Cosmic Rays and Extensive Air Showers

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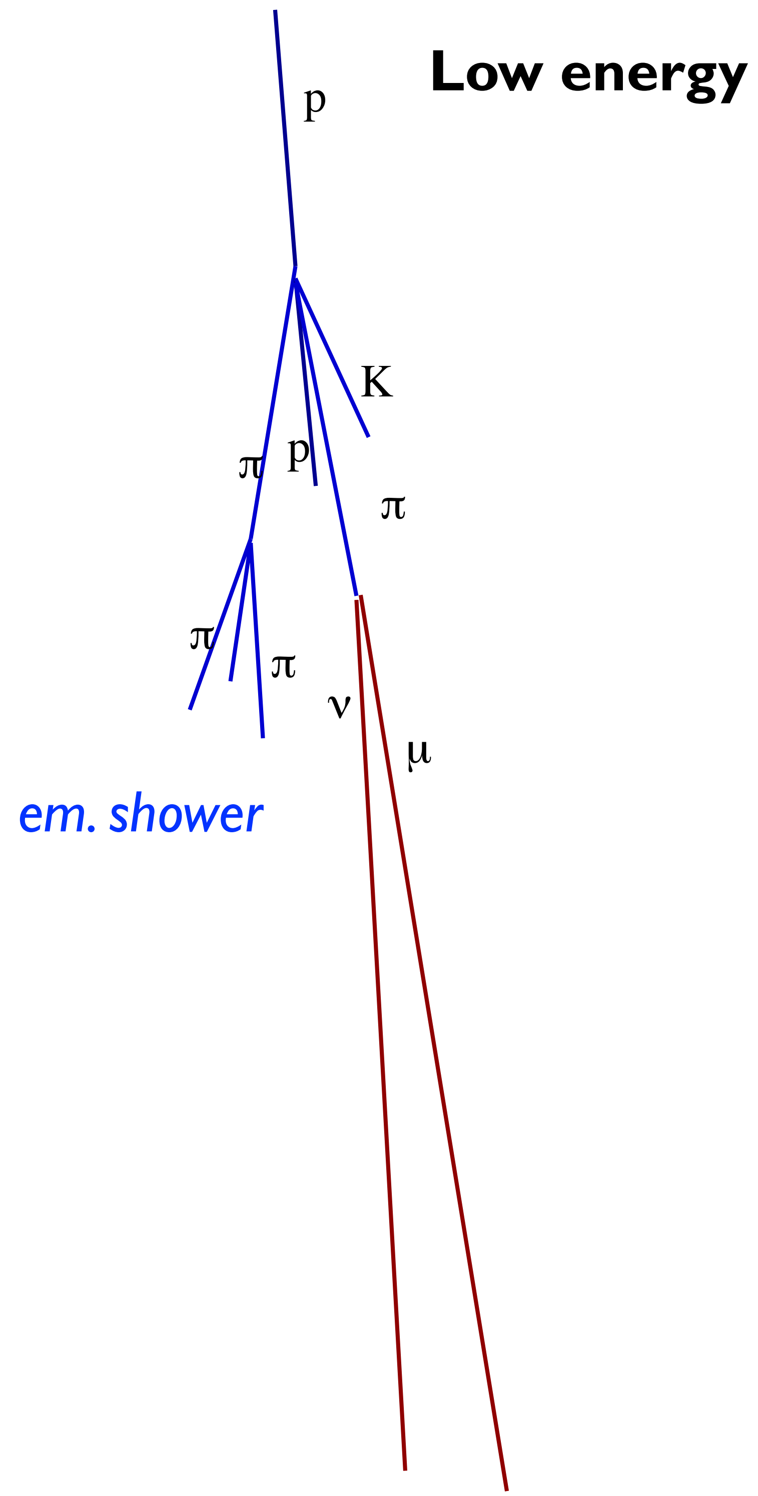
1 Phenomenology of extensive air showers

Hadronic cascades

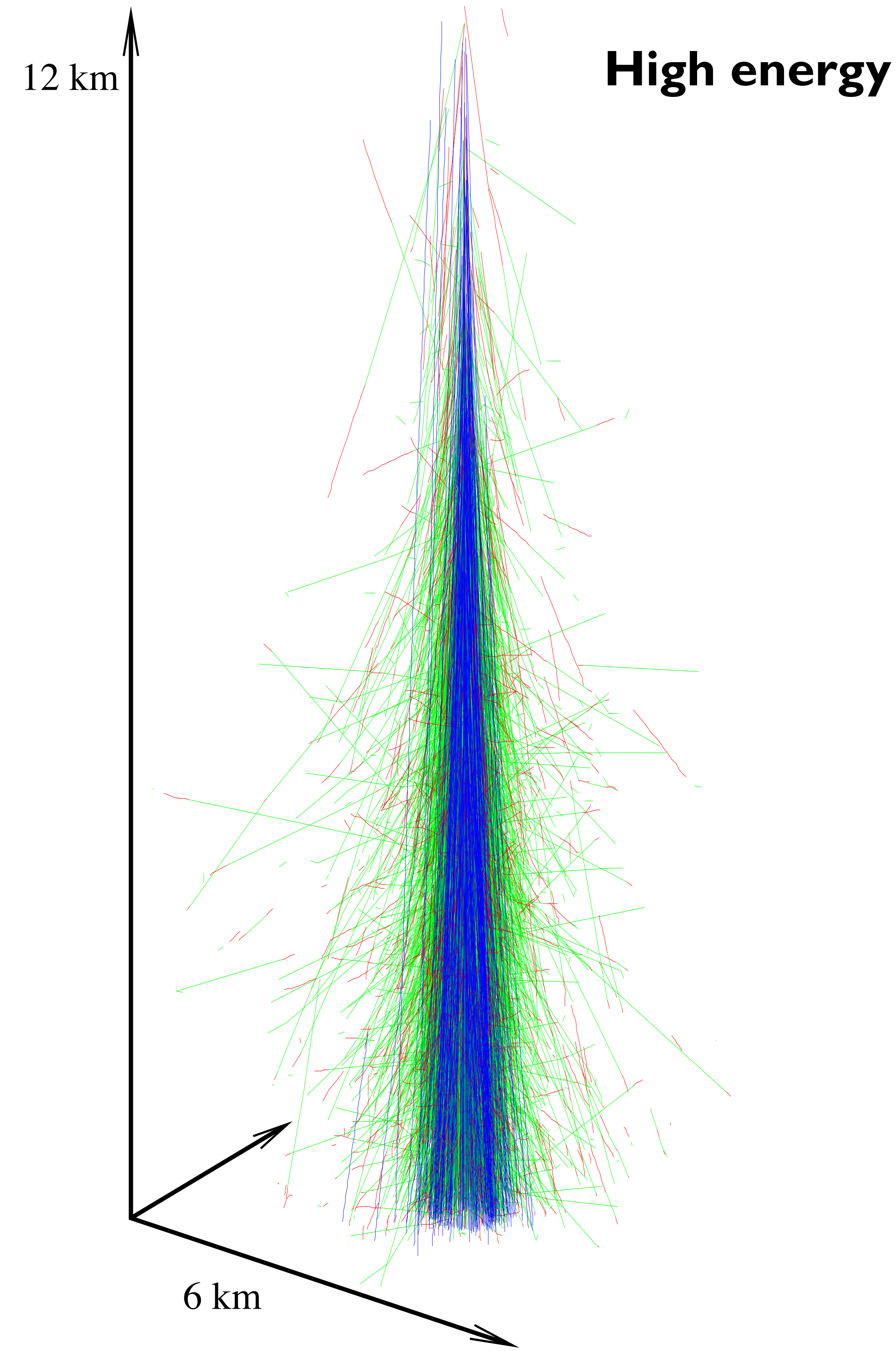


Typical energies above which particles interact

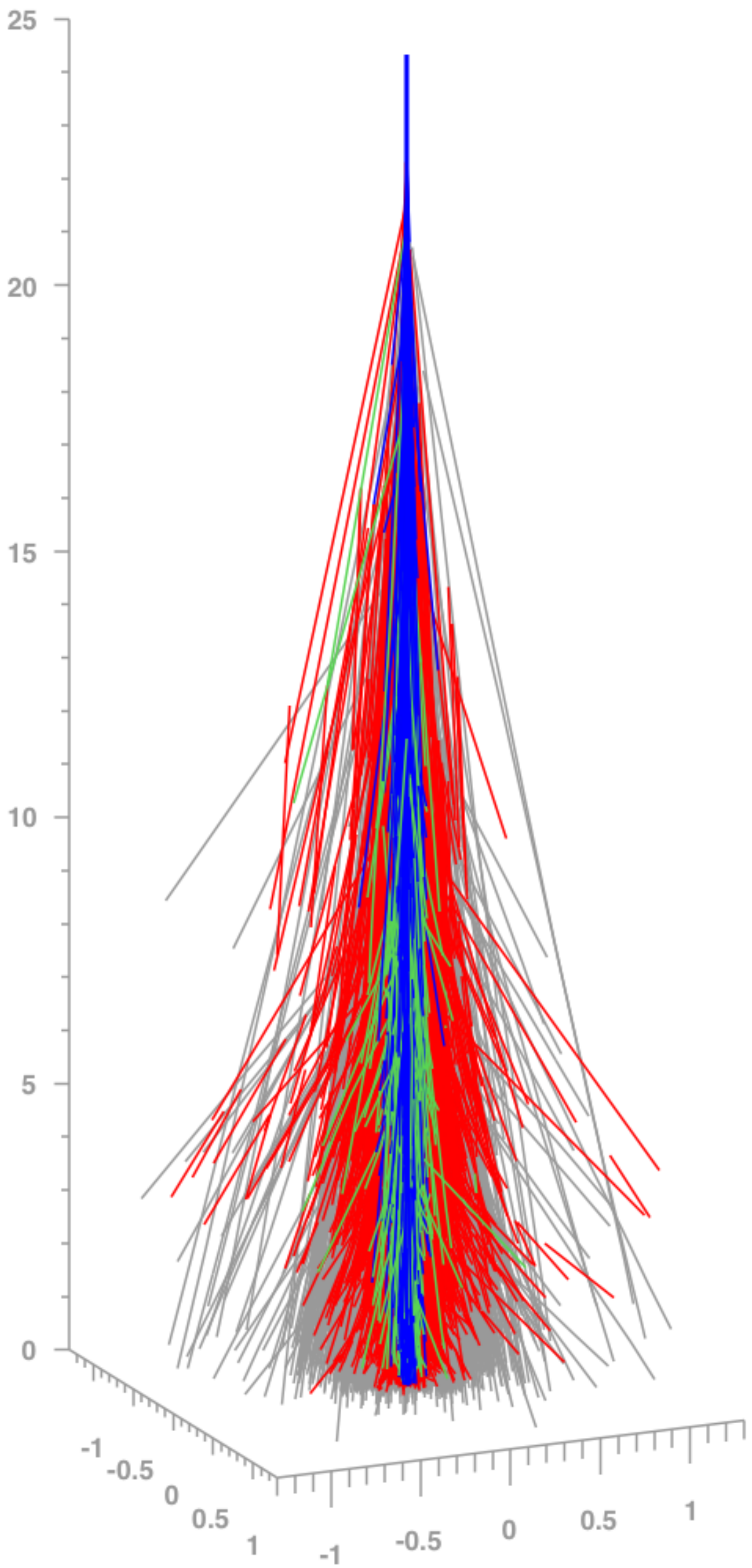
$$E_{\pi^\pm} \sim 30\,\mathrm{GeV}$$

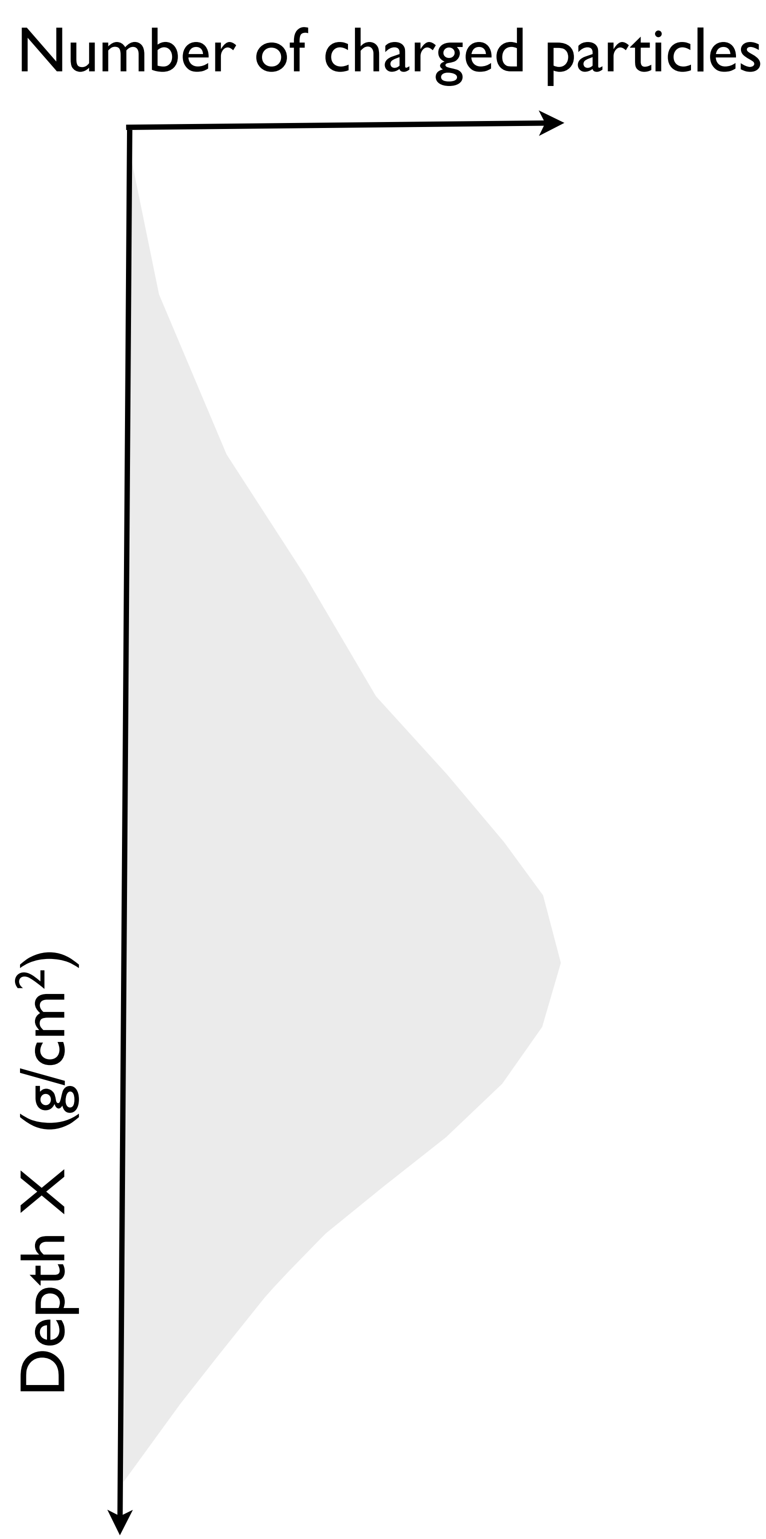
$$E_K \sim 200\,\mathrm{GeV}$$

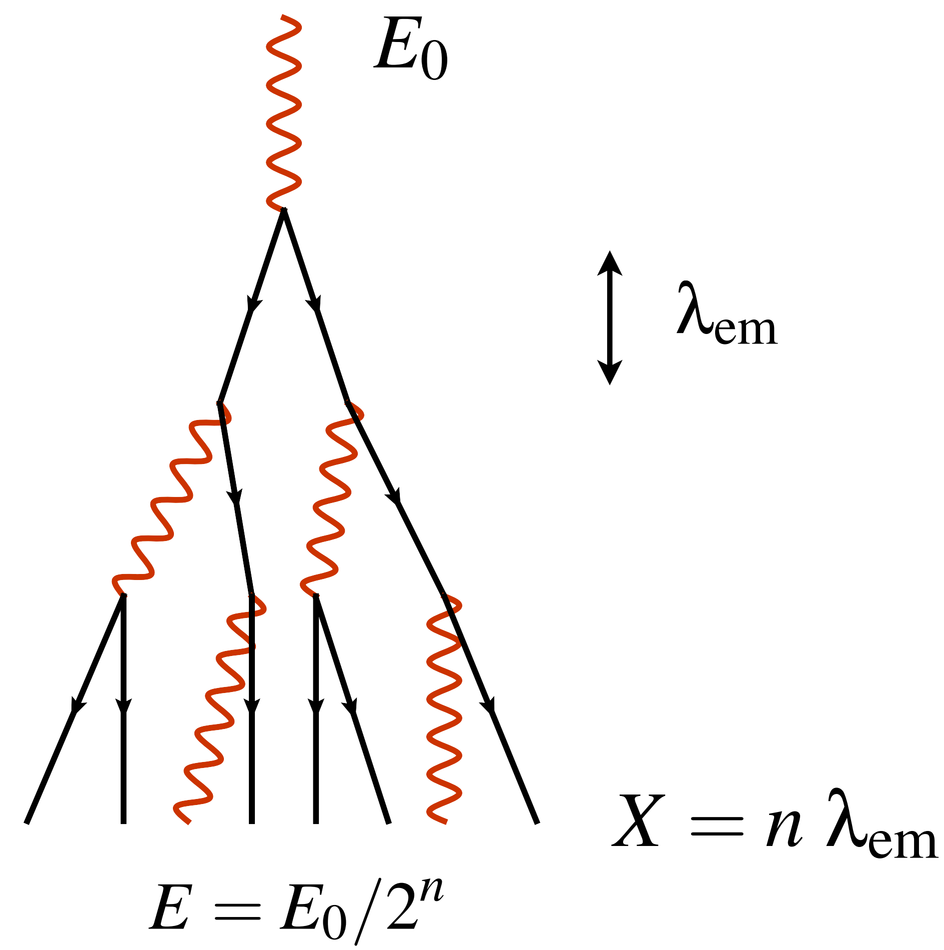
$$E_{\pi^0} \sim 10^{19}\,\mathrm{eV}$$



Electromagnetic showers: Heitler model







Shower maximum: $E = E_c$

$$N_{\mathrm{max}} = E_0/E_c$$

$$X_{\mathrm{max}} \sim \lambda_{\mathrm{em}} \ln(E_0/E_c)$$

Electromagnetic showers: Cascade equations

Energy loss of electron: $$\frac{\mathrm{d}E}{\mathrm{d}X} = -\alpha - \frac{E}{X_0}$$

Critical energy: $E_c = \alpha\, X_0 \sim 85\,\mathrm{MeV}$

Radiation length: $X_0 \sim 36\,\mathrm{g/cm^2}$

Cascade equations

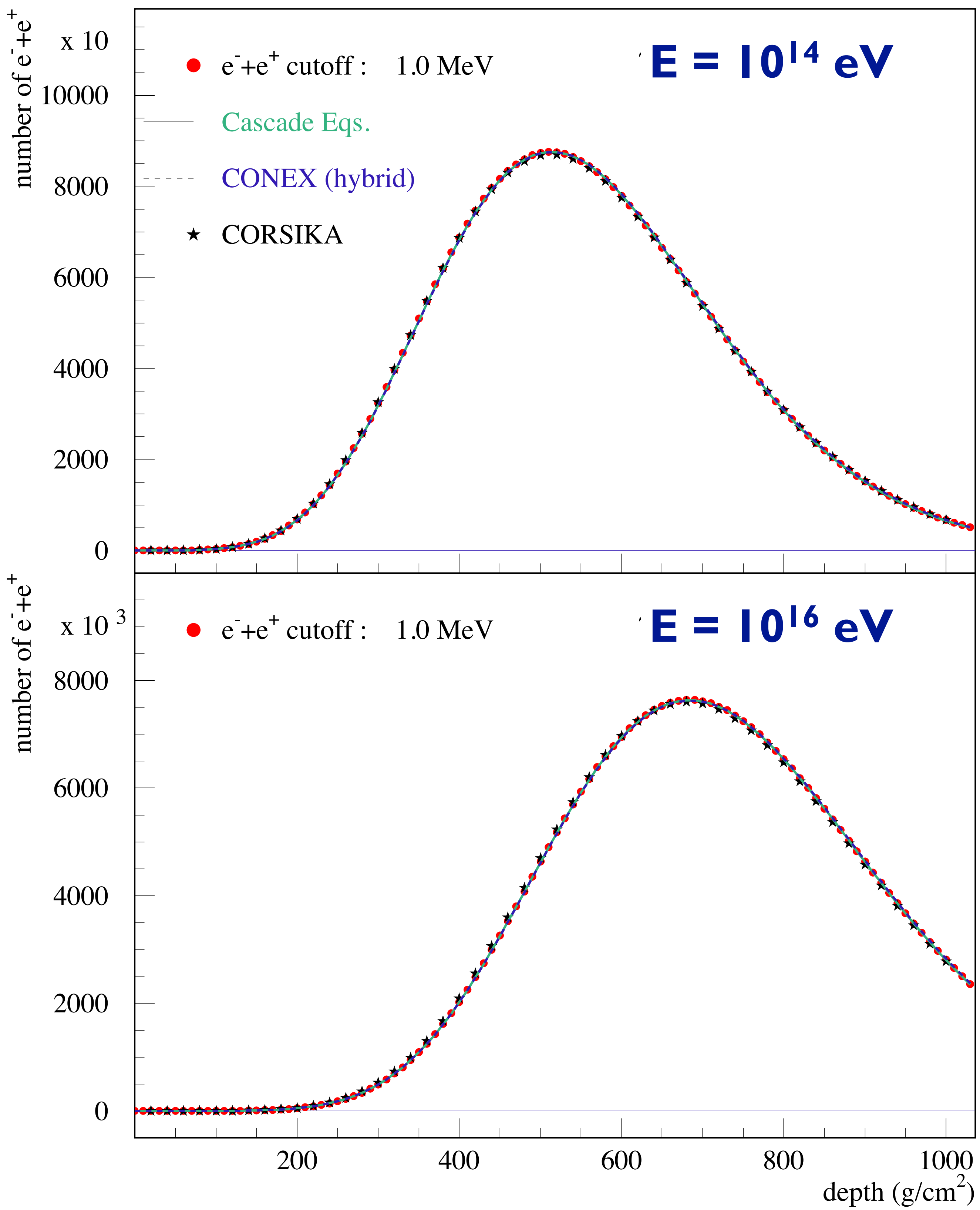
$$\frac{\mathrm{d}\Phi_e(E)}{\mathrm{d}X} = -\frac{\sigma_e}{\langle m_{\mathrm{air}}\rangle}\Phi_e(E) + \int_E^\infty \frac{\sigma_e}{\langle m_{\mathrm{air}}\rangle}\Phi_e(\tilde{E})P_{e\to e}(\tilde{E},E)\mathrm{d}\tilde{E}$$

$$+ \int_E^\infty \frac{\sigma_\gamma}{\langle m_{\mathrm{air}}\rangle}\Phi_\gamma(\tilde{E})P_{\gamma\to e}(\tilde{E},E)\mathrm{d}\tilde{E} \;+\; \alpha\frac{\partial\Phi_e(E)}{\partial E}$$

$$X_{\max} \approx X_0 \ln\left(\frac{E_0}{E_c}\right) \qquad N_{\max} \approx \frac{0.31}{\sqrt{\ln(E_0/E_c) - 0.33}}\frac{E_0}{E_c}$$

(Rossi & Greisen, Rev. Mod. Phys. 13 (1940) 240)

Mean longitudinal shower profile



Calculation with cascade Eqs.

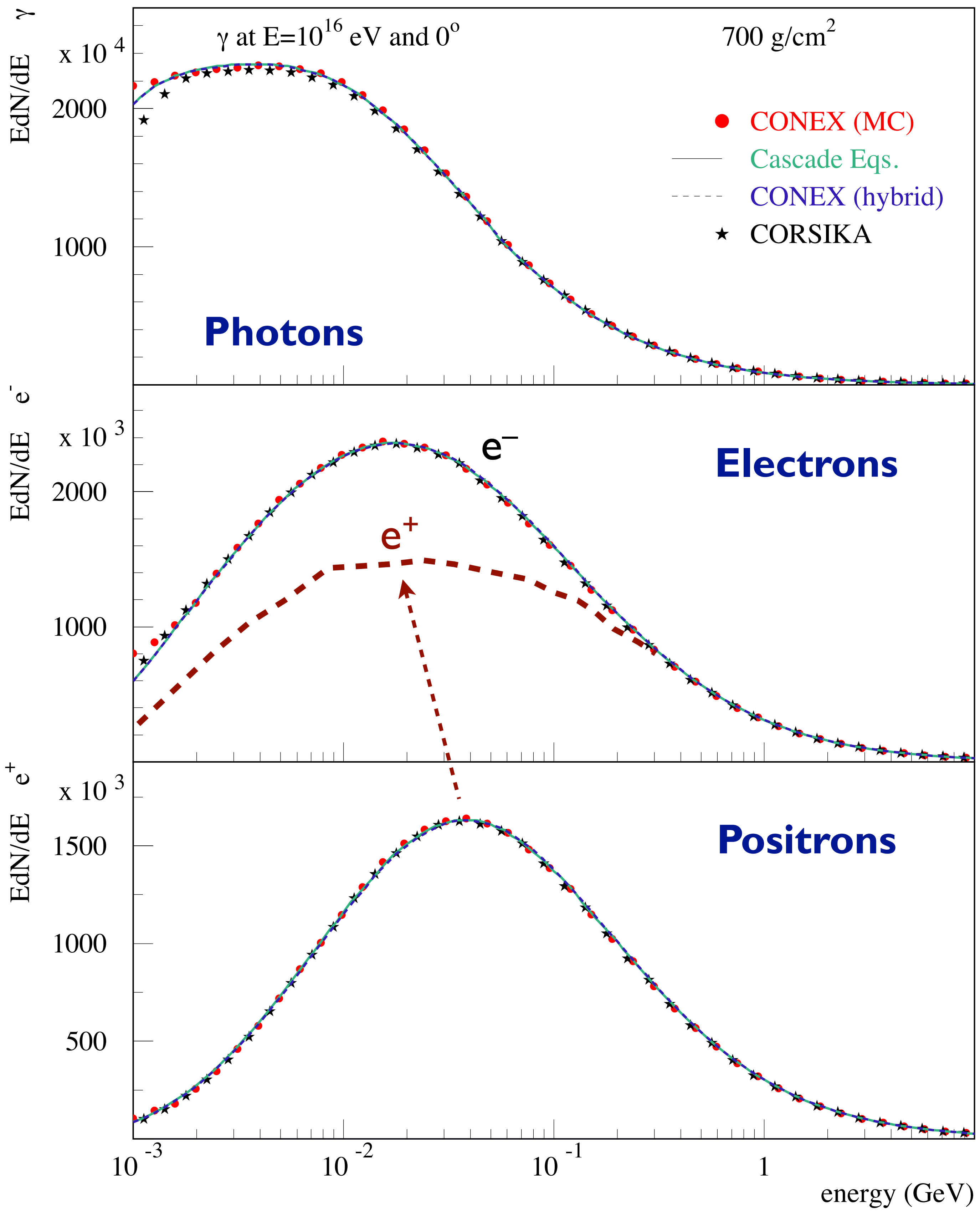
Photons
- Pair production
- Compton scattering

Electrons
- Bremsstrahlung
- Moller scattering

Positrons
- Bremsstrahlung
- Bhabha scattering

(Bergmann et al., Astropart.Phys. 26 (2007) 420)

Energy spectra of secondary particles

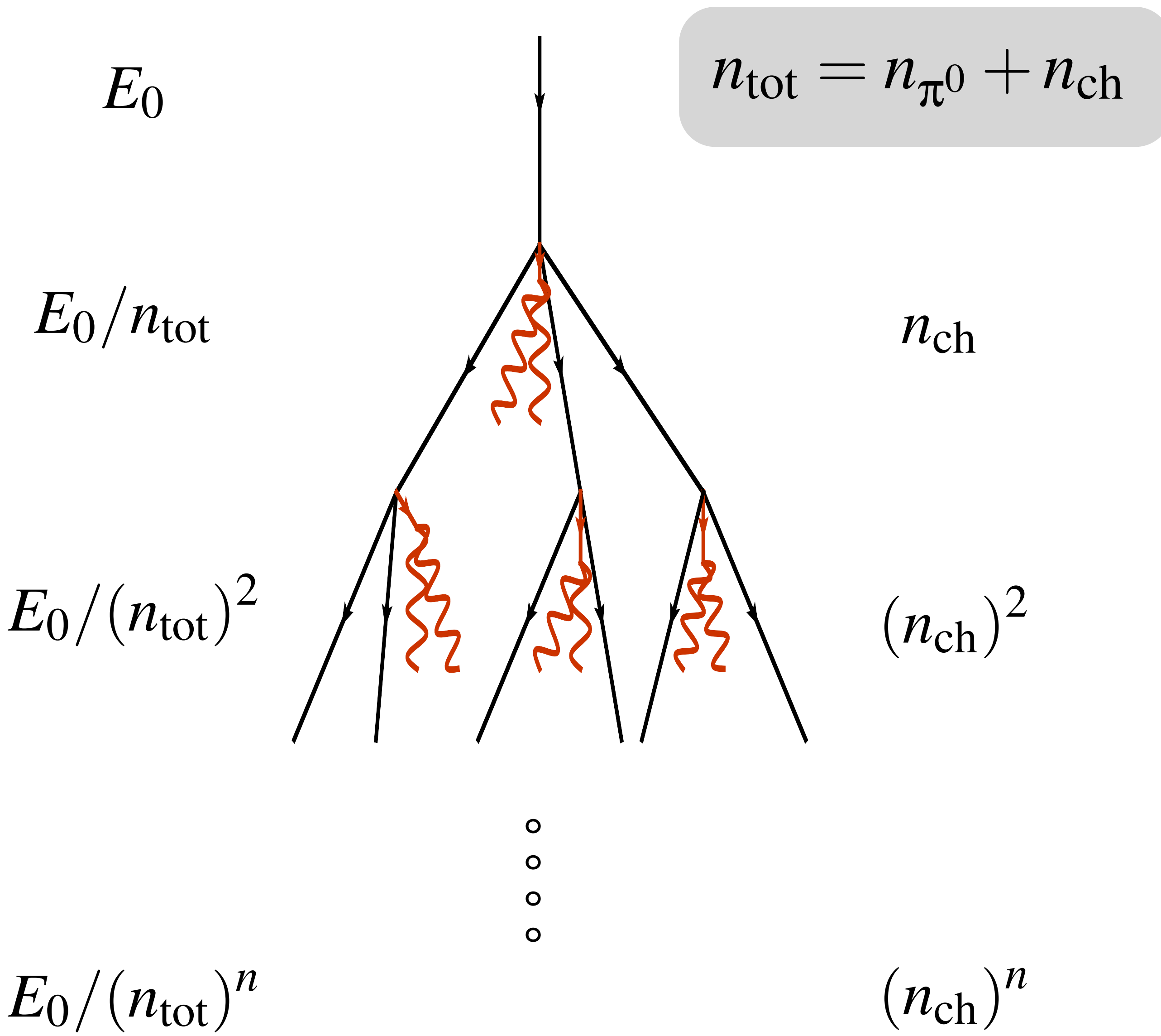


Number of photons divergent

- Typical energy of electrons and positrons $E_c \sim 80$ MeV
- Electron excess of 20 - 30%
- Pair production symmetric
- Excess of electrons in target

(Bergmann et al., Astropart.Phys. 26 (2007) 420)

Muon production in hadronic showers



Primary particle proton

π^0 decay immediately

$\pi^{\pm}$ initiate new cascades

$$N_\mu = \left(\frac{E_0}{E_{dec}}\right)^\alpha$$

$$\alpha = \frac{\ln n_{ch}}{\ln n_{tot}} \approx 0.82 \ldots 0.95$$

Assumptions:

- cascade stops at $E_{part} = E_{dec}$
- each hadron produces one muon

(Matthews, Astropart.Phys. 22, 2005)

Superposition model

Proton-induced shower

$$N_{\max} = E_0/E_c$$

$$X_{\max} \sim \lambda_{\text{eff}} \ln(E_0)$$

$$N_\mu = \left(\frac{E_0}{E_{\text{dec}}}\right)^\alpha \qquad \alpha \approx 0.9$$

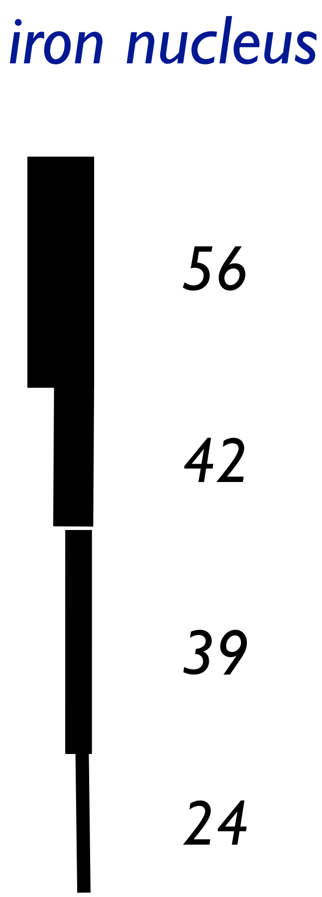
Assumption: nucleus of mass *A* and energy E_0 corresponds to *A* nucleons (protons) of energy $E_n = E_0/A$

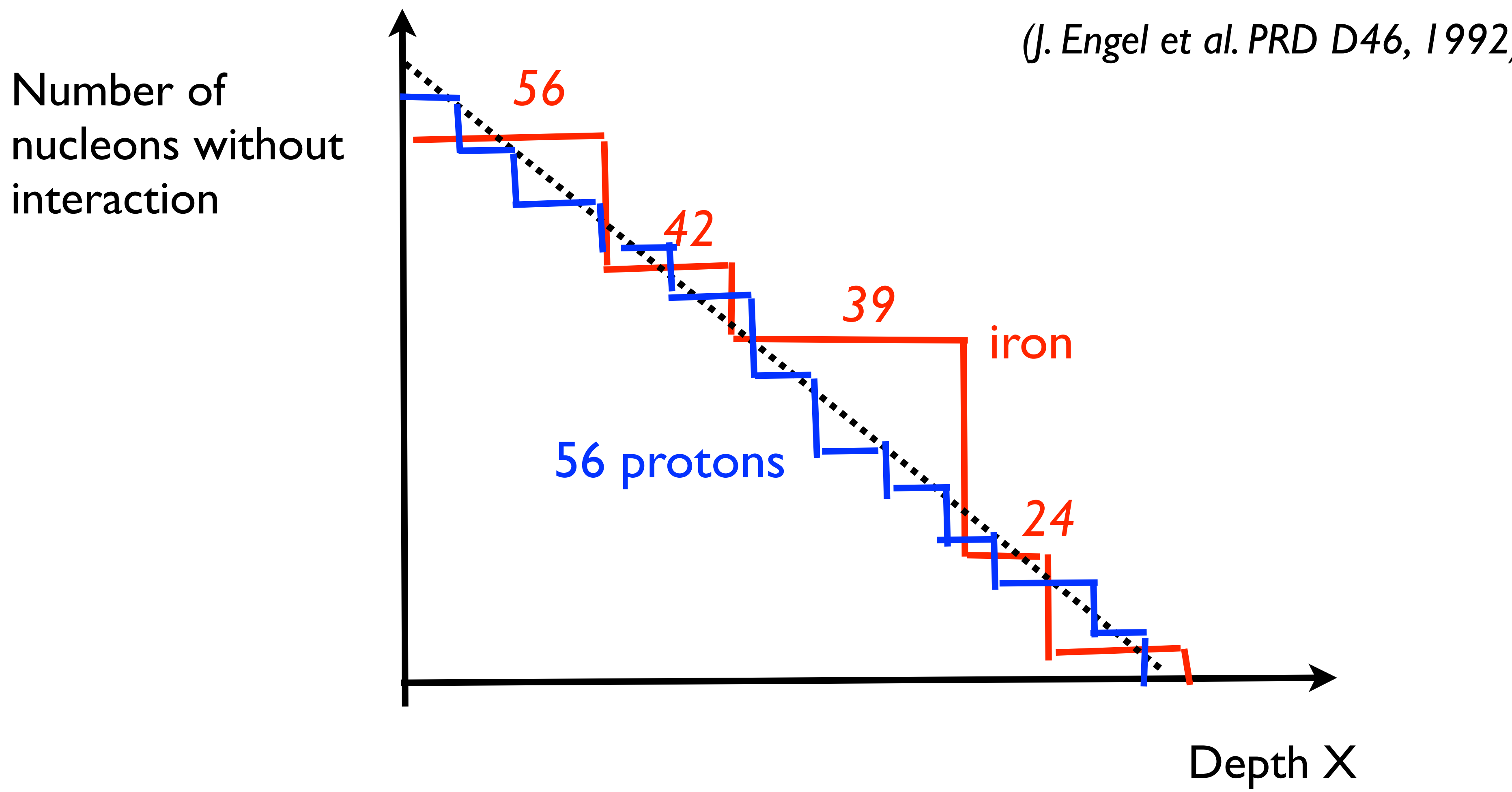
$$N_{\max}^A = A\left(\frac{E_0}{AE_c}\right) = N_{\max}$$

$$X_{\max}^A \sim \lambda_{\text{eff}} \ln(E_0/A)$$

$$N_\mu^A = A\left(\frac{E_0}{AE_{\text{dec}}}\right)^\alpha = A^{1-\alpha} N_\mu$$

Superposition model: correct prediction of mean Xmax



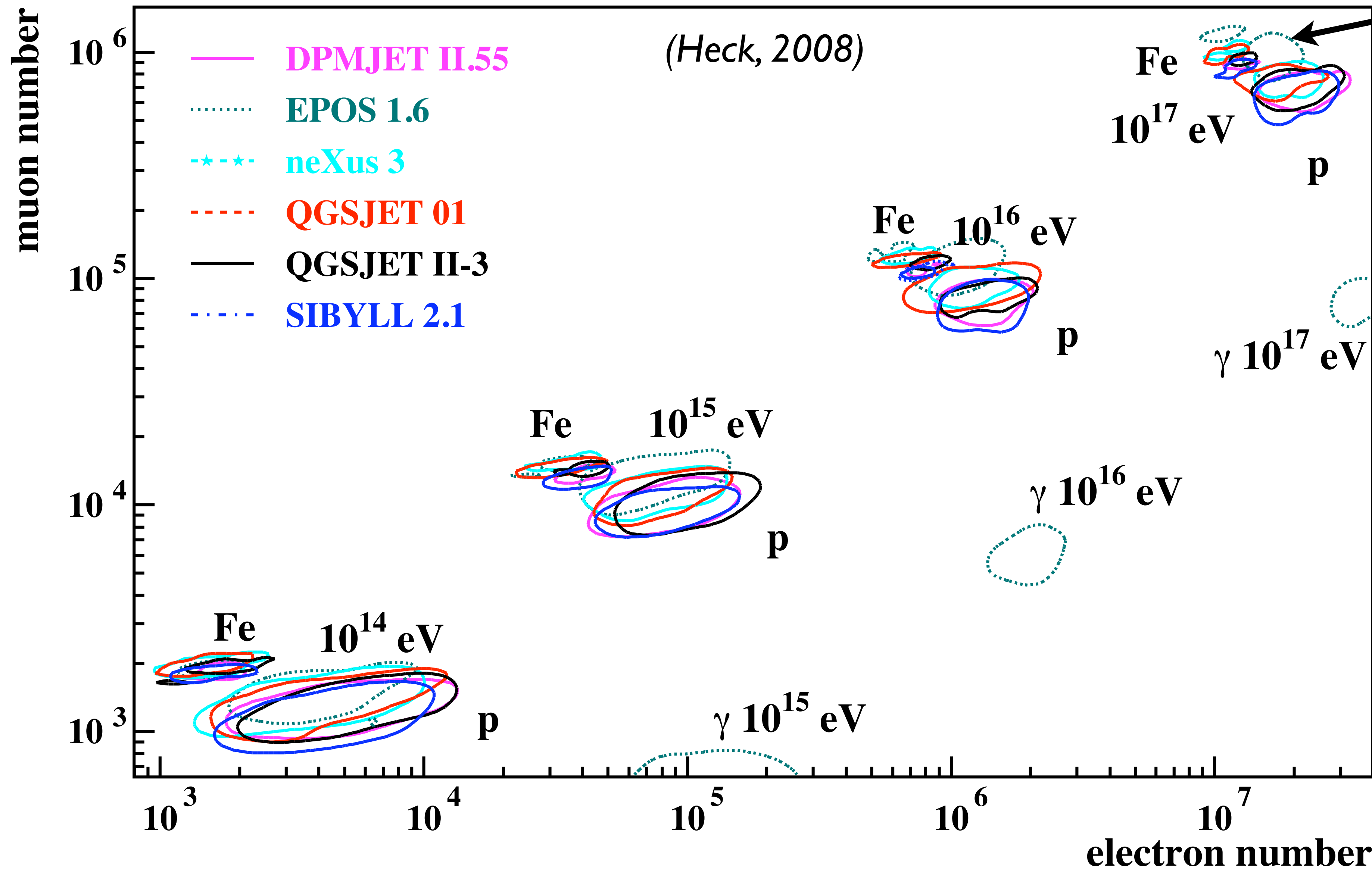


Glauber approximation (unitarity)

$$n_{\text{part}} = \frac{\sigma_{\text{Fe}-\text{air}}}{\sigma_{\text{p}-\text{air}}}$$

Superposition and semi-superposition models applicable to inclusive (averaged) observables

Electron and muon numbers of showers at ground



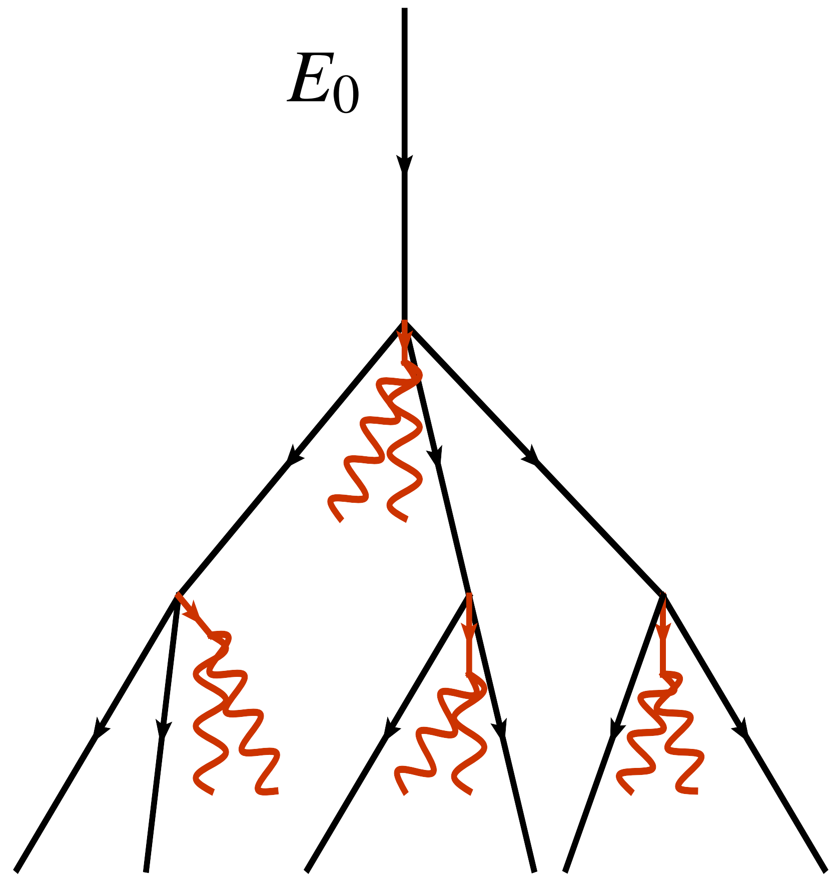
EPOS: largest muon number

vertical showers, sea level detector

$$N_\mu^{(FE)} \approx 1.4\, N_\mu^{(p)}$$

Dominating uncertainty of composition and energy measurements due to hadronic interaction models

Electromagnetic energy and energy transfer



Hadronic energy	Electromagnetic energy
$\frac{2}{3}E_0$	$\frac{1}{3}E_0$
$\frac{2}{3}\left(\frac{2}{3}E_0\right)$	$\frac{1}{3}E_0 + \frac{1}{3}\left(\frac{2}{3}E_0\right)$
⋮	⋮

After n generations …

$$E_{\rm had} = \left(\frac{2}{3}\right)^n E_0$$

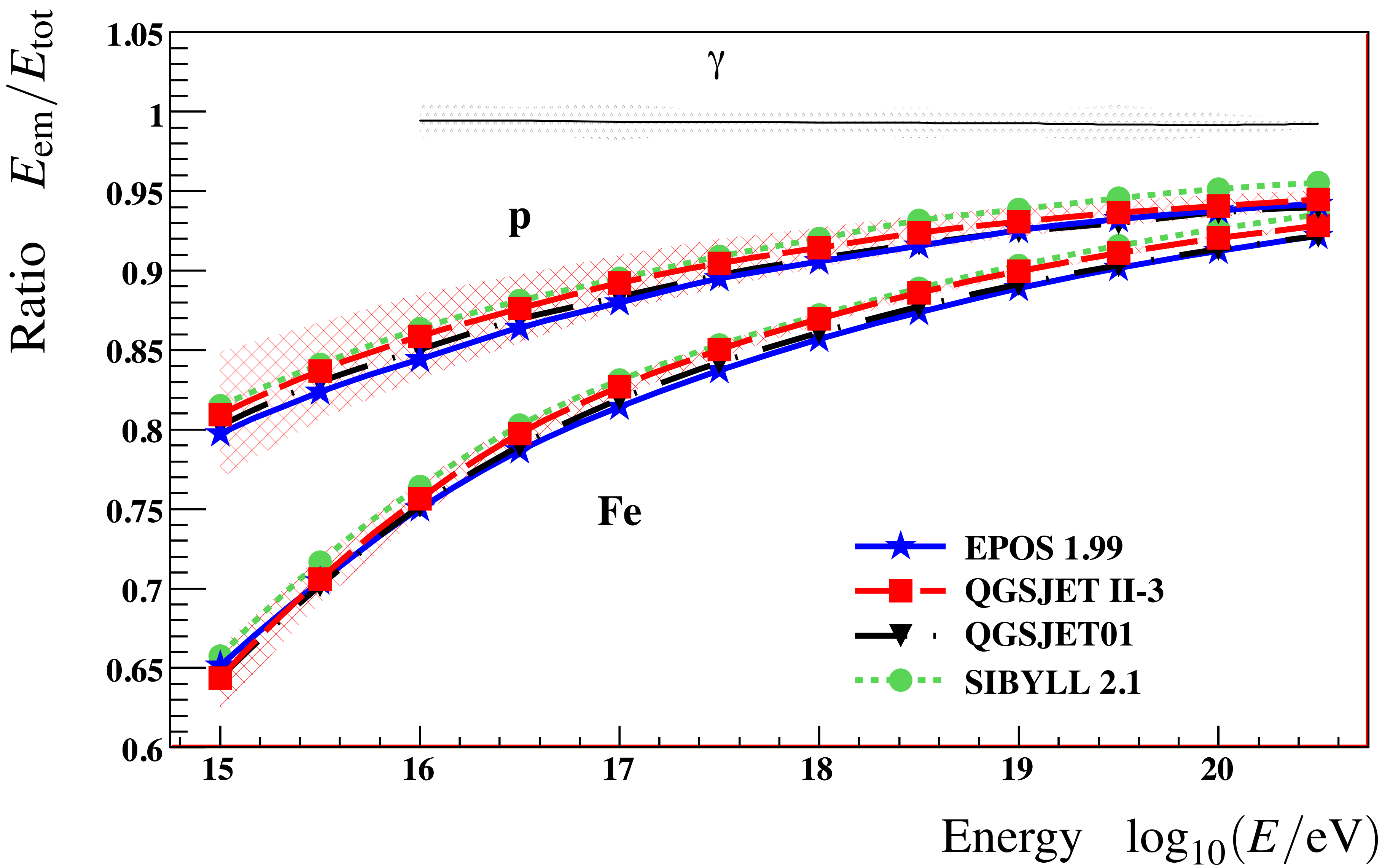
$$E_{\rm em} = \left[1 - \left(\frac{2}{3}\right)^n\right] E_0$$

$n = 5, \;\; E_{\rm had} \sim 12\%$

$n = 6, \;\; E_{\rm had} \sim 8\%$

Fraction of energy transferred to em. shower

(RE, Pierog, Heck, ARNPS 2011)

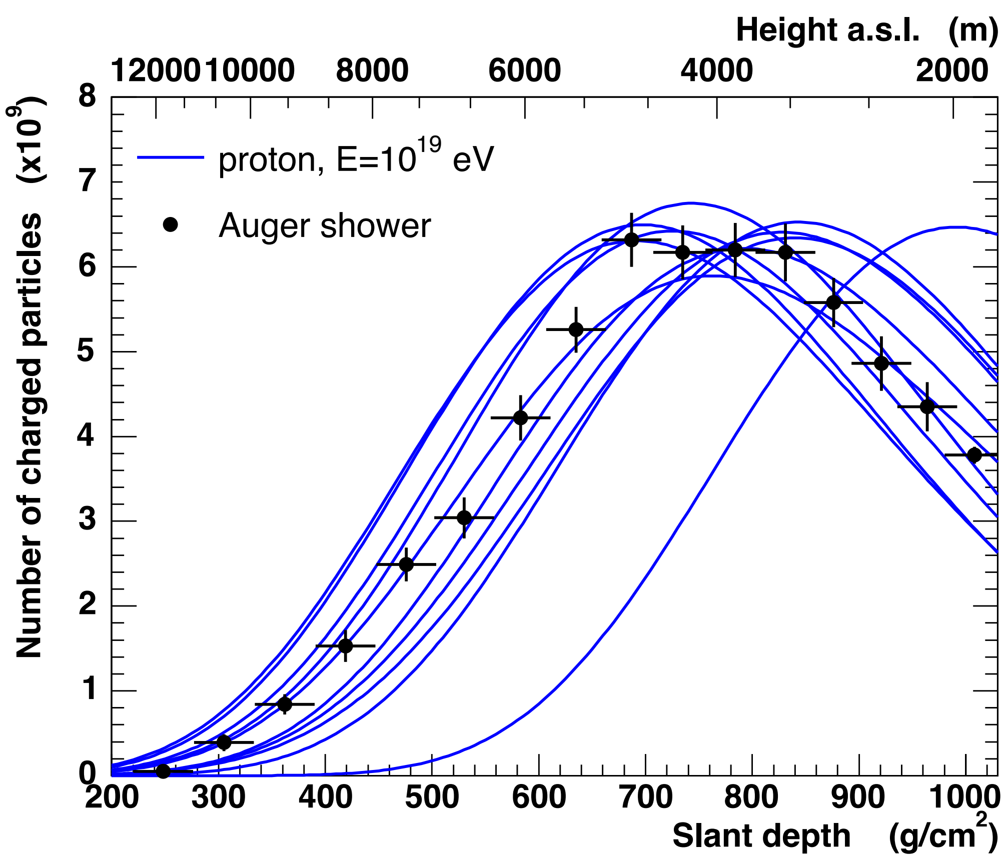


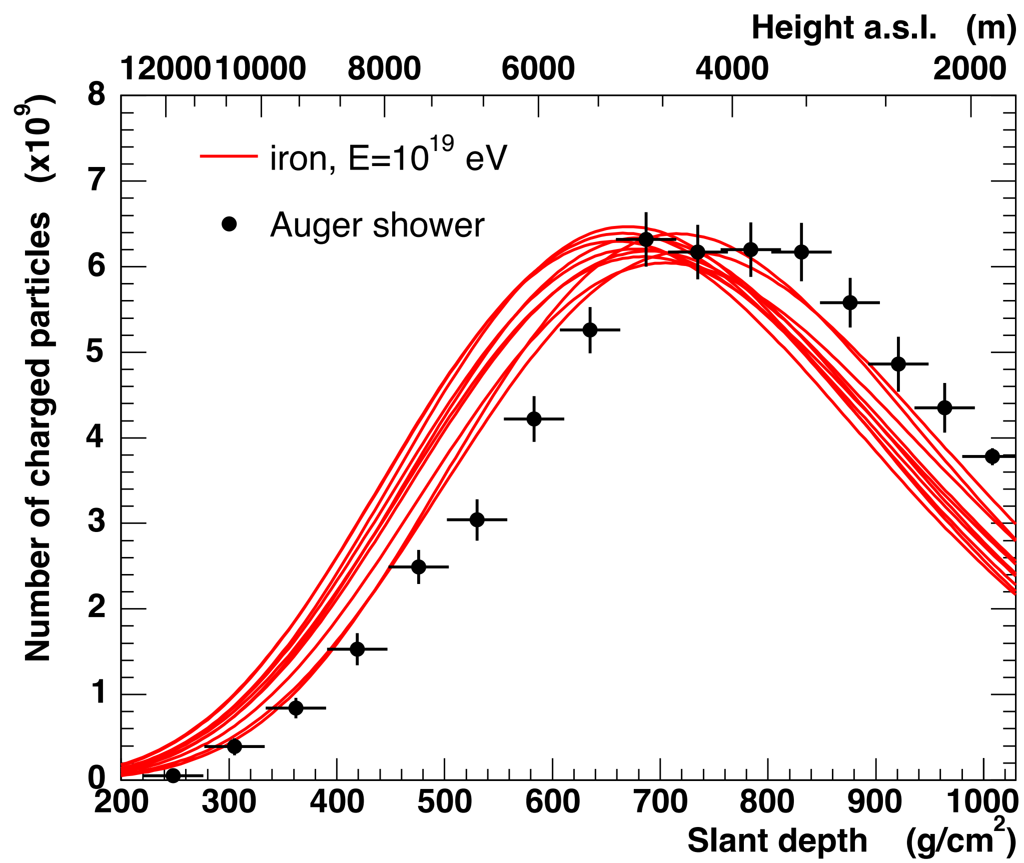
Ratio of em. to total shower energy

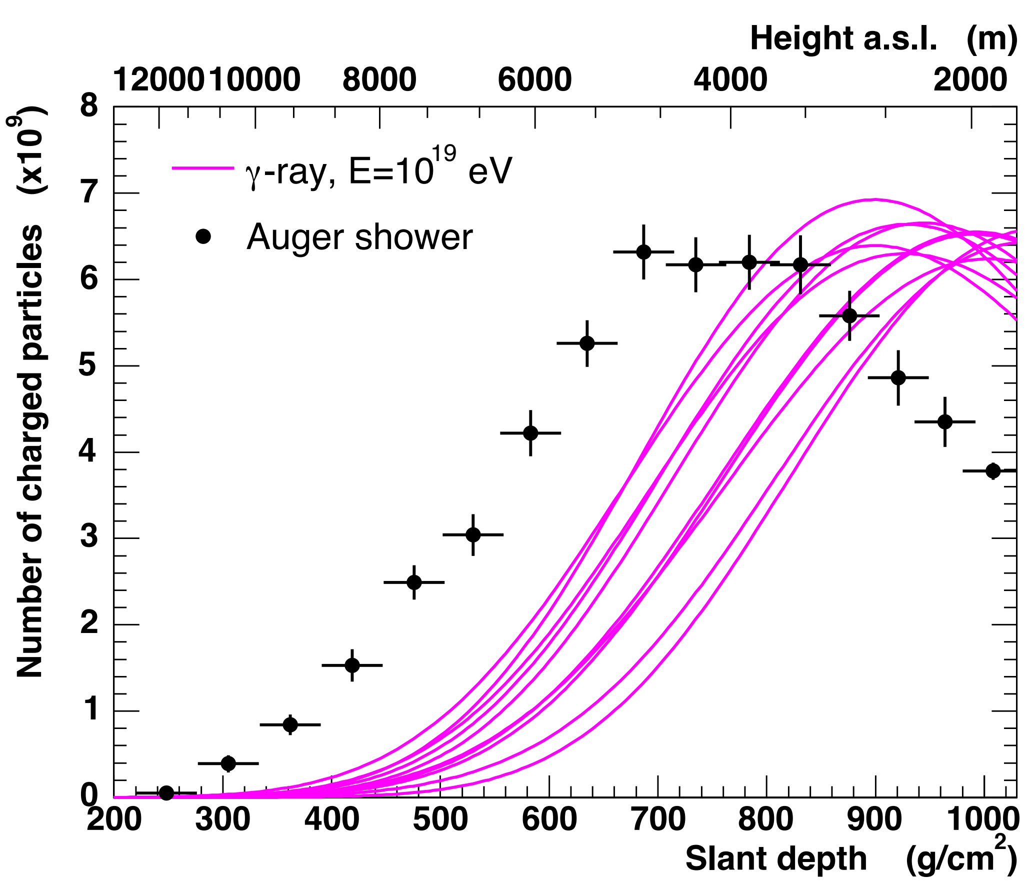
Detailed Monte Carlo simulation with CONEX

Only small influence of the modelling of hadronic interactions

Longitudinal shower profile







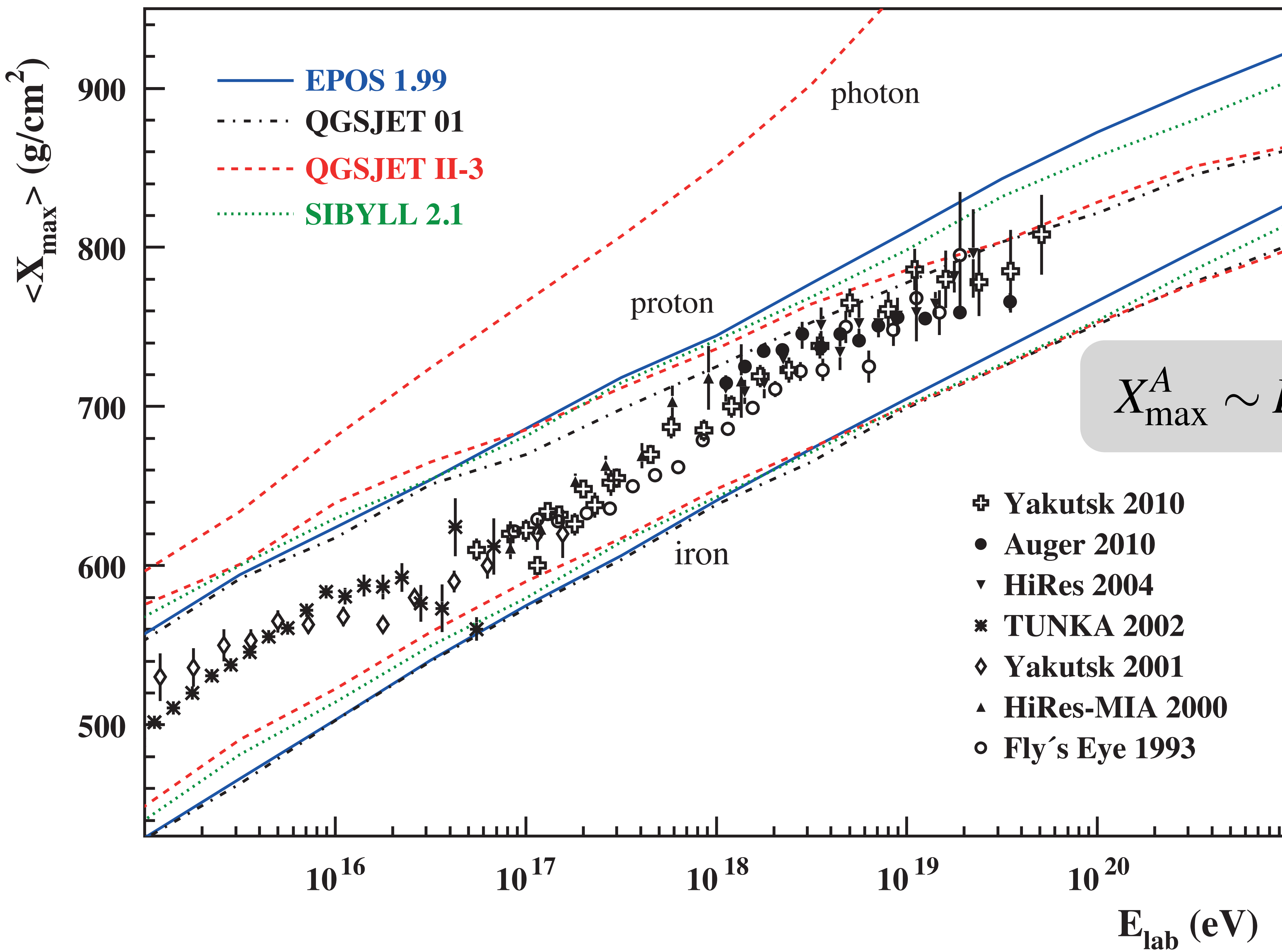
$$N_{\max} = E_0/E_c$$

$$X_{\max} \sim D_{\rm e} \ln(E_0/E_c)$$

Superposition model:

$$X_{\max}^A \sim D_e \ln(E_0/AE_c)$$

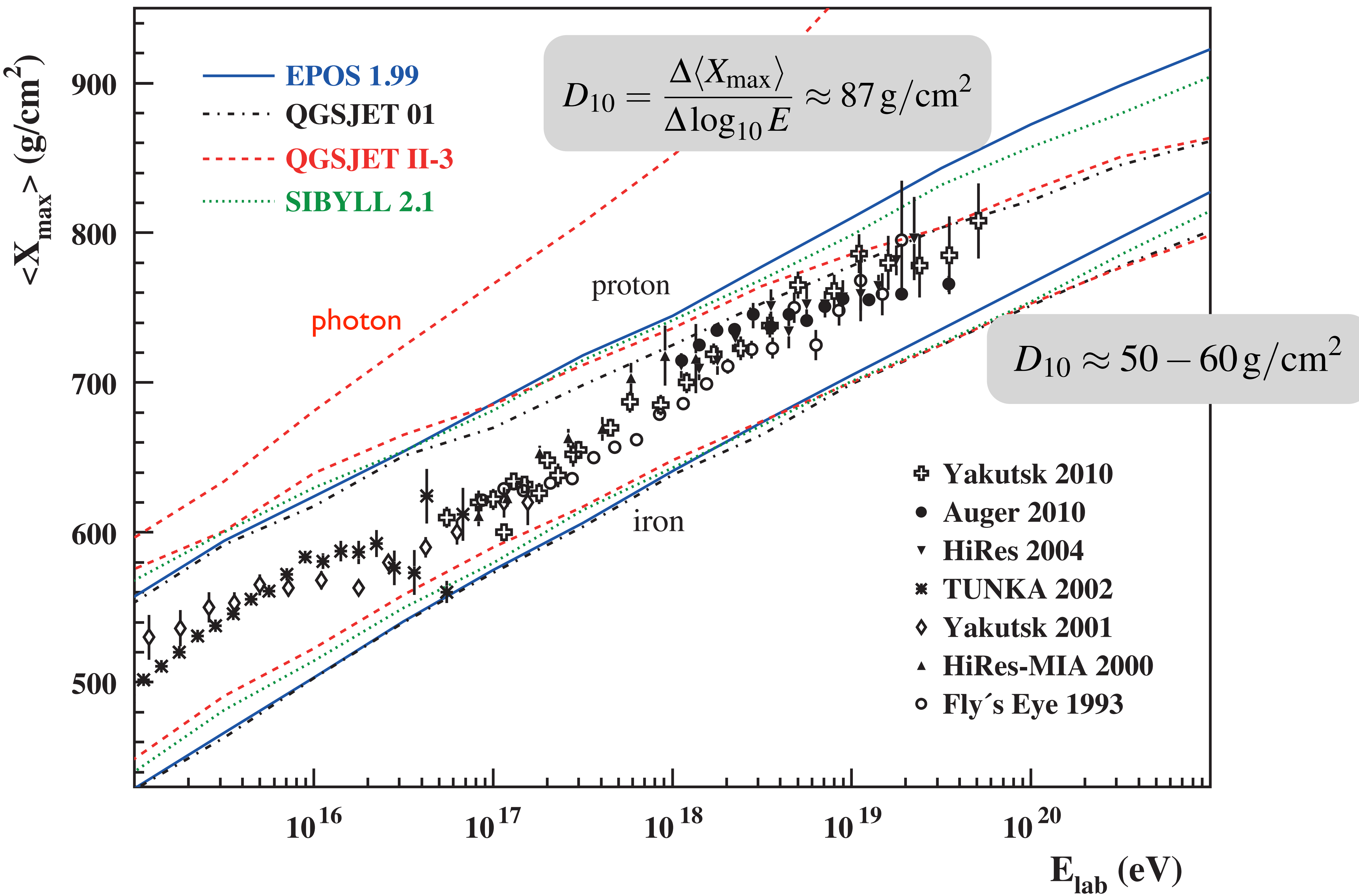
Mean depth of shower maximum



$$X^A_{\max} \sim D_e \ln(E_0/AE_c)$$

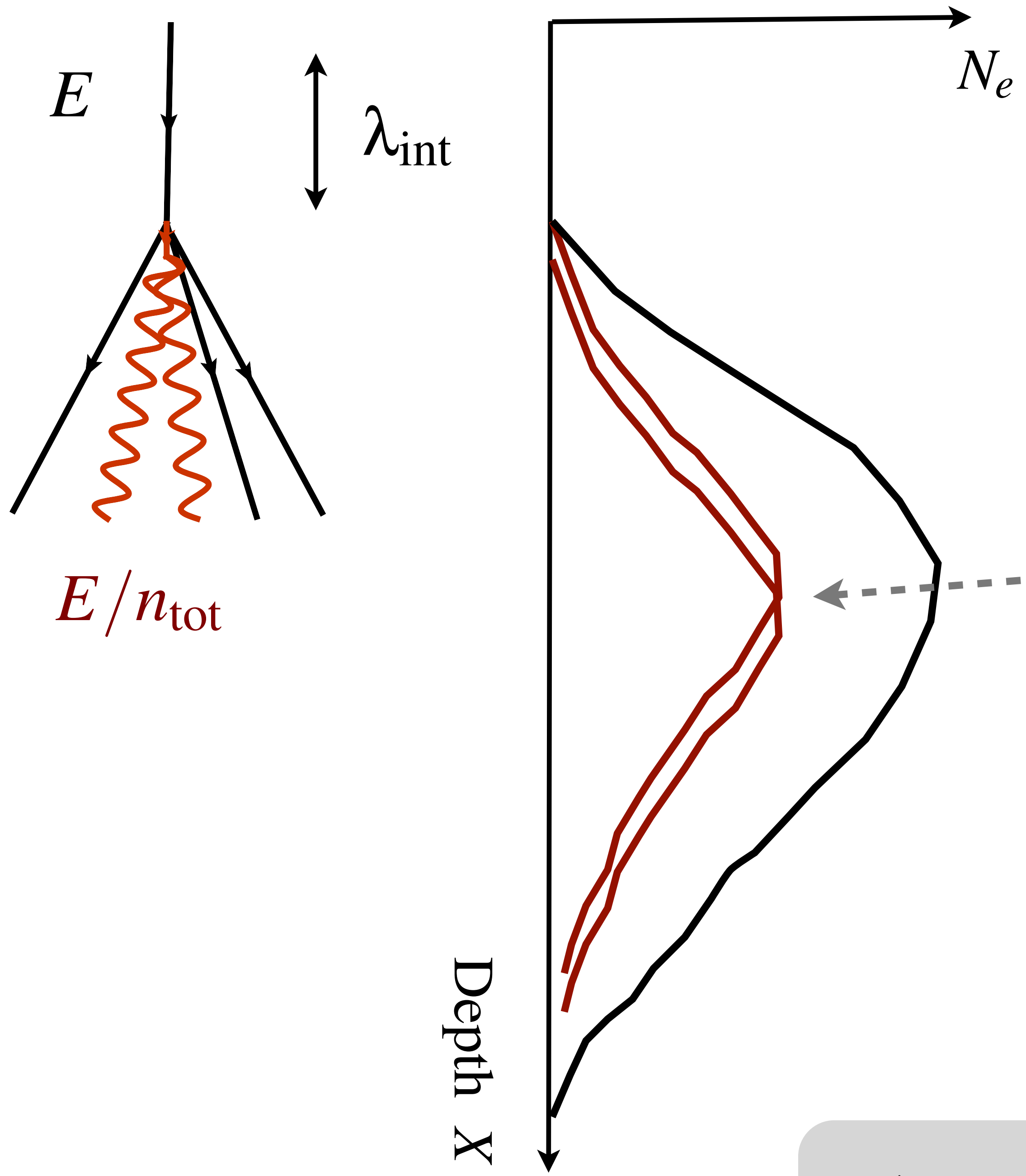
(RE, Pierog, Heck, ARNPS 2011)

Different slopes for em. and hadronic showers



(RE, Pierog, Heck, ARNPS 2011)

Derivation of elongation rate theorem



$$\langle X_{\max}(E)\rangle = \langle X_{\max}^{\mathrm{em}}(E/n_{\mathrm{tot}})\rangle + \lambda_{\mathrm{int}}$$

$$\langle X_{\max}^{\mathrm{em}}\rangle \sim X_0 \ln(E/n_{\mathrm{tot}})$$

$$\langle X_{\max}(E)\rangle = X_0 \log(E/n_{\mathrm{tot}}) + c + \lambda_{\mathrm{int}}$$

taking derivative $\log E$

$$\frac{\mathrm{d}\langle X_{\max}(E)\rangle}{\mathrm{d}\log E} = X_0 - X_0 \frac{\mathrm{d}\log n_{\mathrm{tot}}}{\mathrm{d}\log E} + \frac{\mathrm{d}\lambda_{\mathrm{int}}}{\mathrm{d}\log E}$$

Elongation rate of em. shower

Elongation rate theorem

X_0 = 36 g/cm^2

$$D_e^{\mathrm{had}} = X_0(1 - B_n - B_\lambda)$$

(Linsley, Watson PRL46, 1981)

$$B_n = \frac{d\ln n_{\mathrm{tot}}}{d\ln E}$$

Large if multiplicity of high energy particles rises very fast, **zero in case of scaling**

$$B_\lambda = -\frac{1}{X_0}\frac{d\lambda_{\mathrm{int}}}{d\ln E}$$

Large if cross section rises rapidly with energy

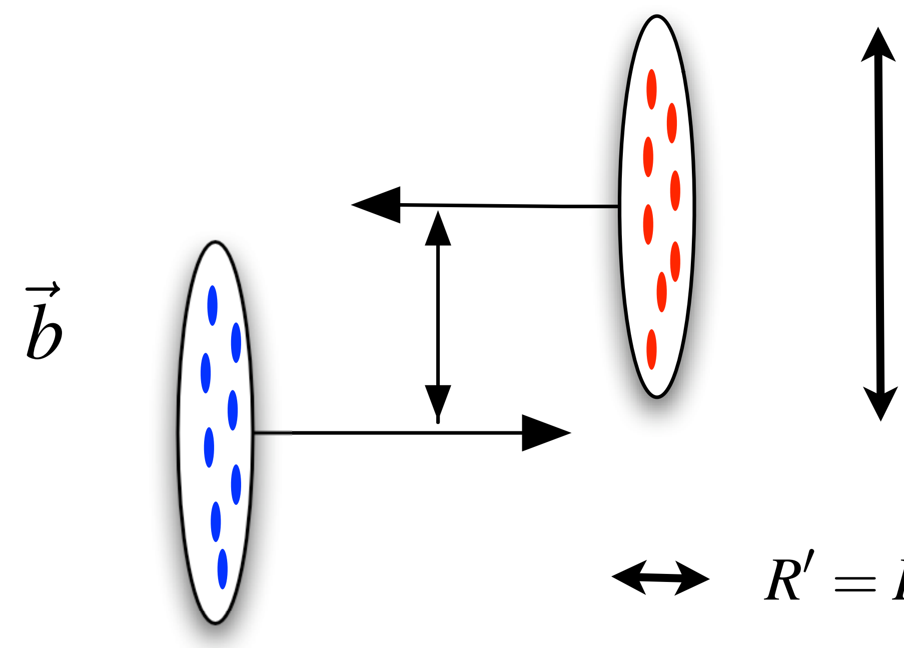
Note: $D_{10} = \log(10) D_e$

2 Modeling hadronic interactions at high energy

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)



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

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

Heisenberg uncertainty relation

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

Longitudinal momenta of secondaries

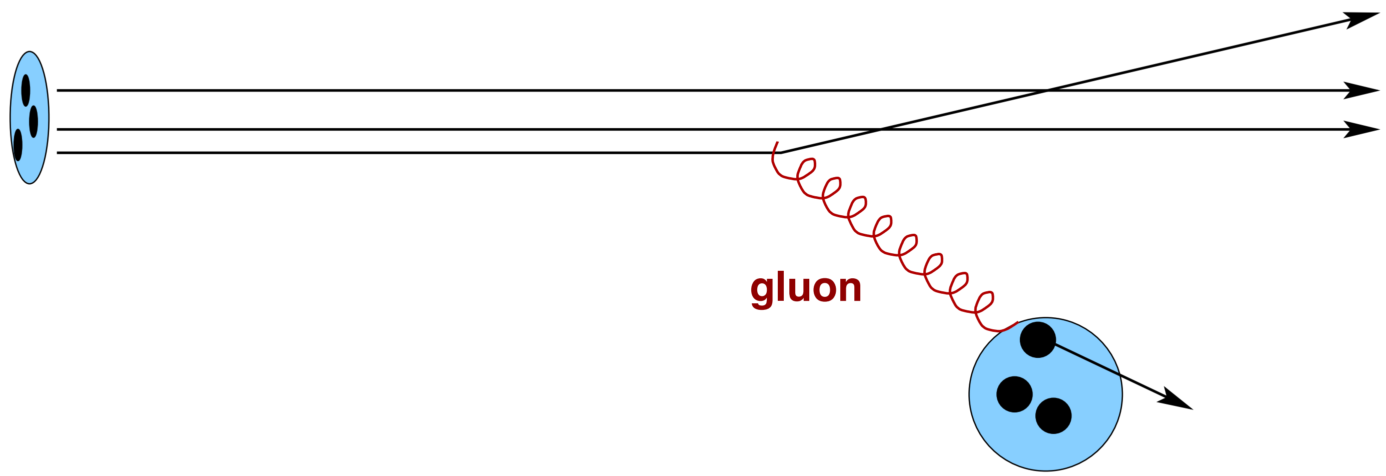
$$\langle p_{\parallel} \rangle \sim \Delta p_{\parallel} \approx \frac{1}{R'} \approx \frac{1}{5} E_p$$

Transverse momenta of secondaries

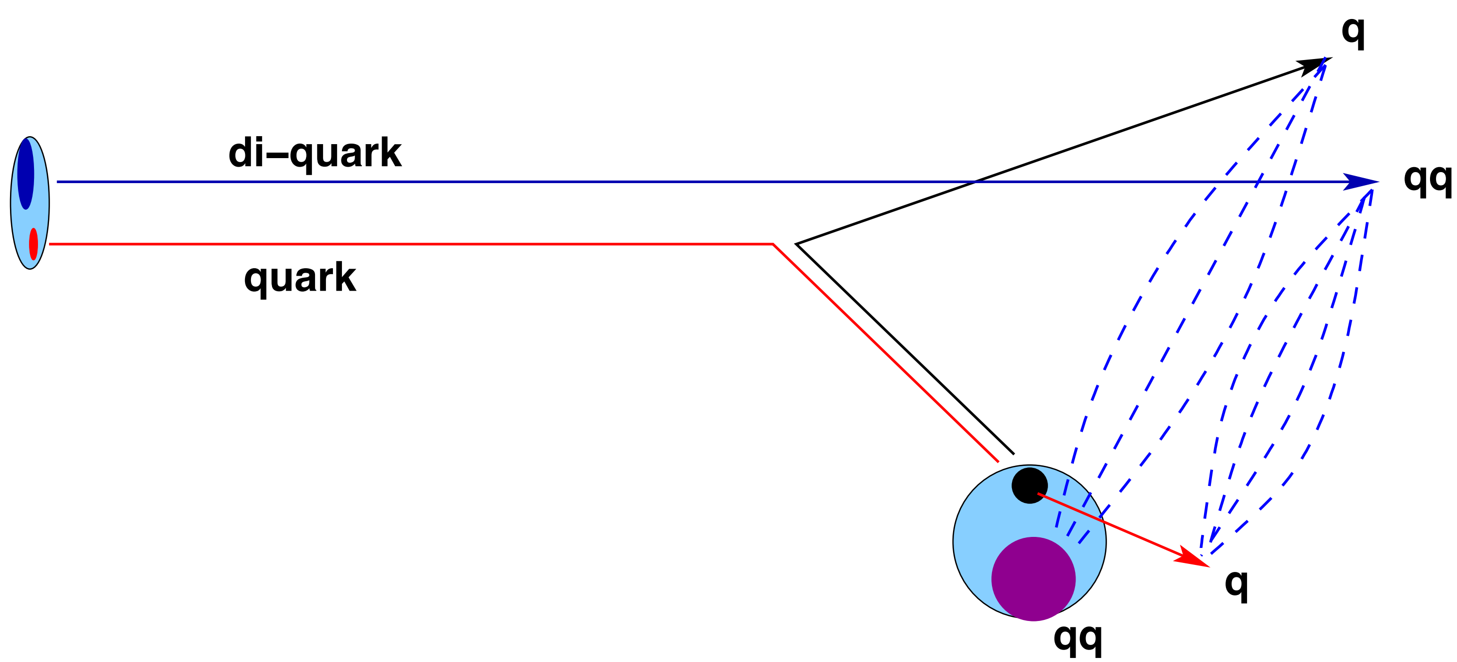
$$\langle p_{\perp} \rangle \sim \Delta p_{\perp} \sim \frac{1}{R} \approx 200\,\mathrm{MeV}$$

QCD-inspired interpretation: color flow model

Partonic view:



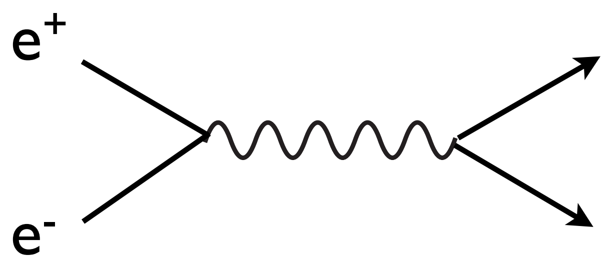
Color flow:



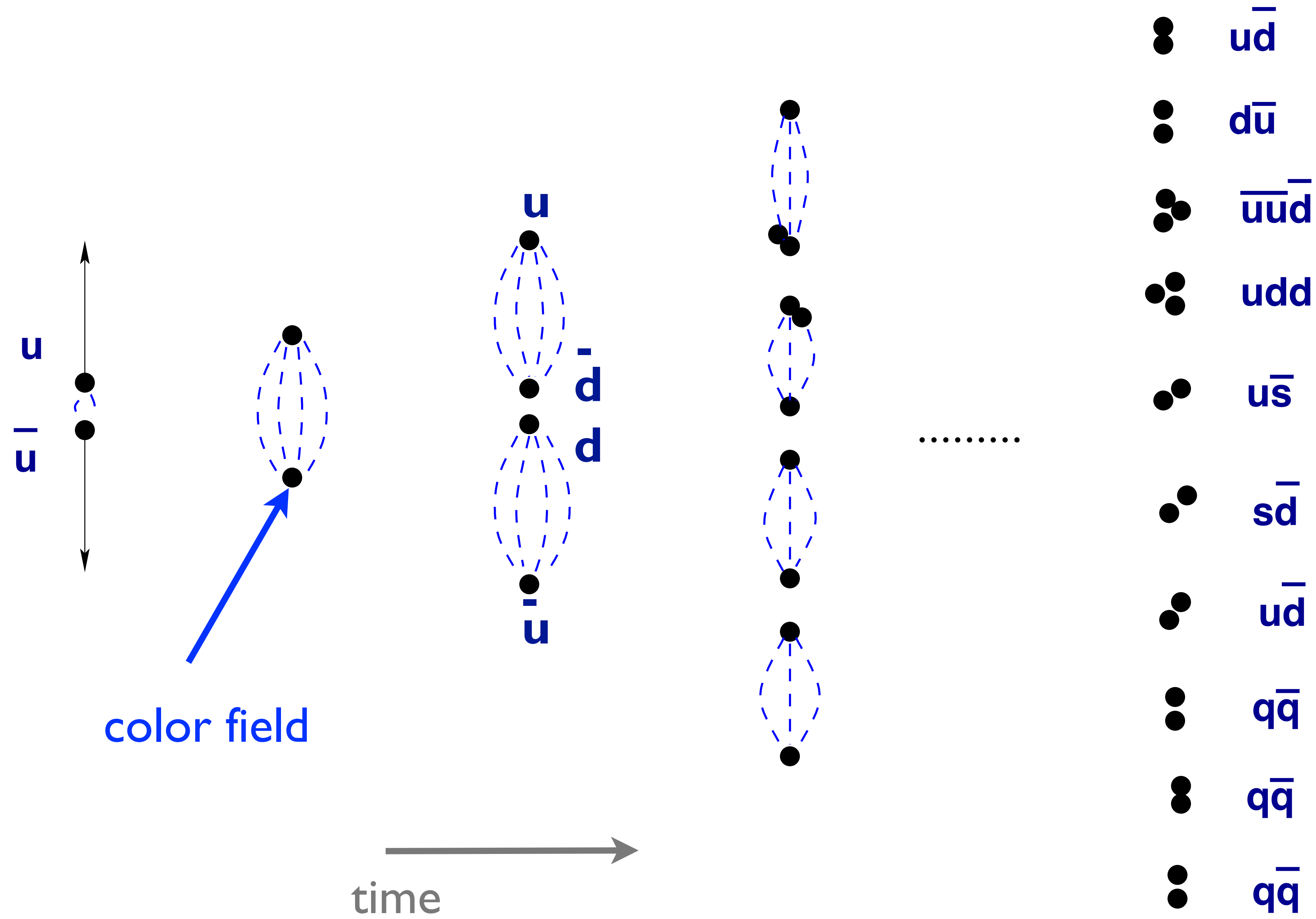
One-gluon exchange:
two color fields (strings)

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

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

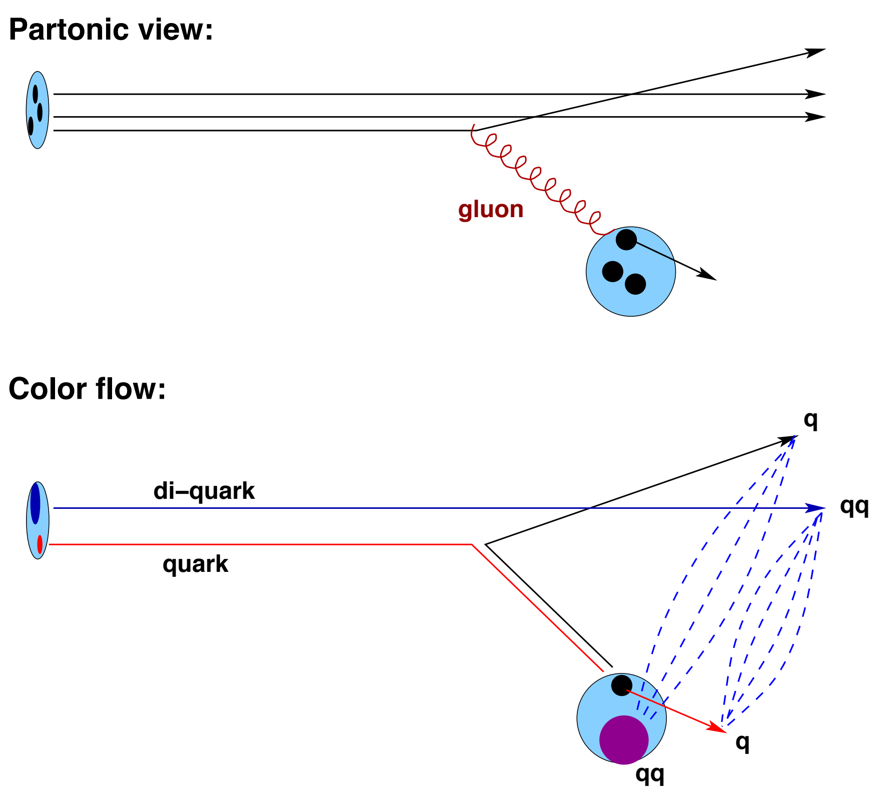
New variable $\frac{\mathrm{d}p_\parallel}{E} = \mathrm{d}y$

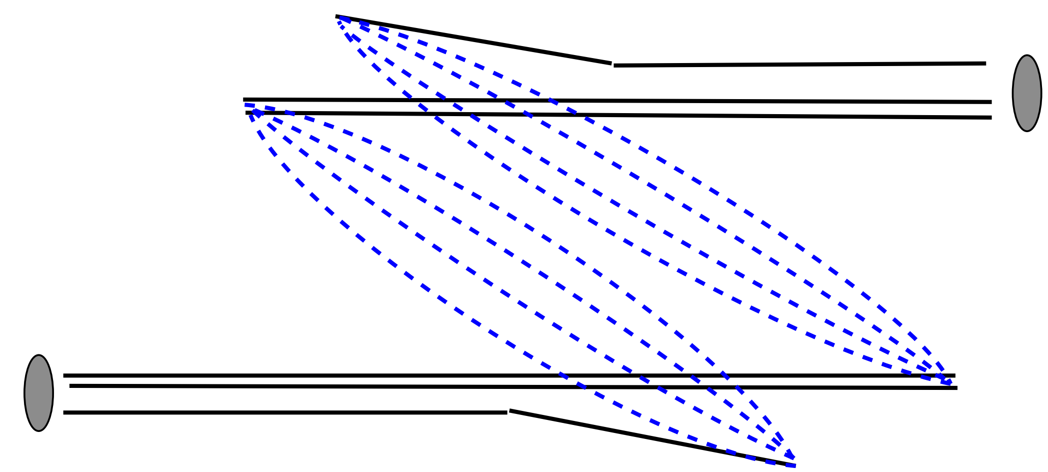
$$= \frac{1}{2}\, f_\perp(p_\perp)\, \mathrm{d}^2 p_\perp\, f_\parallel(y)\, \mathrm{d}y$$

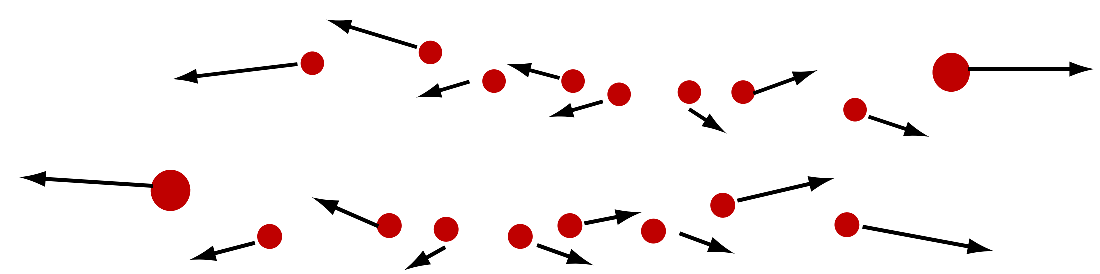
$\beta^{-1} \ldots$ effective temperature

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

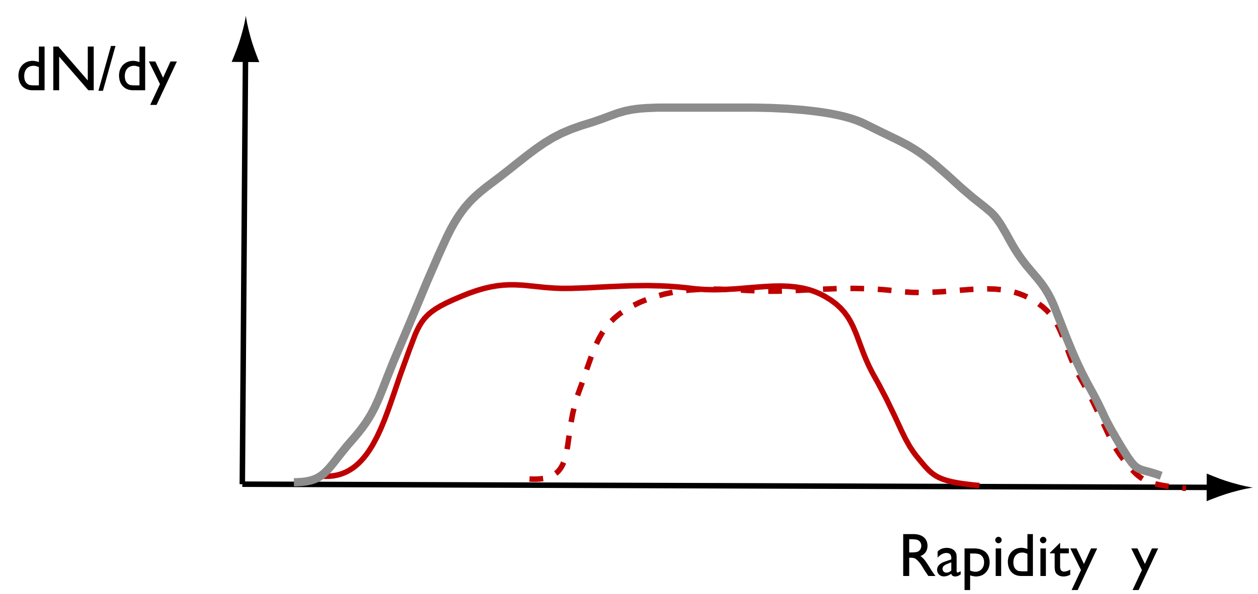
Final state particles: two-string model







Lab. system → **CM system**



Rapidity and pseudorapidity

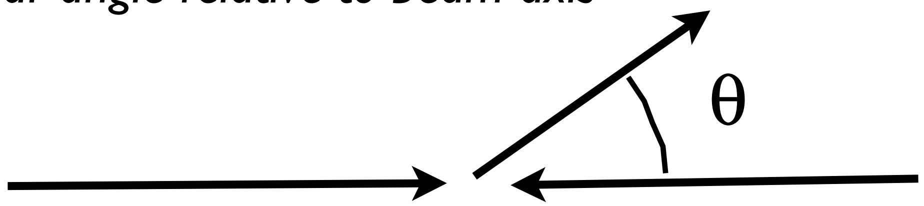
$$\frac{\mathrm{d}p_{\parallel}}{E} = \mathrm{d}y$$

Rapidity

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

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

Polar angle relative to beam axis



Rapidity of massless particles

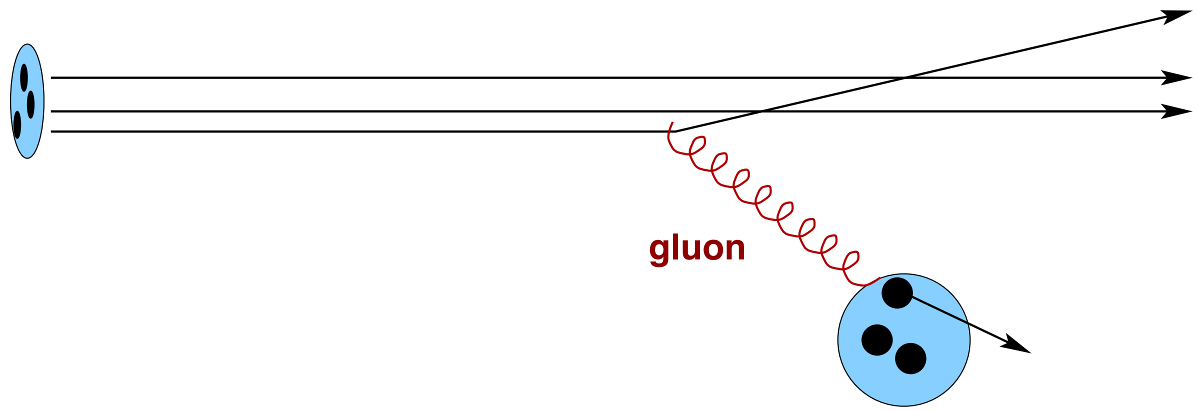
$$y = \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta} = -\ln\tan\frac{\theta}{2}$$

Experiments without particle identification: **pseudorapidity**

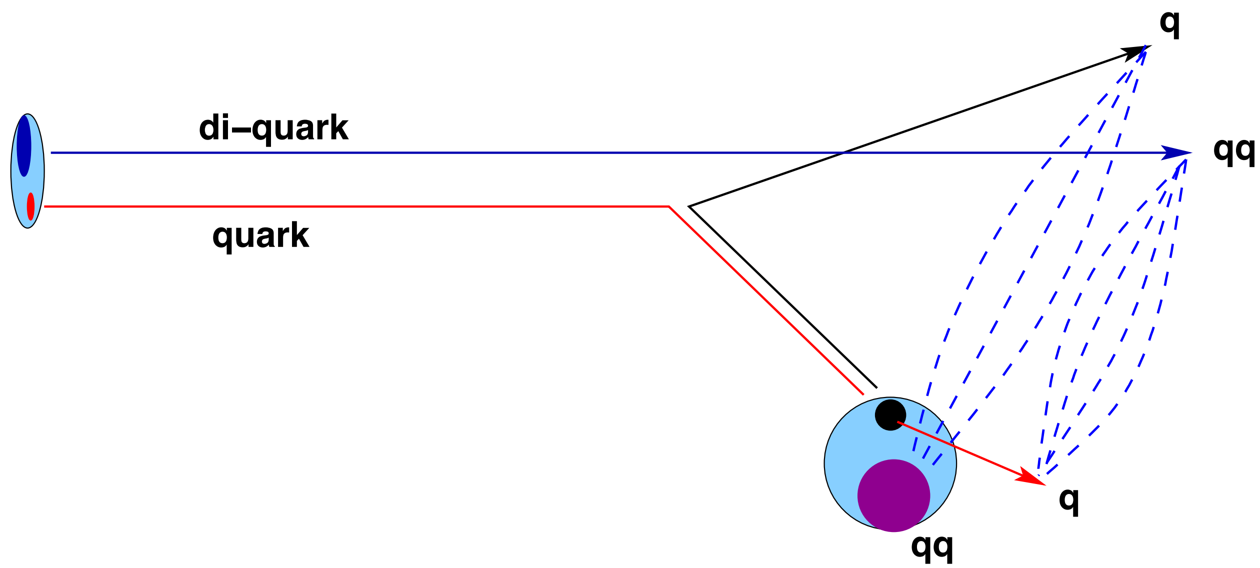
$$\eta = -\ln\tan\frac{\theta}{2}$$

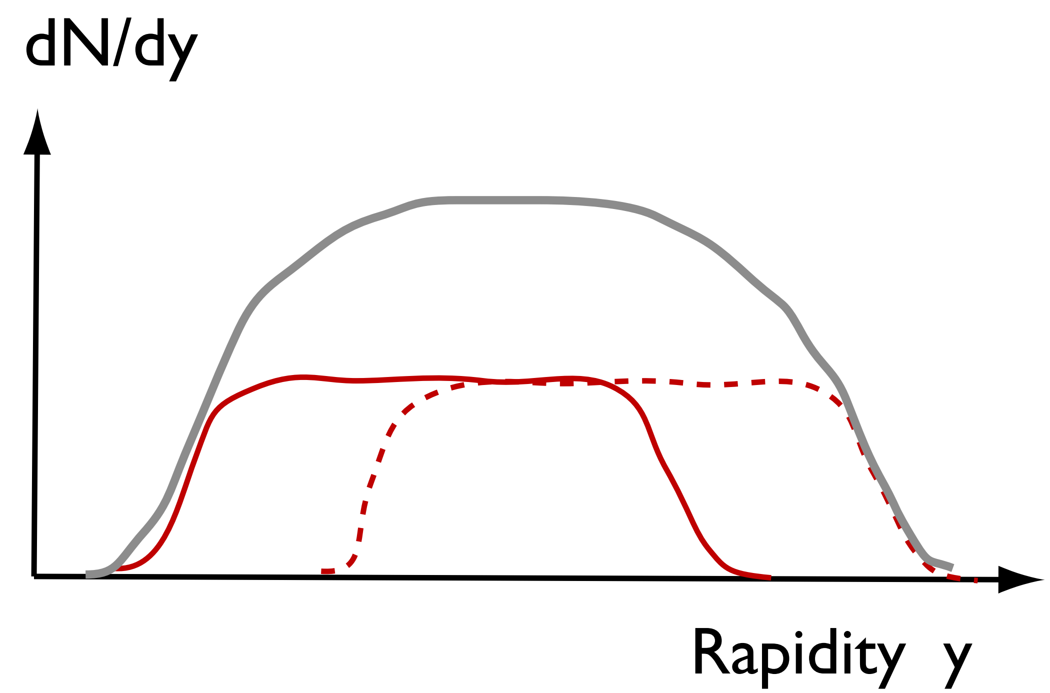
Standard color flow and final state particles

Partonic view:



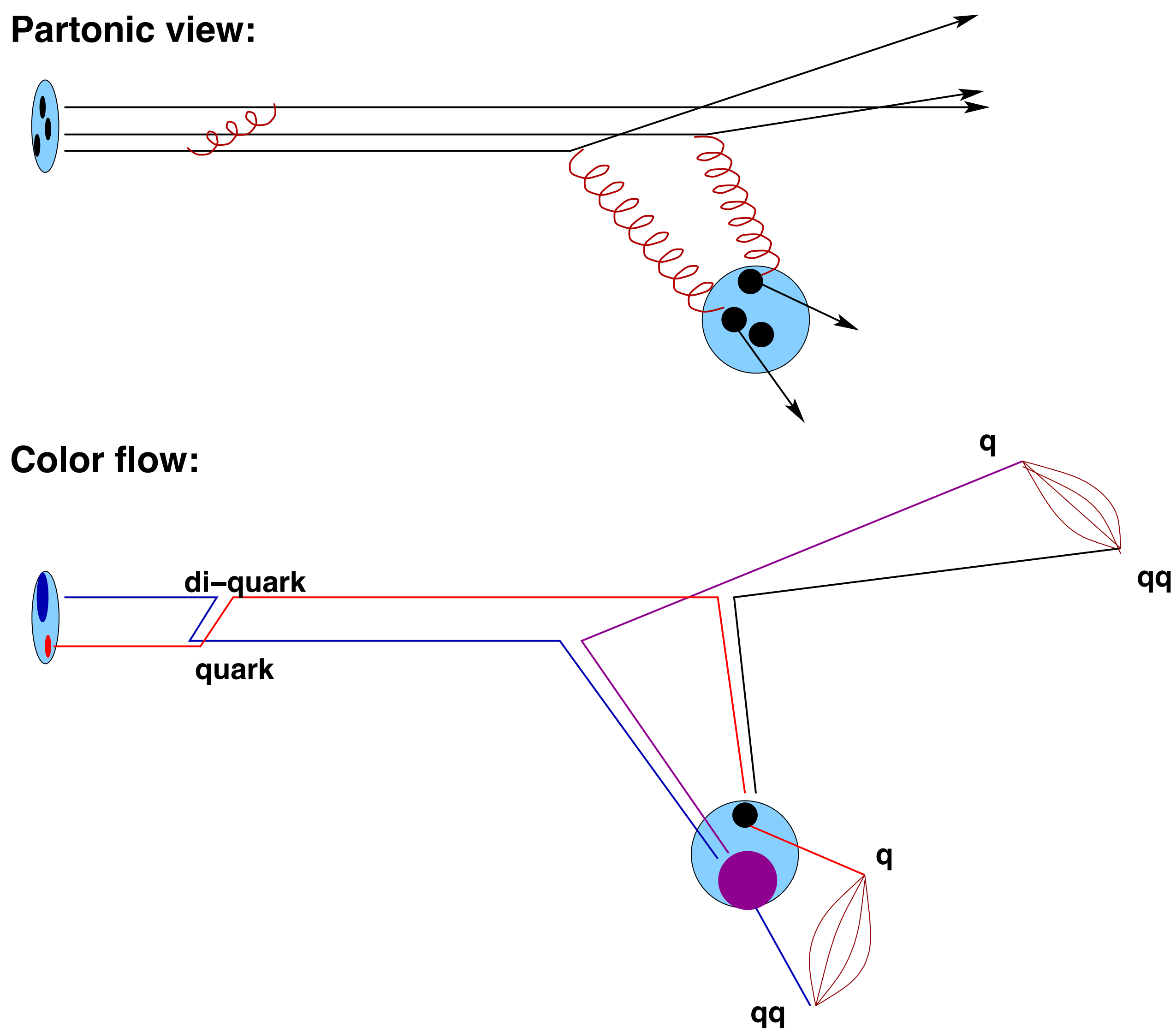
Color flow:



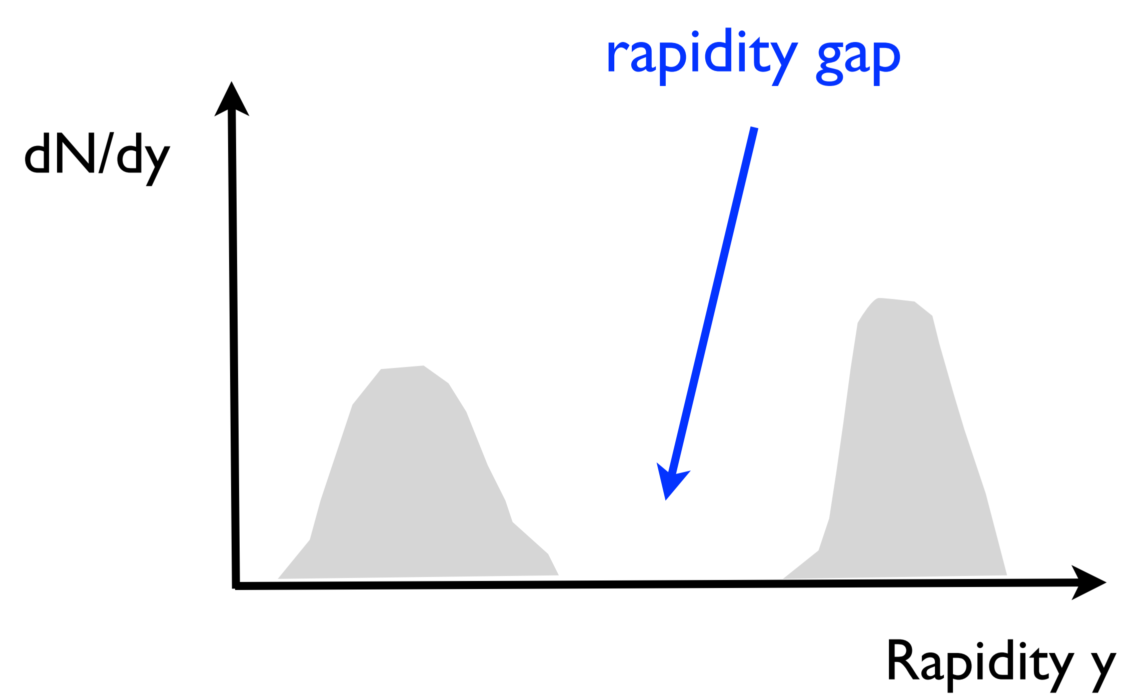


One-gluon exchange:
two color fields (strings)

Other predicted color flow configurations

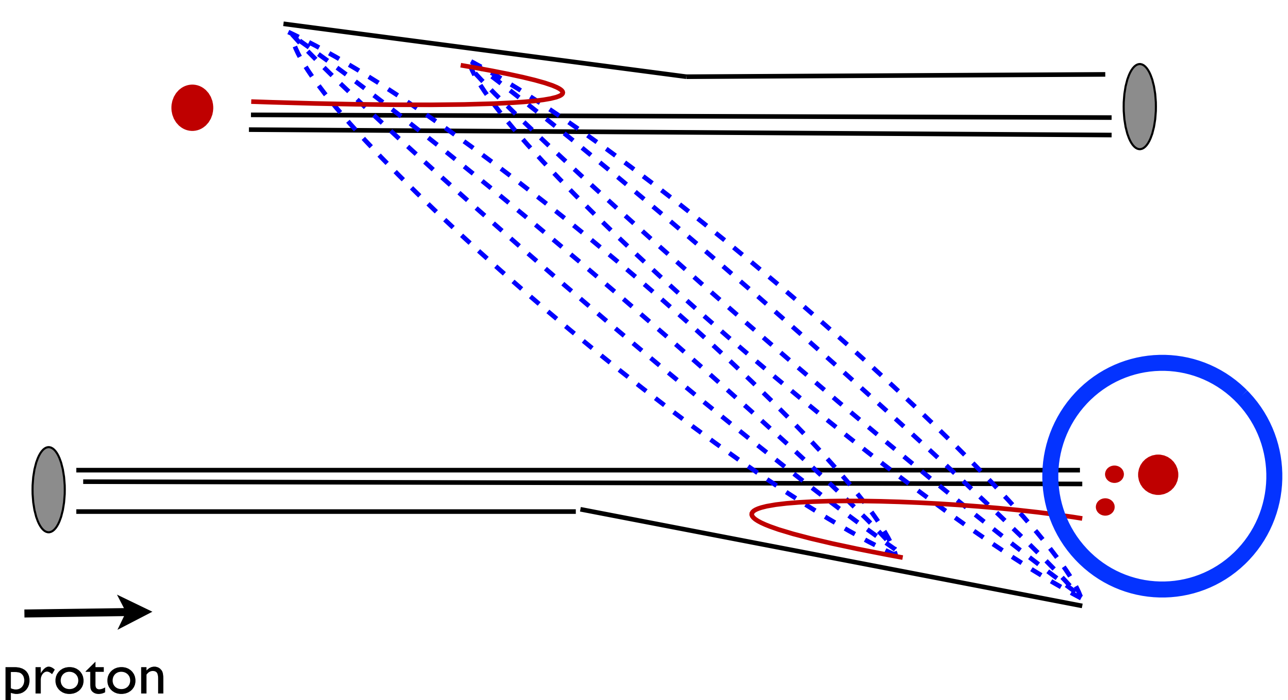


Two-gluon exchange:
diffraction dissociation



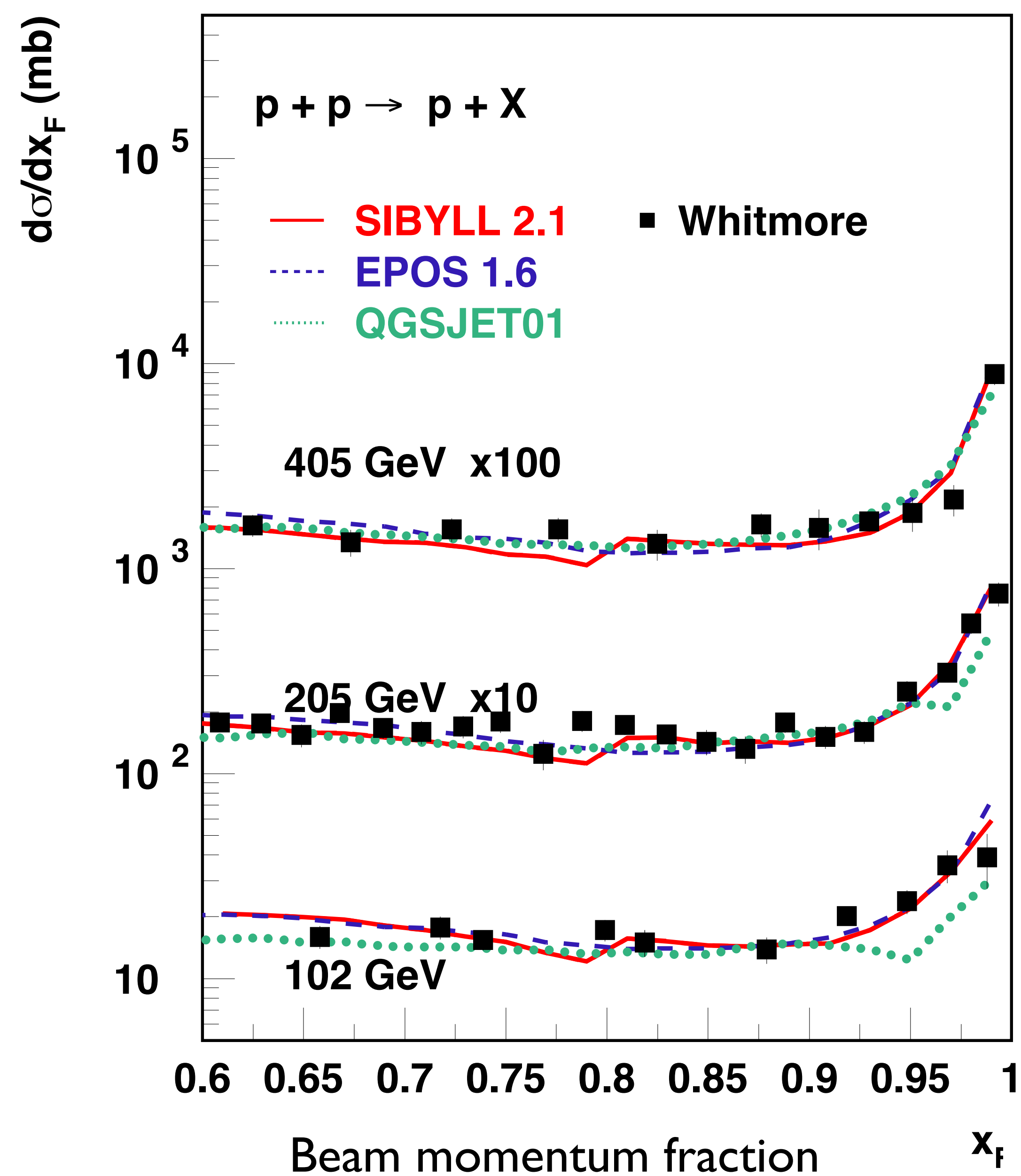
At very high energy (multi-gluon exchange):
Almost 50% of all events are elastic/diffractive scattering

Particle production spectra (i)

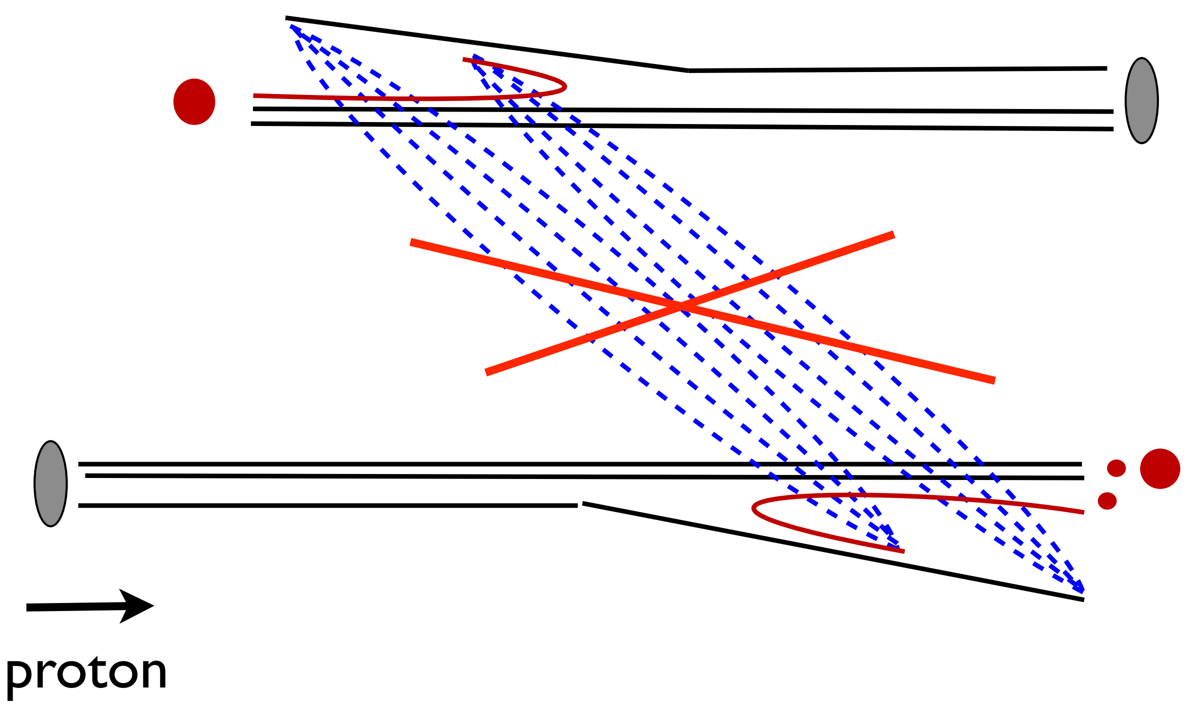


Fluctuations: Generation of sea quark anti-quark pair and leading/excited hadron

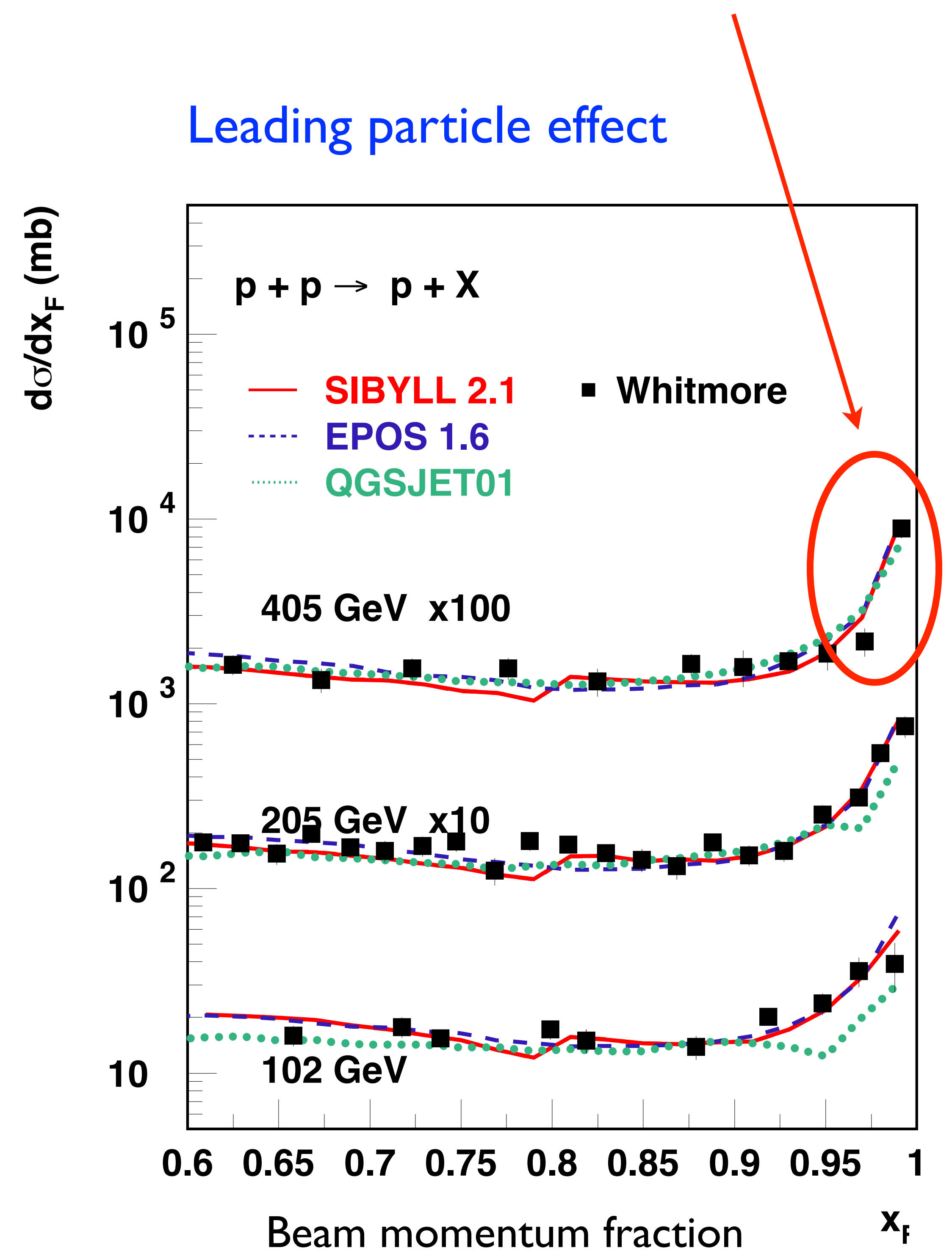
Leading particle effect



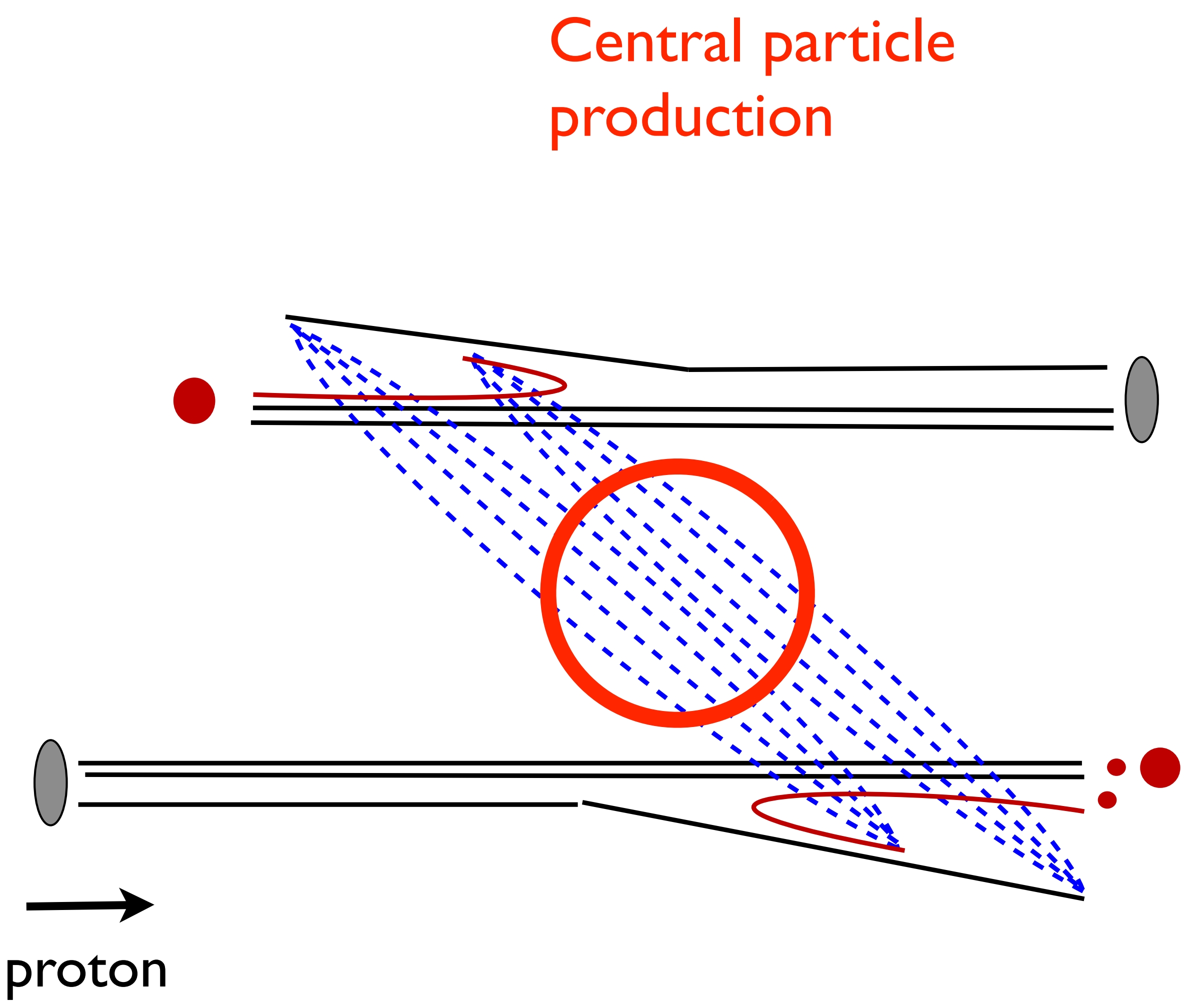
Particle production spectra (i)

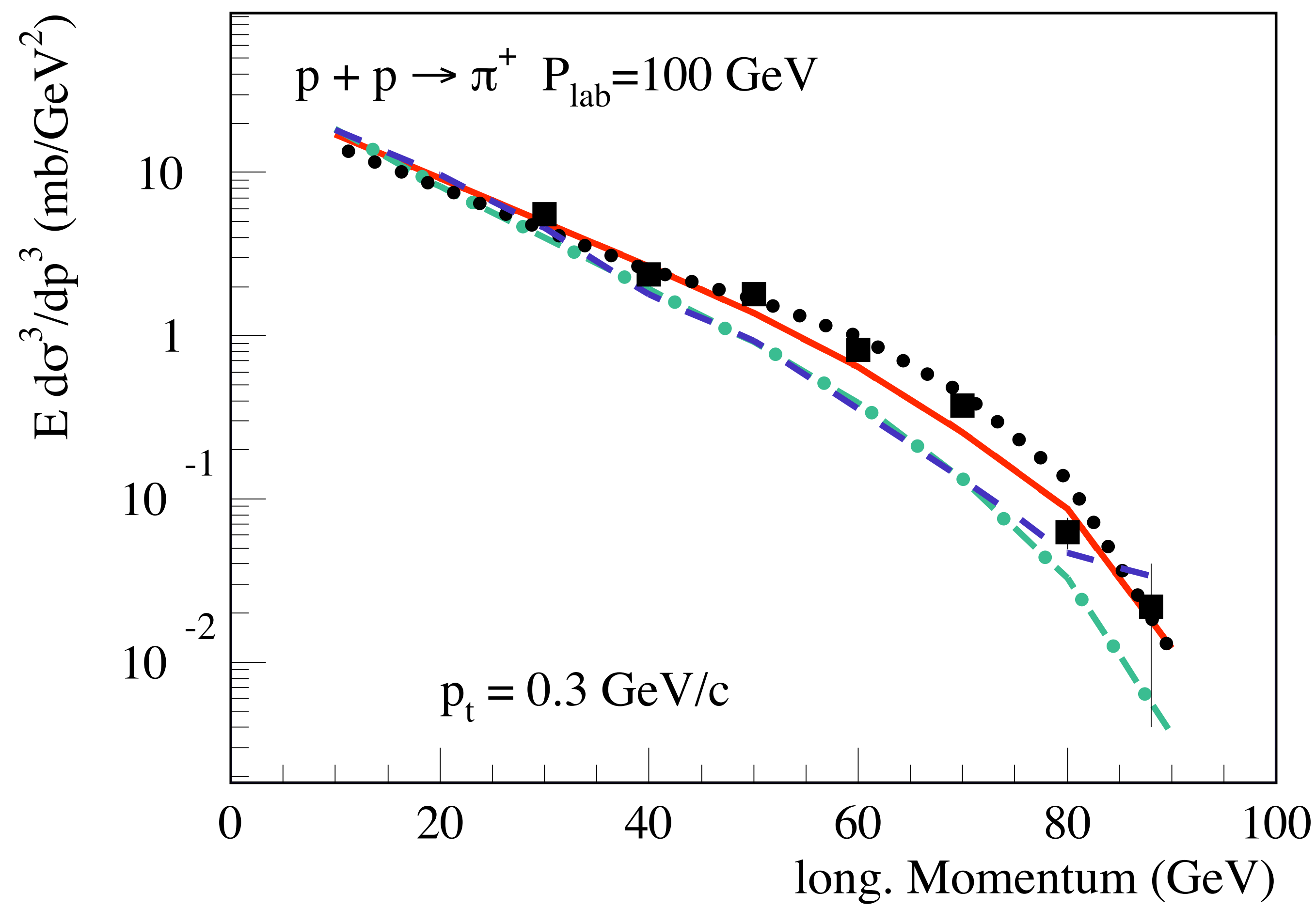


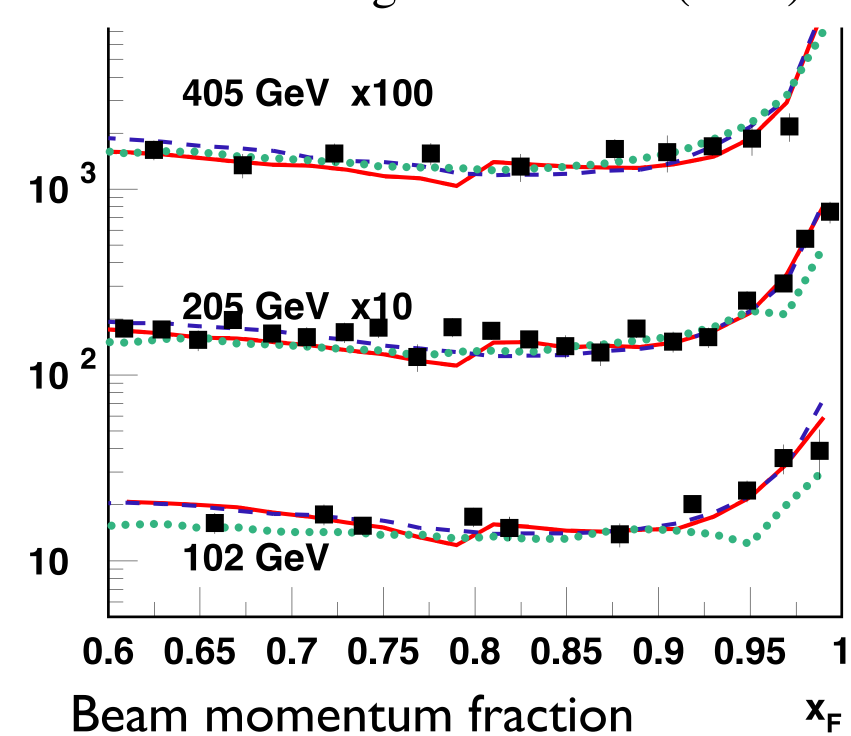
Fluctuations: Generation of sea quark anti-quark pair and leading/excited hadron



Particle production spectra (ii)

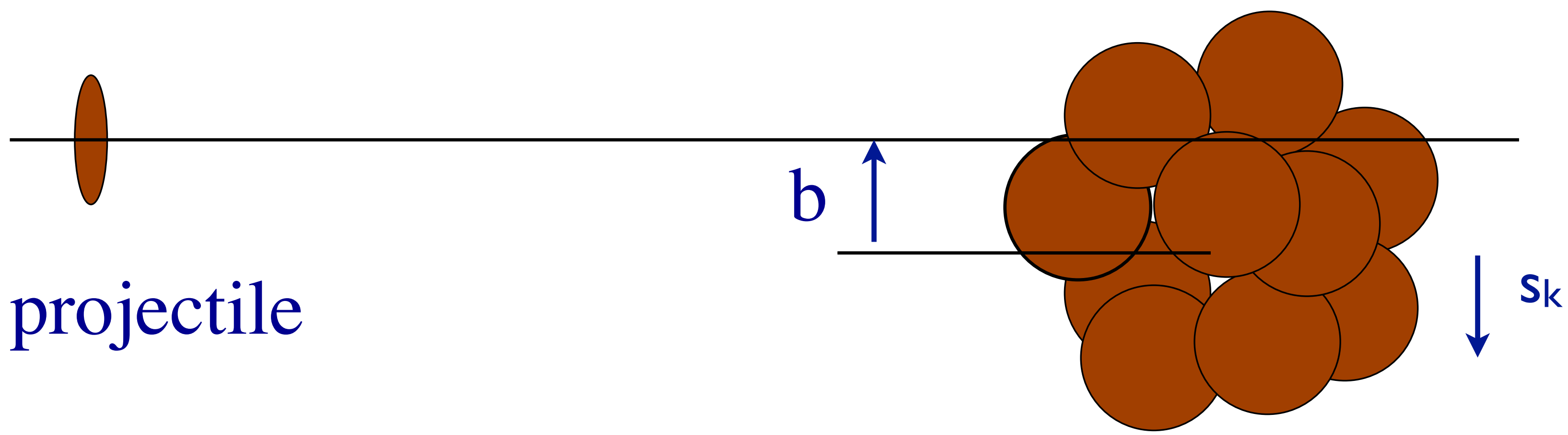






Fluctuations: Generation of sea quark anti-quark pair and leading/excited hadron

Interaction of hadrons with nuclei



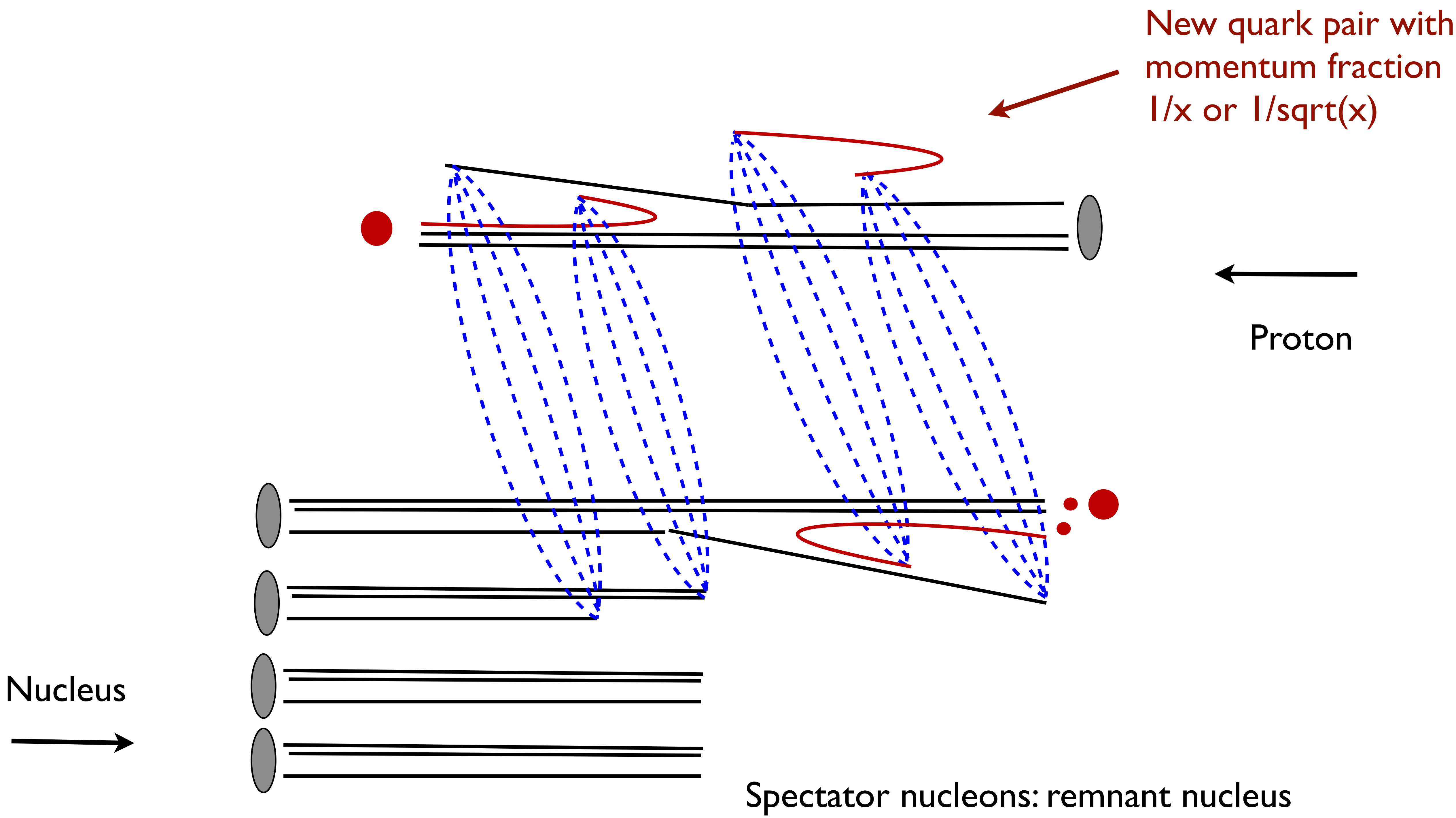
Glauber approximation:

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

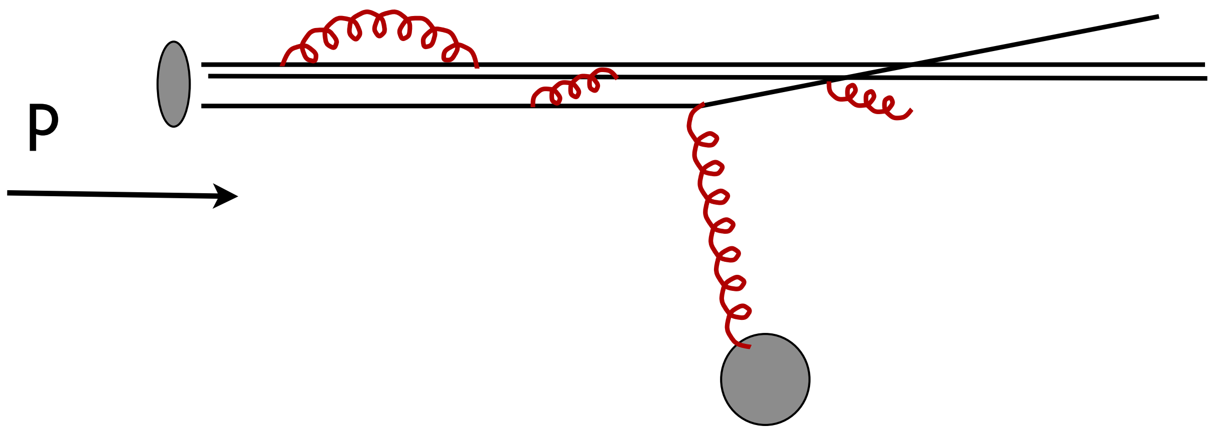
$$\sigma_{\text{prod}} \approx \int d^2\vec{b} \left[1 - \exp\left\{ -\sigma_{\text{ine}}^{NN} T_A(\vec{b}) \right\} \right]$$

Coherent superposition of elementary nucleon-nucleon interactions

String configuration for nucleus as target



Transition from intermediate to high energy

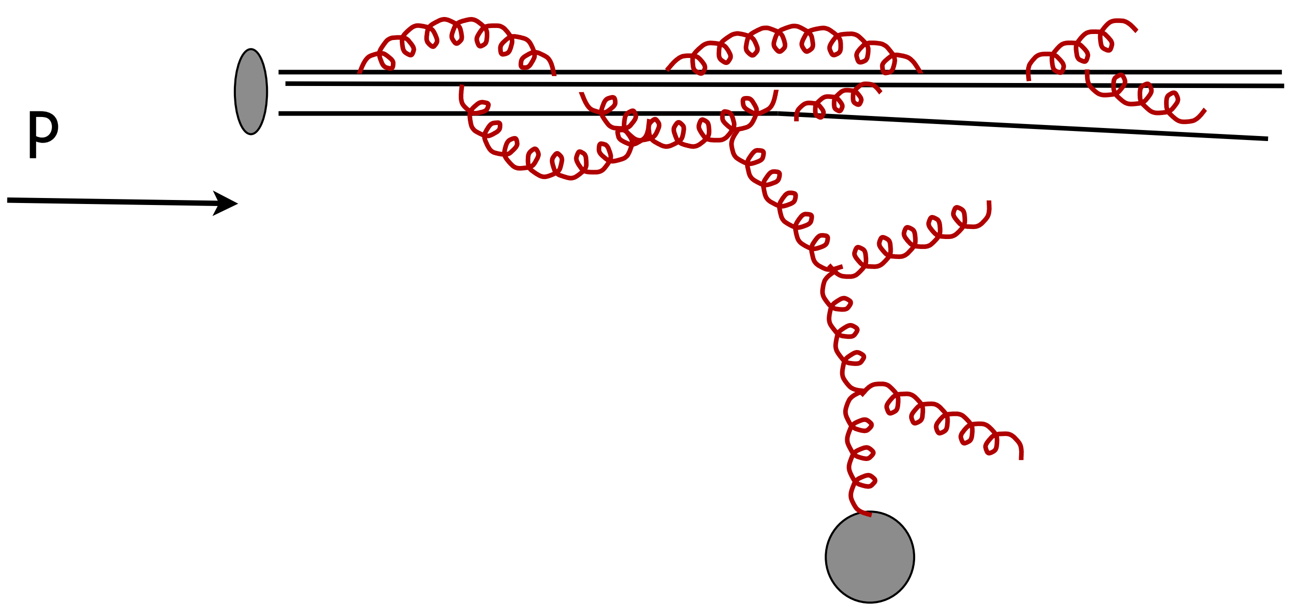


Intermediate energy:

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

Lifetime of fluctuations

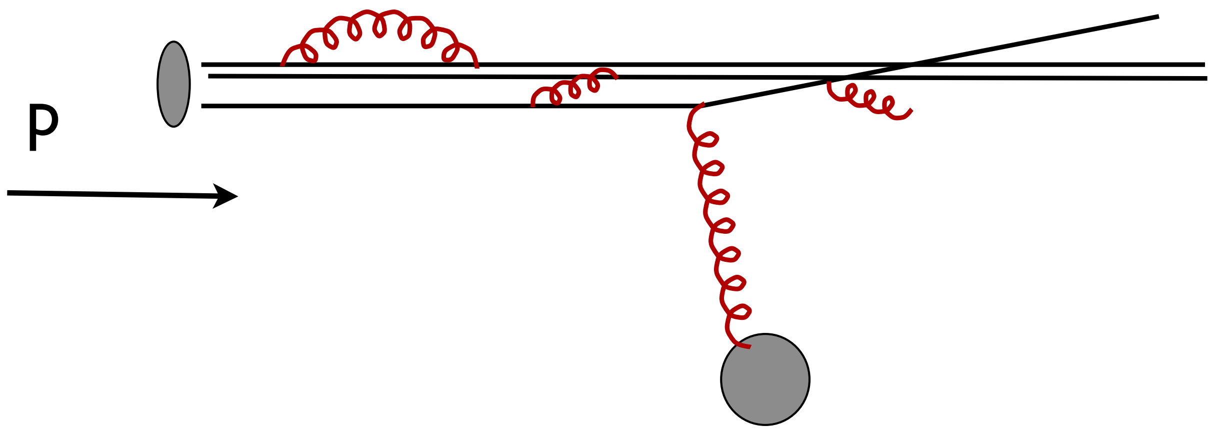
$$\Delta t \approx \frac{1}{\Delta E} = \frac{1}{\sqrt{p^2+m^2}-p} = \frac{1}{p(\sqrt{1+m^2/p^2}-1)} \approx \frac{2p}{m^2}$$



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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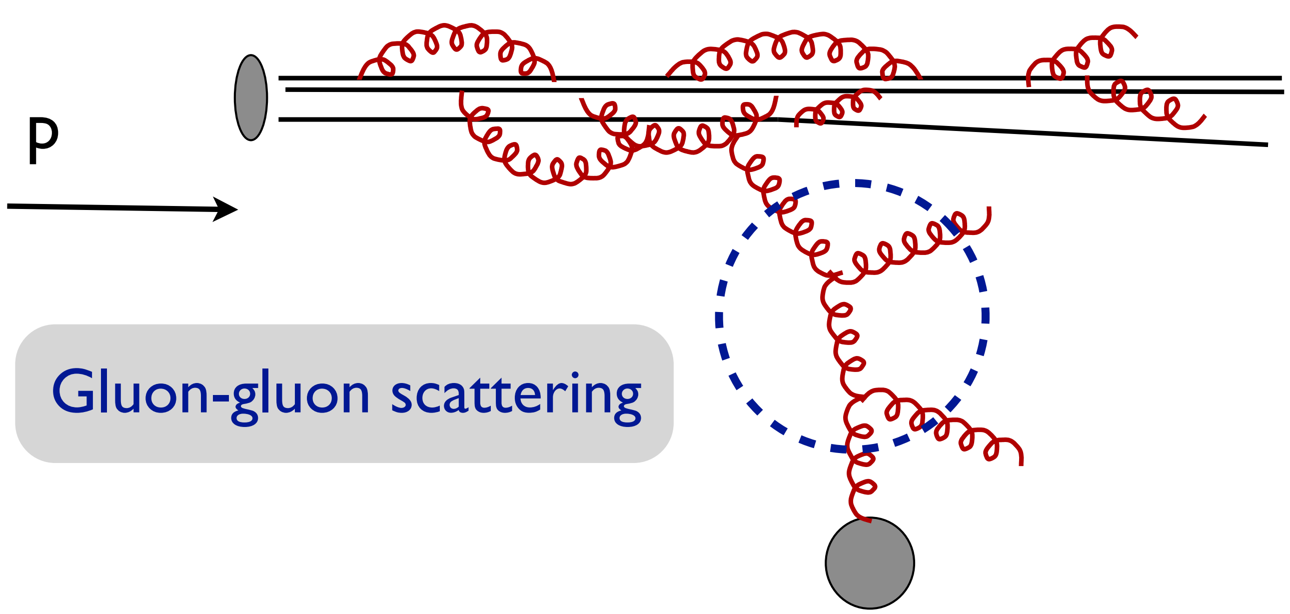
- dominated by valence quarks

Lifetime of fluctuations

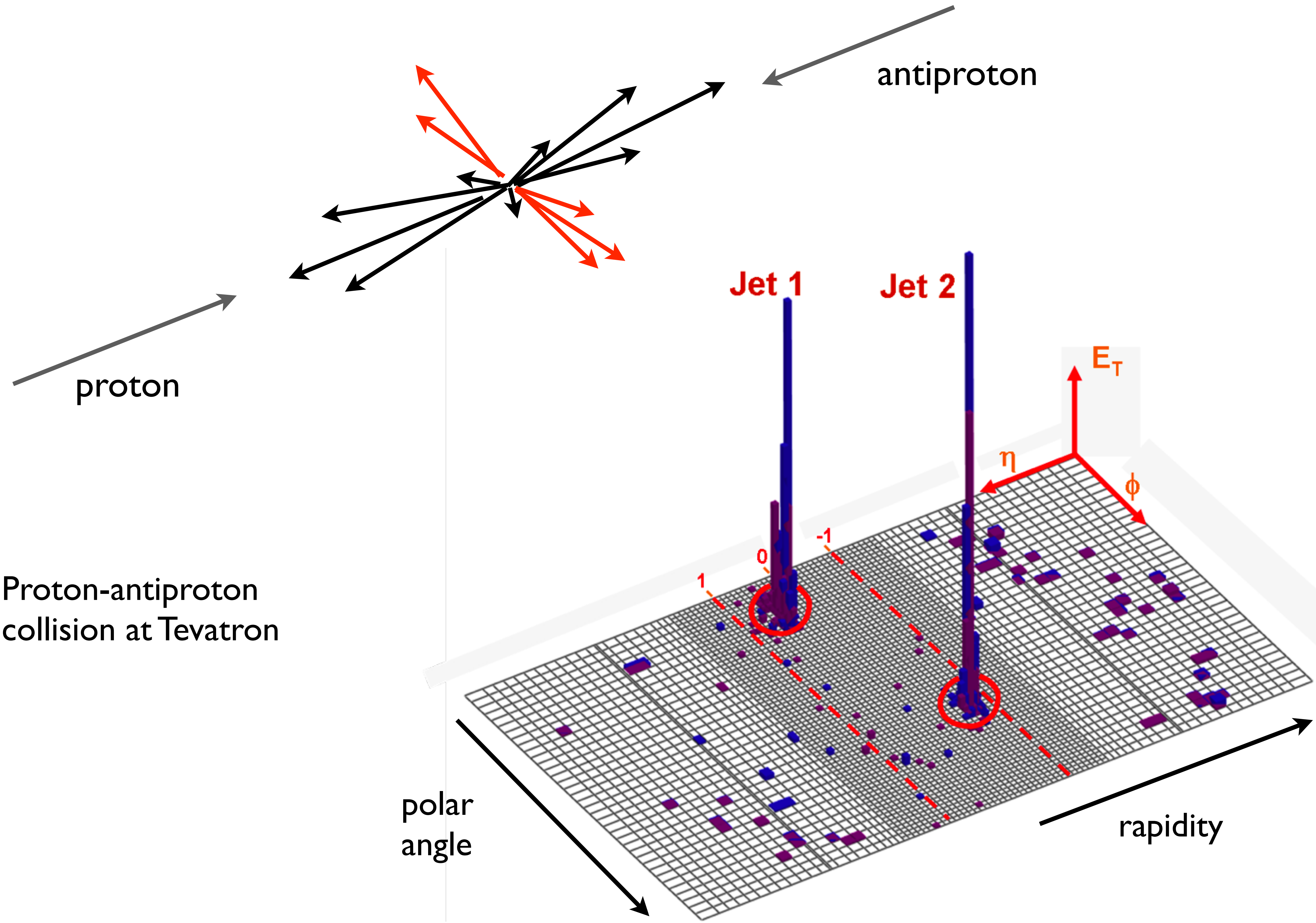
$$\Delta t \approx \frac{1}{\Delta E} = \frac{1}{\sqrt{p^2 + m^2} - p} = \frac{1}{p(\sqrt{1 + m^2/p^2} - 1)} \approx \frac{2p}{m^2}$$



High energy regime:

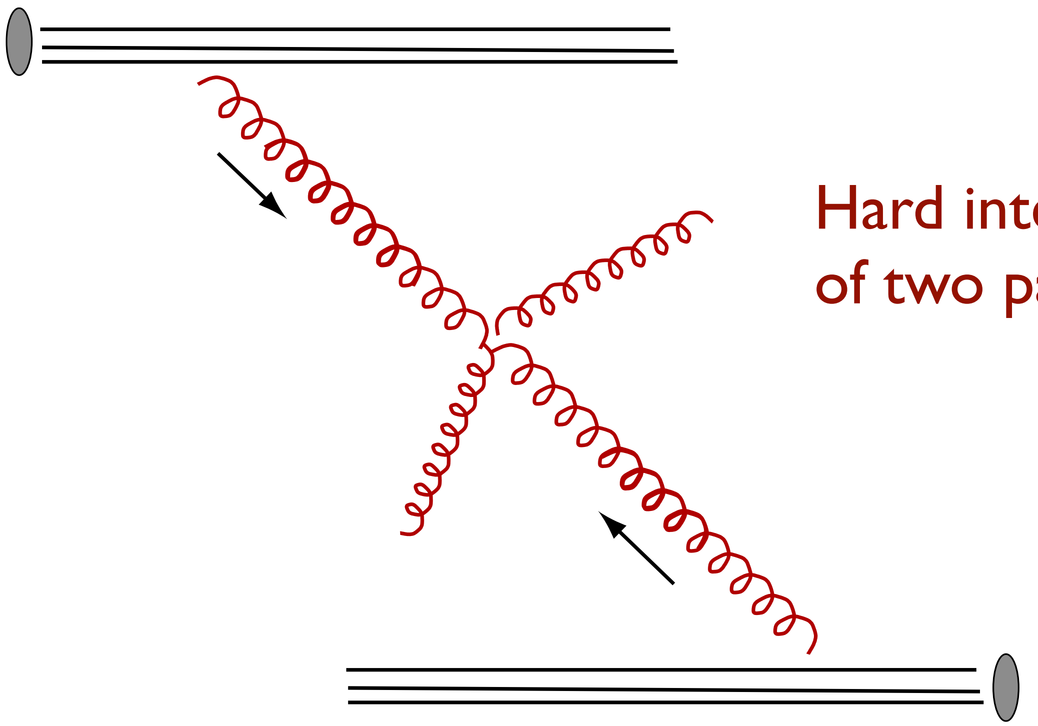
- E_{lab} > 21,000 GeV
- E_{cm} > 200 GeV
- dominated by gluons and sea quarks

Scattering of quarks and gluons: jet production



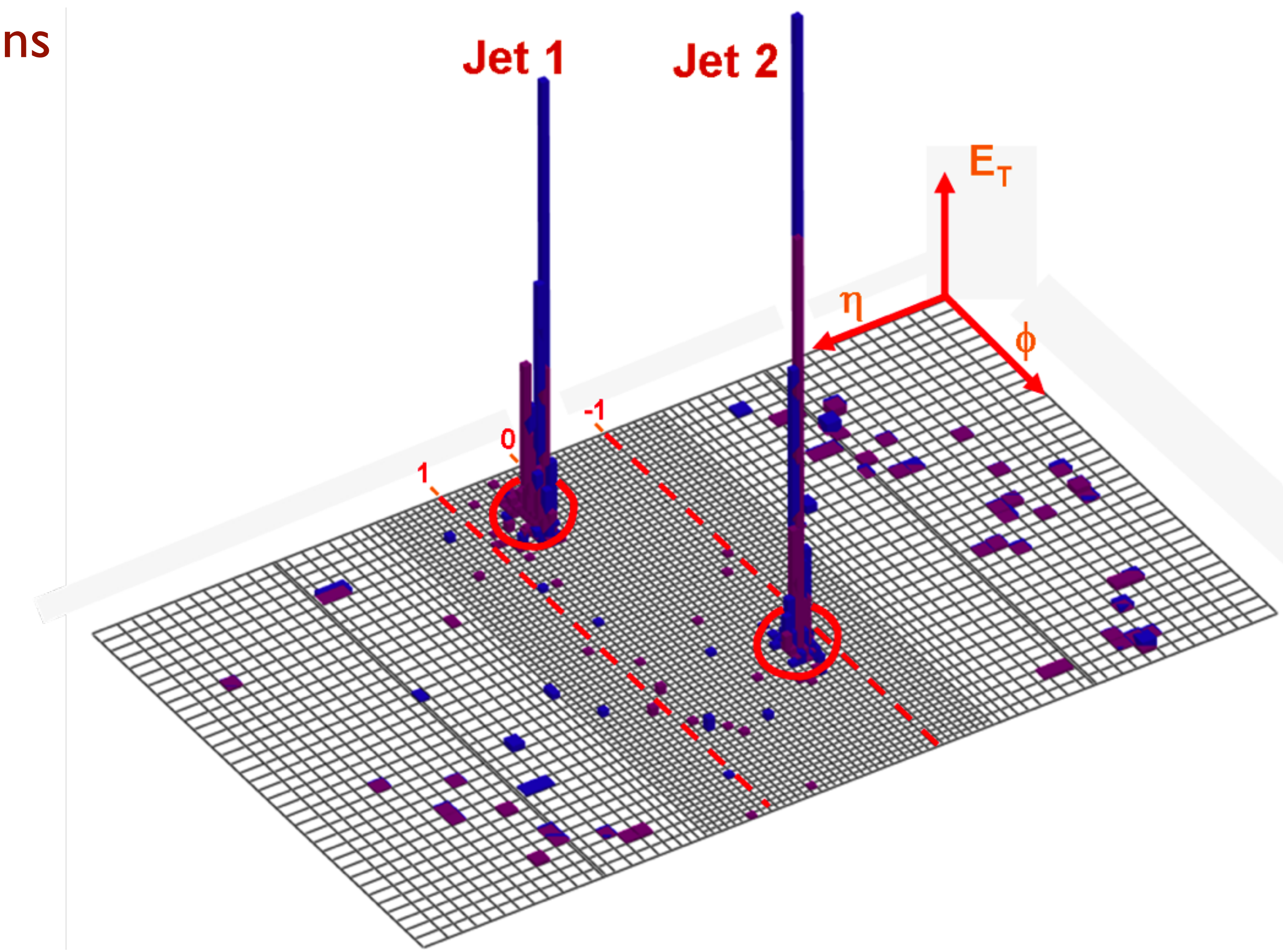
Proton-antiproton collision at Tevatron

Interpretation within perturbative QCD



Hard interaction of two partons

QCD predictions known for parton-parton cross sections



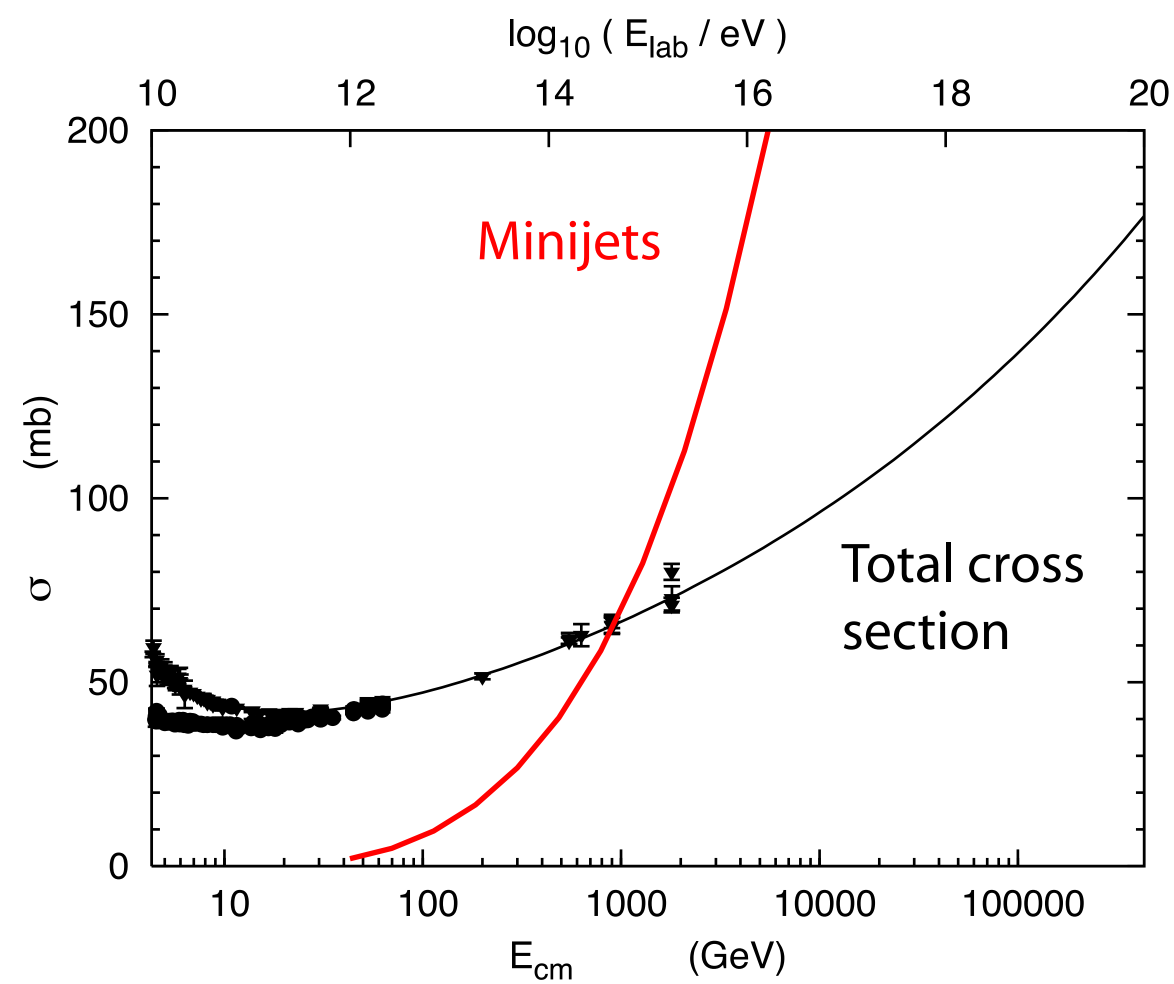
Terminology

Soft interaction: no large momentum transfer

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

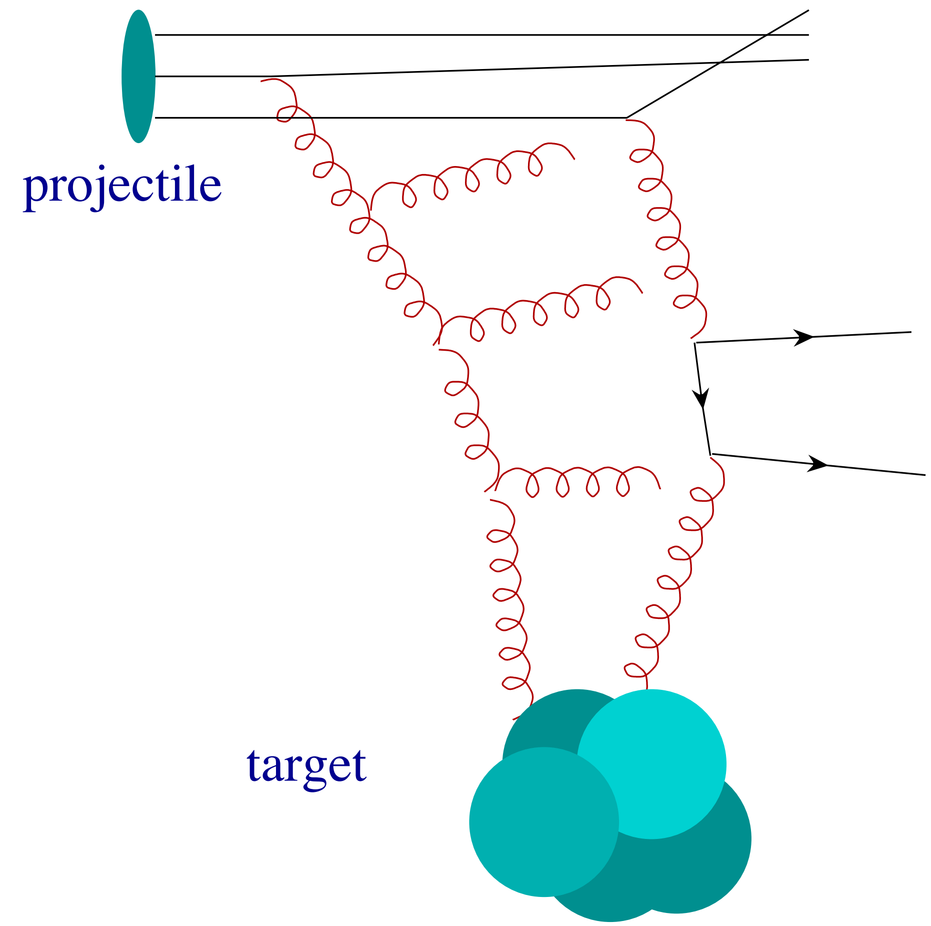
Minijet production in interaction models

Proton-proton cross section



Average number of minijet pairs

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



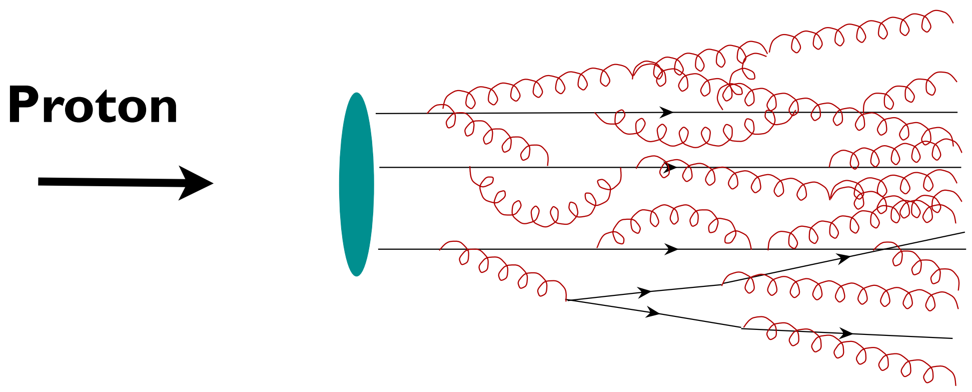
Equivalent expression implemented in all models

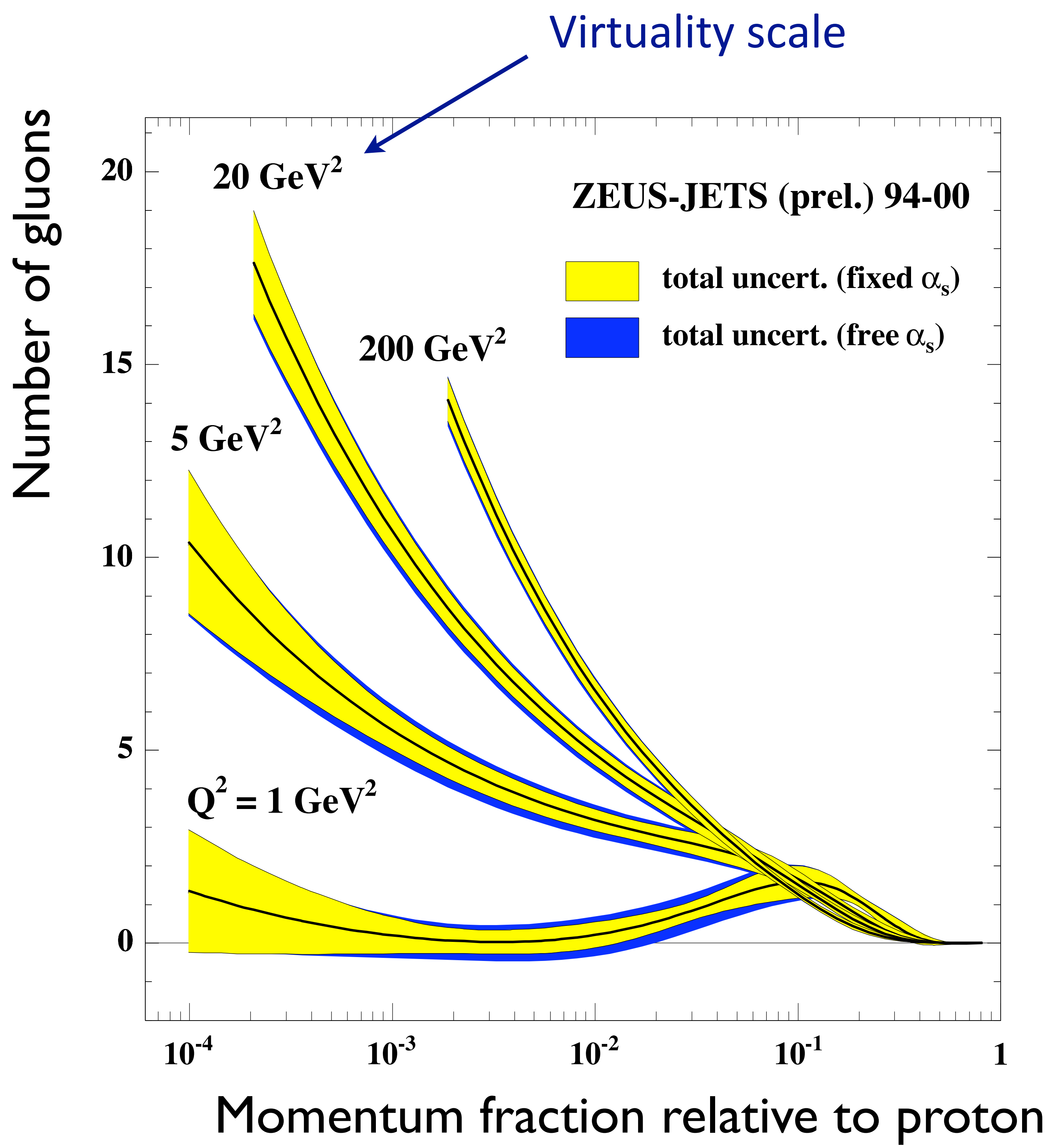
$$\sigma_{QCD} = \sum_{i,j,k,l} \frac{1}{1+\delta_{kl}} \int dx_1\, dx_2 \int_{p_\perp^{\rm cutoff}} dp_\perp^2\; f_i(x_1,Q^2)\; f_j(x_2,Q^2)\; \frac{d\sigma_{i,j\to k,l}}{dp_\perp}$$

Rapid increase of gluon density at low x

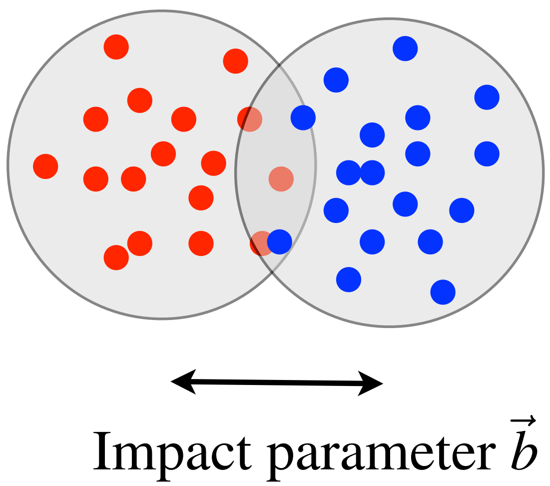
Data from HERA ep collider

$$xg(x, Q^2) \sim x^{-0.3...0.4}$$

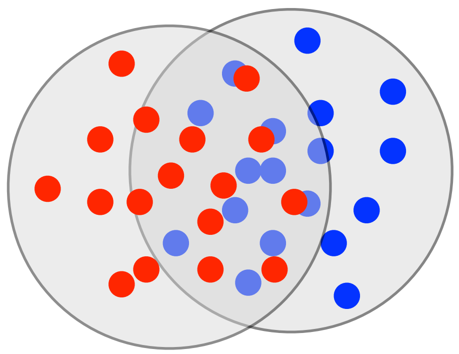




Poissonian probability distribution



Peripheral collision:
only very few parton-pairs interacting



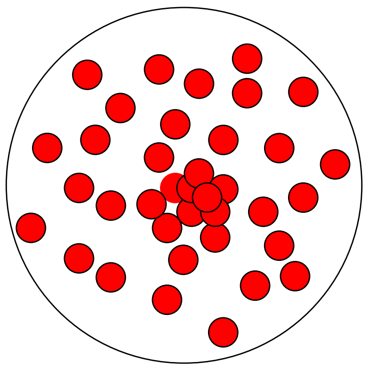
Central collision:
many parton-pairs interacting

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

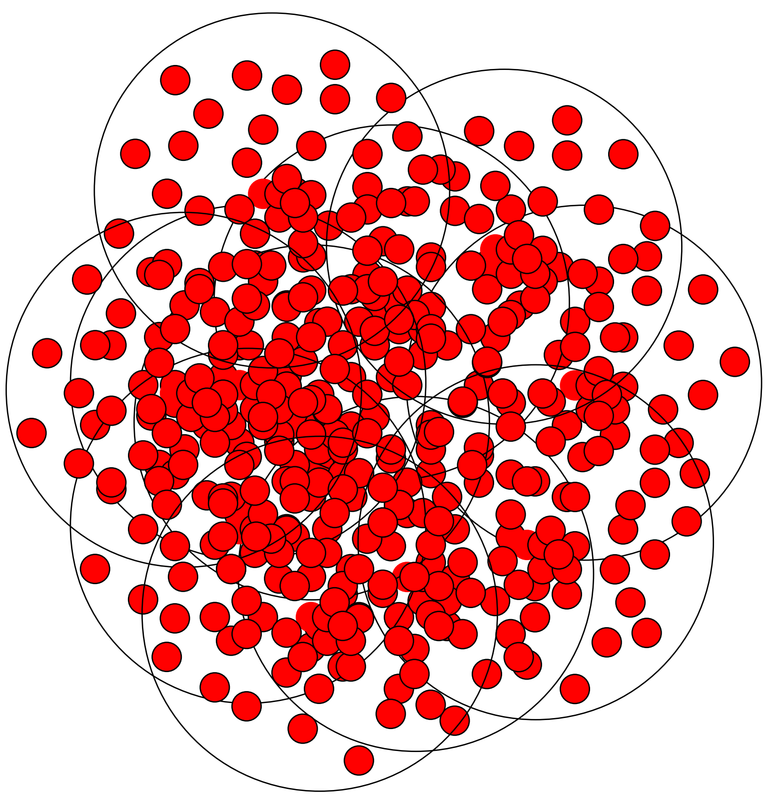
mean number of interactions for given impactparameter of collision

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

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

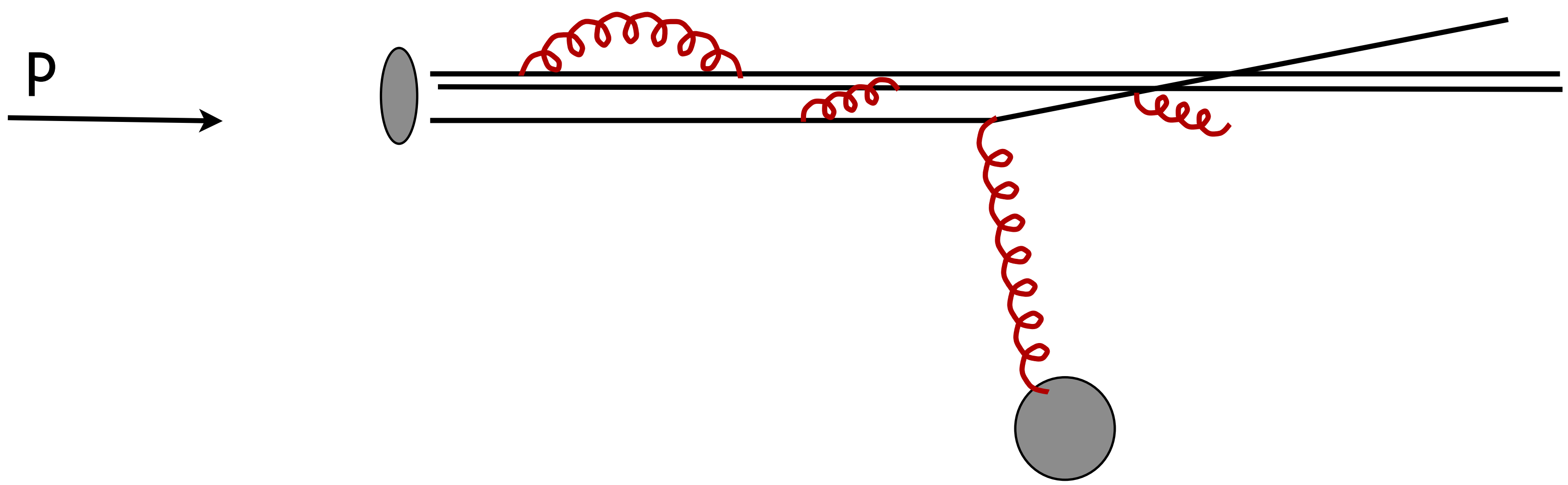
$$\pi R_0^2 \simeq \frac{\alpha_s(Q_s^2)}{Q_s^2} \cdot xg(x, Q_s^2)$$

size of proton

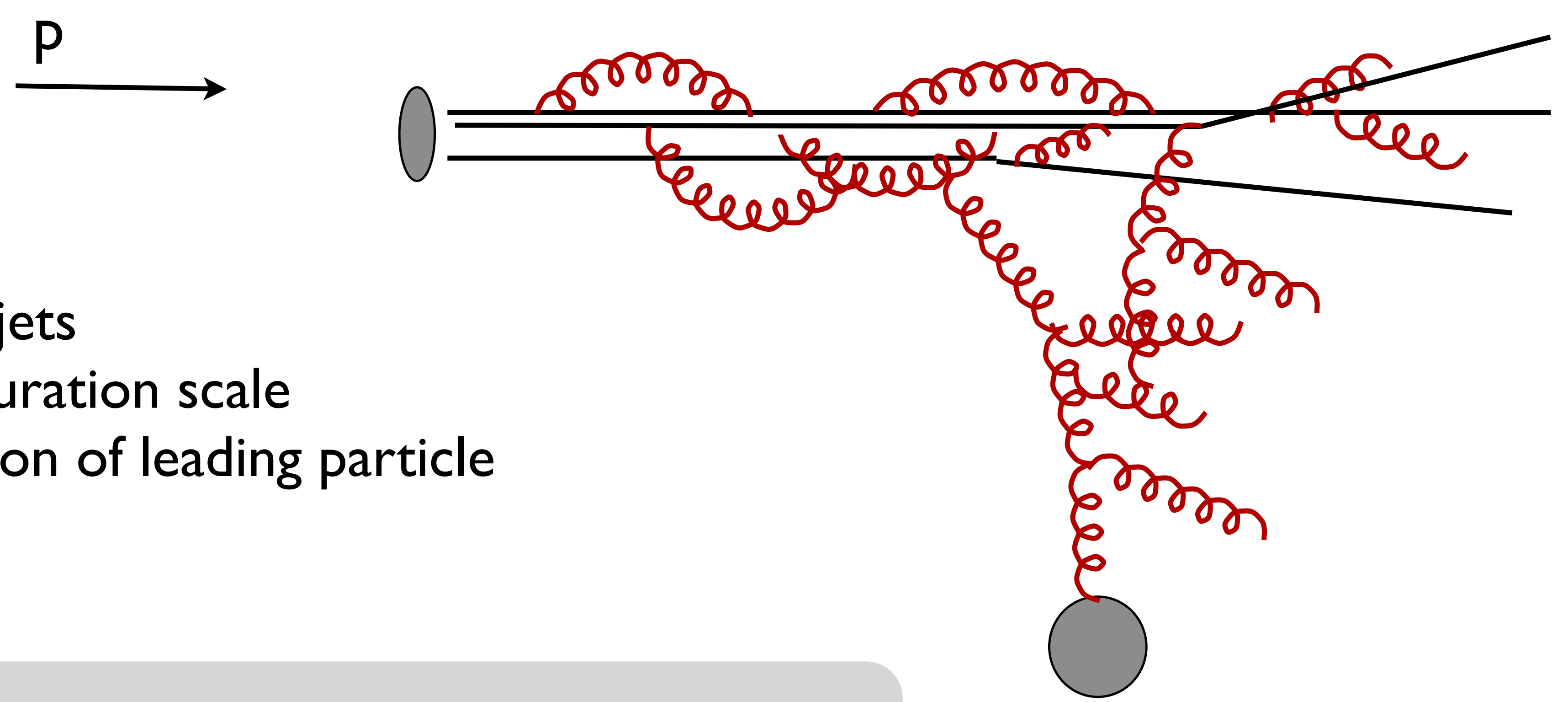
Size of one gluon

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

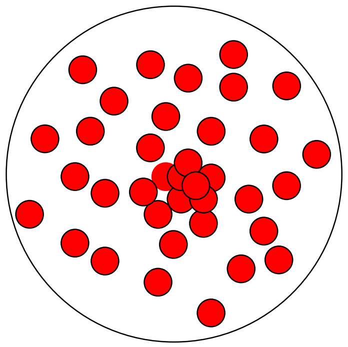
Not implemeted as dominating process in current models

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

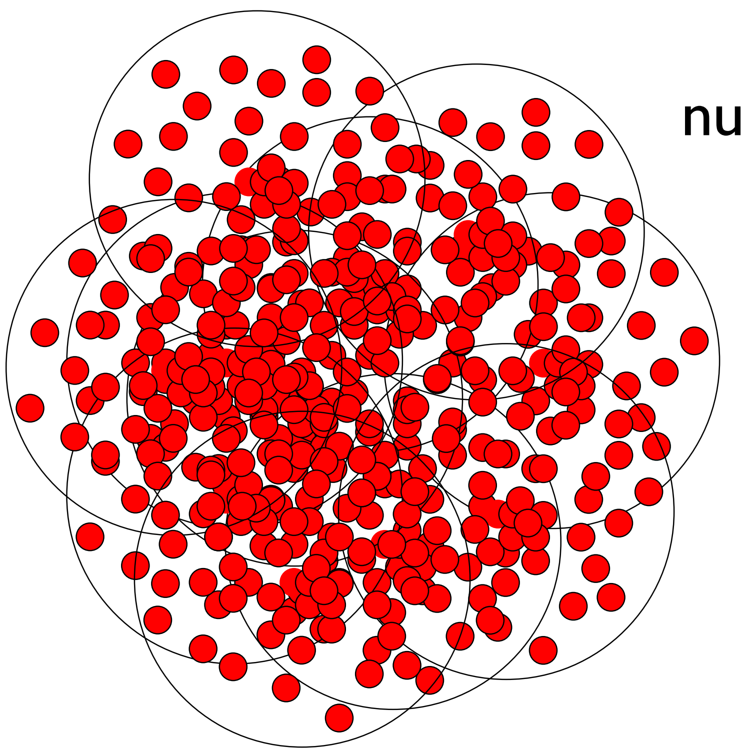
Comparison of high energy interaction models

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 and II.04 *(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

SIBYLL 2.1: modification of minijet threshold



nucleon



nucleus

SIBYLL: simple geometric criterion

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

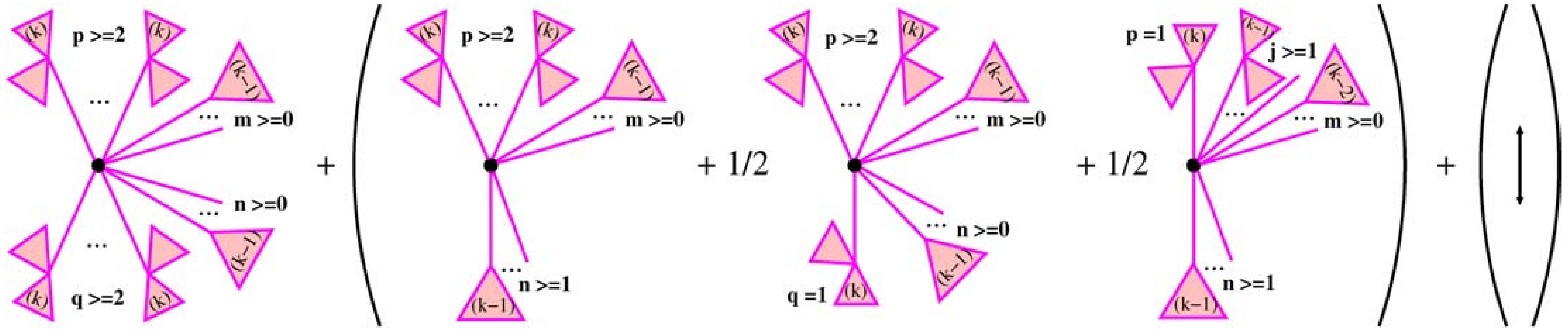
$$xg(x, Q^2) \sim \exp\left[\frac{48}{11 - \frac{2}{3}n_f} \ln \frac{\ln \frac{Q^2}{\Lambda^2}}{\ln \frac{Q_0^2}{\Lambda^2}} \ln \frac{1}{x}\right]^{\frac{1}{2}}$$

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

No dependence on impact parameter !

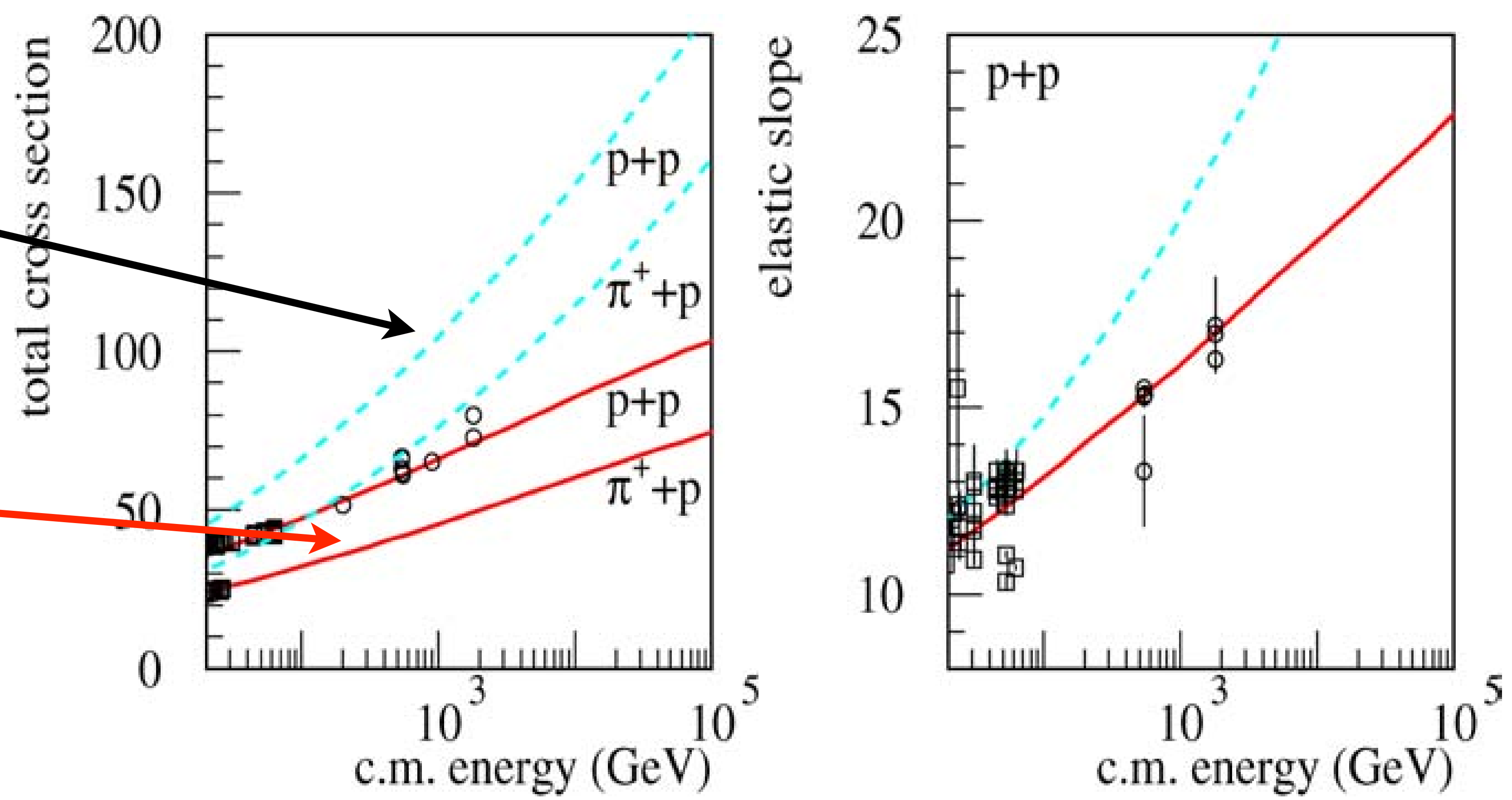
QGSJET II: high parton density effects

Re-summation of enhanced pomeron graphs



Without enhanced graphs

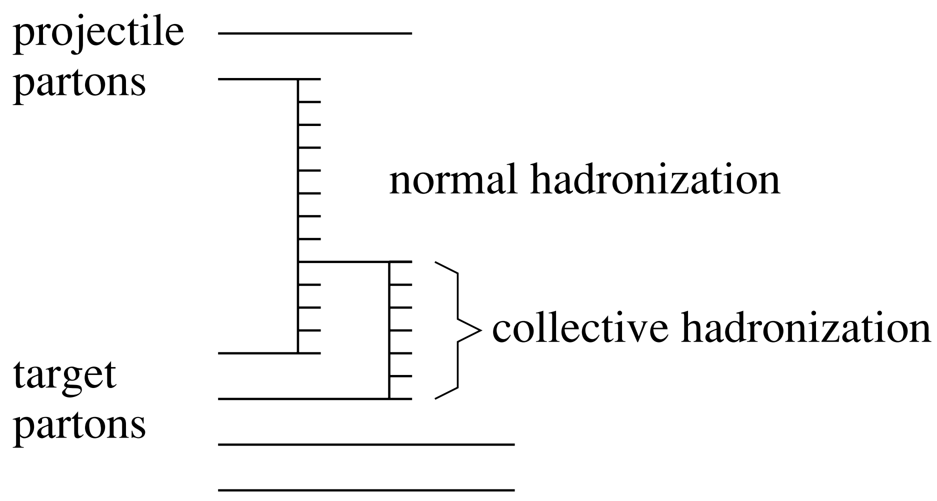
With enhanced graphs



(Ostapchenko, PLB 2006, PRD 2006)

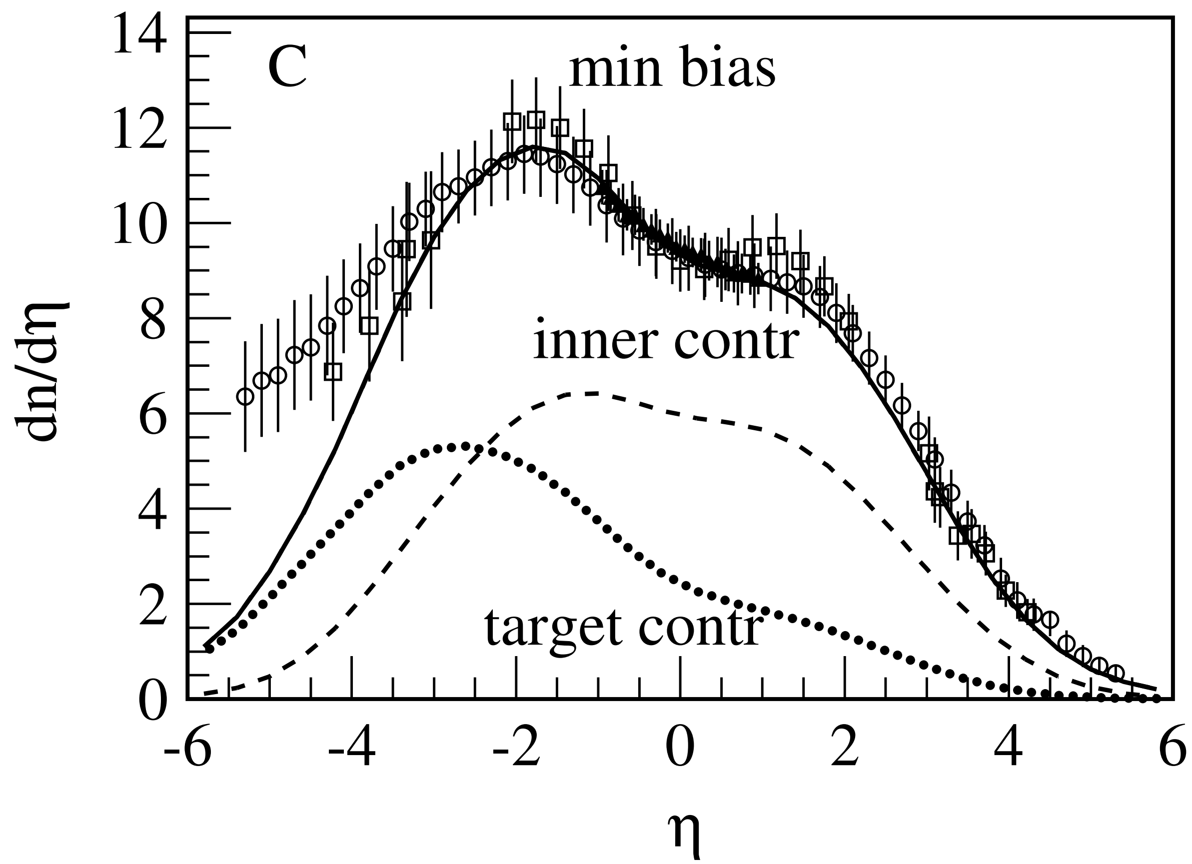
EPOS 1.9 – high parton density effects

(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

Uncertainty in energy extrapolation !



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

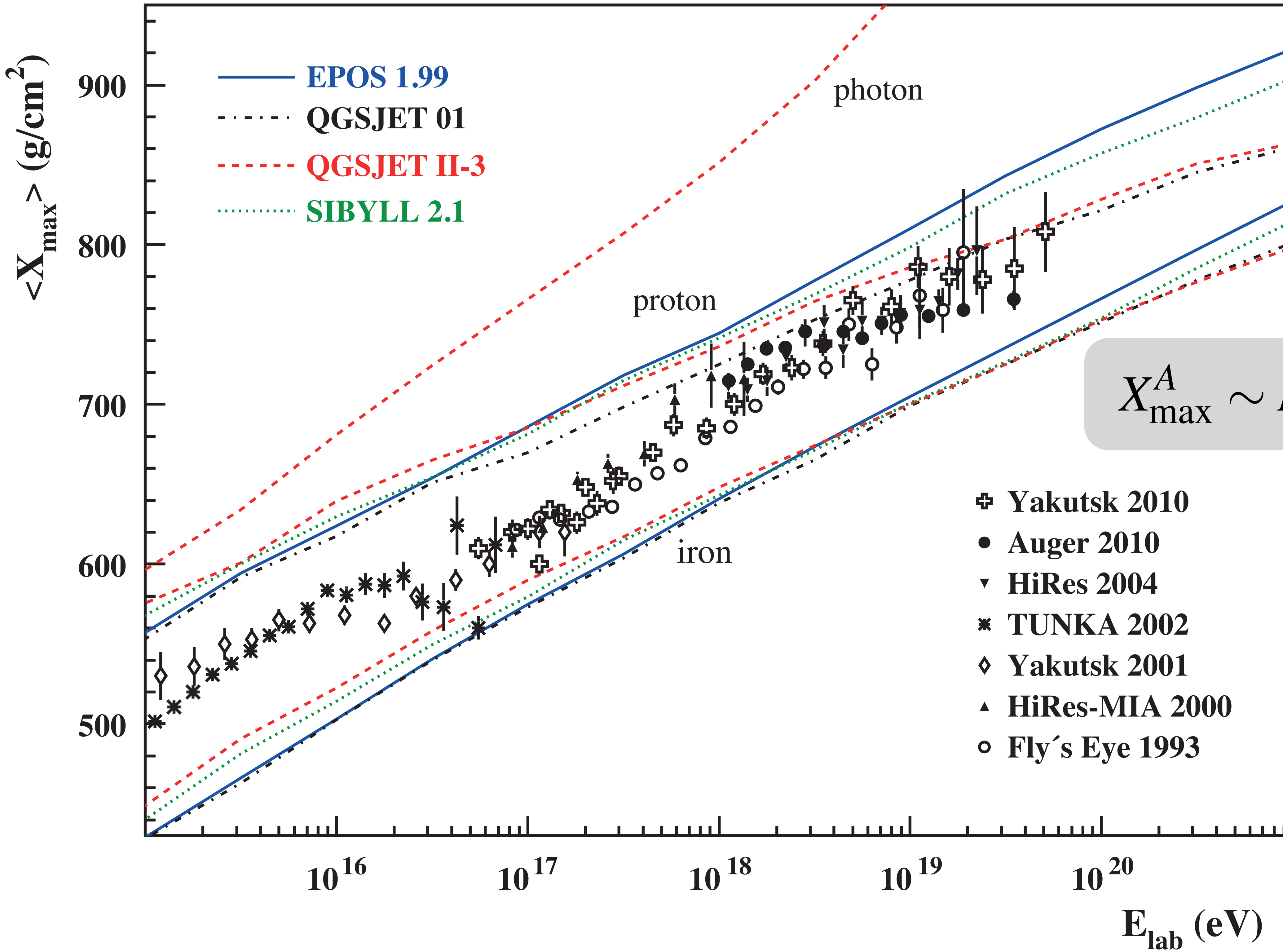
$$b_0 = w_B \sqrt{\sigma_{\text{inel}\,pp}/\pi}$$

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

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

3 Applications (putting things together)

Mean depth of shower maximum



$$X_{\max}^{A} \sim D_e \ln(E_0/AE_c)$$

(RE, Pierog, Heck, ARNPS 2011)

Elongation rates and model features

Elongation rate theorem

$$D_{10}^{\text{had}} = \ln 10\, X_0 (1 - B_n - B_\lambda)$$

(Linsley, Watson PRL46, 1981)

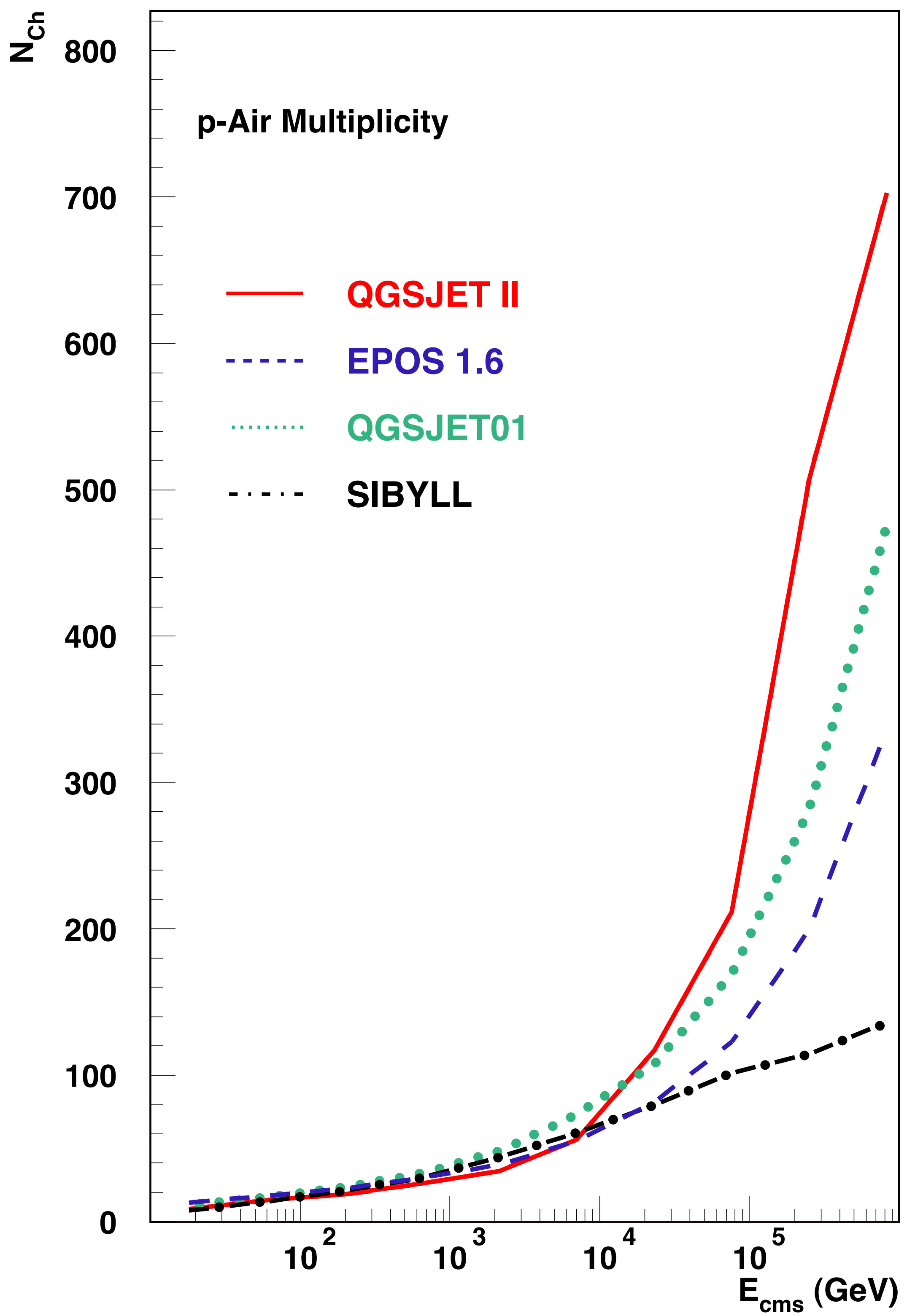
factor ~ 87 g/cm^2

$$B_n = \frac{d \ln n_{\text{tot}}}{d \ln E}$$

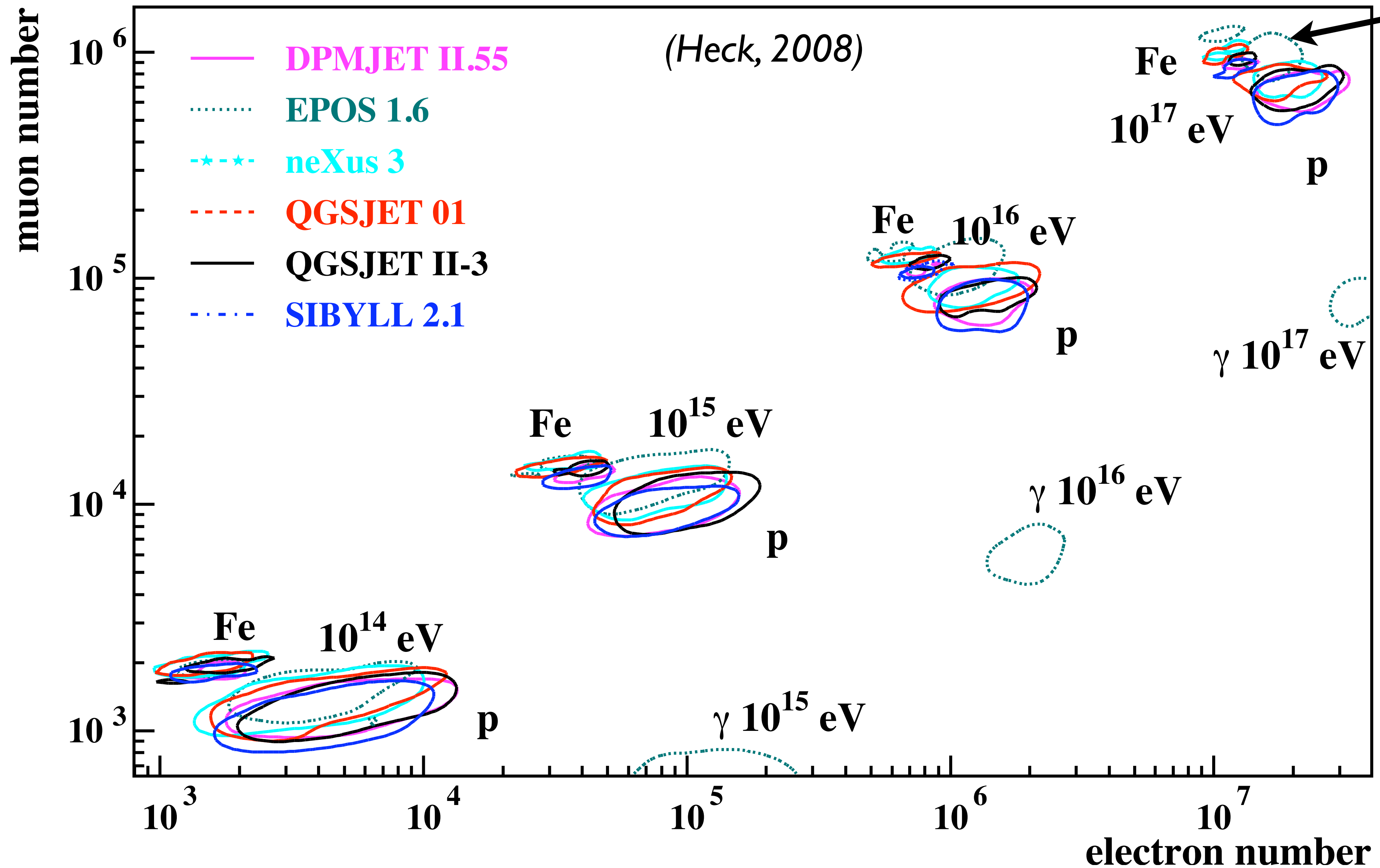
Large if multiplicity of high energy particles rises very fast, **zero in case of scaling**

$$B_\lambda = -\frac{1}{X_0} \frac{d\lambda_{\text{int}}}{d \ln E}$$

Large if cross section rises rapidly with energy



Electron and muon numbers of showers at ground



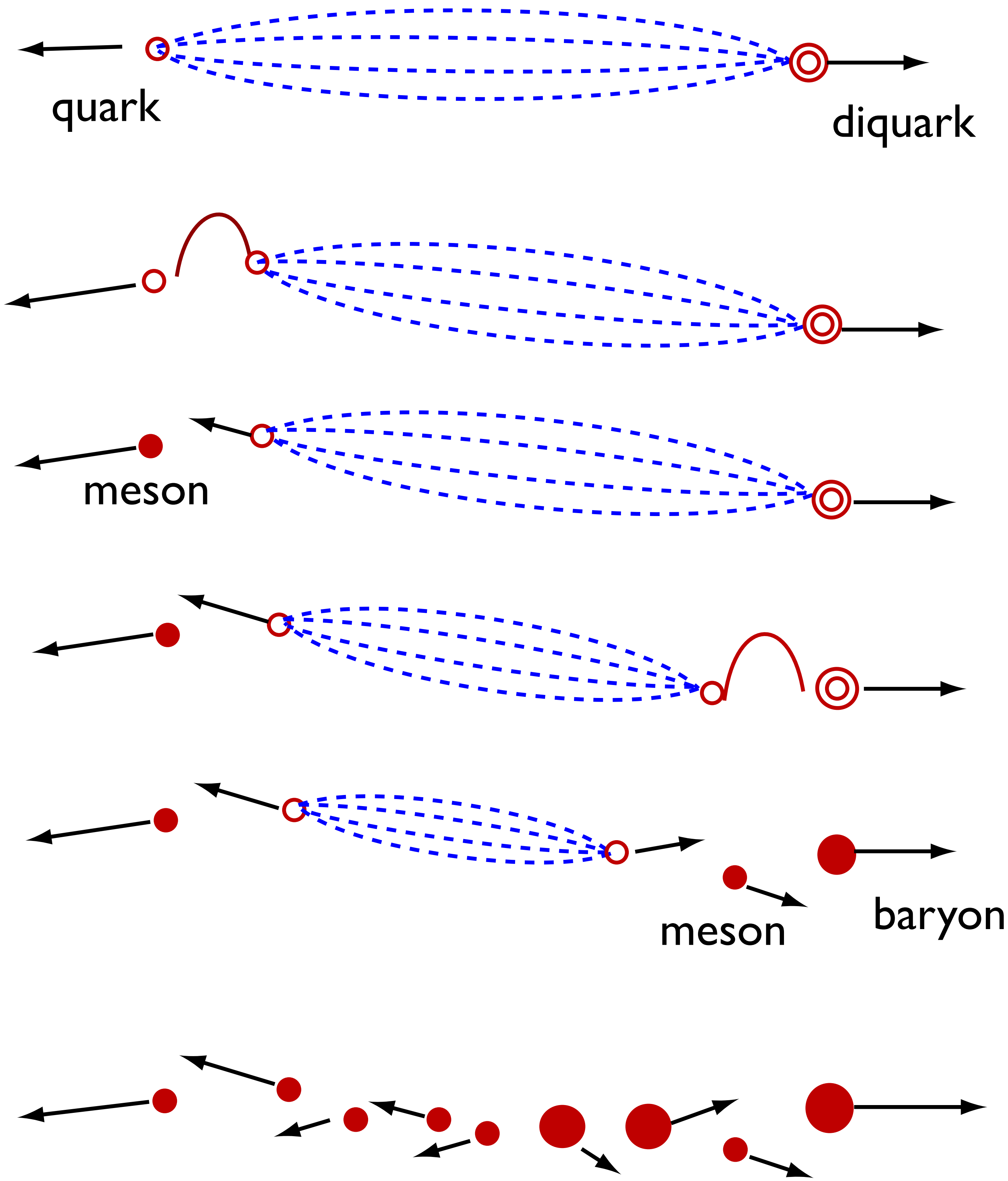
EPOS: largest muon number

vertical showers, sea level detector

$$N_\mu^{(FE)} \approx 1.4\, N_\mu^{(p)}$$

Dominating uncertainty of composition and energy measurements due to hadronic interaction models

Modification of ratio of neutral to charged pions



$$N_\mu = \left(\frac{E_0}{E_{\mathrm{dec}}}\right)^\alpha$$

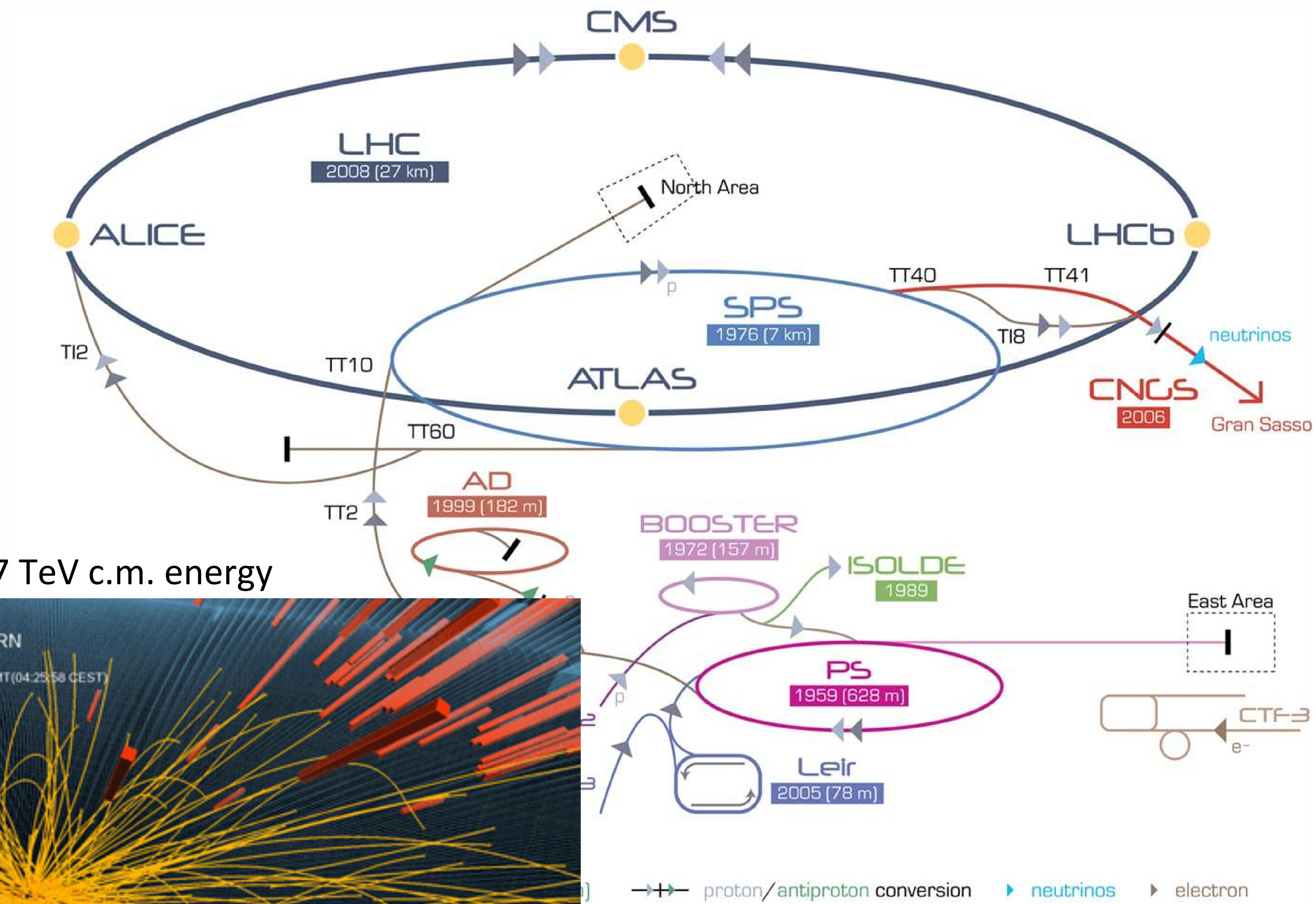
$$\alpha = \frac{\ln(n_{\mathrm{ch}})}{\ln(n_{\mathrm{tot}})}$$

Particle ratios:
quark counting and
SU(3) symmetry !

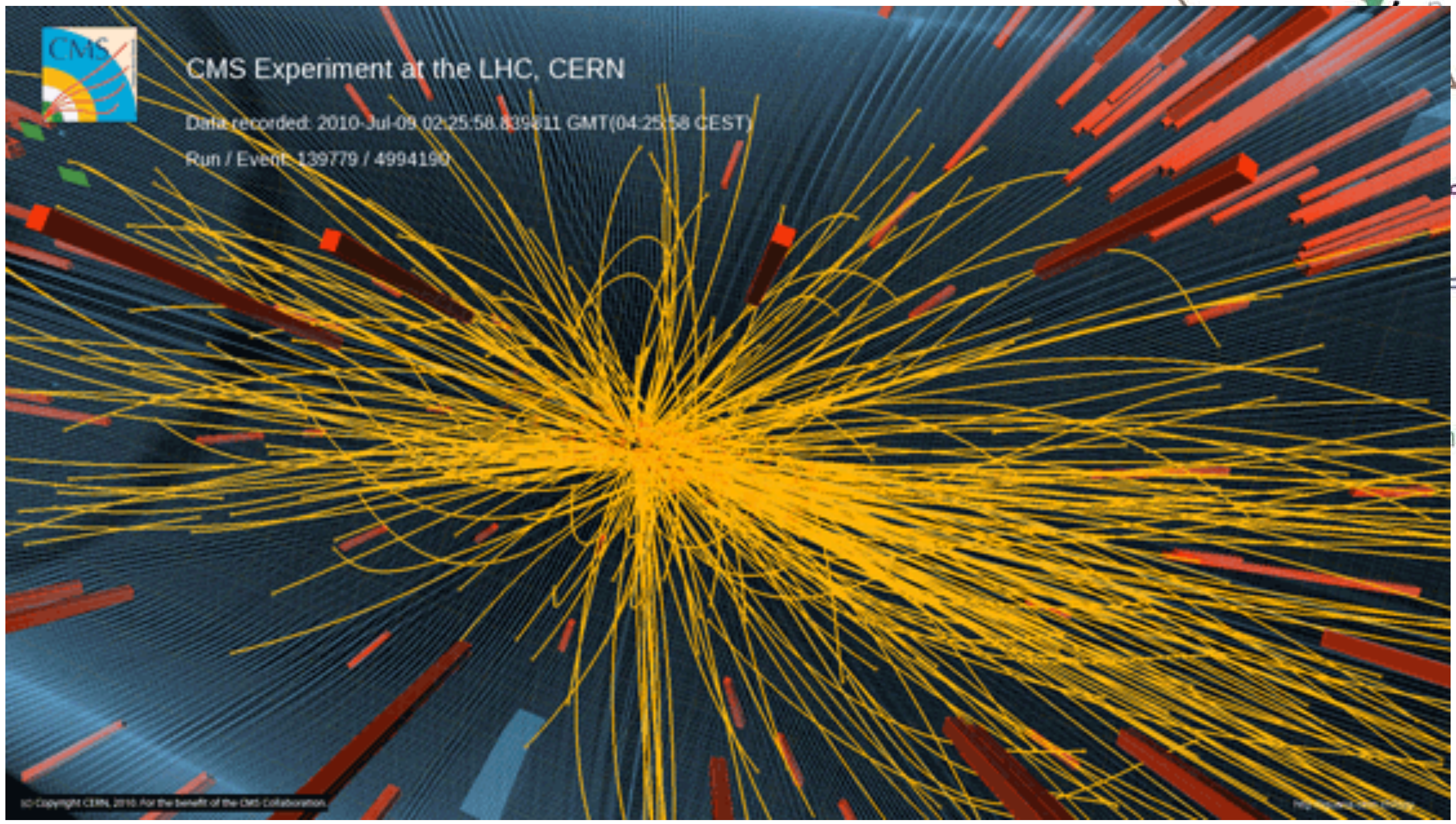
EPOS 1.6x: higher rate of baryon-antibaryon pairs

4 What do we learn from LHC

The Large Hadron Collider (LHC)

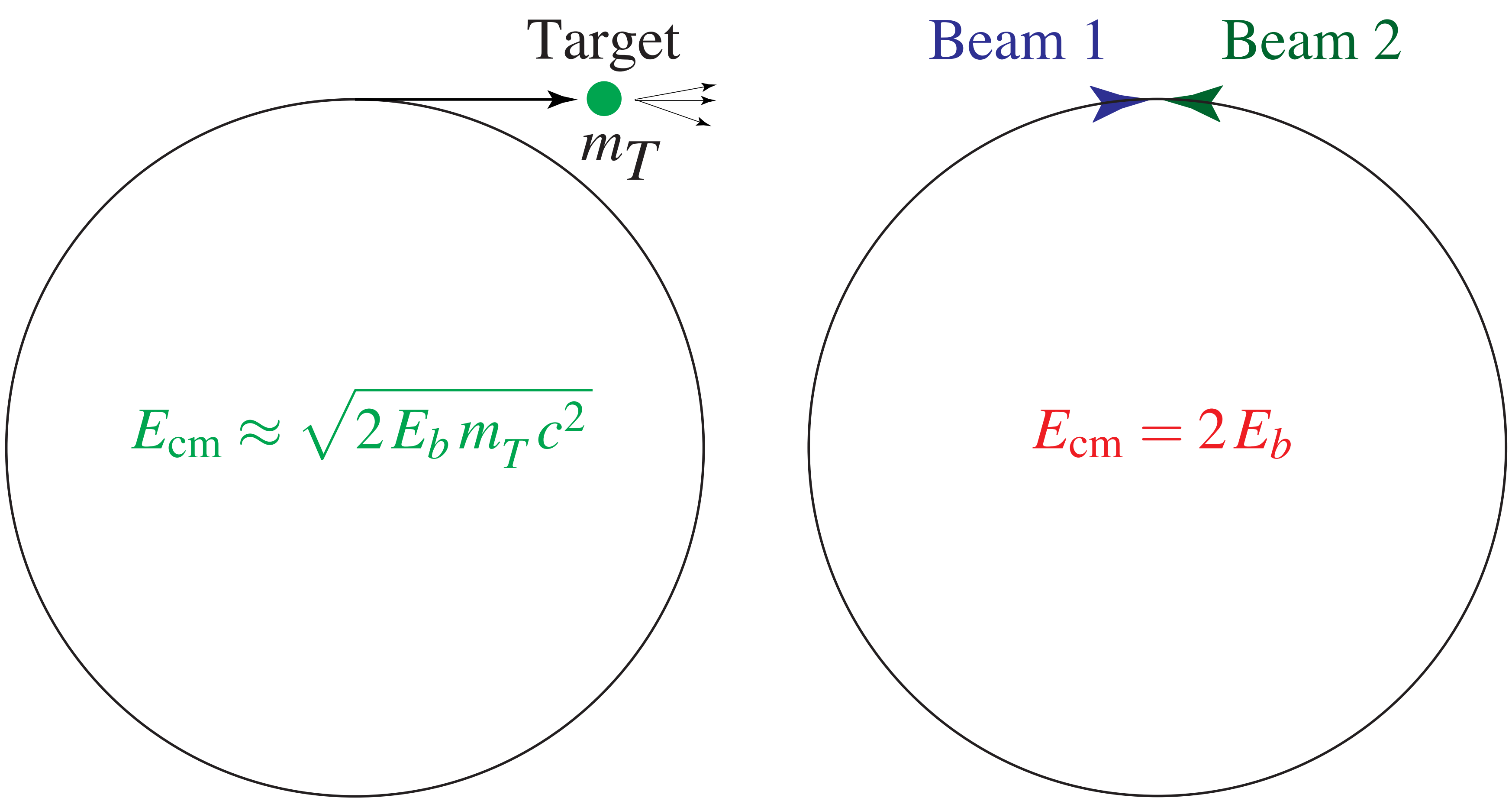


Proton-proton event at 7 TeV c.m. energy



Fixed target vs. collider experiments

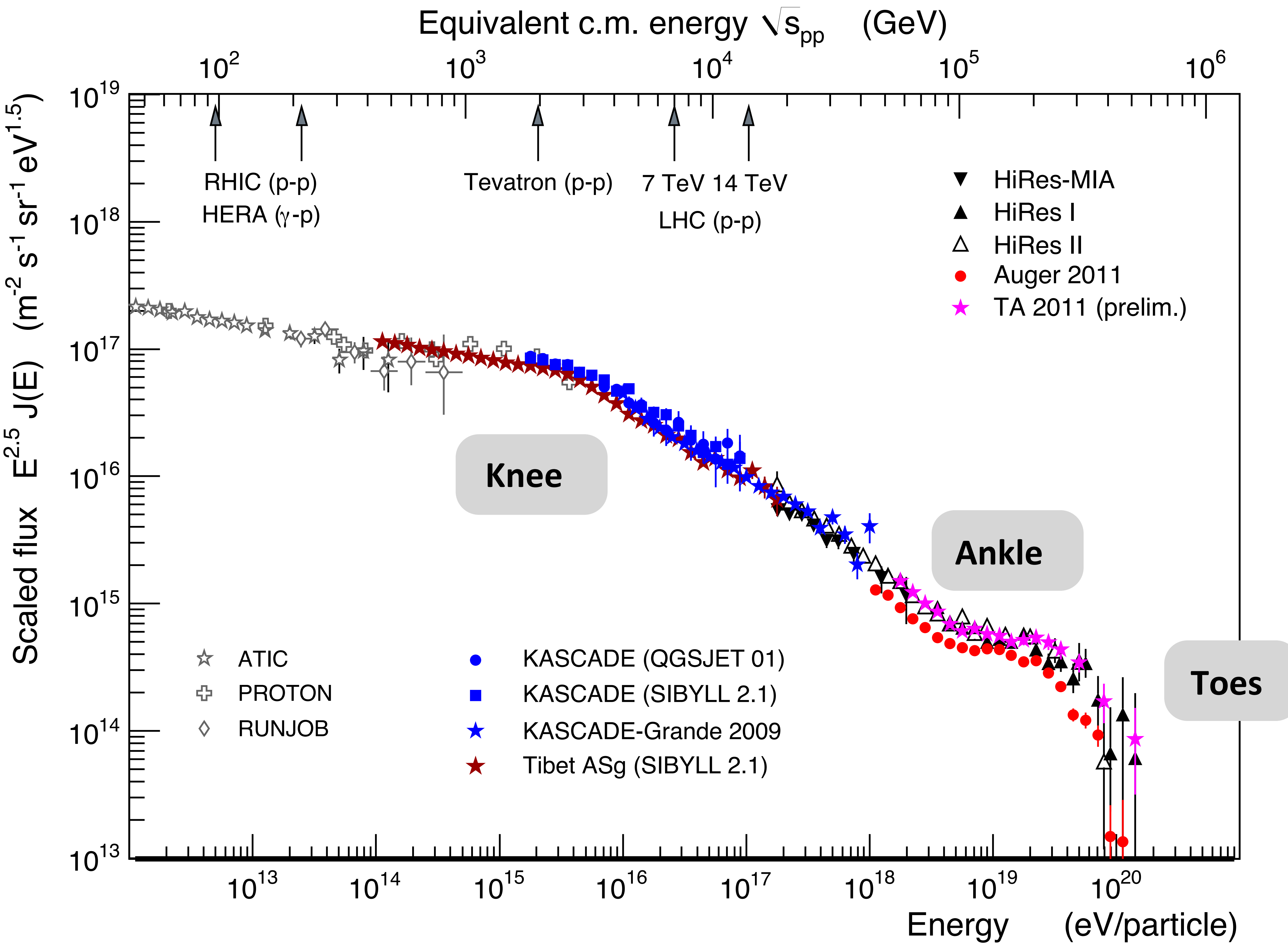
Scaling of interaction energies



Fixed target: Forward direction (beam fragmentation region) covered by detectors

Colliders: Beam direction measurements very challenging (if not impossible)

Energy spectrum and collider energies

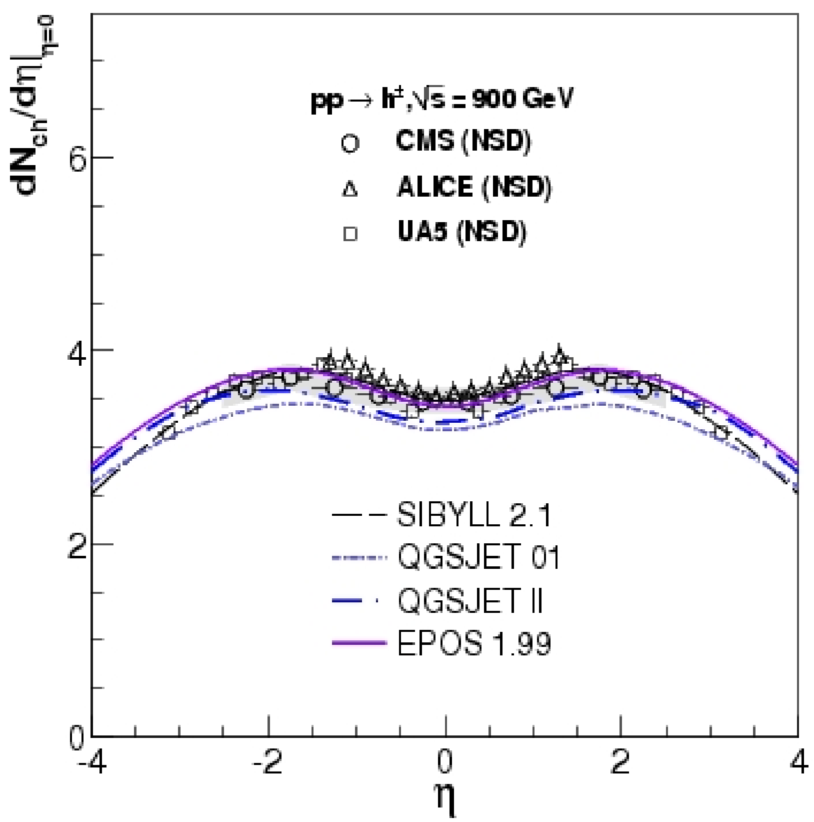


LHC data probe the region beyond the knee

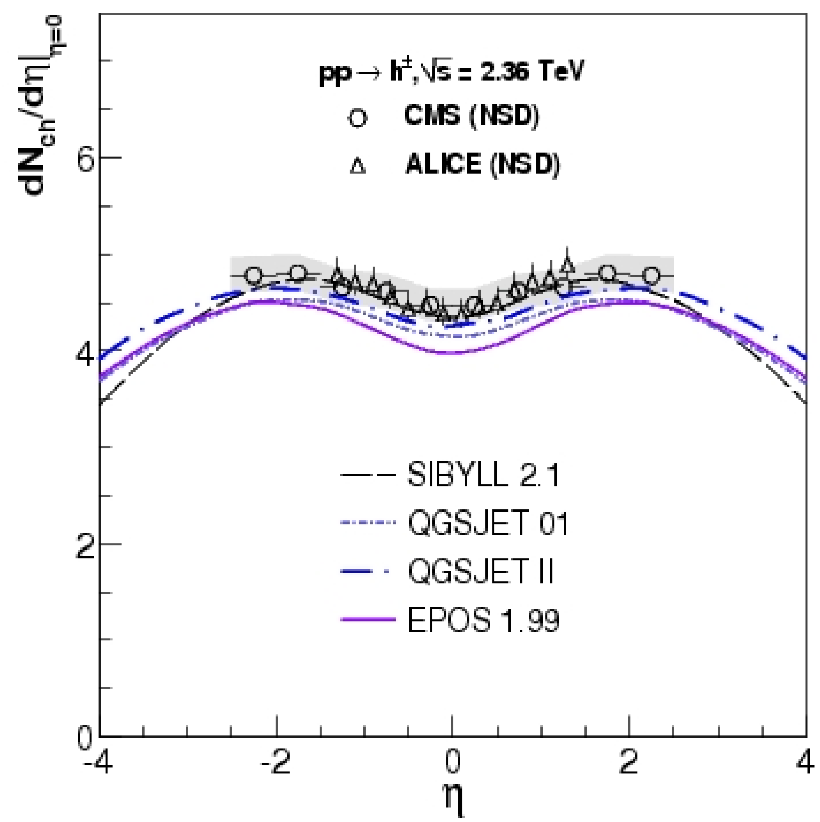
Pseudorapidity distribution of charged particles

Protons: $E_{lab} = 3 \times 10^{16}$ eV

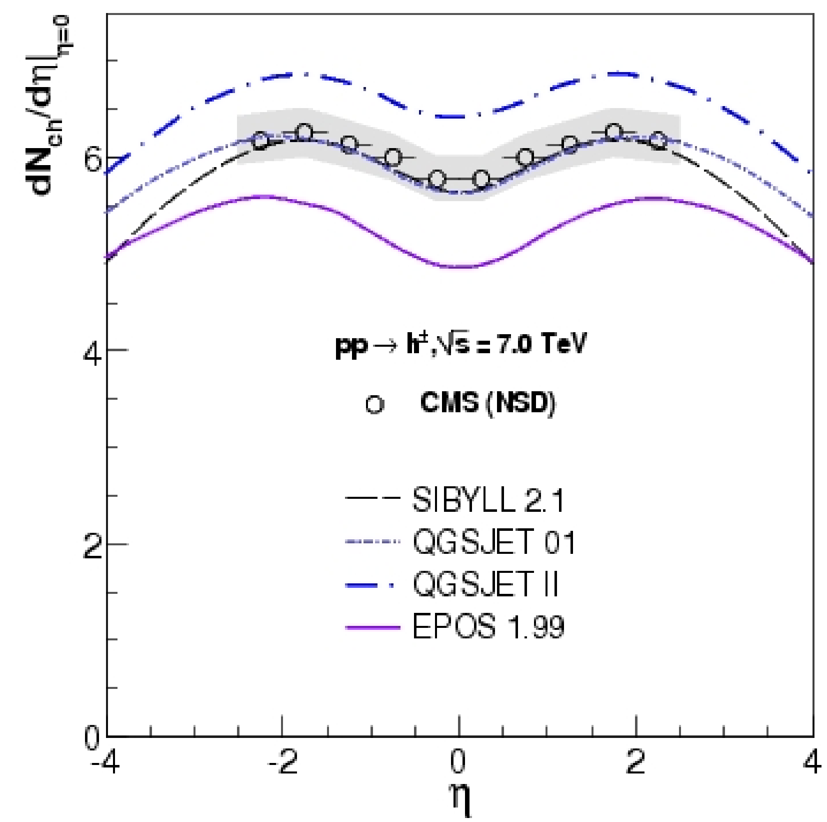
0.9 TeV

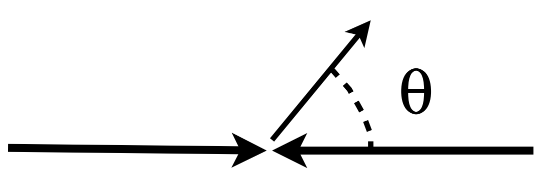


2.36 TeV



7.0 TeV





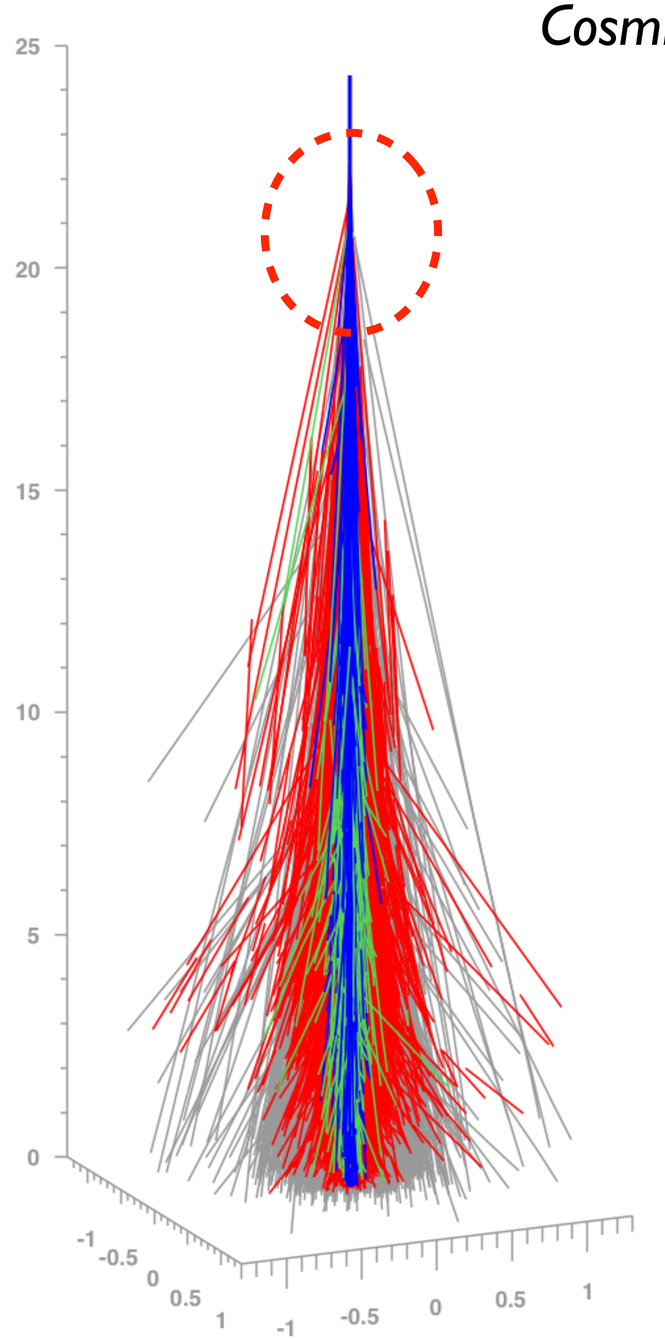
$$\eta = -\ln \tan \frac{\theta}{2}$$

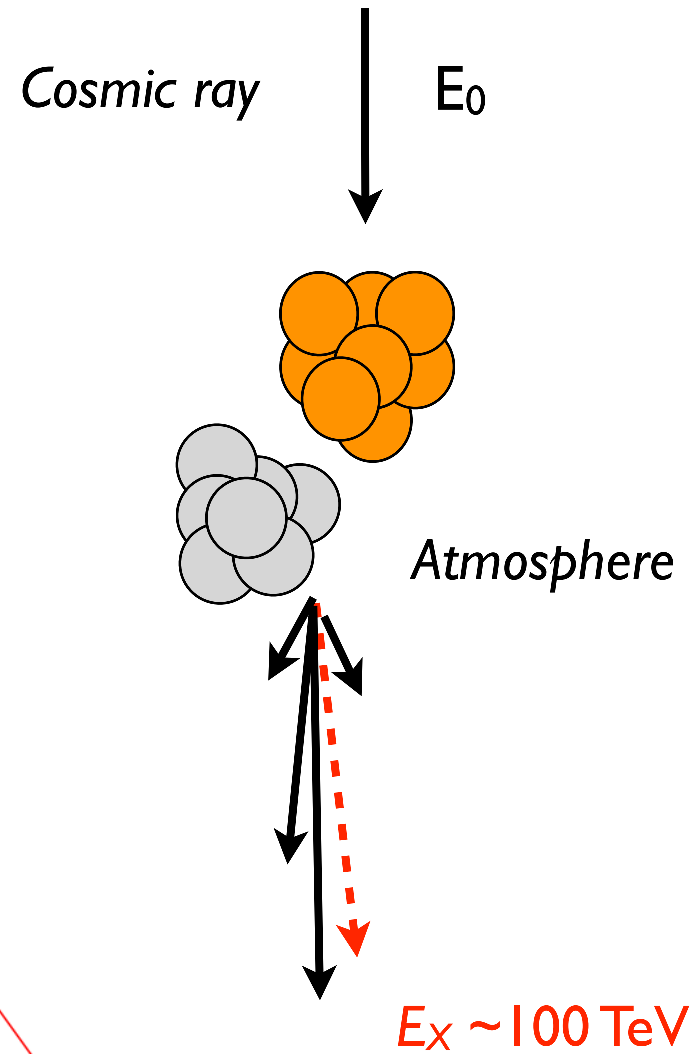
LHC: Exotic scenarios for knee very unlikely, model predictions bracket LHC data on secondary particle multiplicity

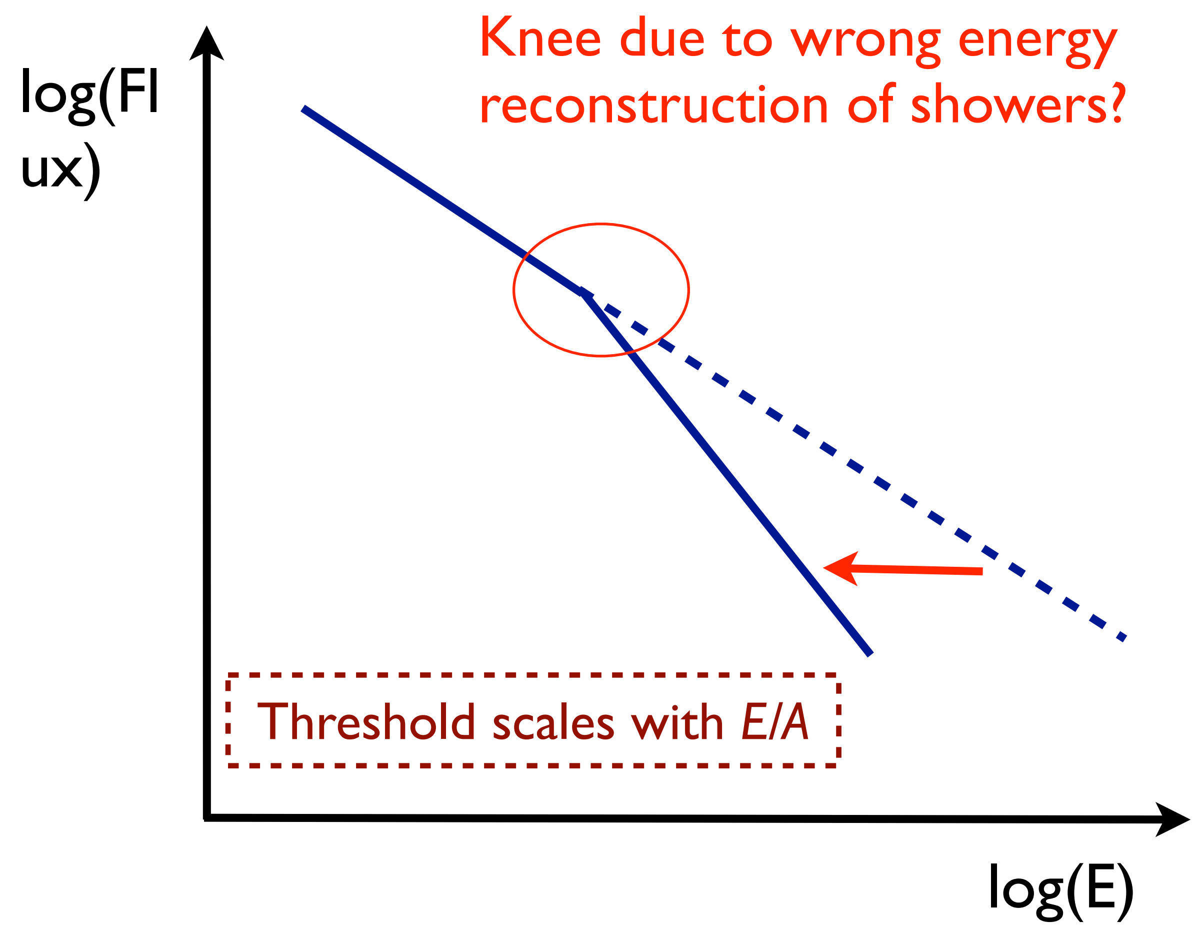
(D'Enterria at al. Astropart Phys 35, 2011)

Exotic models for the knee

Petrukhin, NPB 151 (2006) 57
Barcelo at al. JACP 06 (2009) 027
Dixit et al. EPJC 68 (2010) 573
Petrukhin NPB 212 (2011) 235

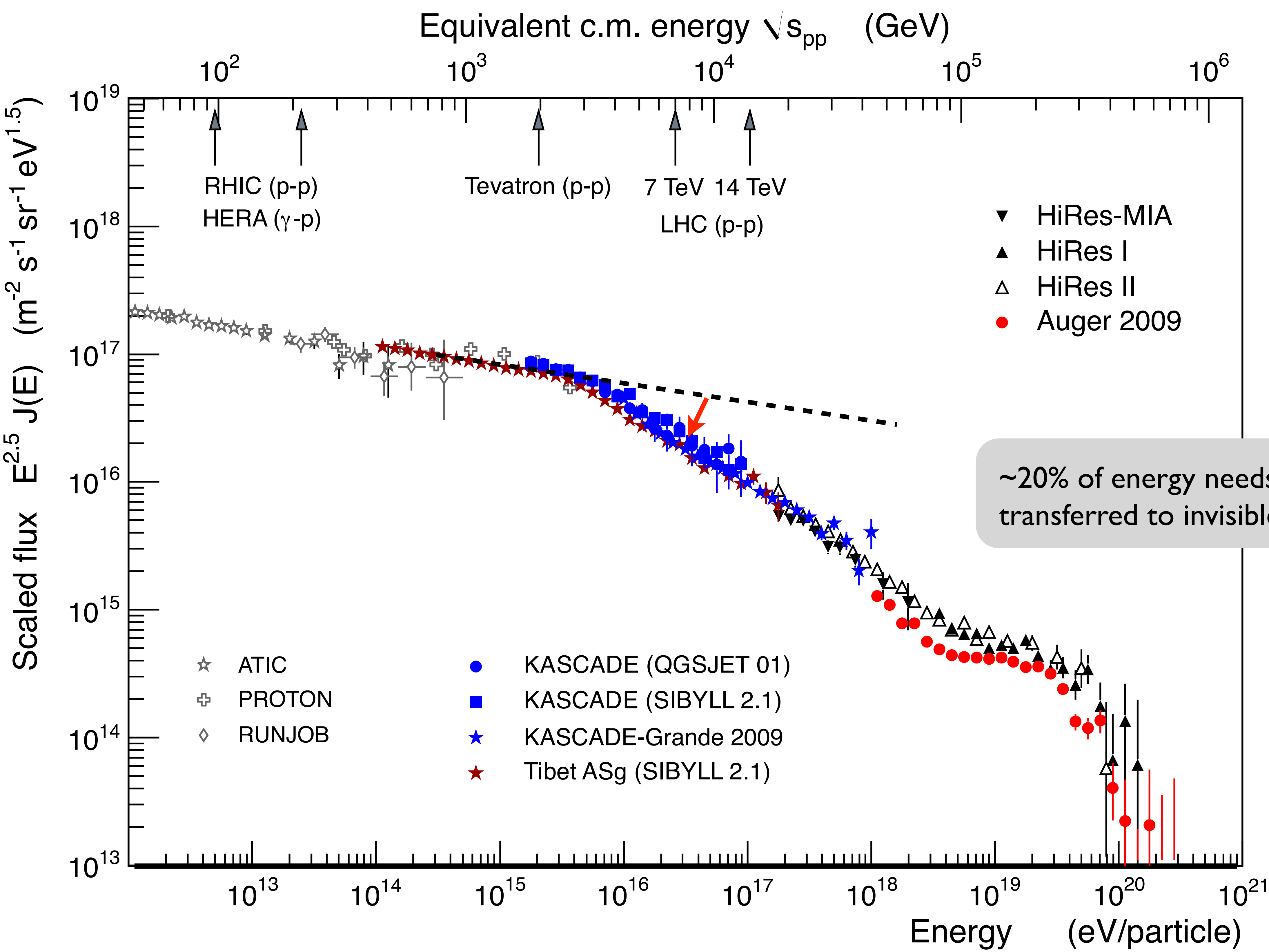






New physics: scaling with nucleon-nucleon cms energy

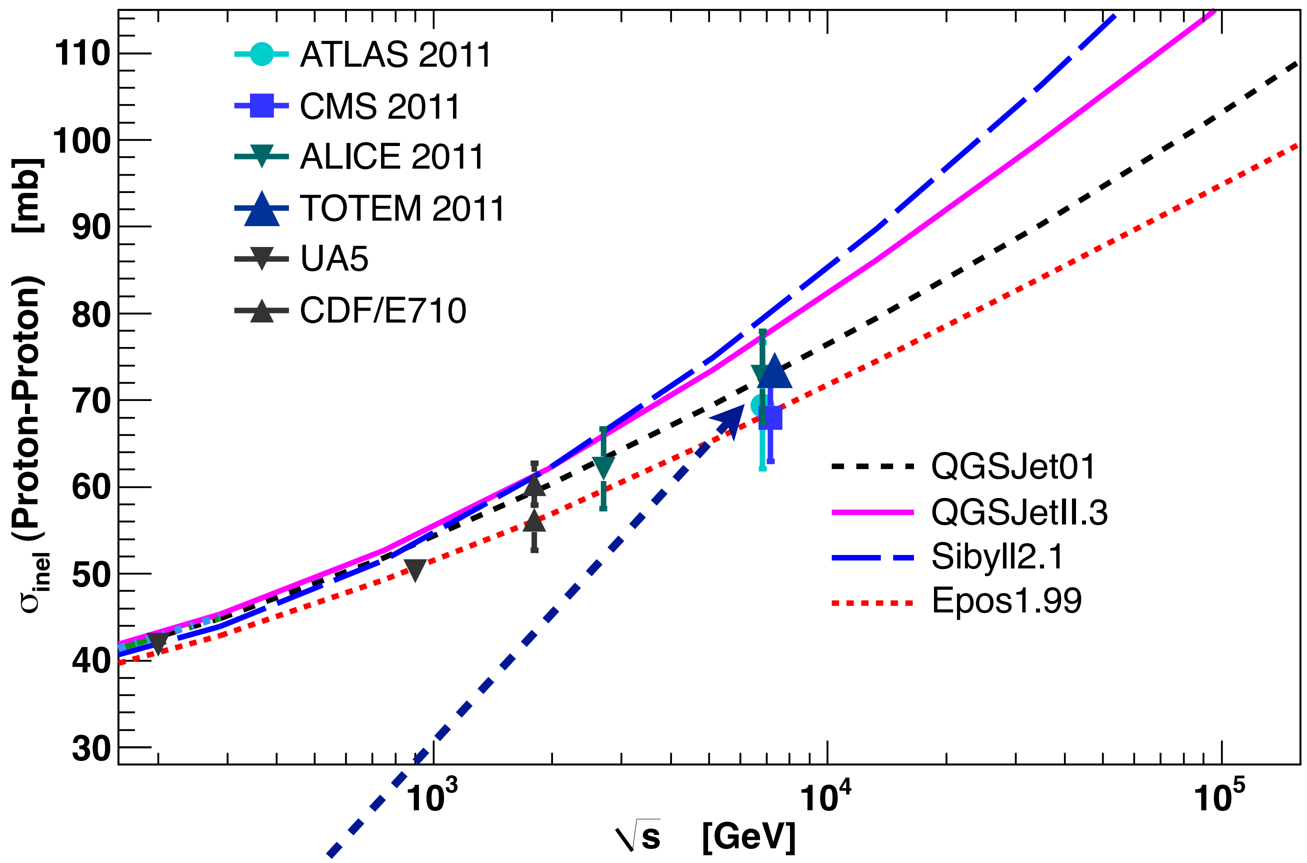
LHC data probe the region beyond the knee

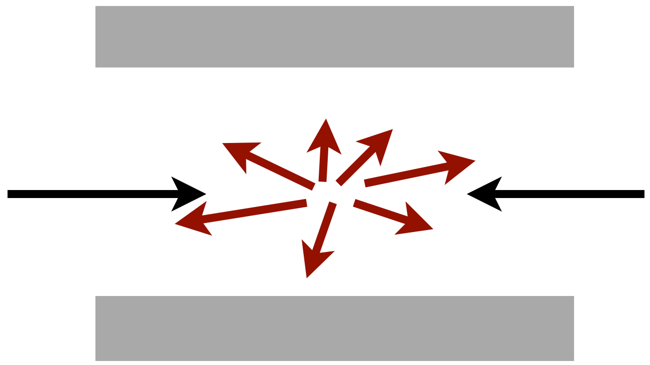


~20% of energy needs to be transferred to invisible channel

Cross section measurements at LHC

Inelastic proton-proton cross section





$$\frac{\Delta p}{p} = \xi > 5 \times 10^{-6}$$

$$\sigma_{\mathrm{ATLAS}} = 60.3 \pm 0.05 \pm 0.5 \pm 2.1\mathrm{mb}$$

$$\sigma_{\mathrm{TOTEM}} = 73.6 \pm 0.6 + 1.8 - 1.3\mathrm{mb}$$

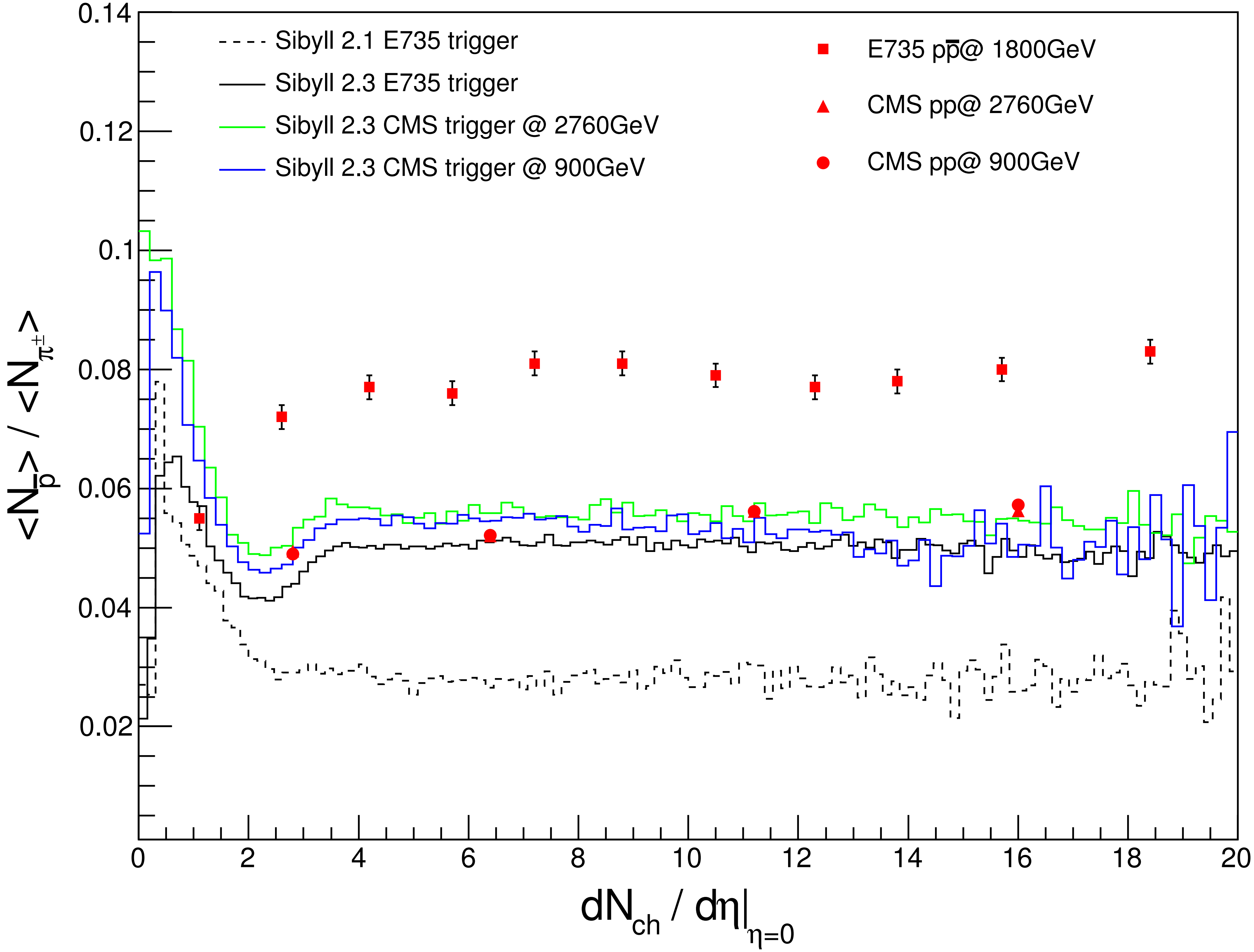
N_{trk} Pt (MeV)	3 200	4 200	3 250	4 250	σ_{tot}
CMS	59.7	58.6	58.9	57.3	
Q-II-03	65.2	64.6	63.0	62.0	77.5
SYBILL-2.1	71.5	71.0	70.2	69.3	79.6

(CMS, DIS Workshop, Brookhaven)

No big surprise given Tevatron measurements, but re-tuning of model cross sections needed

$$\sigma_{\mathrm{ALICE}} = 72.7 \pm 1.1 \pm 5.1\mathrm{mb}$$

LHC data: Baryon production lower than assumed



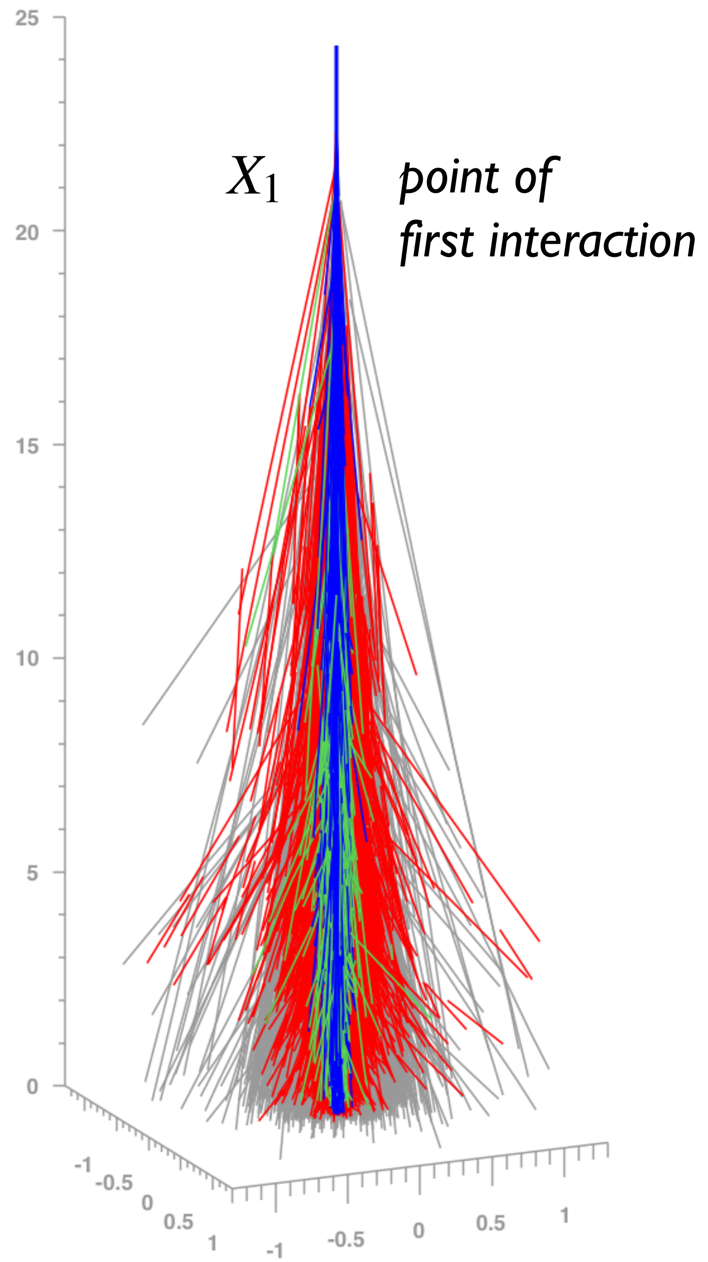
Tevatron E735 (1800 GeV)

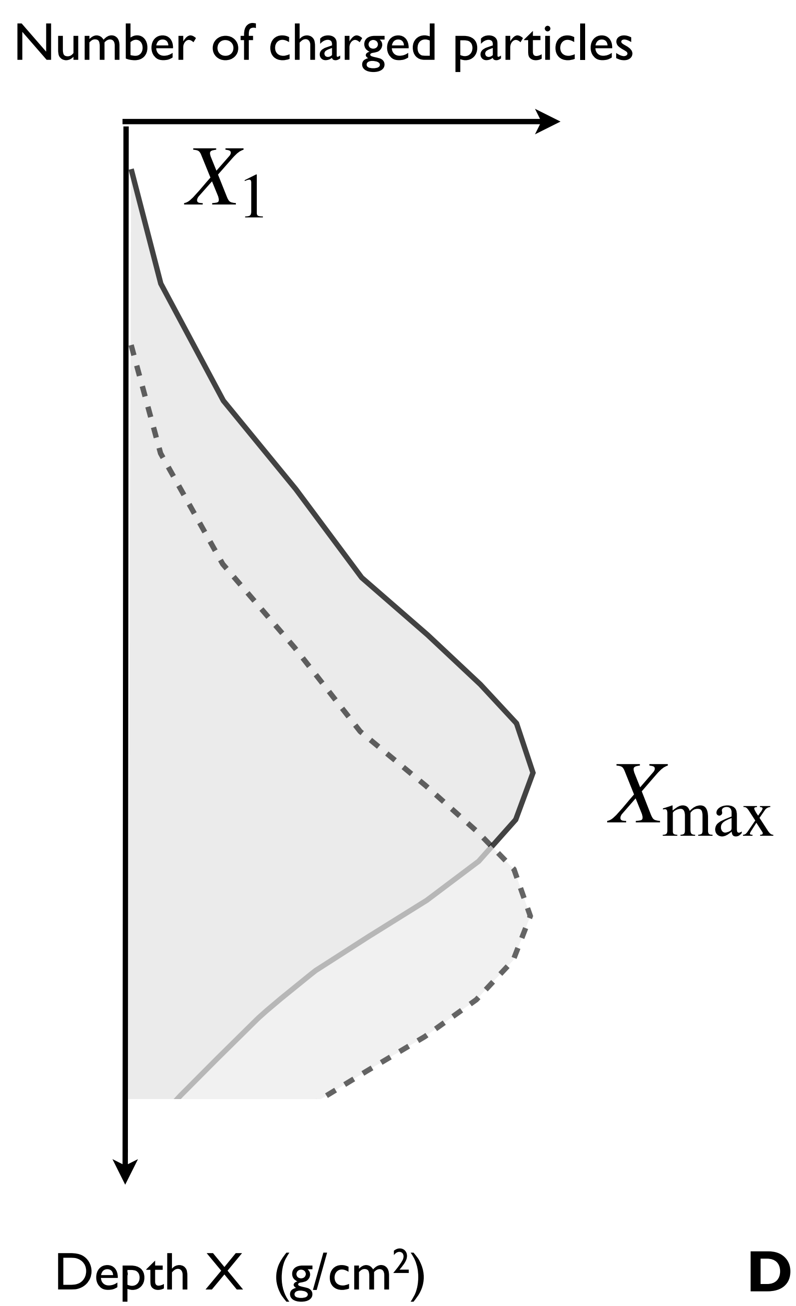
LHC CMS (900, 2760 GeV)

(Riehn et al., 2012)

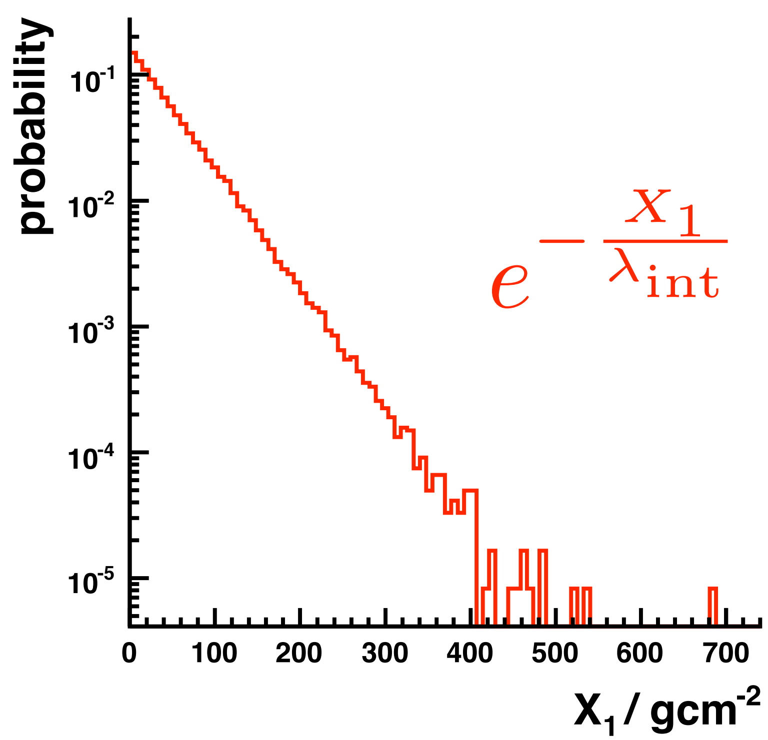
5 What do we learn from air showers

Cross section measurement with air showers





Depth of first interaction



$$\sigma_{\rm prod} = \frac{\langle m_{\rm air} \rangle}{\lambda_{\rm int}}$$

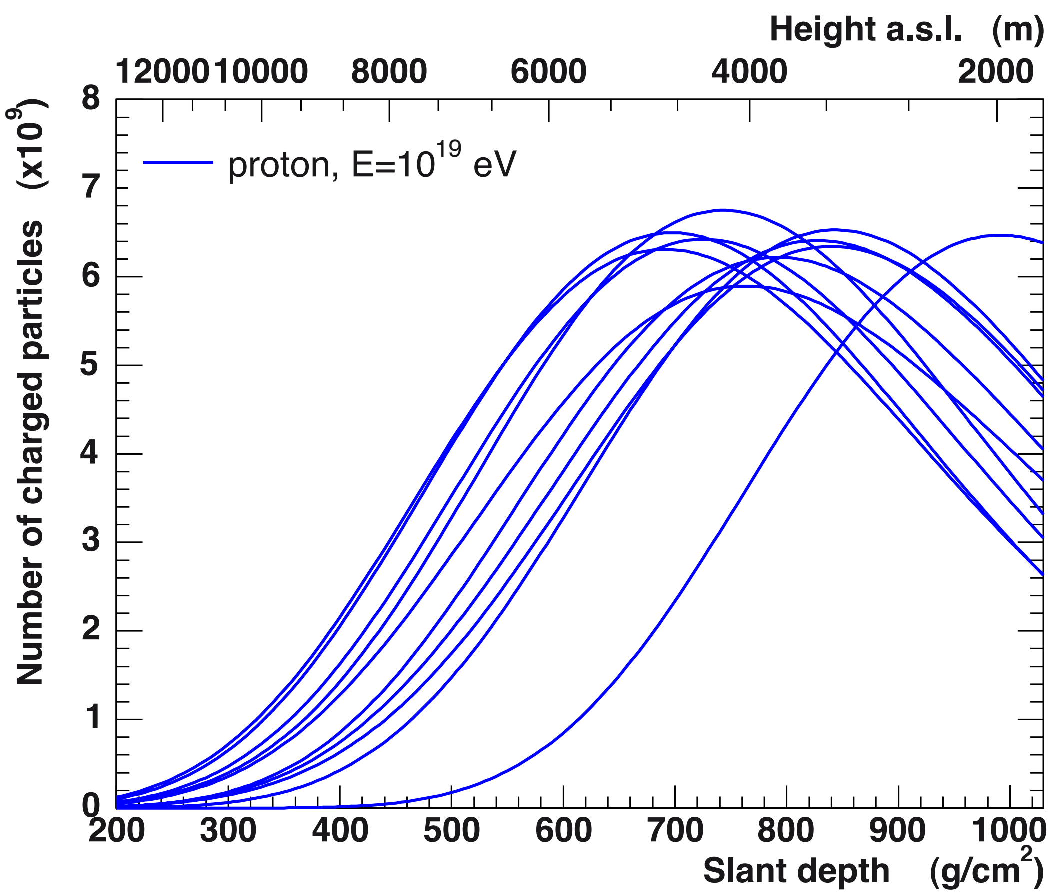
Difficulties

- mass composition (protons?)
- X_1 cannot be measured directly

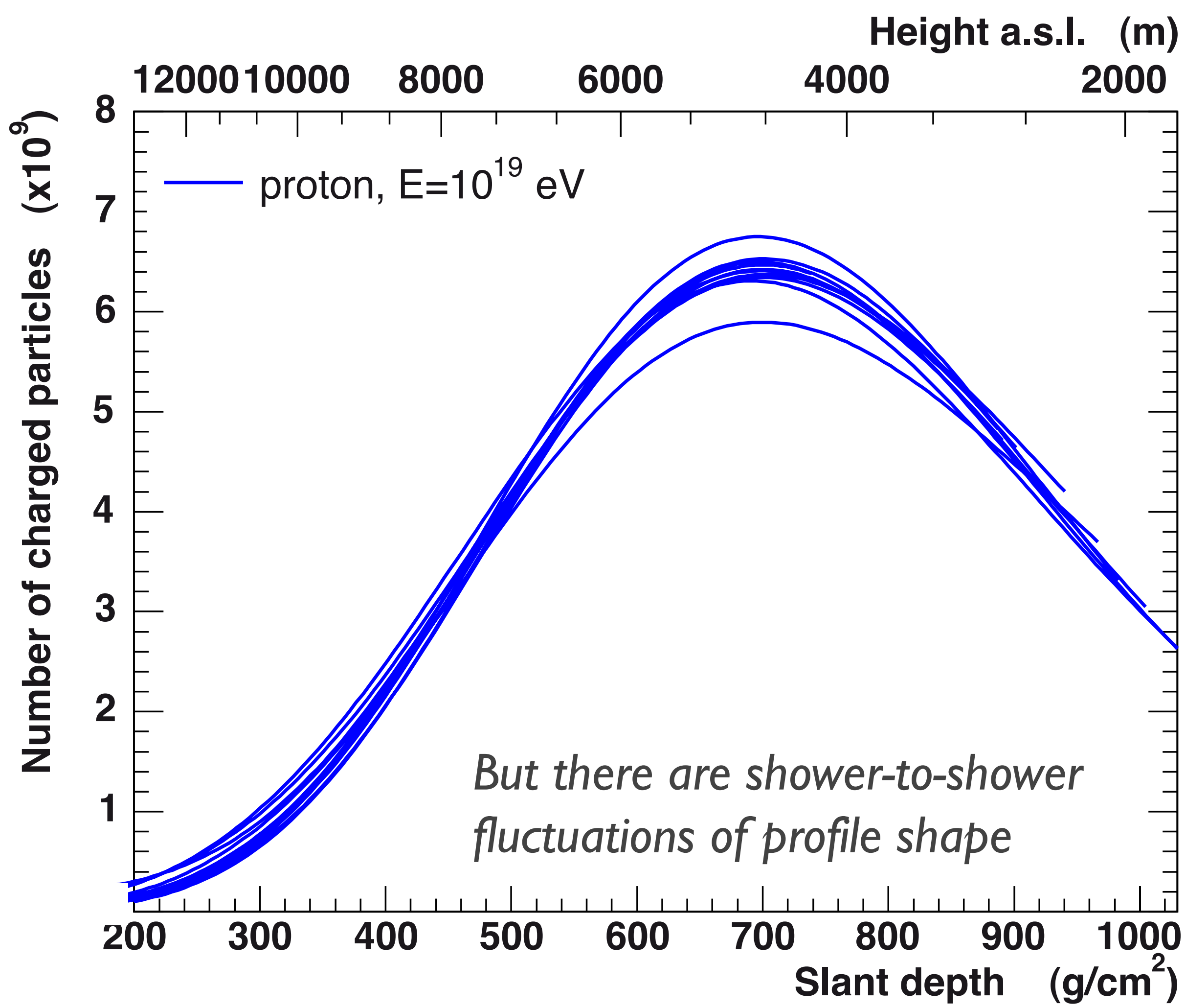
(R. Ulrich et al. NJP 11, 2009, and talk at this meeting)

Universality features of high-energy showers (i)

Simulated shower profiles



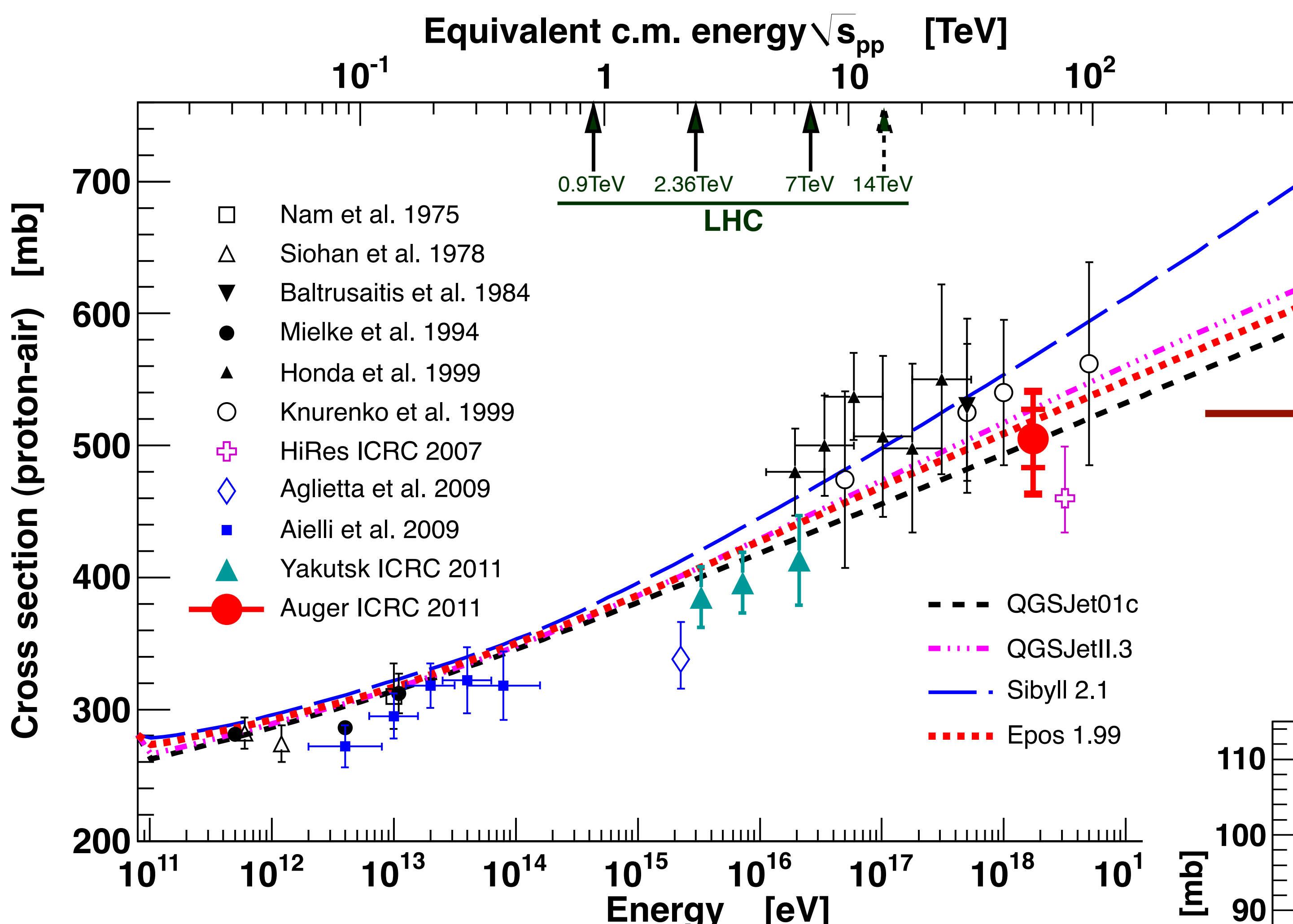
Profiles shifted in depth



Depth of X_l and X_{max} strongly correlated, use X_{max} for analysis

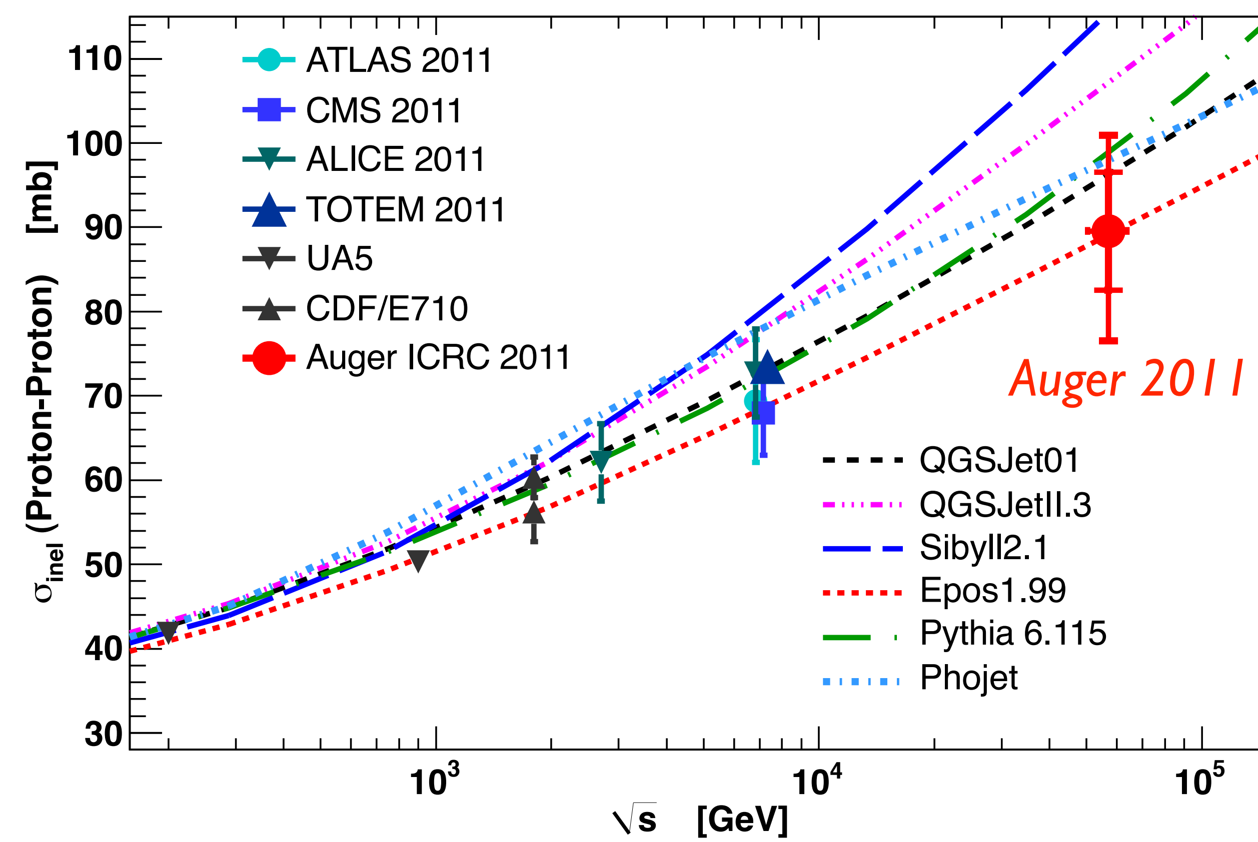
Selection of protons: select very deep showers

High-energy frontier: proton-air cross section



Conversion from p-air to p-p cross section always model-dependent

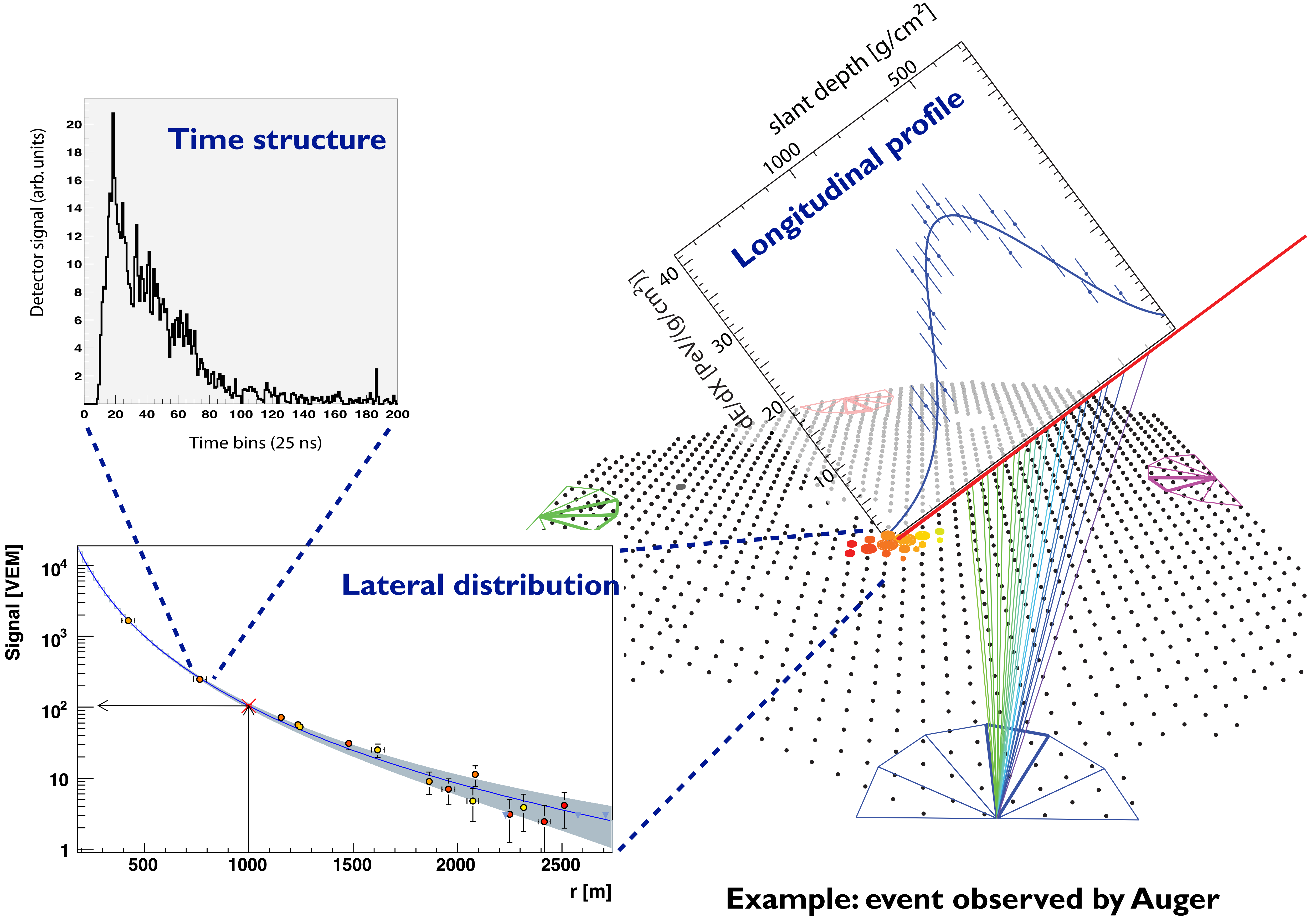
Glauber model



Cross section independent of LHC data, very good agreement with extrapolated data

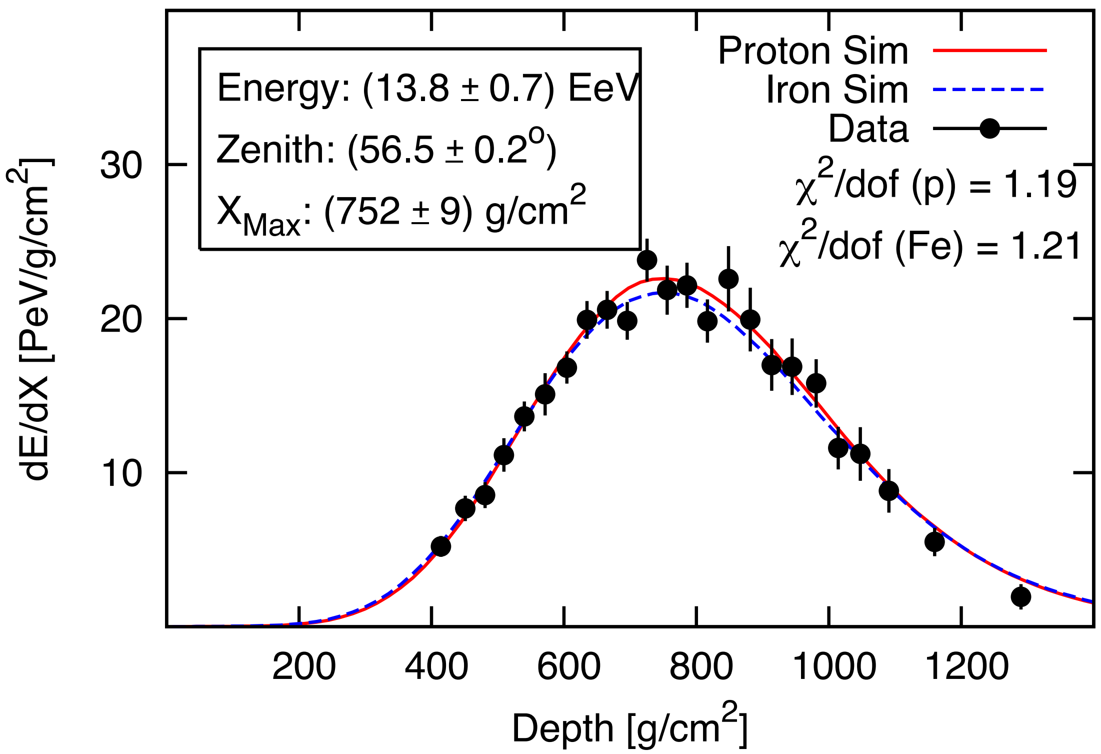
(Pierre Auger Collab. 1107.4804, Phys. Rev. Lett. 2012)

Several shower observables



Example: event observed by Auger

Discrepancy: shower profile and muons at ground

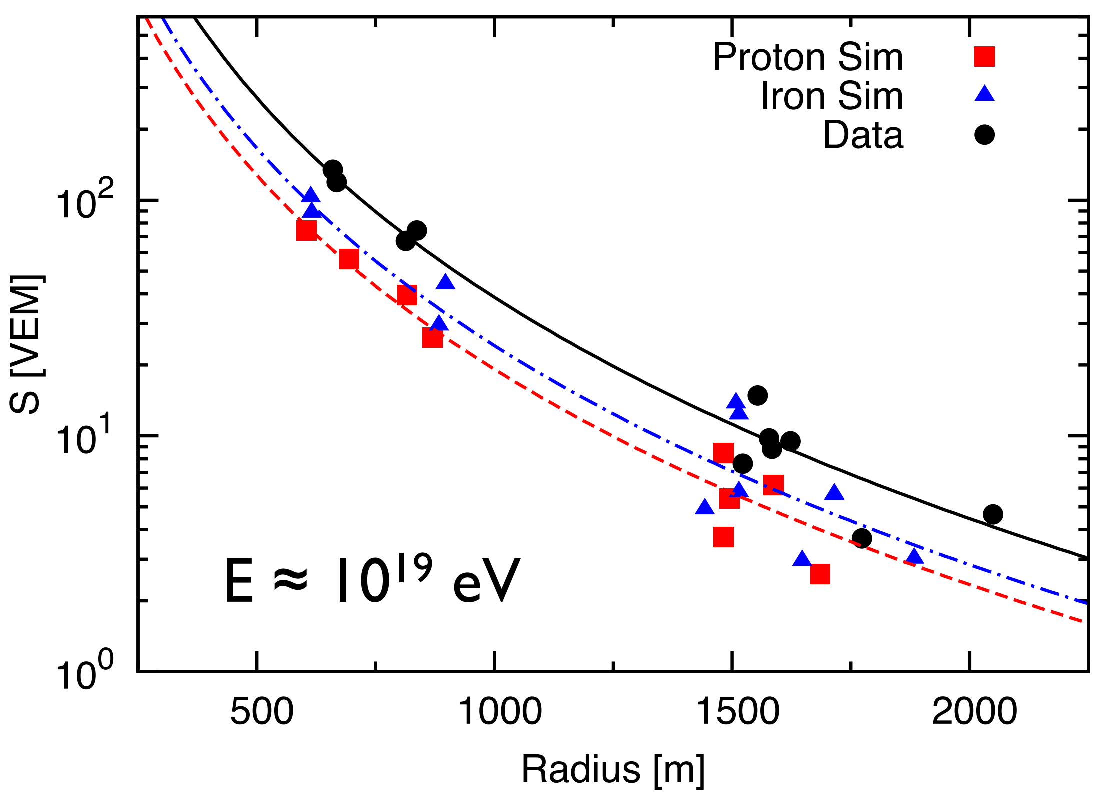


Phenomenological model ansatz

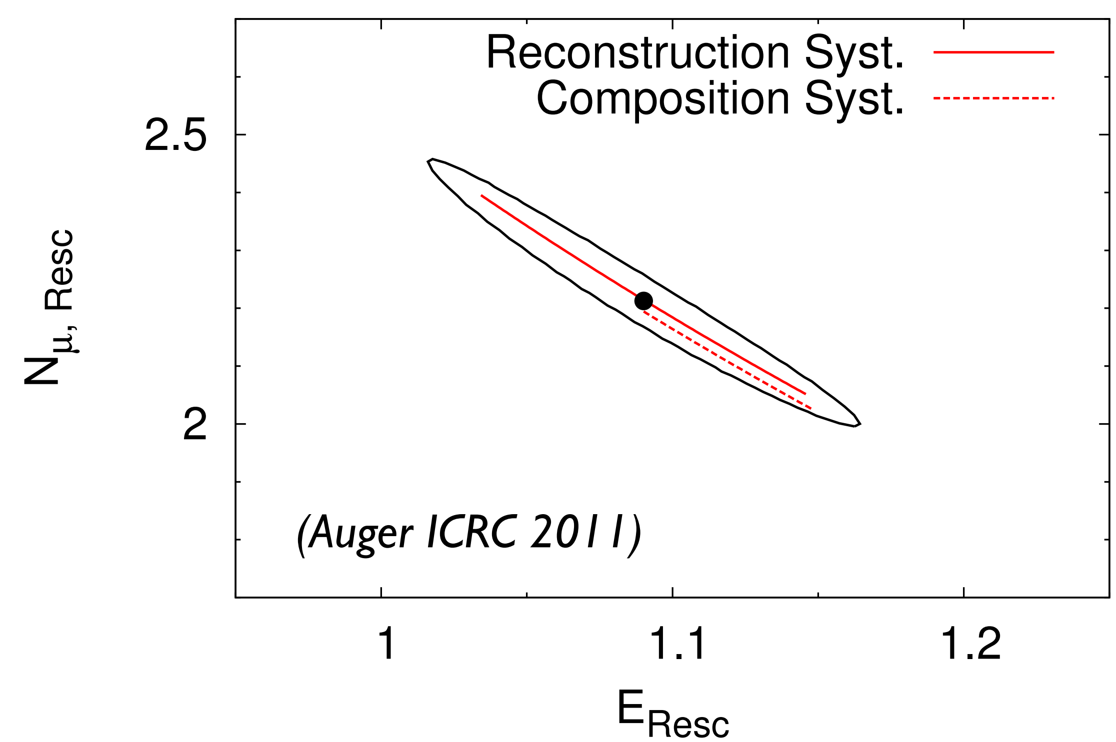
Energy scaling: em. particles and muons

Muon scaling: hadronically produced muons and muon interaction/decay products

Full detector simulation after re-scaling

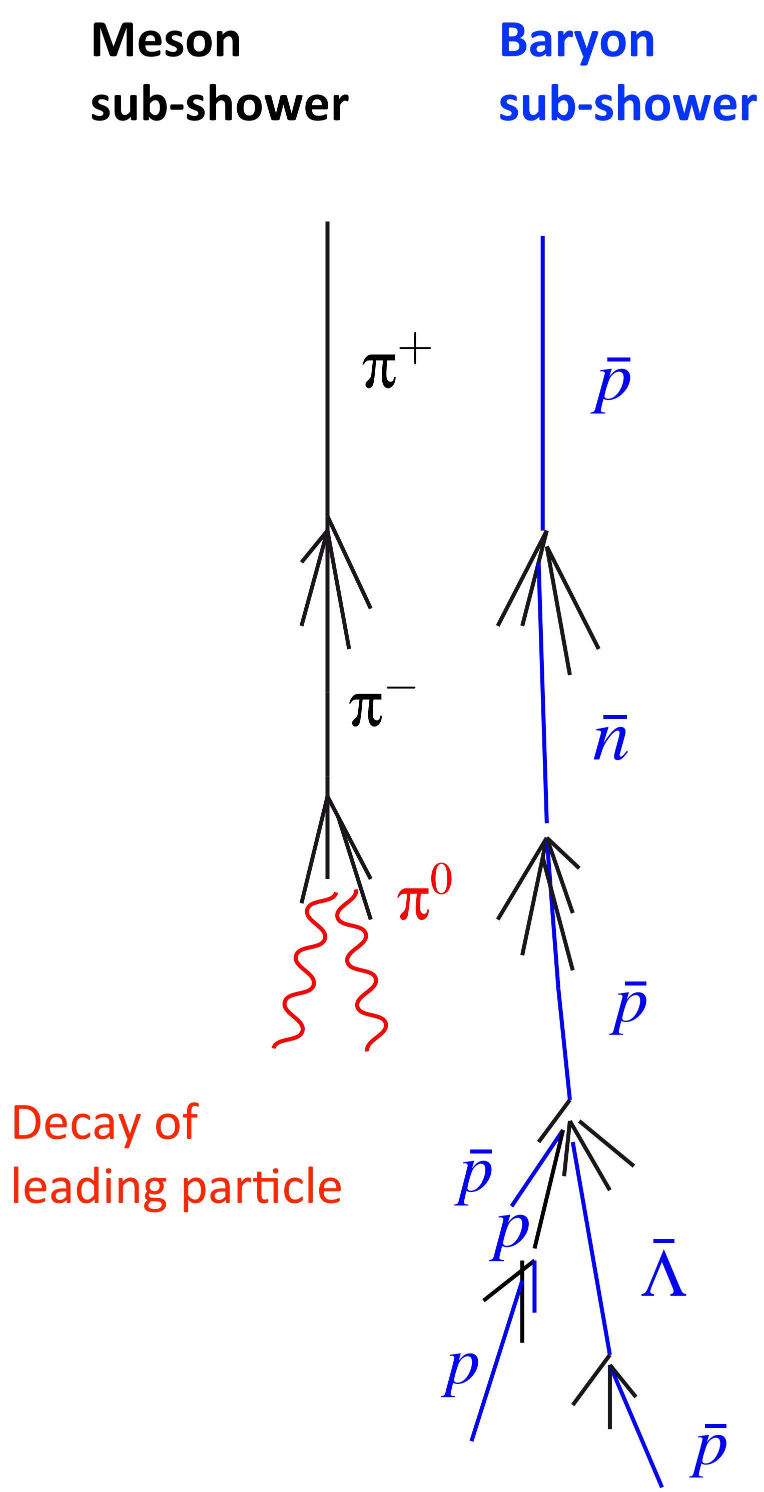


QGSJET II.03 (proton reference)



(Cazon, this meeting)

Enhancement of muon number in air showers



(Pierog, Werner PRL 101, 2008)

1 Baryon-Antibaryon pair production *(Pierog, Werner)*

- Baryon number conservation
- Low-energy particles: large angle to shower axis
- Transverse momentum of baryons higher
- **Enhancement of mainly low-energy muons**

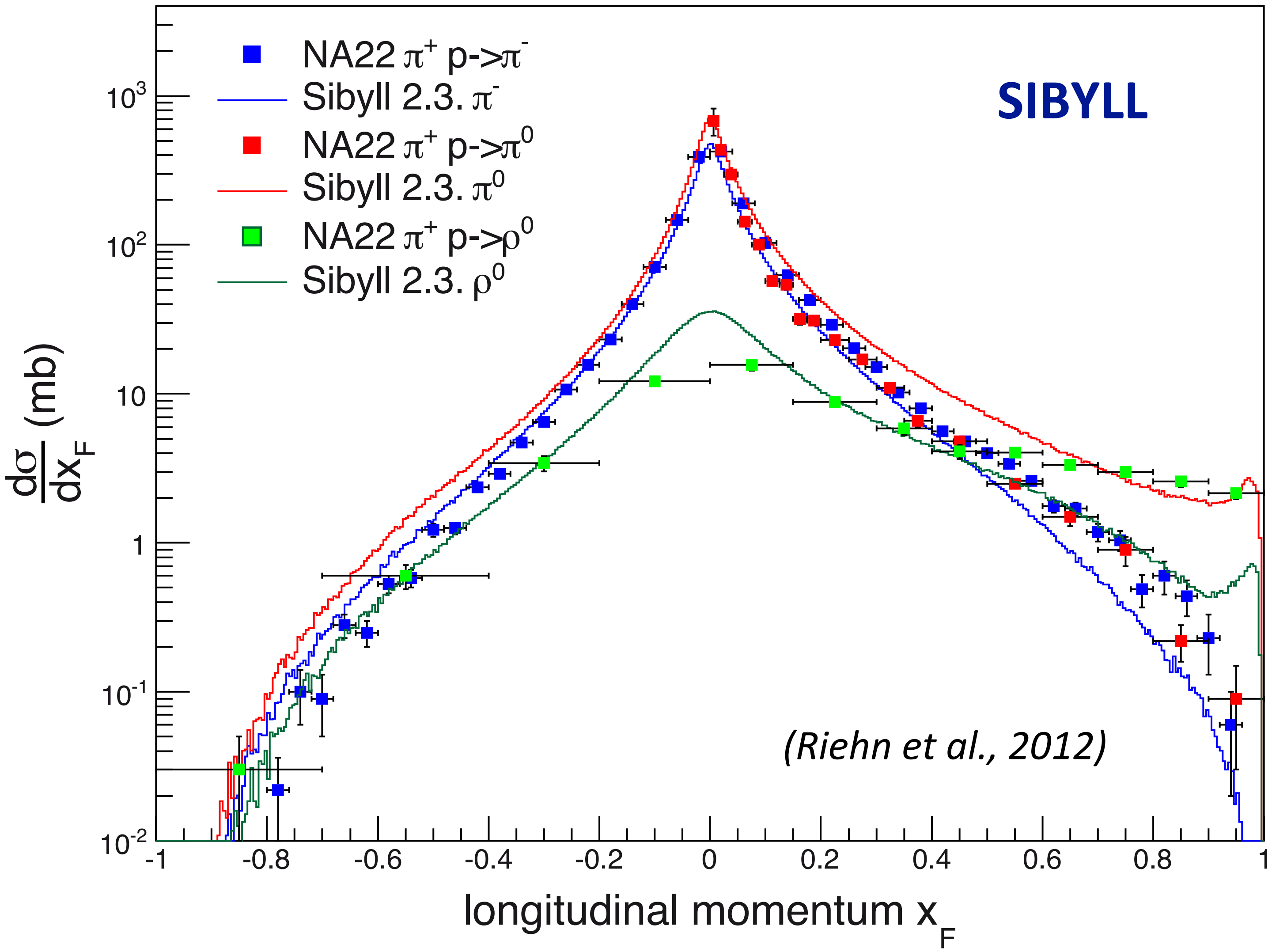
2 Leading particle effect for pions *(Drescher, Ostapchenko)*

- Leading particle for a π could be ρ^0 and not π^0
- Decay of ρ^0 almost 100% into two charged pions

3 Chiral symmetry restoration *(Farrar, Allen)*

- **Proton primaries, applies above energy threshold**
- Pion production suppressed relative to baryons
- Large inelasticity of the events
- Faster increase of total cross section (reduction of fluctuations)

Leading particle for π-air interactions

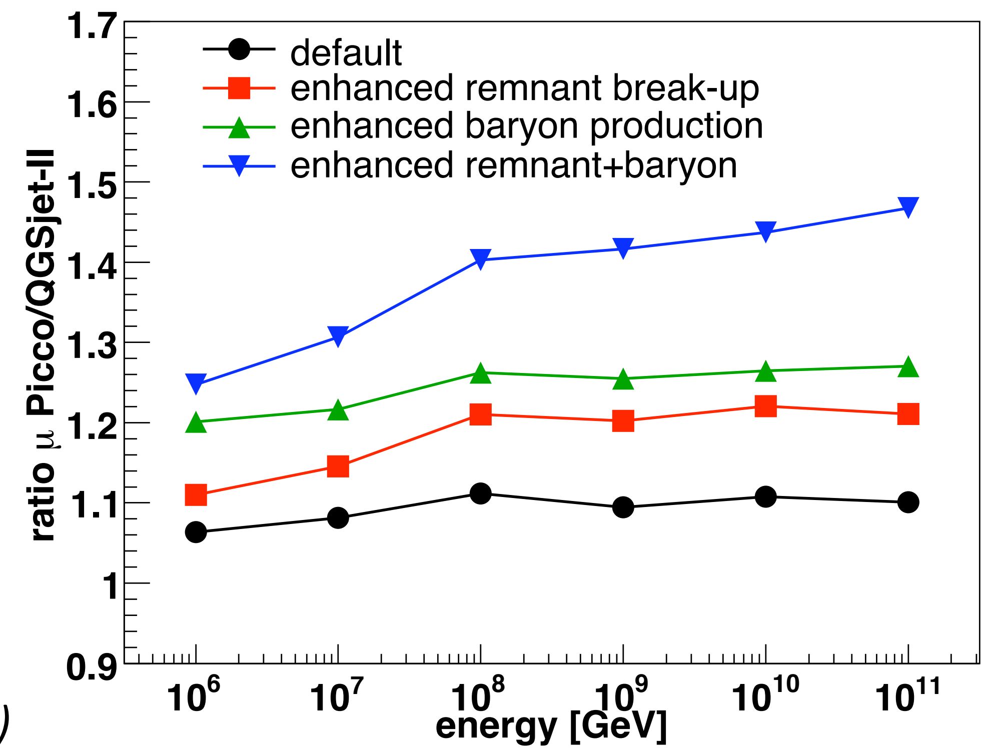


Fixed-target data: NA22
at 250 GeV (22 GeV c.m.s.)

$\rho^0 \longrightarrow \pi^+ \pi^-$

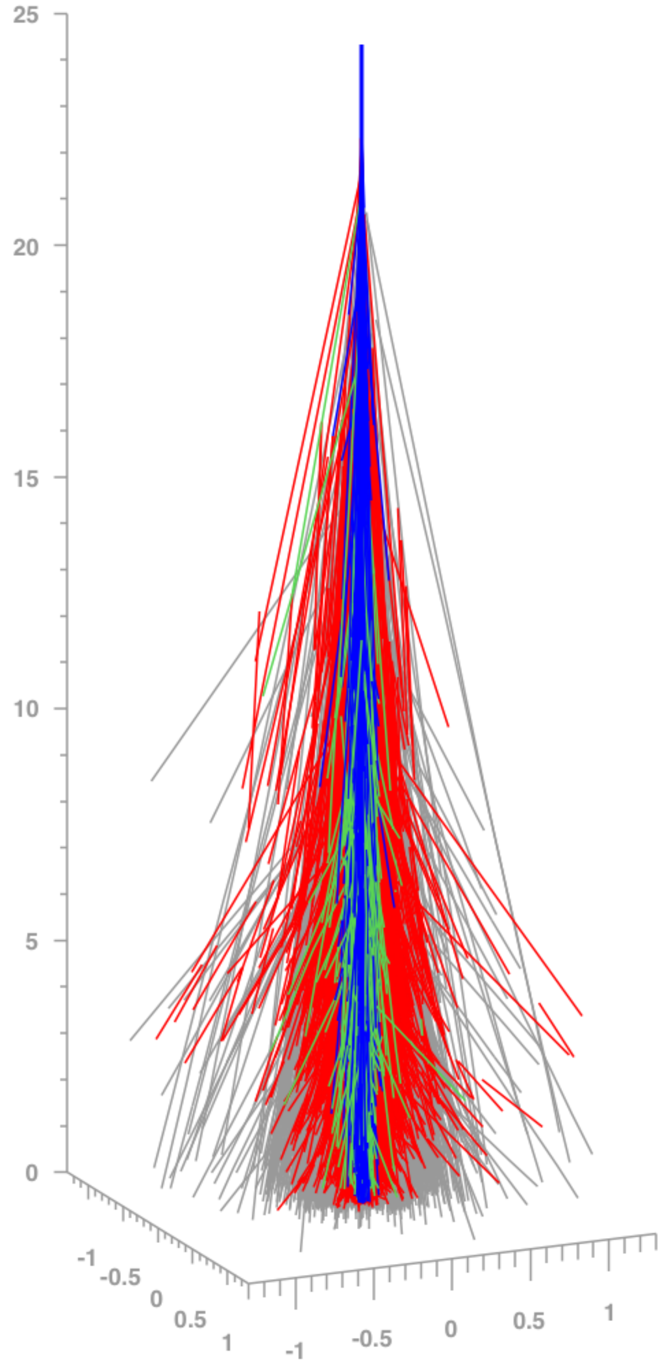
$\pi^0 \longrightarrow \gamma \gamma$

More work needed to clarify situation

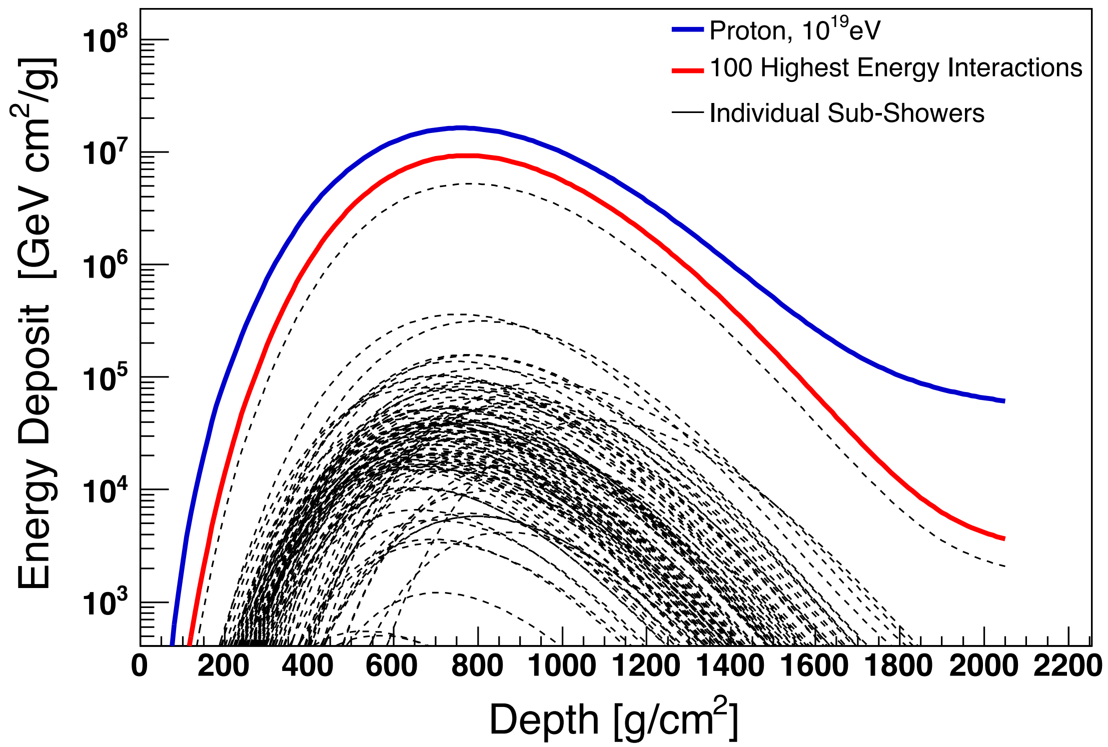


(Drescher Phys. Rev. D77, 2008)

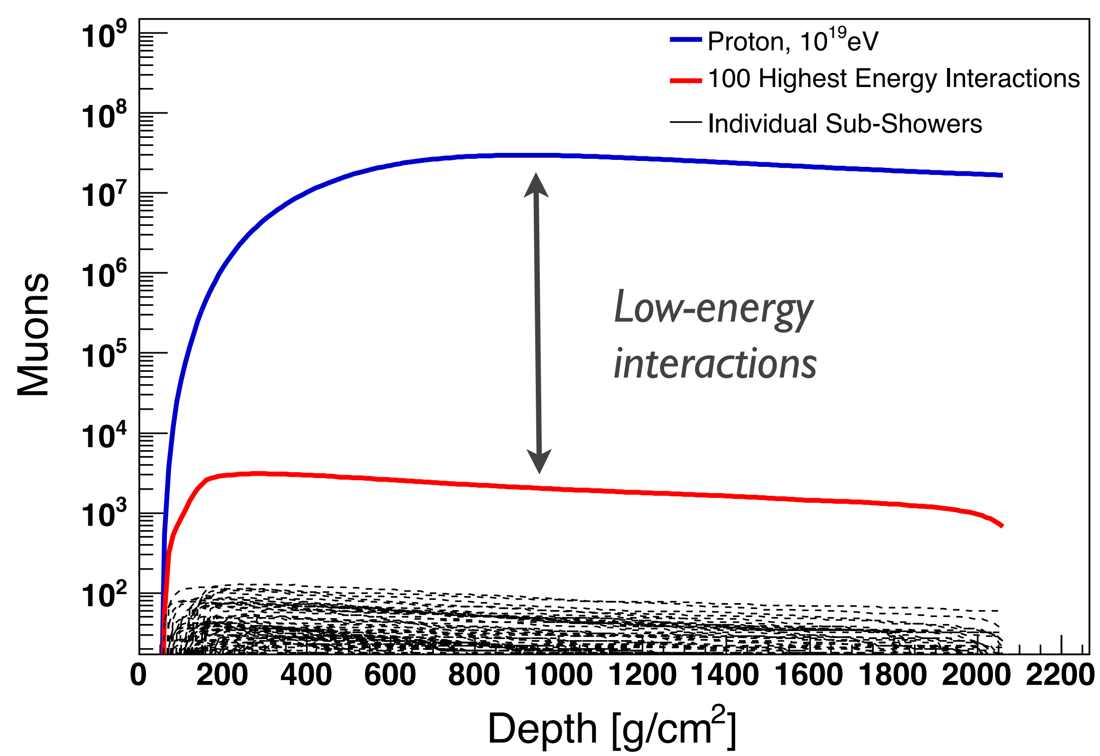
Summary of role of hadronic interactions



Electrons



Muons



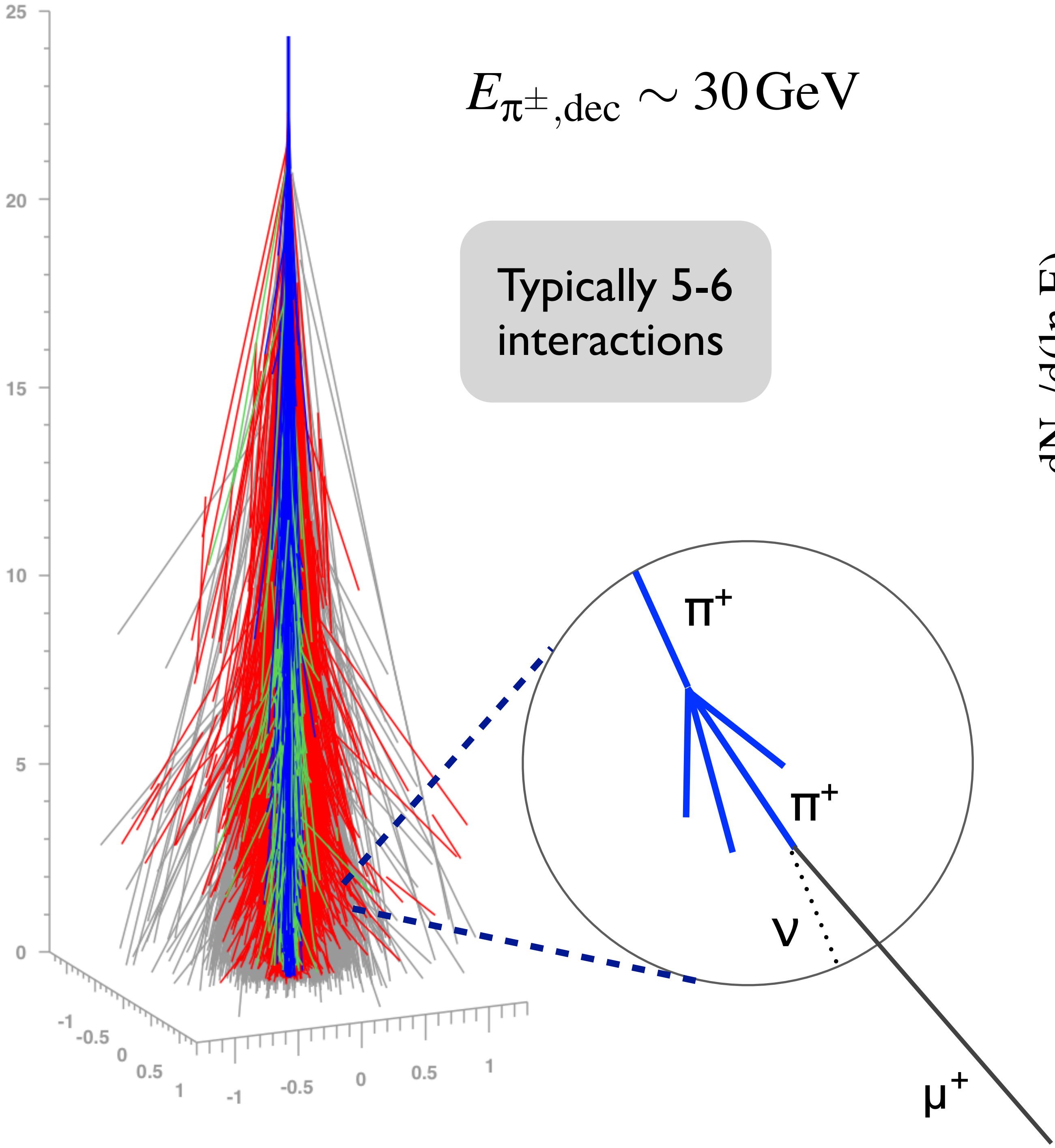
Shower particles produced in 100 interactions of highest energy

Electrons/photons: high-energy interactions

Muons/hadrons: low-energy interactions

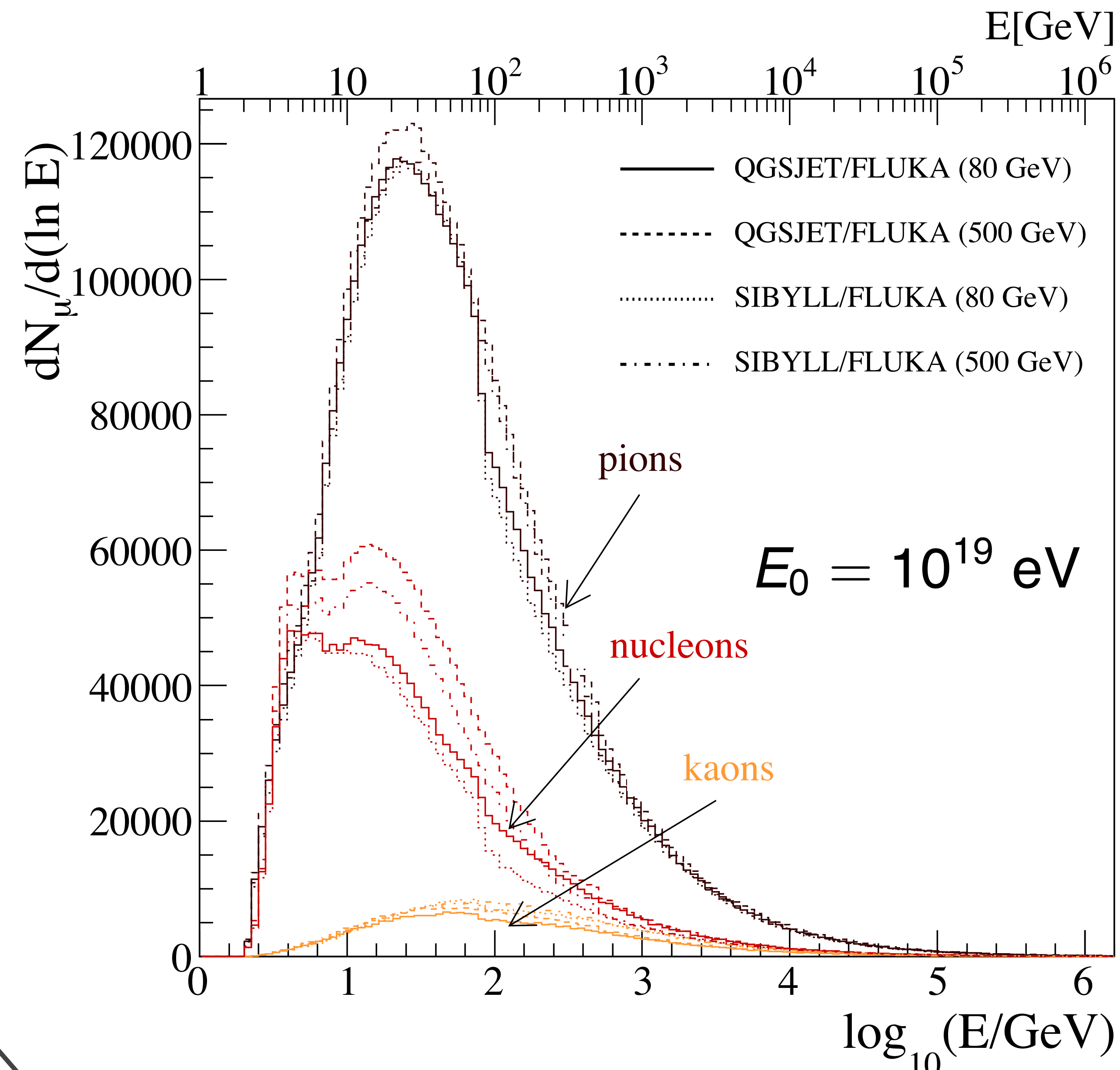
(Ralf Ulrich, 2012)

Muon production at large lateral distance



Muon observed at 1000 m from core

Energy distribution of last interaction that produced a detected muon



(Maris et al. ICRC 2009)