EPOS Hadronic Interaction Model : Past and Future

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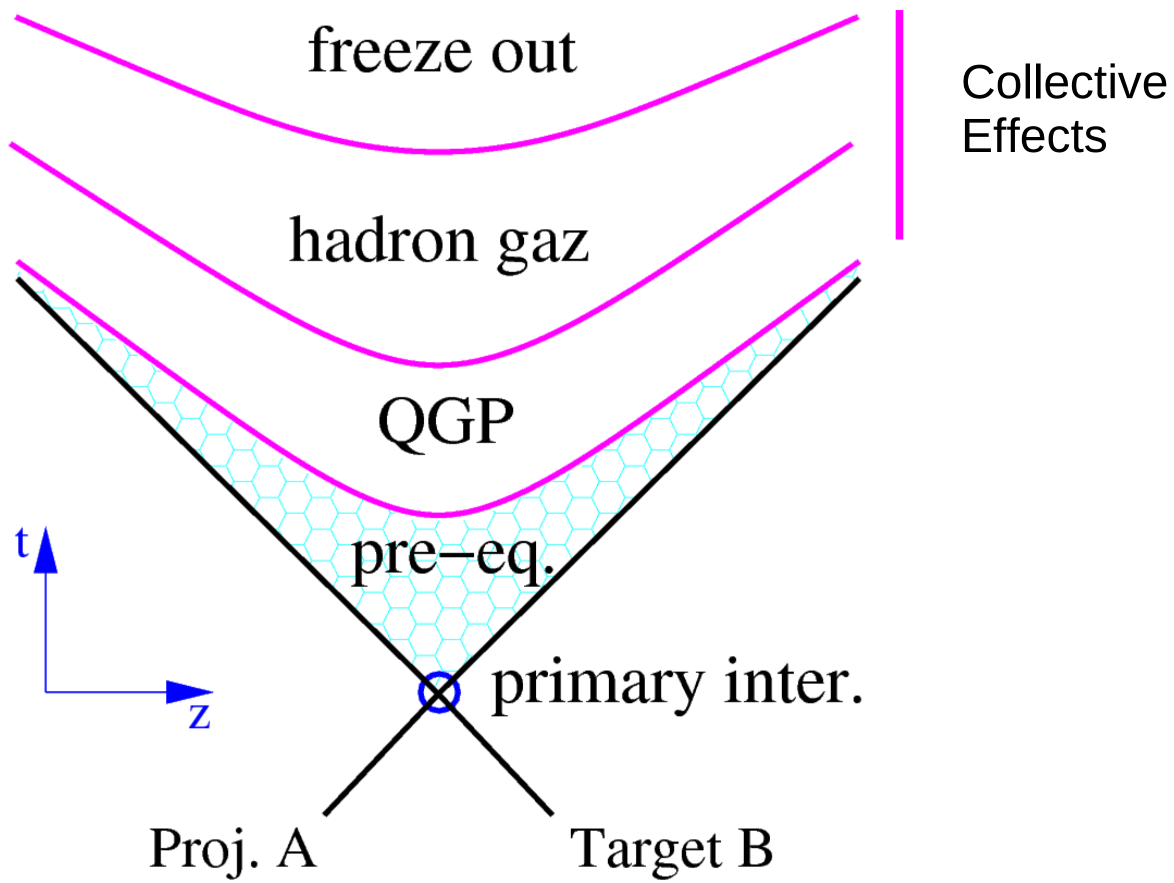
High Energy Hadronic Interactions

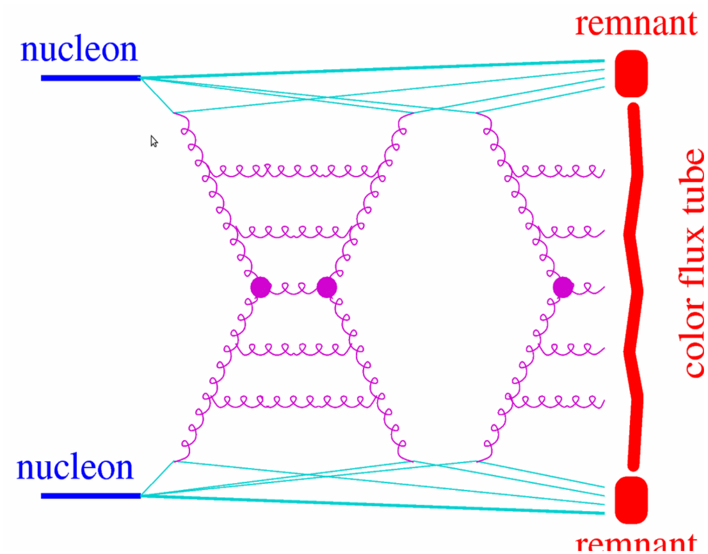


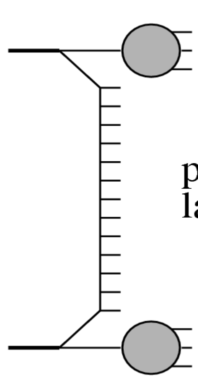
General case : valid for pp if enough particles are produced !

Outline

- **EPOS LHC**
  - Energy sharing
  - Parton multiple scattering
  - Outshell remnants
  - Screening, Shadowing and Strings
- **Collective effects**
- **EPOS 3/4**
- **Core-Corona in EAS**
- **EPOS QGP ?**

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) for pp or Heavy Ion

*T.Pierog and K. Werner

EPOS : History

Evolution of models by K. Werner et al. :

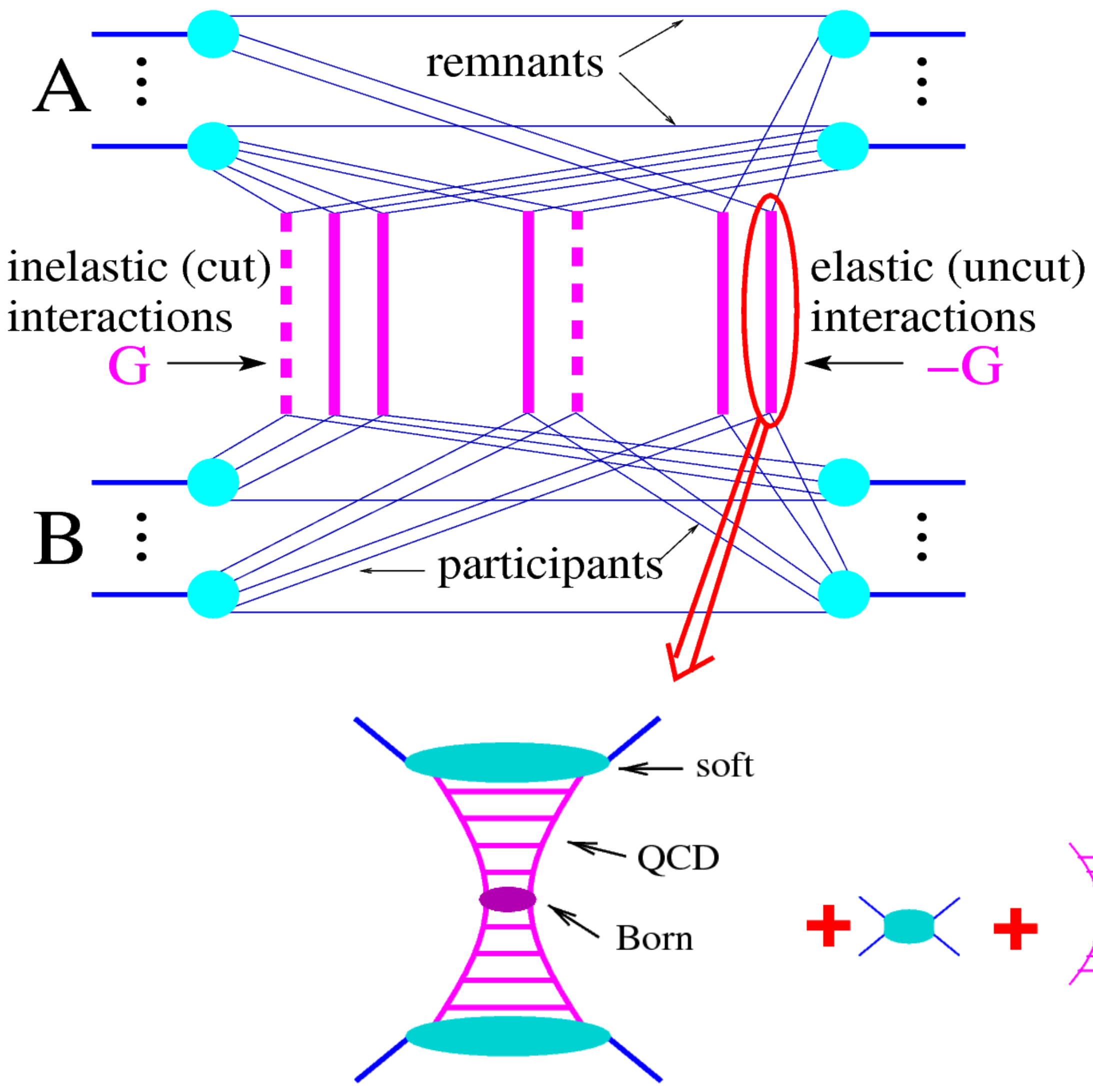
- VENUS (93) : soft physic
- NEXUS 2 (00): first realization of Parton-Based Gribov-Regge Theory (PBGRT) with soft, semi-hard and hard Pomerons
- NEXUS 3.97 (03) : enhanced diagrams in PBGRT and new remnant treatment
- EPOS 1.6 (06) : PBGRT + remnants + Effective treatment of higher order effect and high density effect + new diffraction ...
- EPOS 1.99 (09) : Correction of cross section and inelasticity for air showers.
- EPOS LHC (12) : Re-tune using LHC data and correction of effective flow.
- EPOS 2 (not released) : Real event-by-event hydro calculation (includ. pp)
- EPOS 3 (not released) : New saturation scale for proper jet cross-section
- EPOS 4 : 2020- (still under development)
    - New hard scattering calculation includingf heavy flavors
    - Soft + Factorisation and binary scaling for hard
    - 3D+1 viscous event-by-event hydro calculation (includ. pp)

EPOS : Parameters

- **Data used to constrain parameters (~100) :**
  - ➡ string fragmentation : e+e- data,
  - ➡ hard Pomeron : DIS data,
  - ➡ soft Pomeron and vertices : pp,πp,Kp, pA cross sections
  - ➡ diffraction : pp low energy and LHC diffraction and multiplicity distributions
  - ➡ excitation functions : multiplicity in pp from SPS to LHC,
  - ➡ string ends and remnants : NA49 data
  - ➡ collective and screening effects : RHIC and LHC

- **One set of parameters for all energies and system**
  - ➡ not designed to be tuned by users

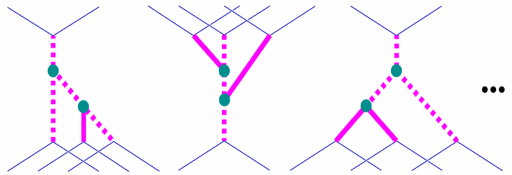
Parton-Based Gribov-Regge Theory



Energy sharing at the cross section level

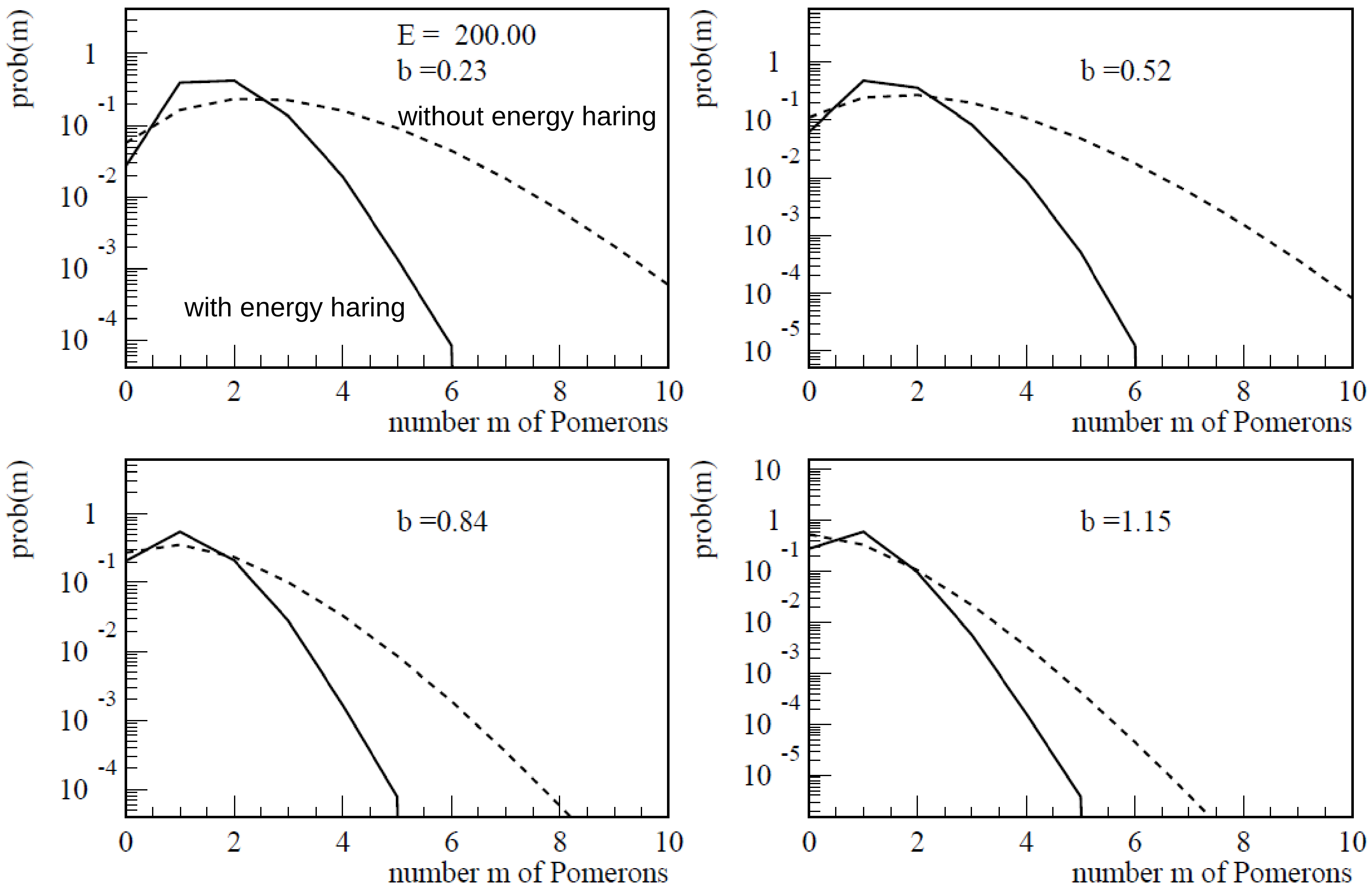
- Energy shared between cut and uncut diagrams (Pomeron)
- Reduced number of elementary interactions
- Generalization to (h)A-B
- Particle production from momentum fraction matrix (Markov chain metropolis)

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

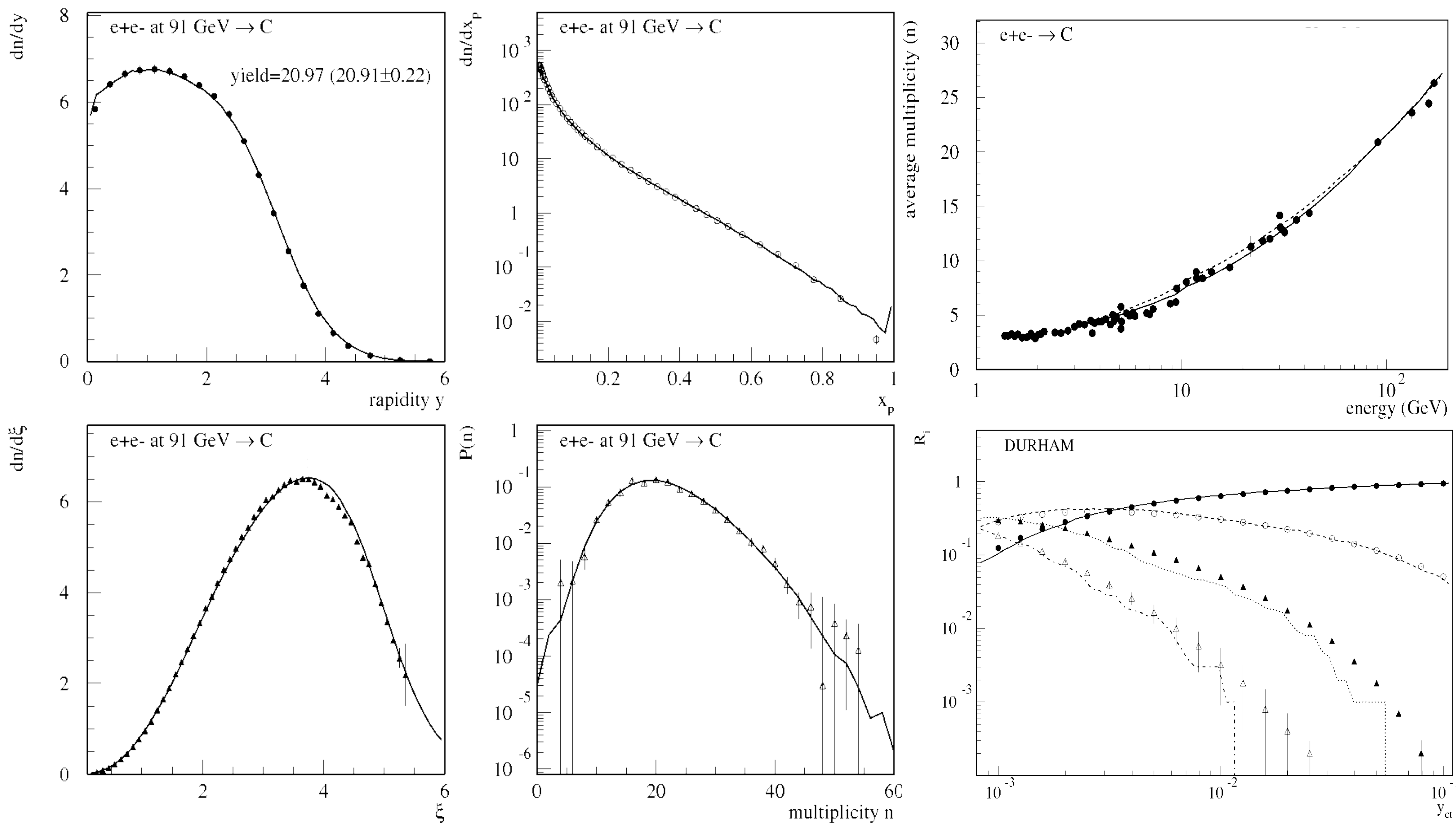


Number of cut Pomerons

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

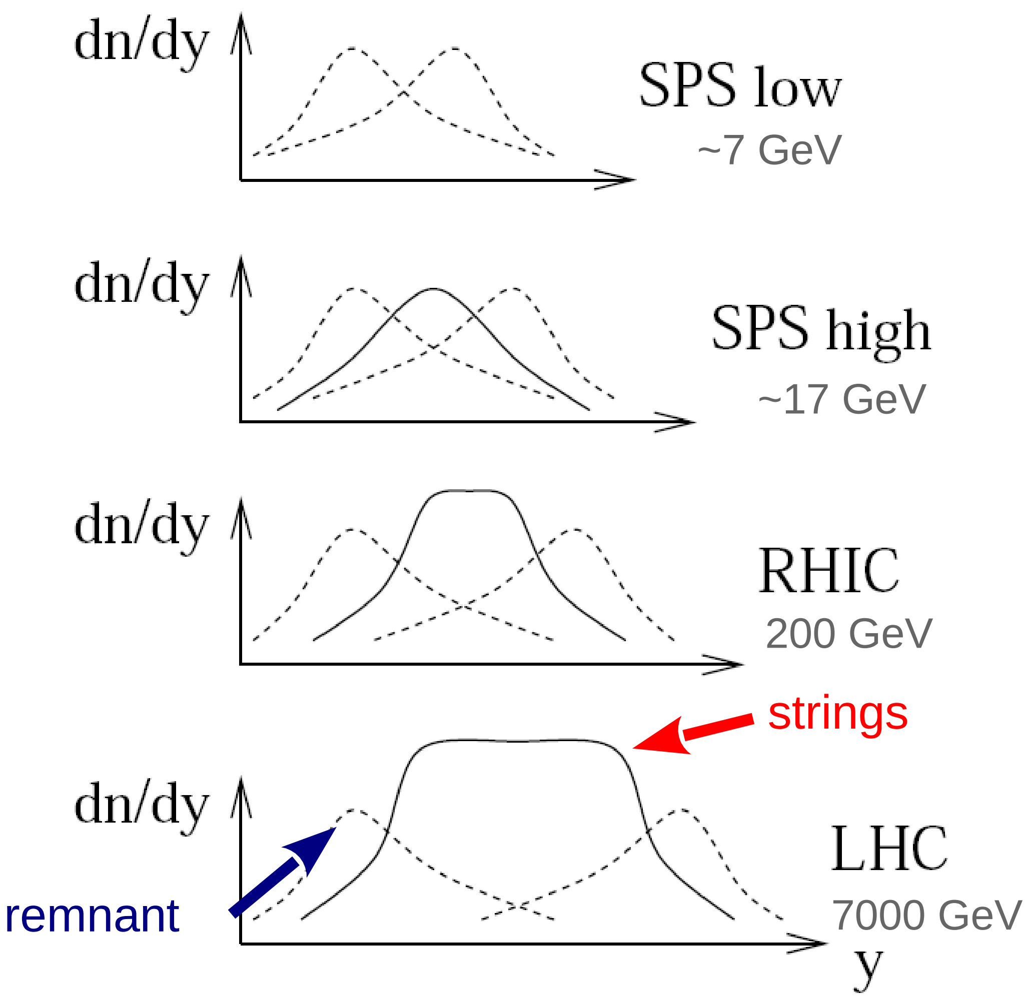


Test at LEP


e+e- at 91 GeV → C
yield=20.97 (20.91±0.22)
dn/dy
rapidity y
dn/dx_p
x_p
e+e- → C
average multiplicity ⟨n⟩
energy (GeV)
dn/dξ
ξ
P(n)
multiplicity n
DURHAM
R_i
y_ct

Remnants

Forward particles mainly from projectile remnant

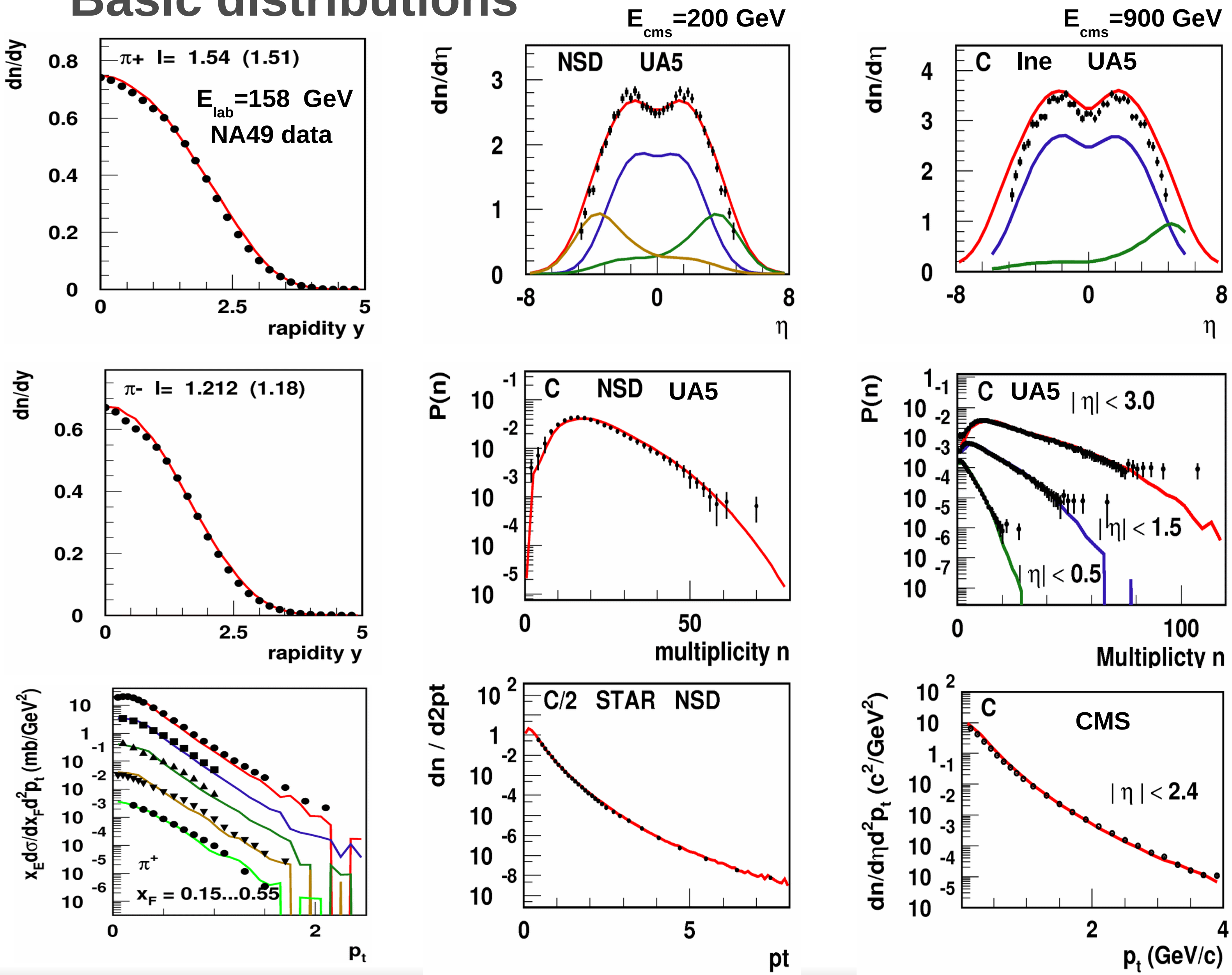


- At very low energy only particles from remnants
- At low energy (fixed target experiments) (SPS) strong mixing
- At intermediate energy (RHIC) mainly string contribution at mid-rapidity with tail of remnants.
- At high energy (LHC) only strings at mid-rapidity (baryon free)

Different contributions of particle production at different energies or rapidities

Basic Distributions

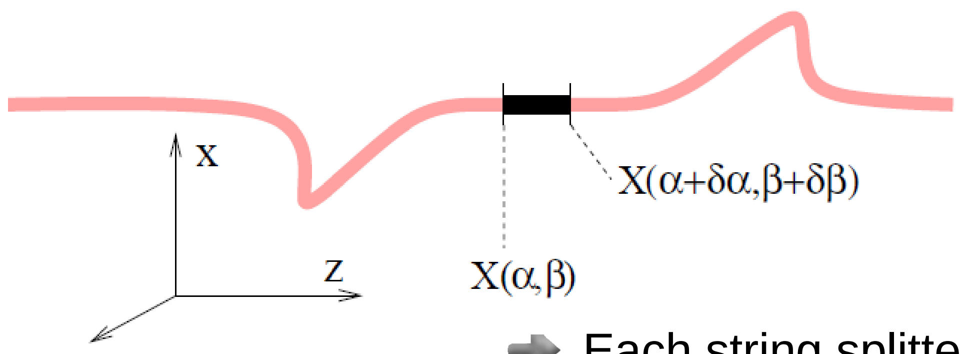
Basic distributions

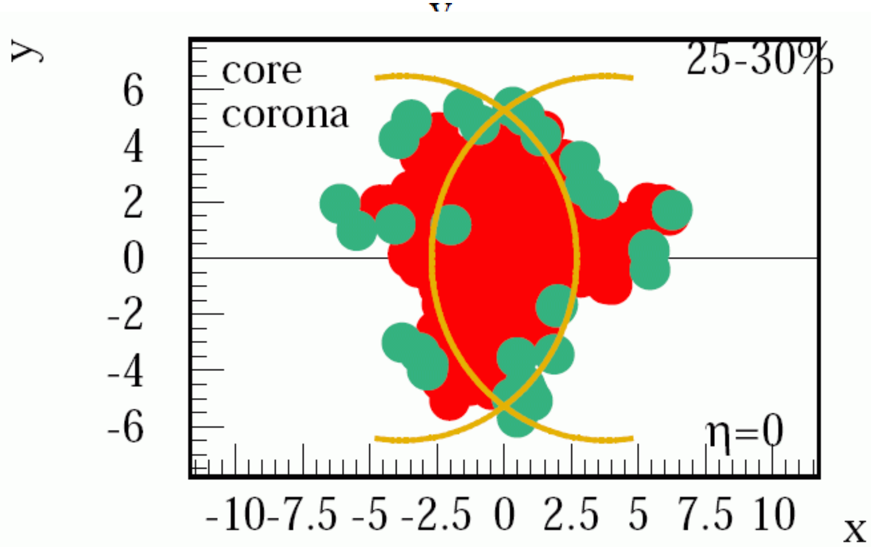


High Density Core Formation

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**



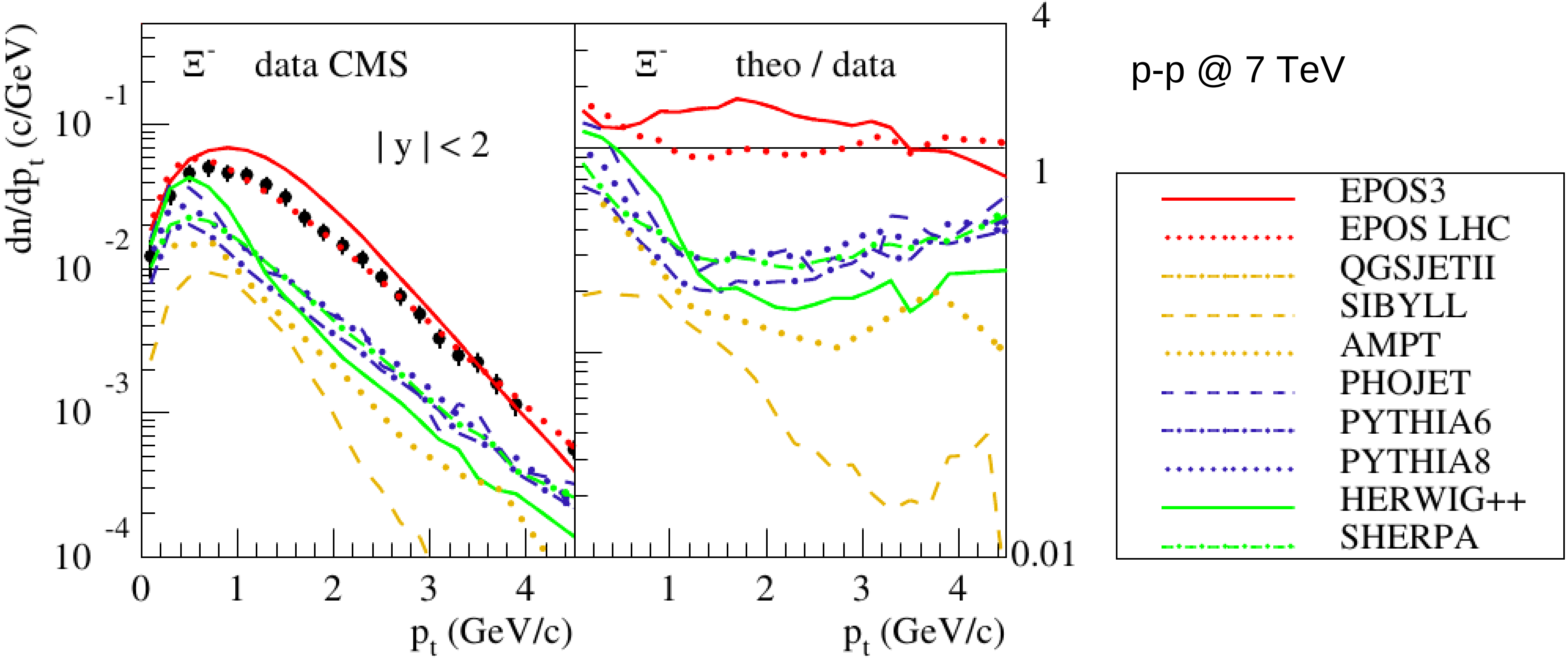


- Each string splitted into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space
- If energy density from segments high enough
  - segments fused into core
    - flow from hydro-evolution
    - statistical hadronization
- If low density (corona)
  - segments remain hadrons

Core in p-p

Detailed description can be achieved with core in pp

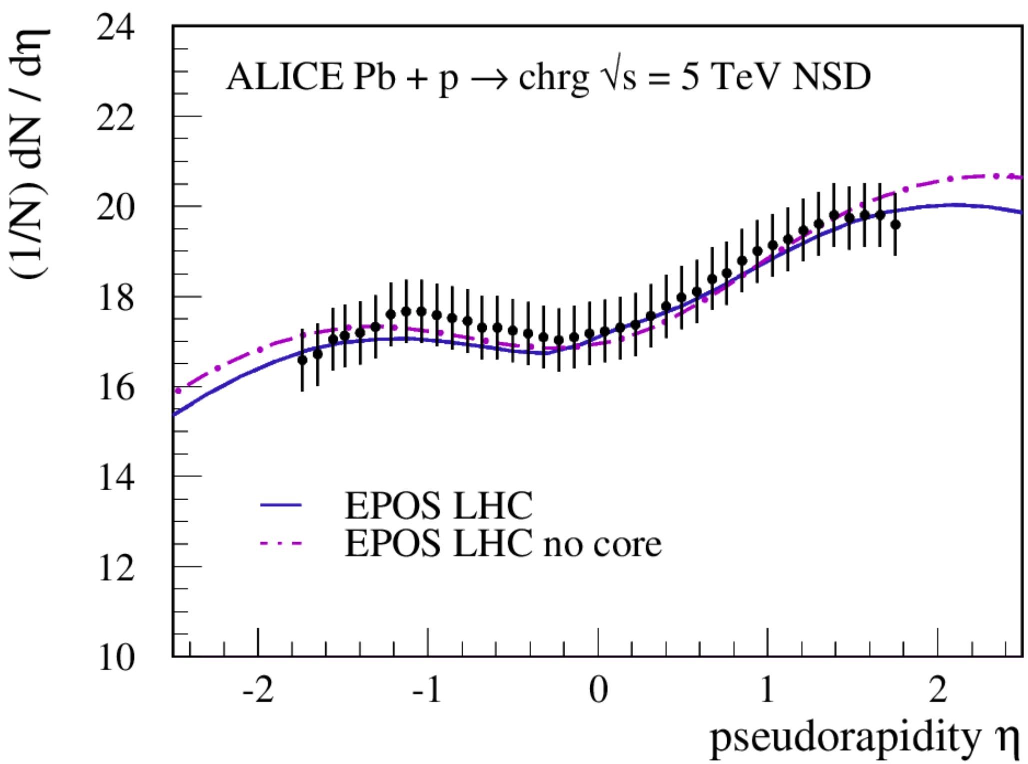
- identified spectra: different strangeness between string (low) and stat. decay (high)
- p_t behavior driven by collective effects (statistical hadronization + flow)
  - larger effect for multi-strange baryons (yield AND $<p_t>$)

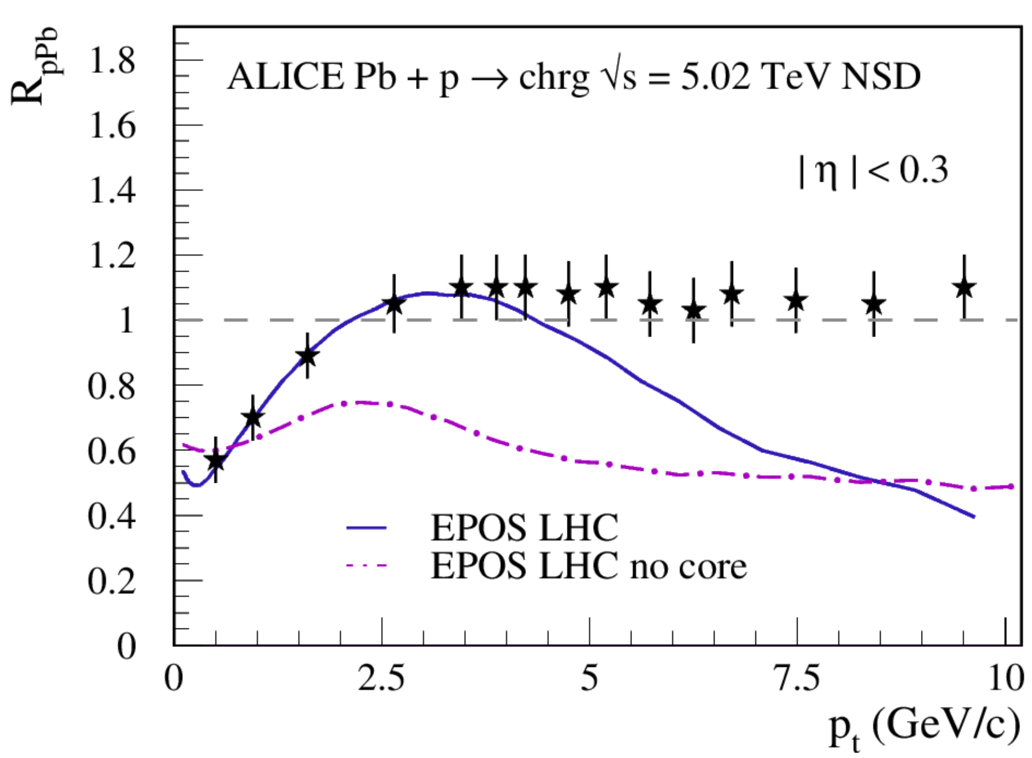


Saturation

Limitations in EPOS LHC

- Good results at low/medium p_t in Pb-p
- Problems for high p_t : no binary scaling
  - same correction for soft and hard scales
    - Solution = variable minimum for hard scale

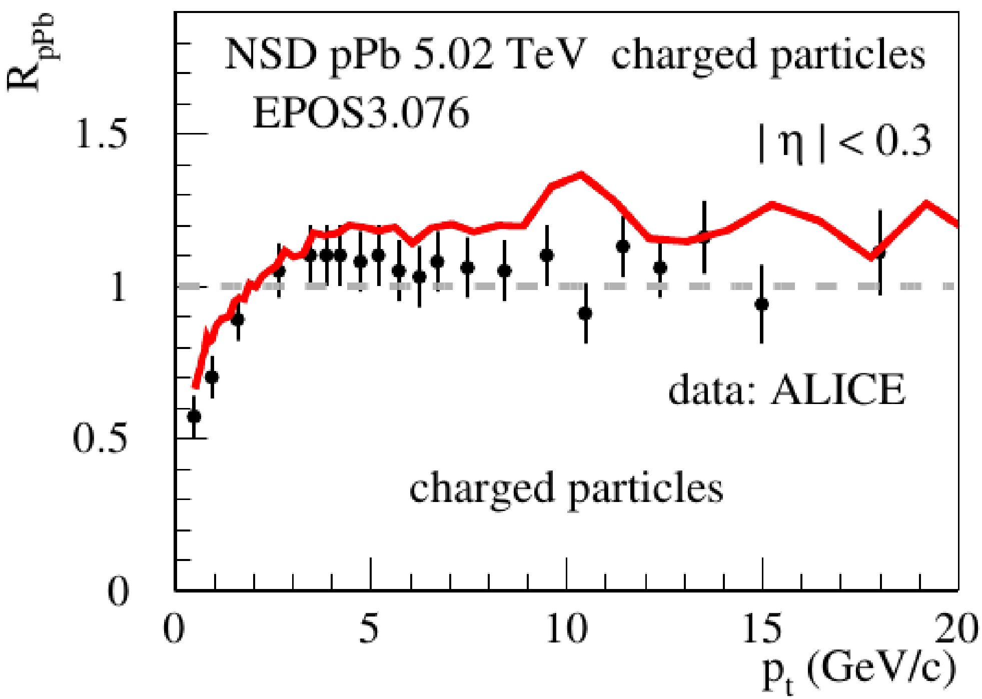


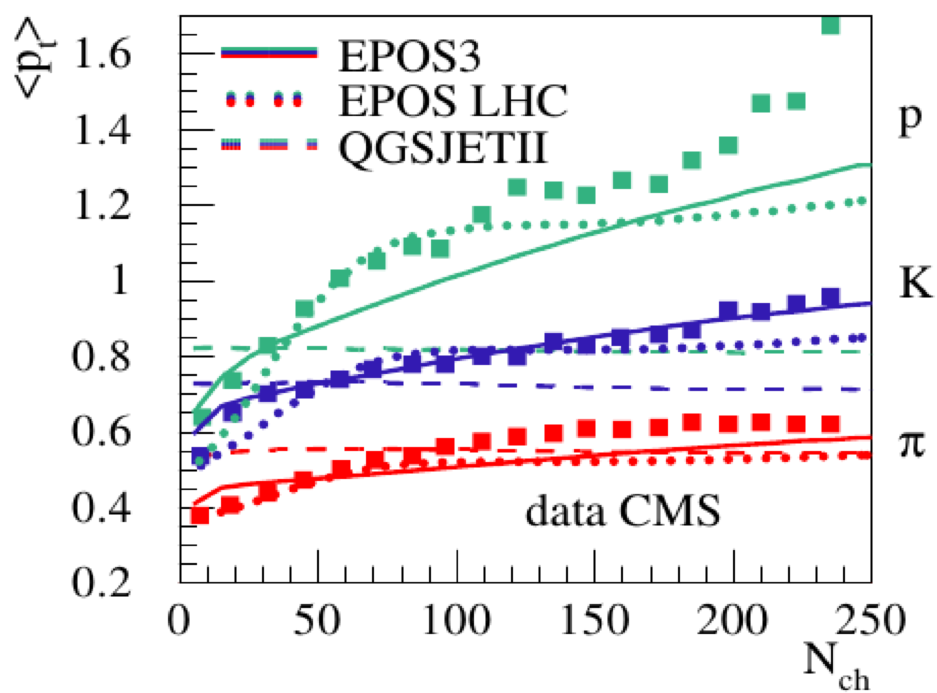


EPOS 3/4

Introduce a different min. hard scale for each Pomeron

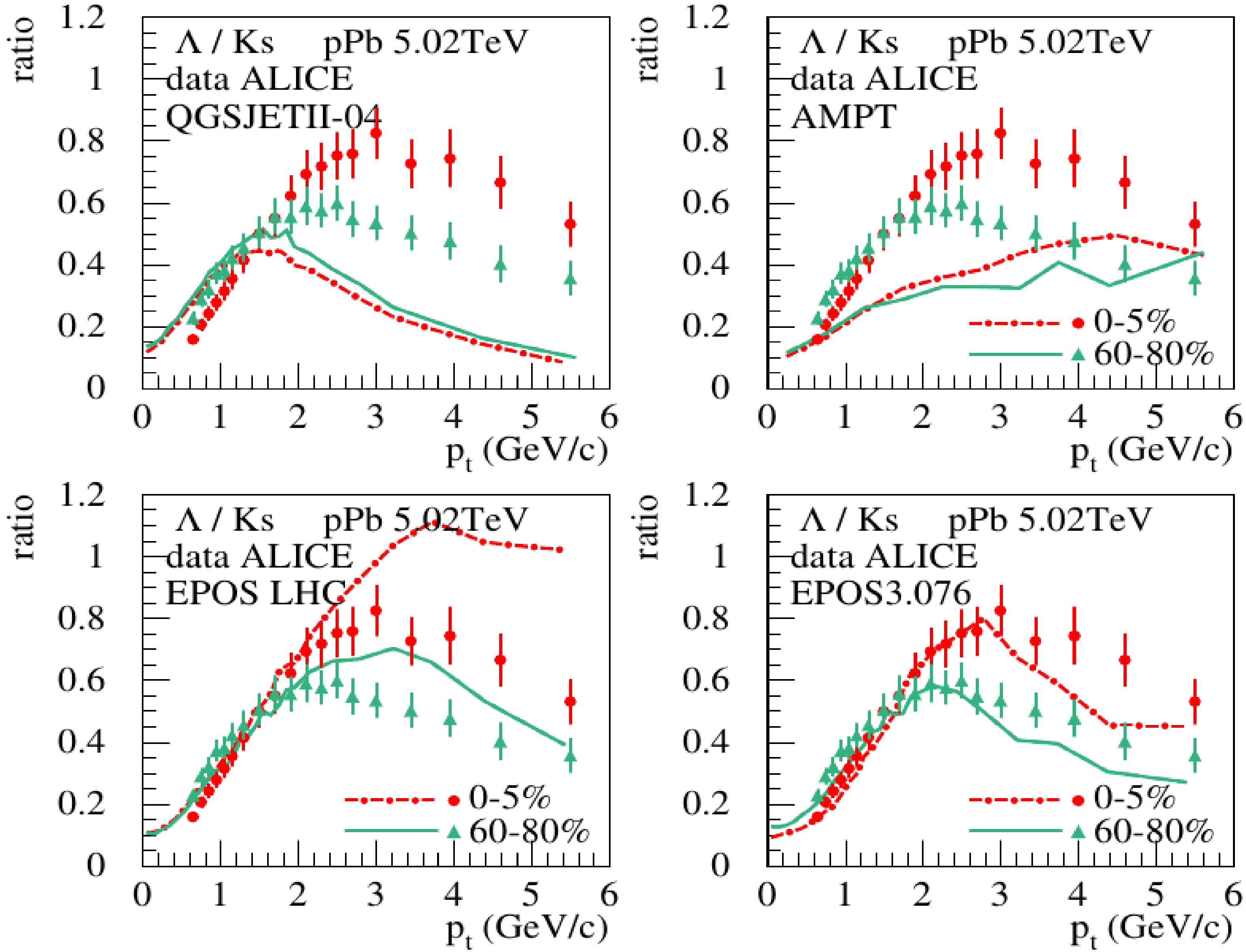
- Multiplicity dependent hard component (as observed @LHC)
- restore factorisation and binary scaling for high p_t
- intermediate p_t due to flow based on real hydro simulations
  - mass splitting





Real 3D Hydro

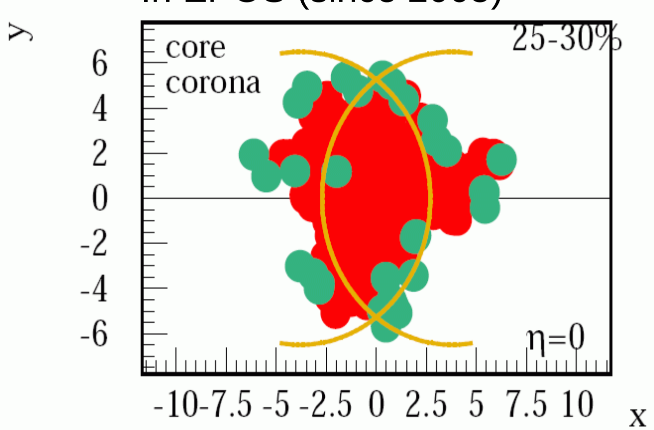
Particle ratio characteristic of collective flow effect.

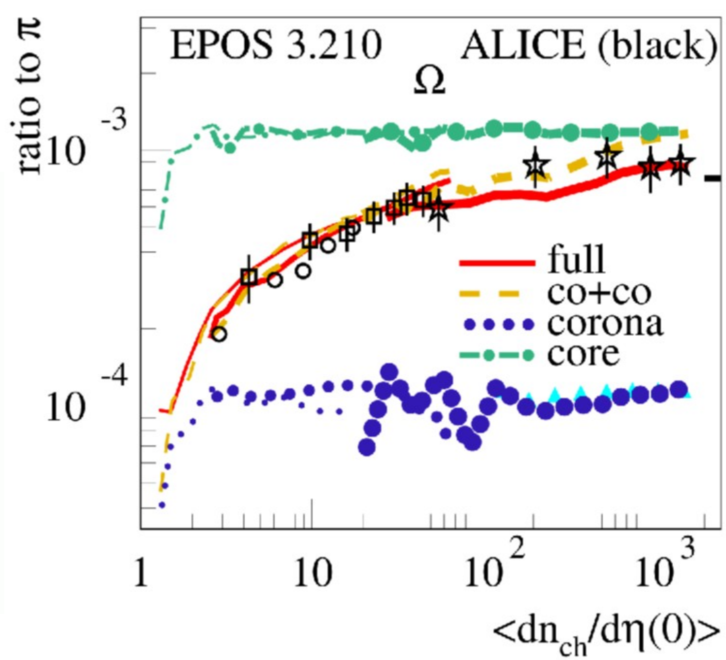


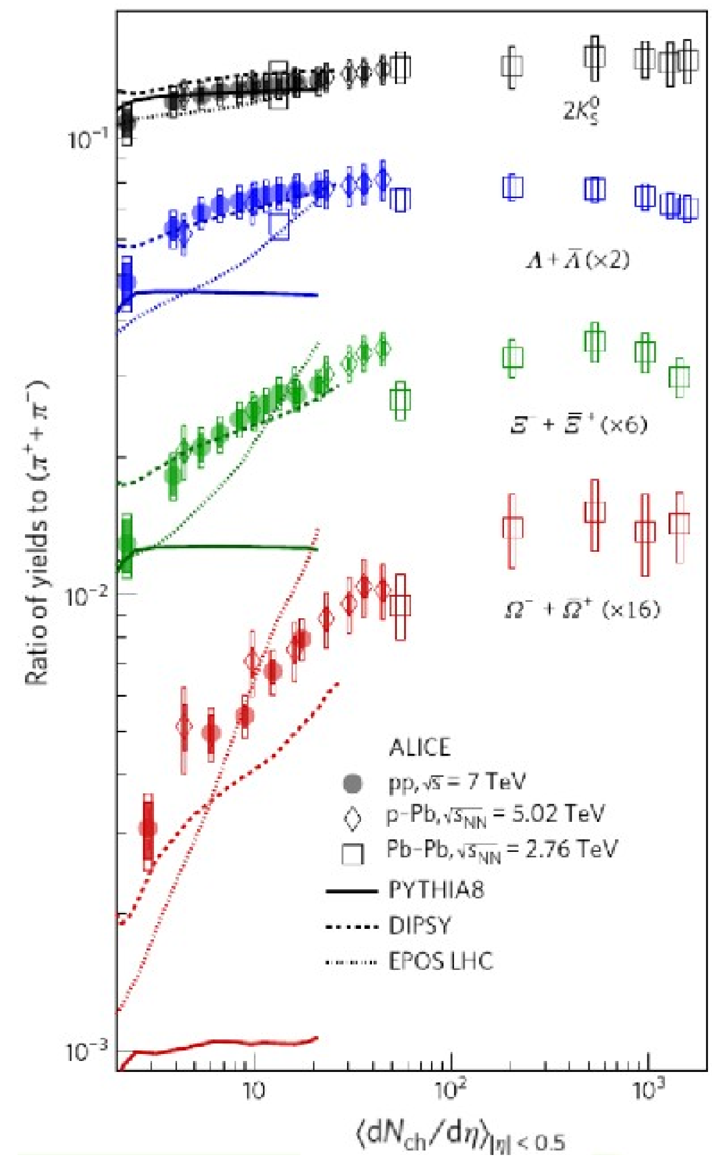
Core-Corona Approach

- **Mixing of core and corona hadronization needed to achieve detailed description of p-p data**
  - ➜ Evolution of particle ratios from pp to PbPb
  - ➜ Particle correlations (ridge, Bose Einstein correlations)
  - ➜ Pt evolution, …
- **Both hadronizations are universal but the fraction of each change with particle density**
- **2 simultanous source of particles**

In EPOS (since 2005)



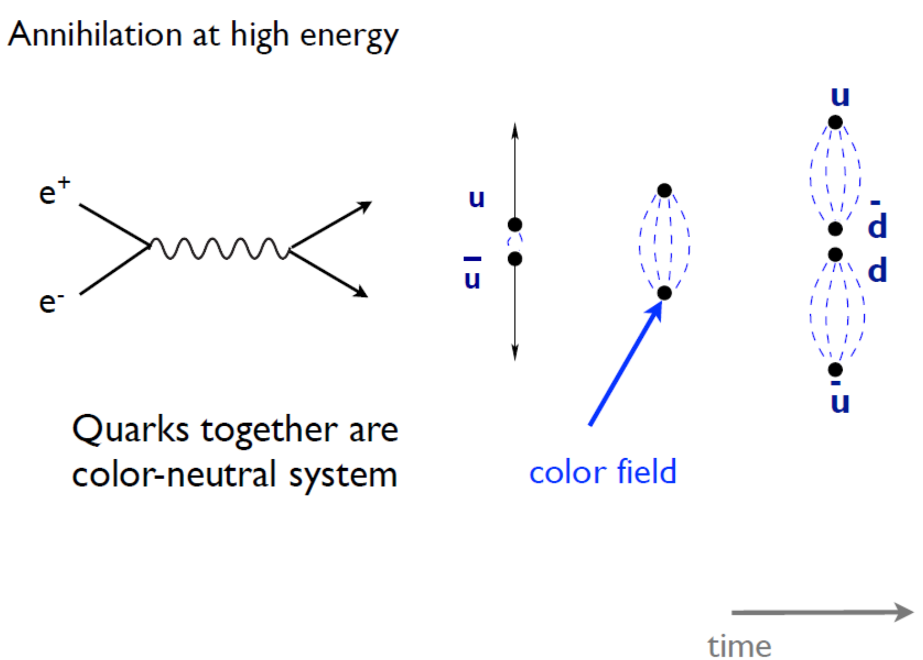


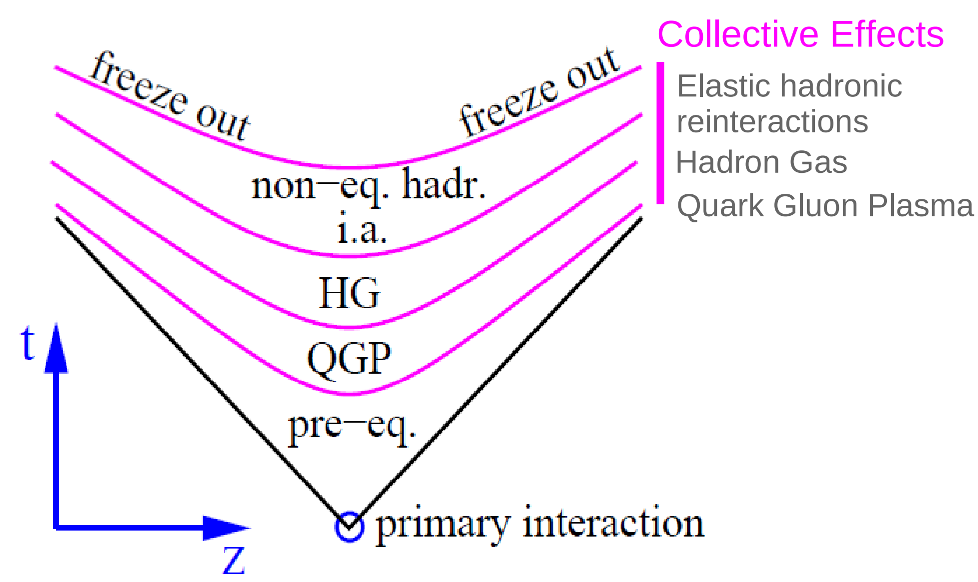


Hadronization Models

2 models well established for 2 extreme cases

➡ String Fragmentation vs Collective hadronization (statistical models)





In dilute systems… CORONA
→ "high" π^0 fraction

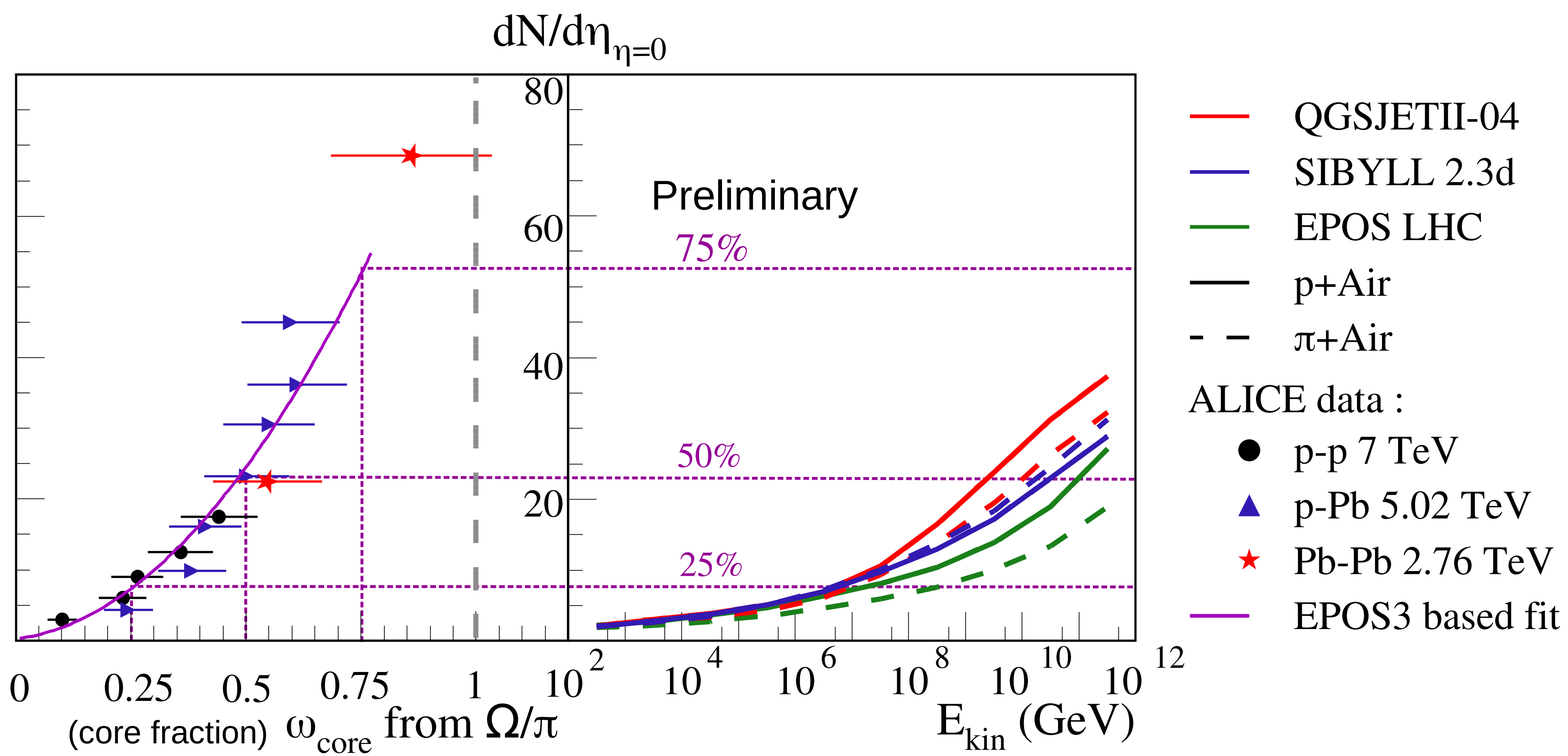
In dense systems… CORE
→ "low" π^0 fraction

➡ Important consequences for muon production in air showers !

Particle Densities in Air Showers

Is particle density in air shower high enough to expect core formation ?

- Core formation start quite early according to ALICE data
- Cosmic ray primary interaction likely to have 50% core at mid-rapidity !



Core-Corona appoach and CR

To test if a QGP like hadronization can account for the missing muon production in EAS simulations a core-corona approach can be artificially apply to any model

- Particle ratios from statistical model are known (tuned to PbPb) and fixed : core
- Initial particle ratios given by individual hadronic interaction models : corona
- Using CONEX, EAS can be simulated mixing corona hadronization with an arbitrary fraction ω_{core} of core hadronization:

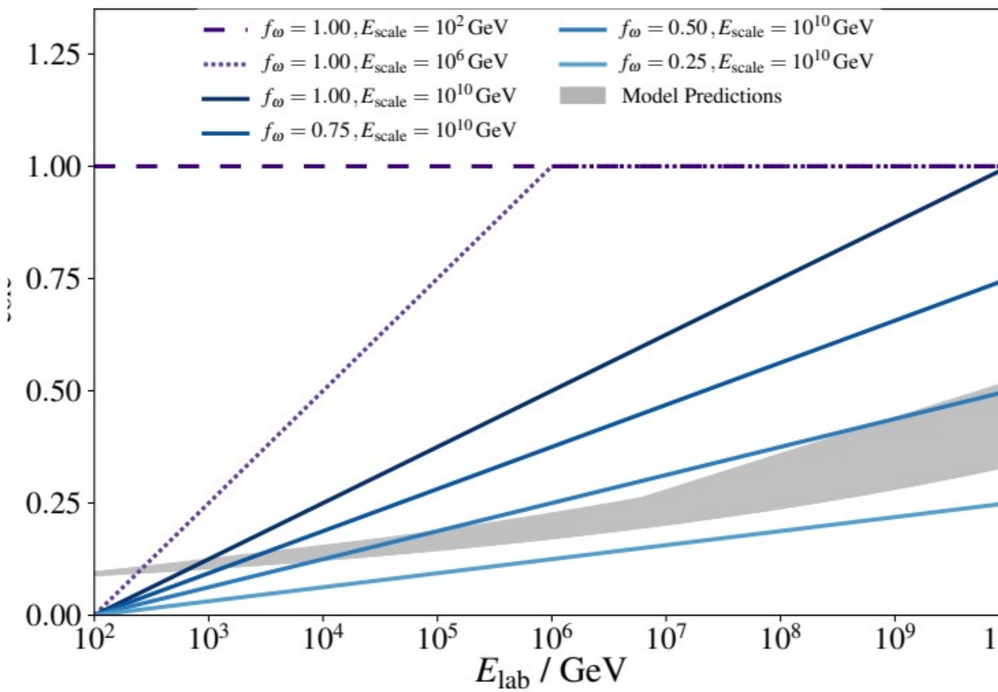
$$N_i = \omega_{\rm core}\, N_i^{\rm core} + (1-\omega_{\rm core})\, N_i^{\rm corona}$$

$$\omega_{\rm core}(E_{\rm lab}) = f_\omega \underbrace{F(E_{\rm lab}; E_{\rm th}, E_{\rm scale})}_{\frac{\log_{10}(E_{\rm lab}/E_{\rm th})}{\log_{10}(E_{\rm scale}/E_{\rm th})} \text{ for } E_{\rm lab} > E_{\rm th}}$$

$$E_{\rm th} = 100\,{\rm GeV}$$

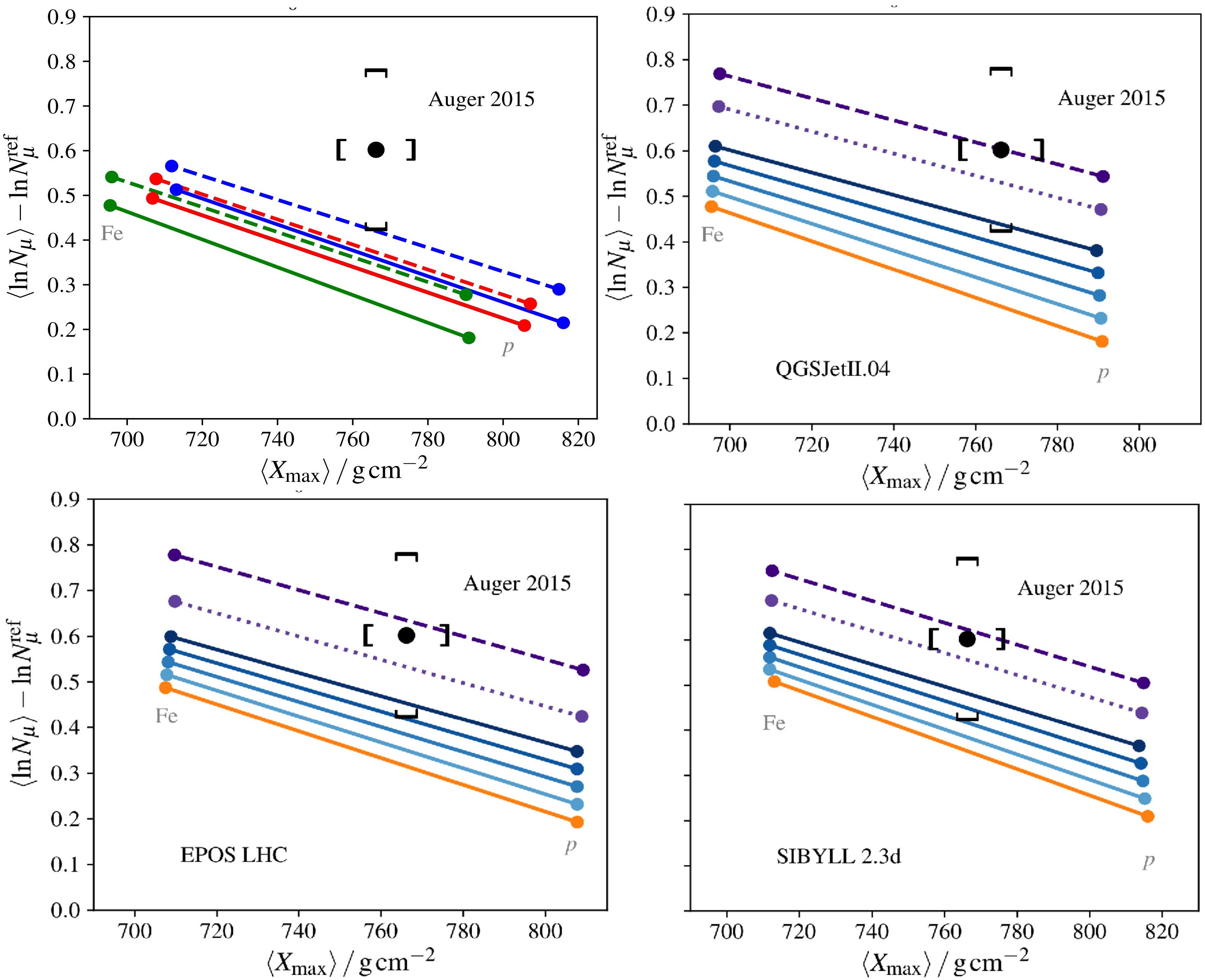
Different scenarii can be studied playing with f_ω and E_{scale}.

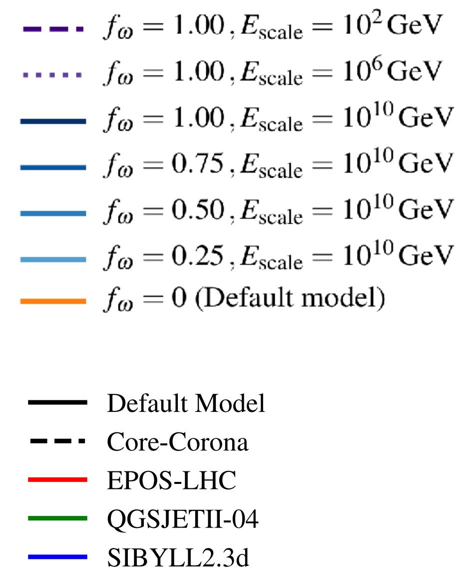
Note : the leading particle is NOT modified (projectile remnant)



Plot by M. Perlin

Results for X_{max}-N_{mu} correlation



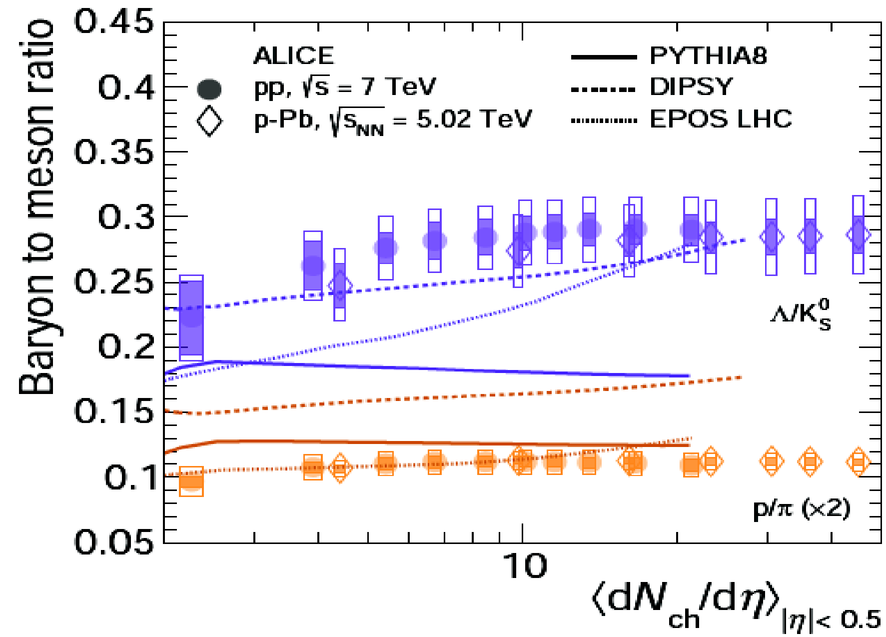


Plot by M. Perlin

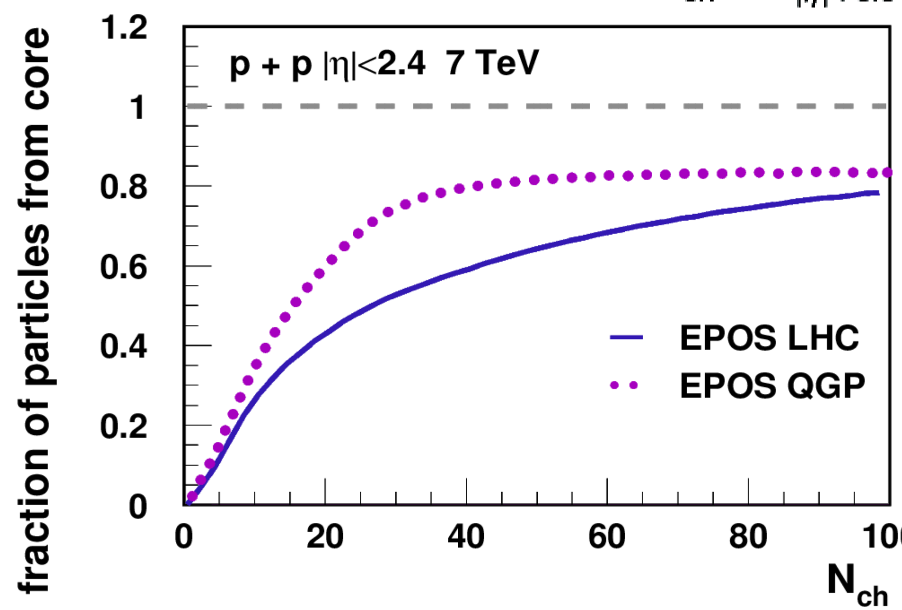
Forward core fraction unknown and not necessarily lower that at mid-rapidity (saturation effect)

Modified EPOS with Extended Core

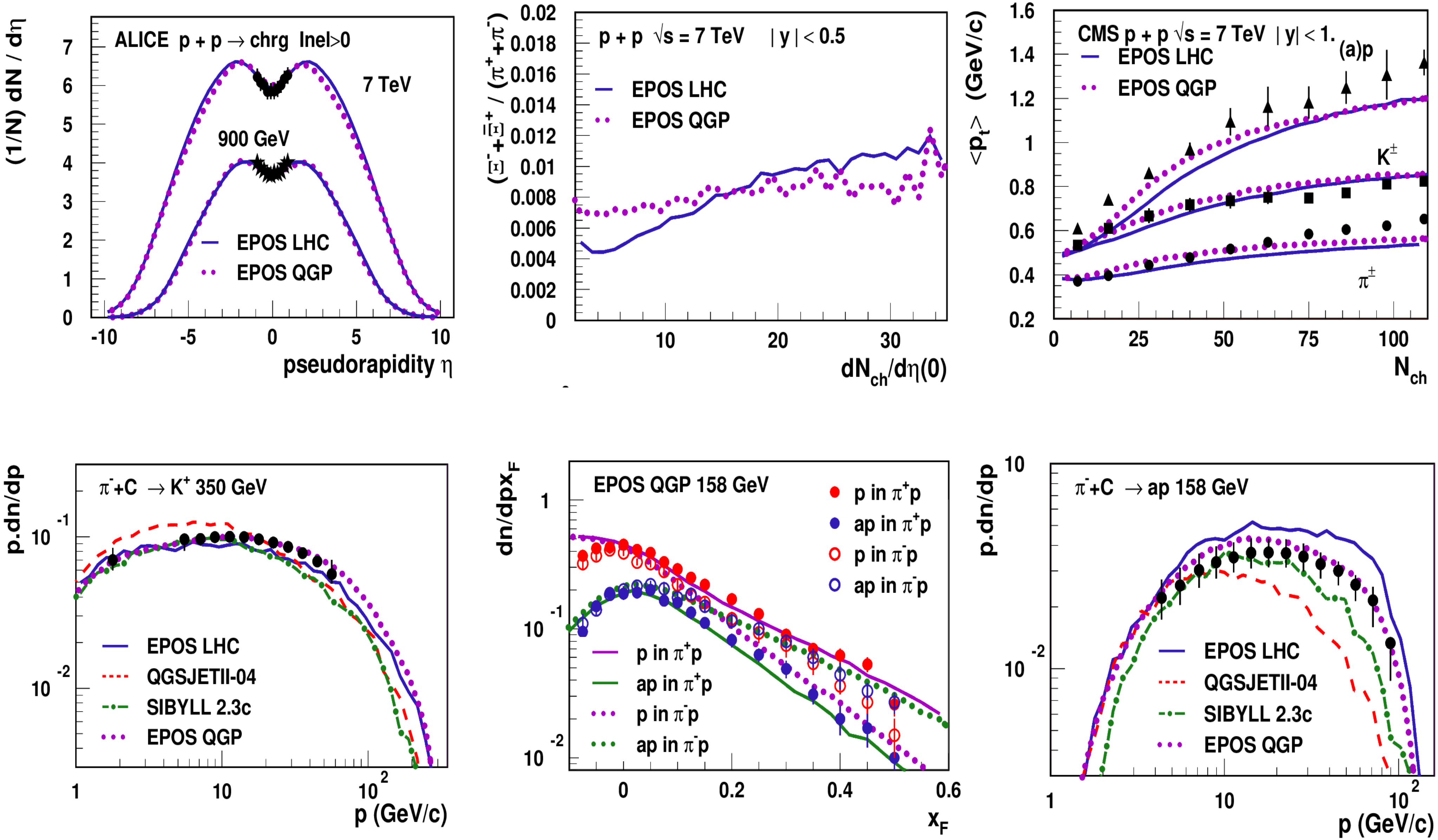
- **Core in EPOS LHC appear too late**
  - Recent publication show the evolution of chemical composition as a function of multiplicity
  - Large amount of (multi)strange baryons produced at lower multiplicity than predicted by EPOS LHC



- **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) as in EPOS 4
  - Faster development than EPOS 4 and less changes (easier to track physical effect)

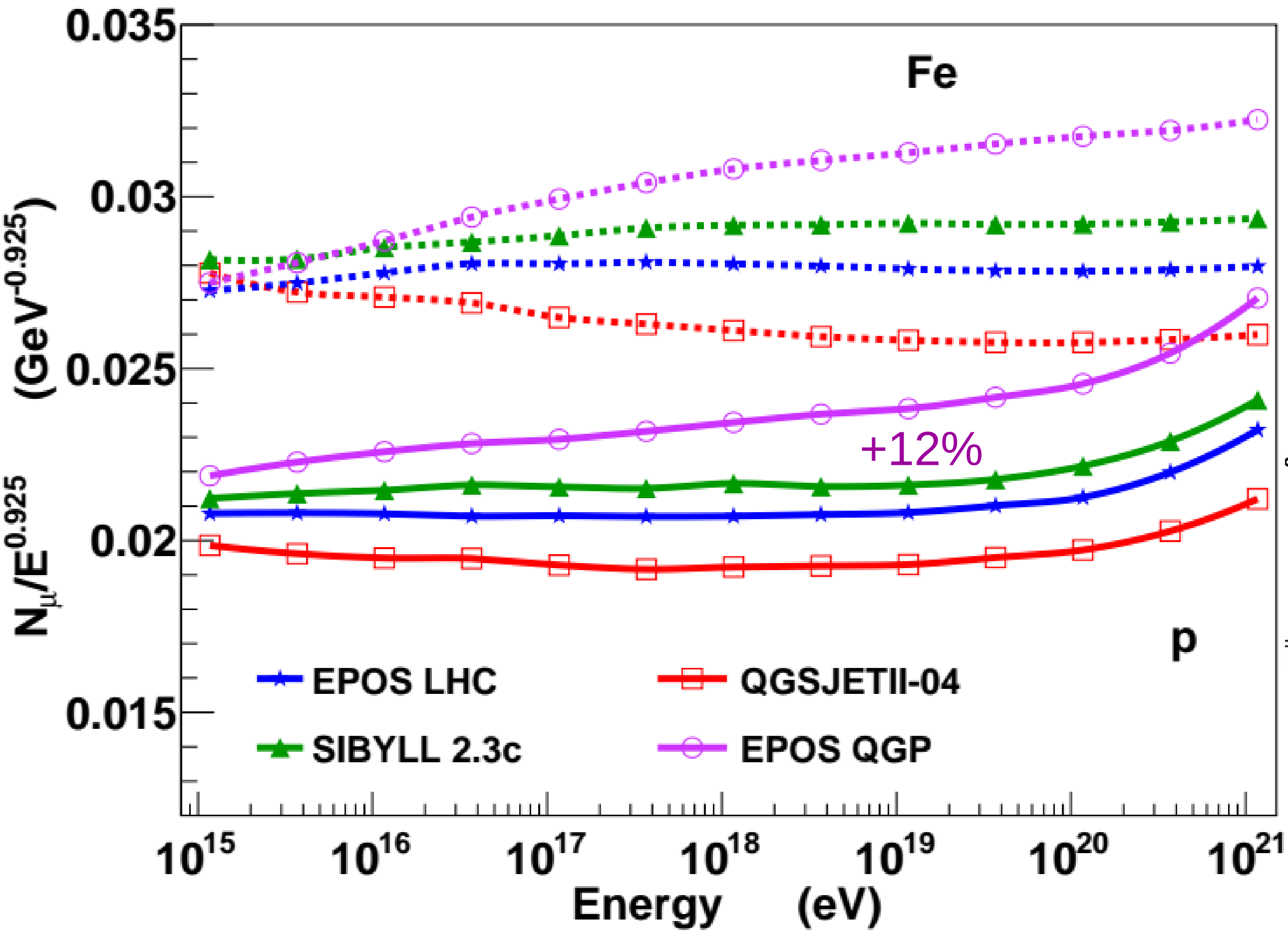


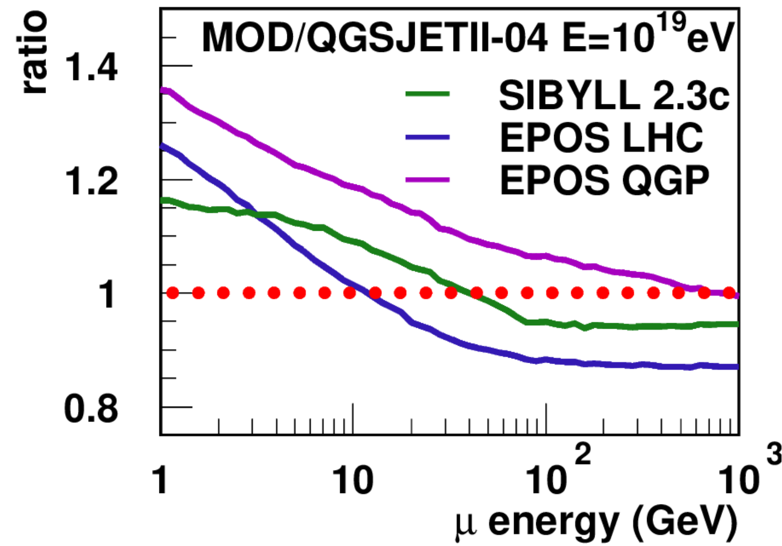
Preliminary Version with Minimum Constraints

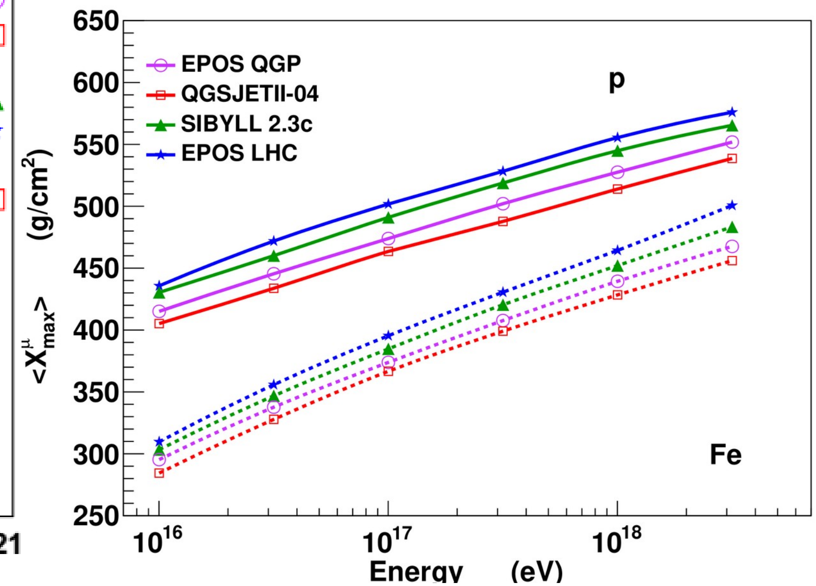


EPOS QGP for Air Showers

Significant changes in number, energy distribution and production height of muons
and all in the “right” direction ...





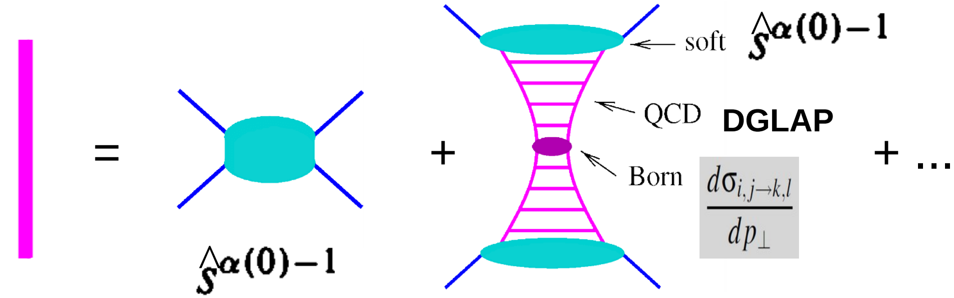


Summary on EPOS

- **EPOS important for EAS as only model comparable to all LHC data (heavy ions with collective effects)**
- **Hadronic interactions with EPOS 4:**
  - ➡ Consistent treatment for all kind of system : final state depends on the energy used for each event (multiplicity) not only on the energy available (collective hadronization when density of particles is high)
  - ➡ Hydro on event-by-event basis (slow) or effective flow (fast) tune on real hydro
  - ➡ Pomeron mass and number dependent hard scale :
    - ➡ Improvement of hard events (jets) in MB
  - ➡ Heavy flavor (charm and beauty)
  - ➡ (very) long development time (and not compatible (yet) with EAS)
- **Update of EPOS LHC with latest LHC results for EAS simulations on a smaller time scale**

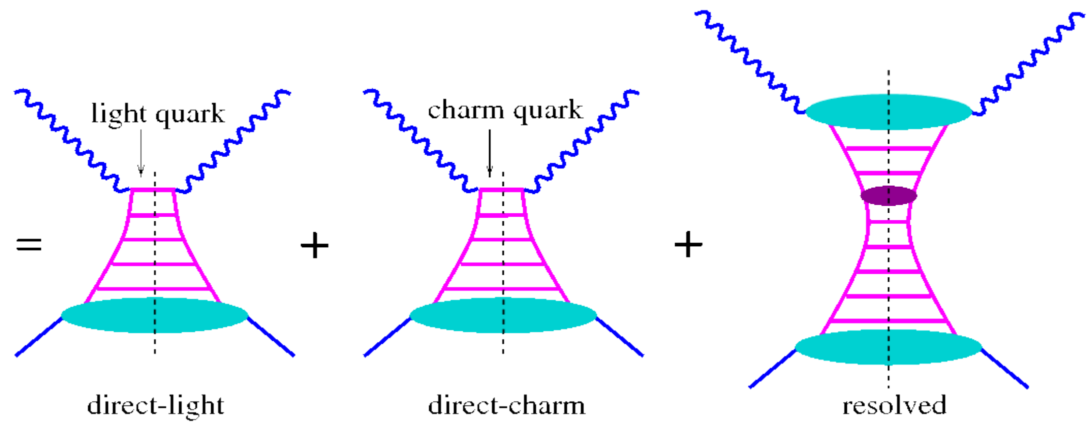
EPOS : Pomeron definition

Semi-hard Pomeron :



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

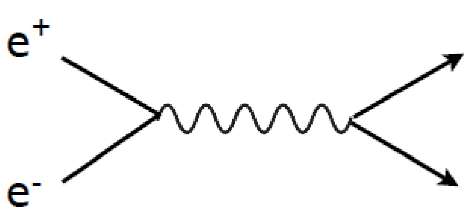
$\sigma_T =$



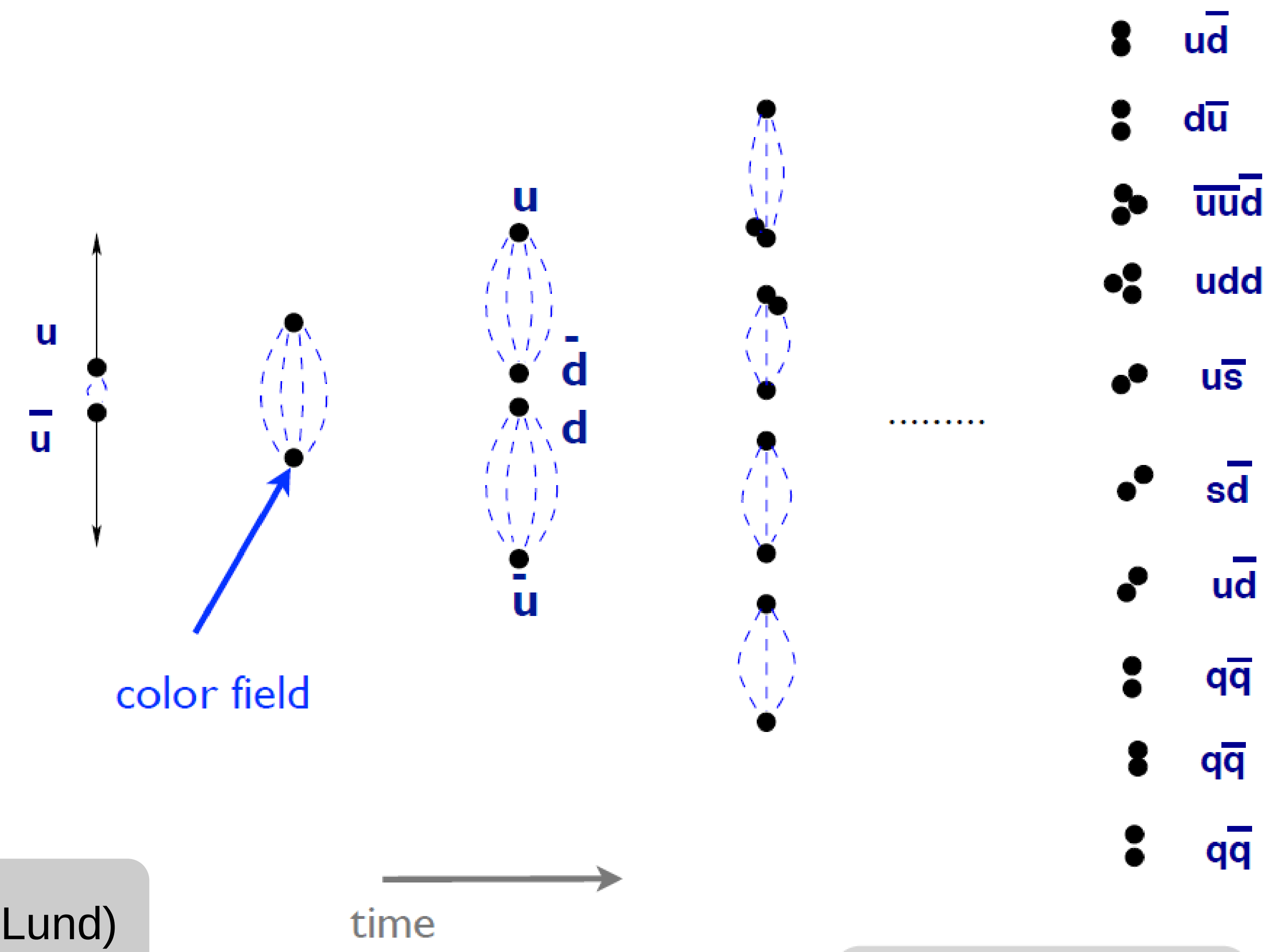
- Theory based Pomeron definion
  - pQCD based so large increase at small x (no saturation)
  - produce too high cross section
  - corrections needed using enhanced diagrams (triple Pomeron vertex)
    - effective coupling vertex

Simplest case: e^+e^- annihilation into quarks

Annihilation at high energy



Quarks together are color-neutral system

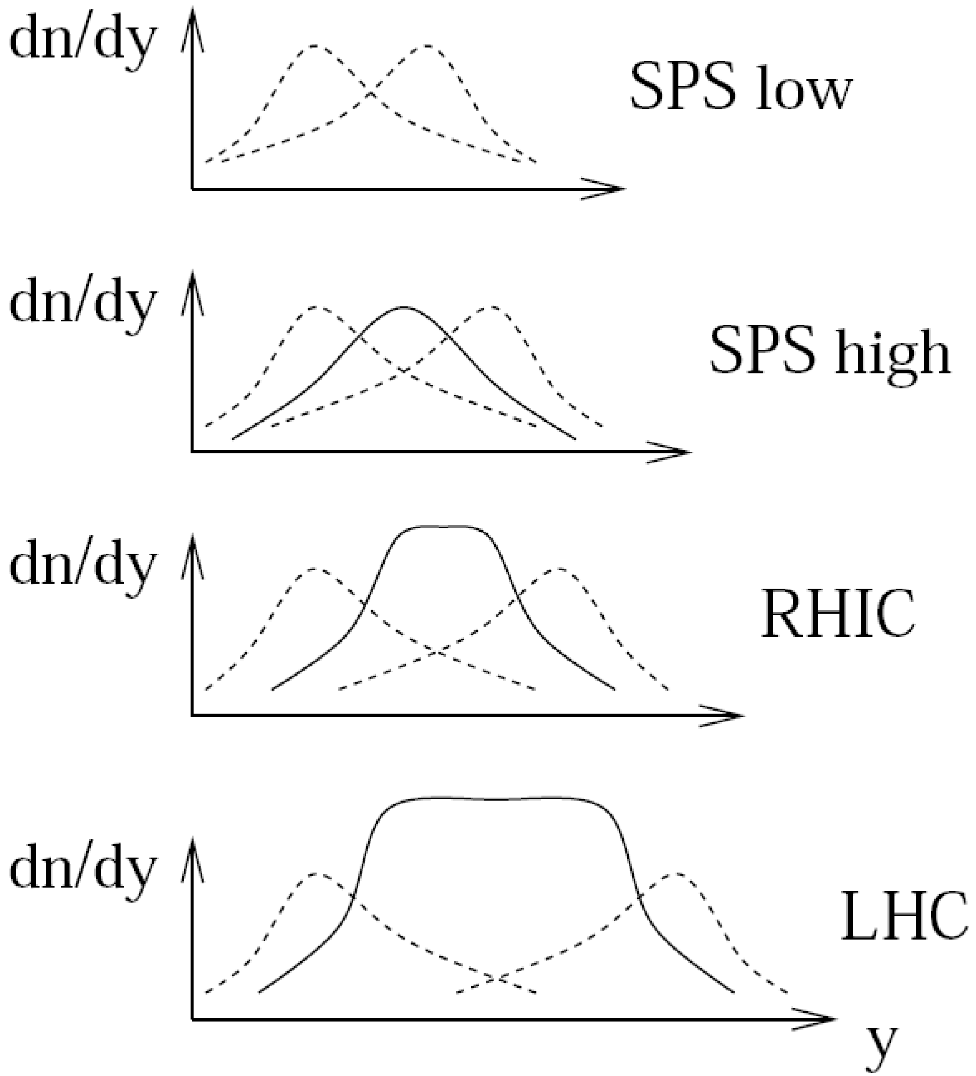


Area law used in EPOS (not Lund)

Chain of hadrons

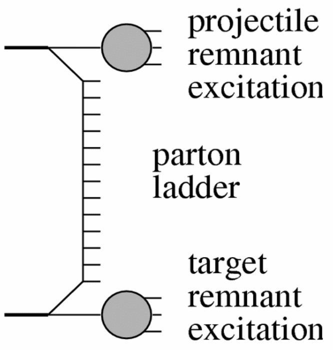
String fragmentation

Remnants



Free remnants in EPOS:

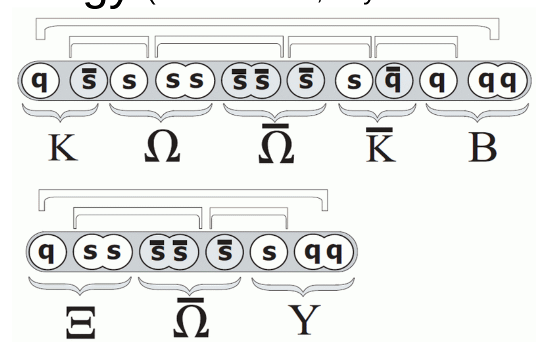
- from both diffractive or inelastic scattering
- excited state with $P(M) \sim 1/(M^2)^\alpha$
- dominant contribution at low energy
- forward region at high energy
- depending on quark content and mass (excitation):
  - resonance
  - string
  - droplet (if #q>3)
  - string+droplet



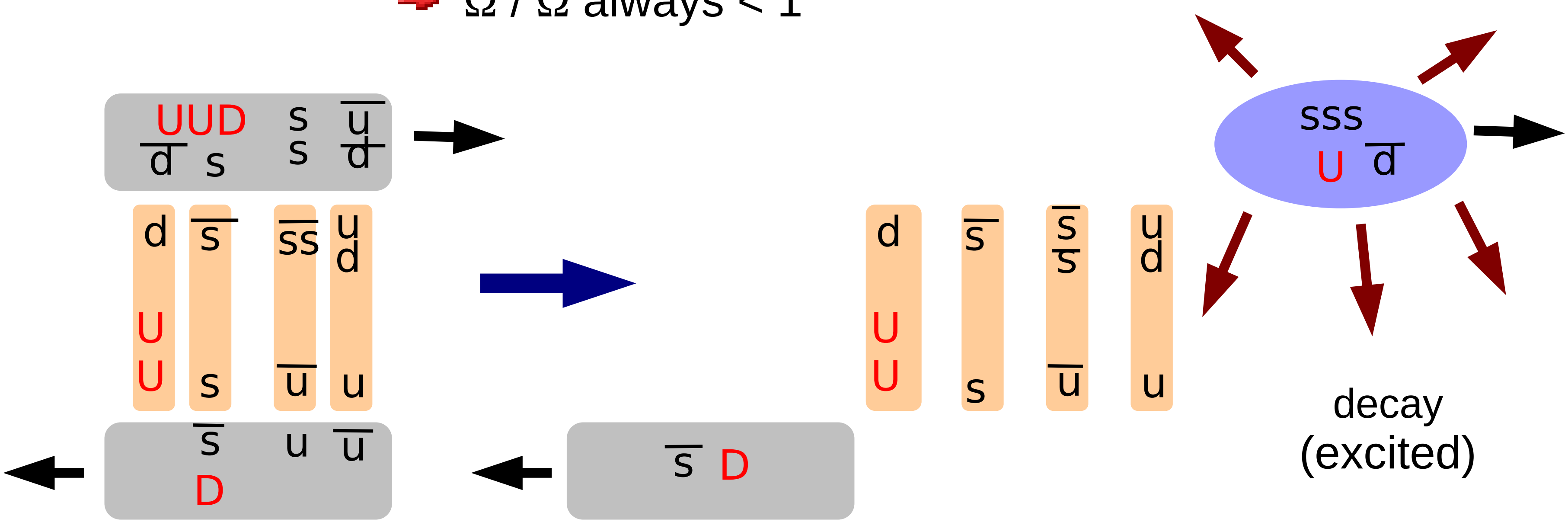
Baryons and Remnants

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)

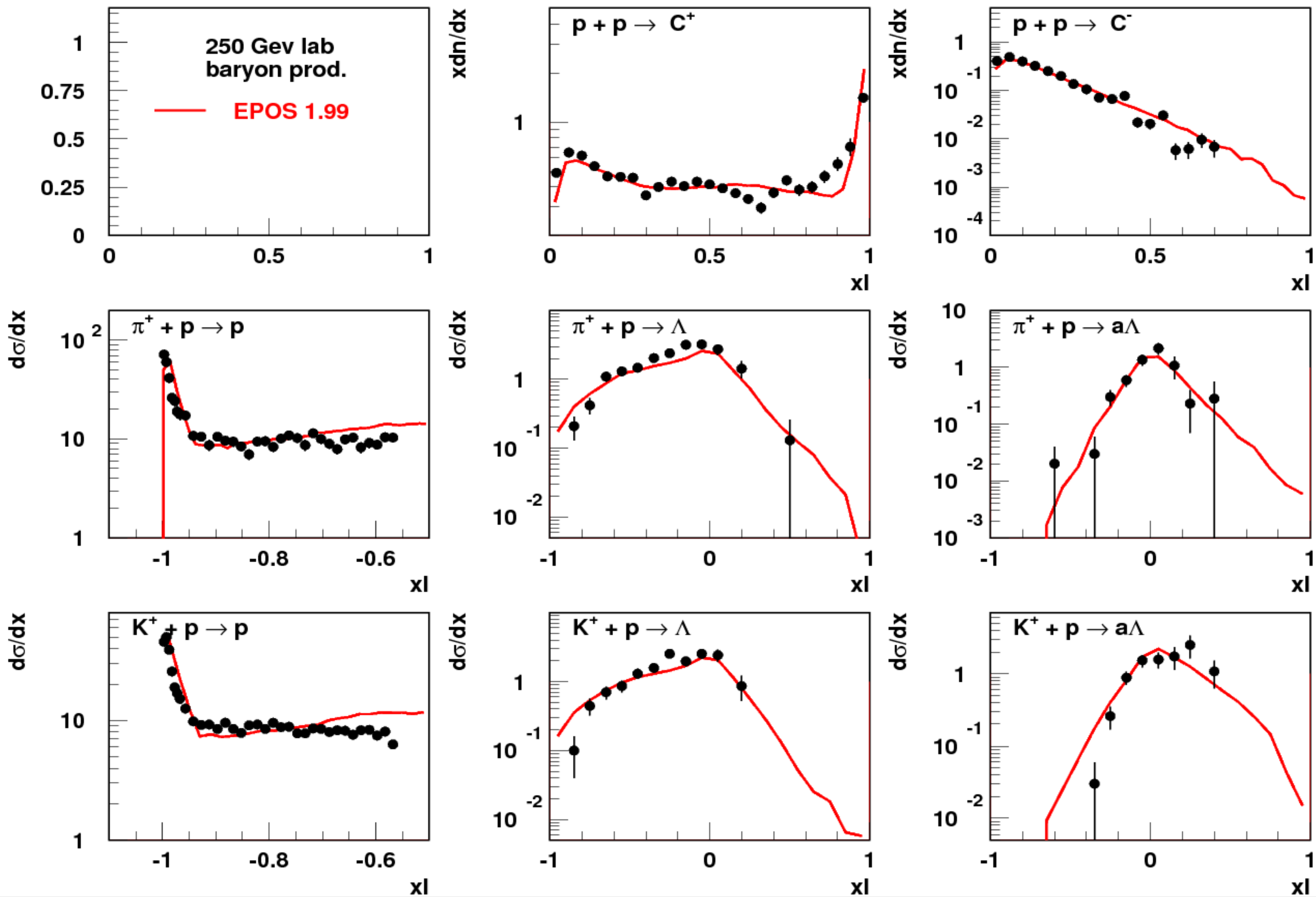


- EPOS
  - No “first string” with valence quarks : all strings equivalent
  - Wide range of excited remnants (from light resonances to heavy quark-bag)
    - $\bar{\Omega}$ / Ω always < 1



Baryon Production

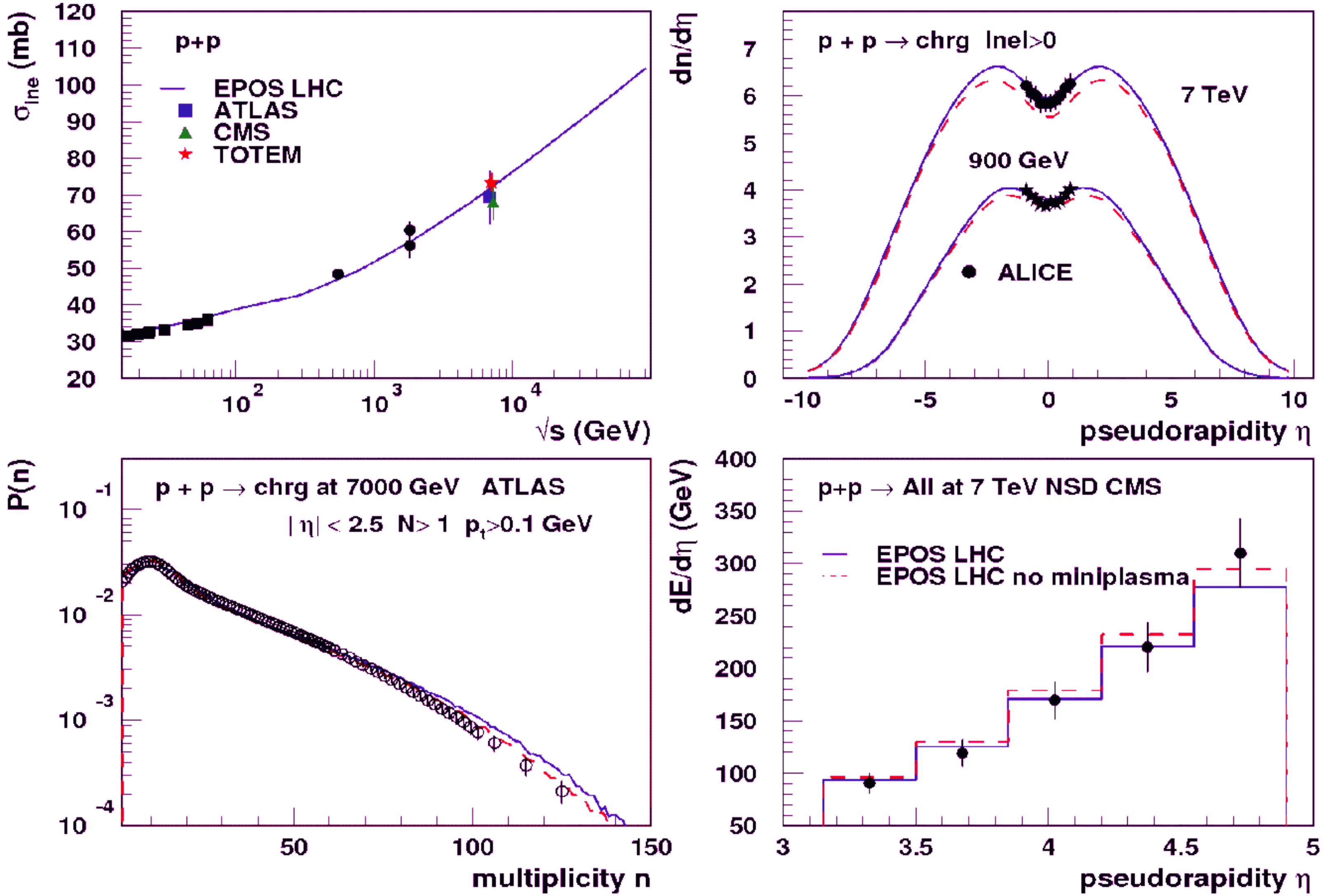
Baryon production for fixed target exp.



EPOS LHC

Effective flow treatment

- hydro replaced by tuned asymmetric p_t boost



EPOS LHC

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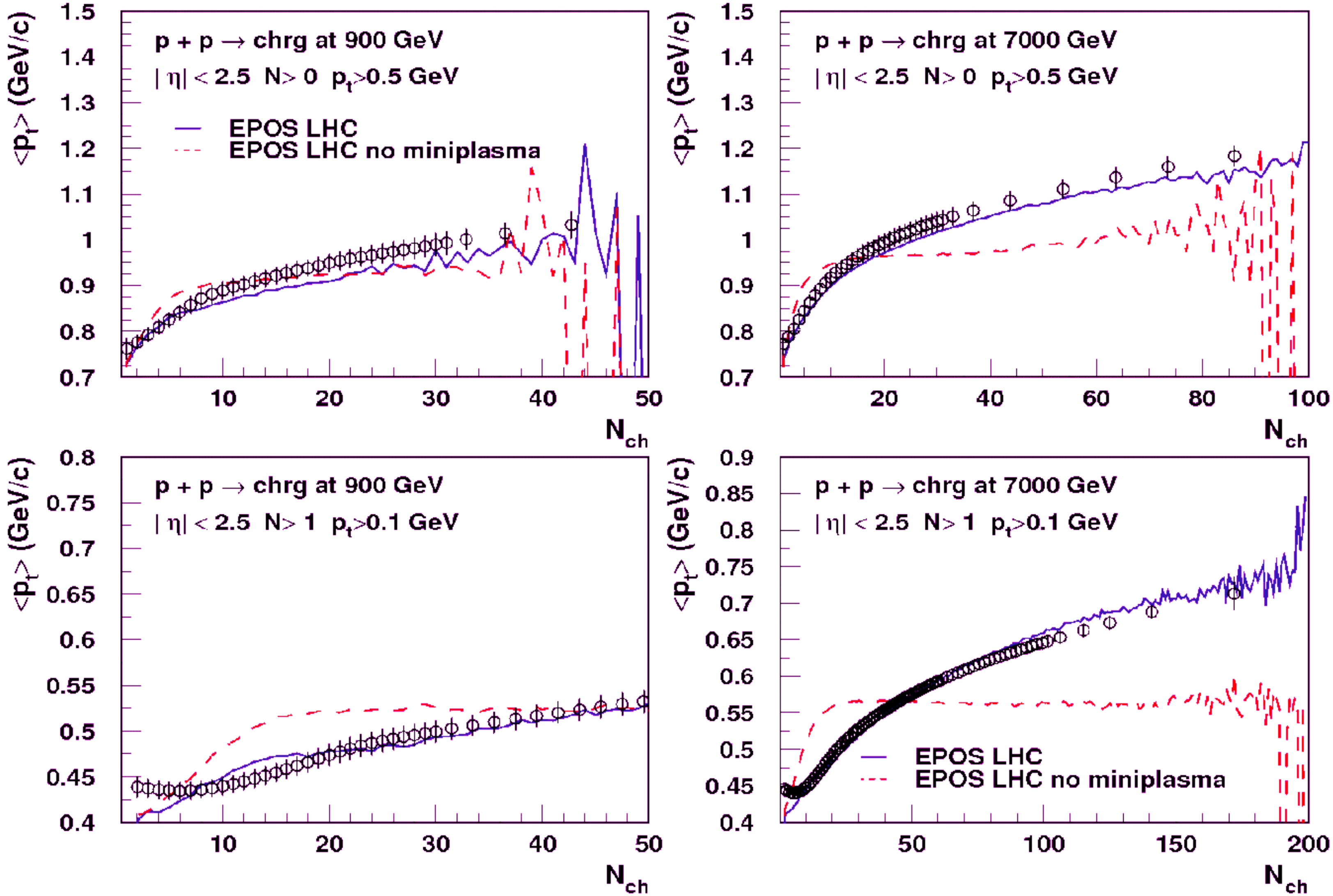
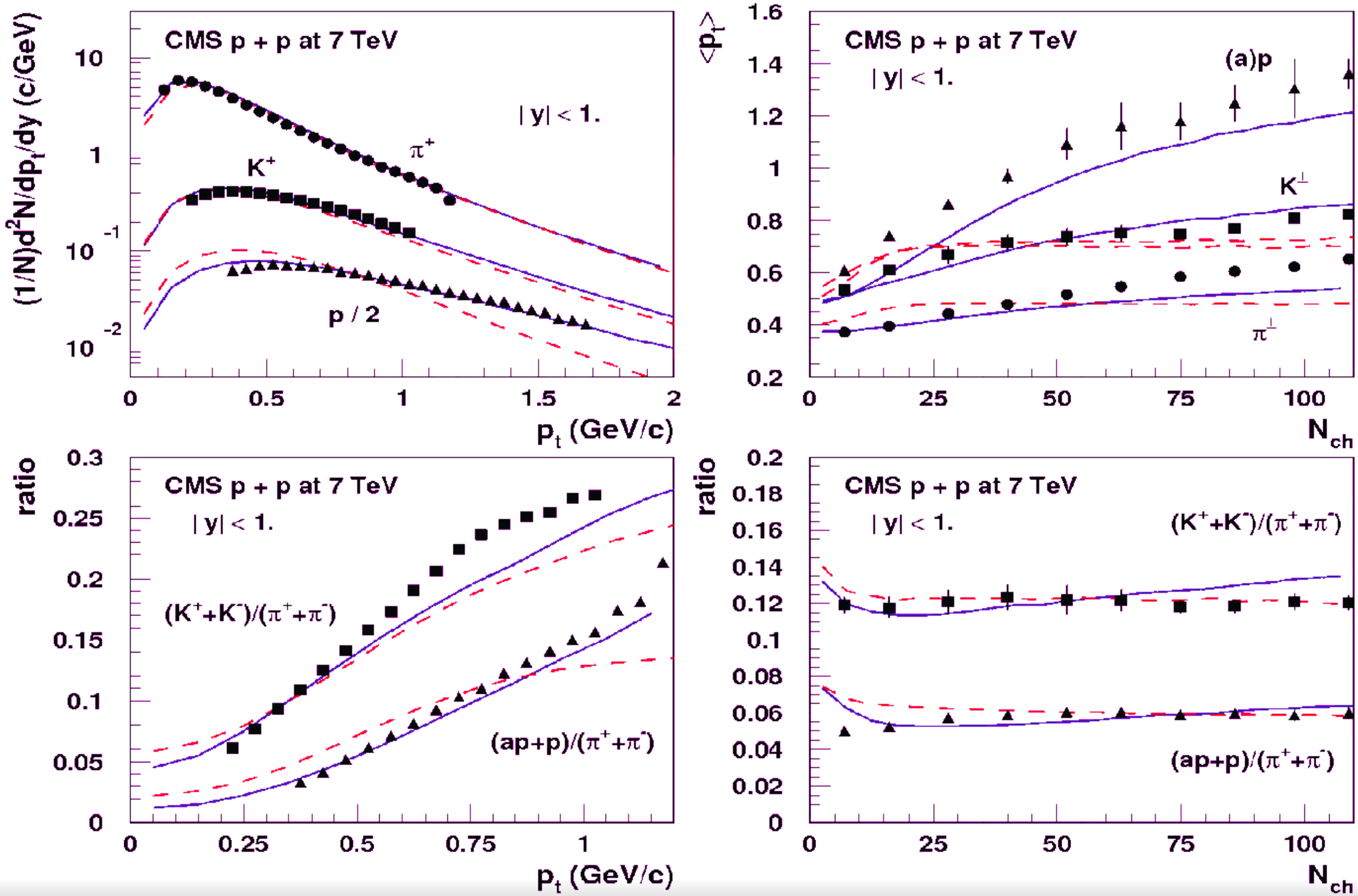


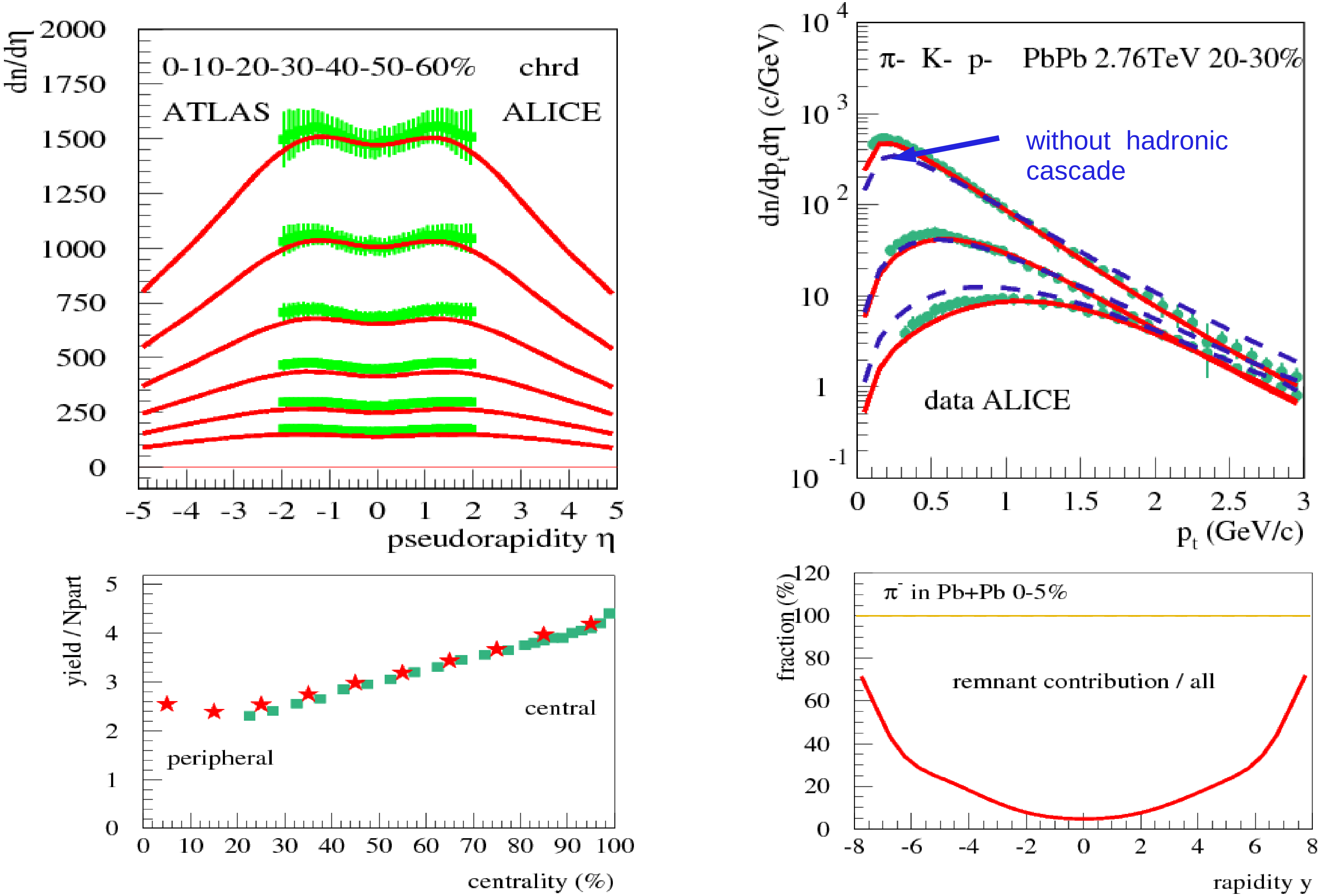
EPOS LHC

Detailed description can be achieved

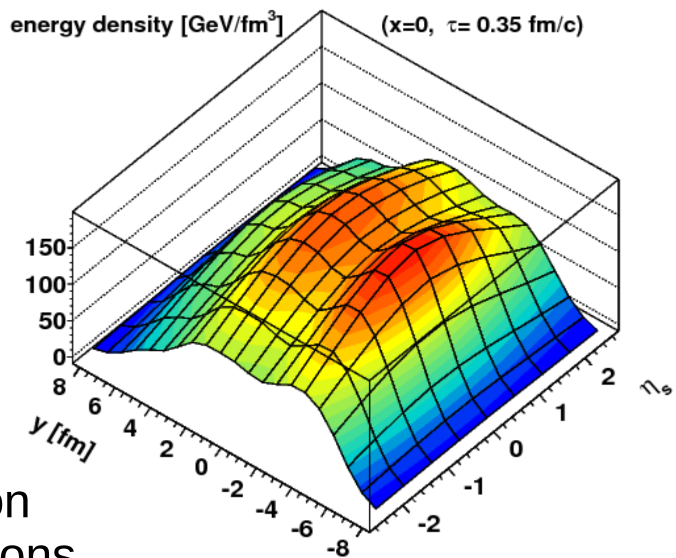
- identified spectra
- p_t behavior driven by collective effects (statistical hadronization + flow)



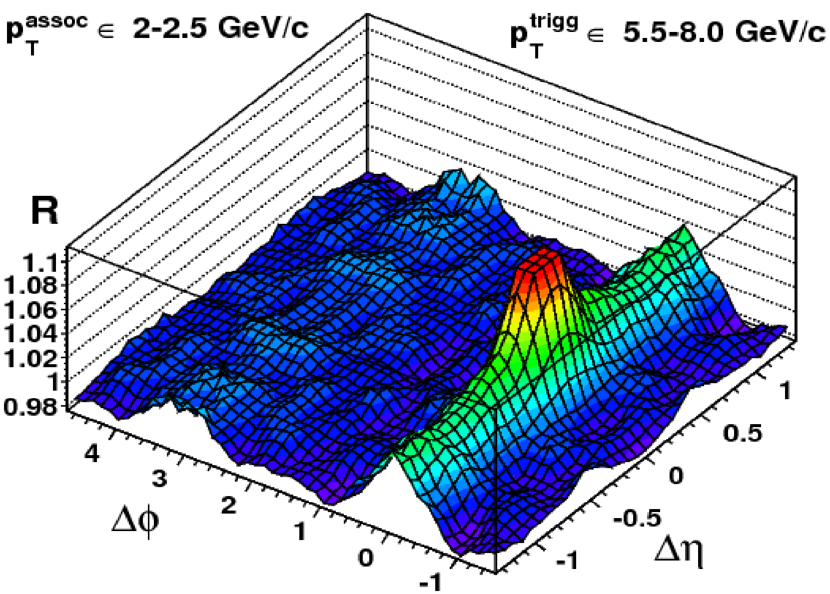
PbPb @ LHC


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
$dn/dp_td\eta$ (c/GeV)
10^4
10^3
10^2
10
1
10^{-1}
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

Correlations in PbPb@LHC



di-hadron correlations



Fourier coefficient for most central events