Particle physics in extensive air showers

MPI@LHC, Prague, 21.11.2019

Ralf Ulrich (KIT), Hans Dembinski (MPIK) for the CORSIKA 8 Projec

Take-home message

- High-energy cosmic rays initiate air showers
  - Cosmic-ray **mass composition** can tell us about astrophysical sources
  - Requires **accurate simulation** of air showers (hadron cascades)
  - Background for IceCube and future neutrino observatories, and multi-messenger observations
  - Particle physics at sqrt(s) = 300 TeV!
- Muon mystery
  - **Data/MC mismatch** in muon density in air showers, new particle/QCD physics?
  - **Eight experiments** combined **muon density** measurements from **0.5 PeV to 10 EeV** and established mismatch at **8σ**
- Potential solution from the LHC
  - Smoking gun: Energy fraction carried by neutral pions too high?
  - **proton-oxygen** collisions to clarify **nuclear effects**, planned for 2023
  - Also needed: high precision forward measurements in pp and pPb

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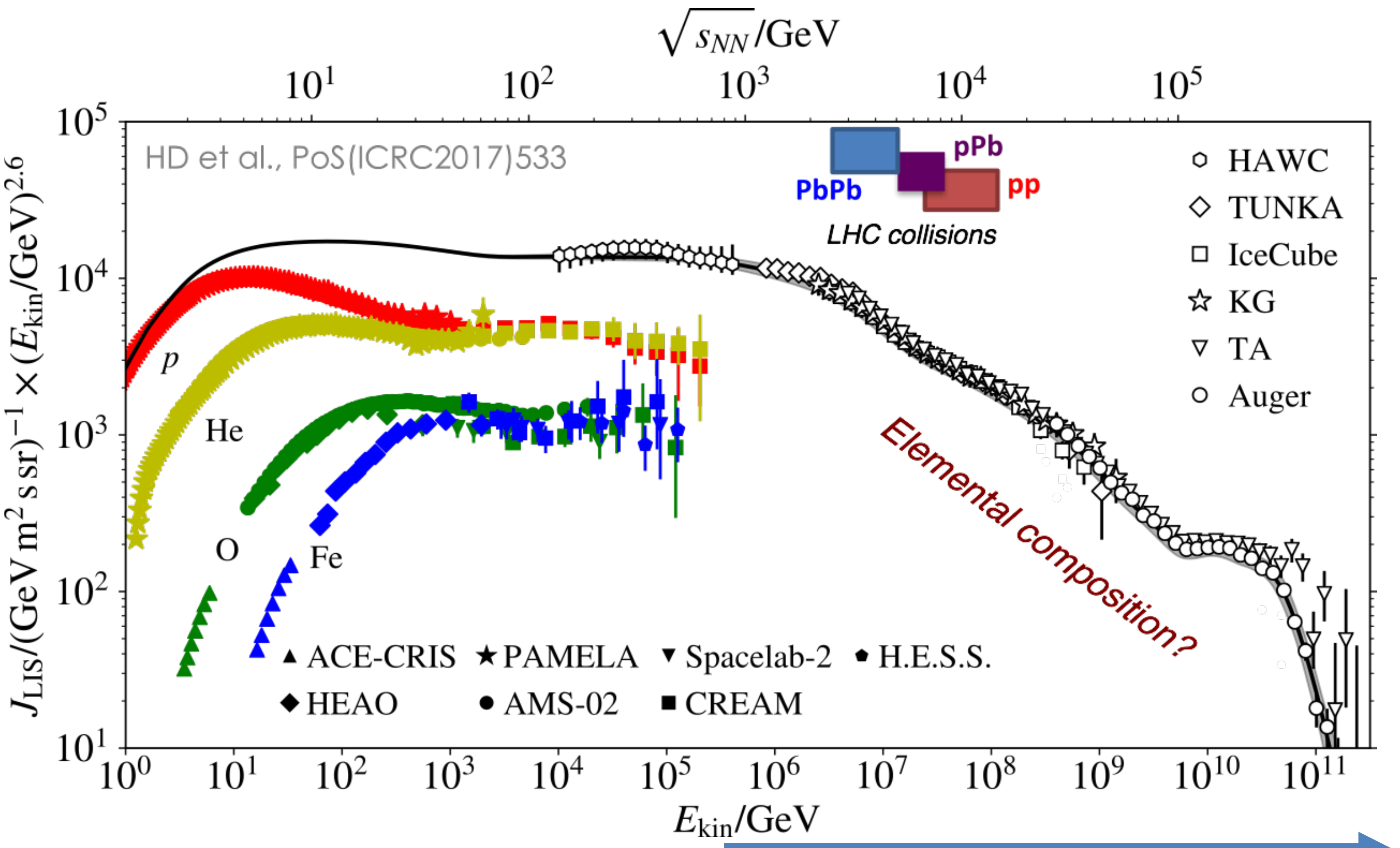
High-energy cosmic rays



Regime of air shower detection

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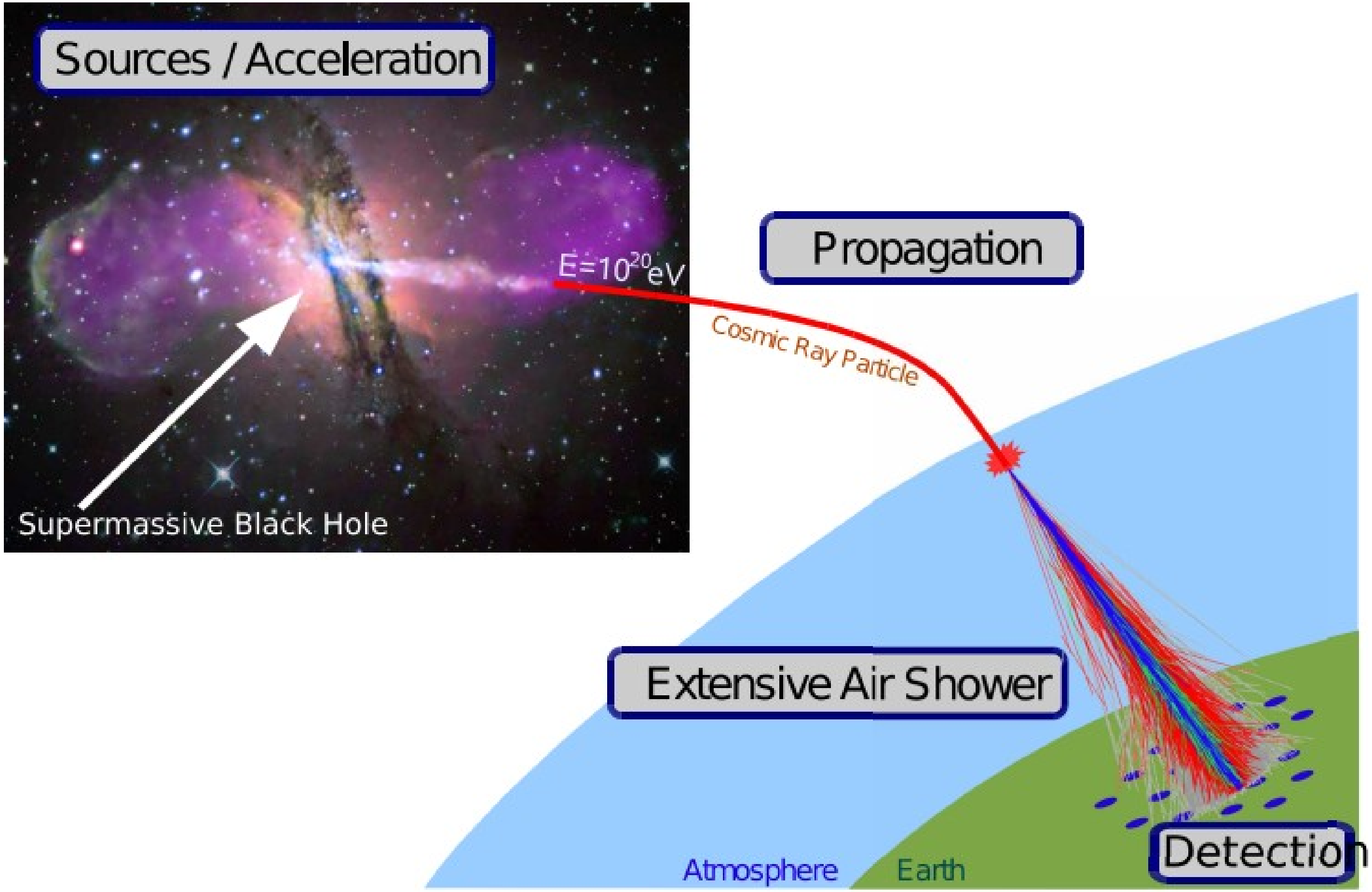
Big ultra-high cosmic ray questions



- What are they?
- Where do they come from?
- How do they interact?

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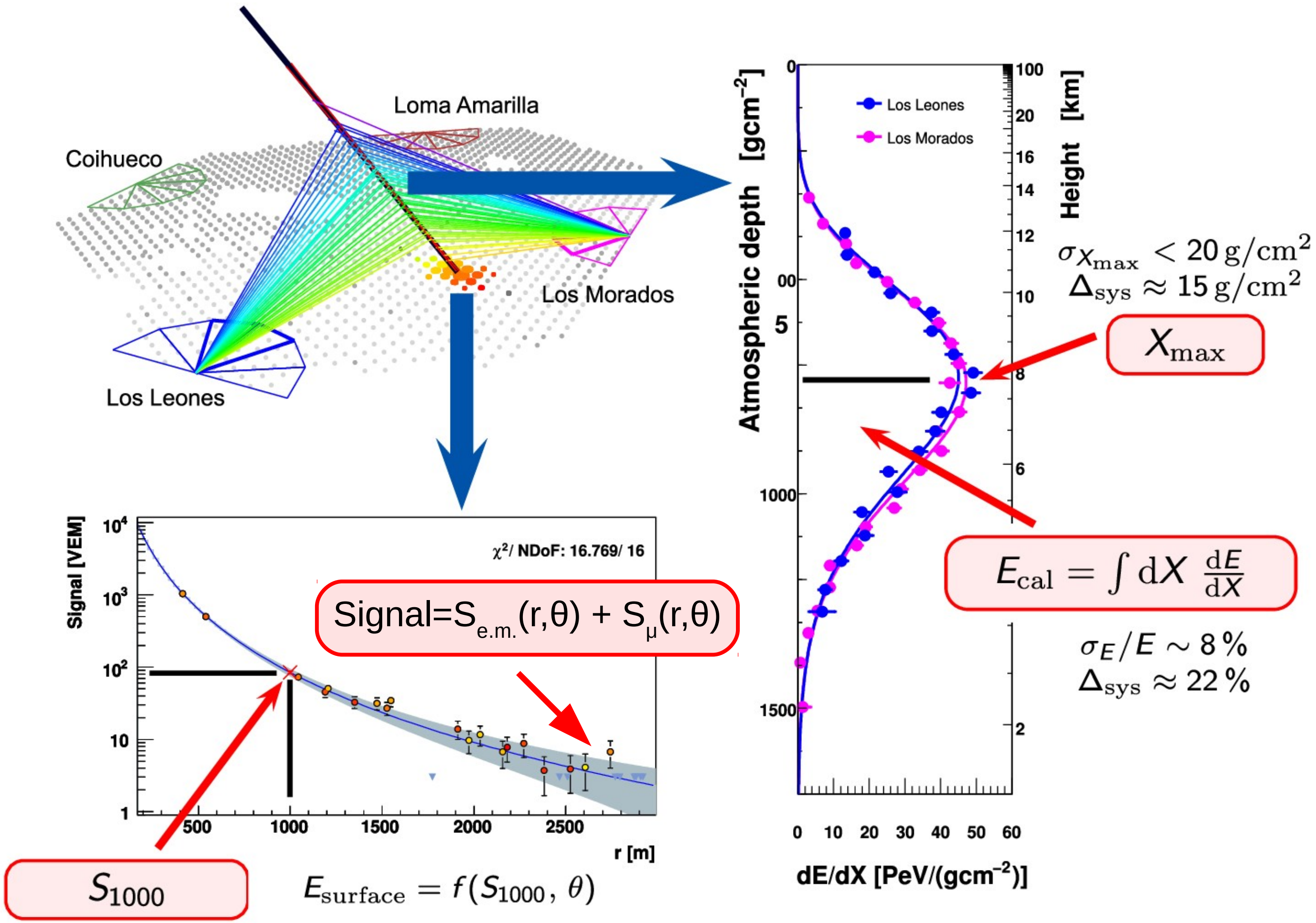
Air shower observables



Atmosphere as calorimeter

Telescopes measure dE/dX and timing

Surface detectors measure particle fluxes and timing

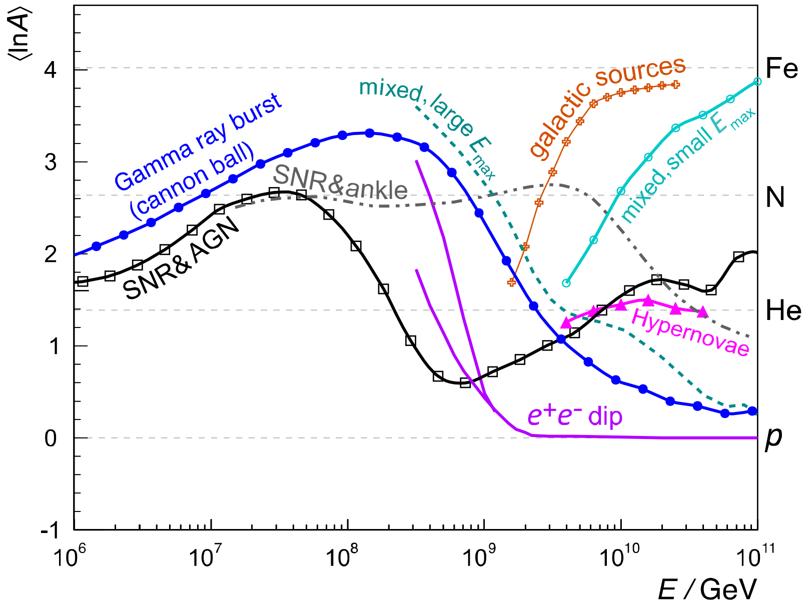
$$X_{max} \propto \ln\left(\frac{E_0}{A}\right)$$

$$E_0 = E_{cal} + E_{invisible}$$

$$E_0 \propto S_{1000}$$

$$N_\mu \propto S_\mu \propto \left(\frac{E_0}{A}\right)^\beta$$ (β~0.9)

Cosmic ray mass composition

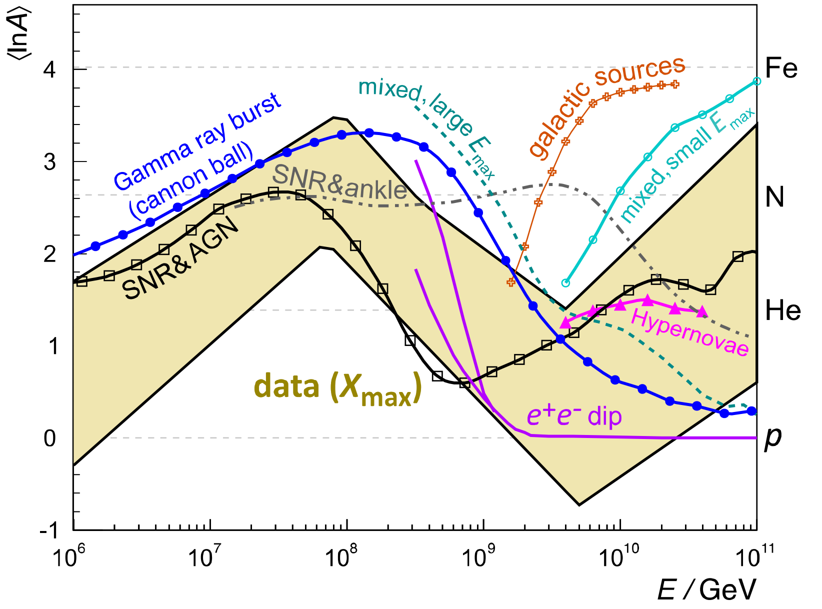


Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

Astrophysical models of cosmic rays?

- Mass composition (c.f. <ln A>) of cosmic rays carries imprint of sources and propagation

Cosmic ray mass composition

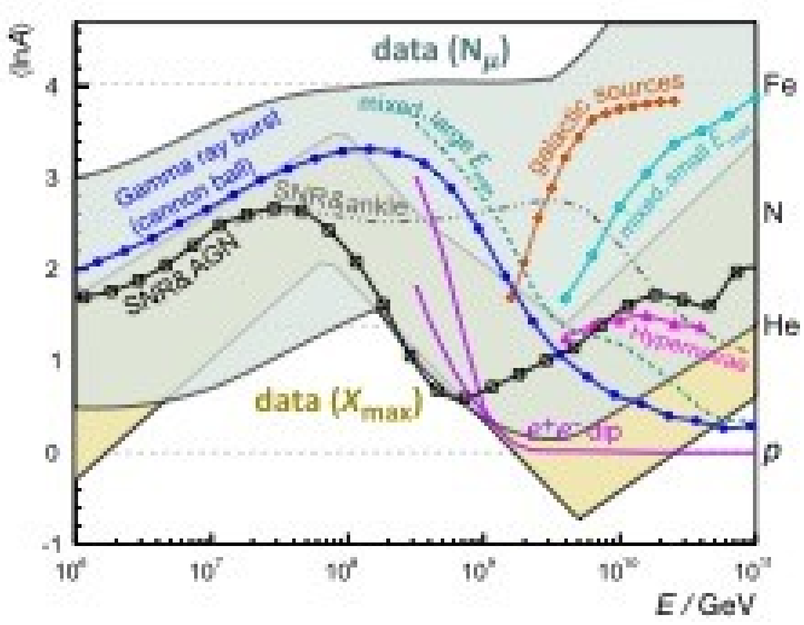


Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

Astrophysical models of cosmic rays?

- Mass composition (c.f. <ln A>) of cosmic rays carries imprint of sources and propagation
- Accuracy of <ln A> limited by uncertainty in description of hadronic interactions in air showers

Cosmic ray mass composition



Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

Astrophysical models of cosmic rays?

- Mass composition (c.f. <ln A>) of cosmic rays carries imprint of sources and propagation
- Accuracy of <ln A> limited by uncertainty in description of hadronic interactions in air showers
- **Muon mystery (I):** Muon predictions in air showers are inconsistent with X_{max}

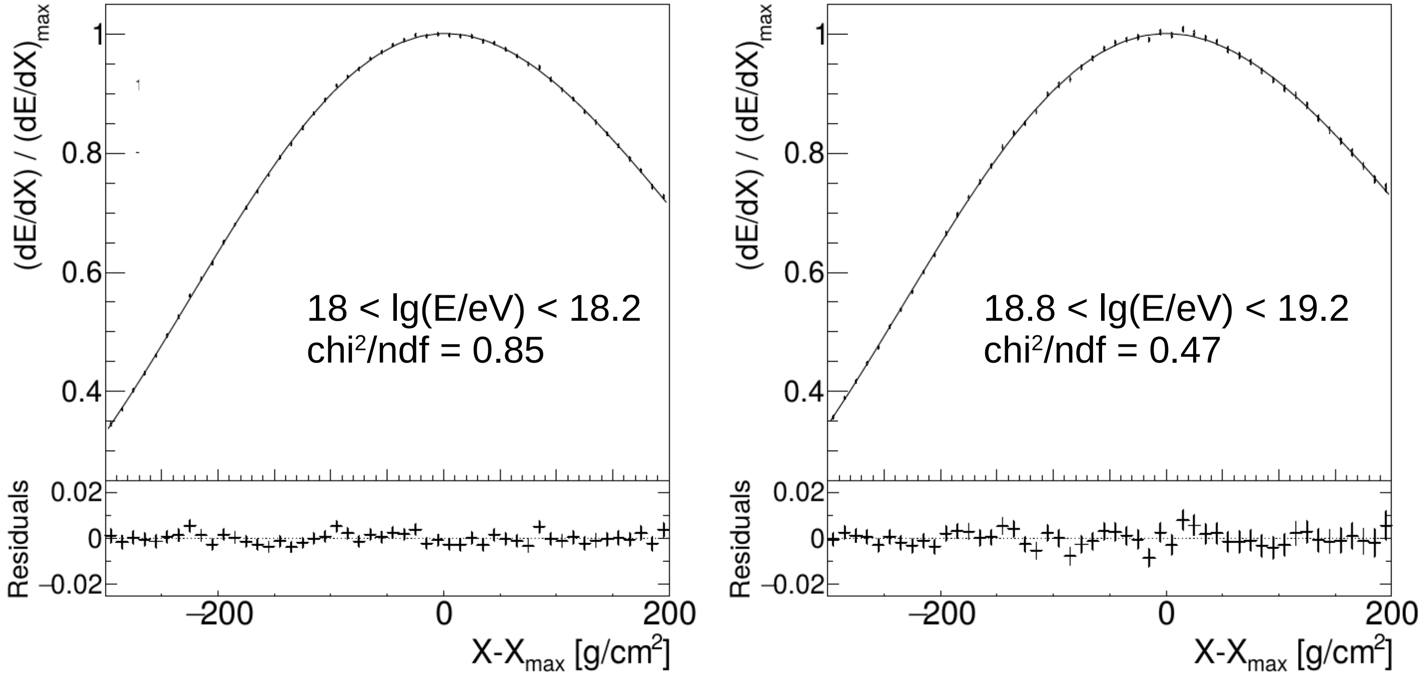
There is a general difficulty to predict muon production in air showers

Model dependence is large and not well understood

Average longitudinal dE/dX profile

Gaisser-Hillas function

$$f_{\mathrm{GH}}(X) = (\mathrm{d}E/\mathrm{d}X)_{\mathrm{max}} \left(\frac{X - X_0}{X_{\mathrm{max}} - X_0}\right)^{\frac{X_{\mathrm{max}} - X_0}{\lambda}} \exp\left(\frac{X_{\mathrm{max}} - X}{\lambda}\right)$$



Transformation

$$R = \sqrt{\lambda/|X_0'|}$$

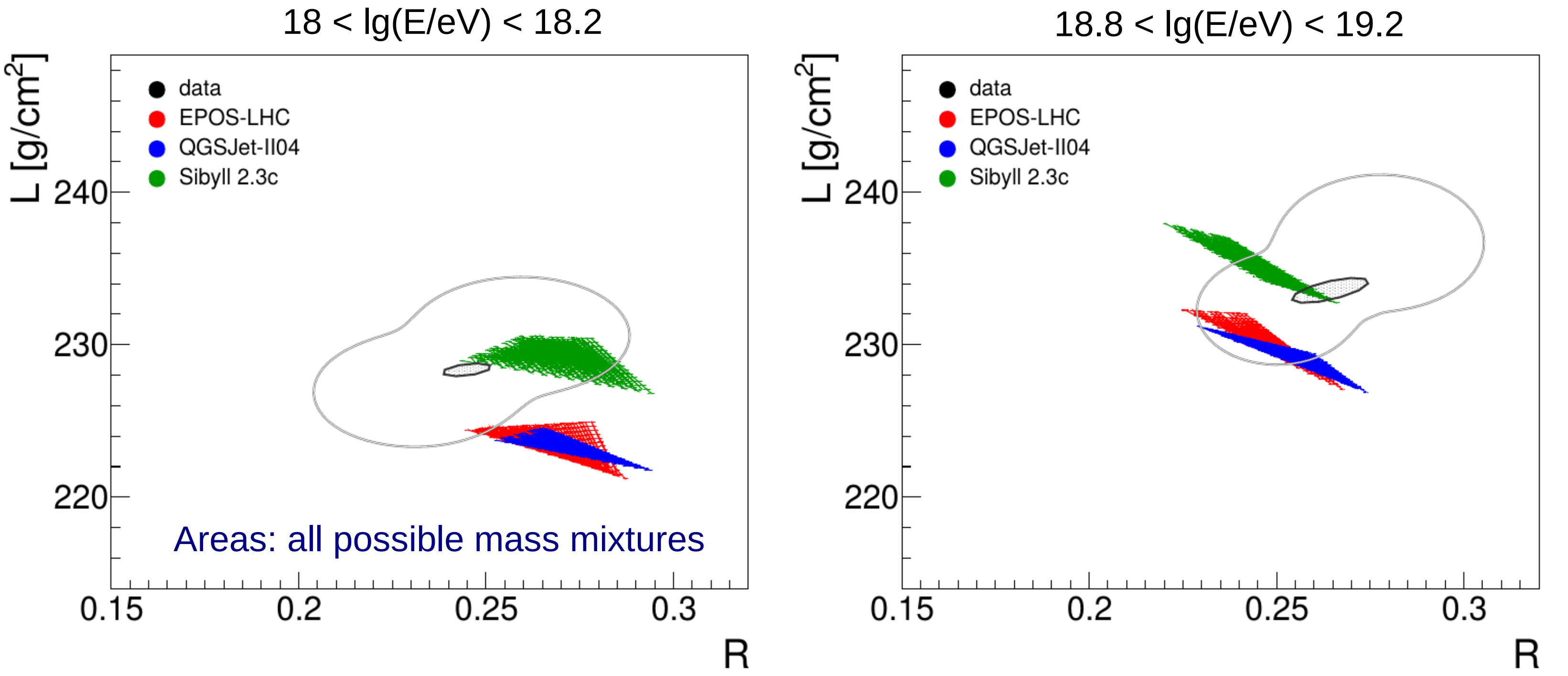
$$L = \sqrt{|X_0'|\lambda}$$

$$X_0' = X_0 - X_{\mathrm{max}}$$

$$(\mathrm{d}E/\mathrm{d}X)' = \left(1 + R\,\frac{X'}{L}\right)^{R^{-2}} \exp\left(-\frac{X'}{R\,L}\right)$$

JCAP 03 (2019) 018

Longitudinal shower development



Remarkable: shape of dE/dX profiles becomes sensitive to mass and models

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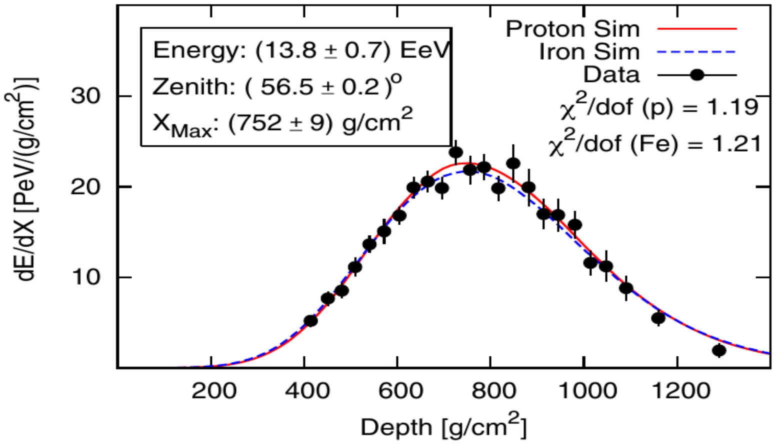
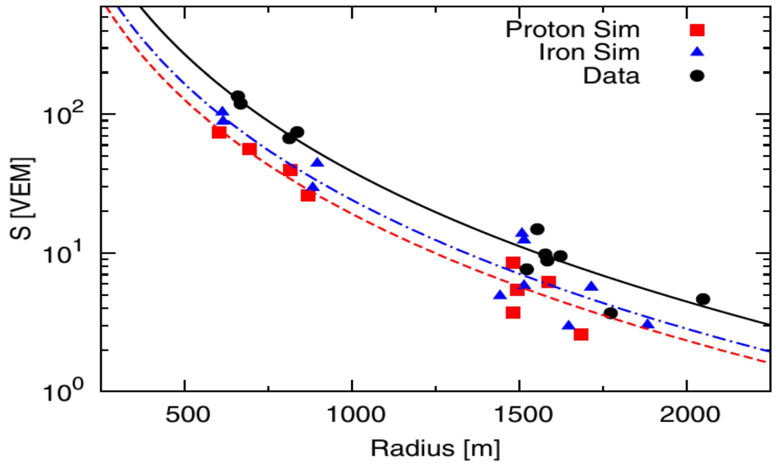
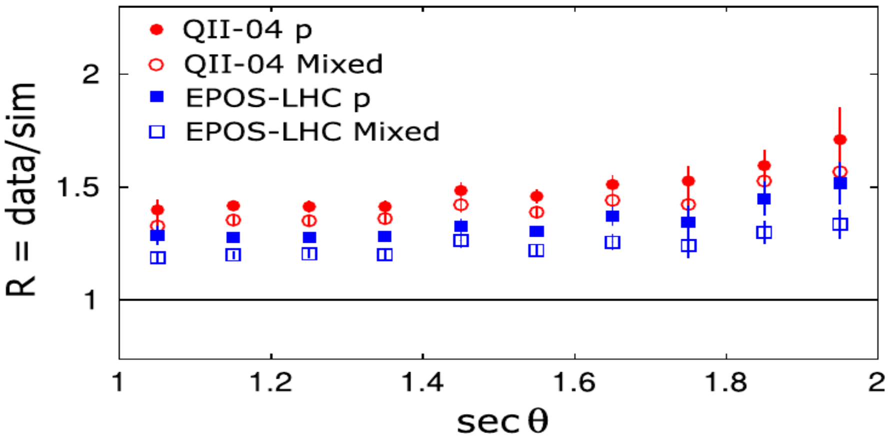
Signal deficiency at ground level





Attempt of consistent description of longitudinal and lateral shower data

… **fails**



Problems become worse at higher zenith angles

PRL 117, 192001 (2016)

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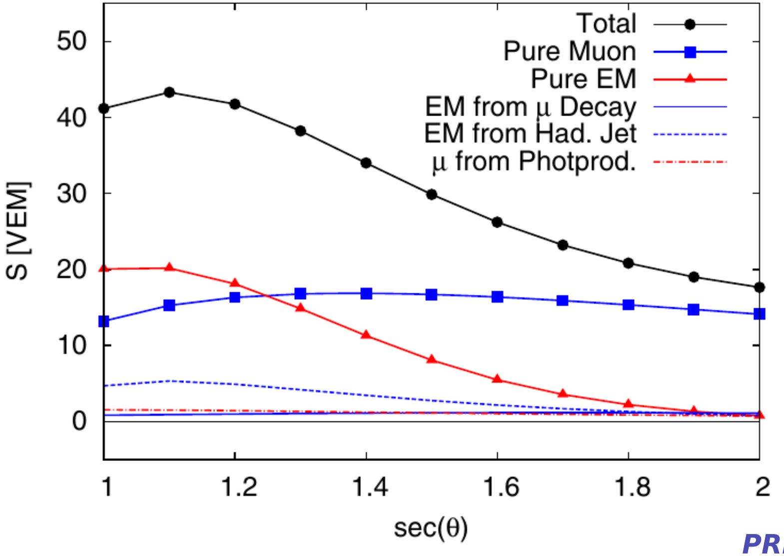
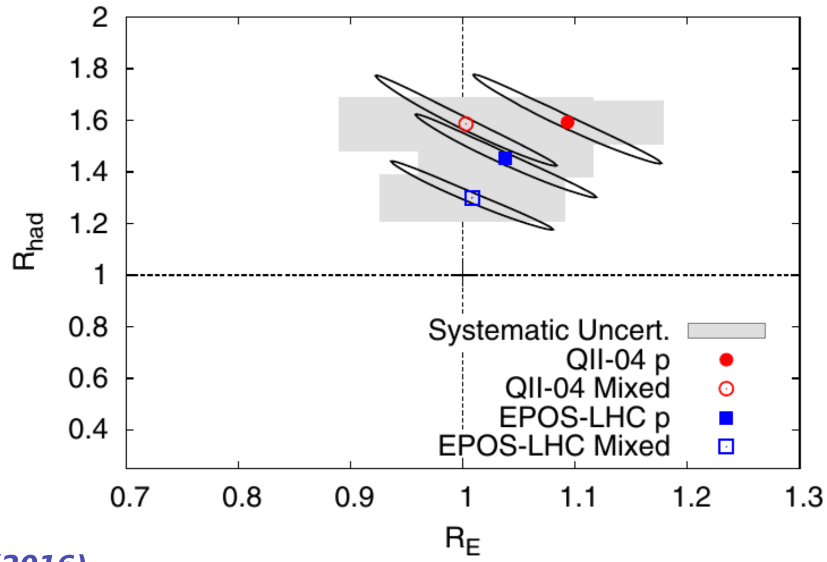
Hadron/Muon component in data is too large





PRL 117, 192001 (2016)

- Scale E.M. and had. part of MC showers by R_E and R_{had} to fit data:

$$S_{resc}(R_E, R_{had}) = R_E\, S_{EM} + R_{had}\, R_E^{\alpha}\, S_{had}$$

- While R_E = 1 is possible and mostly consistent with data
- R_{had} is significantly above 1
- None of the models/assumptions reproduces data

→ myon mystery (II)

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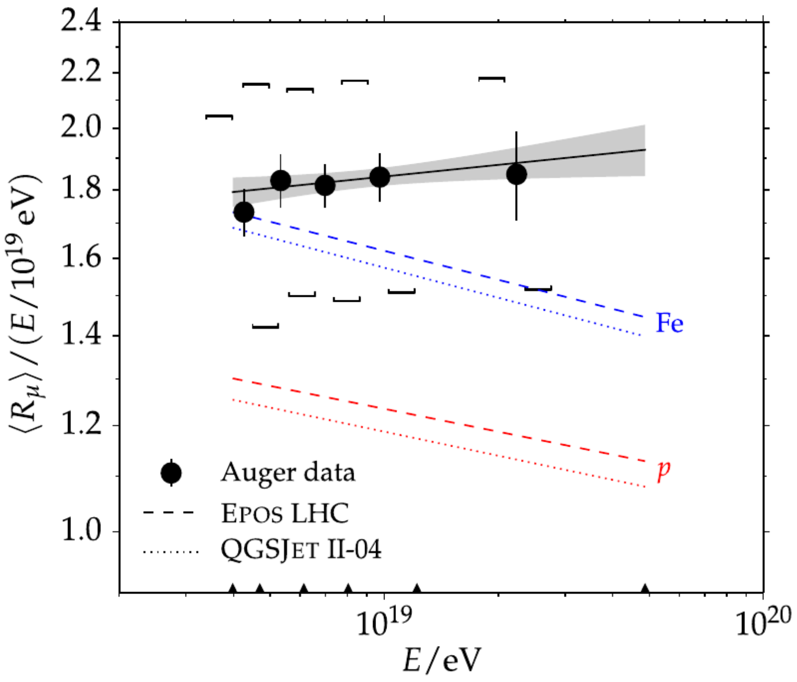
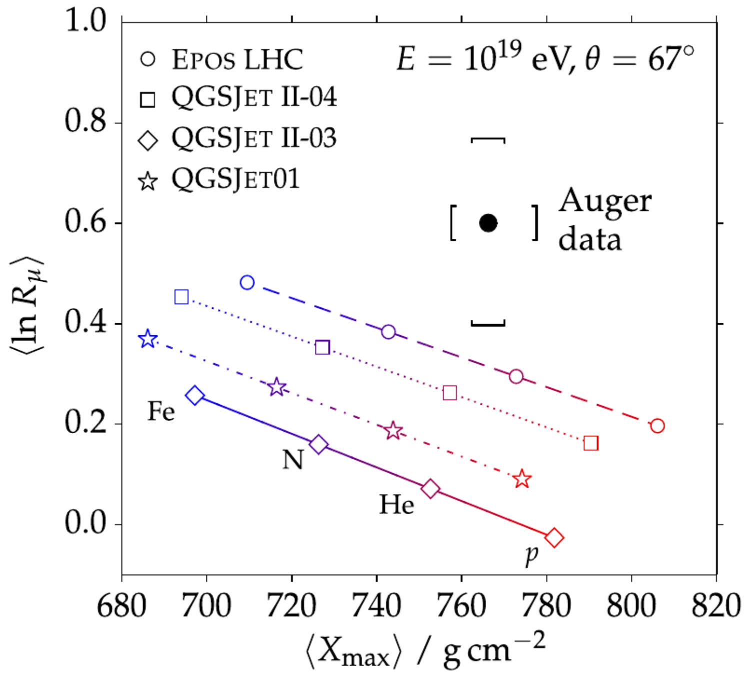
Muon content at ground level

Inclined showers: 62 – 80 deg

→ electromagnetic component is ~absorbed



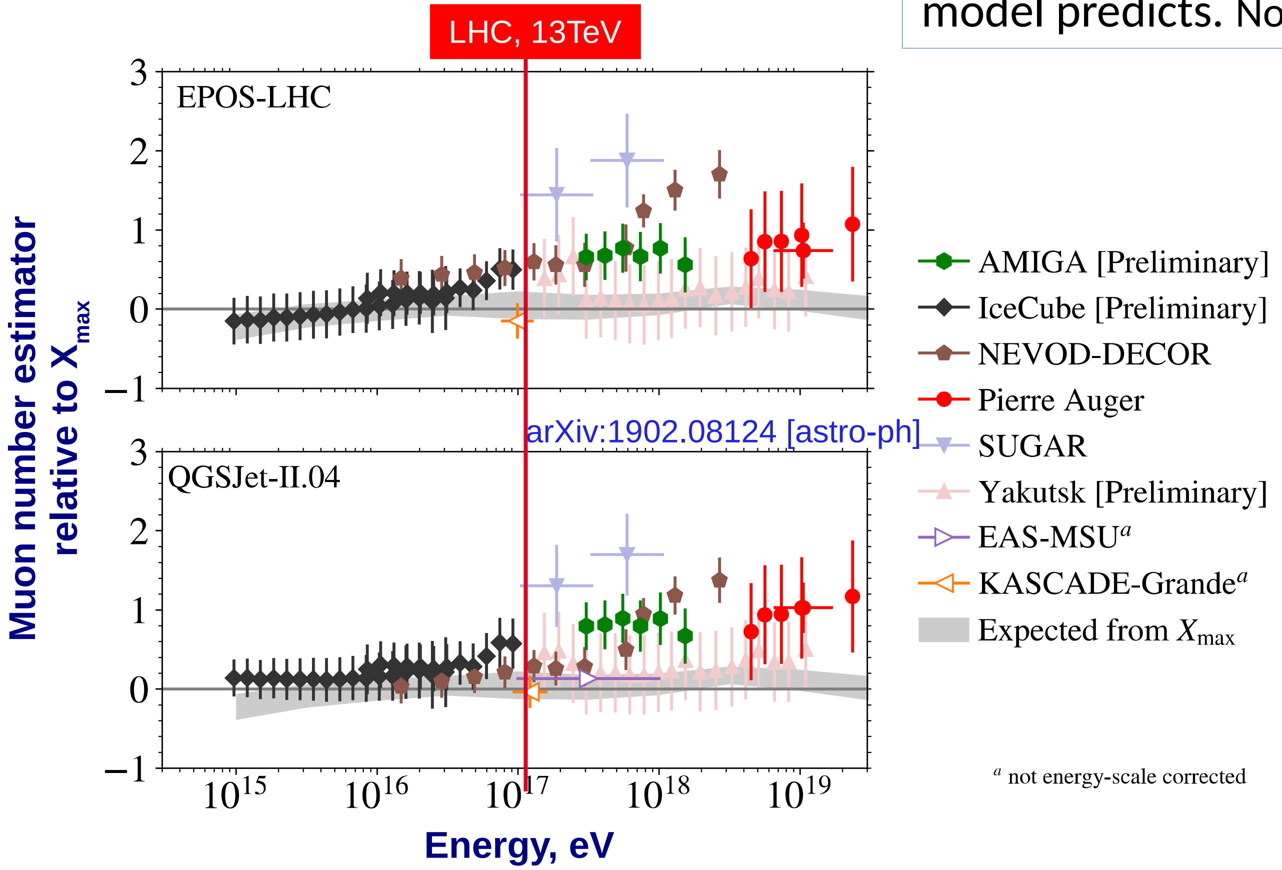


myon mystery (II)

Phys. Rev. D 91 (2015) 032003

Muon mystery (III)

Muon number **rises faster with energy** than any model predicts. Non-zero positive slope at **8σ** significance



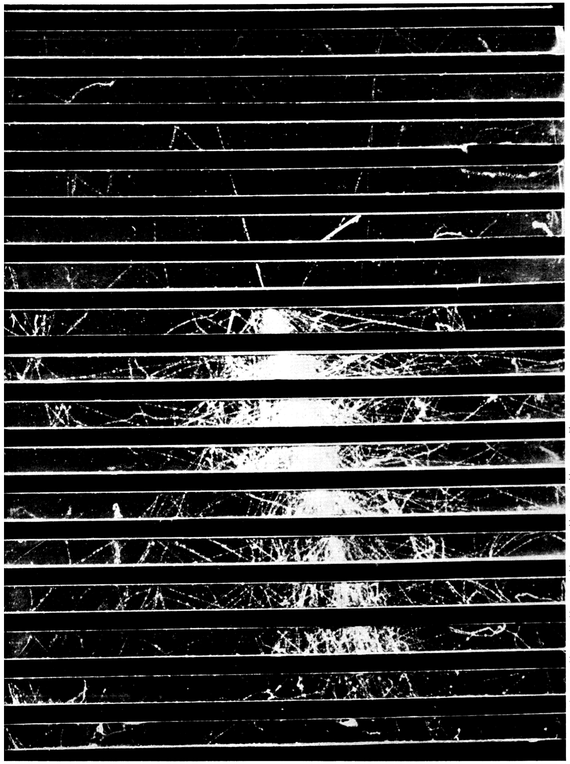
What are we observing here?

- Collective effects?
  arXiv:1902.09265 [hep-ph]
- Strange fireball?
  PRD 95 (2017) 063005
- Exotic physics?
  arxiv:1307.2322 [astro-ph]
- ???

→ **unsolved !**

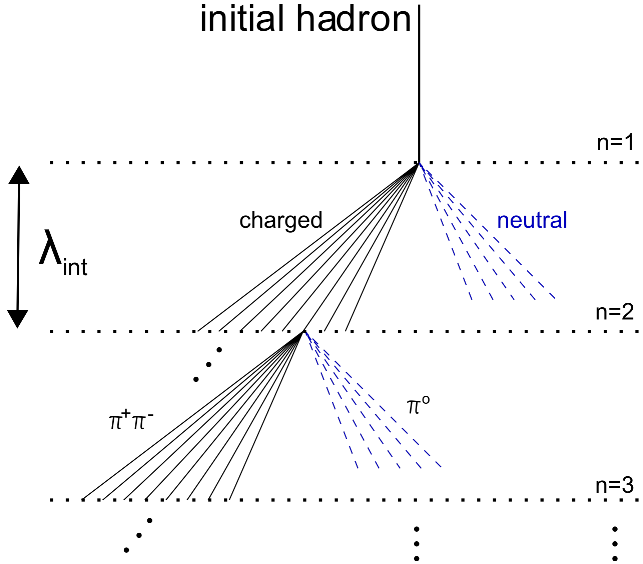
- Converted very different muon measurements to universal **z-scale**
- Cross-calibrated energy scales of experiments by matching all-particle fluxes

Air shower cascades



10 GeV proton in cloud chamber with lead absorbers at 3027 m altitude

Heitler-Matthews model of air shower



Cascade stops after O(10) steps (energy-dependent)
Pions/Kaons decay into GeV **muons** at the end of cascade

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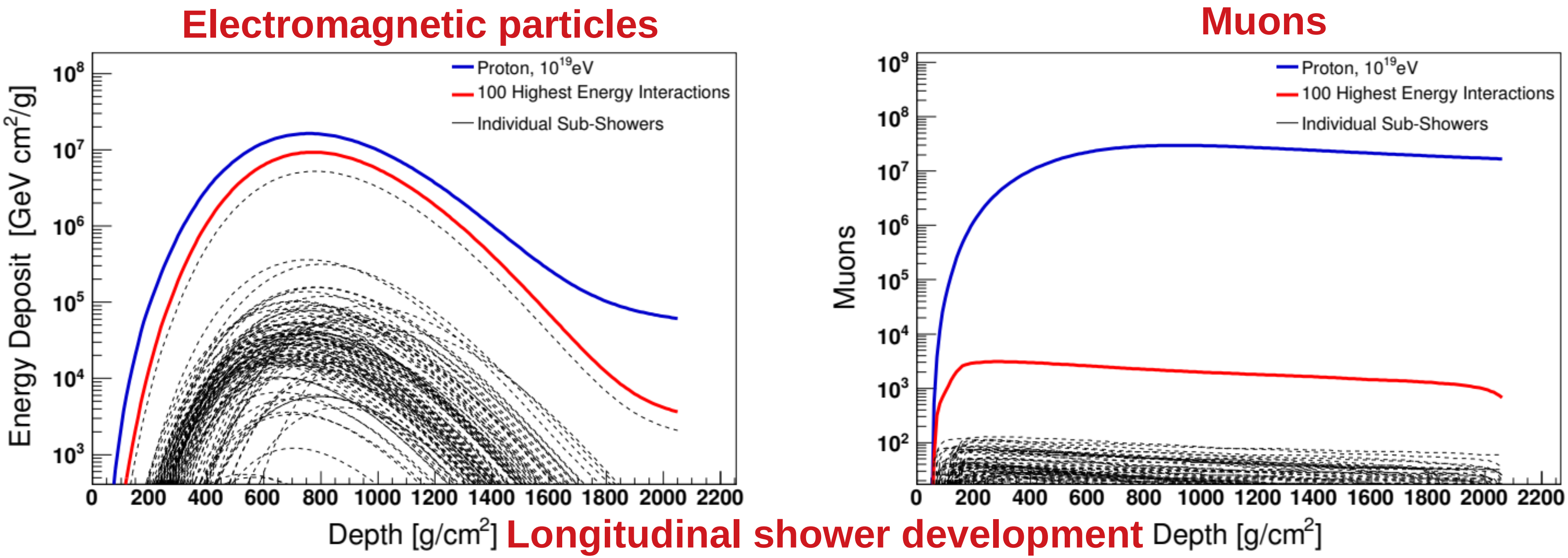
Air shower physics



- Electromagnetic shower features are very sensitive to **high-energy interactions**
- Muon observables are a **magnifying glass** into small features of interactions over a wide energy range. Consider 10 shower generation: **Total effect ~ effect^{10}**

  → 50% on muon number ~ 4% per interaction

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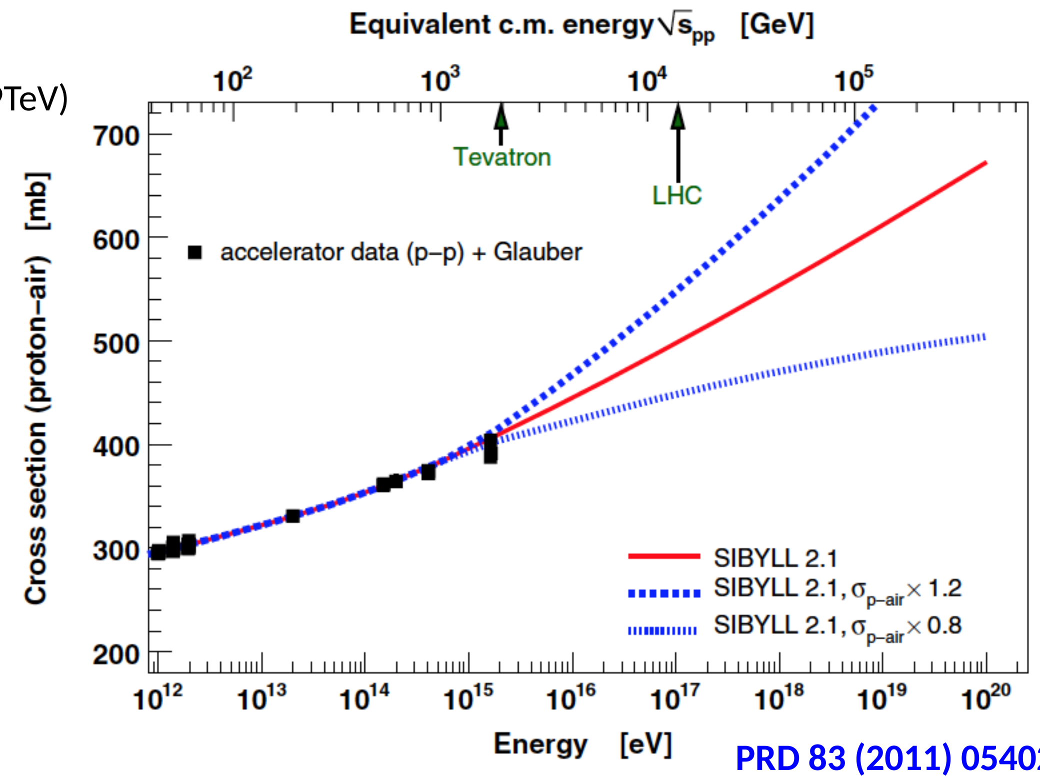
Modify hadronic interaction features

Ad-hoc modify features at LHC energy scale with factor $\boldsymbol{f_{LHC\text{-}pO}}$ *and extrapolate up to* 10^{19} *eV proton shower*

(with $f_{LHC\text{-}pO}$*: relative effect strength in LHC pO collisions at 9TeV)*

Modified features

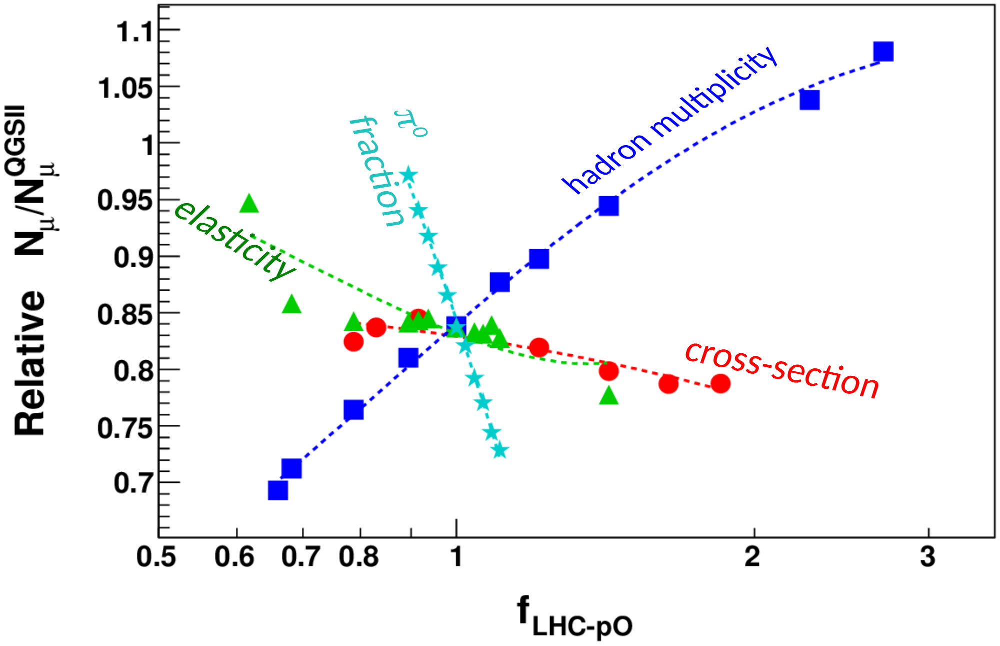
- **cross-section**: inelastic cross-section of all interactions
- **hadron multiplicity**: total number of secondary hadrons
- **elasticity**: $E_{leading}/E_{total}$ (lab frame)
- $\boldsymbol{\pi^0}$ **fraction**: (no. of π^0) / (all pions)



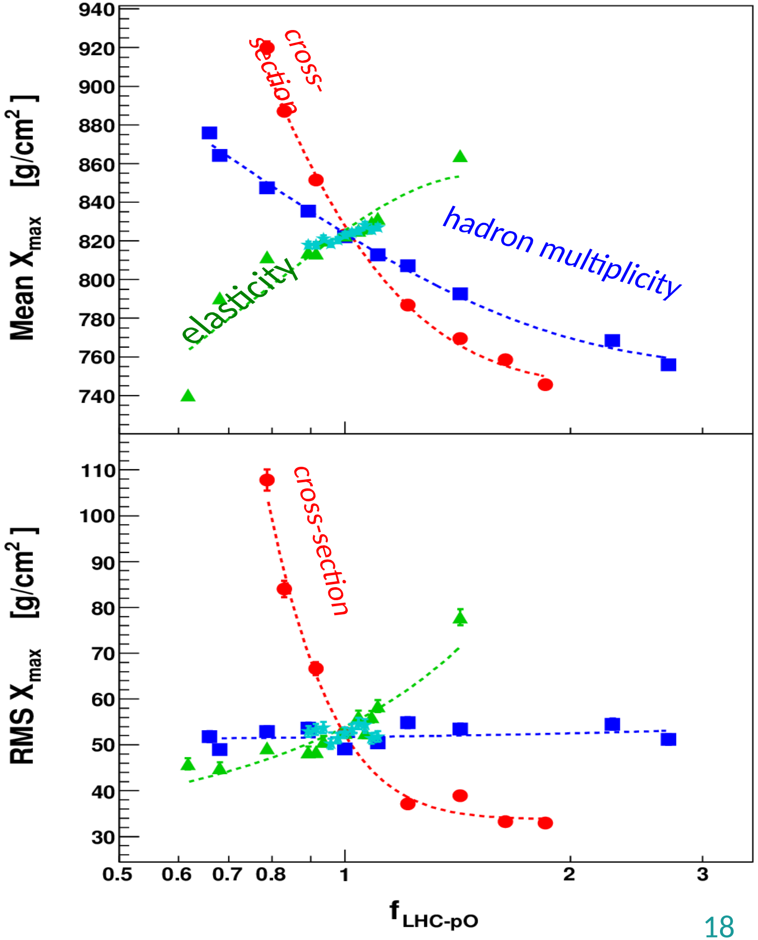
PRD 83 (2011) 054026

Importance of interaction features

Muons



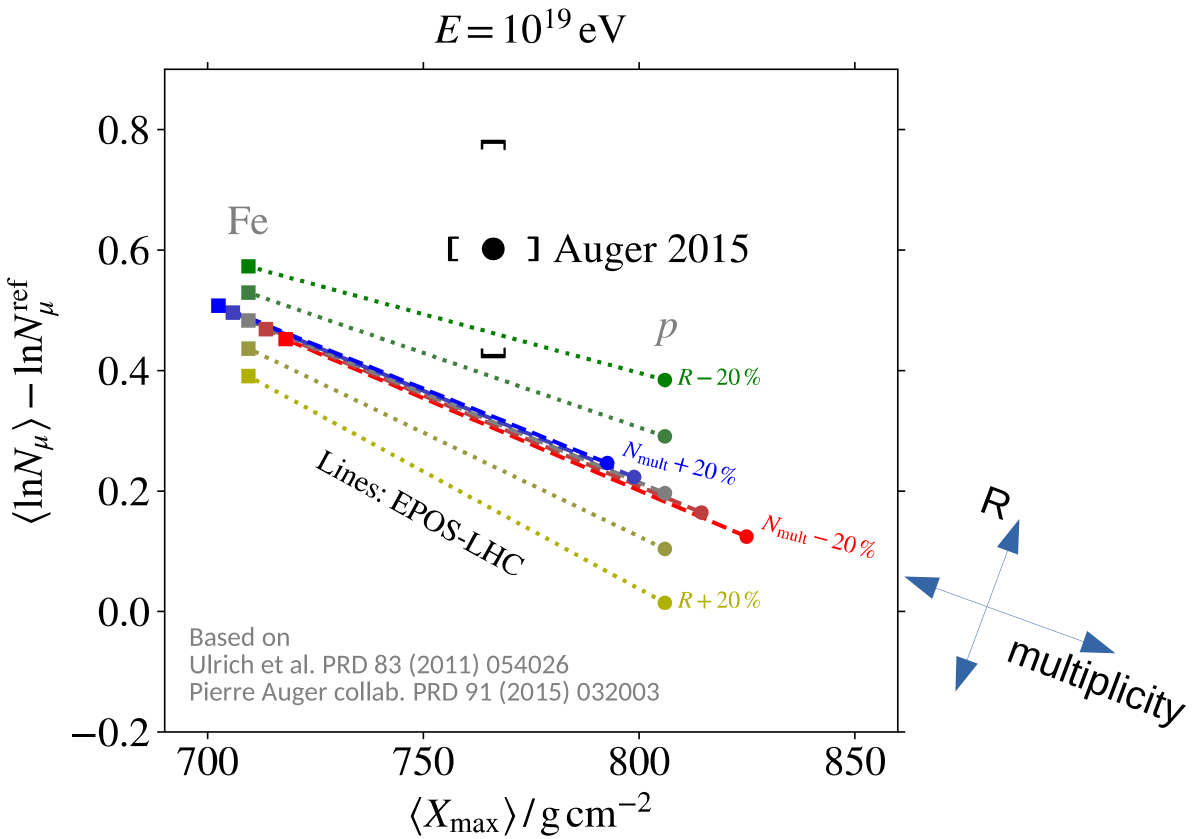
Electromagnetic particles



Large impact on muon number

- Neutral pion fraction
- Hadron multiplicity

Projected impact of changes



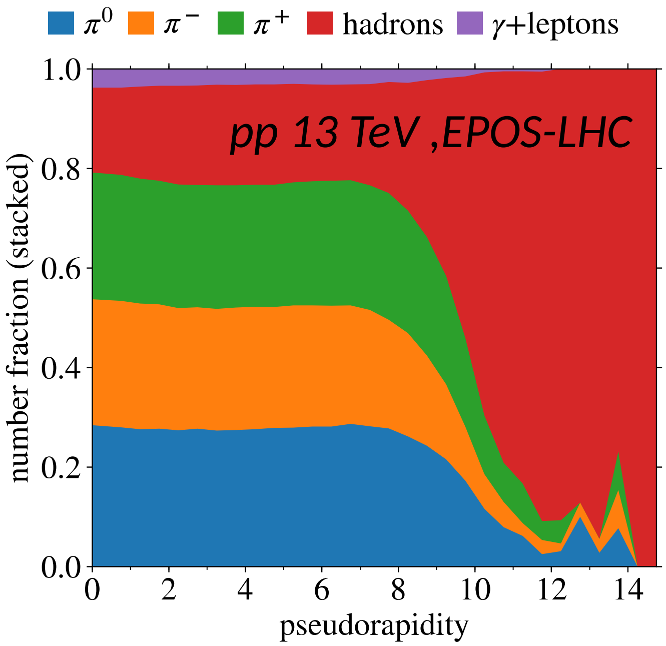
- Changing hadron multiplicity does not solve muon puzzle

- Need to change energy fraction R of neutral pions

$$R = \frac{\sum E_{\pi^0}}{\sum E_{\text{long-lived hadron}}}$$

Possibilities to reduce R

- Nuclear effects are very important for air shower phenomology
  D'Enterria, T. Pierog, G. Sun, Astrophys.J. 874 (2019) 152
- Are collective nuclear effects in πN or πO collisions reducing R?

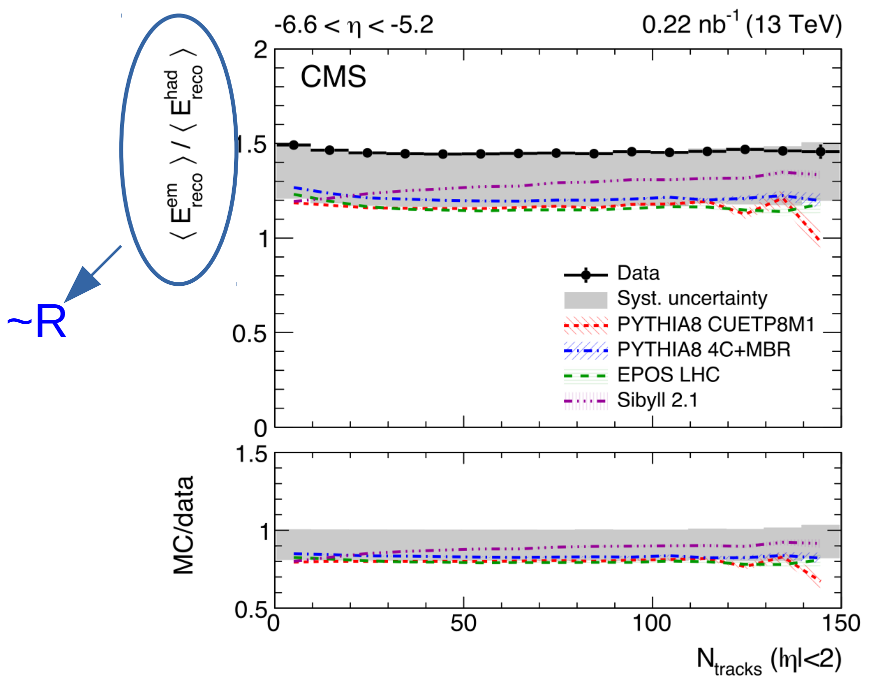


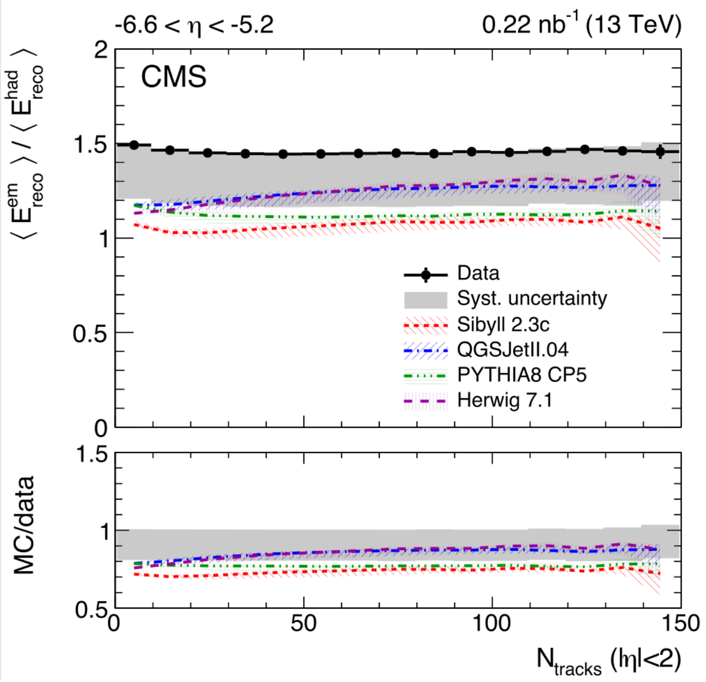
Collective effects may reduce pion fraction, EPOS-LHC predicts drop in *R* at eta = 0
https://arxiv.org/pdf/1902.09265.pdf

QGP in air showers could enhance strangeness production, reducing pion fraction
https://arxiv.org/pdf/1612.07328.pdf

Enhancement of strangeness observed in central collisions in *pp*, *p*Pb
ALICE, Nature Phys. 13 (2017) 535

...or is R already too low?

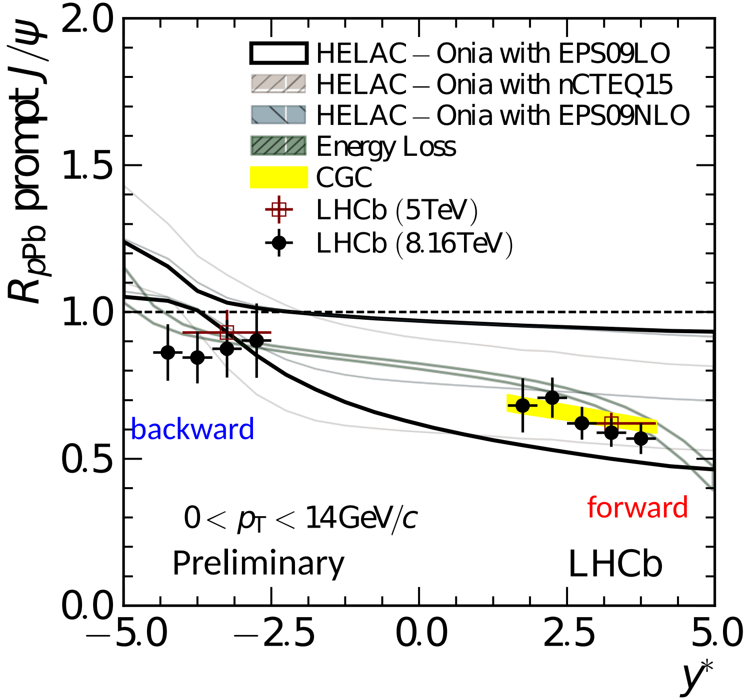


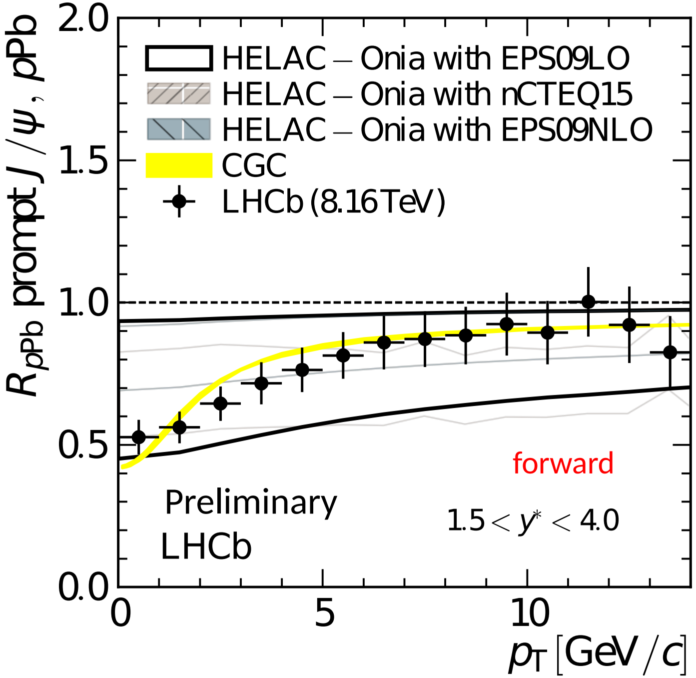


CMS, Eur.Phys.J. C 79 (2019) no.11, 893

- CMS measurements give higher R than models for 5.2 < |eta| < 6.6
- Models should have higher *R* and then would yield even fewer muons!
- But this is in *pp*, what about ***p*O**?

Nuclear effects in prompt J/Ψ production





LHCb, Phys. Lett. B 774 (2017) 159

- Up to 50 % suppression in forward direction
- Especially strong where relevant for CR!
- But: how in pO collisions?

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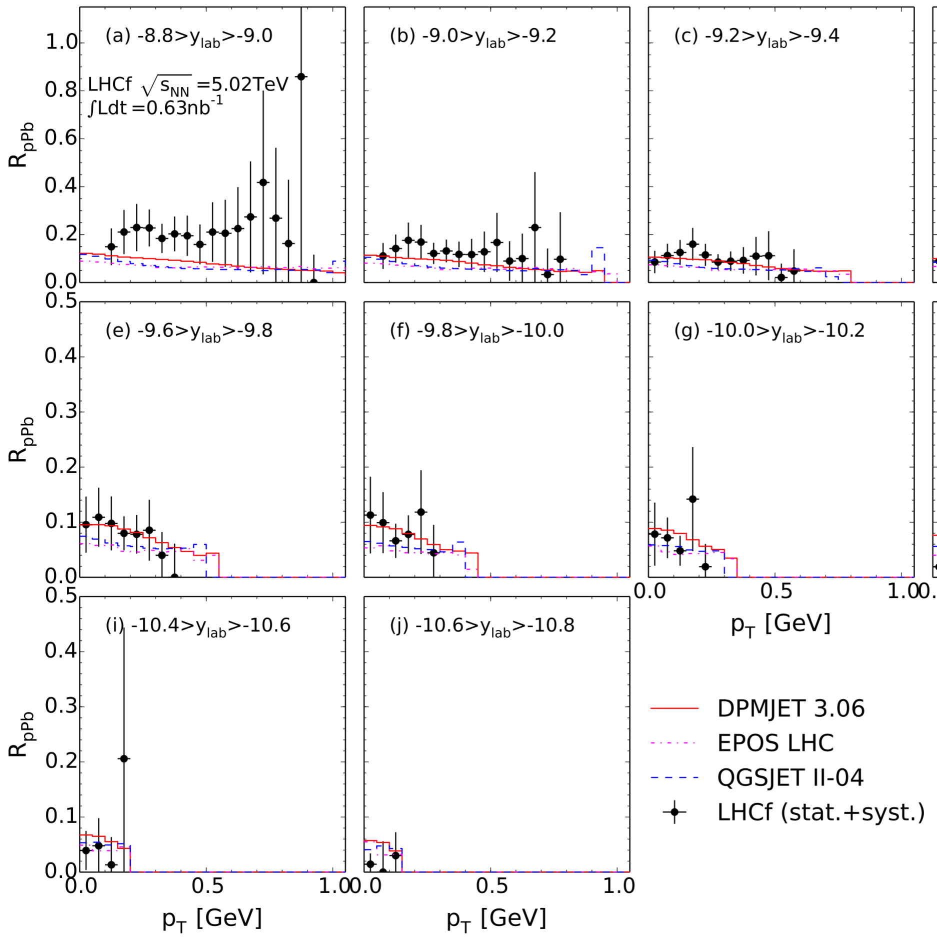
Nuclear effects in π^0 production



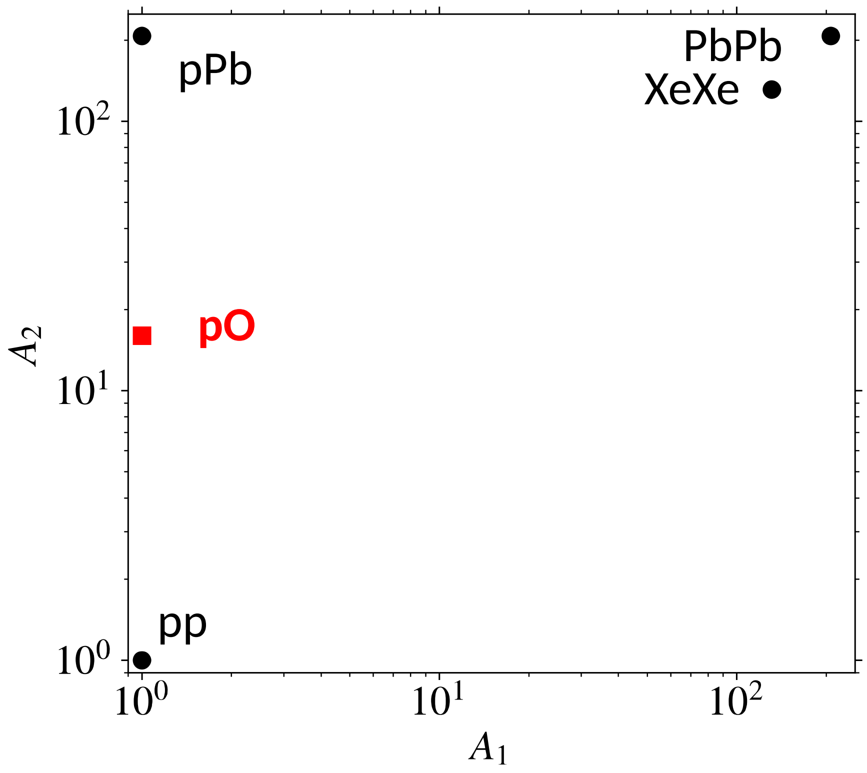
Very strong nuclear effects for π^0 production in far forward

But: How much in pO collisions?

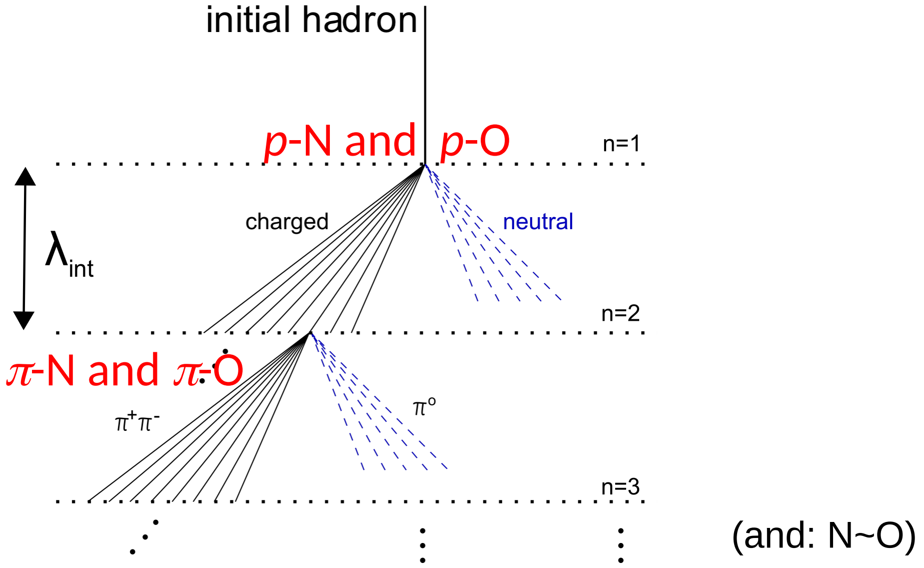
LHCf, Eur. Phys. J. C (2013) 73:2421

Proton-oxygen collisions at the LHC

Collision systems at the LHC



Collision systems in air showers



- Only proton-oxygen collisions mimic interactions in air showers
- Need pp, pPb, and **pO** to understand nuclear effects

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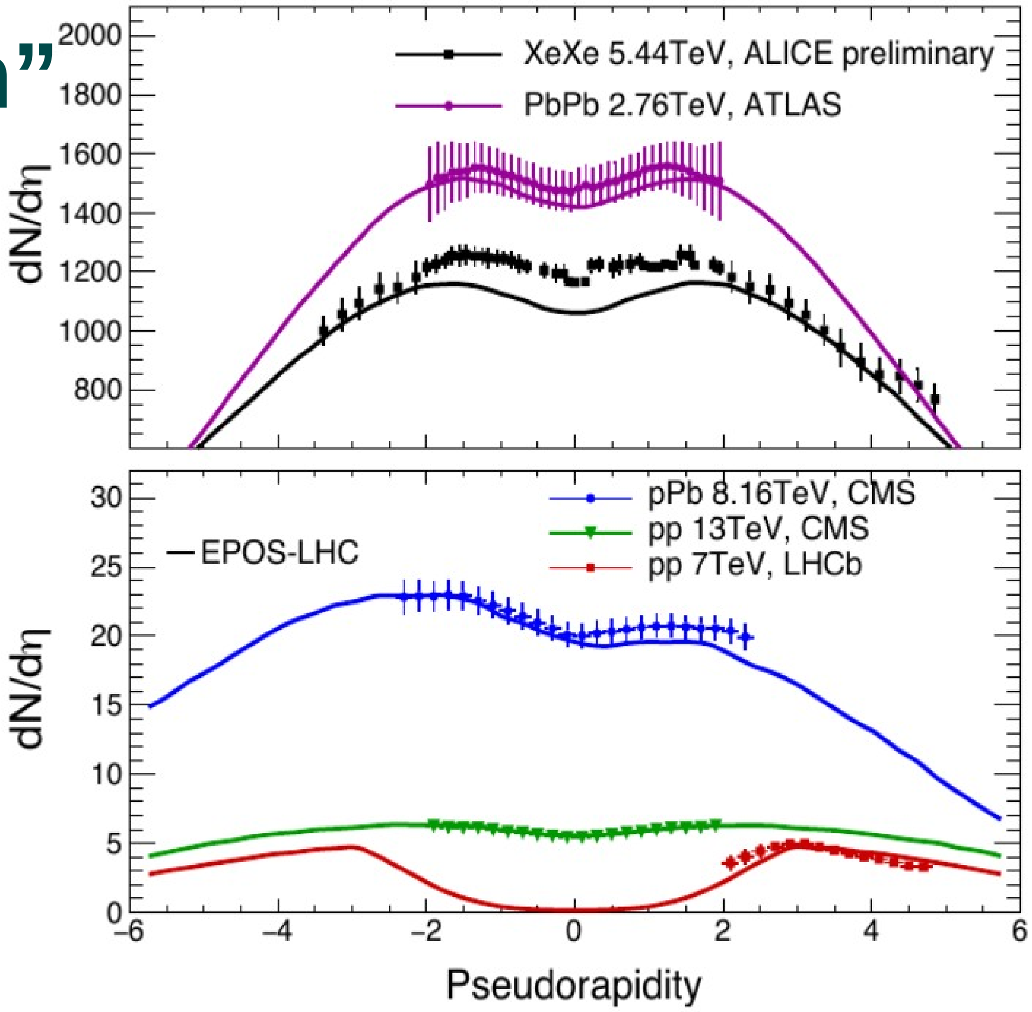
Nuclear “interpolation”

- Interpolation in A does not work well, system differences are too large
- X_{max} sensitive to **cross sections**, hadron multiplicities
- Muons sensitive to multiplicity, **e.m./had ratios, π^0 production**
- **Nuclear modifications in forward-direction** expected and relevant



ALICE Xe-Xe arXiv:1807.09061; ATLAS Pb-Pb arXiv:1504.04337; CMS p-Pb arXiv:1710.09355v2; CMS p-p arXiv:1507.05915v2; LHCb p-p arXiv:1402.4430

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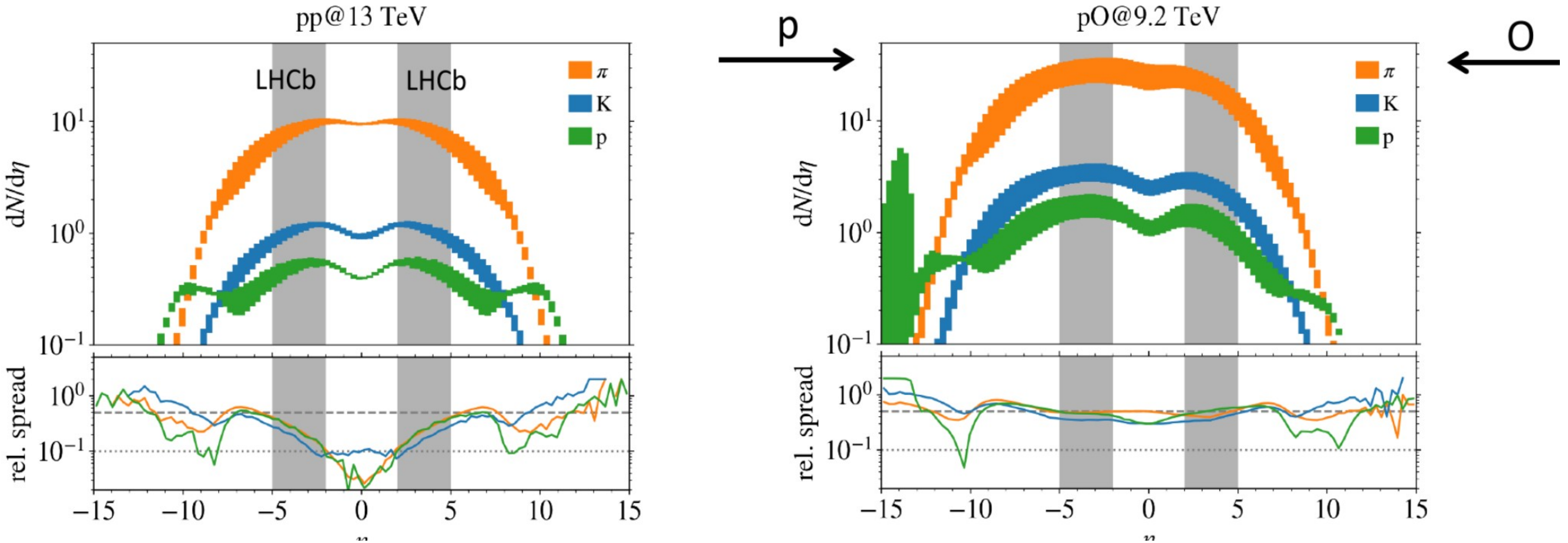
Tuning matters – and depends on data

Shown is spread between EPOS-LHC, QGSJetII.4 and SIBYLL 2.3



Models mostly tuned to p+p data at |η| < 2: p+p 10 % model spread, **p+O 50 % model spread**

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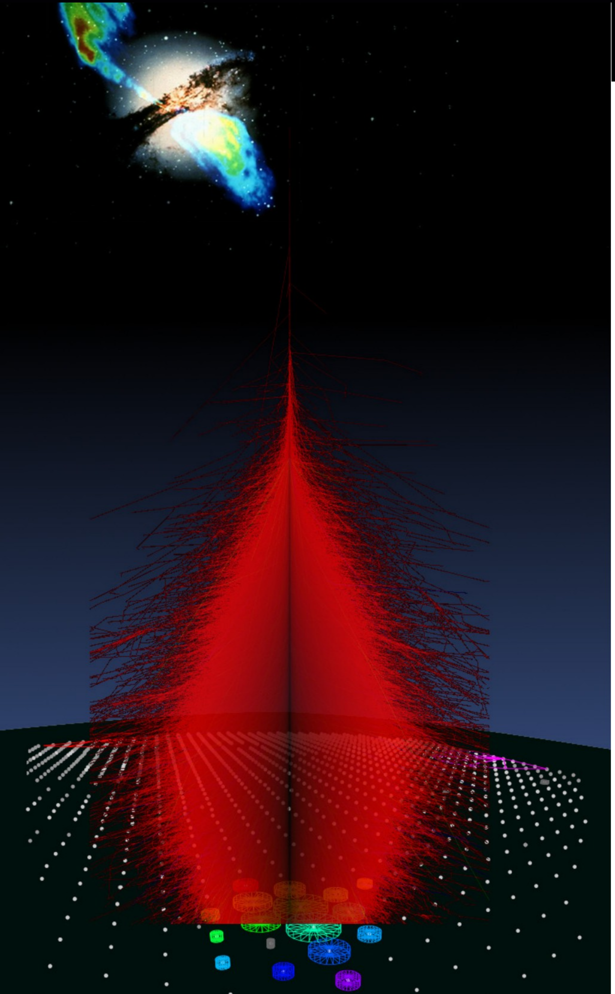
Proposed LHC schedule for Run 3

Z. Citron et al., CERN-LPCC-2018-07

Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-1}
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

- one week can be enough to push uncertainties to <~5% (→ Auger)
- 2 nb^{-1} (10 x minimum) will also allow to measure charm (→ IceCube)
- Latest planning moved oxygen-week to **2023**

Summary



- Muon Puzzle in air showers experimentally established
  - Statement by eight leading air shower experiments (8σ)
- Problem not in the data, theory has to change
  - None of the hadronic interaction models reproduces muon data (neither pre- nor post-LHC)
  - Suggests common missing QCD effect, perhaps QGP-related?
- pO and OO collisions planned for 2023
  - Probably 2 nb^{-1} of pO
  - Data should be analyzed by **ALICE**, **ATLAS**, **CMS**, **LHCb** and **LHCf**
- Key forward measurements to be done at the LHC
  - In pp, pPb, and pO
    - Energy ratio *R* of π^0 to long-lived hadrons at forward rapidity
    - Production cross-sections for π^0, $\pi^{+/-}$, K, *p*
  - Precise measurements needed to 5 % or better