The Muon Puzzle in Cosmic Ray Induced Air Showers and possible solutions

Hans Dembinski, TU Dortmund

Overview

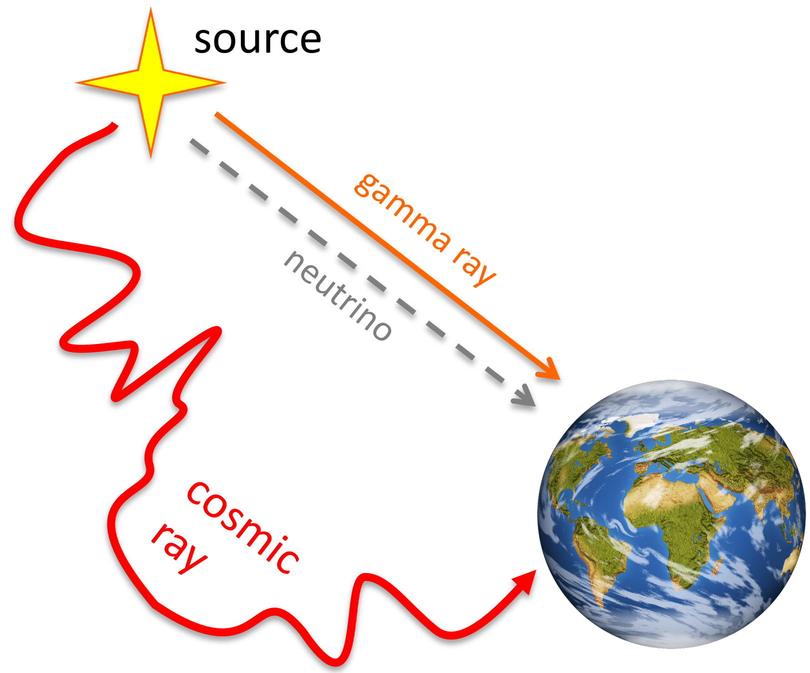
- Muon Puzzle in high-energy cosmic rays
  - Cosmic rays induce air showers in atmosphere
  - Need to understand air showers
    - To narrow down source candidates of high-energy cosmic rays
    - Predict atmospheric background for neutrino and gamma ray observatories
  - Muon production not correctly described in simulations (8σ offset)
  - Experimental proof through unprecedented international collaboration of eight air shower experiments

- Muon Puzzle suggests mismodeling of soft-QCD
  - Soft-QCD is based on phenomenology, typically Gribov-Regge theory
  - Muon Puzzle suggests "new physics": QGP formation in small systems
  - Study forward hadron production in *pp*, *p*-Pb, and *p*-O at highest energies available at LHC
    - Light hadron production important
    - Nuclear effects important
    - Ratio of electromagnetic and hadronic energy flow is a key variable

Astroparticle physics

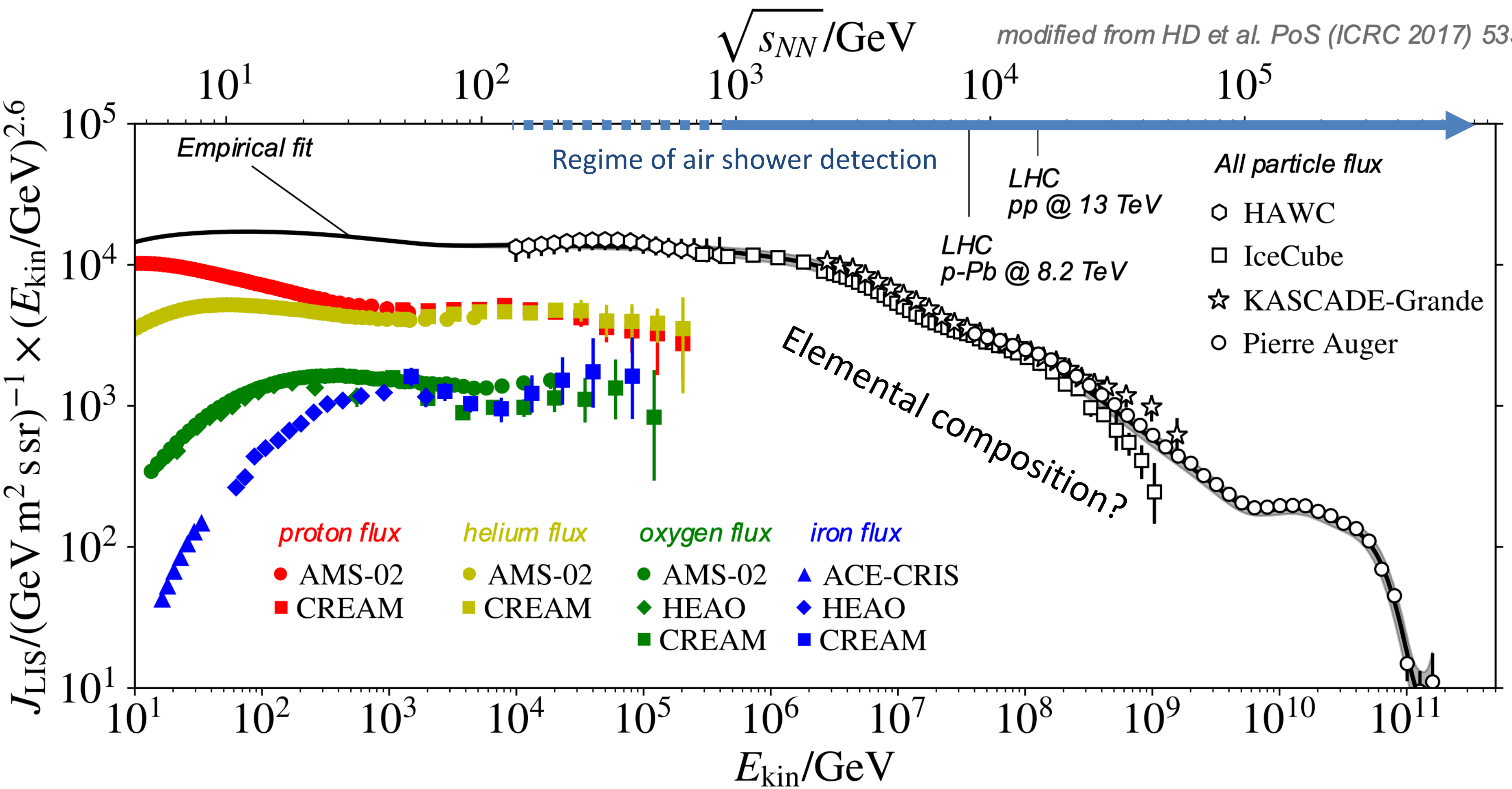
- Astroparticles are messengers of high-energy non-thermal universe
  - Black holes and neutron stars formation and exotics: dark matter decay…
- Messengers
  - Gamma rays
    - Pointing ☺
    - Abundant ☺
    - $E_{max} \sim 100$ TeV ☹
  - Neutrinos
    - Pointing ☺
    - Rare ☹
    - $E_{max} > 10^{11}$ GeV ☺
  - Cosmic rays (nuclei)
    - No pointing ☹
    - Abundant ☺
    - $E_{max} > 10^{11}$ GeV ☺

generates background



Sky looks "foggy" in cosmic ray "light"

Cosmic rays (CR) = relativistic bare nuclei from space



Air showers?

Cosmic-ray induced air showers

Artist impression of an air shower

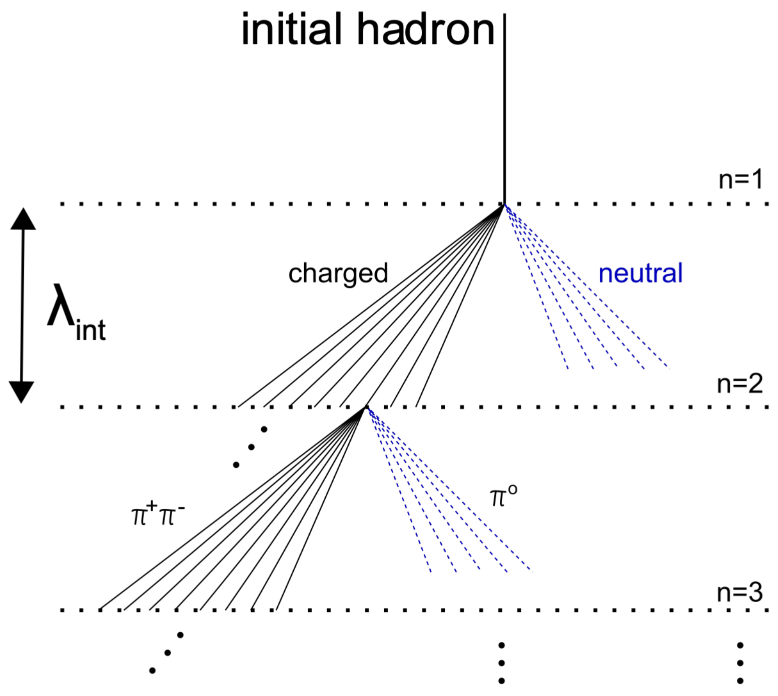
Image credit: Rebecca Pitt, Discovering Particles, CC BY-ND-NC 2.0

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

K.-H. Kampert and A.A. Watson, Eur. Phys. J. H37 (2012) 359-412

Air showers in a nutshell

Heitler-Matthews model of air shower
J. Matthews, Astropart. Phys. 22 (2005) 387-397



Cascade stops after 5-10 steps (energy-dependent)

- Simplified shower: only pions
- Charged pions
    - Reintract at high energy (hadronic cascade)
    - Decay at low energy into muons
- Neutral pions decay immediately and feed parallel electromagnetic shower

Bulk of muons and neutrinos produced at end of hadronic cascade

- Need to understand hadronic interactions and energy transfer
- Forward physics and soft-QCD

Fluorescence Detector

UV light from excited N_2

4 x 6 telescopes, 30° x 30°

+ 3 high-elevation telescopes

Surface Detector Array

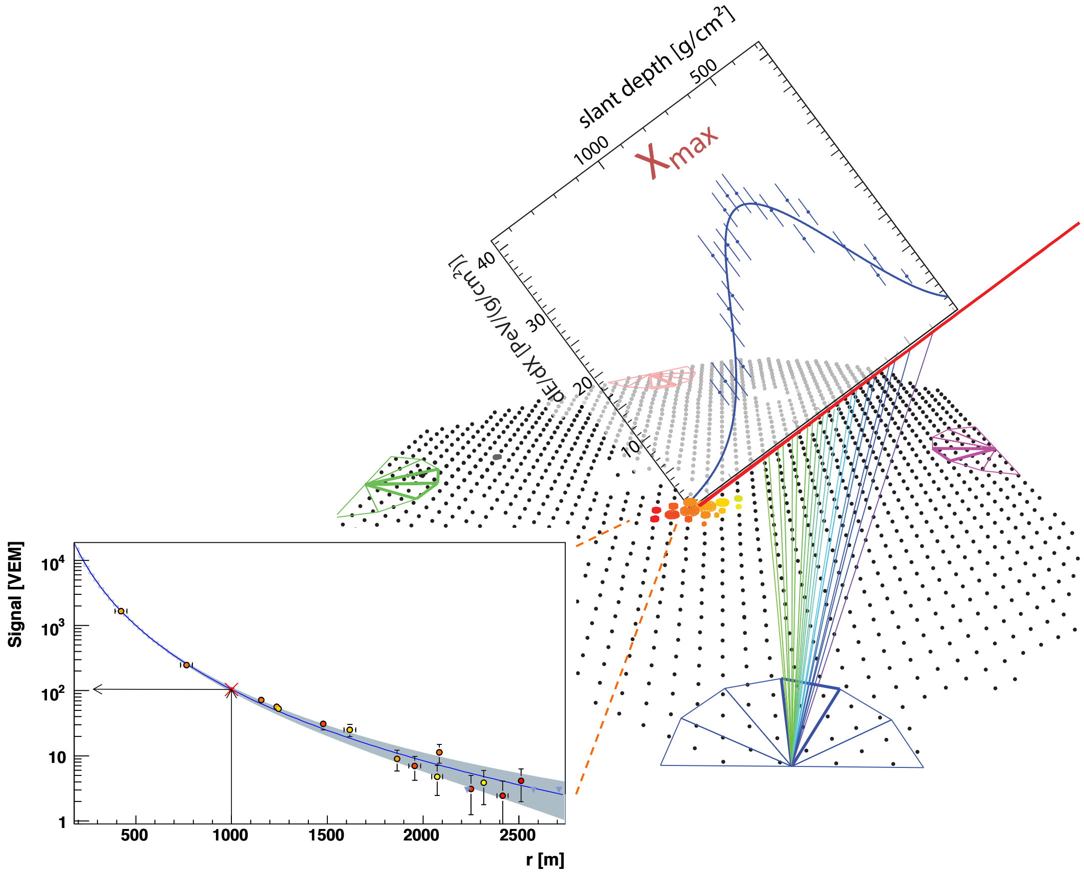
charged particle + photon detector

1500 m grid: 1660 stations (3000 km^2)

+ 750 m grid: 71 stations, (25 km^2)

High-energy cosmic ray detection

Example: event observed with Pierre Auger Observatory

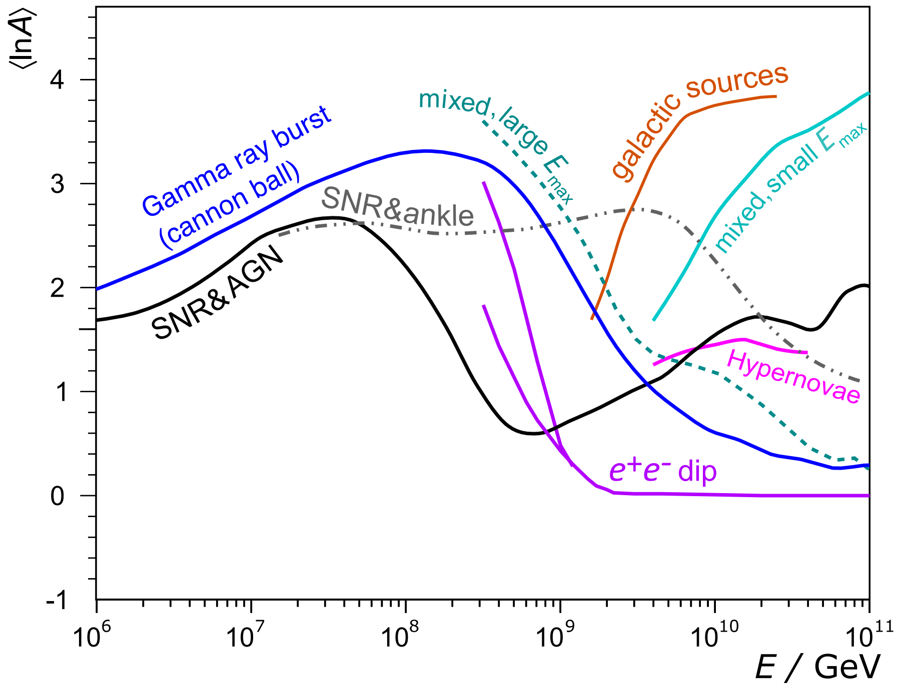


- **Direction** from particle arrival times
- **Energy** from size of **eγ component**
- **Mass** from **depth of shower maximum** and size of **muonic component**

X_{max} Shower depth and Mass
Iron depth = proton depth - **100 g cm-2 at same CR energy**

N_{μ} Number of muons and Mass
Iron yield = **+40 %** of proton yield **at same CR energy**

CR elemental (mass) composition

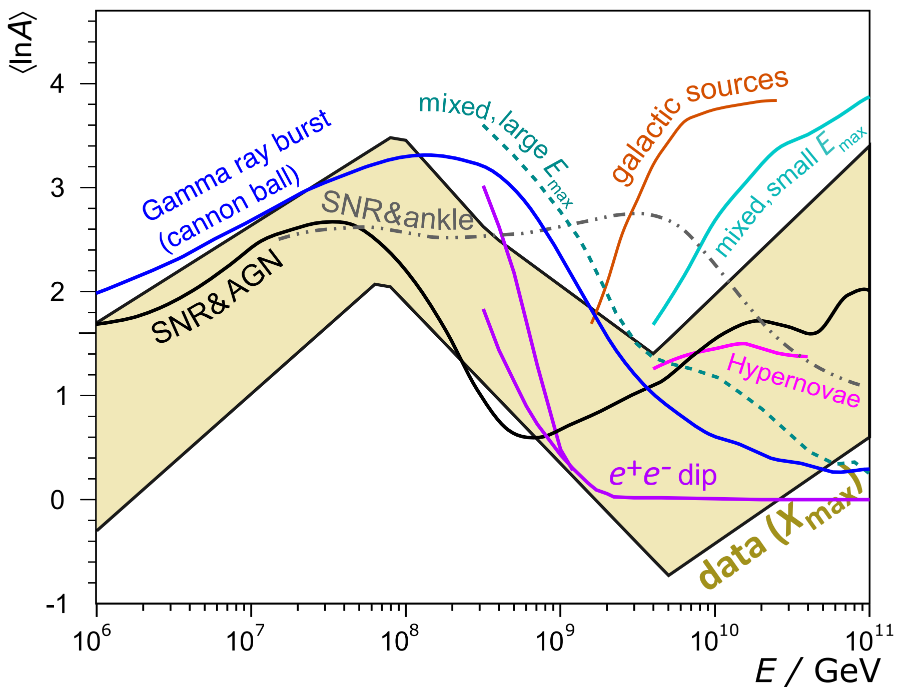


Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

Astrophysical origins of cosmic rays?

- Mass composition (<lnA>) of cosmic rays carries imprint of sources and propagation

CR elemental (mass) composition



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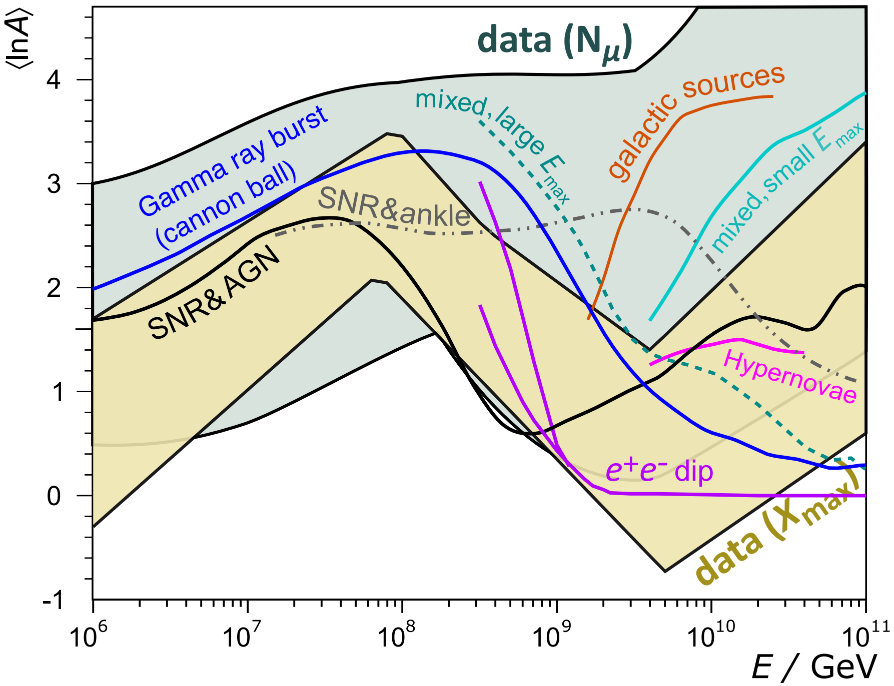

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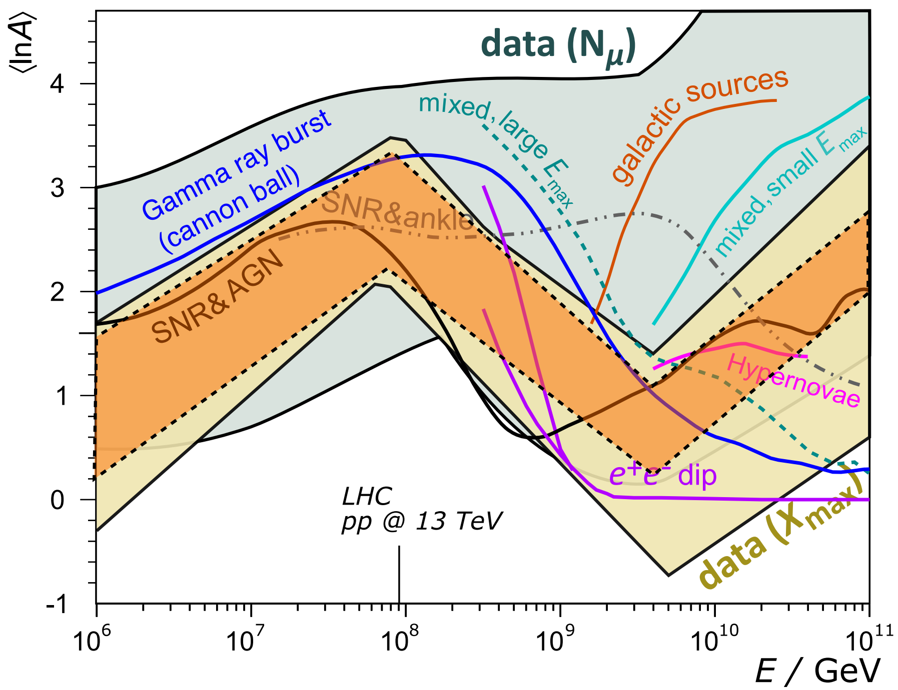
- **Muon Puzzle:** Muon predictions in air showers are inconsistent with X_{max}

CR elemental (mass) composition



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Potential solution from precision measurements at the LHC

- Forward production cross-sections of π, K, p
- Forward measurements of R = (energy in neutral pions) / (energy in other hadrons)

Muon Puzzle: Timeline

2018
- Telescope Array collab., PRD 98 (2018) 022002;
- S. Müller for the Pierre Auger collab., preliminary AMIGA results, UHECR 2018
- IceCube collab., ISVHECRI 2018 preliminary
- NEVOD-DECOR collab., Astropart. Phys. 98 (2018) 13
- SUGAR collab., PRD 98 (2018) 023014
- Yakutsk, unpublished preliminary results

2017 KASCADE-Grande collab., Astropart. Phys. 95 (2017) 25

2016 Pierre Auger collab. PRL 117 (2016) 192001

2015 **Pierre Auger collab. PRD 91 (2015) 032003**

2010 NEVOD-DECOR collab., Phys. Atom. Nucl. 73 (2010) 1852

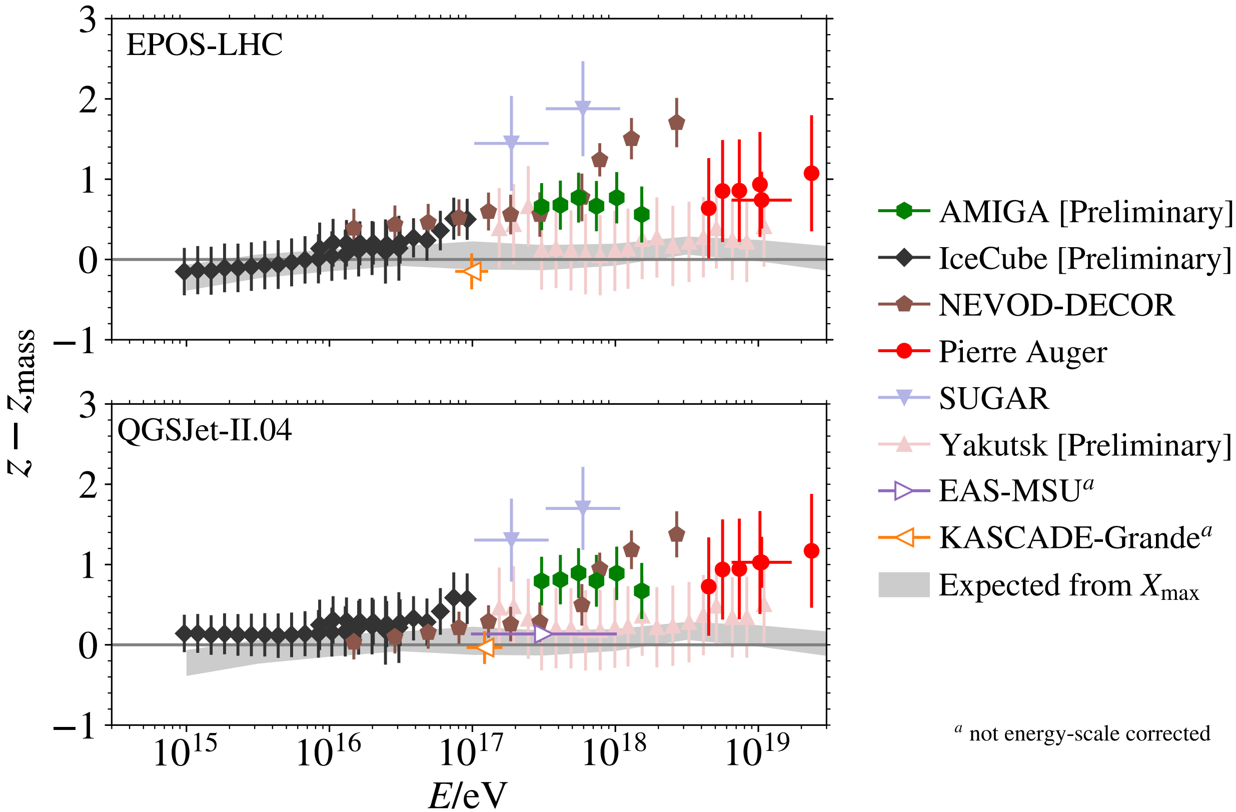
...

2000 HiRes-MIA collab., PRL 84 (2000) 4276

Muon deficit in simulated showers

HD et al. for the EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array and Yakutsk EAS Array collaborations, EPJ Web of Conferences **210**, 02004 (2019)

- Converted very diverse measurements from individual experiments into z-values
- Cross-calibrated energy scales of experimented by matching fluxes (main systematic)

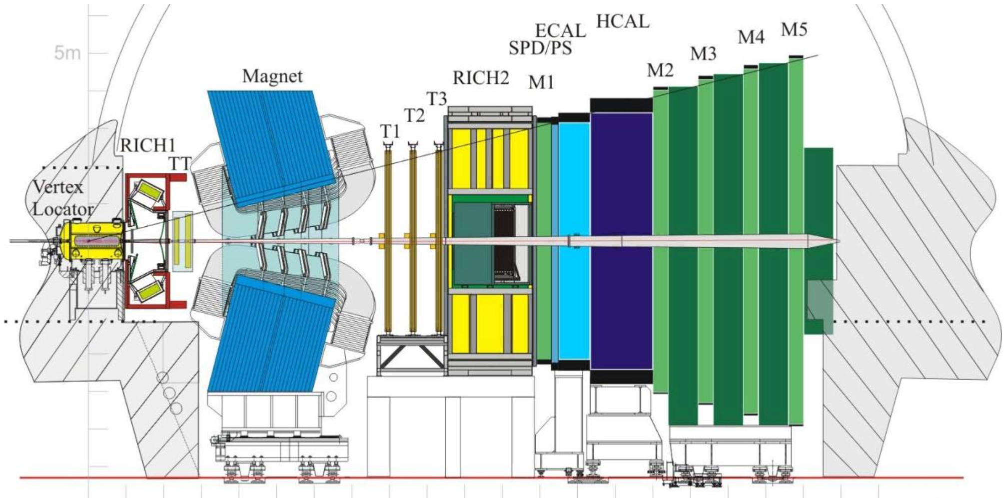


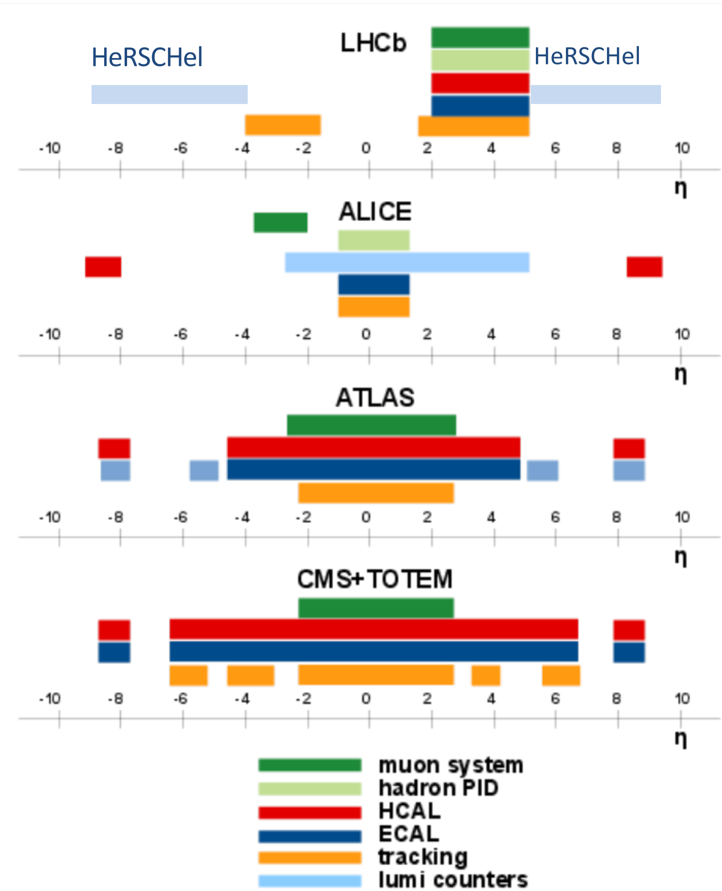
$$z = \frac{\ln N_\mu - \ln N_{\mu,p}^{\text{sim}}}{\ln N_{\mu,\text{Fe}}^{\text{sim}} - \ln N_{\mu,p}^{\text{sim}}}$$

- Slope is non-zero at 8σ
- Deficit in air shower simulations starting around 4 x 10^{16} eV or $\sqrt{s}$ ~ **8 TeV**

LHCb detector

JINST 3 (2008) S08005
IJMP A 30 (2015) 1530022

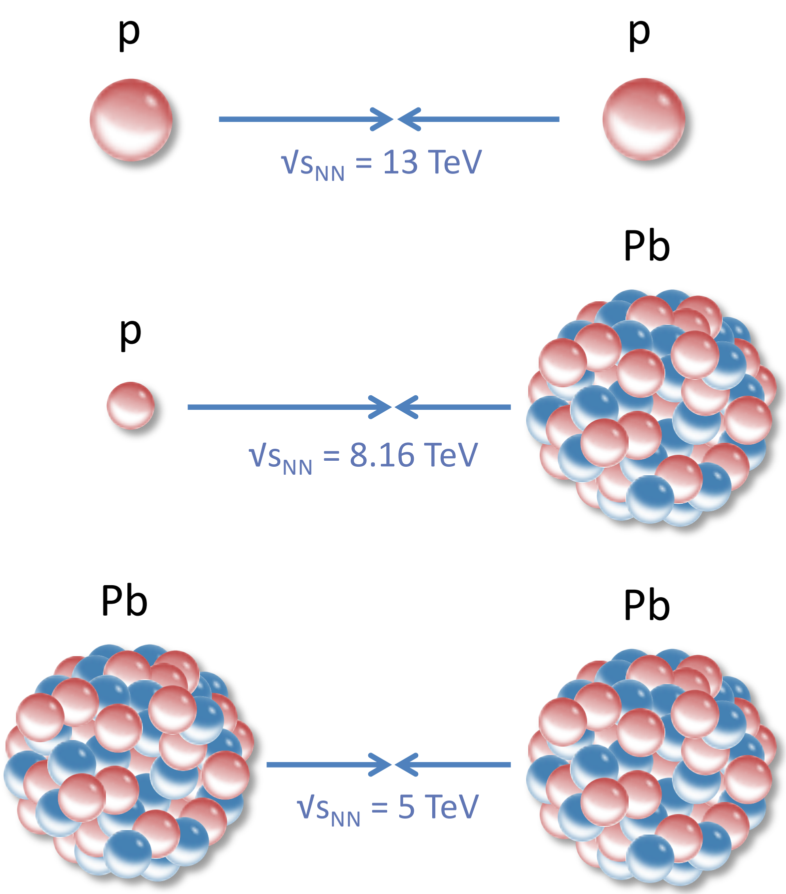




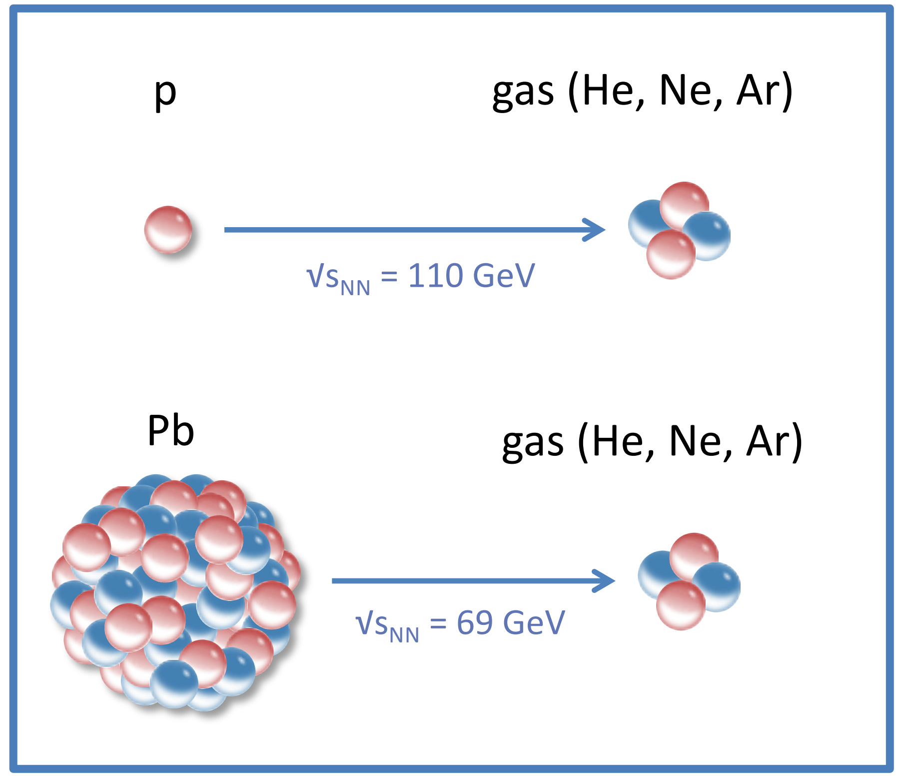
Single-arm forward spectrometer

- Fully instrumented at $2 < \eta < 5$
- Very good momentum and vertex resolution
- Good particle identification
- **Optimal**: μ, p, K^{+-}, π^{+-}

Collisions at the LHC



Fixed target: LHCb only, lower $\sqrt{s}$

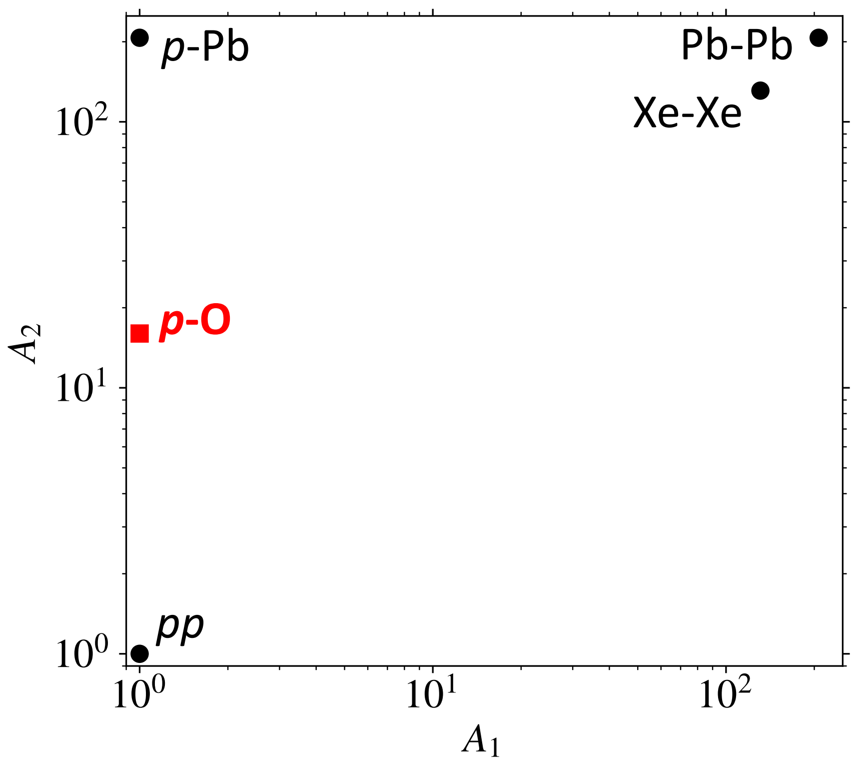


Short Xe-Xe run in 2017

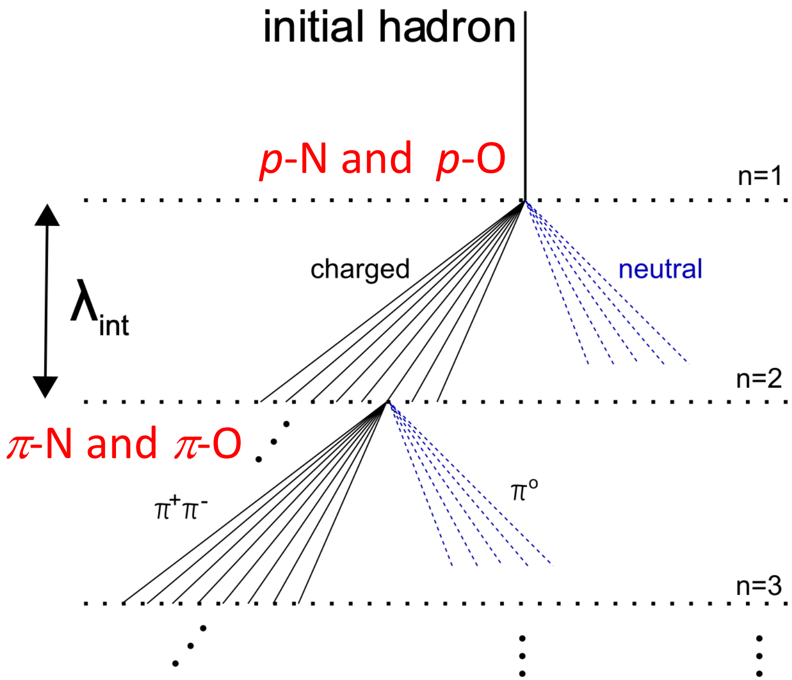
Planned: *p*-O and O-O runs in 2023

Collisions at the LHC and air showers

Collision systems at the LHC



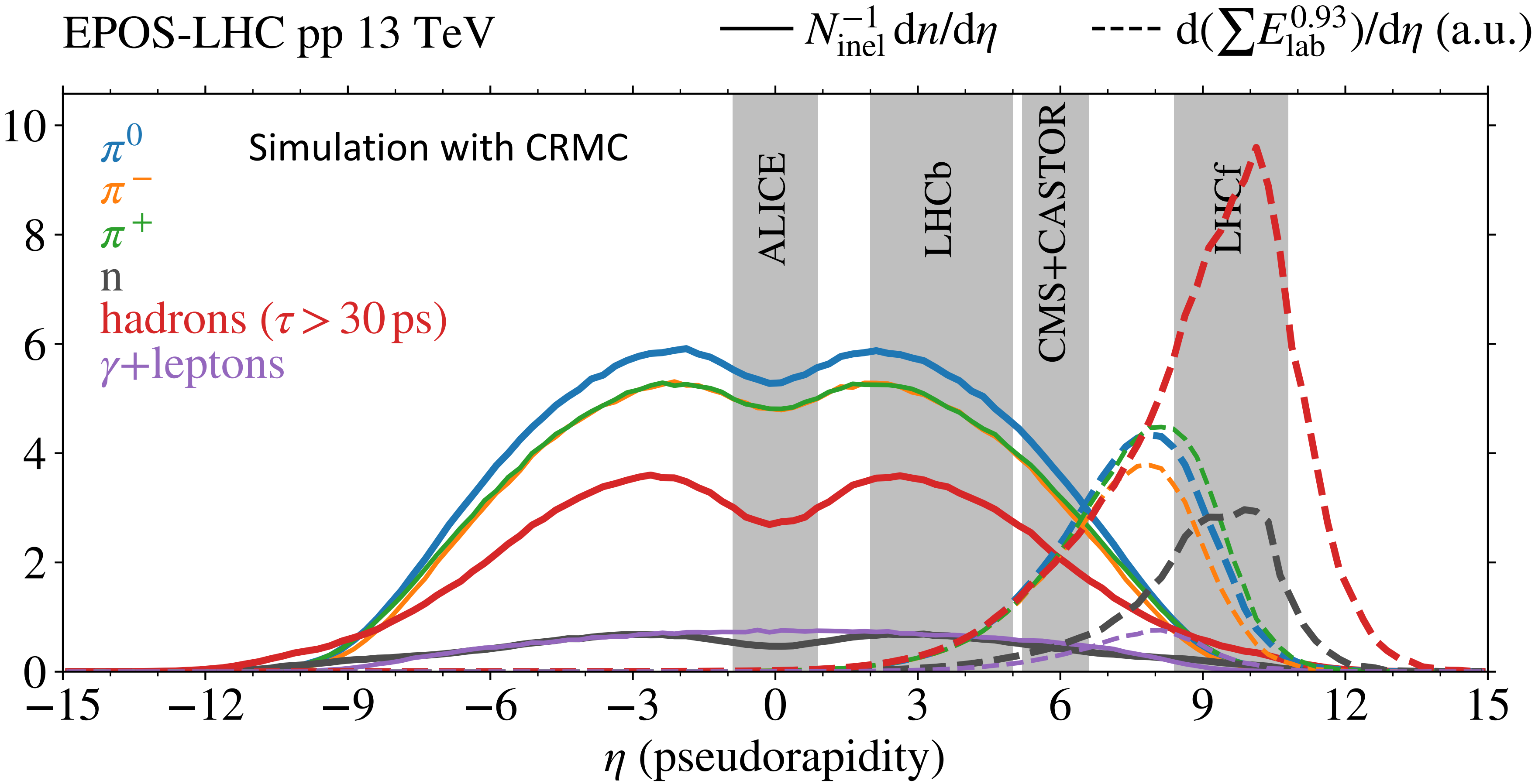
Air shower collision systems



- *p*-O collisions mimic air shower interactions
- Need *pp*, *p*-Pb, and *p*-O to understand nuclear effects

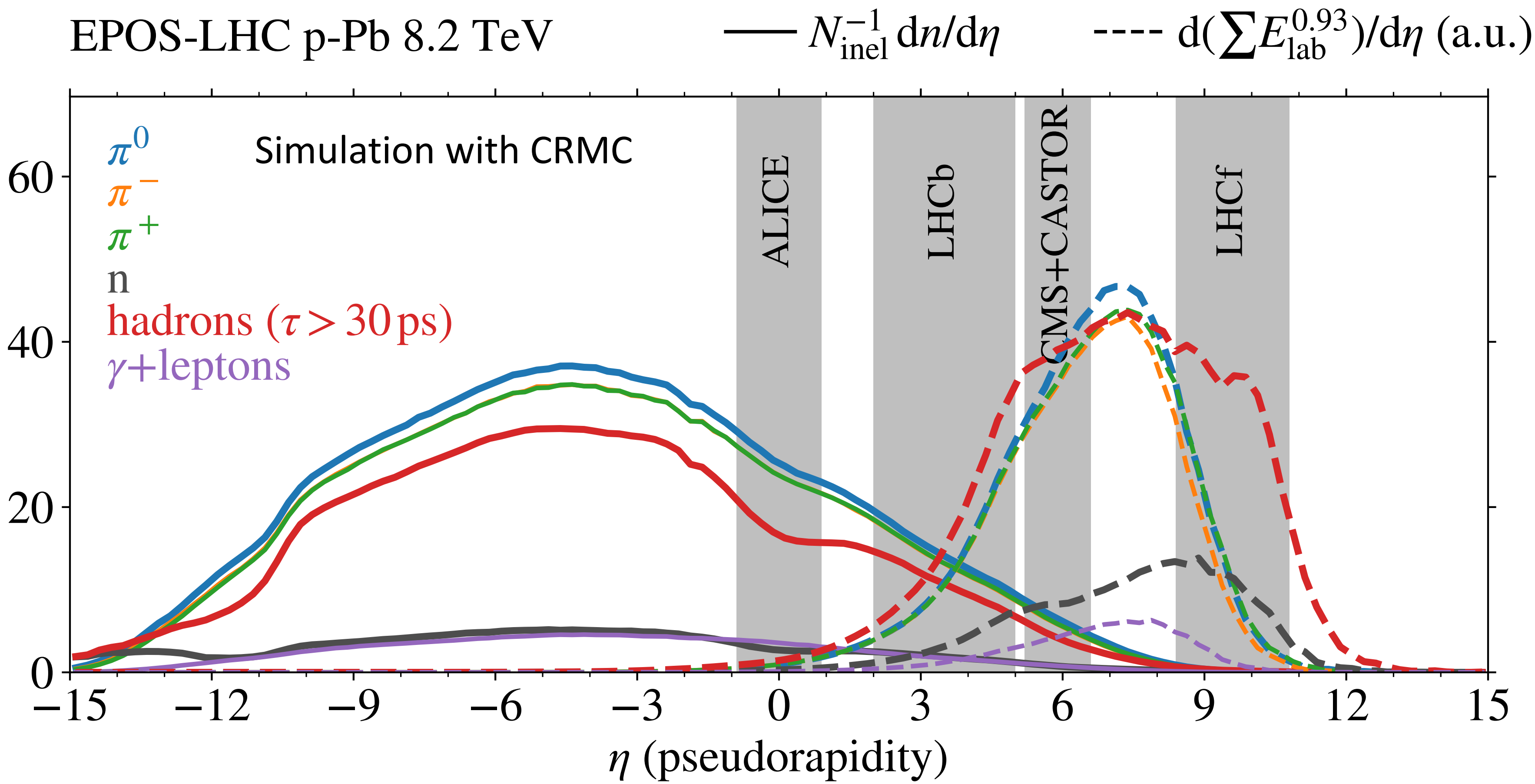
Forward production pp

„Muon weight"



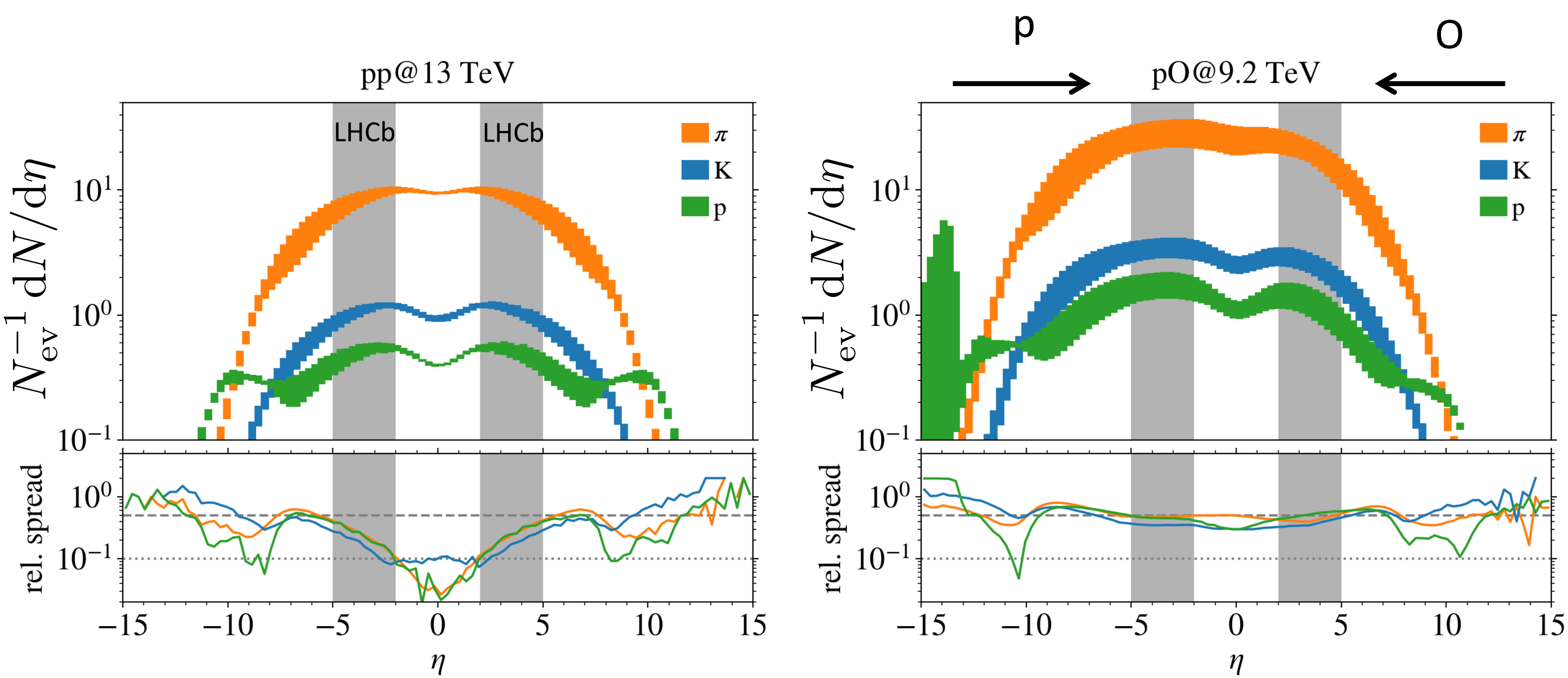
Forward production pPb

„Muon weight“



Model variation in hadron spectra

- Simulations done with CRMC
- Model spread: EPOS-LHC, QGSJet-II.04, SIBYLL-2.3

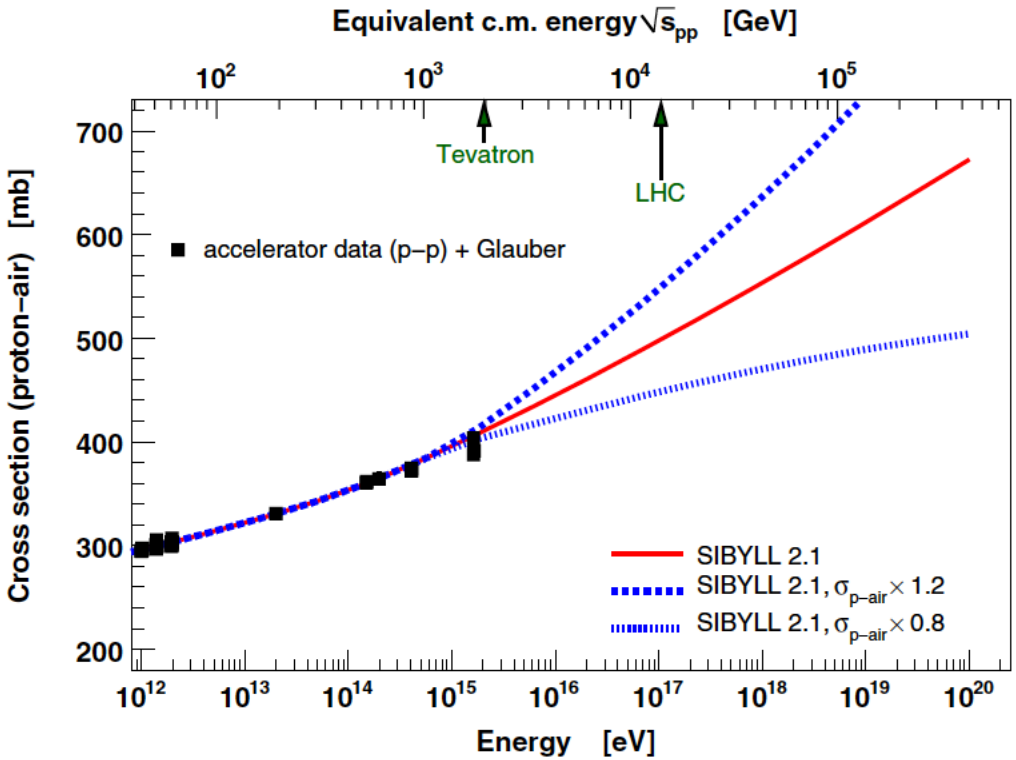


- Models mostly tuned to *pp* data at $|\eta| < 2$
- *pp* 10 % model spread, but 50 % spread at eta = 5
- 50 % spread also in *p*-O

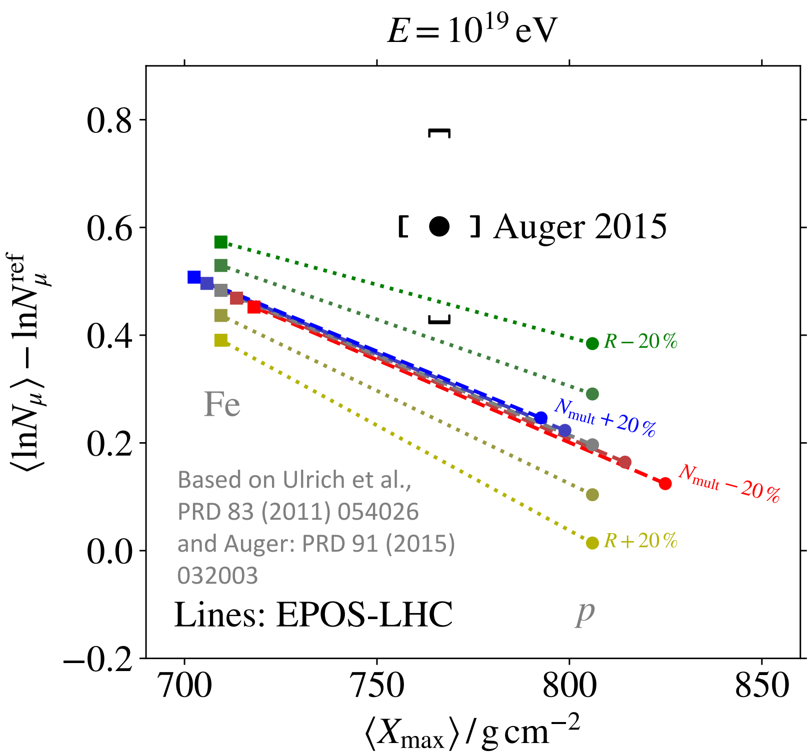
Impact of LHC measurements

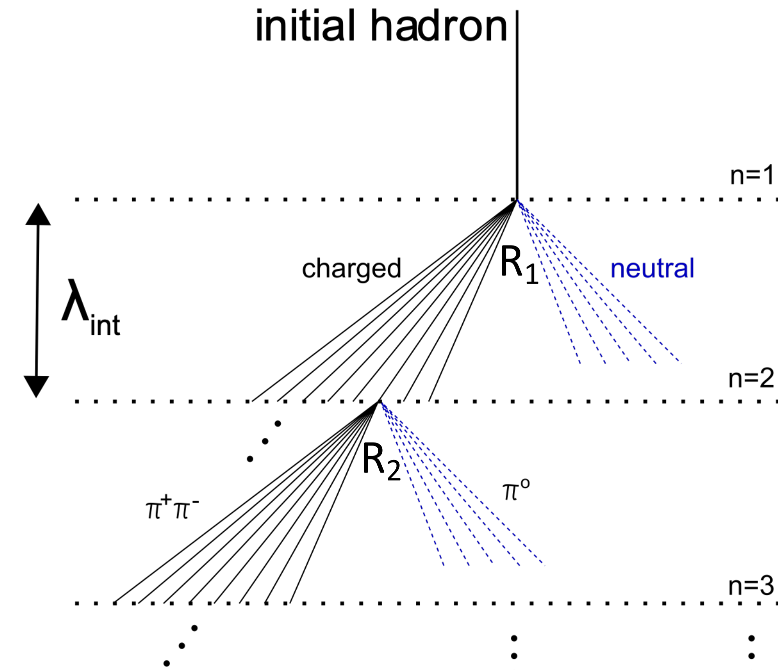
R. Ulrich et al PRD 83 (2011) 054026
Ad-hoc modify features at LHC energy scale with factor $\mathbf{f_{LHC\text{-}pO}}$
and extrapolate up to 10^{19} eV proton shower

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



Impact of LHC measurements





- X_{max} sensitive to: inel. cross-section, hadron multiplicity
- N_μ sensitive to: **energy ratio R**, hadron multiplicity
- **Strong nuclear modification in forward-produced hadrons**

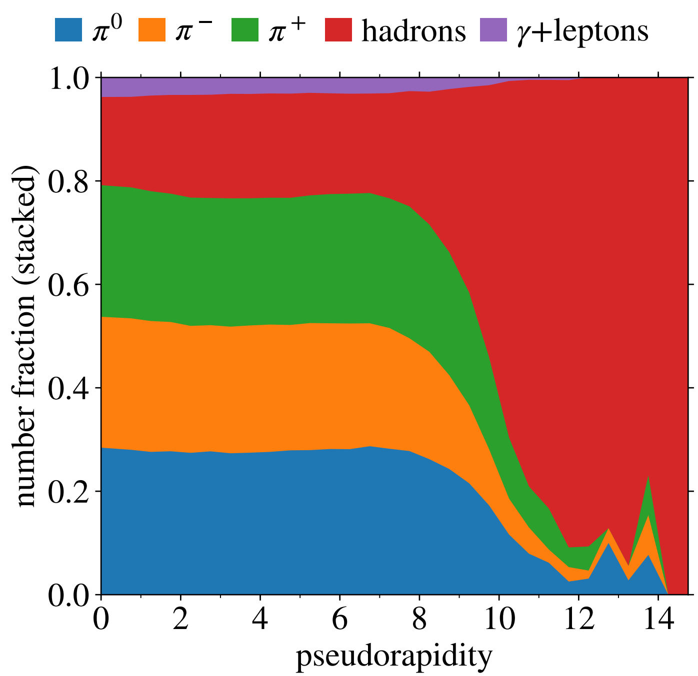
$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

needs to be known to 5 %

Possibilities to reduce energy ratio *R*

- Iso-spin symmetry: $\pi^+ : \pi^- : \pi^0 \sim 1:1:1$ so need to reduce π production
- Is strangeness enhanced in hadron-nuclear collisions, reducing π yield?

pp 13 TeV, EPOS-LHC



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

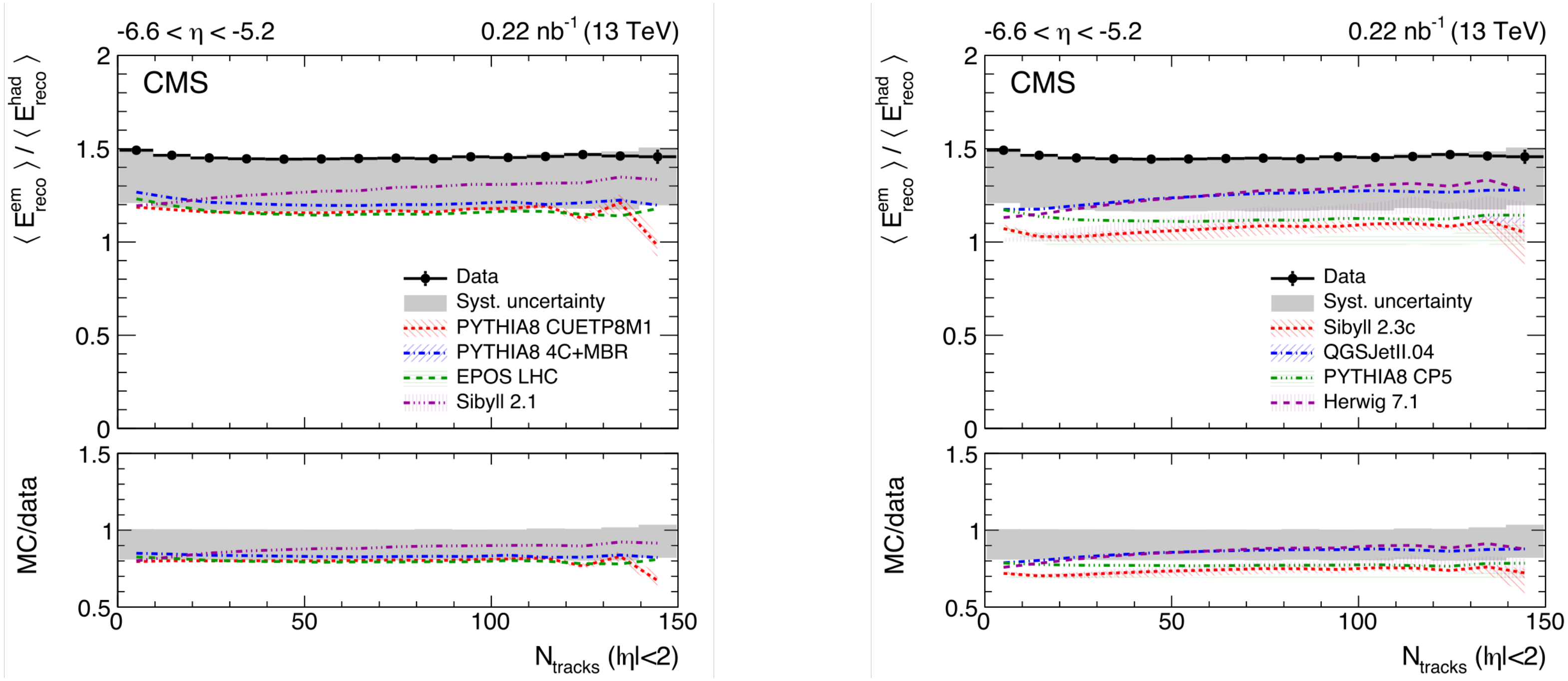
QGP in air showers could enhancing strangeness production, reducing pion fraction
https://arxiv.org/pdf/1612.07328.pdf

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

R in models seems too low in pp

pp @ 13 TeV

CMS collab. Eur.Phys.J. C79 (2019) no.11, 893



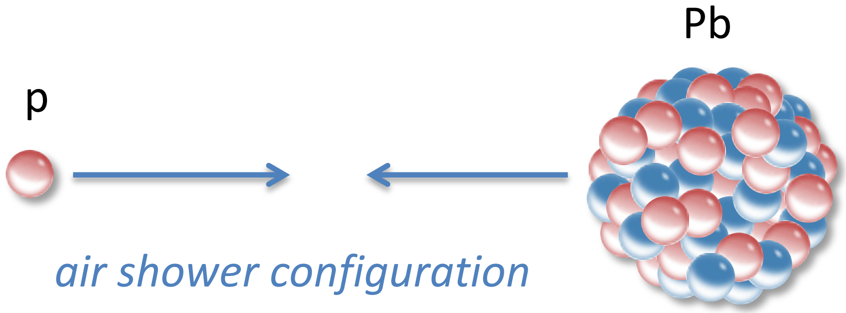
- CMS measurements give higher R than models for 5.2 < |eta| < 6.6
- Models should have higher R and should yield even fewer muons!
- Evidence points to nuclear effects

Nuclear effects

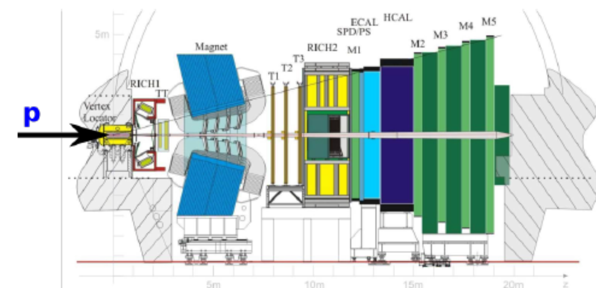
Nuclear modification factor

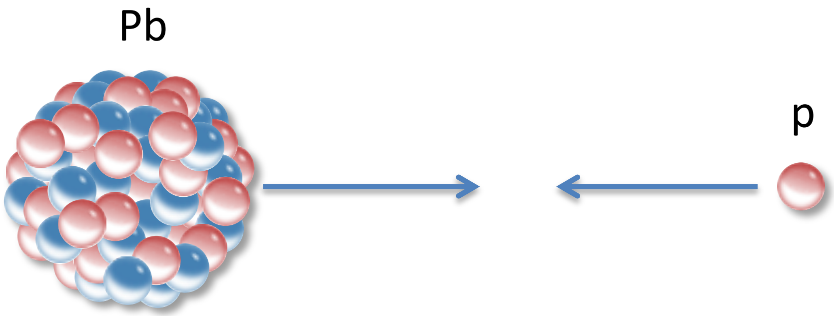
$$R_{pA} = \frac{\text{cross-section for pA}}{\text{A x cross-section for pp}}$$

Superposition model: $R_{pA} = 1$

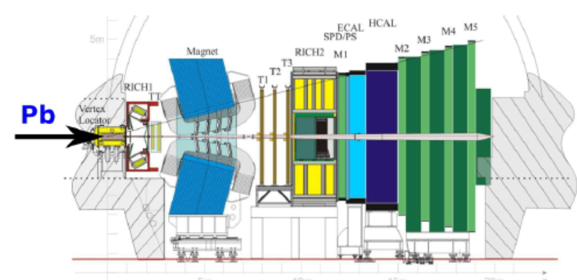


“forward”



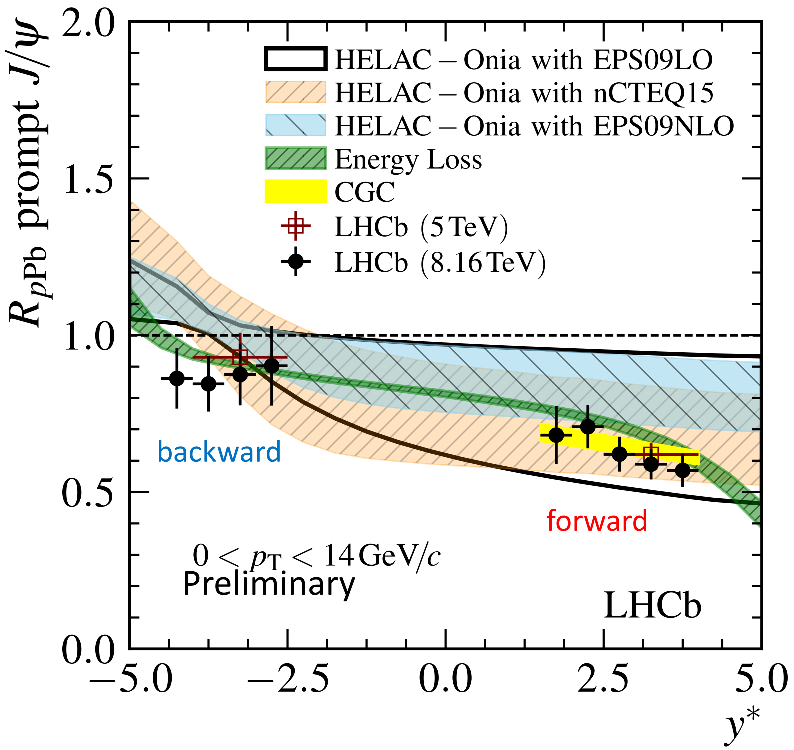


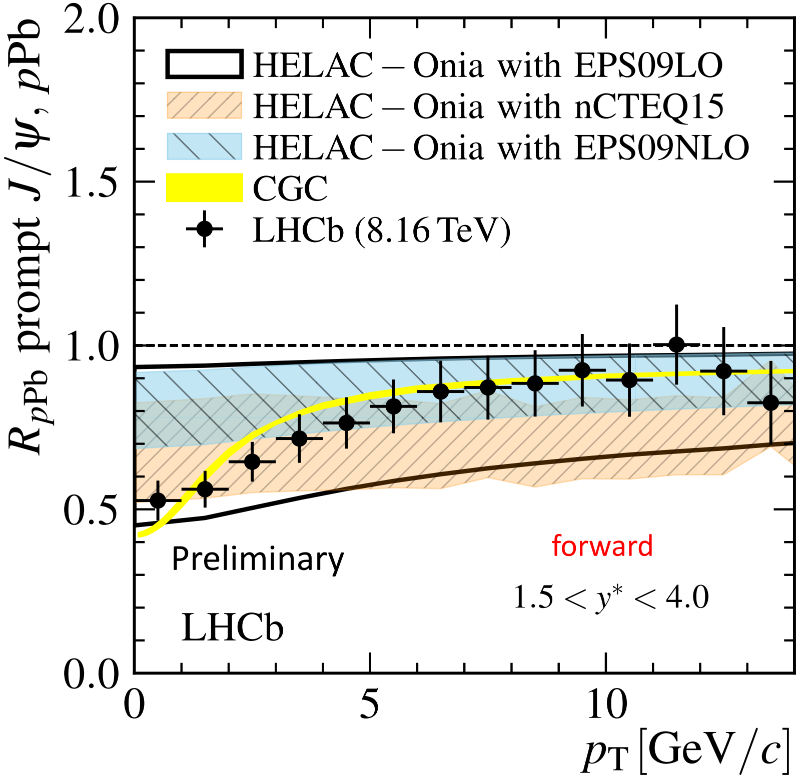
“backward”



Nuclear effects in forward J/Ψ production

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

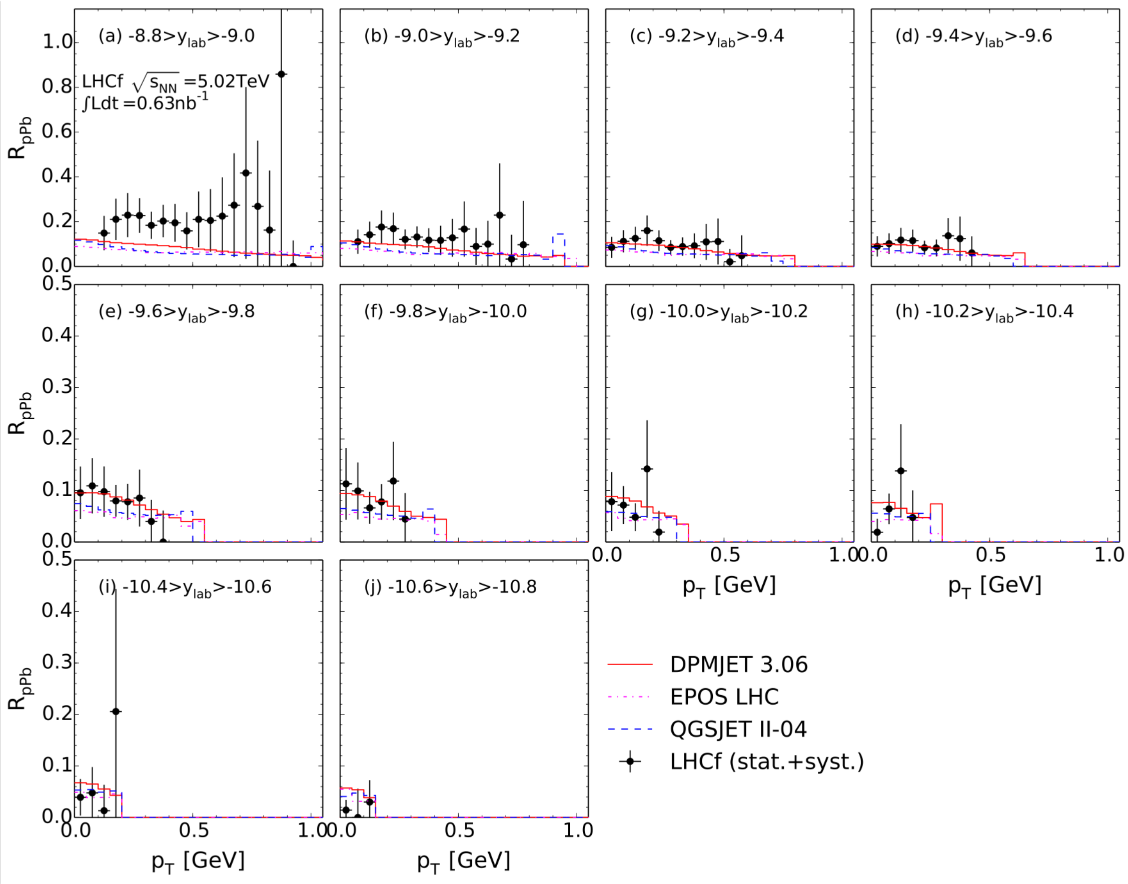




- Up to 50 % suppression in forward direction
- Especially strong where relevant for CR!

Nuclear effects in forward π^0 producton

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



Strong suppression for π^0 production in far forward (as predicted by current models)

Proton-oxygen collisions at the LHC

arXiv.org > hep-ph > arXiv:1812.06772v1

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High Energy Physics – Phenomenology

Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

Z. Citron, A. Dainese, J.F. Grosse-Oetringhaus, J.M. Jowett, Y.-J. Lee, U.A. Wiedemann, M. Winn (editors), A. Andronic, F. Bellini, E. Bruna, E. Chapon, H. Dembinski, D. d'Enterria, I. Grabowska-Bold, G.M. Innocenti, C. Loizides, S. Mohapatra, C.A. Salgado, M. Verweij, M. Weber (chapter coordinators), J. Aichelin, A. Angerami, L. Apolinario, F. Arleo, N. Armesto, R. Arnaldi, M. Arslandok, P. Azzi, R. Bailhache, S.A. Bass, C. Bedda, N.K. Behera, R. Bellwied, A. Beraudo, R. Bi, C. Bierlich, K. Blum, A. Borissov, P. Braun-Munzinger, R. Bruce, G.E. Bruno, S. Bufalino, J. Castillo Castellanos, R. Chatterjee, Y. Chen, Z. Chen, C. Cheshkov, T. Chujo, Z. Conesa del Valle, J.G. Contreras Nuno, L. Cunqueiro Mendez, T. Dahms, N.P. Dang, H. De la Torre, A.F. Dobrin, B. Doenigus, L. Van Doremalen, X. Du, A. Dubla, M. Dumancic, M. Dyndal, L. Fabbietti, E.G. Ferreiro, F. Fionda, F. Fleuret, S. Floerchinger, G. Giacalone, A. Giammanco, P.B. Gossiaux, G. Graziani, V. Greco, A. Grelli, F. Grosa, M. Guilbaud, T. Gunji, V. Guzey, C. Hadjidakis, S. Hassani, M. He, I. Helenius, P. Huo, P.M. Jacobs, P. Janus, M.A. Jebramcik, J. Jia, A.P. Kalweit, H. Kim, M. Klasen, S.R. Klein, M. Klusek-Gawenda, J. Kremer, G.K. Krintiras, F. Krizek, E. Kryshen, A. Kurkela, A. Kusina, J.-P. Lansberg, R. Lea, M. van Leeuwen, W. Li, J. Margutti et al. (83 additional authors not shown)

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Proposed schedule for Run 3

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	

- 200 μb^{-1} is enough statistics to push statistical error below 5 % in LHCb
- 2 nb^{-1} (10 x minimum) will be requested, also allows to measure charm
- Latest plans moved oxygen-week to 2023

Summary

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  - Need to understand air showers
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  - Muon production not correctly described in simulations (8σ offset)
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