Max-Planck-Institut für Kernphysik Heidelberg

Science case for recording proton-oxygen collisions at the LHC

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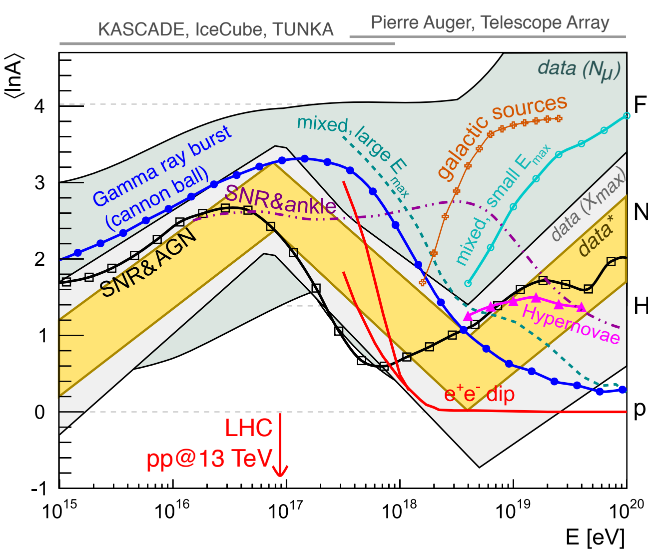
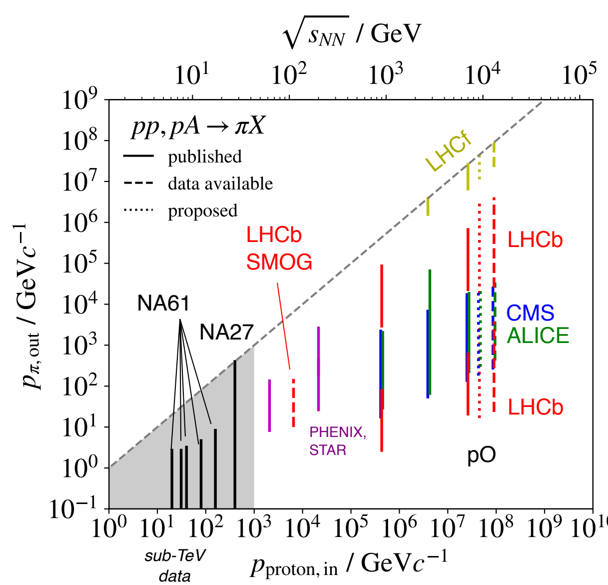
LHC WG Forward Physics and Diffraction | 2018-03-20



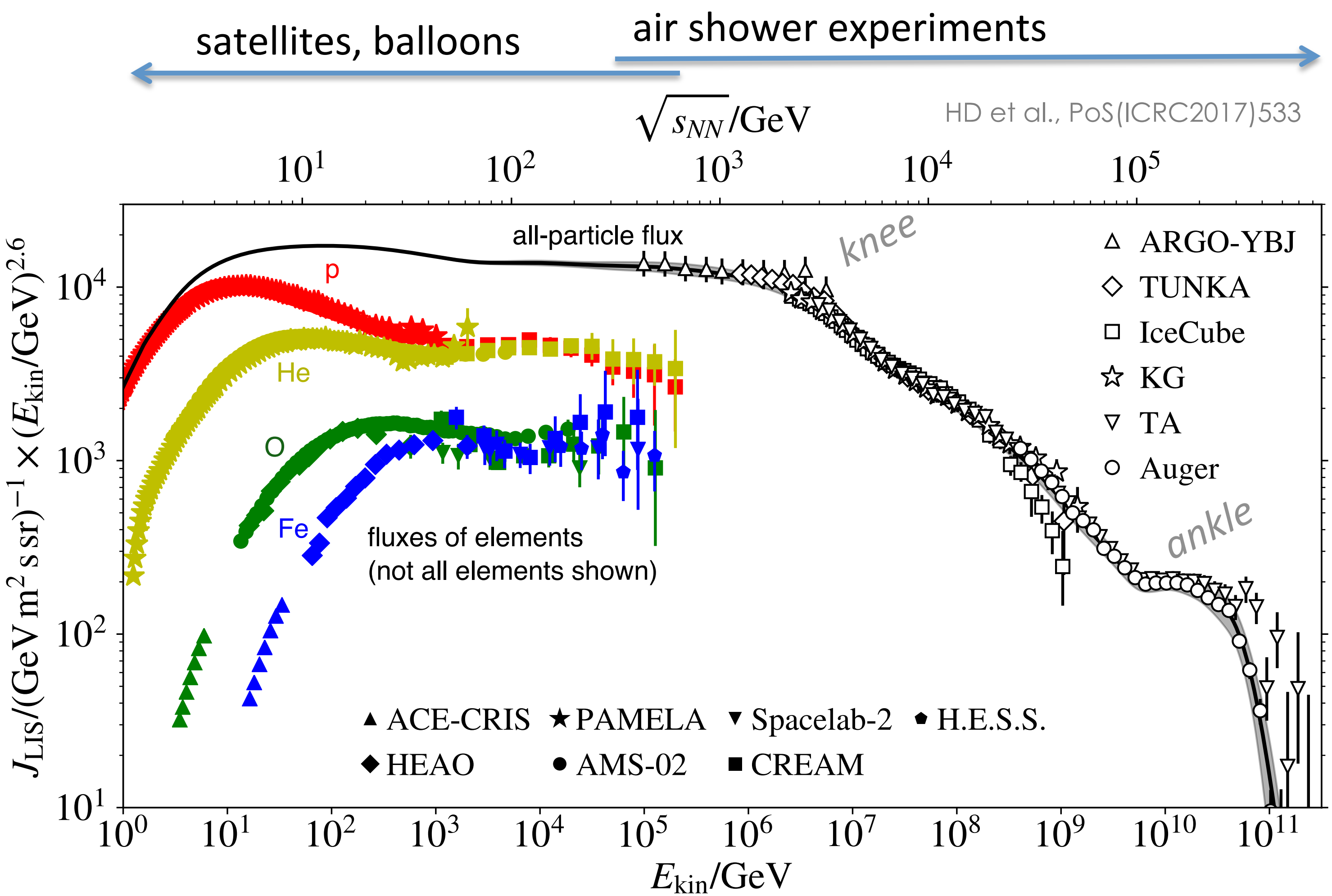


Take-home message

- Active discussion around proton-oxygen science case
  - e-group: proton-oxygen-science-case (subscriptions welcome! ☺)
  - Participating (not exhaustive)
    - LHC WG Forward Physics and Diffraction
    - ATLAS: Astroparticle Forum, Heavy-Ion group
    - LHCf: Hiroaki Menjo (liaison)
    - LHC: John Jowett
    - Theorists: Tanguy Pierog (EPOS), Felix Riehn + Ralph Engel (SIBYLL-2.3), Anatoli Fedynitch (DPMJet-III)
- Science case for pO runs
  - Tanguy Pierog (EPOS): "All type of min-biased data are welcome"
  - R. Ulrich et al PRD 83 (2011) 054026 is specific
    - Quantities that need to be measured at LHC to what precision
- Main question: pp and pPb at 13 TeV enough?
  - **No**, need **measurement of intermediate pA system**
  - Short pO run of O(100 M) events sufficient
  - pO system is special because setup is only 1-2 days (Jowett)

- Need **pIon between pp and pPb** to study nuclear **saturation** effects
- Need commitment from experiments to analyze this data

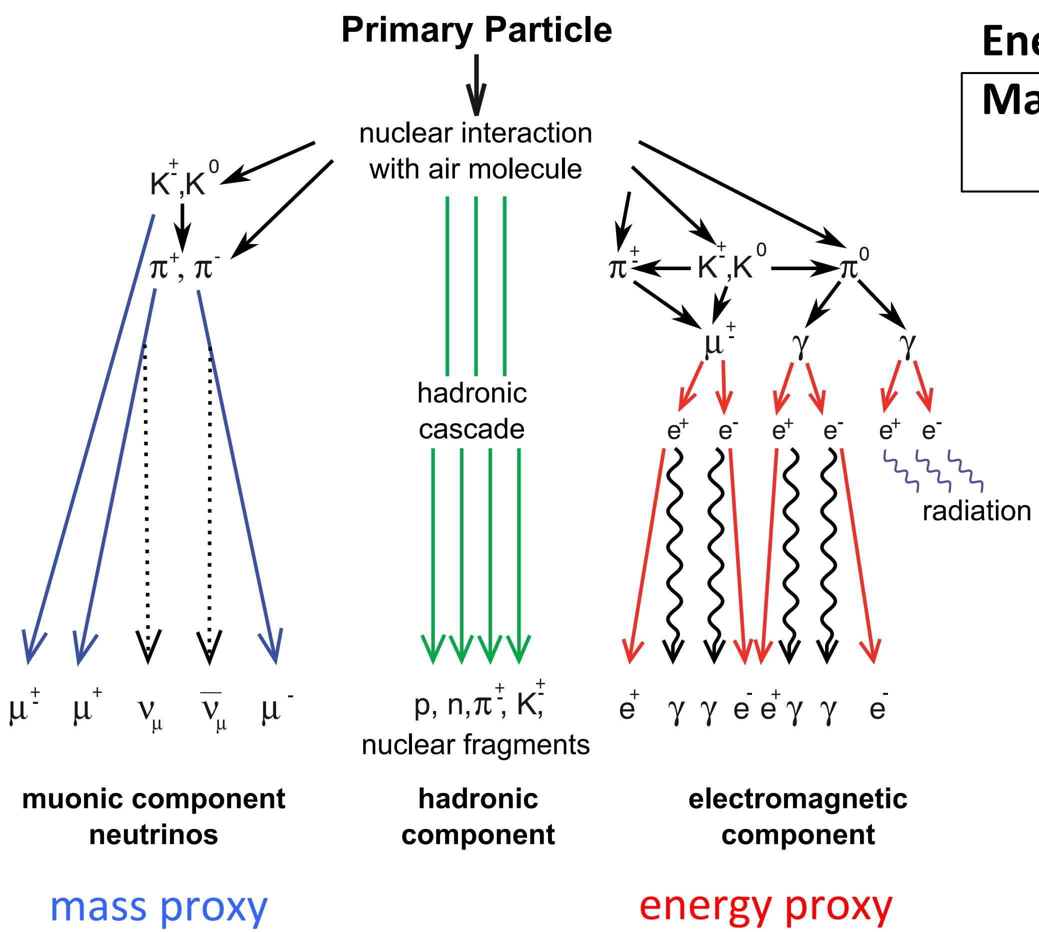
Cosmic rays



- **Cosmic rays**: naked high-energy nuclei from outer space
- Above 10^6 GeV: Total flux well known, elemental composition uncertain
- Total flux is tip of the iceberg, physics information in the elemental composition

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

Nμ

Number of muons and Mass

Iron-induced showers produce **40 % more muons** than proton-induced showers **at the same energy**

Xmax

Shower depth and Mass

Iron-induced showers penetrate **100 g cm-2 less** than proton-induced showers **at the same energy**

Bottleneck for a field: Inferring the mass

Cosmic ray observables
to test astrophysical theories

Directions

- No point sources found

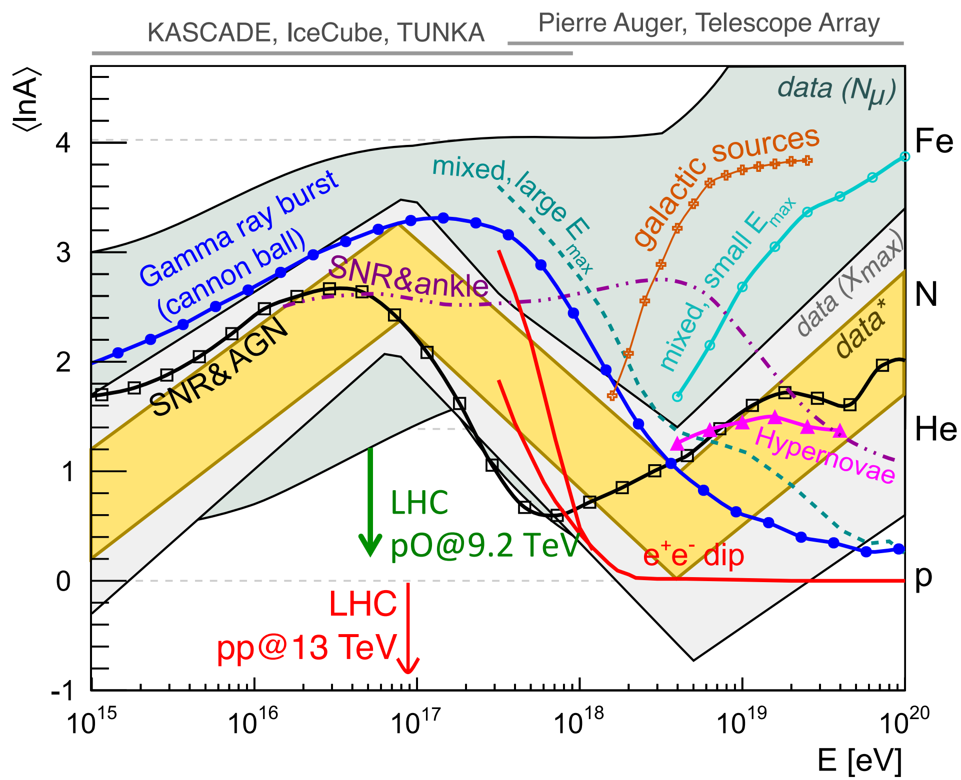
Energy spectrum

- Small uncertainties
- Weakly discriminating

Mass composition

- **Large uncertainties (theoretical)**
- **Strongly discriminating**

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



Mass composition differs **greatly** in astrophysical theories of CR origin,
but accuracy of measurement poor because of **uncertainties in air shower models**

Hadronic interaction models

low c.m. energy → high c.m. energy

Reference systems used for model tuning

LHC:
pp @ 7, 8, 13 TeV
pPb @ 5 TeV

RHIC:
pp @ 62, 200 GeV
AuAu @ 130 GeV

SPS: pC, πC @ 12 GeV

...

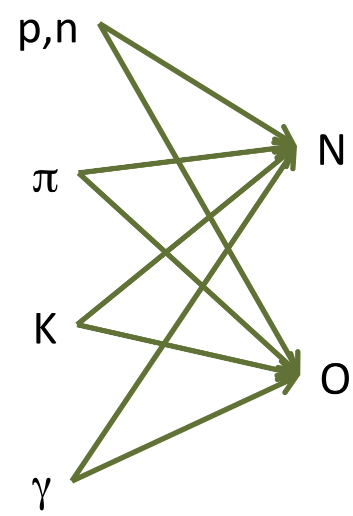
Hadronic interaction model

Glauber
Gribov-Regge
pQCD

Theory & Phenomenology

Pomerons
Mini-jets
Multi-parton interactions

Systems in air showers



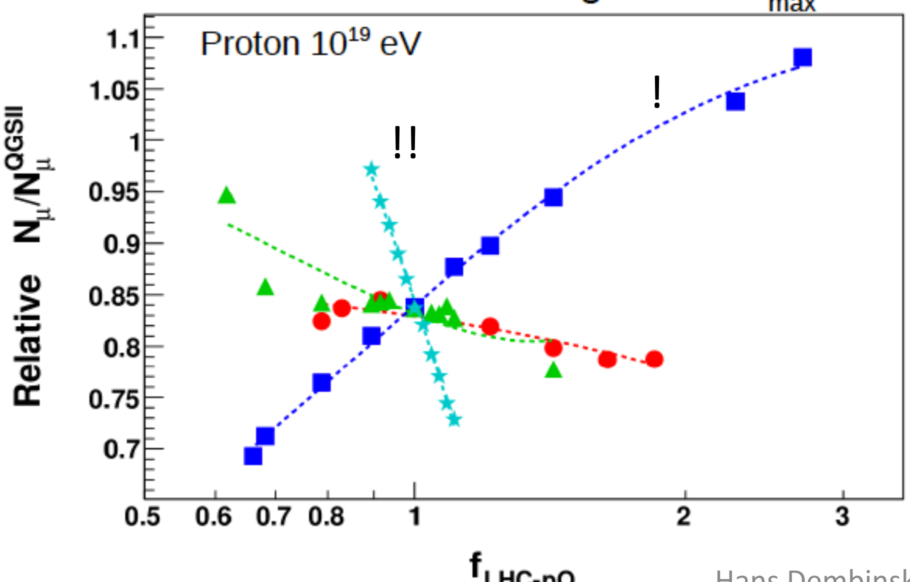
Precision in target system cannot be better than **measurement accuracy in reference systems**

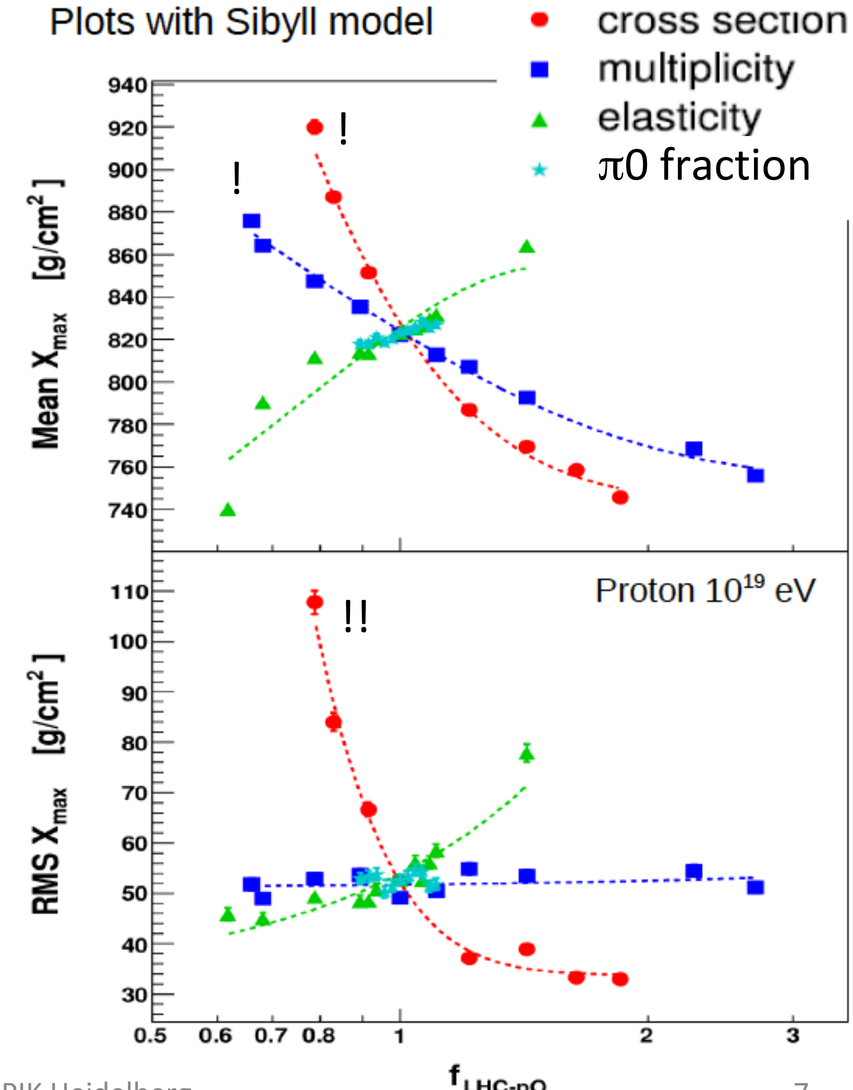
Important features in hadron production

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/cm^2 $\langle X_{max} \rangle$

Plots with Sibyll model

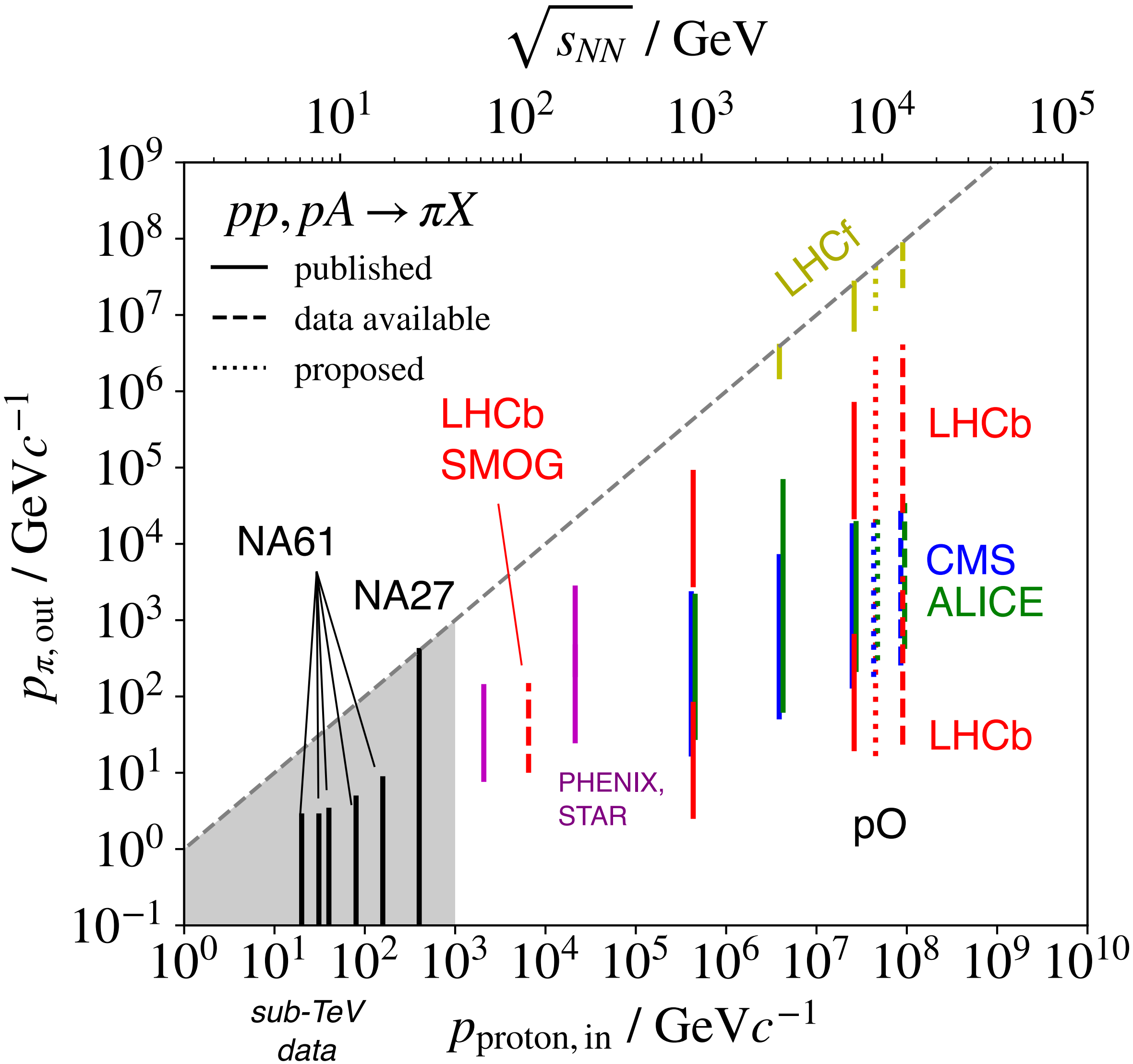




Reminder

- Run II: pp @ 13 TeV, pPb at 8.2 TeV, data available
- Run III: pO at 10 TeV proposed
  - Short run of O(100) M events
- Central question
  - Existing data on pp & pPb enough for cosmic ray physics?
  - Can important quantities for air showers be interpolated from measurements at pp and pPb to pO?
- Important quantities for air shower physics in pO
  - Inelastic cross-section
  - Hadron multiplicity
  - "Elasticity"
  - $\pi 0$ fraction

Data on pion spectra

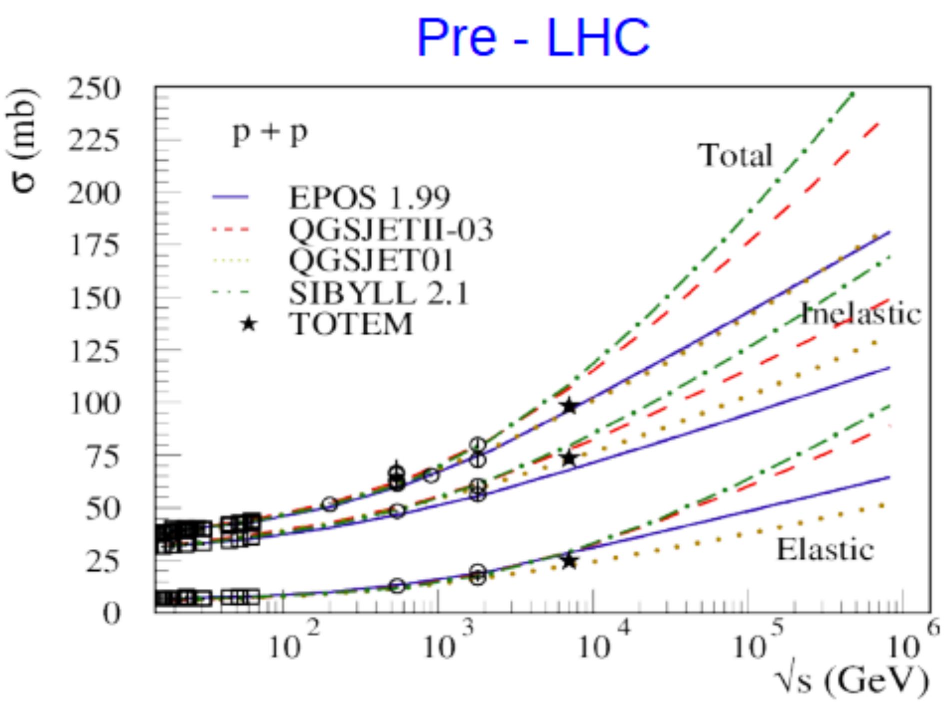


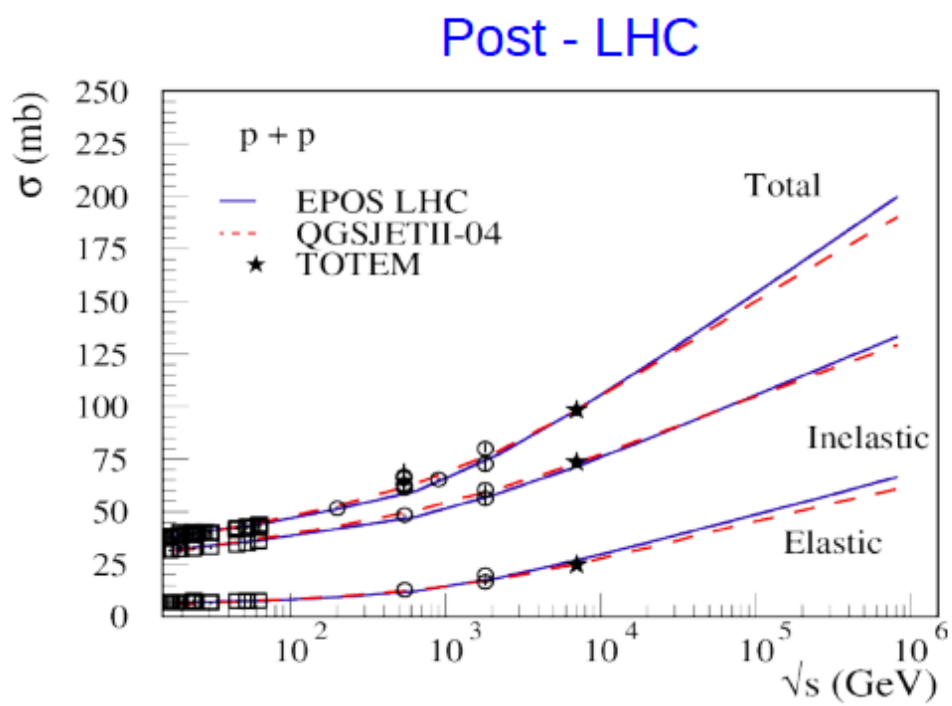
Phase space of air shower interactions as covered by various experiments
(beam-beam collisions transformed to equivalent fixed-target system)

LHCb significantly increases coverage

Inelastic cross-section

Tanguy Pierog, AFTER workshop, Freudenstadt Germany, 2015



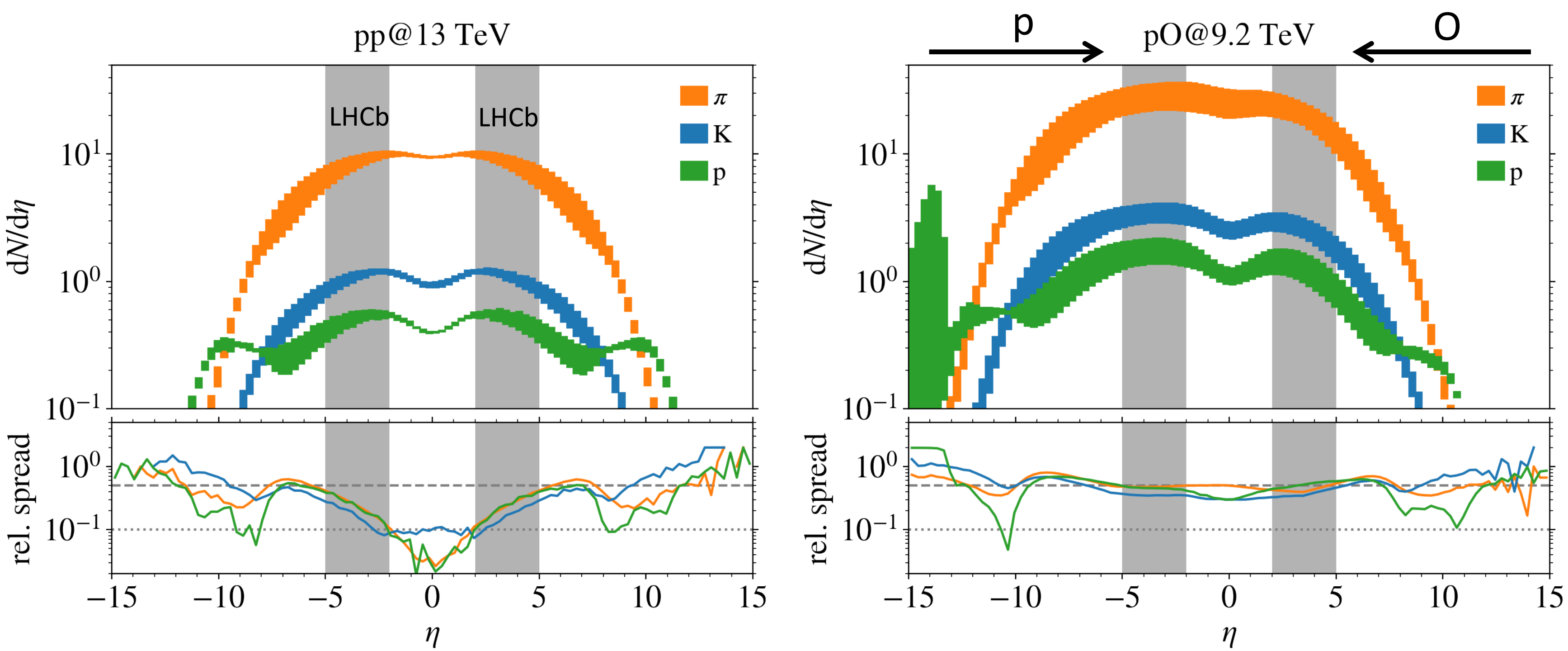


- pp inelastic cross-section now known to 3 %, see e.g. ATLAS arXiv:1606.02625
- Similar for pPb, about 4 %, CMS arxiv:1509.03893
- Interpolation to pO with Glauber should have similar precision

OK, if you **trust Glauber**

Simulated hadron production

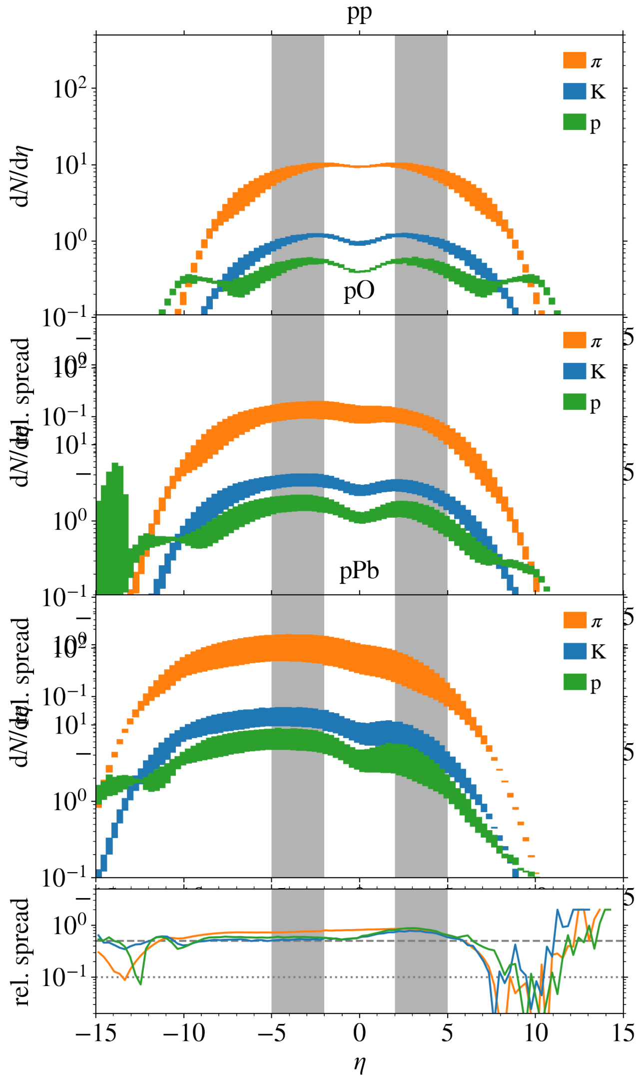
- Simulations done with CRMC: R. Ulrich et al. https://web.ikp.kit.edu/rulrich/crmc.html
- Model spread: EPOS-LHC, QGSJet-II.04, SIBYLL-2.3

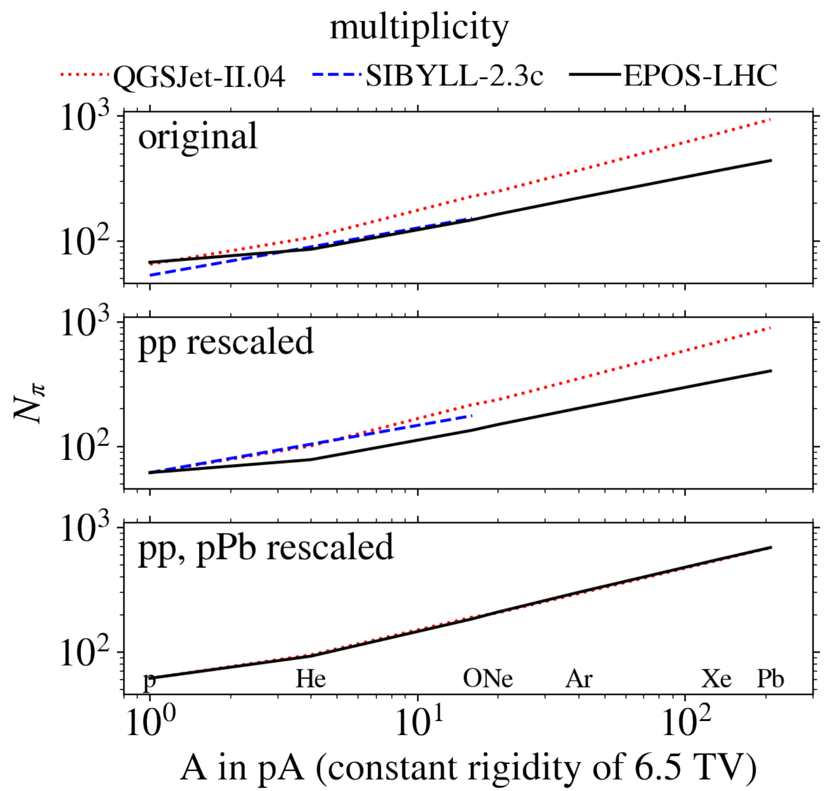


Models mostly tuned to pp data at |eta| < 2

- |eta| < 2: pp 10 % model spread, **pO 50 %** model spread
- eta = 5: **pp and pO 50 %** model spread

Multiplicity in pIon systems

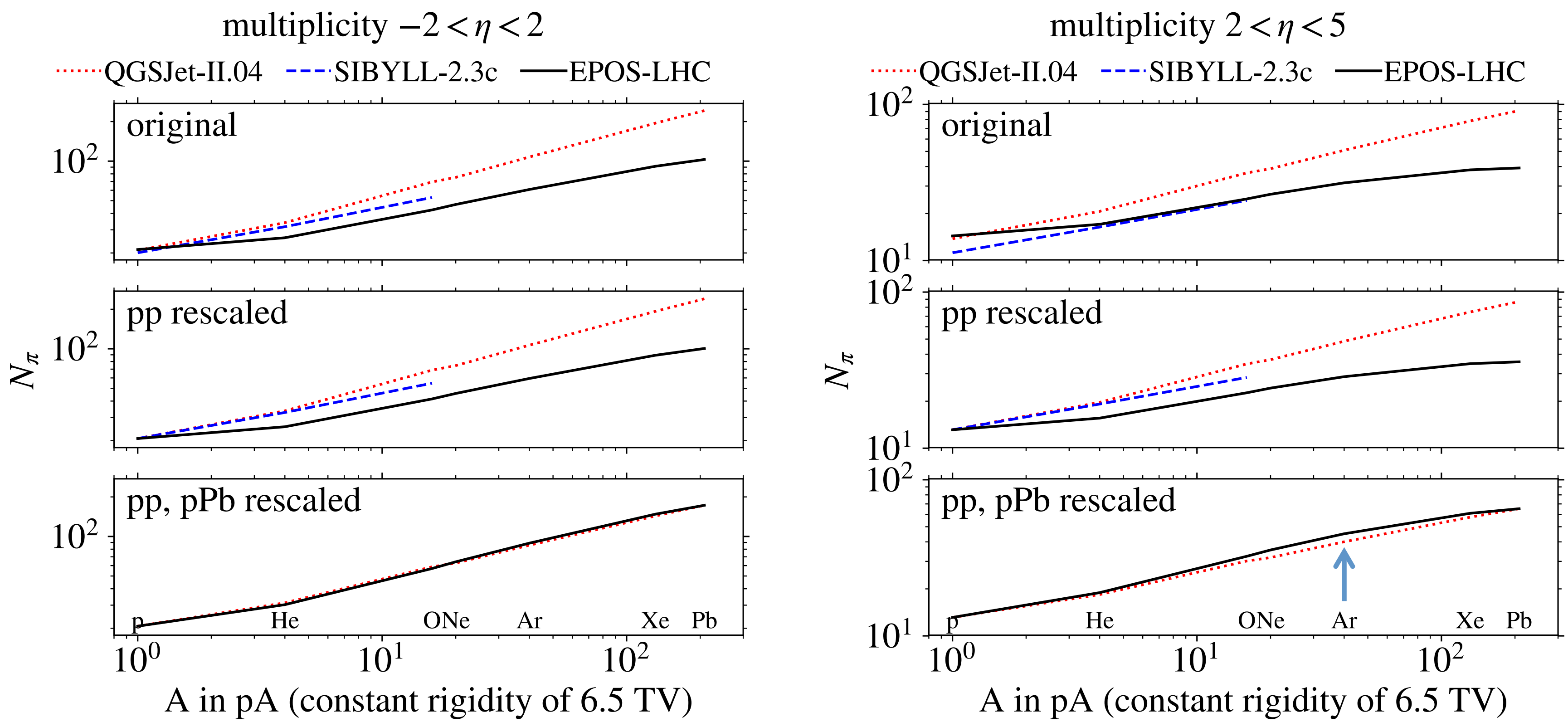




Simultaneous rescaling to pp and pPb: apply correction *a + b log(A)*, with *a* and *b* such that models converge at pp and pPb

pp and pPb together seem to constrain pO, but **need measurement to confirm. Also...**

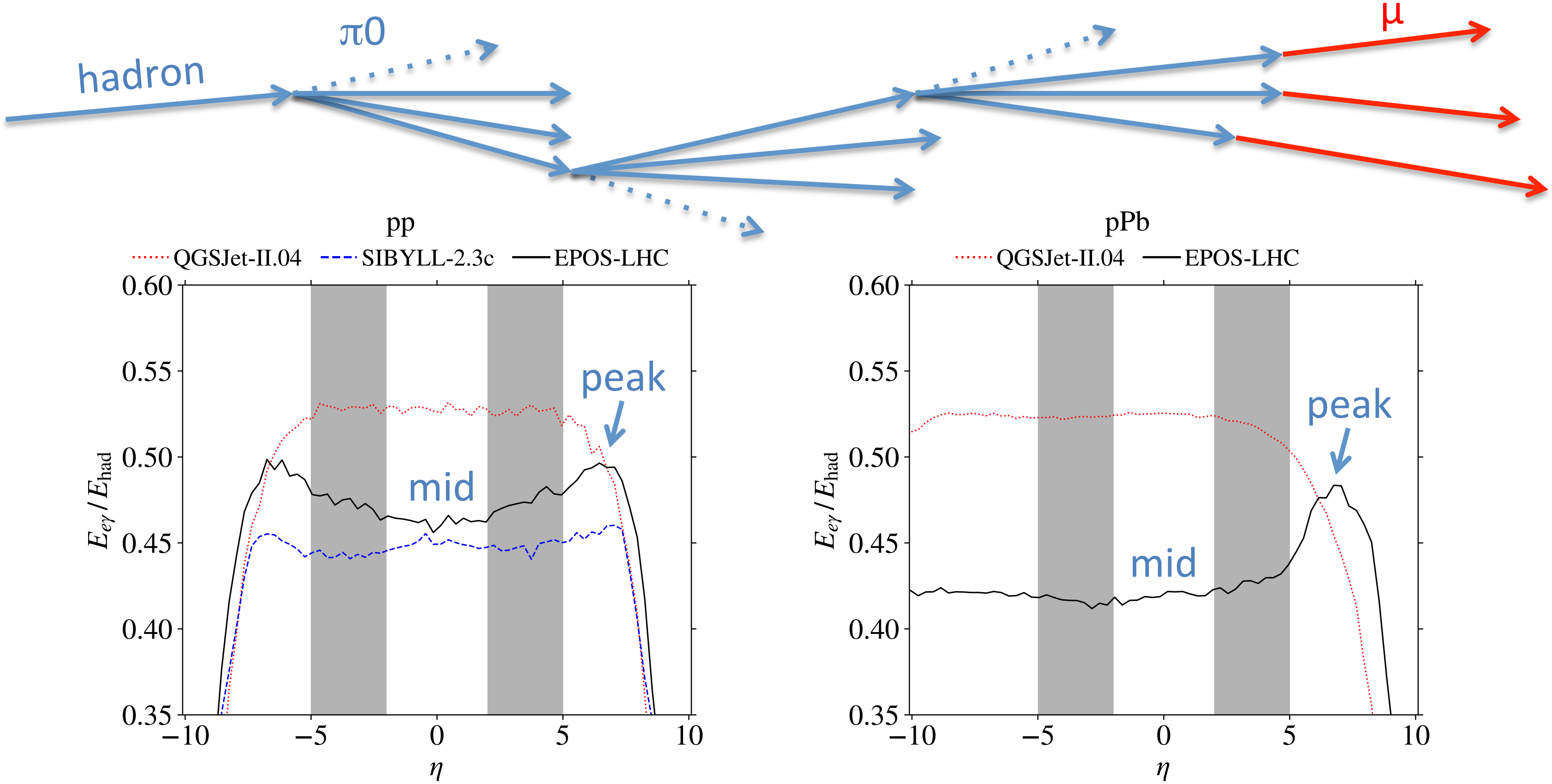
Multiplicity in forward rapidity



- Saturation visible in EPOS, not in QGSJet-II.04
- **7 % deviation in pO** even if models are fixed to same values in pp and pPb
  - **4 % shift in Nμ, 7 g cm-2 shift in Xmax**; comparable to exp. uncertainties
- Maximum deviation of **11 % in pAr**; best system to find which model is correct

em-hadron energy ratio

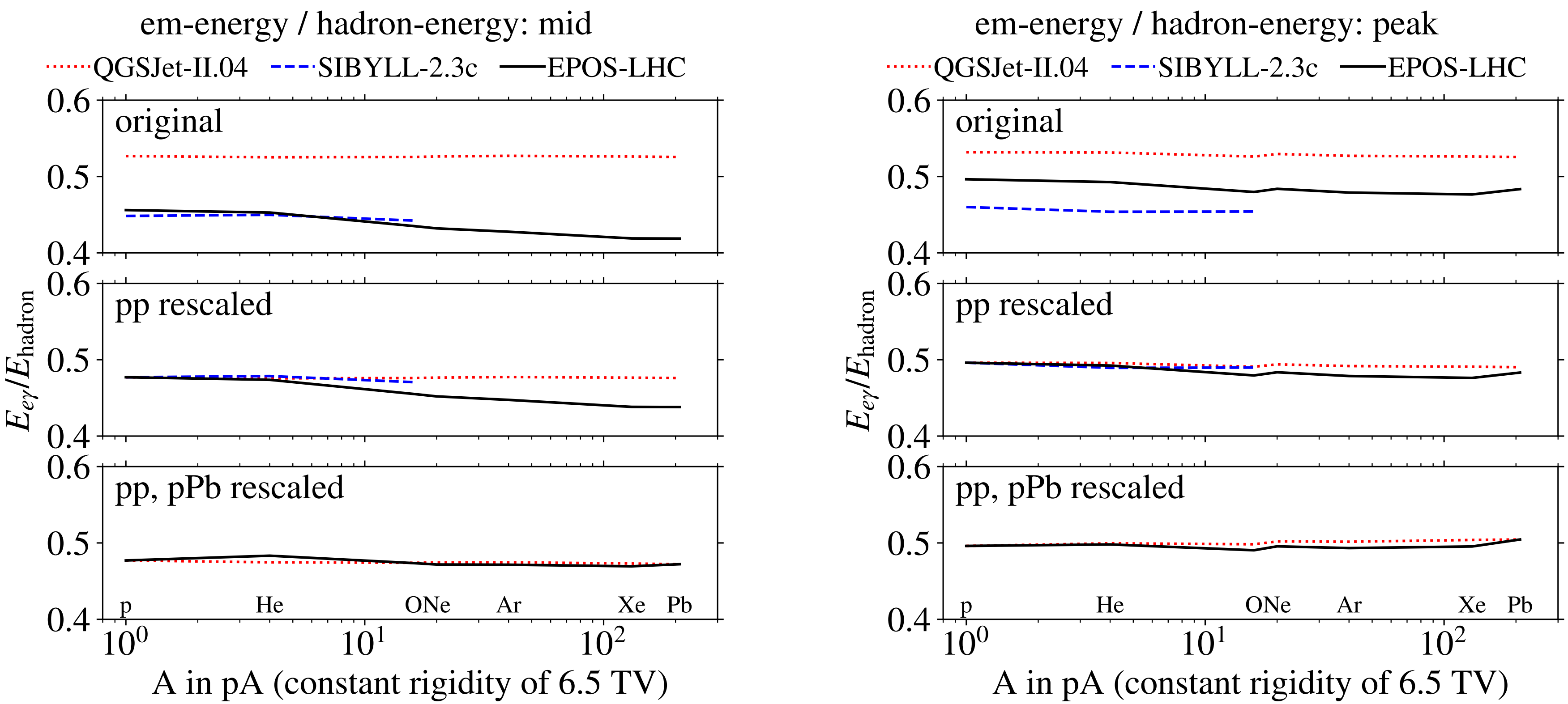
- Hadronic energy "lost" to π0 (which decay to photons) cannot be used to produce muons in later steps of air shower development
- Equivalent observable $E_{e\gamma}/E_{hadrons}$



Model predictions differ by **13 % & different shape**: only EPOS has **forward peaks**

> 15 % shift in Nμ

em-had. energy ratio in plon systems



pp and pPb together seem to constrain pO, but **need measurement to confirm!**

Model deviations were not anticipated by model builders

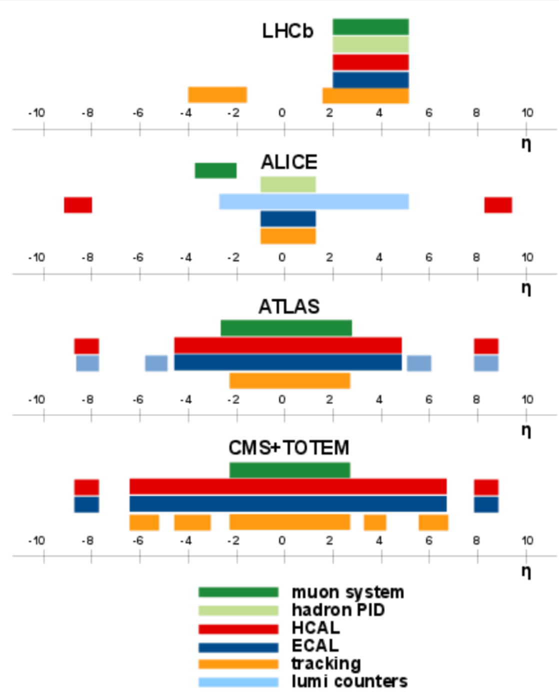
Summary pO runs

- Why pO?
  - pO collisions reproduce **first interaction** in $5x10^7$ GeV air showers
  - pO important reference system for tuning
  - Why oxygen, not nitrogen? oxygen already used as support gas for lead
  - Perhaps pO can be interpolated from pp and pPb, but need measurement to verify!
  - **Saturation of pion multiplicity** observed in EPOS-LHC, not in other models
    - Model discrepancy has significant effect on air shower observables

- What to measure?
  - Inelastic cross-section
  - π, K, p spectra
    - Inclusive production, double-differential
  - Energy flows
    - Separate eγ flow from hadron flow

- Required luminosity
  - **100M events,** about **Lint = 0.2 nb^{-1}**

- Detectors with most impact
  - ALICE: Hadron PID at mid rapidity
  - LHCb: Hadron PID for 2 < eta < 5
  - LHCf: gamma and neutrons at eta > 8.4
  - CASTOR: EM/Had. energy flow at 5.2 < eta < 6.5



This meeting

- Looking forward to meet you all in person
- Other science interest in min-bias data?
- Who has manpower to analyze pO data?