Forschungszentrum Karlsruhe
in der Helmholtz-Gemeinschaft

Karlsruhe Institute of Technology

High Energy Cosmic Ray Interactions

(Lecture 2: Intermediate energy physics)

Ralph Engel

Karlsruhe Institute of Technology (KIT)

Outline

Lecture 1 – Basics, low-energy interactions

- Energies, projectile and target particles
- Cross sections
- Particle production threshold: resonances
- Hadronic interactions of gamma-rays

Lecture 2 – Intermediate energy physics

- Intermediate energy range: two-string models
- String fragmentation
- Rapidity, Feynman scaling
- Inclusive fluxes, spectrum weighted moments

Lecture 3 – Highest energies, air shower phenomenology

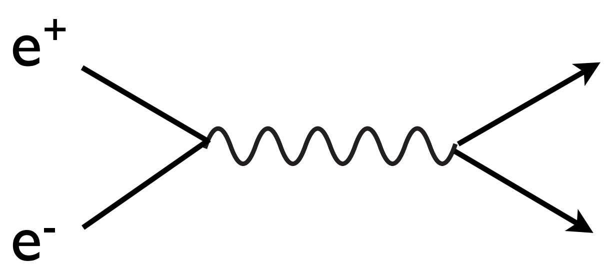
- Minijets, multiple interactions, scaling violation
- Model predictions, uncertainties
- elongation rate theorem
- Outlook: accelerator measurements

Multiparticle production (intermediate energy)

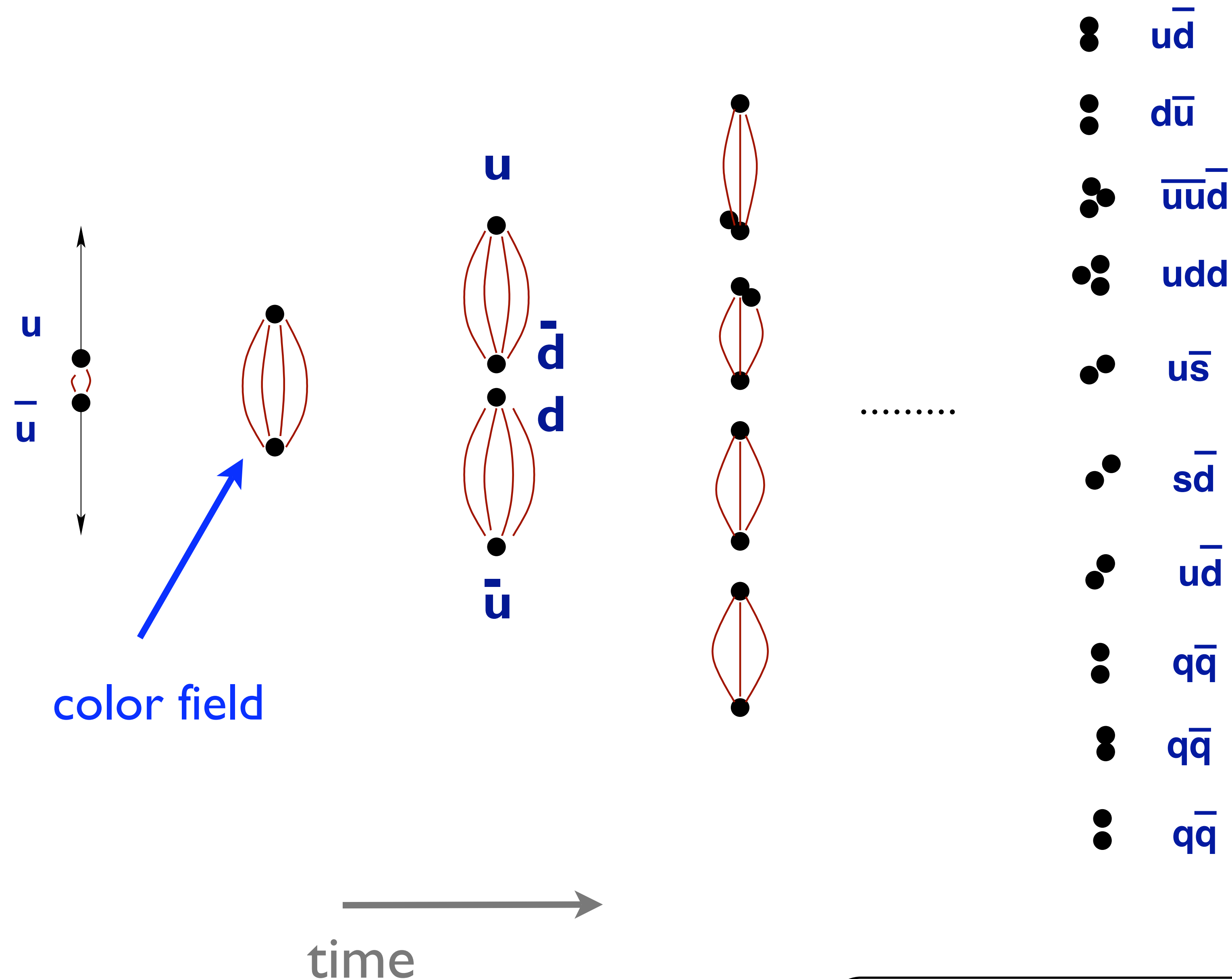
Typical examples: FLUKA, DPMJET, SIBYLL

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

Annihilation at high energy



Quarks together are
color-neutral system

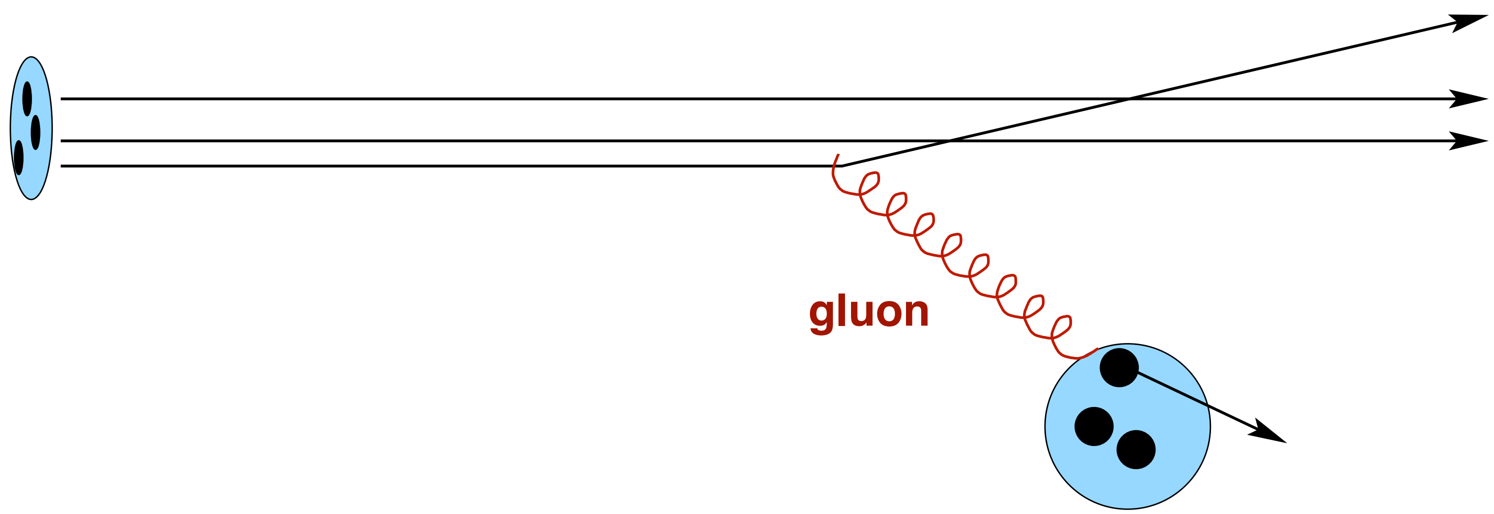


Chain of hadrons

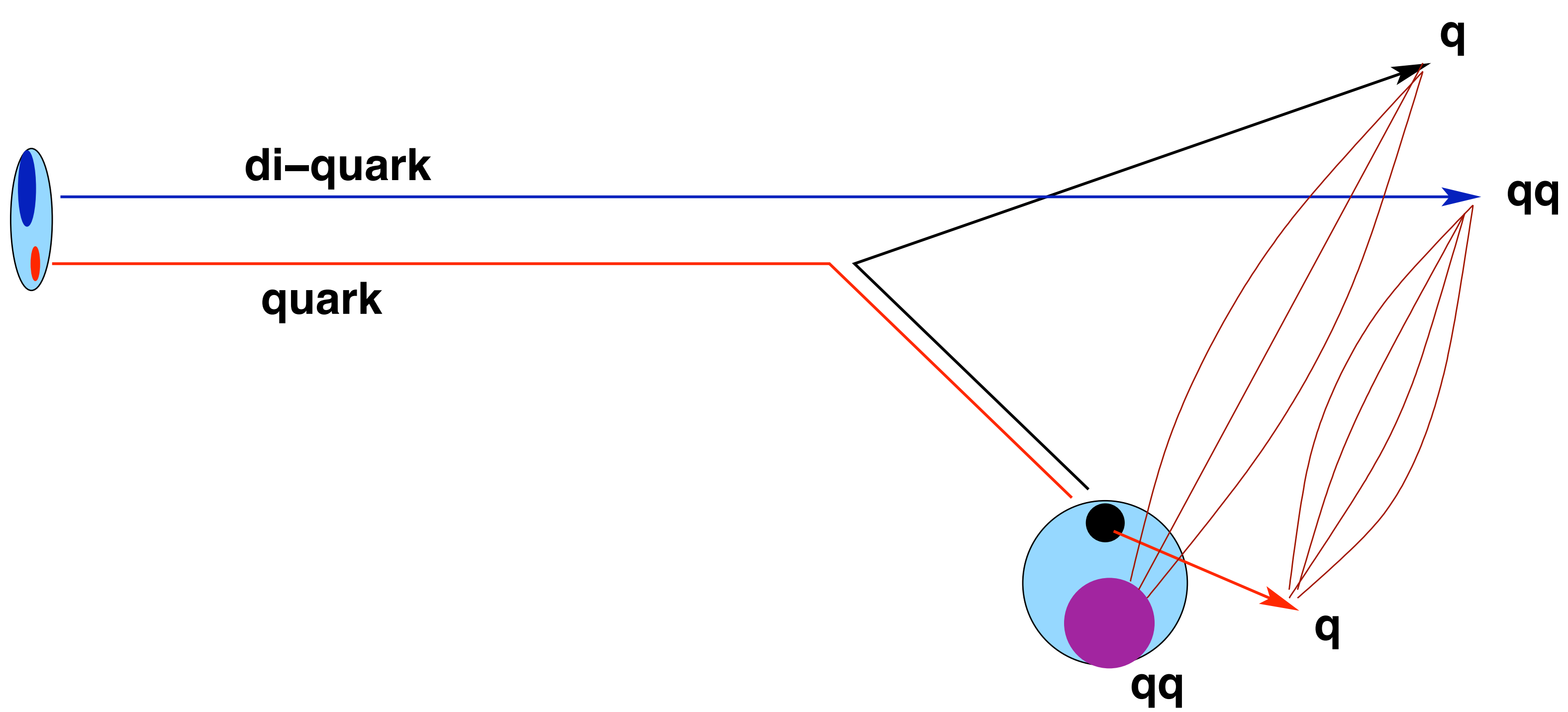
String fragmentation

QCD color flow configurations (i)

Partonic view:



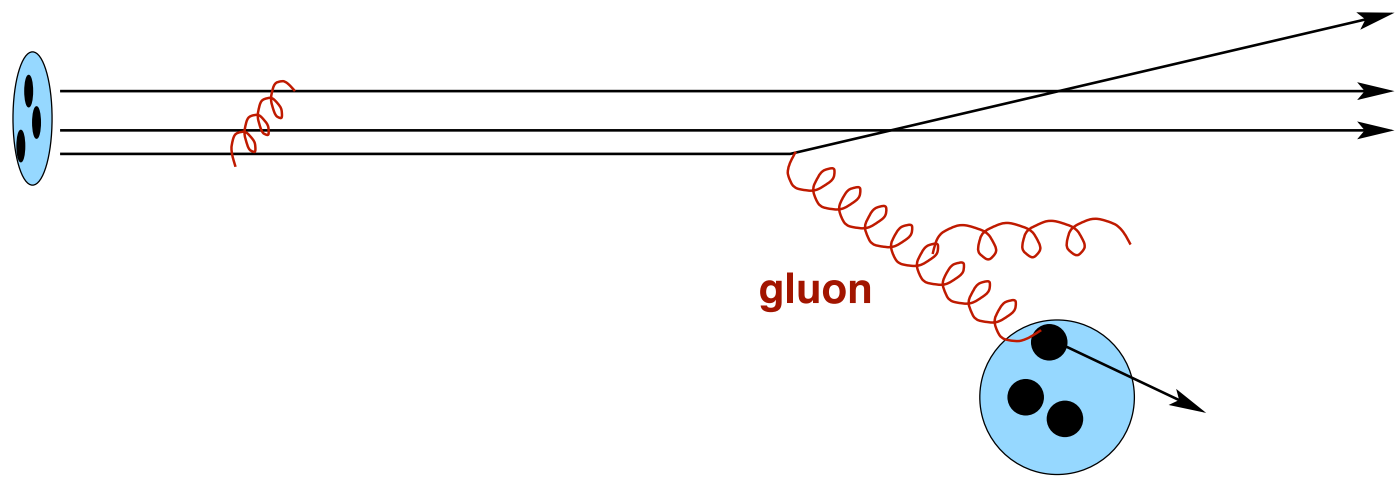
Color flow:



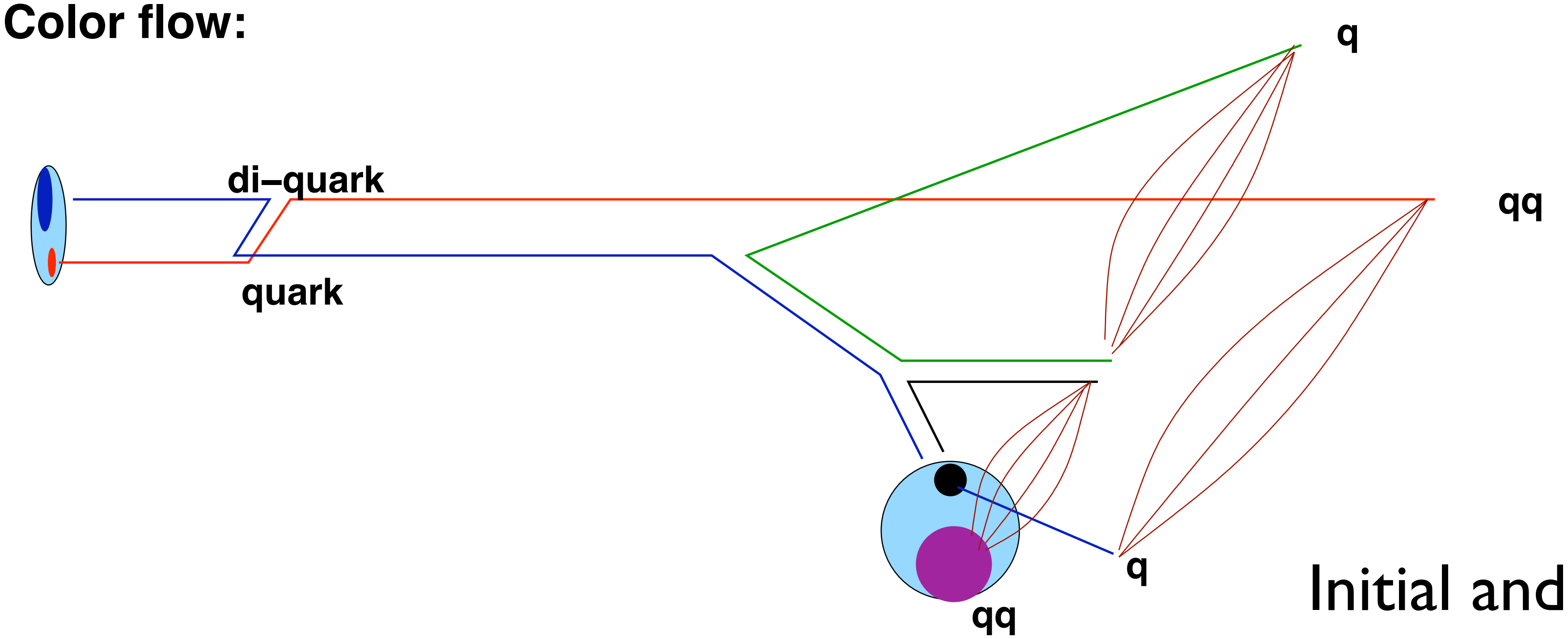
One-gluon exchange:
two color fields (strings)

QCD color flow configurations (ii)

Partonic view:

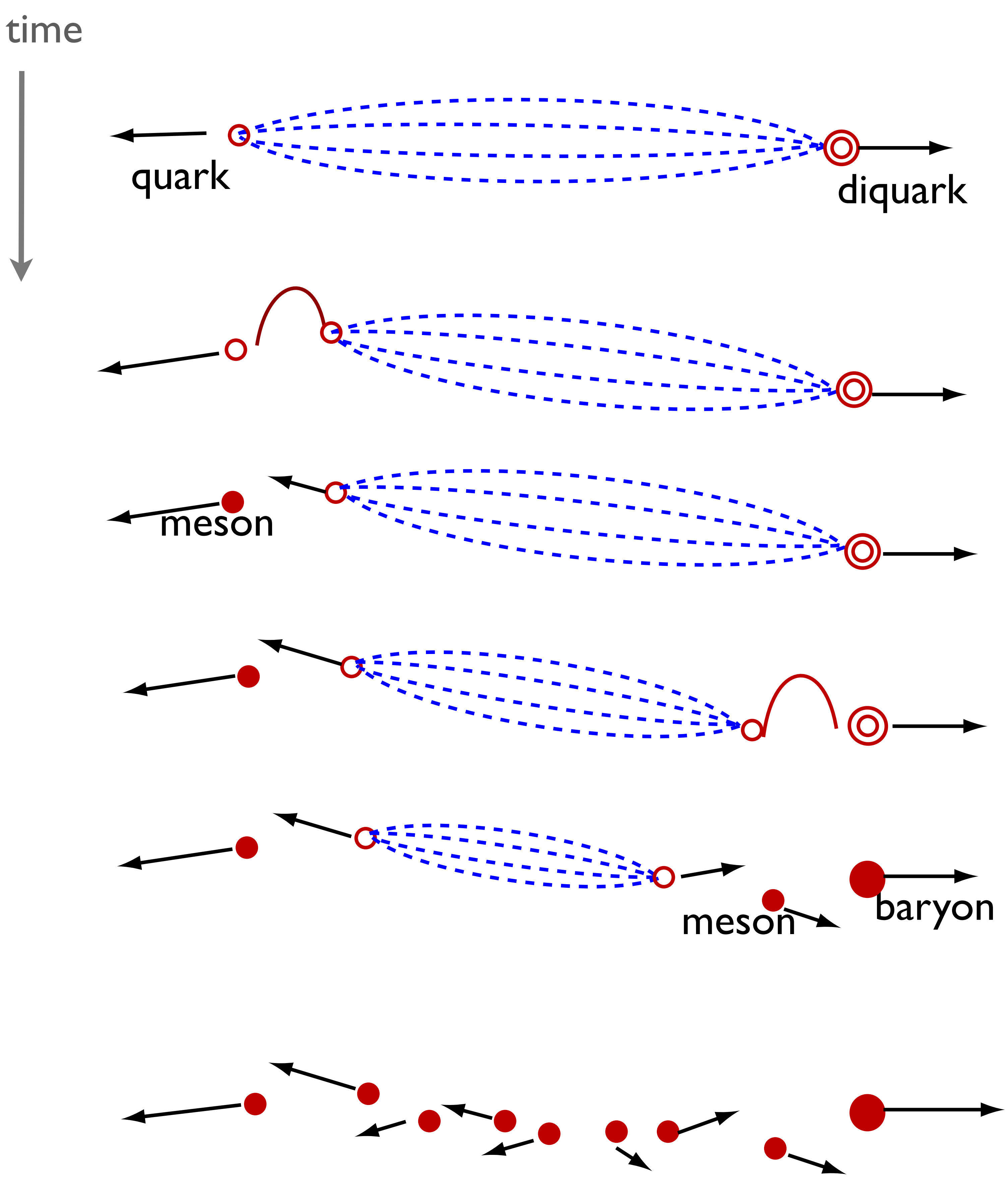


Color flow:



Initial and final state radiation does not change topology

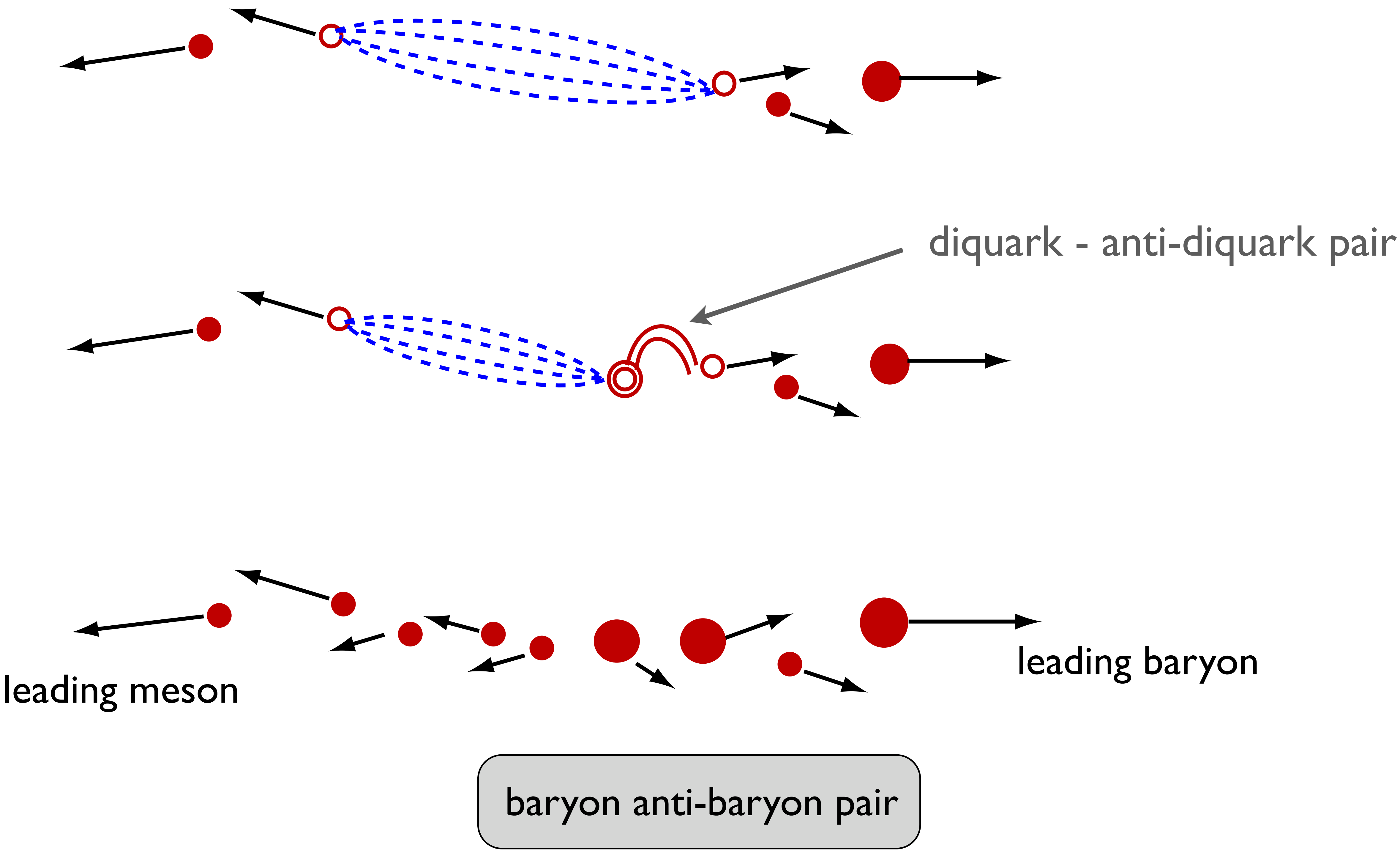
Leading particle effect



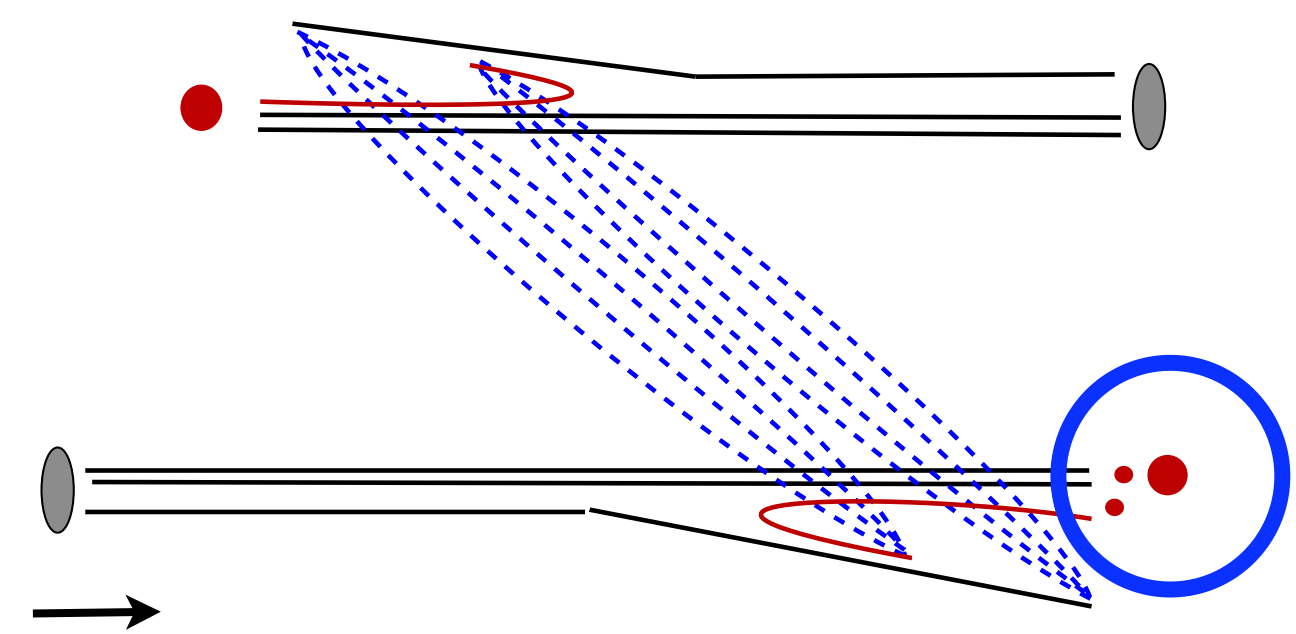
Chain of hadrons:

- large long. momenta near string ends
- small trans. momenta
- correlation of particles due to quark-antiquark pairs
- leading particle effect

Baryon pair production

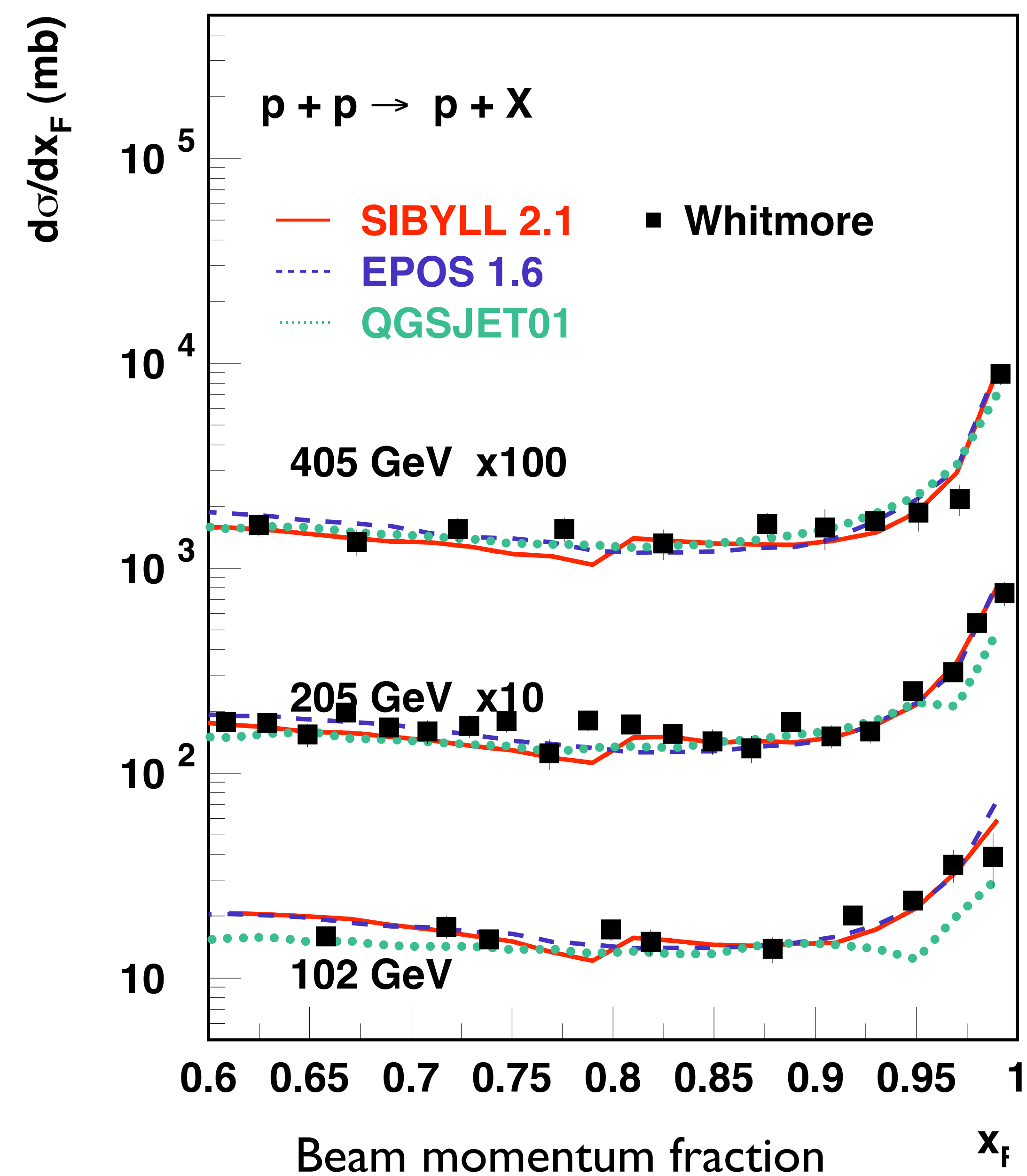


Particle production spectra (i)



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

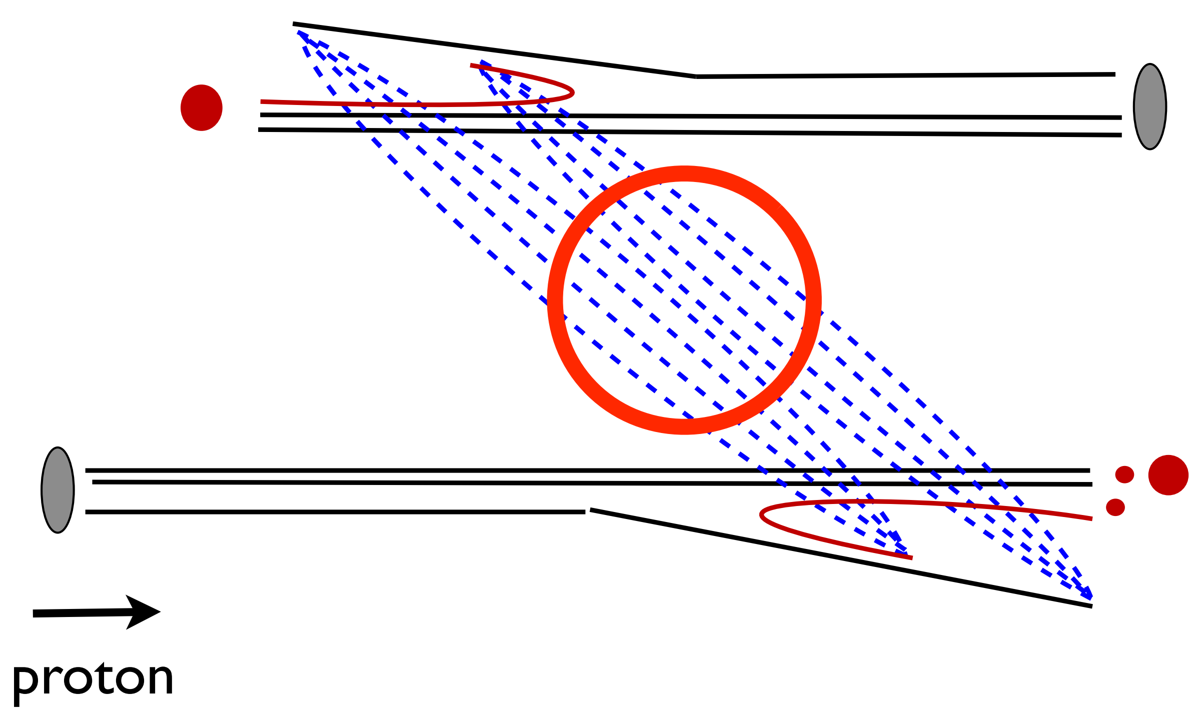
Leading particle effect

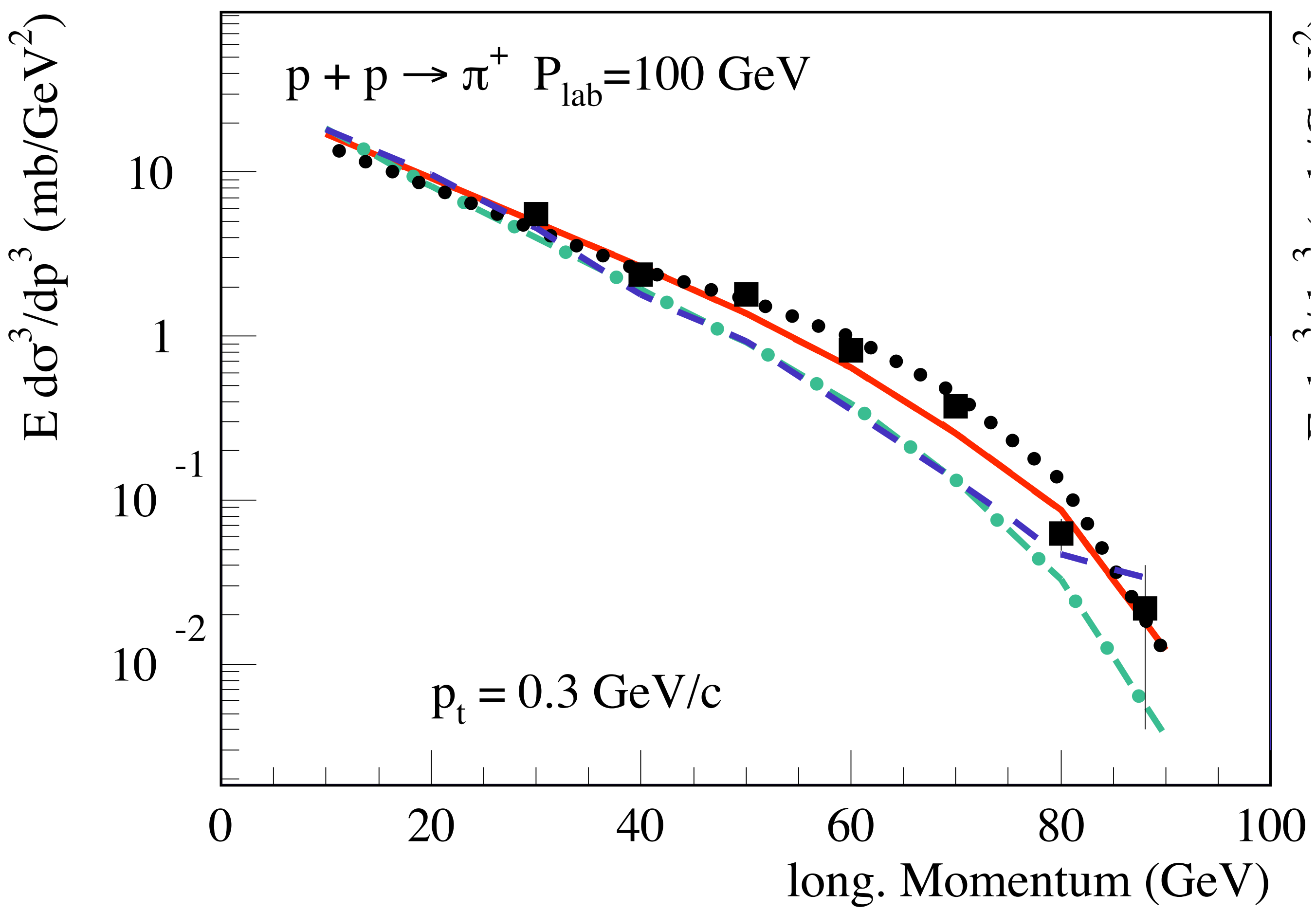


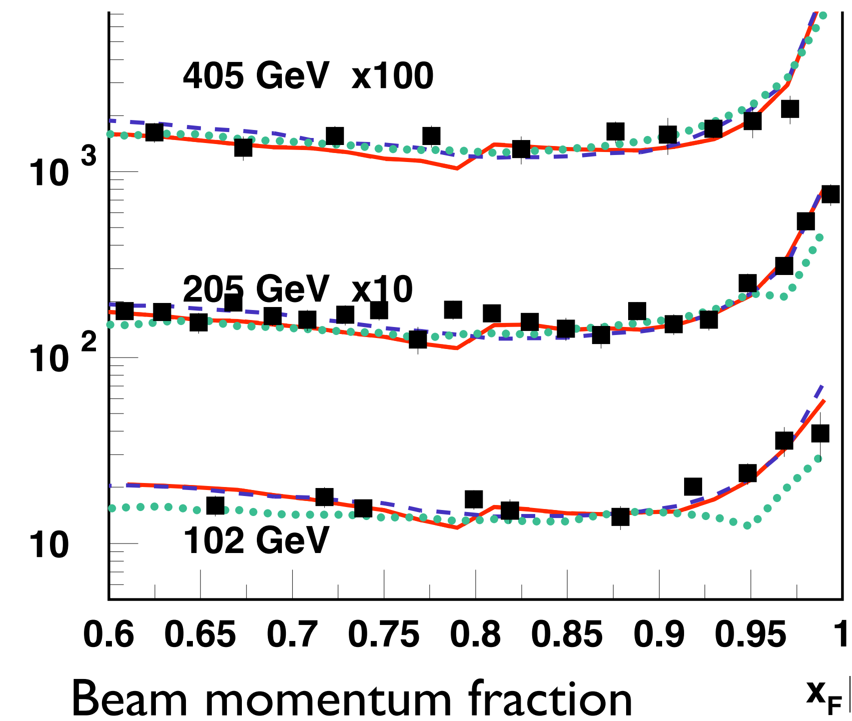
Beam momentum fraction

Particle production spectra (ii)

Central particle production



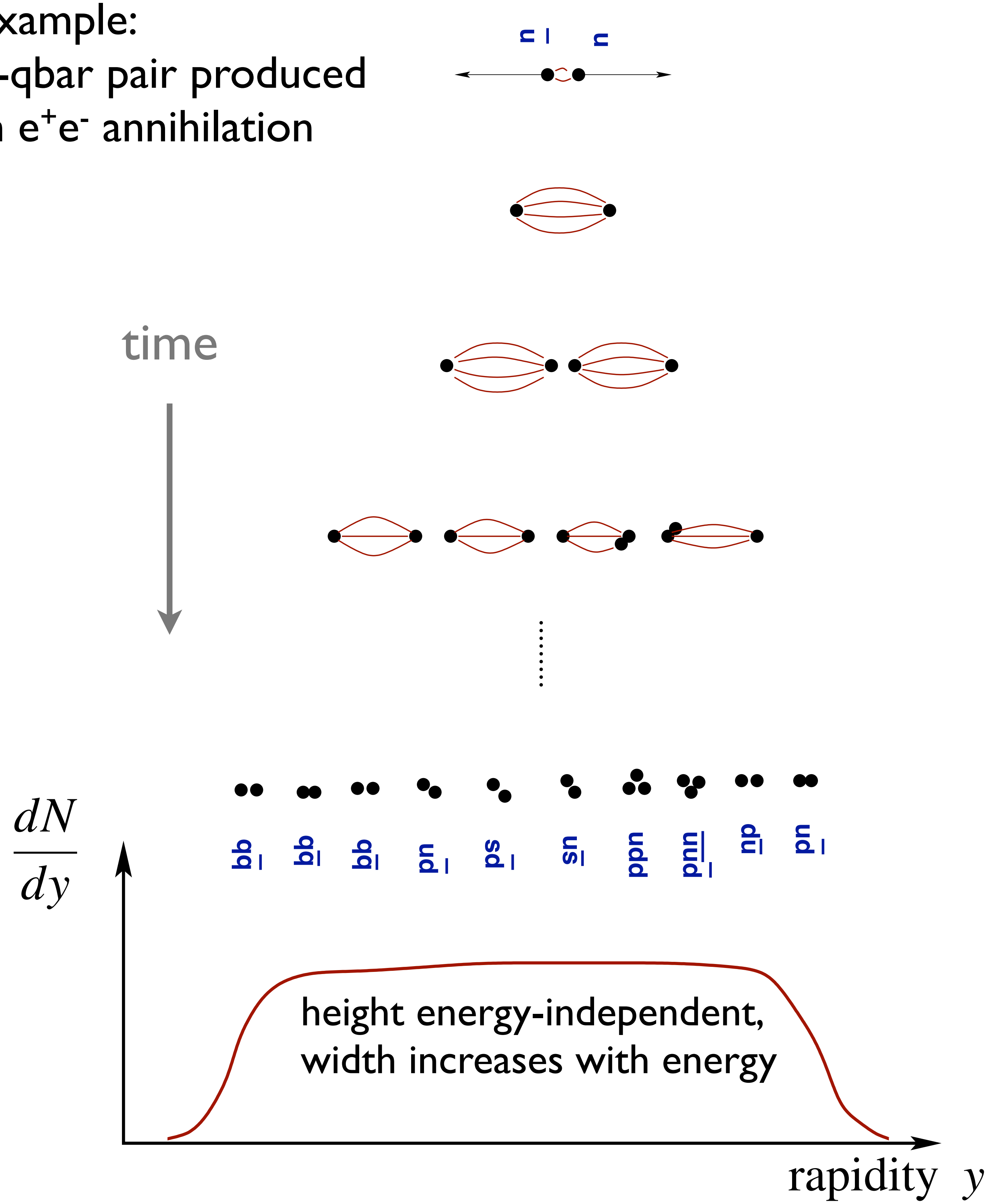




Fluctuations: Generation of sea quark anti-quark pair and leading/excited hadron

String fragmentation and rapidity

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



Rapidity

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

Rapidity of massless particles

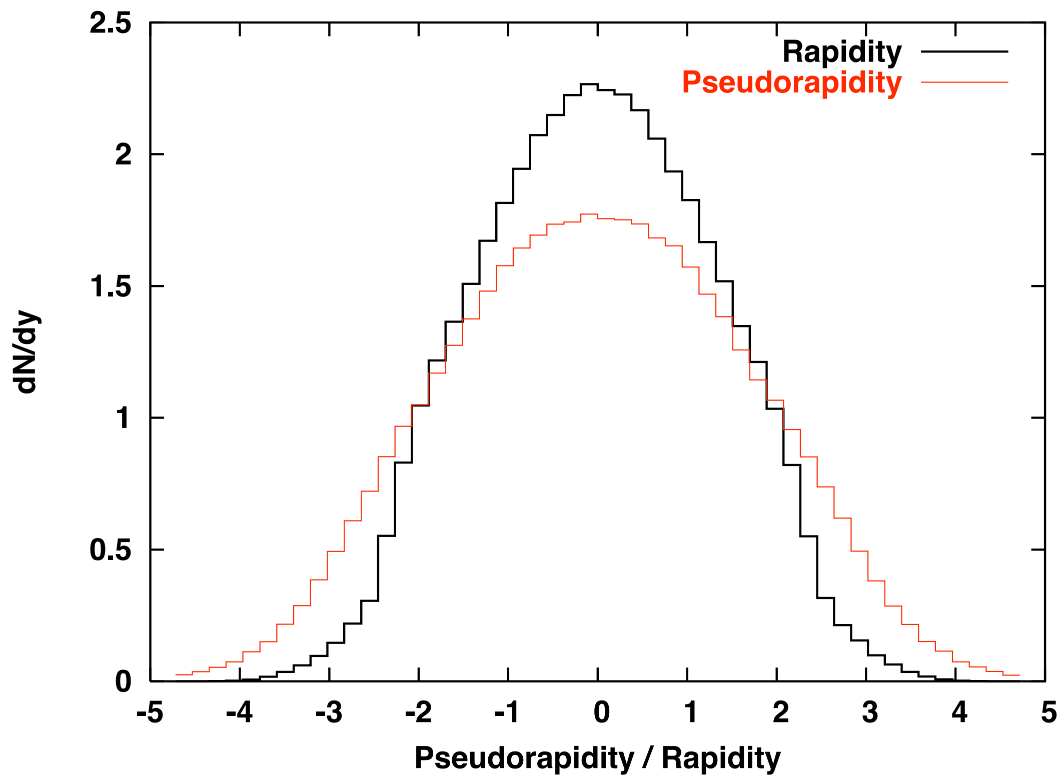
$$y = \frac{1}{2} \ln \frac{1 + \cos\theta}{1 - \cos\theta} = -\ln \tan \frac{\theta}{2}$$

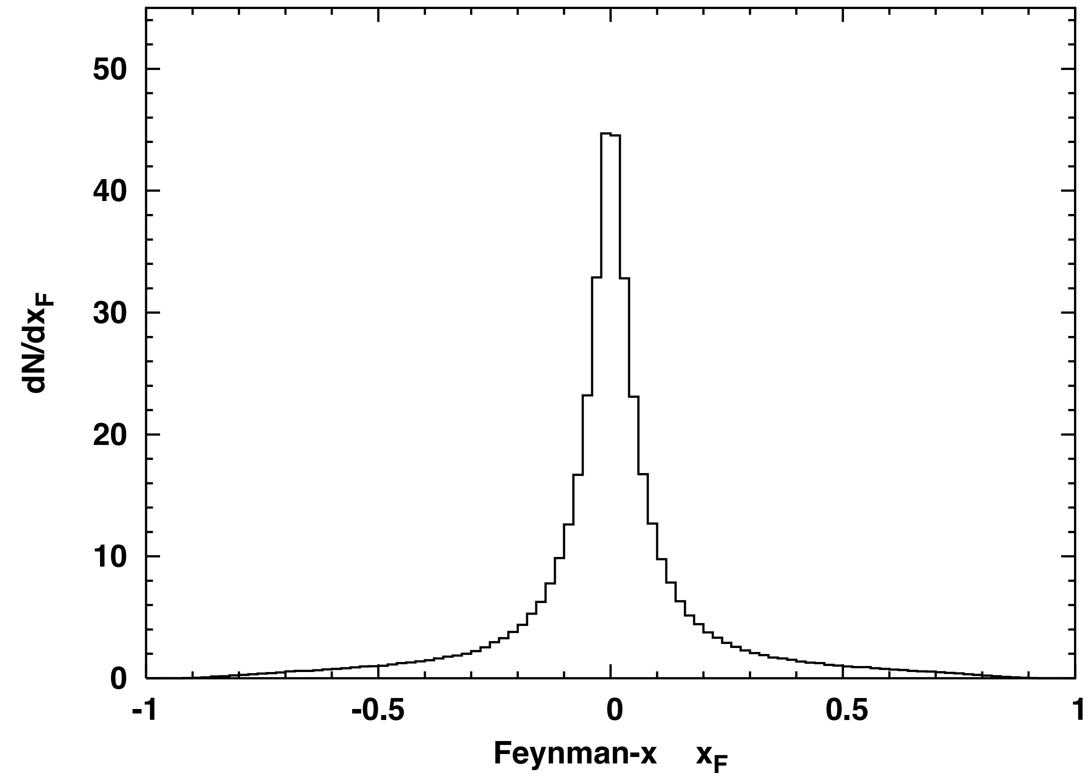
Pseudorapidity

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

Rapidity and pseudorapidity

Example: 100 GeV p-p collisions,
charged secondaries

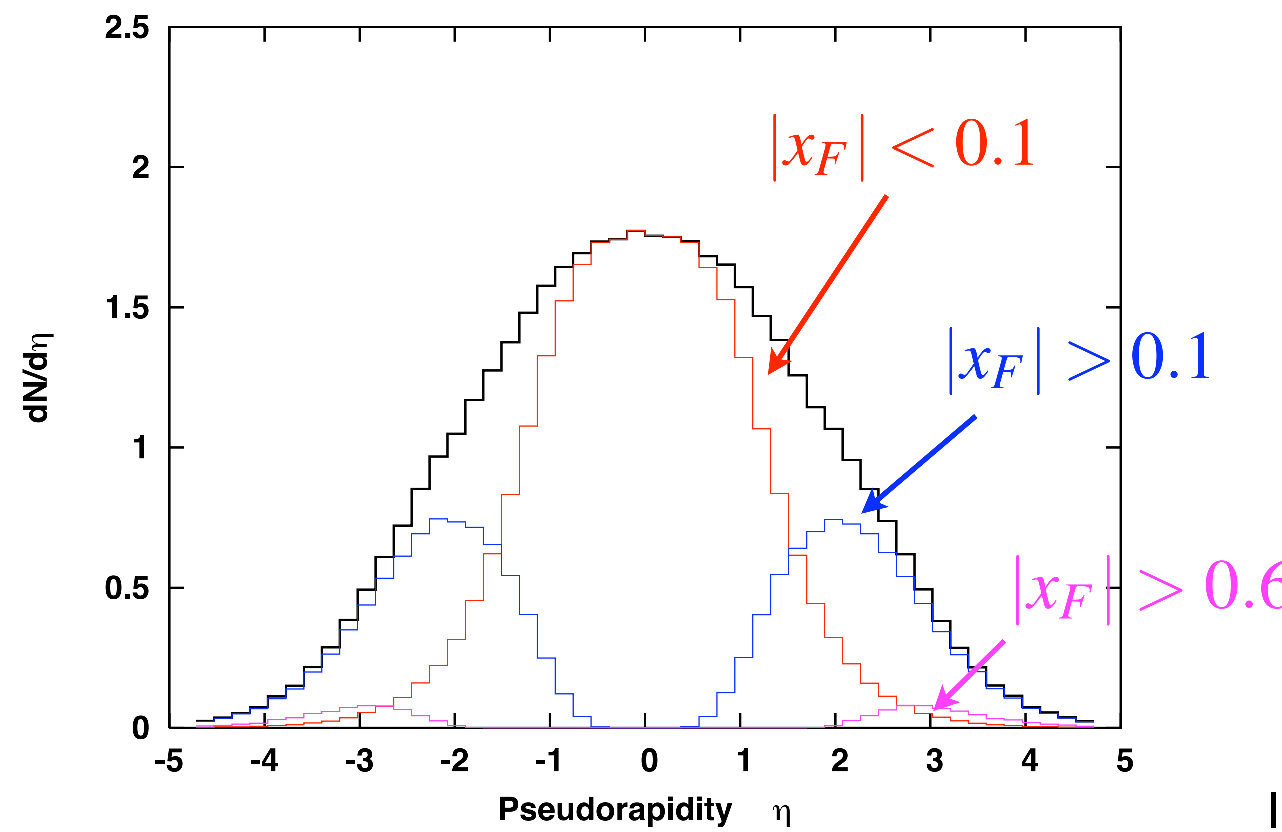




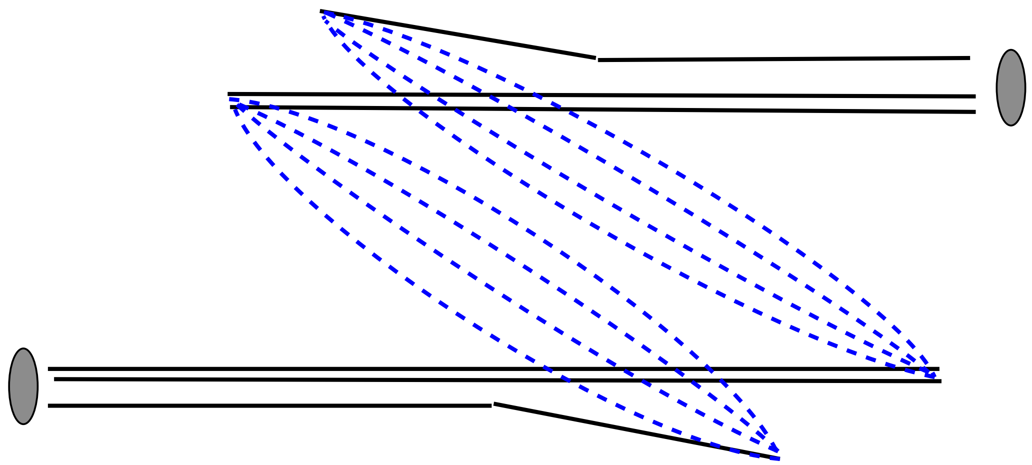
Rapidity and pseudorapidity very similar

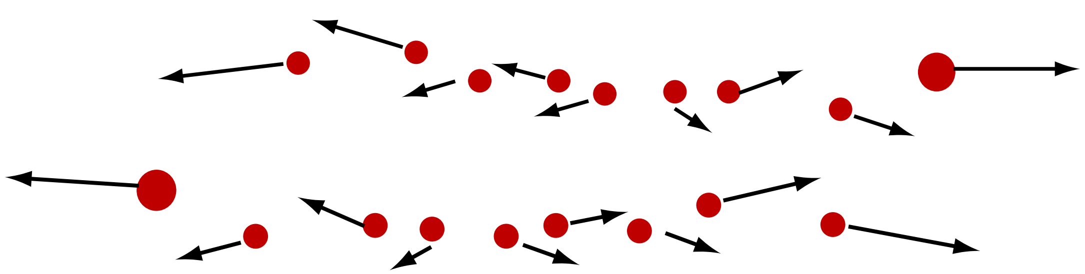
Feynman-x

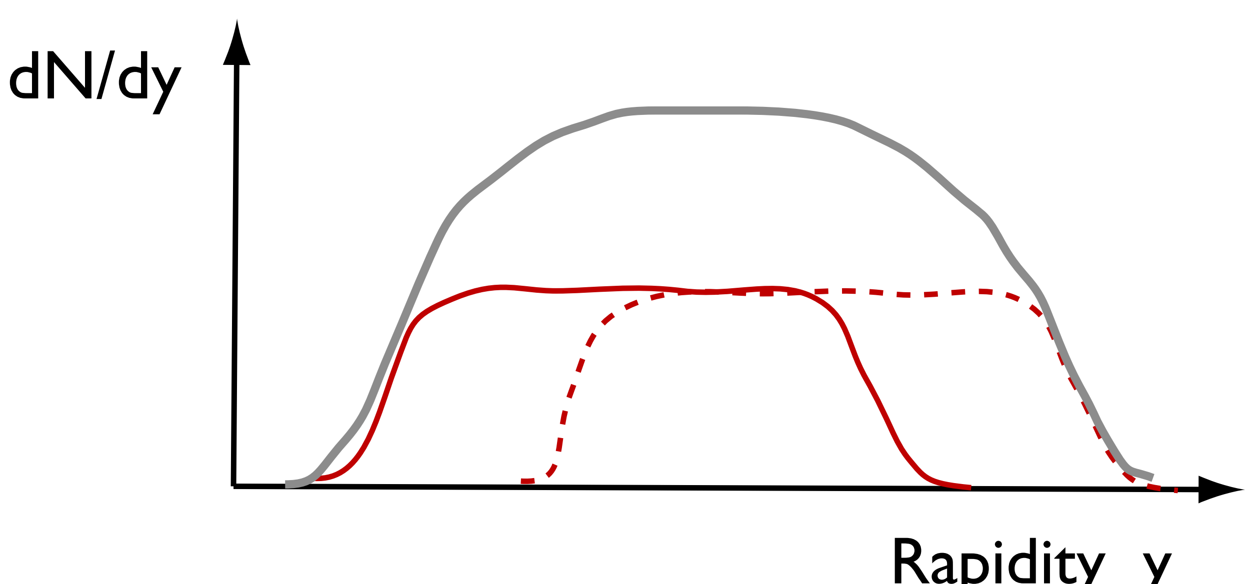
$$x_F = \frac{p_\parallel}{p_{\max}} \approx \frac{2p_\parallel}{\sqrt{s}}$$



Predictions of two-string models







Two-string models:

- Feynman-scaling
- long-range correlations
- leading particle effect
- delayed threshold for baryon pair production

Feynman scaling

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

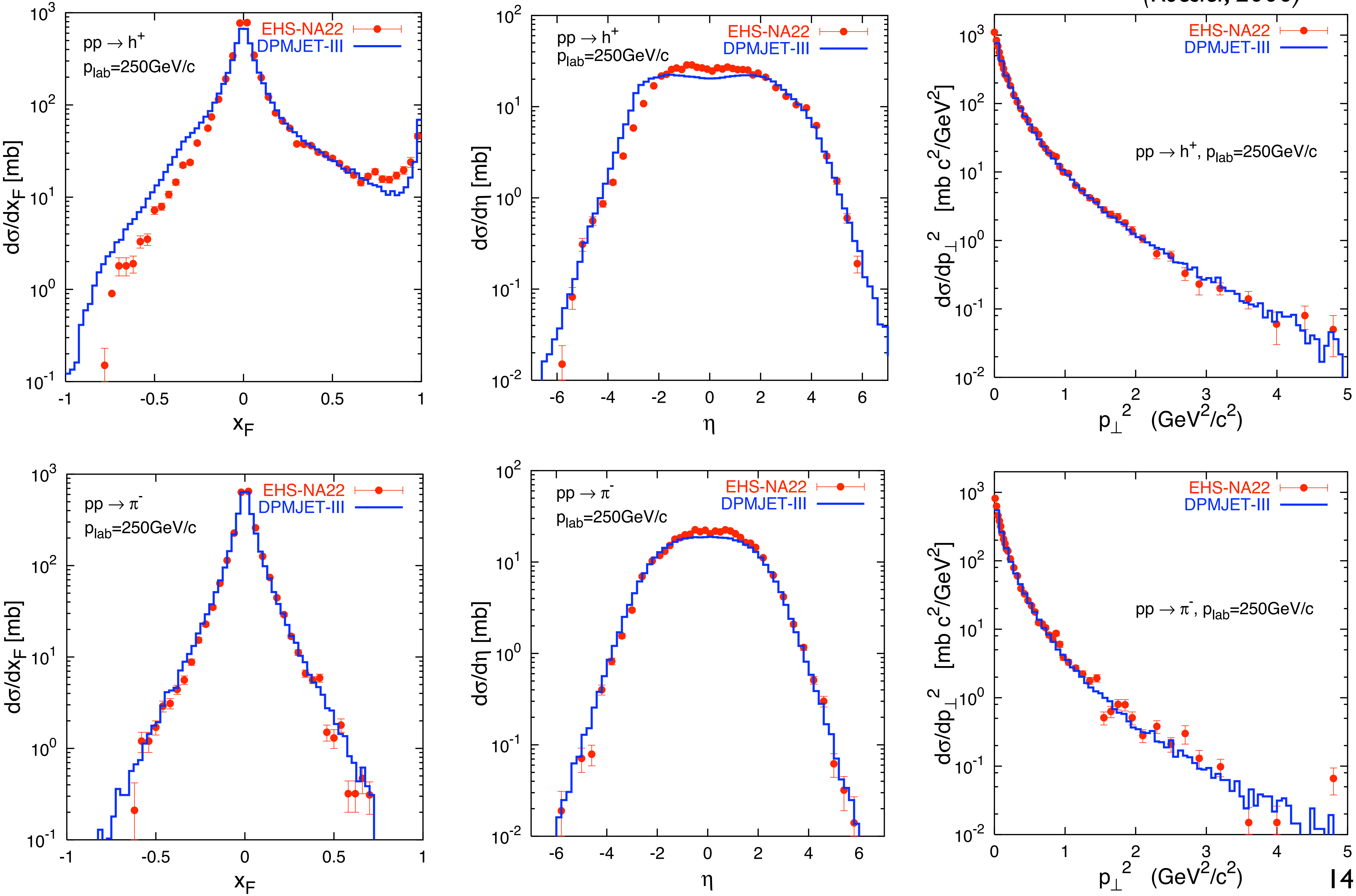
Distribution independent of energy

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

(*Capella et al., Physics Reports 1994*)

NA22 European Hybrid Spectrometer data

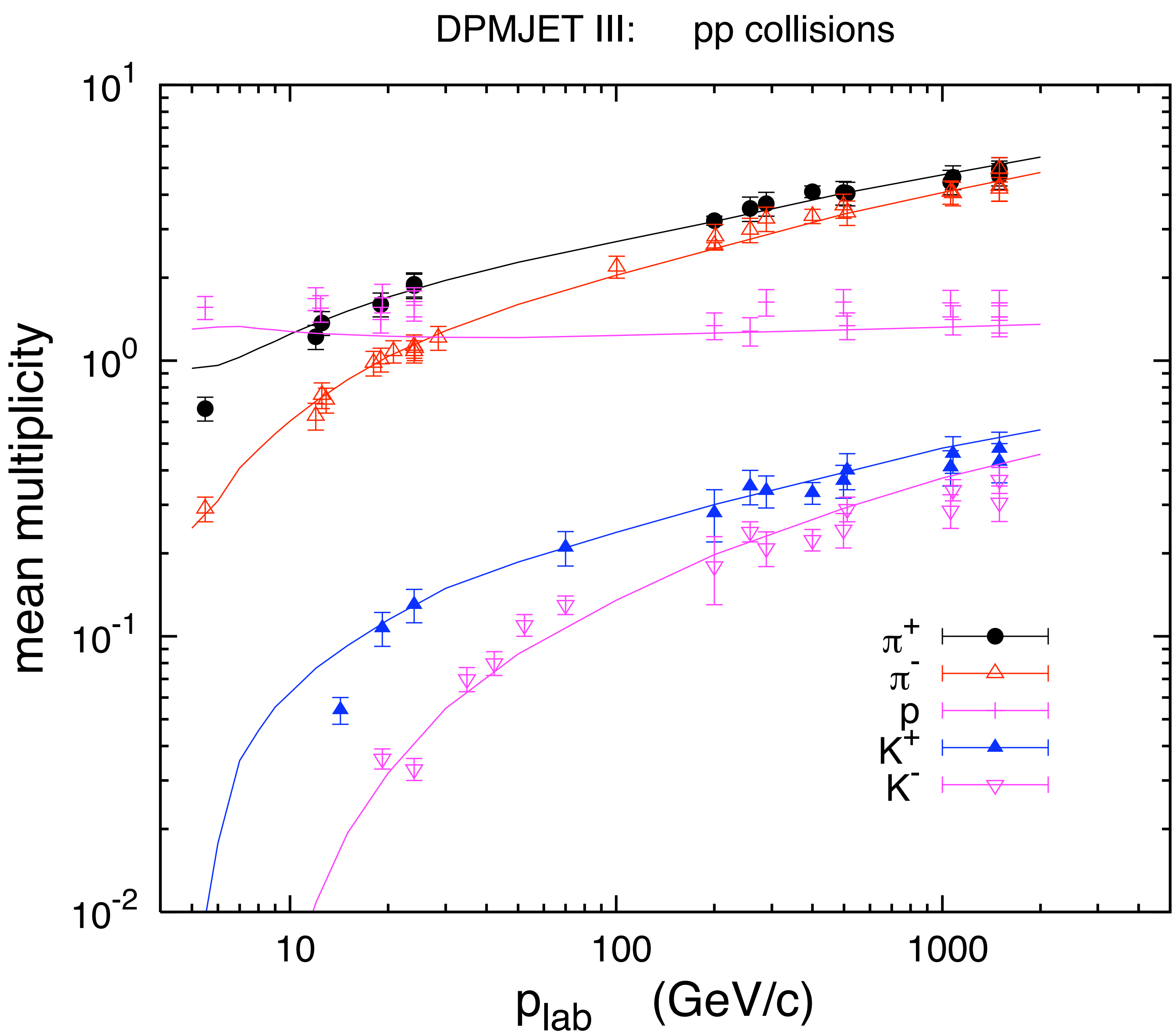
(Roesler, 2006)



Secondary particle multiplicities

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

	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

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

Leading particles

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

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charged	7.69 ± 0.06	7.64
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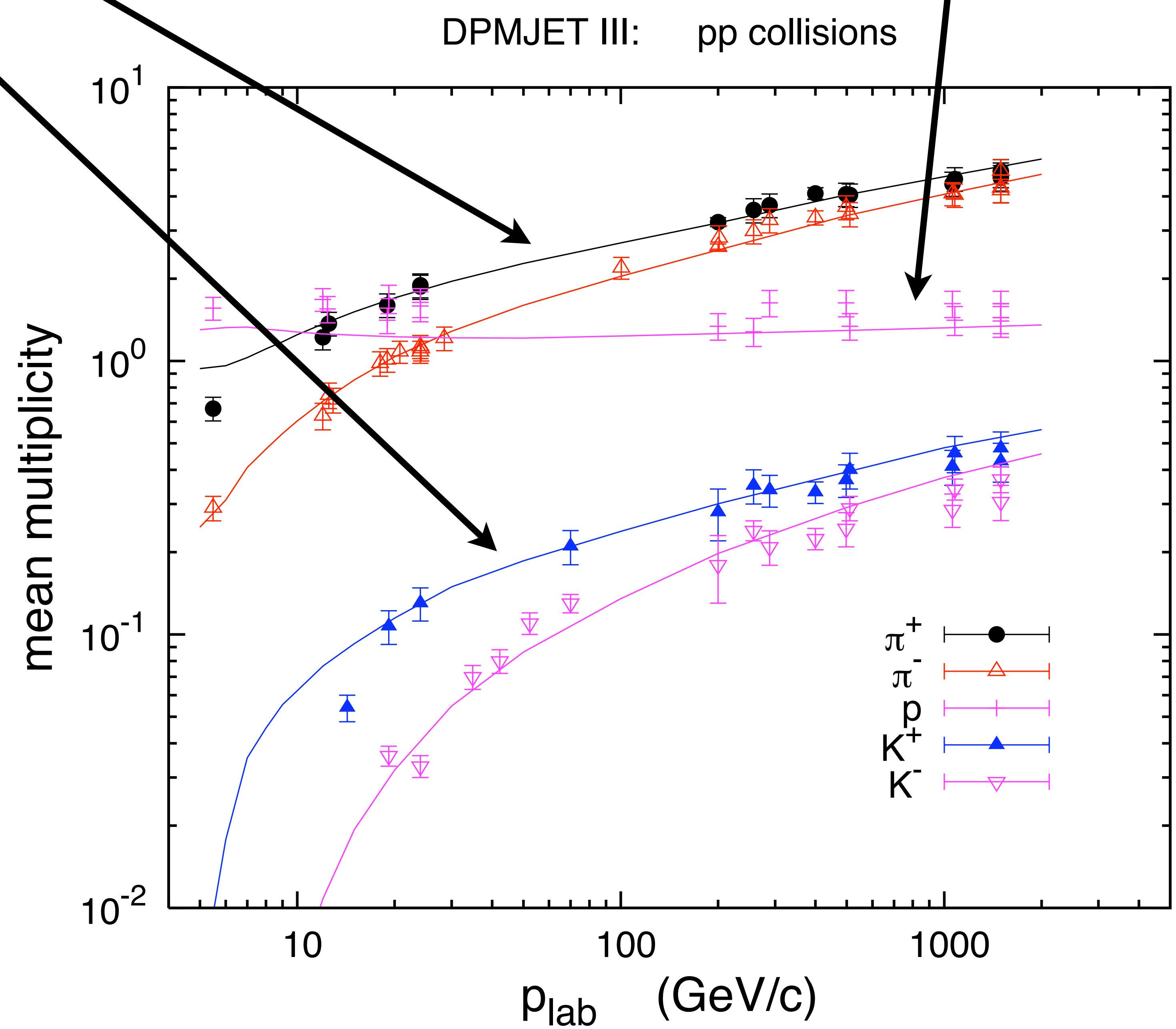
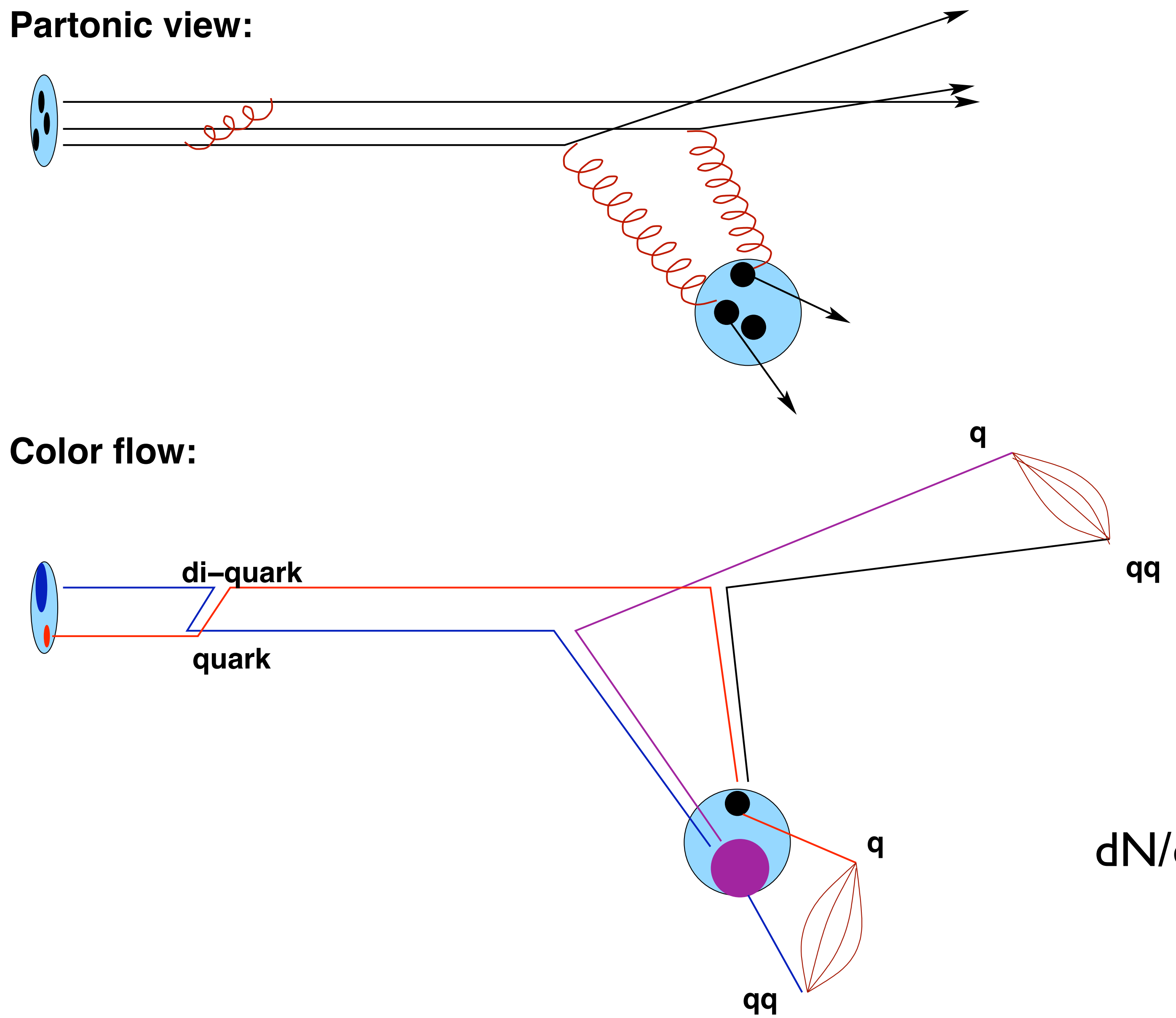
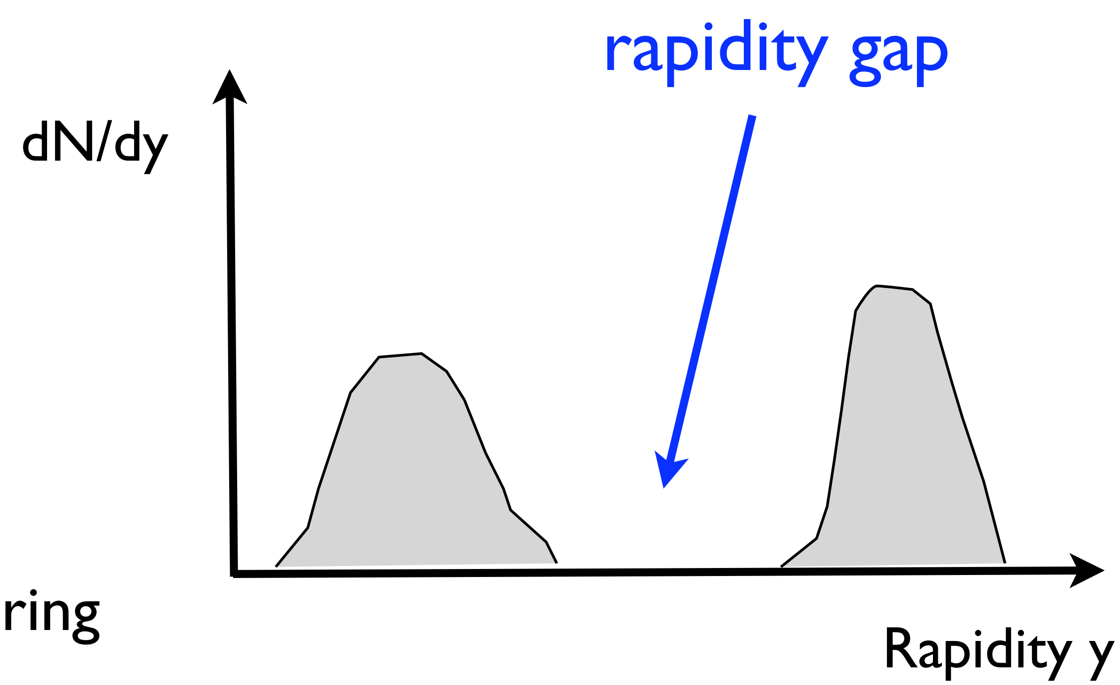


Other predicted color flow configurations



Two-gluon exchange:
diffraction dissociation



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

Basic features of multiparticle production

Particle production threshold (low energy)

- resonances, nearly isotropic decay
- energy loss ~20% in pγ interactions

Multiparticle production (intermediate energy)

- 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% $\pi^\pm$
  - situation different if kaons are included
  - baryons are pair-produced, delayed threshold
  - scaling of secondary particle distributions
- diffraction (rapidity gaps)
  - elastic scattering
  - low-mass diffraction dissociation
  - large multiplicity fluctuations

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

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

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

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

energy-independent yield function

Elementary math

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

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

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})

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

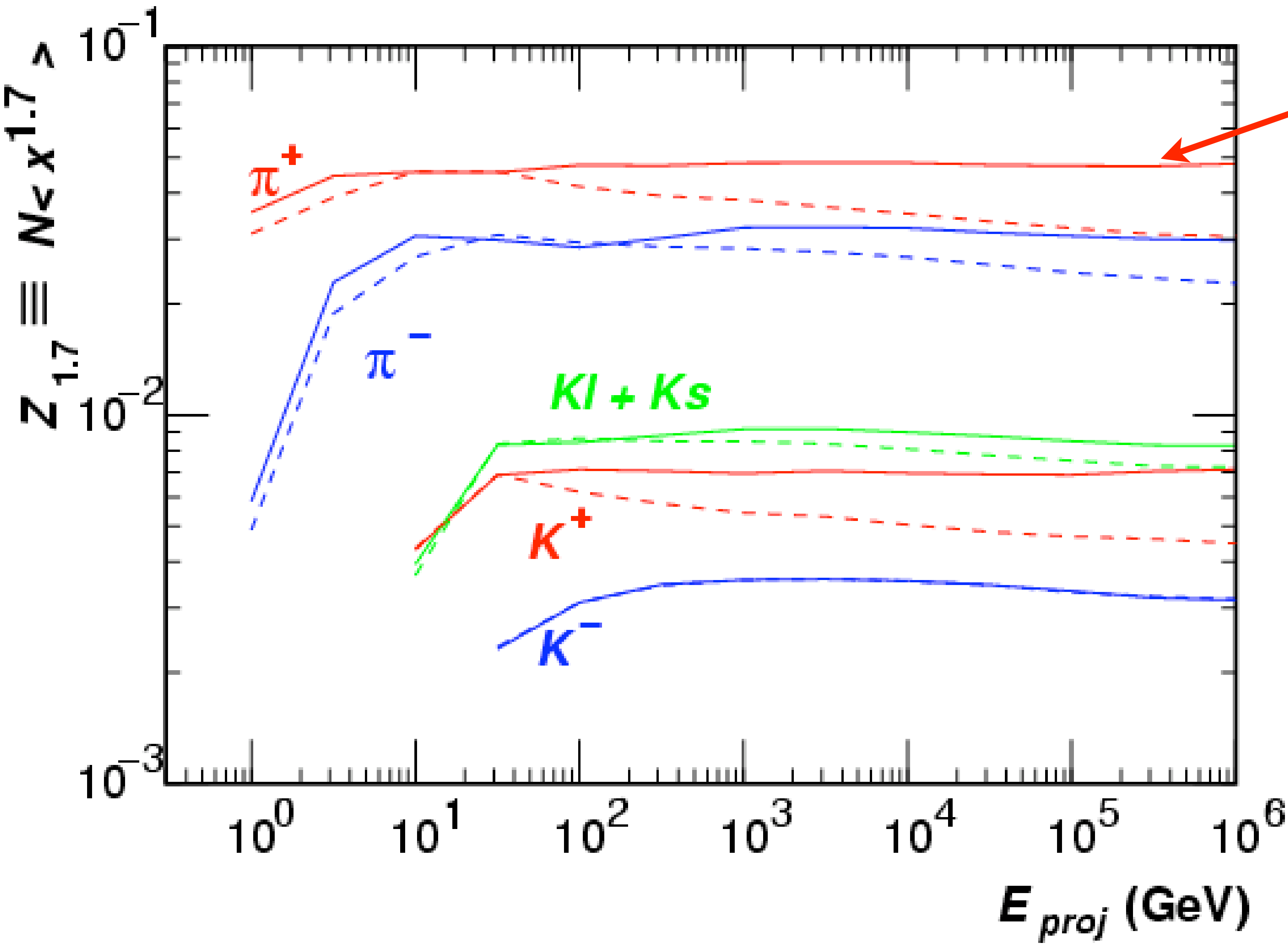
20% of p energy

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

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

Spectrum weighted moments for $\alpha = 2.7$

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)