Proton-oxygen collisions for cosmic ray research: an update

HL-LHC Workshop, June 2018, CERN

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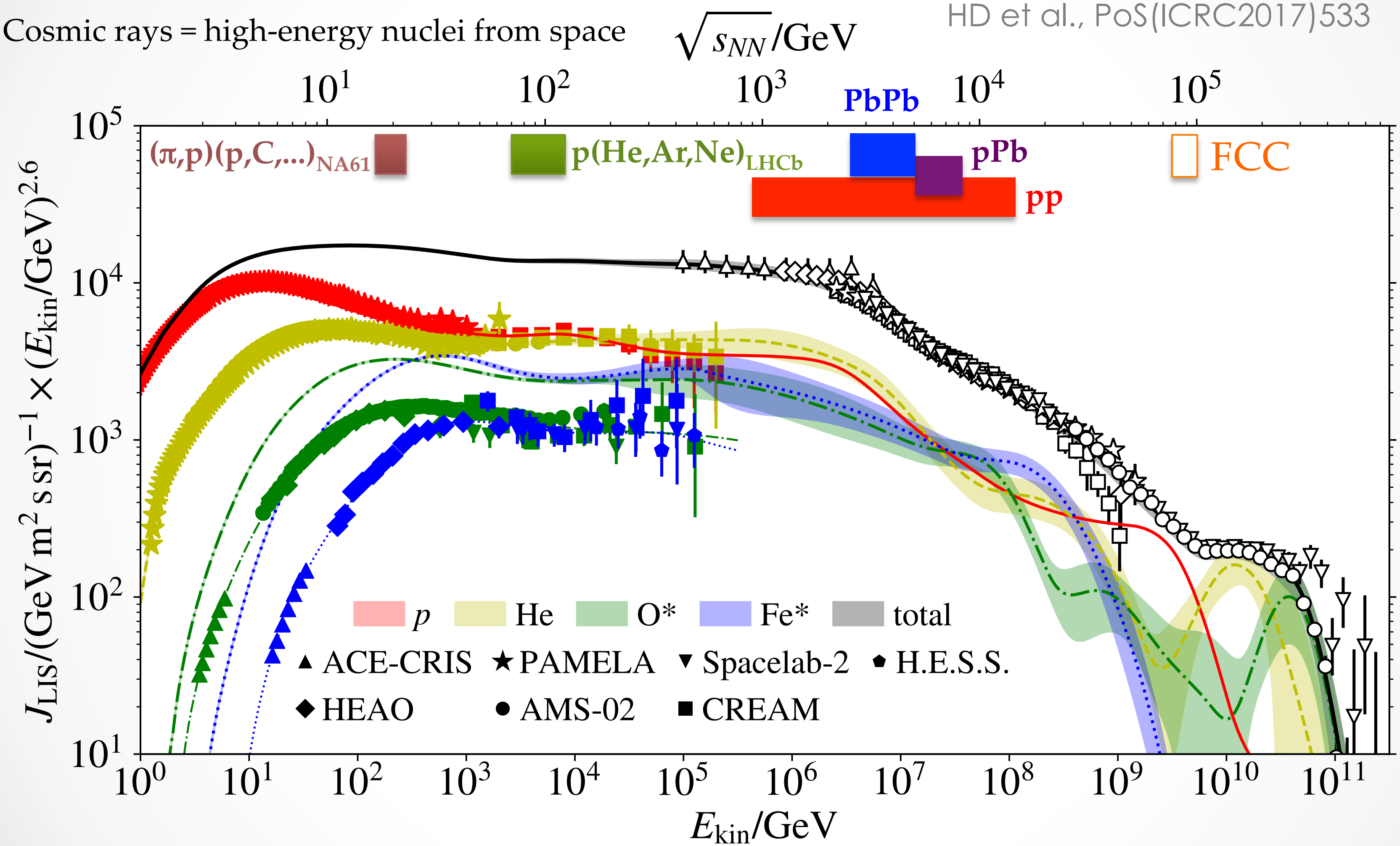
CERN and cosmic rays

Cosmic rays = high-energy nuclei from space

HD et al., PoS(ICRC2017)533



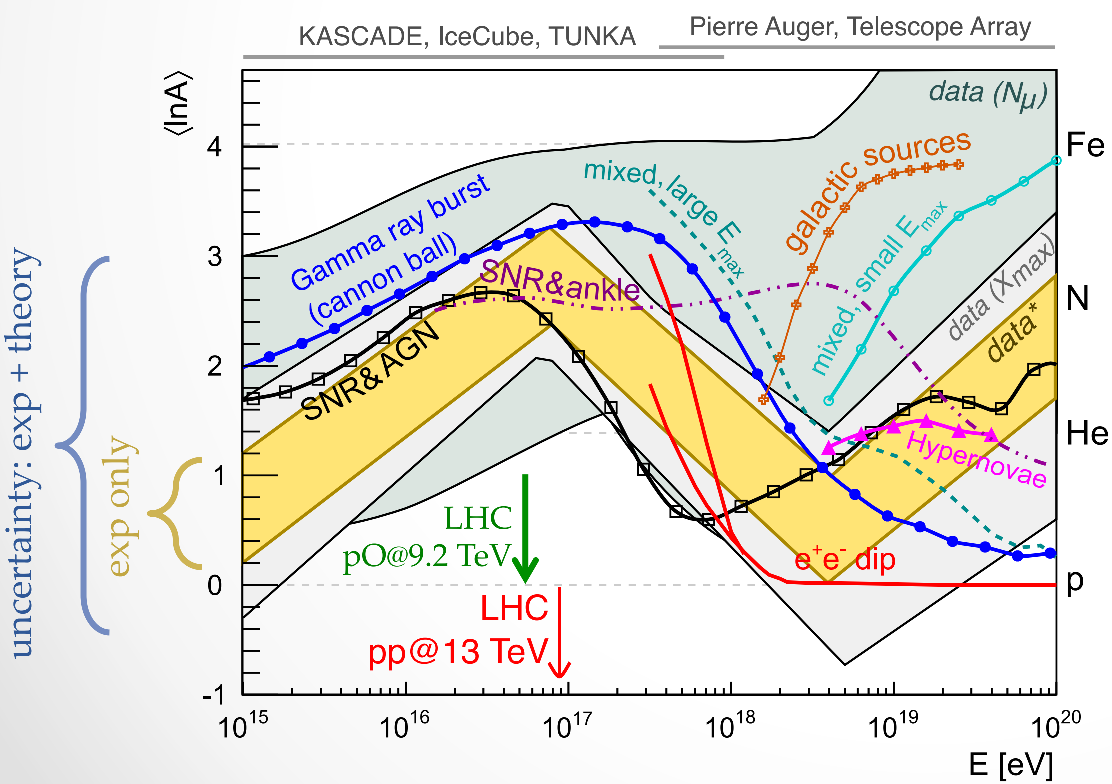
SPS (NA61) and LHC cover **three orders of magnitude** in c.m.s. energy

Where do cosmic rays come from?

No pointing (cosmic ray sky looks isotropic), but elemental composition is revealing

Elemental composition parametrized by <lnA> = mean-logarithmic mass of cosmic rays as a function of cosmic ray energy (bands – empirical evidence, lines – astrophysical theories)

Based on Kampert & Unger, Astropart. Phys. 35 (2012) 660–678



lnA inferred from experimental data using **simulated hadronic showers in air**

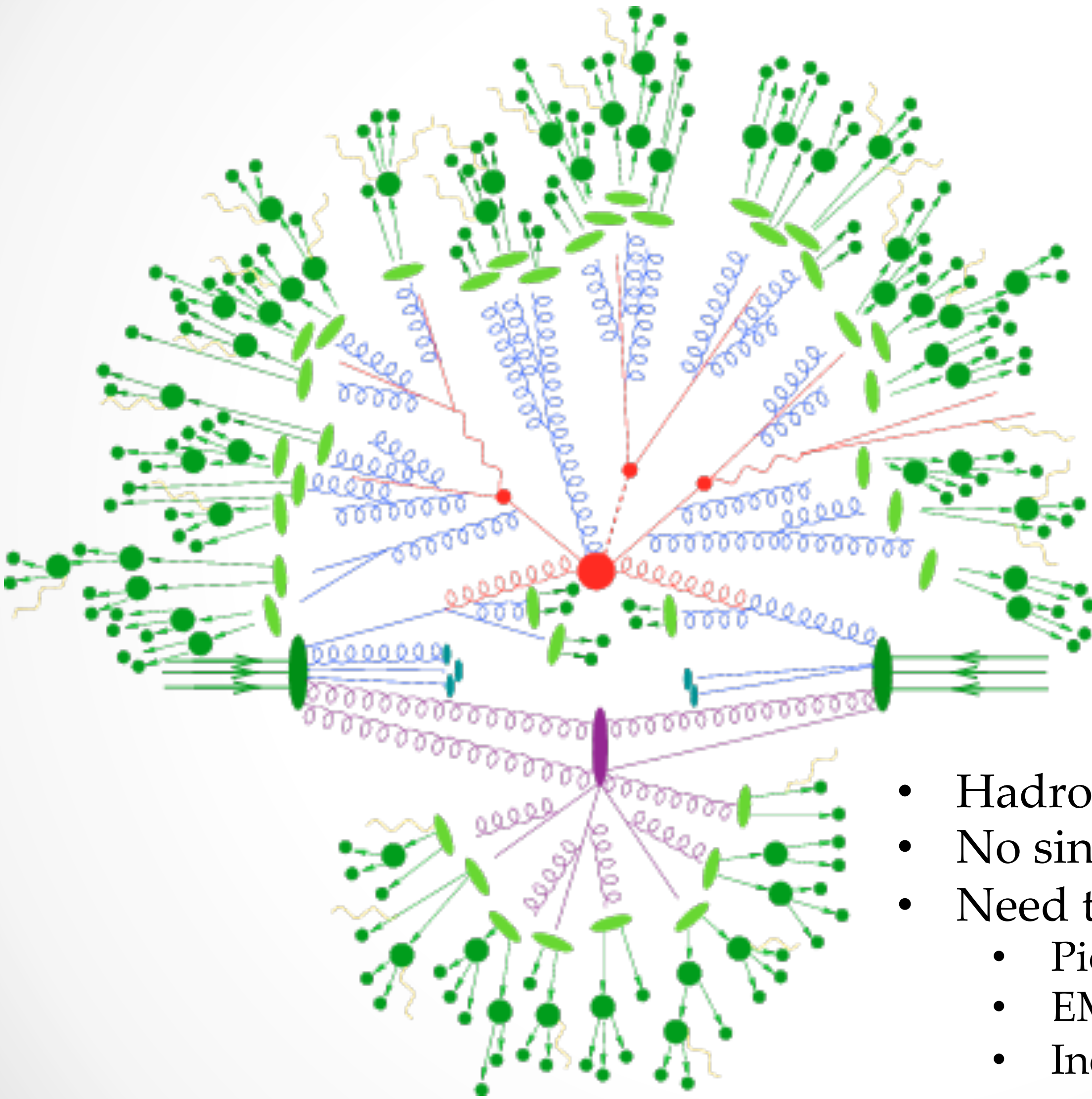
Experimental uncertainties:
10 % of proton-iron difference

Theoretical uncertainties:
Up to **100 %** of proton-iron difference

Muon puzzle: not enough muons produced in simulations by **all models**

Only input from LHC can resolve this
Need predictions to be better than 10 %

How to fix the issue?



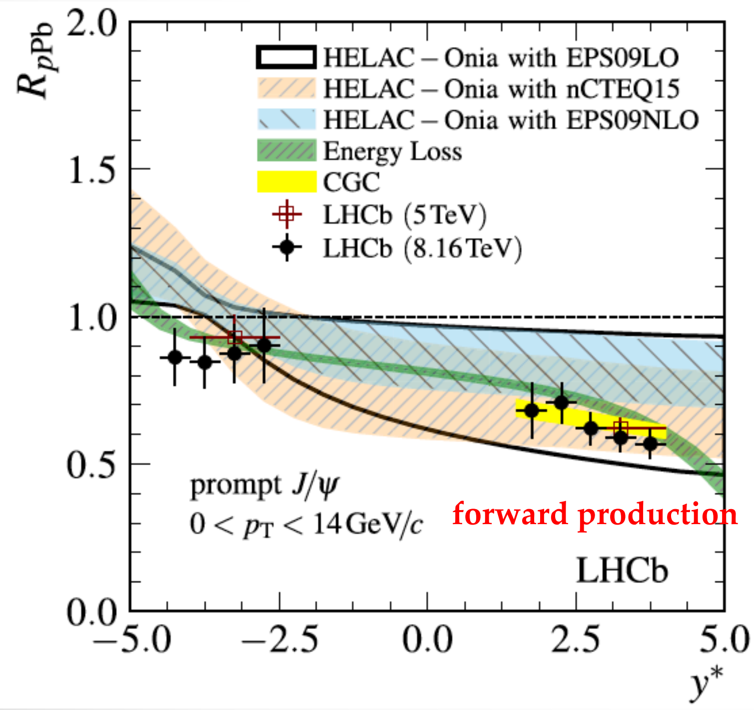
- Hadronic interactions are complex
- No single “smoking gun”
- Need to accurately predict…
  - Pion spectra in forward rapidity
  - EM energy flow in forward rapidity
  - Inelastic cross-section

Nuclear effects poorly understood

Hadronic interaction models used in air shower simulation must predict **p-air (nitrogen & oxygen)**, but can only be tuned to **p-p** and **p-Pb** with current data

Non-trivial nuclear effects severely affect forward production of particles (most important in air showers, because dominant for energy transport)

Recent example: J/Psi production measured by LHCb, Physics Letters B 774 (2017) 159-178



Nuclear modification factor

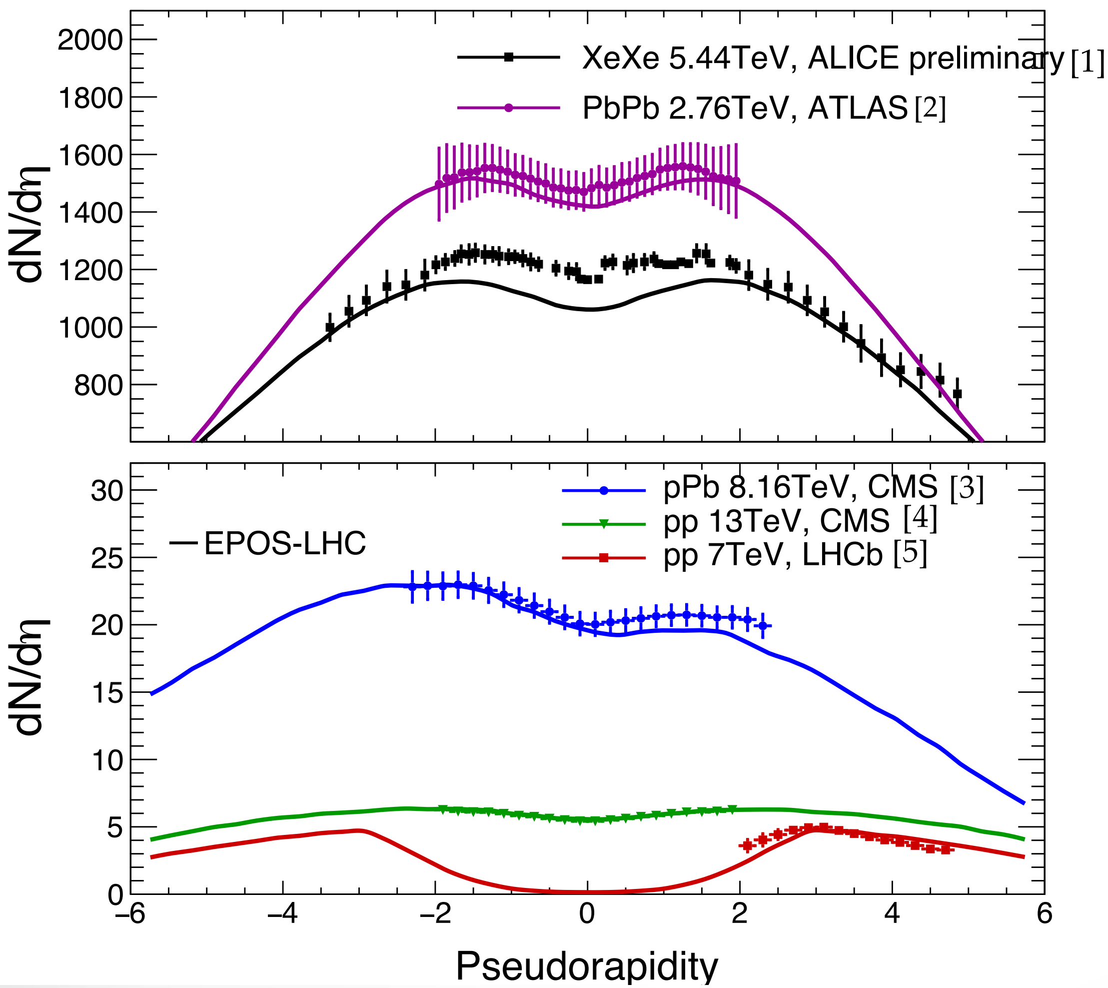
$$R_{pA} = \frac{\text{cross-section for pA}}{\text{A x cross-section for pp}}$$

- Strong deviation from RpA = 1 for forward production
- **50 % uncertainty** in PDF-based predictions
- Same effect expected in pion production

Cannot translate this from p-Pb to p-O

Interpolate pO from pp and pPb?

Spectra of charged particles (plot and sims by Ralf Ulrich)



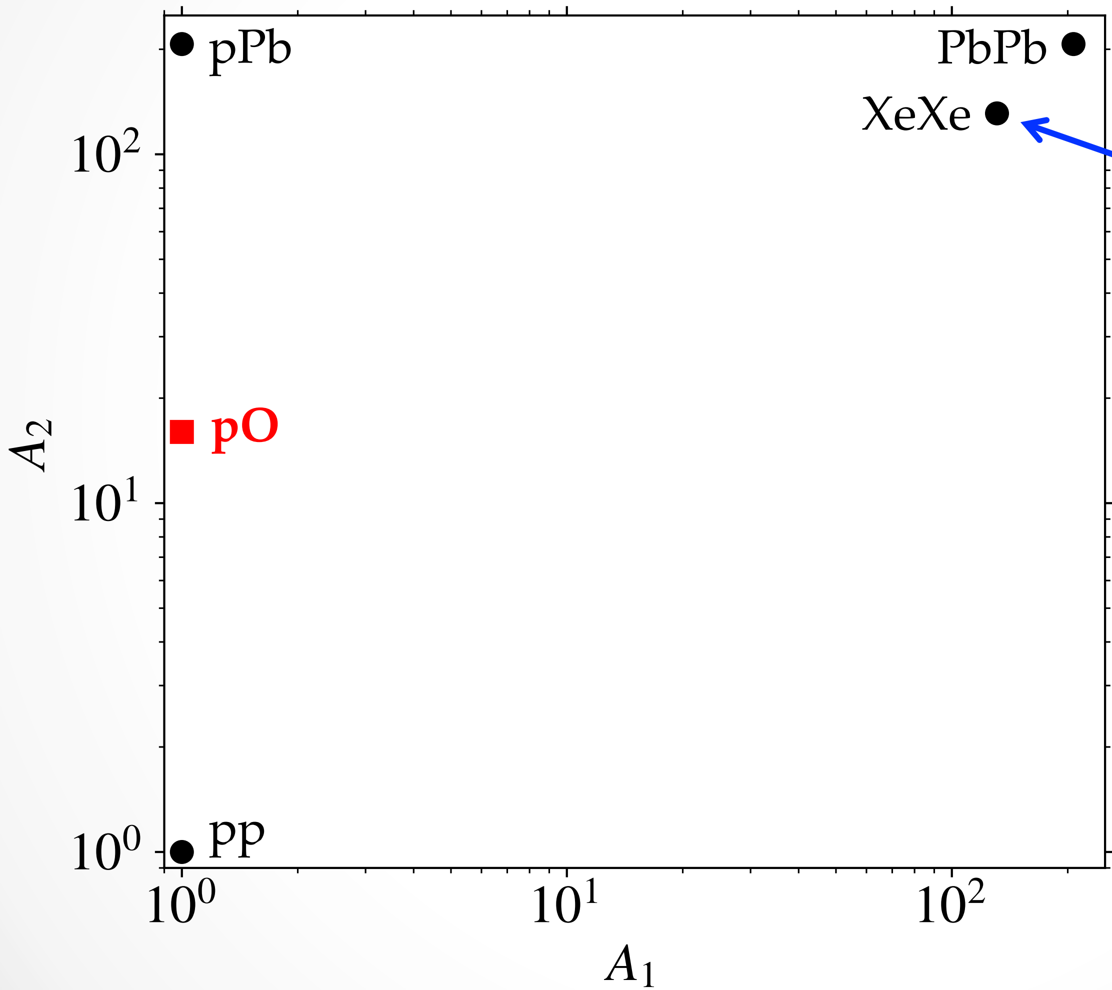
EPOS-LHC describes **p-p**, **p-Pb**, and **Pb-Pb**

...but underestimates central collisions in **Xe-Xe**

Need p-O
Light ions different from heavy irons (shape, core-corona, ...)

[1] arxiv:1805.04432
[2] JHEP 1509 (2015) 050
[3] JHEP 1801 (2018) 045
[4] Phys.Lett. B751 (2015) 143
[5] Eur. Phys. J. C (2014) 74:2888

Explored nuclear systems at LHC

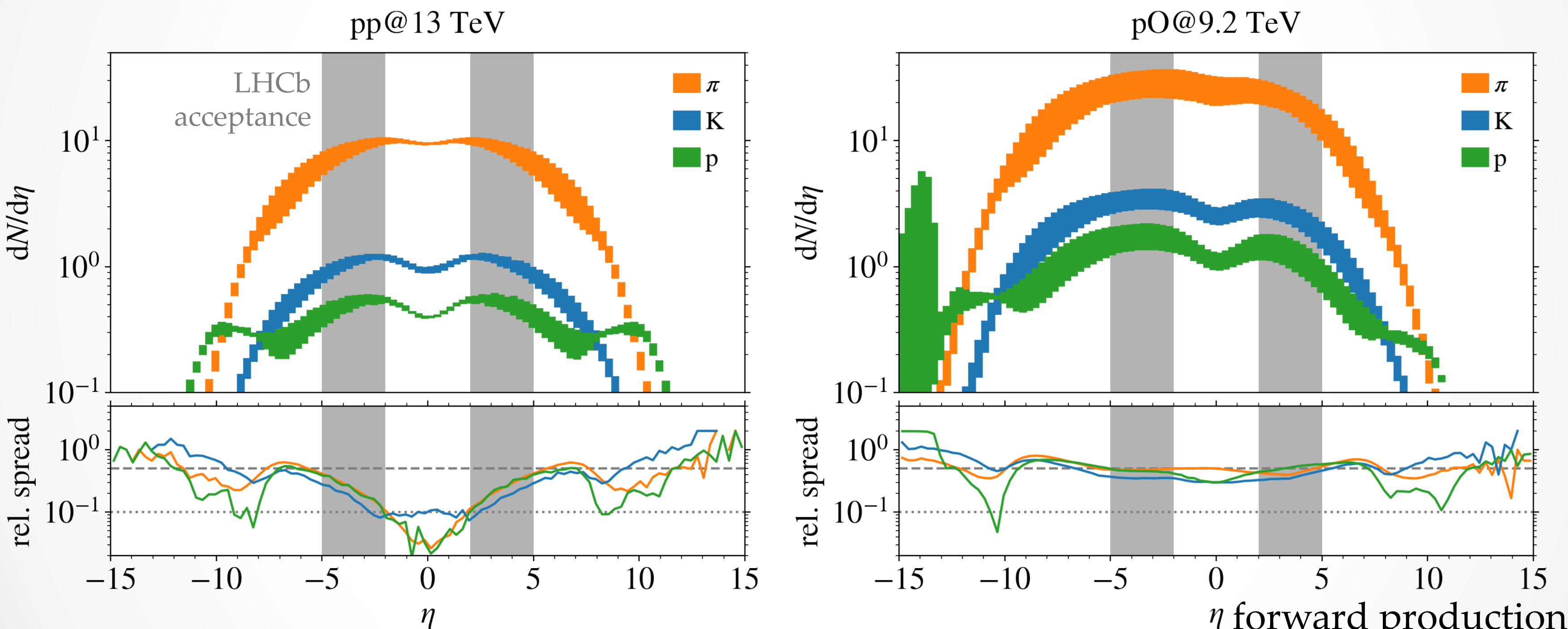


EPOS-LHC off although XeXe close to PbPb

No reason to trust prediction for pO

Impact of proton-oxygen collisions

- Simulations of hadron spectra with CRMC: https://web.ikp.kit.edu/rulrich/crmc.html
- Bands indicate model spread from leading models: EPOS-LHC, QGSJet-II.04, SIBYLL-2.3



- Models tuned to proton-proton data at |eta| < 2 so good agreement there, but **50 %** model spread in proton-oxygen
- Need to reduce to **10 %** spread in proton-oxygen

Summary

- Wanted: p-O collisions to accurately simulate hadronic showers in air
  - Current uncertainties 50 % in pion multiplicity, need better than 10 %
  - Needed by community of >900 scientists (Auger, TA, IceCube, ...)
    - Important topic at the big CR conferences ICRC and ISVHECRI
  - Moderate luminosity sufficient **(100 M events)**
  - Interest expressed by LHCf and members of LHCb, CMS, ATLAS

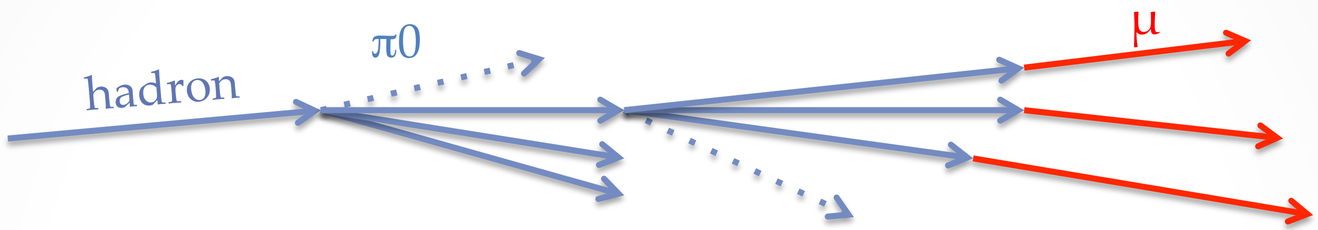
- Nuclear effects in proton-ion collisions poorly understood
  - Cannot simply interpolate p-O from p-p and p-Pb
  - Effects largest for forward production which dominates air showers

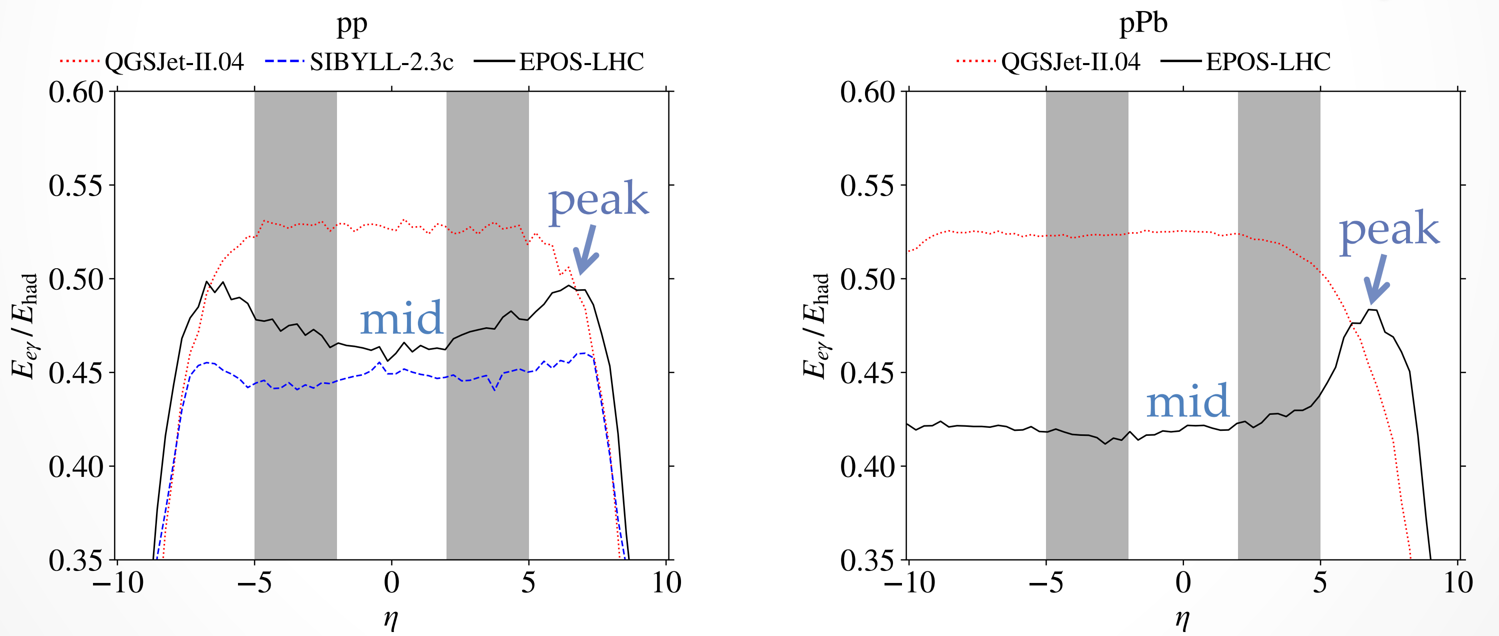
- Measurements in p-O
  - Inelastic cross-section
  - Spectra of light hadrons π, K, p
  - π^0, n with LHCf in very forward range
  - Identified energy flow, separated by hadrons and $e\gamma$

Backup

em-hadron energy ratio

- Hadronic energy "lost" to π^0s cannot produce muons in late shower
- "Energy loss" described by observable $E_{e\gamma}/E_{hadrons}$

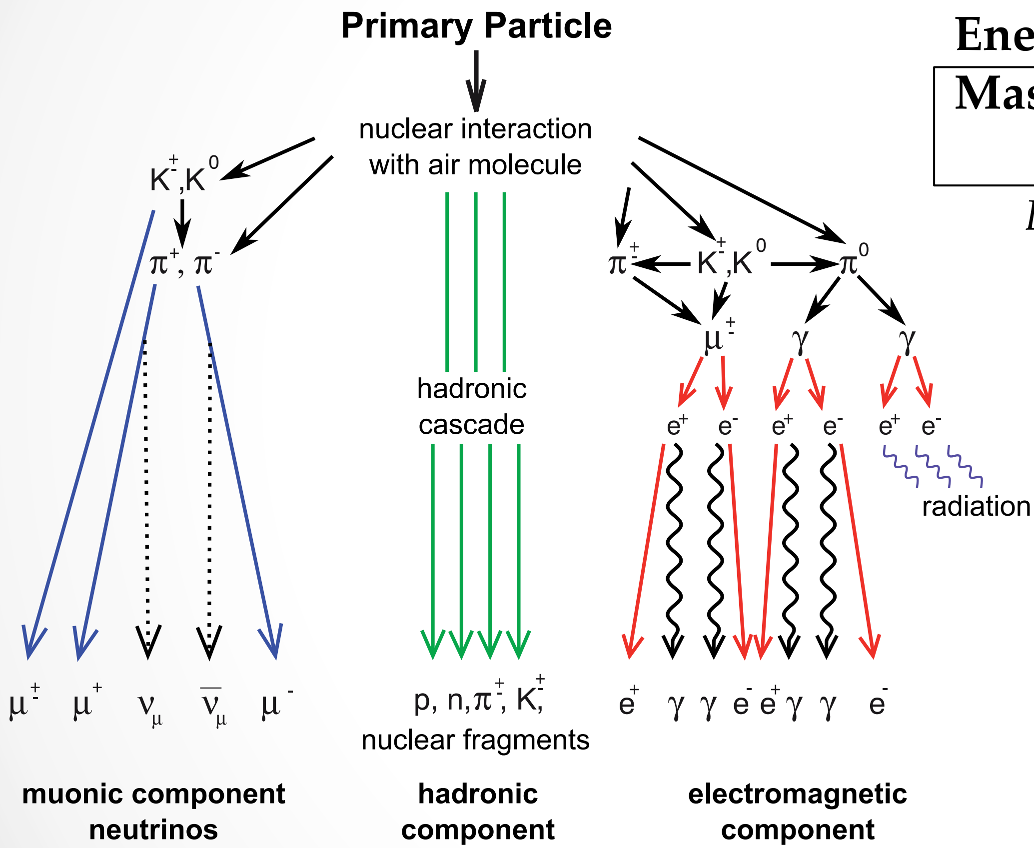




- Model predictions differ by **13 %** and in **shape**: only EPOS has forward peaks
- Translates to > **15 % shift in N_μ**, **best bet to solve muon puzzle**

Air shower observables

Haungs et al., JoP Conf. Ser. 632 (2015) 012011



Direction from particle arrival times
Energy from size of **eγ component**

Mass from size of **muonic component** and **depth of shower maximum**

Limited by theoretical uncertainties

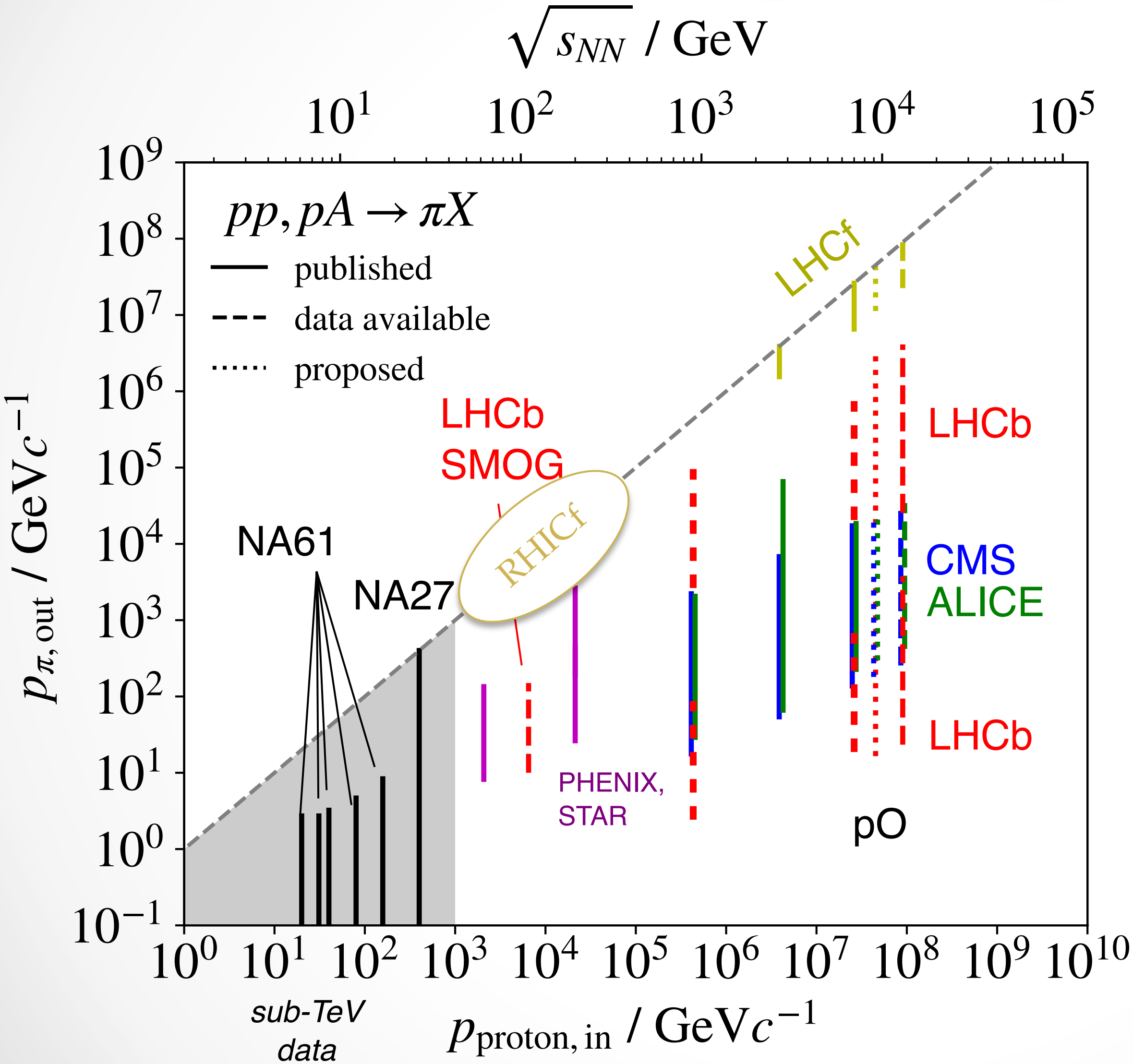
N_μ

Number of muons and Mass
Iron = **1.4** x proton yield
at same CR energy

X_{max}

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

Data on pion spectra



Phase space of air shower interactions as covered by various experiments
(beam-beam collisions transformed to equivalent fixed-target system)

LHCb could significantly increases coverage

Important features in hadron production

Slide: Tanguy Pierog, AFTER workshop, Freudenstadt Germany, 2015; plots: R. Ulrich et al PRD 83 (2011) 054026

- **Sensibility depends on observable and parameter :**
  - ➔ effect of uncertainties at LHC on air shower observables
    - $f_{LHC\text{-}pO}$ = modification factor@LHC
  - ➔ 20% difference in multiplicity is about
    - ➔ 10% muons
    - ➔ 20 gr/cm² $\langle X_{max} \rangle$