SMR/1842-15

International Workshop on QCD at Cosmic Energies III

28 May - 1 June, 2007

Lecture Notes

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Hadron Nucleus collisions in Air Showers

- Introduction
- air shower simulations
- hh scattering
- hA scattering
- High density effects at high densities/energies
- Model comparison/air-shower properties

Why are ultra high energy cosmic rays interesting?

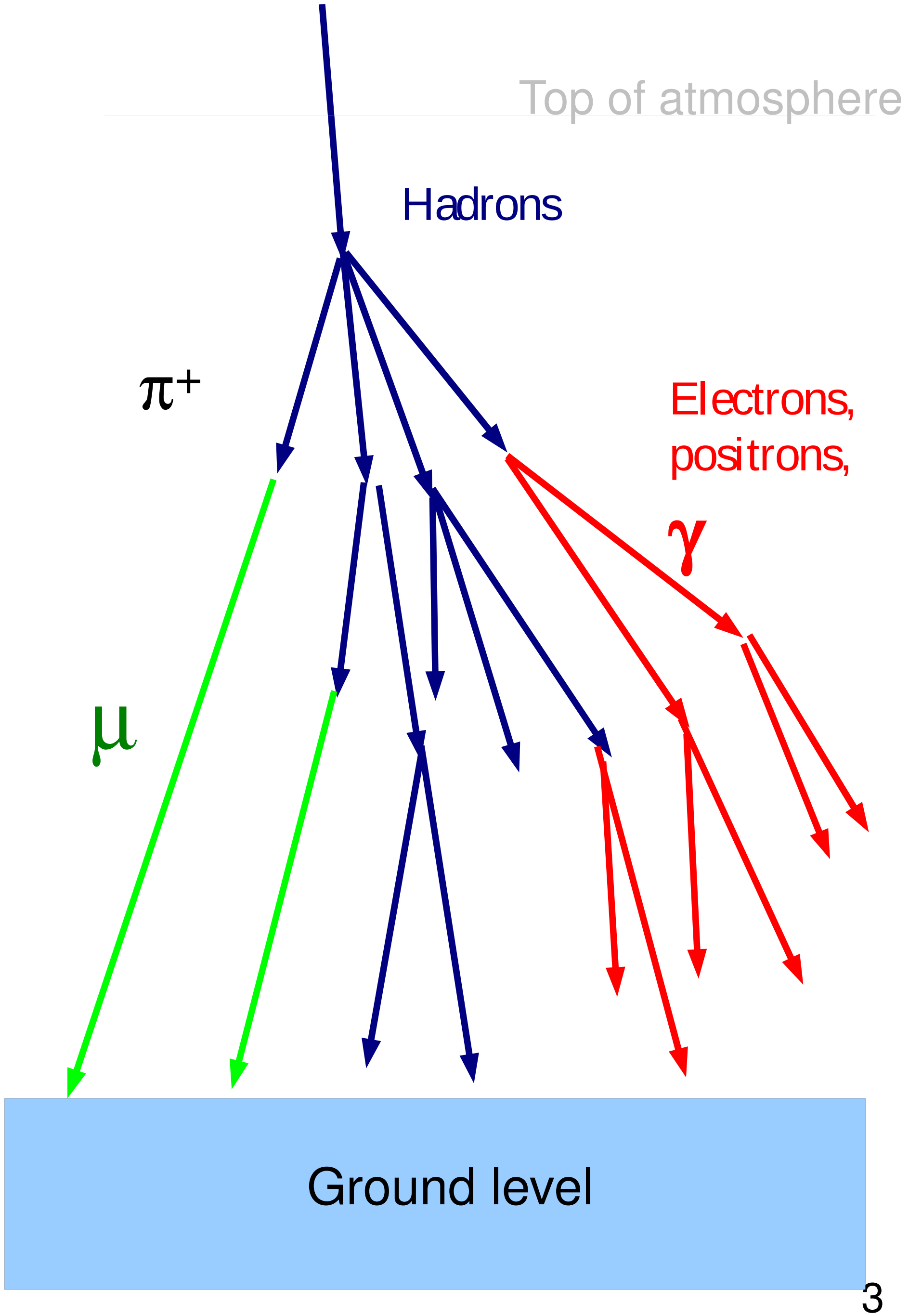
- **Origin unclear**
    - Bottom-up: acceleration
        - Study astrophysical objects,
    - Top-down: decay of some heavy object
        - Study exotic physics
- **Propagation:**
    - interaction with CMB
    - Interaction with magnetic fields (IGMF, GMF)
- **Interaction in the atmosphere**
    - Determine primary
    - Learn about high energy physics

Detection of UHECR

Direct detection not possible:
Flux very low:
E>1e20 eV
-> 1 particle/km^2/century

indirect detection via
AIR SHOWERS
induced by UHECRs

Reconstruct primary from shower properties:
- Energy,
- Arrival direction,
- Particle type



Air shower interactions

Hadrons: hadronic interactions
p-Air π-Air,K-Air
decays

Main theoretical uncertainty:

- higher energies
- π induced reactions
- phase space different from collider experiments
- inelastic cross section

Electrons/Gammas:
Bremsstrahlung
Pair Creation
inverse Compton
energy-loss
photo-nuclear effect
LPM
....

Muons: energy loss
bremsstrahlung ...

See Barone,Predazzi
for review

Gribov Regge Theory for pp interaction

Watson Sommerfeld transform of Amplitude A(s,t),
(similar to partial wave expansion),
has poles at $l=\alpha(t)$

$$A(s,t)=\beta(t)\eta(t)s^{\alpha(t)}$$

Assume one dominating pole for $s\rightarrow\infty$

$$\alpha(t)=\alpha(0)+\alpha' t$$

Regge trajectory

$$\beta(t)=\beta(0)e^{-B_0 t/2}$$

residue

$$\eta(t)=\frac{-1+\xi e^{-i\alpha(t)}}{\sin(\pi\alpha(t))}$$

signature factor

Optical theorem $$\sigma_{tot}=\frac{1}{s}\mathrm{Im}\,A(s,t=0)\sim s^{\alpha(0)-1}$$

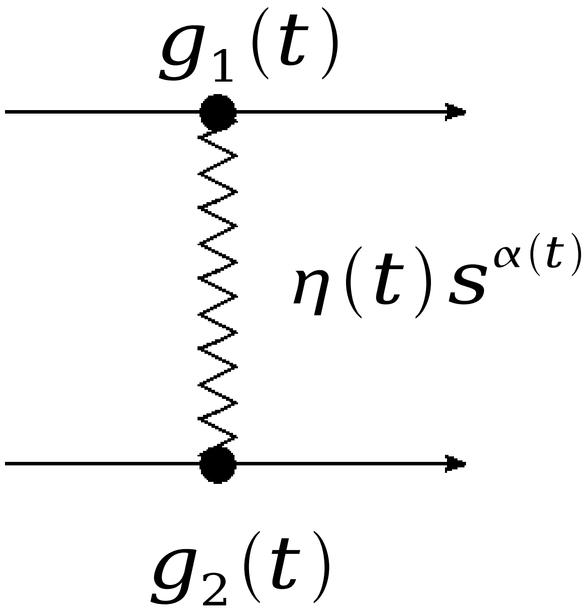
Reggeon $\alpha(0)\sim.5$

Pomeron for $\alpha(0)>1$
slowly rising cross section

$$A(s,t)=\eta(t)g_1(t)g_2(t)s^{\alpha(t)}$$

$$\frac{d\sigma_{el}}{dt}\sim s^{2\alpha(0)-2}e^{-B|t|}$$

$$B=B_0+2\alpha'\ln s$$



Shrinkage of diffractive peak
increase of interaction range

$$\sigma_{tot}\sim s^{\alpha(0)-1}$$

$$\alpha(0)\approx 1.07$$

Violation of Froissart bound
-> Multiple Pomeron exchange

Eikonal formalism recovers unitarity

$$\sigma_{tot}=2\int d^2b[1-e^{-\chi(s,b)}]$$
$$\sigma_{el}=\int d^2b[1-e^{-\chi(s,b)}]^2$$
$$\sigma_{inel}=\int d^2b[1-e^{-2\chi(s,b)}]$$

$\chi(s,b)$

Eikonal

$$\chi(s,b)\sim\int d^2q_t e^{-iq_t b}\,\mathrm{Im}(A(s,q_t))$$
$$\sim\frac{g_1 g_2 s^{\alpha(0)-1}}{4\pi B}e^{-b^2/2\mathrm{B}}$$

Poisson distribution: $P_n=\frac{(2\chi(s,b))^n}{n!}e^{-2\chi(s,b)}$

String end distributions

Gribov-Regge only gives number of (cut) Pomerons, nothing about their mass.

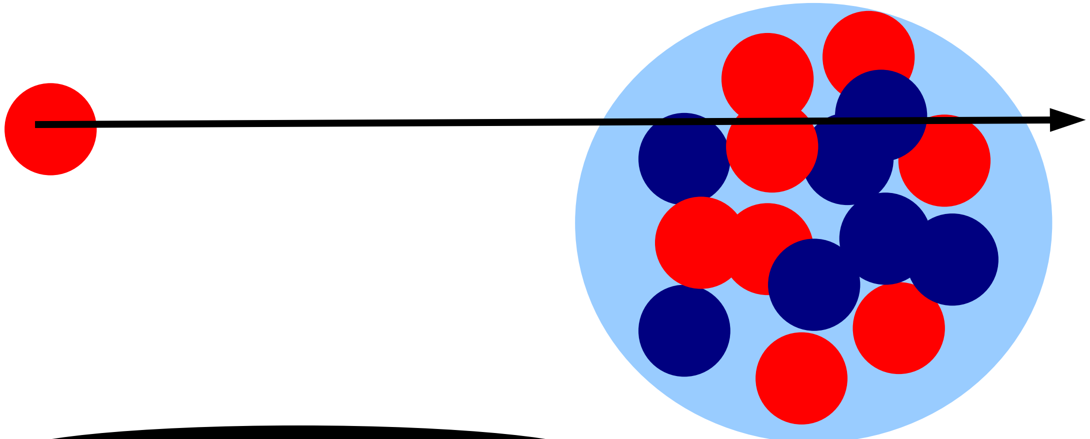
Assume following distribution of string ends (or Pomeron ends)

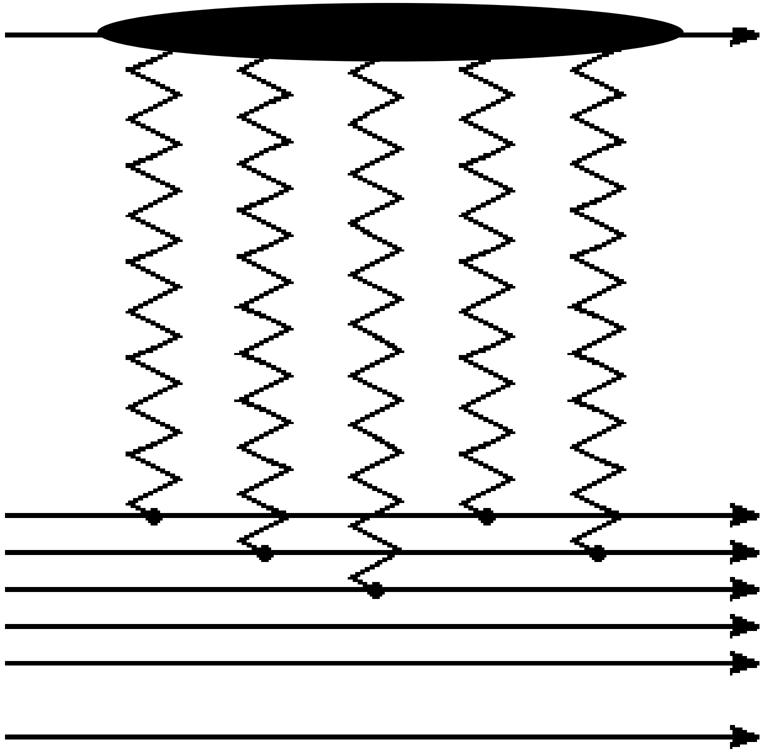
$$f(x) \sim x_1^{\alpha_q} x_2^{\alpha_q} \ \ldots \ (1 - \sum_i x_i)^{\alpha_{remn}}$$

$\alpha_q \approx -\frac{1}{2}$ Momentum fraction distribution of (anti-) quarks

$\alpha_{remn} \approx \frac{3}{2}$ Momentum fraction distribution of remnant

Generalization to hadron Nucleus collisions with Glauber Gribov





Projectile interacts coherently with target

String end distributions influence remnant x

more complicated:
- virtual correction (elastic rescattering)
- energy sharing

Perturbative processes

$\alpha_s(Q^2)$ running coupling constant small at large pt

Inclusive jet cross section:

$$\sigma_{jet} = K \sum_{i,j} \int_{p_t^2 > p_{t,0}^2} dp_t^2 \int dx_1 dx_2 \frac{d\sigma_{i,j}(x_1 x_2 s, p_t^2)}{dp_t^2}$$
$$\times f_{A,i}(x_{1,} Q^2) f_{B,j}(x_{2,} Q^2)$$

K K~2 factor accounts for NLO corrections

$d\sigma(\hat{s}, p_t^2)/dp_t^2$ Differential parton-parton cross section

$f_{A,i}(x_{1,} Q^2)$ Parton distribution function

Multiple jet production if a single event

·Inclusive jet cross section $\sigma_{jet} > \sigma_{tot}$

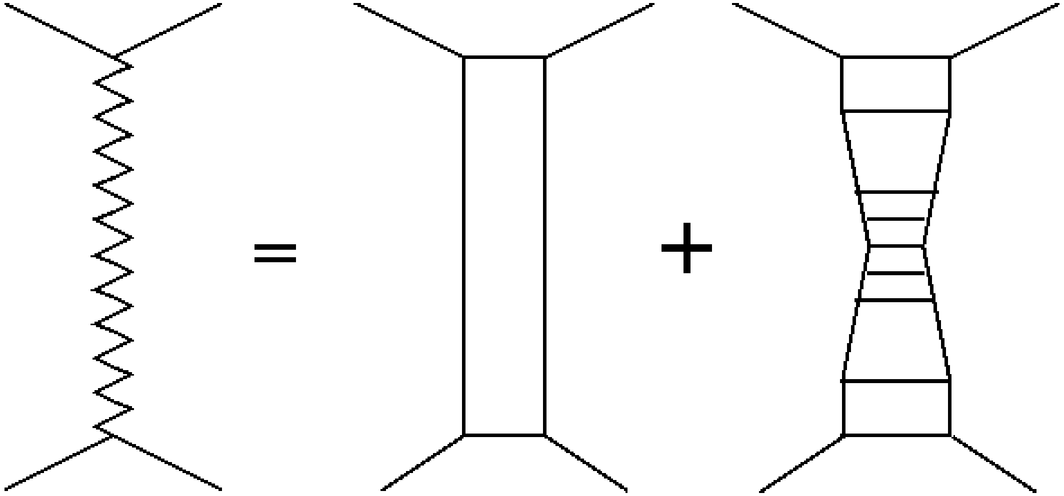
·Multiple jets

Define hard eikonal: $$\chi_{hard}(s,b) = \frac{1}{2}\sigma_{jet} A(s,b)$$

$A(s,b)$ Overlap function of hadrons

Total inelastic cross-section: $$\sigma_{inel} = \int d^2 b \left[1 - e^{-2\chi_{soft}(s,b) - 2\chi_{hard}(s,b)} \right]$$

Matching soft and hard scattering with the semihard Pomeron



Soft pre-evolution

QCD latter
+ hard process

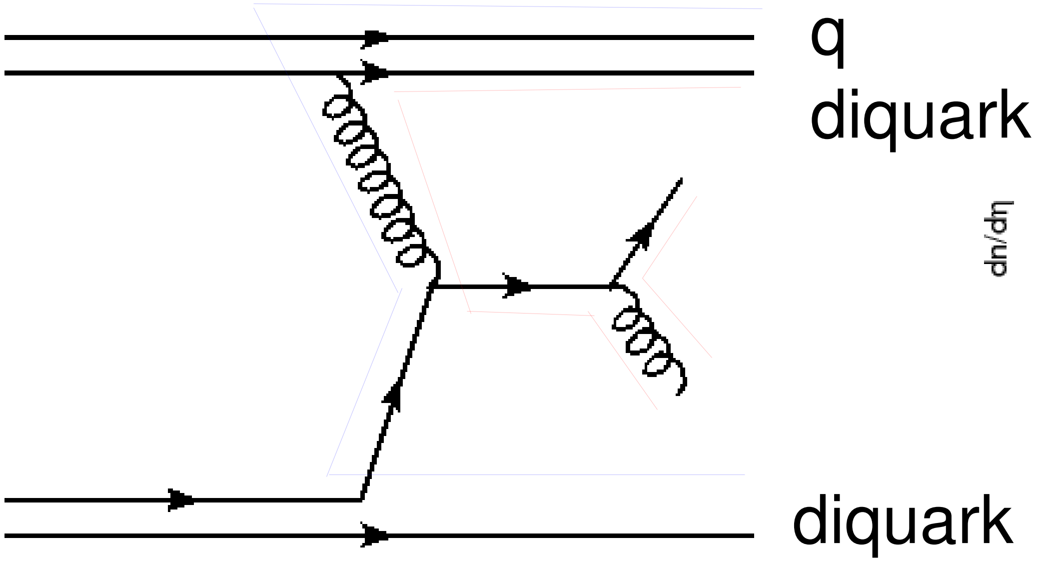
Soft pre-evolution: string ends for hard partons

Used in QGSJet, Nexus, Epos

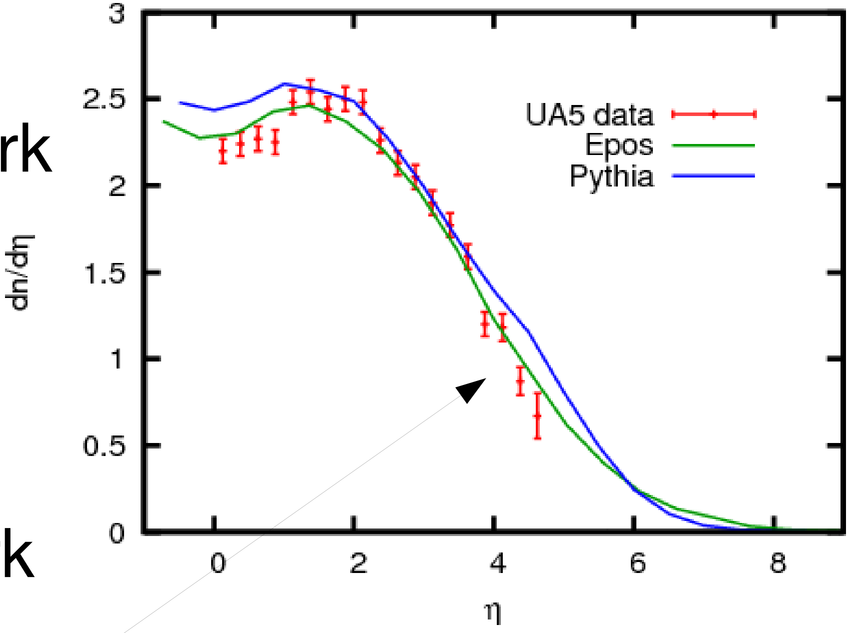
String ends for hard scatterings

No information from pQCD how to match hard partons to soft strings.

Usually employed: color flow



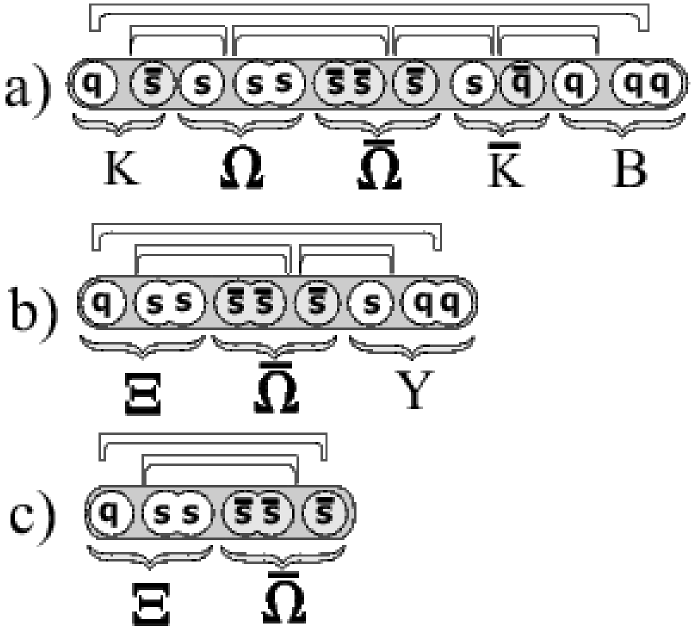
q----diquark q------g-----diquark

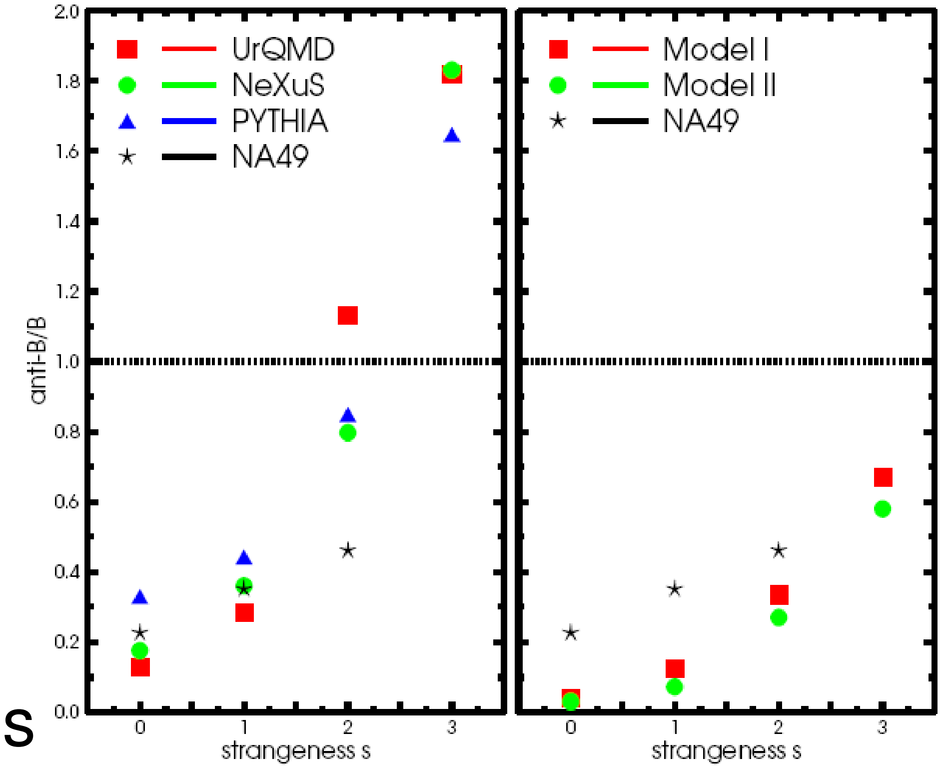


Better soft pre-evolution with $1/\sqrt{x}$ stringends

Another argument for soft pre-evolution: $\frac{\bar{\Omega}}{\Omega}$

Bleicher et al.,
Phys.Rev.Lett.88:202501,2002.



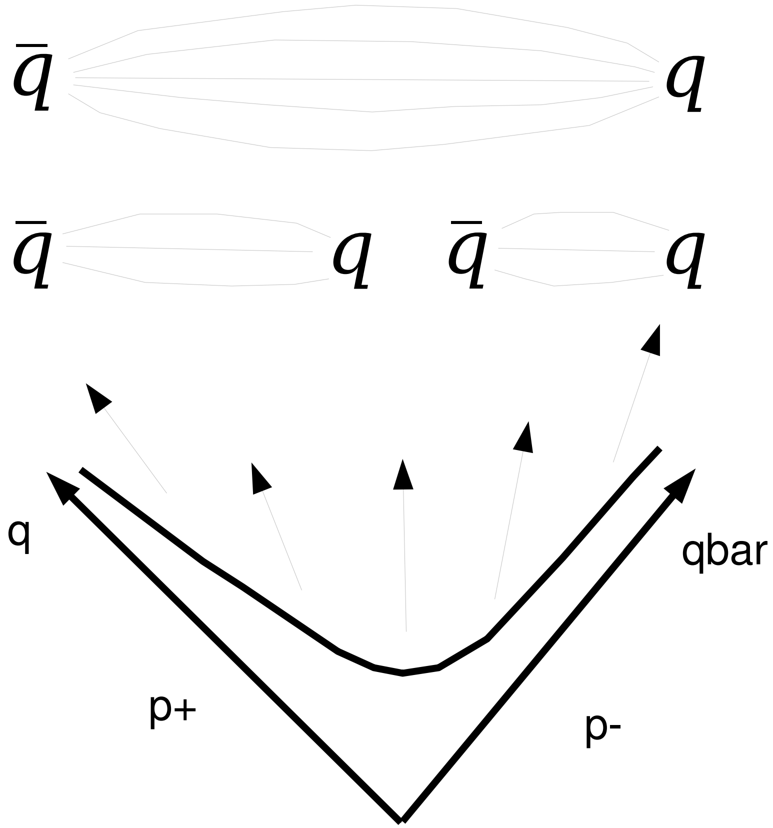


Omega production
suppressed in di-quark strings

Fragmentation of partons into hadrons

Pomeron = Cylinder ---> cut ---> 2 Strings

Inspired from QCD-flux tube between color charges



string dynamics governed by Nambu-Goto Lagrangian

Fragmentation via fragmentation function or area law (Atrtu-Menessier)

Break probability determines multiplicity

hard partons (gluons) are mapped onto string as kinks”.

Scattering on a dense target

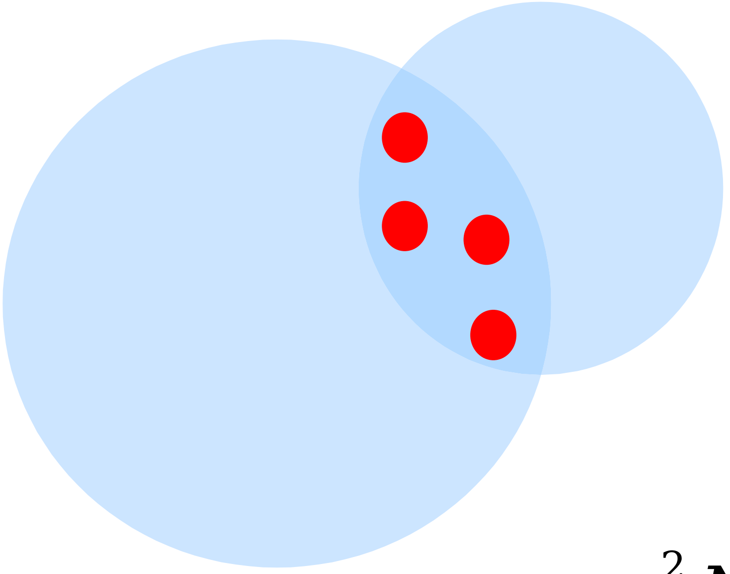
At high energies, dense systems the independent interaction picture is not valid any more.
Partons overlap - re-interact

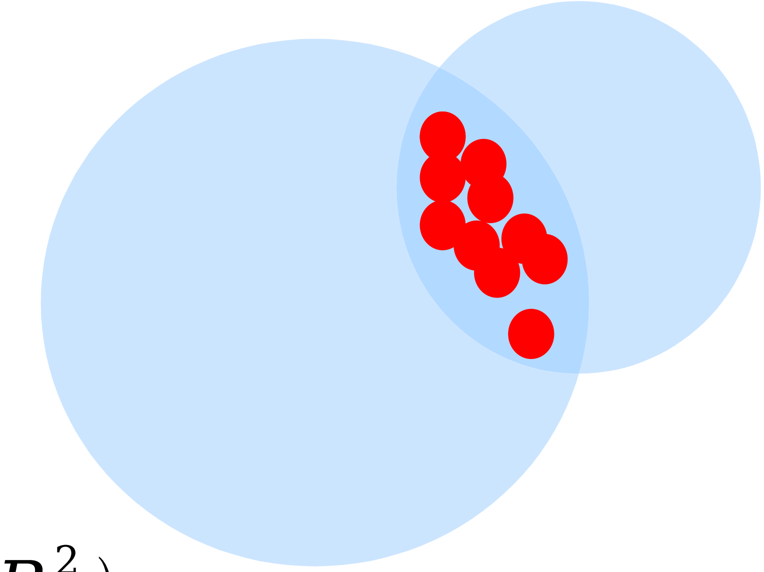
How to deal with rescattering?
Many approaches :

string fusion	(DPMJET,Armesto,Ranft)
enhanced diagrams	(QGSJet-II S.Ostapchenko)
s-dependent pt-cutoff	(Sibyll, R.Engel)
Black Disk/CGC	(BBL,HJD,Dumitru Strikman)
effective treatment	(Epos, K.Werner)
shadowing of PDF	(Hijing)

Pajares, EPJC43 (05) 9 (hep-ph/0501125);
Armesto et al., PRL77 (96) 3736 (hep-ph/9607239)

String fusion





$$\eta = \pi r^2 N / (\pi R_A^2)$$

$$\eta_c = 1.12 - 1.5$$

Low energy

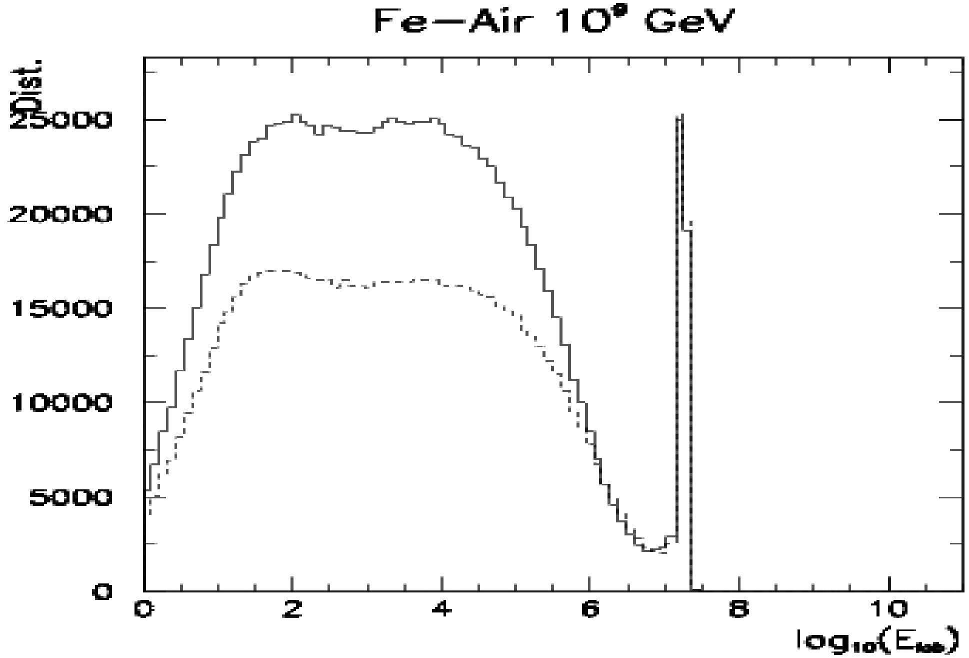
High energy/density

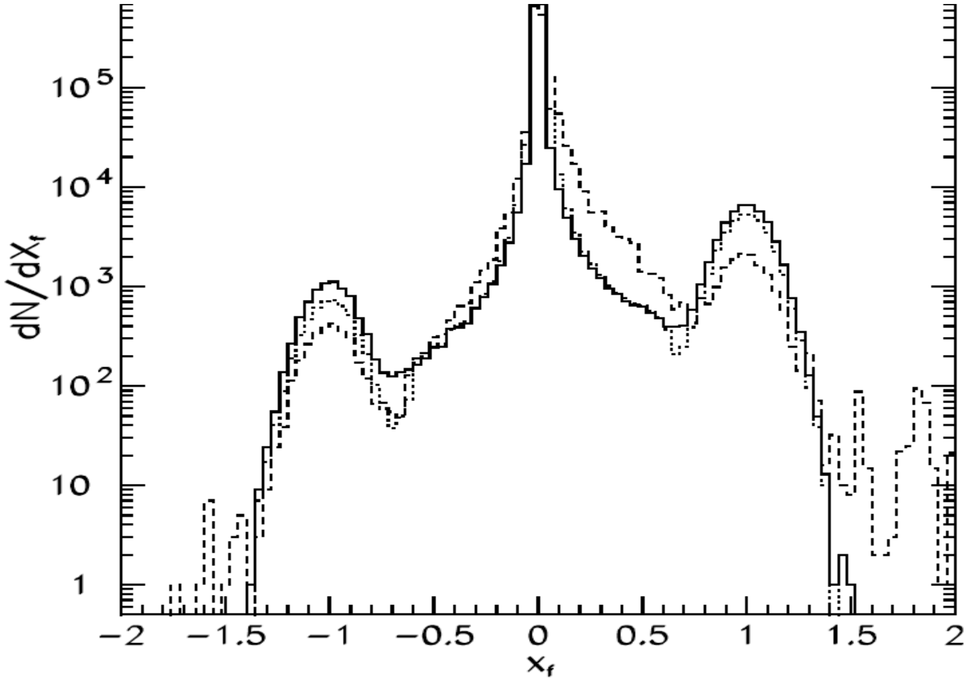
- String fusion takes place when the parent partons overlap
- Only fusion of pairs is allowed, only soft strings
- Implements non-linear effects on the string level (a posteriori)

Consequences of string fusion

- •reduction of multiplicity
- •enhanced strangeness
- •enhanced baryon production
- •enhanced correlations backward/forward

But:
Effects are small
for Air showers
e.g. no Xmax change

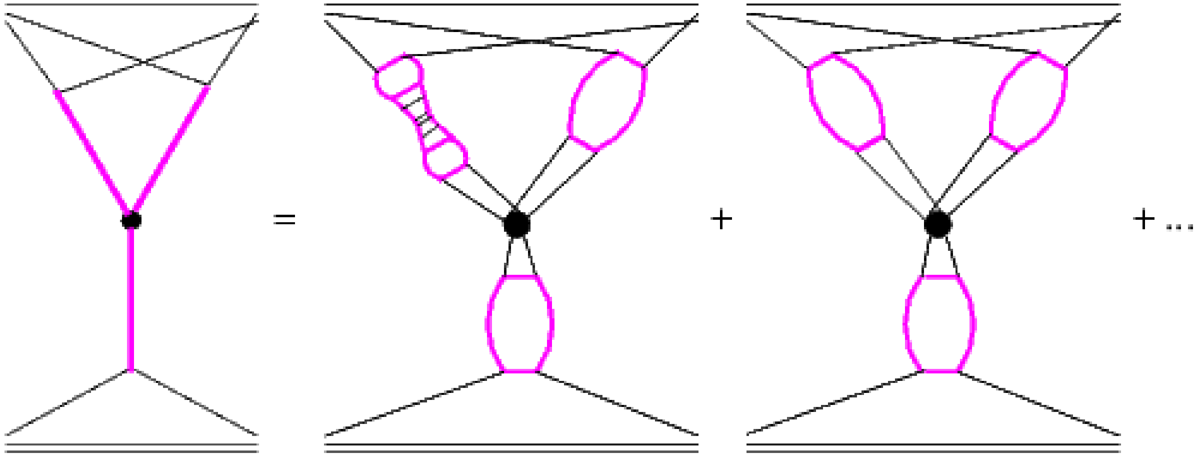




Enhanced Diagrams

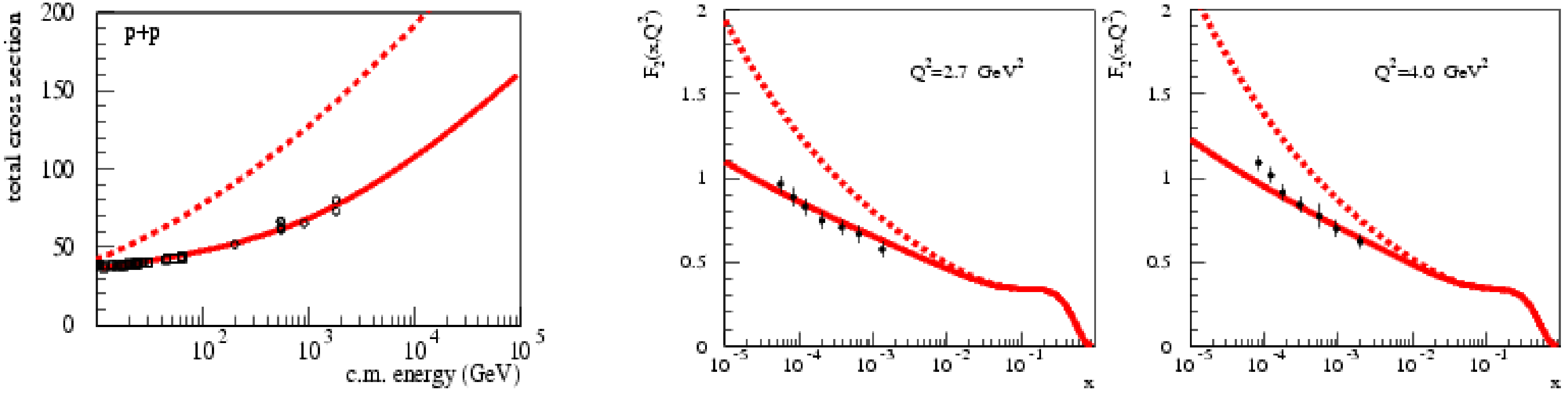
Ostapchenko
Nucl.Phys.Proc.Suppl.B151(2006)143

Non-linear effects by interaction between soft Pomerons
resummation of all orders



Reduces cross section, multiplicity, enhances inelasticity

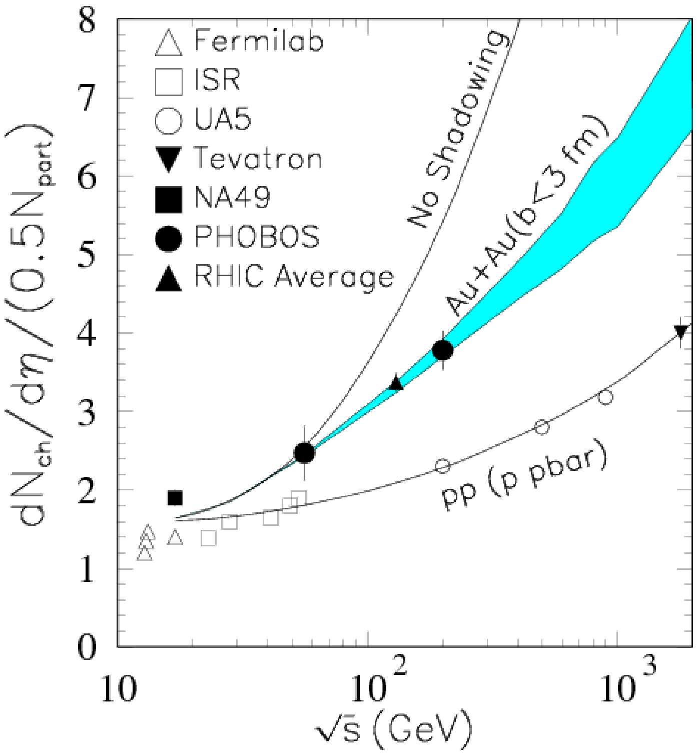
Total cross section and SF $F_2(x, Q^2)$ with (without) enhanced graphs:

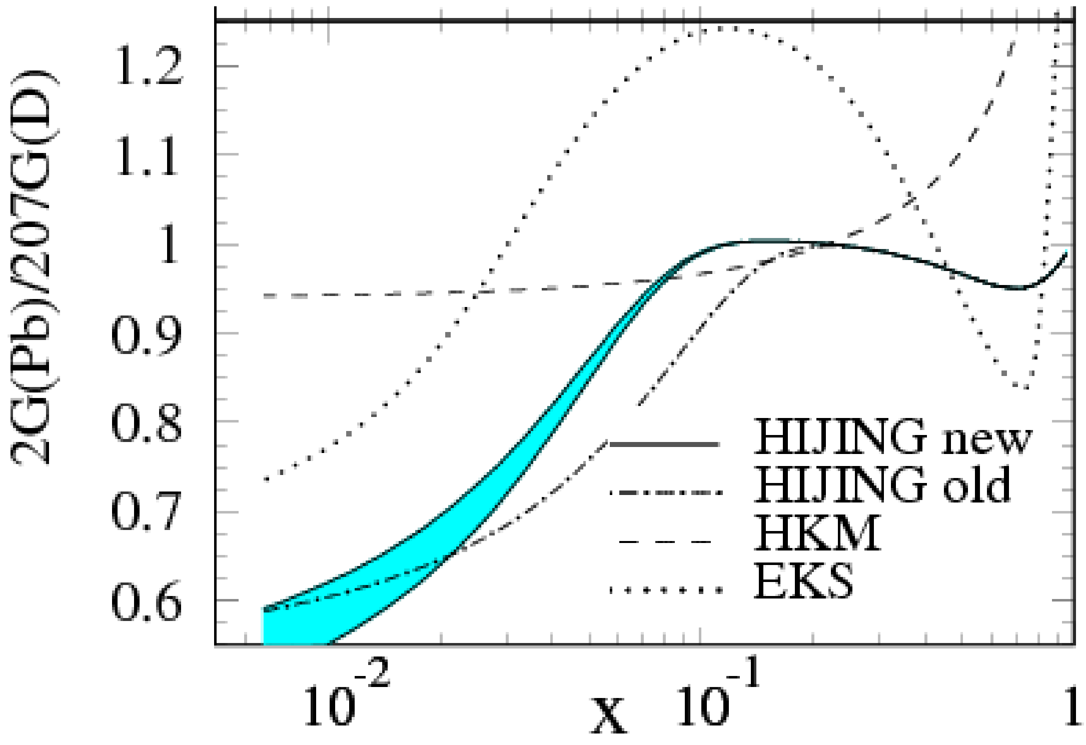


Shadowing structure functions

Wang,Li,
Phys.Lett.B527:85-91,2002.

$$
\begin{aligned}
f_a^A(x,Q^2) &= A R_a^A(x,Q^2) f_a^N(x,Q^2) \\
R_q^A(x) &= 1.0 + 1.19 \log^{1/6} A \, (x^3 - 1.2x^2 + 0.21x) \\
&- s_q \, (A^{1/3}-1)^{0.6}(1 - 3.5\sqrt{x}) \exp(-x^2/0.01) \\
R_g^A(x) &= 1.0 + 1.19 \log^{1/6} A \, (x^3 - 1.2x^2 + 0.21x) \\
&- s_g \, (A^{1/3}-1)^{0.6}(1 - 1.5x^{0.35}) \exp(-x^2/0.004),
\end{aligned}
$$





Energy dependent pt cutoff

PQCD cross section diverges for low pt
cutoff needed, but energy dependent.

e.g. Sibyll uses:

$$p_{t,min} = 1 + 0.065\, e^{0.9\sqrt{\ln s}}$$

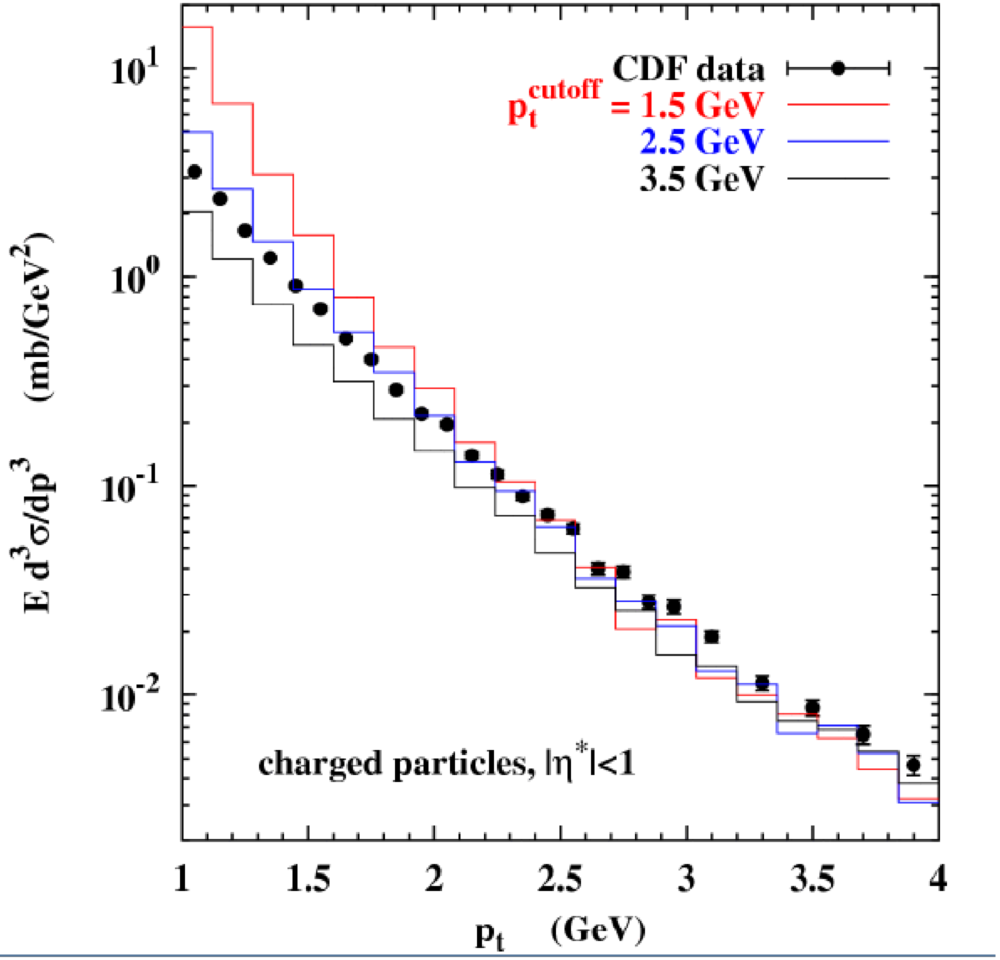
Saturation momentum Qs(s)
can be associated with pt-cutoff

But:

- Independent of centrality
- independent of A

Many others have pt-cutoff
like Pythia, Herwig,a.s.o.

From R.Engel:



Empirical treatment of high parton density in EPOS

Ansatz for parton density in target/projectile:

$$Z_T(j) = \sum_i Z_T(i,j)$$

$$\begin{aligned} Z_T(i,j) &= z_0 \exp(-b_{ij}^2/2{b_0}^2) \\ &+ \sum_{\text{target nucleons } j' \neq j} z_0' \exp(-b_{ij'}^2/2{b_0}^2), \end{aligned}$$

Partons interact in nucleon i and j

Additional split ladders

$$b_0 = w_B \sqrt{\sigma_{\text{inel}\,pp}/\pi}$$

$$\begin{aligned} z_0 &= w_Z \ln s/s_M , \\ z_0' &= w_Z \sqrt{(\ln s/s_M)^2 + {w_M}^2} , \end{aligned}$$

Coefficients for density depend on log(s)

Treat high density effects (enhanced diagrams) effectively instead of explicitly

K.Werner, T.Pierog, F.Liu

Phys.Rev.C74:044902,2006.

Quantities that depend on Z:

Amplitude changes due to the density

elastic screening:

parameterized Amplitide:

$$\alpha(x_1)^{\beta}(x_2)^{\beta} \rightarrow \alpha(x_1)^{\beta}(x_2)^{\beta+\epsilon}$$

$$\varepsilon=\alpha_s \beta_s Z$$

Reduces small-x contributions as a function of Z

collective fragmentation:

absorb into remnant

change hadronization parameters as a function of Z

$$p_B \rightarrow p_B - \alpha_B Z$$

$$p_D \rightarrow p_D(1+\alpha_D Z)$$

.....

Split ladder

Approach of the black disk limit

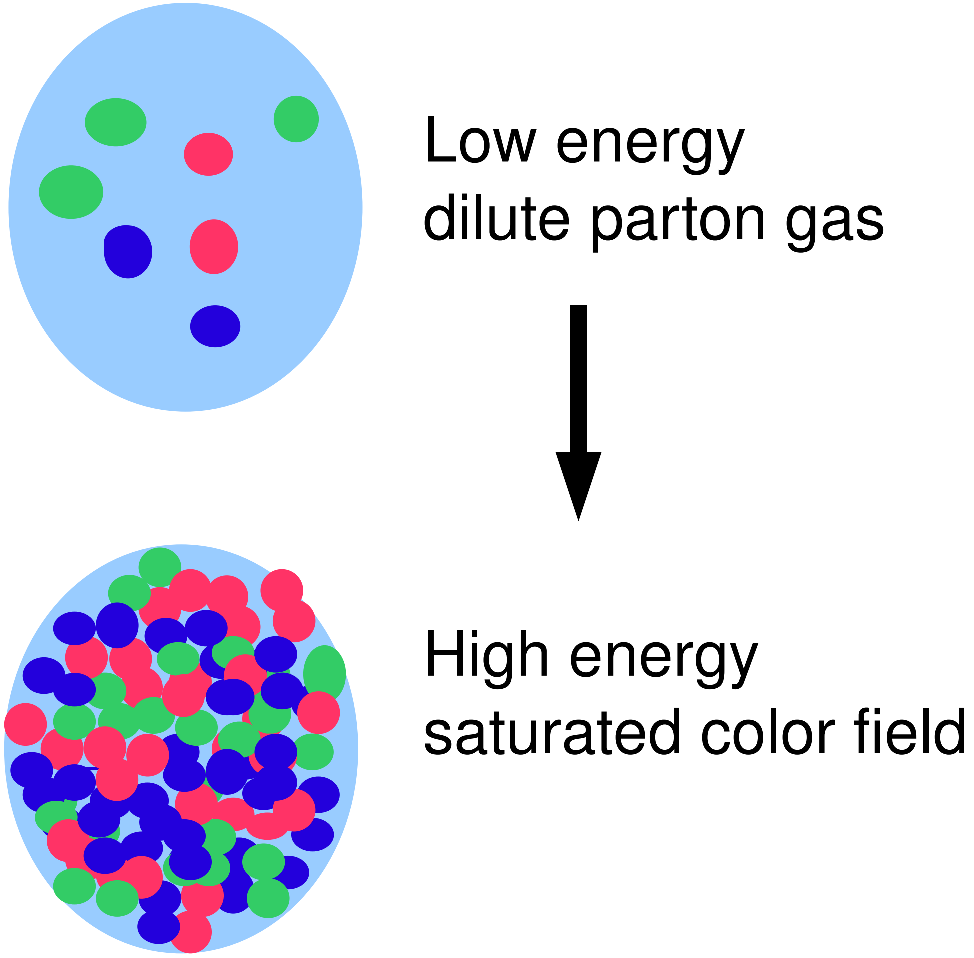
Gluon structure function rises fast at small x

A hadron hitting a dense target $x_2 = 4 p_t^2 / (x_1 s)$
interaction probability of quarks interacting inelastically
reaches unity

scattering incoming quarks off dense target,
projectile breaks up -> no leading particle effect

importance for air showers:
- reduced forward scattering
- faster absorption if atmosphere (lower Xmax)

Color Glass Condensate



Low energy
dilute parton gas

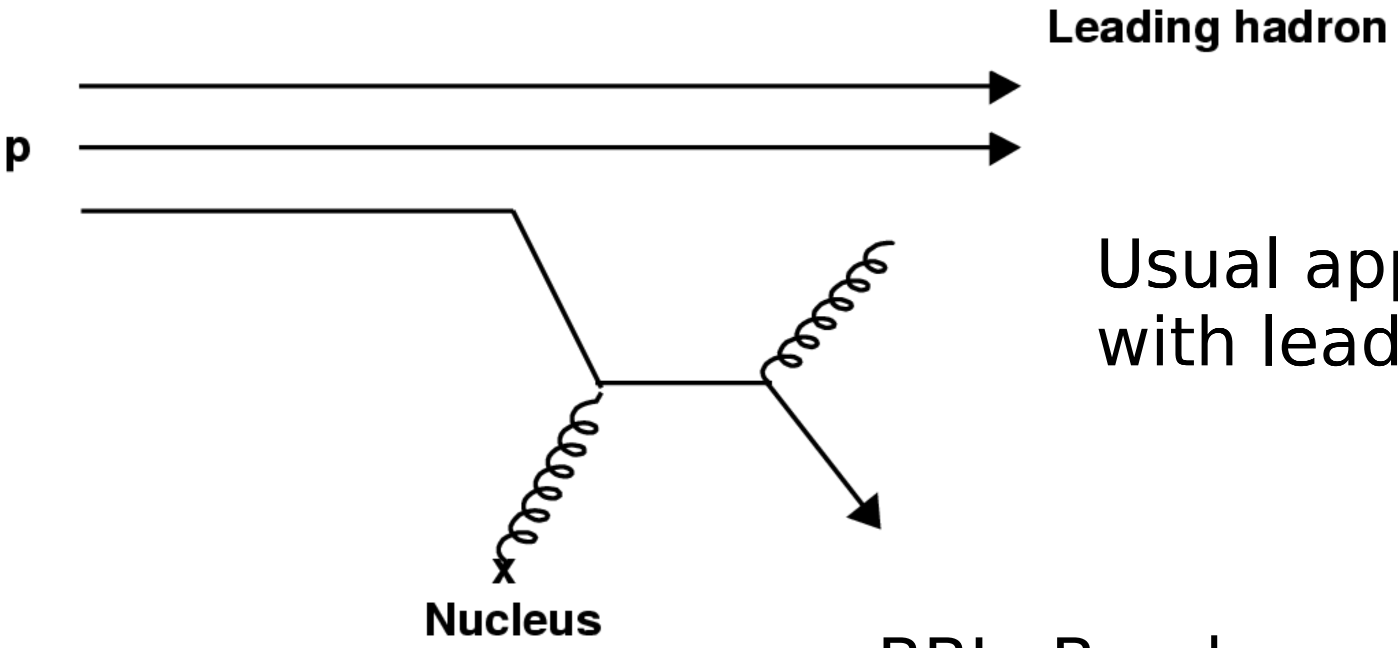
High energy
saturated color field

Gluon density grows
rapidly with smaller x

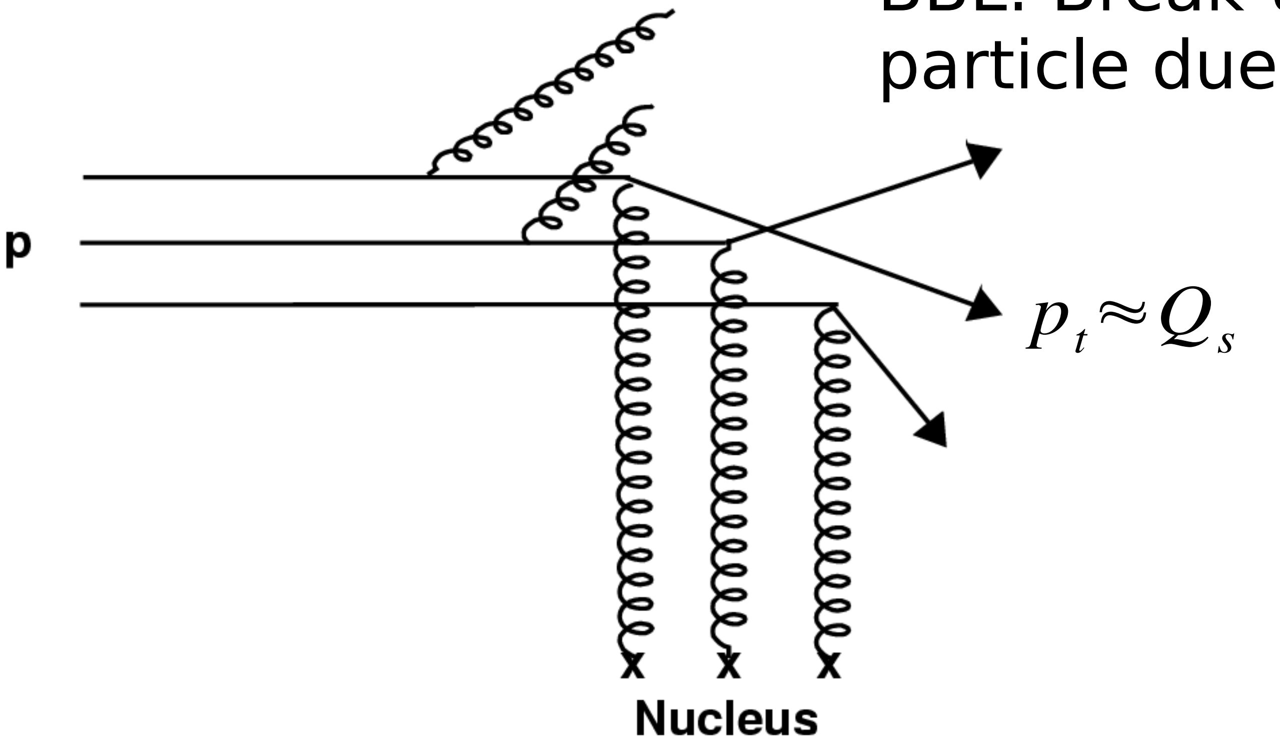
partons saturate at
$\rho \sim 1/\alpha_s$

typical Momentum
is Qs(x)

alpha(Qs)<<1
McLerran-Venugopalan
(MV Model)



Usual approach
with leading particle



BBL: Break-up of leading
particle due to dense target

Forward quark-Nucleus scattering:

Dumitru,Jalilian-Marian
PRL 89 (2002)

$$\frac{\mathrm{d}\sigma^{qA}}{\mathrm{d}q^-\mathrm{d}^2q_t\mathrm{d}^2b} = \delta(q^- - p^-)\ C(q_t)$$

$$\begin{aligned} C(q_t) \quad = \quad & \int \frac{\mathrm{d}^2r_t}{(2\pi)^2} e^{iq_tr_t} \left\{ \exp\left[-2Q_s^2 \int_\Lambda \frac{\mathrm{d}^2p_t}{(2\pi)^2}\frac{1}{p_t^4}\left(1-e^{ip_tr_t}\right)\right] \right. \\ & \left. -2\exp\left[-Q_s^2\int_\Lambda \frac{\mathrm{d}^2p_t}{(2\pi)^2}\frac{1}{p_t^4}\right] + 1 \right\} \end{aligned}$$

--->

$$\mathrm{d}\sigma^{\mathrm{el}}/\mathrm{d}^2b = \left[1-e^{-Q_s^2/4\pi\Lambda^2}\right]^2 \quad , \quad \mathrm{d}\sigma^{\mathrm{tot}}/\mathrm{d}^2b = 2\left[1-e^{-Q_s^2/4\pi\Lambda^2}\right]$$

Limits for qA cross section :

$$C(q_t) \quad =$$

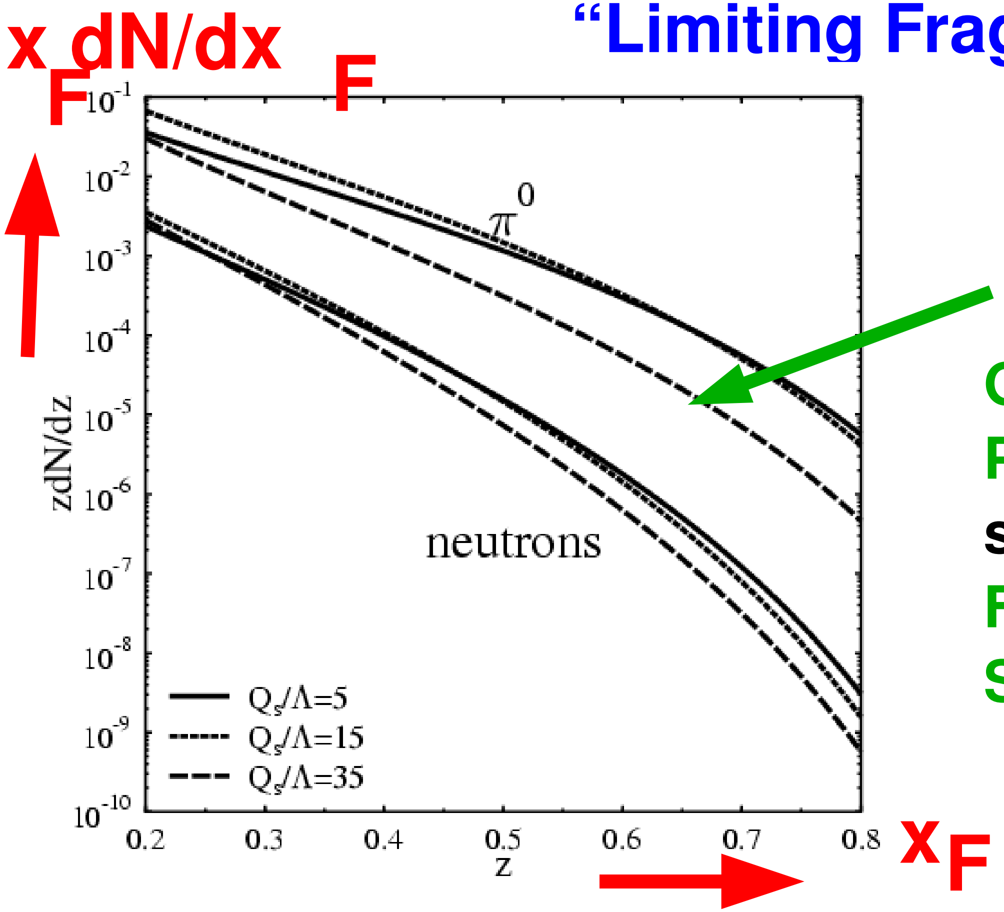
$$q_t \gg Q_s \ : \qquad \frac{1}{2\pi^2}\frac{Q_s^2}{q_t^4}\left[1+\frac{4}{\pi}\frac{Q_s^2}{q_t^2}\log\frac{q_t}{\Lambda} + \mathcal{O}\left(\frac{Q_s^2}{q_t^2}\right)\right]$$

$$q_t \lesssim Q_s \ : \qquad \frac{1}{Q_s^2\log Q_s/\Lambda}\exp\left(-\frac{\pi q_t^2}{Q_s^2\log Q_s/\Lambda}\right)$$

If one assumes indep. fragm. of scattered partons :

$$x_F \frac{d\sigma^{pA\to hX}}{dx_F\, d^2k_t\, d^2b} = \underbrace{\int_{x_F}^{1} dx\, \frac{x}{x_F}\, f_{q/p}(x,Q_s^2)\, D_{h/q}\left(\frac{x_F}{x},Q_s^2\right)}\, \frac{d\sigma^{qA}}{d^2q_t\, d^2b}$$

“Limiting Fragmentation” curve in BBL



Long. distribution steepens

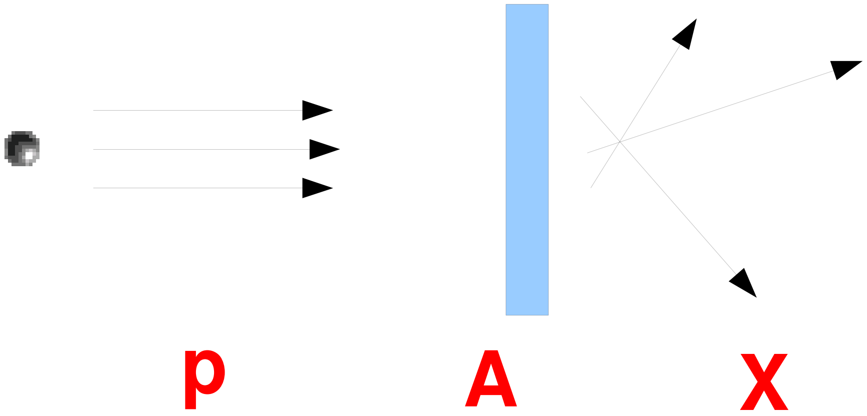
Gerland, A.D., Strikman
PRL 90 (2003)
see also
Frankfurt, Guzey, McDermott,
Strikman: PRL 87 (2001)

Shattering the proton

Probability for quark to be scattered to qt~0 (with color exchange !) :

$$\int_0^{\Lambda} \mathrm{d}^2 q_t \frac{\mathrm{d}\sigma^{\mathrm{in}}}{\mathrm{d}^2 b \mathrm{d}^2 q_t} \simeq 1 - \exp\left(-\frac{\pi\Lambda^2}{Q_s^2 \log Q_s/\Lambda}\right) \simeq \frac{\pi\Lambda^2}{Q_s^2 \log Q_s/\Lambda}$$

--> suppression of “beam-jet remnants” (soft physics) in the BBL



$$\langle q_t \rangle \sim Q_s$$

All partons resolved at scale Qs, coherence of proton destroyed completely.

Monte Carlo implementation

- Choose model as function of density, energy

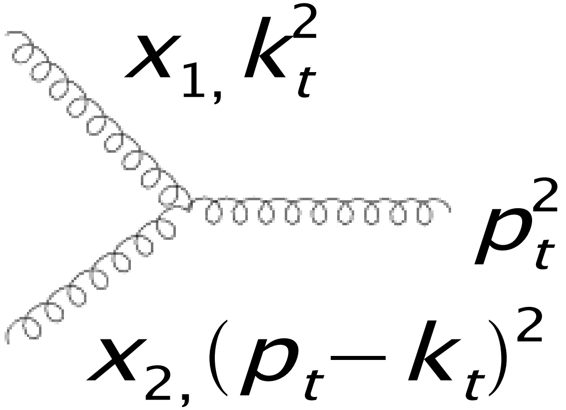
$$Q_s(b, x_F = 0.001) > 1\,\mathrm{GeV}$$

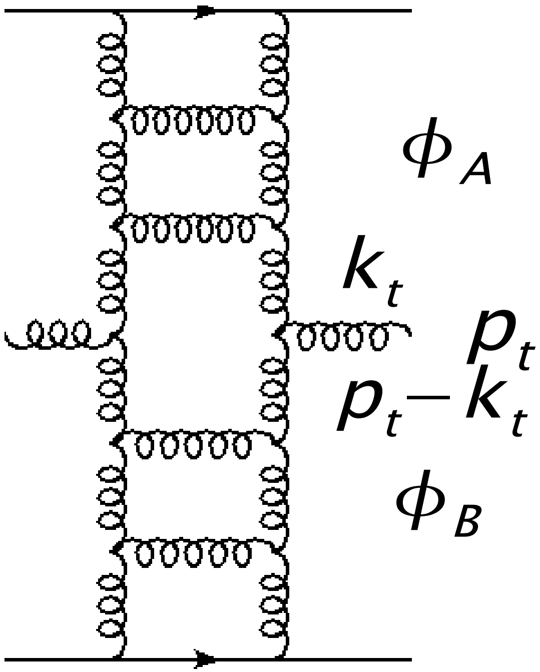
→ BBL
else
→ Sibyll (standard pQCD EG, $p_t(s)$ cut-off)

- Generate leading partons according to PDF
- Generate gluons from kt-factorization formula
- Valence quarks and gluons form strings with kinks:
  - Collinear g absorbed (low q_t)
  - Low invariant mass of quarks forms diquark
    recovers leading particle effect for low Q_S

Kt factorization

GLR 1983





$$\frac{dN}{dy\, d^2 p_t\, d^2 x} = \frac{4\pi N_c}{N_c^2 - 1}$$

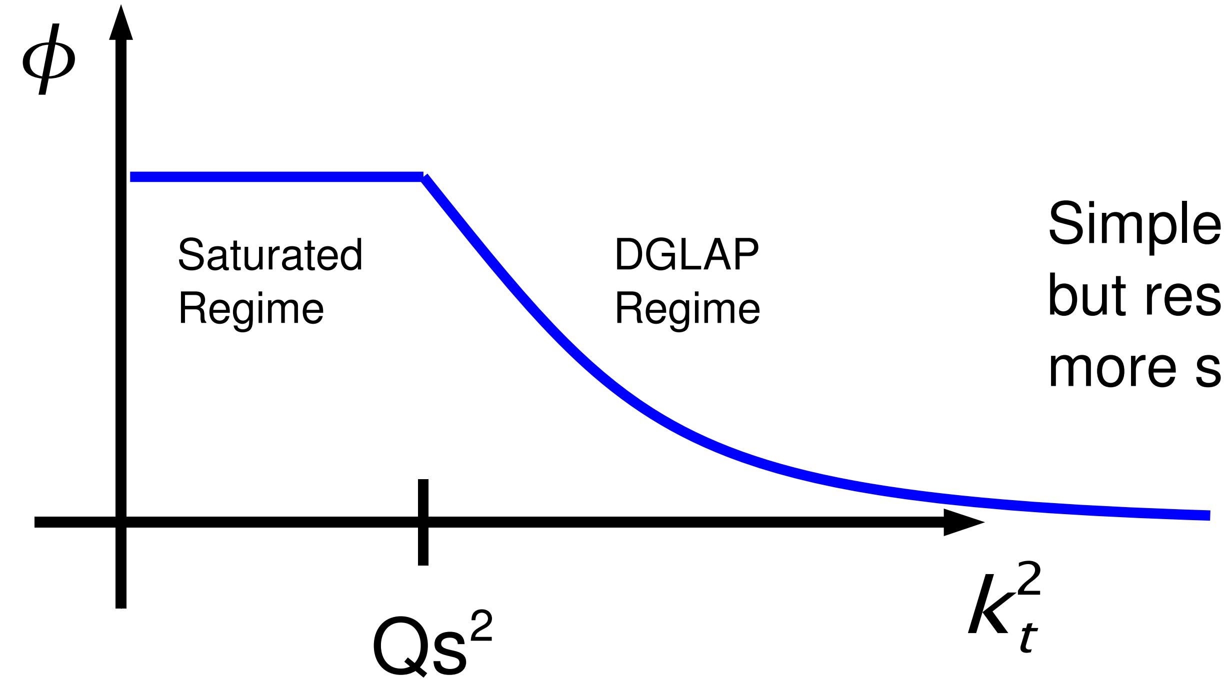
$$\times \frac{1}{p_t^2} \int^{p_t^2} dk_t^2\, \alpha_s\, \phi_A(x_{1,} k_t^2)\, \phi_B(x_{2,} (p_t - k_t)^2)$$

$\phi_A(x_{1,} k_t^2)$ Unintegrated gluon distribution function
use numerical integration instead of
approximations

Unintegrated gluon distribution functions

e.g.
Kharzeev et al.
Nuc.Phys.A 747

$$\phi_A(x,k_t^2) \sim \frac{1}{\alpha_s(Q_s^2)} \frac{Q_s^2}{max(Q_s^2,k_t^2)} (1-x)^4$$



Simple Ansatz
but results are similar to
more sophisticated choices

Saturation scale

$$Q_s^2(x) = 2\,\mathrm{GeV}^2 \left(\frac{n_{part}}{1.53}\right)\left(\frac{0.01}{x}\right)^{\lambda}$$

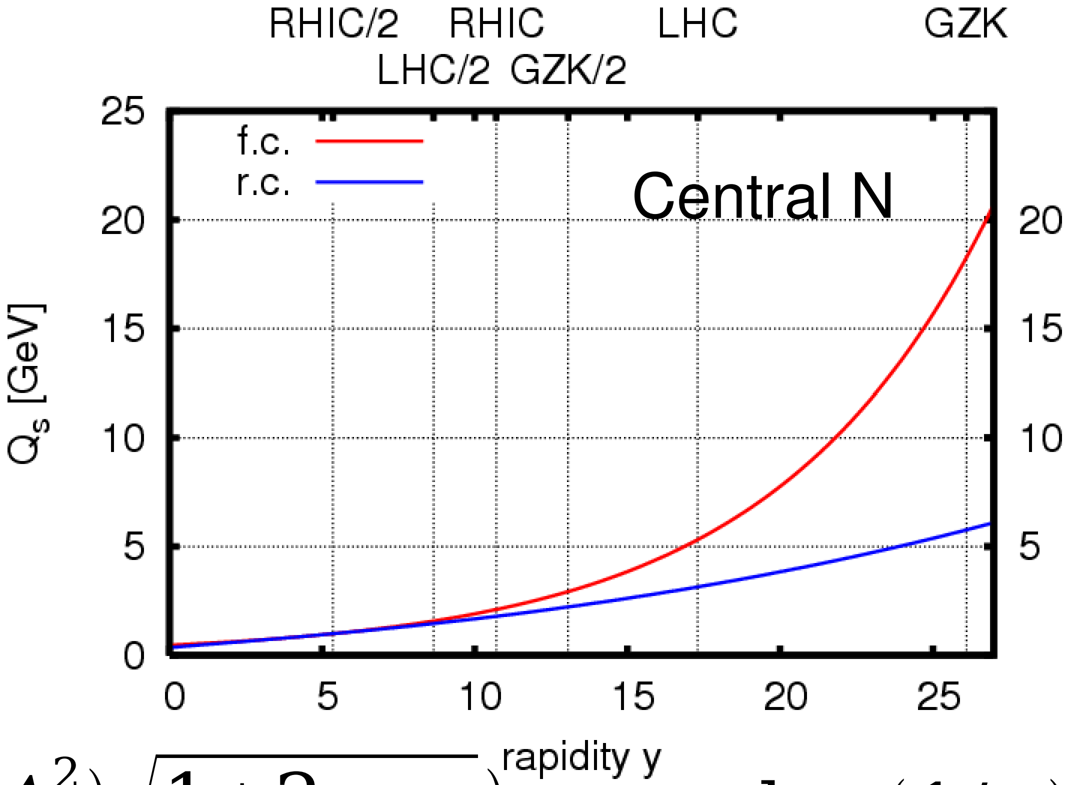
Fixed coupling evolution

$$n_{npart,A} = A\,T_A\left(1-(1-\sigma\,T_B)^B\right)$$

From Glauber model

$\lambda = 0.2 - 0.3$: determines growth with energy

n_{part} depends on properties of both nuclei → saturation scale not universal ???

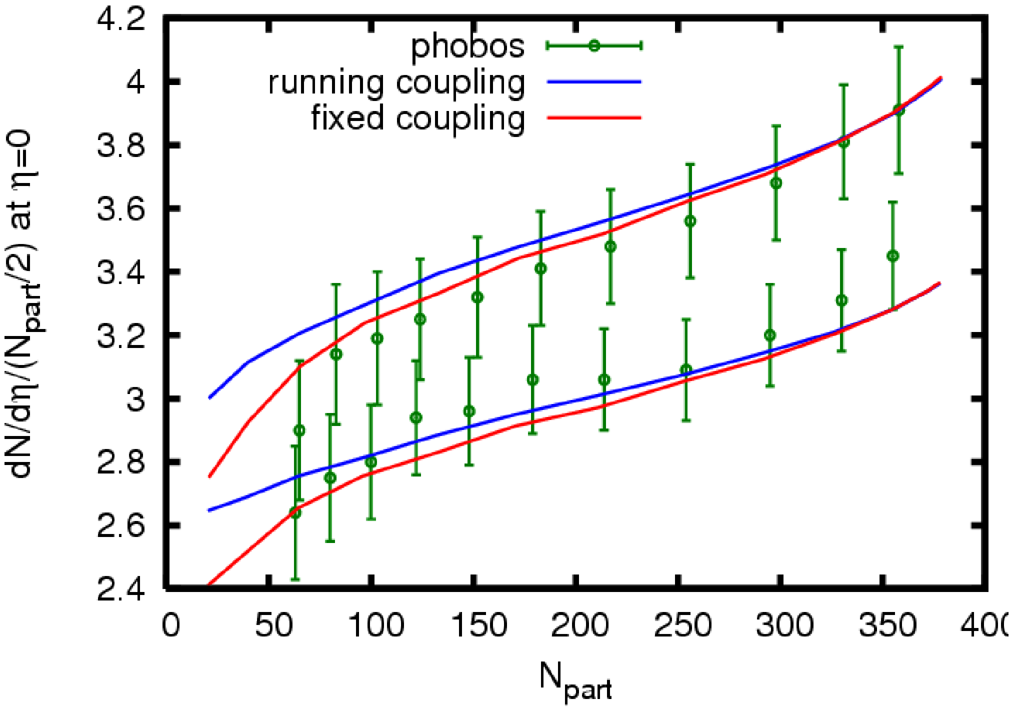


Running coupling evolution:

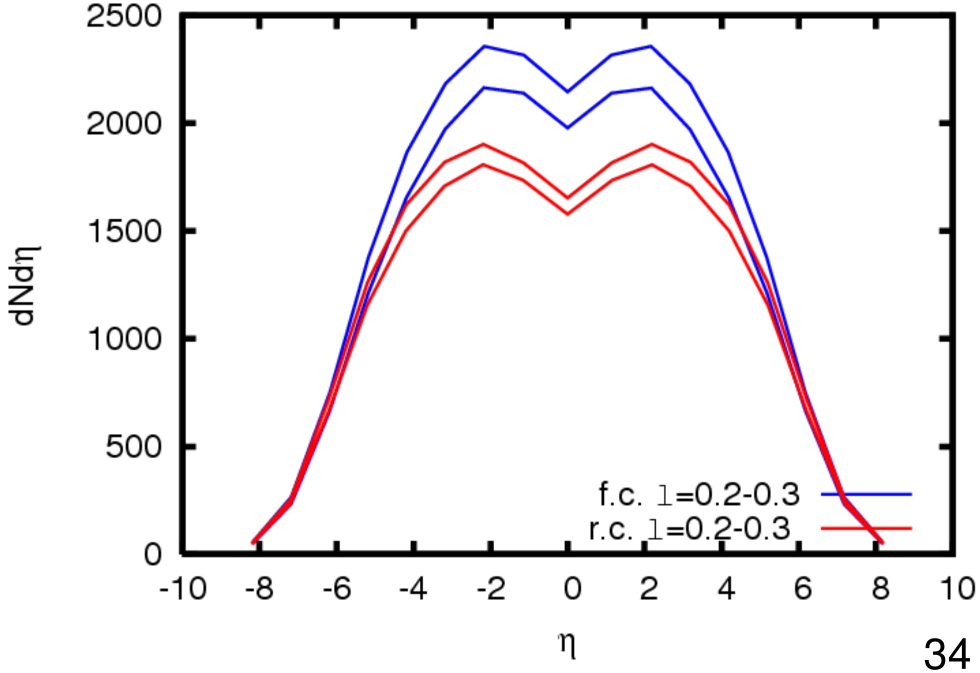
$$Q_s^2(x) = \Lambda^2 \exp\left(\log(Q_0^2/\Lambda^2)\sqrt{1+2c\,\alpha\,y}\right) \qquad y = \log(1/x)$$

kt Factorization results

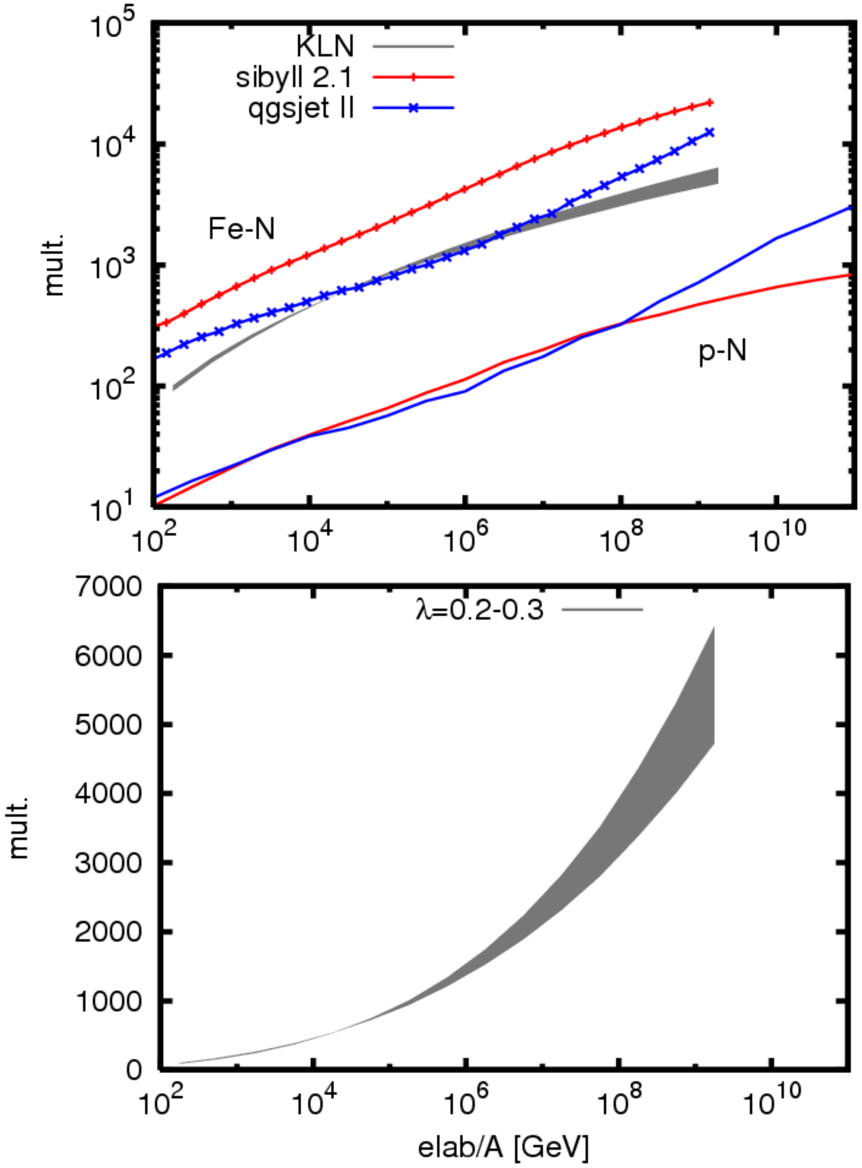
Good description of Multiplicity at mid rapidity for all centralities
200 and 130 GeV



Pb-Pb at 5500 GeV,
b=2.4 fm



Iron Air: total multiplicities



Central Fe-N collisions (running coupling)

total multiplicity as function of Elab/A

Uncertainty due to λ =0.2-0.3

Generation of leading quarks and strings in BBL

x-distribution: $P_i(x) = f_i(Q_s^2(x), x)$

$f_i(Q^2,x)$: GRV98 parton distribution functions

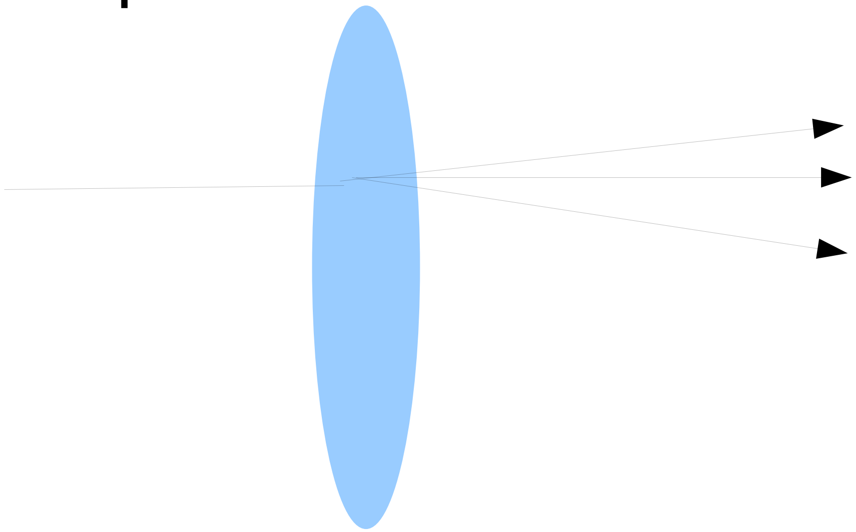
p_t distribution given by $C(p_t)$ $p_t \approx Q_s^2(x)$

$\bar{q}$------g --------g -------g-------g-------g------q_1
$\bar{q}$ ---------g -------g-------g-------g------q_2
$\bar{q}$------g --------g -------g-------g-------g------q_3

Gluons ordered in rapidity (x)

No energy loss of partons (L.Frankfurt,yesterday)
- would make effect even stronger

Diquark recombination at low transverse momentum



Check invariant mass between two quarks

if $M_{\mathrm{diquark}} < m_\rho = 0.77$ GeV

Recombine quarks to diquark recovers leading particle effect

Diquark recombination: central pN

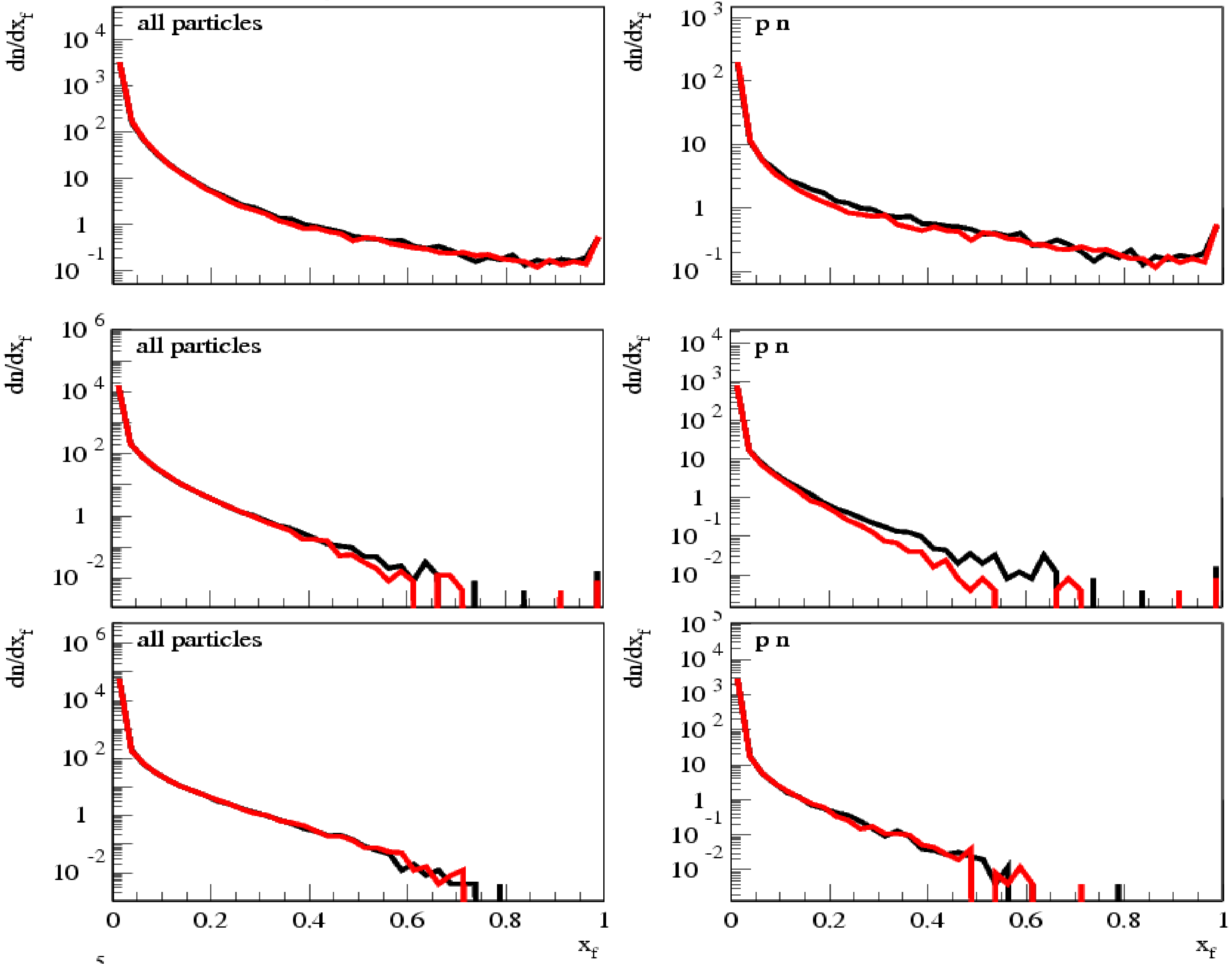
All particles

baryons

RHIC

LHC

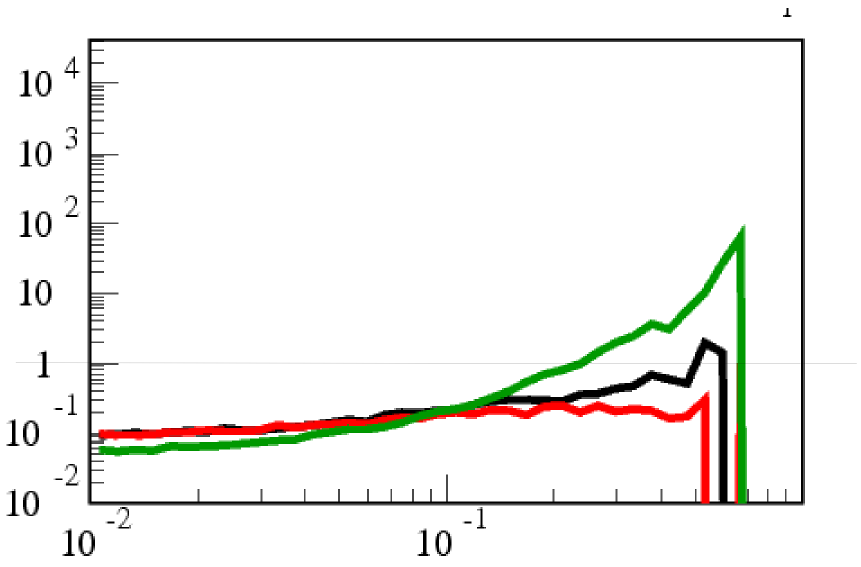
GZK



Baryon to meson ratio for forward direction central pN at LHC energies

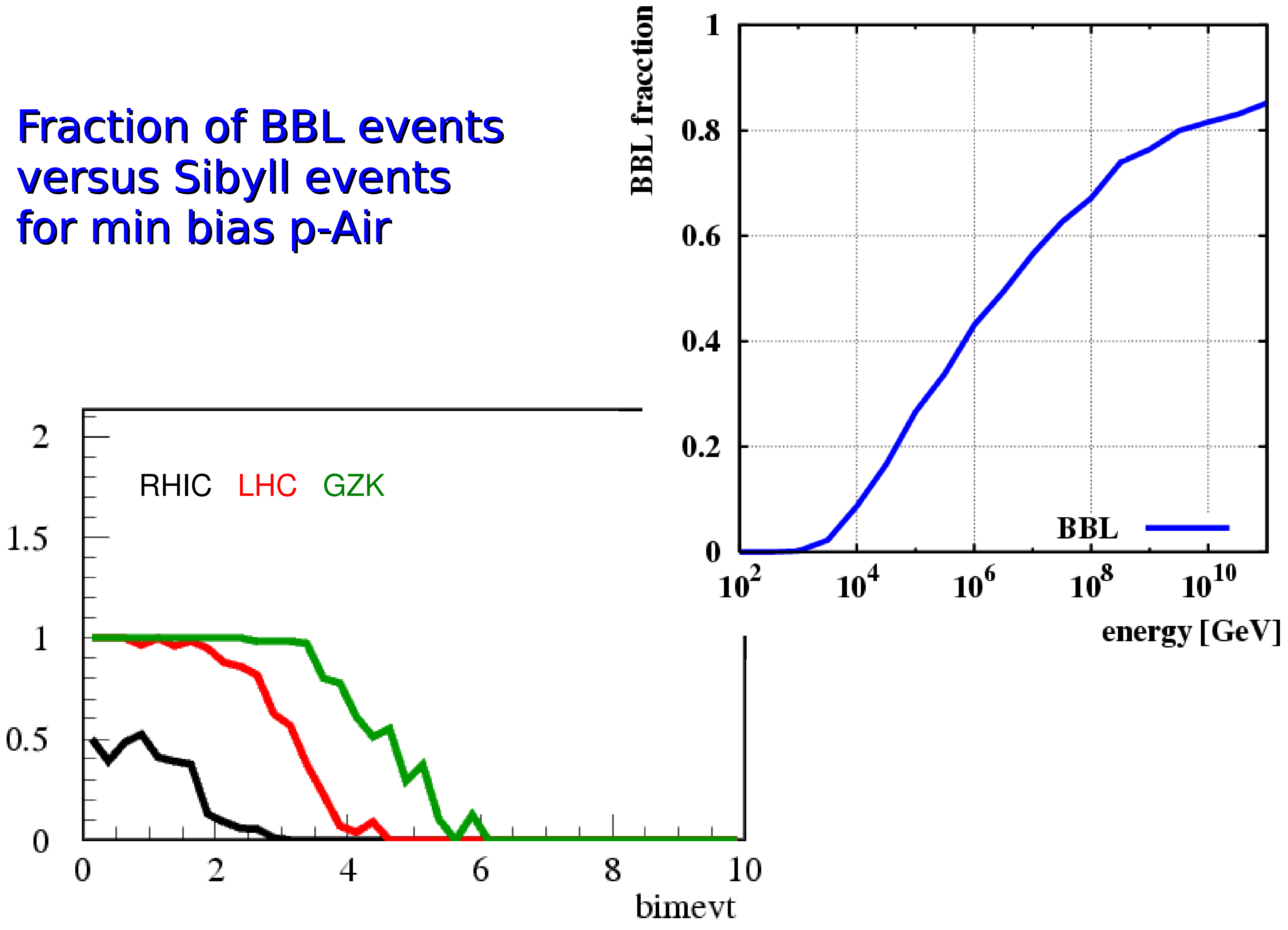
Ratio of baryon to meson production in forward region

Green: QGSJet-II
Red: BBL w.o. recombination
Black: BBL w recombination



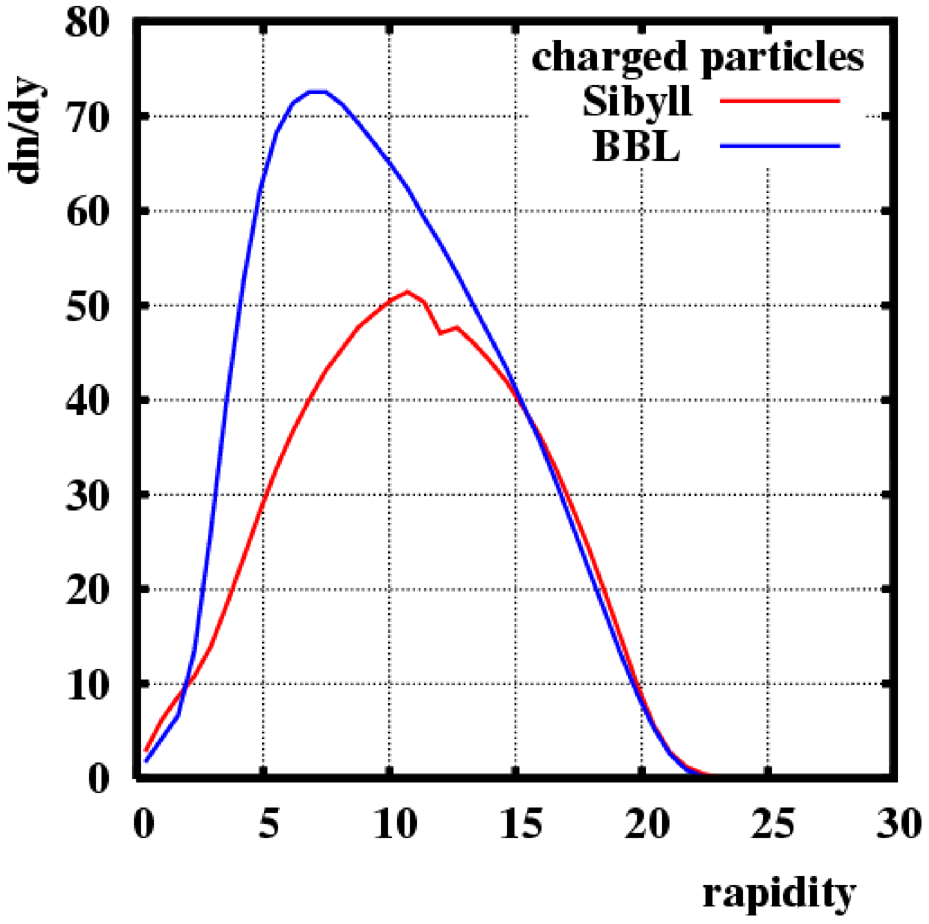
Without recombination: leading baryon completely suppressed

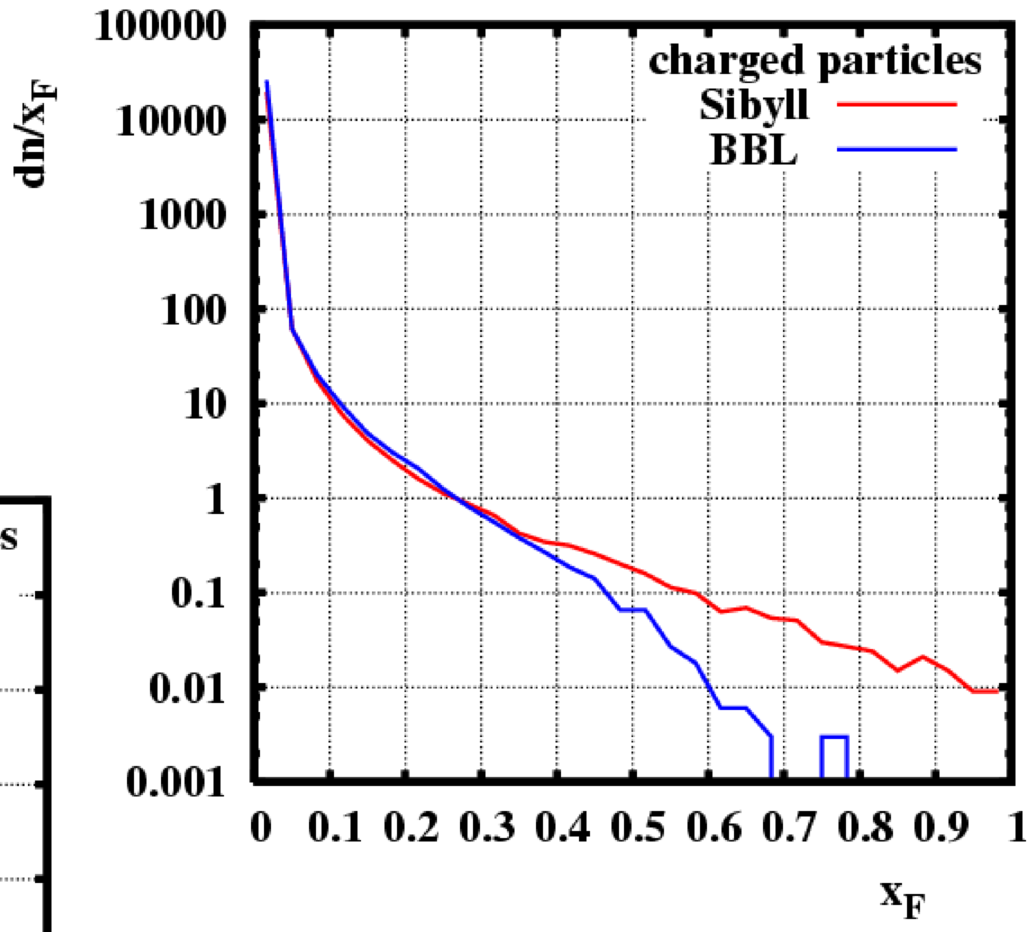
Fraction of BBL events
versus Sibyll events
for min bias p-Air



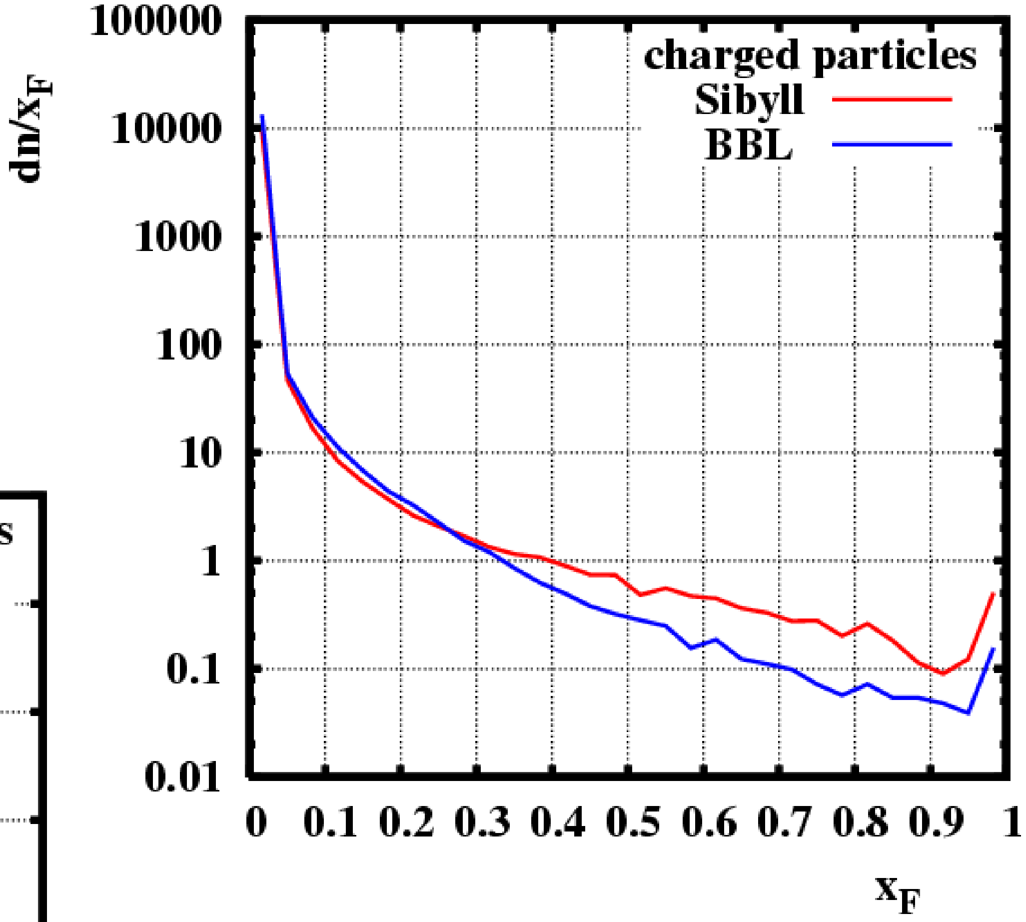
Central p-Air events

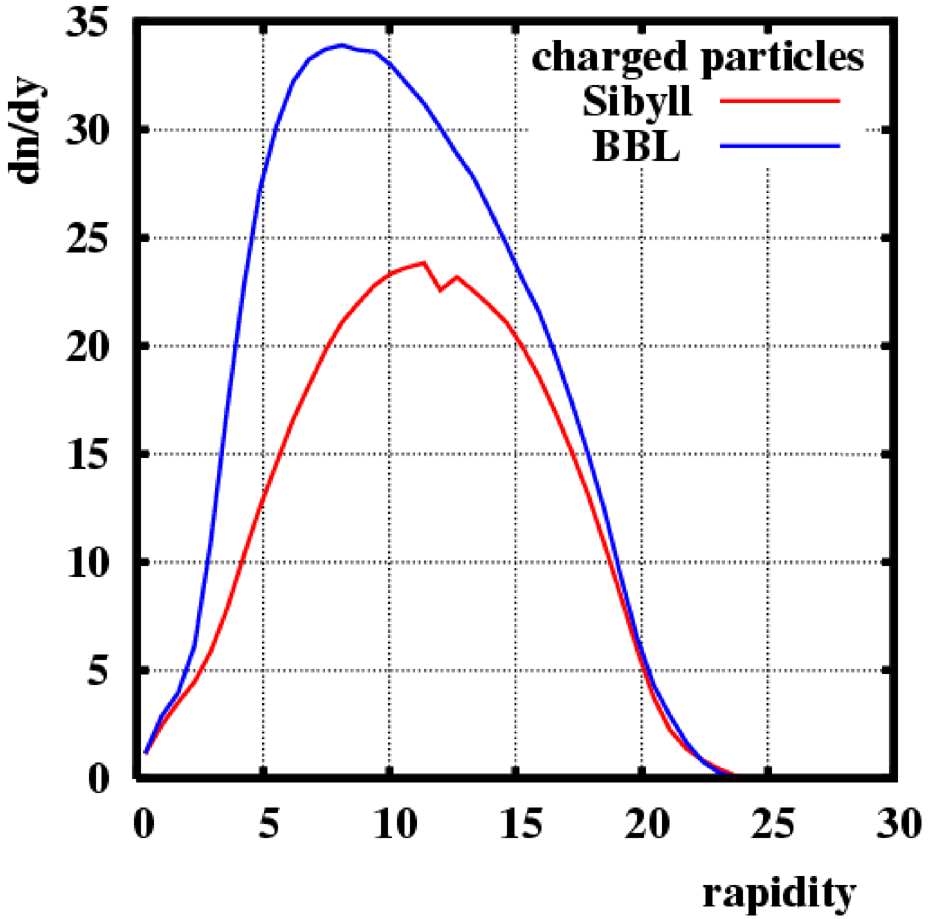
E=10^{10} GeV





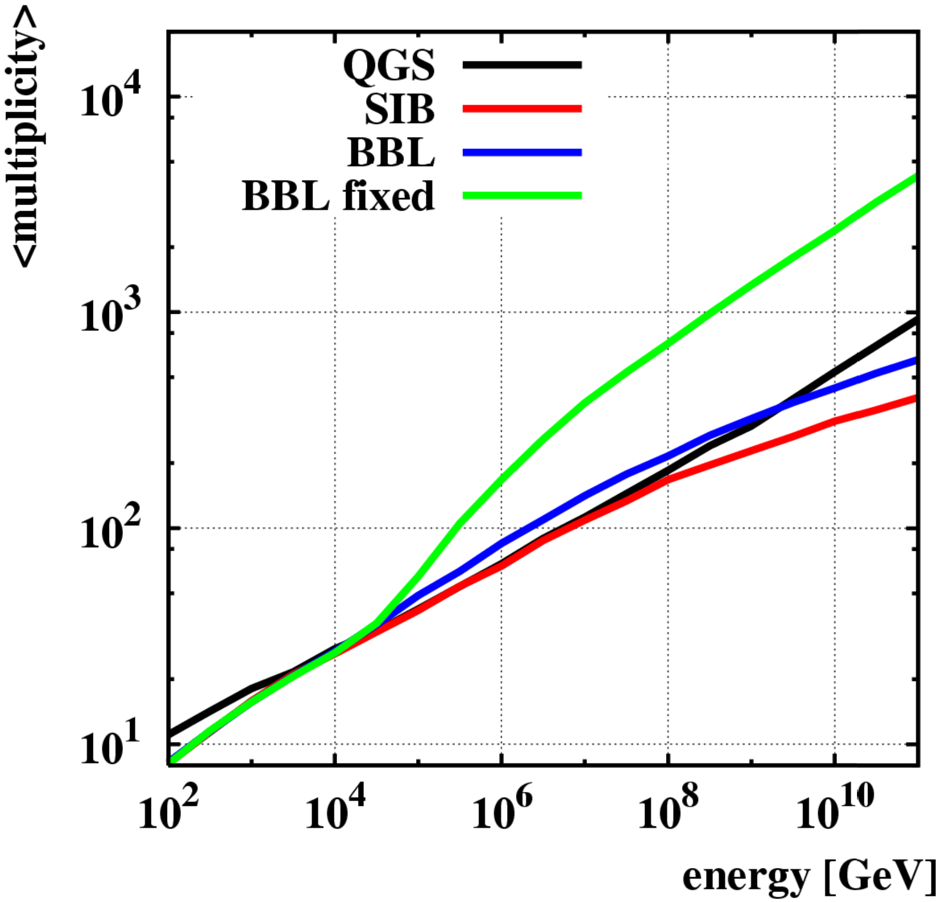
Minimum bias
p-Air events





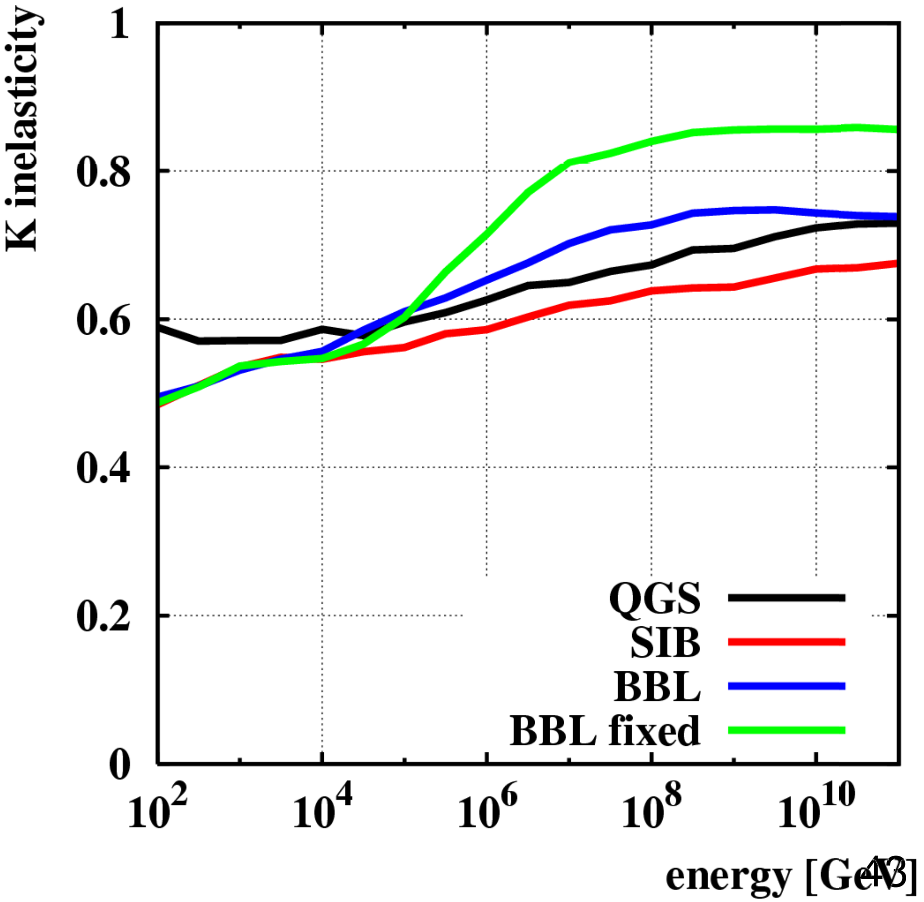
Event shape

Multiplicity

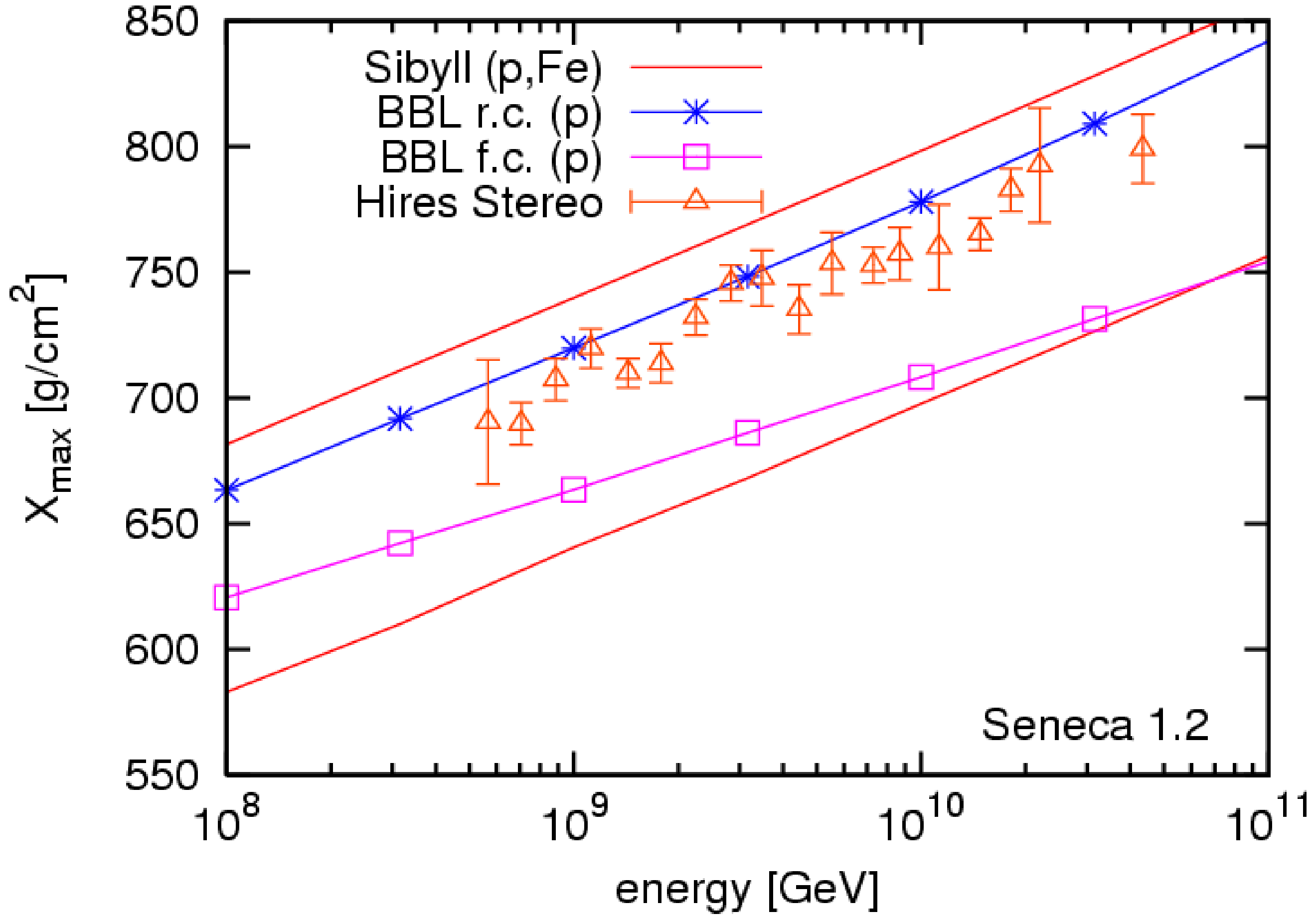


Inelasticity

K=1-<x_F of fastest particle>



X_{max} plot for fixed and running coupling



- Xmax sensitive to evolution scenario

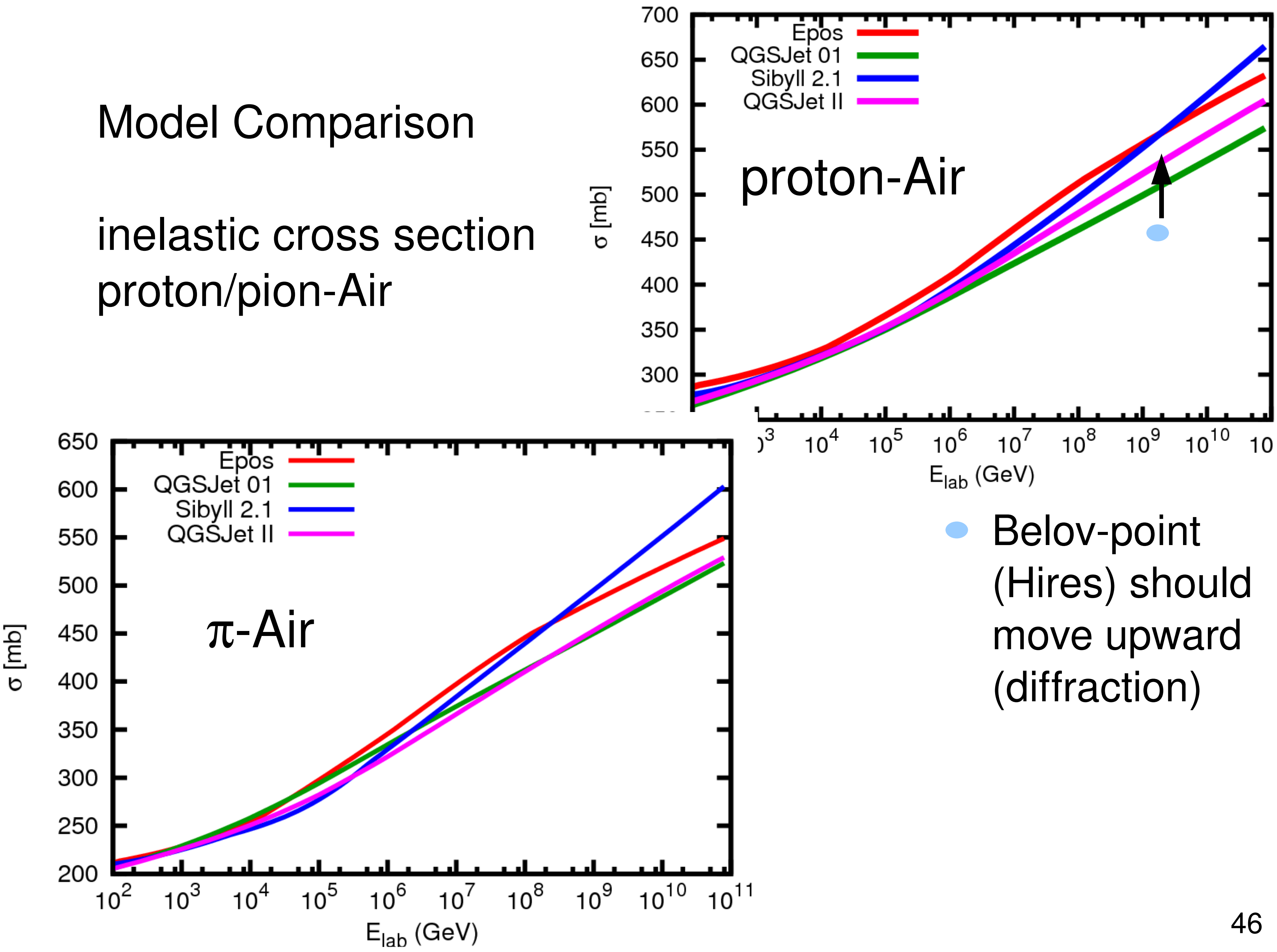
H.D, Dumitru, Strikman
Phys.Rev.Lett.94:231801,2005

Model comparisons show density effects in observables relevant for Air Showers:

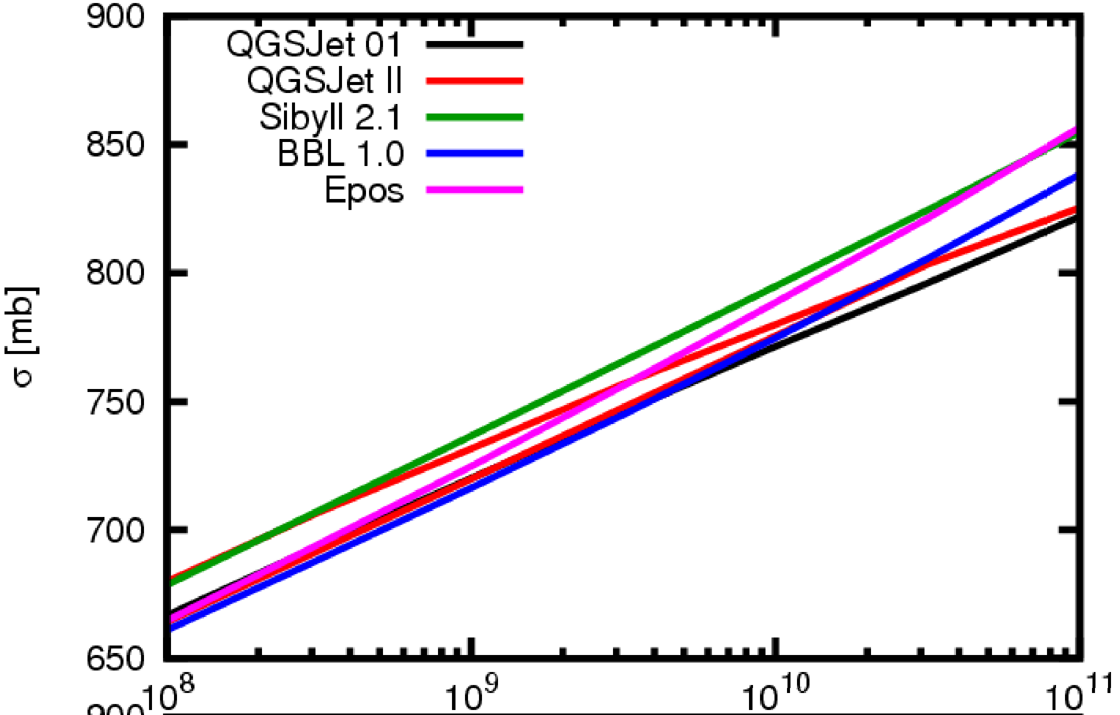
- QGSJet 01 versus QGSJet-II
- Sibyll versus Sibyll/BBL
- Epos

Model Comparison

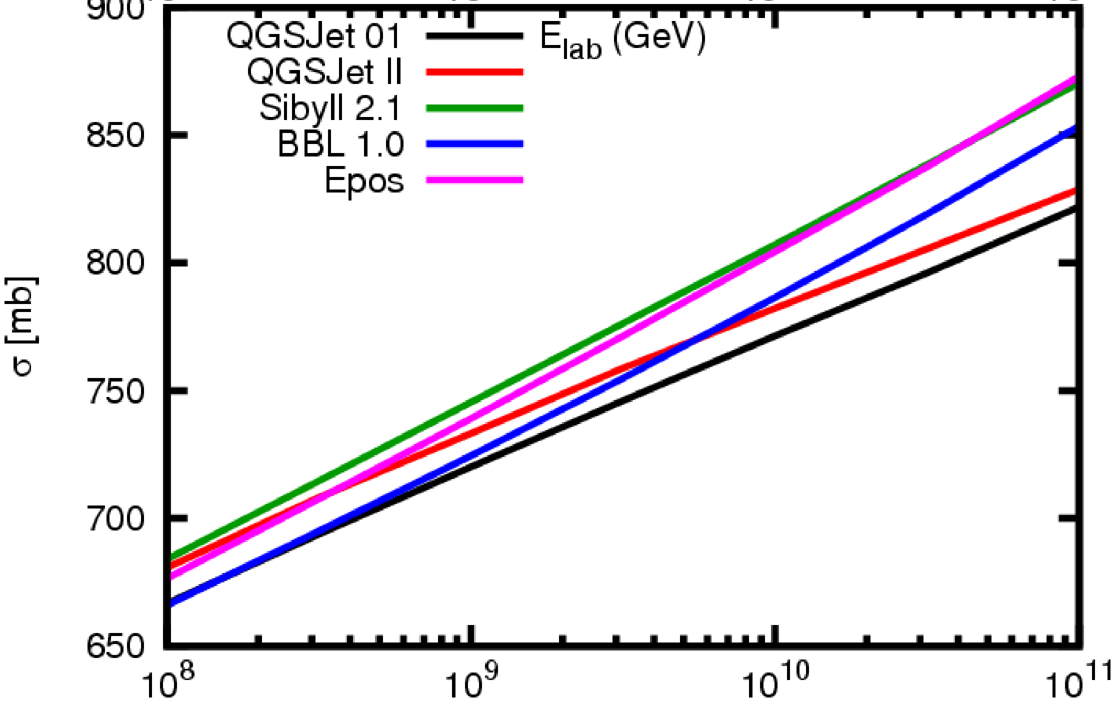
inelastic cross section proton/pion-Air



- Belov-point (Hires) should move upward (diffraction)

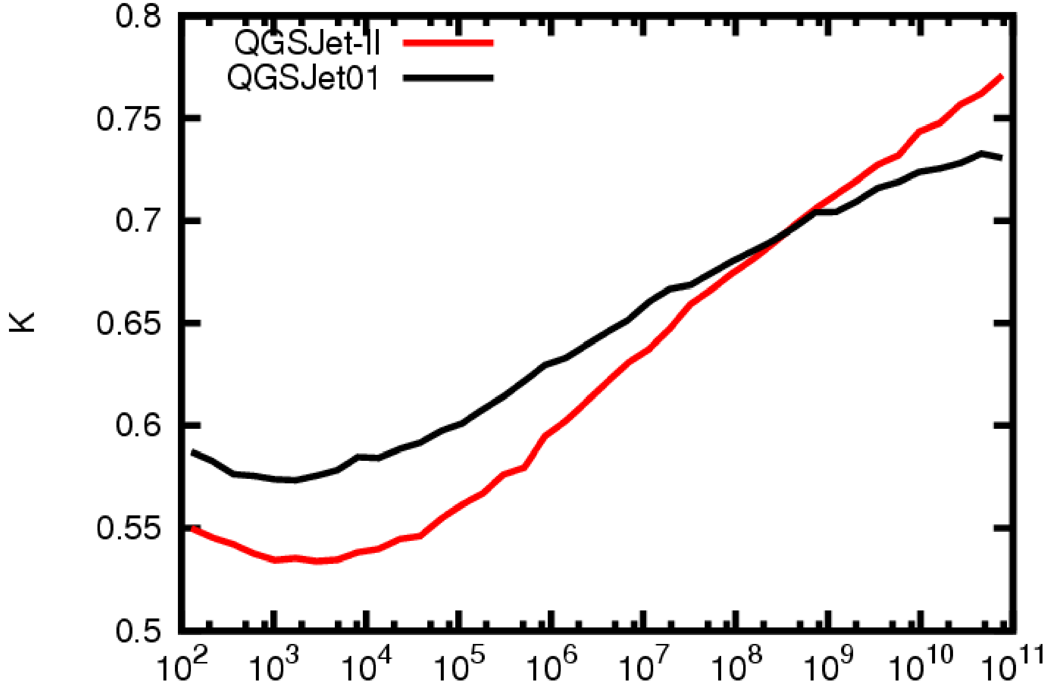


X_{max} of models

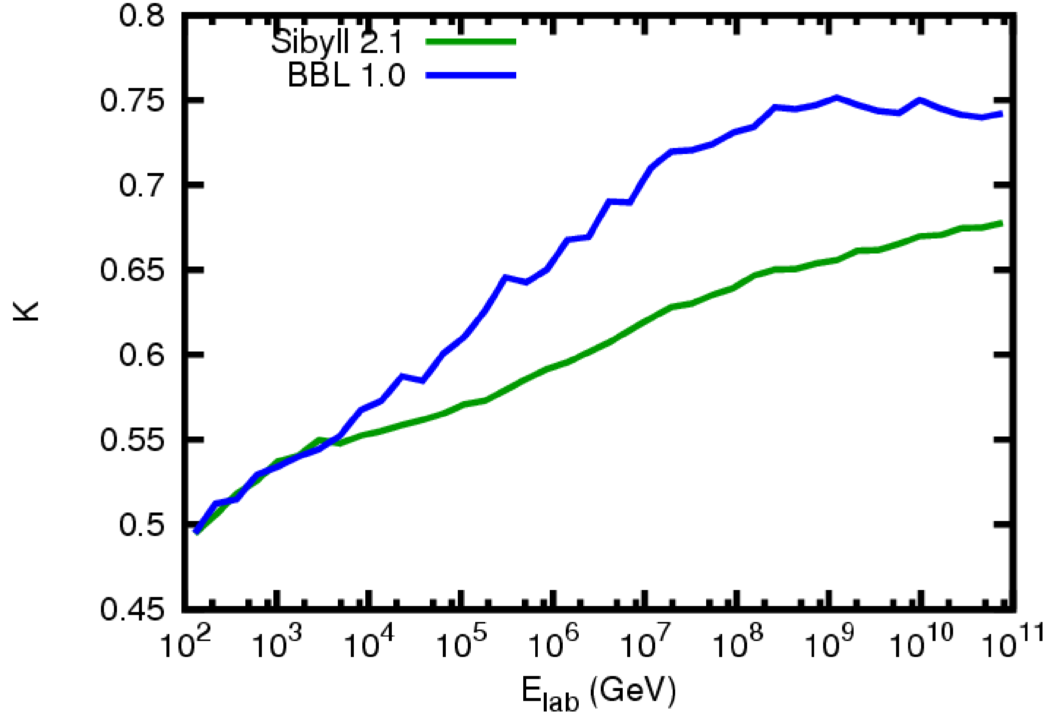


Xmax of models
for same
inelastic cross
section
from QGSJet01
particle production
even more different

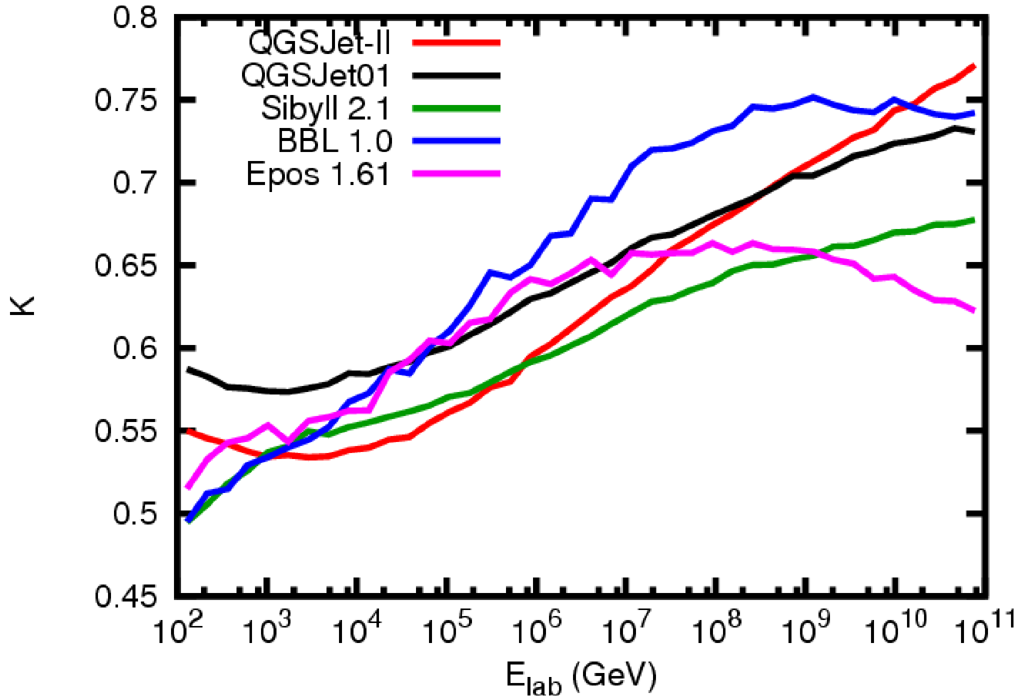
Inelasticity QGSJET01 – QGSJet- II



Inelasticity BBL – Sibyll-2.1



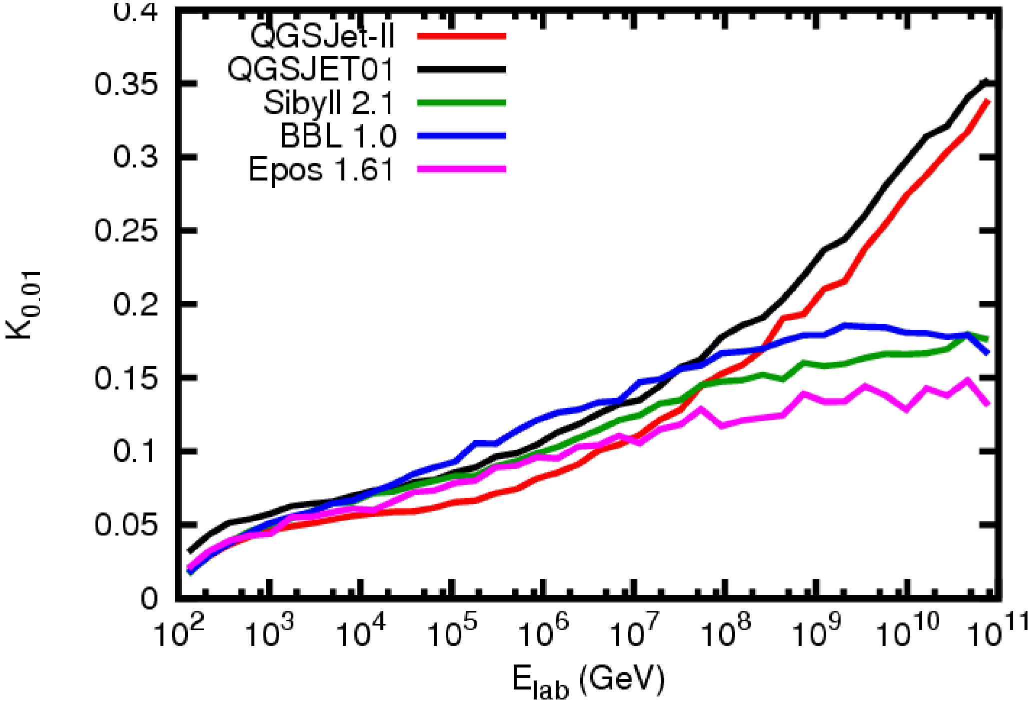
Inelasticity of all models



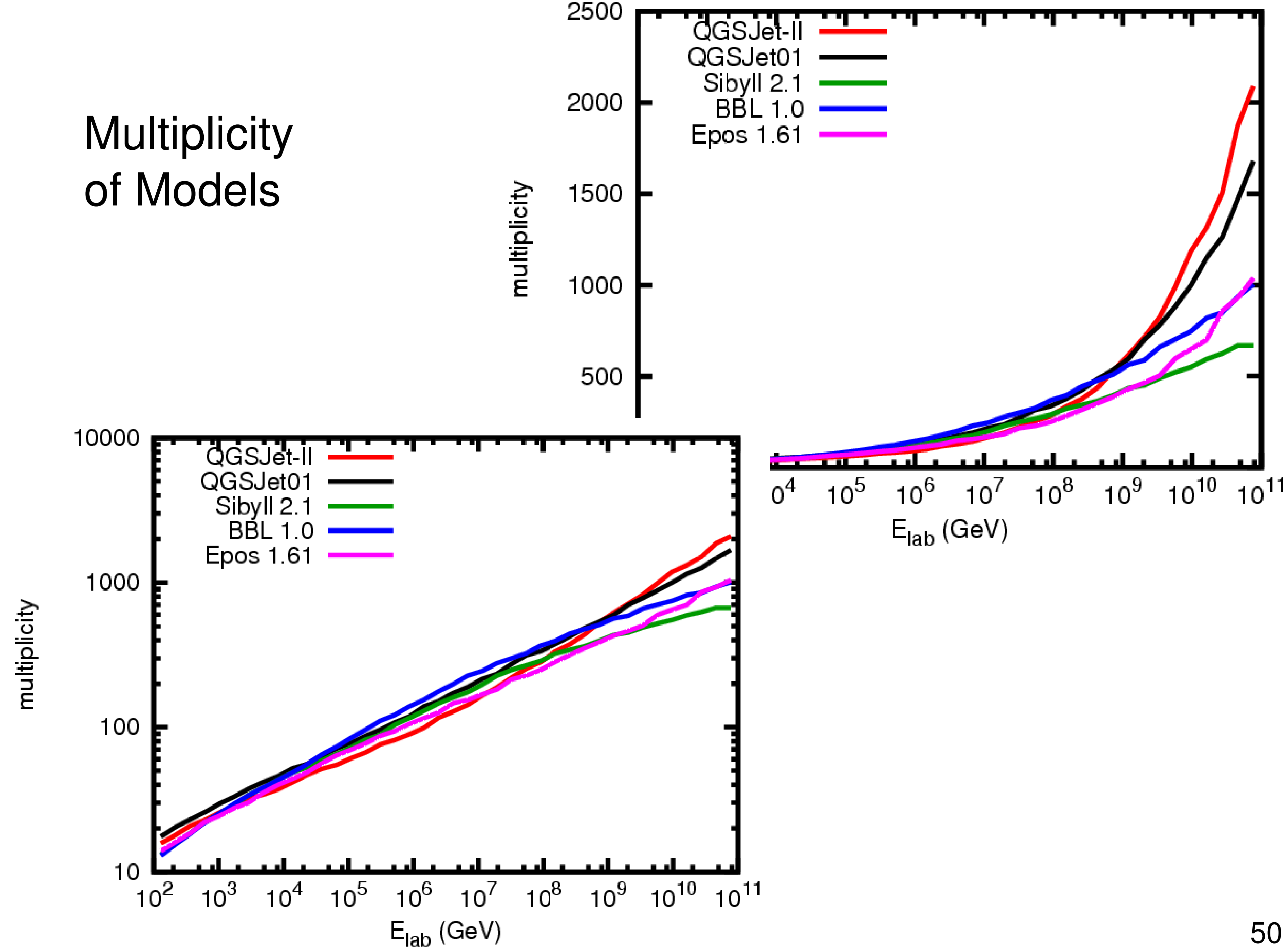
Inelasticity $K_{0.01}$

of all models

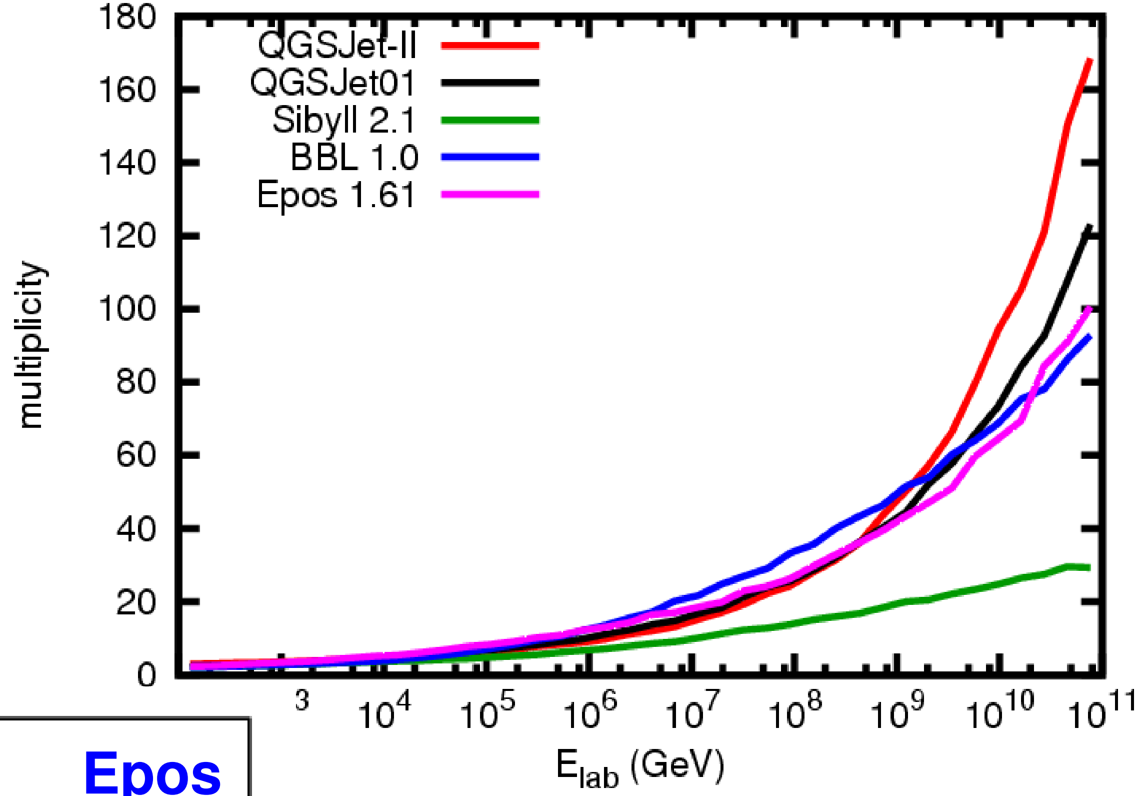
$$K_{0.01} = 1 - \int_{0.01}^{1} x_F \frac{dn}{dx_F} dx_F$$

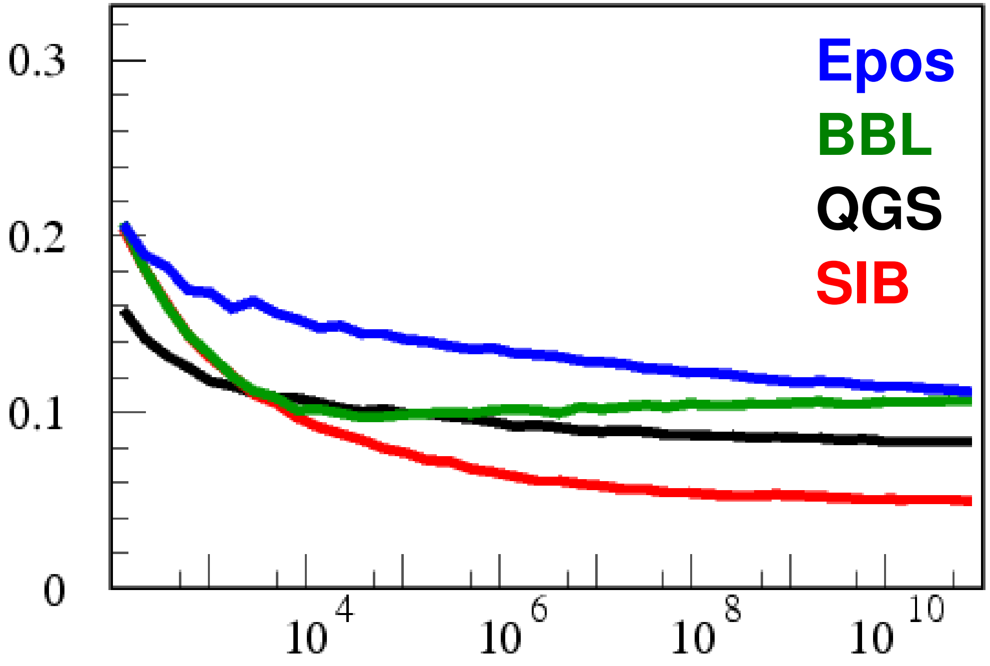


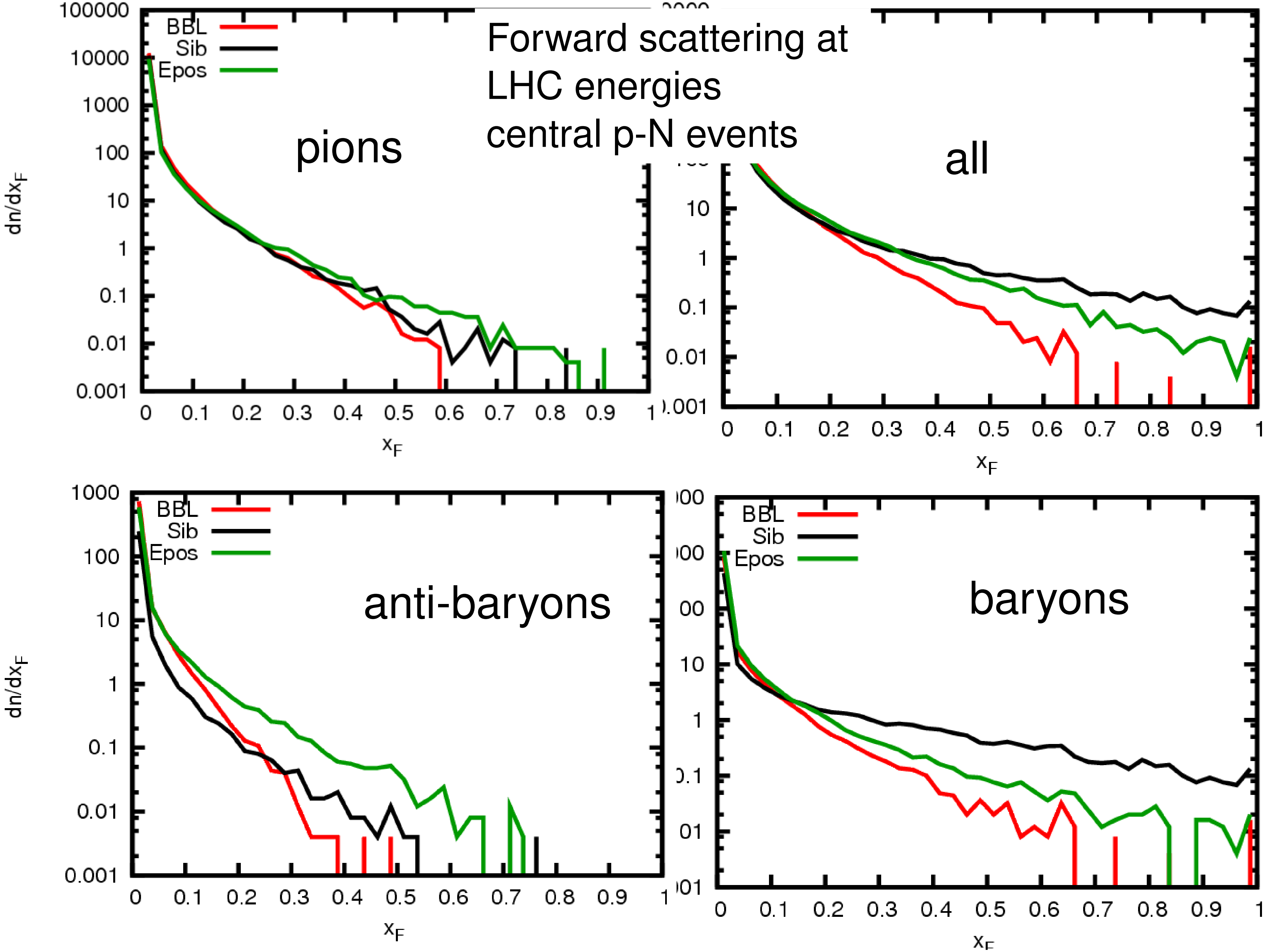
Multiplicity of Models



Baryons and baryon/meson ratio





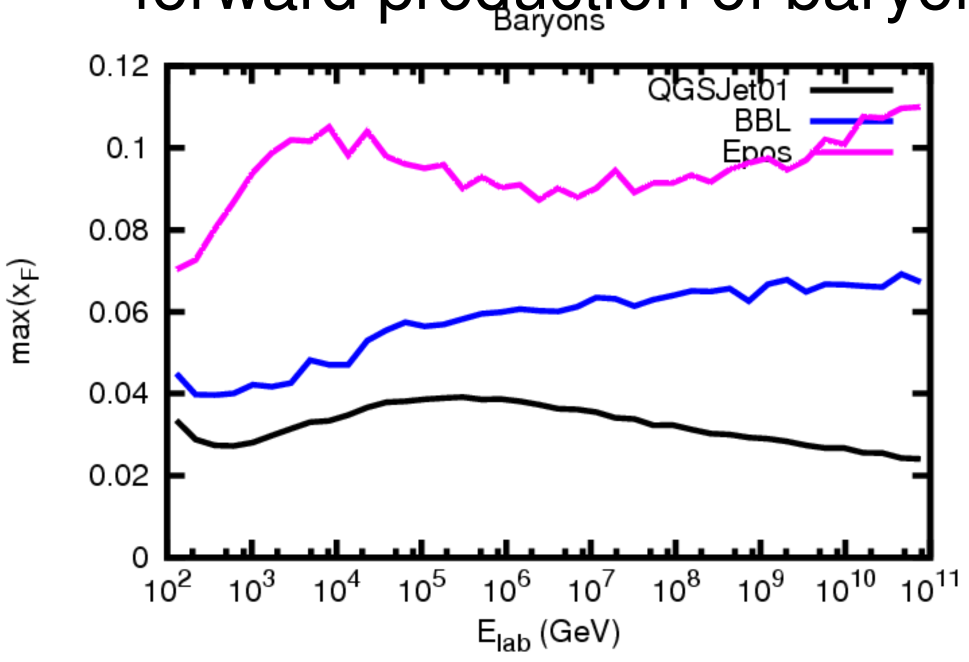


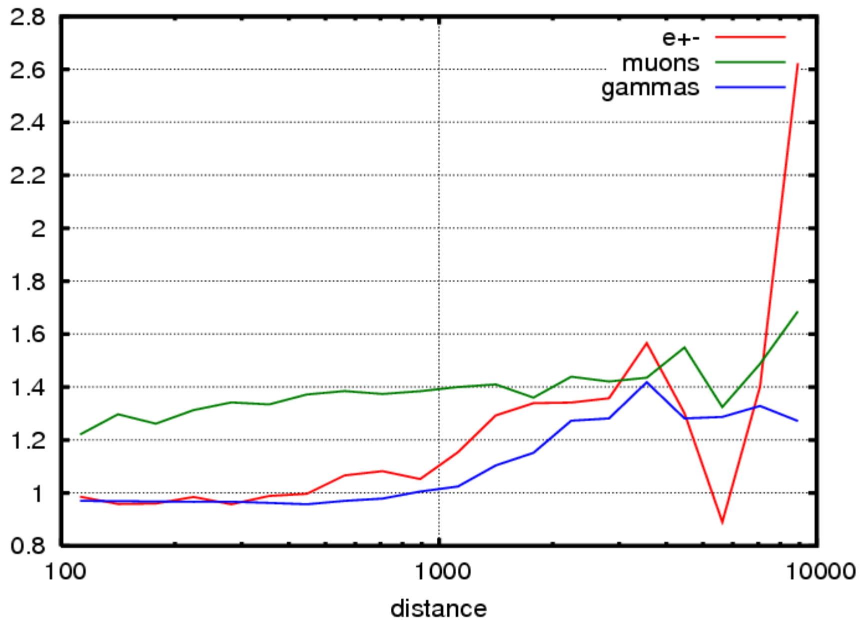
Forward scattering at LHC energies central p-N events

More Muons from Epos due to enhanced production of baryons

Produce more particles which stay in the hadronic channel of an air shower (p/n instead of pi0)

max(xF of baryon for $\pi^{\pm}$ – Air) forward production of baryons





Conclusion

- hadron Nucleus collisions main uncertainty for Air-shower simulations
- many approaches for high density/small x
- leading particle suppression in black disk limit
- checking models thoroughly with data is good (Epos)
- extrapolation to high energies still unclear