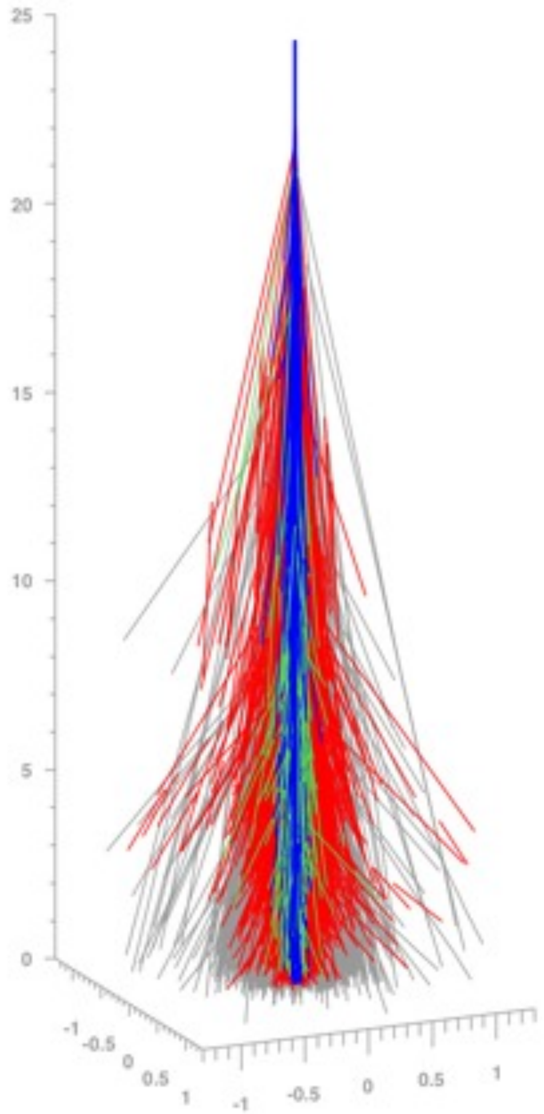
Air Showers and Hadronic Interactions (2/3)



Ralph Engel

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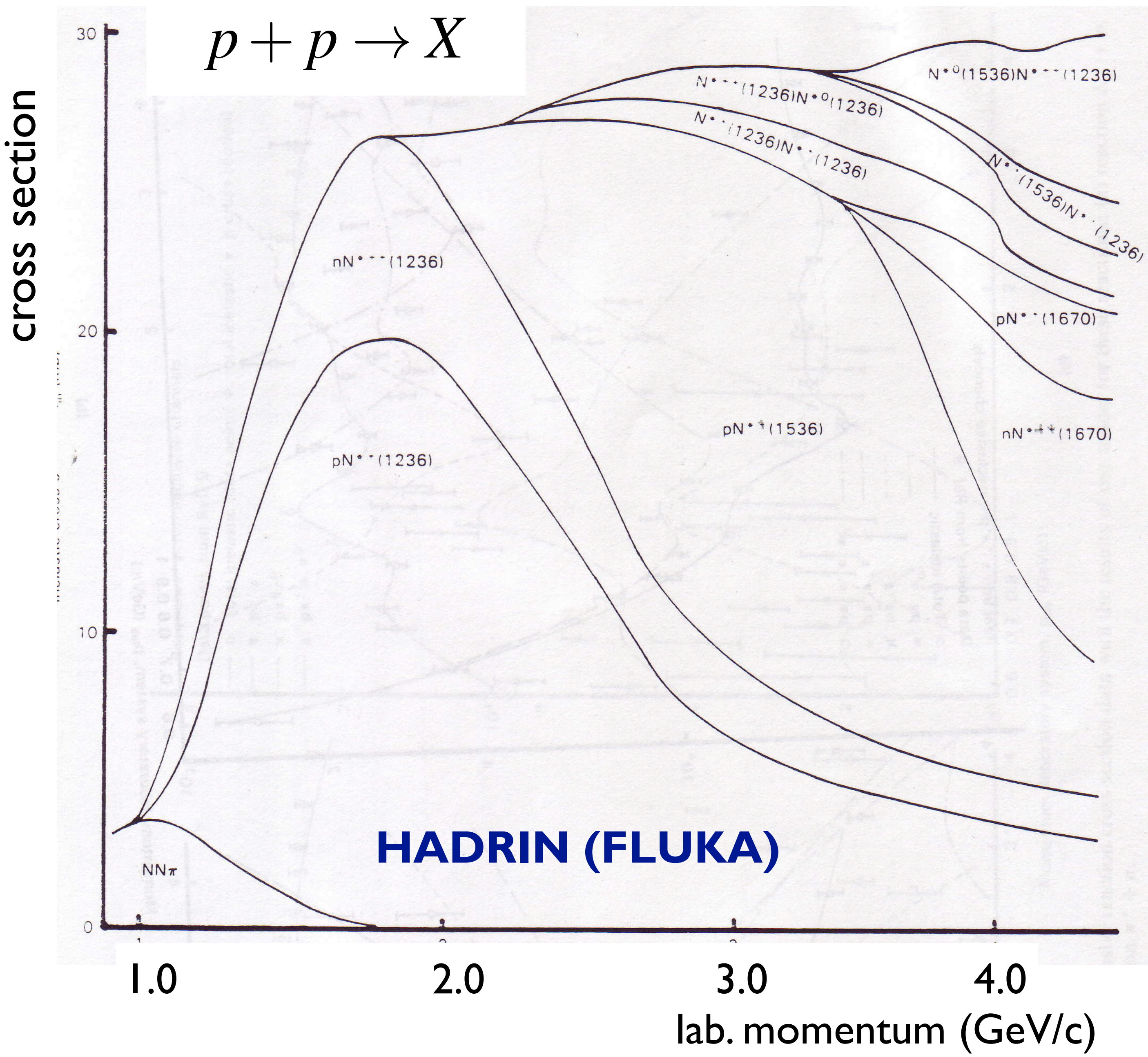
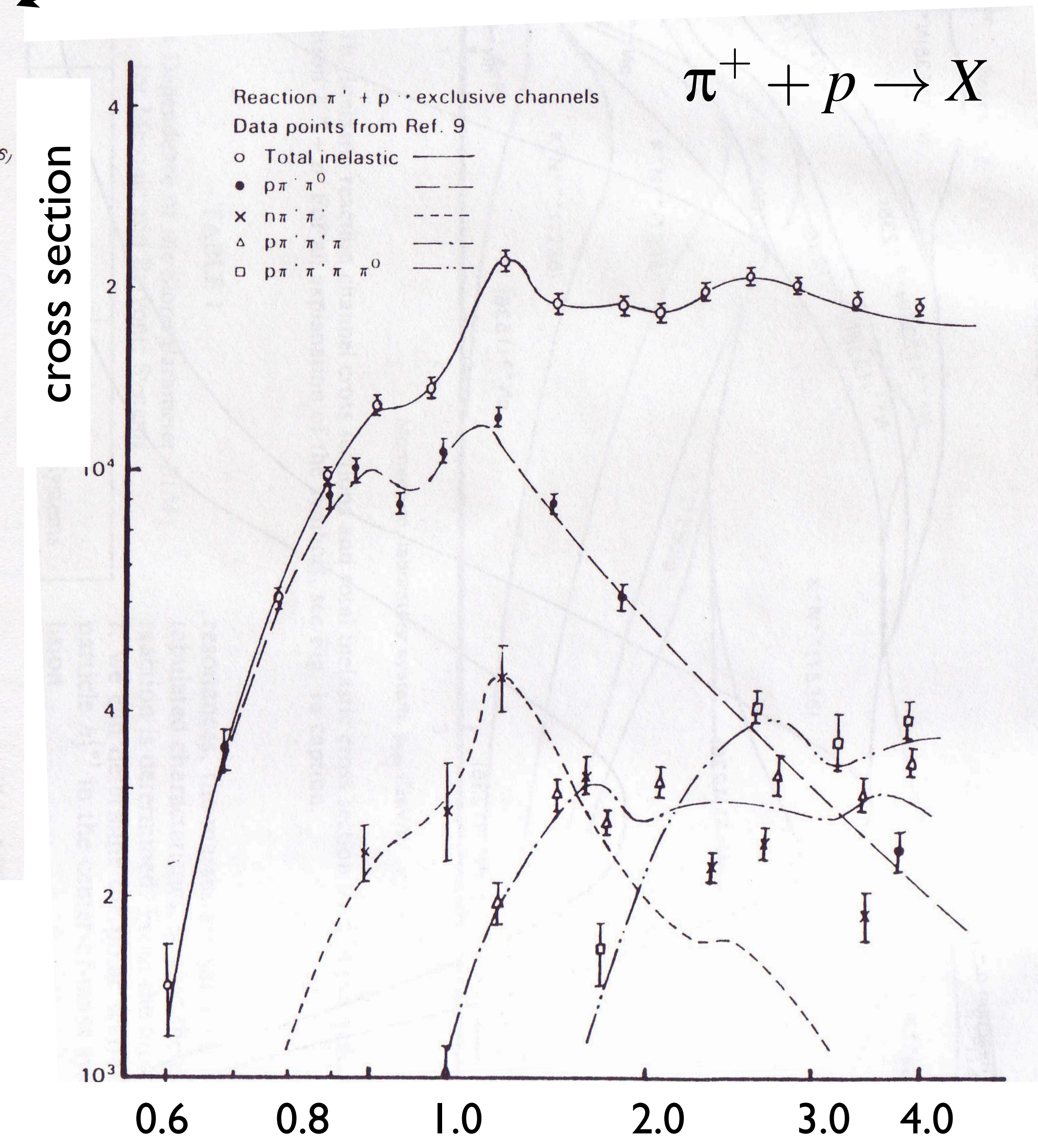
Karlsruhe Institute of Technology

Example: resonances in HADRIN

Large number of resonances





(Hänßgen, Ranft, Comp. Phys. Commun. 39, 1984)

Summary: Modeling of resonance region

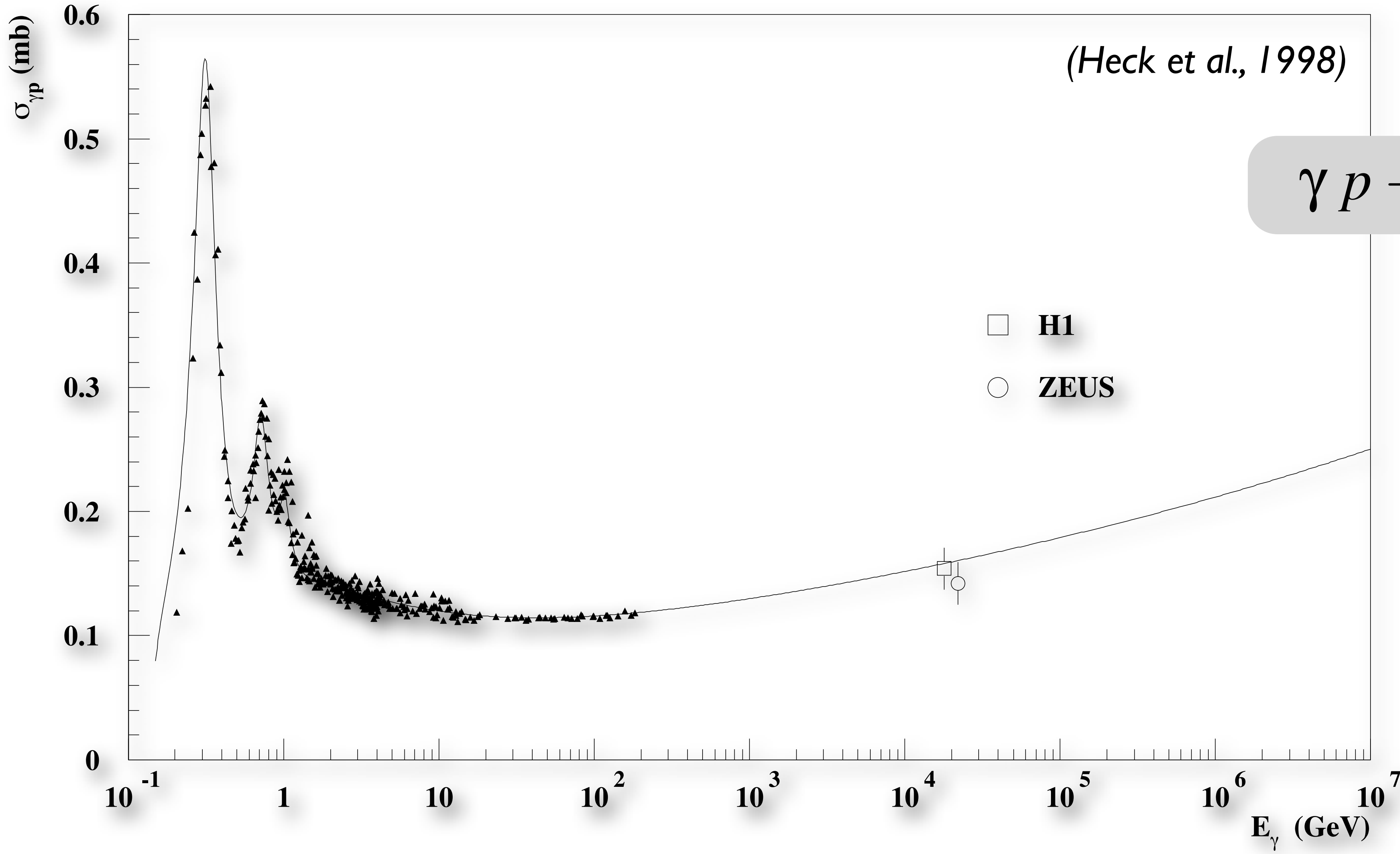
No fundamental problem in resonance region

- Large amount of data exists (still not perfect)
- Careful implementation needed
- Several simulation codes available

Application to GZK processes

- Processes reasonably well understood
- Remarkable coincidence of energy thresholds
- Light nuclei disintegrate very fast
- Largest uncertainties coming from IR and UR background fields

Simulation concepts: energy ranges



$\gamma\, p \longrightarrow X$

Resonances (fireball)

Scaling region (longitudinal phase space)

Minijet region (scaling violation)

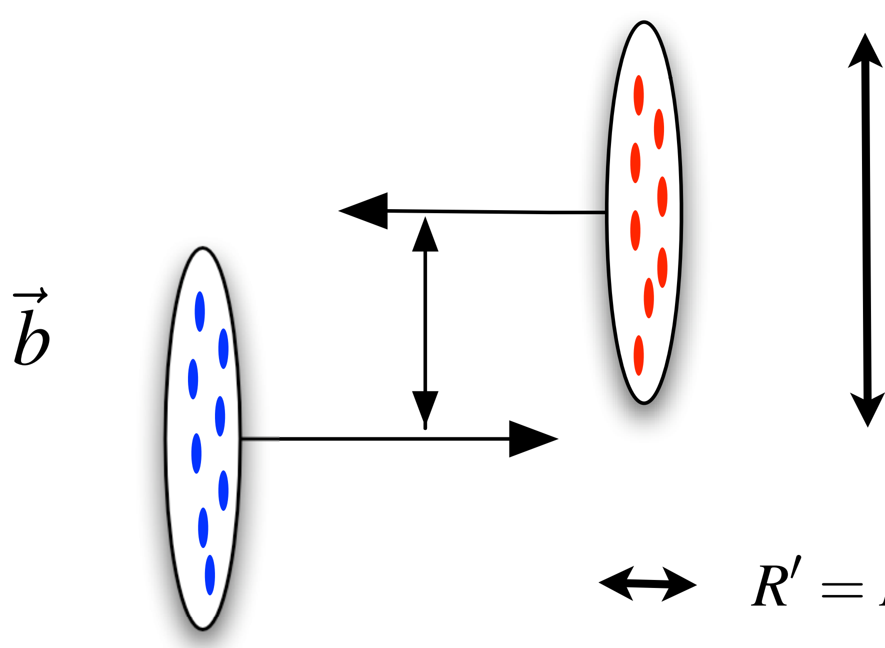
???

Particle production at intermediate energies

Expectations from uncertainty relation

Assumptions:

- protons built up of partons
- partons liberated in collision process
- partons fragment into hadrons (pions, kaons,...) after interaction
- interaction viewed in c.m. system (other systems equally possible)



$$R \approx 1\mathrm{fm} \approx 5\mathrm{GeV}^{-1}$$

$$R' = R/\Gamma = R\left(\frac{m_p}{E_p}\right)$$

Heisenberg uncertainty relation

$$\Delta x\, \Delta p_x \simeq 1$$

Longitudinal momenta of secondaries

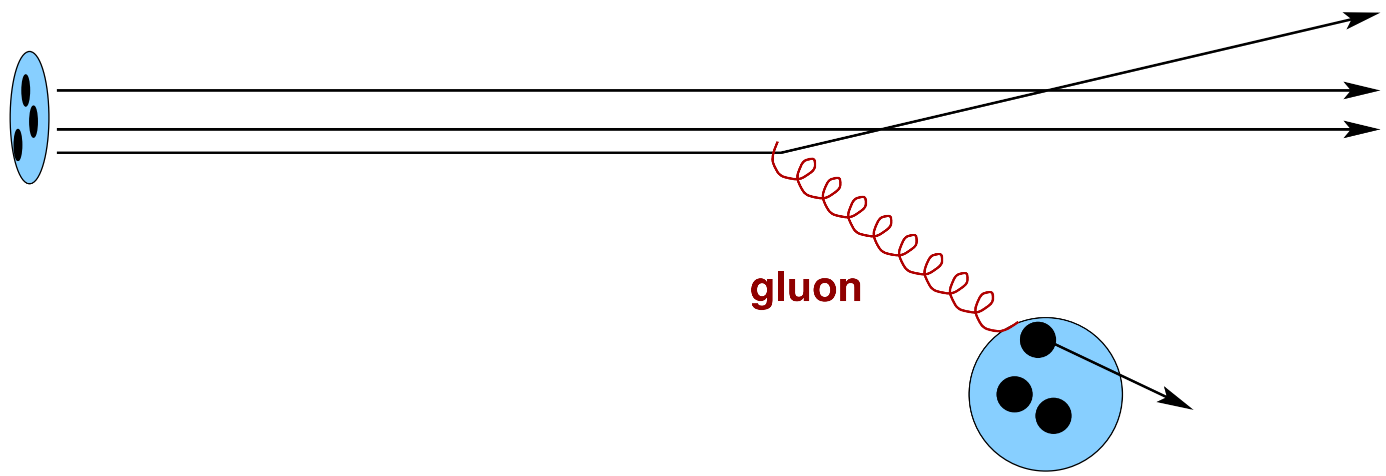
$$\langle p_{\parallel} \rangle \sim \Delta p_{\parallel} \approx \frac{1}{R'} \approx \frac{1}{5} E_p$$

Transverse momenta of secondaries

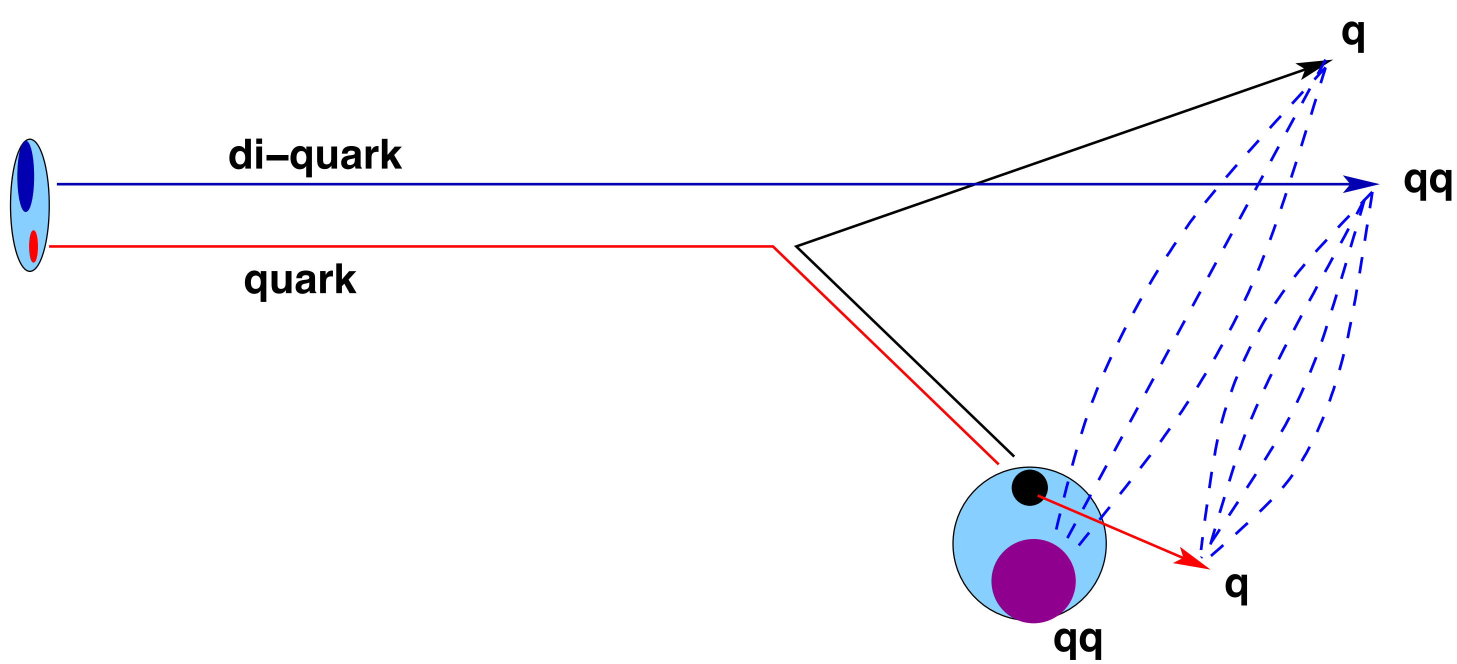
$$\langle p_{\perp} \rangle \sim \Delta p_{\perp} \sim \frac{1}{R} \approx 200\,\mathrm{MeV}$$

QCD-inspired interpretation: color flow model

Partonic view:



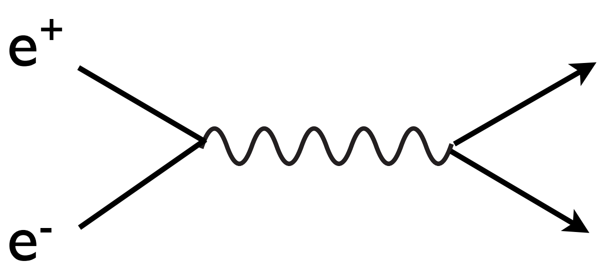
Color flow:



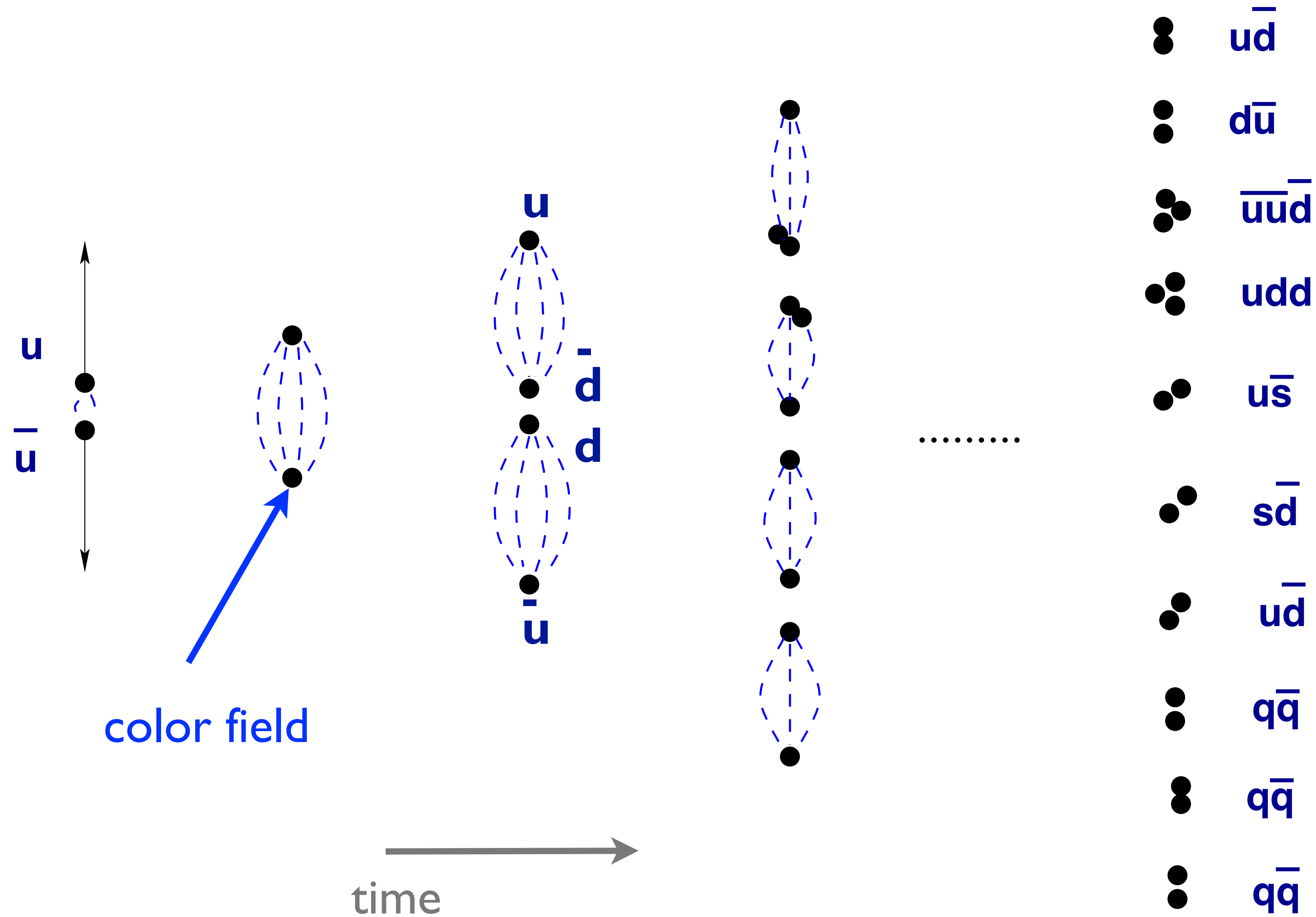
One-gluon exchange:
two color fields (strings)

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

Annihilation at high energy



Quarks together are color-neutral system



Confinement in QCD

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \lambda\, r$$

String fragmentation

Kinematic distribution of secondary particles

Ansatz

- Lorentz-invariant for transformations along string
- Transverse momenta result of vacuum fluctuations

Lorentz invariant function

$$\mathrm{d}N = f(p)\, \delta(p^2 - m^2)\, \mathrm{d}^4 p$$

$$p = (E, \vec{p})$$

$$= f(p)\, \frac{\mathrm{d}^3 p}{2E}$$

Separation of long. and transverse degrees of freedom

$$= \frac{1}{2} f(p)\, \mathrm{d}^2 p_\perp\, \frac{\mathrm{d}p_\parallel}{E}$$

New variable $\frac{\mathrm{d}p_\parallel}{E} = \mathrm{d}y$

$$= \frac{1}{2}\, f_\perp(p_\perp)\, \mathrm{d}^2 p_\perp\, f_\parallel(y)\, \mathrm{d}y$$

$\beta^{-1} \ldots$ effective temperature

$$\sim \exp(-\beta p_\perp^2)\, \mathrm{d}^2 p_\perp \quad f_\parallel(y)\, \mathrm{d}y$$

Rapidity and pseudorapidity

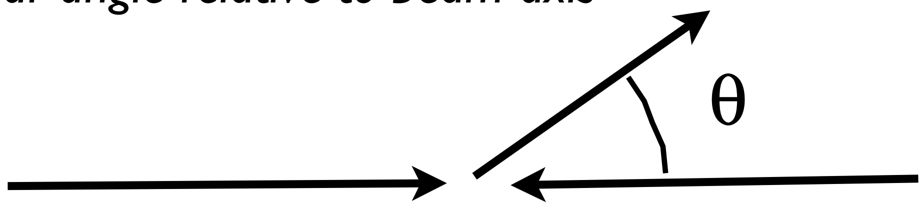
$$\frac{\mathrm{d}p_{\parallel}}{E} = \mathrm{d}y$$

Rapidity

$$y \;=\; \frac{1}{2}\ln\frac{E+p_{\parallel}}{E-p_{\parallel}} \;=\; \ln\frac{E+p_{\parallel}}{m_{\perp}}$$

Transverse mass $\quad m_{\perp} = \sqrt{m^2 + p_{\perp}^2}$

Polar angle relative to beam axis



Rapidity of massless particles

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

Experiments without particle identification: **pseudorapidity**

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

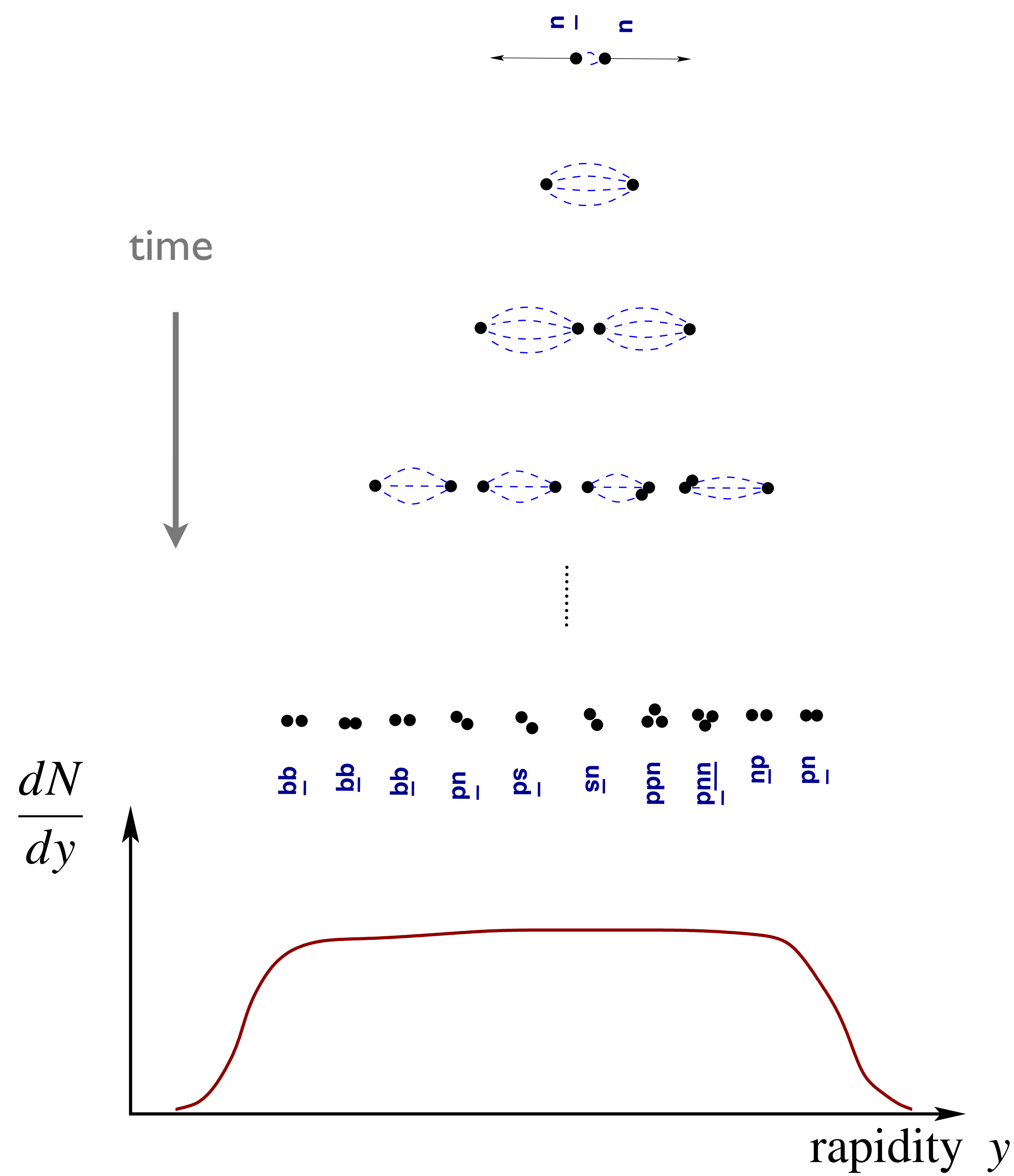
String fragmentation and rapidity

Lorenz transformation of rapidity

$$y' = y + \text{const.}$$

$$f_{\|}(y') \; = \; f_{\|}(y) \; = \; \rho$$

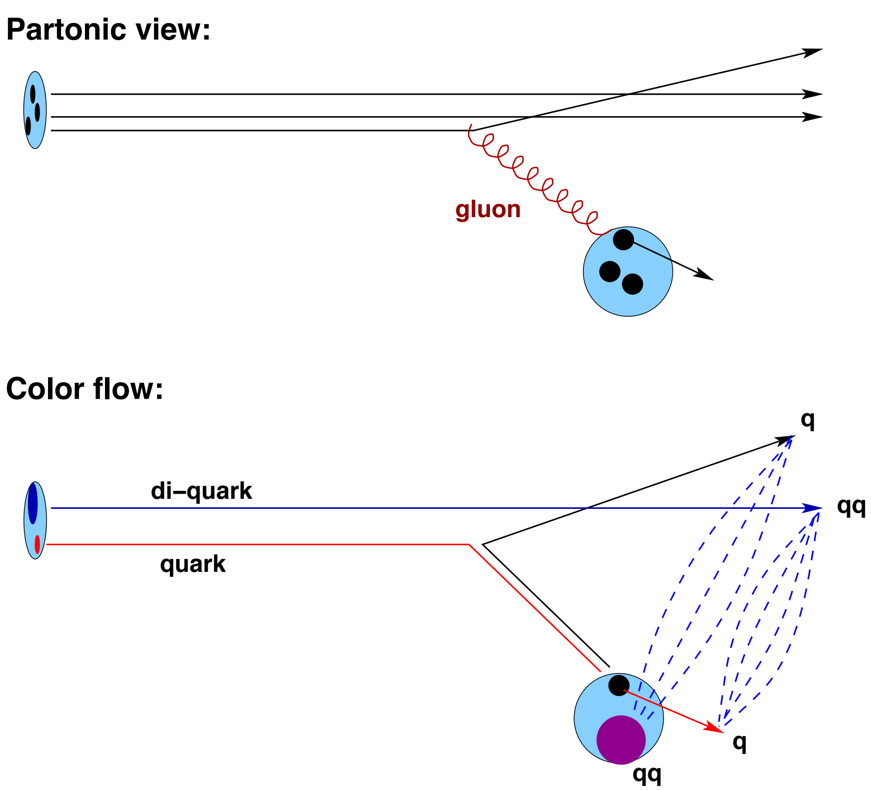
Particle density independent of rapidity

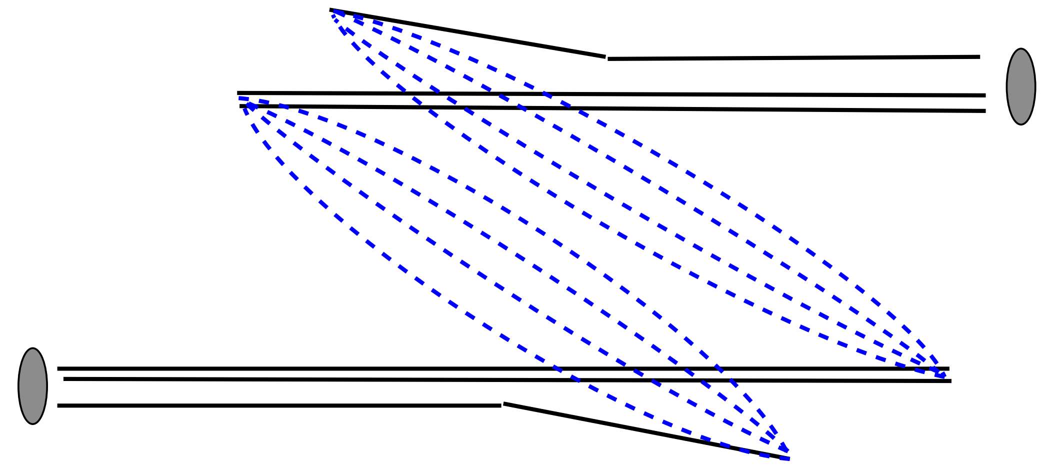


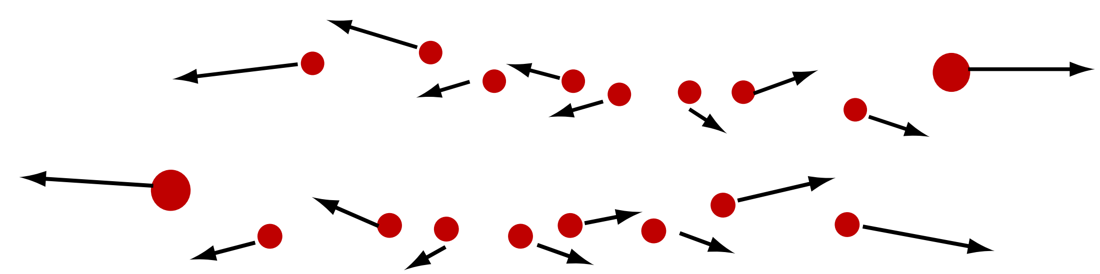
Total width energy-dependent

$$y_{\max} - y_{\min} \sim \log(s/m^2)$$

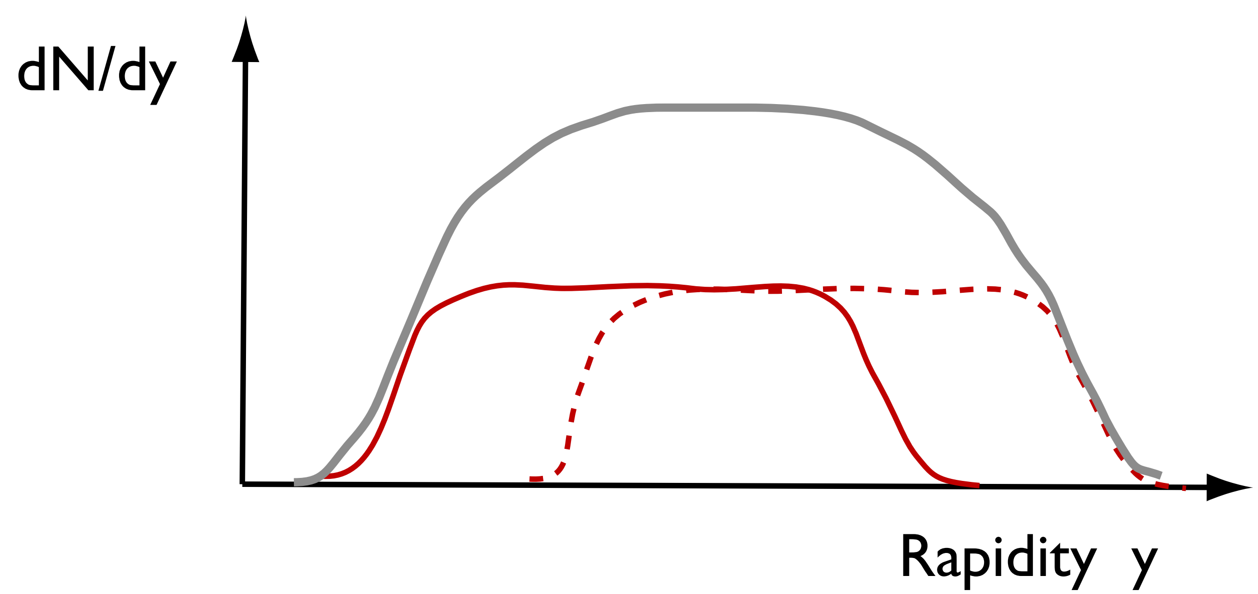
Final state particles: two-string model







Lab. system → **CM system**



Momentum fractions of string ends

Asymmetric momentum sharing of valence quarks: most energy given to di-quark

Quark in nucleon
(example: SIBYLL)

$$f_{\mathrm{q|nuc}}(x) \sim \frac{(1-x)^3}{(x^2+\mu^2)^{\frac{1}{4}}}$$

Many other parametrizations work well in describing data (example: DPMJET, FLUKA)

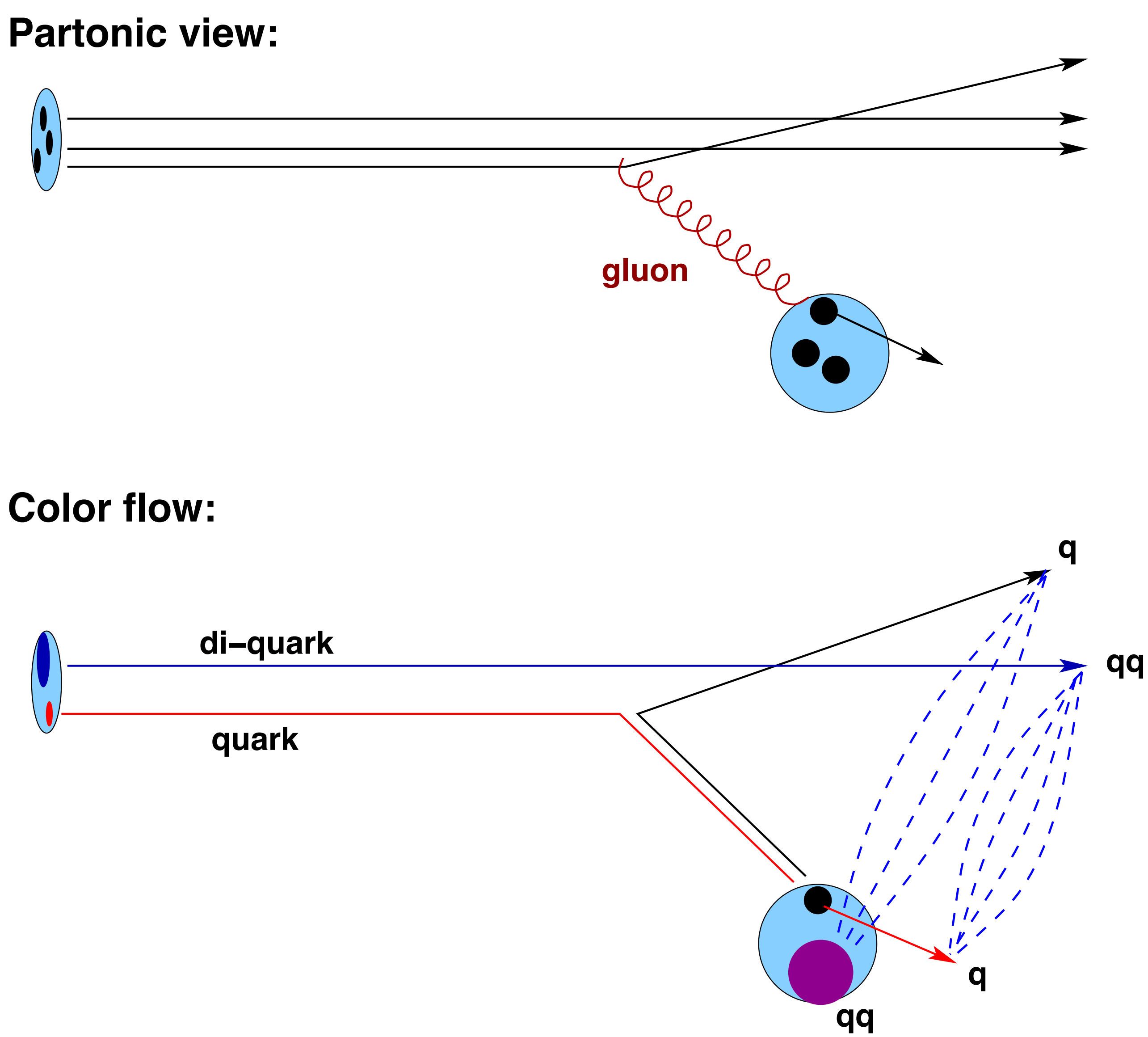
$$f_{\mathrm{q|nuc}}(x) \sim \frac{(1-x)^{\frac{3}{2}}}{\sqrt{x}}$$

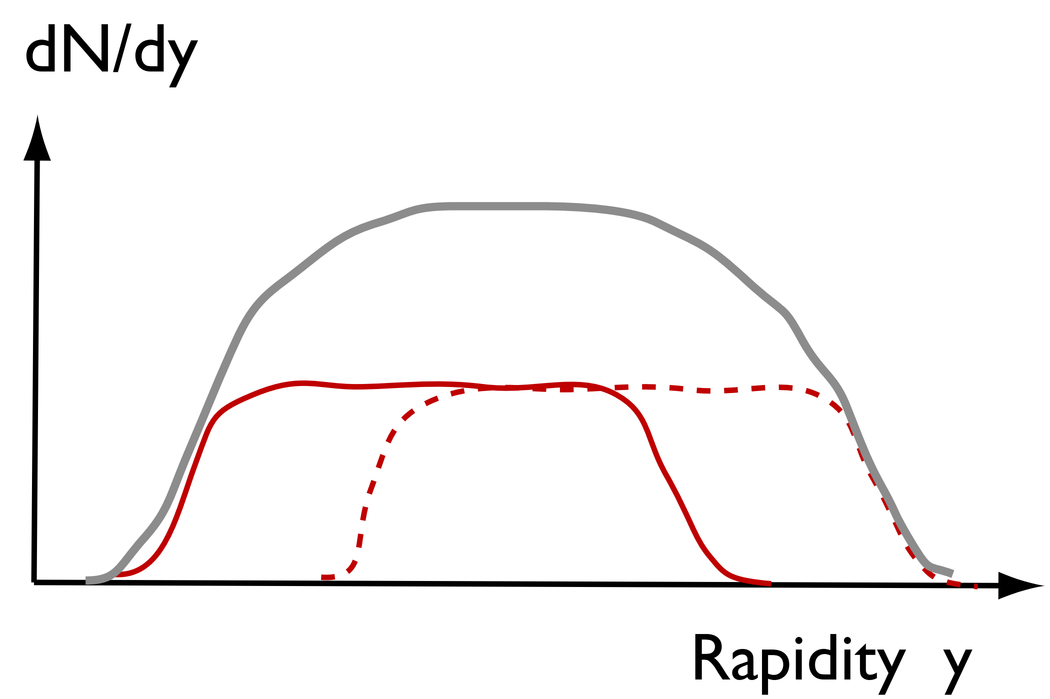
$$f_{\mathrm{q|mes}}(x) \sim \frac{1}{\sqrt{x(1-x)}}$$

Sea quark momentum fractions

$$f_{\mathrm{q_{sea}}}(x) \sim \frac{1}{x}$$ or $$f_{\mathrm{q_{sea}}}(x) \sim \frac{1}{\sqrt{x}}$$

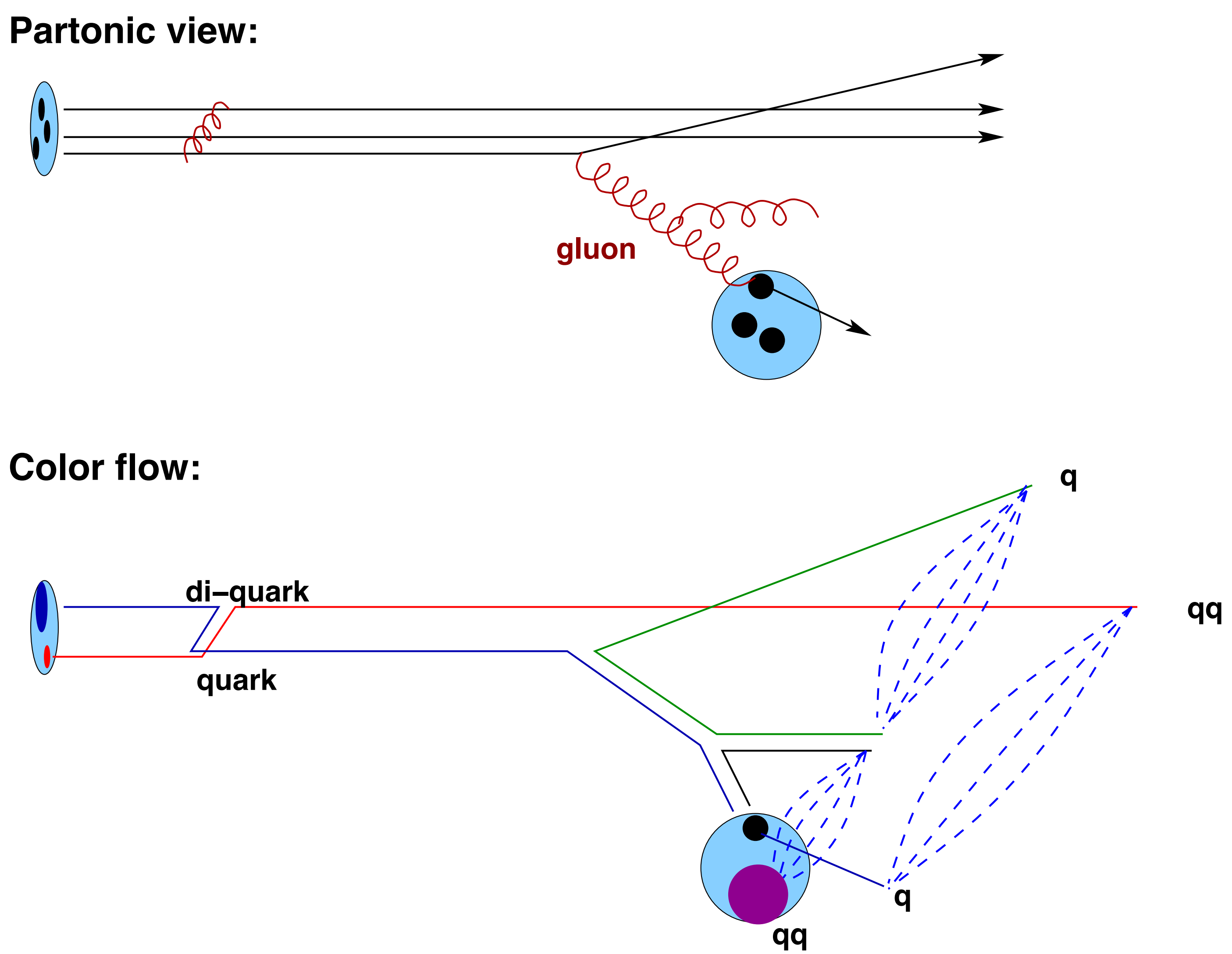
Color flow and final state particles (i)



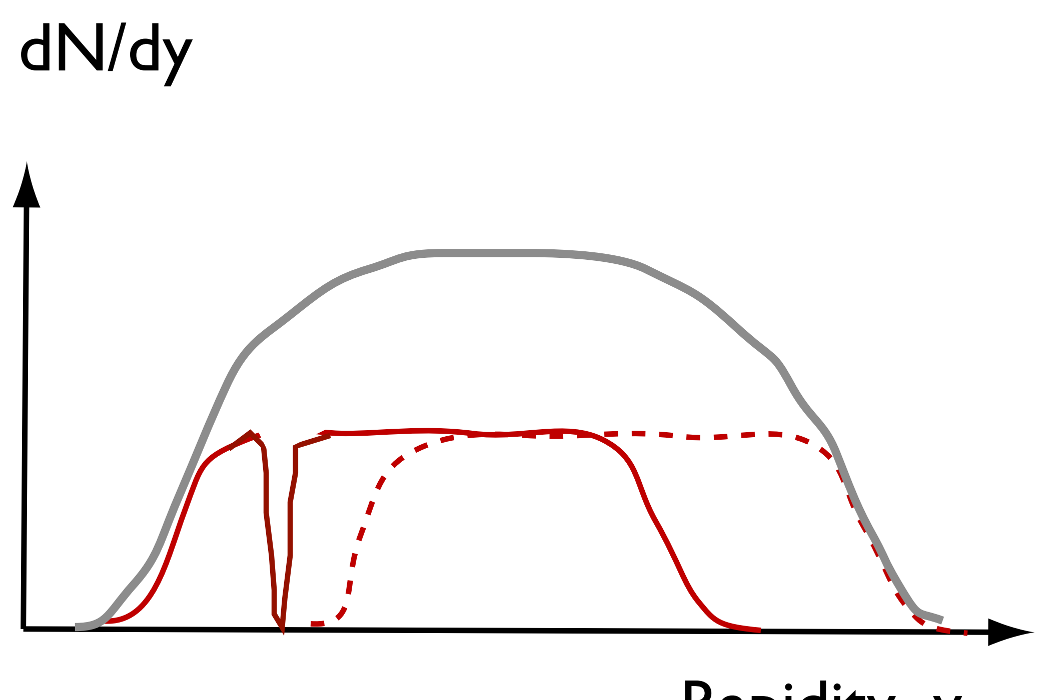


One-gluon exchange:
two color fields (strings)

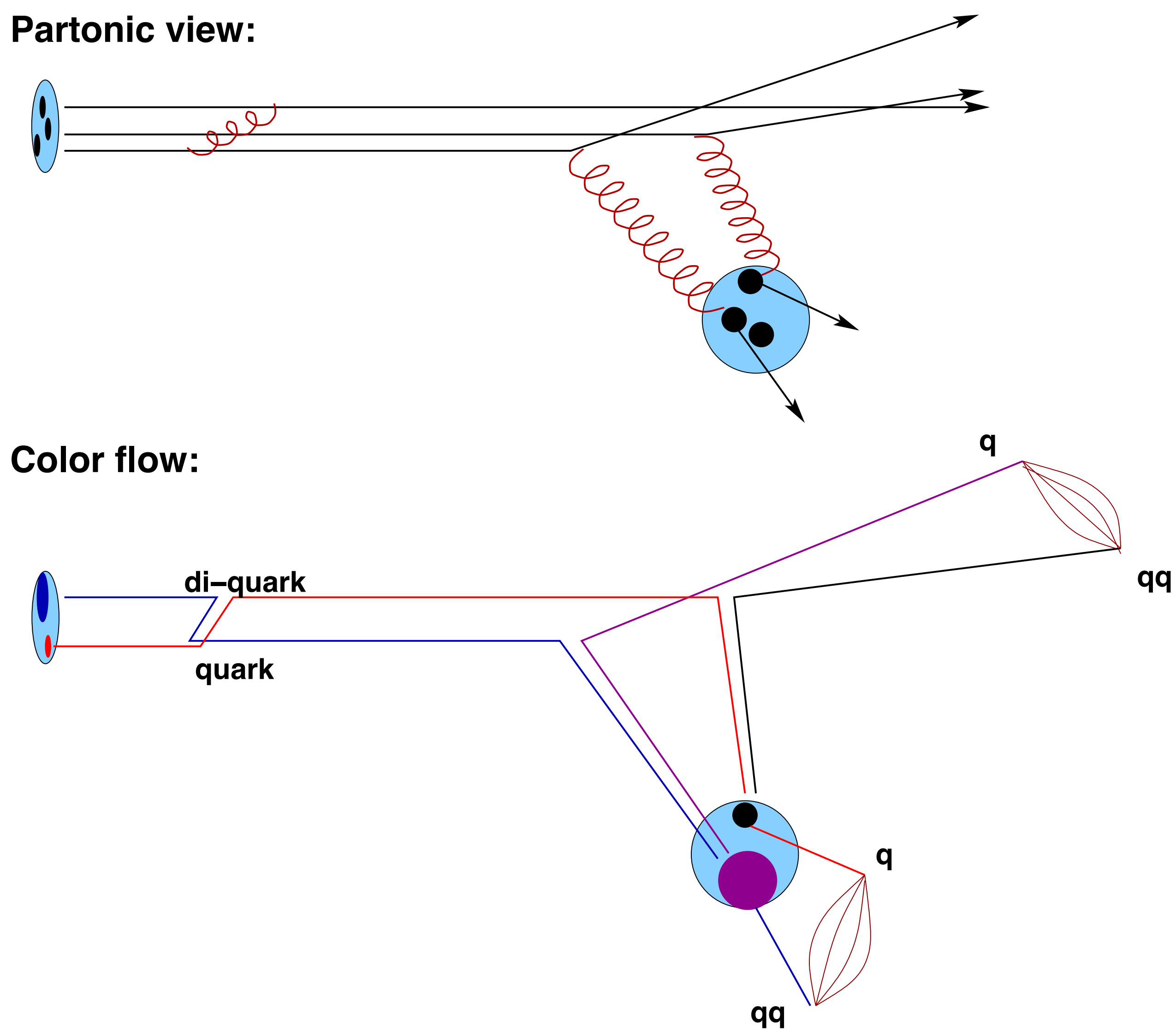
Color flow and final state particles (ii)



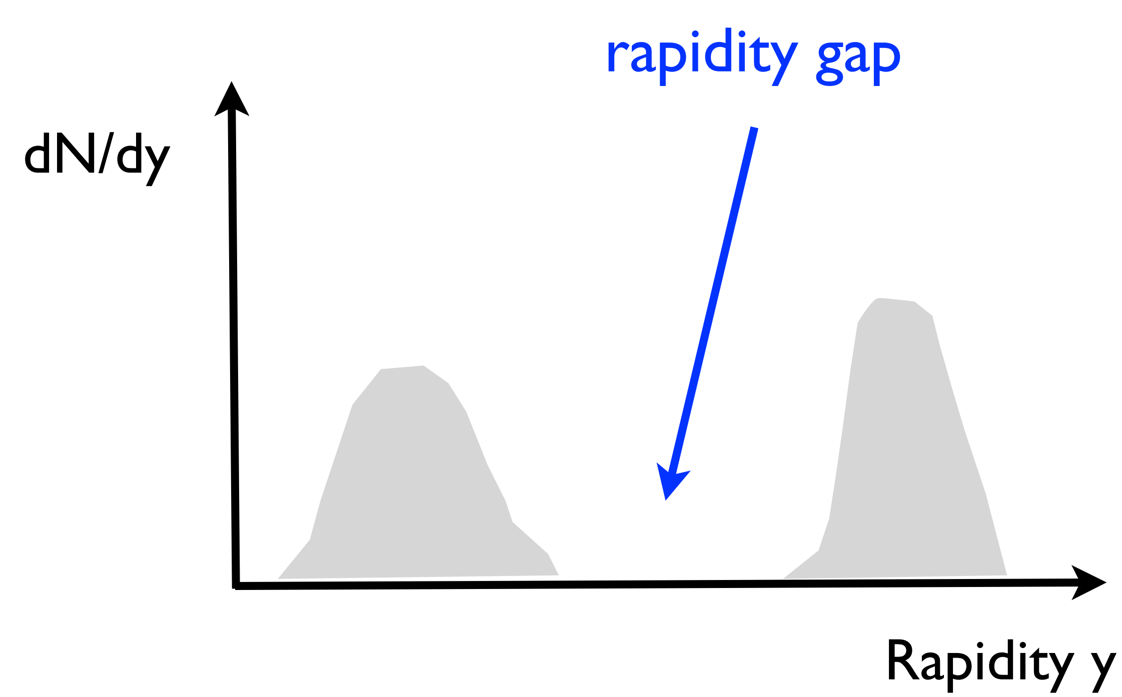
Initial and final state radiation does not change topology



Other predicted color flow configurations

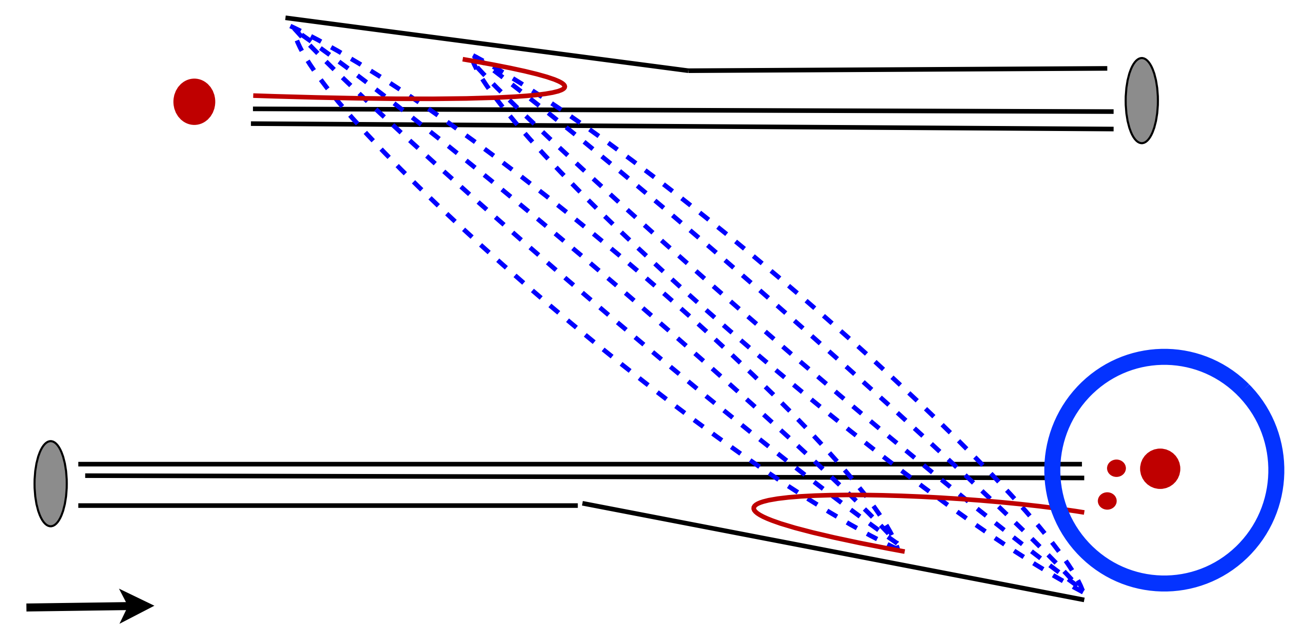


Two-gluon exchange:
diffraction dissociation



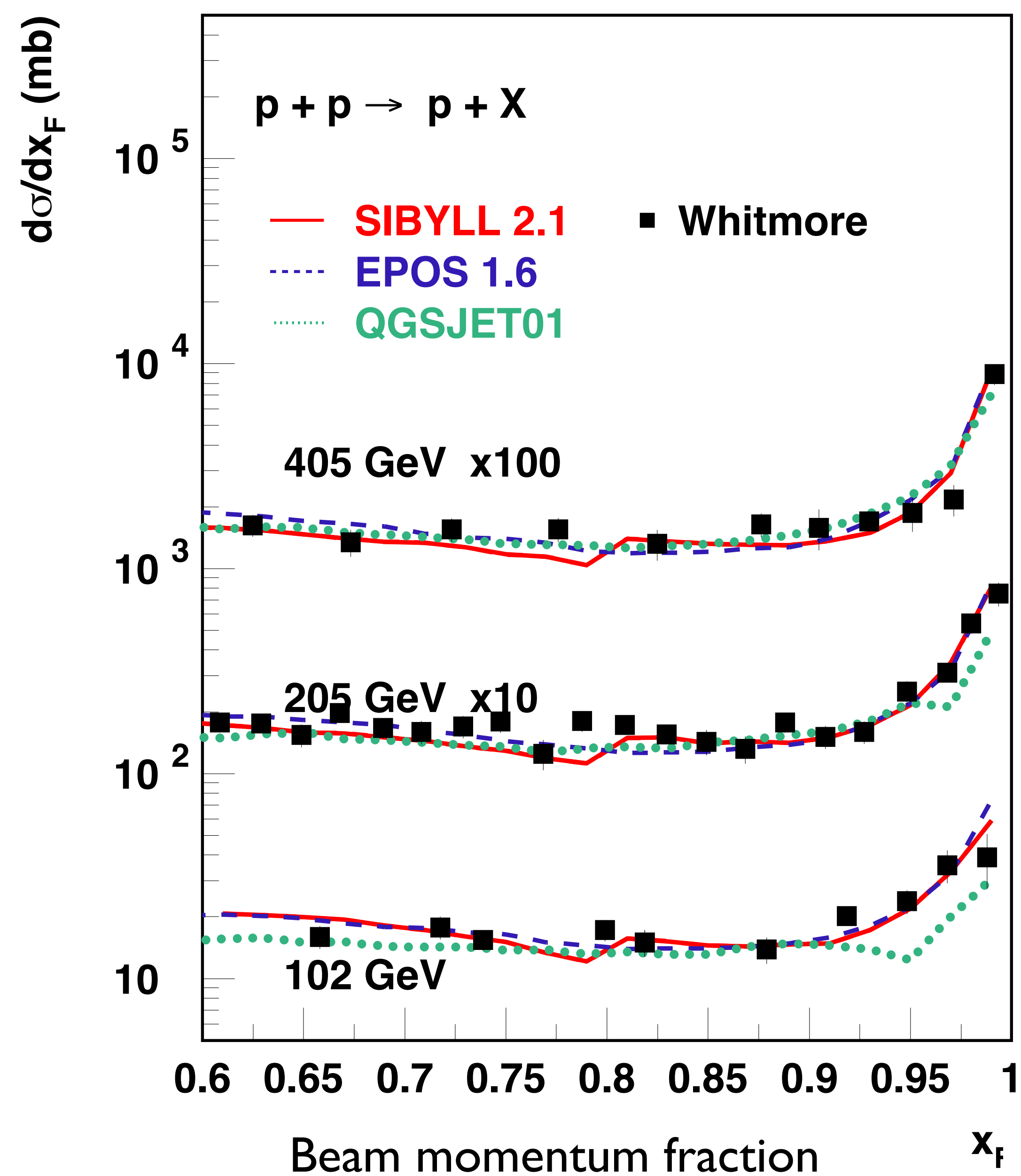
At very high energy (multi-gluon exchange):
Almost 50% of all events are elastic/diffractive scattering

Particle production spectra (i)

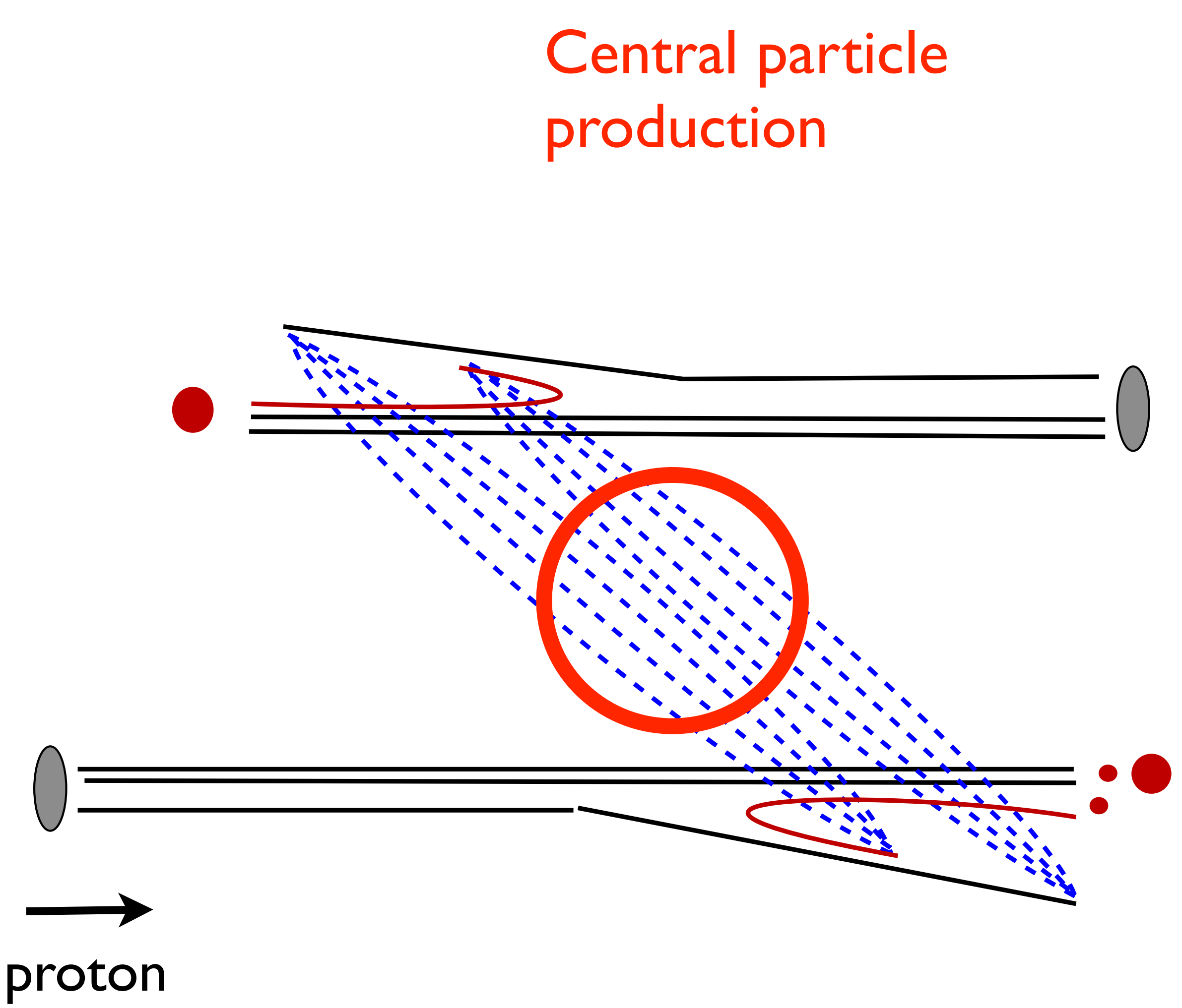


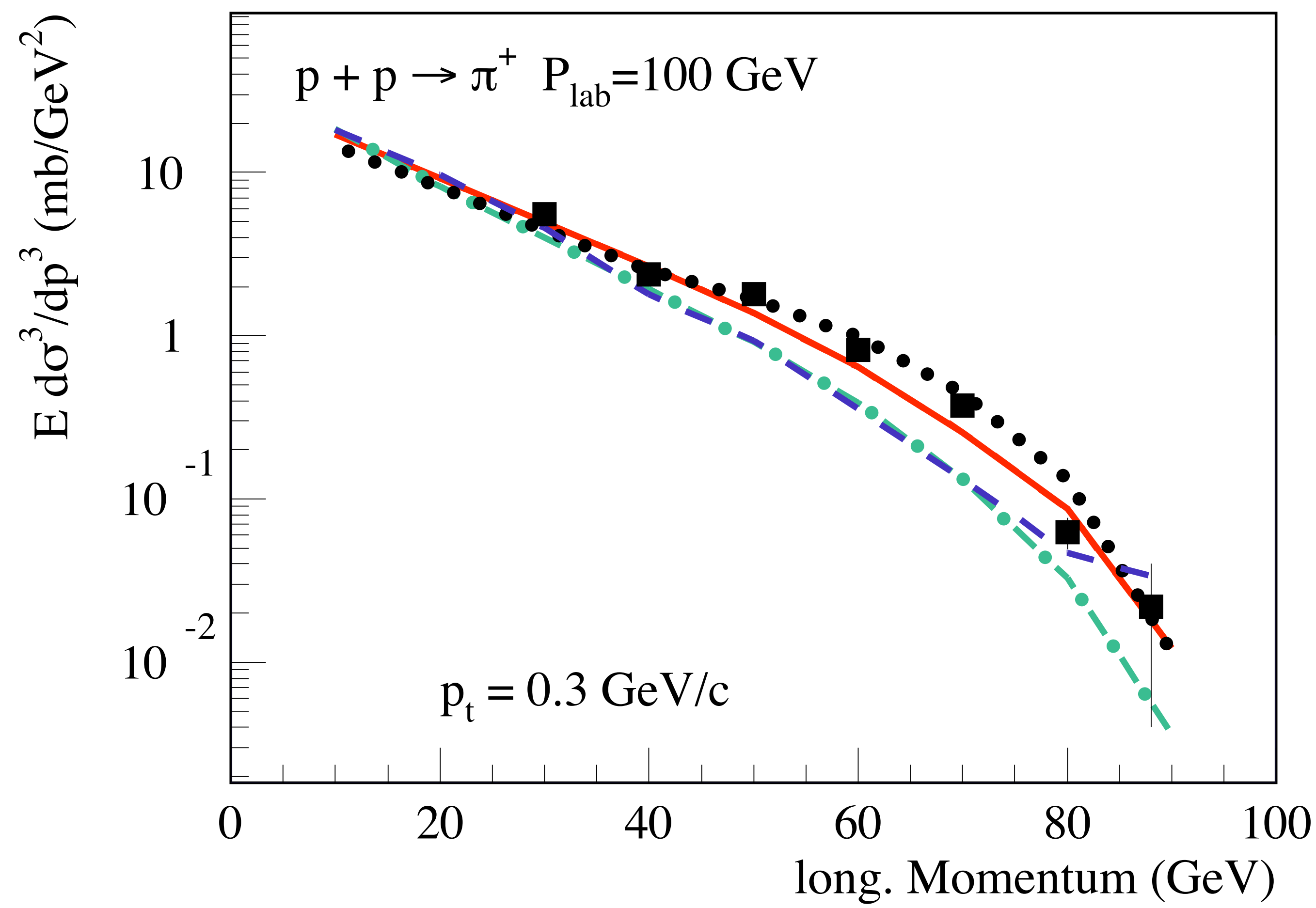
Fluctuations: Generation of sea quark anti-quark pair and leading/excited hadron

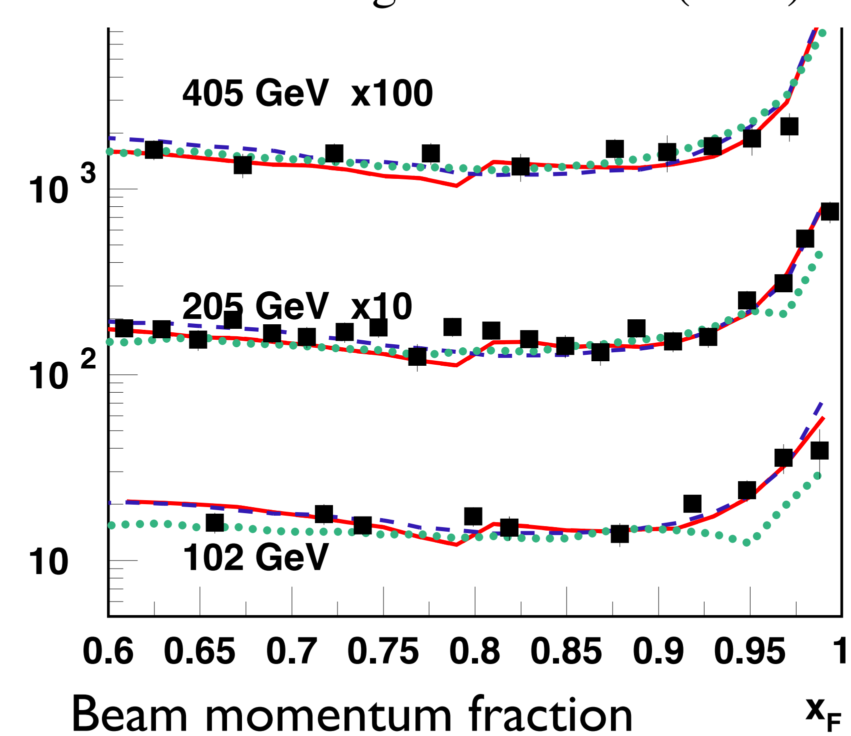
Leading particle effect



Particle production spectra (ii)



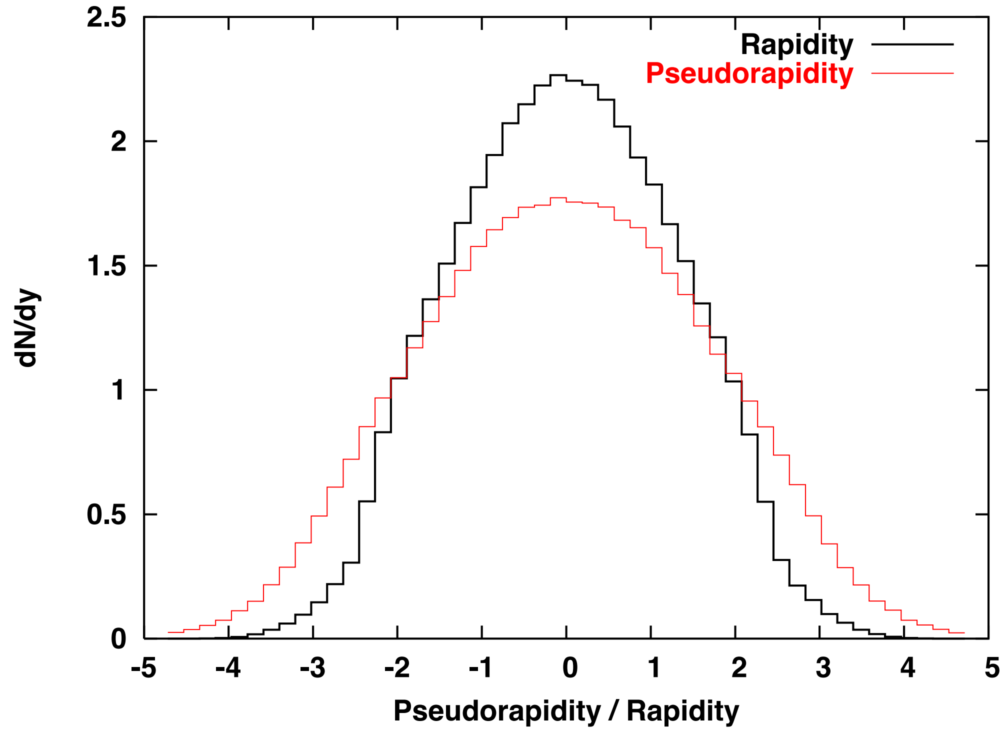


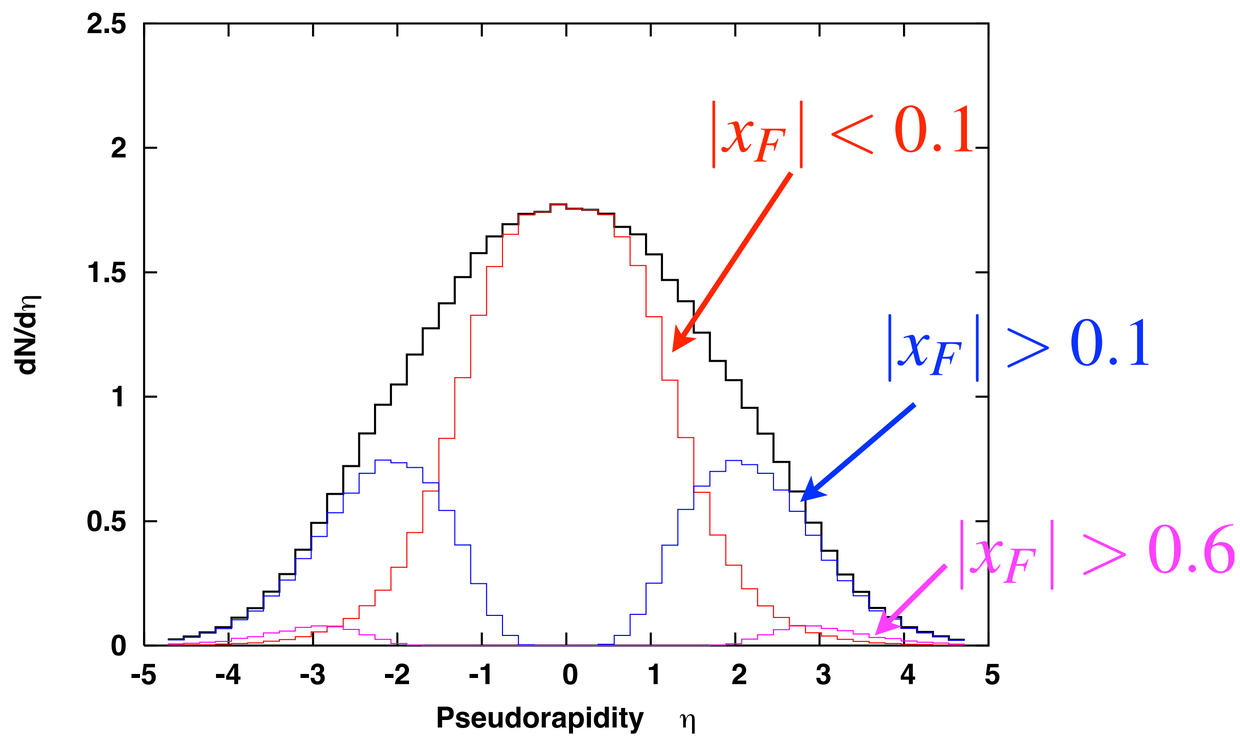


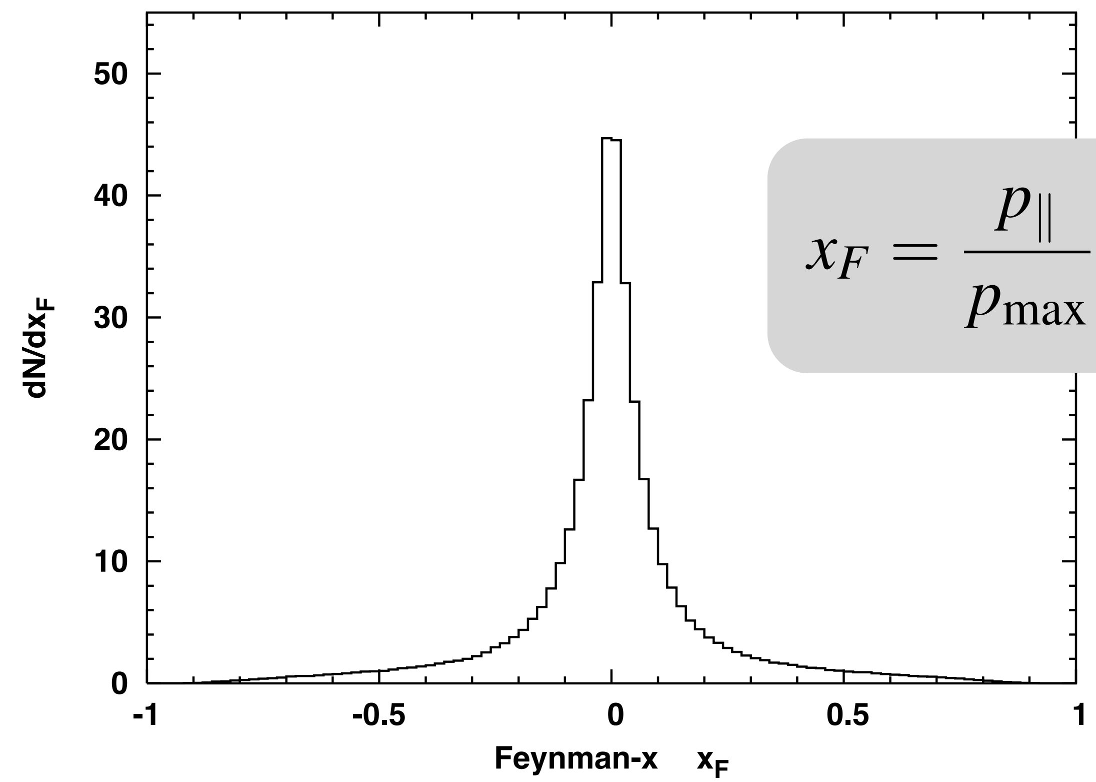
Fluctuations: Generation of sea quark anti-quark pair and leading/excited hadron

Hypothesis of Feynman scaling

Example: 100 GeV p-p collisions,
charged secondaries







$$x_F = \frac{p_\|}{p_{\max}} \approx \frac{2p_\|}{\sqrt{s}}$$

Feynman scaling

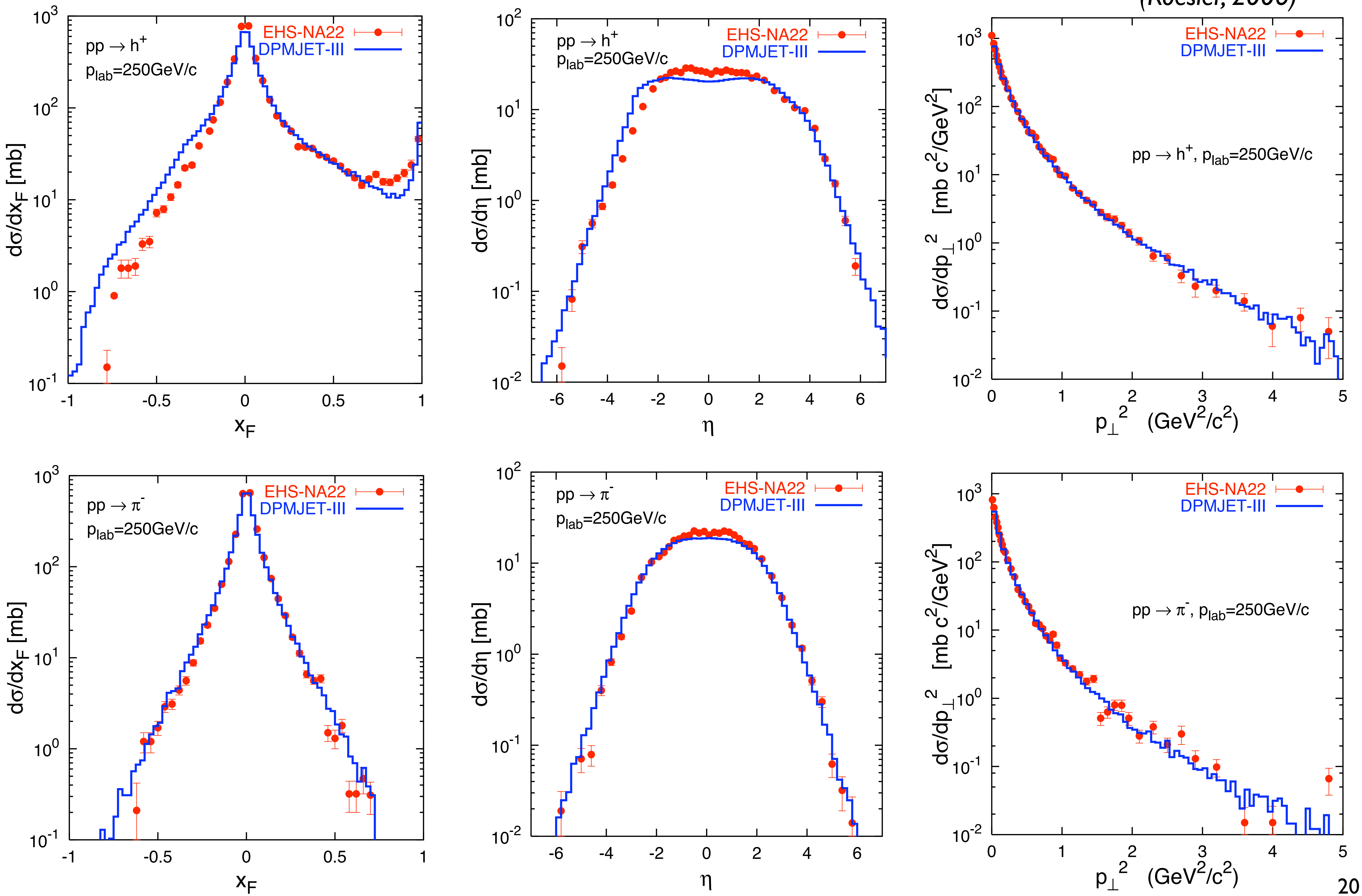
$$2E\,\frac{dN}{d^3p} = \frac{dN}{dy\,d^2p_\perp} \longrightarrow f(x_F, p_\perp)$$

Implication: distribution of high-energy
independent of energy

$$\frac{dN}{dx} \approx \tilde{f}(x) \qquad x = E/E_{\mathrm{prim}}$$

NA22 European Hybrid Spectrometer data

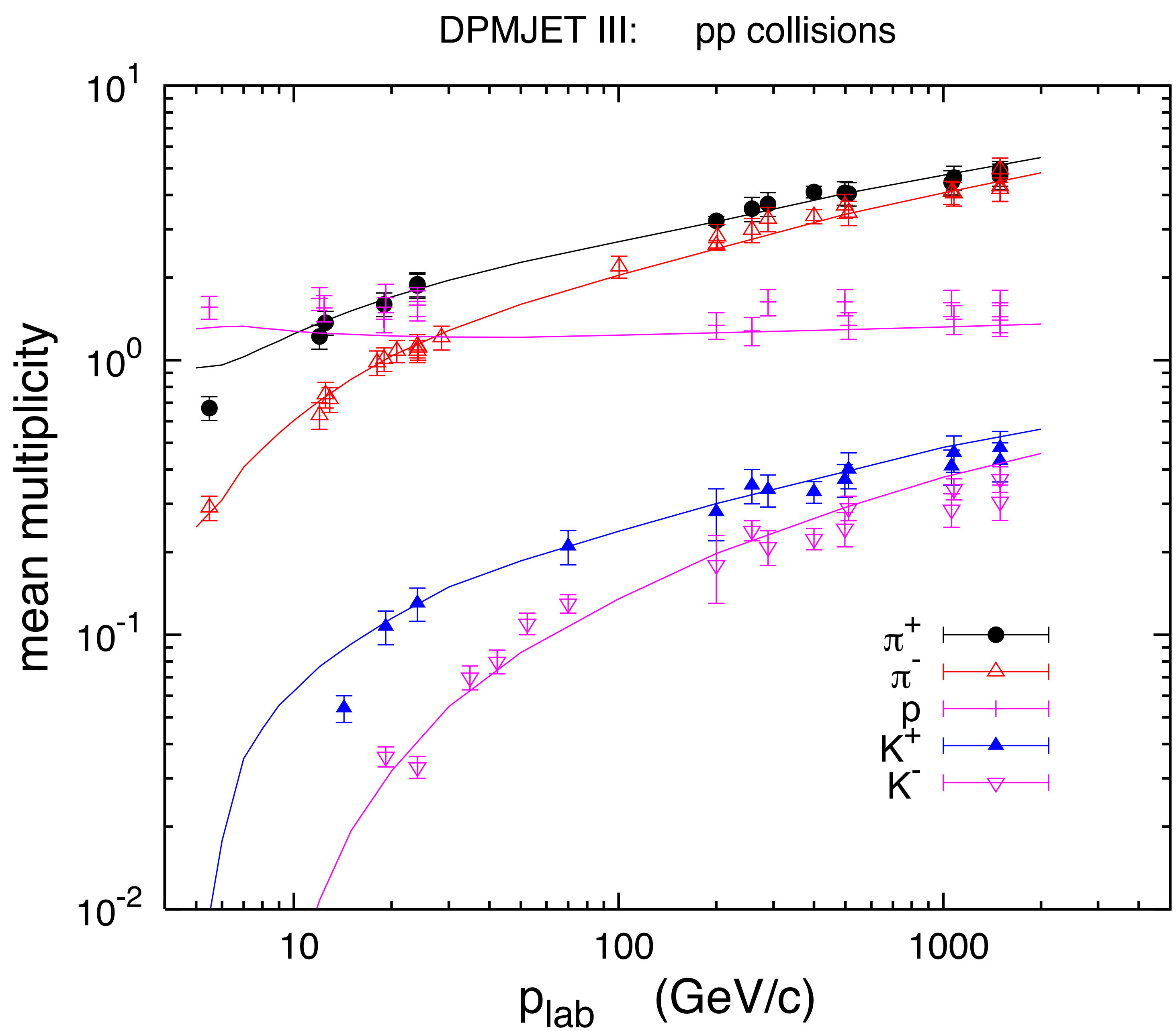
(Roesler, 2006)



Secondary particle multiplicities

proton - proton, $E_{lab} = 200 GeV$

	Exp.	DPMJET-III
charged	7.69 ± 0.06	7.64
neg.	2.85 ± 0.03	2.82
p	1.34 ± 0.15	1.26
n	0.61 ± 0.30	0.66
π^+	3.22 ± 0.12	3.20
π^-	2.62 ± 0.06	2.55
K^+	0.28 ± 0.06	0.30
K^-	0.18 ± 0.05	0.20
Λ	0.096 ± 0.01	0.10
$\bar{\Lambda}$	0.0136 ± 0.004	0.0105



Secondary particle multiplicities

Power-law increase of number of secondary particles

$$n_{\mathrm{ch}} \sim s^{0.1}$$

Leading particles

proton - proton, $E_{lab} = 200$GeV

	Exp.	DPMJET-III
charged	7.69 ± 0.06	7.64
neg.	2.85 ± 0.03	2.82
p	1.34 ± 0.15	1.26
n	0.61 ± 0.30	0.66
π^+	3.22 ± 0.12	3.20
π^-	2.62 ± 0.06	2.55
K^+	0.28 ± 0.06	0.30
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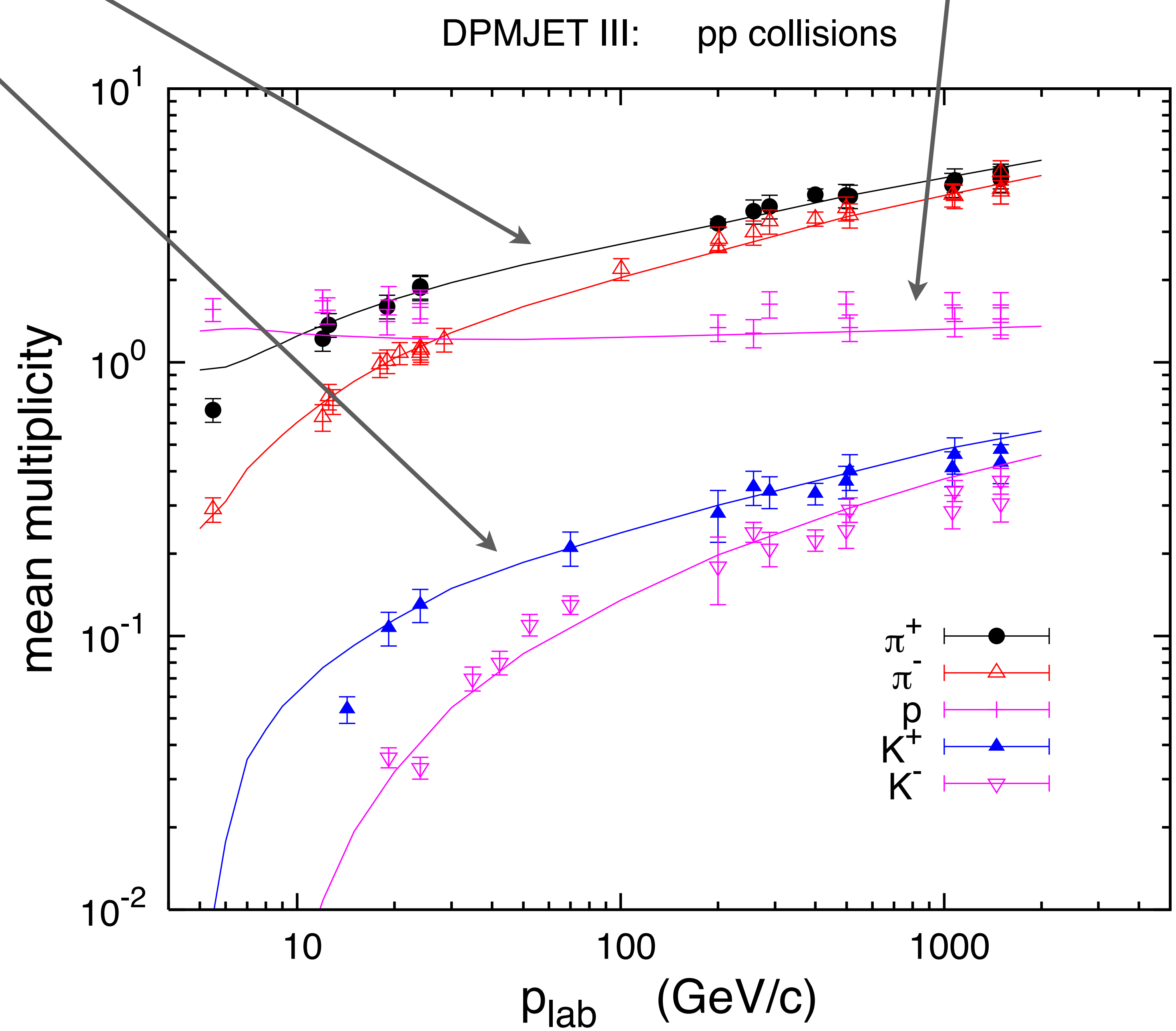
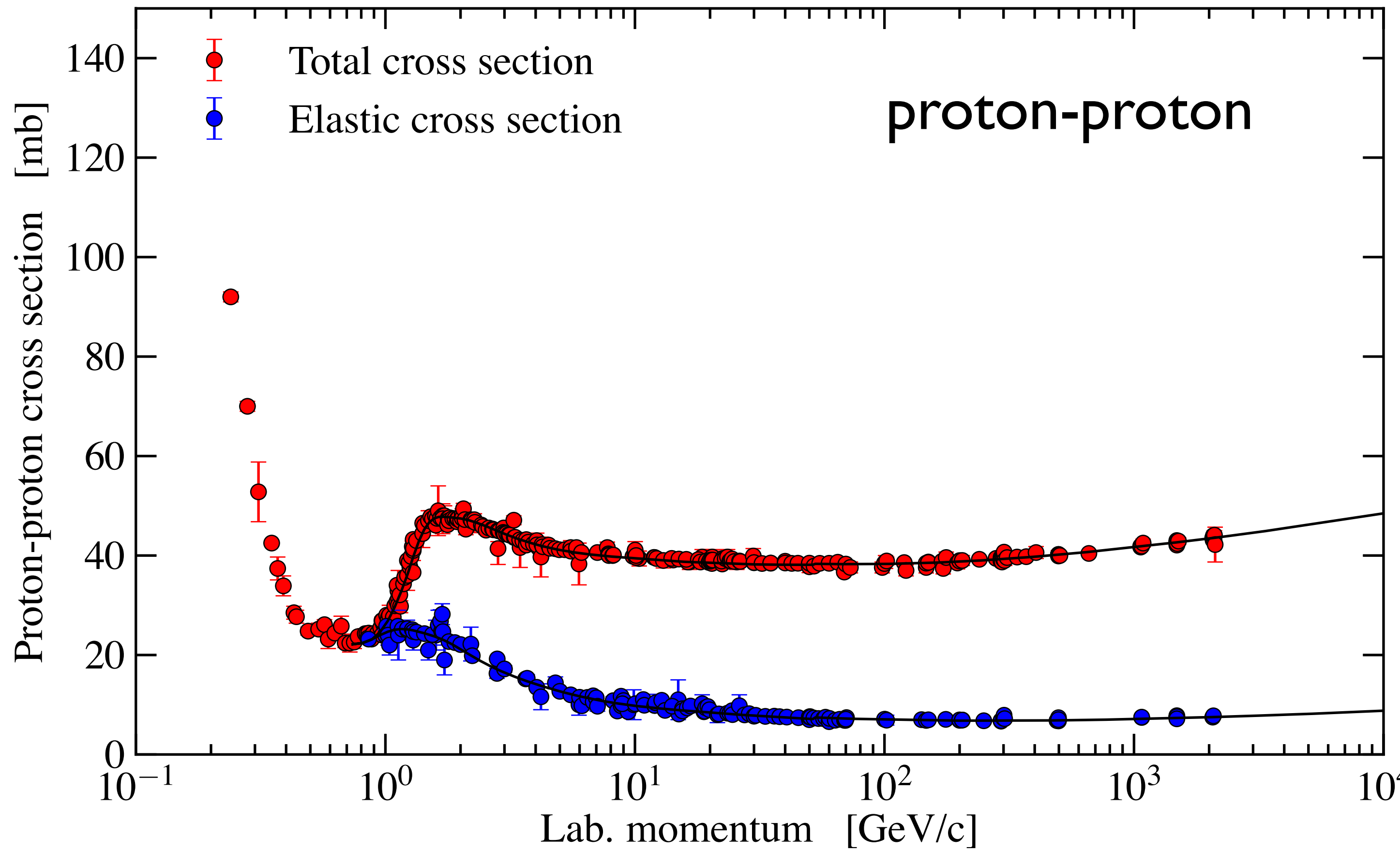
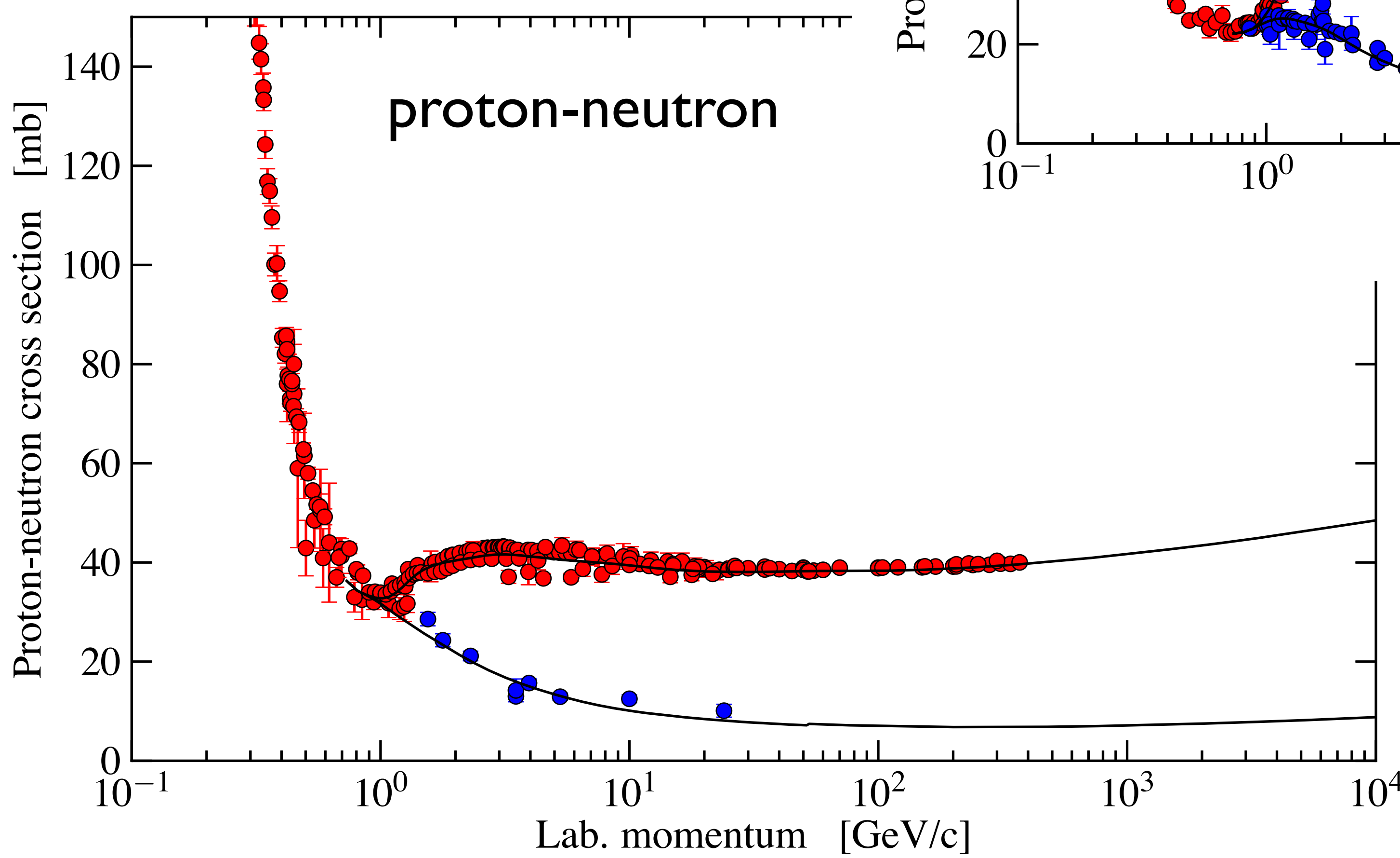
Λ	0.096 ± 0.01	0.10
$\bar{\Lambda}$	0.0136 ± 0.004	0.0105



Parametrization of cross sections

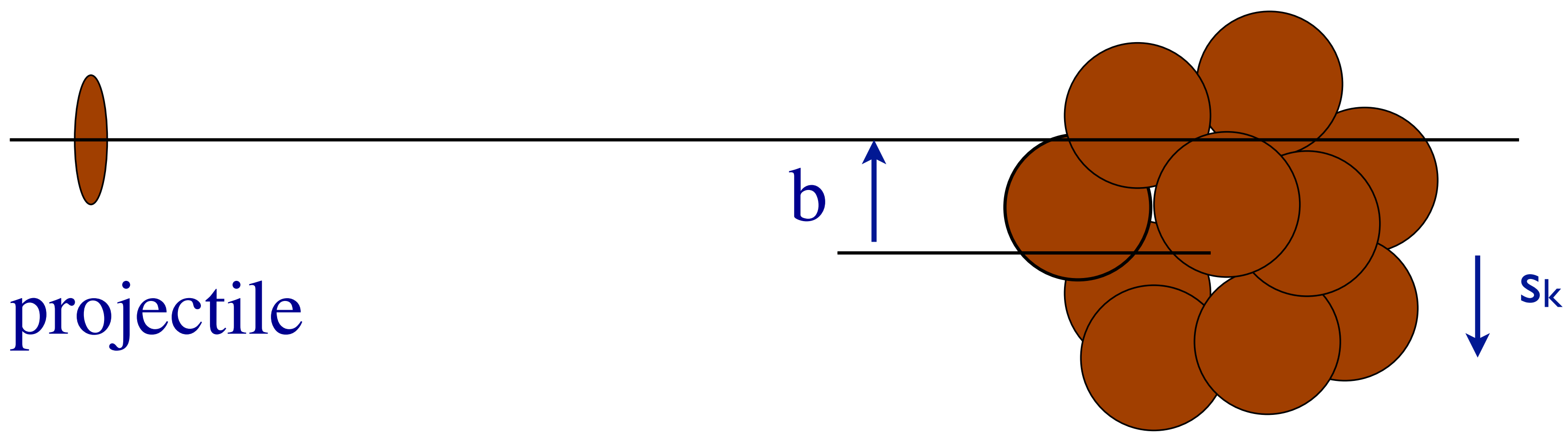
Examples of used parametrizations





All relevant total cross sections measured at low energy

Interaction of hadrons with nuclei



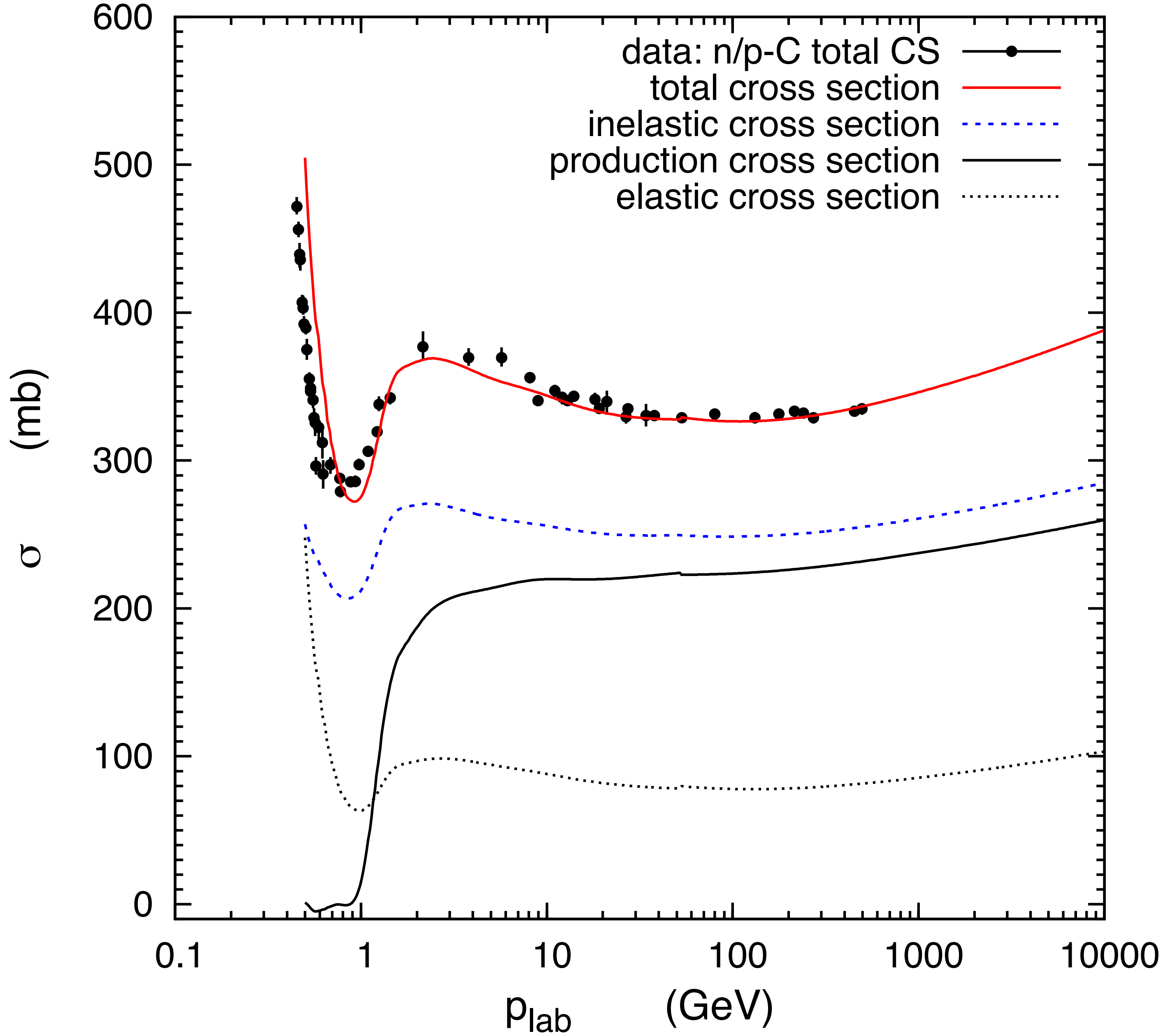
Glauber approximation:

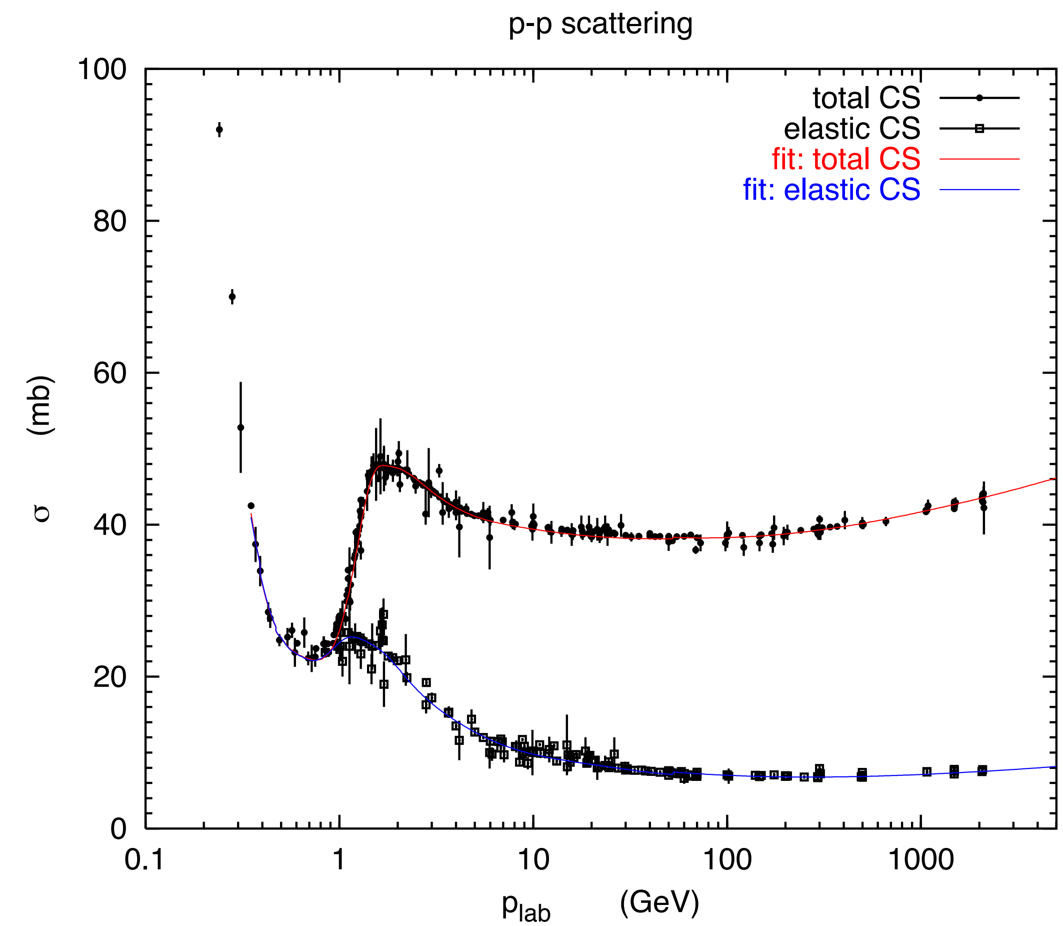
$$\sigma_{\rm inel} = \int d^2\vec{b} \left[1 - \prod_{k=1}^{A} \left(1 - \sigma_{\rm tot}^{NN} T_N(\vec{b} - \vec{s}_k) \right) \right] \approx \int d^2\vec{b} \left[1 - \exp\left\{ -\sigma_{\rm tot}^{NN} T_A(\vec{b}) \right\} \right]$$

$$\sigma_{\rm prod} \approx \int d^2\vec{b} \left[1 - \exp\left\{ -\sigma_{\rm ine}^{NN} T_A(\vec{b}) \right\} \right]$$

Coherent superposition of elementary nucleon-nucleon interactions

Example: proton-carbon cross section

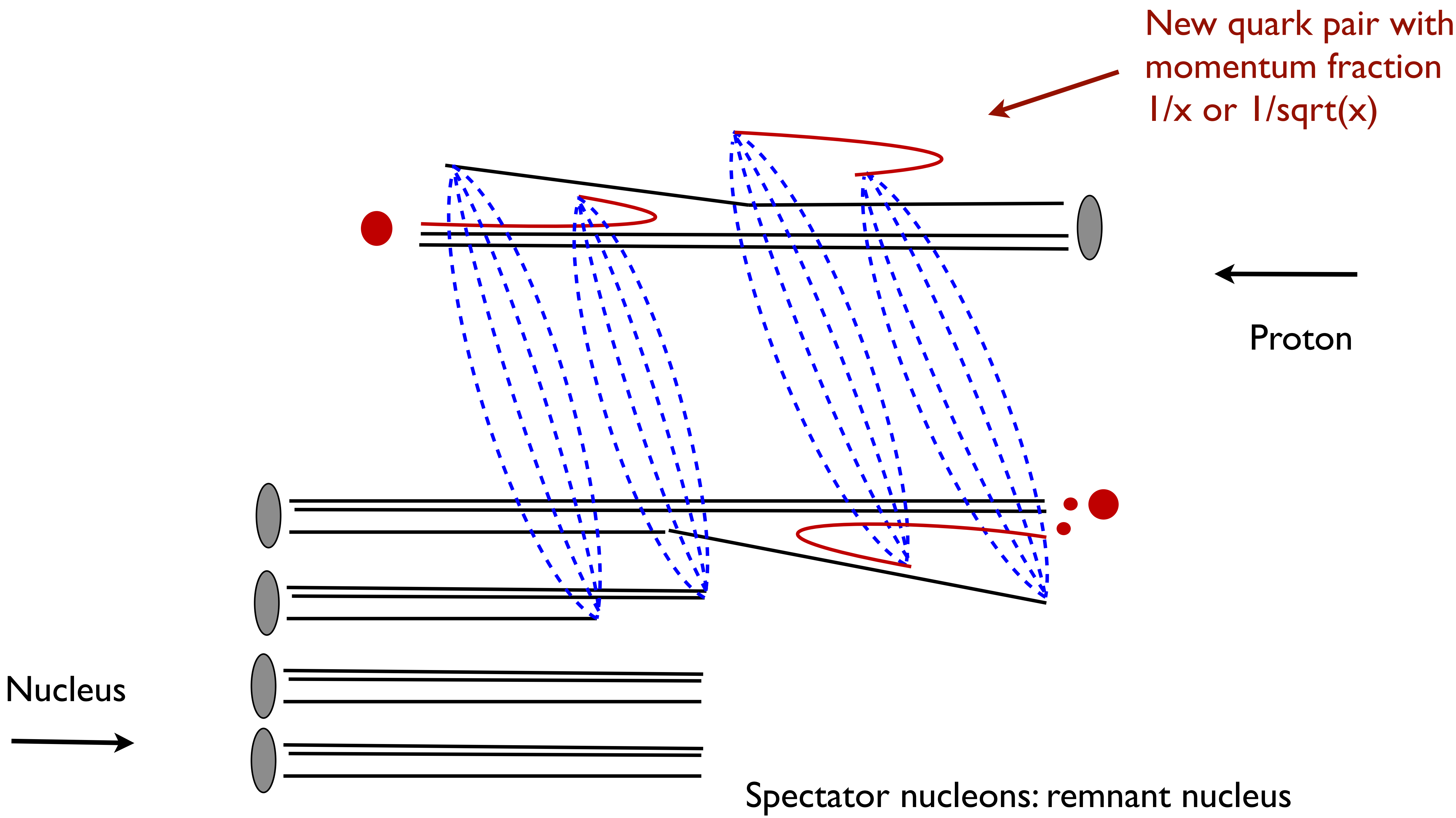




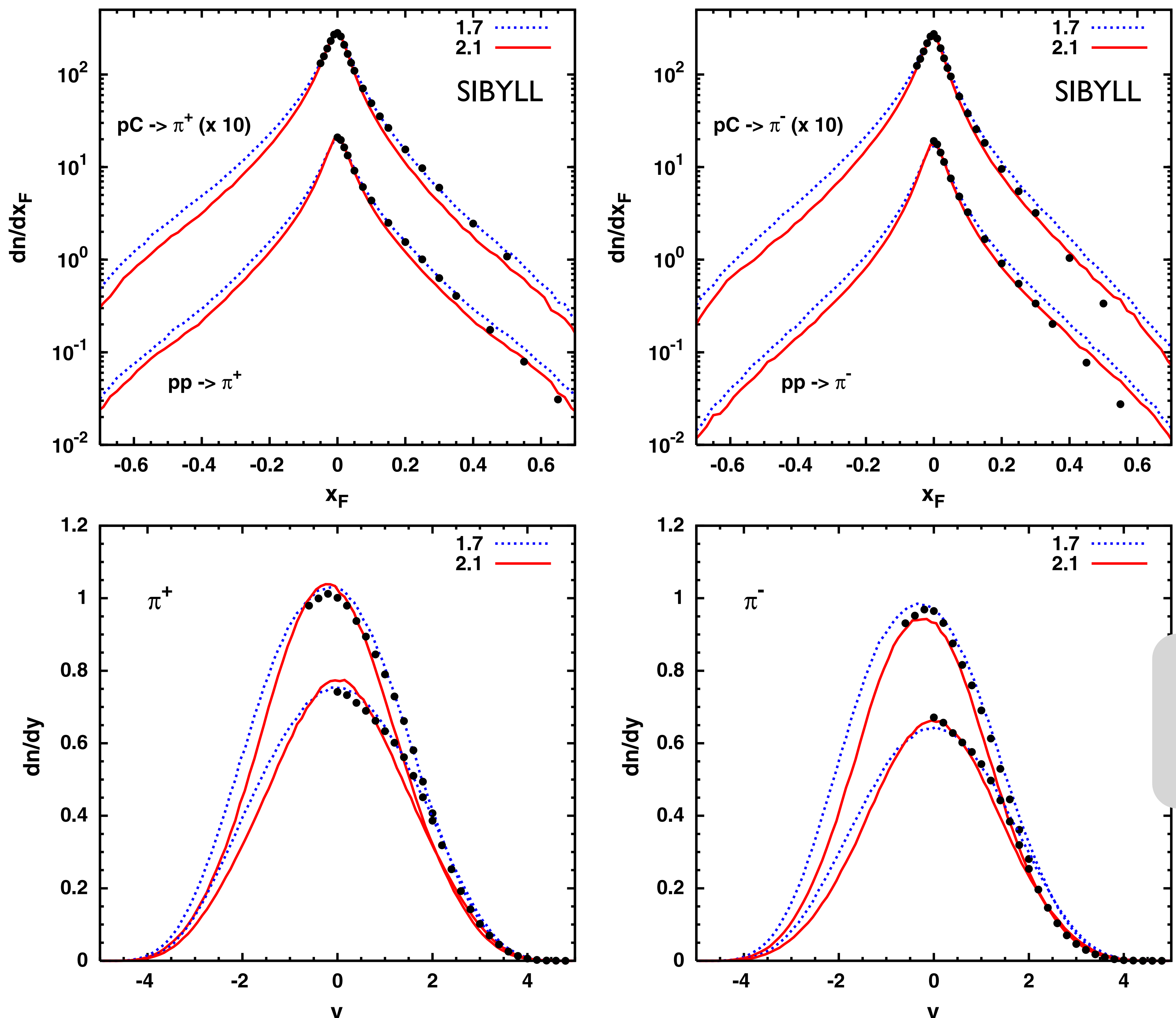
$$\sigma_{\text{prod}}^{\text{pC}} = \frac{A\sigma_{\text{ine}}^{\text{pp}}}{\langle n_{\text{part}} \rangle}$$

Number of participating target nucleons (1.8 at 100 GeV)

String configuration for nucleus as target



SIBYLL: central & leading particle production

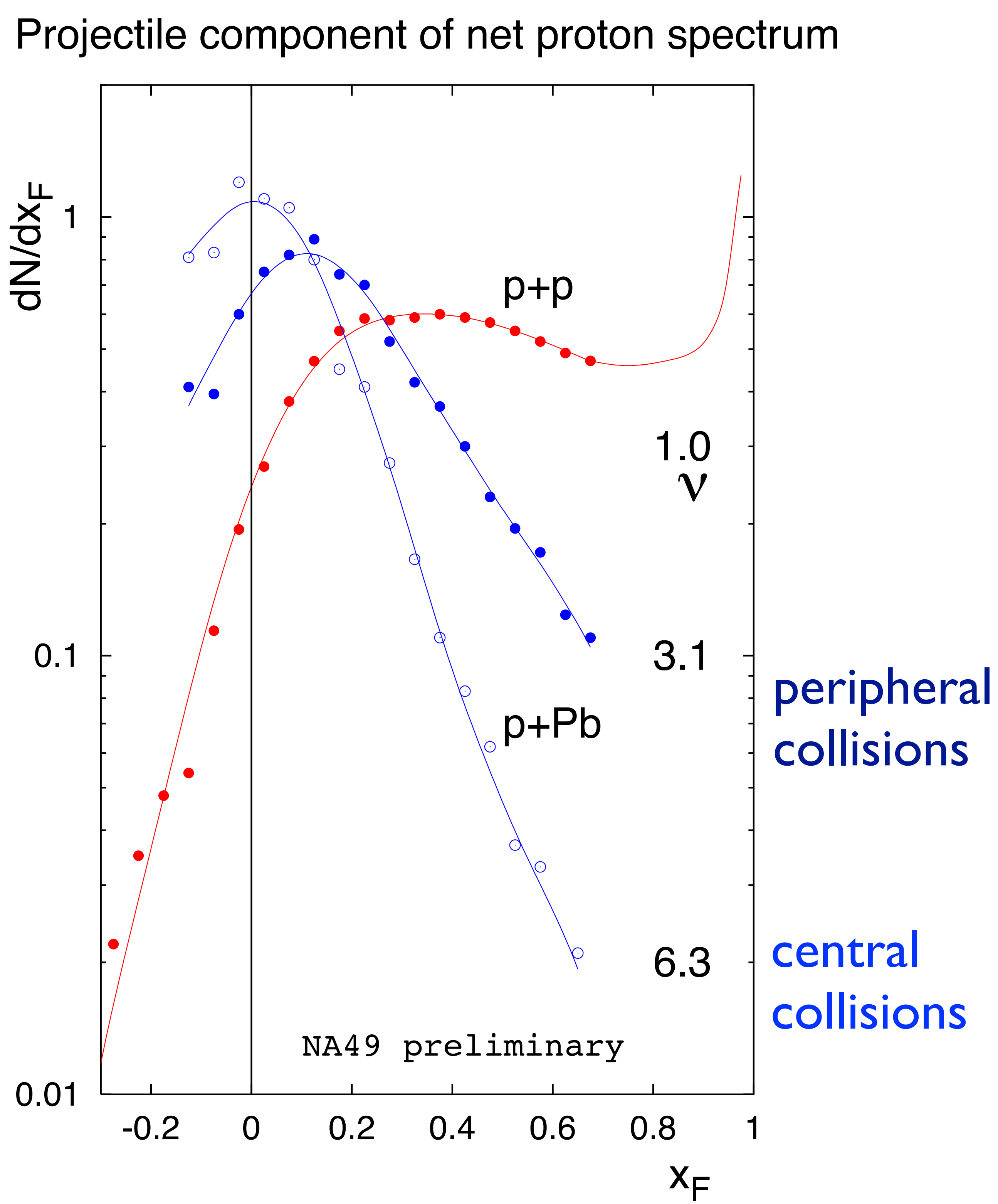


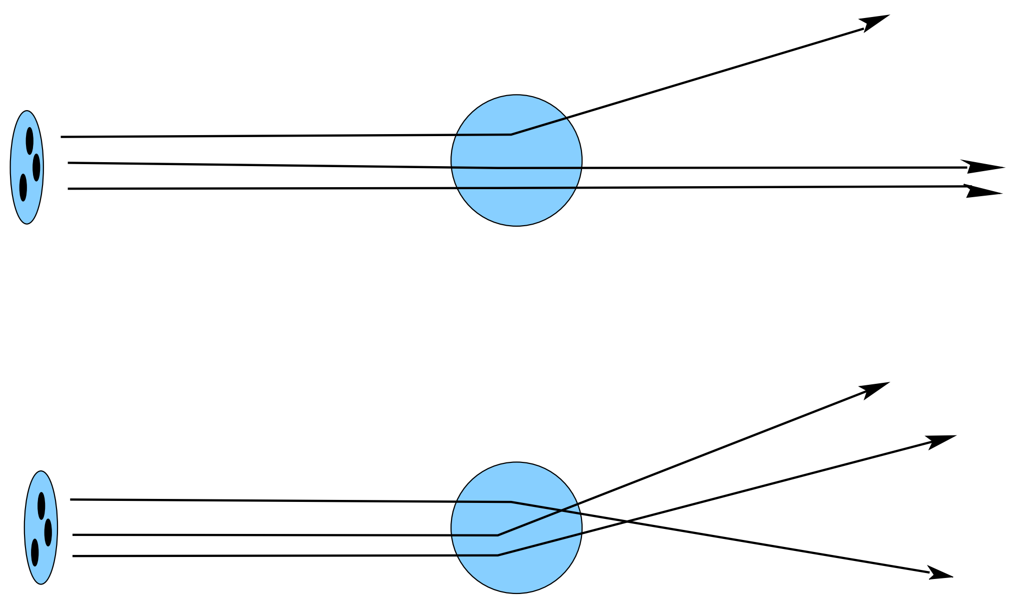
NA49 p-p and p-C at 158 GeV

Proton-proton and proton-nucleus distributions very similar

(Ahn et al., PRD80 (2009) 094003)

Leading particle effect and nuclei





E_{lab} = 149 GeV

Central collisions:

- no leading particle effect,
- secondaries of highest energy are mesons

Basic features of multiparticle production

- Leading particle effect
  - ~50% of energy carried by leading nucleon
  - incoming proton: 66% proton, 33% neutron

- Secondary particles
  - power-law increase of multiplicity
  - quark counting: ~33% π^0, 66% $\pi^\pm$
  - transverse momentum energy-independent
  - scaling of secondary particle distributions
  - baryons are pair-produced, delayed threshold

- Total cross sections
  - no good microscopic model (Regge theory)
  - often parametrization of data used
  - Glauber model for nuclei

- Diffraction (rapidity gaps)
  - elastic scattering & low-mass diffraction dissociation
  - large multiplicity fluctuations

Comparison of low/intermediate energy models

DPMJET II & III *(Ranft / Roesler, RE, Ranft, Bopp)*	• microscopic (universal) model • resonances for low energy hadron projectiles (HADRIN, NUCRIN) • two- and multi-string model
FLUKA *(Ferrari, Sala, Ranft, Roesler)*	• microscopic (universal) model • resonances (PEANUT), photodissociation • two-string model, DPMJET at high energy
GHEISHA *(Fesefeld)*	• parametrization of data (GEANT 3) • wide range of projectiles/targets • limited to E_{lab} < 500 GeV
UrQMD (Bleicher et al.)	• combination of microscopic model with data parametrization (no Glauber calc.) • optimized for interactions of nuclei
SOPHIA *(Mücke, RE, et al.)*	• dedicated photon-nucleon model • resonances, two-strings, E_{lab} < 500 GeV
RELDIS *(Pshenichnov)*	• dedicated photodissociation model for nuclei, wide range of nuclei

Example: Waxman-Bahcall neutrino limit (i)

Maximum ``reasonable´´neutrino flux due to interaction of cosmic rays in sources

Assumptions:

- sources accelerate only protons (other particles yield fewer neutrinos)
- injection spectrum at sources known (power law index -2)
- each proton interacts once on its way to Earth (optically thin sources)

Proton flux at sources

$$\Phi_p(E_p) = \frac{dN_p}{dE_p dA dt d\Omega} = A\, E_p^{-\alpha}$$

Master equation

$$\boxed{\Phi_\nu(E_\nu) = \int \frac{dN_\nu}{dE_\nu}(E_p)\, \Phi_p(E_p)\, dE_p}$$

Number of neutrinos produced in interval $E_\nu ... E_\nu + dE_\nu$, per proton interaction

Spectrum weighted moments (i)

$$\Phi_\nu(E_\nu) = \int \frac{dN_\nu}{dE_\nu}(E_p)\, \Phi_p(E_p)\, dE_p$$

Aim: re-writing of equation for scaling of yield function

Scaling of neutrino yield

$$x = \frac{E_\nu}{E_p}$$

fraction of proton energy given to neutrino

$$\boxed{\frac{dN_\nu}{dE_\nu}(E_p) = \frac{1}{E_p}\frac{dN_\nu}{dx}} \qquad (1)$$

energy-independent yield function

Elementary math

$$dE_p = \frac{E_\nu}{x^2}\, dx \qquad (2)$$

$$\Phi_p(E_p) = A\, E_p^{-\alpha} = A \left(\frac{E_\nu}{x}\right)^{-\alpha} = x^\alpha\, A\, E_\nu^{-\alpha} \qquad (3)$$

Spectrum weighted moments (ii)

$$\Phi_\nu(E_\nu) = \int \frac{dN_\nu}{dE_\nu}(E_p)\, \Phi_p(E_p)\, dE_p$$

substitutions (1) - (3)

$$\Phi_\nu(E_\nu) \;=\; \int_0^1 x^{\alpha-1}\, \frac{dN_\nu}{dx}\, A\, E_\nu^{-\alpha}\, dx$$

$$\Phi_\nu(E_\nu) \;=\; \left[\int_0^1 x^{\alpha-1}\, \frac{dN_\nu}{dx}\, dx\right] A\, E_\nu^{-\alpha}$$

Spectrum weighted moment
(just a number that depends
only on particle physics)

Proton flux
(but with neutrino energy
instead of proton energy)

Example: Waxman-Bahcall neutrino limit (ii)

Proton spectrum
with $\alpha = 2$

$$\Phi_\nu(E_\nu) = \left[\int_0^1 x \, \frac{dN_\nu}{dx} \, dx\right] A \, E_\nu^{-2}$$

Spectrum weighted moment for α=2:
mean energy fraction of proton given to neutrino
times number of neutrinos per interaction

Relevant interaction & decay chain (33% of all interactions with small E_{cm})

$$p + \gamma \longrightarrow n \, \pi^+ \longrightarrow n \, \mu^+ \, \nu_\mu \longrightarrow n \, \underbrace{e^+ \, \nu_e \, \bar{\nu}_\mu \, \nu_\mu}$$

20% of p
energy

each particle has 25% of the
energy of the π^+

$$\Phi_{\nu_\mu}(E_{\nu_\mu}) = 0.33 \times 0.2 \times 0.25 \;\; A E_{\nu_\mu}^{-2}$$

Atmospheric muons and neutrinos

Atmosphere is dense target, secondary particles can interact or decay

Spectrum weighted moment

Example: pion flux in atmosphere at depth X

$$\frac{d\Phi_\pi(E,X)}{dX} = -\left(\frac{1}{\Lambda_\pi} + \frac{\varepsilon_\pi}{E\,X\cos\theta}\right)\Phi_\pi(E,X) \;+\; \frac{Z_{N\pi}}{\lambda_N}\Phi_N(E)e^{-X/\Lambda_N}$$

Regeneration of particle flux through interaction

$$\Lambda_N = \lambda_N/(1 - Z_{NN})$$

Loss of pions due to decay

$$\varepsilon_\pi = \frac{m_\pi h_0}{\tau_\pi\ \cos\theta}$$

$$X_v = X_0 E^{-h/h_0}$$

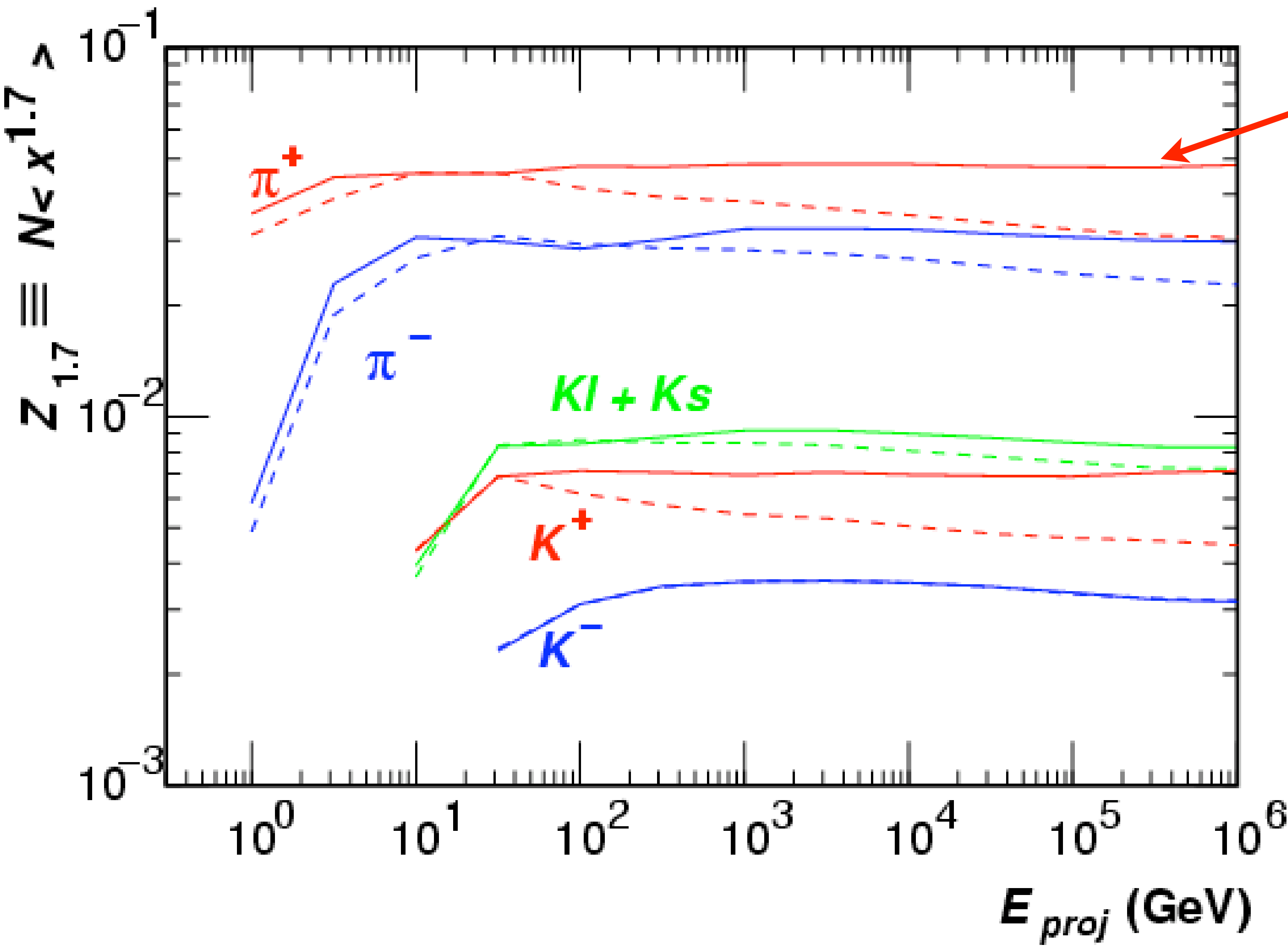
Generation of pions by primary nucleons

Muon and neutrino fluxes:
pion and kaon flux have to be folded with decay distributions

(Gaisser, Cosmic Rays and Particle Physics, 1990)

Spectrum weighted moments for α = 2.7

Detailed simulation of interactions for air target with DPMJET



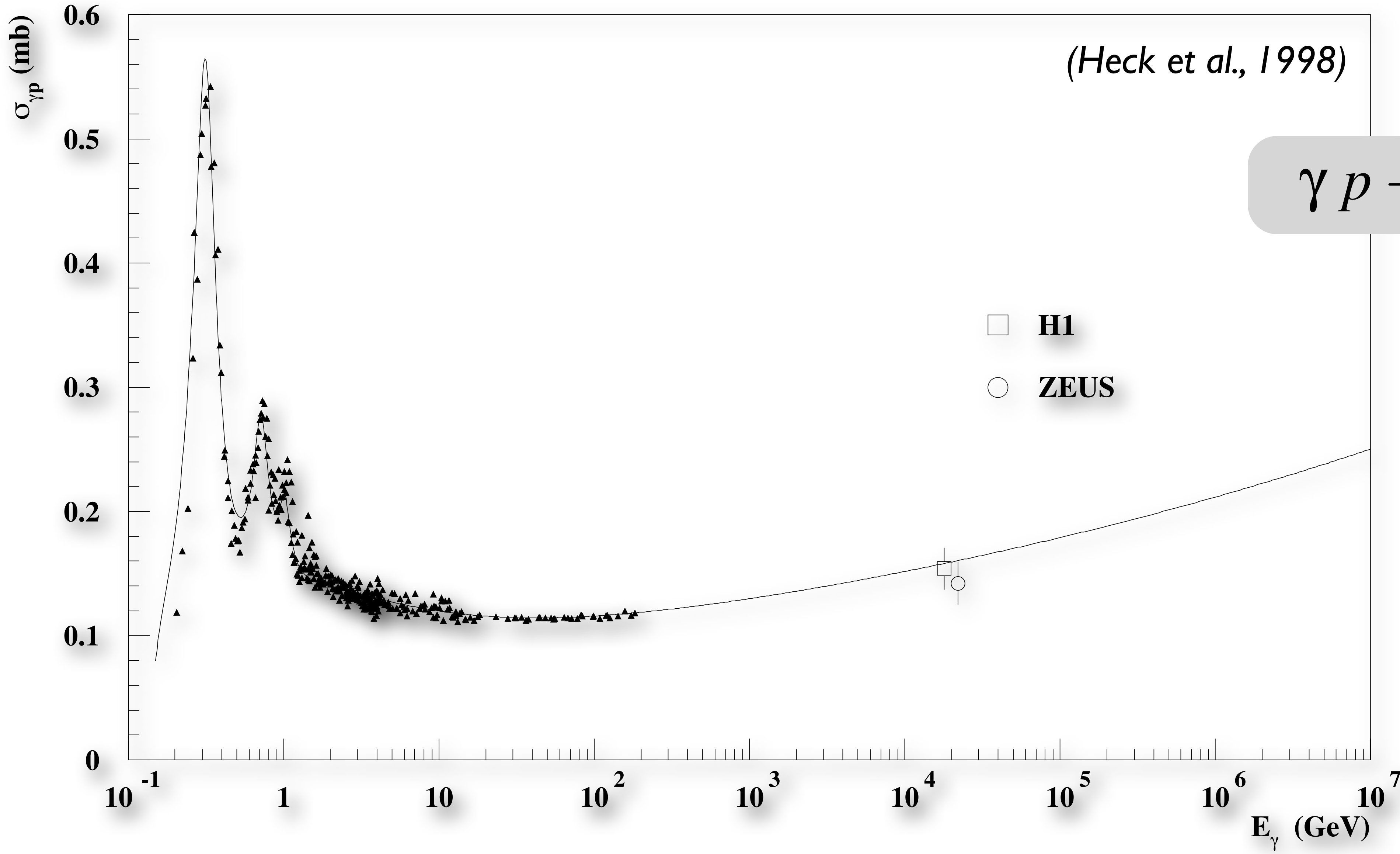
p + air → π^+ X

Dashed/solid lines: uncertainty due to possible scaling violation

(Honda et al., C2CR 2005)

Particle production at high and ultra-high energies

Simulation concepts: energy ranges



$$\gamma\, p \longrightarrow X$$

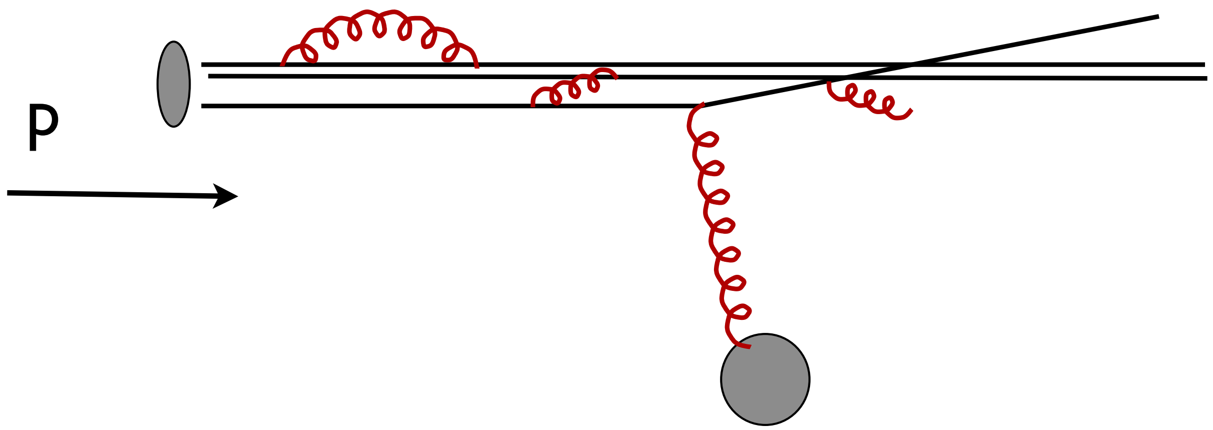
Resonances (fireball)

Scaling region (longitudinal phase space)

Minijet region (scaling violation)

???

Transition from intermediate to high energy

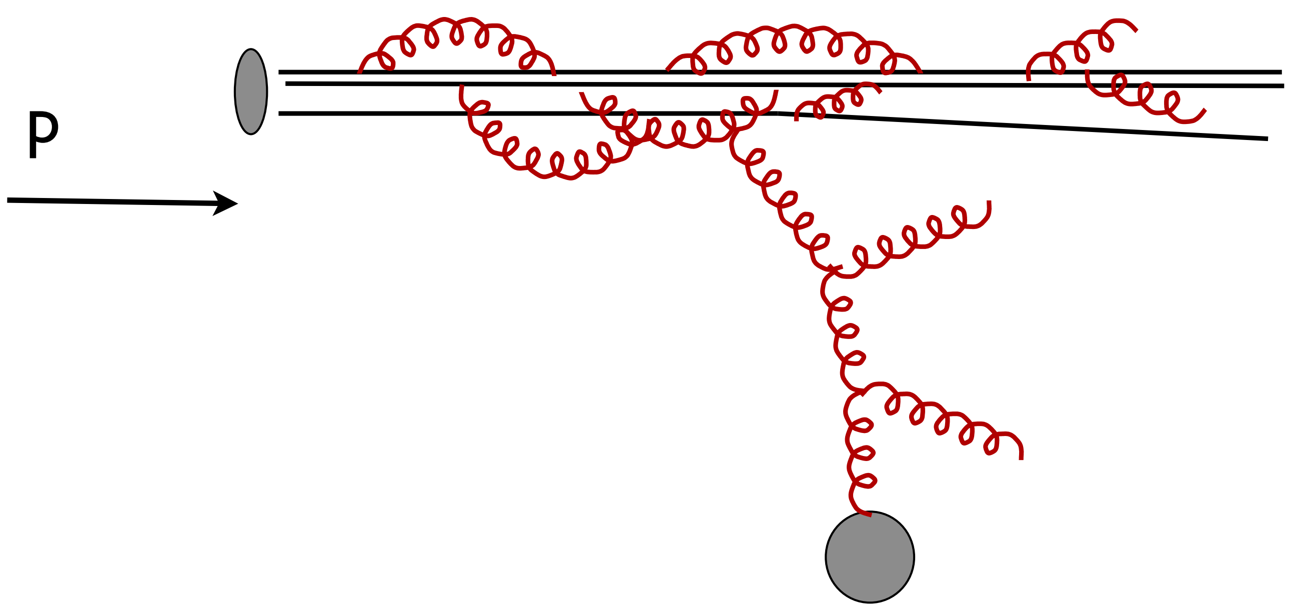


Intermediate energy:

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

Lifetime of fluctuations

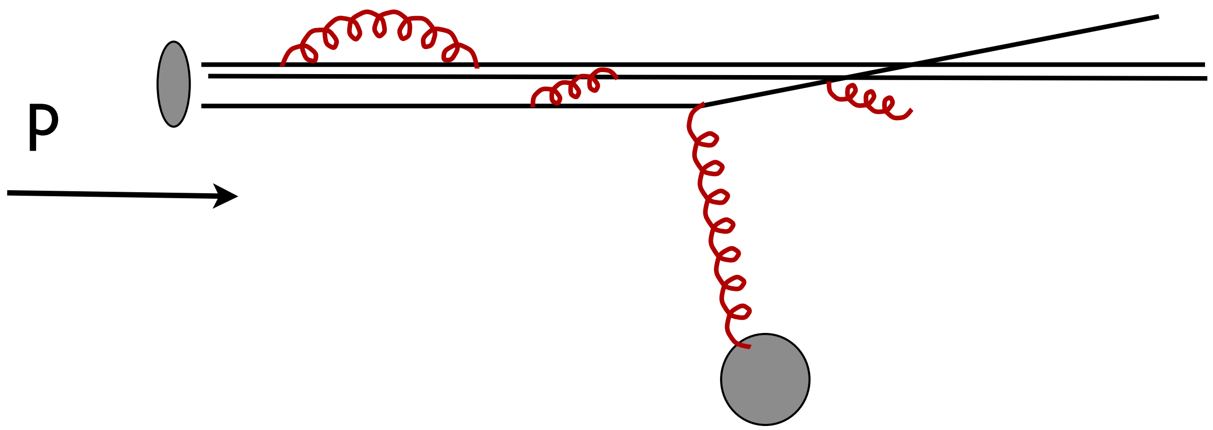
$$\Delta t \approx \frac{1}{\Delta E} = \frac{1}{\sqrt{p^2+m^2}-p} = \frac{1}{p(\sqrt{1+m^2/p^2}-1)} \approx \frac{2p}{m^2}$$



High energy regime:

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

Transition from intermediate to high energy



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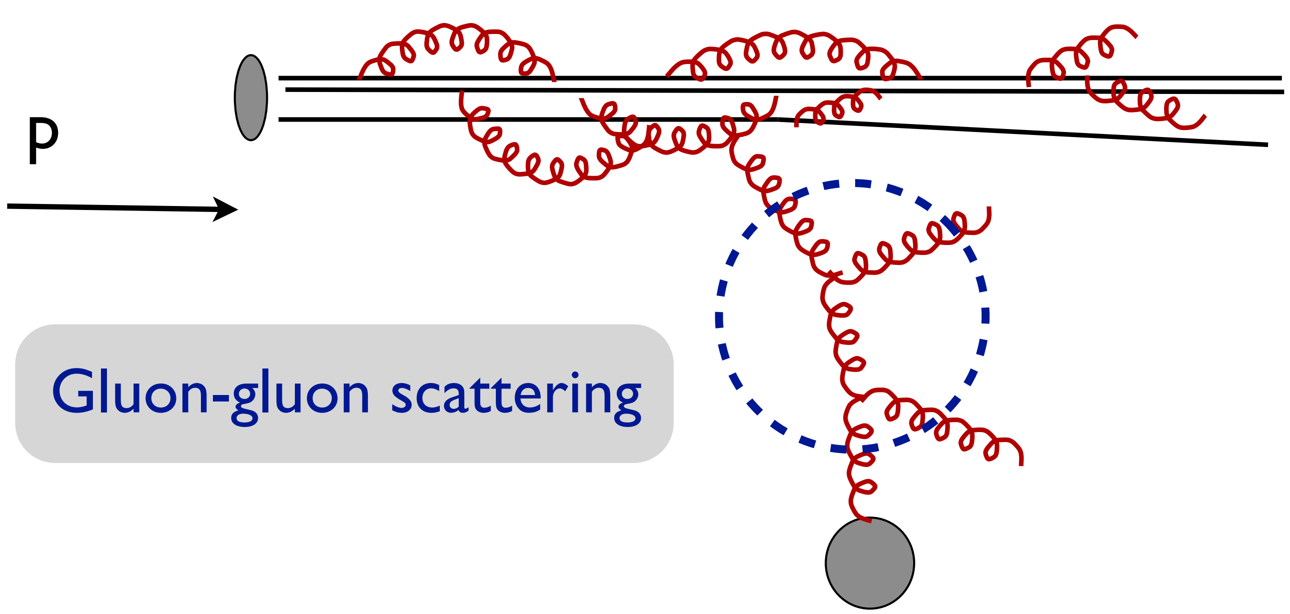
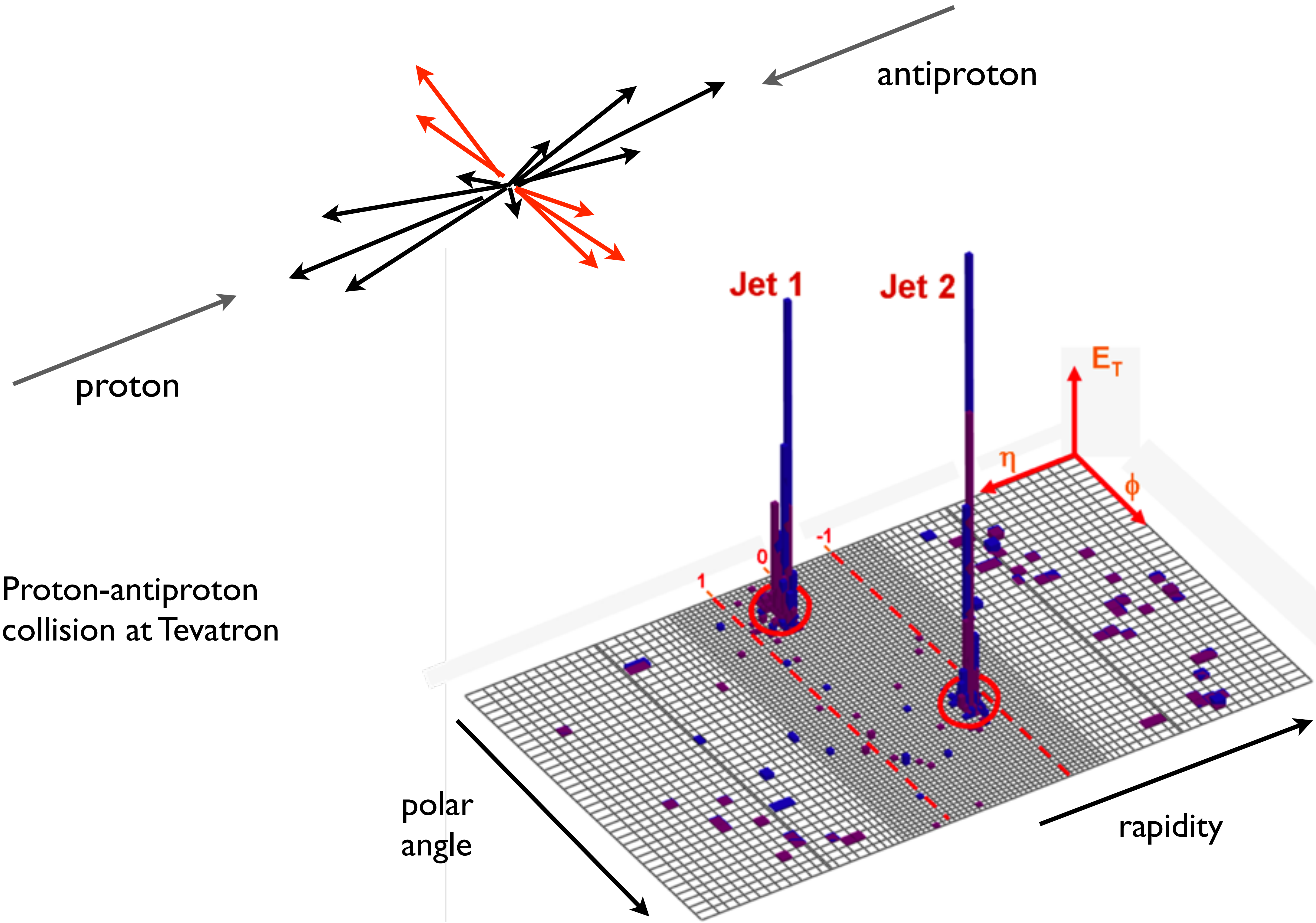


High energy regime:

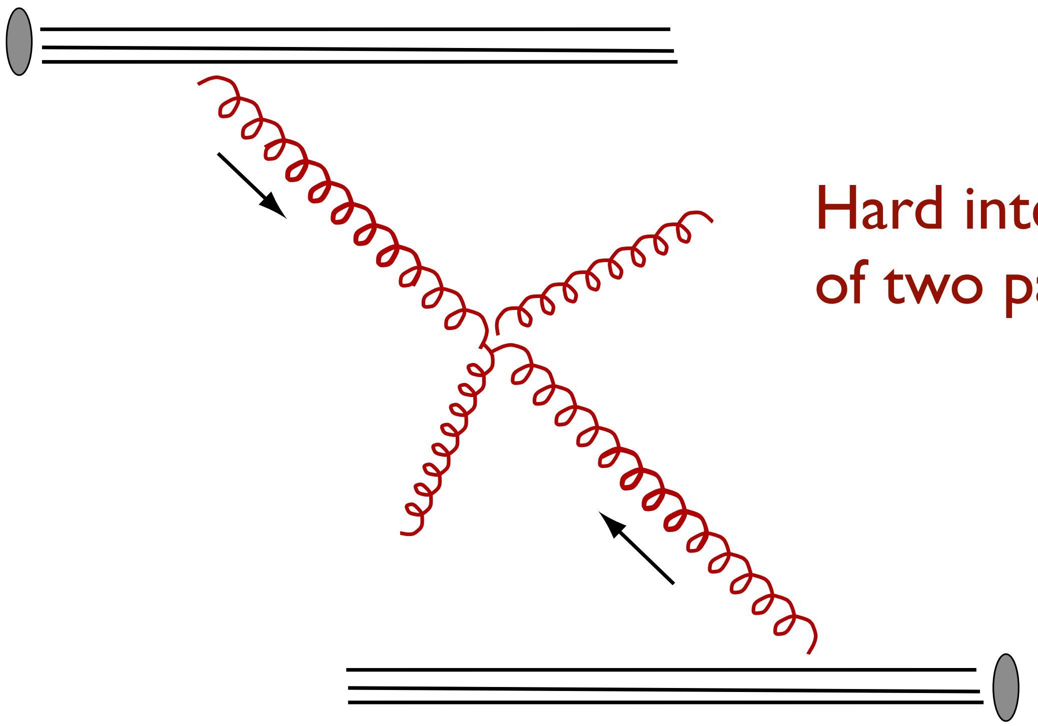
- E_{lab} > 21,000 GeV
- E_{cm} > 200 GeV
- dominated by gluons and sea quarks

Scattering of quarks and gluons: jet production

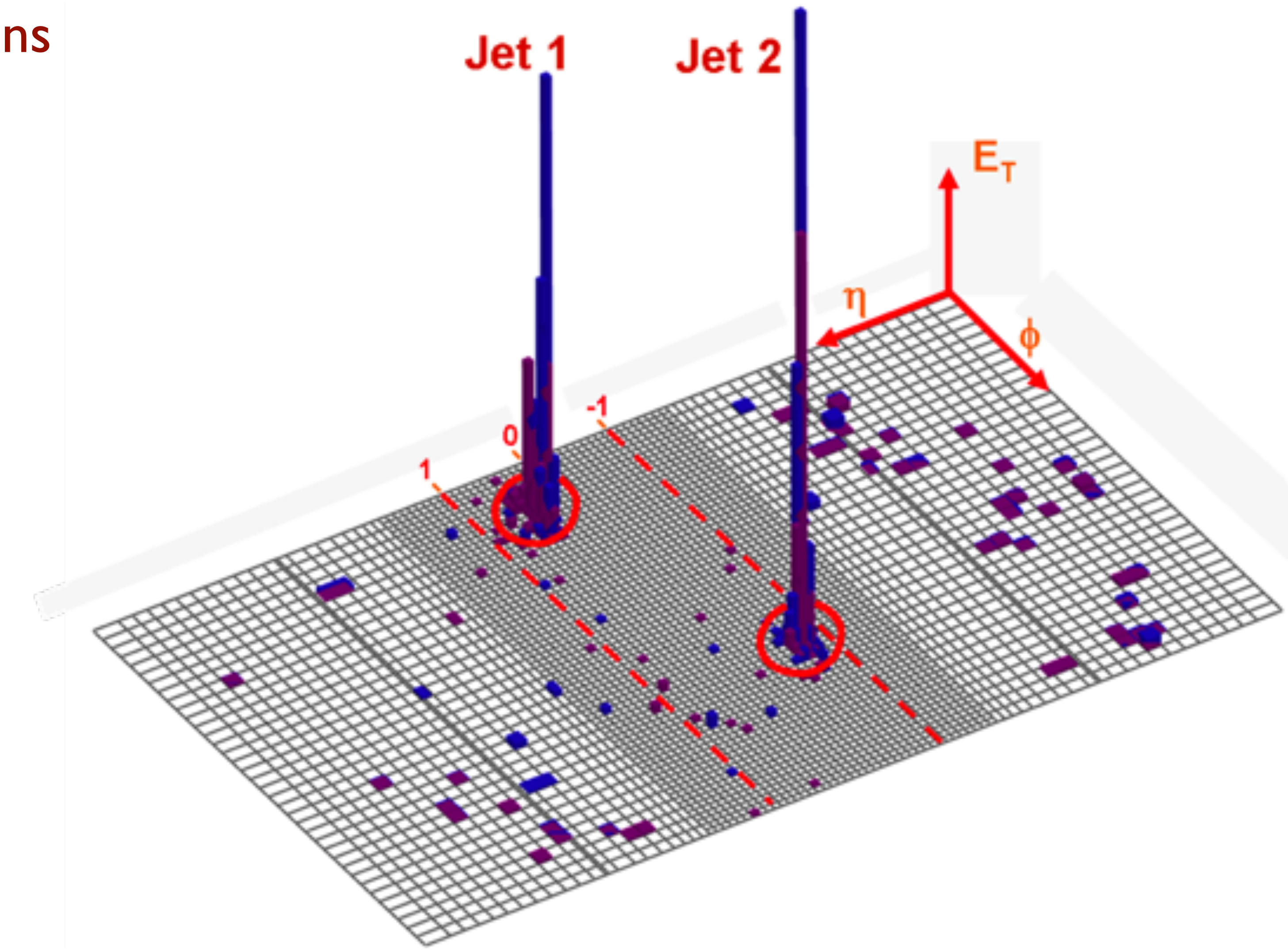


Proton-antiproton collision at Tevatron

Interpretation within perturbative QCD



Hard interaction
of two partons

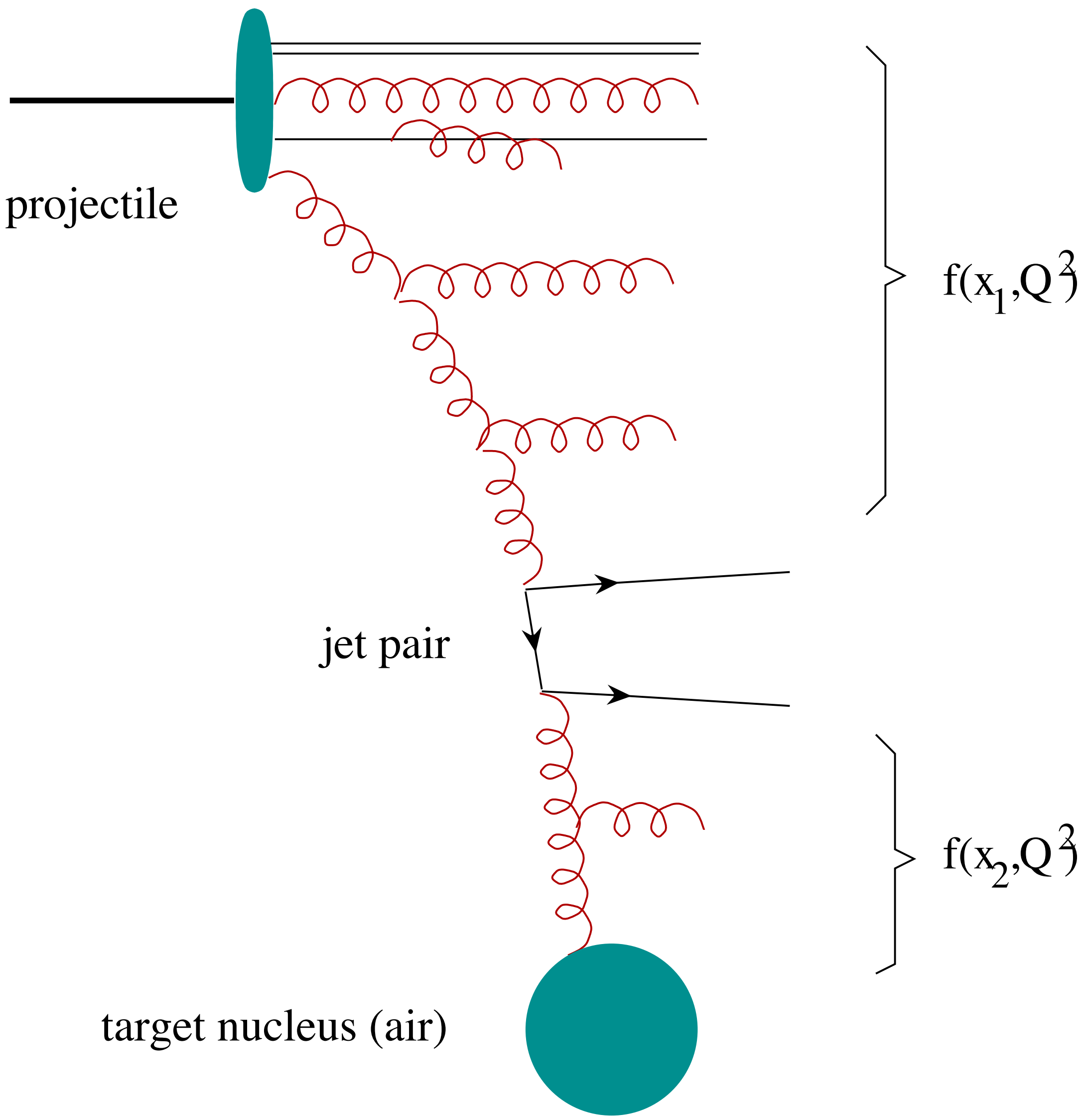


QCD predictions known
for parton-parton cross sections

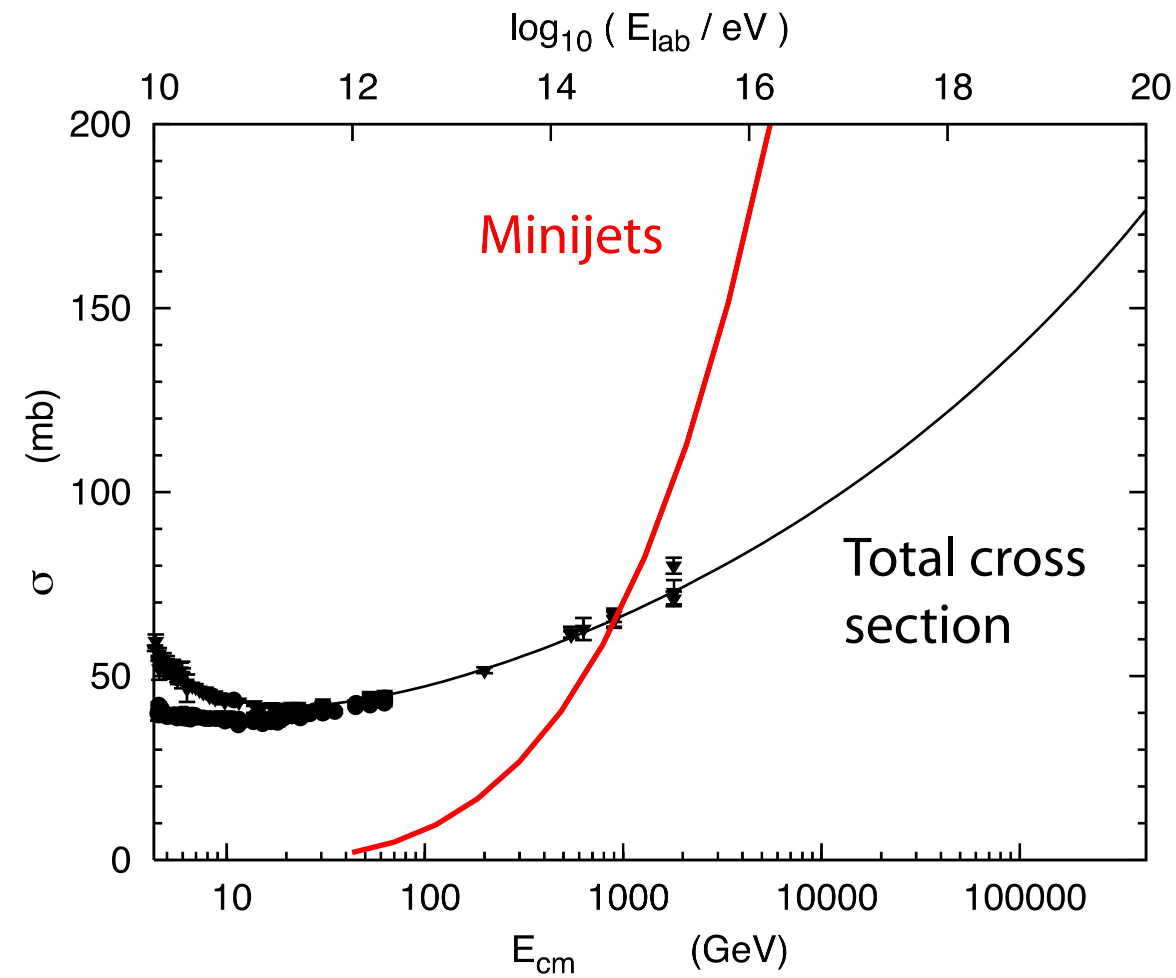
Terminology

Soft interaction: no large momentum transfer
Hard interaction: large momentum transfer ($|t| > 2\ \mathrm{GeV}^2$)

QCD parton model: minijets

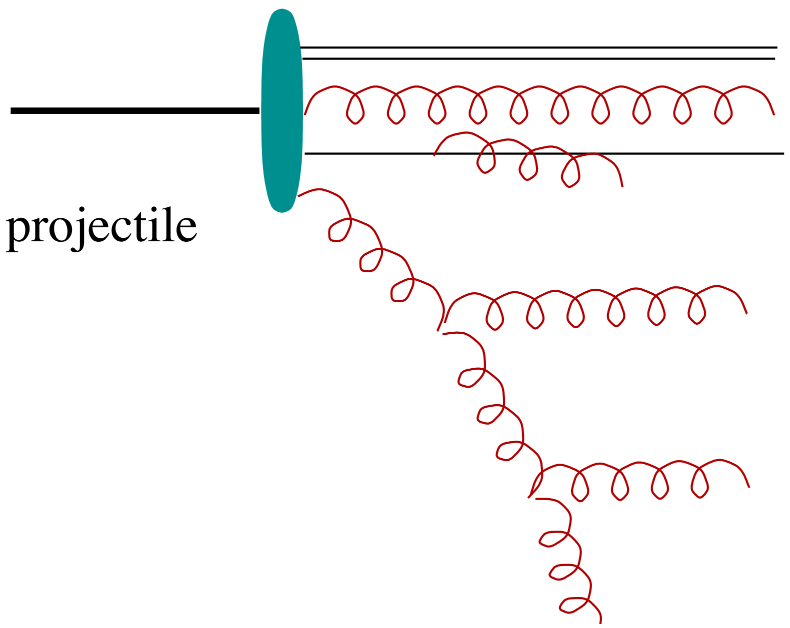


Proton-proton cross section



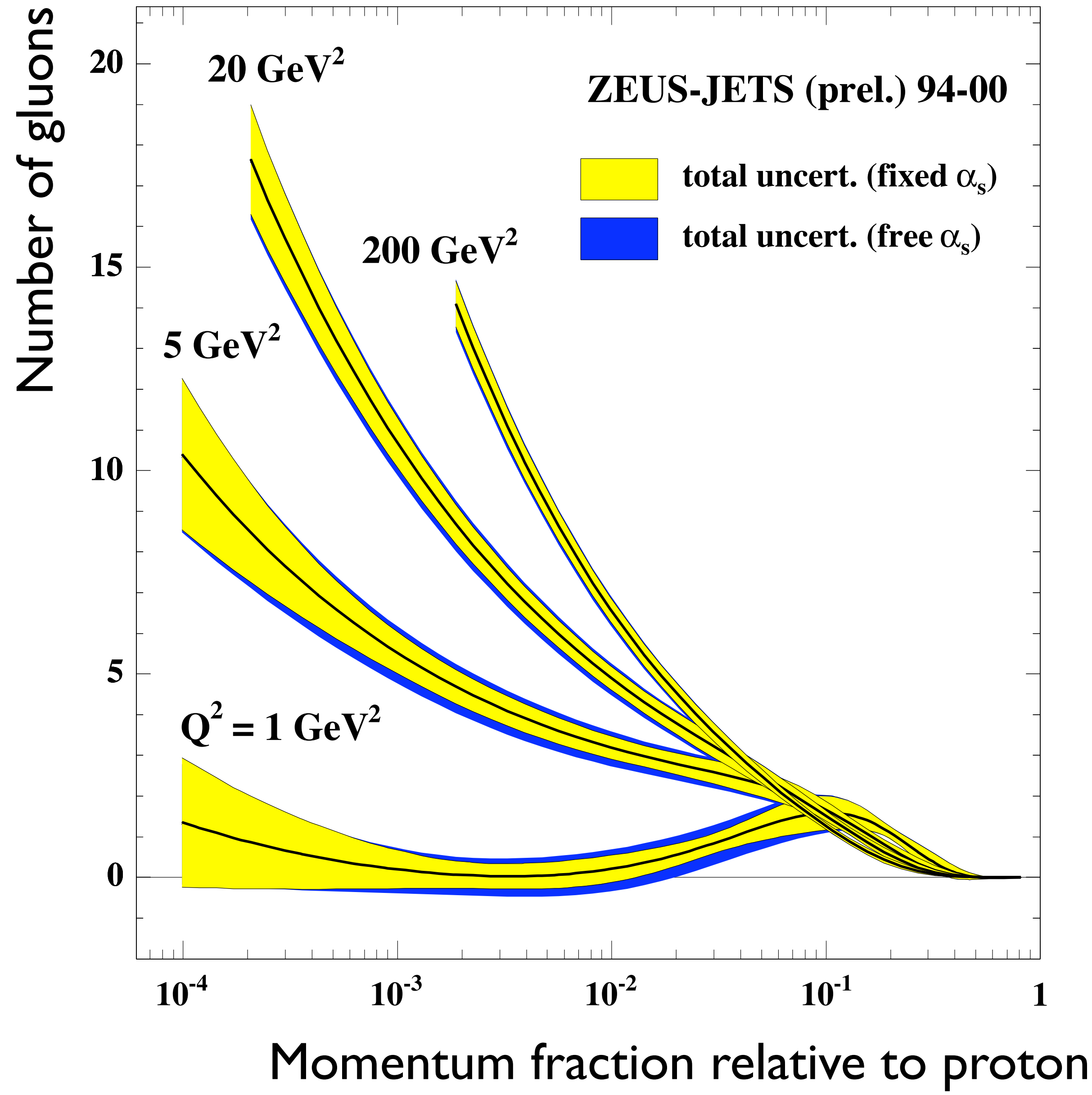
$$\sigma_{QCD} = \sum_{i,j,k,l} \frac{1}{1+\delta_{kl}} \int dx_1\, dx_2 \int_{p_\perp^{\rm cutoff}} dp_\perp^2\, f_i(x_1,Q^2)\, f_j(x_2,Q^2)\, \frac{d\sigma_{i,j\to k,l}}{dp_\perp}$$

Perturbative QCD predictions for parton densities



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

HERA data

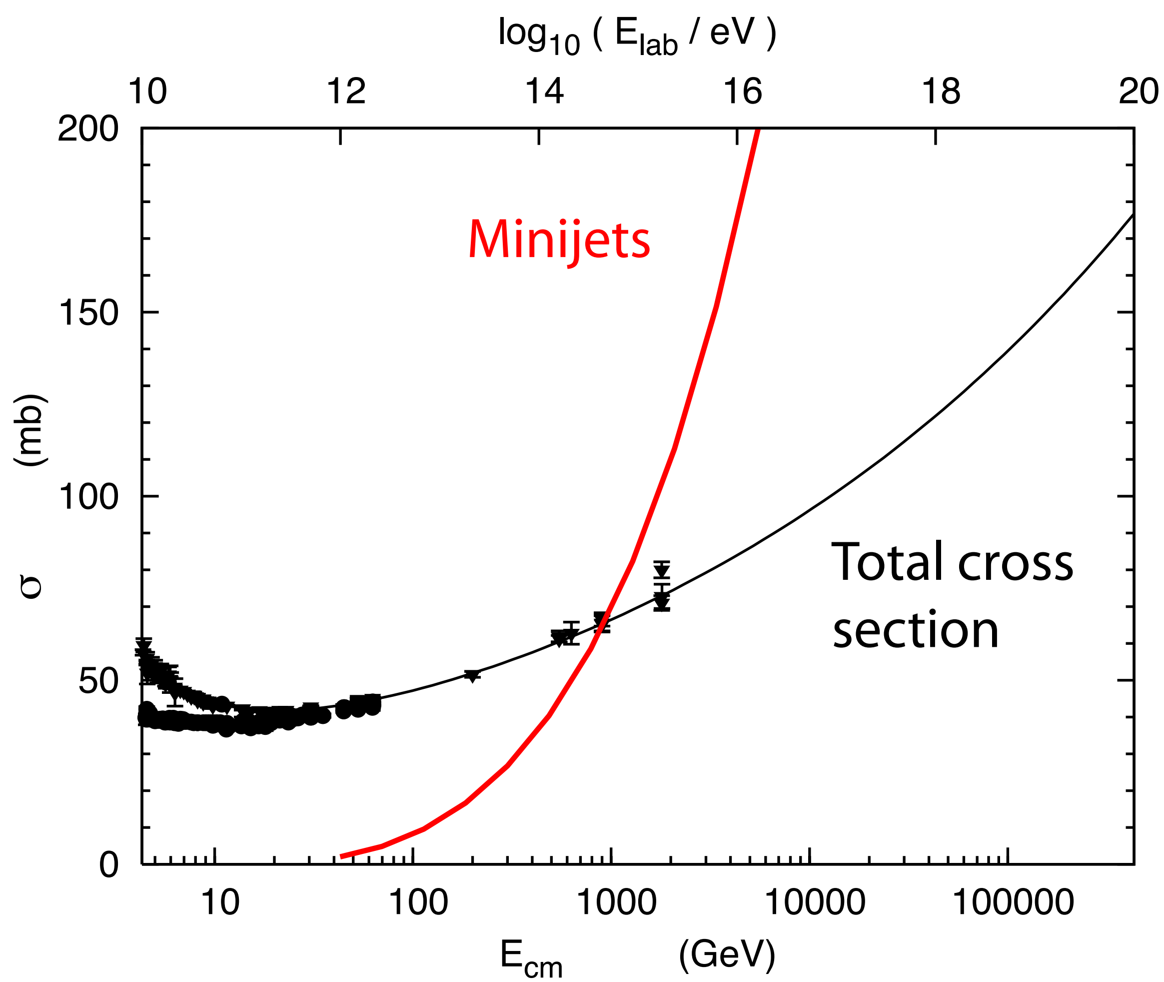


$$\frac{d f_i(x, Q^2)}{d \log Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dy}{y} \sum_j f_j(y, Q^2)\, P_{j \to i}\left(\frac{x}{y}\right)$$

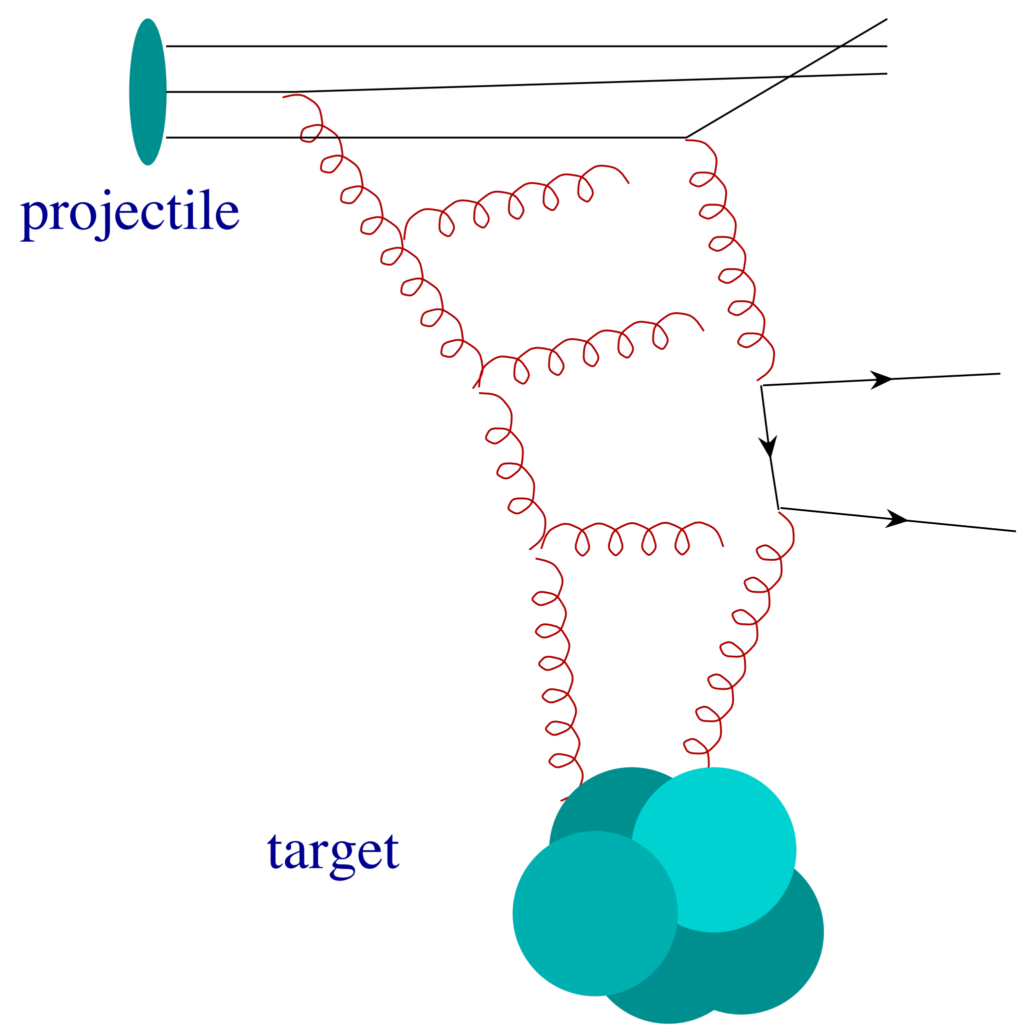
Prediction of perturbative QCD

Solution: Multiple parton-parton interactions

Proton-proton cross section



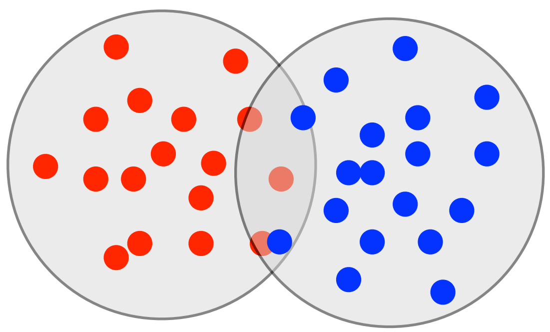
QCD prediction:
inclusive cross section



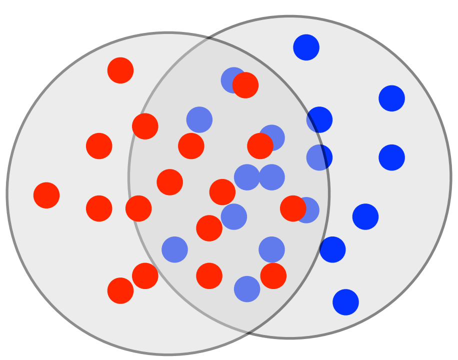
Average number of minijet pairs

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

Poissonian probability distribution



Peripheral collision:
only very few parton-pairs interacting



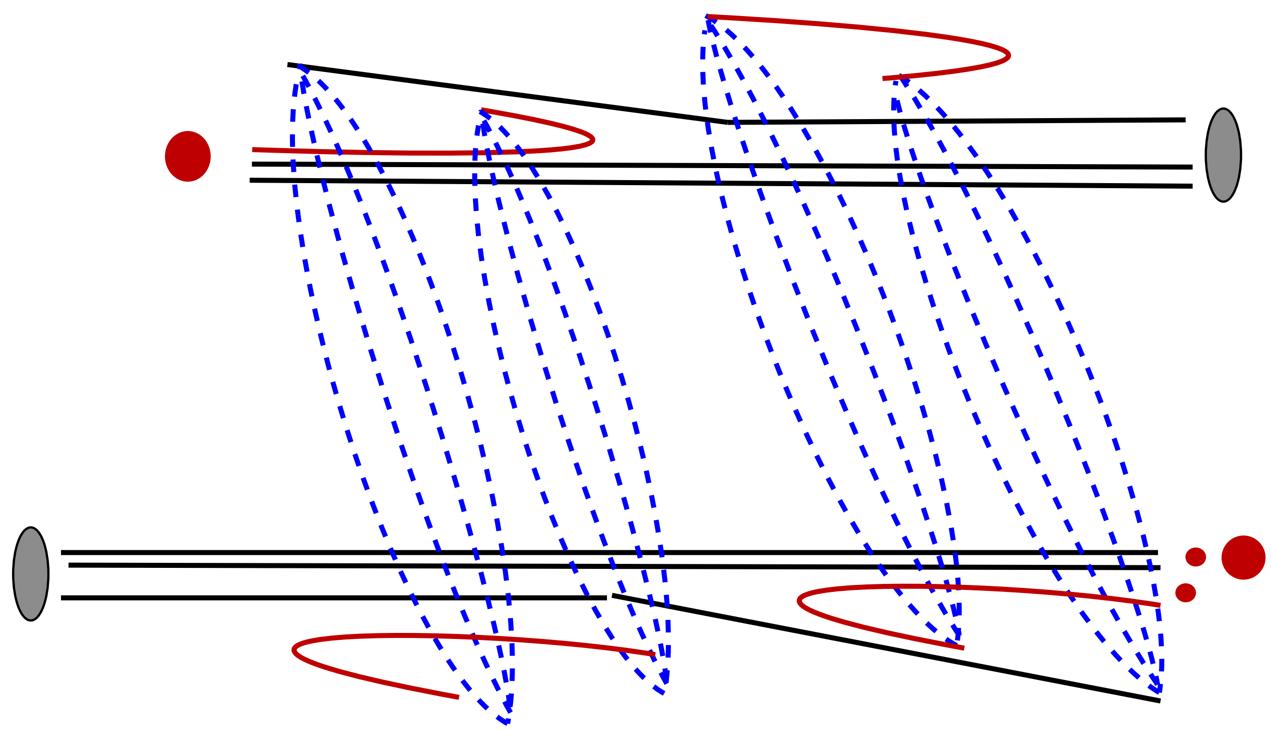
Central collision:
many parton-pairs interacting

$$P_n = \frac{\langle n_{\mathrm{hard}}(\vec{b})\rangle^n}{n!} \exp\left(-\langle n_{\mathrm{hard}}(\vec{b})\rangle\right)$$

mean number of interactions for given impactparameter of collision

Need to know mean number of interactions as function of impact parameter

Interaction of two parton pairs



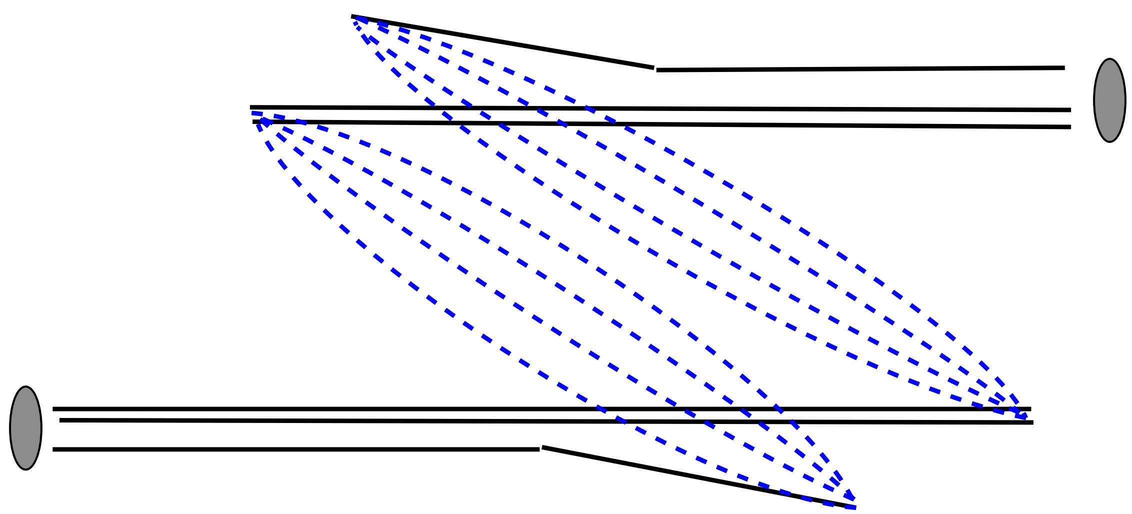
Two soft interactions

Generic diagram of interaction of two parton pairs

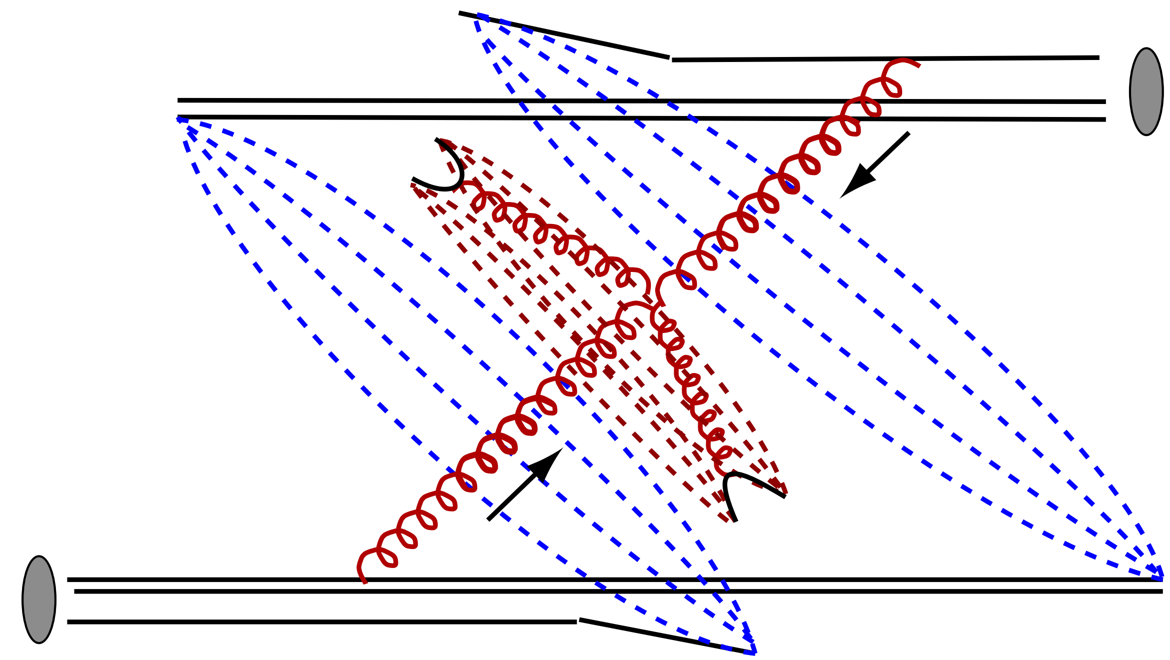
- gluon exchange between each pair produces two strings
- sea quarks needed for string ends (different combinations possible)
- other sea quark pairs possible but not explicitly simulated
- each string fragments into hadrons with small transverse momenta

Multiple soft and hard interactions

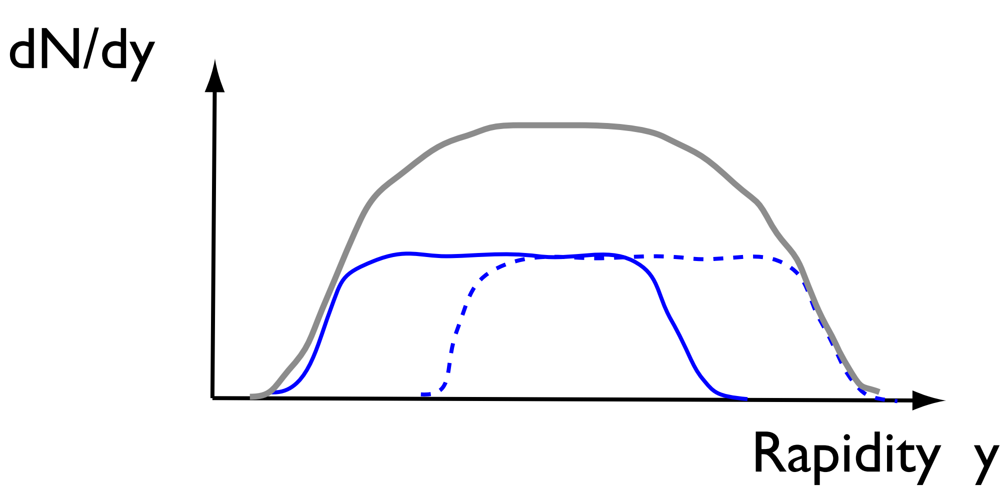
$$\sigma_{n_s,n_h} = \int d^2b \, \frac{[n_{\rm soft}(b,s)]^{n_s}}{n_s!} \, \frac{[n_{\rm hard}(b,s)]^{n_h}}{n_h!} \, e^{-n_{\rm hard}(b,s) - n_{\rm soft}(b,s)}$$

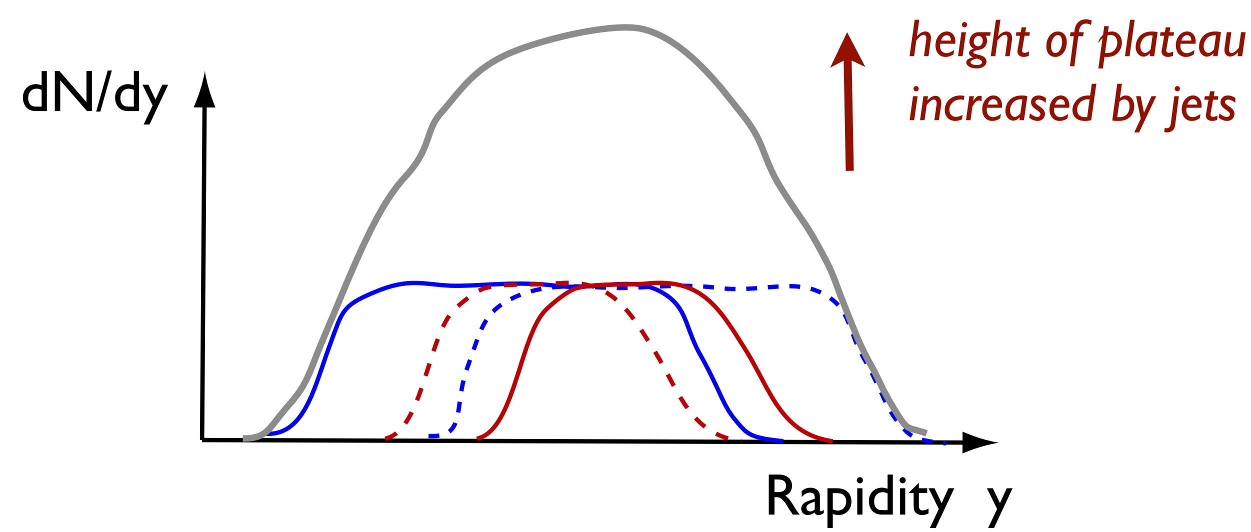


n_s=1, n_h=0



n_s=1, n_h=1

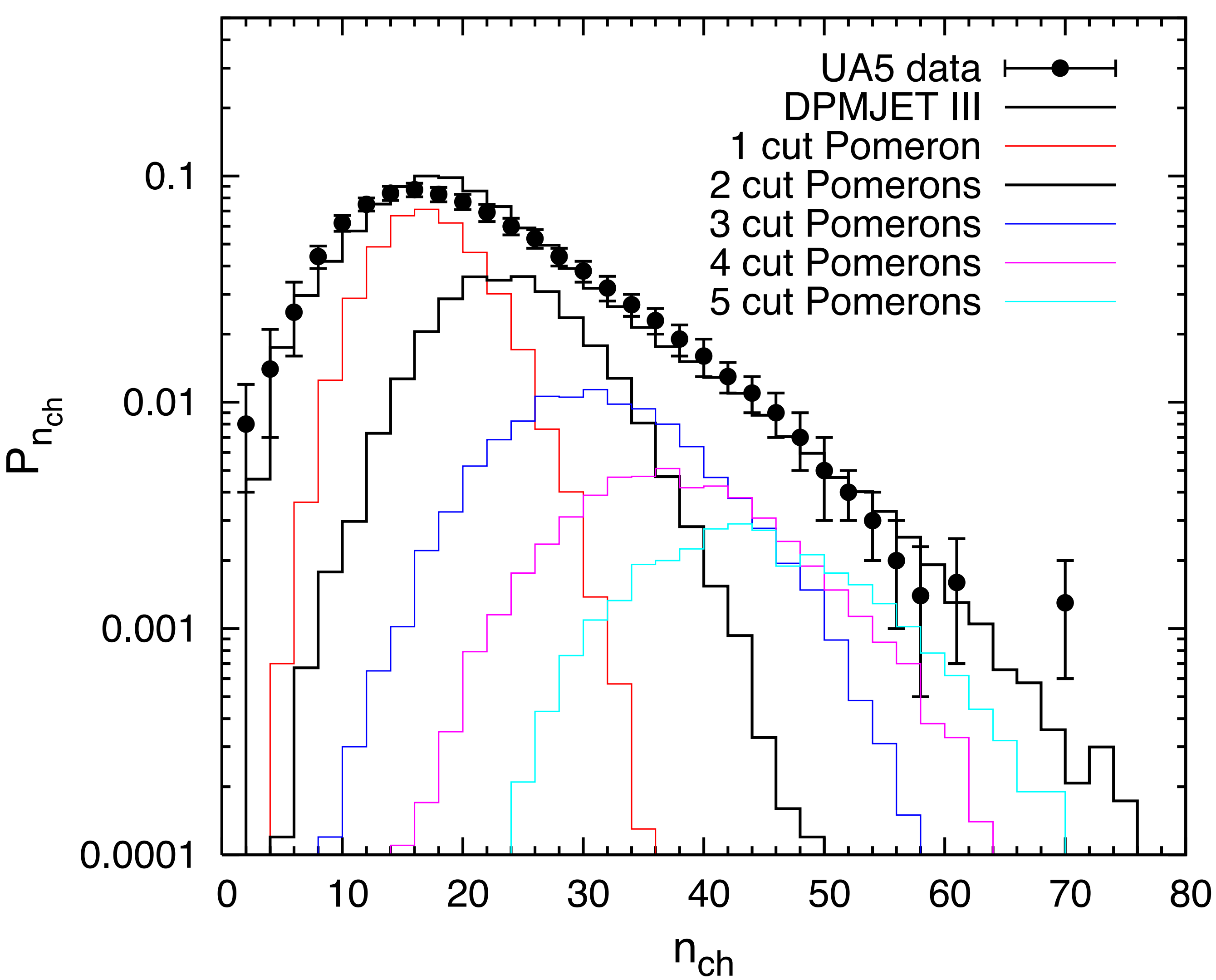


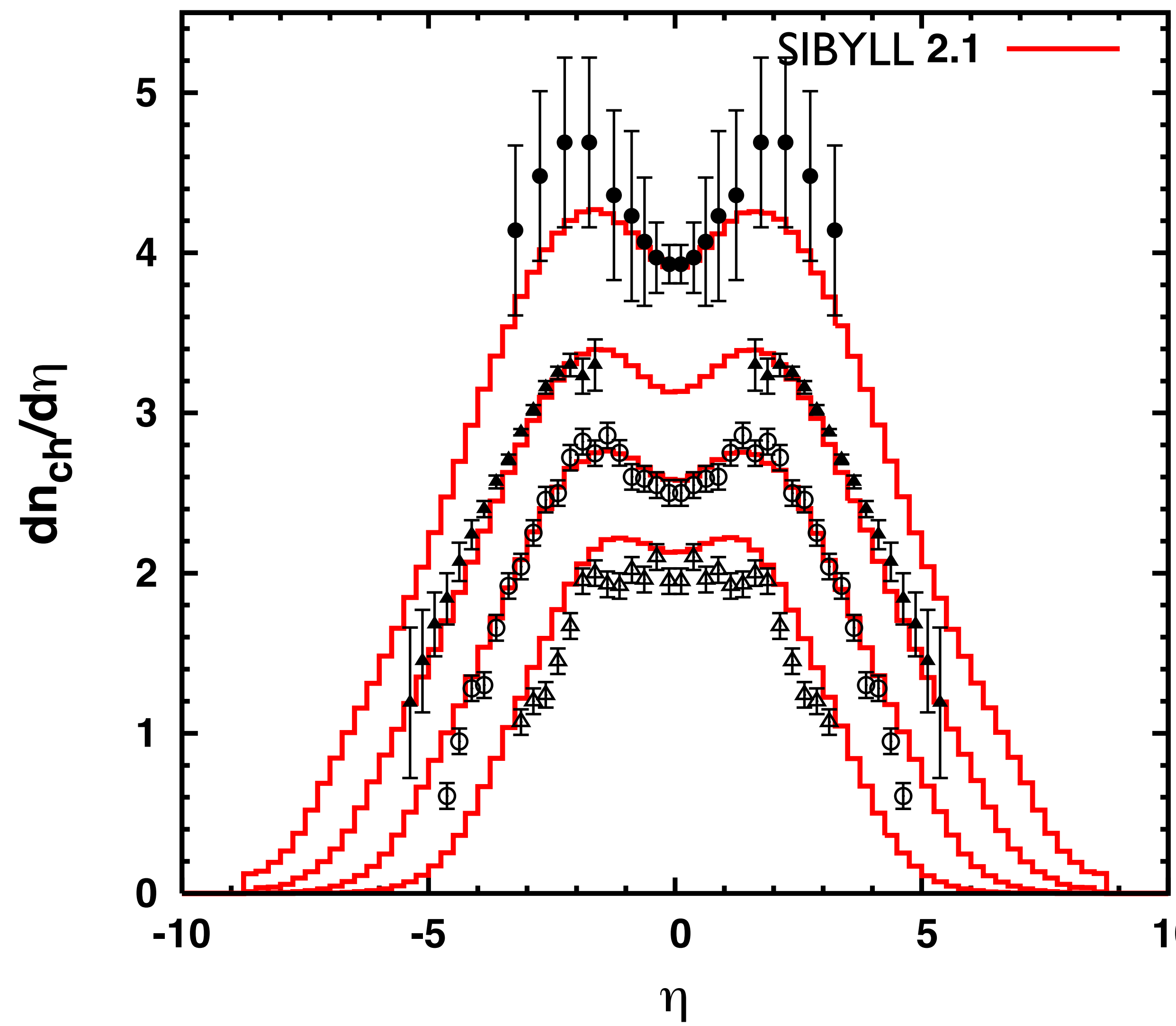


Comparison with collider data

Note: one cut pomeron means
one soft or hard interaction

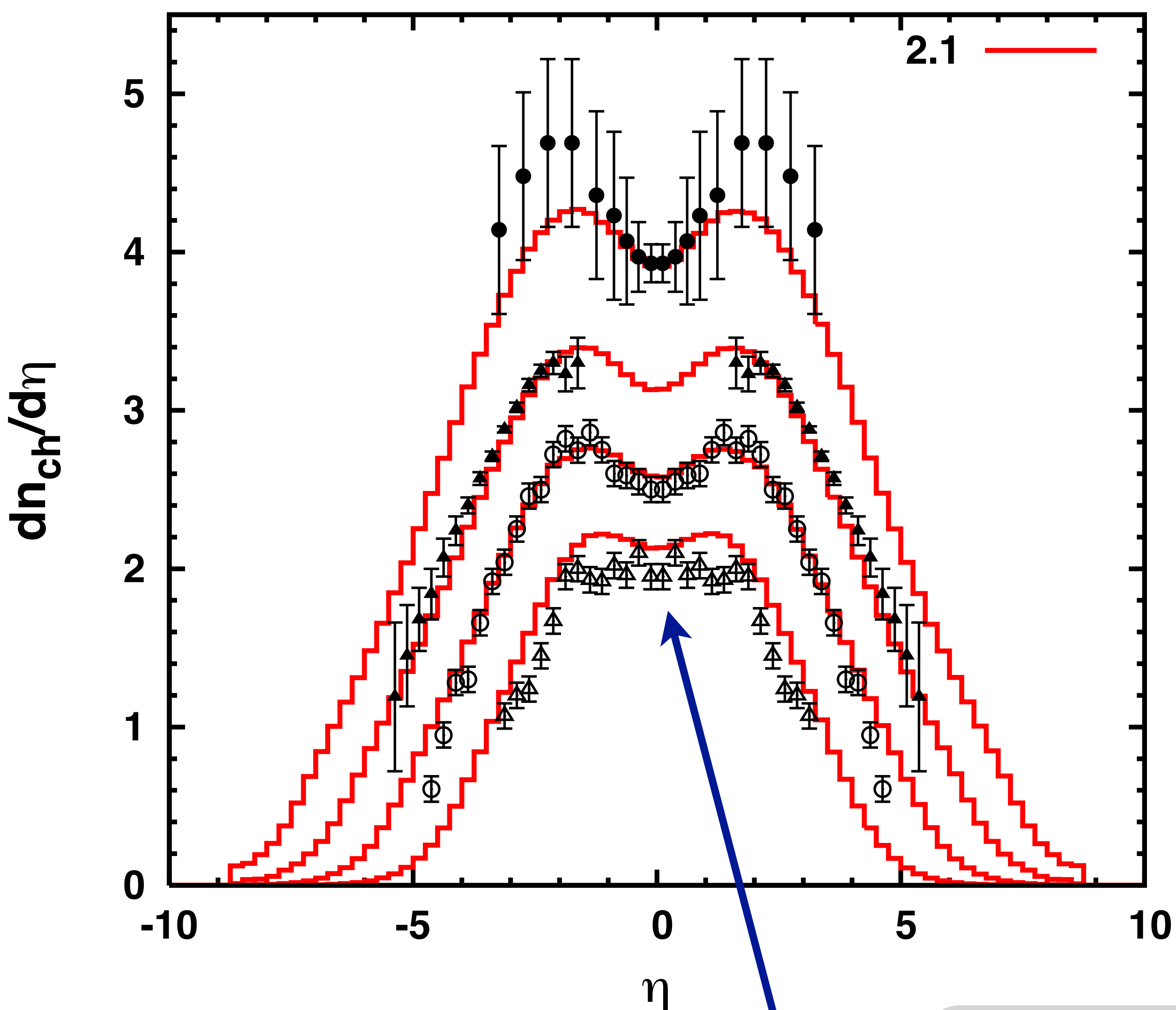
Charged particle multiplicity
distribution at 200 GeV cms.





Charged particle
pseudorapidity distributions

Violation of Feynman scaling



Feynman scaling

$$2E \frac{dN}{d^3p} = \frac{dN}{dy\, d^2p_\perp} \longrightarrow f(x_F, p_\perp)$$

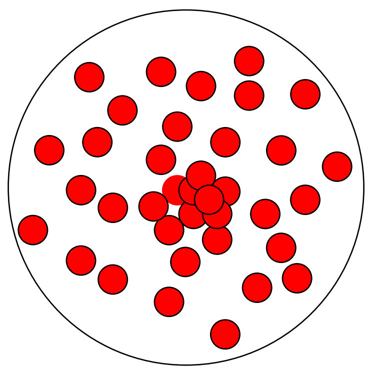
With Feynman scaling:
distribution independent of energy

$$\frac{dN}{dx} \approx \tilde{f}(x) \qquad x = E/E_{\text{prim}}$$

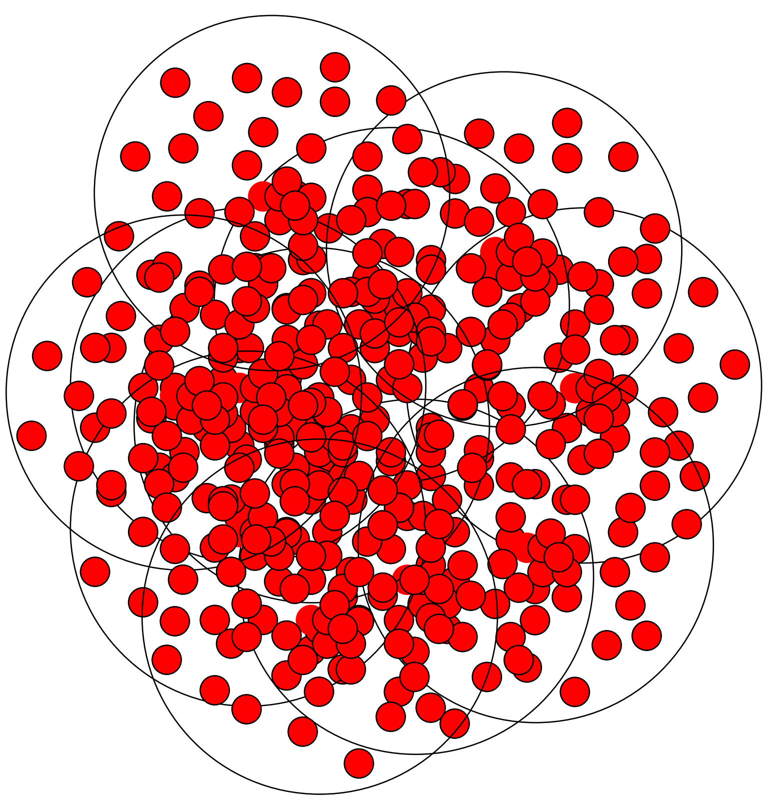
Feynman scaling violated for small $|x_F|$

$$\frac{dN}{dy\, d^2p_\perp} \approx \frac{dN}{dy}\, g(p_\perp^2)$$

Problem: Very high parton densities (saturation)



nucleon



nucleus

RHIC data very important

Saturation:

- parton wave functions overlap
- number of partons does not increase anymore at low x
- extrapolation to very high energy unclear

Simple geometric criterion

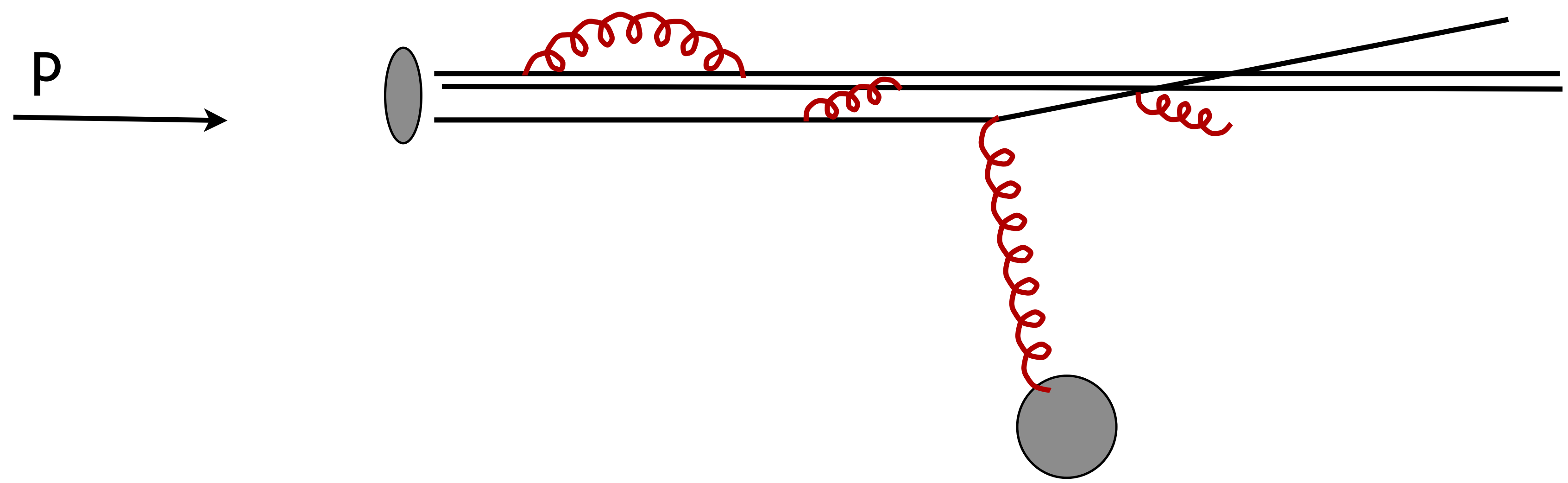
$$\pi R_0^2 \simeq \frac{\alpha_s(Q_s^2)}{Q_s^2} \cdot xg(x, Q_s^2)$$

size of proton

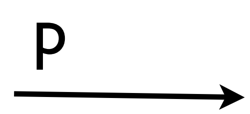
Size of one gluon

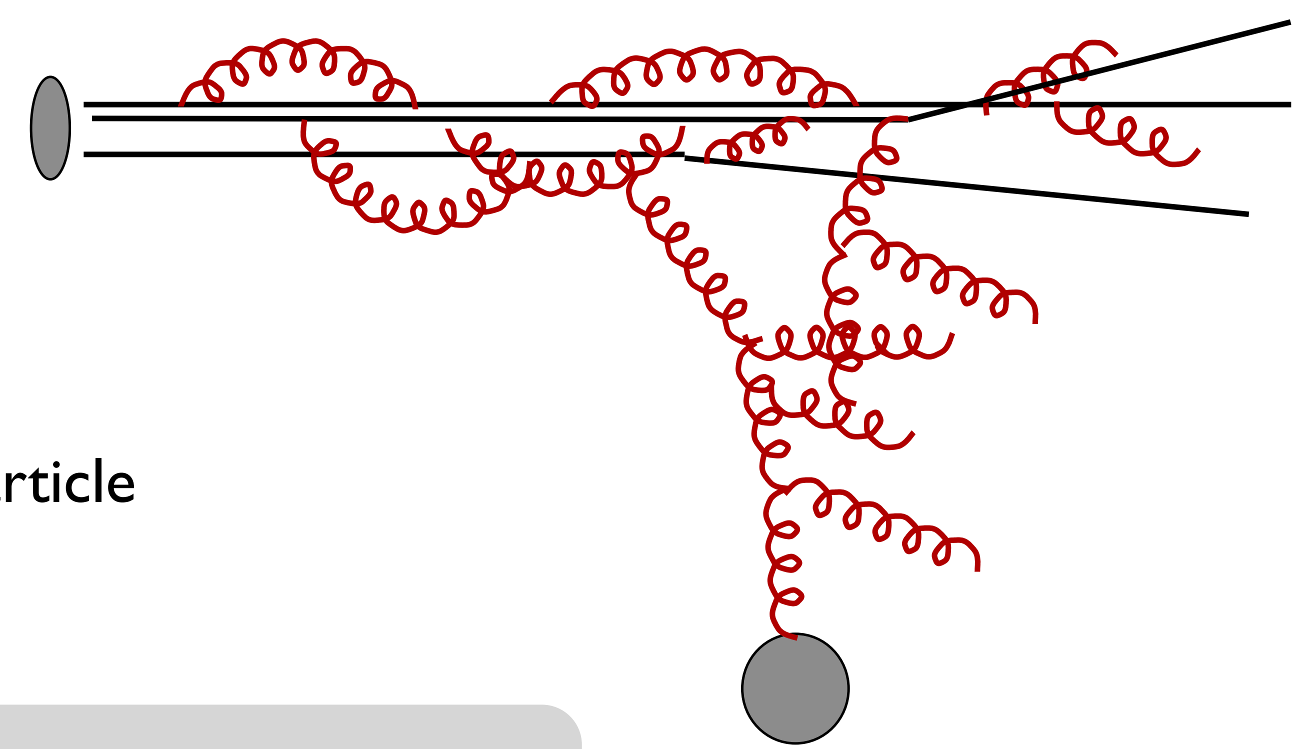
number of gluons

Black disk scenario of high energy scattering ?



High energy scattering





Black Disk Model

- large number of minijets
- high perturbative saturation scale
- complete disintegration of leading particle

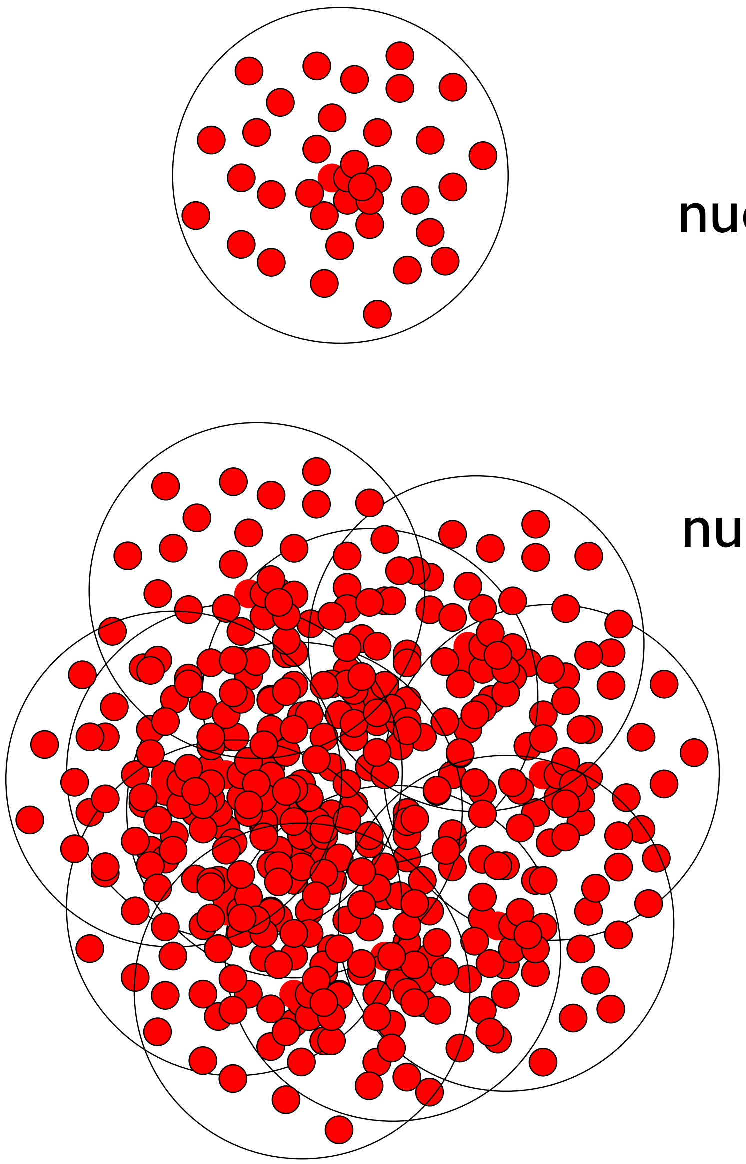
Not implemeted as dominating process in current models

(Drescher et al. Phys. Rev. Lett. 94, 2005)

Comparison of high energy interaction models

DPMJET II.5 and III *(Ranft / Roesler, RE, Ranft, Bopp)*	• universal model • saturation for hard partons via geometry criterion • HERA parton densities
EPOS *(Pierog, Werner)*	• universal model • saturation by RHIC data parametriztions • custom-developed parton densities
QGSJET 01 *(Kalmykov, Ostapchenko)*	• no saturation corrections • old pre-HERA parton densities • replaced by QGSJET II
QGSJET II.03 *(Ostapchenko)*	• saturation correction for soft partons via pomeron-resummation • custom-developed parton densities
SIBYLL 2.1 *(Engel, RE, Fletcher, Gaisser, Lipari, Stanev)*	• saturation for hard partons via geometry criterion • HERA parton densities

High parton densities: modification of minijet threshold



SIBYLL: simple geometric criterion

$$\pi R_0^2 \simeq \frac{\alpha_s(Q_s^2)}{Q_s^2} \cdot xg(x, Q_s^2)$$

$$xg(x,Q^2) \sim \exp\left[\frac{48}{11-\frac{2}{3}n_f}\ln\frac{\ln\frac{Q^2}{\Lambda^2}}{\ln\frac{Q_0^2}{\Lambda^2}}\ln\frac{1}{x}\right]^{\frac{1}{2}}$$

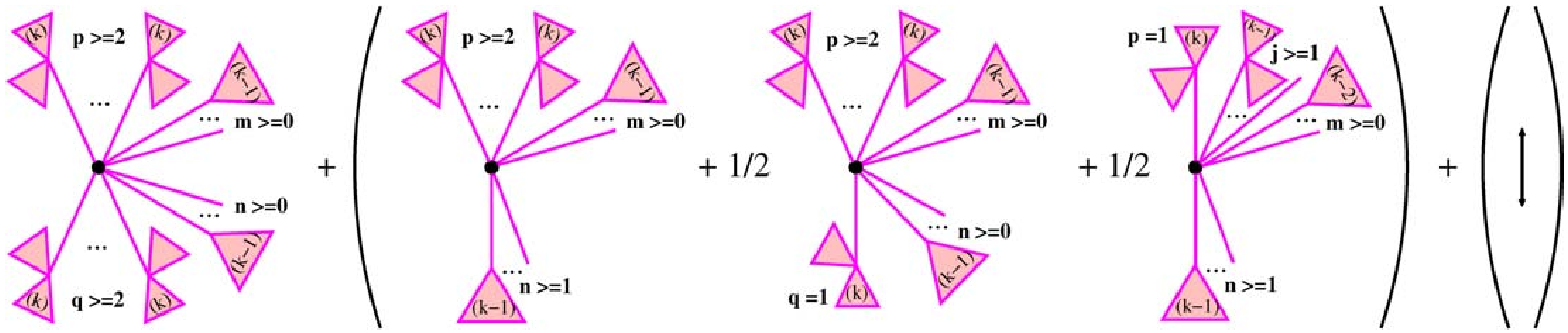
No dependence on impact parameter !

SIBYLL: $$p_\perp(s) = p_\perp^0 + 0.065\mathrm{GeV}\exp\left\{0.9\sqrt{\ln\ s}\right\}$$

DPMJET: $$p_\perp(s) = p_\perp^0 + 0.12\mathrm{GeV}\left(\log_{10}\frac{\sqrt{s}}{50\mathrm{GeV}}\right)^3$$

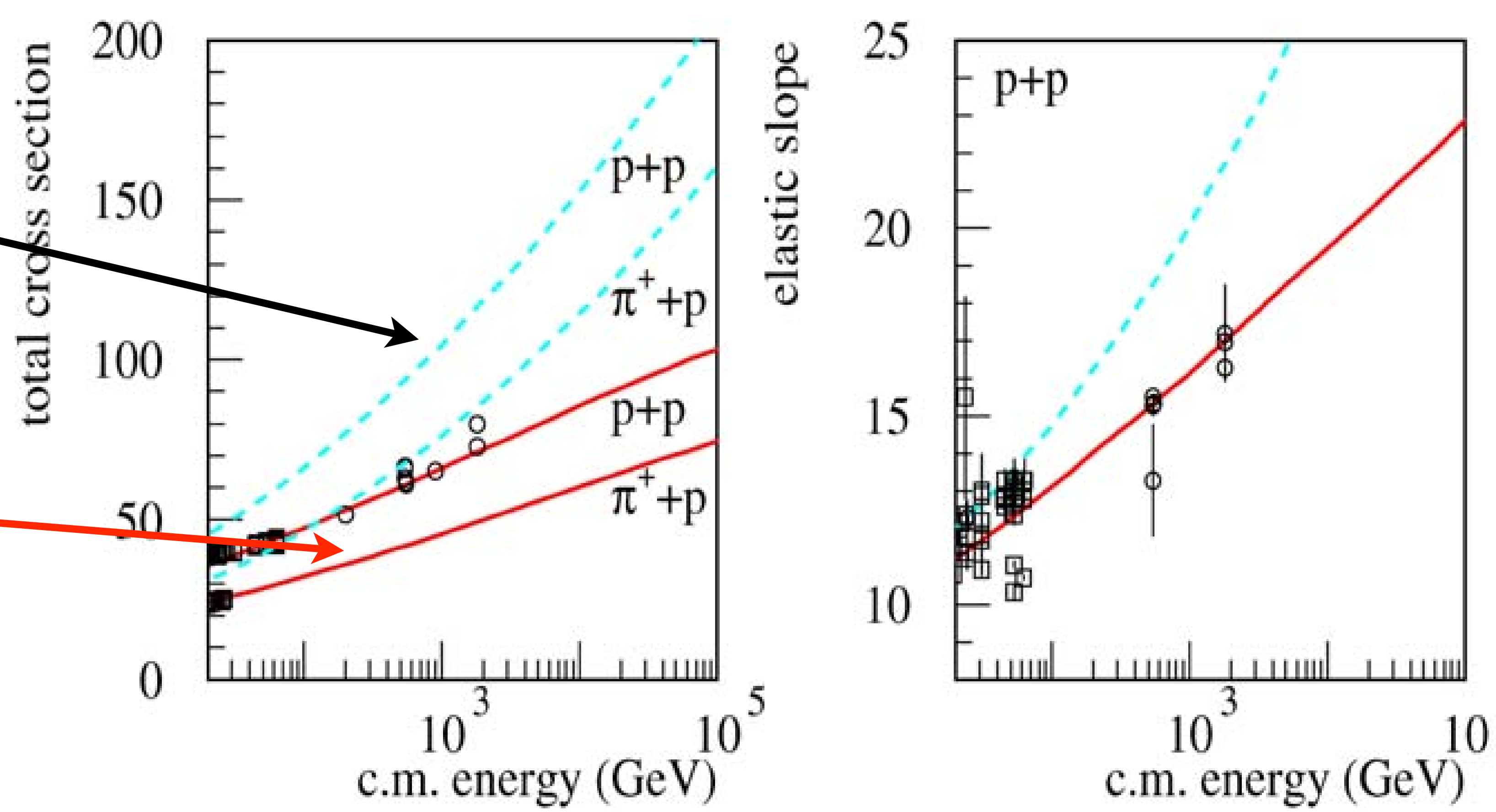
QGSJET II: high parton density effects

Re-summation of enhanced pomeron graphs



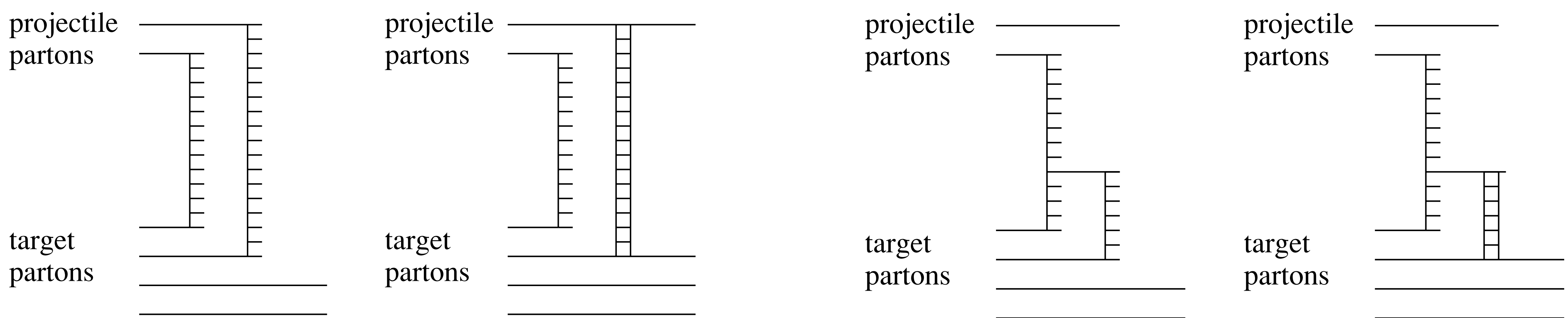
Without enhanced graphs

With enhanced graphs



(Ostapchenko, PLB 2006, PRD 2006)

EPOS 1.6x – high parton density effects (i)

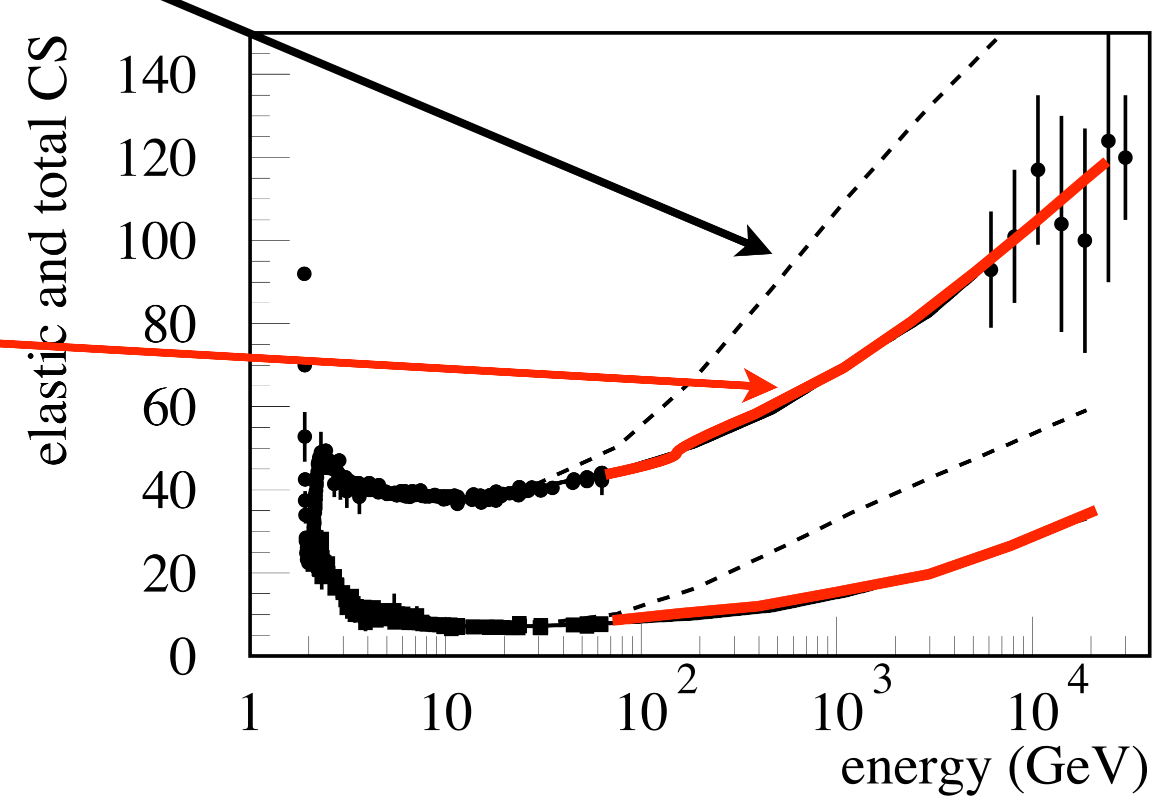


No effective coupling

$$A_{\text{pom}} \sim (x_1 x_2)^{\beta}$$

With effective coupling

$$A_{\text{pom}} \sim x_1^{\beta} x_2^{\beta-\varepsilon}$$



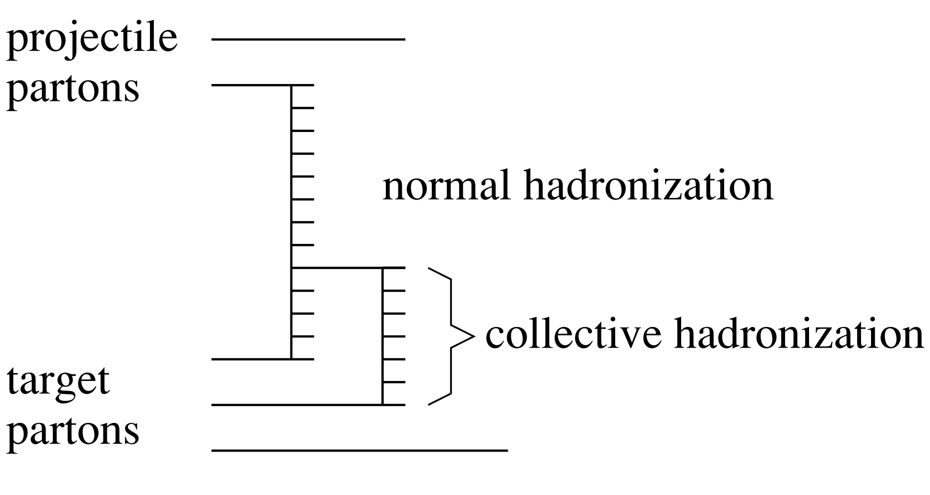
Parametrization

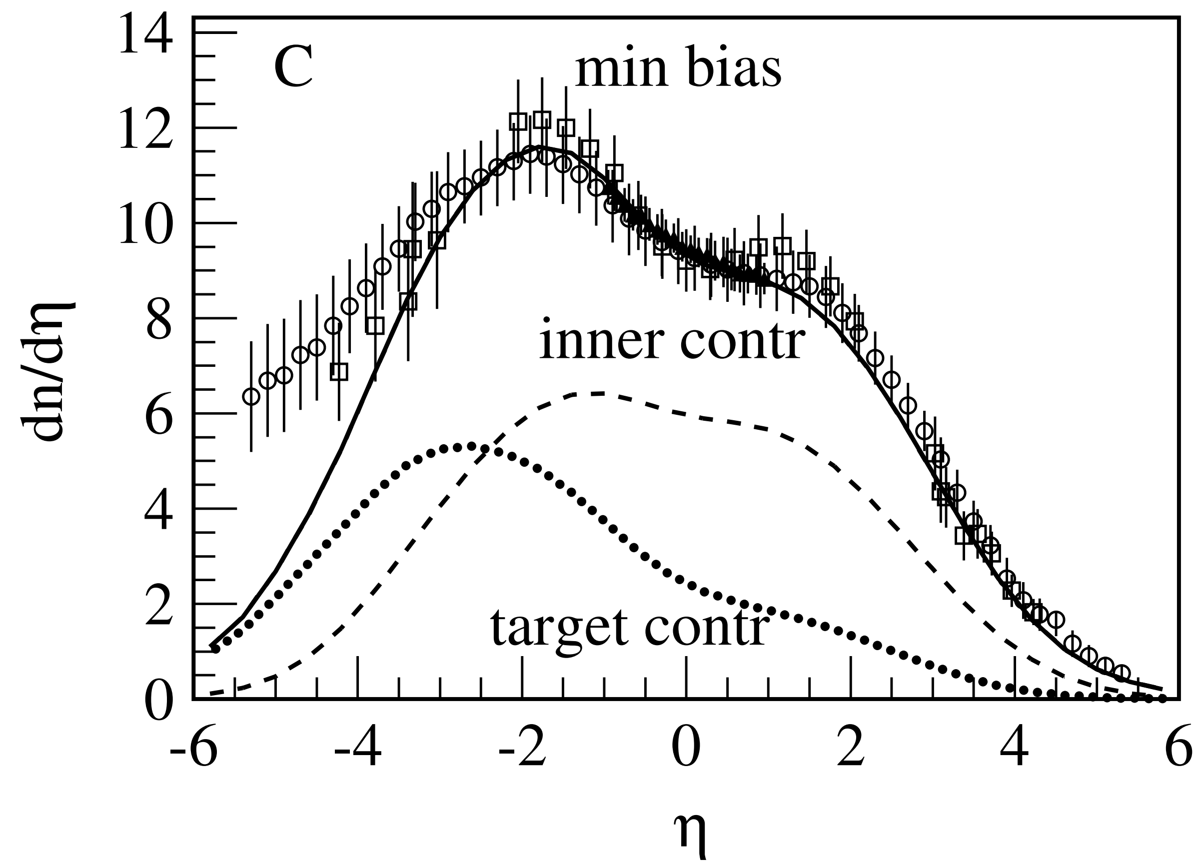
$$\varepsilon_S = a_S\, \beta_S Z,$$
$$\varepsilon_H = a_H\, \beta_H Z,$$

(Werner et al., PRC 2006)

EPOS 1.6x – high parton density effects (ii)

(Werner et al., PRC 2006)





Coefficient	Corresponding variable	Value
s_M	Minimum squared screening energy	$(25\ \text{GeV})^2$
w_M	Defines minimum for z_0'	6.000
w_Z	Global Z coefficient	0.080
w_B	Impact parameter width coefficient	1.160
a_S	Soft screening exponent	2.000
a_H	Hard screening exponent	1.000
a_T	Transverse momentum transport	0.025
a_B	Break parameter	0.070
a_D	Diquark break probability	0.110
a_S	Strange break probability	0.140
a_P	Average break transverse momentum	0.150

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

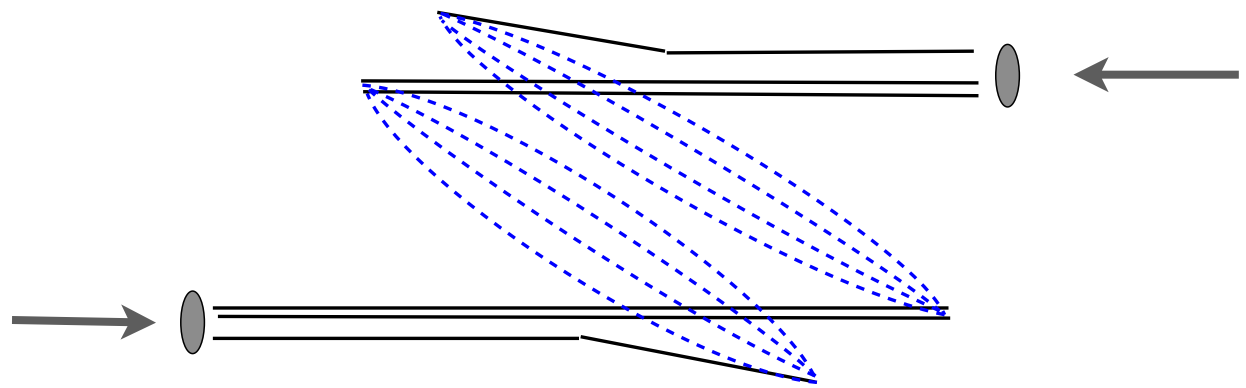
$$b_0 = w_B\,\sqrt{\sigma_{\text{inel}\,pp}/\pi}$$

$$z_0 = w_Z\ \log s/s_M,$$

$$z_0' = w_Z\,\sqrt{(\log s/s_M)^2 + w_M{}^2},$$

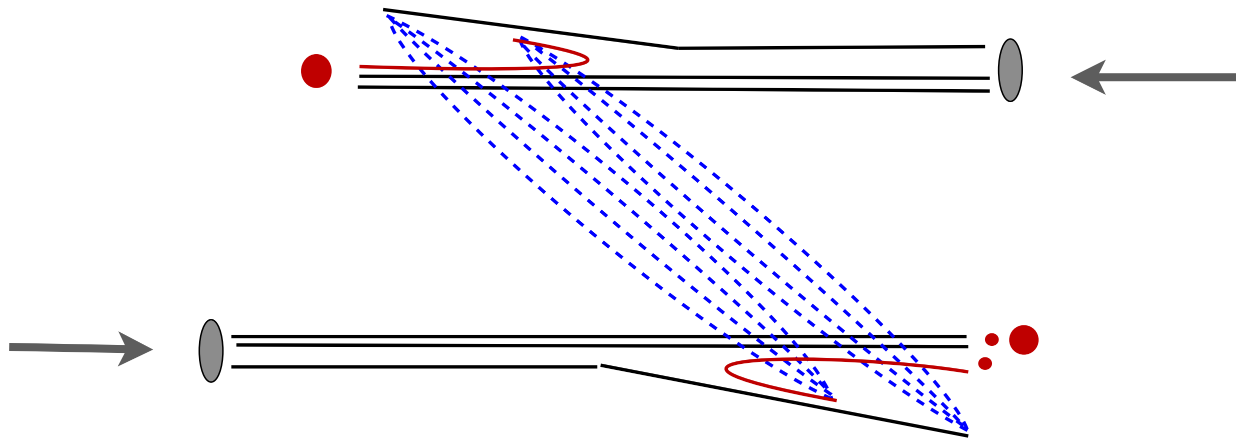
Uncertainty in energy extrapolation !

Different implementations



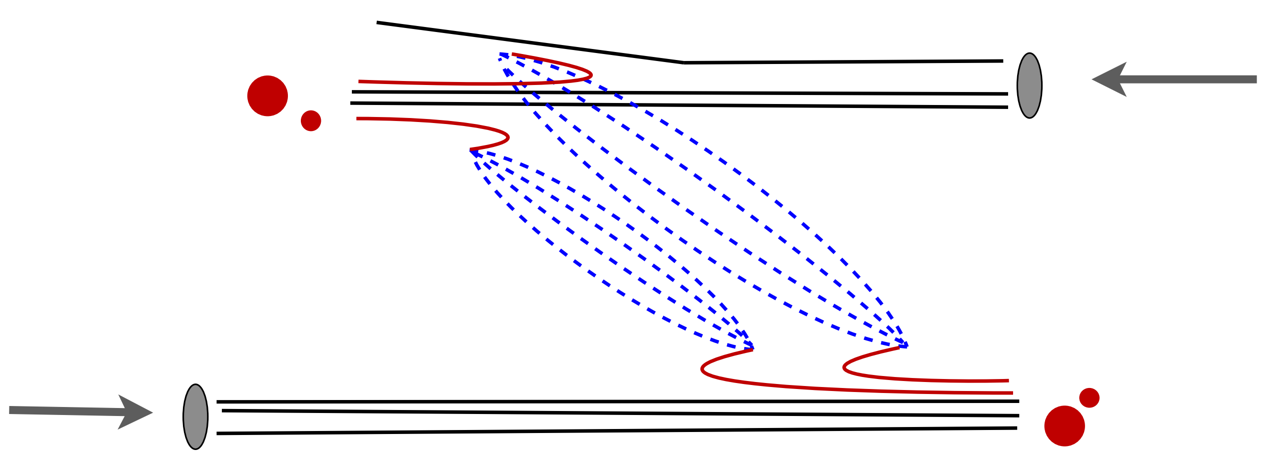
SIBYLL:

strings connected to valence quarks;
first fragmentation step with harder
fragmentation function



QGSJET:

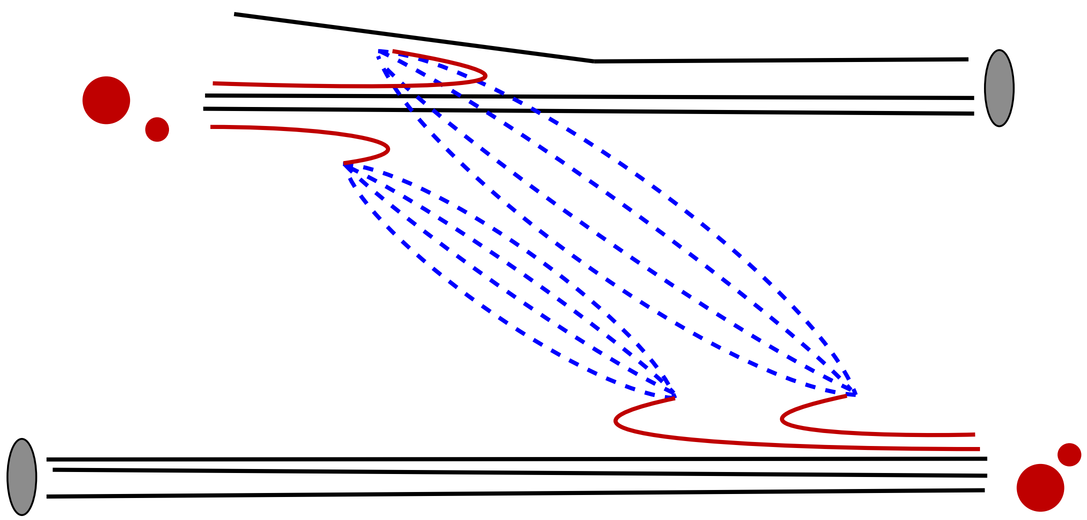
fixed probability of strings connected to
valence quarks or sea quarks;
explicit construction of remnant hadron

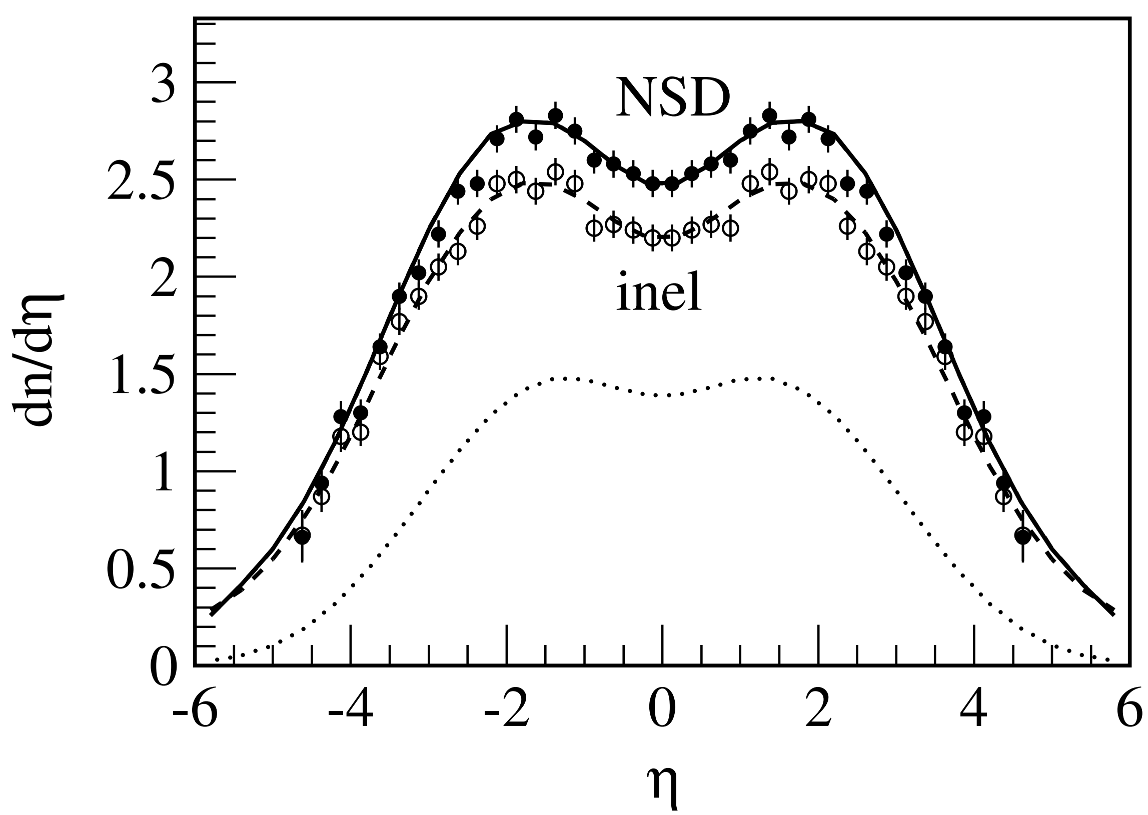


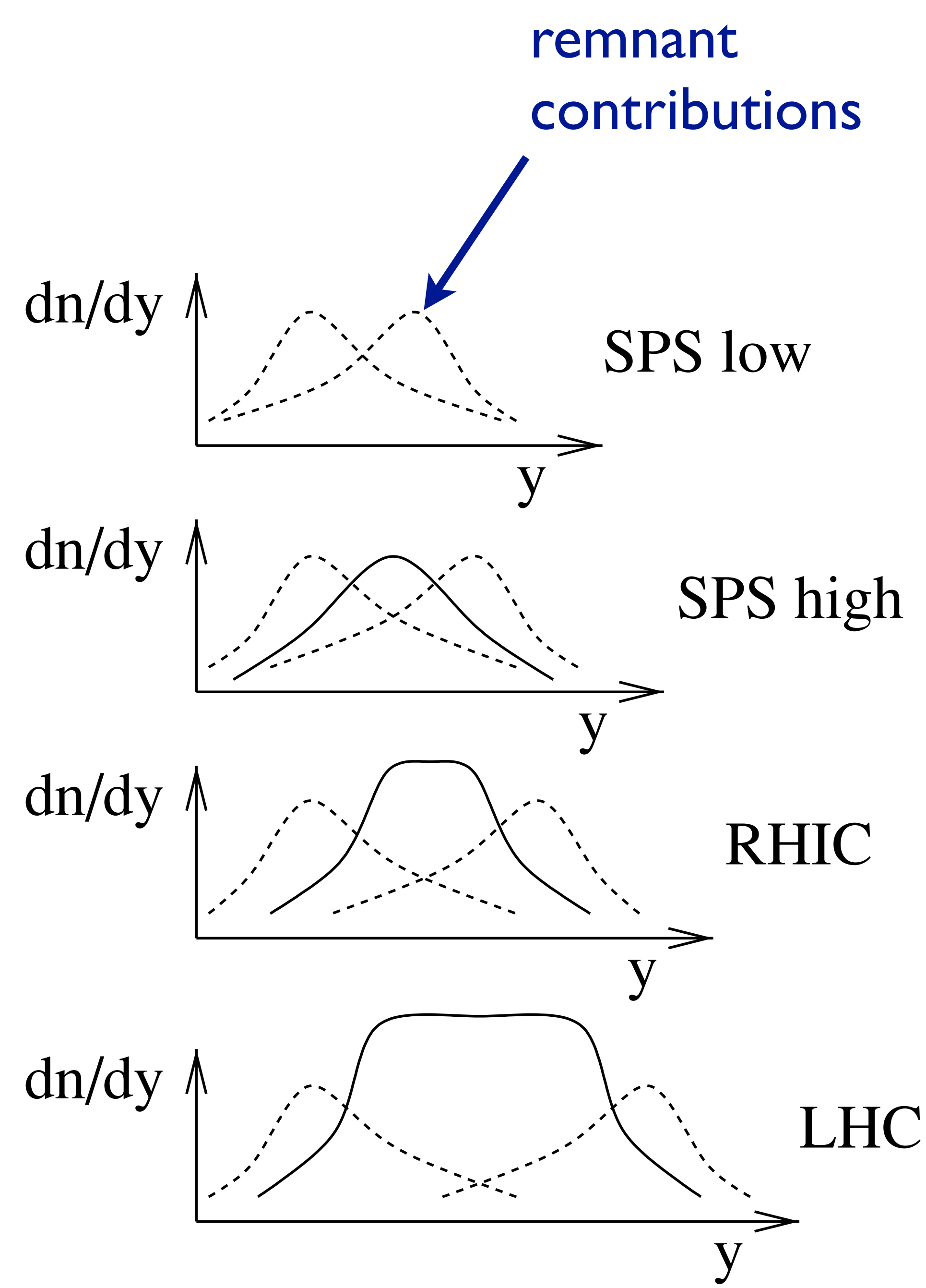
EPOS:

strings always connected to sea quarks;
bags of sea and valence quarks fragmented
statistically

EPOS: remant vs. string contributions

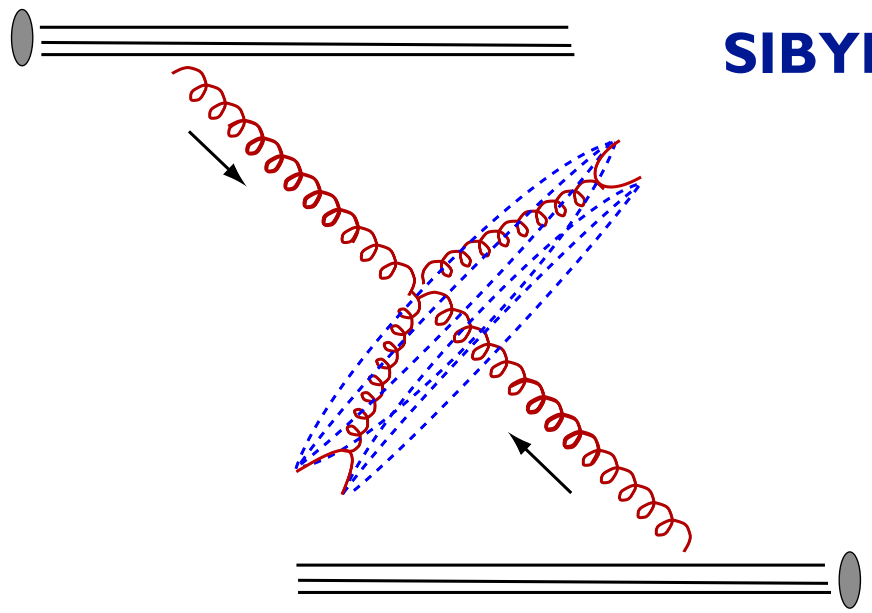






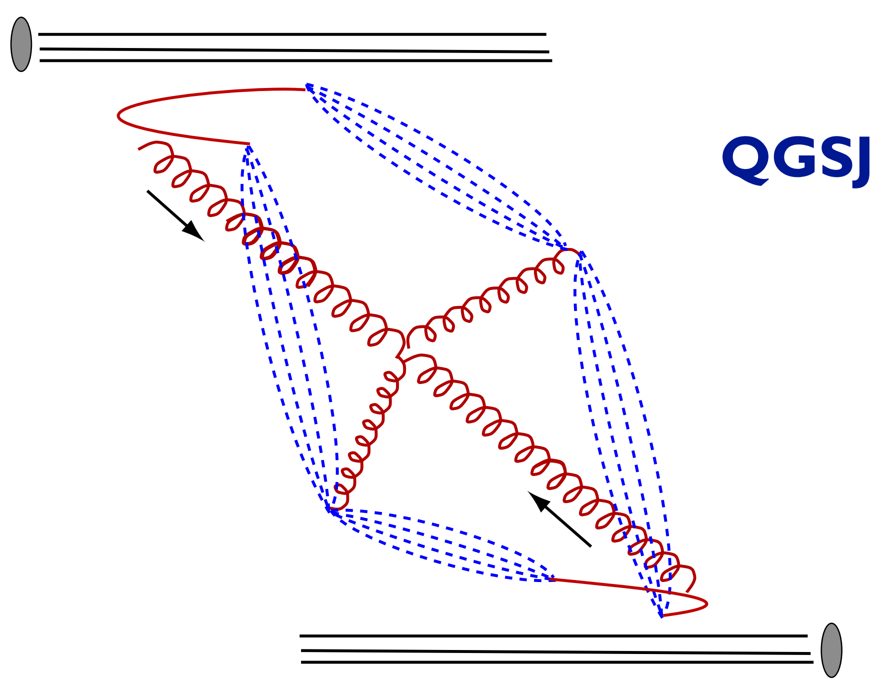
EPOS: change from remanant-dominated to string-dominated particle production

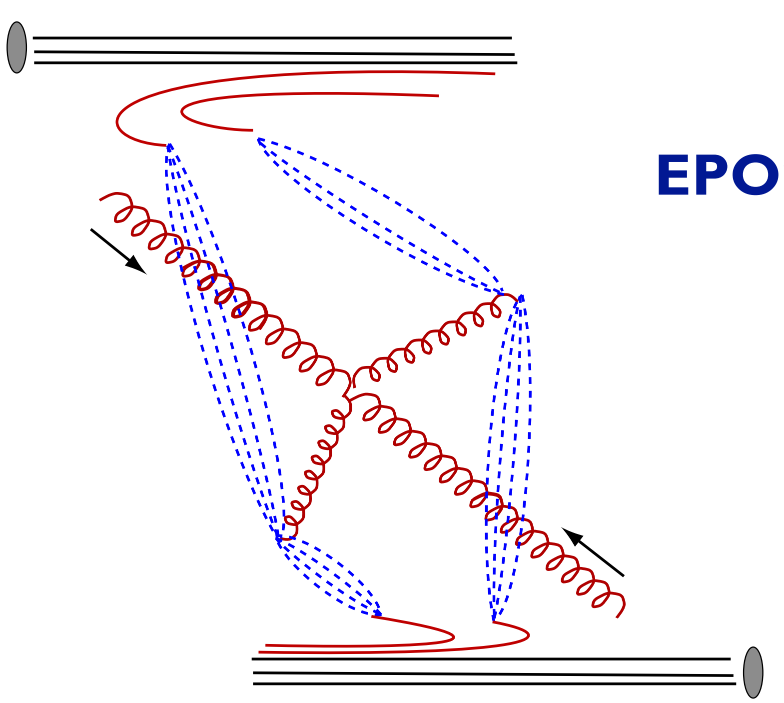
Different implementations of two-gluon scattering


SIBYLL

Kinematics etc. given by parton densities and perturbative QCD

Two strings stretched between quark pairs from gluon fragmentation


QGSJET


EPOS

Interaction models for high and ultra-high energies

Minijet production changes characteristics of interactions

- Predicted within perturbative QCD
- Natural source of scaling violations
- Parameters for calculation very uncertain
- Saturation effects very important, not really understood

Models construction

- Construction elements very similar
- Model philosophies complementary
- Tuned to data from fixed target and collider experiments
- Differences in treatment of key questions for high-energy extrapolation

Difference between models does probably not cover full range of uncertainty