# Hadronic Interaction Models & Cosmic Ray Composition

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*"Avoid models as much as you can!"*

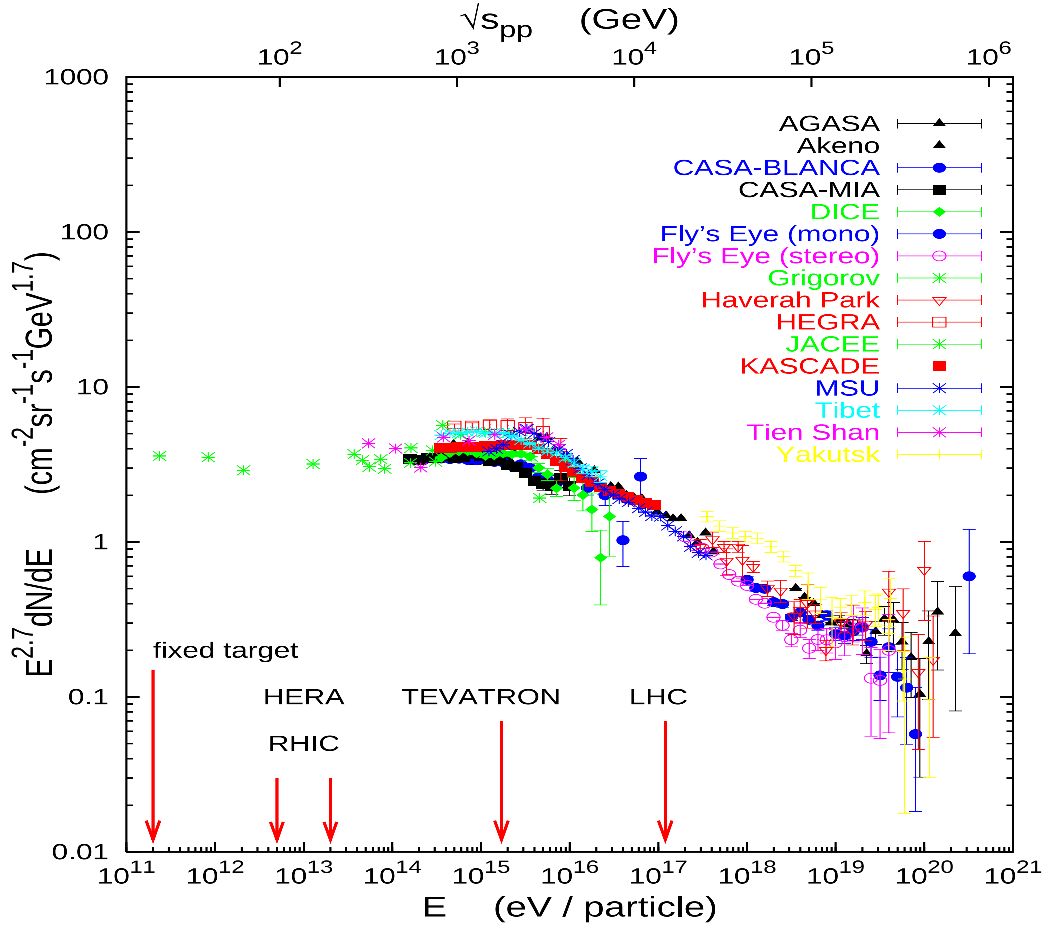
*"Important issues are INPUT OF REAL DATA ..."*

A. Watson

# Layout

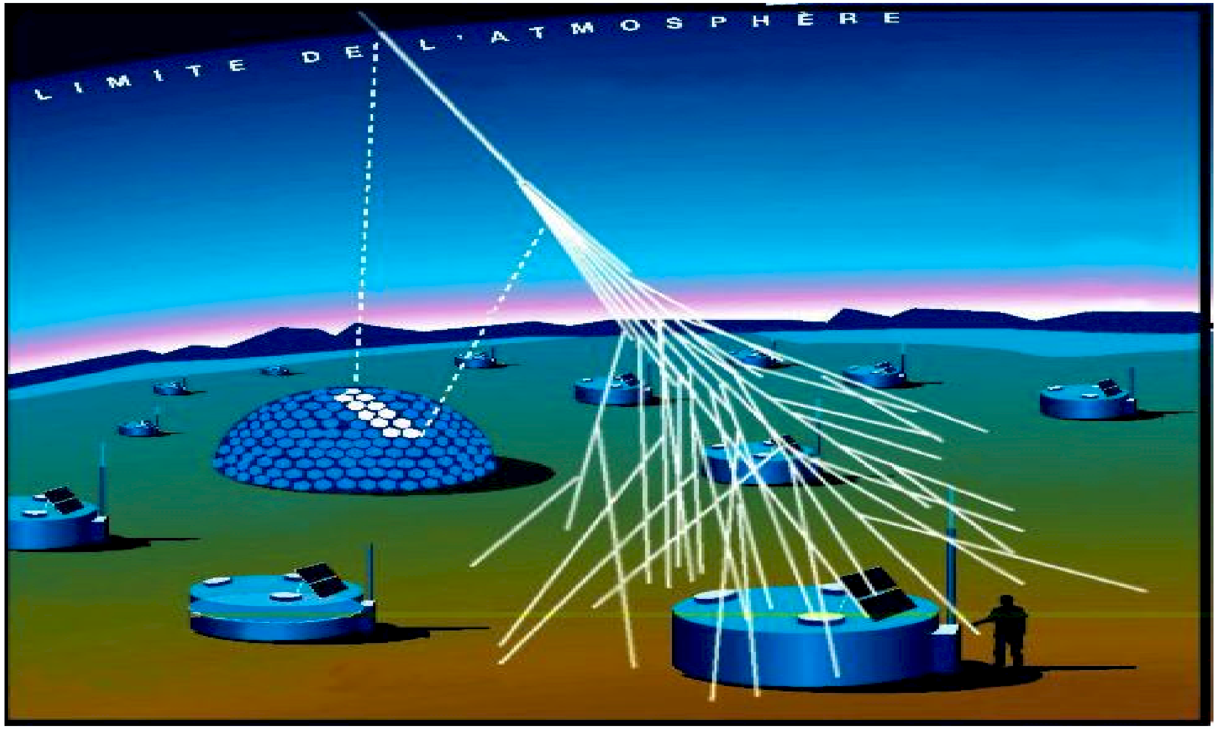
- EAS techniques & models of hadronic interactions
- High energy interactions: basic scheme
  - qualitative picture
  - 'elementary' interaction
  - multiple scattering approach
  - non-linear effects
- CR composition
  - 'knee' region & composition studies by KASCADE
  - transition to very high energies & KASCADE-Grande
  - UHECR: HiRes & Pierre Auger
- Potential changes?

In CR applications models are probed far beyond accelerator range




$\Rightarrow$ allows to test model consistency at higher energies & different kinematics

# EAS technique of UHECR detection




- ground observations (using the atmosphere as the target)
  - primary energy $\Longleftrightarrow$ charged particle density at ground
  - CR composition $\Longleftrightarrow$ muon density at ground
- measurements of fluorescence light
  - primary energy $\Longleftrightarrow$ integrated light
  - CR composition $\Longleftrightarrow$ shower maximum position $X_{\max}$

Data analysis requires good understanding of air shower development

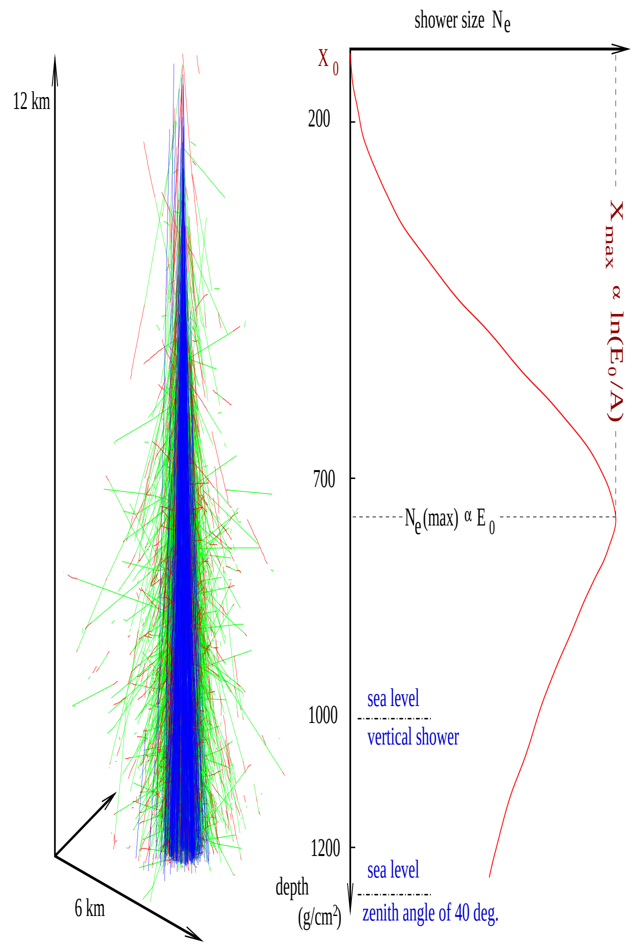
- backbone - hadron cascade
- $\Rightarrow$ interaction models important

Requirements to CR interaction models:

- cross section predictions
- description of general hA (AA) collisions
- importance of "forward" region
- predictive power (no re-tuning possibilities)

But:

- low sensitivity to "fine" details
  (smoothed by EAS development)
- charm, ..., new rare processes - irrelevant:
  - small inclusive cross sections
  - produced mainly at central rapidities




$\Rightarrow$ CR interaction models $\equiv$ models of "typical" (mb level) interactions

Example models:

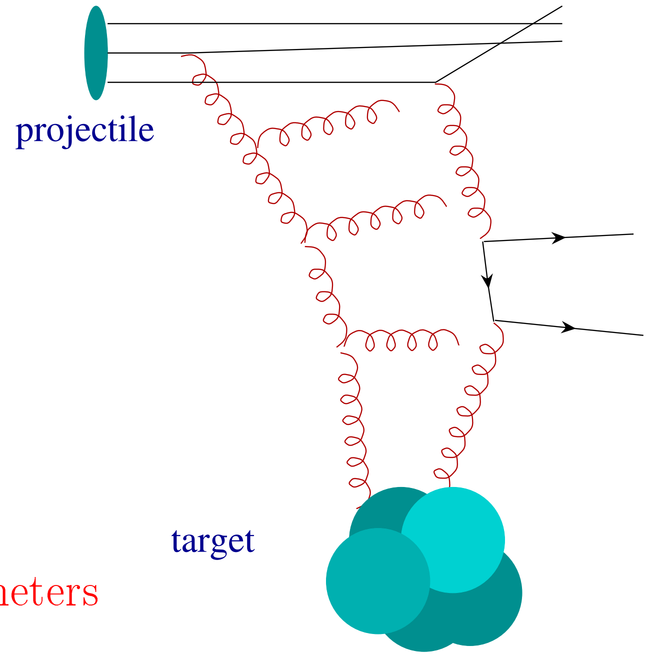
- SIBYLL 2.1 (Engel, Gaisser, Lipary & Stanev): CR analog of PITHYA
- QGSJET / QGSJET-II (Kalmykov & SO / SO): based on QGS model (Kaidalov & Ter-Martyrosian, 1982) approach; Pomeron-Pomeron interactions
- EPOS (Pierog & Werner): separate treatment of 'dense' (central 'core') and 'dilute' (peripheral 'corona') interaction regions; parameterized treatment of saturation

## High energy interactions: qualitative picture

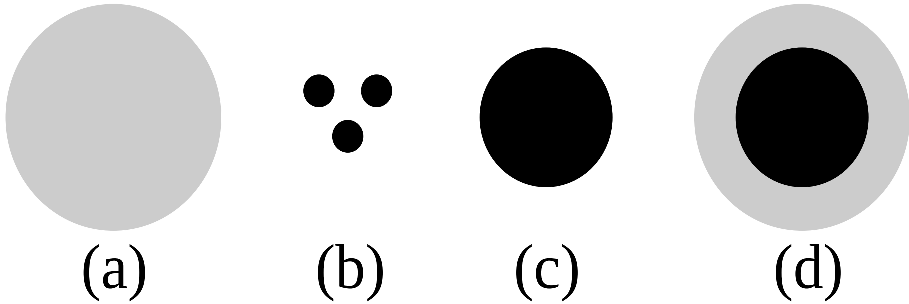
Hadronic interactions - multiple scattering processes (parton cascades):

Single scattering:

- (a) 'soft' (all $|q^2| \sim p_t^2 < Q_0^2$, $Q_0 \sim 1$ GeV$^2$) cascade
  - large effective area ($\Delta b^2 \sim 1/|q^2|$)
  - slow energy rise
  
  $\Rightarrow$ dominant at relatively low energies
- (b) cascade of 'hard' partons (all $|q^2| \gg Q_0^2$)
  - small effective area
  - rapid energy rise
  
  $\Rightarrow$ important at very high energies and small impact parameters
- (c) 'semi-hard' scattering (some $|q^2| > Q_0^2$)
  - large effective area
  - rapid energy rise
  
  $\Rightarrow$ dominates at high energies and over a wide $b$-range




*(picture from R. Engel)*



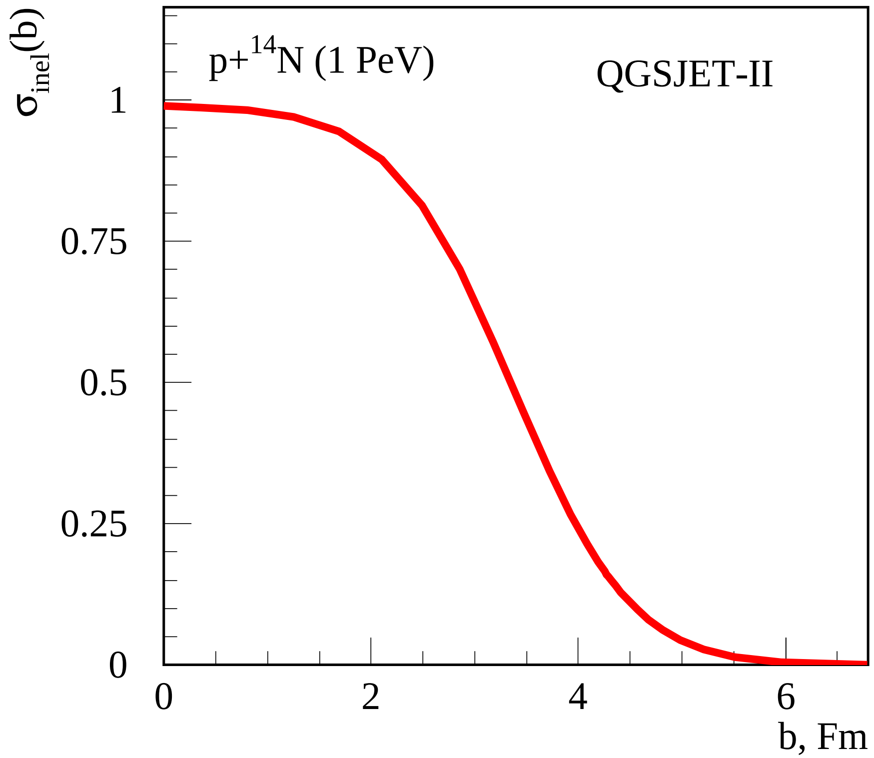
## 'Central' & peripheral collisions:

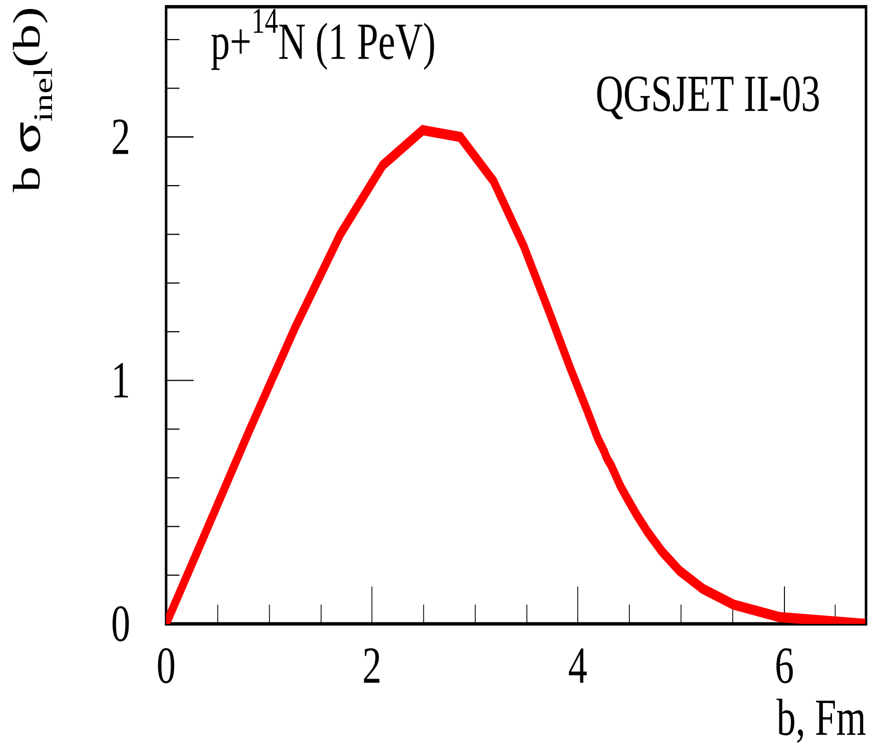
**relative importance for $N_{h-\mathrm{air}}^{\mathrm{ch}}$?**

What is 'central'?

- 'black disc' limit: $\sigma^{\mathrm{inel}}(b) \sim 1 \Rightarrow \sigma^{\mathrm{el}}/\sigma^{\mathrm{tot}} \simeq 1/2$
- experiment: $\sigma_{pp}^{\mathrm{el}}/\sigma_{pp}^{\mathrm{tot}} \simeq 1/4$ @ $\sqrt{s} = 1.8$ TeV

Interaction profile & $b$-contributions to $\sigma_{p-\mathrm{air}}^{\mathrm{inel}}$ @ $E_0 = 10^6$ GeV:



# 'Elementary' interaction

General model strategy:

- describe 'elementary' interactions (parton cascades)
  - scattering amplitude
  - hadronization procedure (conversion of partons into hadrons)

- apply Reggeon approach to treat multiple scattering processes

- describe particle production as a superposition of a number of 'elementary' processes

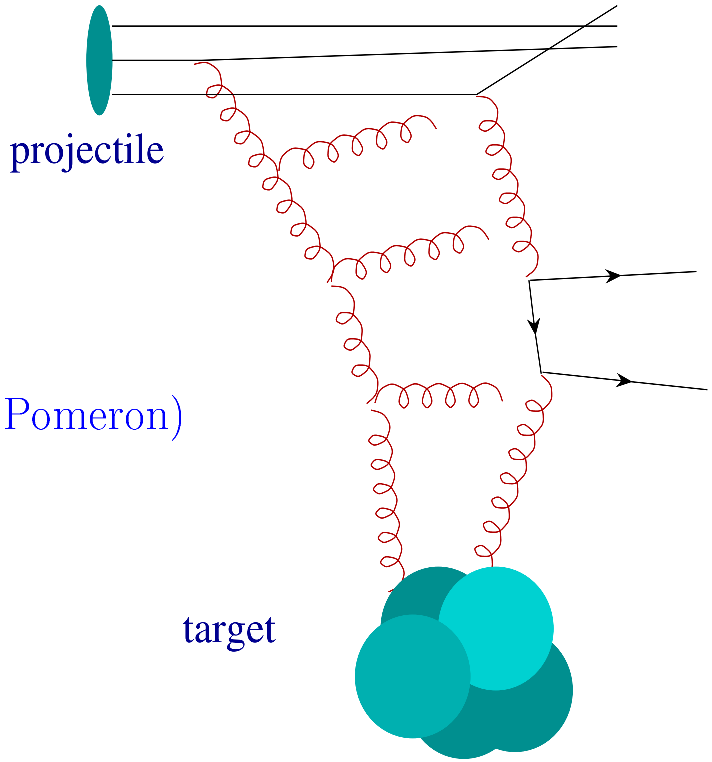
Parton cascades start at low virtualities

For example (QGSJET, neXus, EPOS):

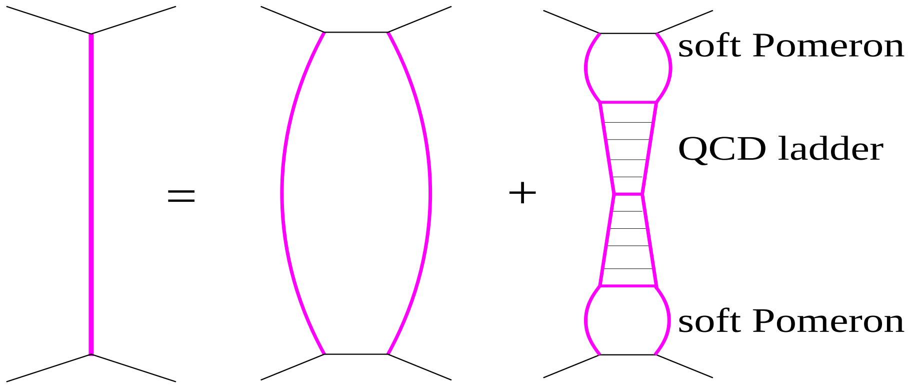
- $Q_0^2$ - cutoff between 'soft' and perturbative physics

- 'Soft' interactions (all $\left|q^2\right|$ - small $\Rightarrow \alpha_s(q^2) > 1$):
  - pQCD is inapplicable $\Rightarrow$ Regge pole amplitude ('soft' Pomeron)

- 'Semi-hard' processes ($|q^2| > Q_0^2 \Rightarrow \alpha_s(q^2) \ll 1$)
  - 'soft' Pomeron for $\left|p_t^2\right| < Q_0^2$
  - QCD parton ladder for $\left|p_t^2\right| > Q_0^2$



General interaction ⇒ 'general Pomeron':




- particle production: perturbative (=calculable) parton cascade + string hadronization

'Minijet' scheme (e.g., SIBYLL) - similar but without 'soft pre-evolution' ⇒ smaller $K_{\rm inel}$, $\langle N_{\rm ch}\rangle$

Important: direct relation between the eikonal and inclusive jet cross section

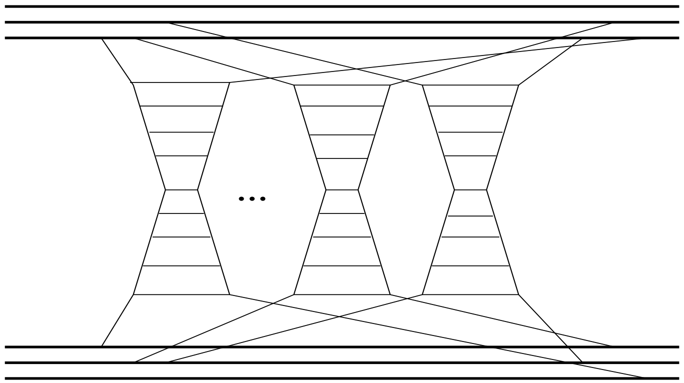
$$2\int d^2b\, \chi_{ad}^{\mathbb{P}_{\rm sh}}(s,b) \;\equiv\; \sigma_{ad}^{\rm jet}(s,Q_0^2)$$

$$\sigma_{ad}^{\rm jet}(s,Q_0^2) \;=\; \sum_{I,J=q,\bar q,g} \int_{p_t^2>Q_0^2} dp_t^2 \int dx^+ dx^- \,\frac{d\sigma_{IJ}^{2\to 2}(x^+x^-s,p_t^2)}{dp_t^2} \times f_{I/a}(x^+,M_F^2)\, f_{J/d}(x^-,M_F^2)$$

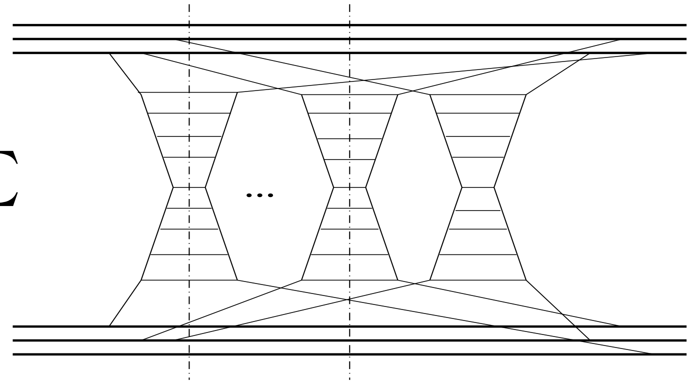
## Reggeon calculus (Gribov, 1968)

General interaction - superposition of many 'elementary' processes:

$\sigma_{ad}^{\rm tot} = \quad {\rm Im}$

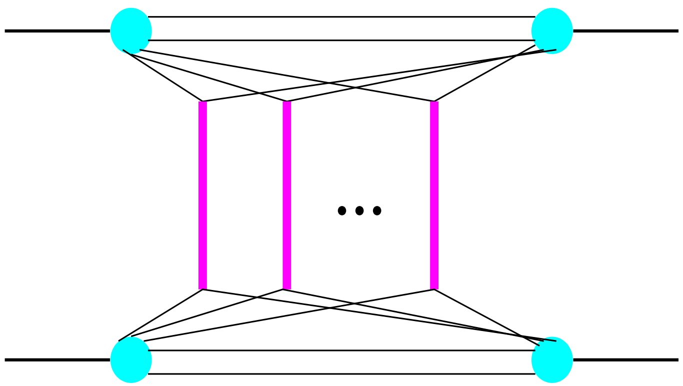


$= \sum$

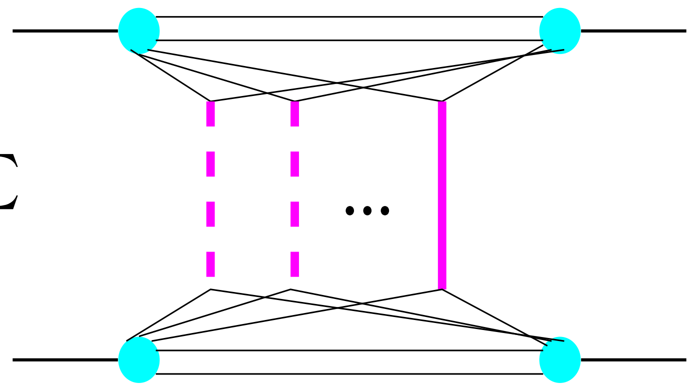


Or (Abramovskii-Gribov-Kancheli cutting rules)

$\sigma_{ad}^{\rm tot} = \quad {\rm Im}$



$= \sum$



Contribution with $m$ inelastic and $n$ elastic subprocesses (diffraction neglected):

$$\sigma_{ad}^{(m,n)}(s) \; = \int d^2b \, \frac{\left[2\chi_{ad}^{\mathbb{P}}(s,b)\right]^n}{n!} \, \frac{\left[-2\chi_{ad}^{\mathbb{P}}(s,b)\right]^n}{n!}$$

Physical quantity - 'topological' cross sections ($m$ inelastic processes):

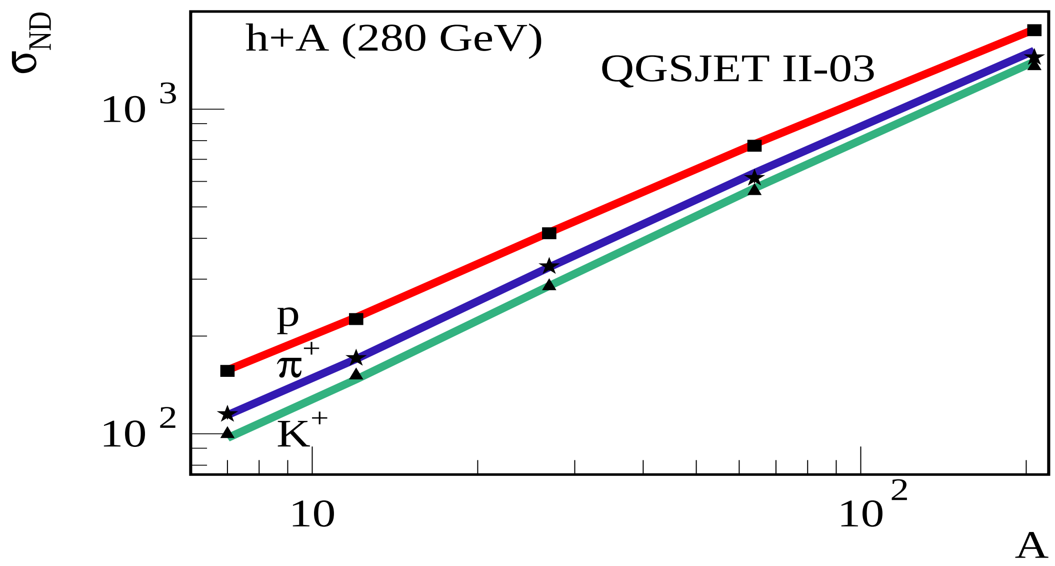
$$\sigma_{ad}^{(m)}(s) \;=\; \sum_{n=0}^{\infty} \sigma_{ad}^{(m,n)}(s) = \int d^2b\, \frac{\left[2\chi_{ad}^{\mathbb{P}}(s,b)\right]^n}{n!}\, e^{-2\chi_{ad}^{\mathbb{P}}(s,b)}$$

$\Rightarrow$ inelastic cross section:

$$\sigma_{ad}^{\rm inel}(s) \;=\; \sum_{m=1}^{\infty} \sigma_{ad}^{(m,)}(s) = \int d^2b\, \left[1 - e^{-2\chi_{ad}^{\mathbb{P}}(s,b)}\right]$$

Parameter-free generalization to hadron-nucleus (nucleus-nucleus) scattering

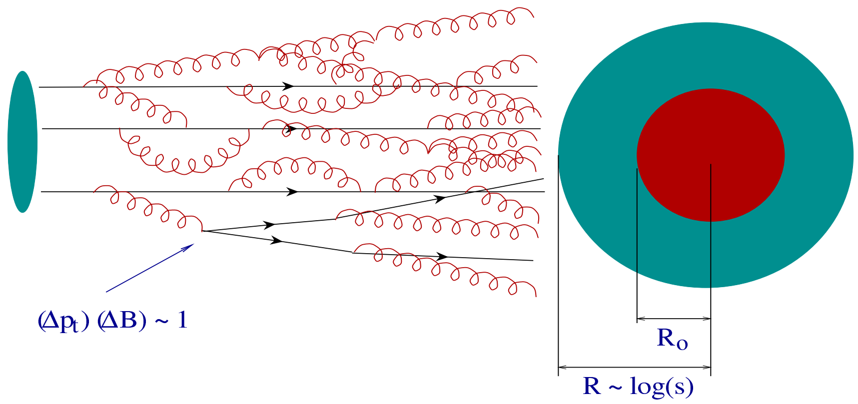
E.g., predicted non-diffractive hadron-nucleus cross section vrs. experimental data



# Non-linear effects

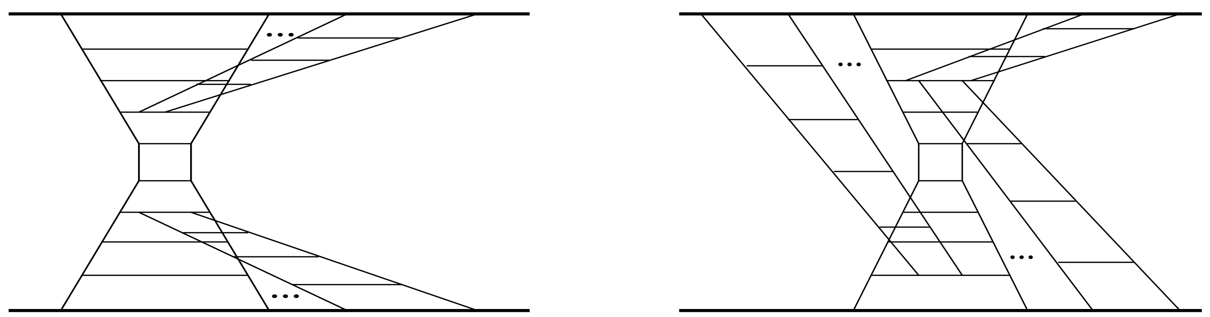
Large $s$, small $b$, large $A$:

- many partons closely packed
- $\Rightarrow$ parton cascades overlap and interact with each other
- $\Rightarrow$ parton shadowing (slower rise of parton density)
- saturation (maximal possible density reached)

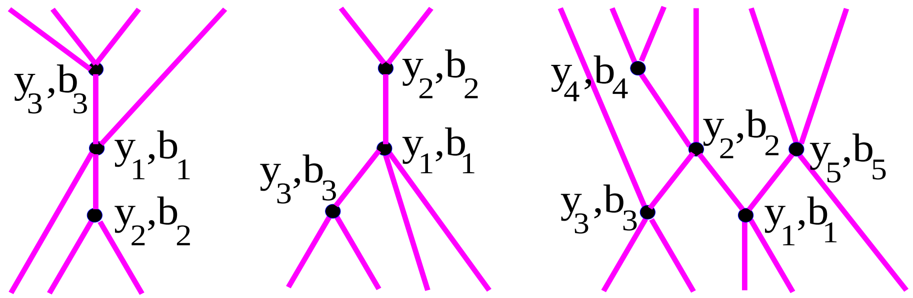



*(picture from R. Engel)*

Non-linear effects in QCD: interaction between parton ladders



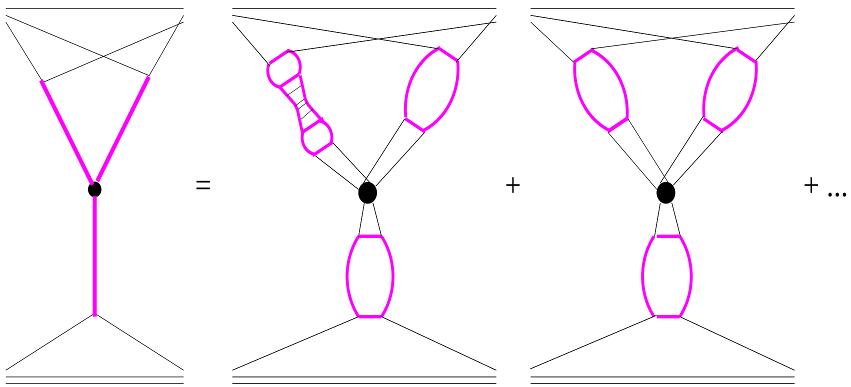
Pomeron approach: non-linear effects ≡ Pomeron-Pomeron interactions



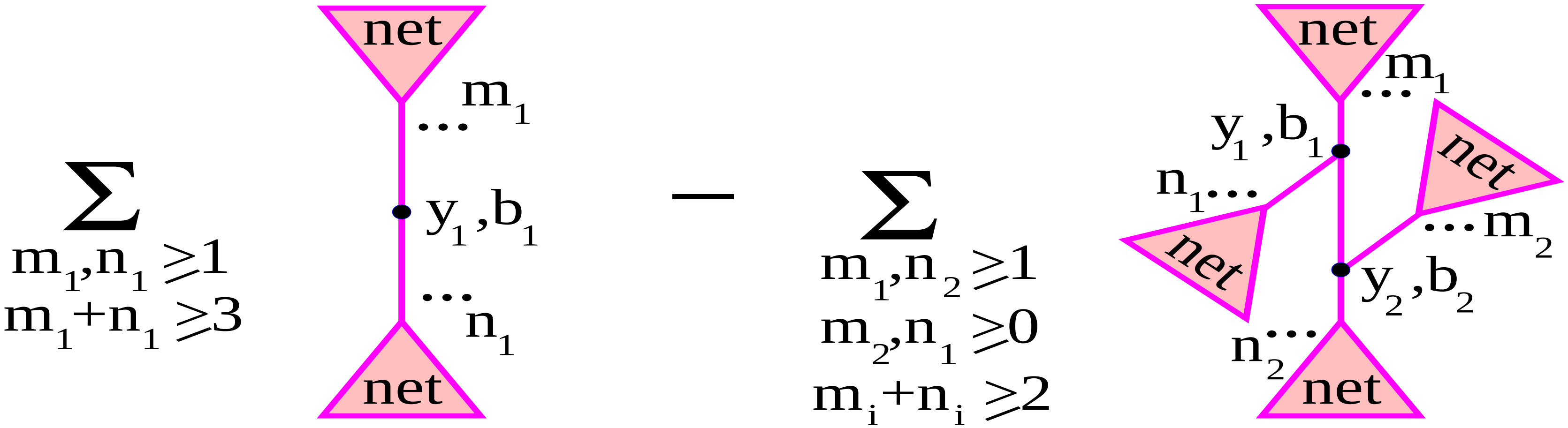

QGSJET II: all order re-summation of Pomeron 'nets' (SO, 2006, 2008)

Basic assumptions:

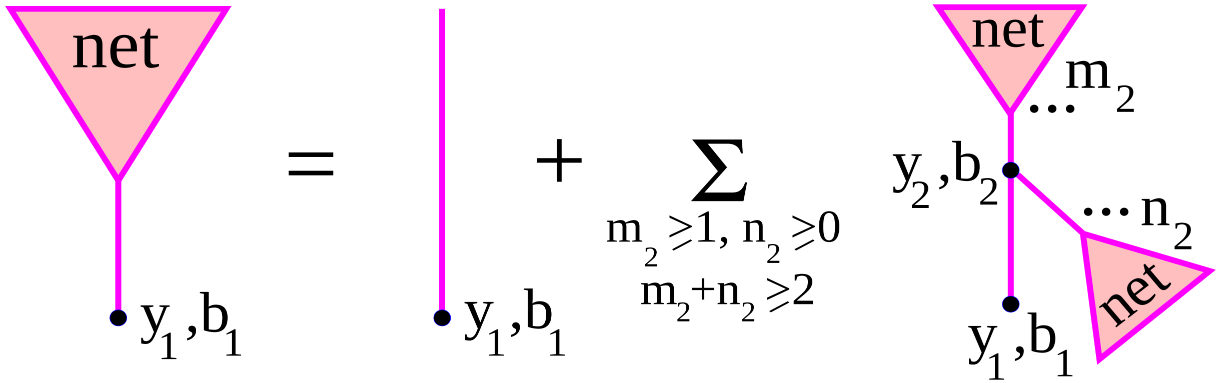
- neglect saturation effects above a fixed $Q_0^2$ scale
- Pomeron-Pomeron coupling - only at $|q|^2 < Q_0^2$
- $\Rightarrow$ only "soft" Pomeron coupling



Summary contribution of all 'net'-like enhanced graphs:



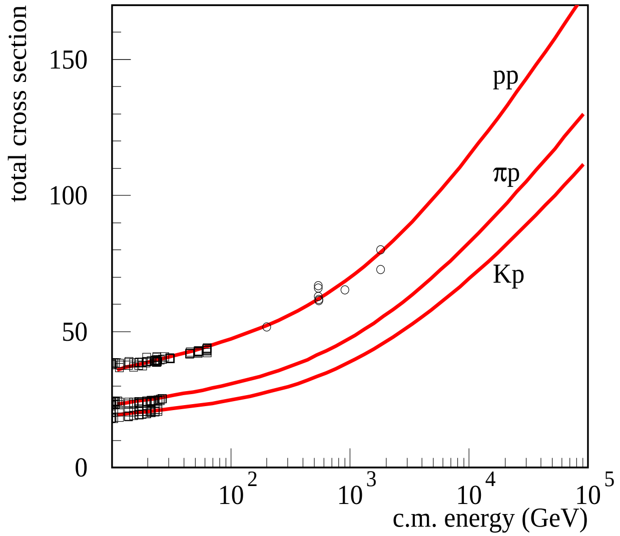

Expressed via 'net-fan' contributions (parton $(y,b)$-distributions 'probed' during interaction):

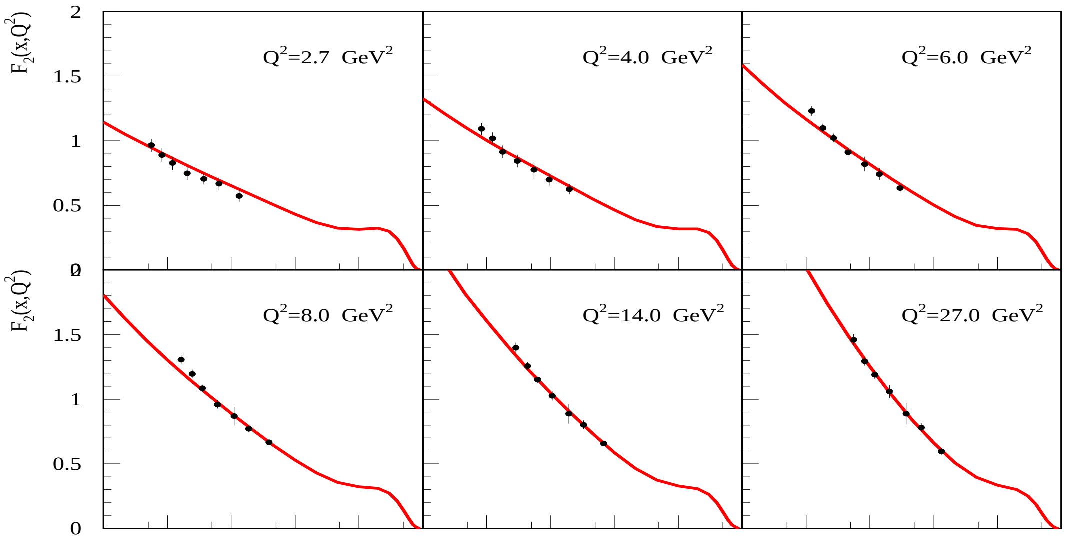


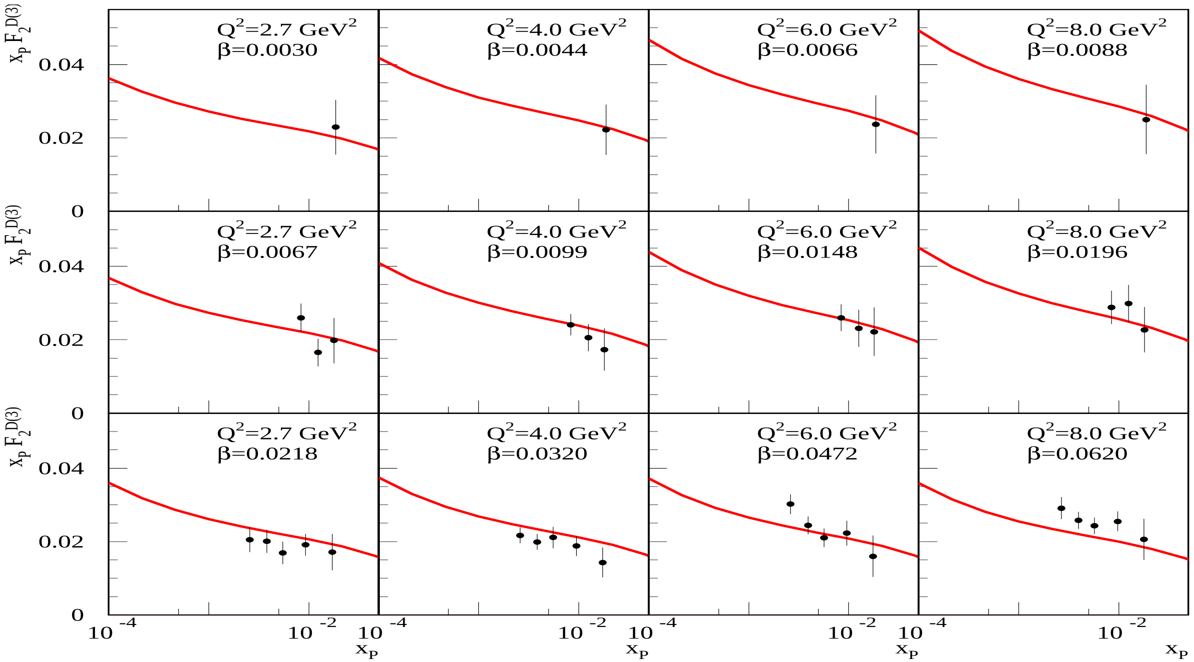

Similar (recursive) representations obtained for the complete set of AGK cuts

⇒ MC implementation

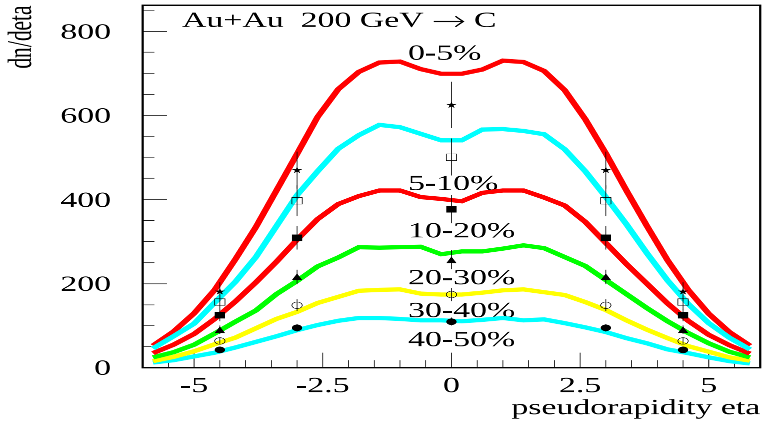
• allows to get consistency between cross sections & structure functions (total and diffractive):



• (parameter-free) $A$-enhancement of screening effects in $hA$ $(AA)$ collisions (e.g., at RHIC)




• preserves QCD factorization for inclusive jet cross section

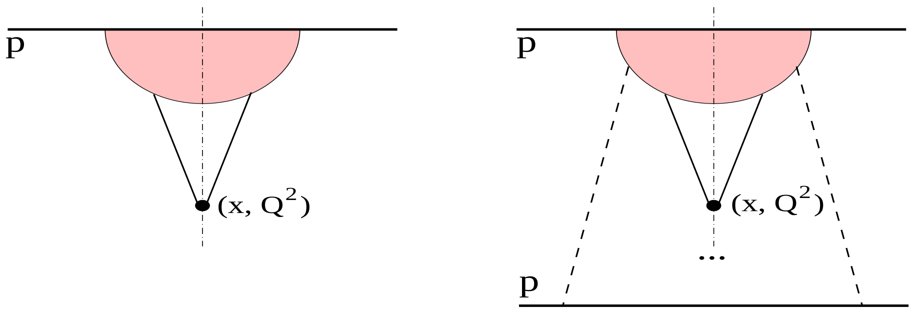
$$\sigma_{ad}^{\rm jet}(s,Q_0^2) = \sum_{I,J=q,\bar{q},g} \int_{p_t^2>Q_0^2} dp_t^2 \int dx^+ dx^- \; f_{I/a}^{\rm scr}(x^+,M_F^2)\; f_{J/d}^{\rm scr}(x^-,M_F^2)\; \frac{d\sigma_{IJ}^{2\to 2}(x^+x^-s,p_t^2)}{dp_t^2}$$

• but: $\int d^2b\; \chi_{ad}^{\mathbb{P}_{\rm sh}}(s,b) \neq \sigma_{ad}^{\rm jet}(s,Q_0^2)$ - due to non-factorizable contributions

Why?

• inclusive spectra - expressed via PDFs of free hadrons

• eikonal - expressed via 'parton distributions' probed during interaction:

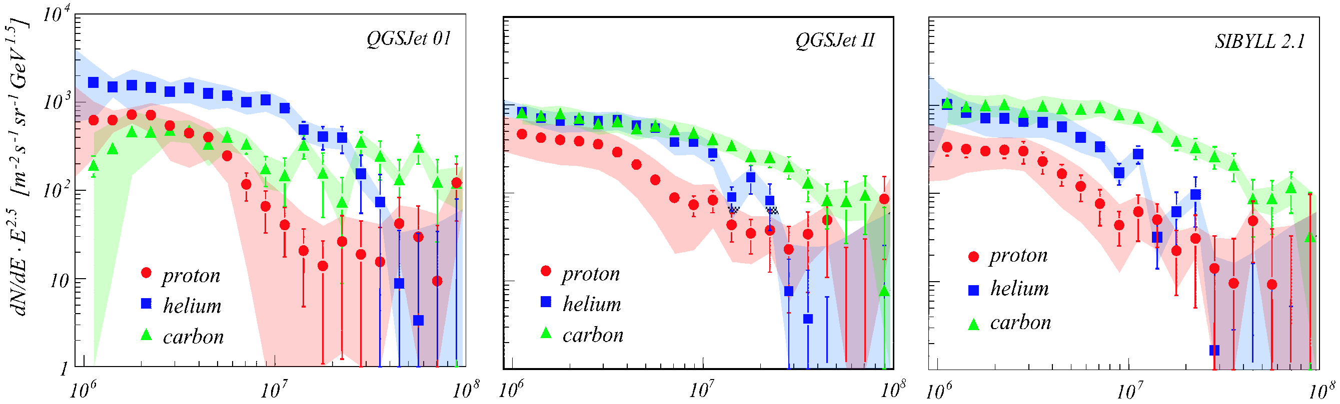


# CR composition

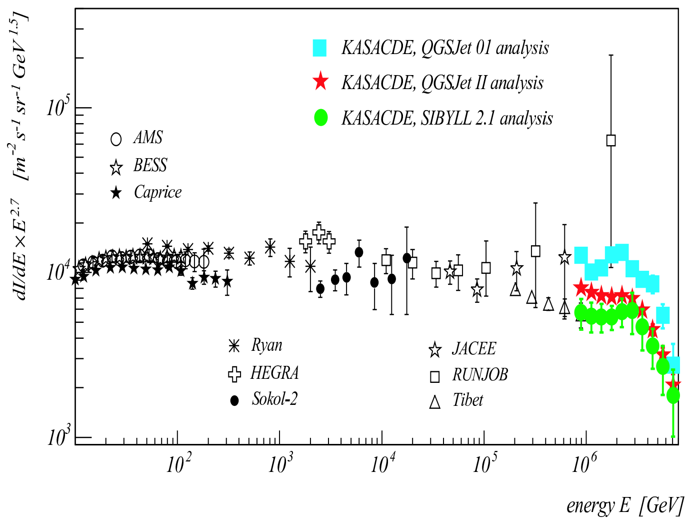
CR studies in the 'knee' region ($E_0 \sim 10^{15} \div 10^{16}$ eV) - generally consistent with each other

KASCADE $N_e/N_\mu$-deconvolution:

- a moderate model dependence
- consistent with rigidity-dependent 'knee' position (at least, for $p$ & $He$)

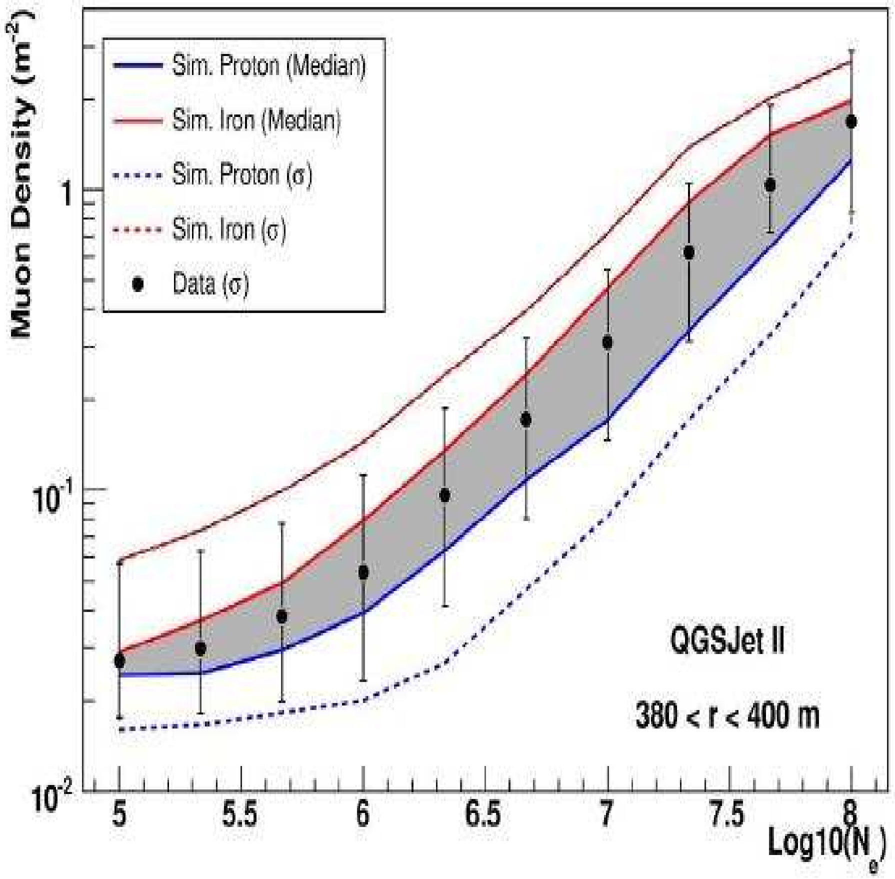


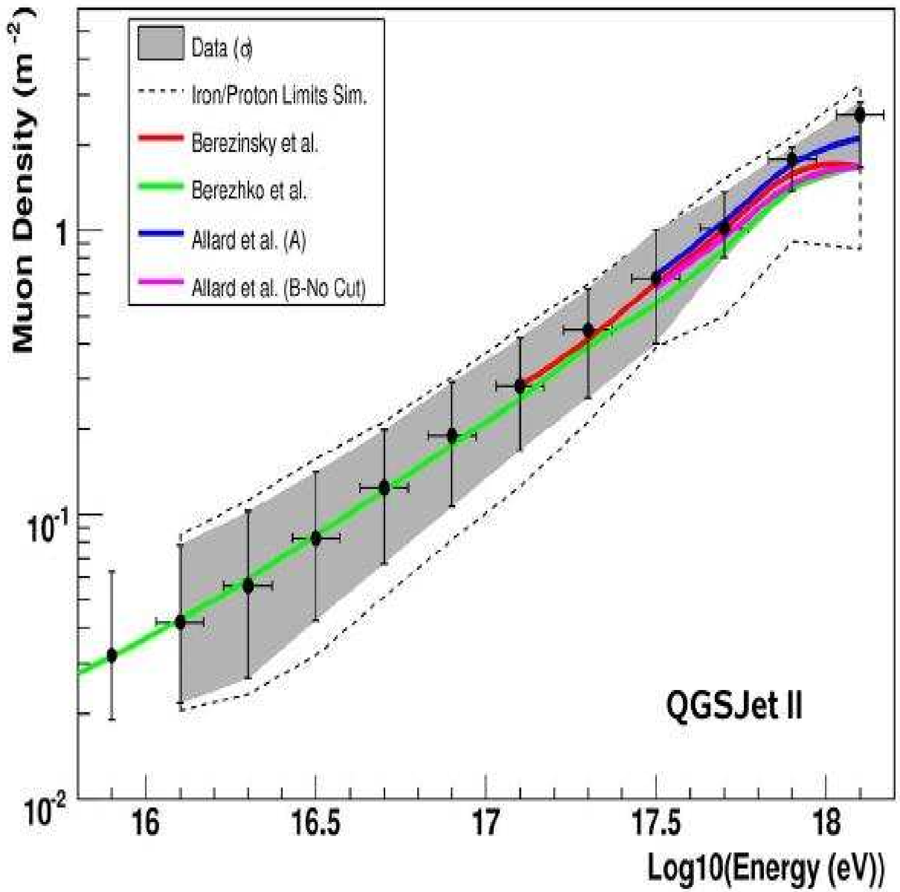

Proton spectrum - consistent with direct measurements:



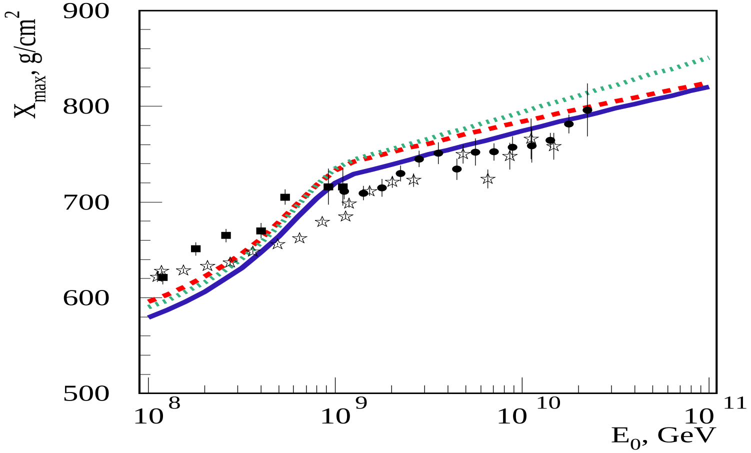
KASCADE-Grande: $\rho_\mu(400 \text{ m})$ up to $10^{18}$ eV

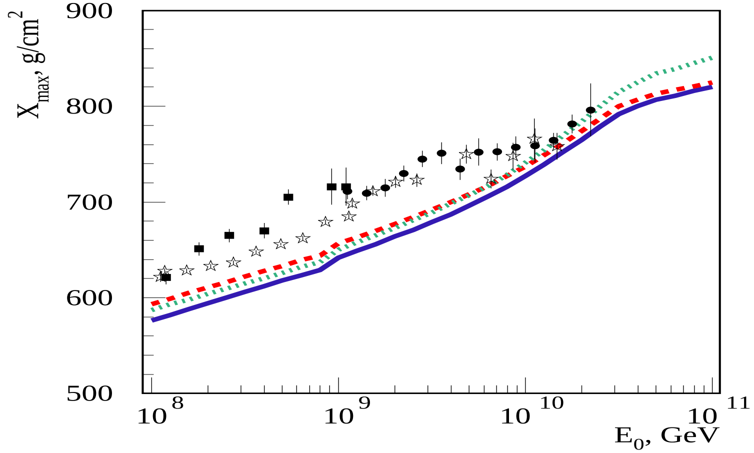
- consistent with model predictions (bounded by $p$ / Fe)
- consistent with astrophysical models (but can not discriminate them)

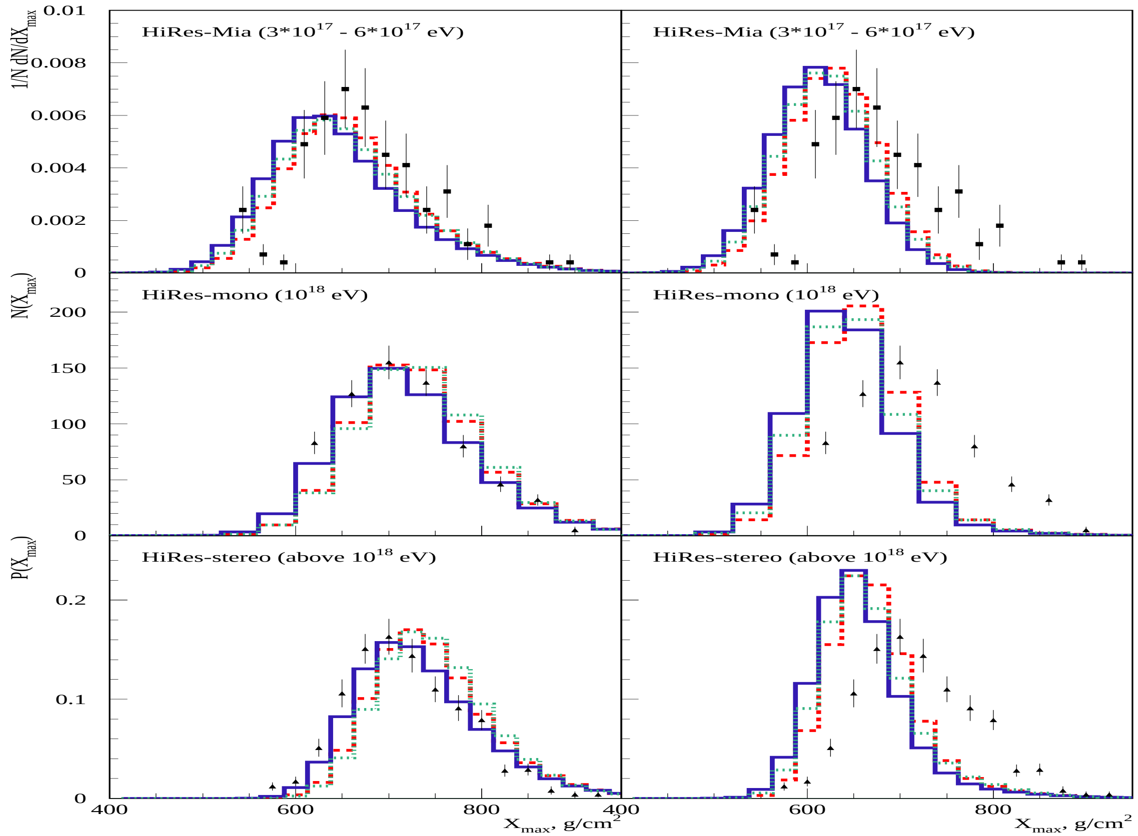


Galactic-extragalactic transition: HiRes data rather favor the 'dip' scenario, reject 'ankle' models

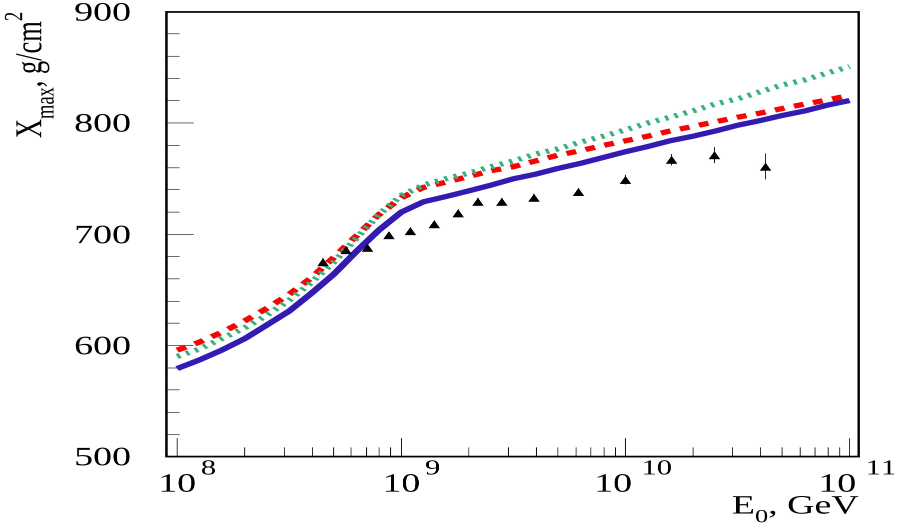


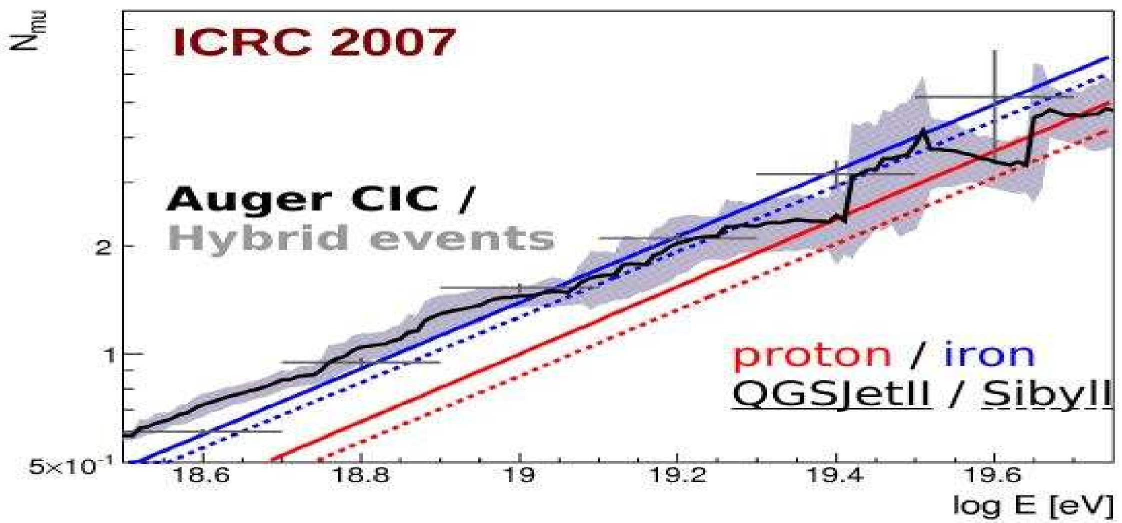



Pierre Auger AGN correlations - also support the 'dip' picture

Contradiction with Pierre Auger composition studies:



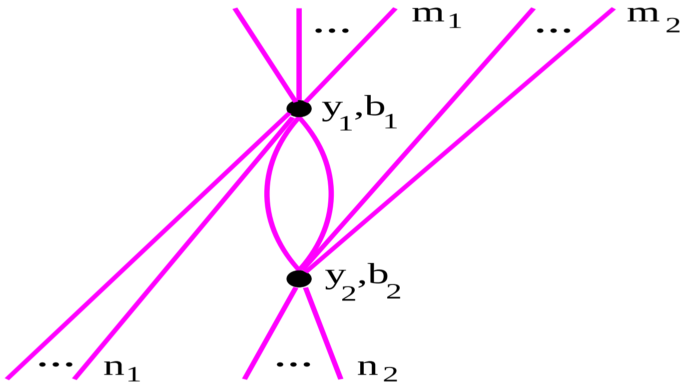

Strong contradiction with Pierre Auger results on $N_\mu$ (based on EAS universality, CIC):



## Potential changes?

QGSJET-II update: 'Pomeron loops' (in progress):

- small at low parton density ($\sim G^2$)
- suppressed at high density:
$\sim \sum_{n_1=0}^{\infty} \frac{(-\chi_{d\mathbb{P}}^{\mathbb{P}}(s_0 e^{y_1}, b_1))^{n_1}}{n_1!} = e^{-\chi_{d\mathbb{P}}^{\mathbb{P}}(s_0 e^{y_1}, b_1)}$




Still a finite correction at large $b$:

- of importance for $\sigma^{\rm tot}$, $\sigma^{\rm diffr}$
- will lead to smaller 3P-coupling
- $\Rightarrow$ smaller nuclear screening
- $\Rightarrow$ higher $N^{\rm ch}_{\rm h-air}$, $K^{\rm inel}_{\rm h-air}$

But only a moderate effect expected

What else:

- BFKL evolution: at NLO close DGLAP
- saturation at $Q^2 > Q_0^2$: irrelevant for $\sigma_{\rm inel}$ $\Rightarrow$ additional suppresion of particle production
- independent hadronization of valence quarks: for central collisions $\Rightarrow$ hard to expect a big effect

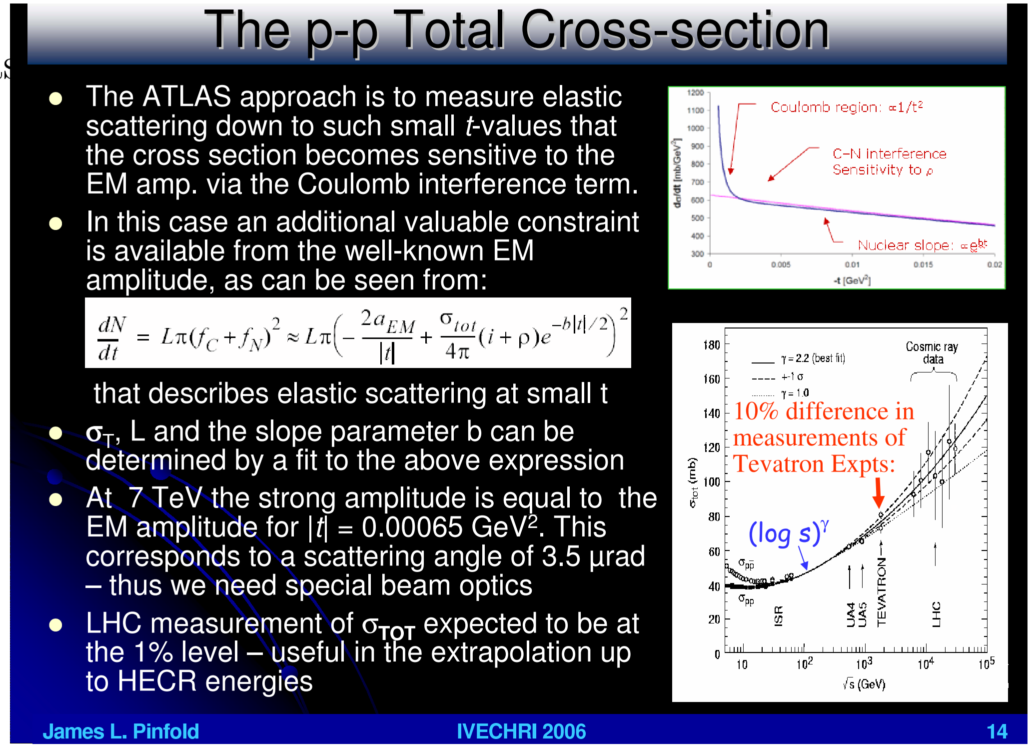
# Extra slides

Hadronic cross sections - of crucial importance for EAS applications

- $\sigma^{\rm inel}_{h-{\rm air}}$ - direct impact on $X_{\rm max}$
- model calibration:
  - particle production: mainly with fixed target $hp$ data
  - energy extrapolation: mainly inferred from $\sigma^{\rm tot}_{pp}(s)$ behavior

$\Rightarrow$ measurement of $\sigma^{\rm tot}_{pp}$ with 1% accuracy ($\sim$ 10 mb) - most important LHC contribution:

- allows to obtain $\sigma^{\rm inel}_{p-{\rm air}}$ (Glauber + inelas
- significantly improves model calibration

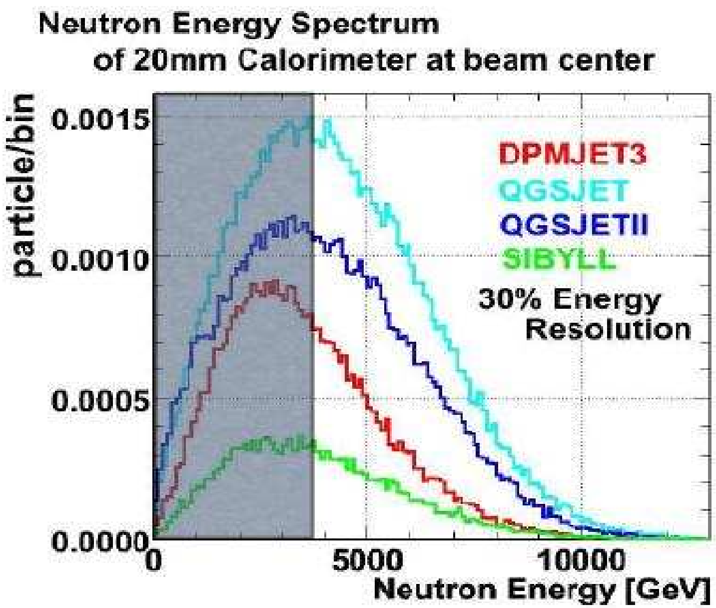


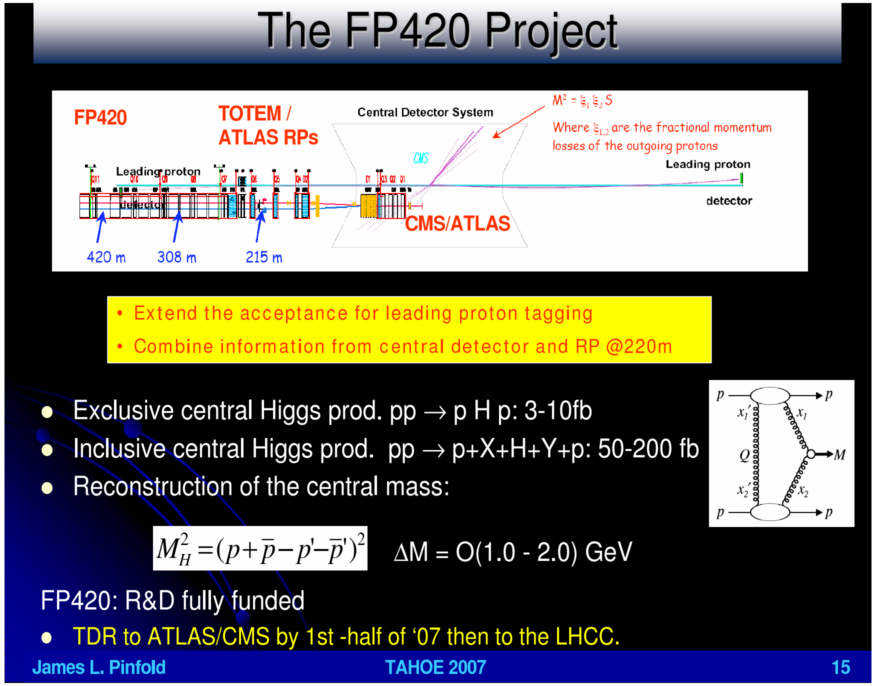
## FP420 experiment:

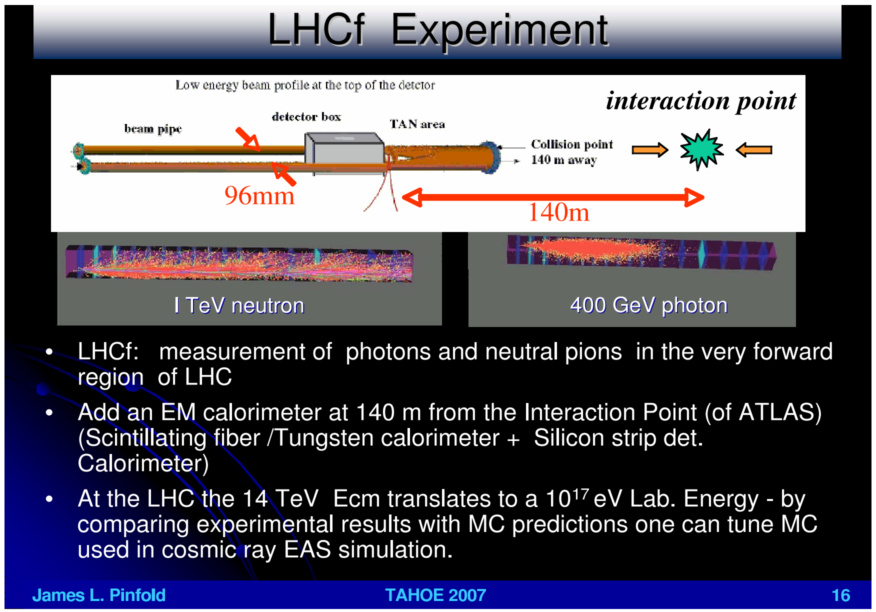
- designed to study diffractive Higgs production
- can measure 'soft' diffraction

## LHCf experiment:

- measurement of forward neutrons and gammas
- allows to test inelasticity at 0.1 EeV!
- sensitive to projectile diffraction



# Good-Walker scheme for diffraction

Low mass diffraction - 2-component eikonal scheme: $|a\rangle = \frac{1}{\sqrt{2}}|1_a\rangle + \frac{1}{\sqrt{2}}|2_a\rangle$

$|k_a\rangle$ - diffractive eigenstates for hadron $a$;

couple to a Pomeron with different strength $\lambda_{k/a}$ $(\lambda_{k/a} + \lambda_{k/a} = 2)$

$$\sigma^{\rm inel}_{pp}(s) \; = \; \int d^2b \, \frac{1}{4} \sum_{i,j=1}^{2} \left[1 - e^{-2\lambda_{i/p}\,\lambda_{j/p}\,\chi^{\mathbb{P}}_{pp}(s,b)}\right]$$

$$\sigma^{\rm s-diffr}_{pp}(s) \; = \; 2\int d^2b \, \frac{1}{4} \sum_{j=1}^{2} \left[e^{-\lambda_{1/p}\,\lambda_{j/p}\,\chi^{\mathbb{P}}_{pp}(s,b)} - e^{-\lambda_{2/p}\,\lambda_{j/p}\,\chi^{\mathbb{P}}_{pp}(s,b)}\right]^2$$

$$\frac{1}{4} \sum_{i,j=1}^{2} \left[1 - e^{-2\lambda_{i/p}\,\lambda_{j/p}\,\chi^{\mathbb{P}}_{pp}(s,b)}\right] \; = \; \begin{cases} 1, & b \to 0 \\ 2\chi^{\mathbb{P}}_{pp}(s,b) - 2\,(2 - \lambda_{1/p}\,\lambda_{2/p})^2\,(\chi^{\mathbb{P}}_{pp}(s,b))^2 + ..., & b \to \infty \end{cases}$$

Higher diffraction $\Rightarrow$ cross sections reduced at high energies (inelastic screening)

Topological cross section ($n$ inelastic sub-processes):

$$\sigma^{(n)}_{ad}(s) \; = \; \int d^2b \, \frac{1}{4} \sum_{i,j=1}^{2} \frac{\left[2\lambda_{i/a}\,\lambda_{j/d}\,\chi_{ad}(s,b)\right]^n}{n!} e^{-2\lambda_{i/a}\,\lambda_{j/d}\,\chi_{ad}(s,b)}$$

$\Rightarrow$ larger multiplicity fluctuations in non-diffractive collisions

Gluon density saturation - only at small $b$: