Update on the WHISP combined analysis of muon measurements from air shower experiments

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ISCRA 2021, June 8, 2021

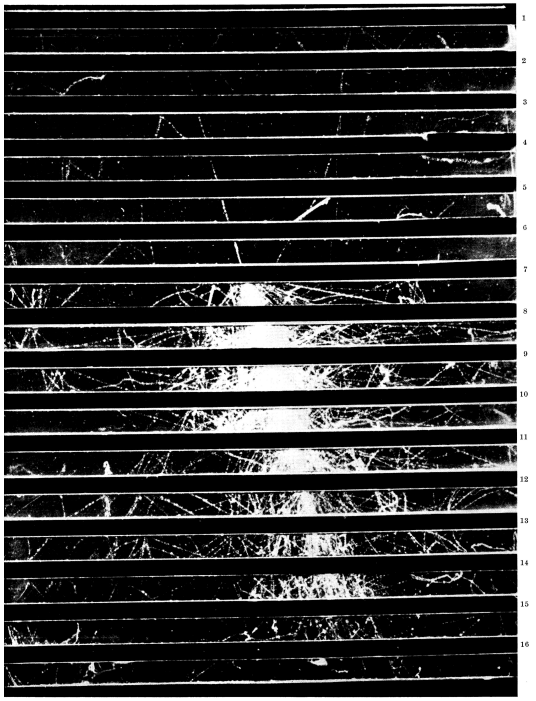
Overview

- Muon puzzle in cosmic-ray included air showers
  - Unresolved physics discrepancy in simulated vs. measured showers
  - Bottleneck for progress in cosmic ray physics
  - Introduces large uncertainties also for neutrino and gamma ray observatories
  - Meta-analysis of muon data by WHISP group established muon discrepancy at 8σ
- This talk
  - Review of WHISP results and studies of robustness of significance
  - Connection of muon puzzle to hadronic physics

Cosmic-ray induced air showers

Artist impression of an air shower
Image credit: Rebecca Pitt, Discovering Particles, CC BY-ND-NC 2.0

10 GeV proton in cloud chamber with lead absorbers at 3027 m altitude
K.-H. Kampert and A.A. Watson,
Eur. Phys. J. H37 (2012) 359-412

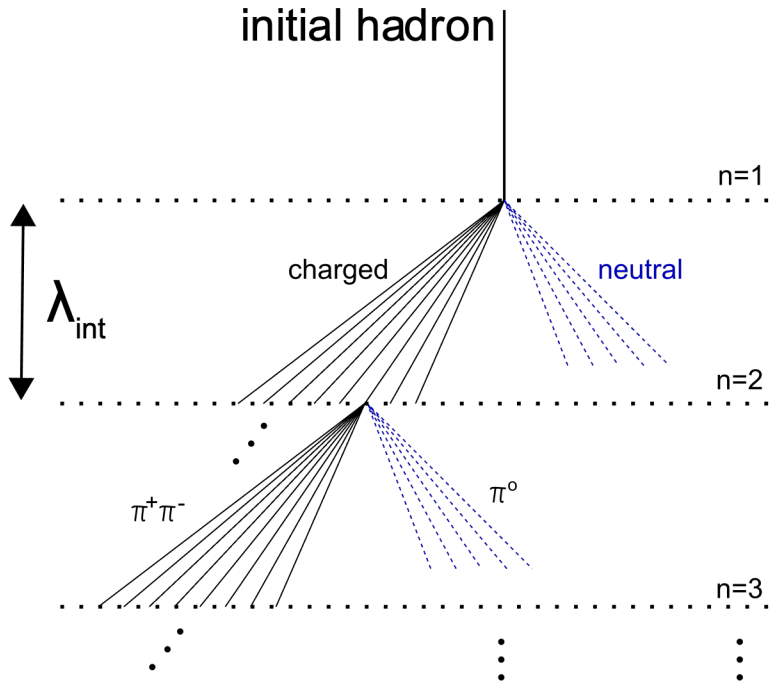


Air showers in a nutshell

Heitler-Matthews model of air shower
J. Matthews, Astropart. Phys. 22 (2005) 387-397

$$N_\mu(E, A) = A^{(1-\beta)} \left(\frac{E}{\xi_h}\right)^\beta$$

$$\text{with } \beta = \frac{\ln(\alpha\, N_{\text{mult}})}{\ln N_{\text{mult}}}$$



Cascade stops after 5-10 steps
(energy-dependent)

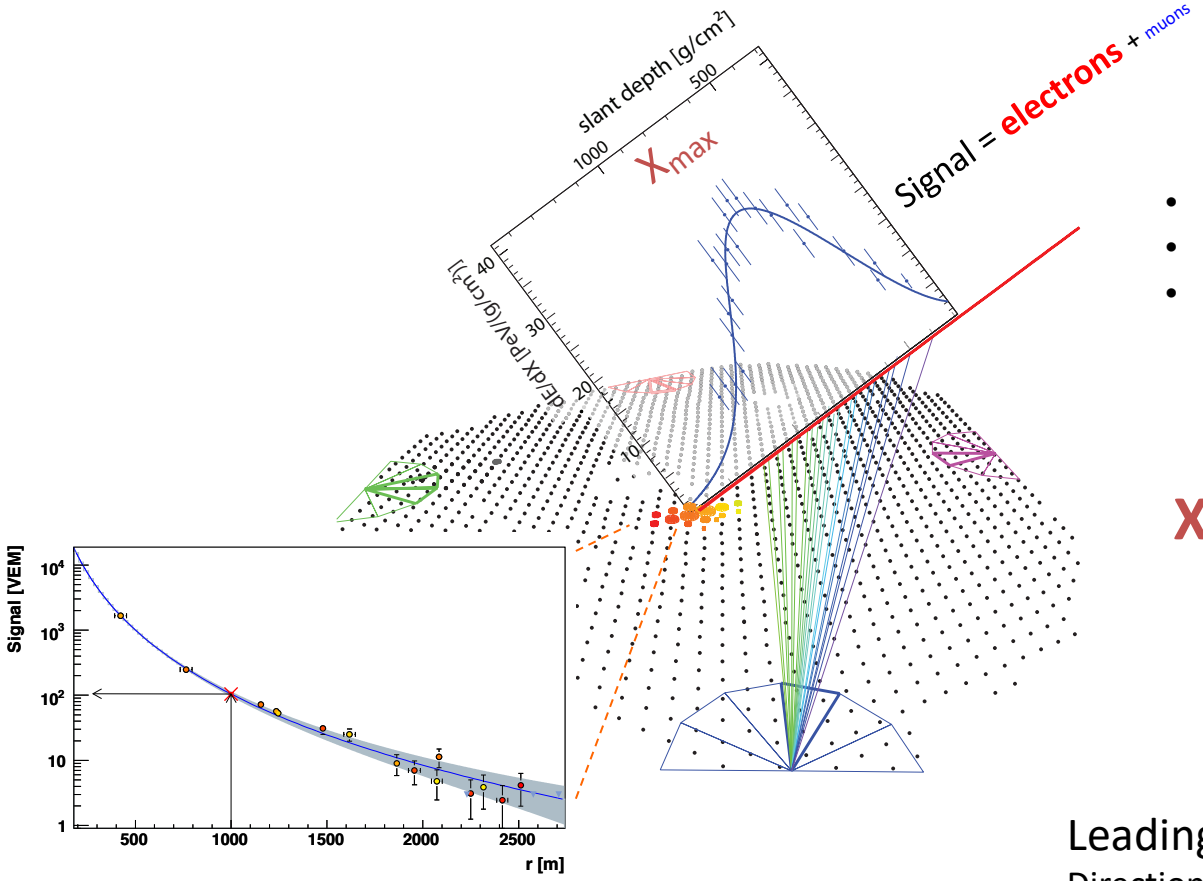
$$\frac{\Delta N_\mu}{N_\mu} \approx k\,\frac{\Delta\alpha}{\alpha}$$

ξ_h … pion critical energy
N_{mult} … hadron multiplicity
α … energy fraction of charged pions
k … number of cascade steps

- Muon number very sensitive to α
- Reduce neutral pion yield to increase α

High-energy cosmic ray detection

Example: event observed with Pierre Auger Observatory



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

- **Direction** from particle arrival times
- **Energy** from size of **eγ component**
- **Mass** from **depth of shower maximum** and size of **muonic component**

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

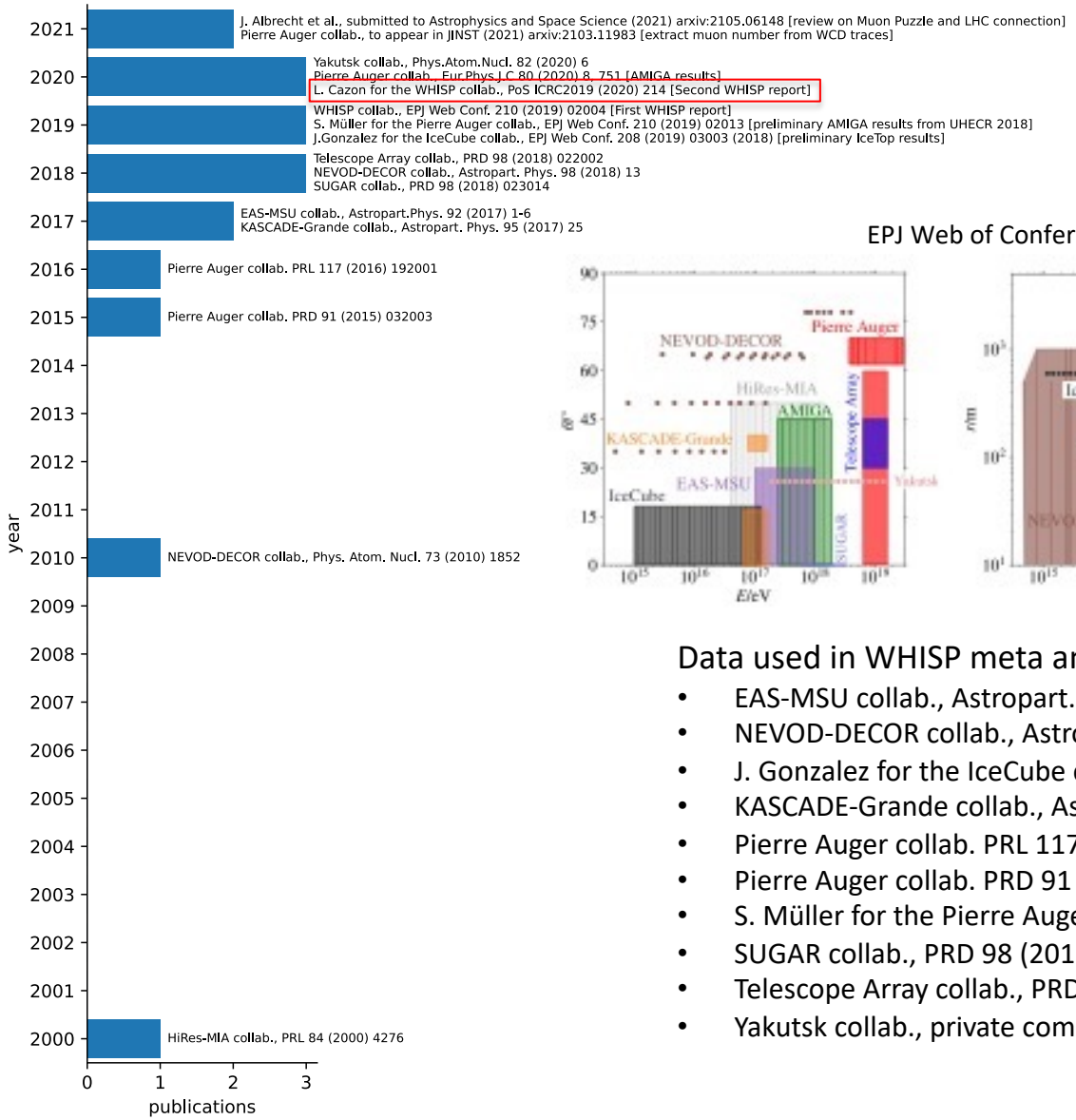
N_μ Number of muons and Mass
Iron yield = **+40 %** of proton yield
at same CR energy

Vertical showers Signal = **electrons** + **photons** + muons
Inclined showers Signal = electrons + photons + **muons**

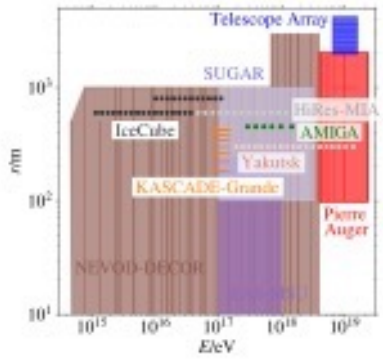
Leading experimental accuracies

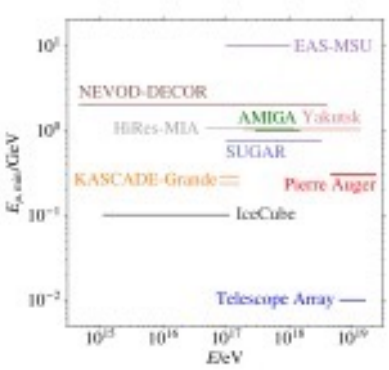
Direction	$0.5 - 1.5^{\circ}_{\mathrm{stat}}$	
Energy	10-20 $\%_{\mathrm{stat}}$	**14 $\%_{\mathrm{sys}}$**
X_{max}	15 – 25 $\mathrm{gcm^{-2}}_{\mathrm{stat}}$	**10 g $\mathrm{cm^{-2}}_{\mathrm{sys}}$**
N_μ	20 $\%_{\mathrm{stat}}$	**11 $\%_{\mathrm{sys}}$**

Muon Puzzle



EPJ Web of Conferences **210**, 02004 (2019)





Data used in WHISP meta analysis 2018

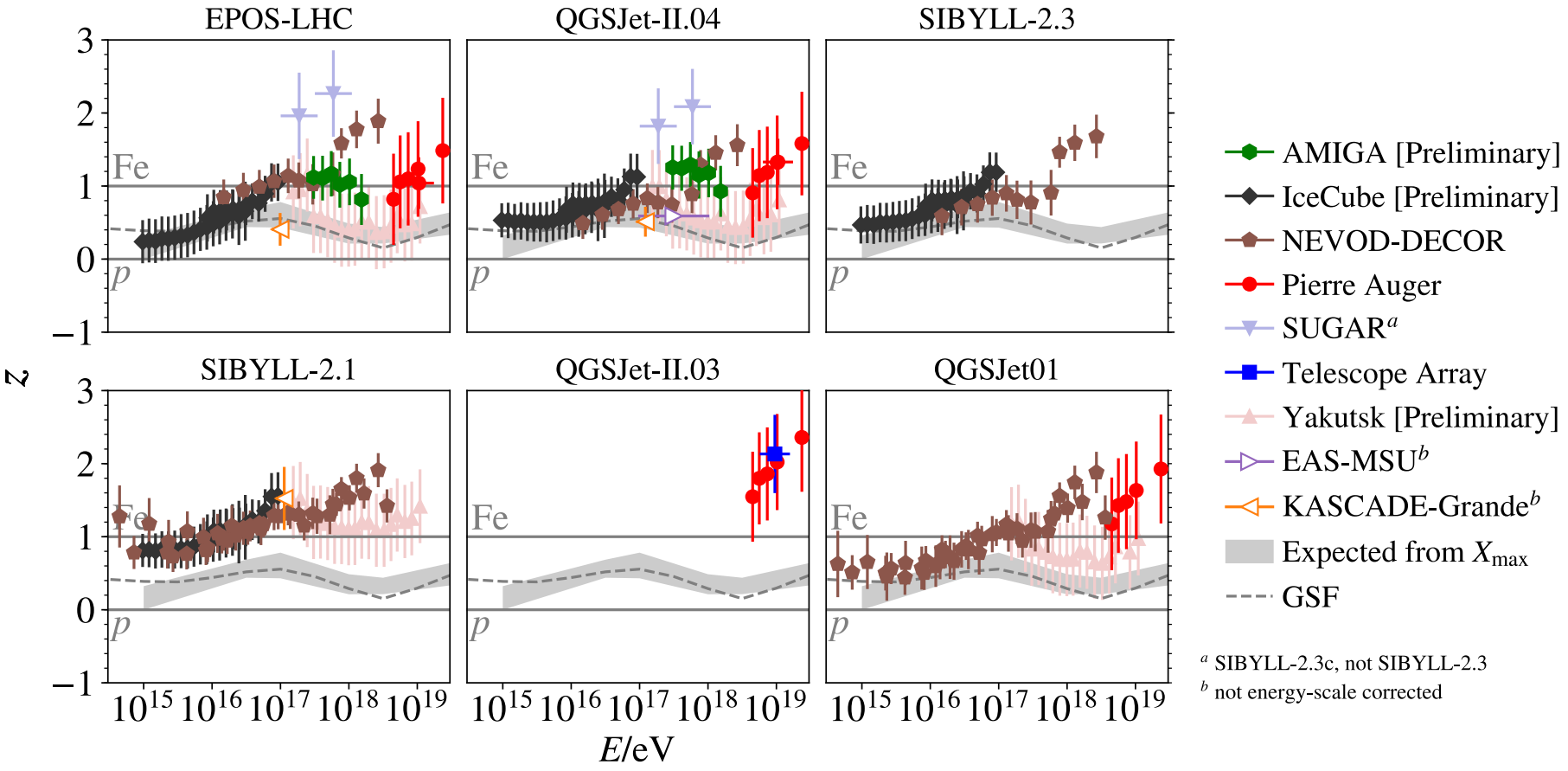
- EAS-MSU collab., Astropart.Phys. 92 (2017) 1-6
- NEVOD-DECOR collab., Astropart. Phys. 98 (2018) 13
- J. Gonzalez for the IceCube collab., EPJ Web Conf. 208 (2019) 03003 (2018)
- KASCADE-Grande collab., Astropart. Phys. 95 (2017) 25
- Pierre Auger collab. PRL 117 (2016) 192001
- Pierre Auger collab. PRD 91 (2015) 032003
- S. Müller for the Pierre Auger collab., EPJ Web Conf. 210 (2019) 02013
- SUGAR collab., PRD 98 (2018) 023014
- Telescope Array collab., PRD 98 (2018) 022002
- Yakutsk collab., private comm.

After adjusting energy-scales

EPJ Web of Conferences **210**, 02004 (2019)

Abstract muon scale
independent of experiment,
dependent on air shower model

$$z = \frac{\ln(N_\mu^{\rm det}) - \ln(N_{\mu p}^{\rm det})}{\ln(N_{\mu\,\rm Fe}^{\rm det}) - \ln(N_{\mu p}^{\rm det})}$$

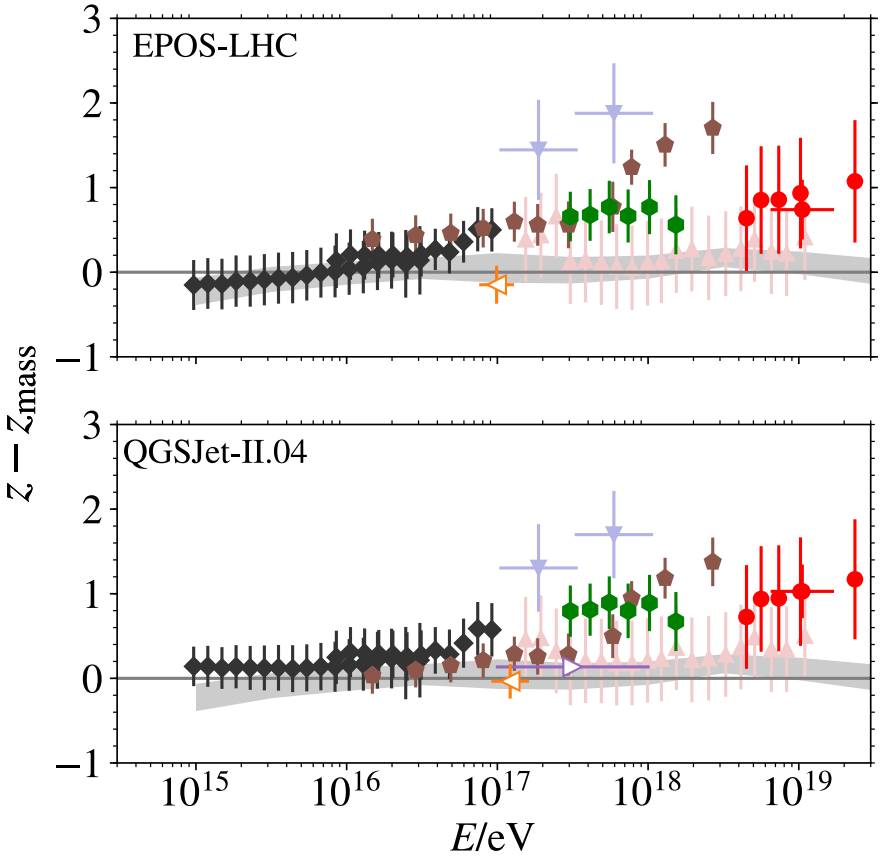


[a] SIBYLL-2.3c, not SIBYLL-2.3
[b] not energy-scale corrected

Muon deficit in simulated showers

EPJ Web of Conferences **210**, 02004 (2019)

$$z = \frac{\ln(N_\mu^{\mathrm{det}}) - \ln(N_{\mu p}^{\mathrm{det}})}{\ln(N_{\mu\mathrm{Fe}}^{\mathrm{det}}) - \ln(N_{\mu p}^{\mathrm{det}})}$$



$$z_{\mathrm{mass}} = \frac{\langle \ln A \rangle}{\ln 56}$$

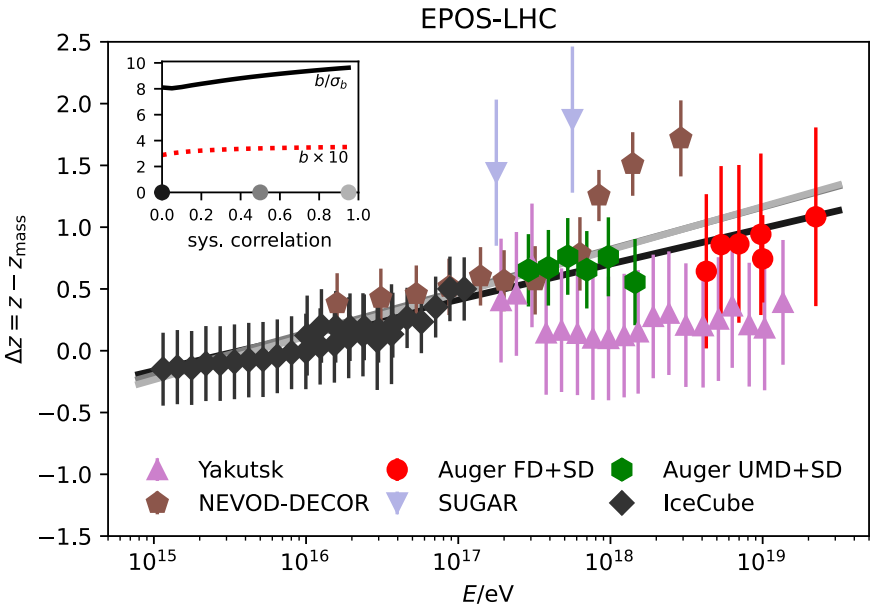
(equality is approximate, approximation error negligible)

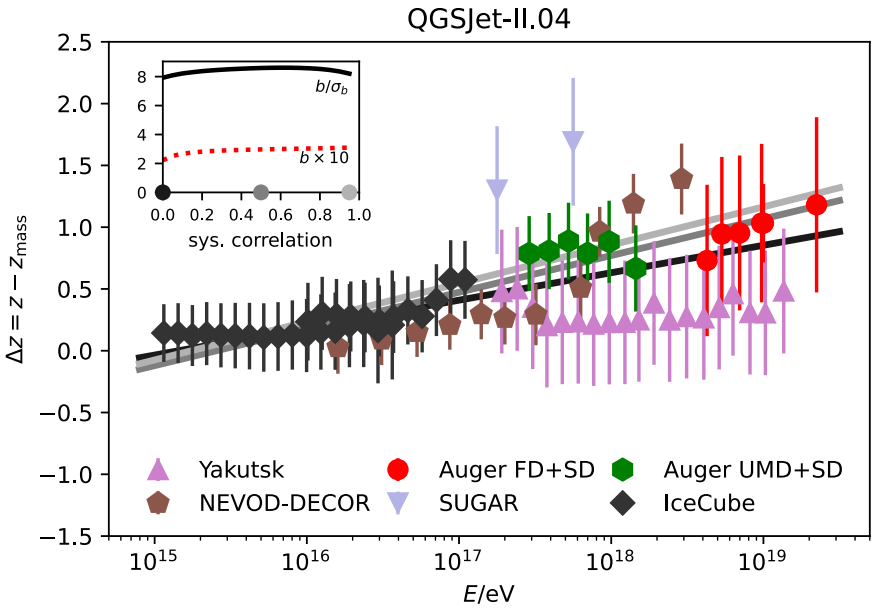
- AMIGA [Preliminary]
- IceCube [Preliminary]
- NEVOD-DECOR
- Pierre Auger
- SUGAR
- Yakutsk [Preliminary]
- EAS-MSU[a]
- KASCADE-Grande[a]
- Expected from X_{max}

[a] not energy-scale corrected

Deficit in air shower simulations starting around 4 x 10^{16} eV or $\sqrt{s} \sim$ **8 TeV**, should be visible at LHC

Line fit and slope significance





- Subtract z_{mass} using <lnA> from GSF model
  - Composition based mainly on X_{max} measurements
- Fit of line model a + b ln(E) to data
  - Evidence for Muon Puzzle quantified by significance of positive slope b > 8σ
  - Correlated systematic uncertainties dominate, unknown positive correlation coefficient
  - Scan over assumed correlation coefficient showed that result is robust against choice

Further studies of WHISP data

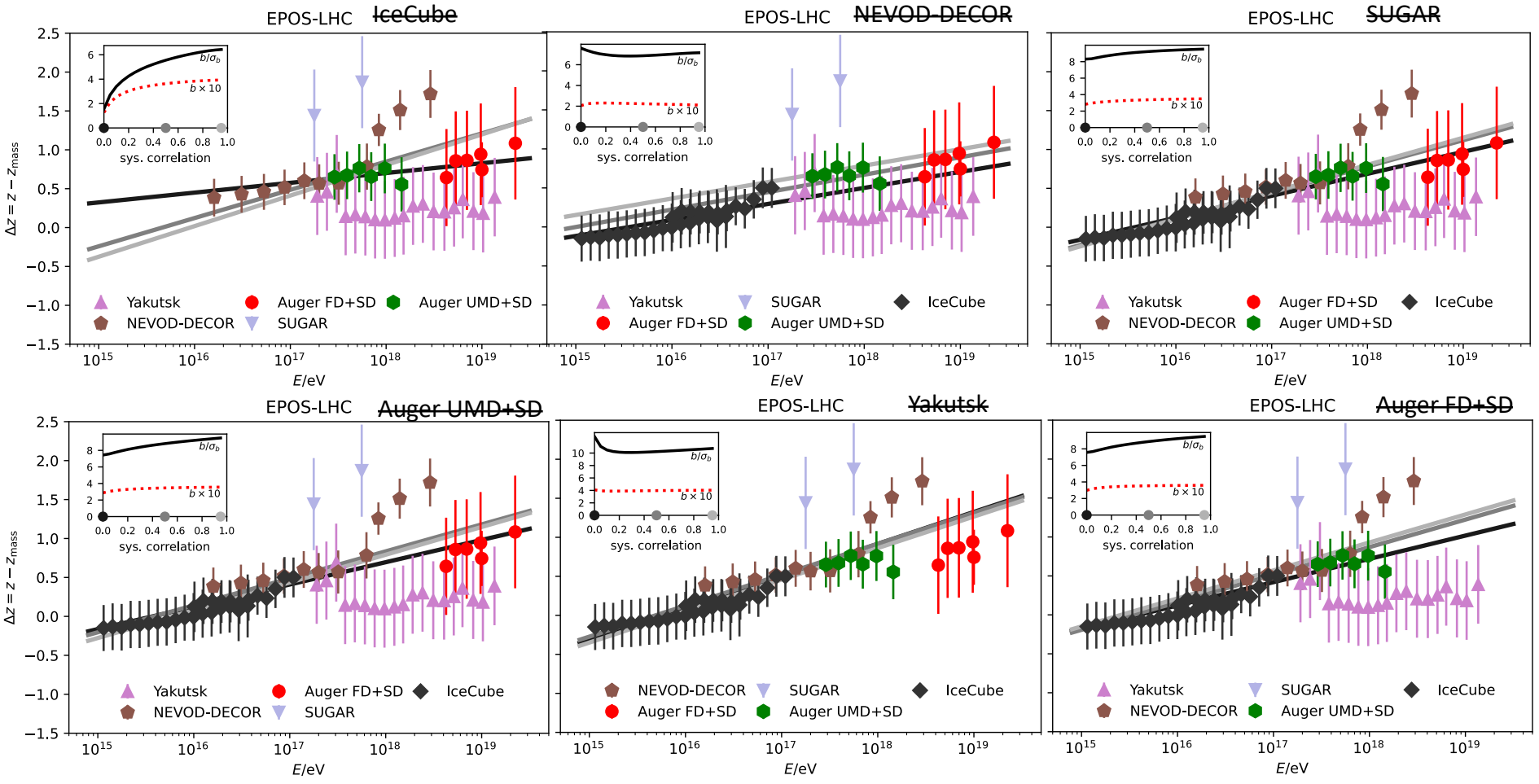
- Q: Which experiments are driving significance?

  A: N-1 study: re-do line fit while taking one experiment out at a time

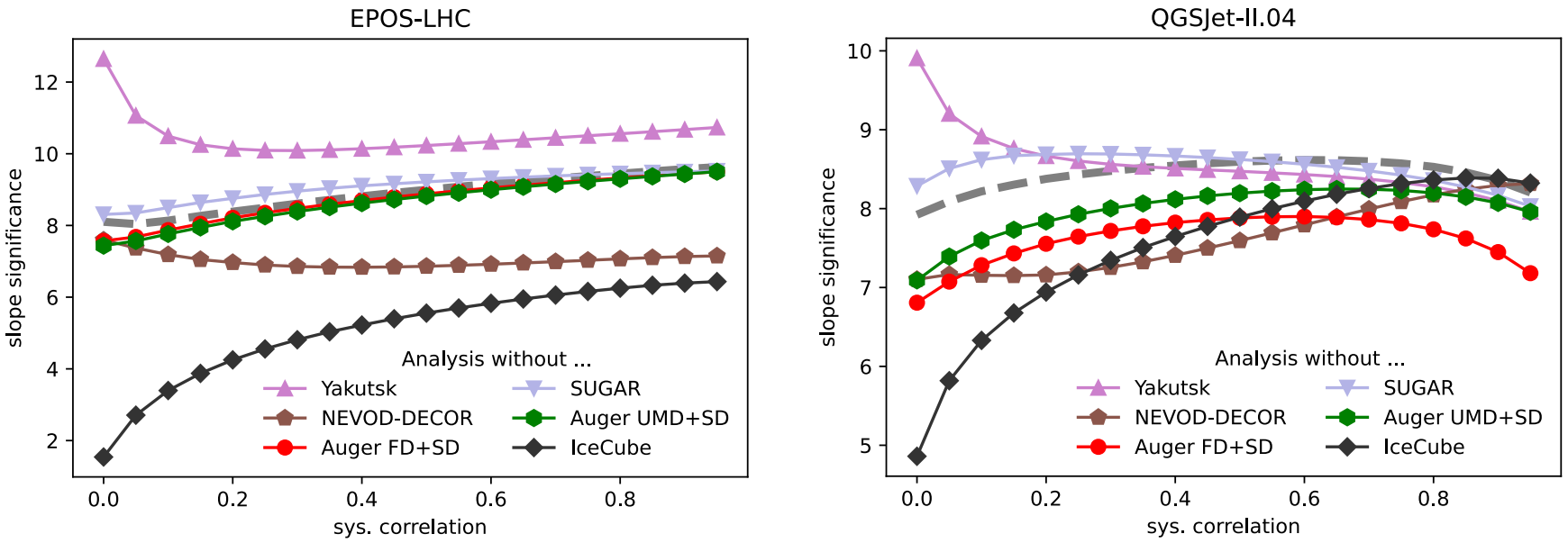
- Q: What if correlation coefficient is varied independently for each data set?

  A: Global optimization (Bayesian optimization) to find minimum and maximum significance for variation over 6D coefficient space

N-1 Study

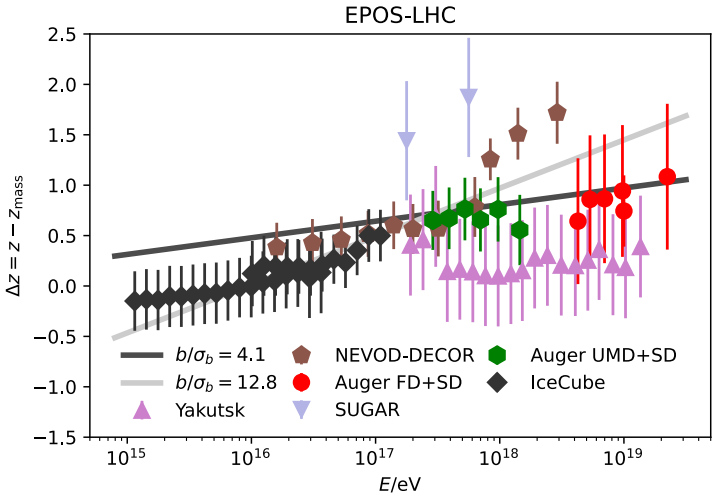

EPOS-LHC ~~IceCube~~
EPOS-LHC ~~NEVOD-DECOR~~
EPOS-LHC ~~SUGAR~~
EPOS-LHC ~~Auger UMD+SD~~
EPOS-LHC ~~Yakutsk~~
EPOS-LHC ~~Auger FD+SD~~
$\Delta z = z - z_{\mathrm{mass}}$
b/σ_b
$b \times 10$
sys. correlation
Yakutsk
Auger FD+SD
Auger UMD+SD
NEVOD-DECOR
SUGAR
IceCube
E/eV

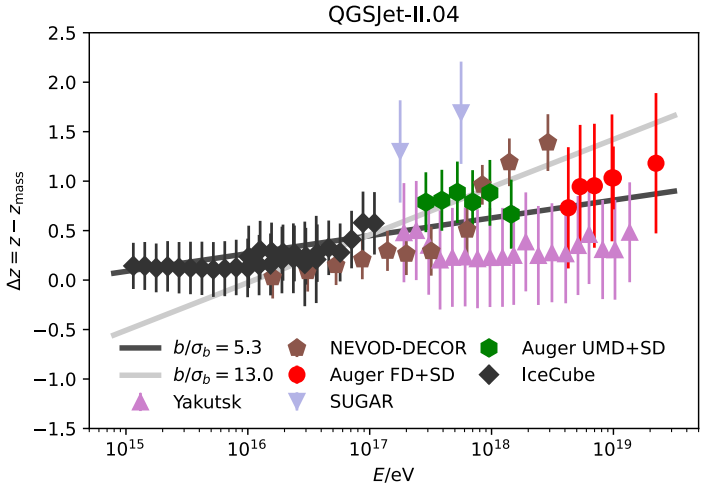
N-1 Study: summary

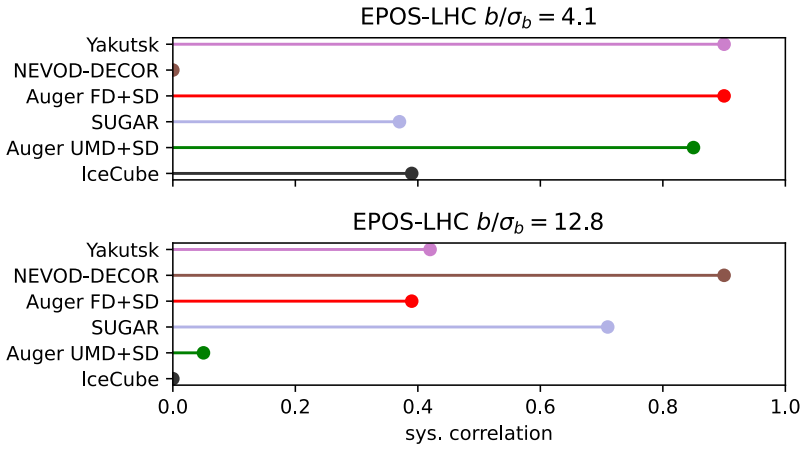


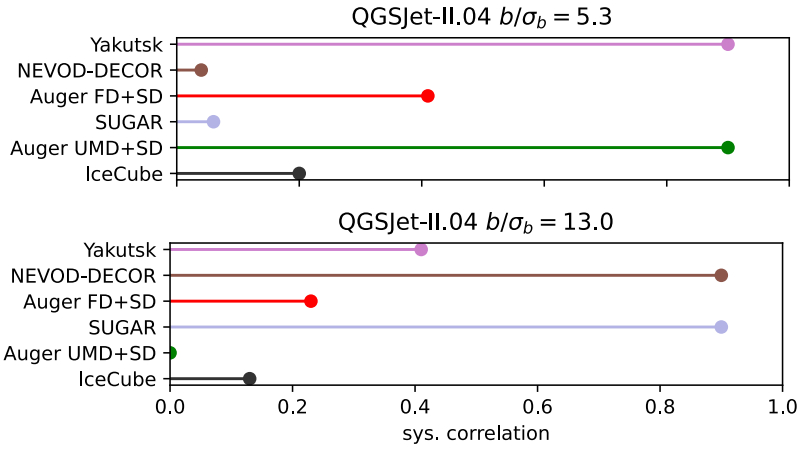
- Results stable against removal of individual experiments
  - IceCube very important as anchor at low end (lever arm)
  - NEVOD-DECOR also important
  - Sys. correlation < 0.5 is probably not realistic
  - Reduction of significance smaller for QGSJet-II.04
- Removal of SUGAR *increases* significance, effect of χ^2/n_{dof} scaling

Variation of correlation coefficients





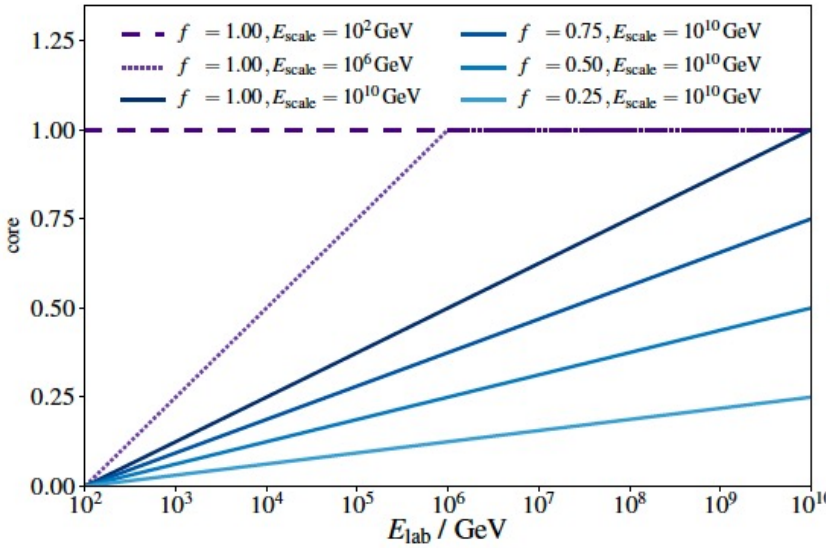


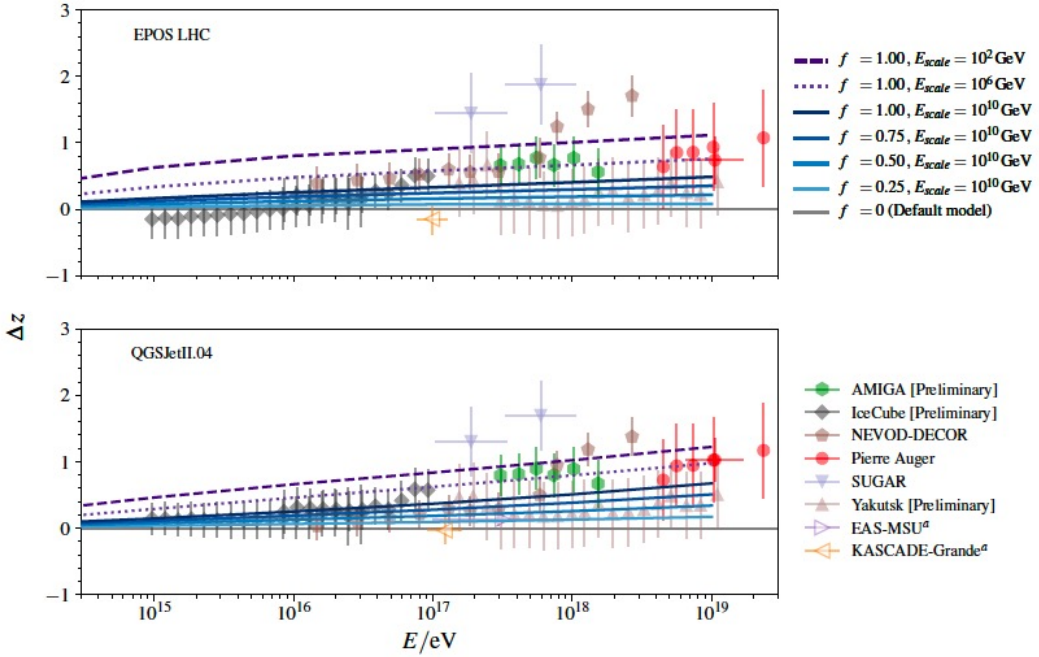


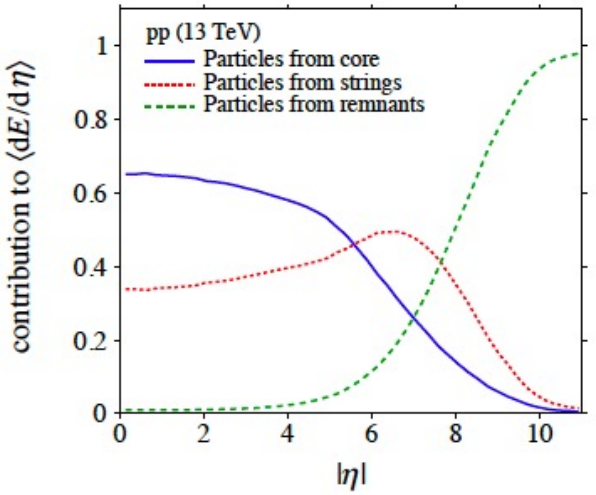
- Search over 6D space with global optimization technique called Bayesian optimization
- Minimum significance found by scan at 4σ for EPOS-LHC and 5σ QGSJet-II.04, still significant
- Values below 0.5 probably not realistic; minimum > 5σ if scan restricted to [0.5, 0.9]

Potential solution to Muon Puzzle

S. Baur, HD, M. Perlin, T. Pierog, R. Ulrich, K. Werner, arxiv:1902.09265v2



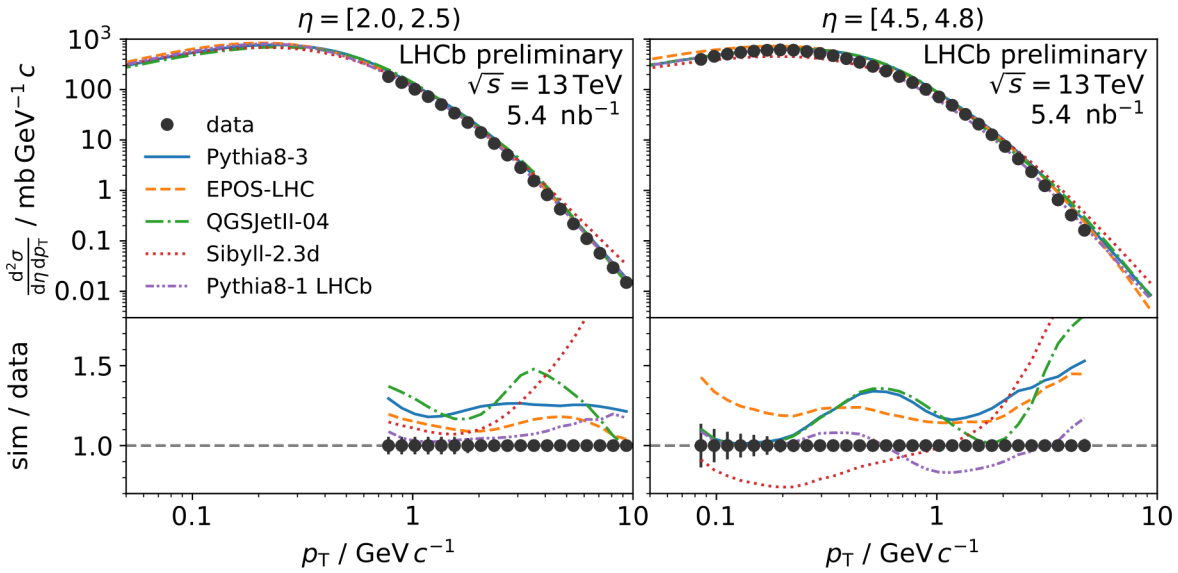


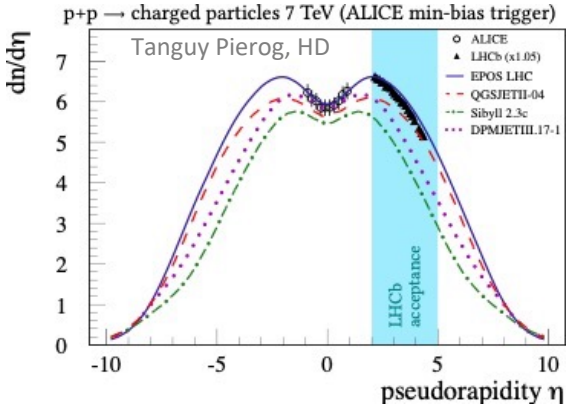


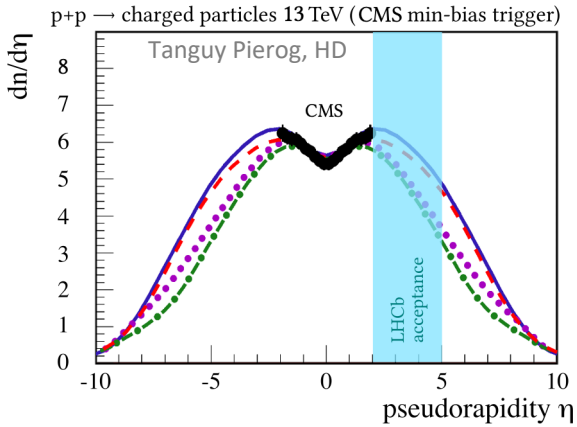
- Need to reduce forward production yield of π^0
- Natural solution: strangeness enhancement from statistical hadronization ("core")
- Already observed at mid-rapidity: ALICE, Nature Phys. 13 (2017) 535-539
- Need more data on **forward** strangeness production at LHC, can be obtained with LHCb

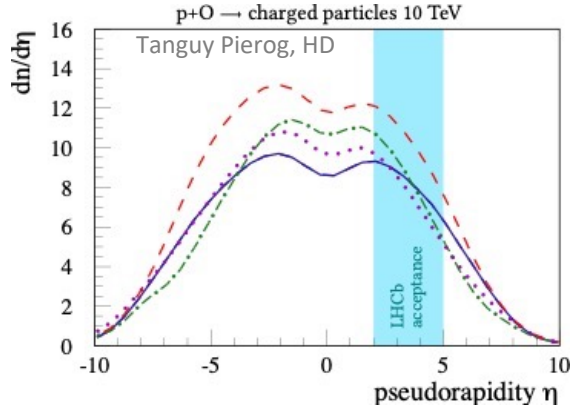
LHCb measurements

LHCb-PAPER-2021-010-001 in preparation,
preliminary results presented at Moriond QCD 2021 and Meson 2021









- First double-differential forward charged particle spectrum at 13 TeV
- High-precision measurement up to 2.3 %
  - > factor 10 more accurate than current model spread
  - High precision needed to control model extrapolation
- Outlook: Extend to p-Pb and identified hadron spectra

Prospect for proton-oxygen run

Z. Citron et al., CERN Yellow Rep. Monogr. 7 (2019) 1159-1410

Year	Systems, $\sqrt{s_{\mathrm{NN}}}$	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 $\mu\mathrm{b}^{-1}$ and 200 $\mu\mathrm{b}^{-1}$
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	

- 200 μb^{-1} is enough statistics to push statistical error below 5 % in LHCb
- 2 nb^{-1} (10 x minimum) was requested, also allows to measure charm
- Mid-term budget plan allocated no resources to do oxygen-week in Run 3
  - Delay bad for cosmic ray community, critical for **LHCf** which cannot measure after Run 3
  - Strong response by cosmic ray community in open letter from LHCf to LHCC
- Large interest also from heavy-ion community expressed in OppOrtunities workshop 2021 [workshop summary arxiv:2103.01939]

Summary & Outlook

- Muon Puzzle in cosmic-ray induced air showers
  - Not enough GeV muons produced by all air shower simulations above a few PeV
  - Significance of results of meta-analysis robust against
    - Removal of individual data sets
    - Exhaustive search in space of systematic correlations
  - Results with updated z-values to be shown by D. Soldin at the ICRC 2021, including AGASA points

- Solution to Muon Puzzle requires changes to hadronization in soft-QCD interactions
  - Natural candidate: universal strangeness enhancement seen by ALICE in pp, p-Pb
  - Nuclear effects uncertain: need **p-O** data with forward acceptance from colliders
  - Review of muon puzzle and connection to LHC

    J. Albrecht et al., arxiv:2105.06148
    submitted to Astrophysics and Space Science (2021)

- Coming soon: double differential cross-section of charged particle production in p-p at 13 TeV with LHCb (LHCb-PAPER-2021-010-001)