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E5a/
Physik

A proton-oxygen run for cosmic rays and impact on the Muon Puzzle

Hans Dembinski, TU Dortmund

Workshop on forward physics and QCD with LHC, EIC, and cosmic rays
Jan 20-23, 2021

Overview

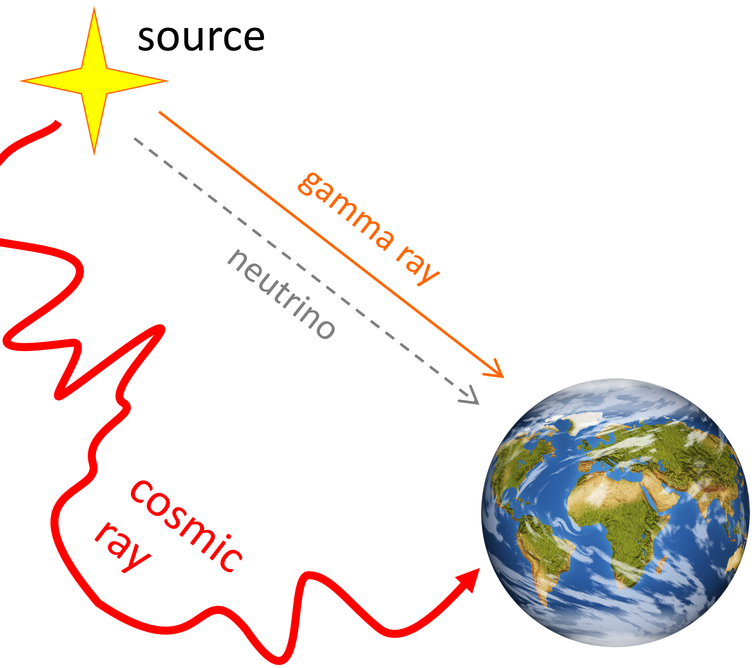
- Muon puzzle in cosmic-ray included air showers
  - Unresolved physics discrepancy in simulated vs. measured showers
  - Bottleneck for progress in cosmic ray physics
    - Accurate experimental data, but cannot interpret data unambiguously without solving this
  - Creates large uncertainties also for neutrino and gamma ray observatories

- Need high-energy nobias p-O LHC data for astroparticle physics
  - Forward production cross-sections for light hadrons in p-O collisions
  - Forward production of c- and b-mesons (leptonic decays: bkg for neutrino observatories)

Astroparticle physics

- Astroparticles are messengers of high-energy non-thermal universe
  - Black holes and neutron stars formation and exotics: dark matter decay…
  - Tremendous energies: GeV   TeV = 10^3 GeV   **PeV** = 10^6 GeV   **EeV** = 10^9 GeV
- Messengers
  - Gamma rays
    - Pointing ☺
    - Abundant ☺
    - E_{max} ~ 100 TeV ☹
  - Neutrinos
    - Pointing ☺
    - Rare ☹
    - E_{max} > 100 EeV ☺
  - Cosmic rays (nuclei)
    - No pointing ☹
    - Abundant ☺
    - E_{max} > 100 EeV ☺

generates background



Sky looks "foggy" in cosmic ray "light"

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

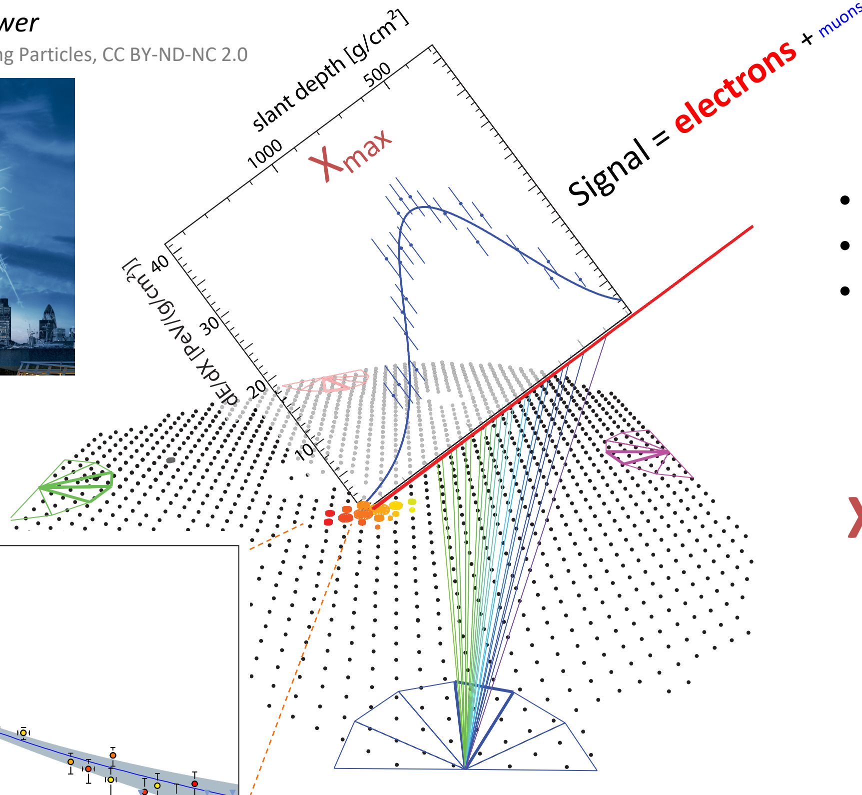

PIERRE AUGER OBSERVATORY
Fluorescence Detector
UV light from excited N_2
4 x 6 telescopes, 30° x 30°
+ 3 high-elevation telescopes
Surface Detector Array
charged particle + photon detector
1500 m grid: 1660 stations (3000 km^2)
+ 750 m grid: 71 stations, (25 km^2)

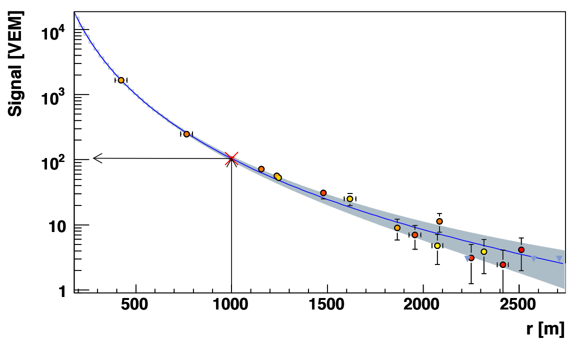
High-energy cosmic ray detection

Example: event observed with Pierre Auger Observatory

Artist impression of air shower

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





$$E_{\text{cal}} = \int_0^\infty \left(\frac{dE}{dX}\right)_{\text{ionization}} dX$$

- **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

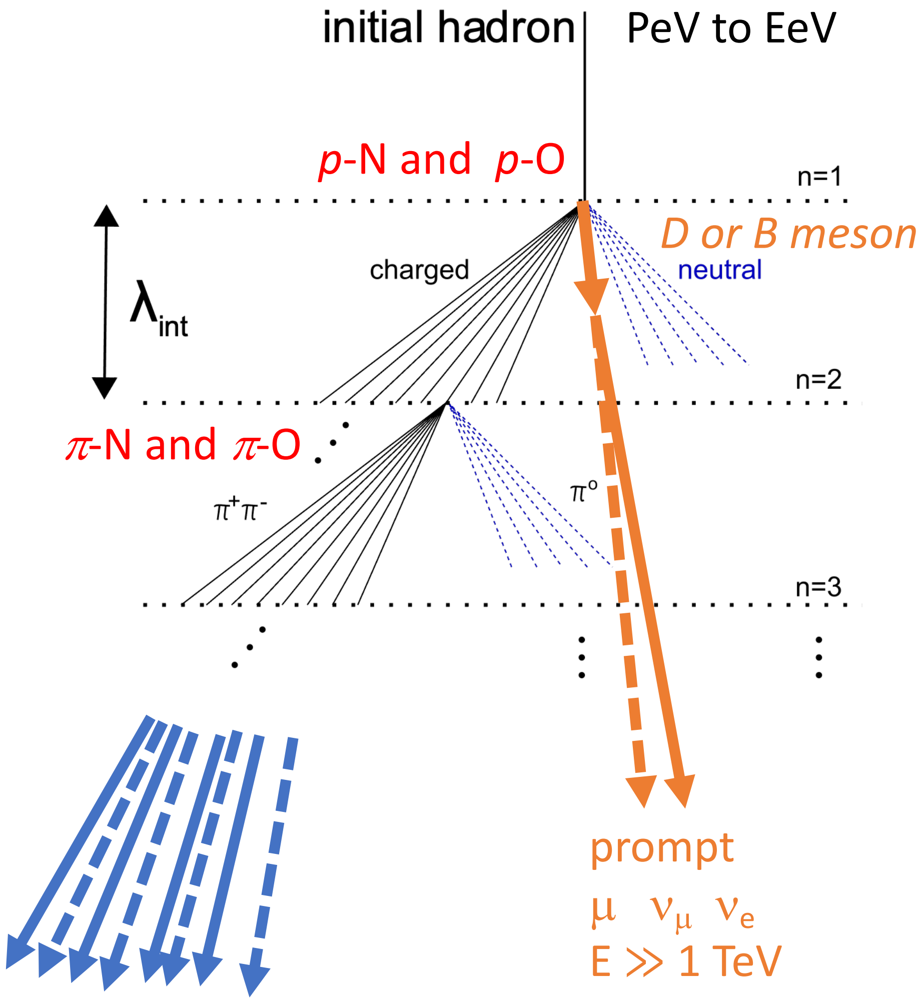
Iron yield = **+40 %** of proton yield **at same CR energy**

Vertical showers	Signal = **electrons** + **photons** + muons
Inclined showers	Signal = electrons + photons + **muons**

Experimental accuracies

Direction	$0.5 – 1.5°_{stat}$	
Energy	$10\text{-}20\ \%_{stat}$	**$14\ \%_{sys}$**
X_{max}	$15 – 25\ gcm^{-2}_{stat}$	**$10\ g\ cm^{-2}_{sys}$**
N_μ	$20\ \%_{stat}$	**$11\ \%_{sys}$**

High-energy lepton production in air showers



Prompt lepton production
- Very rare, but very high energy
- Ancestor: forward produced D or B meson from first interaction

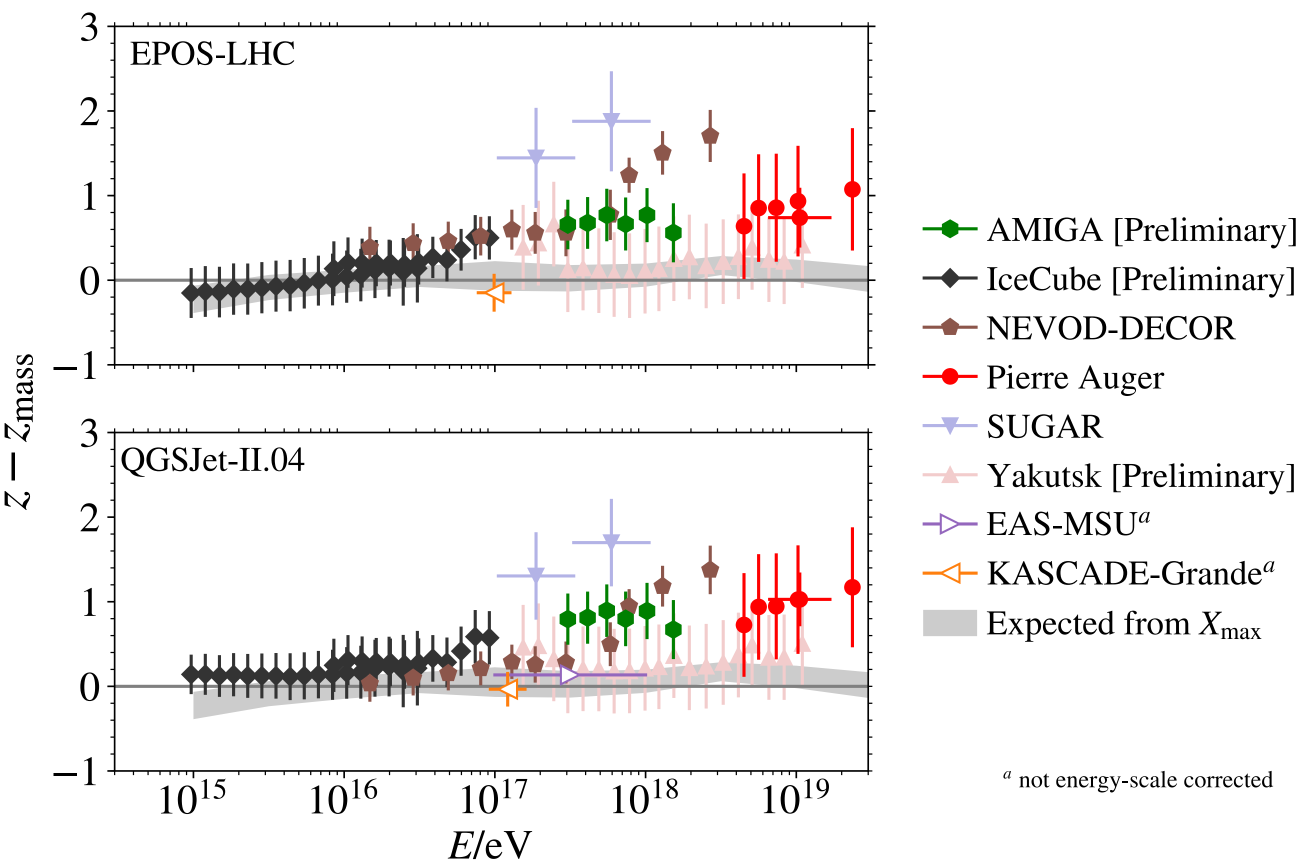
Conventional lepton production (bulk)
- Hadronic cascade with 5-10 steps
  - Intermediate particles: π, K, p, n, …
  - Exponential descrease in energy
- π, K decay at E ≈ 10 GeV
- Sensitive to forward production and energy flow in hadronic cascade
- "Energy loss" through π^0 mesons

Conventional μ ν_μ ν_e produced when mesons decay, average energy about E ≈ 10 GeV

Muon deficit in simulated showers

Conventional muons

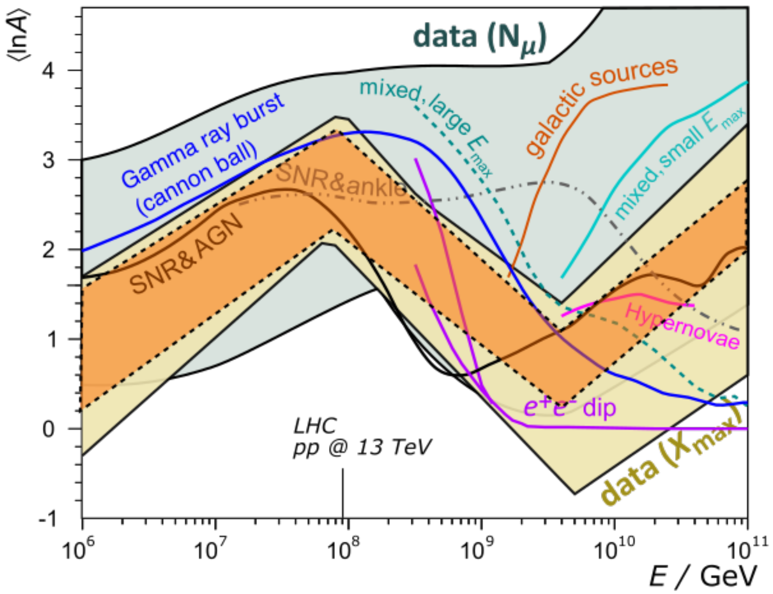
HD et al. for the EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array and Yakutsk EAS Array collaborations, EPJ Web of Conferences **210**, 02004 (2019)



Air shower muons produced in light meson decays at end of hadronic cascade

Deficit in air shower simulations starting around 4 x 10^{16} eV or $\sqrt{s} \sim$ **8 TeV**

CR elemental (mass) composition



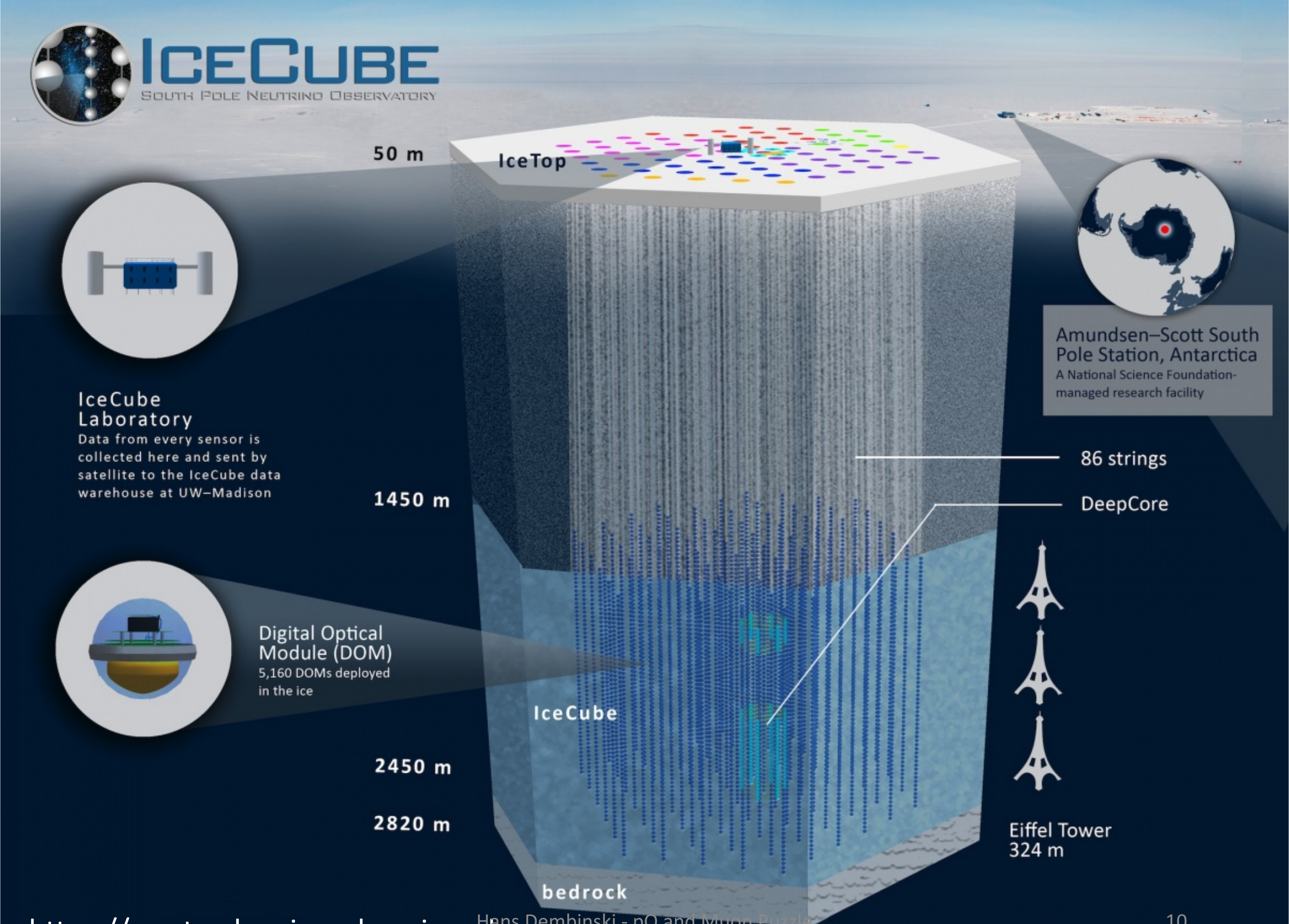
Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660

Astrophysical origins of cosmic rays?

- Mass composition (<lnA>) of cosmic rays carries imprint of sources and propagation
- **Muon Puzzle:** Muon predictions in air showers are inconsistent with X_{max}
- Uncertainties of <lnA> limited by uncertainty in description of hadronic interactions

How to resolve this?

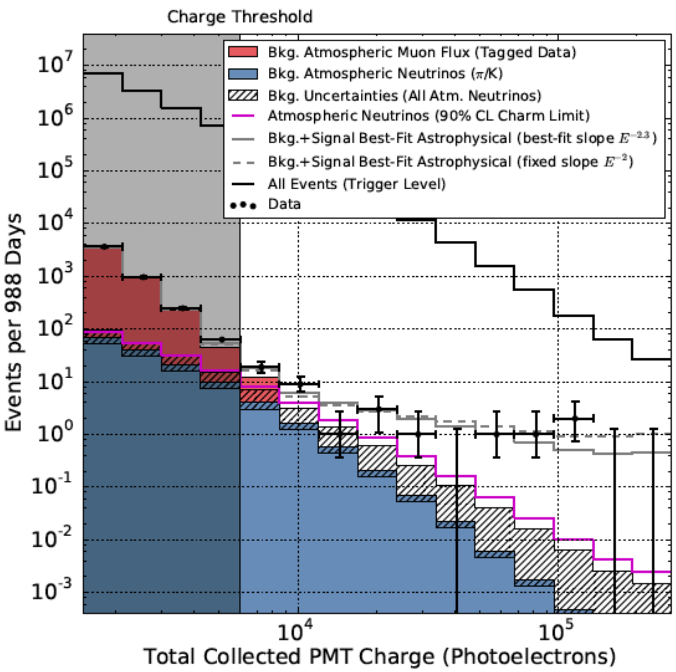
- Air shower experts connect inconsistencies to hadronic interaction properties
- Collider community provides dedicated reference measurements

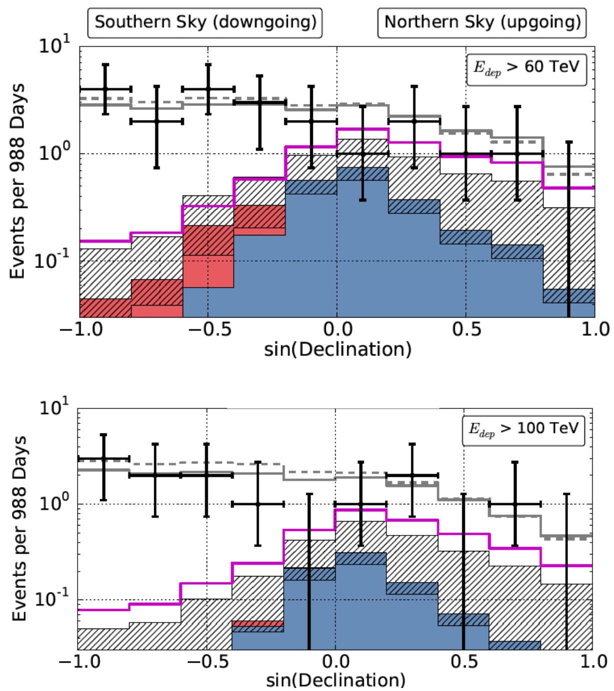


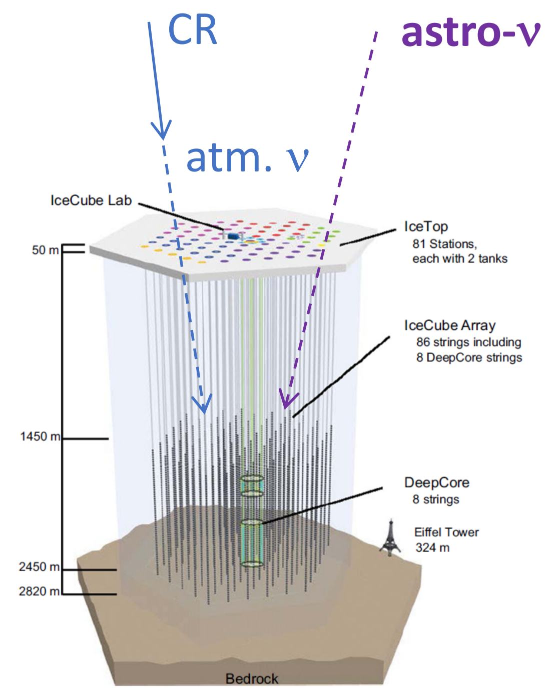
https://masterclass.icecube.wisc.edu

Diffuse atmospheric lepton flux

IceCube collab. Phys.Rev.Lett. 113 (2014) 101101



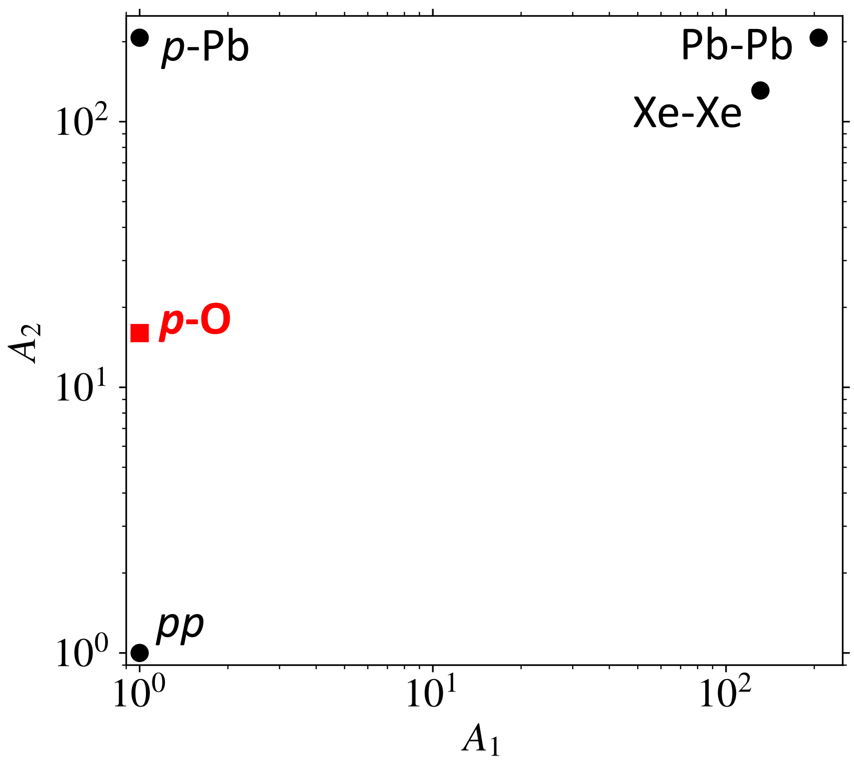




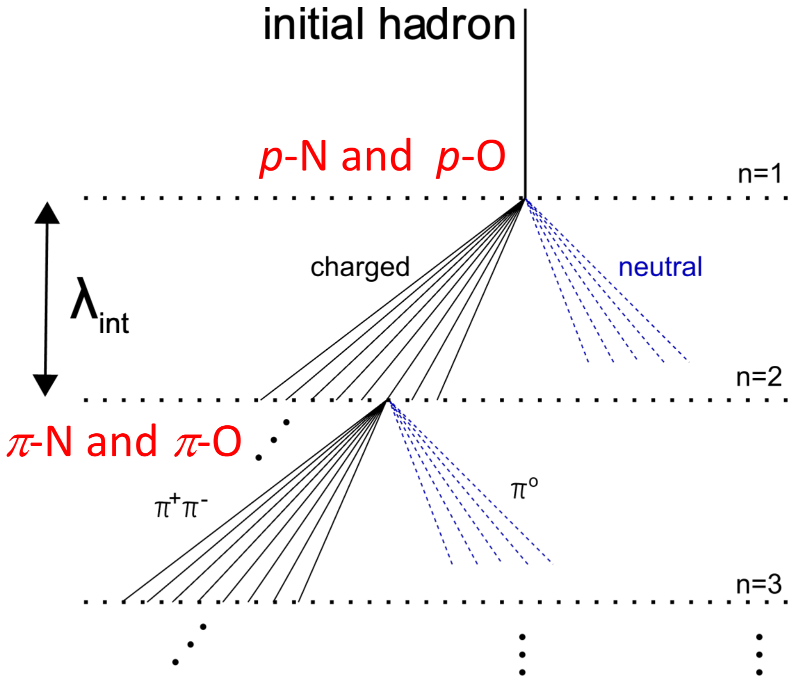
- Most astroneutrinos detected from above, despite high atmospheric background
- **>50 %** uncertainty in atmospheric lepton flux: about **30 %** from uncertain CR mass composition
- Double gain from better LHC measurements
  - More accurate cosmic ray composition
  - More accurate atm. lepton production

Collisions at the LHC and air showers

Collision systems at the LHC



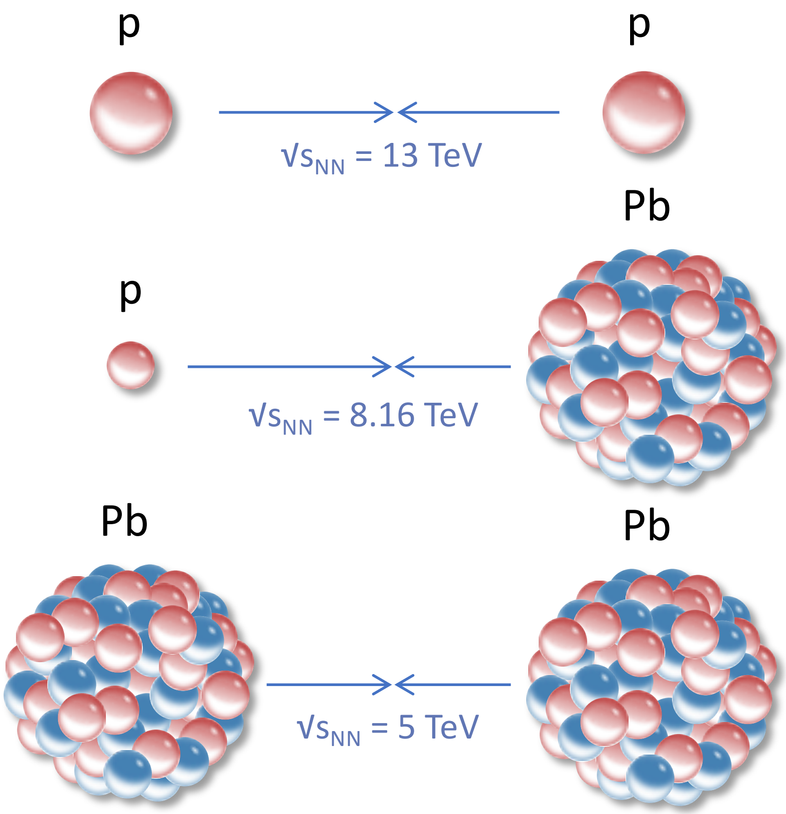
Air shower collision systems



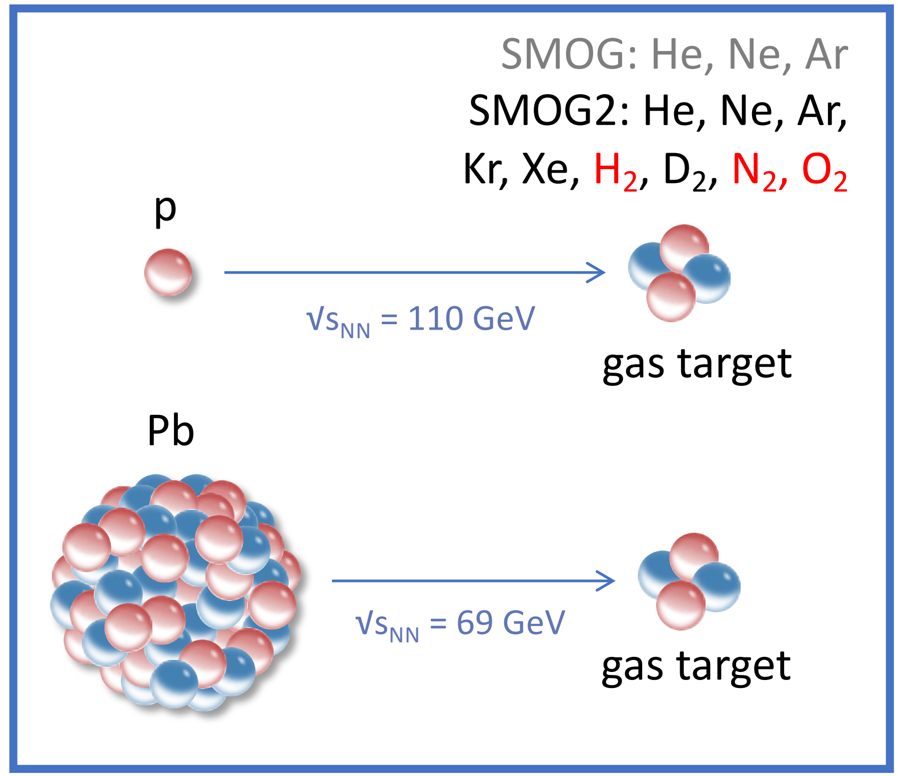
- *p*-O collisions mimic air shower interactions
- Should be transferable to *π*-O (backup)
- Need *p*-*p*, *p*-Pb, and *p*-O to understand nuclear effects in forward production

Collisions at the LHC

SMOG2 TRD: https://cds.cern.ch/record/2673690/files/LHCB-TDR-020.pdf



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

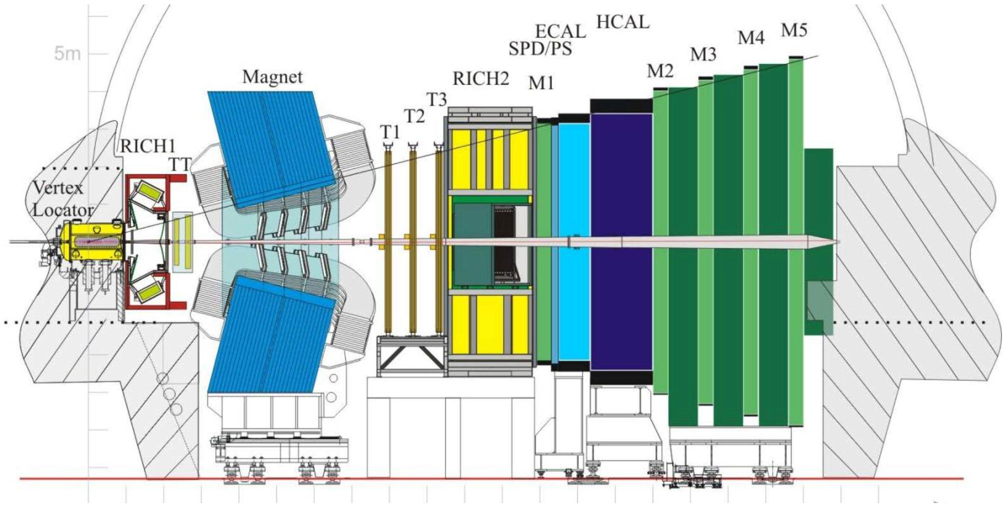


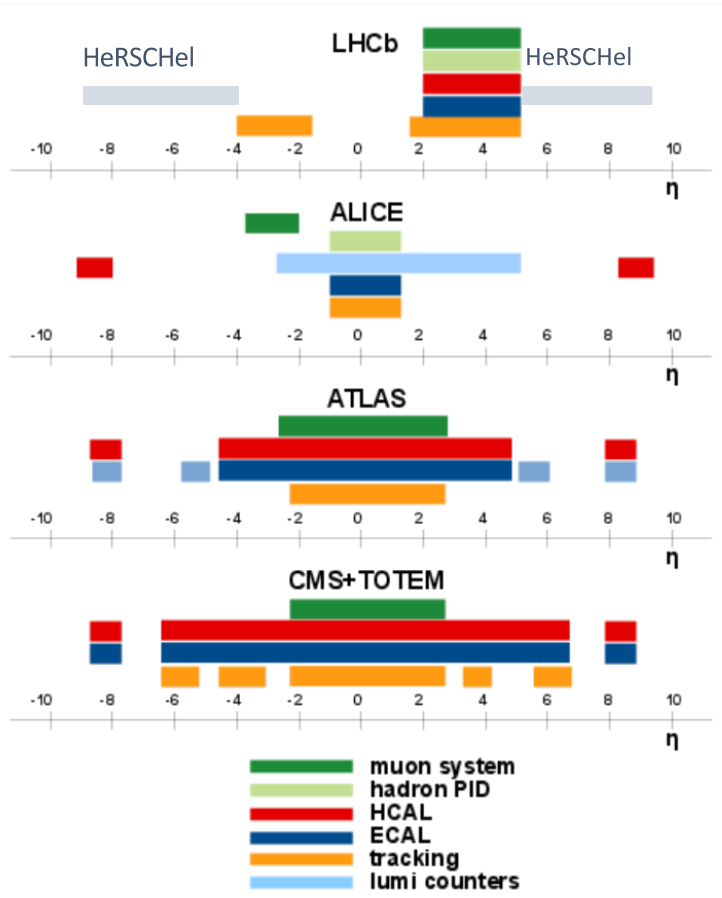
Short Xe-Xe run in 2017

Planned but currently endangered: *p*-O and O-O runs in 2023

LHCb detector

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





Forward spectrometer

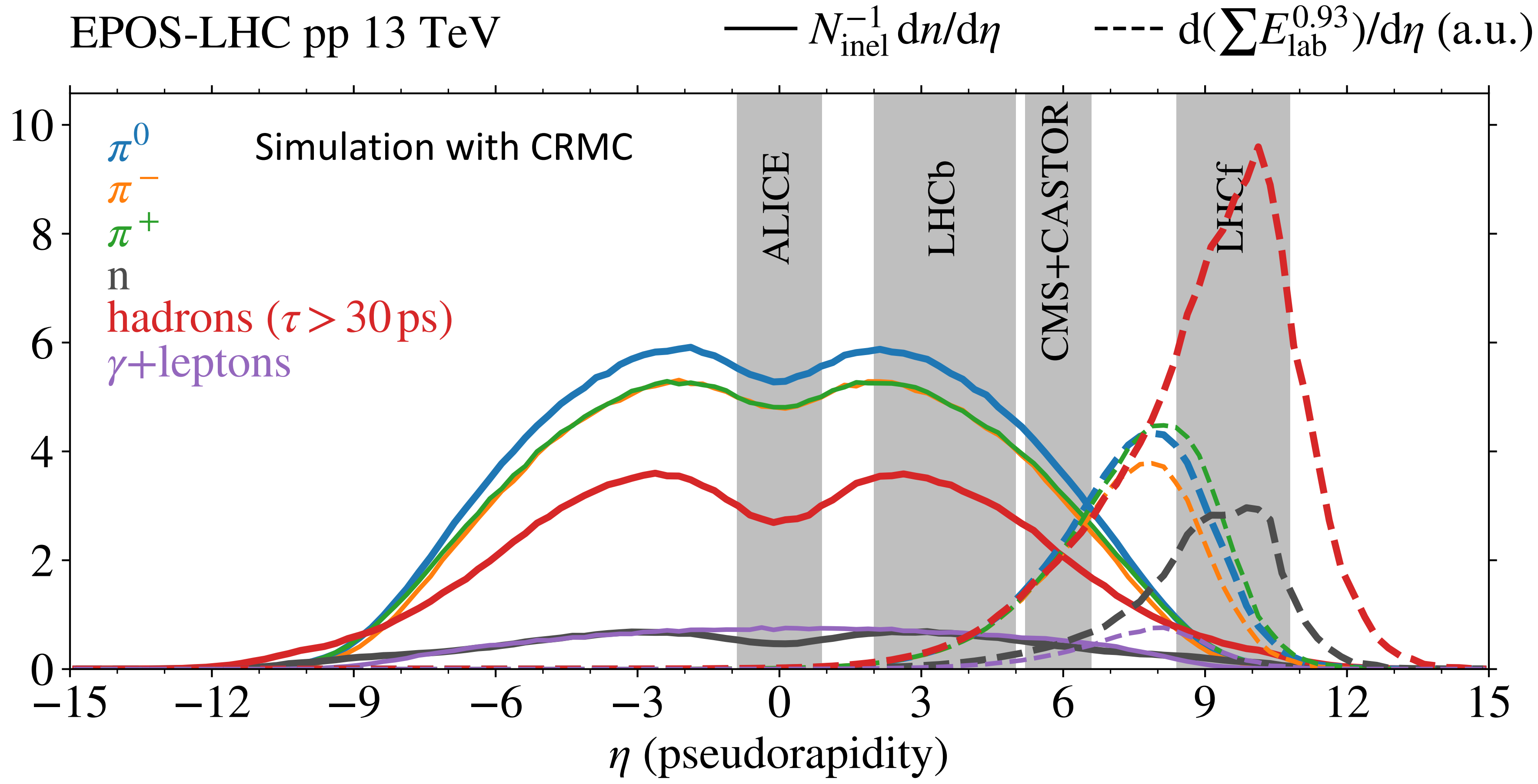
- Acceptance
  - $2 < \eta < 5$
  - $0.08 < (p_T / \text{GeV } c^{-1}) < 10$
- Very good momentum and vertex resolution
- Particle identification over full acceptance
- **Optimal**: μ, p, K^{+-}, π^{+-}
- HeRSCHel detector to tag diffractive events

Relevant LHCb production cross-sections

- Inelastic cross-section
  - pp @ 7 TeV JHEP 02(2015)129
  - pp @ 13 TeV JHEP 06(2018)100
- Charged particle multiplicities
  - pp @ 7 TeV EPJ C (2012) 72:1947
  - pp @ 7 TeV EPJ C (2014) 74:2888
- Energy flow
  - pp @ 7 TeV EPJ C (2013) 73:2421
- Prompt hadron production ratios
  - pp @ 0.9, 7 TeV EPJ C (2012) 72:2168
- anti-proton production
  - pHe @ 110 GeV PRL 121 (2018) 222001
- Long-range near-side angular correlation
  - pPb @ 5 TeV PLB 762 (2016) 473-483
- K_s^0 production (s-hadron production)
  - pp @ 0.9 TeV PLB 693 (2010) 69-80
- ϕ production (s-hadron production)
  - pp @ 7 TeV PLB 703 (2011) 267-273
- J/ψ production (c-hadron production)
  - pPb @ 5 TeV JHEP 02(2014)072
- D^+ production (c-hadron production)
  - pp @ 13 TeV JHEP 10(2017)090
- Λ_c^+ production (c-hadron production)
  - pPb @ 5 TeV JHEP 02(2019)102
- $\psi(2S)$ production (c and b-hadron production)
  - pPb @ 5 TeV JHEP 03(2016)133
- D^+, D^0, D^+_s, D^{*+} production (c-hadron production)
  - pp @ 5 TeV JHEP06(2017)147
  - pp @ 7 TeV Nucl. Phys. B (2013) 1
  - pp @ 13 TeV JHEP 03 (2016) 159
- B^+, B^0, B^0_s, Λ_b^+ production (b-hadron production)
  - pp @ 7 TeV JHEP 08 (2013) 117, 2013
  - pPb @ 8.2 TeV PRD 99 (2019) 052011
  - (B^+ only) pp @ 13 TeV JHEP 12 (2017) 026
- Υ production (b-hadron production)
  - pPb @ 5 TeV JHEP 07(2014)094
  - pPb @ 8 TeV JHEP 11(2018)194

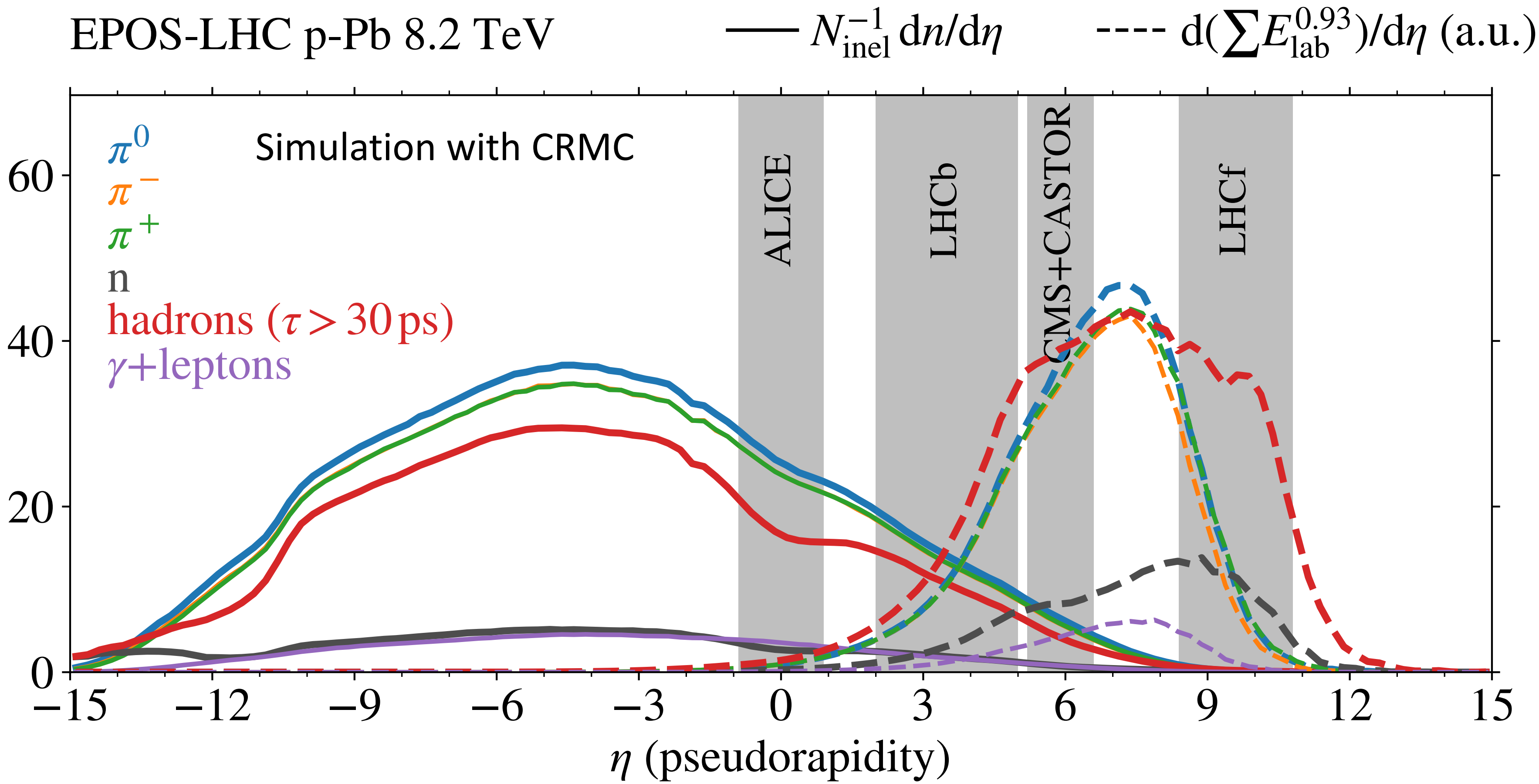
Forward production p-p

„Muon weight“



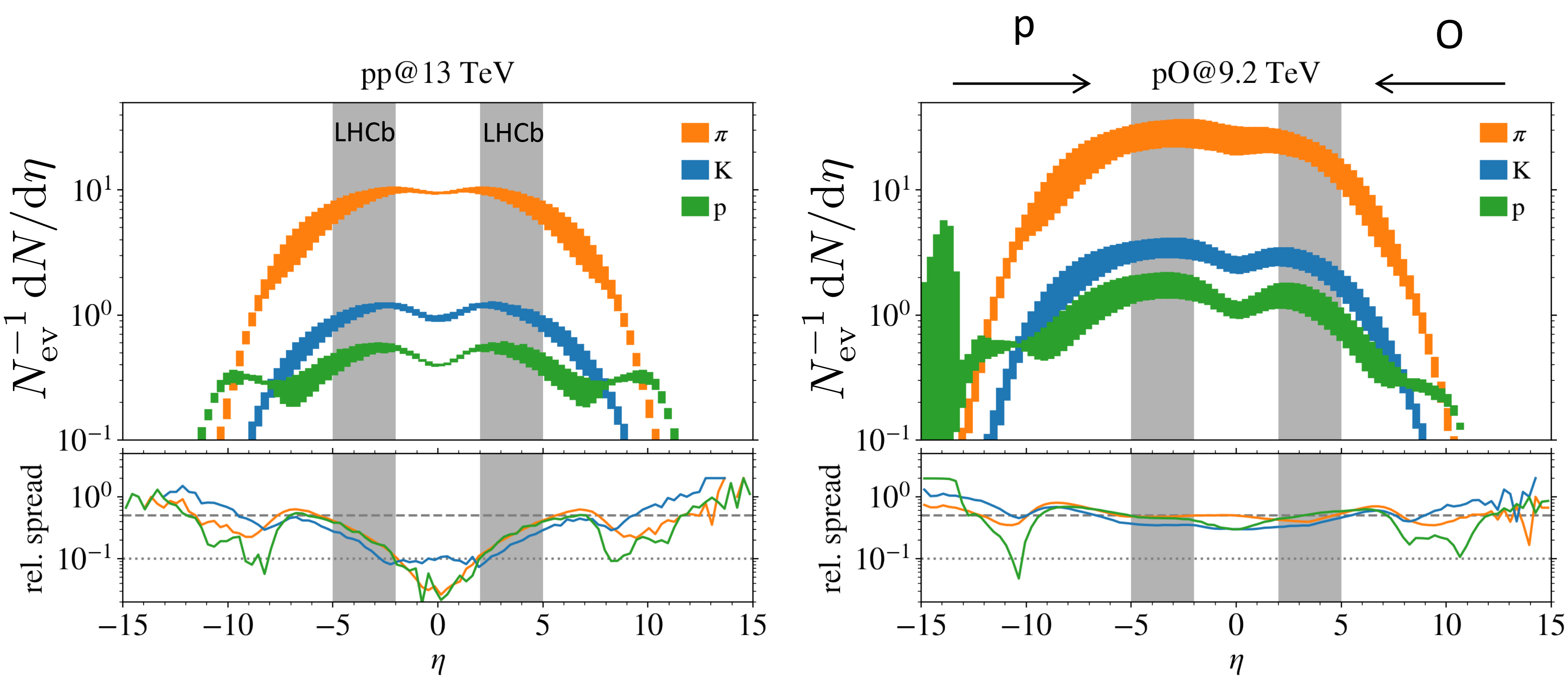
Forward production p-Pb

„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 |η| < 2
- *pp* 10 % model spread, but 50 % spread at eta = 5
- 50 % spread also in *p*-O

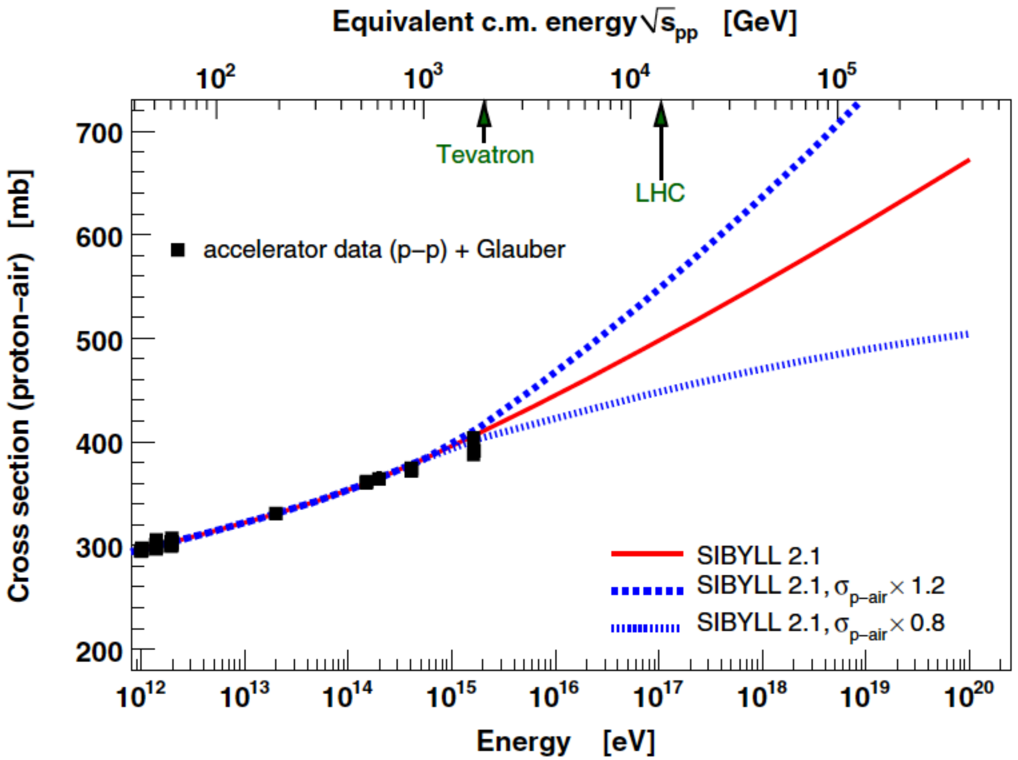
Impact of LHC measurements

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

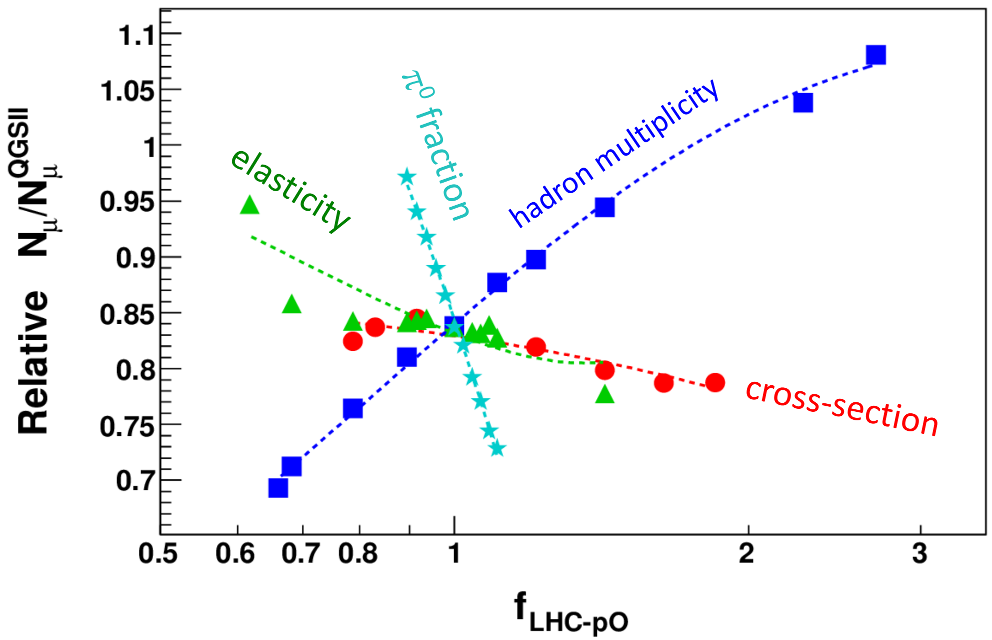
- **cross-section**: inelastic cross-section of all interactions
- **hadron multiplicity**: total number of secondary hadrons
- **elasticity**: $E_{leading}/E_{total}$ (lab frame)
- **π^0 fraction**: (no. of π^0) / (all pions)

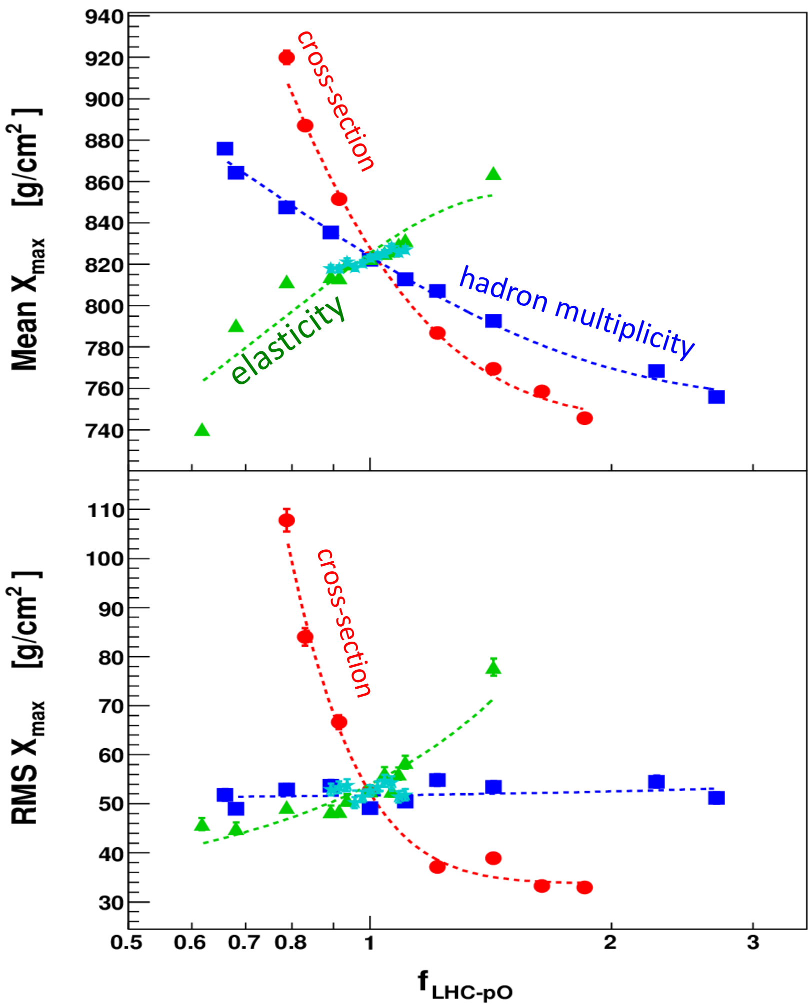


Importance of interaction features

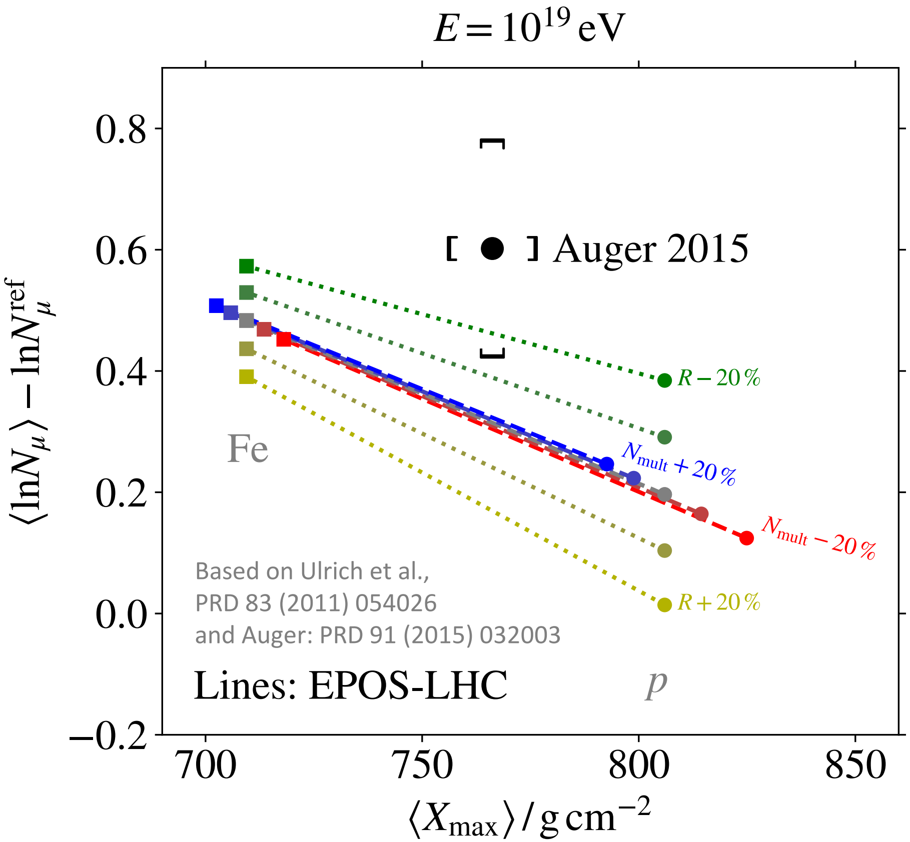
Modified features

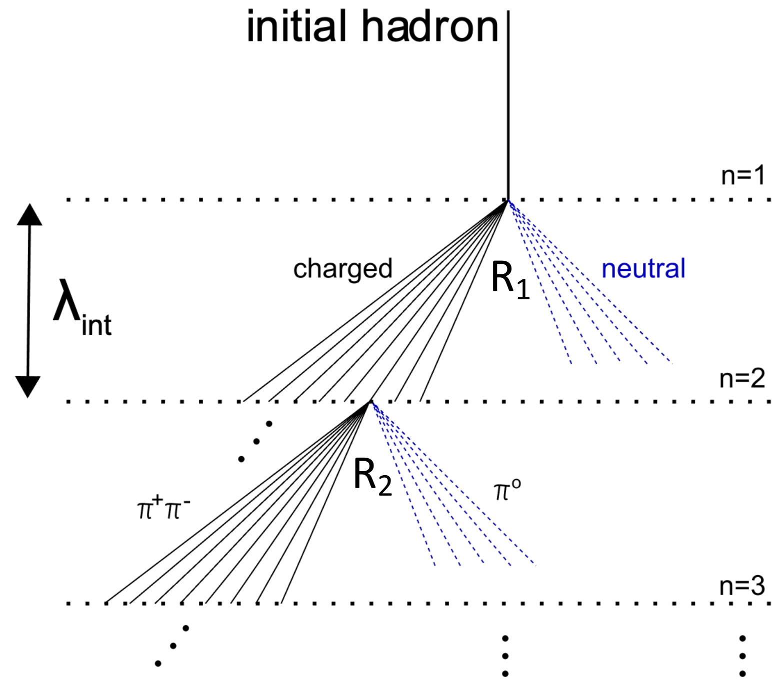
- **cross-section**: inelastic cross-section of all interactions
- **hadron multiplicity**: total number of secondary hadrons
- **elasticity**: $E_{leading}/E_{total}$ (lab frame)
- **π^0 fraction**: (no. of π^0) / (all pions)





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**

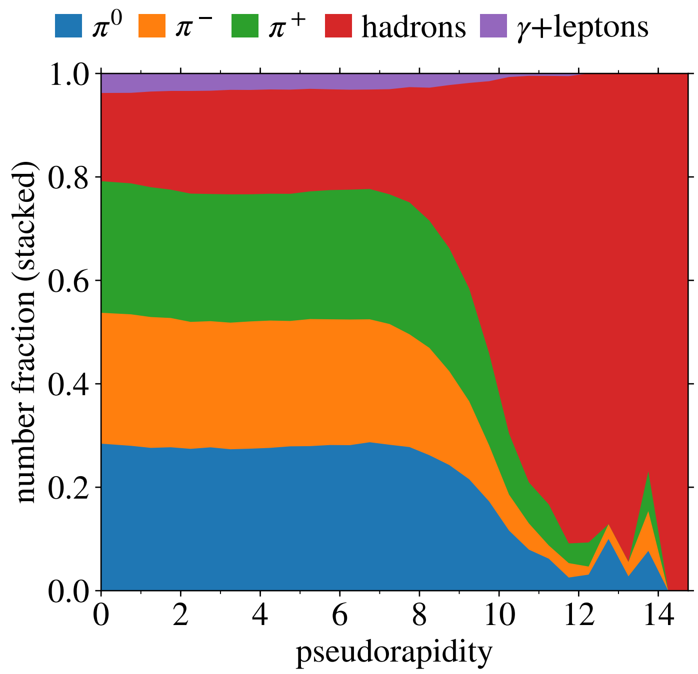
$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

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 yield enhanced in hadron-nuclear collisions, reducing π yield?

pp 13 TeV, EPOS-LHC



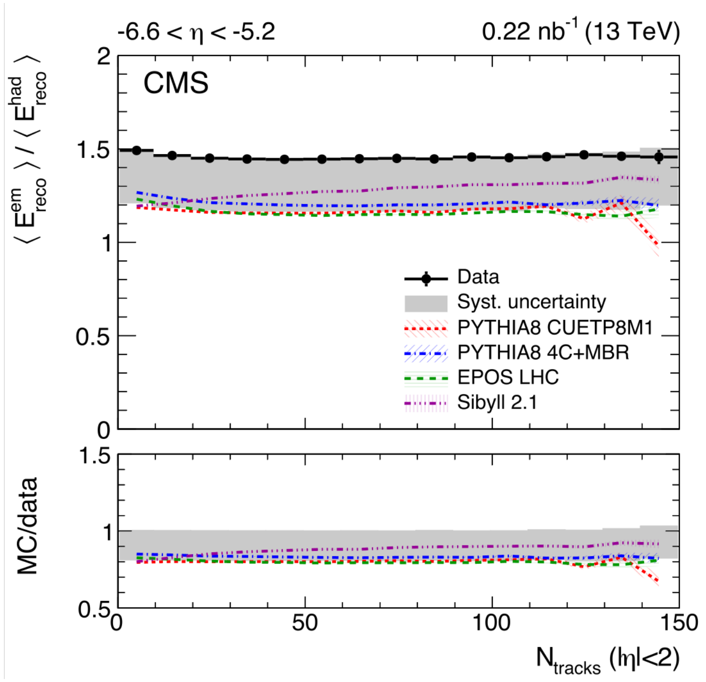
Collective effects may reduce pion fraction, EPOS-LHC predicts drop in R at eta = 0
https://arxiv.org/pdf/1902.09265.pdf

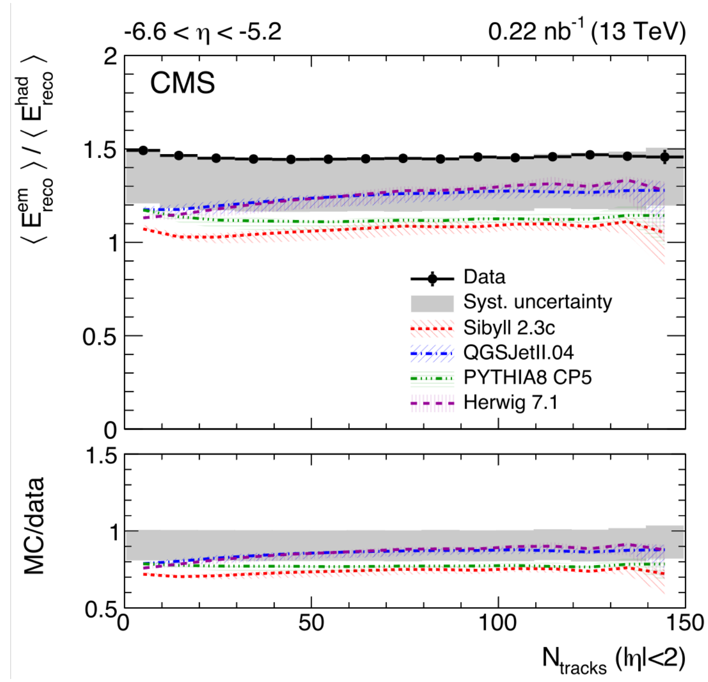
QGP in air showers could enhancing strangeness production, reducing pion fraction
https://arxiv.org/pdf/1612.07328.pdf

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

Proton-oxygen collisions at the LHC

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)

(Submitted on 17 Dec 2018)

Proposed schedule for Run 3 (2018)

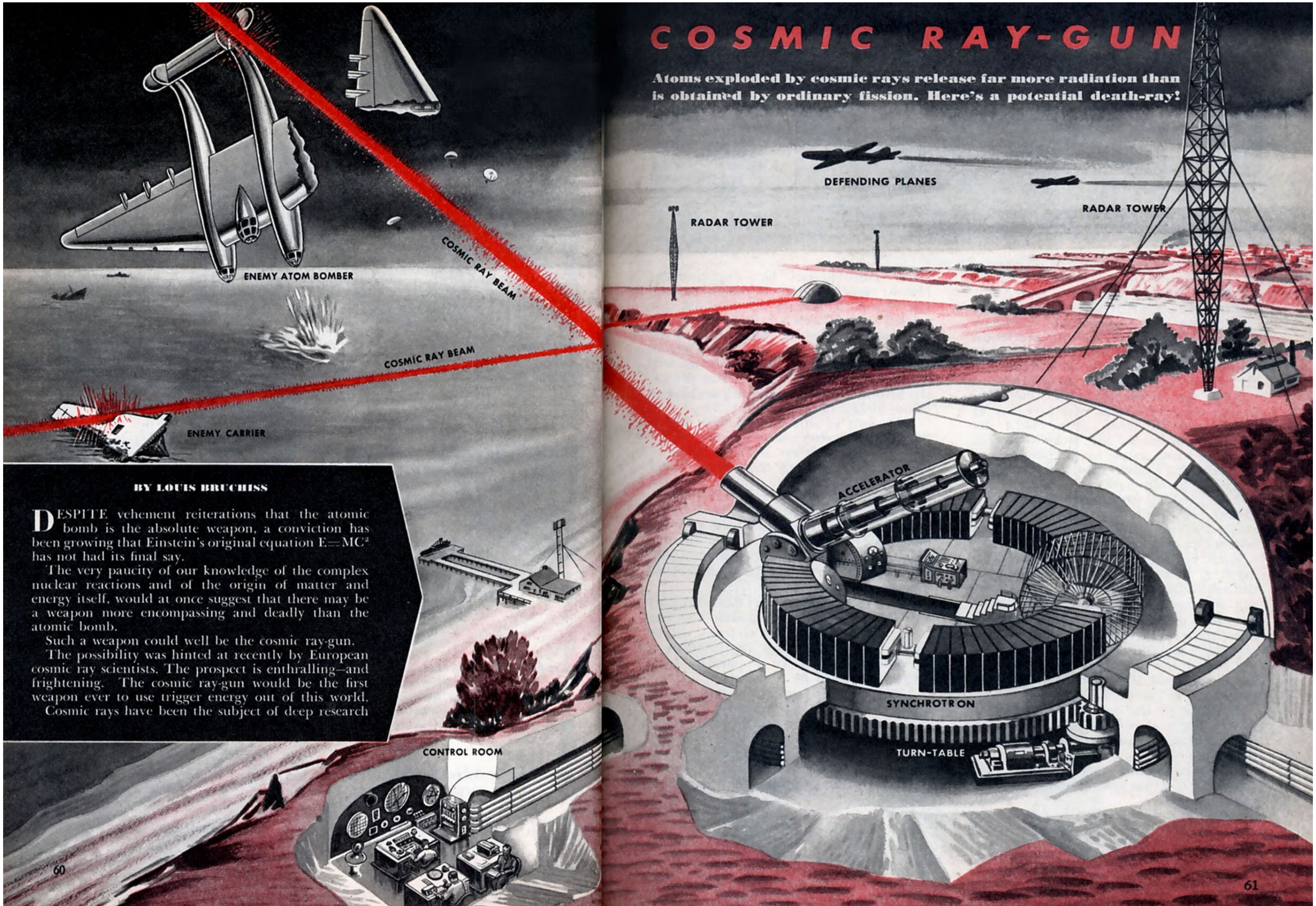
Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-1}
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 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) was requested, also allows to measure charm
- Mid-term budget plan allocated no resources to do oxygen-week in Run 3
  - Delay very bad for cosmic ray experiments, critical for **LHCf** which cannot measure after Run 3
  - Strong response by cosmic ray community in open letter from LHCf to LHCC

Needed data for astroparticle physics

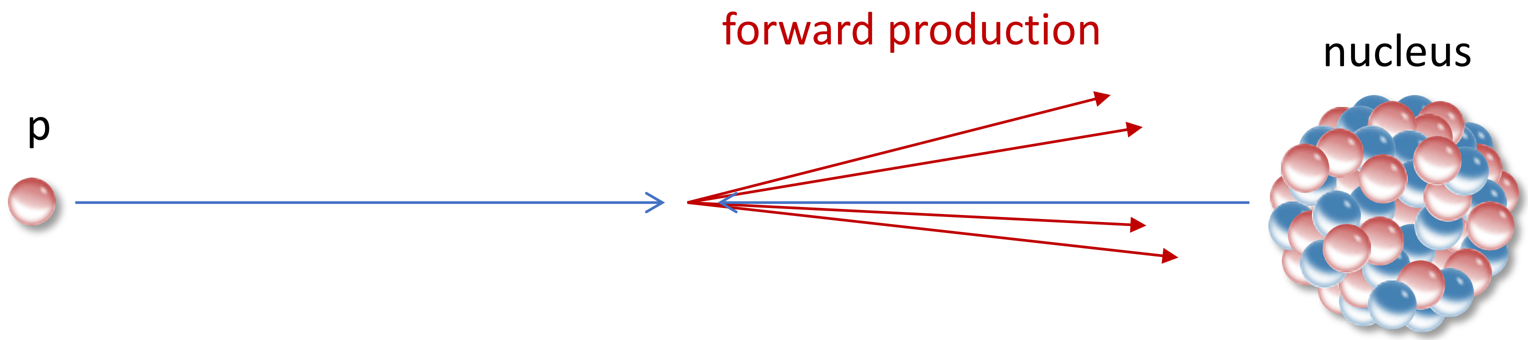
- Collider: p-p, p-Pb, p-O
  - Mimics first interaction in air shower
  - Min-bias data, ideally zero-bias data
  - ALICE, CMS mid-rapidity; LHCb forward
    - Measure rapidity distributions of identified hadrons π, K, p vs. centralicity
  - LHCf extreme forward
    - Measure rapidity distribution of π^0, n
  - ATLAS, CMS, ALICE, LHCb
    - Measure ρ, ϕ for conventional lepton production
    - Measure D, B, μ for prompt lepton production
  - Nuclear modification of these spectra in pA
  - p_T not directly important, but needed to integrate p_T distribution
  - Currently ongoing (supported by German national grant)
    - Measure inclusive spectra of π, K, p at p-p 13 TeV, p-Pb 8.2 TeV
    - Demonstrate impact on air showers with CORSIKA 8 air shower program

- Fixed target (SMOG2): p-p(gas), Pb-p(gas), O-p(gas), p-O(gas)
  - Mimics intermediate stage in air shower
  - Same measurements as in collider mode
  - Highest cms energy every achieved in fixed target experiment
  - p_T distribution important for lateral spread of muons in air showers
  - Model/data discrepancies seen at lower cms energy by NA61
  - Complement but cannot replace p-O collider measurements due to lower sqrt(s)


COSMIC RAY-GUN
Atoms exploded by cosmic rays release far more radiation than is obtained by ordinary fission. Here's a potential death-ray!
BY LOUIS BRUCHISS
DESPITE vehement reiterations that the atomic bomb is the absolute weapon, a conviction has been growing that Einstein's original equation E=MC² has not had its final say.
The very paucity of our knowledge of the complex nuclear reactions and of the origin of matter and energy itself, would at once suggest that there may be a weapon more encompassing and deadly than the atomic bomb.
Such a weapon could well be the cosmic ray-gun.
The possibility was hinted at recently by European cosmic ray scientists. The prospect is enthralling—and frightening. The cosmic ray-gun would be the first weapon ever to use trigger energy out of this world.
Cosmic rays have been the subject of deep research
ENEMY ATOM BOMBER
COSMIC RAY BEAM
COSMIC RAY BEAM
ENEMY CARRIER
CONTROL ROOM
DEFENDING PLANES
RADAR TOWER
RADAR TOWER
ACCELERATOR
SYNCHROTRON
TURN-TABLE
60
61

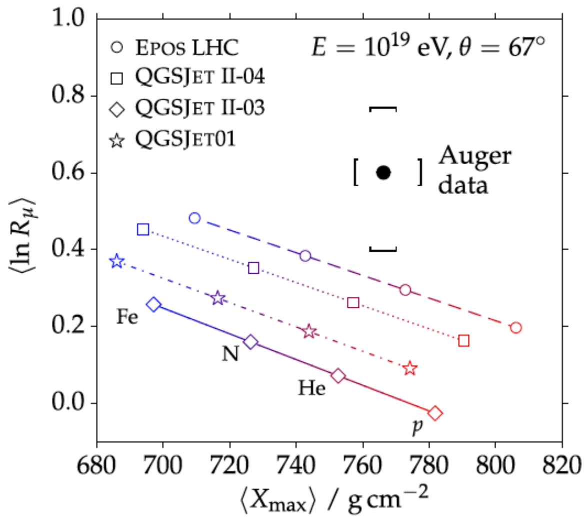
Backup

Nuclear effects



For forward produced particles
longitudinal parton momentum high (high x)
Compton wavelength small
Large contribution from valence quarks

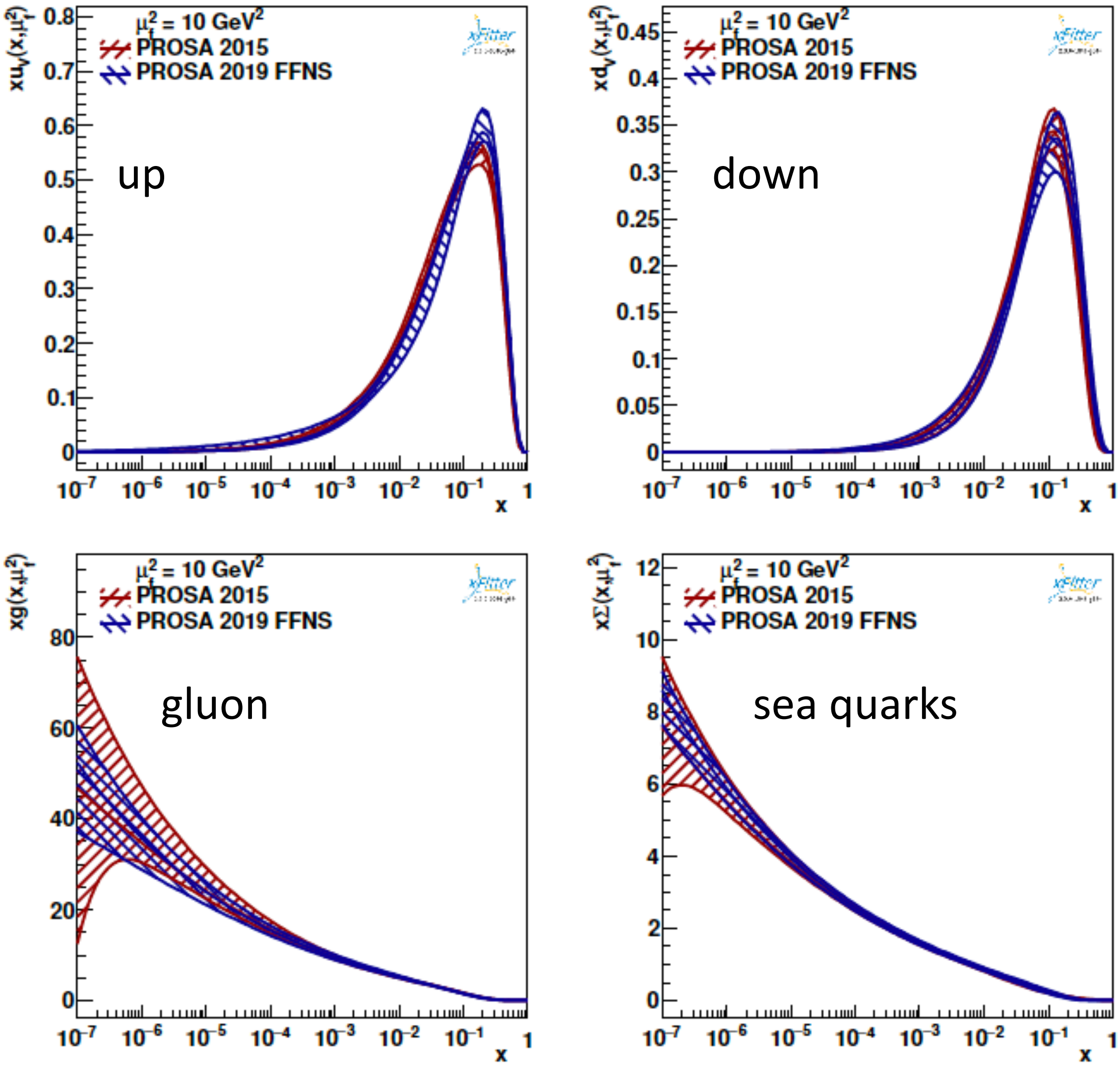
For forward produced particles
longitudinal parton momentum low (low x)
Compton wavelength large
Large contribution from gluons



- Model lines **parallel**, because of superposition in **projectile**
- Model line **offsets** from nuclear effects in **target**

- Essential: Measure *p*-O
- Bonus: Measure O-O

(Proton) Parton density functions



PROSA collab.
JHEP04(2020)118

- Low x
  - Large uncertainties
  - Large contribution to cross-sections
  - Note scaling with x
- Gluon density ≫ sea quark density (about 8x)
- Data down to $x \approx 10^{-6}$

Nuclear modification

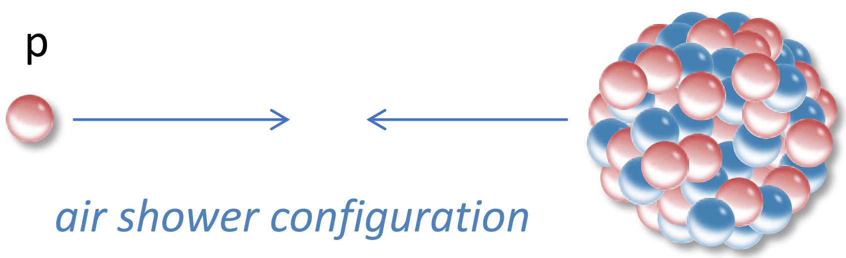
Nuclear modification factor

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

Superposition: $R_{pA} = 1$

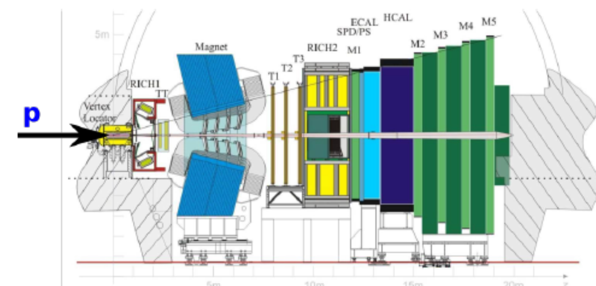
p

Pb



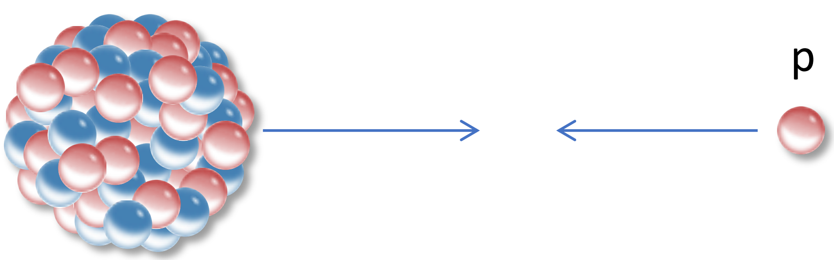
air shower configuration

"forward"

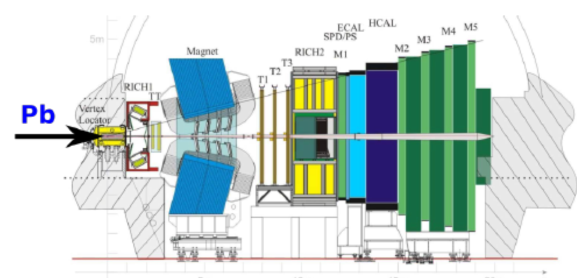


Pb

p

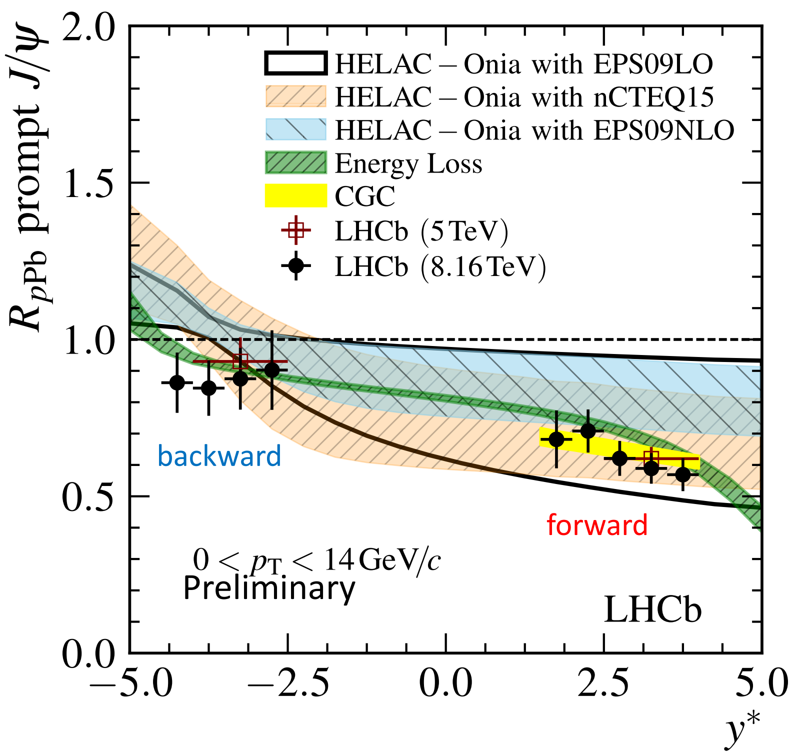


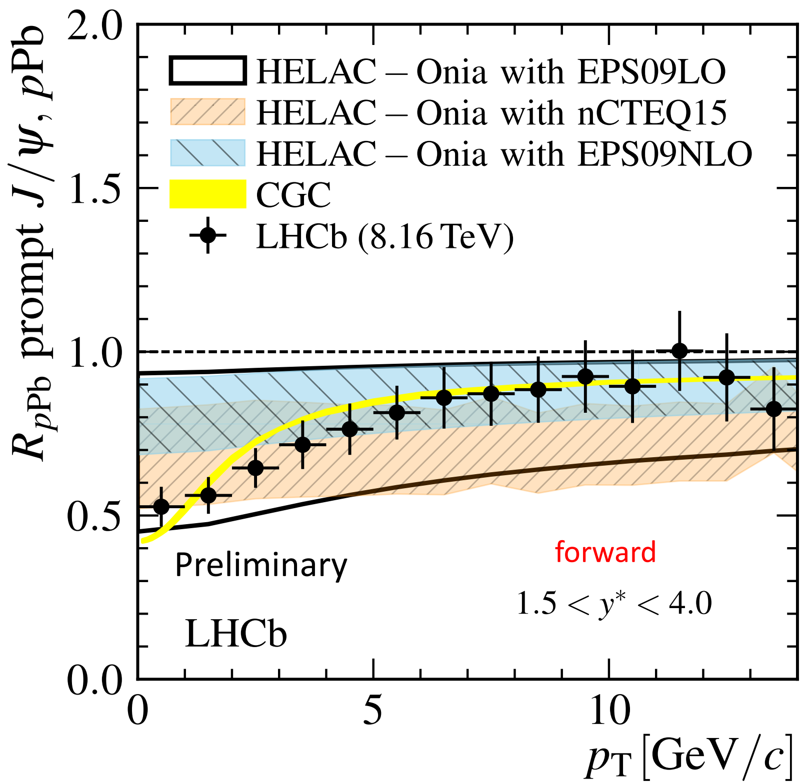
"backward"



Nuclear effects in forward J/Ψ production

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

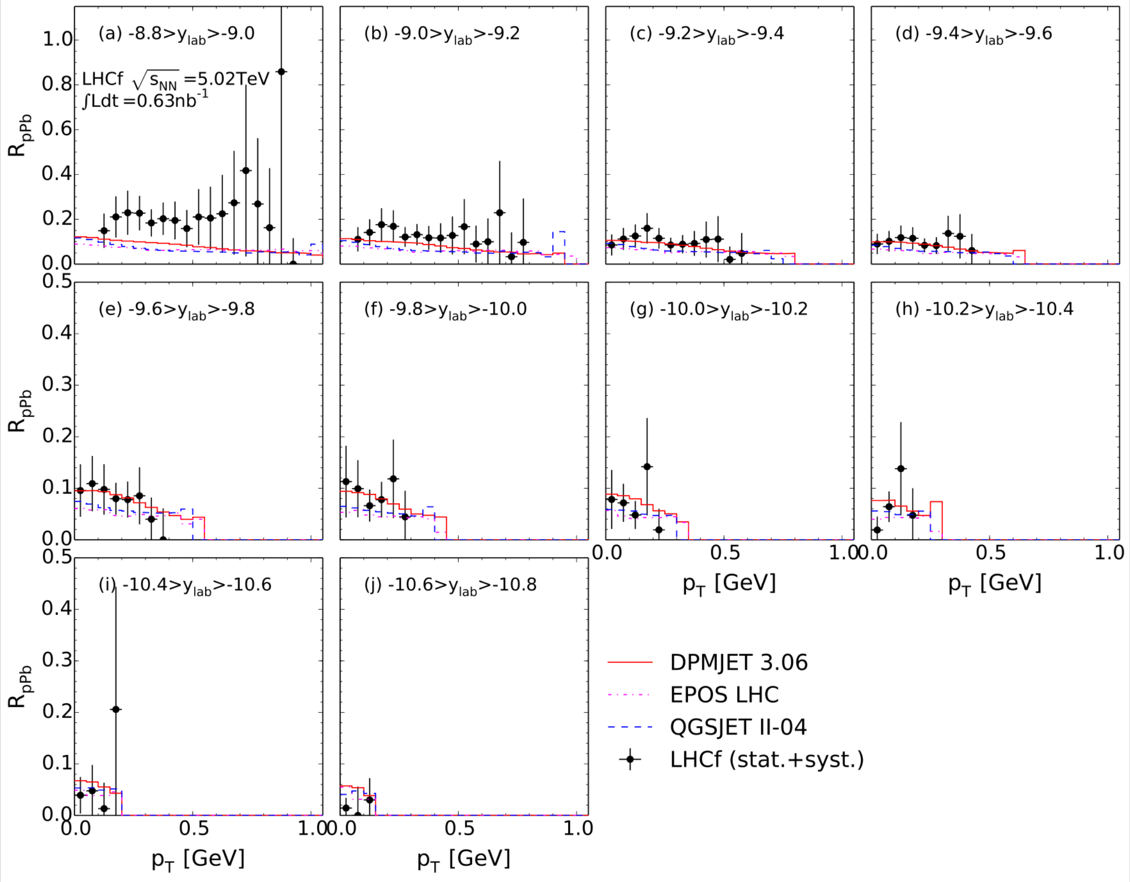




- Up to 50 % suppression in forward direction
- Especially strong where relevant for CR!

Nuclear effects in forward π^0 producton

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

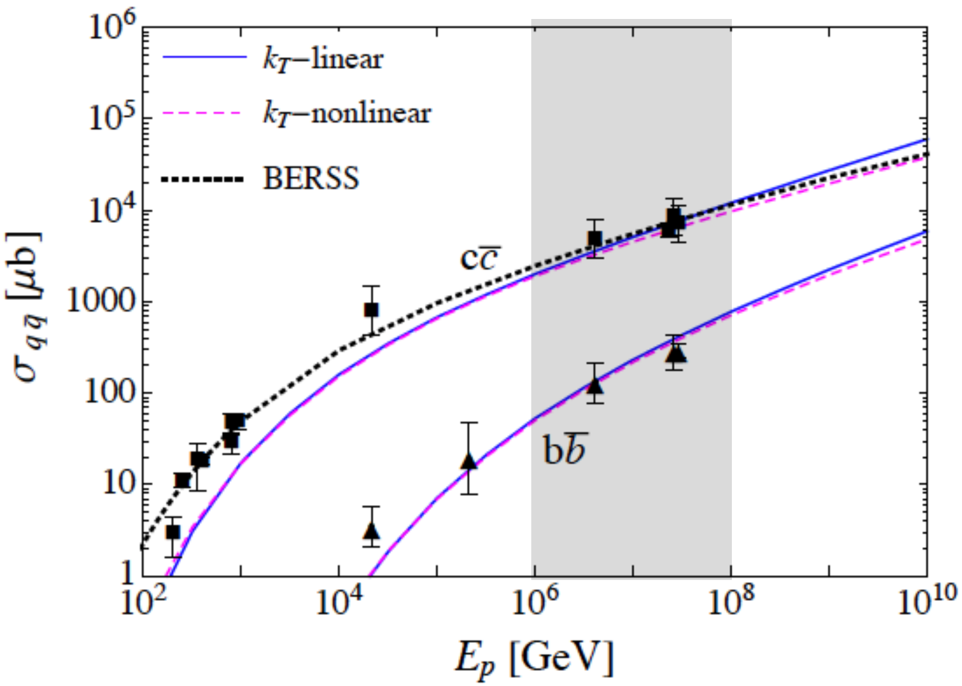


Strong suppression for π^0 production in far forward (as predicted by current models)

Importance of c,b-hadrons for prompt lepton production

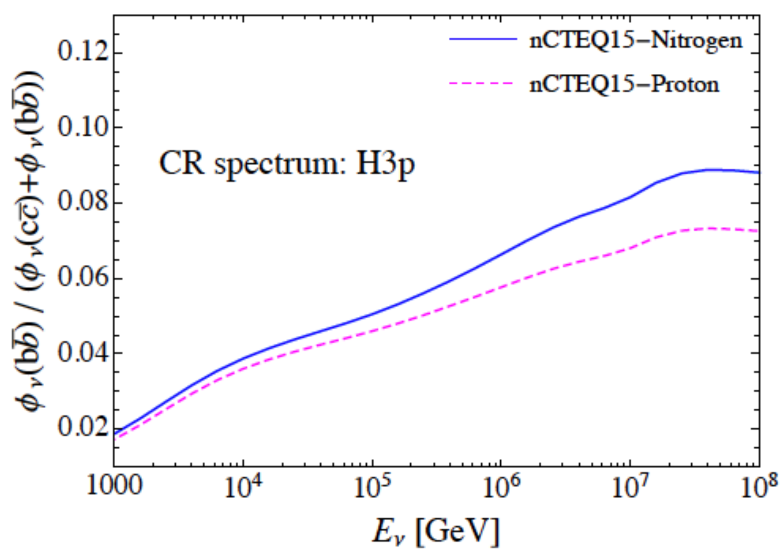
Bhattacharya et al., JHEP11(2016)167

Energy range of interest for IceCube



How to make a prompt lepton

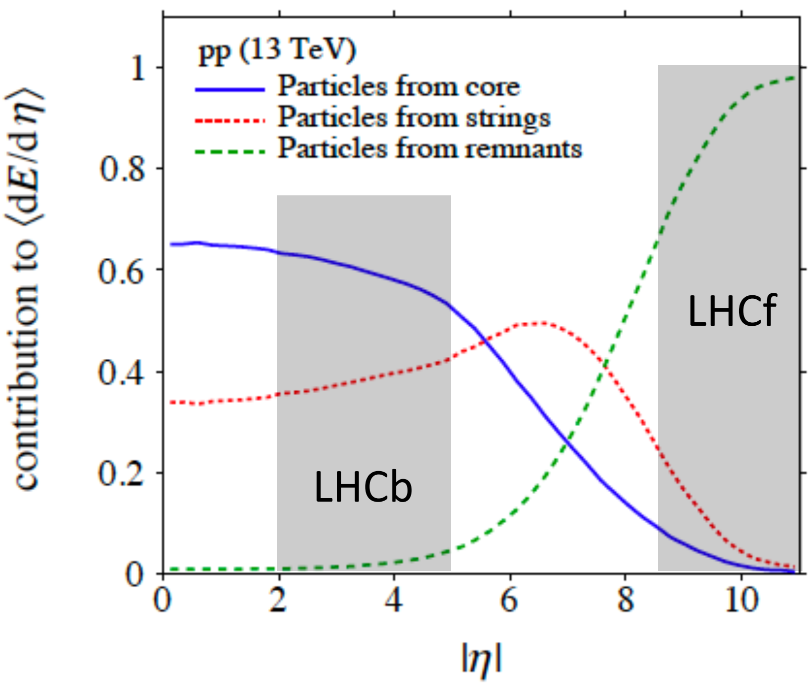
- qqbar -> hadronization -> decay
- Large uncertainties in hadronization
- Hadronization measured in ep, but certain effects only visible in pp

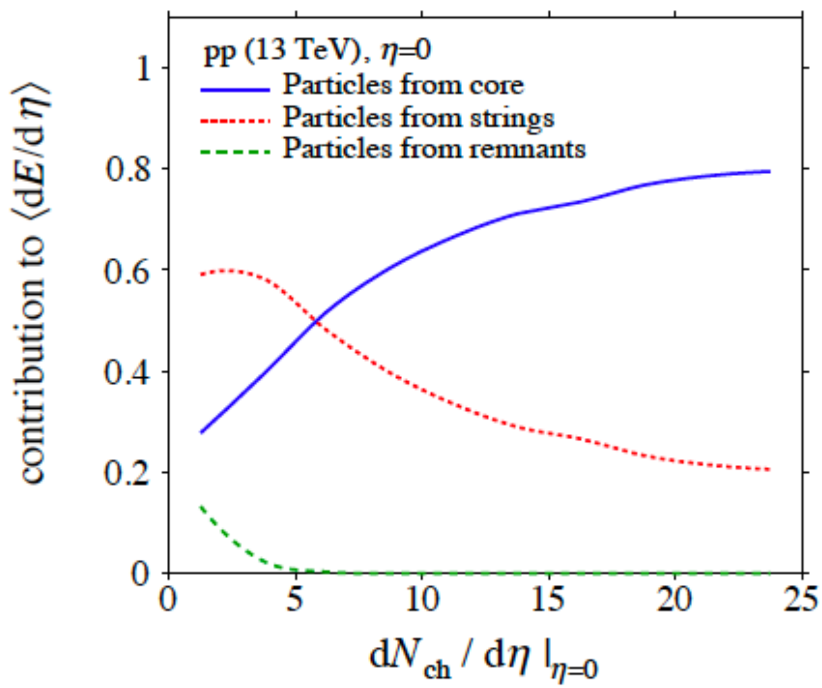


Forward production and QGP

Baur, Dembinski, Perlin, Pierog, Ulrich, Werner (2019) arXiv:1902.09265

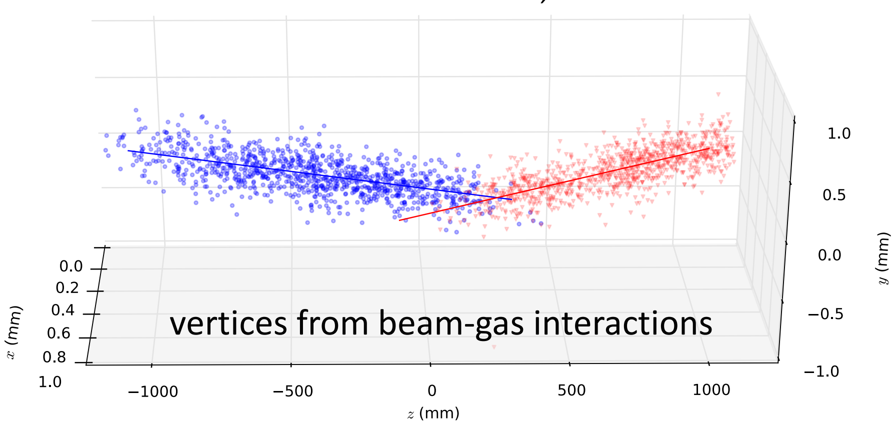
EPOS model: LHCb covers transition from core (QGP formation) to peripherial physics

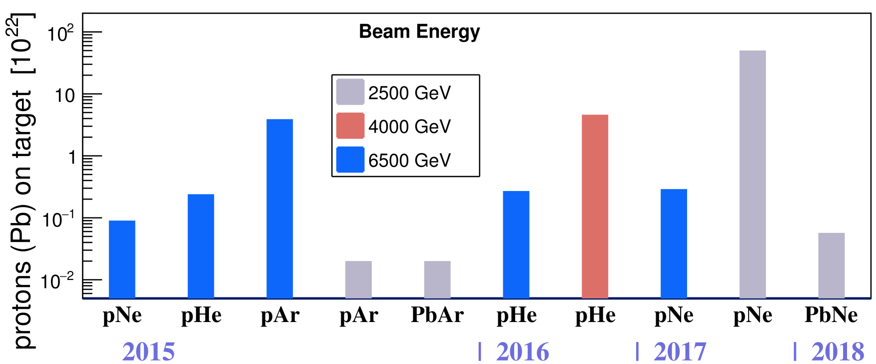




Need to measure hadron spectra as function of centralicity proxy like $dN_{ch}/d\eta|_{\eta = 0}$

LHCb SMOG system





JINST 9 (2014) P12005

System for **M**easuring **O**verlap with **G**as

- Inject He, Ne, Ar at ~2x10^{-7} mbar
- Designed to measure beam profile
- Allows data taking in **fixed target mode**

SMOG2

- More gas targets
  He, Ne, Ar, Kr, Xe, H_2, D_2, N_2, O_2
- Higher gas density, well controlled (accurate luminosity)
- Can run parasitically during normal operation
- Smaller acceptance $3 < \eta < 5$, but not an issue