Soft QCD and the Production of Secondary Cosmic Rays

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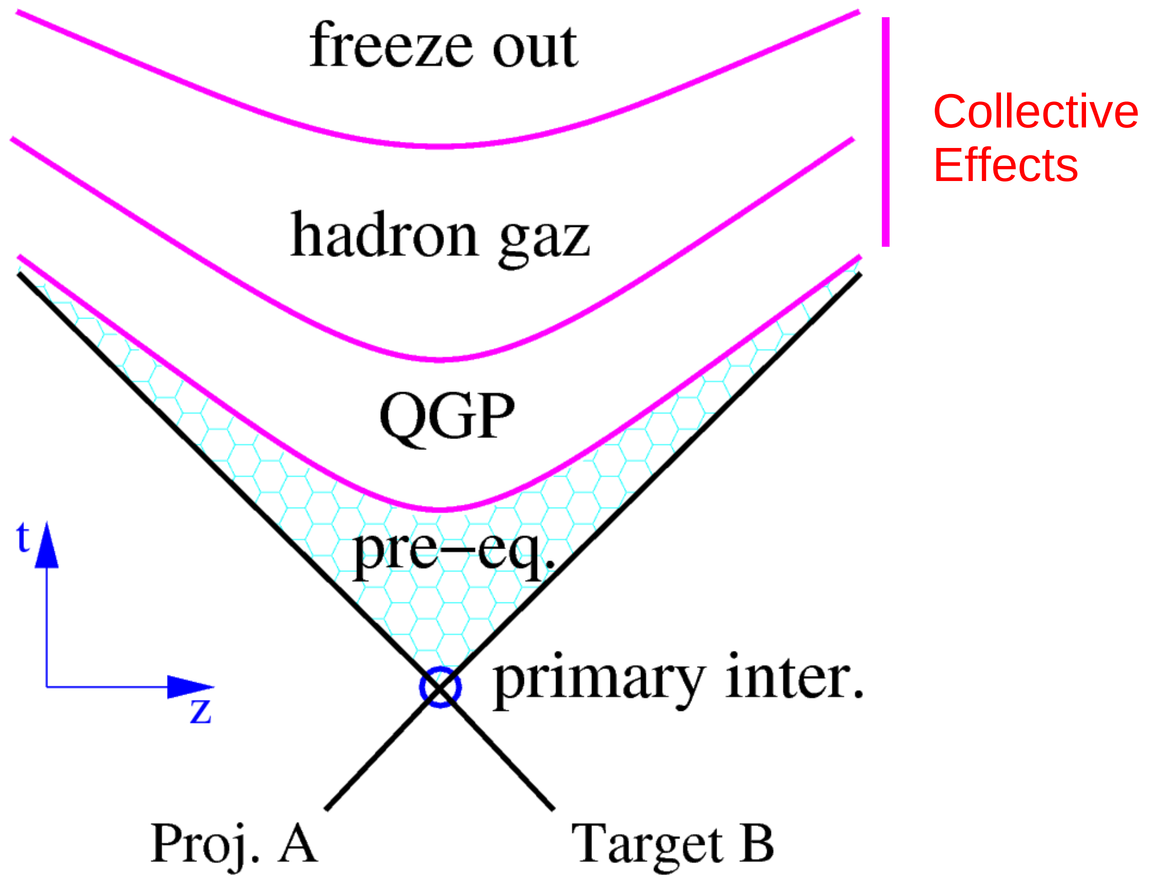
Outline

- **EAS : Longitudinal distributions**
  - Heitler model: X_{max}
  - Longitudinal Profile
  - Energy Deposit
- **EAS : Particles at ground**
  - Heitler model: N_μ
  - Particles at ground
  - Muon puzzle
  - Muon production depth
- **EAS : Link with hadronic interactions**
  - Hadronic Observables
  - Hadronic interaction models for Cosmic Rays

Goal of Today's Lecture...



The complete description of hadronic interactions is universal …
my biased view !

What can be used as projectile/target ?

- **Any charged particle with sufficiently long life time can be accelerated** (electrons (e^-), positrons (e^+), protons (p), nuclei (A), hadrons (h), leptons (l) ...) **:**

e^+ vs e^- → l vs p (A) → p vs p → h vs A → A vs A

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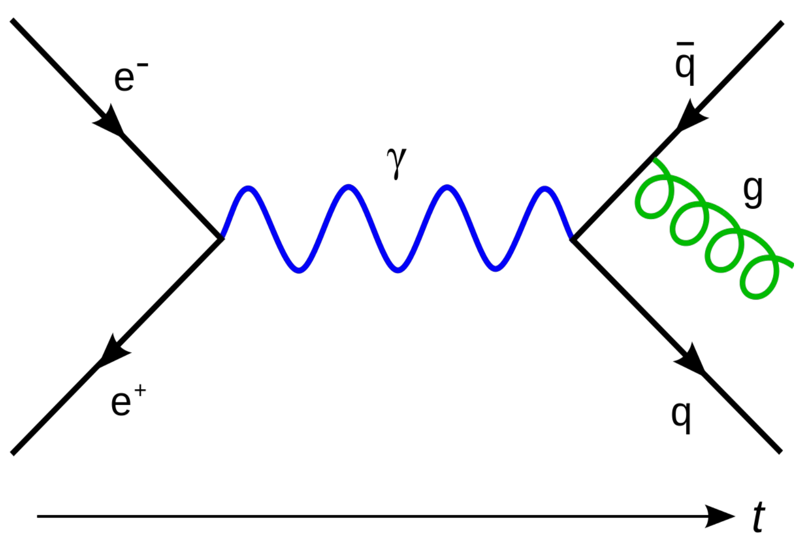
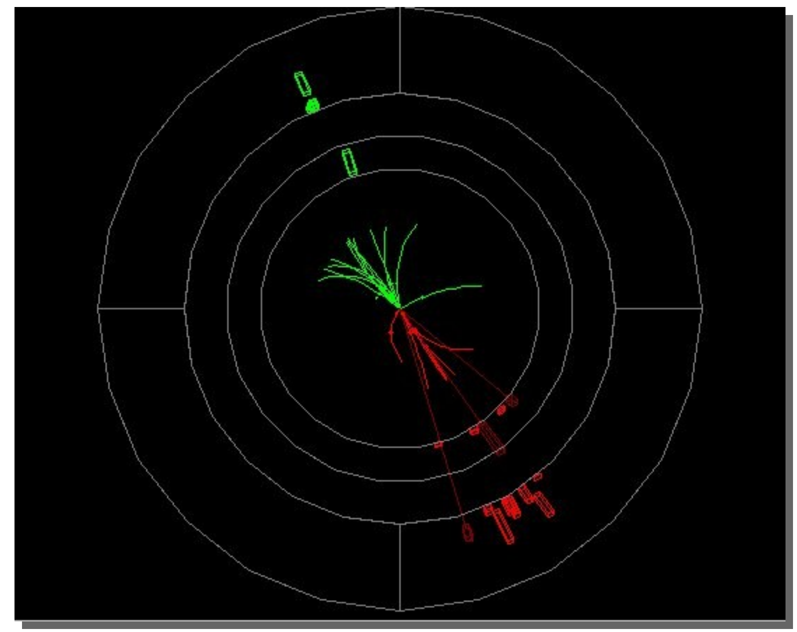
- fundamental particles
- study of new particles
- “clean”
- difficult to go to very high energies

(~100 GeV/c)





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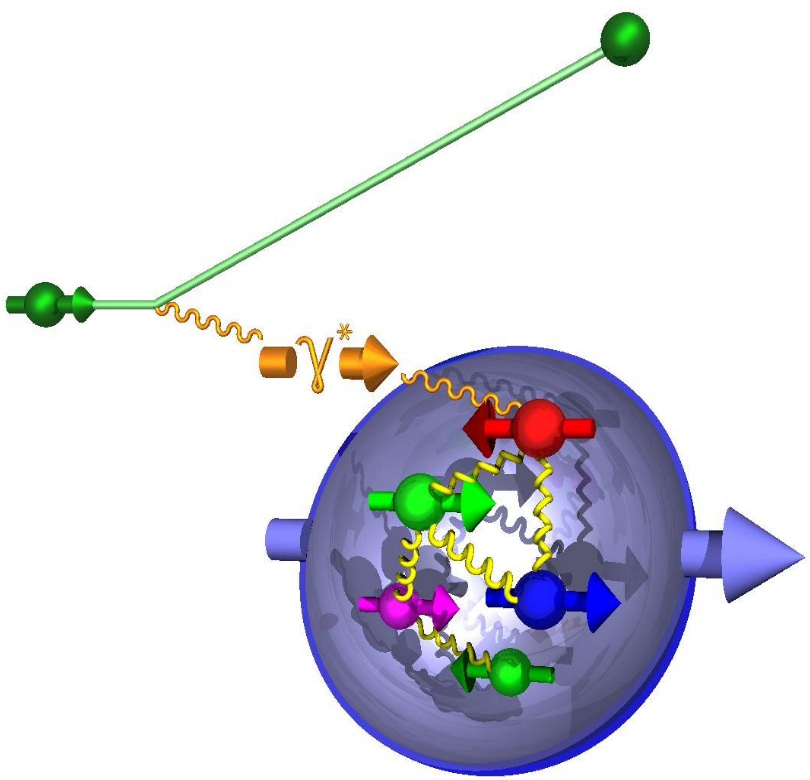
- one particle with inner structure
- study proton structure
- asymmetric detectors



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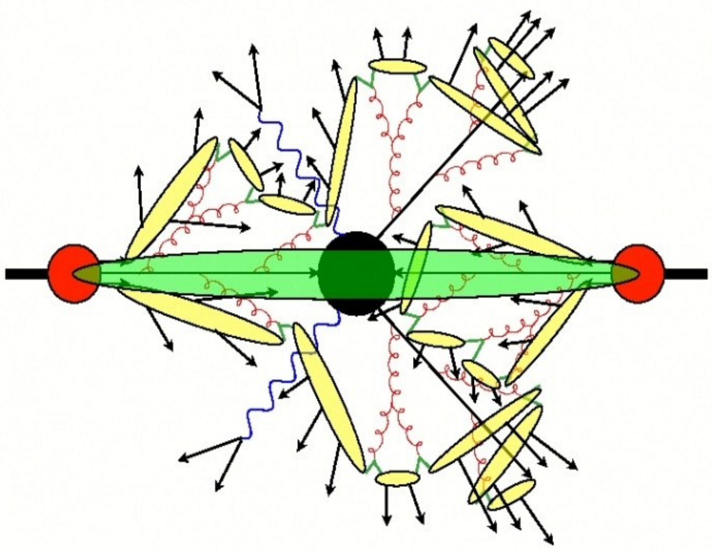
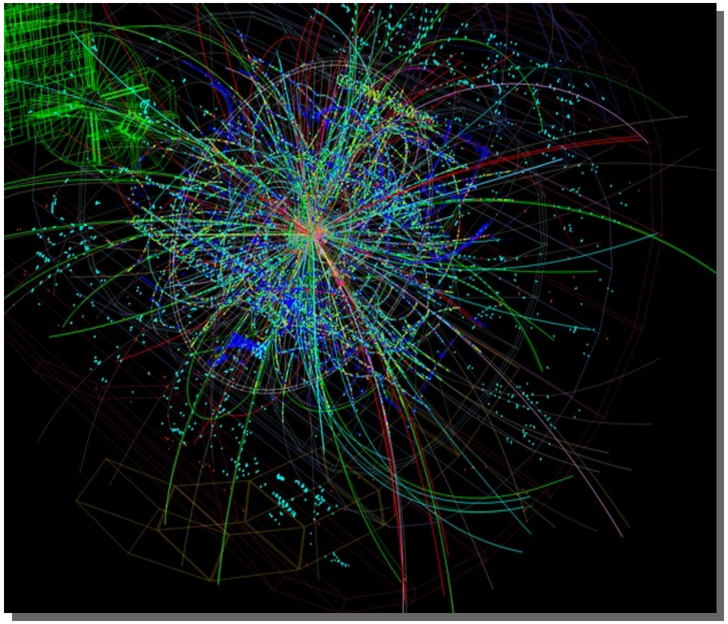


- complex particles
- study of new particles
- multiple interactions of inner structure
- “dirty”
- very high energy possible

  (~10 TeV/c)



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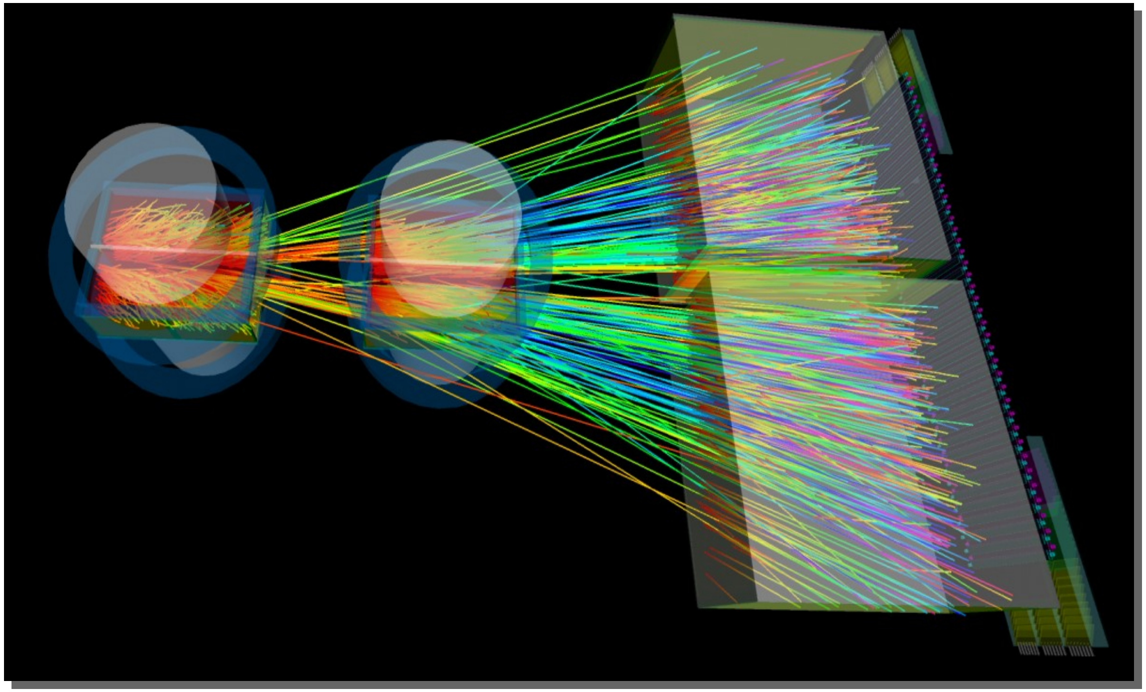

NA61

- complex particles with short life time
- important to understand particle cascade
- fixed target only: “forward” physics
- only low energy possible (~10 GeV/c)

What can be used as projectile/target ?

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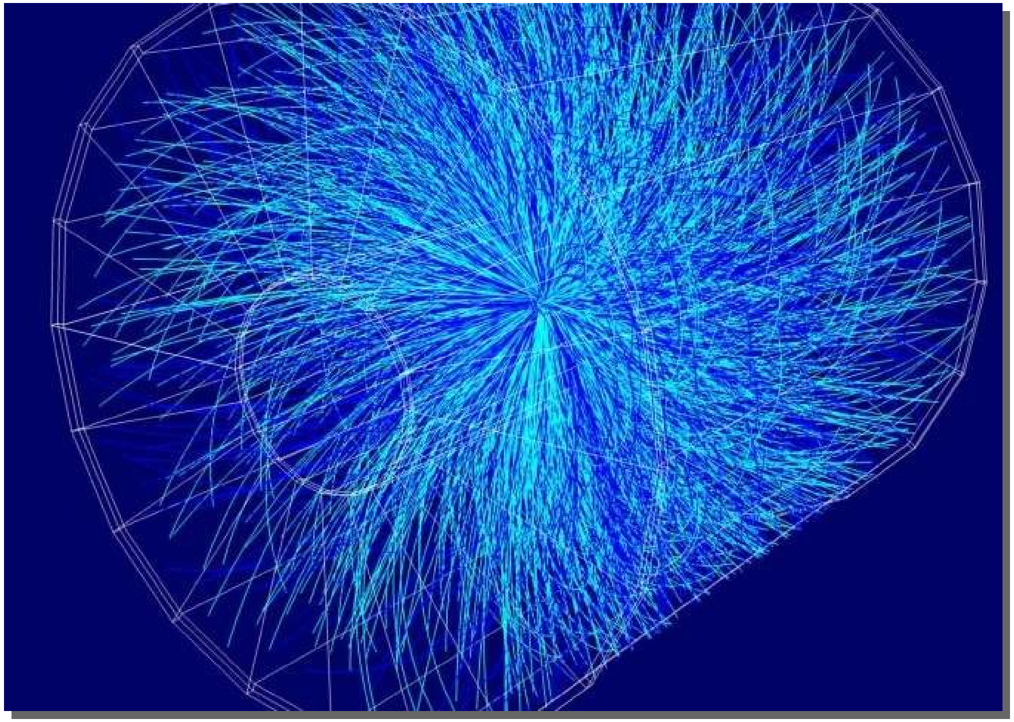

ALICE

- very complex particles
- study the very early state of the Universe
- very “dirty”
- very high energy densities

What can be used as projectile/target ?

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(~100 GeV/c)

l vs p (A)
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- study proton structure
- asymmetric detectors

p vs p
- complex particles
- study of new particles
- multiple interactions of inner structure
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- very high energy possible

(~10 TeV/c)

h vs A
- complex particles with short life time
- important to understand particle cascade
- fixed target only:

  "forward" physics
- only low energy possible

(~10 GeV/c)

A vs A
- very complex particles
- study the very early state of the Universe
- very "dirty"
- very high energy densities

- **Different particles = different structure of matter**

What can be used as projectile/target (2) ?

- **Any charged particle with sufficiently long life time can be accelerated** (electrons (e^-), positrons (e^+), protons (p), nuclei (A), hadrons (h), leptons (l) ...) **:**

e^+ vs e^- → l vs p (A) → p vs p → h vs A → A vs A

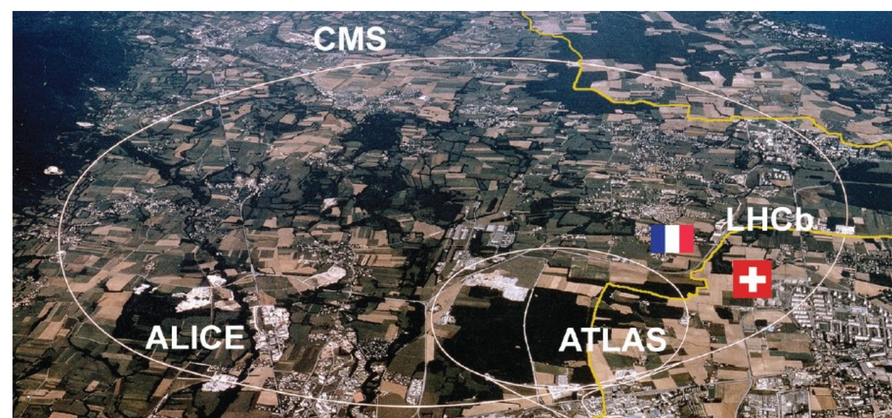
e^+ vs e^-
- LEP (CERN)
- SLC/PEP (SLAC)
- KEKB (KEK)

l vs p (A)
- HERA (DESY)
- (SLAC)
- (CERN)
- (FNAL)

p vs p
- LHC (CERN)
- Tevatron (FNAL)
- RHIC (BNL)

h vs A
- SPS (CERN)
- (FNAL)

A vs A
- LHC (CERN)
- RHIC (BNL)



- **Different particles = different detectors**

What can be used as projectile/target (3) ?

- **Any charged particle with sufficiently long life time can be accelerated** (electrons (e^-), positrons (e^+), protons (p), nuclei (A), hadrons (h), leptons (l) …) **:**

e^+ vs e^- →	l vs p (A) →	p vs p →	h vs A →	A vs A
Pythia	Pythia	Pythia	Pythia	Pythia
HERWIG	HERWIG	HERWIG	QGSJET	QGSJET
Phojet	RAPGAP	SHERPA	Sibyll	Sibyll
EPOS	Cascade	Phojet	DPMJet	DPMJet
	Phojet	DIPSY	Hijing	AMBT
	EPOS	QGSJET	DIPSY	Hijing
		Sibyll	EPOS	DIPSY
		DPMJet		Hydro models
		EPOS		EPOS

- **Different particles = different physics = different models**

What can be used as projectile/target (3) ?

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e^+ vs e^-	l vs p (A)	p vs p	h vs A	A vs A
Pythia	Pythia	Pythia	Pythia	Pythia
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	Phojet	DIPSY	Hijing	AMBT
	EPOS	QGSJET	DIPSY	Hijing
		Sibyll	EPOS	DIPSY
		DPMJet		Hydro models
		EPOS		EPOS

High Energy Physics models
Cosmic Ray models
Both

- **Different particles = building blocks for a complete approach**

What is measured by detectors ?

- **2 types of scatterings**
  - elastic : only momentum transfer between projectile and tartget : particle shape
  - inelastic : new particles are produced : standard model

- **Only particles with long enough life time can be directly observed :**
  - proton, neutron, charged pions, charged kaons, electrons, muons and photons
  - easier to measure charged particles

- **Hadronic models necessary to compare theory processes with data by a proper hadronization of more fundamental particles**
  - hadronization can not be calculated from first principles (non-perturbative QCD process)
  - phenomenological approach compared to data to fix (tune) parameters
    - importance of the different “building blocks”
    - different type of particle scattering

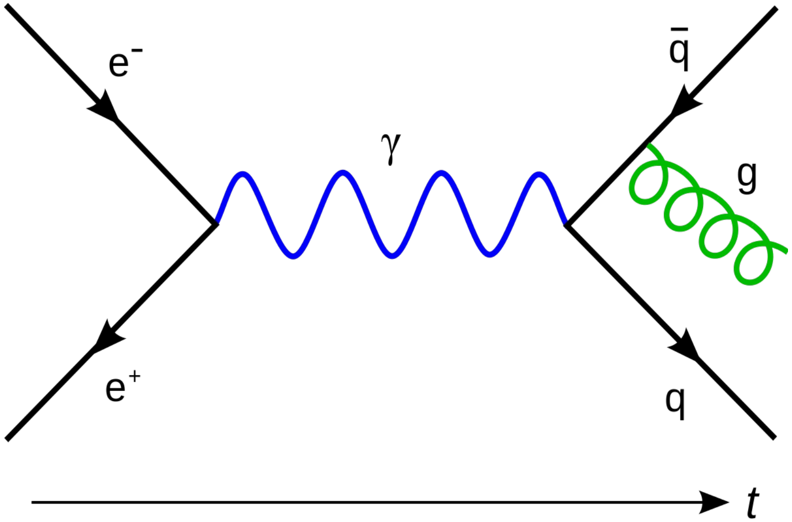
"soft" Low Momentum Particle Production

- **All high energy physics analysis** (top, Higgs, Electroweak, super-symmetry, …) **rely on the hadronic interaction models :**
  - directly : pQCD, hadronization of top jets, particle decay, missing energy …
  - indirectly : detector simulations, background, underlying events …

- **Different type of hadronic models**
  - all based on Monte Carlo methods : intensive use of random numbers
  - High Energy Physics models (HEP) : event build around a selected hard process (can be used as minium bias event generator)
    - fast and precise
    - need data to fine tune the parameters (low predictive power for "soft")
  - Cosmic Ray models (CR) : minimum bias event generator only
    - slow and do not include very rare hard processes
    - one set of parameter to reproduce all relevant data

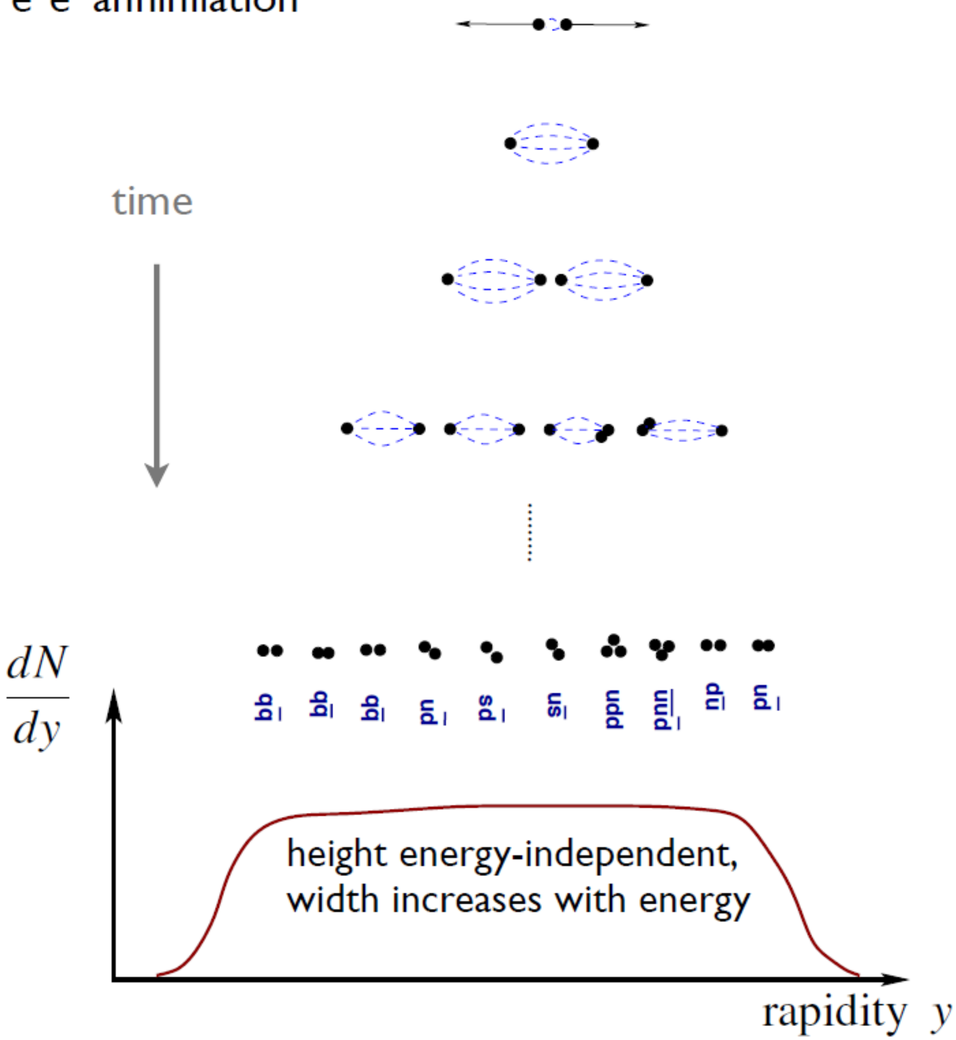
Hadronization of Quarks

e^+ vs e^- → l vs p (A) → p vs p → h vs A → A vs A



String fragmentation and rapidity

Example:
q-qbar pair produced
in e^+e^- annihilation



Rapidity

$$y = \frac{1}{2}\ln\frac{E + p_{||}}{E - P_{||}}$$

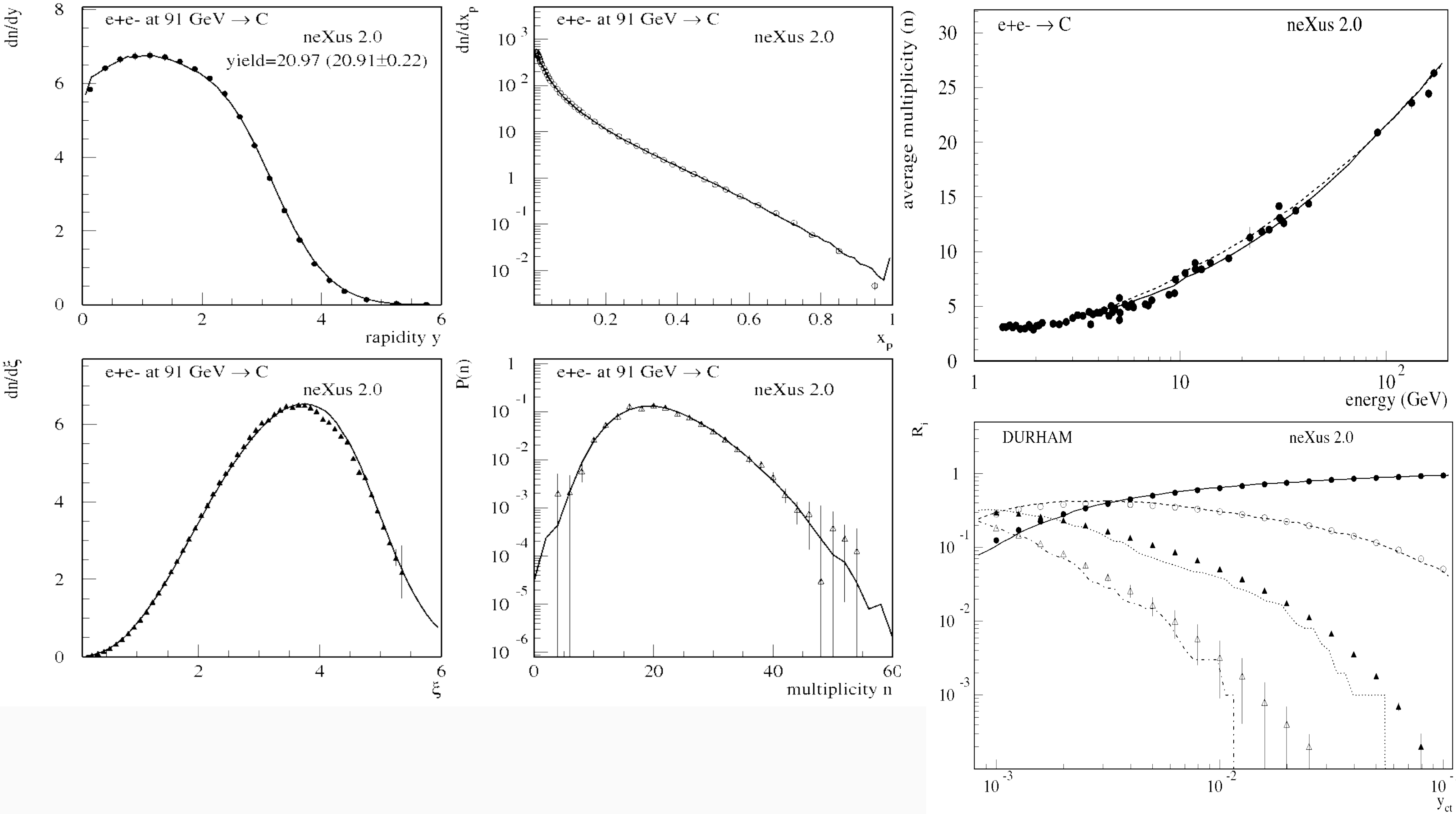
Rapidity of massless particles

$$y = \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta} = -\ln\tan\frac{\theta}{2}$$

Pseudorapidity (all particles)

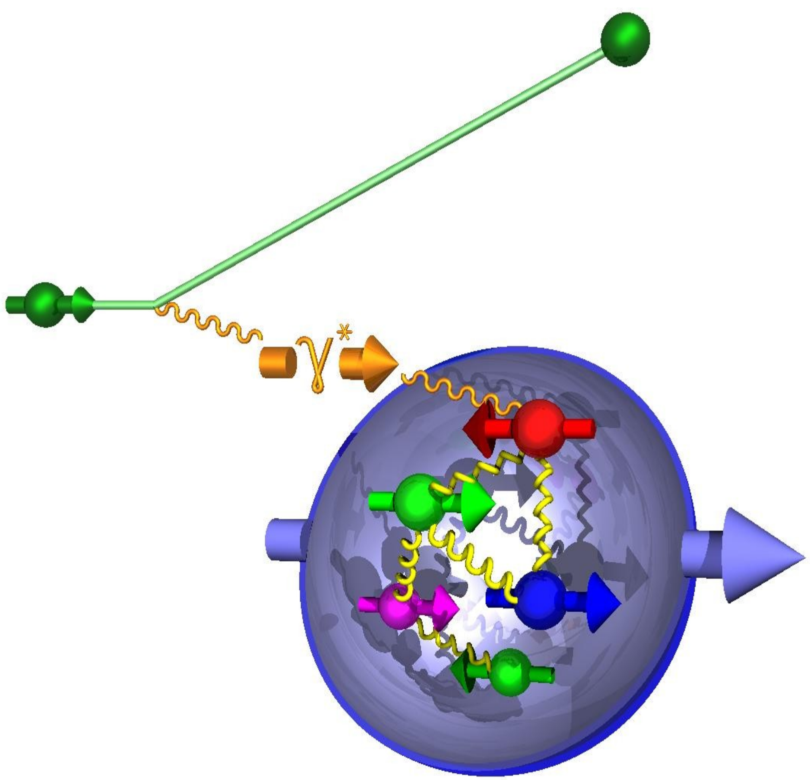
$$\eta = -\ln\tan\frac{\theta}{2}$$

Test at LEP

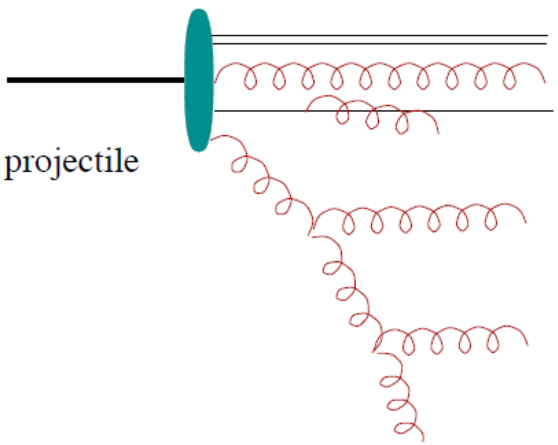

e+e- at 91 GeV → C
neXus 2.0
yield=20.97 (20.91±0.22)
dn/dy
rapidity y
dn/dx_p
x_p
dn/dξ
ξ
P(n)
multiplicity n
e+e- → C
average multiplicity (n)
energy (GeV)
DURHAM
R_i
y_ct

Parton Distributions

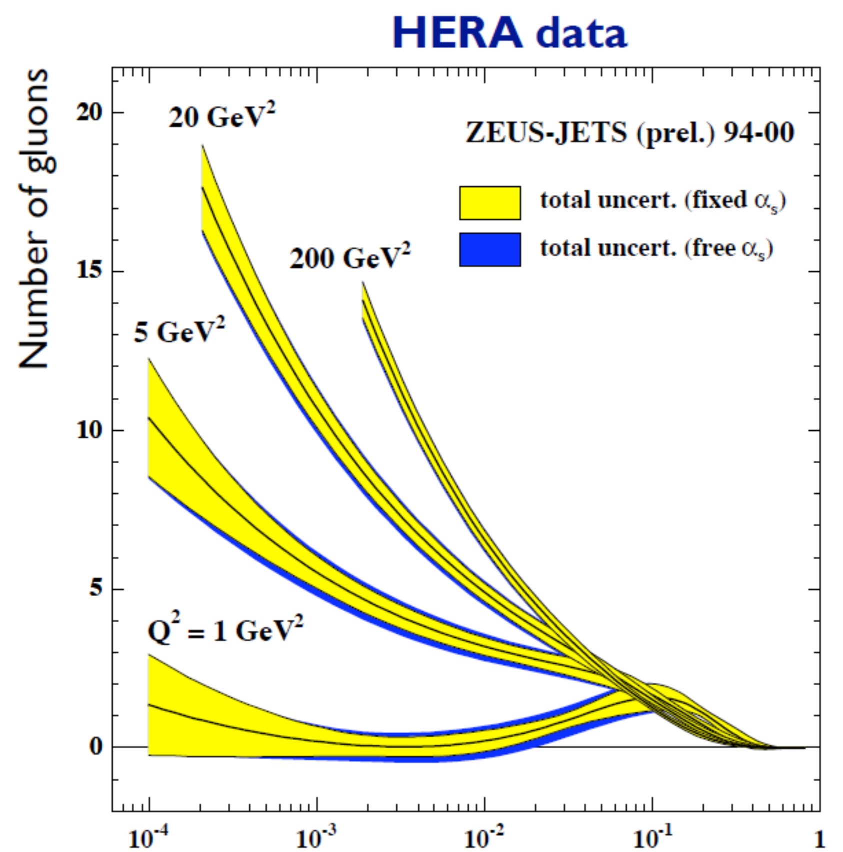
e$^+$ vs e$^-$ → l vs p (A) → p vs p → h vs A → A vs A



Perturbative QCD predictions for parton densities



Evolution of parton number
given by DGLAP equation
(and non-linear versions of it)

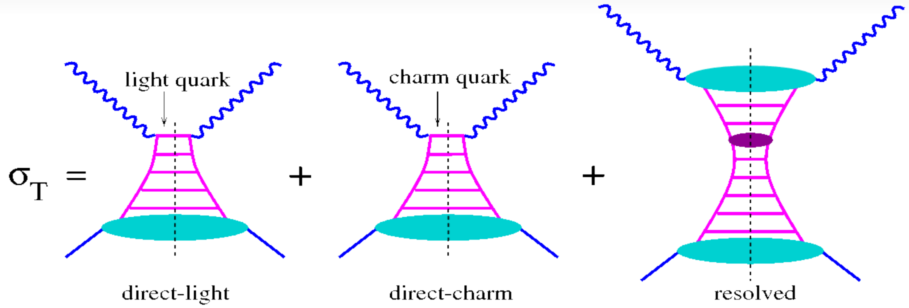


$$\frac{d f_i(x,Q^2)}{d\log Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dy}{y}\sum_j f_j(y,Q^2)\, P_{j\to i}\left(\frac{x}{y}\right)$$

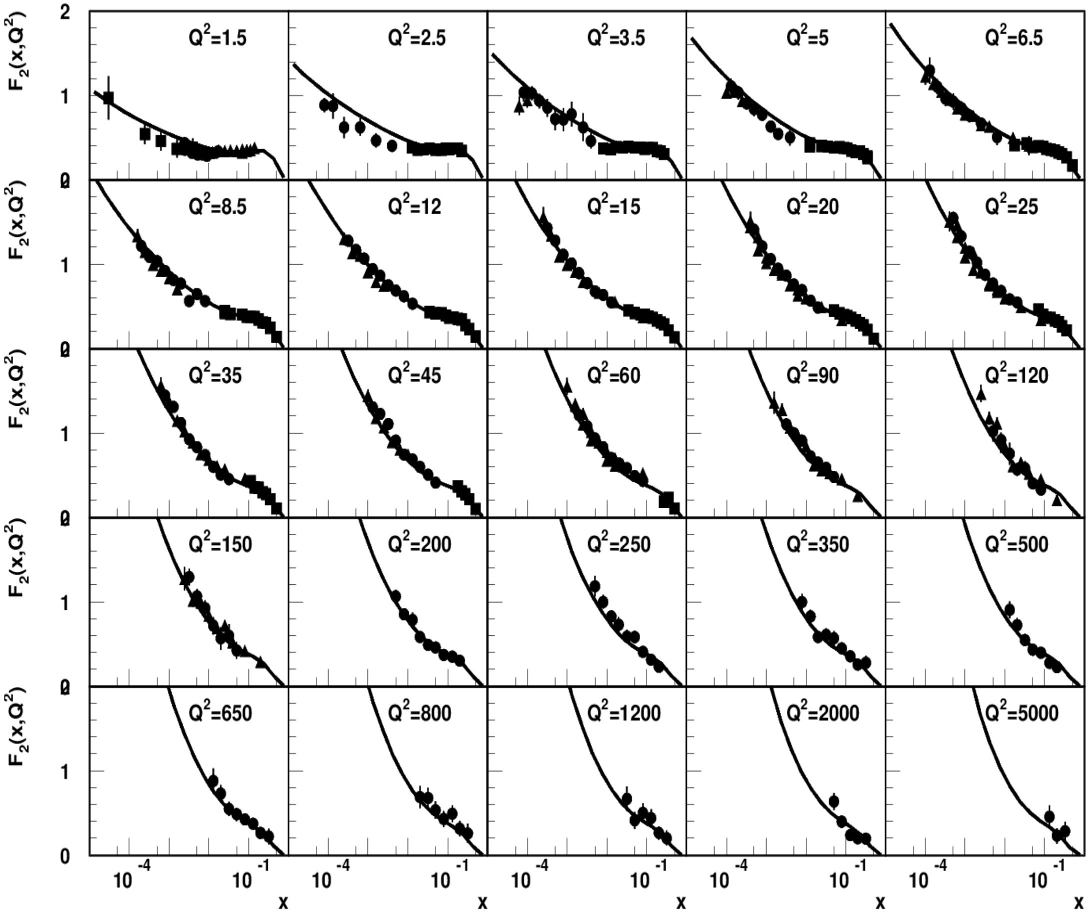
Prediction of
perturbative QCD

Test of parton interactions using deep inelastic scattering

- **Theory based parton distribution function (pdf)**
  - pQCD based for small x and large Q^2
  - Regge "soft" parametrization at small x and low Q^2
  - explicit fit of data only for valence quarks

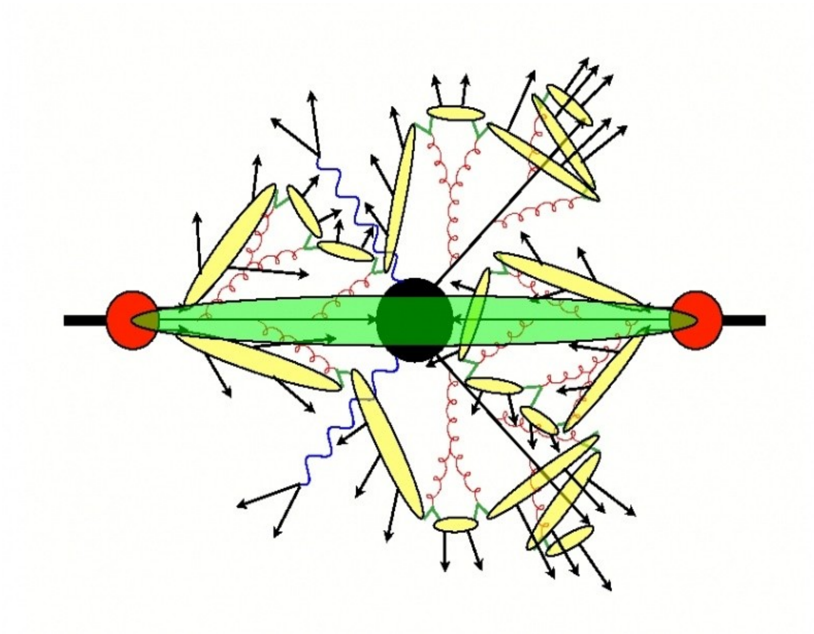


- **External pdf**
  - HEP models
  - fit of data (including uncertainty) for low Q^2
  - pQCD based evolution for large Q^2

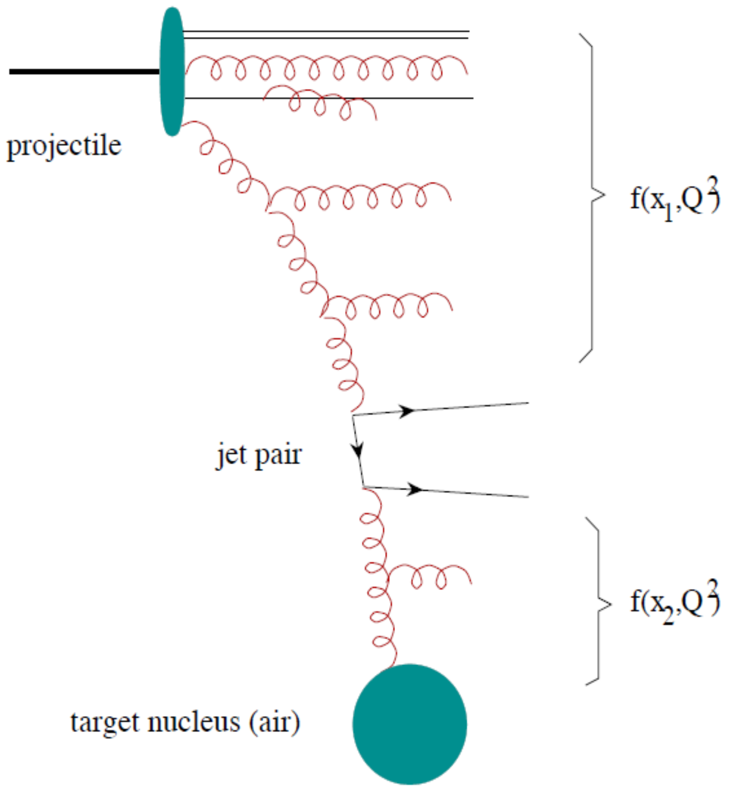


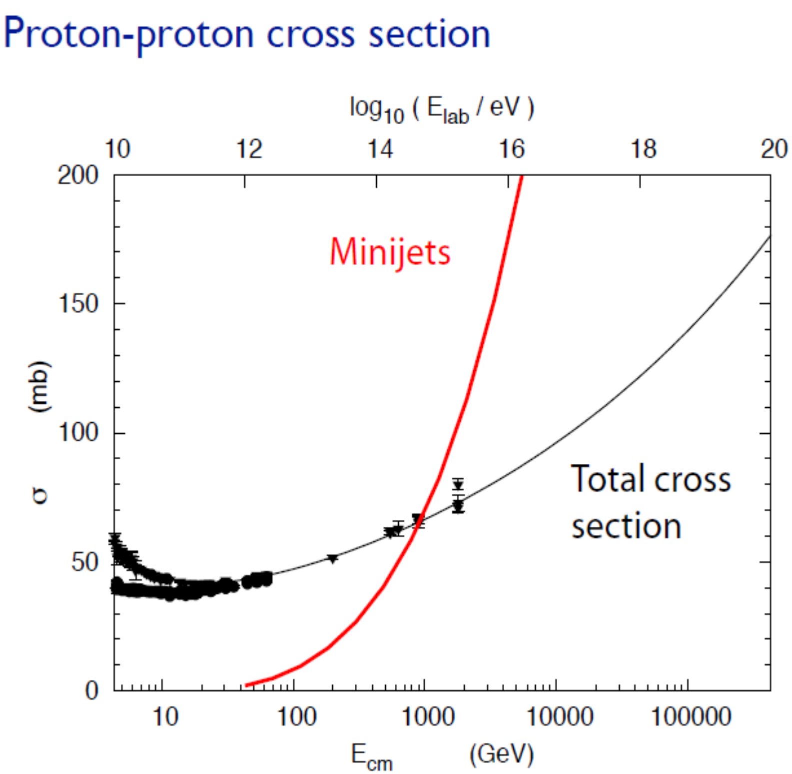
Parton Interactions

e^+ vs e^- → l vs p (A) → p vs p → h vs A → A vs A



QCD parton model: minijets

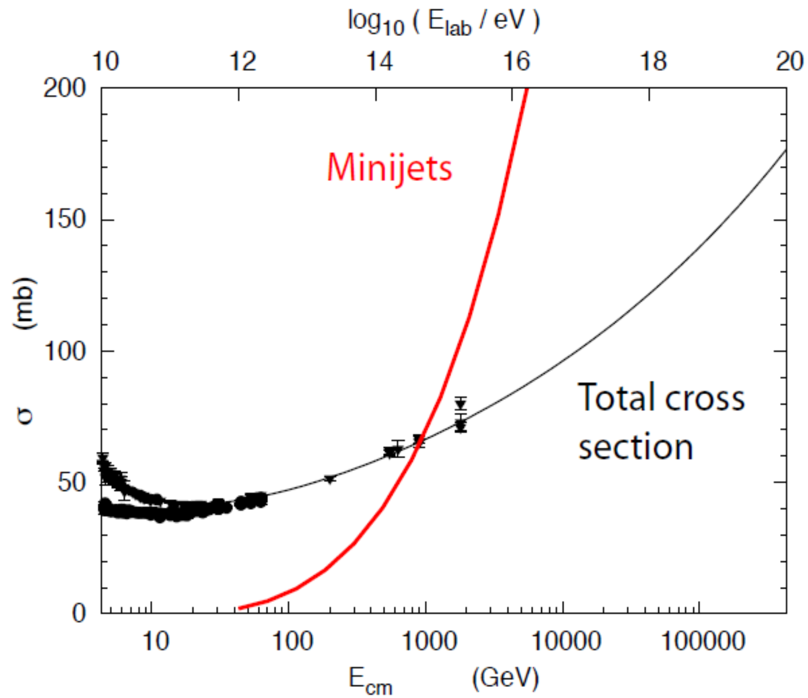




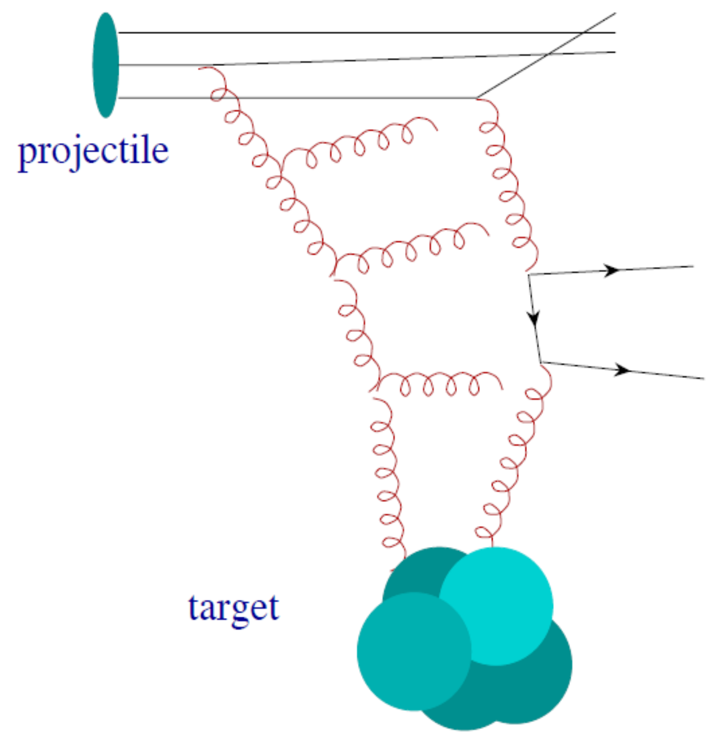
$$\sigma_{QCD} = \sum_{i,j,k,l} \frac{1}{1+\delta_{kl}} \int dx_1\, dx_2 \int_{p_\perp^{\text{cutoff}}} dp_\perp^2\, f_i(x_1,Q^2)\, f_j(x_2,Q^2)\, \frac{d\sigma_{i,j\to k,l}}{dp_\perp}$$

Solution: Multiple parton-parton interactions (MPI)

Proton-proton cross section



QCD prediction:
inclusive cross section



Average number of minijet pairs

$$\langle n_{\mathrm{jet}} \rangle = \frac{\sigma_{\mathrm{QCD}}}{\sigma_{\mathrm{ine}}}$$

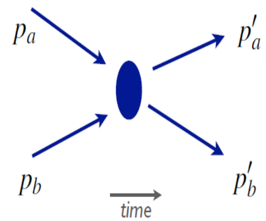
MPI depends on model

- **High Energy Physics models**
  - <n_{jet}> and cross-section (fit) are independent
  - no soft multiple scattering
  - no constrain from total cross-section to have independent access of inclusive class of events (Higgs, electroweak, etc ...)
- **Cosmic Ray models**
  - Gribov Regge Theory (GRT) used to compute total cross-section
  - Parton model approach
    - fix σ_{hard} (pQCD) and σ_{tot} (data)
    - GRT using <n_{jet}> as final goal to reach
  - or Pomeron approach
    - first built the Pomeron from soft and hard component
    - then add corrections to the bare amplitude to fit the total cross-section using GRT
    - <n> is a consequence of the Pomeron choice and the cross-section.

Pomeron Definition

$$A(s,t) = \eta(\alpha(t))\,\beta(t)\left(\frac{s}{s_0}\right)^{\alpha(t)}$$

Amplitude of elementary parton-parton interaction=mini-jet



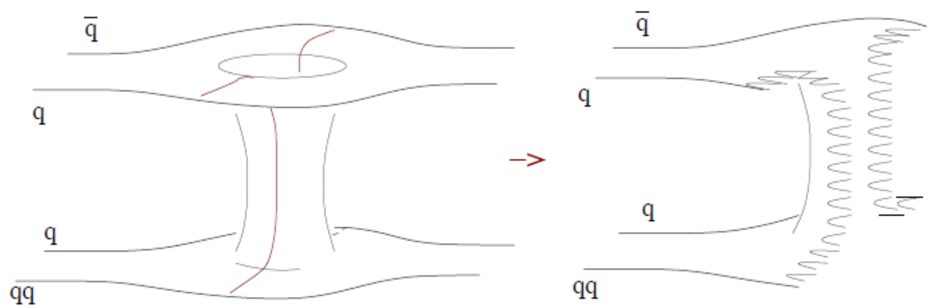
Lorentz-invariant description with Mandelstam variables

$$s = (p_a + p_b)^2$$

$$t = (p'_a - p_a)^2$$

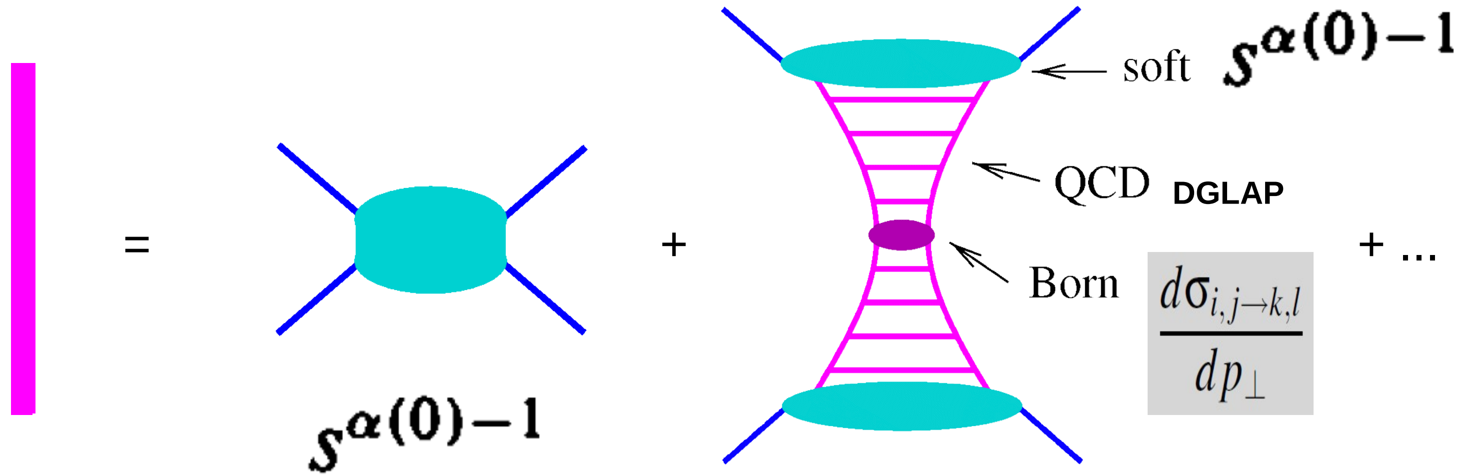
- Quasi-particle that effectively accounts for all exchanged hadronic states
- Amplitude exhibits power-law dependence on energy
- Regge trajectory of Pomeron: exchanged particles might be glue balls $(\alpha(t))$
- Pomeron trajectory only phenomenologically known
- Large N_c-n_f approximation of QCD: Pomeron corresponds to cylinder topology
- Final state configuration: leading contribution is two chains (strings) of hadrons
- Gluon-gluon scattering in pQCD corresponds to ´hard´ contribution to Pomeron

Multiple exchanges & interaction of quasi-particles (Pomerons):
Gribov´s Reggeon Field Theory



Pomeron in Models

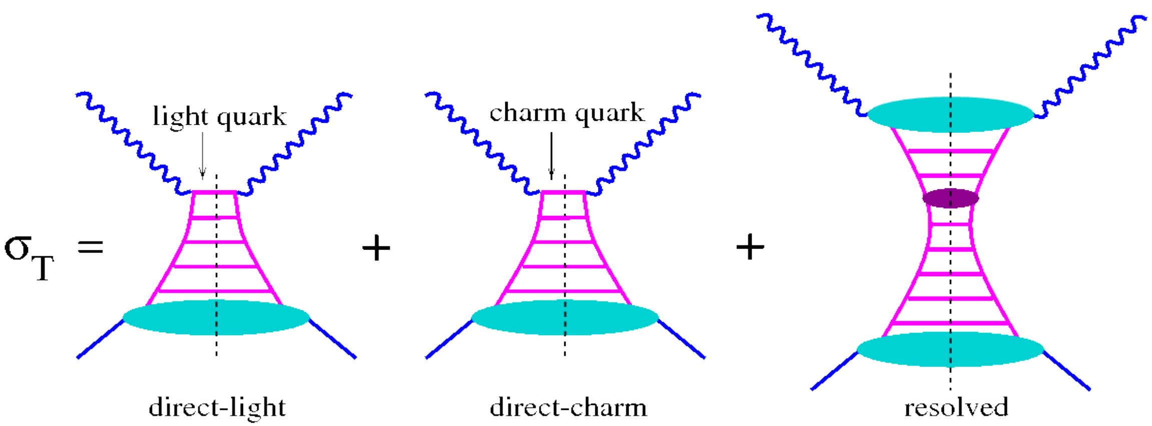
Semi-hard Pomeron :



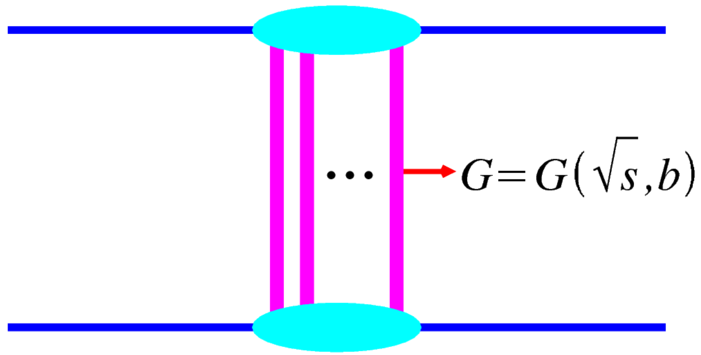
$s^{\alpha(0)-1}$

$\frac{d\sigma_{i,j\to k,l}}{dp_\perp}$

Test of semi-hard Pomeron with Deep Inelastic Scattering: (Parton Distribution Function from HERA)



Gribov-Regge Based Models



Multiple elementary scattering

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

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

where G(energy,impact parameter) = Pomeron amplitude

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

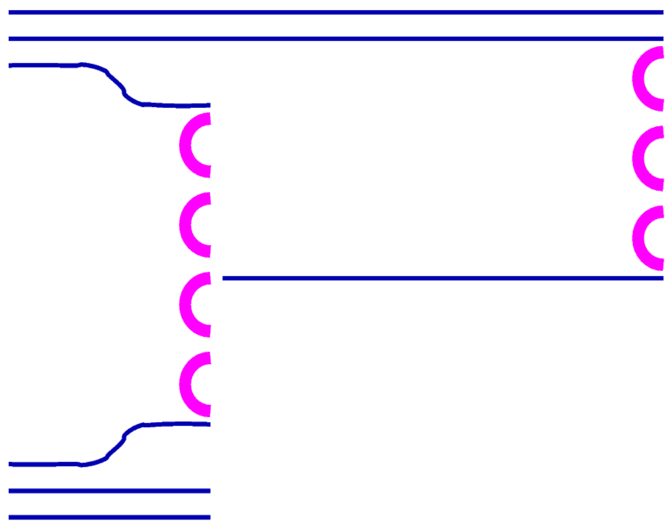
Successful description of hadronic cross-sections

But

Energy conservation NOT considered between the elementary interactions G

No possibility to deduce directly particle production !

Particle Production in GR based Models

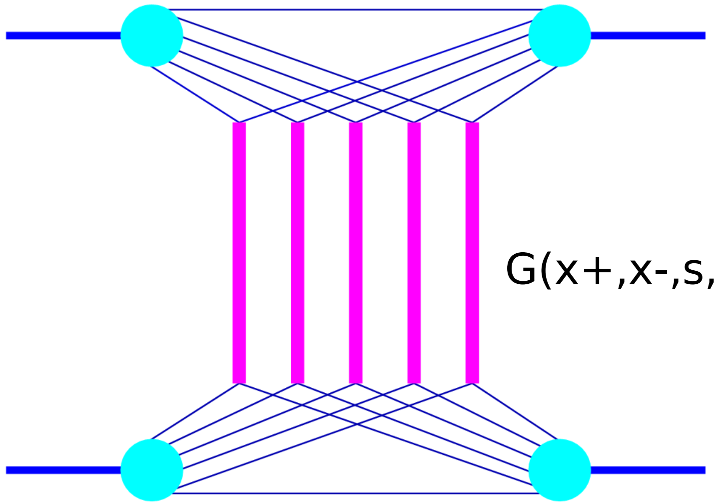


- **Number of strings from GR**
  - ➔ No energy conservation
- **Energy sharing**
  - ➔ Not consistent with cross-section
- **String fragmentation**
  - ➔ Proper energy conservation

Link between cross-section and particle production not consistent !

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

Cross Section Calculation with Energy Conservation



- Gribov-Regge but with energy sharing at parton level
  (Parton Based Gribov Regge Theory: H.J. Drescher et al., Phys. Rept. 350 (2001) 93)
- amplitude parameters fixed from QCD and pp cross section (semi-hard Pomeron)
- cross section calculation take into account interference term

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

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

Particle Production in EPOS

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

- m cut Pomerons from :

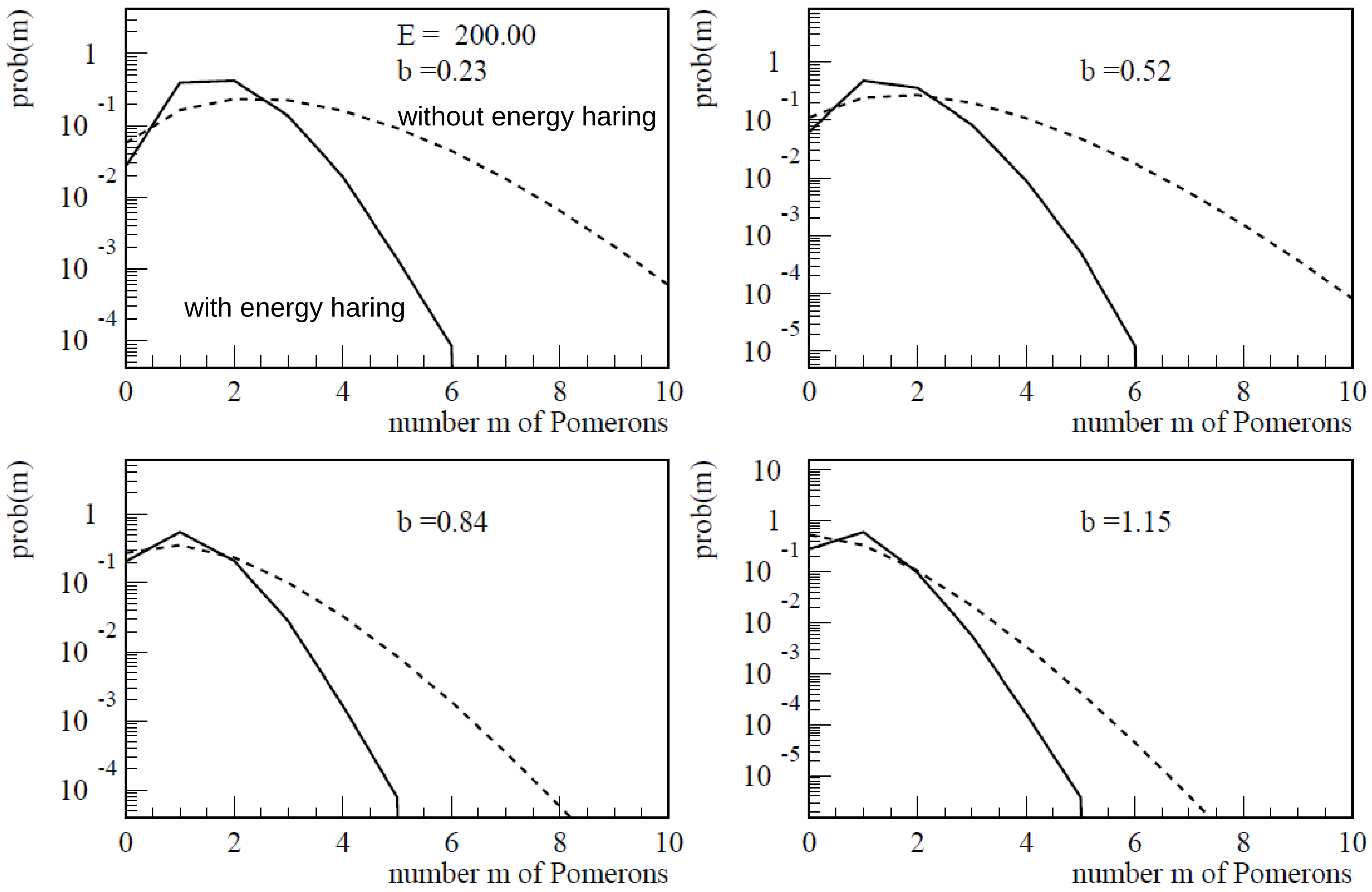
$$\Omega_{AB}^{(s,b)}(m,X^+,X^-) = \prod_{k=1}^{AB}\left\{\frac{1}{m_k!}\prod_{\mu=1}^{m_k} G(x_{k,\mu}^+,x_{k,\mu}^-,s,b_k)\right\}\ \Phi_{AB}\left(x^{\mathrm{proj}},x^{\mathrm{targ}},s,b\right)$$

  - m and X fixed together by a complex Metropolis (Markov chain)
- $2\mathrm{m}$ strings formed from the m elementary interactions
  - energy conservation : energy fraction of the $2\mathrm{m}$ strings given by X
- consistent scheme : energy sharing reduce the probability to have large m

Consistent treatment of cross section and particle production:
number AND distribution of cut Pomerons depend on cross section

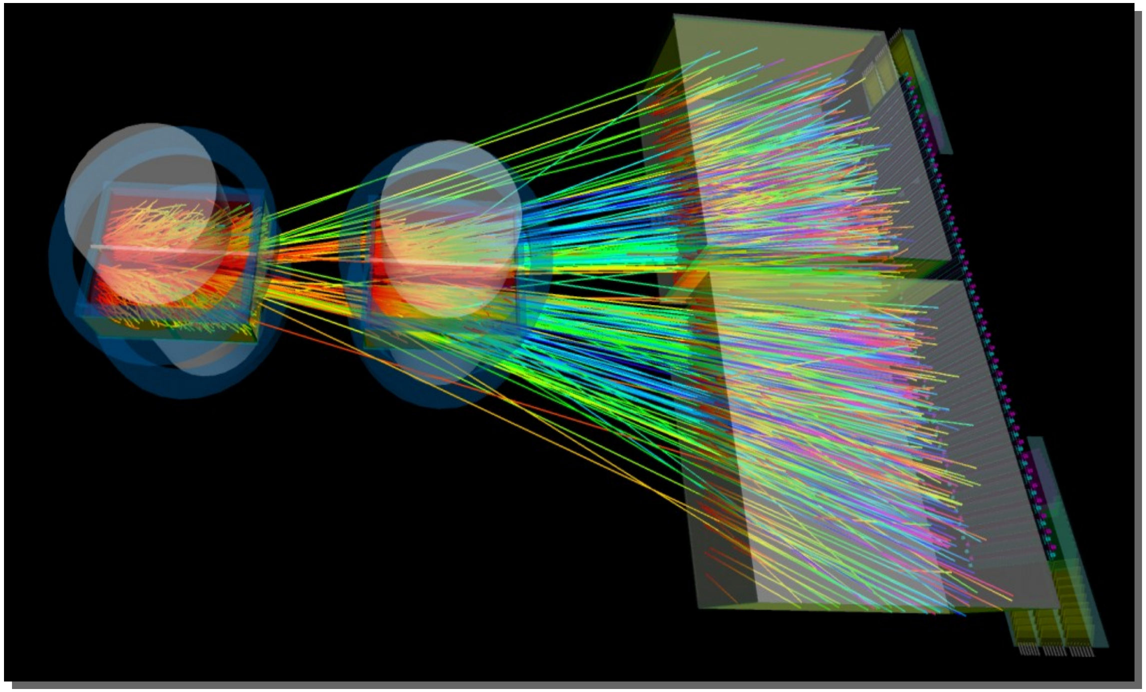
Number of cut Pomerons

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

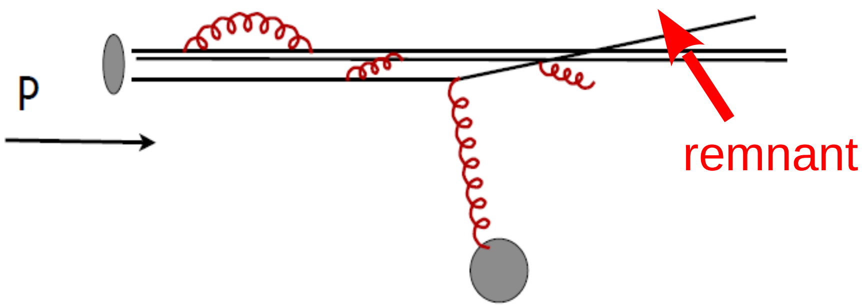


Hadron Interactions

e^+ vs e^- → l vs p (A) → p vs p → h vs A → A vs A



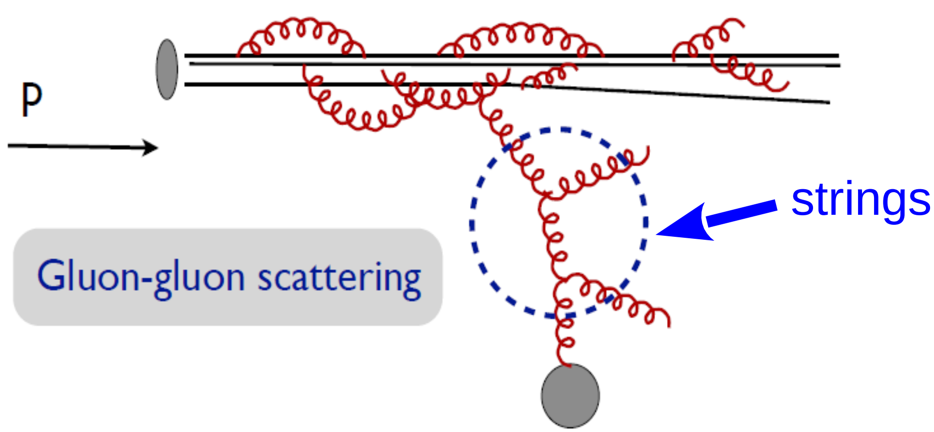
Transition from intermediate to high energy



Intermediate energy:

- E_{lab} < 1,500 GeV
- E_{cm} < 50 GeV
- dominated by valence quarks

Increase of effective nucleon radius due to small x partons

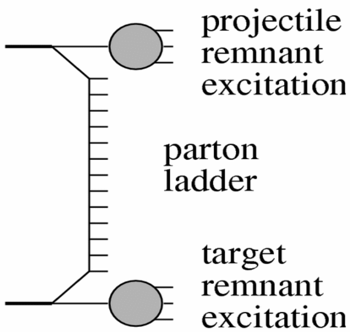


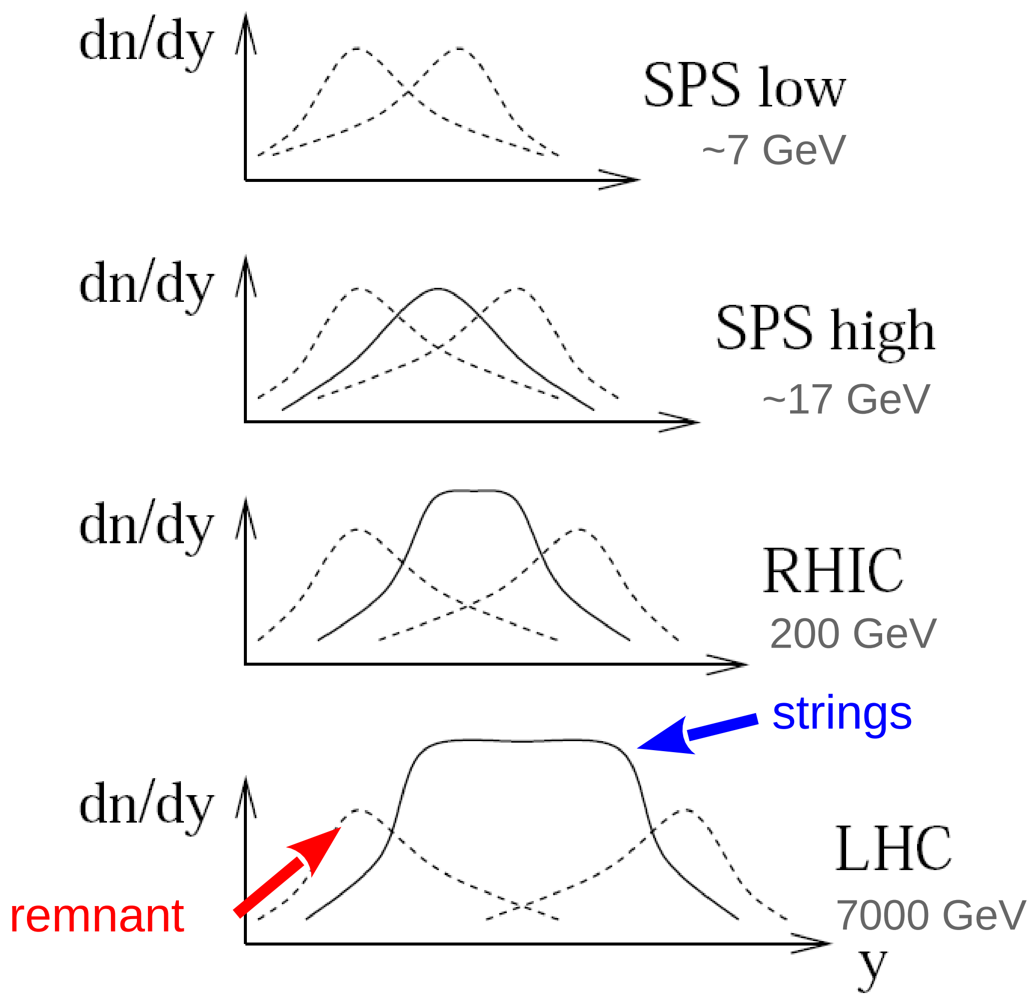
High energy regime:

- E_{lab} > 21,000 GeV
- E_{cm} > 200 GeV
- dominated by gluons and sea quarks

Remnants

Forward particles mainly from projectile remnant





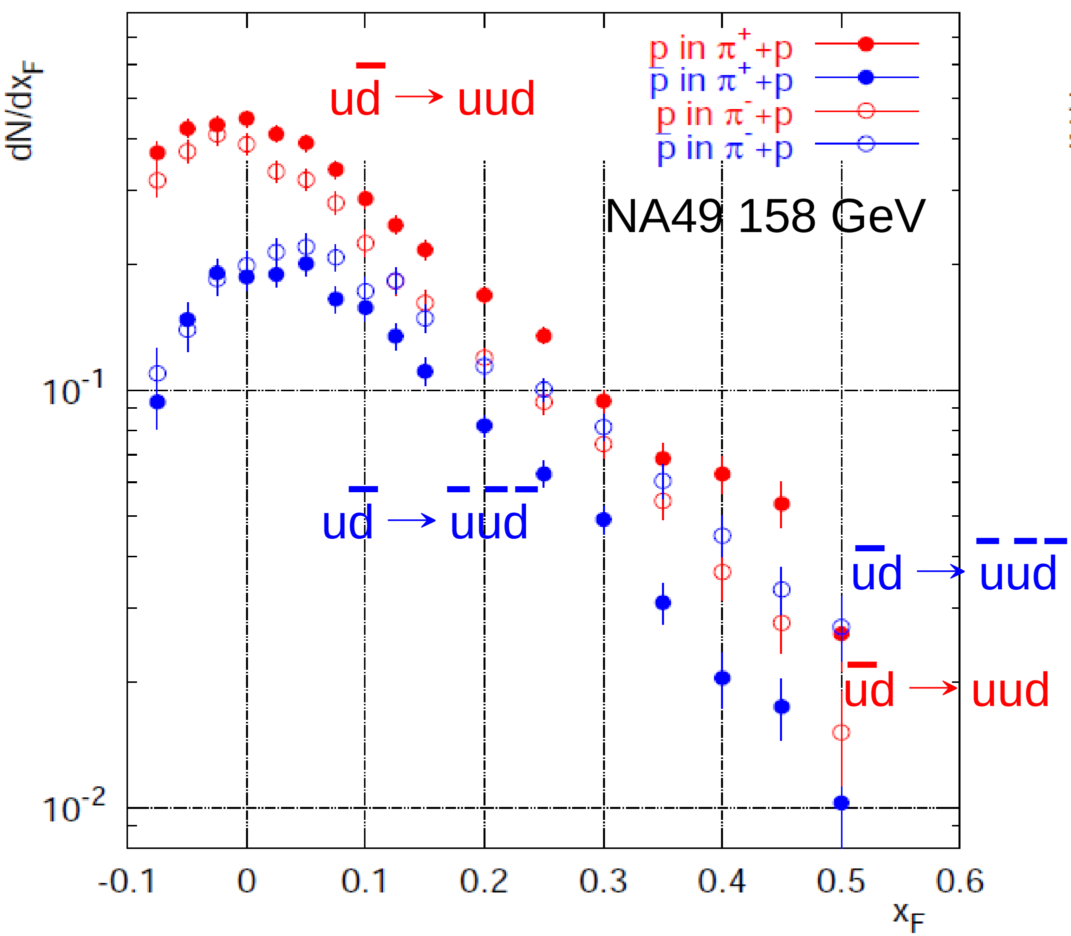
- At very low energy only particles from remnants
- At low energy (fixed target experiments) (SPS) strong mixing
- At intermediate energy (RHIC) mainly string contribution at mid-rapidity with tail of remnants.
- At high energy (LHC) only strings at mid-rapidity (baryon free)

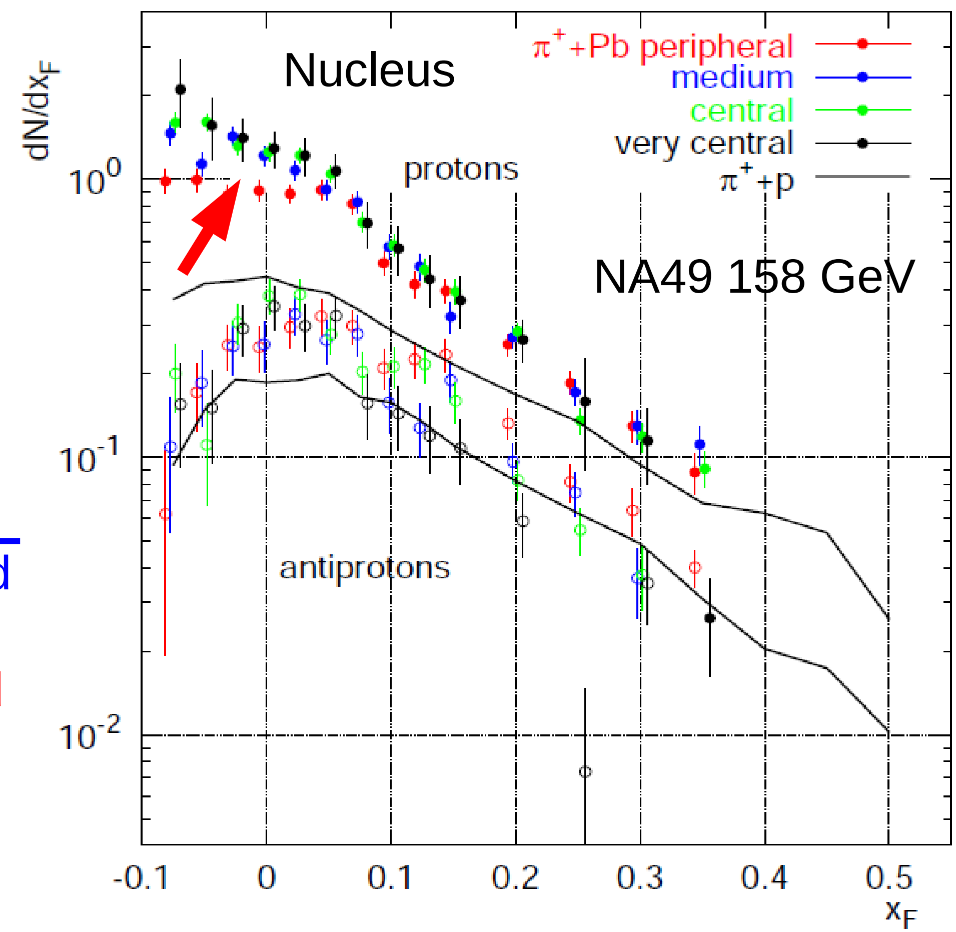
Different contributions of particle production at different energies or rapidities

Leading Particle Effect

Remnant (leading particle) effect

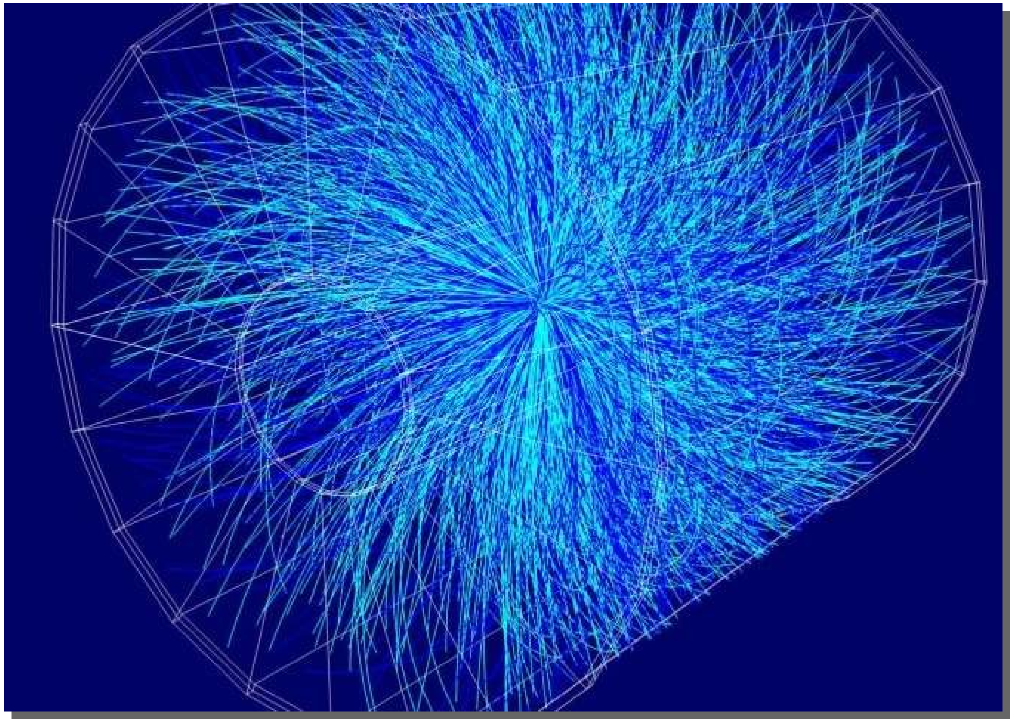
- Different forward production depending on the projectile
- Low energy : even the target hadronization can change “forward” distributions



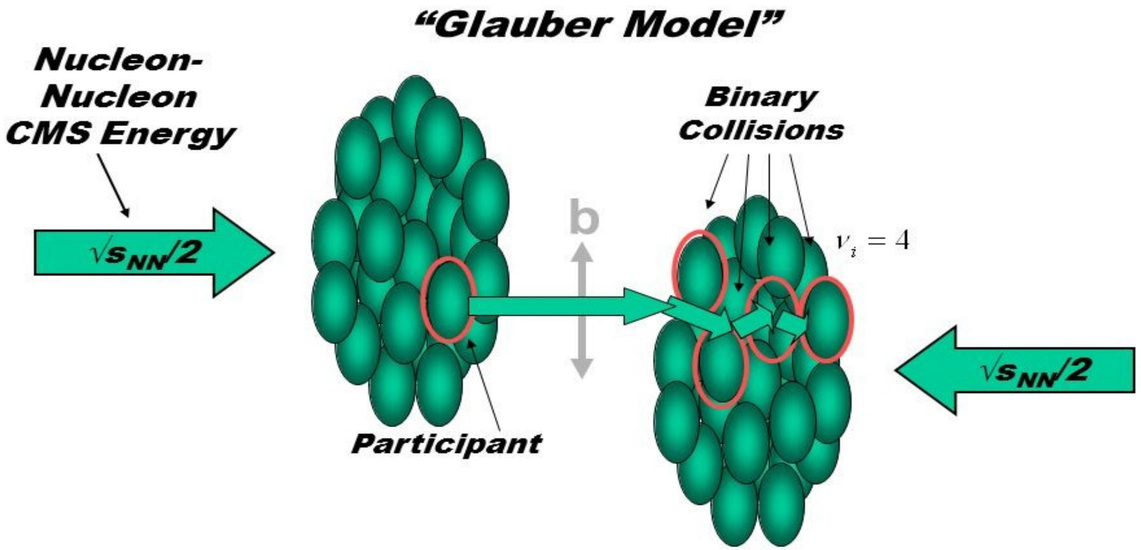


Nucleus Interactions

e$^+$ vs e$^-$ → l vs p (A) → p vs p → h vs A → A vs A

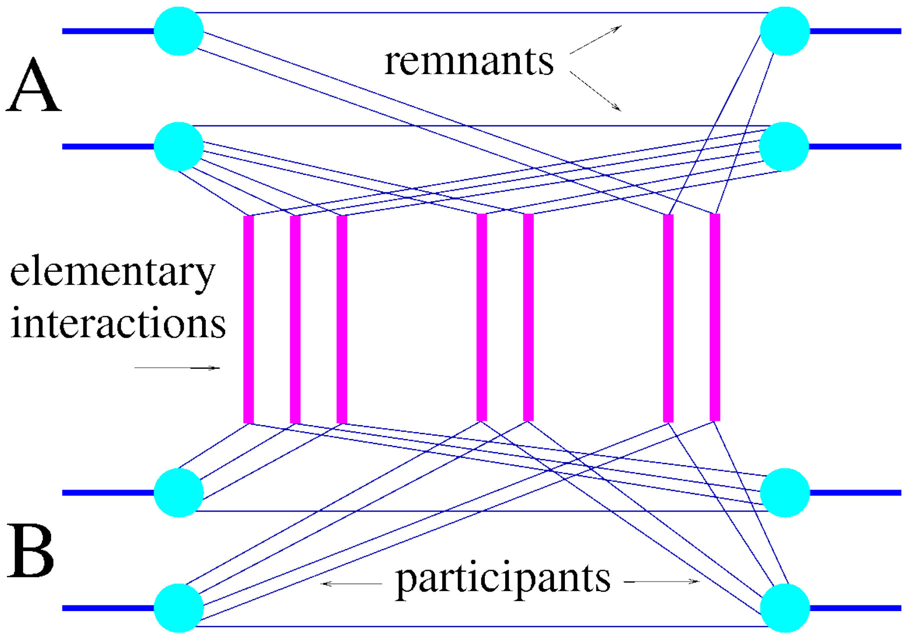


Nucleus Interactions



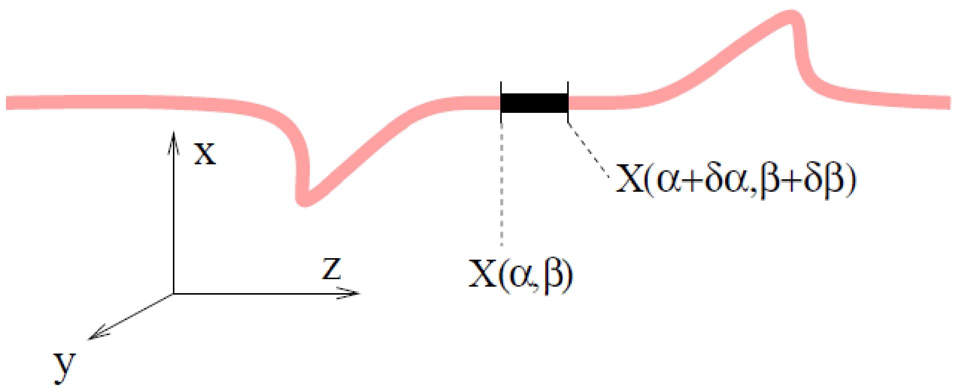
- **Glauber model**
  - Simple non-coherent approach
  - all collisions taken independently
  - works well for rare hard processes which will happen only once per participant
  - cross-section calculation with some corrections

- **Gribov Regge extension to nuclei**
  - coherent approach
  - energy conservation can be taken into account
  - good for cross-section and multiplicity
  - special care for hard processes

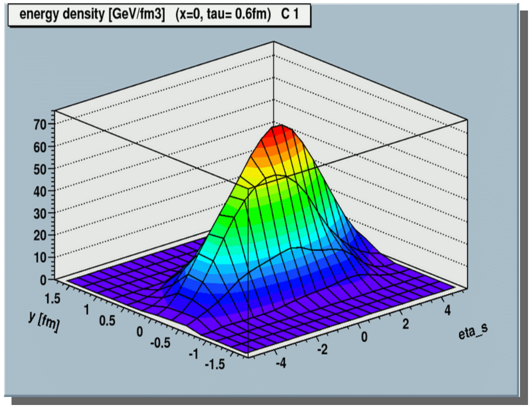


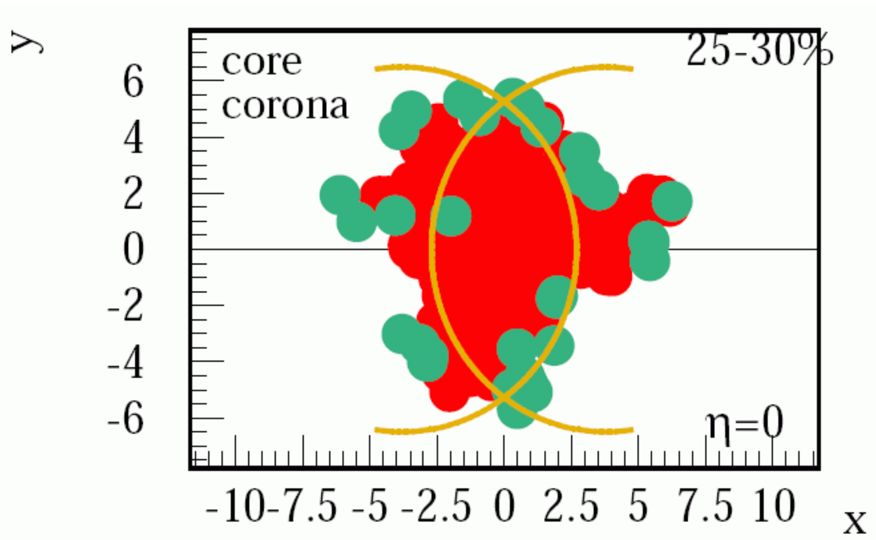
High Density Core Formation

- **Heavy ion (HI) collisions :**
  - the usual procedure has to be modified, since the density of strings will be so high that they cannot possibly decay independently : **core**



Energy density



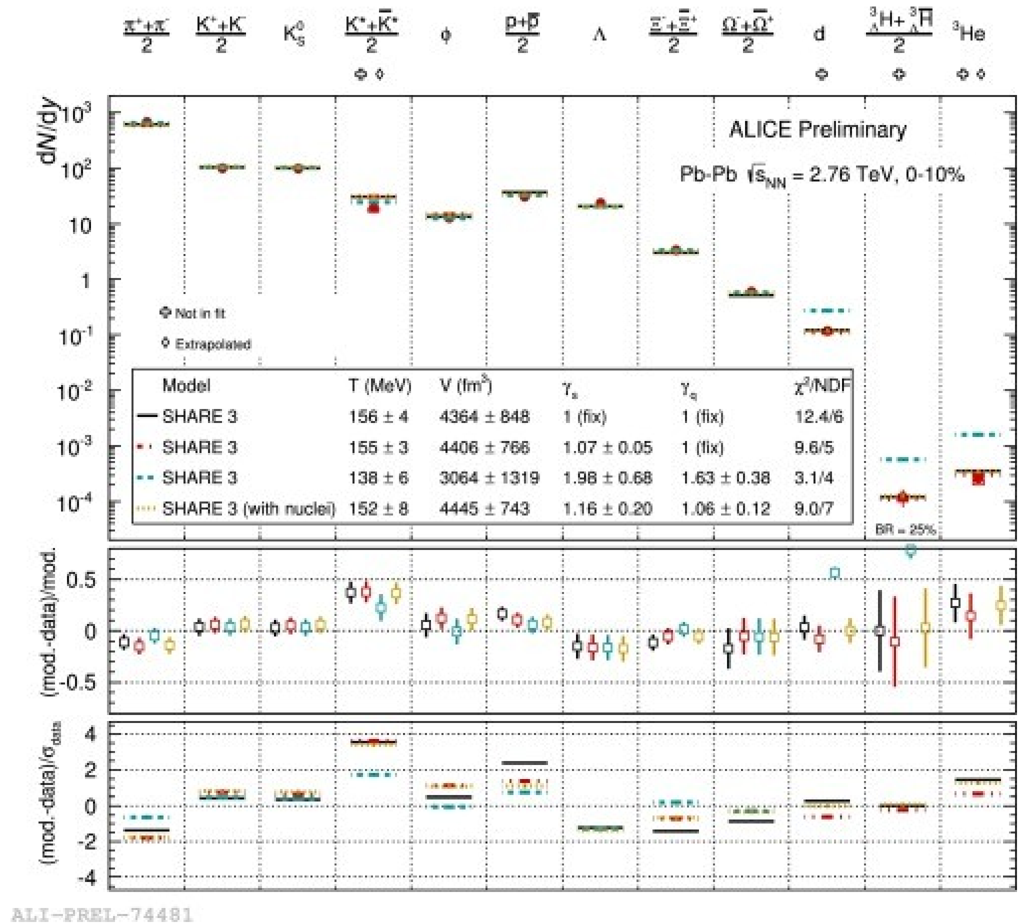


- Each string splitted into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space
- If energy density from segments high enough
  - segments fused into core
    - hydrodynamical-evolution
    - statistical hadronization
- If low density (corona)
  - segments remain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

Core Hadronization

- **2 types of hadronization**
  - ➡ Corona (low density = pp ?) : standard string hadronization (in vacuum)
  - ➡ Core (high density = HI ?) : collective (thermal) hadronization (in medium)

- **Thermal hadronization**
  - ➡ Good description of all particle yields in a central heavy ion collision with 2 parameters (temperature and chemical potential)
  - ➡ Apply to extended source and based on conservation laws only.



- **Energy/system/centrality evolution fixed by core/corona ratio !**
  - ➡ No need to change hadronization of a given system (color reconnection ?)

Collective Hadronization

- One decade of RHIC experiments (heavy ion, pp, and dAu scattering,up to 200 GeV)

heavy ion collisions produce matter which expands as an almost ideal fluid

- mainly because azimuthal anisotropies (particle correlations) can be explained on the basis of ideal hydrodynamics (mass splitting, ridge, etc ...)

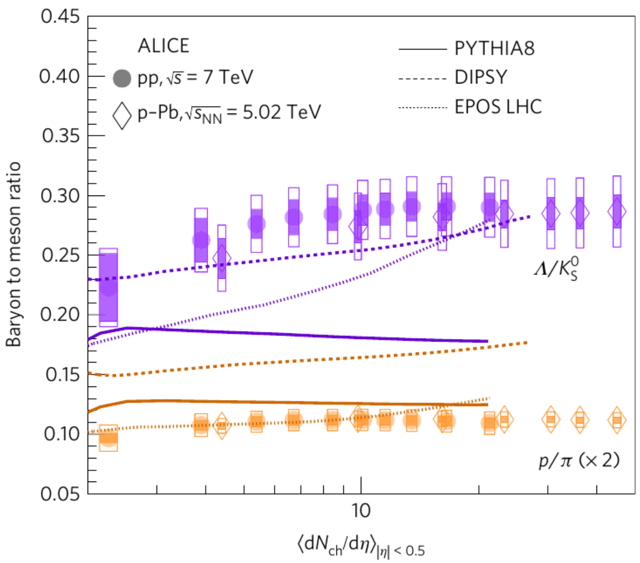
LHC pp results: first signs for collective behavior as well … ?

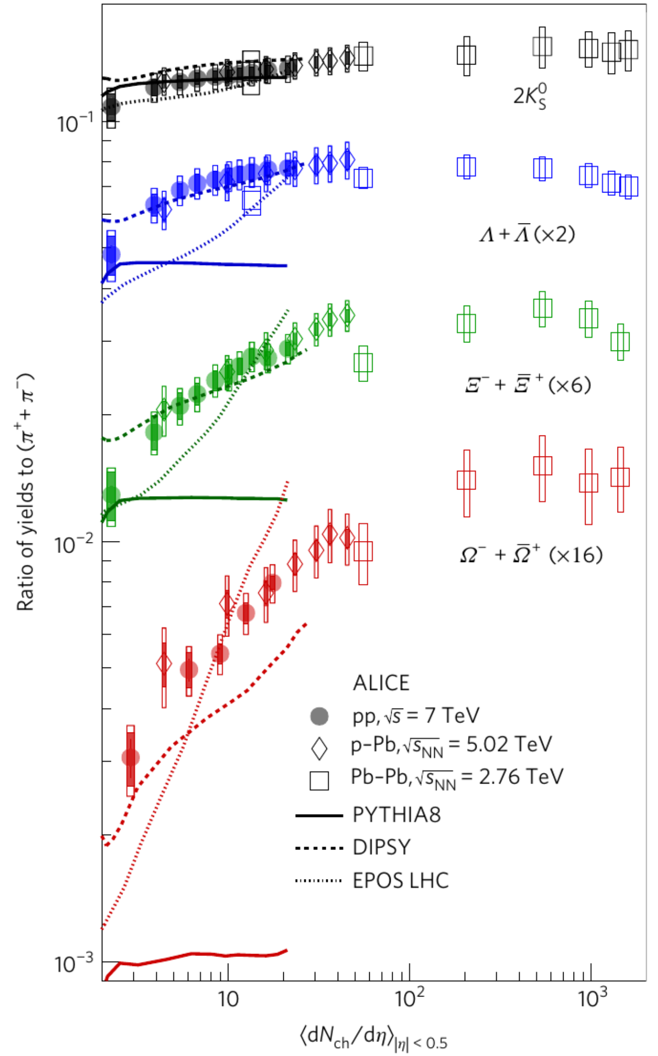
Global Approach

Moving from projectile/target to energy density (particle number)

- New point of view on particle production
- Continuity in particle ration evolution between pp, pPb and PbPb
- No model can reproduce every thing
  - PYTHIA : string only
  - DIPSY : overlapping strings with modified parameters
  - EPOS LHC : core/corona

Nature Letters DOI: 10.1038/NPHYS4111

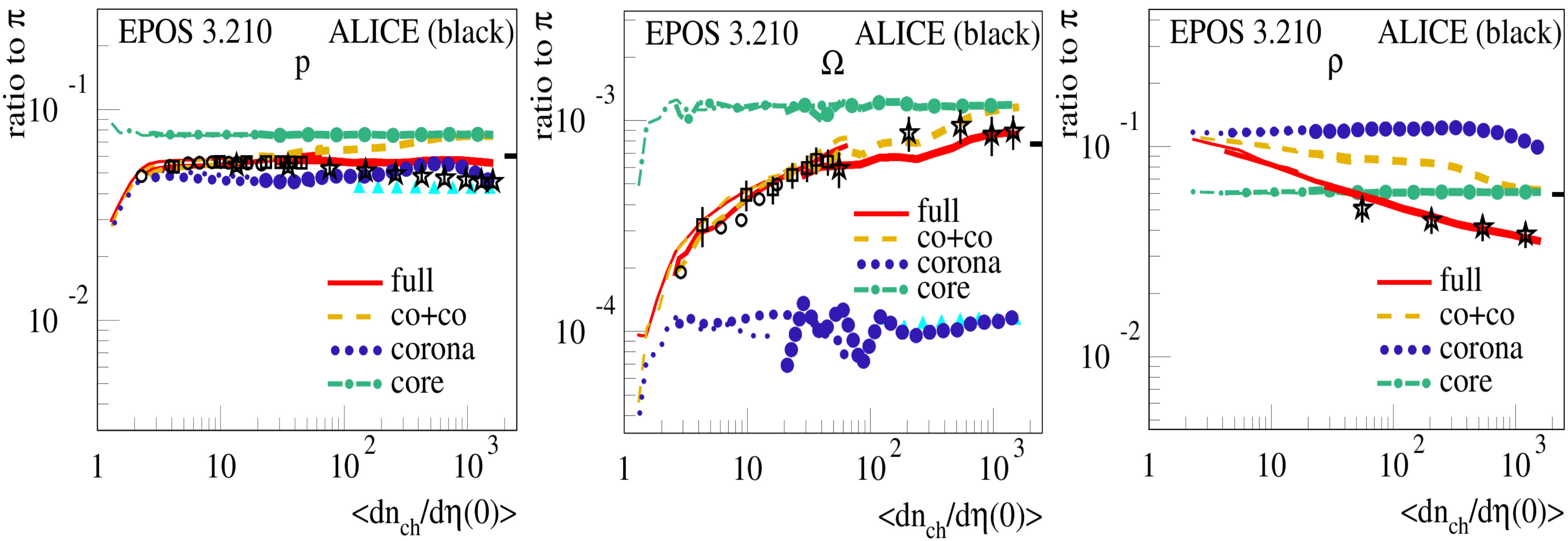




Global Approach : Core+Corona

Moving from projectile/target to energy density (particle number)

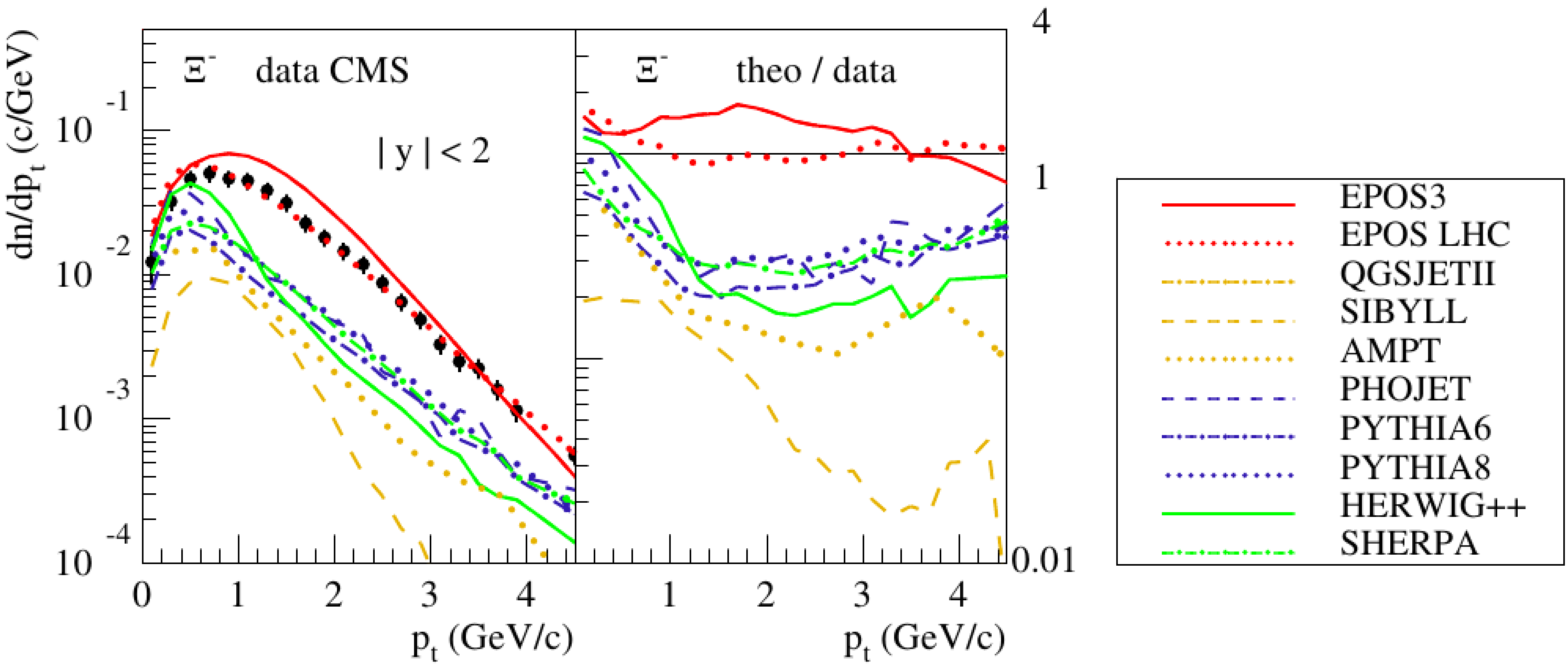
- New point of view on particle production
- Good description achieved with core/corona + hadron reinteractions (hadron gas)
  - Same physics for all systems but different mixtures of the 2 components (low + high energy density hadronization)



Global Approach : EPOS

Detailed description can be achieved

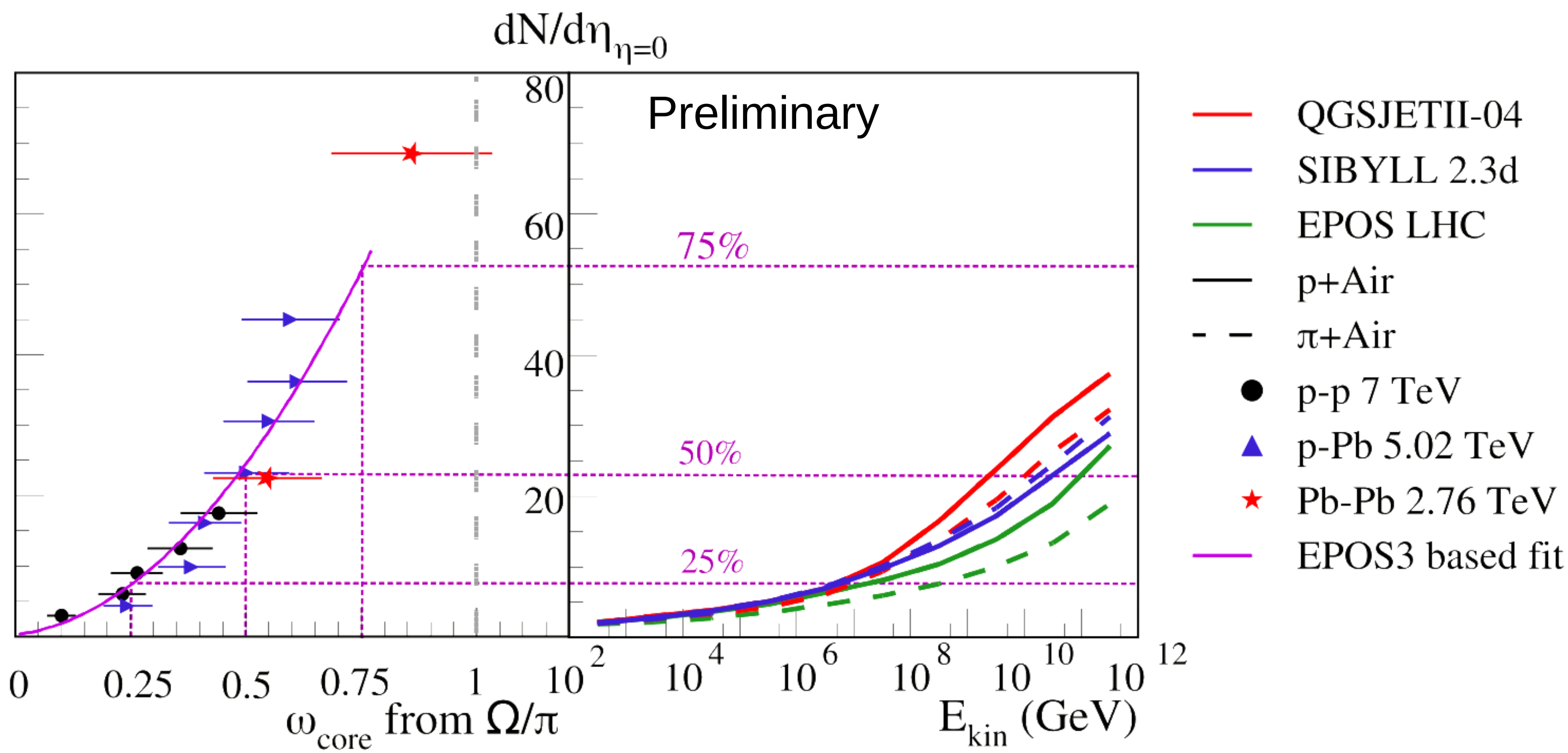
- identified spectra
- p_t behavior driven by collective effects (statistical hadronization + flow)
  - large effect for multi-strange baryons (yield AND $<p_t>$)



Particle Densities in Air Showers

Is particle density in air shower high enough to expect core formation ?

- Core formation start quite early according to ALICE data
- Cosmic ray primary interaction likely to have 50% core at mid-rapidity … but forward can be different !



Core-Corona appoach and EAS

To test if a QGP like hadronization can account for the missing muon production in EAS simulations a core-corona approach can be artificially apply to any model

- Particle ratios from statistical model are known (tuned to PbPb) and fixed : core
- Initial particle ratios given by individual hadronic interaction models : corona
- Using CONEX, EAS can be simulated mixing corona hadronization with an arbitrary fraction ω_{core} of core hadronization:

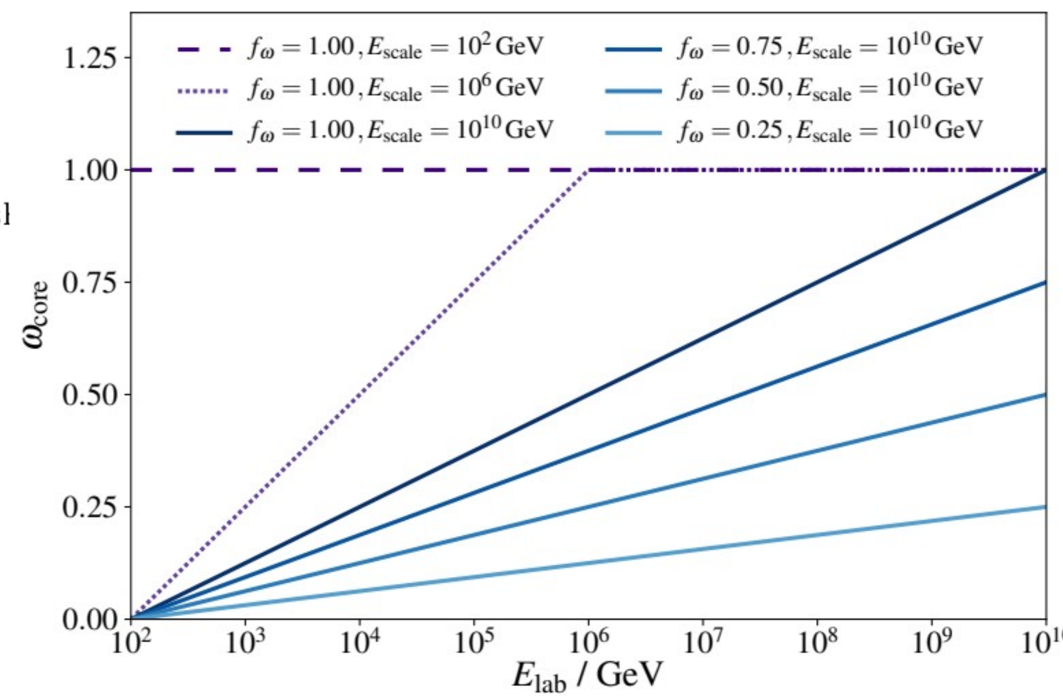
$$N_i = \omega_{\rm core}\, N_i^{\rm core} + (1 - \omega_{\rm core})\, N_i^{\rm corona}$$

$$\omega_{\rm core}(E_{\rm lab}) = f_\omega\, \underbrace{F(E_{\rm lab}; E_{\rm th}, E_{\rm scale})}_{\frac{\log_{10}(E_{\rm lab}/E_{\rm th})}{\log_{10}(E_{\rm scale}/E_{\rm th})} \text{ for } E_{\rm lab} > E_{\rm th}}$$

$$E_{\rm th} = 100\,{\rm GeV}$$

Different scenarii can be studied playing with f_ω and E_{scale}.

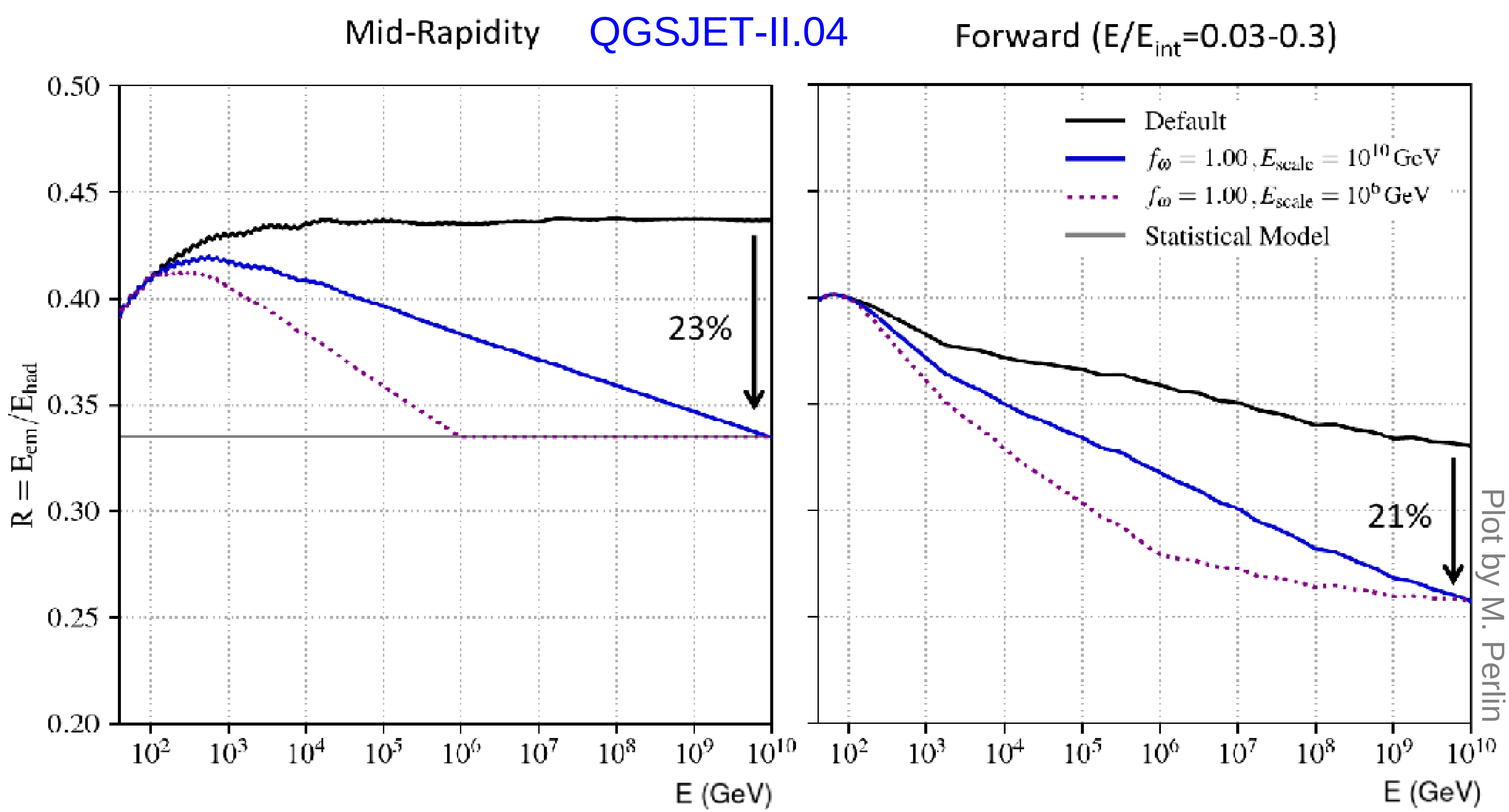
Note : the leading particle is NOT modified (projectile remnant)



Evolution of hadronization from core to corona

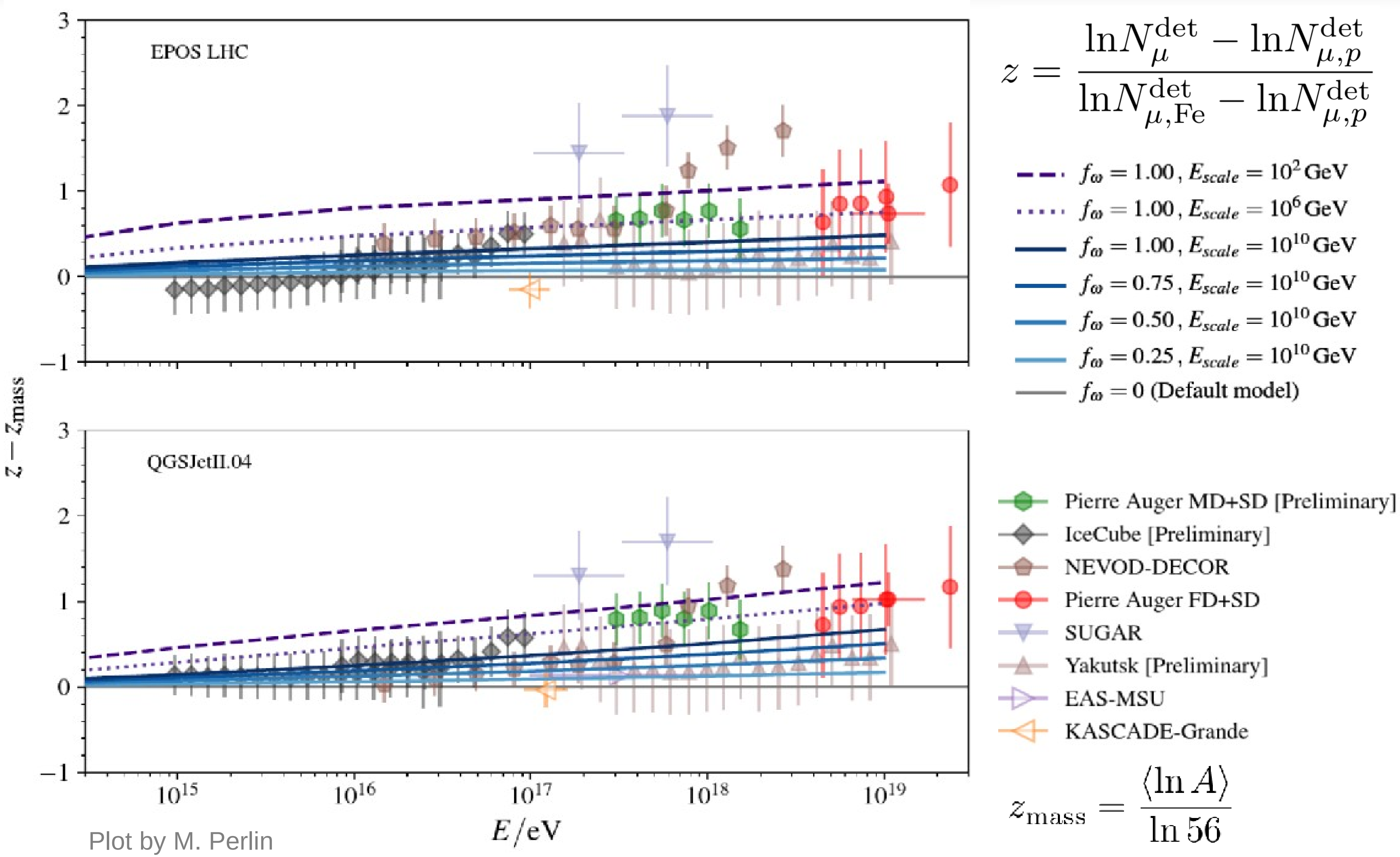
The relative fraction of π^0 depends on the hadronization scheme

➡ Change of ω_{core} with energy changes $c = \frac{N_{\pi^0}}{N_{mult}}$ or $R(\eta) = \frac{\langle \mathrm{d}E_{\mathrm{em}}/\mathrm{d}\eta \rangle}{\langle \mathrm{d}E_{\mathrm{had}}/\mathrm{d}\eta \rangle}$ which define the muon production in air showers.



Ref: <https://arxiv.org/abs/1902.09265>

Results for z-scale



$$z = \frac{\ln N_\mu^{\rm det} - \ln N_{\mu,p}^{\rm det}}{\ln N_{\mu,\rm Fe}^{\rm det} - \ln N_{\mu,p}^{\rm det}}$$

$$z_{\rm mass} = \frac{\langle \ln A \rangle}{\ln 56}$$

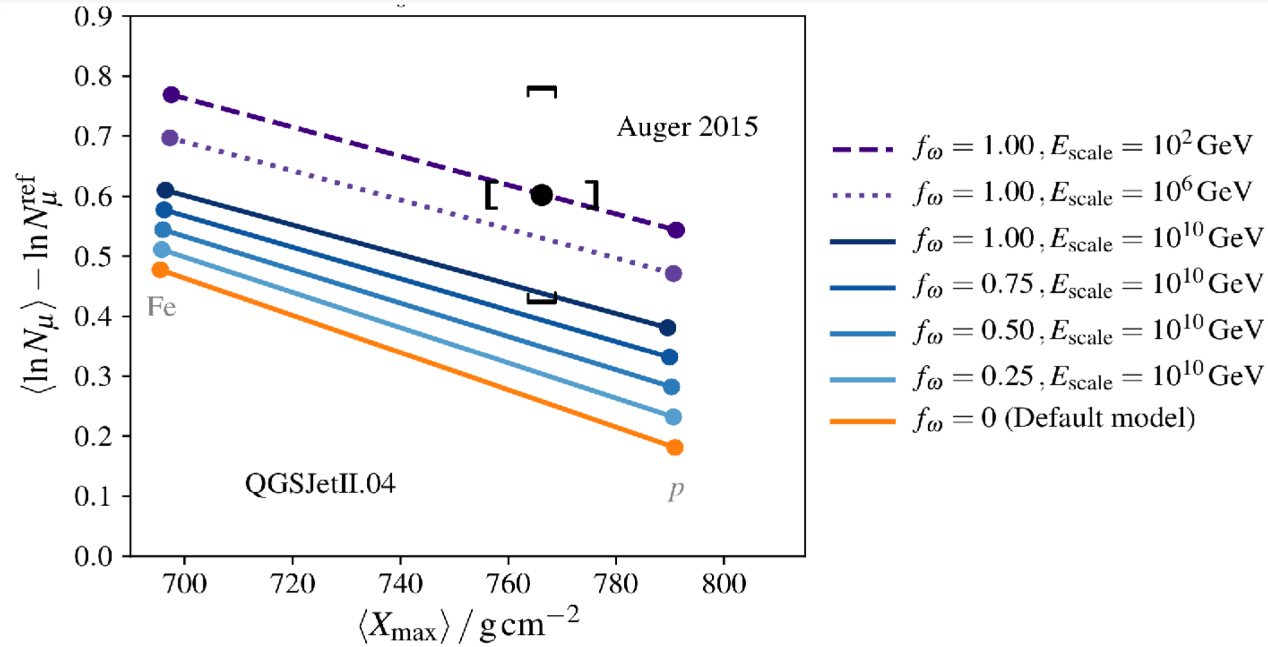
Plot by M. Perlin

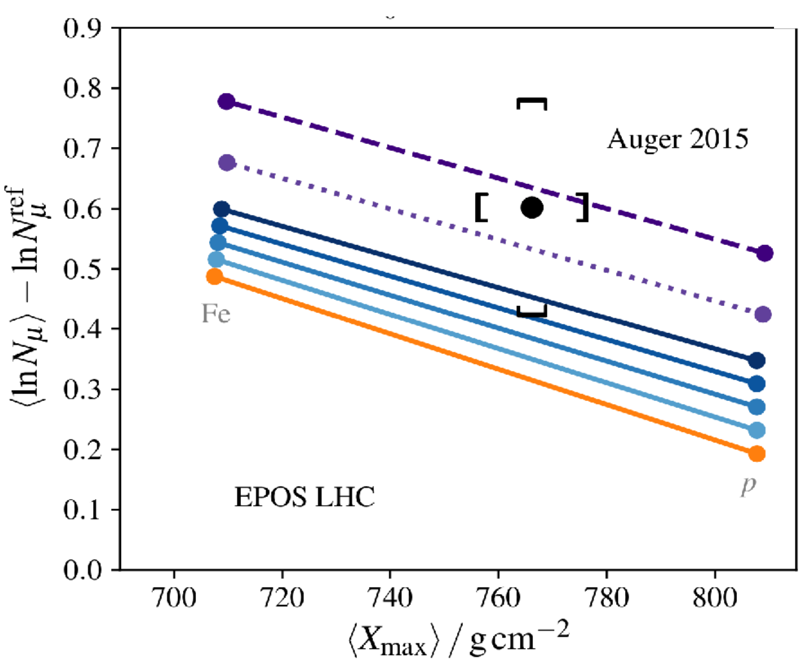
Ref: <https://arxiv.org/abs/1902.09265>

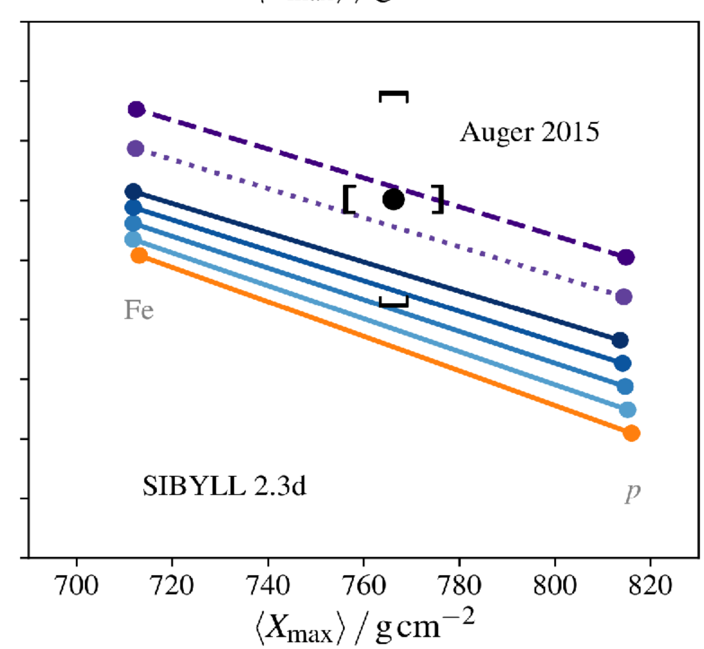
Complete Picture and Muon Puzzle

Significant effect on EAS observed if core-corona introduced in models

- No change in X_{max}
- Needs a large part of core hadronization at maximum energy to reach Auger point
- Sibyll with higher mass (deep X_{max}) need less

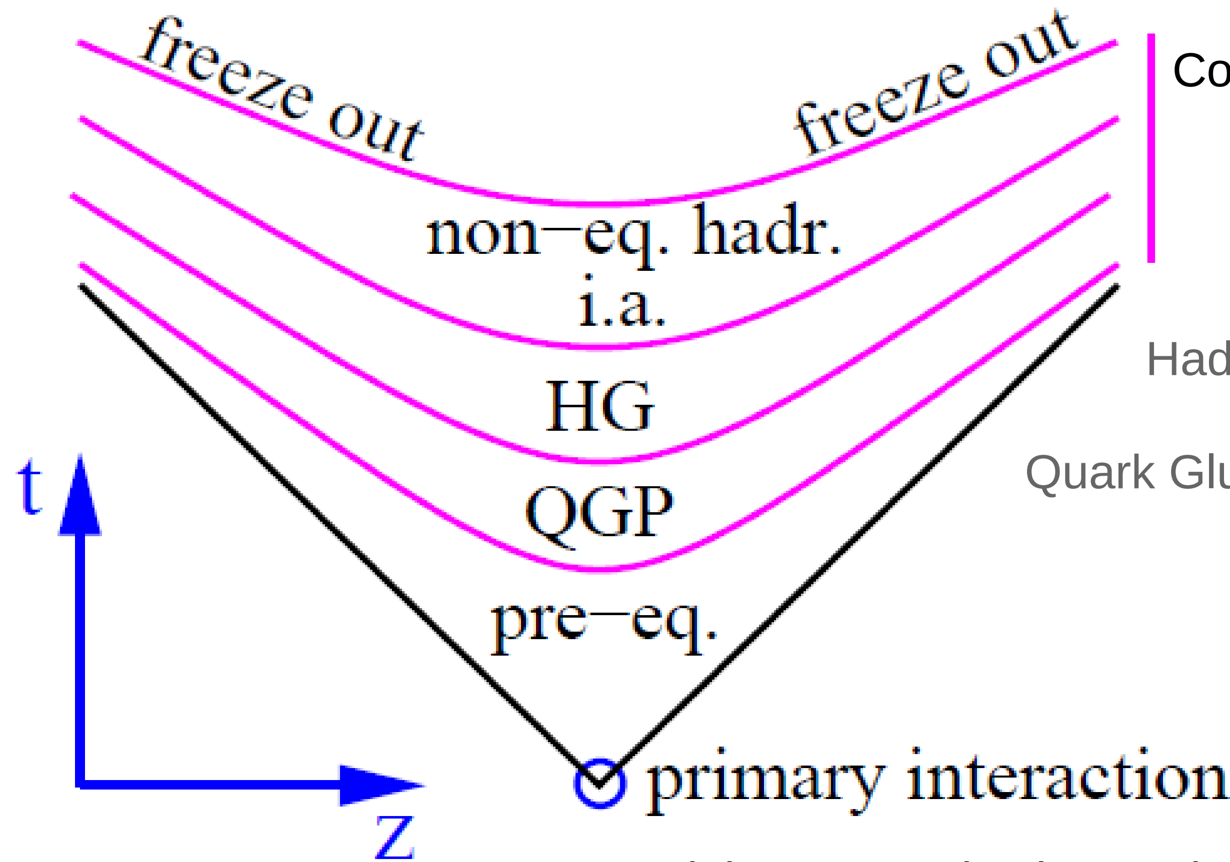






Plot by M. Perlin

High Energy Hadronic Interactions



Collective Effects

Elastic hadronic reinteractions

Hadron Gas

Quark Gluon Plasma

High Energy Physics models

References : Ralph Engel PhD Thesis (1997)
K. Werner, Phys.Rept. 232, Nos. 2-5 (1993) 87-299
K. Werner, arXiv:hep-ph/0206111v1

References for High Energy Models (new)

- **DPMJET III**
  - J. Ranft, R. Engel, S. Roesler, Nucl. Phys. B Proc. Suppl.122, 392 (2003)
  - A. Fedynitch, Cascade equations and hadronic interactions at very high energies. PhD thesis, KIT, Karlsruhe, Dept.Phys. (2015)
  - A. Fedynitch, R. Engel, 14th Inter-national Conference on Nuclear Reaction Mechanisms:Varenna, Italy, p. 291. CERN, Geneva (2015)
- **EPOS LHC**
  - T. Pierog at al., Phys. Rev. **C92** (2015) 034906 arXiv:1306.0121 [hep-ph]
- **QGSJETII-04**
  - S. Ostapchenko, Phys. Rev. **D83** (2011) 014018
  - S. Ostapchenko, Phys. Rev. **D89** (2014) 074009
- **SIBYLL 2.3d**
  - F. Riehn et al. Phys. Rev. **D102** (2020), 063002 arXiv:1912.03300 [hep-ph]

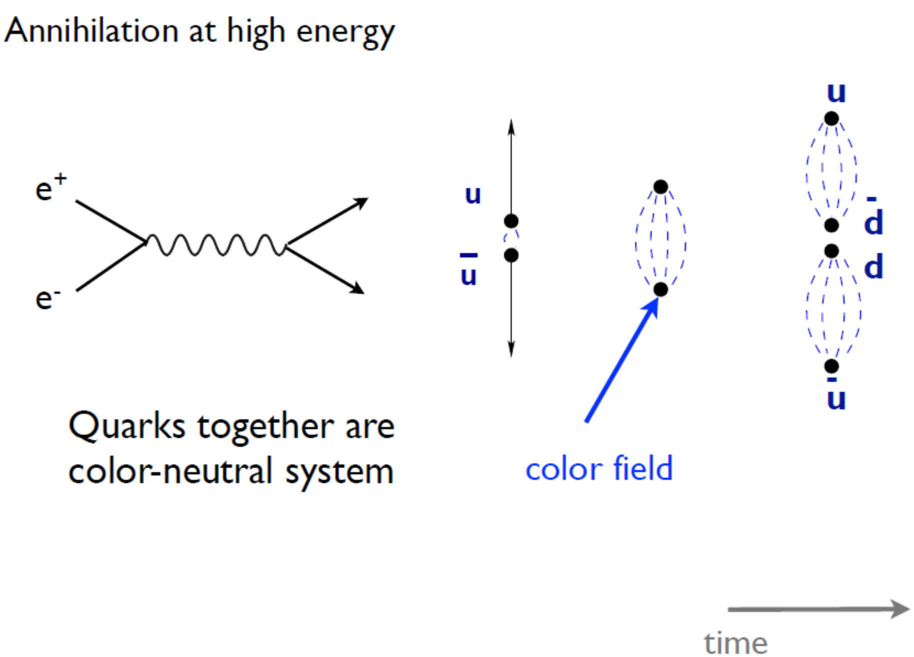
References for High Energy Models (old)

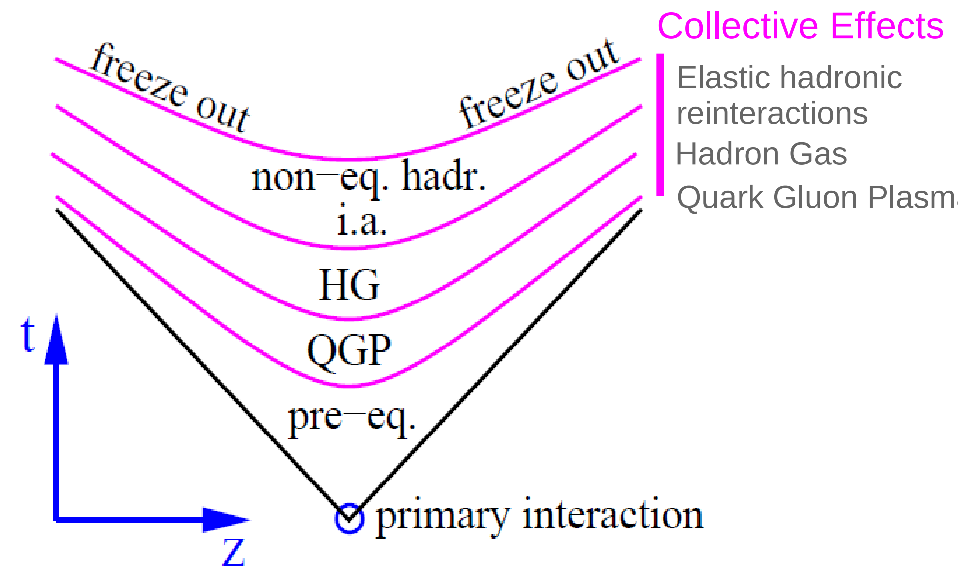
- **DPMJET II**
  - J. Ranft, Phys. Rev. **D51**, 64 (1995)
- **EPOS 1.99**
  - K. Werner et al., Phys. Rev. **C74** (2006) 044902
  - T. Pierog et al., ICRC 2009 Proceedings
- **QGSJET 01**
  - N.N. Kalmykov et al., Nucl. Phys. B (Proc. Suppl.) 52B (1997) 17
- **QGSJETII-03**
  - S. Ostapchenko, Phys. Rev. **D74** (2006) 014026
  - Nucl. Phys. B (Proc. Suppl.) 151 (2006) 143 & 147
- **SIBYLL 2.1**
  - R. Engel et al., Proc. 26th ICRC (Salt Lake City) 1 (1999) 415
  - E.-J. Ahn et al., Phys. Rev. **D80** (2009) 094003

Hadronization Models

2 models well established for 2 extreme cases

- String Fragmentation vs Collective hadronization (statistical models)





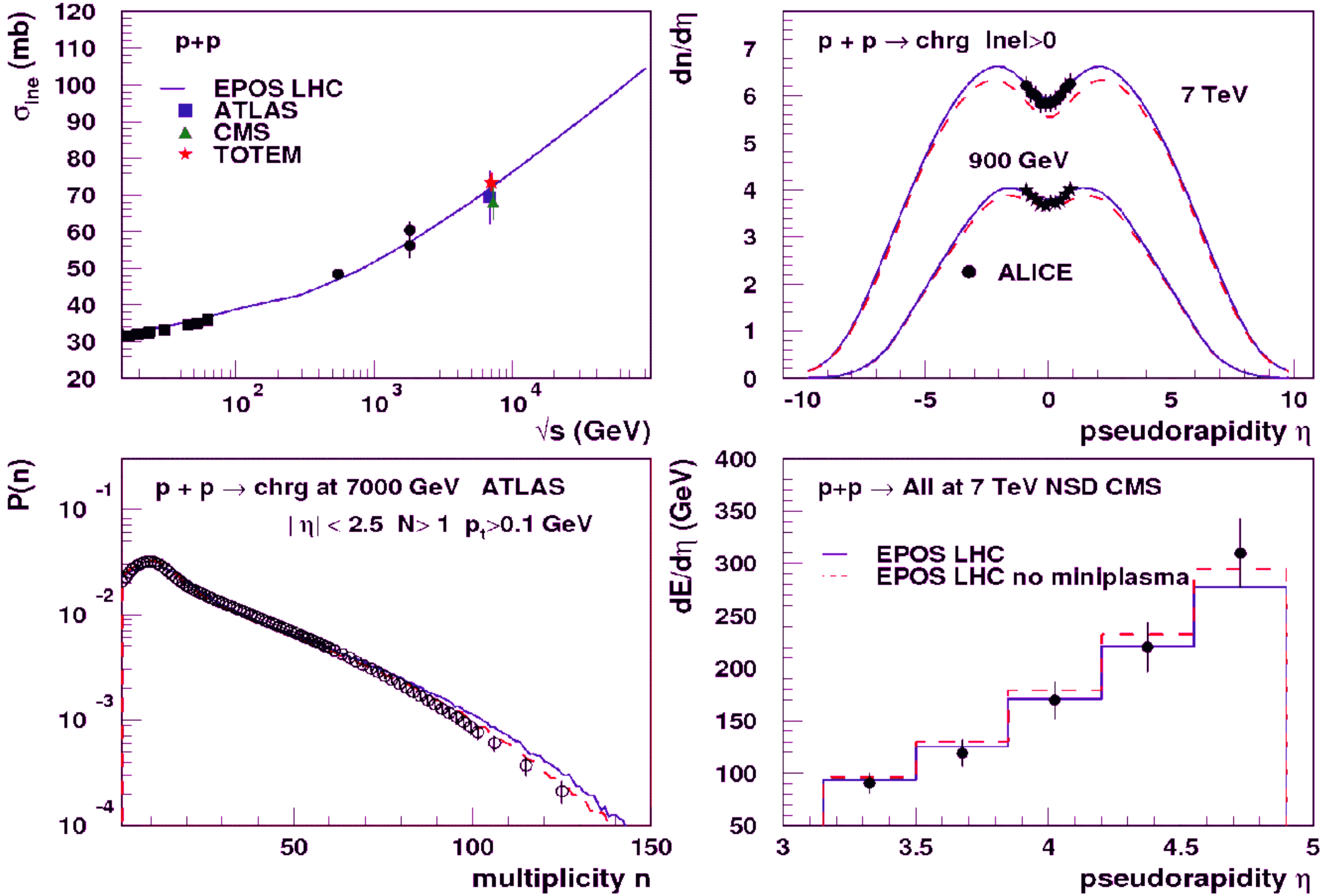
In dilute systems… CORONA
→ "high" π^0 fraction

In dense systems… CORE
→ "low" π^0 fraction

- Core-corona = mixing of the two for proton-proton, hadron-Air, ..

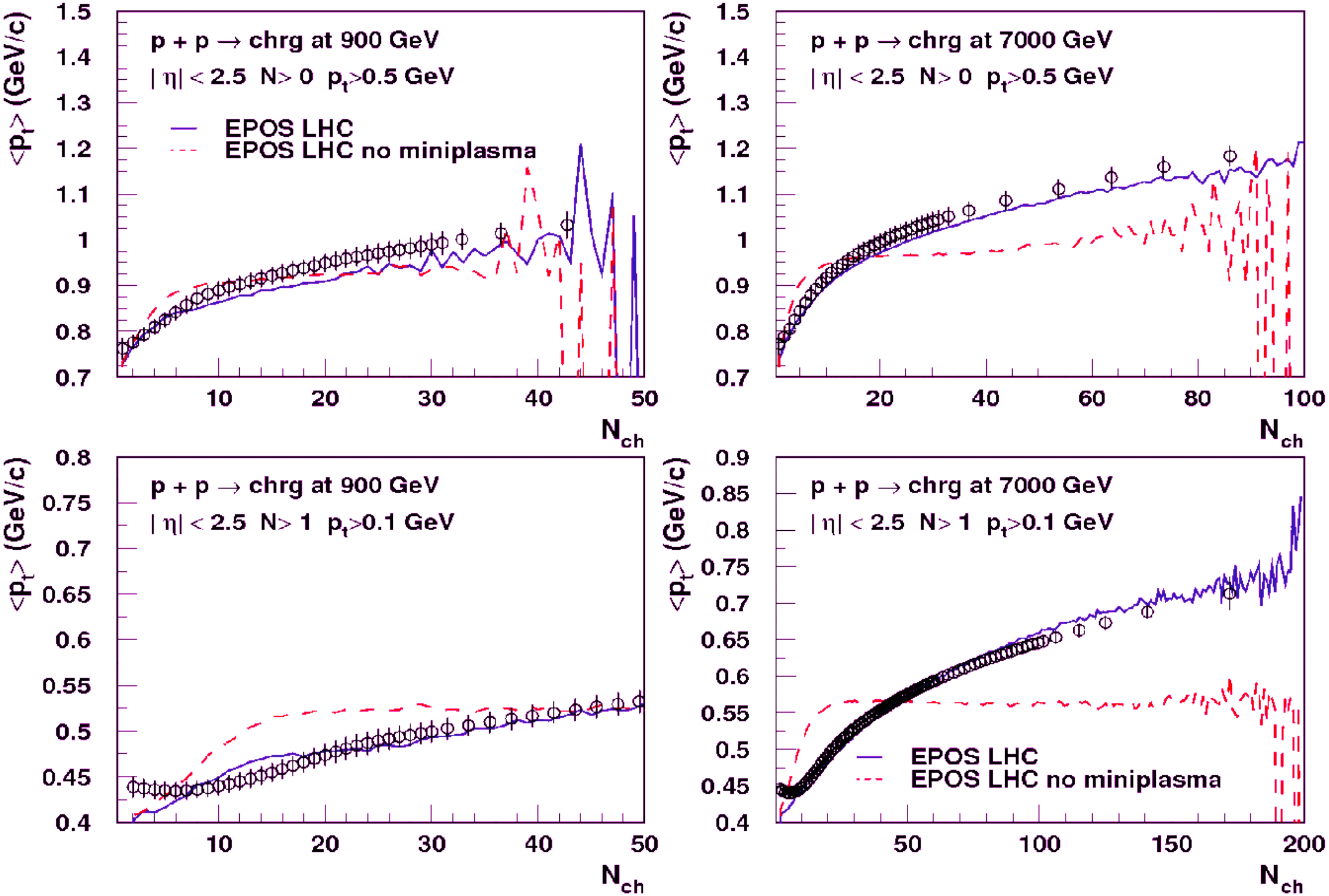
EPOS LHC

- Effective flow treatment



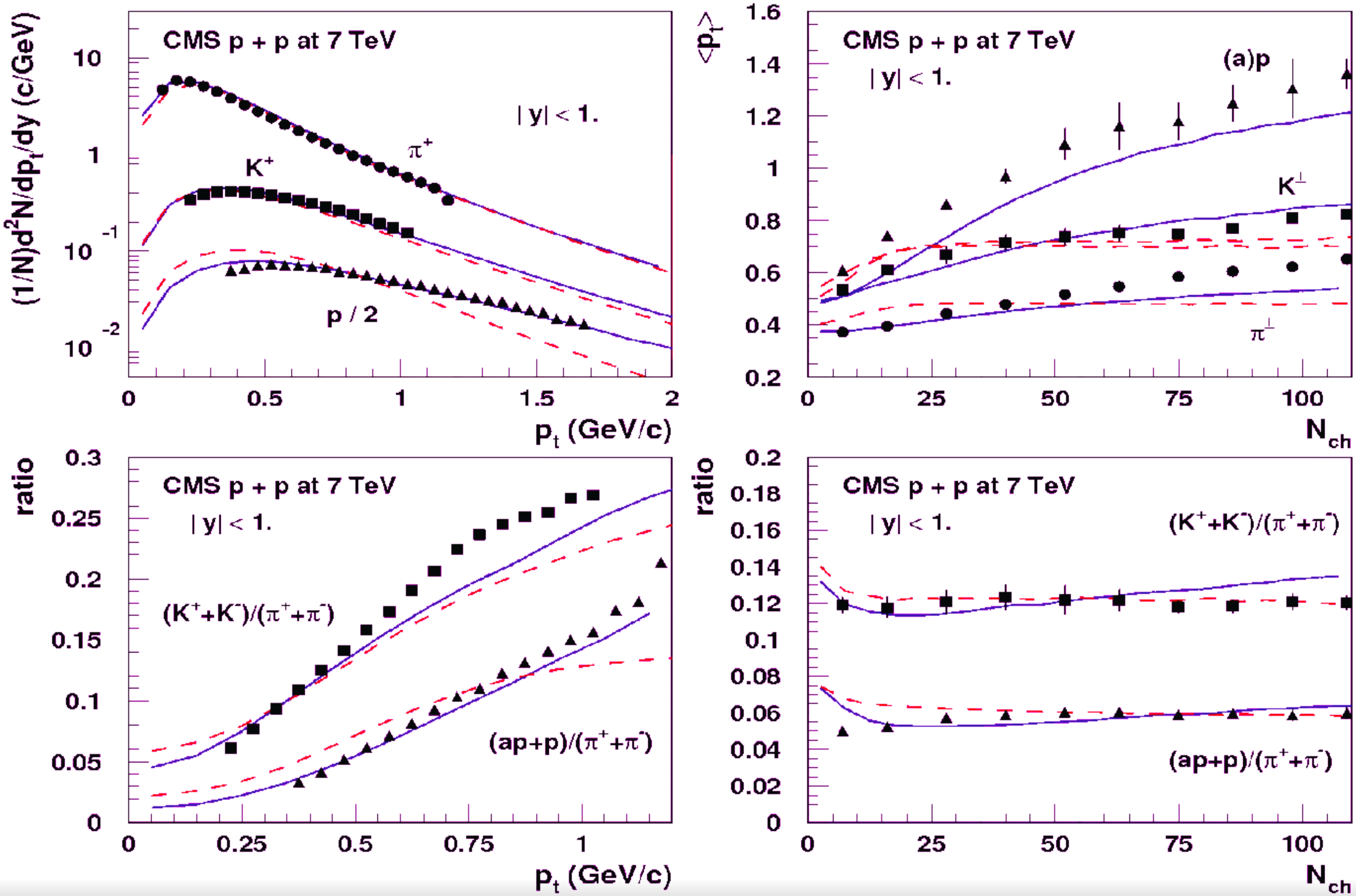
EPOS LHC

- **Effective flow treatment**



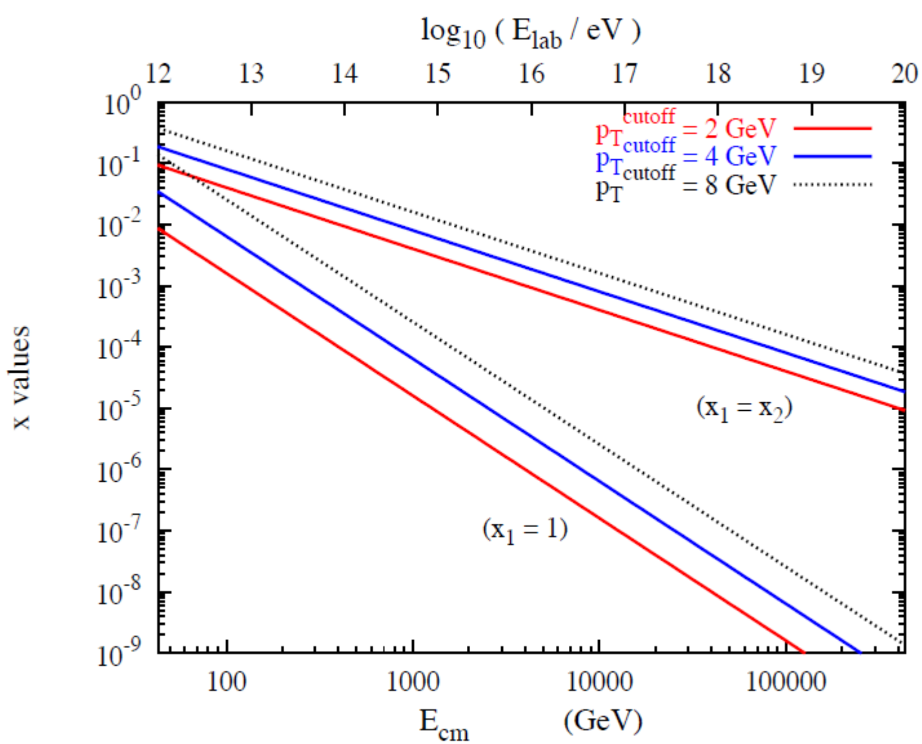
EPOS LHC

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

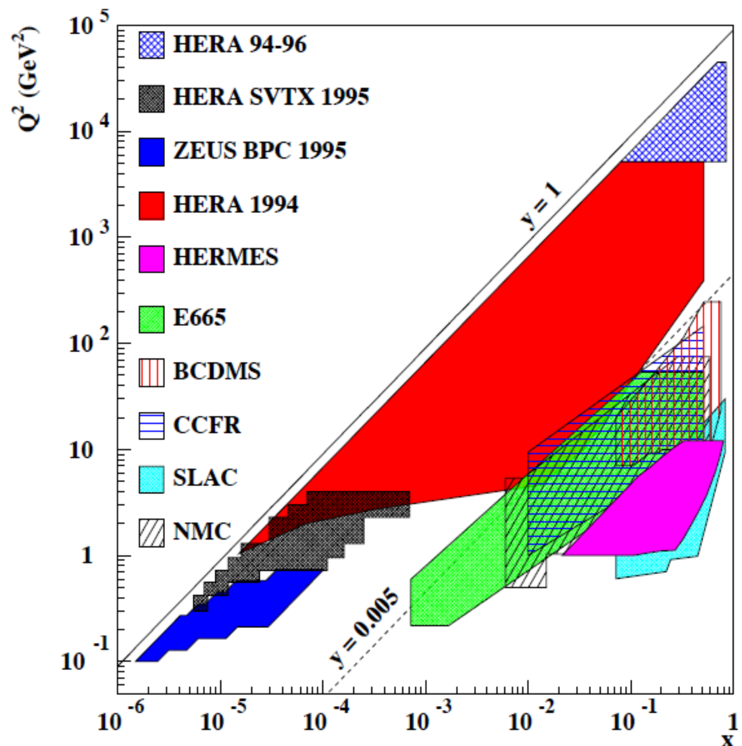


Parton densities not known at very low x

Range of x values (momentum fractions) needed in calculation

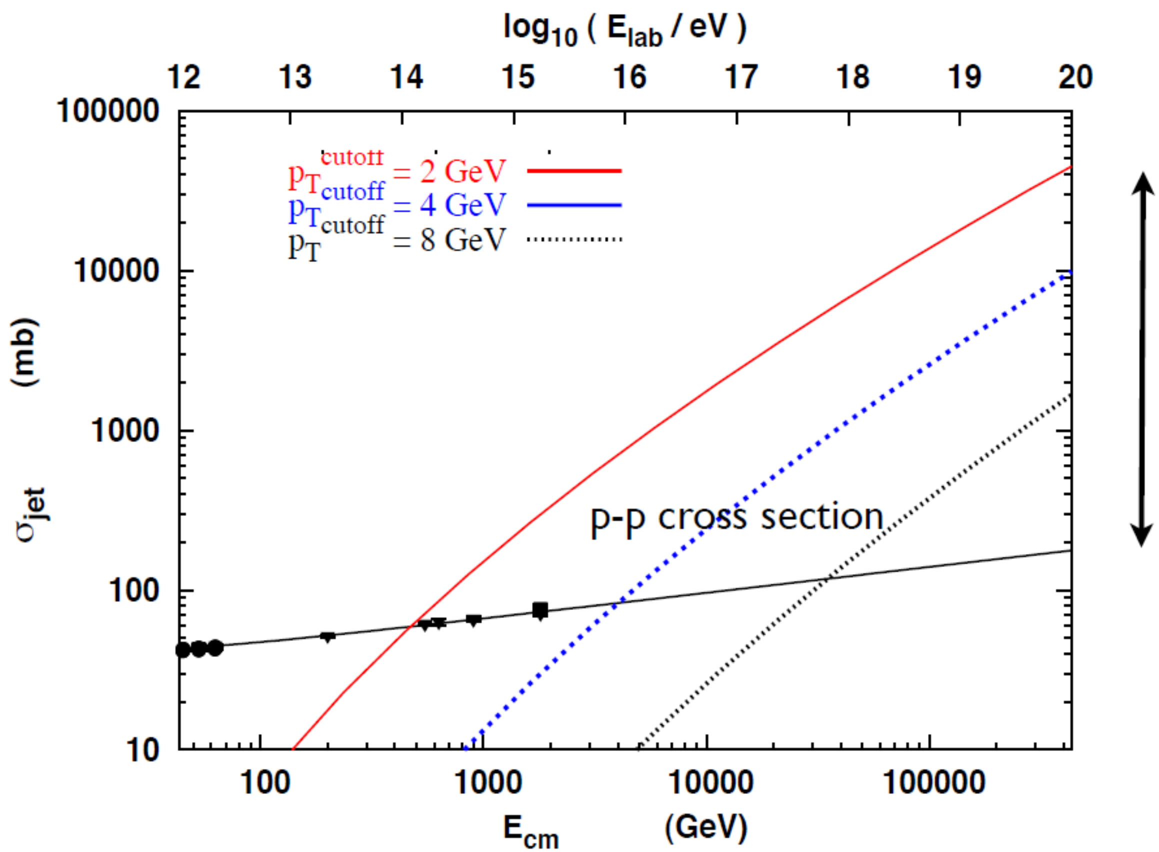


HERA measurement range



$$\hat{s} = x_1 x_2 s \geq 4p_\perp^2$$

Dependence on transverse momentum cutoff



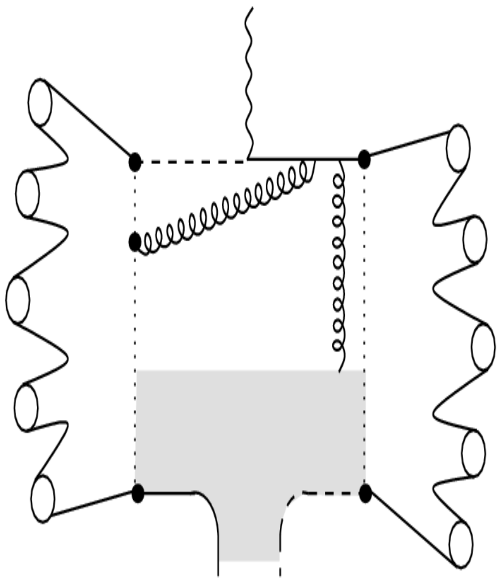
Factor ~ 150

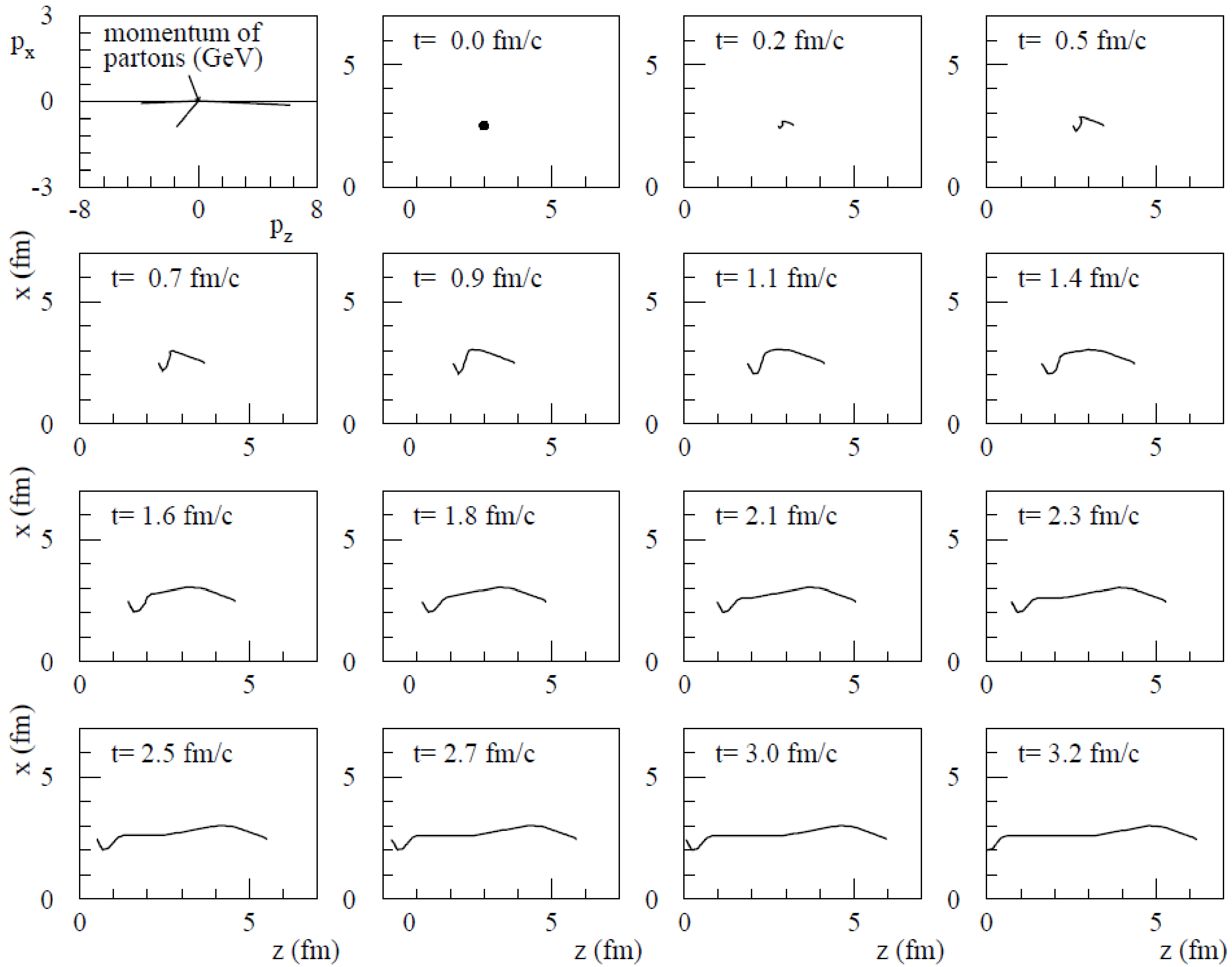
Selecting different values for cutoff does not help

Cross section of new interaction process of minijet production cannot simply be added to cross section from soft interactions

From cut Pomerons to hadrons: string fragmentation

planar representation of a cylindrical semi-hard Pomeron





Are fragmentation parameters universal ?

- **In principle yes but …**
  - ➔ Only EPOS (Pythia) uses LEP data
    - Without remnant and statistical hadronization of high density regions (Pythia) : NO
    - If everything is taken into account : YES (it seems ...)
  - ➔ QGSJET and SIBYLL use hadronic interaction data at low energy to fix parameters for string fragmentation
    - possible bias due to remnant contribution
- **String fragmentation models**
  - ➔ Lund fragmentation function (Pythia)
  - ➔ Area law (EPOS)

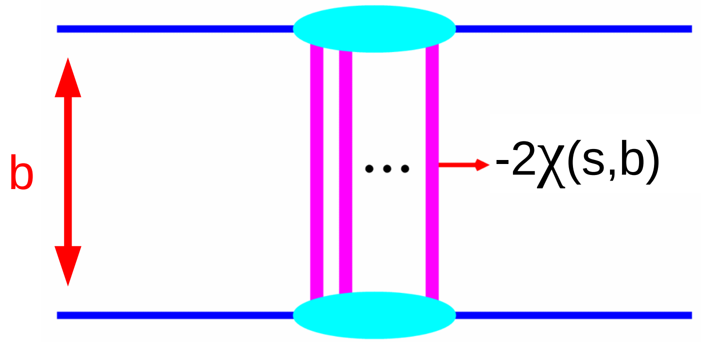
Cross Section Calculation

Gribov-Regge for multiple scattering :

- elastic amplitude : -2χ(s,b)
- sum n interactions :
  - Gribov :

$$\frac{(-2\chi)^n}{n!} \rightarrow \exp(-2\chi)$$

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



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

Not the same χ in different models

- χ(s,b) parameters fixed with pp cross-section
- pp to pA or AA cross section from GRT (including nuclear effect in QGSJETII)

classical GRT: energy conservation not taken into account at this level

Particle Production from Pomerons

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

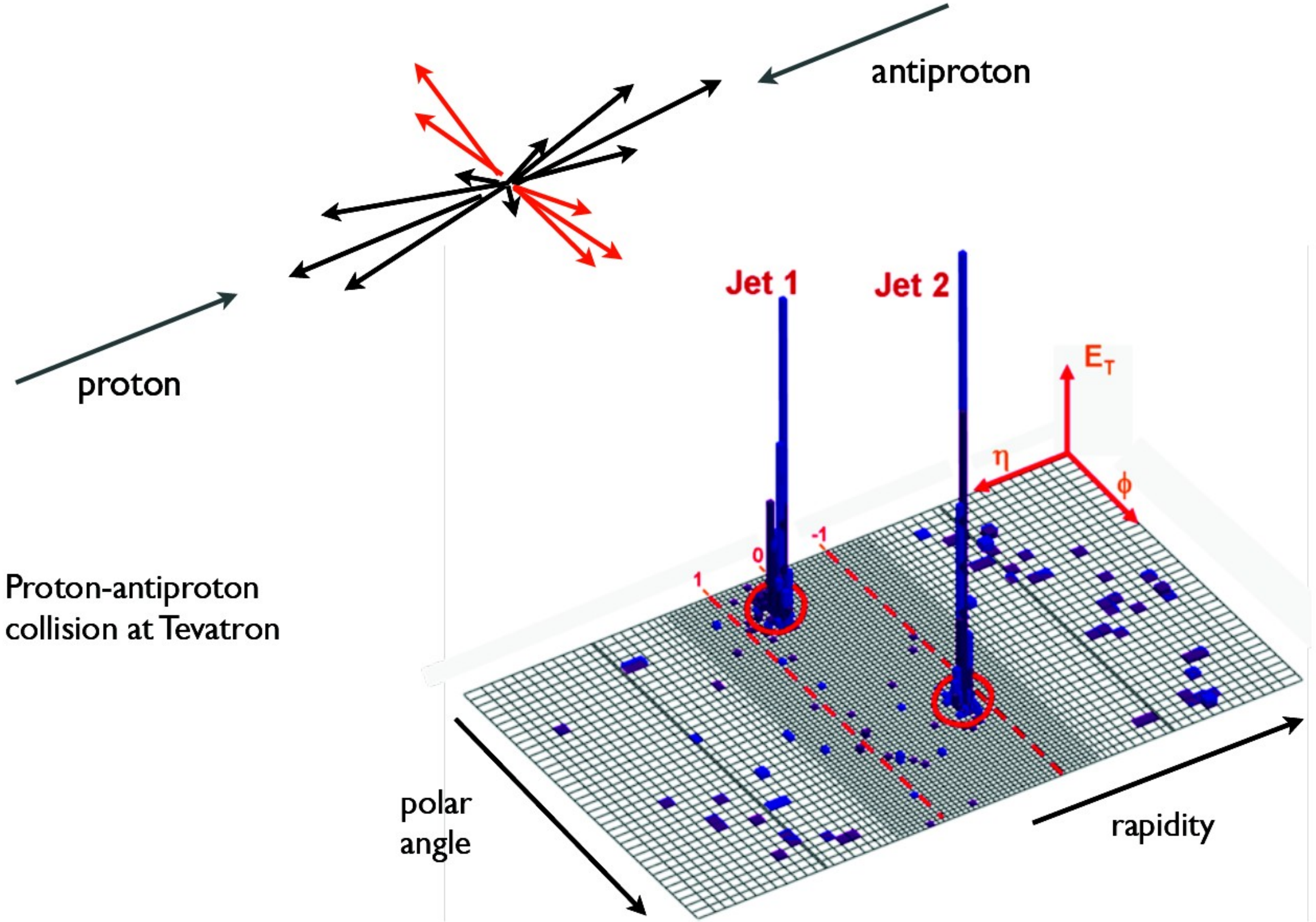
- n cut Pomerons from :

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

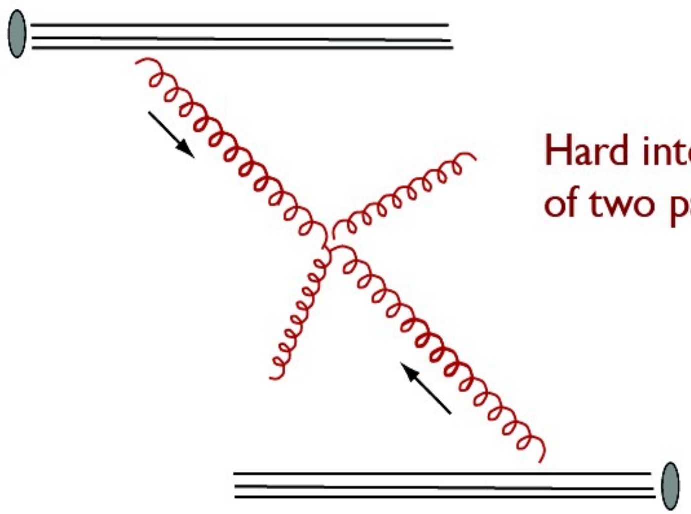
  - no energy sharing accounted for (interference term)
- 2n strings formed from the n elementary interactions
  - energy conservation : energy shared between the 2n strings
  - particles from string fragmentation

- inconsistency : energy sharing should be taken into account when fixing n
  - alternative approach with energy conservation from the beginning (EPOS)

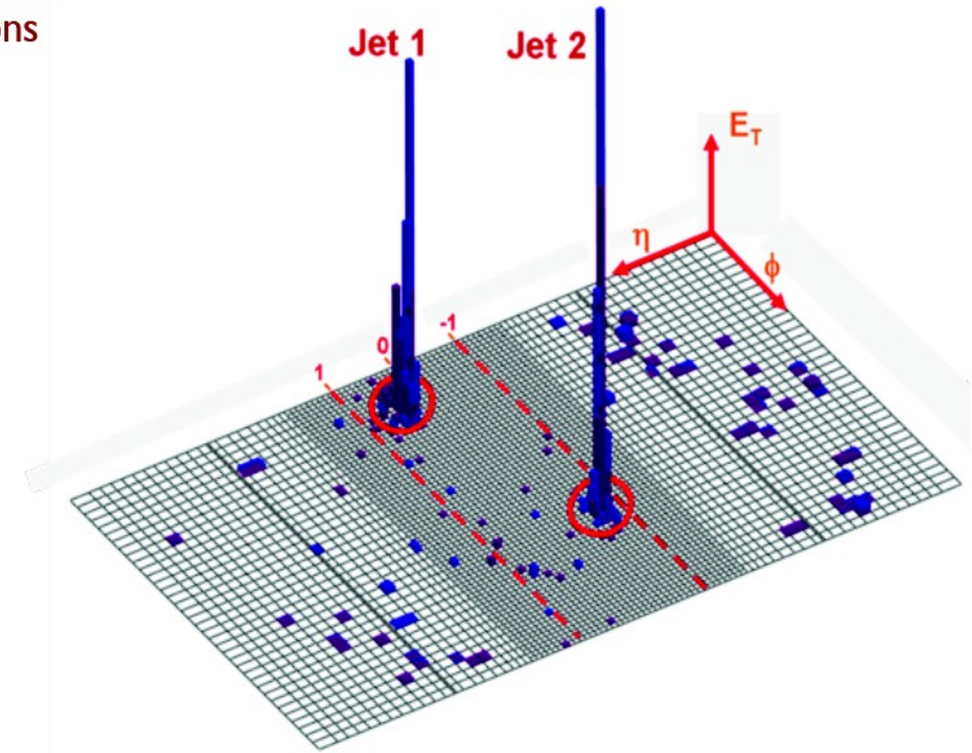
Scattering of quarks and gluons: jet production



Interpretation within perturbative QCD



QCD predictions known
for parton-parton cross sections

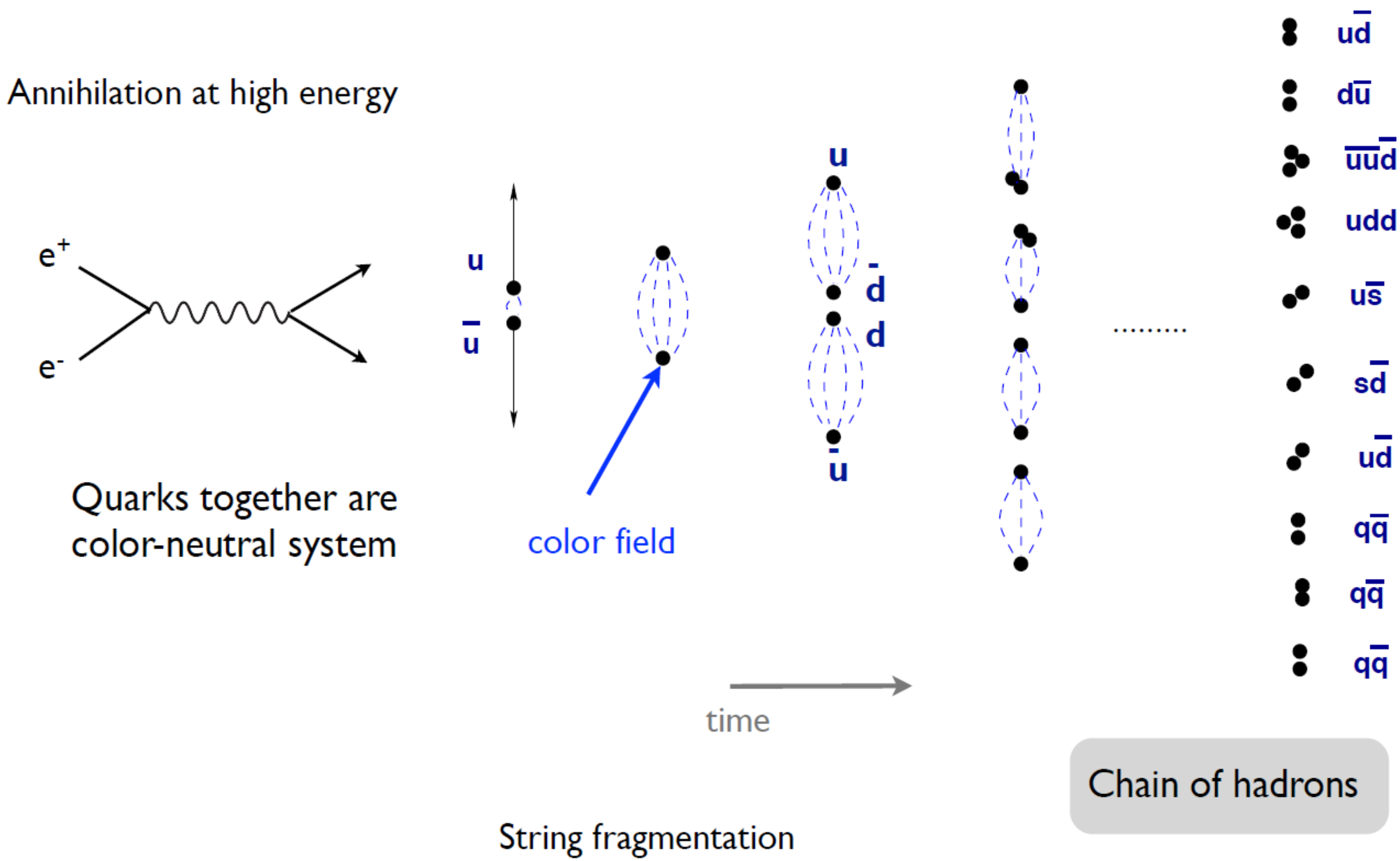


Terminology

Soft interaction: no large momentum transfer

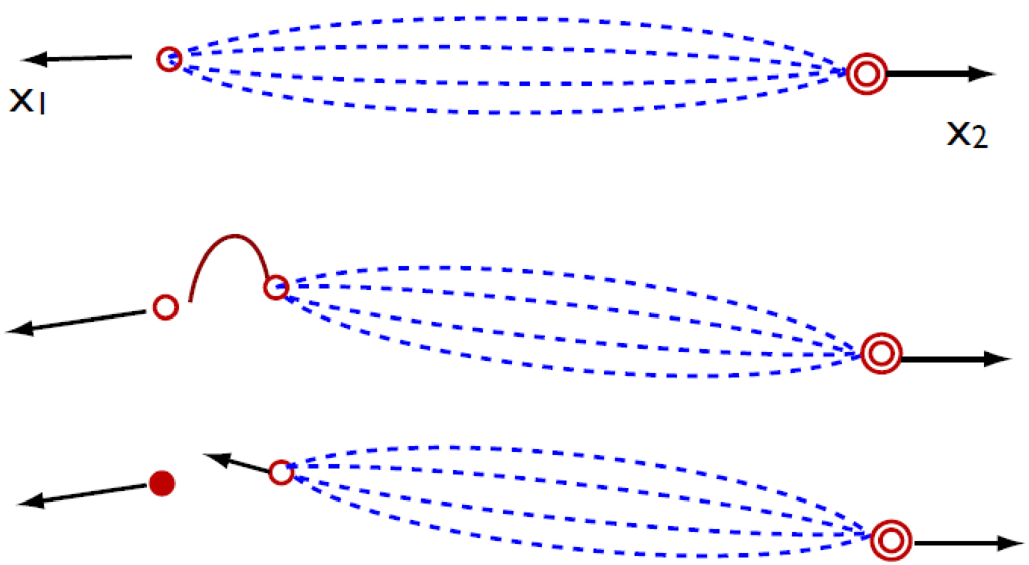
Hard interaction: large momentum transfer ($|t| > 2$ GeV^2)

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



Fragmentation function (SIBYLL)

String characterized by momentum fractions of partons at ends



$$E_{\mathrm{str}} = \frac{1}{2}\sqrt{s}(x_1 + x_2)$$

$$p_{\mathrm{str}} = \frac{1}{2}\sqrt{s}(x_1 - x_2)$$

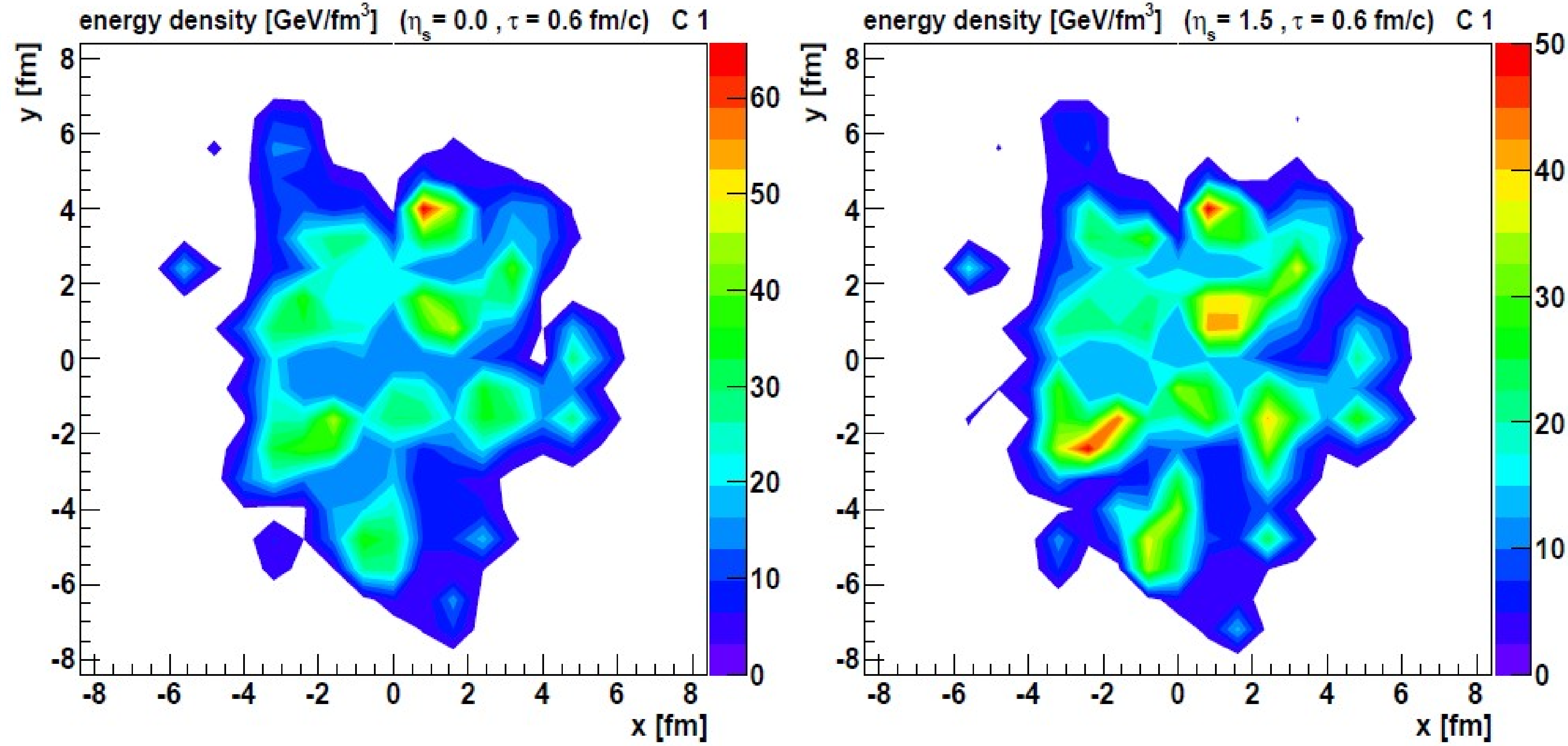
$$m_\perp^2 = p_\perp^2 + m^2$$

Momentum fraction z of new meson relative to quark at string end

$$f(z) = \frac{(1-z)^a}{z} \exp\left\{ -\frac{b m_\perp^2}{z} \right\}$$

Event-by-Event Energy Density : AuAu

- Bumpy structure of energy density in transverse plane, but translational invariance
  - pseudorapidity extension of flux tubes (strings)

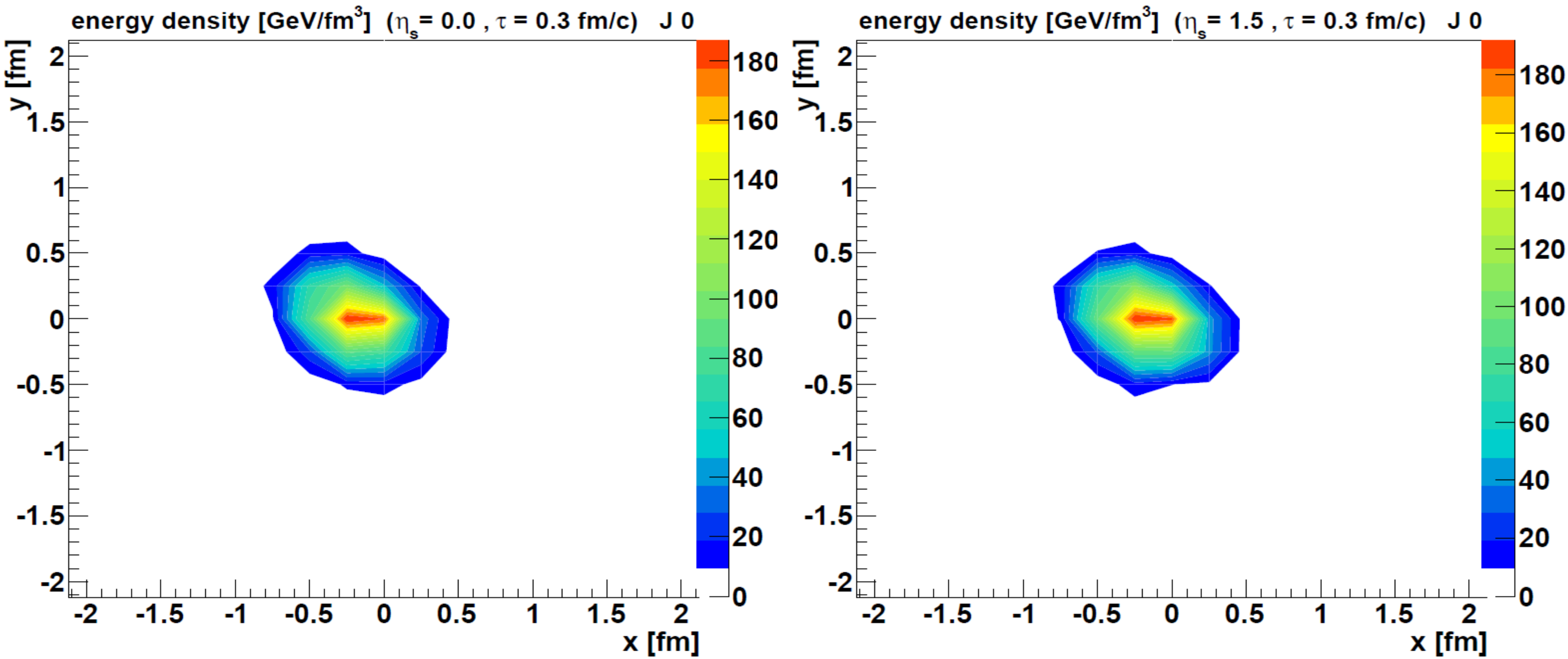


Initial energy density in the transverse plane for two different η_s

Event-by-Event Energy Density : pp

➜ Random azimuthal asymmetries of initial energy density but translational invariance

- pseudorapidity extension of flux tubes (strings)



Initial energy density in the transverse plane for two different η_s