Max-Planck-Institut für Kernphysik Heidelberg

Karlsruher Institut für Technologie

Future proton-oxygen beam collisions at the LHC for air shower physics

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PoS(ICRC2019)235

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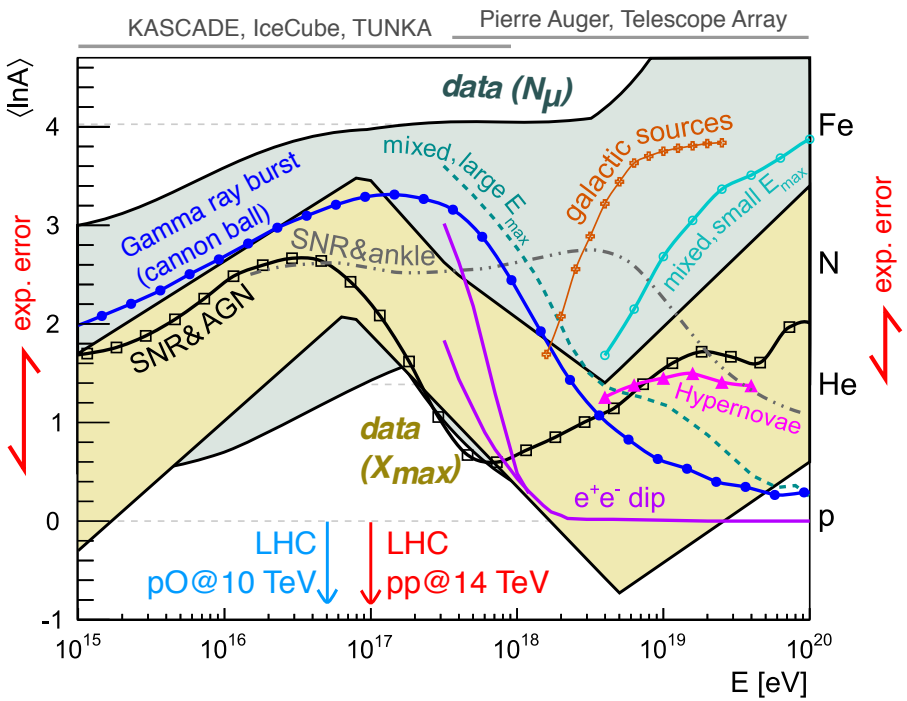
Take-home message

- p-O and O-O collisions at LHC planned for 2023
  - Science case in Yellow Report *CERN-LPCC-2018-07, arXiv:1812.06772*
  - 1 week of data taking to collect 2 nb^{-1}
  - Support from ATLAS, CMS, ALICE; strong support from LHCf and LHCb

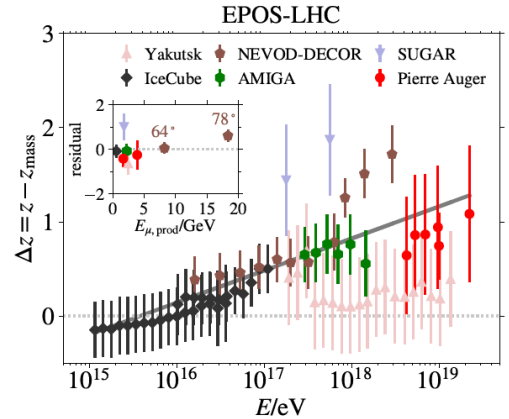
- Primary motivation from understanding cosmic-ray induced air showers and solving *Muon Puzzle*
  - Solve Muon Puzzle by measuring **energy fraction** carried by π^0
  - Measure **nuclear effects** in light ion collisions
  - Measuring **rapidity spectra** and improve accuracy of depth of shower maximum predictions to better than 10 %

Motivation



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

X_{max} depth of shower maximum
N_μ number of muons in shower



8σ Muon Puzzle, see *L. Cazon et al. PoS(ICRC2019)214*

HD et al (EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, Pierre Auger, SUGAR, Telescope Array, and Yakutsk EAS collab.) EPJ Web Conf. 210 (2019) 02004

Astrophysical origins of cosmic rays?

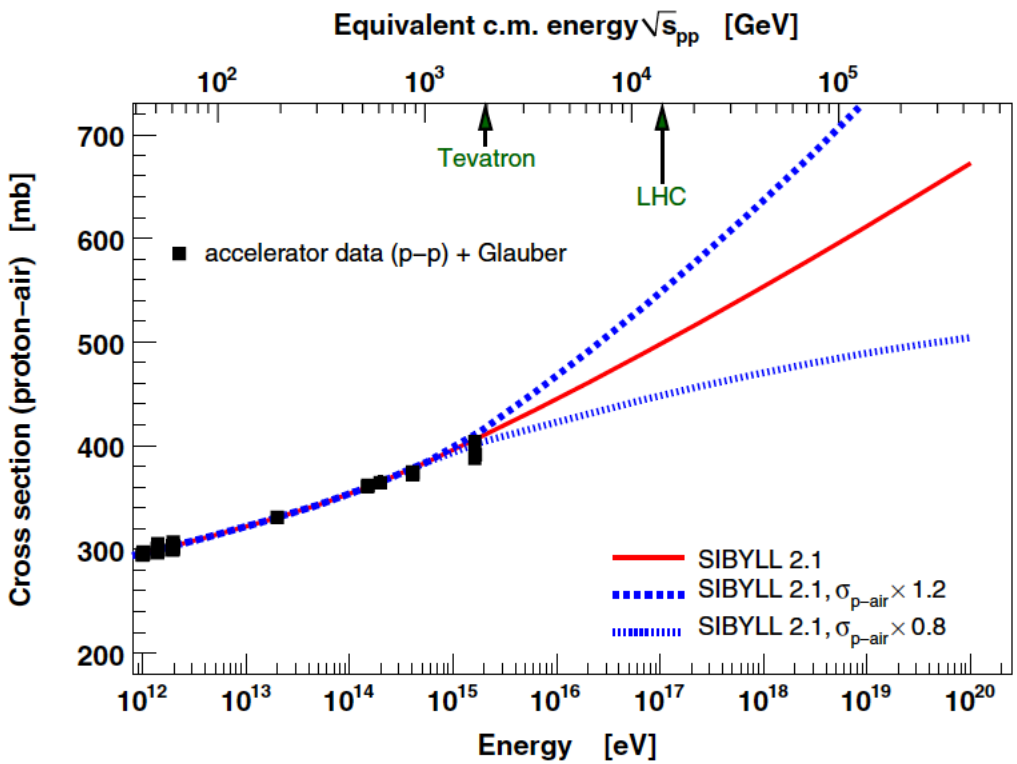
- Mass composition (<lnA>) carries imprint of sources & propagation, inferred from $\mathbf{X_{max}}$ & $\mathbf{N_\mu}$
- Accuracy of <lnA> limited by **hadronic interaction generators** used in air shower simulations (achievable is 10 % of p-Fe distance)
- **Muon Puzzle: 8σ** discrepancy between air shower simulations and data from 8 experiments
- LHC can simulate first interaction of **50 PeV** air shower with p-O collision at √s = **10 TeV**

Impact of hadronic interactions

R. Ulrich, R. Engel, M. Unger, 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

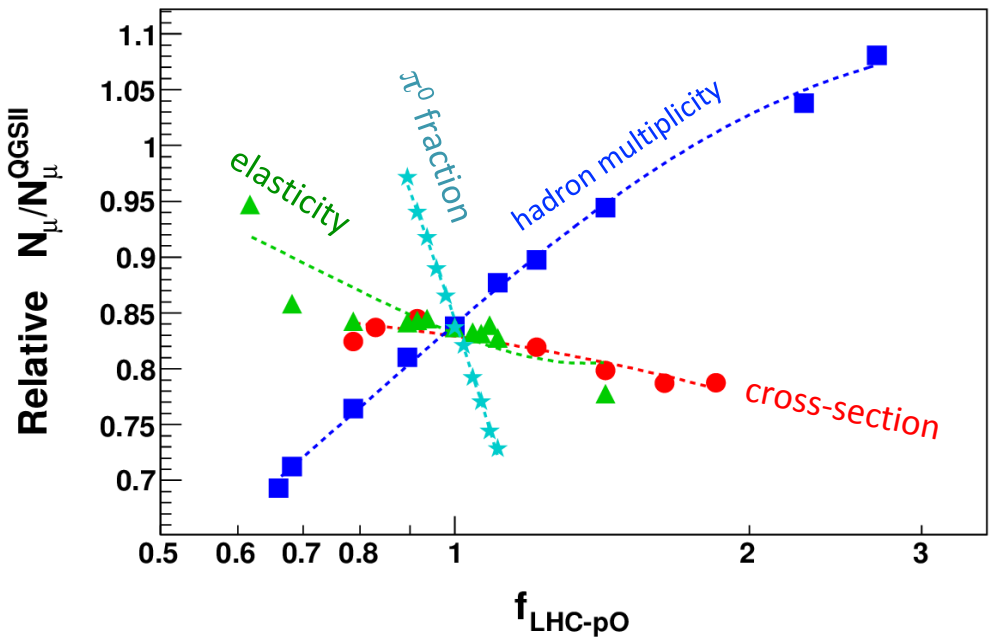
Modified features

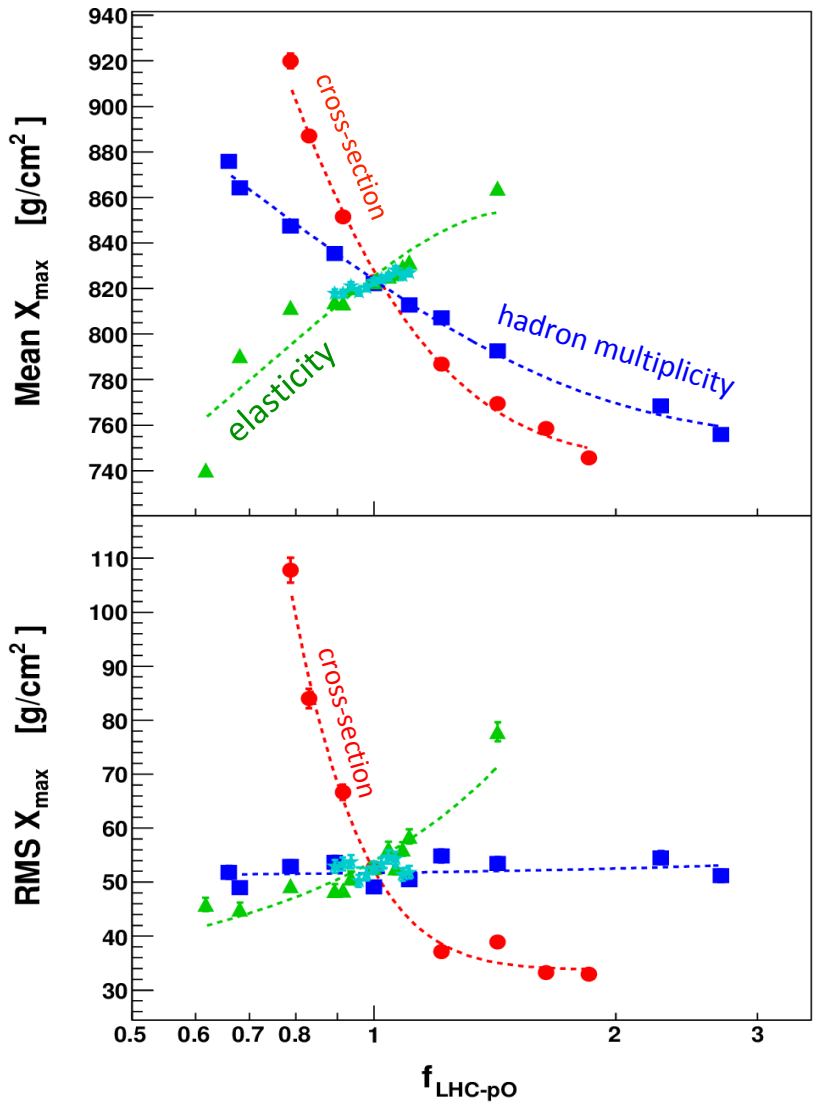
- **cross-section**: inelastic cross-section of all interactions
- **hadron multiplicity**: total number of secondary hadrons
- **elasticity**: $E_{leading}/E_{total}$ (lab frame)
- **π^0 fraction**: (no. of π^0) / (all pions)



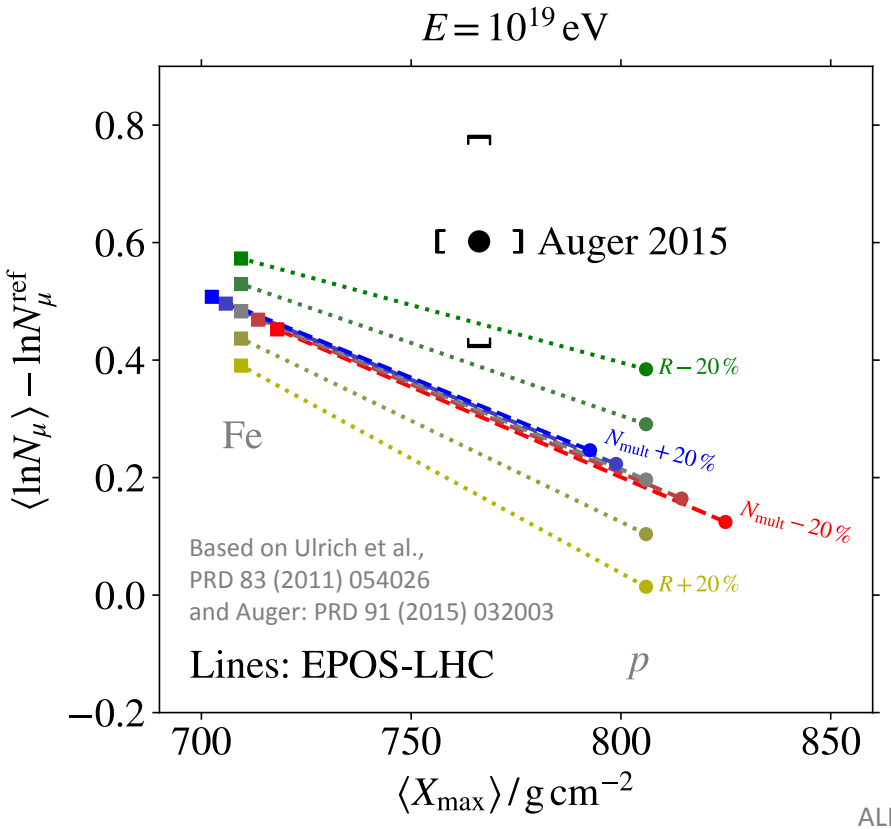
Impact of hadronic interactions

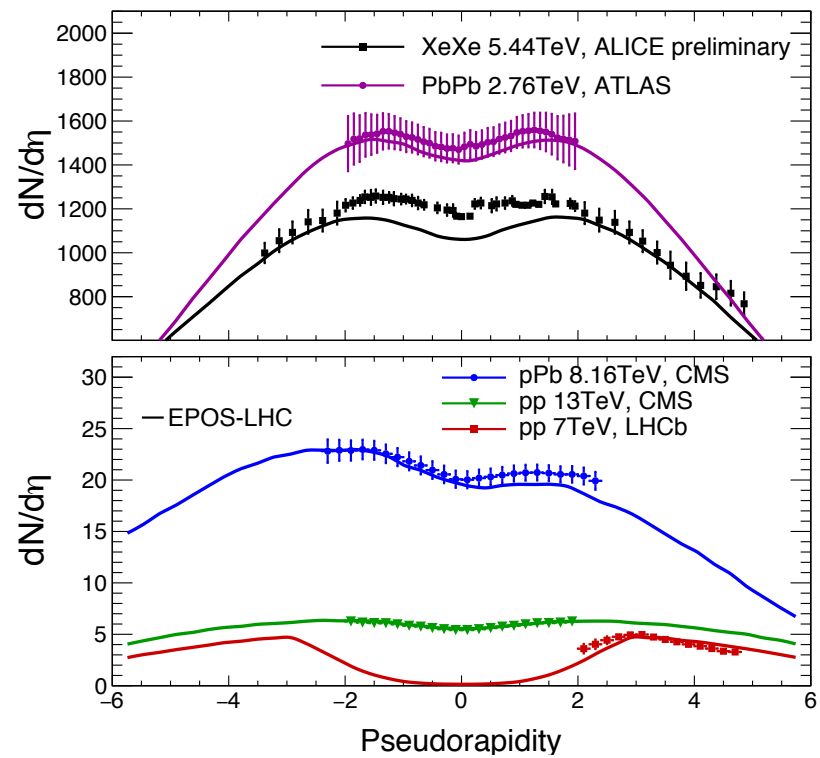
- X_{max} sensitive to
  - inelastic cross-section (*very* sensitive)
    High-precision measurements from LHC, see e.g. *LHCb collab. JHEP 1806 (2018) 100* and refs. therein
  - hadron multiplicity
- N_μ sensitive to
  - **π^0 fraction (*very* sensitive)**
  - hadron multiplicity





Impact of LHC measurements





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

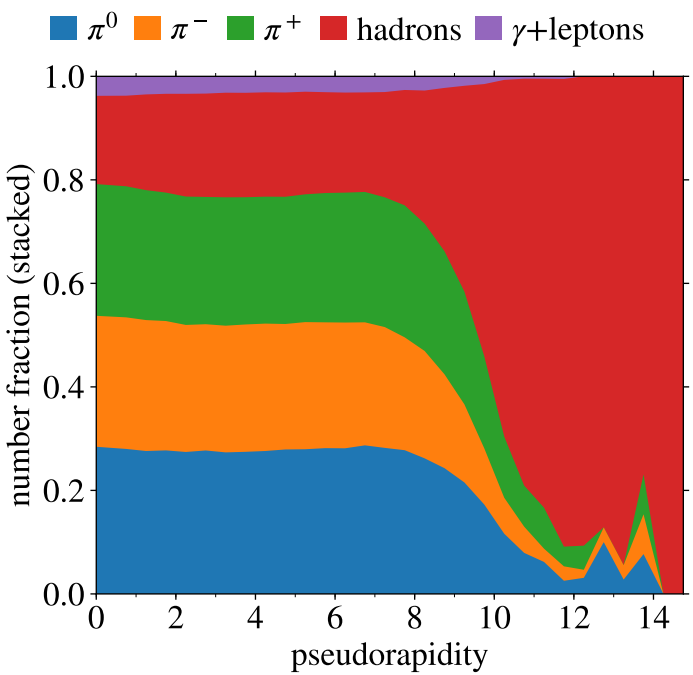
- Need to reduce π^0 **fraction** to solve the Muon Puzzle or rather ***R***
- Measure **hadron multiplicity** to improve X_{max} and N_μ predictions
- Expected: **nuclear modification** of forward-produced hadrons

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

Possibilities to reduce *R*

$N_{\pi\text{-charged}} = 2N_{\pi\text{-neutral}}$ (isospin symmetry), but π/hadron ratio not fixed

pp 13 TeV, EPOS-LHC



Collective effects may reduce pion fraction, EPOS-LHC predicts drop in R at eta = 0

S. Baur, HD, T. Pierog, R. Ulrich, K. Werner, arXiv:1902.09265

Also see *T. Pierog et al. PoS(ICRC2019)387*

Strangeness production in p-O underestimated?

L.A. Anchordoqui, H. Goldberg, T.J. Weiler, Phys. Rev. D 95, 063005 (2017) arXiv:1612.07328

Enhancement of strangeness production observed in central collisions in pp and p-Pb

ALICE collab., Nature Phys. 13 (2017) 535

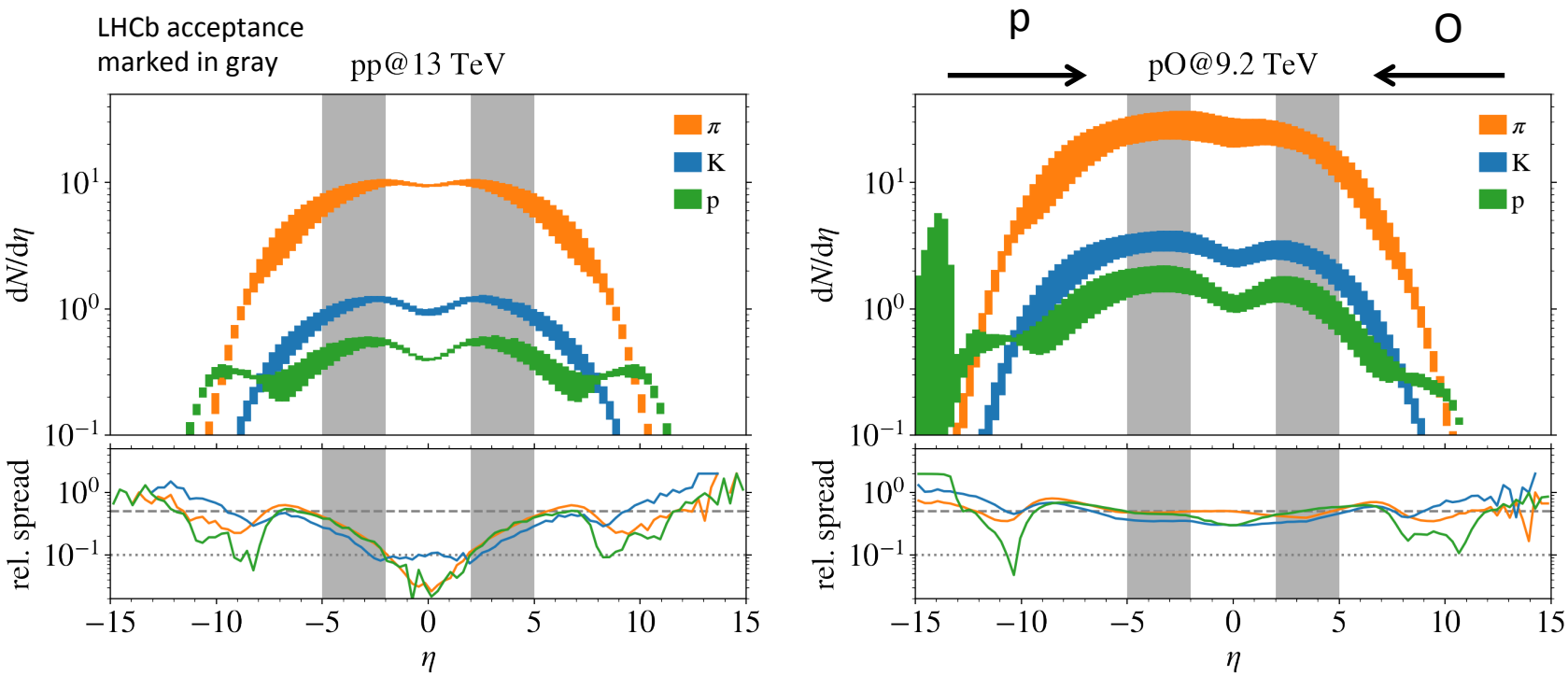
R in pp at 5.2 < |eta| < 6.6 **higher** than in models

CMS collab. CMS-PAS-FSQ-18-001 (2019)

Also see *S. Baur et al. PoS(ICRC2019)188*

Nuclear modification uncertainties

- Simulation of pions, kaons, protons spectra with CRMC *https://web.ikp.kit.edu/rulrich/crmc.html*
- Model spread of EPOS-LHC, QGSJet-II.04, SIBYLL-2.3 for pions, kaons, protons



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

Proton-Oxygen at the LHC

Cornell University

We gratefully acknowledge support from the Simons Foundation and member institutions.

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)

(Submitted on 17 Dec 2018)

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Section **11.3** by HD, R. Ulrich, T. Pierog et al. with p-O science case

Proposed run schedule

Z. Citron et al., CERN-LPCC-2018-07, arXiv:1812.06772 [hep-ph]

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	

- Latest plans moved data taking to 2023
- 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

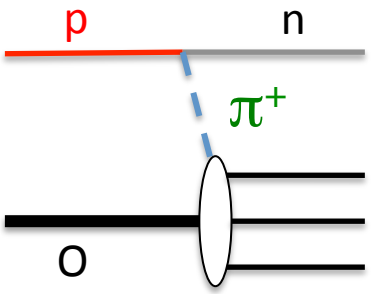
Summary

- p-O and O-O collisions at LHC planned for 2023
  - Science case in Yellow Report CERN-LPCC-2018-07
  - 1 week of data taking to collect **2 nb^{-1}**
  - Support from ATLAS, CMS, ALICE; strong support from **LHCf** and **LHCb**

- Primary motivation from cosmic-ray induced air showers
  - Potentially solve Muon Puzzle by measuring π^0 **energy fraction**
  - Clarify size of **nuclear effects** in light ion collisions
  - Measure **rapidity spectra** to achieve X_{max} accuracy better than 10 gcm^{-2}

- Proposed measurements at the LHC
  - ATLAS & CMS (no PID): measure separately energy flows in ECal, HCal
  - ALICE, LHCb (has PID): measure identified rapidity spectra of π, K, p
  - LHCf: measure π^0 and neutrons in very forward

Outlook

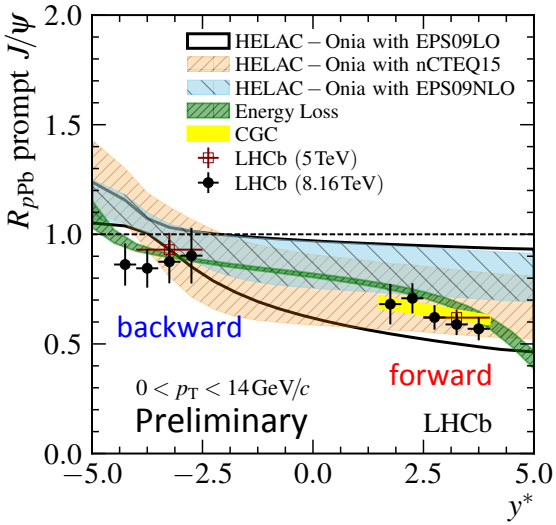


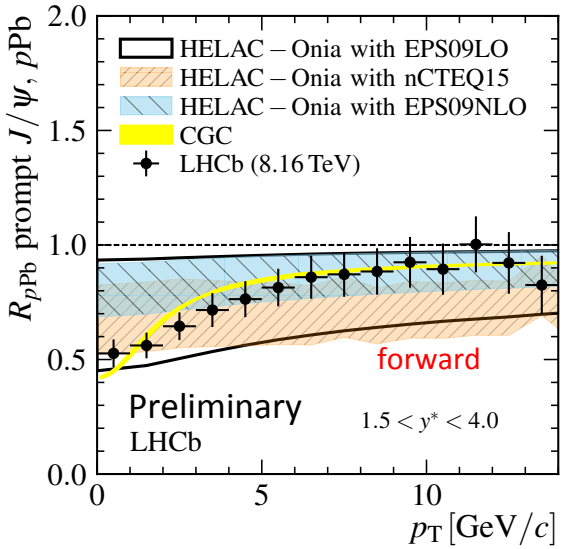
- π-O interactions with **forward neutron tagging**?
  - Need to tag "single diffractive" events with isolated neutron
    V.A. Petrov et al., Eur.Phys.J. C65 (2010) 637-647
  - Model-dependent pre-evolution (pomeron interactions of p-O)

- CORSIKA 8
  - Successor of CORSIKA 7 in modular C++
  - **Unified** tool to simulate air showers and LHC events
  - Allow for **ad hoc tuning** of generator output
  - See Posters 30-31 Jul, **Great Hall, 4th Floor**
    D. Baack PS3-142, HD PS3-157, M. Reininghaus PS3-206

- Bonus problem: simulations of **100 GeV air showers** very uncertain
  - Large discrepancies in muon & electron LDF found in 100 GeV showers
    H. Schoorlemmer, A. Pastor, R.D. Parsons, PoS(ICRC2019)417;
    also see *arXiv:1904.0513* (accepted by PRD)
  - Potential to measure muon LDF of 100 GeV showers with CTA
    A.M.W. Mitchell, HD, R.D. Parsons, PoS(ICRC2019)351;
    also see *Astropart. Phys. 111 (2019) 23*

Nuclear effects in prompt J/ψ production



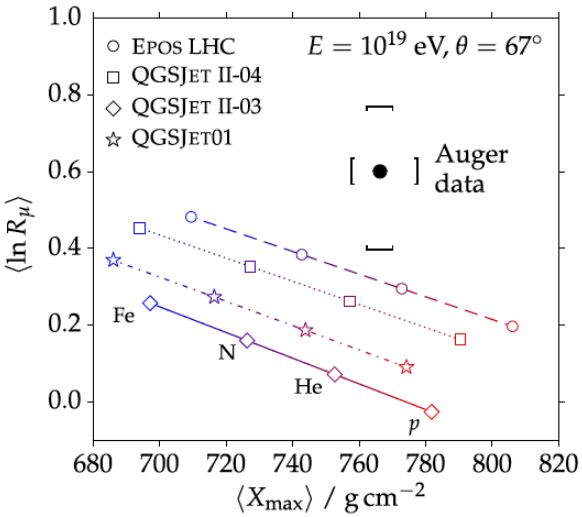


LHCb collab.
Phys. Lett. B774 (2017) 159

Up to 50 % suppression in forward direction

Especially strong where relevant for CR!

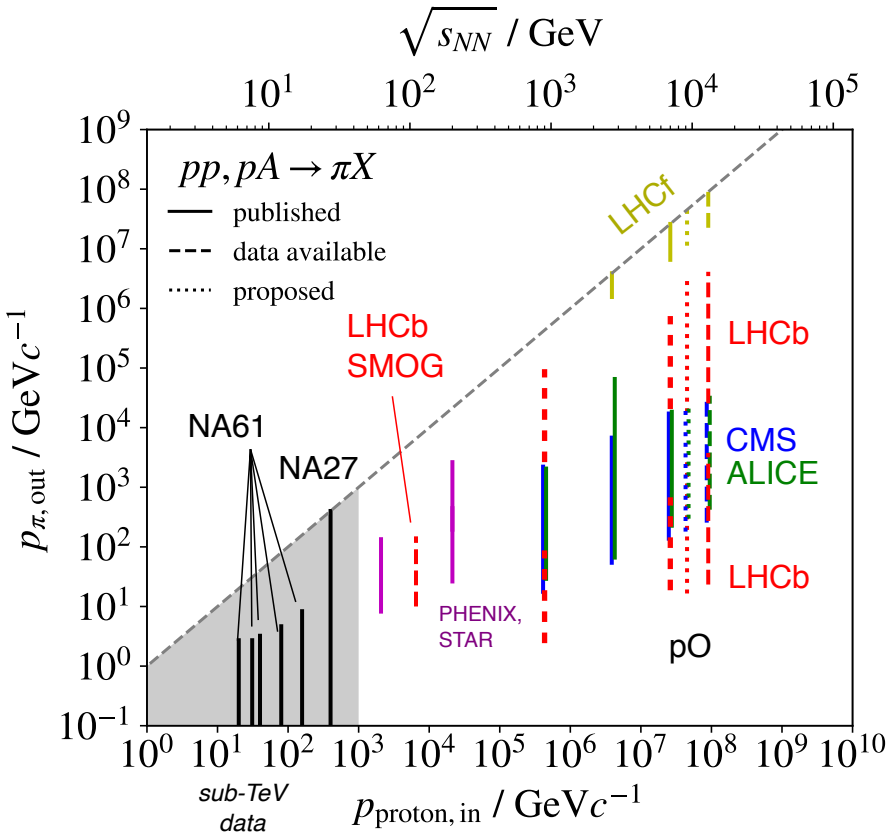
Similar effects *expected* in pion production



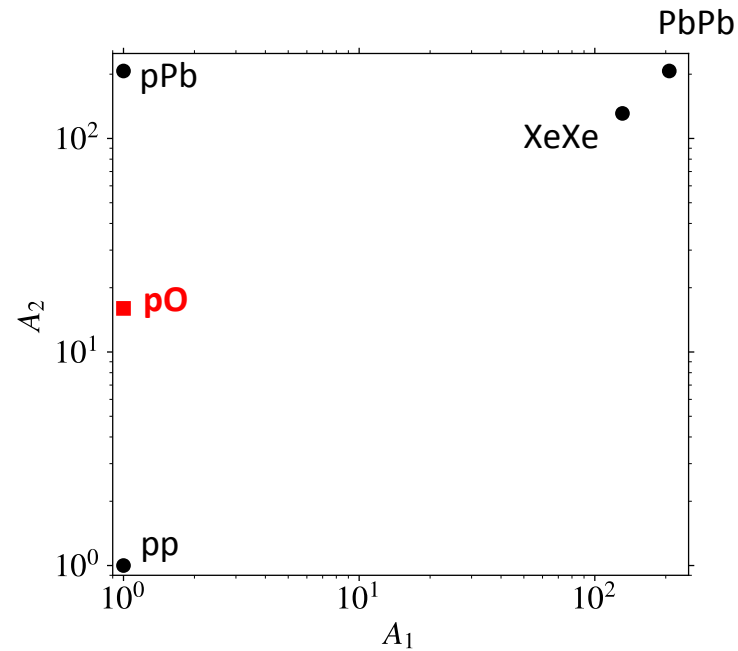
- Model lines **parallel**, because of approx. superposition
- Model line **offsets** from nuclear effects (forward effects)

Only need to measure pO, not FeO!

LHC and data on pion production



LHC collision systems



- Most common interaction in air shower is **π-N**, use **p-O** as proxy
- Need more data on light hadron production in forward direction
- Do properties scale from **pp** to **p-O** to **p-Pb** or different regimes?

LDF spread

R.D. Parsons and H. Schoorlemmer, arXiv:1904.0513, submitted to PRD

- CORSIKA simulations
  - 100 GeV to 100 TeV
  - UrQMD for E < 80 GeV
  - Varying high-energy model
- Huge discrepancies in eγ-LDF and μ-LDF in 100 GeV showers
- Correlated effects in LDFs
  - QGSJet-II.04 high
  - UrQMD low