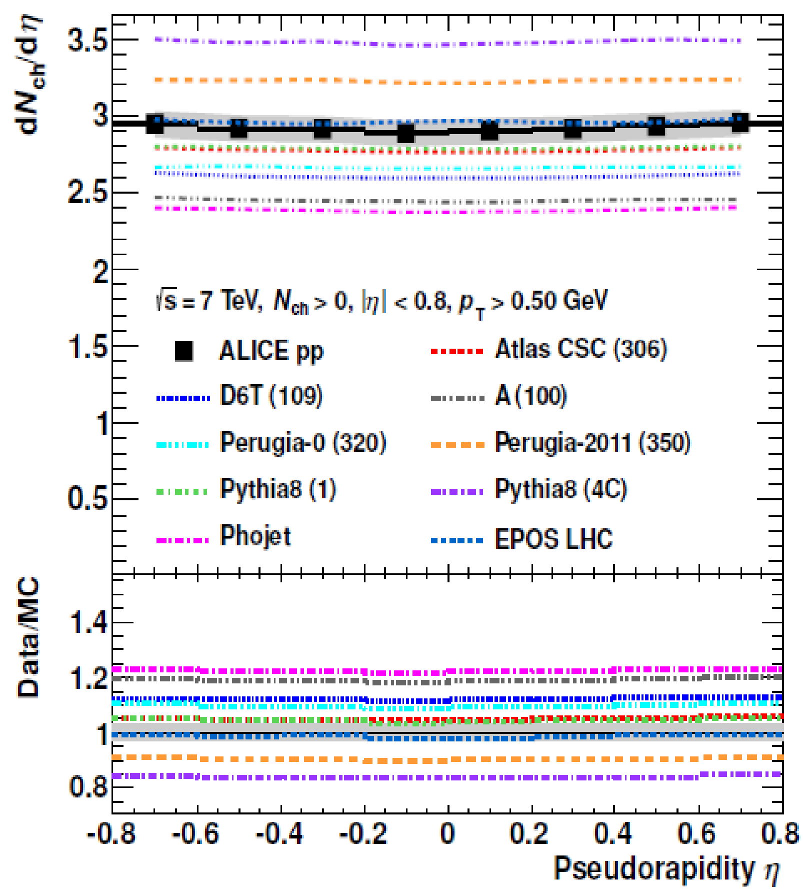
- **EPOS 3 (2016)**
  - introduce saturation scale Q_s^2 COMPUTED Pomeron-by-Pomeron.
  - impose factorization and binary scaling for hard processes above saturation scale
  - good initial conditions for event-by-event 3D full hydro calculation or fast effective hydro
  - production (and interaction) of heavy flavor particles (charm and beauty)
  - more complete treatment of diffraction taking into account latest LHC data
  - description of (available) NA61 data

LHC Data

Excellent results for soft physics

- cross-section, multiplicity, pt distributions, identified spectra,energy flow, etc ...
- energy evolution

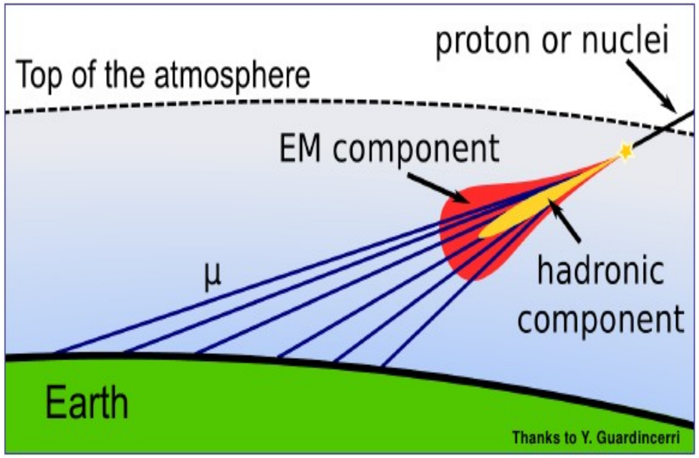




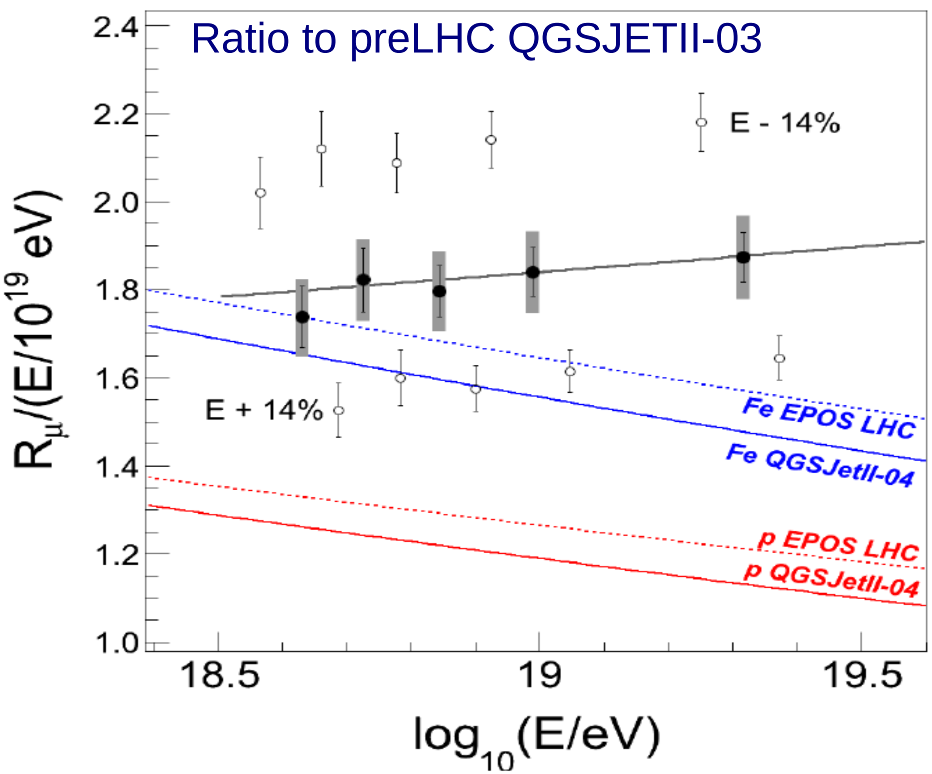
PAO: Direct Muon Measurement

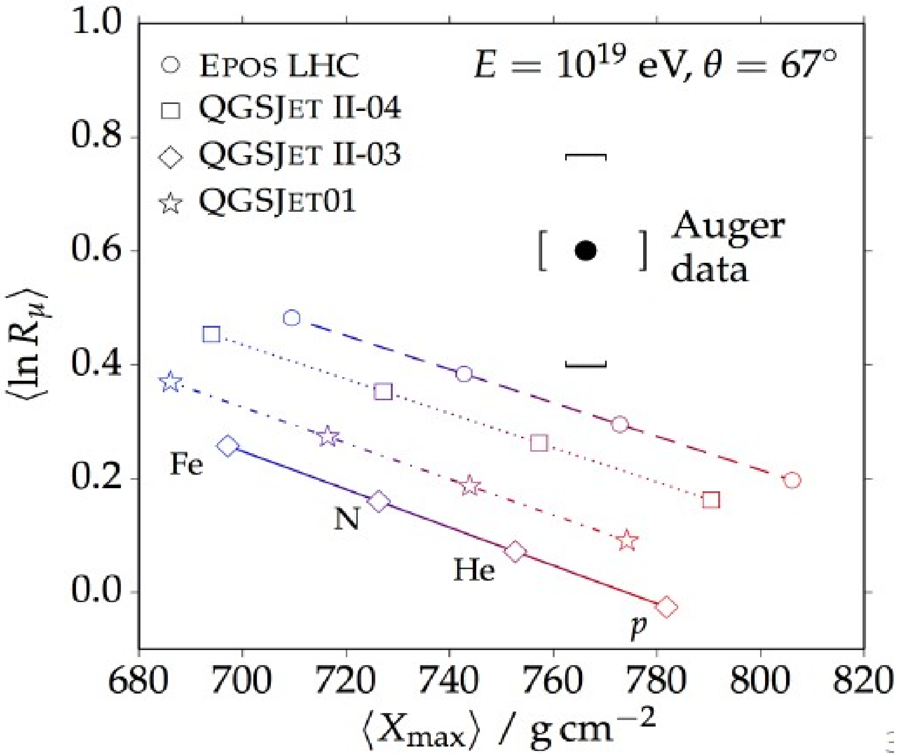
Old showers contain only muon component

- direct muon counting with very inclined showers (>60°) by comparing to simulated muon maps (geometry and geomagnetic field effects)
- EM halo accounted for
- correction between true muon number and reconstructed one from map by MC (<5%)



R_μ/E_{FD} in energy bins

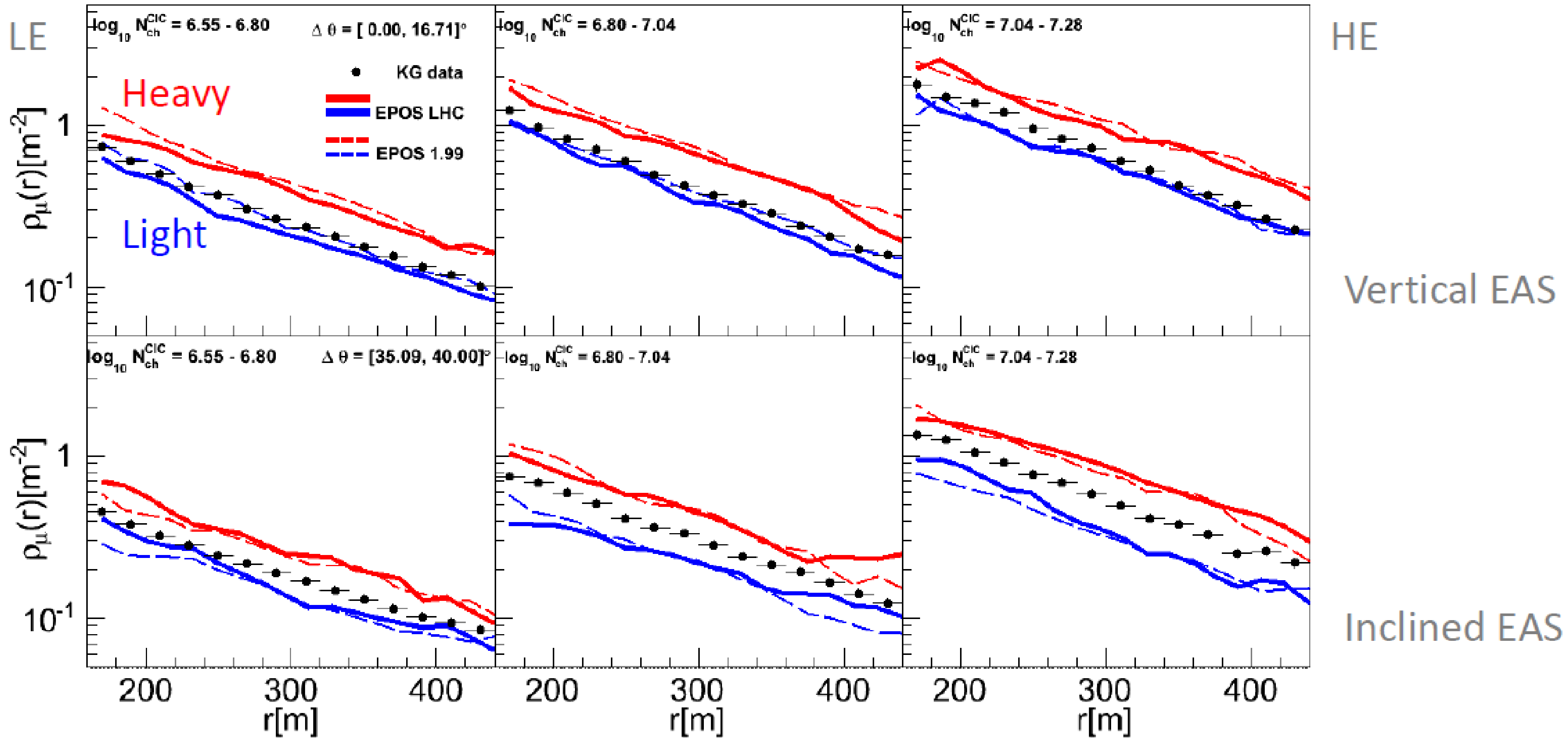




KASCADE-Grande

Muon density indicates a high number of muon

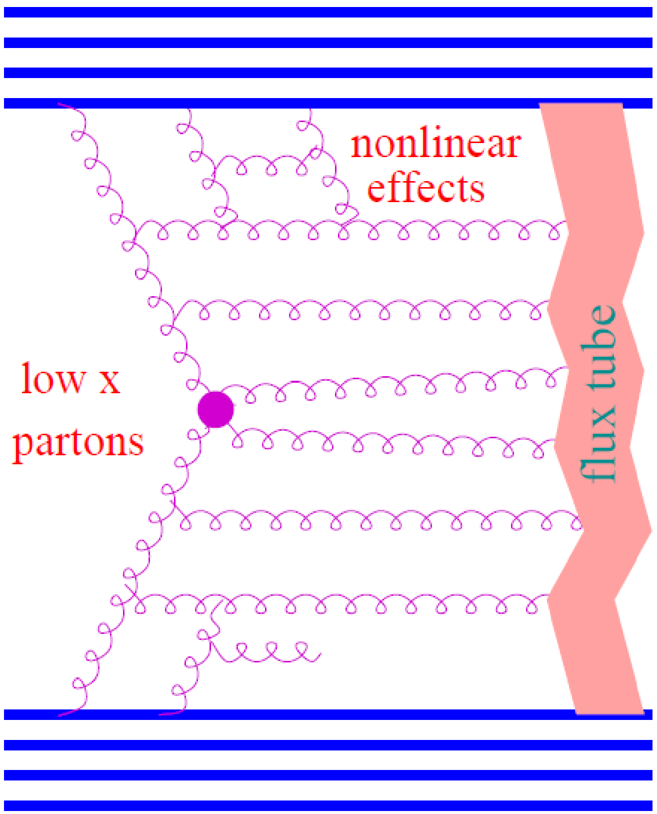
- ➡ EPOS LHC consistent with data
- ➡ attenuation length smaller than in data (like other models)



J.C. Arteaga, ICRC 2015

Elementary scatterings - flux tubes

- same energy sharing between the parallel scatterings is taken into account for cross section and particle production
  - multiplicity evolution fixed by cross-section
- many elementary collisions happening in parallel
- elementary scattering = “parton ladder” + soft component

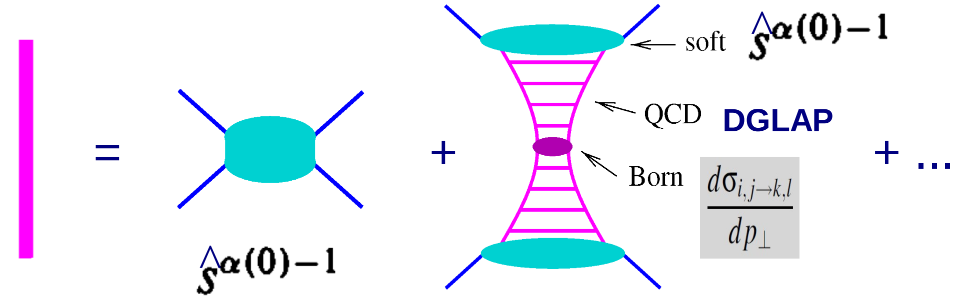


- Parton evolutions from the projectile and the target side towards the center (small x)
- Evolution equation
  - DGLAP
- Parton ladder = quasilongitudinal color field (“flux tube”)
  - relativistic string
- Intermediate gluons
  - kink singularities in relativistic strings
- Fragmentation : production of quark-antiquark pairs
  - fragments – identified with hadrons

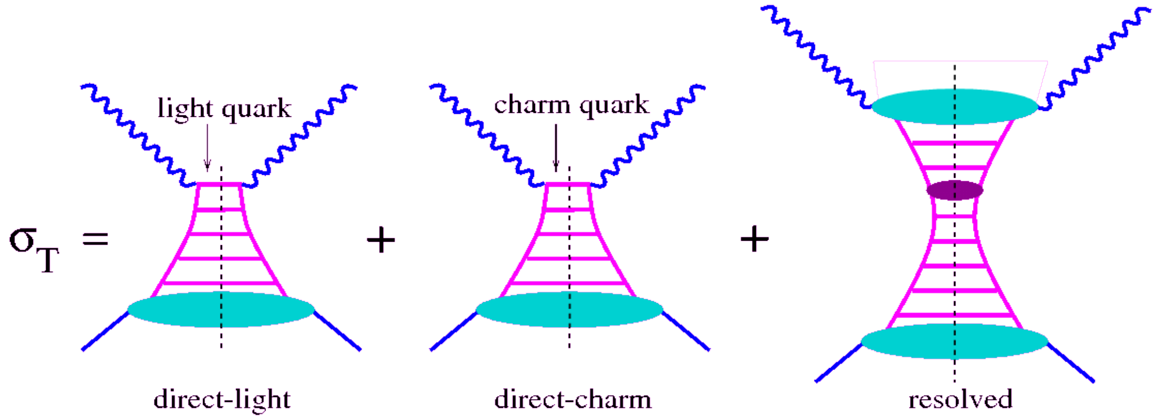
Parton-based Gribov-Regge Theory, H. J. Drescher, M. Hladik, S. Ostapchenko, T.Pierog, and K. Werner, Phys. Rept. 350 (2001) 93-289;

EPOS : Pomeron definition

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

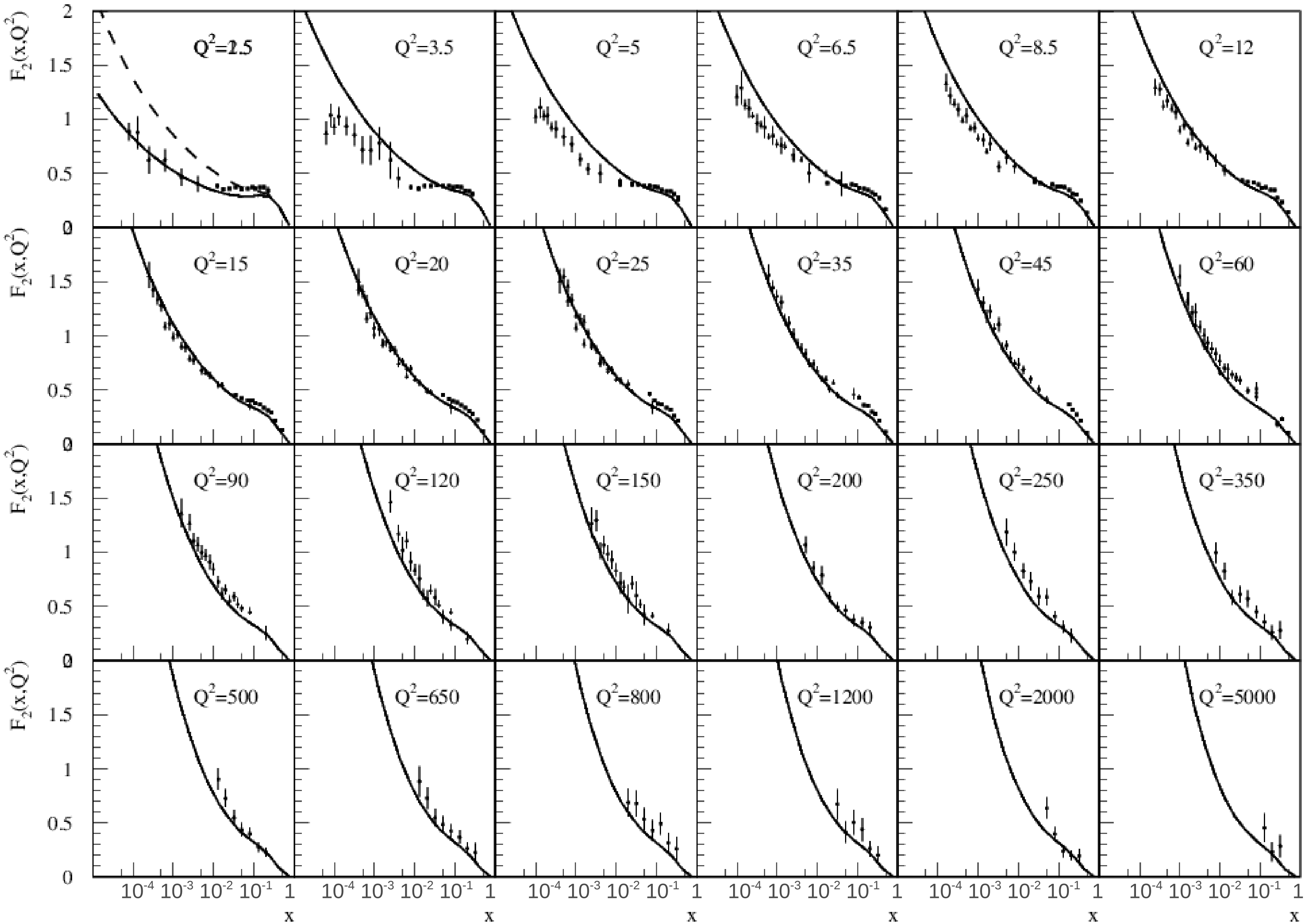


Test of semi-hard Pomeron with DIS: (Parton Distribution Function from HERA)

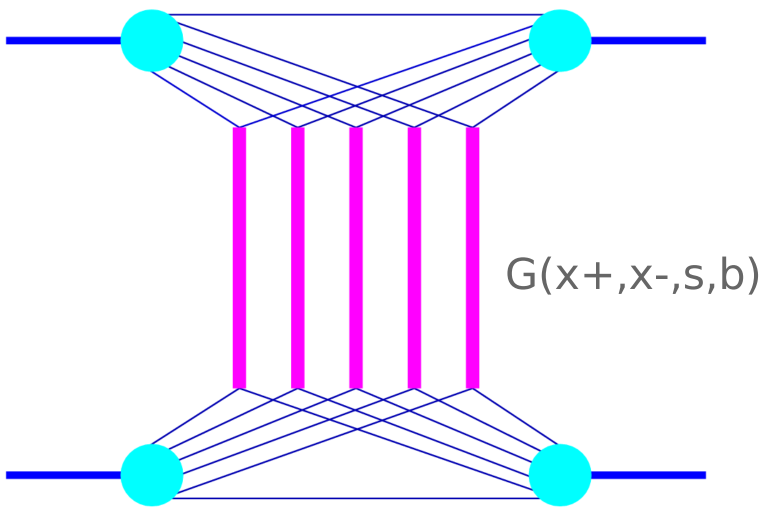


- Theory based Pomeron definion
  - pQCD based (DGLAP and Born)
    - large increase at small x (without saturation)
  - External pdf only for valence quark
  - F2 from HERA used to fix parameters for sea quarks and gluons

EPOS Parton Distribution Function



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

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

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

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

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 :

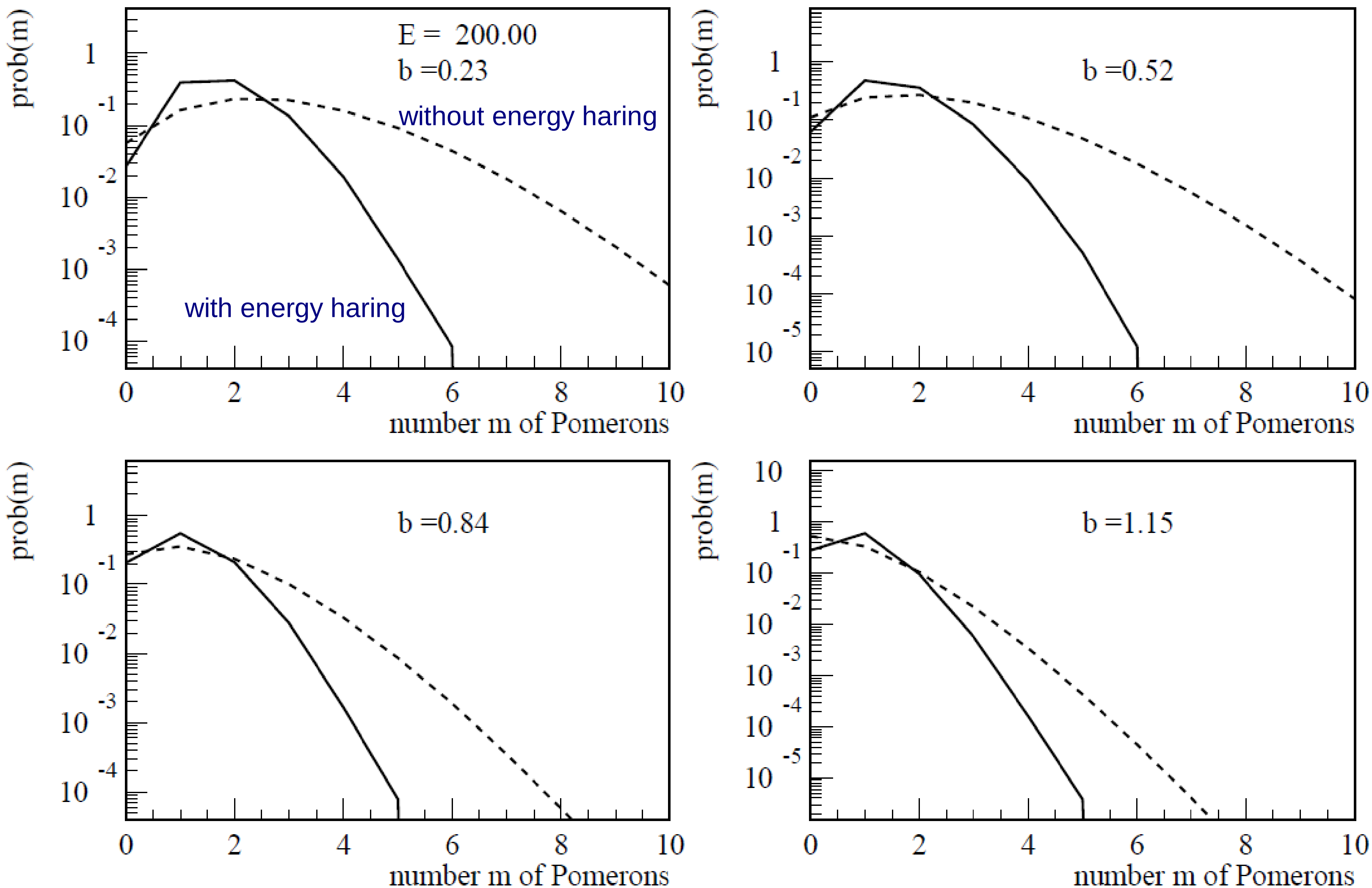
$$\Omega^{(s,b)}_{AB}(m, X^+, X^-) = \prod_{k=1}^{AB} \left\{ \frac{1}{m_k!} \prod_{\mu=1}^{m_k} G(x^+_{k,\mu}, x^-_{k,\mu}, s, b_k) \right\} \Phi_{AB}\left(x^{\text{proj}}, x^{\text{targ}}, s, b\right)$$

  - m and X fixed together by a complex Metropolis (Markov chain)
- 2m 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

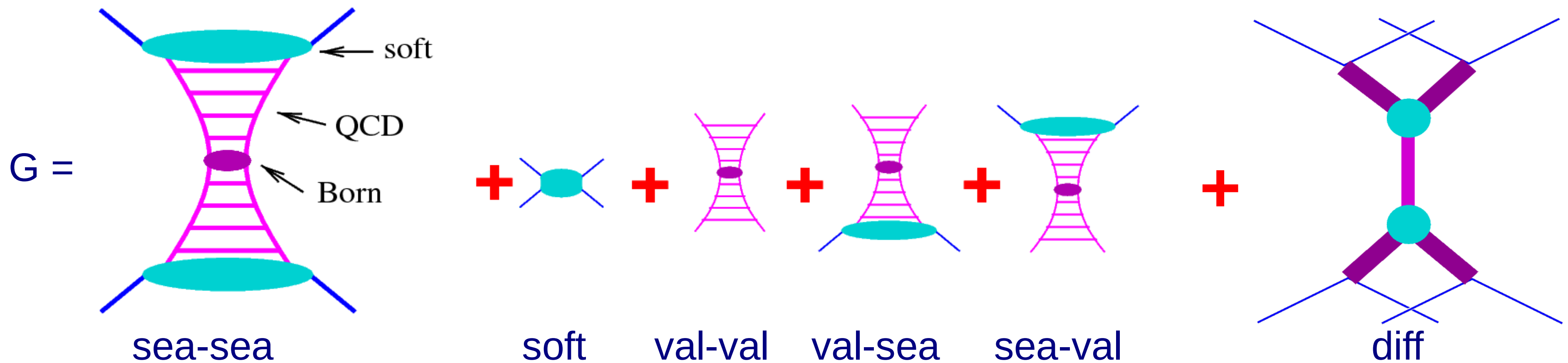
Number of cut Pomerons

Fluctuations reduced by energy sharing (mean can be changed by parameters)

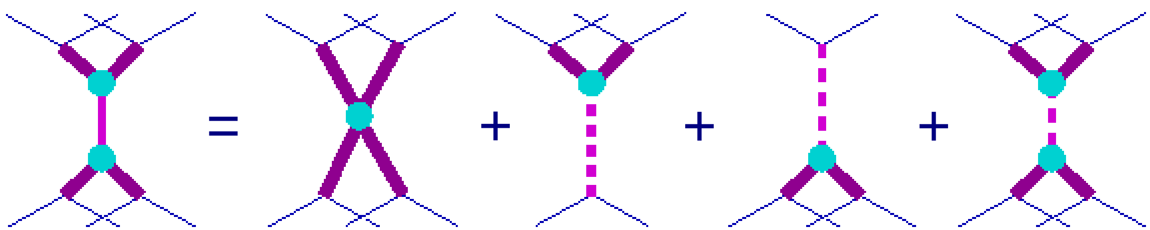


Diffraction in PBGRT

- **Using the same formalism**
  - ➡ Diffraction from an additional diagram

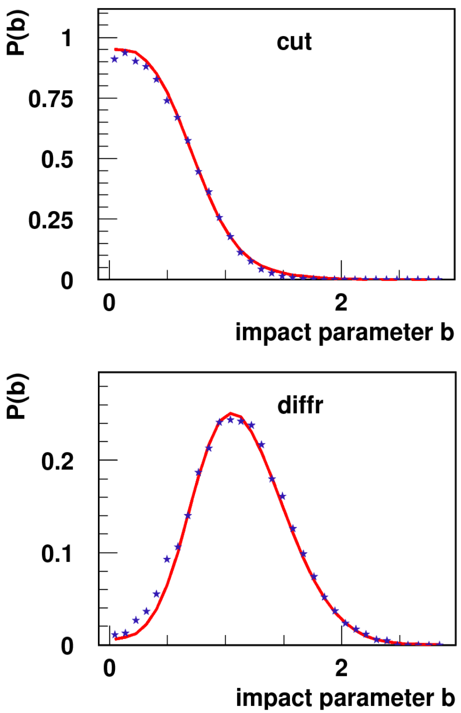


  - ➡ Same form as soft (Regge pole) but with different amplitude and width
  - ➡ Low mass and high mass diffraction from the same diagram



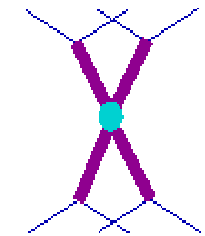
  - ➡ Parameters extracted from single diffractive (SD) cross-section
  - ➡ Events with only "diff" type diagrams are diffractive

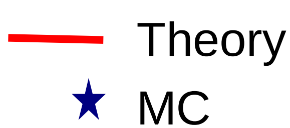
Low Mass Diffraction

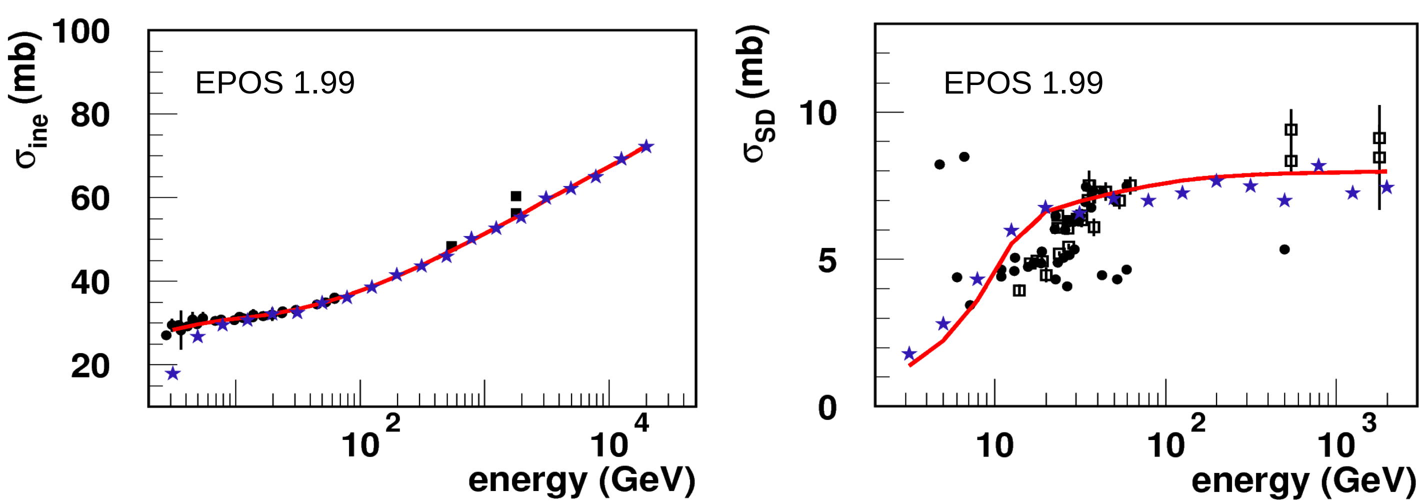


Diffractive event = event with only cut diff. diagrams

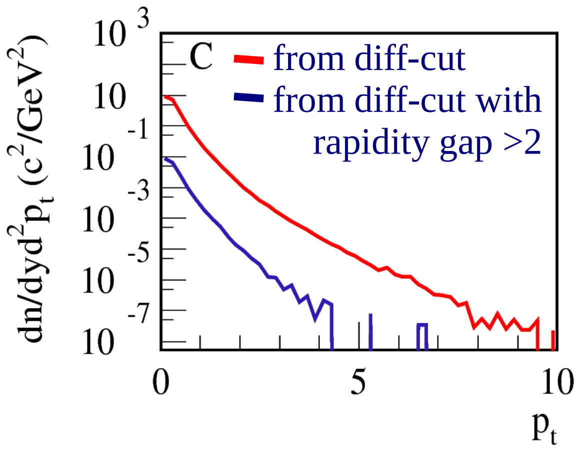
- Multiple cut-diff diagrams possible
- Remnant mass given by momentum fraction transfer
- No particle production directly from diagram
- Reggeon (single string or resonance) possible
- cut-diff diagrams used for remnant mass in non-diffractive events too (cut Pomeron)



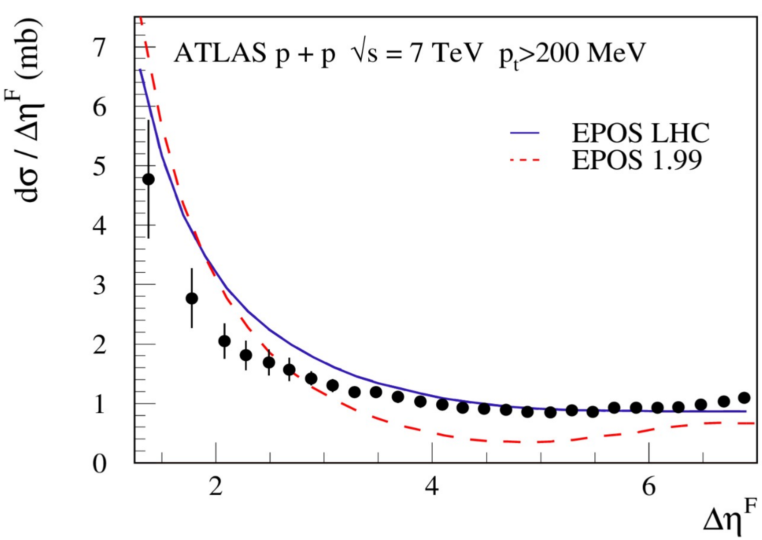




High Mass and Central Diffraction



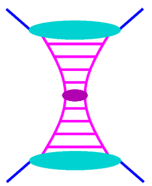
Projectile not excited :
1 rapidity gap



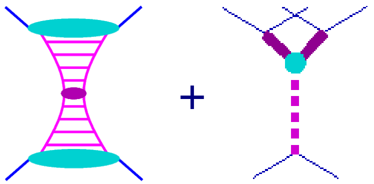
Same scheme but with particle production

- Do not change cross-section
- If only non-diffractive Pomeron are present, no mass given to remnant.
- 0, 1 or 2 rapidity gap depending on diagram exchange

Projectile and target not excited :
2 rapidity gaps

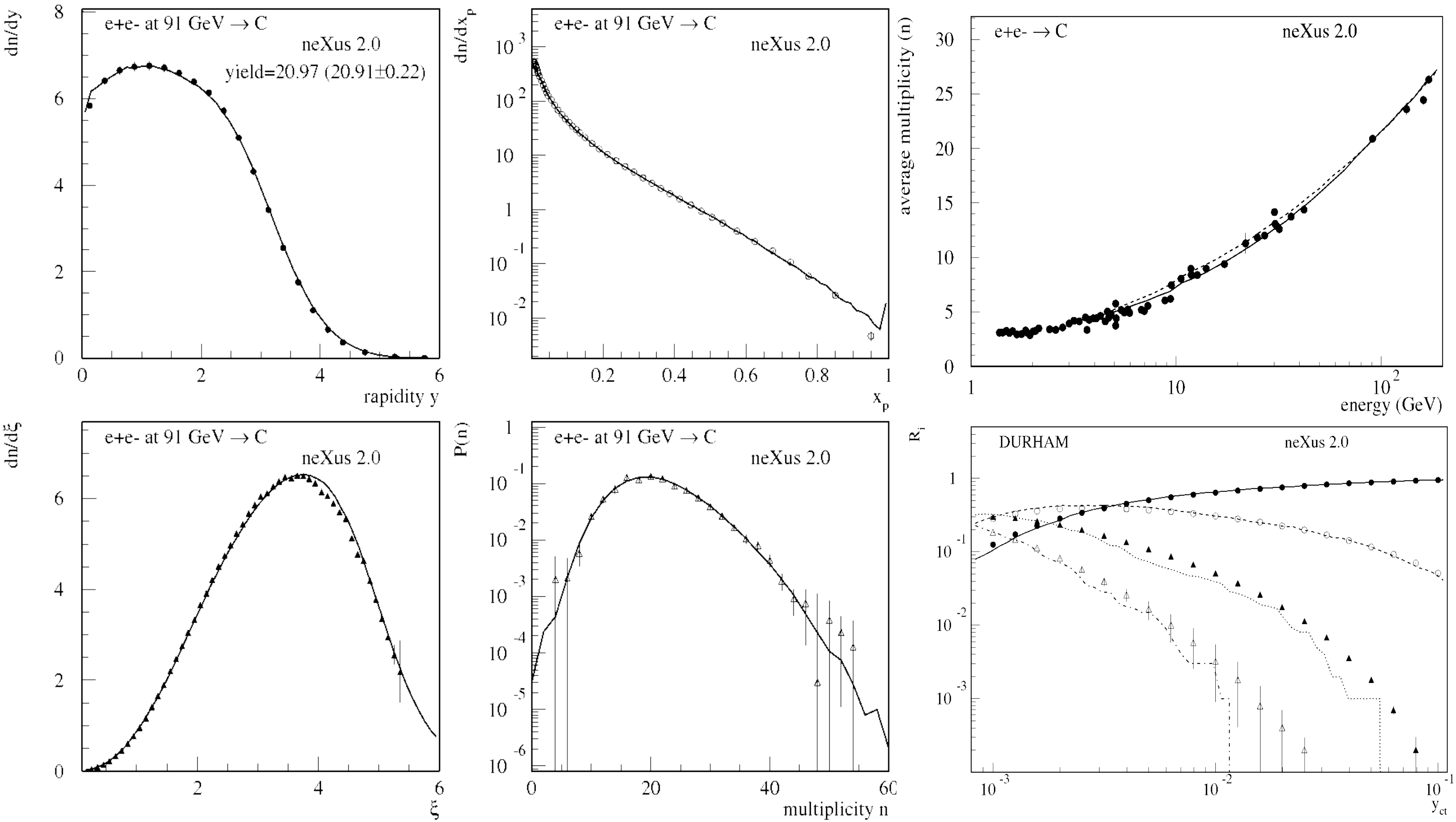


Only projectile not excited :
1 rapidity gaps



- Additional multiplicity contribution in ND events
- Work in progress

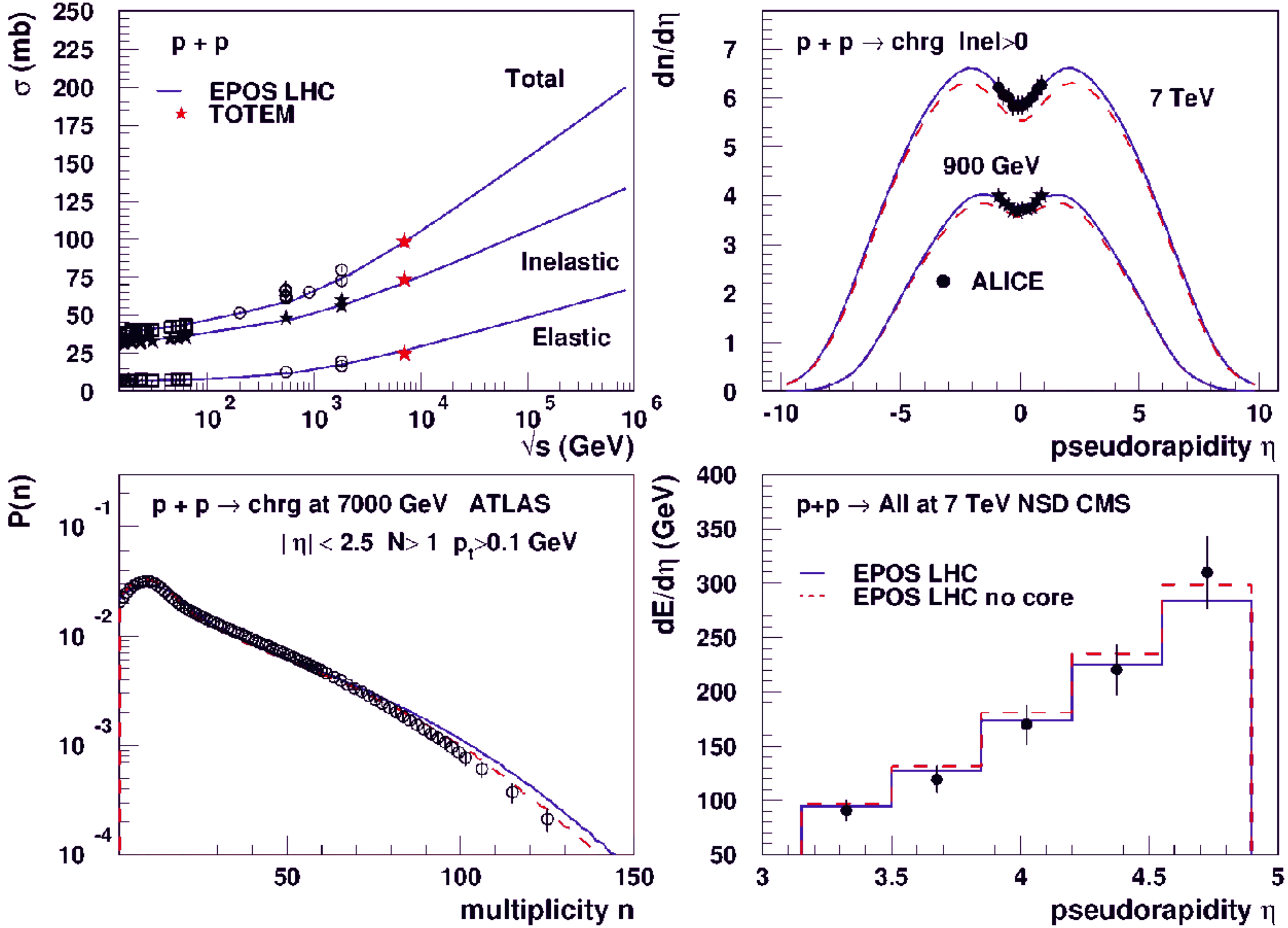
Test of string fragmentation with LEP data



Area law

Core Effect on Total Multiplicity

- Core hadronization doesn't change general event description.

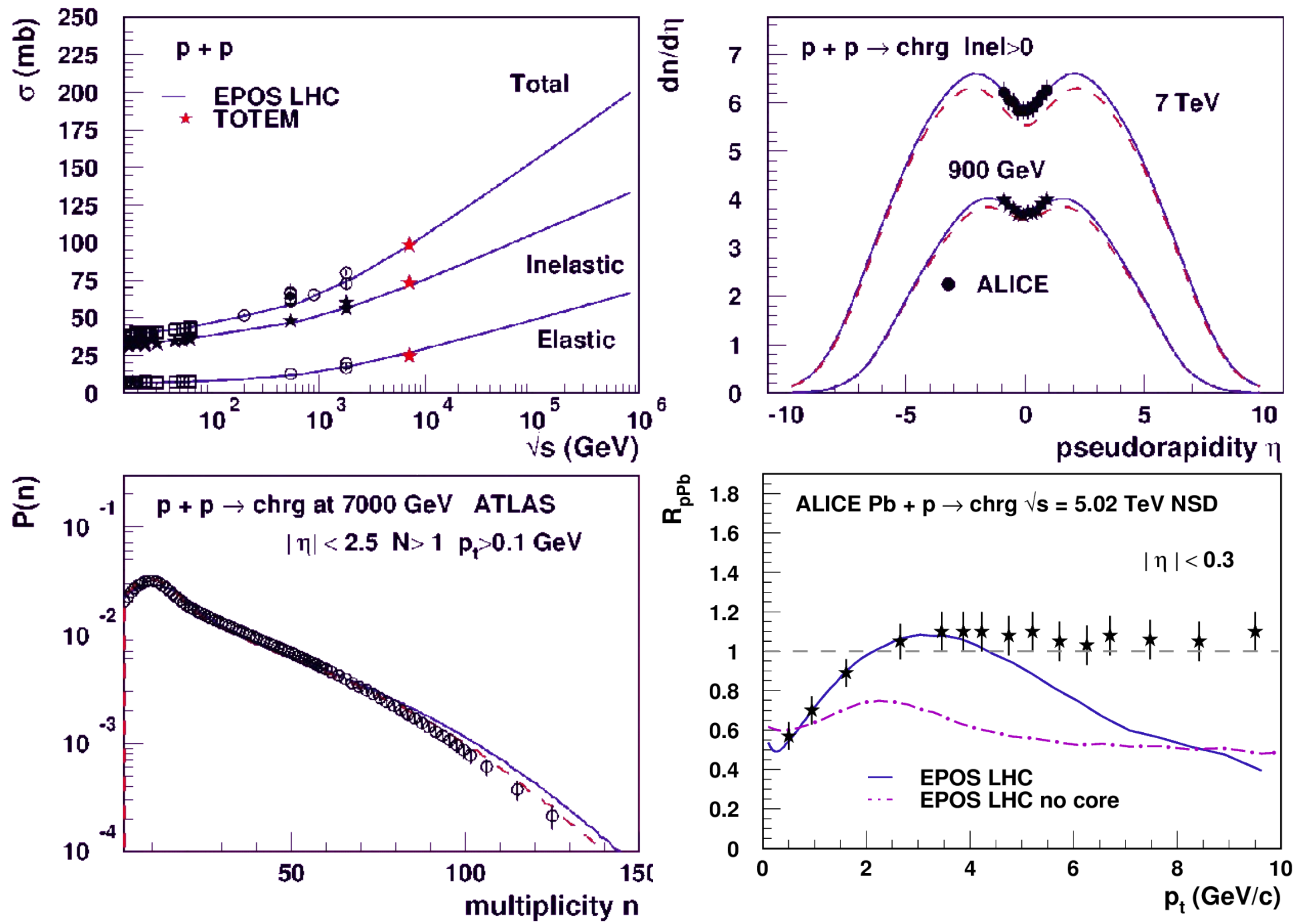


Fixed Q_0^2 (old)

- **Excellent results for soft physics**
  - ➡ cross-section, multiplicity, etc ...

- **Problem for hard processes**
  - ➡ lack of high pt
  - ➡ no binary scaling for pA or AB

Since Q_0^2 is fixed both low and high pt are suppressed: in contradiction with data.



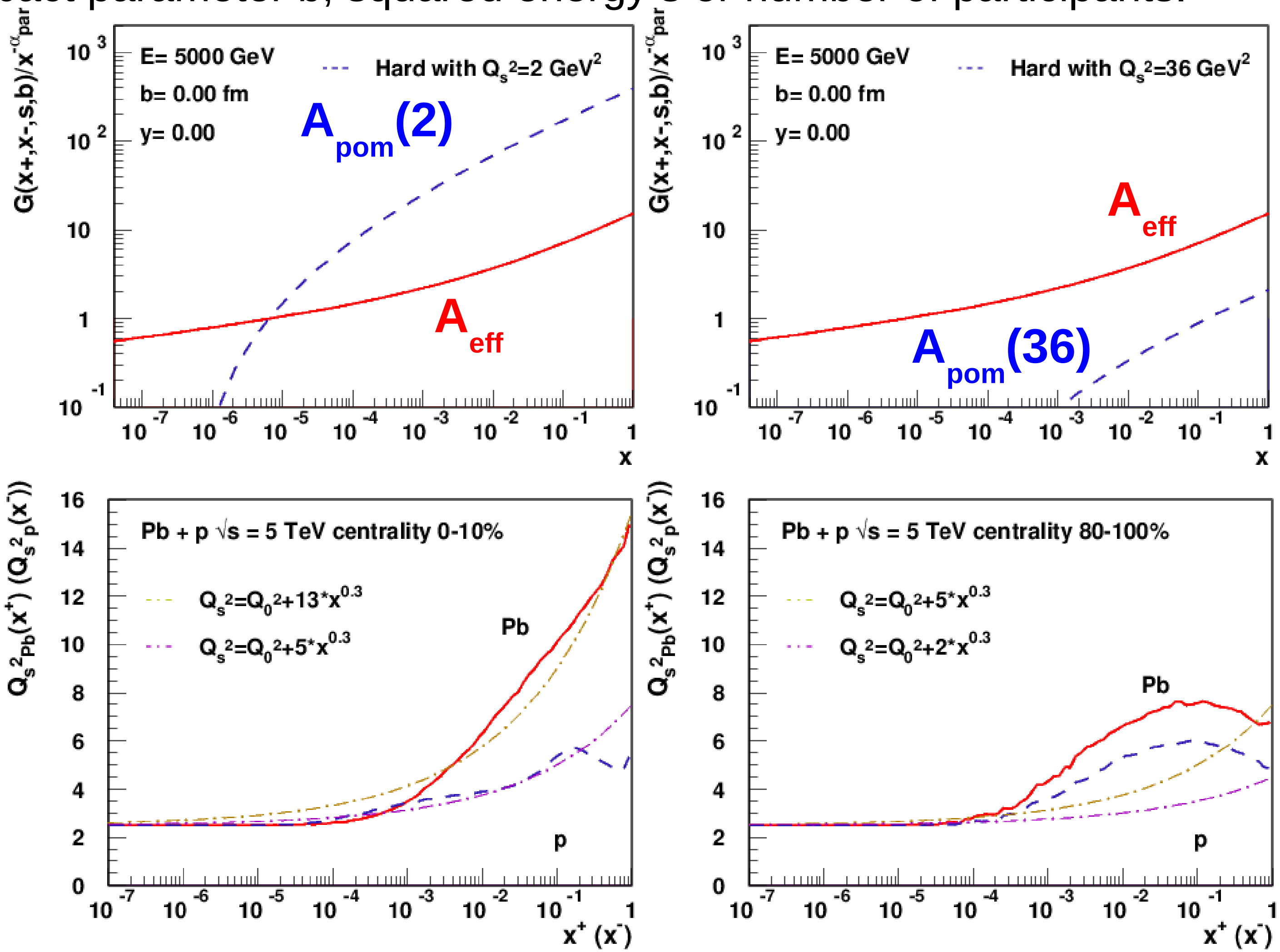
Variable $Q_s^2(s,x,b,A)$ (new)

- **Inspired by CGC**
  - different saturation scale event-by-event and even Pomeron-by-Pomeron depending on momentum fraction x, impact parameter b, squared energy s or number of participants.

- **EPOS 3.1xx**
  - A_{eff} tuned to reproduce cross-sections and used in MC to produce Pomeron distributions
  - Define Q_s^2 such that

$$N_{bin} A_{pom}(Q_s^2) = N_{col} A_{eff}(s,x,b,A)$$

to produce ISR and born process in Pomeron hadronization.



Predicted $Q_s^2(s,x,b,A)$

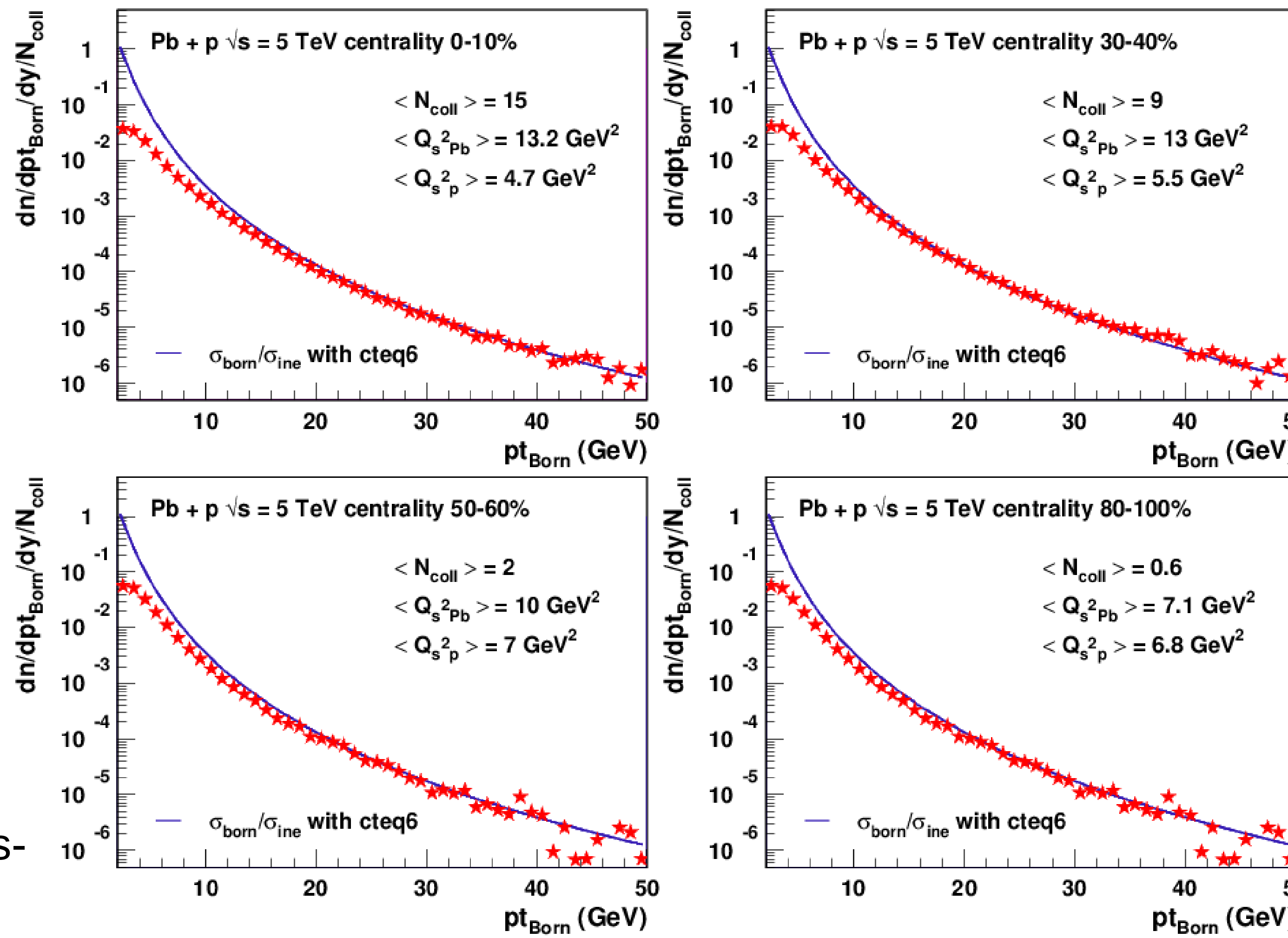
- **Inspired by CGC**
  - different saturation scale event-by-event and even Pomeron-by-Pomeron depending on momentum fraction x, impact parameter b, squared energy s or number of participants.

- **EPOS 3.1xx**
  - A_{eff} tuned to reproduce cross-sections and used in MC to produce Pomeron distributions
  - Define Q_s^2 such that

$$N_{bin} A_{pom}(Q_s^2) = N_{col} A_{eff}(s,x,b,A)$$

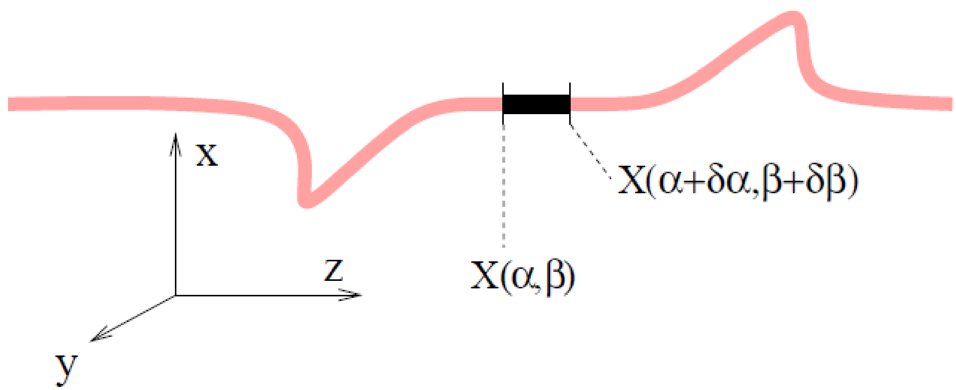
to produce ISR and born process in Pomeron hadronization.

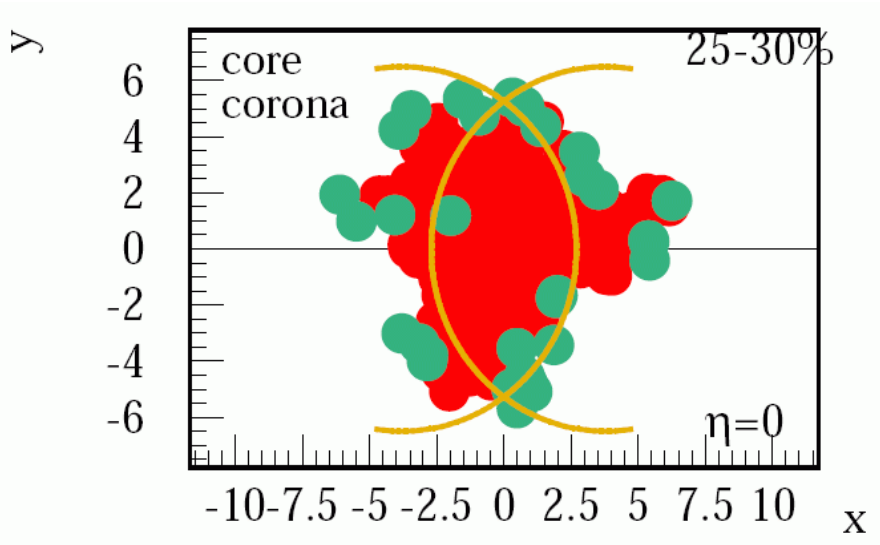
  - Scaling of inclusive cross-section by construction



High Density Core Formation

- **Heavy ion collisions or very 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 splitted 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 : hydrodynamical evol.
- If low density (corona)
  - segments remain hadrons

Hydro (Yuri Karpenko)

- **After core formation, use it as initial conditions for hydro evolution using Lattice QCD EoS**
- **Israel-Stewart formulation, η − τ coordinates, η/S = 0.08, ζ/S = 0**

$$\partial_{;\nu} T^{\mu\nu} = \partial_\nu T^{\mu\nu} + \Gamma^\mu_{\nu\lambda} T^{\nu\lambda} + \Gamma^\nu_{\nu\lambda} T^{\mu\lambda} = 0$$

$$\gamma\left(\partial_t + v_i \partial_i\right)\pi^{\mu\nu} = -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\text{NS}}}{\tau_\pi} + I^{\mu\nu}_\pi \qquad \gamma\left(\partial_t + v_i \partial_i\right)\Pi = -\frac{\Pi - \Pi_{\text{NS}}}{\tau_\Pi} + I_\Pi$$

- $T^{\mu\nu} = \epsilon u^\mu u^\nu - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$,
- $\partial_{;\nu}$ denotes a covariant derivative,
- $\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$ is the projector orthogonal to u^μ,
- $\pi^{\mu\nu}$, Π shear stress tensor, bulk pressure
- $\pi^{\mu\nu}_{\text{NS}} = \eta(\Delta^{\mu\lambda}\partial_{;\lambda}u^\nu + \Delta\nu\lambda\partial_{;\lambda}u^\mu) - \frac{2}{3}\eta\Delta^{\mu\nu}\partial_{;\lambda}u^\lambda$
- $\Pi_{\text{NS}} = -\zeta\partial_{;\lambda}u^\lambda$
- $I^{\mu\nu}_\pi = -\frac{4}{3}\pi^{\mu\nu}\partial_{;\gamma}u^\gamma - [u^\nu\pi^{\mu\beta} + u^\mu\pi^{\nu\beta}]u^\lambda\partial_{;\lambda}u_\beta$
- $I_\Pi = -\frac{4}{3}\Pi\partial_{;\gamma}u^\gamma$

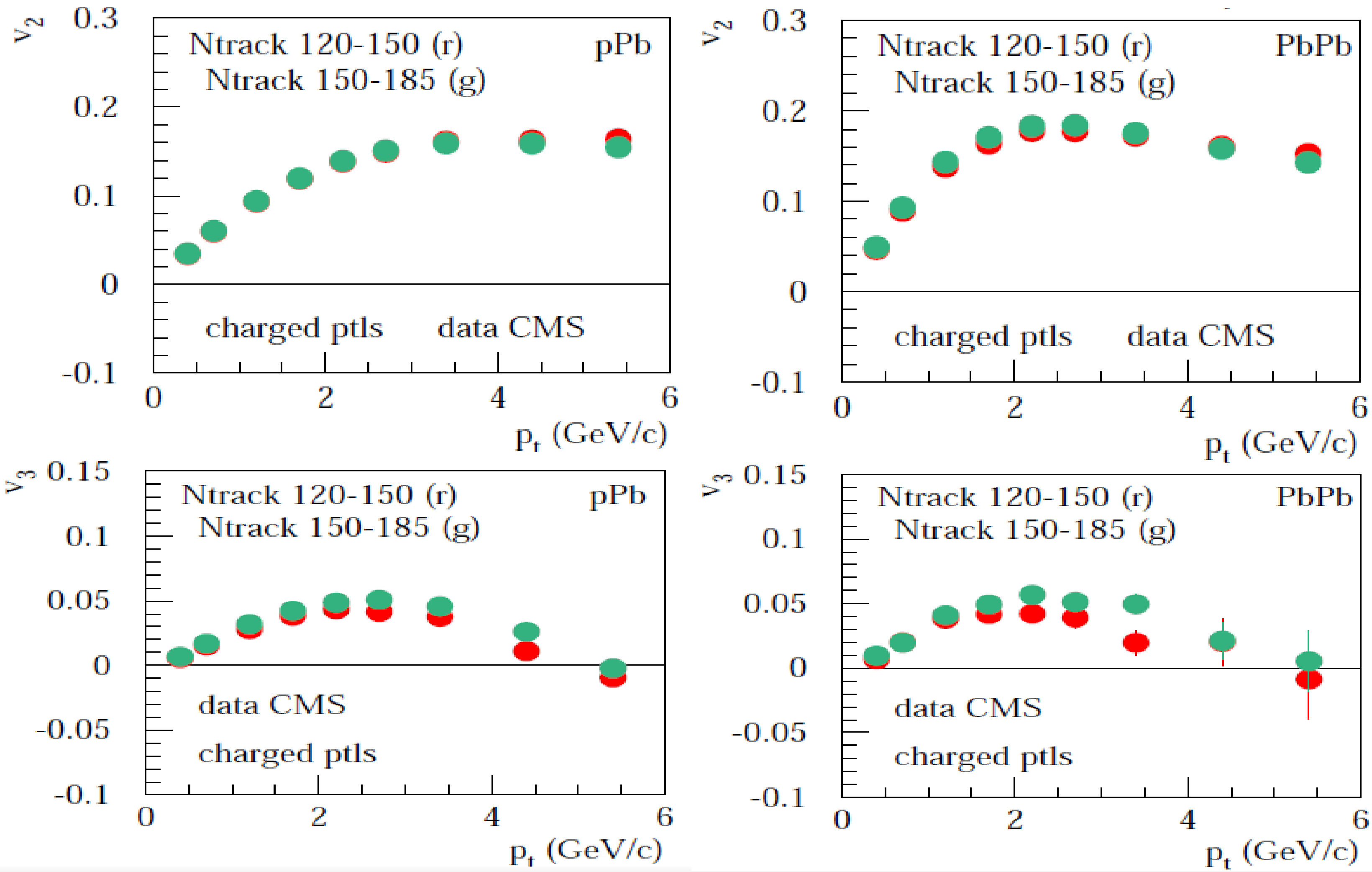
- **Freeze out at 164 MeV: Cooper-Frye, equilibrium distr**
- **Hadronic afterburner:**
  - ➜ UrQMD (Marcus Bleicher, Jan Steinheimer) : implementing new update (Ω)

Flow : pPb vs PbPb in Data

- **Very similar behavior observed in data in both systems**
  - ➡ very little change of v2 with multiplicity ; high v2 at high pt ; different shapes
  - ➡ small increase of v3 with multiplicity ; low v3 at high pt ; same shape

v2

v3

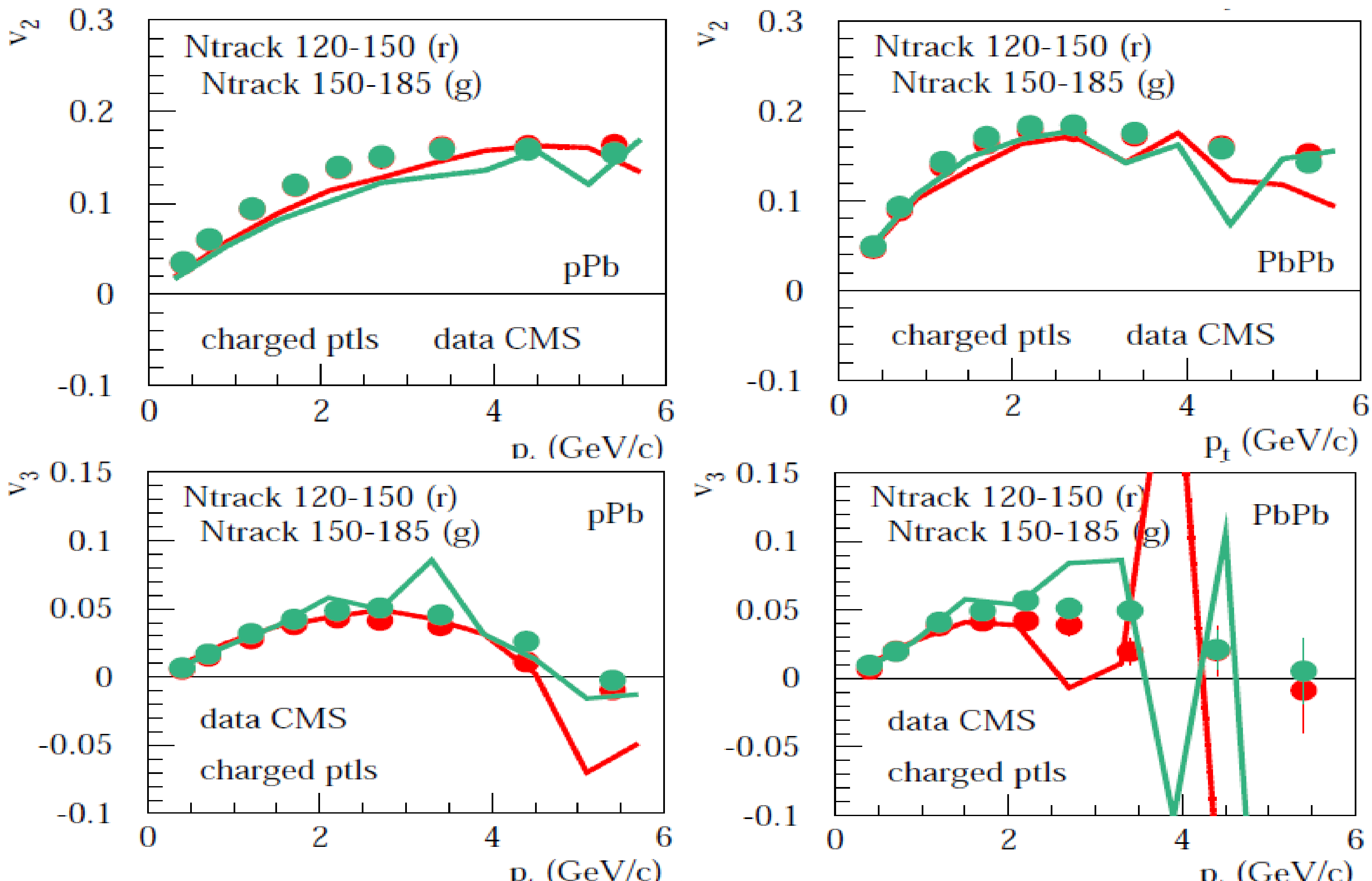


Flow : pPb vs PbPb in Simulations

- **Very similar behavior than in data in both systems**
  - ➡ very little change of v2 with multiplicity ; high v2 at high pt ; different shapes
  - ➡ small increase of v3 with multiplicity ; low v3 at high pt ; same shape

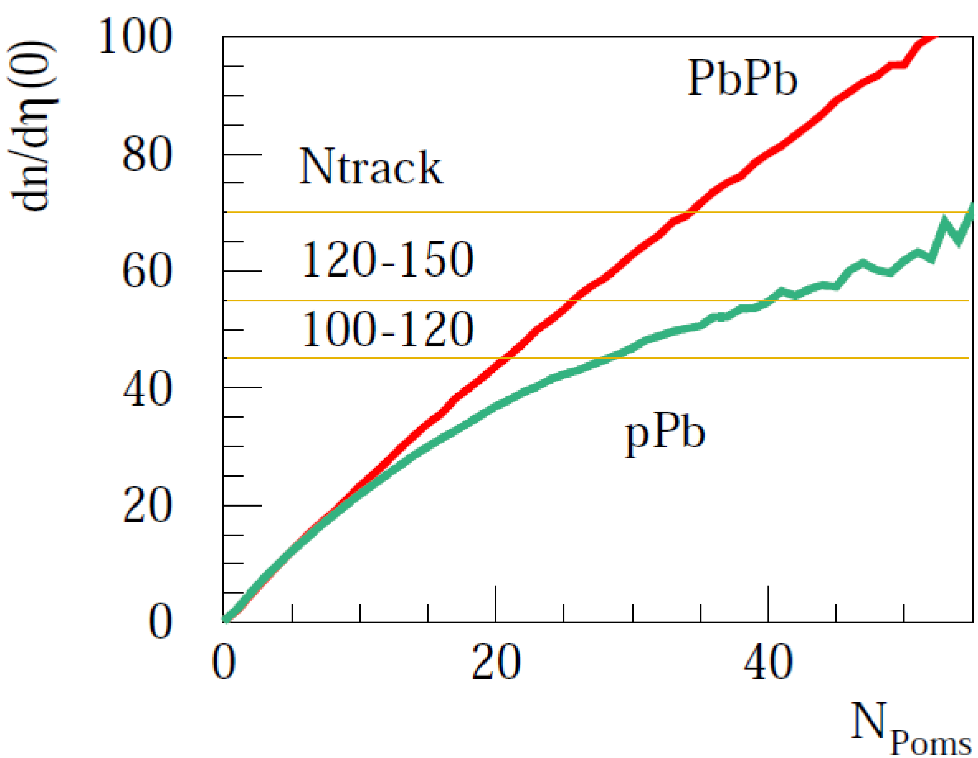
v2

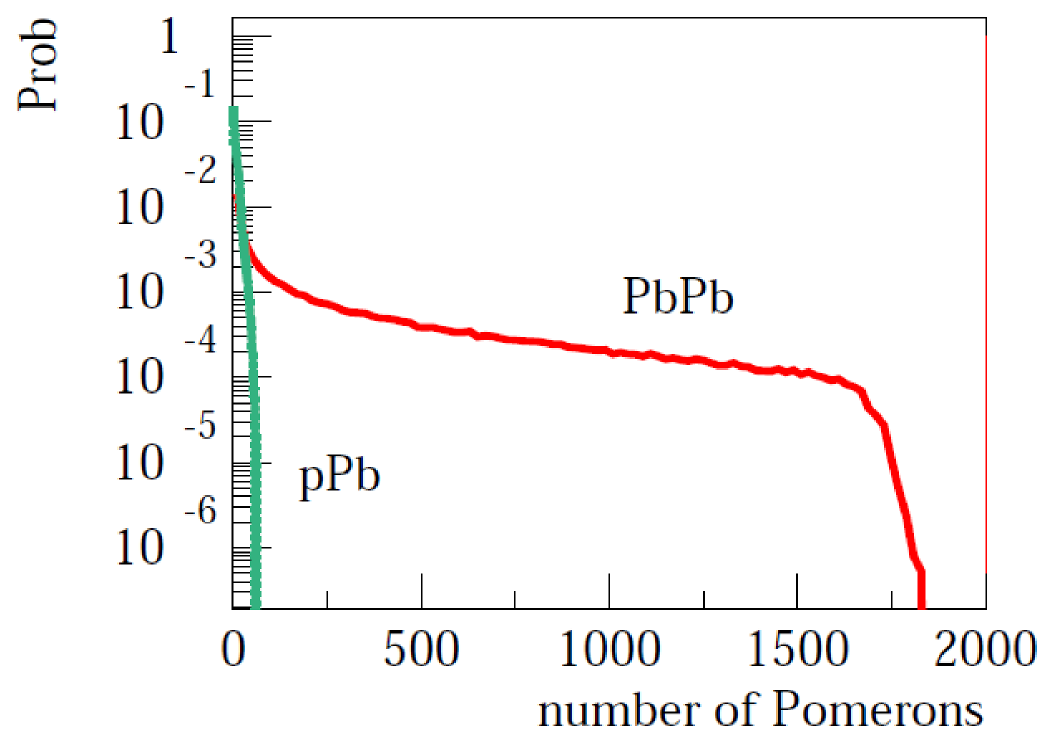
v3



Origin of the Particles

- **Multiplicity strongly correlated to the number of Pomeron**
  - common pPb/PbPb multiplicity (Ntrack>100) corresponds to very different geometry
    - high density rare events in pPb (lot of MPI)
    - peripheral collisions with larger number of binary collisions





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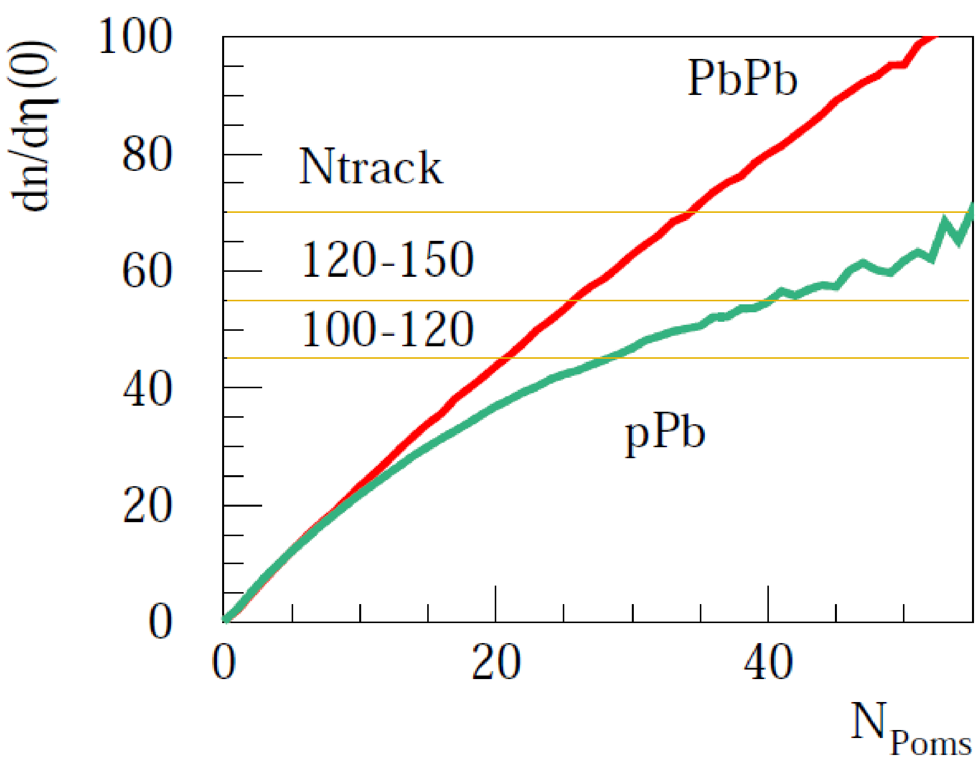
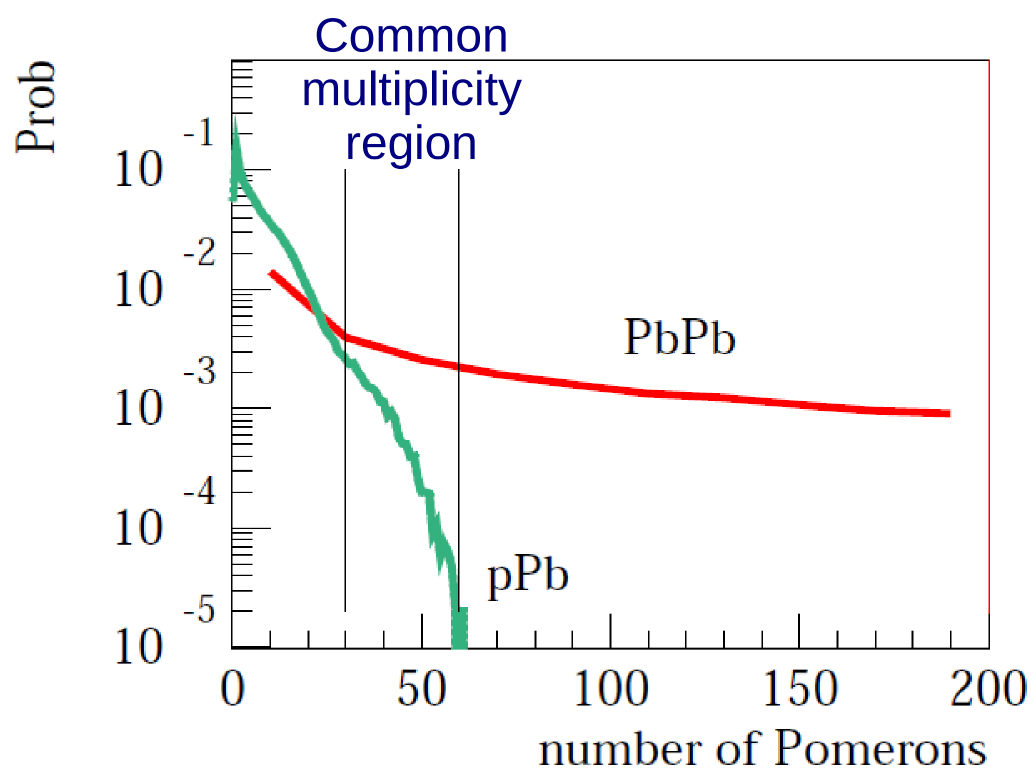
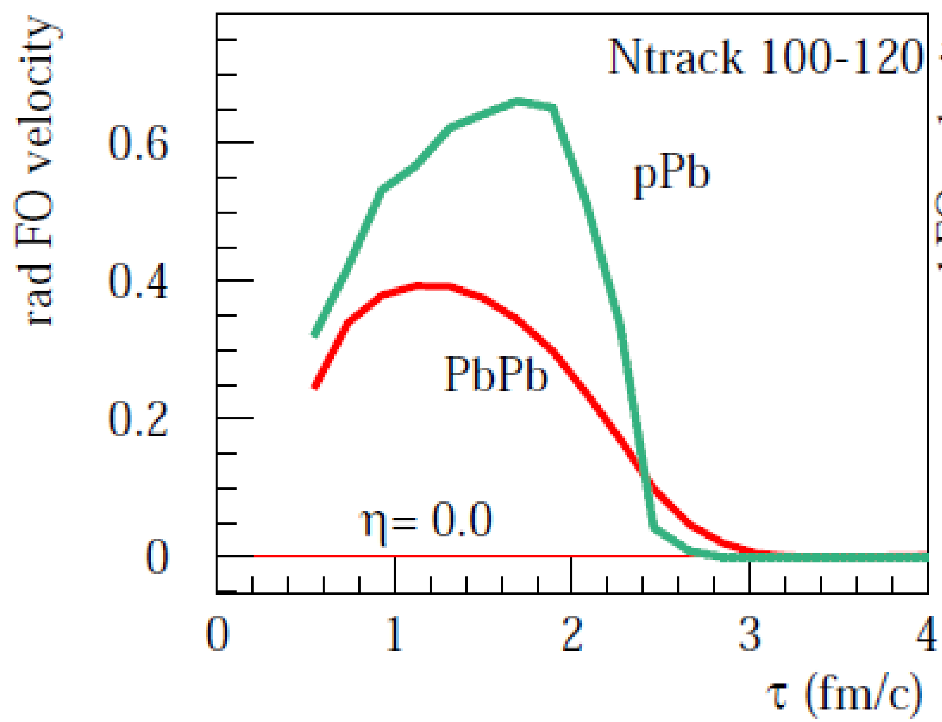
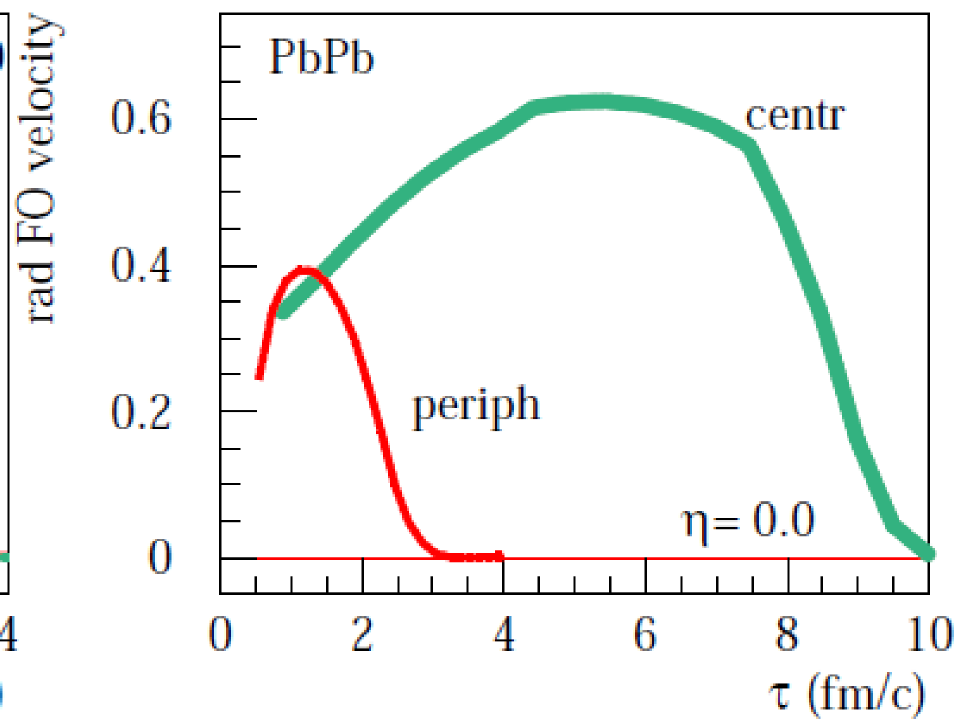




Origin of the Radial Flow

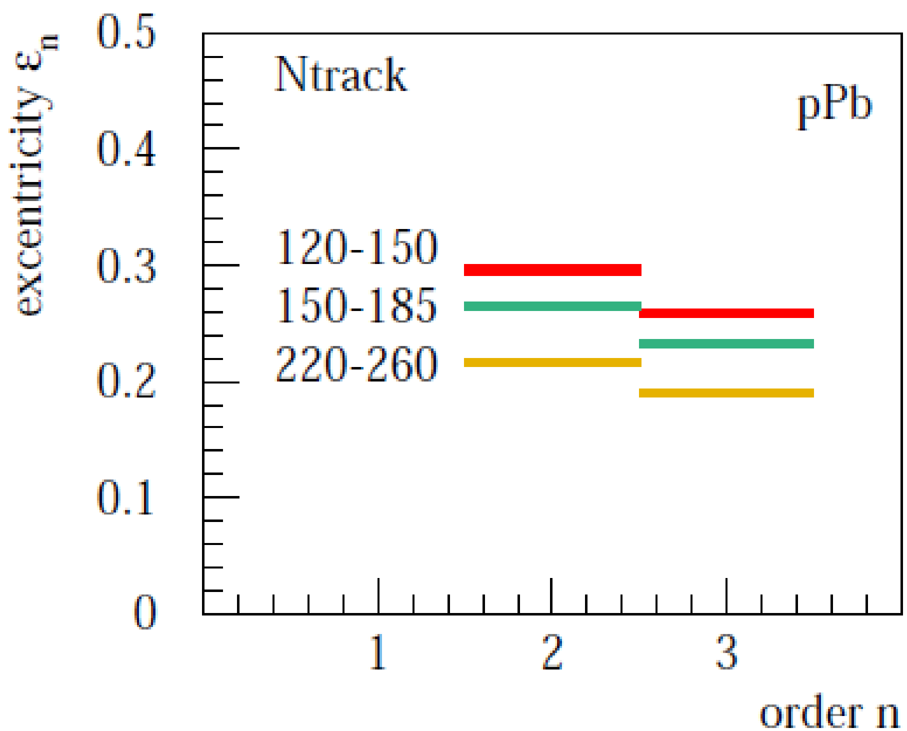
- **Multiplicity strongly correlated to the number of Pomeron**
  - common pPb/PbPb multiplicity (Ntrack>100) corresponds to very different geometry
  - Radial flow much higher in pPb than in PbPb (for same mult.)
    - pPb as high as in PbPb central collisions

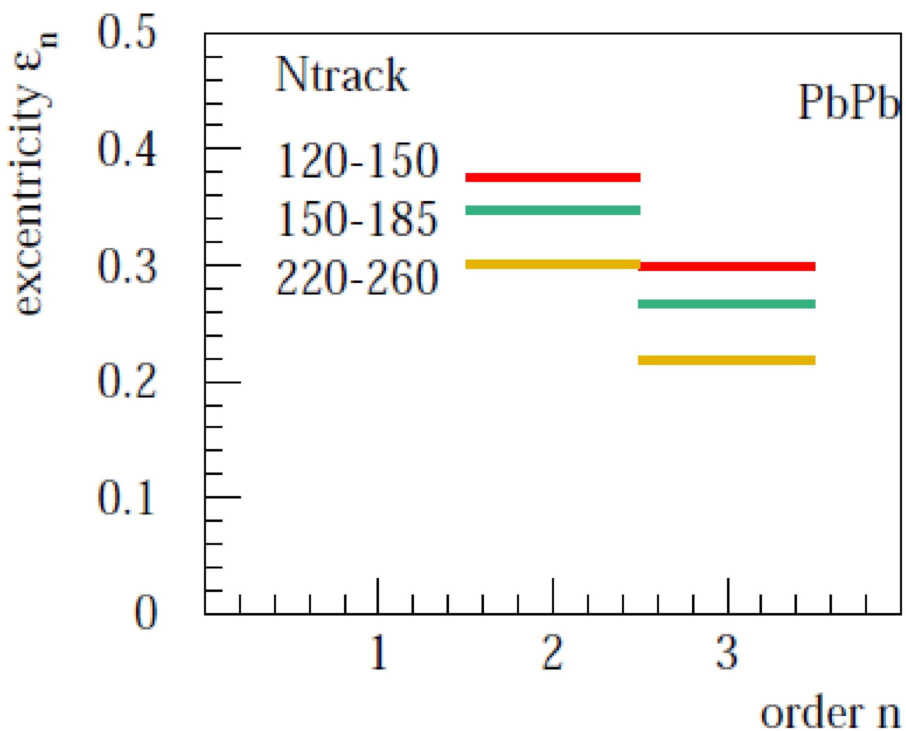




Origin of the Higher Order Flows

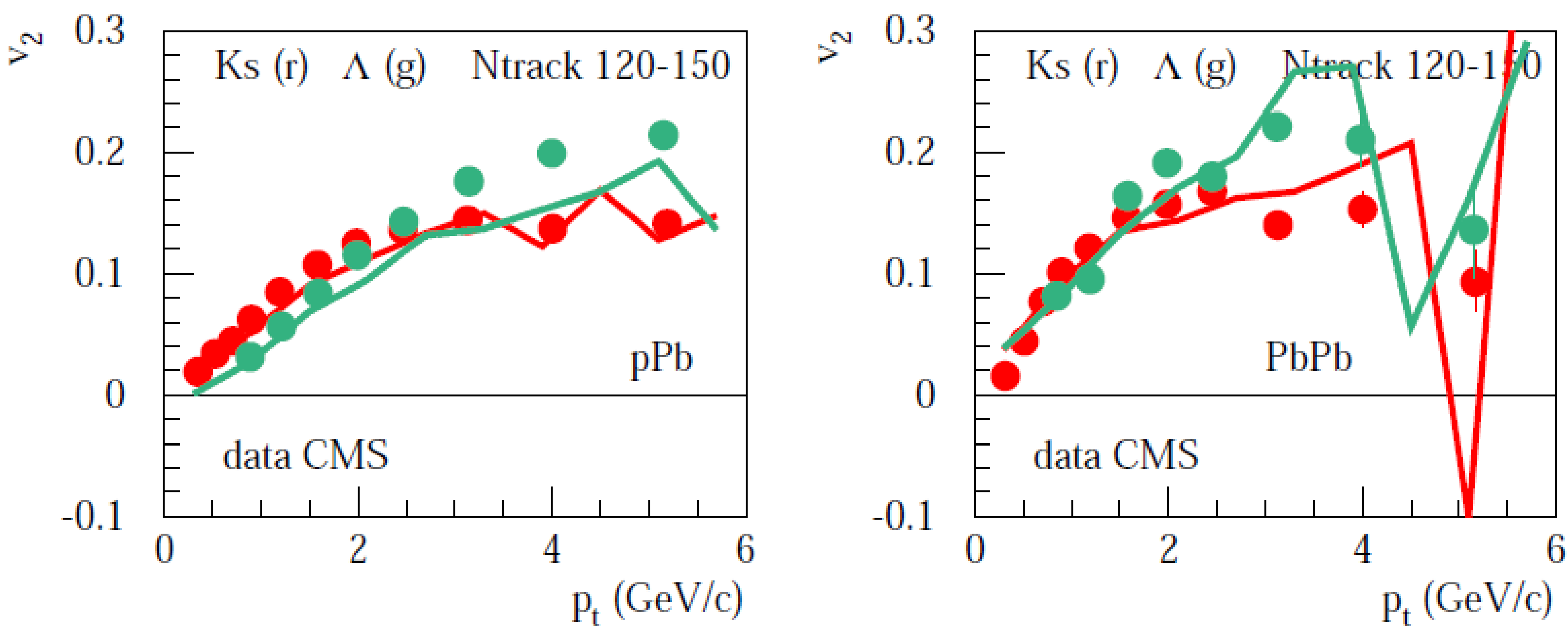
- **Multiplicity strongly correlated to the number of Pomeron**
  - common pPb/PbPb multiplicity (Ntrack>100) corresponds to very different geometry
  - Radial flow much higher in pPb than in PbPb (for same mult.)
  - Excentricity higher for v2 and v3
    - Higher excentricity compensate the lower flow to get similar magnitude in v2 and v3 !





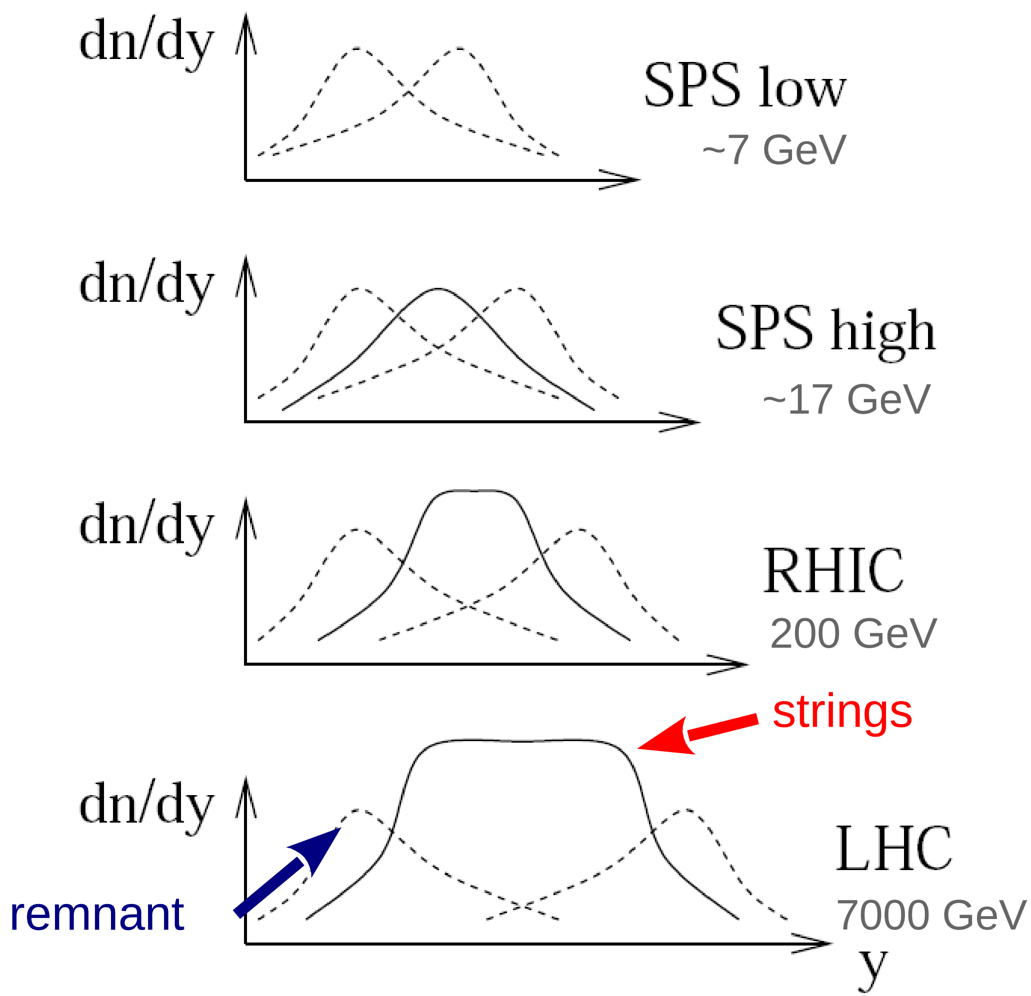
Mass Splitting

- Mass splitting well reproduce using hydro for both pPb and PbPb
  - Higher in pPb than in PbPb (larger radial flow)



Remnants

Forward particles mainly from projectile remnant



Forward hadronization from remnant :

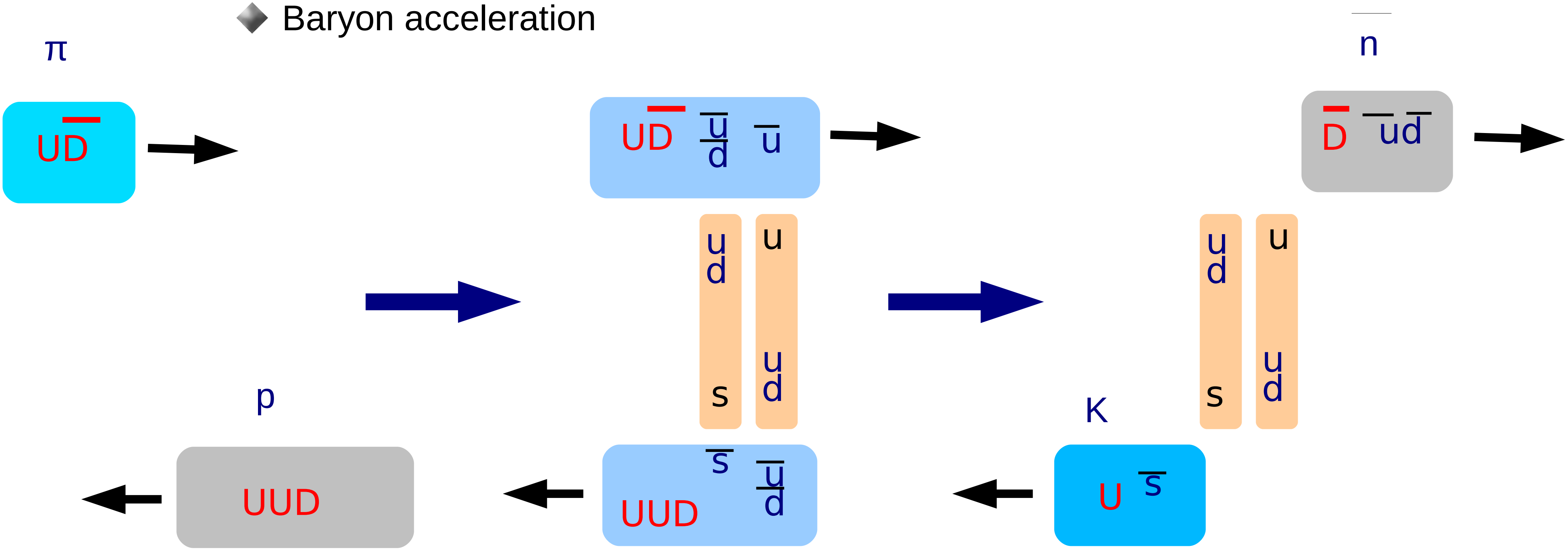
- At very low energy only particles from remnants
- At low energy (fixed target experiments) (SPS) strong mixing
- At intermediate energy (RHIC) mainly string contribution at mid-rapidity with tail of remnants.
- At high energy (LHC) only strings at mid-rapidity (baryon free)

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

Remnants in EPOS

In EPOS : any possible quark/diquark transfer

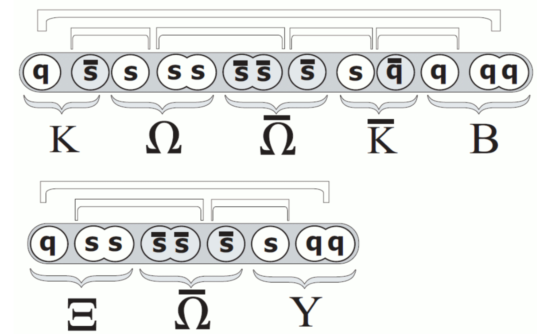
- Diquark transfer between string ends and remnants
- Baryon number can be removed from nucleon remnant :
  - Baryon stopping
- Baryon number can be added to pion/kaon remnant :
  - Baryon acceleration



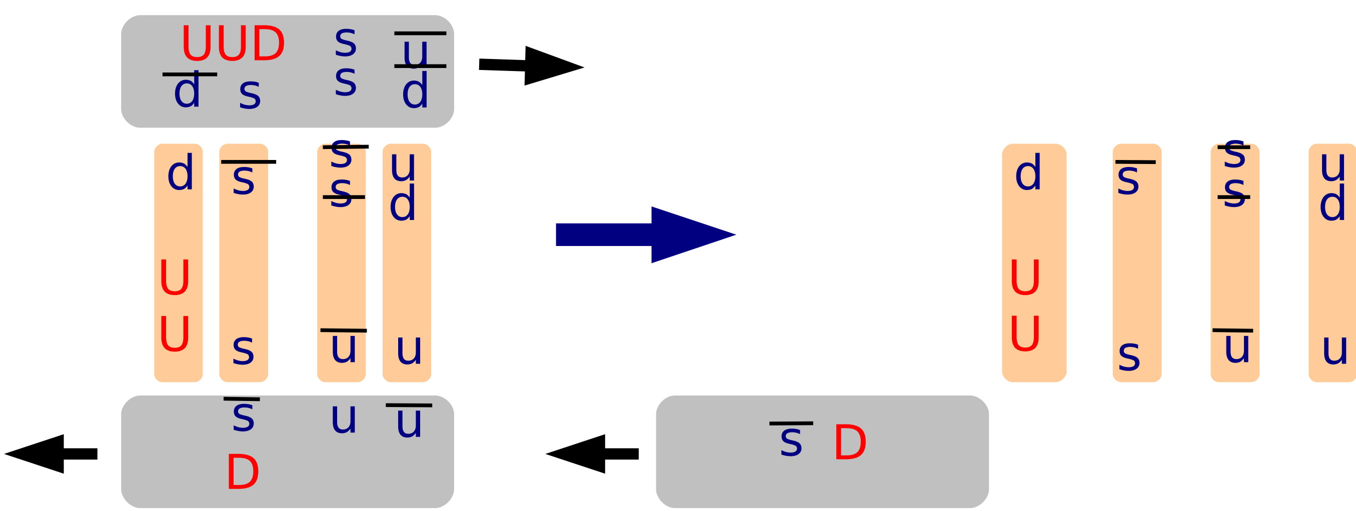
Baryons and Remnants

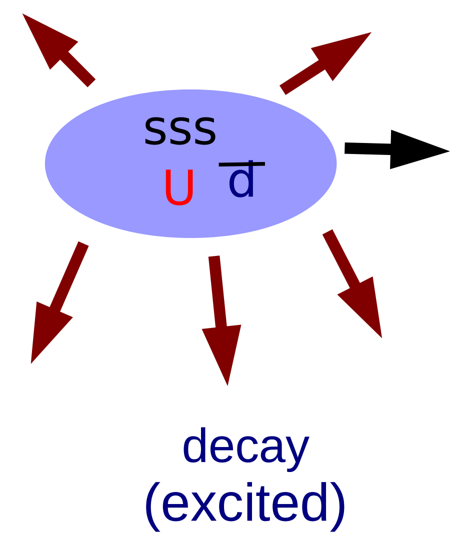
Parton ladder string ends :

- 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)

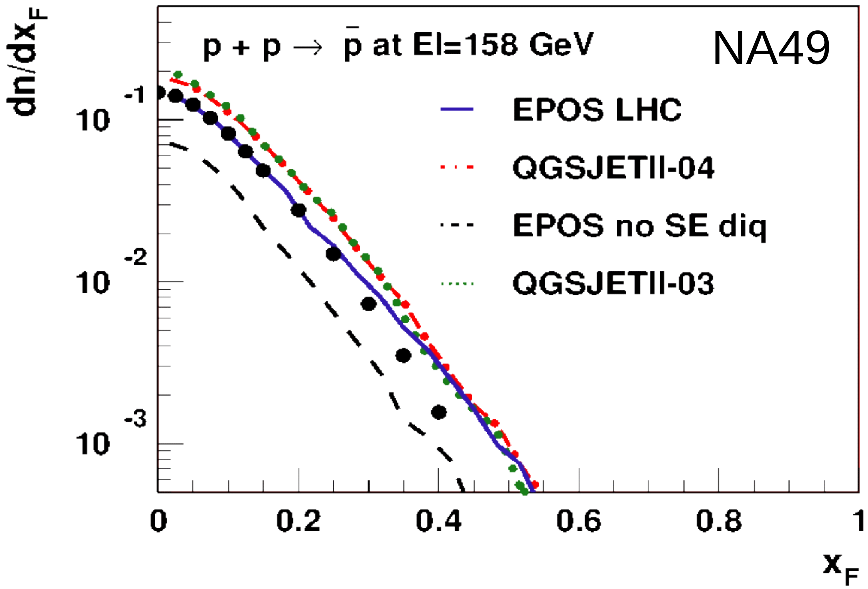


- EPOS
  - No “first string” with valence quarks : all strings equivalent
  - Wide range of excited remnants (hadronization via light resonance decay, string fragmentation or heavy quark-bag statistical decay)
    - $\bar{\Omega}$ / Ω always < 1



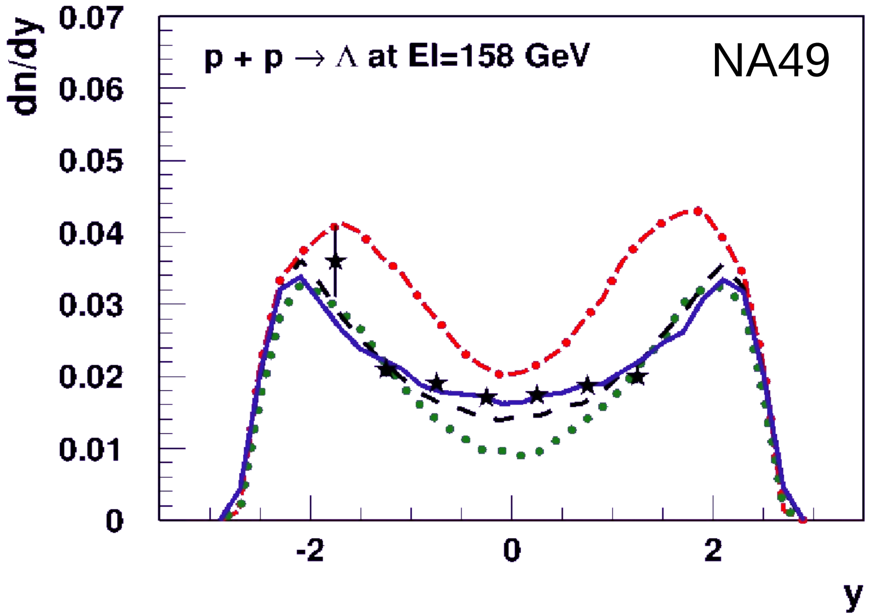


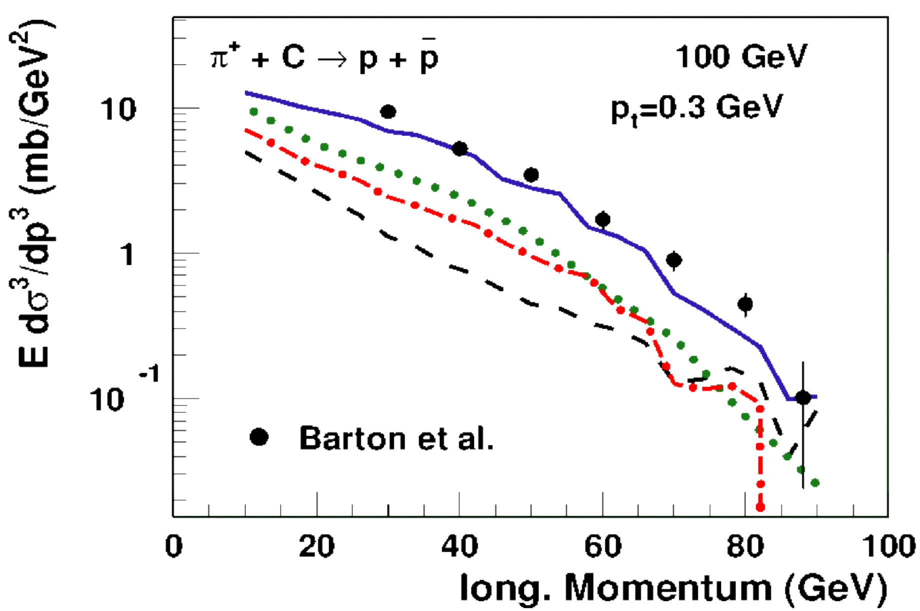
Forward Baryons (low energy)



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

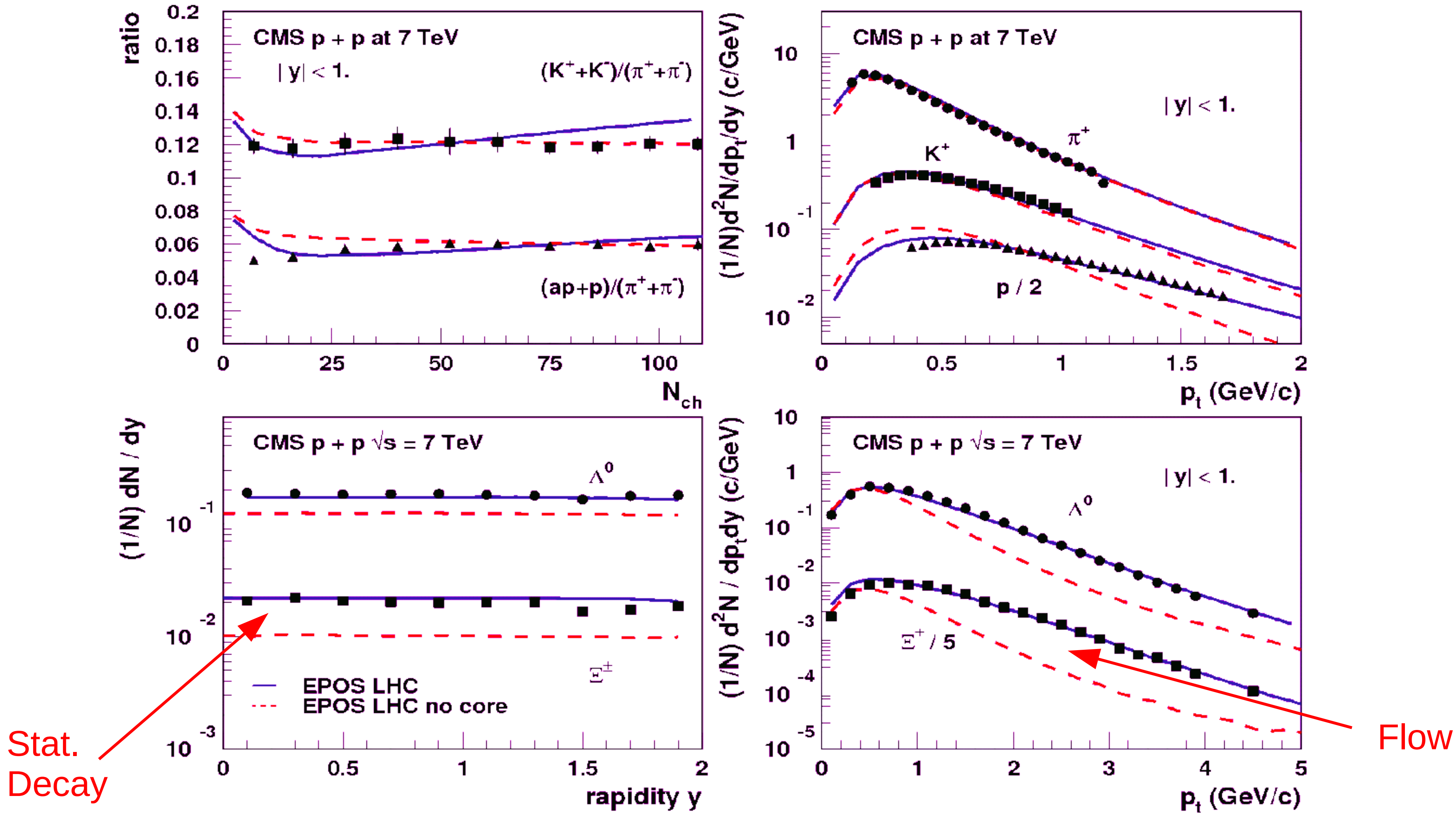
Without remnant, string fragmentation has to be changed for baryon production





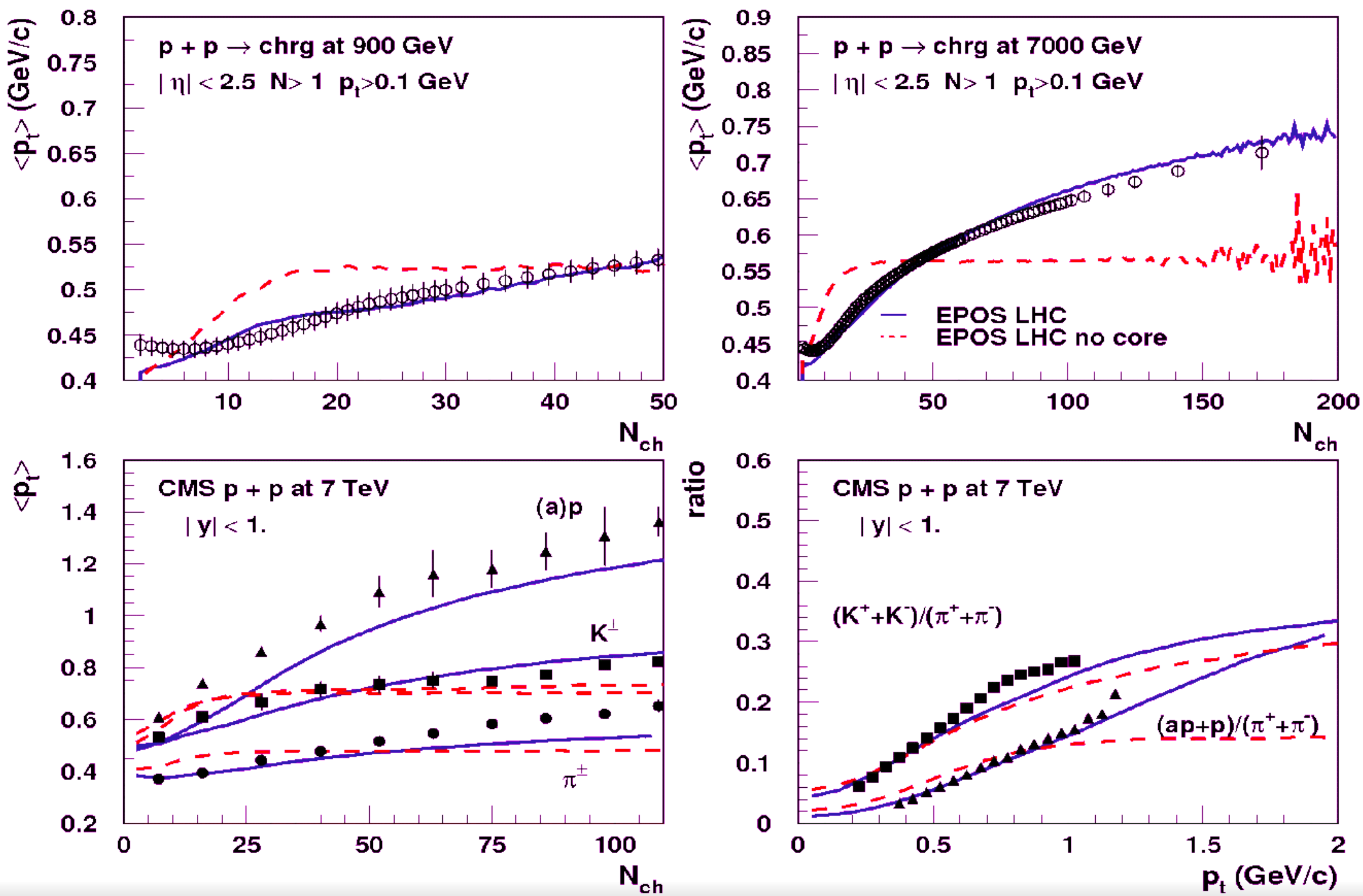
Core Effect on Particle Yield

- **Core hadronization change particle ratio**
  - ➡ heasier to produce strange baryons



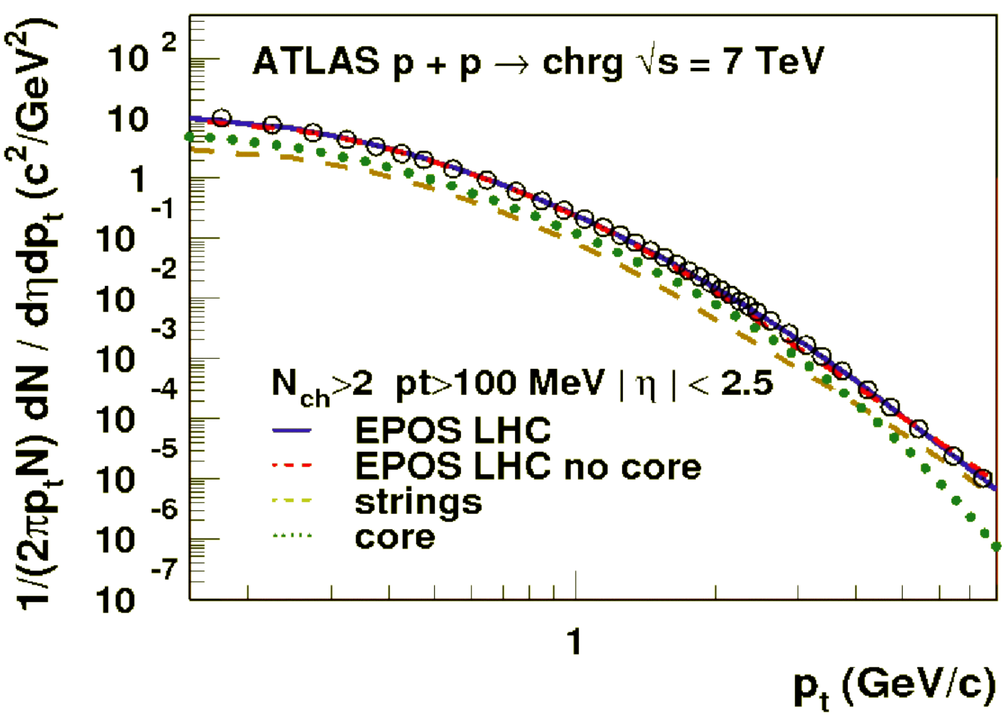
EPOS LHC

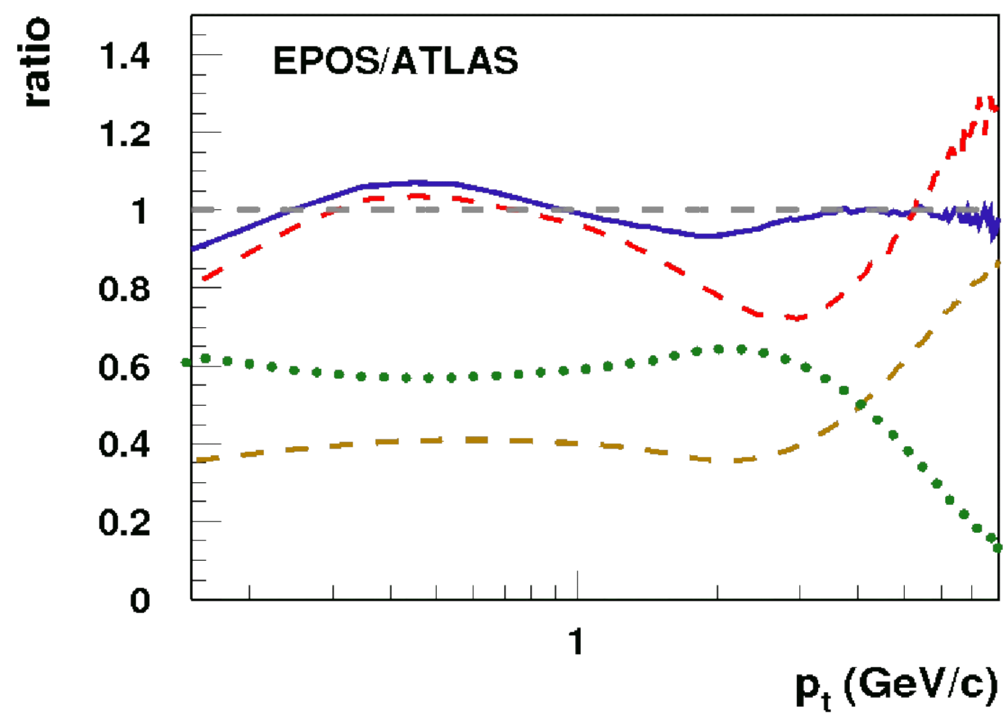
- **Detailed description can be achieved**
  - identified spectra
  - p_t behavior driven by collective effects (flow)



EPOS LHC

- **Detailed description can be achieved**
  - p_t behavior driven by collective effects (flow)
    - particles with $p_t \sim 0.5$ GeV/c boosted up to p_t=2-3 GeV/c
    - high p_t particles ($p_t \sim 10$ GeV/c) suppressed by energy loss in fluid
  - spectrum dominated by string (jet) particles only for $p_t > 5$ GeV/c



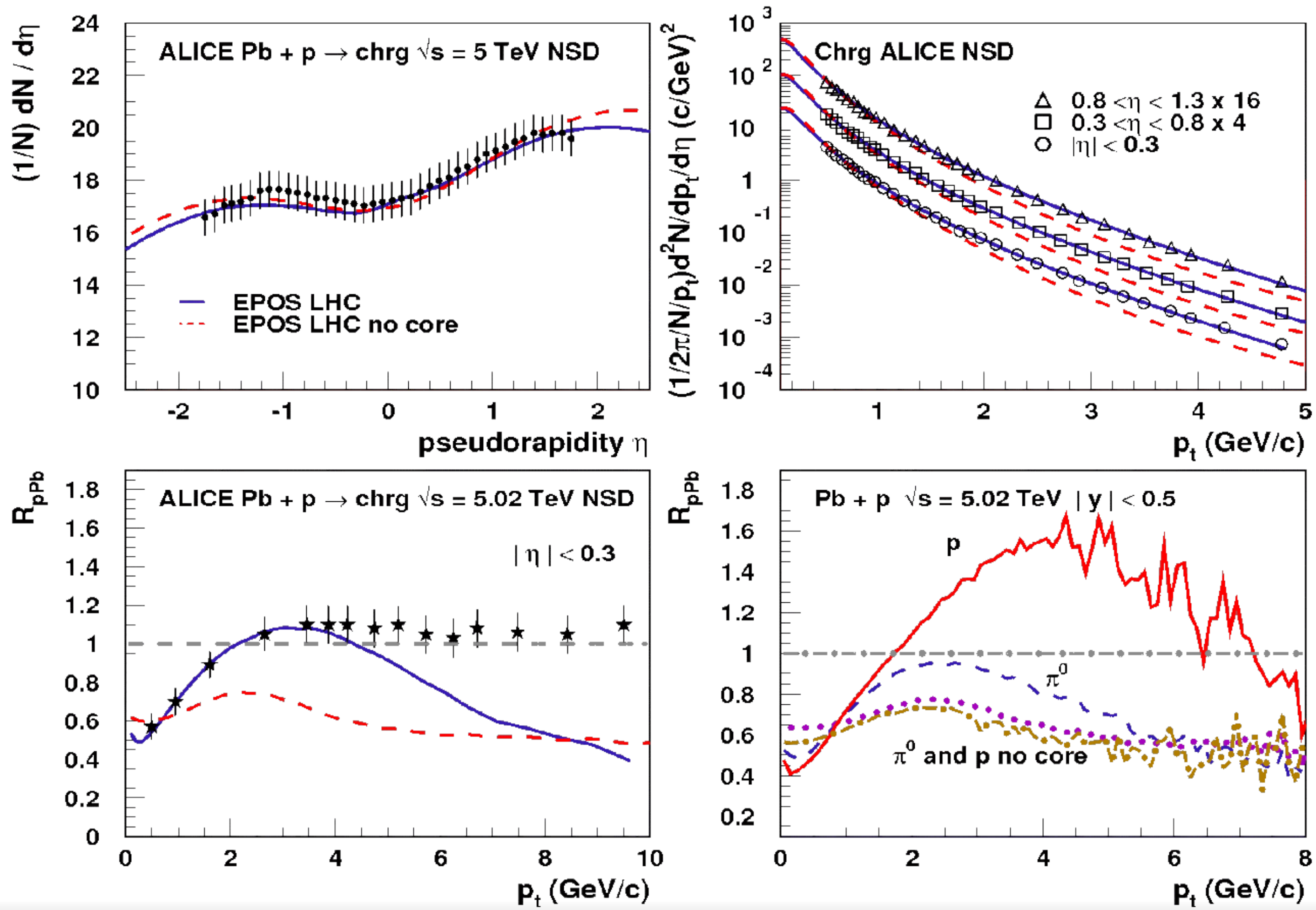


p-Pb : Increased Effects

- **Flow depends on N_{ch}**
  - large N_{ch} more often in pPb than in pp but same strength for same N_{ch}
  - R_{pPb} mass dependent (like in dAu @ RHIC) : for p_t < 6 GeV/c, R_{ppb}=1 by chance ?

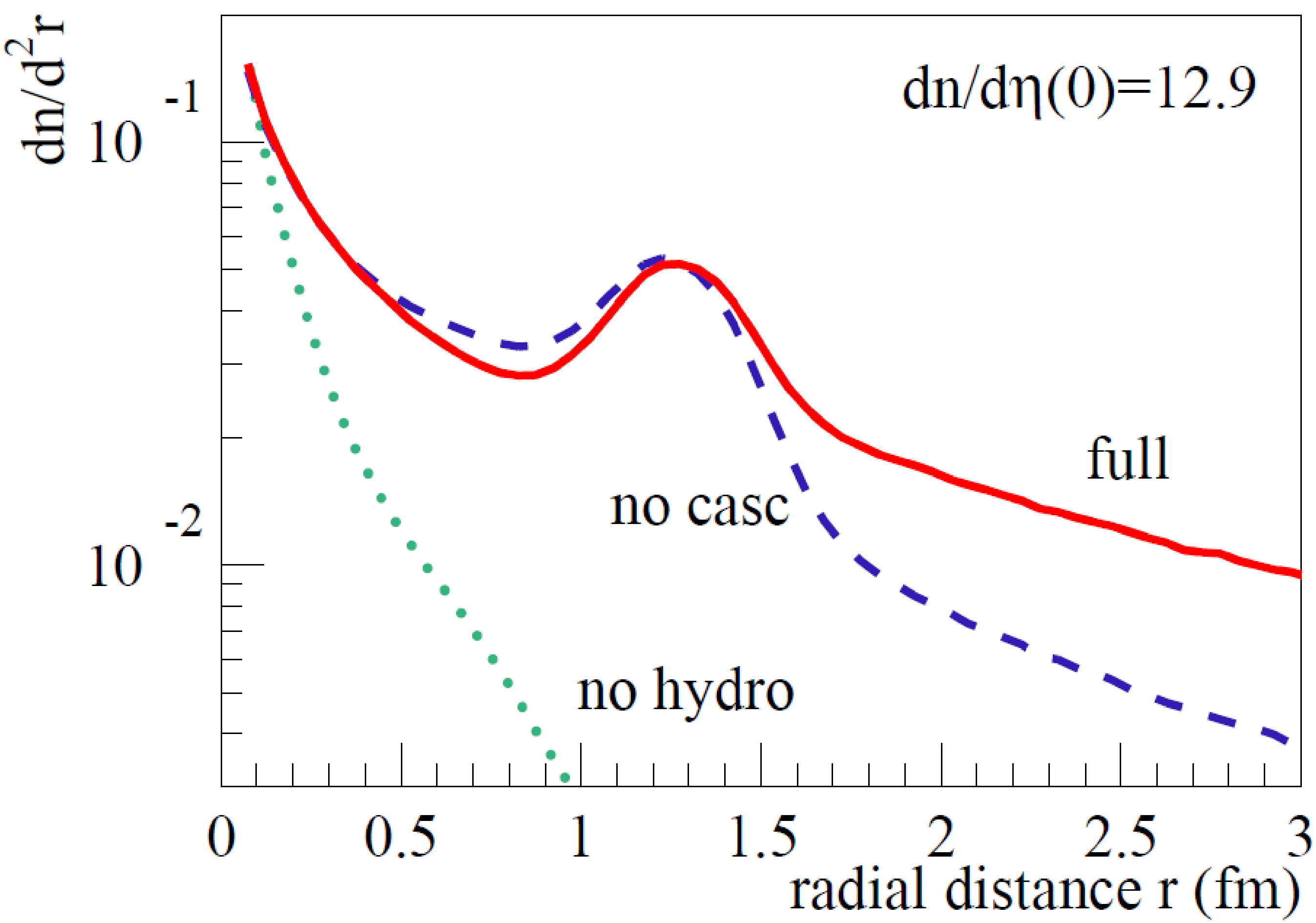
MPI reduction correct for low p_t : mutliplicity well reproduced (no tuning).

Initial state suppression artificially too strong at high p_t



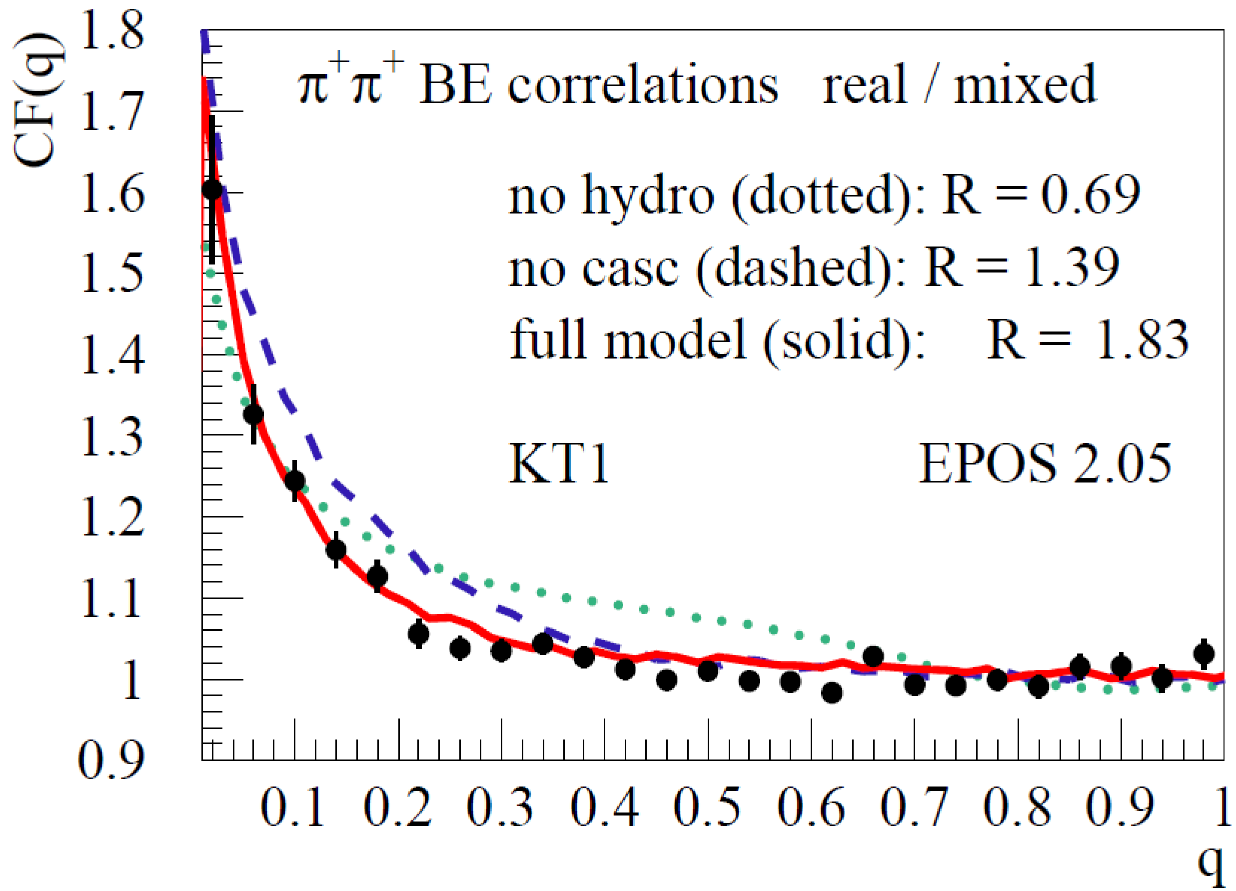
Radius of Particle Emission

- Space-time structure strongly affected (here 900 GeV)



Bose-Einstein Correlations

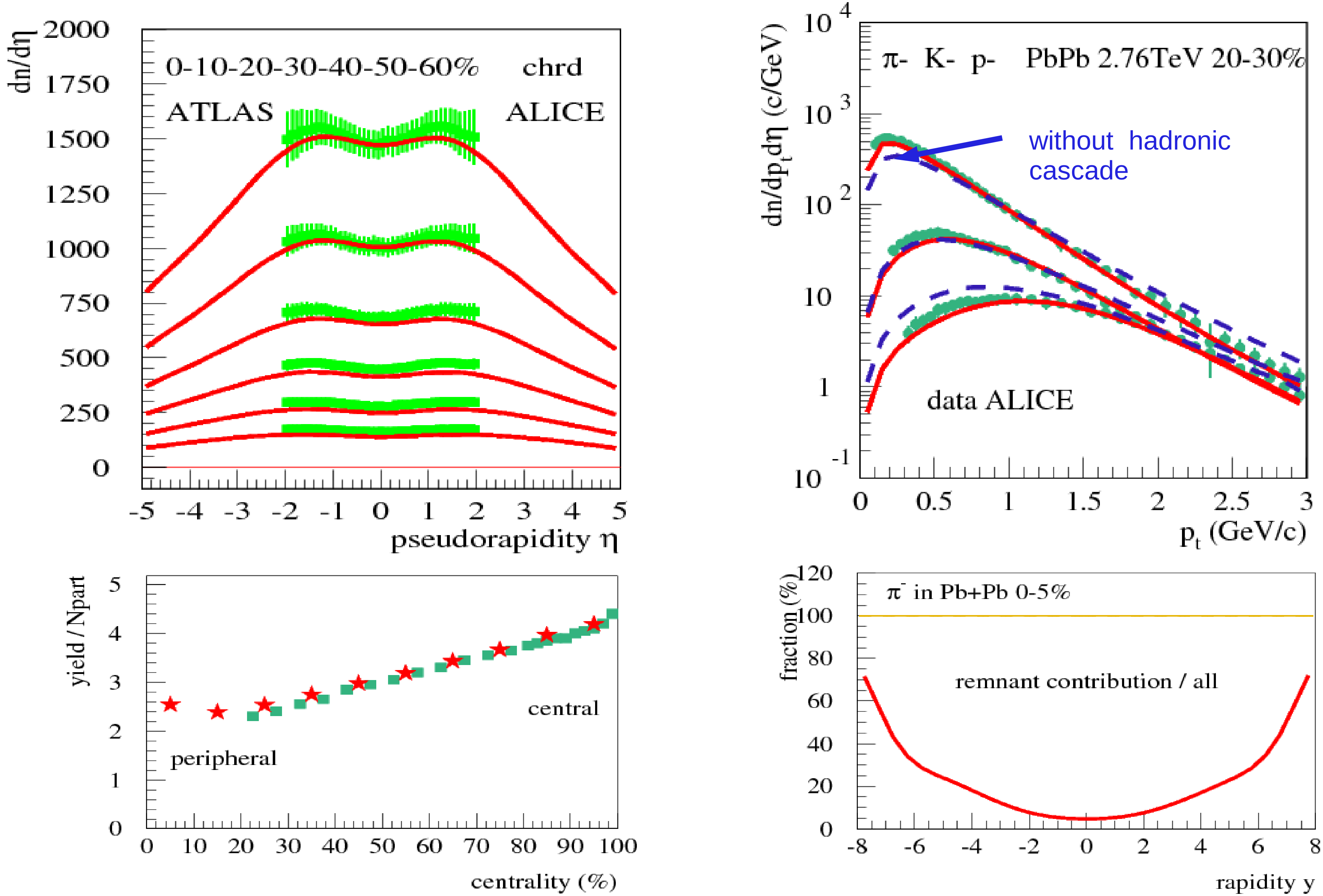
➡ Consequences for Bose-Einstein correlations



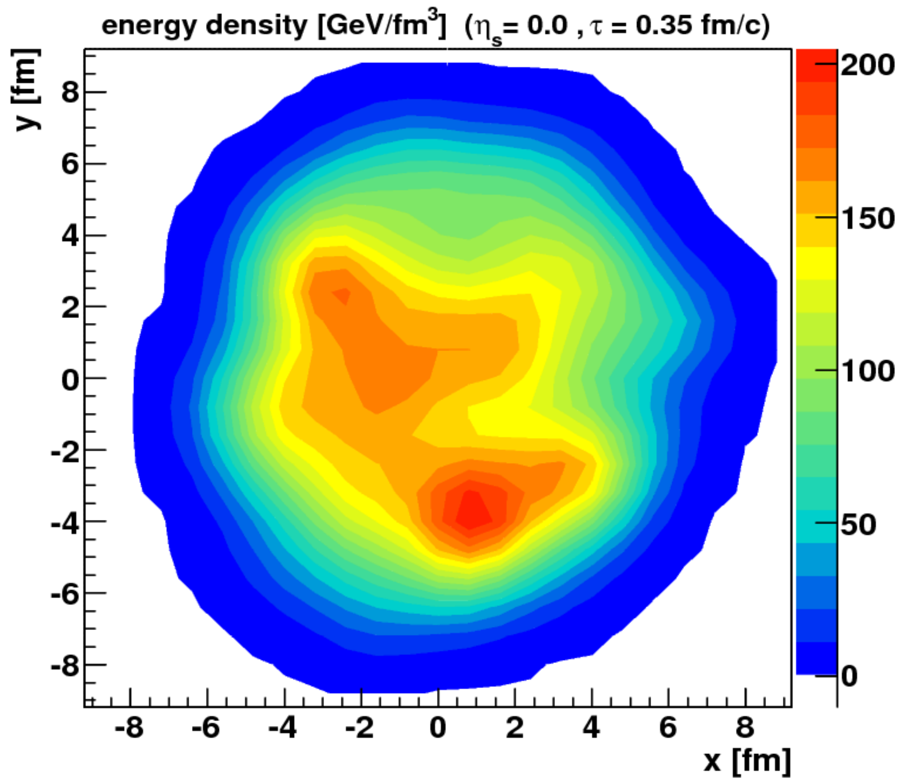
ALICE data.

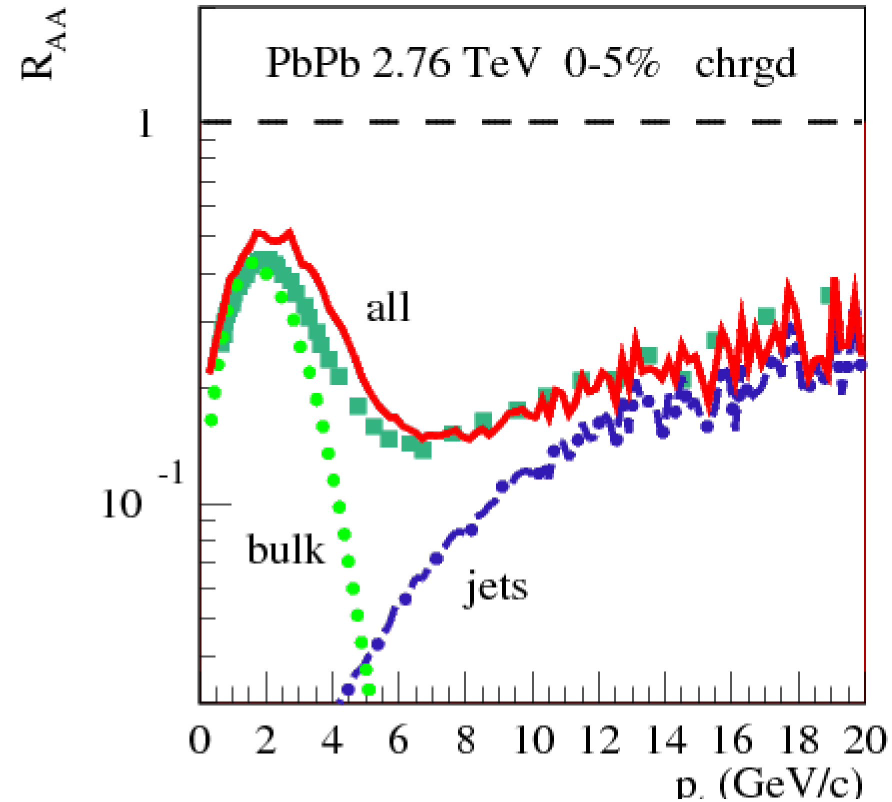
Radii R from exponential fit.
KT1= [100, 250], KT3= [400, 550], KT5= [700, 1000]

PbPb @ LHC

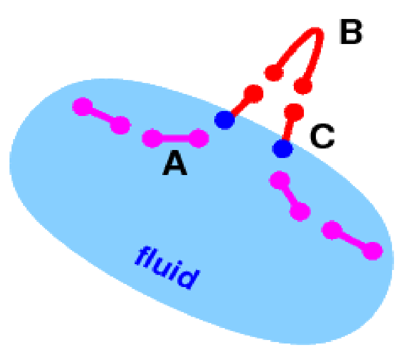

dn/dη
2000
1750
1500
1250
1000
750
500
250
0
0-10-20-30-40-50-60% chrd
ATLAS ALICE
-5 -4 -3 -2 -1 0 1 2 3 4 5
pseudorapidity η
10^4
10^3
10^2
10
1
10^{-1}
$dn/dp_t d\eta$ (c/GeV)
π- K- p- PbPb 2.76TeV 20-30%
without hadronic cascade
data ALICE
0 0.5 1 1.5 2 2.5 3
p_t (GeV/c)
yield / Npart
5
4
3
2
1
0
central
peripheral
0 10 20 30 40 50 60 70 80 90 100
centrality (%)
fraction (%)
120
100
80
60
40
20
0
π^- in Pb+Pb 0-5%
remnant contribution / all
-8 -6 -4 -2 0 2 4 6 8
rapidity y

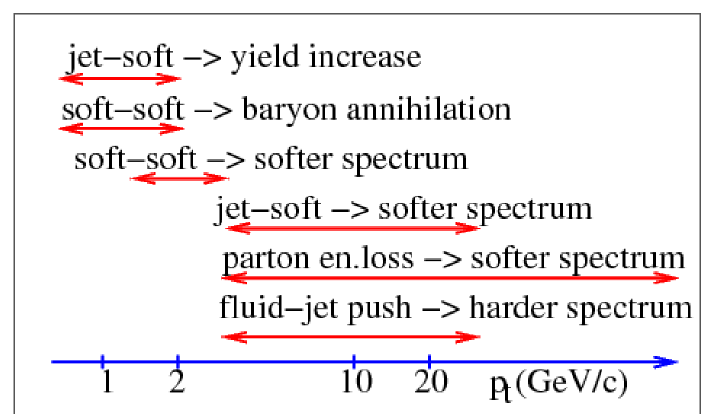
jets in PbPb @ LHC



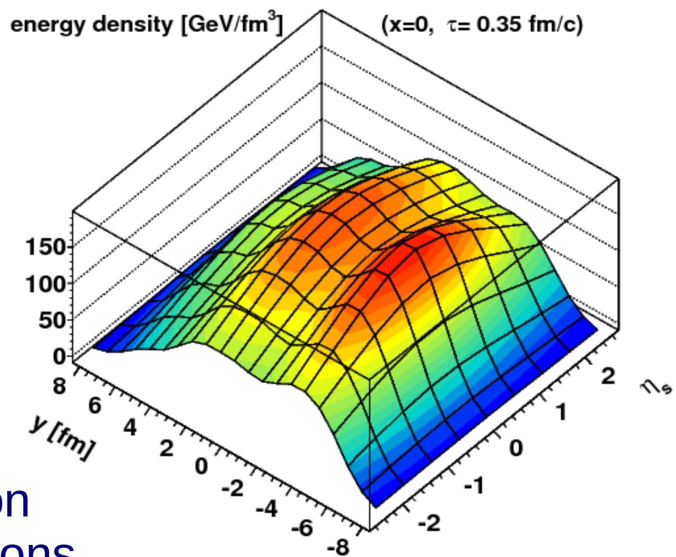


- **Jet interacts in bulk of matter**
  - ➡ parton energy loss
  - ➡ boost at the surface

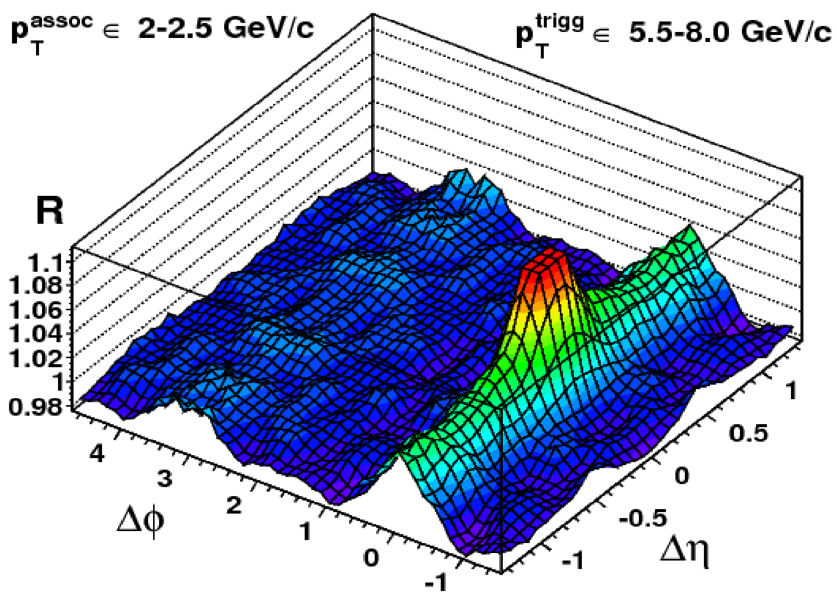




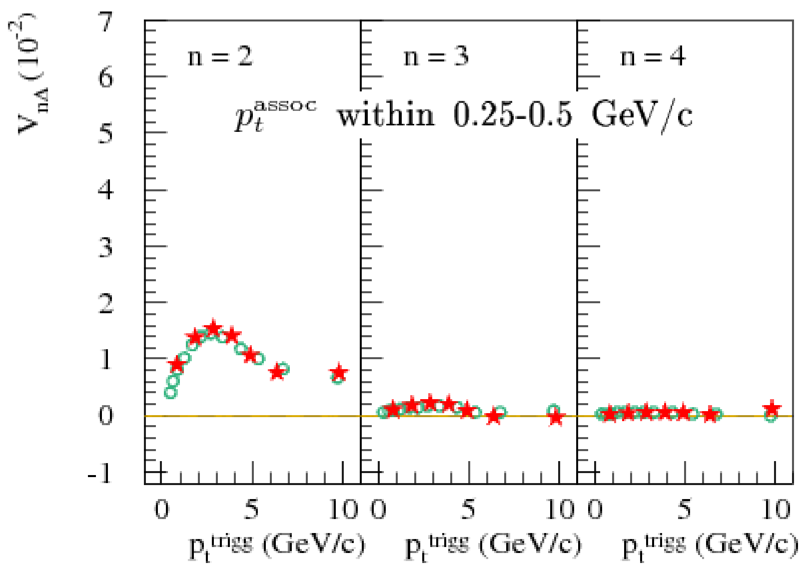
Correlations in PbPb@LHC

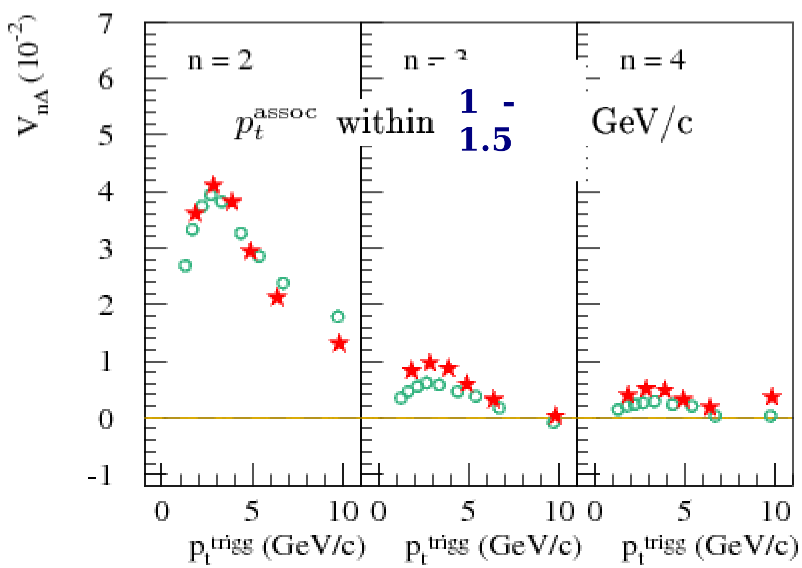


di-hadron correlations

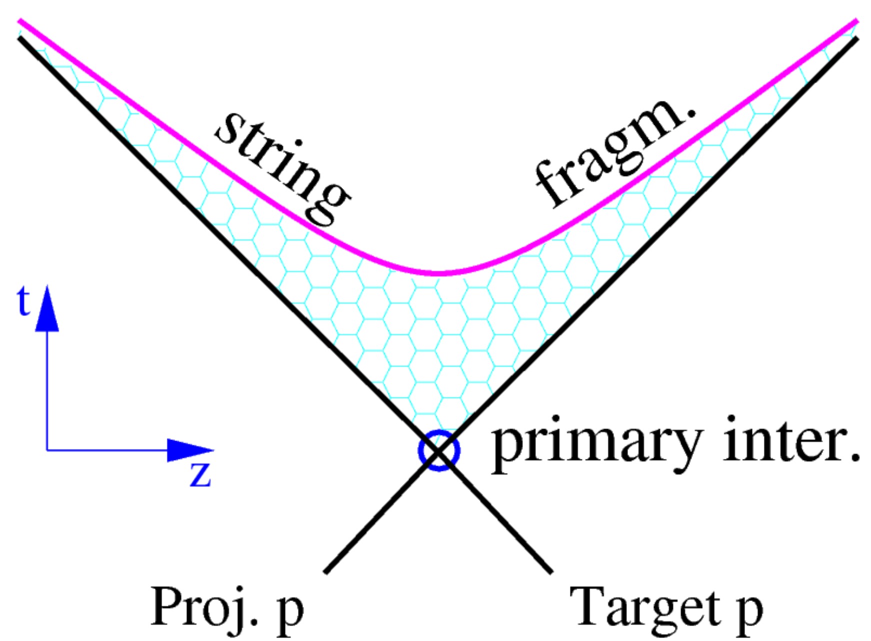


Fourier coefficient for most central events





High Energy Hadronic Interactions : HEP view

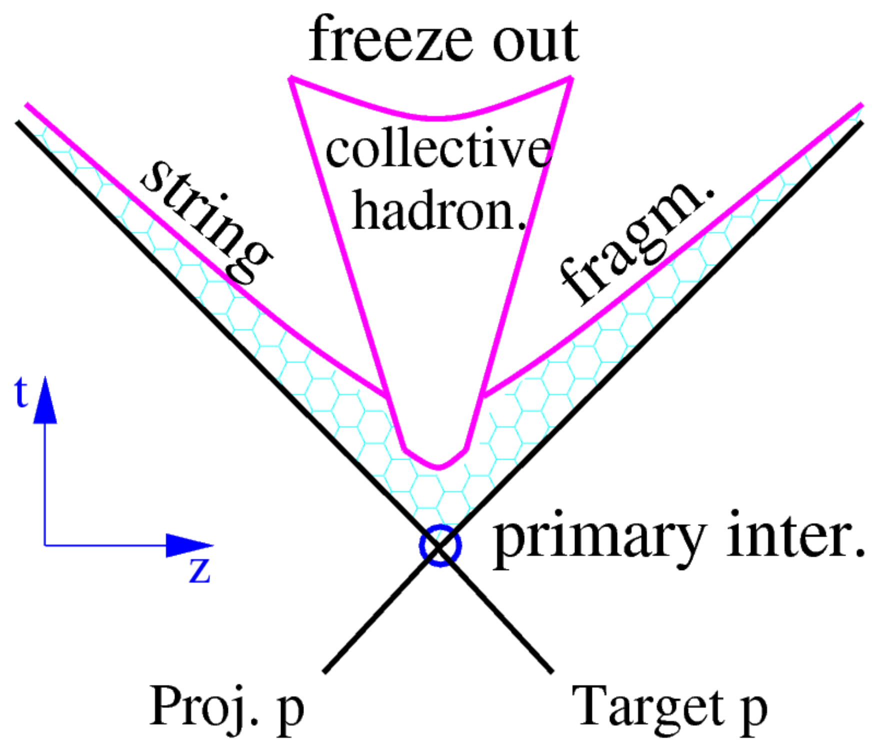


MPI

Problem with some observables (UE, <pt>, ratios ...)

High Energy Hadronic Interactions : EPOS LHC

- **Local high energy densities have different hadronization :**
  - Microcanonical decay
  - flow



General case : valid for pp if enough particles are produced !