pO runs at the LHC

Hans Dembinski,
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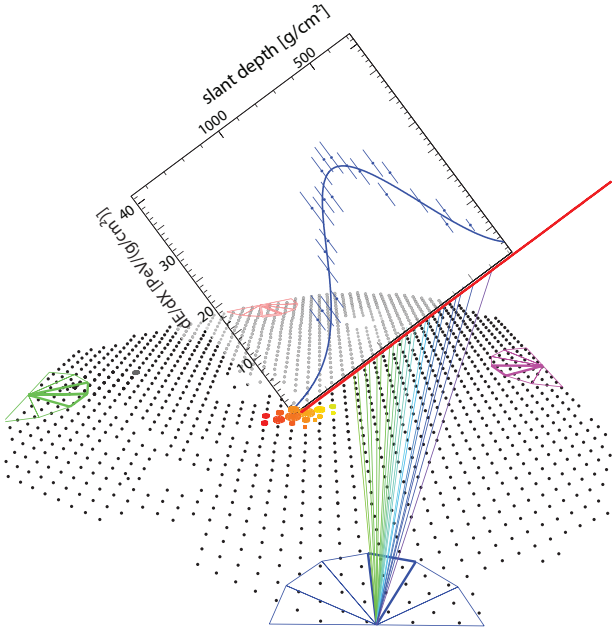
LHC Working Group on Forward Physics and Diffraction, 19 Dec 2018, CERN



Summary

- Recap
  - Cosmic ray mass composition is inferred from air shower measurements, carries important imprint of sources
  - Progress blocked by large uncertainties in hadronic interactions
  - **High accuracy (5 %)** LHC measurements of pO expected to resolve this
  - Forward measurements very important:
    energy flow, separately for π^0 and hadrons
    π, K, p spectra

- News
  - **Muon puzzle** established at **8 sigma** (UHECR 2018)
  - **p+O** discussed in **HL-LHC yellow report**
  - Proposed run schedule: **2022** p-O at 9.9 TeV, Lint = 200 μb^{-1} for experiments: ALICE, ATLAS, CMS, LHCb

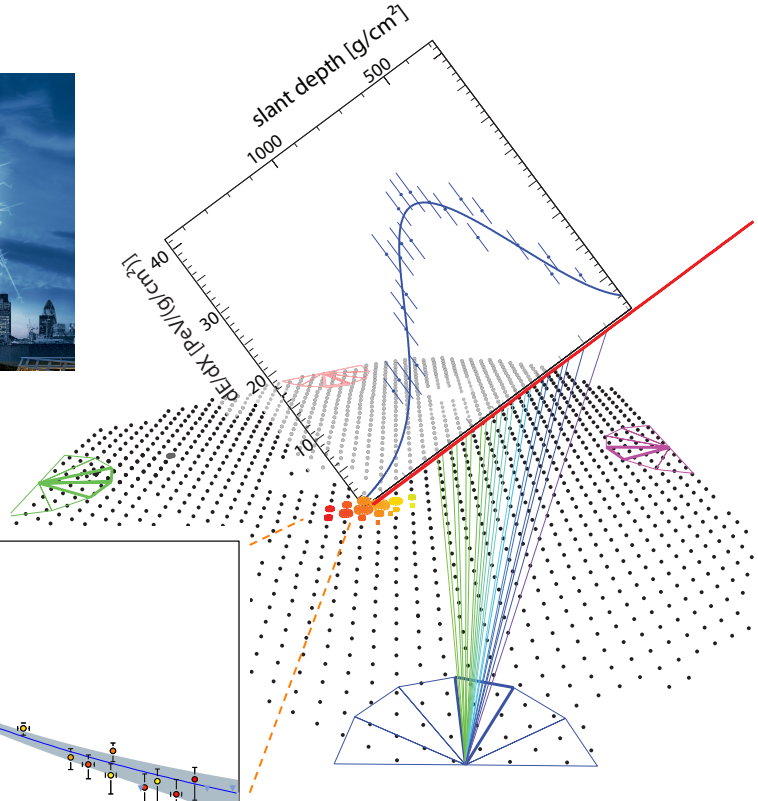
UHE cosmic ray detection

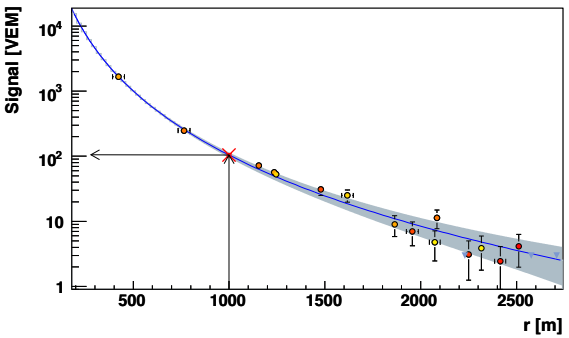
Artist impression of air shower

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

UHE cosmic ray detection

Example: event observed with Pierre Auger Observatory





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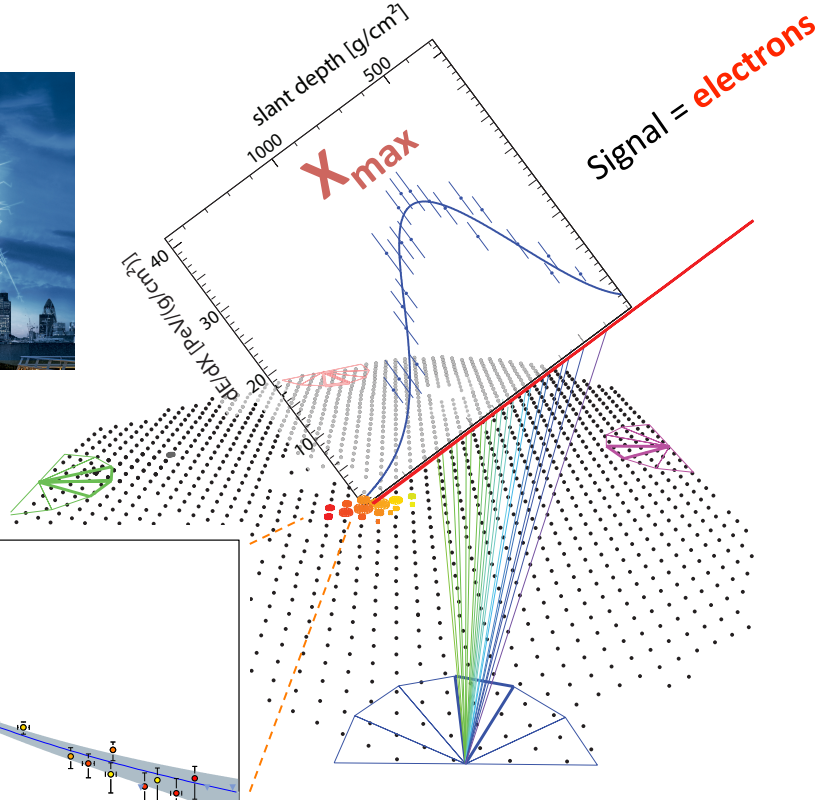

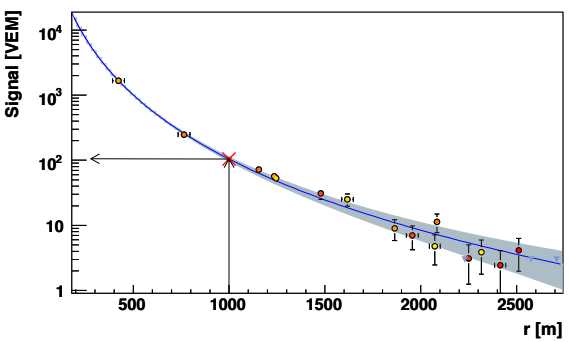

Signal = **electrons** + **photons** + **muons** N_μ

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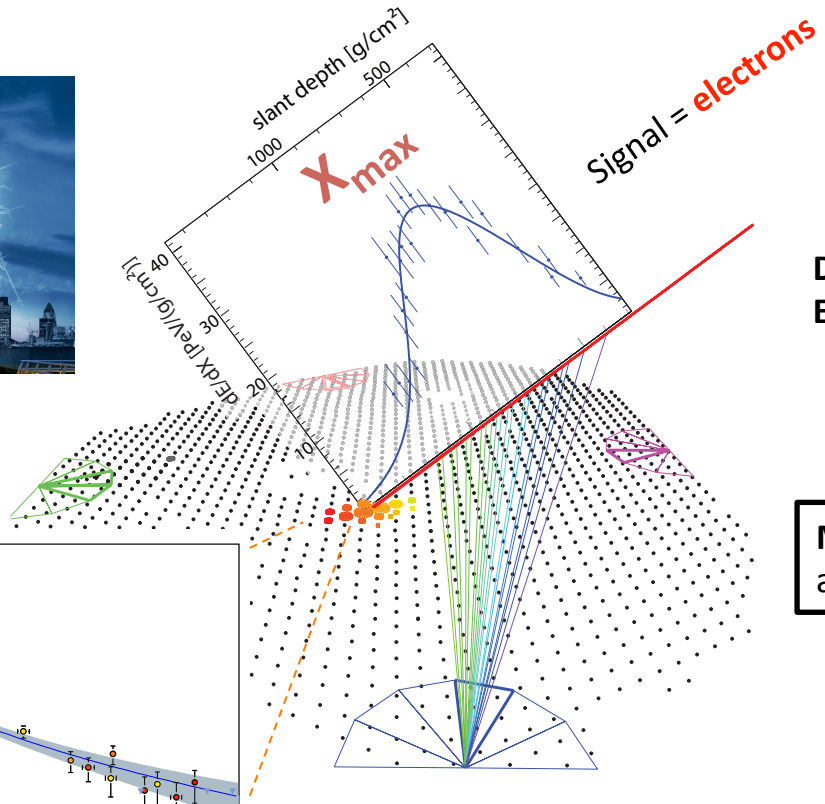
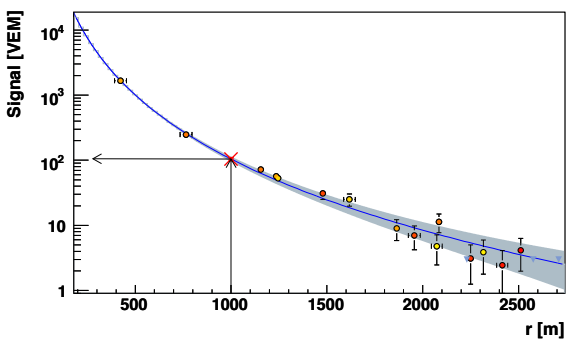




Direction from particle arrival times ✔
Energy from size of **eγ component** ✔

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

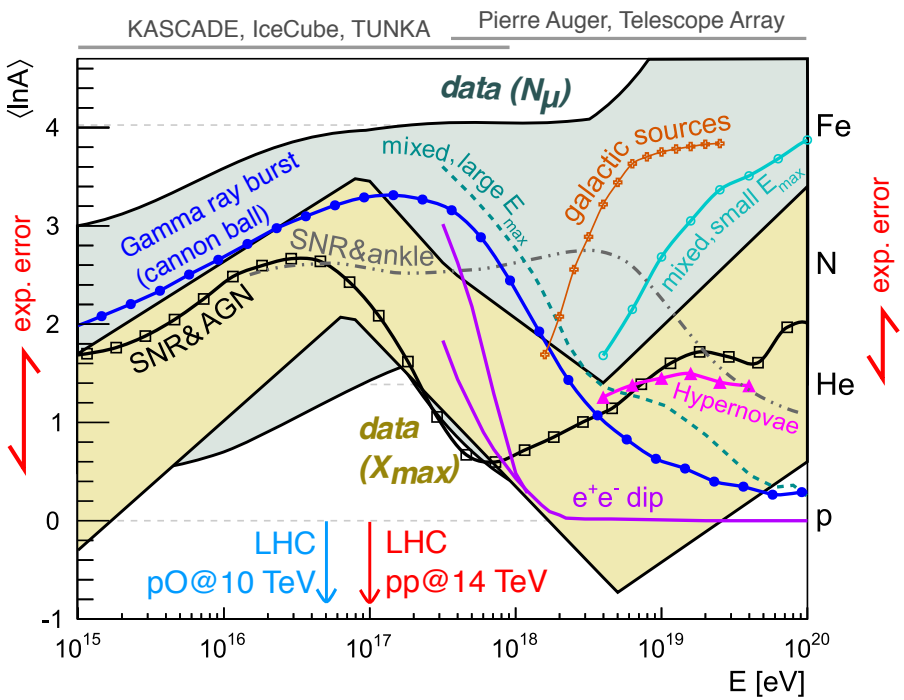
Mass from **depth of shower maximum** and **size of muonic component**

Signal = **electrons** + **photons** + **muons** **N_μ**

Instrumental uncertainties (Auger)

Direction	negligible	
Energy	14 $\%_{sys}$	
X_{max}	10 g $cm^{-2}{}_{sys}$	(Fe – p = 100 g cm-2)
N_μ	11 $\%_{sys}$	(Fe / p = 1.4)

Cosmic ray mass composition



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

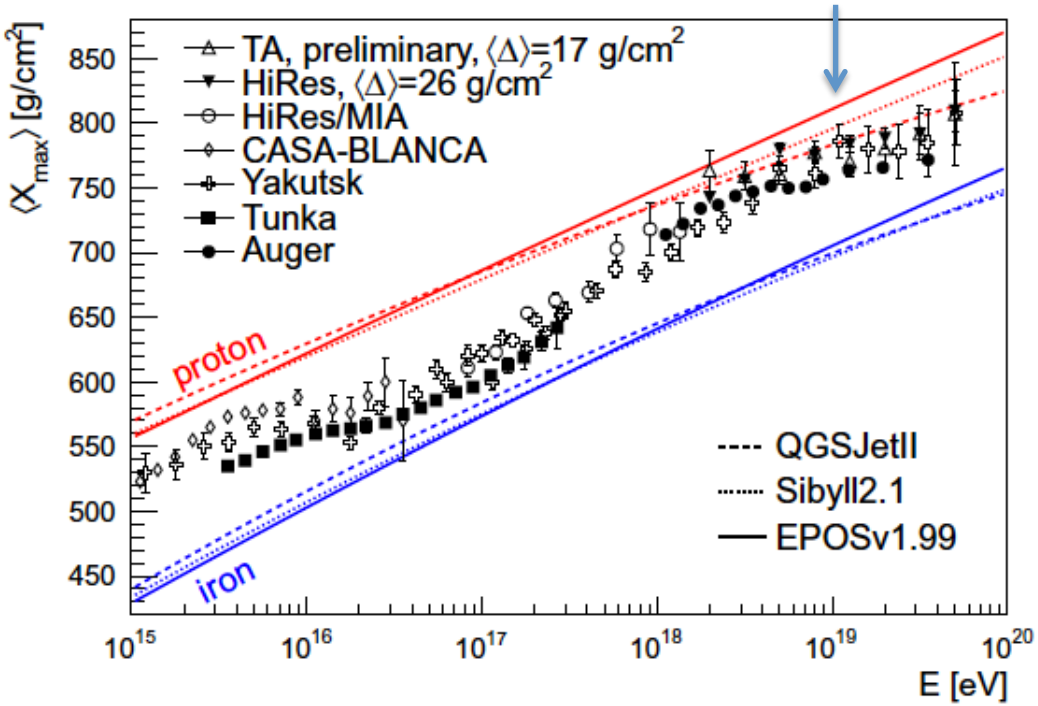
- Mass composition (<lnA>) carries imprint of cosmic-ray sources
- Uncertainties in hadronic interaction models dominate <lnA>, not experimental uncertainties
- **Muon Puzzle:** Muon measurements have much larger spread and are not consistent with X_{max}

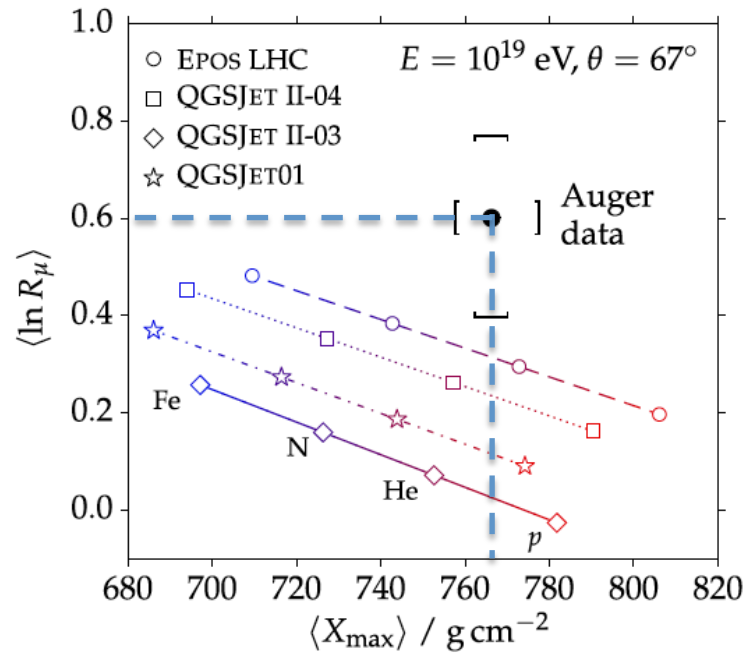
Indirect search for physics beyond the standard model at 100 TeV scale

Model dependence of mass

Heitler-Matthews model (and simulations): $\langle \ln A \rangle = \mathbf{a} + \mathbf{b}\, X_{max} = \mathbf{c} + \mathbf{d} \langle \ln N_\mu \rangle$

a, b, c, d are model dependent





Using number of muons $\mathbf{N_\mu}$ and depth $\mathbf{X_{max}}$ of shower maximum produces conflicting results

A=220, radon? *A=1 to 4, p to helium?*

From UHECR 2018

Tests of EM component

- Proton-air cross-section (next slide)
- Longitudinal shape
  - F. Diogo (Auger), ICRC 2015 arXiv:1509.03732v1
    - Average profiles parameterized by width L and asymmetry R
    - Agreement for EPOS-LHC, QGSJet-II.04, some tension for SIBYLL-2.1
- Moments of X_{max} distribution
  - J. Bellido (Auger), ICRC 2017 arXiv:1708.06592v2; Auger: JCAP 1302 (2013) 026
    - First two moments of X_{max} distribution converted to first two moments of lnA
    - EPOS-LHC, SIBYLL-2.3 ok; partially unphysical second moments for QGSJet-II.04
- Lateral density profile
  - S. de Ridder (IceCube) ICRC 2017 arXiv:1710.01194v1
    - <lnA> computed from <β> and in-ice energy loss (TeV muons)
    - Agreement for QGSJet-II.04, SIBYLL-2.3
    - Disagreement for SIBYLL-2.1, EPOS-LHC
- Attenuation with zenith angle
  - D. Ivanov (Telescope Array) TeVPA 2018
    - Agreement to 45 deg with QGSJet-II.03

From UHECR 2018

Tests of Muon component

- Lateral density (rest of talk)
- Production depth/height
  - Auger: PRD 90 (2014) 012012, PRD 90 (2014) 039904, PRD 92 (2015) 019903; disagreement for QGSJet-II.04 and EPOS-LHC
  - KASCADE-Grande: Astropart. Phys. 34 (2011) 476; disagreement with QGSJet-II.02
- Attenuation with zenith angle
  - KASCADE-Grande: Astropart. Phys. 95 (2017) 25; disagreement with all current models
- High-energy muons: multiplicity
  - ALICE: JCAP 1601 (2016) 032; consistent with QGSJet-II.04
- TeV muons: flux
  - IceCube: Astropart. Phys. 78 (2016) 1; disagreement for SIBYLL-2.1, potentially fixed by adding charm
  - T. Fuchs (IceCube), ECRS 2016, arXiv:1701.04067; agreement for SIBYLL-2.1
- TeV muons: lateral-separation
  - D. Soldin (IceCube), ISVHECRI 2018; partial agreement for SIBYLL-2.1/2.3, disagreement for EPOS-LHC, QGSJet-II.04
- Rise-time
  - Auger: PRD 96 (2017) 122003; disagreement for QGSJet-II.04 and EPOS-LHC
  - Auger: PRD 93 (2016) 072006; disagreement for EPOS-LHC (500-2000 m), QGSJet-II.04 (500-1000 m), agreement for QSGJet-II.04 (1000-2000 m)

Motivation summary

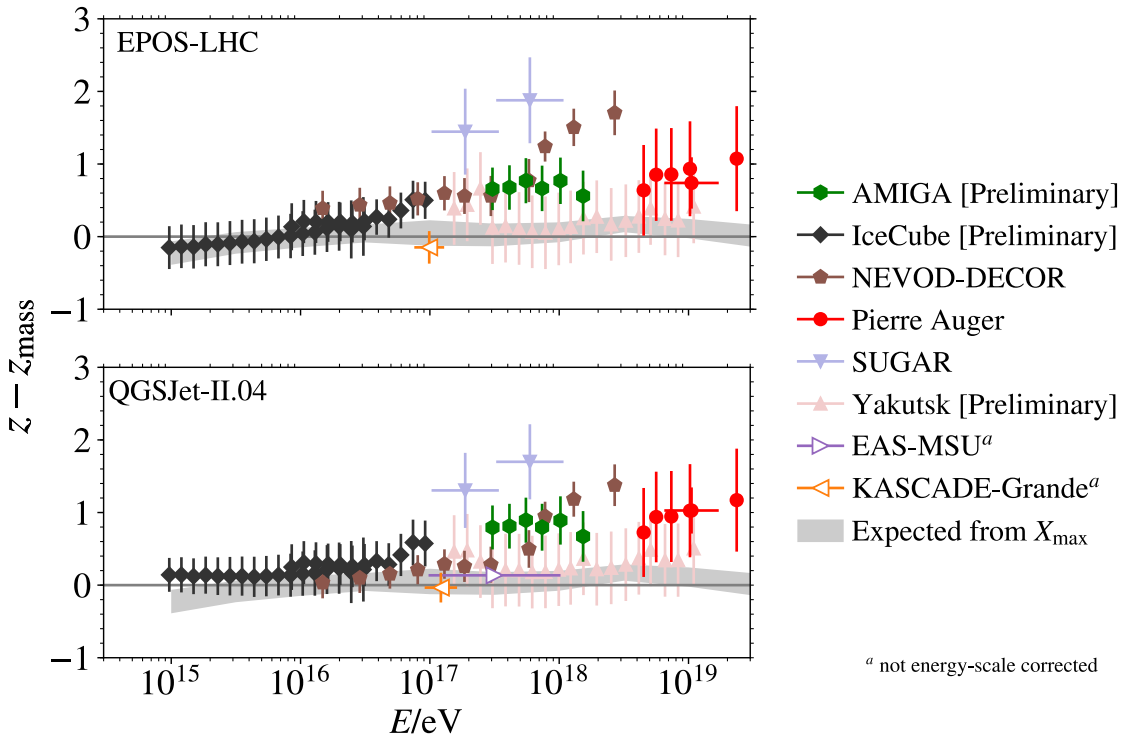
- Cosmic ray research would greatly benefit from precise knowledge of cosmic ray mass
- Air shower measurements are very accurate, accurate simulations of hadronic cascade missing
- Air shower measurements can narrow down where models fail, but only LHC measurements can pin-point and resolve it

News on Muon Puzzle

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

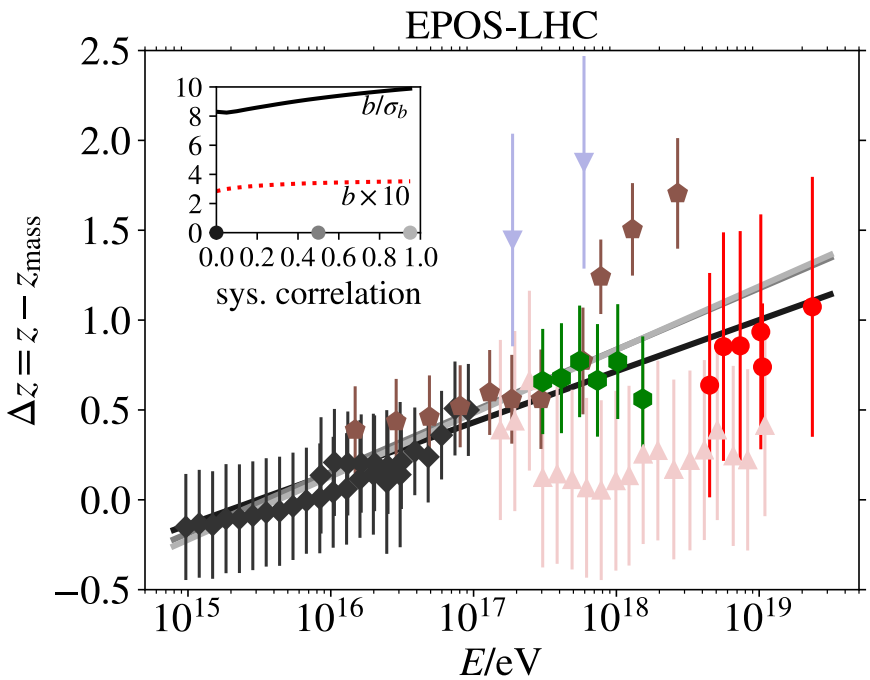
All measurements converted to z-scale $z = \frac{\ln N_{\mu}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}{\ln N_{\mu,\mathrm{Fe}}^{\mathrm{det}} - \ln N_{\mu,p}^{\mathrm{det}}}$

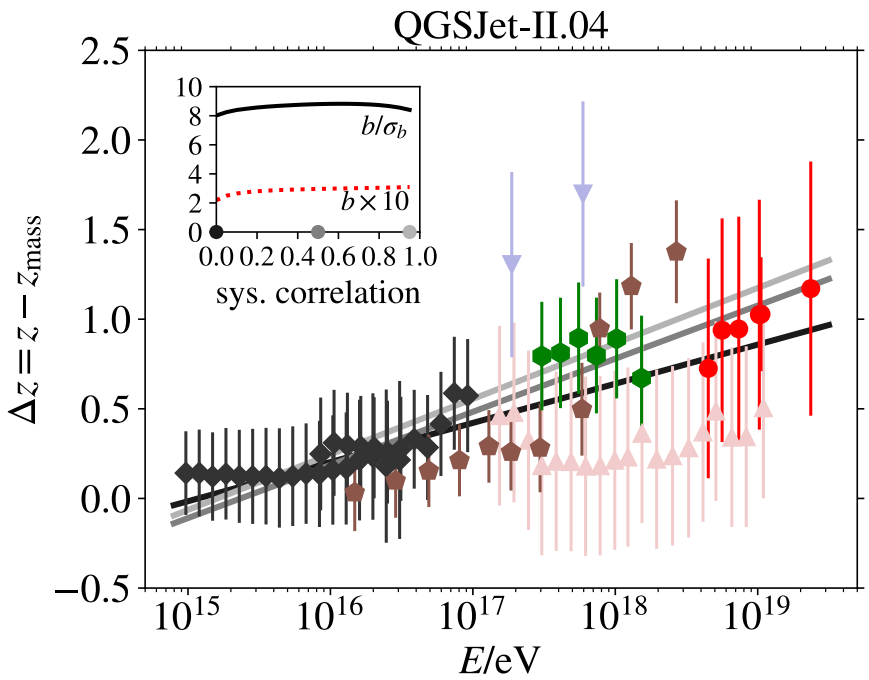
- Systematic discrepancies starting around 5×10^{16} eV, equiv. to $\sqrt{s_{nn}}$ **= 10 TeV**



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

Muon Puzzle strongly confirmed





Fitted line to data $$\Delta z = a + b[\log_{10}(E/\mathrm{eV}) - 16]$$

Fit corrected for over- and underestimation of uncertainties, assuming various levels of systematic correlation for points from the same experiment

Slope deviates from zero by 8 sigma

Main points

- Muon Puzzle is experimentally established
- Increasing deviation with shower energy, start in the reach of LHC
- Problem is likely **not** in the first interaction
  - muons are produced after about **6 hadronic interactions**, Heitler-Matthews-model

$$\frac{N_\mu}{N_{\mu,\mathrm{MC}}} = \left(\frac{N_{\mathrm{hadrons}}}{N_{\mathrm{hadrons,MC}}}\right)^6 =? \ (1.05)^6 \approx 1.34$$

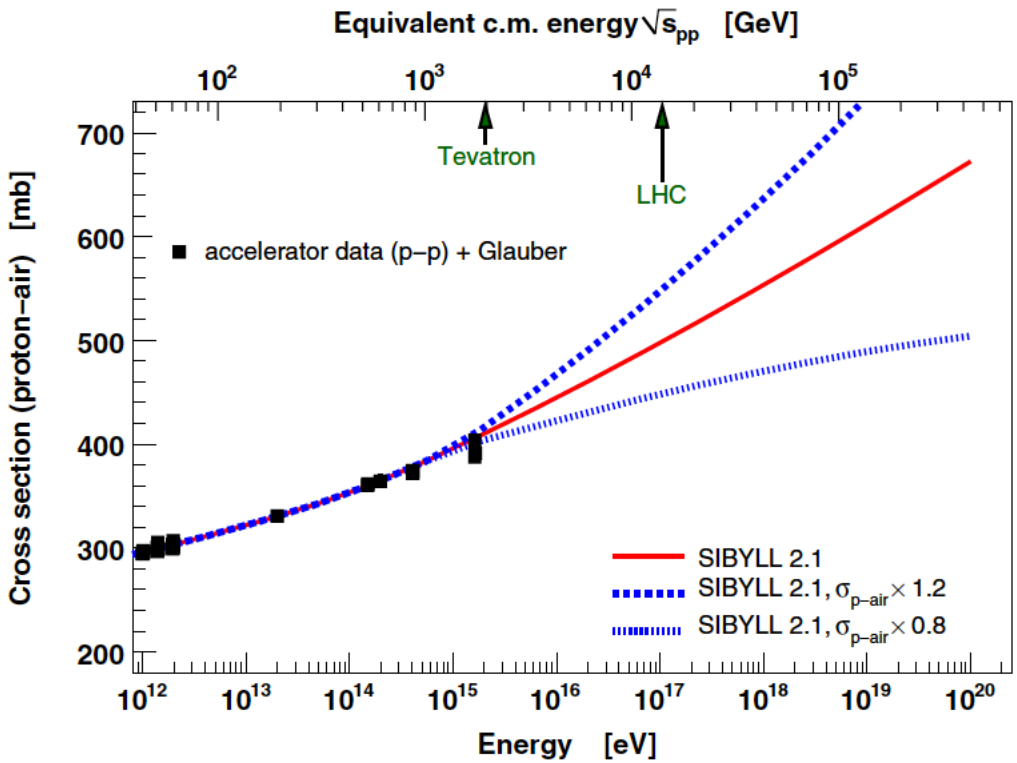
5 % measurements needed at the LHC to solve this

Modified hadronic interactions

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

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 hadronic features

Modified features

- **cross-section**: inelastic cross-section of all interactions
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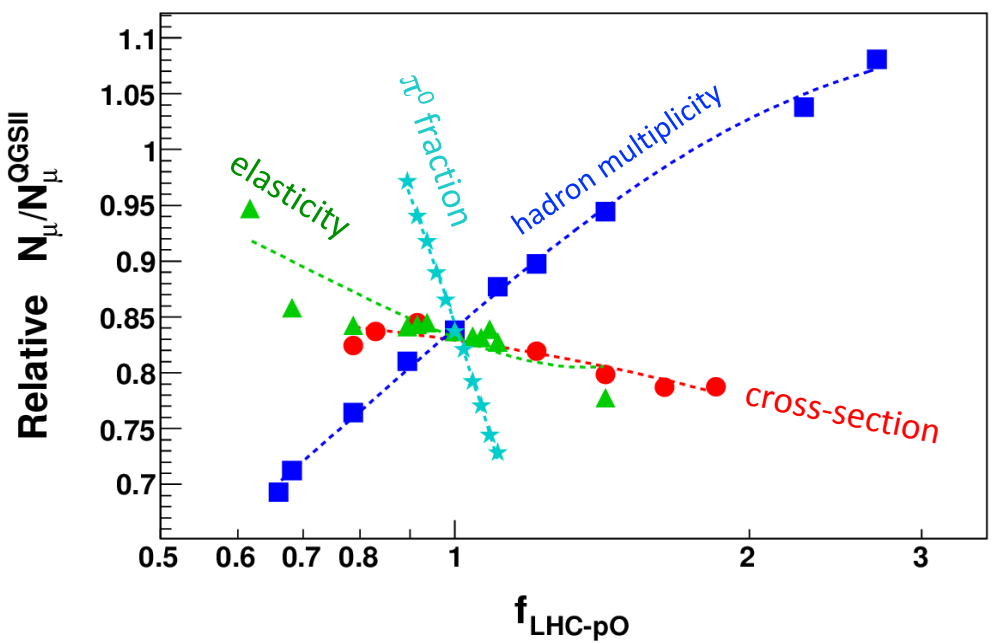
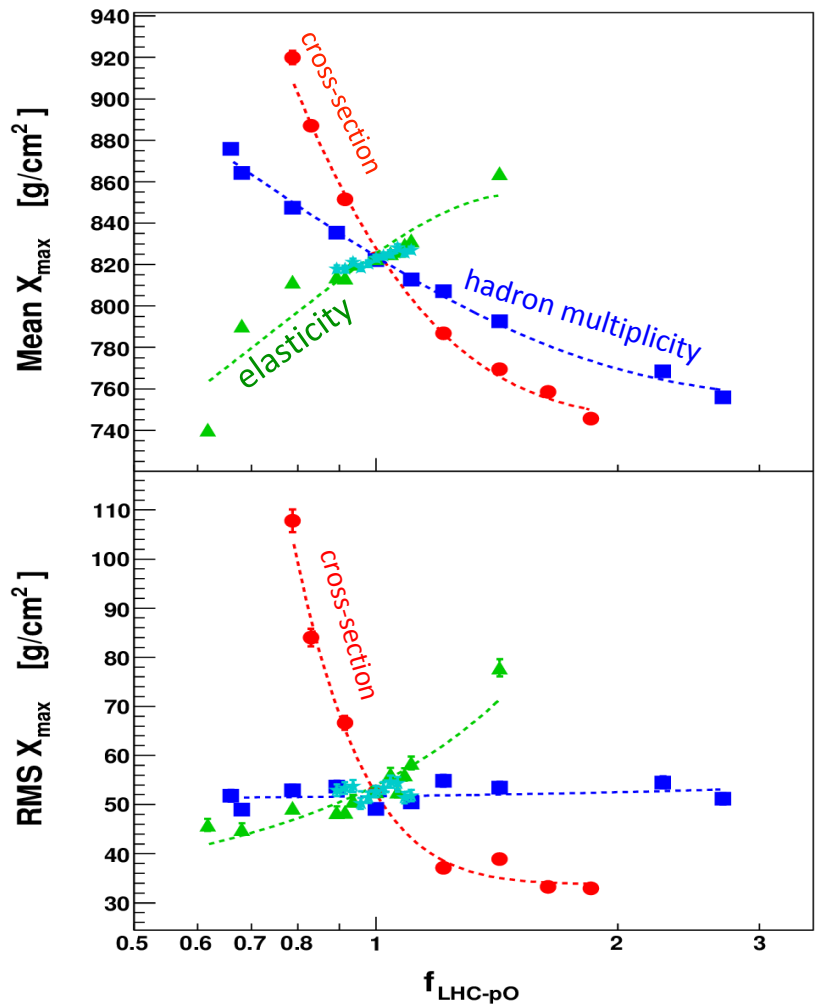
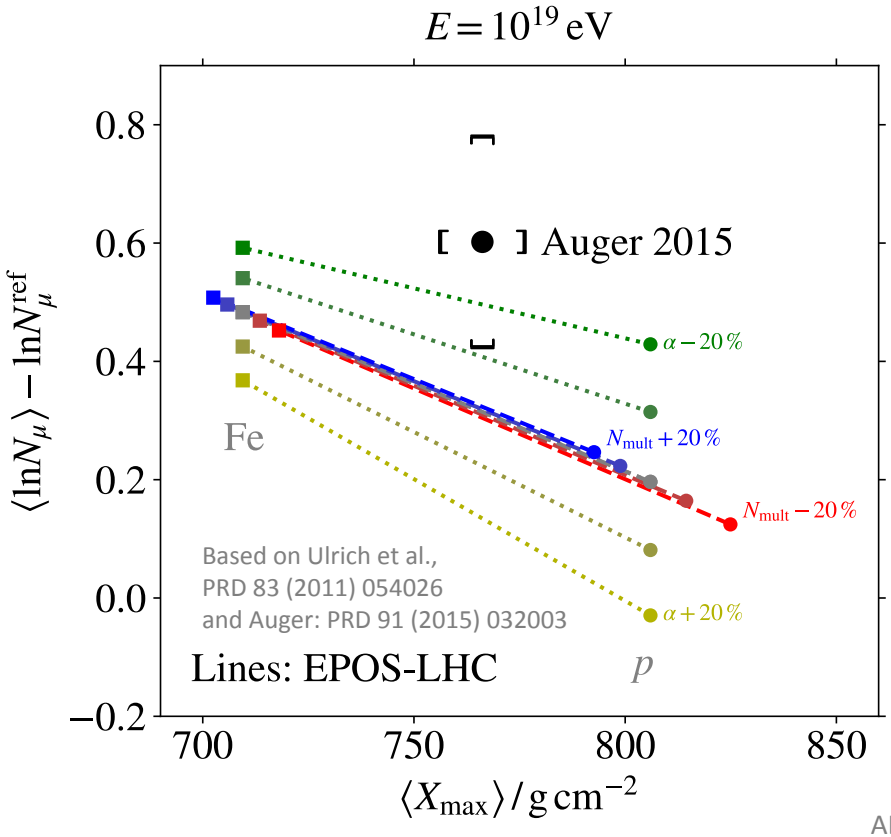
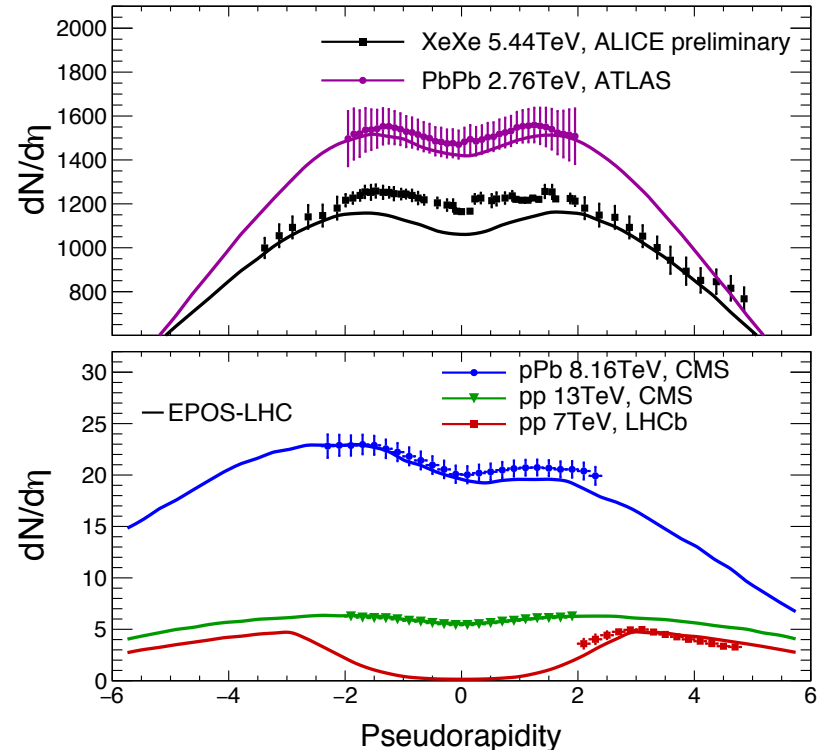




Impact of LHC measurements





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

HL-LHC Yellow Report

https://arxiv.org/abs/1812.06772

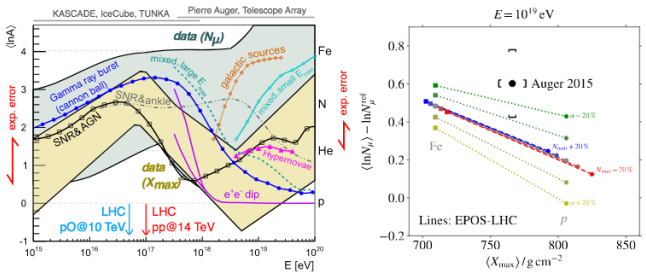


Fig. 104: Left: Mass composition of cosmic rays quantified by $\langle \ln A \rangle$ as a function of cosmic ray energy E. See Ref. [982] for references to data (bands) and model predictions (markers and lines), and the text for a discussion. Right: Impact of changes of the hadron multiplicity N_{mult} (dashed lines) and the energy fraction α (dotted lines) which goes into neutral pions in collisions at the LHC energy scale on EPOS-LHC predictions for X_{max} and $\ln N_\mu$ in 10^{19} eV air showers, compared to Auger data [983]. The model lines represent all values that can be obtained for any mixture of cosmic nuclei from proton (bottom right) to iron (top left). The dashed and dotted lines represent modifications of N_{mult} and α in steps of $\pm 10\%$ from their nominal values.

11.3 Proton-oxygen collisions for cosmic ray research

Coordinators: Hans Dembinski (MPI for Nuclear Physics, Heidelberg)

Contributors: T. Pierog (Karlsruhe Institute of Technology), R. Ulrich (Karlsruhe Institute of Technology)

The recent coincident observations of gamma rays and neutrinos from the flaring blazar TXS 0506+056 confirmed that active galactic nuclei produce high-energy cosmic rays [984]. This long awaited finding demonstrates that sources of cosmic rays are linked to the most violent places in our universe. Measurements of cosmic rays contribute to the understanding of the high-energy universe. Since cosmic rays are charged and bent by magnetic fields in space onto chaotic paths, their arrival directions at Earth are highly isotropic, but their mass composition carries an imprint of the source physics. Precision measurements of minimum-bias events in proton-oxygen collisions have the unique power to resolve current ambiguities in the mass composition measured with atmospheric air-shower techniques.

Cosmic rays are nuclei from protons to iron (heavier elements are negligible). The energy-dependent mass composition of cosmic rays is characteristic for different source scenarios, as shown in Fig. 104, left-hand-side, which displays predictions (lines and markers) of the mean-logarithmic-mass $\langle \ln A \rangle$ of cosmic rays. Above particle energies of 10^{15} eV, $\langle \ln A \rangle$ can only be indirectly inferred from extensive air showers, huge secondary particle cascades produced by collisions between cosmic rays and nuclei in the atmosphere. The two leading observables to infer $\langle \ln A \rangle$ are the depth X_{max} of the shower maximum in the atmosphere (yellow band in Fig. 104), and the number N_μ of muons produced in the shower (green band in Fig. 104). The width of those bands has two main contributions: the experimental uncertainties, and the hadronic model uncertainties inherent in converting the air shower observables into $\langle \ln A \rangle$.

Leading experiments achieve an instrumental accuracy of 10 % of the proton-iron difference, which would strongly discriminate between source scenarios, but air shower simulations are required to convert N_μ and X_{max} to $\langle \ln A \rangle$ and this adds a large model uncertainty. The simulations use the multi-

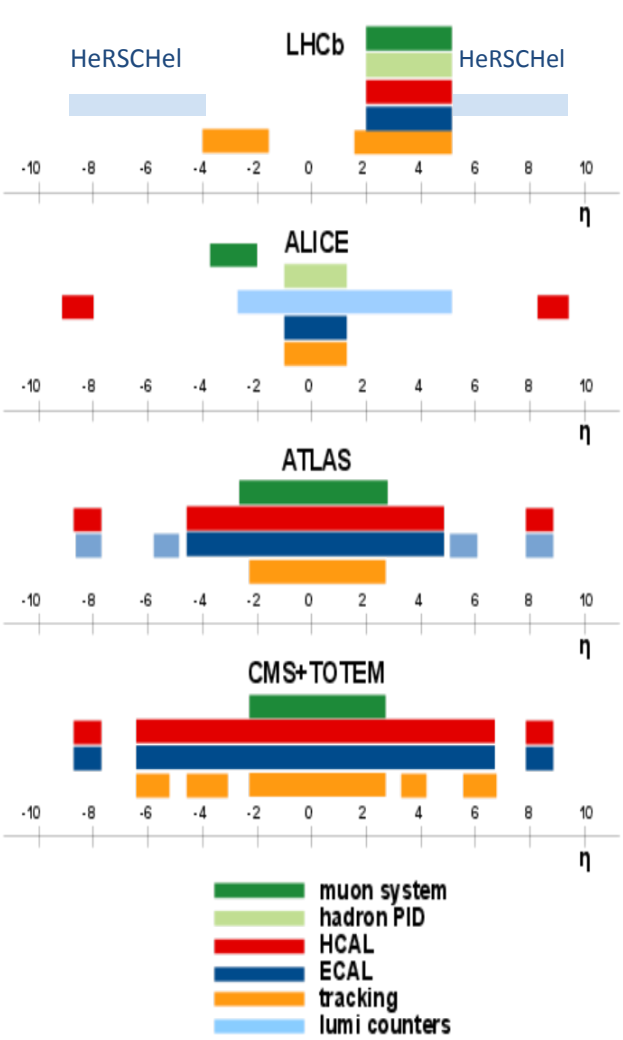
- Section 2.5: technical feasibility of p-O run
- Section 11: Opportunities of proton-ion collisions
- Section 11.1: O+O, Ar+Ar, Kr+Kr
- Section 11.3: p+O for cosmic ray research

- Section 12: Luminosity requirements

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	

Measurements in p+O

- Differential cross-section for production of π, K, p
  - Needs hadron PID
  - ALICE: $|\eta| < 0.9$
  - LHCb: $2 < \eta < 5$
- Energy flow separated by hadrons and eγ
  - Needs good Ecal and Hcal
  - ATLAS, CMS & CASTOR up to $|\eta| = 6.6$
- LHCf: π^0, n in very forward range for elasticity, $\eta > 8.4$



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Fitting data with correlated errors

10 points, two groups with systematic offset and correlated errors

Fit line y = a + b x

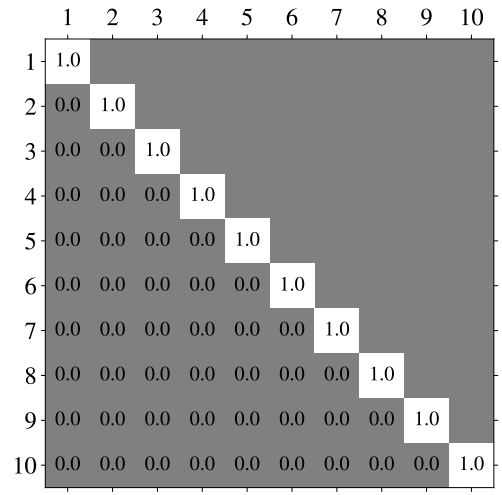
Truth: a = 1, b = 2

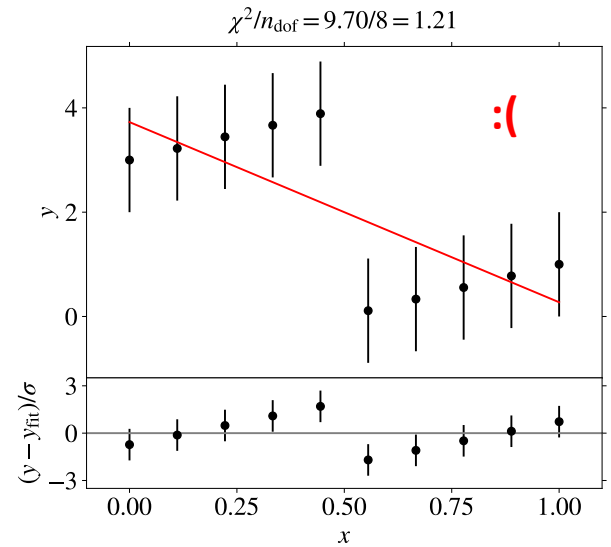
Generalized least-squares, minimize

$$Q = (\vec{y} - \vec{y}_{\text{fit}})^T C^{-1} (\vec{y} - \vec{y}_{\text{fit}})$$

C ... covariance matrix of data

correlation ignored





correlation correctly handled