High Energy Shower Physics: Hadronic Interaction Models

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ISAPP school "High-Energy Astrophysics: Sources and Detection", Orsay, France

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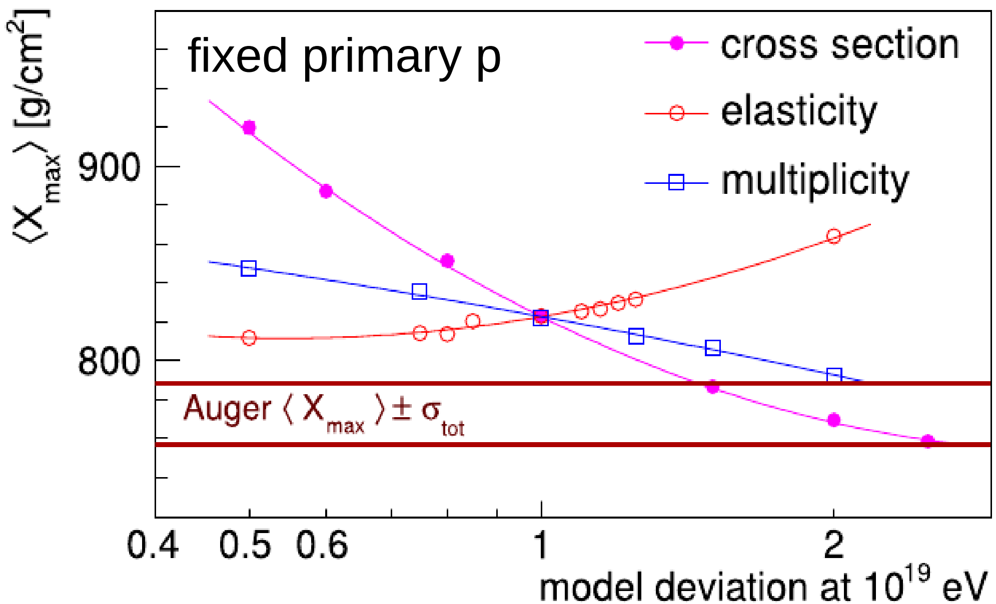
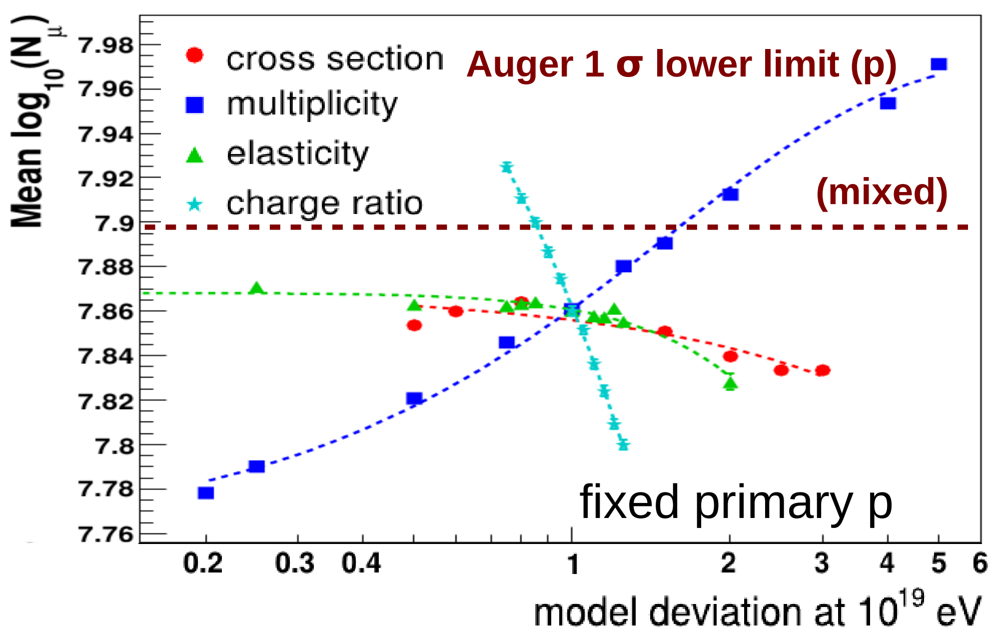
Sensitivity to Hadronic Interactions



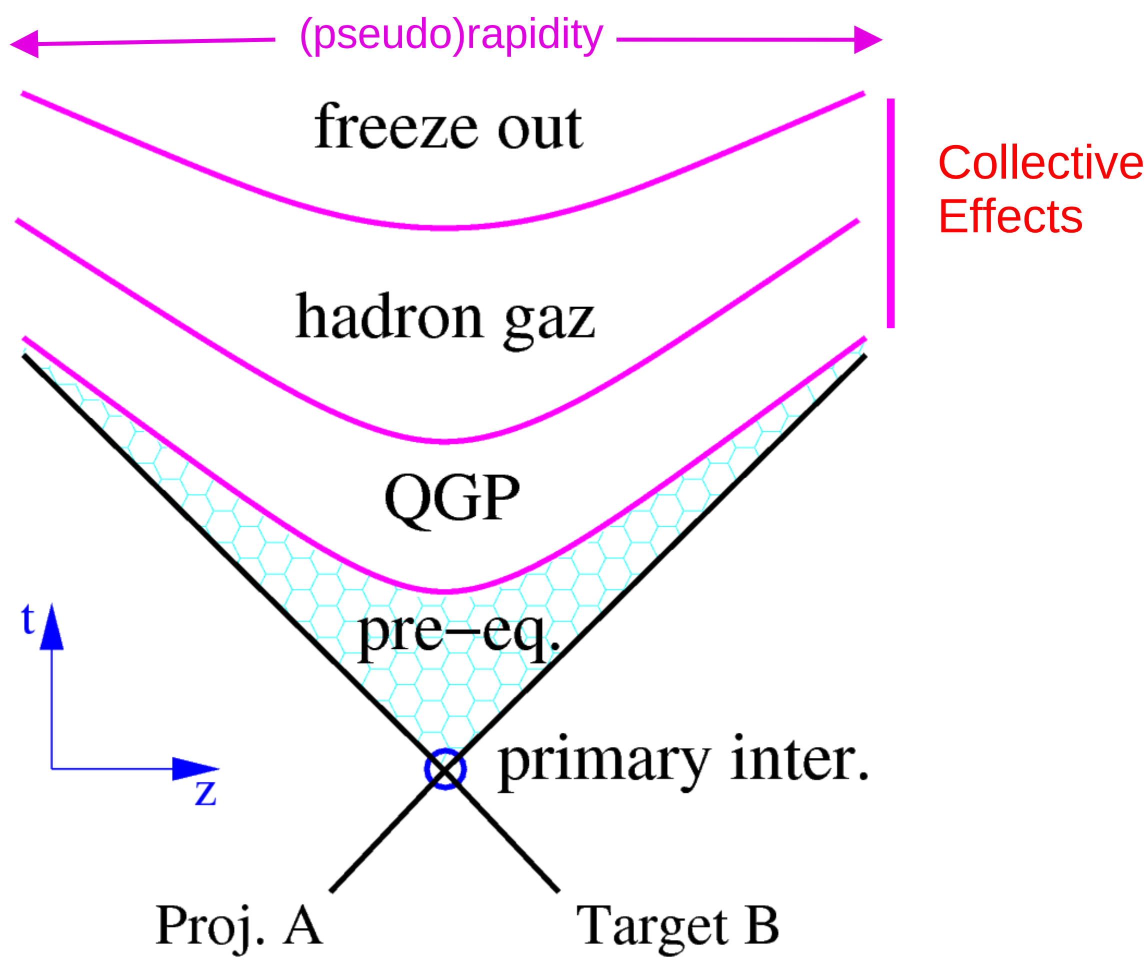


From R. Ulrich (KIT)

- **Air shower development dominated by few parameters**
  - ➡ mass and energy of primary CR
  - ➡ cross-sections (p-Air and (π-K)-Air)
  - ➡ (in)elasticity
  - ➡ multiplicity
  - ➡ charge ratio and baryon production
- **Change of primary = change of hadronic interaction parameters**
  - ➡ cross-section, elasticity, mult. …
- **Model tuned to accelerator data**

Theory AND data are important to constrain the hadronic model parameters.

Goal of Today's Lecture...



The complete description of hadronic interactions is universal …
and important for air showers
(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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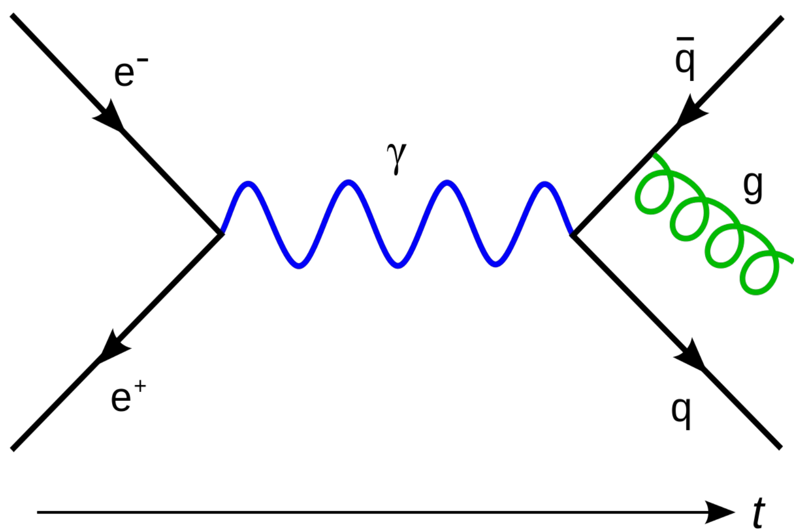
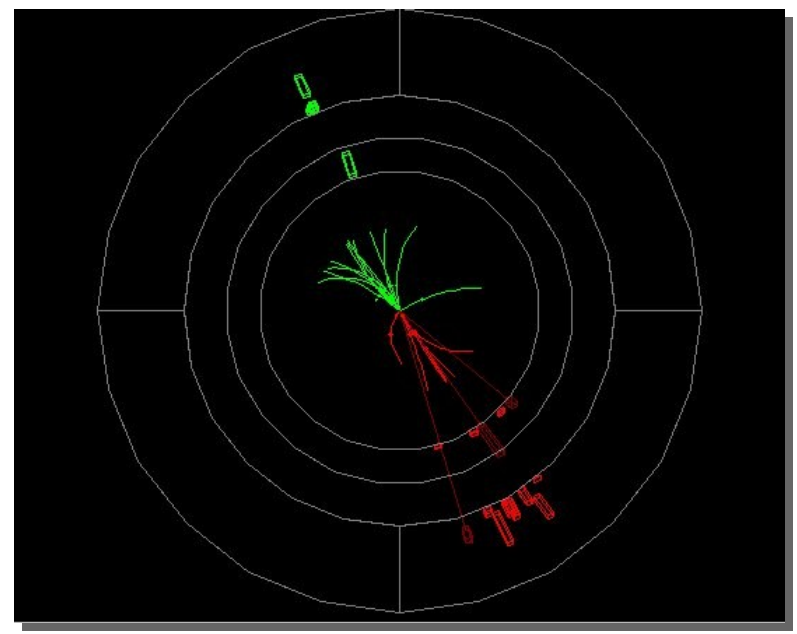
- fundamental particles
- study of new particles
- “clean”
- difficult to go to very high energies

  (~100 GeV/c)





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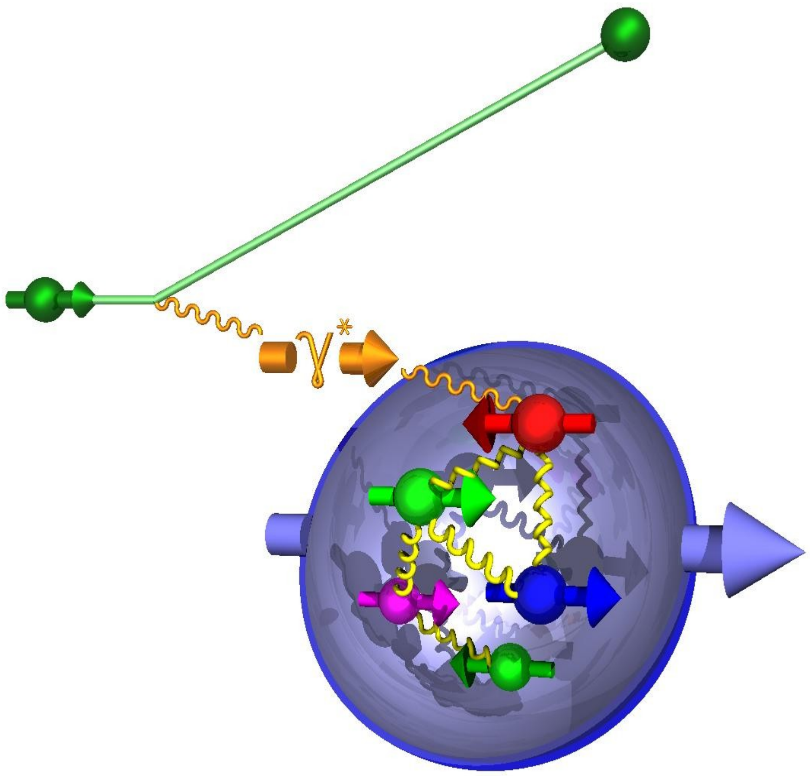
- one particle with inner structure
- study proton structure
- asymmetric detectors



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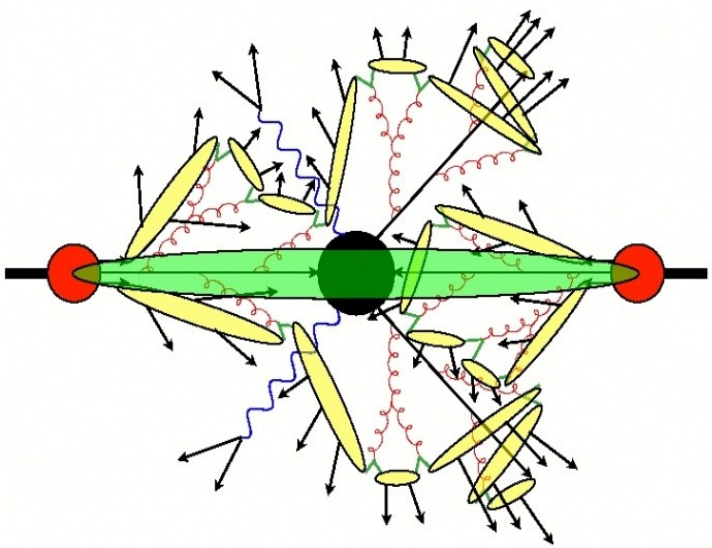
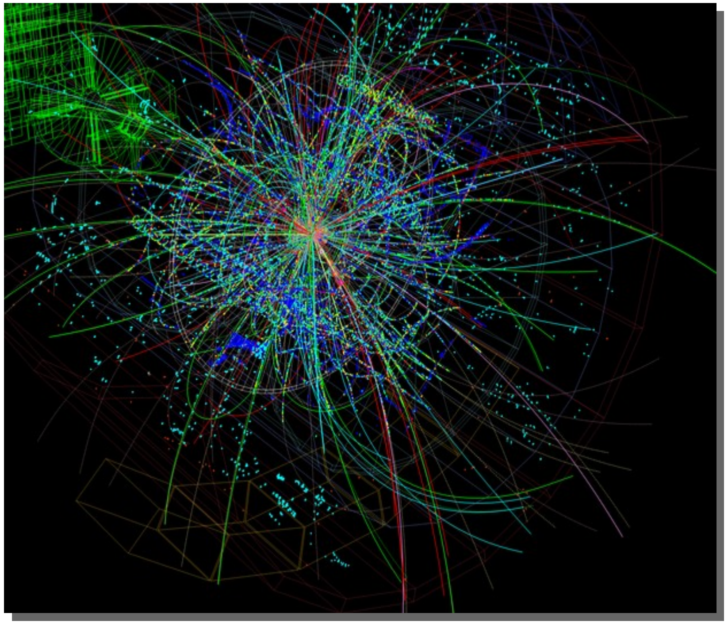


- complex particles
- study of new particles
- multiple interactions of inner structure
- “dirty”
- very high energy possible

  (~10 TeV/c)



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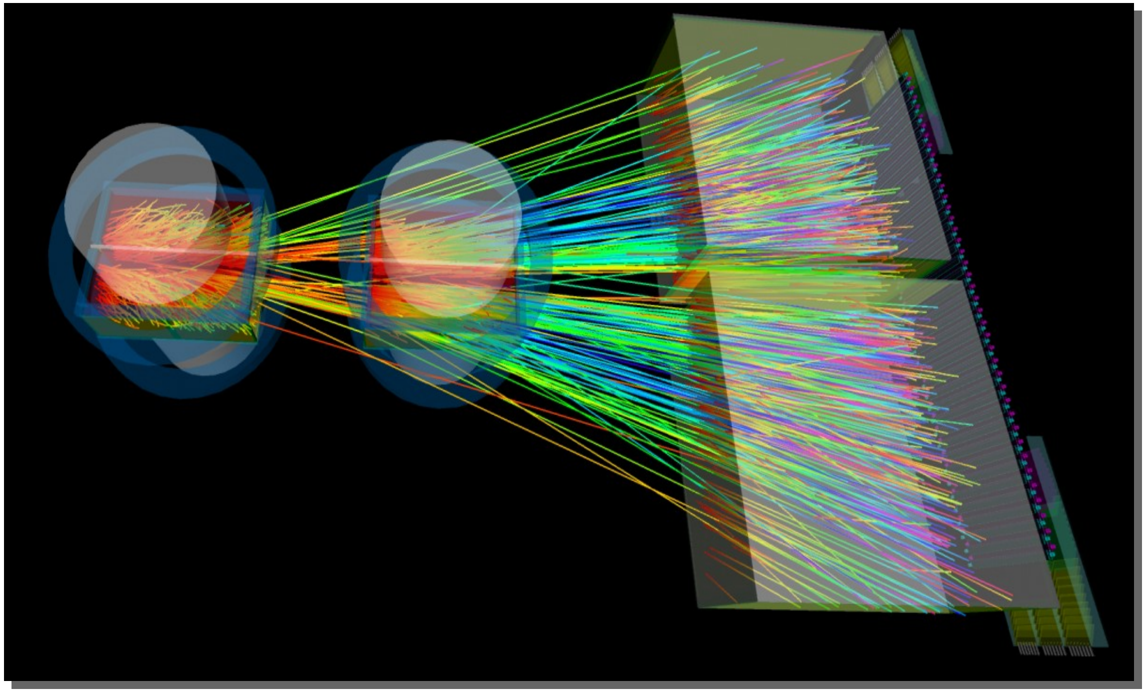

NA61

- 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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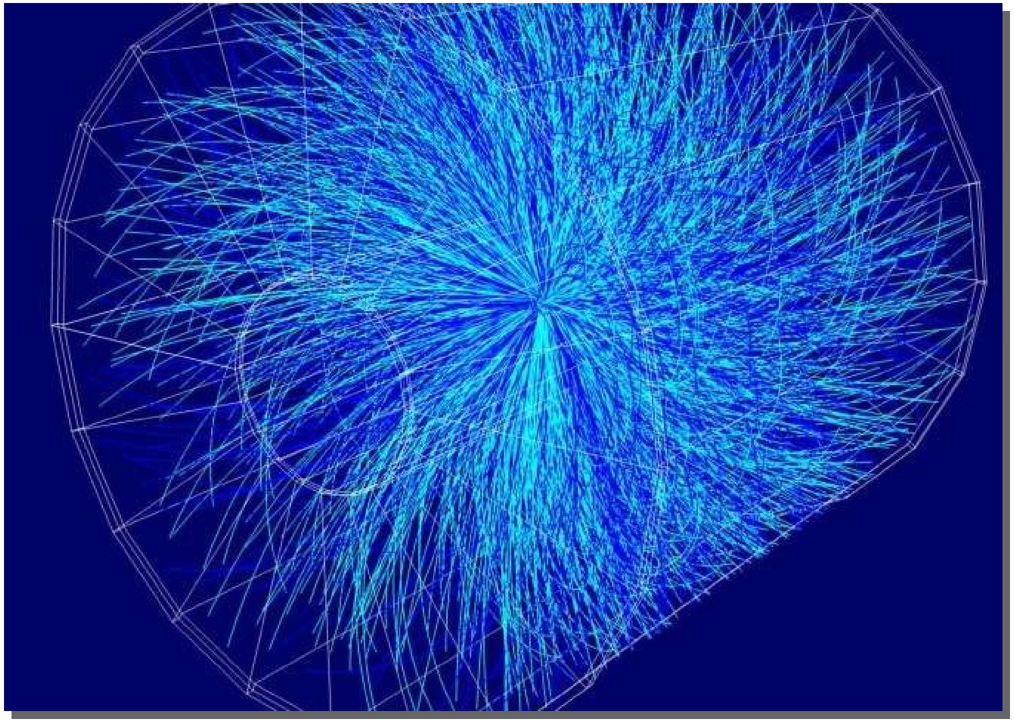

ALICE

- 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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e^+ vs e^-
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  (~100 GeV/c)

l vs p (A)
- one particle with inner structure
- 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

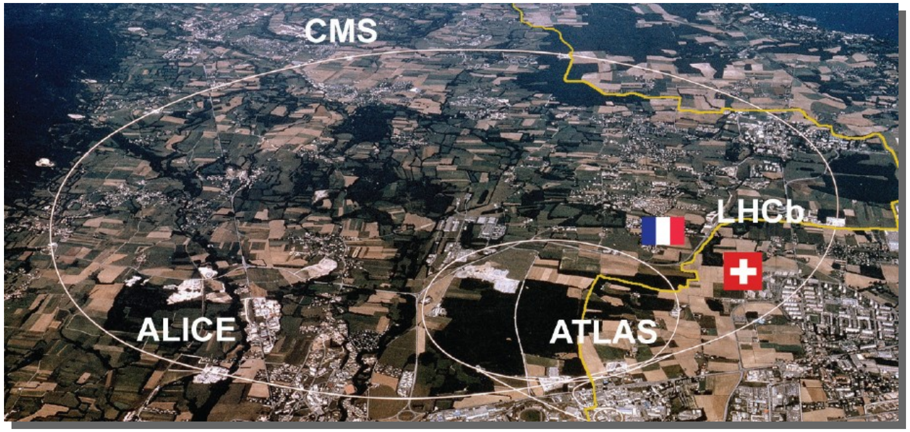
e$^+$ vs e$^-$
- LEP (CERN)
- SLC/PEP (SLAC)
- KEKB (KEK)

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) …) **:**

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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
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**

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High Energy Physics models
Models used for Cosmic Ray

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

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

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High Energy Physics models
Models used for Cosmic Ray
Used for HEP and CR

- Only few for EAS simulations ! (hadron projectile + nuclear target + very high energy)

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

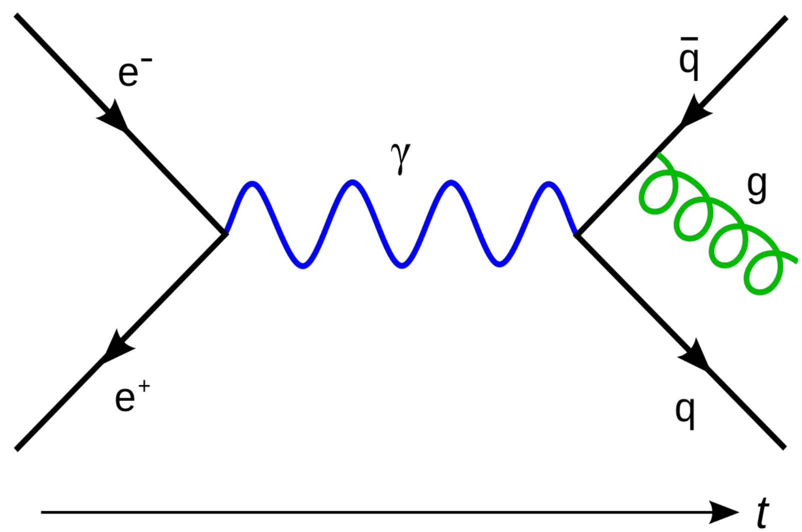
"soft" Low Momentum Particle Production

- **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

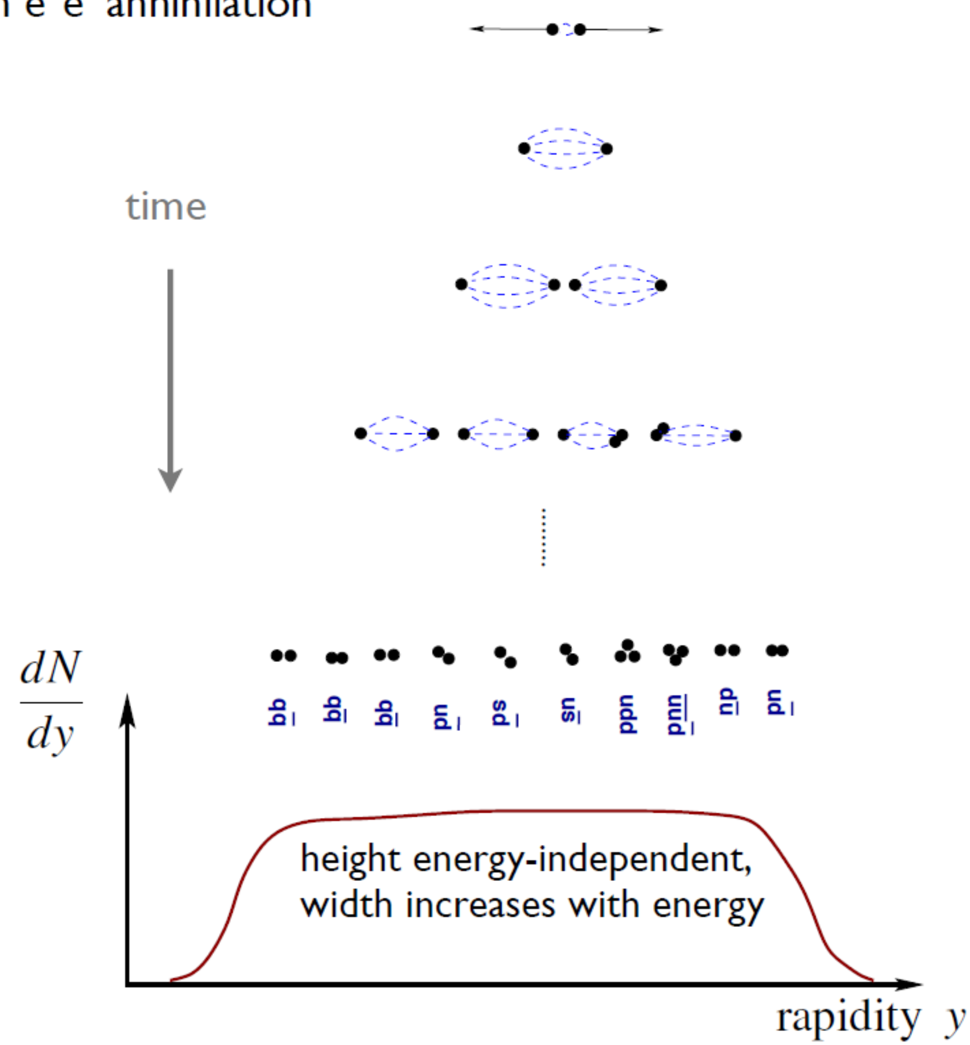
Hadronization of Quarks

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

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

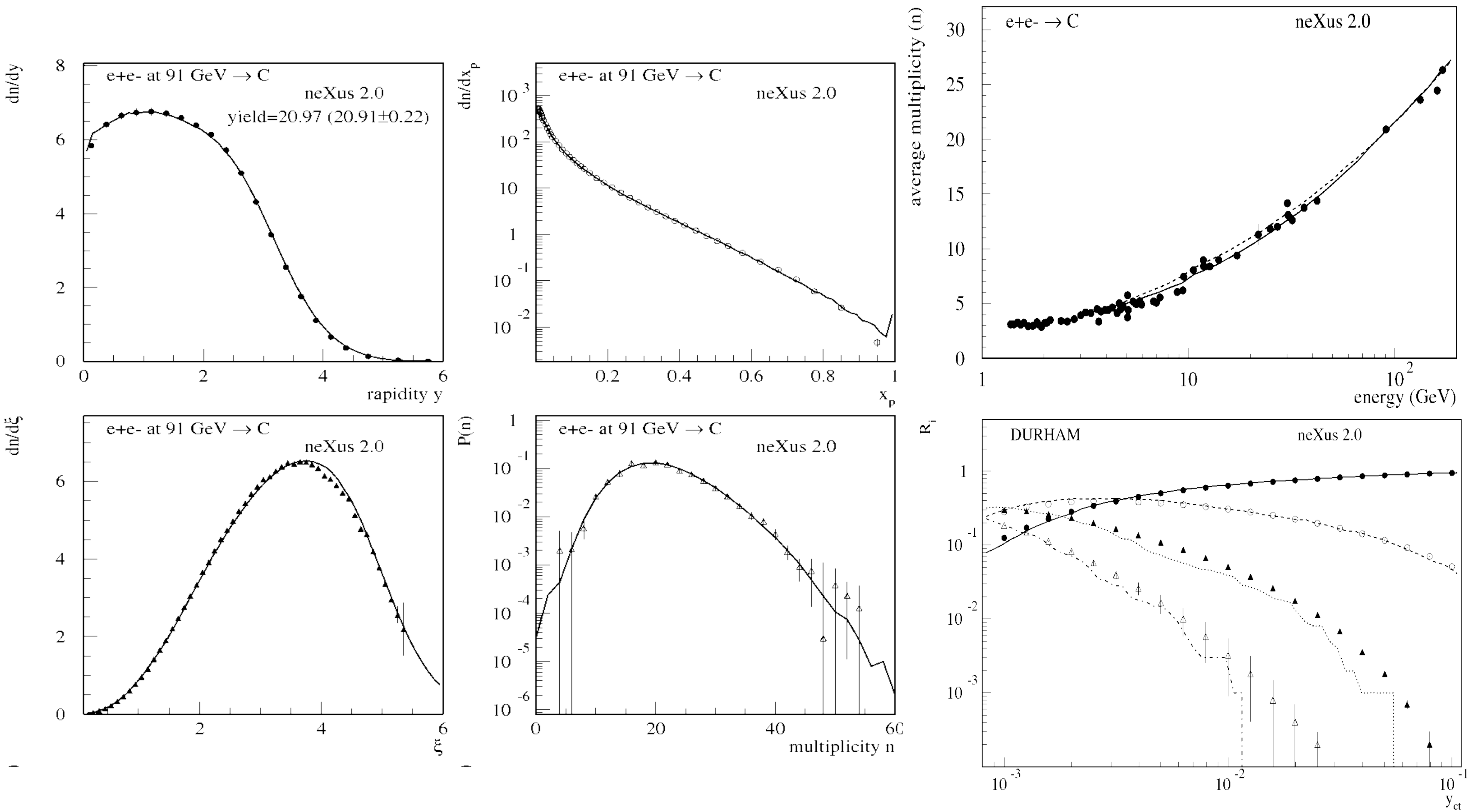
Rapidity of massless particles

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

Pseudorapidity (all particles)

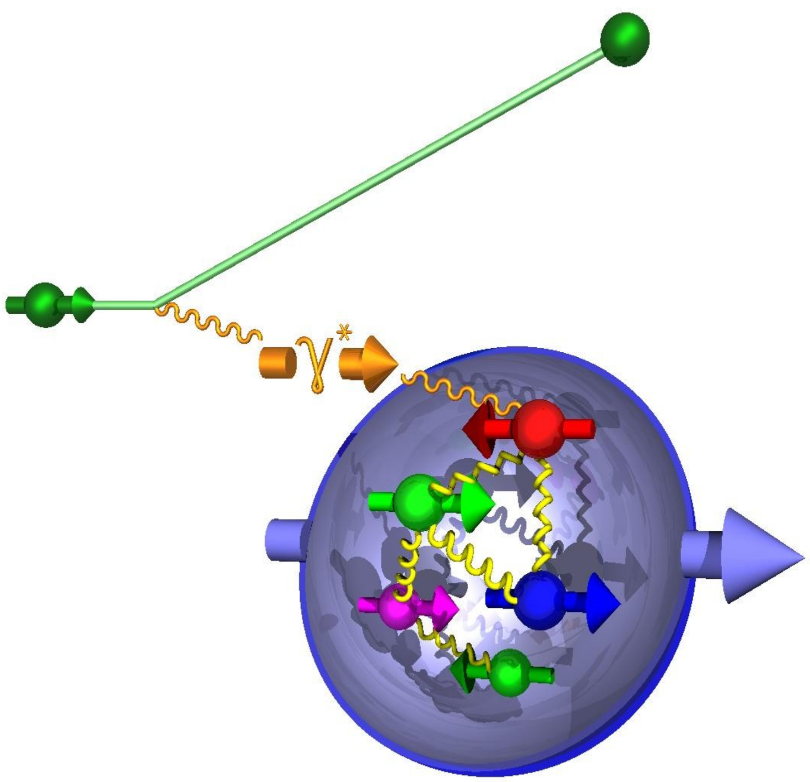
$$\eta = -\ln\tan\frac{\theta}{2}$$

Test at LEP

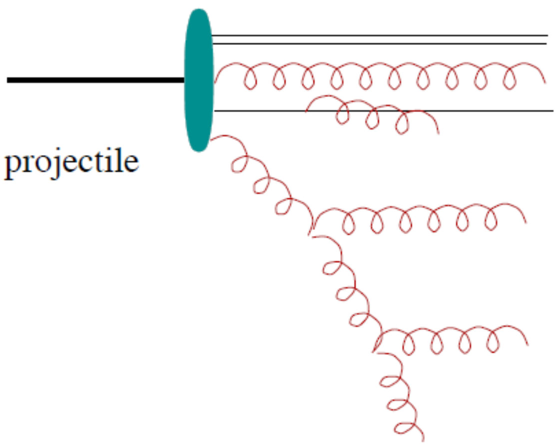

e+e- at 91 GeV → C
neXus 2.0
yield=20.97 (20.91±0.22)
dn/dy
rapidity y
dn/dx_p
x_p
e+e- → C
average multiplicity (n)
energy (GeV)
dn/dξ
ξ
P(n)
multiplicity n
DURHAM
R_i
y_ct

Parton Distributions

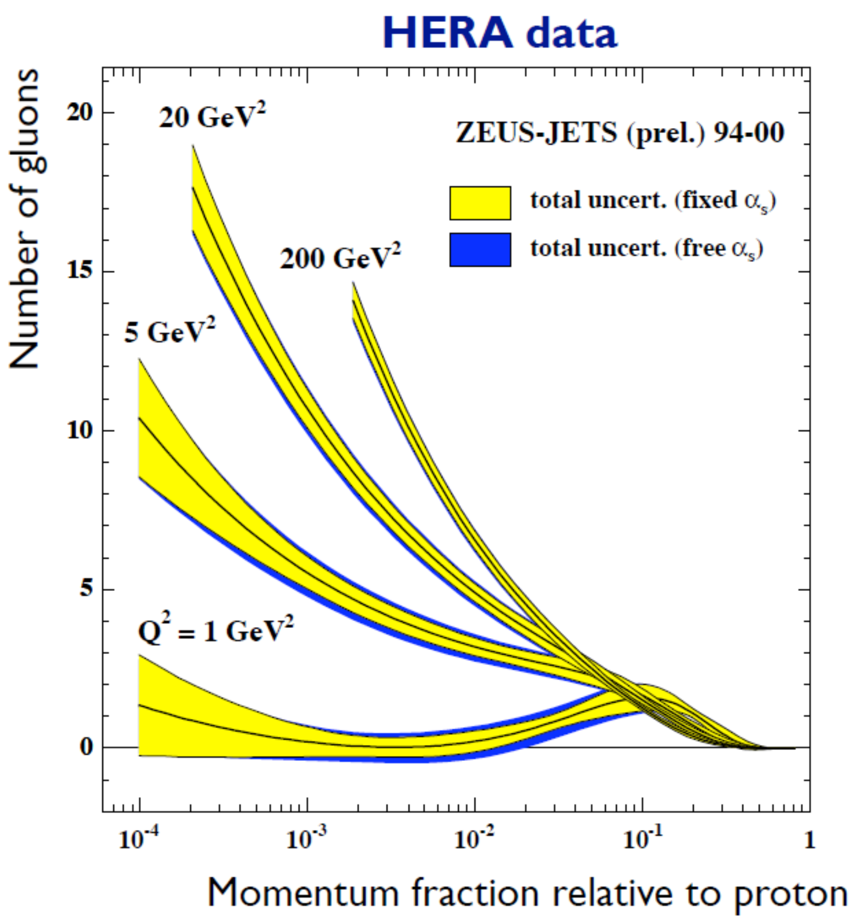
e$^+$ vs e$^-$ → l vs p (A) → p vs p → h vs A → A vs A



Perturbative QCD predictions for parton densities



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



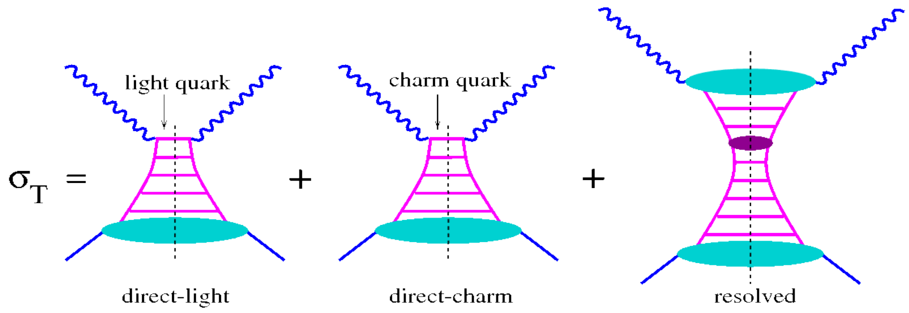
$$\frac{d f_i(x,Q^2)}{d\log Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{dy}{y}\sum_j f_j(y,Q^2)\,P_{j\to i}\left(\frac{x}{y}\right)$$

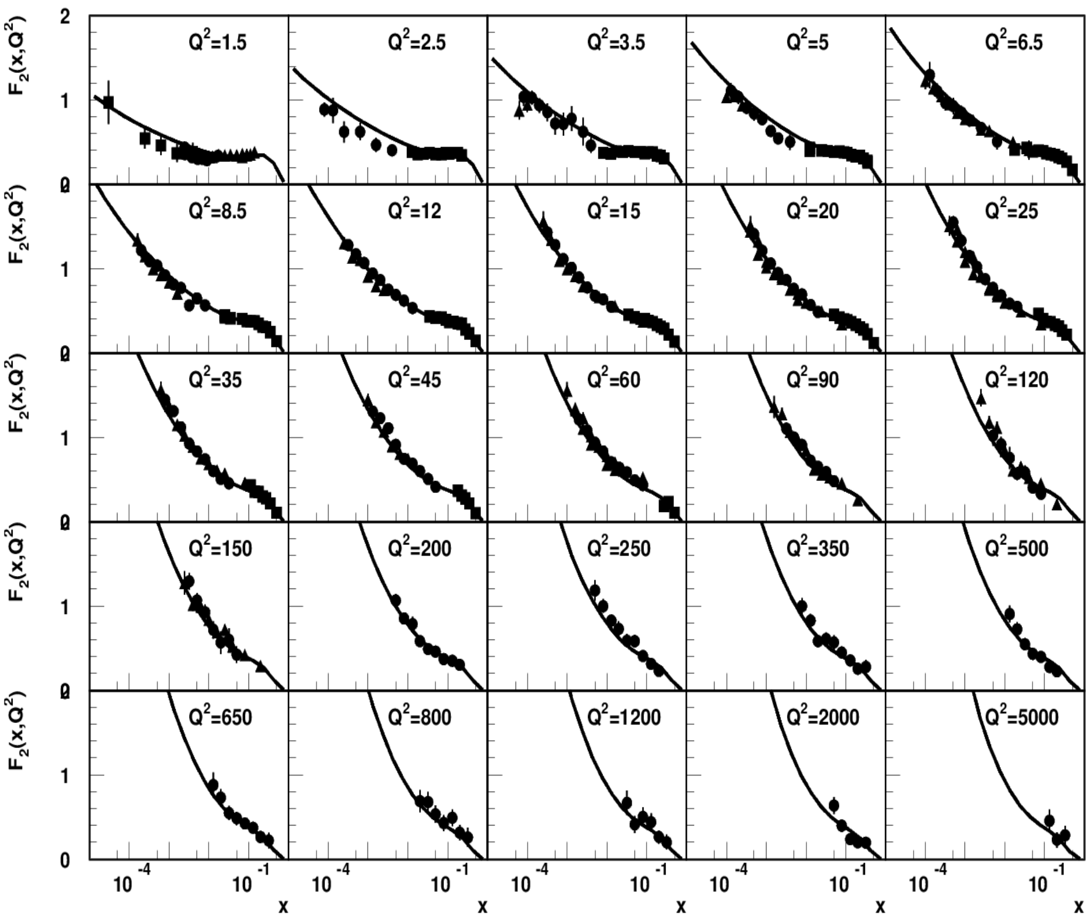
Prediction of
perturbative QCD

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

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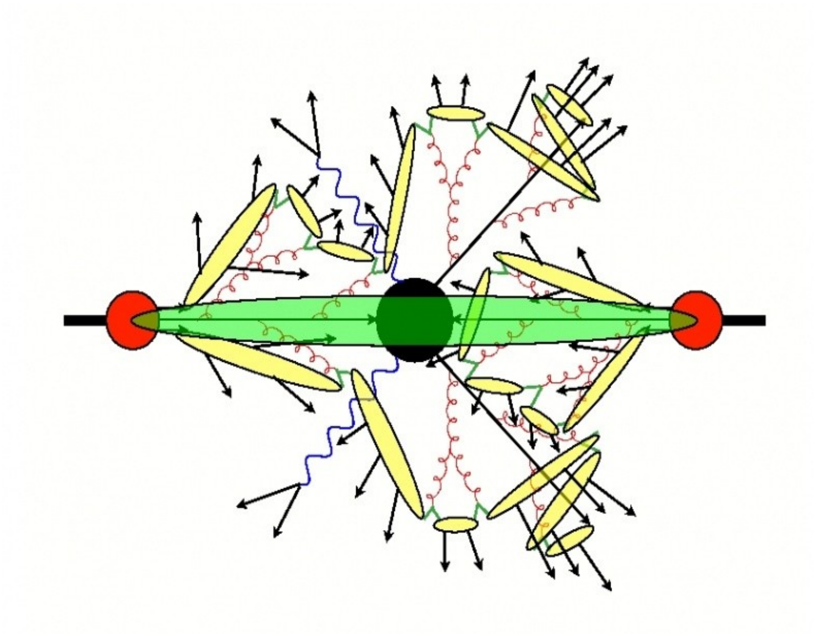
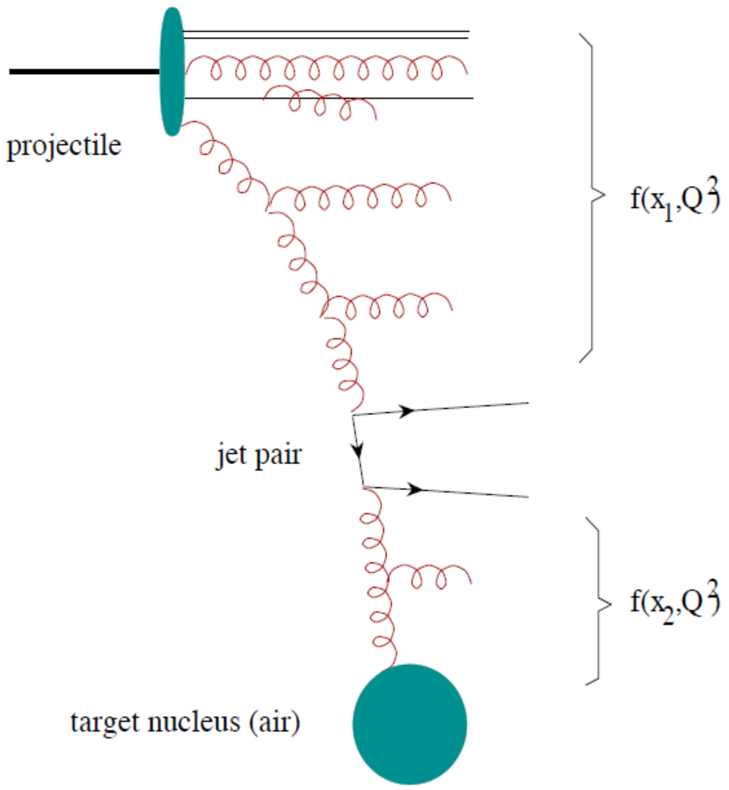
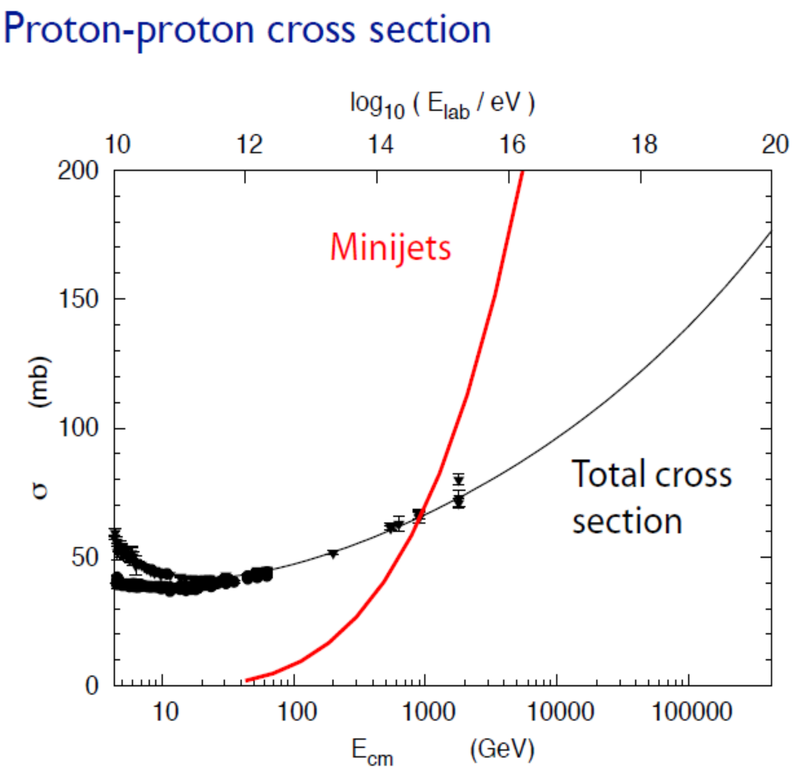


QCD parton model: minijets

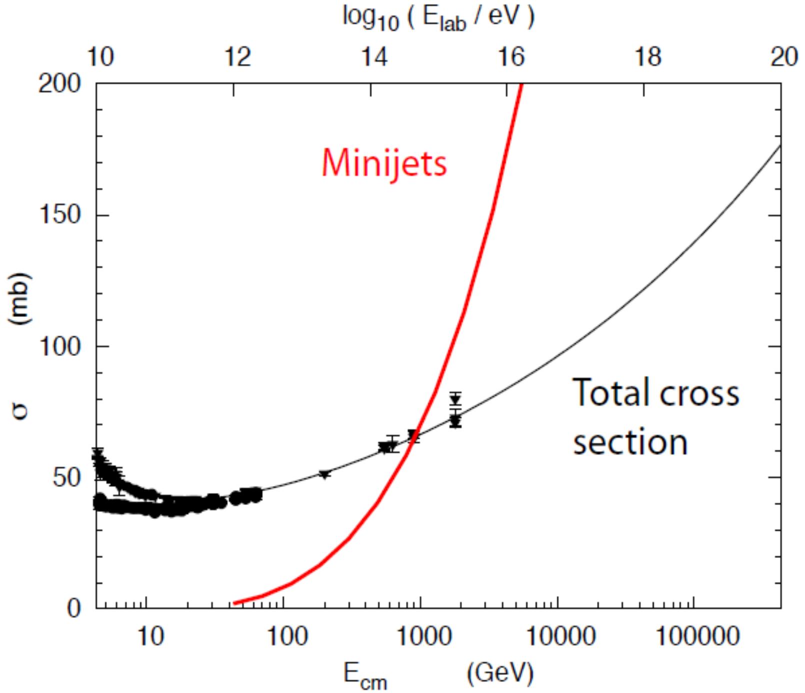




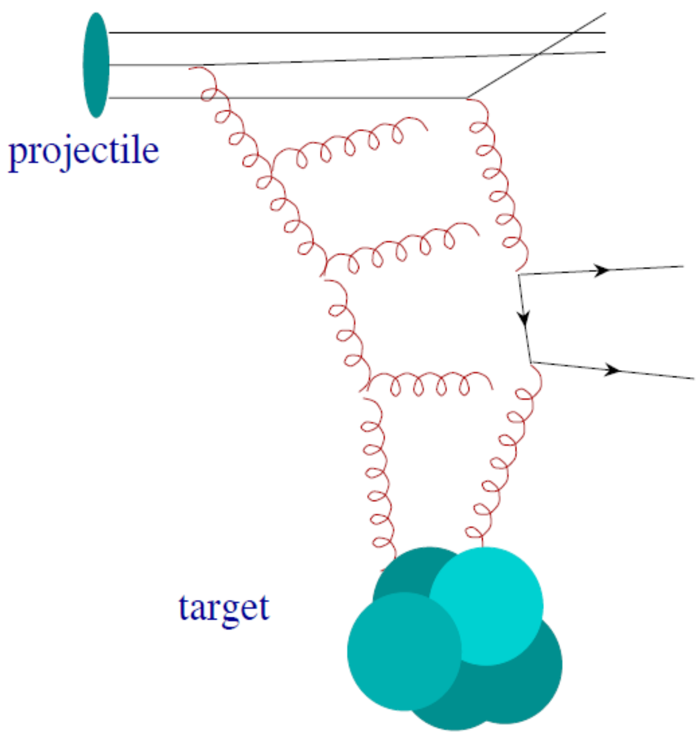
$$\sigma_{QCD} = \sum_{i,j,k,l} \frac{1}{1+\delta_{kl}} \int dx_1\, dx_2 \int_{p_\perp^{\mathrm{cutoff}}} dp_\perp^2\; f_i(x_1,Q^2)\; f_j(x_2,Q^2)\; \frac{d\sigma_{i,j\to k,l}}{dp_\perp}$$

Solution: Multiple parton-parton interactions (MPI)

Proton-proton cross section



QCD prediction:
inclusive cross section



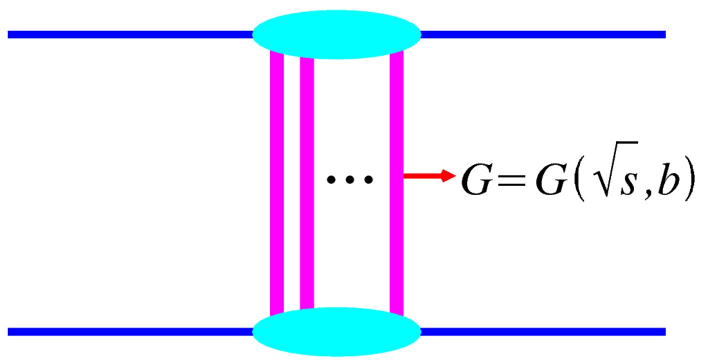
Average number of minijet pairs

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

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 (=excited state of quantum vaccuum) 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.

Gribov-Regge Based Models



Multiple elementary scattering

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

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

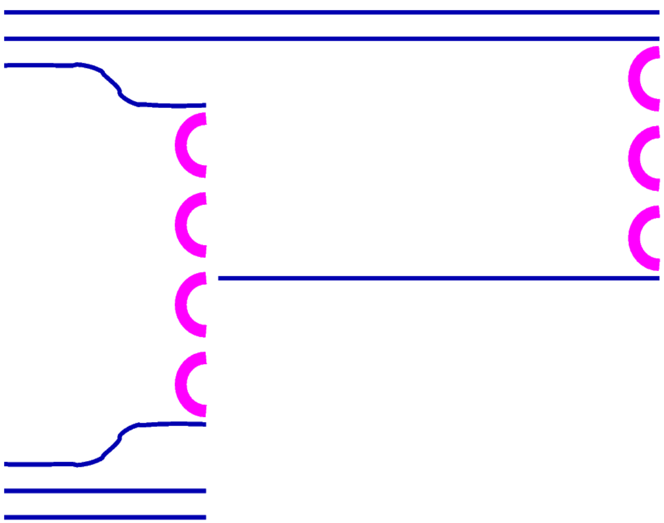
where G(energy,impact parameter) = Pomeron amplitude

- 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

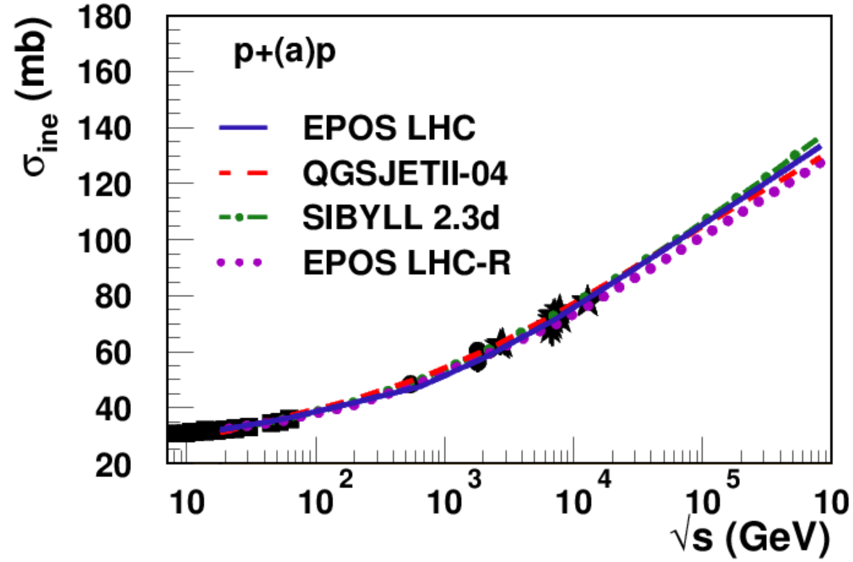
Link between cross-section and particle production not consistent !

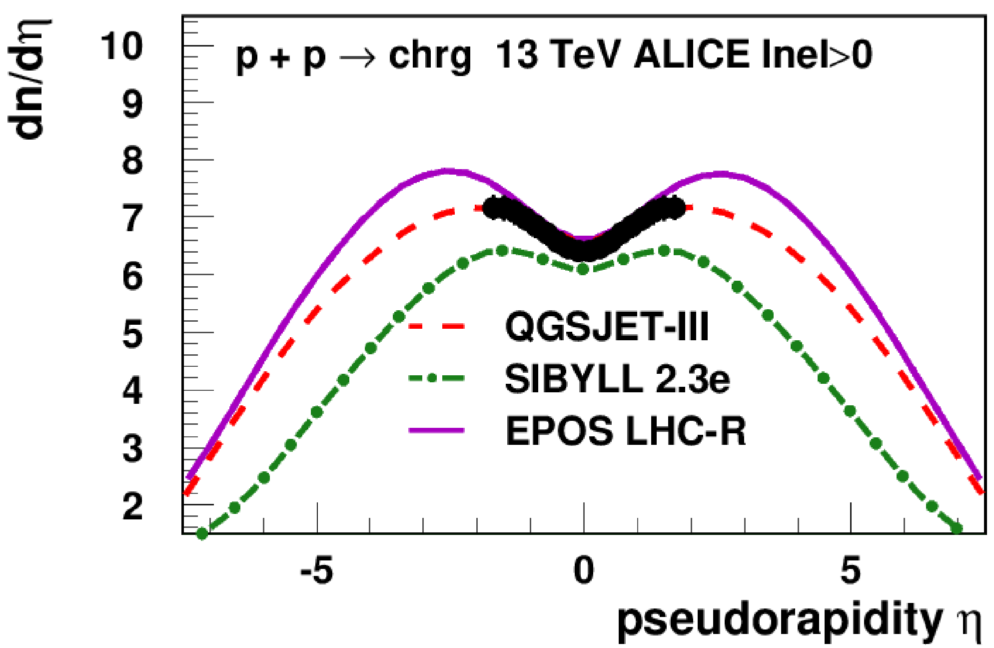
Parton-Based Gribov-Regge Therory* (PBGRT) developed to solve the problem :
same formalisme for cross section and particle production
used first in NEXUS and now in EPOS

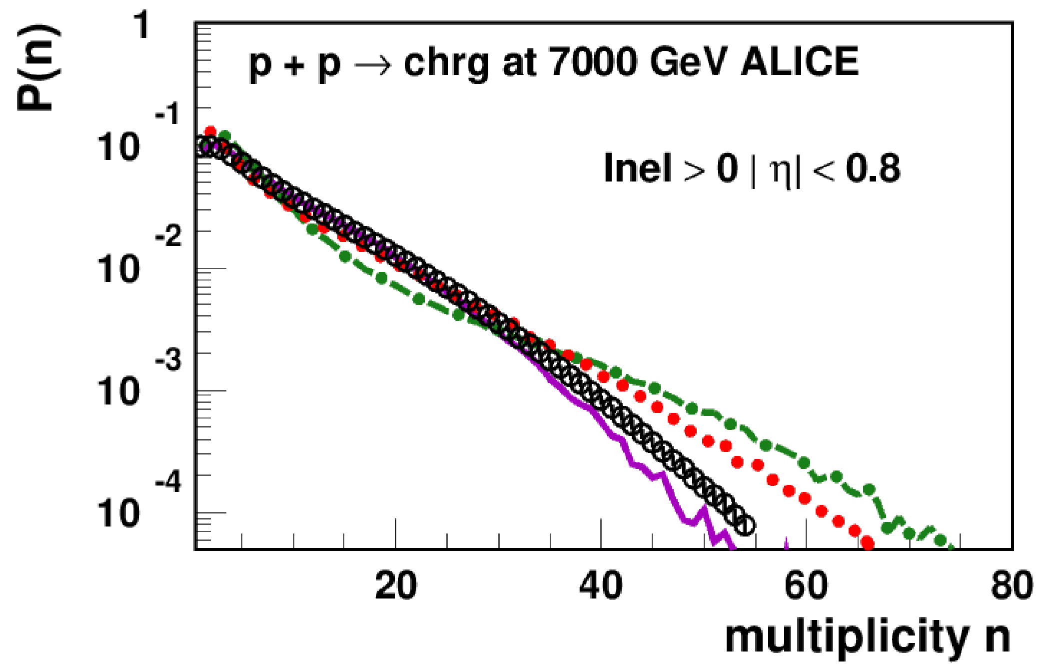
Cross-section and Multiplicity

Basic measurements !

- Cross-section use as input
- Data up to 13 TeV in p-p
  - Sibyll has a clear difference with other models (and data) : too narrow !
  - Different fluctuations







Hadron Interactions

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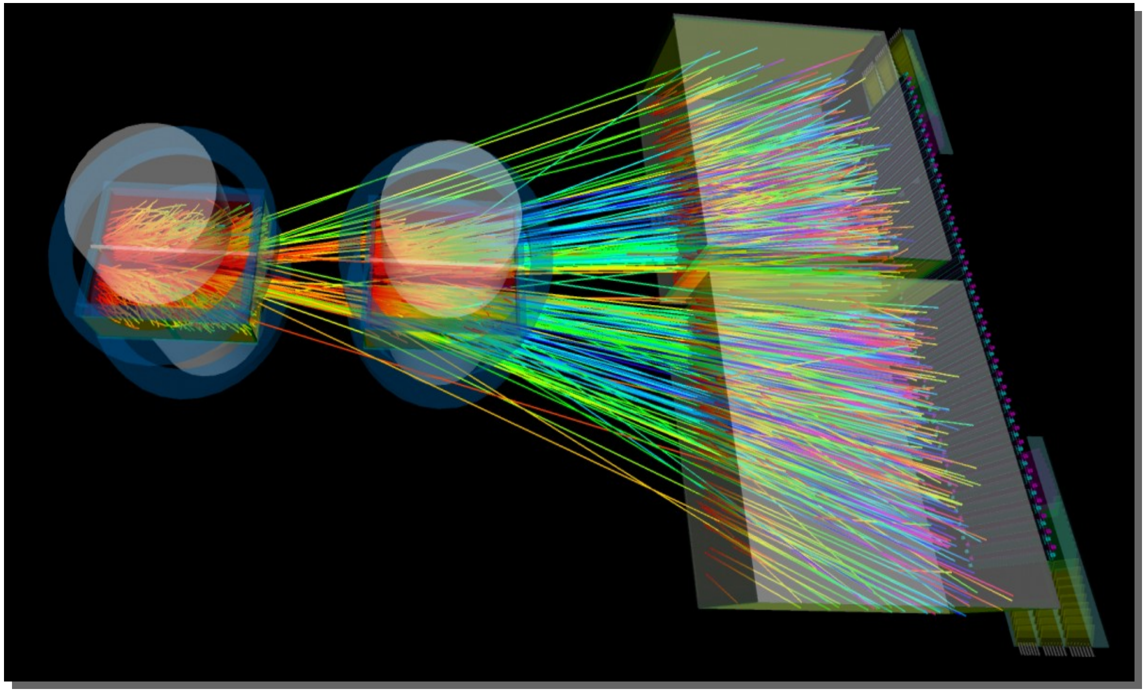
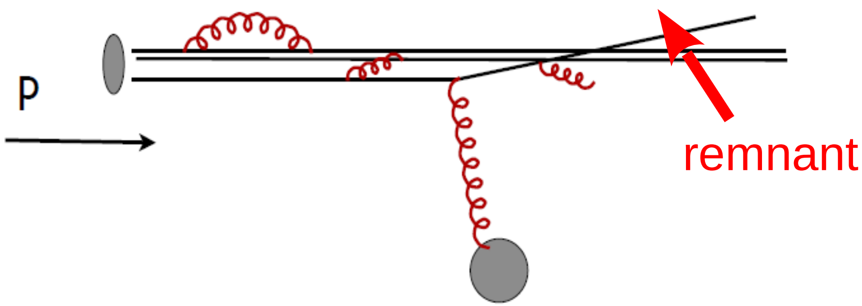


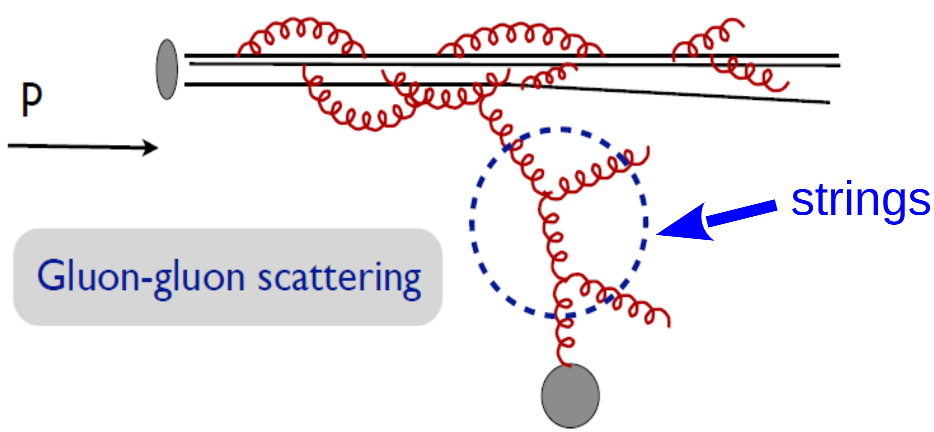
Transition from intermediate to high energy



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

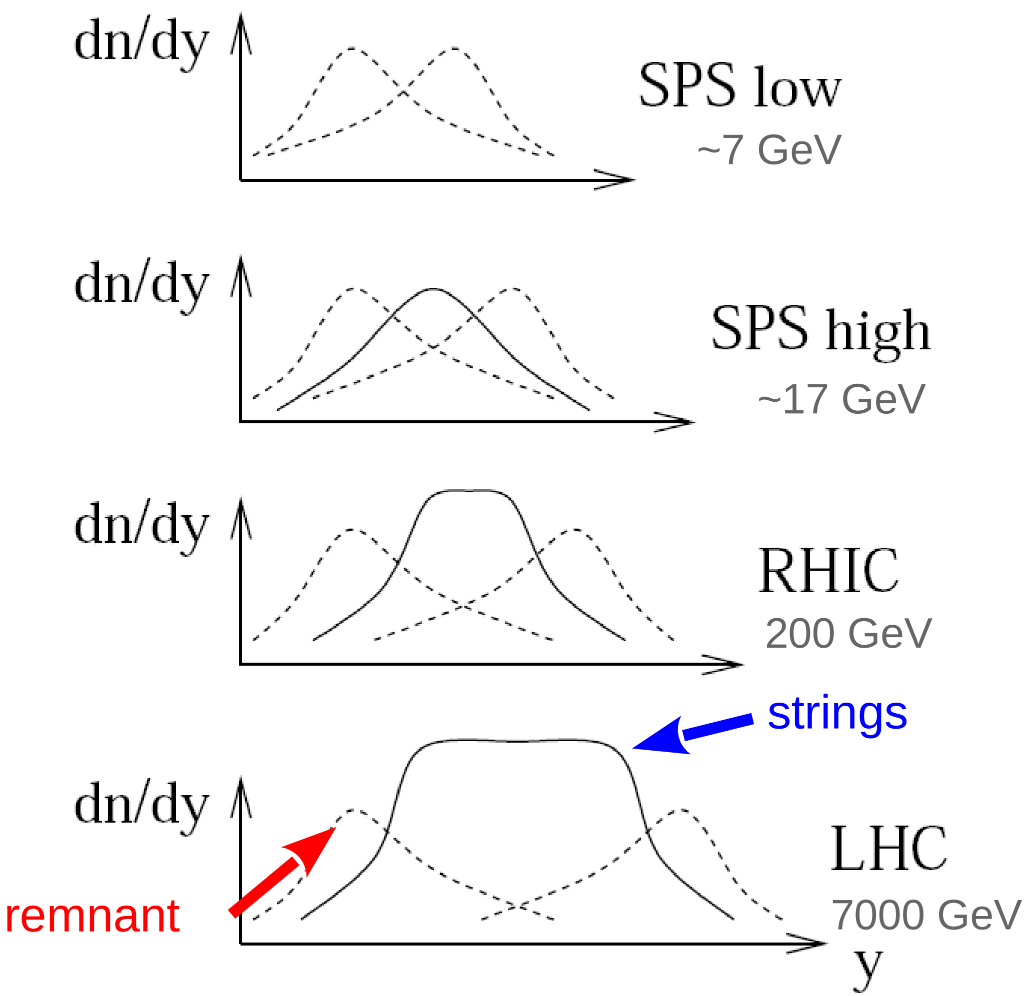


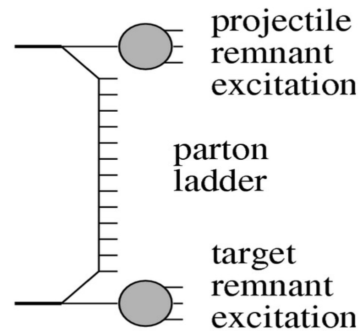
High energy regime:

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

Remnants

Forward particles mainly from projectile remnant





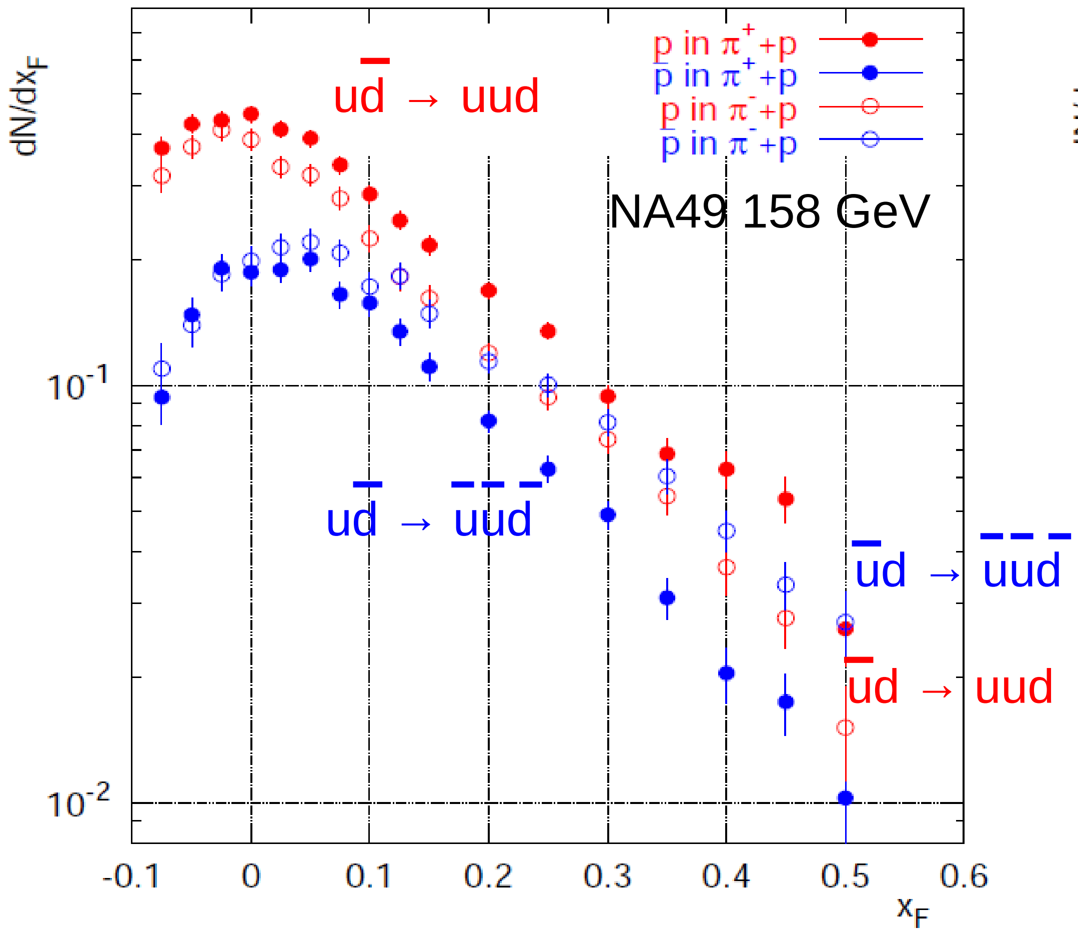
- At very low energy only particles from remnants
- At low energy (fixed target experiments) (SPS) strong mixing
- At intermediate energy (RHIC) mainly string contribution at mid-rapidity with tail of remnants.
- At high energy (LHC) only strings at mid-rapidity (baryon free)

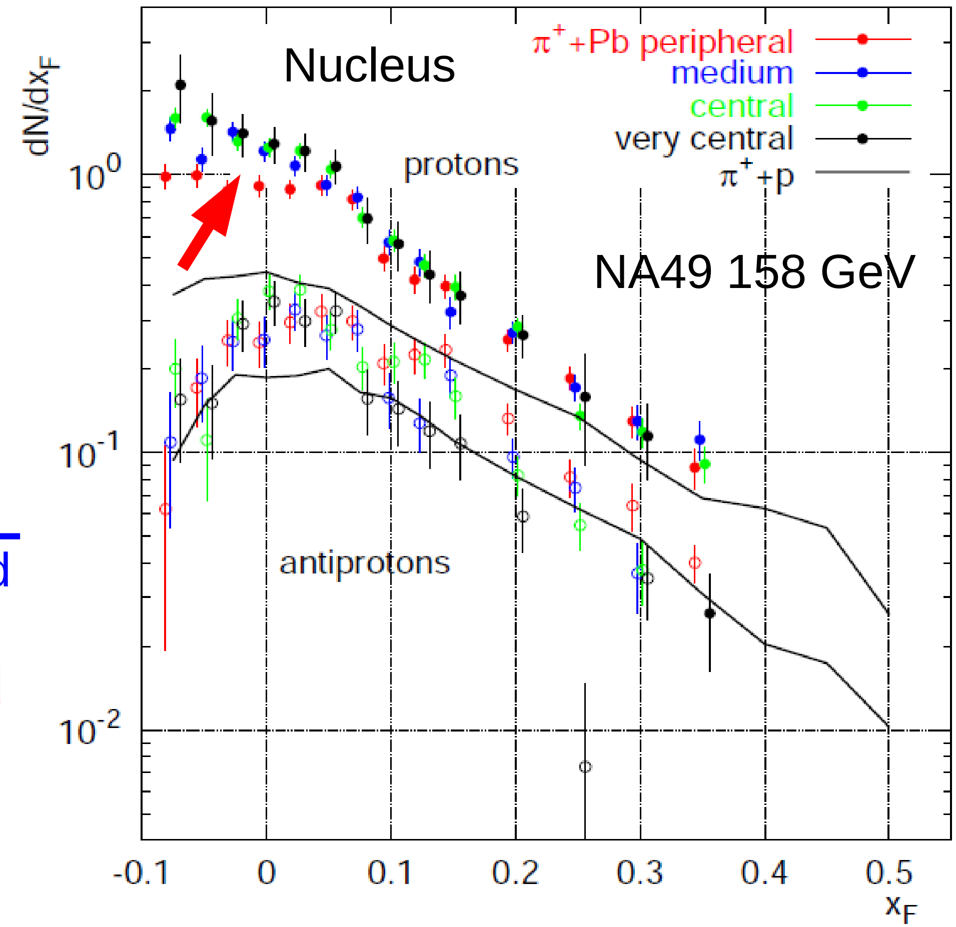
Different contributions of particle production at different energies or rapidities

Leading Particle Effect

Remnant (leading particle) effect

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

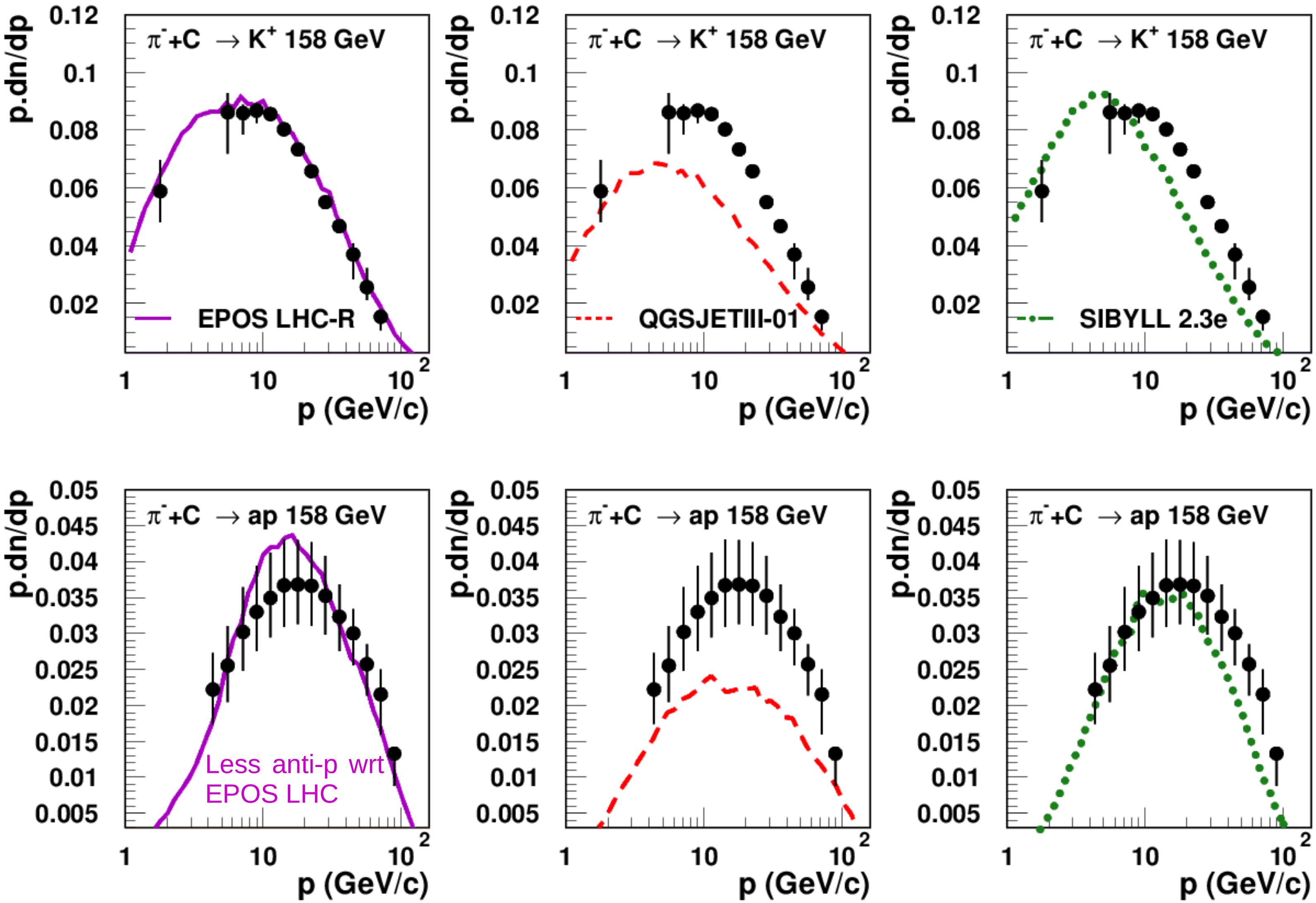




Kaons and Baryons

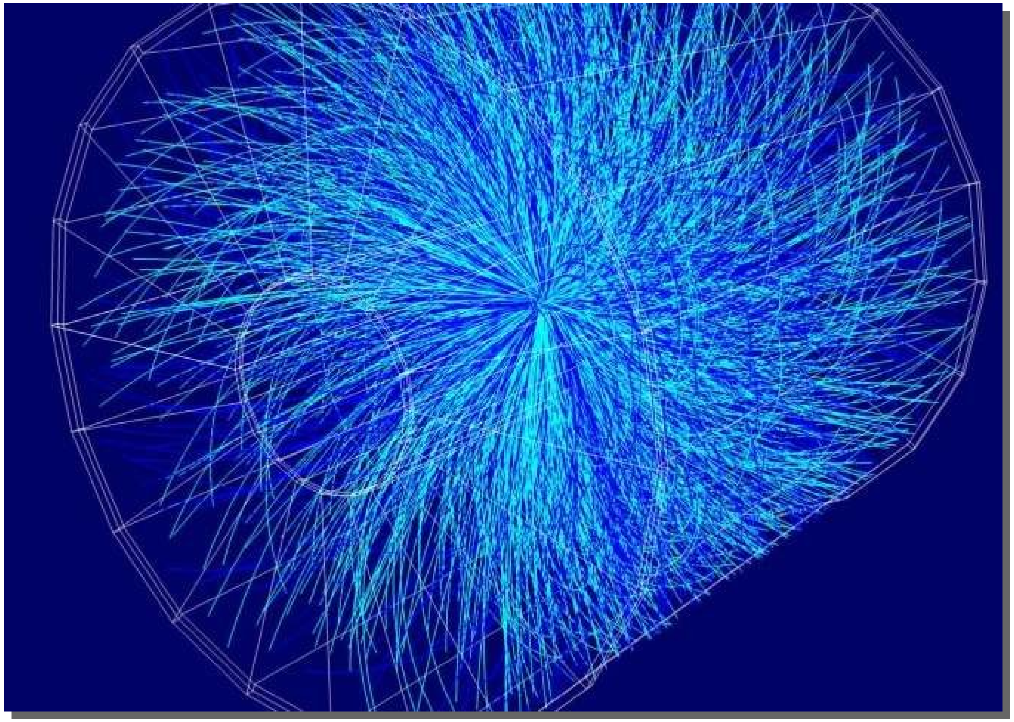
Only EPOS properly reproduce NA61 data (and many others)

➡ QGSJETIII not flexible enough !

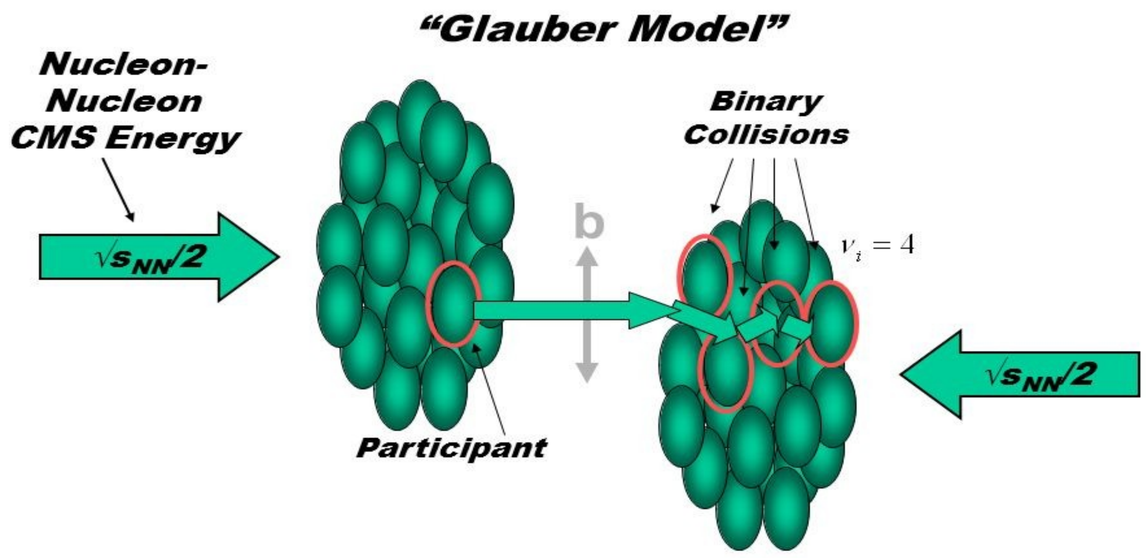


Nucleus Interactions

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

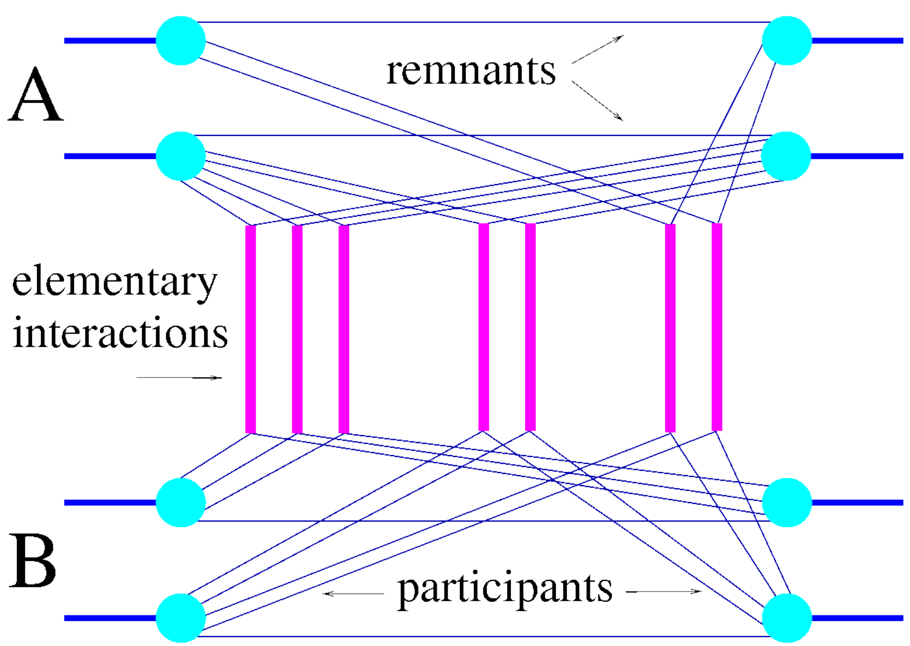


Nucleus Interactions



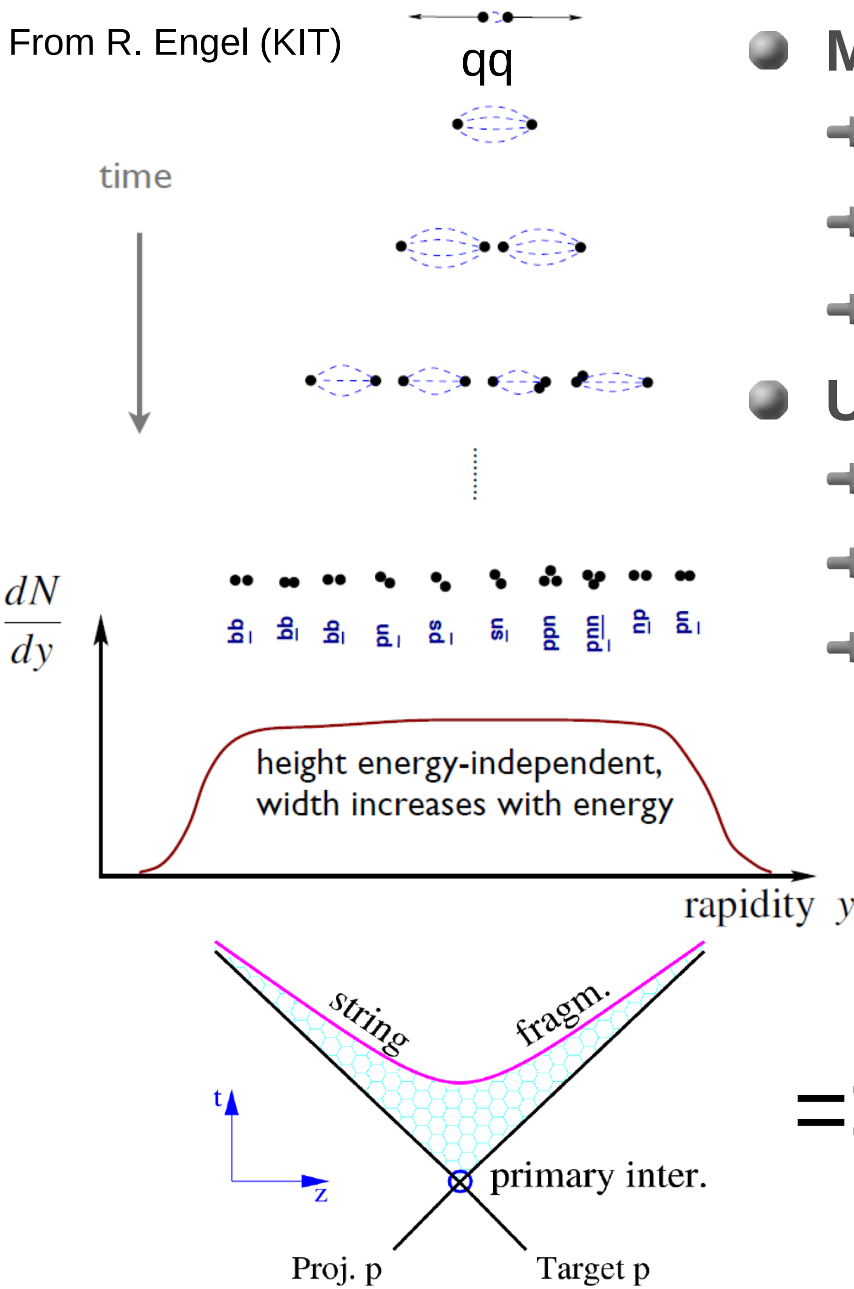
- **Glauber model**
  - Simple non-coherent approach
  - all collisions taken independently
  - works well for rare hard processes which will happen only once per participant
  - cross-section calculation with some corrections

- **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



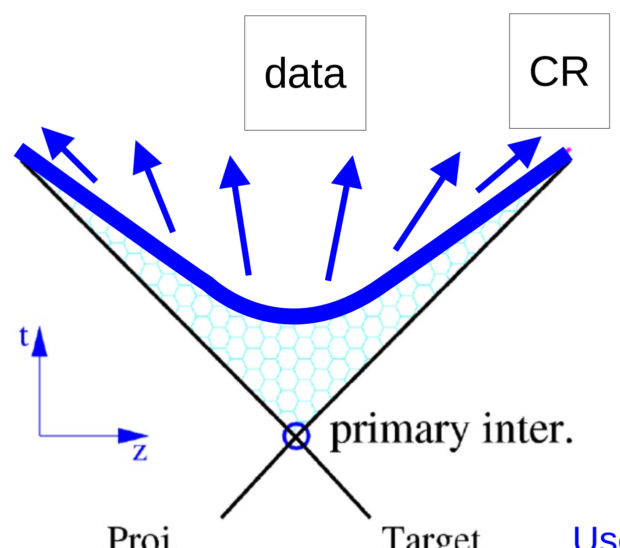
Cosmic Ray Models (Sibyll and QGSJET)

From R. Engel (KIT)



- **Models optimized for EAS simulations**
  - ➡ Fast
  - ➡ Focus on observables a priori important for EAS
  - ➡ Minimum parameter set for predictive power
- **Universal scheme for particle production**
  - ➡ String fragmentation
  - ➡ Tuned on p-p, h-A and A-A data (A small)
  - ➡ Reasonable description of averaged quantities

=>



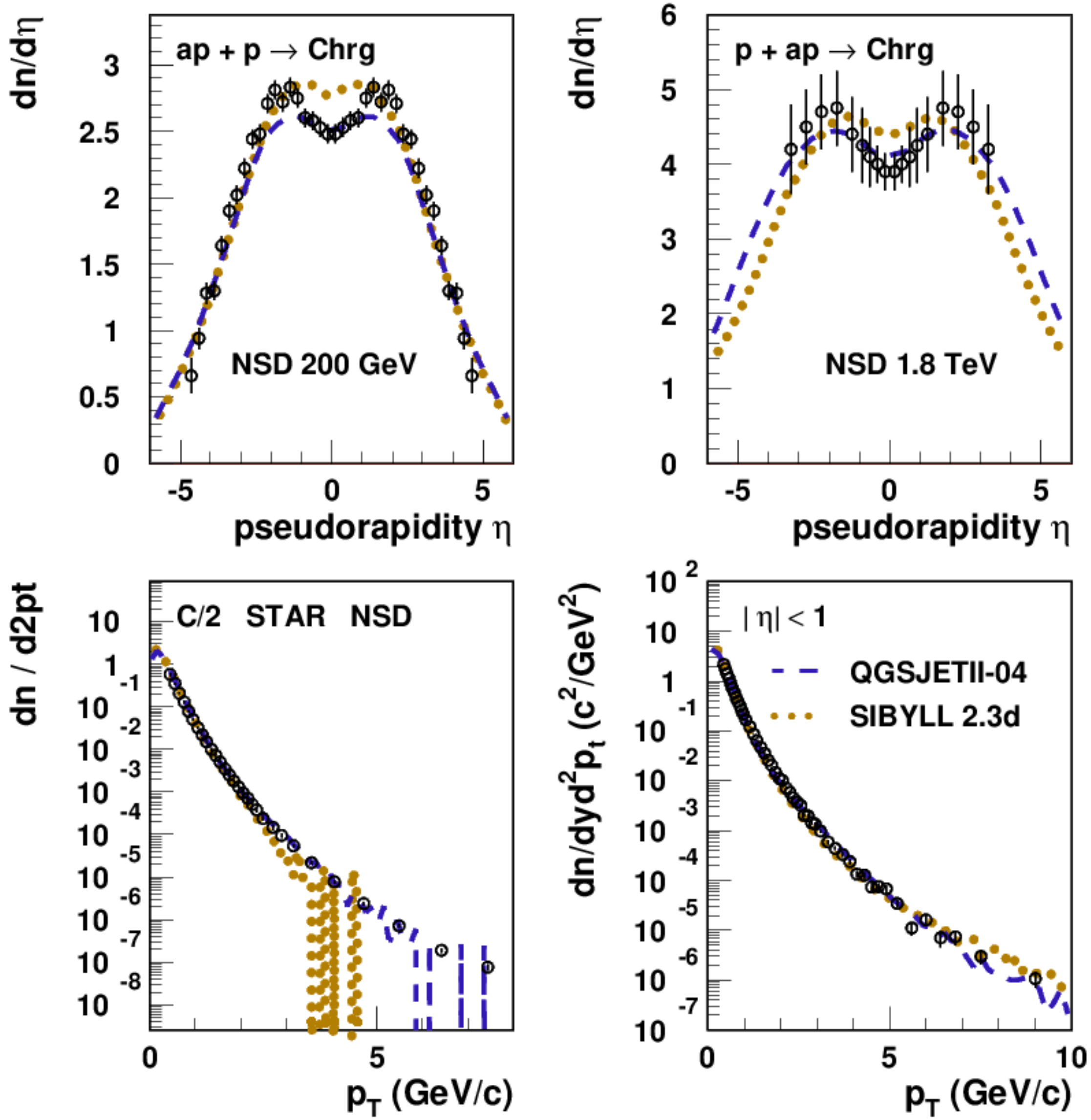
Particles produced uniformly

(Superposition of strings in pp-pA-AA → number of strings increases with energy and mass)

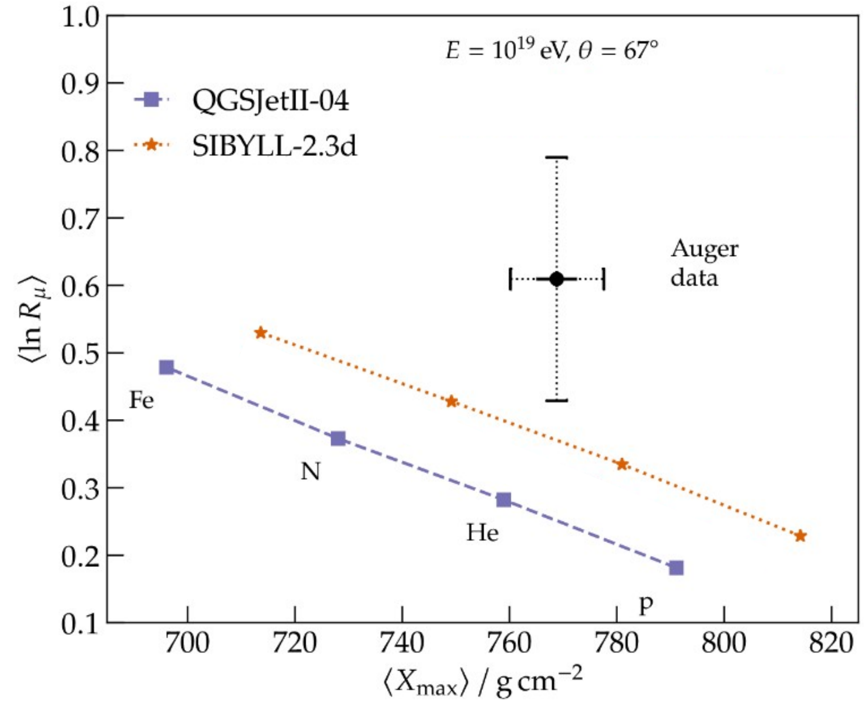
Used in dilute systems = CORONA

Problem with EAS: “muon puzzle”

Reasonable accelerator data description



Auger Coll.,
Phys. Rev. Lett. 2021



- Deficit of muons in simulations for a given mass
- Inconsistent description of EAS data (different primary CR masses from different observables)

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 ...)

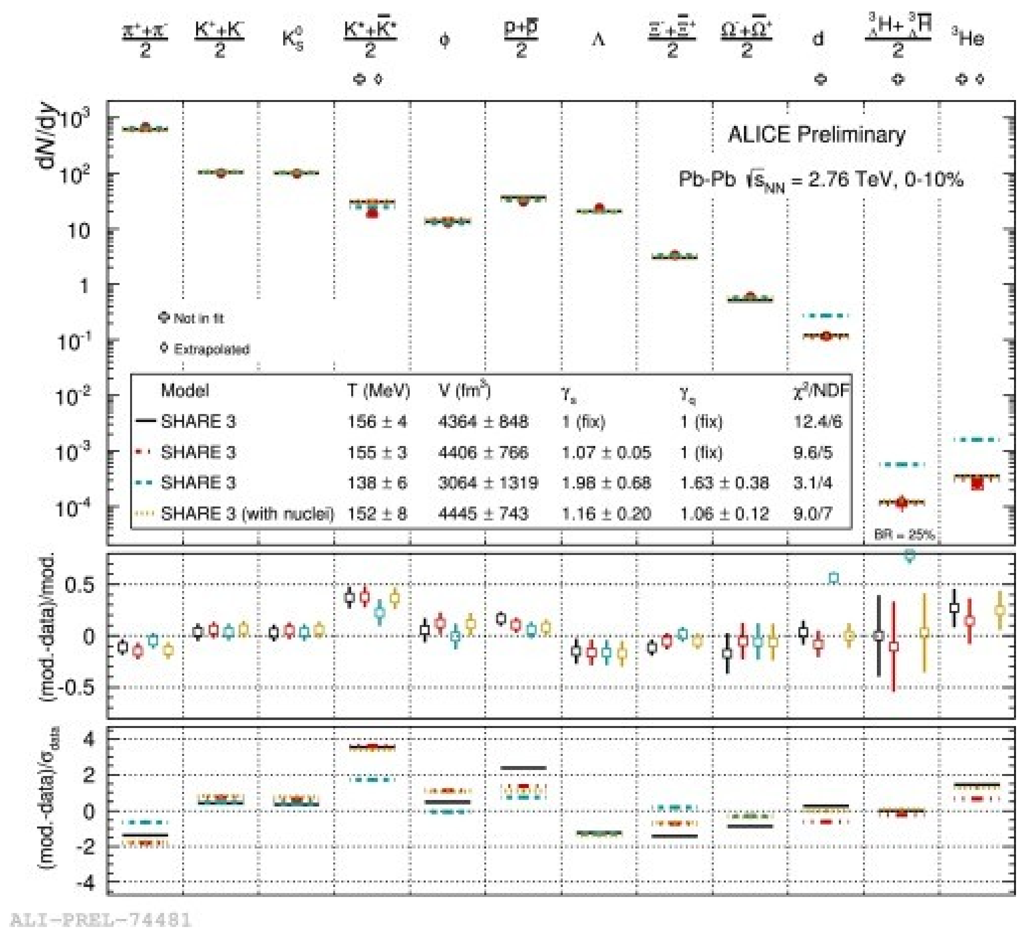
LHC pp results: first signs for collective behavior as well … ?

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 ?)

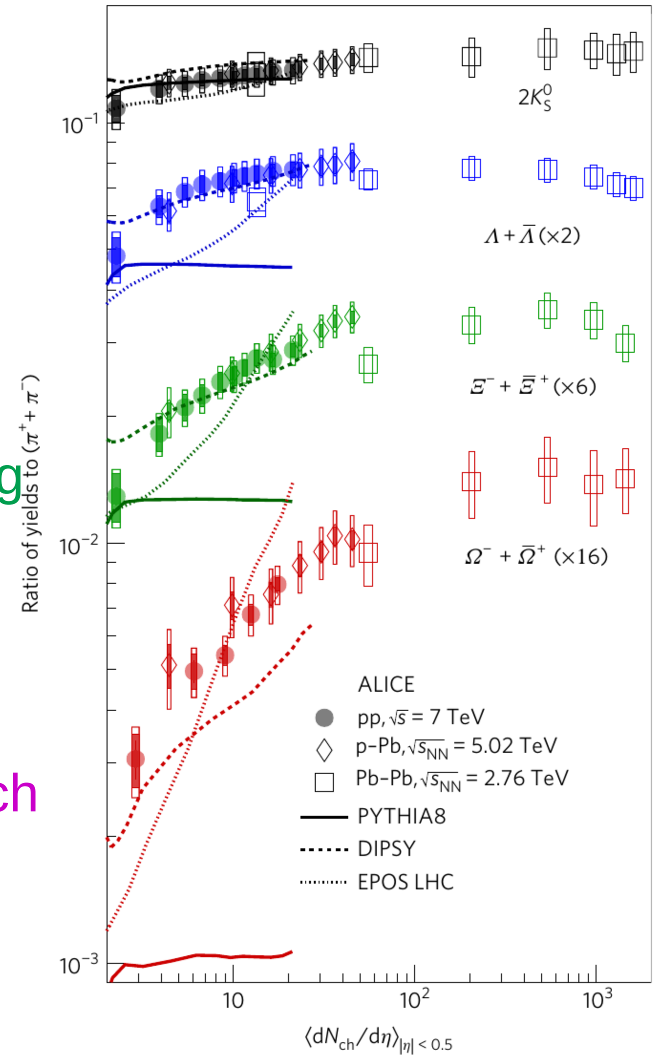


Main Result of the LHC

A lot of data from LHC* to confirm the Standard Model, but the most important (for me) :

Nature Letters DOI: 10.1038/NPHYS4111

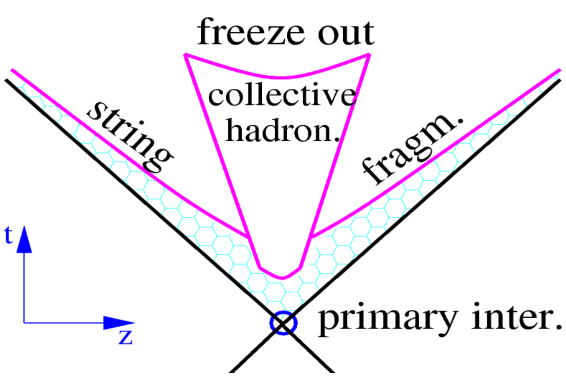
- New point of view on particle production
- Continuity in particle ratio evolution between pp, pPb and PbPb
- With LHC, heavy Ion community finally meet the High Energy Physics community !
  - Pythia fails to describe the data
    - New Pythia/Angantyr to test string physics with heavy ion collisions (and then usable for EAS**)
  - Qualitative description of data by EPOS
    - Model based on a global approach from e+-e- to Pb-Pb
    - Confirmation of the core-corona model (K. Werner, 2005)



* See review talk by J. Boyd, this conference ** See C. Gaudu PoS(ICRC2025)267

Core-Corona (co-co)

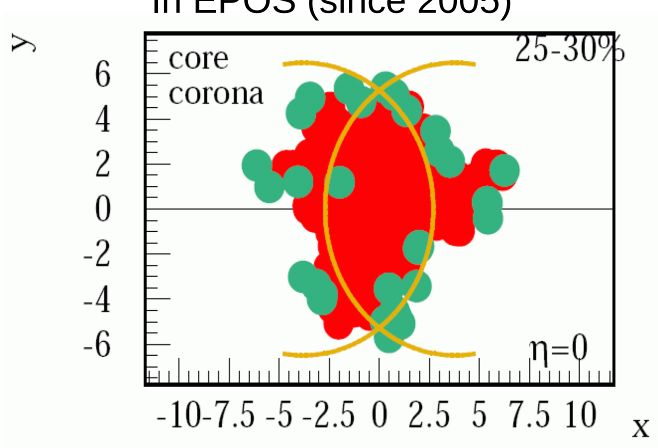
- **Core hadronization** = thermal hadronization of Quark Gluon Plasma
- **Mixing of core and corona hadronization (string) needed to achieve detailed description of p-p data** (K.Werner, Phys.Rev.C 109 (2024) 1, 014910)
  - Evolution of particle ratios from pp to PbPb
  - Particle correlations (ridge, Bose Einstein correlations)
  - Pt evolution, …
- **Both hadronizations are universal but the fraction of each change with particle density**



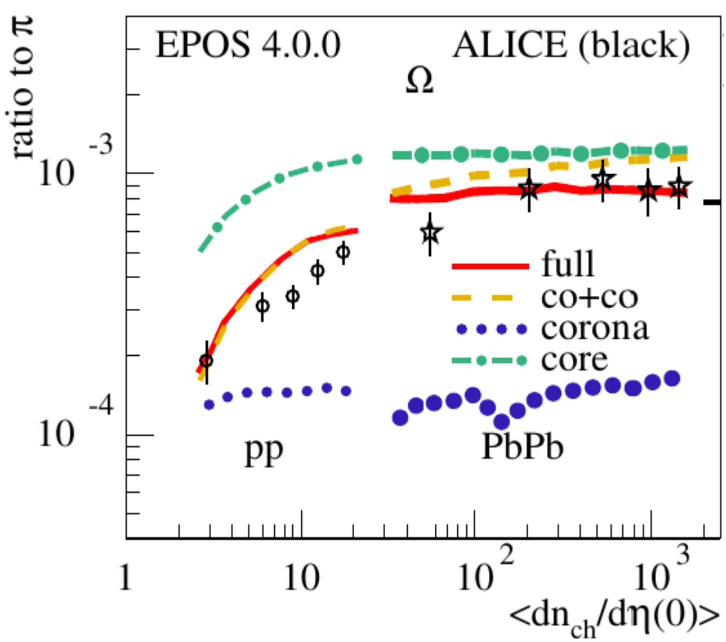
Difference high/low multiplicity

- **2 simultaneous source of particles**

In EPOS (since 2005)



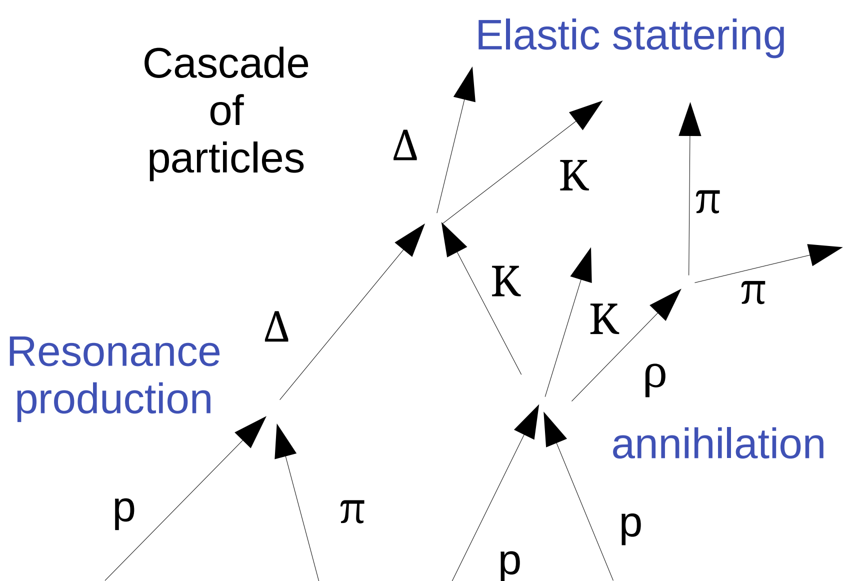
p-p ,Pb-p, Pb-Pb data

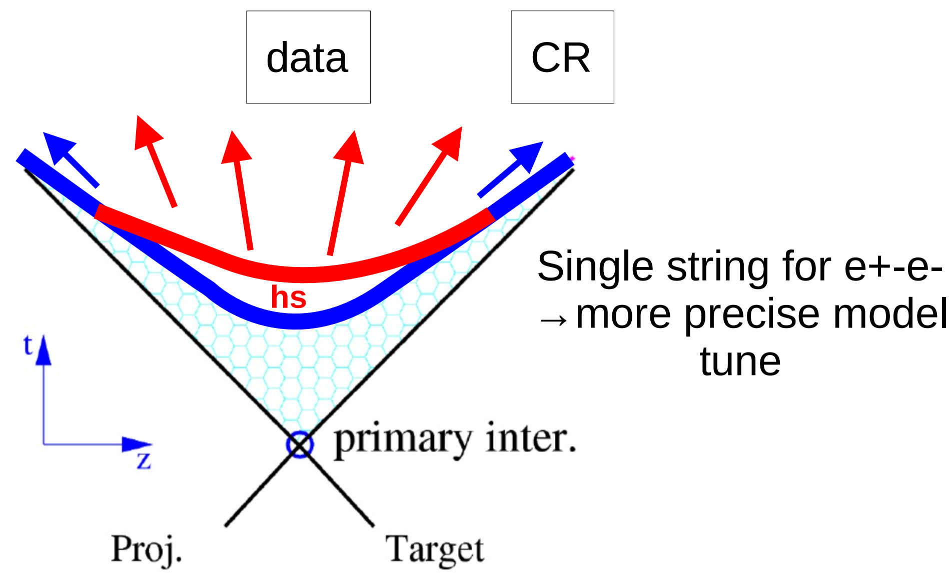


Hadronic reScattering (HS)

Important effect when particles are close to each others

- Re-interaction of hadrons* after parton hadronization (space-time evolution)
- “traditionally” used only for heavy ion collisions (even NOT in pp until recently)
- Impact “slow” particles at mid-rapidity more than “fast” forward particles
- Significant to large impact at midrapidity in heavy ion collisions !
    - Applied to all system (from e+-e- to PbPb) now !





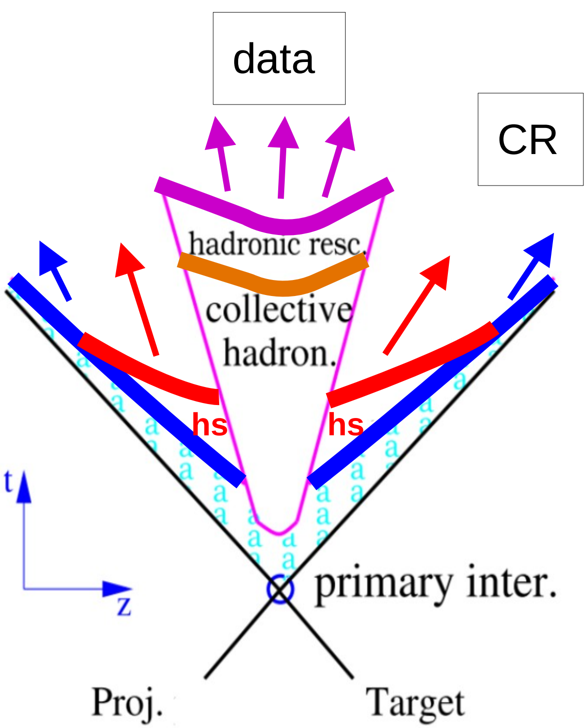
Difference small/large rapidity (emission angle)

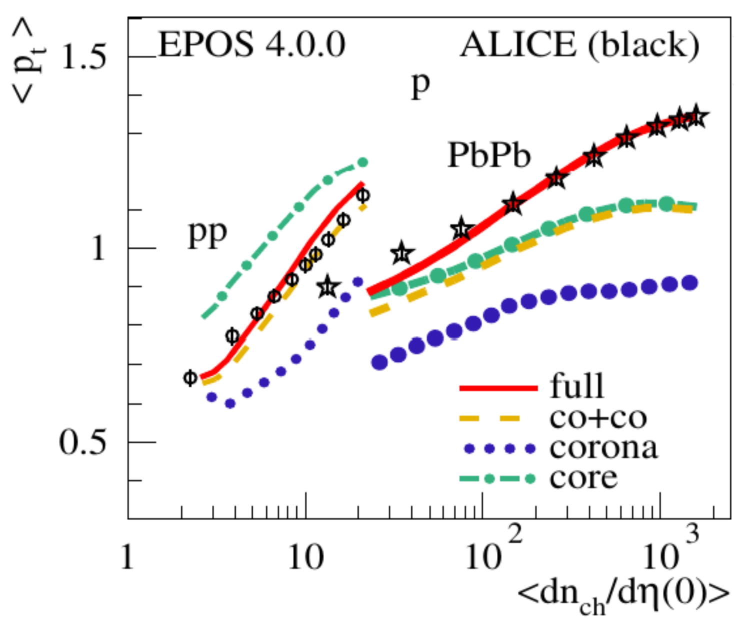
* using UrQMD 3.4, Bleicher at al., J.Phys. G25 (1999) 1859

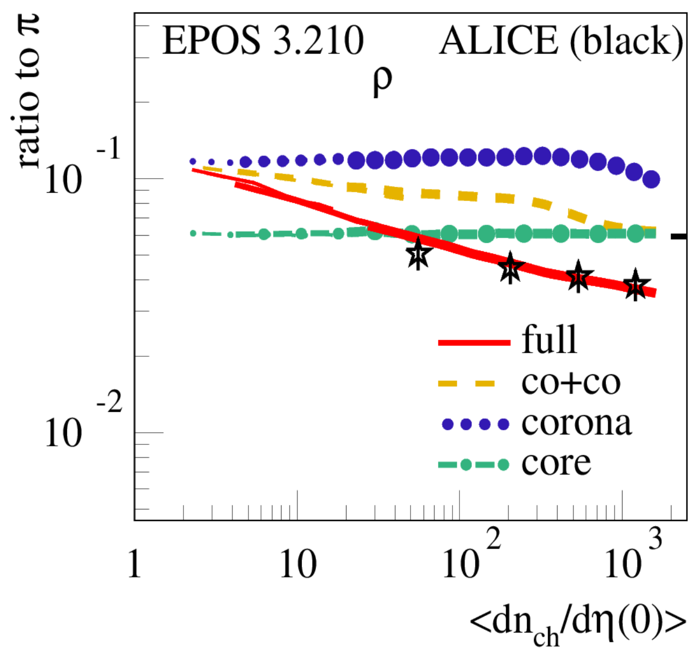
Global Approach

Collective effects are important to tune properly the models !

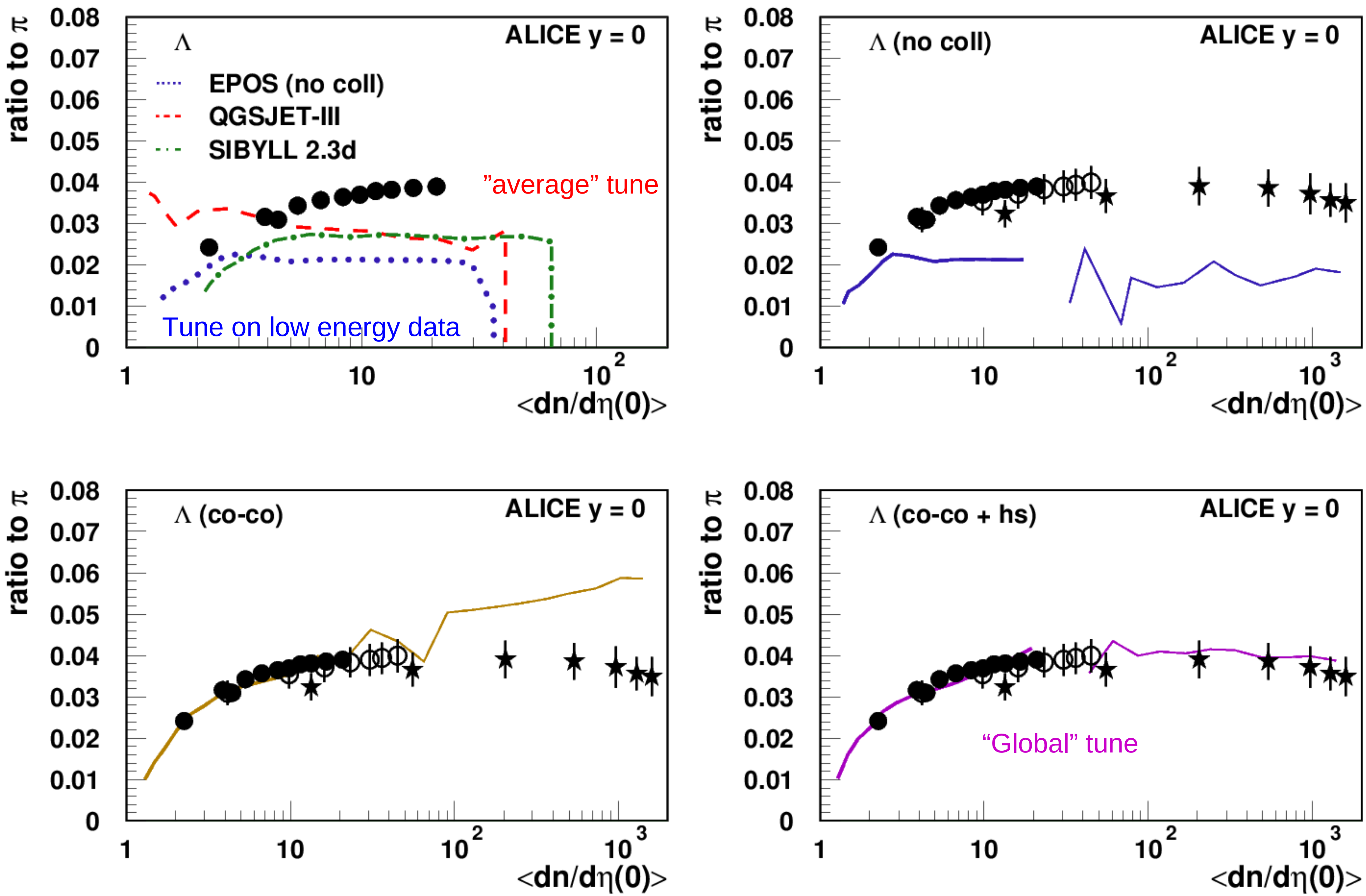
- Change multiplicity/elasticity and hadronization depending on particle density
  - Introduce energy + centrality dependence in accelerator data comparisons
  - Modify model parameters
    - Multiple mid-rapidity particle production mechanisms
- Change particle ratios in string fragmentation depending on phase-space
    - Forward particle production not the same than at mid-rapidity







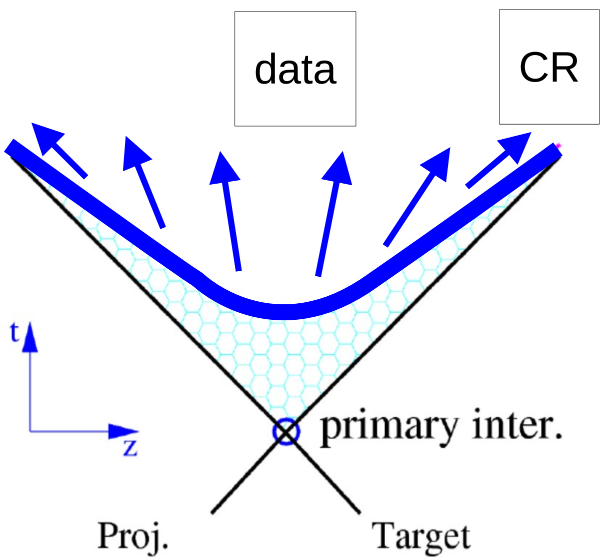
Example: Lambda particle in p-p and Pb-Pb @ LHC



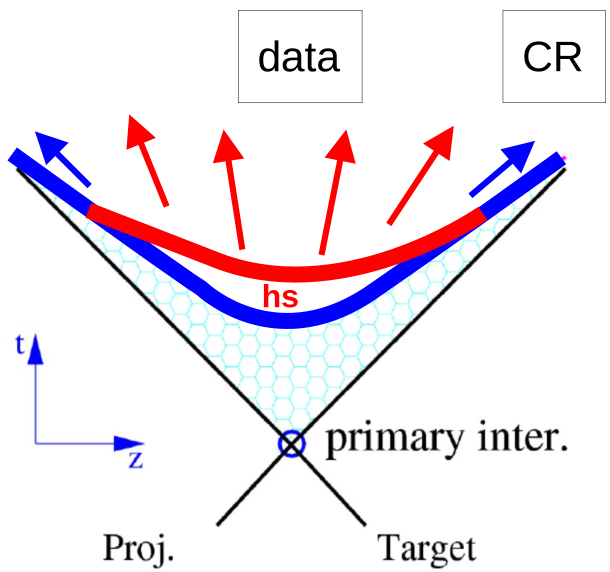
What did we learn ?

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

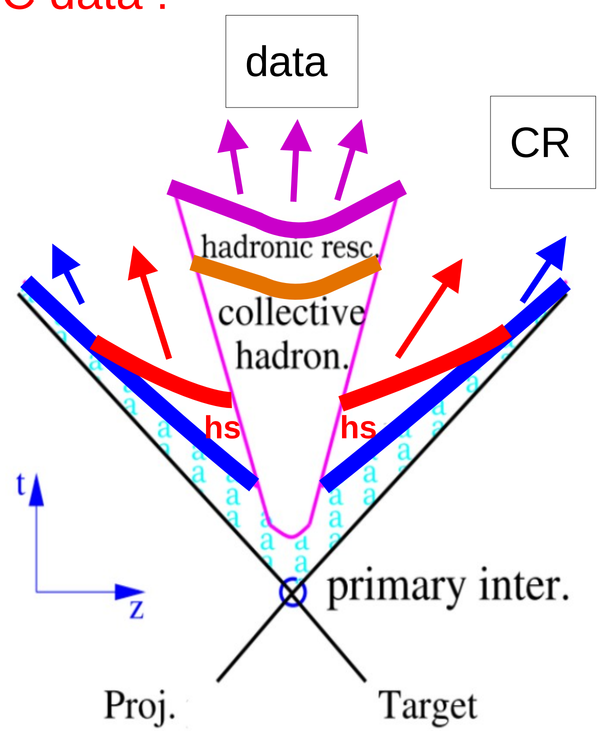
- New point of view on particle production
- Good description achieved with core/corona + hadron rescattering (hadron gas)
  - Same physics for all systems but different mixtures of the 2 components (low + high energy density hadronization)
  - Important paradigm for CR models : uniformity of **forward/midrapidity** hadronization and **high/low energy** is **broken** by LHC data !



No collective effects



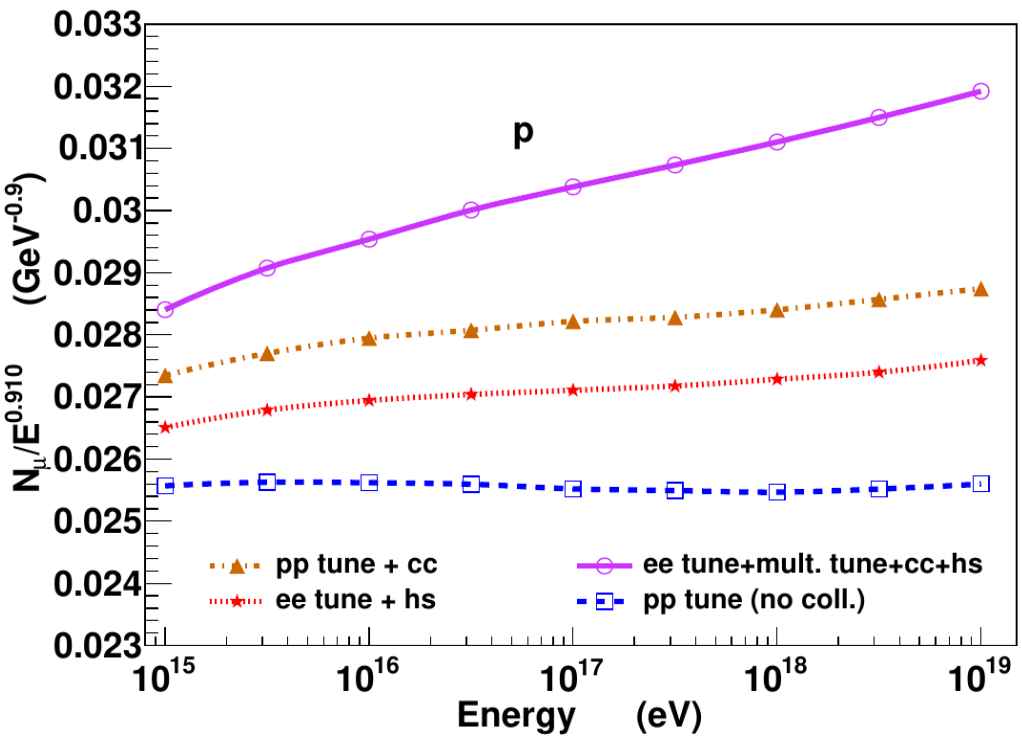
Hadronic reScattering (hs)

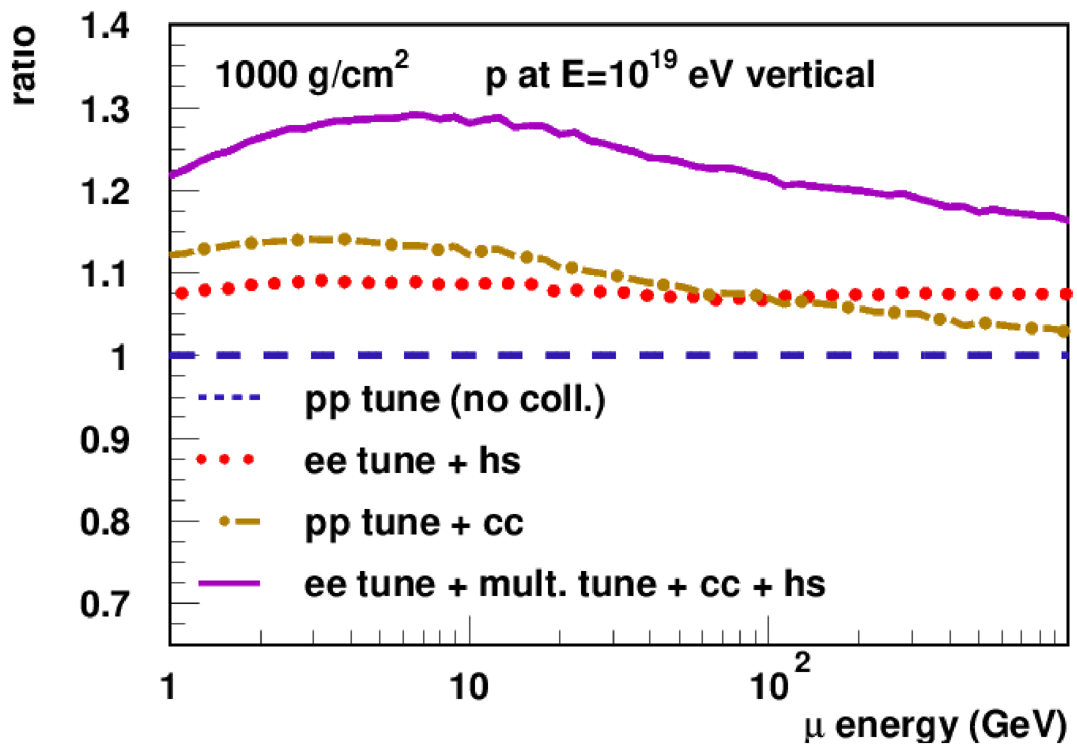


Impact on Air Showers

Changes with new tune taking into account collective effects (LHC)

- Increase the number of muons by ... 10 to 20% (different slope) !
  - Impact of core-corona on baryon/strangeness prod. AND change in multiplicity/elasticity to accommodate hydrodynamical evolution (flow)
  - Impact of tune based on full LEP data with hs instead of just p-p/p-A
- Change in muon energy spectrum !
  - More baryon from core-corona (low energy μ) and more ρ^0 (all μ)



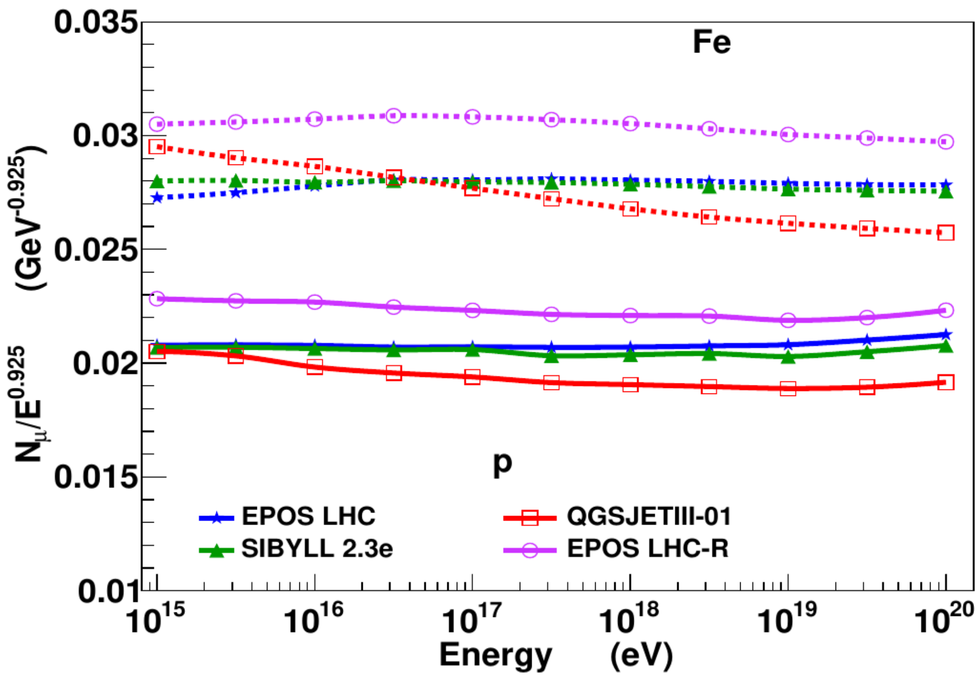


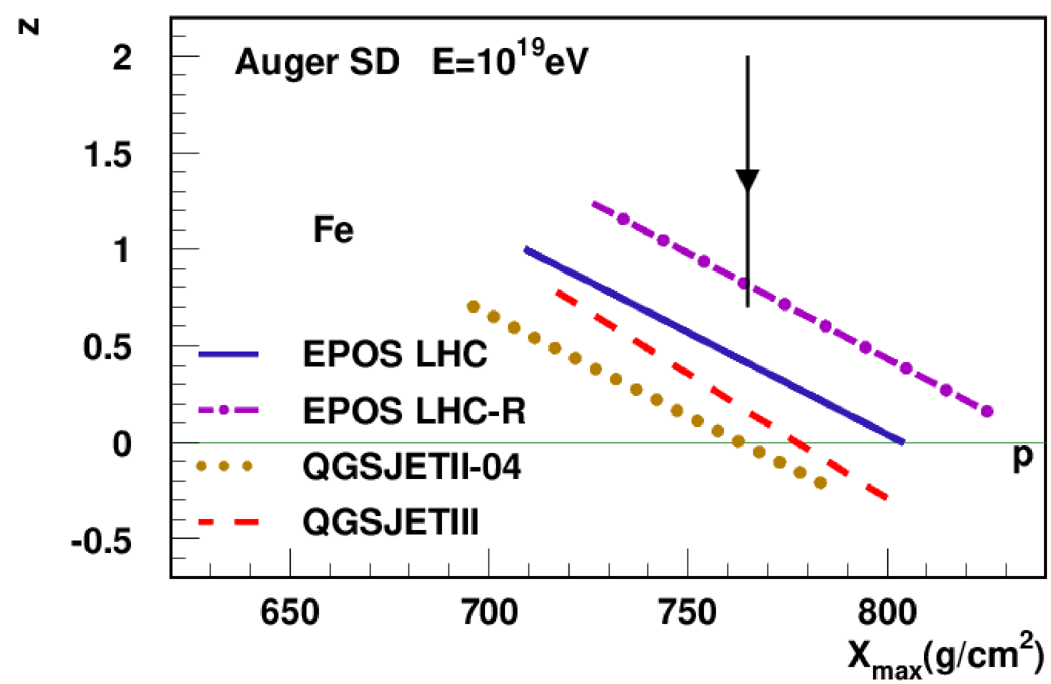
Muon Puzzle Solved ?

EPOS.LHC-R, first model producing a deeper X_{max} and more muons and being compatible with all measured accelerator data :

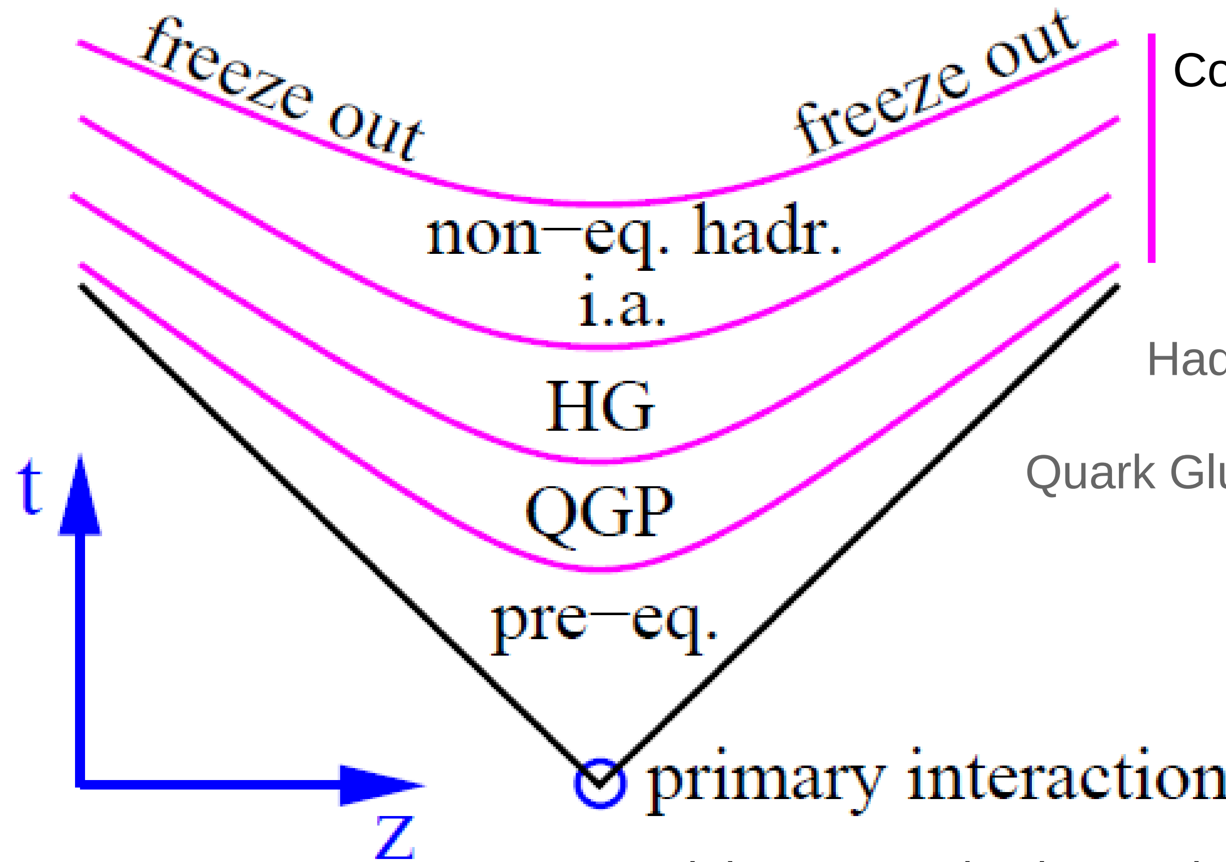
- Deeper X_{max} give larger <lnA> reducing the gap with measured muon content
- Increase of muons further decrease the gap to reach Auger systematics
- Increased number of high energy muons
- Change not large enough in QGSJET update

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





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

- **QGSJETIII**
  - S. Ostapchenko, Phys. Rev. **D109** (2024) no.3, 034002, arXiv:2401.06202 [hep-ph]
  - S. Ostapchenko, Phys. Rev. **D109** (2024) no.9, 094019, arXiv:2403.16106 [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]
- **EPOS.LHC-R**
  - T. Pierog at al., PoS(ICRC2025)358 (2025)
- **EPOS LHC**
  - T. Pierog at al., Phys. Rev. **C92** (2015) 034906 arXiv:1306.0121 [hep-ph]

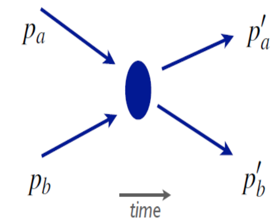
References for High Energy Models (old)

- **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

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



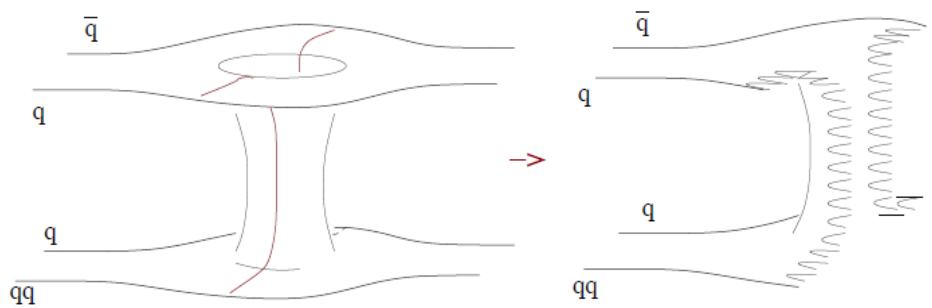
Lorentz-invariant description with Mandelstam variables

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

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

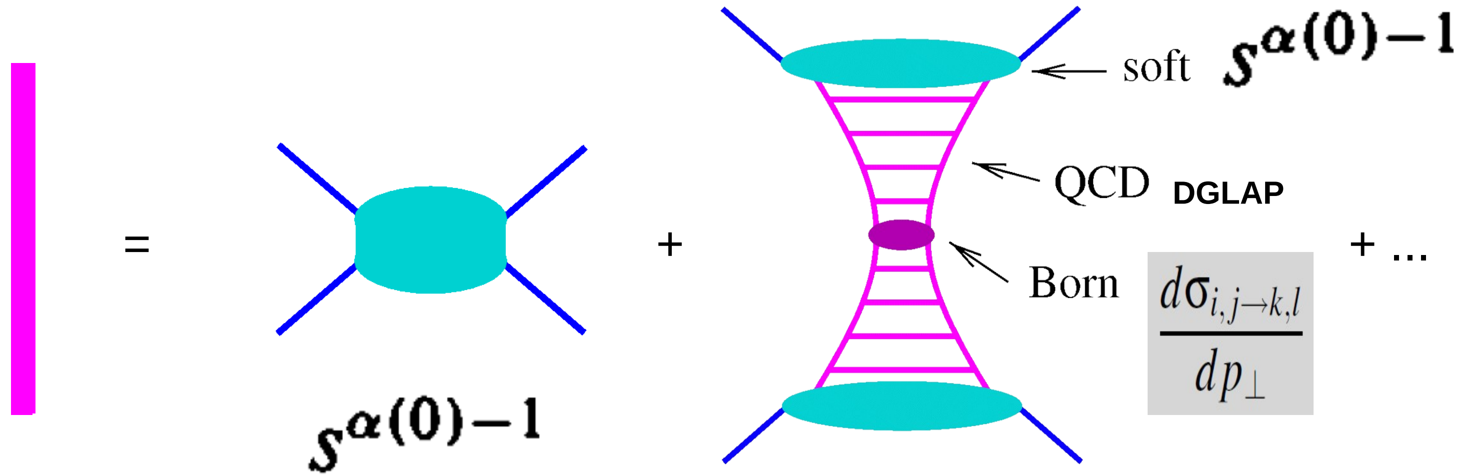
- Quasi-particle that effectively accounts for all exchanged hadronic states
- Amplitude exhibits power-law dependence on energy
- Regge trajectory of Pomeron: exchanged particles might be glue balls ($\alpha(t)$)
- Pomeron trajectory only phenomenologically known
- Large N_c-n_f approximation of QCD: 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

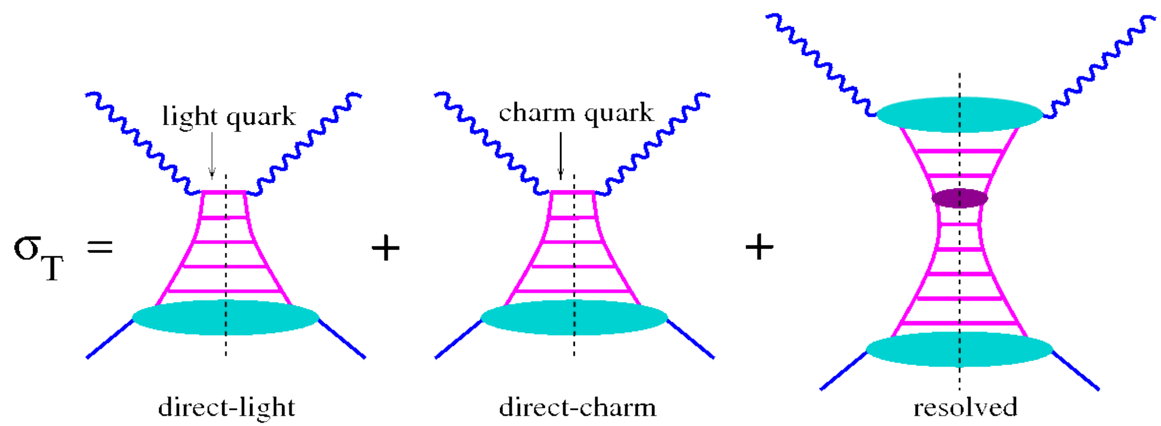


Pomeron in Models

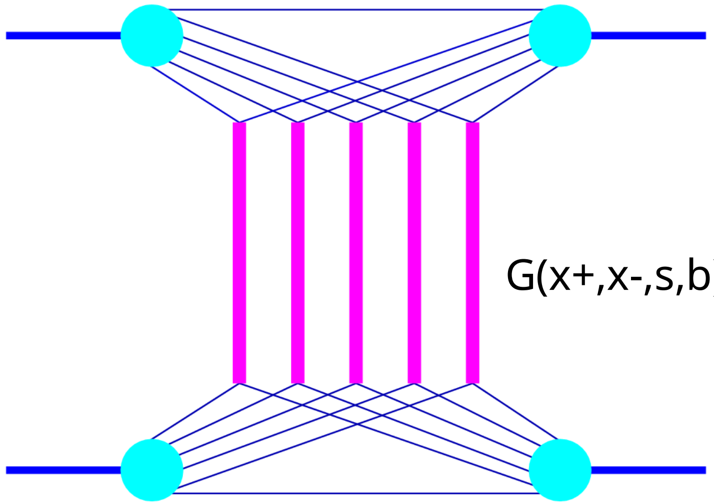
Semi-hard Pomeron :



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



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

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

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

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 :

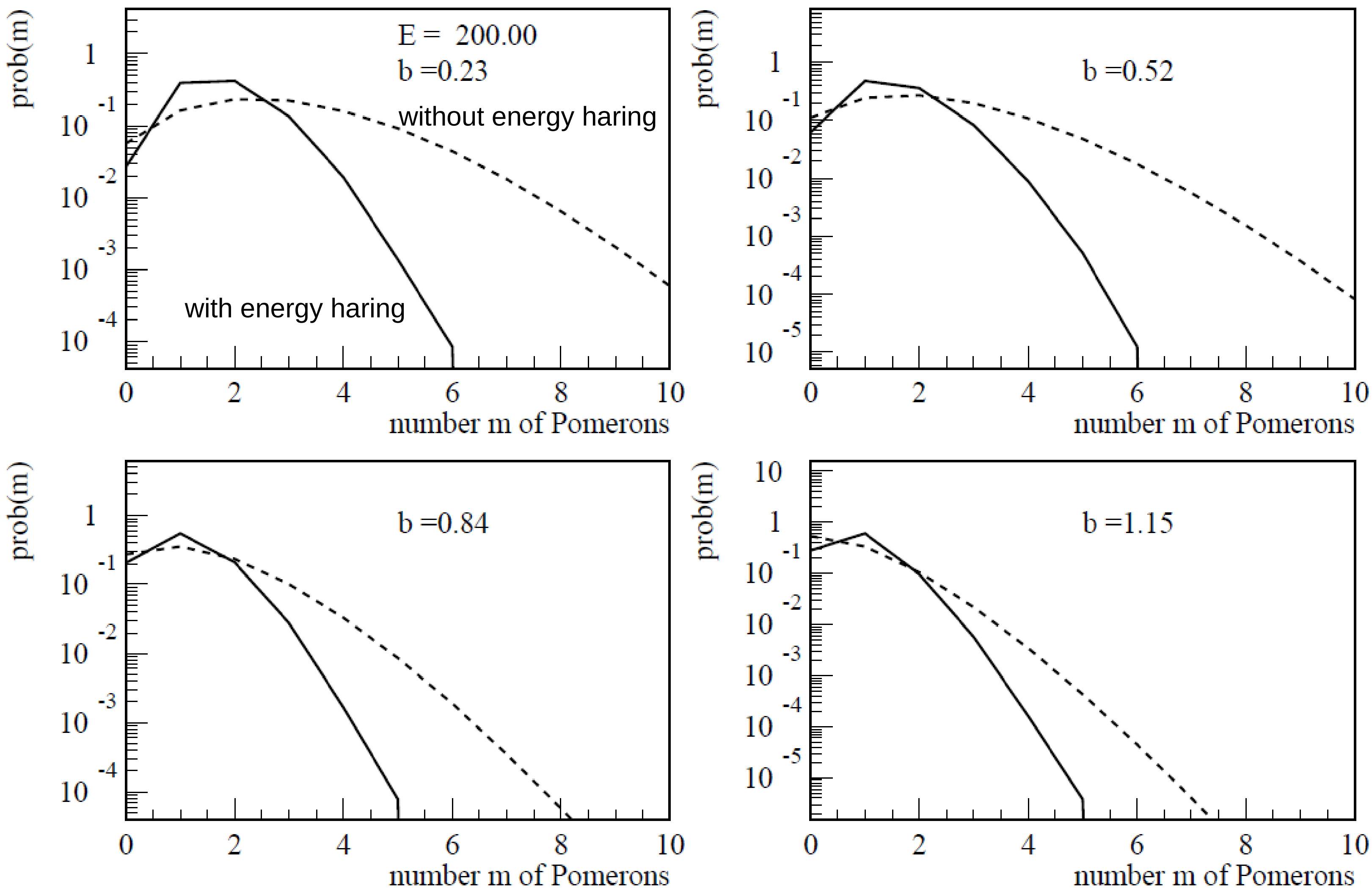
$$\Omega_{AB}^{(s,b)}(m, X^+, X^-) = \prod_{k=1}^{AB} \left\{ \frac{1}{m_k!} \prod_{\mu=1}^{m_k} G(x_{k,\mu}^+, x_{k,\mu}^-, s, b_k) \right\} \Phi_{AB}\left(x^{\text{proj}}, x^{\text{targ}}, s, b\right)$$

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

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

Number of cut Pomerons

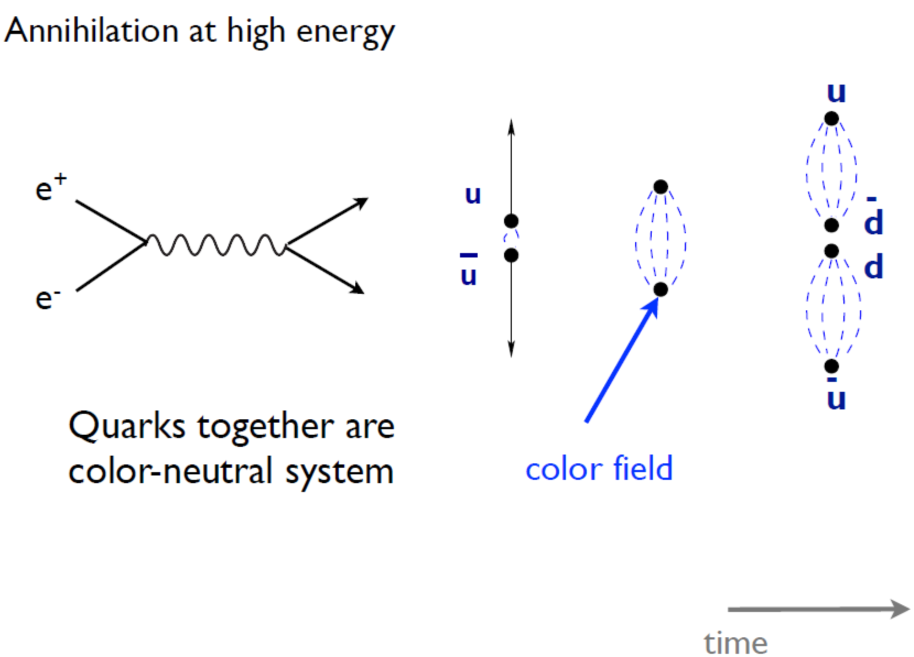
Fluctuations reduced by energy sharing (mean can be changed by parameters)

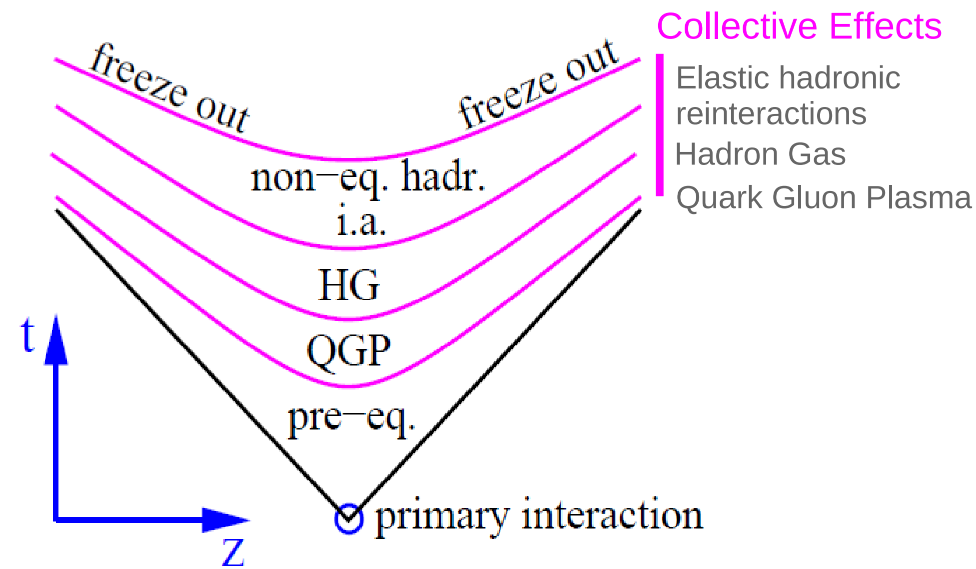


Hadronization Models

2 models well established for 2 extreme cases

- String Fragmentation vs Collective hadronization (statistical models)





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

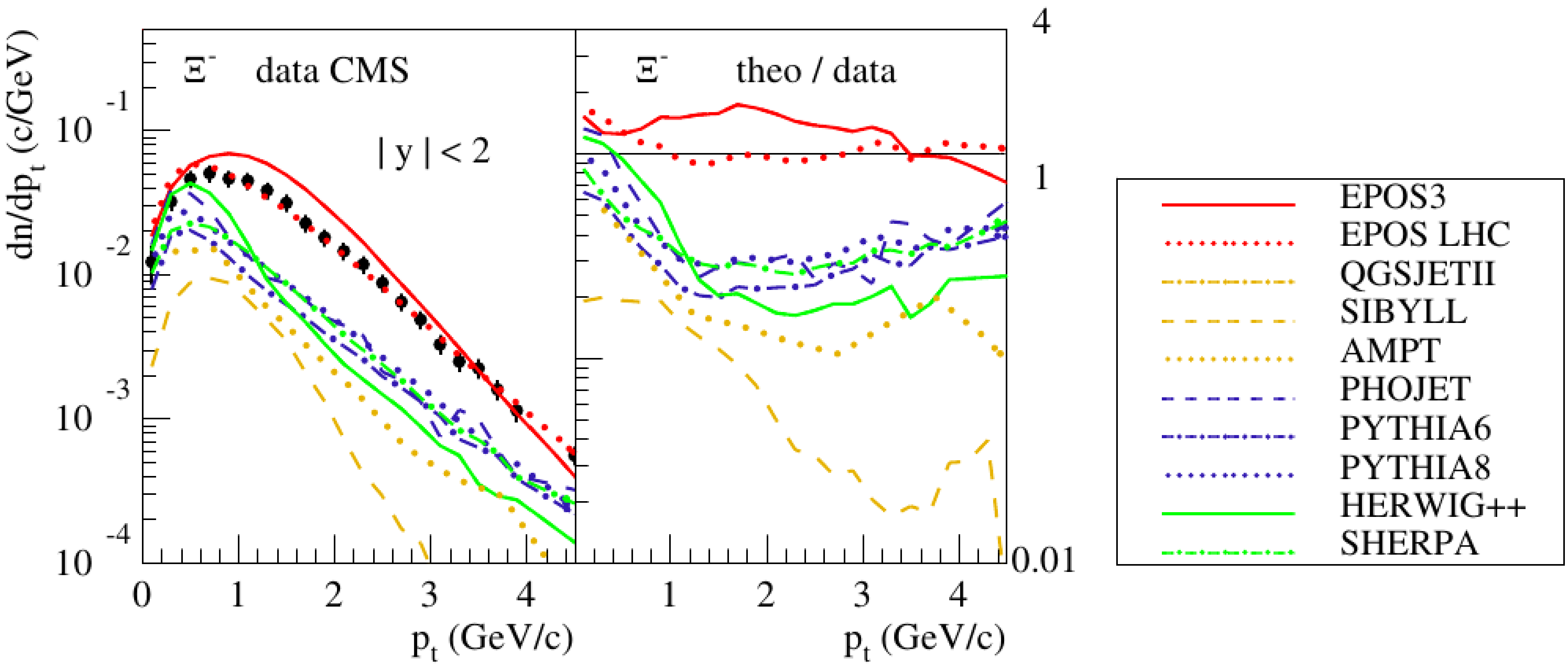
In dense systems… CORE
→ "low" π^0 fraction

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

Global Approach : EPOS

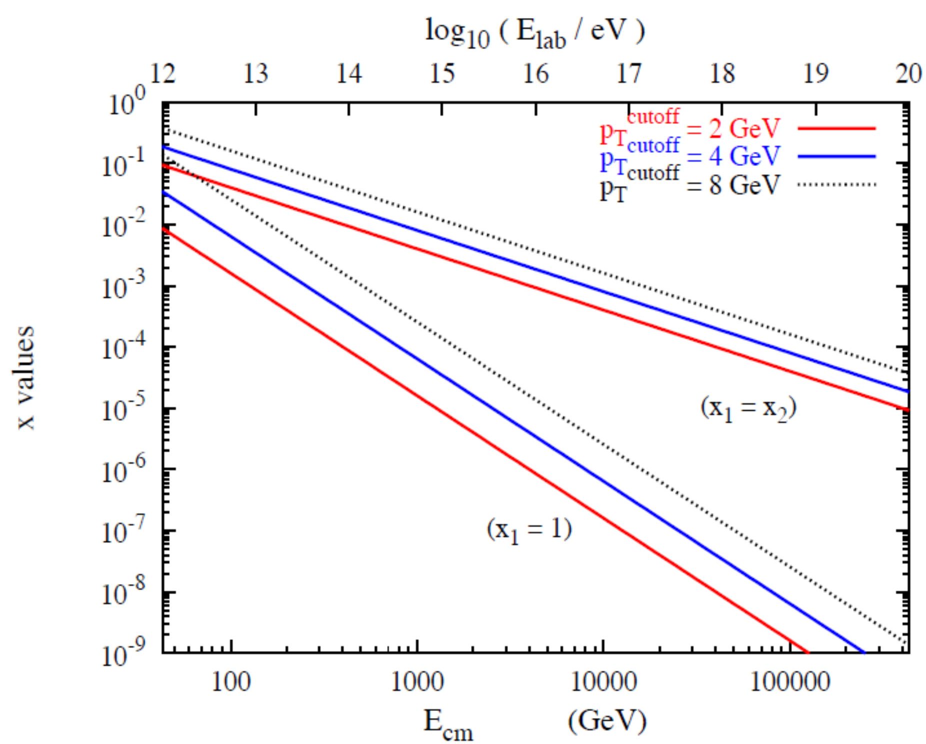
Detailed description can be achieved

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

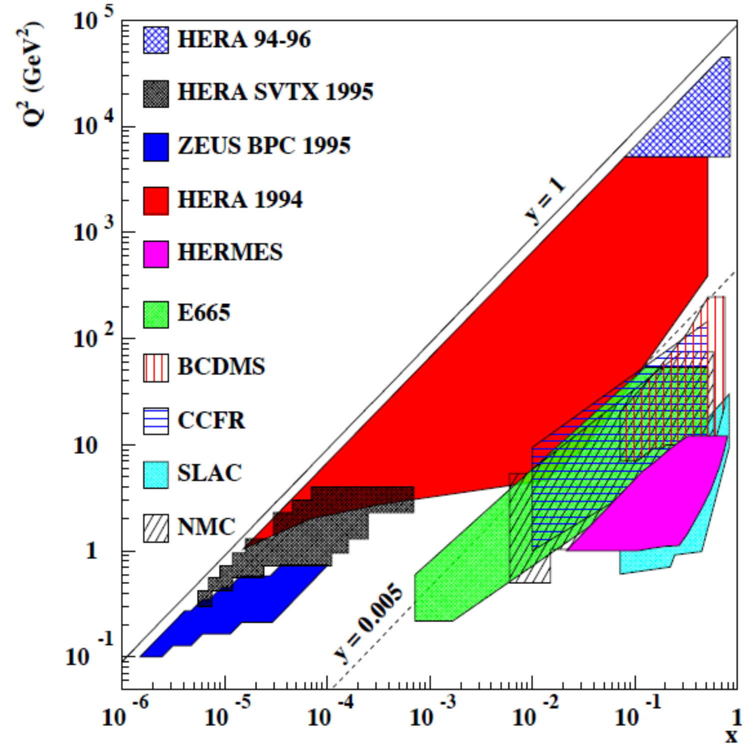


Parton densities not known at very low x

Range of x values (momentum fractions)
needed in calculation

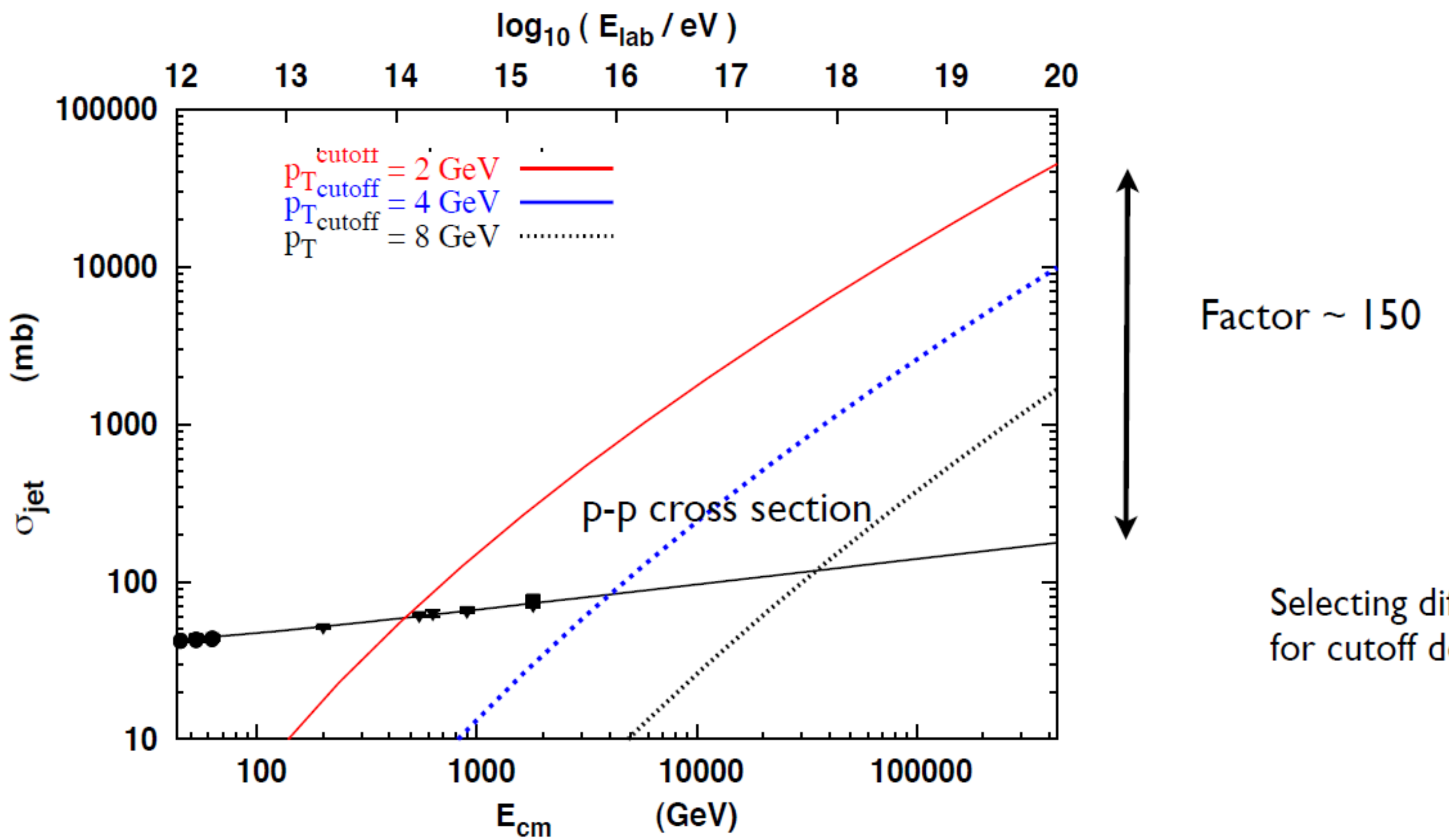


HERA measurement range



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

Dependence on transverse momentum cutoff

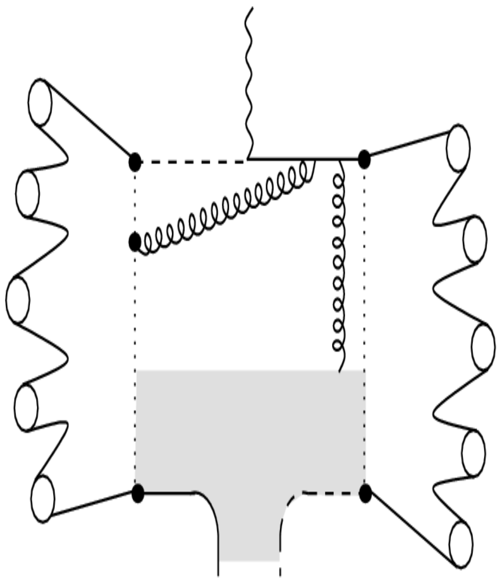


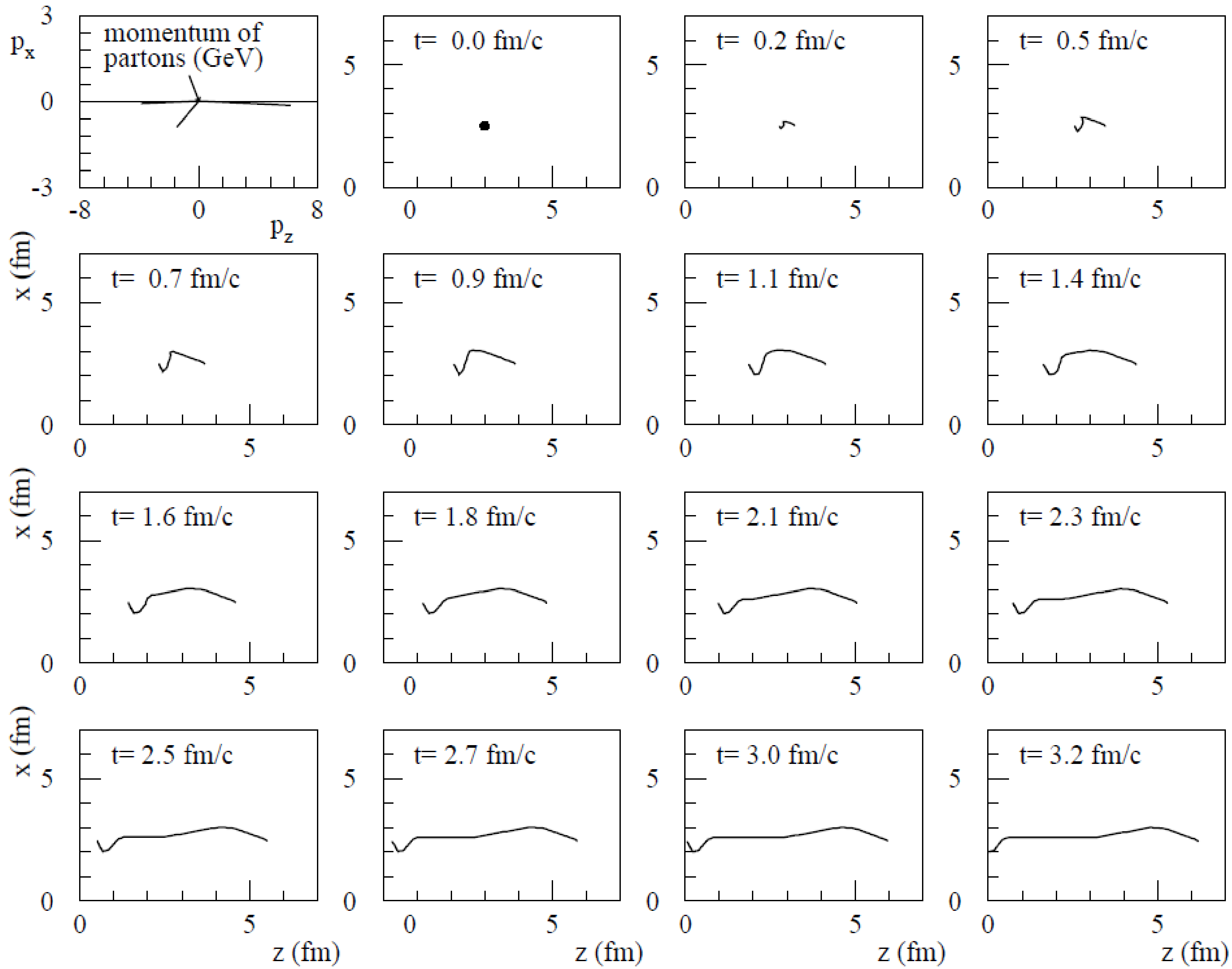
Selecting different values for cutoff does not help

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 ?

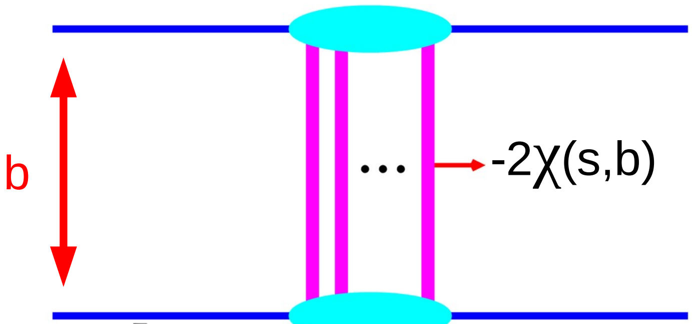
- **In principle yes but …**
  - Only EPOS (Pythia) uses LEP data
    - Without remnant and statistical hadronization of high density regions (Pythia) : NO
    - If everything is taken into account : YES (it seems ...)
  - QGSJET and SIBYLL use hadronic interaction data at low energy to fix parameters 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 :

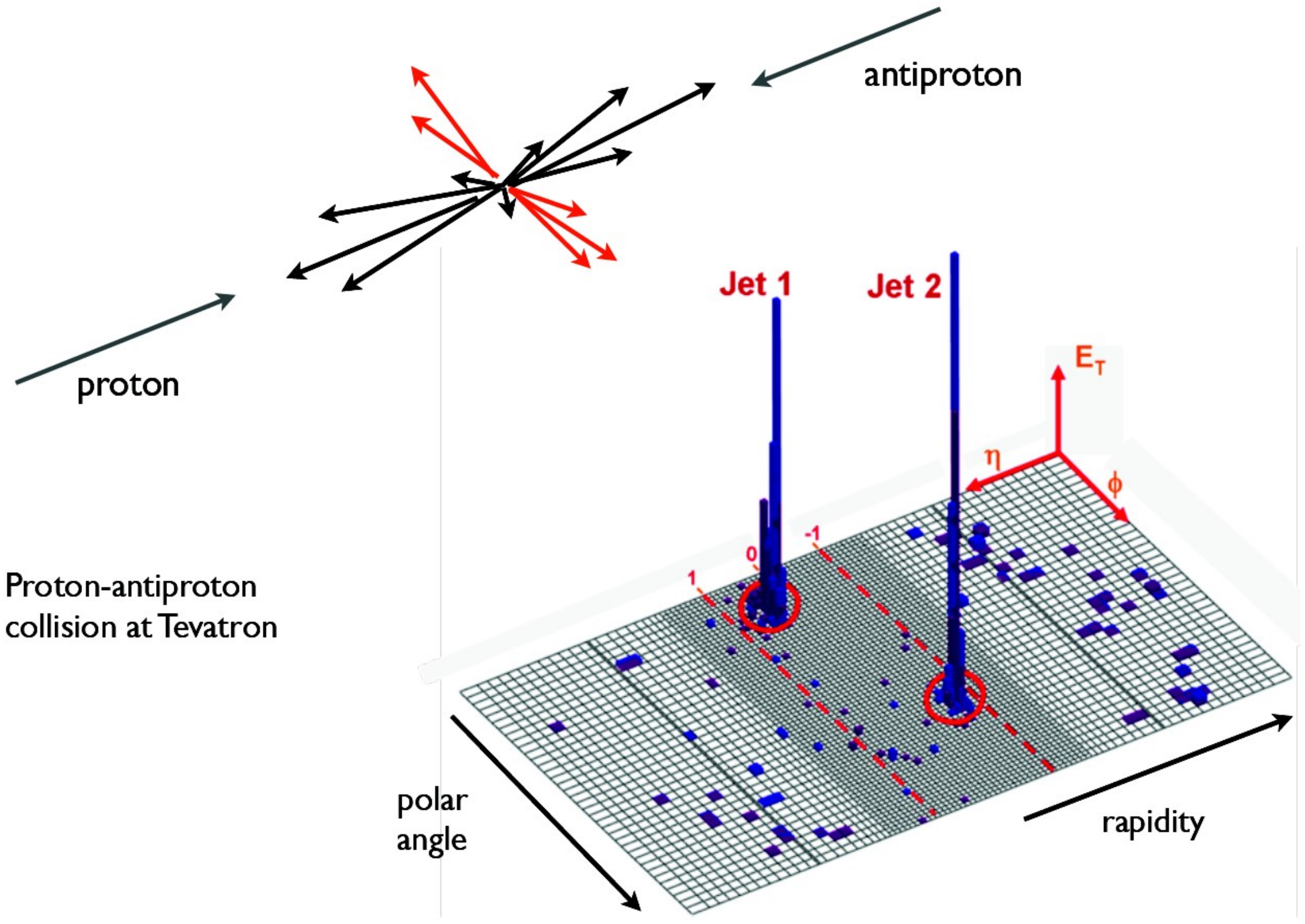
$$P(n)=\frac{(2\chi)^{n}}{n!}.\exp(-2\chi)$$

  - 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

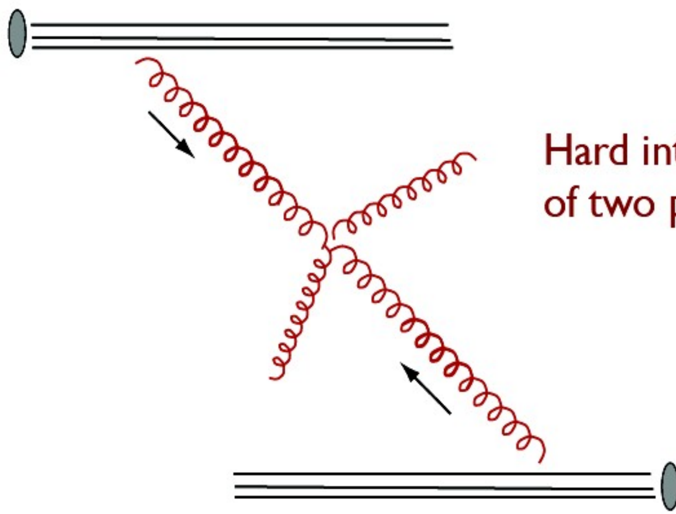
- inconsistency : energy sharing should be taken into account when fixing n

  - alternative approach with energy conservation from the beginning (EPOS)

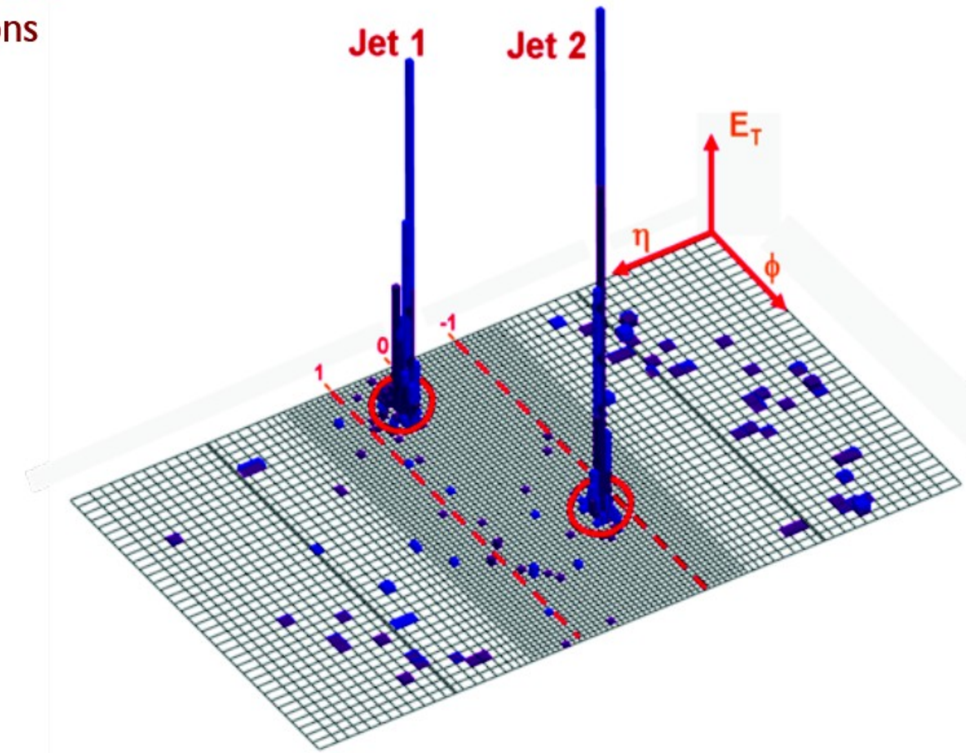
Scattering of quarks and gluons: jet production



Interpretation within perturbative QCD



Hard interaction
of two partons



QCD predictions known
for parton-parton cross sections

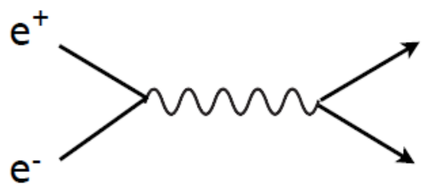
Terminology

Soft interaction: no large momentum transfer

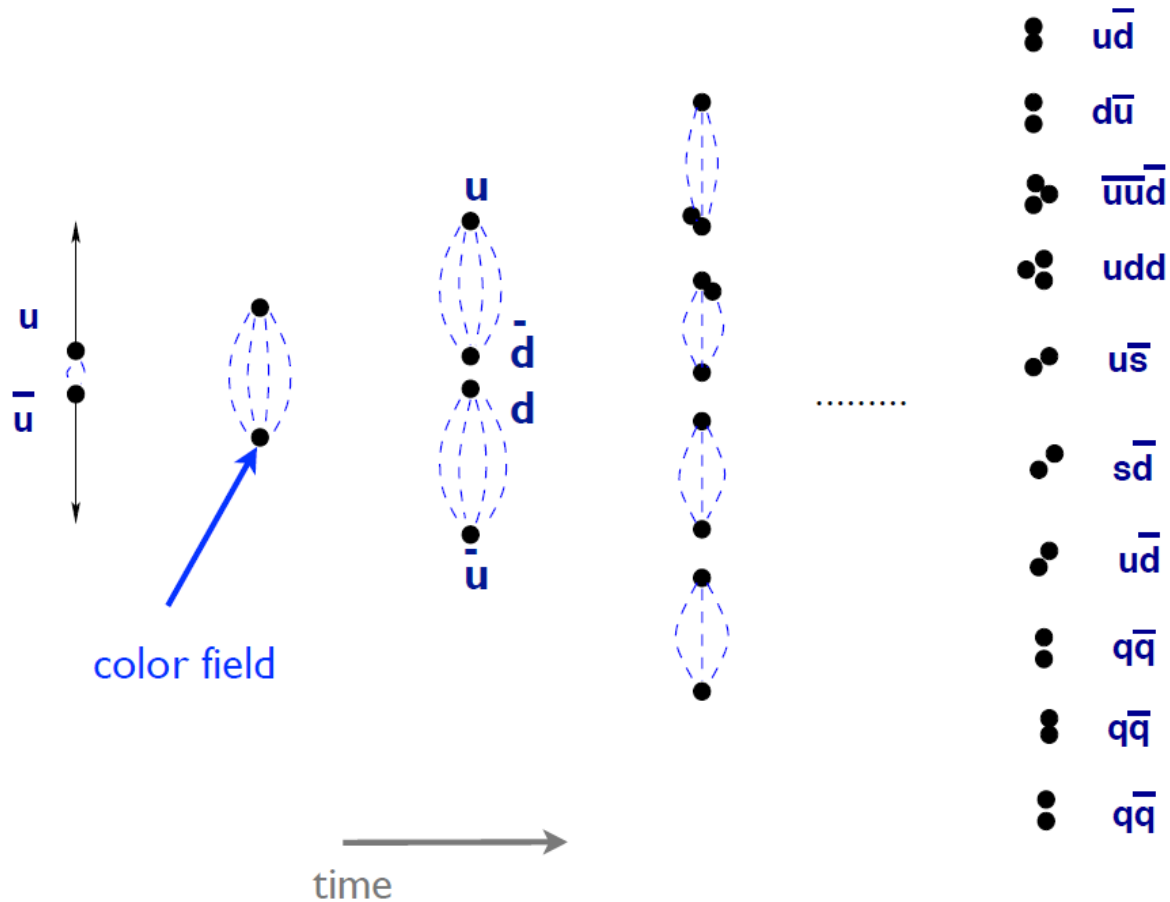
Hard interaction: large momentum transfer ($|t| > 2$ GeV^2)

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

Annihilation at high energy



Quarks together are color-neutral system

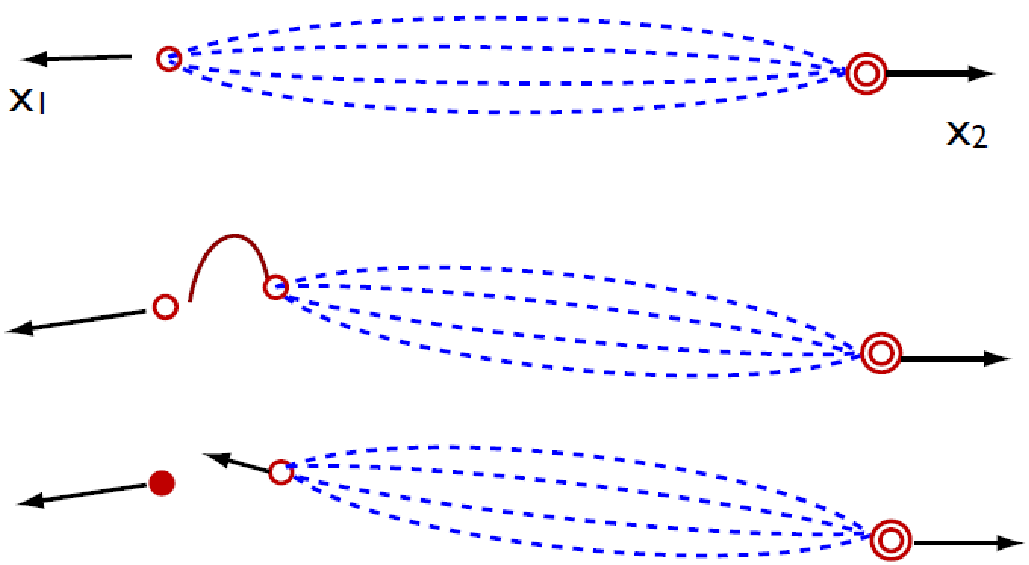


String fragmentation

Chain of hadrons

Fragmentation function (SIBYLL)

String characterized by momentum fractions of partons at ends



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

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

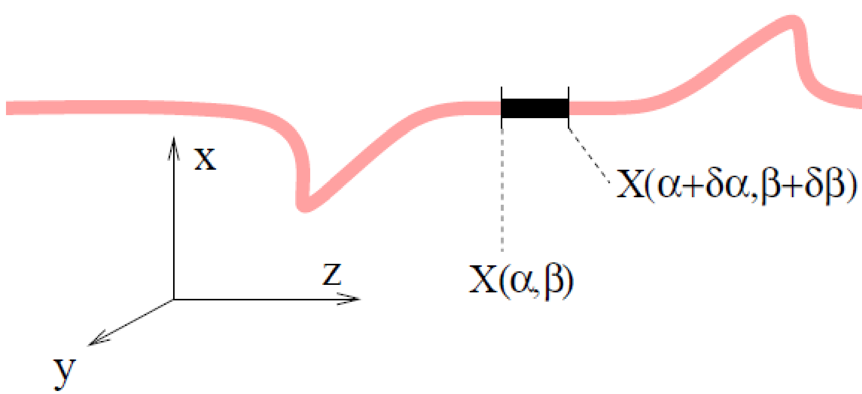
Momentum fraction z of new meson relative to quark at string end

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

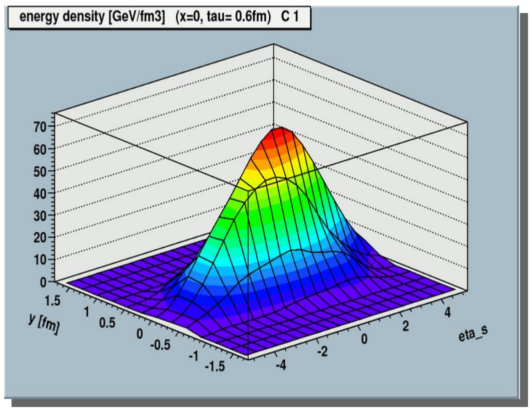
$$f(z) = \frac{(1-z)^a}{z} \exp\left\{-\frac{bm_\perp^2}{z}\right\}$$

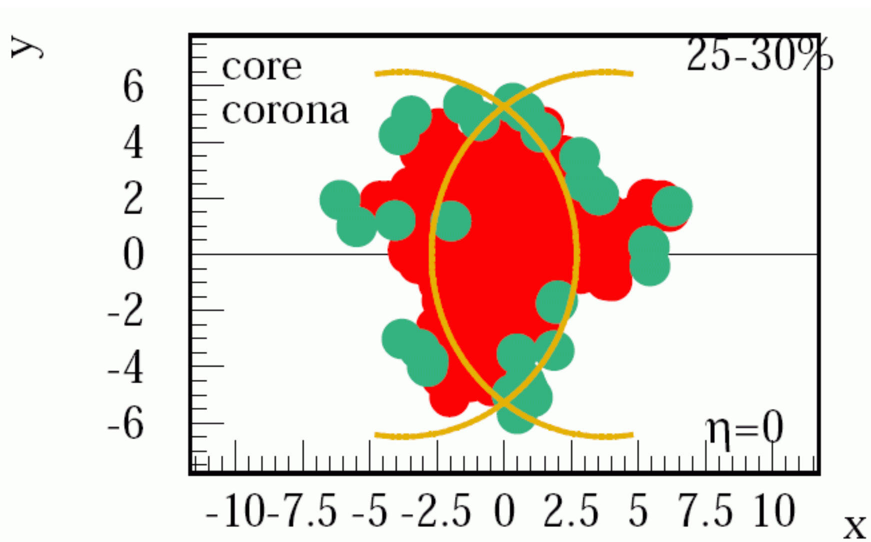
High Density Core Formation

- **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

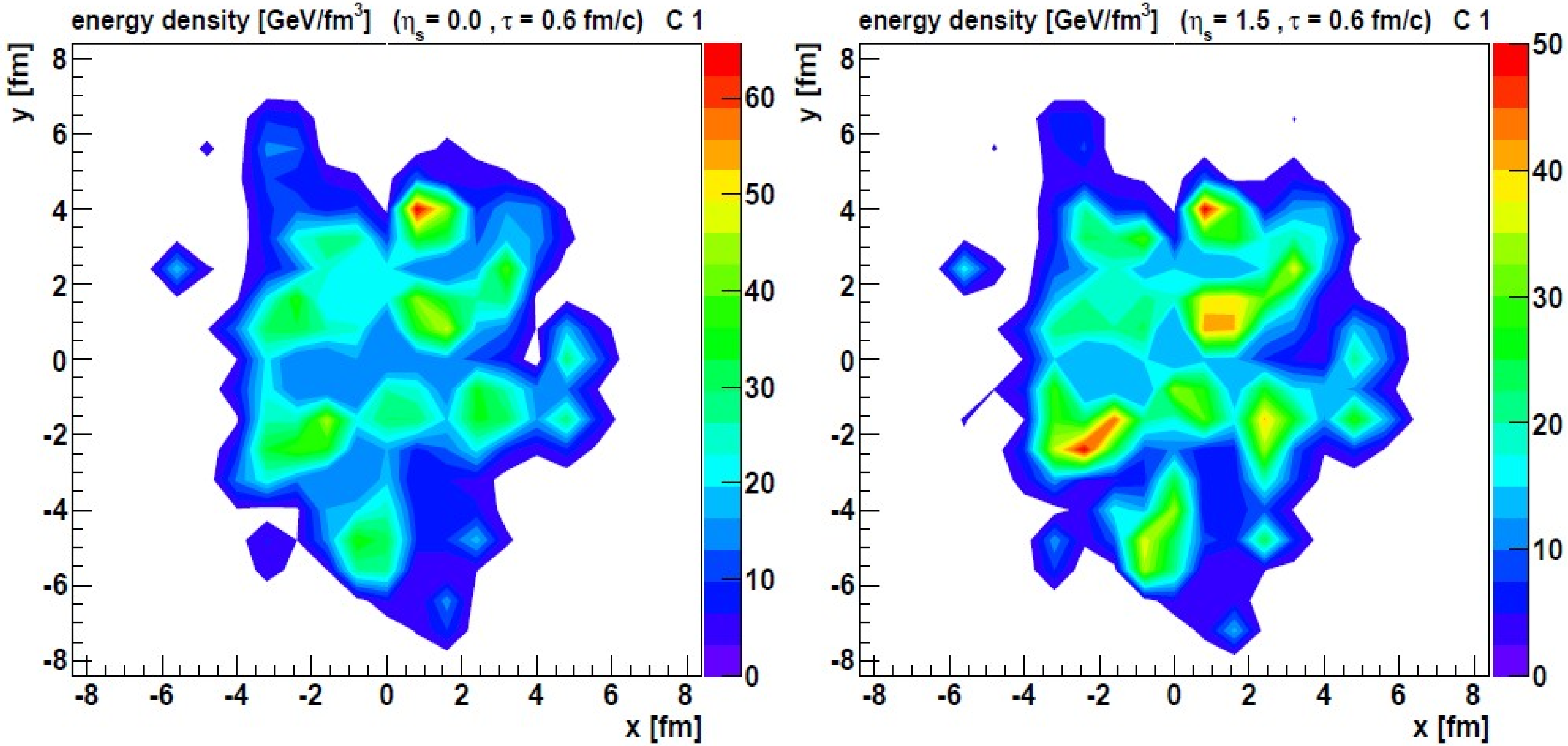




- Each string splitted into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space
- If energy density from segments high enough
  - segments fused into core
    - hydrodynamical-evolution
    - statistical hadronization
- If low density (corona)
  - segments remain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

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

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

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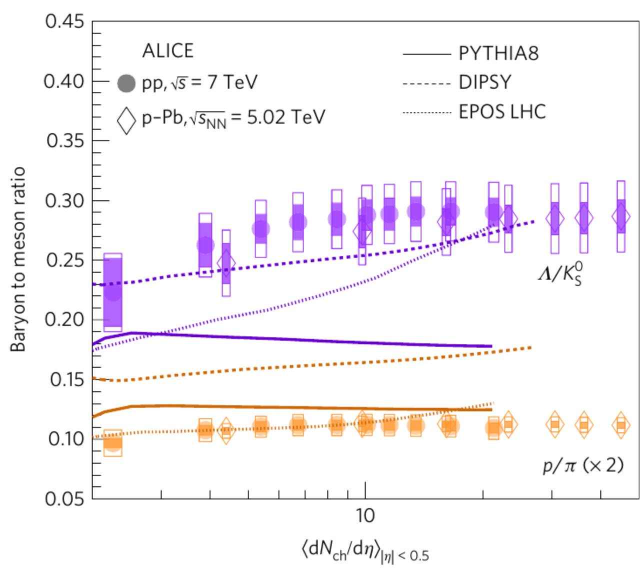
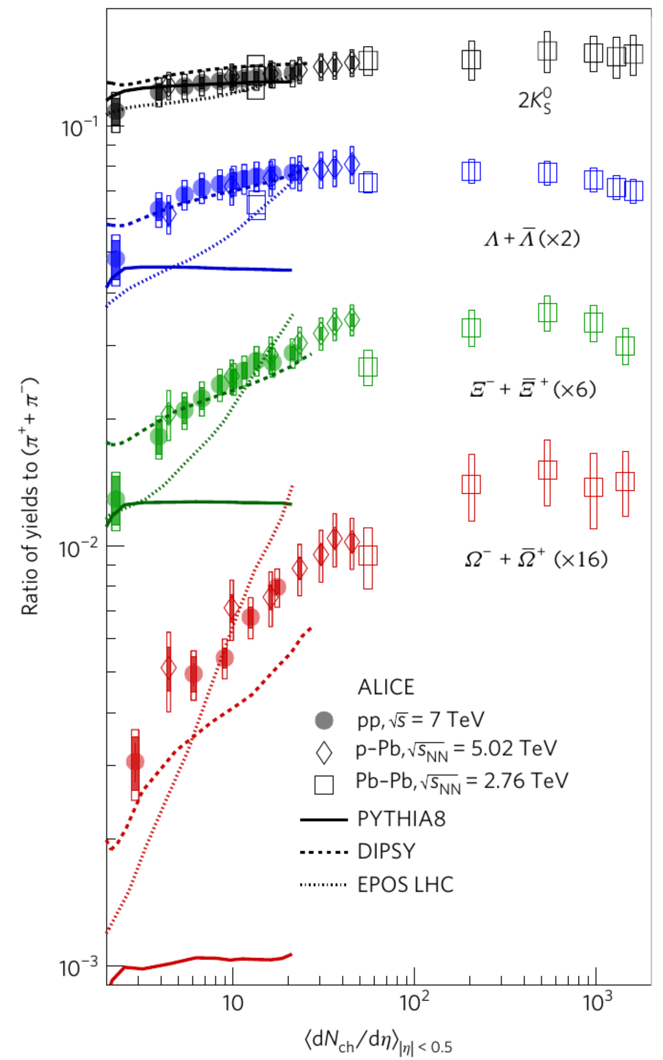
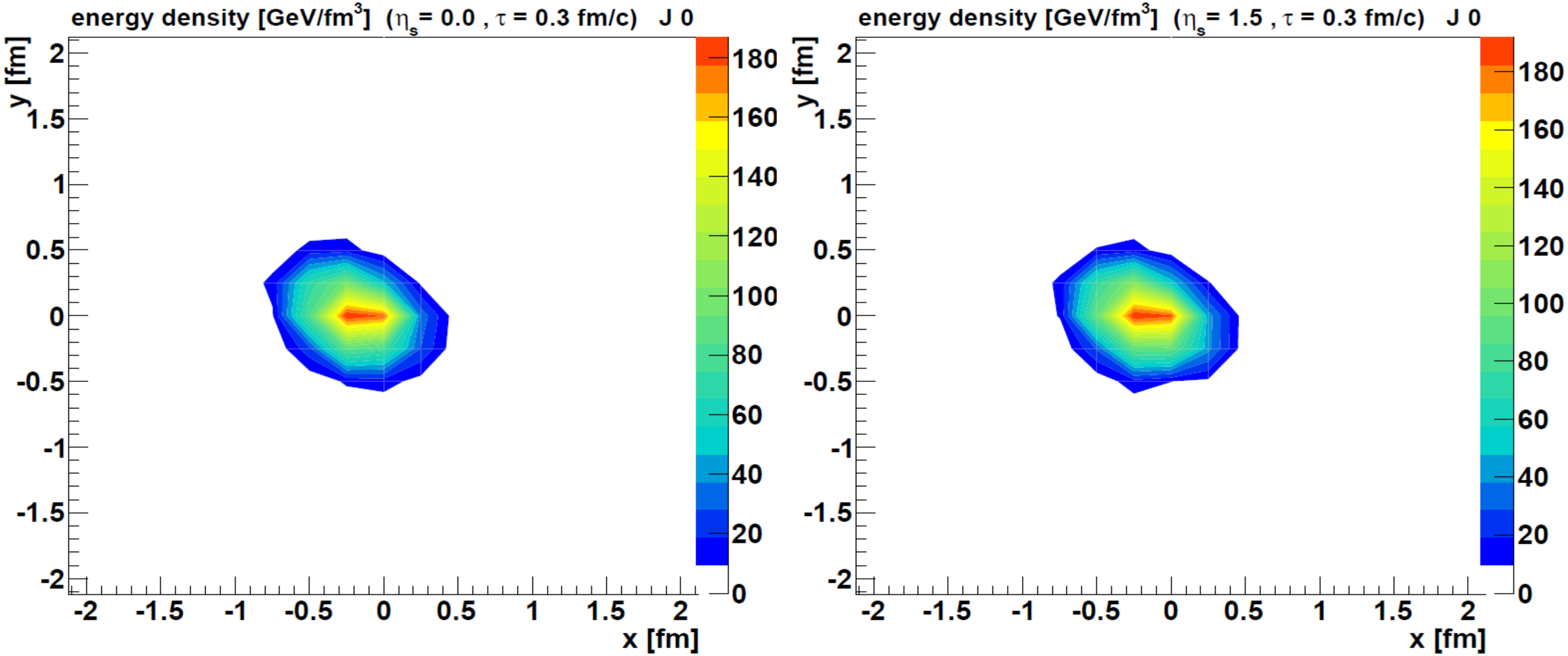




Event-by-Event Energy Density : pp

- 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