Air Shower simulations with CORSIKA

Part 2

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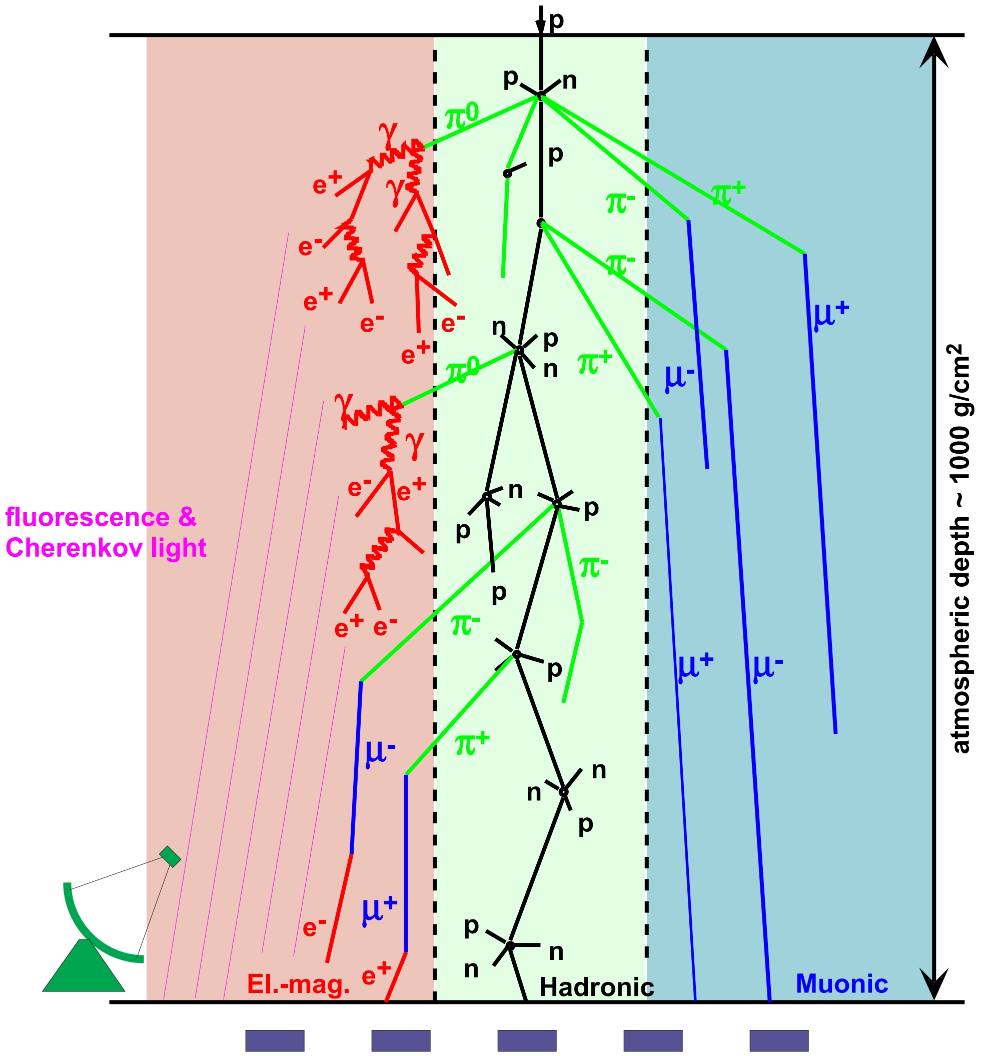
A qualitative overview

(... while Ralph and Tanguy
provide the hard, quantitative info)

Schematic Shower Development

energy
particle type
direction ???



detector response: energy deposits, times,
efficiencies, thresholds, ...

One primary particle produces millions (billions) of secondaries:
i.e. an air shower

Shower development depends on:

- hadronic interactions,
- electromagnetic interactions,
- particle production,
- decays,
- transport, ...

Complex interplay of many effects:

- no analytic solution possible
- no test beam for calibration available

(at least for really high energies)

p, n, π : close to axis

μ, e, γ : widely scattered

$N_{e,\gamma} : N_{\mu} : N_{had} = 10000 : 100 : 1$

$E_{e,\gamma} \sim$ 10 Mev, $E_{\mu} \sim$ 1 Gev

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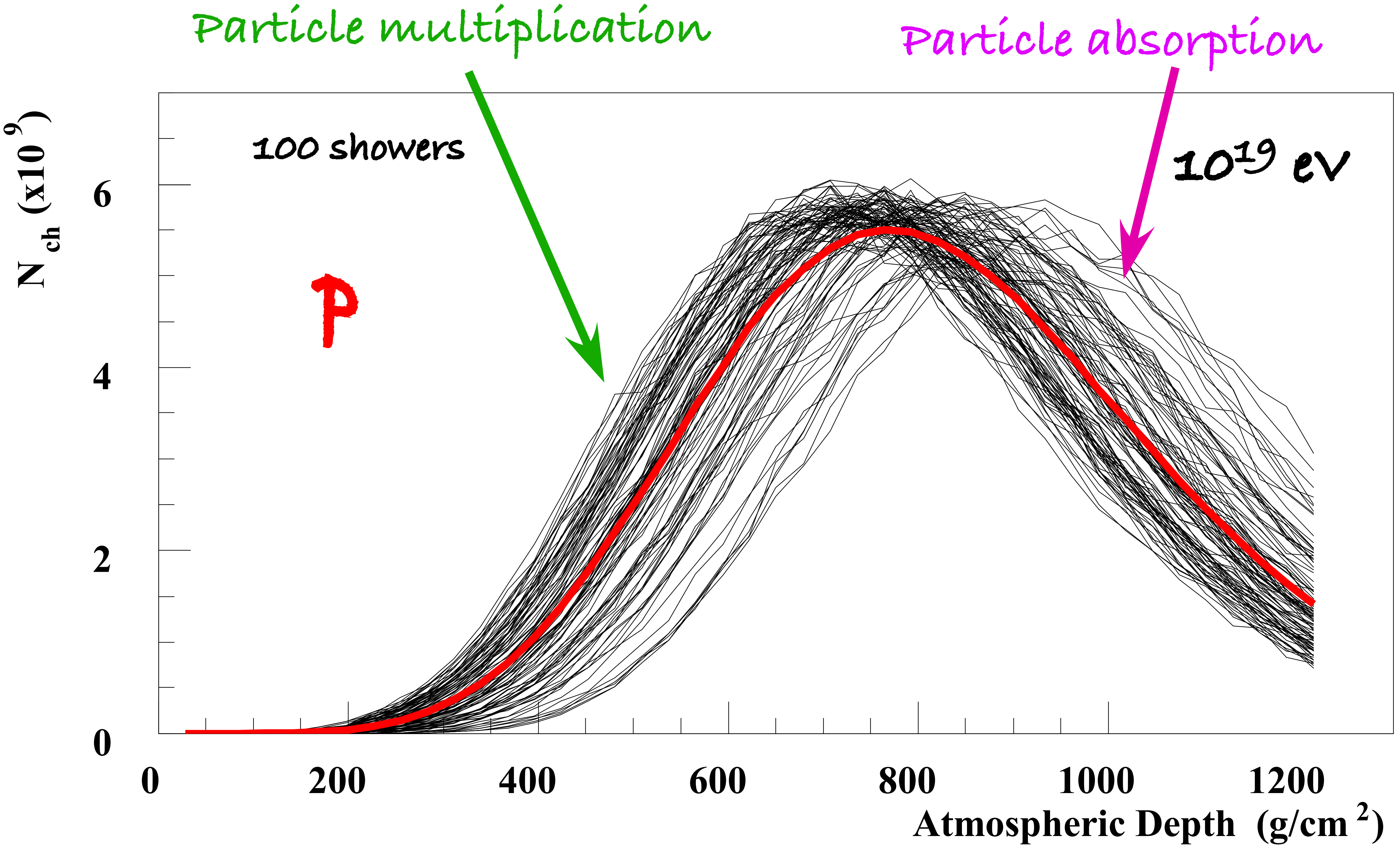

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Longitudinal Shower Profiles

difference in X_{max},
but large fluctuations

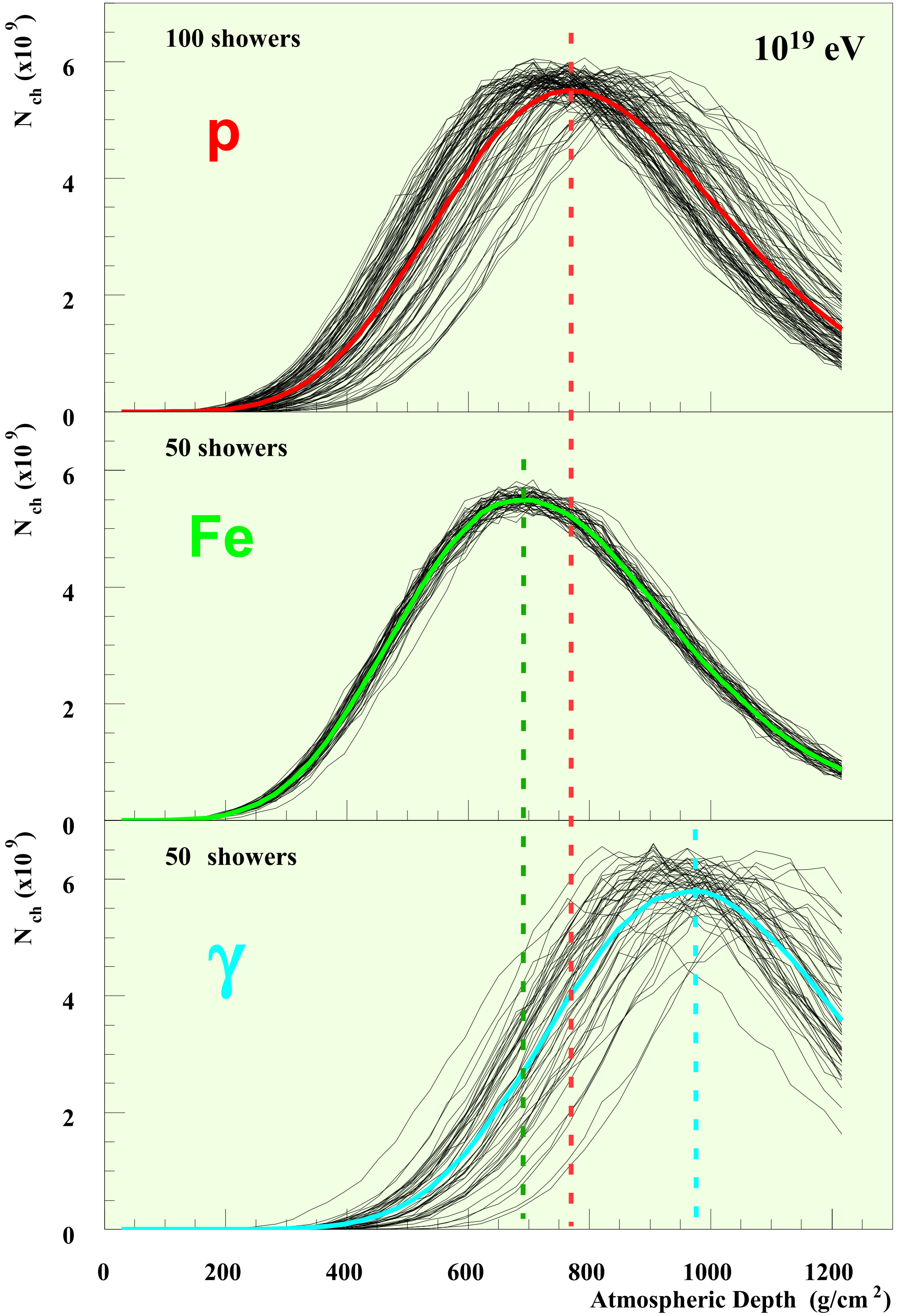
differences between
hadrons and photons are large

differences between
proton and iron (or nuclei)
are subtle

On average Fe have:

- higher 1st interaction, since σ_{int} larger,
- more secondaries, since $N_{sec} \sim \ln(E)$,
- more μ, less e,γ at ground,
- smaller fluctuations,
  since superposition of 56 subshowers
- faster signal rise, since μs faster

than p showers.



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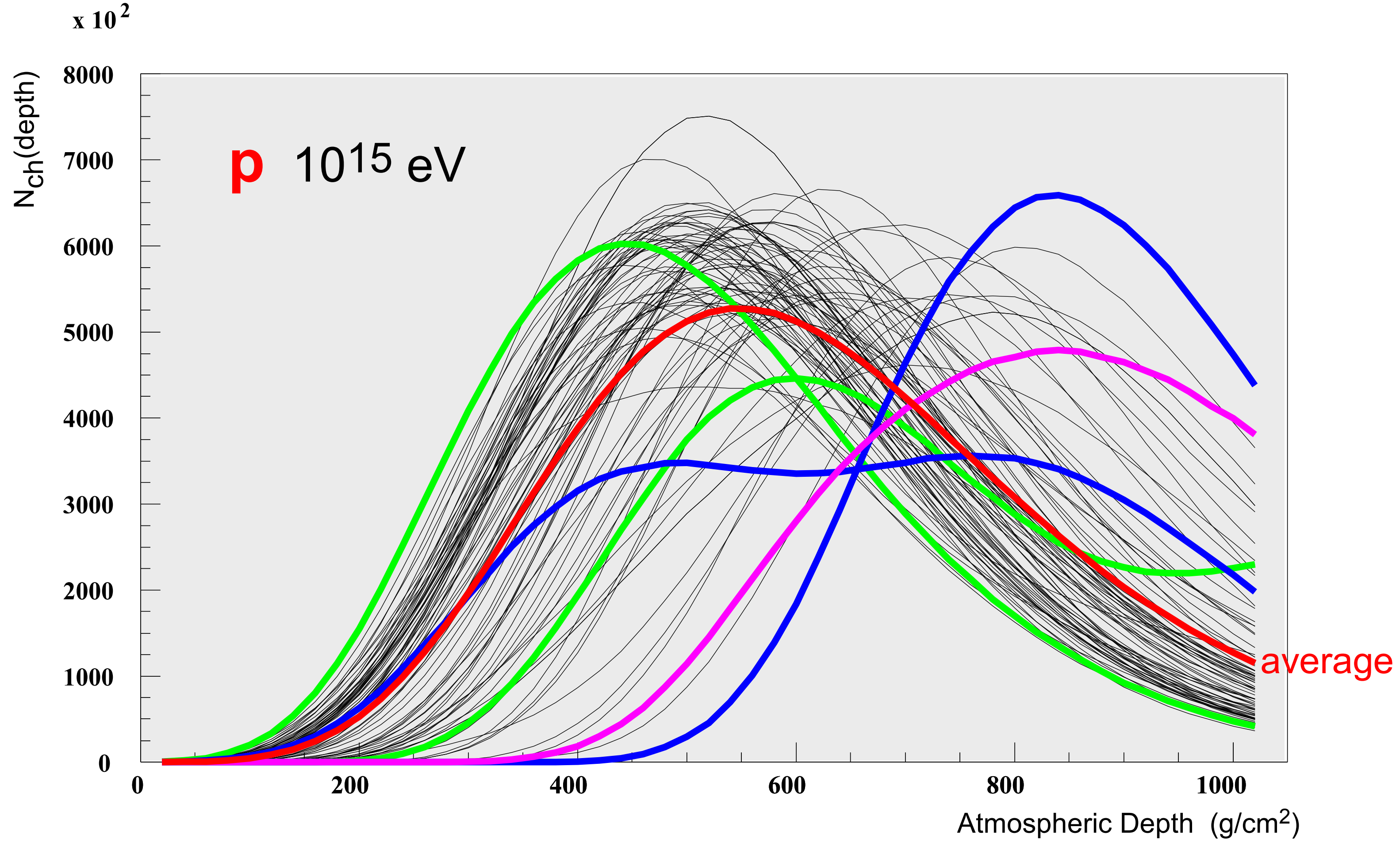
Longitudinal Shower Development



at lower energies:

large fluctuations

"strange" shower curves because of fluctuations in height and type of first few interactions.

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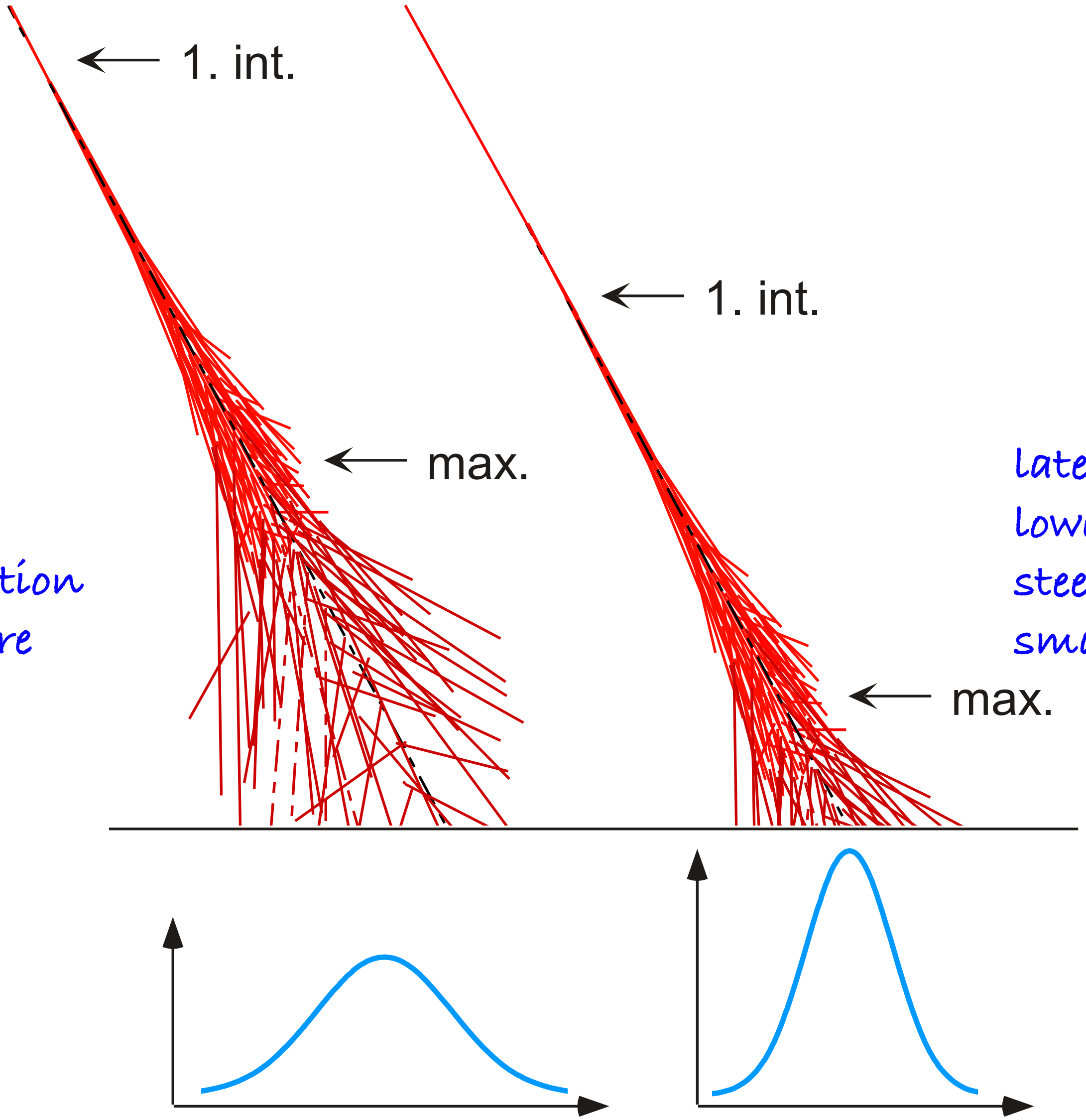
Lateral Distribution



early start,
high maximum,
flat lateral distribution
large front curvature
more muons

late start,
lower maximum,
steep lateral distribution
small front curvature
fewer muons

lateral distribution is sensitive to X_{max} (i.e. to particle type)

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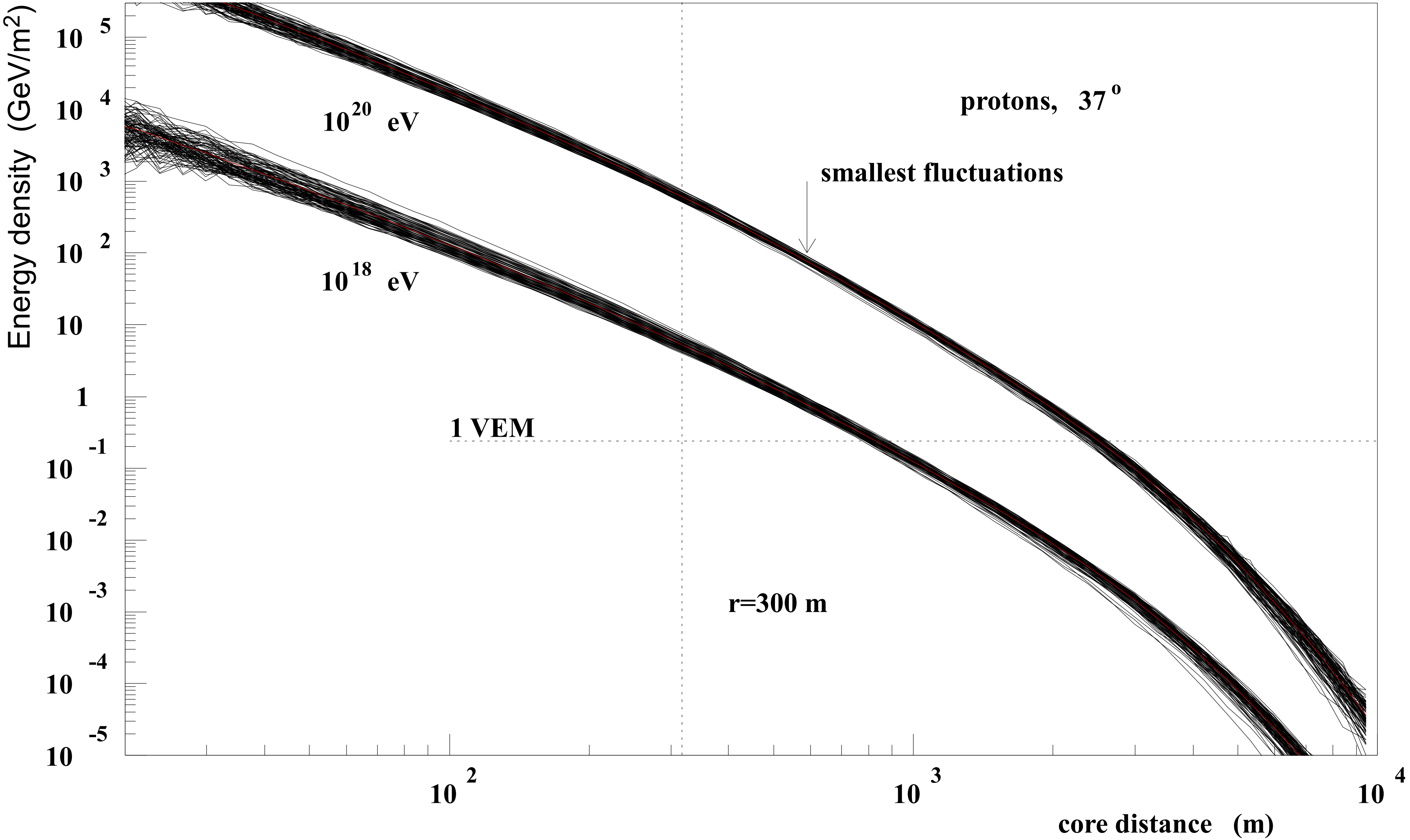
Lateral distribution of energy deposit: protons 37^0



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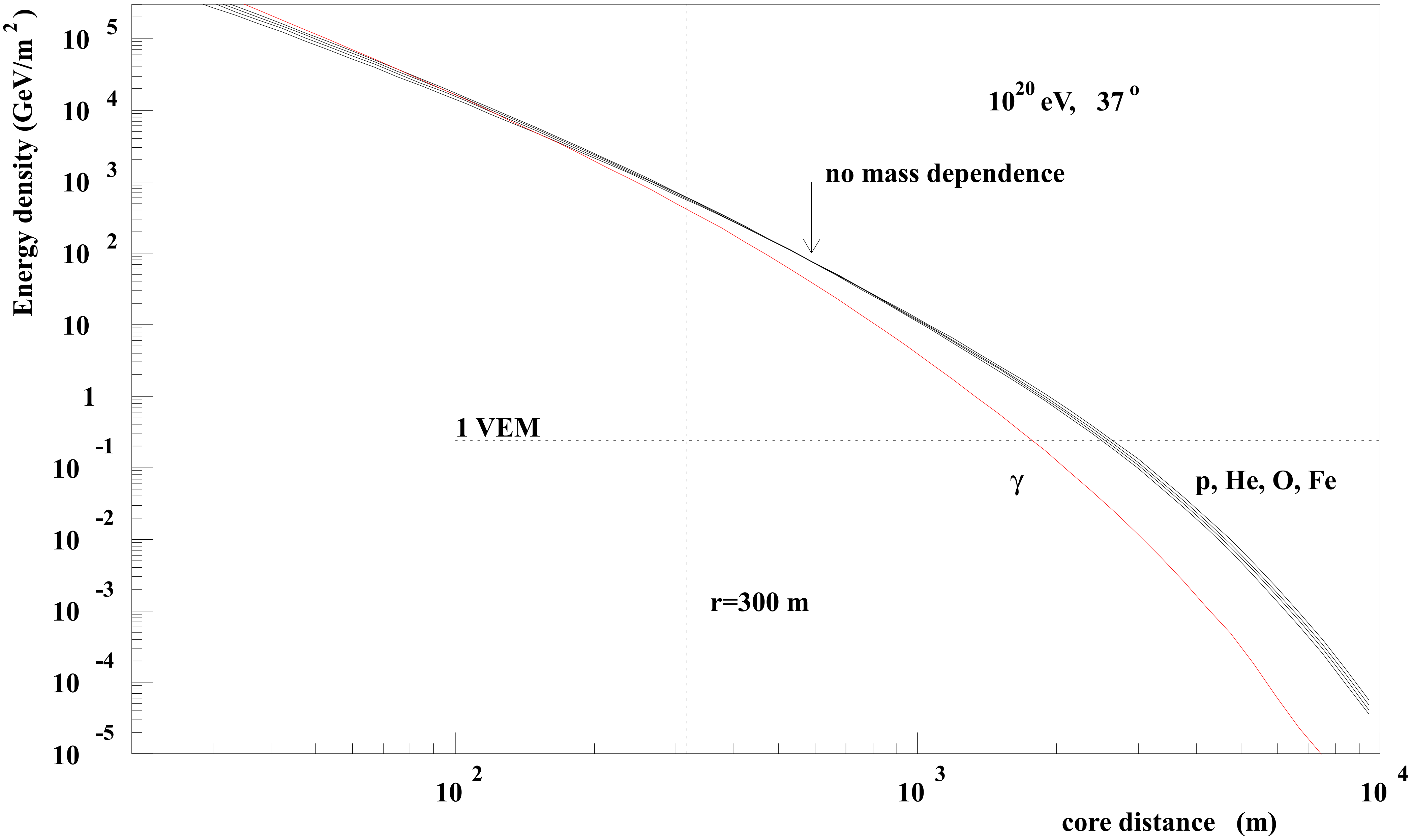
Lateral distribution of energy deposit: different masses



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How to build an air-shower model?

1. The detector medium:
   Atmospheric composition, density as function of height

2. The beam: p, He, ... Fe, γ, ν, exotics ???
   p, e, γ, μ, K, Λ, Σ, ... (all known particles)

3. Particle interactions
   cross sections & particle production
   for electromagnetic and
   for nuclear & hadronic interactions

4. Particle tracking in magnetic field,
   ionisation, energy loss, Cherenkov light
   multiple scattering, decays, absorption

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   cross sections & particle production
   for electromagnetic and
   for nuclear & hadronic interactions

This is crucial !

4. Particle tracking in magnetic field,
   ionisation, energy loss, Cherenkov light
   multiple scattering, decays, absorption

How to build a hadronic interaction model?

1. invent a model for p-p collisions (simple or elaborate)
2. tune to reproduce experimental results for p-p
3. extrapolate to higher energies

add:

4. diffractive processes
5. hard processes
6. p-N, π-N and N_1-N_2
7. nuclear physics
8. fragmentation of strings into hadrons

....

Problems arise mostly with 4. - 8.

Agreement with p-N, π-N and N-N data is usually worse than with p-p data.

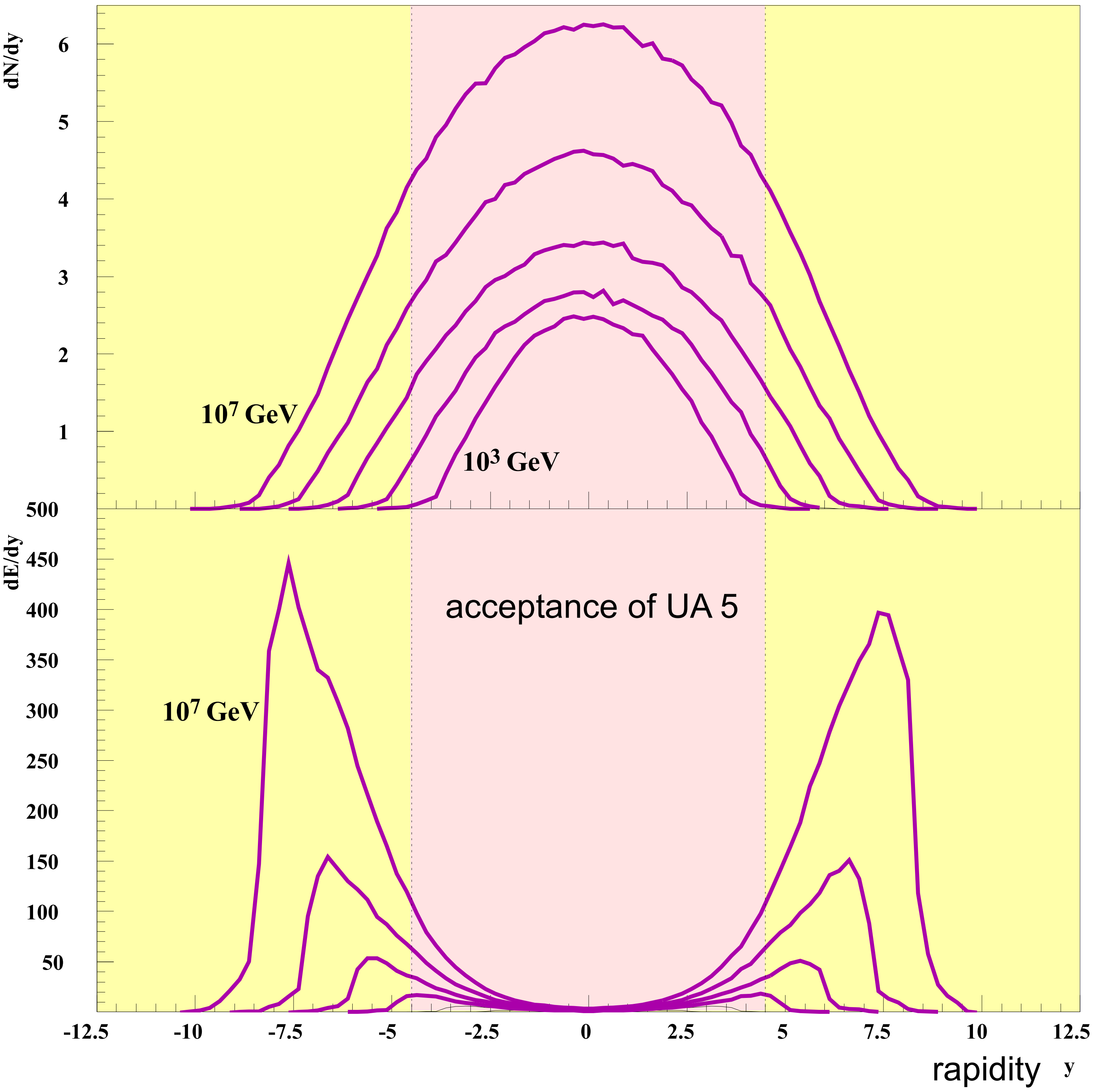
Anything to learn from Accelerator Experiments ?

	In air showers:	At accelerators:
Projectiles:	p, He, ... Fe, ... γ, (ν) $p, n, \pi^{\pm}, K^{\pm,0}, \Lambda, \Delta$, ...	$p, \bar{p}, e^{+}, e^{-}, A, \gamma, \nu$, $n, \pi^{\pm}, K^{\pm,0}$
Targets:	O_2, N_2, Ar in air	p, e^{-}, A
Energies:	$E = 10^{9} \ldots\ldots 10^{21}$ eV (= 10^{9} TeV !!) (all are important !!!)	$E < 1$ TeV (soon ~ 8 TeV) $E < 200$ GeV for nuclei & mesons colliding: $E_{lab,pp} = 1.7 \times 10^{15}$ eV (1.3×10^{17} eV) $E_{lab,AA} = 8.5 \times 10^{13}$ eV
Emission angle:	very forward ($\eta_{peak} \sim 3.2 + 1.2 \times \log_{10}(E/\mathrm{TeV})$ $\sim 4 - 14$) "soft interactions" QCD does not work	high p_T ($\lvert\eta\rvert < 3 - 5$) "hard interactions", QCD

particle density

energy density

p-p non-diffractive interactions



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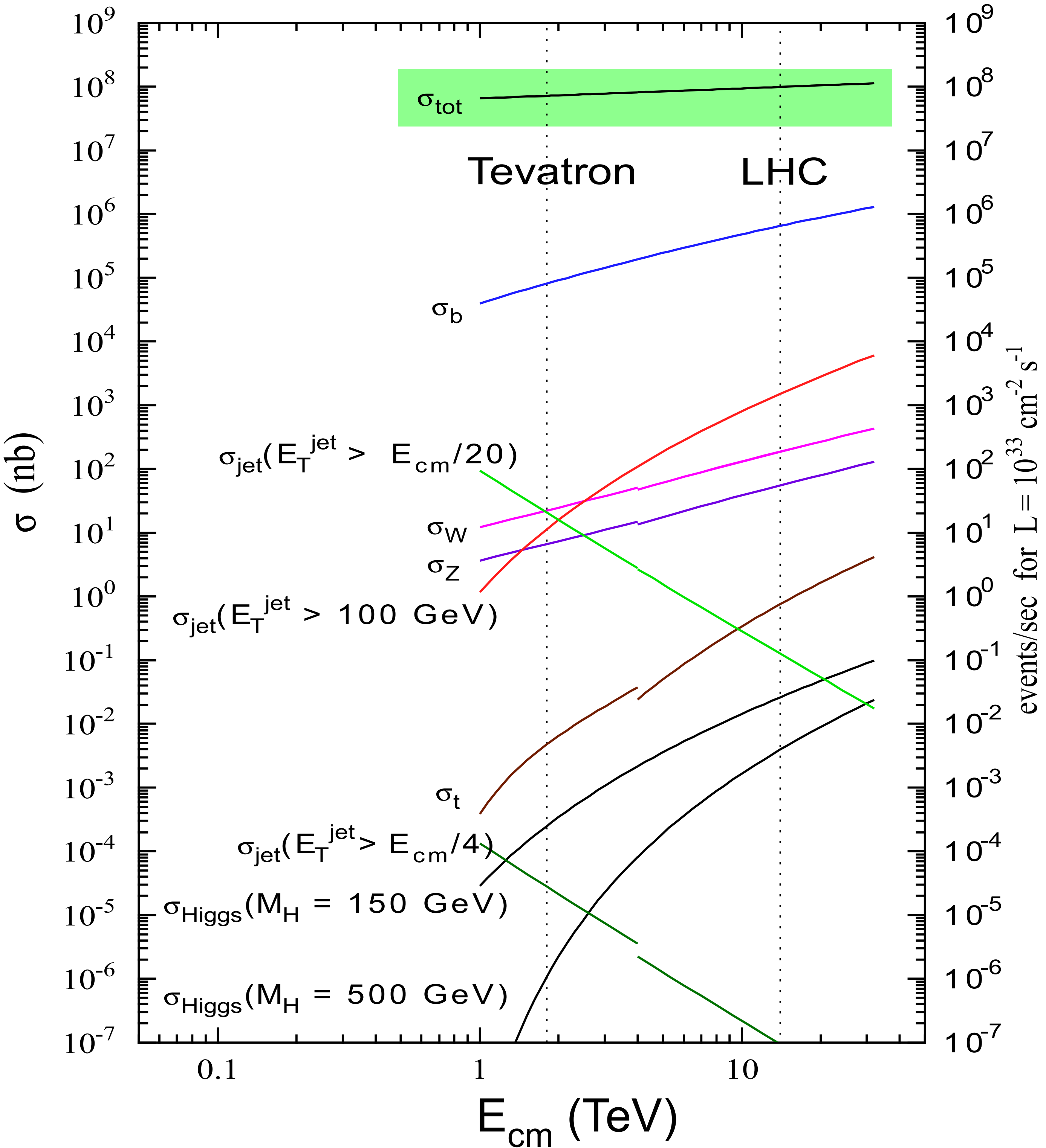
proton - (anti)proton cross-sections



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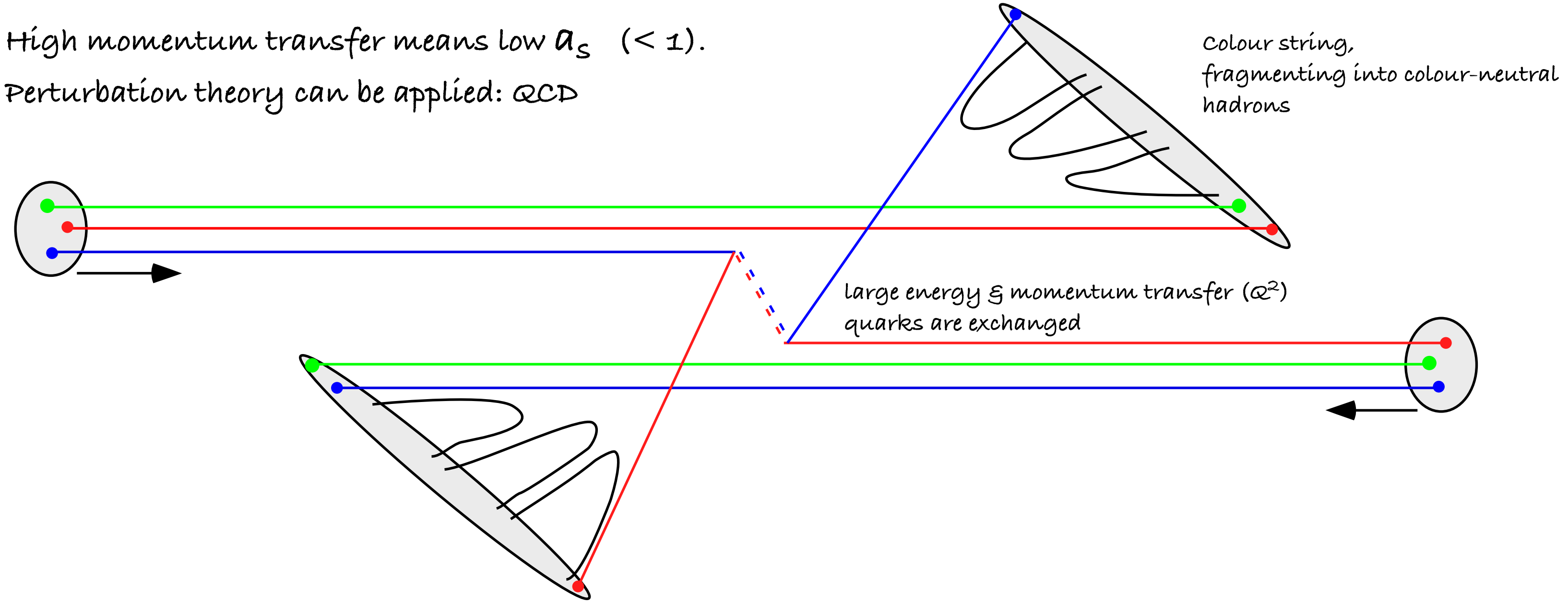
Hard:

High momentum transfer means low a_s (< 1).

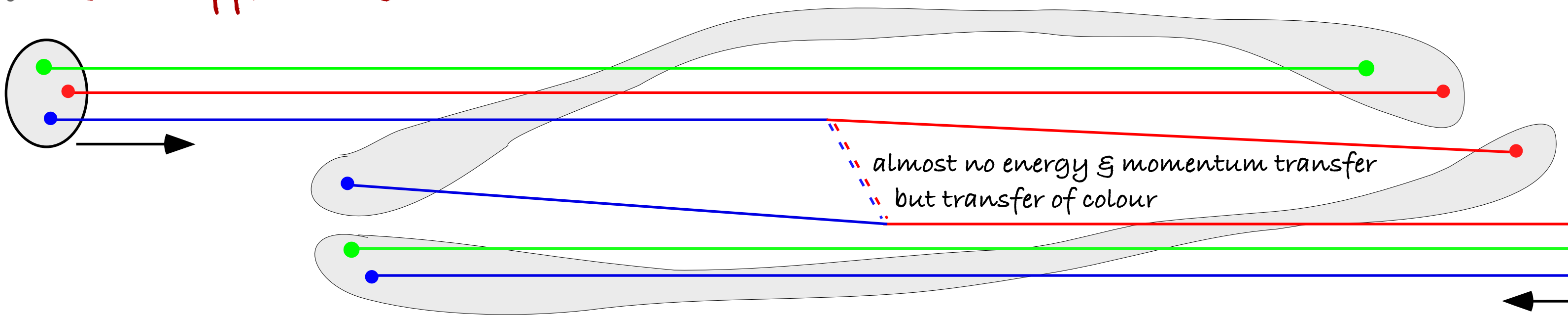
Perturbation theory can be applied: QCD



Colour string,
fragmenting into colour-neutral
hadrons

large energy & momentum transfer (Q^2)
quarks are exchanged

Soft: non-diffractive

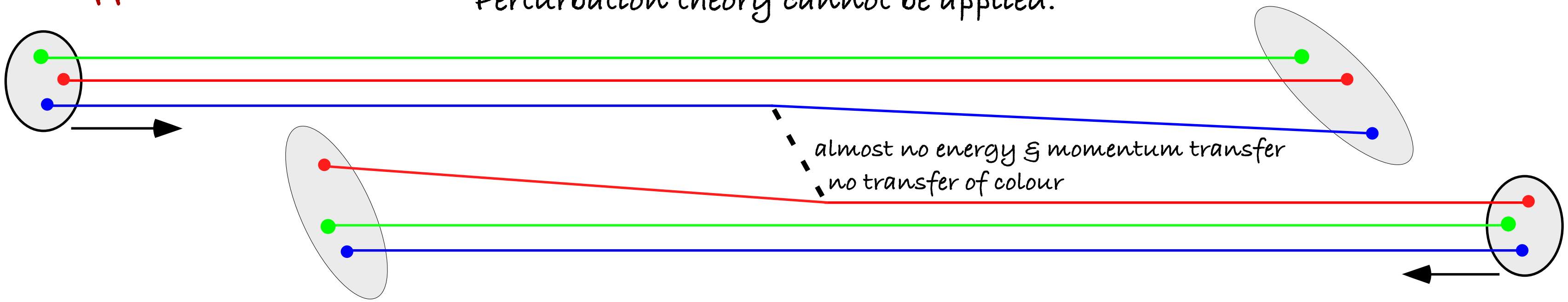


almost no energy & momentum transfer
but transfer of colour

Soft: diffractive

Low momentum transfer means large a_s (> 1).

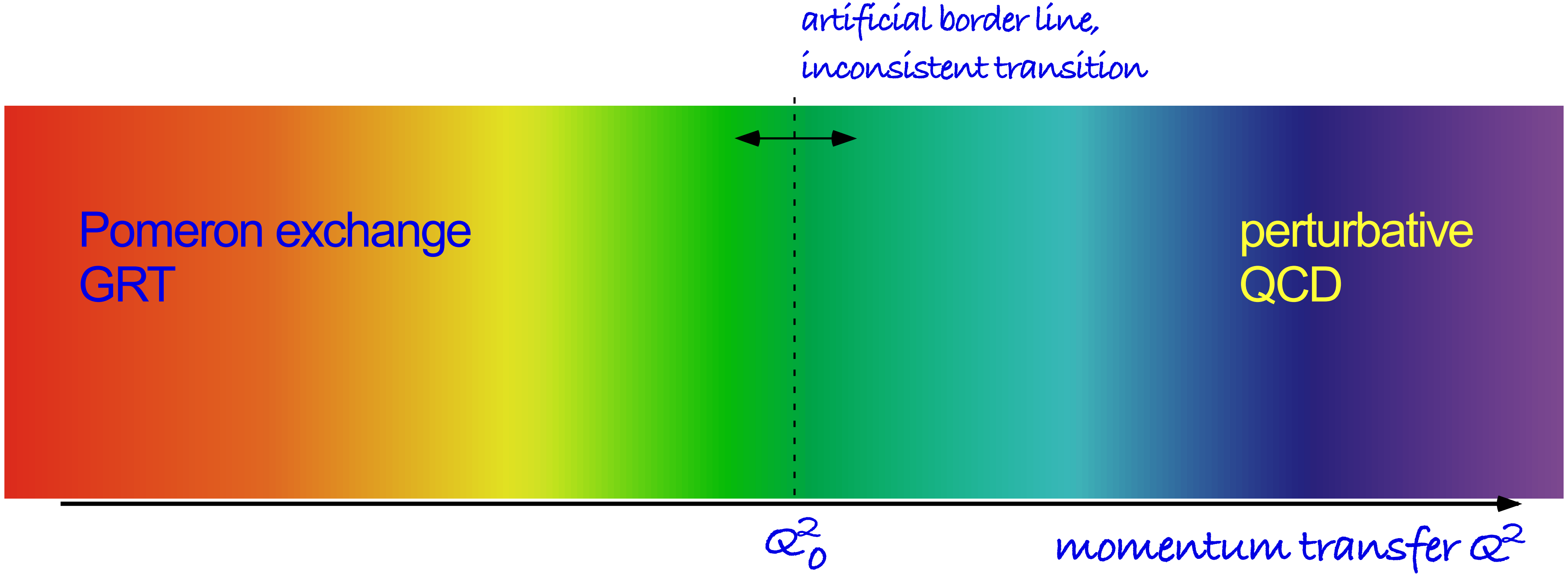
Perturbation theory cannot be applied.



almost no energy & momentum transfer
no transfer of colour

Soft: scattering off the nucleon as a whole (not off the quarks)

Soft: fundamentally different treatment of interactions **Hard:**



artificial border line,
inconsistent transition

Pomeron exchange
GRT

perturbative
QCD

Q_0^2

momentum transfer Q^2

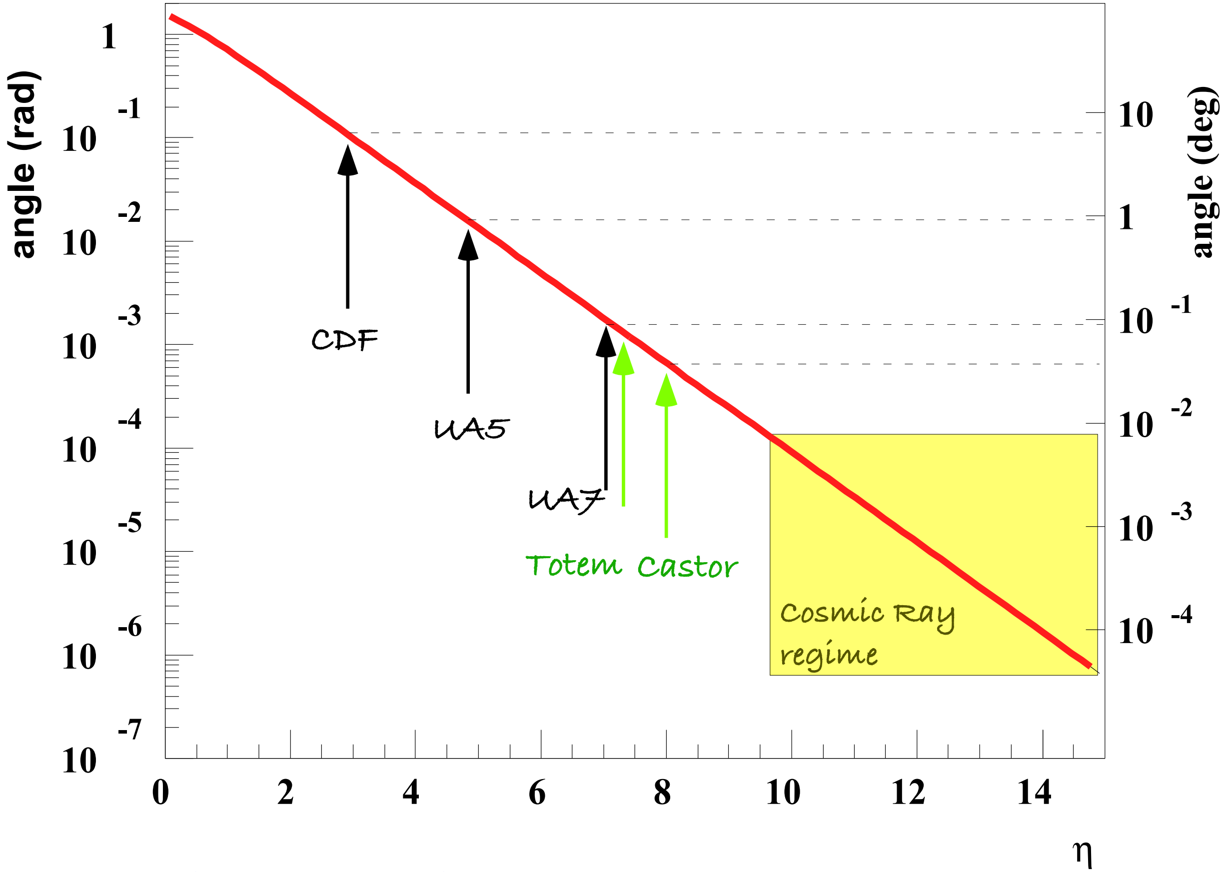
CR codes:

emphasis on soft reactions,
hard processes added for
higher energies

HEP codes:

emphasis on hard processes,
soft “underlying reactions” are
crudely parametrized to get
background at $\eta \sim 3\text{-}5$

Angle as Function of Pseudo Rapidity η



Atlas/CMS $\eta < 5$ calorimeter
$\eta < 2.5$ tracking

LHCb $1.9 < \eta < 4.9$

Totem $3 < \eta < 7$

LHCf 0°, only neutrals
140 m from interaction point

aim at:

- total cross section σ_{tot}
- elastic cross section: $\left.\frac{d\sigma}{dt}\right|_{t=0}$, ρ parameter
- diffractive cross section: $\frac{d\sigma^2}{dt\, dM_x}$

but:

increasing difficulty ↓

Energy flux

particle number

momentum

particle type

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So far : CR and HEP cover "virtually exclusive" kinematical regions

CR regime is not (yet) described by a fundamental theory, based on first principles

But: CR models need predictive power for extrapolation to high energies, small angles and small Q^2

(e.g. from a solid theoretical basis)

consistent calculation of

cross-sections and particle production in nuclear collisions

consistent treatment of

soft, hard and diffractive interactions (i.e. no artificial boundaries)
of all sorts of hadrons and nuclei with nucleons and nuclei
over the whole CR energy range (10^9 .... 10^{21} eV)

News from Relativistic Heavy Ion Collider (RHIC):

- closer to CR: Nucleus - Nucleus collisions
  partly even with O, N beams
- first results require already modifications of models.

News from LHC p-p: CMS, CASTOR, TOTEM, LHC-f ...

Soon: results from LHC nuclei

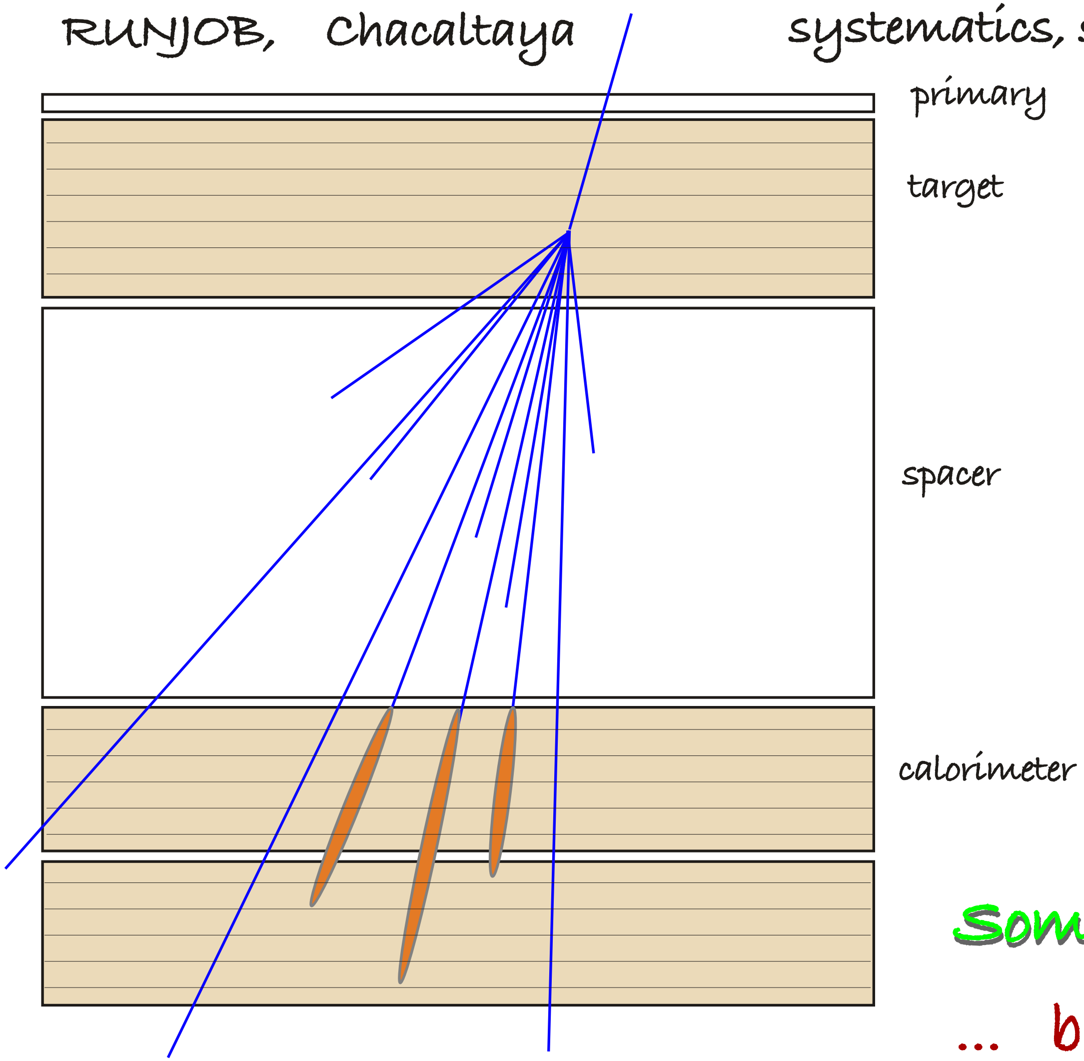
The more data available,
the more the models will be constrained, and
the better the extrapolations to CR energies.

Anything to learn from Hadronic CR Reactions ?

e.g. balloon or high-altitude experiments YES, ...

RUNJOB, Chacaltaya

systematics, small exposure (few 100 hours $\cdot$ m^2)



Target to induce reaction

X-Ray Films, Emulsions,
to measure secondary tracks (mm)

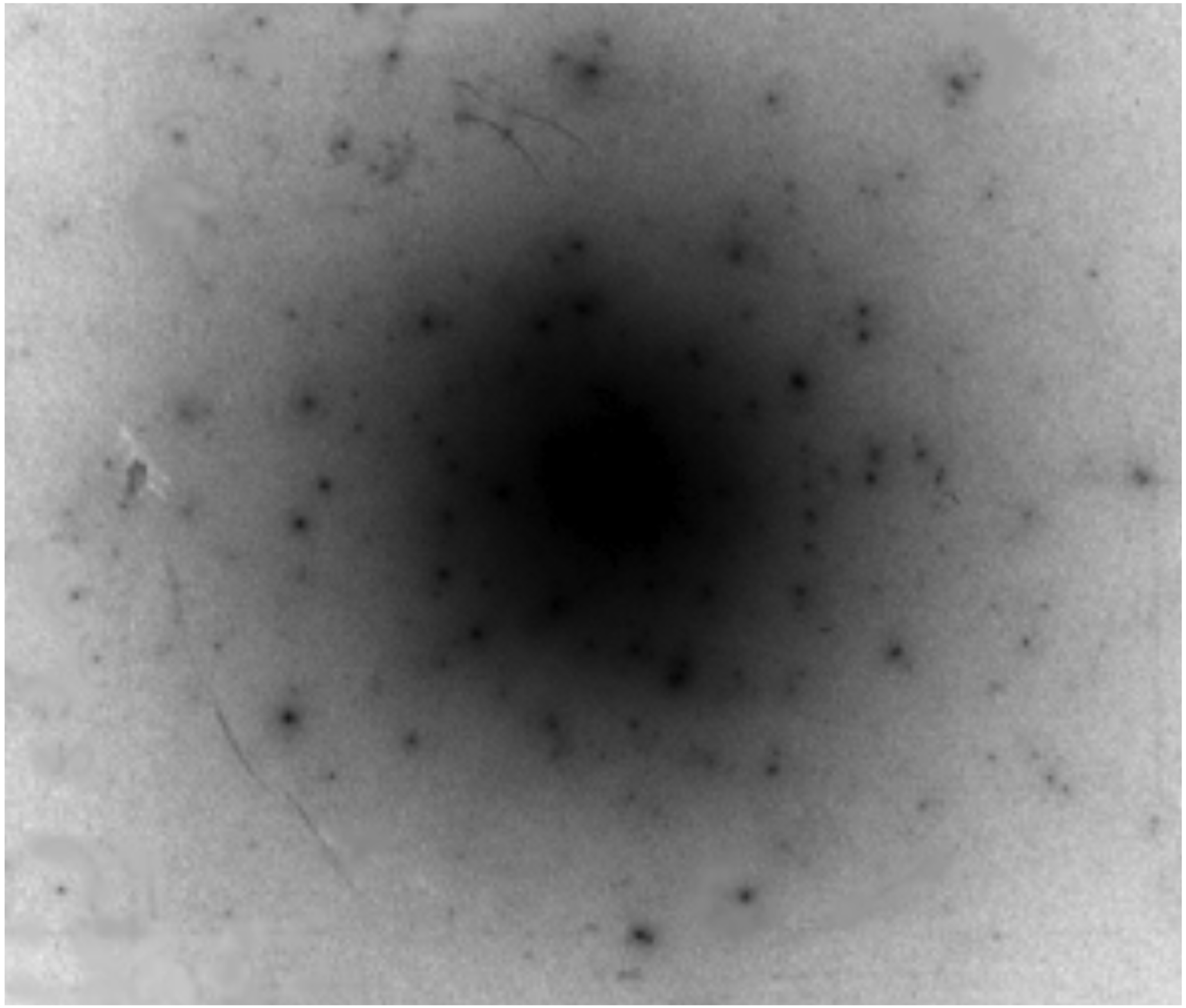
Energy determination by blackening of
X-ray films
electromag. sub-showers ($E_\gamma > 1$ TeV)
hadronic energy not measured

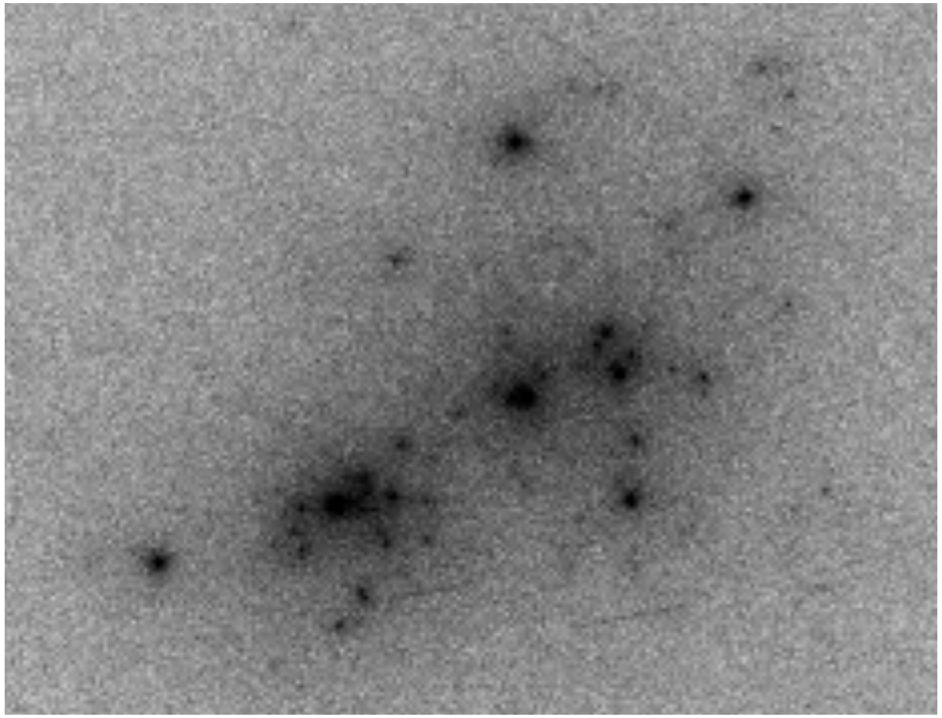
Charge/Mass:
via ionisation

Some reaction of ~10^{15} eV particles seen!

... but still work to be done
to be useful for model builders.

Examples of emulsion chamber events (one layer each)





Are there theoretical guidelines for soft interactions?

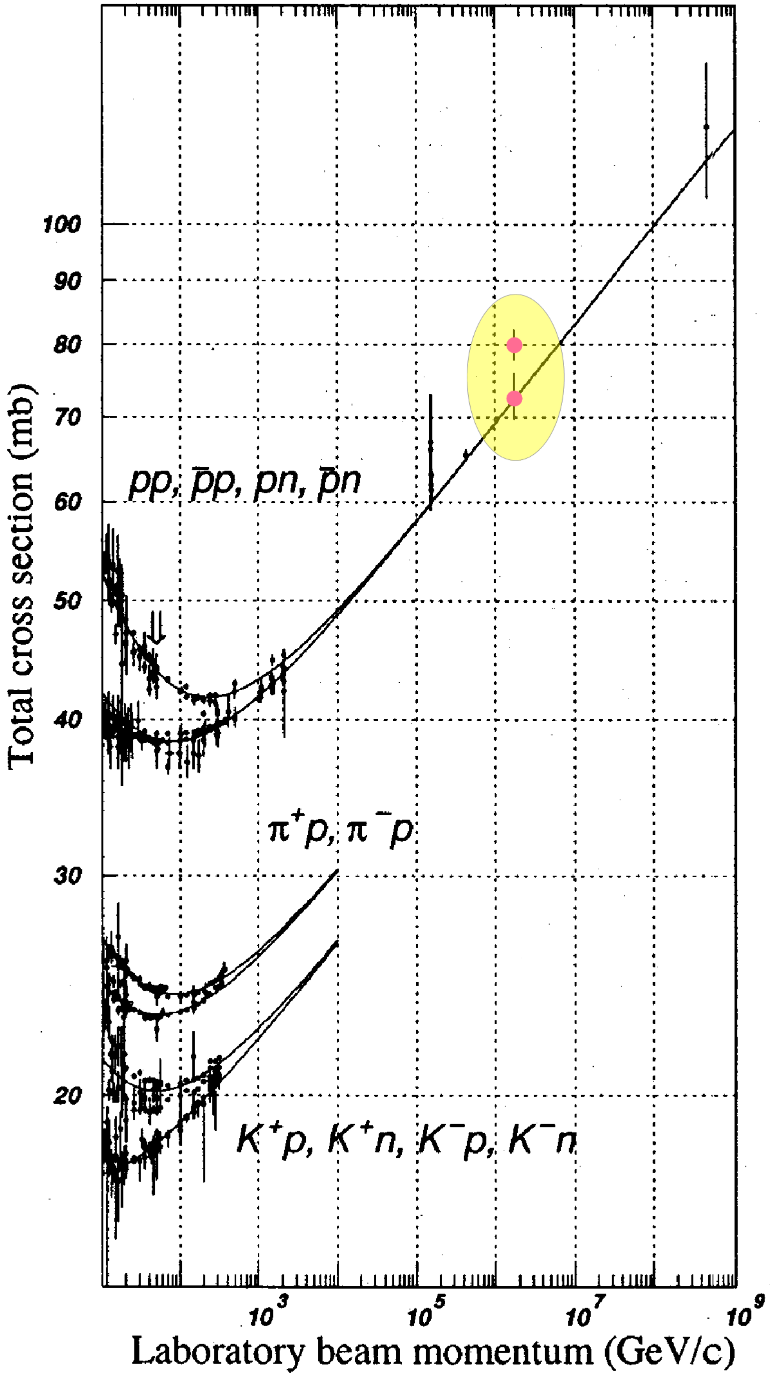
Yes : Gribov - Regge Theory (GRT)
of multi - Pomeron exchange
(a relativistic quantum field theory)

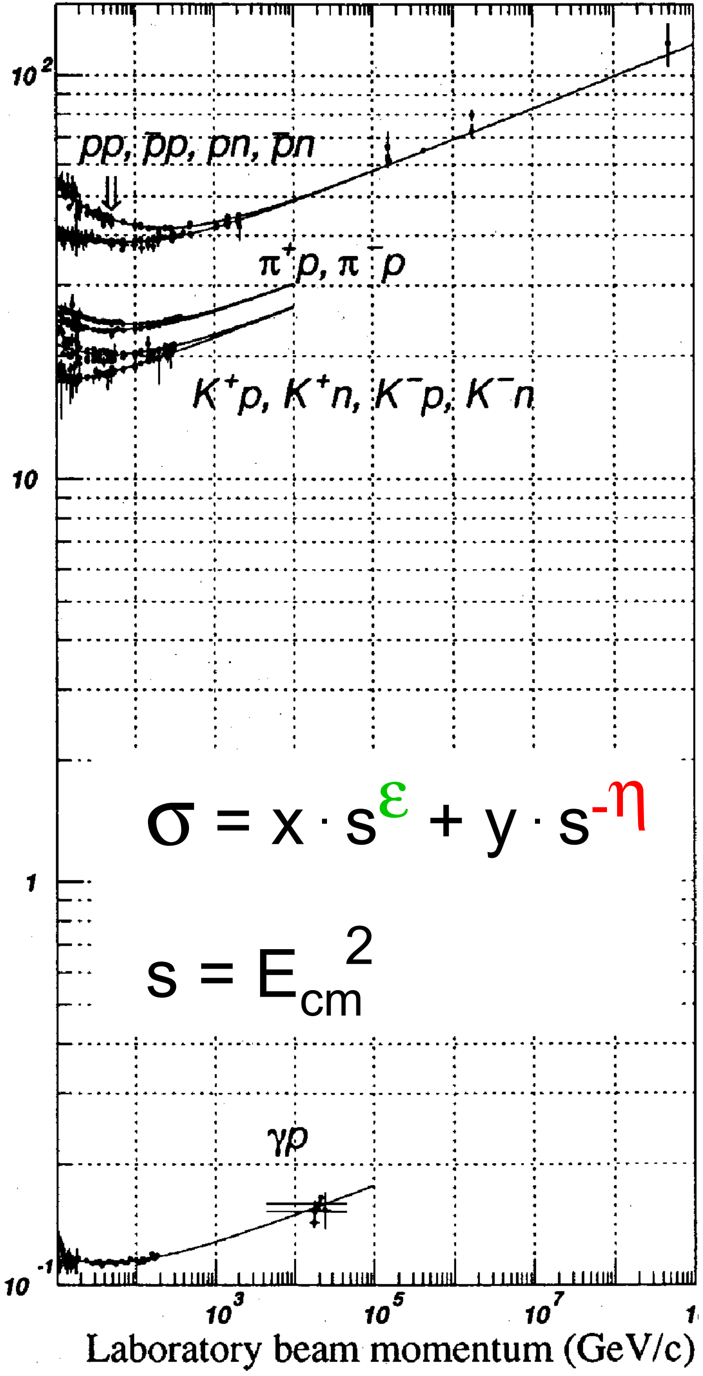
successful for
elastic scattering
total cross-section

extension to particle production :
not without uncertainty but
relatively few free parameters and
seems to work fine up to highest energies

The best theoretical model we have at the moment !

Cross-sections described by “Reggeon” and “Pomeron” Exchange

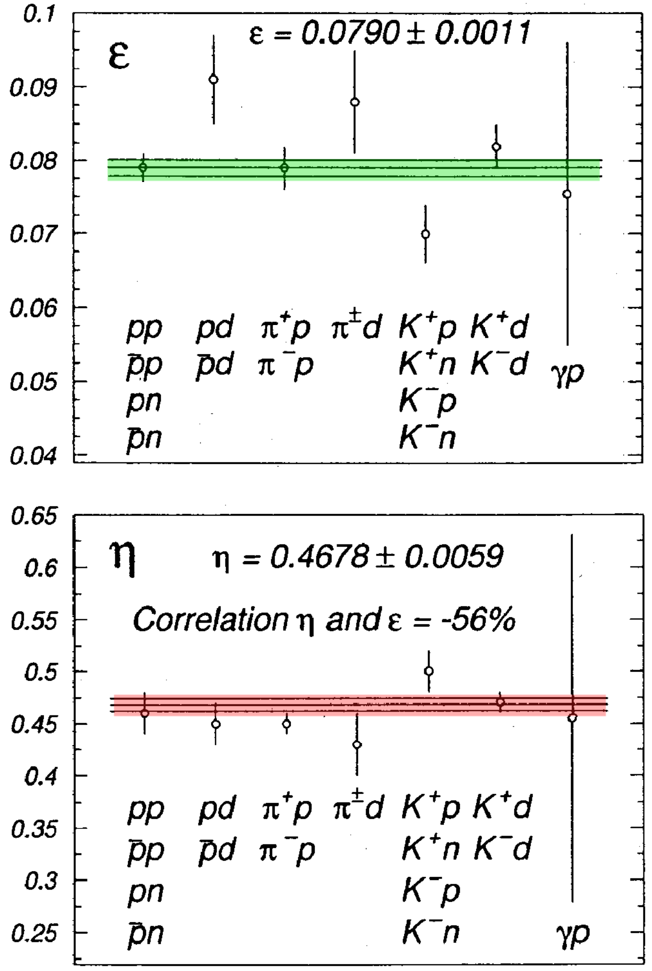




$$\sigma = x \cdot s^{\varepsilon} + y \cdot s^{-\eta}$$

$$s = E_{cm}^{2}$$

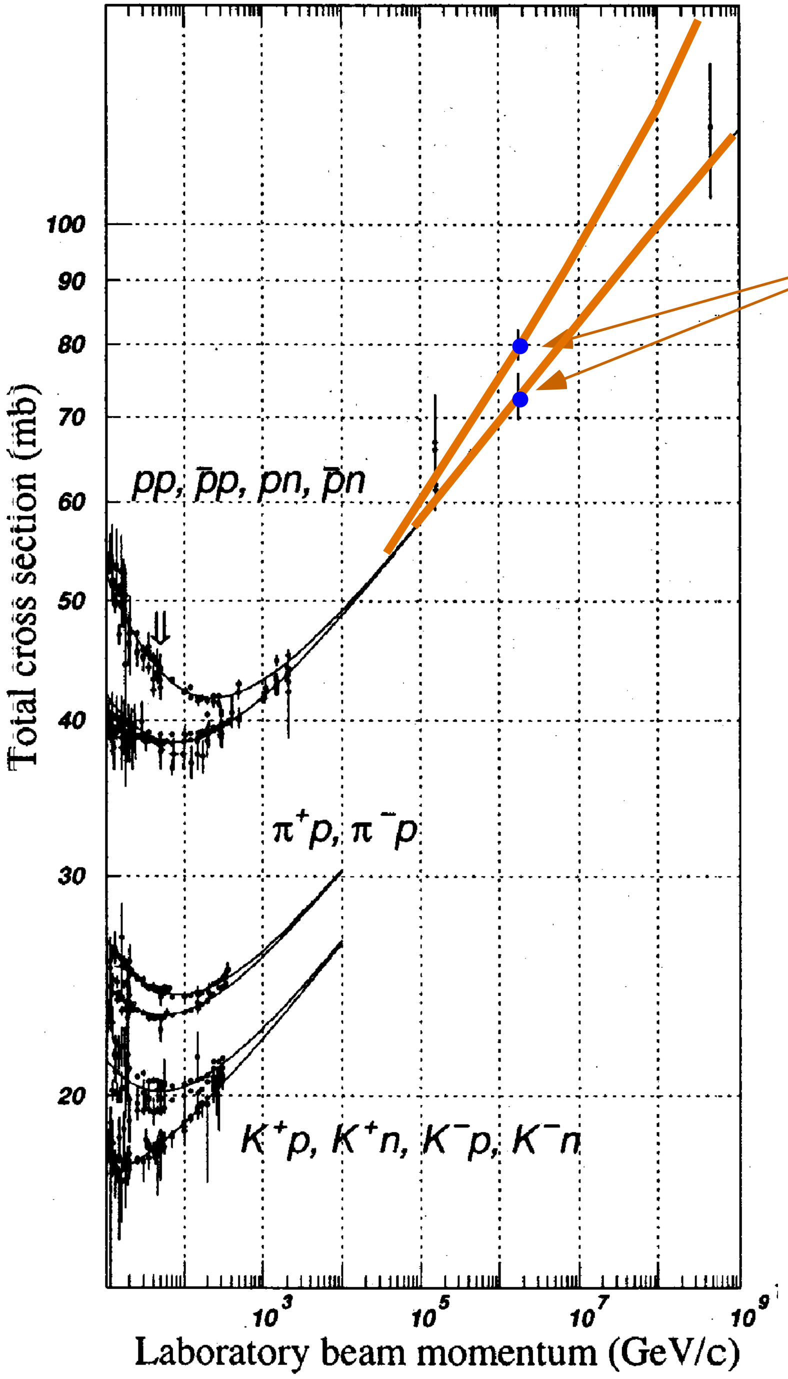
“Pomeron”



“Reggeon”

from Particle Data Book 1996

Experimental results are not always unique ...



10% difference in measurements of Tevatron Experiments:

Which is correct ???

How to extrapolate to higher energies?

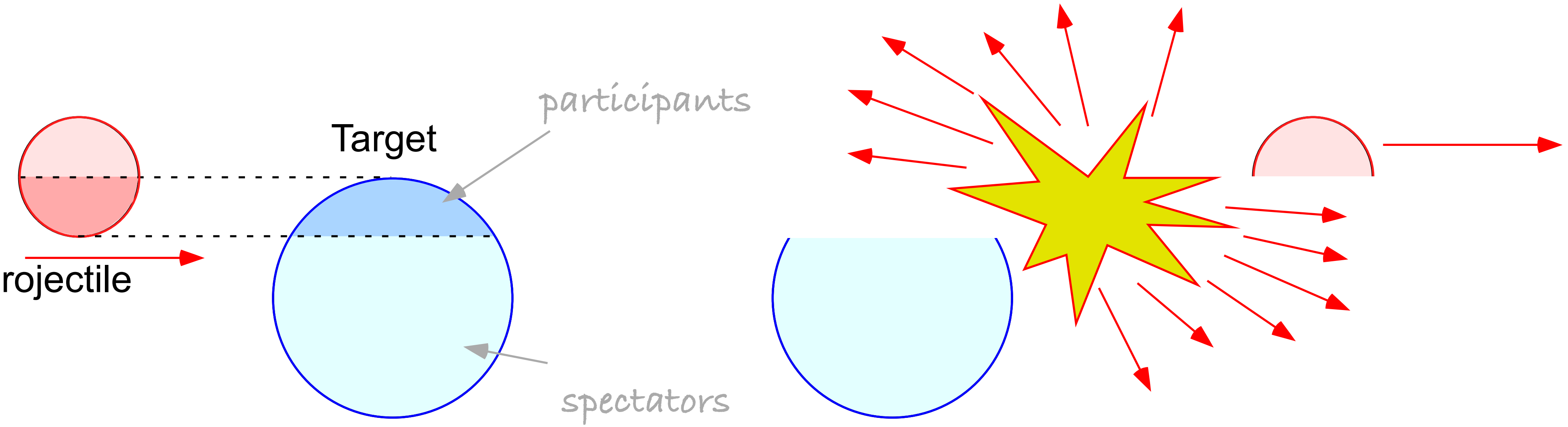
LHC results will resolve this soon.

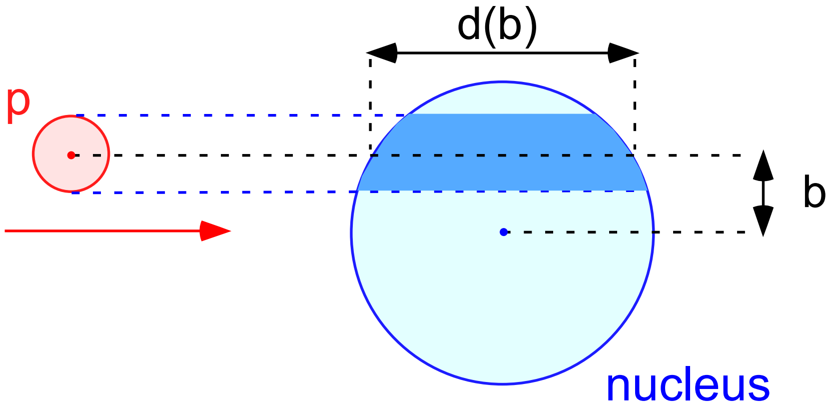
Glauber Theory of nucleon-nucleus and nucleus-nucleus collisions

(a geometric model)

1st collision: p, He, C, ... Fe collide with N, O, Ar

at energies: 10^{10} ... 10^{21} eV





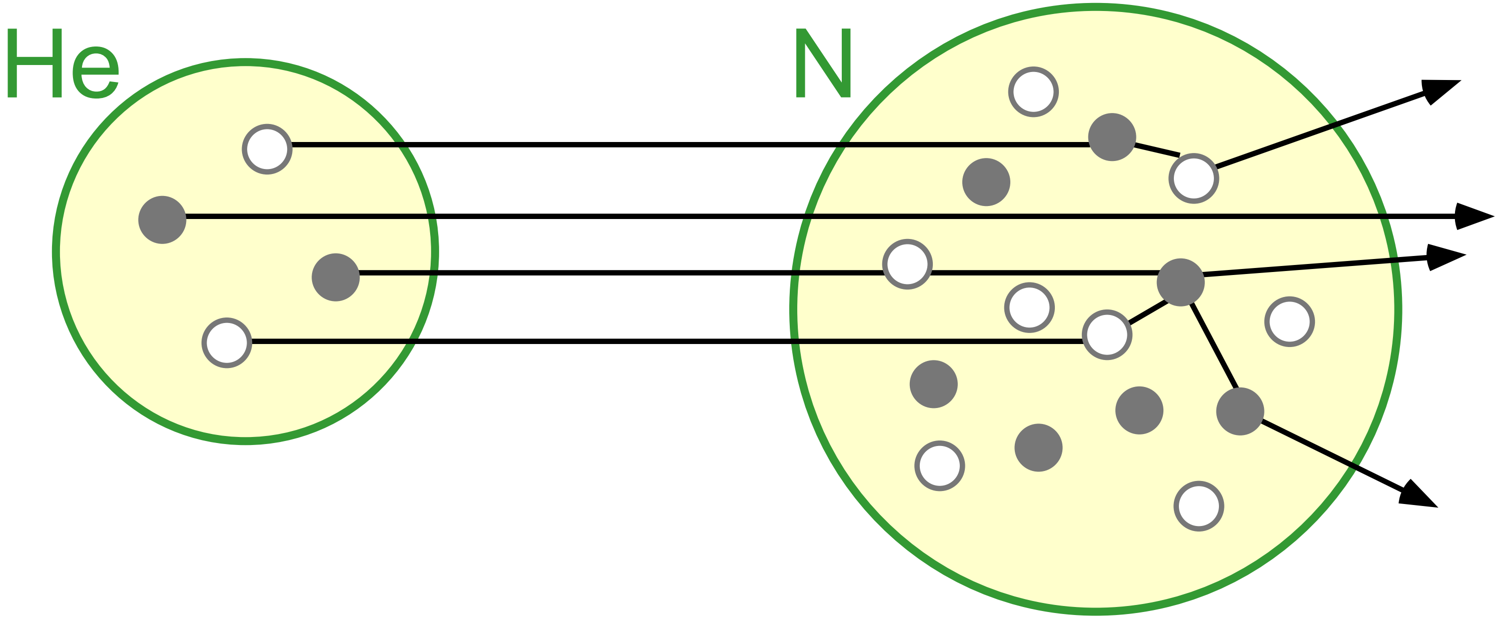
$$\left.\begin{array}{c} d(b) \\ \rho(r) \\ \sigma(p\text{-}p) \end{array}\right\} \longrightarrow \begin{array}{l} \sigma(p\text{-nucleus}) \\ \text{no. of target participants} \end{array}$$

Analogous for nucleus-nucleus collisions.
Works rather well !

Problem: multiple interactions

Monte Carlo version of Glauber Theory

- assume nucleon distribution in projectile & target
- track each nucleon in space and time
- perform nucleon-nucleon collisions



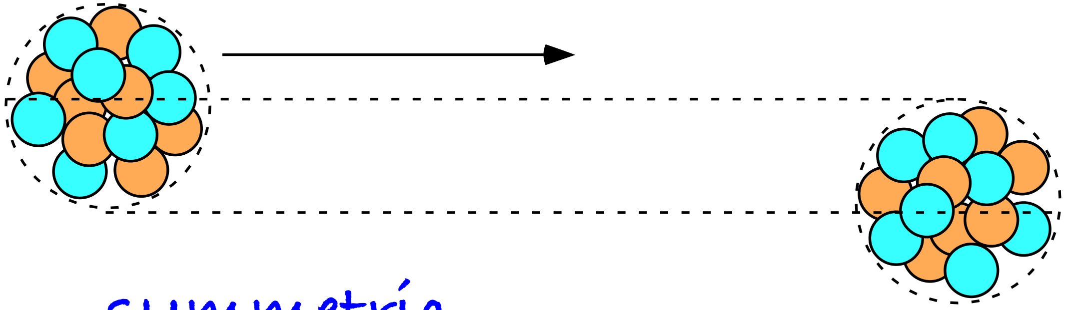
Collision of one projectile nucleon with multiple target nucleons.
Collision of multiple projectile nucleon with one target nucleons.

How does a nucleon after its first collision interact with a second nucleon ?

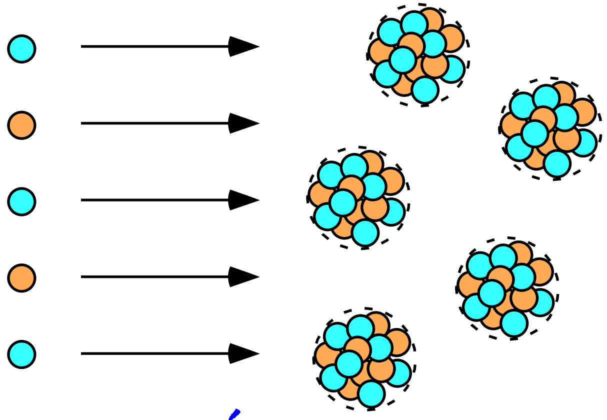
Superposition Model

... assumes that nucleus (A) is a superposition of
A free nucleons which interact independently.

Good assumption since binding energies $(< 8 \times 10^6 \text{ eV})$
are much smaller than energies of CR nucleons $(> 10^{14} \text{ eV})$.



symmetric



asymmetric

Implementation partly not sophisticated enough.

Example: CORSIKA

Standard Tool in Air Shower Physics,

used successfully by many CR / γ ray experiments
in very different energy ranges (10^{10} - 10^{21} eV)

combines best packages available for :

- hadronic interaction at high/low energies
  (QGSJET, SIBYLL, DPMJET, EPOS ..... FLUKA, UrQMD .....)
- electromagnetic interactions
  (EGS4)
- detailed particle transport
  (scattering, energy loss, Cherenkov light, deflection in magnetic fields, ...)
- decays and branching ratios

follow individual particles with all their interactions
(& apply some tricks to reduce computing time and particle output)

... delivers a large file with all particles arriving at ground level

Hadronic interaction models in CORSIKA:

HDPM	J.N. Capdevielle et al. KfK 4998 (1992)	discontinued
SIBYLL 1.6	T.K. Gaisser et al. Phys. Rev. D50 (1994) 5710 & D46 (1992) 5013	
2.1	major revision: E.J. Ahn et al., Phys. Rev. D 80 (2009) 094003	
VENUS	K. Werner Phys. Rep. 232 (1993) 87	discontinued
neXus	S.S. Ostapchenko, K. Werner et al., Phys. Rev. Lett. 86 (2001) 3606 2001 first version available,	2003 discontinued
QGSJET	N.N. Kalmykov, S.S. Ostapchenko, Phys. At. Nucl. 56 (1993) 346	
QGSJET II	S.S. Ostapchenko	
DPMJET	J. Ranft et al., Phys. Rev. D51 (1995) 64	updated 2001, now vers. 2.5
EPOS	K. Werner et al. still new, parameters to be fixed	2009, now vers. 1.99

Gribov-Regge

Is there anything better ?

Low energy hadronic interactions: typ. < 100 GeV

important, since most of the measured secondaries are low-energy

FLUKA

UrQMD

(GHEISHA)

resonances, intranuclear cascades, nuclear fragments, nuclear physics, (can in principle all be measured but is difficult ....)

e.g. **FLUKA :**

hadron-nucleon:	elastic, exchange phase shifts, data, eikonal	< 3-5 GeV/c resonances & decays	low E π,K special	high E DPM & hadronization
hadron-nucleus:	< 4-5 GeV/c intra-nuclear cascades		high E GRT, Glauber	

\+ evaporation, fission, Fermi breakup, γ-de-excitation

A simple example : HDPM
... based on the dual parton mode

Collision with colour exchange forms two colour strings which fragment into jets of observable hadrons.

Hadrons from each string form a Gaussian in rapidity space. Parametrize position y_j and width σ as function of E to reproduce $p\text{-}\bar{p}$ non-diffractive results.

(+ extrapolate S_{tot}

put in p_T, π:K:N, charged/neutral, ...

add 3rd Gaussian for nucleus in p-A,

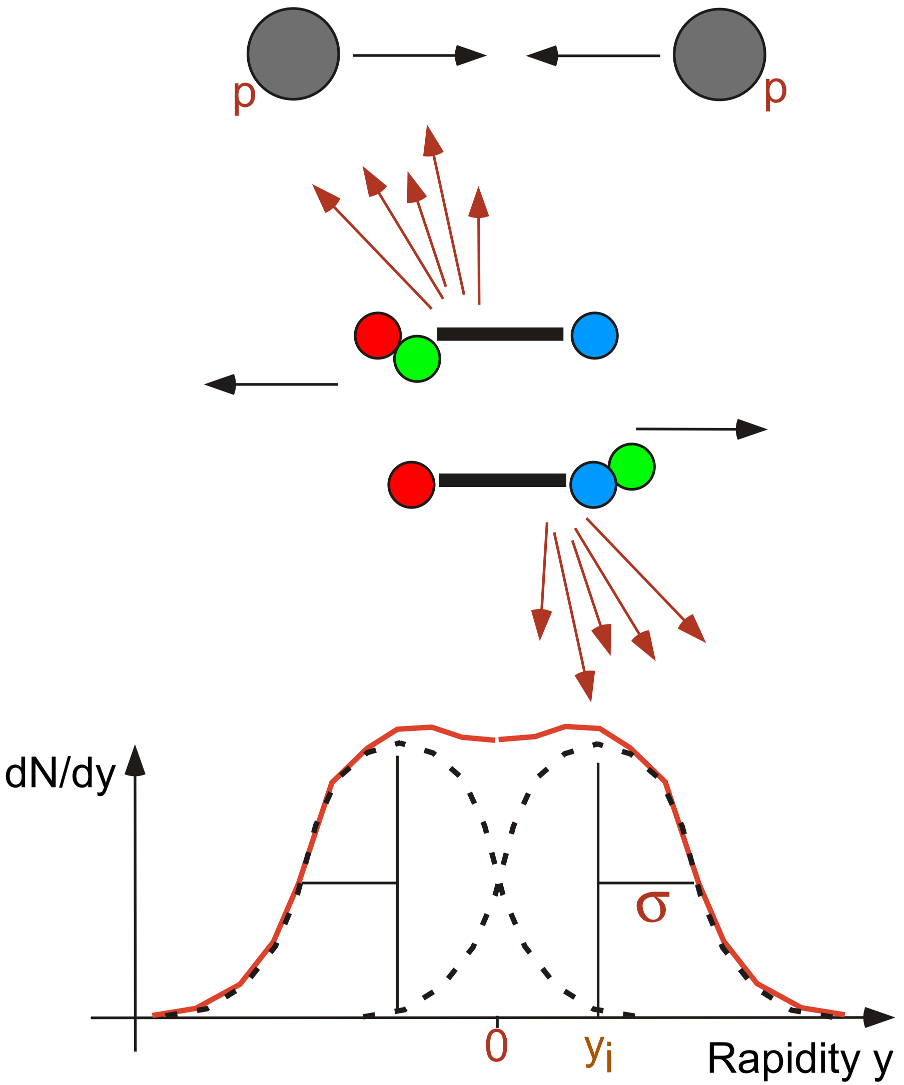
A-A : superposition of independent p-A collisions,

add diffraction ...)

ad hoc,

lots of free parameters,

no predictive power



Rapidity:

$$y = \frac{1}{2} \ln \frac{E+p_L}{E-p_L}$$

Pseudorapidity:

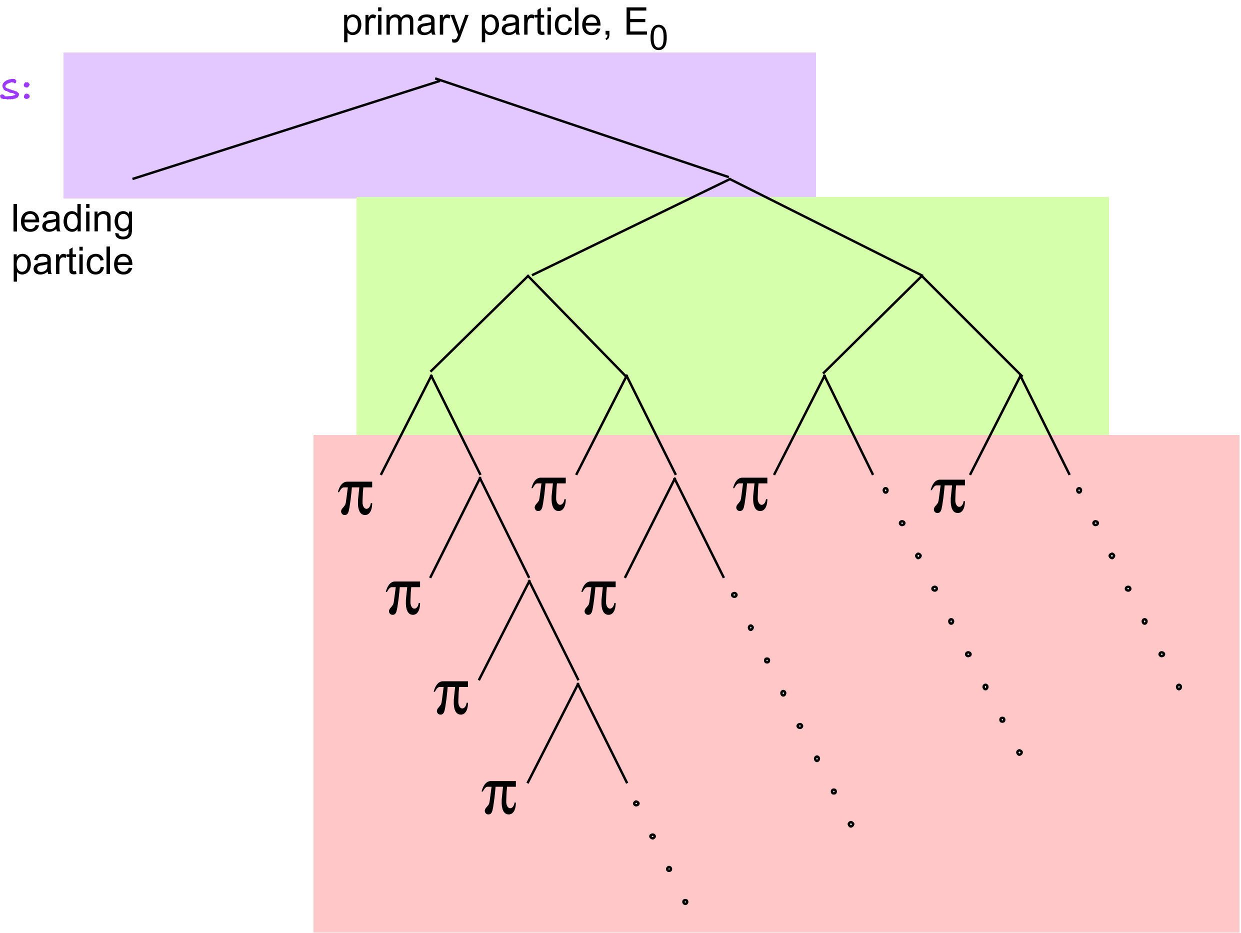
$$\eta = \frac{1}{2} \ln \frac{p+p_L}{p-p_L}$$

$\eta = -\ln(\tan(\theta/2))$

$\eta \sim y$
for high energies
(or zero mass)

(Pseudo)rapidity
is additive in Lorentz
transformation.

A simple hadronic interaction model: the Hillas Splitting Algorithm



1. split primary energy at random in 2 parts:
   $x E_0$, $(1-x) E_0$
   leading particle: $x E_0$

2. split rest, in N steps, randomly into
   2 portions each. Total: 2^N portions

3. split each portion at random in 2 parts:
   $x' E$, $(1-x') E$
   pion: $x' E$

   continue until a threshold energy
   ($> m_p$) is reached.

Originally used in MOCCA: (produces only pions as secondaries)
x, x' uniformly distributed between 0 1
N = 2

Very simple, very fast, but gives only a qualitative description of hadronic shower.

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Shower development (qualitatively)

correlated!

crucial:

- inelastic cross-sections (s_{inel})
- hadronic particle production
  (inelasticity k_{inel} i.e. fraction of energy converted into secondaries)

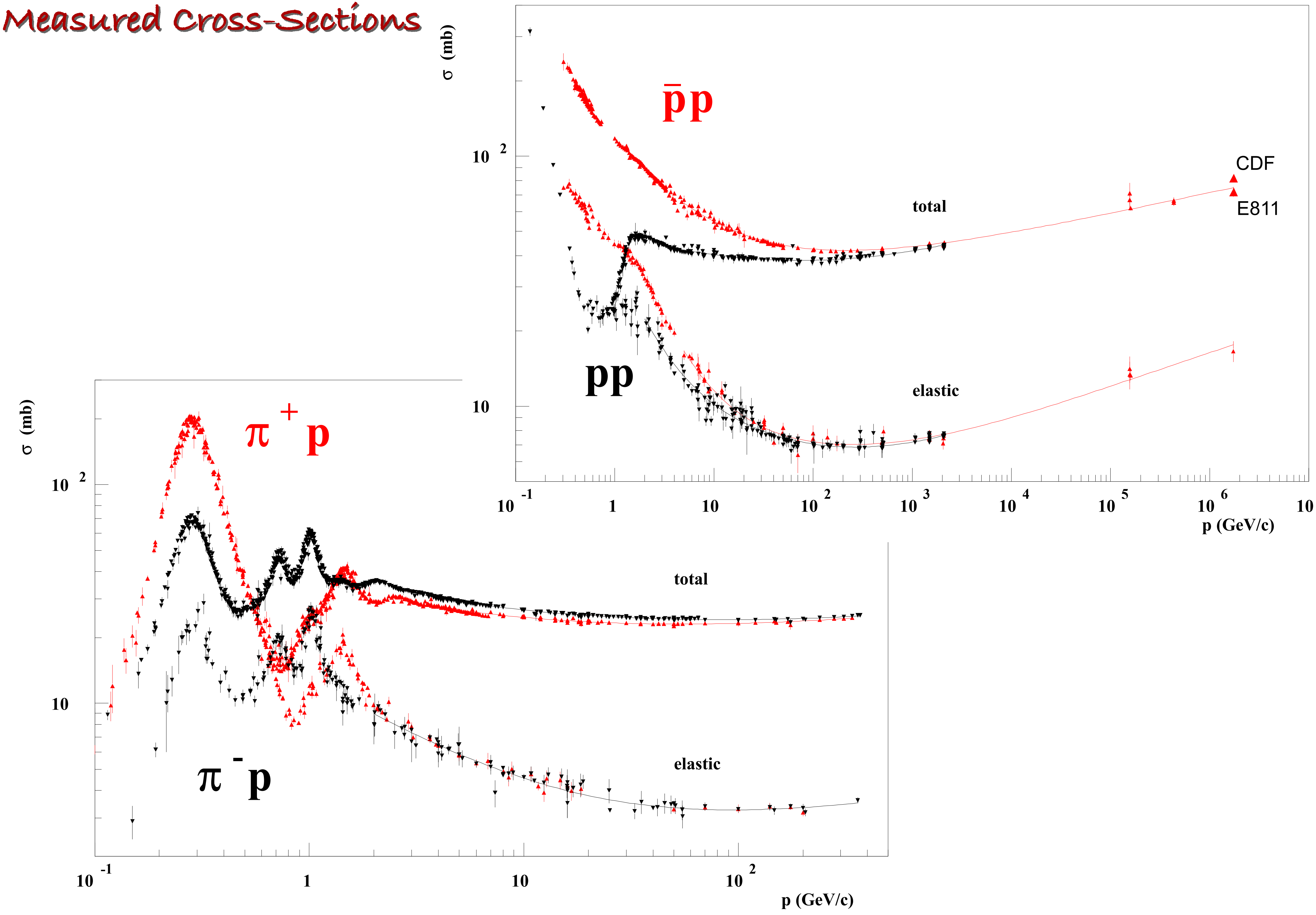
large cross-sections,
high inelasticity } make short showers

small cross-sections,
low inelasticity } make long showers

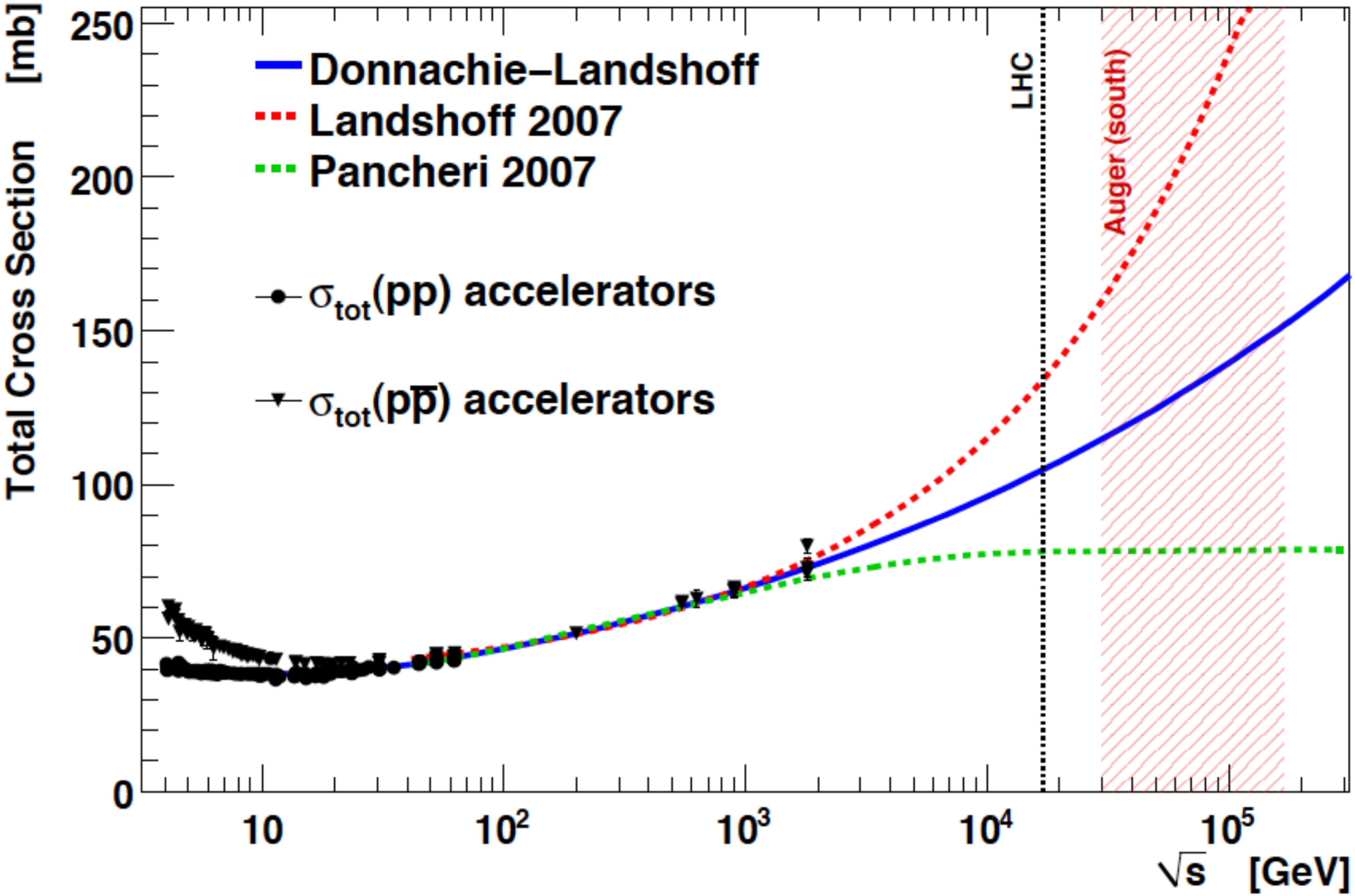
less crucial:

nuclear fragmentation, dE/dx, decays, tracking,
electromagnetic reactions, ...

Measured Cross-Sections



Predicted p-p Cross-Sections



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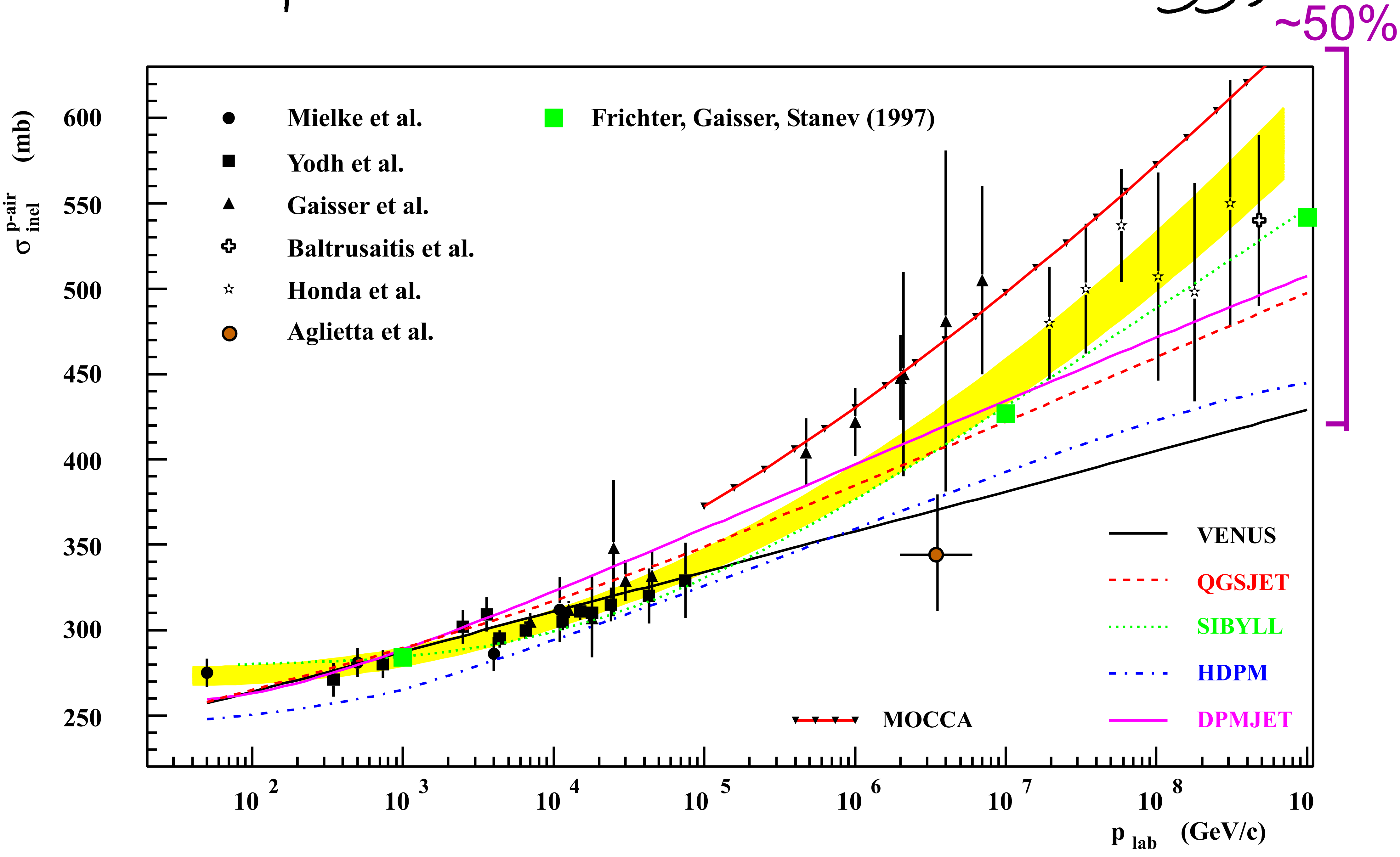
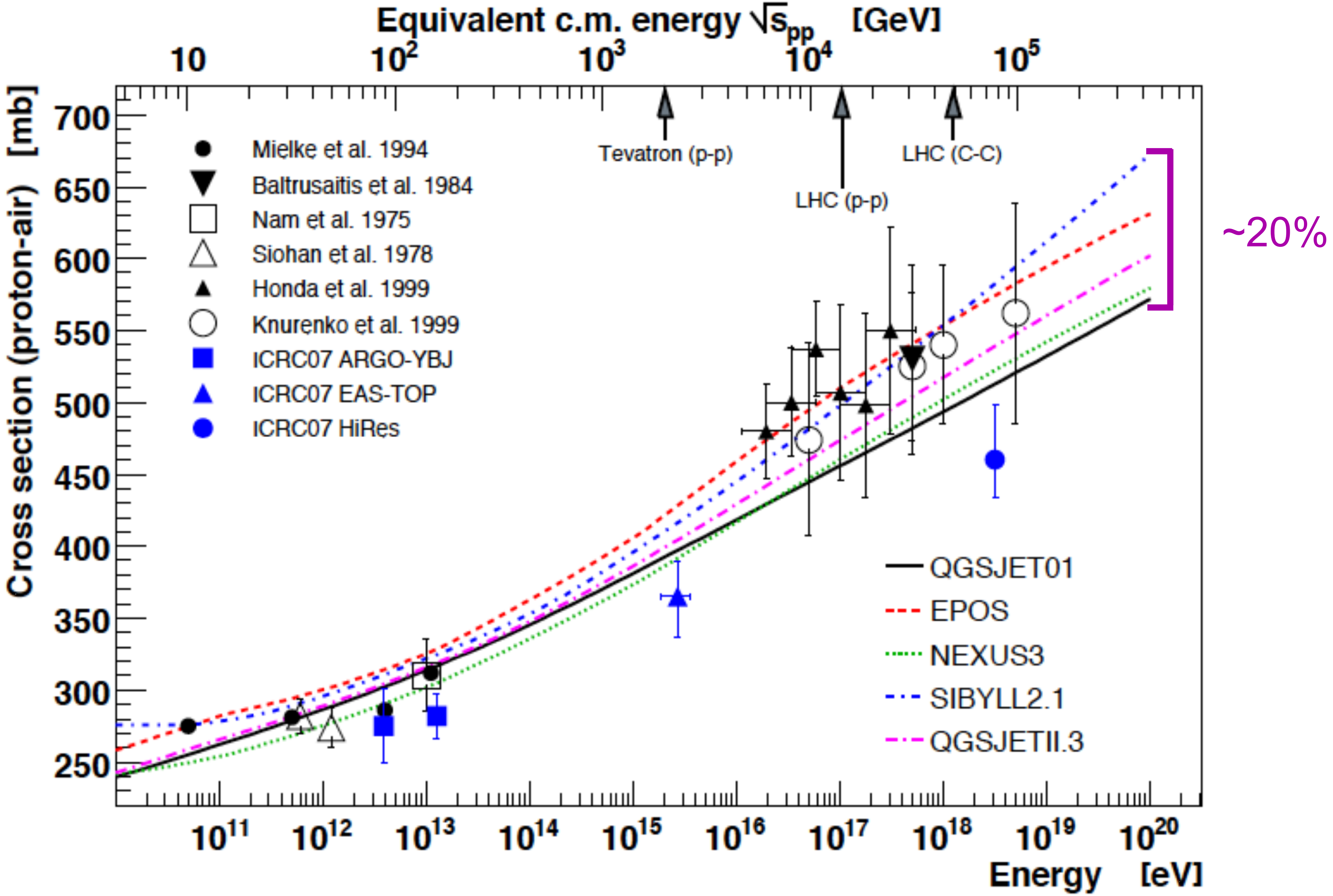
p-Air Inelastic Cross-Sections 1997



p-Air Inelastic Cross-Sections 2008



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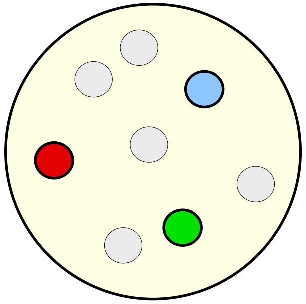
HERA measured structure functions at small x

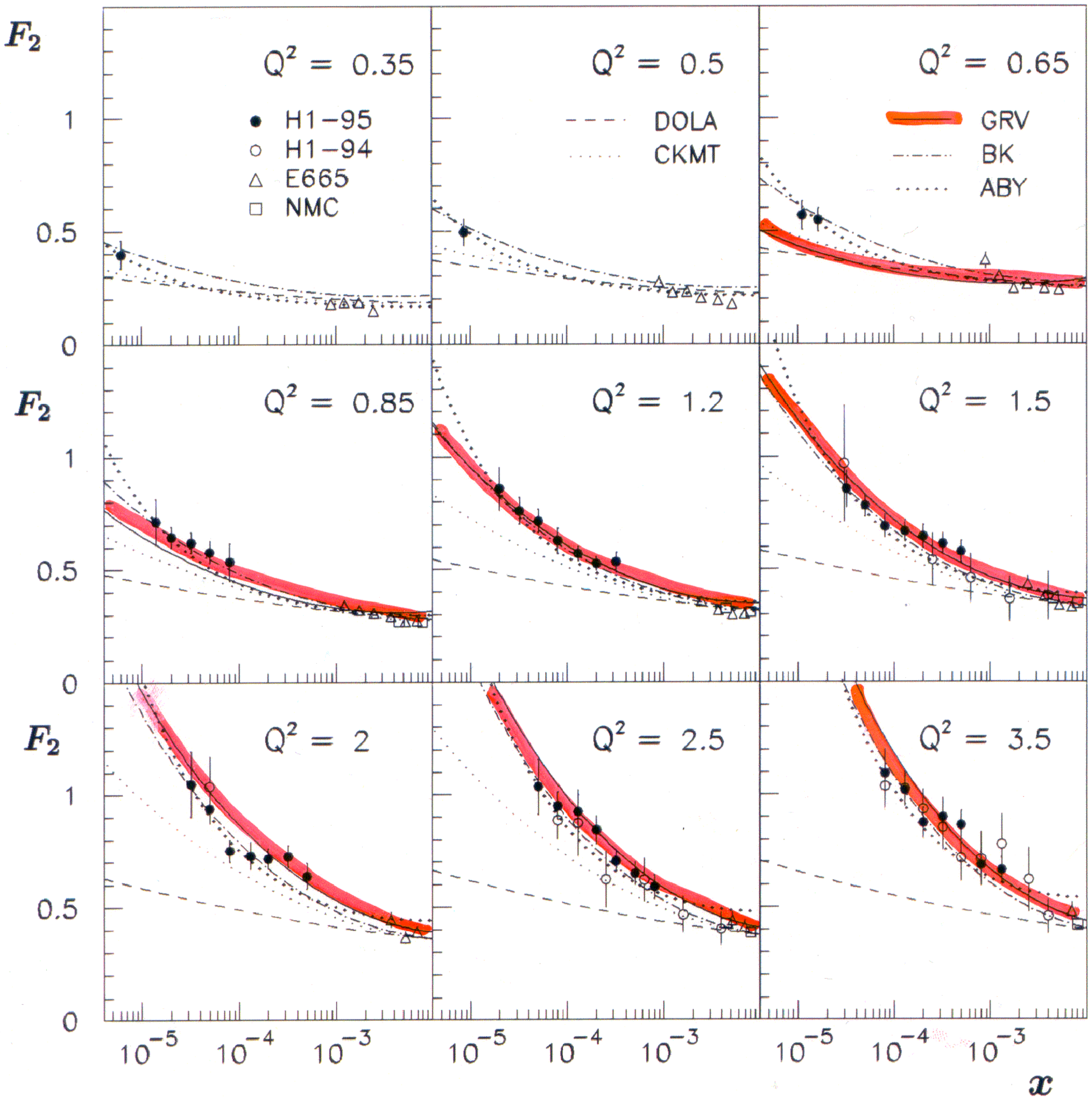


The more partons (quarks & gluons)
there are in a nucleon
at small x,

the more likely a collision is to
happen with a
high-energy projectile,

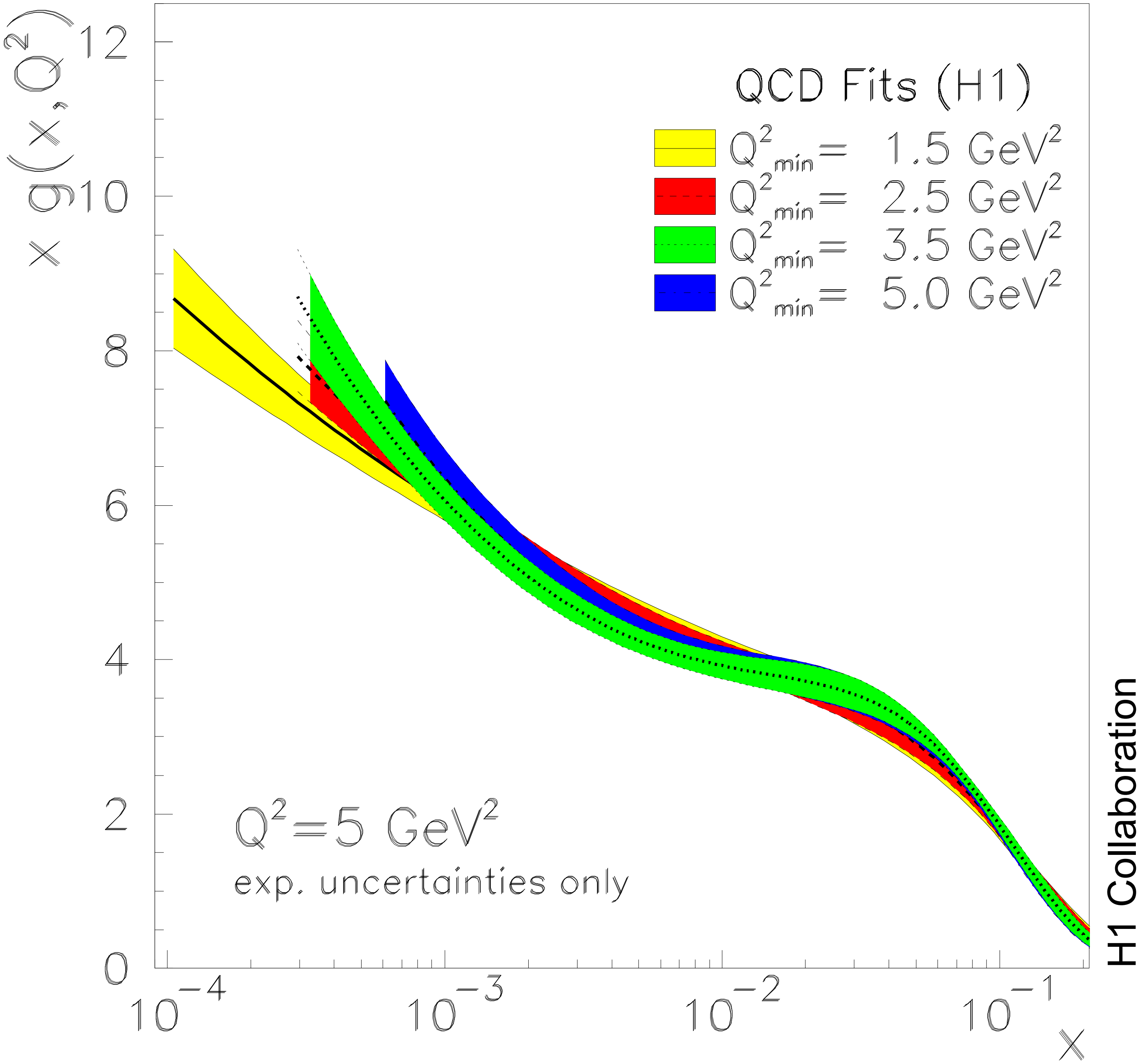
and the higher is the
interaction cross-section.

HERA data help with extrapolation of cross-sections to high energies.



x = momentum fraction of a parton

Gluon density at low x



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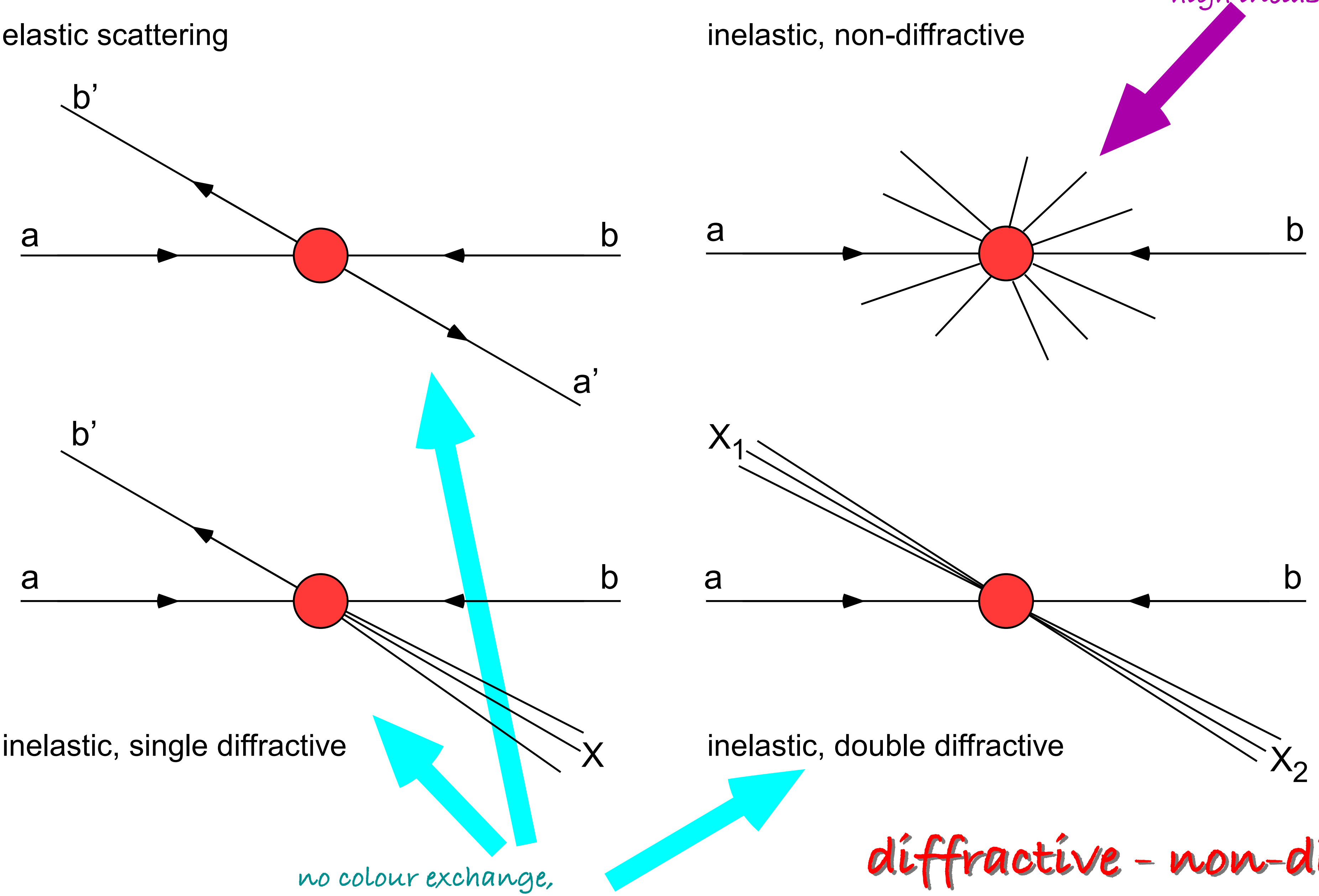
Soft Hadronic Interaction Types



elastic scattering

inelastic, non-diffractive

inelastic, single diffractive

inelastic, double diffractive

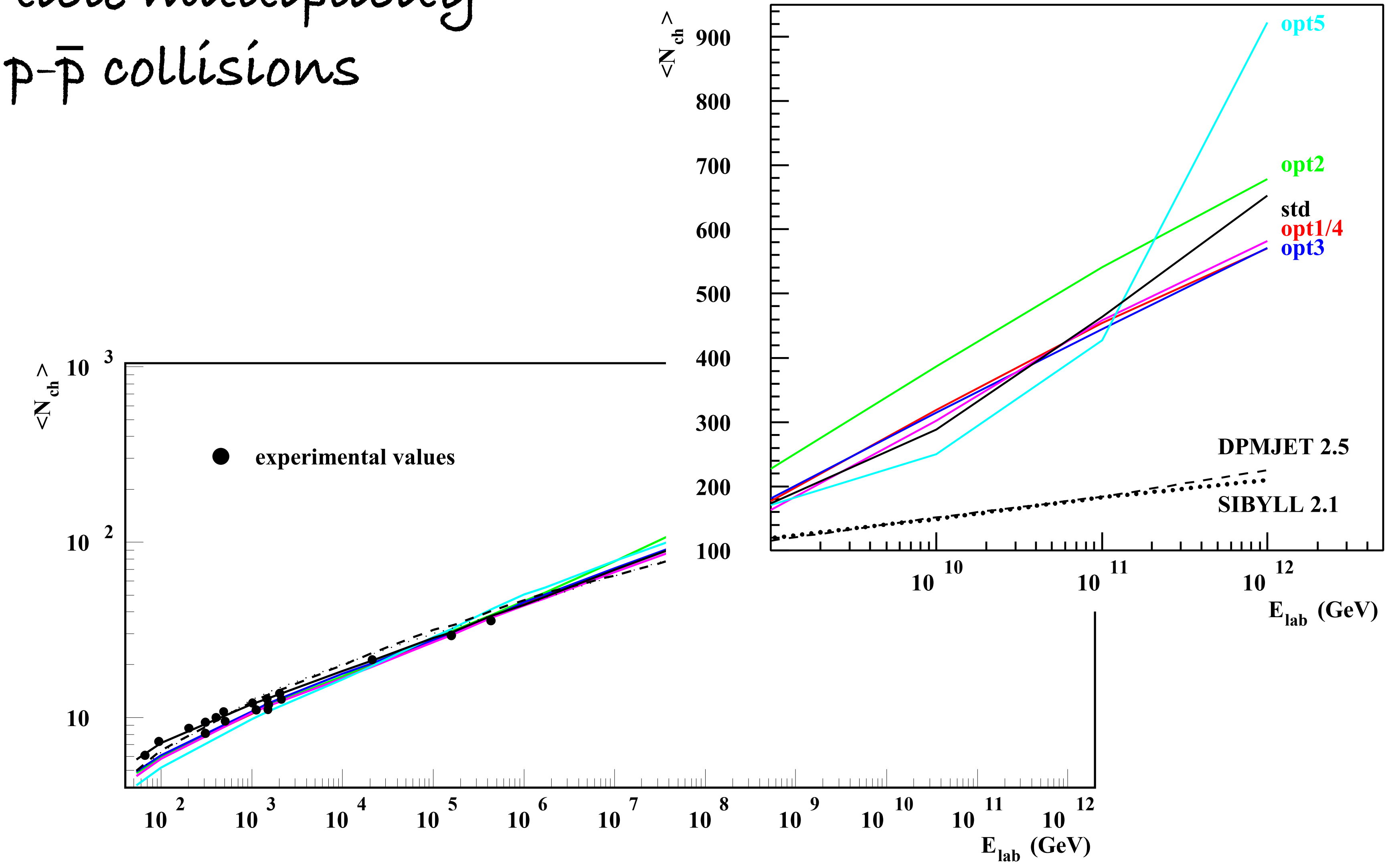
particle production,
colour exchange,
high center-of-mass energy,
high inelasticity

no colour exchange,
low center-of-mass energy,
low inelasticity

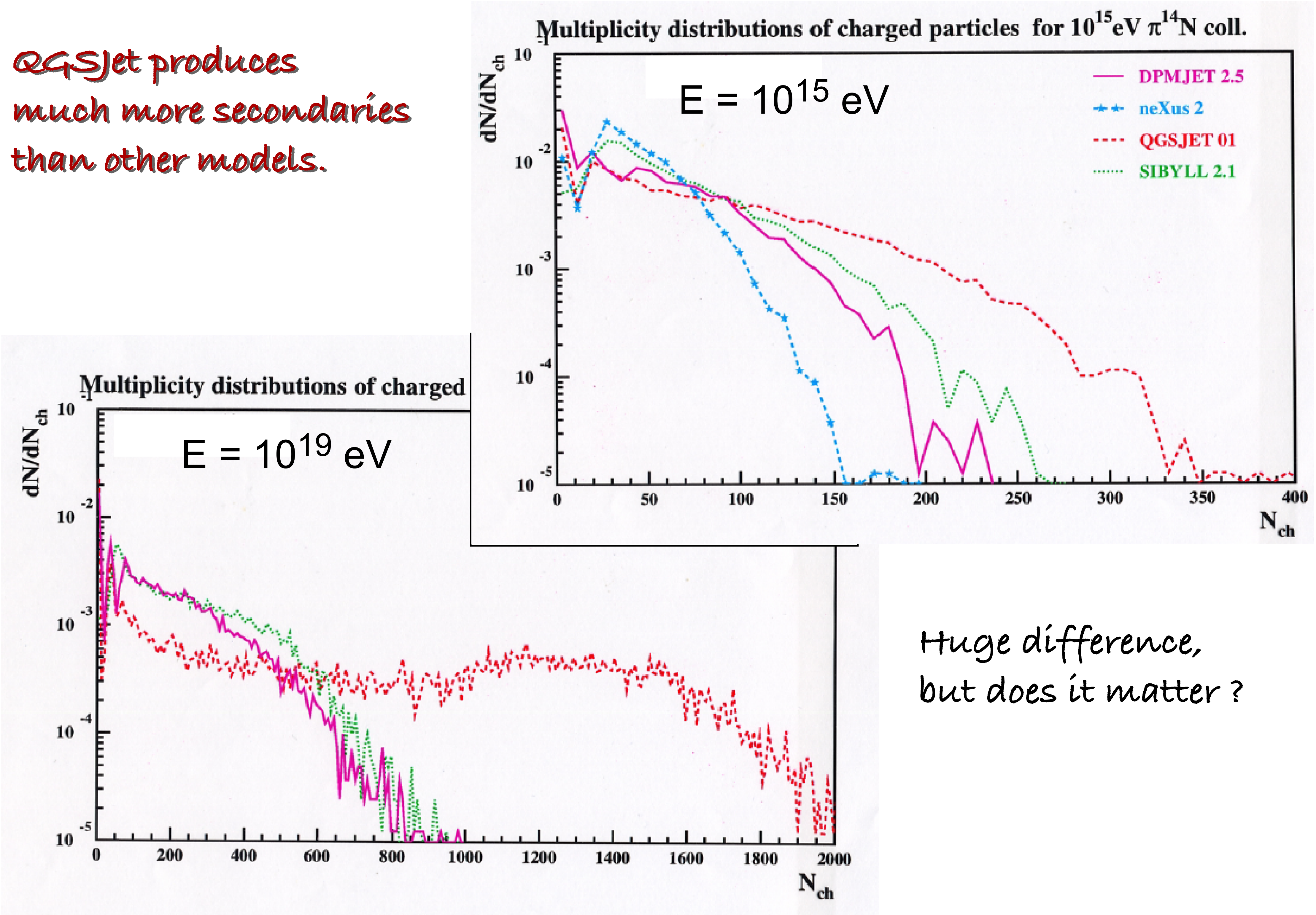
diffractive - non-diffractive
ratio is very important

Results on particle production

particle multiplicity
in p-p̄ collisions

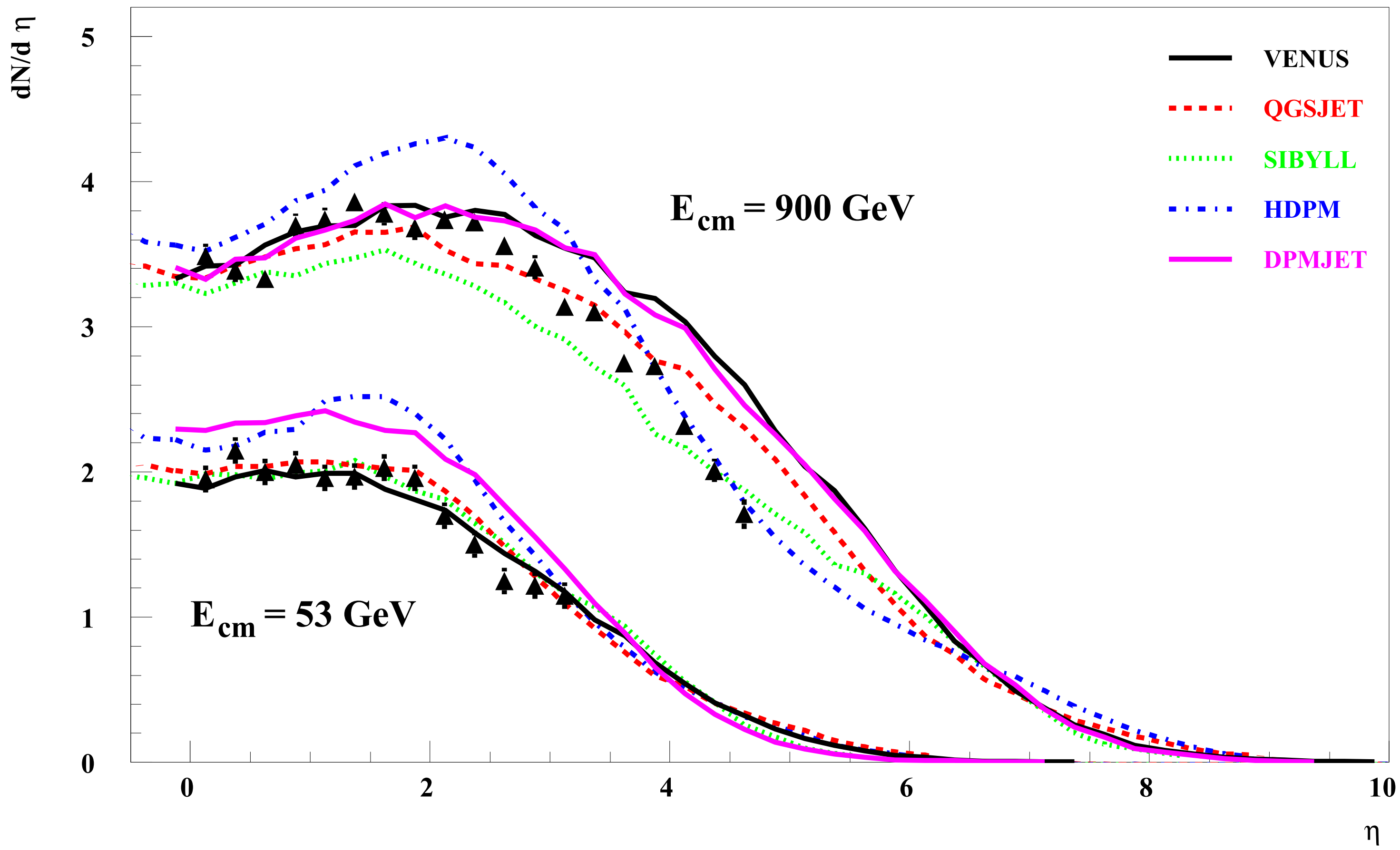


QGSJet produces much more secondaries than other models.



Huge difference, but does it matter ?

UA5 results at the SPPS



Rapidity:

$$y = \frac{1}{2} \ln \frac{E+p_L}{E-p_L}$$

Pseudorapidity:

$$\eta = \frac{1}{2} \ln \frac{p+p_L}{p-p_L}$$

$$\eta = - \ln (\tan(\theta/2))$$

η ~ y
for high energies
(or zero mass)

(Pseudo)rapidity
is additive in Lorentz
transformation.

Pseudorapidity (η) distributions initially not very well described:

models can fit either dN/dη (η=0) or

the tail to large η-values,

but not both.

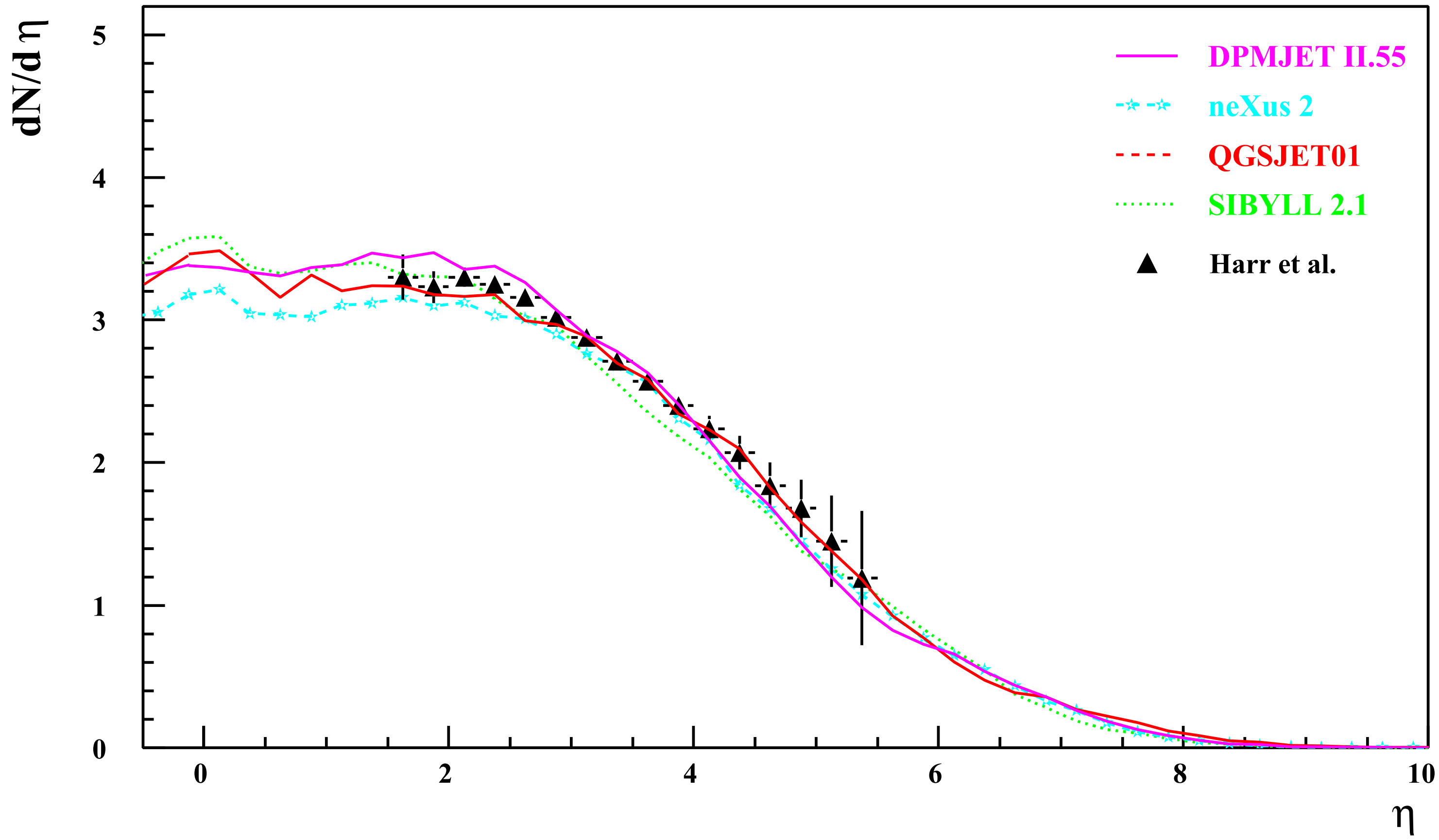
are models wrong or badly tuned?

Another experiment at the same collider ....

E_{cm} = 630 GeV

P238 (Harr et al.)

Simulations including experimental trigger



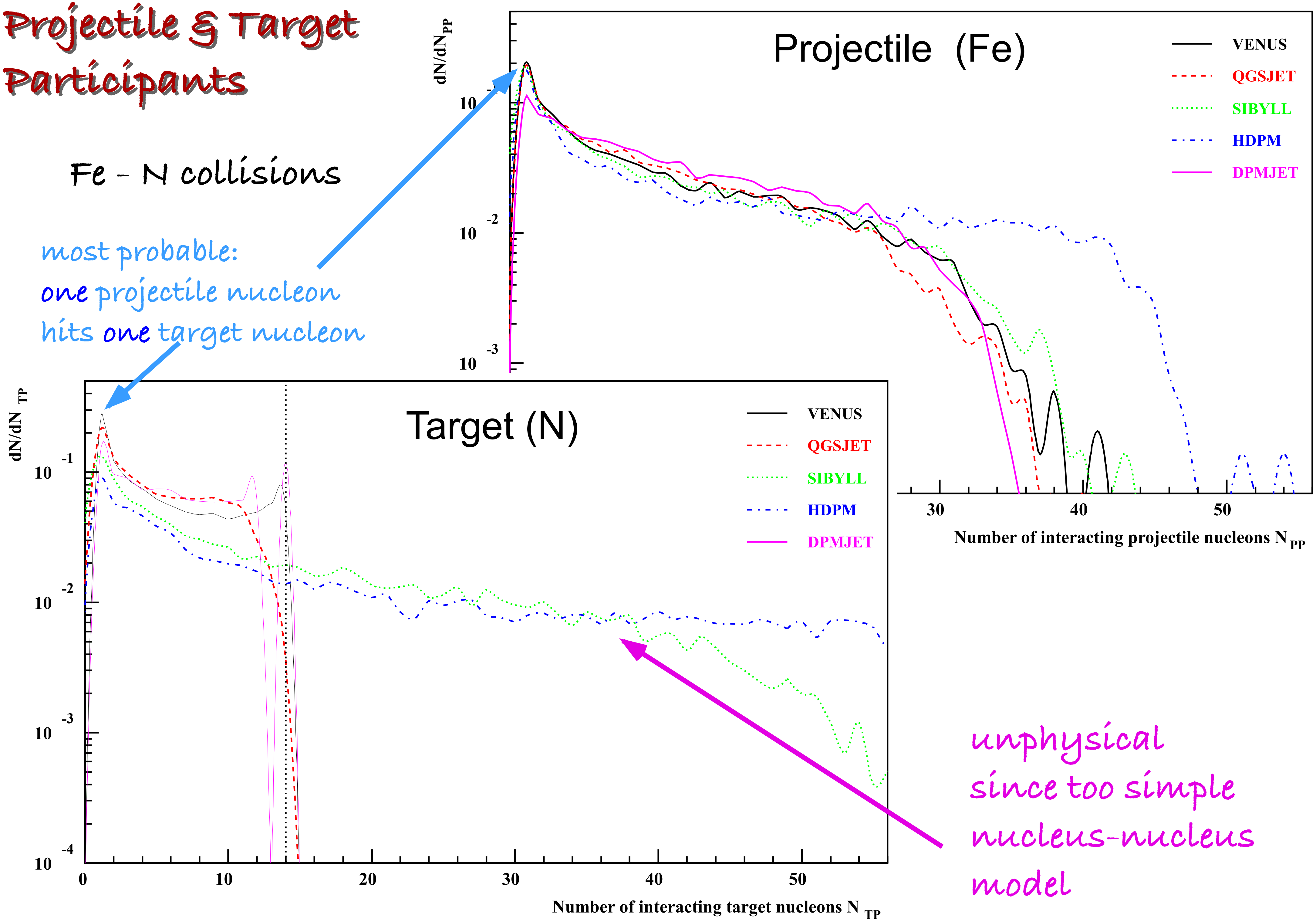
New experimental results in contradiction to older UA5 distributions, but very good agreement with simulations.

Experimental results are not always to be taken at face value.

Projectile & Target Participants

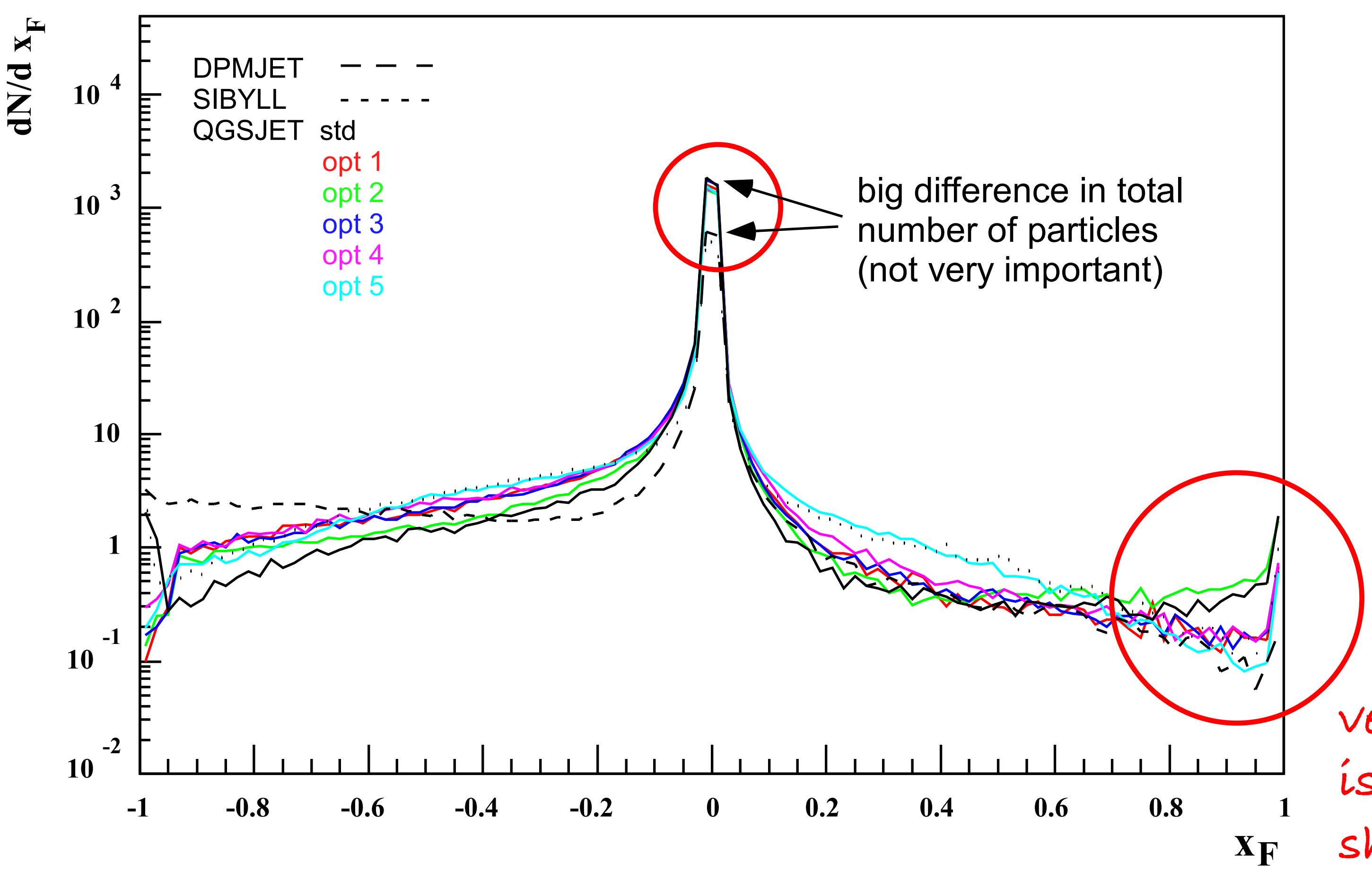
Fe - N collisions

most probable:
one projectile nucleon
hits one target nucleon



unphysical
since too simple
nucleus-nucleus
model

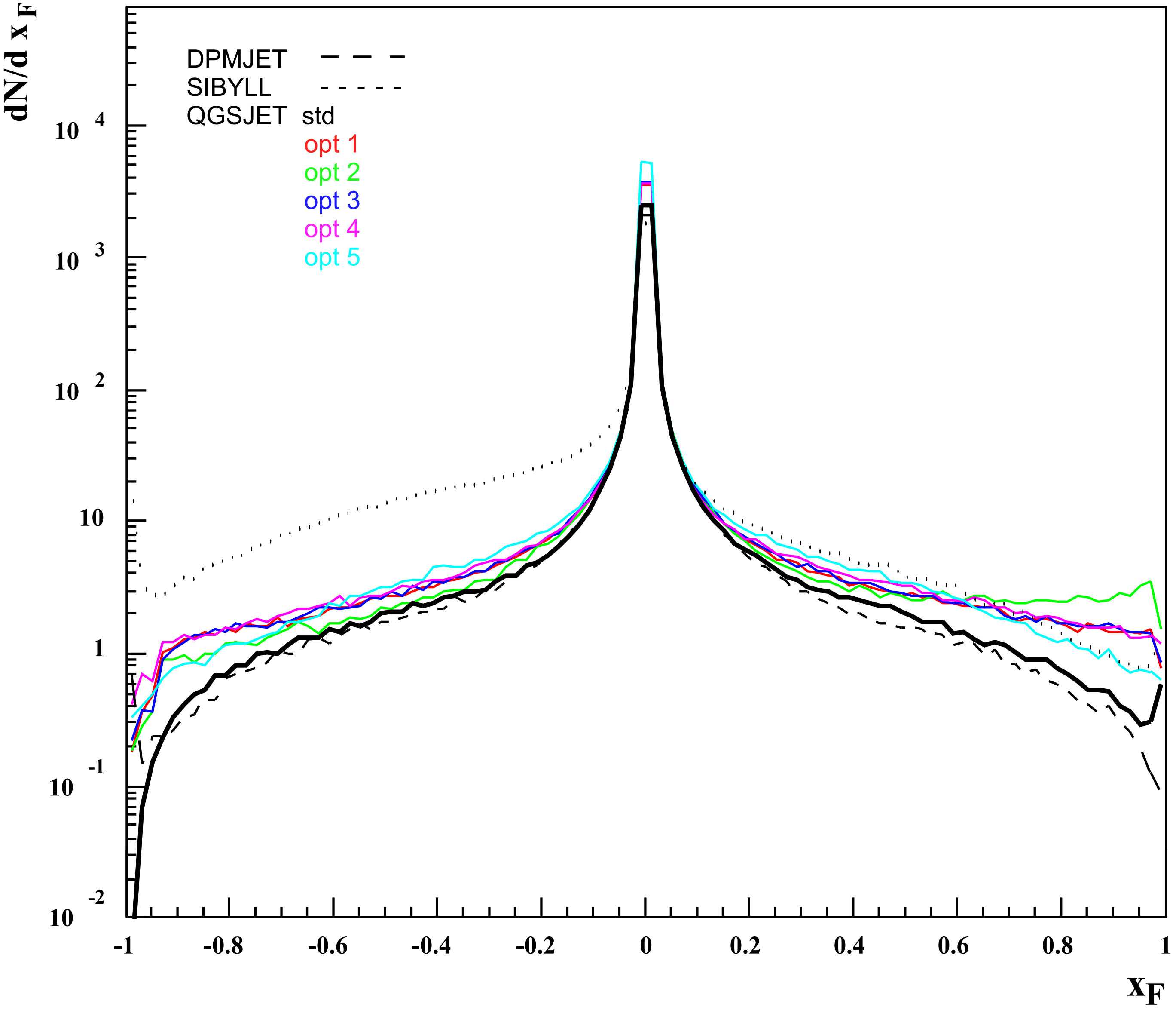
Feynman x distribution in p-N collisions



big difference in total number of particles (not very important)

very forward region is important for shower development

Feynman x distribution in N-N collisions ...
... should be symmetric as well



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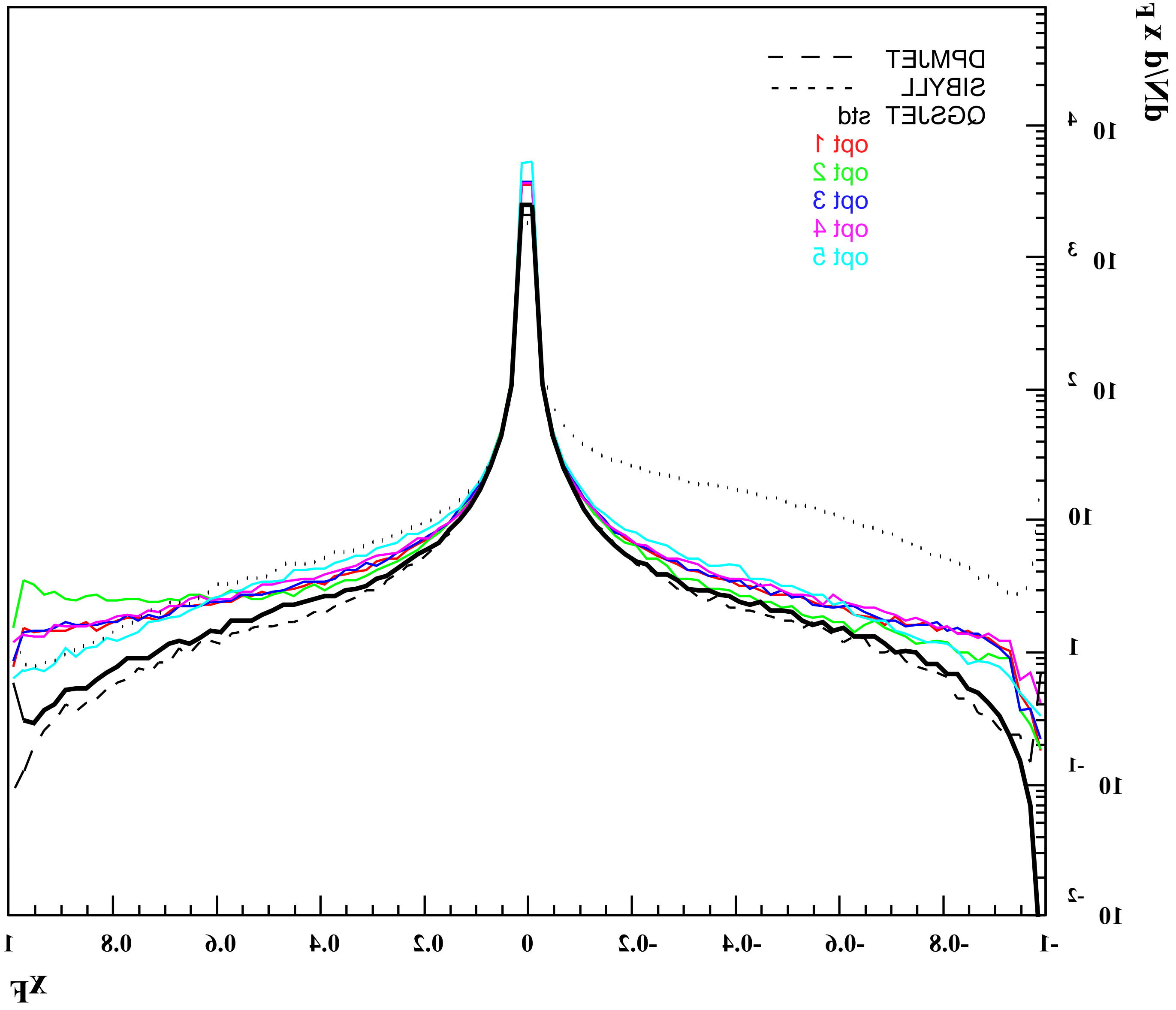
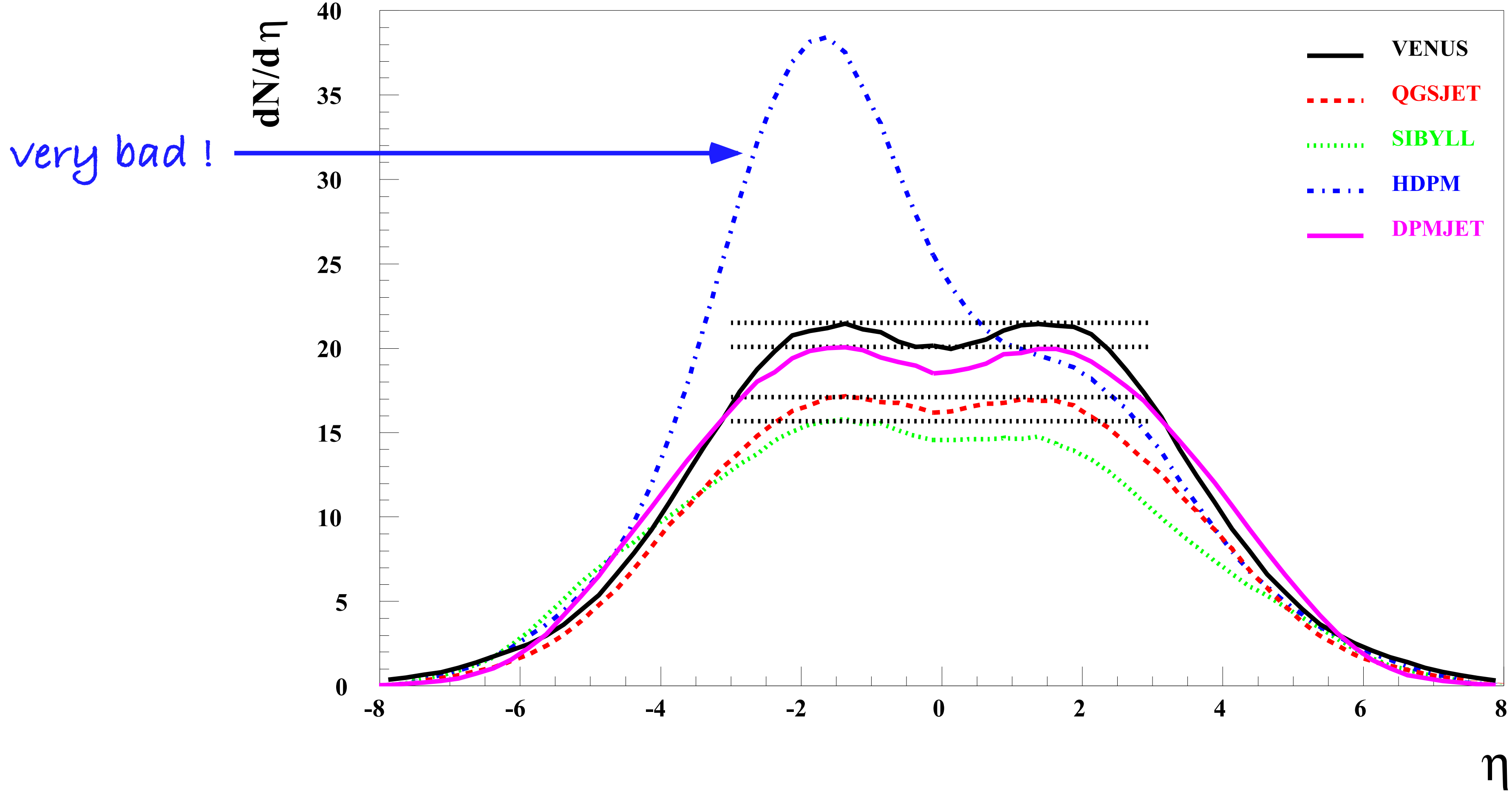

DPMJET
SIBYLL
QGSJET std
opt 1
opt 2
opt 3
opt 4
opt 5
dN/dp x F
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
x_F

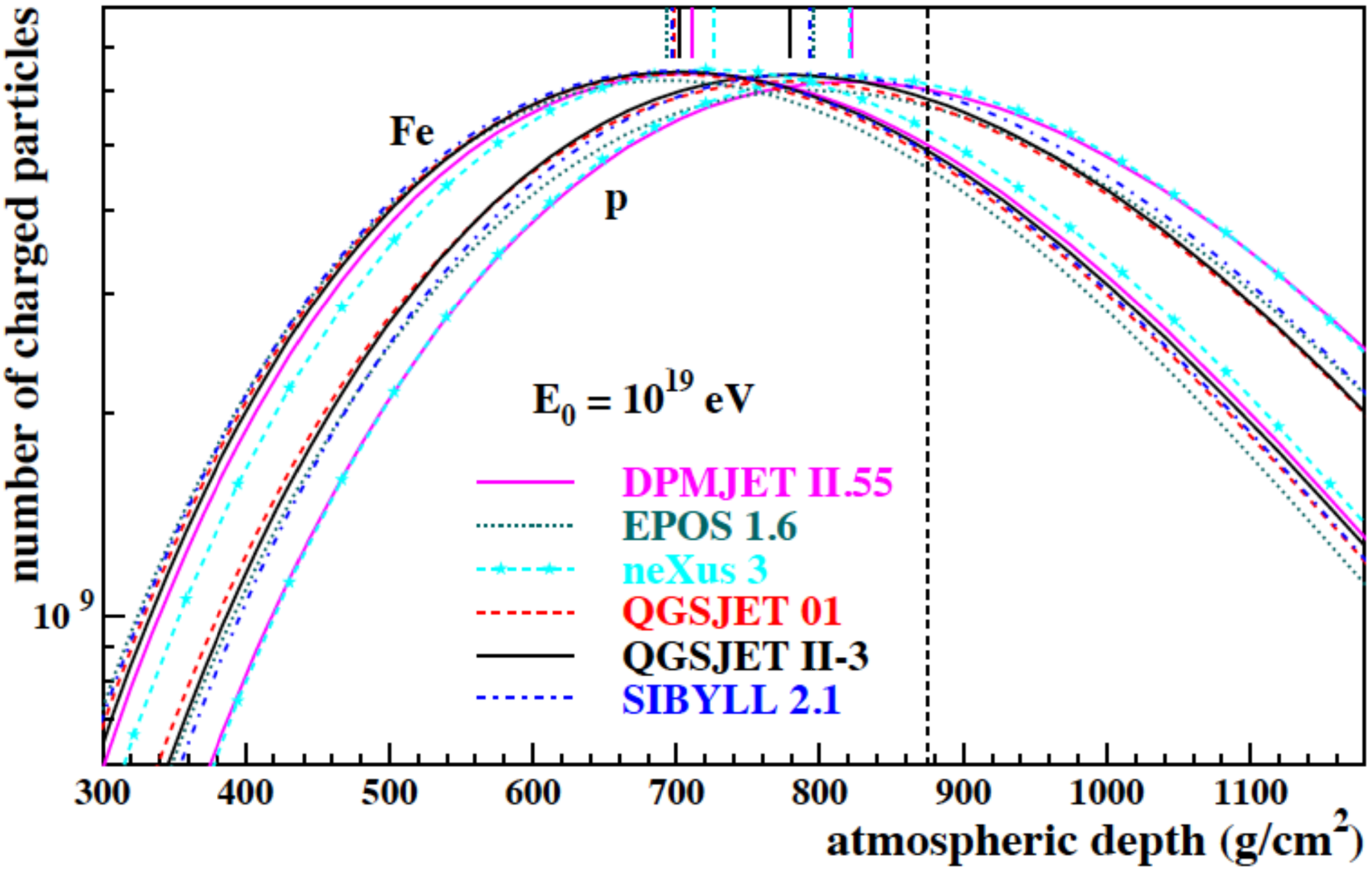
Nitrogen-Nitrogen Collisions



… should be perfectly symmetric,
if nuclear interactions are treated well.

Average Longitudinal Shower Development

QGSJet well in line with other models.
High multiplicity partly compensated by lower cross-section and partly irrelevant since mostly low-energy particles produced.



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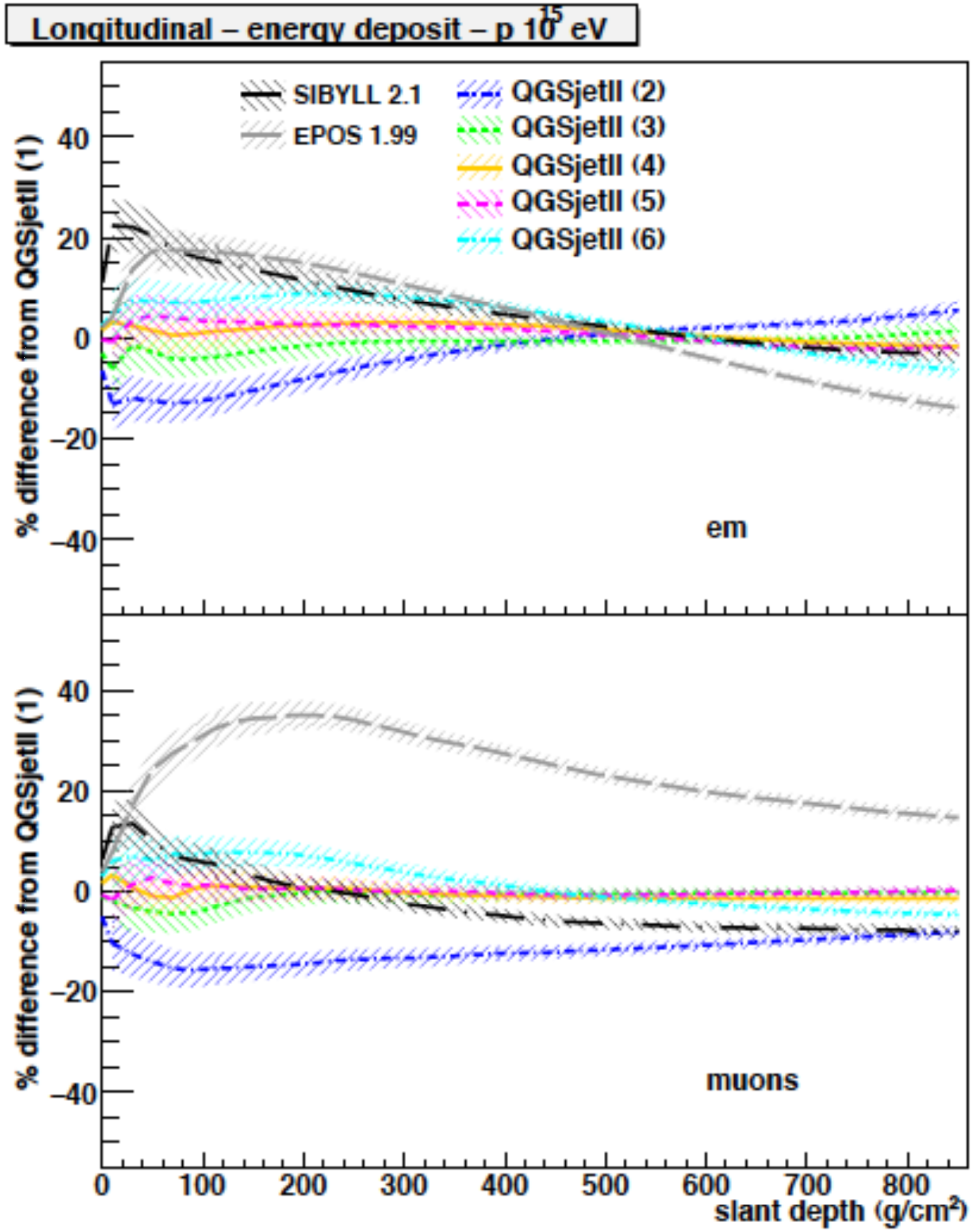
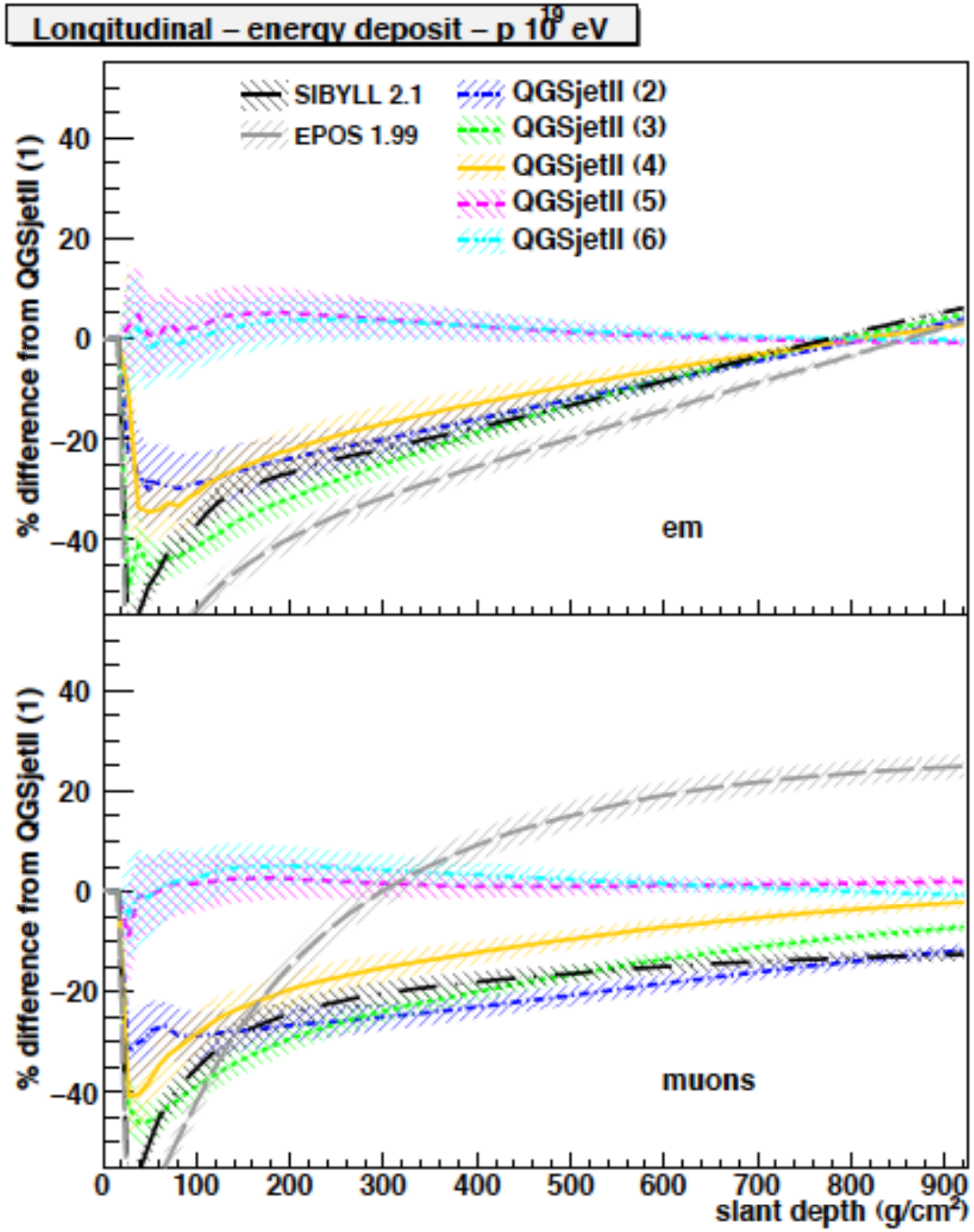
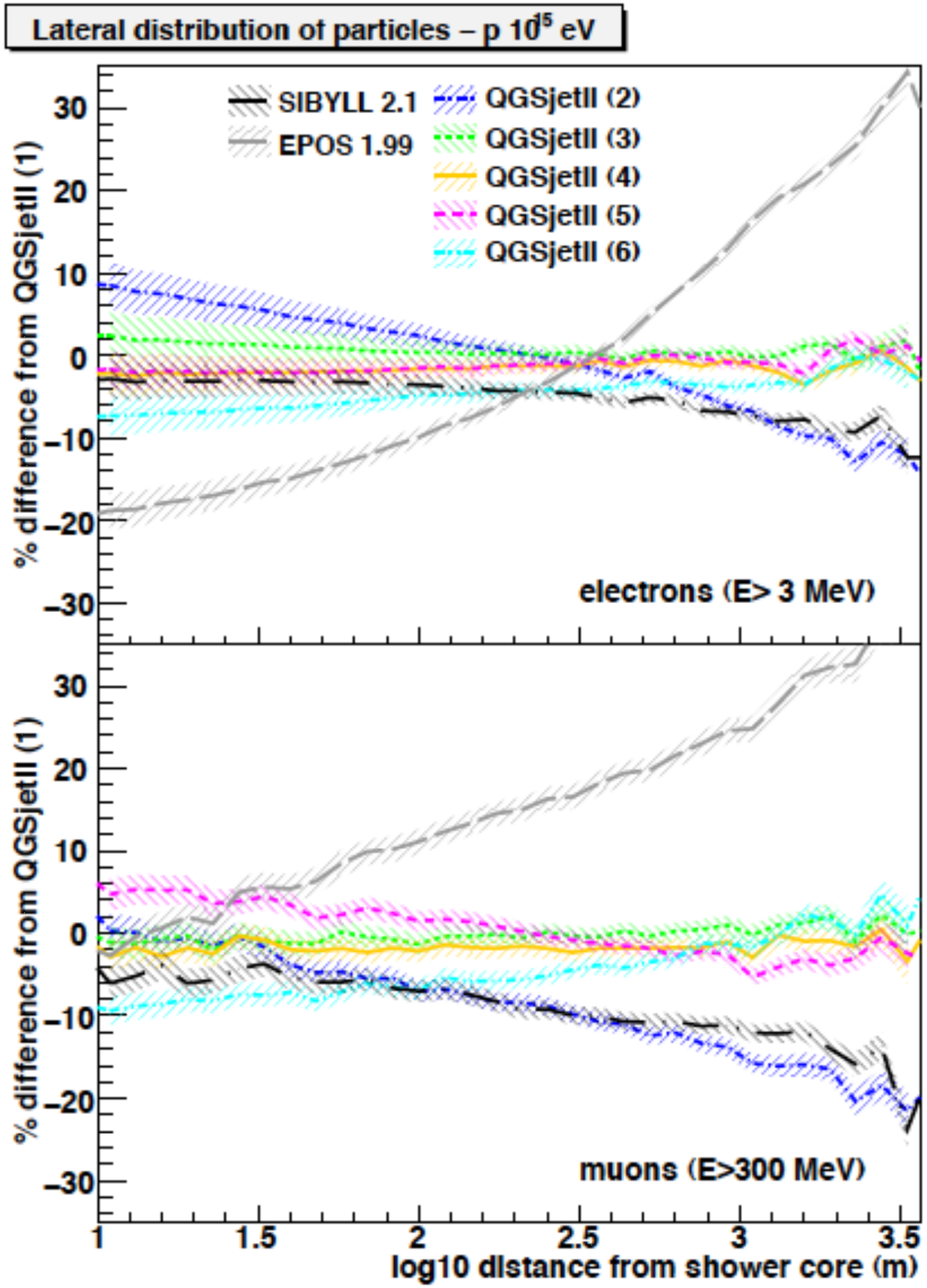
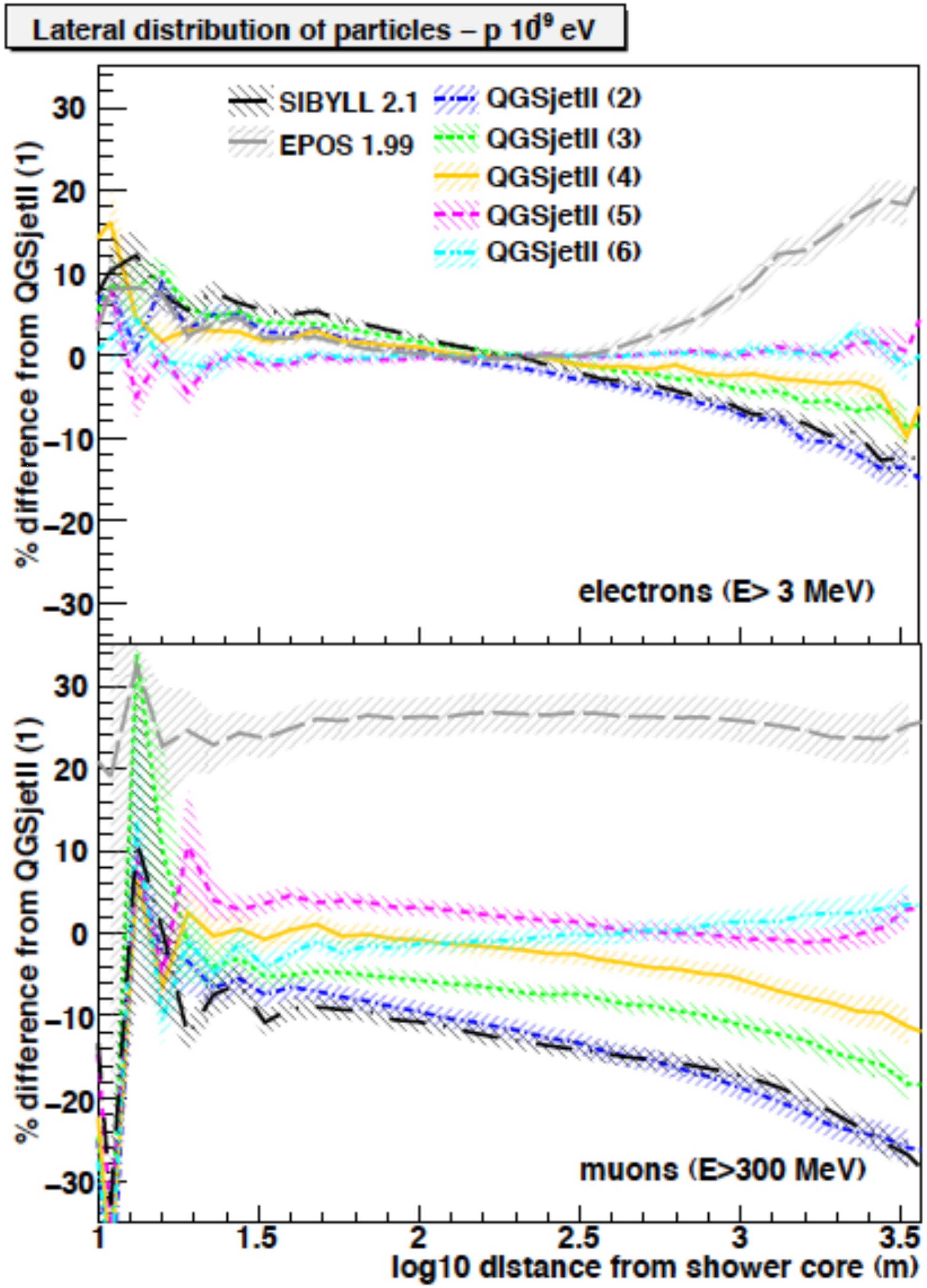
Longitudinal distribution





Lateral distribution


Lateral distribution of particles – p 10^{15} eV


Lateral distribution of particles – p 10^{19} eV

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Summary & Outlook

- Great improvements in EAS simulations in past few years. Soft hadronic and nuclear interactions modeled on basis of Gribov- Regge & Glauber Theory.

- Assumption of a mixed CR composition (p, He, ... Fe) and extrapolation of models from 100 GeV range yields amazingly good agreement with CR data from $\sim 10^{12}$ .... 10^{19} eV.

- New accelerator experiments will provide new experimental input to cross-sections, diffraction and hadronic particle production under small angles.

- Astroparticle experiments increasingly constrain models at higher energies.

Only HEP and Astroparticle physicists together can solve the problem of origin of the high energy cosmic rays and its hadronic interactions in the atmosphere.