EPOS Model for p-p Collisions

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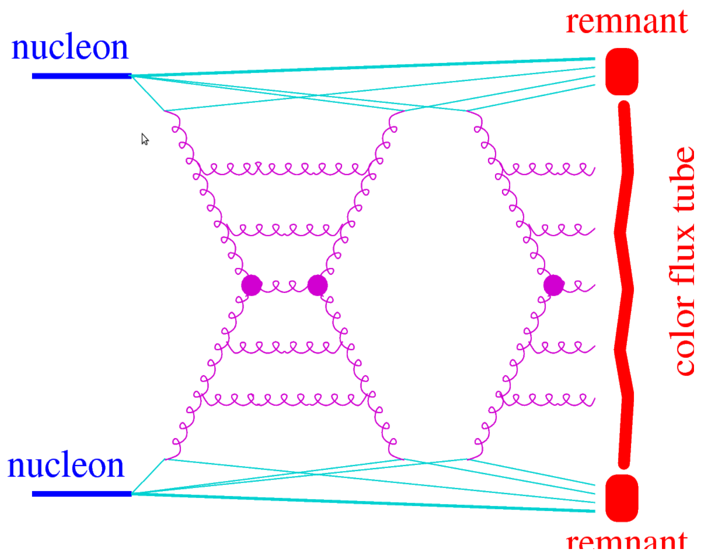
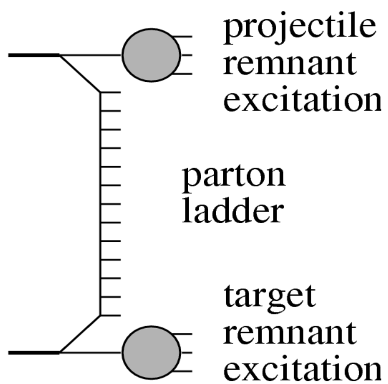
The EPOS Model





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, B. Guiot 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 : 2015 (still under development)
    - High mass and central diffraction
    - 3D+1 viscous event-by-event hydro calculation (includ. pp)
    - New saturation scale : parton distribution functions and jet cross-section

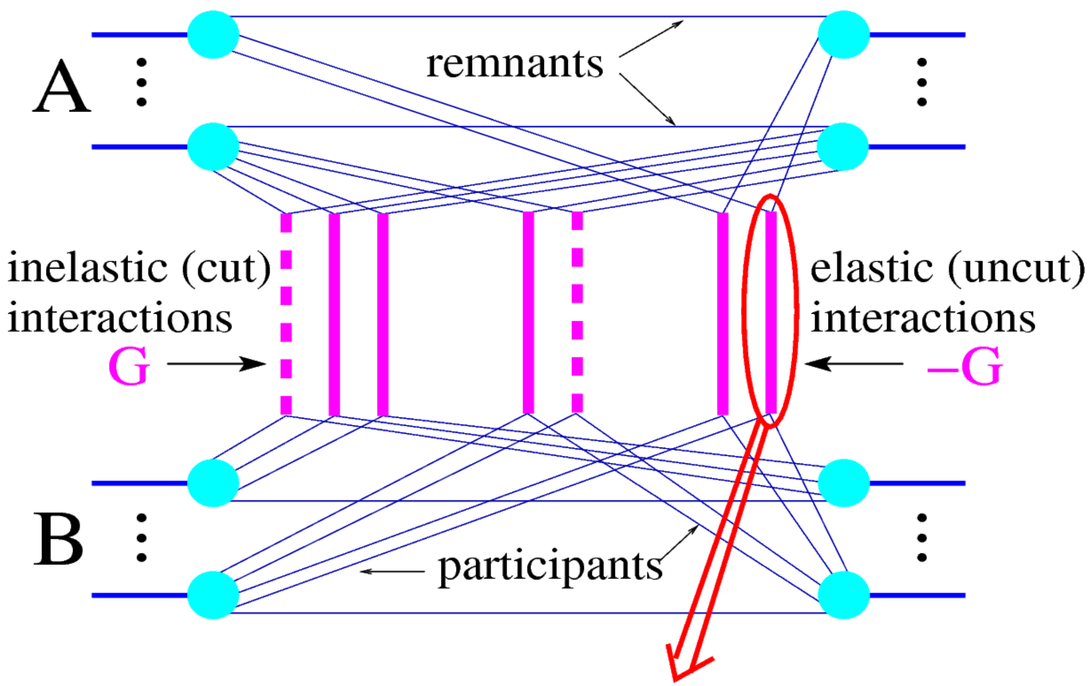
EPOS : Parameters

- **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 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

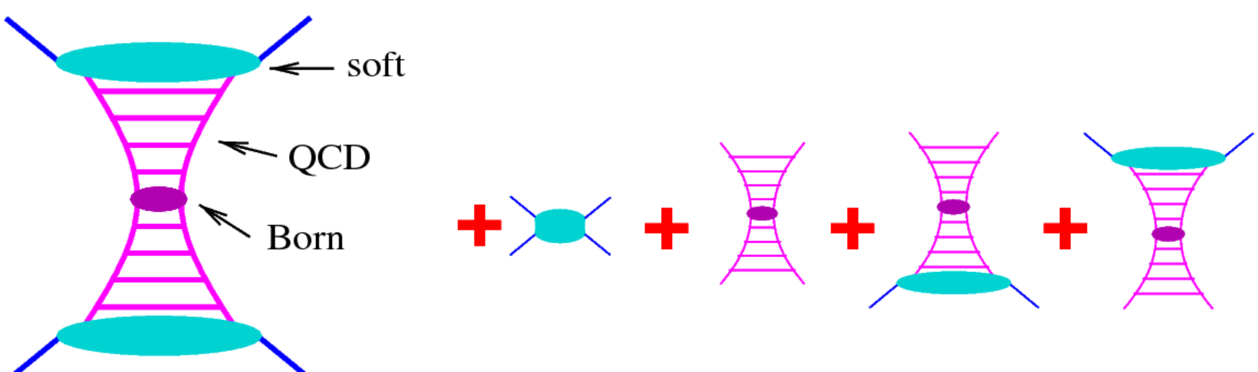
Outline

- **EPOS Model**
  - Energy sharing
  - Parton multiple scattering (MPI)
  - Screening, Shadowing and Strings
  - Outshell remnants

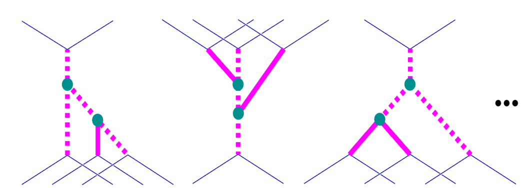
Parton-Based Gribov-Regge Theory



- **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)

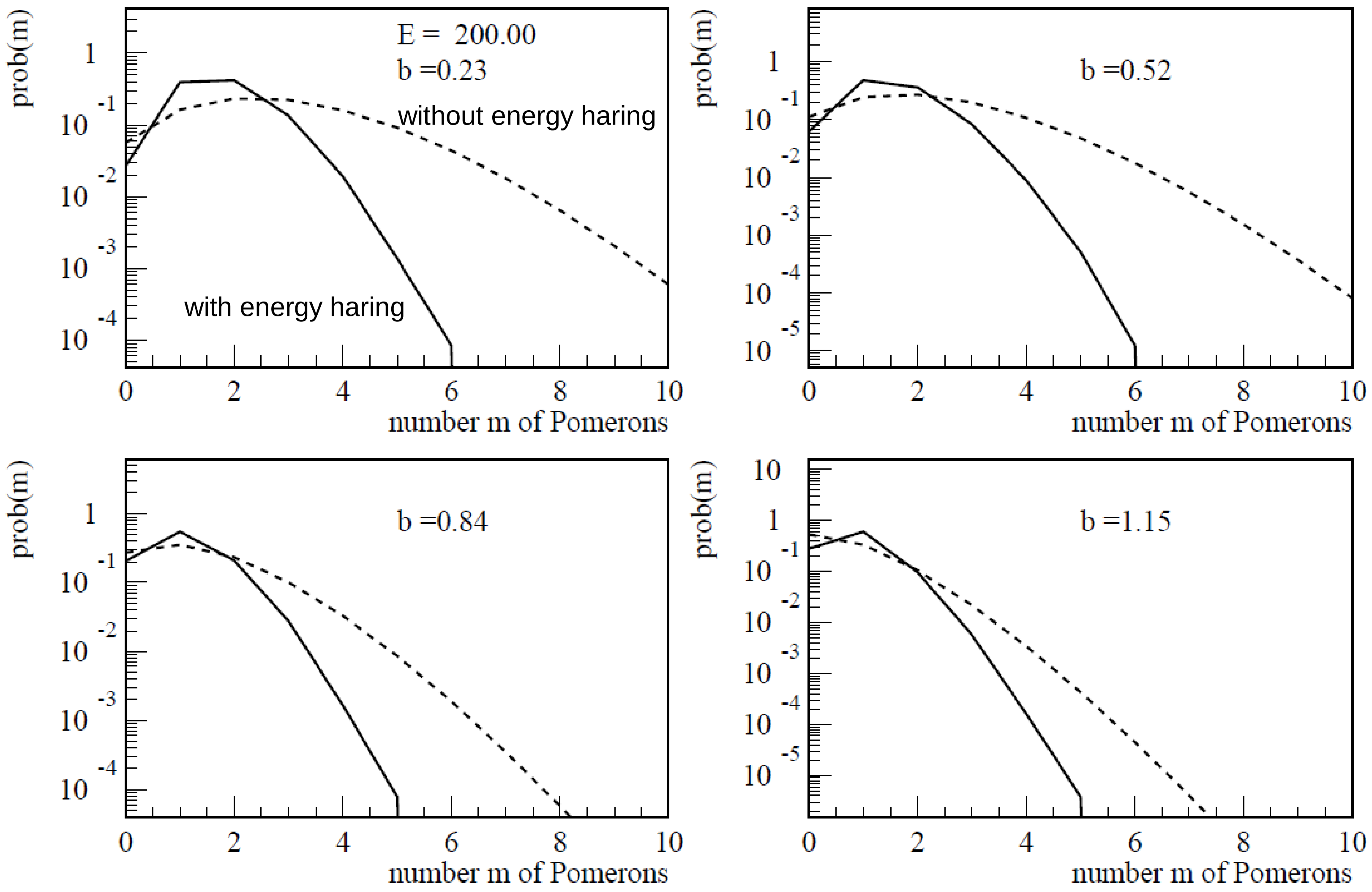


Non-linear effect (screening) absorbed in modified vertex functions



Number of Inelastic Parton Scattering

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



EPOS – high parton density effects

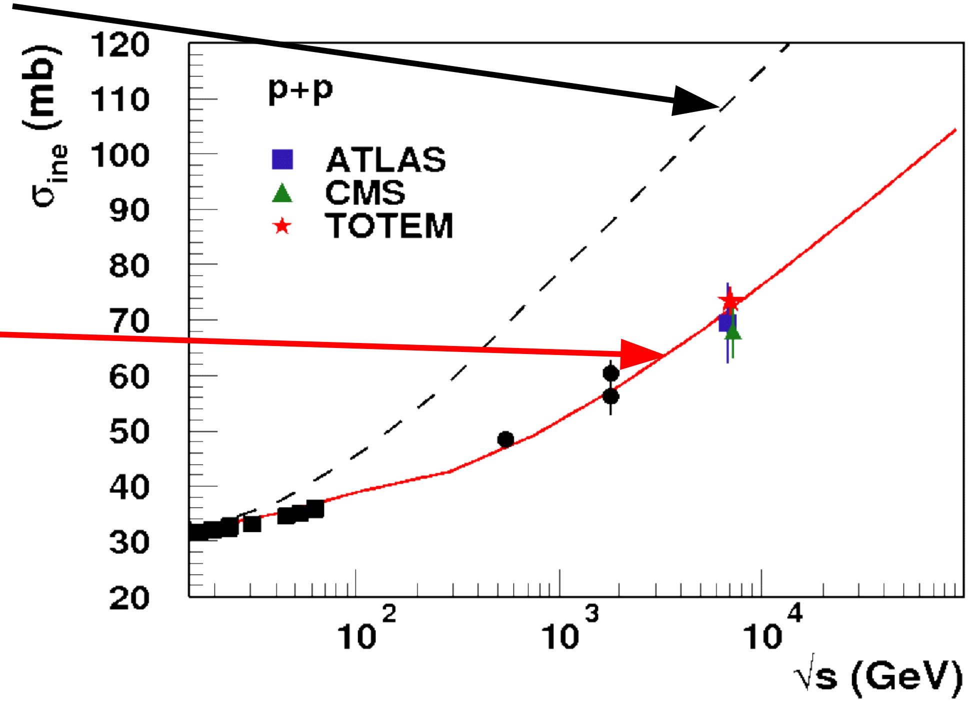
- Theory based Pomeron definion
  - pQCD based (DGLAP)
    - large increase at small x (no saturation)
  - produce too high cross section
  - corrections needed using enhanced diagrams (triple Pomeron vertex)
    - effective coupling vertex

No effective coupling

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

With effective coupling

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



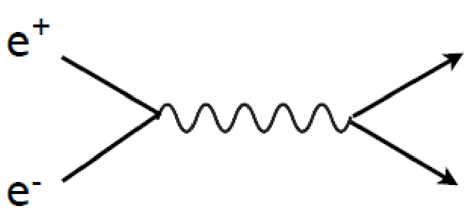
Parametrization

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

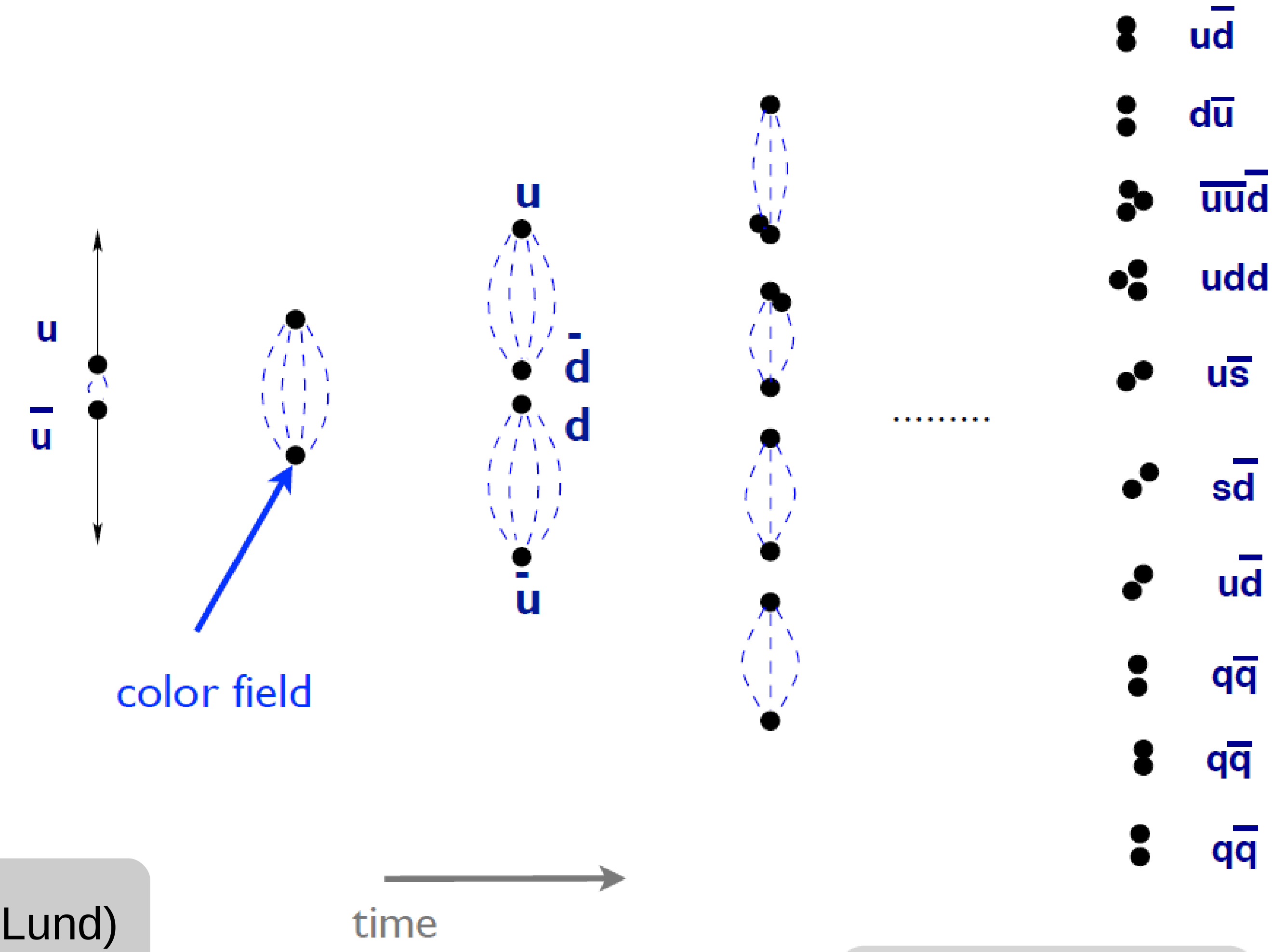
$$\varepsilon_H = a_H\, \beta_H\, Z(\mathrm{s,b})$$

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

Annihilation at high energy



Quarks together are color-neutral system

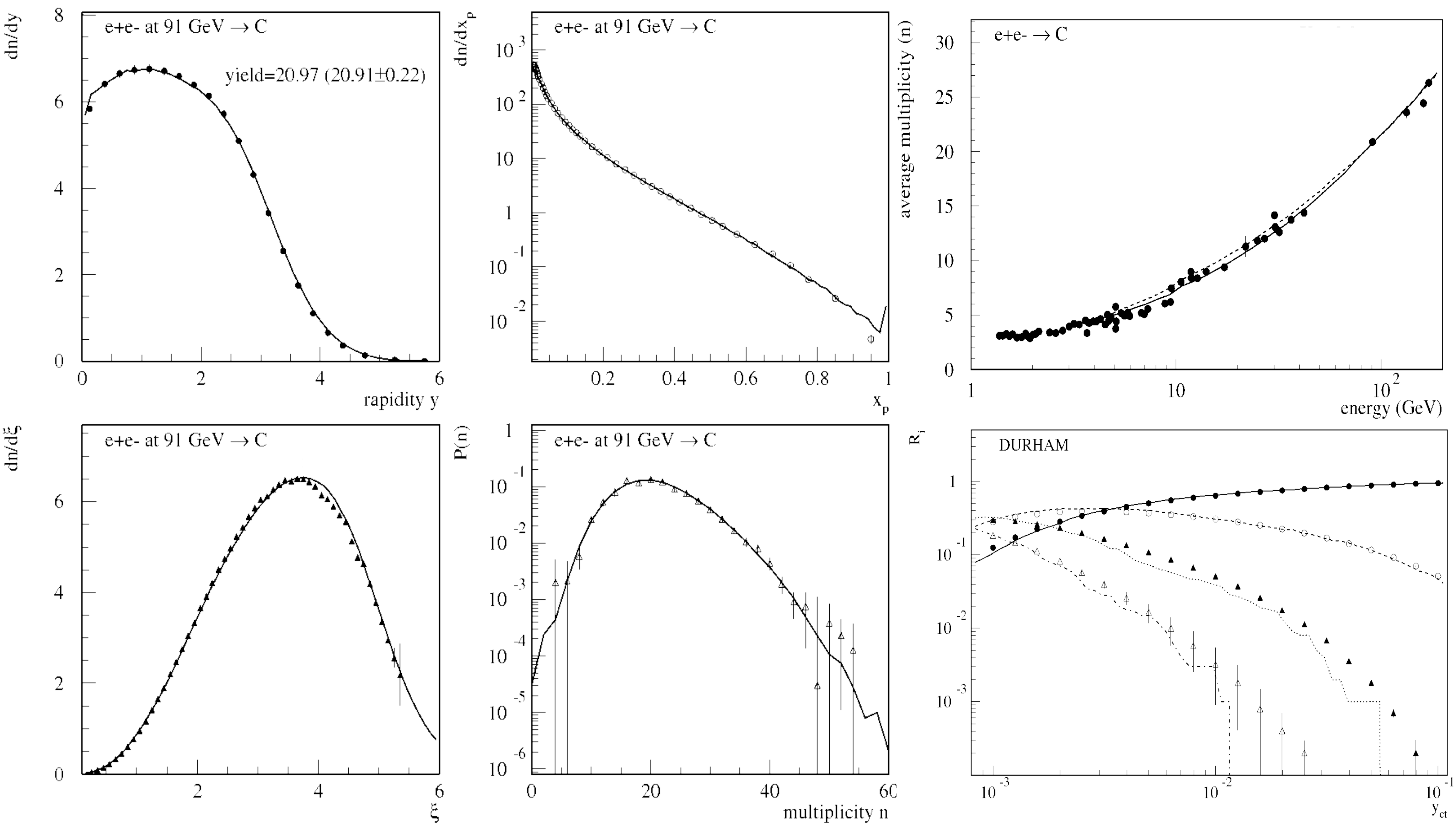


Area law used in EPOS (not Lund)

Chain of hadrons

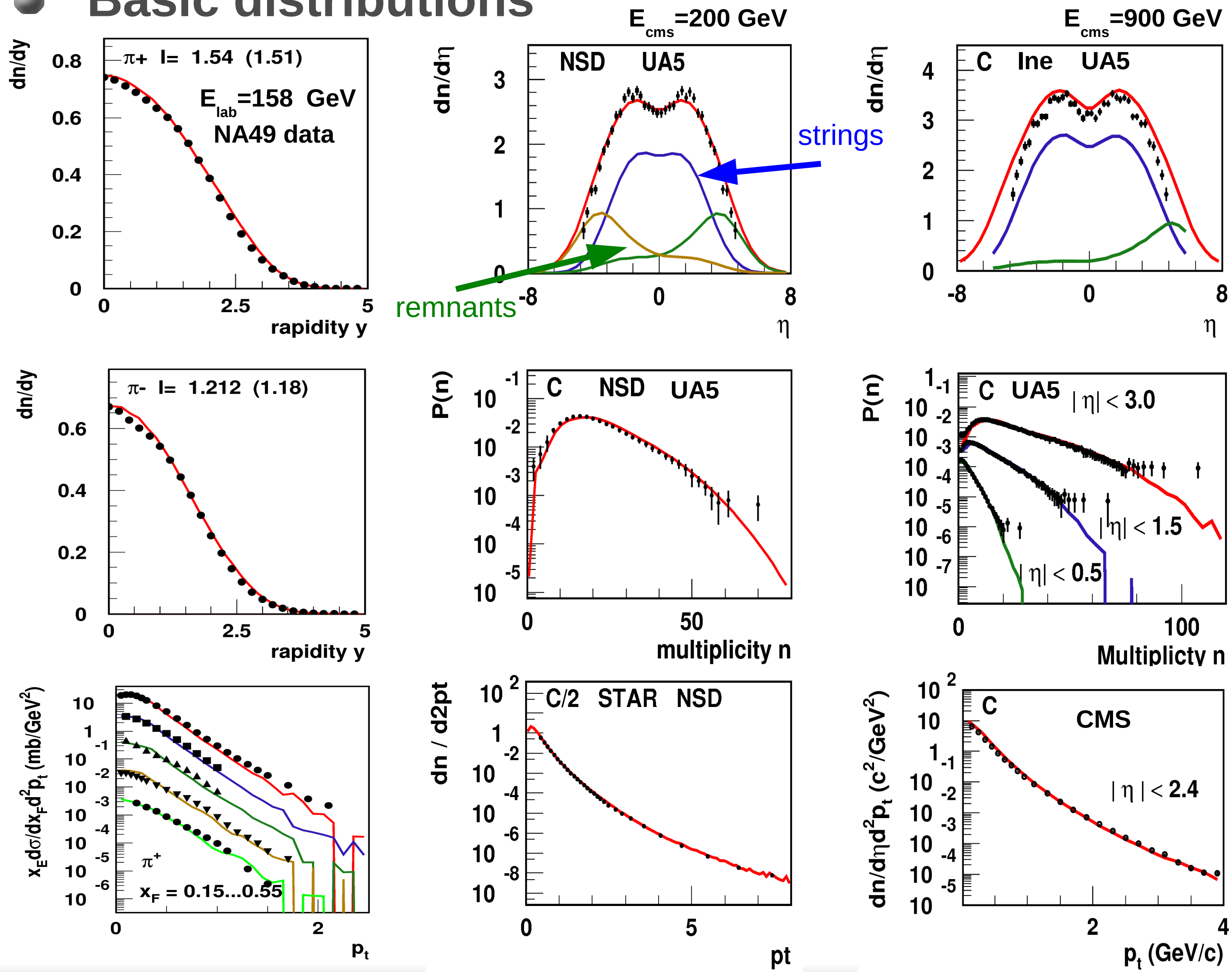
String fragmentation

Test at LEP


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

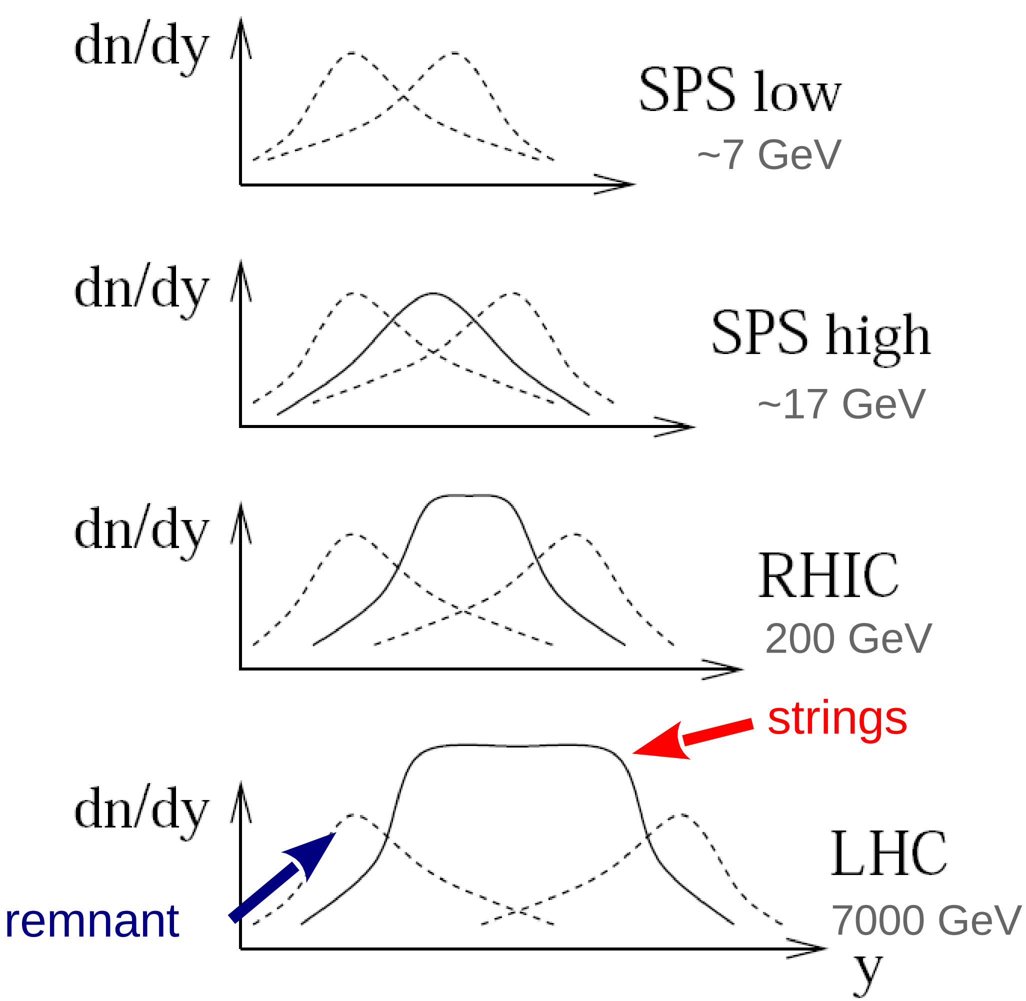
Basic Distributions

Basic distributions



Remnants

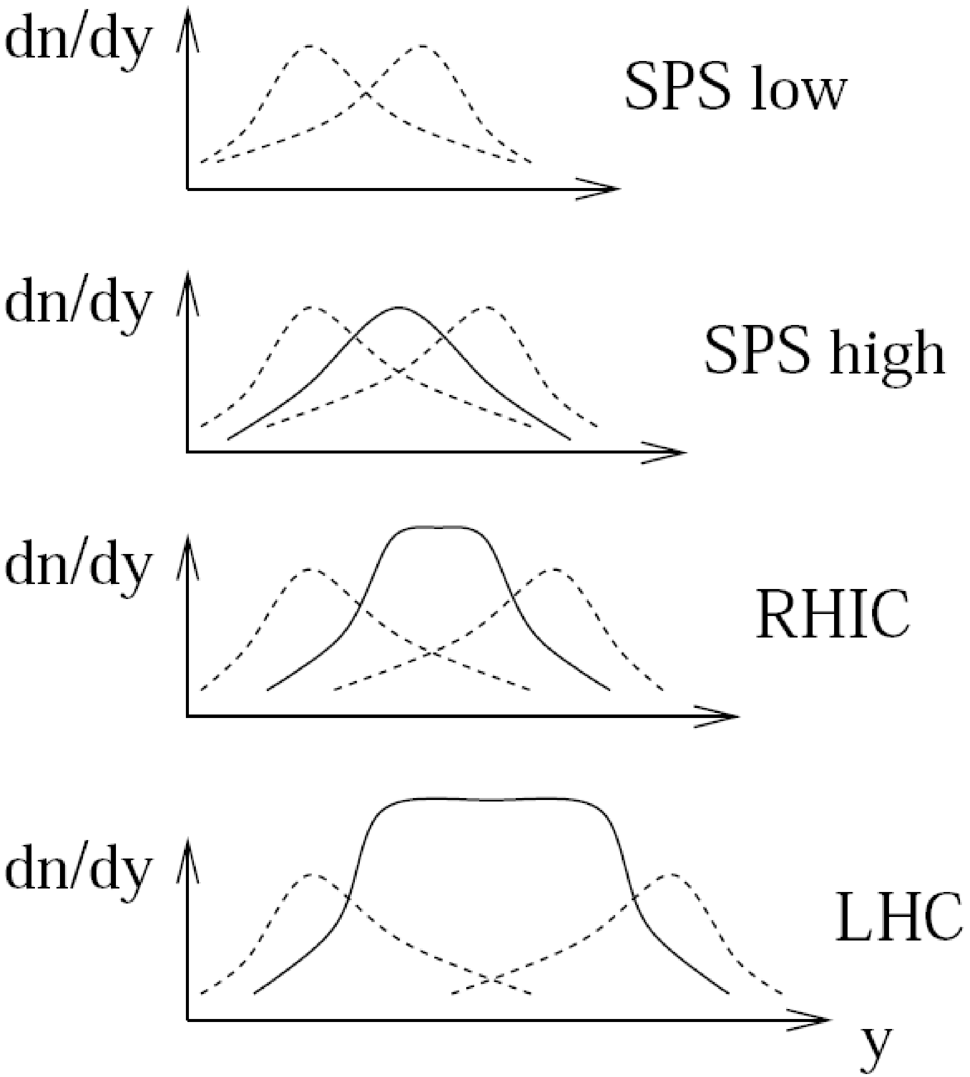
Forward particles mainly from projectile remnant



- 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)

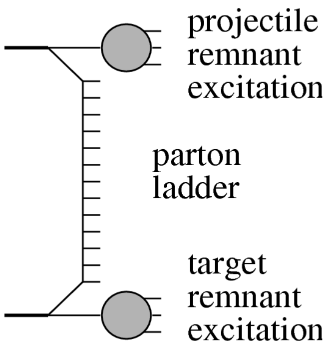
Different contributions of particle production at different energies or rapidities

Remnants



Free remnants in EPOS:

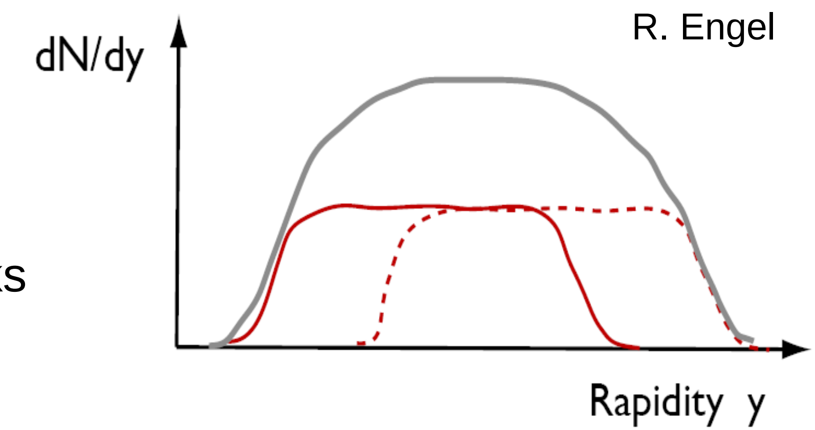
- from both diffractive or inelastic scattering
- excited state with $P(M) \sim 1/(M^2)^\alpha$
- very large contribution at low energy
- forward region at high energy
- depending on quark content and mass (excitation):
  - resonance
  - string
  - droplet (if #q>3)
  - string+droplet

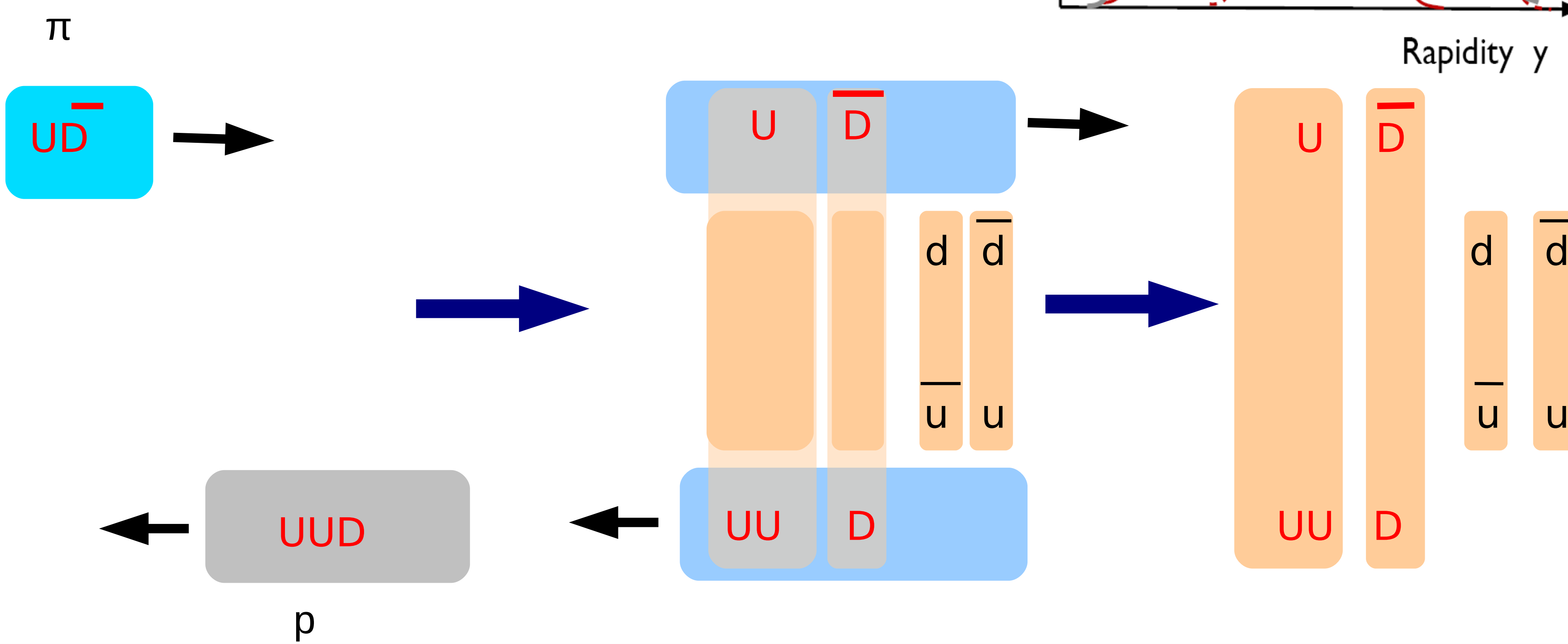


Remnants in PYTHIA

In PYTHIA : valence quarks attached to main string

- limited quark exchange
- very hard baryon and meson spectra
- string fragmentation
  - forward particle limited by valence quarks

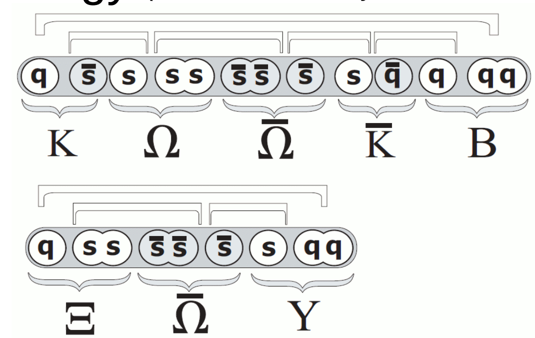




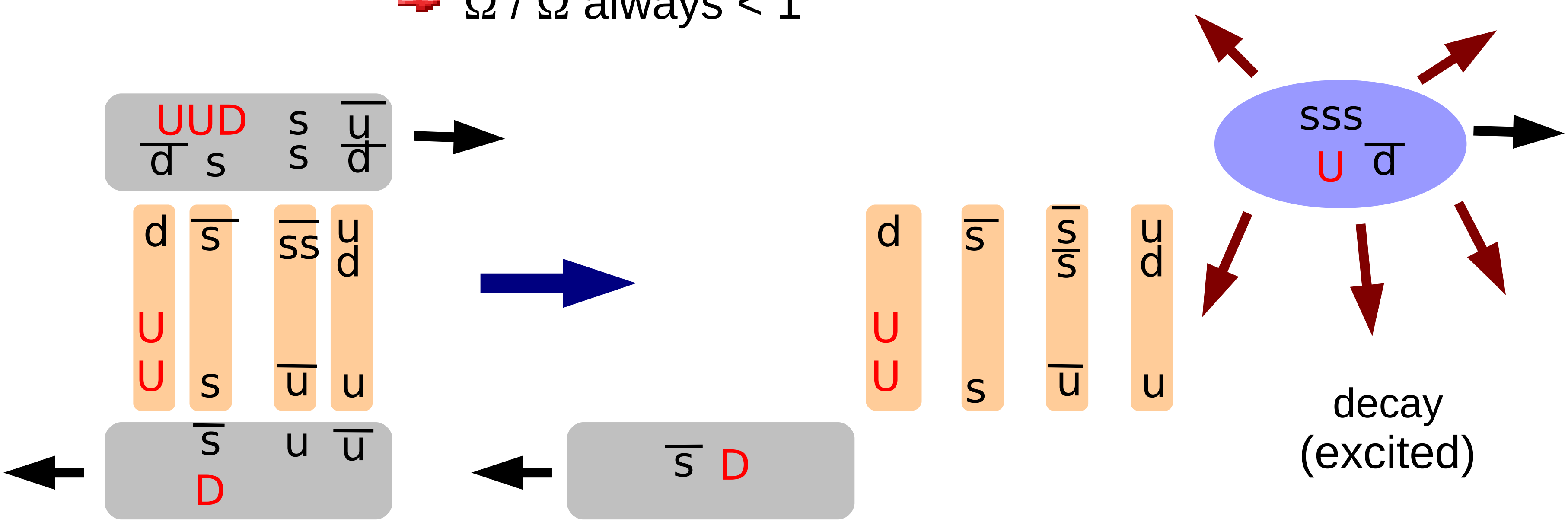
Baryons and Remnants

Parton ladder string ends :

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

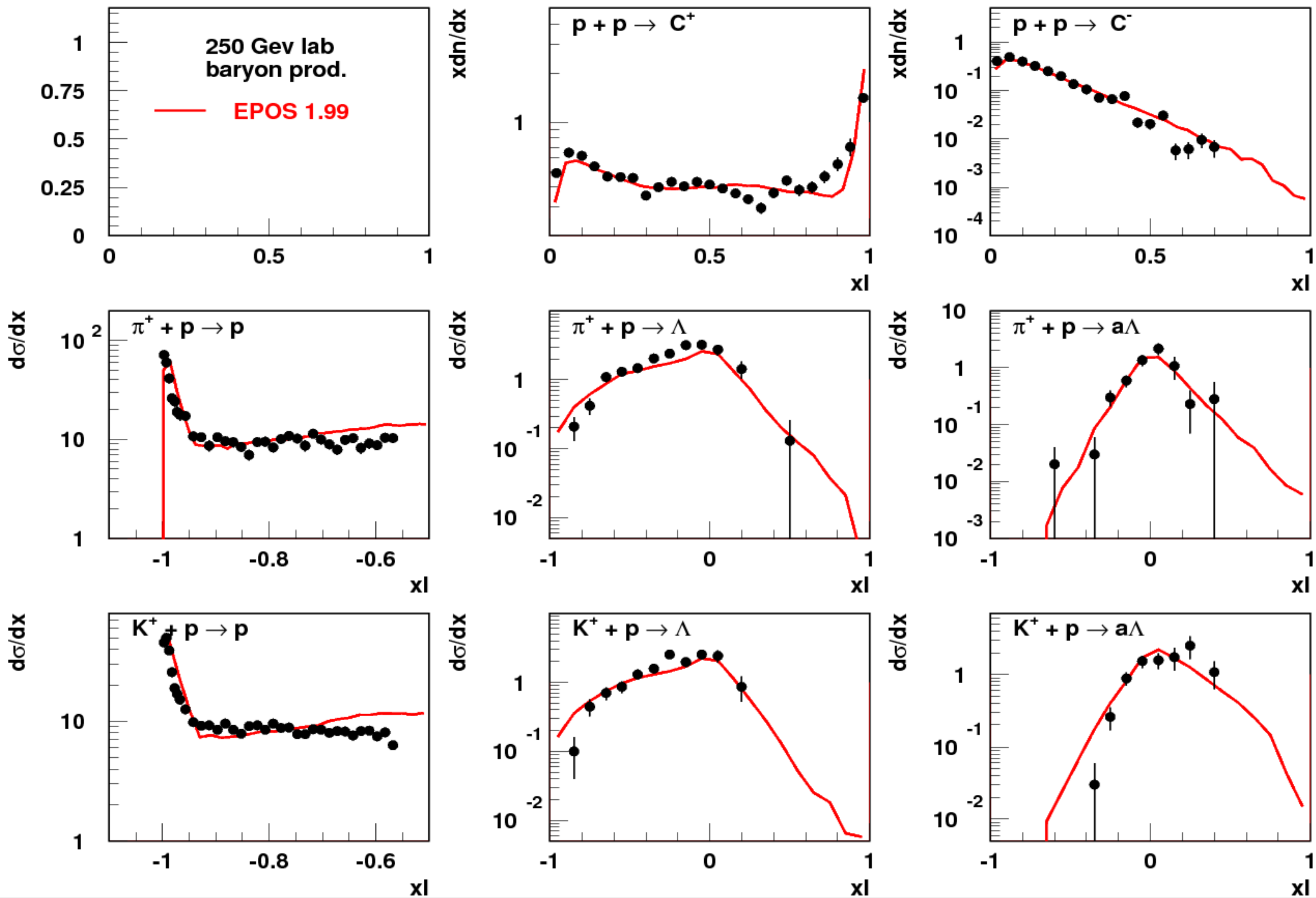


- EPOS
  - No “first string” with valence quarks : all strings equivalent
  - Wide range of excited remnants (from light resonances to heavy quark-bag)
    - $\bar{\Omega} / \Omega$ always < 1



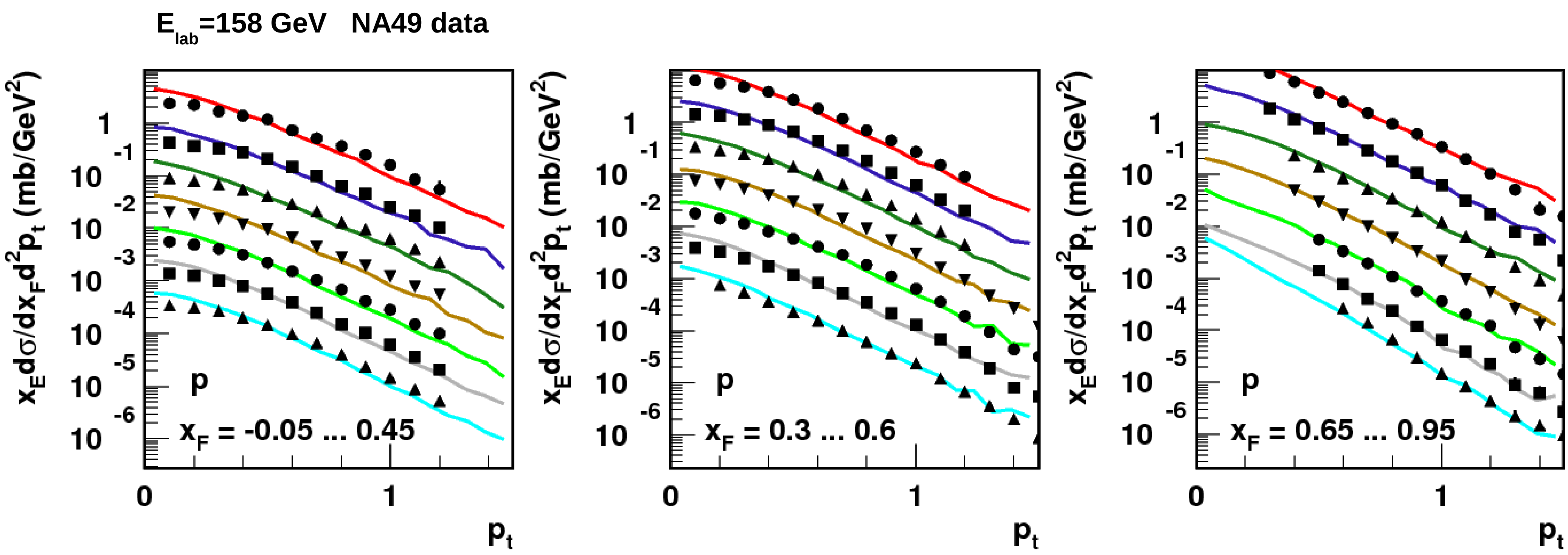
Baryon Production

- Baryon production for fixed target exp.



Proton Xf Distribution

- **Leading proton**
  - Tests from 100 GeV lab to 300 GeV cms
  - Very forward proton from diffractive events



Summary

Hadronic interactions with EPOS :

- 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)

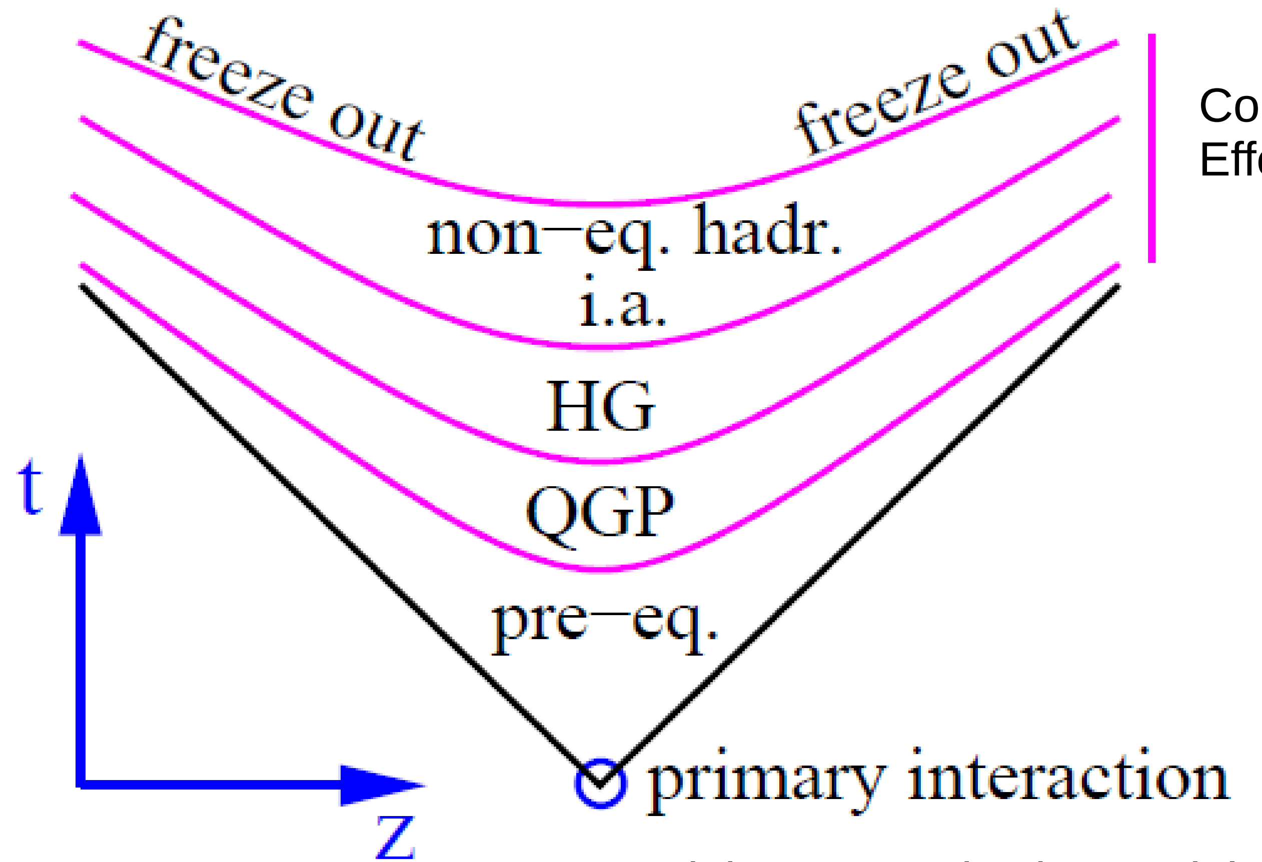
Low energy p-p collisions :

- Remnants AND strings needed to reproduce NA49 data
- Important data to fix remnant parameters

EPOS on-going developments :

- Replace effective screening by saturation scale :
  - Improvement of hard events (jets) in MB
- Breit-Wigner width used in string fragmentation
- Introduce Pion exchange
- Test with cosmic ray data

High Energy Hadronic Interactions



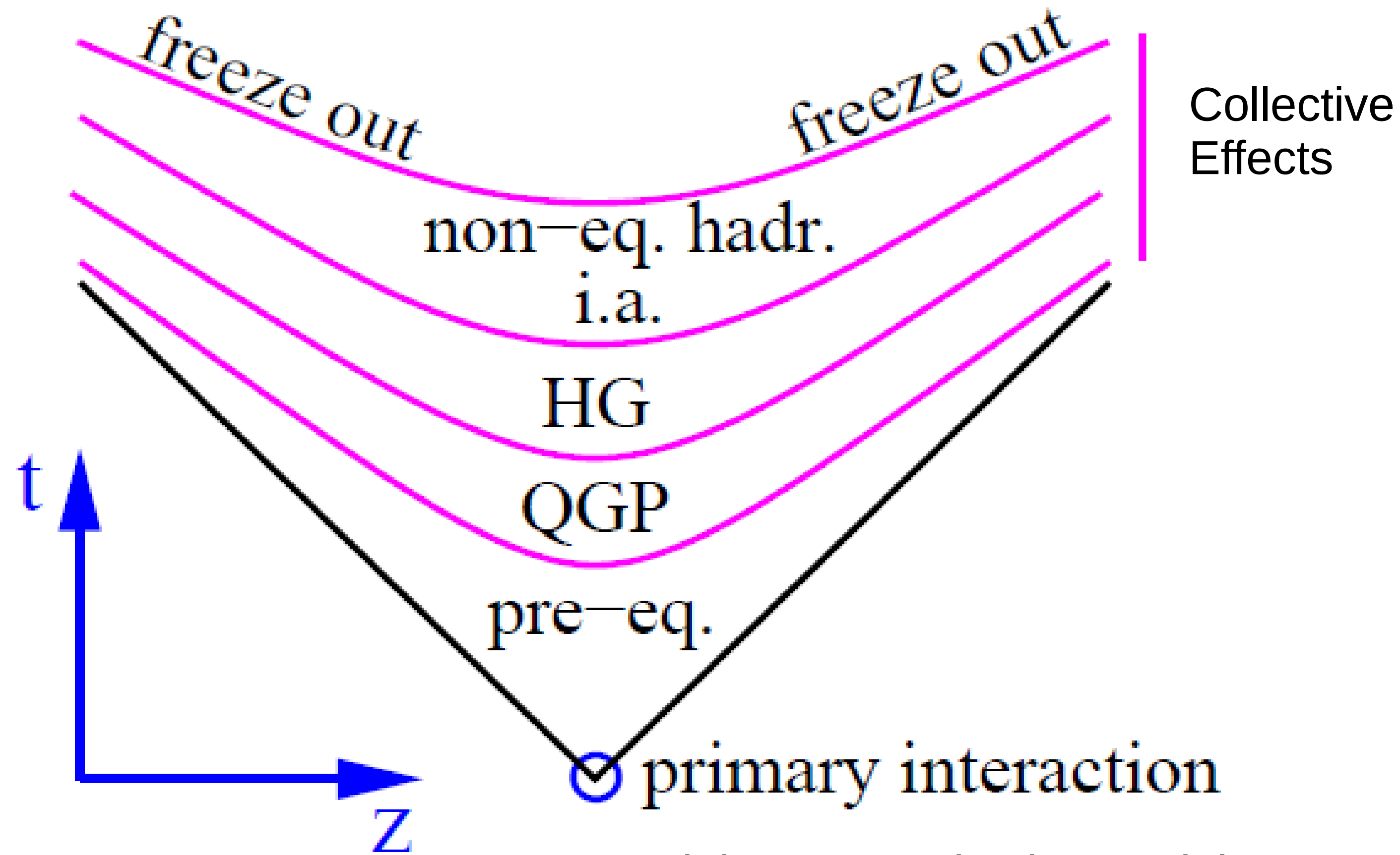
Collective Effects

High Energy Physics models

General case : valid for pp if enough particles (high energy) are produced !

Thank you

High Energy Hadronic Interactions

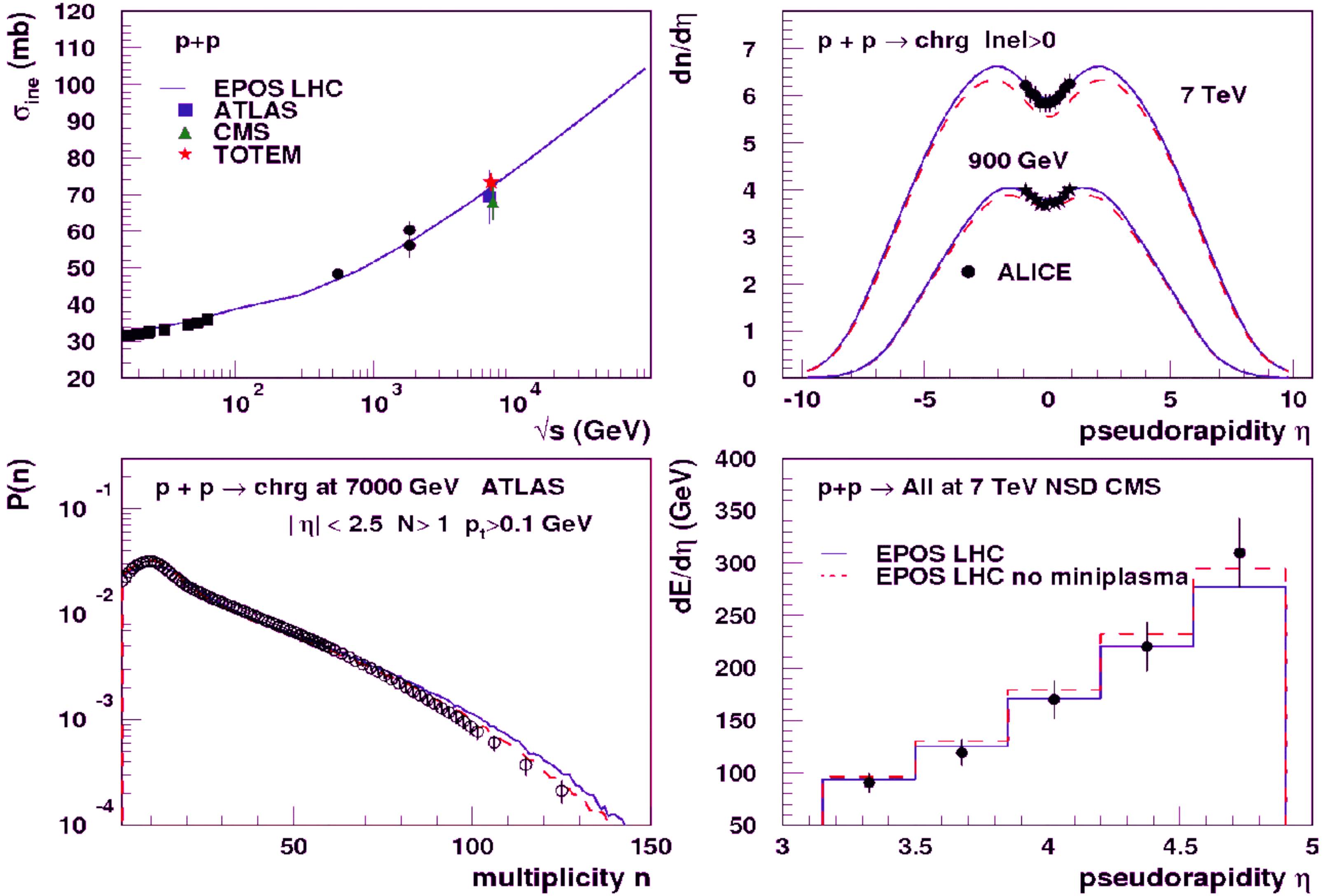


High Energy Physics models

References : arXiv:1004.0805, arXiv:1010.0400, arXiv:1011.0375

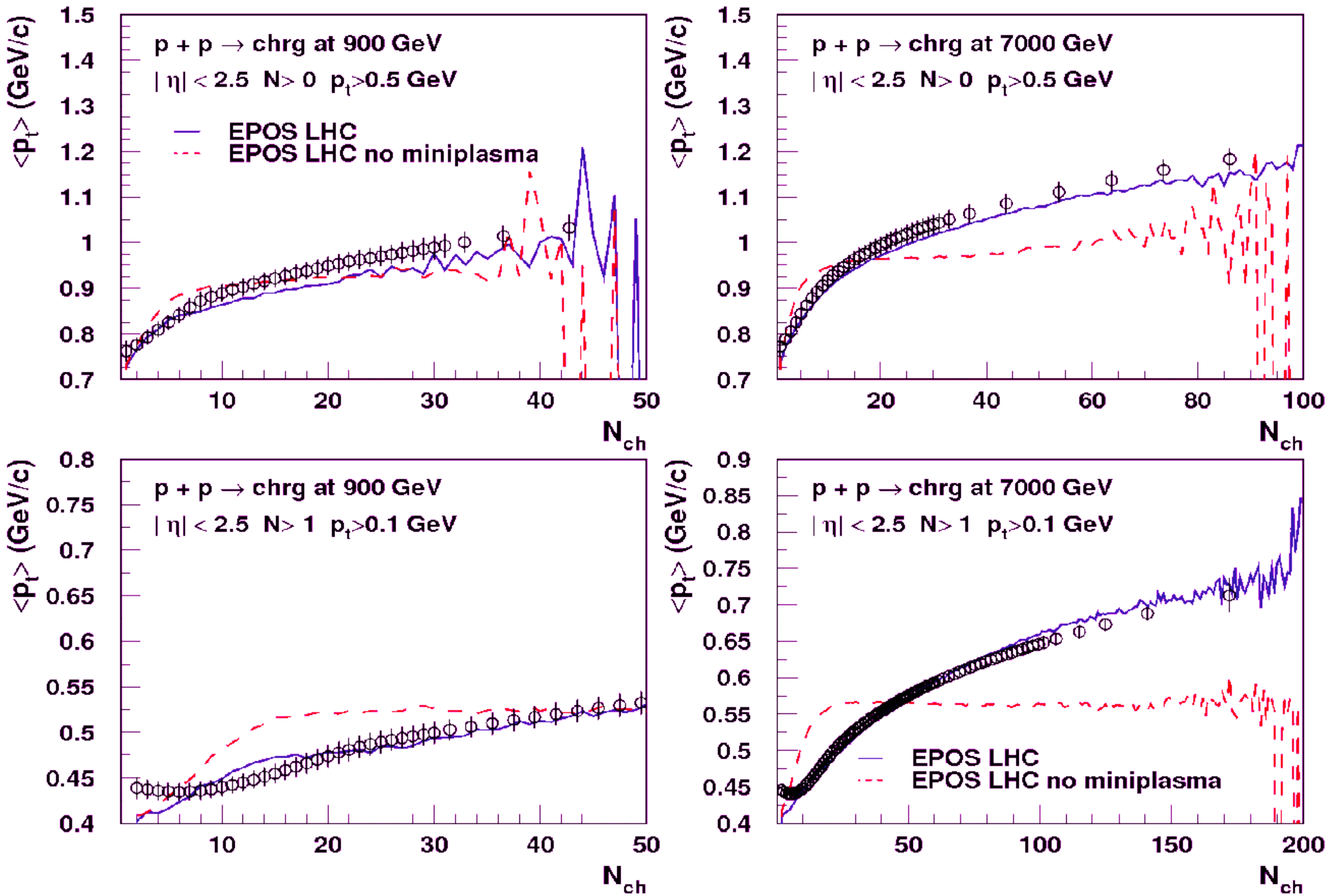
EPOS LHC

- **Effective flow treatment**



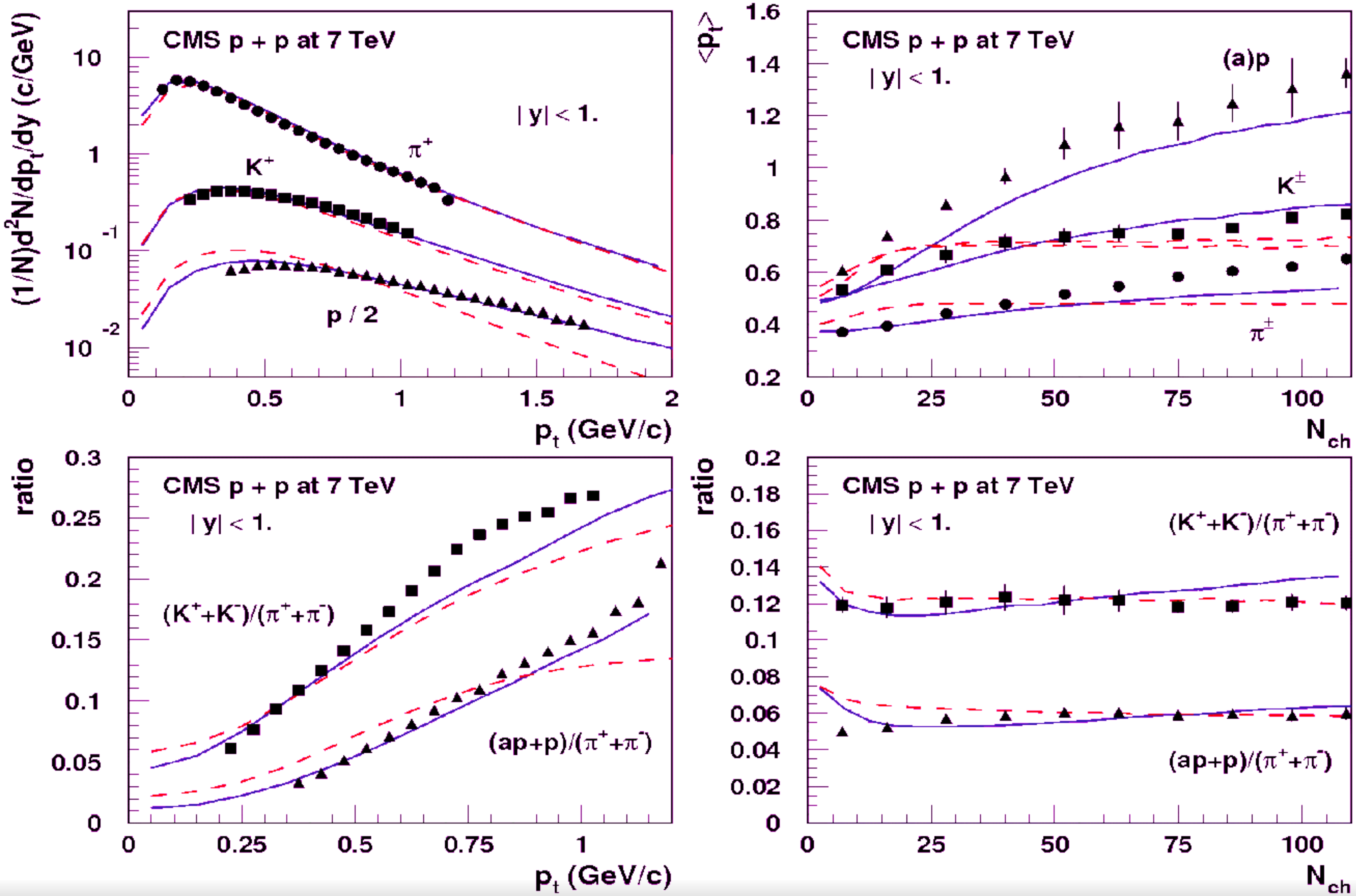
EPOS LHC

- **Effective flow treatment**



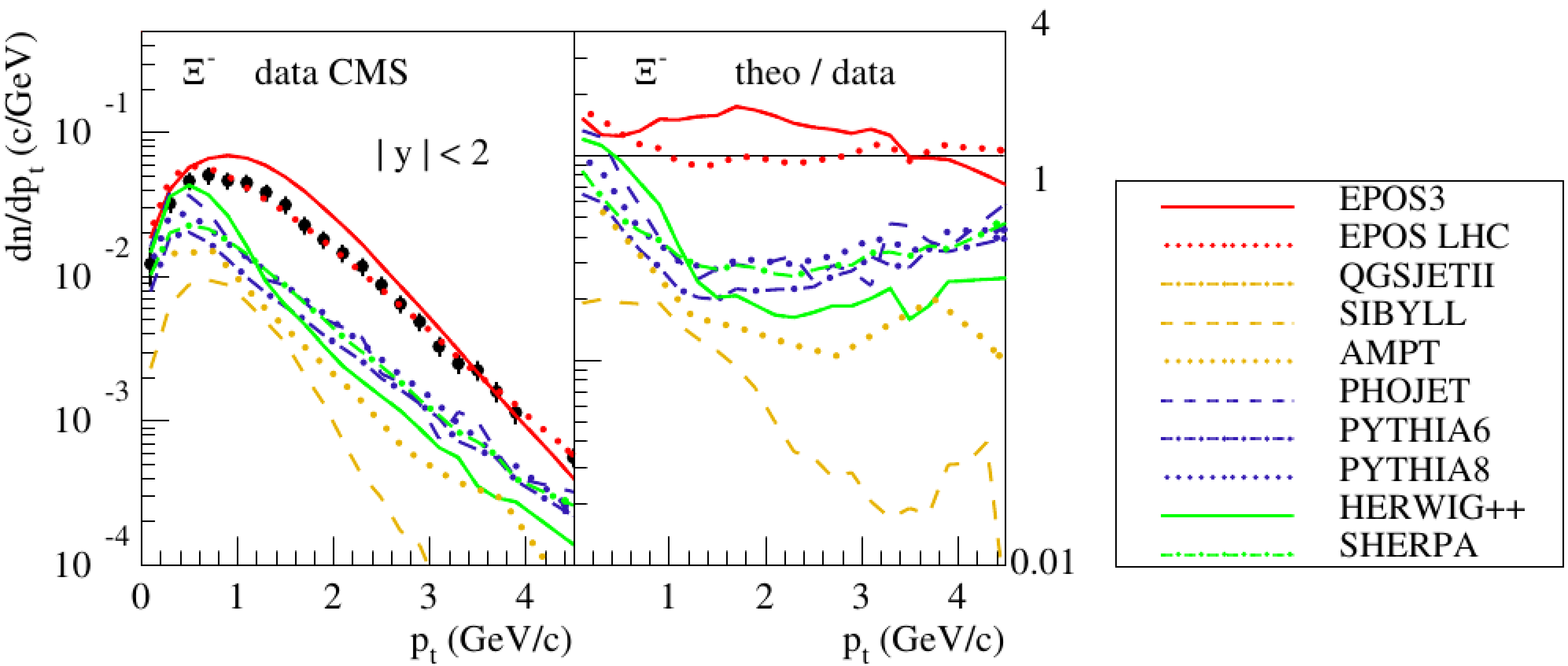
EPOS LHC

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



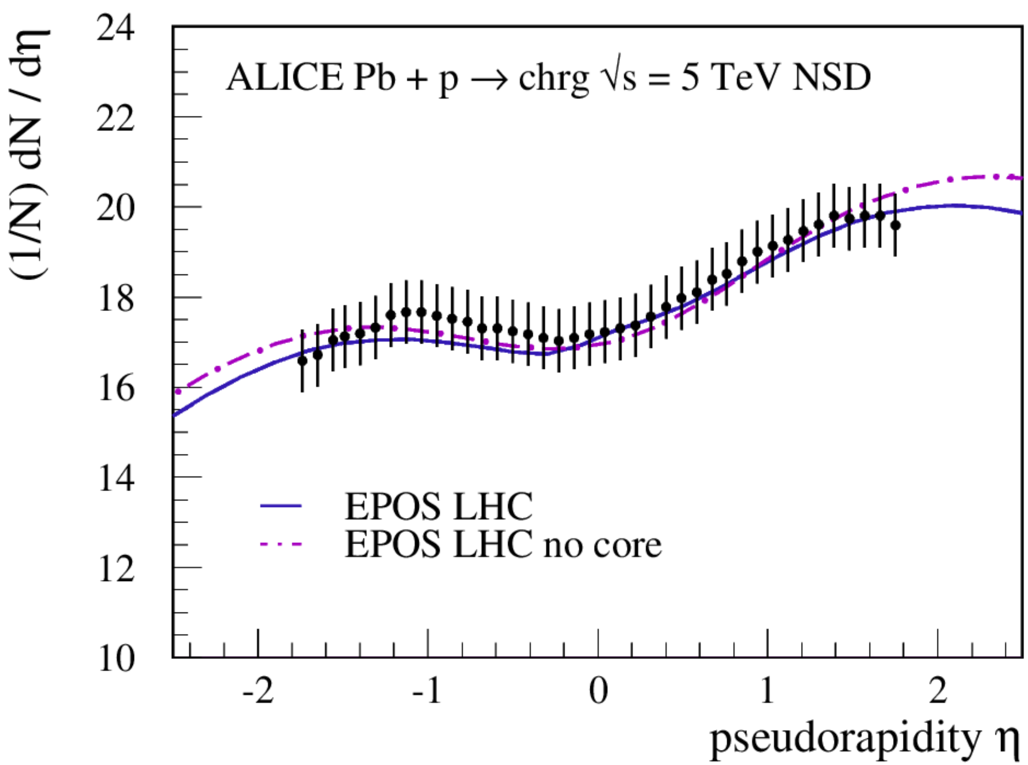
EPOS LHC

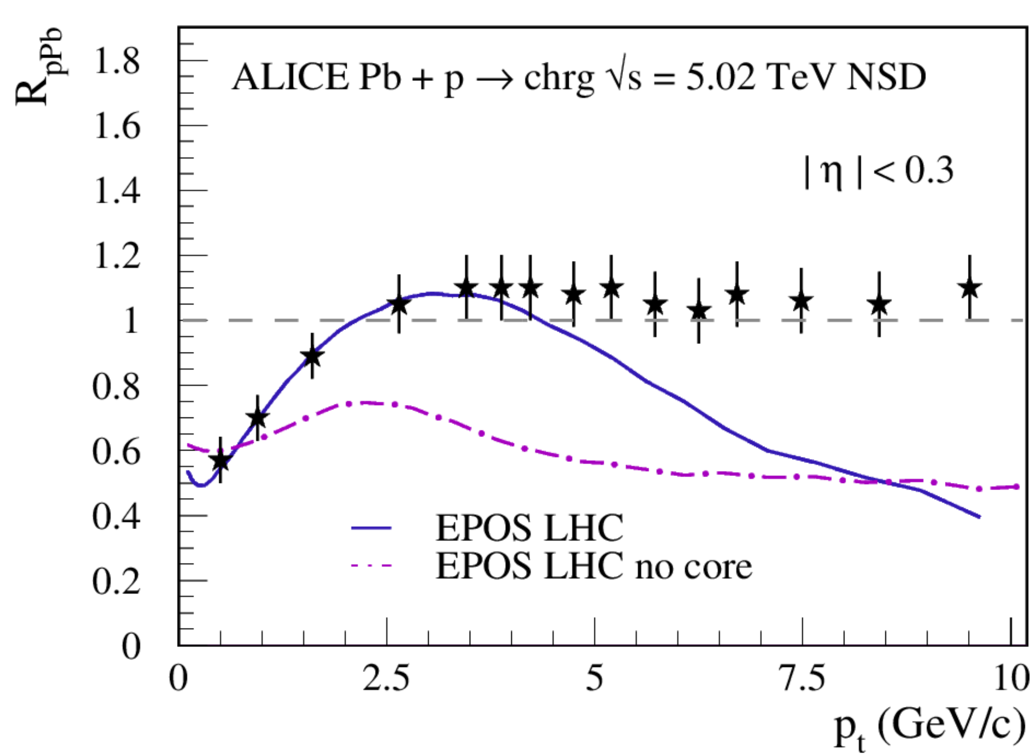
- **Detailed description can be achieved**
  - identified spectra
  - p_t behavior driven by collective effects (statistical hadronization + flow)
    - large effect for multi-strange baryons (yield AND $<p_t>$)



EPOS LHC

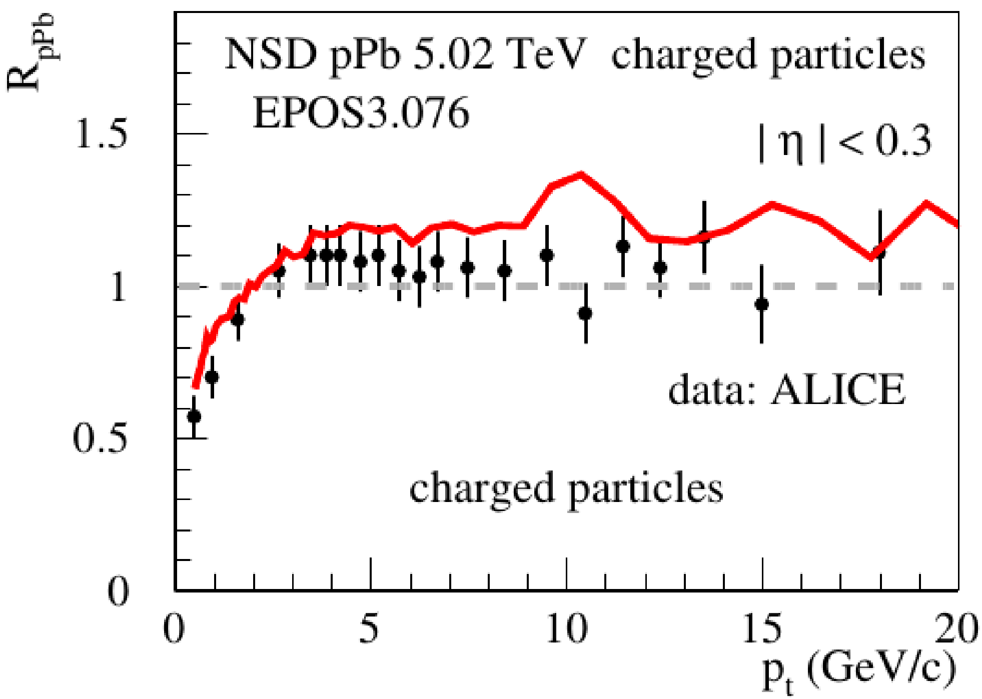
- **Detailed description can be achieved**
  - Good results at low/medium p_t in Pb-p
  - Problems for high p_t : no binary scaling
    - same correction for soft and hard scales
      - Q^2 dependent screening

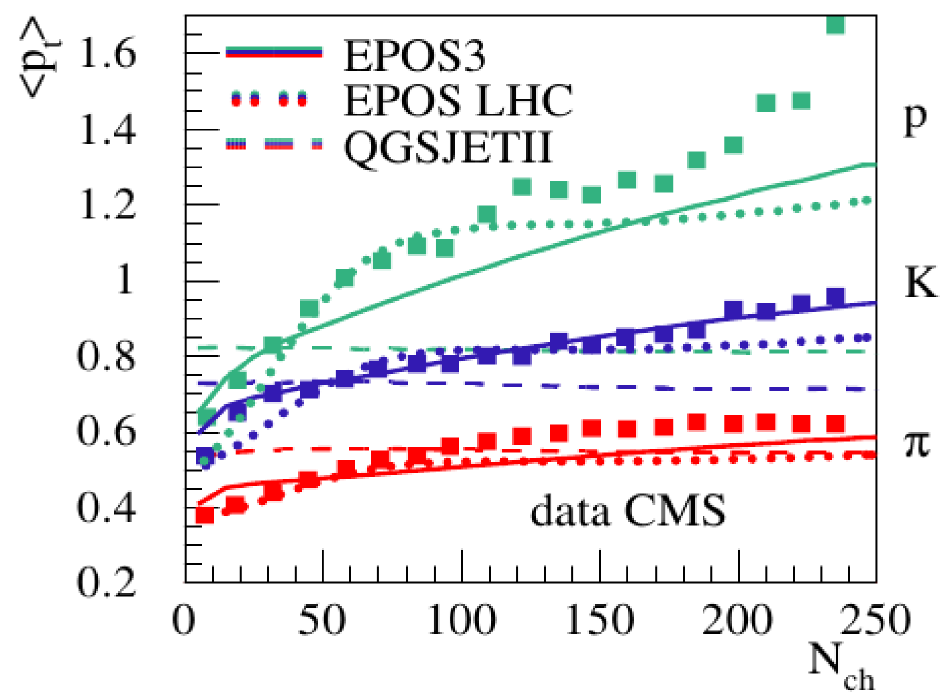




EPOS 3

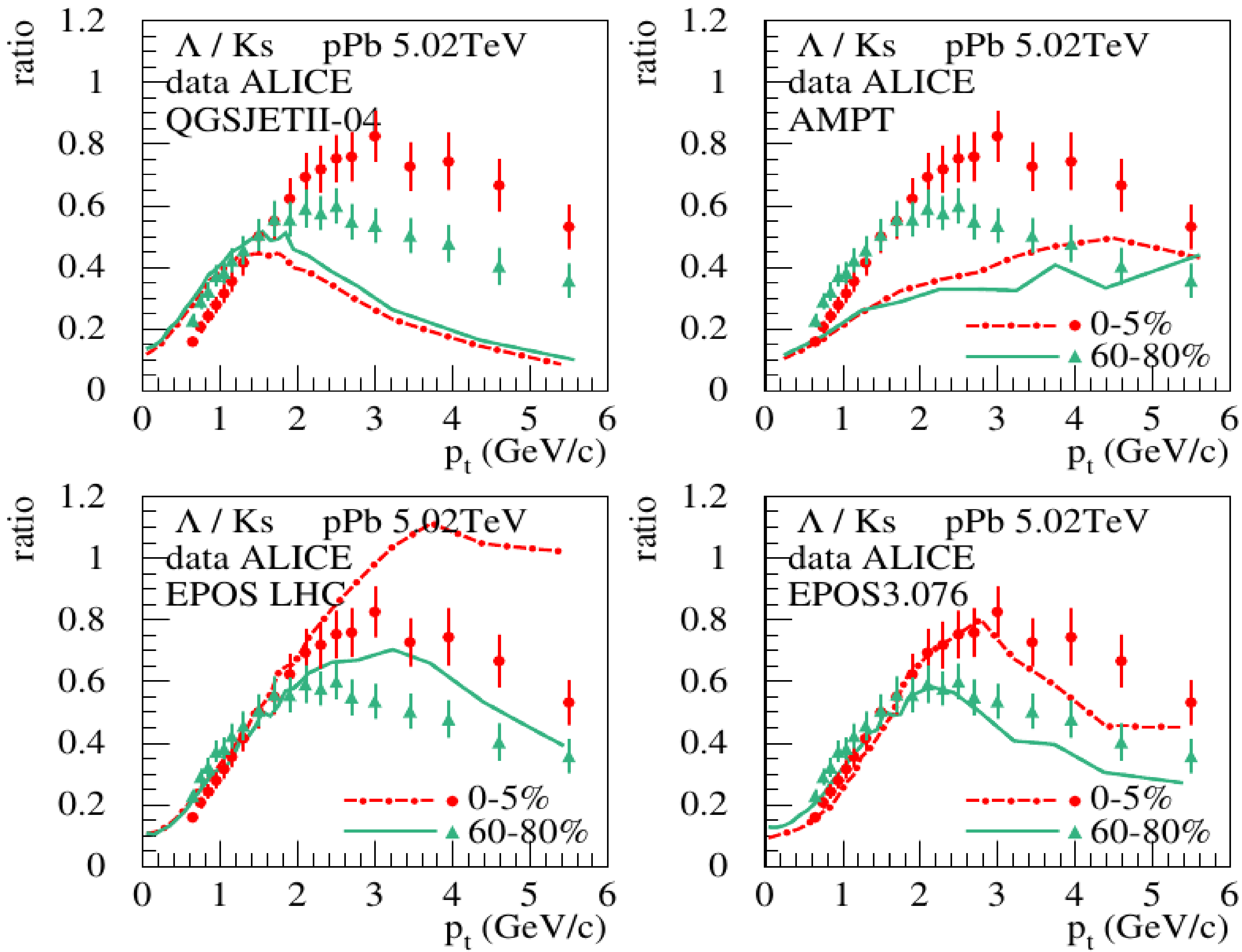
- **Use saturation scale to have a Q^2 dependent screening**
  - restore binary scaling for high p_t
  - intermediate p_t due to flow
    - mass splitting



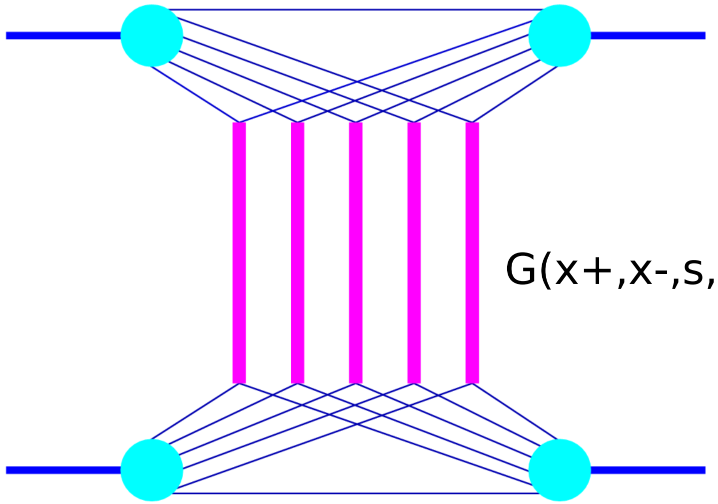


EPOS 3

Particle ratio characteristic of collective flow effect.



Cross Section Calculation : EPOS



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

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

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

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

Particle Production in EPOS

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

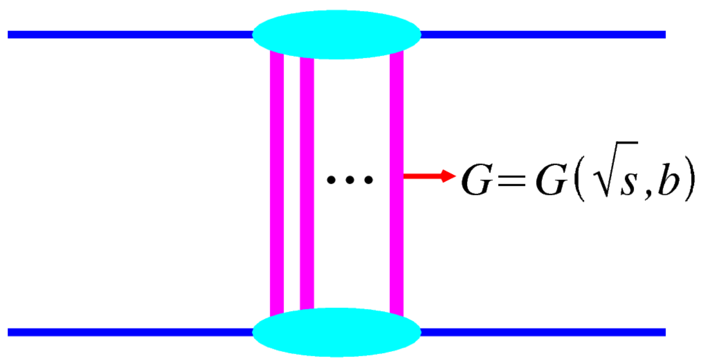
- m cut Pomerons from :

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

  - m and X fixed together by a complex Metropolis (Markov chain)
- $2\mathrm{m}$ strings formed from the m elementary interactions
  - energy conservation : energy fraction of the $2\mathrm{m}$ 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

Gribov-Regge Based Models



Multiple elementary scattering

- **Using Gribov-Regge** (GR) : cross section from optical theorem :

$$\sigma_{ine}(\sqrt{s})=\int d^2b\,(1-\exp(-G(\sqrt{s},b)))$$

where G(energy,impact parameter) = elementary interaction

- Probability for the number of elementary interactions (Pomeron) per event

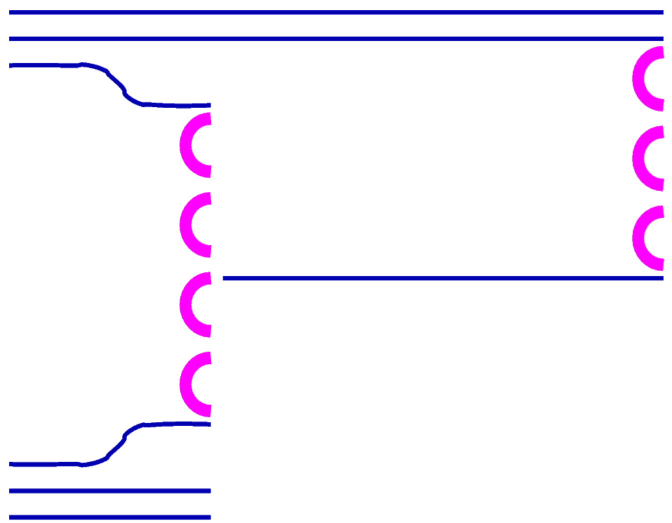
Successful description of hadronic cross-sections

But

Energy conservation NOT considered between the elementary interactions G

No possibility to deduce directly particle production !

Particle Production in GR based Models



- **Number of strings from GR**
  - ➡ No energy conservation
- **Energy sharing**
  - ➡ Not consistent with cross-section
- **String fragmentation**
  - ➡ Proper energy conservation

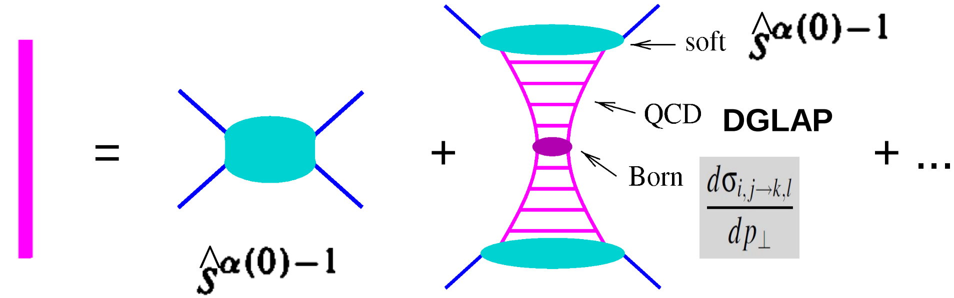
Link between cross-section and particle production not consistent !

Parton-Based Gribov-Regge Therory* (PBGRT) developed to solve the problem :
same formalisme for cross section and particle production
used first in NEXUS and now in EPOS

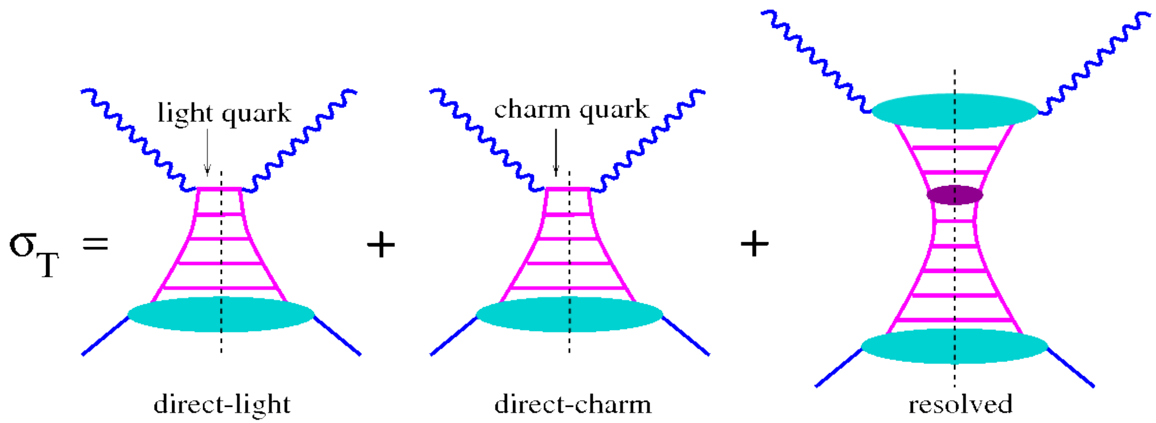
* H.J. Drescher et al., Phys.Rep. 350:93-289 (2001)

EPOS : Pomeron definition

Semi-hard Pomeron :



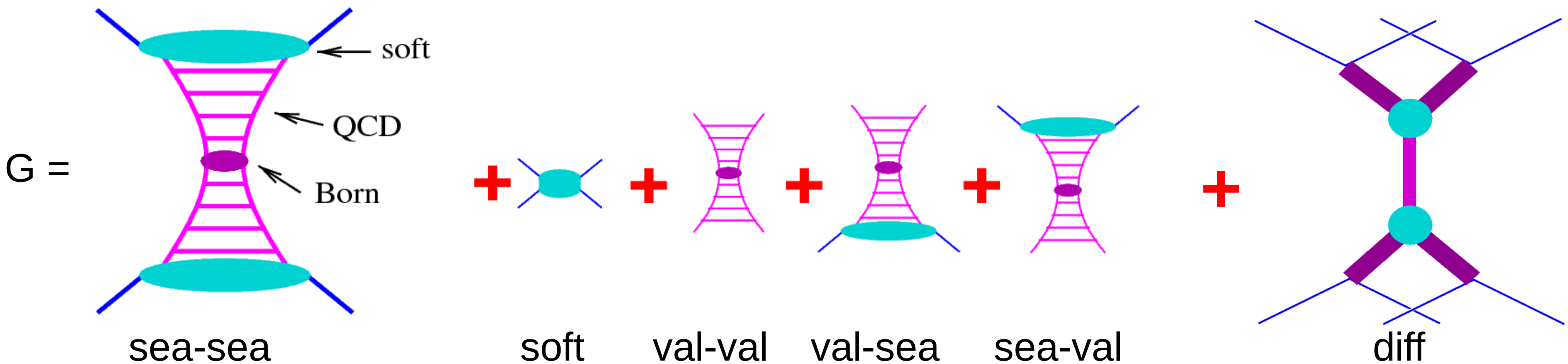
Test of semi-hard Pomeron with DIS: (Parton Distribution Function from HERA)



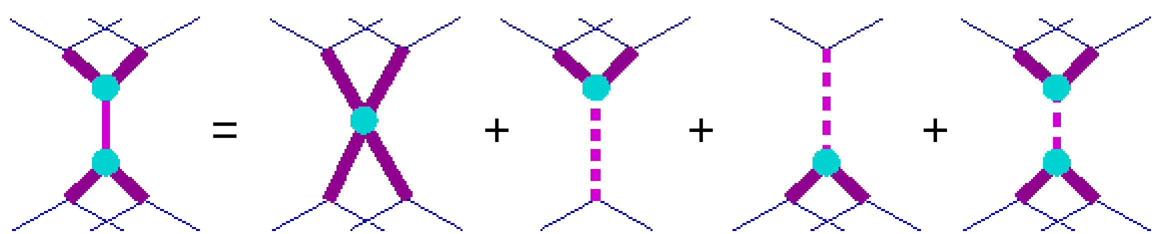
- Theory based Pomeron definion
  - pQCD based so large increase at small x (no saturation)
  - produce too high cross section
  - corrections needed using enhanced diagrams (triple Pomeron vertex)
    - effective coupling vertex

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

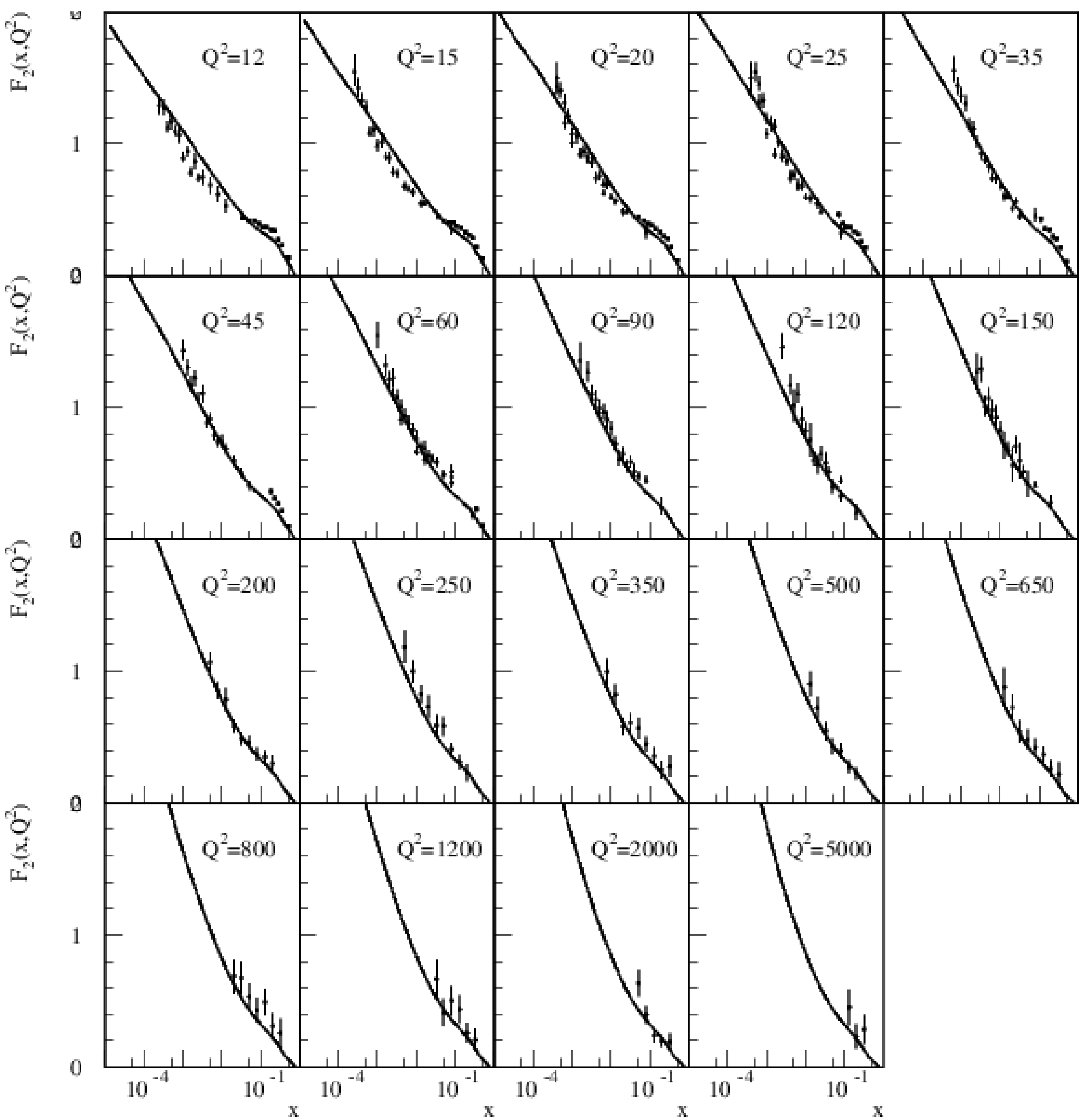


  - ➡ Parameters extracted from single diffractive (SD) cross-section
  - ➡ Events with only “diff” type diagrams are diffractive

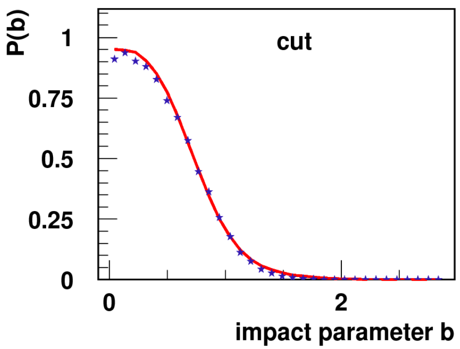
Parton Distribution Function

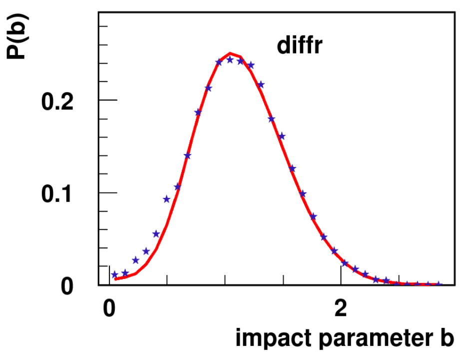
- **PDF based and DGLAP and initial soft parametrization with saturation**

Preliminary from EPOS 3



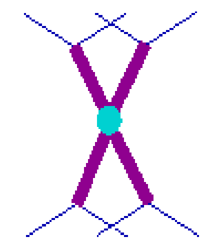
Low Mass Diffraction

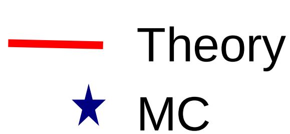


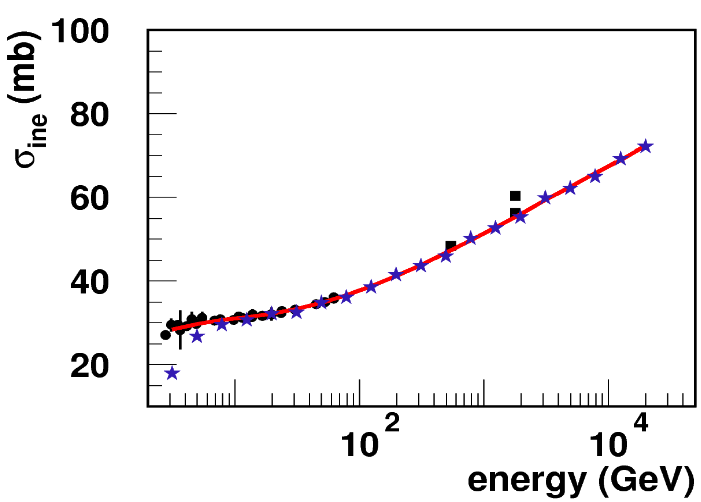


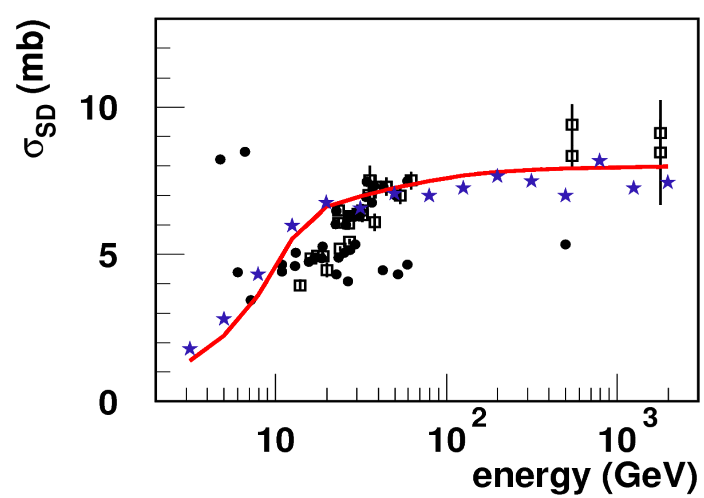
Diffractive event = event with only cut diff. diagrams

- Multiple cut-diff diagrams possible
- For each cut-diff diagram probability P_{dif} not to excite remnant
  - More cut-diff = more excitation : $(1-P_{dif}^{\ n})$
  - Important in pA
- No particle production directly from diagram
- P_{dif} (~0.25) fixes SD, DD (or elastic) probability.

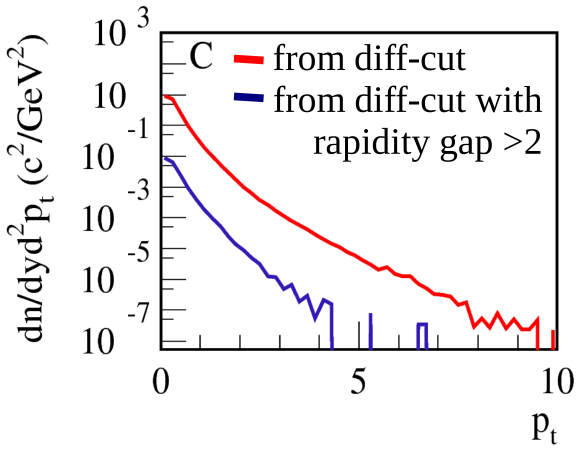








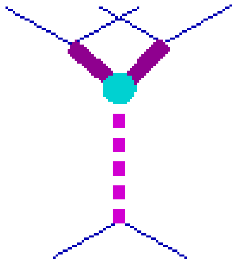
High Mass Diffraction



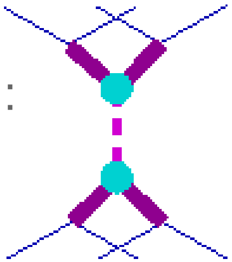
Same scheme but with particle production

- Do not change cross-section
- For each cut-diff probability P_{HM}(mass,b,...) to remain as real (soft or semi-hard) cut diagram
- 0, 1 or 2 rapidity gap depending on P_{dif}

Projectile not excited :
1 rapidity gap



Projectile and target not excited :
2 rapidity gaps

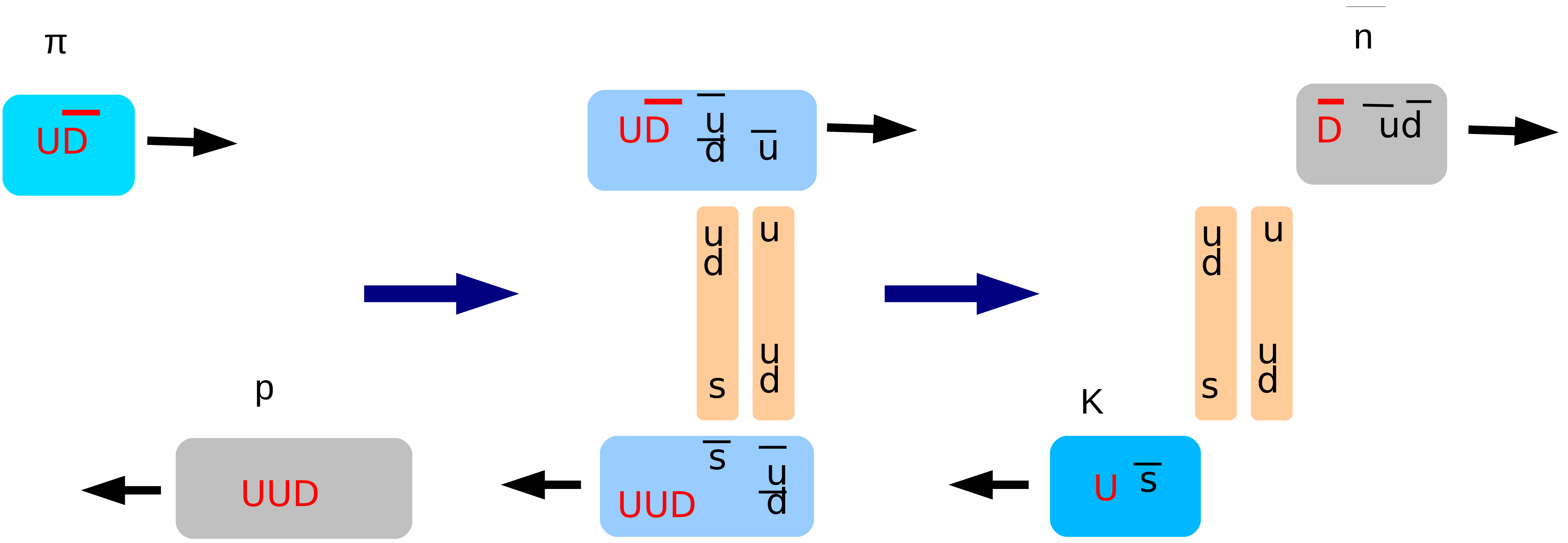


- Additional multiplicity contribution in ND events
- Work in progress

Remnants in EPOS

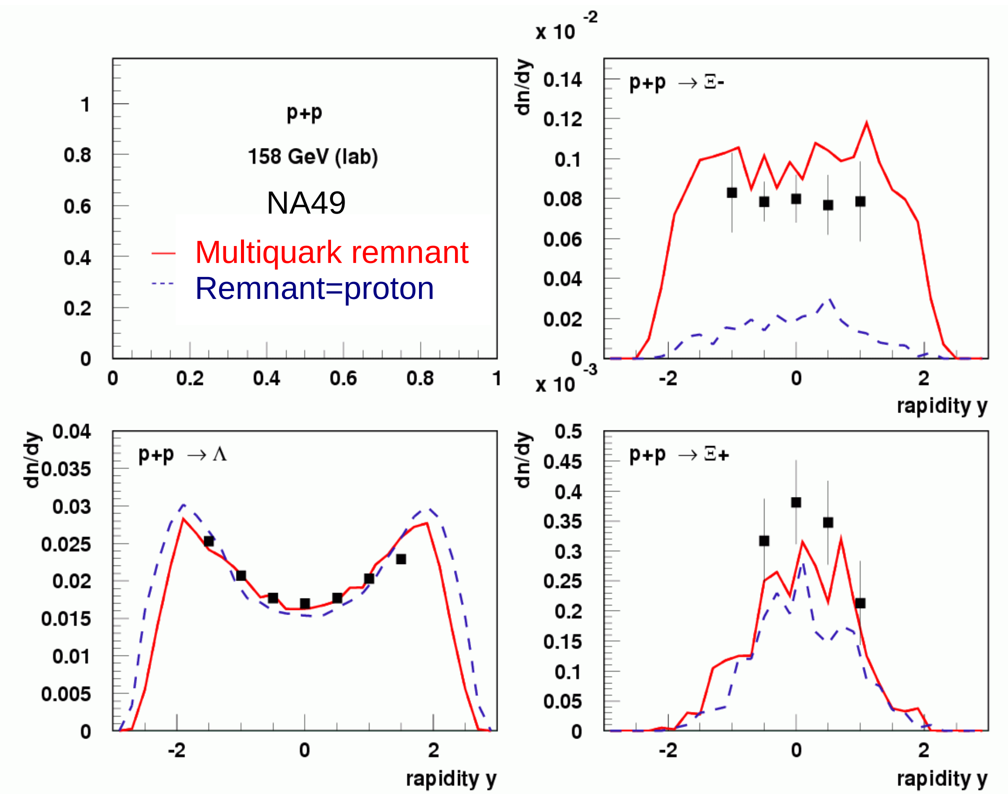
In EPOS : any possible quark/diquark transfer

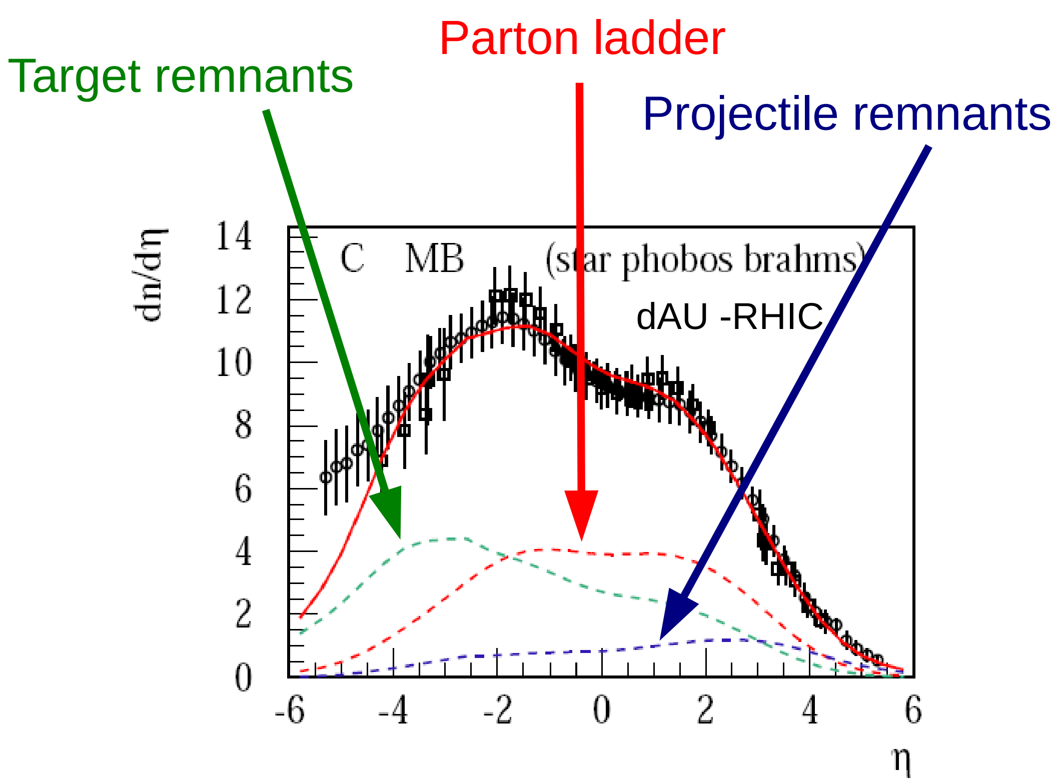
- Diquark transfer between string ends and remnants
- Baryon number can be removed from nucleon remnant :
  - Baryon stopping
- Baryon number can be added to pion/kaon remnant :
  - Baryon acceleration



Properties of Free Remnants

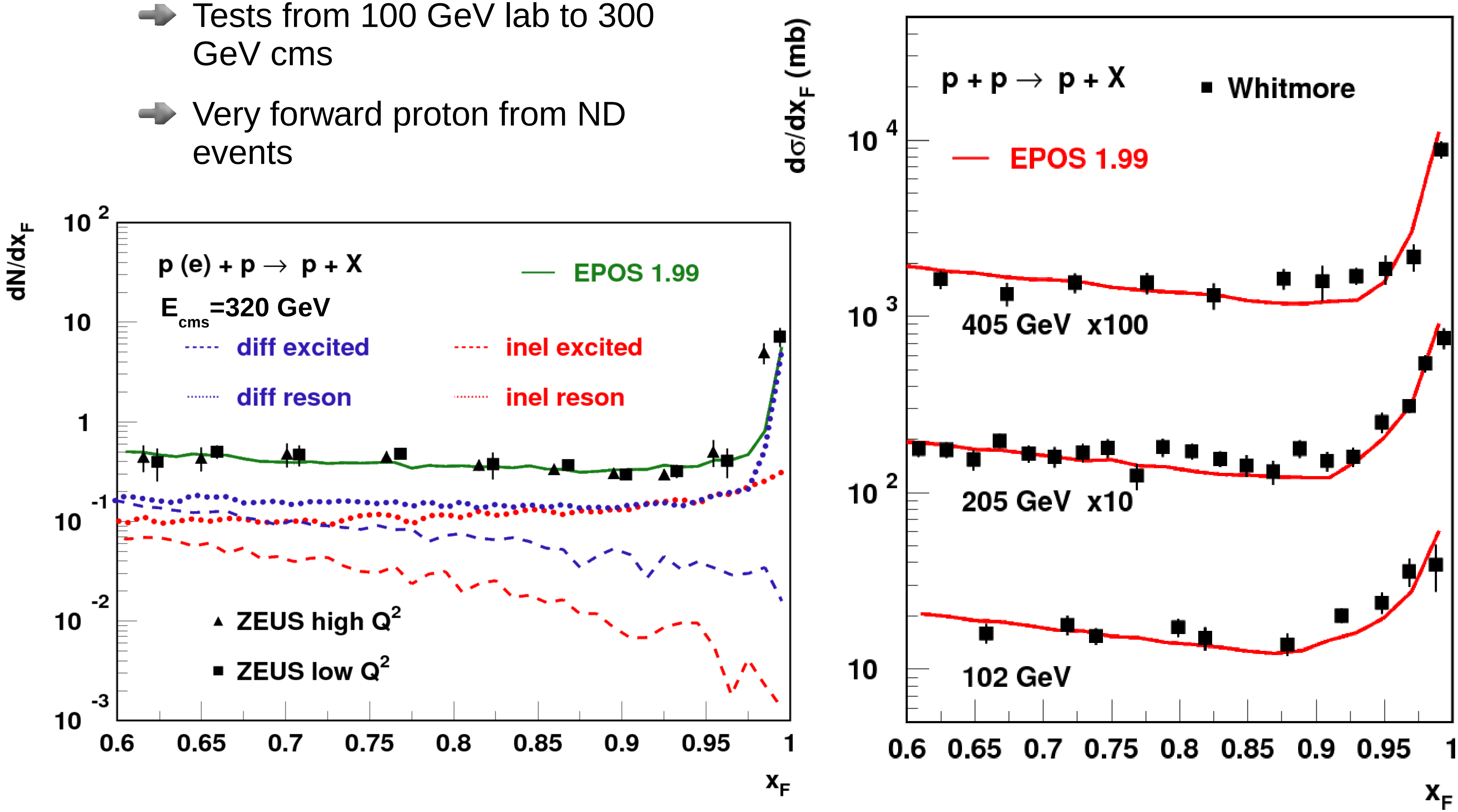
- **Valence quark not necessarily connected to parton ladder :**
  - Necessary to have aΩ/Ω < 1 (NA49 data)
  - Very broad remnant distribution
  - Can be used to describe effective enhanced diagrams (higher mass)
  - Very important for Cosmic Ray (leading particle)



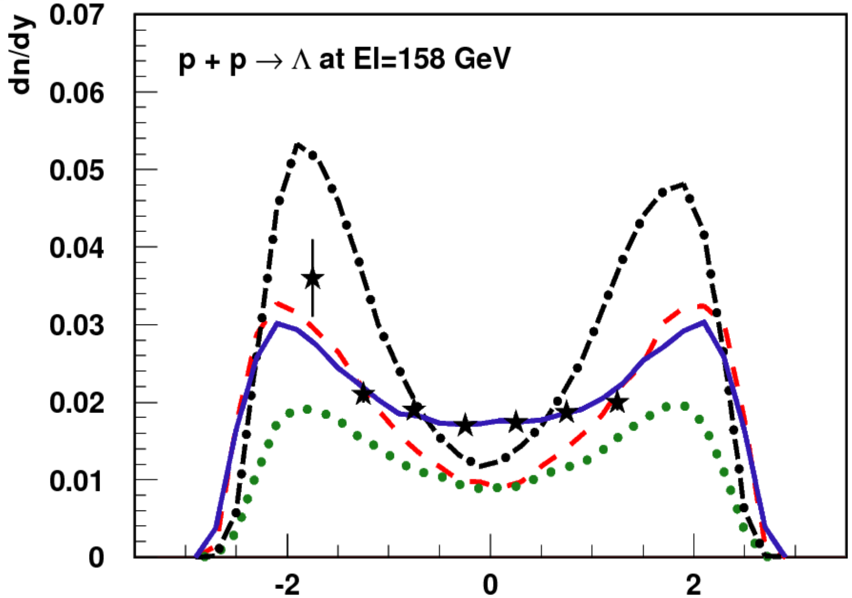


Proton Xf Distribution

- **Leading proton**
  - Tests from 100 GeV lab to 300 GeV cms
  - Very forward proton from ND events

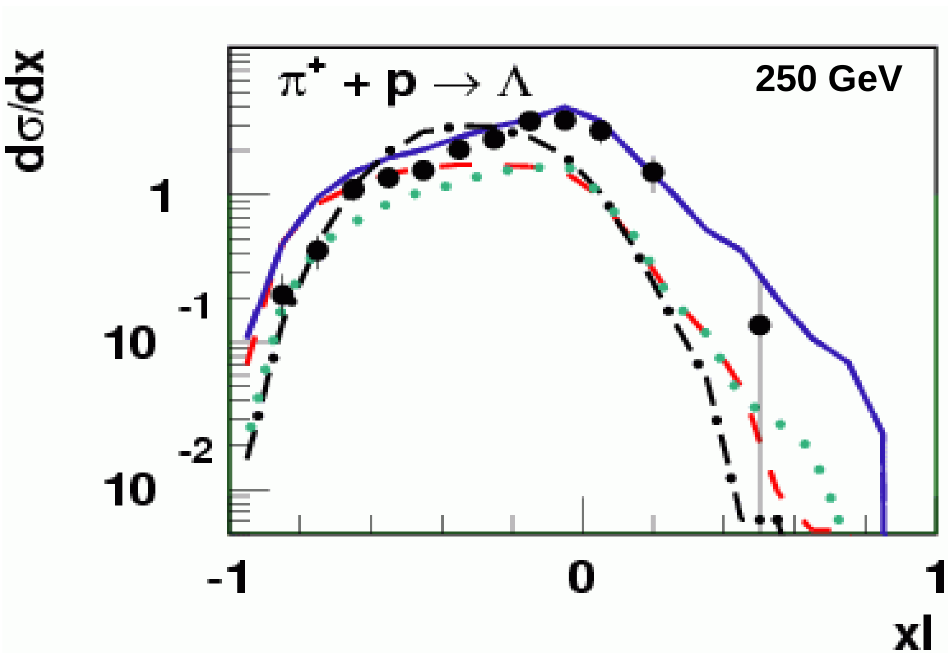


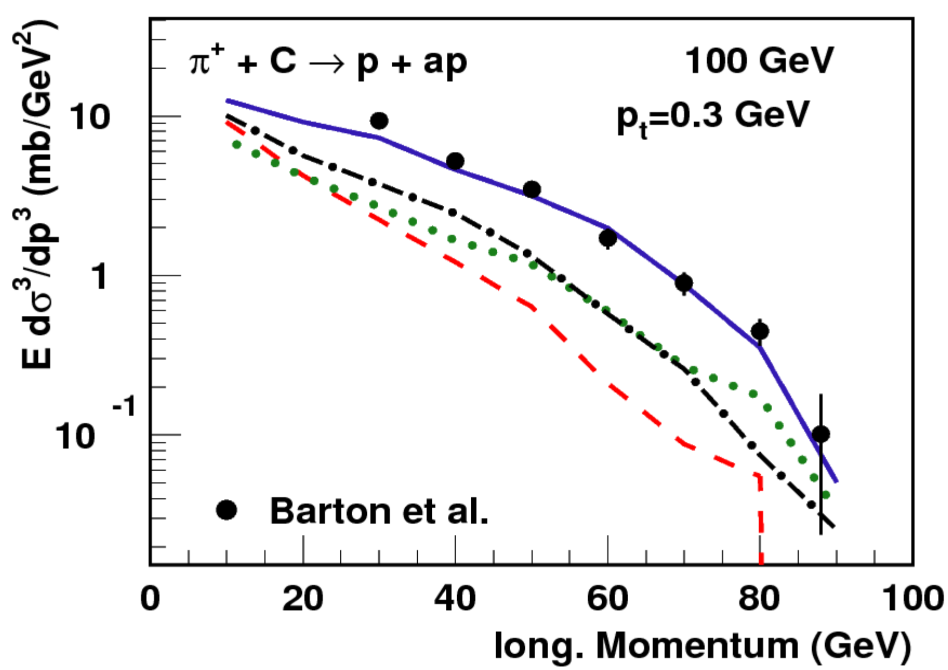
Baryon Spectra



- 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

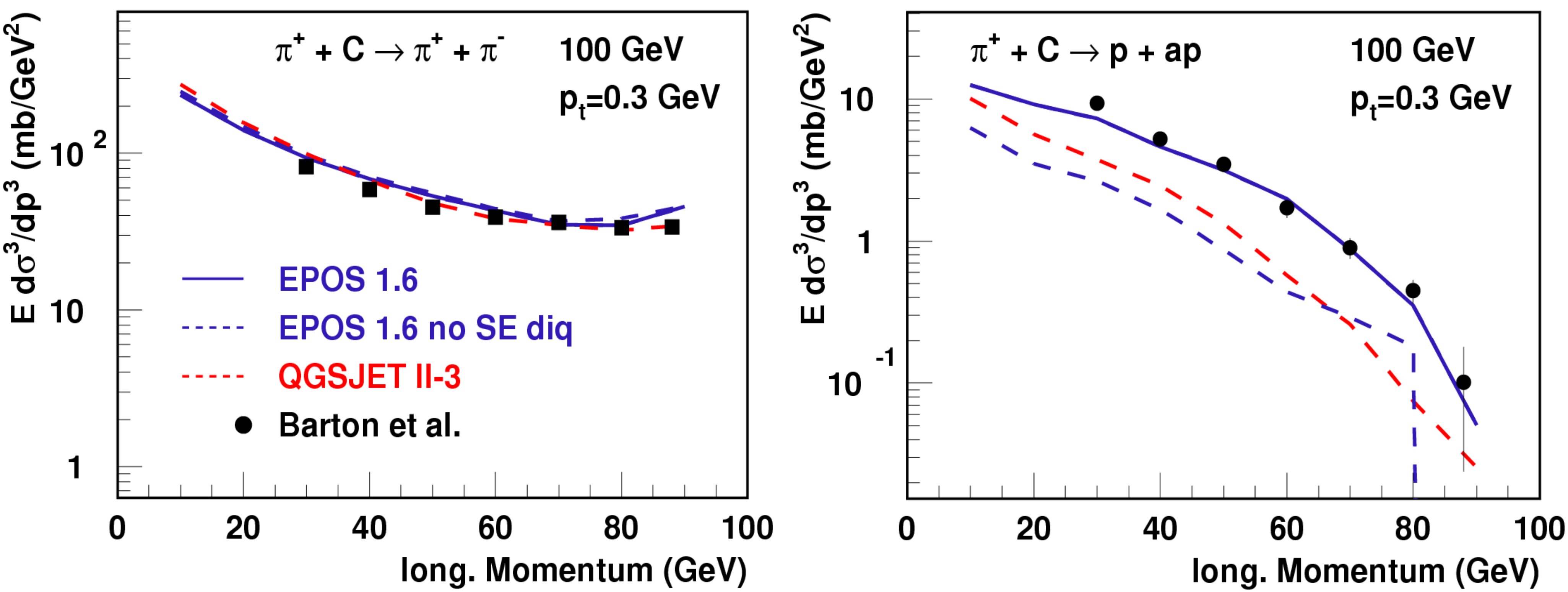




Baryons in Pion-Carbon

Very few data for baryon production from meson projectile, but for all :

- strong baryon acceleration (probability ~20% per string end)
- proton/antiproton asymmetry (valence quark effect)
- target mass dependence



Remnant contributions in LHCf