# Modelling MB pp,pA Collisions at the LHC and in Cosmic Rays : EPOS case


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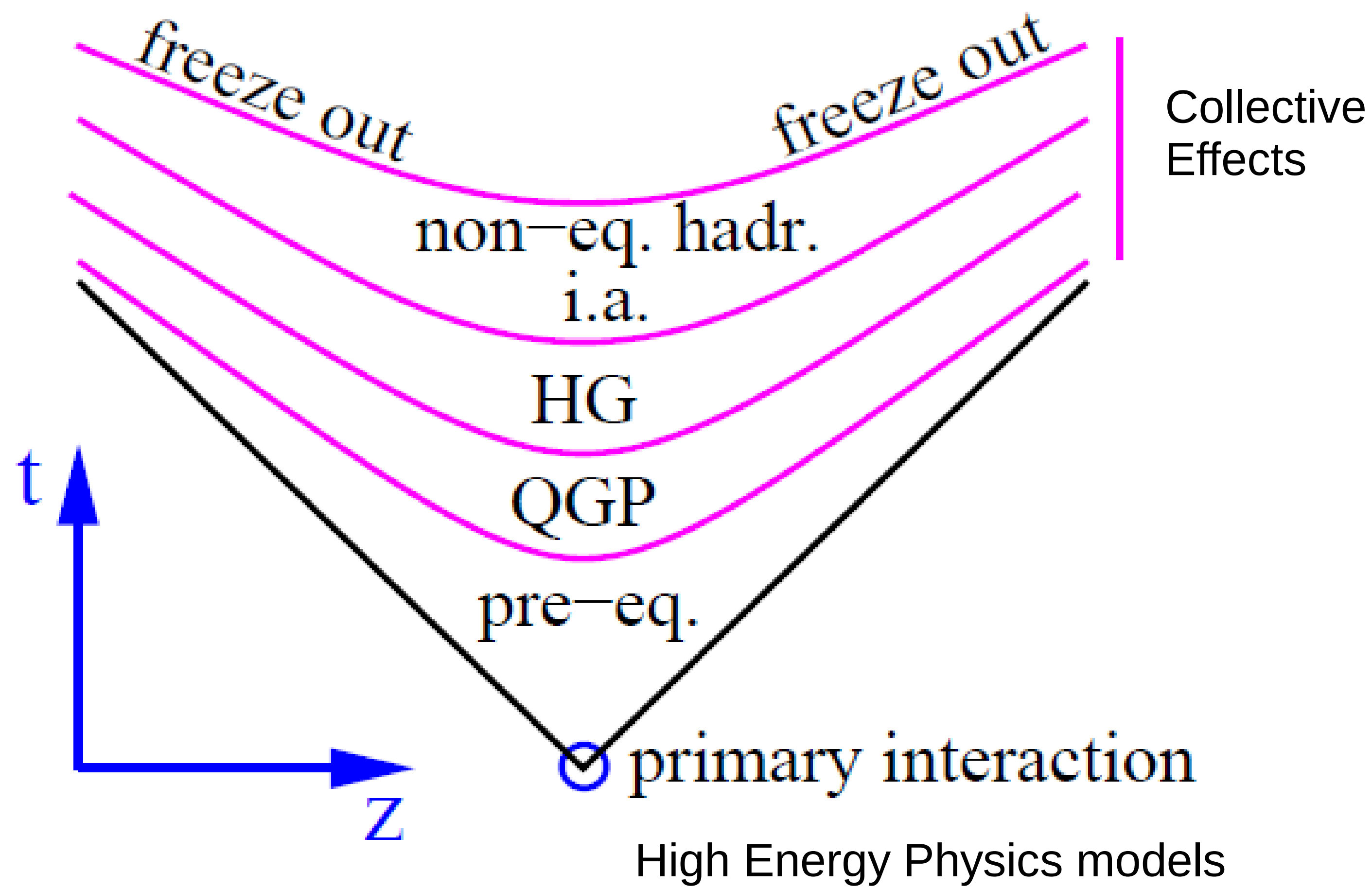
**Prospectives IPHC, Strasbourg, France**

**March the 18th 2015**

# High Energy Hadronic Interactions

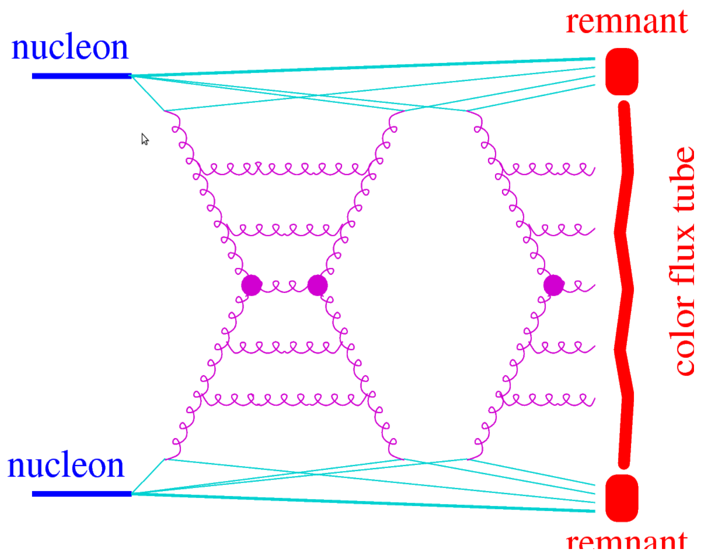


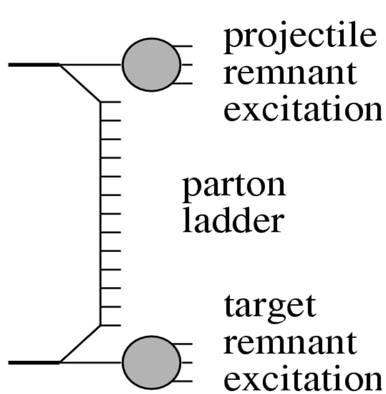

General case : valid for pp if enough particles are produced !
and particle physics can be done not only in accelerator but with air showers

# Outline

- **EPOS LHC**
  - Energy sharing
  - Parton multiple scattering
  - Outshell remnants
  - Screening, Shadowing and Strings
- **Collective effects**
- **EPOS 3**
- **Extensive Air Shower (EAS)**
  - LHC to EAS
- **Muon Production Depth (MPD)**
  - EAS to Hadronic Physics

# 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

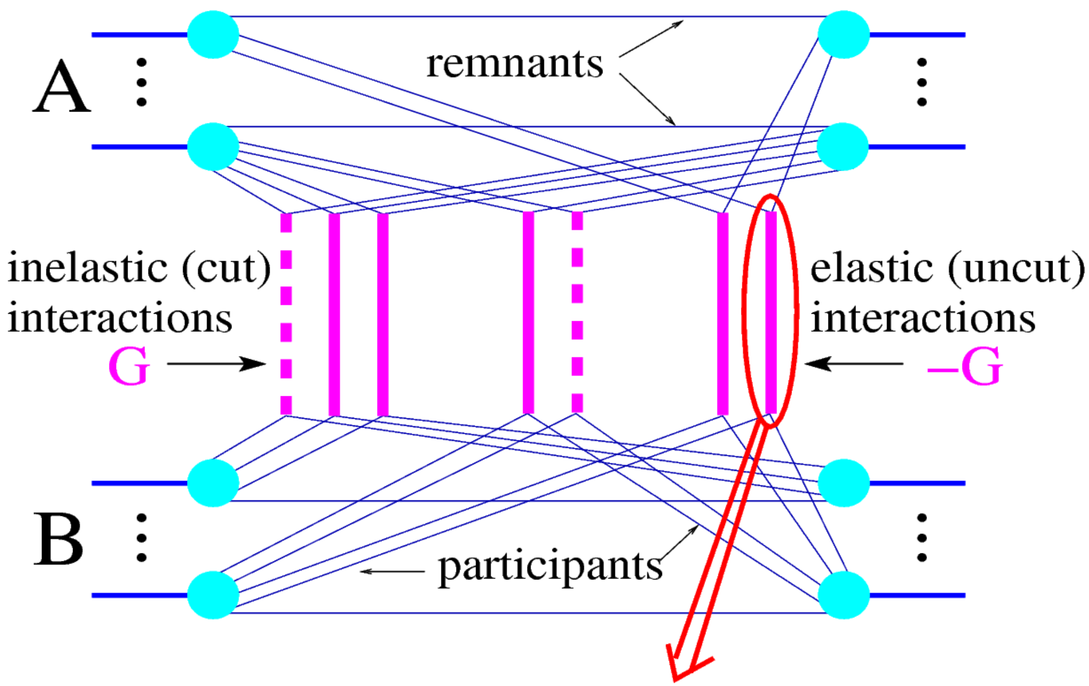
- **Evolution of models by K. Werner et al. :**
  - VENUS (93) : soft physic
  - NEXUS 2 (00): first realization of Parton-Based Gribov-Regge Theory (PBGRT) with soft, semi-hard and hard Pomerons
  - NEXUS 3.97 (03) : enhanced diagrams in PBGRT and new remnant treatment.
  - EPOS 1.6 (06) : PBGRT + remnants + 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

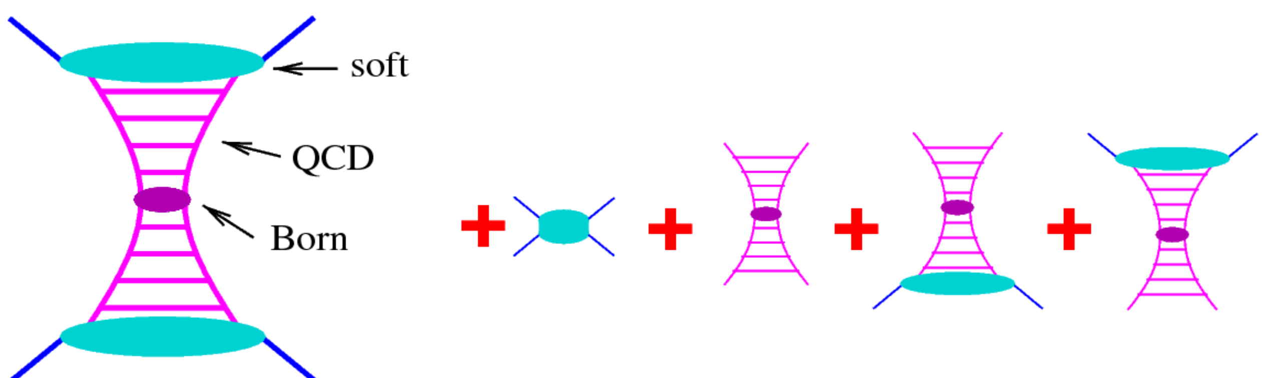
- **Data used to constrain parameters (~100) :**
  - ➜ string fragmentation : e+e- data,
  - ➜ hard Pomeron : DIS data,
  - ➜ soft Pomeron and vertices : pp,πp,Kp, pA cross sections
  - ➜ diffraction : pp low energy diffraction and multiplicity distributions
  - ➜ excitation functions : multiplicity in pp from SPS to Tevatron,
  - ➜ 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

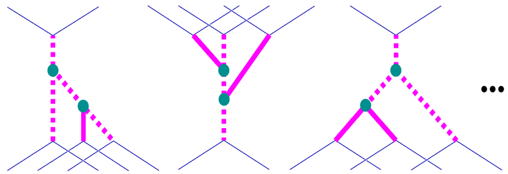
# Parton-Based Gribov-Regge Theory




- **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)

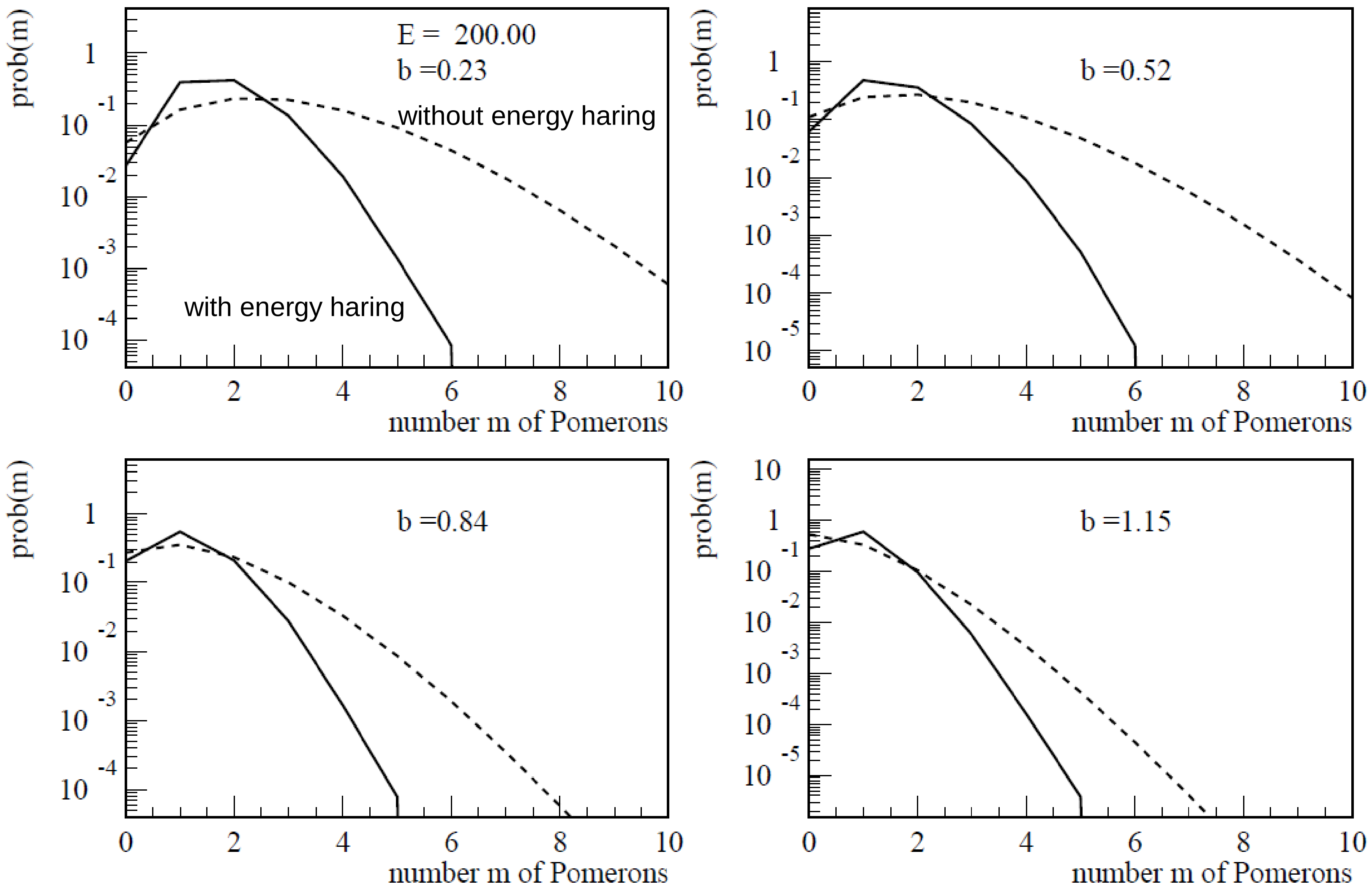



Non-linear effect (screening) absorbed in modified vertex functions



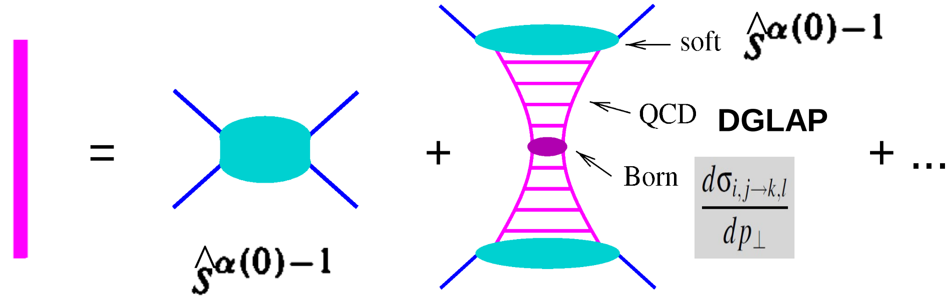
# Number of cut Pomerons

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

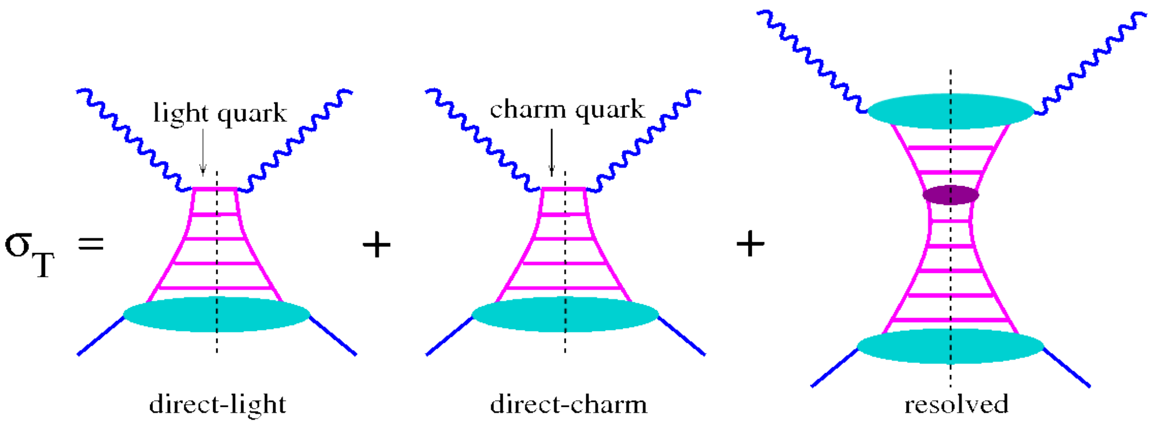


# EPOS : Pomeron definition

Semi-hard Pomeron :

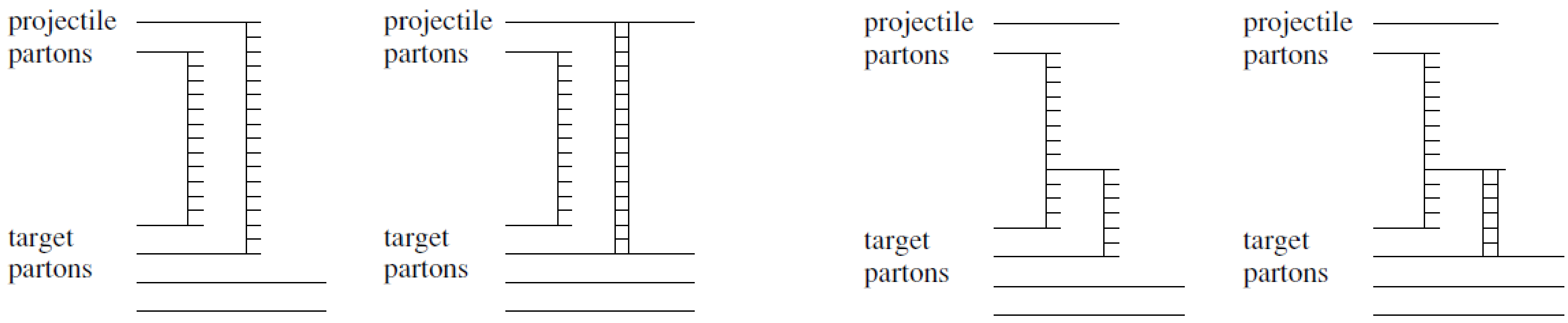



Test of semi-hard Pomeron with DIS: (Parton Distribution Function from HERA)




- 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

# EPOS – high parton density effects

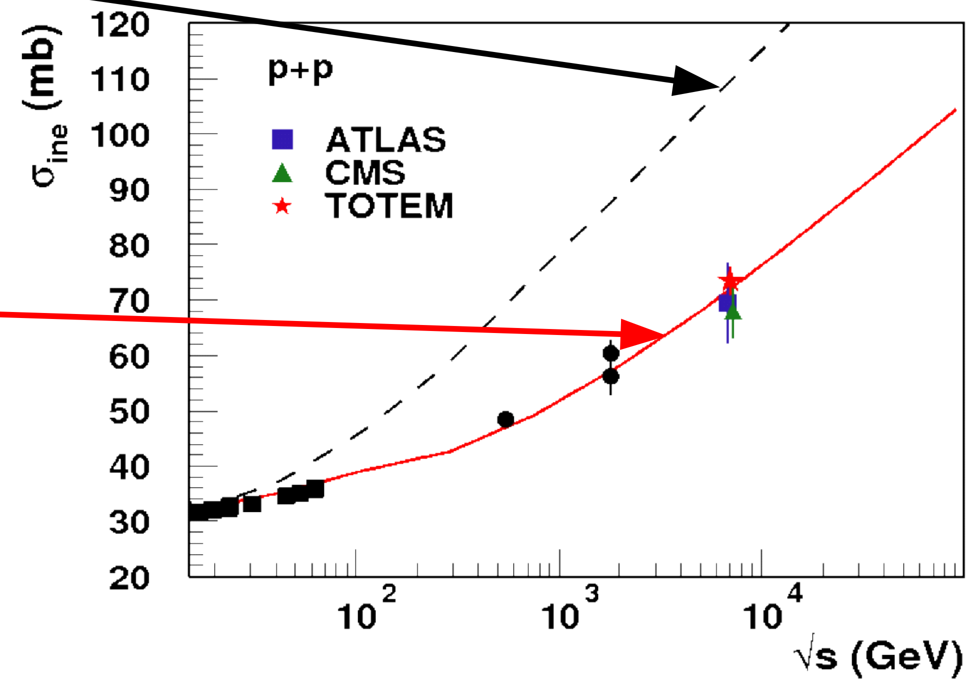



No effective coupling

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

With effective coupling

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



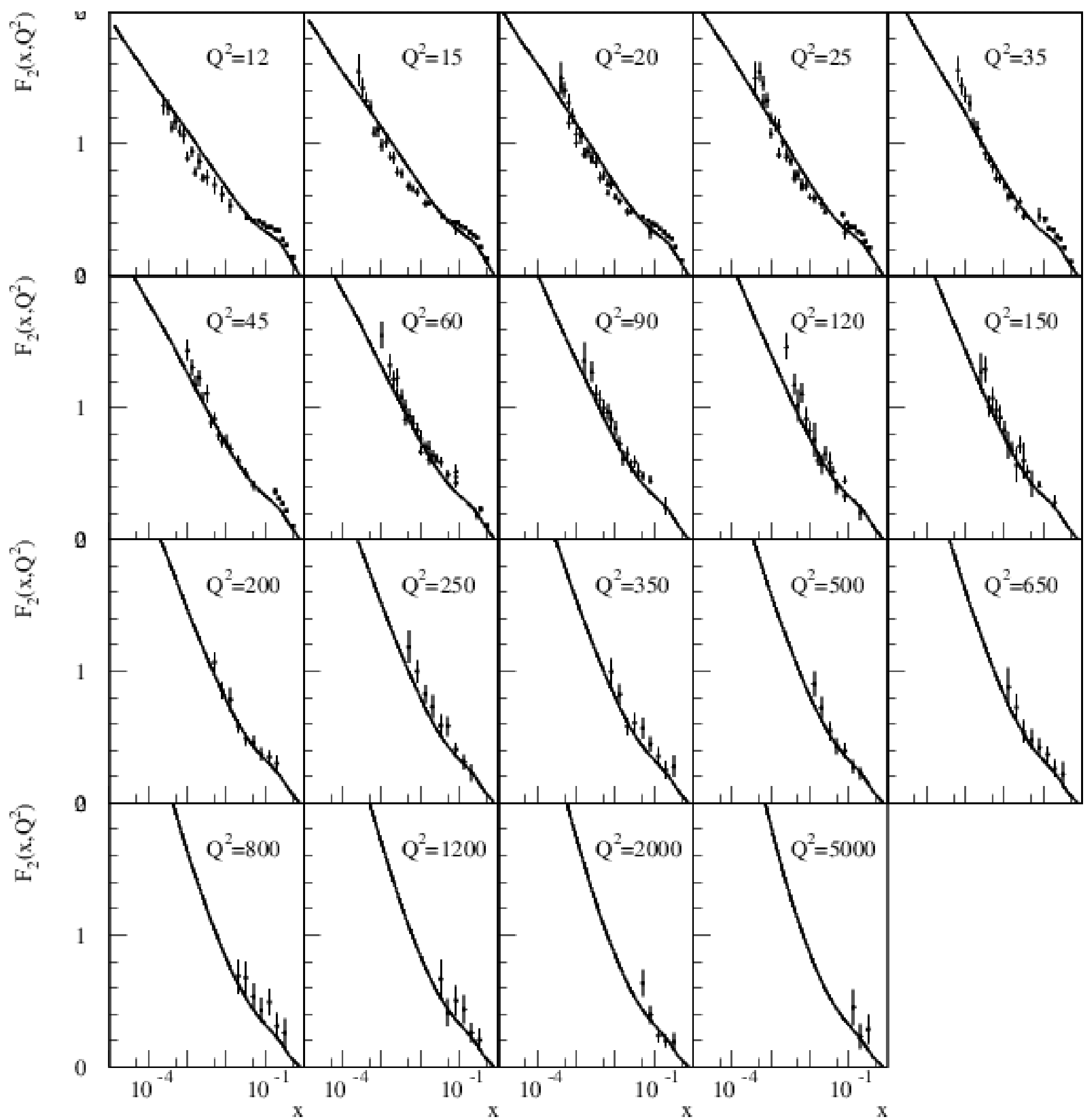

Parametrization

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

# Parton Distribution Function

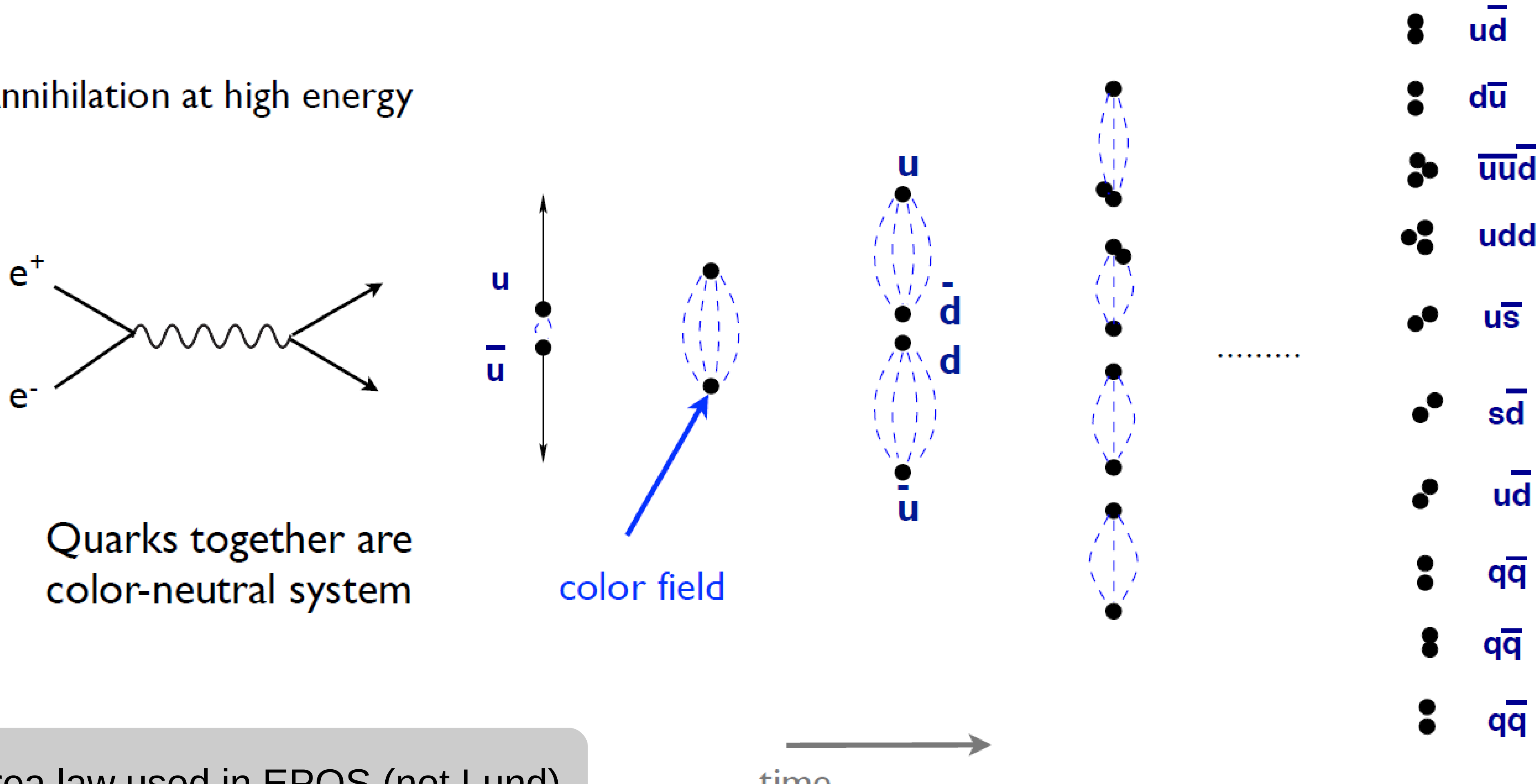
- **PDF based and DGLAP and initial soft parametrization with saturation**

Preliminary from EPOS 3



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

Annihilation at high energy



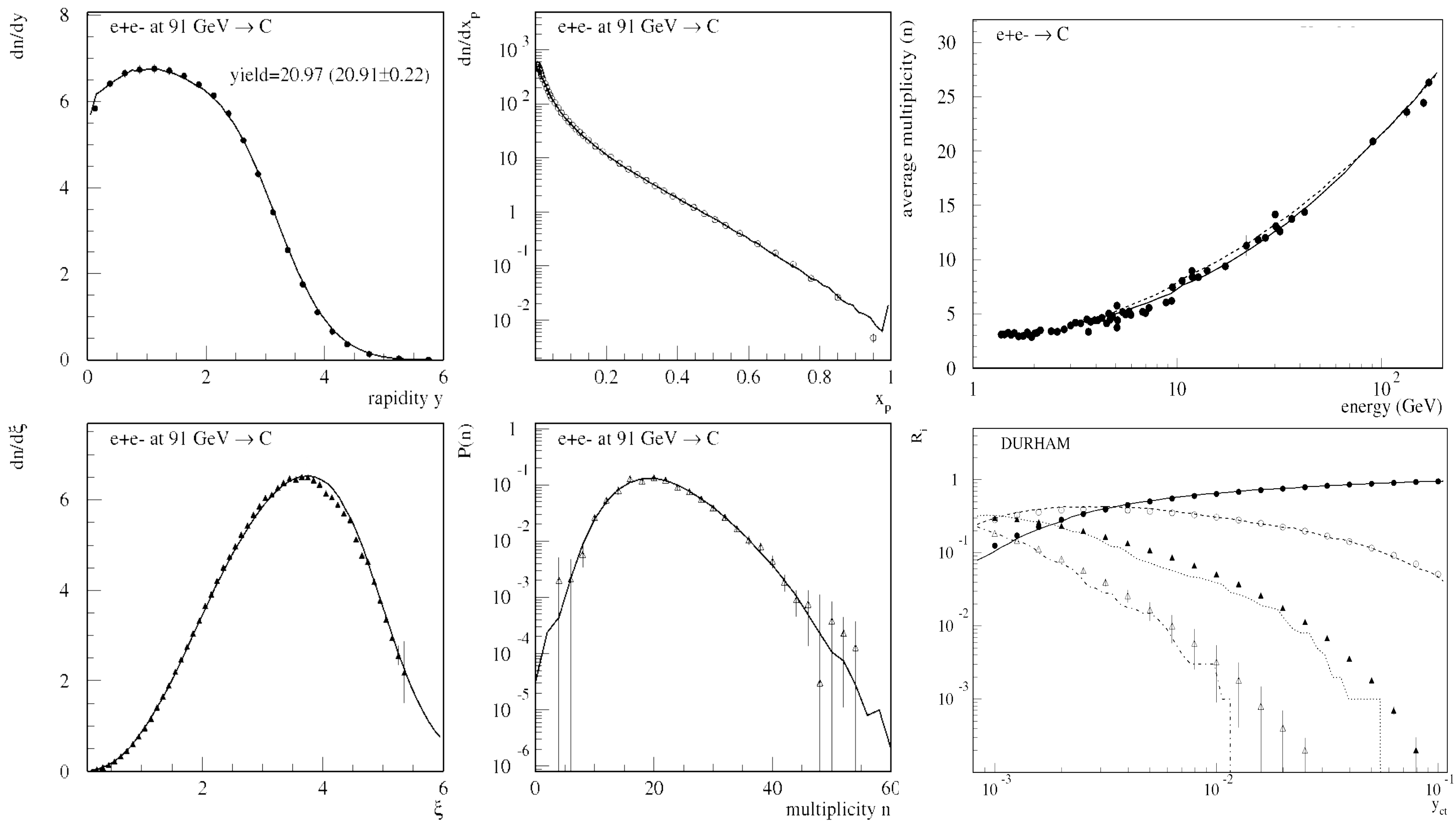

Quarks together are color-neutral system

Area law used in EPOS (not Lund)

Chain of hadrons

String fragmentation

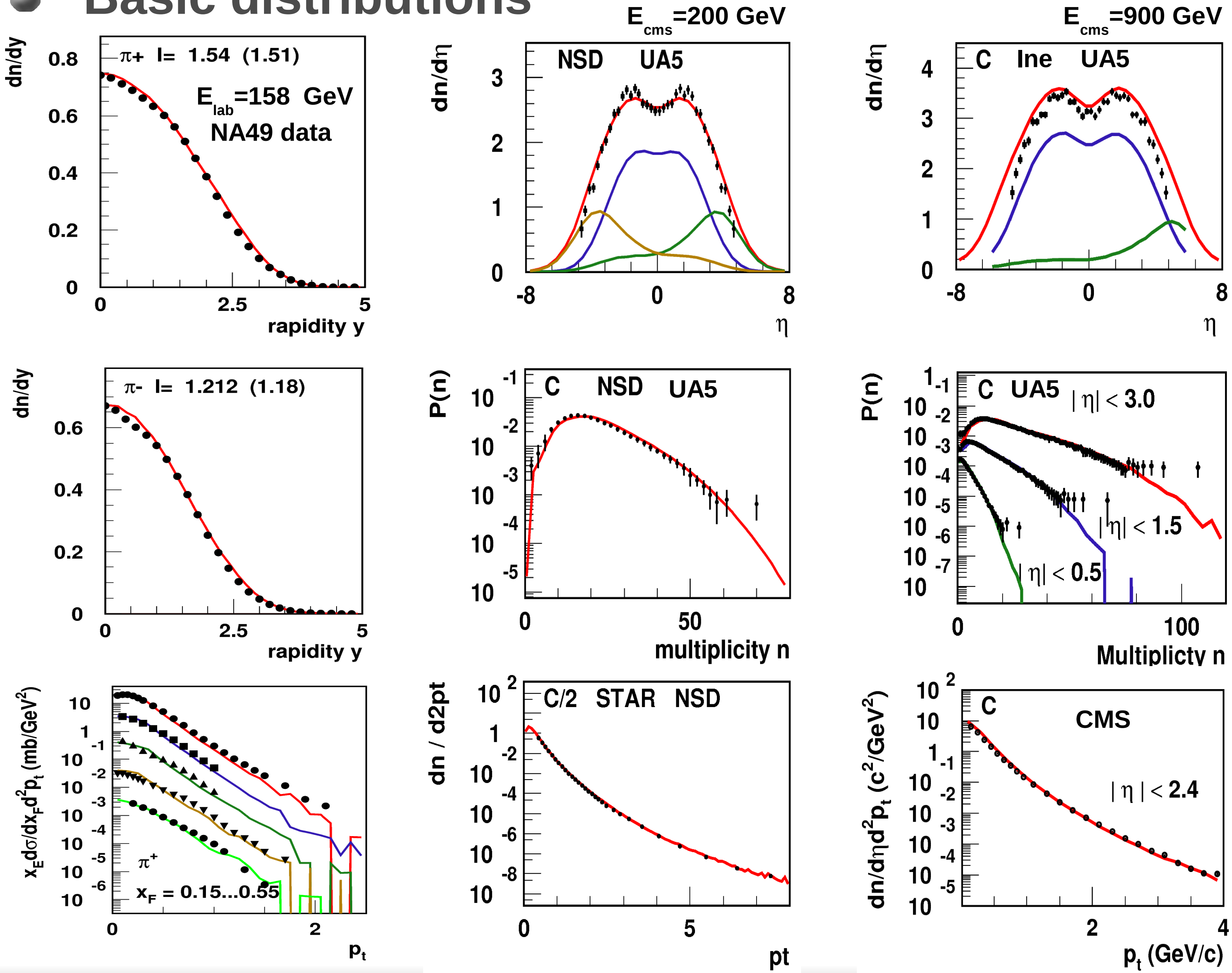
# Test at LEP



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

# Basic Distributions

## Basic distributions

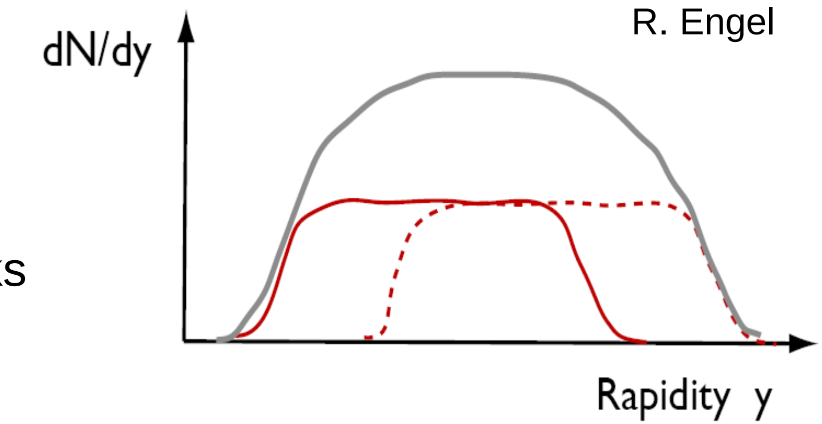


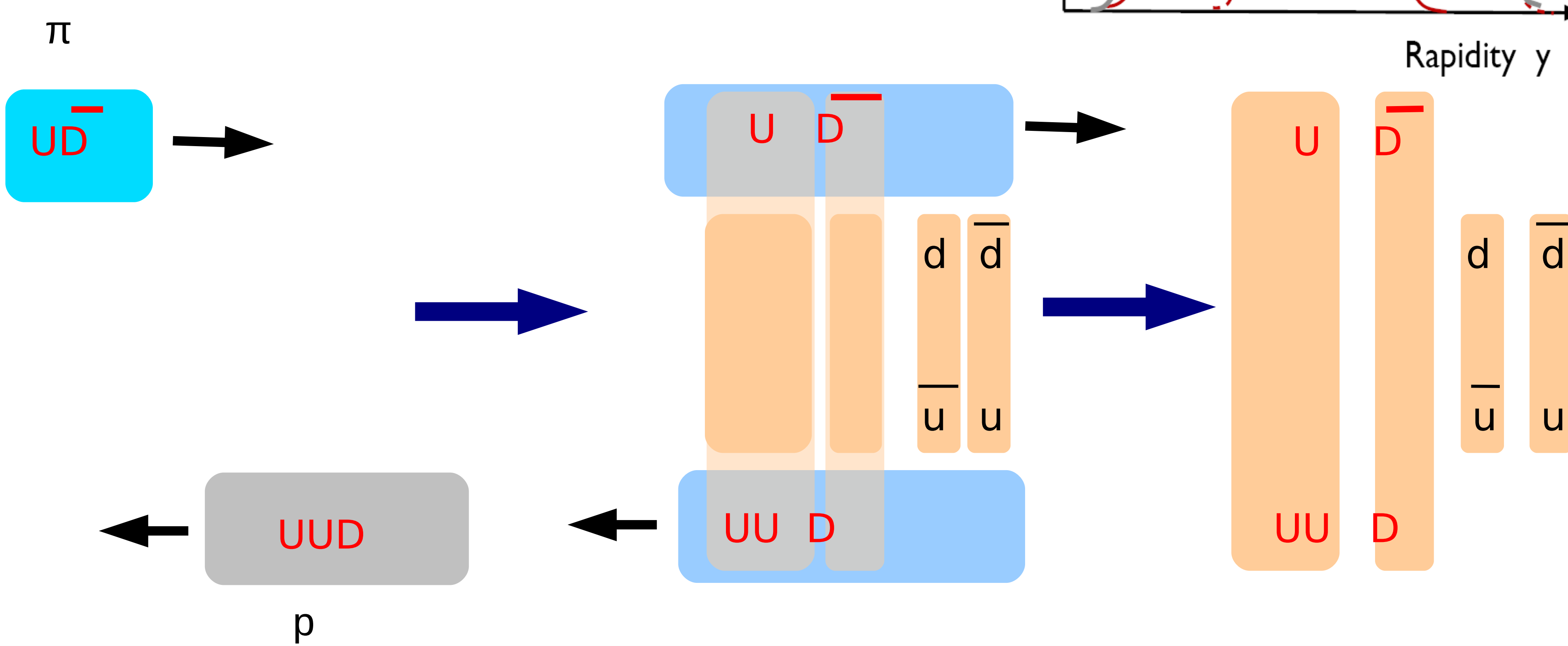
# Remnants in PYTHIA

## 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

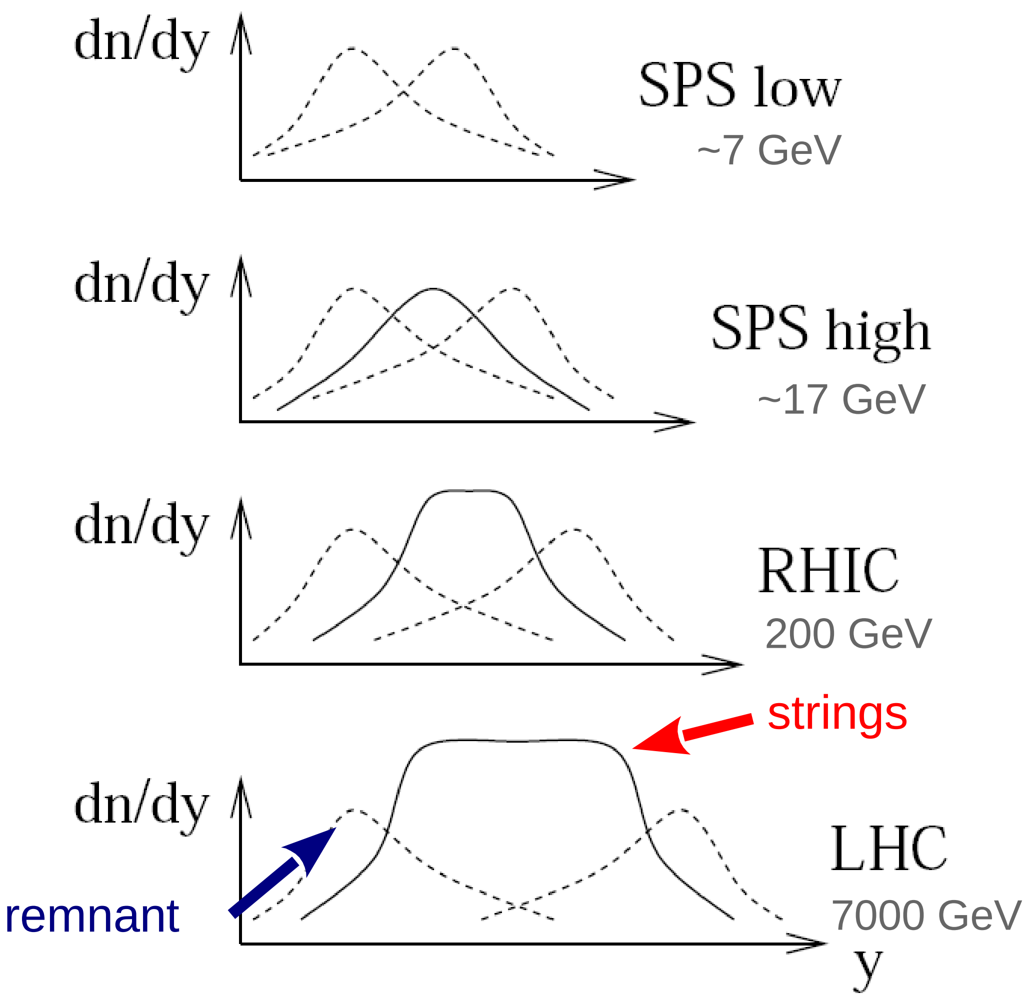
R. Engel



# Remnants

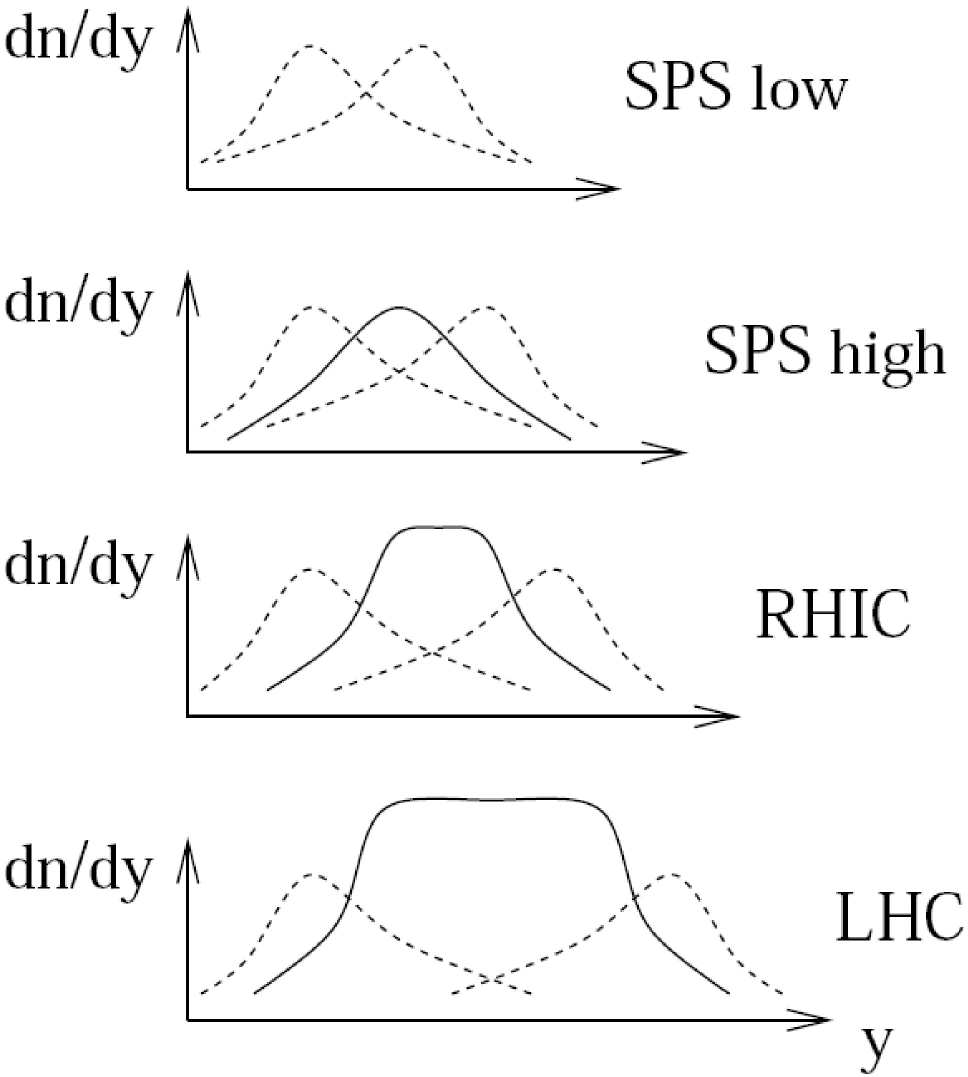
**Forward particles mainly from projectile remnant**




- 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)

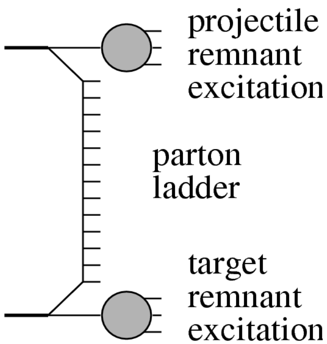
**Different contributions of particle production at different energies or rapidities**

# Remnants




## Free remnants in EPOS:

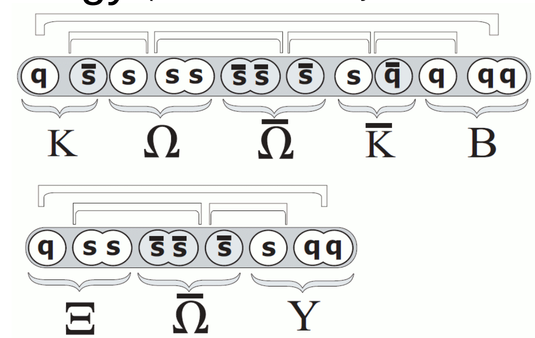
- from both diffractive or inelastic scattering
- excited state with $P(M) \sim 1/(M^2)^\alpha$
- dominant contribution at low energy
- forward region at high energy
- depending on quark content and mass (excitation):
  - resonance
  - string
  - droplet (if #q>3)
  - string+droplet



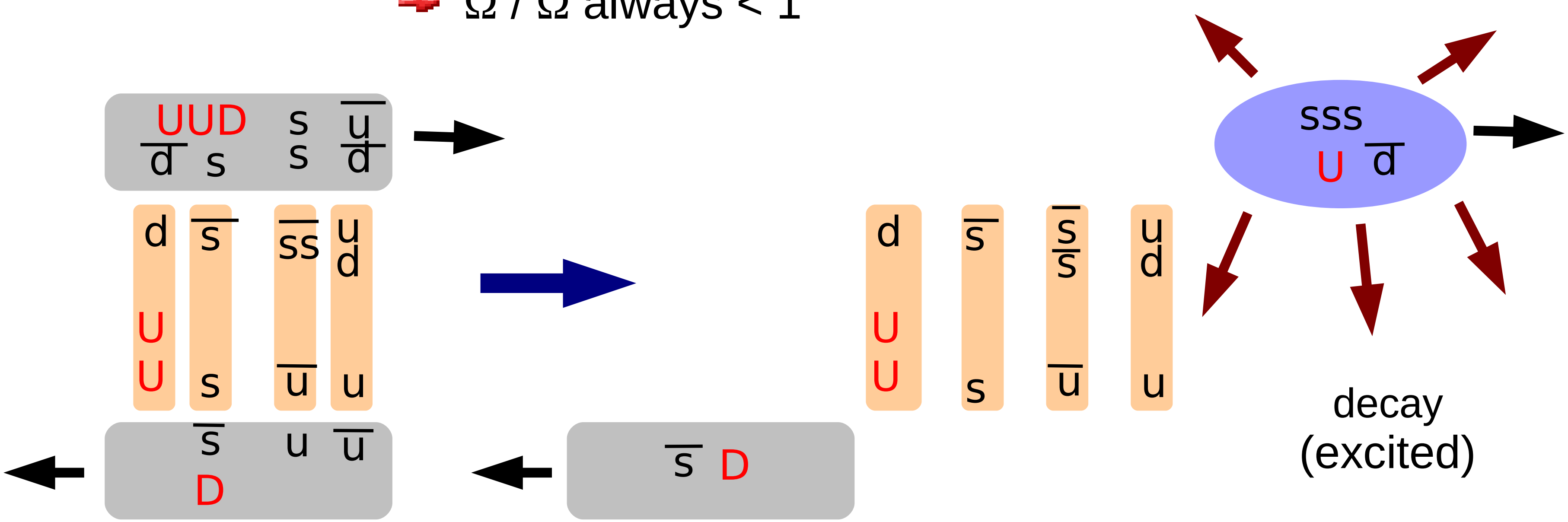
# Baryons and Remnants

## Parton ladder string ends :

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

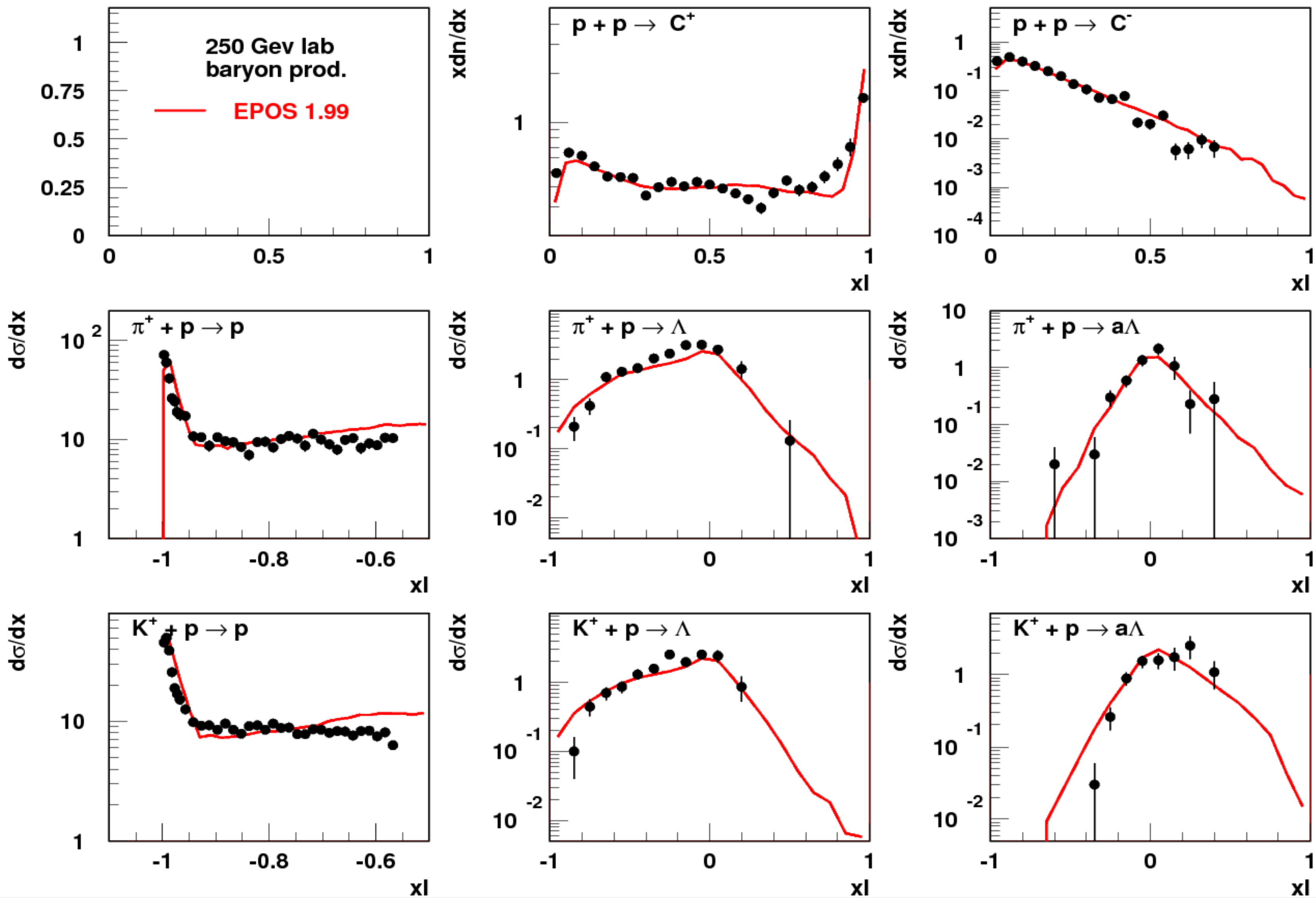



- EPOS
  - No “first string” with valence quarks : all strings equivalent
  - Wide range of excited remnants (from light resonances to heavy quark-bag)
    - $\bar{\Omega}$ / $\Omega$ always < 1



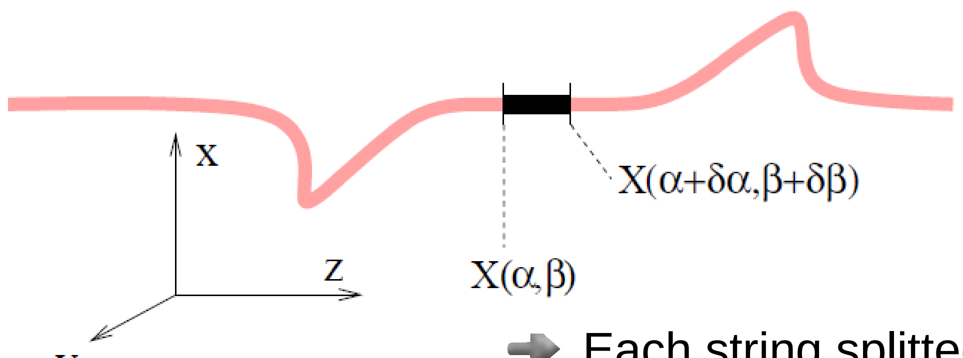
# Baryon Production

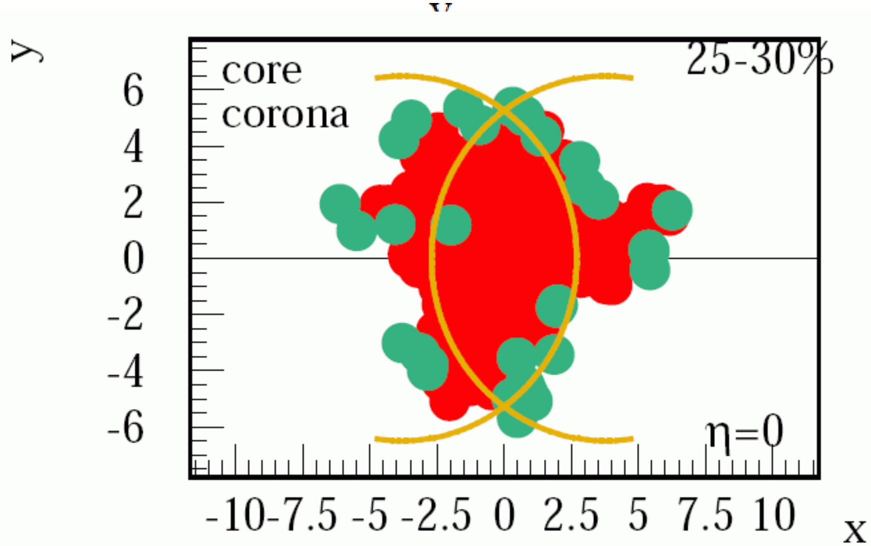
- **Baryon production for fixed target exp.**



# 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**

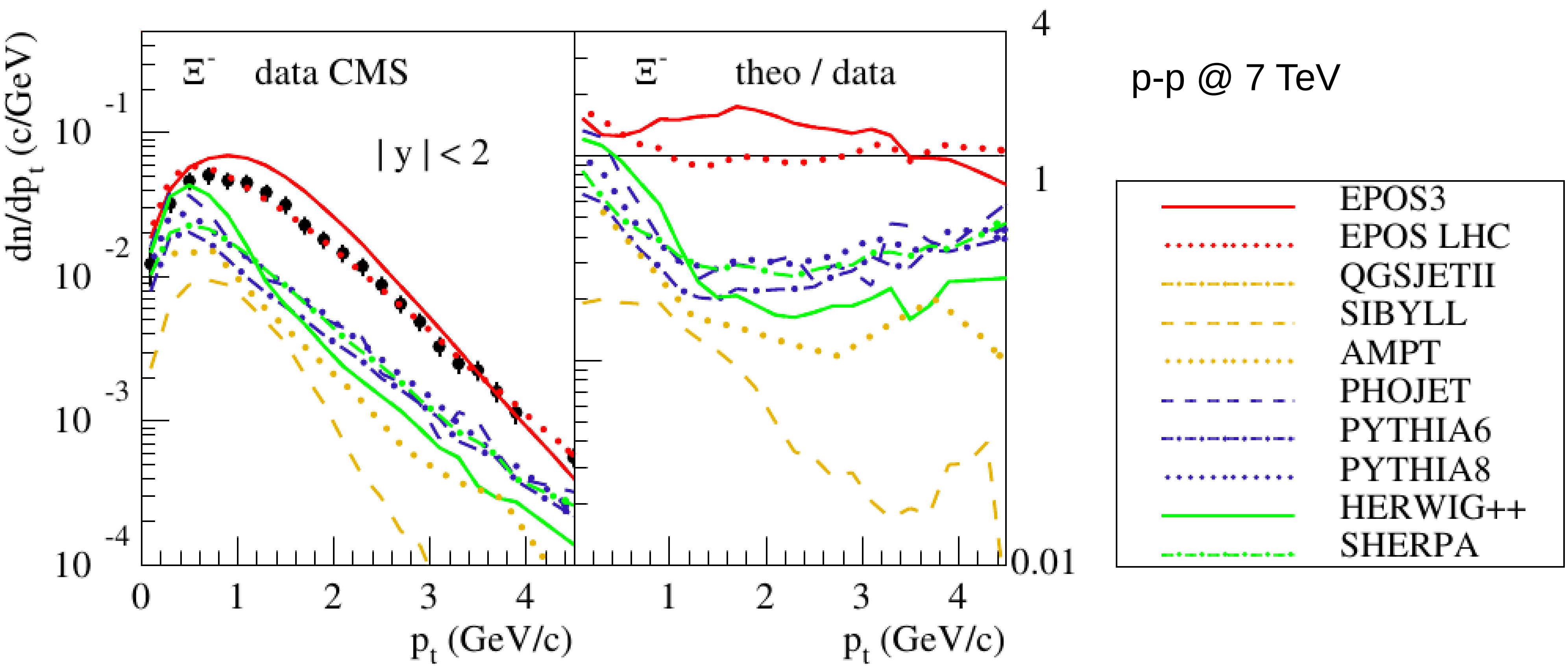



- Each string splitted into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space
- If energy density from segments high enough
  - segments fused into core
    - flow from hydro-evolution
    - statistical hadronization
- If low density (corona)
  - segments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

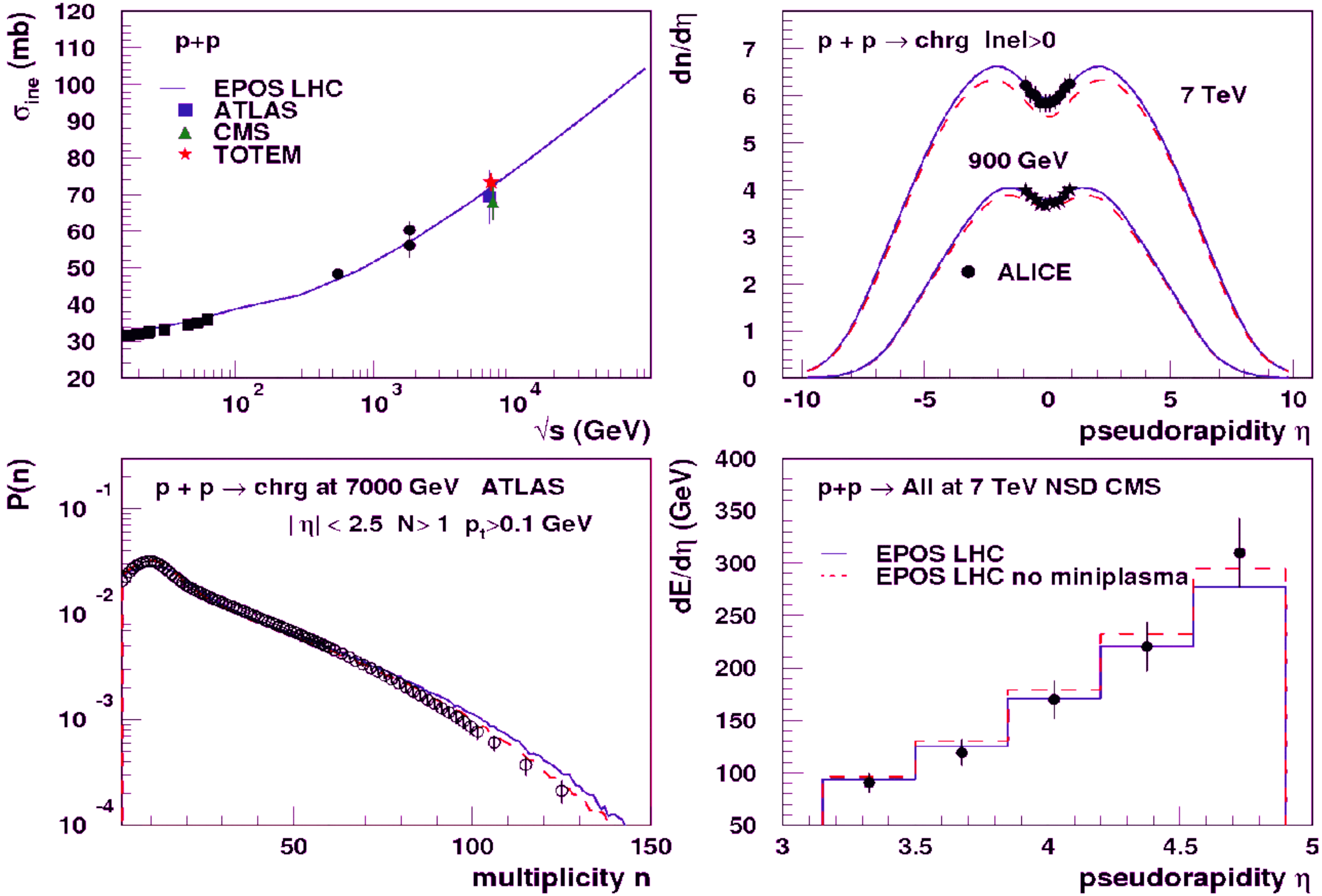
# Core in p-p

- **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 $\langle p_t \rangle$)



# EPOS LHC

- **Effective flow treatment**
  - hydro replaced by tuned asymmetric $p_t$ boost



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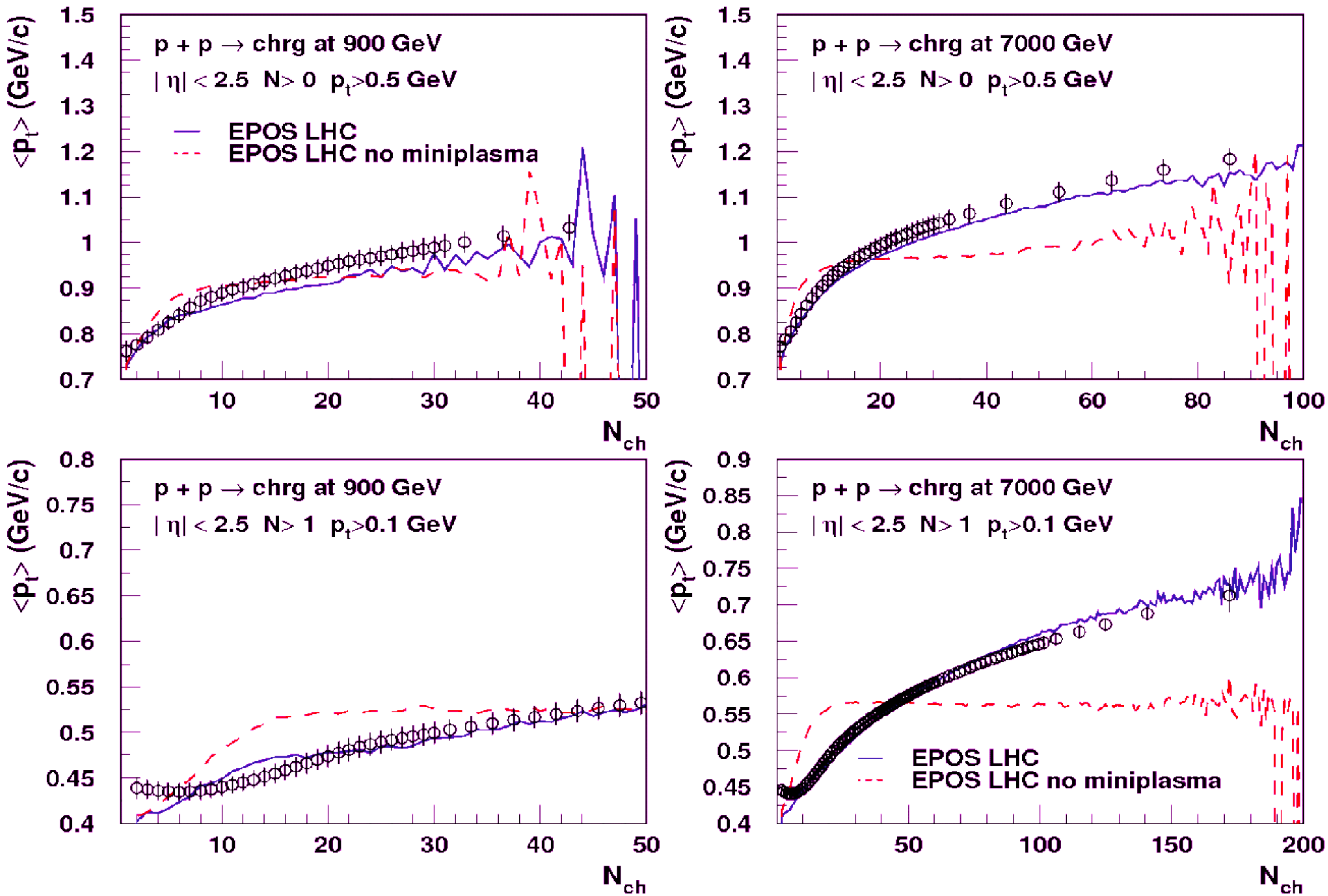
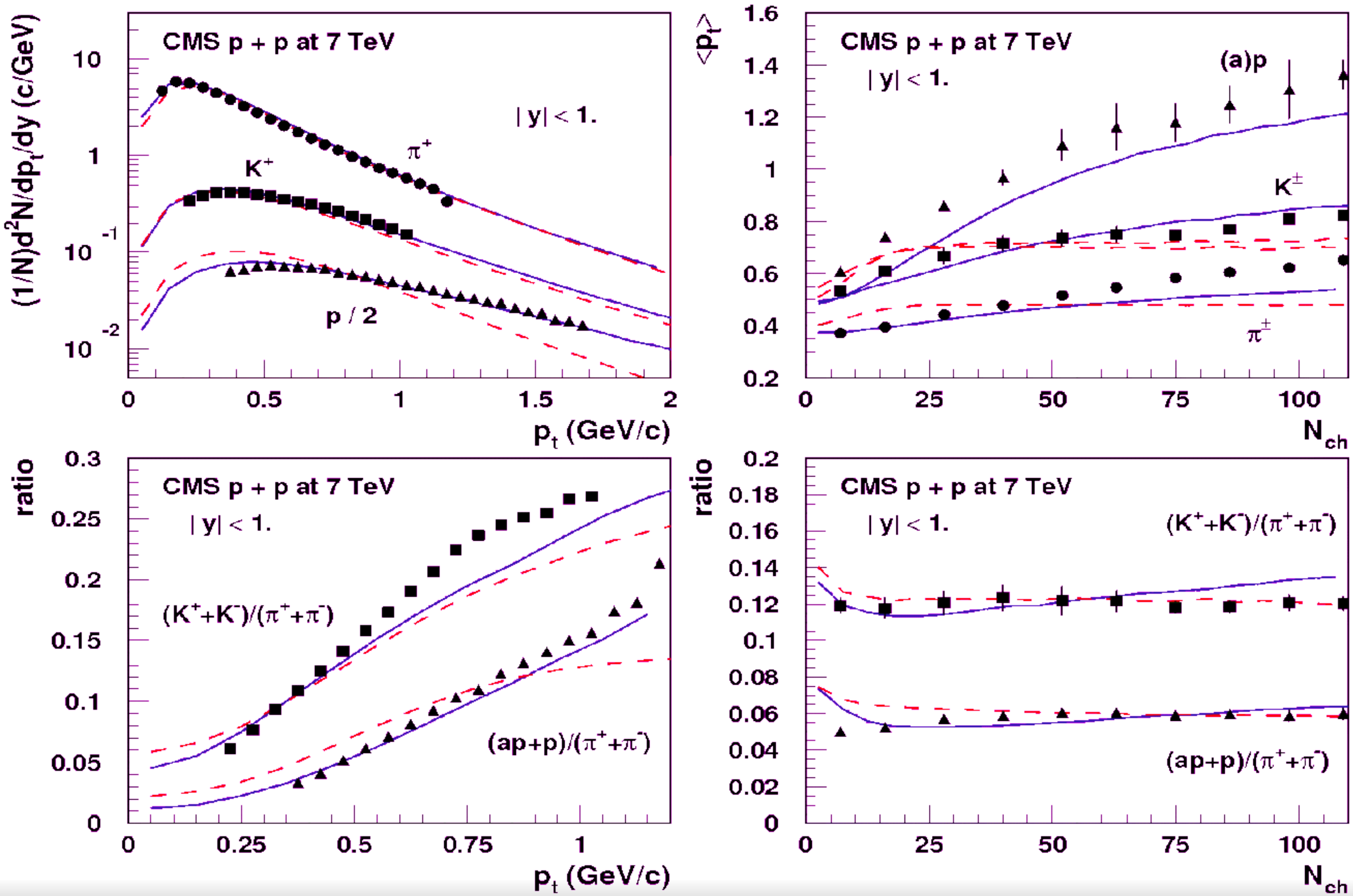


# EPOS LHC

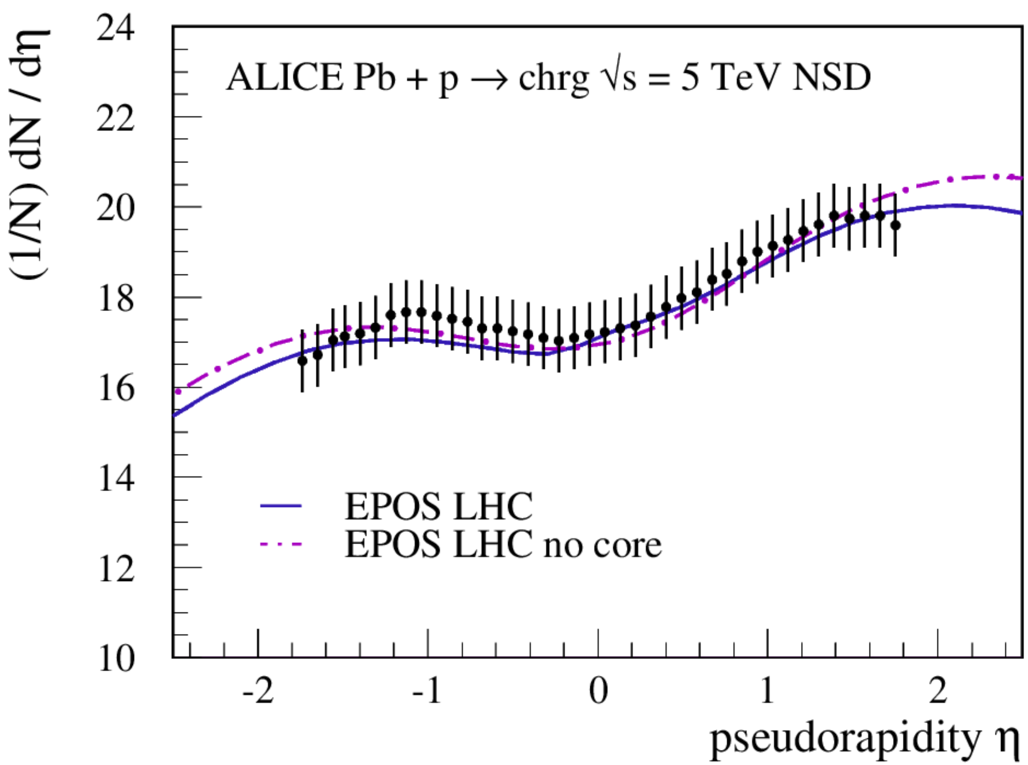
- **Detailed description can be achieved**
  - identified spectra
  - $p_t$ behavior driven by collective effects (statistical hadronization + flow)

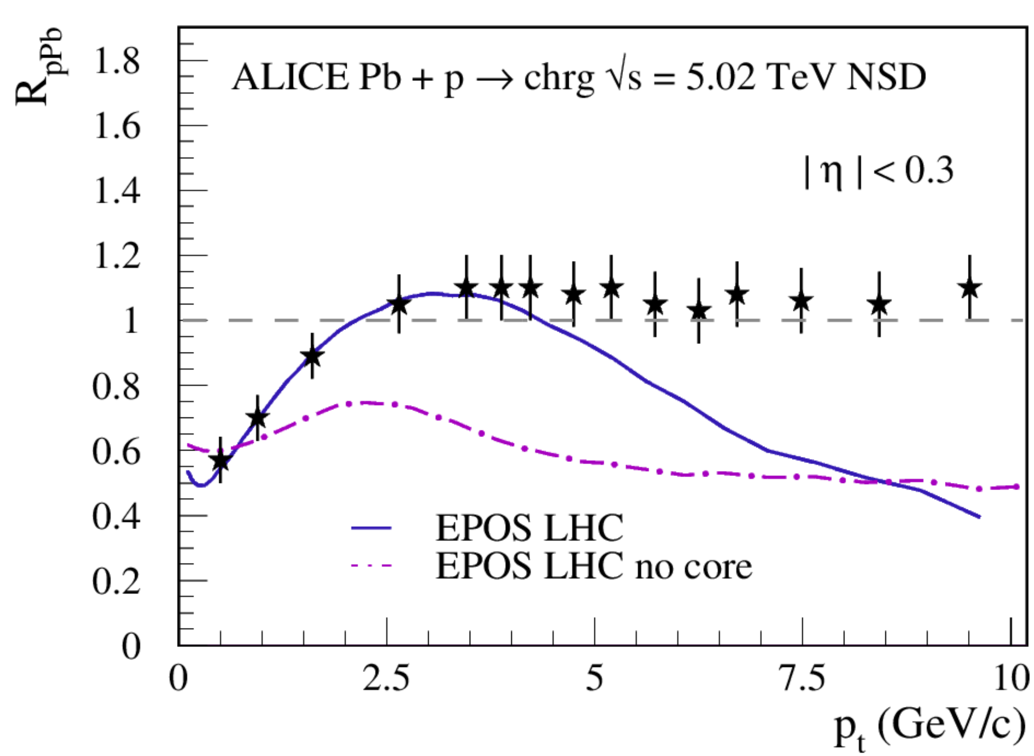


# Saturation

- **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

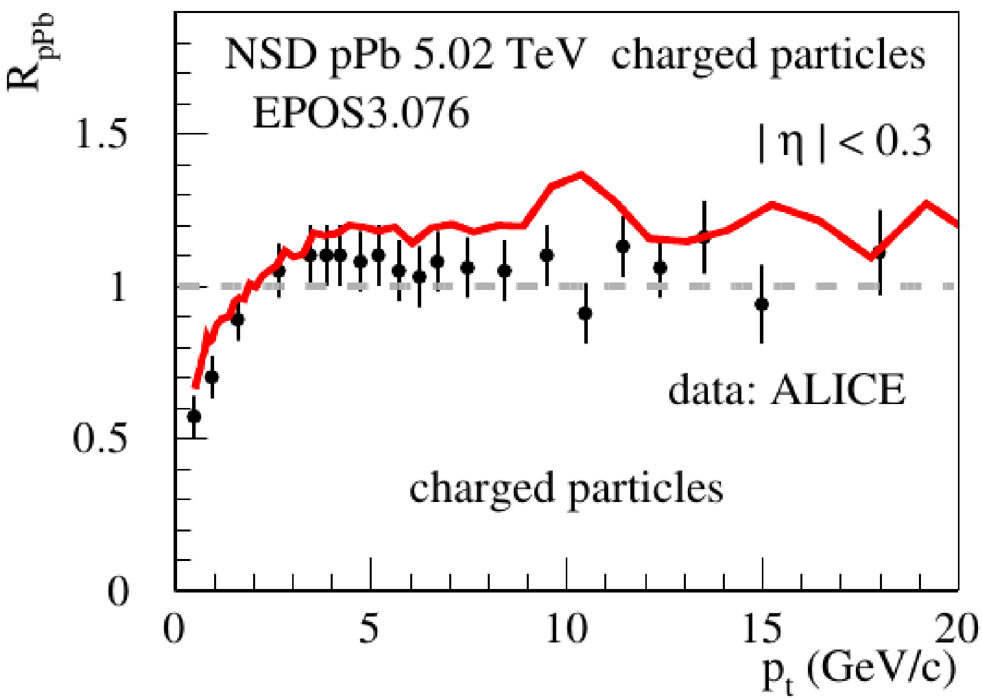
  → $Q^2$ dependent screening

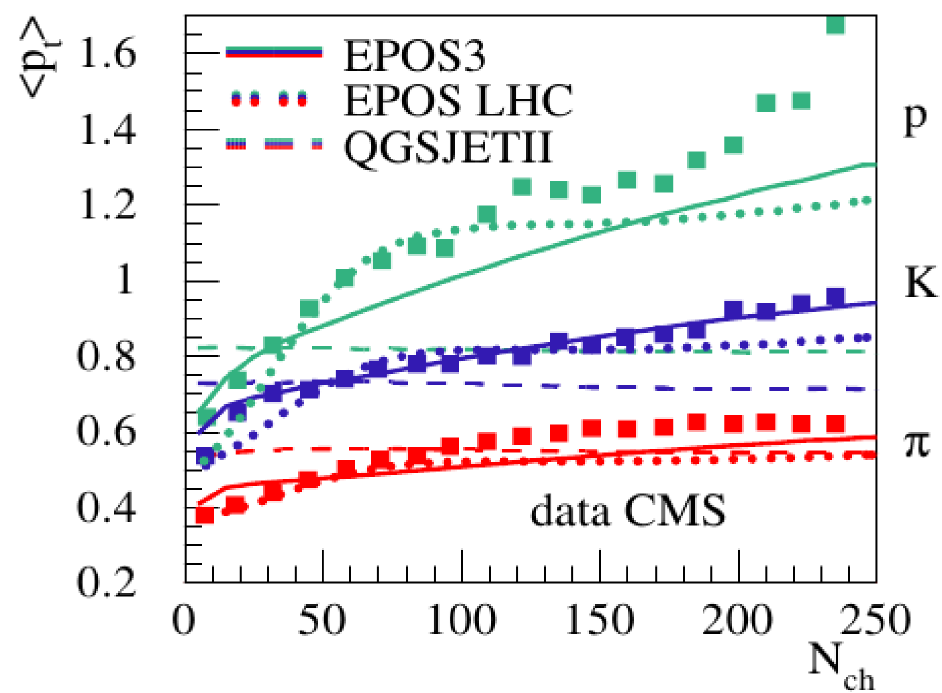


# EPOS 3

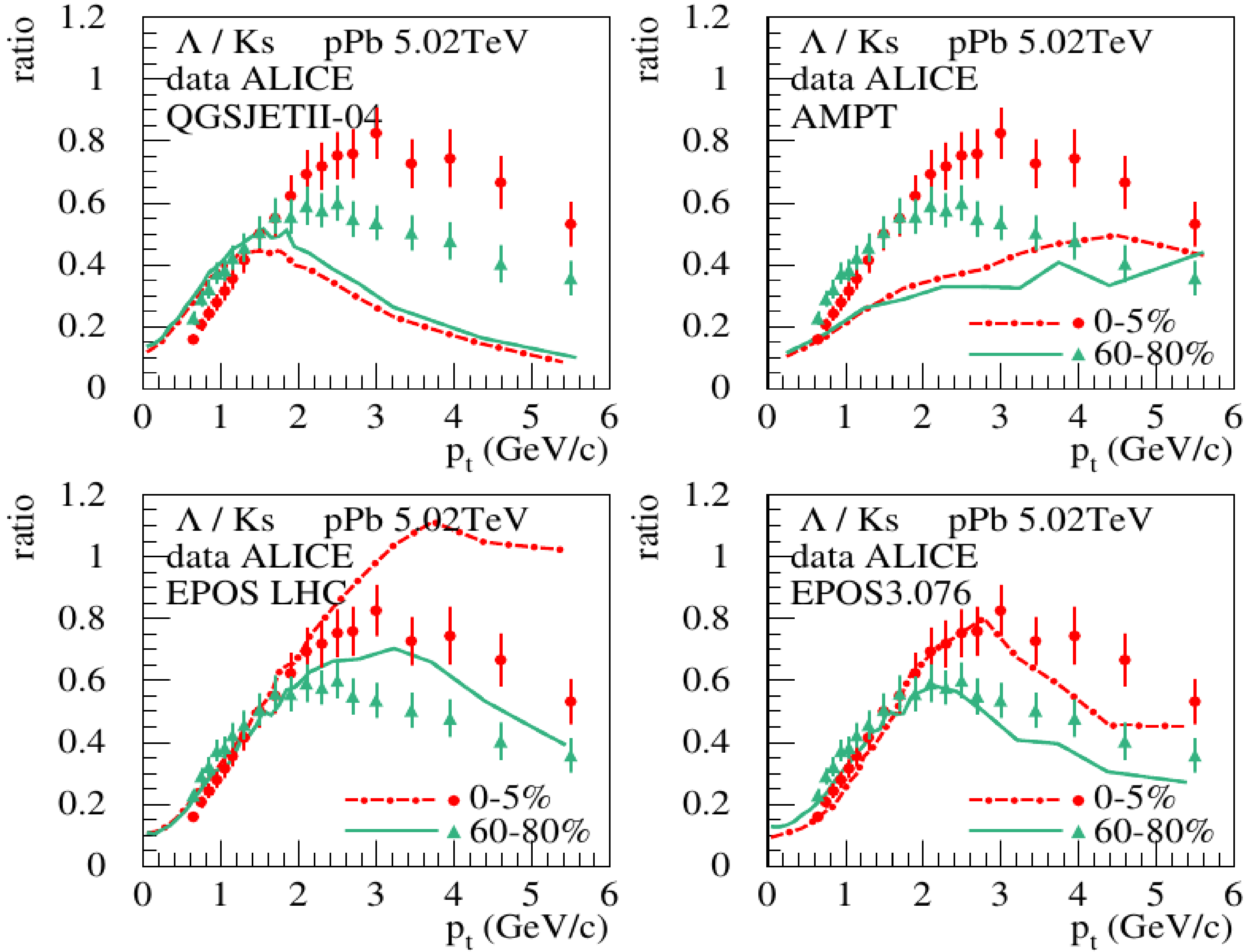
- **Use saturation scale to have a $Q^2$ dependent screening**
  - restore binary scaling for high $p_t$
  - intermediate $p_t$ due to flow based on real hydro simulations
    - mass splitting



# Real 3D Hydro

**Particle ratio characteristic of collective flow effect.**



# Summary on EPOS

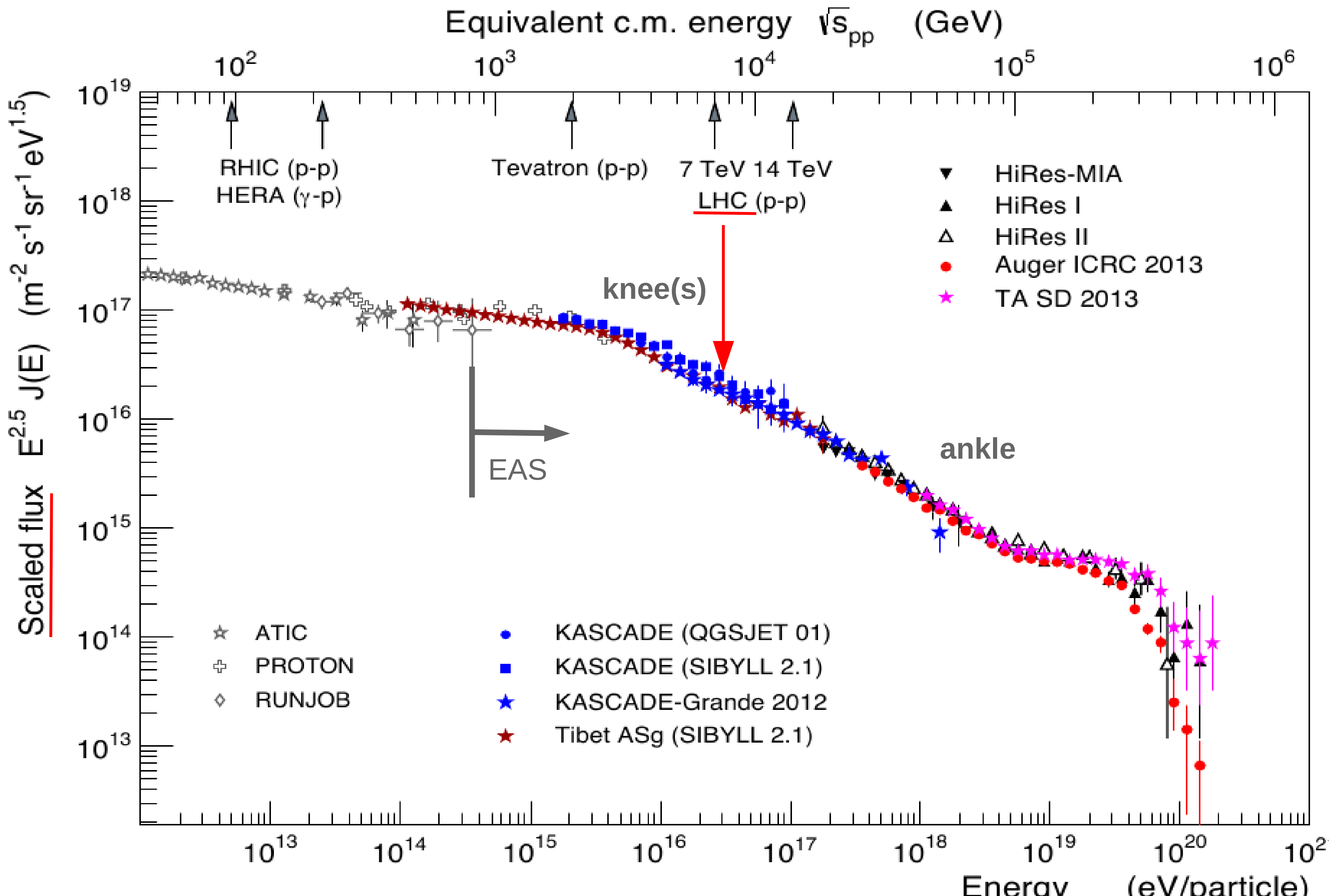
## Hadronic interactions with EPOS:

- 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)
- Hydro on event-by-event basis (slow) or effective flow (fast) tune on real hydro
- Replace effective screening by saturation scale :
  - Improvement of hard events (jets) in MB
- Heavy flavor (charm and beauty)

## EPOS on-going developments :

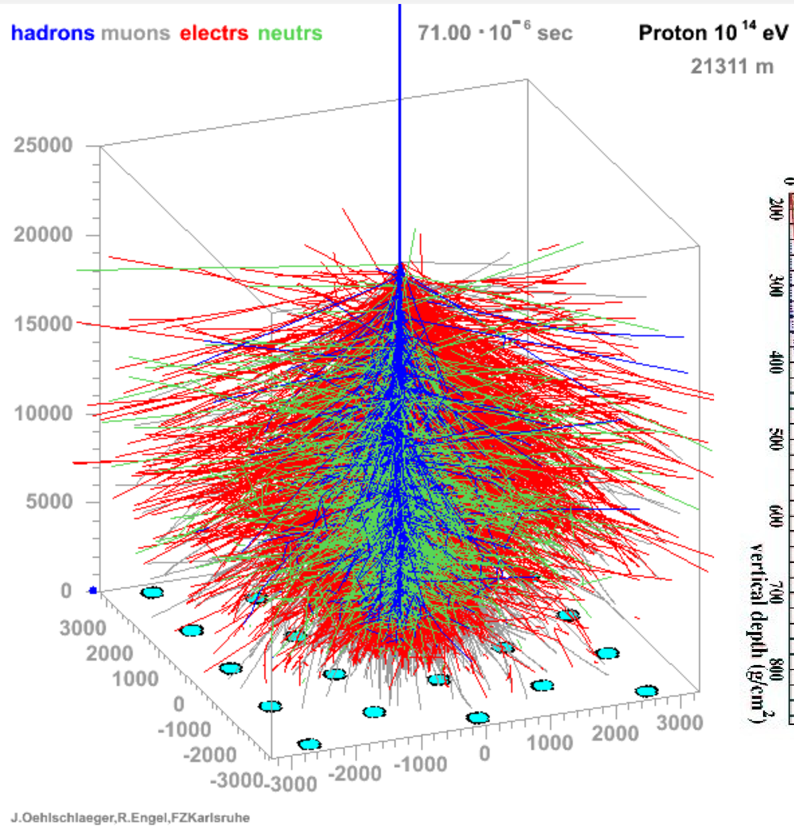
- Selection of hard processes (specific born Pt)
- Both at the same time : underlaying events
- Test with cosmic ray data ...

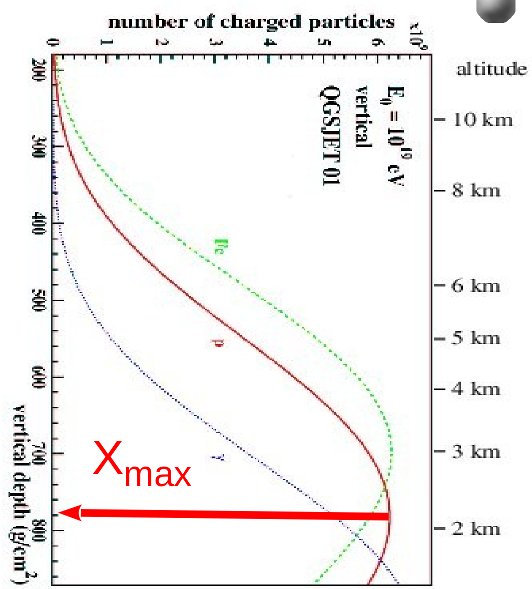
# Cosmic Ray Spectrum




R. Engel (KIT)

# Extensive Air Shower Observables



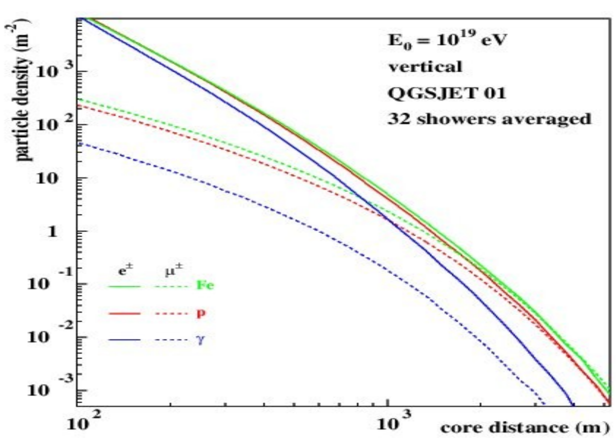




- **Longitudinal Development**
  - number of particles vs depth

$$X = \int_h^\infty dz\, \rho(z)$$

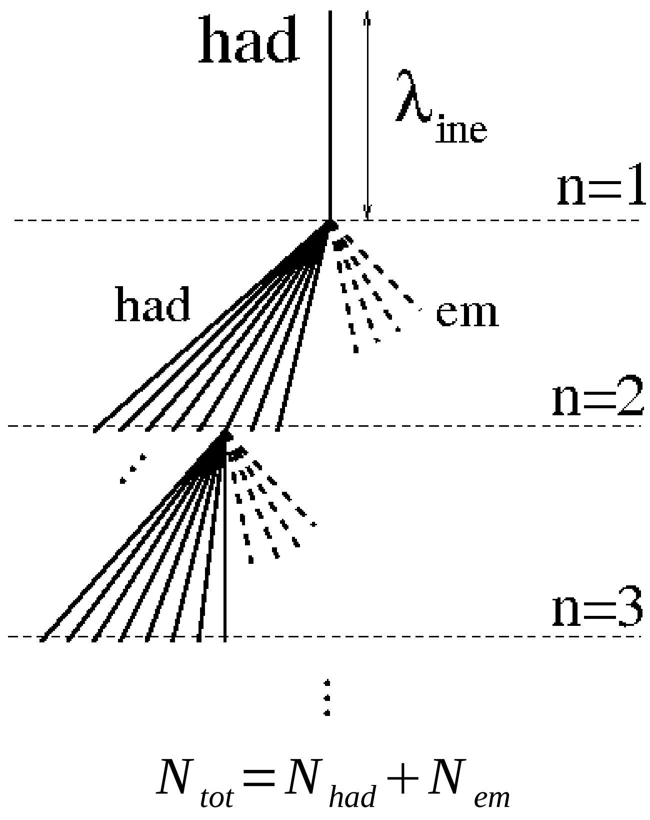
  - Larger number of particles at $X_{max}$

    For many showers
    - mean : $<X_{max}>$
    - fluctuations : RMS $X_{max}$




- **Lateral distribution function (LDF)**
  - particle density at ground vs distance to the impact point (core)
  - can be muons or electrons/gammas or a mixture of all.

# Simplified Shower Development




J. Matthews, Astropart.Phys. 22 (2005) 387-397

- **Using generalized Heitler model and superposition model :**

$$X_{max} \sim \lambda_e \ln\left((1-k).E_0/(2.\mathrm{N}_{tot}.A)\right) + \lambda_{ine}$$

- Model independent parameters :
  - $E_0$ = primary energy
  - A = primary mass
  - $\lambda_e$ = electromagnetic mean free path
- Model dependent parameters :
  - k = elasticity
  - $N_{tot}$ = total multiplicity
  - $\lambda_{ine}$ = hadronic mean free path (cross section)

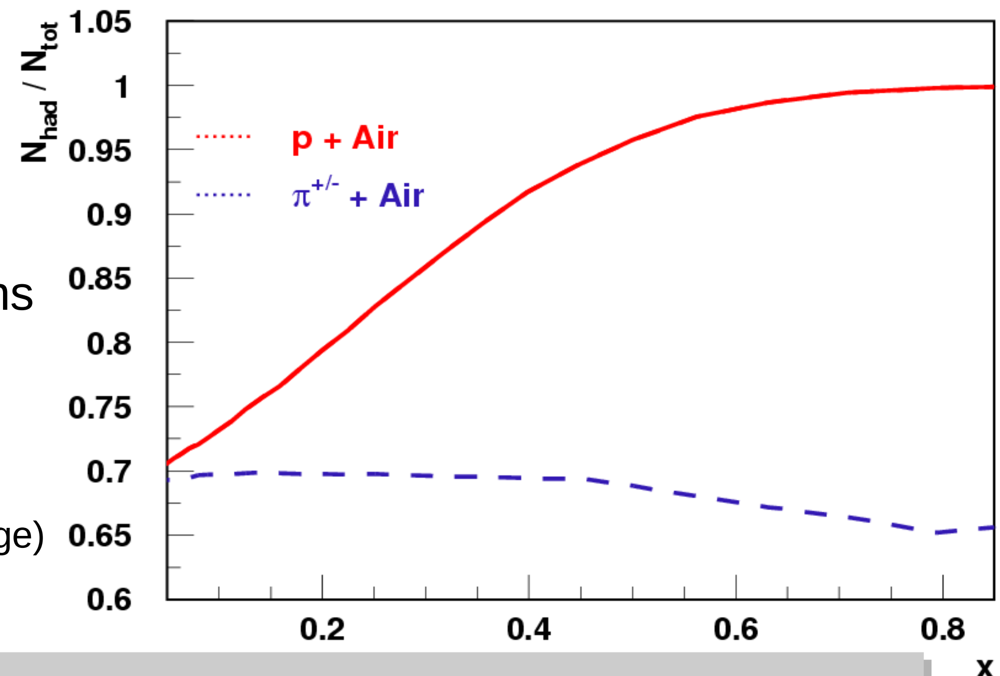
# Muon Number

- **From Heitler**

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\alpha, \quad \alpha = \frac{\ln N_{\pi^{ch}}}{\ln(N_{\pi^{ch}} + N_{\pi^0})}$$

→ after n generations

- In real shower, not only pions : Kaons and (anti)Baryons (but 10 times less …)
- Baryons do not produce leading $\pi^0$
- With leading baryon, energy kept in hadronic channel = muon production
- Cumulative effect for low energy muons
- High energy muons
  - important effect of first interactions and baryon spectrum (LHC energy range)

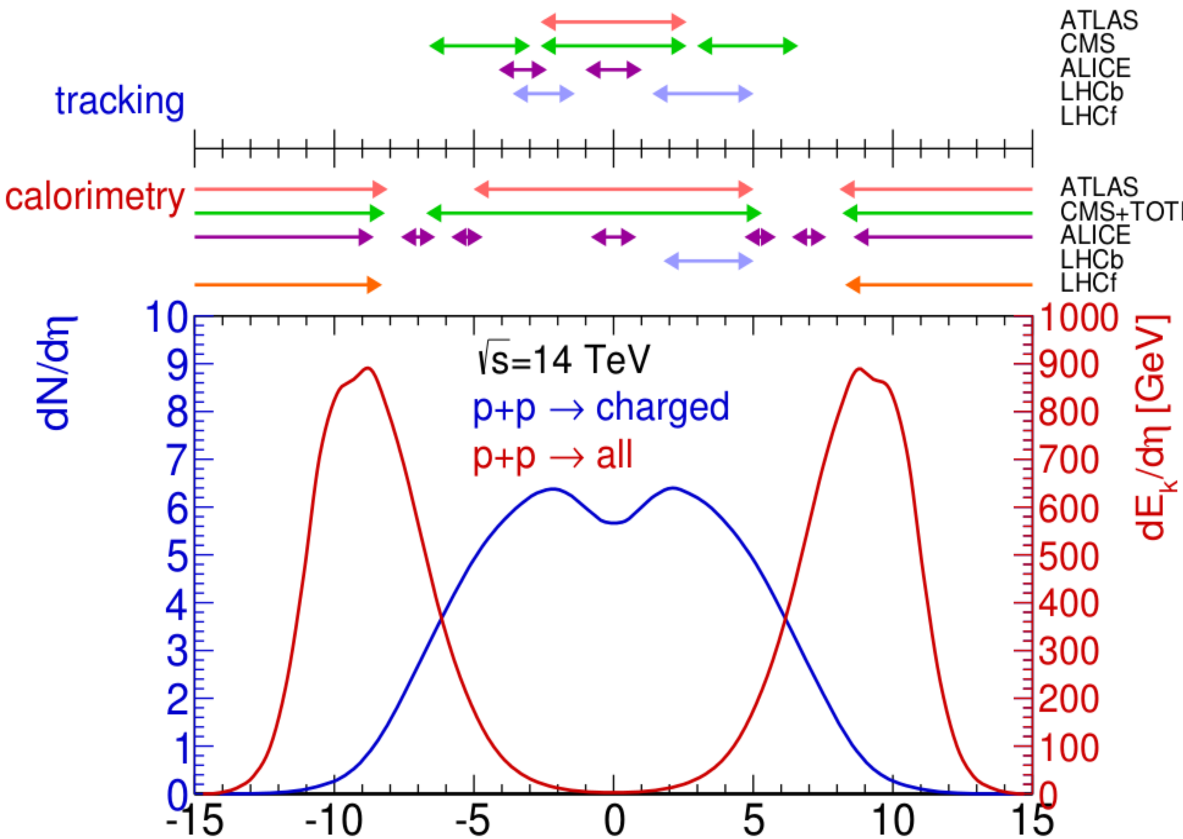



**Muon number depends on the number of (anti)B in p- or π-Air interactions at all energies**

More fast (anti)baryons = more muons

T. Pierog et al.,Phys.Rev.Lett. 101 (2008) 171101

# Ideal Measurements for CR




**Direct measurement of particles important for air shower development difficult at LHC !**
(excluded by kin. and techn. limits)

- **Inelastic cross-section (and all other obs.) for p-Air and pion-Air**
  - ➡ LHC: p-p or p-Pb … pO ?
- **Average elasticity/inelasticity** (energy fraction of the leading particle)
  - ➡ LHC: SD with proton tagging only
- **Multiplicity of id. particles in forward region ($x_F$~0.1)**
  - ➡ LHC: tracking for eta<7 (id<5)
- **EM/Had Forward Energy flow ($x_F$>0.1)**
  - ➡ LHC: ZDCs for neutral particles only

# Cosmic Ray Hadronic Interaction Models

- **Theoretical basis :**
  - pQCD (large $p_t$)
  - Gribov-Regge (cross section with multiple scattering)
  - energy conservation
- **Phenomenology (models) :**
  - hadronization
    - string fragmentation
    - EPOS : high density effects (statistical hadronization and flow)
  - diffraction (Good-Walker, ...)
  - higher order effects (multi-Pomeron interactions)
  - remnants
- **Comparison with data to fix parameters**
  - one set of parameter for all systems/energies

# Cosmic Ray Hadronic Interaction Models

- **Theoretical basis :**
  - pQCD (large $p_t$)
  - Gribov-Regge (cross section with multiple scattering)
  - energy conservation

EPOS 1.99/LHC
QGSJet01/II-03/II-04
Sibyll 2.1

- **Phenomenology (models) :**
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- **Comparison with data to fix parameters**

**Better predictive power than HEP models thanks to link between total cross section and particle production (GRT) tested on a broad energy range (including EAS)**

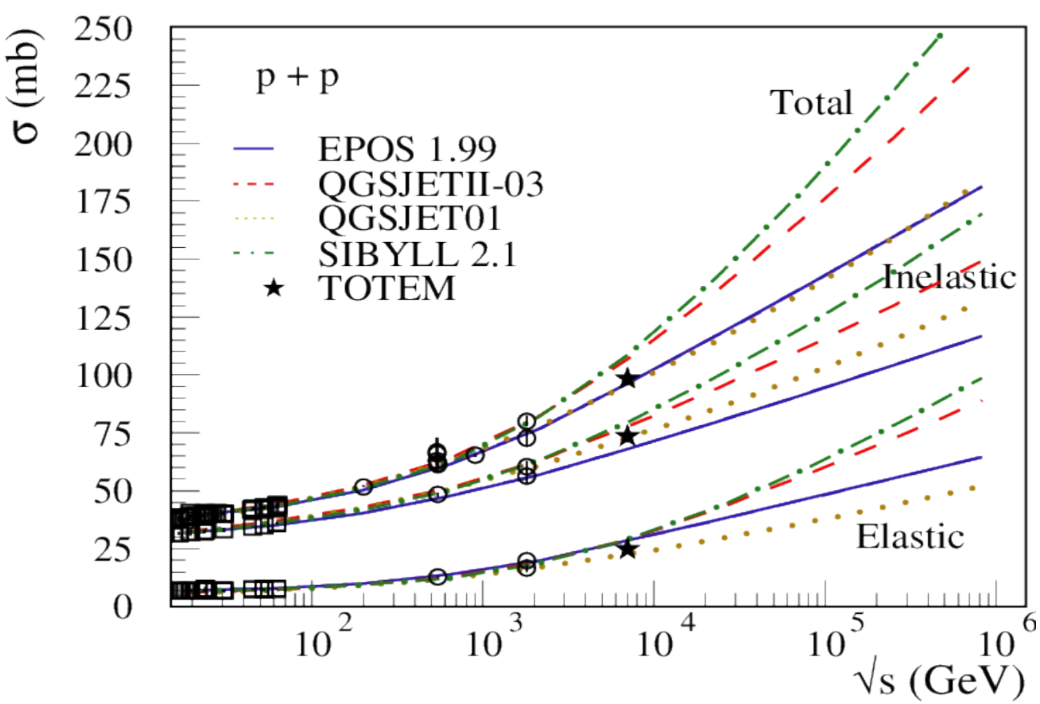
# Data for Hadronic Interaction Models

- **Theoretical basis :**
  - pQCD : **PDF and jets**
  - Gribov-Regge : **All cross-sections and particle multiplicities**
  - energy conservation : **Correlations (various triggers, proton tagging, multiplicity windows or dependence)** **Model killer !**
- **Phenomenology :**
  - hadronization : **Particle identification and pt and multiplicity dep.**
  - diffraction : **Energy loss, rapidity gaps**
  - higher order effects : **Nuclear modification factor**
  - remnants : **Baryon stopping (baryon ratio)**
- **Comparison with data to fix parameters**
  - all type of min bias data are welcome to constrain hadronic interaction models for air showers
  - specific interest in forward measurement to check extrapolation for air showers

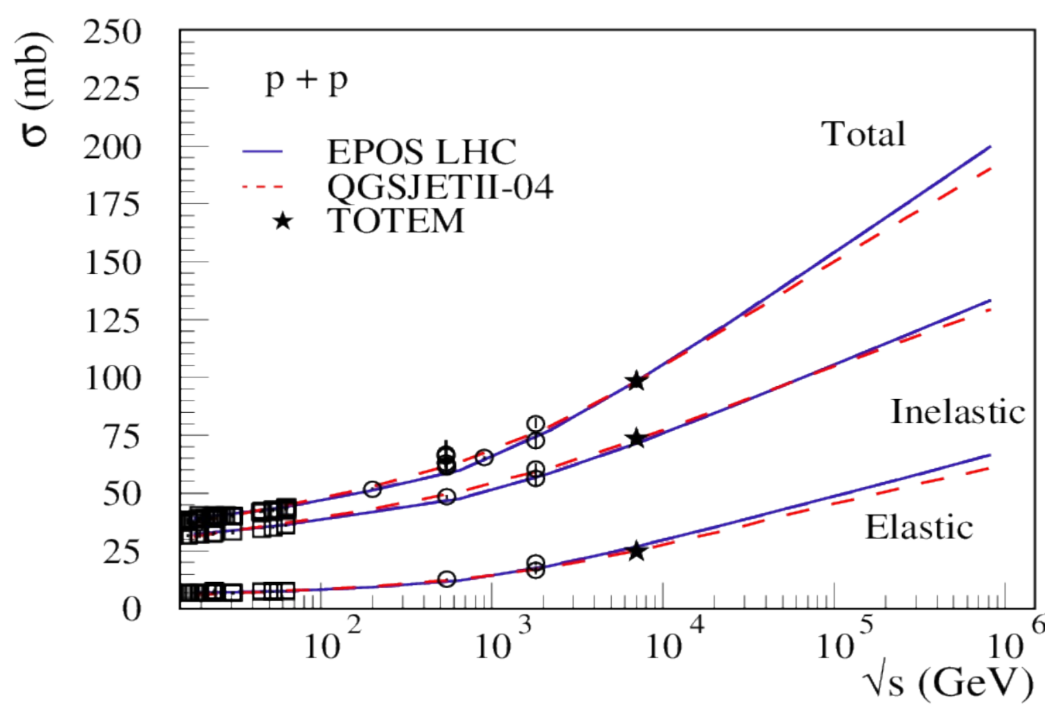
# Cross Sections

- Same cross sections at pp level up to LHC
  - weak energy dependence : no room for large change beyond LHC
- other LHC measurements of inelastic cross-section (ALICE, ATLAS, CMS) test the difference between models (diffraction)

**Pre - LHC**



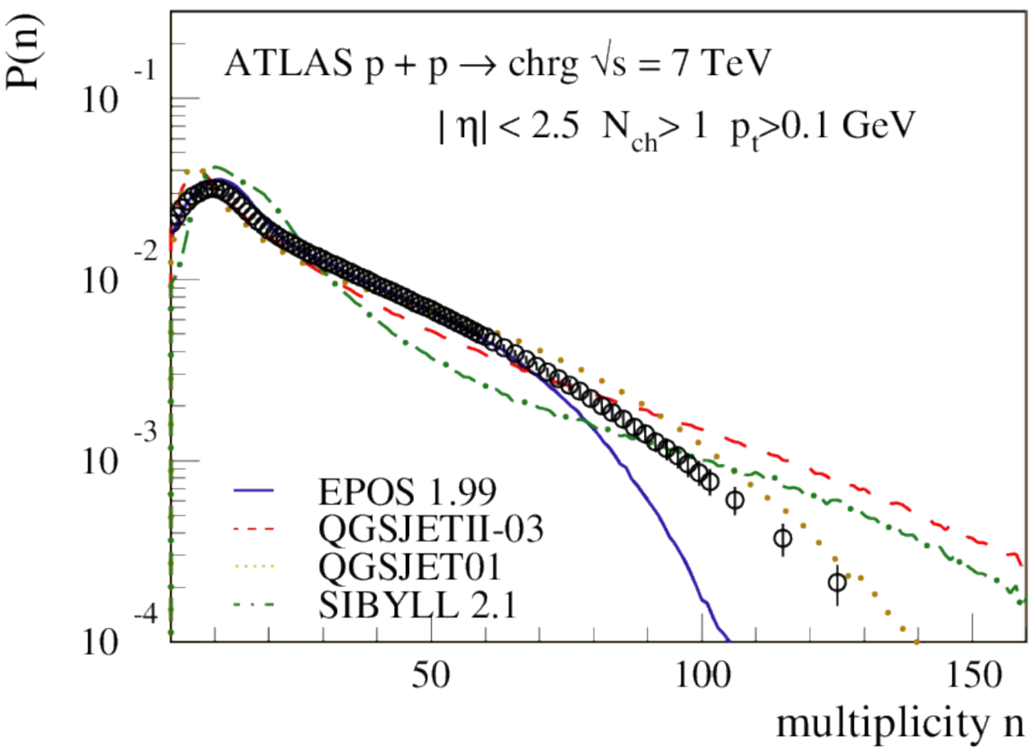

**Post - LHC**



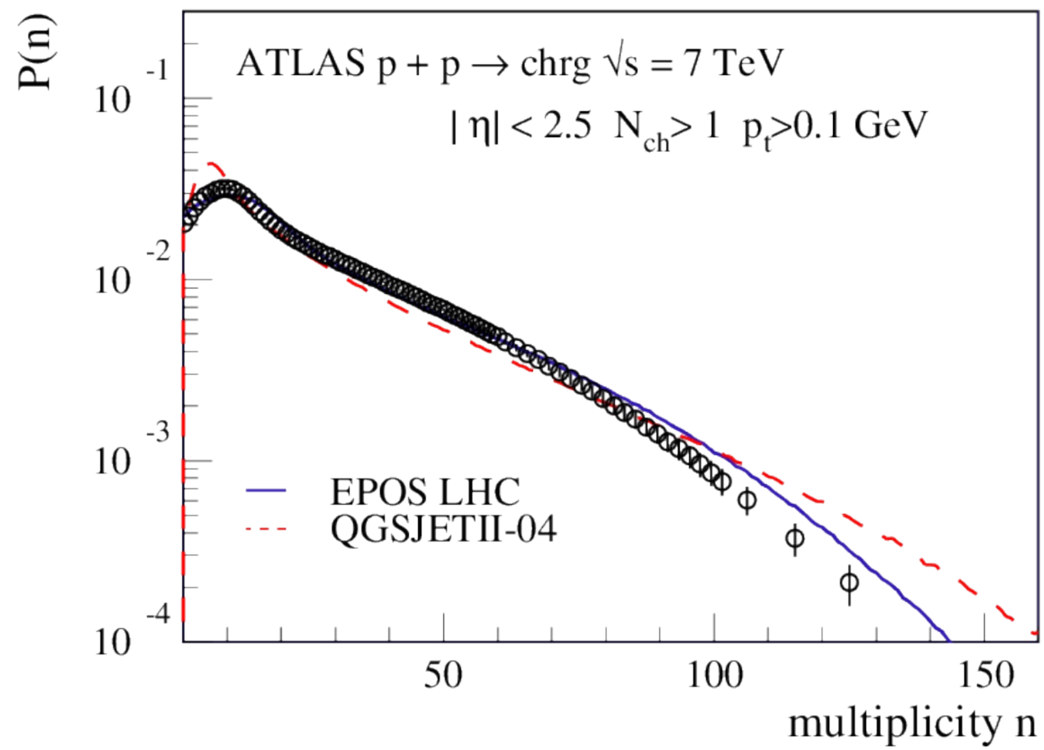
# Multiplicity

- **Consistent results**
  - Better mean after corrections
    - difference remains in shape
  - Better tail of multiplicity distributions
    - corrections in EPOS LHC (flow) and QGSJETII-04 (minimum string size)

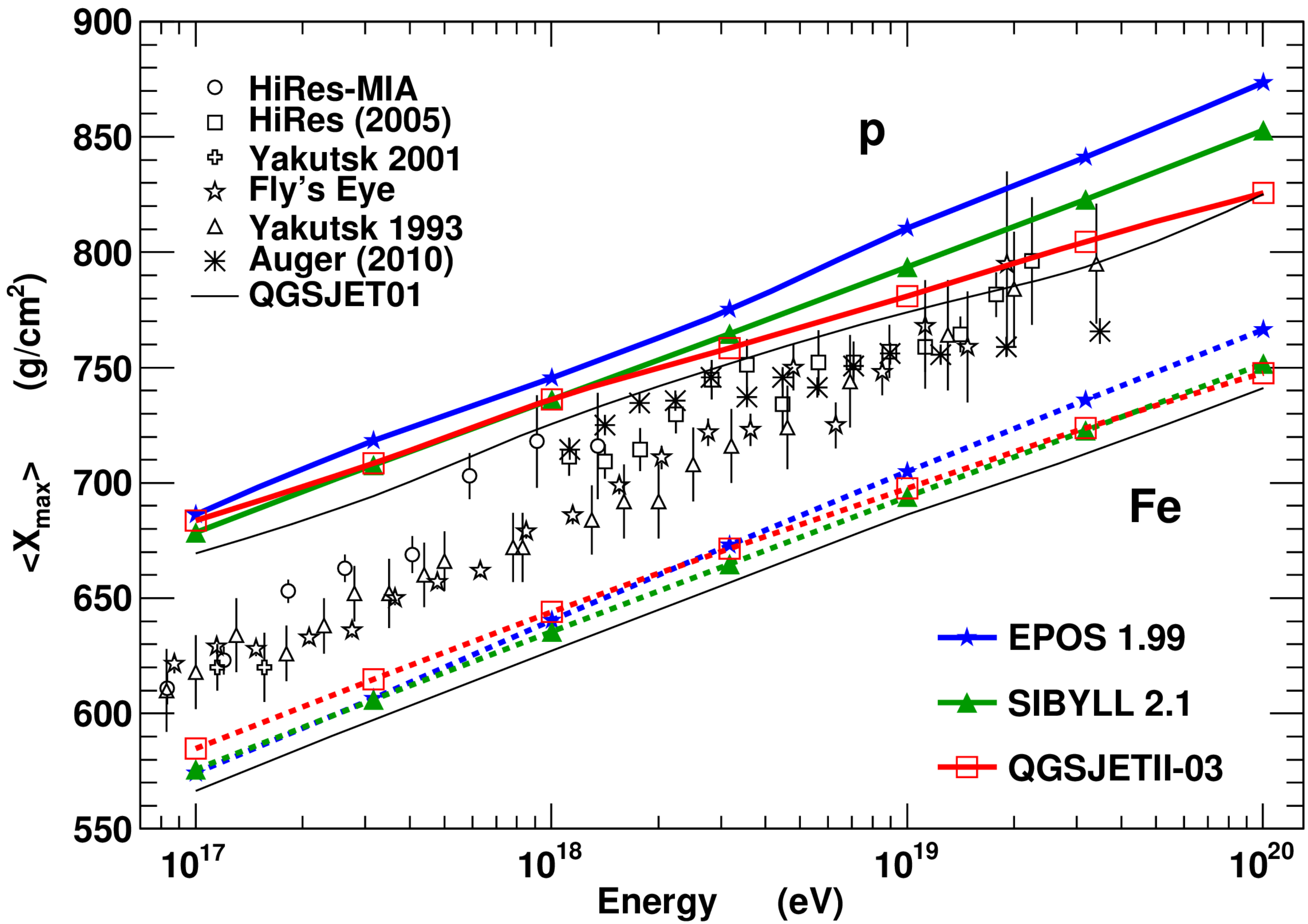
Pre - LHC



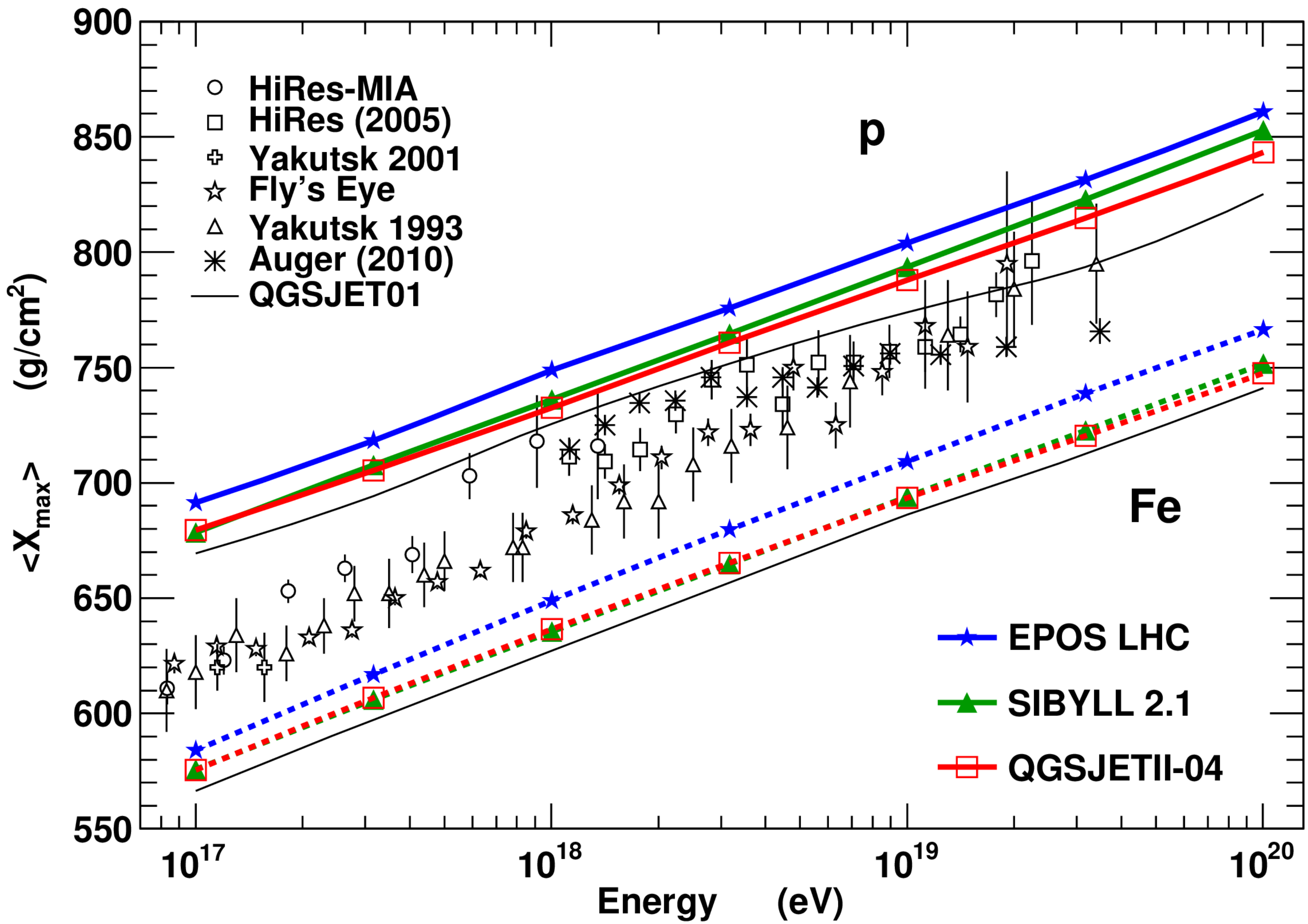

Post - LHC



# EAS with Old CR Models : $X_{max}$

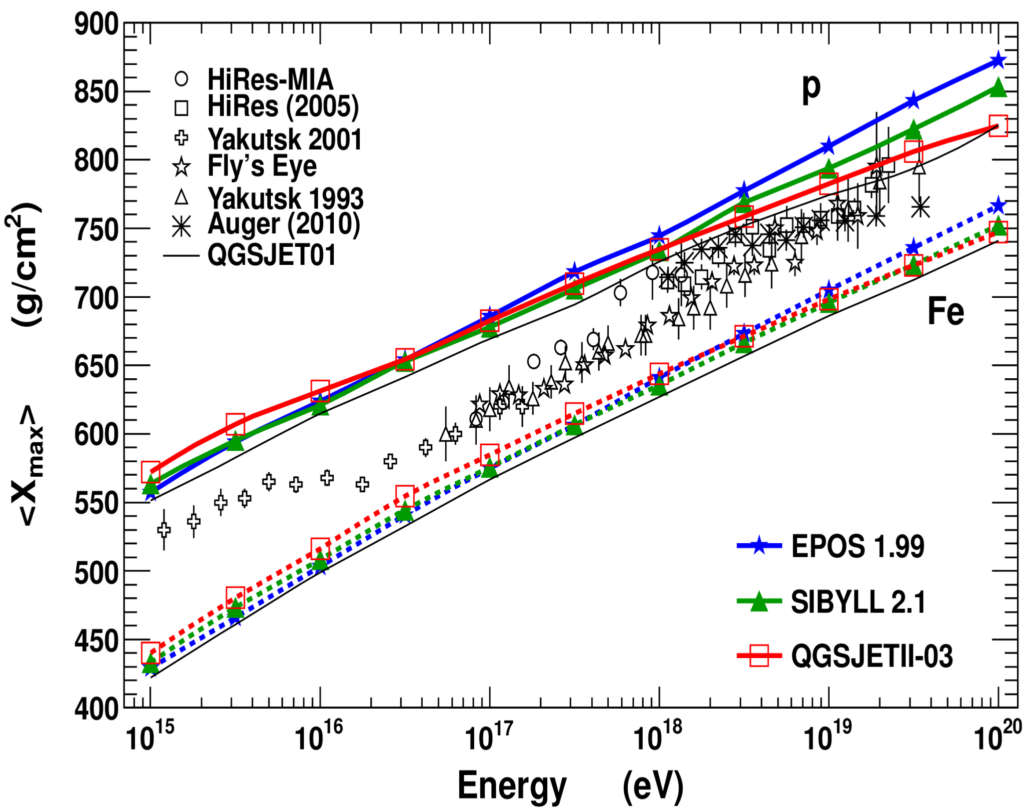


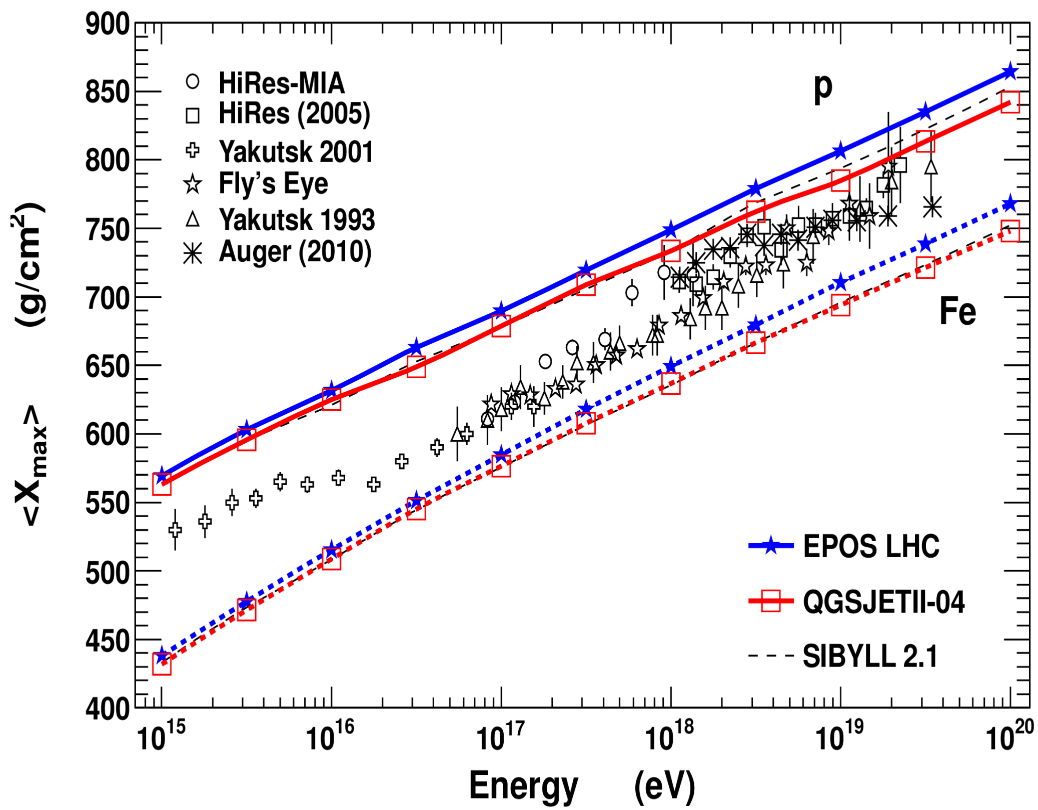
# EAS with Re-tuned CR Models : $X_{max}$



# EAS with Re-tuned CR Models : $X_{max}$

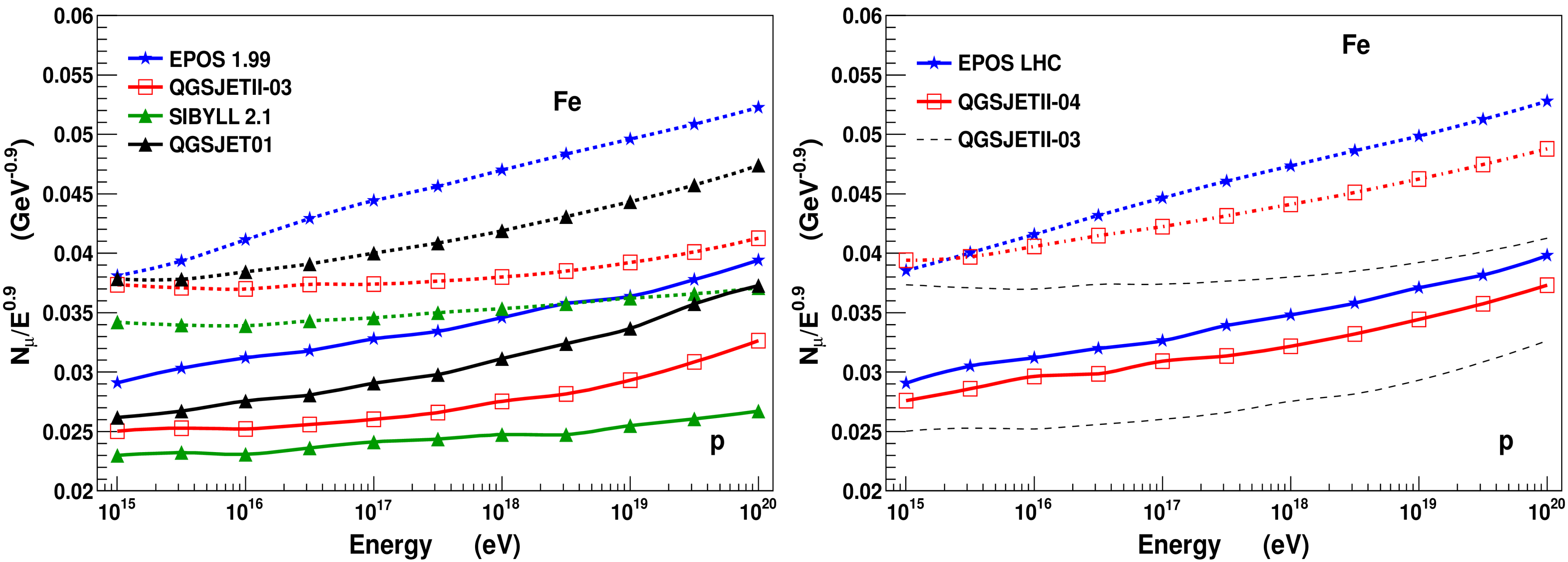
- **Cross section and multiplicity fixed at 7 TeV**
  - ➡ smaller slope for EPOS and larger for QGSJETII
  - ➡ re-tuned model converge to old Sibyll 2.1 predictions
    - ◆ reduced uncertainty from ~50 g/cm$^2$ to ~20 g/cm$^2$ (difference proton/iron is about 100 g/cm$^2$)



# EAS with Re-tuned CR Models : Muons

- **Effect of LHC hidden by other changes**
  - Corrections at mid-rapidity only for EPOS
  - Changes in QGSJET motivated by pion induced data
  - EPOS LHC ~ EPOS 1.99 and only -7% for QGSJETII-04



# Counterexample : Muon Production Depth

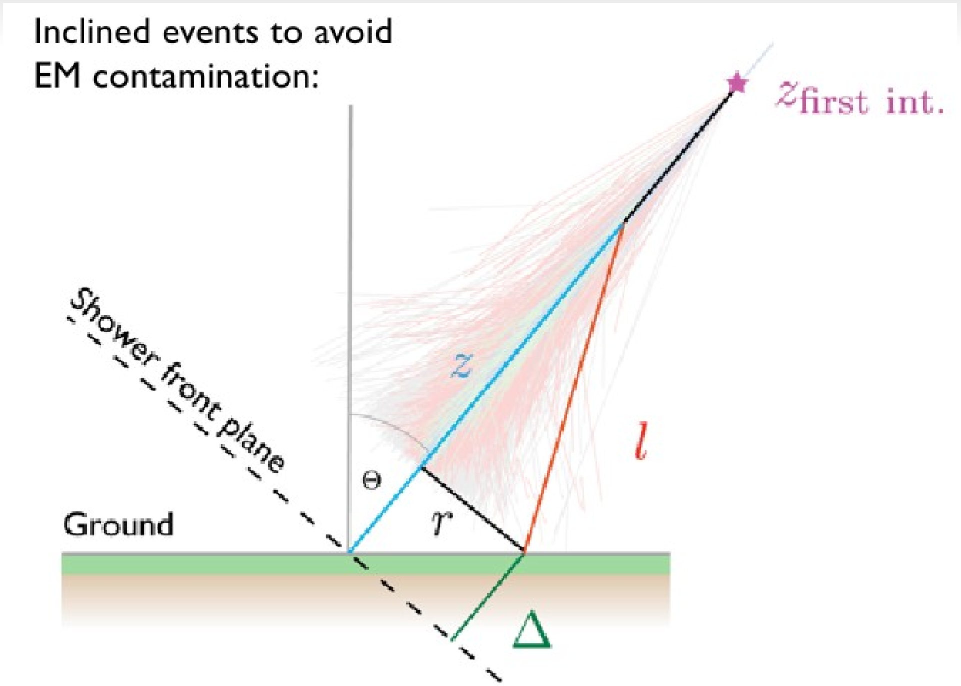
- **Independent SD mass composition measurement**
  - geometric delay of arriving muons

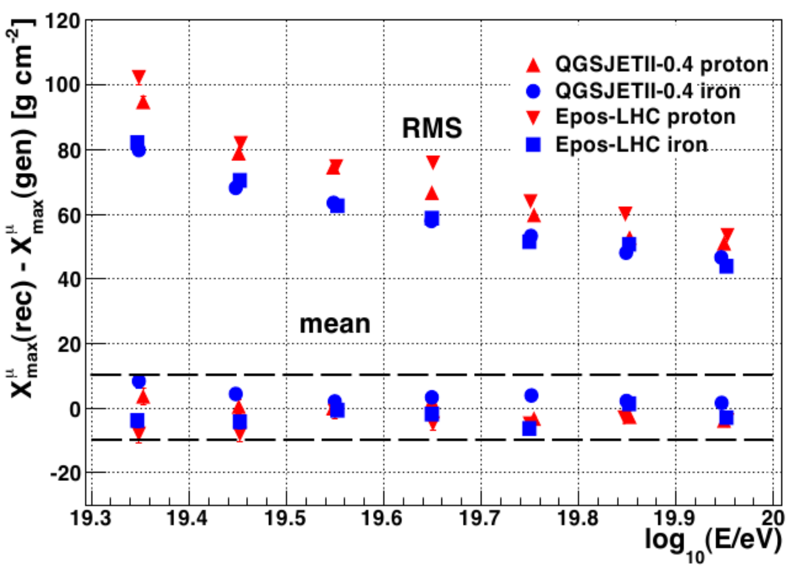
$$c \cdot t_g = l - (z - \Delta) = \sqrt{r^2 + (z-\Delta)^2} - (z - \Delta)$$

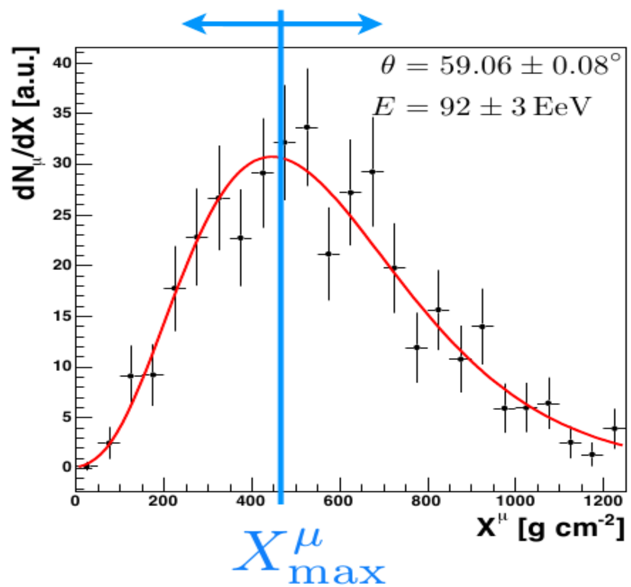
  - mapped to muon production distance

$$z = \frac{1}{2}\left(\frac{r^2}{ct_g} - ct_g\right) + \Delta$$

  - decent resolution and no bias

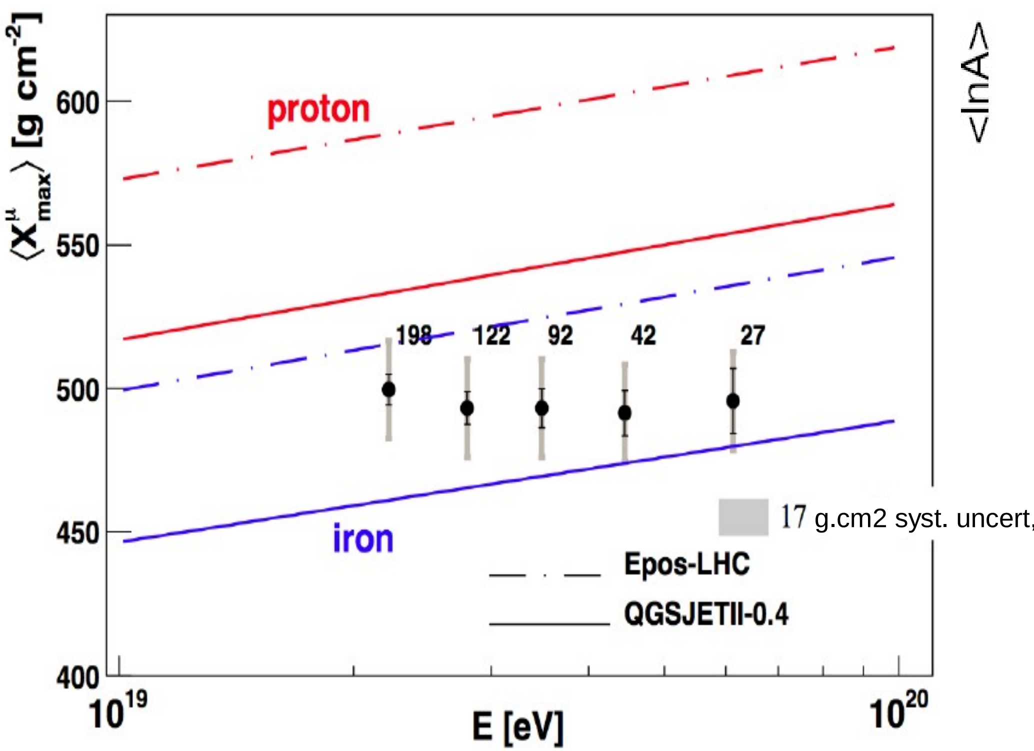


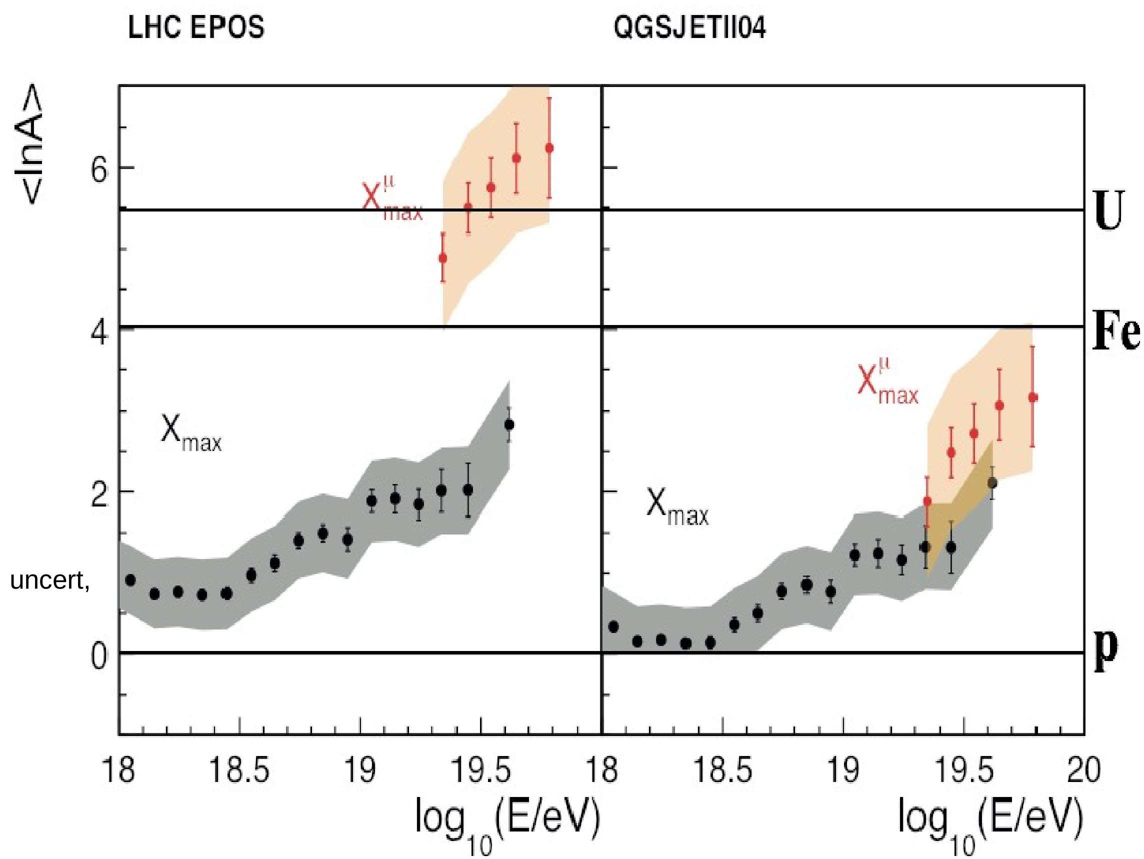



# Muon Production Depth and EPOS

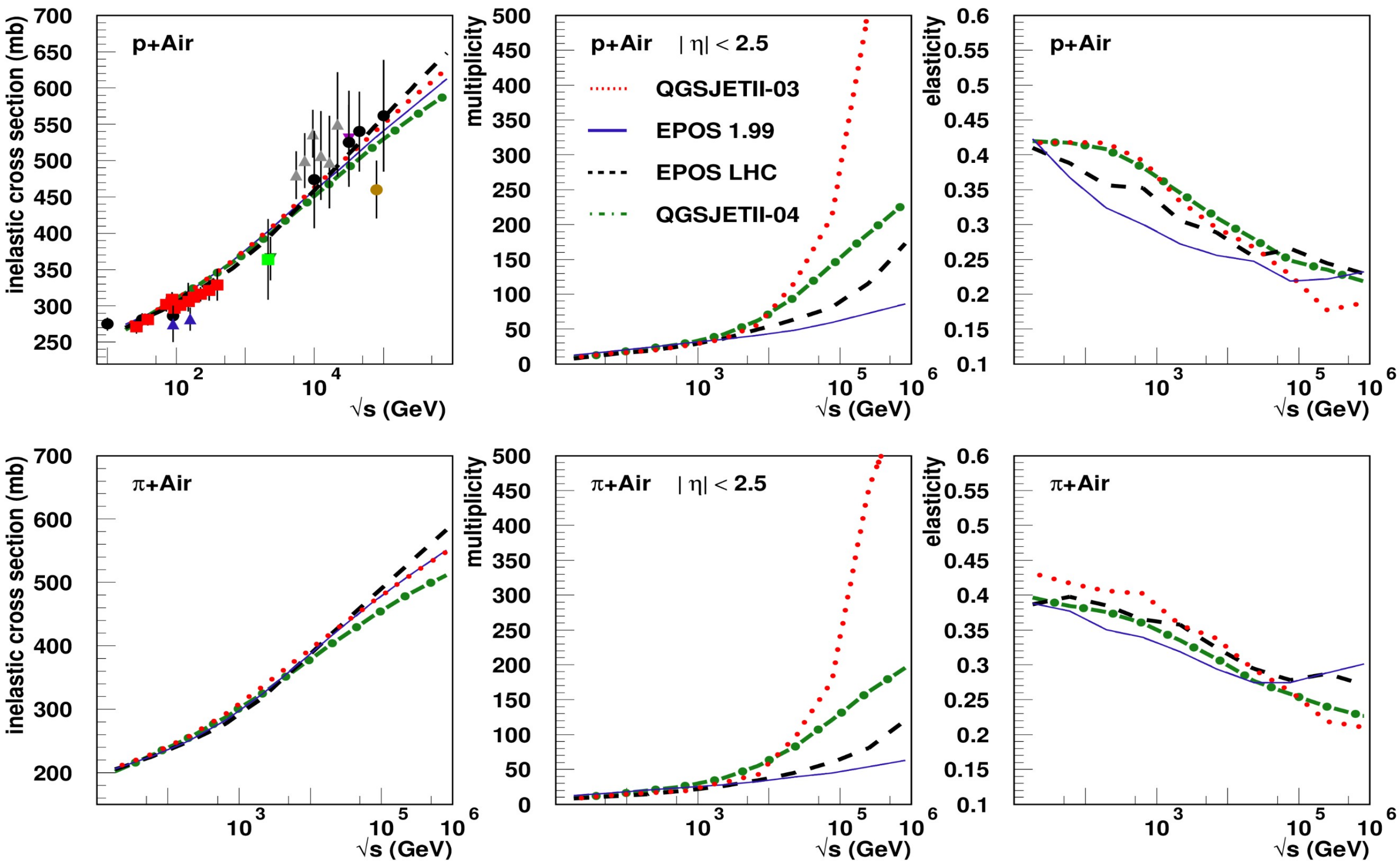
- **2 independent mass composition measurements**
  - both results should be between p and Fe
  - both results should give the same mean logarithmic mass for the same model
  - problem with EPOS appears after corrections motivated by LHC data



# Difference EPOS 1.99/EPOS LHC

- **EPOS 1.99 to EPOS LHC**
  - ➔ tune cross section to TOTEM value
  - ➔ ~~change old flow calculation to a more realistic one~~
  - ➔ introduce central diffraction and improve rapidity gap distributions

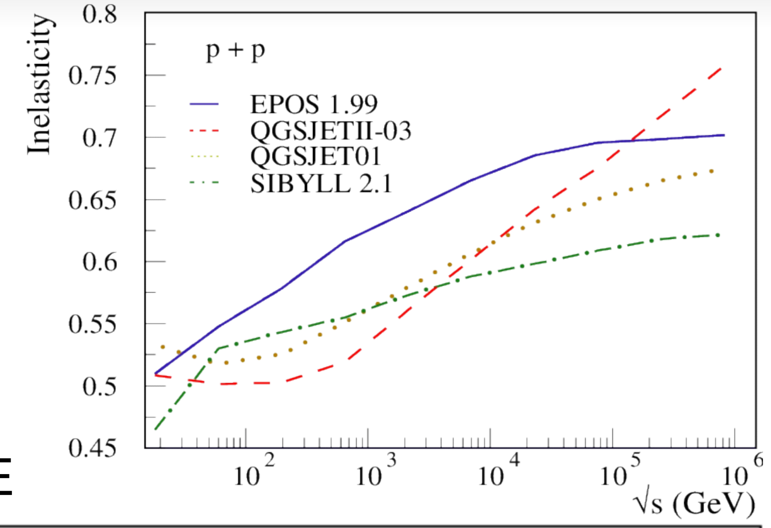


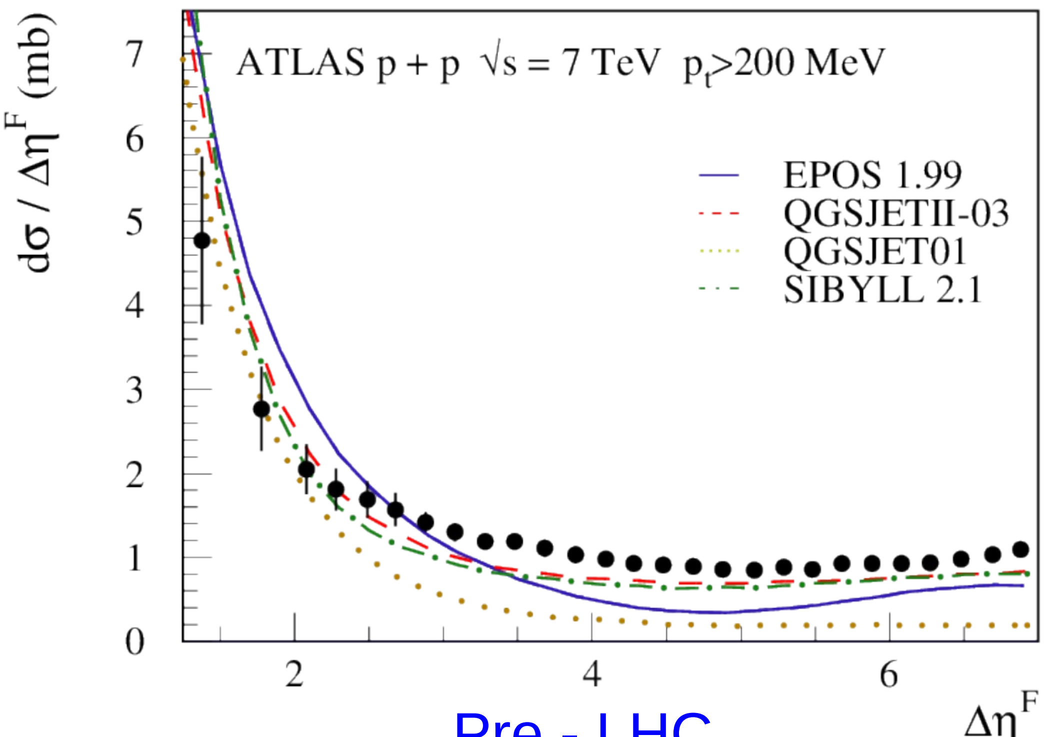

- shallower MPD
  - ➔ larger multiplicity
  - ➔ larger cross-section (small)
- deeper MPD
  - ➔ larger elasticity

**Elasticity should be the source of the difference**

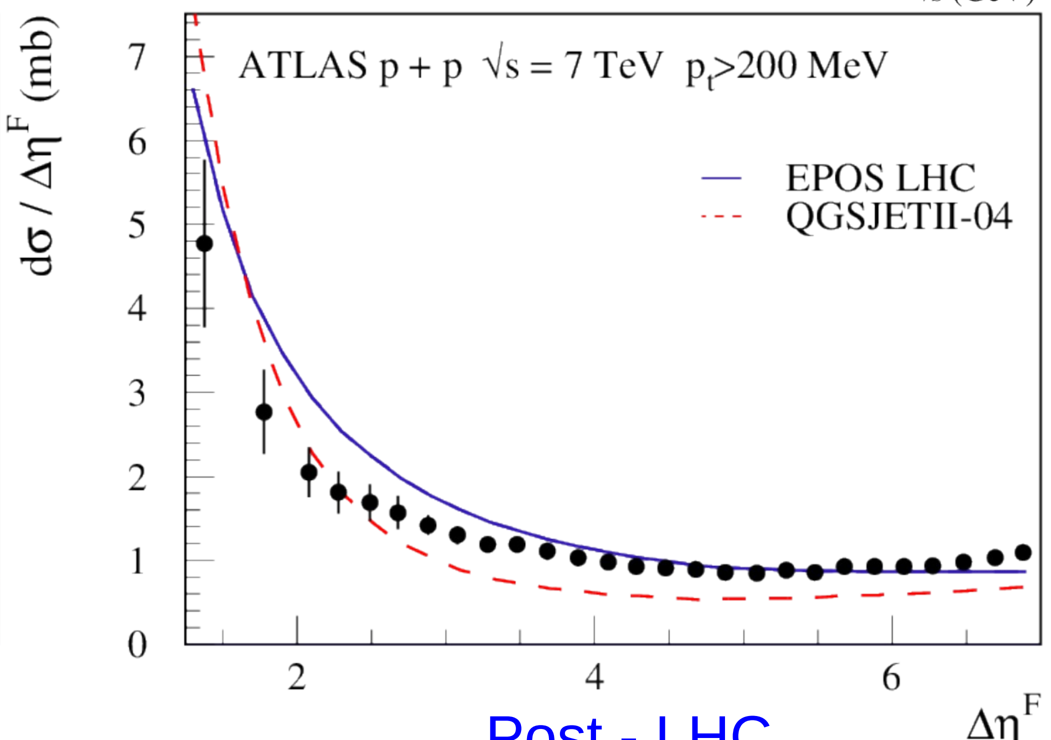
# (In)elasticity

- **Difficult to measure : larger uncertainty**
  - Difference in diffraction
    - low mass / high mass / central diffraction
  - difference for pions/Kaons/nucleons
    - very few data (and at low energy)
  - Rapidity gap : first precise measurement at high E



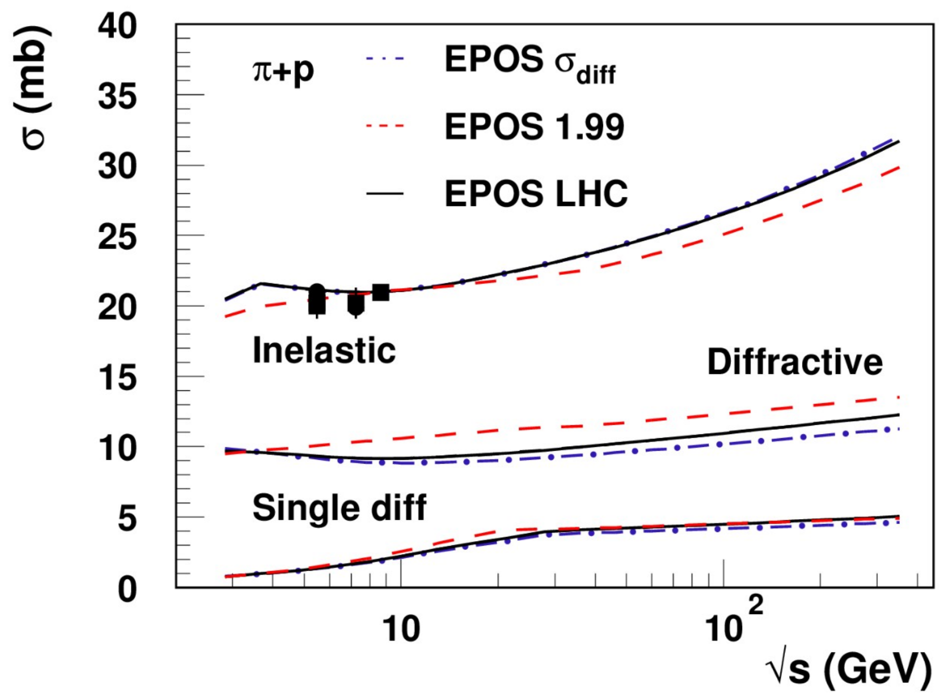

Pre - LHC



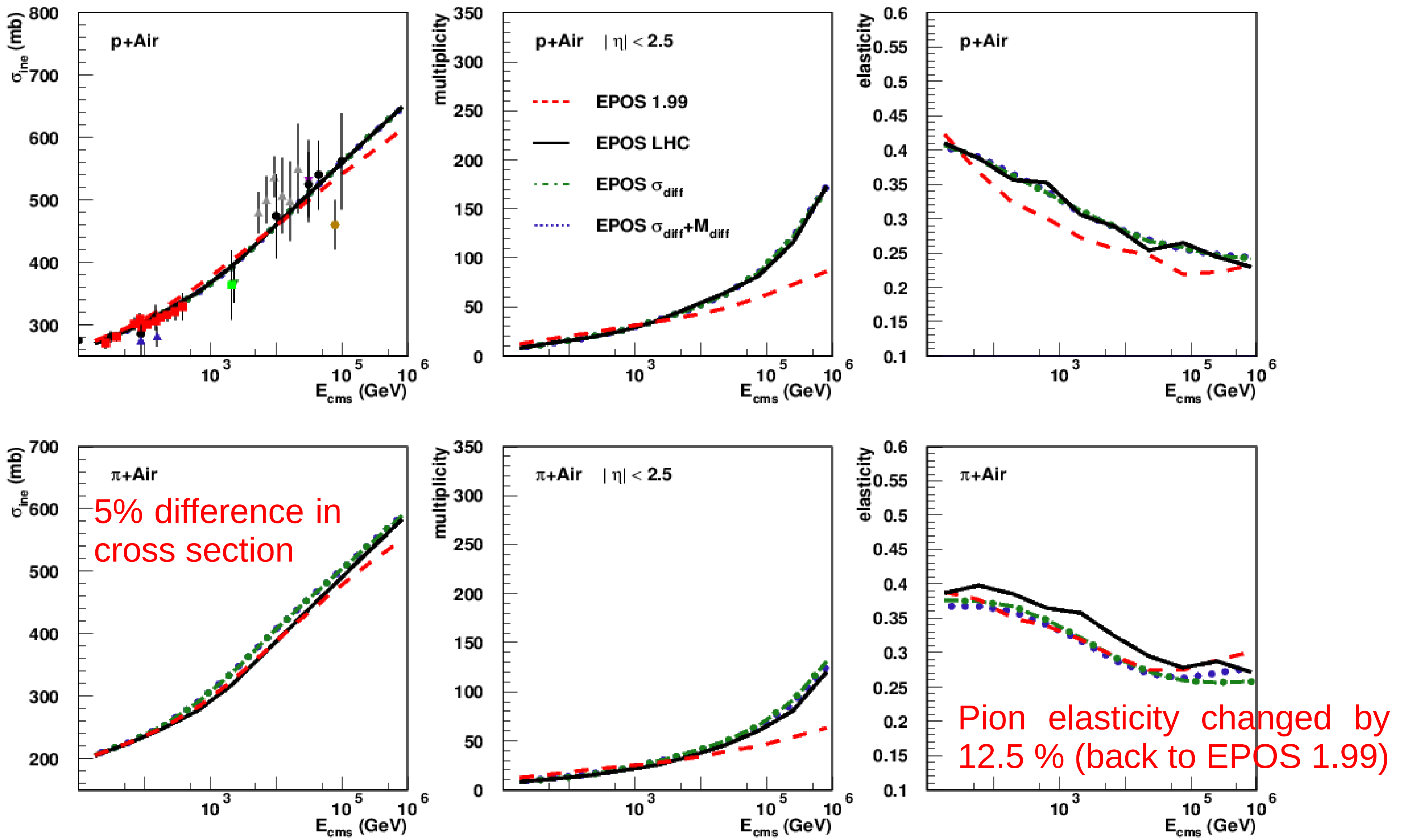

Post - LHC

# Pion Diffraction and MPD

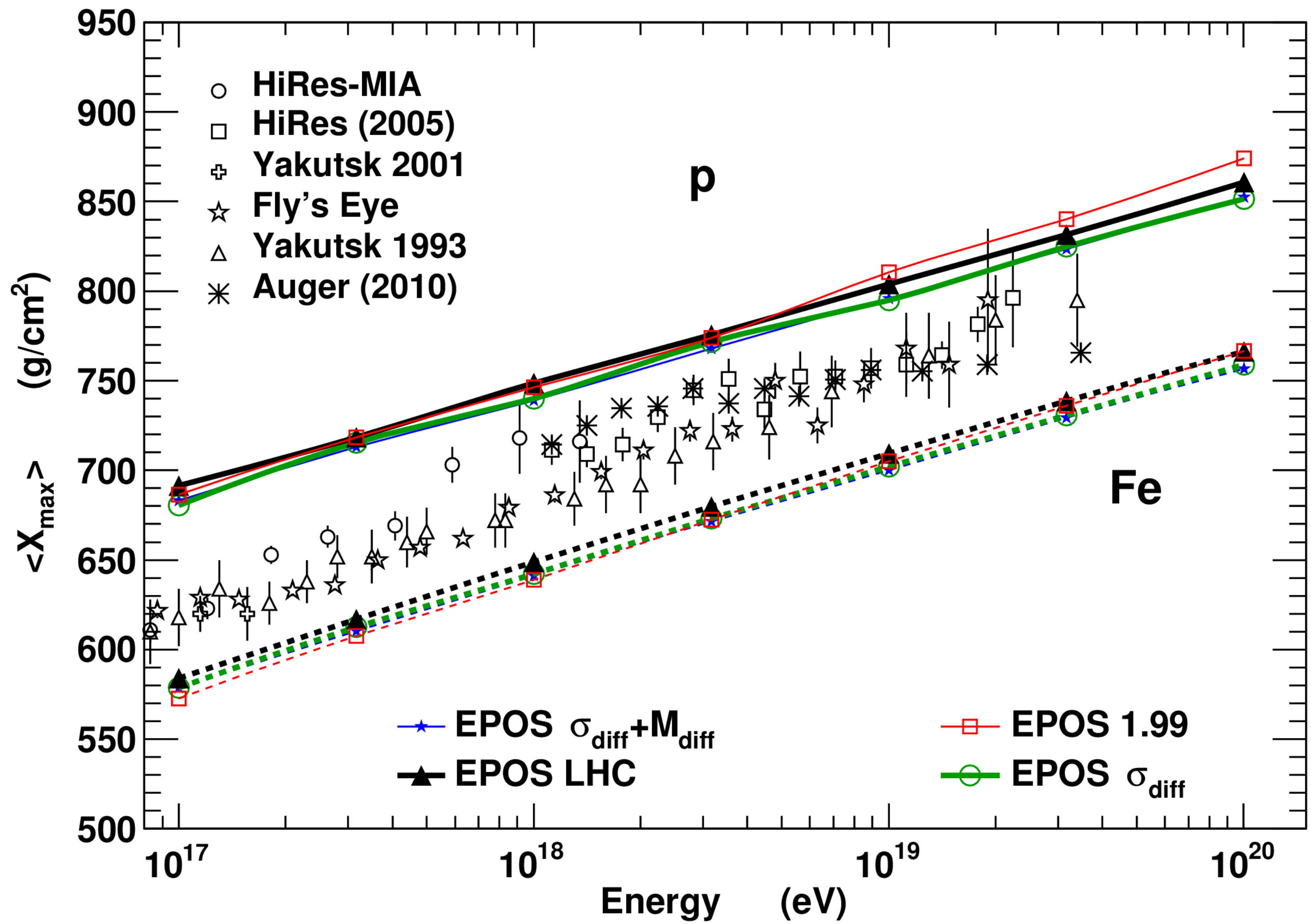
- **Rapidity gap measurement fixed by LHC**
  - ➡ should not change proton interactions
- **MPD driven by long chain of pion-Air interaction**
  - ➡ Modify in EPOS only pion diffraction
  - ➡ Test cross-section and diffractive mass distribution
  - ➡ first check existing pion data to tune parameter to REDUCE pion diffraction and INCREASE diffractive mass
- **2 "tunes"**
  - ➡ EPOS (LHC) $\sigma_{diff}$ : diffractive cross section reduced
  - ➡ EPOS (LHC) $\sigma_{diff}$ + $M_{diff}$: diffractive cross-section reduced and mass increased



# Extrapolation to CR interactions



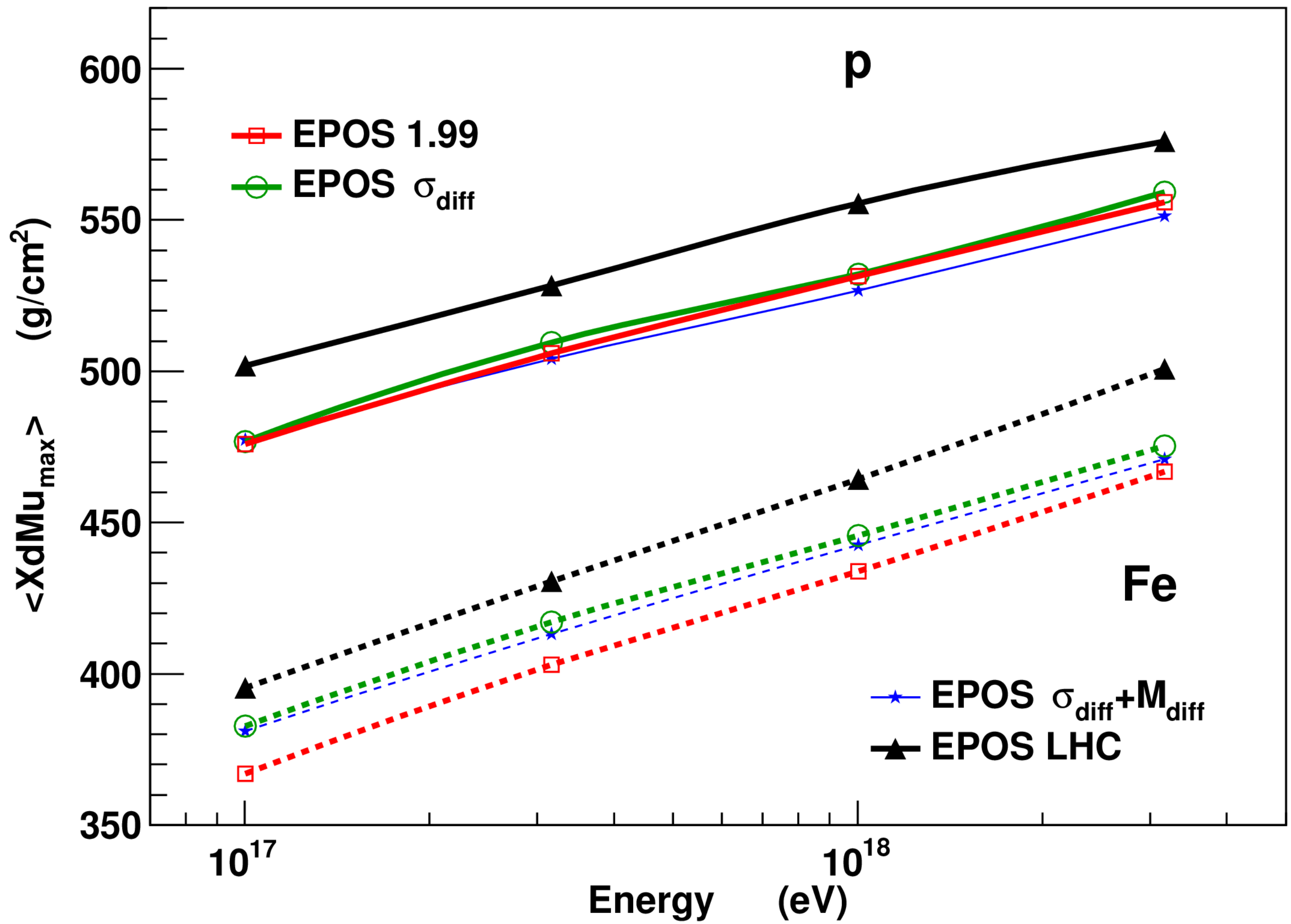
# $<X_{max}>$


950
900
850
800
750
700
650
600
550
500
$<X_{max}>$ (g/cm$^2$)
HiRes-MIA
HiRes (2005)
Yakutsk 2001
Fly's Eye
Yakutsk 1993
Auger (2010)
p
Fe
EPOS $\sigma_{diff}$+$M_{diff}$
EPOS LHC
EPOS 1.99
EPOS $\sigma_{diff}$
$10^{17}$
$10^{18}$
$10^{19}$
$10^{20}$
Energy (eV)

-10 g/cm$^2$

# $<X^{\mu}_{max}>$

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




-30 g/cm² back to EPOS 1.99

Little influence of diffractive mass

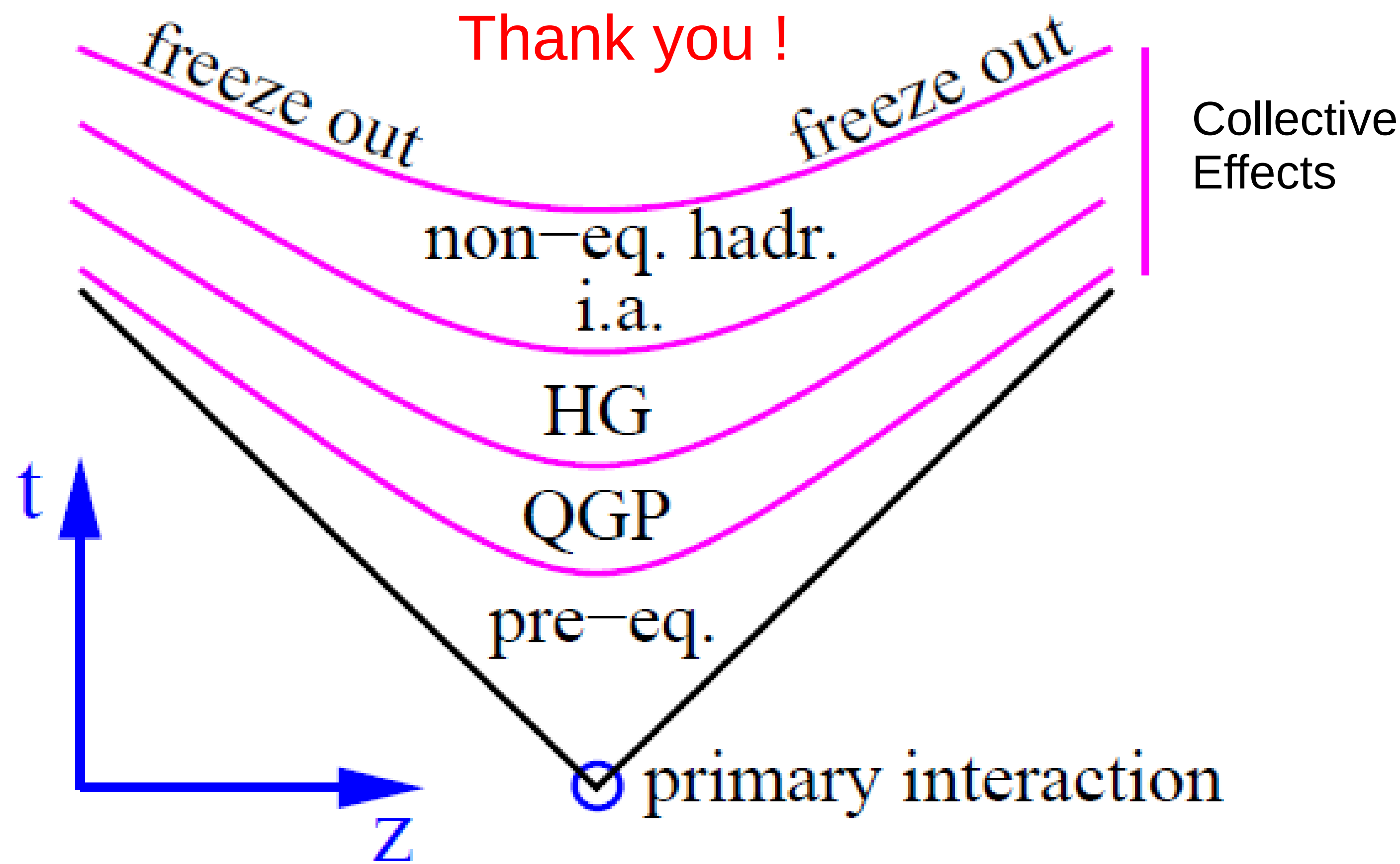
# Summary on EAS

- **LHC data not usable directly to analyze air showers but important to constrain hadronic models used to analyze data !**
  - ➡ any min-bias measurement is useful and correlation with forward emission are even more constraining

- **First LHC run :**
  - ➡ strong constrains on energy evolution of particle production and cross-section
  - ➡ results converge between models both air shower observable like $X_{max}$ and number of muons at ground (differences reduced by a factor of 2)

- **Inelasticity linked to diffraction (cross-section and mass distribution)**
  - ➡ very strong sensitivity of MPD on pion diffraction which is badly measured
    - ◆ MPD can be used to constrain models

# High Energy Hadronic Interactions




High Energy Physics models

General case : valid for pp if enough particles are produced !
and particle physics can be done not only in accelerator but with air showers

References : arXiv:1004.0805, arXiv:1010.0400, arXiv:1011.0375, arXiv:1104.2405
arXiv:1104.3269, arXiv:1203.5704 , arXiv:1306.0121, arXiv:1312.1233