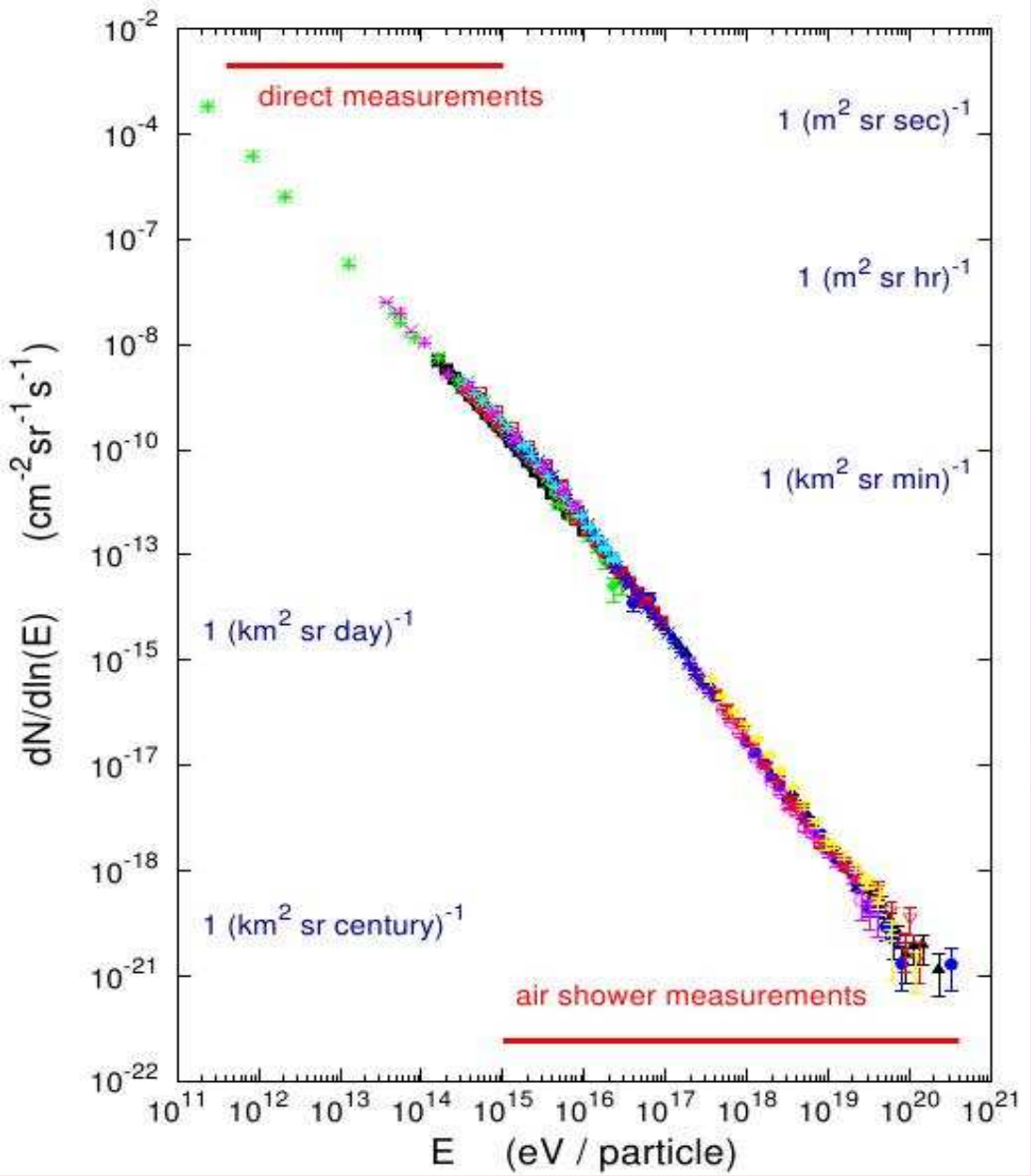
Very High Energy Cosmic Rays: Status, Puzzles, and the Impact of LHC data

Sergey Ostapchenko (NTNU, Trondheim)

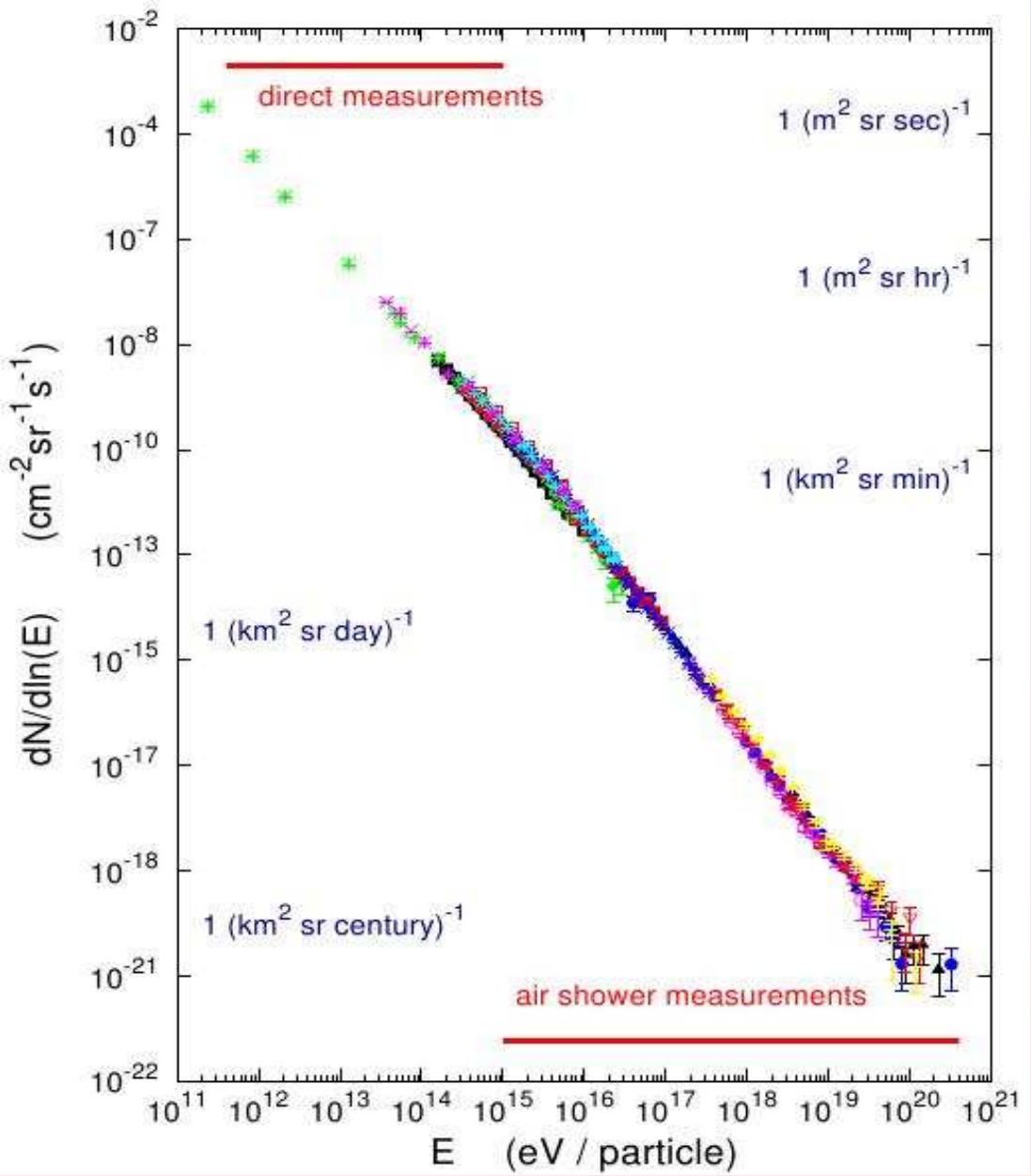
ISMD-2011, Hiroshima, September 26-30, 2011

High Energy Cosmic Rays



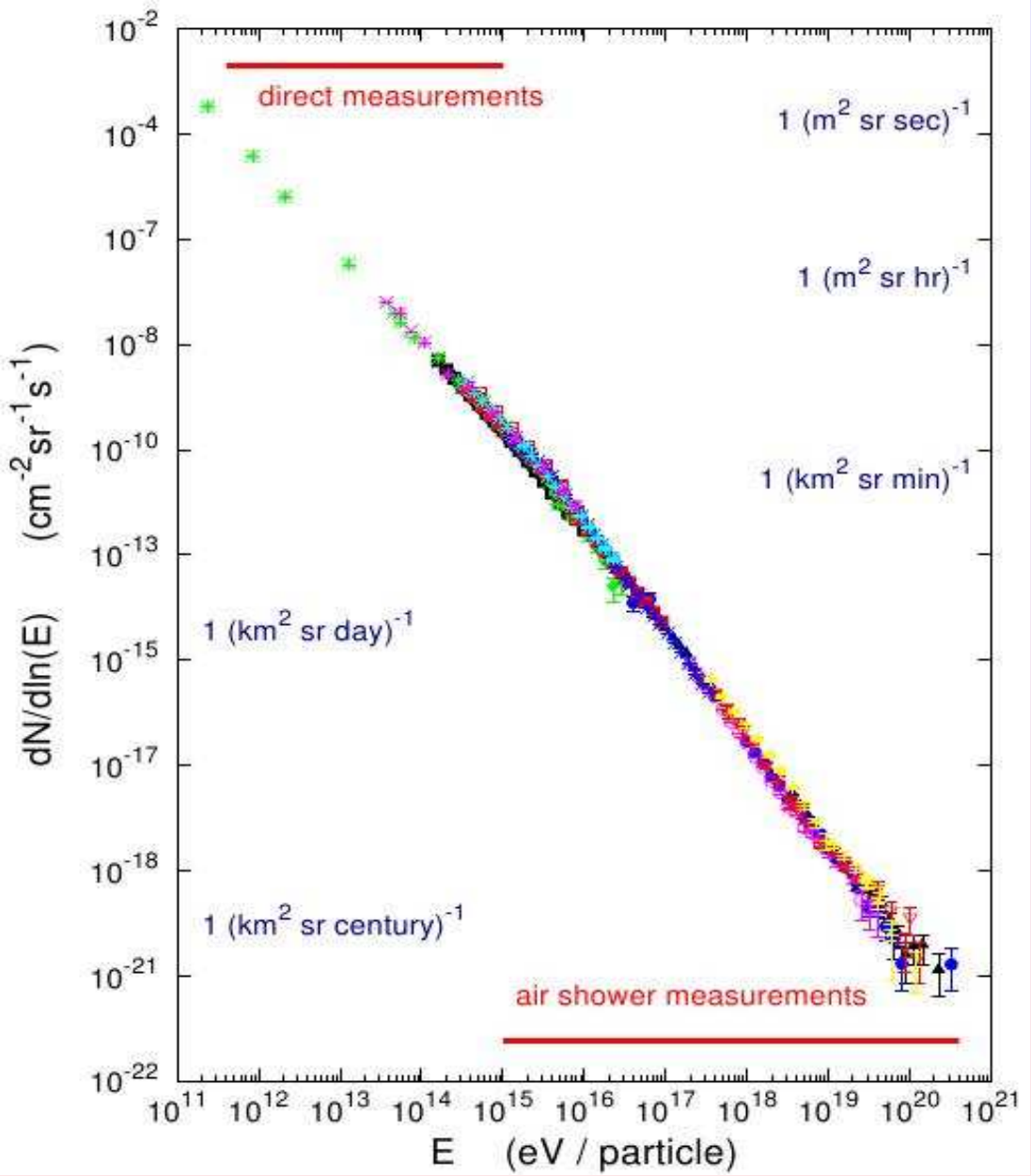
- almost featureless spectrum
- extends over > 10 orders of magnitude
- flux steeply falling down with energy
- $\Rightarrow$ direct detection till $\sim 10^{15}$ eV only
- primary particles – protons & nuclei (up to Fe)

High Energy Cosmic Rays



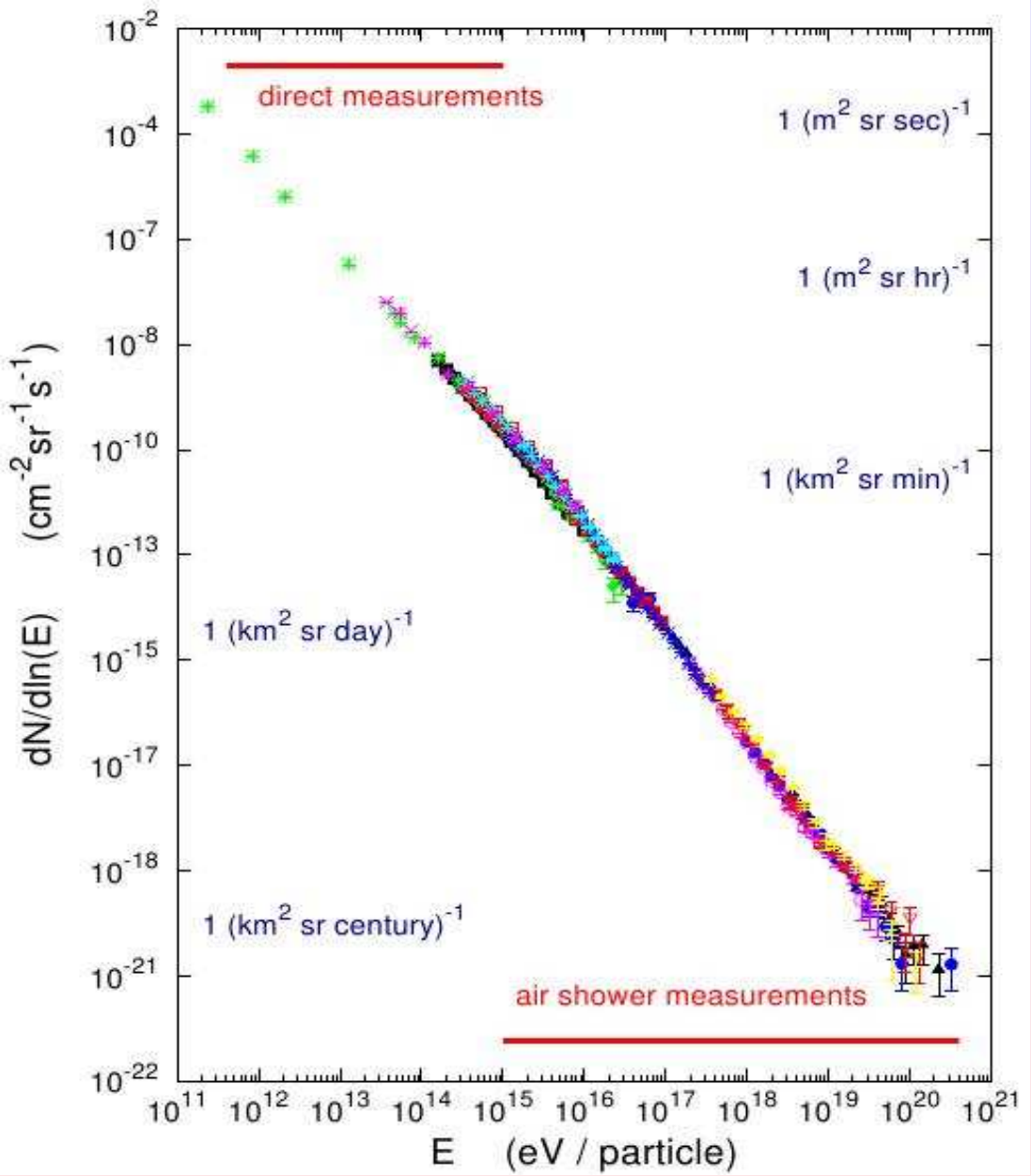
- almost featureless spectrum
- extends over > 10 orders of magnitude
- flux steeply falling down with energy
- $\Rightarrow$ direct detection till $\sim 10^{15}$ eV only
- primary particles – protons & nuclei (up to Fe)

High Energy Cosmic Rays



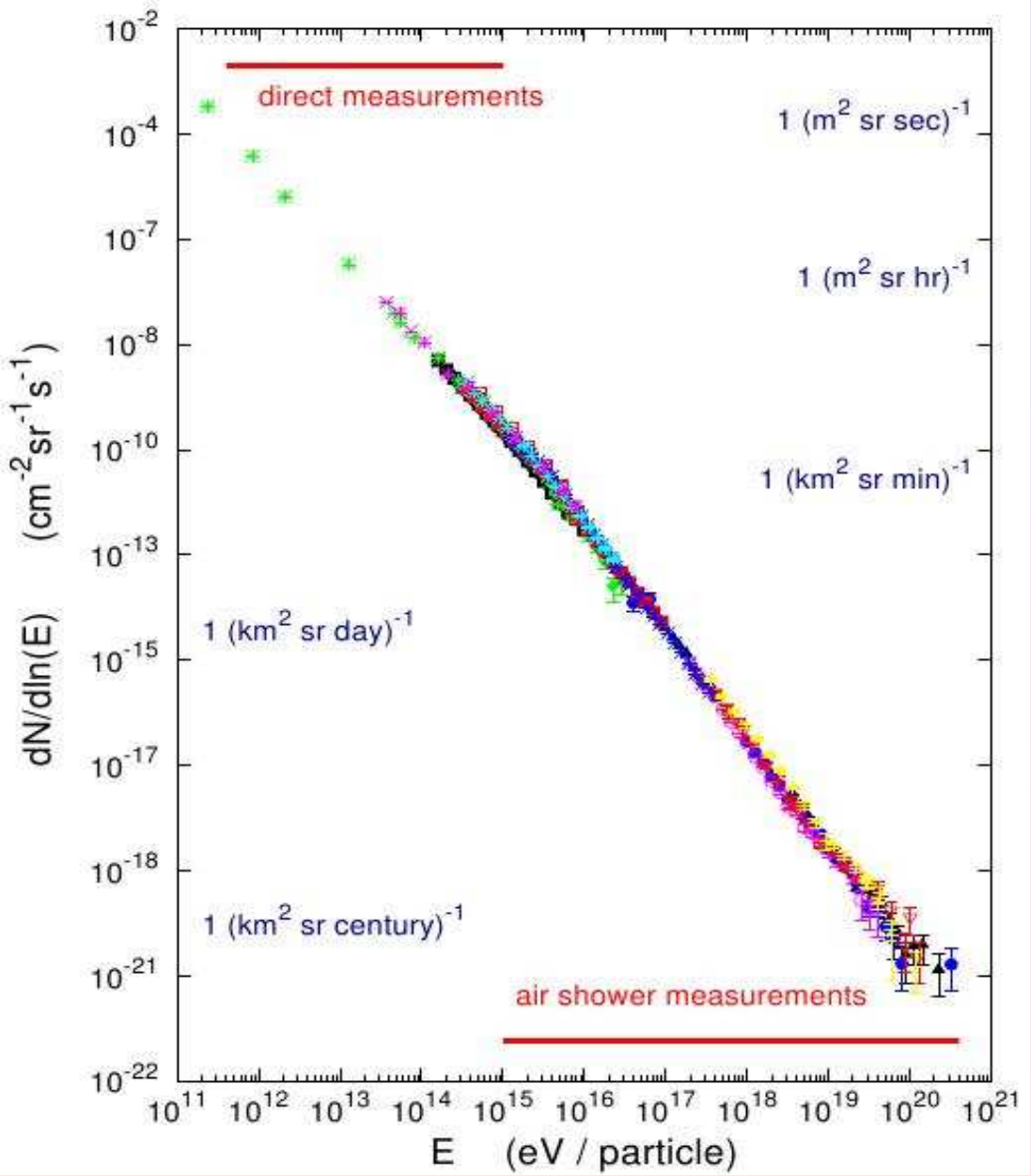
- almost featureless spectrum
- extends over > 10 orders of magnitude
- flux steeply falling down with energy
- $\Rightarrow$ direct detection till $\sim 10^{15}$ eV only
- primary particles – protons & nuclei (up to Fe)

High Energy Cosmic Rays



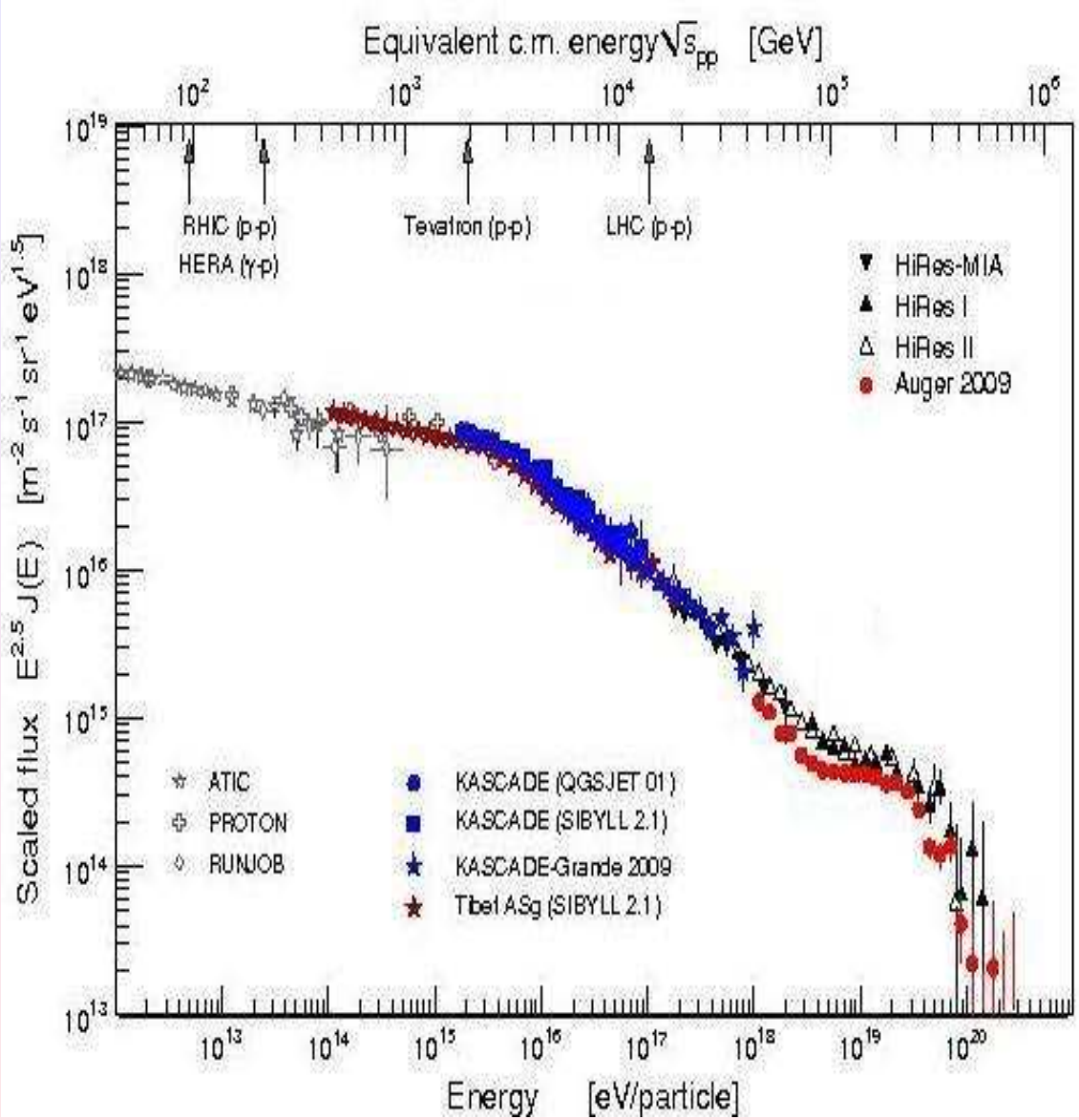
- almost featureless spectrum
- extends over > 10 orders of magnitude
- flux steeply falling down with energy
- $\Rightarrow$ direct detection till $\sim 10^{15}$ eV only
- primary particles – protons & nuclei (up to Fe)

High Energy Cosmic Rays



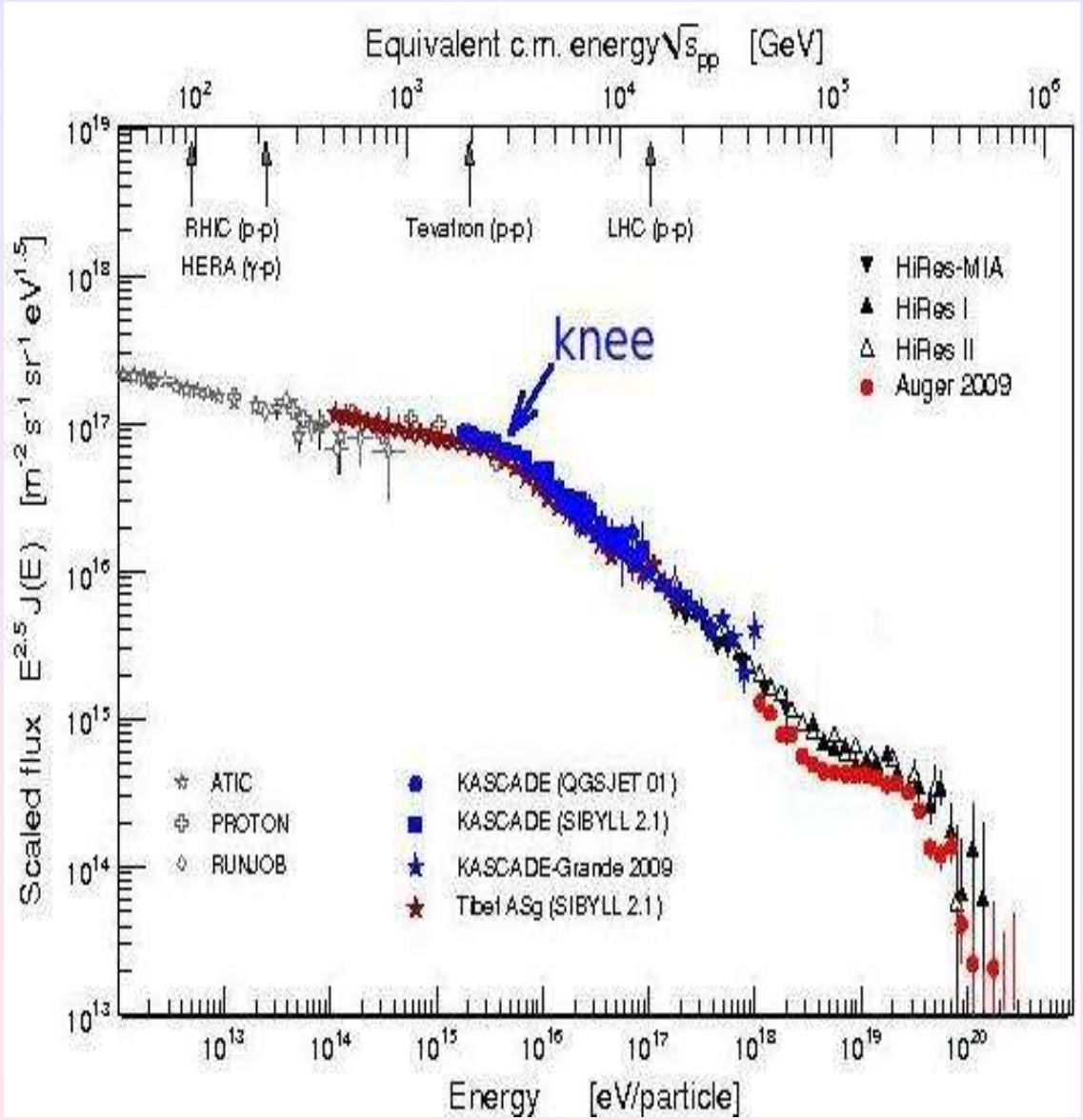
- almost featureless spectrum
- extends over > 10 orders of magnitude
- flux steeply falling down with energy
- $\Rightarrow$ direct detection till $\sim 10^{15}$ eV only
- primary particles – protons & nuclei (up to Fe)

High Energy Cosmic Rays



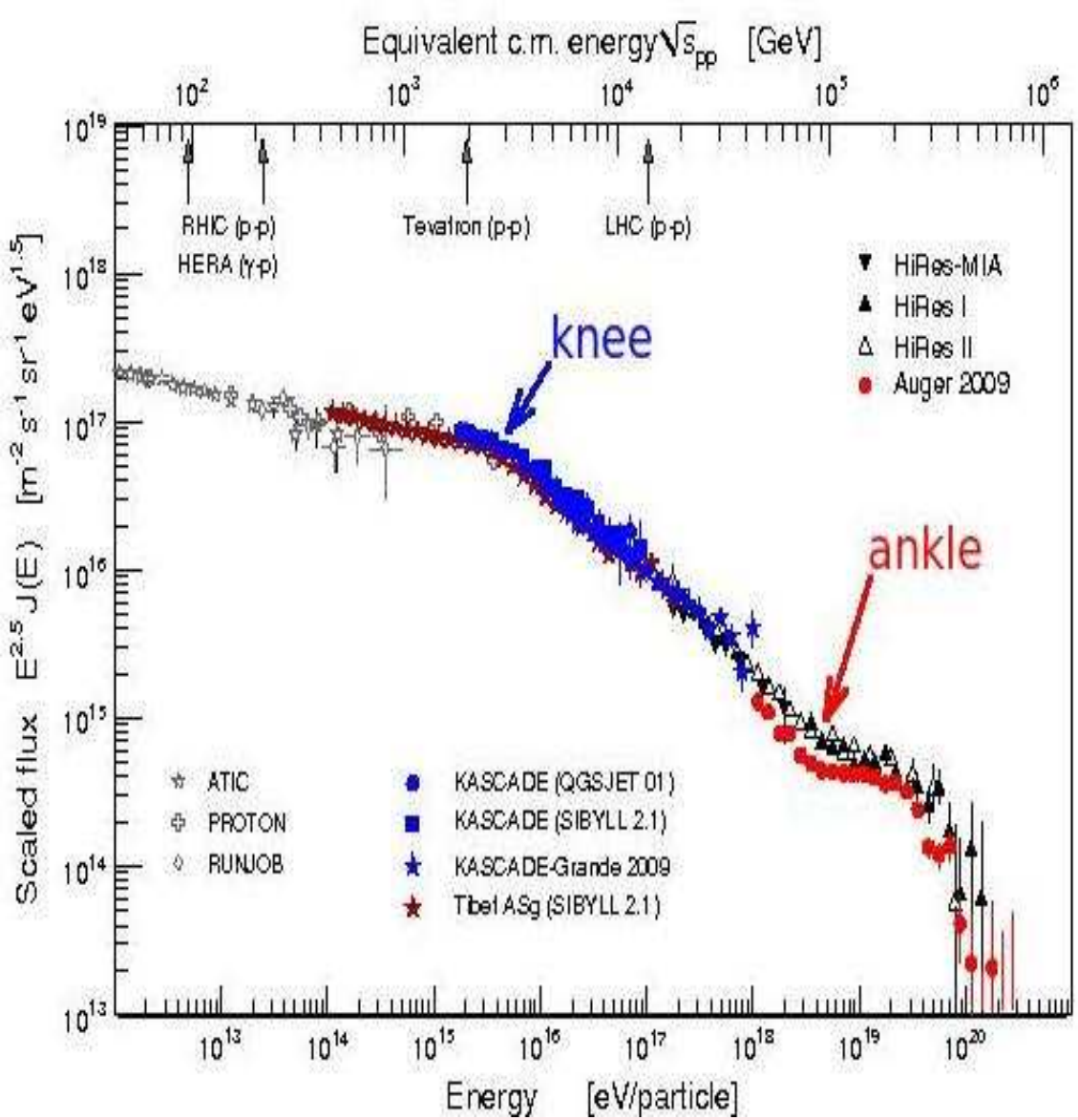
- flux $\times E^{2.5}$:
  'leg'-like shape

High Energy Cosmic Rays



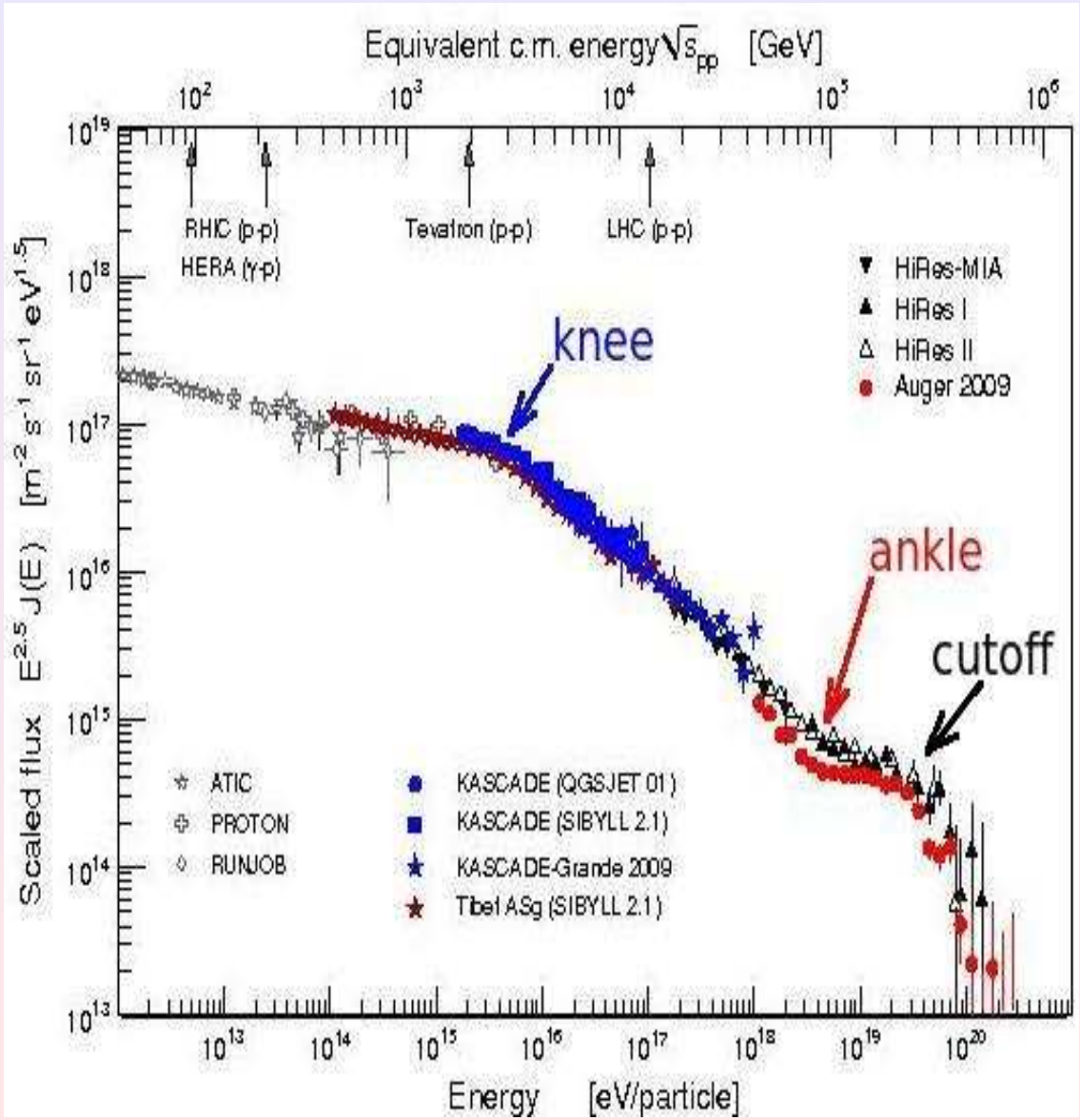
- flux $\times E^{2.5}$: 'leg'-like shape
- 'knee' around 3×10^{15} eV (effect of galactic acceleration / propagation)

High Energy Cosmic Rays



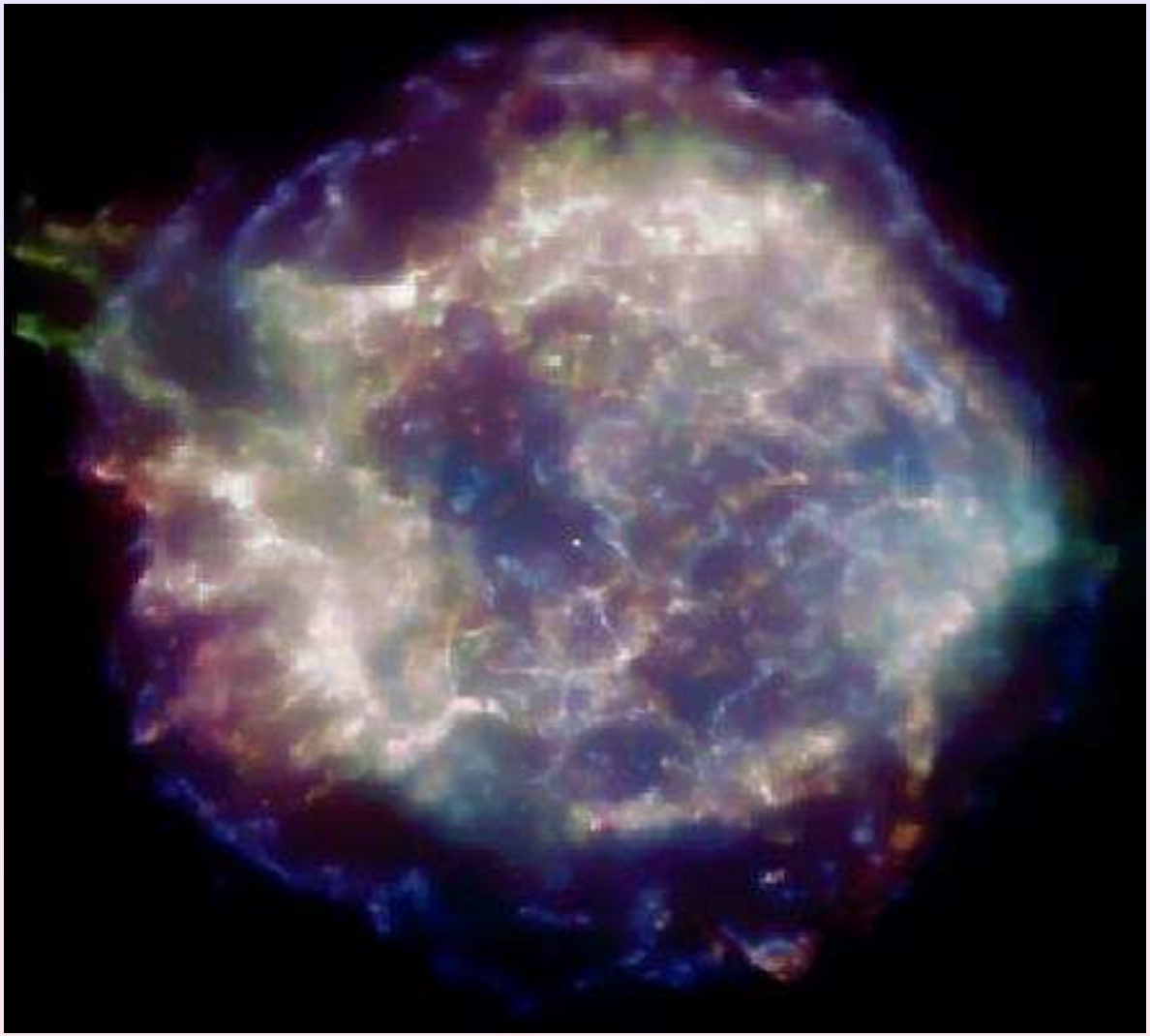
- flux $\times E^{2.5}$: 'leg'-like shape
- 'knee' around 3×10^{15} eV (effect of galactic acceleration / propagation)
- 'ankle' at few $\times 10^{18}$ eV (galactic / extragalactic transition?)

High Energy Cosmic Rays



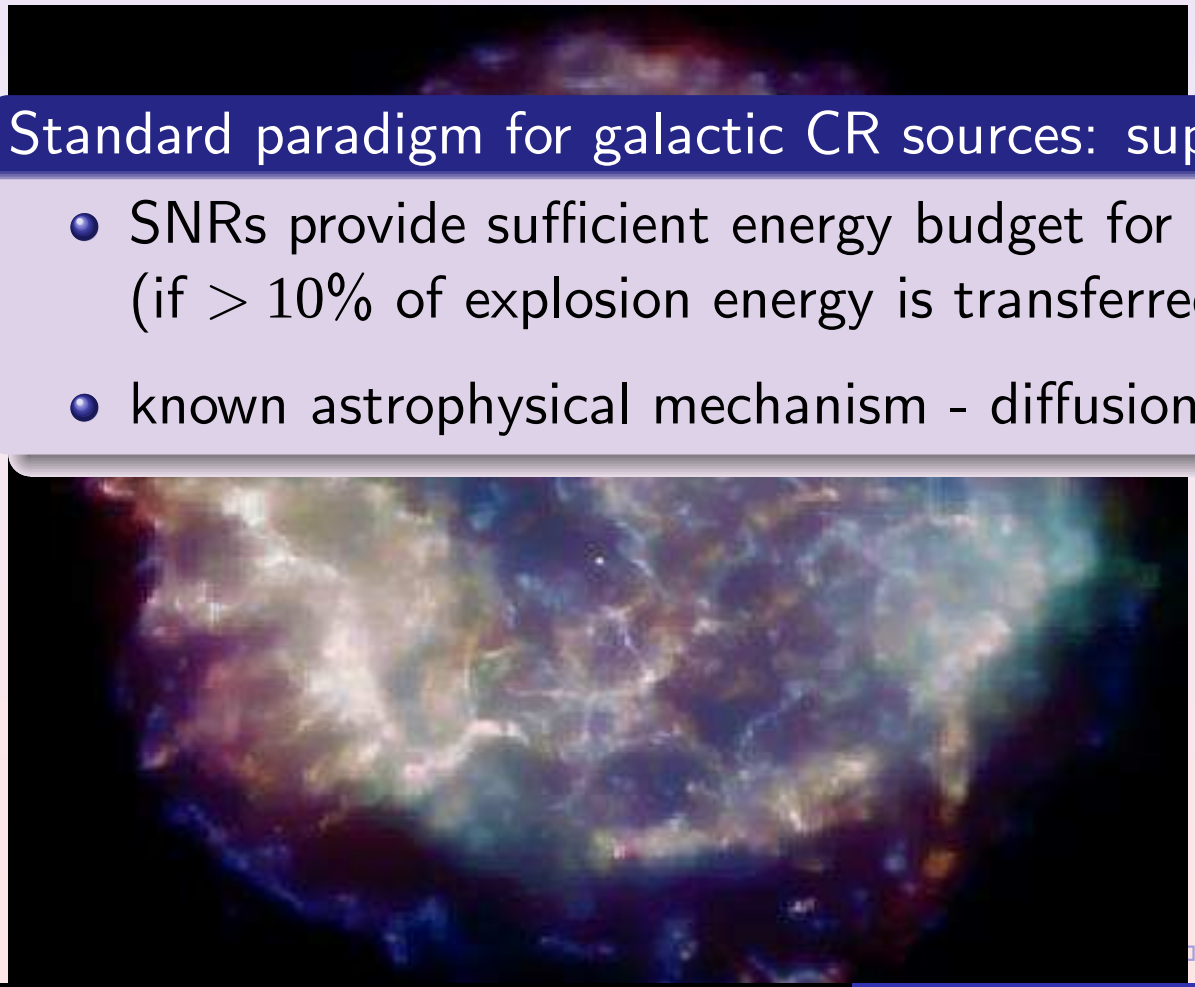
- flux $\times E^{2.5}$: 'leg'-like shape
- 'knee' around 3×10^{15} eV (effect of galactic acceleration / propagation)
- 'ankle' at few $\times 10^{18}$ eV (galactic / extragalactic transition?)
- cutoff at $\sim 10^{20}$ eV (interaction with background γs?)

Galactic Cosmic Rays



X-ray image of SNR Cas A

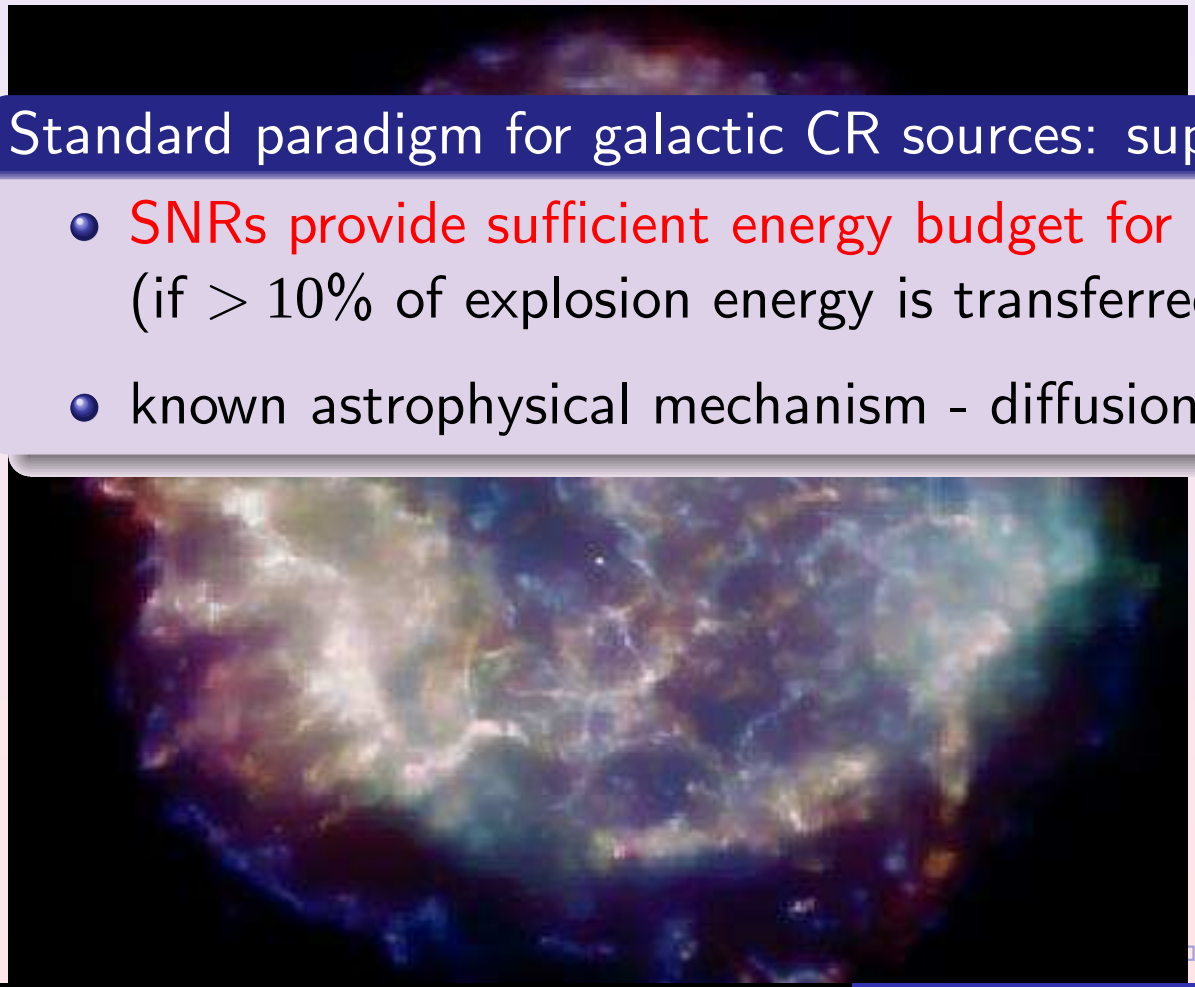
Galactic Cosmic Rays



Standard paradigm for galactic CR sources: supernova remnants

- SNRs provide sufficient energy budget for CRs
  (if $> 10\%$ of explosion energy is transferred to CRs)
- known astrophysical mechanism - diffusion shock acceleration

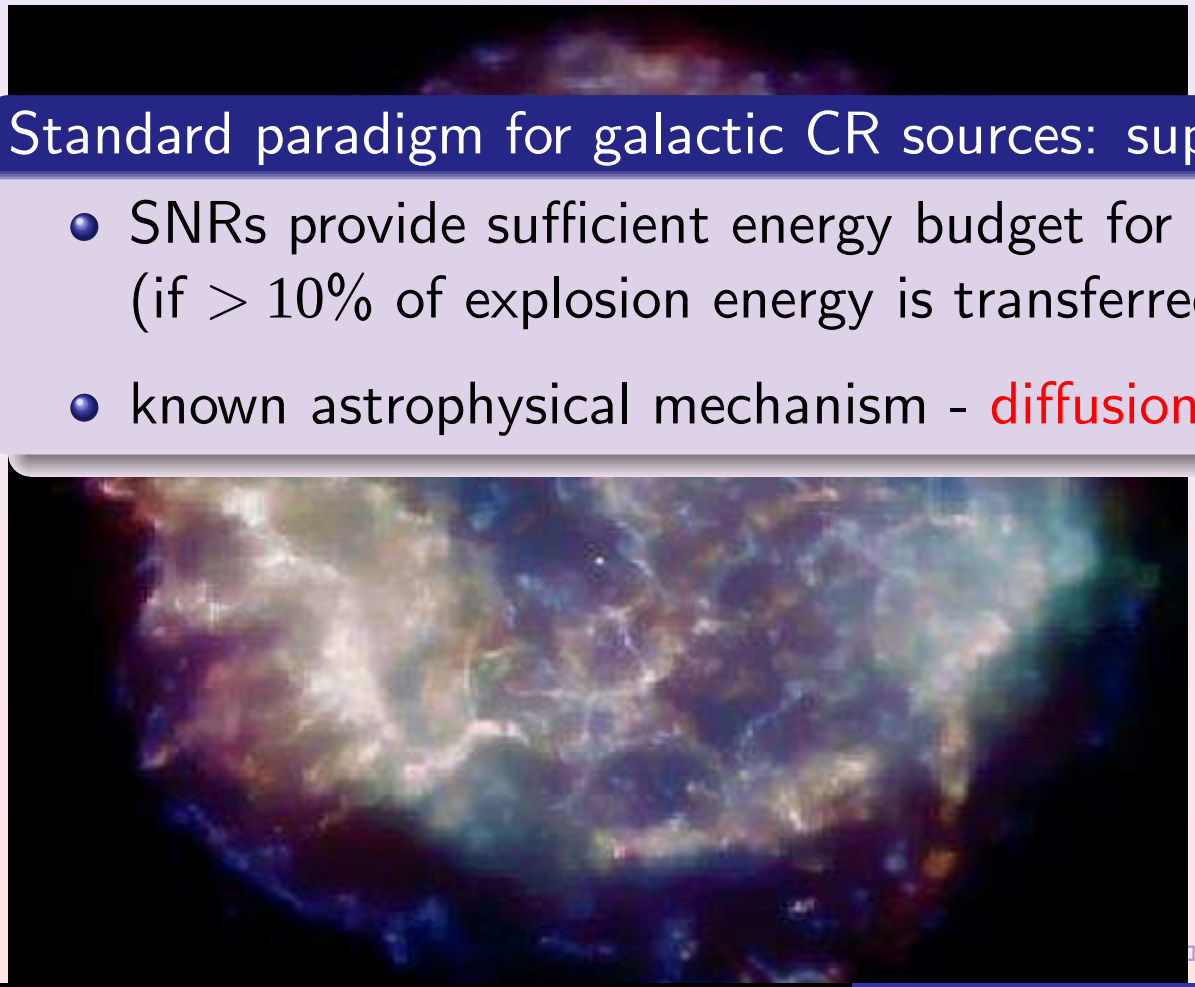
Galactic Cosmic Rays



Standard paradigm for galactic CR sources: supernova remnants

- SNRs provide sufficient energy budget for CRs
  (if $> 10\%$ of explosion energy is transferred to CRs)
- known astrophysical mechanism - diffusion shock acceleration

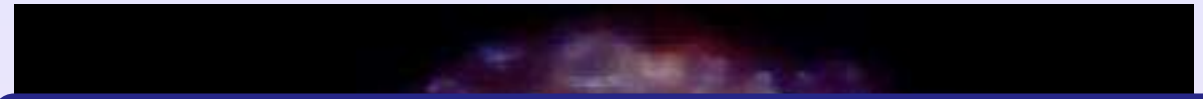
Galactic Cosmic Rays



Standard paradigm for galactic CR sources: supernova remnants

- SNRs provide sufficient energy budget for CRs
  (if $> 10\%$ of explosion energy is transferred to CRs)
- known astrophysical mechanism - diffusion shock acceleration

Galactic Cosmic Rays



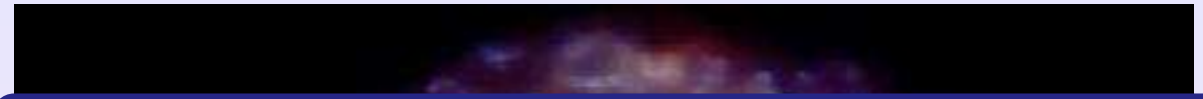
Standard paradigm for galactic CR sources: supernova remnants

- SNRs provide sufficient energy budget for CRs
  (if $> 10\%$ of explosion energy is transferred to CRs)
- known astrophysical mechanism - diffusion shock acceleration

CR 'knee' as an acceleration cutoff

- DSA is able to accelerate protons up to the 'knee' ($\sim 10^{15}$ eV)
- $\Rightarrow$ the knee can be the signature of proton acceleration cutoff
- acceleration (by magnetic fields) depends on particle rigidity $E/Z \Rightarrow$ nuclei can be accelerated to (Z-times) higher energies
- $\Rightarrow$ rigidity-dependent partial 'nuclear knees' may be expected (e.g. $E_{He}^{\mathrm{knee}} = 2E_{p}^{\mathrm{knee}}$, $E_{Fe}^{\mathrm{knee}} = 26E_{p}^{\mathrm{knee}}$)

Galactic Cosmic Rays



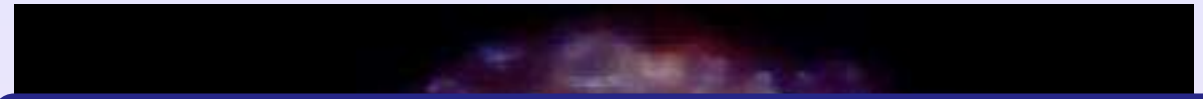
Standard paradigm for galactic CR sources: supernova remnants

- SNRs provide sufficient energy budget for CRs
  (if $> 10\%$ of explosion energy is transferred to CRs)
- known astrophysical mechanism - diffusion shock acceleration

CR 'knee' as an acceleration cutoff

- DSA is able to accelerate protons up to the 'knee' ($\sim 10^{15}$ eV)
- $\Rightarrow$ the knee can be the signature of proton acceleration cutoff
- acceleration (by magnetic fields) depends on particle rigidity $E/Z \Rightarrow$ nuclei can be accelerated to (Z-times) higher energies
- $\Rightarrow$ rigidity-dependent partial 'nuclear knees' may be expected (e.g. $E_{He}^{\mathrm{knee}} = 2E_{p}^{\mathrm{knee}}$, $E_{Fe}^{\mathrm{knee}} = 26E_{p}^{\mathrm{knee}}$)

Galactic Cosmic Rays



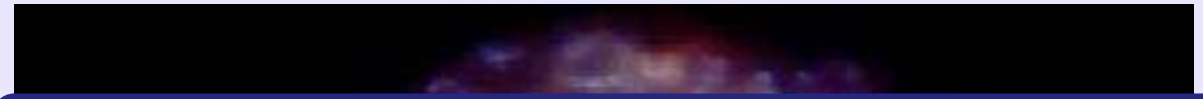
Standard paradigm for galactic CR sources: supernova remnants

- SNRs provide sufficient energy budget for CRs
  (if $> 10\%$ of explosion energy is transferred to CRs)
- known astrophysical mechanism - diffusion shock acceleration

CR 'knee' as an acceleration cutoff

- DSA is able to accelerate protons up to the 'knee' ($\sim 10^{15}$ eV)
- $\Rightarrow$ the knee can be the signature of proton acceleration cutoff
- acceleration (by magnetic fields) depends on particle rigidity $E/Z \Rightarrow$ nuclei can be accelerated to (Z-times) higher energies
- $\Rightarrow$ rigidity-dependent partial 'nuclear knees' may be expected
  (e.g. $E_{He}^{\mathrm{knee}} = 2E_{p}^{\mathrm{knee}}$, $E_{Fe}^{\mathrm{knee}} = 26E_{p}^{\mathrm{knee}}$)

Galactic Cosmic Rays



Standard paradigm for galactic CR sources: supernova remnants

- SNRs provide sufficient energy budget for CRs
  (if $> 10\%$ of explosion energy is transferred to CRs)
- known astrophysical mechanism - diffusion shock acceleration

CR 'knee' as an acceleration cutoff

- DSA is able to accelerate protons up to the 'knee' ($\sim 10^{15}$ eV)
- $\Rightarrow$ the knee can be the signature of proton acceleration cutoff
- acceleration (by magnetic fields) depends on particle rigidity $E/Z \Rightarrow$ nuclei can be accelerated to (Z-times) higher energies
- $\Rightarrow$ rigidity-dependent partial 'nuclear knees' may be expected
  (e.g. $E_{He}^{\mathrm{knee}} = 2E_{p}^{\mathrm{knee}}$, $E_{Fe}^{\mathrm{knee}} = 26E_{p}^{\mathrm{knee}}$)

Galactic Cosmic Rays

Alternative explanation for the 'knee': propagation effect

- above certain energy CRs aren't efficiently scattered by turbulent magnetic fieds of the Galaxy
- $\Rightarrow$ CR escape from the Galaxy also produces rigidity-dependent 'knees'

Galactic Cosmic Rays

Alternative explanation for the 'knee': propagation effect

- above certain energy CRs aren't efficiently scattered by turbulent magnetic fieds of the Galaxy
- $\Rightarrow$ CR escape from the Galaxy also produces rigidity-dependent 'knees'

Galactic Cosmic Rays

Alternative explanation for the 'knee': propagation effect

- above certain energy CRs aren't efficiently scattered by turbulent magnetic fieds of the Galaxy
- $\Rightarrow$ CR escape from the Galaxy also produces rigidity-dependent 'knees'

Galactic Cosmic Rays

Alternative explanation for the 'knee': propagation effect

- above certain energy CRs aren't efficiently scattered by turbulent magnetic fieds of the Galaxy
- $\Rightarrow$ CR escape from the Galaxy also produces rigidity-dependent 'knees'

Speculative scenario

- more exotic 'knee' explanations assume a sudden change of hadronic physics above certain energy scale
- $\Rightarrow$ 'knee' position defined by total energy of the primary particle (independent on Z)

Galactic Cosmic Rays

Alternative explanation for the 'knee': propagation effect

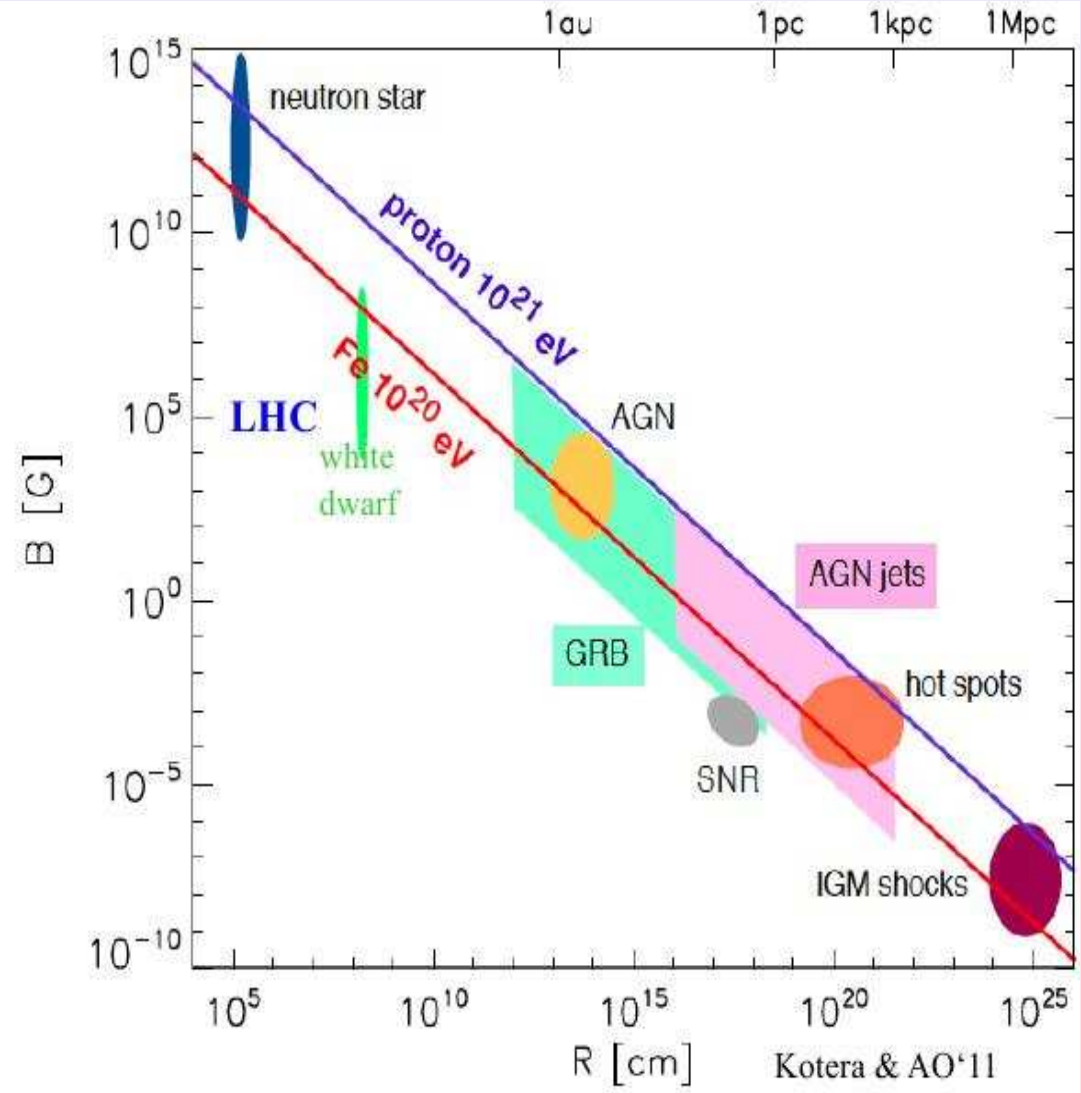
- above certain energy CRs aren't efficiently scattered by turbulent magnetic fieds of the Galaxy
- $\Rightarrow$ CR escape from the Galaxy also produces rigidity-dependent 'knees'

Speculative scenario

- more exotic 'knee' explanations assume a sudden change of hadronic physics above certain energy scale
- $\Rightarrow$ 'knee' position defined by total energy of the primary particle (independent on Z)

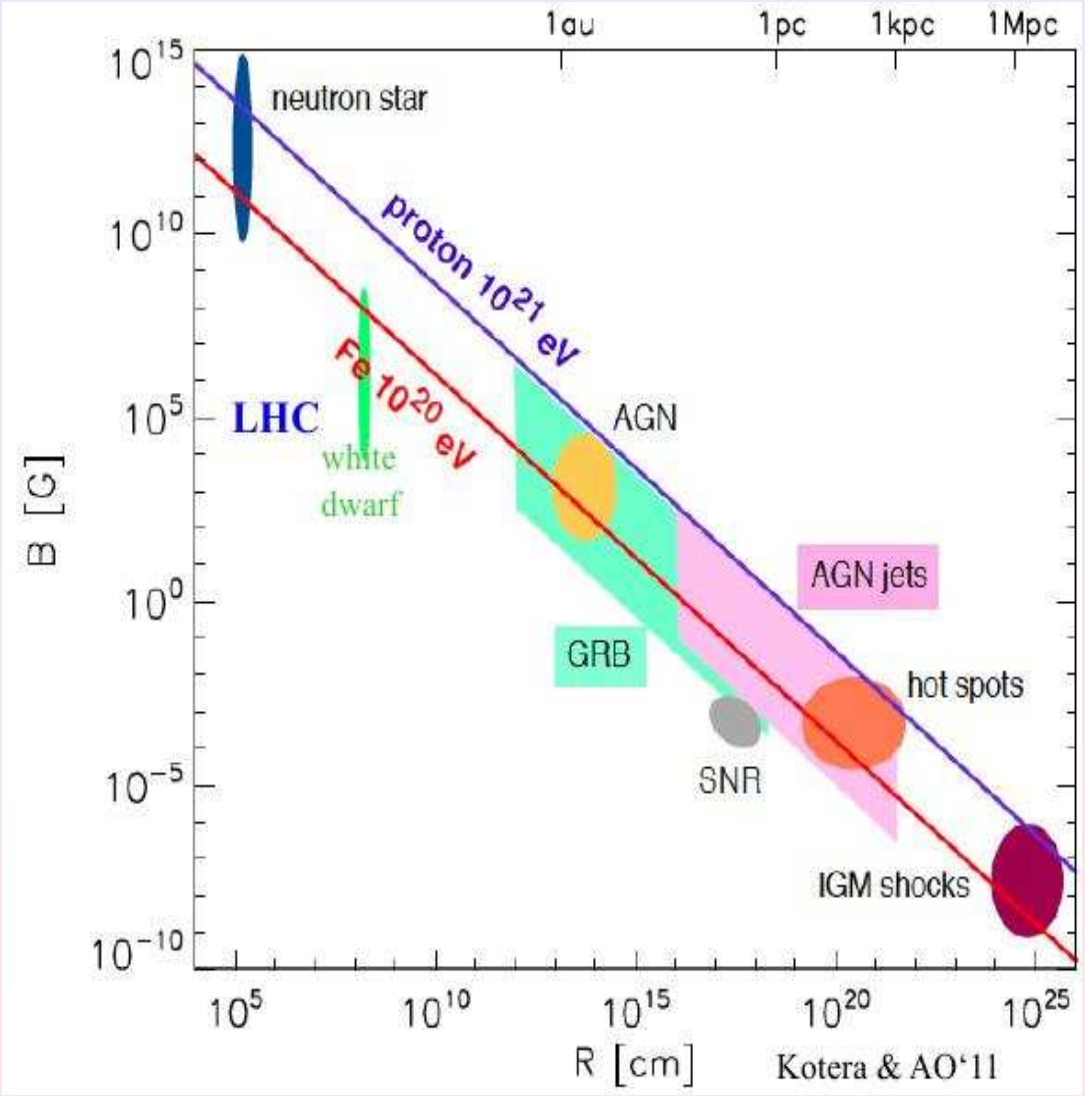
Ultra-High Energy Cosmic Rays (UHECR)

Potential UHECR sources – Hillas's condition: CRs to be retained in the source for sufficiently long time $\Rightarrow E_{\rm max} \propto B_{\rm source}\, R_{\rm source}$



Ultra-High Energy Cosmic Rays (UHECR)

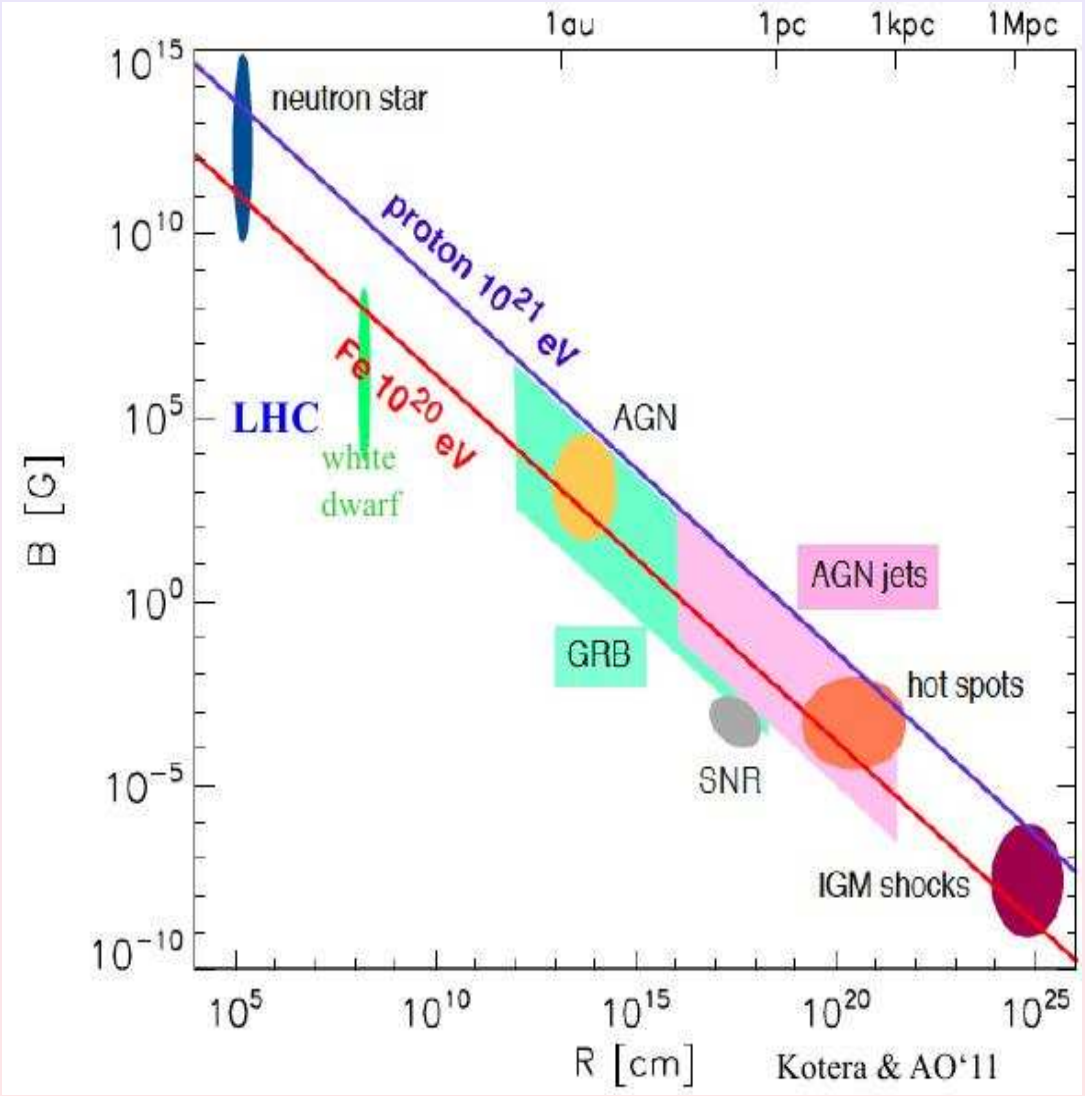
Potential UHECR sources – Hillas's condition: CRs to be retained in the source for sufficiently long time $\Rightarrow E_{\rm max} \propto B_{\rm source}\, R_{\rm source}$



- additional constaints – from energy losses in the source
- $\Rightarrow$ UHECR sources – most likely extragalactic
- favorable option – Active Galactic Nuclei (AGN)

Ultra-High Energy Cosmic Rays (UHECR)

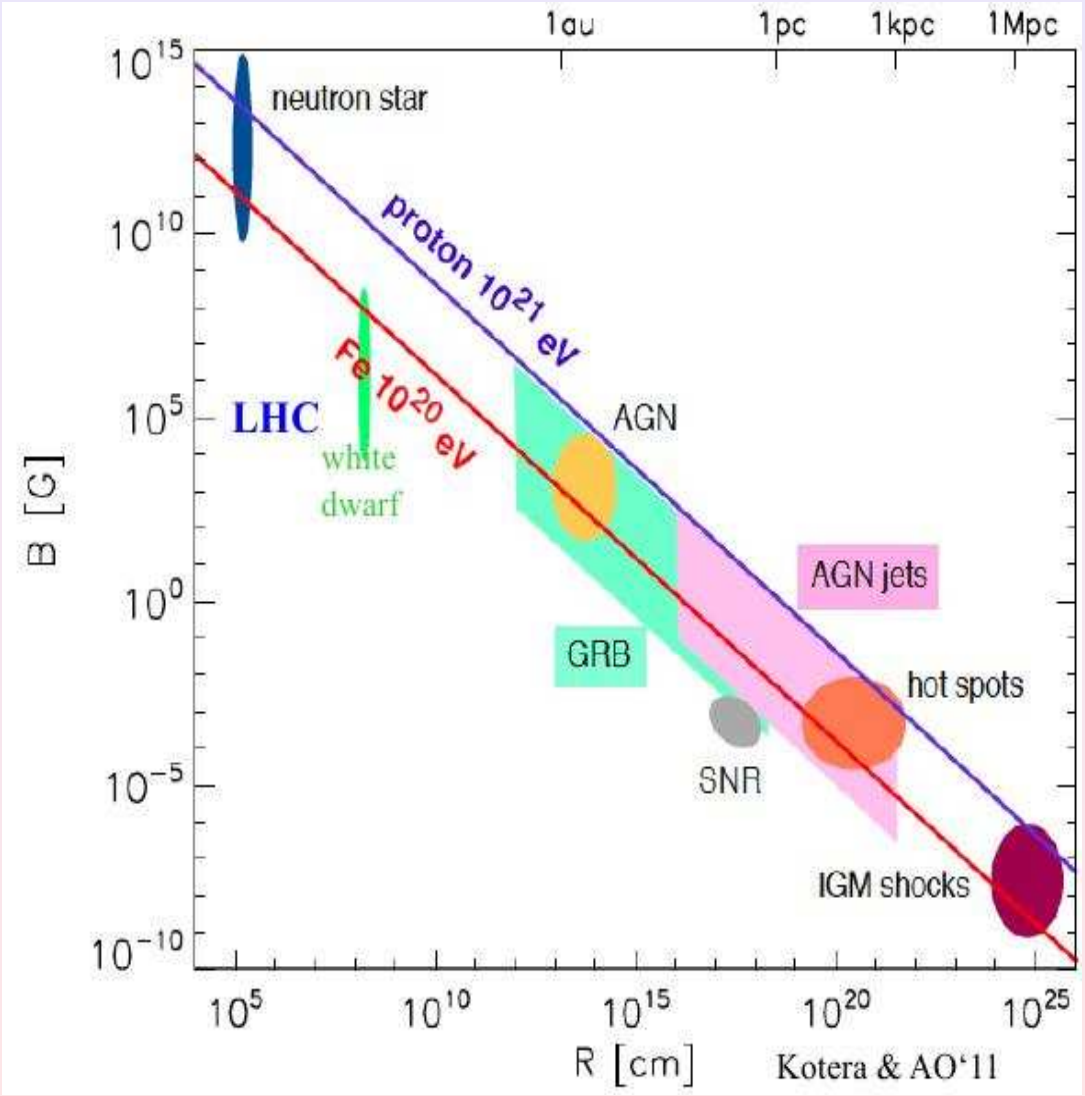
Potential UHECR sources – Hillas's condition: CRs to be retained in the source for sufficiently long time $\Rightarrow E_{\rm max} \propto B_{\rm source}\, R_{\rm source}$



- additional constaints – from energy losses in the source
- $\Rightarrow$ UHECR sources – most likely extragalactic
- favorable option – Active Galactic Nuclei (AGN)

Ultra-High Energy Cosmic Rays (UHECR)

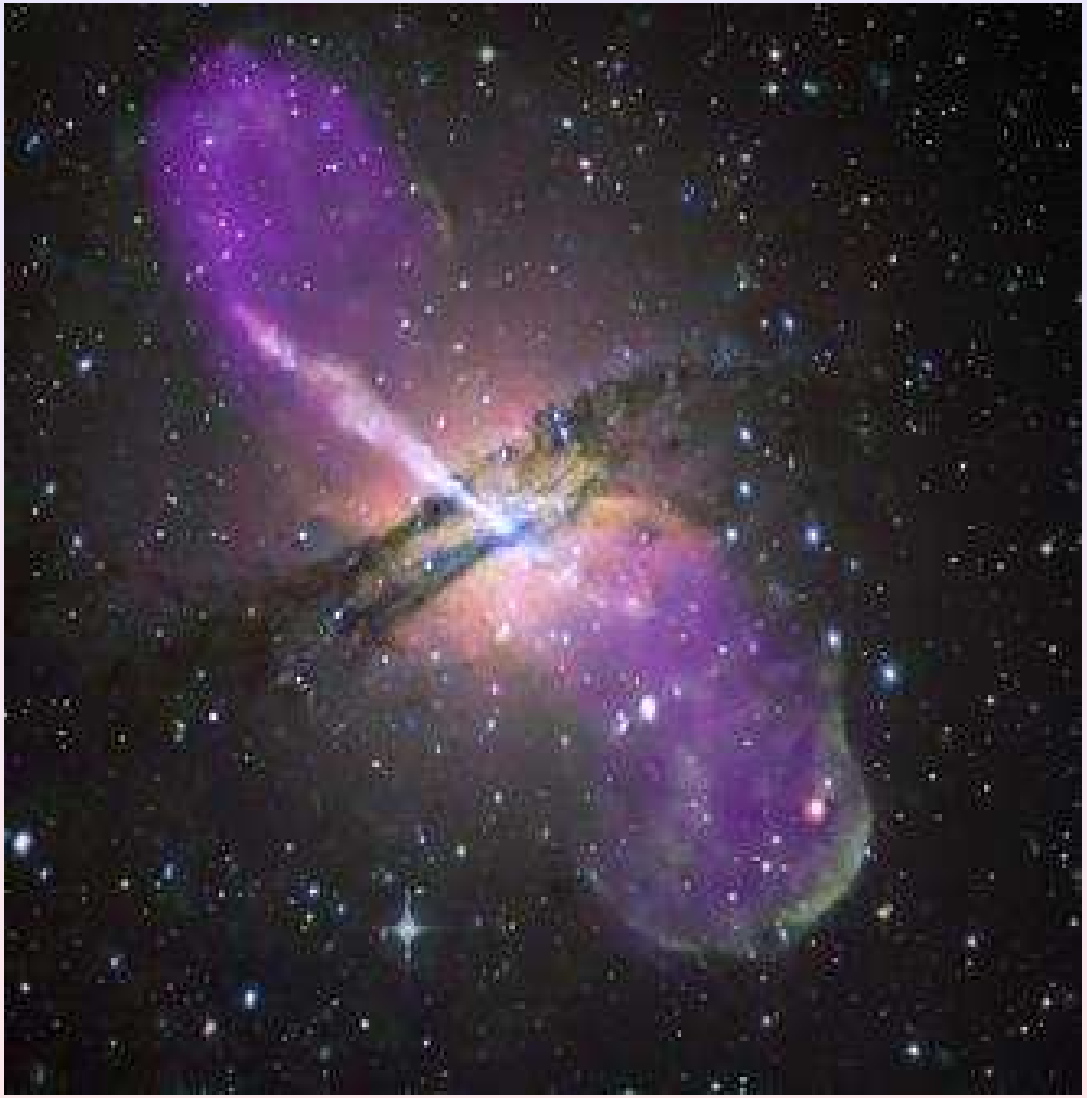
Potential UHECR sources – Hillas's condition: CRs to be retained in the source for sufficiently long time $\Rightarrow E_{\rm max} \propto B_{\rm source}\, R_{\rm source}$



- additional constaints – from energy losses in the source
- $\Rightarrow$ UHECR sources – most likely extragalactic
- favorable option – Active Galactic Nuclei (AGN)

Ultra-High Energy Cosmic Rays (UHECR)

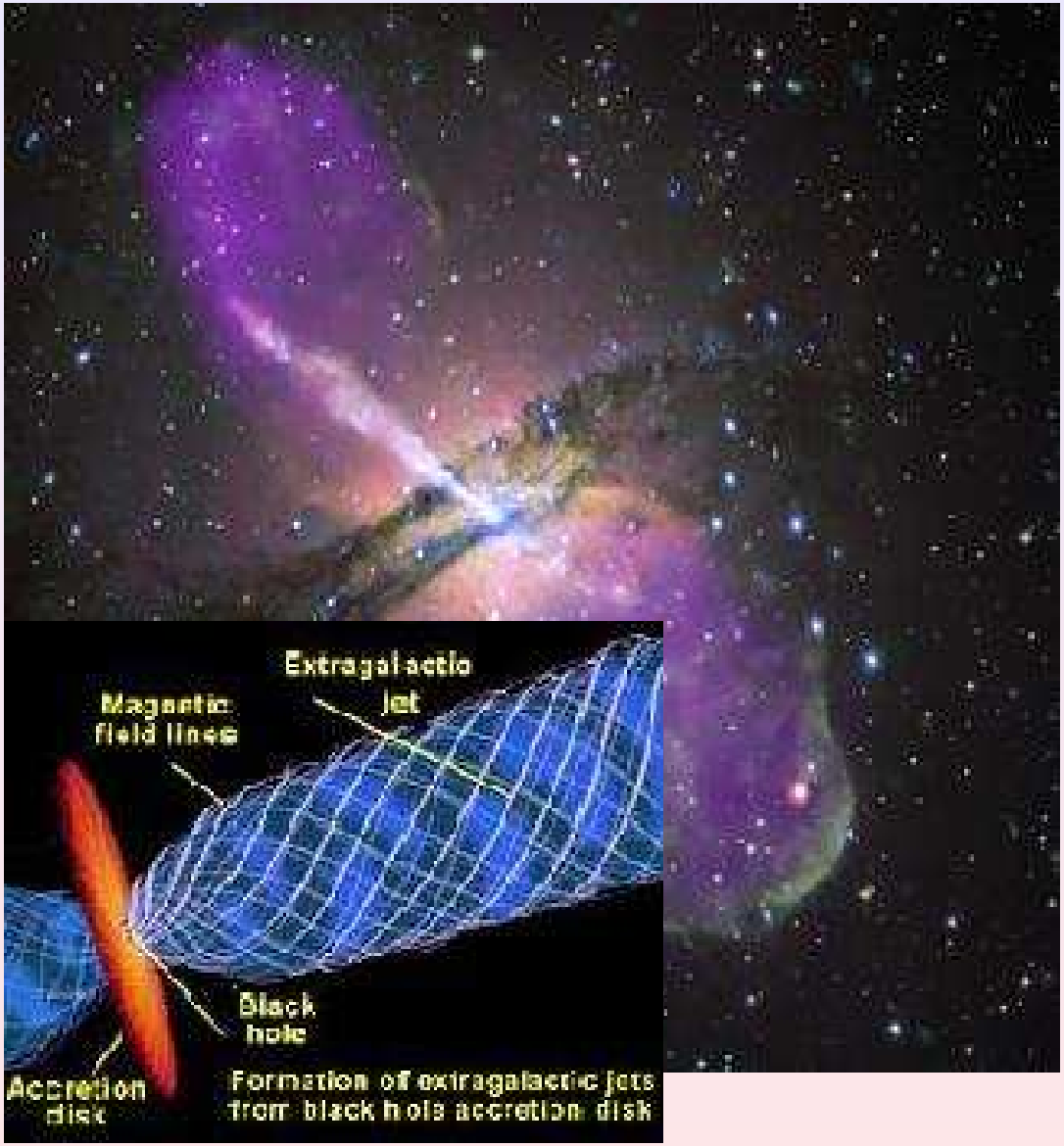
nearest to us AGN – Centaurus A:



- additional constaints – from energy losses in the source
- $\Rightarrow$ UHECR sources – most likely extragalactic
- favorable option – Active Galactic Nuclei (AGN)

Ultra-High Energy Cosmic Rays (UHECR)

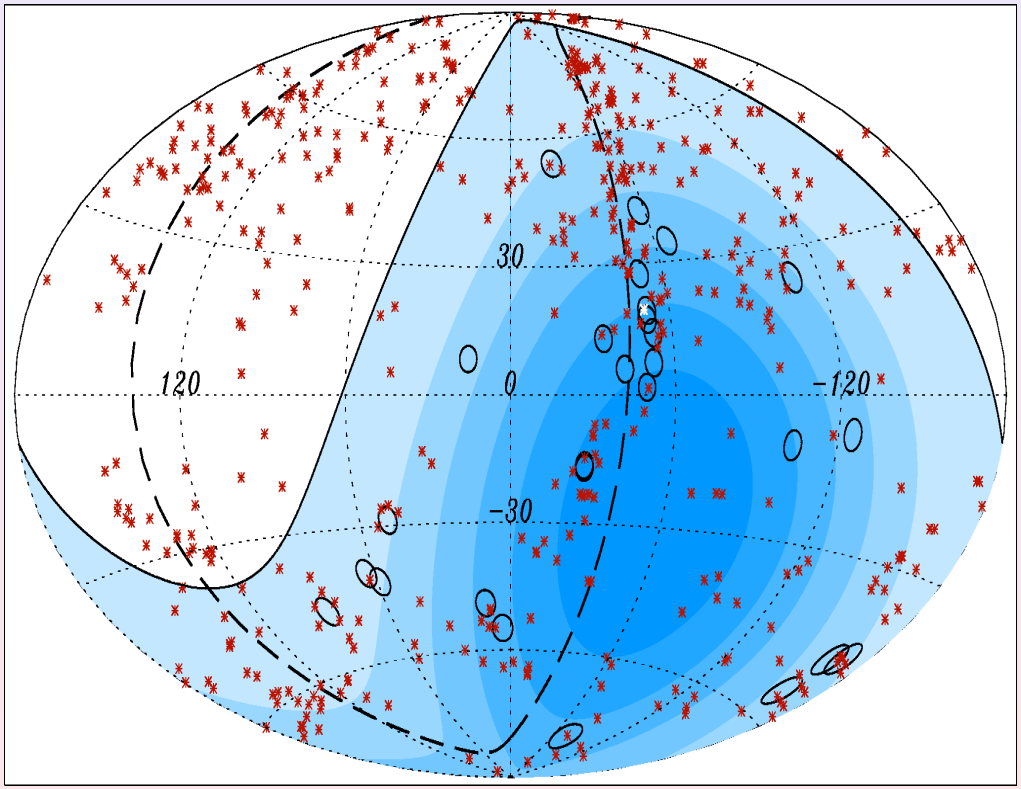
nearest to us AGN – Centaurus A:



- additional constaints – from energy losses in the source
- $\Rightarrow$ UHECR sources – most likely extragalactic
- favorable option – Active Galactic Nuclei (AGN)
- CR acceleration possible near the black hole or in a jet/lobe

AGNs already established as UHECR sources?

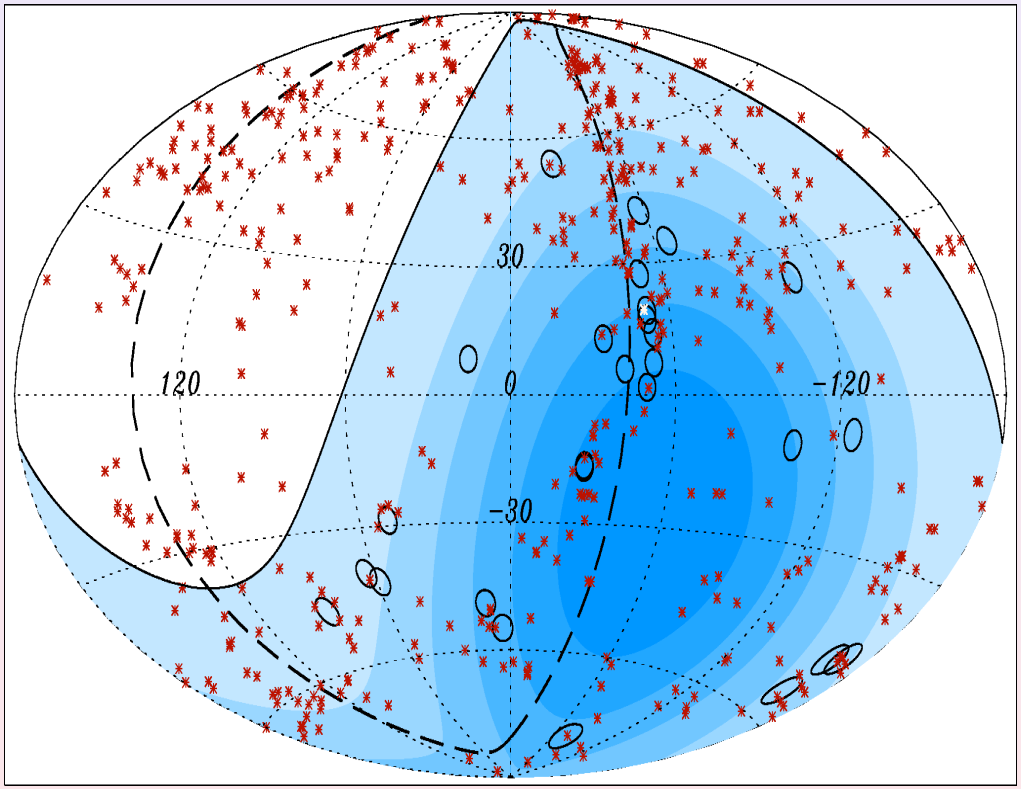
Pierre Auger Collaboration: correlation of UHECR arrival directions with nearby AGNs at 3σ level *[Science 318 (2007) 938]*



- correlation angular scale (3^o) – consistent with expected deflections for protons
- considerable excess of events in the direction of CenA

AGNs already established as UHECR sources?

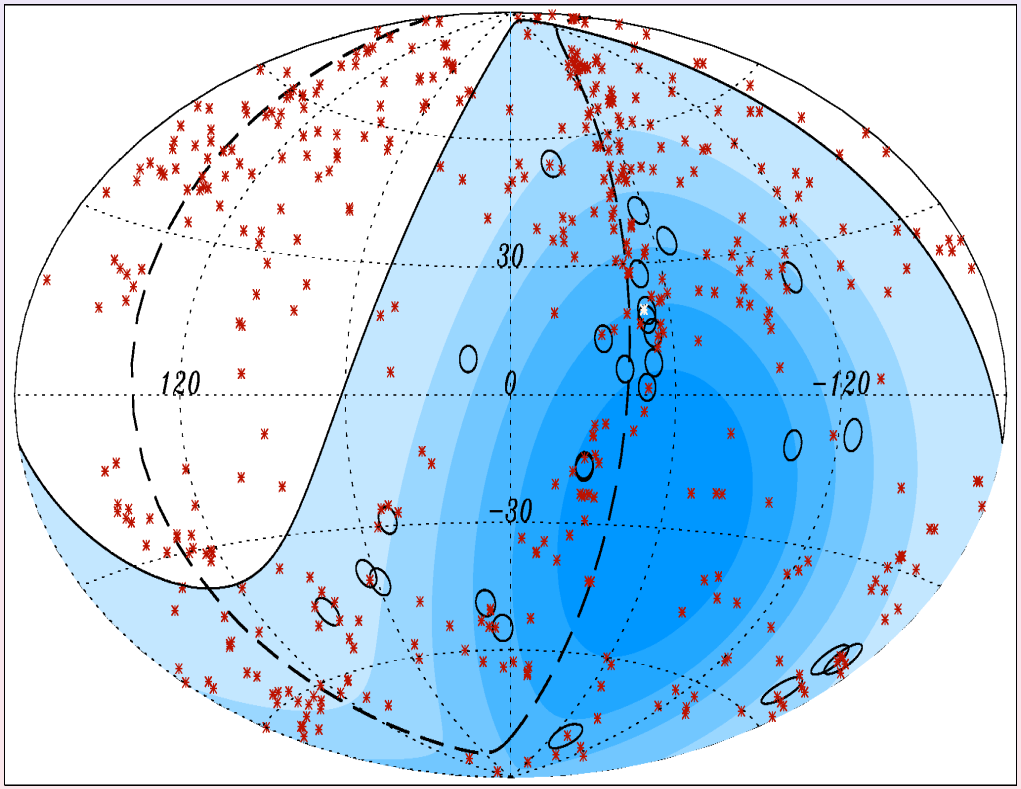
Pierre Auger Collaboration: correlation of UHECR arrival directions with nearby AGNs at 3σ level *[Science 318 (2007) 938]*



- correlation angular scale (3^o) – consistent with expected deflections for protons
- considerable excess of events in the direction of CenA

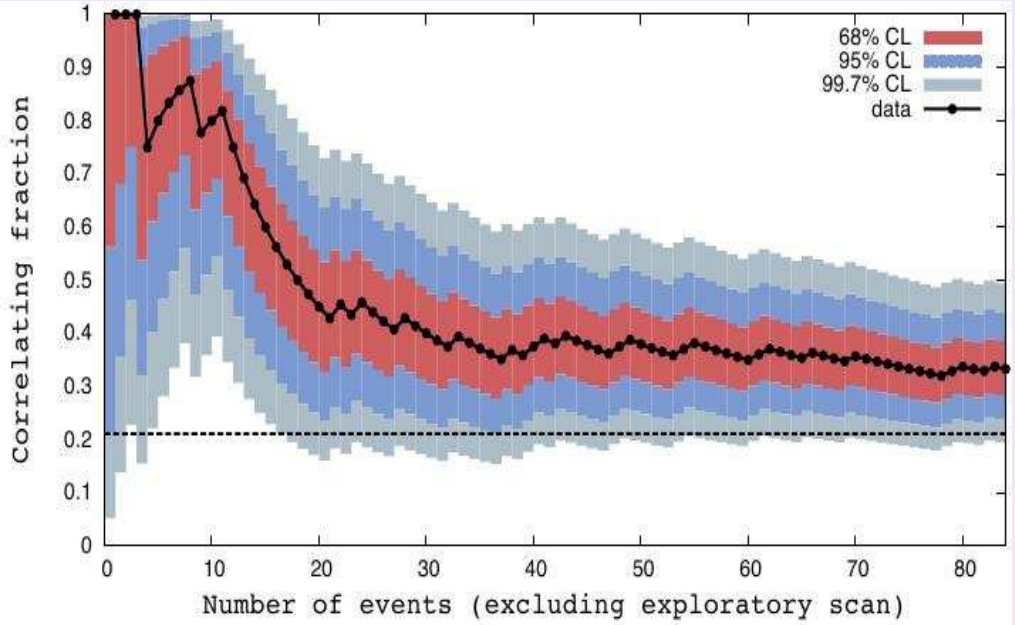
AGNs already established as UHECR sources?

Pierre Auger Collaboration: correlation of UHECR arrival directions with nearby AGNs at 3σ level *[Science 318 (2007) 938]*



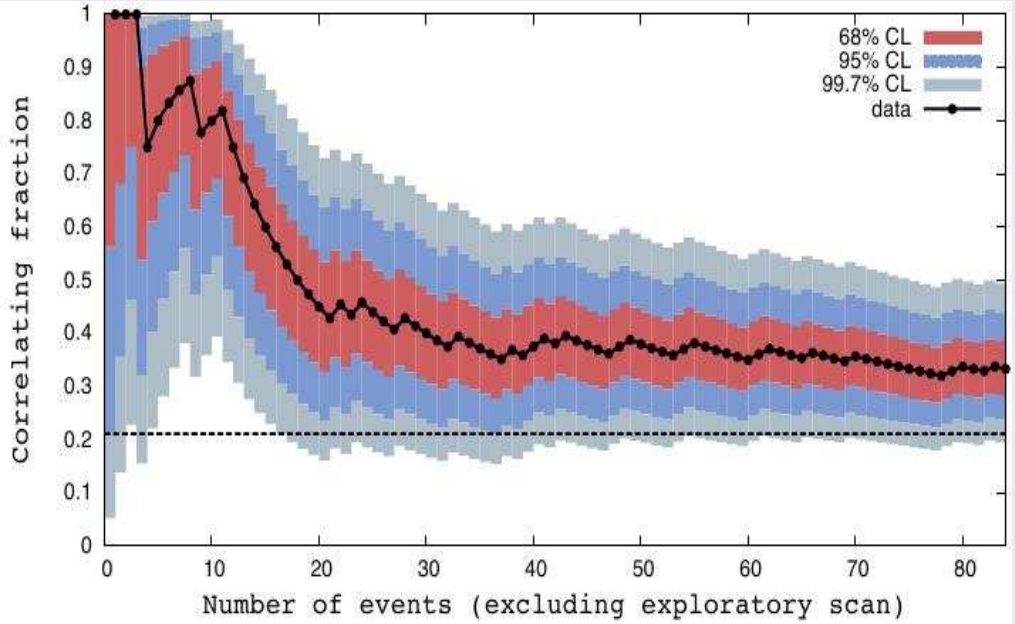
- correlation angular scale (3^o) – consistent with expected deflections for protons
- considerable excess of events in the direction of CenA

AGNs already established as UHECR sources?



- however: correlation signal weakened for larger event sample
- now: 2σ deviation from isotropic distribution

AGNs already established as UHECR sources?

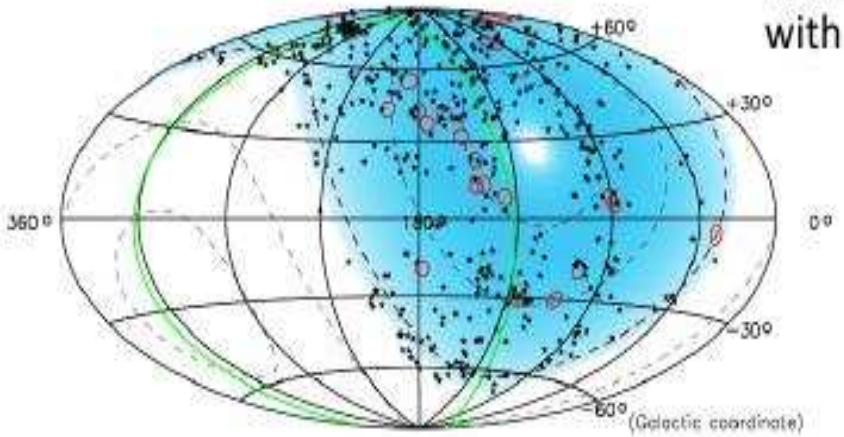


- however: correlation signal weakened for larger event sample
- now: 2σ deviation from isotropic distribution

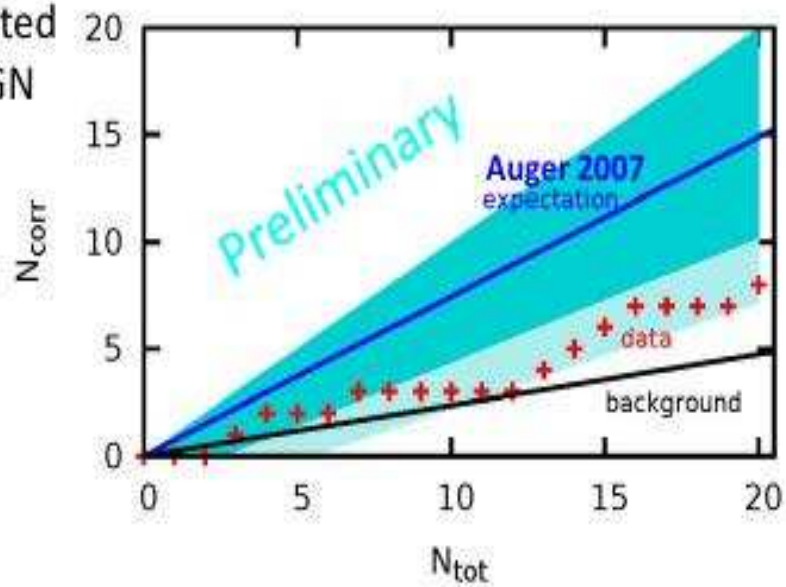
AGNs already established as UHECR sources?

Telescope Array Collaboration: 8 events out of 20 correlate with AGNs *[Sagawa, talk at TeVPA-2011]*

- TA SD data beyond 57 EeV
- Veron catalog 12th edition AGN
  - z<0.018
- Correlations of data with AGN within 3.1°



Number of TA data correlated with AGN

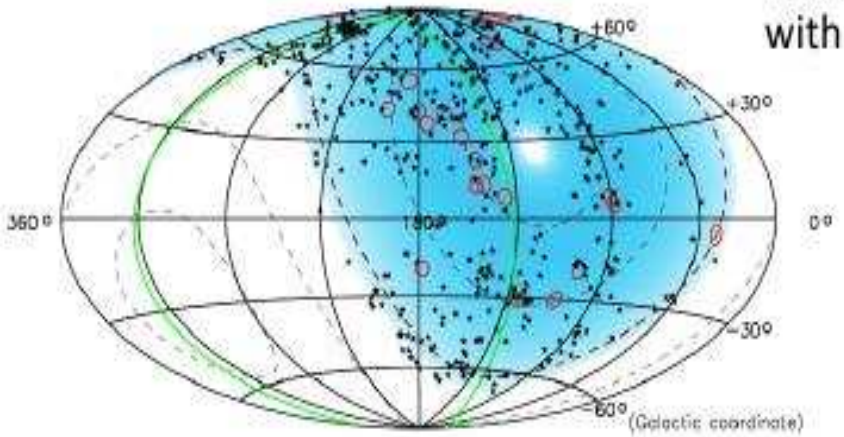


Number of TA data

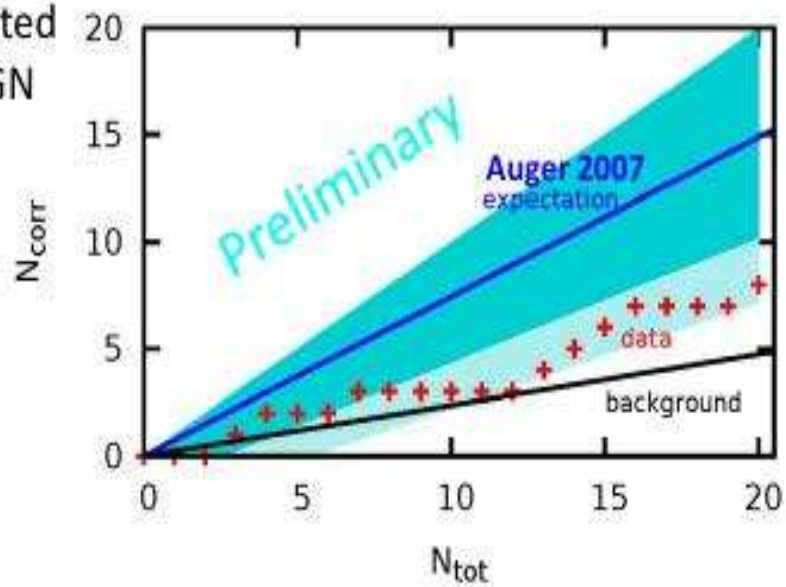
AGNs already established as UHECR sources?

Telescope Array Collaboration: 8 events out of 20 correlate with AGNs *[Sagawa, talk at TeVPA-2011]*

- TA SD data beyond 57 EeV
- Veron catalog 12th edition AGN
  - z<0.018
- Correlations of data with AGN within 3.1°



Number of TA data correlated with AGN



Number of TA data

- $\Rightarrow$ consistent both with the isotropy and with the AGN correlation hypothesis

Propagation in extragalactic space & GZK cutoff

- why restrict oneself with nearby sources?

Propagation in extragalactic space & GZK cutoff

- why restrict oneself with nearby sources?
- the Universe is filled with 2.7K cosmological background radiation (CMB)

Propagation in extragalactic space & GZK cutoff

- why restrict oneself with nearby sources?
- the Universe is filled with 2.7K cosmological background radiation (CMB)
- $\Rightarrow$ UHE protons quickly loose energy on CMB
  [Greisen, PRL 16 (1966); Zatsepin & Kuzmin, JETP Lett. 4 (1966)]

$$p + \gamma_{\mathrm{CMB}} \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

$\Rightarrow$ beyond ~ 100 Mpc the Universe is opaque for UHECR

Propagation in extragalactic space & GZK cutoff

- why restrict oneself with nearby sources?
- the Universe is filled with 2.7K cosmological background radiation (CMB)
- $\Rightarrow$ UHE protons quickly loose energy on CMB
  [Greisen, PRL 16 (1966); Zatsepin & Kuzmin, JETP Lett. 4 (1966)]

$$p + \gamma_{\mathrm{CMB}} \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

  $\Rightarrow$ beyond ~ 100 Mpc the Universe is opaque for UHECR
- for a uniform distribution of extragalactic CR sources results in a spectral cutoff at $E \sim 5 \times 10^{19}$ eV (GZK-cutoff)

Propagation in extragalactic space & GZK cutoff

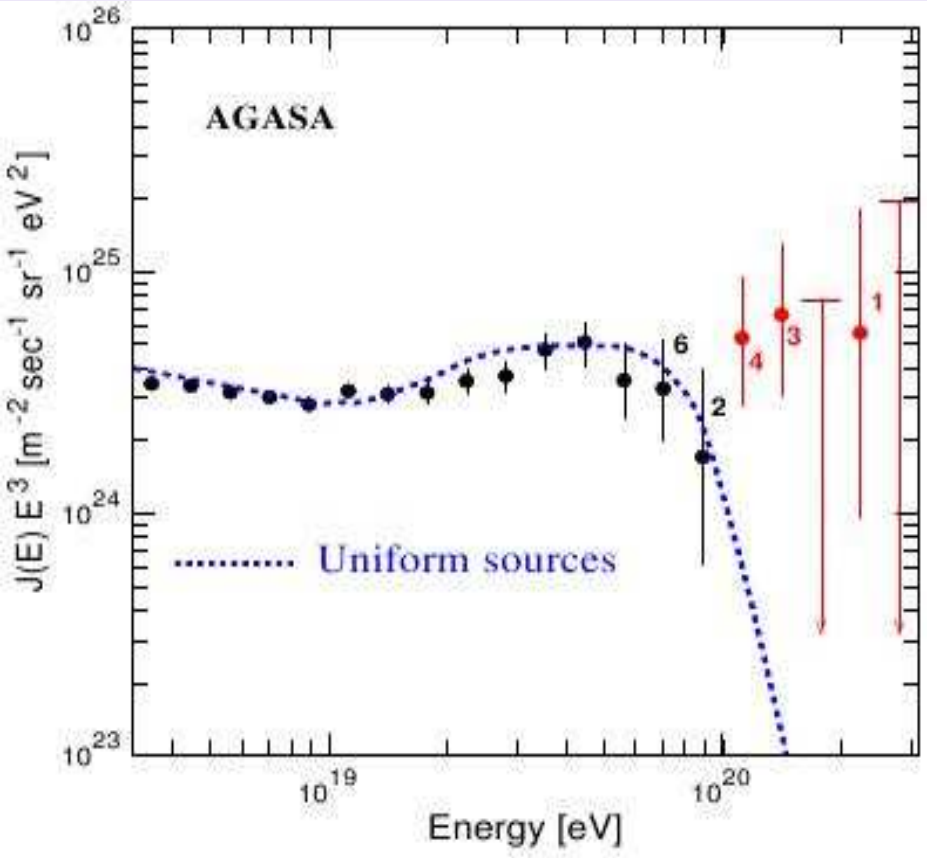
- why restrict oneself with nearby sources?
- the Universe is filled with 2.7K cosmological background radiation (CMB)
- $\Rightarrow$ UHE protons quickly loose energy on CMB
  [Greisen, PRL 16 (1966); Zatsepin & Kuzmin, JETP Lett. 4 (1966)]

$$p + \gamma_{\mathrm{CMB}} \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

  $\Rightarrow$ beyond ~ 100 Mpc the Universe is opaque for UHECR
- for a uniform distribution of extragalactic CR sources results in a spectral cutoff at $E \sim 5 \times 10^{19}$ eV (GZK-cutoff)
- in turn, UHE nuclei loose energy via photodisintegration on IR photons: $A + \gamma \rightarrow (A-1) + p/n \Rightarrow$ similar cutoff

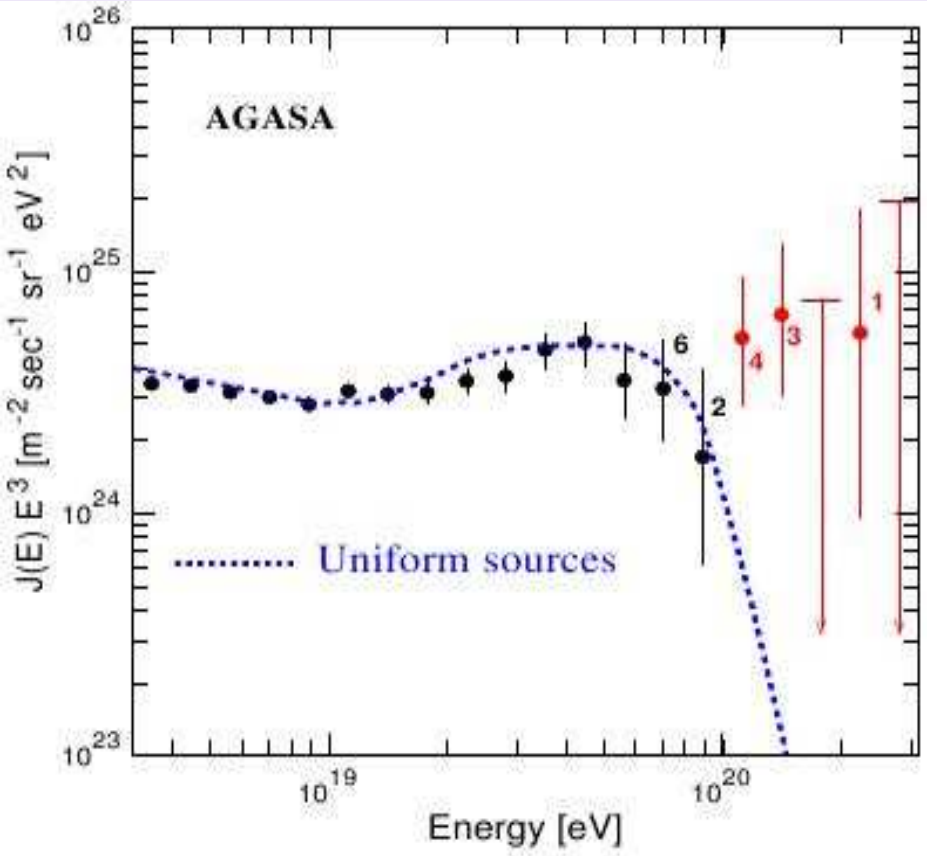
Trans-GZK events & physics beyond the Standard Model?

Observation of trans-GZK events by the AGASA Collaboration *[PRL 81 (1998)]*



Trans-GZK events & physics beyond the Standard Model?

Observation of trans-GZK events by the AGASA Collaboration *[PRL 81 (1998)]*

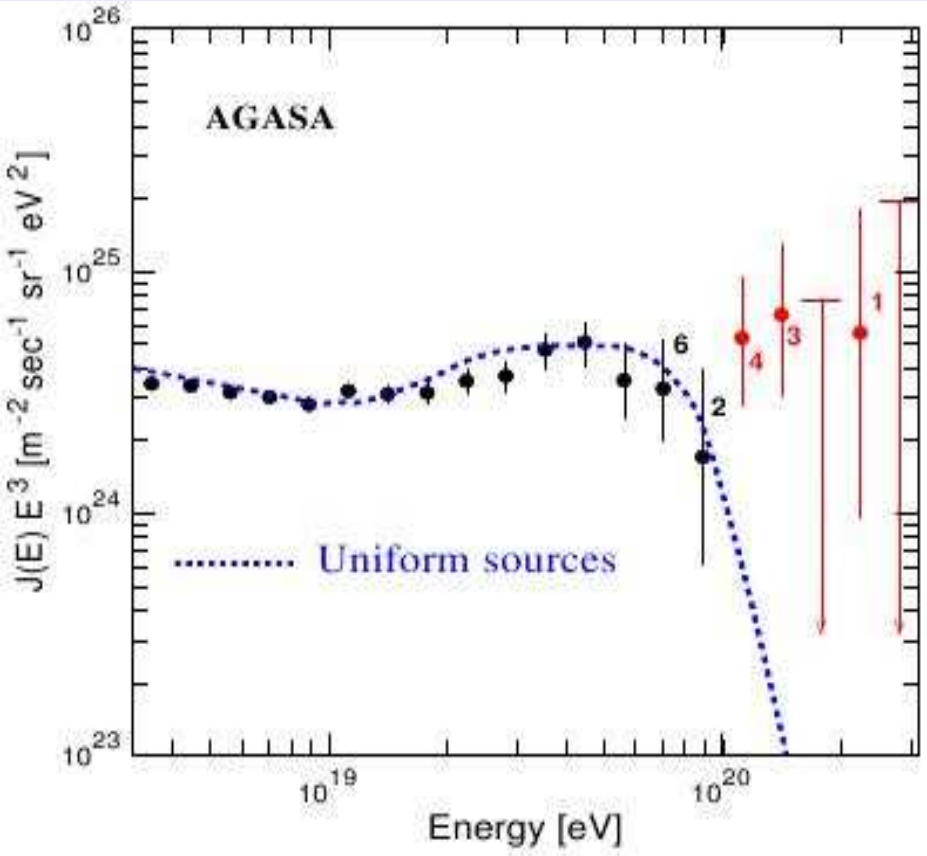


$\Rightarrow$ non-SM explanations of UHECR origin:

- decays of cosmological relics: topological defects, superheavy X-particles
- Lorentz invariance violation
- 'Z-birst': annihilation of UHE (anti-)neutrinos with DM ones

Trans-GZK events & physics beyond the Standard Model?

Observation of trans-GZK events by the AGASA Collaboration *[PRL 81 (1998)]*

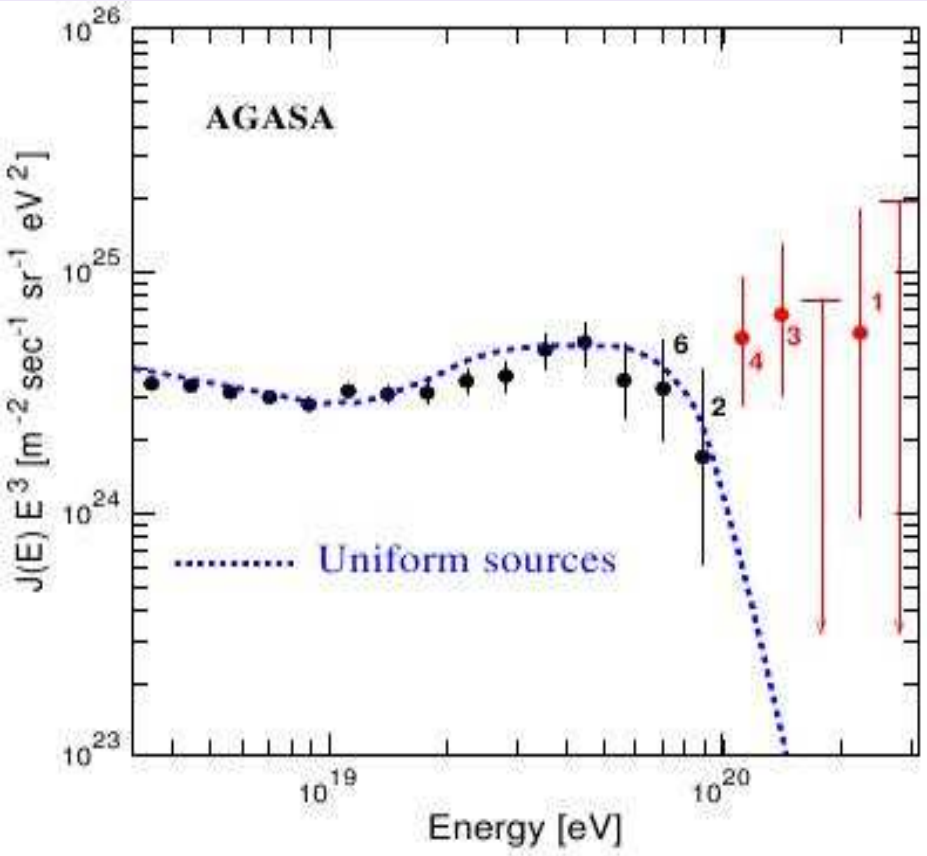


$\Rightarrow$ non-SM explanations of UHECR origin:

- decays of cosmological relics: topological defects, superheavy X-particles
- Lorentz invariance violation
- 'Z-birst': annihilation of UHE (anti-)neutrinos with DM ones

Trans-GZK events & physics beyond the Standard Model?

Observation of trans-GZK events by the AGASA Collaboration *[PRL 81 (1998)]*

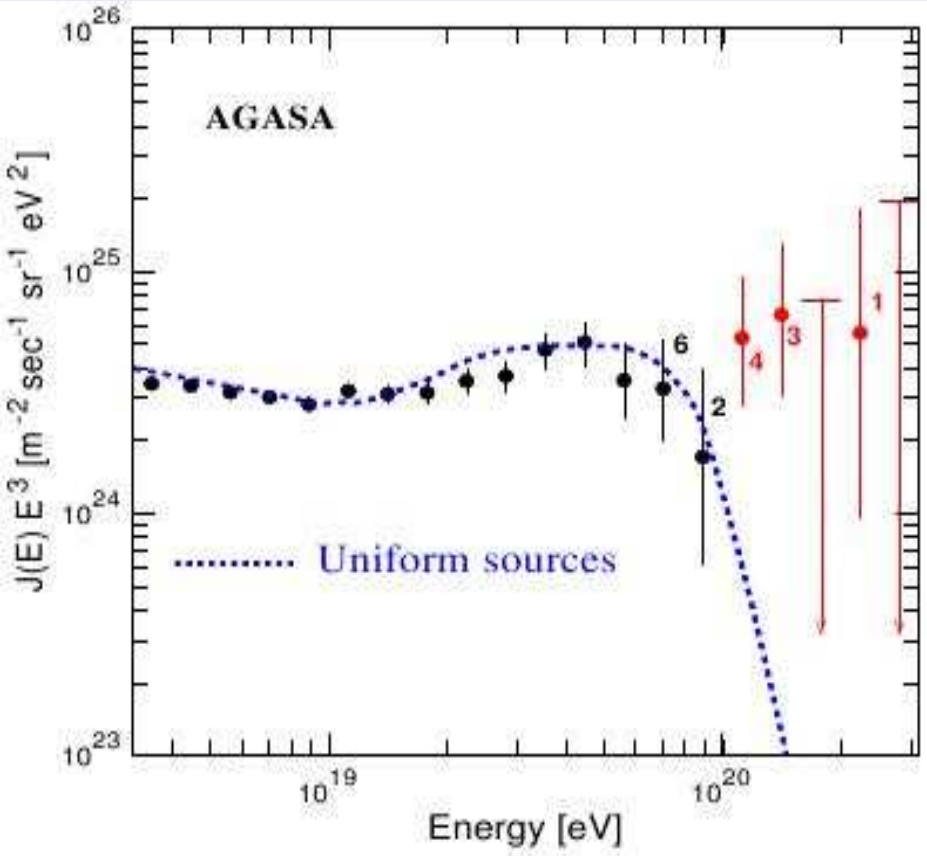


$\Rightarrow$ non-SM explanations of UHECR origin:

- decays of cosmological relics: topological defects, superheavy X-particles
- Lorentz invariance violation
- 'Z-birst': annihilation of UHE (anti-)neutrinos with DM ones

Trans-GZK events & physics beyond the Standard Model?

Observation of trans-GZK events by the AGASA Collaboration *[PRL 81 (1998)]*



$\Rightarrow$ non-SM explanations of UHECR origin:

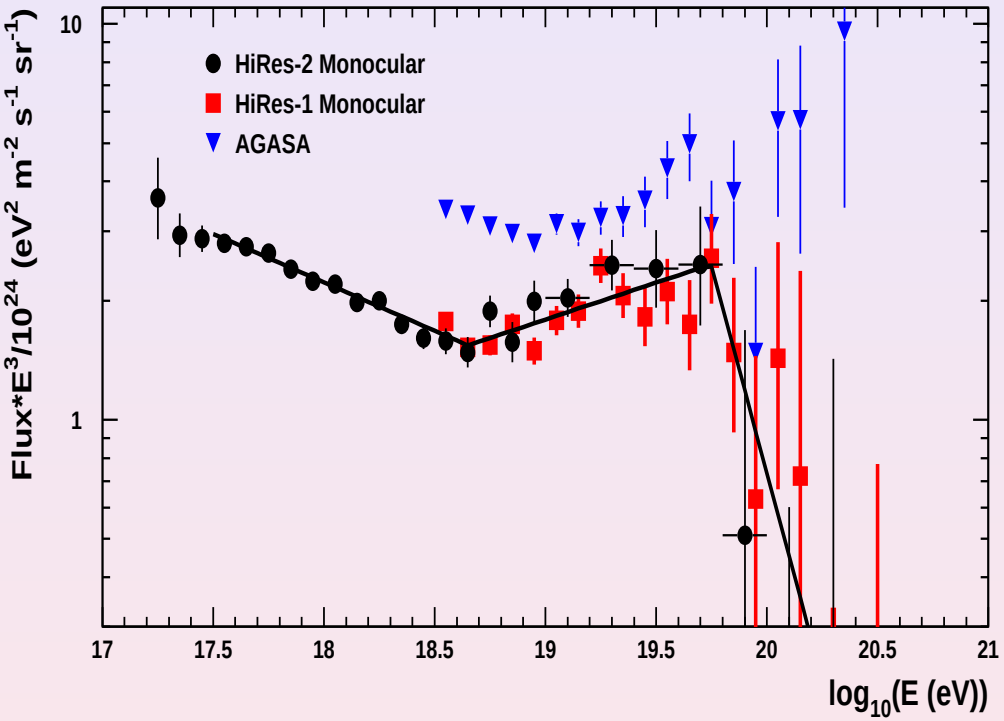
- decays of cosmological relics: topological defects, superheavy X-particles
- Lorentz invariance violation
- 'Z-birst': annihilation of UHE (anti-)neutrinos with DM ones

Trans-GZK events & physics beyond the Standard Model?

Now: UHECR cutoff – observed by 3 independent collaborations

Trans-GZK events & physics beyond the Standard Model?

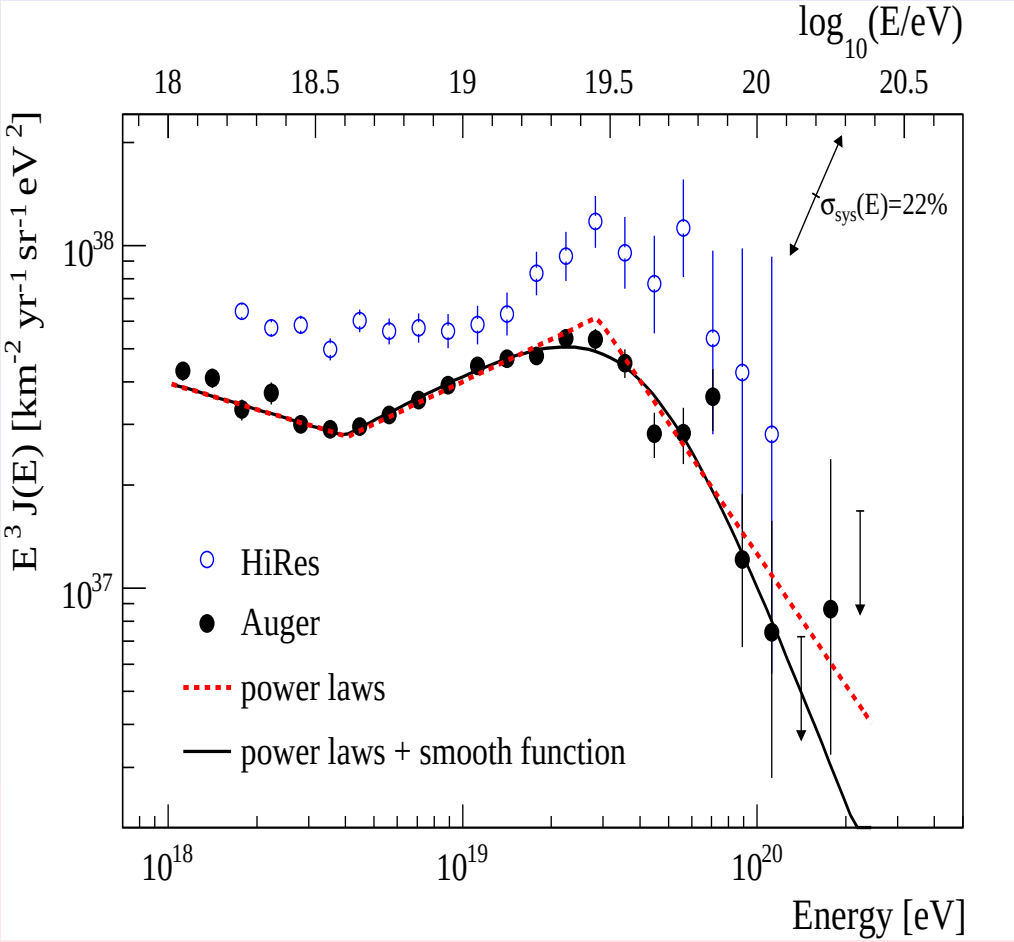
Now: UHECR cutoff – observed by 3 independent collaborations



- HiRes Collaboration *[PRL 100 (2008)]*: GZK-cutoff observed with 5σ significance

Trans-GZK events & physics beyond the Standard Model?

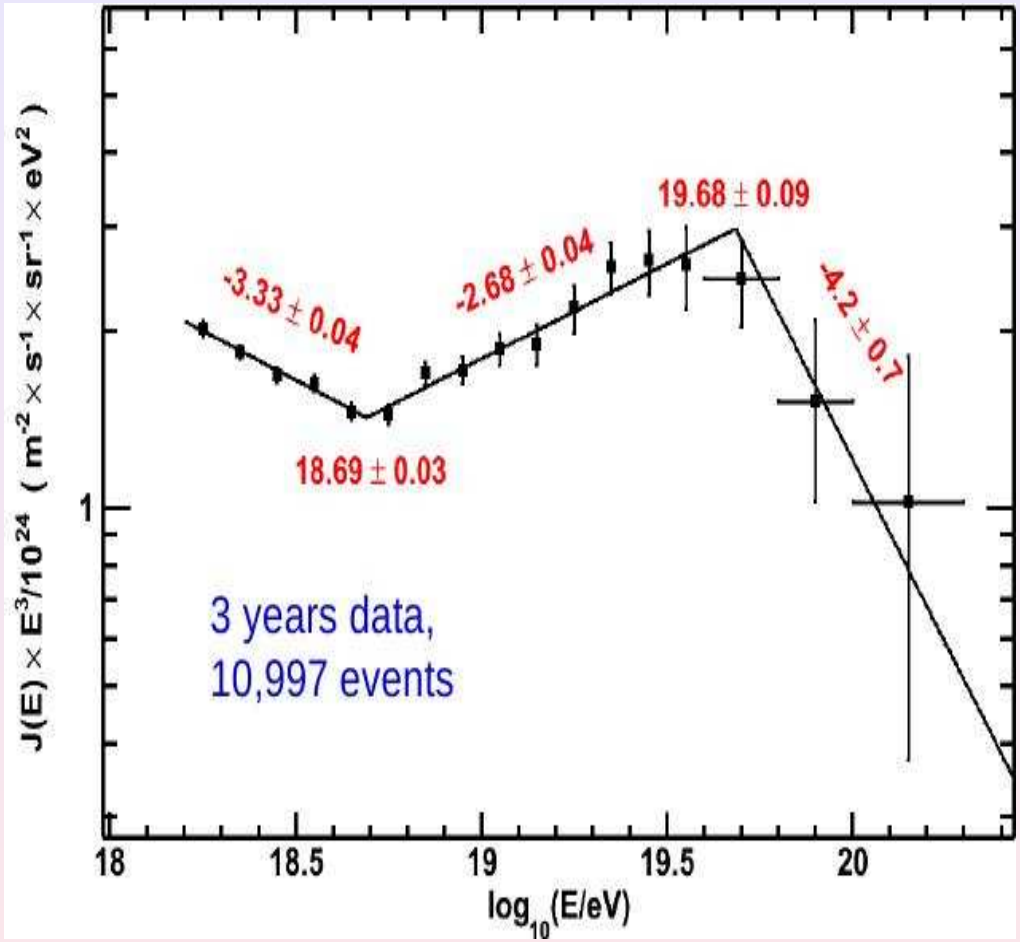
Now: UHECR cutoff – observed by 3 independent collaborations



- HiRes Collaboration *[PRL 100 (2008)]*: GZK-cutoff observed with 5σ significance
- Pierre Auger Collab. *[PRL 101 (2008)]*: cutoff observed with 6σ significance

Trans-GZK events & physics beyond the Standard Model?

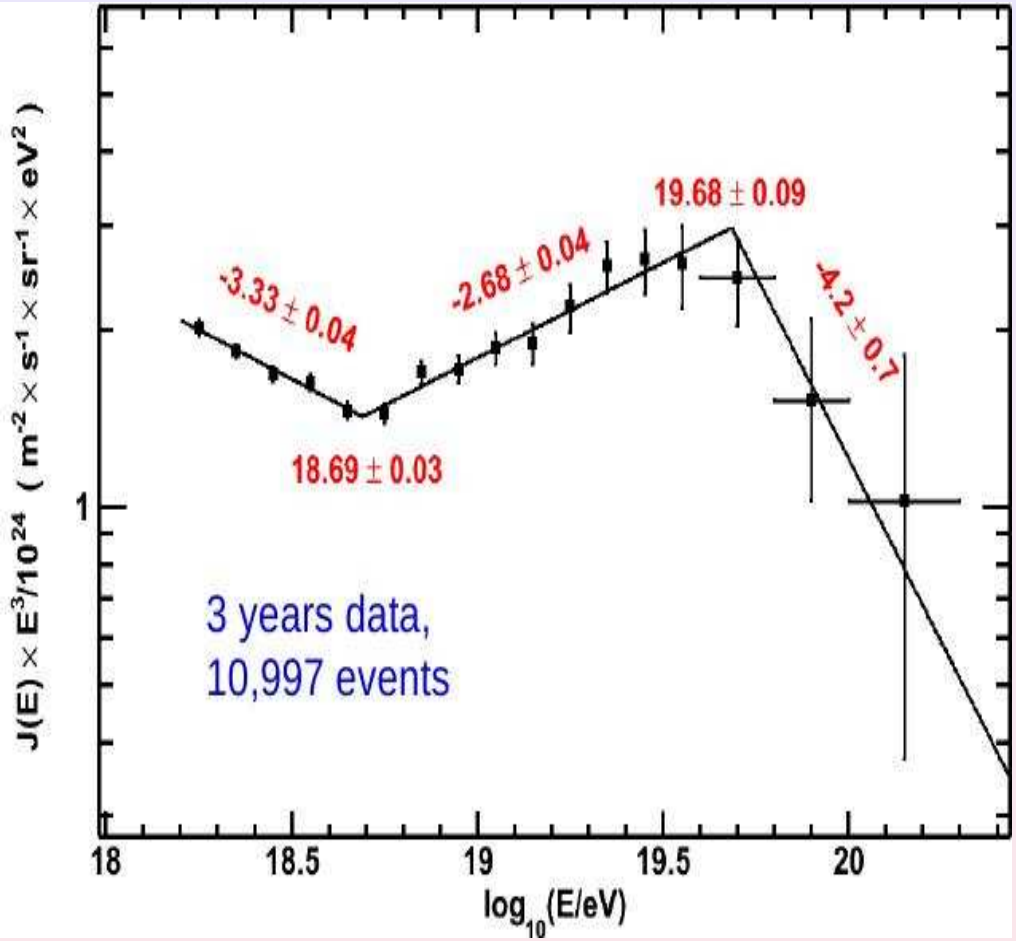
Now: UHECR cutoff – observed by 3 independent collaborations



- HiRes Collaboration *[PRL 100 (2008)]*: GZK-cutoff observed with 5σ significance
- Pierre Auger Collab. *[PRL 101 (2008)]*: cutoff observed with 6σ significance
- Telescope Array Collab. *[Stokes, ICRC-2011]*: cutoff observed with 3.9σ significance

Trans-GZK events & physics beyond the Standard Model?

Now: UHECR cutoff – observed by 3 independent collaborations



- HiRes Collaboration *[PRL 100 (2008)]*: GZK-cutoff observed with 5σ significance
- Pierre Auger Collab. *[PRL 101 (2008)]*: cutoff observed with 6σ significance
- Telescope Array Collab. *[Stokes, ICRC-2011]*: cutoff observed with 3.9σ significance

- trans-GZK story - finally over

UHECR cutoff: GZK or not?

- UHECR also loose energy via e^+e^--pair production on CMB:

$$p + \gamma \rightarrow p + e^+ + e^-$$

UHECR cutoff: GZK or not?

- UHECR also loose energy via e^+e^--pair production on CMB:

$$p + \gamma \rightarrow p + e^+ + e^-$$

- if UHECR are protons: spectral 'dip' will be produced

UHECR cutoff: GZK or not?

- UHECR also loose energy via e^+e^--pair production on CMB:

$$p + \gamma \rightarrow p + e^+ + e^-$$

- if UHECR are protons: spectral 'dip' will be produced
- 'dip' model for galactic-extragalactic transition
  [Berezinsky & Grigor'eva, A&A 199 (1988)]
  - transition takes place well before the 'ankle'
  - observed CR 'ankle' $\equiv$ pair production 'dip'
  - energy-relation between GZK cutoff and the 'ankle' (='dip') – well reproduced

UHECR cutoff: GZK or not?

- UHECR also loose energy via e^+e^--pair production on CMB:

$$p + \gamma \rightarrow p + e^+ + e^-$$

- if UHECR are protons: spectral 'dip' will be produced
- 'dip' model for galactic-extragalactic transition
  [Berezinsky & Grigor'eva, A&A 199 (1988)]
  - transition takes place well before the 'ankle'
  - observed CR 'ankle' $\equiv$ pair production 'dip'
  - energy-relation between GZK cutoff and the 'ankle' (='dip') – well reproduced

UHECR cutoff: GZK or not?

- UHECR also loose energy via e^+e^--pair production on CMB:

$$p + \gamma \rightarrow p + e^+ + e^-$$

- if UHECR are protons: spectral 'dip' will be produced
- 'dip' model for galactic-extragalactic transition
  [Berezinsky & Grigor'eva, A&A 199 (1988)]
  - transition takes place well before the 'ankle'
  - observed CR 'ankle' $\equiv$ pair production 'dip'
  - energy-relation between GZK cutoff and the 'ankle' (='dip') – well reproduced

UHECR cutoff: GZK or not?

- UHECR also loose energy via e^+e^--pair production on CMB:

$$p + \gamma \rightarrow p + e^+ + e^-$$

- if UHECR are protons: spectral 'dip' will be produced
- 'dip' model for galactic-extragalactic transition
  [Berezinsky & Grigor'eva, A&A 199 (1988)]
  - transition takes place well before the 'ankle'
  - observed CR 'ankle' $\equiv$ pair production 'dip'
  - energy-relation between GZK cutoff and the 'ankle' (='dip')
    – well reproduced

UHECR cutoff: GZK or not?

- UHECR also loose energy via e^+e^--pair production on CMB:

$$p + \gamma \rightarrow p + e^+ + e^-$$

- if UHECR are protons: spectral 'dip' will be produced
- 'dip' model for galactic-extragalactic transition
  [Berezinsky & Grigor'eva, A&A 199 (1988)]
  - transition takes place well before the 'ankle'
  - observed CR 'ankle' $\equiv$ pair production 'dip'
  - energy-relation between GZK cutoff and the 'ankle' (='dip') – well reproduced
- if UHECR = Fe: no pronounced 'dip'
- $\Rightarrow$ galactic-extragalactic transition – at the 'ankle'

UHECR cutoff: GZK or not?

- UHECR also loose energy via e^+e^--pair production on CMB:

$$p + \gamma \rightarrow p + e^+ + e^-$$

- if UHECR are protons: spectral 'dip' will be produced
- 'dip' model for galactic-extragalactic transition
  [Berezinsky & Grigor'eva, A&A 199 (1988)]
  - transition takes place well before the 'ankle'
  - observed CR 'ankle' $\equiv$ pair production 'dip'
  - energy-relation between GZK cutoff and the 'ankle' (='dip') – well reproduced
- if UHECR = Fe: no pronounced 'dip'
- $\Rightarrow$ galactic-extragalactic transition – at the 'ankle'

UHECR cutoff: GZK or not?

- UHECR also loose energy via e^+e^--pair production on CMB:

$$p + \gamma \rightarrow p + e^+ + e^-$$

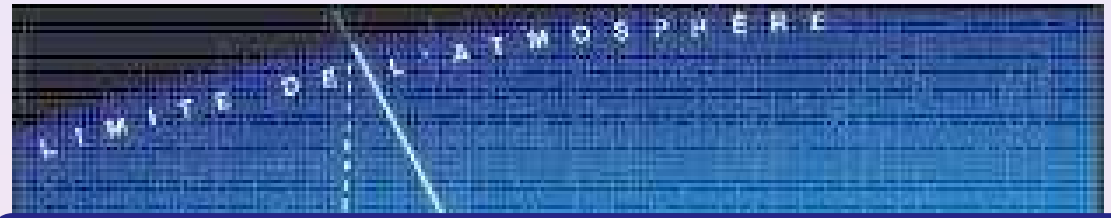
- if UHECR are protons: spectral 'dip' will be produced
- 'dip' model for galactic-extragalactic transition
  [Berezinsky & Grigor'eva, A&A 199 (1988)]
  - transition takes place well before the 'ankle'
  - observed CR 'ankle' $\equiv$ pair production 'dip'
  - energy-relation between GZK cutoff and the 'ankle' (='dip') – well reproduced
- if UHECR = Fe: no pronounced 'dip'
- $\Rightarrow$ galactic-extragalactic transition – at the 'ankle'

$\Rightarrow$ measurements of CR composition – key to the UHECR puzzle

Extensive Air Shower (EAS) techniques of CR detection

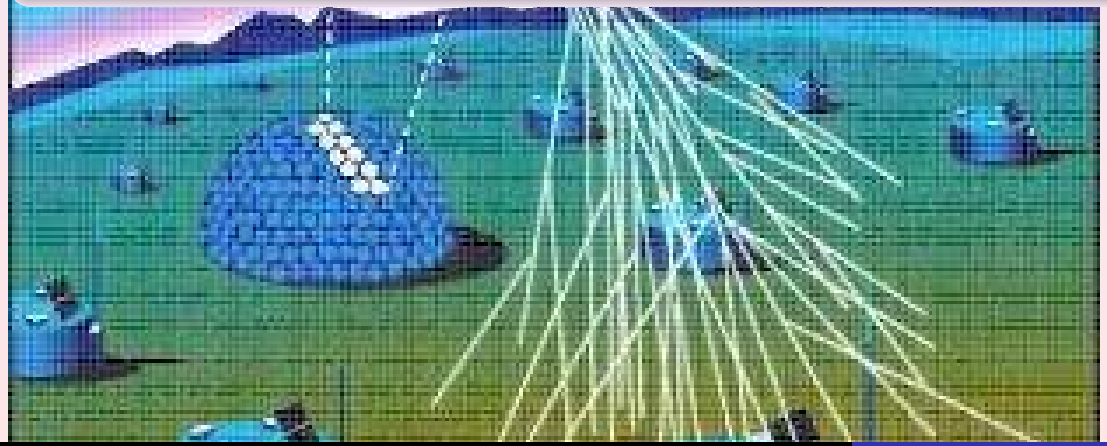
observations of nuclear-e/m cascades induced by CR particles:

Extensive Air Shower (EAS) techniques of CR detection

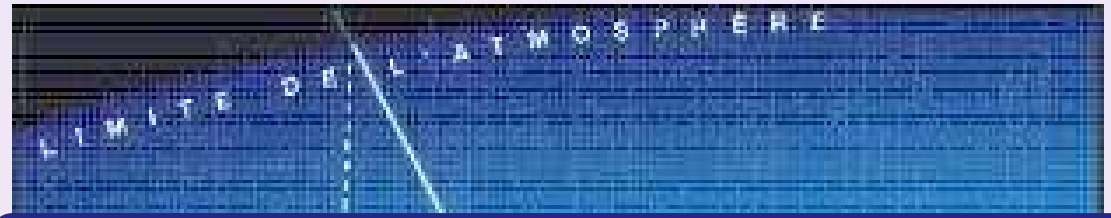


ground-based observations (= thick target experiments)

- primary CR energy $\Longleftrightarrow$ charged particle density at ground
- CR composition $\Longleftrightarrow$ muon density at ground

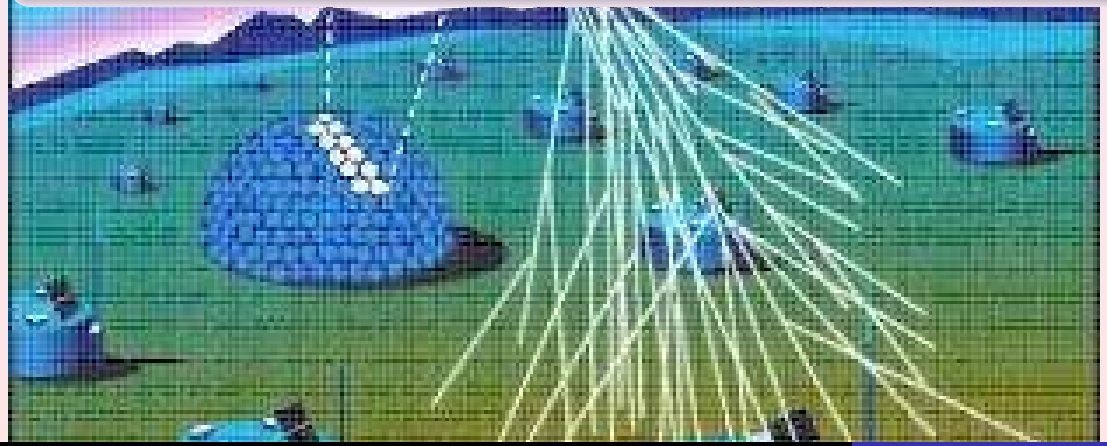


Extensive Air Shower (EAS) techniques of CR detection

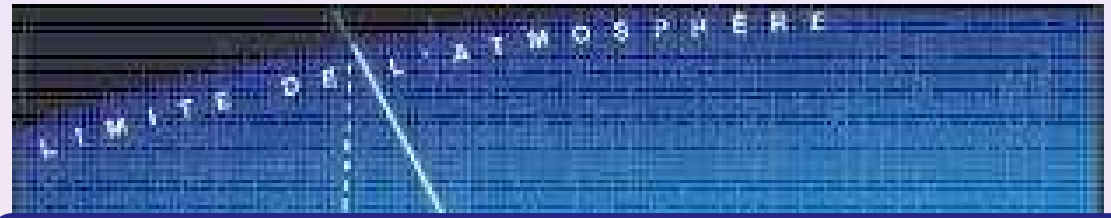


ground-based observations (= thick target experiments)

- primary CR energy $\Longleftrightarrow$ charged particle density at ground
- CR composition $\Longleftrightarrow$ muon density at ground

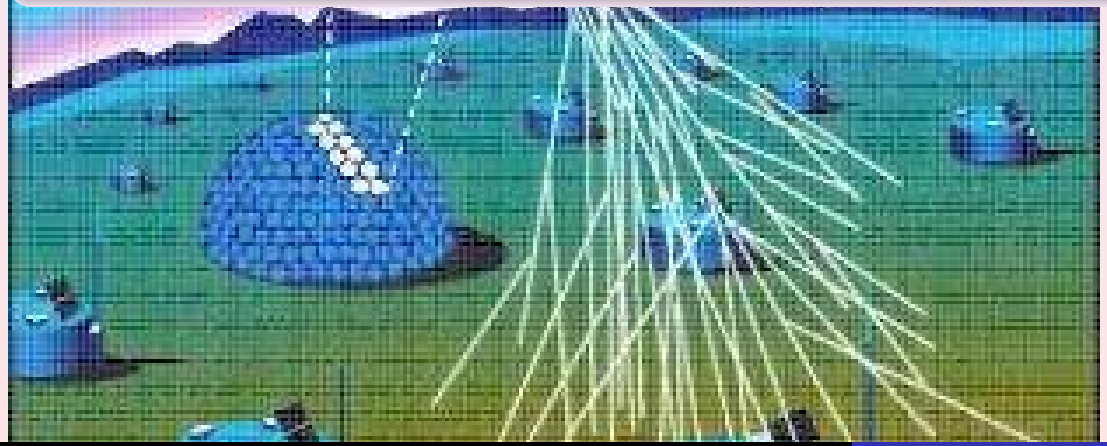


Extensive Air Shower (EAS) techniques of CR detection

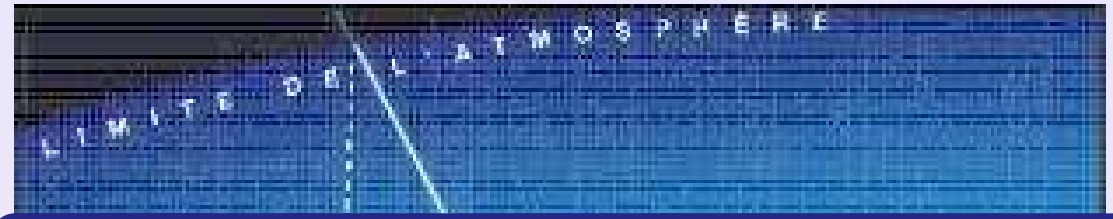


ground-based observations (= thick target experiments)

- primary CR energy $\Longleftrightarrow$ charged particle density at ground
- CR composition $\Longleftrightarrow$ muon density at ground

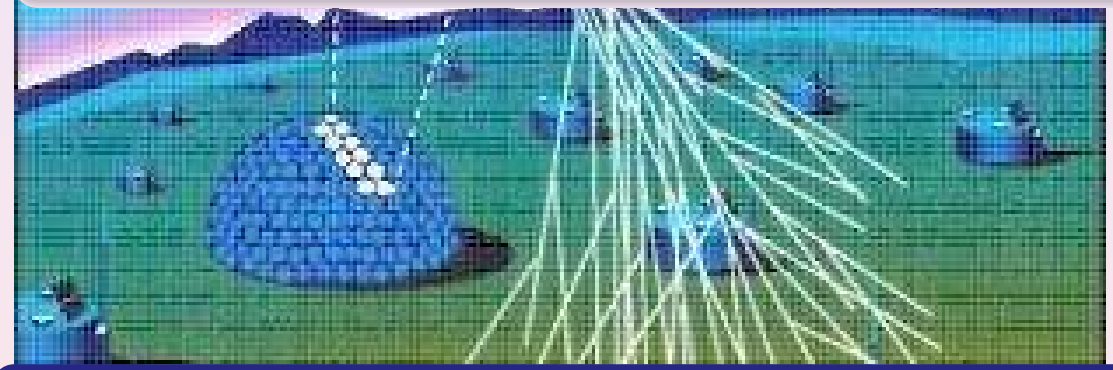


Extensive Air Shower (EAS) techniques of CR detection



ground-based observations (= thick target experiments)

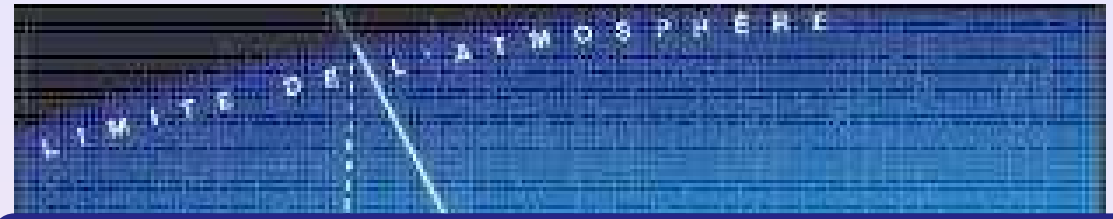
- primary CR energy $\Longleftrightarrow$ charged particle density at ground
- CR composition $\Longleftrightarrow$ muon density at ground



measurements of EAS fluorescence light

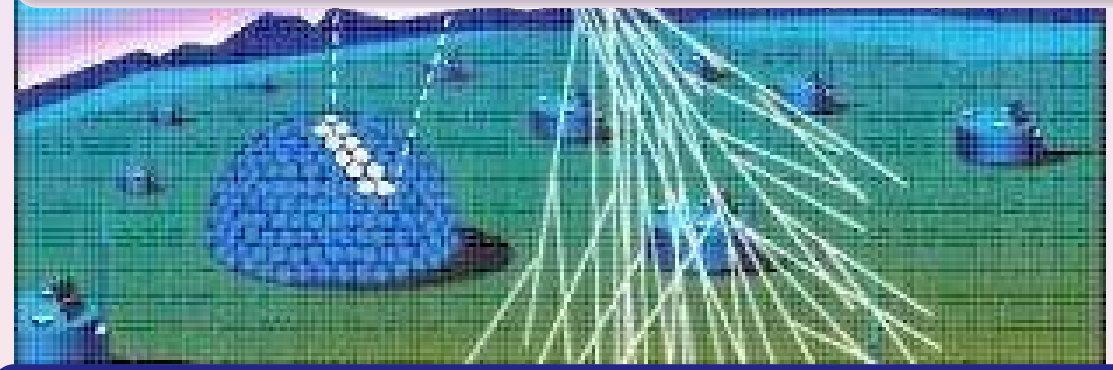
- primary CR energy $\Longleftrightarrow$ integrated light
- CR composition $\Longleftrightarrow$ shower maximum position $X_{\max}$

Extensive Air Shower (EAS) techniques of CR detection



ground-based observations (= thick target experiments)

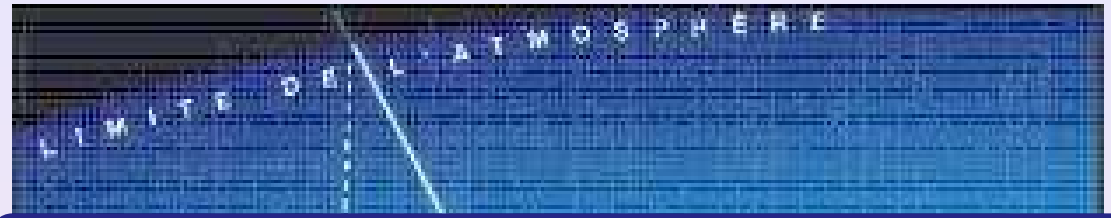
- primary CR energy $\Longleftrightarrow$ charged particle density at ground
- CR composition $\Longleftrightarrow$ muon density at ground



measurements of EAS fluorescence light

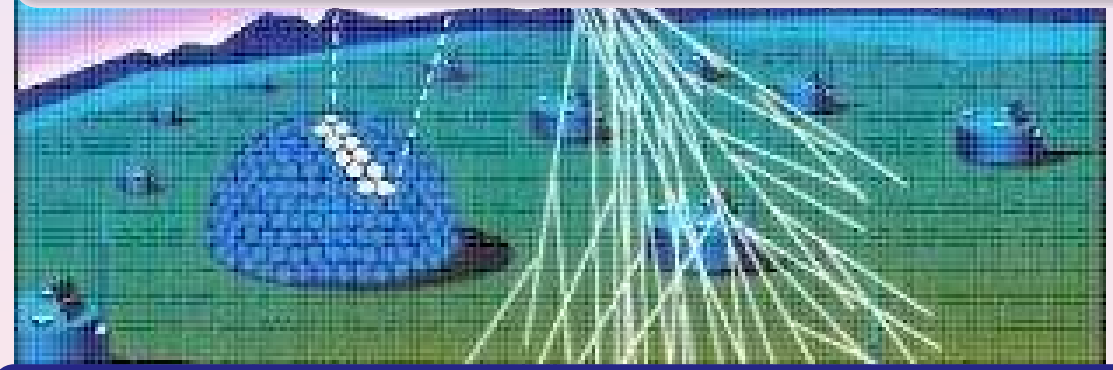
- primary CR energy $\Longleftrightarrow$ integrated light
- CR composition $\Longleftrightarrow$ shower maximum position $X_{\max}$

Extensive Air Shower (EAS) techniques of CR detection



ground-based observations (= thick target experiments)

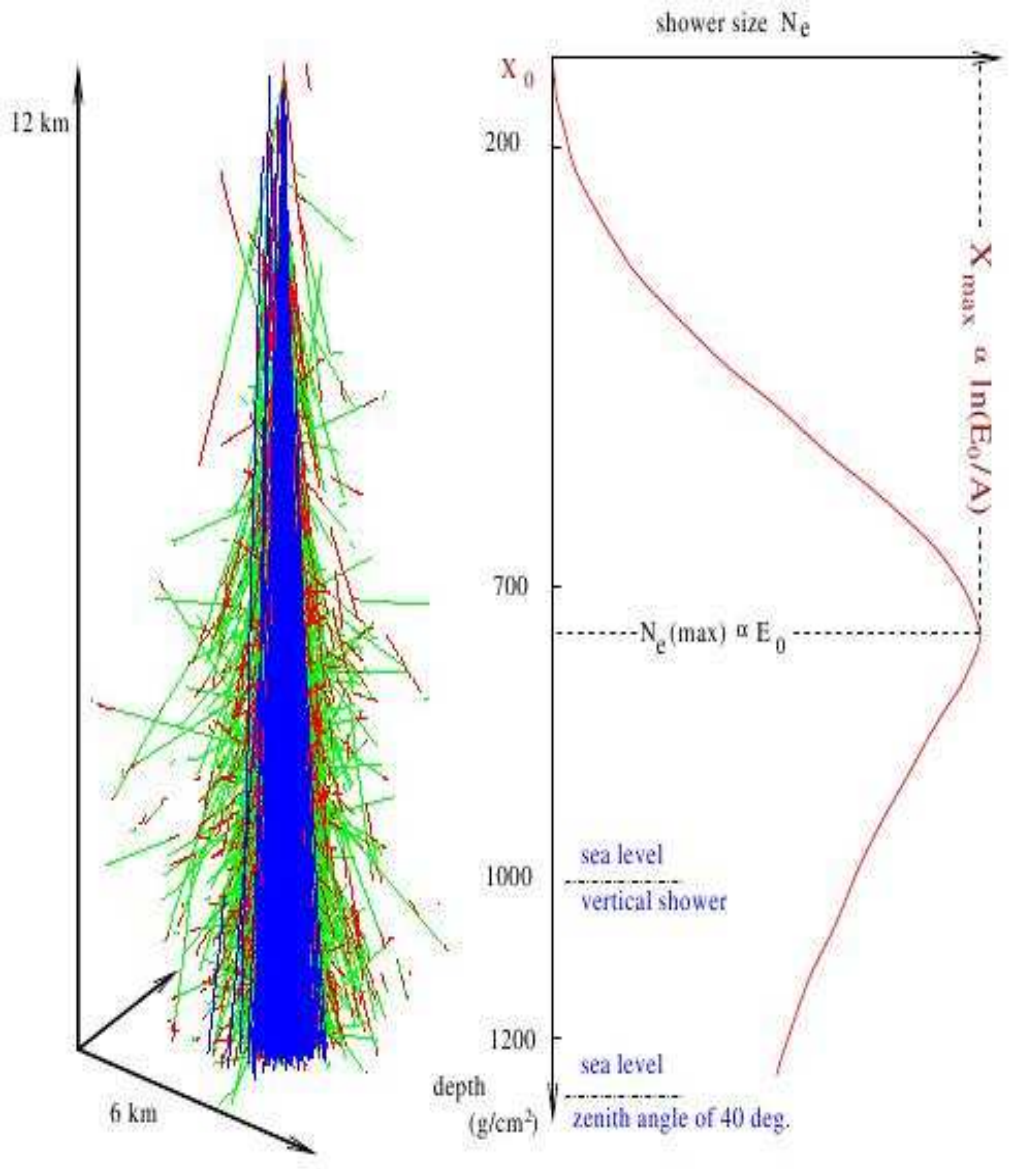
- primary CR energy $\Longleftrightarrow$ charged particle density at ground
- CR composition $\Longleftrightarrow$ muon density at ground



measurements of EAS fluorescence light

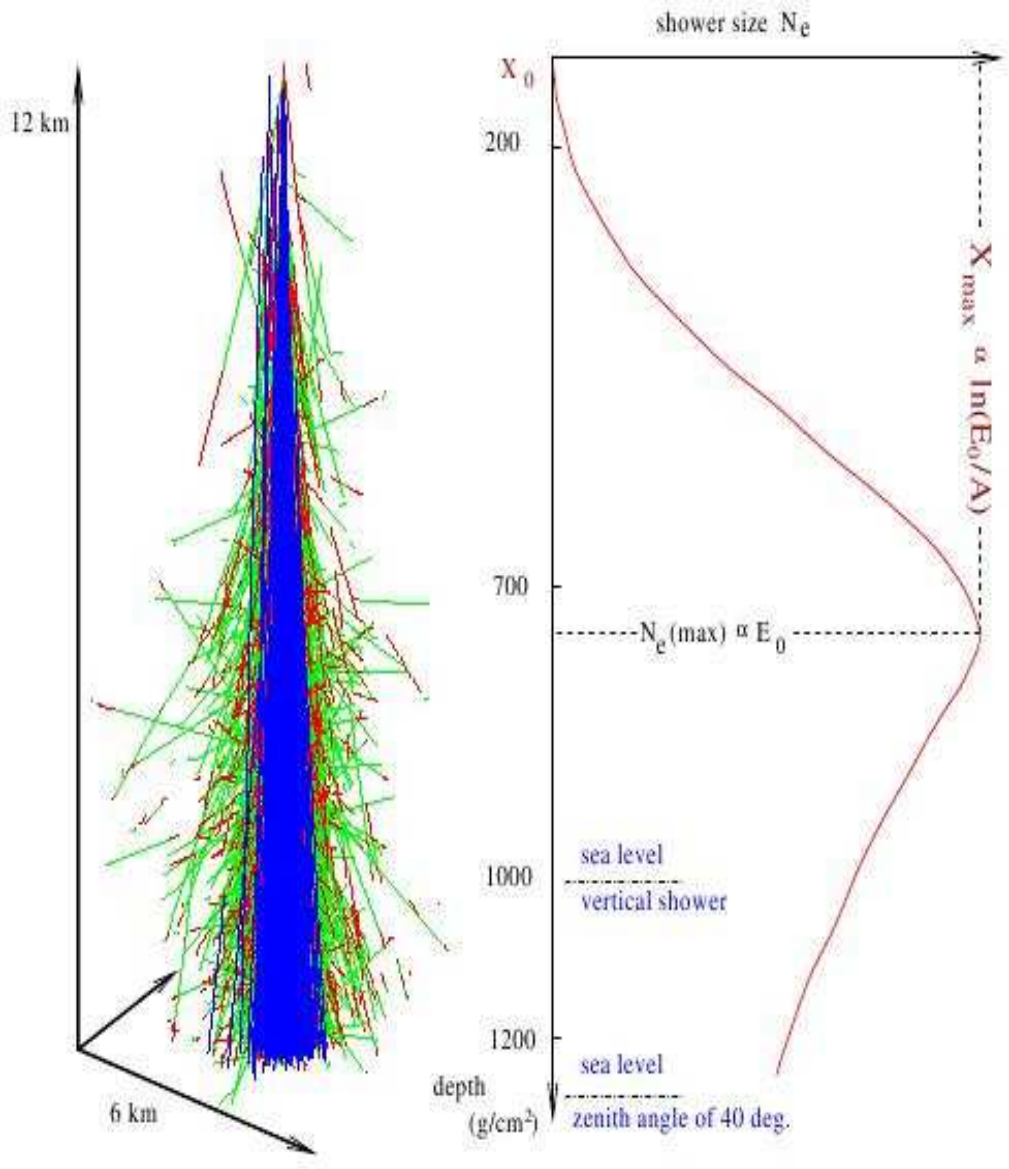
- primary CR energy $\Longleftrightarrow$ integrated light
- CR composition $\Longleftrightarrow$ shower maximum position $X_{\max}$

Extensive air shower development



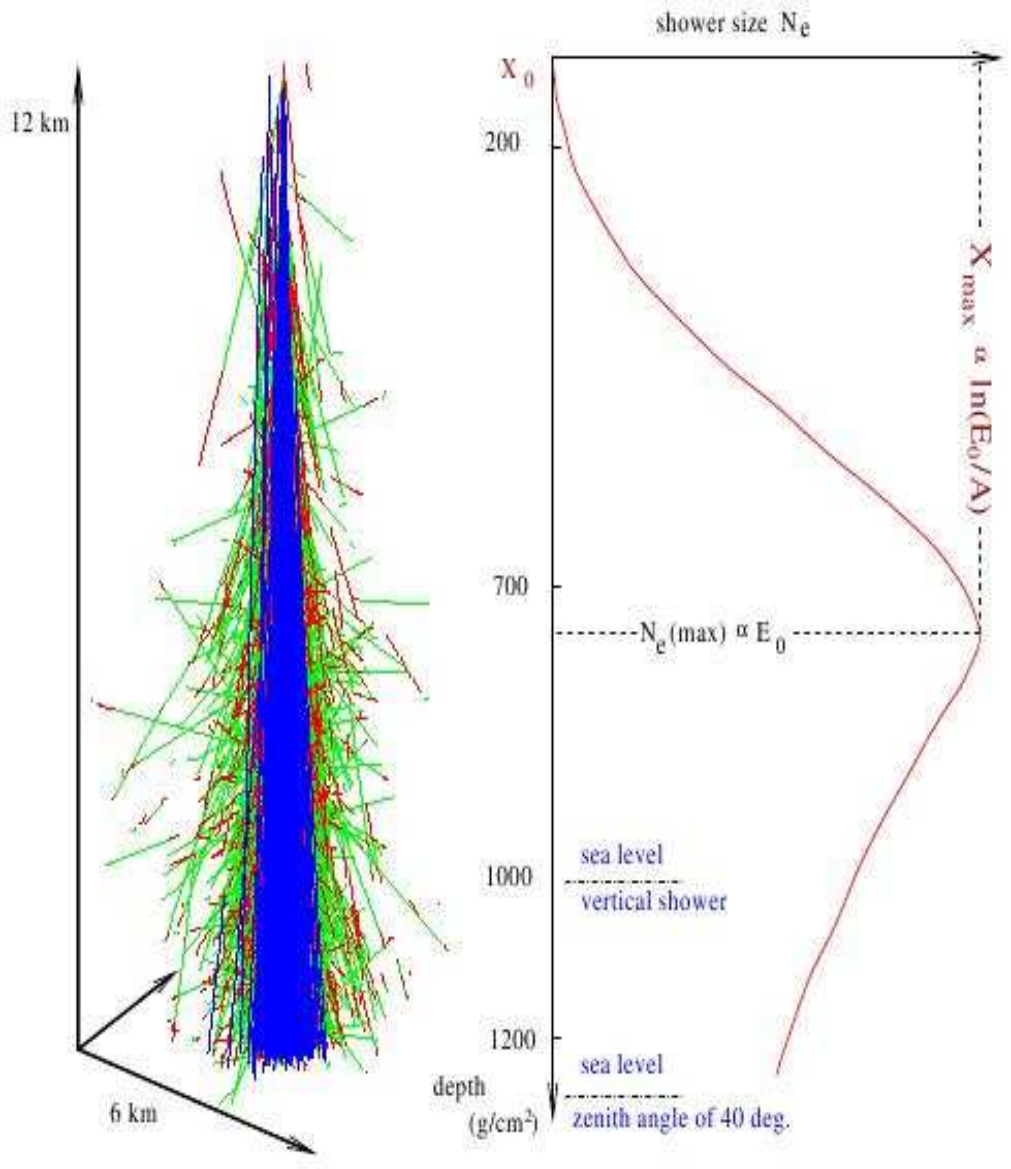
- EAS development – driven by interactions of primary / 'leading' secondary particles
- $\Rightarrow$ hadronic cascade = EAS backbone
- secondary cascades – well averaged
- observables used for CR composition studies – most sensitive to hadronic physics
- e.g. $X_{\max}$: to $\sigma^{\text{inel}}_{p-\text{air}}$ and to 'inelasticity' $K^{\text{inel}}_{p-\text{air}}$
- N_μ: to $N^{\text{ch}}_{\pi-\text{air}}\big|_{E\sim\sqrt{E_0}}$

Extensive air shower development



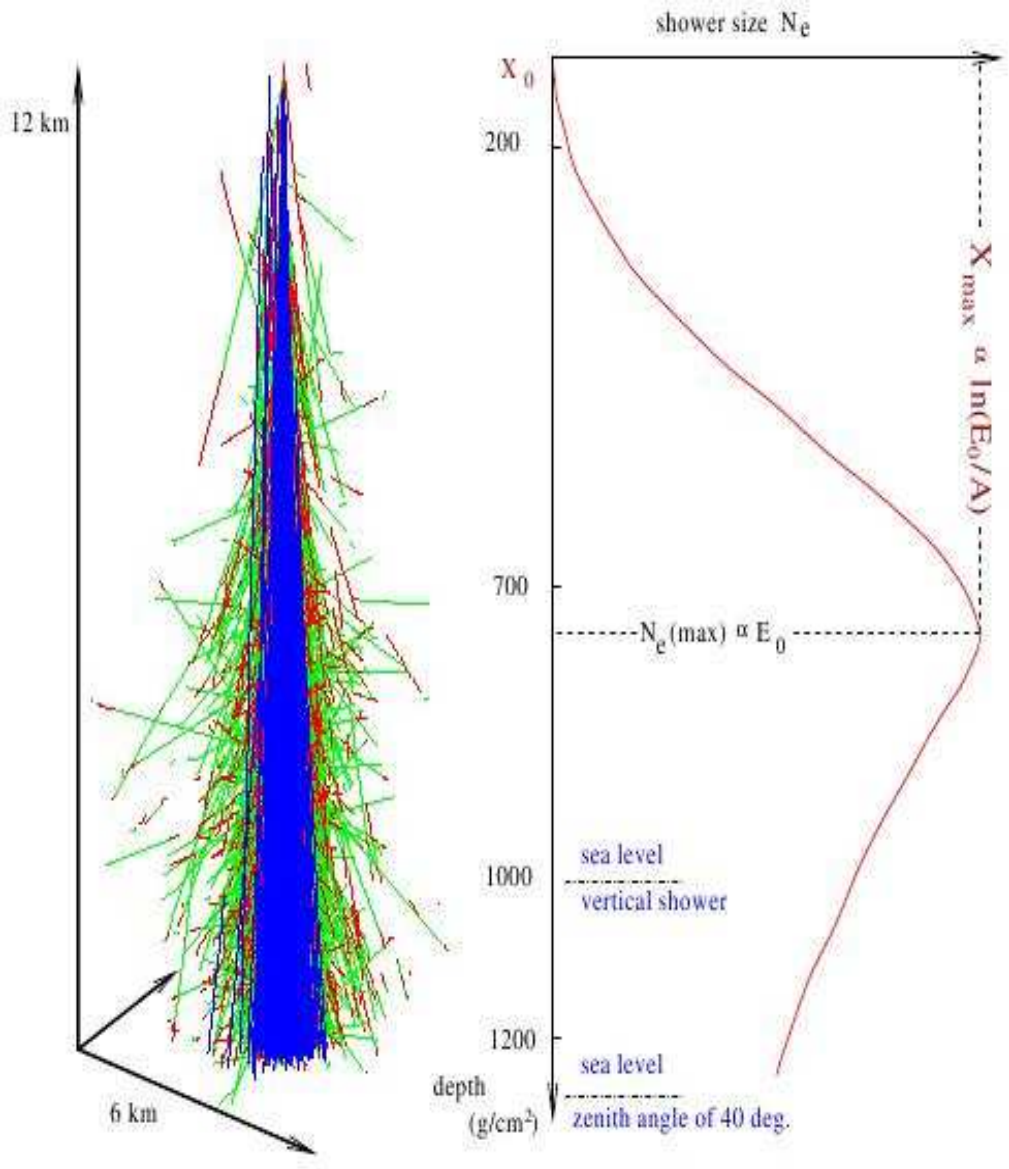
- EAS development – driven by interactions of primary / 'leading' secondary particles
- $\Rightarrow$ hadronic cascade $=$ EAS backbone
- secondary cascades – well averaged
- observables used for CR composition studies – most sensitive to hadronic physics
- e.g. $X_{\max}$: to $\sigma^{\text{inel}}_{p-\text{air}}$ and to 'inelasticity' $K^{\text{inel}}_{p-\text{air}}$
- N_μ: to $N^{\text{ch}}_{\pi-\text{air}}\big|_{E\sim\sqrt{E_0}}$

Extensive air shower development



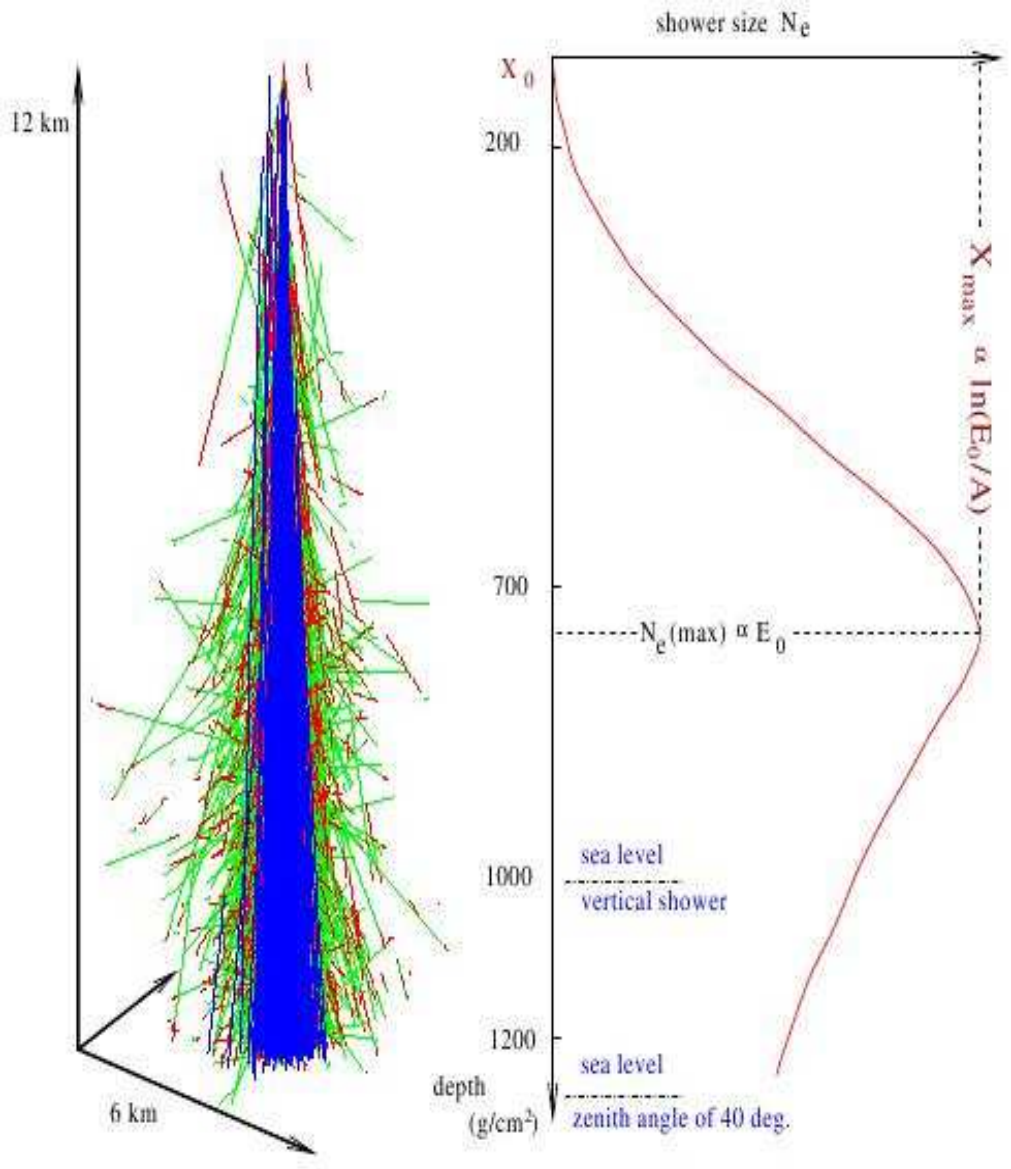
- EAS development – driven by interactions of primary / 'leading' secondary particles
- $\Rightarrow$ hadronic cascade = EAS backbone
- secondary cascades – well averaged
- observables used for CR composition studies – most sensitive to hadronic physics
- e.g. $X_{\max}$: to $\sigma^{\text{inel}}_{p-\text{air}}$ and to 'inelasticity' $K^{\text{inel}}_{p-\text{air}}$
- N_μ: to $N^{\text{ch}}_{\pi-\text{air}}\big|_{E\sim\sqrt{E_0}}$

Extensive air shower development



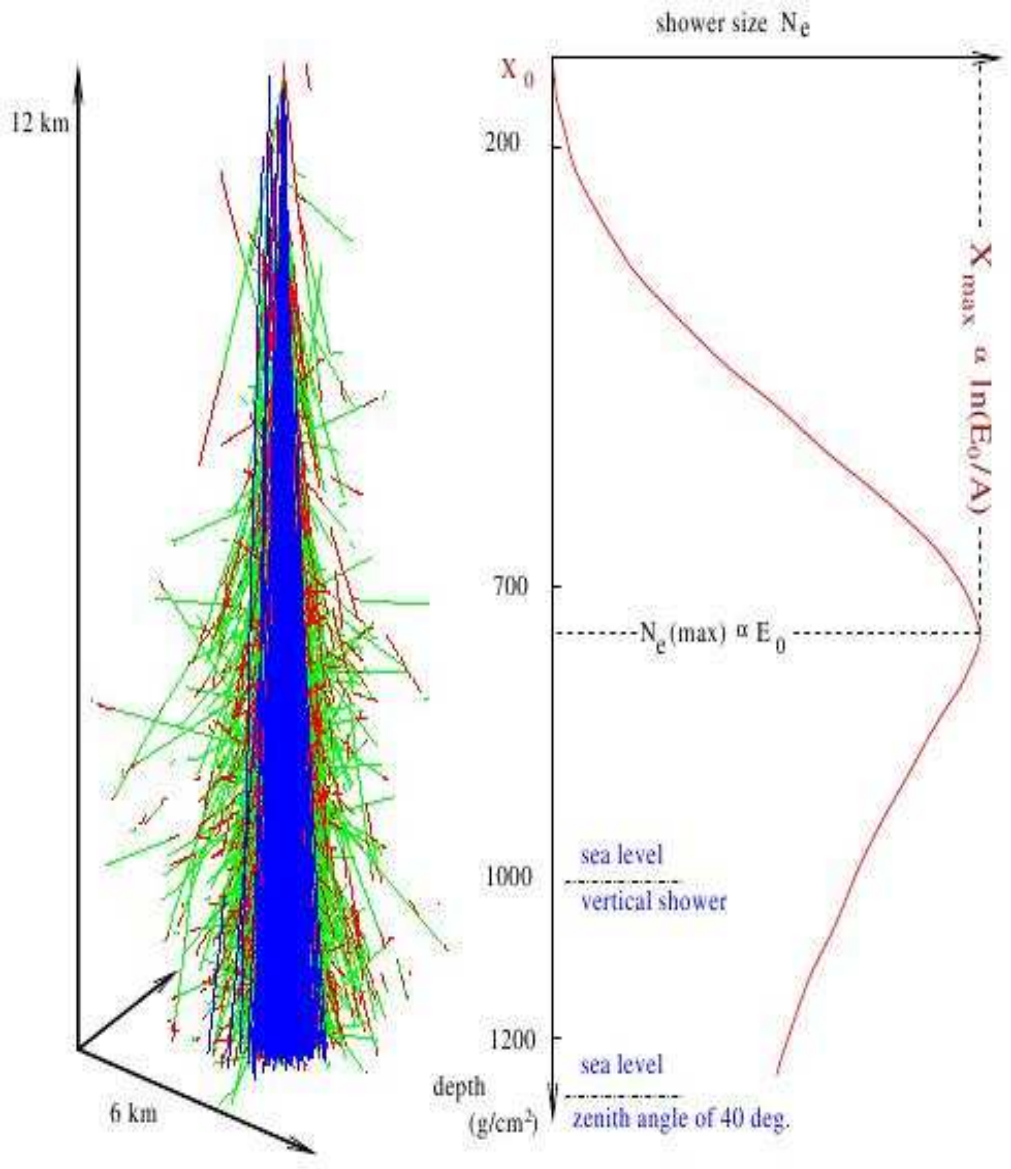
- EAS development – driven by interactions of primary / 'leading' secondary particles
- $\Rightarrow$ hadronic cascade = EAS backbone
- secondary cascades – well averaged
- observables used for CR composition studies – most sensitive to hadronic physics
- e.g. $X_{\max}$: to $\sigma^{\text{inel}}_{p-\text{air}}$ and to 'inelasticity' $K^{\text{inel}}_{p-\text{air}}$
- N_μ: to $N^{\text{ch}}_{\pi-\text{air}}\big|_{E\sim\sqrt{E_0}}$

Extensive air shower development



- EAS development – driven by interactions of primary / 'leading' secondary particles
- $\Rightarrow$ hadronic cascade = EAS backbone
- secondary cascades – well averaged
- observables used for CR composition studies – most sensitive to hadronic physics
- e.g. $X_{\max}$: to $\sigma^{\text{inel}}_{p-\text{air}}$ and to 'inelasticity' $K^{\text{inel}}_{p-\text{air}}$
- N_μ: to $N^{\text{ch}}_{\pi-\text{air}}\big|_{E\sim\sqrt{E_0}}$

Extensive air shower development



- EAS development – driven by interactions of primary / 'leading' secondary particles
- $\Rightarrow$ hadronic cascade = EAS backbone
- secondary cascades – well averaged
- observables used for CR composition studies – most sensitive to hadronic physics
- e.g. $X_{\max}$: to $\sigma^{\text{inel}}_{p-\text{air}}$ and to 'inelasticity' $K^{\text{inel}}_{p-\text{air}}$
- N_μ: to $N^{\text{ch}}_{\pi-\text{air}}\big|_{E\sim\sqrt{E_0}}$

Extensive air shower development

CR composition studies with fluorescence detectors (FD)

- most sensitive to primary particle interactions (via X_{max})
- $\Rightarrow$ suffer from uncertainties of $\sigma^{\mathrm{inel}}_{p-\mathrm{air}}\Big|_{E_0}$, $K^{\mathrm{inel}}_{p-\mathrm{air}}\Big|_{E_0}$
- seeing it optimistic: probe proton-air (nucleus-air) interactions at maximal energies (up to $\sim 10^{21}$ eV)

Extensive air shower development

CR composition studies with fluorescence detectors (FD)

- most sensitive to primary particle interactions (via $X_{\max}$)
- $\Rightarrow$ suffer from uncertainties of $\sigma^{\text{inel}}_{p-\text{air}}\Big|_{E_0}$, $K^{\text{inel}}_{p-\text{air}}\Big|_{E_0}$
- seeing it optimistic: probe proton-air (nucleus-air) interactions at maximal energies (up to $\sim 10^{21}$ eV)

Extensive air shower development

CR composition studies with fluorescence detectors (FD)

- most sensitive to primary particle interactions (via $X_{\max}$)
- $\Rightarrow$ suffer from uncertainties of $\sigma^{\text{inel}}_{p-\text{air}}\Big|_{E_0}$, $K^{\text{inel}}_{p-\text{air}}\Big|_{E_0}$
- seeing it optimistic: probe proton-air (nucleus-air) interactions at maximal energies (up to $\sim 10^{21}$ eV)

Extensive air shower development

CR composition studies with fluorescence detectors (FD)

- most sensitive to primary particle interactions (via $X_{\max}$)
- $\Rightarrow$ suffer from uncertainties of $\sigma^{\text{inel}}_{p-\text{air}}\Big|_{E_0}$, $K^{\text{inel}}_{p-\text{air}}\Big|_{E_0}$
- seeing it optimistic: probe proton-air (nucleus-air) interactions at maximal energies (up to $\sim 10^{21}$ eV)

CR composition studies with ground-based detectors (SD)

- most sensitive to interactions of secondary pions (also kaons & (anti-)nucleons) at intermediate energies ($E \sim \sqrt{E_0}$)

Nucleus-induced air showers & superposition model

For average (only!) air shower characteristics: $A-$induced EAS of energy E – equivalent to A proton-induced showers of energy E/A

- N of 'wounded' nucleons per collision: $\langle \nu_A \rangle = A\,\sigma^{\rm inel}_{p-{\rm air}}/\sigma^{\rm inel}_{A-{\rm air}}$ (valid up to target diffraction)
- nuclear m.f.p. is $\sigma^{\rm inel}_{p-{\rm air}}/\sigma^{\rm inel}_{A-{\rm air}}$ shorter
- however, each nucleon interacts with probability: $w_{\rm int} = \dfrac{\sigma^{\rm inel}_{p-{\rm air}}}{\sigma^{\rm inel}_{A-{\rm air}}}$

Nucleus-induced air showers & superposition model

For average (only!) air shower characteristics: $A-$induced EAS of energy E – equivalent to A proton-induced showers of energy E/A

- N of 'wounded' nucleons per collision: $\langle \nu_A \rangle = A\,\sigma^{\rm inel}_{p-{\rm air}}/\sigma^{\rm inel}_{A-{\rm air}}$ (valid up to target diffraction)
- nuclear m.f.p. is $\sigma^{\rm inel}_{p-{\rm air}}/\sigma^{\rm inel}_{A-{\rm air}}$ shorter
- however, each nucleon interacts with probability: $w_{\rm int} = \dfrac{\sigma^{\rm inel}_{p-{\rm air}}}{\sigma^{\rm inel}_{A-{\rm air}}}$

Nucleus-induced air showers & superposition model

For average (only!) air shower characteristics: $A-$induced EAS of energy E – equivalent to A proton-induced showers of energy E/A

- N of 'wounded' nucleons per collision: $\langle \nu_A \rangle = A\sigma^{\rm inel}_{p-{\rm air}}/\sigma^{\rm inel}_{A-{\rm air}}$ (valid up to target diffraction)
- nuclear m.f.p. is $\sigma^{\rm inel}_{p-{\rm air}}/\sigma^{\rm inel}_{A-{\rm air}}$ shorter
- however, each nucleon interacts with probability: $w_{\rm int} = \dfrac{\sigma^{\rm inel}_{p-{\rm air}}}{\sigma^{\rm inel}_{A-{\rm air}}}$

Nucleus-induced air showers & superposition model

For average (only!) air shower characteristics: $A-$induced EAS of energy E – equivalent to A proton-induced showers of energy E/A

- N of 'wounded' nucleons per collision: $\langle \nu_A \rangle = A\,\sigma^{\rm inel}_{p-{\rm air}}/\sigma^{\rm inel}_{A-{\rm air}}$ (valid up to target diffraction)
- nuclear m.f.p. is $\sigma^{\rm inel}_{p-{\rm air}}/\sigma^{\rm inel}_{A-{\rm air}}$ shorter
- however, each nucleon interacts with probability: $w_{\rm int} = \dfrac{\sigma^{\rm inel}_{p-{\rm air}}}{\sigma^{\rm inel}_{A-{\rm air}}}$

Nucleus-induced air showers & superposition model

For average (only!) air shower characteristics: $A-$induced EAS of energy E – equivalent to A proton-induced showers of energy E/A

- N of 'wounded' nucleons per collision: $\langle \nu_A \rangle = A\,\sigma^{\rm inel}_{p-{\rm air}}/\sigma^{\rm inel}_{A-{\rm air}}$ (valid up to target diffraction)
- nuclear m.f.p. is $\sigma^{\rm inel}_{p-{\rm air}}/\sigma^{\rm inel}_{A-{\rm air}}$ shorter
- however, each nucleon interacts with probability: $w_{\rm int} = \dfrac{\sigma^{\rm inel}_{p-{\rm air}}}{\sigma^{\rm inel}_{A-{\rm air}}}$
- $\Rightarrow \langle X^A_{\rm max}(E)\rangle \simeq \langle X^p_{\rm max}(E/A)\rangle; \quad \langle N^A_{e/\mu}(E)\rangle \simeq A\cdot\langle N^p_{e/\mu}(E/A)\rangle$

Nucleus-induced air showers & superposition model

For average (only!) air shower characteristics: $A-$induced EAS of energy E – equivalent to A proton-induced showers of energy E/A

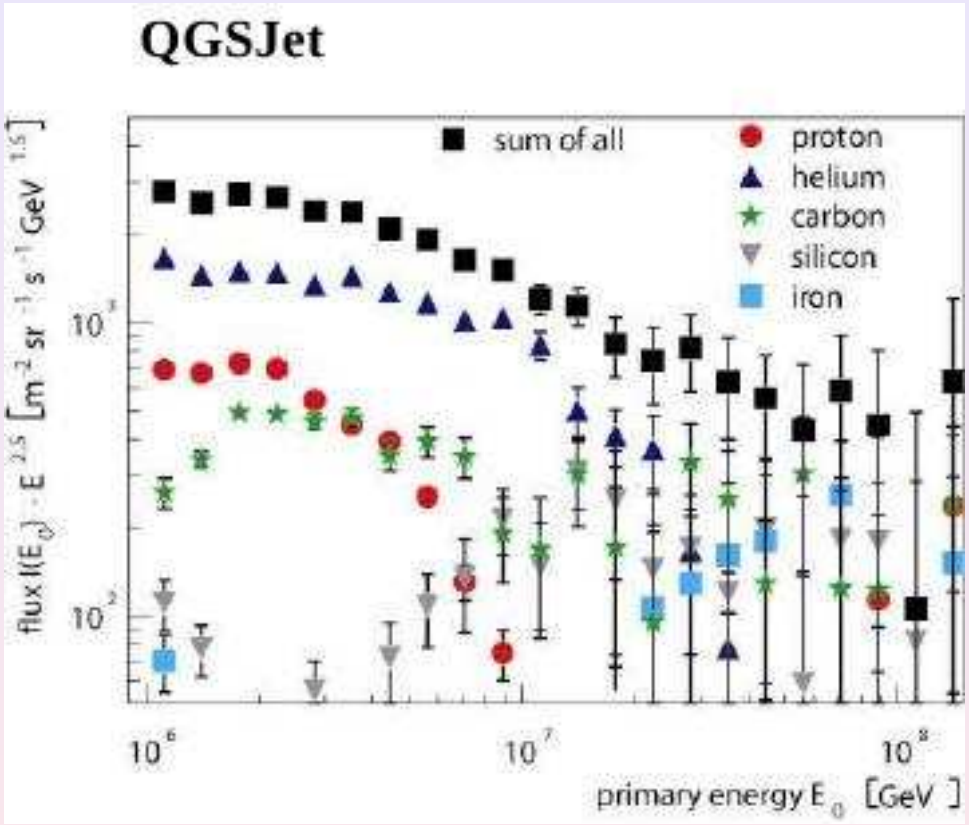
- N of 'wounded' nucleons per collision: $\langle \nu_A \rangle = A\,\sigma^{\rm inel}_{p-{\rm air}}/\sigma^{\rm inel}_{A-{\rm air}}$ (valid up to target diffraction)
- nuclear m.f.p. is $\sigma^{\rm inel}_{p-{\rm air}}/\sigma^{\rm inel}_{A-{\rm air}}$ shorter
- however, each nucleon interacts with probability: $w_{\rm int} = \dfrac{\sigma^{\rm inel}_{p-{\rm air}}}{\sigma^{\rm inel}_{A-{\rm air}}}$
- $\Rightarrow \langle X^A_{\rm max}(E)\rangle \simeq \langle X^p_{\rm max}(E/A)\rangle; \quad \langle N^A_{e/\mu}(E)\rangle \simeq A\cdot\langle N^p_{e/\mu}(E/A)\rangle$
- $\langle X^p_{\rm max}(E)\rangle \simeq {\rm const} + ER\ln E,\ ER \equiv d\langle X^p_{\rm max}(E)\rangle/dE;$
  $\langle N^p_{e/\mu}(E/A)\rangle \propto E^{\alpha_{e/\mu}},\ \alpha_e \simeq 1.1,\ \alpha_\mu \simeq 0.9$

Nucleus-induced air showers & superposition model

For average (only!) air shower characteristics: $A-$induced EAS of energy E – equivalent to A proton-induced showers of energy E/A

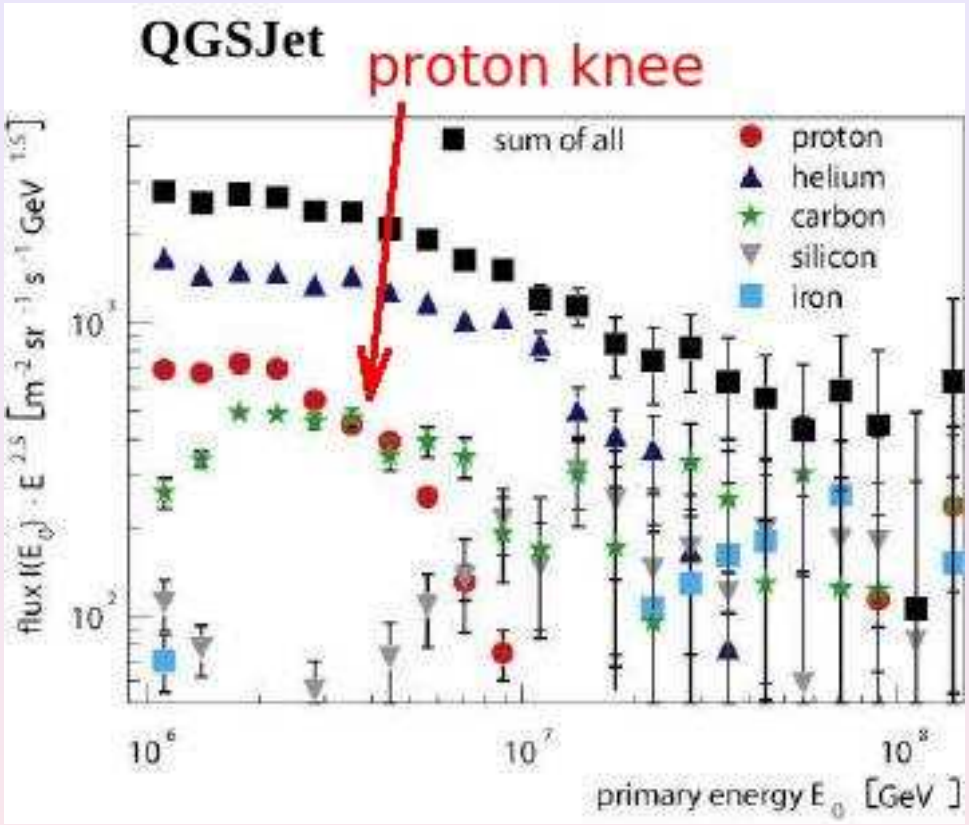
- N of 'wounded' nucleons per collision: $\langle \nu_A \rangle = A\,\sigma^{\rm inel}_{p-{\rm air}}/\sigma^{\rm inel}_{A-{\rm air}}$ (valid up to target diffraction)
- nuclear m.f.p. is $\sigma^{\rm inel}_{p-{\rm air}}/\sigma^{\rm inel}_{A-{\rm air}}$ shorter
- however, each nucleon interacts with probability: $w_{\rm int} = \dfrac{\sigma^{\rm inel}_{p-{\rm air}}}{\sigma^{\rm inel}_{A-{\rm air}}}$
- $\Rightarrow \langle X^A_{\rm max}(E)\rangle \simeq \langle X^p_{\rm max}(E/A)\rangle; \quad \langle N^A_{e/\mu}(E)\rangle \simeq A\cdot\langle N^p_{e/\mu}(E/A)\rangle$
- $\langle X^p_{\rm max}(E)\rangle \simeq {\rm const} + ER\ln E,\ ER \equiv d\langle X^p_{\rm max}(E)\rangle/dE;$
  $\langle N^p_{e/\mu}(E/A)\rangle \propto E^{\alpha_{e/\mu}},\ \alpha_e \simeq 1.1,\ \alpha_\mu \simeq 0.9$
- $\Rightarrow \langle X^A_{\rm max}(E)\rangle \simeq \langle X^p_{\rm max}(E)\rangle - ER\ln A$
  $\langle N^A_e(E)\rangle \simeq \langle N^p_e(E)\rangle A^{0.1}; \quad \langle N^A_\mu(E)\rangle \simeq \langle N^p_\mu(E)\rangle A^{-0.1}$
  – nucleus-induced air showers reach their maxima earlier, have more $e^\pm$ and less muons

CR composition at the 'knee'



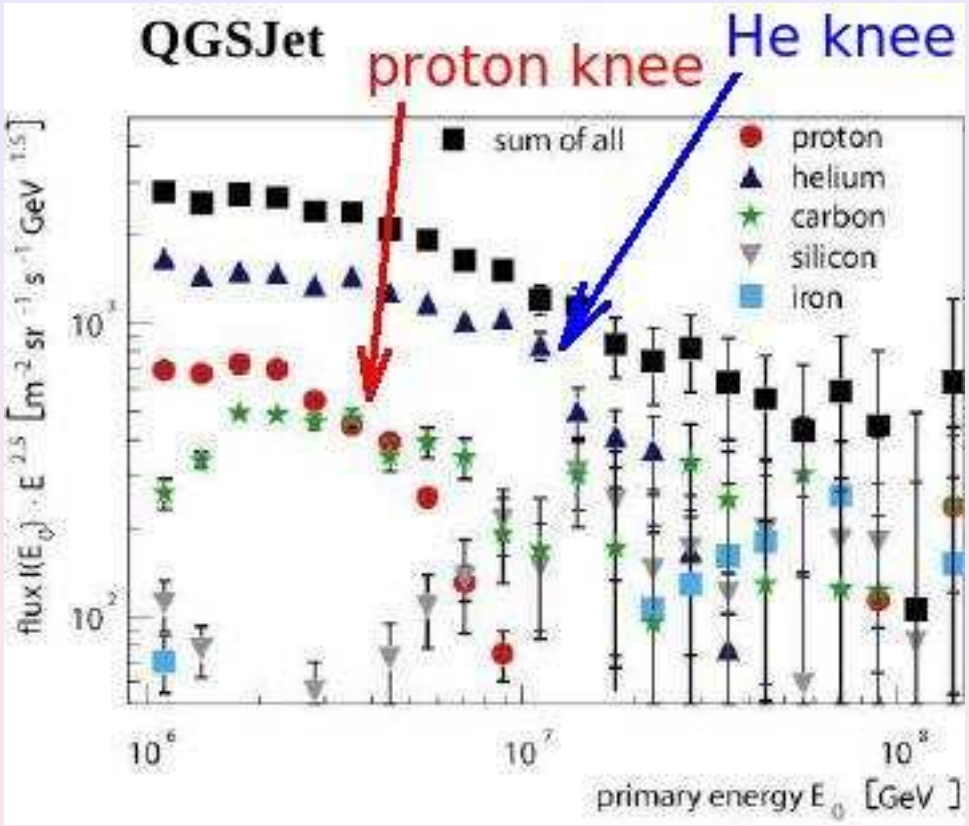
- CR spectra for individual mass groups obtained by the KASCADE Collab. *[Astrop. Phys. 24(2005)]*

CR composition at the 'knee'



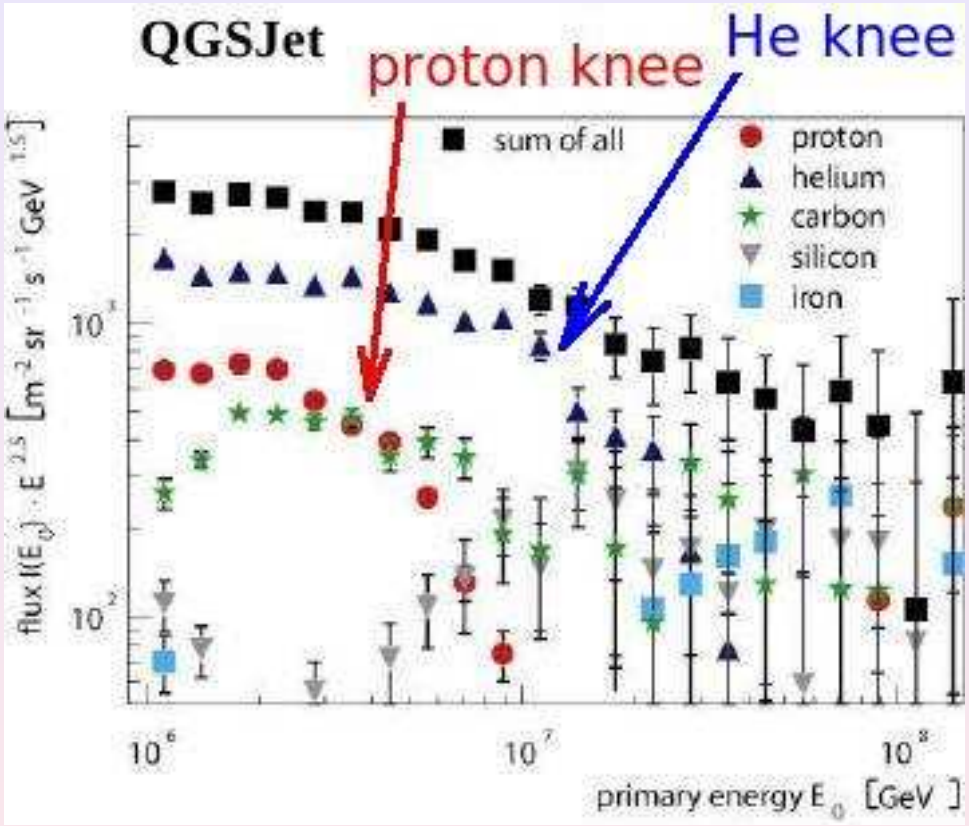
- CR spectra for individual mass groups obtained by the KASCADE Collab. *[Astrop. Phys. 24(2005)]*
- partial 'knees' seen for light elements

CR composition at the 'knee'



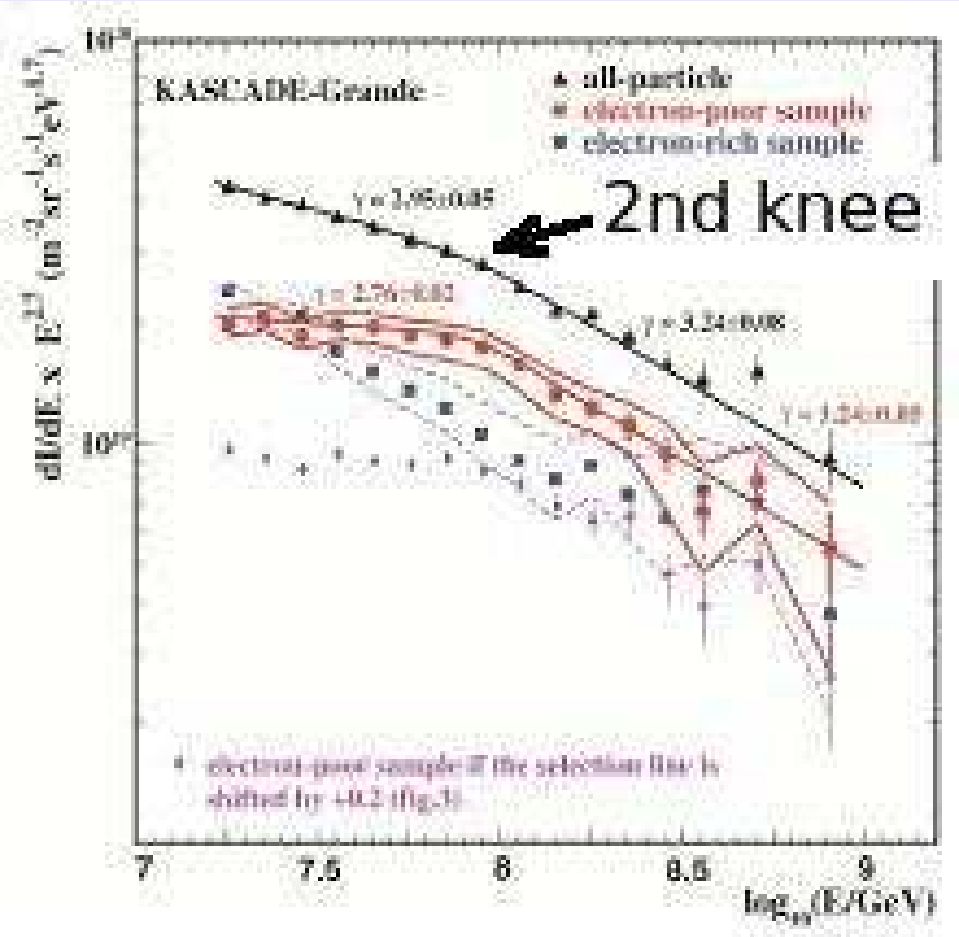
- CR spectra for individual mass groups obtained by the KASCADE Collab. *[Astrop. Phys. 24(2005)]*
- partial 'knees' seen for light elements
- 'knee' positions seem rigidity-dependent

CR composition at the 'knee'



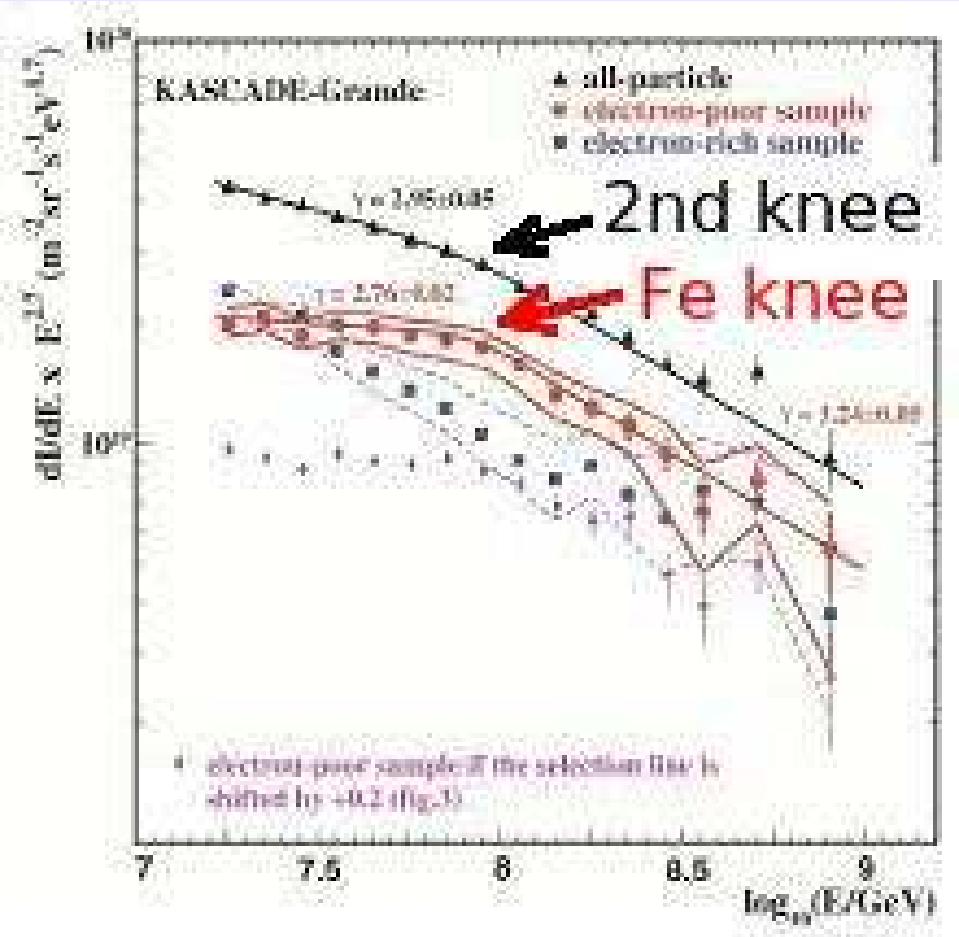
- CR spectra for individual mass groups obtained by the KASCADE Collab. *[Astrop. Phys. 24(2005)]*
- partial 'knees' seen for light elements
- 'knee' positions seem rigidity-dependent
- situation with heavier CRs – unclear

CR composition at the 'knee'



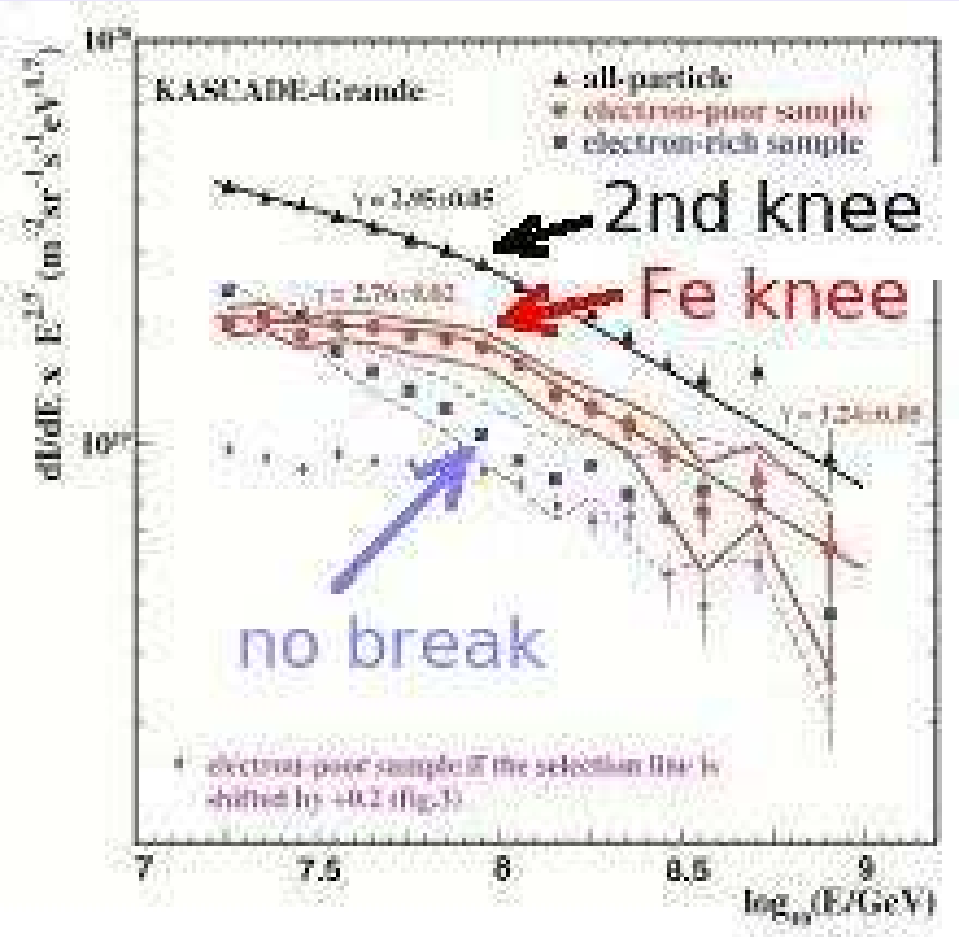
- 2nd 'knee' observed recently at 10^{17} eV by KASCADE-Grande *[PRL (2011) in press]*

CR composition at the 'knee'



- 2nd 'knee' observed recently at 10^{17} eV by KASCADE-Grande *[PRL (2011) in press]*
- caused by a spectral break for heavy CRs (Fe)

CR composition at the 'knee'



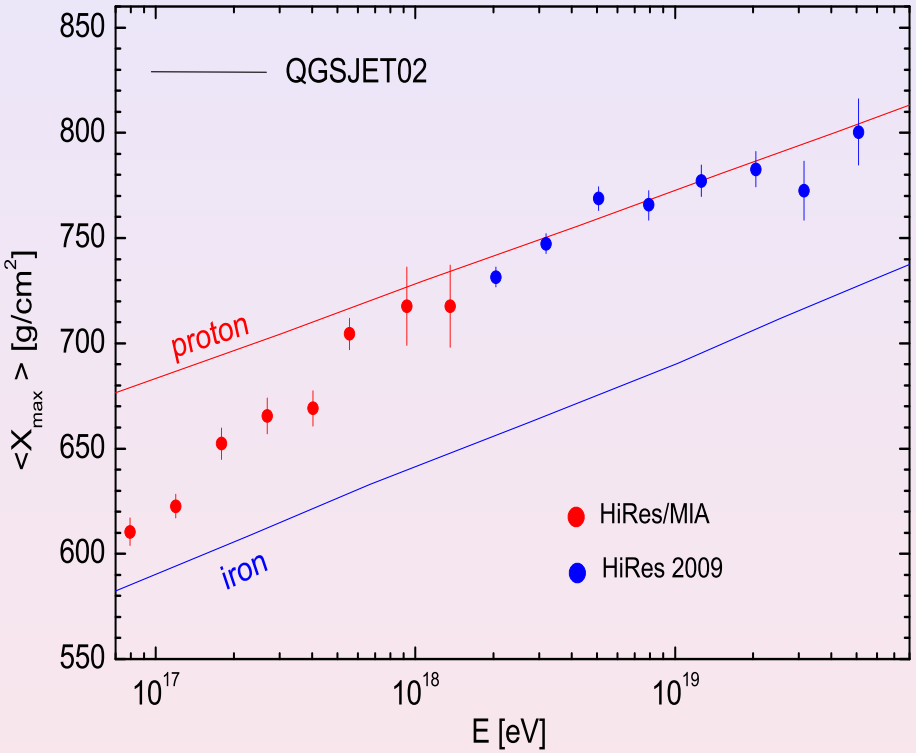
- 2nd 'knee' observed recently at 10^{17} eV by KASCADE-Grande *[PRL (2011) in press]*
- caused by a spectral break for heavy CRs (Fe)
- astrophysical (rigidity-dependent) origin of the CR 'knee' finally confirmed

UHECR composition from $X_{\max}$ observations

EAS maximum position $X_{\max}$ – the key to the UHECR composition

UHECR composition from $X_{\max}$ observations

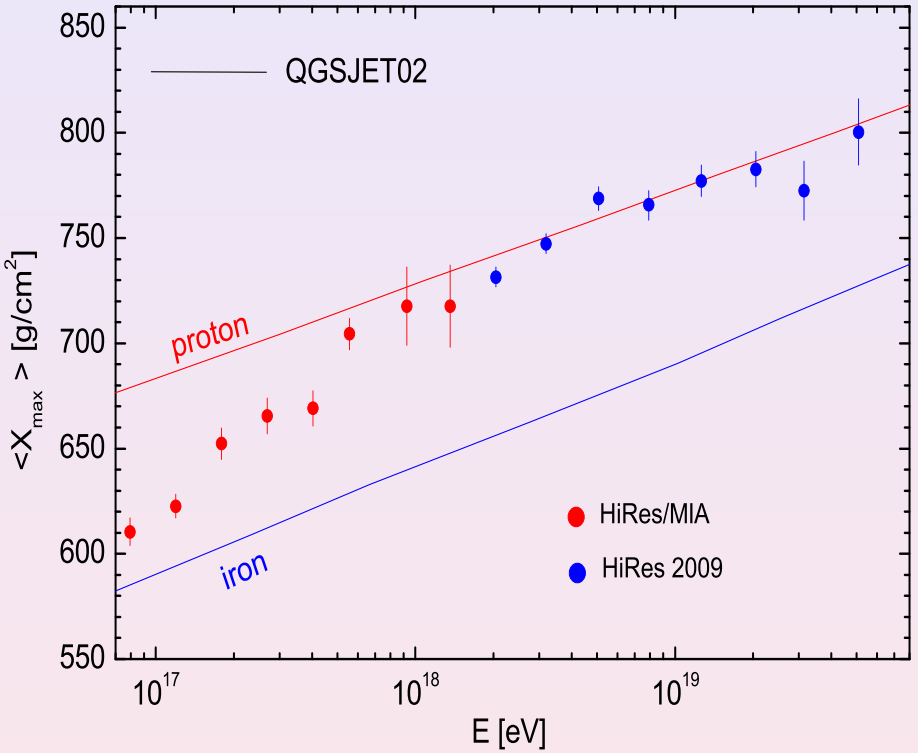
EAS maximum position $X_{\max}$ – the key to the UHECR composition



- spectatular results from HiRes Collab. *[PRL (2005); PRL (2010)]*: *p*-dominated composition above 10^{18} eV
- strong support for the 'dip' model: transition from galactic *Fe* to extragalactic *p* component at 10^{17} eV

UHECR composition from $X_{\max}$ observations

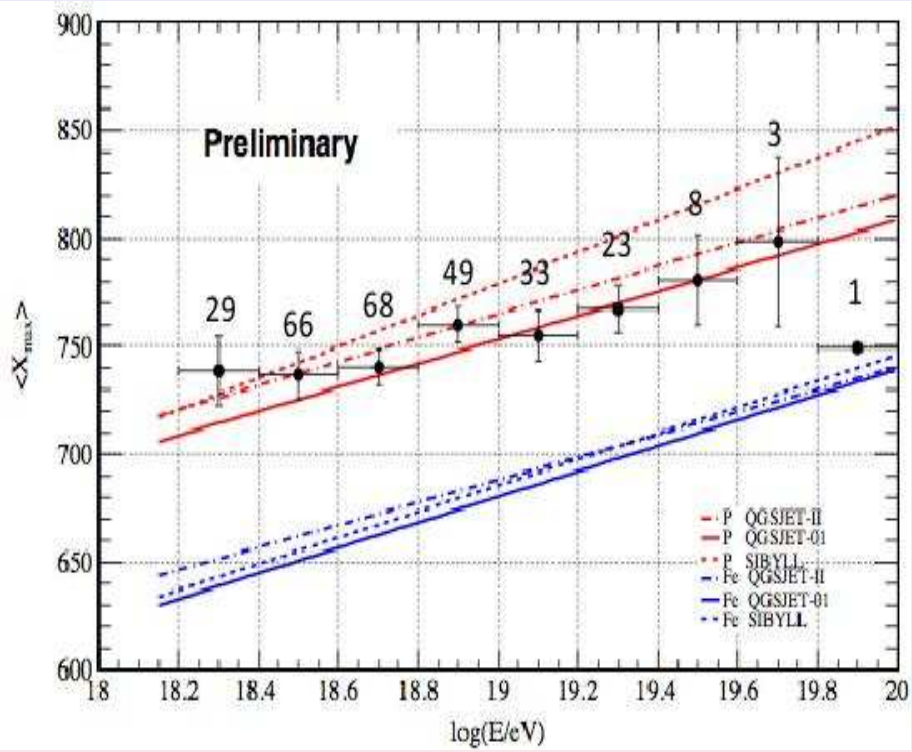
EAS maximum position $X_{\max}$ – the key to the UHECR composition



- spectatular results from HiRes Collab. *[PRL (2005); PRL (2010)]*: p-dominated composition above 10^{18} eV
- strong support for the 'dip' model: transition from galactic Fe to extragalactic p component at 10^{17} eV

UHECR composition from $X_{\max}$ observations

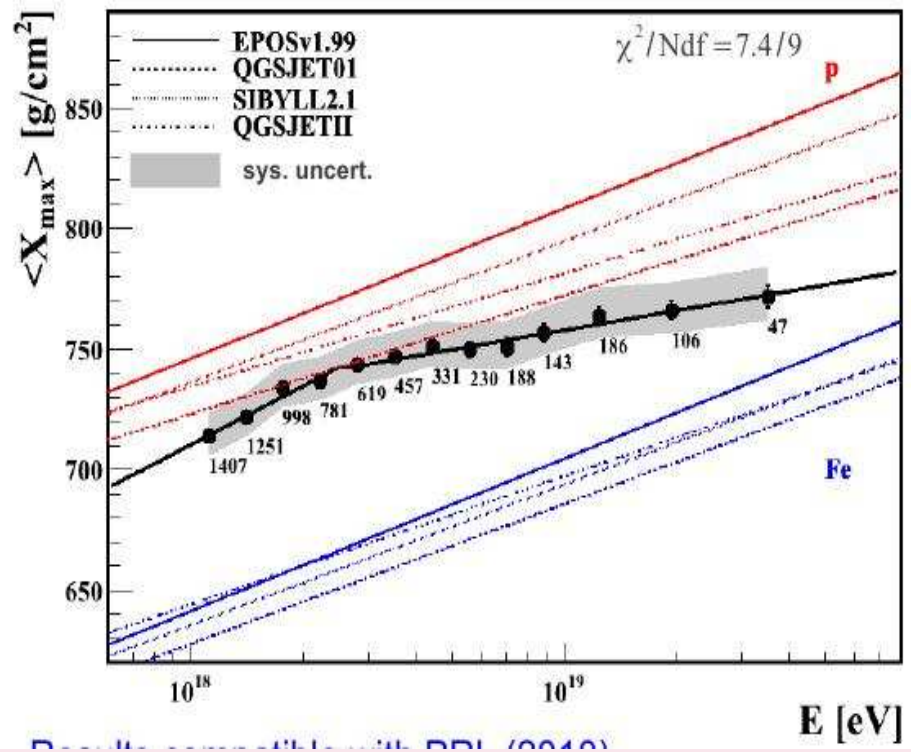
EAS maximum position $X_{\max}$ – the key to the UHECR composition



- spectatular results from HiRes Collab. *[PRL (2005); PRL (2010)]*: p-dominated composition above 10^{18} eV
- supported by data of Telescope Array Collab. *[Tameda, ICRC-2011]*

UHECR composition from $X_{\max}$ observations

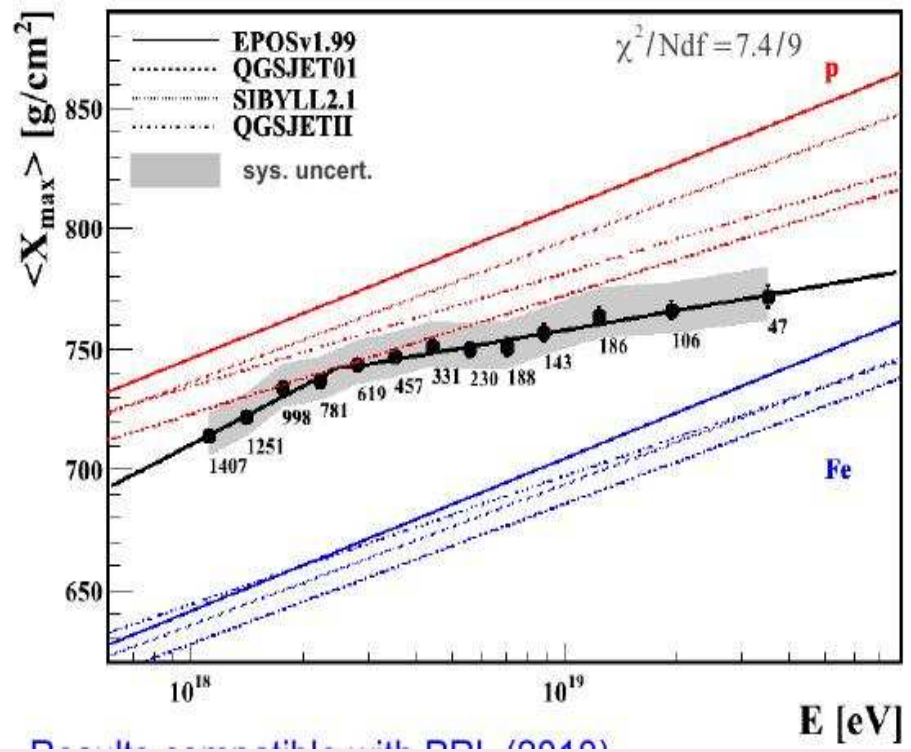
EAS maximum position $X_{\max}$ – the key to the UHECR composition



- Pierre Auger Collab.: change from light to heavy CRs above 10^{19} eV *[PRL (2010); Facal San Luis, ICRC-2011]*
- interpretation of data – strongly model-dependent!

UHECR composition from $X_{\max}$ observations

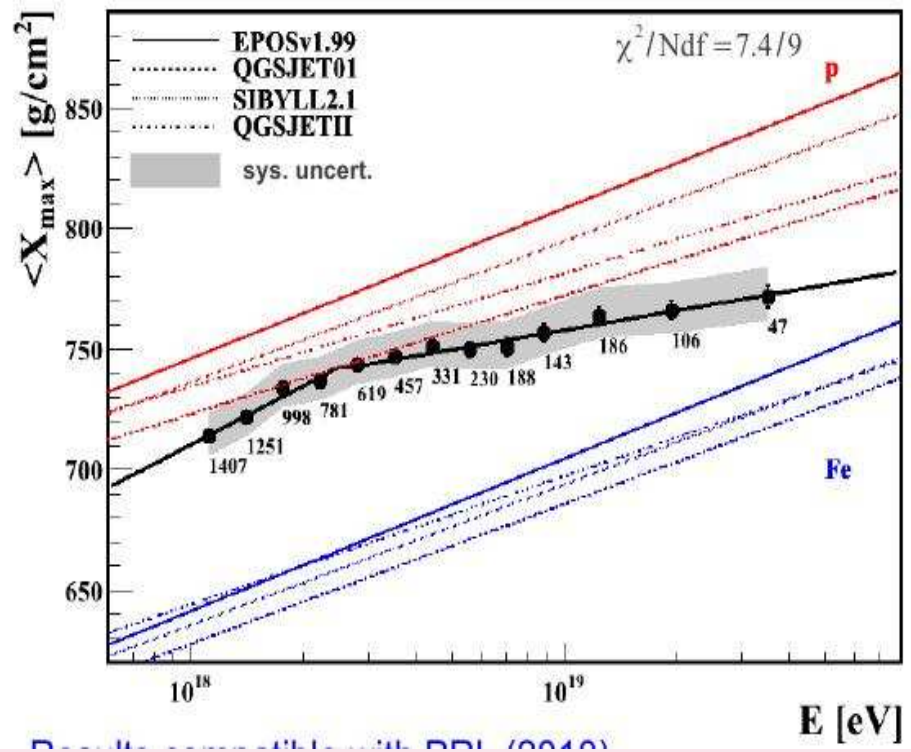
EAS maximum position $X_{\max}$ – the key to the UHECR composition



- Pierre Auger Collab.: change from light to heavy CRs above 10^{19} eV *[PRL (2010); Facal San Luis, ICRC-2011]*
- interpretation of data – strongly model-dependent!

UHECR composition from $X_{\max}$ observations

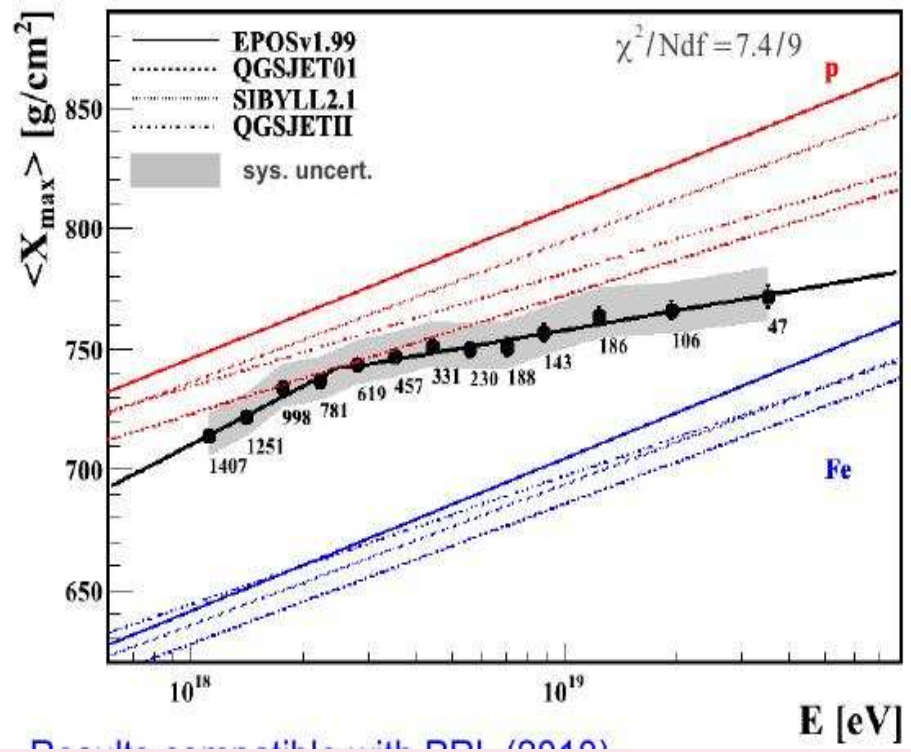
EAS maximum position $X_{\max}$ – the key to the UHECR composition



- Pierre Auger Collab.: change from light to heavy CRs above 10^{19} eV *[PRL (2010); Facal San Luis, ICRC-2011]*
- interpretation of data – strongly model-dependent!
- is it possible to reduce model-dependence?!

UHECR composition from $X_{\rm max}$ observations

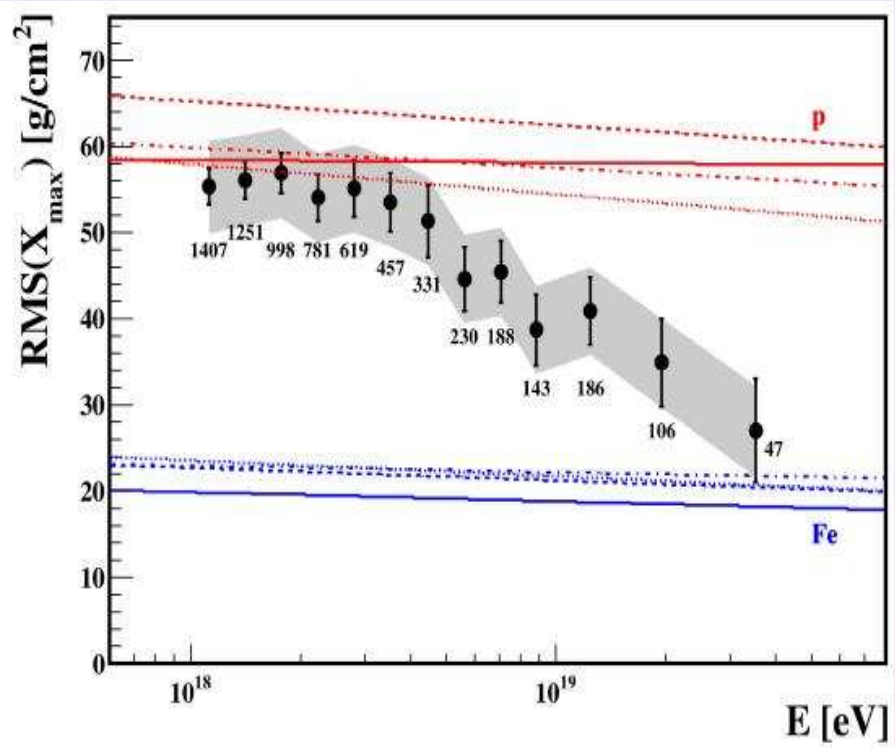
EAS maximum position $X_{\rm max}$ – the key to the UHECR composition



- Pierre Auger Collab.: change from light to heavy CRs above 10^{19} eV *[PRL (2010); Facal San Luis, ICRC-2011]*
- interpretation of data – strongly model-dependent!
- is it possible to reduce model-dependence?!

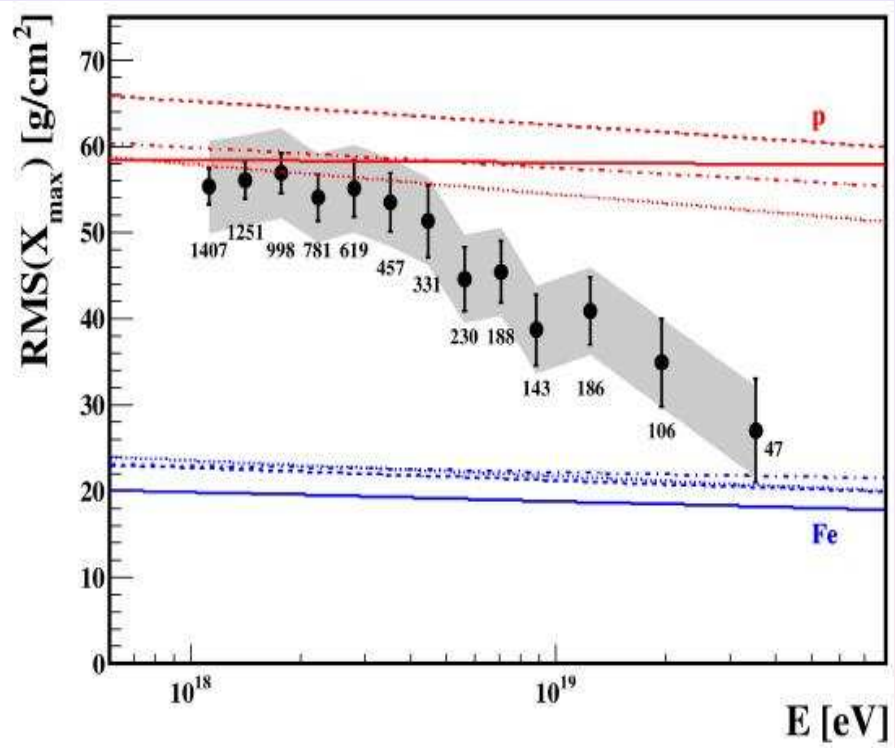
- yes, by studying shower fluctuations, e.g. RMS($X_{\rm max}$) *[Aloisio, Berezinsky, Blasi & SO, PRD 77 (2008)]*

UHECR composition from RMS($X_{\max}$)



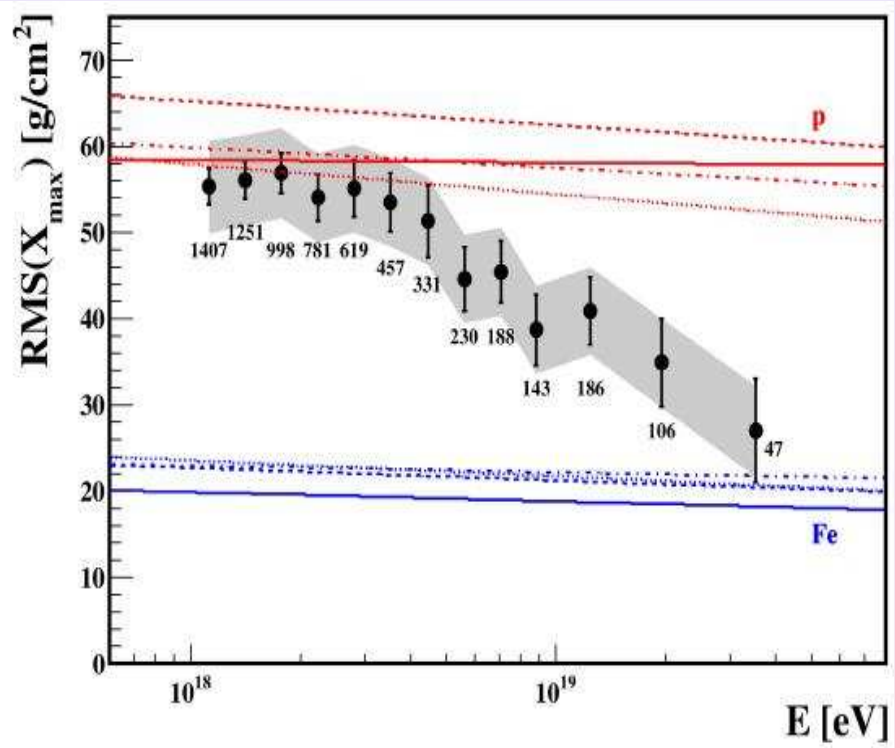
- RMS($X_{\max}$) measured by the Pierre Auger Collab. *[PRL (2010); Facal San Luis, ICRC-2011]*
- model-dependence strongly reduced
- but: almost pure *Fe* at the highest energies?!

UHECR composition from RMS($X_{\max}$)



- RMS($X_{\max}$) measured by the Pierre Auger Collab. *[PRL (2010); Facal San Luis, ICRC-2011]*
- model-dependence strongly reduced
- but: almost pure *Fe* at the highest energies?!

UHECR composition from RMS($X_{\max}$)



- RMS($X_{\max}$) measured by the Pierre Auger Collab. *[PRL (2010); Facal San Luis, ICRC-2011]*
- model-dependence strongly reduced
- but: almost pure *Fe* at the highest energies?!

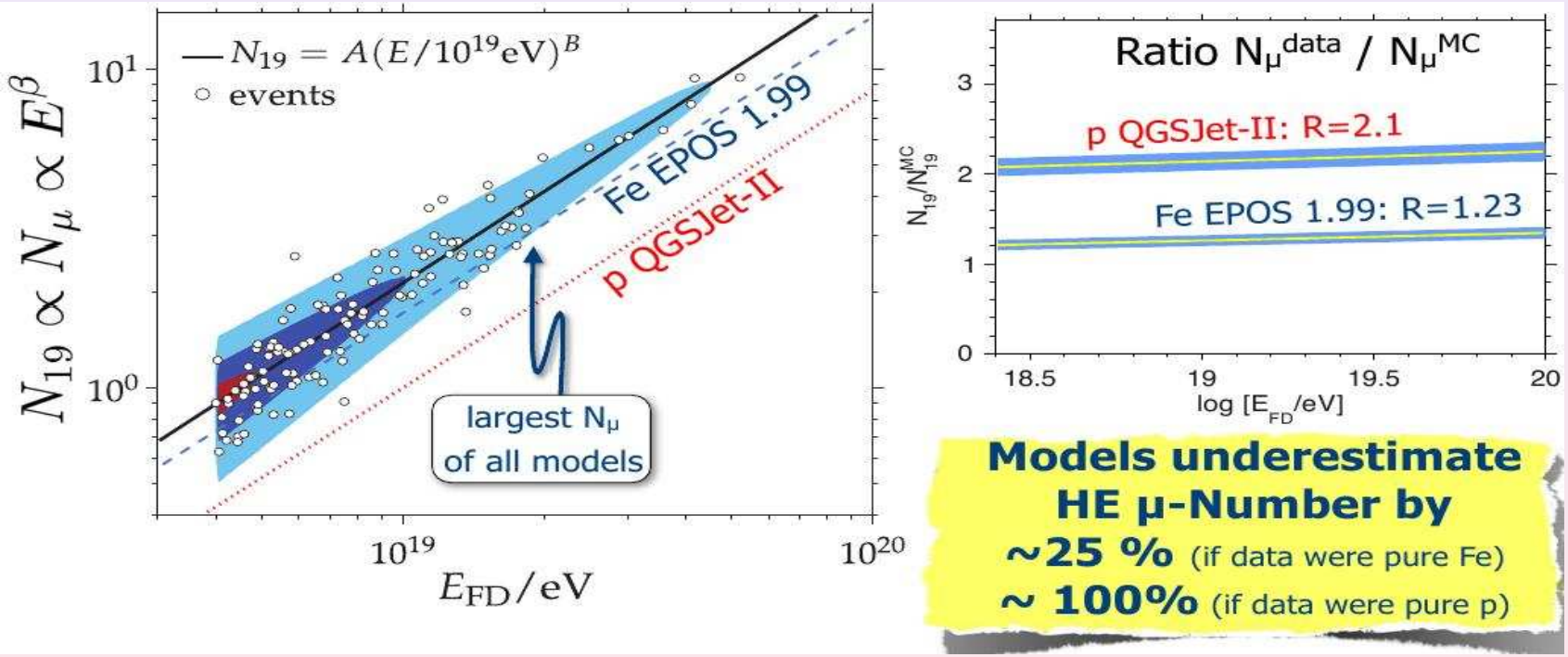
UHECR composition from muon component?

Alternative approach – study of muon densities at ground

UHECR composition from muon component?

Alternative approach – study of muon densities at ground

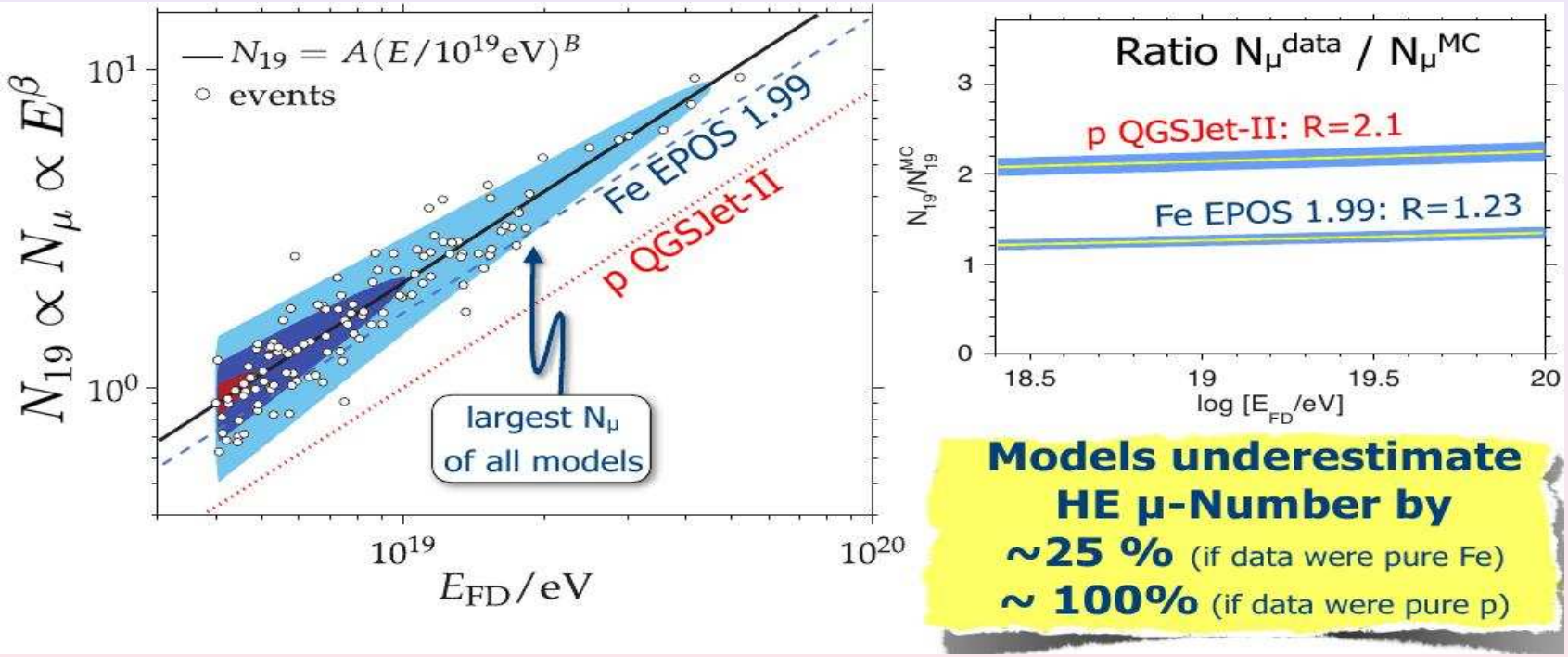
- Pierre Auger Collab.: strong muon excess observed compared to model predictions! *[Rodriguez, ICRC-2011]*



UHECR composition from muon component?

Alternative approach – study of muon densities at ground

- Pierre Auger Collab.: strong muon excess observed compared to model predictions! *[Rodriguez, ICRC-2011]*

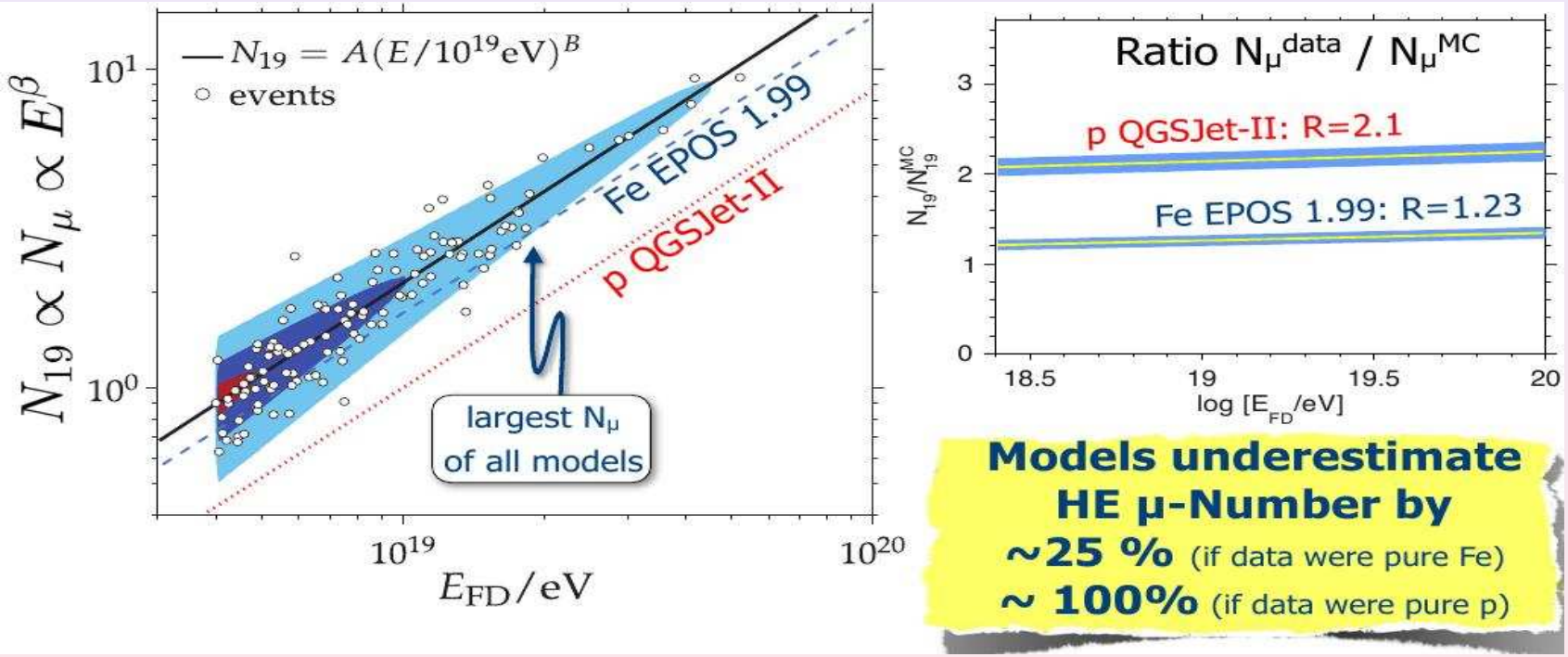


- may be UHECR are gold nuclei?!

UHECR composition from muon component?

Alternative approach – study of muon densities at ground

- Pierre Auger Collab.: strong muon excess observed compared to model predictions! *[Rodriguez, ICRC-2011]*



- may be UHECR are gold nuclei?!
- highly unlikely, rather CR interaction models should be wrong

CR interaction models

- similar physics content for all MC generators used in CR field:
  - multiple scattering
  - soft & hard processes
  - nonlinear effects, e.g. parton shadowing (not in all models)

CR interaction models

- similar physics content for all MC generators used in CR field:
  - multiple scattering
  - soft & hard processes
  - nonlinear effects, e.g. parton shadowing (not in all models)

CR interaction models

- similar physics content for all MC generators used in CR field:
  - multiple scattering
  - soft & hard processes
  - nonlinear effects, e.g. parton shadowing (not in all models)

CR interaction models

- similar physics content for all MC generators used in CR field:
  - multiple scattering
  - soft & hard processes
  - nonlinear effects, e.g. parton shadowing (not in all models)

CR interaction models

- similar physics content for all MC generators used in CR field:
  - multiple scattering
  - soft & hard processes
  - nonlinear effects, e.g. parton shadowing (not in all models)
- representative models:
  - QGSJET (Kalmykov & SO, 1993–1997)
  - SIBYLL 1.7/2.1 (Ahn, Engel, Gaisser, Lipari & Stanev, 1994/1999)
  - QGSJET II-03/04 (SO, 2006/2011)
  - EPOS (Liu, Pierog & Werner, 2006-2011)

CR interaction models

- similar physics content for all MC generators used in CR field:
  - multiple scattering
  - soft & hard processes
  - nonlinear effects, e.g. parton shadowing (not in all models)
- representative models:
  - QGSJET (Kalmykov & SO, 1993–1997)
  - SIBYLL 1.7/2.1 (Ahn, Engel, Gaisser, Lipari & Stanev, 1994/1999)
  - QGSJET II-03/04 (SO, 2006/2011)
  - EPOS (Liu, Pierog & Werner, 2006-2011)
- all the models based on similar ideas / qualitative approaches

CR interaction models

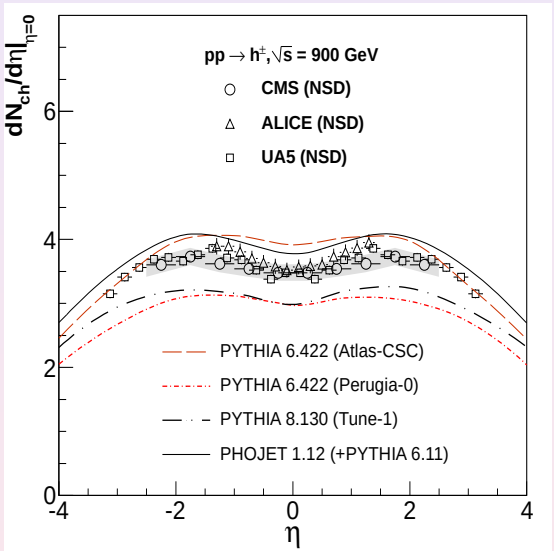
- similar physics content for all MC generators used in CR field:
  - multiple scattering
  - soft & hard processes
  - nonlinear effects, e.g. parton shadowing (not in all models)
- representative models:
  - QGSJET (Kalmykov & SO, 1993–1997)
  - SIBYLL 1.7/2.1 (Ahn, Engel, Gaisser, Lipari & Stanev, 1994/1999)
  - QGSJET II-03/04 (SO, 2006/2011)
  - EPOS (Liu, Pierog & Werner, 2006-2011)
- all the models based on similar ideas / qualitative approaches
- differ in implementations, theory input, etc. $\Rightarrow$ in predictions

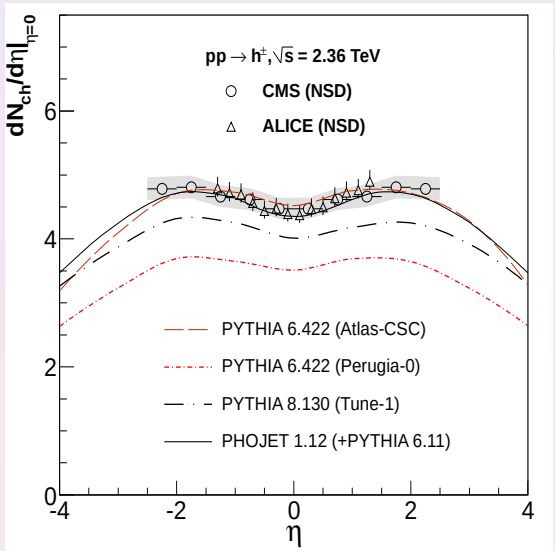
CR interaction models

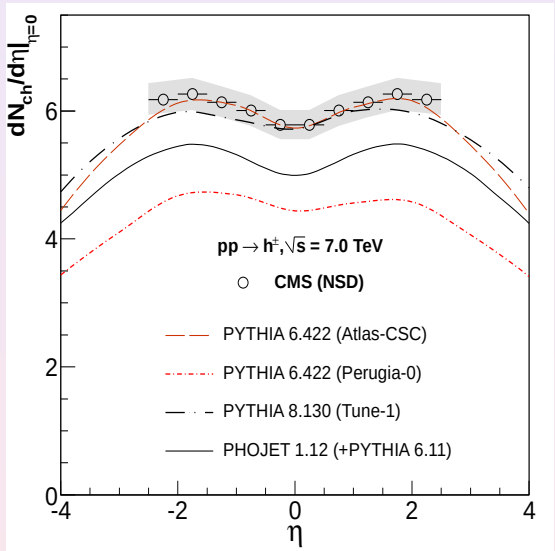
- similar physics content for all MC generators used in CR field:
  - multiple scattering
  - soft & hard processes
  - nonlinear effects, e.g. parton shadowing (not in all models)
- representative models:
  - QGSJET (Kalmykov & SO, 1993–1997)
  - SIBYLL 1.7/2.1 (Ahn, Engel, Gaisser, Lipari & Stanev, 1994/1999)
  - QGSJET II-03/04 (SO, 2006/2011)
  - EPOS (Liu, Pierog & Werner, 2006-2011)
- all the models based on similar ideas / qualitative approaches
- differ in implementations, theory input, etc. $\Rightarrow$ in predictions
- model updates / cross checks with new data – necessary

MC generators & LHC data

- LHC data: $N_{\mathrm{ch}}(s)$ rises quicker than predicted by most MCs



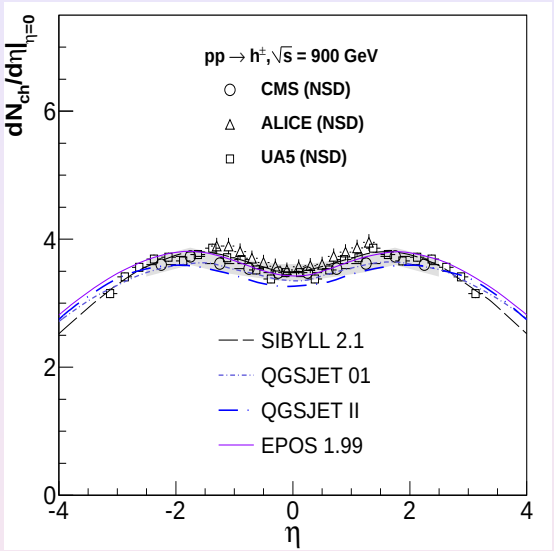


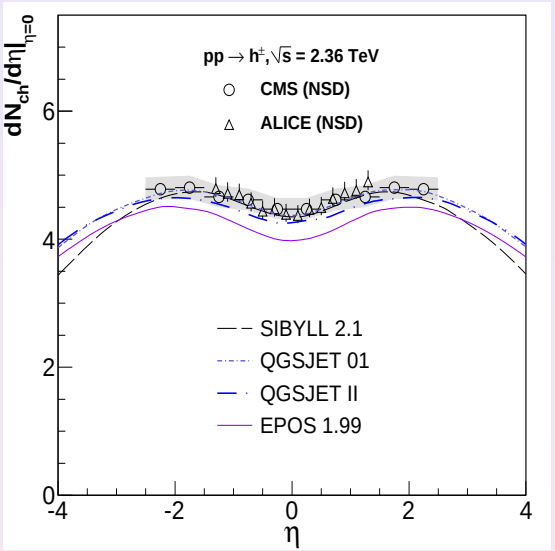


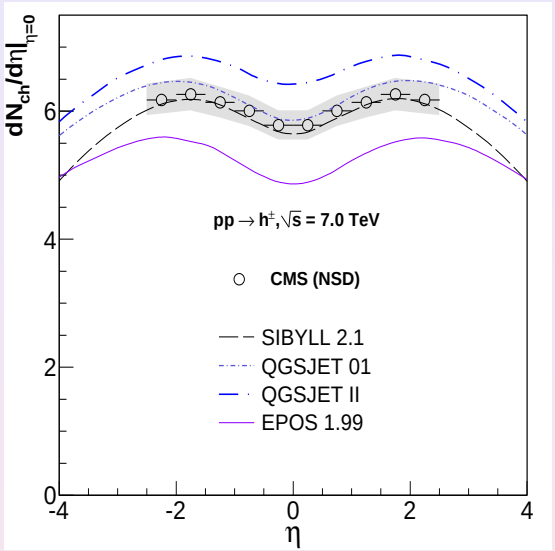
[plots from d'Enterria et al., Astrop. Phys. 35 (2011)]

MC generators & LHC data

- $N_{\mathrm{ch}}(s)$ - described better by CR interaction models



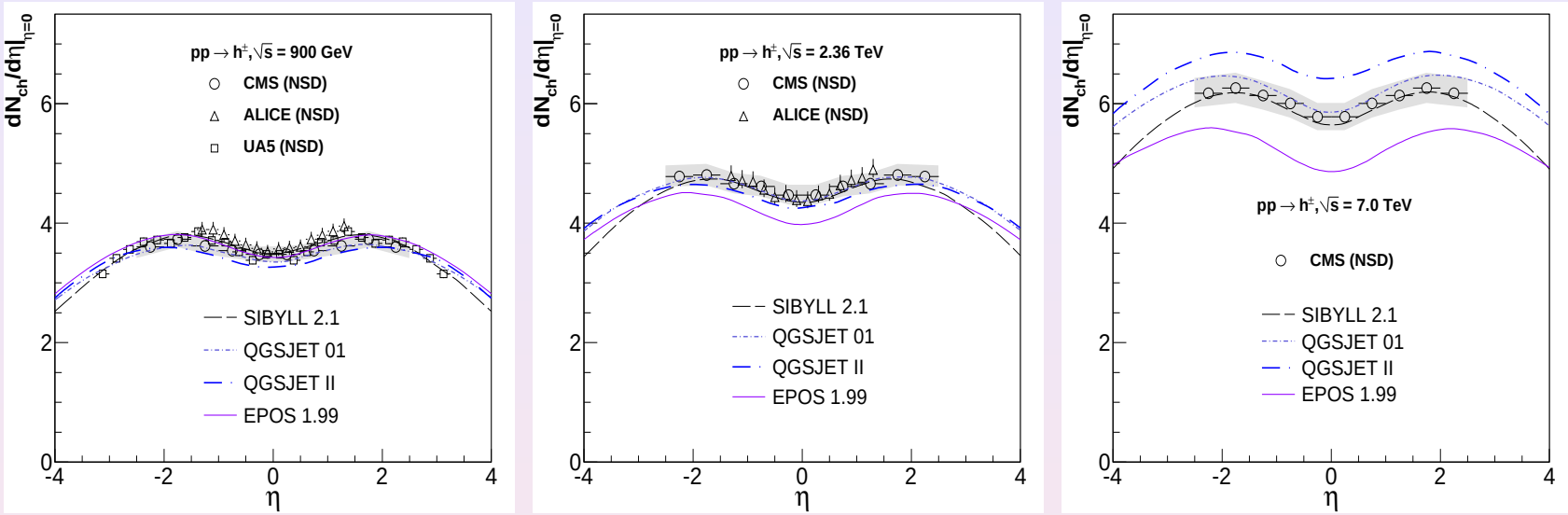




[plots from d'Enterria et al., Astrop. Phys. 35 (2011)]

MC generators & LHC data

- $N_{\mathrm{ch}}(s)$ - described better by CR interaction models

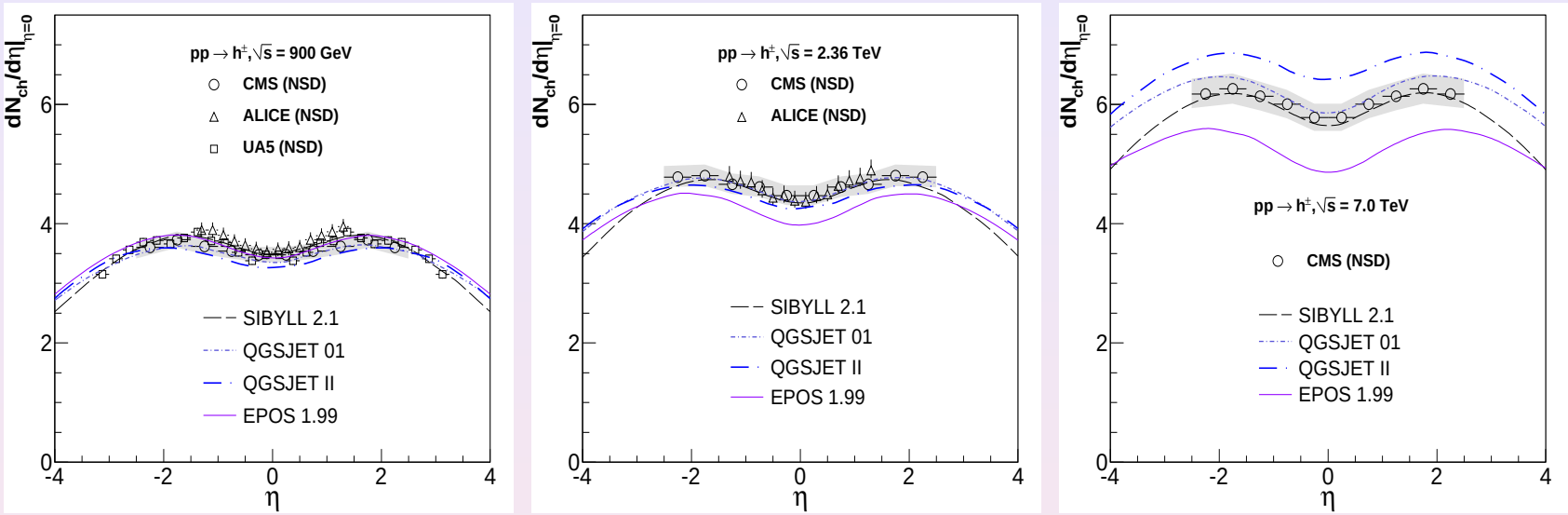


[plots from d'Enterria et al., Astrop. Phys. 35 (2011)]

- most of the models agree with the data within 10% (surprisingly, the oldest models perform best)

MC generators & LHC data

- $N_{\mathrm{ch}}(s)$ - described better by CR interaction models

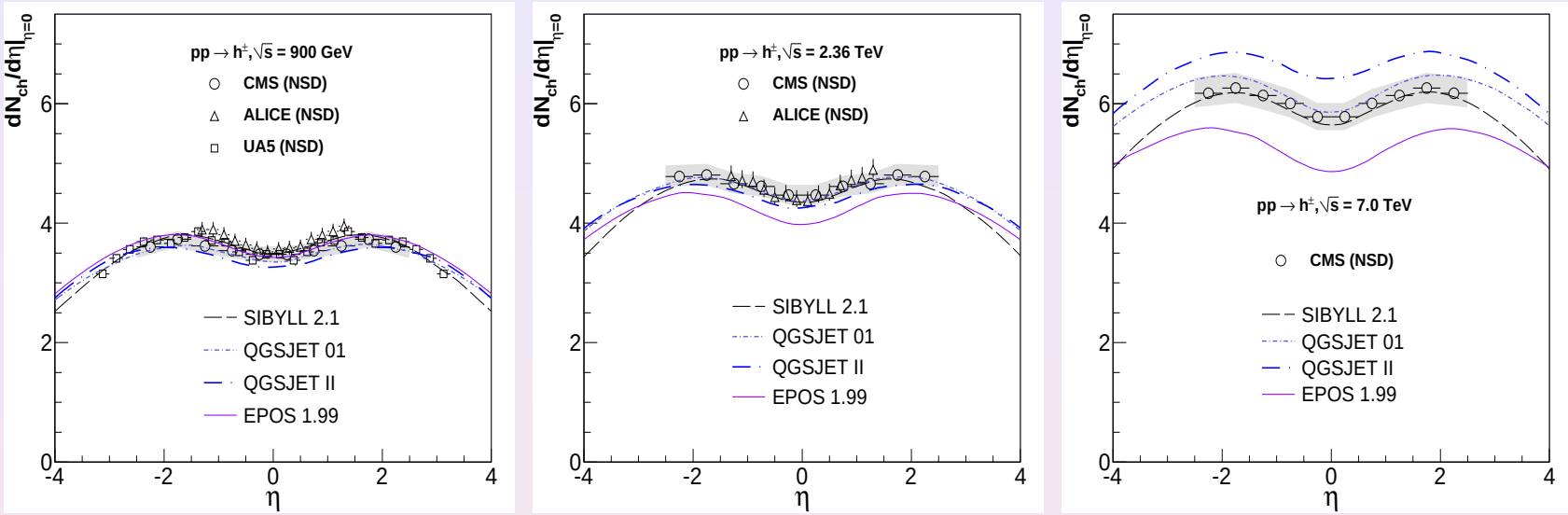


[plots from d'Enterria et al., Astrop. Phys. 35 (2011)]

- most of the models agree with the data within 10% (surprisingly, the oldest models perform best)
- CR MCs: tuned to data over a wide energy range
  $\Rightarrow$ loose in details, win in predictive power

MC generators & LHC data

- $N_{\mathrm{ch}}(s)$ - described better by CR interaction models

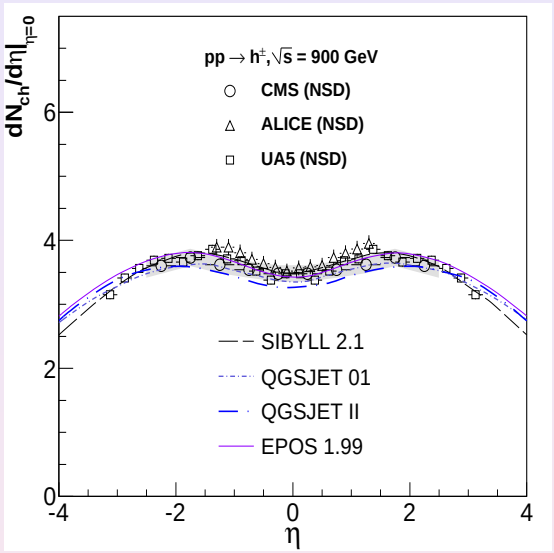


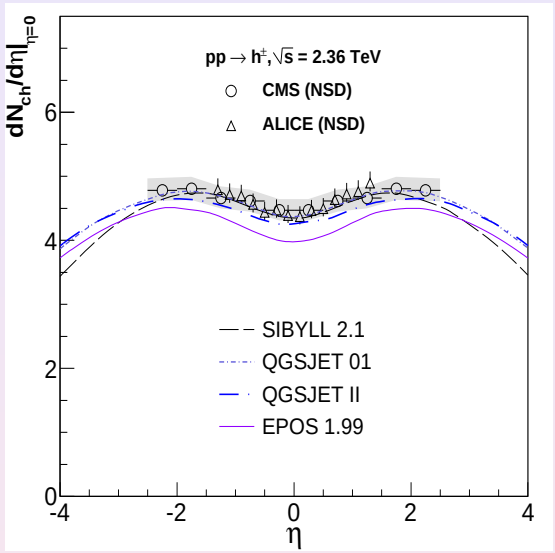
[plots from d'Enterria et al., Astrop. Phys. 35 (2011)]

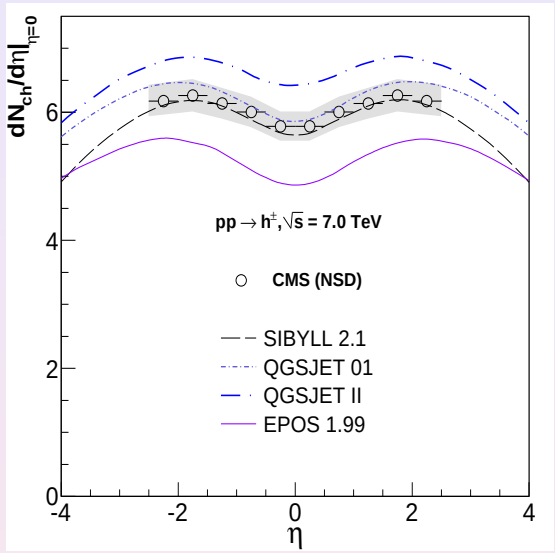
- most of the models agree with the data within 10% (surprisingly, the oldest models perform best)
- CR MCs: tuned to data over a wide energy range
  $\Rightarrow$ loose in details, win in predictive power
- however: none of the models describes all the observables

MC generators & LHC data

- $N_{\mathrm{ch}}(s)$ - described better by CR interaction models







[plots from d'Enterria et al., Astrop. Phys. 35 (2011)]

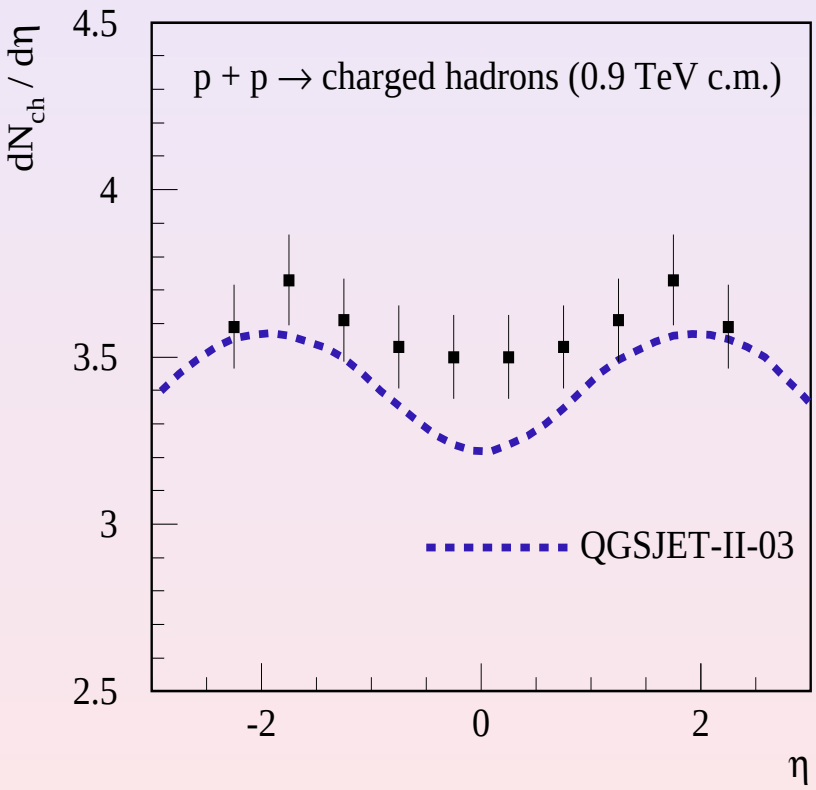
- however: none of the models describes all the observables

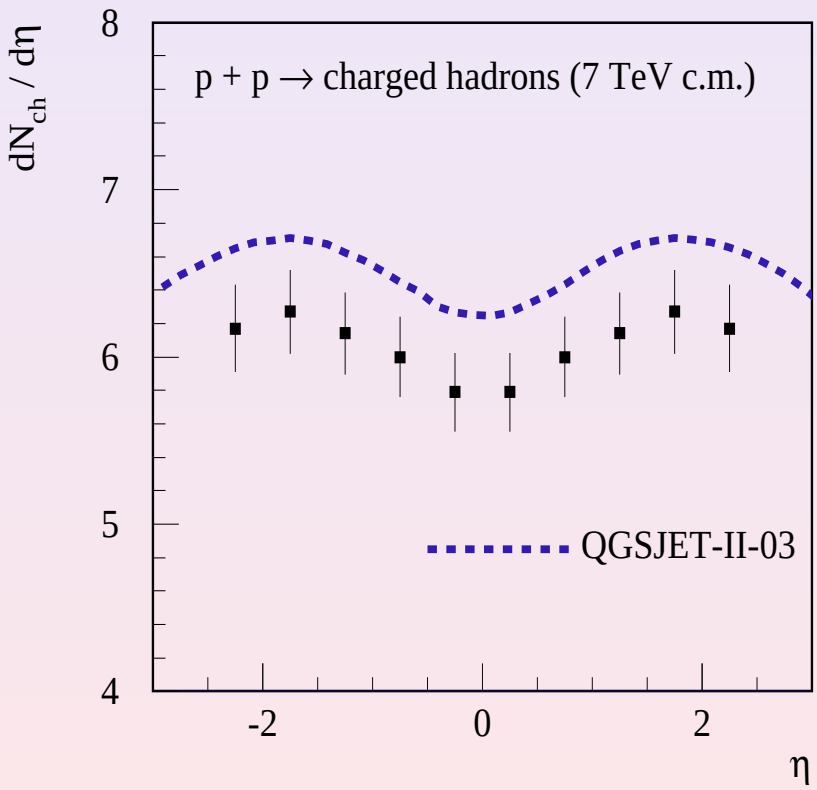
Effect of model retuning to LHC data?

- in the following investigated using the QGSJET-II model

Multiplicity adjustrment

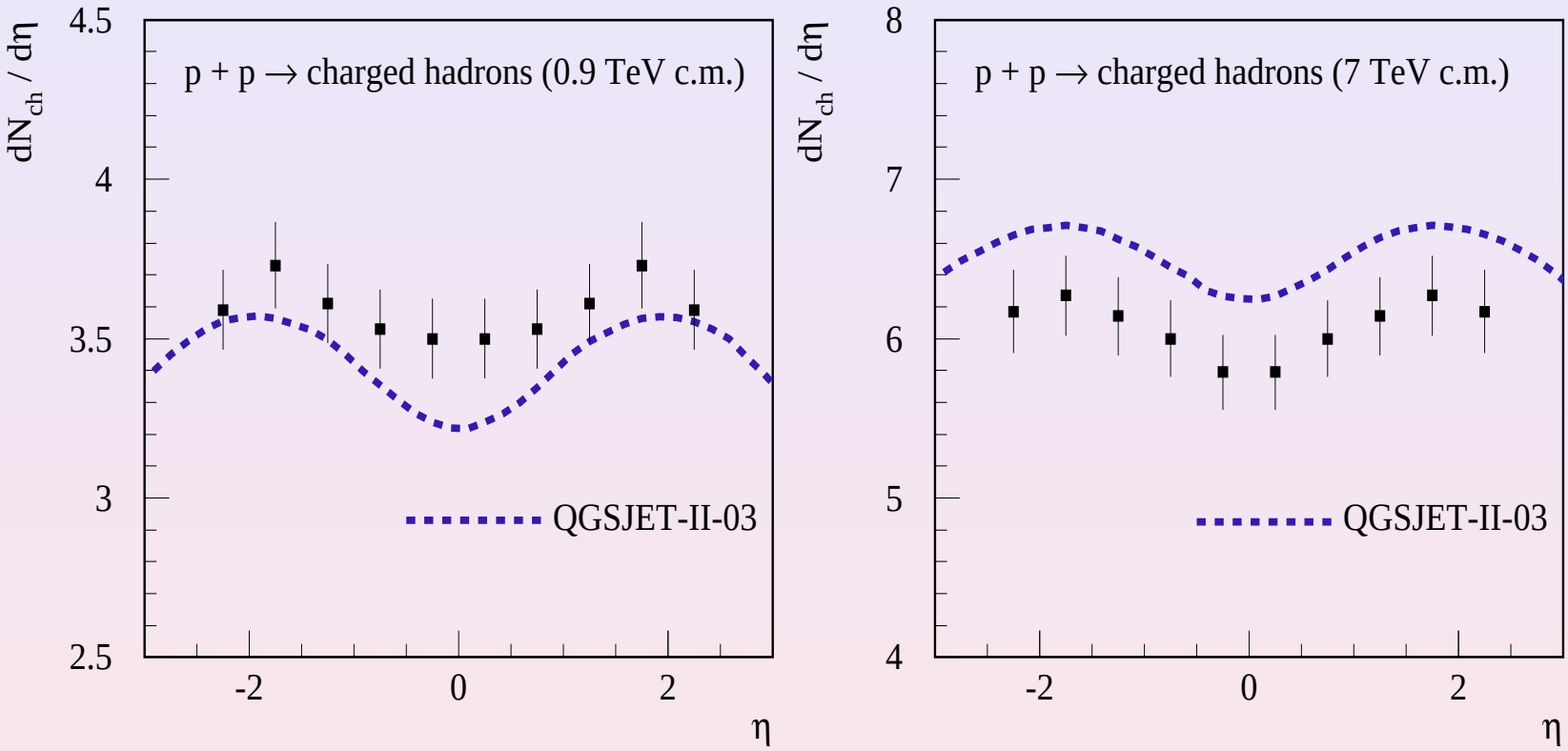
- $N_{\mathrm{ch}}(s)$-rise: too steep in QGSJET-II-03





Multiplicity adjustrment

- $N_{\mathrm{ch}}(s)$-rise: too steep in QGSJET-II-03

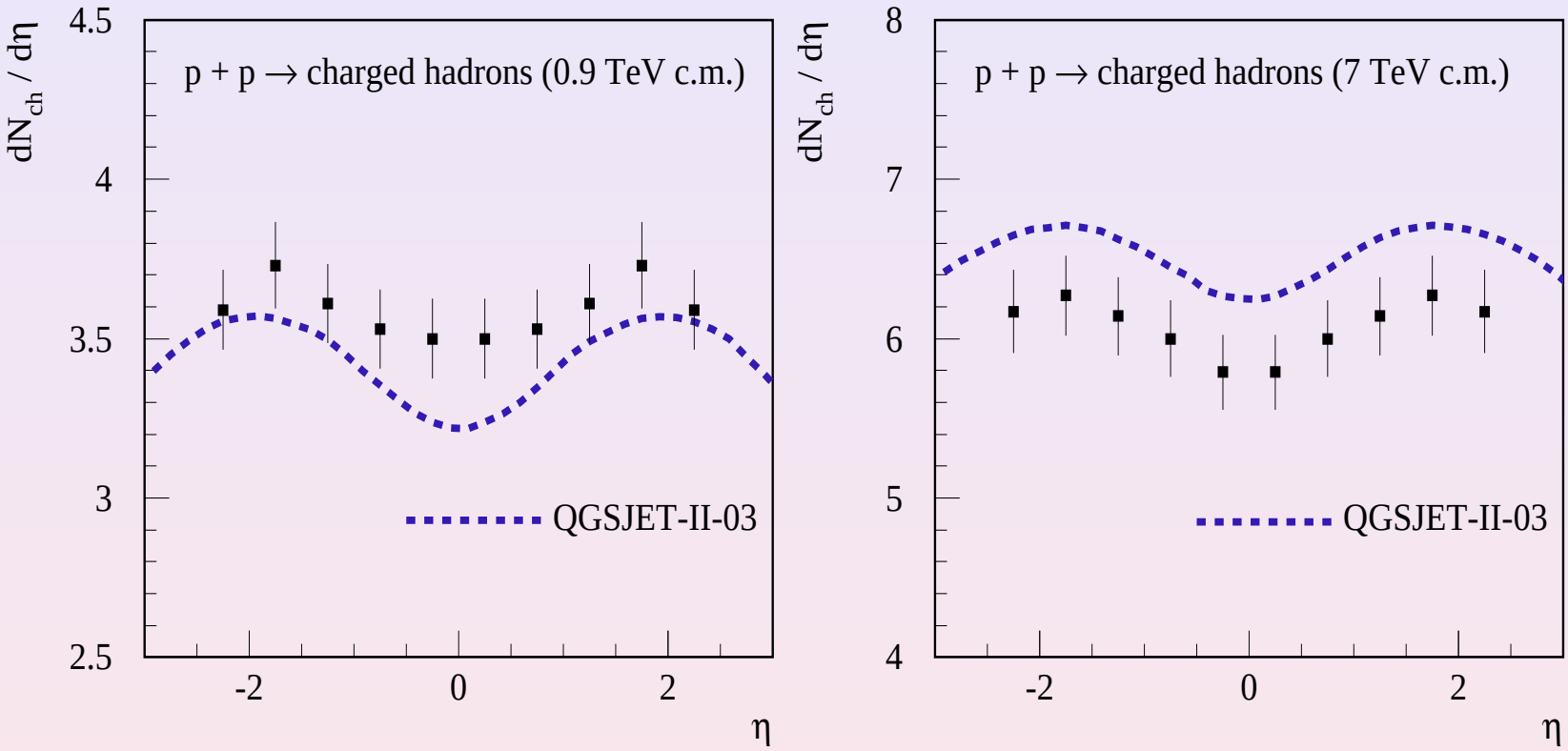


not easy to correct:

- hadronization parameters – tuned at fixed target energies
- general model parameters – tuned to cross sections & SFs

Multiplicity adjustrment

- $N_{\mathrm{ch}}(s)$-rise: too steep in QGSJET-II-03



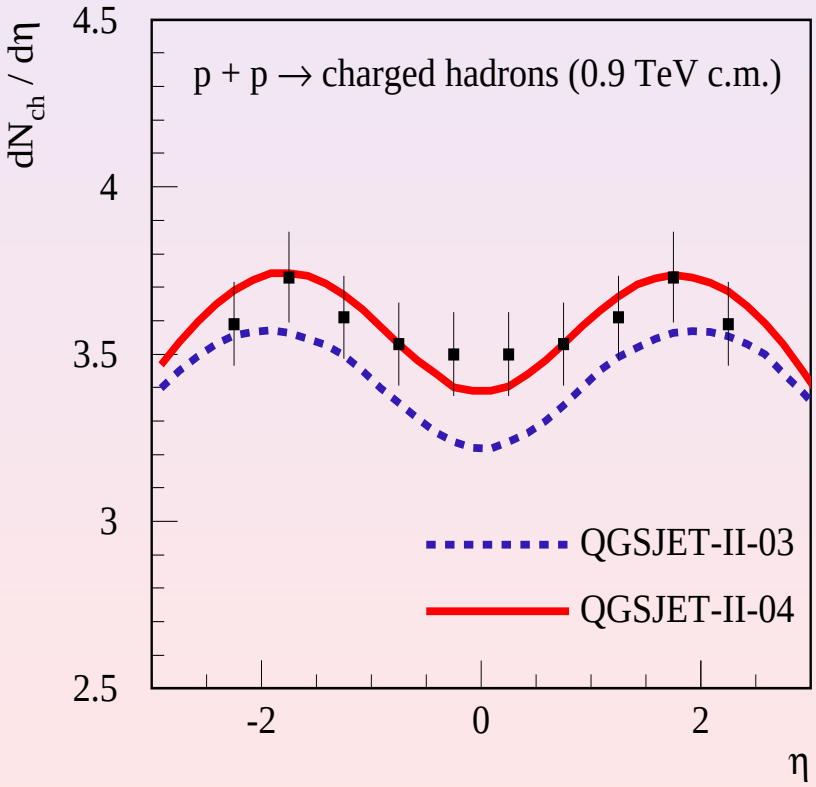
not easy to correct:

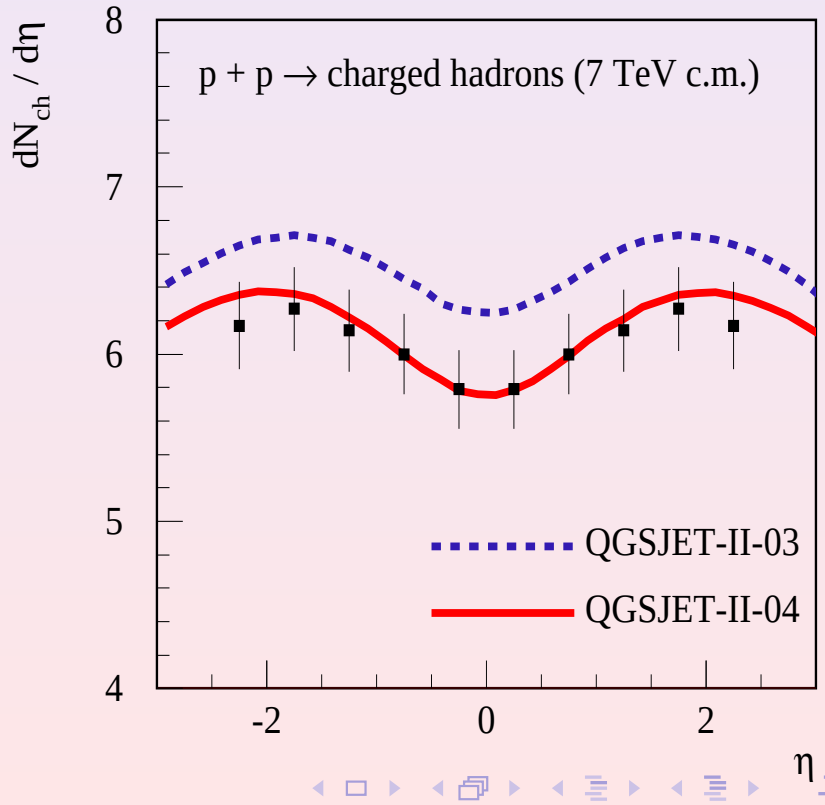
- hadronization parameters – tuned at fixed target energies
- general model parameters – tuned to cross sections & SFs

Multiplicity adjustrment

changing the cutoff Q_0^2 between soft & hard processes
$(2.5 \rightarrow 3\,\mathrm{GeV}^2)$

- parton saturation operates over a larger kinematic space
- $\Rightarrow$ slows down multiplicity rise

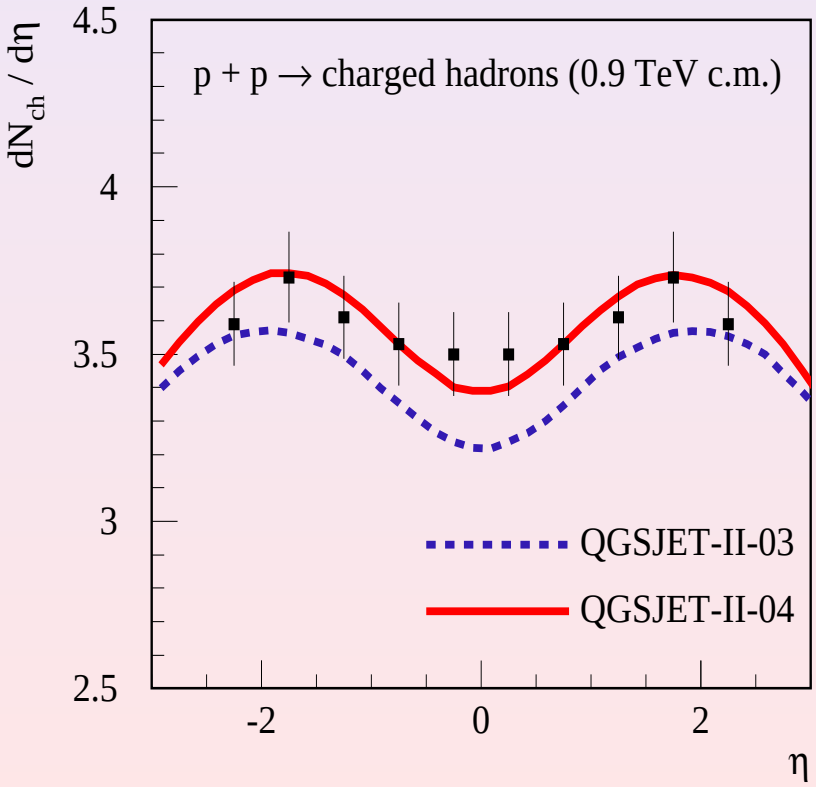


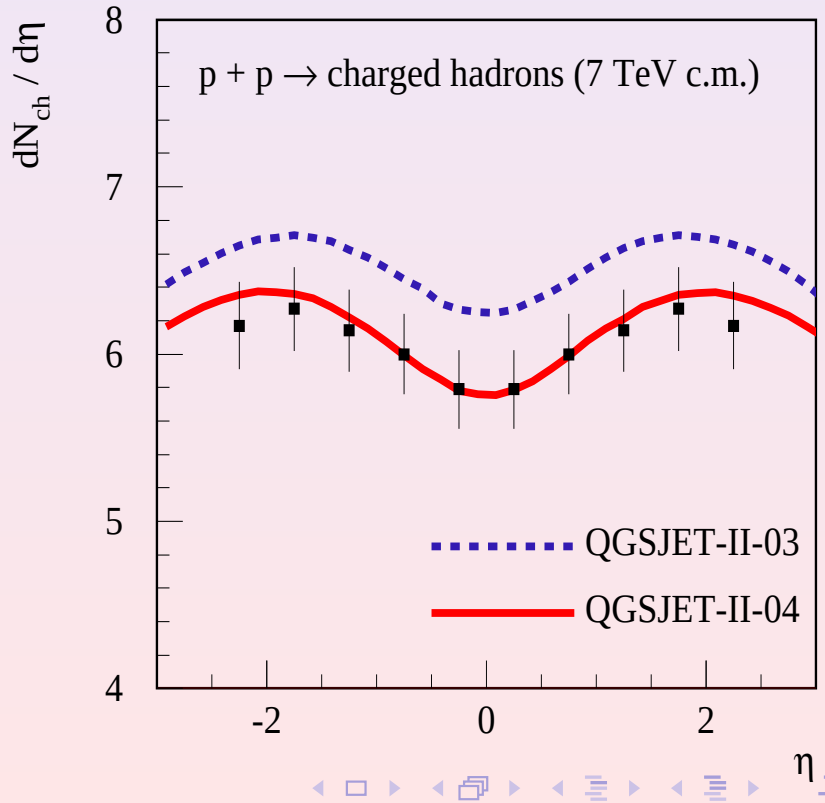


Multiplicity adjustrment

changing the cutoff Q_0^2 between soft & hard processes $(2.5 \rightarrow 3\,\mathrm{GeV}^2)$

- parton saturation operates over a larger kinematic space
- $\Rightarrow$ slows down multiplicity rise

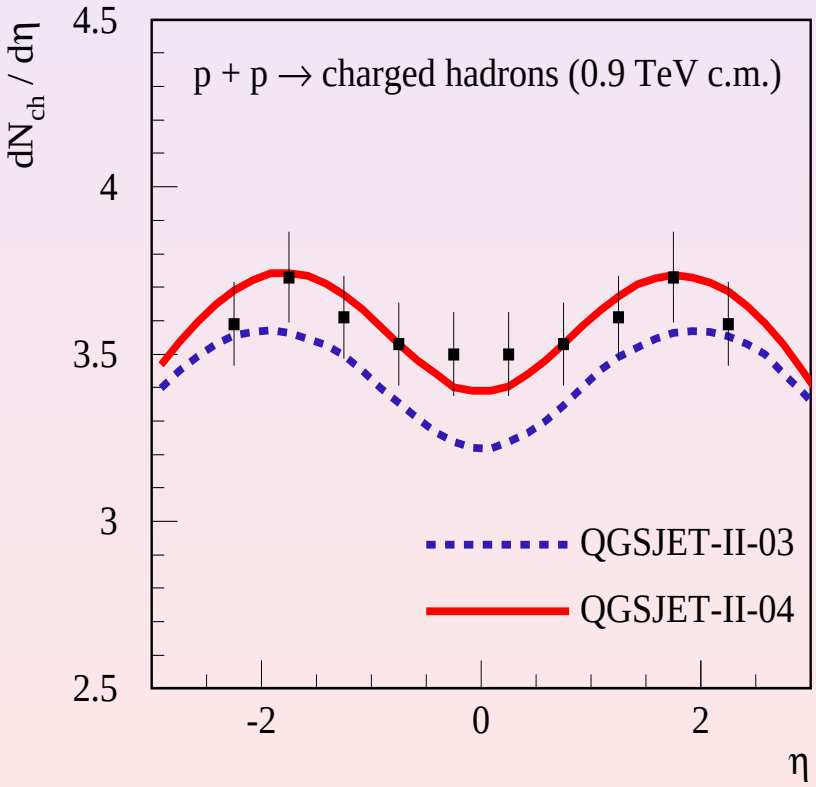


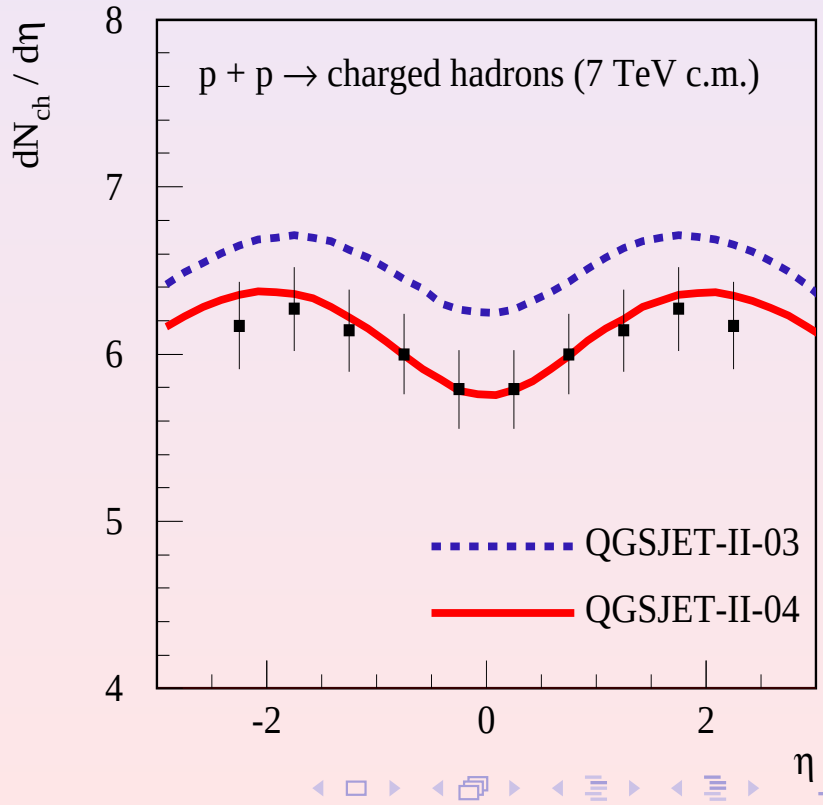


Multiplicity adjustrment

changing the cutoff Q_0^2 between soft & hard processes $(2.5 \rightarrow 3\,\mathrm{GeV}^2)$

- parton saturation operates over a larger kinematic space
- $\Rightarrow$ slows down multiplicity rise

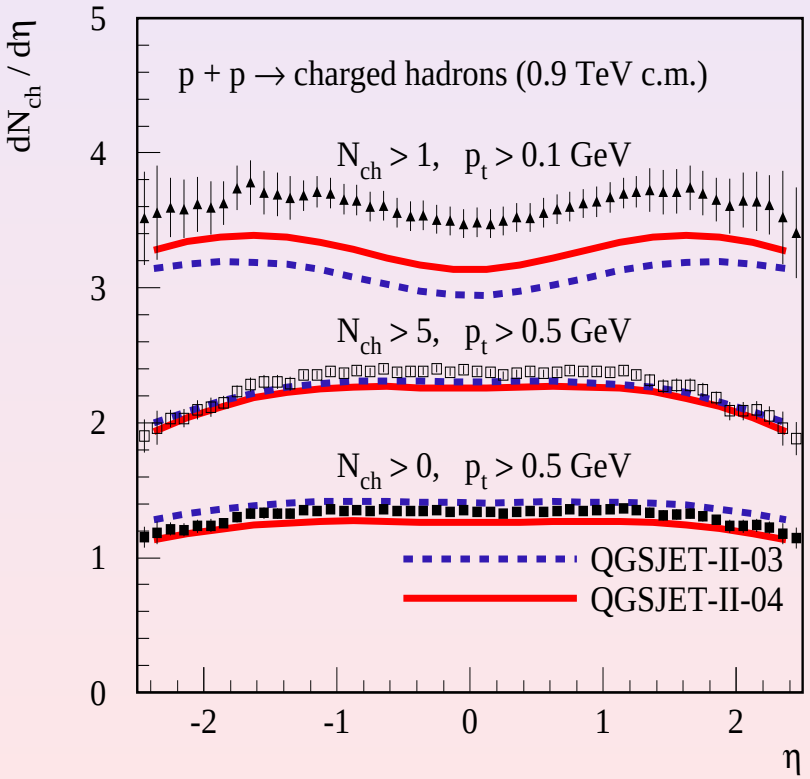


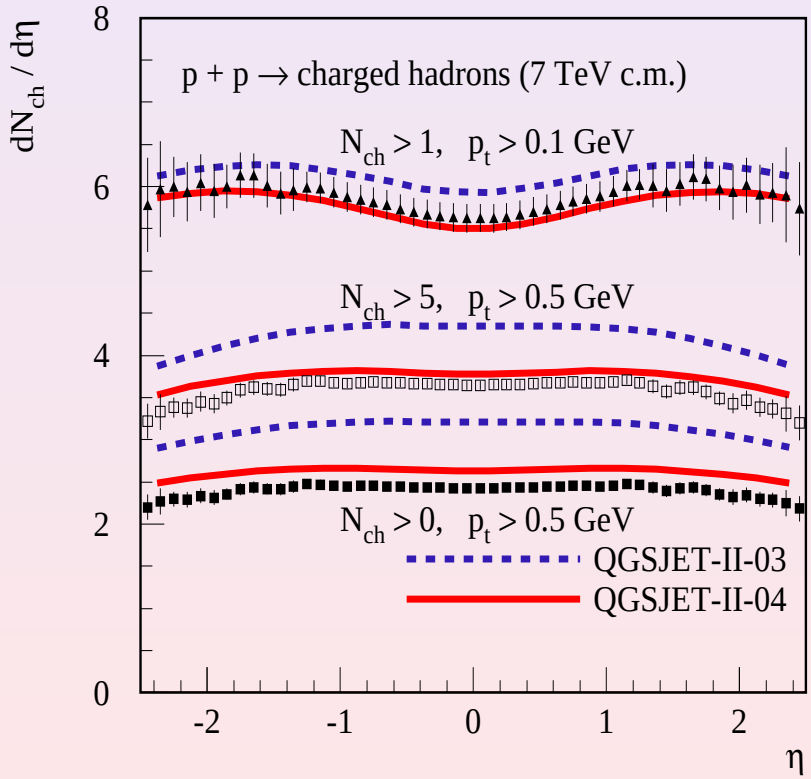


Multiplicity: cross check with ATLAS data

$dN_{\mathrm{ch}}/d\eta$: model-independent results from ATLAS

- qualitatively the same trend
- the level of (dis)agreement varies for different event selections

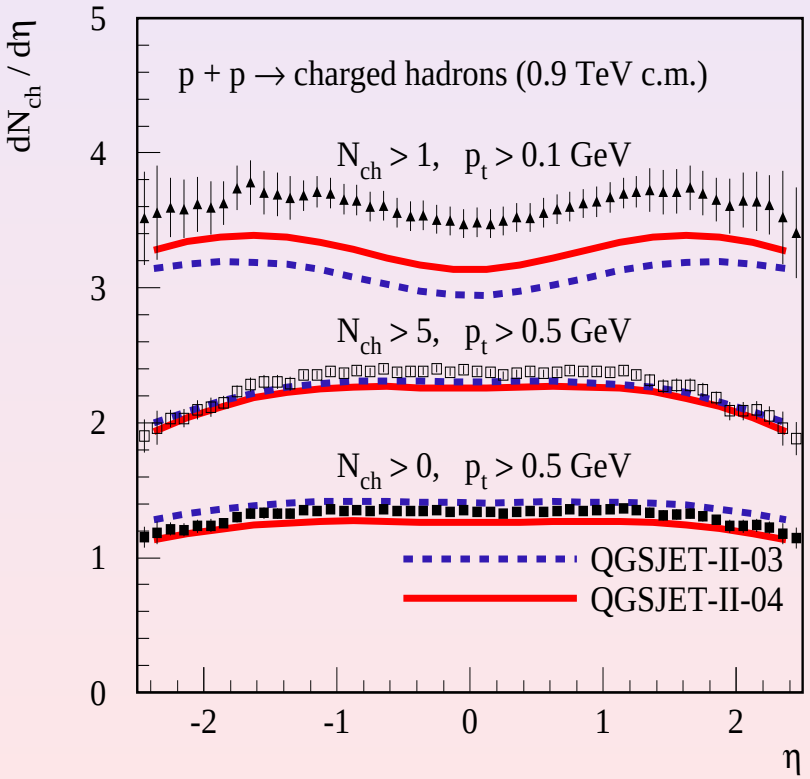


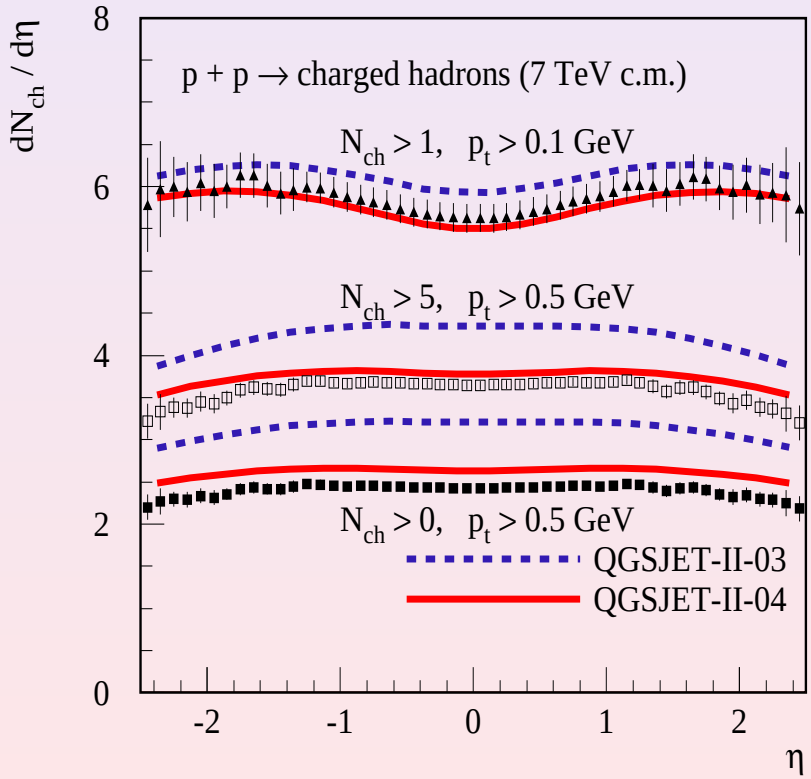


Multiplicity: cross check with ATLAS data

$dN_{\mathrm{ch}}/d\eta$: model-independent results from ATLAS

- qualitatively the same trend
- the level of (dis)agreement varies for different event selections

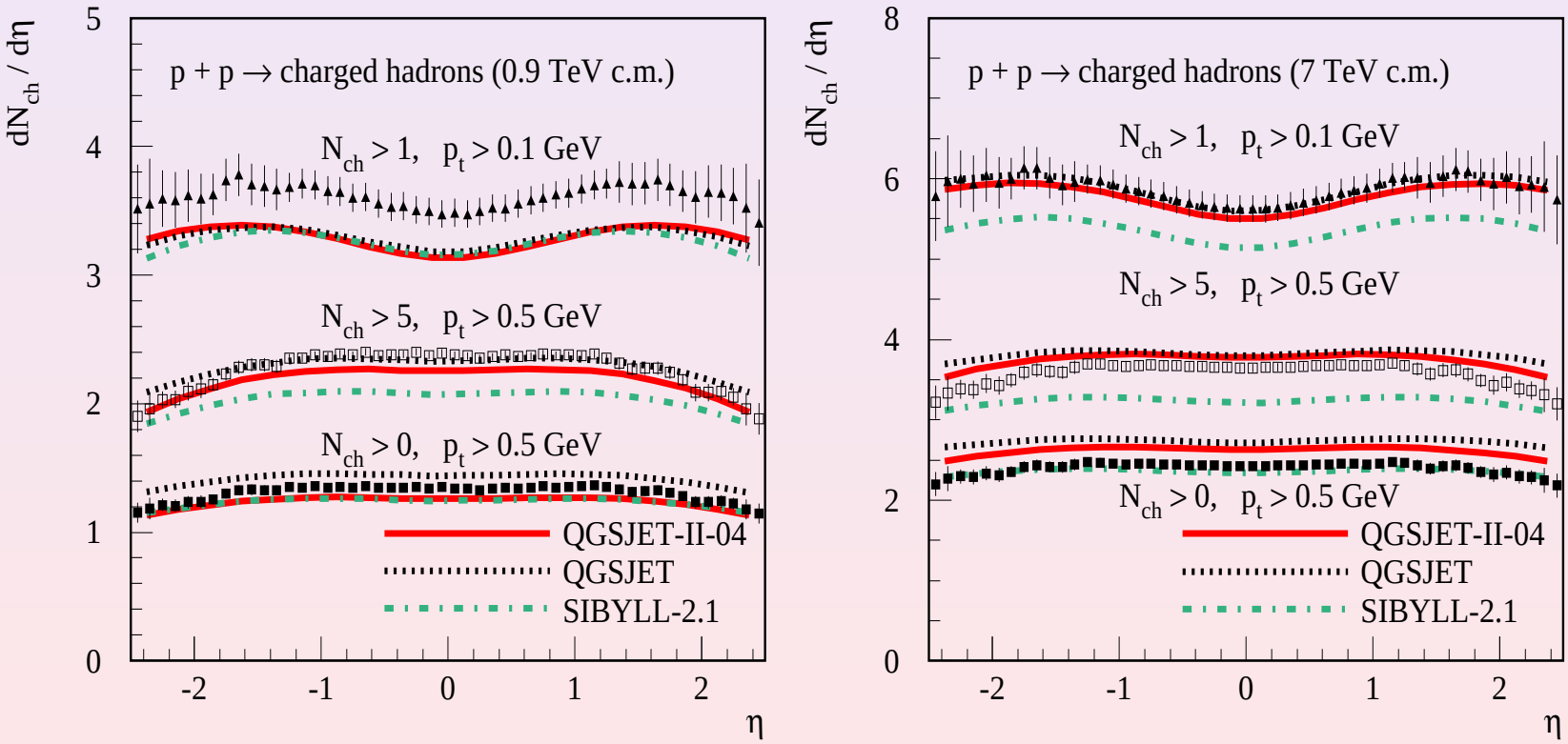




Multiplicity: cross check with ATLAS data

$dN_{\mathrm{ch}}/d\eta$: model-independent results from ATLAS:

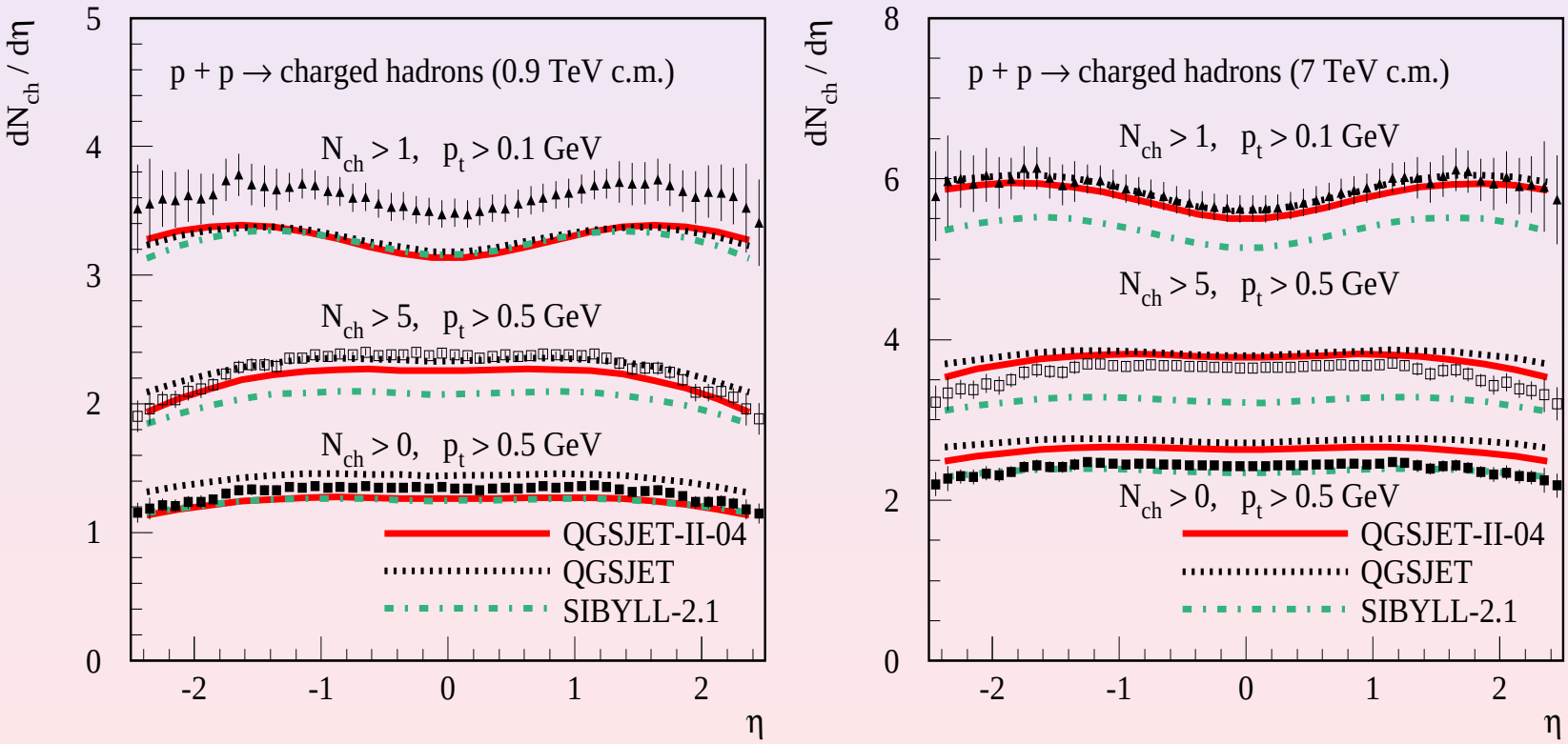
- overall multiplicity corrections at $\sim 10\%$ level
- $\Rightarrow$ insignificant for air shower predictions



Multiplicity: cross check with ATLAS data

$dN_{\mathrm{ch}}/d\eta$: model-independent results from ATLAS:

- overall multiplicity corrections at $\sim 10\%$ level
- $\Rightarrow$ insignificant for air shower predictions



Production of (anti-)baryons

Generally, enhanced production of (anti-)baryons may increase EAS muon content *[Pierog & Werner, PRL (2008)]*

- more energy kept in the hadronic cascade
- more cascade steps (no decay for nucleons) $\Rightarrow$ higher N_μ

Production of (anti-)baryons

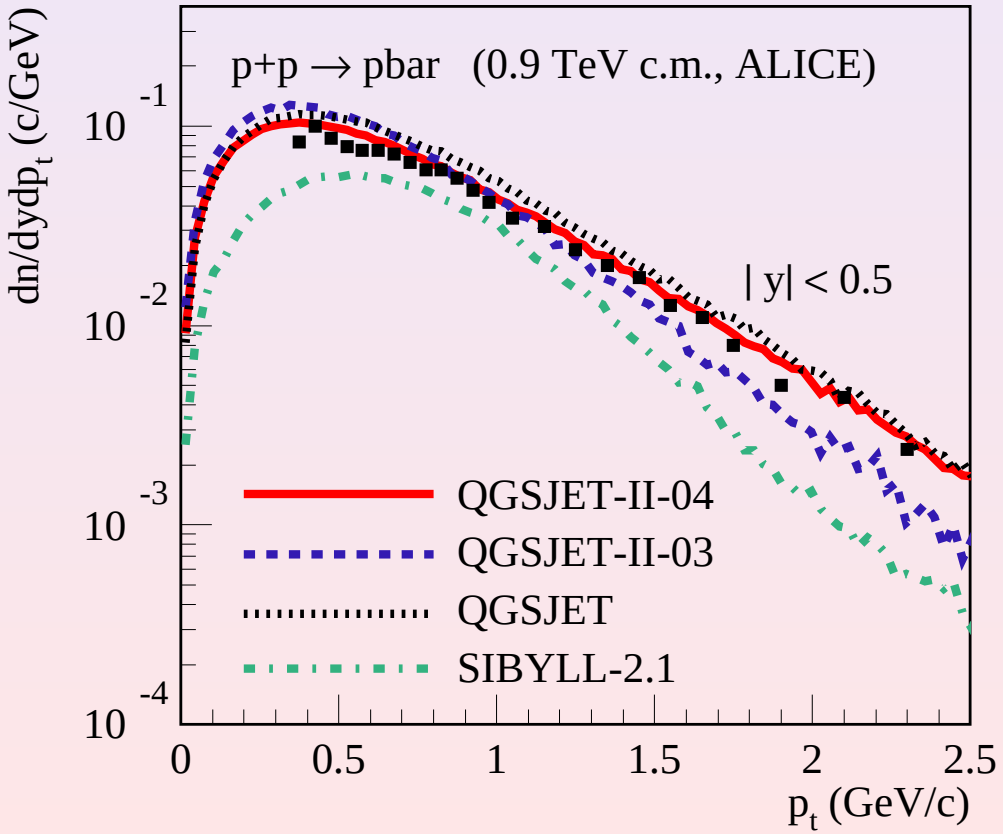
Generally, enhanced production of (anti-)baryons may increase EAS muon content *[Pierog & Werner, PRL (2008)]*

- more energy kept in the hadronic cascade
- more cascade steps (no decay for nucleons) $\Rightarrow$ higher N_μ

Production of (anti-)baryons

Generally, enhanced production of (anti-)baryons may increase EAS muon content *[Pierog & Werner, PRL (2008)]*

- more energy kept in the hadronic cascade
- more cascade steps (no decay for nucleons) $\Rightarrow$ higher N_μ

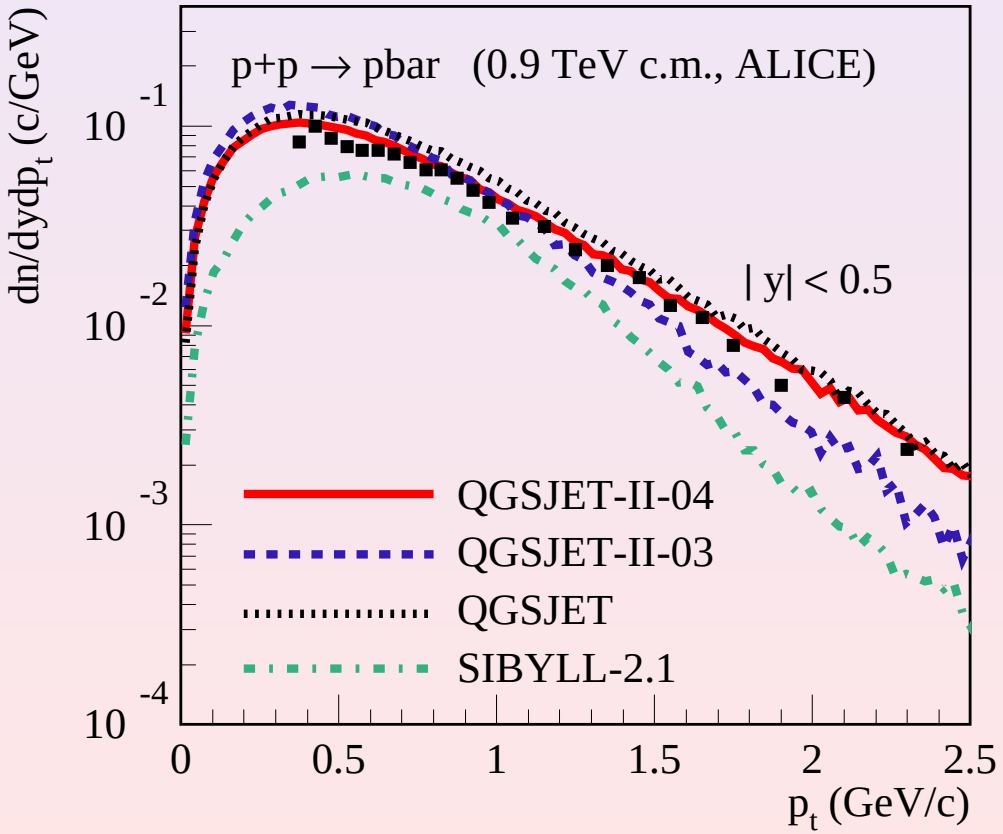


- $\bar{p}$-production at LHC: no excess compared to most model predictions
- $\Rightarrow$ no corrections for N_μ

Production of (anti-)baryons

Generally, enhanced production of (anti-)baryons may increase EAS muon content *[Pierog & Werner, PRL (2008)]*

- more energy kept in the hadronic cascade
- more cascade steps (no decay for nucleons) $\Rightarrow$ higher N_μ

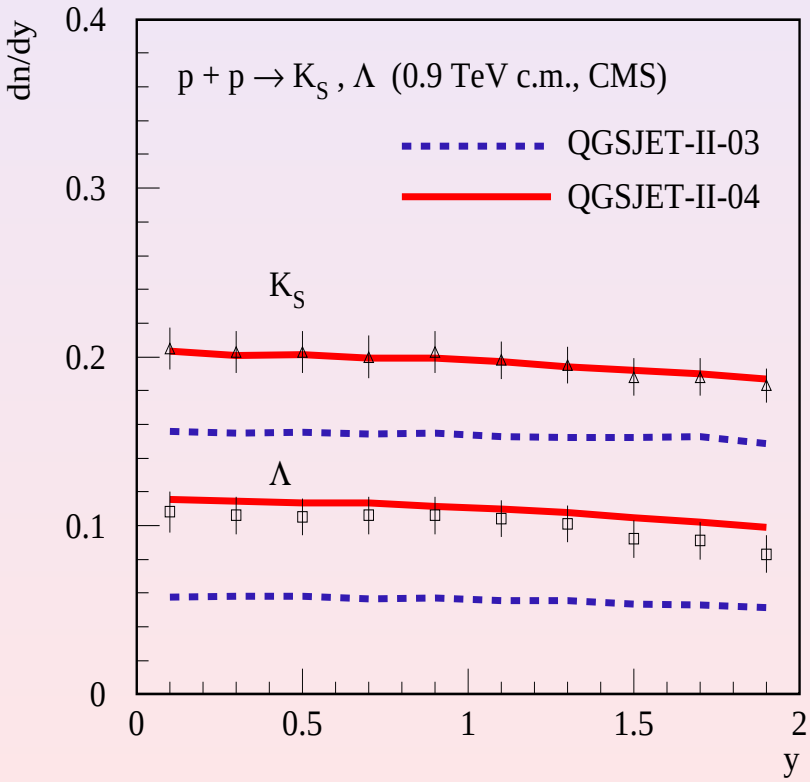


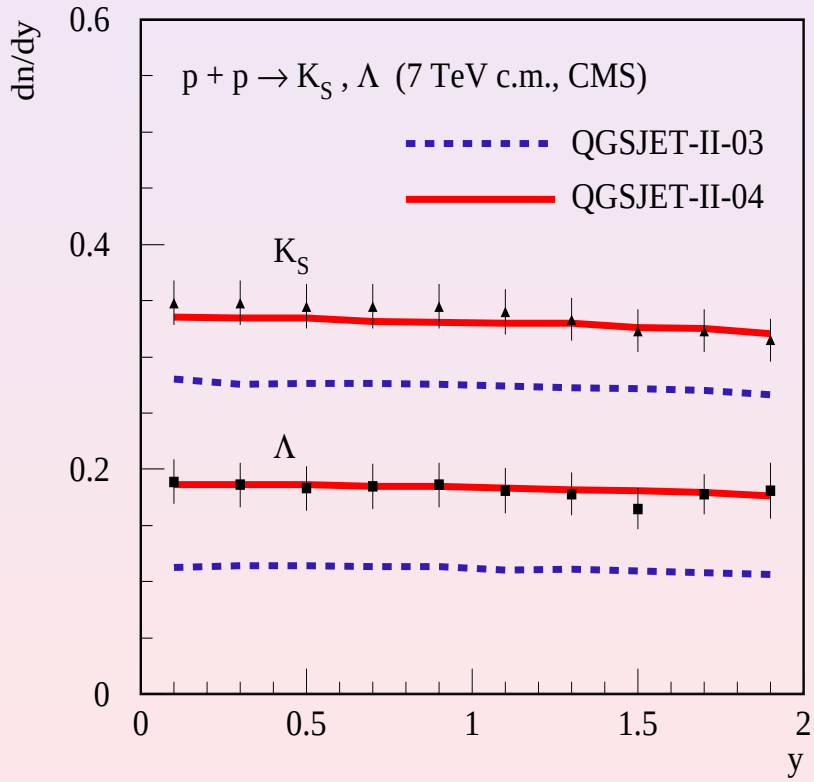
- $\bar{p}$-production at LHC: no excess compared to most model predictions
- $\Rightarrow$ no corrections for N_μ

Production of strange particles

Enhancement of strange particle production may also increase N_μ

- more energy channeled into hadronic cascade
- QGSJET-II-03: noticeable correction required by LHC data

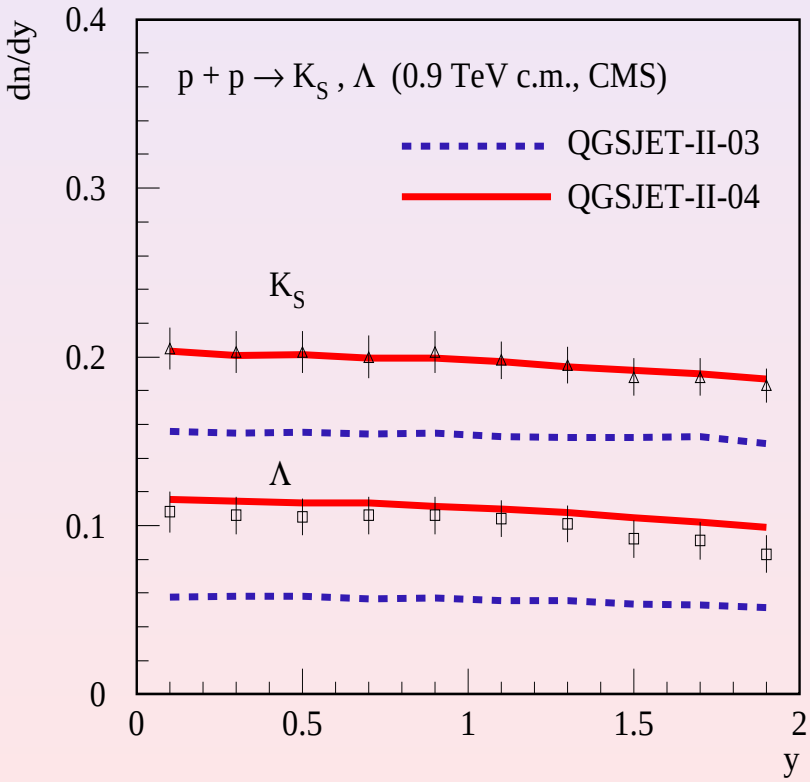


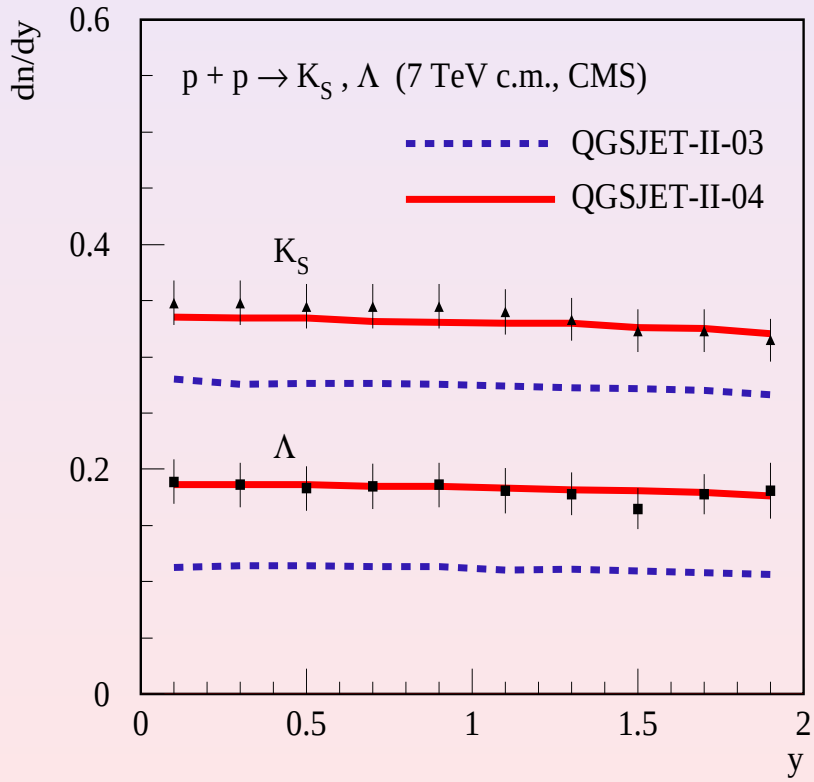


Production of strange particles

Enhancement of strange particle production may also increase N_μ

- more energy channeled into hadronic cascade
- QGSJET-II-03: noticeable correction required by LHC data

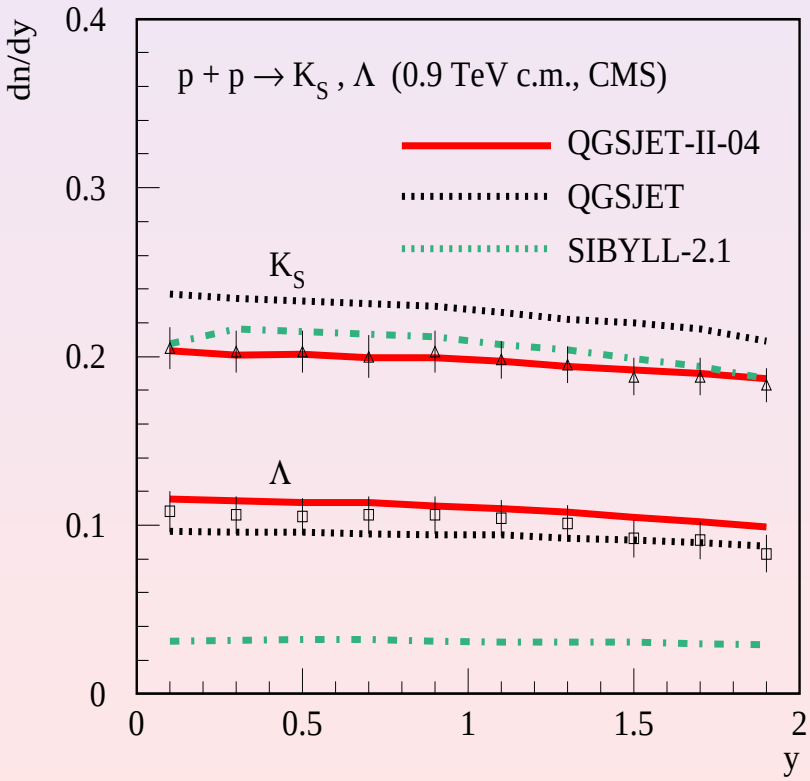


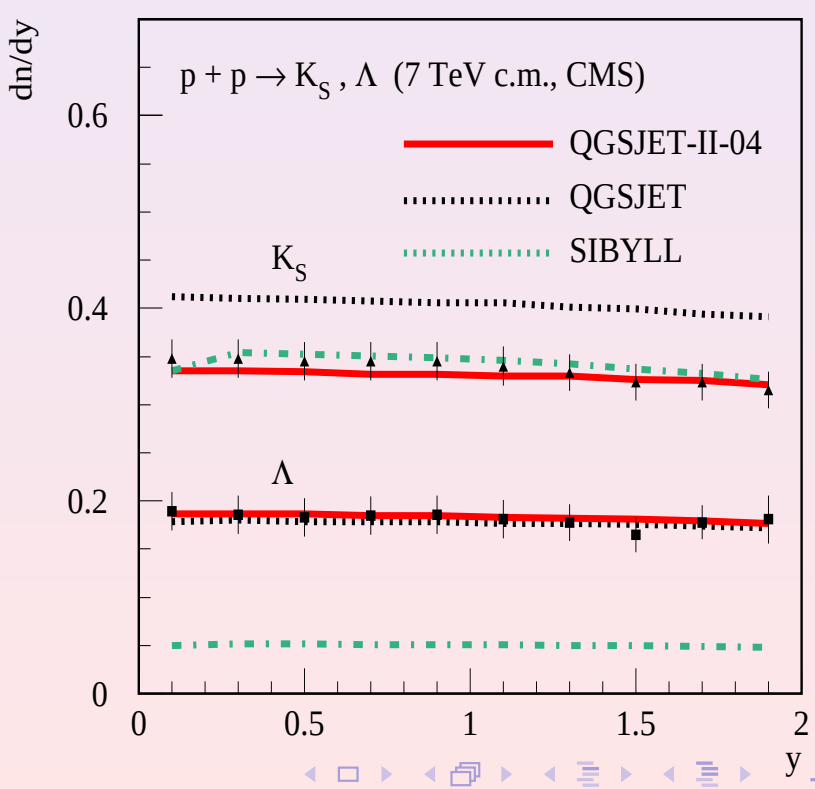


Production of strange particles

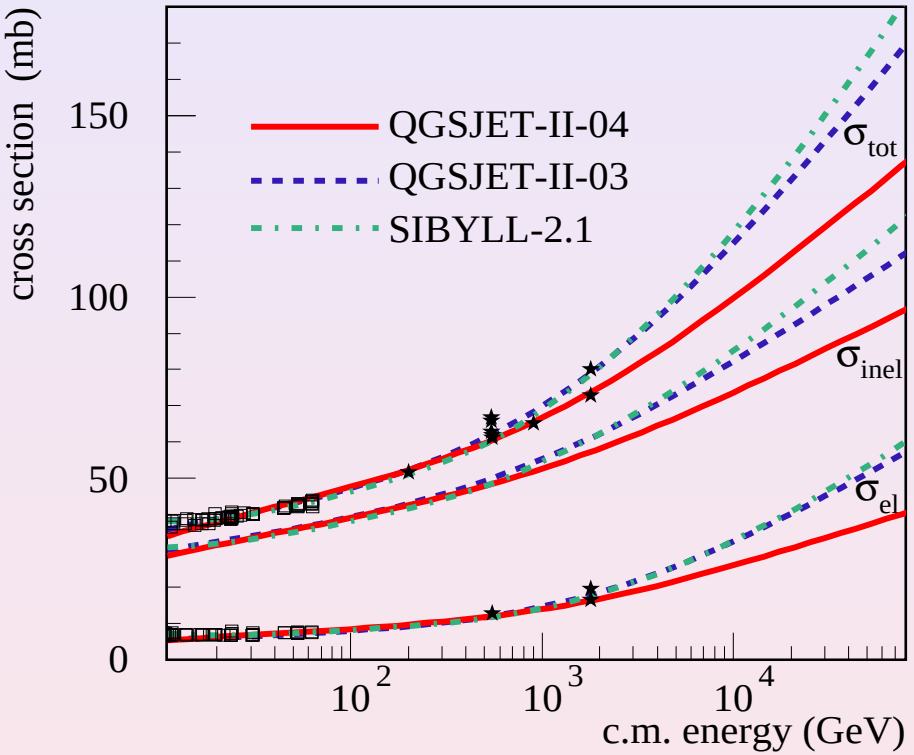
Enhancement of strange particle production may also increase N_μ

- more energy channeled into hadronic cascade
- QGSJET-II-03: noticeable correction required by LHC data
- higher kaon yields in older models (QGSJET, SIBYLL)



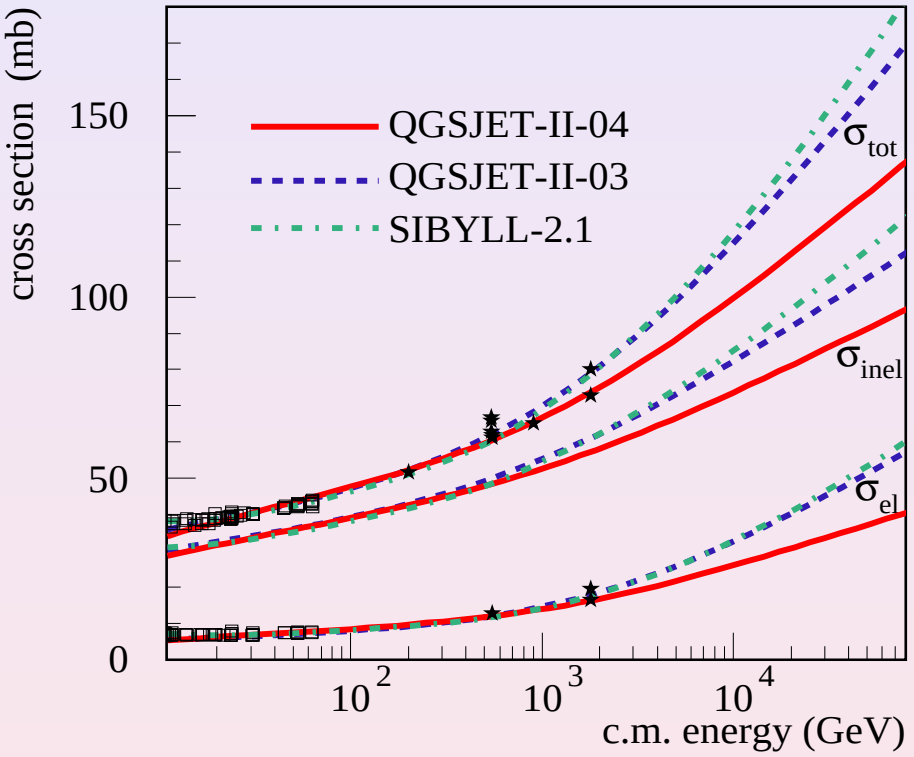


Inelastic cross section



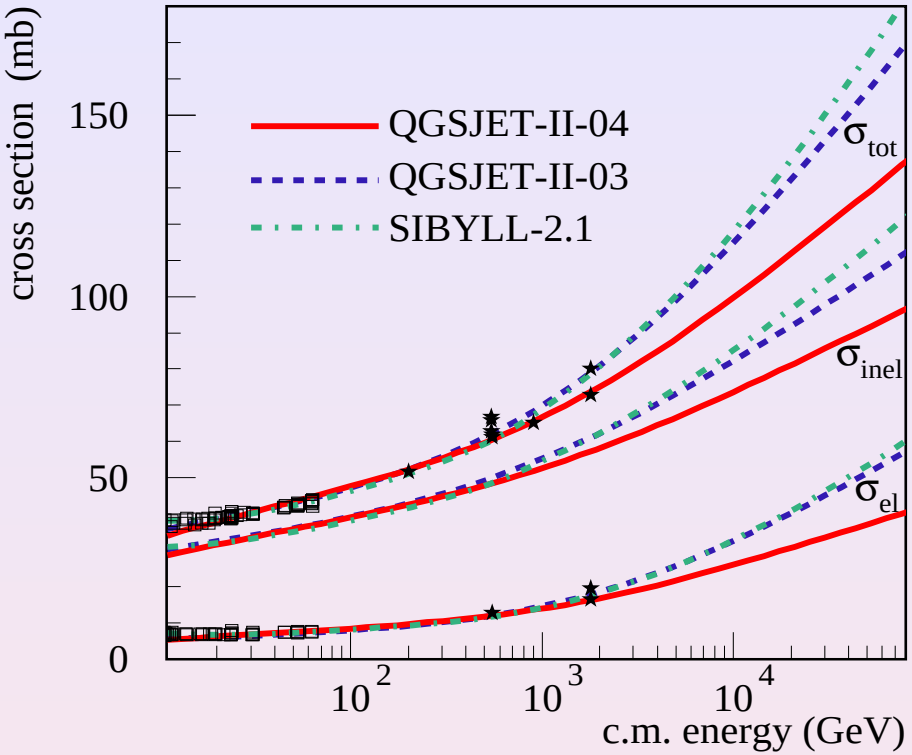
- side-effect of higher Q_0^2-cutoff: slower rise of cross sections
- e.g., σ_{pp}^{tot} - consistent with E710 data at 1.8 TeV

Inelastic cross section



- side-effect of higher Q_0^2-cutoff: slower rise of cross sections
- e.g., σ_{pp}^{tot} - consistent with E710 data at 1.8 TeV

Inelastic cross section



- side-effect of higher Q_0^2-cutoff: slower rise of cross sections
- e.g., σ_{pp}^{tot} - consistent with E710 data at 1.8 TeV
- lower cross sections now supported by LHC data

	QGSJET-II-04	QGSJET-II-03	SIBYLL	ATLAS
MBTS_{AND}	54.1	62.3	68.4	51.9 ± 5.7
MBTS_{OR}	60.8	69.8	74.7	58.7 ± 6.5

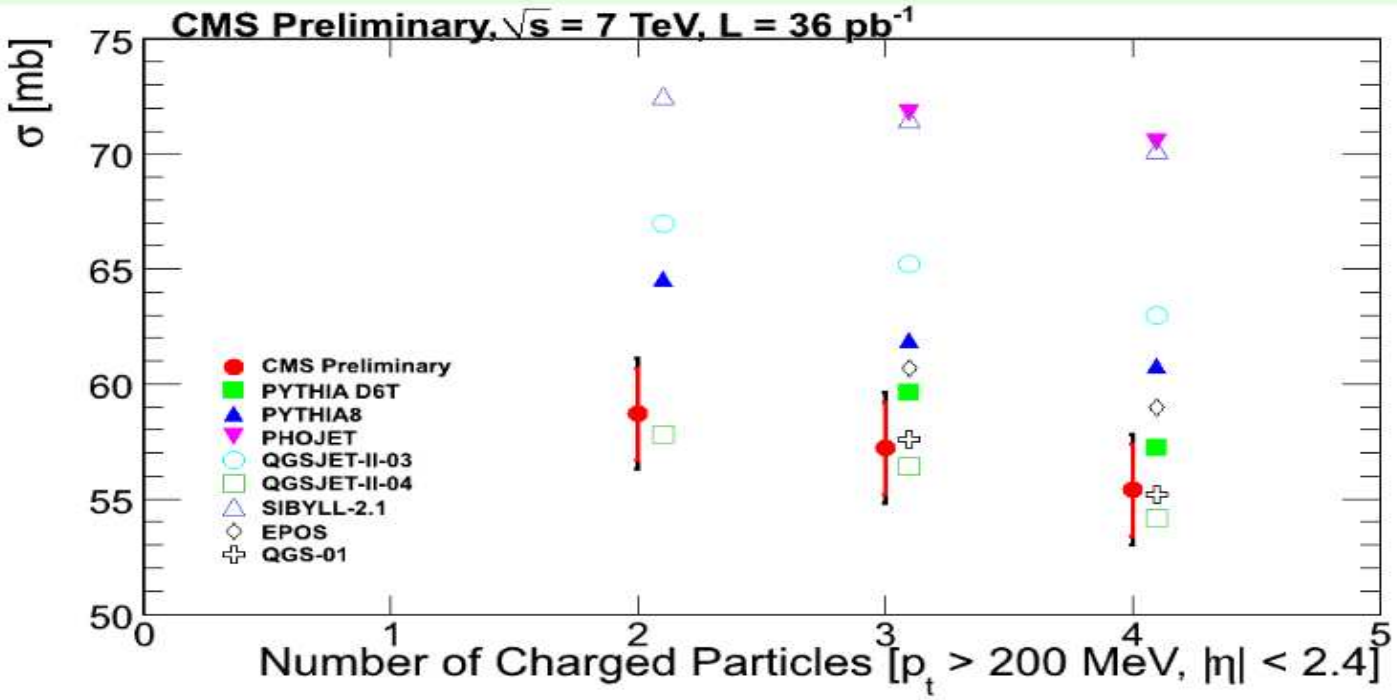
Table: Model predictions for "visible" cross sections (in mb) at $\sqrt{s} = 7$ TeV for ATLAS MB triggers: at least one charged hadron at $-3.84 < \eta < -2.09$ and/or at $2.09 < \eta < 3.84$ ($\text{MBTS}_{\text{AND/OR}}$).

Inelastic cross section

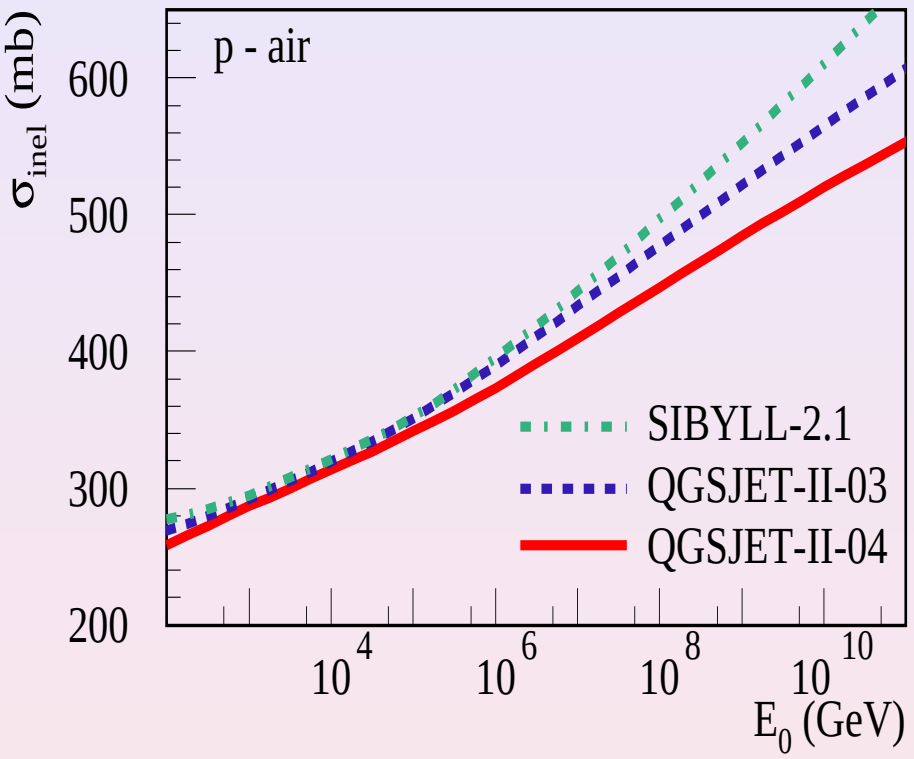
Similar results by ALICE & CMS:

	QGSJET-II-04	QGSJET-II-03	SIBYLL	ALICE
2.76 TeV	47.4	52.5	56.2	47.2 ± 3.3
7 TeV	55.1	63.6	69.1	54.2 ± 3.8

Comparison with Models and Extrapolation to σ_{inel} (pp)

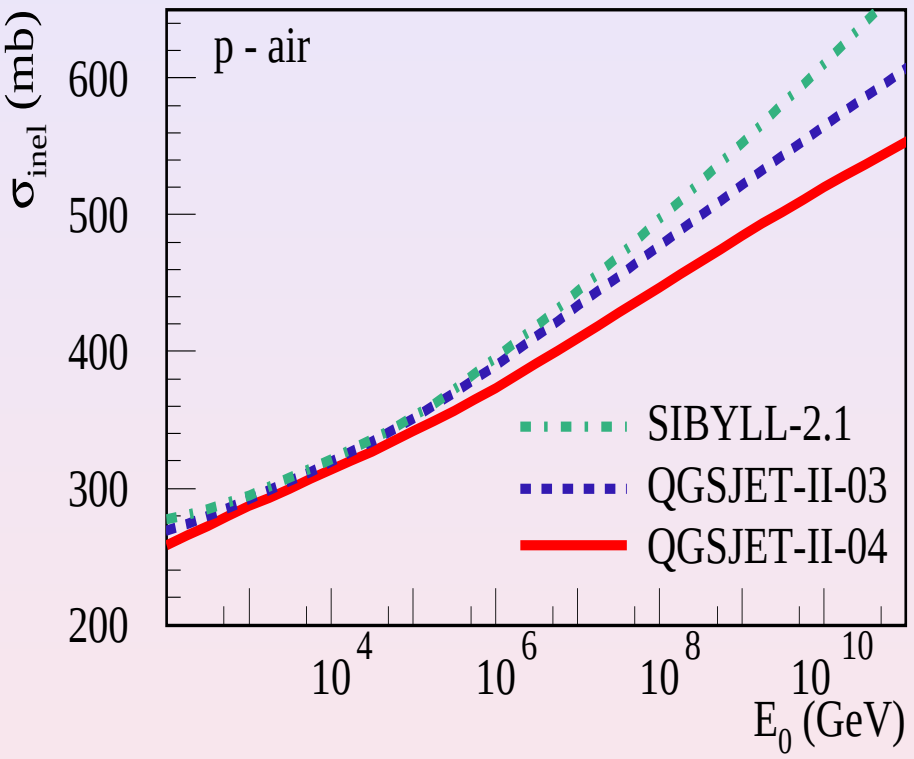


Proton-air cross section & $X_{\max}$



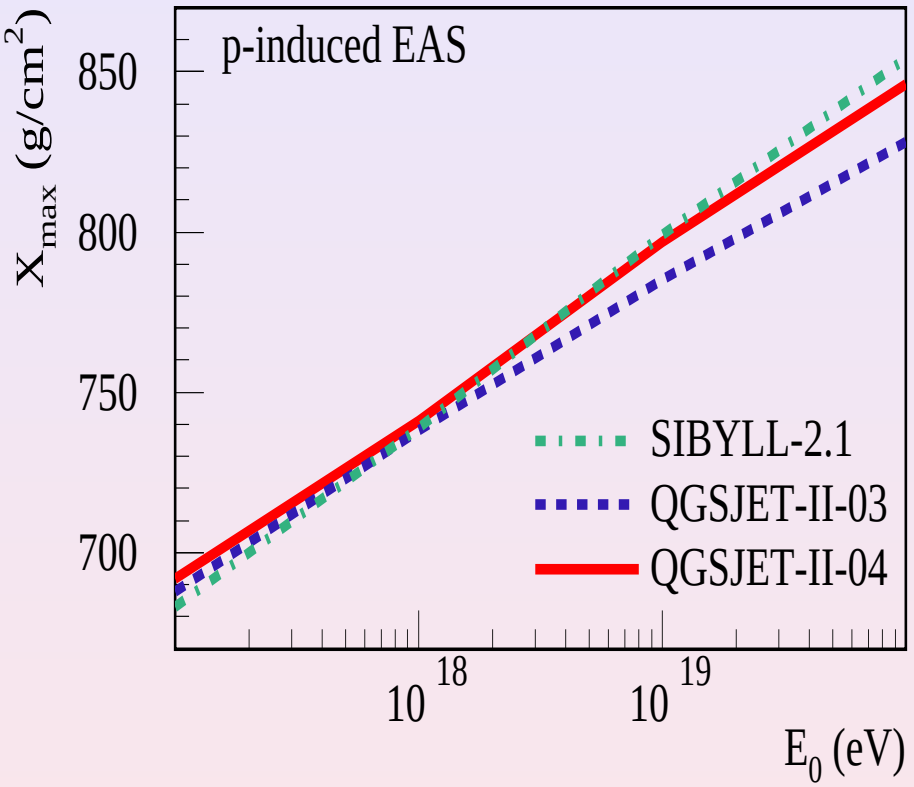
- reduction of σ_{pp}^{inel}
  $\Rightarrow$ slower energy-rise of proton-air cross section
- deeper shower penetration

Proton-air cross section & $X_{\max}$



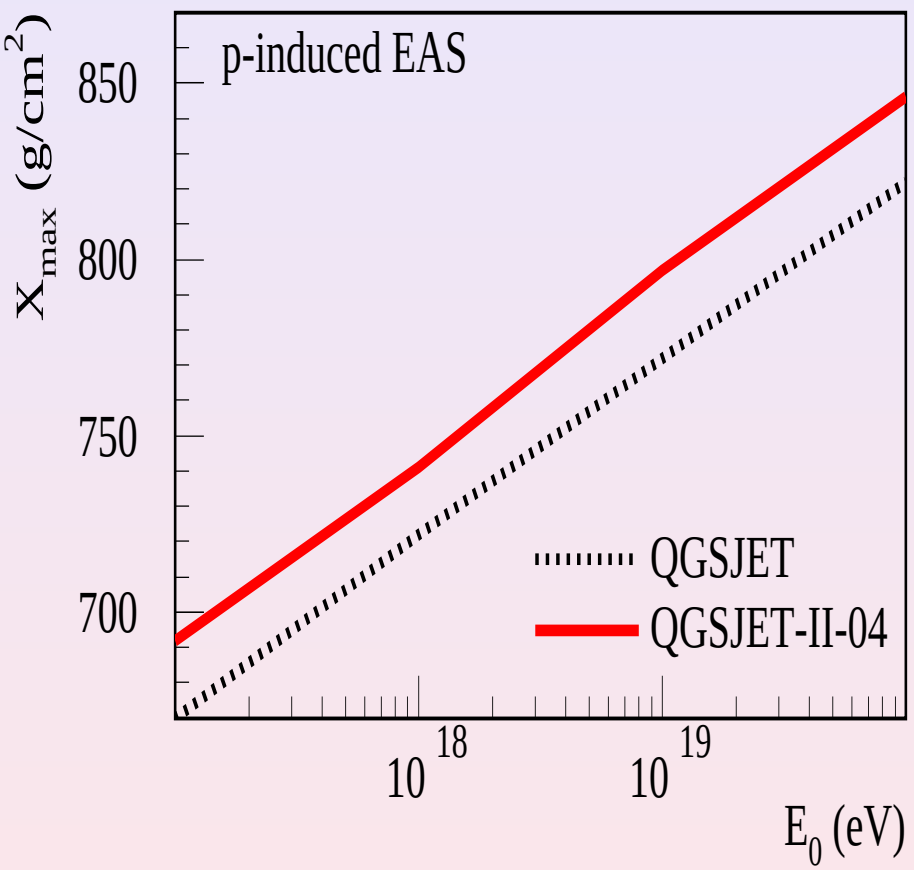
- reduction of σ_{pp}^{inel}
  $\Rightarrow$ slower energy-rise of proton-air cross section
- deeper shower penetration

Proton-air cross section & $X_{\max}$



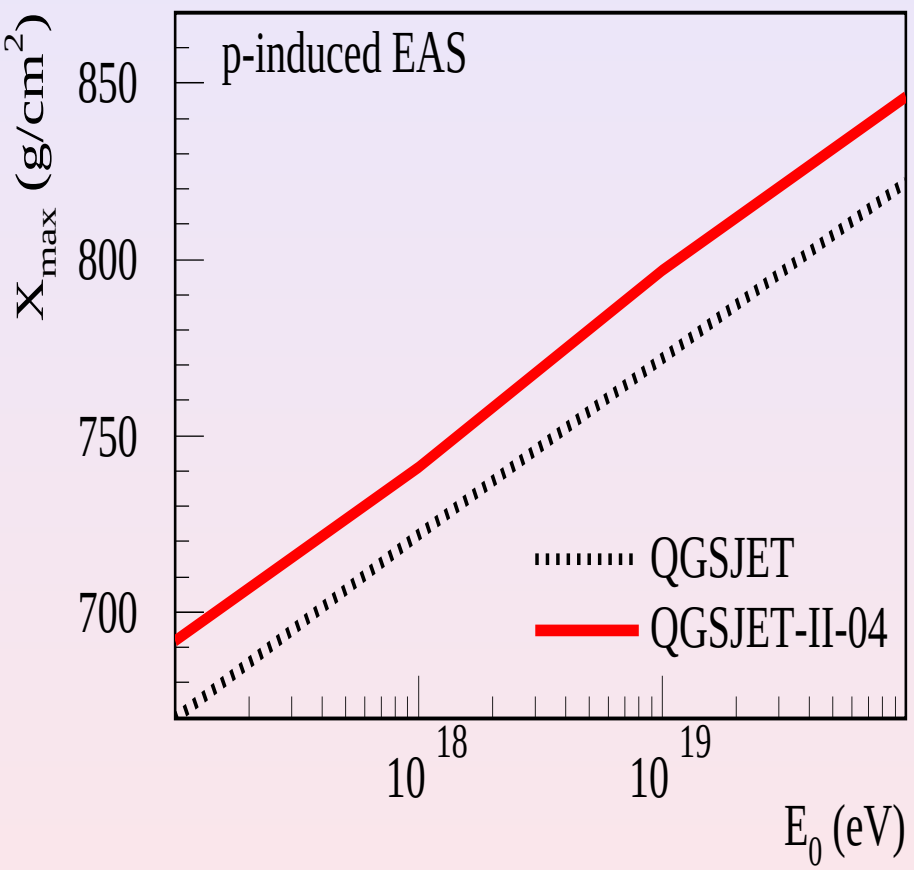
- elongation rate (ER) reduced above 1 EeV
- NB: similarity between QGSJET-II-04 and SIBYLL - misleading (ER-increase will be even larger there)

Proton-air cross section & $X_{\max}$



- elongation rate (ER) reduced above 1 EeV
- NB: similarity between QGSJET-II-04 and SIBYLL - misleading (ER-increase will be even larger there)
- however: inelasticity-related uncertainty remains

Proton-air cross section & $X_{\max}$



- elongation rate (ER) reduced above 1 EeV
- NB: similarity between QGSJET-II-04 and SIBYLL - misleading (ER-increase will be even larger there)
- however: inelasticity-related uncertainty remains
- QGSJET/QGSJET-II-04: large $X_{\max}$ difference

Impact on CR composition studies

- overall effect of the retuning on air shower predictions:
  - less than 10% change for muon number (N_μ)
  - shower maximum $X_{\max}$ shifted deeper above 10^{18} eV (by less than 20 g/cm^2 at 10^{20} eV)

Impact on CR composition studies

- overall effect of the retuning on air shower predictions:
  - less than 10% change for muon number (N_μ)
  - shower maximum $X_{\max}$ shifted deeper above 10^{18} eV (by less than 20 g/cm^2 at 10^{20} eV)

Impact on CR composition studies

- overall effect of the retuning on air shower predictions:
  - less than 10% change for muon number (N_μ)
  - shower maximum $X_{\max}$ shifted deeper above 10^{18} eV (by less than 20 g/cm^2 at 10^{20} eV)

Impact on CR composition studies

- overall effect of the retuning on air shower predictions:
  - less than 10% change for muon number (N_μ)
  - shower maximum $X_{\max}$ shifted deeper above 10^{18} eV (by less than 20 g/cm^2 at 10^{20} eV)
- good news for KASCADE(-Grande):
  - hadronic physics at & around the 'knee' – robust

Impact on CR composition studies

- overall effect of the retuning on air shower predictions:
  - less than 10% change for muon number (N_μ)
  - shower maximum $X_{\max}$ shifted deeper above 10^{18} eV (by less than 20 g/cm^2 at 10^{20} eV)
- good news for KASCADE(-Grande):
  - hadronic physics at & around the 'knee' – robust

Impact on CR composition studies

- overall effect of the retuning on air shower predictions:
  - less than 10% change for muon number (N_μ)
  - shower maximum $X_{\max}$ shifted deeper above 10^{18} eV (by less than 20 g/cm^2 at 10^{20} eV)
- good news for KASCADE(-Grande):
  - hadronic physics at & around the 'knee' – robust
- bad news for Pierre Auger:
  - difficult to accomodate the results with collider data
  - last hope for $X_{\max}$ – smaller 'inelasticity' K_{inel} (to approach heavy composition with $\langle X_{\max} \rangle$)
  - explanation of muon excess – extremely difficult

Impact on CR composition studies

- overall effect of the retuning on air shower predictions:
  - less than 10% change for muon number (N_μ)
  - shower maximum $X_{\max}$ shifted deeper above 10^{18} eV (by less than 20 g/cm^2 at 10^{20} eV)
- good news for KASCADE(-Grande):
  - hadronic physics at & around the 'knee' – robust
- bad news for Pierre Auger:
  - difficult to accomodate the results with collider data
  - last hope for $X_{\max}$ – smaller 'inelasticity' K_{inel} (to approach heavy composition with $\langle X_{\max} \rangle$)
  - explanation of muon excess – extremely difficult

Impact on CR composition studies

- overall effect of the retuning on air shower predictions:
  - less than 10% change for muon number (N_μ)
  - shower maximum $X_{\max}$ shifted deeper above 10^{18} eV (by less than 20 g/cm^2 at 10^{20} eV)
- good news for KASCADE(-Grande):
  - hadronic physics at & around the 'knee' – robust
- bad news for Pierre Auger:
  - difficult to accomodate the results with collider data
  - last hope for $X_{\max}$ – smaller 'inelasticity' K_{inel} (to approach heavy composition with $\langle X_{\max} \rangle$)
  - explanation of muon excess – extremely difficult

Impact on CR composition studies

- overall effect of the retuning on air shower predictions:
  - less than 10% change for muon number (N_μ)
  - shower maximum $X_{\max}$ shifted deeper above 10^{18} eV (by less than 20 g/cm^2 at 10^{20} eV)
- good news for KASCADE(-Grande):
  - hadronic physics at & around the 'knee' – robust
- bad news for Pierre Auger:
  - difficult to accomodate the results with collider data
  - last hope for $X_{\max}$ – smaller 'inelasticity' K_{inel} (to approach heavy composition with $\langle X_{\max} \rangle$)
  - explanation of muon excess – extremely difficult

Summary

1. considerable progress in studing (ultra-)high energy CRs
   - astrophysical origin of the CR 'knee' established
   - high energy (GZK?) cutoff firmly confirmed
   - first hints towards astrophysical sources of UHECR

Summary

1. considerable progress in studing (ultra-)high energy CRs
   - astrophysical origin of the CR 'knee' established
   - high energy (GZK?) cutoff firmly confirmed
   - first hints towards astrophysical sources of UHECR

Summary

1. considerable progress in studing (ultra-)high energy CRs
   - astrophysical origin of the CR 'knee' established
   - high energy (GZK?) cutoff firmly confirmed
   - first hints towards astrophysical sources of UHECR

Summary

1. considerable progress in studing (ultra-)high energy CRs
   - astrophysical origin of the CR 'knee' established
   - high energy (GZK?) cutoff firmly confirmed
   - first hints towards astrophysical sources of UHECR

Summary

1. considerable progress in studing (ultra-)high energy CRs
   - astrophysical origin of the CR 'knee' established
   - high energy (GZK?) cutoff firmly confirmed
   - first hints towards astrophysical sources of UHECR
2. decisive tool – measurements of CR composition
   - however: results depend strongly on hadronic MC models

Summary

1. considerable progress in studing (ultra-)high energy CRs
   - astrophysical origin of the CR 'knee' established
   - high energy (GZK?) cutoff firmly confirmed
   - first hints towards astrophysical sources of UHECR
2. decisive tool – measurements of CR composition
   - however: results depend strongly on hadronic MC models

Summary

1. considerable progress in studing (ultra-)high energy CRs
   - astrophysical origin of the CR 'knee' established
   - high energy (GZK?) cutoff firmly confirmed
   - first hints towards astrophysical sources of UHECR
2. decisive tool – measurements of CR composition
   - however: results depend strongly on hadronic MC models
3. first lessons from LHC data:
   - CR interaction models behave reasonably well
   - only cosmetic corrections seem to be needed
   - exception: reduction of $\sigma_{pp}^{\mathrm{inel}}$ required (for most of the models)

Summary

1. considerable progress in studing (ultra-)high energy CRs
   - astrophysical origin of the CR 'knee' established
   - high energy (GZK?) cutoff firmly confirmed
   - first hints towards astrophysical sources of UHECR
2. decisive tool – measurements of CR composition
   - however: results depend strongly on hadronic MC models
3. first lessons from LHC data:
   - CR interaction models behave reasonably well
   - only cosmetic corrections seem to be needed
   - exception: reduction of $\sigma_{pp}^{\mathrm{inel}}$ required (for most of the models)

Summary

1. considerable progress in studing (ultra-)high energy CRs
   - astrophysical origin of the CR 'knee' established
   - high energy (GZK?) cutoff firmly confirmed
   - first hints towards astrophysical sources of UHECR
2. decisive tool – measurements of CR composition
   - however: results depend strongly on hadronic MC models
3. first lessons from LHC data:
   - CR interaction models behave reasonably well
   - only cosmetic corrections seem to be needed
   - exception: reduction of $\sigma_{pp}^{\mathrm{inel}}$ required (for most of the models)

Summary

1. considerable progress in studing (ultra-)high energy CRs
   - astrophysical origin of the CR 'knee' established
   - high energy (GZK?) cutoff firmly confirmed
   - first hints towards astrophysical sources of UHECR
2. decisive tool – measurements of CR composition
   - however: results depend strongly on hadronic MC models
3. first lessons from LHC data:
   - CR interaction models behave reasonably well
   - only cosmetic corrections seem to be needed
   - exception: reduction of $\sigma_{pp}^{\mathrm{inel}}$ required (for most of the models)

Summary

1. considerable progress in studing (ultra-)high energy CRs
   - astrophysical origin of the CR 'knee' established
   - high energy (GZK?) cutoff firmly confirmed
   - first hints towards astrophysical sources of UHECR
2. decisive tool – measurements of CR composition
   - however: results depend strongly on hadronic MC models
3. first lessons from LHC data:
   - CR interaction models behave reasonably well
   - only cosmetic corrections seem to be needed
   - exception: reduction of $\sigma_{pp}^{\mathrm{inel}}$ required (for most of the models)
4. impact on experimental CR studies:
   - astrophysical origin of the CR 'knee' – supported by LHC data (no exotic physics observed at mb level)
   - UHECR compostion puzzle – further aggravated: small room to explain the 'muon excess', X_{max} / RMS(X_{max}) inconsistences

Summary

1. considerable progress in studing (ultra-)high energy CRs
   - astrophysical origin of the CR 'knee' established
   - high energy (GZK?) cutoff firmly confirmed
   - first hints towards astrophysical sources of UHECR
2. decisive tool – measurements of CR composition
   - however: results depend strongly on hadronic MC models
3. first lessons from LHC data:
   - CR interaction models behave reasonably well
   - only cosmetic corrections seem to be needed
   - exception: reduction of $\sigma_{pp}^{\mathrm{inel}}$ required (for most of the models)
4. impact on experimental CR studies:
   - astrophysical origin of the CR 'knee' – supported by LHC data (no exotic physics observed at mb level)
   - UHECR compostion puzzle – further aggravated: small room to explain the 'muon excess', X_{max} / RMS(X_{max}) inconsistences

Summary

1. considerable progress in studing (ultra-)high energy CRs
   - astrophysical origin of the CR 'knee' established
   - high energy (GZK?) cutoff firmly confirmed
   - first hints towards astrophysical sources of UHECR
2. decisive tool – measurements of CR composition
   - however: results depend strongly on hadronic MC models
3. first lessons from LHC data:
   - CR interaction models behave reasonably well
   - only cosmetic corrections seem to be needed
   - exception: reduction of $\sigma_{pp}^{\mathrm{inel}}$ required (for most of the models)
4. impact on experimental CR studies:
   - astrophysical origin of the CR 'knee' – supported by LHC data (no exotic physics observed at mb level)
   - UHECR compostion puzzle – further aggravated: small room to explain the 'muon excess', X_{max} / RMS(X_{max}) inconsistences

Prospects

1. expected/desirable theoretical progress:
   - reliable QCD treatment of 'dense' parton systems
     $\Rightarrow$ of $N_{\mathrm{ch}}(s) \Rightarrow$ muon content of air showers
   - good understanding of 'baryon stopping' mechanism $\Rightarrow$ of X_{max}

Prospects

1. expected/desirable theoretical progress:
   - reliable QCD treatment of 'dense' parton systems
     $\Rightarrow$ of $N_{\mathrm{ch}}(s) \Rightarrow$ muon content of air showers
   - good understanding of 'baryon stopping' mechanism $\Rightarrow$ of X_{max}

Prospects

1. expected/desirable theoretical progress:
   - reliable QCD treatment of 'dense' parton systems
     $\Rightarrow$ of $N_{\mathrm{ch}}(s) \Rightarrow$ muon content of air showers
   - good understanding of 'baryon stopping' mechanism $\Rightarrow$ of X_{max}

Prospects

1. expected/desirable theoretical progress:
   - reliable QCD treatment of 'dense' parton systems
     $\Rightarrow$ of $N_{\mathrm{ch}}(s)$ $\Rightarrow$ muon content of air showers
   - good understanding of 'baryon stopping' mechanism $\Rightarrow$ of X_{max}
2. expected/desirable input from LHC:
   - measurements of total & diffractive cross sections by TOTEM
     $\Rightarrow$ reliable understanding of RMS(X_{max})
   - studies of 'baryon stopping' by LHCf $\Rightarrow$ understanding of X_{max}
   - just an unrealistic dream: pion-proton collisions at LHC?

Prospects

1. expected/desirable theoretical progress:
   - reliable QCD treatment of 'dense' parton systems
     $\Rightarrow$ of $N_{\mathrm{ch}}(s)$ $\Rightarrow$ muon content of air showers
   - good understanding of 'baryon stopping' mechanism $\Rightarrow$ of X_{max}
2. expected/desirable input from LHC:
   - measurements of total & diffractive cross sections by TOTEM
     $\Rightarrow$ reliable understanding of RMS(X_{max})
   - studies of 'baryon stopping' by LHCf $\Rightarrow$ understanding of X_{max}
   - just an unrealistic dream: pion-proton collisions at LHC?

Prospects

1. expected/desirable theoretical progress:
   - reliable QCD treatment of 'dense' parton systems
     $\Rightarrow$ of $N_{\mathrm{ch}}(s)$ $\Rightarrow$ muon content of air showers
   - good understanding of 'baryon stopping' mechanism $\Rightarrow$ of X_{max}
2. expected/desirable input from LHC:
   - measurements of total & diffractive cross sections by TOTEM
     $\Rightarrow$ reliable understanding of RMS(X_{max})
   - studies of 'baryon stopping' by LHCf $\Rightarrow$ understanding of X_{max}
   - just an unrealistic dream: pion-proton collisions at LHC?

Prospects

1. expected/desirable theoretical progress:
   - reliable QCD treatment of 'dense' parton systems
     $\Rightarrow$ of $N_{\mathrm{ch}}(s)$ $\Rightarrow$ muon content of air showers
   - good understanding of 'baryon stopping' mechanism $\Rightarrow$ of X_{max}
2. expected/desirable input from LHC:
   - measurements of total & diffractive cross sections by TOTEM
     $\Rightarrow$ reliable understanding of RMS(X_{max})
   - studies of 'baryon stopping' by LHCf $\Rightarrow$ understanding of X_{max}
   - just an unrealistic dream: pion-proton collisions at LHC?

Backup

UHECR composition from RMS($X_{\max}$)?

- RMS($X_{\max}$) for proton-induced showers
  - mainly dominated by m.f.p. $\lambda_p \propto 1/\sigma^{\text{inel}}_{p-\text{air}}$
  - also sensitive to the collision geometry: large 'stopping power' (K_{inel}) for small b, small K_{inel} for large b

UHECR composition from RMS($X_{\rm max}$)?

- RMS($X_{\rm max}$) for proton-induced showers
  - mainly dominated by m.f.p. $\lambda_p \propto 1/\sigma^{\rm inel}_{p-{\rm air}}$
  - also sensitive to the collision geometry: large 'stopping power' ($K_{\rm inel}$) for small b, small $K_{\rm inel}$ for large b

UHECR composition from RMS($X_{\rm max}$)?

- RMS($X_{\rm max}$) for proton-induced showers
  - mainly dominated by m.f.p. $\lambda_p \propto 1/\sigma^{\rm inel}_{p-{\rm air}}$
  - also sensitive to the collision geometry: large 'stopping power' ($K_{\rm inel}$) for small b, small $K_{\rm inel}$ for large b

UHECR composition from RMS($X_{\rm max}$)?

- RMS($X_{\rm max}$) for proton-induced showers
  - mainly dominated by m.f.p. $\lambda_p \propto 1/\sigma^{\rm inel}_{p-{\rm air}}$
  - also sensitive to the collision geometry: large 'stopping power' ($K_{\rm inel}$) for small b, small $K_{\rm inel}$ for large b
- RMS($X_{\rm max}$) for nucleus-induced showers
  - mainly dominated by the collision geometry: (more 'participants' for central collisions)
  - sensitive to nuclear fragmentation (up to factor of 2 difference for RMS($X_{\rm max}$) *[Kalmykov & SO, Phys. At. Nucl. 56 (1993)]*
  - NB: superposition model inapplicable

UHECR composition from RMS($X_{\rm max}$)?

- RMS($X_{\rm max}$) for proton-induced showers
  - mainly dominated by m.f.p. $\lambda_p \propto 1/\sigma^{\rm inel}_{p-{\rm air}}$
  - also sensitive to the collision geometry: large 'stopping power' ($K_{\rm inel}$) for small b, small $K_{\rm inel}$ for large b
- RMS($X_{\rm max}$) for nucleus-induced showers
  - mainly dominated by the collision geometry: (more 'participants' for central collisions)
  - sensitive to nuclear fragmentation (up to factor of 2 difference for RMS($X_{\rm max}$) *[Kalmykov & SO, Phys. At. Nucl. 56 (1993)]*
  - NB: superposition model inapplicable

UHECR composition from RMS($X_{\rm max}$)?

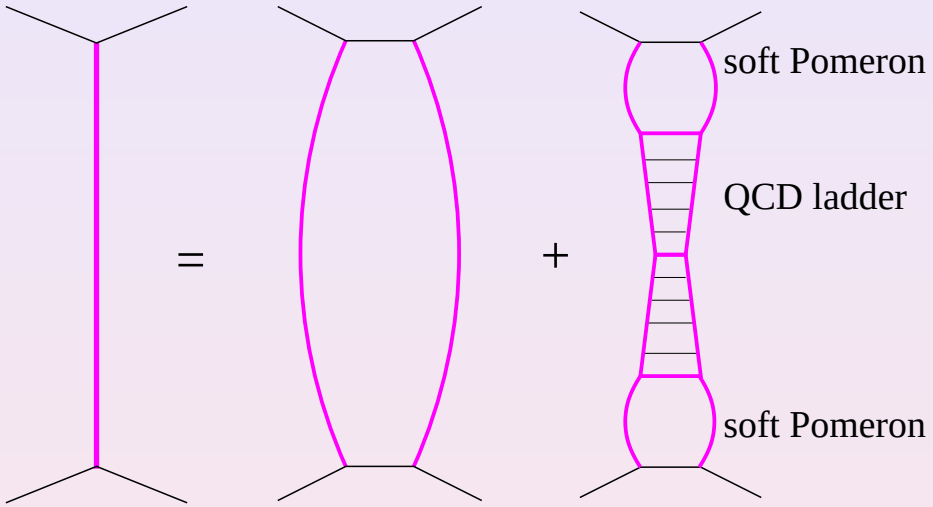
- RMS($X_{\rm max}$) for proton-induced showers
  - mainly dominated by m.f.p. $\lambda_p \propto 1/\sigma^{\rm inel}_{p-{\rm air}}$
  - also sensitive to the collision geometry: large 'stopping power' ($K_{\rm inel}$) for small b, small $K_{\rm inel}$ for large b
- RMS($X_{\rm max}$) for nucleus-induced showers
  - mainly dominated by the collision geometry: (more 'participants' for central collisions)
  - sensitive to nuclear fragmentation (up to factor of 2 difference for RMS($X_{\rm max}$) *[Kalmykov & SO, Phys. At. Nucl. 56 (1993)]*
  - NB: superposition model inapplicable

UHECR composition from RMS($X_{\rm max}$)?

- RMS($X_{\rm max}$) for proton-induced showers
  - mainly dominated by m.f.p. $\lambda_p \propto 1/\sigma^{\rm inel}_{p-{\rm air}}$
  - also sensitive to the collision geometry: large 'stopping power' ($K_{\rm inel}$) for small b, small $K_{\rm inel}$ for large b
- RMS($X_{\rm max}$) for nucleus-induced showers
  - mainly dominated by the collision geometry: (more 'participants' for central collisions)
  - sensitive to nuclear fragmentation (up to factor of 2 difference for RMS($X_{\rm max}$) *[Kalmykov & SO, Phys. At. Nucl. 56 (1993)]*
  - NB: superposition model inapplicable

QGSJET-II model

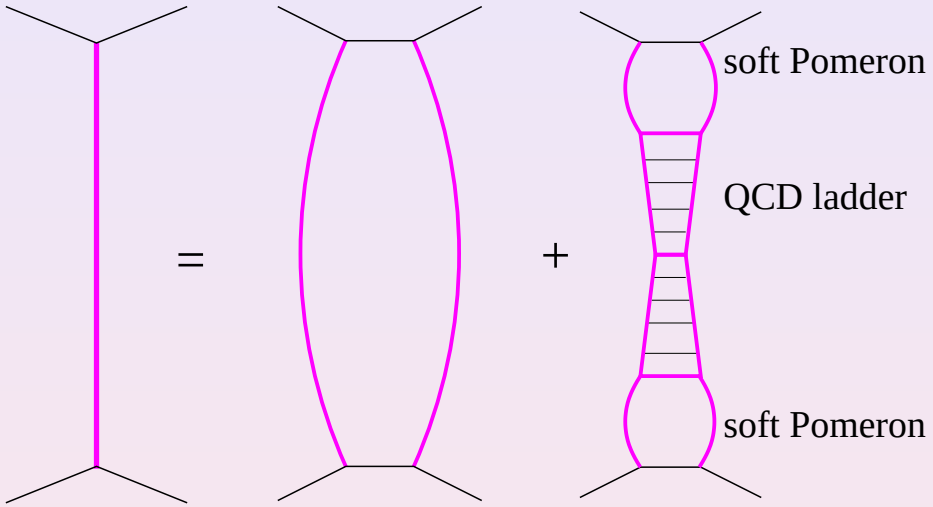
- based on combined treatment of soft & hard parton processes



- soft processes ($q^2 < Q_0^2$): 'soft Pomeron'
- hard processes ($q^2 > Q_0^2$): DGLAP formalism
- taken together: 'semihard Pomeron'

QGSJET-II model

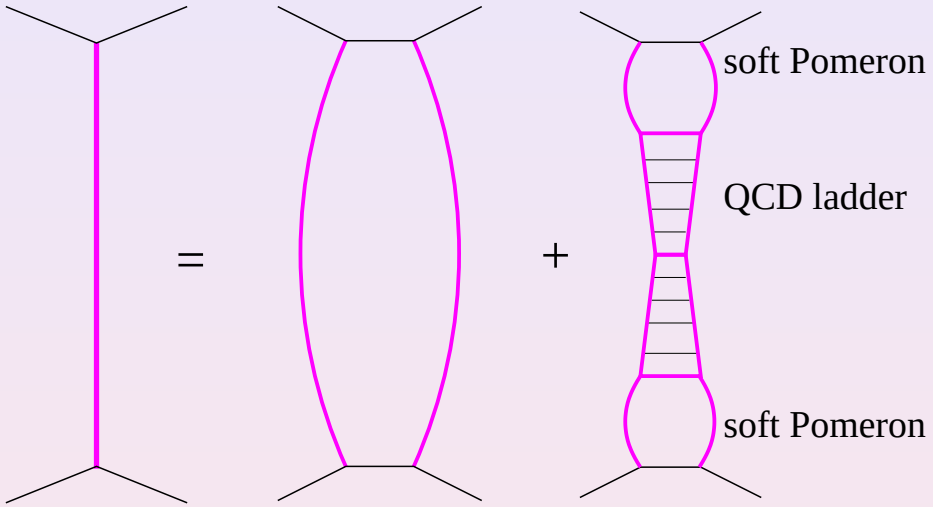
- based on combined treatment of soft & hard parton processes



- soft processes ($q^2 < Q_0^2$): 'soft Pomeron'
- hard processes ($q^2 > Q_0^2$): DGLAP formalism
- taken together: 'semihard Pomeron'

QGSJET-II model

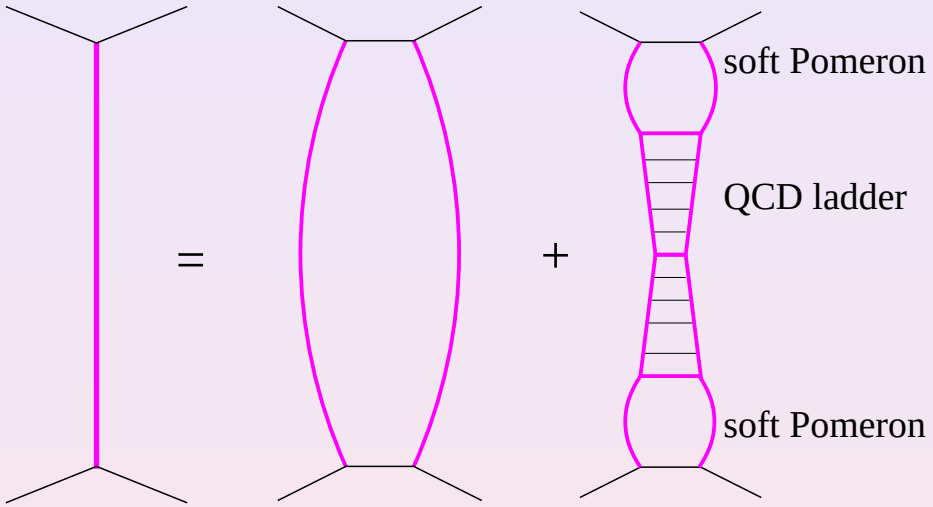
- based on combined treatment of soft & hard parton processes



- soft processes ($q^2 < Q_0^2$): 'soft Pomeron'
- hard processes ($q^2 > Q_0^2$): DGLAP formalism
- taken together: 'semihard Pomeron'

QGSJET-II model

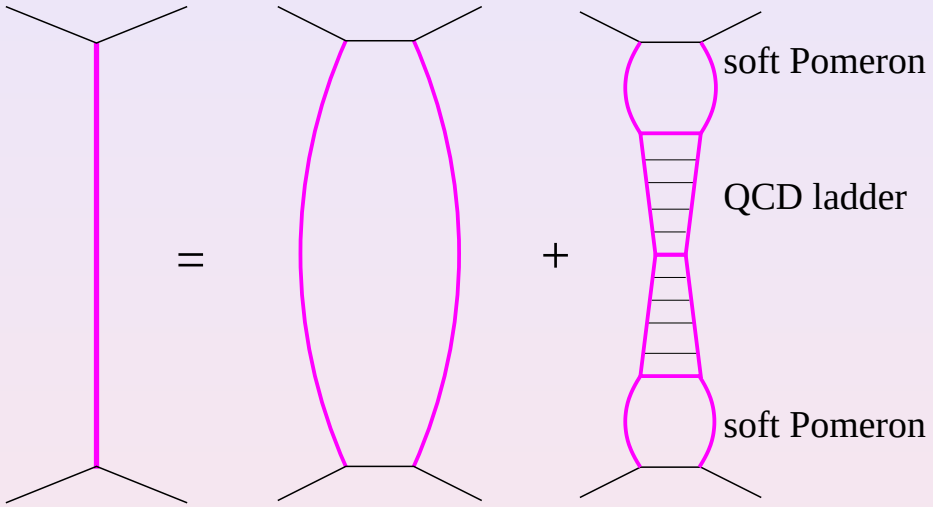
- based on combined treatment of soft & hard parton processes



- soft processes ($q^2 < Q_0^2$): 'soft Pomeron'
- hard processes ($q^2 > Q_0^2$): DGLAP formalism
- taken together: 'semihard Pomeron'

QGSJET-II model

- based on combined treatment of soft & hard parton processes

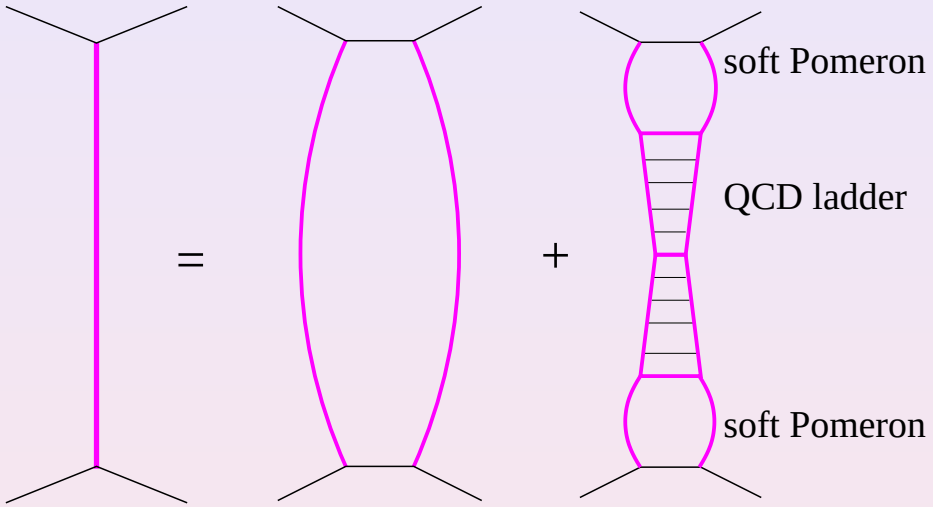


- soft processes ($q^2 < Q_0^2$): 'soft Pomeron'
- hard processes ($q^2 > Q_0^2$): DGLAP formalism
- taken together: 'semihard Pomeron'

- nonlinear processes (parton shadowing / saturation): Pomeron-Pomeron interactions

QGSJET-II model

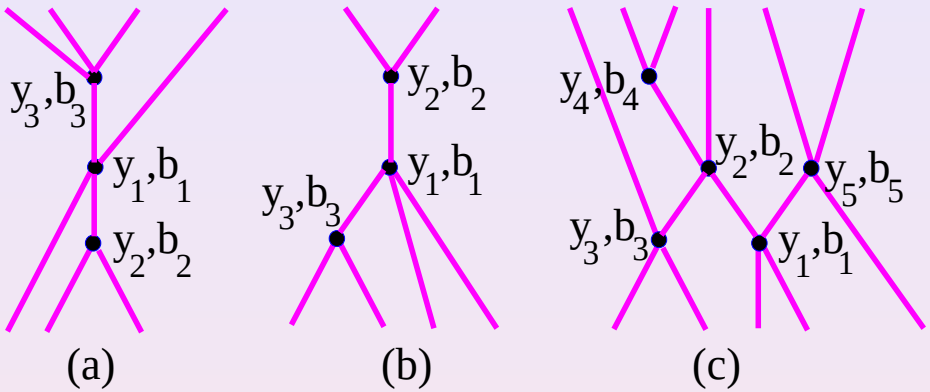
- based on combined treatment of soft & hard parton processes



- soft processes ($q^2 < Q_0^2$): 'soft Pomeron'
- hard processes ($q^2 > Q_0^2$): DGLAP formalism
- taken together: 'semihard Pomeron'

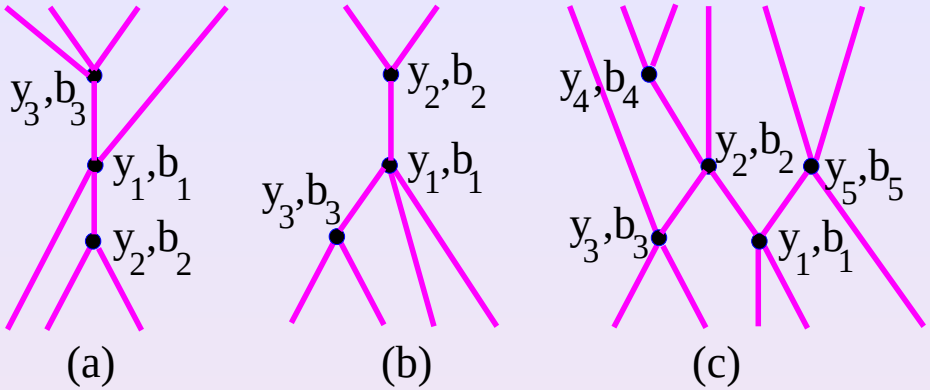
- nonlinear processes (parton shadowing / saturation): Pomeron-Pomeron interactions
  - NB: in this model saturation may be reached for soft ($q^2 < Q_0^2$) partons only

New version of QGSJET-II (QGSJET-II-04)

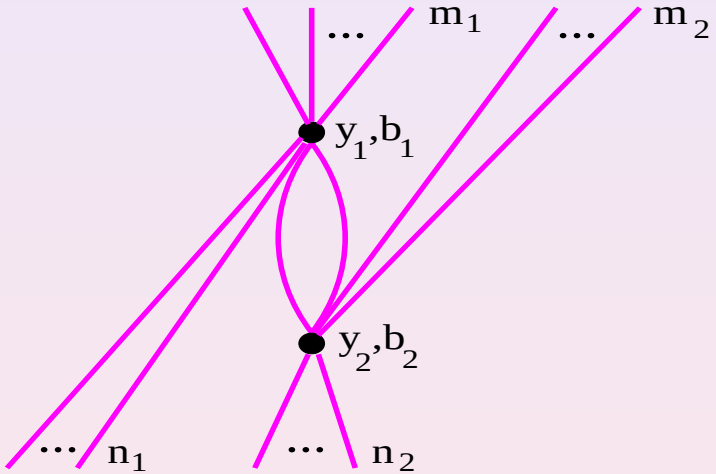


- QGSJET-II-03: only dominant ('net-like') Pomeron-Pomeron interactions

New version of QGSJET-II (QGSJET-II-04)

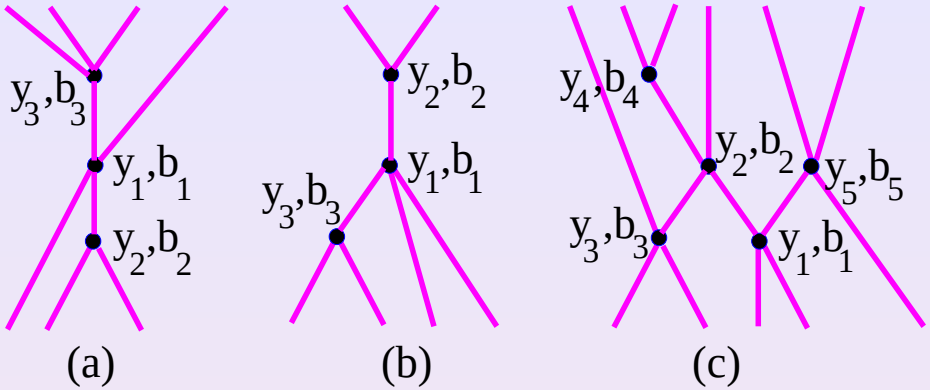


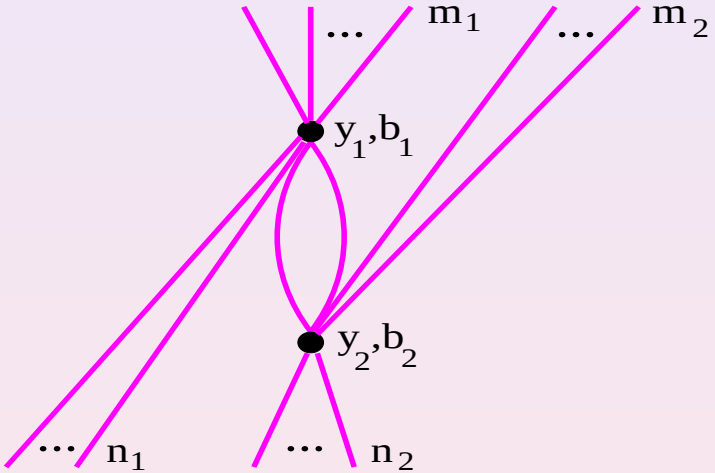
- QGSJET-II-03: only dominant ('net-like') Pomeron-Pomeron interactions



- QGSJET-II-04: also 'Pomeron loops' included
- small at low parton density
- suppressed at high density
- still a finite correction at large b $\Rightarrow$ influence cross sections & particle production

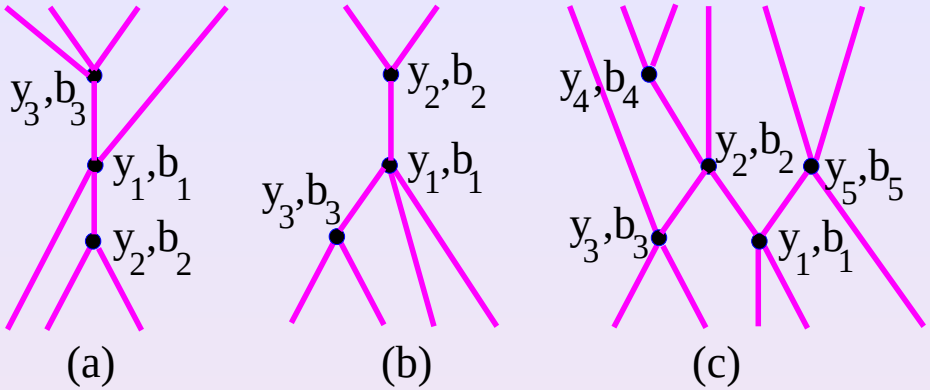
New version of QGSJET-II (QGSJET-II-04)

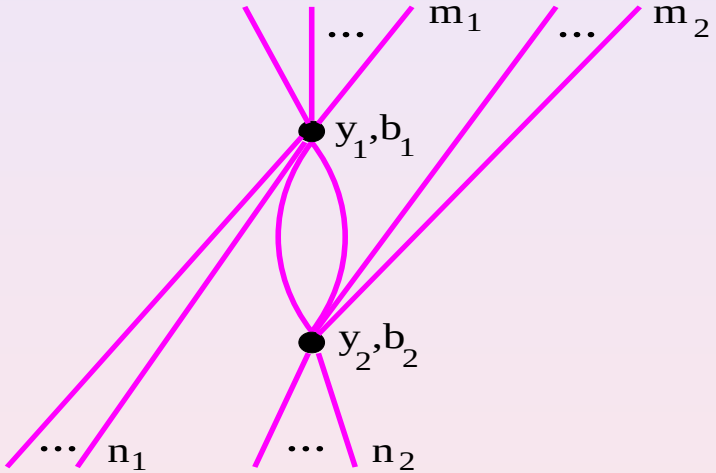




- QGSJET-II-03: only dominant ('net-like') Pomeron-Pomeron interactions
- QGSJET-II-04: also 'Pomeron loops' included
- small at low parton density
- suppressed at high density
- still a finite correction at large b $\Rightarrow$ influence cross sections & particle production

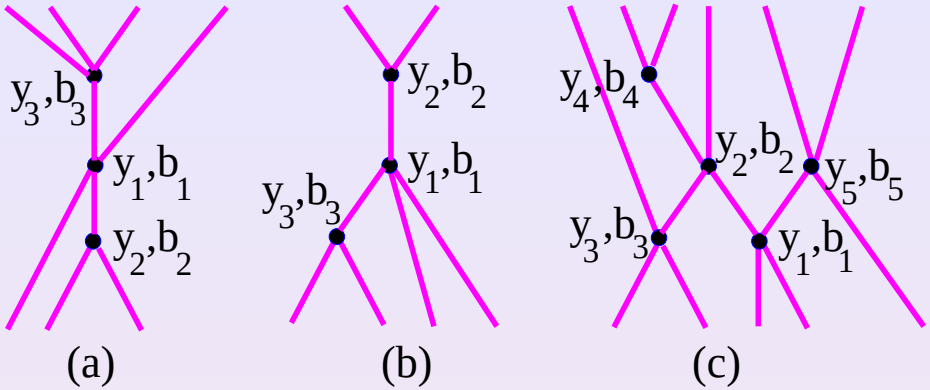
New version of QGSJET-II (QGSJET-II-04)

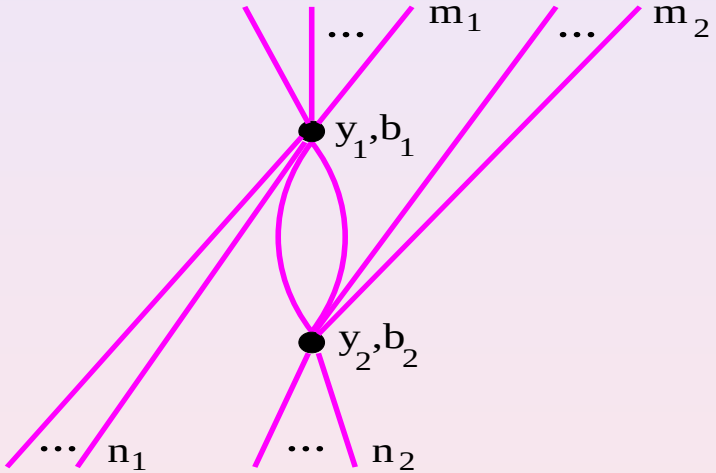




- QGSJET-II-03: only dominant ('net-like') Pomeron-Pomeron interactions
- QGSJET-II-04: also 'Pomeron loops' included
- small at low parton density
- suppressed at high density
- still a finite correction at large b $\Rightarrow$ influence cross sections & particle production

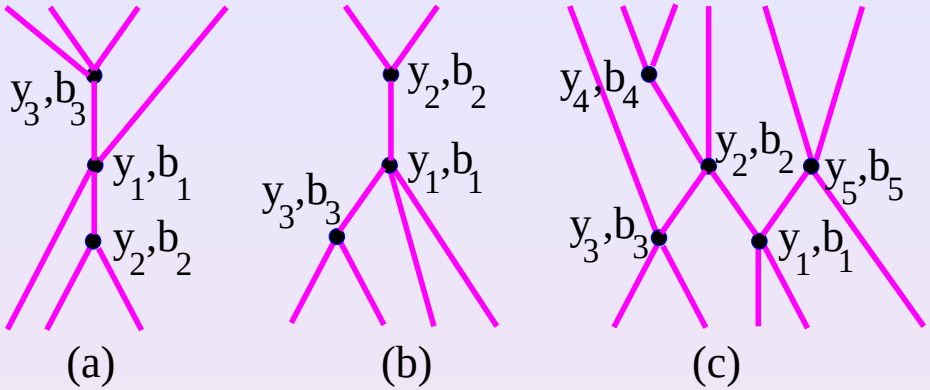
New version of QGSJET-II (QGSJET-II-04)



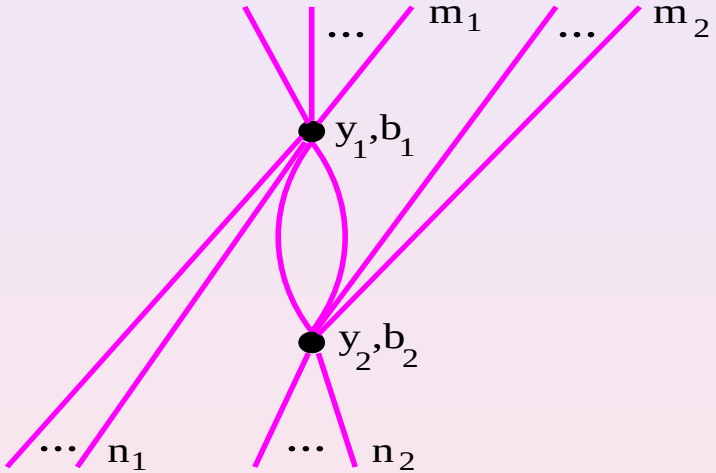


- QGSJET-II-03: only dominant ('net-like') Pomeron-Pomeron interactions
- QGSJET-II-04: also 'Pomeron loops' included
- small at low parton density
- suppressed at high density
- still a finite correction at large b $\Rightarrow$ influence cross sections & particle production

New version of QGSJET-II (QGSJET-II-04)



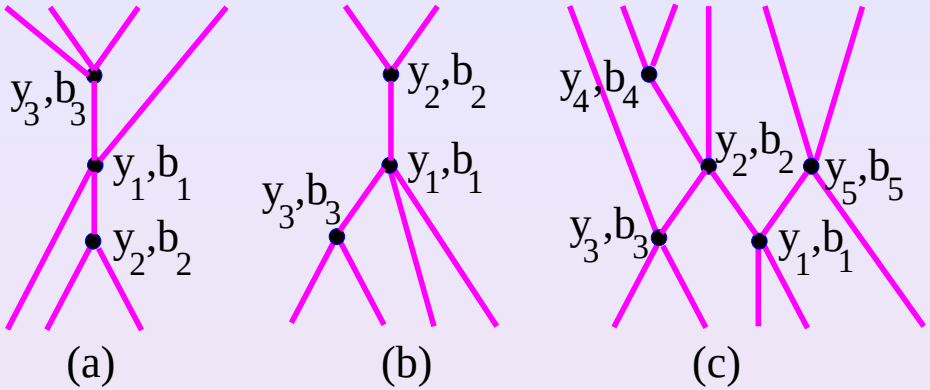
- QGSJET-II-03: only dominant ('net-like') Pomeron-Pomeron interactions



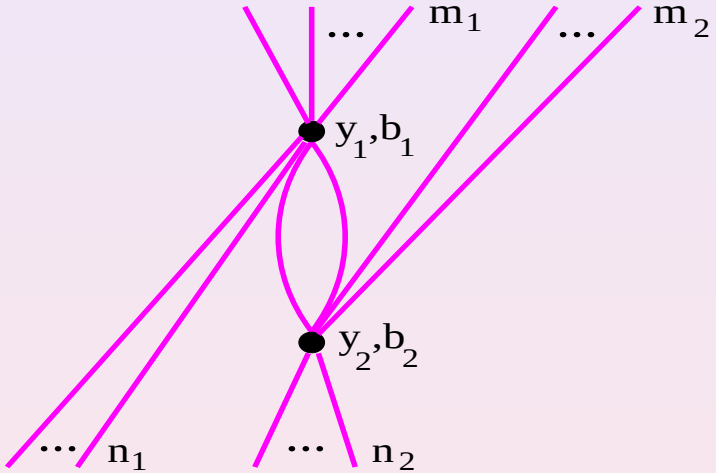
- QGSJET-II-04: also 'Pomeron loops' included
- small at low parton density
- suppressed at high density
- still a finite correction at large b $\Rightarrow$ influence cross sections & particle production

- however: small impact on EAS characteristics
  if the model is calibrated to the same data set *[SO, 2009]*

New version of QGSJET-II (QGSJET-II-04)



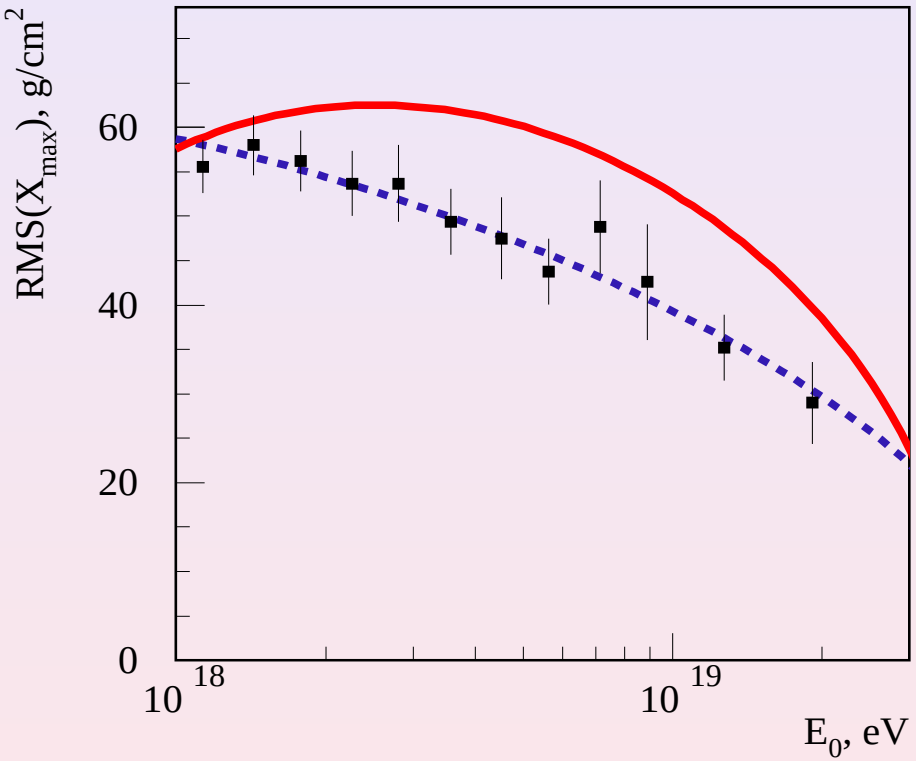
- QGSJET-II-03: only dominant ('net-like') Pomeron-Pomeron interactions



- QGSJET-II-04: also 'Pomeron loops' included
- small at low parton density
- suppressed at high density
- still a finite correction at large b $\Rightarrow$ influence cross sections & particle production

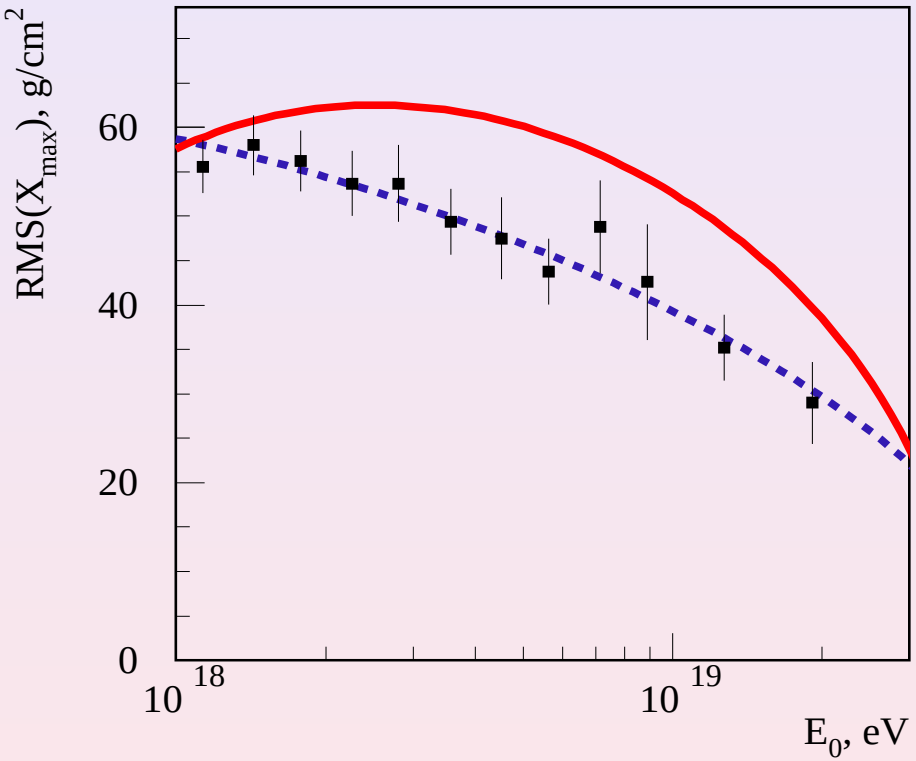
- however: small impact on EAS characteristics if the model is calibrated to the same data set *[SO, 2009]*
- discussed above: impact of calibration to LHC data

UHECR composition?



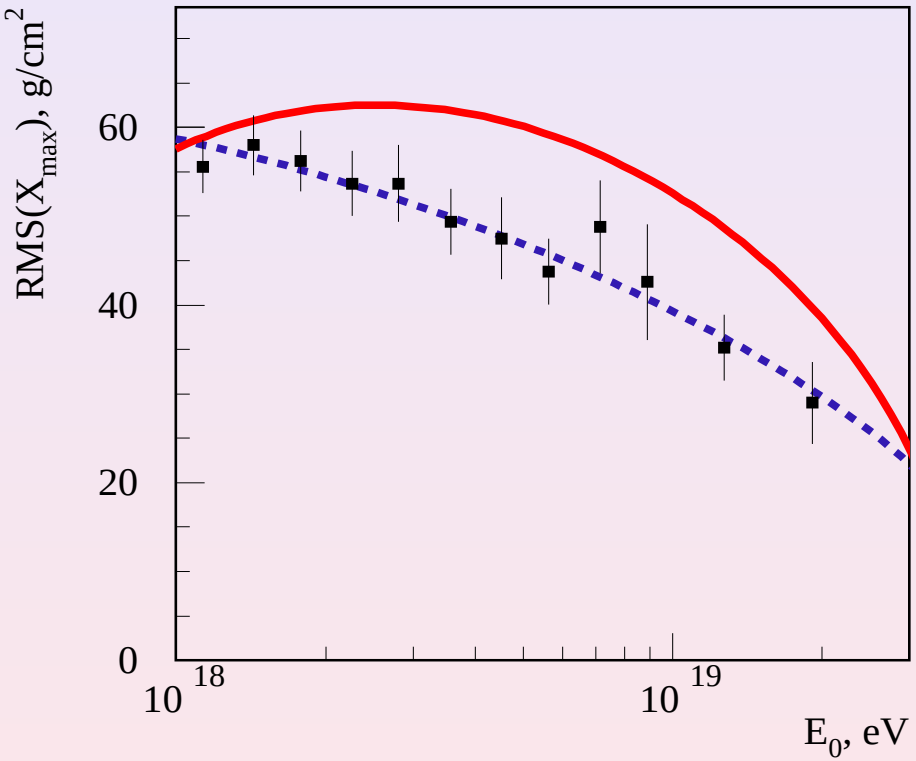
- PAO data on RMS($X_{\max}$): heavy-dominated composition at 1 EeV!

UHECR composition?



- PAO data on RMS($X_{\max}$): heavy-dominated composition at 1 EeV!
- indeed, consider 2 cases for 2-component composition): change from pure p to Fe at $E_0 = 1 \div 30$ EeV, or from a mixture (60% Fe and 40% p at 1 Eev)

UHECR composition?



- PAO data on RMS($X_{\max}$): heavy-dominated composition at 1 EeV!
- indeed, consider 2 cases for 2-component composition): change from pure p to Fe at $E_0 = 1 \div 30$ EeV, or from a mixture (60% Fe and 40% p at 1 Eev)
- 2nd option supported by the data