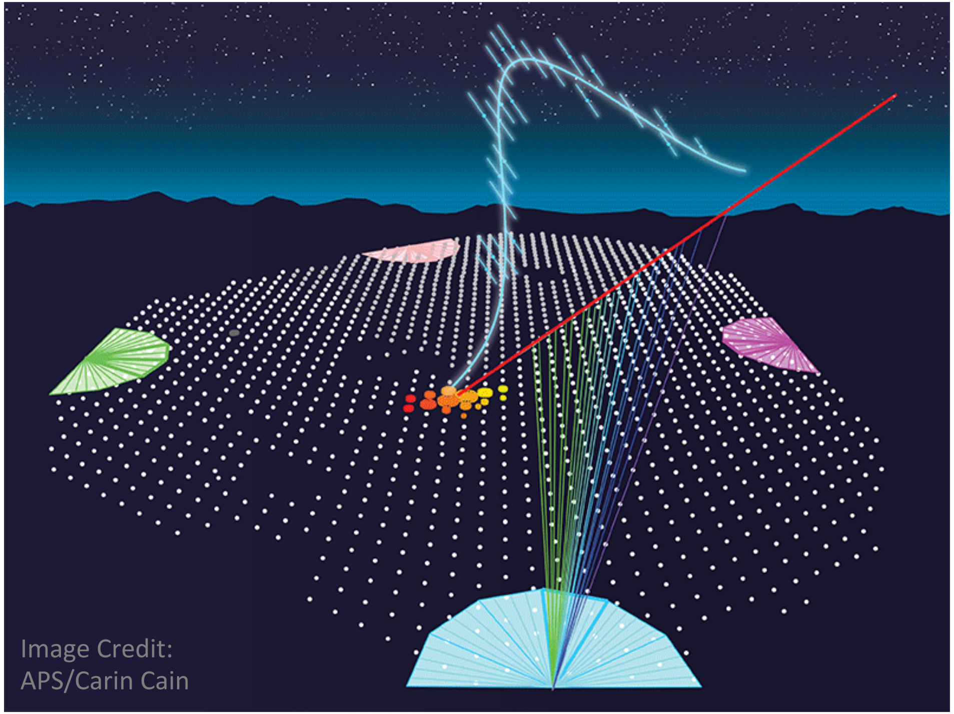
Proton-oxygen collisions at the LHC

Hans Dembinski, MPIK Heidelberg

CFNS workshop on Forward Physics And Instrumentation From Colliders To Cosmic Rays
Oct 2018

Air showers and cosmic ray mass



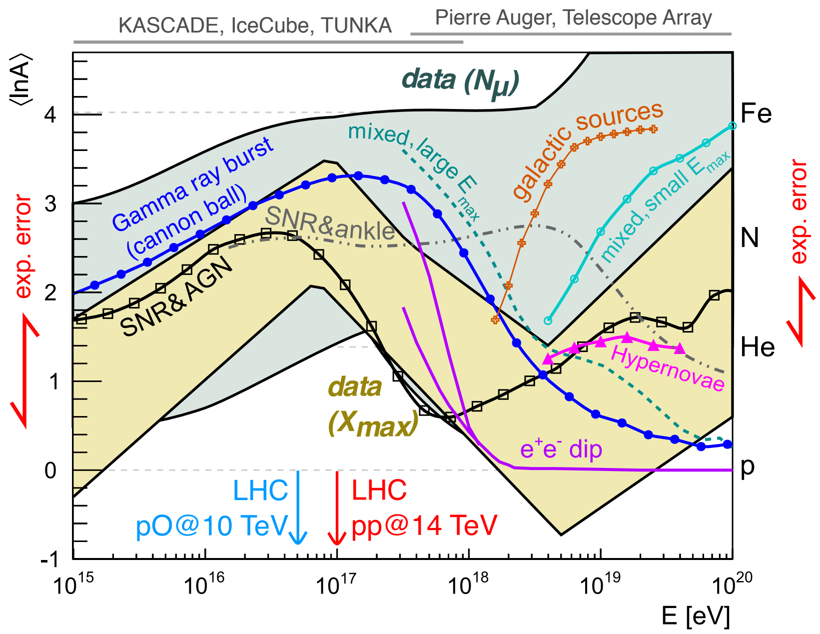
Direction from particle arrival times

Energy from size of **eγ component**

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

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



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

Motivation

Astrophysical origins of cosmic rays?

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

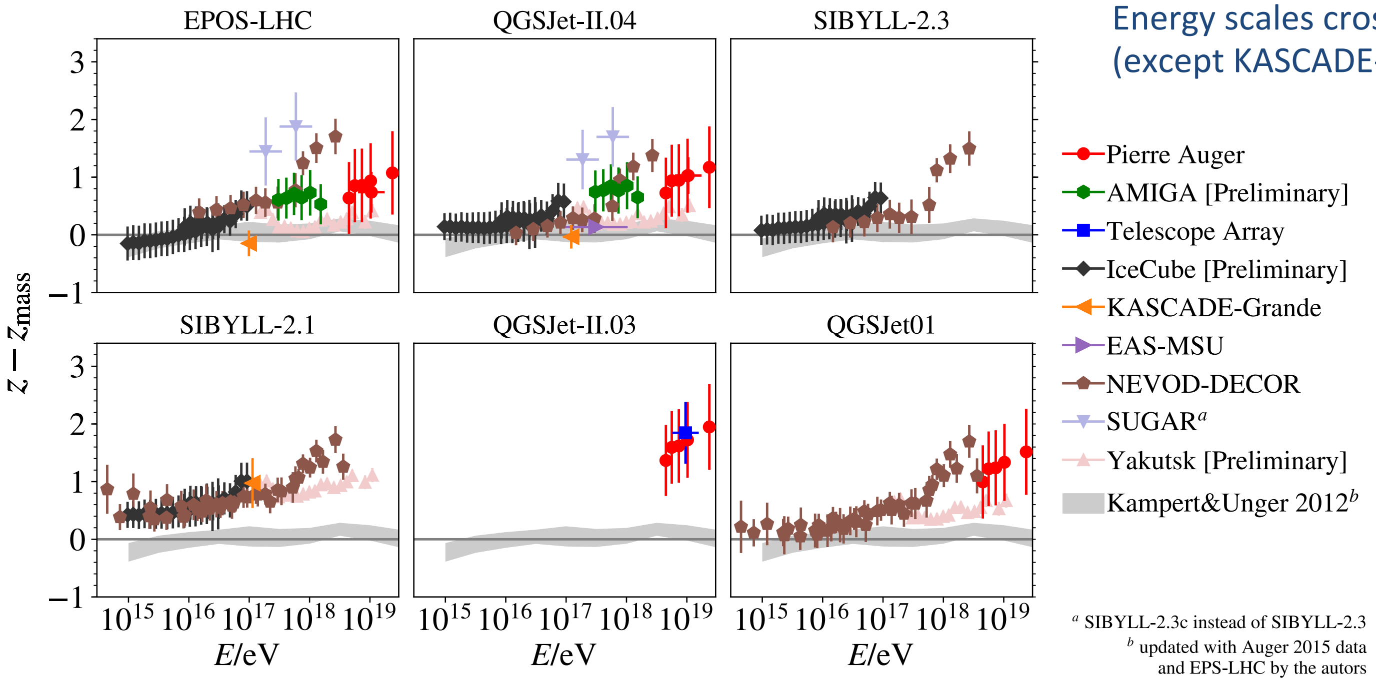
Combined approach to get precise unambiguous <lnA> data

- Cosmic ray community probes air showers and **quantifies inconsistencies**
- Collider community provides **relevant reference measurements** for model tuning

Indirect search for physics beyond the standard model at 100 TeV scale

Compilation of muon measurements

- WHISP report at UHECR 2018 conference, Oct 8-12 2018
- Comprehensive compilation of muon measurements from air shower experiments



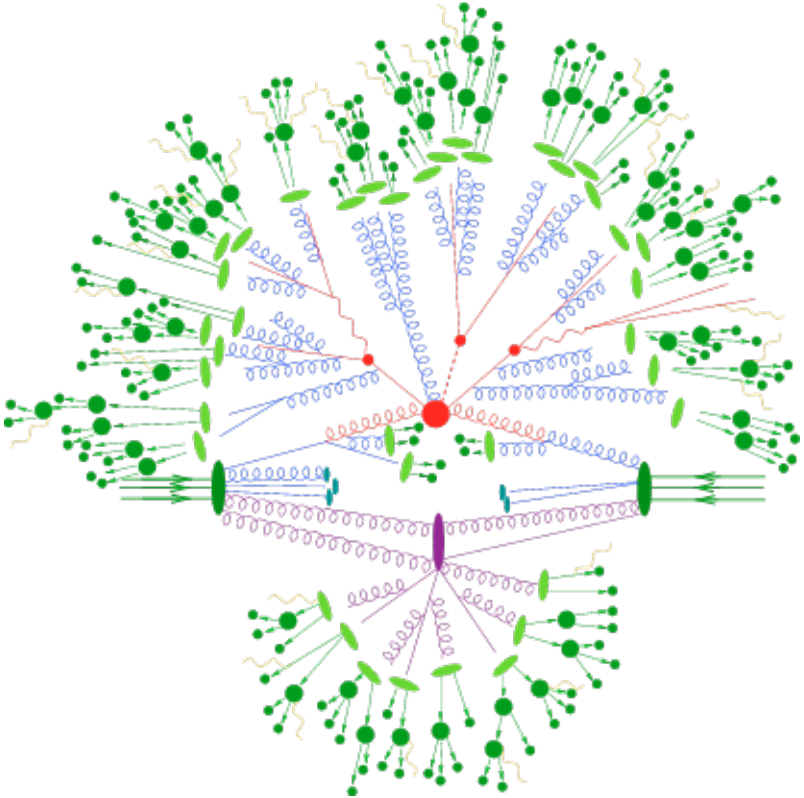
[a] SIBYLL-2.3c instead of SIBYLL-2.3
[b] updated with Auger 2015 data and EPS-LHC by the autors

Energy scales cross-calibrated (except KASCADE-Grande, EAS-MSU)

Systematic discrepancies reported by majority of experiments starting around 5×10^{16} eV equiv. to **$s^{1/2}$ = 10 TeV**

Apart from shower energy, possible dependence on shower age, lateral distance, muon energy threshold

How to fix the issue?



- No simple key measurement
- Need to accurately know and extrapolate several features
- Focus on measuring these features accurately in references systems, use models to predict interactions in unavailable target systems

Modeling air shower interactions

extrapolation to **higher energy** & **different collision systems**

Reference systems used for model tuning

LHC:
pp @ **0.9** ... **14** TeV
pPb @ **5** ... **8.14** TeV
PbPb @ **2.76** ... **5** TeV
SPS:
pC, πC @ **O(10)** GeV

Other experiments:
RHIC, Tevatron, ...

Hadronic interaction models
EPOS, QGSJet, SIBYLL

Theory &
Phenomenology

Glauber
Gribov-Regge
pQCD
...

Pomerons
Mini-jets
Multi-parton interactions

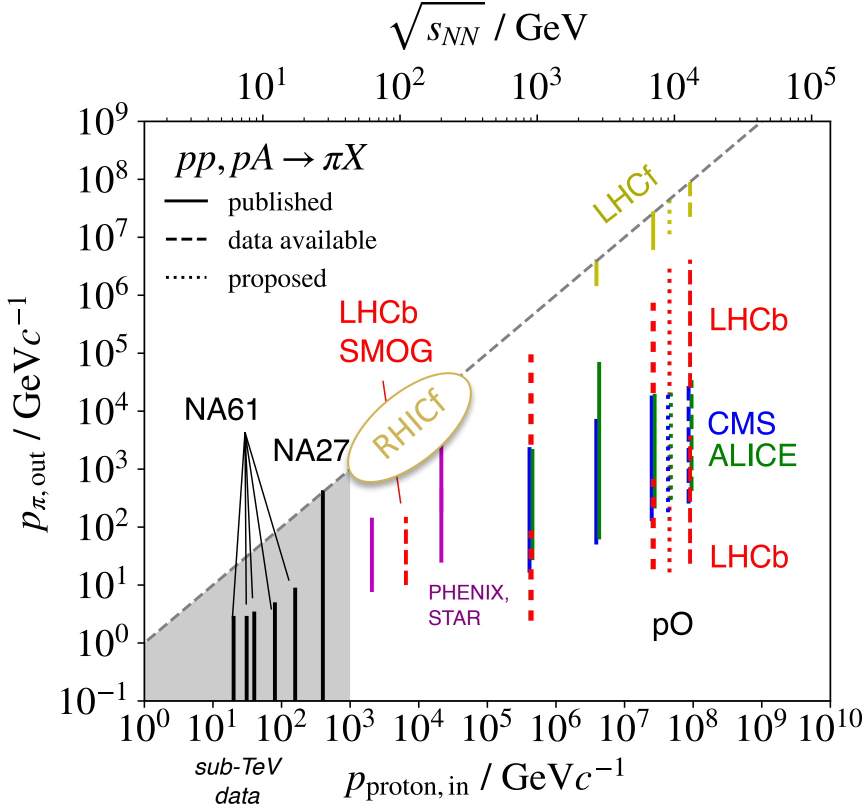
Systems in air showers
sorted by frequency of occurring

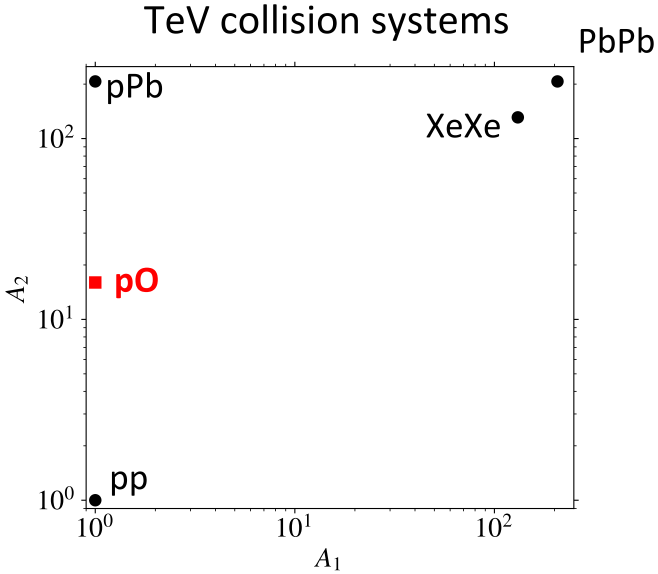
π(N, O)
K(N, O)
(p, n)(N, O)
...
Fe(N, O)

@ **1** GeV ... **1000** TeV

- **Light hadron production** important
- **Full rapidity range**, mid-rapidity alone not enough

Data on pion spectra





Only **LHCb** at LHC with hadron PID at η > 2

Analyses of pp @ 13 TeV at MPIK

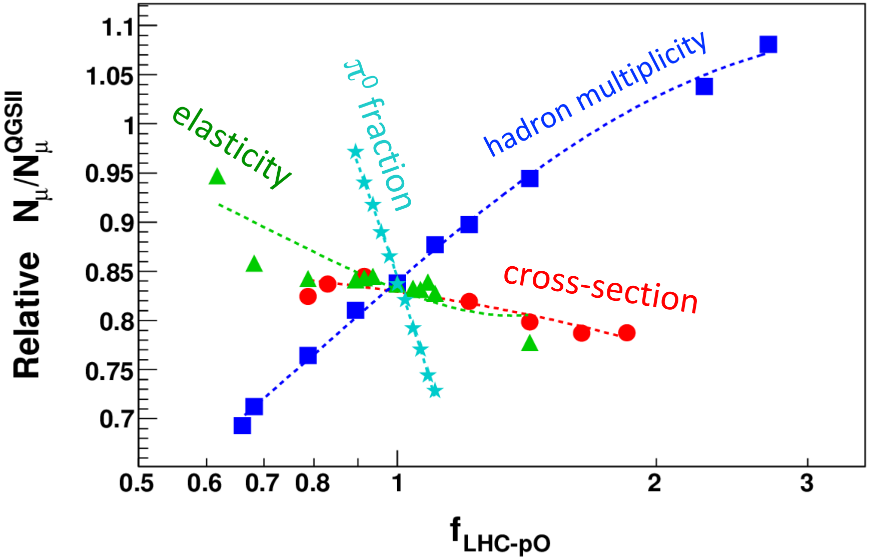
Oxygen beam at LHC

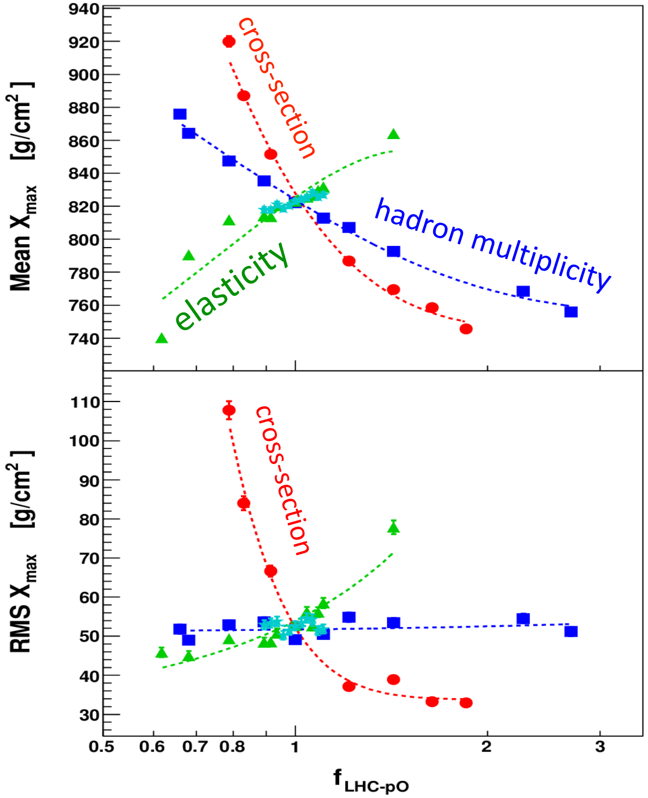
- Low-luminosity oxygen beam comparably easy to do
  - Oxygen in lead source as support gas
  - Rapid set-up following 2012 p-Pb and 2017 Xe-Xe runs
  - Almost scheduled at end of 2018, but didn’t happen
- To be done during LHC Run 3 (2021-2023)
- Upcoming Yellow Report about physics at HL-LHC with subsection about proton+oxygen science case

- Questions asked
  - Project quantitative impact of measurements?
  - Is p+p and p+Pb data sufficient?

Important features in hadron production

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

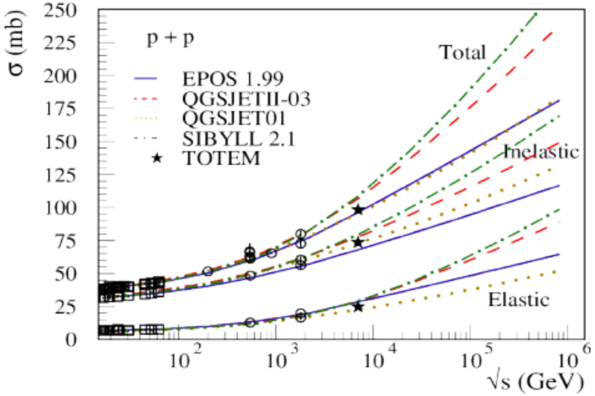




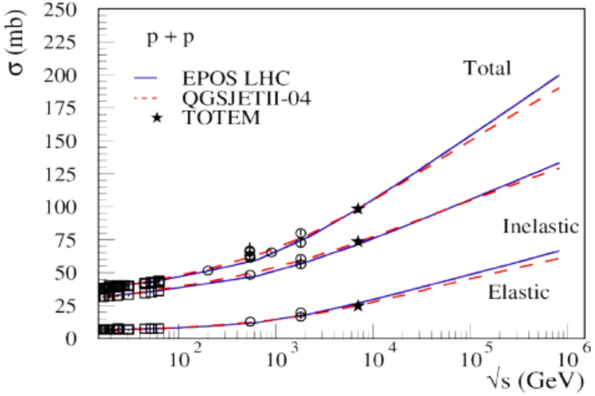
Inelastic cross-section

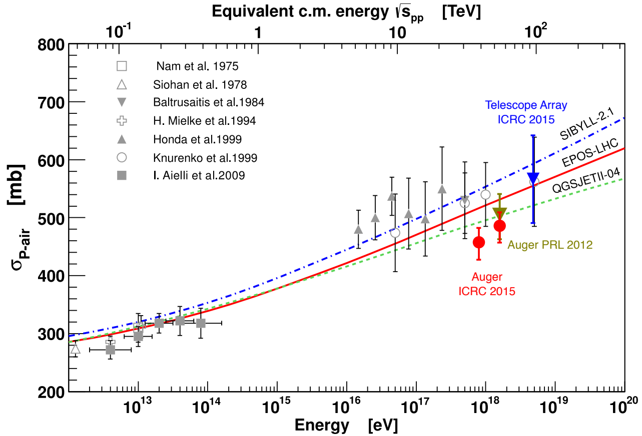
Tanguy Pierog, AFTER workshop, Freudenstadt Germany, 2015

Pre - LHC



Post - LHC

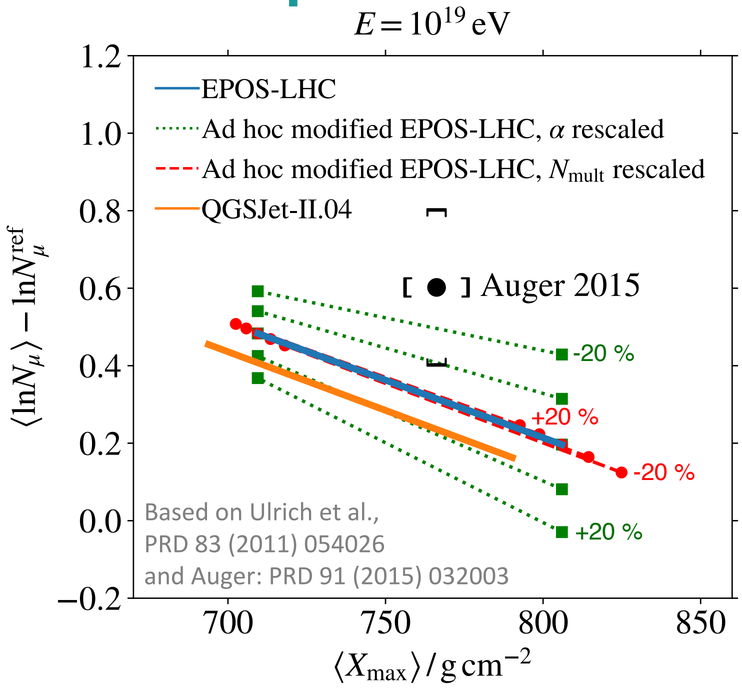


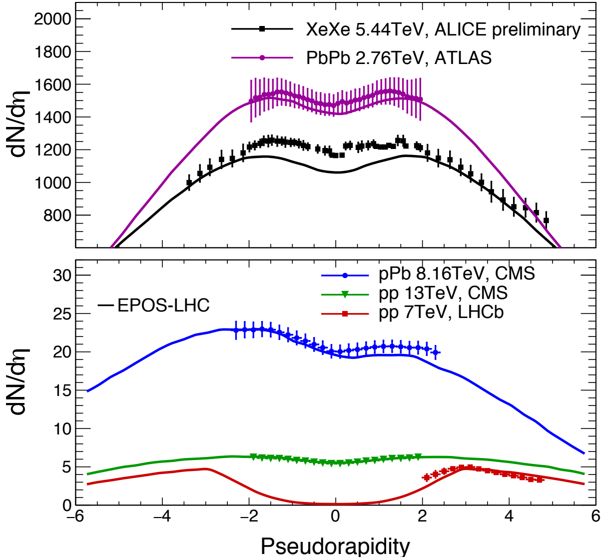


Auger: R. Ulrich et al. PoS(ICRC2015)401;
P. Abreu et al., PRL 109, 062002 (2012)
Telescope Array: R.U. Abbasi et al.,
PRD 92, 032007 (2015)

- pp inelastic cross-section now known to 3 %, see e.g. ATLAS arXiv:1606.02625
- Similar for p+Pb, about 4 %, CMS arxiv:1509.03893
- Glauber interpolation to p+O could have similar precision
- p+O collisions to cross-check Glauber interpolation

Impact of LHC measurements





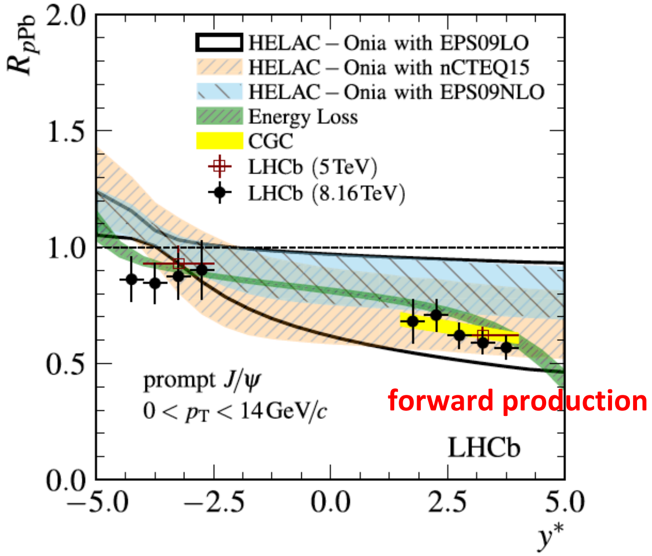
ALICE Xe-Xe arXiv:1807.09061; ATLAS Pb-Pb arXiv:1504.04337; CMS p-Pb arXiv:1710.09355v2; CMS p-p arXiv:1507.05915v2; LHCb p-p arXiv:1402.4430

- X_{max} sensitive to: **inelastic cross-section**, hadron multiplicity
- N_μ sensitive to: **energy fraction lost to π^0**, hadron multiplicity
- **Nuclear modification in forward-produced hadrons** expected and important

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)

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



Nuclear modification factor

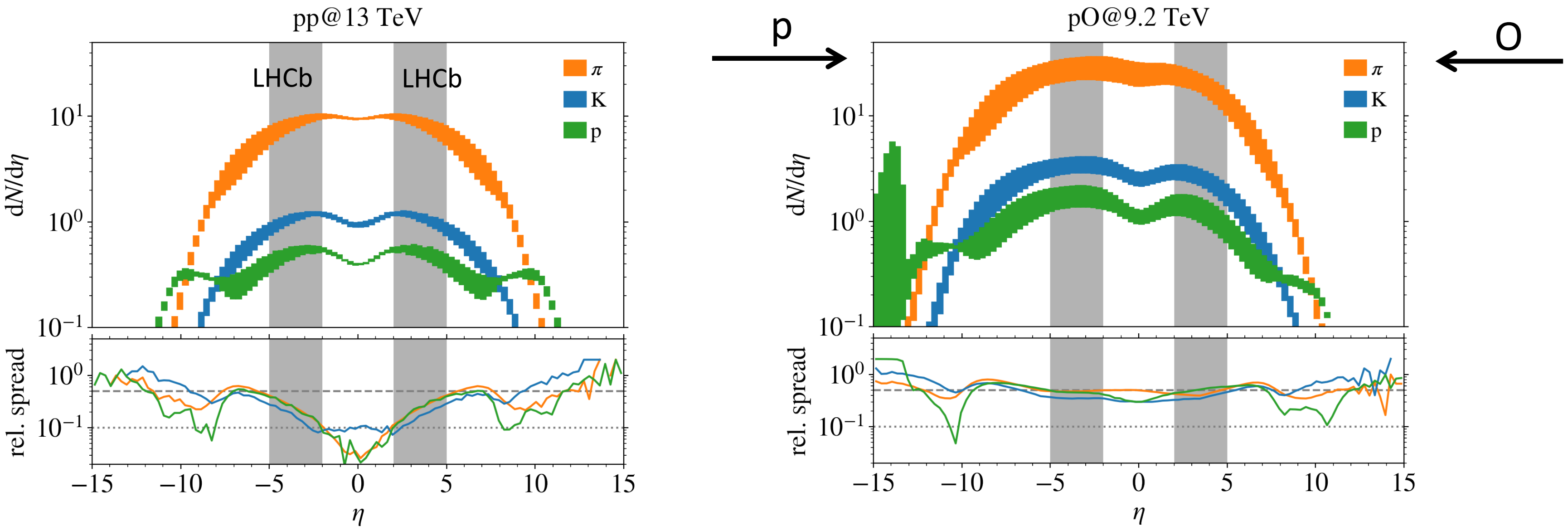
$$R_{pA} = \frac{\text{cross-section for pA}}{\text{A x cross-section for pp}}$$

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

Cannot translate this from p-Pb to p-O

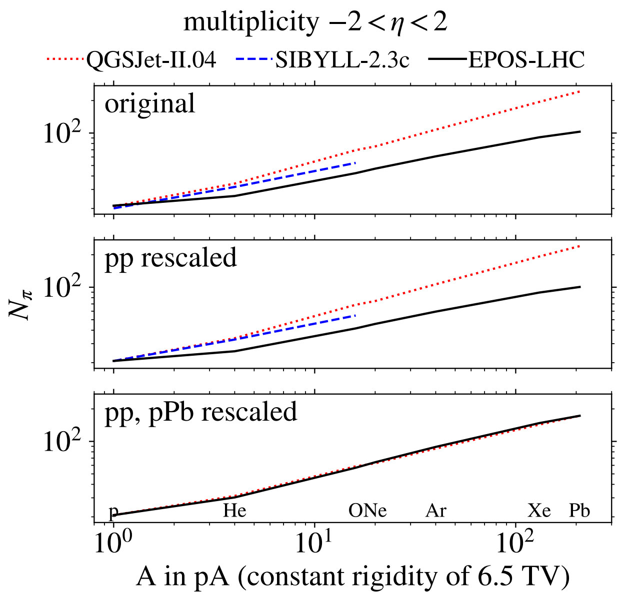
Hadron spectra

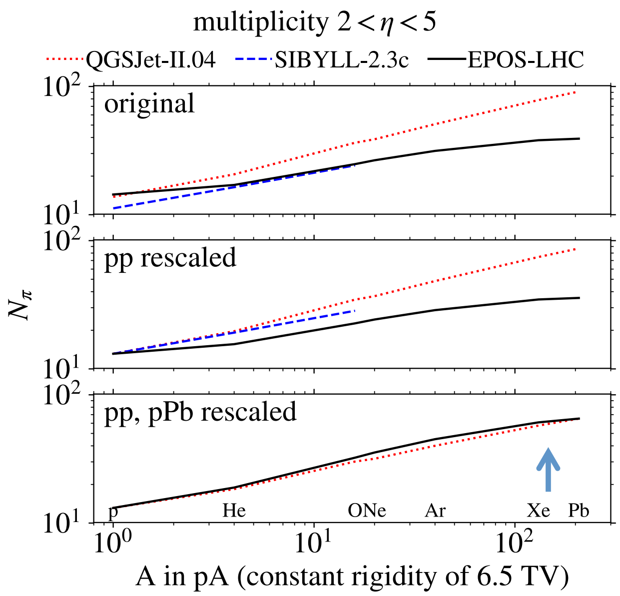
- Simulations done with CRMC by R. Ulrich et al. https://web.ikp.kit.edu/rulrich/crmc.html
- Model spread: EPOS-LHC, QGSJet-II.04, SIBYLL-2.3



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

Hadron spectra vs. system

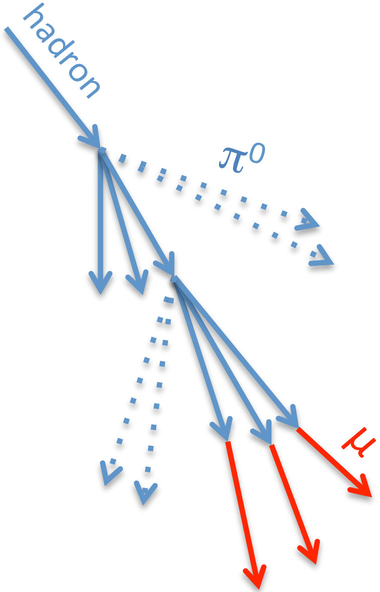


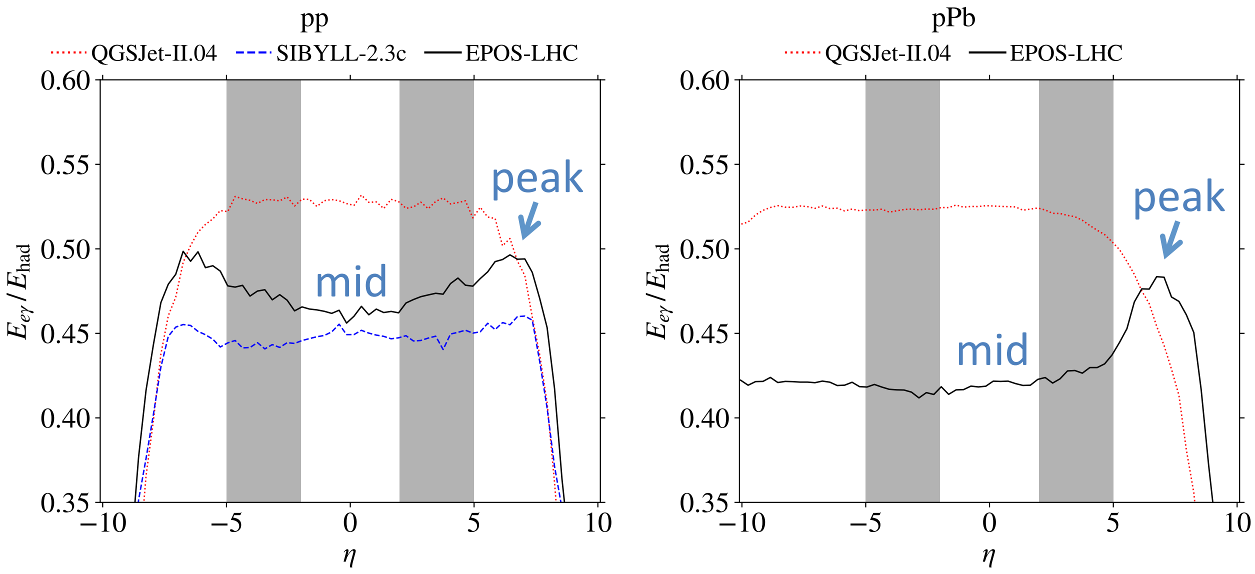


- Saturation visible in EPOS, not in QGSJet-II.04
- **7 % deviation in pO** even if models could be fixed to same values in pp and pPb (50 % otherwise)
    - 4 % shift in N_μ, 7 g cm-2 shift in X_{max} (comparable to exp. uncertainties)
- p+p and p+Pb may be able to constrain p+O, need measurement to confirm

Energy flow ratio

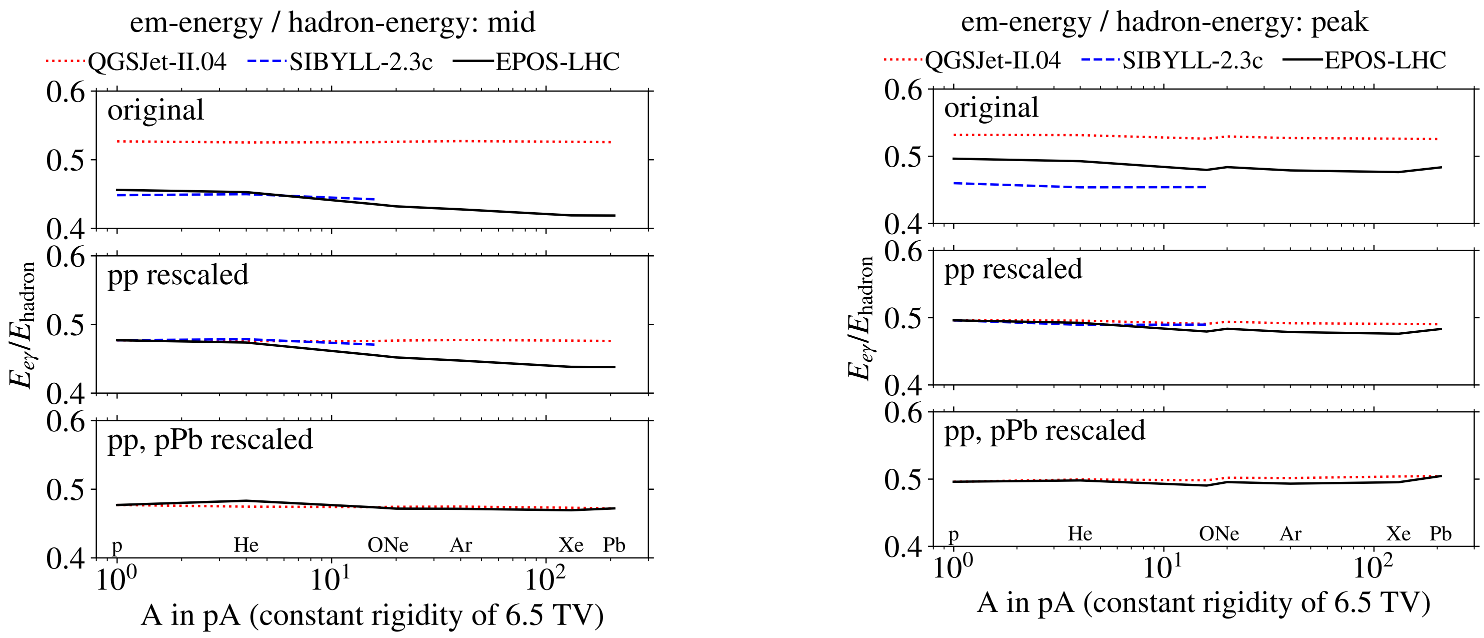
- Hadronic energy "lost" to π^0s cannot produce muons in late shower
- "Energy loss" described by observable $E_{e\gamma}/E_{hadrons}$





- Model predictions differ by **15 %** and in **shape**: only EPOS has forward peaks
- Translates to about **20 % shift in N_μ** **-> high impact on Muon Puzzle**

Energy flow ratio vs. system



- p+p and p+Pb together may be able to constrain p+O, but shape evolution not clear
- Need to measure it in p+O

Summary

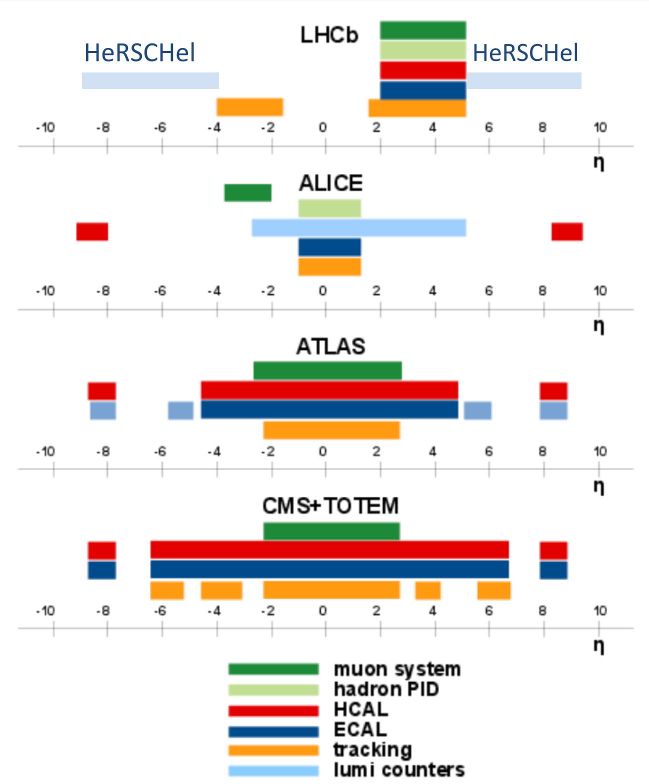
- Wanted: p-O collisions to accurately simulate hadronic showers in air
  - Current uncertainties 50 % in pion multiplicity, need better than 10 %
  - Needed by community of 900+ scientists (Auger, TA, IceCube, ...)
  - Moderate luminosity sufficient **(100 M events)**
  - Interest expressed by LHCf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

- Nuclear effects in proton-ion collisions cannot be accurately predicted (yet)
  - Cannot simply interpolate p-O from p-p and p-Pb
  - Effects largest in forward production which dominates air showers

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

BACKUP

LHCb



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