Hadronic Interaction Models and Ultra-High Energy Cosmic Rays

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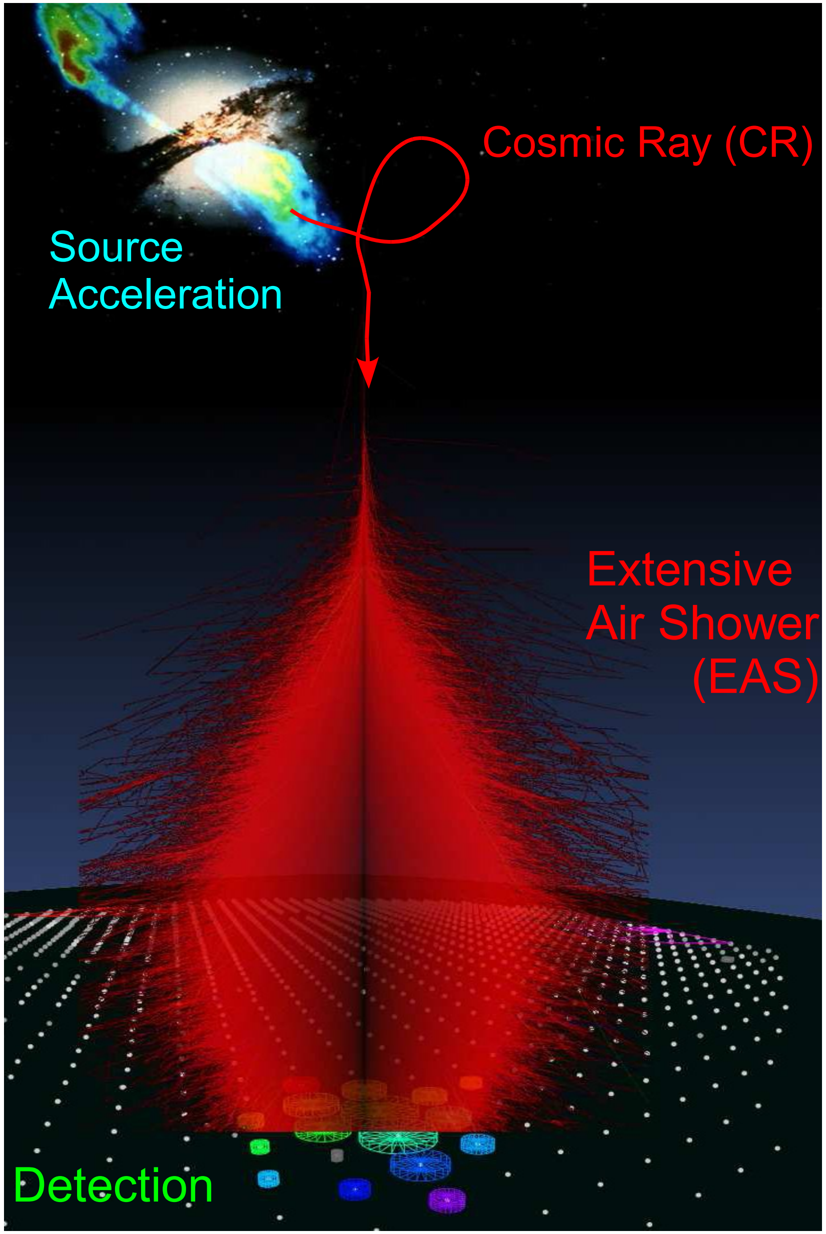
Preamble



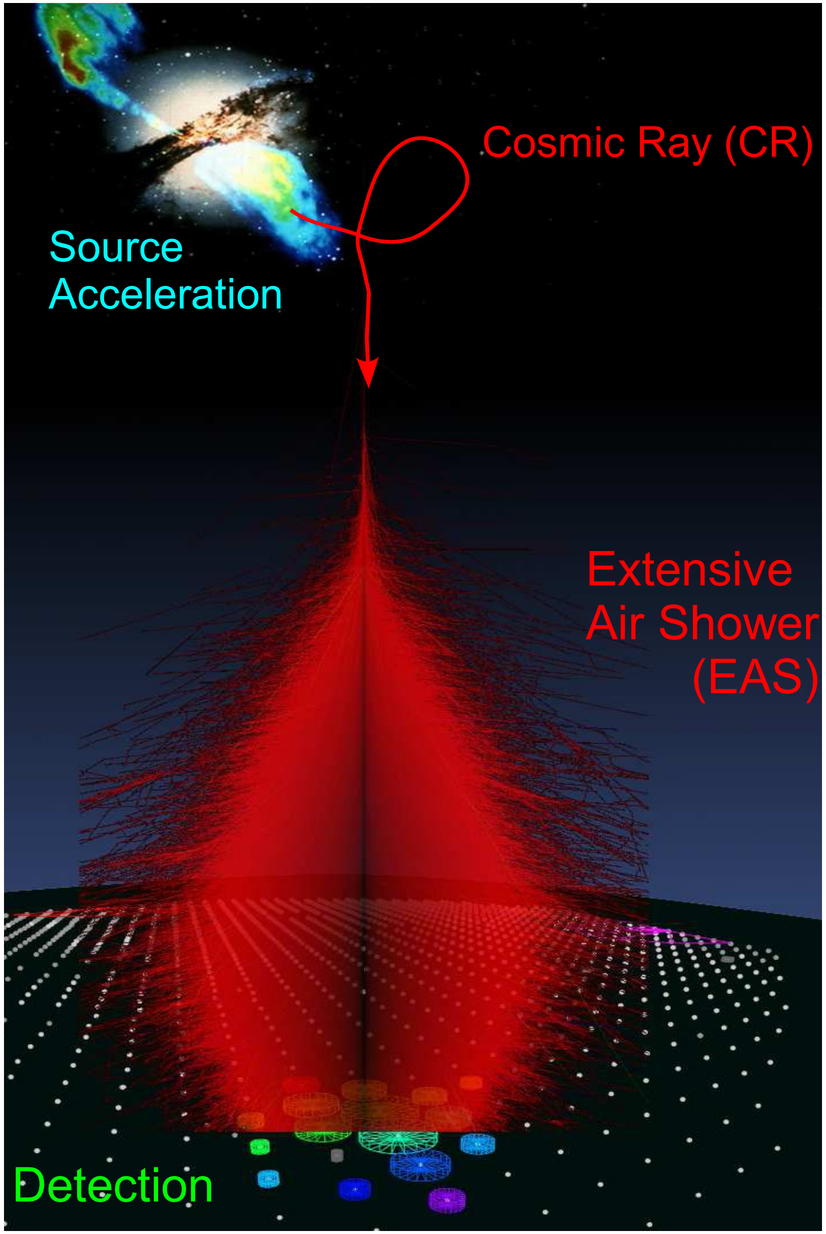
From R. Ulrich (KIT)

- **Goal of Astroparticle Physics :**
  - Astronomy with high energy particles
- **Why hadronic interactions matter for Astrophysics ?**
  - May be a little at the source to escape acceleration :

    charged $\rightarrow$ neutral $\rightarrow$ charged
  - A bit more during propagation
    - interaction with medium on the way to Earth can change mass distribution
  - A lot for detection
    - Detection using Earth's atmosphere as calorimeter :

Mass and Energy of Cosmic Ray only if EAS well described !

Preamble



From R. Ulrich (KIT)

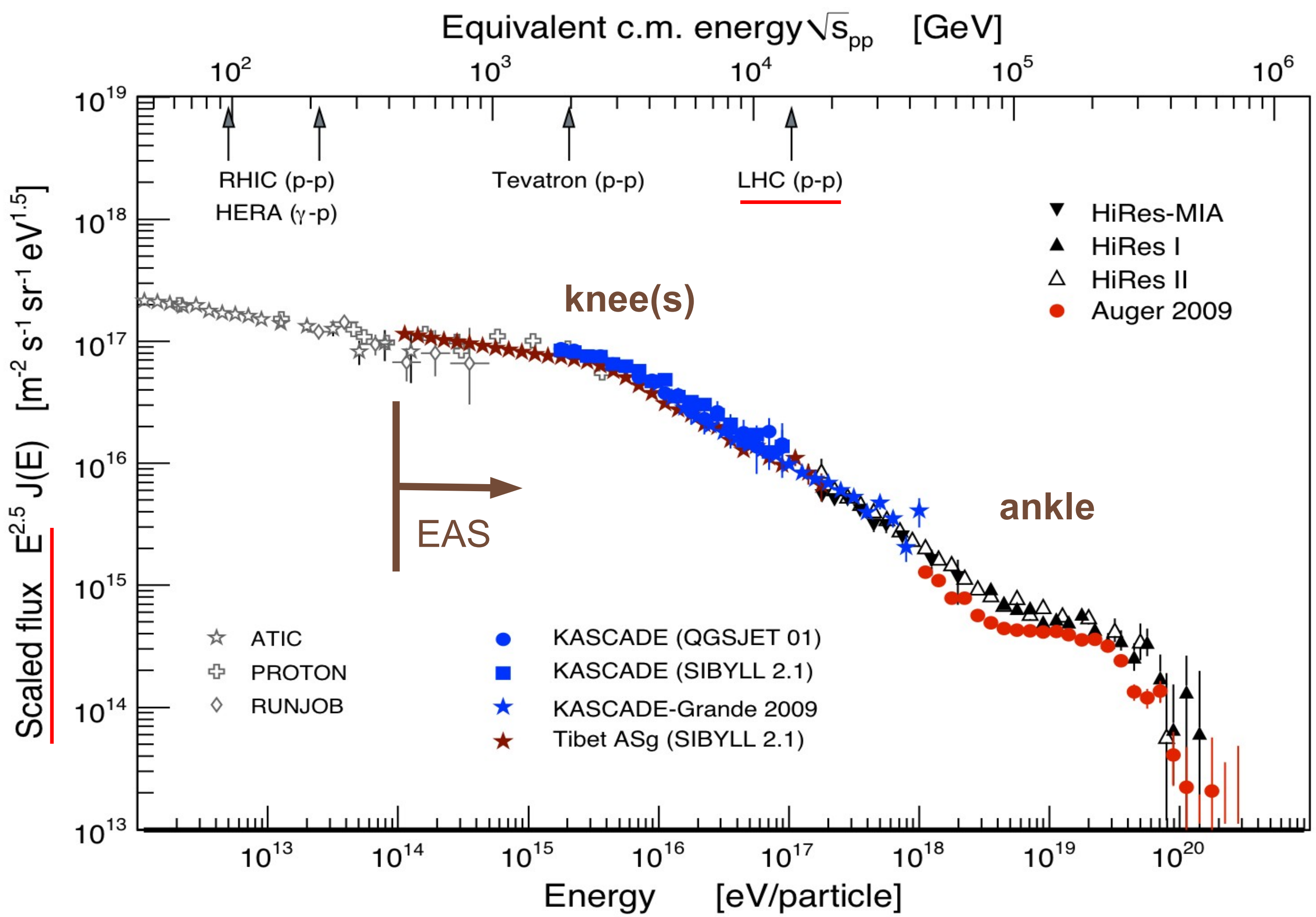
- **Goal of Astroparticle Physics :**
  - Astronomy with high energy particles
- **Why Astrophysics matter for hadronic interactions ?**
  - If the source mechanism is well understood we could have a known beam at ultra-high energy (10^{10} GeV and more)
    - source detection + known magnetic field = limit on CR mass
  - reasonable minimum limits from CR abundance :
    - low = hydrogen (proton)
    - high = iron (A=56)

EAS measurements should be between proton and iron simulated showers !

Outline

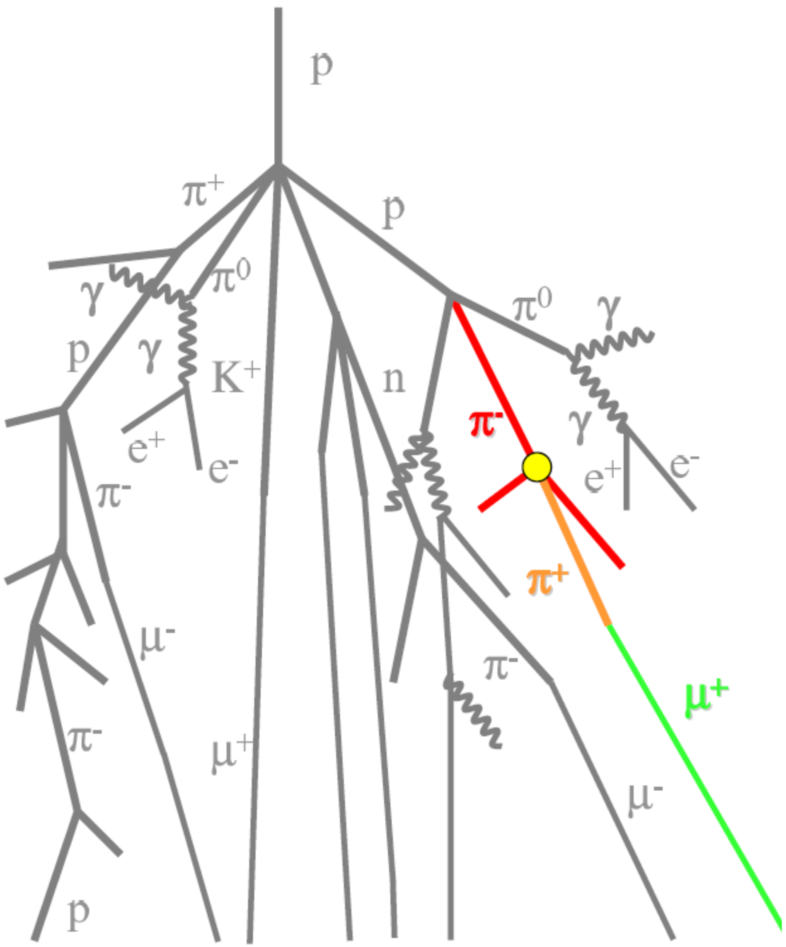
- **Introduction**
  - Basic concepts
- **Hadronic Models in EAS**
  - Needs
  - Constraints
- **LHC data**
  - Comparison with minimum bias data
- **Consequences**
  - LHC simulations
  - EAS simulations

Cosmic Ray Spectrum



- **Origins of spectrum properties**
  - mostly unknown
  - depend on primary CR mass
- **Most of analysis based on EAS simulations**
  - CORSIKA
  - AIRES
  - COSMOS
  - CONEX, ...

Extensive Air Shower



From R. Ulrich (KIT)

$$A + air \rightarrow \text{hadrons}$$
$$p + air \rightarrow \text{hadrons}$$
$$\pi + air \rightarrow \text{hadrons}$$

main source of uncertainties

intial γ from π^0 decay

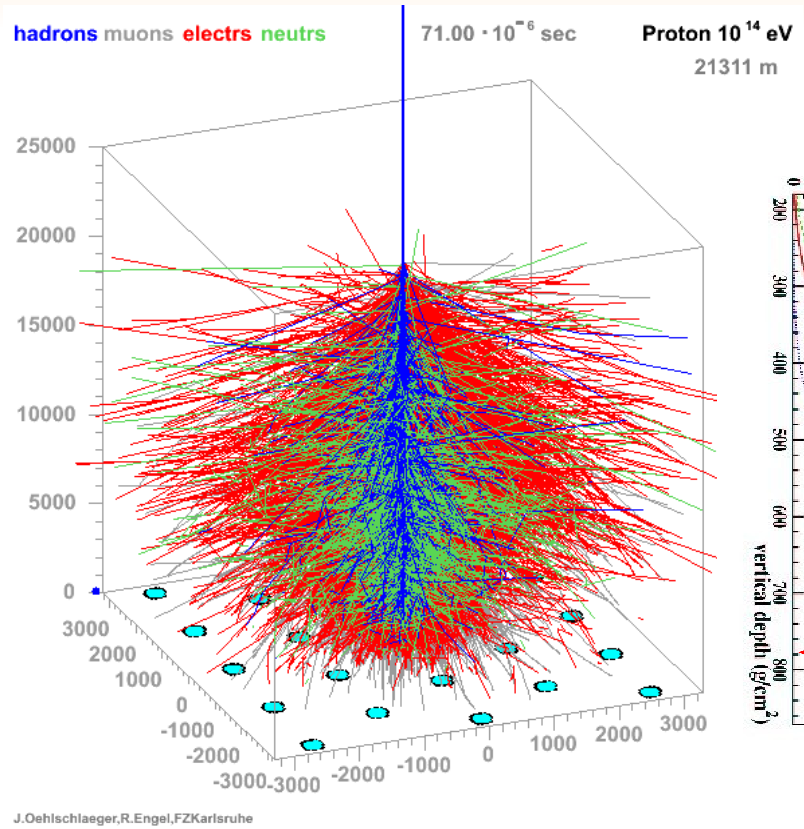
$$e^{\pm} \rightarrow e^{\pm} + \gamma$$
$$\gamma \rightarrow e^{+} + e^{-}$$

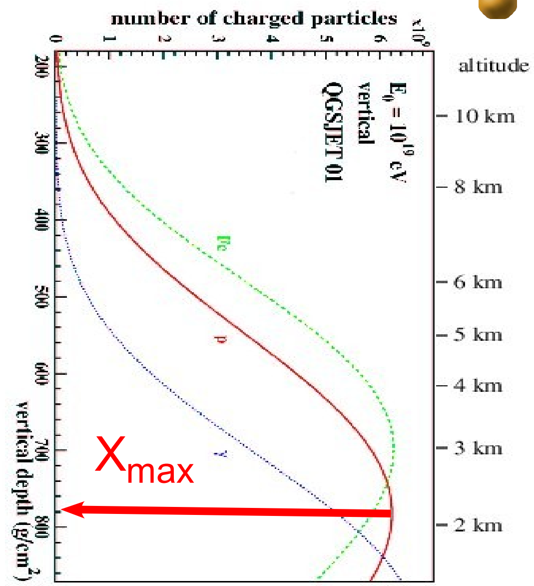
well known

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}/\bar{\nu_{\mu}}$$

- **Cascade of particle in Earth's atmosphere**
  - Number of particles at maximum
    - 99,88% of electromagnetic (e/m) particles
    - 0.1% of muons
    - 0.02% hadrons
  - Energy
    - from 100% hadronic to 90% in e/m + 10% in muons at ground (vertical)

Extensive Air Shower Observables



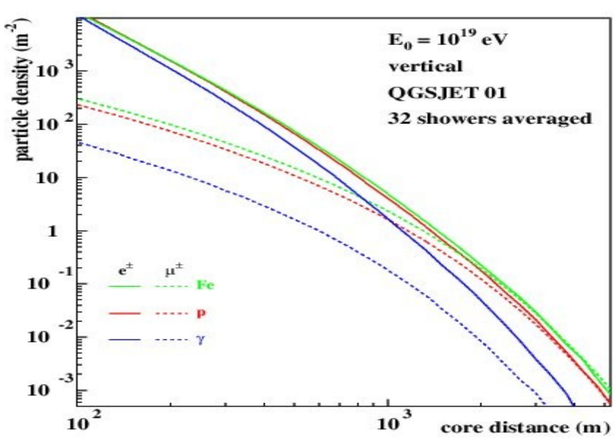


- **Longitudinal Development**
  - number of particles vs depth

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

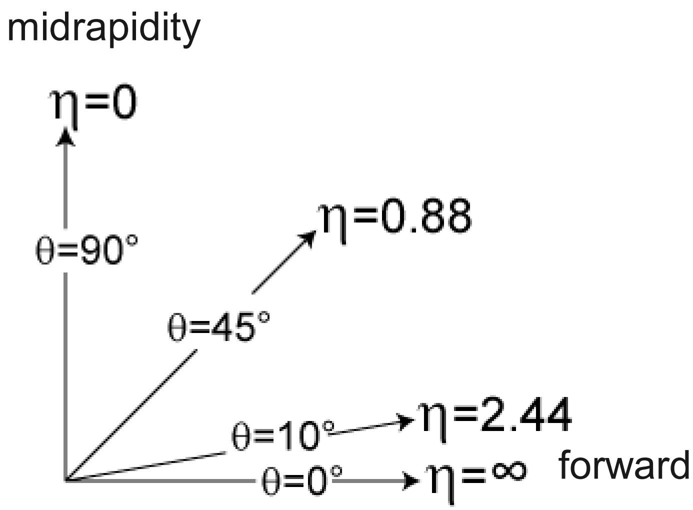
  - Larger number of particles at X_{max}

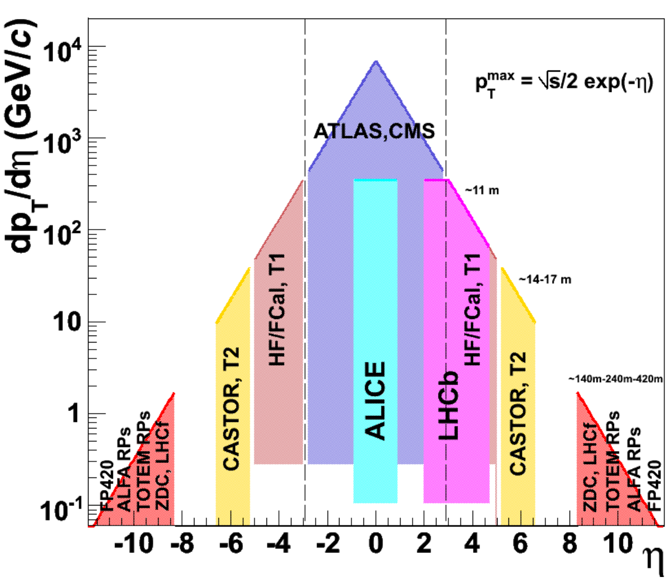
    For many showers
    - mean : $<X_{max}>$
    - fluctuations : RMS X_{max}



- **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.

Some more definitions





- **Pseudorapidity**
  - emission angle of a particle from interaction point ("midrapidity" : η=0) :

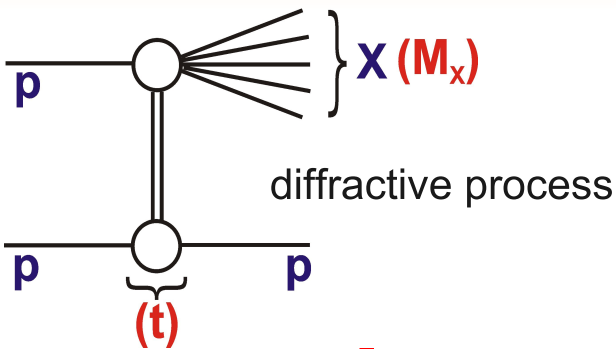
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right] \qquad \eta = \frac{1}{2}\ln\left(\frac{|\mathbf{p}| + p_{\mathrm{L}}}{|\mathbf{p}| - p_{\mathrm{L}}}\right)$$

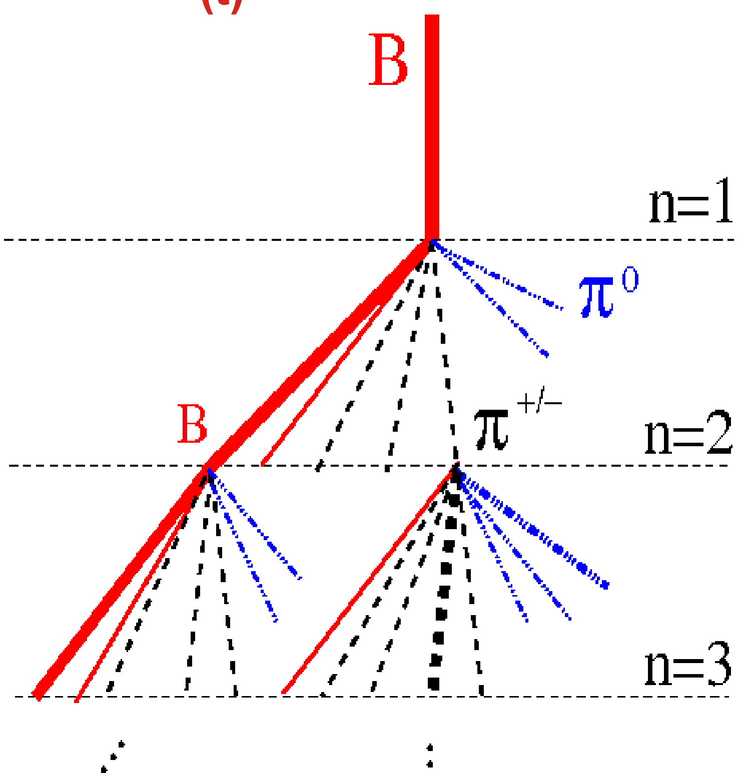
  - when the mass of the particle is known the rapidity is used :

$$y = \frac{1}{2}\ln\left(\frac{E + p_{\mathrm{L}}}{E - p_{\mathrm{L}}}\right)$$

  - for EAS development, "forward" particles (with large η) are most important
- **Transverse momentum**
  - $p_t = \sqrt{p_x^2 + p_y^2}$
- **Multiplicity**
  - number of particles in a given η and p_t range

Models for Air Shower Simulation





Thickness = amount of energy

- **Hadronic models for simulations :**
  - mainly soft (low p_t (< 2 GeV/c)) physics + diffraction (forward region)
  - should handle p-, π-Air, K-Air and A-Air interactions
  - should be able to run at 10^6 GeV center-of-mass (cms) energy
  - Single set of parameters
  - models used for EAS analysis :
    - QGSJET01/II
    - SIBYLL 2.1
    - EPOS 1.99
    - ...

Hadronic Interaction Models

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

Pb : CR physic dominated by soft interactions

Pb : Gribov-Regge do not take into account energy conservation ...

- **Phenomenology (models) :**
  - string fragmentation
  - beam remnants
  - diffraction (Good-Walker, ...)
  - higher order effects

Need Parameters !

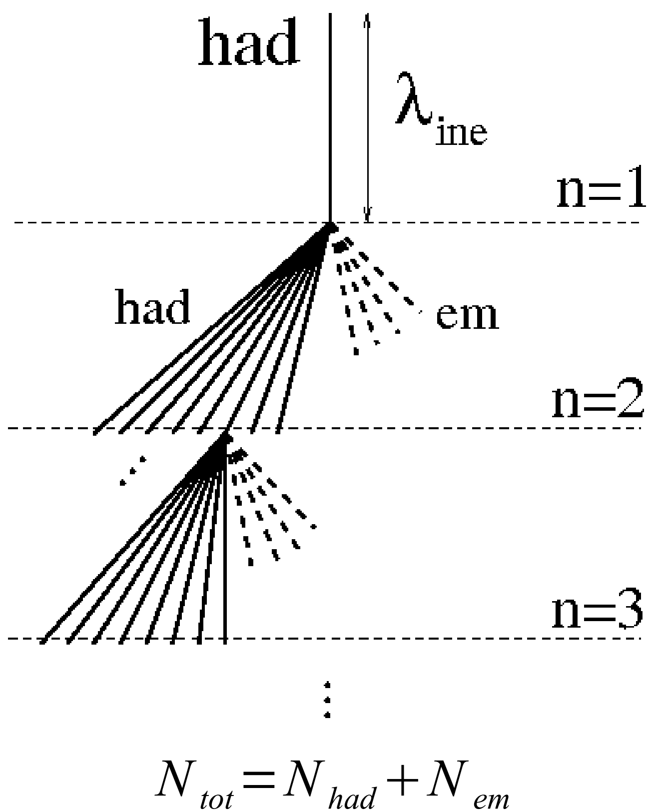
- **Comparison with data to fix parameters :**
  - minimum theory requirement with few parameters and limited data set (QGSJET approach) : better predictive power

... or ...

  - more detailed data with more parameters (EPOS approach) : nothing neglected

What is the minimum to describe EAS correctly ?

<X_{max}> Theory



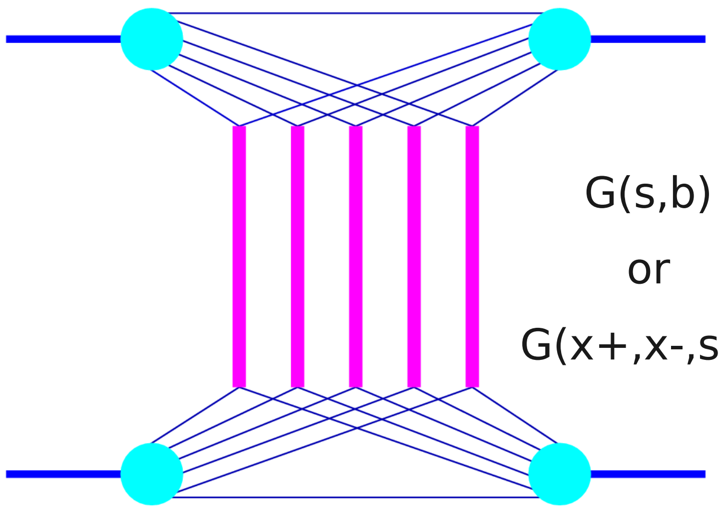
J. Matthews, Astropart.Phys. 22 (2005) 387-397

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

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

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

Cross Section and Multiplicity in Models

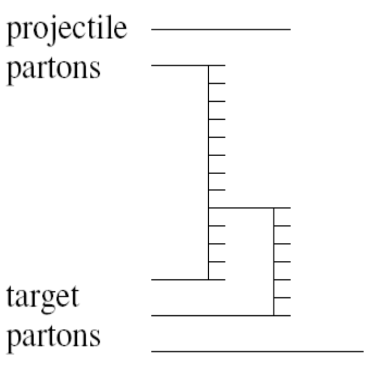


G(s,b)

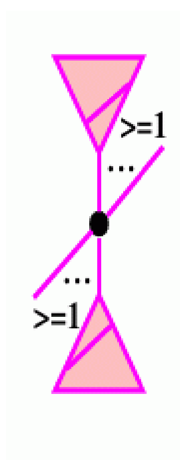
or

G(x+,x-,s,b)

EPOS



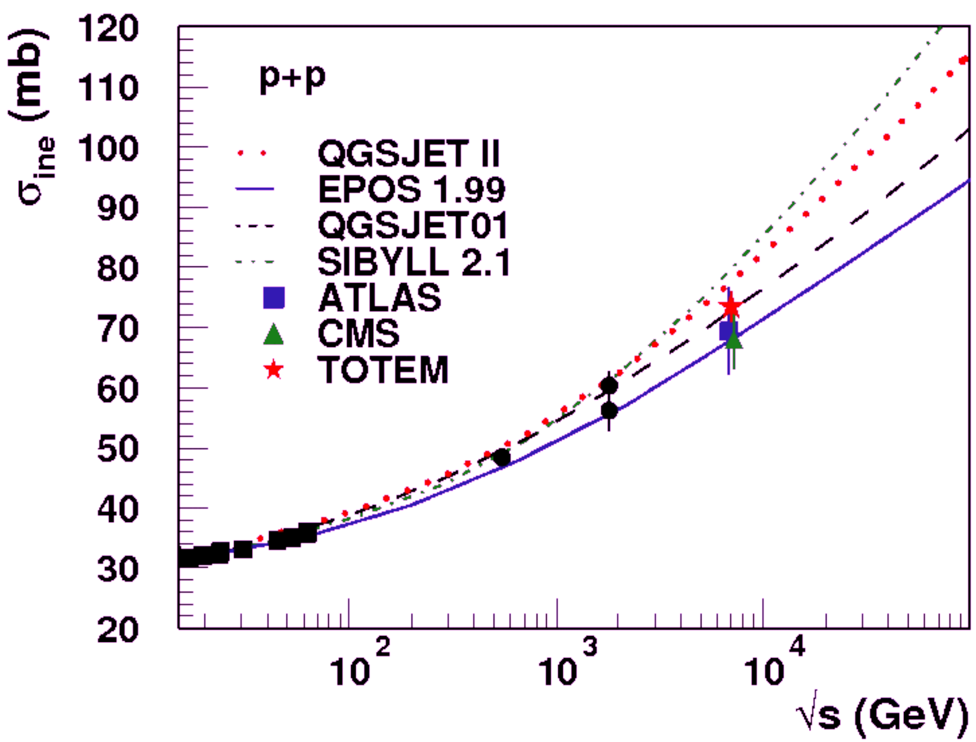
QGSJET II

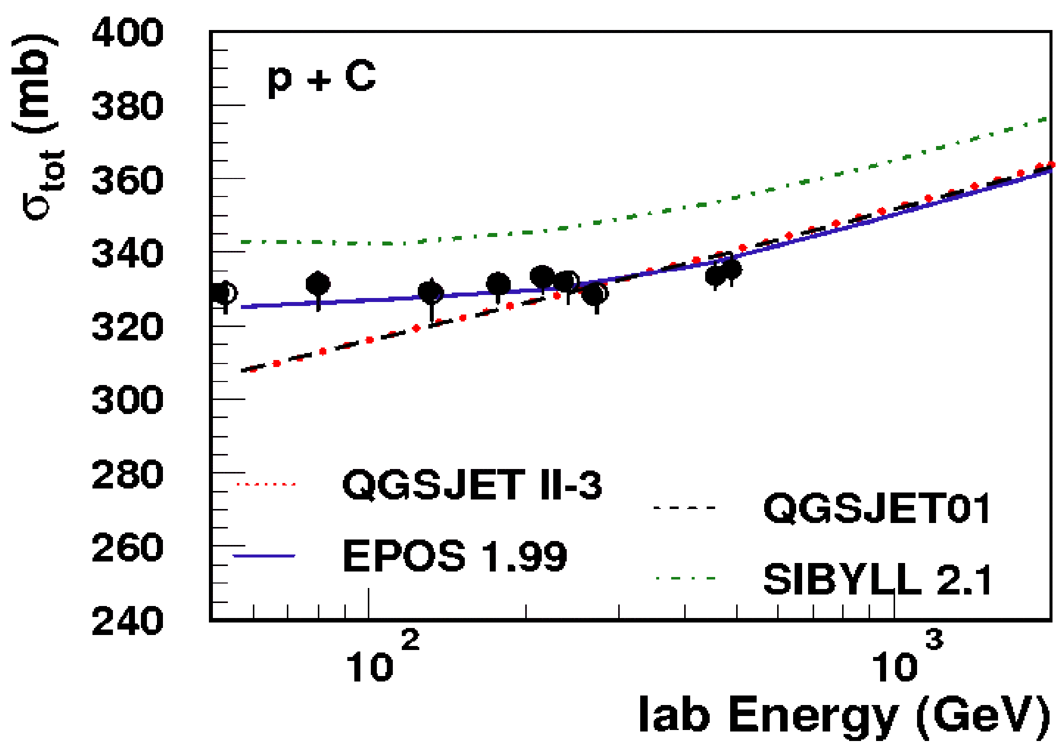


- **Gribov-Regge and optical theorem**
  - Basis of all models (multiple scattering) but
    - Classical approach for QGSJET and SIBYLL (no energy conservation for cross section calculation)
    - Parton based Gribov-Regge theory for EPOS (energy conservation at amplitude level)
- **pQCD**
  - Minijets with cutoff in SIBYLL
  - Same hard Pomeron (DGLAP convoluted with soft part : not cutoff) in QGS and EPOS but
    - No enhanced diagram in Q01
    - Generalized enhanced diagram in QII
    - Simplified non linear effect in EPOS
      - Phenomenological approach

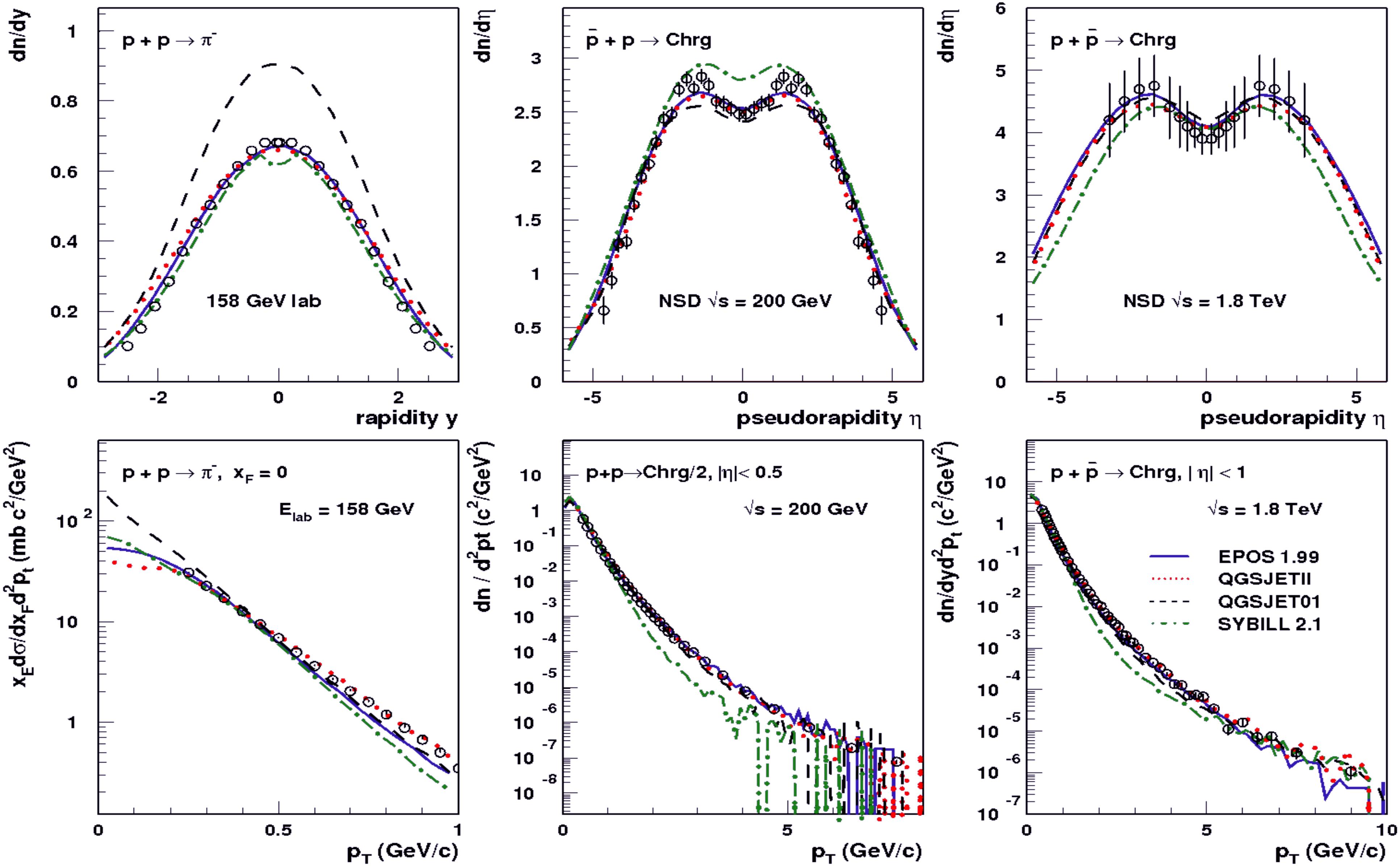
Cross Section

- Same cross section at pp level and low energy (data)
- extrapolation to pA or to high energy
  - different amplitude and scheme : different extrapolations
- multiple scattering + screening needed to use pQCD hard amplitude in inelastic cross section calculation ($\sigma_{hard} > \sigma_{ine}$)

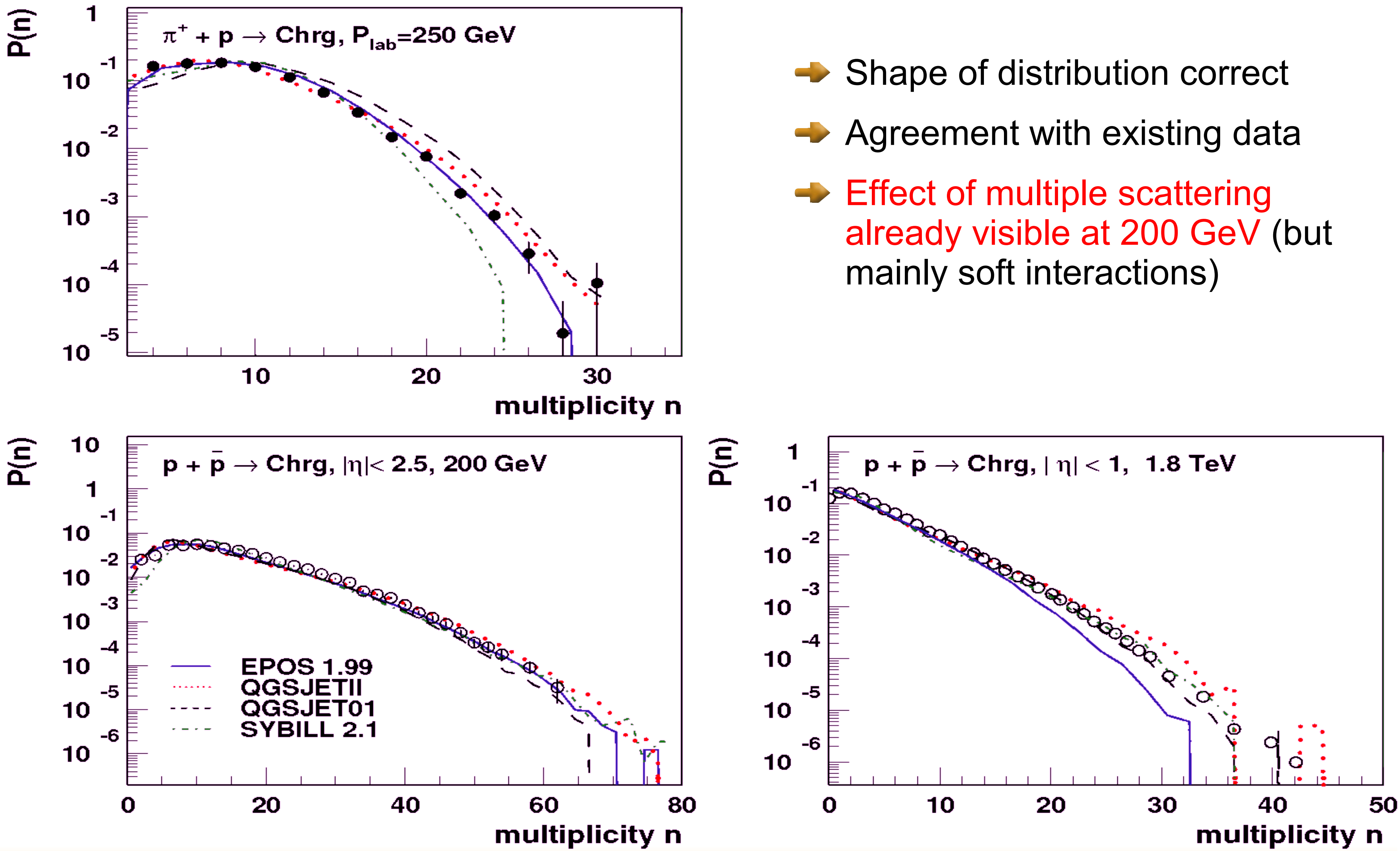




Pseudorapidity and p_T



Multiplicity

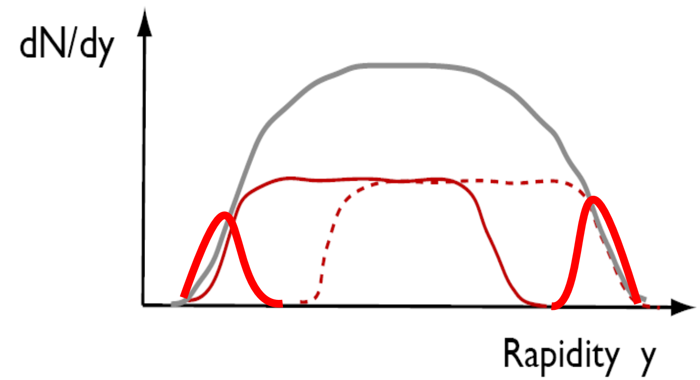


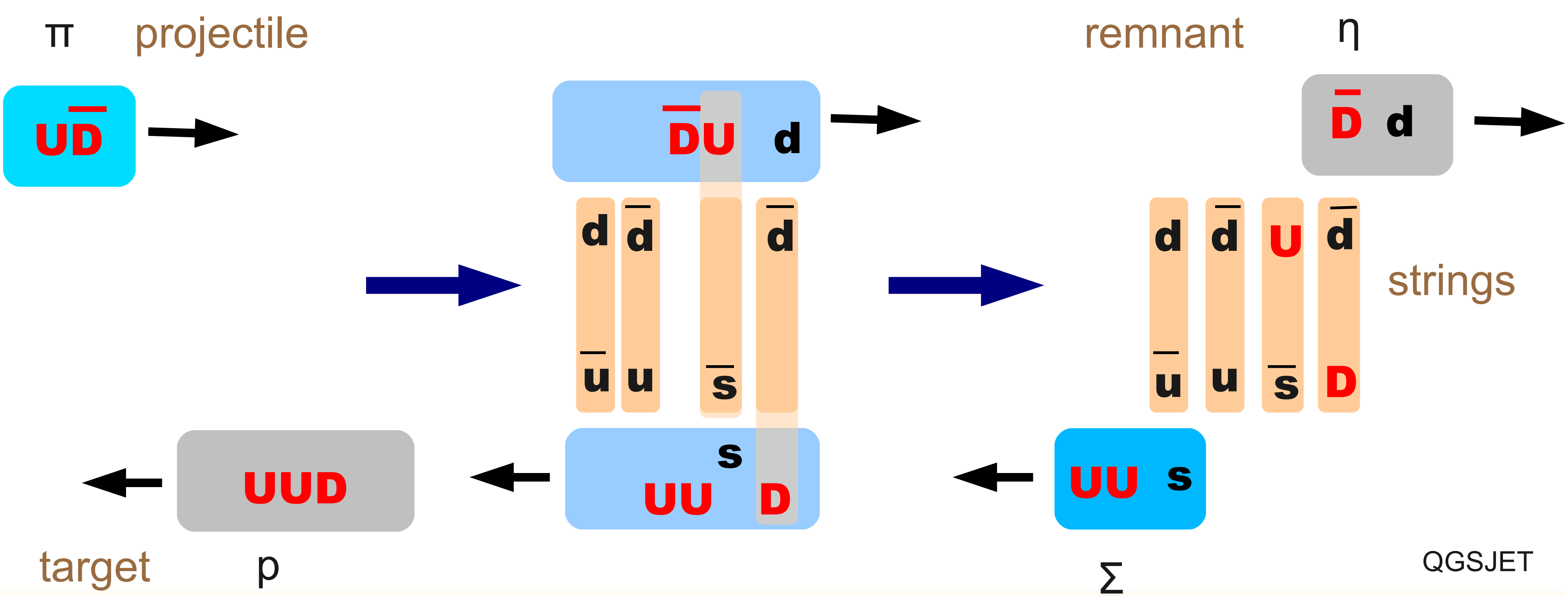
- Shape of distribution correct
- Agreement with existing data
- Effect of multiple scattering already visible at 200 GeV (but mainly soft interactions)

Beam Remnants

Forward particle production dominated by beam remnants

- No strong theory
- Each model has its own approach
- Can be tested at low energy

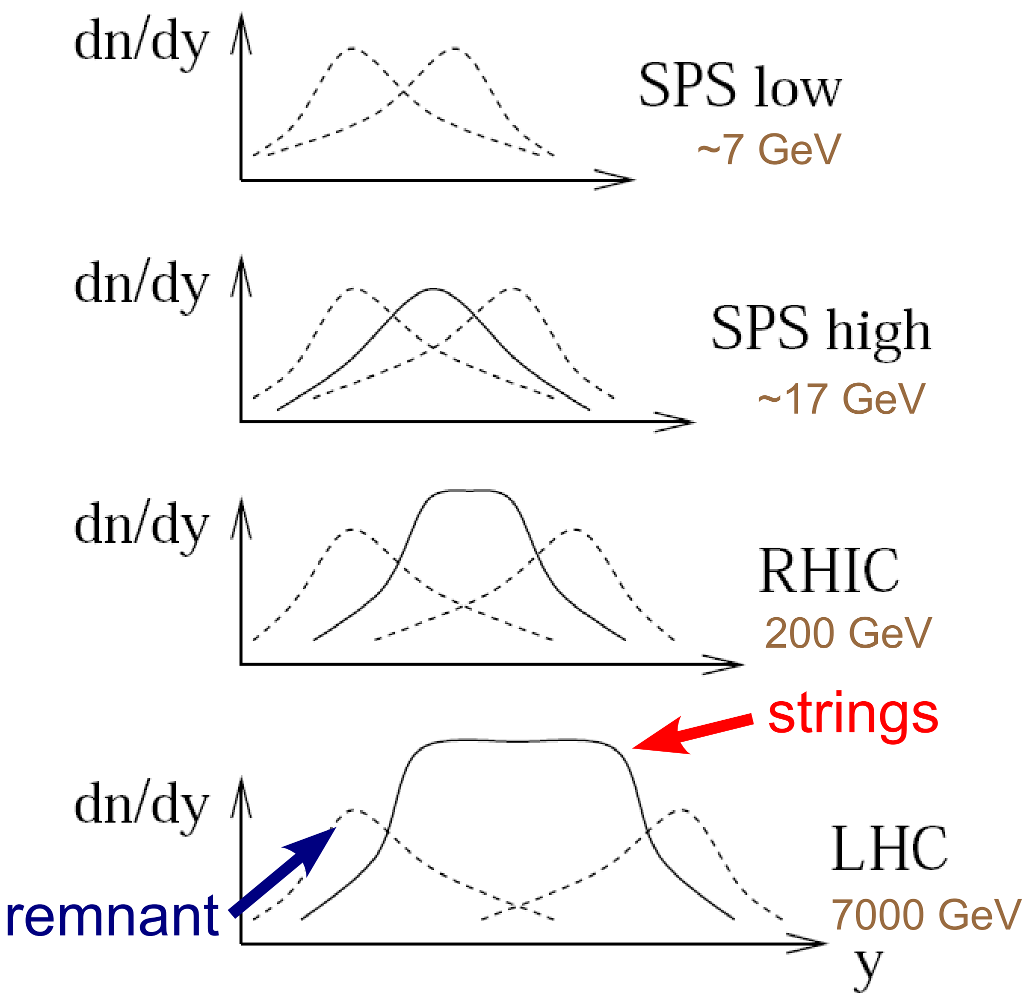




Forward Spectra

Forward particles mainly from projectile remnant

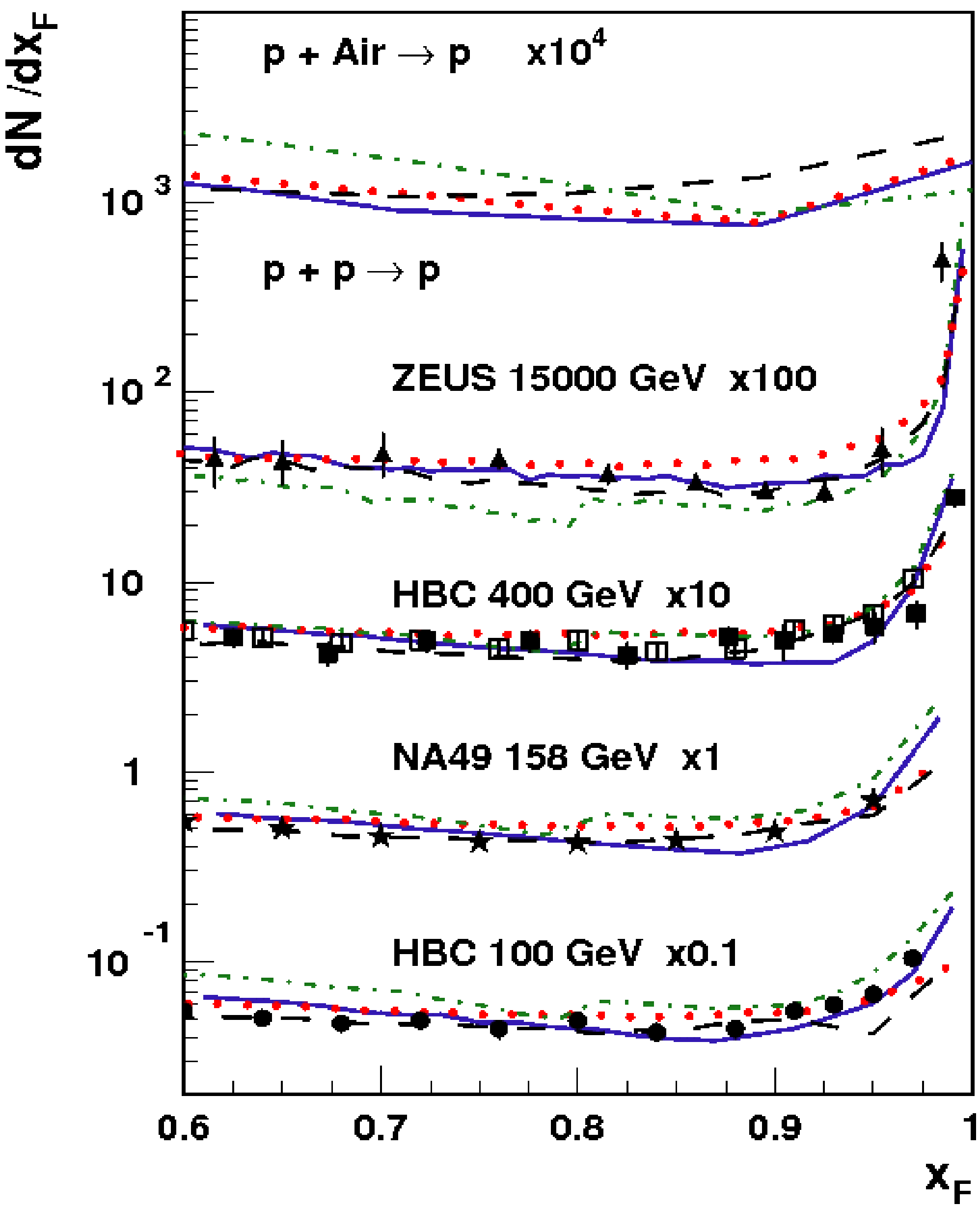
The (in)elasticity is closely related to diffraction and forward spectra



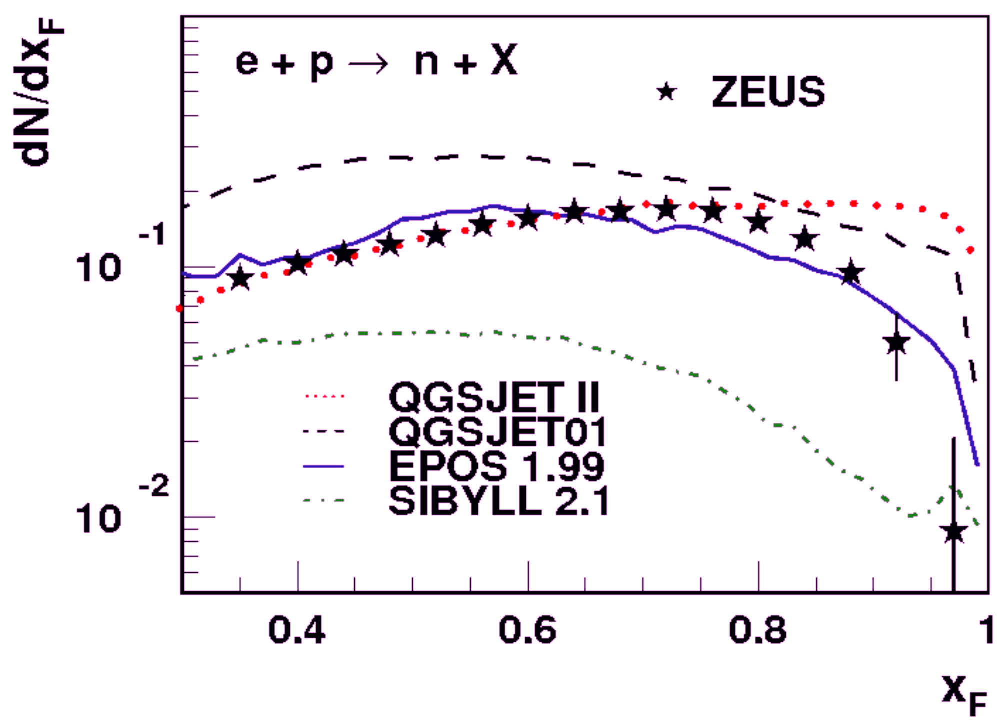
- At very low energy only particles from remnants
- At low energy (fixed target experiments) (SPS) strong mixing
- At intermediate energy (RHIC) mainly string contribution at mid-rapidity with tail of remnants.
- At high energy (LHC) only strings at mid-rapidity (baryon free)

Different contributions of particle production at different energies or rapidities

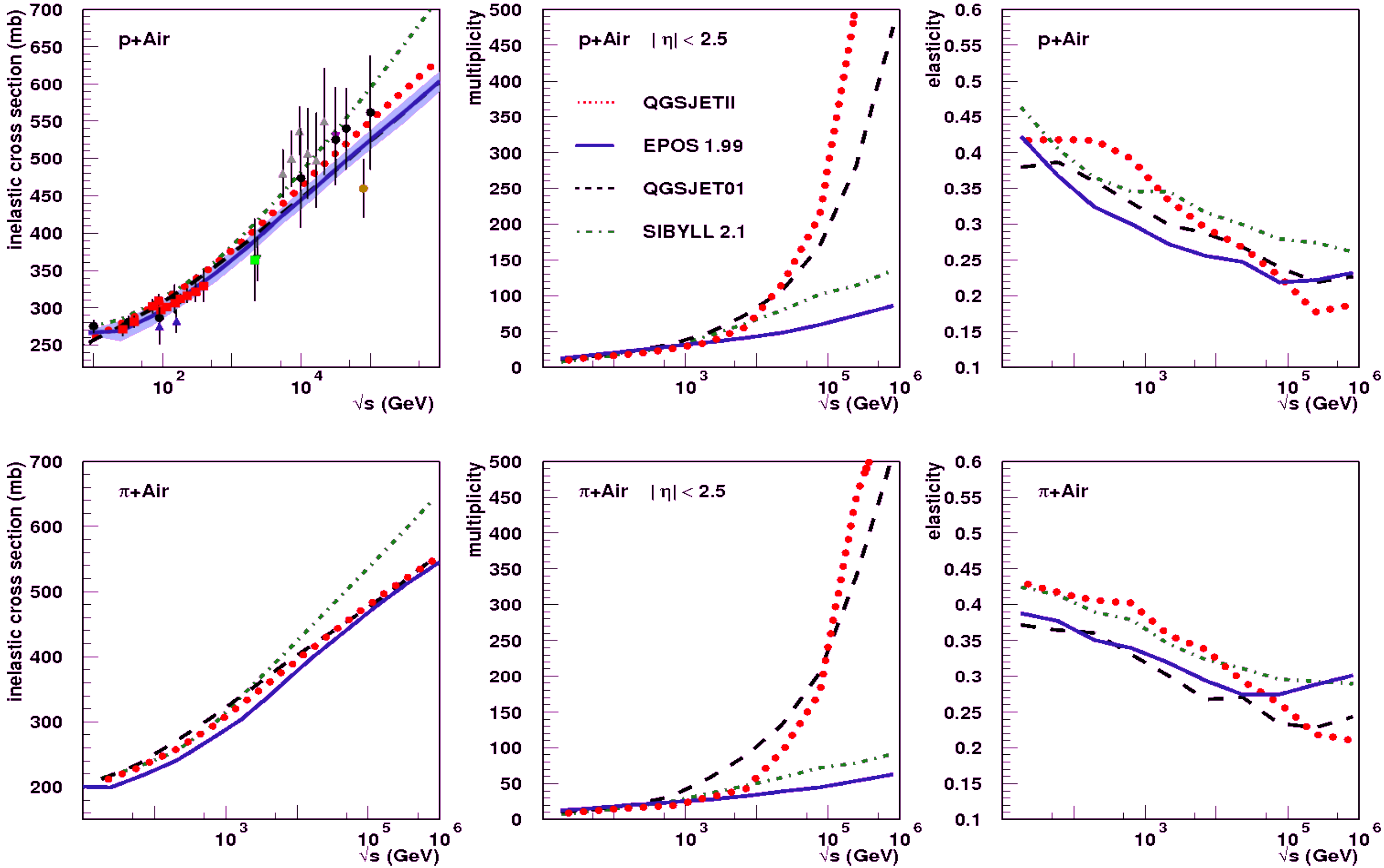
Diffraction and x_F Distributions



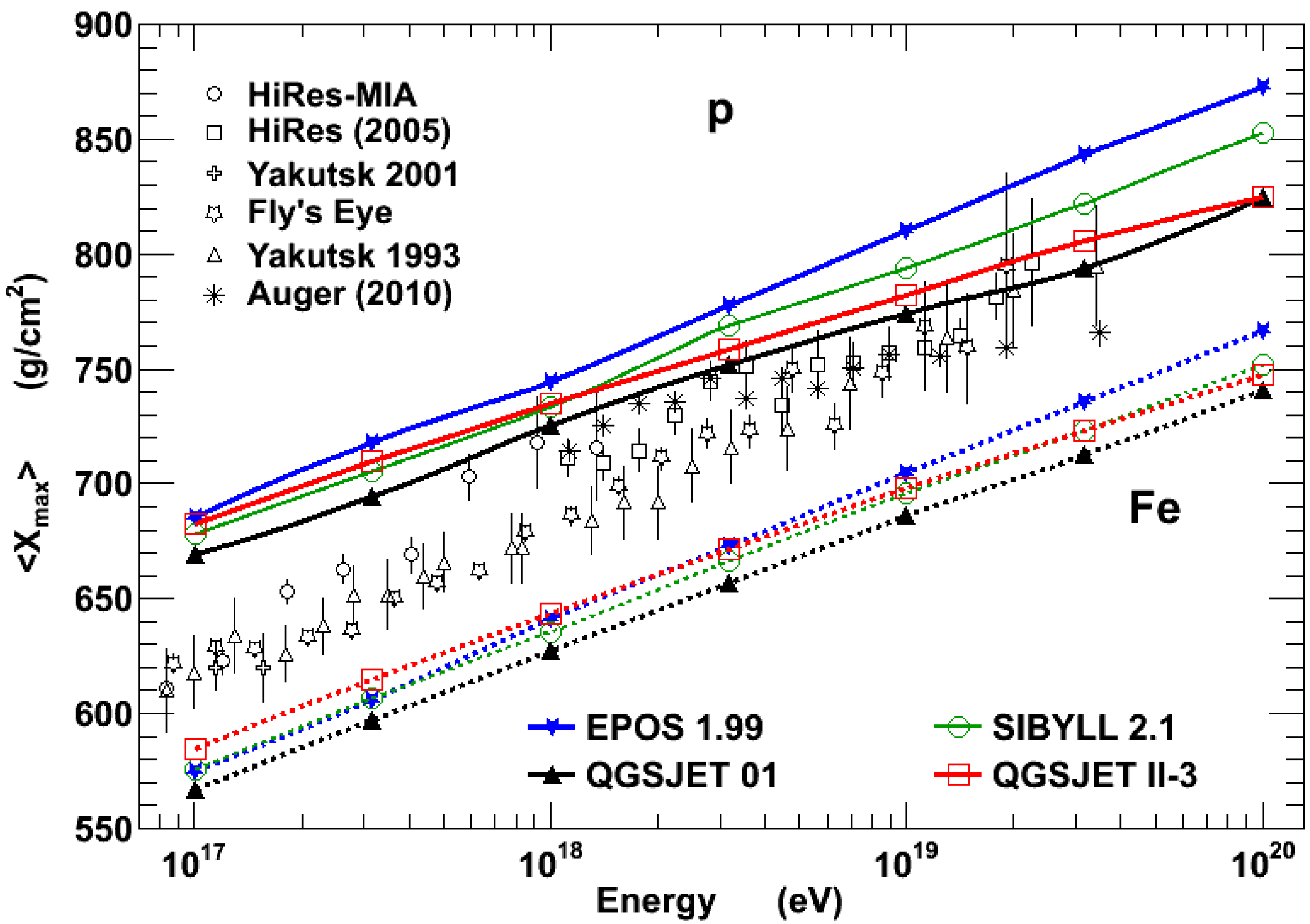
- most of the data at low energy (fixed target experiment)
- extrapolation tested with HERA data
  - more data available now (gamma)
- large differences for neutrons



Ultra-High Energy Hadronic Model Predictions



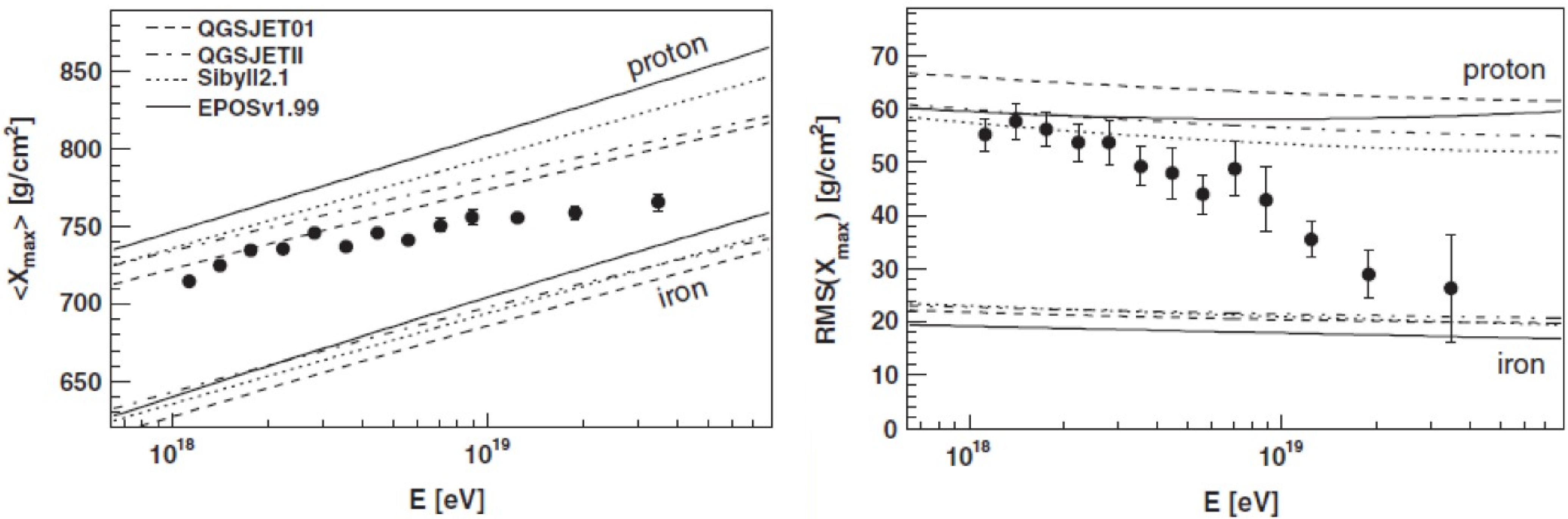
<Xmax>



Large spread of model predictions = large uncertainties on CR mass

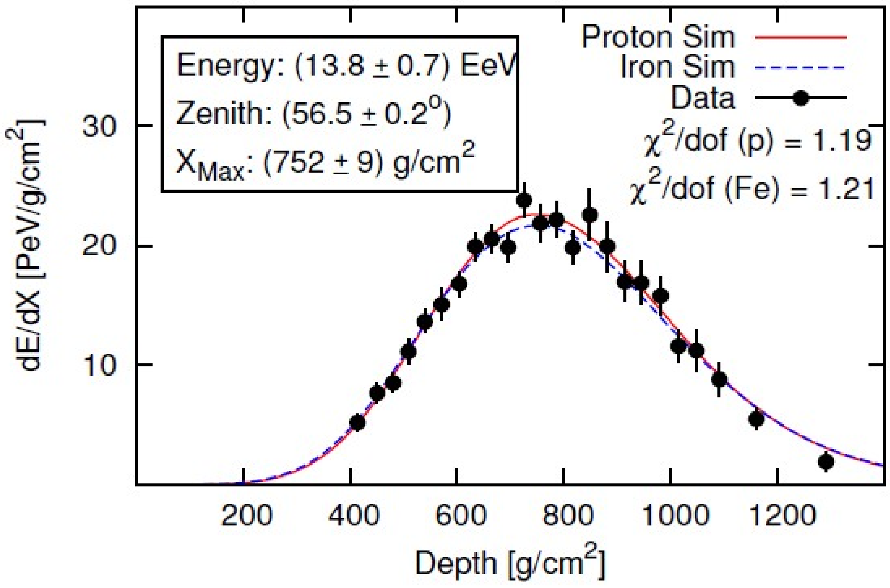
But no contradiction with data ...

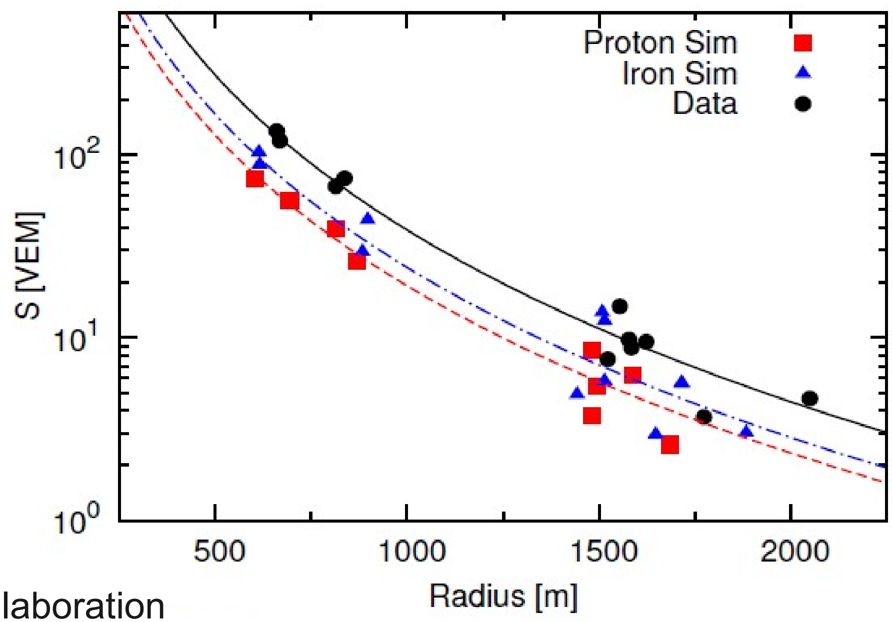
X_{max} Auger



- **EPOS and SIBYLL**
  - (almost) consistent with light mix to heavy mix $<X_{max}>$ and RMS
- **QGSJETII**
  - $<X_{max}>$ and RMS not really consistent at high E (because of $<X_{max}>$ only)
- **QGSJET01**
  - inconsistent description of $<X_{max}>$ and RMS (because of $<X_{max}>$ and RMS)

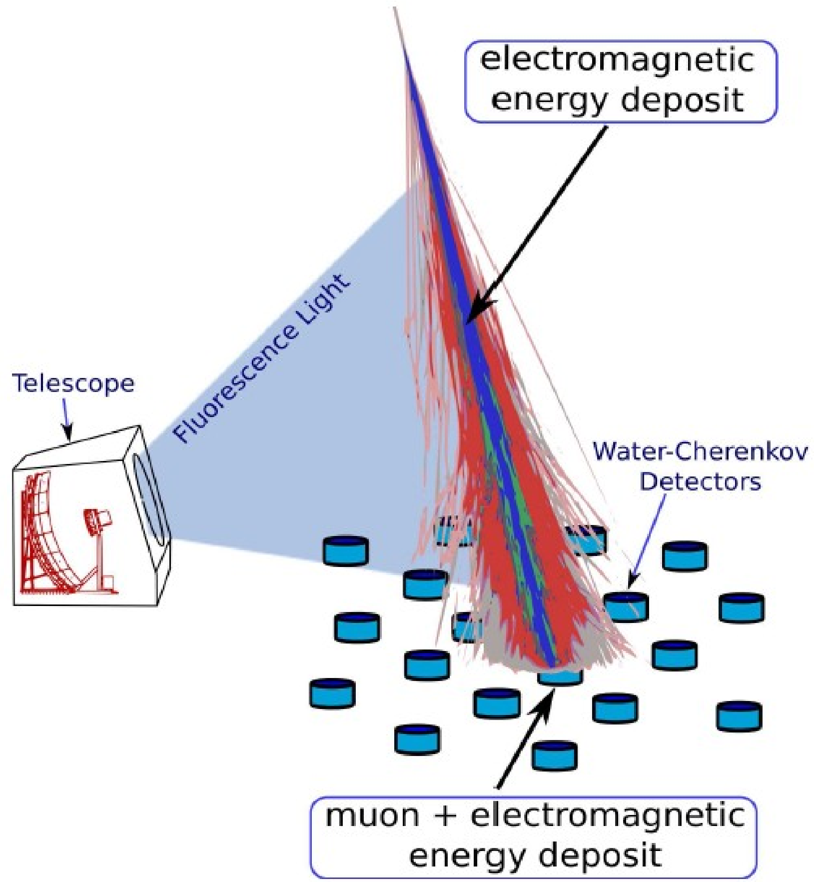
Hybrid Measurements





PAO collaboration

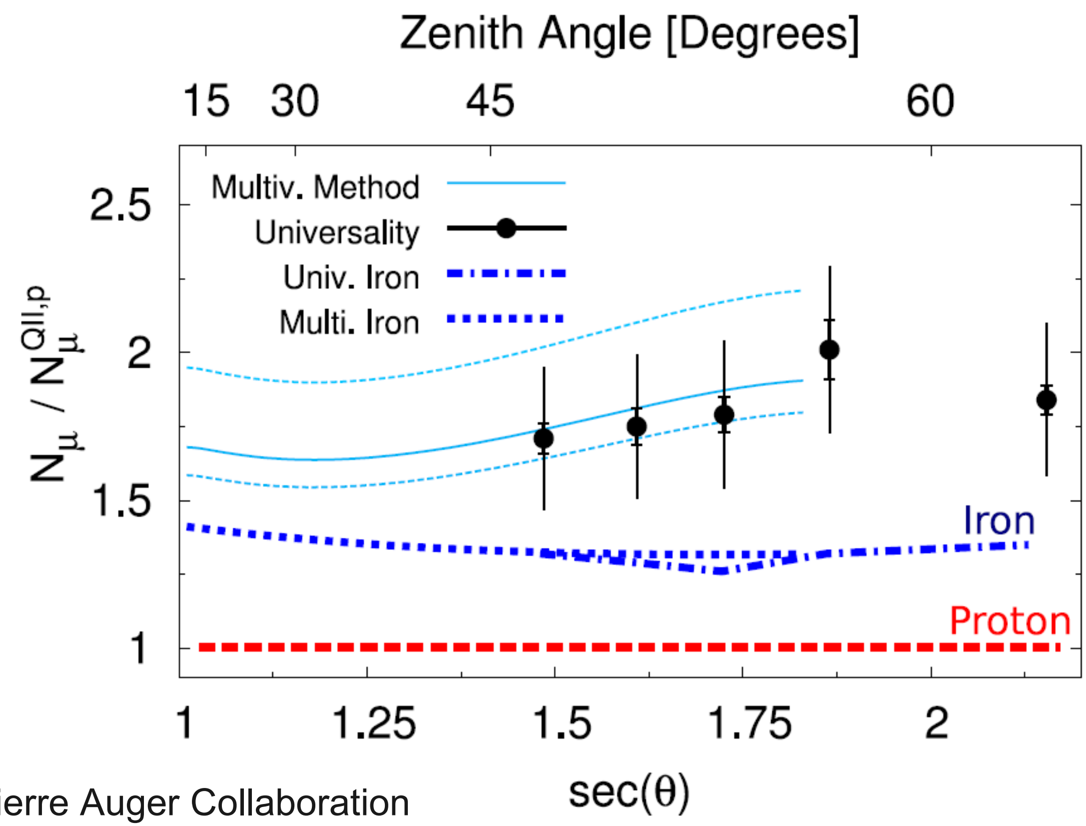
fix initial conditions : mass + energy



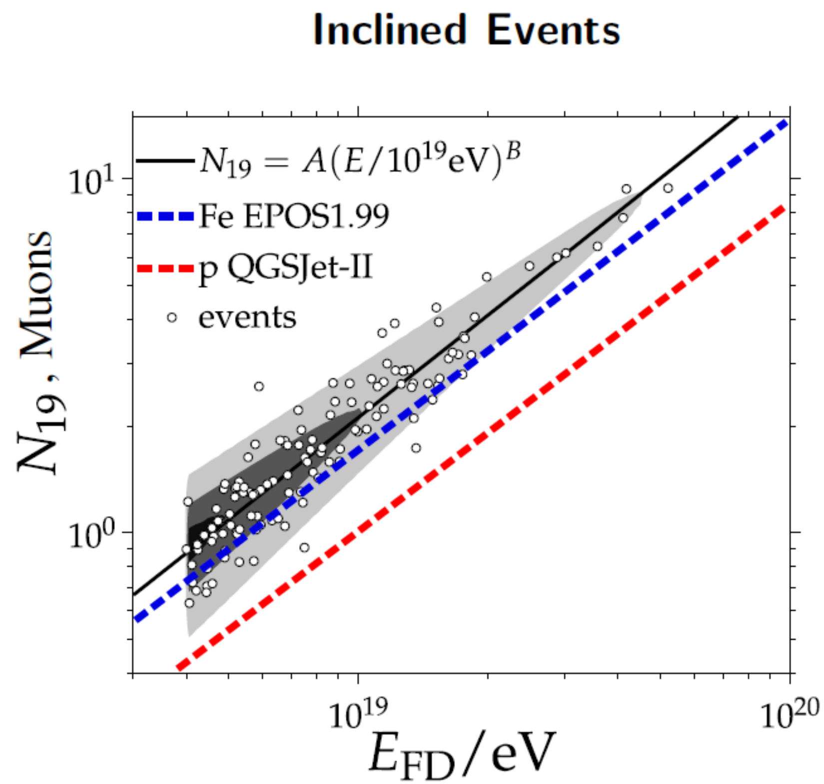
missing component = muons

Muon Deficit in EAS Simulations

- **No hadronic model predicts as many muons as observed in EAS**
  - ➔ up to a factor of 2 at large angle
  - ➔ no clear solution
    - more baryons
    - flatter LDF (muons@1000m in Auger) : larger p_t for forward pions



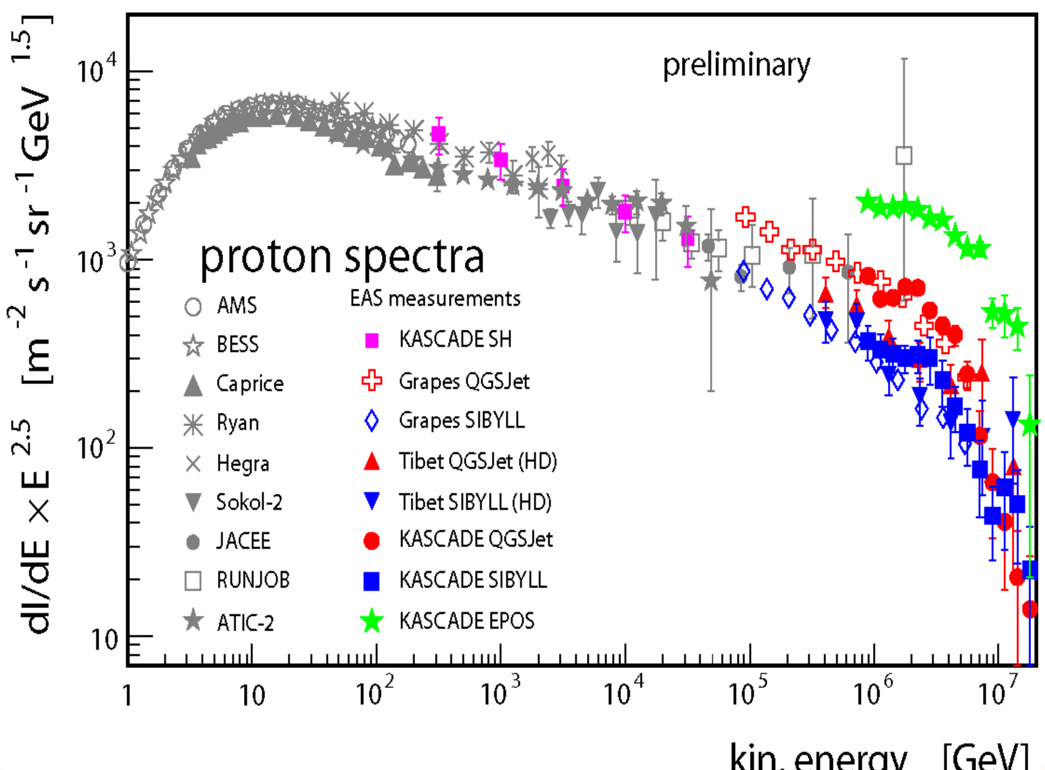
Pierre Auger Collaboration

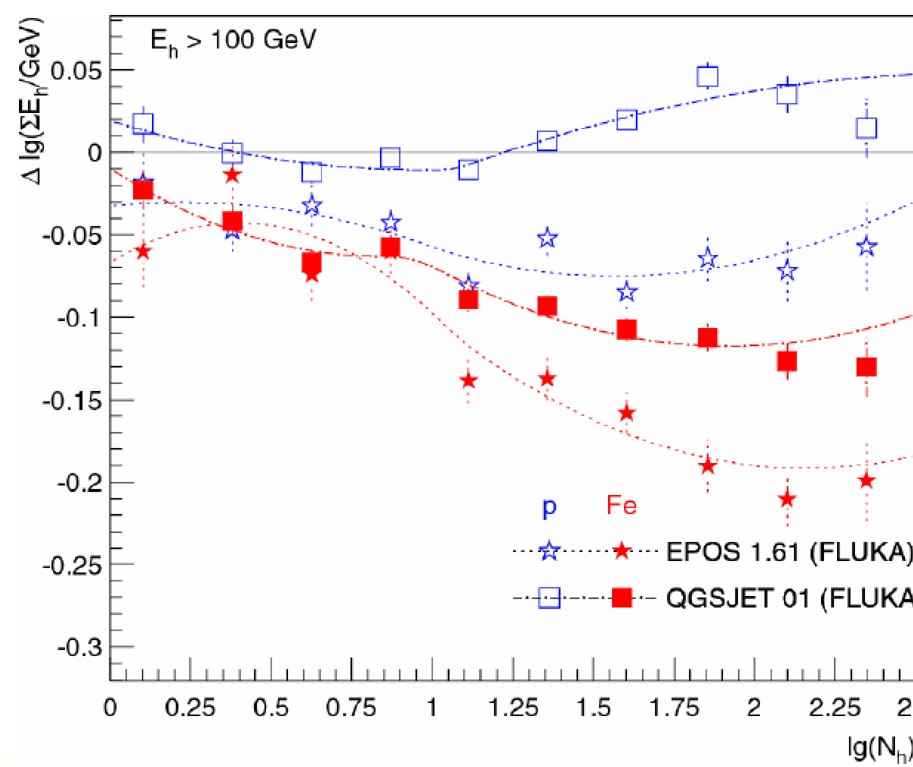


More Tests with EAS

- **EPOS 1.6 (2006) and KASCADE data**
  - Large muon number :
    - proton flux to high: not enough electron at ground
  - not enough energy per hadron

Showers develop to fast using EPOS 1.6
more screening in nuclear cross-section





KASCADE Hadron Correlation

Jörg R. Hörandel, RU Nijmegen
Jens Milke, IWR, FZK

- EPOS 1.6 is not compatible with KASCADE measurements
  → can not be recommended for air shower simulations
- QGSJET-II has some deficiencies
  → should be used for simulations with care
- QGSJET 01 and SIBYLL 2.1 still most compatible models

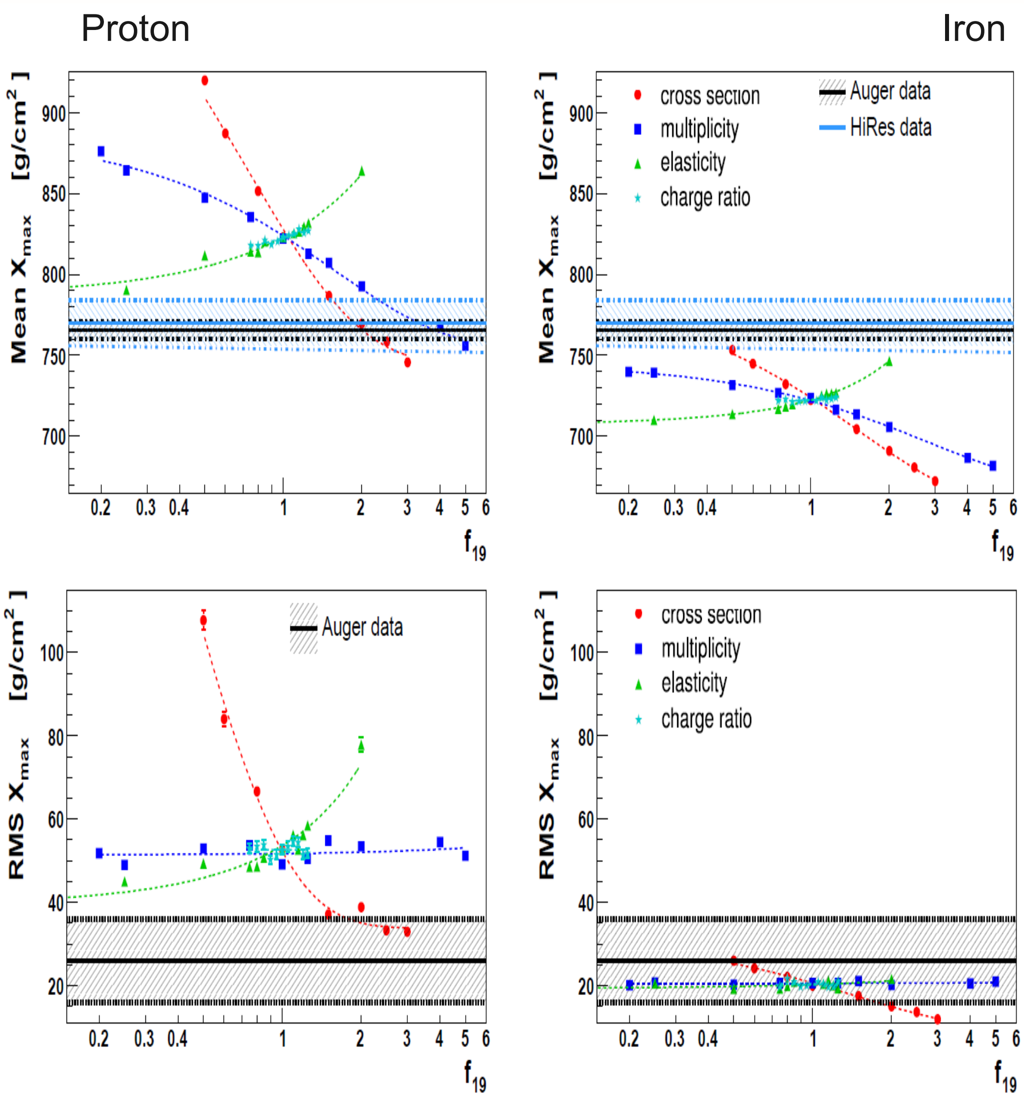
QGSJET 98
~~VENUS~~
~~SIBYLL 1.6~~

~~DPMJET II.5~~
DPMJET II.55
QGSJET 01
SIBYLL 2.1
~~NEXUS 2~~

~~EPOS 1.6~~
(QGSJET II)

- EPOS 1.99
  - these data used to understand problem with cross section and inelasticity
  - extrapolation constrained by EAS data

Uncertainties in Model Extrapolation

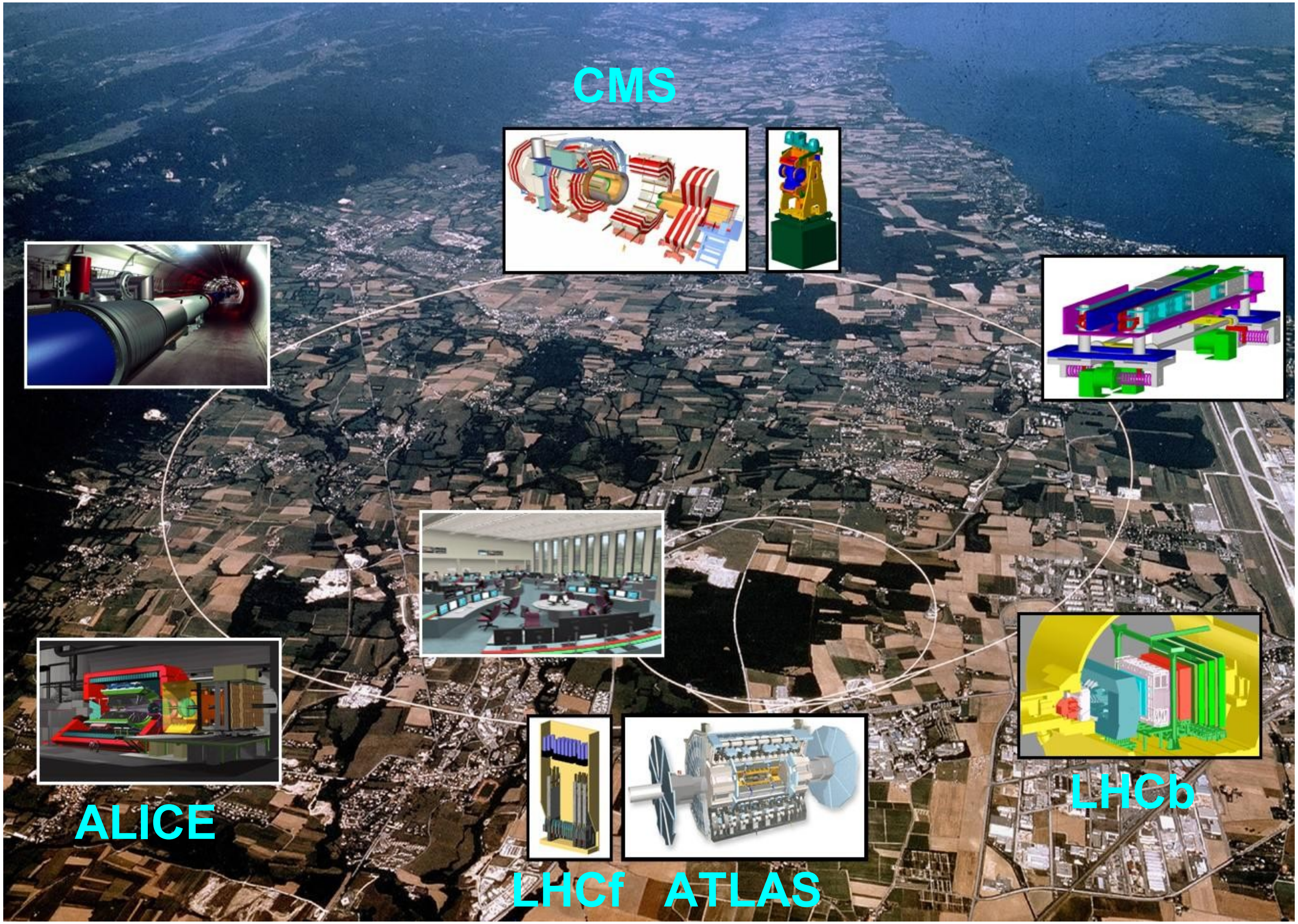


Plots by R. Ulrich (KIT)

- **Hadronic models used for EAS simulations :**
  - good agreement with pre-LHC data
  - large discrepancies were model are extrapolated (kinematic range and/or energy and mass)
  - compatible with most of CR data (within proton/iron limit) but no consistent description
  - muons not reproduced at high energy

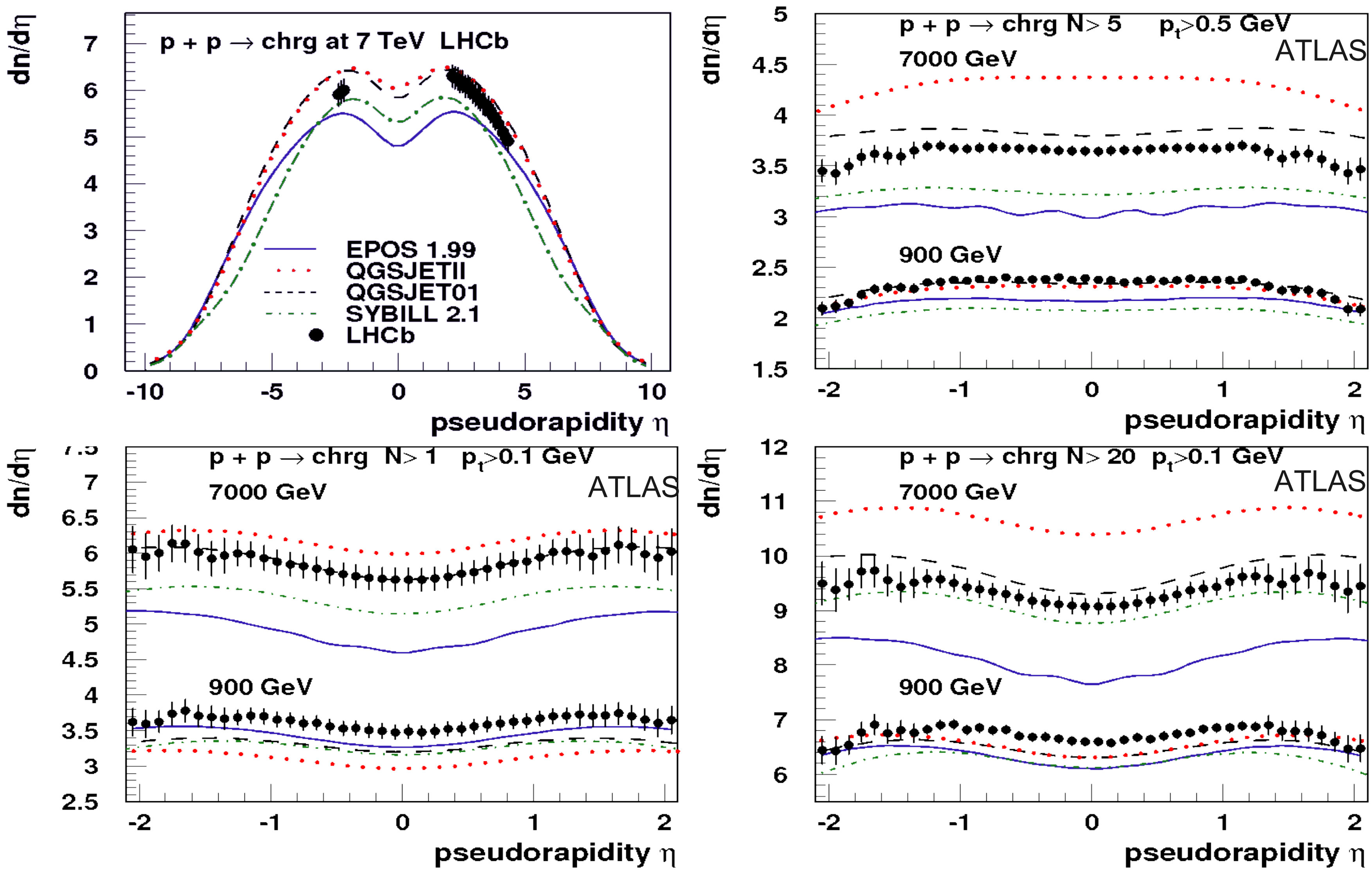
Can the large uncertainties be reduced by the LHC ?

LHC Detectors



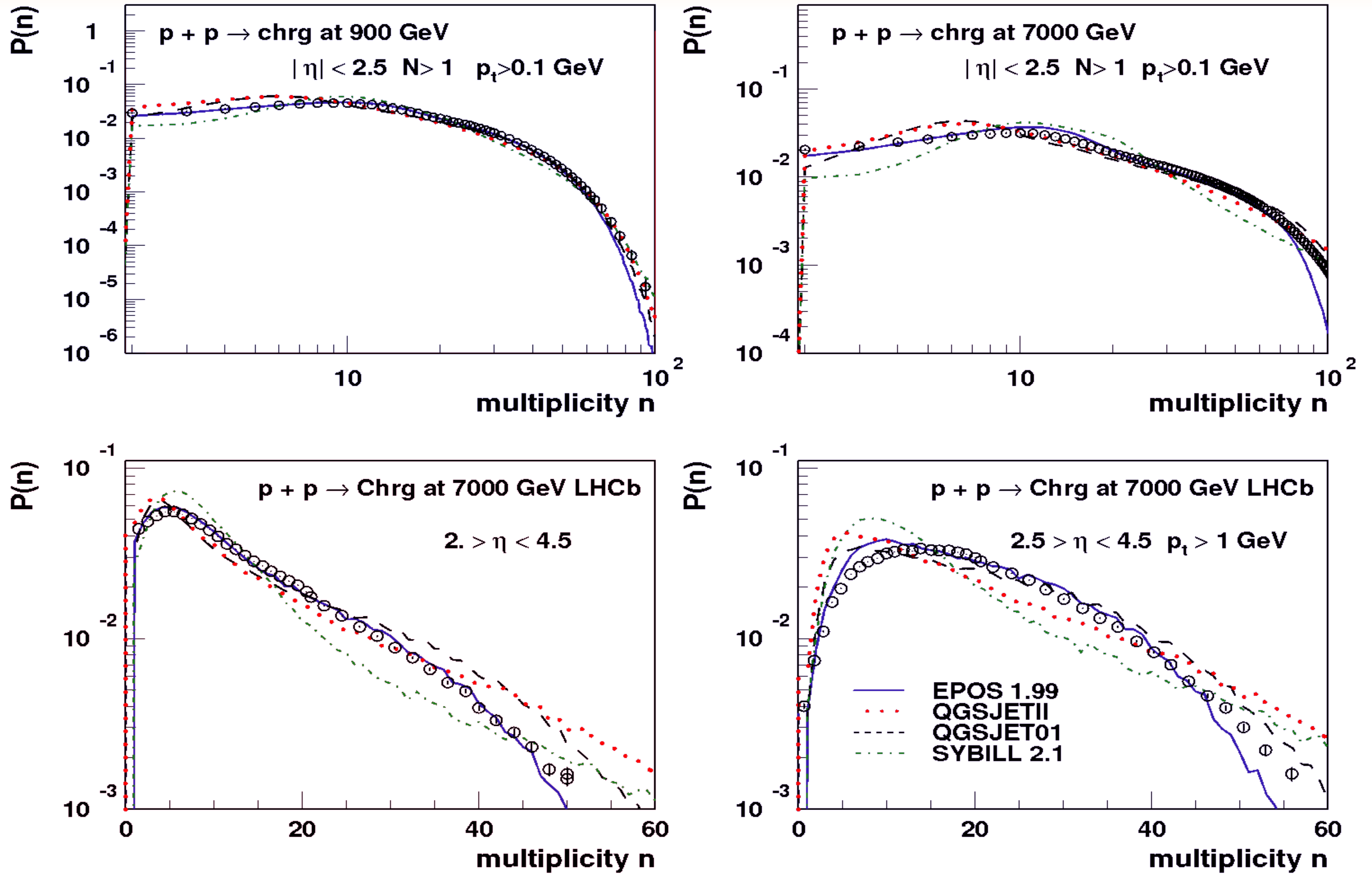
Pseudorapidity Distributions

- No model with perfect prediction : **but data well bracketed**



Predictions ! … newest model released in march 2009

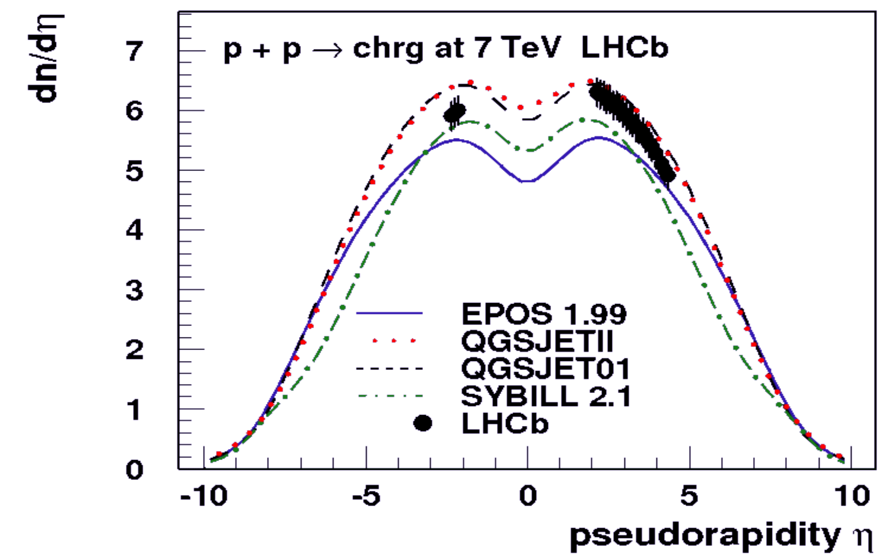
Multiplicity Distributions

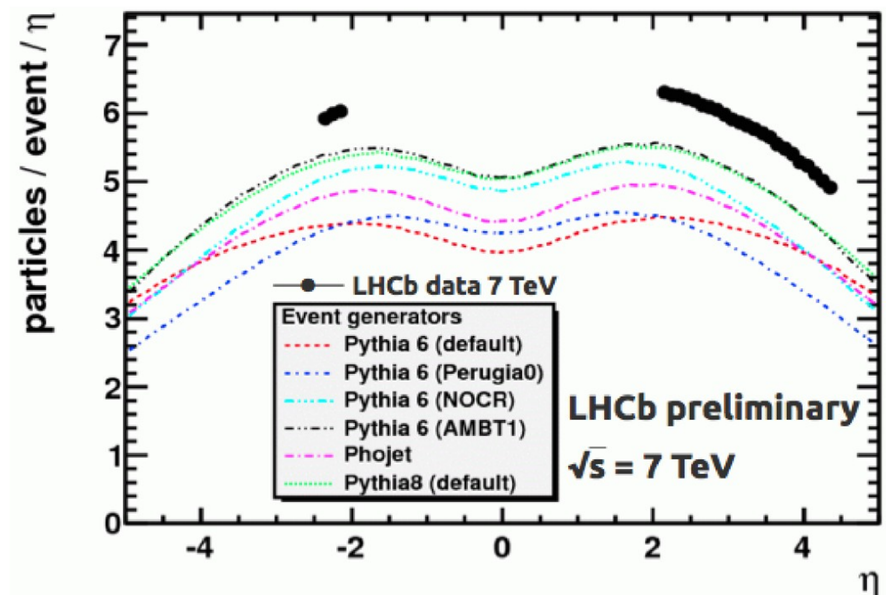


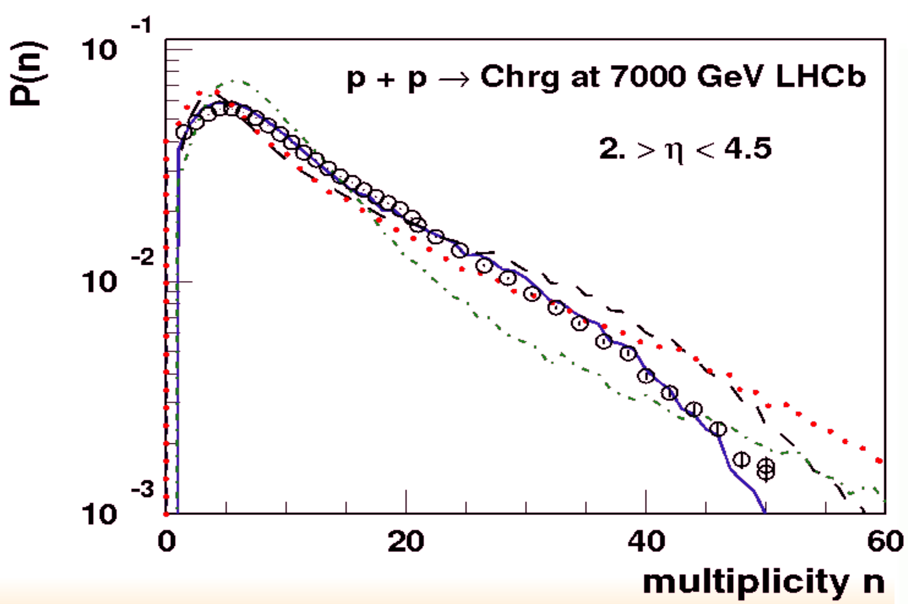
- **Forward multiplicity from LHCb : new test for models**

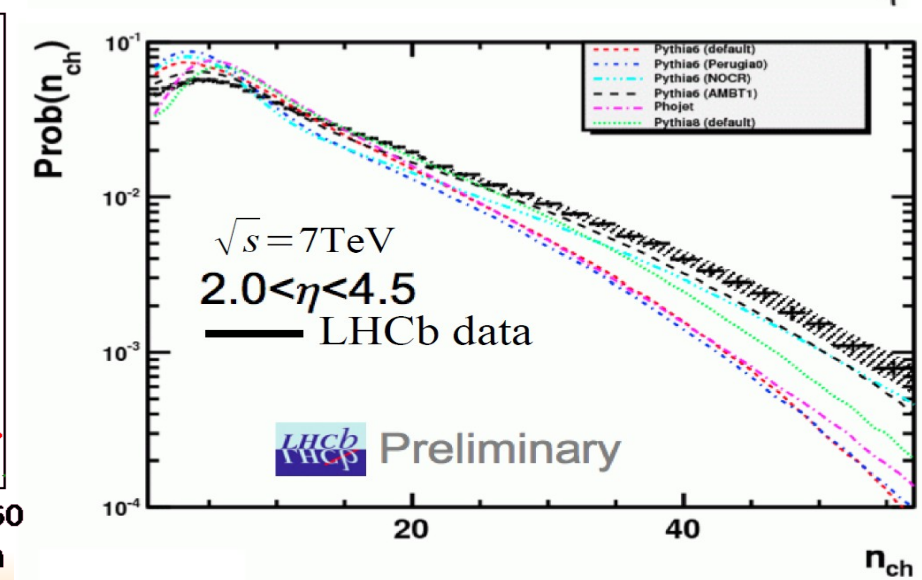
Pseudorapidity Distributions

- No model with perfect prediction : **but better than HEP MC**

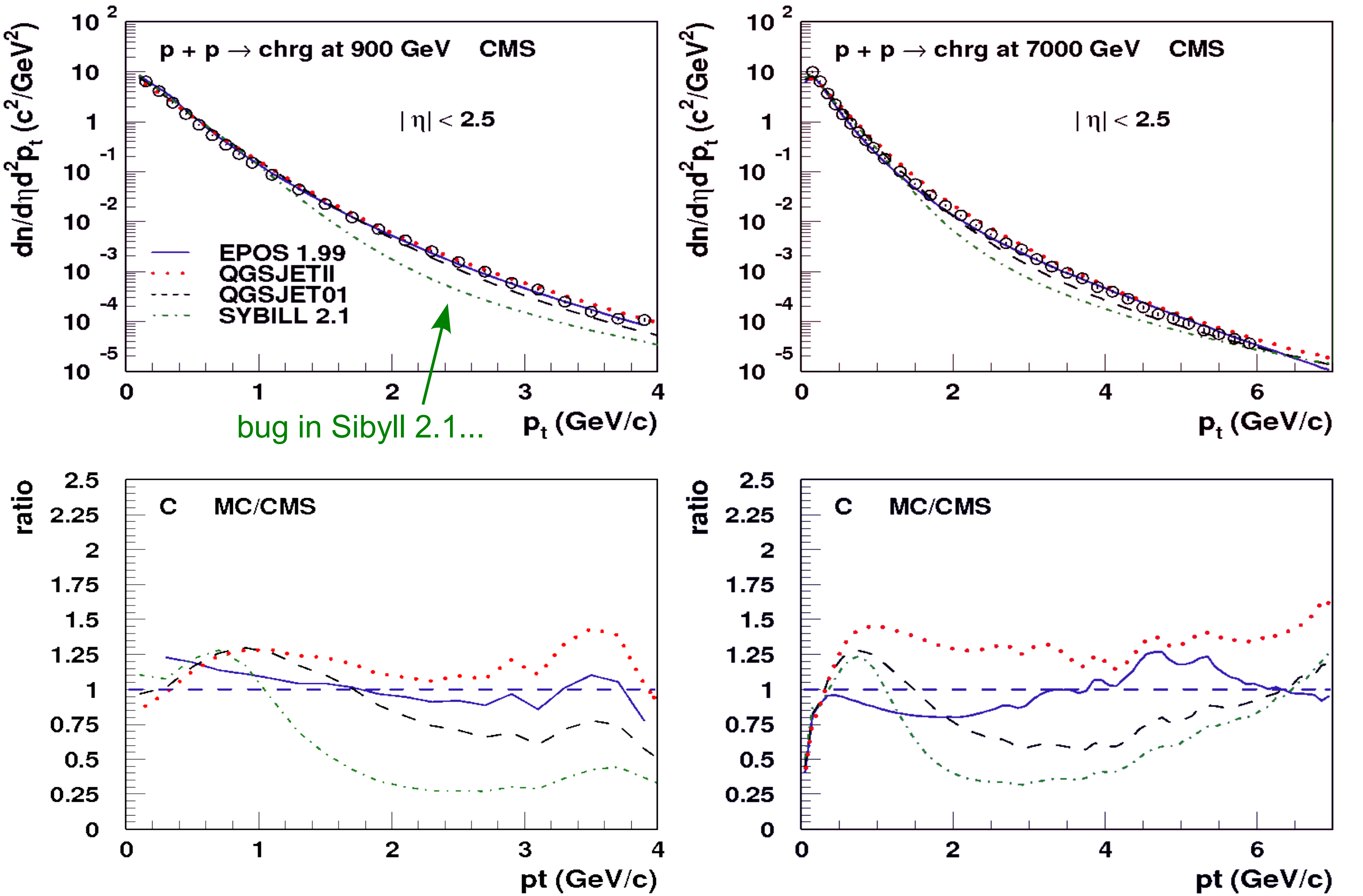






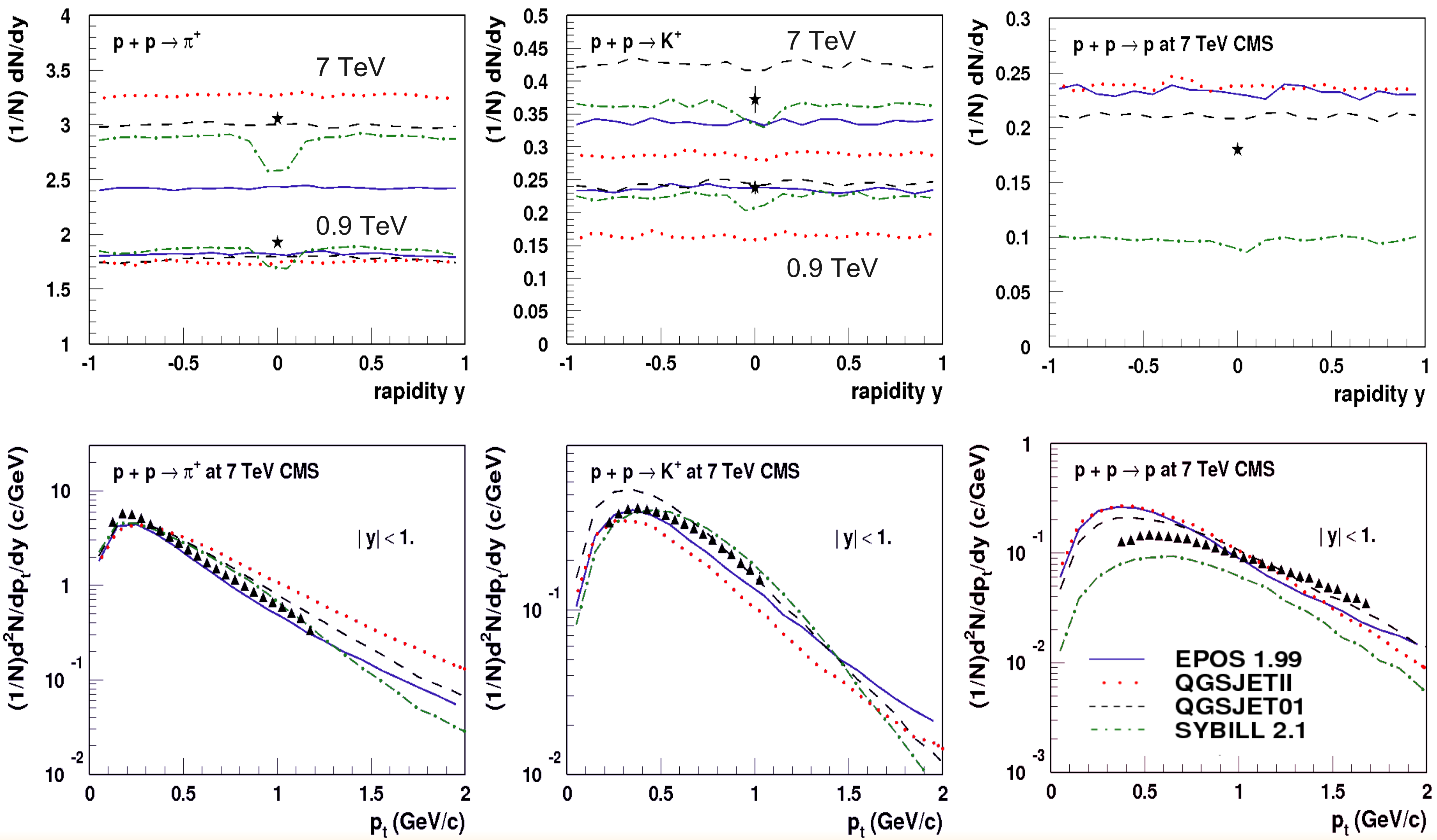


Pt @ LHC


p + p → chrg at 900 GeV CMS
|η| < 2.5
EPOS 1.99
QGSJETII
QGSJET01
SYBILL 2.1
bug in Sibyll 2.1...
dn/dηd²p_t (c²/GeV²)
p_t (GeV/c)
p + p → chrg at 7000 GeV CMS
|η| < 2.5
C MC/CMS
ratio
pt (GeV/c)
C MC/CMS

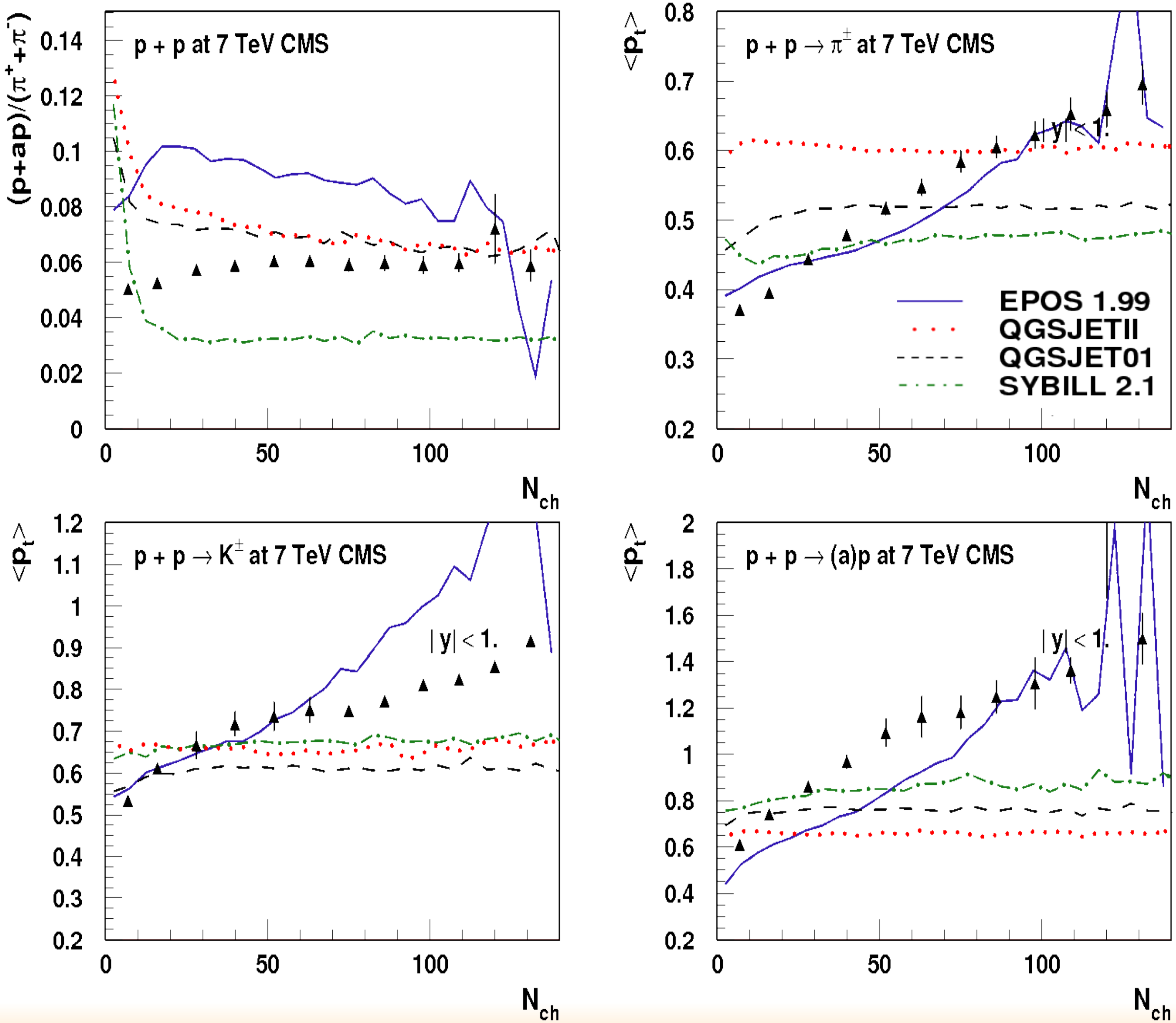
Identified Particles @ LHC

- New results from CMS (last week) :



Identified Particles @ LHC

- New results from CMS (last week) :

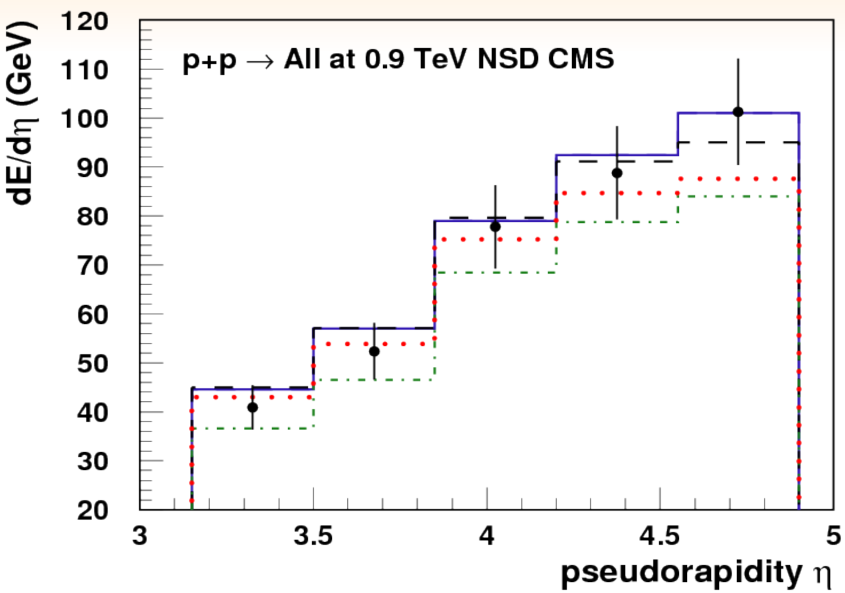


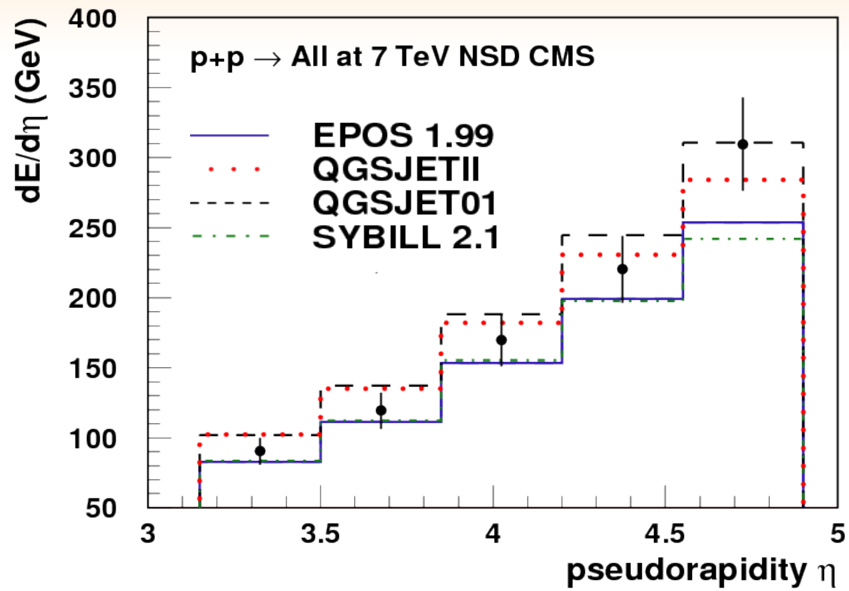
➜ baryon production not very well described

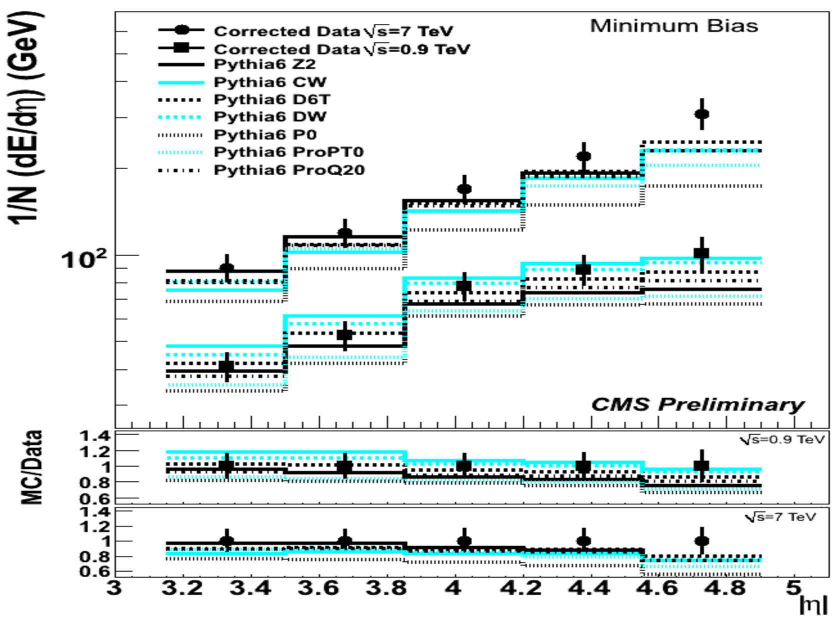
➜ Specific behavior for p_t qualitatively described by EPOS only

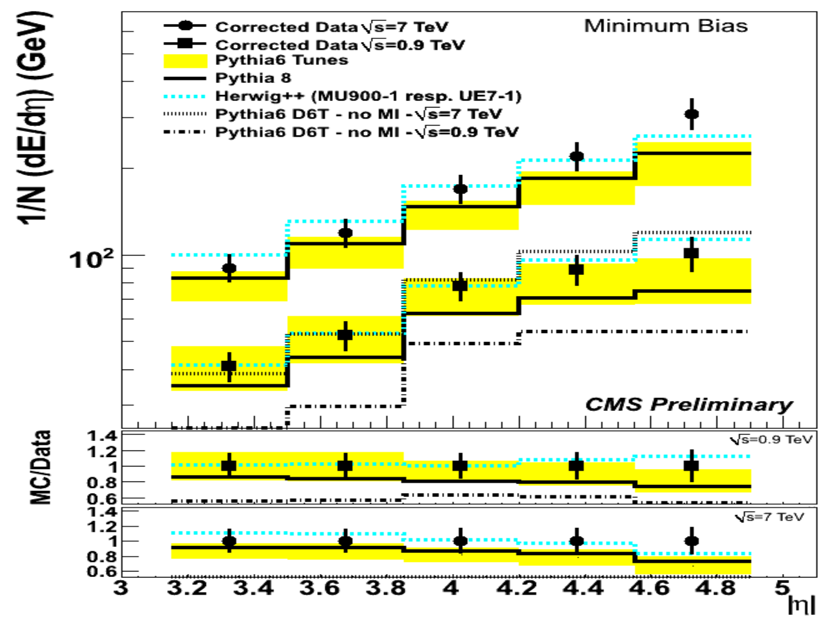
- flow due to collective effect (mini-plasma)
- mass and centrality effect

CMS Forward Spectra



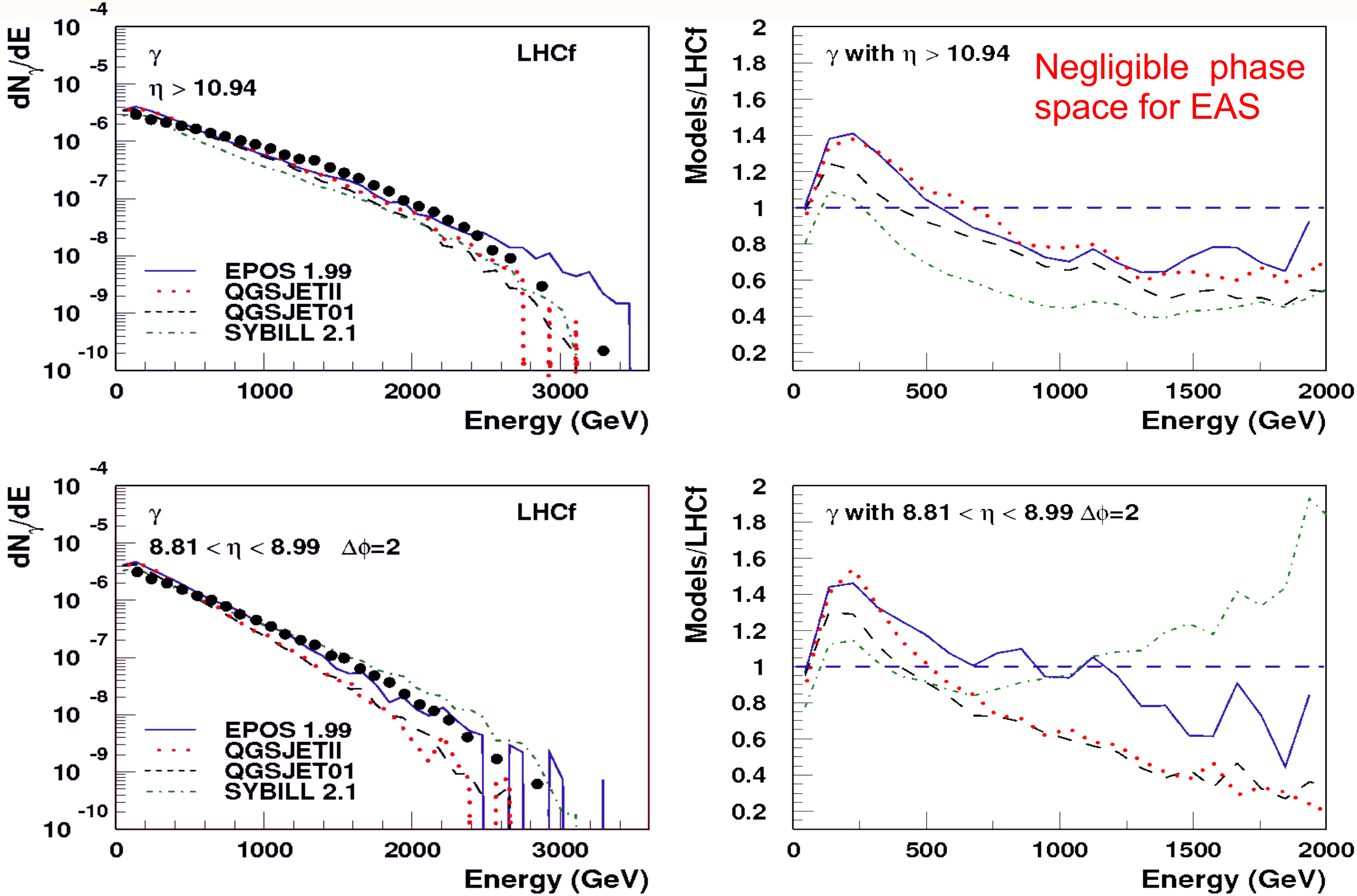






- CMS forward calorimeter → **better than HEP models**

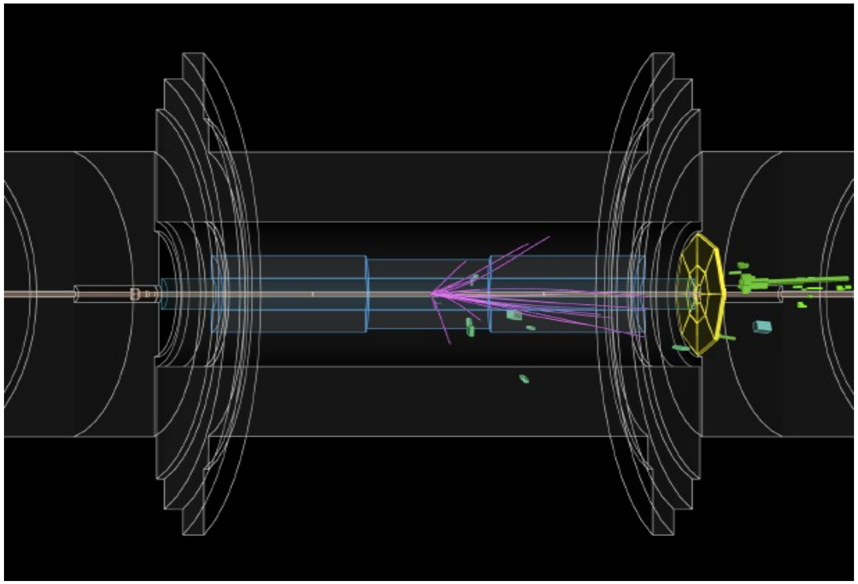
Forward Spectra



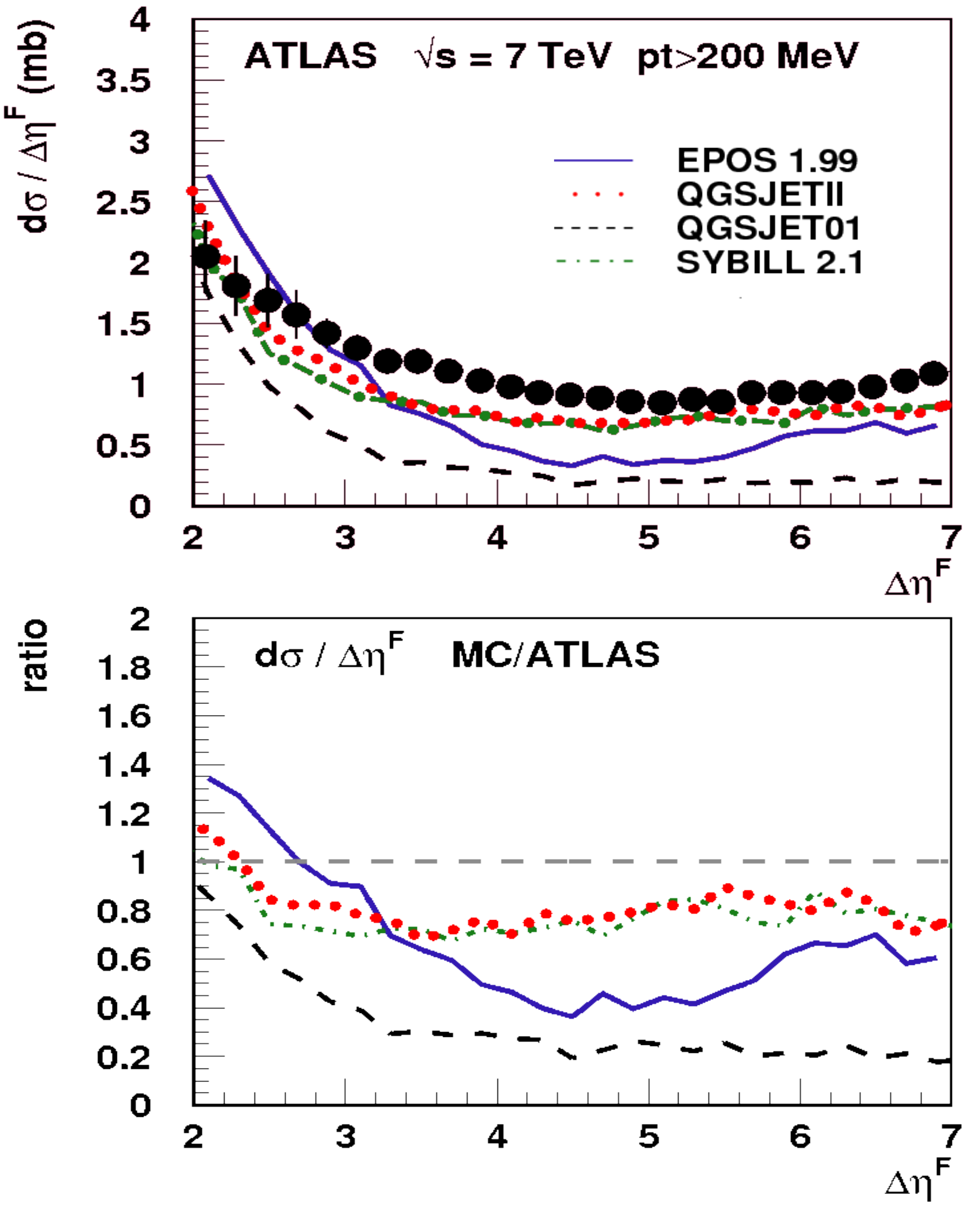
- **Fitting of LHCf data → effect on air shower development under investigation**

Rapidity Gap

ATLAS detector



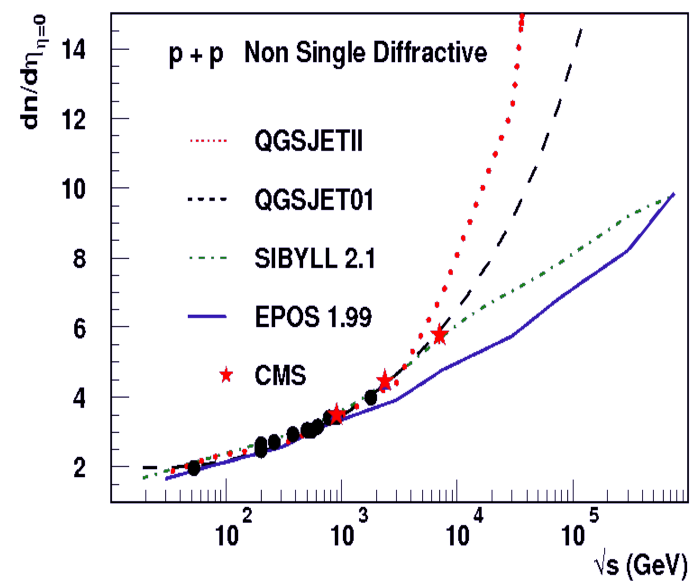
ATLAS Collaboration



- **Rapidity gap closely related to diffraction**
  - diffractive cross-section
  - AND diffractive mass distribution
- **Hard constraint for CR**
  - change elasticity

Comparison to LHC data

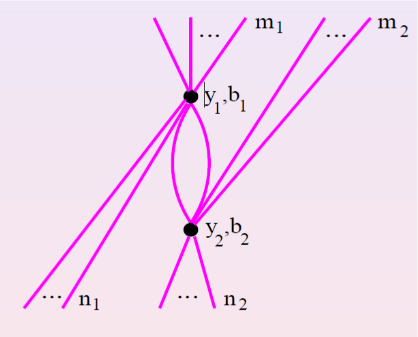
- **Globaly hadronic models for CR reproduce LHC data**
  - ➔ Data bracketed by models : even imprecise the extrapolations are not wrong
    - exclude explanations of the knee in the CR spectrum due to a change in hadronic physics : change at the CR source
  - ➔ room for improvement with really nice and new data
    - cross section well measured at LHC
    - multiplicity distributions for various kinematic ranges
    - access to forward spectra and diffraction and energy 2 orders of magnitude higher than before



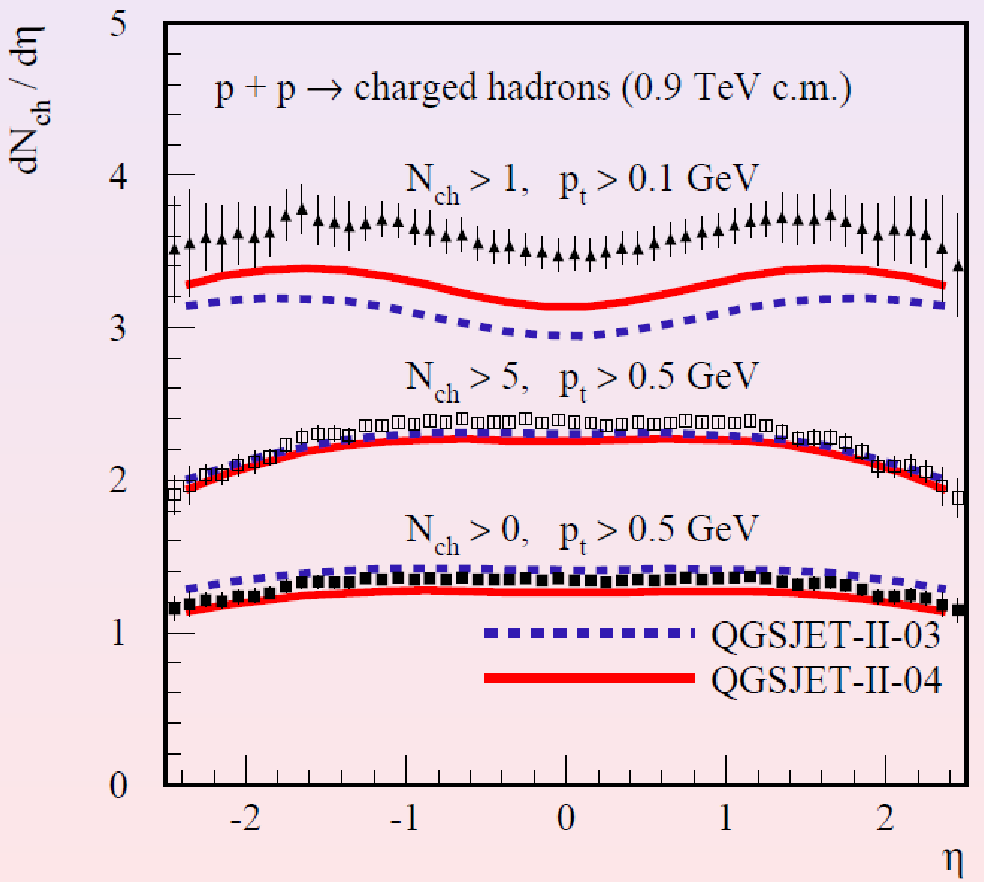
- **Can LHC data be fully described by CR models after retuning ?**
  - ➔ Try with latest model QGSJETII and EPOS

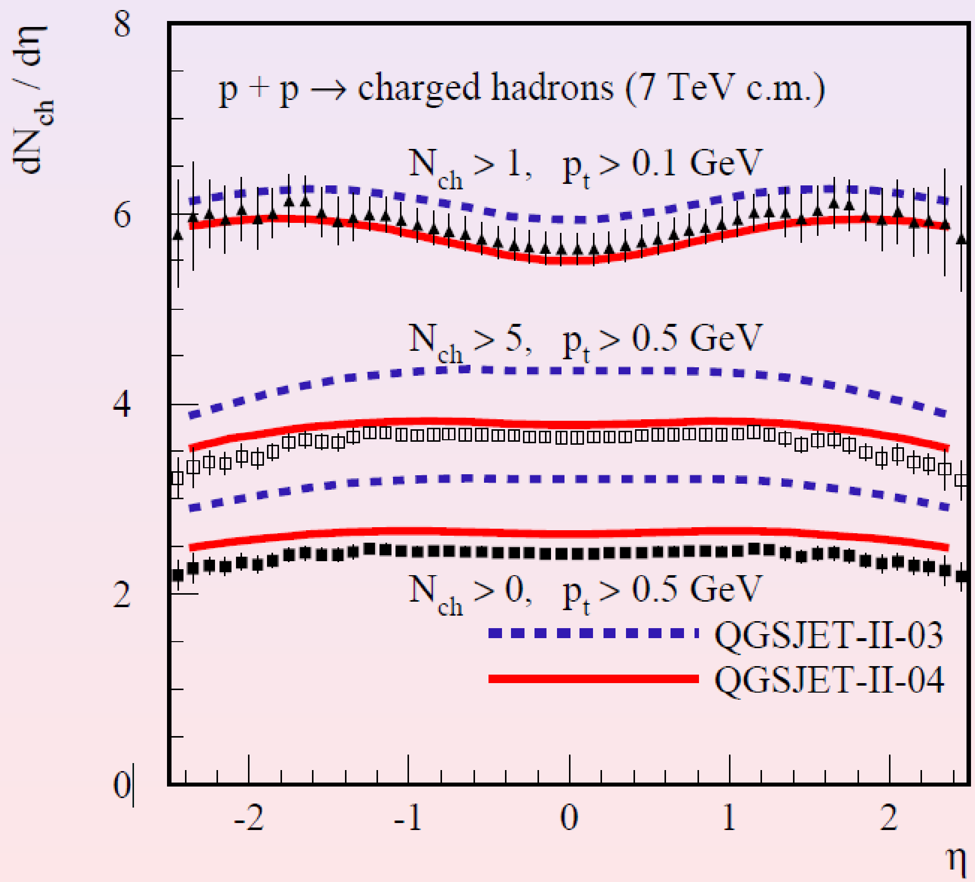
QGSJETII-04

- **After retuning some parameters and with loop diagrams, very good description of main LHC data for CR**



from S. Ostapchenko





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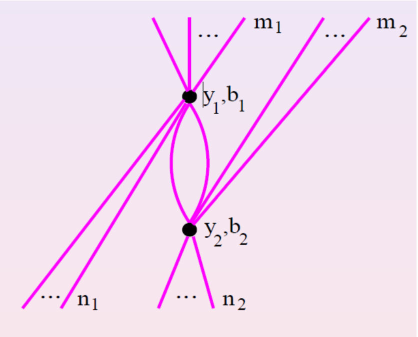
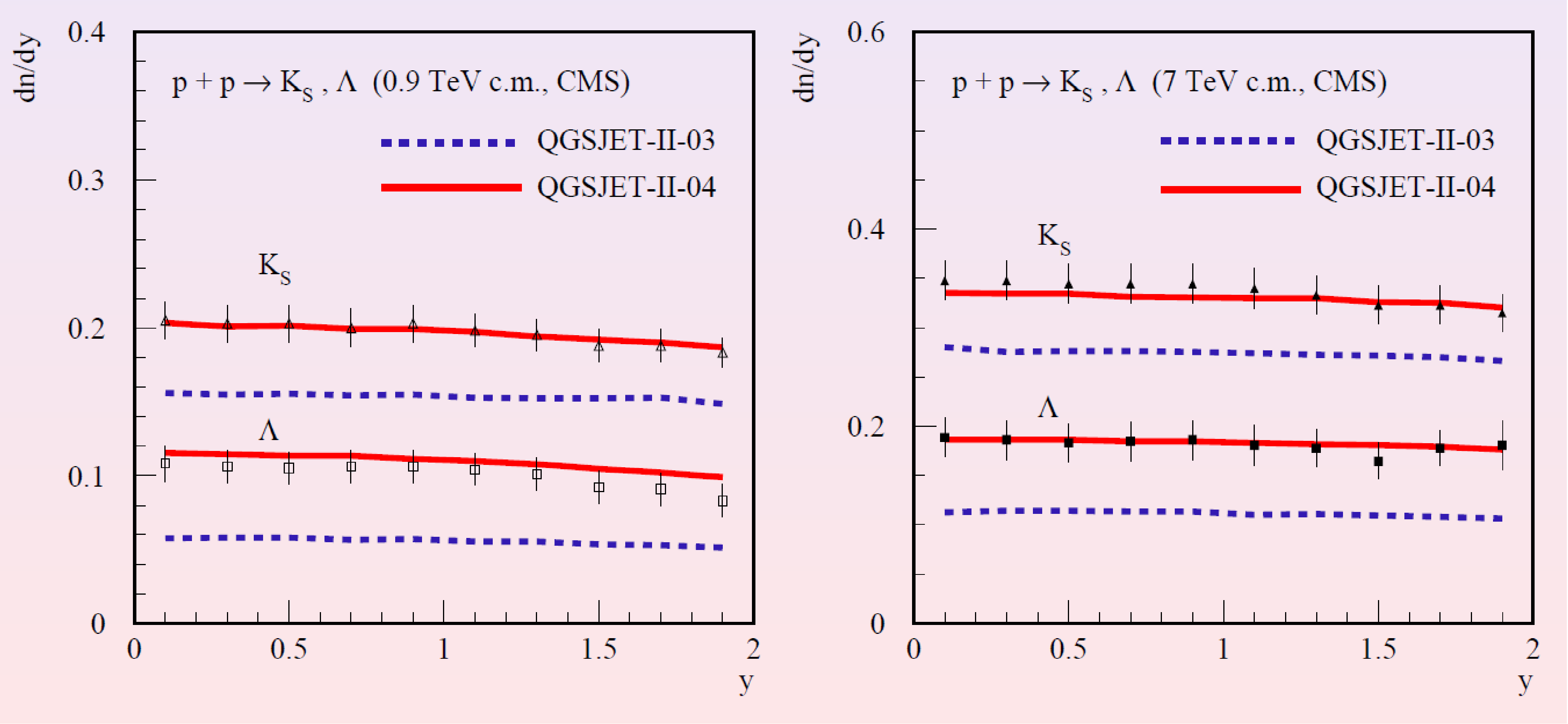
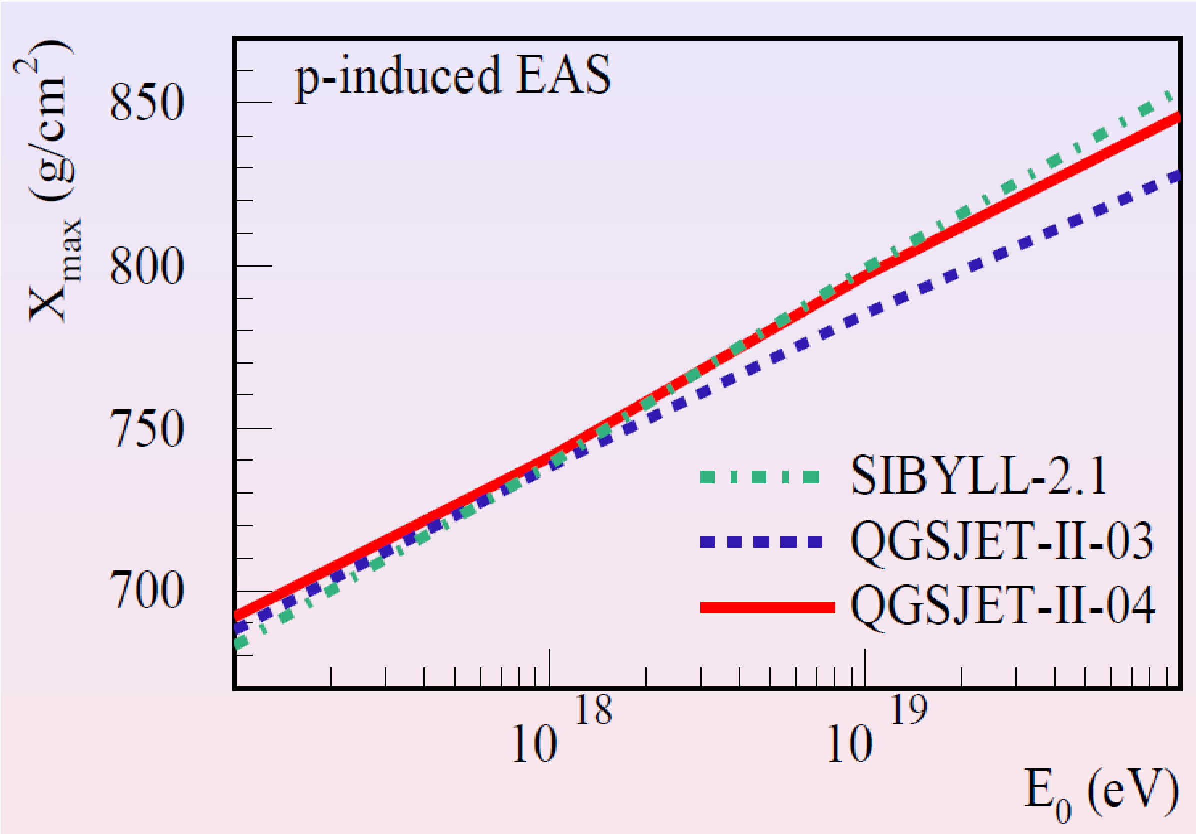


from S. Ostapchenko



QGSJETII-04

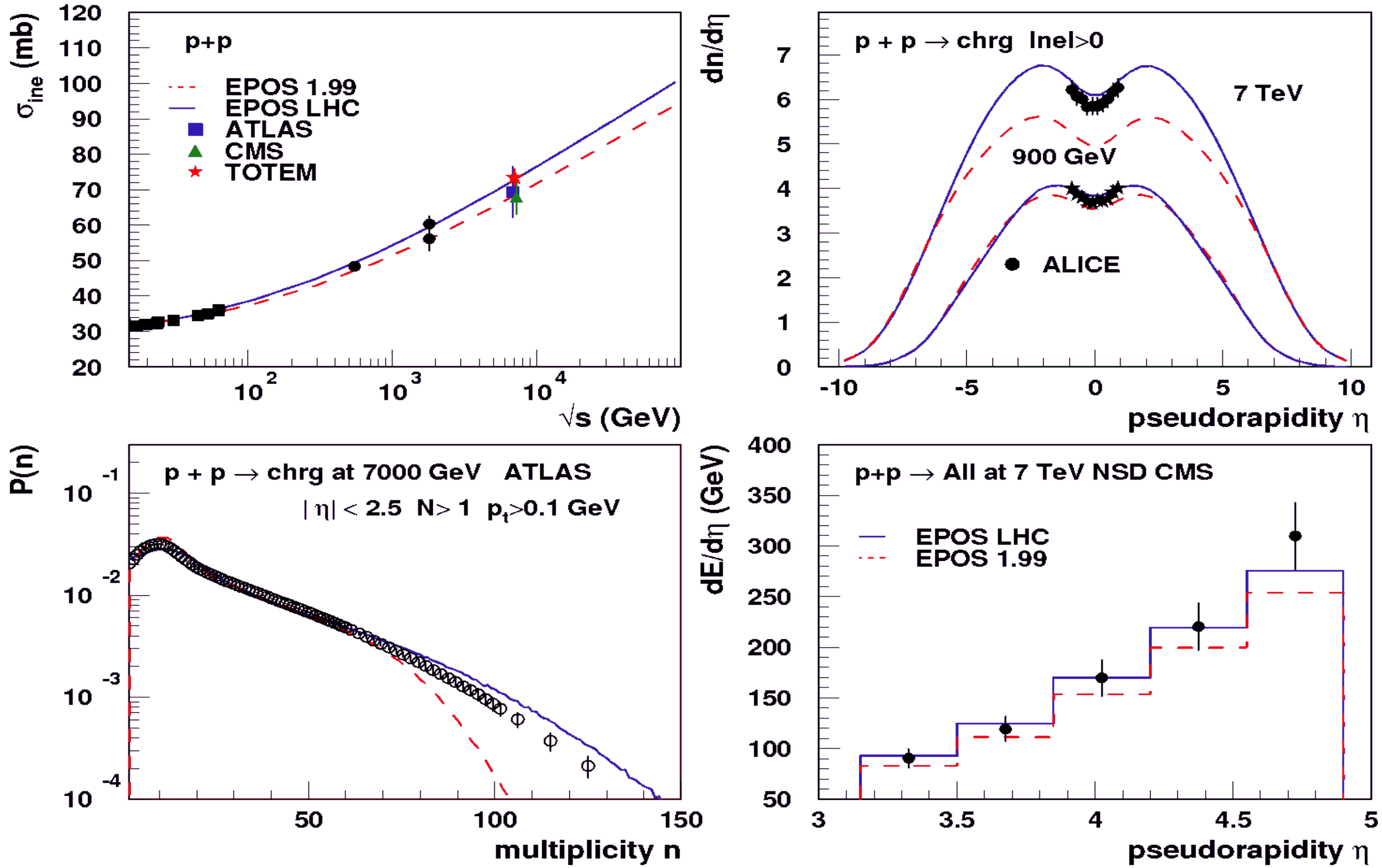
- **Consequences on EAS development**
  - deeper showers
  - slightly more muons (less than 10% increase)
- **Consequences for LHC**
  - difficult to use because of the limited type of particles
  - correlation p_t vs N_{ch} ?



from S. Ostapchenko

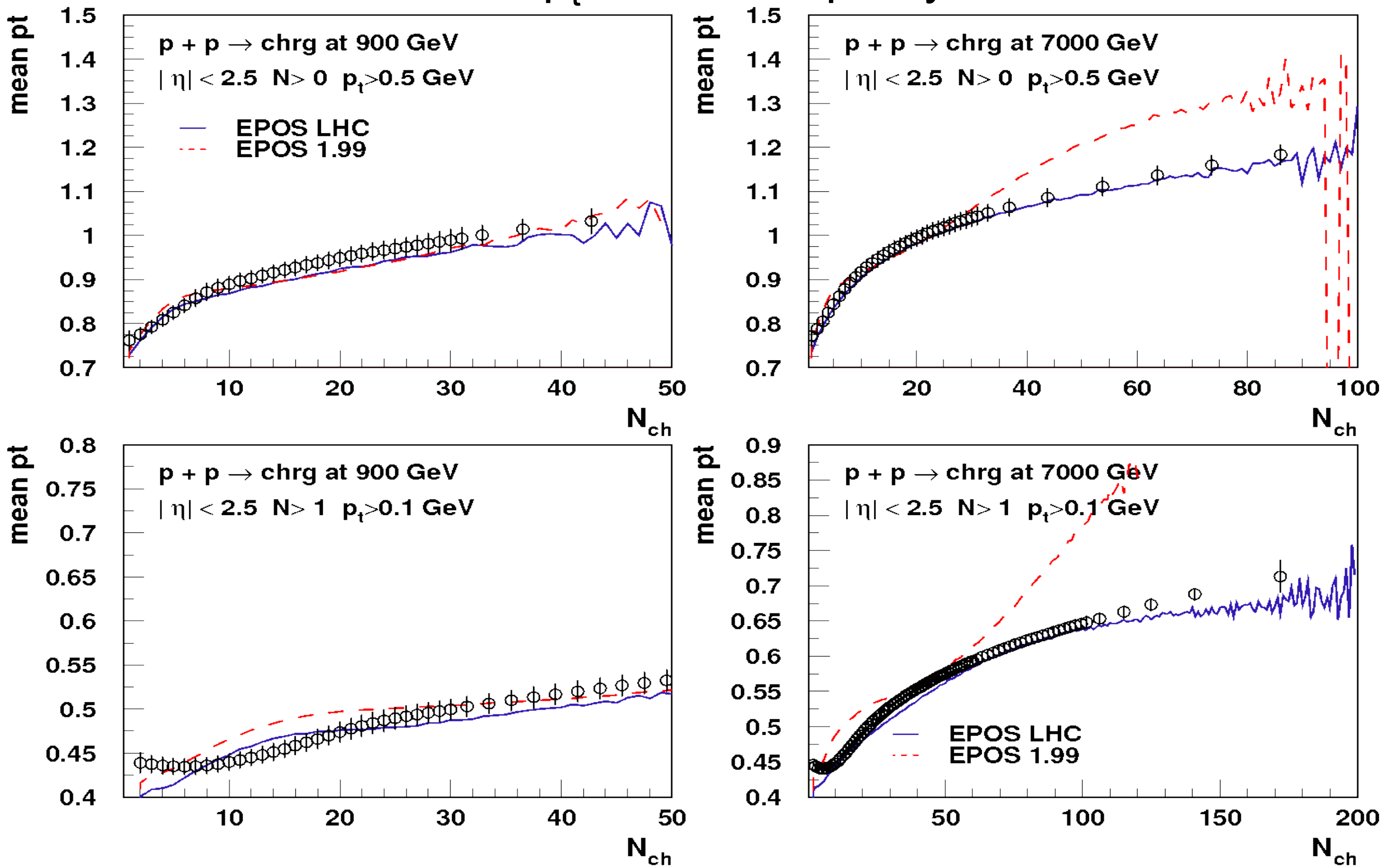
EPOS LHC

- **Small change needed**
  - tune cross section to TOTEM value
  - change old flow calculation to a more realistic one
  - keep compatibility with lower energies



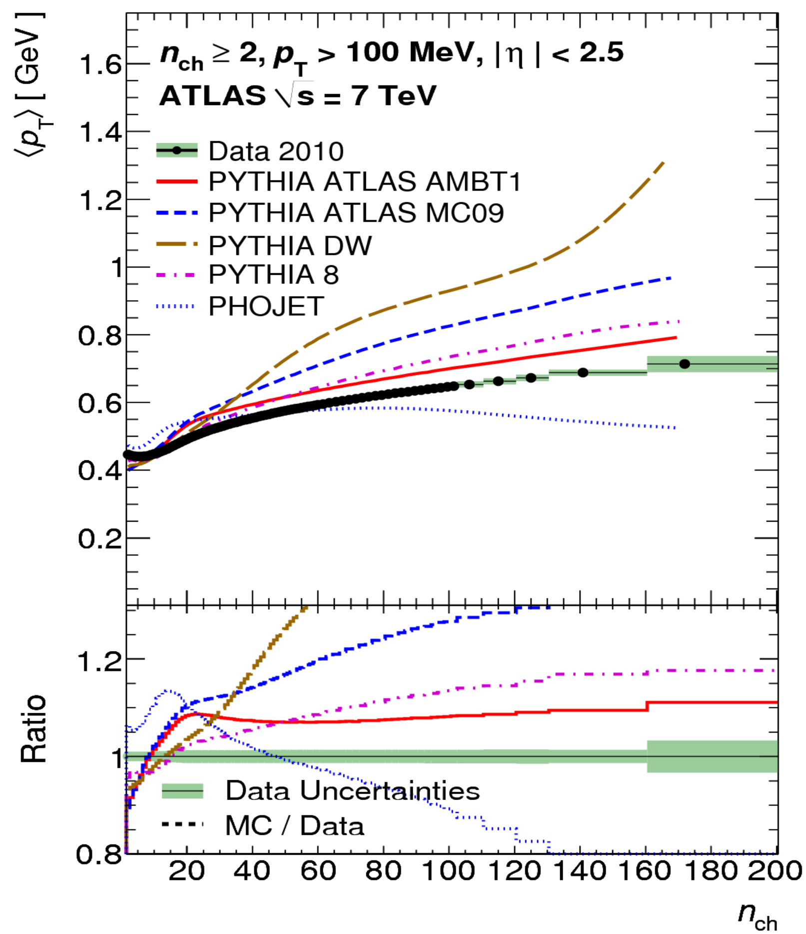
EPOS LHC

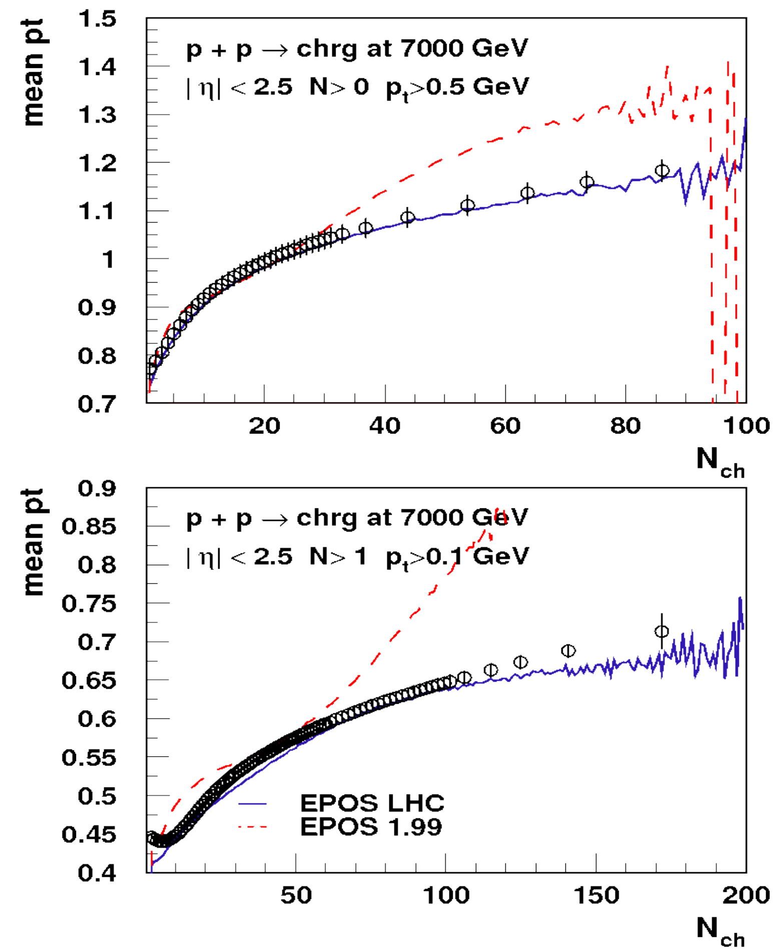
- **Detailed description can be achieved**
  - multiplicities (ATLAS and ALICE)
  - p_t distributions
  - evolution of $<p_t>$ with multiplicity



EPOS LHC

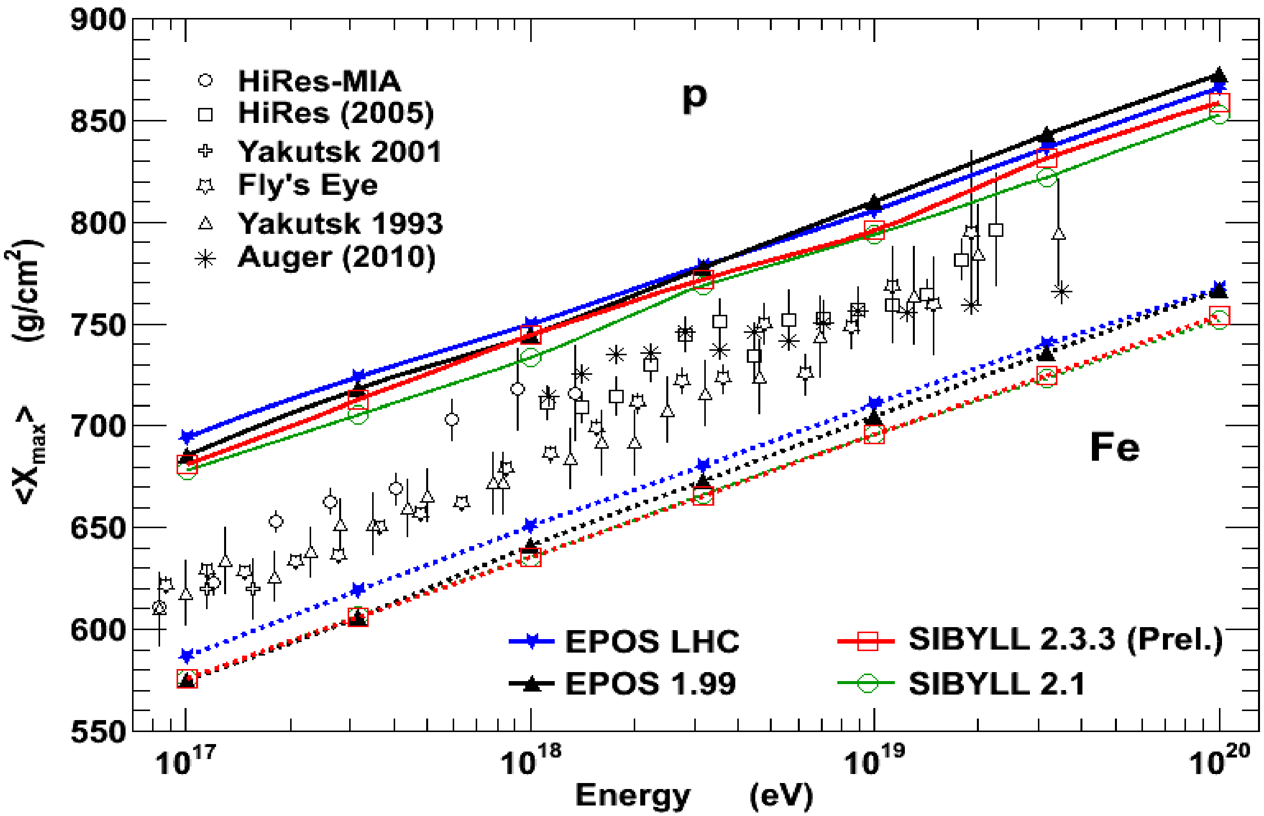
- **Detailed description can be achieved**
  - better than HEP MC used by LHC collaborations
  - can be used as min bias generator at LHC
    - not suitable for rare events (high p_t jets or electroweak)

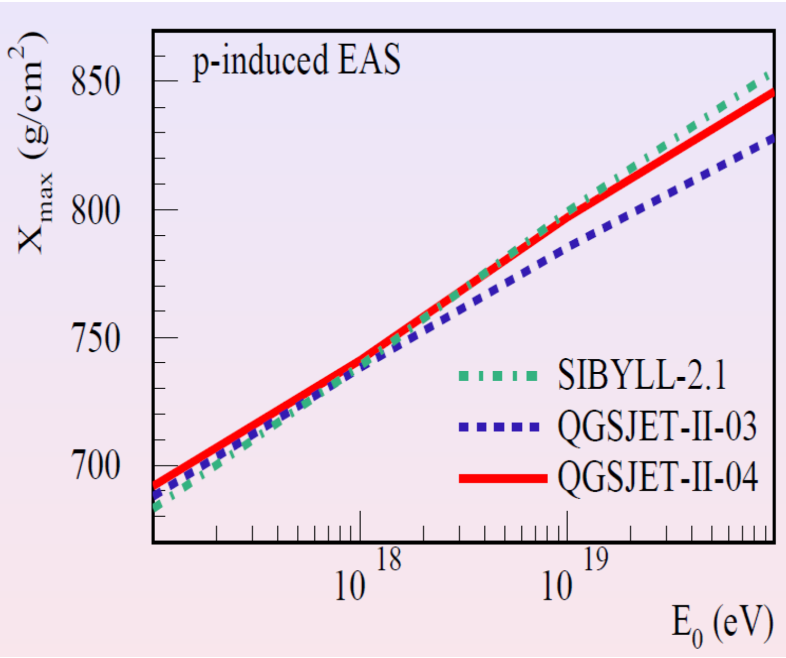




EAS with Re-tuned CR Models

- Cross section and multiplicity fixed at 7 TeV
  - smaller $<X_{max}>$ 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)

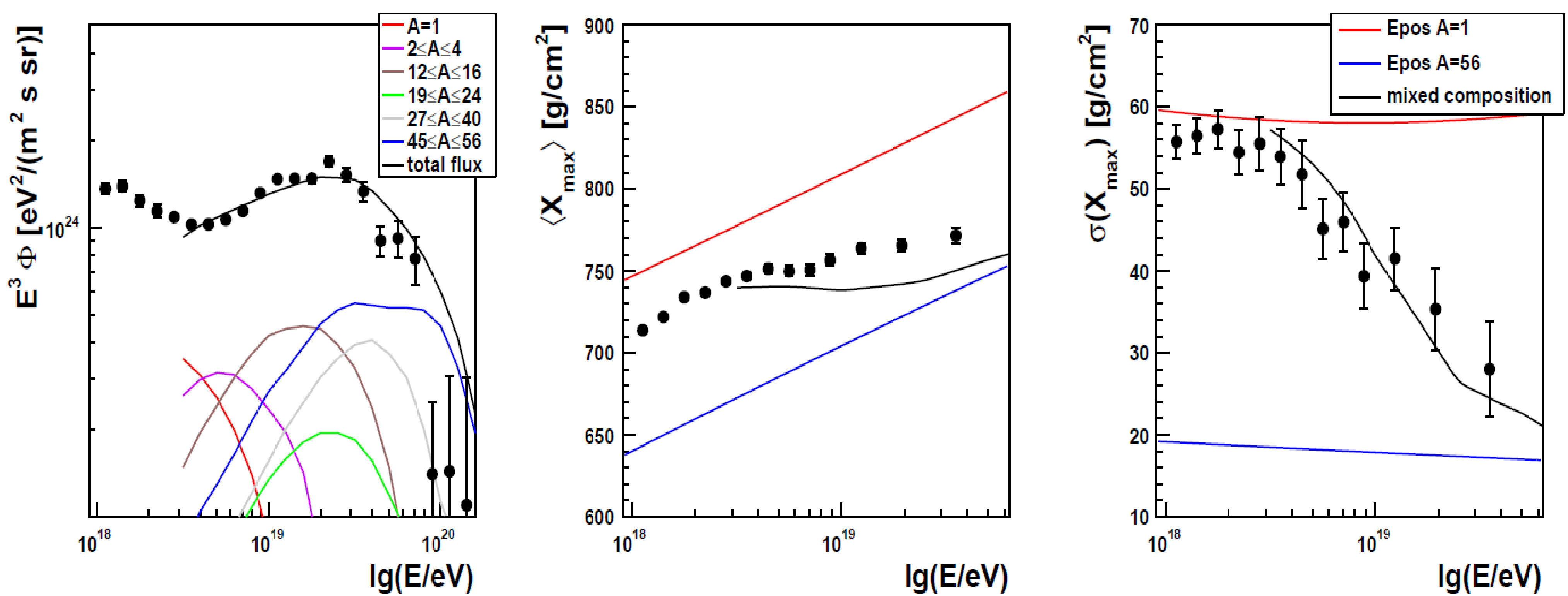




from S. Ostapchenko

Application to Astrophysics

- **Reduced uncertainty allows a better mass measurement**
  - global fit
  - constraint on source mass distribution and spectrum



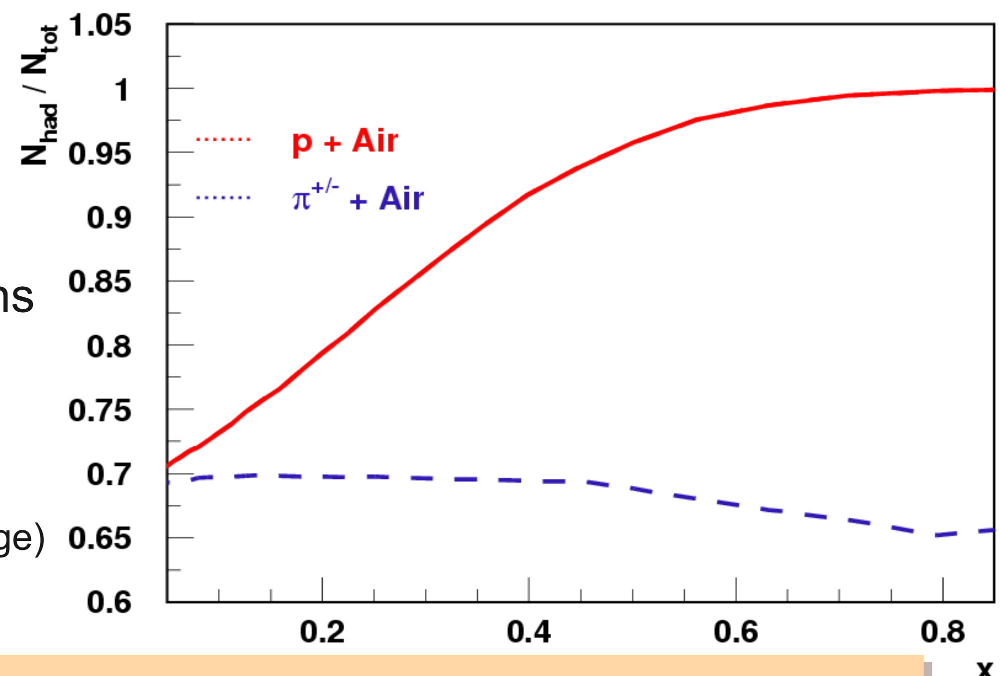
Allard et al. [arXiv:1111.3290] with EPOS 1.99

Mass Measurement : Muon Number

- **From Heitler**

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

- In real shower, not only pions : Kaons and (anti)Baryons (but 10 times less …)
- Baryons do not produce leading π^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)



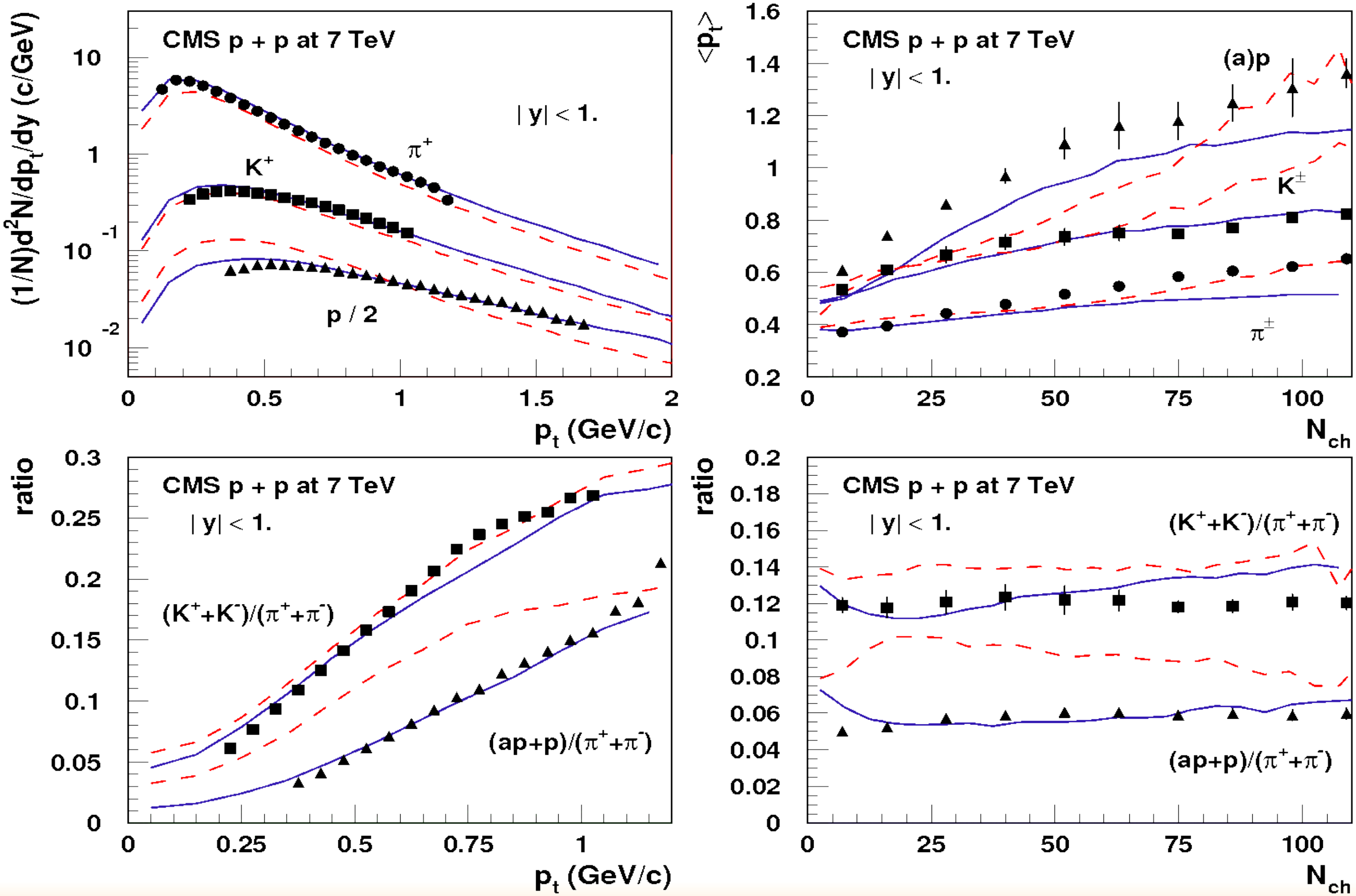
Muon number depends on the number of (anti)B in p- or π-Air interactions at all energies

More fast (anti)baryons = more muons

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

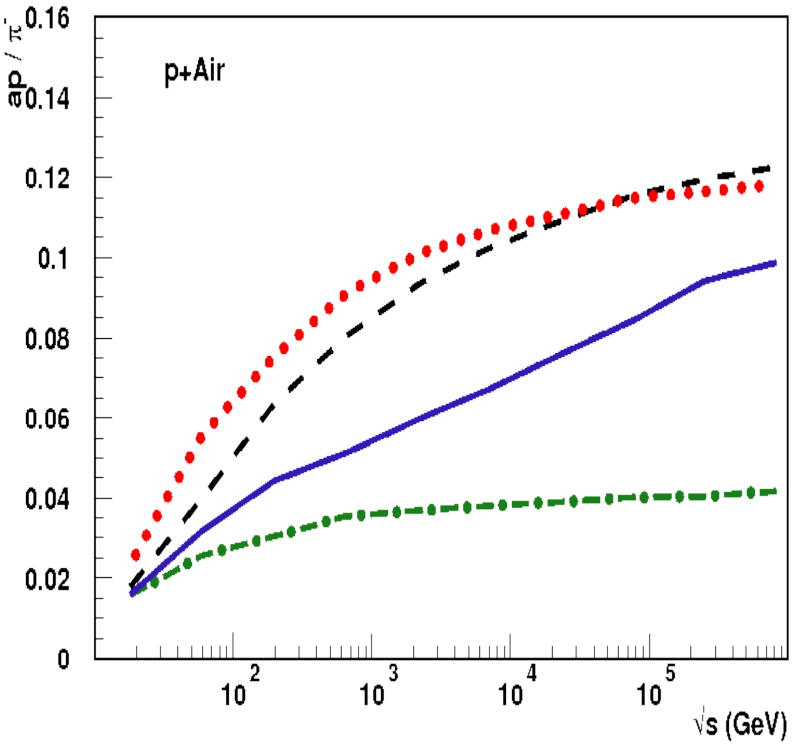
EPOS LHC

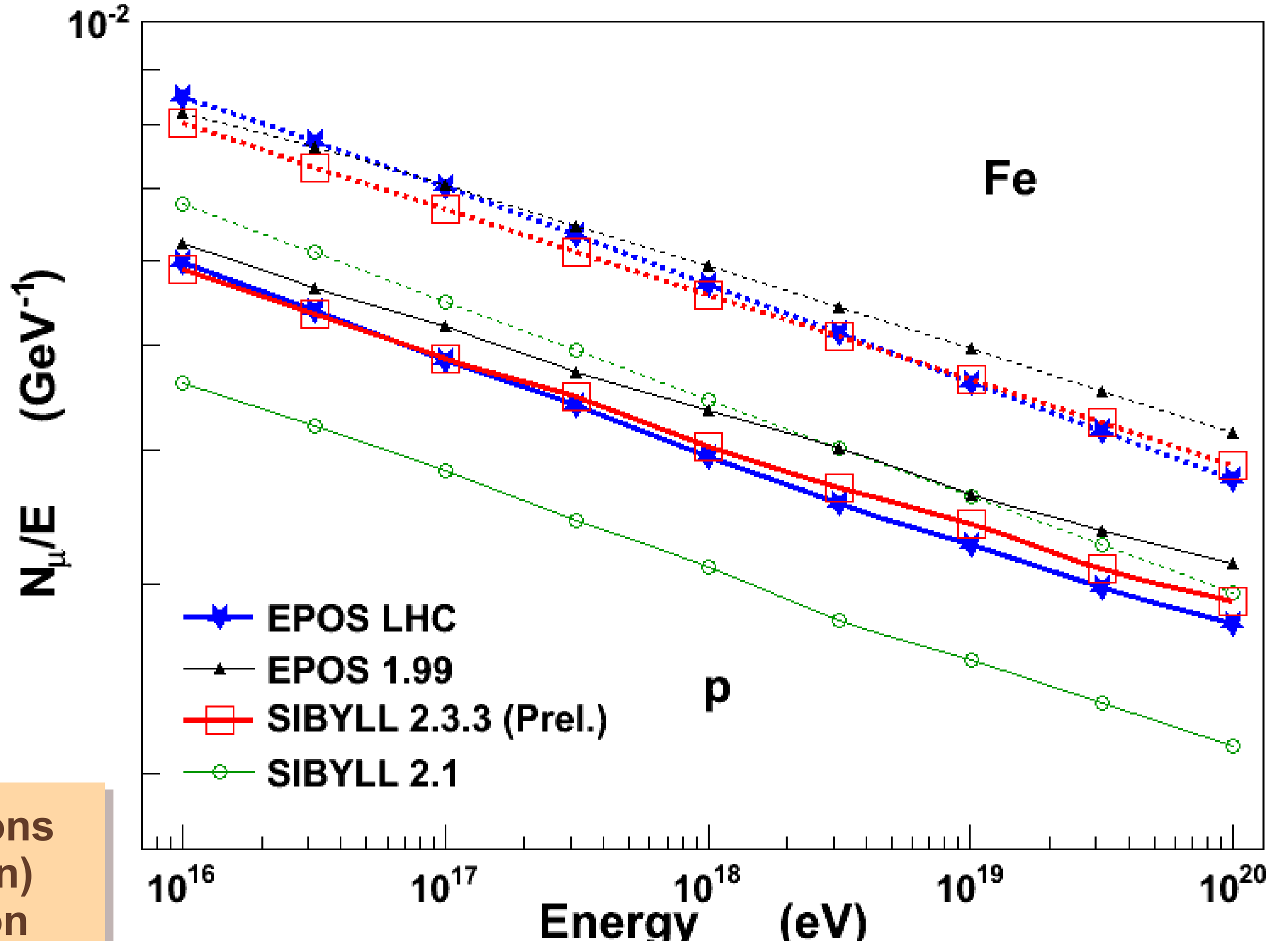
- **Detailed description can be achieved**
  - identified spectra
  - p_t behavior driven by collective effects (statistical hadronization + flow)



Number of Muons and LHC

Discrepancy (baryon and pion spectra) between models
=
Large differences in the number of muons
Reduced a lot by LHC data !





2 times less baryons = 35 % less muons (~difference between proton and iron) + muon energy spectrum depends on baryon energy spectrum !

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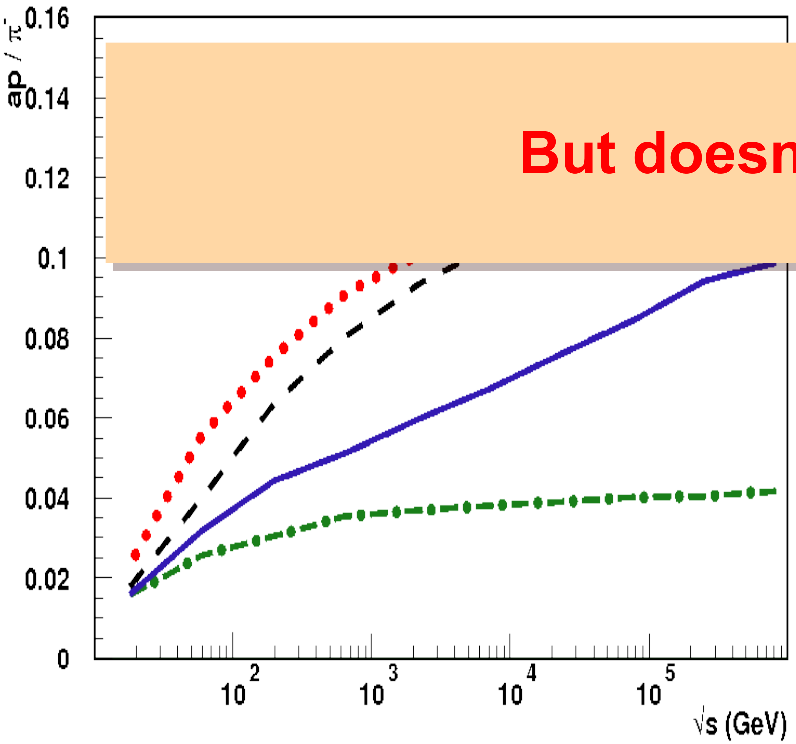

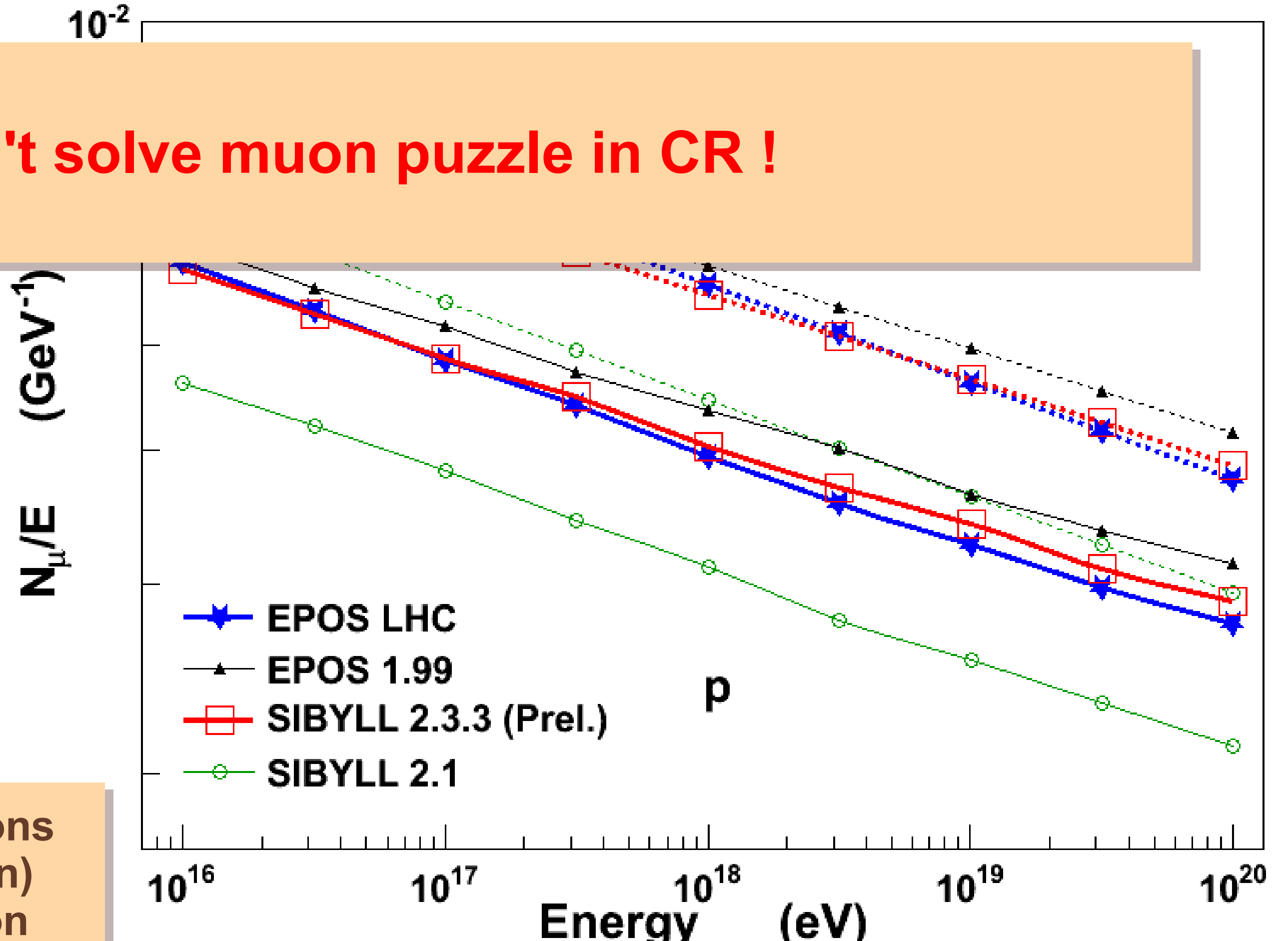

But doesn't solve muon puzzle in CR !

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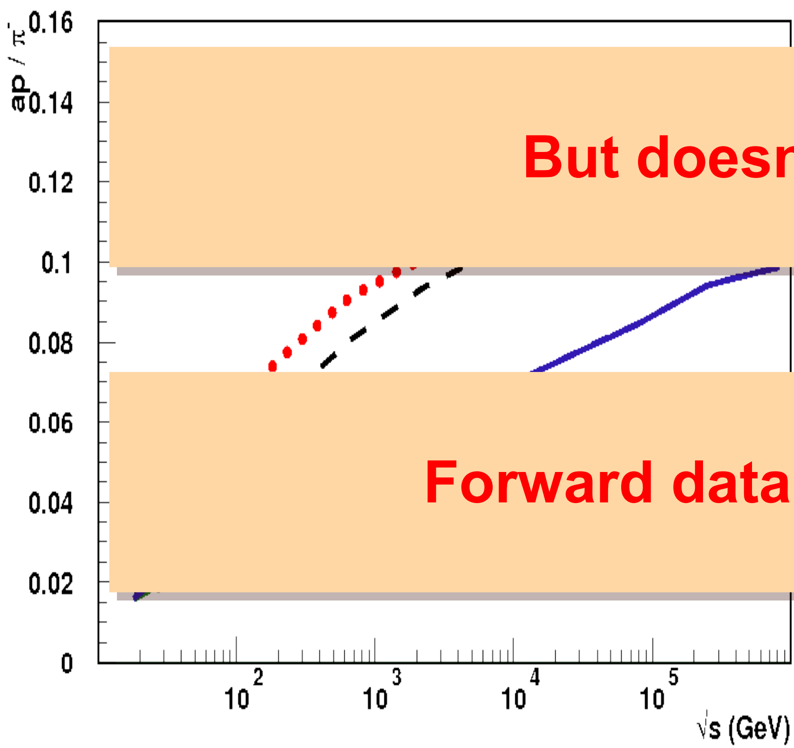
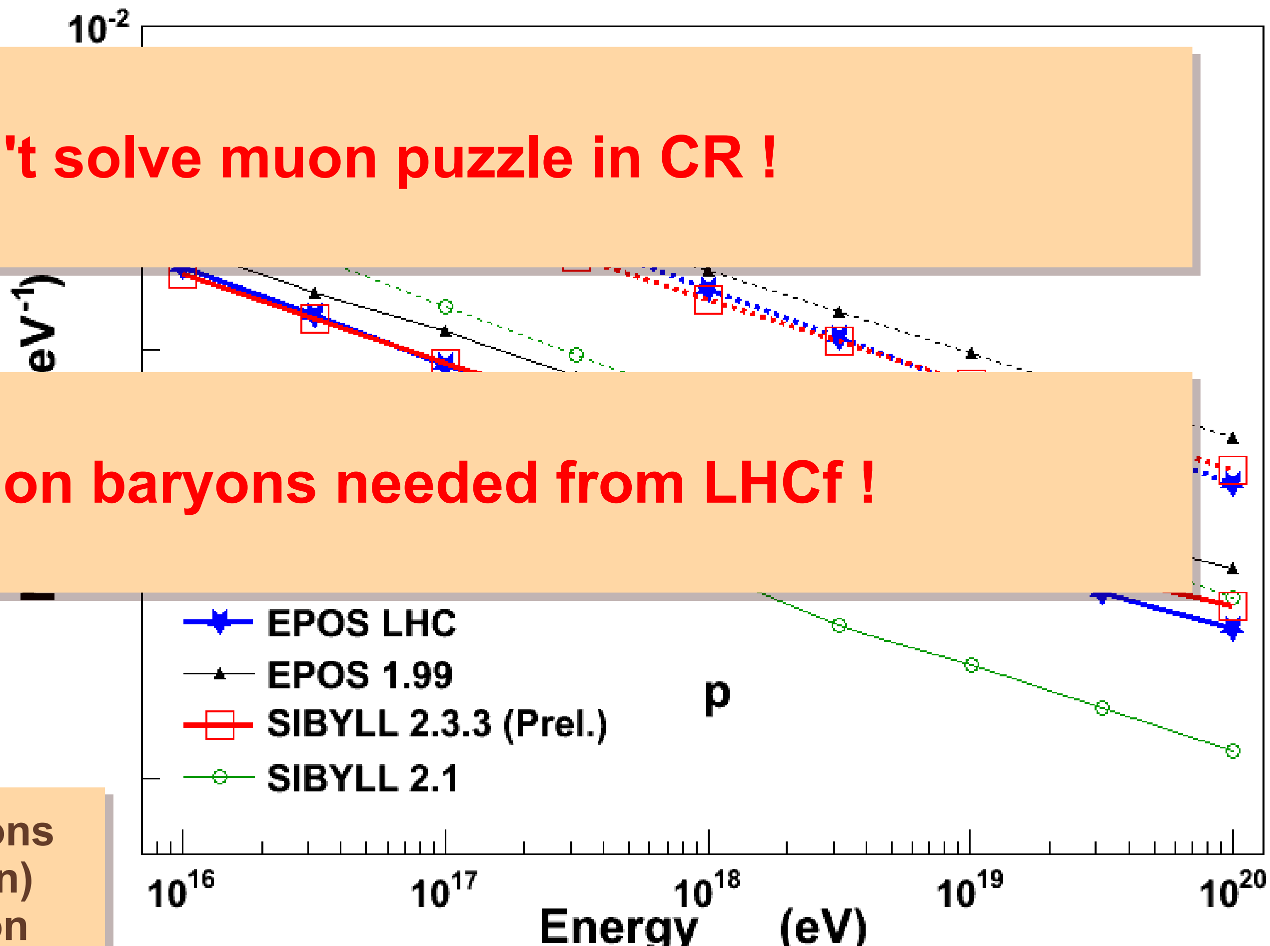




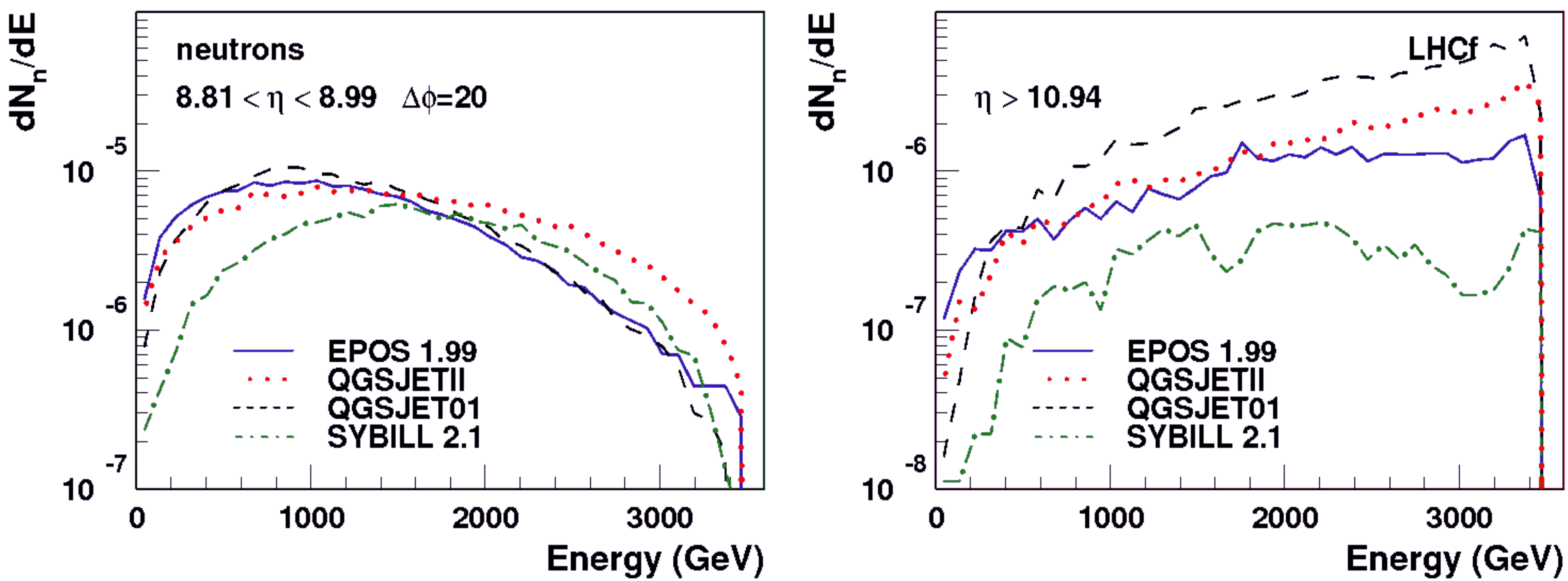
But doesn't solve muon puzzle in CR !

Forward data on baryons needed from LHCf !

2 times less baryons = 35 % less muons (~difference between proton and iron) + muon energy spectrum depends on baryon energy spectrum !

LHCf for neutrons

- **Very forward measurement at LHCf**
  - very different predictions from models
  - important for inelasticity and shower development
  - one possible origin of the muon puzzle



Summary

- **Hadronic interaction models for CR reproduce LHC data in a reasonable way**
  - No change of hadronic physics around the knee (10^{15} eV)
  - Large uncertainties in $<X_{max}>$ simulations due to hadronic models reduced by precise fit of LHC data to the value of the exp. resolution
  - Muon puzzle needs forward baryon and p_t measurements :
    - NA61 will help here.
    - LHC energies important for high energy muons :
      - need more baryon measurements (forward)
    - Depending on the result, other mechanism may be needed … or not !
- **Hadronic interaction models for CR can be re-tuned to LHC data without too many changes**
  - Better predictive power than HEP MC models
  - EPOS LHC precise enough to be used for min. bias analysis
  - All CR models available with hepMC interface !
    - CRMC interface already in GENSER

History of Models

(HDPM)

Old generation :

	Ostapchenko et al.	Engel et al.	Ranft et al.	Werner et al.	
	QGSJET01	SIBYLL	DPMJET 2	VENUS	~2000

All Glauber based

But differences in hard, remnants, diffraction …

semi-hard

soft

NEXUS

Ostapchenko, Werner, et al.

Attempt to get everything describe in a consistent way (energy sharing)

New generation :

	QGSJET II	(DPMJET III)	**EPOS**	~2005-now
	Ostapchenko et al.	Ranft et al.	Werner and Pierog	

Theory ++ :

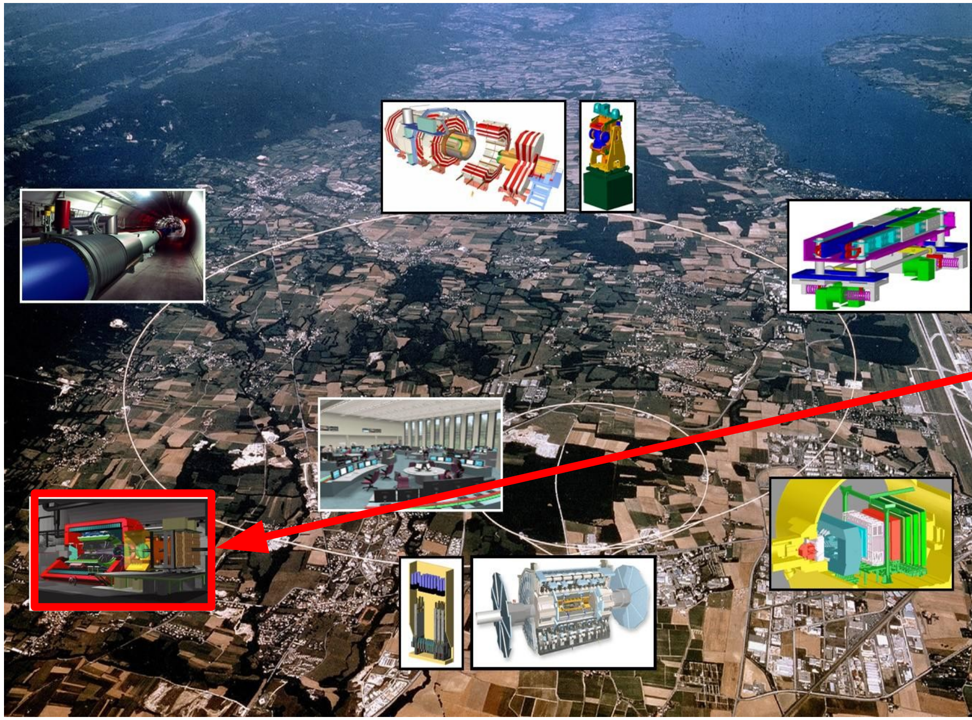
- **Fan diagrams**
- **diffraction**
- **optimized for CR**

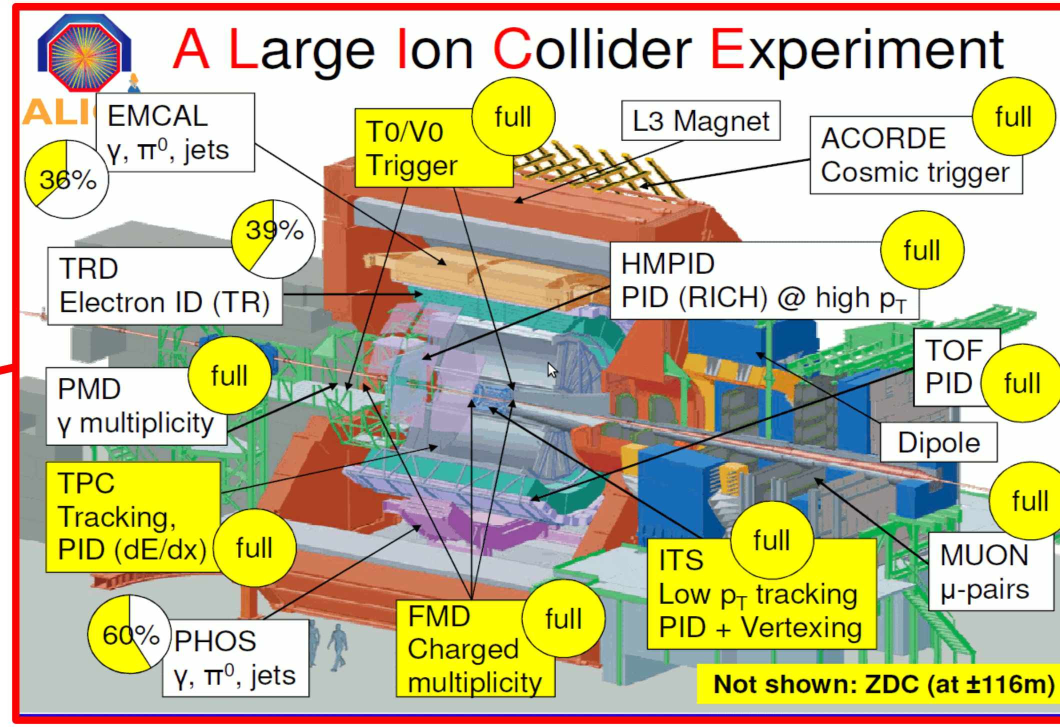
Phenomenology ++ :

- **Nuclear effect**
- **High density effect (QGP)**
- **all type of data studied**

Only model used in HEP/HI (SPS, RHIC, LHC)

LHC data : ALICE

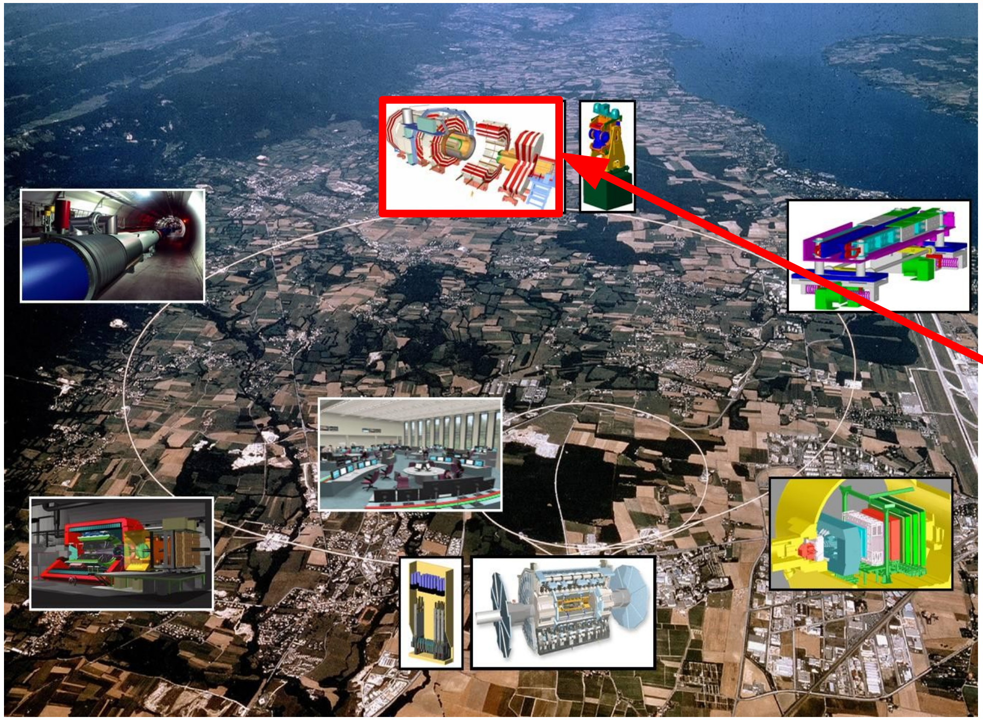


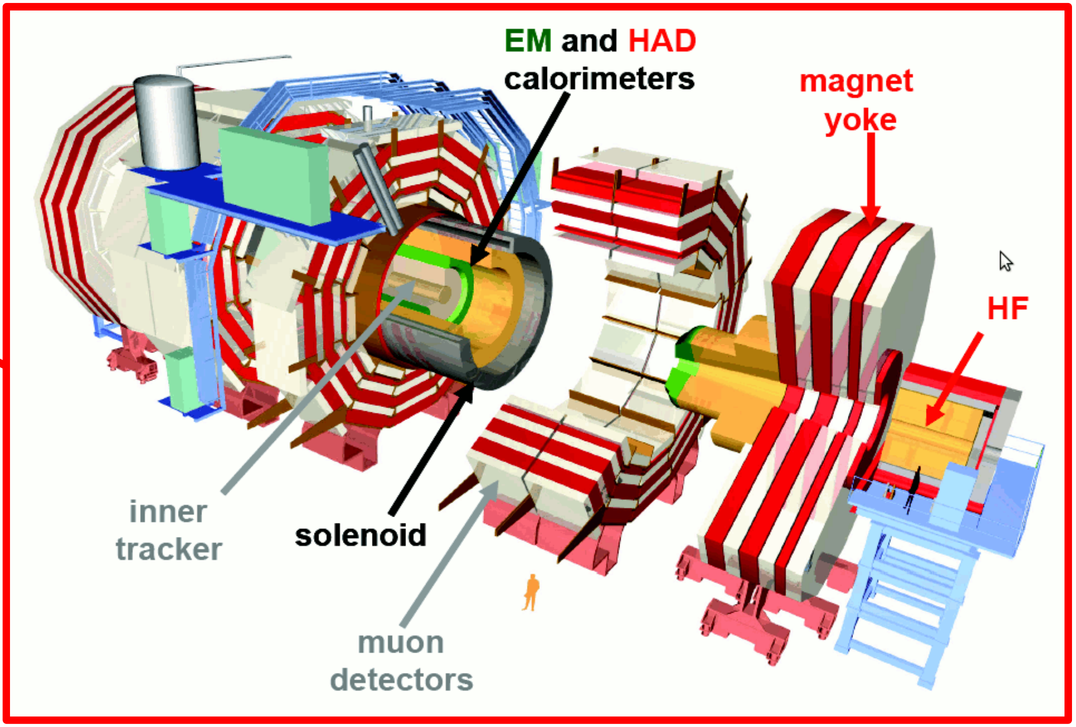


- **Published data (0.9, 2.36 and 7 TeV) :**
  - Charged particles = charged hadrons and charged leptons (~1.5%)
  - Various triggers (Inelastic, NSD@900GeV, NSD@2.36TeV, Inel>0)
- ➔ Particle density of charged particles at η=0 vs energy
- ➔ Pseudorapidity (η) distributions of charged particles
- ➔ Multiplicity distributions of identified charged particles

NSD = Non Single Diffractive = proj & targ destroyed

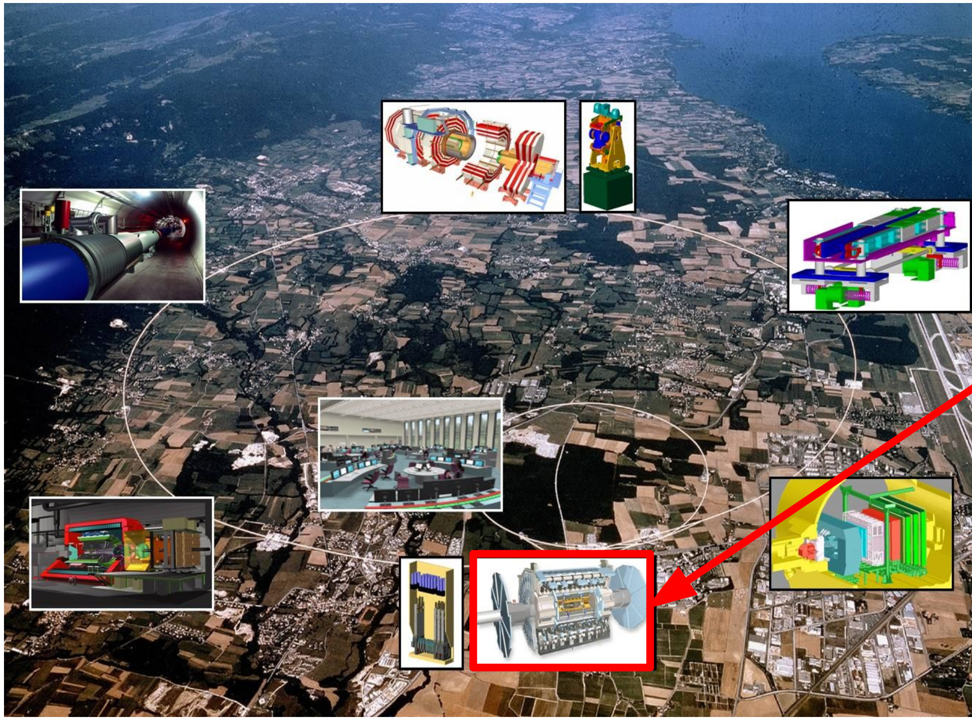
LHC data : CMS

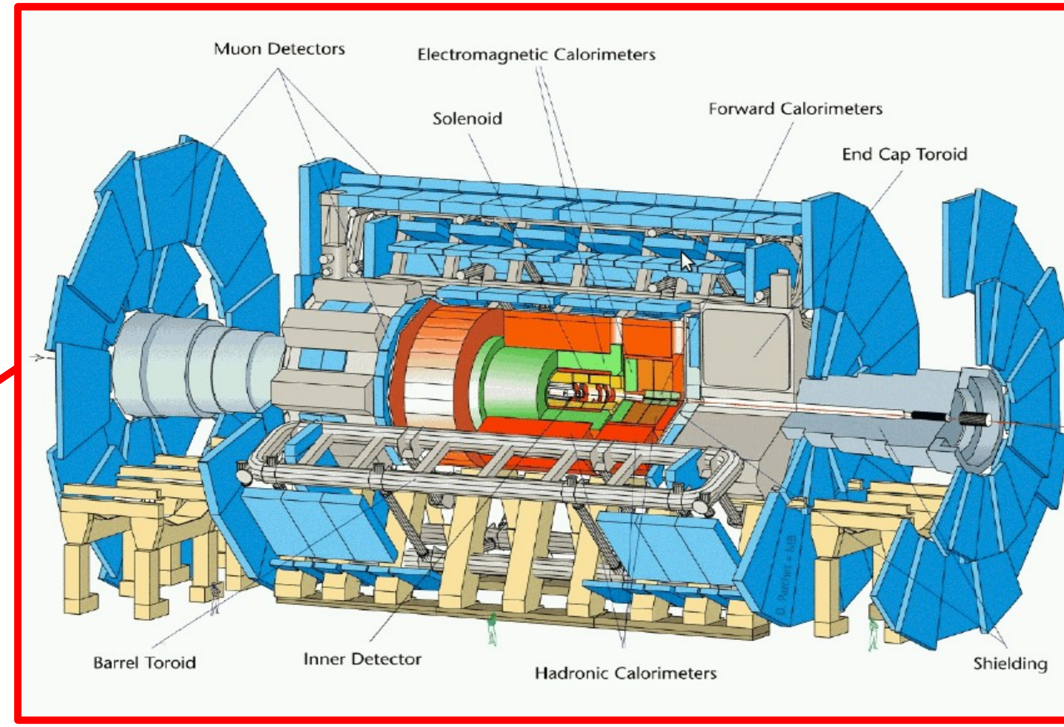




- **Published data (7 TeV 2011) :**
  - Pseudorapidity (η) distributions of charged particles
  - Transverse momentum distributions of charged particles
  - Forward calorimetric measurements
  - Inelastic cross section

LHC data : ATLAS





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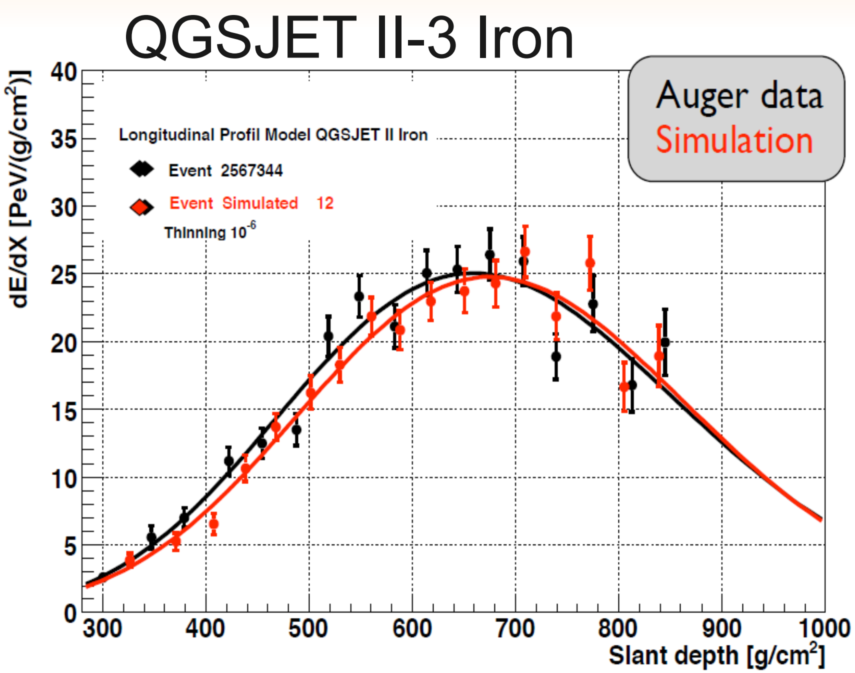
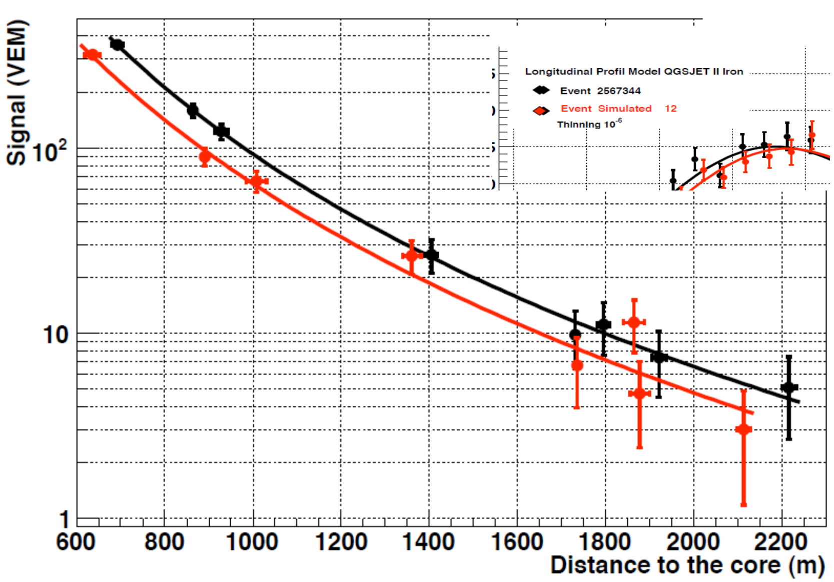
  - Transverse momentum distributions of charged particles
  - inelastic cross section

FD and SD mismatch





- **AUGER**
  - Comparison event-by-event
    - Fix simulated FD profile with data
    - Compare measured SD signal with simulated one

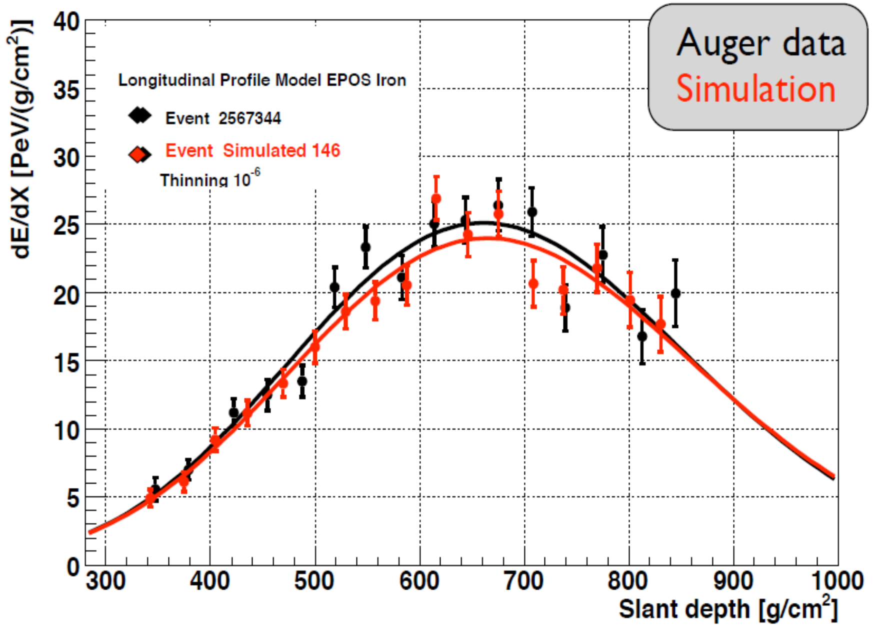
SD systematically lower in simulation : ~25 % shift in energy scale + ~50 % deficit in muon number (for QGSJETII-03)

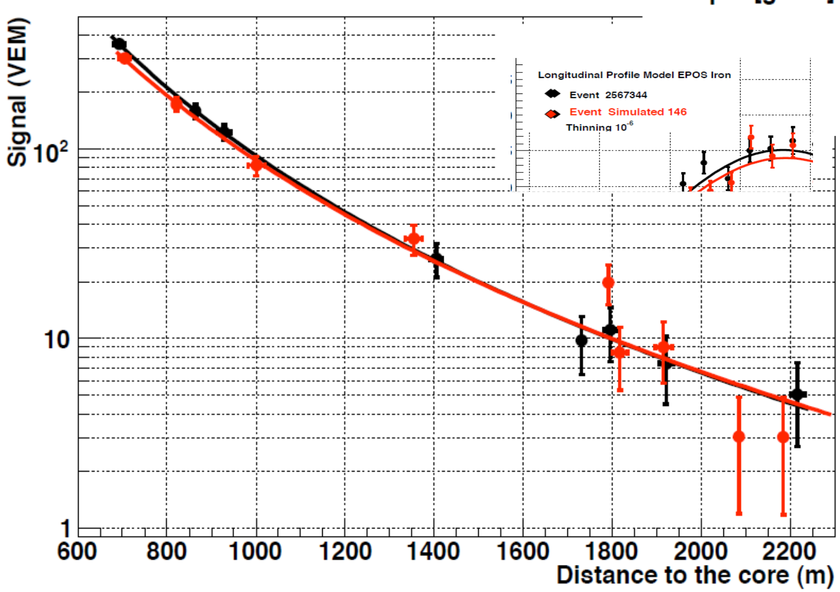
- **TA**
  - Spectrum reconstruction
    - Spectrum using QGSJETII-03 for energy reconstruction
    - Renormalize energy using event seen by FD and SD using FD energy as reference

27 % shift in energy scale needed

FD and SD mismatch

EPOS 1.6 Iron





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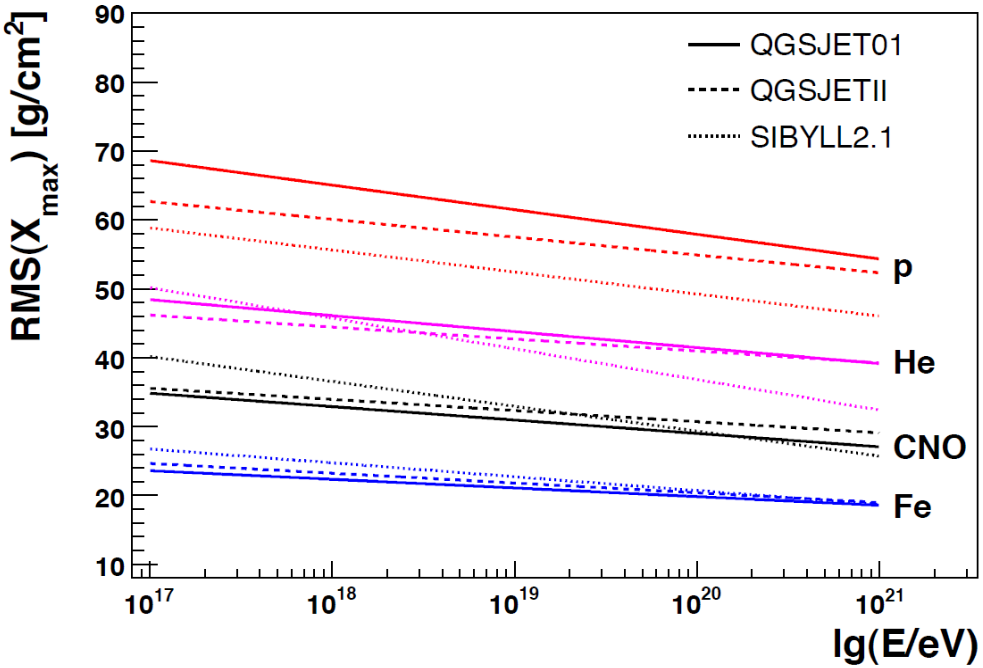
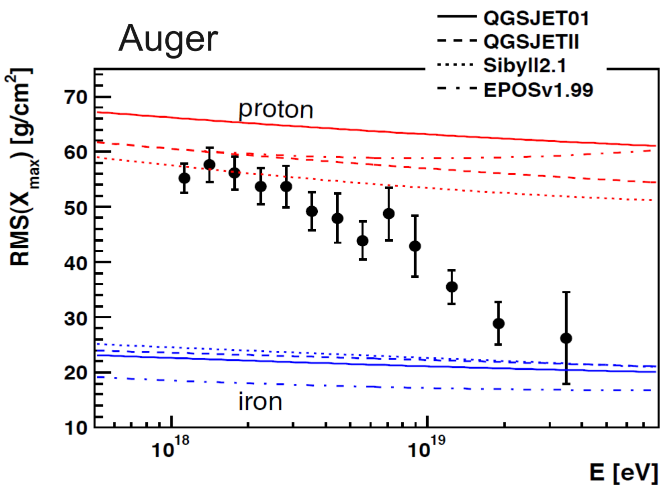
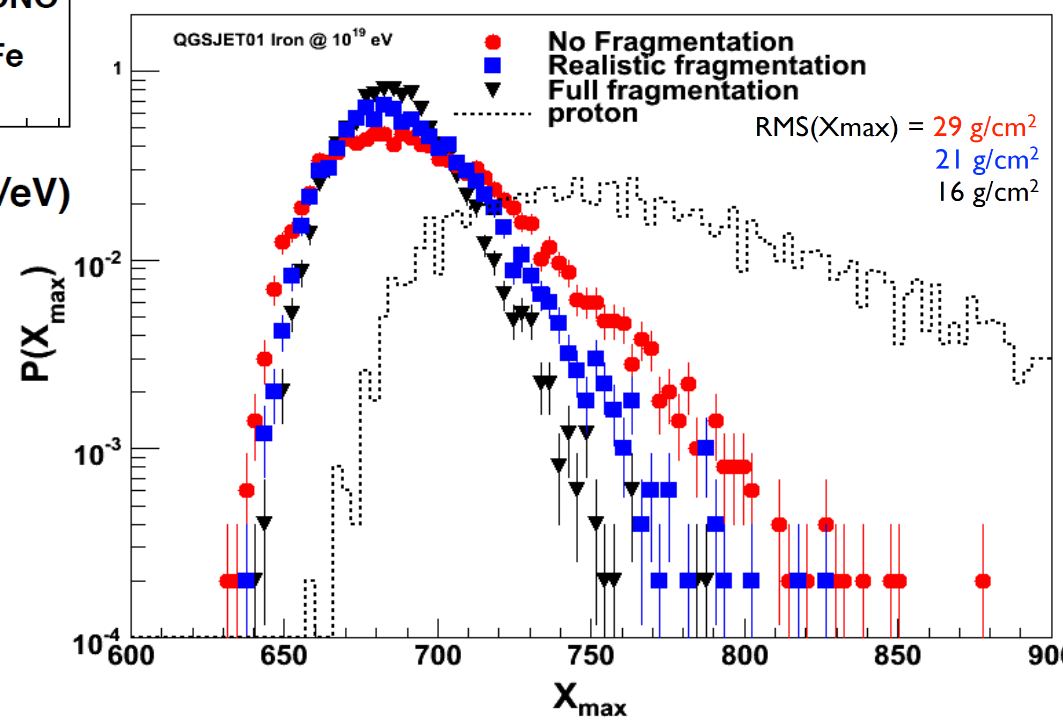
Xmax Fluctuations

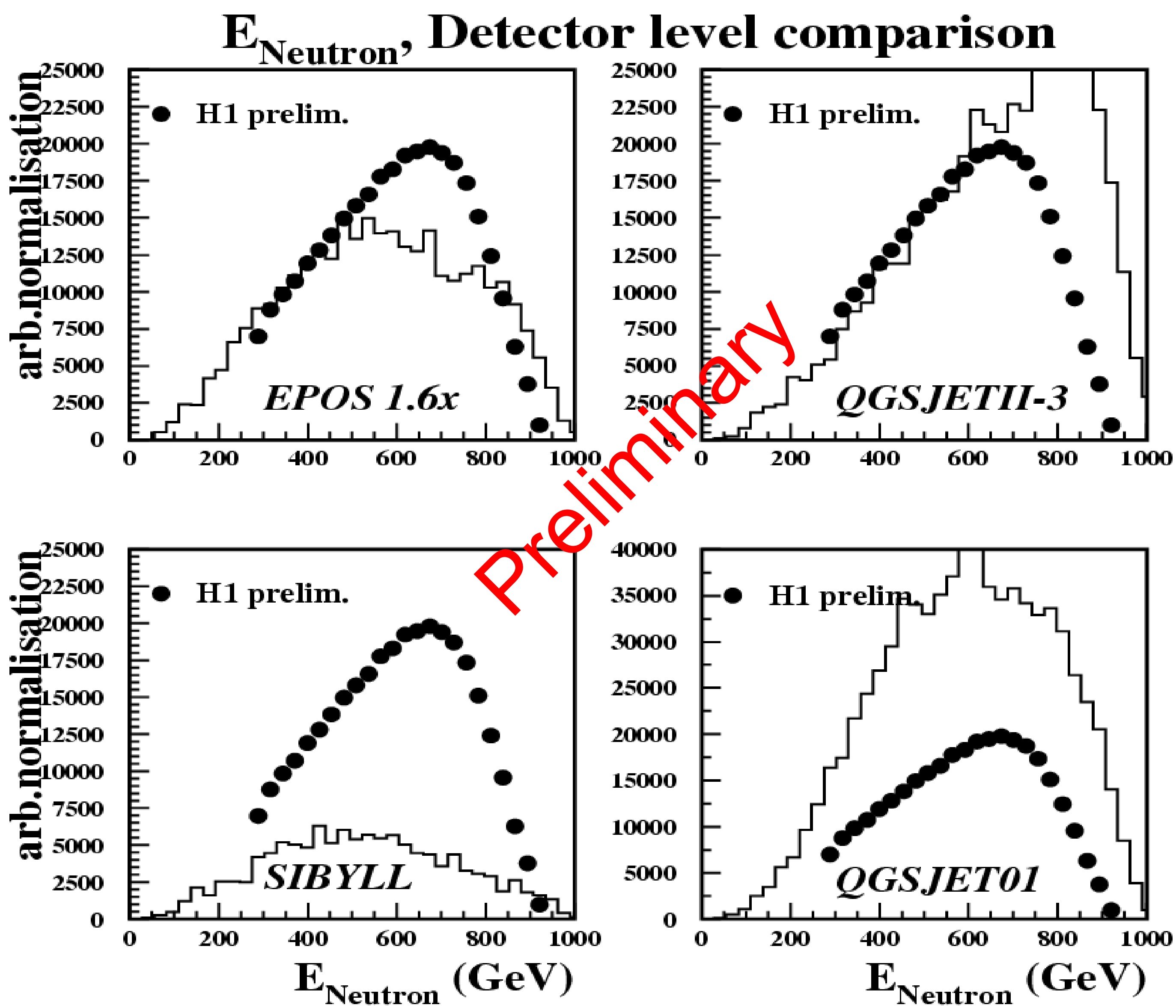




- **Much smaller differences between models**
  - RMS for heavy primary very stable
  - Reduced uncertainties for data analysis

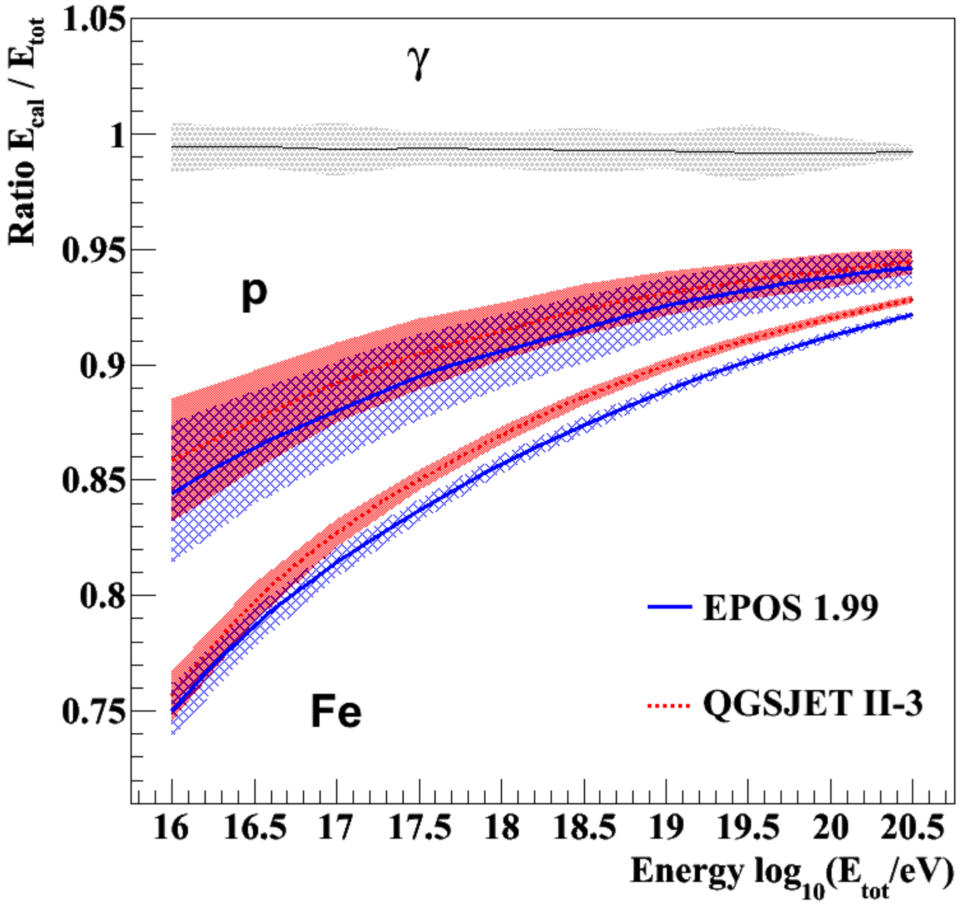


Forward Neutron Distributions



Analysis by A. Bunyatian

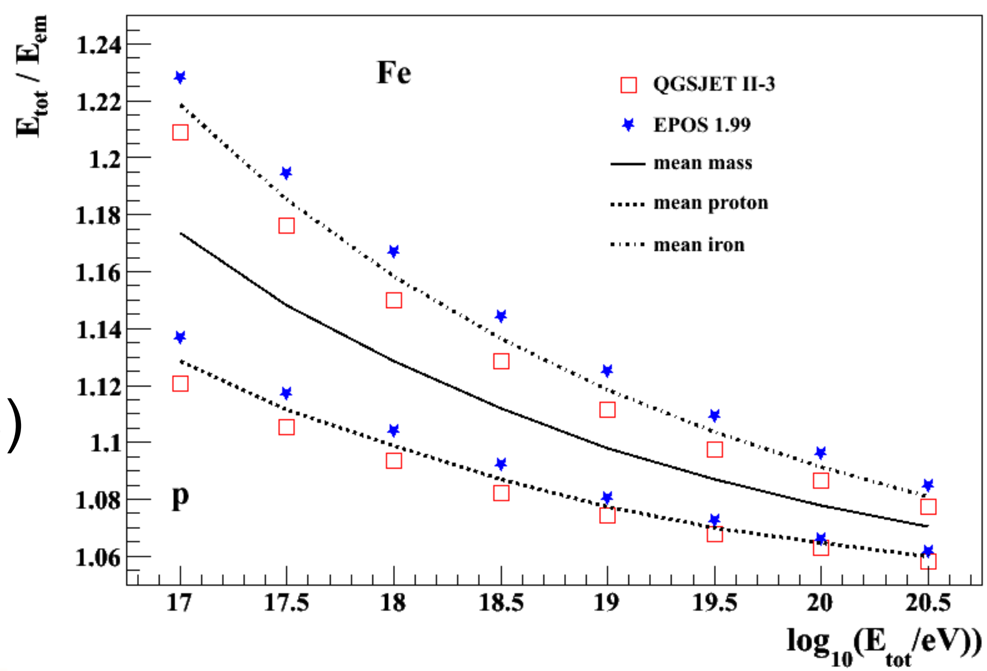
Energy Deposit



- **From Heitler model**

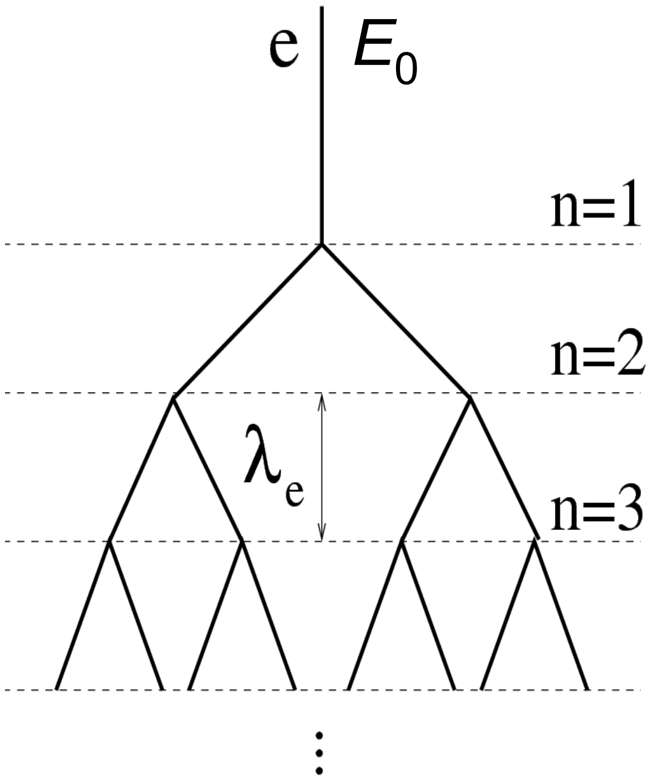
$$E_{em} = \left[1 - \left(\frac{N_{em}}{N_{tot}}\right)^{n(A)}\right] E_0$$

- **Energy deposit depends on muon number**
  - Primary mass dependent
  - Hadronic model dependent



- **Average value used**
  - Small error due to models (~1-2%)
  - Main uncertainty from unknown mass (~5-2%)

Toy Model for Electromagnetic Cascade(skip)



Primary particle : photon/electron

Heitler toy model :

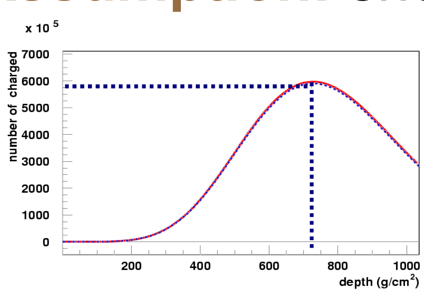
- 2 particles produced with equal energy

2^n particles after *n* interactions

$$n = X/\lambda_e$$

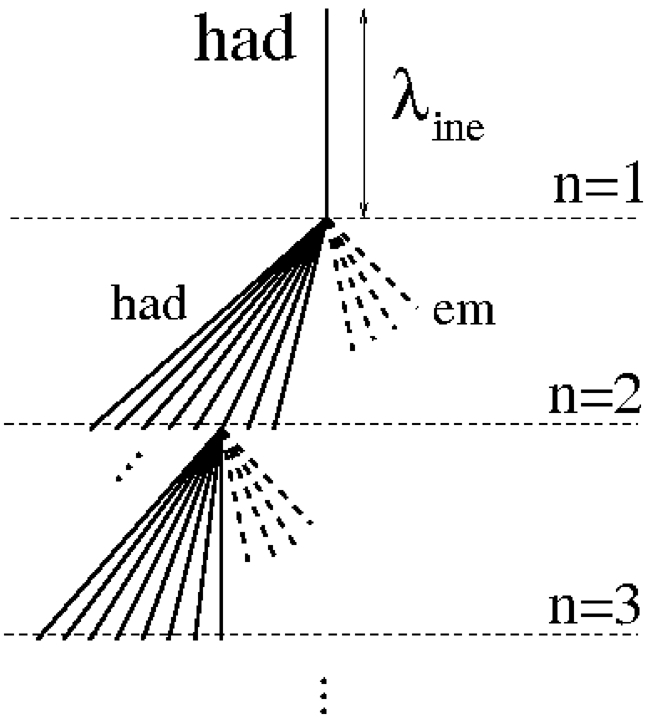
$$N(X) = 2^n = 2^{X/\lambda_e} \qquad E(X) = E_0/2^{X/\lambda_e}$$

Assumption: shower maximum reached if $E(X) = E_c$ (critical energy)



$$N_{max} = E_0/E_c \qquad X_{max} \sim \lambda_e \ln(E_0/E_c)$$

Toy Model for Hadronic Cascade



$$N_{tot} = N_{had} + N_{em}$$

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

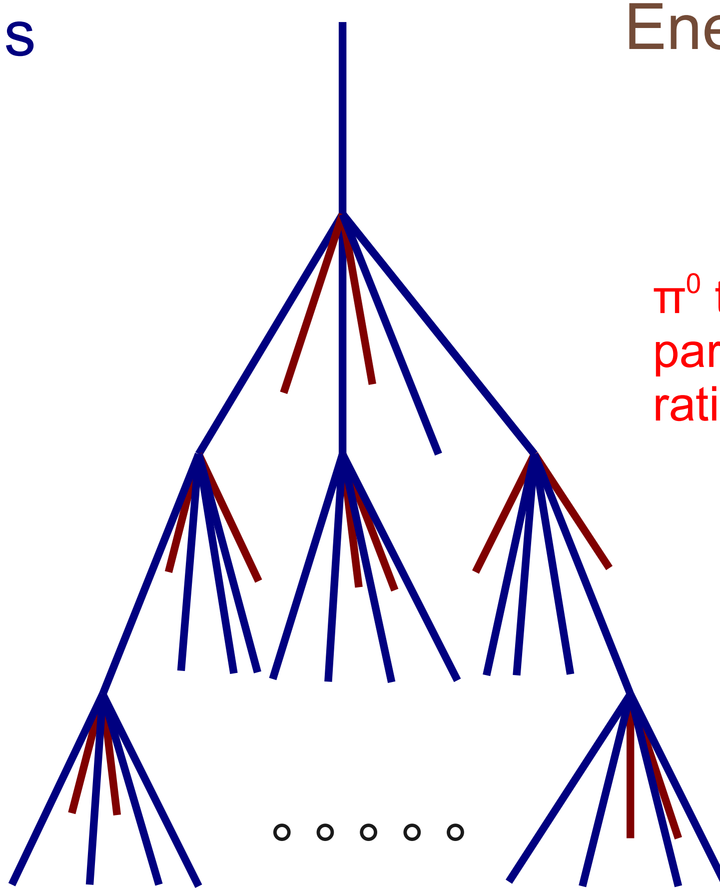
$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\alpha, \quad \alpha = \frac{\ln N_{had}}{\ln N_{tot}}$$

Primary particle : hadron

Using a simple generalized Heitler model to understand EAS characteristics :

- fixed interaction length
- equally shared energy
- 2 types of particles :
  - N_{had} continuing hadronic cascade until decay at E_{dec} producing muons (charged pions).
  - N_{em} transferring their energy to electromagnetic shower (neutral pions).

Energy Transfer : Energy Deposit



Energy of all hadrons

$$E_0$$

$$\frac{2}{3}E_0$$

$$\frac{2}{3}\left(\frac{2}{3}E_0\right)$$

After *n* generations

$$E_{had} = \left(\frac{2}{3}\right)^n E_0$$

Energy of all em. particles

$$0$$

π^0 to all particles ratio → $\frac{1}{3}E_0$

$$\frac{1}{3}E_0 + \frac{1}{3}\left(\frac{2}{3}E_0\right)$$

$$E_{em} = \left[1 - \left(\frac{2}{3}\right)^n\right] E_0$$

Energy in em. ~ 90 %

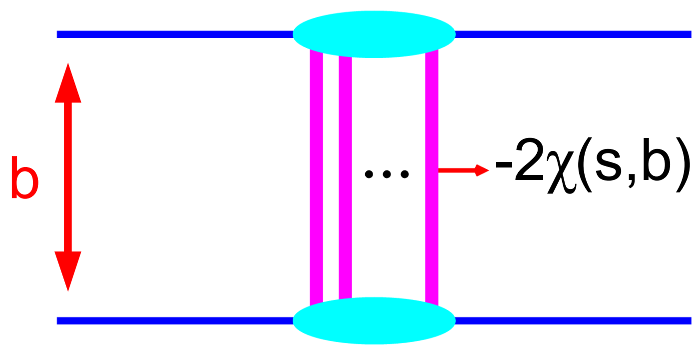
(n=5, E_{had}~12%
n=6, E_{had}~8%)

Cross Section Calculation : SIBYLL / QGSJET

Interaction amplitude given by parameterization (soft) or pQCD (hard) and Gribov-Regge for multiple scattering :

- elastic amplitude : $-2\chi(s,b)$
- sum n interactions :
  - optical theorem : $\frac{(-2\chi)^n}{n!} \rightarrow \exp(-2\chi)$

s = (cms energy)^2
b = impact parameter

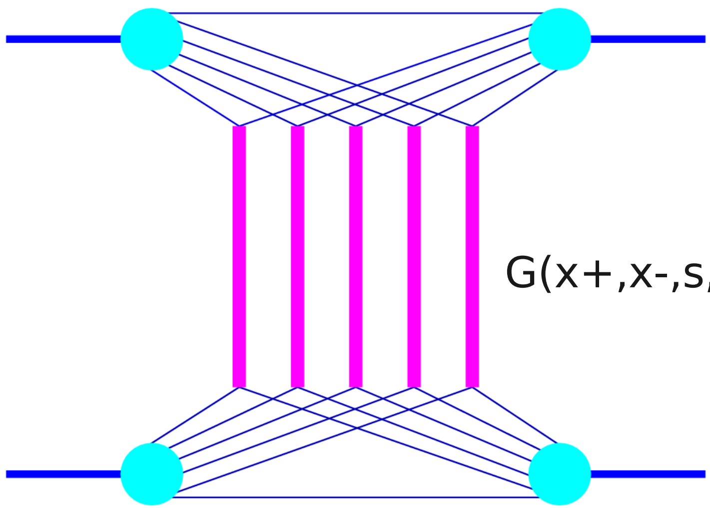


$$\sigma \sim 1 - \exp(-2\chi)$$

Not the same χ in QGSJET01, QGSJETII and SIBYLL

- $\chi(s,b)$ parameters for a given model fixed by pp cross-section
- pp to pA or AA cross section from Glauber
- energy conservation not taken into account at this level

Cross Section Calculation : EPOS



Different approach in EPOS :

- Gribov-Regge but with energy sharing at parton level : MPI with energy conservation !
- amplitude parameters fixed from QCD and pp cross section
- cross section calculation take into account interference term

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

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

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

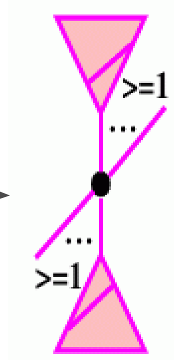
Particle Production in SIBYLL and QGSJET

Number n of exchanged elementary interaction per event fixed from elastic amplitude (cross section) :

- n from :

$$P(n)=\frac{(2\chi)^n}{n!}.\exp(-2\chi)$$

  - no energy sharing accounted for (interference term)
- 2n strings formed from the n elementary interactions
  - in QGSJET II, n is increased by the sub-diagrams
  - energy conservation : energy shared between the 2n strings
  - particles from string fragmentation



- inconsistency : energy sharing should be taken into account when fixing n

  - EPOS approach

Particle Production in EPOS

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

- m from :

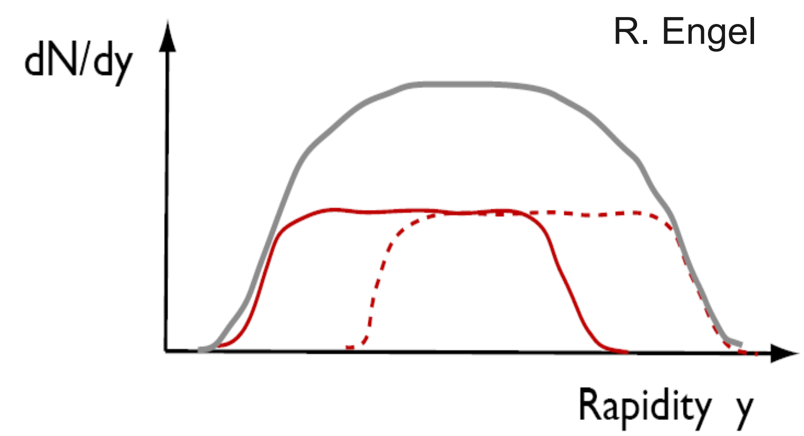
$$\Omega_{AB}^{(s,b)}(m, X^+, X^-) = \prod_{k=1}^{AB} \left\{ \frac{1}{m_k!} \prod_{\mu=1}^{m_k} G(x_{k,\mu}^+, x_{k,\mu}^-, s, b_k) \right\} \Phi_{AB}\left(x^{\mathrm{proj}}, x^{\mathrm{targ}}, s, b\right)$$

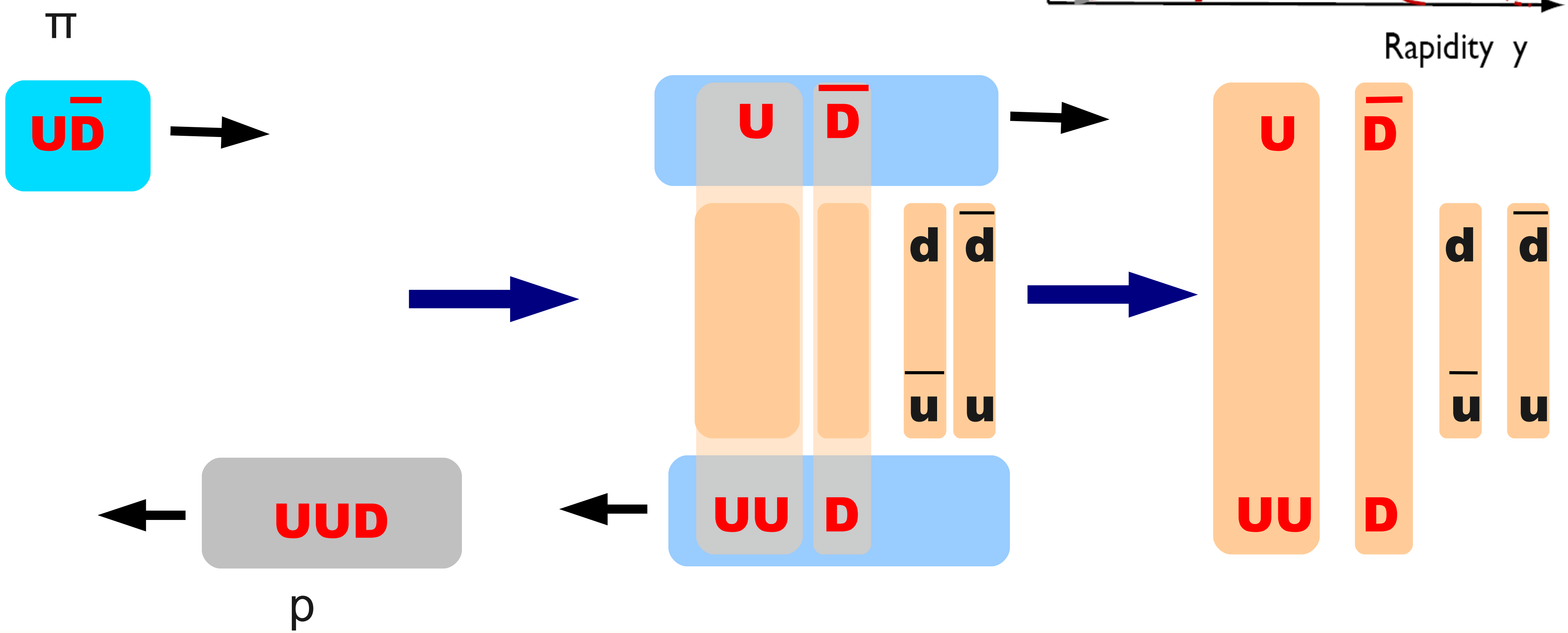
  - m and X fixed together by a complex Metropolis (Markov Chain)
- 2m strings formed from the m elementary interactions
  - energy conservation : energy fraction of the 2m strings given by X
- consistent scheme : energy sharing reduce the probability to have large m
- modified hadronization due to high density effect
  - statistical hadronization instead of string fragmentation
    - larger Pt (flow)

Remnants in SIBYLL

In SIBYLL : valence quarks attached to main string

- limited quark exchange
- very hard baryon and meson spectra
- string fragmentation
  - forward particle can be anything

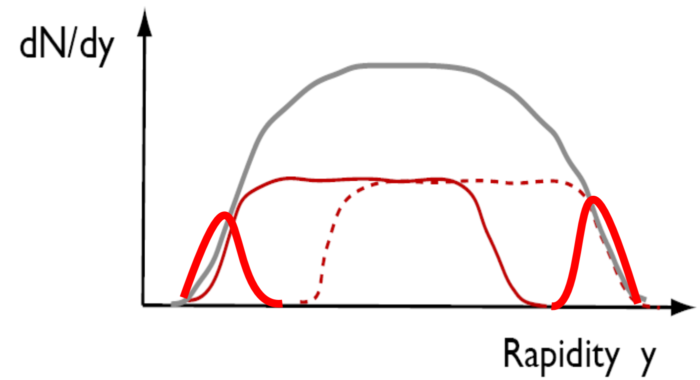


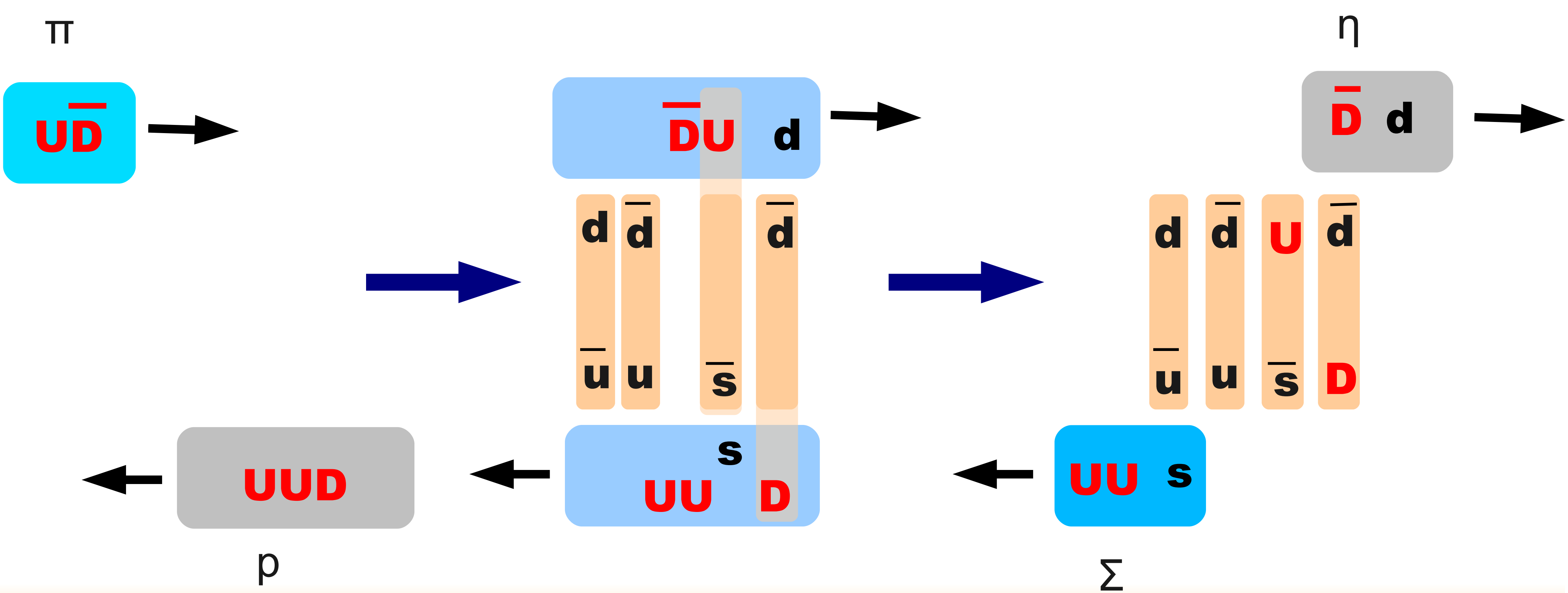


Remnants in QGSJET

In QGSJET : One quark exchange and leading remnant

- Limited quark exchange
  - forward particle same type than proj/targ
- low mass remnant (resonances)
- soft spectra

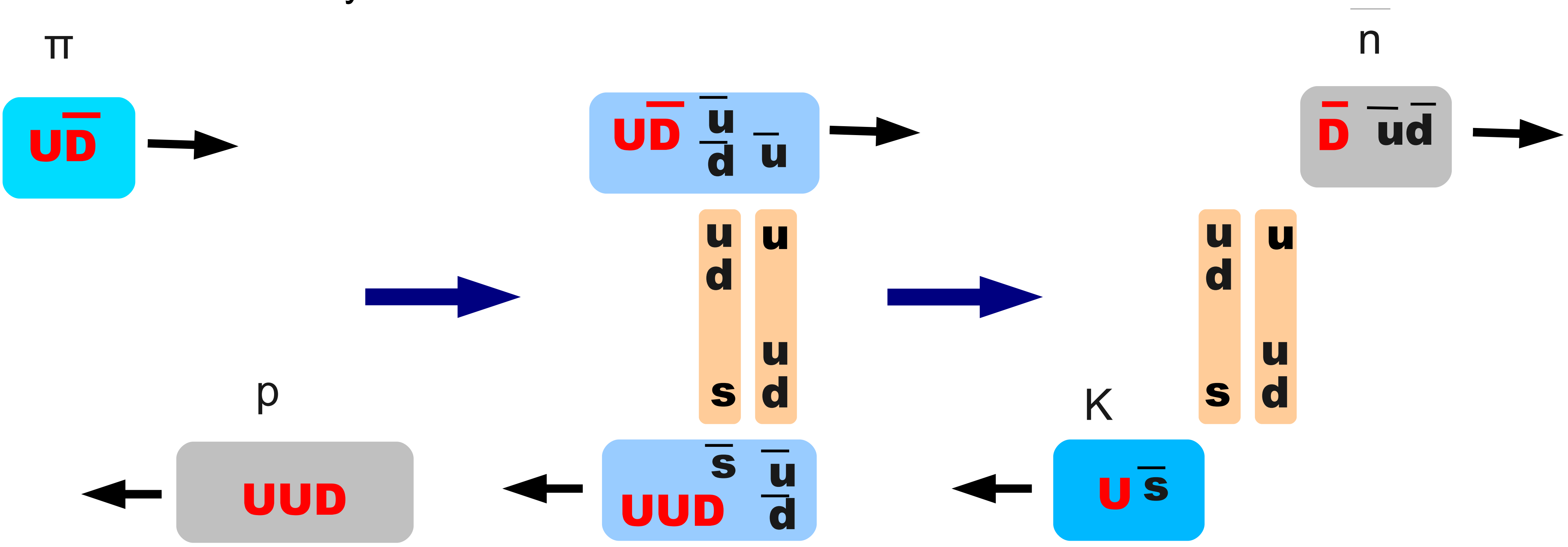




Remnants in EPOS

In EPOS : any possible quark/diquark transfer

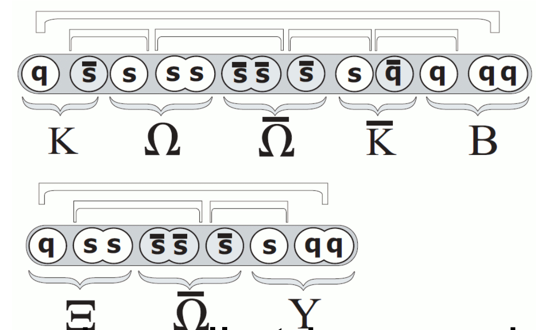
- Diquark transfer between string ends and remnants
- Baryon number can be removed from nucleon remnant :
  - Baryon stopping
- Baryon number can be added to pion/kaon remnant :
  - Baryon acceleration



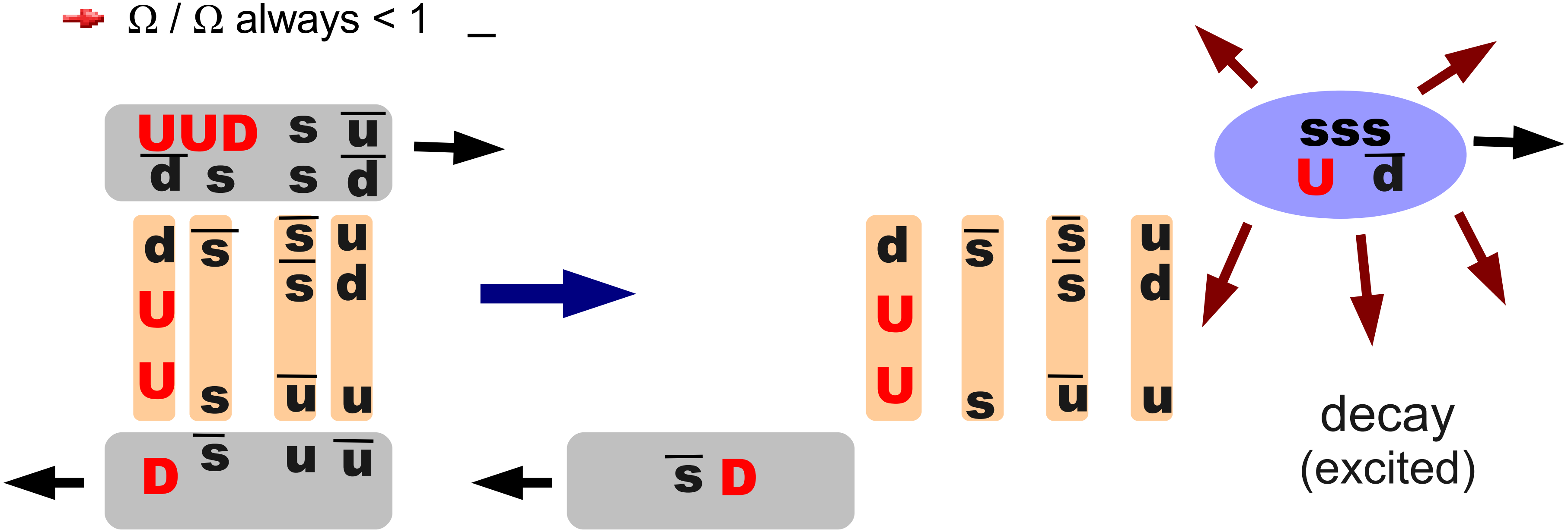
Baryons and Remnants

Parton ladder string ends :

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

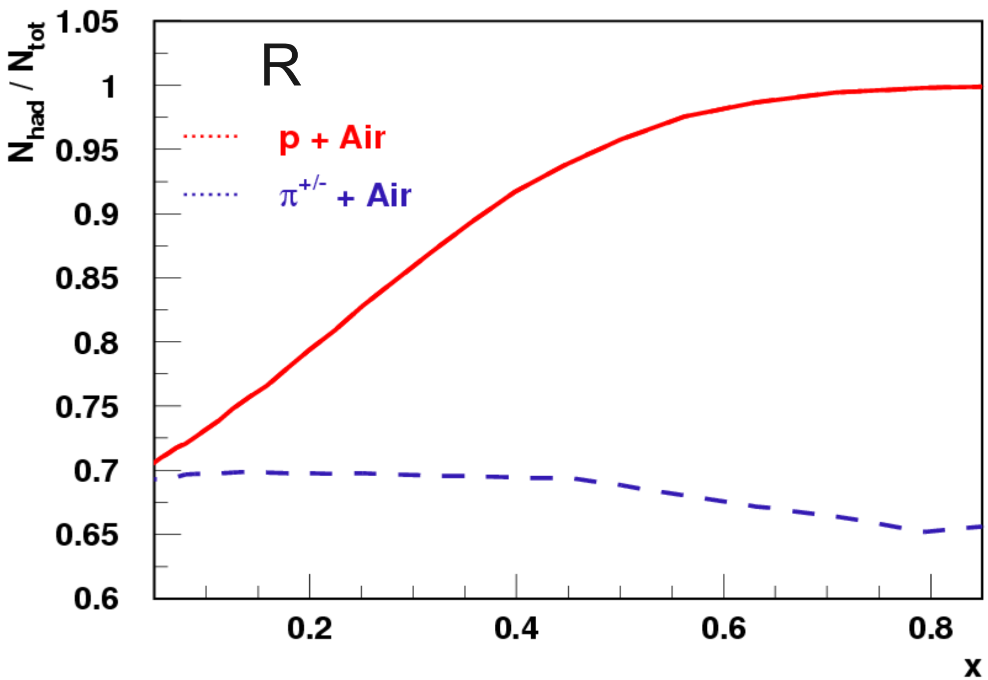


Muon Number

- **From Heitler**

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

➜ In real shower, not only pions : Kaons and (anti)Baryons (but 10 times less ...)



$$\alpha = \frac{\ln(N_{had})}{\ln(N_{tot})} = 1 + \frac{\ln(R)}{\ln(N_{tot})}$$

$$R = \frac{N_{had}}{N_{tot}} \approx \frac{N_{\pi^{ch}} + N_B}{N_{\pi^{ch}} + N_B + N_{\pi^0}}$$

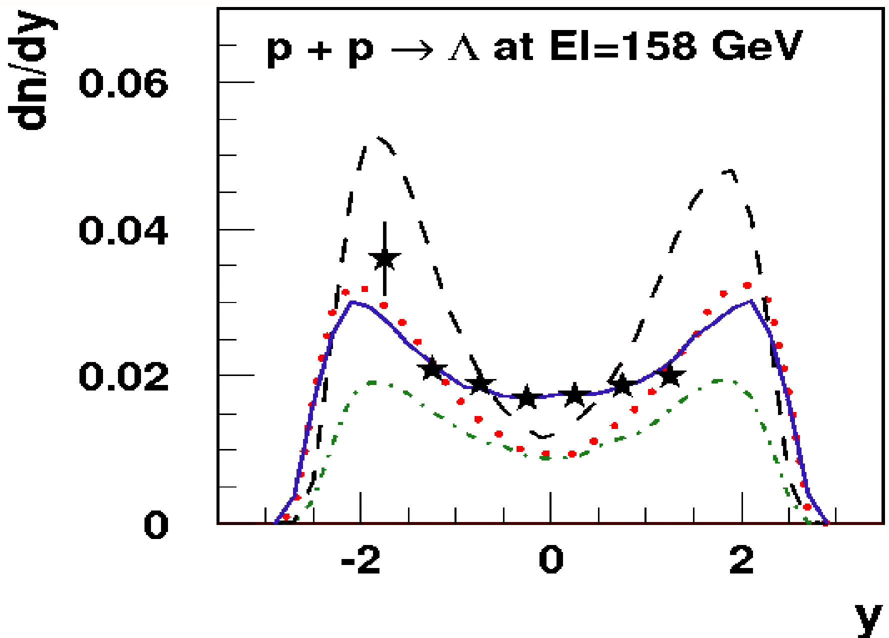
Very important :
in (a)Baryon-Air interactions, no leading neutral pion !
R~1

R depends on the number of (anti)B in p- or π-Air interactions

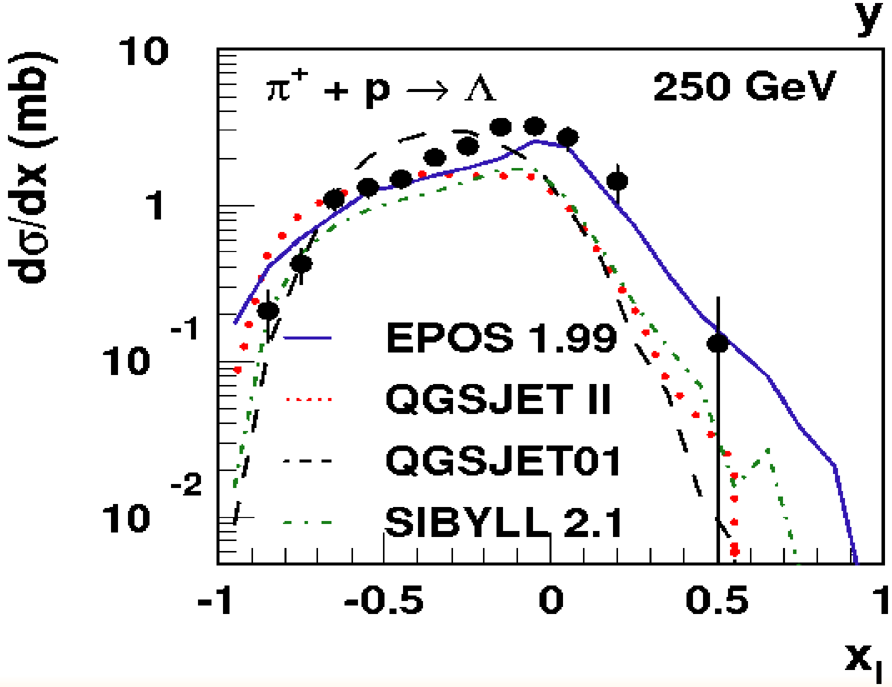
More fast (anti)baryons = $\alpha \to 1$ = more muons

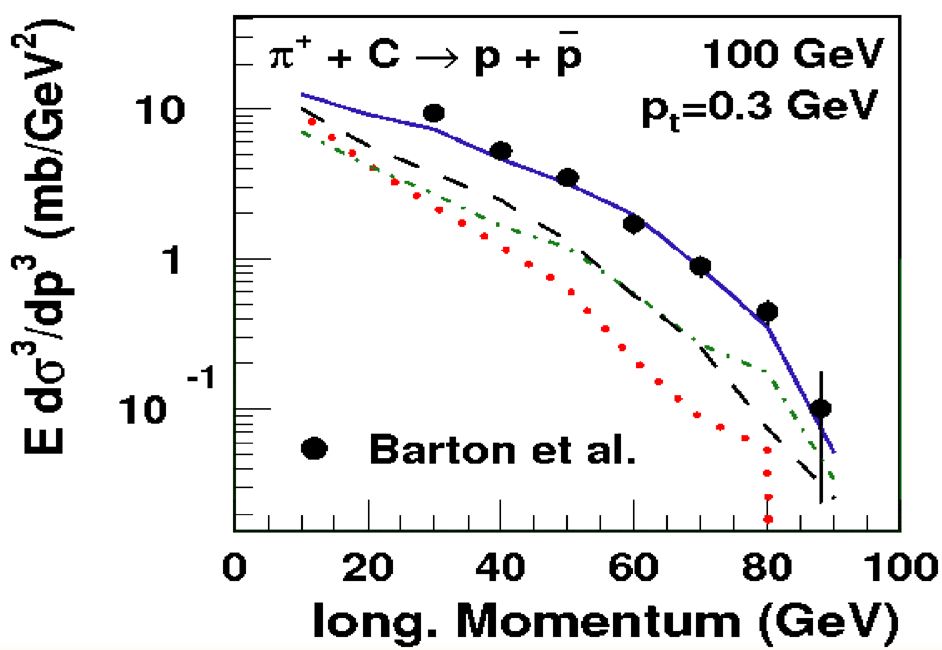
T. Pierog et al.,Phys.Rev.Lett. 101 (2008) 171101

Baryon Forward Spectra



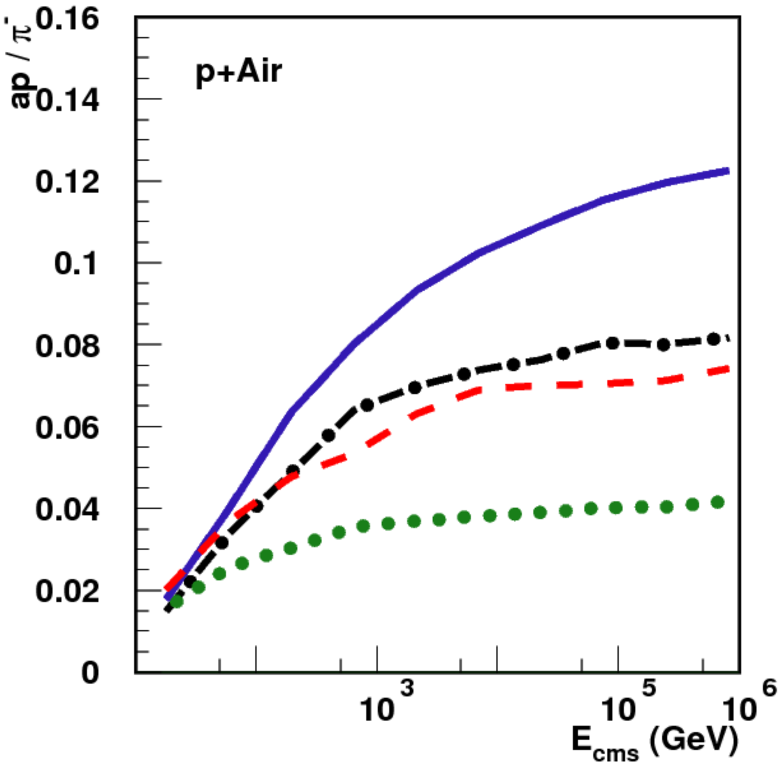
- Large differences between models
- Need a new remnant approach for a complete description (EPOS)
- Problems even at low energy
- No measurement at high energy !

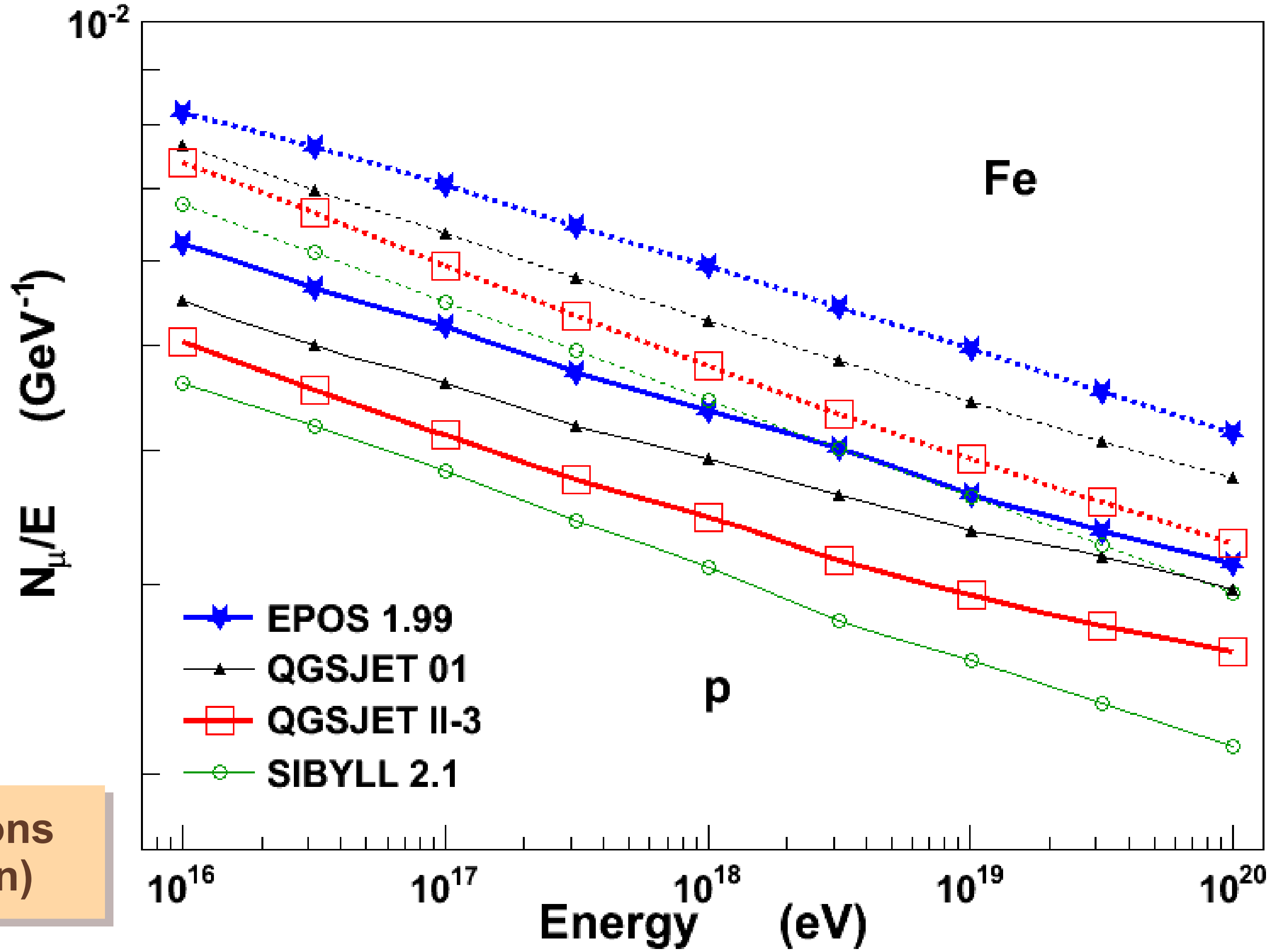




Total Number of Muons

Discrepancy (baryon and pion spectra) between models
=
Large differences in the number of muons





2 times less baryons = 35 % less muons (~difference between proton and iron)