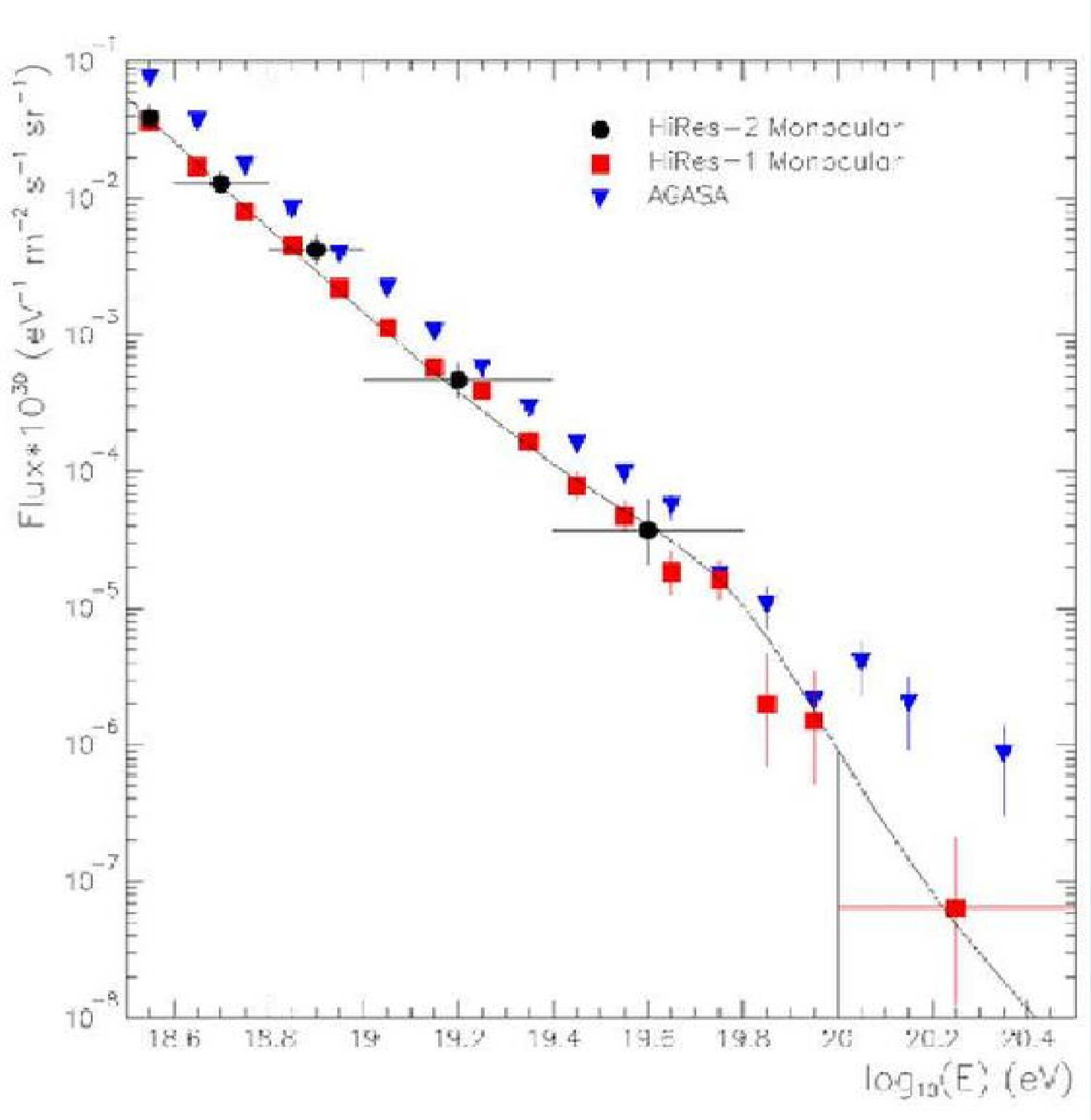
Are cosmic rays still a valuable probe of Lorentz Invariance Violations* in the Auger/TA era?

R. Aloisio, D. Boncioli, A. Di Matteo, P.L. Ghia, ***AFG***, S. Petrera, F. Salamida

Vulcano Workshop May 23 2014

* LIVs for friends

- Some historical notes (1996-1997)



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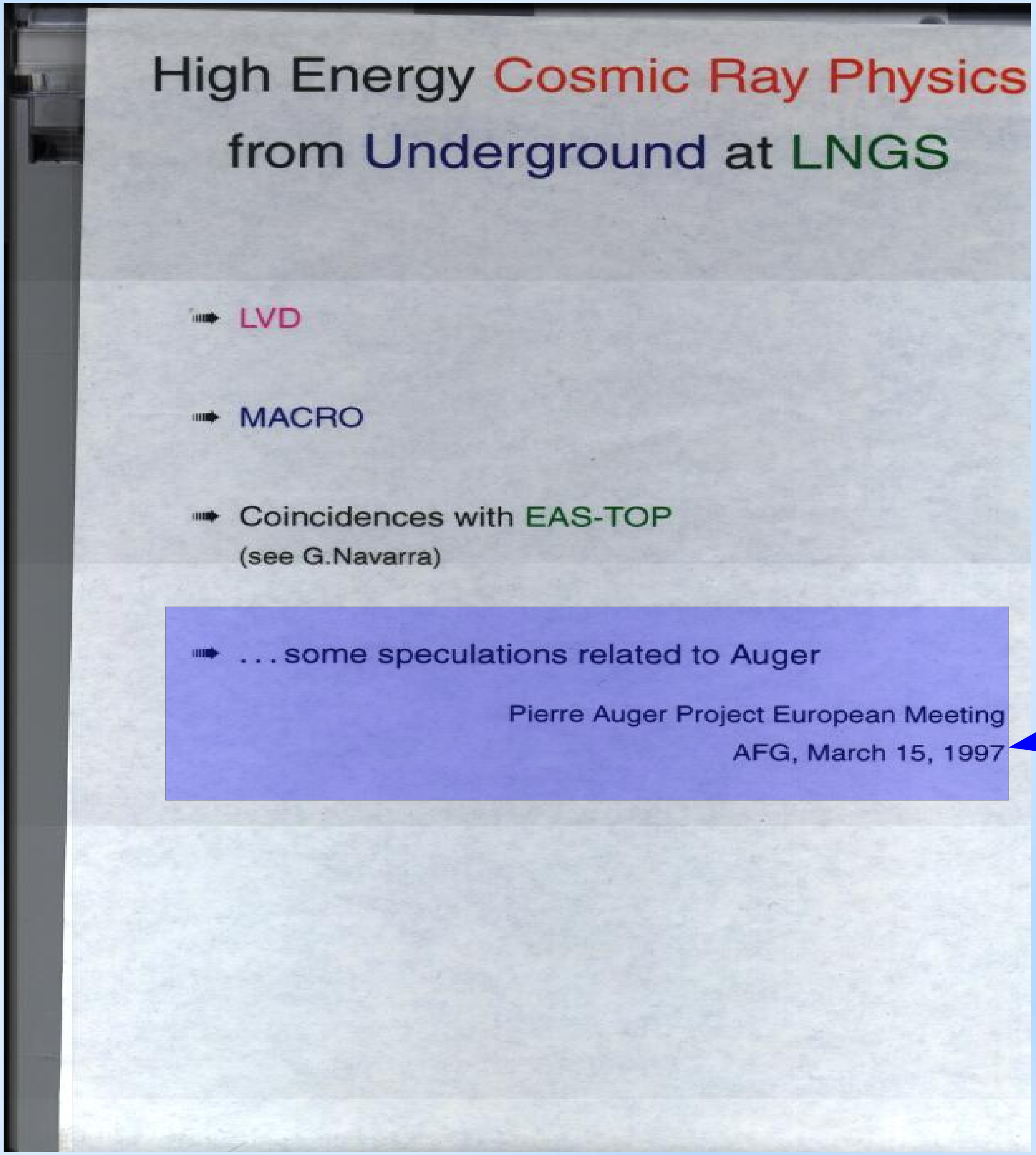

High Energy Cosmic Ray Physics
from Underground at LNGS

- LVD
- MACRO
- Coincidences with EAS-TOP
  (see G.Navarra)
- . . . some speculations related to Auger

Pierre Auger Project European Meeting
AFG, March 15, 1997

- Some historical notes

Pierre Auger Experiment

as laboratory for testing Special Relativity?

(P. Blasi, AFG, in preparation, submitted to XXV ICRC)

Very simple idea: What are the hypotesis leading to the ZKG cutoff?

→ photoproduction $\gamma p \to \pi p$ very well known in Lab. $(\vec{p}_p = 0)$ frame.

→ translates into a threshold for EHE protons in the γ_{3K} reference frame.

→ IF PA experiment will find a sign of ZKG cutoff
↦ *direct* experimental verification of equivalence of reference frames moving with relative $\gamma \simeq 10^{11}$

Other thresholds possible with even larger γ (e.g. pair production by 10^{21} eV γs on IG radio bkg), but more model dependent or less easily (?) detectable

cfr also S. Coleman, S. Glashow (HUTP-97/A008, hep-ph/9703240 5 Mar 1997) who reach similar numerical conclusions, in a slightly more model dependent, more indirect way.

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Lorentz Invariance Violations in UHECRs

- Why LIV?
- ***ALL*** physical laws should be experimentally tested
- to test one has to understand possible violations

$$LI \Rightarrow c = invariant \Rightarrow c^2\, dt^2 - dr^2 = invariant \Rightarrow E^2 - c^2\, p^2 = invariant$$

$$LIV \Rightarrow E^2 - c^2\, p^2 \neq invariant$$

- many other approaches – long history
- D.A. Kirzhnits and V.A. Chechin, Sov. Jour. Nucl. Phys. 15, 585 (1971). (motivated by apparent non detection of GZK in Volcano Ranch)

....

Lorentz Invariance Violations in UHECRs

- Aloisio, Blasi, Ghia, Grillo (2000)
  Completely phenomenological approach

$$E^2 - \vec{p}^{\,2} = \mu^2(E, \vec{p}^{\,2}, m, M); \quad m = particle\, mass$$

$$M = LIV \;\; parameter\left(\stackrel{?}{=}{}^{?}\, m_{Planck} = 1.2\,10^{28}\;\; eV \right) \Rightarrow M \to \infty \quad \mu \to m = invariant$$

At lowest non zero order[+]

$$E_i^2 - \vec{p}_i^{\,2} = \mu_i^2(E, \vec{p}^{\,2}, m_i, M) \approx m_i^2 + f_i \frac{p^{2+n}}{M^n}; n = 1, 2$$

Notice: at this order $\frac{p^{2+n}}{M^n} = \frac{E^n p^2}{M^n} = \frac{E^{2+n}}{M^n}$

Also assume unmodified Energy-Momentum conservation*

+ not necessarily theoretically motivated (SME, EFT).

Lorentz Invariance Violations in UHECRs

- For Nuclei violations are (probably) weaker $M \rightarrow A M$

For the moment consider only protons+

- If $f_P > 0$ then vacuum Cherenkov $p \rightarrow p \gamma$ becomes allowed as soon as

$$E_p > \left(m_p^2 M^n / f_p\right)^{1/(2+n)} \approx 2\, 10^{15}\, eV\, [n=1, f_p=1]$$

=> Very strong bounds from the existence of protons in UHECRs at least up to 10^{18} eV

$$f_p < m_p^2 M / E_p^3 < 10^{-8}$$

+ here and in the following we do not consider bounds from other (e.g. Leptonic) channels

Lorentz Invariance Violations in UHECRs (f<0)

- GZK: $p\,\gamma_{bkg} \rightarrow N\,\pi\,;\quad bkg = CMB\,,\,EBL$

(LI) Threshold: $E_{GZK} \approx \dfrac{m_p m_\pi}{2\,\omega_\gamma} \approx 5\times 10^{19}\,eV$

In case of LIVs $E_i^2 - \vec{p}_i^{\,2} = \mu_i^2(E, \vec{p}^{\,2}, m_i, M) \approx m_i^2 + f_i \dfrac{p^{2+n}}{M^n}\,;\, n=1,2$

For:

$$E_{GZK} \approx \frac{\mu_p(E_{GZK})\,\mu_\pi(E_\pi)}{2\,\omega_\gamma} = \frac{\left(m_p^2 + f_p \dfrac{E_{GZK}^{2+n}}{M^n}\right)^{1/2} \left(m_\pi^2 + f_\pi \dfrac{E_\pi^{2+n}}{M^n}\right)^{1/2}}{2\,\omega_\gamma}$$

$$f_p = f_\pi < -10^{-13}(n=1) \quad \left(-10^{-6}(n=2)\right)$$

No real solutions => the reaction is not allowed

If GZK => very strong limit

Lorentz Invariance Violations in UHECRs

- Nuclei: Photo Dissociation, e.g.

$$(A,Z)\gamma_{bkg} \rightarrow (A-1, Z-1)\, p; \quad bkg = CMB, EBL$$

Threshold: $$E_{PHD}(Fe) \approx \frac{(A m_p \Delta)}{\omega_{bkg}} \approx 6 \times 10^{19}\, eV \approx E_{GZK}$$

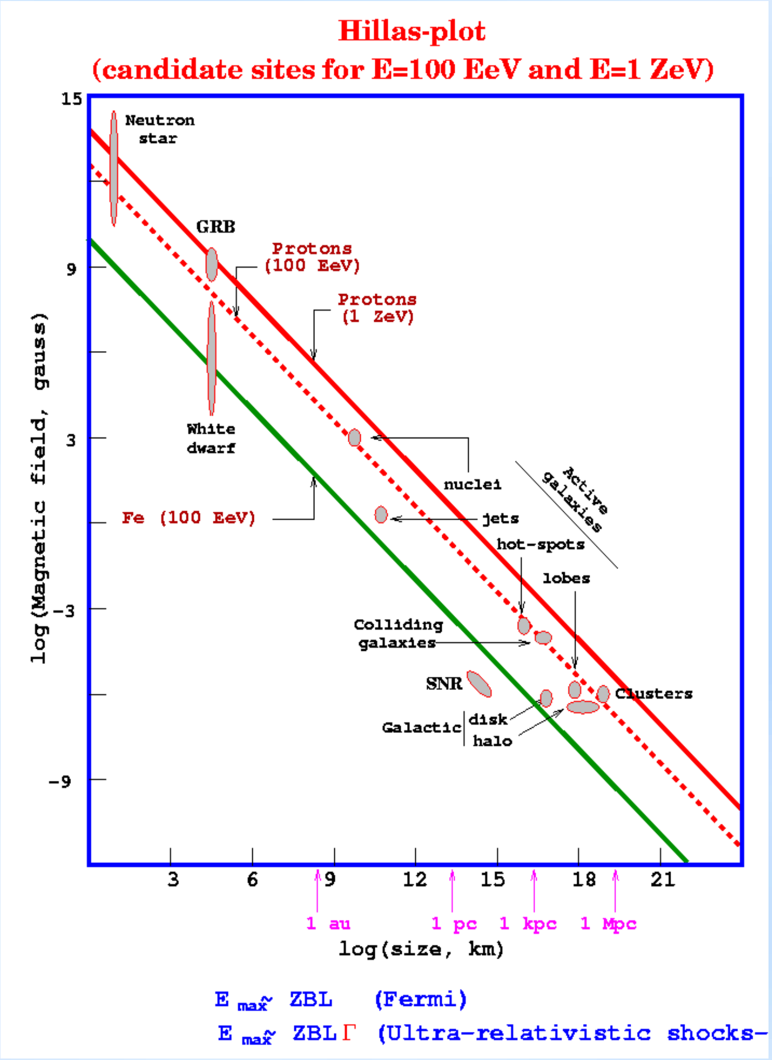
In case of LIVs
(assuming Nucleus(A,Z)= A independent Nucleons)

For: $$f_p = f_\pi < -A\, 10^{-13} (n=1) \quad (-A\, 10^{-6} (n=2))$$

the reaction is not allowed

Lorentz Invariance Violations in UHECRs

Back to good old days (2008, AFG, Edinburgh)



Summarizing:

drop not present: EG sources → LIV
G sources

drop present: If associated with nearby sources → GZK

If no association: flux cut at sources, no conclusion about LI

Lorentz Invariance Violations in UHECRs

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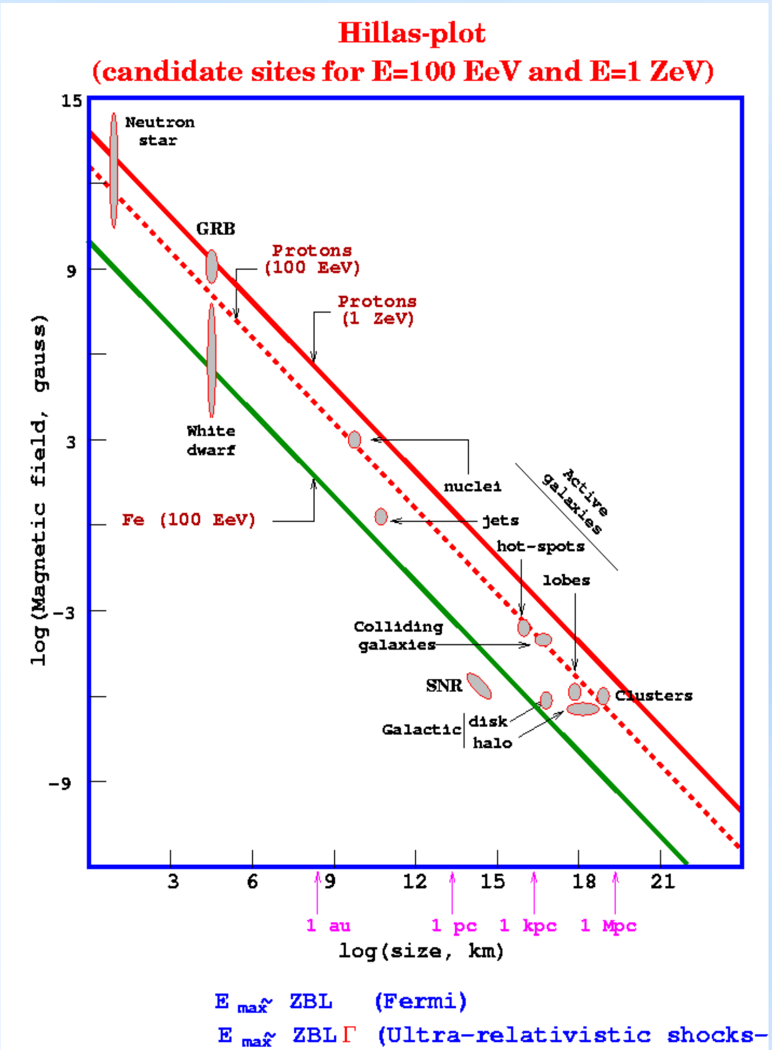

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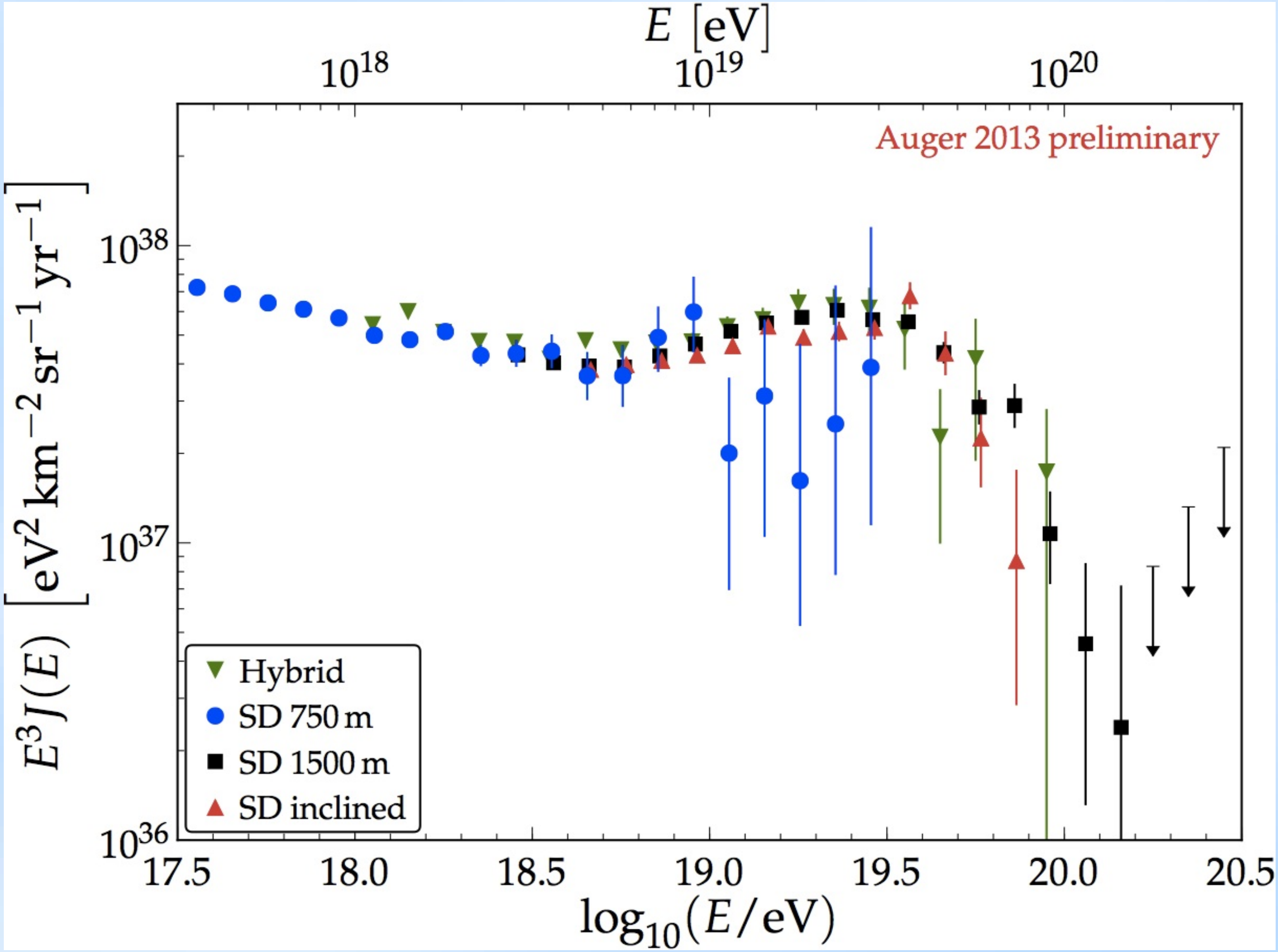
Thanks to Giovanni A-C....

Lorentz Invariance Violations in UHECRs
The end of the story?



Auger, but HiRes, TA very similar drop >20 σ

The Importance of composition: TA

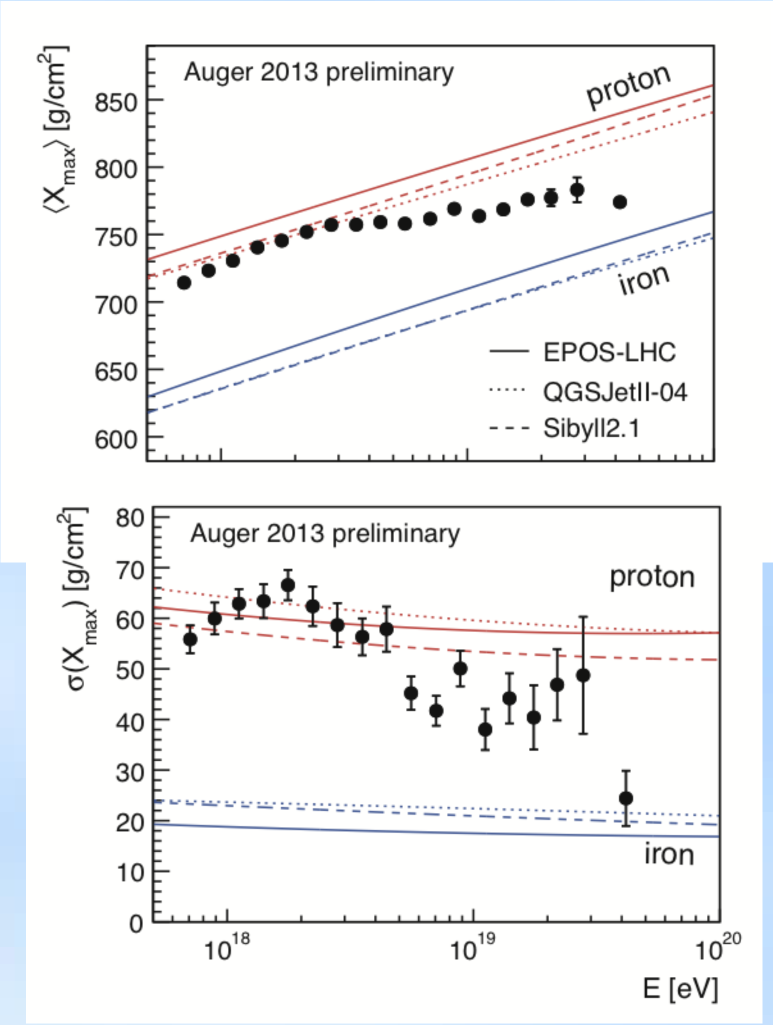
=> UHECRs compatible with protons
But relatively large errors

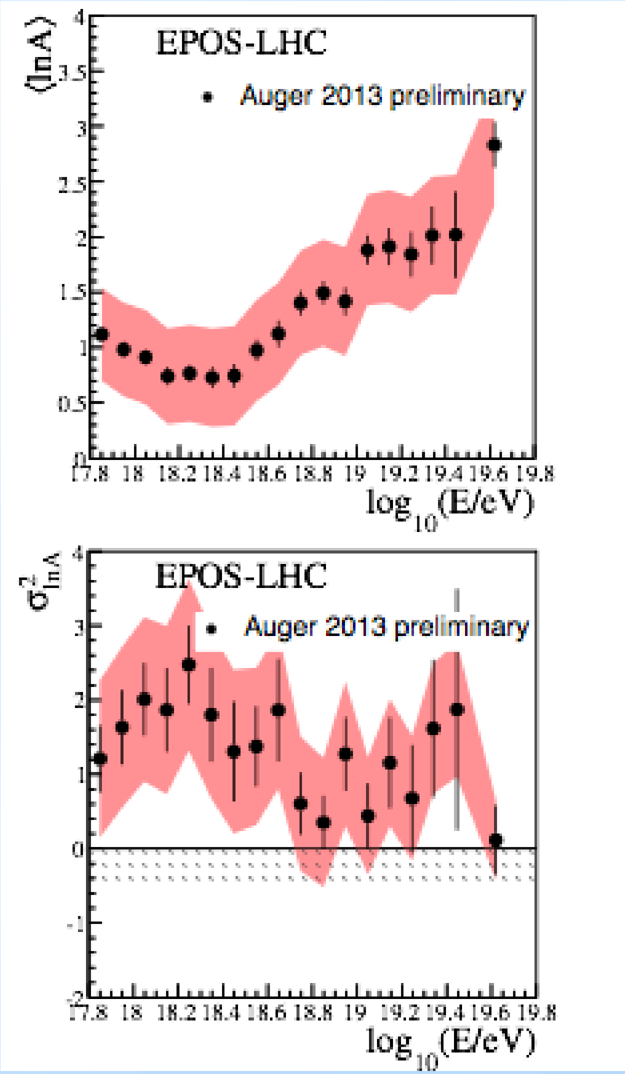
On the other hand, no(?) evidence for correlations with EG sources

=> drop due to sources <=> GZK ?

ICRC 2013

The Importance of composition: Auger





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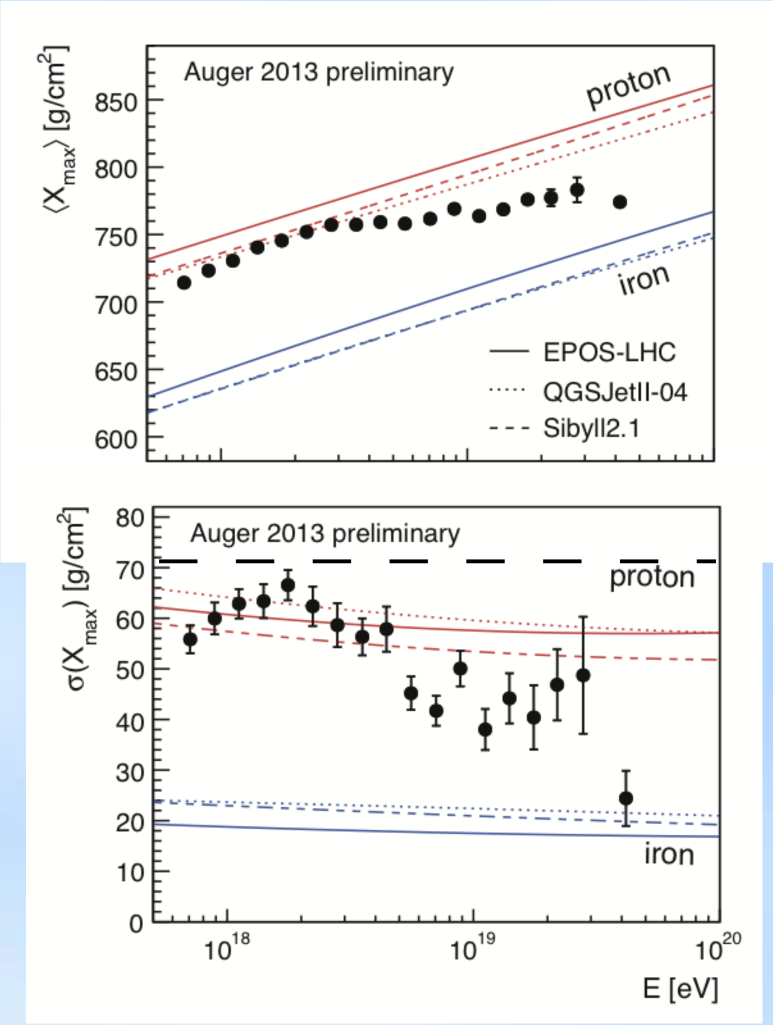
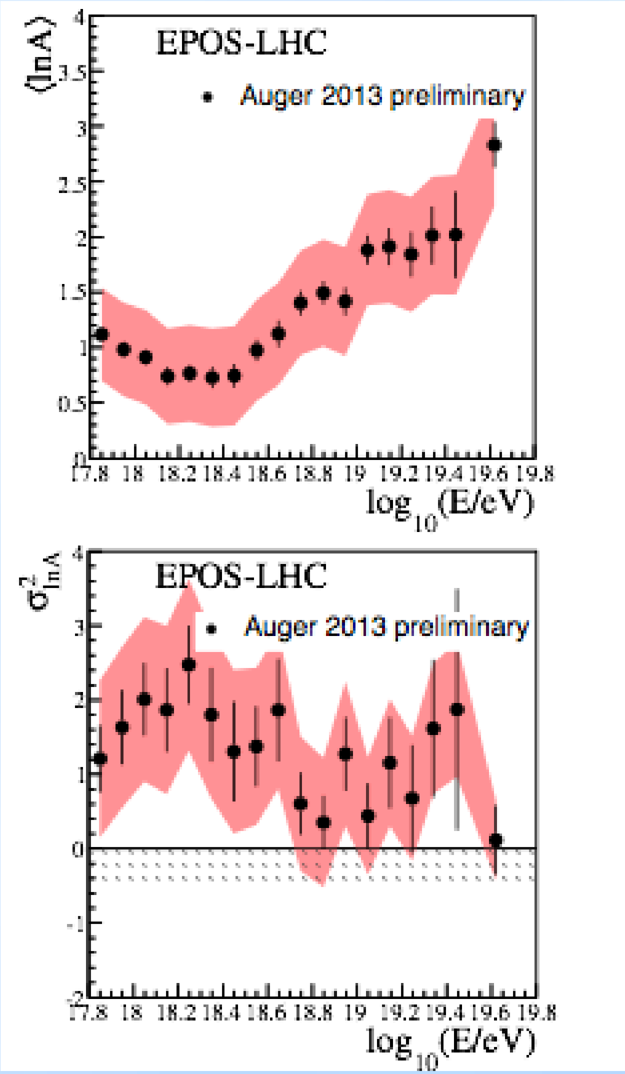




ICRC 2013

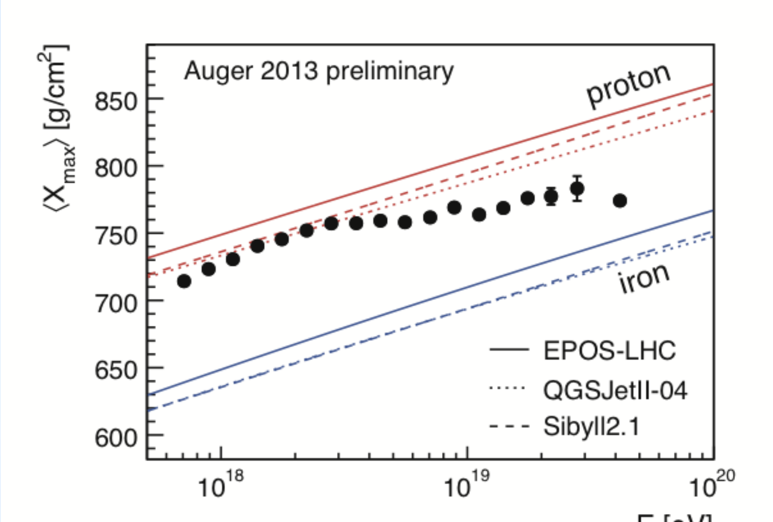
The Importance of composition

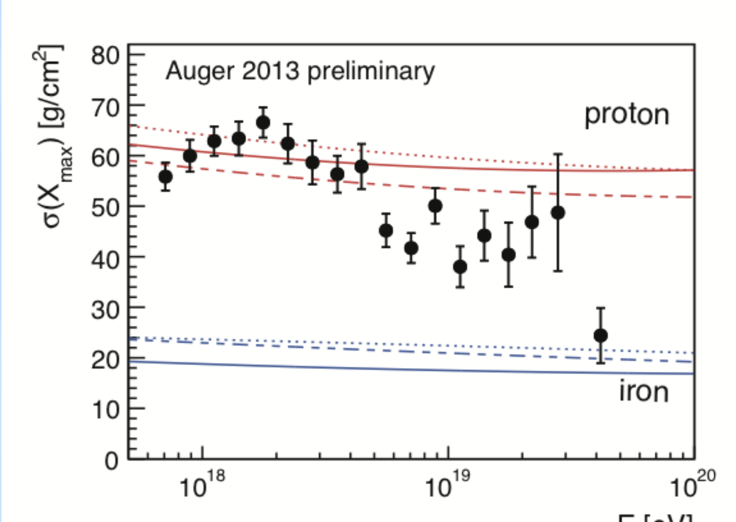
P.Blasi arXiv 1403.2967

(..assuming "standard" hadronic physics)

"The fact that $\sigma(E)$ decreases actually implies that at a given energy the lighter components have started to disappear. For instance, the flux of protons at $10^{19}\,eV$ must have already been dropping, because the dispersion at the same energy is appreciably smaller than for proton induced showers. This simple consideration, together with the proton dominance at$10^{18}\,eV$ implies that Auger data require a proton flux with a pronounced suppression at $E_p^{max} \approx 5\times10^{18}\,eV$

Since this suppression is not associated with energy losses during propagation, the natural conclusion of this line of thought is that the sources of UHECRs accelerate protons up to $\approx 5\times10^{18}\,eV$ and iron (if present) up to $\approx 10^{20}\,eV$."





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==> NO GZK and very little Nuclei Photo-disintegration

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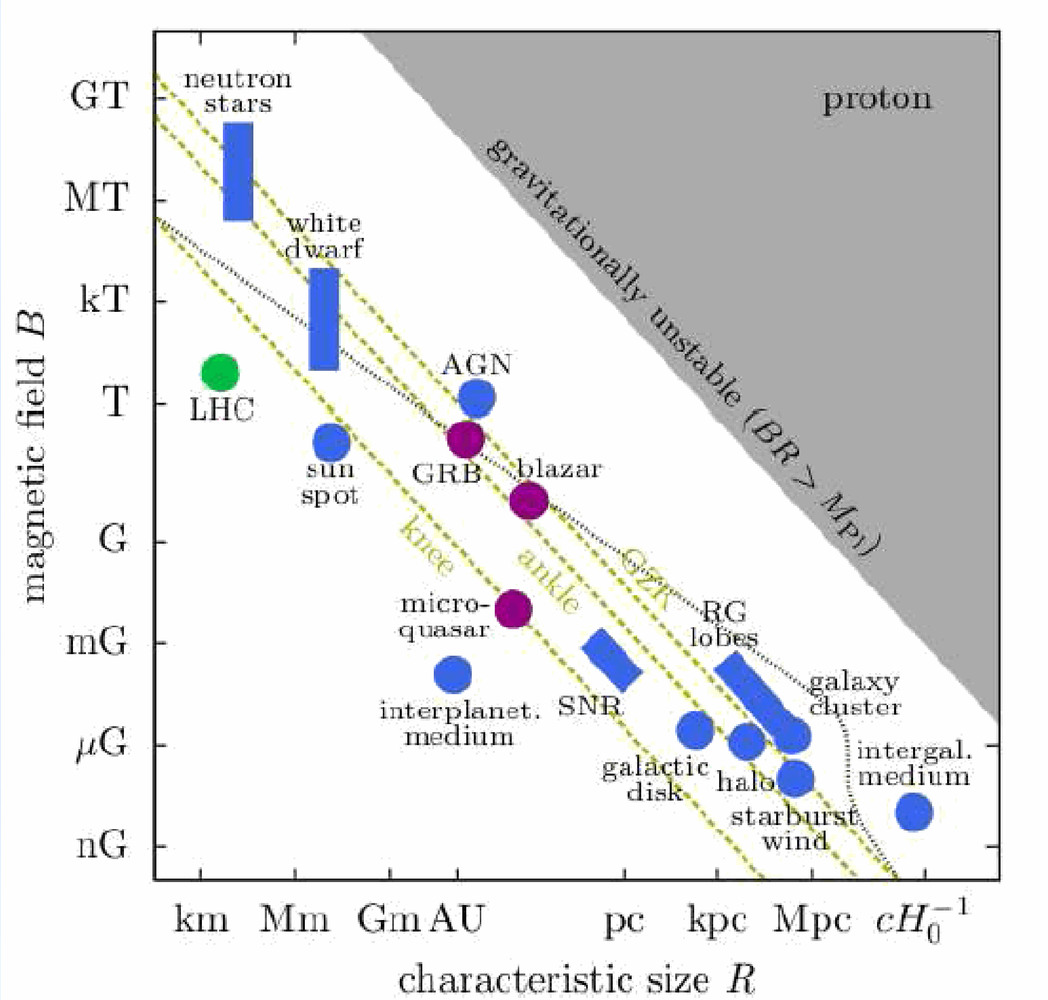
==> NO GZK and very little Nuclei Photo-disintegration

Very little, if any, bounds on LIV

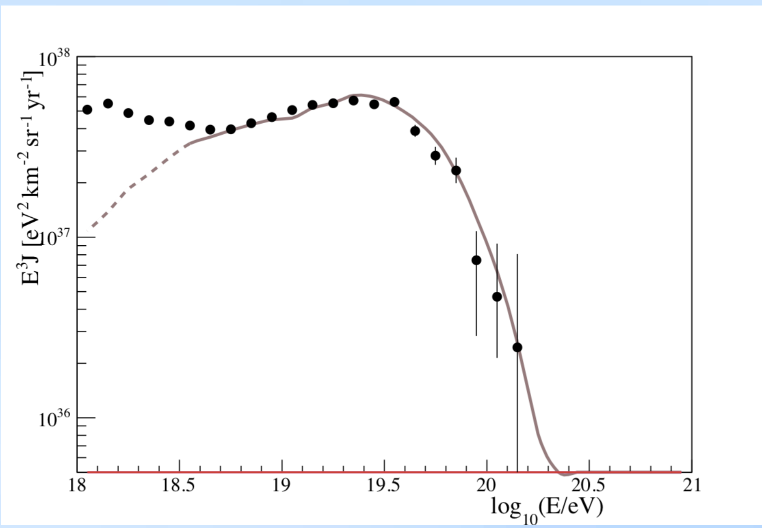
The Importance of composition

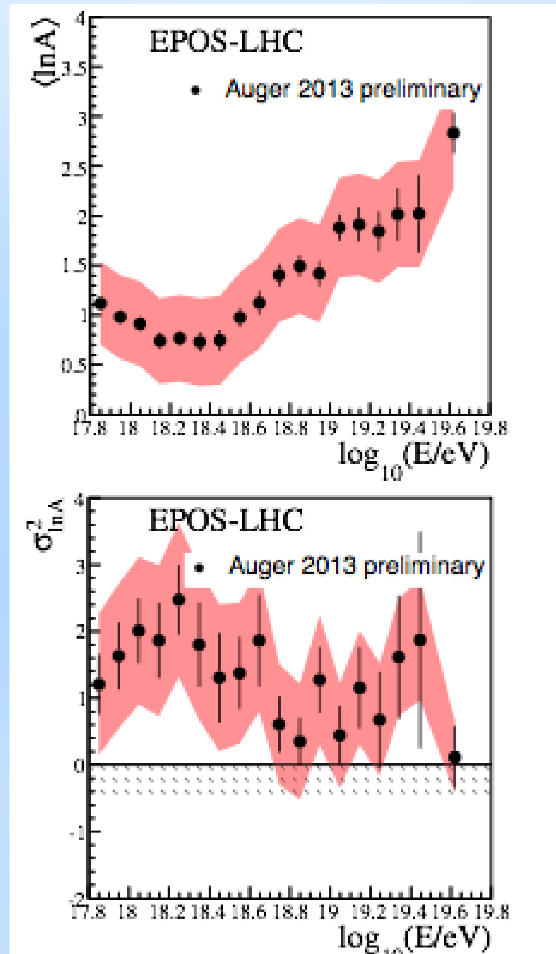
Acceleration to lower energies easier

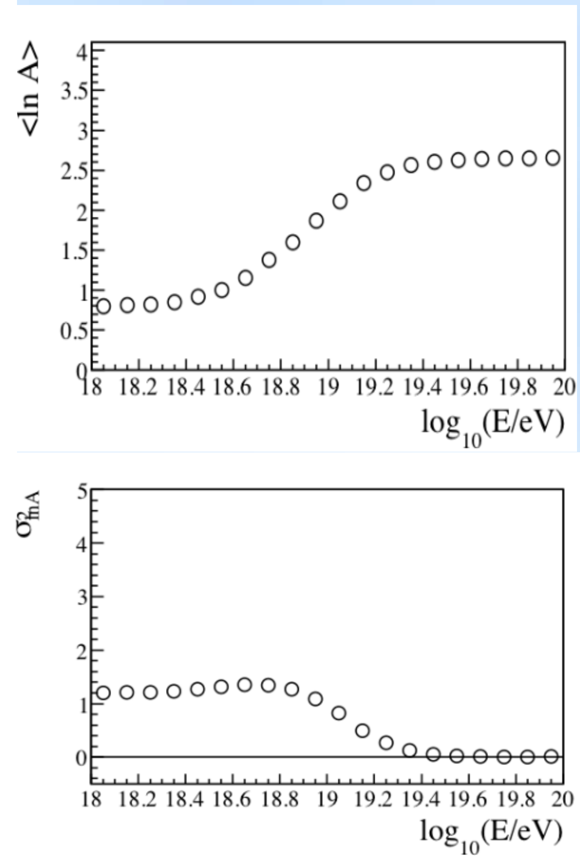


An exercise: uniformly distributed in CV sources of nuclei $dN(Z)/dE \propto E^{-2}$ $(E_Z < Z \times 4 \times 10^{18} eV)$

no interactions in bkg radiation, only energy losses by redshift => LIV







Good (qualitative) description of Auger data

An exercise: uniform sources

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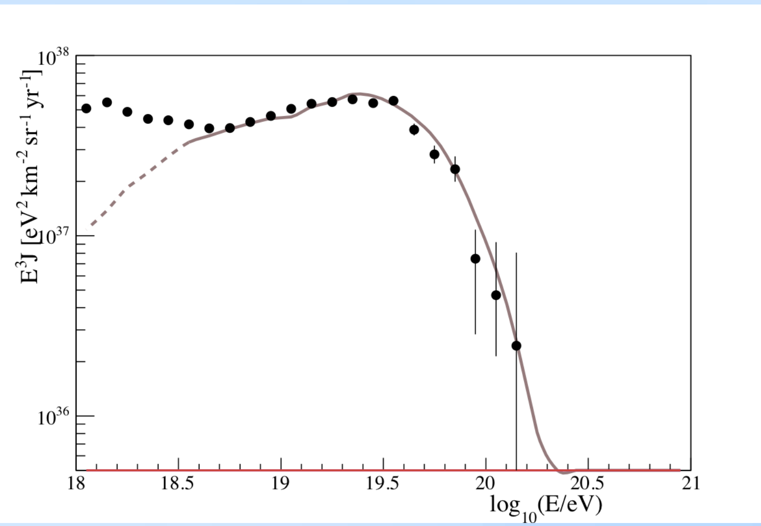

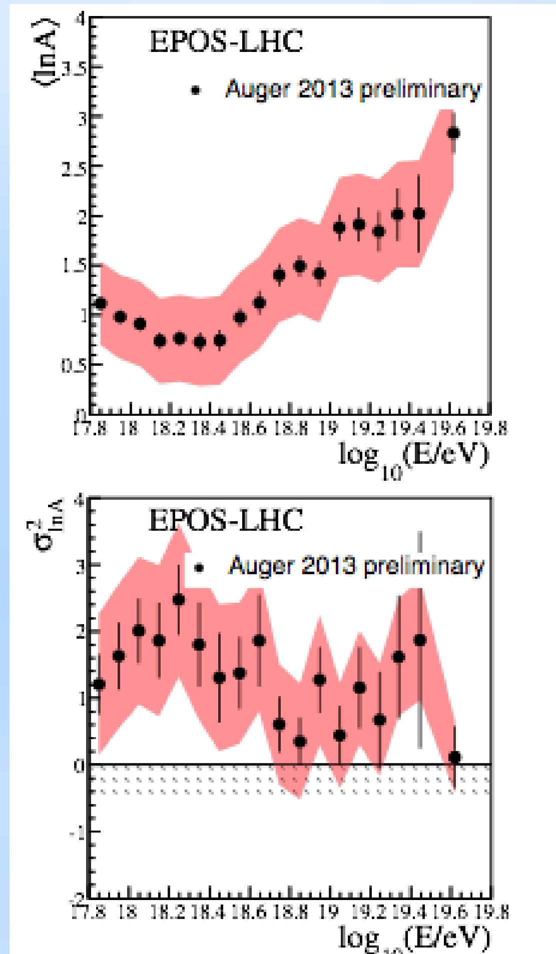

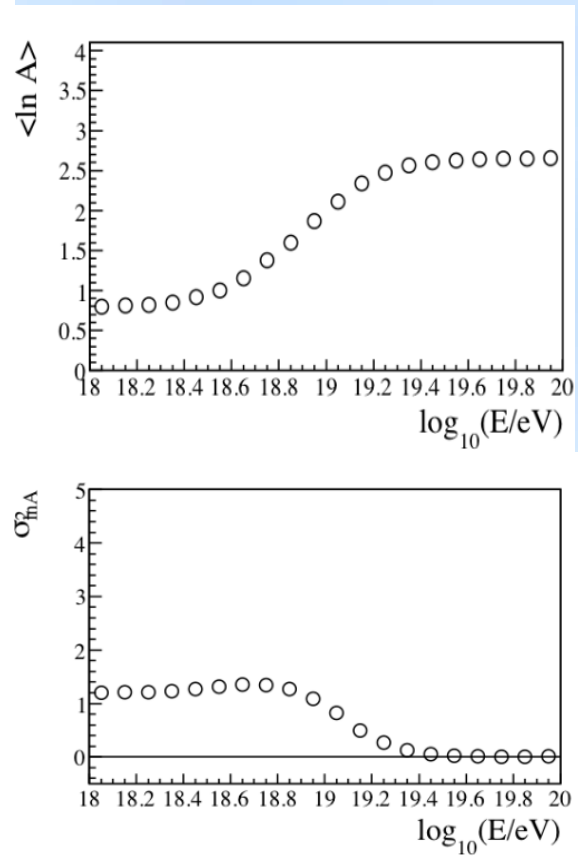

Good (qualitative) description of Auger data

No bounds on LIV for UHECRs propagation in radiation backgrounds.

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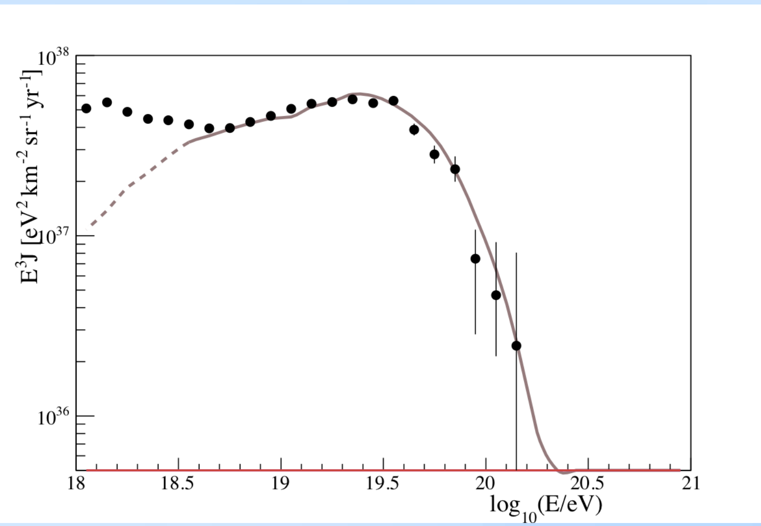
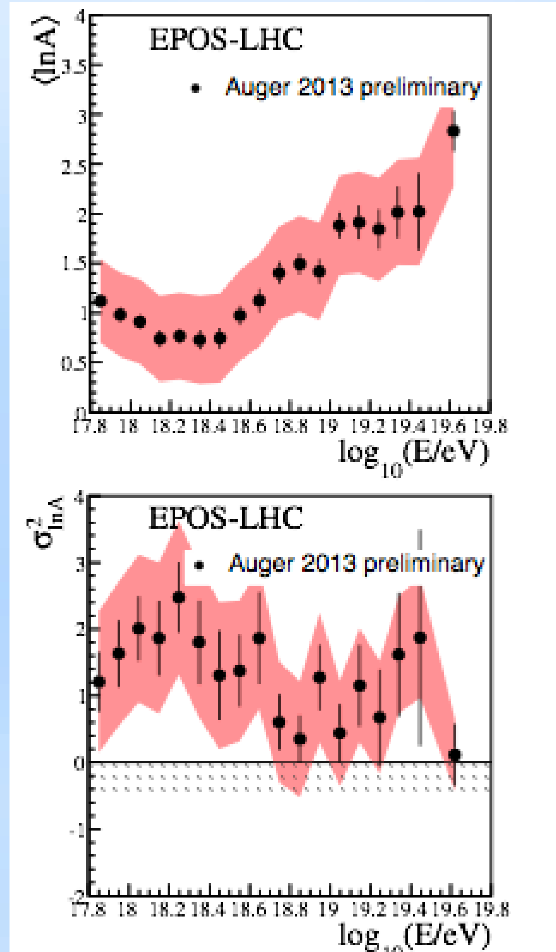
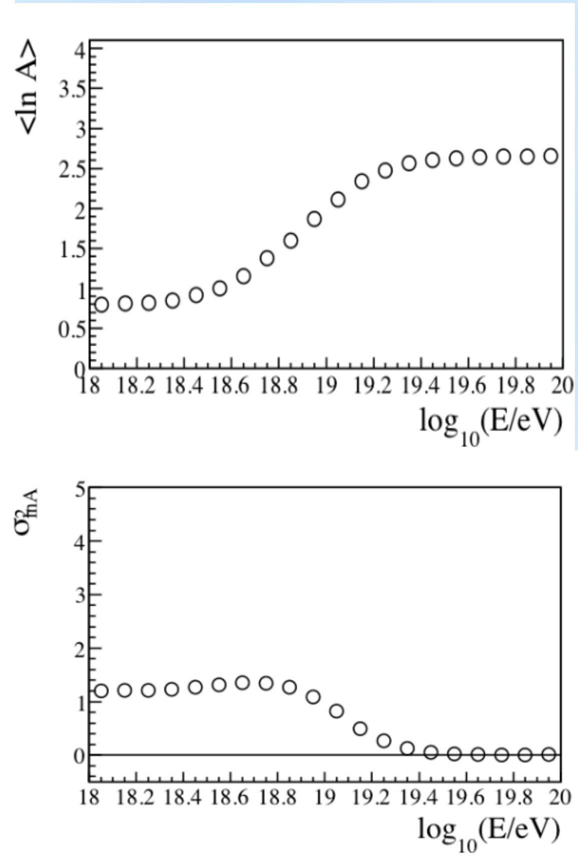






Good (qualitative) description of Auger data

No bounds on LIV for UHECRs propagation in radiation backgrounds. No correlation with EG sources

An exercise:

Clearly other scenarios possible:

- no interactions in bkg radiation, no energy losses
  => Local (Galactic) sources?

- sources not Fermi-like: magnetars? ...other..?

The end of the story?

-TA scenario "protons+GZK" => strong limits on LIV
+HiRes *But would imply EG correlations*

-Auger scenario "nuclei+decline of sources"
=> very weak (if any) limits

Of course, NOT **evidence for LIV!!!!**

Take the Auger scenario: is there more to say?
In fact LIV can affect ALL aspects of UHECRs

- acceleration
- propagation
- interactions

Acceleration

Very little effect of LIV expected:

- If DSA, non (midly) relativistic shocks $\Gamma \ll 10^{11}$
- in DSA ingredient previously relativistic Nuclei
  $E \approx p$ very well verified also in LIV
- possible effects if max E limited by synchrotron losses (work in progress)

- If not DSA (magnetars?...) should be studied in detail (one shot acceleration might be more affected)

Interactions/Decays

No thresholds, so smaller effects expected
Interesting however

Generally: consider a reaction $p_1(p_2) \rightarrow p_{3.} \ldots p_n$
where particle 2 may be absent (decay)
in a LIV world

$$E_i^2 - \vec{p}_i^{\,2} = \mu_i^2(E, \vec{p}^{\,2}, m_i, M) \approx m_i^2 + f_i \frac{p^{2+n}}{M^n}; n = 1, 2$$

so when $|f_i \frac{p^{2+n}}{M^n}| > m_i^2$ important effects are expected:
Interactions might not happen (kinematically), decays might be forbidden (more material in backup and proceedings...)

Interactions/Decays

Consider $\pi^0 \rightarrow \gamma\gamma \quad p_\pi^\mu = q_1^\mu + q_2^\mu$

$$m_\pi^2 + \frac{f_\pi}{M} E_\pi^3 - \frac{f_\gamma}{M}(\omega_1^3 + \omega_2^3) - 2(\omega_1 \omega_2 - q_1 q_2) = 2 q_1 q_2 (1 - \cos\theta)$$

where $q_i = \sqrt{\omega_i^2 - f_\gamma / M\, \omega_i^3}$

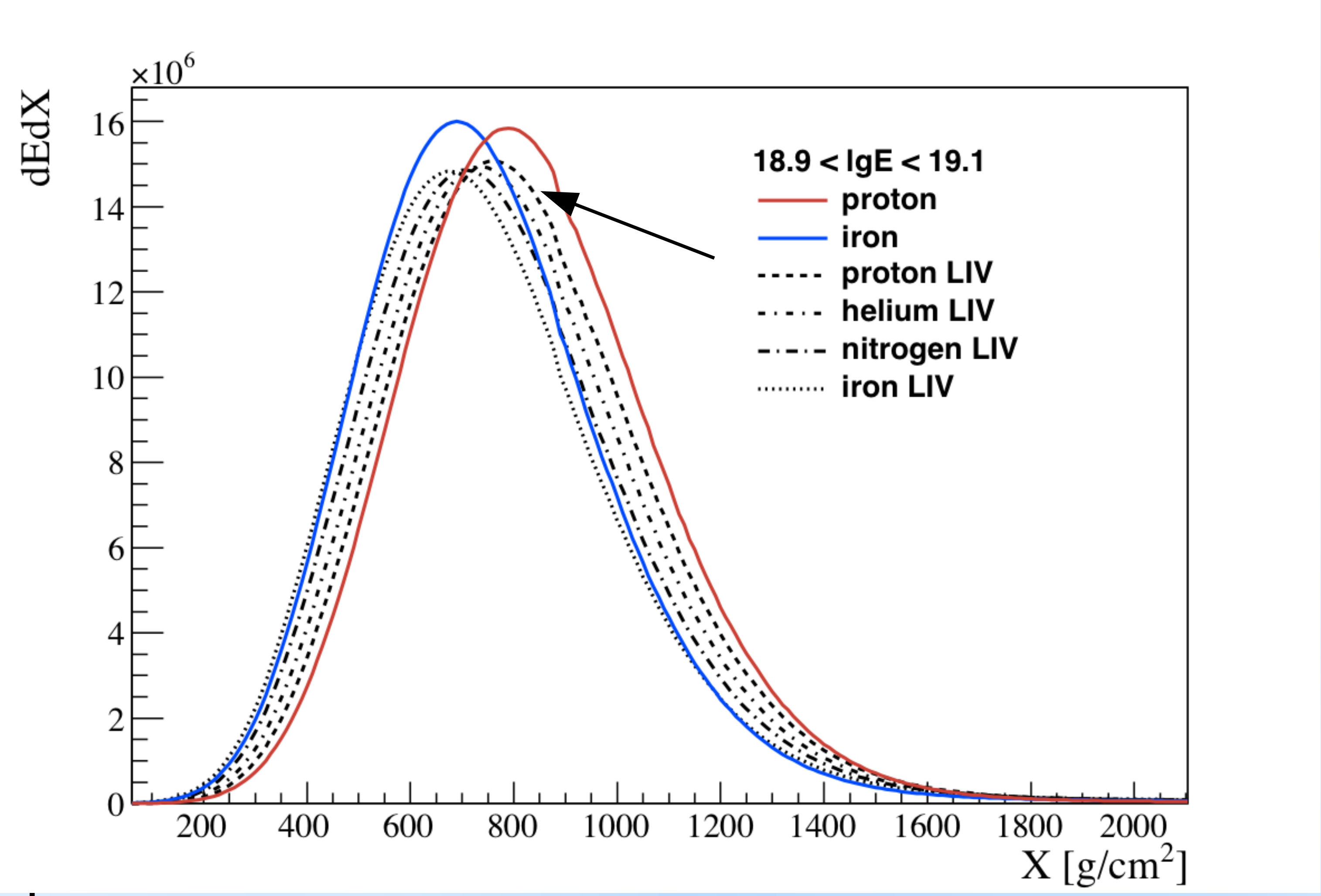
Very strong limits on f_γ; $\quad f_\gamma = 0$ in the following.

This implies that above $E_\pi \approx 2\, 10^{14}\, eV \quad [f_\pi = -1]$
neutral pions would not decay but interact, changing considerably shower development

Interactions/Decays

Generated 100.000 showers in atmosphere with Conex and Epos-LHC as interaction model

Xmax distr.



Protons looking heavier

Interactions/Decays

Generated 100.000 showers in atmosphere with Conex

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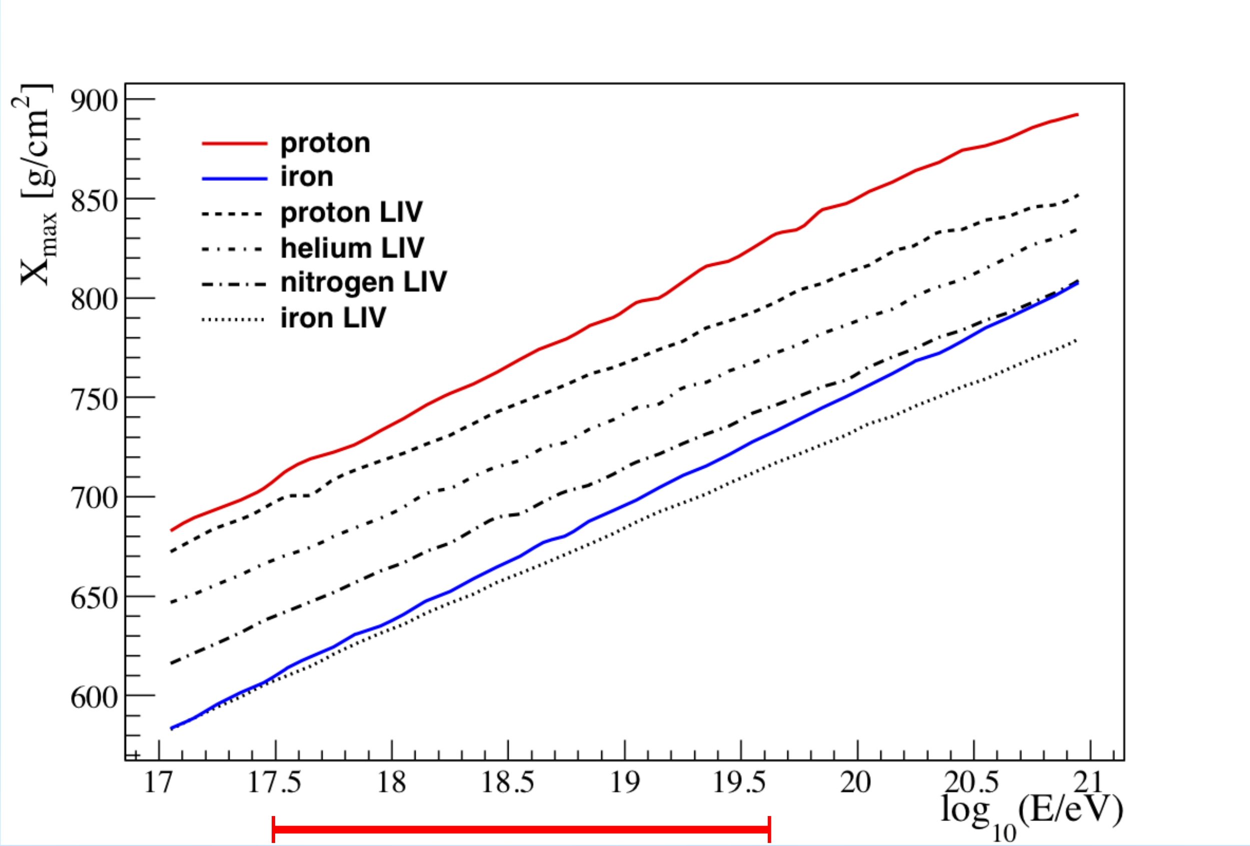

Range PAO data

Protons looking heavier, RMS does not change

Interactions/Decays

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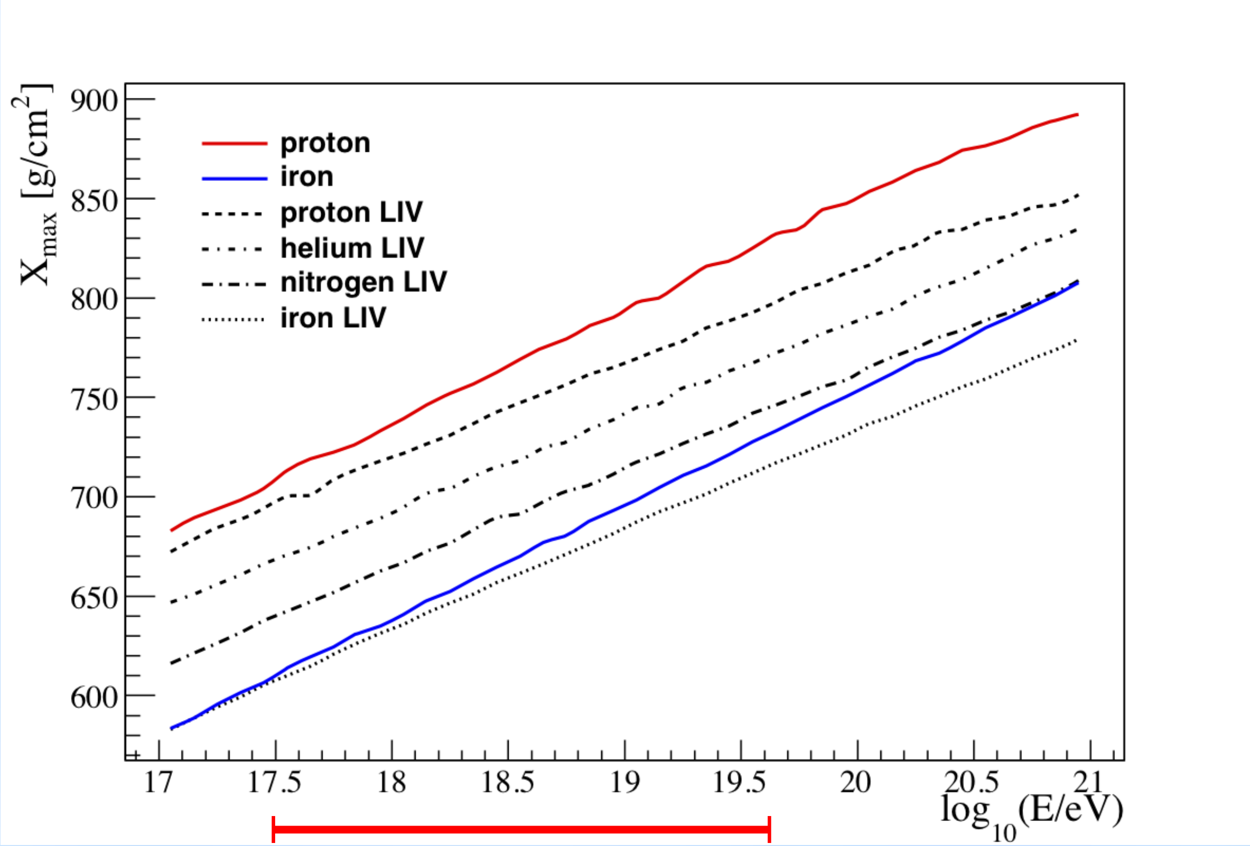

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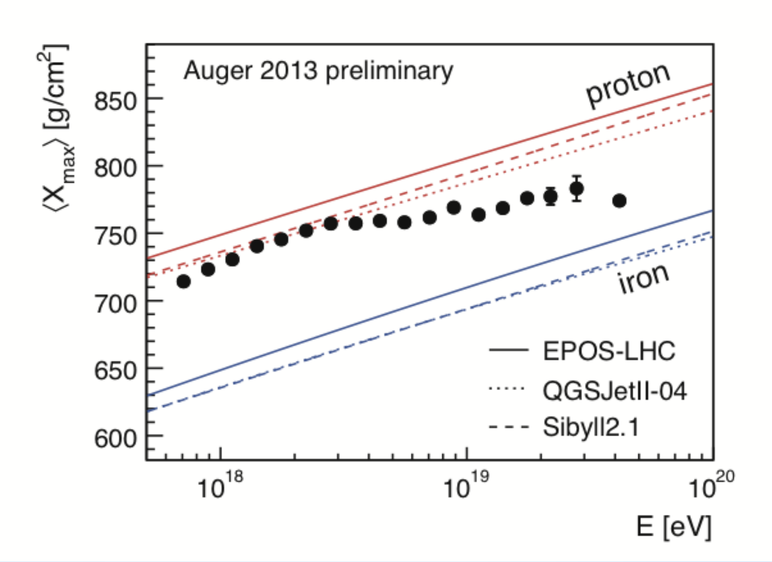

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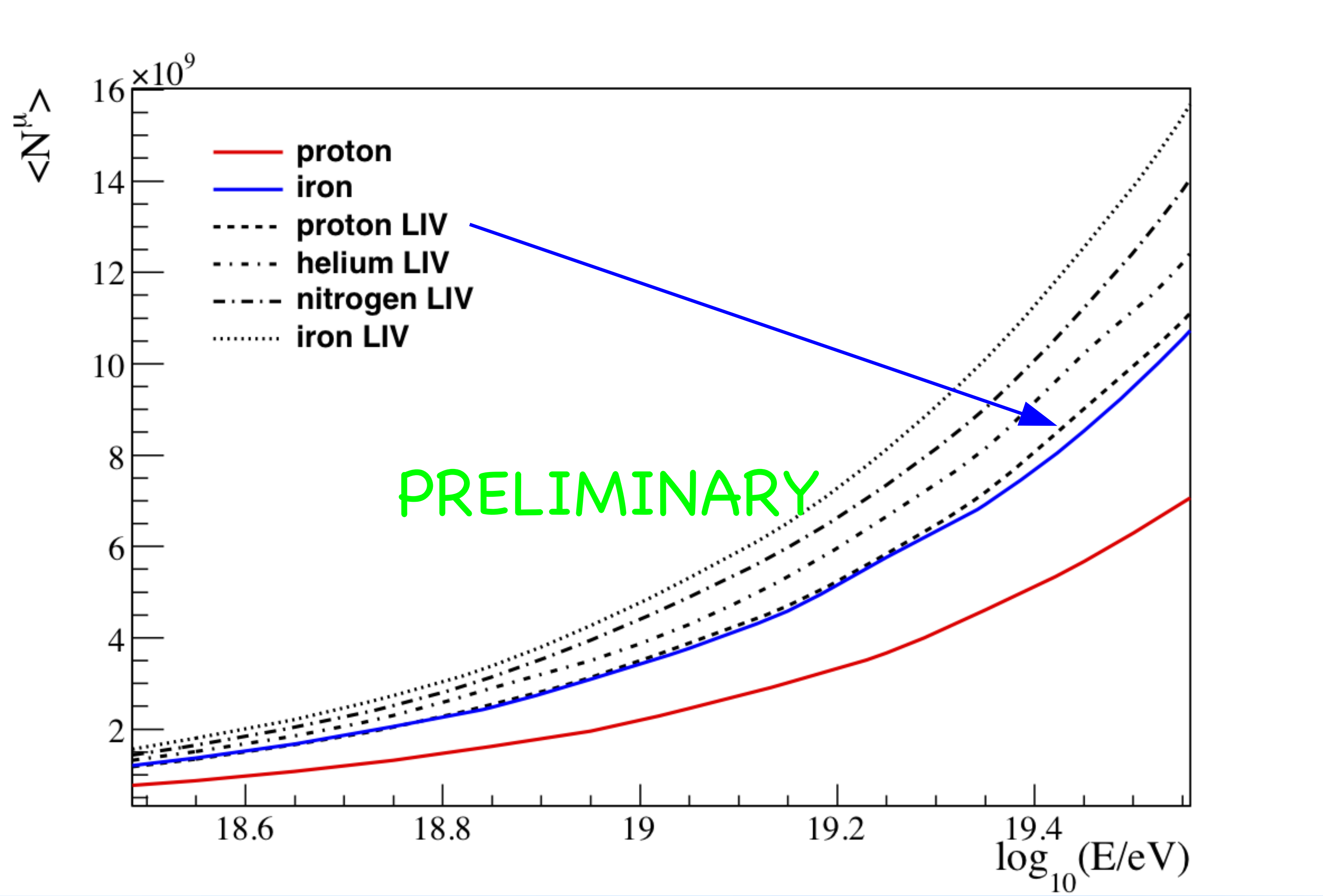
Interactions/Decays

Generated 100.000 showers in atmosphere with Conex EPOS-LHC

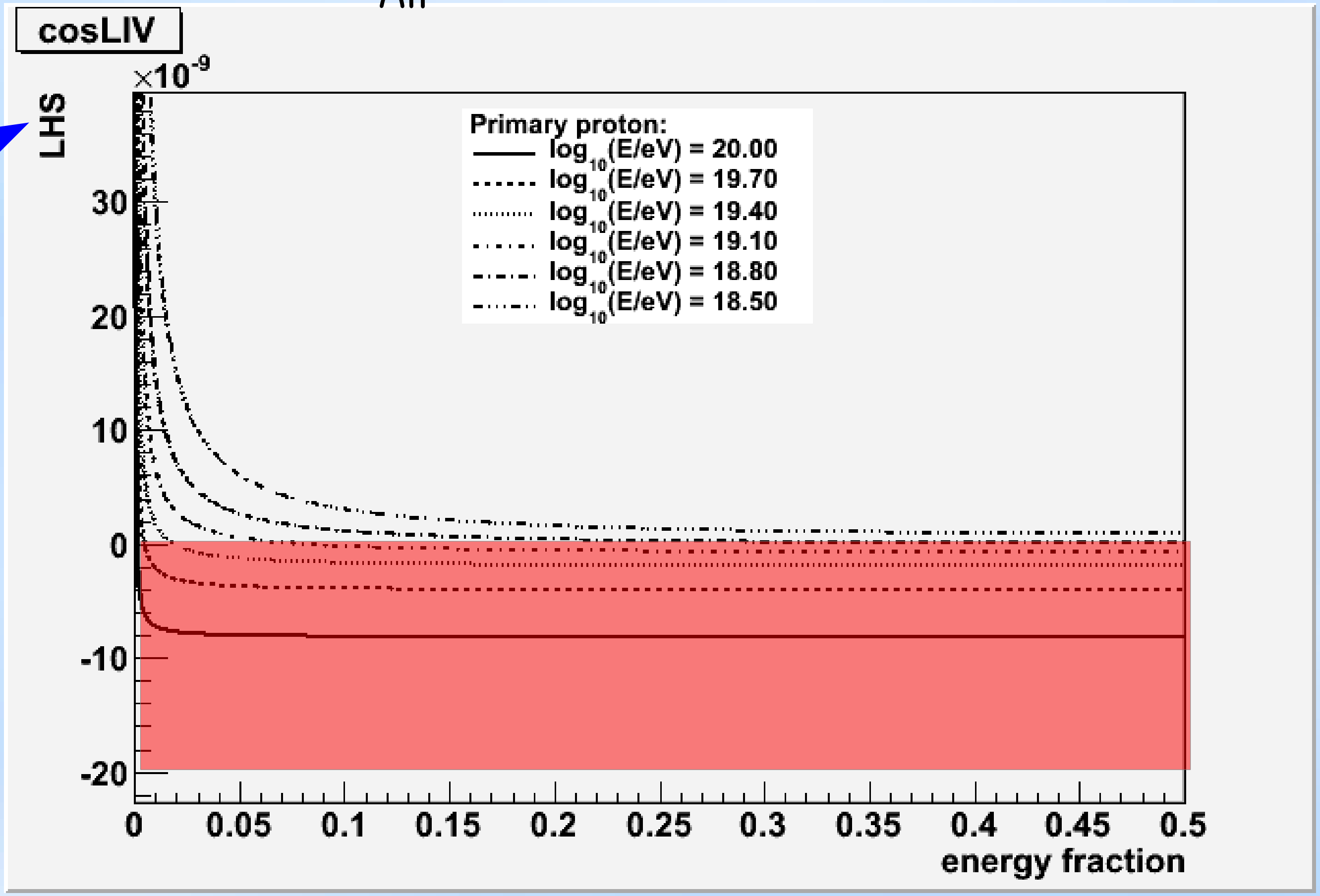
N_μ distr.



Muon production by protons (LIV) similar to Iron

Interactions

Analogous effects for interactions of protons in the atmosphere (here pp_{Air} => pp)



Should be positive

Only protons with $E_p < 10^{19}$ eV interact "normally"

LIV dynamics?

Summary

What limits can we possibly put?

In general, dedicated, detailed simulations needed, work in progress. In general bounds much weaker

Example: if $-5\,10^{-3} < f_p\left(= f_\pi\right) < -10^{-13}$ only effects on propagation (GZK absent), none in interaction/decays

Example: proton unambiguosly detected at 10^{19} eV would imply LIV pars in this range

Conclusions

- LIV bounds status in UHCRs very unclear: very strong limits no longer available
- tension between TA and PAO should be solved
- but even then, definitive statement on correlations with EG sources important
- in the worst (best?) case very difficult to put bounds on LIV parameters appropriate to UHECR physics
- specific, extensive, simulations needed
- accurate measurements needed, especially on UHECRs composition at highest energies: TA, PAO beyond 2015

THANK YOU

Backup

Lorentz Invariance Violations in UHECRs

Back to good old days (2008, AFG, Edinburgh)

There are limits in many simplified cases

n=4

Coleman & Glashow Phys. Rev. D 59, 116008 (1999)

$$\eta_\pi - \eta_p < 5 \times 10^{-24} (\omega/\bar{\omega})^2 \qquad \bar{\omega} = kT_{CMB} = 0.235\,\mathrm{meV}$$

n=5

Aloisio, Blasi, Grillo... ($\eta_1 = \eta_2 = \eta_\pi$)

astro-ph/0001258

Jacobson, Liberati, Mattingly

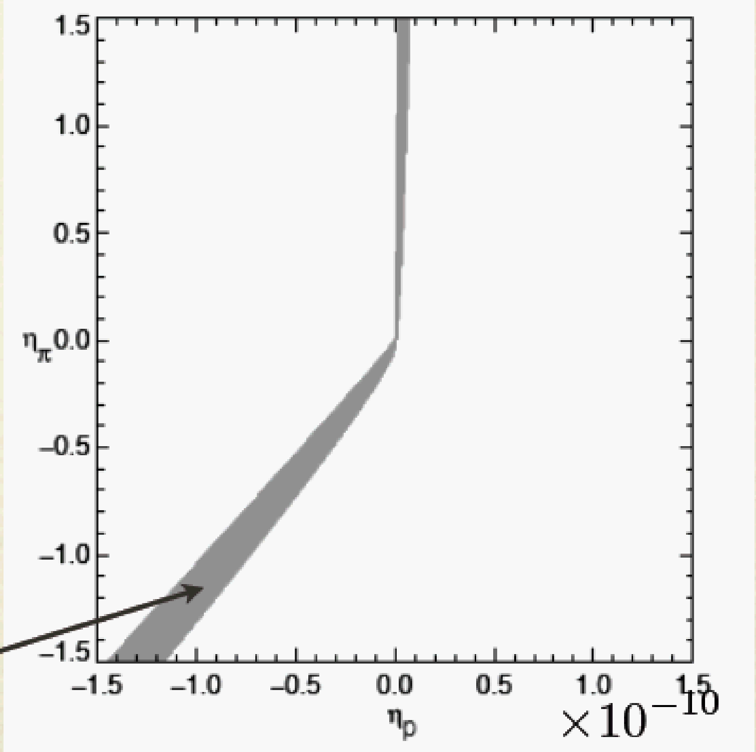
($\eta_1 = \eta_2 \neq \eta_\pi$)

gr-qc/0209264

Loop QG

Alfaro, Palma

hep-th/0208193

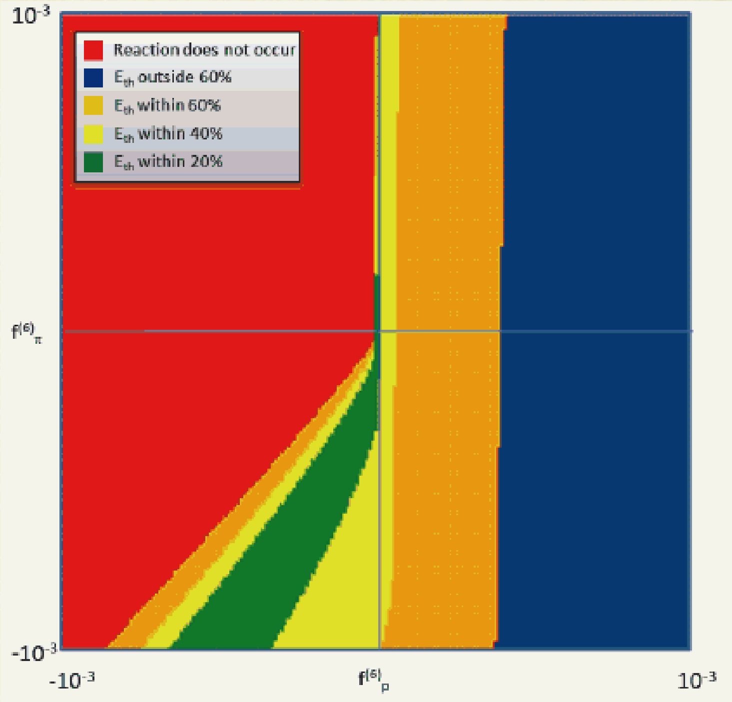


Lorentz Invariance Violations in UHECRs

Back to good old days (2008, AFG, Edinburgh)

n=6

D. Mattingly ($\eta_1=\eta_2\neq\eta_\pi$)
Proceedings of "From Quantum to Emergent Gravity: Theory and Phenomenology", SISSA, June 2007



Though the analysis is stringent, most of the parameter space, mainly in the negative quadrant, is still allowed.

This kind of analysis just looks at the presence and position of the cut-off. But LIV also affects other aspects of UHECR propagation which lead to a distortion of the UHECR spectrum at Earth.

A more thorough study of the whole spectrum around and above 10^{19} eV should then allow to place better constraints.

Interactions/Decays

No thresholds, so smaller effects expected
Interesting however

Method: consider a reaction $p_1(p_2) \rightarrow p_{3.} \ldots p_n$
where particle 2 may be absent (decay)
The quantities $s_{ini} = (p_1^\mu + p_2^\mu)^2$ $s_{fin} = (p_3^\mu + \ldots. + p_n^\mu)^2$
in a LIV world are no longer invariants, but if
energy and momentum are conserved they must be equal
between initial and final state

After trivial (long) calculation

Interactions/Decays

e.g. $p\left(UHECR, p^{\mu}\right) N\left(atm, m\right) \rightarrow N\left(p_1^{\mu}\right) N\left(p_2^{\mu}\right) \pi\left(k_1^{\mu}\right) \ldots \pi\left(k_n^{\mu}\right)$

$$f_p/M\left(E^3 - E_1^3 - E_2^3\right) - f_\pi/M \sum_i E_{\pi i}^3 + 2Em - n m_\pi^2 - 2\left(E_1 E_2 - p_1 p_2\right)$$
$$-2\sum_i \left(E_1 E_i - p_1 k_i\right) - 2\sum_i \left(E_2 E_i - p_2 k_i\right) - 2\sum_{ij} \left(E_i E_j - k_i k_j\right) =$$
$$2 p_1 p_2 (1 - \cos\theta) + 2\sum_i p_1 k_i \left(1 - \cos\theta_{1i}\right) + 2\sum_i p_2 k_i \left(1 - \cos\theta_{2i}\right) +$$
$$2\sum_{ij} k_i k_j \left(1 - \cos\theta_{ij}\right)$$

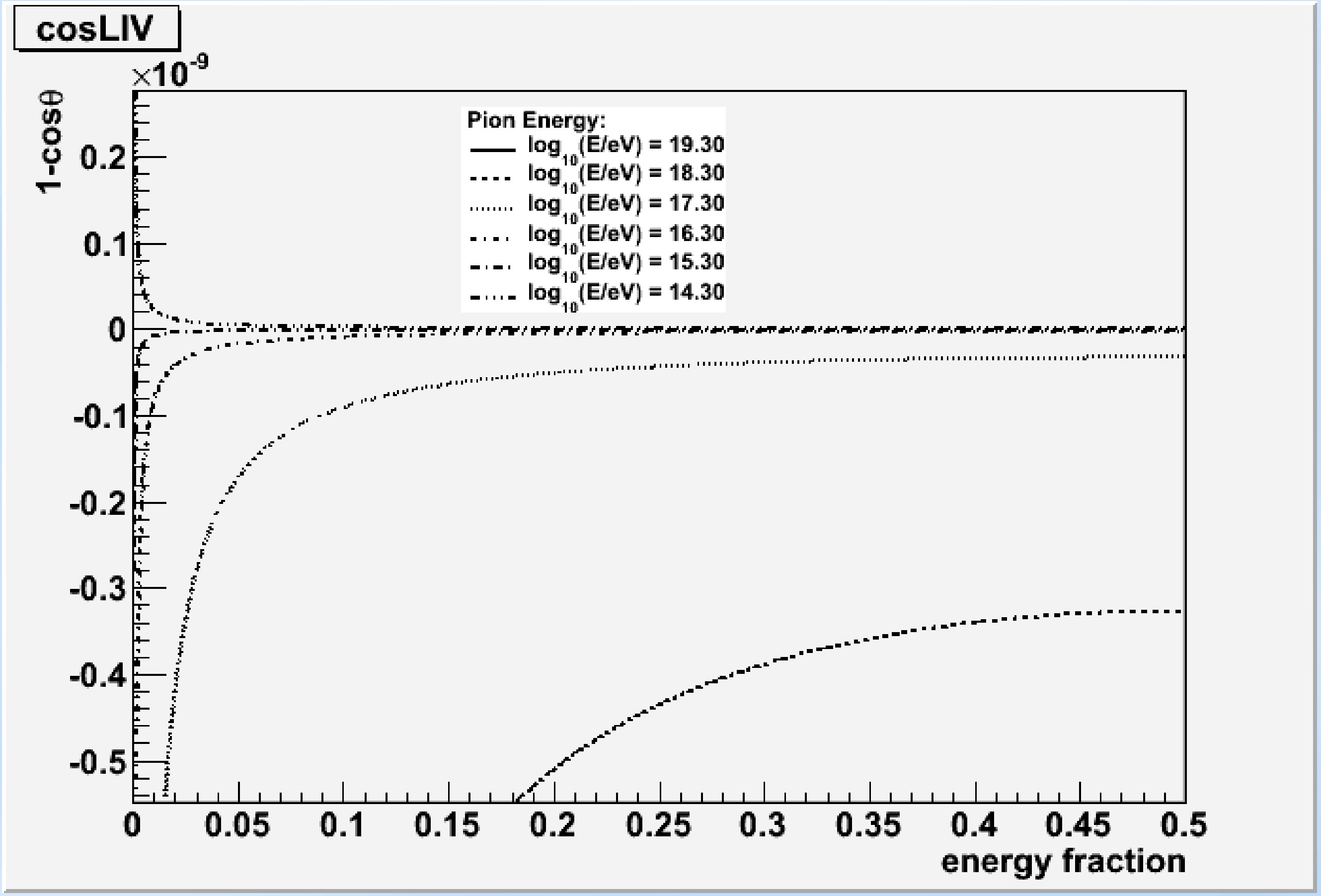
where $p_i = \sqrt{E_i^2 - m^2 - f/M\, E_i^3}$, $k_i = \sqrt{E_{\pi i}^2 - m^2 - f_\pi/M\, E_i^3}$

RHS non negative (by construction)

LHS non negative (LI)

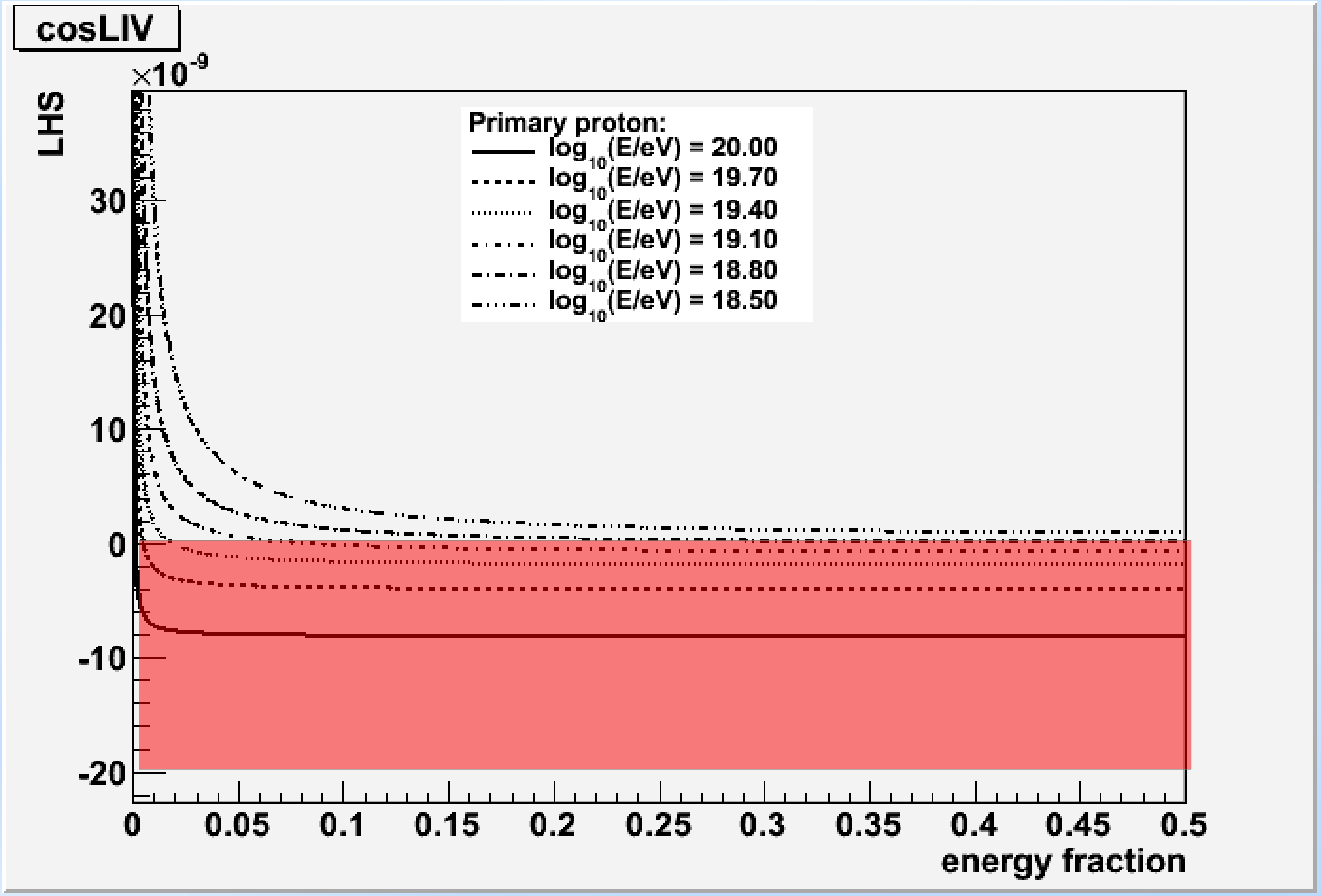
possibly negative (LIV)

If LHS <0 => reaction cannot happen


cosLIV
$\times10^{-9}$
1-cosθ
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Pion Energy:
$\log_{10}(E/eV)$ = 19.30
$\log_{10}(E/eV)$ = 18.30
$\log_{10}(E/eV)$ = 17.30
$\log_{10}(E/eV)$ = 16.30
$\log_{10}(E/eV)$ = 15.30
$\log_{10}(E/eV)$ = 14.30
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5
energy fraction

Interactions

Analogous effects for interactions of protons in the atmosphere (here pp => pp)



Only protons with $E_p < 10^{19}$ eV interact normally