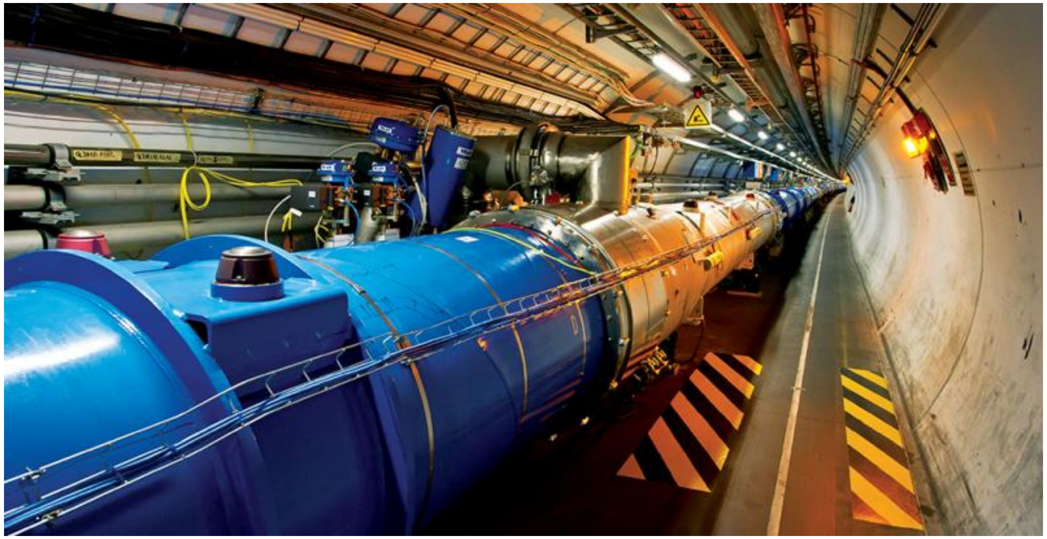
technische universität dortmund

E5a/ Physik

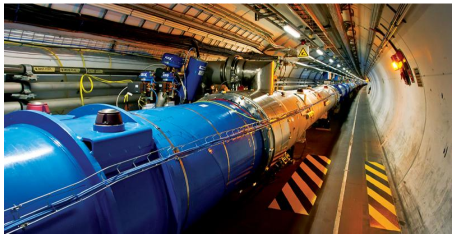
Cosmic rays and colliders: Impact of particle on astroparticle physics

Hans Dembinski, TU Dortmund

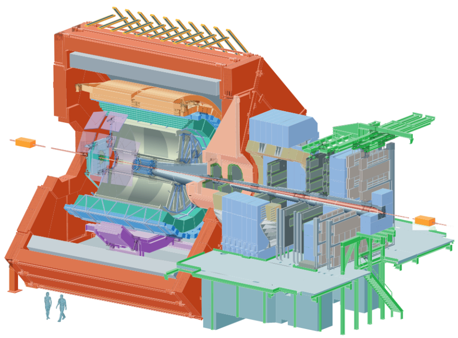
Artist impression of air shower



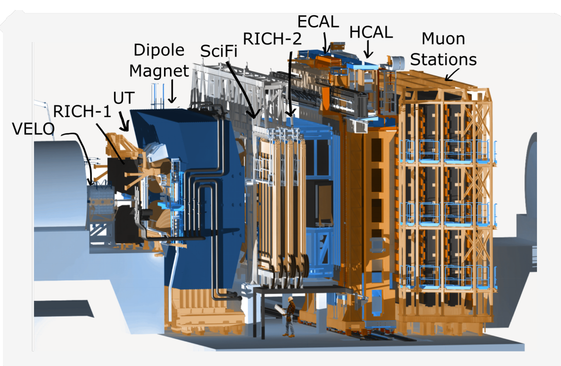
Take-home message



Light-flavour experiments



Heavy-flavour experiments
(also **forward light flavour**!)



Cosmic anti-proton excess

Inelastic p-air cross-section

Atmospheric lepton flux

Muon puzzle in air showers

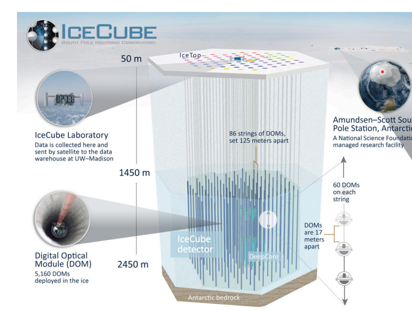
F3, F4 →

Air showers

← **F3, F4**

Cosmic ray experiments

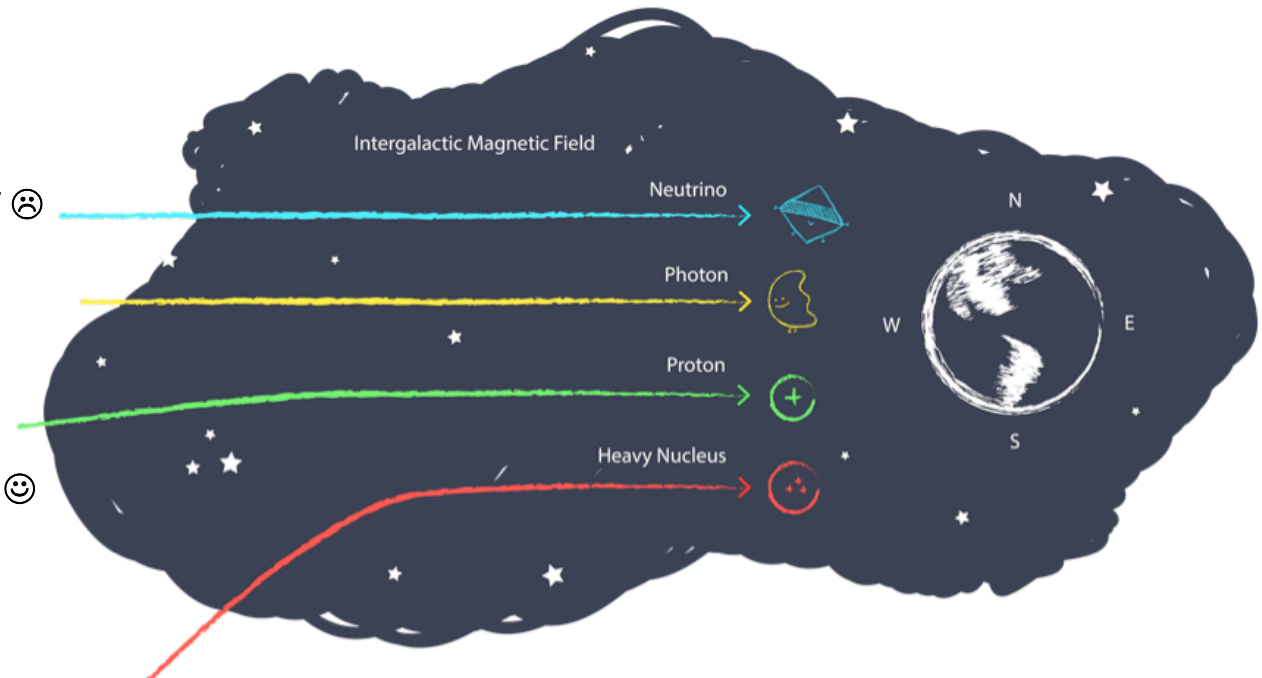
Neutrino experiments



Astroparticle physics

- Astroparticles are messengers of high-energy non-thermal universe
  - Black holes and neutron stars formation and exotics: dark matter decay…
  - Tremendous energies: GeV TeV = 10^3 GeV **PeV** = 10^6 GeV **EeV** = 10^9 GeV
- Messengers
  - Gamma rays
    - Pointing ☺
    - Abundant ☺
    - E_{max} ~ 100 TeV ☹
  - Neutrinos
    - Pointing ☺
    - Rare ☹
    - E_{max} > 100 EeV ☺
  - Cosmic rays (nuclei)
    - No pointing ☹
    - Abundant ☺
    - E_{max} > 100 EeV ☺

generates background



IceCube Masterclass 2016

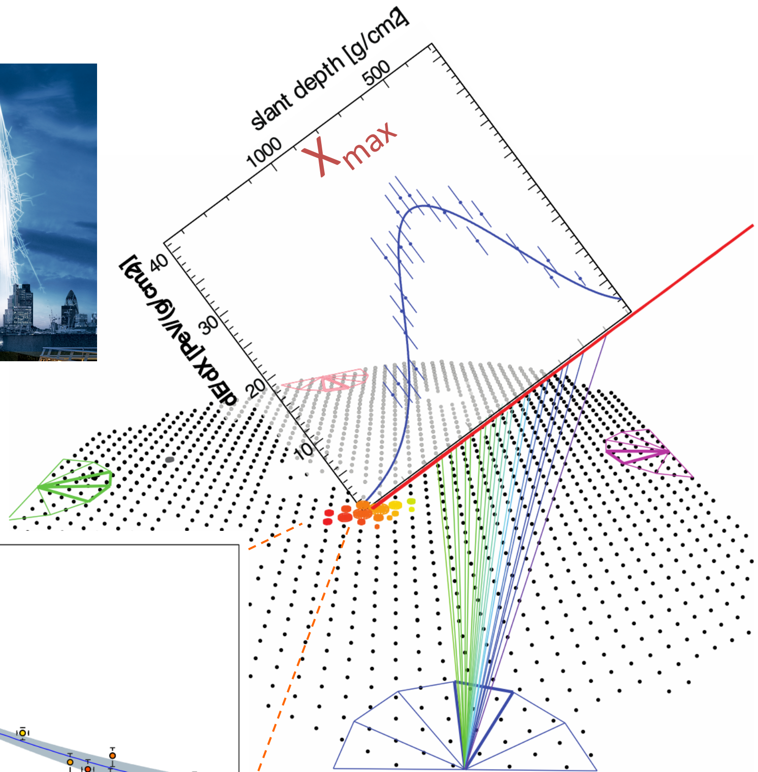
Cosmic-ray induced air showers

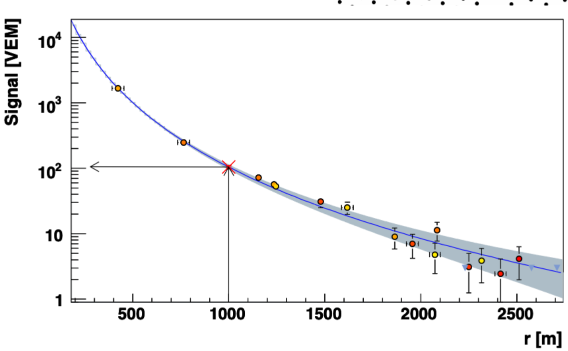
10 GeV proton in cloud chamber with lead absorbers at 3027 m altitude

K.-H. Kampert and A.A. Watson, Eur. Phys. J. H37 (2012) 359-412

Air shower measurement

Example: event observed with Pierre Auger Observatory





Air shower measurement

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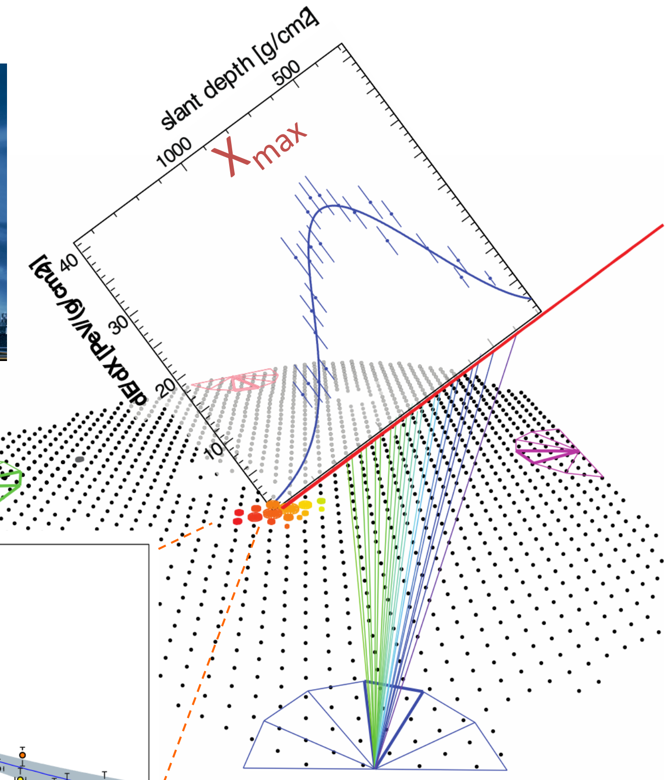
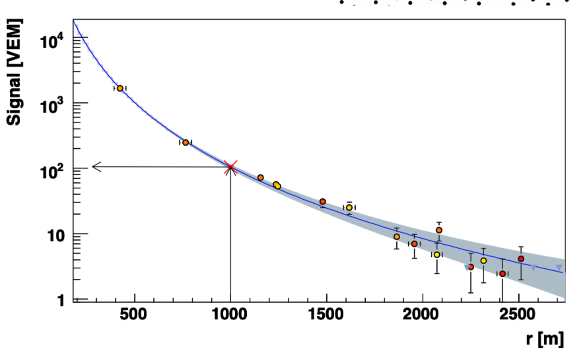




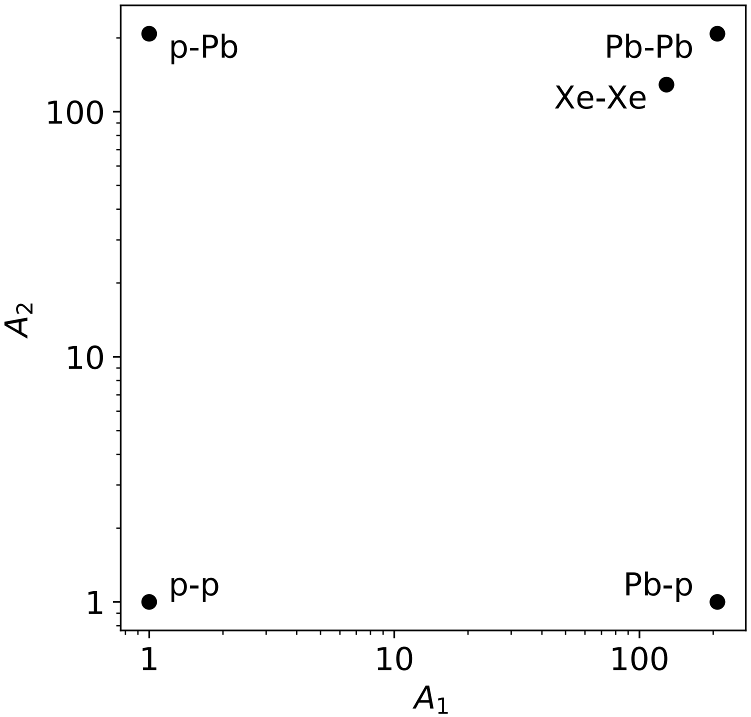
$$E_{\rm cal} = \int_0^\infty \left(\frac{dE}{dX}\right)_{\rm ionization} dX$$

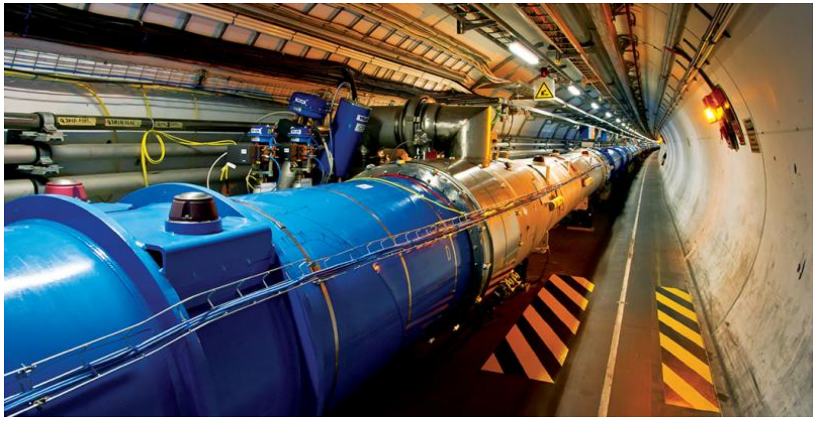
- Direction from particle arrival times
- Energy from integral of light profile
- Mass from
  - Depth of shower maximum $X_{\rm max}$
  - Number of produced muons N_μ

Large Hadron Collider (LHC)

LHC collision systems

Collision systems at the LHC

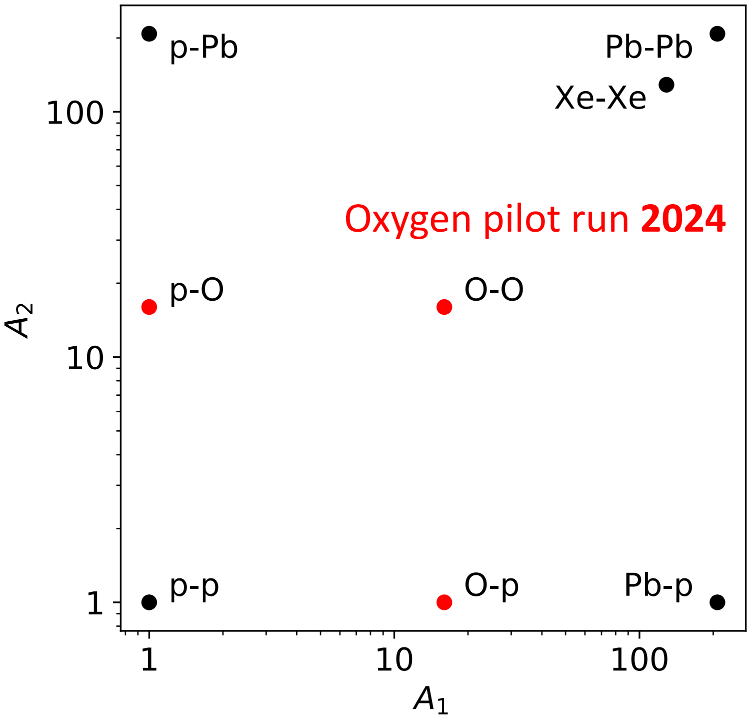


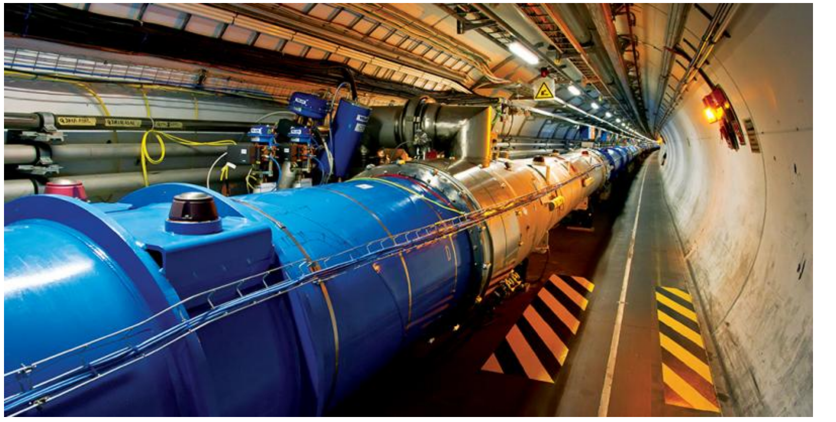


LHC collision systems

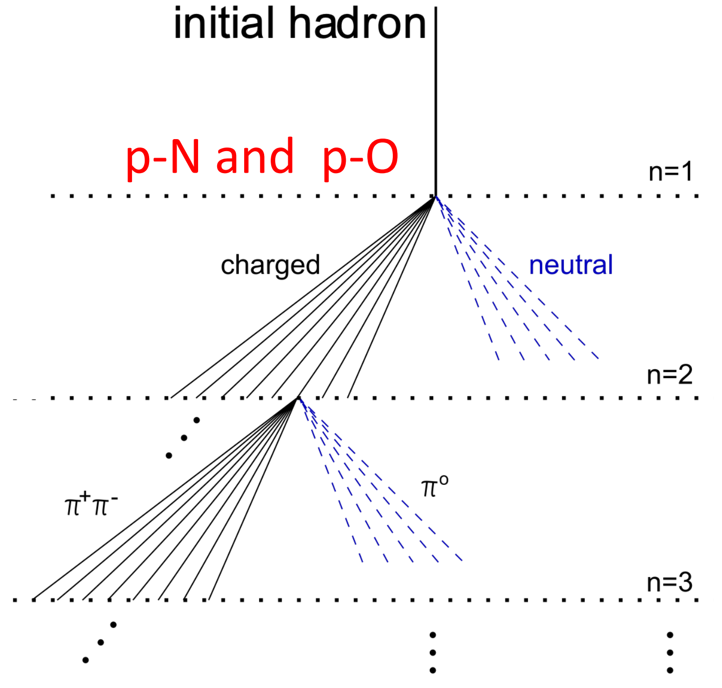
Collision systems at the LHC

Run 3: p-p @ 14 TeV, p-O @ 10 TeV





Air shower cascade



LHC collision systems

Collision systems at the LHC

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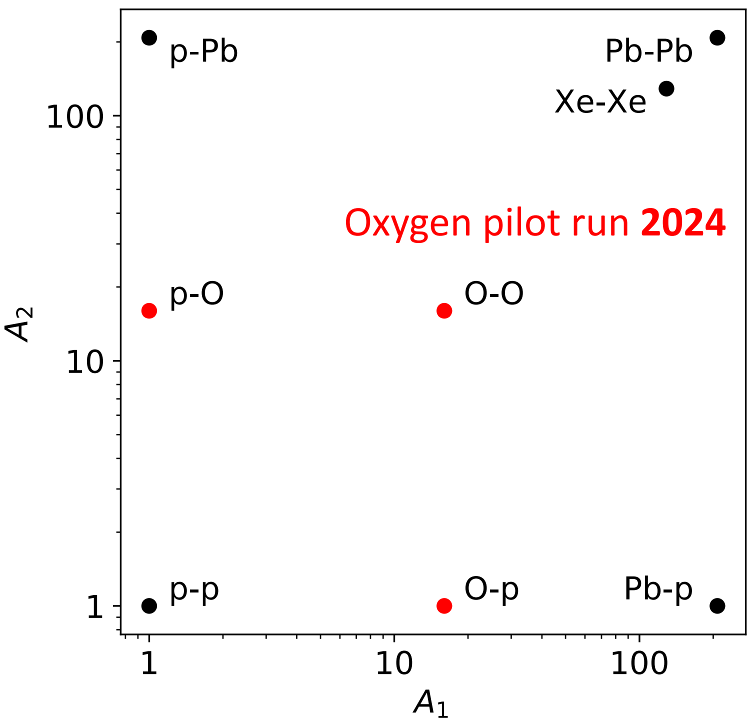
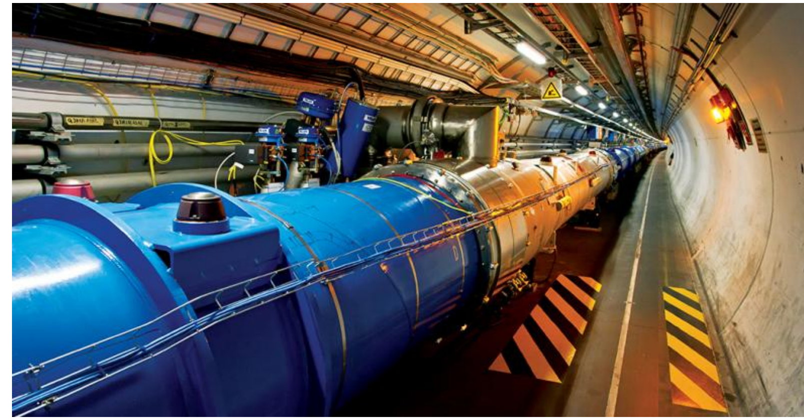
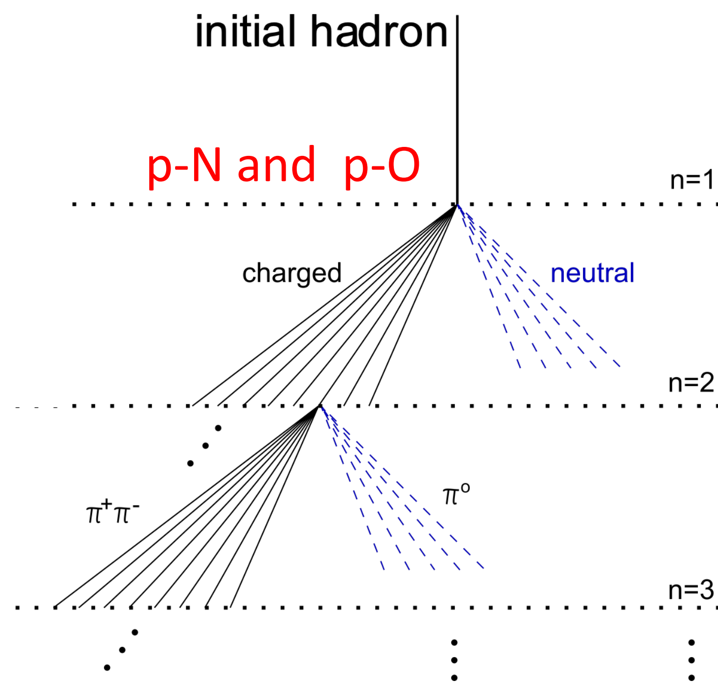




Fixed target data at sub-TeV (LHCb only)

- p+(p,...,O,N,...) @ 0.11 TeV
- Pb+(p,...,O,N,...) @ 0.07 TeV
- O+O, O+p @ 0.08 TeV (in Run 3)

Air shower cascade



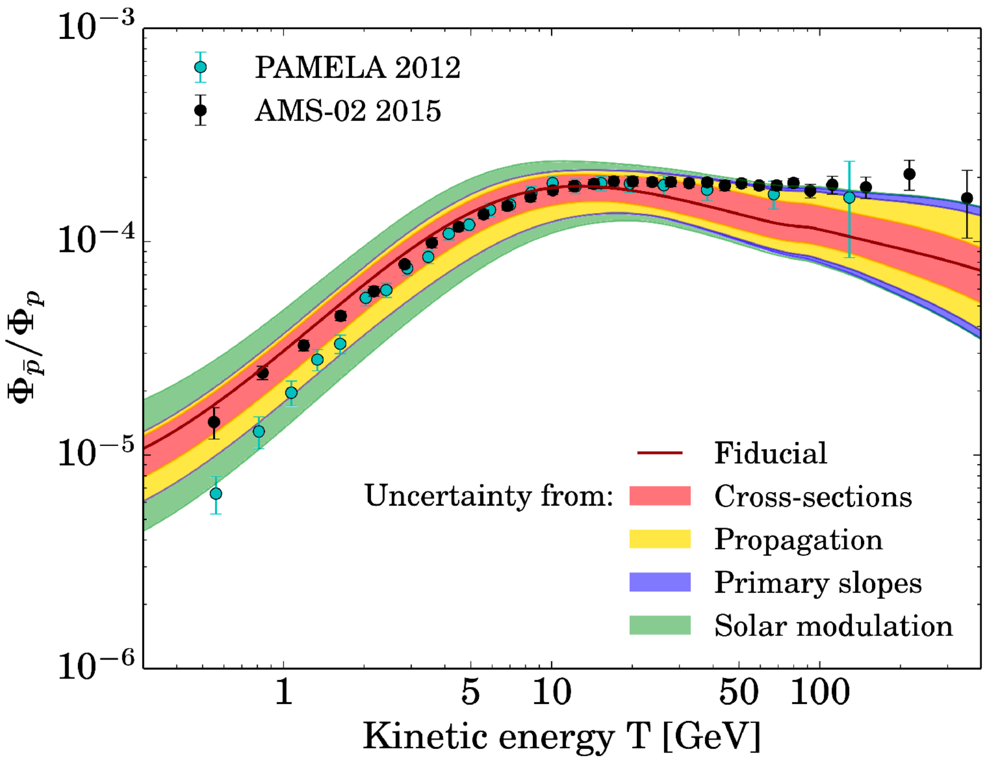
Topic 1: Cosmic anti-proton excess

Cosmic anti-proton flux

- AMS-02 search for dark matter
  - DM → standard model particles → stable SM particles
  - $\pi^0 \to \gamma\gamma, \pi^\pm \to$ neutrinos, $p, \bar{p}$
- Strategy: look for excess in $\bar{p}/p$ flux ratio
  - Low $\bar{p}$ background from cosmic rays + ISM $\to \bar{p} + \ldots$

A potential excess?

JCAP 1509 (2015) no.09, 023

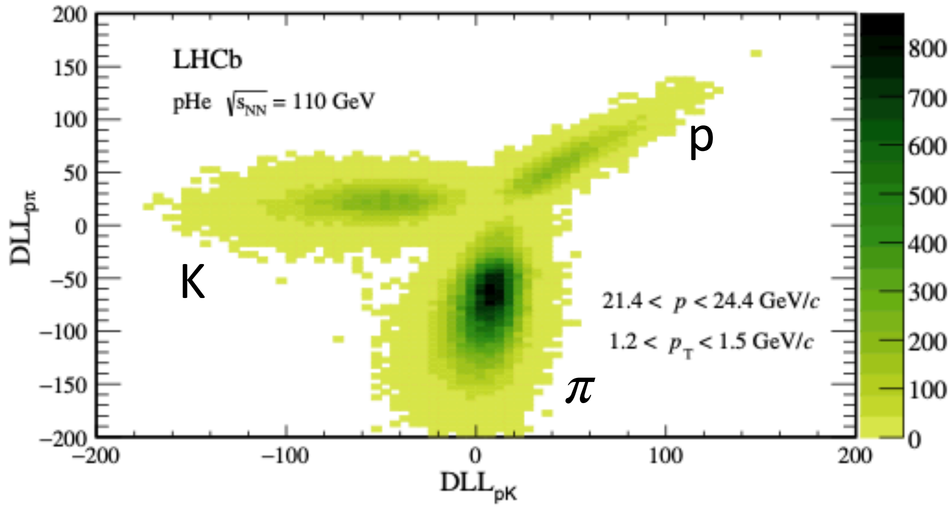


- Excess observed by AMS-02 and PAMELA in cosmic $\bar{p}$ flux
- Conventional $\bar{p}$ production
  - ISM 91 % p, 9 % He
  - $p + p \rightarrow \bar{p} + X$ ***OK***
  - $p + \mathrm{He} \rightarrow \bar{p} + X$ uncertain

  First direct measurement by LHCb in fixed target mode

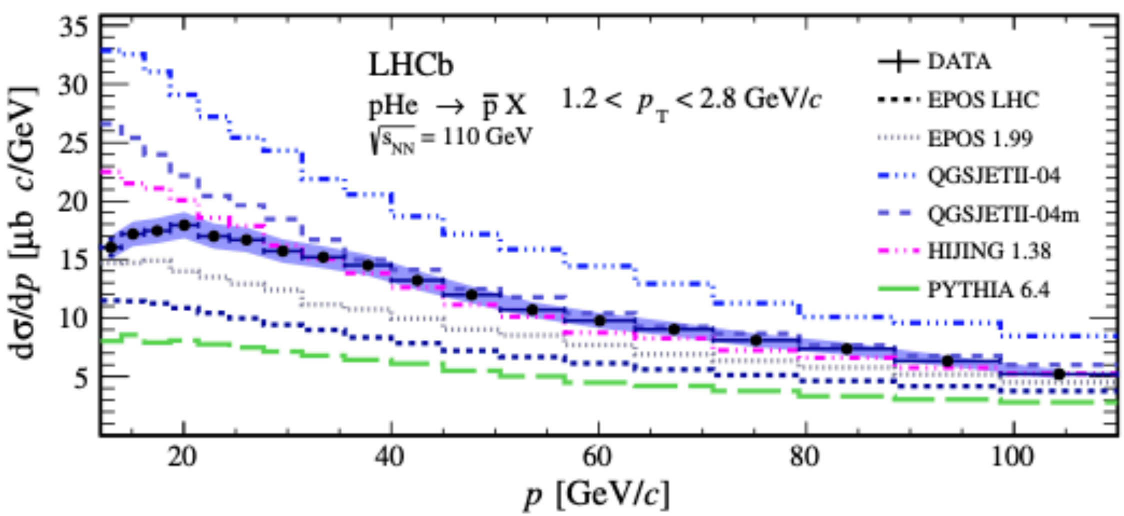
LHCb measurement of $\bar{p}$ production

LHCb, *PRL* 121 (2018) 22, 222001
LHCb, *Eur.Phys.J.C* 83 (2023) 6, 543



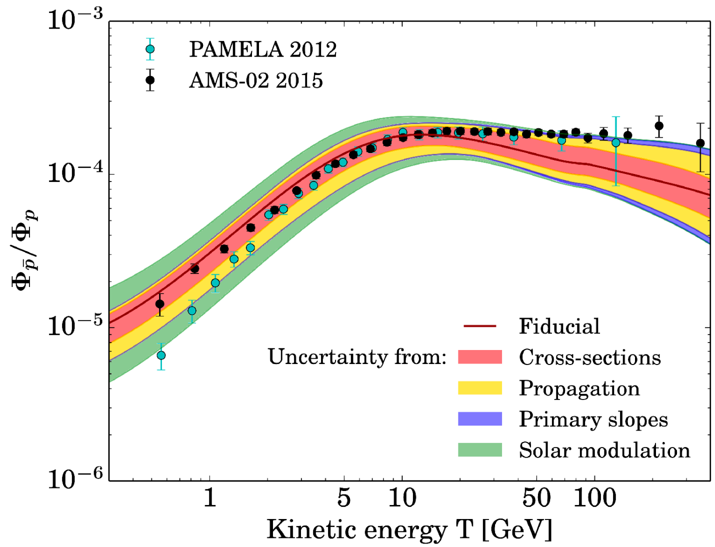
- LHCb run in fixed-target mode with proton beam and He gas
- $\bar{p}$ identification by RICH detectors

Ring Imaging Cherenkov



- Model spread up to 65 % before measurement
- Measurement precision < 10 % in most bins

Topic 1: Summary

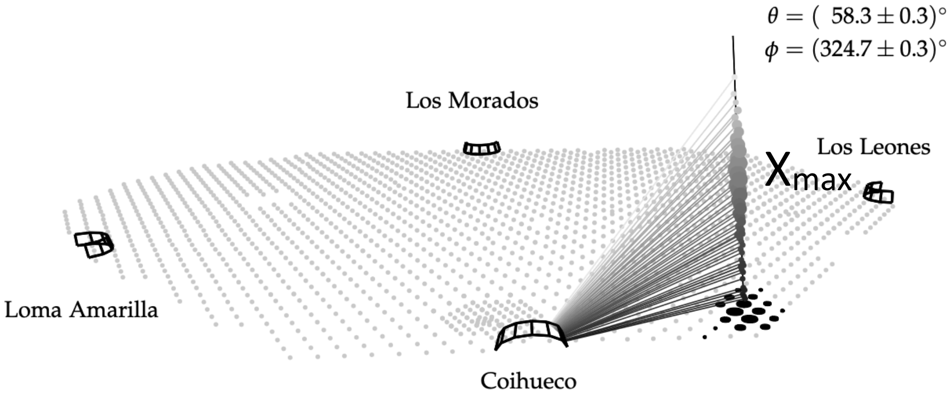


- **Anti-proton flux** measured by **AMS-02** contains excess, cause?
- Conventional **anti-proton production** via cosmic rays uncertain
- Relevant energies accessible by **LHCb in fixed-target mode**
  - Measurement in **p + He(gas)** much better than current model spread
  - LHCb upgrade in Run3: repeat measurement with **p + p(gas)**

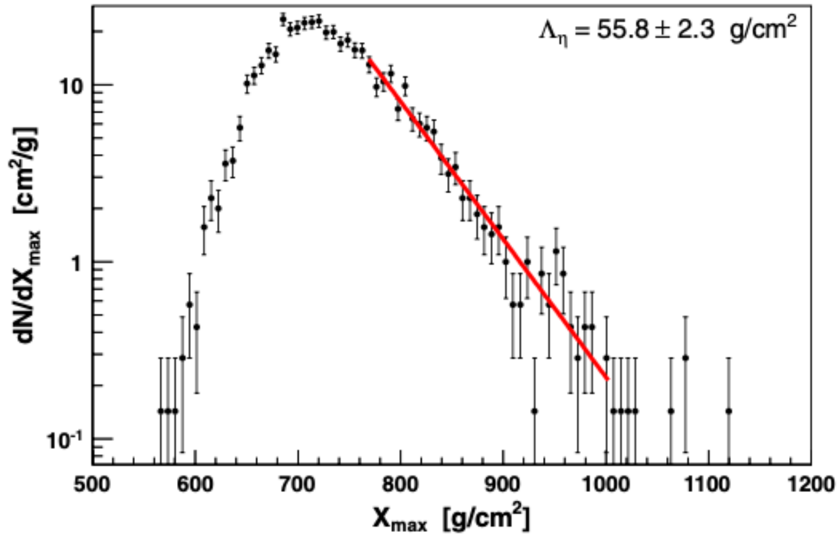
Topic 2: Inelastic p-air cross-section

Shower depth and inelastic cross-section

Auger, Phys.Rev.D 90 (2014) 12, 122005



Auger, PRL 109, 062002 (2012)



first interaction

$$X_{\text{max}} = X_0 + \Delta X_{\text{shower}}$$

measurement *air shower development*

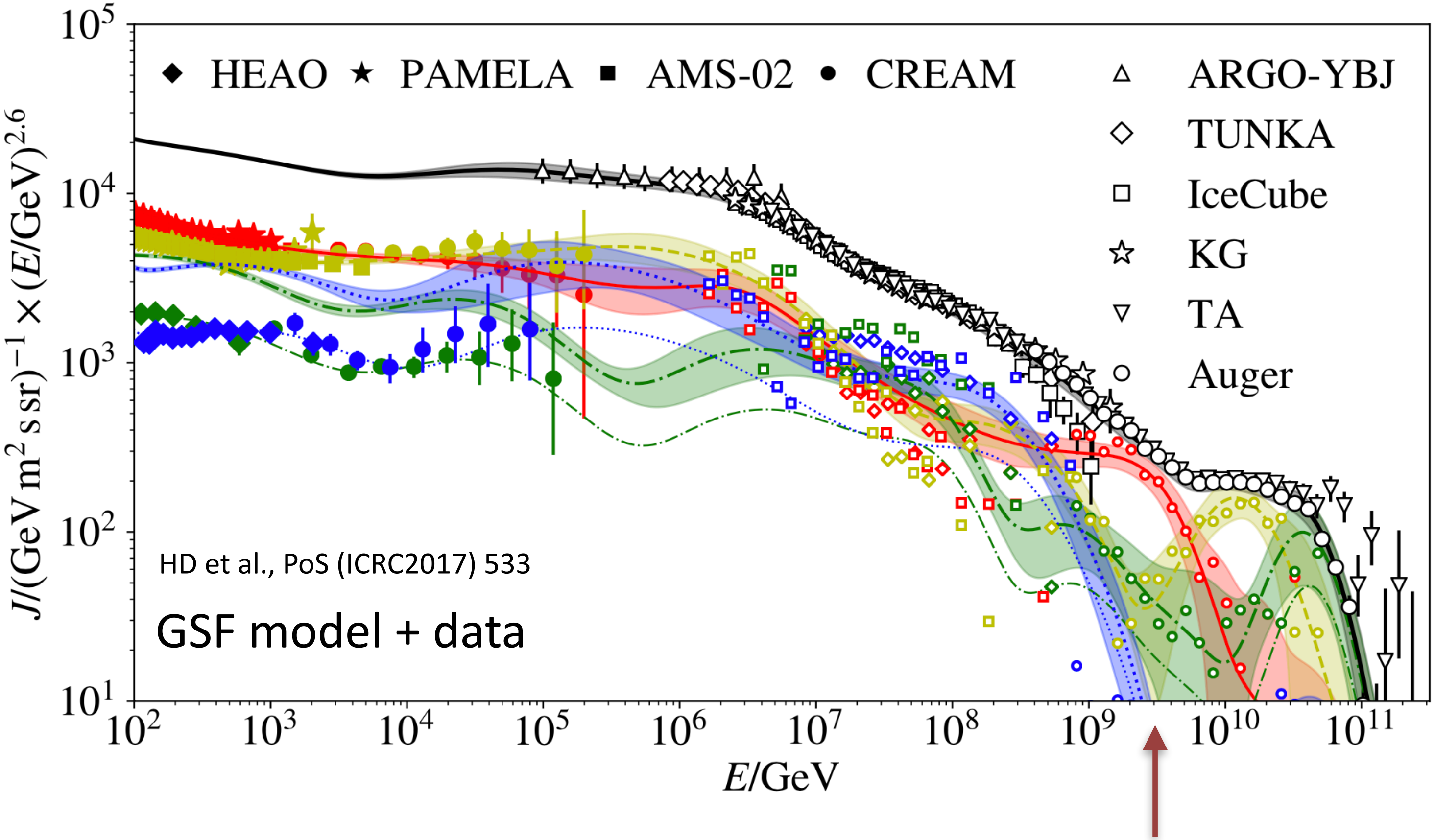
$$X_0 = \frac{\rho_{\text{air}}}{\sigma_{\text{inel},p-\text{air}}} \ln 2$$

inelastic proton-air cross-section

$$\sqrt{s} = 57\,\text{TeV}$$

$$\frac{\mathrm{d}n}{\mathrm{d}X_{\text{max}}} \xrightarrow[X_{\text{max}} \to \infty]{} e^{-X_{\text{max}}/\Lambda_\eta} \qquad \Lambda_\eta \approx X_0$$

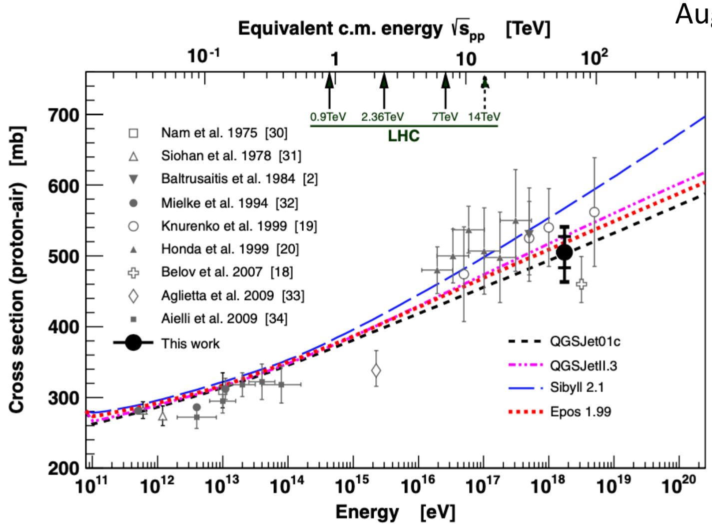
Unique proton-rich window

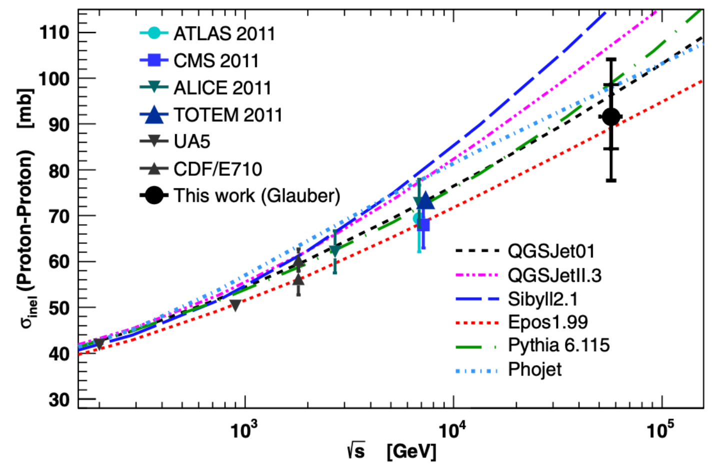


- Need **pure proton** cosmic rays to measure **proton**-air cross-section
- **Unique proton-rich energy window** around $2 \cdot 10^9$ GeV $\rightarrow \sqrt{s} \approx 60$ TeV

Cross-sections p-air, p-p, π-air

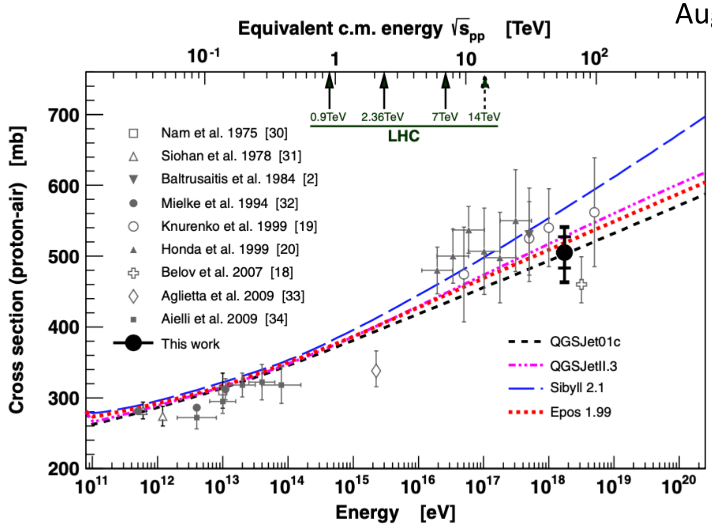
Auger, PRL 109, 062002 (2012)

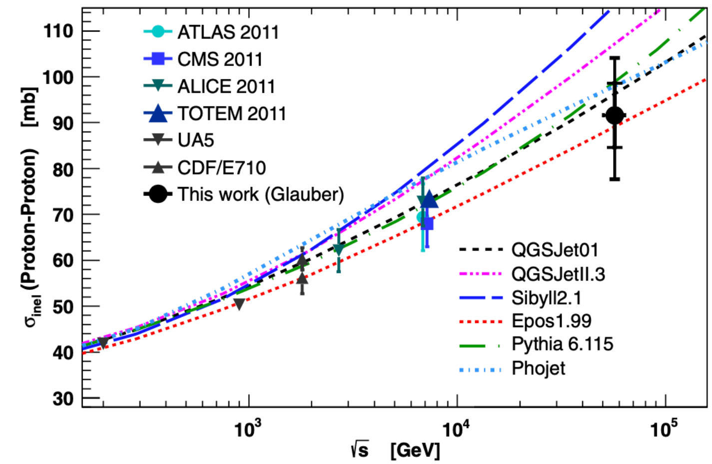




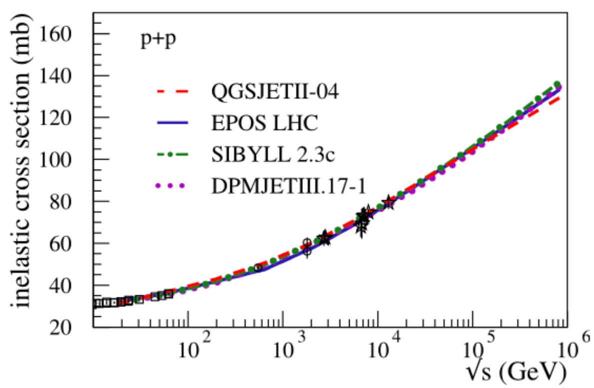
Cross-sections p-air, p-p, π-air

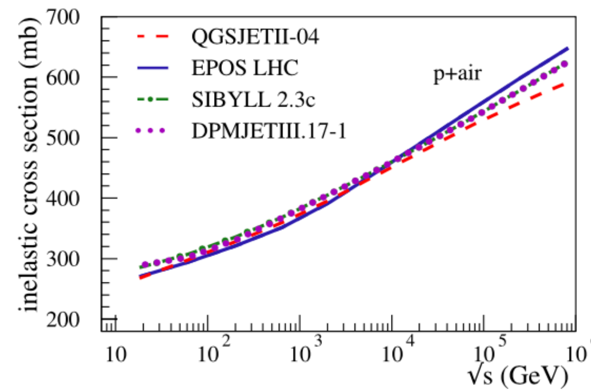
Auger, PRL 109, 062002 (2012)





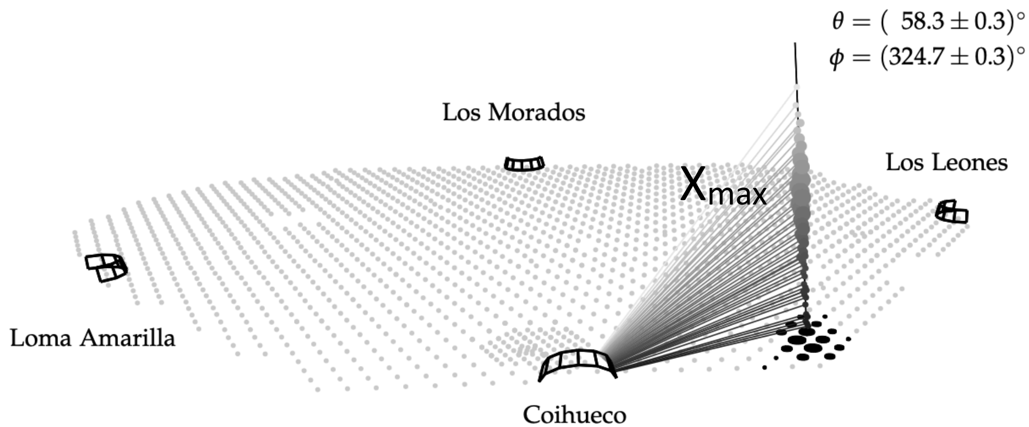
HD, J. Albrecht, W. Rhode, B. Spaan, ..., Astrophys. Space. Sci. **367,** 27 (2022) and references therein





- p+p model predictions fixed by precision measurements of TOTEM, ATLAS
- p+air predictions will be fixed by future p+O data

Topic 2: Summary

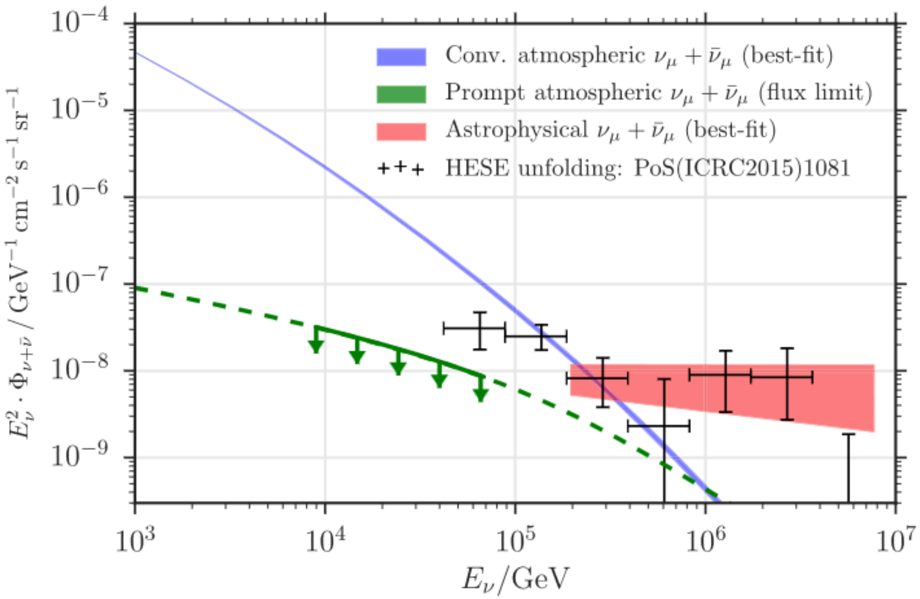


- Depth of shower maximum X_{max}
  - Main observable to infer cosmic ray mass composition (sensitive to CR sources)
  - Very sensitive to $\sigma_{\text{inel},p-\text{air}}$ and further connected via model to $\sigma_{\text{inel},p-p}$
- Measurements to 1 % by ATLAS and TOTEM doubled accuracy of X_{max} predictions
- Vice-versa $\sigma_{\text{inel},p-\text{air}}$ has been inferred from X_{max} measurements at $\sqrt{s} \approx 60\,\text{TeV}$
  - **Unique energy window for particle physics** with ultra high-energy cosmic rays
- **SFB F3 + F4**
  - Global fits of astro and collider data will further constrain $\sigma_{\text{inel},p-\text{air}}$
  - Measurement of inelastic cross-section in p-p at 13.6 TeV and p-O at 10 TeV

Topic 3: Atmospheric lepton flux

Atmospheric lepton flux

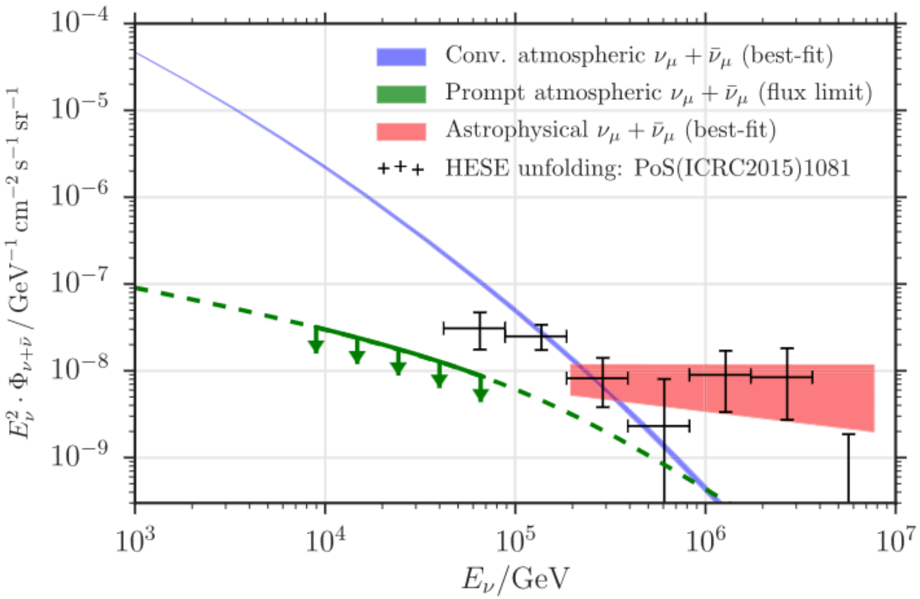
IceCube, Astrophys.J. 833 (2016) 18



- ν_μ flux = astroneutrinos + atm. neutrinos
- atm. neutrino flux = conventional + prompt
  - Conventional: π, K decays (long-lived)
  - Prompt: dominantly charm decays (short-lived)

Atmospheric lepton flux

IceCube, Astrophys.J. 833 (2016) 18



Approximate solutions to cascade equations (Gaisser, Honda, ...)

cosmic ray flux

CR spectrum weighted moments

$$\phi_l(E) \propto \phi_N(E) \sum_h \frac{Z_{N\to h} Z_{h\to l}}{1 + E \cdot C_h}$$

∝ life-time

- ν_μ flux = astroneutrinos + atm. neutrinos
- atm. neutrino flux = conventional + prompt
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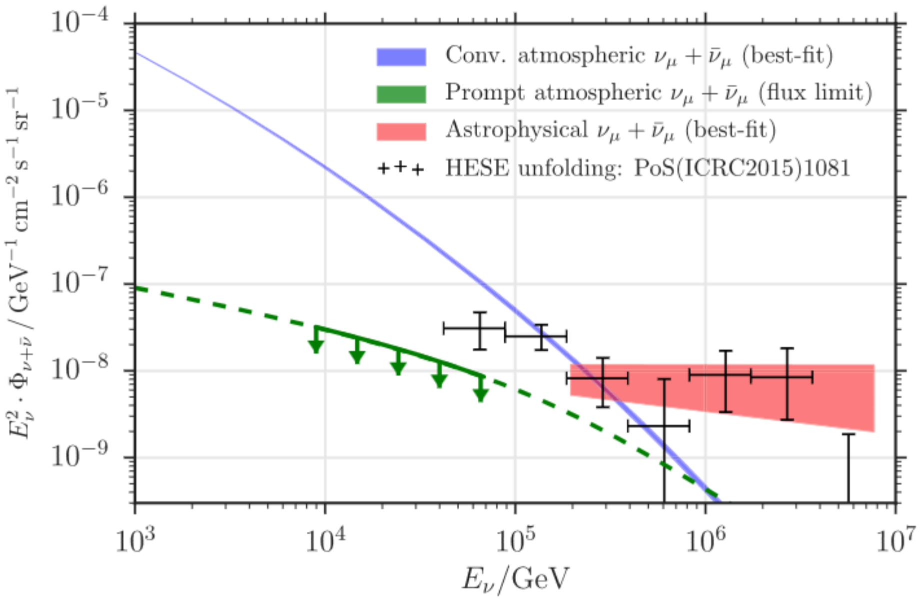
Atmospheric lepton flux

IceCube, Astrophys.J. 833 (2016) 18



Approximate solutions to cascade equations (Gaisser, Honda, ...)

cosmic ray flux — CR spectrum weighted moments

$$\phi_l(E) \propto \phi_N(E) \sum_h \frac{Z_{N\to h} Z_{h\to l}}{1 + E \cdot C_h}$$

$\propto$ life-time

$$Z_{N\to h} = \int_0^1 \mathrm{d}x_{\text{lab}}\, x_{\text{lab}}^{\gamma-1} \frac{\mathrm{d}n_{N\to h}}{\mathrm{d}x_{\text{lab}}}$$

$$x_{\text{lab}} = E_{\text{lab},h} / E_{\text{lab},N}$$

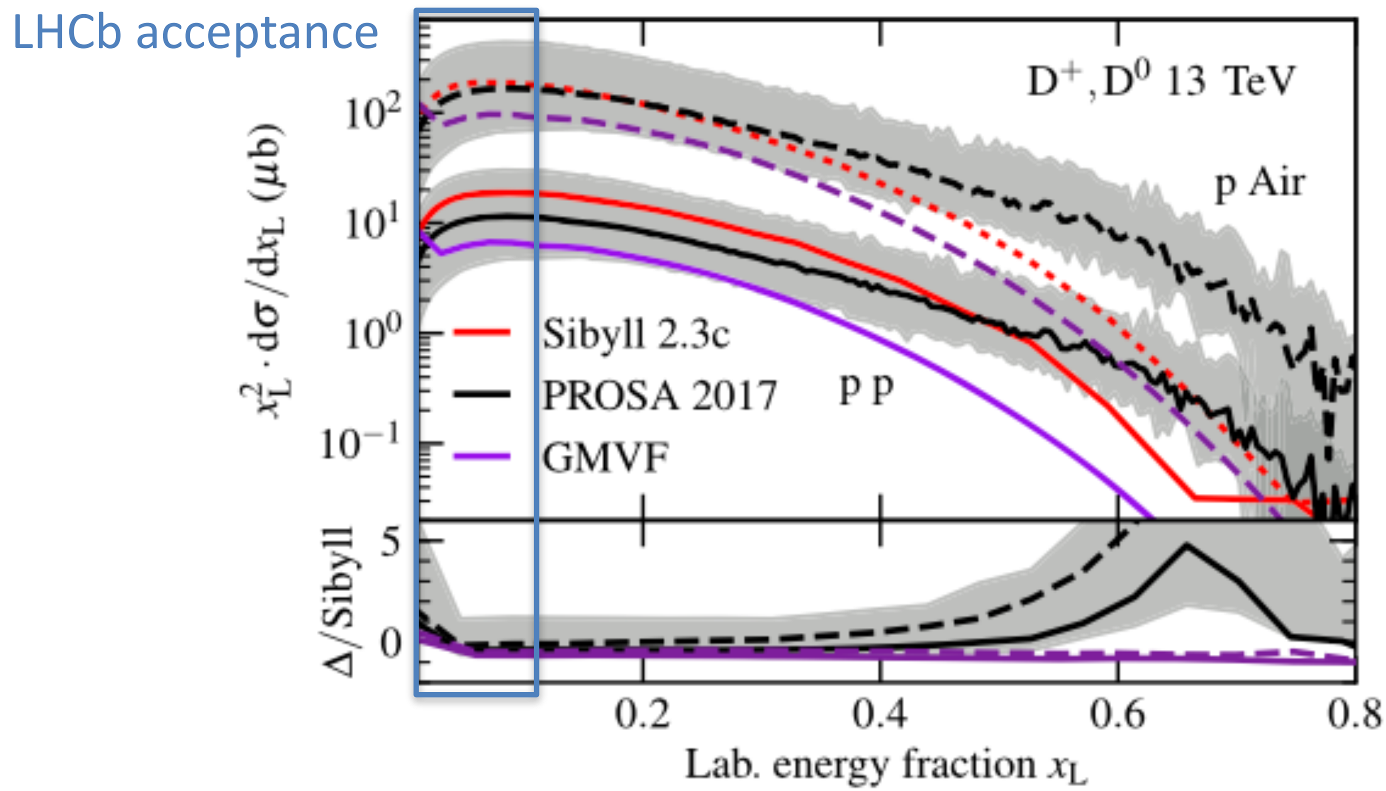
$$\frac{\mathrm{d}n_{N\to h}}{\mathrm{d}x_{\text{lab}}} \sim \sigma_{p+p\to h+X}$$

collider data

- ν_μ flux = astroneutrinos + atm. neutrinos
- atm. neutrino flux = conventional + prompt
  - Conventional: π, K decays (long-lived)
  - Prompt: dominantly charm decays (short-lived)

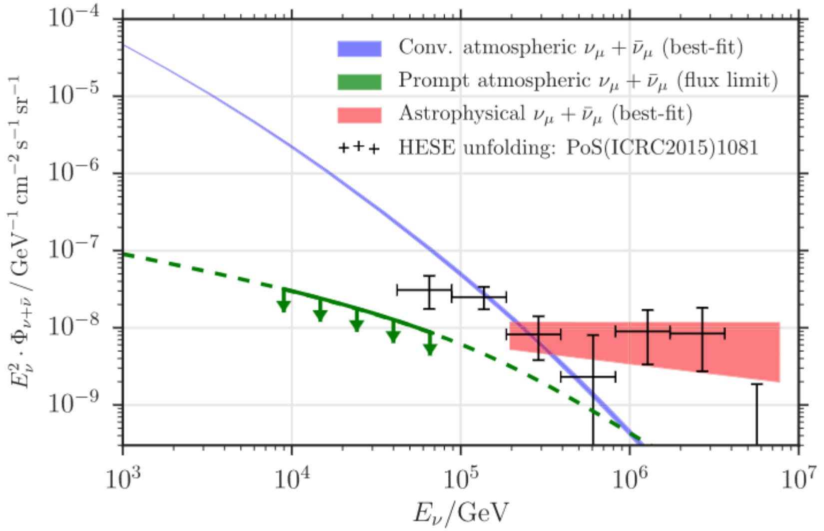
Importance of forward acceptance at LHC

A. Fedynitch et al., Phys.Rev.D 100 (2019) 103018



- LHCb covers largest fraction of charm production cross-section among LHC experiments but atm. flux sensitive to unobserved extreme forward production
- Extrapolation to full cross-section still model-dependent, needs input from astro

Topic 3: Summary

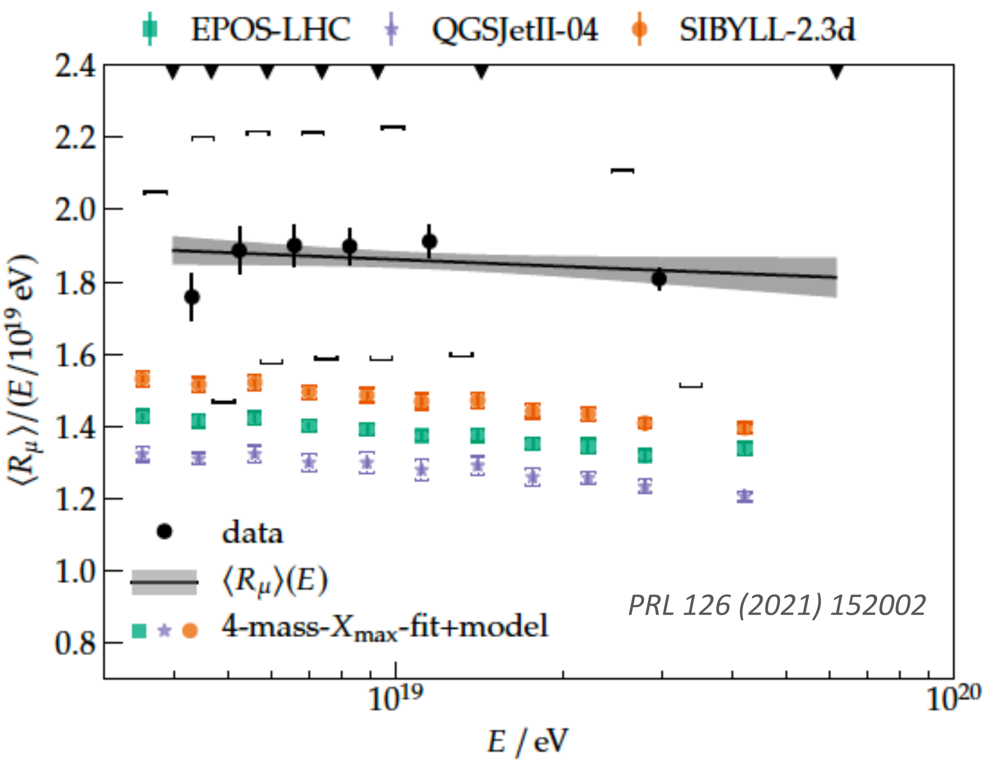


- IceCube neutrino flux = astro + conventional + prompt
  - Conventional flux sensitive to light-flavour production: π, K
  - Prompt flux sensitive to charm production: D mesons
- Best experimental constraints from LHCb, but very forward production unobservable at the LHC
- **SFB F3 + F4**: Constrain very forward phase-space of D production with **global fits of astro and collider data**

Topic 4: Muon puzzle in air showers

Muon puzzle in air showers

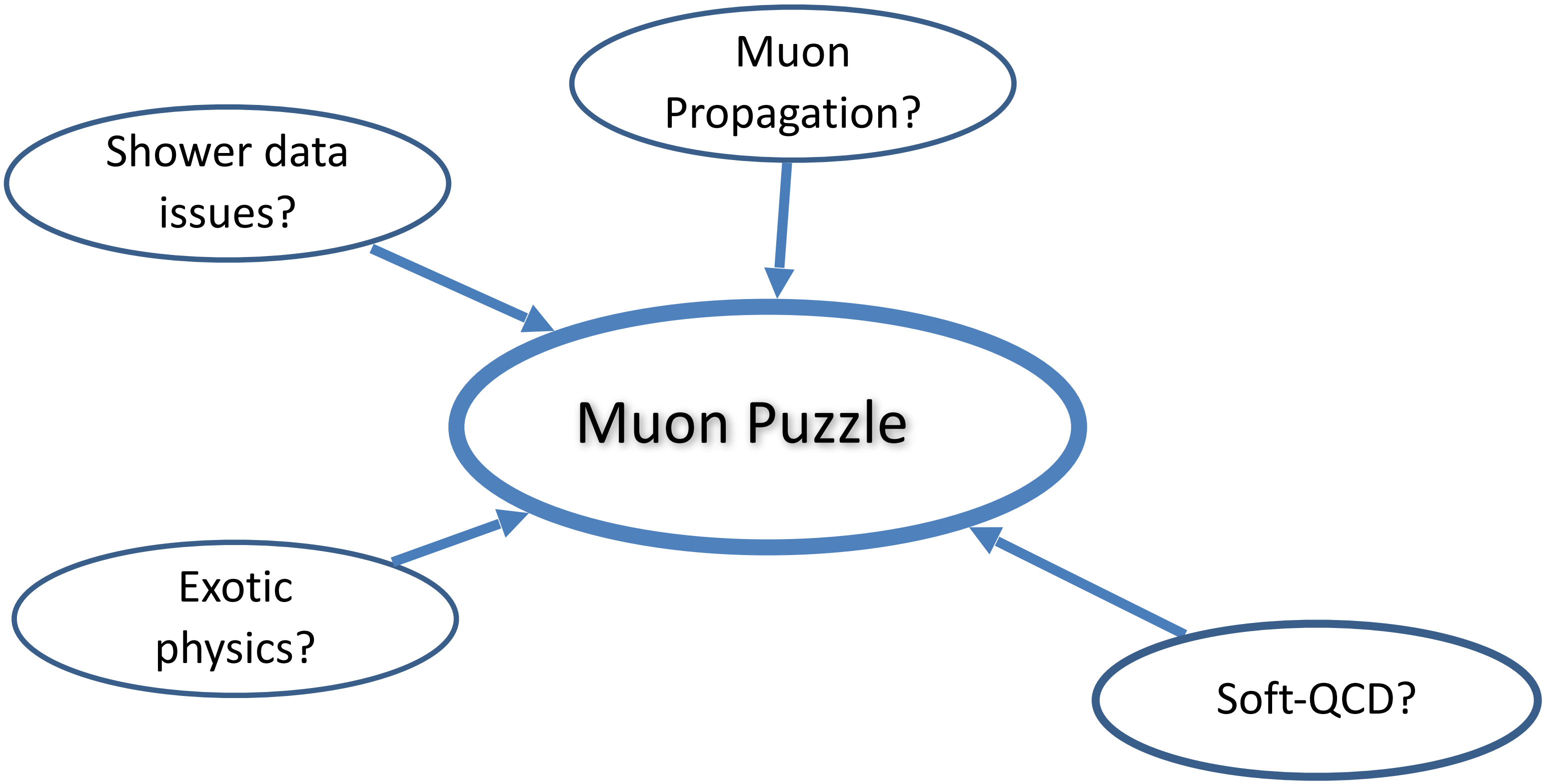
Pierre Auger Observatory
PRD 91 (2015) 032003 Eur. Phys. J. C (2020) 80:751
PRL 117 (2016) 192001 PRL 126 (2021) 152002



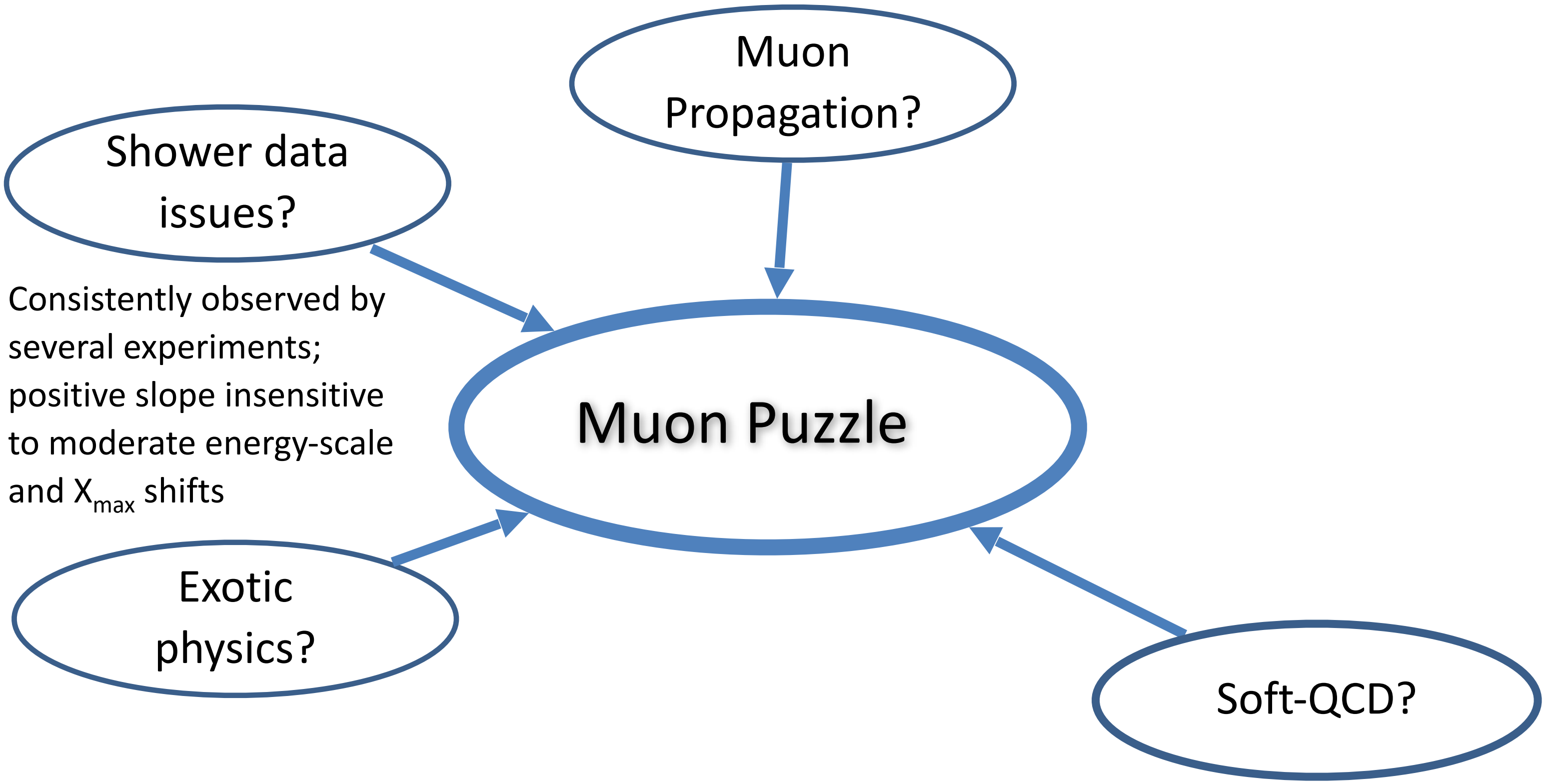
WHISP meta analysis
HD et al., *EPJ Web Conf.* 210 (2019) 02004
L. Cazon et al., *PoS* ICRC2019 (2020) 214
D. Soldin et al., *PoS* ICRC2021 (2021) 349
J.C. Arteaga-Velazquez et al, *PoS* ICRC2023 (2023) 466

- Muon deficit observed in air shower simulations
- Impact on mass reconstruction and indirectly on atm. lepton flux

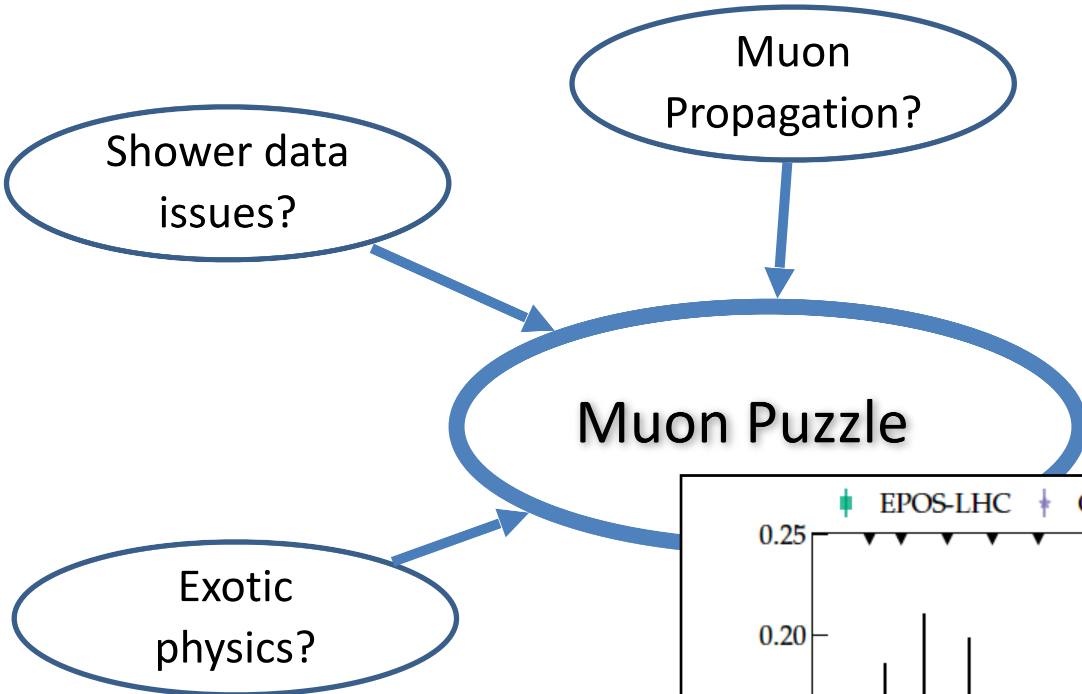
Origin of muon puzzle?

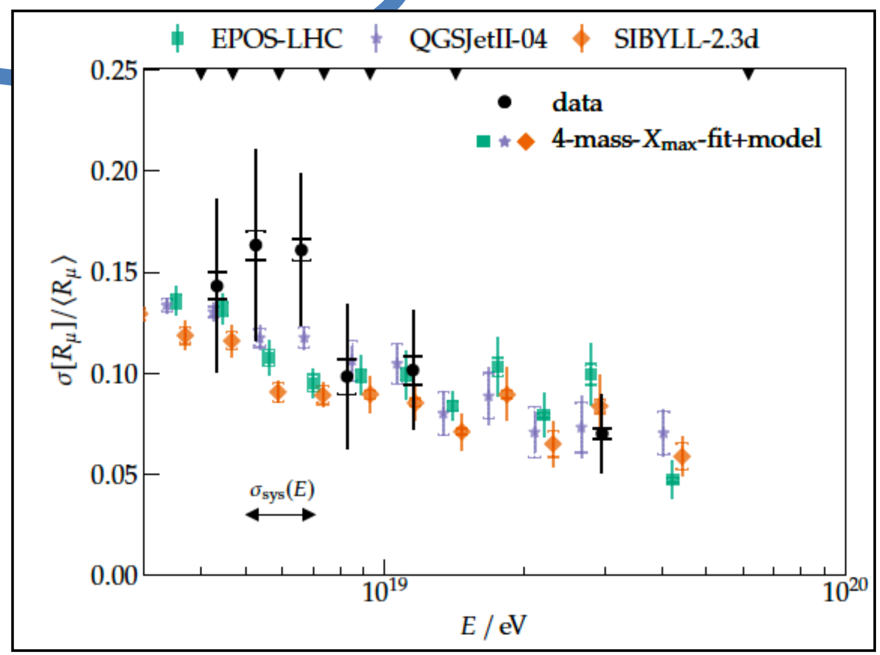


Origin of muon puzzle?



Origin of muon puzzle?

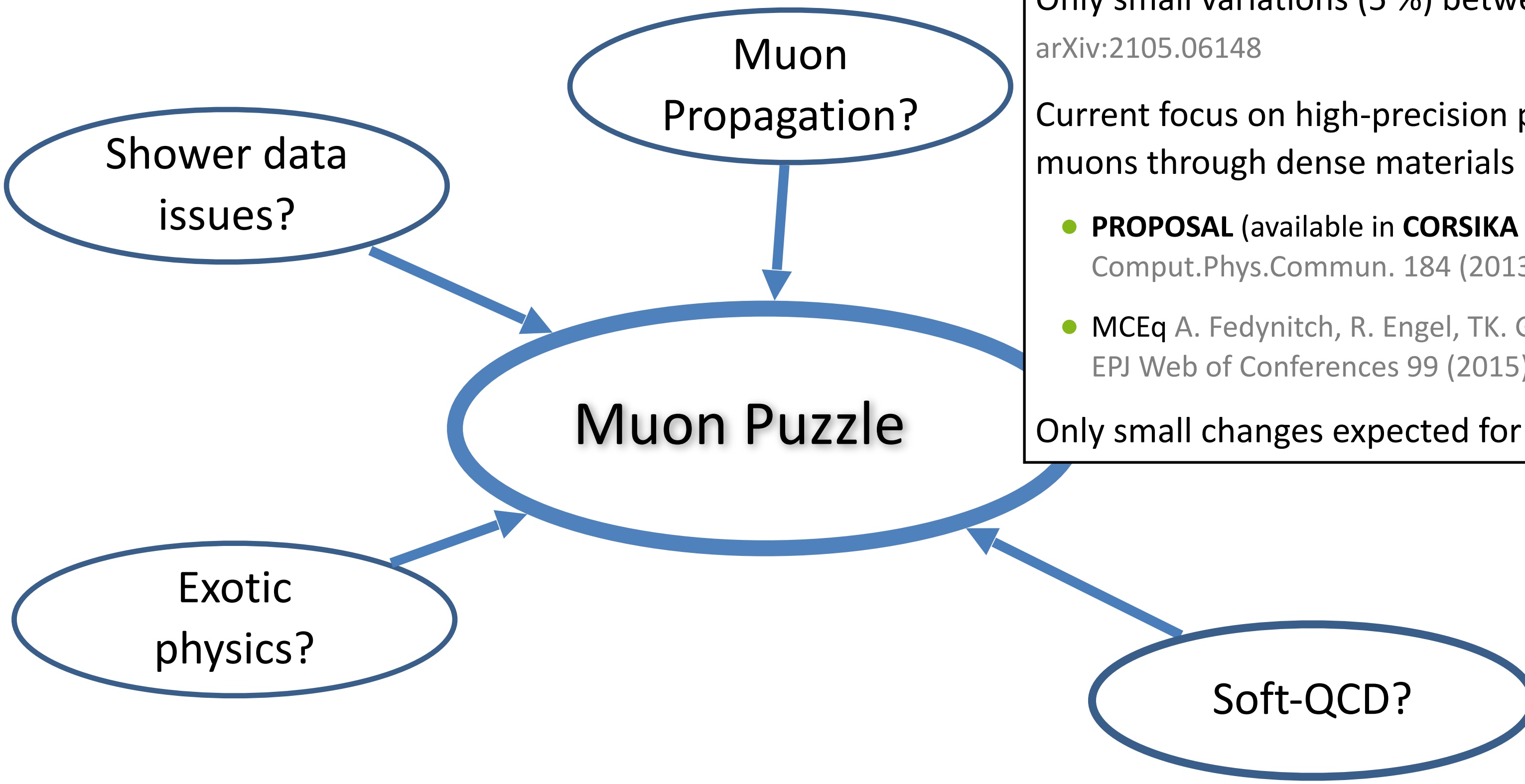




Difficult to change only mean muon number, but keep fluctuations of X_{max} and N_μ same; early onset of muon discrepancy

First measurement of muon fluctuations Pierre Auger collab., PRL 126 (2021) 15, 152002

Origin of muon puzzle?



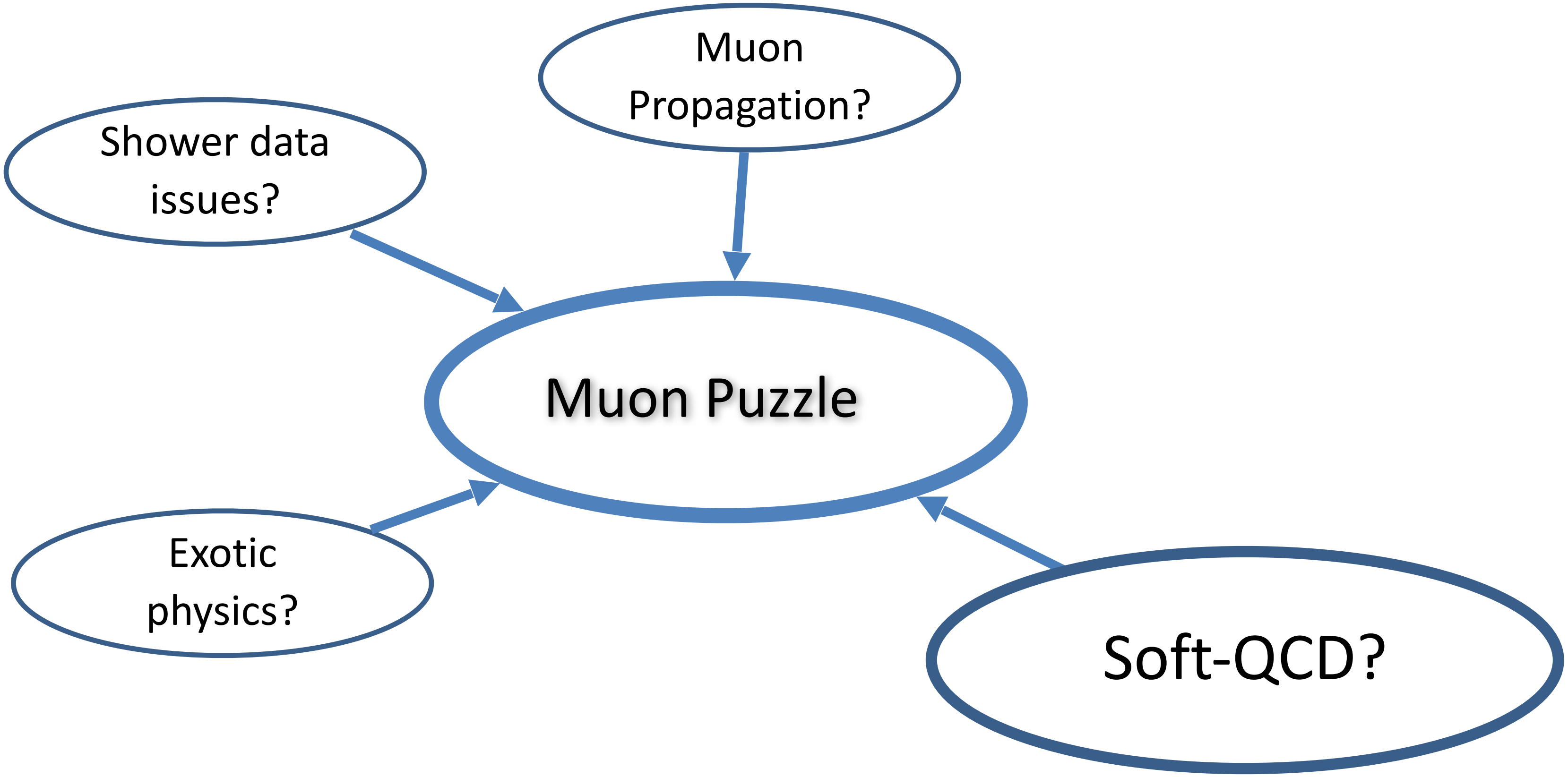
Only small variations (5 %) between shower codes
arXiv:2105.06148

Current focus on high-precision propagation of TeV muons through dense materials

- **PROPOSAL** (available in **CORSIKA 8**), JH. Koehne et al. Comput.Phys.Commun. 184 (2013) 2070-2090
- MCEq A. Fedynitch, R. Engel, TK. Gaisser, T. Stanev, EPJ Web of Conferences 99 (2015) 08001

Only small changes expected for GeV muons in air

Origin of muon puzzle?



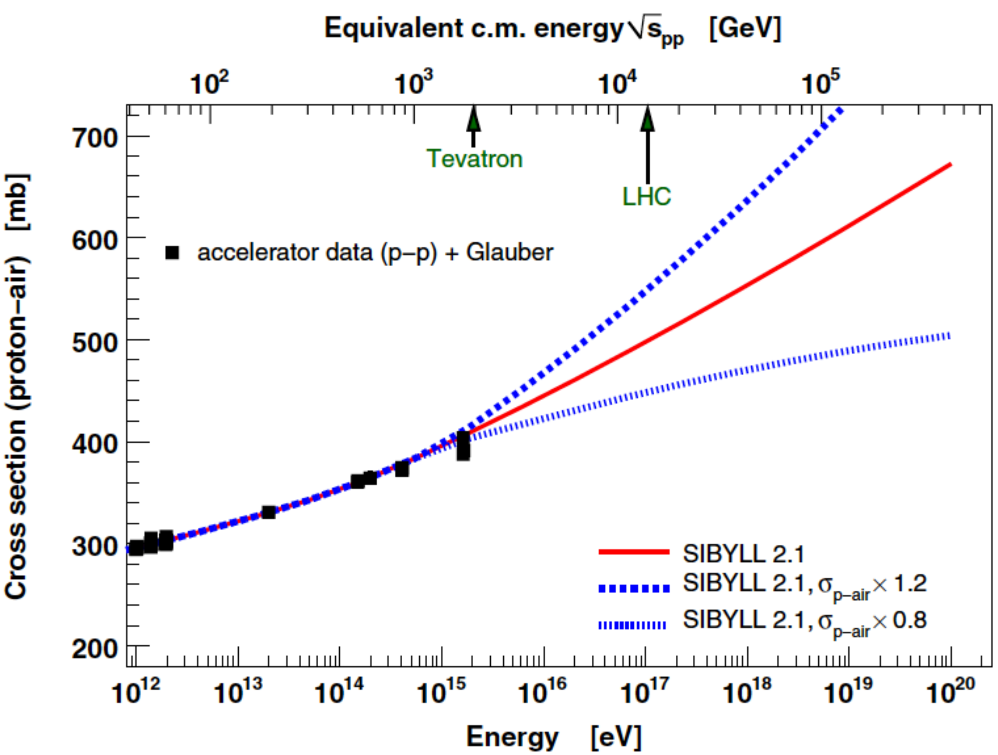
From shower muons to QCD

R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026

- **Modify hadronic features** with **energy-dependent factor *f*(*E*)** in event generator
- Study impact on air shower simulations at ultra-high energies

Modified features

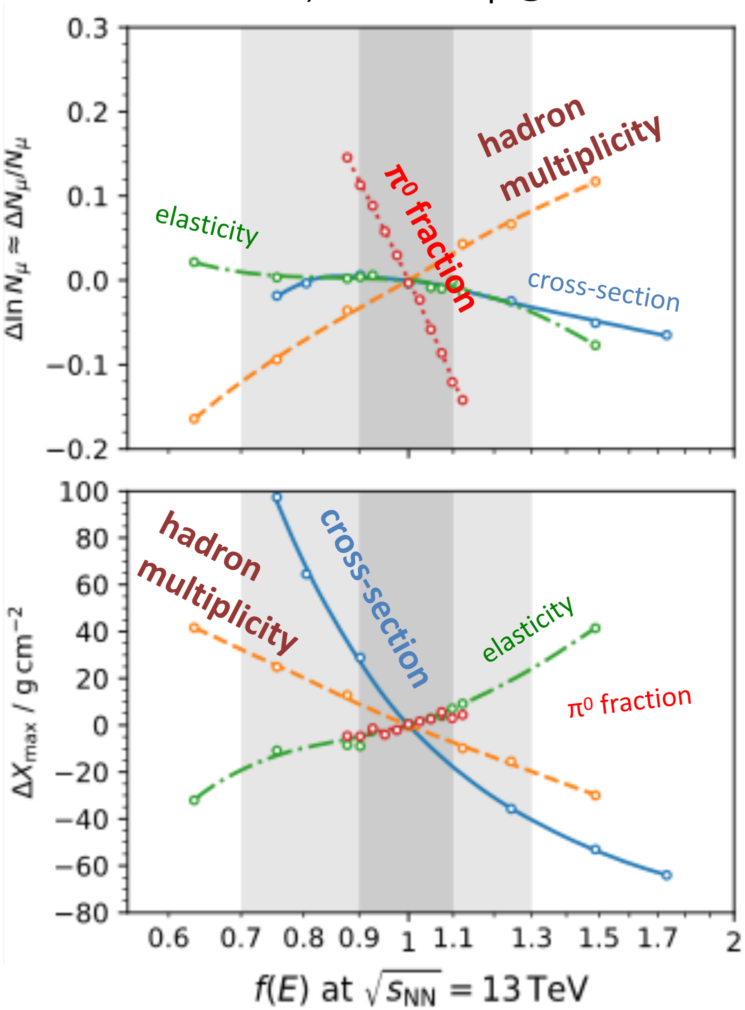
- **cross-sections**
  inelastic cross-section of all interactions
- **hadron multiplicity**
  total number of secondary hadrons
- π^0 **fraction**
- **elasticity** = E_{max} / E_{all}



From shower muons to QCD

R. Ulrich, R. Engel, M. Unger, *Phys.Rev.D* 83 (2011) 054026

CONEX, SIBYLL-2.1 p @ $10^{19.5}$ eV



S. Baur, HD, M. Perlin, T. Pierog, R. Ulrich, K. Werner, *Phys.Rev.D* 107 (2023) 9, 094031

$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

- Only changes to R can solve muon puzzle
- R needs to be known to about 5 % at TeV scale

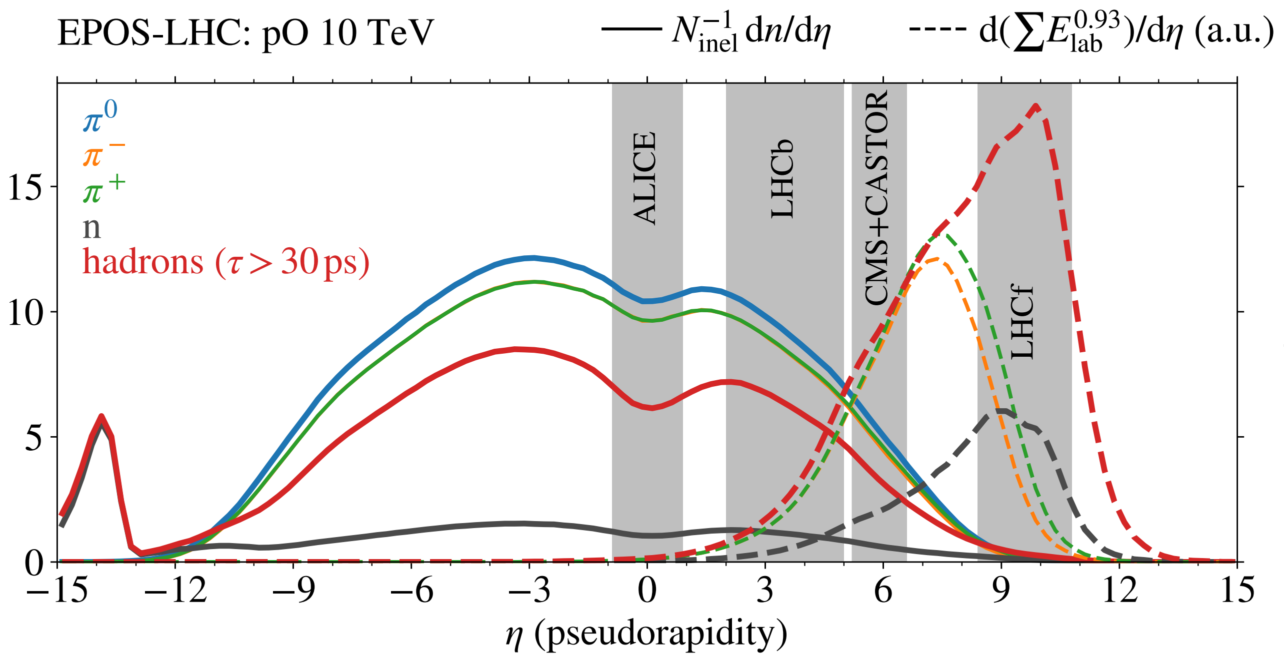
Importance of forward acceptance

HD, J. Albrecht, W. Rhode, B. Spaan, ..., Astrophys. Space. Sci. **367,** 27 (2022)

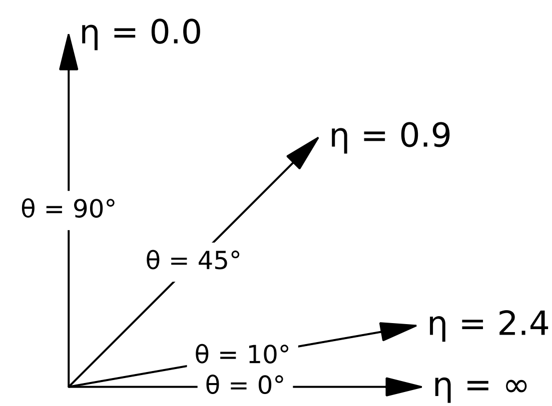
Also see PoS(ICRC2021)463 in arXiv:2112.11761

„Muon production weight“

how many muons would be produced in shower by secondaries in this collision



η related to emission angle

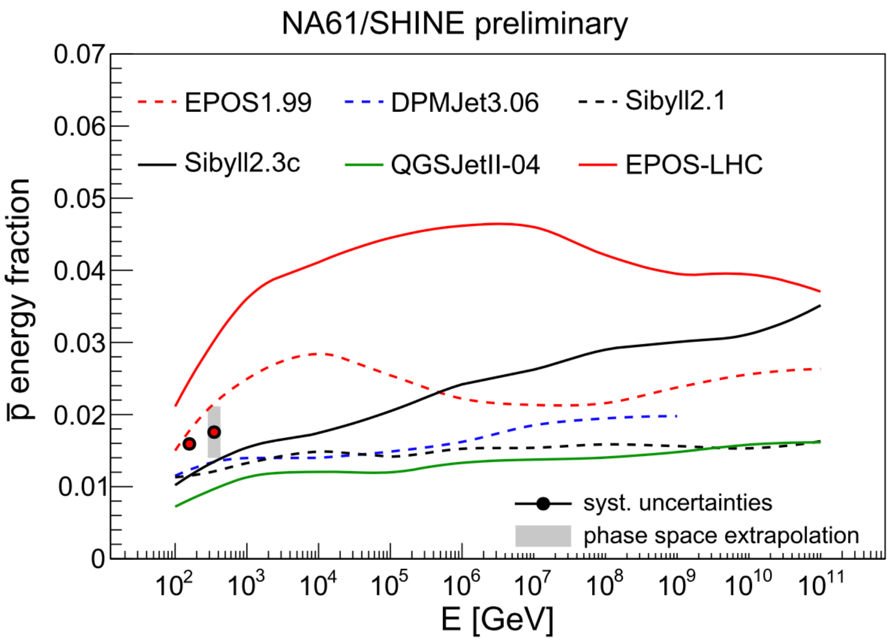


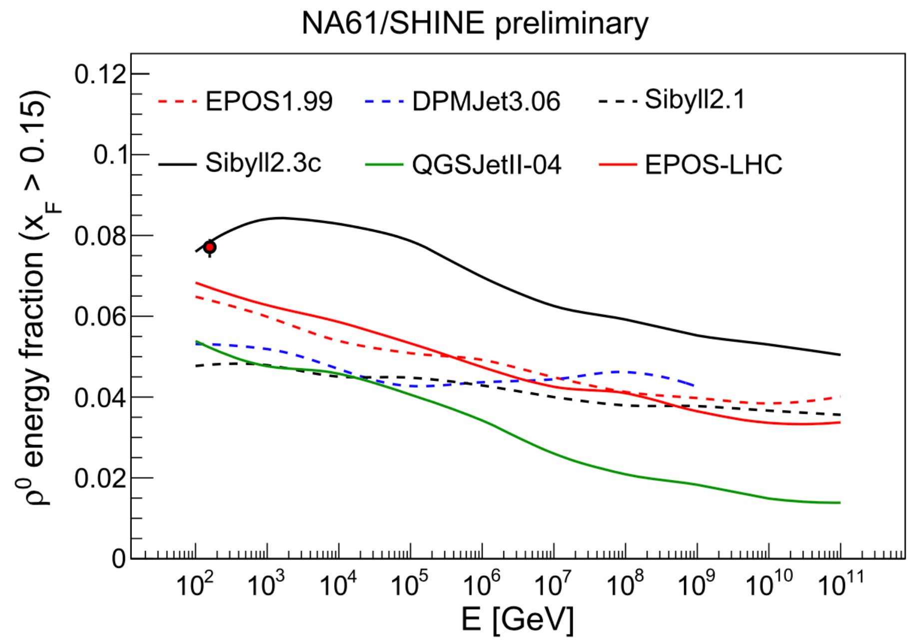
$\eta = -\ln \tan(\theta/2)$

- LHCb is most forward **general purpose** experiment
- Only specialised detectors (calorimeters) cover very forward

How to reduce energy ratio R?

- Enhanced forward baryon and ρ^0 production in π-air collisions





- More baryons and ρ^0 → less π^0

  → **more muons** in air showers

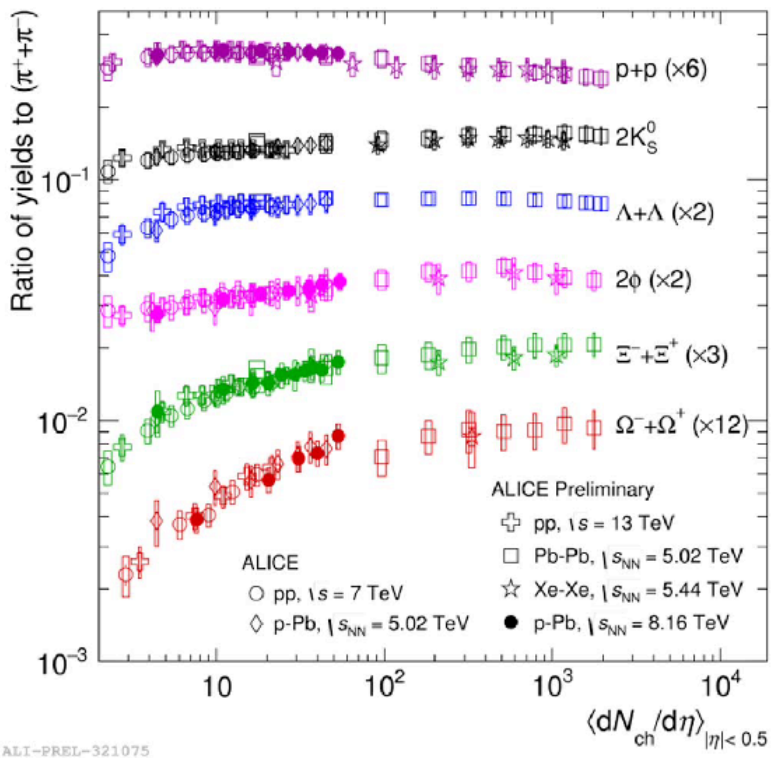
- **Not enough to solve muon puzzle**

T. Pierog, K. Werner, PRL 101 (2008) 171101
M. Unger for NA61/SHINE, PoS ICRC2019 (2020) 446
R. Prado for NA61/SHINE, EPJ Web Conf. 208 (2019) 05006
F. Riehn, R. Engel, A. Fedynitch, TK. Gaisser, T. Stanev, Phys.Rev.D 102 (2020) 6, 063002
F. Riehn et al. *PoS* ICRC2023 (2023) 429

How to reduce energy ratio R?

- Enhanced strangeness production in high-multiplicity events

M. Vasileiou for ALICE, Phys. Scr. 95 (2020) 064007



high "multiplicity" = high particle density

- ALICE discovered density-dependent enhancement of strangeness production ALICE, Nature Phys. 13 (2017) 535

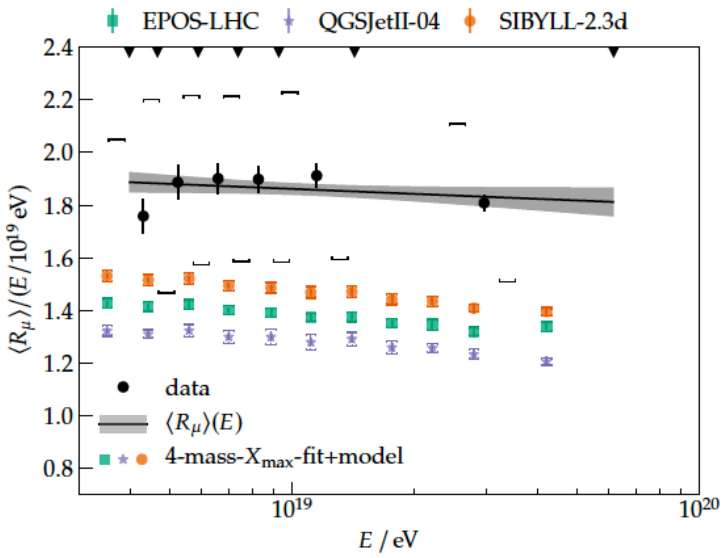
- More strangeness → less π^0 → more muons in air showers
  - *R* reduced by **20 %** in high density events

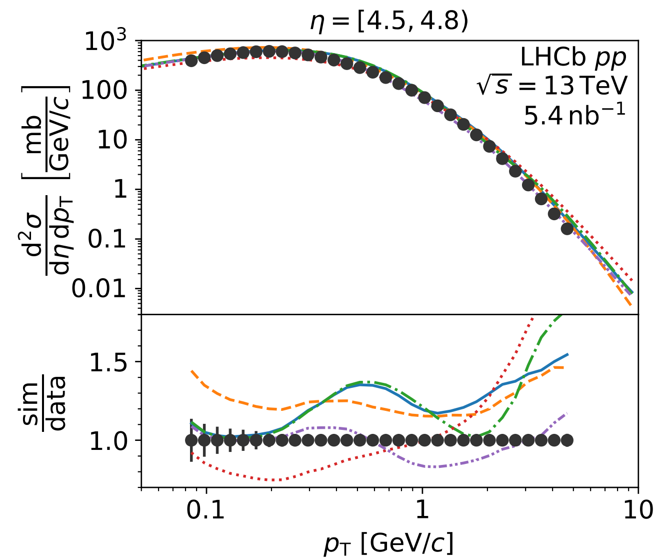
S. Baur, HD, et al, *Phys.Rev.D* 107 (2023) 9, 094031

L. Anchordoqui et al. *JHEAp* 34 (2022) 19-32

- **Open question:** effect in **forward region η ≫ 1 strong enough** to solve muon puzzle?

Topic 4: Summary





LHCb-PAPER-2021-010,
arXiv:2107.10090
p-p @ 13 TeV

- **Muon puzzle**: deficit of GeV muons in simulated air showers
  - If solved, huge impact on cosmic ray research due to **shifts in CR mass composition**
  - Indirect implications for atmospheric lepton flux
- Muon production connected to microscopic variable $R = E_{\pi^0}/E_{\text{other hadrons}}$
- Only LHCb and LHCf constrain *R* in forward region relevant for air showers
- **SFB F4**
  - Multiplicity-dependent analysis of identified hadrons & strangeness production in **p-p @ 13 TeV, p-Pb @ 8.16 TeV, p-He(gas), p-Ne(gas)**

Community-wide projects

- **SFB F3 + F4: CORSIKA 8 + PROPOSAL**
  - CORSIKA: standard air shower simulation code used in astroparticle physics
  - PROPOSAL: high precision muon propagation in different materials
  - Pythia 8 integration is ongoing
  - Essential for global fits and SFB tuning efforts
- **Chromo** HD, A. Fedynitch, A. Prosekin, *PoS* ICRC2023 (2023) 189
  - Fast unified frontend to event generators used in astroparticle and particle physics in Python
- **RIVET**
  - Maps output from event generators to collider measurements; essential for generator tuning
  - **SFB F3 + F4**
    - Added relevant LHCb results to RIVET database
    - Long-term plan to integrate astroparticle data into RIVET
- **CRDB** D. Maurin, HD, ..., *Eur.Phys.J.C* 83 (2023) 971
  - Community database (300k+ data points) of cosmic ray measurements usable for fits/tuning
- **MCPlots**
  - Website to show global agreement of models and collider data
  - With SFB person power could add latest relevant LHCb and astroparticle data

Conclusions and Outlook

- Deep connections between astroparticle experiments...
  - **Pierre Auger Observatory, IceCube**, AMS-02, KM3Net, ...
- ... and collider experiments
  - **LHCb**, ALICE, NA61, ...

- SFB F3 and F4 work combining data of collider and astroparticle experiments with **global fits**
- Support/build/contribute to **tools** essential for global fits

SFB1491

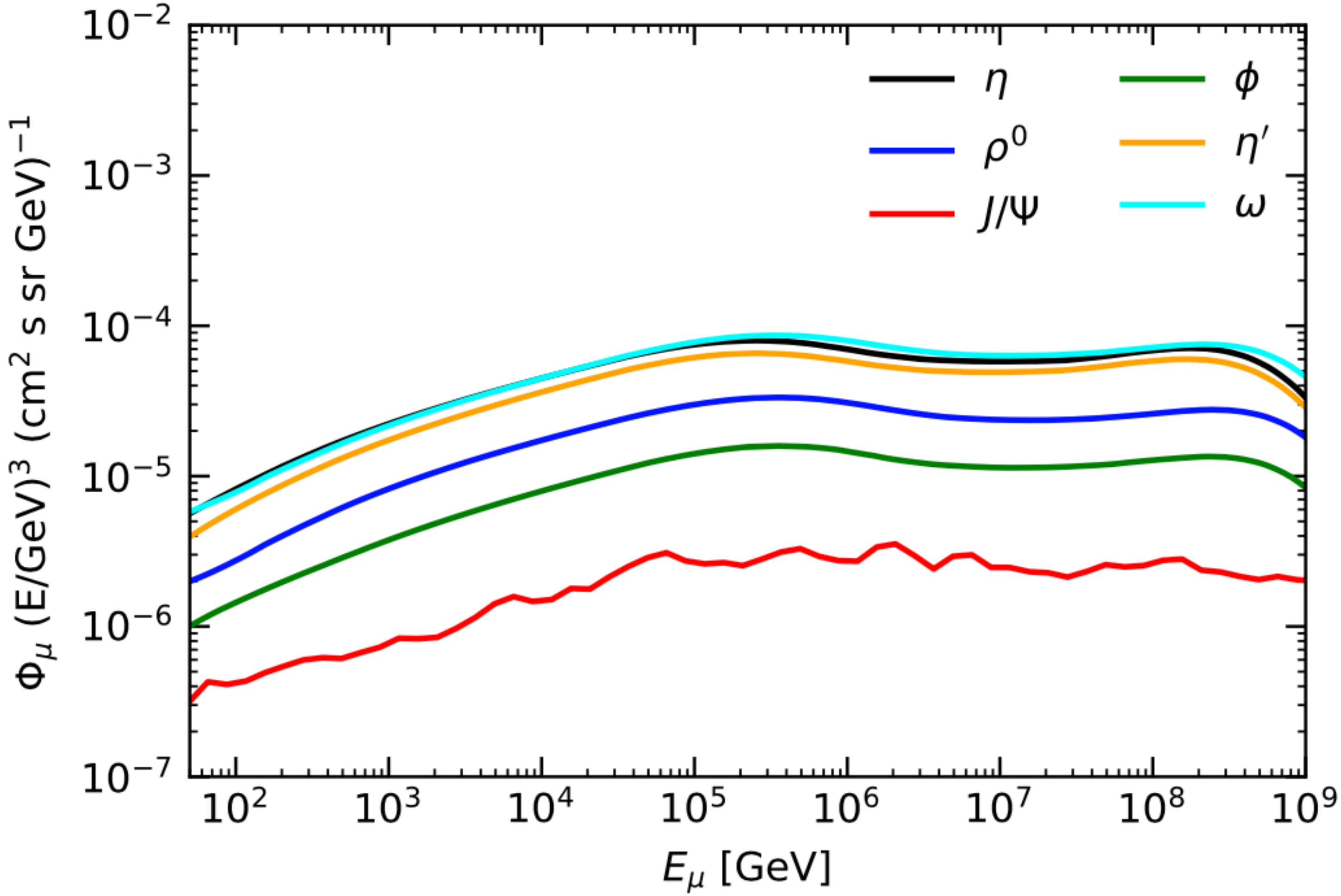
SFB workshop on the tuning of hadronic interaction models

Jan 22-26 2024, Wuppertal

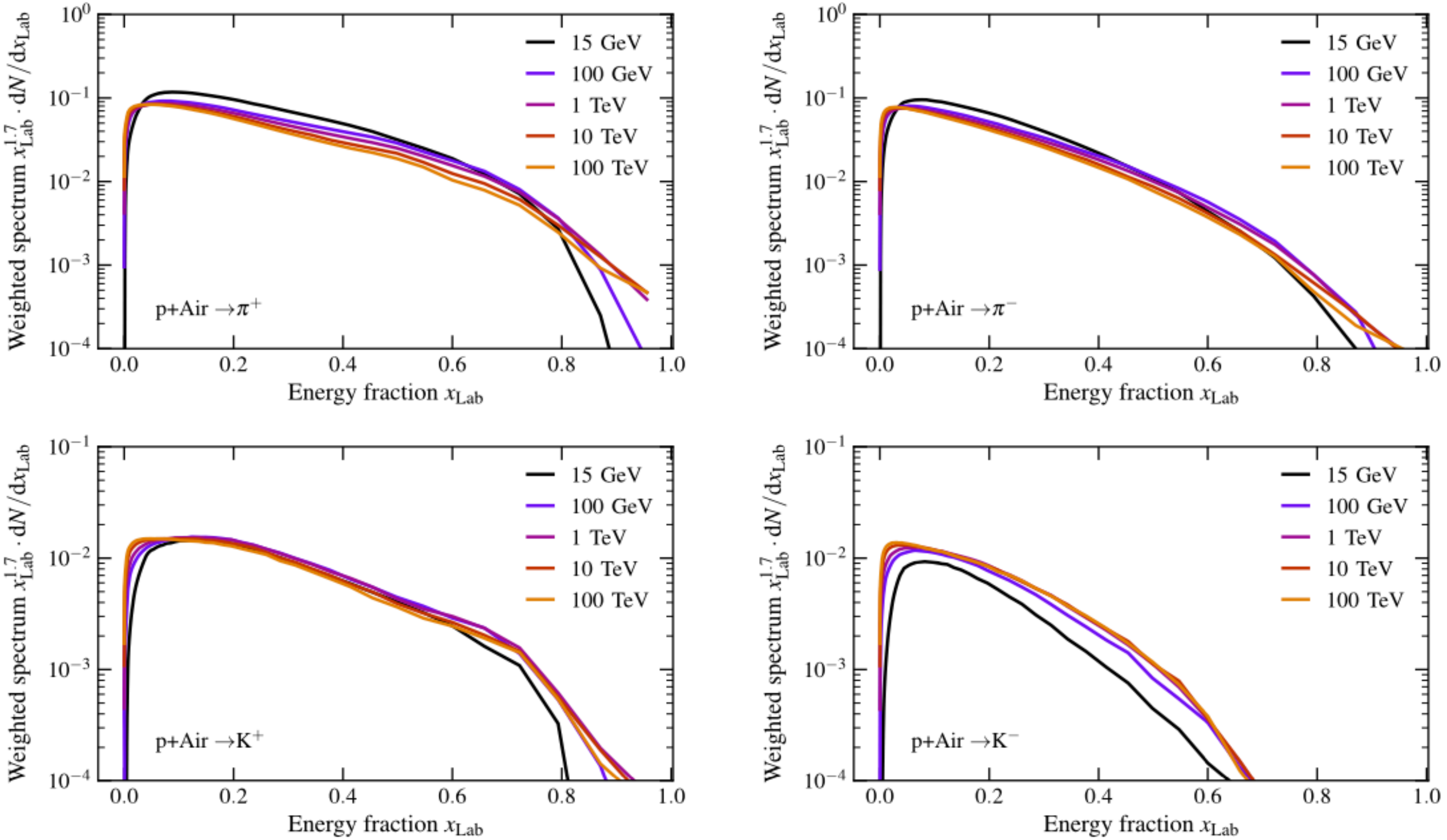
https://indico.uni-wuppertal.de/event/284/

Backup

μ flux from unflavoured



Feynman scaling violations

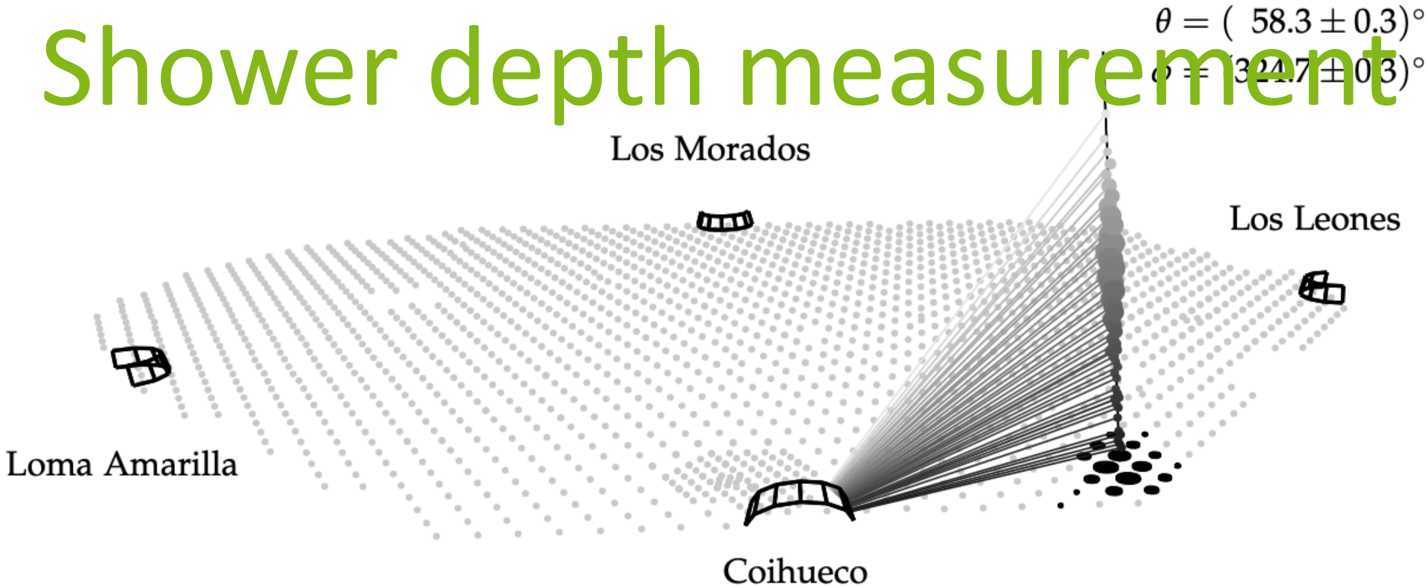


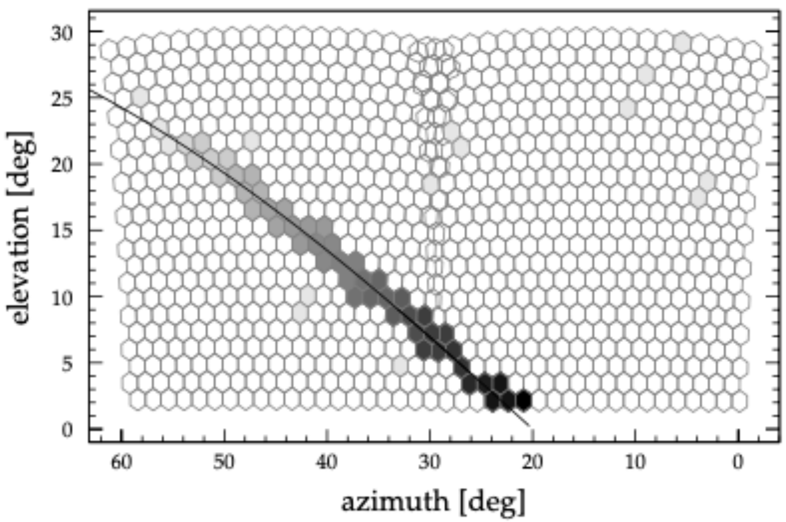
- Feynman scaling: cross-section should be approximately independent of $\sqrt{s}$
- Violations due to multi-parton interactions

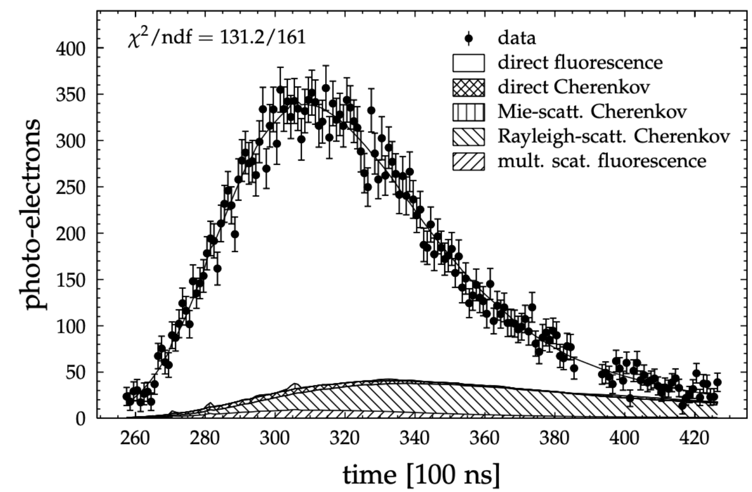
x_F coverage of experiments

Name	P_{Lab} (GeV)	$\sqrt{s}$ (GeV)	x_F spectrum	x_F coverage	Beam config.	Ref.
E-769	250	22	yes	$-0.1 < x_F < 0.8$	p-Nuc	[52,63]
EHS	400	27.4	yes	$0 < x_F < 0.6$	p-p	[53,64]
MPS	800	39	yes	$-0.1 < x_F < 0.4$	p-p	[54]
HERA-B	920	42	no	$-0.1 < x_F < 0.05$	p-Nuc	[55]
STAR	21 TeV	200	no	$-0.03 < x_F < 0.03$	p-p	[57]
PHENIX	21 TeV	200	no	$-0.003 < x_F < 0.003$	p-p	[58]
ALICE	4 PeV	2.76 TeV	no	$-0.005 < x_F < 0.005$	p-p	[59]
	26 PeV	7 TeV	no	$-0.004 < x_F < 0.004$	p-p	[60]
LHCb	26 PeV	7 TeV	no	$0.002 < x_F < 0.1$	p-p	[61]
	90 PeV	13 TeV	no	$0.002 < x_F < 0.1$	p-p	[62]

Shower depth measurement



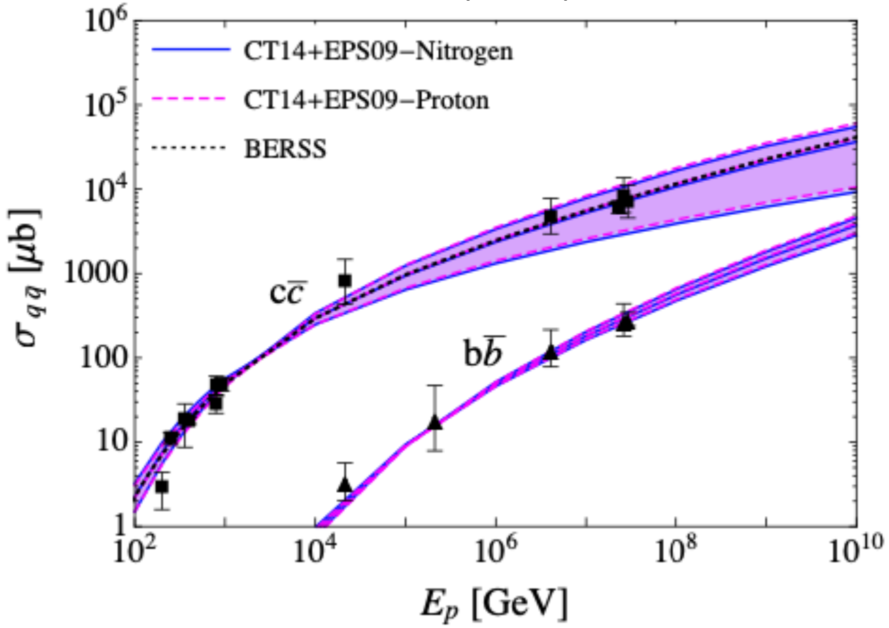




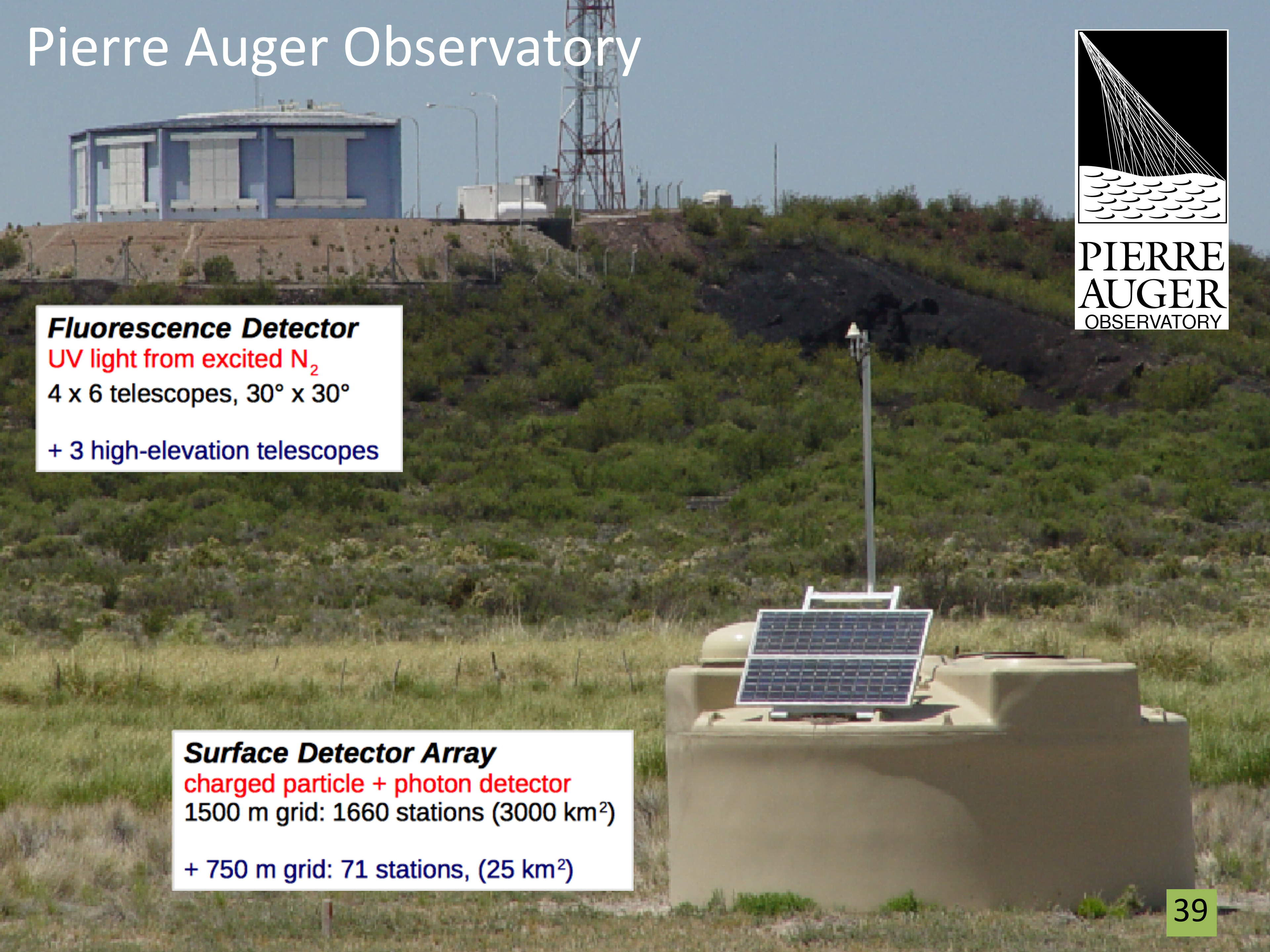
- Challenge: extract unbiased measurement of X_{max} distribution
- Cuts on observation quality, (clouds, brightness), fiducial acceptance

Charm vs. bottom production

A. Bhattacharya et al., *JHEP* 11



Pierre Auger Observatory



Fluorescence Detector
UV light from excited N_2
4 x 6 telescopes, 30° x 30°

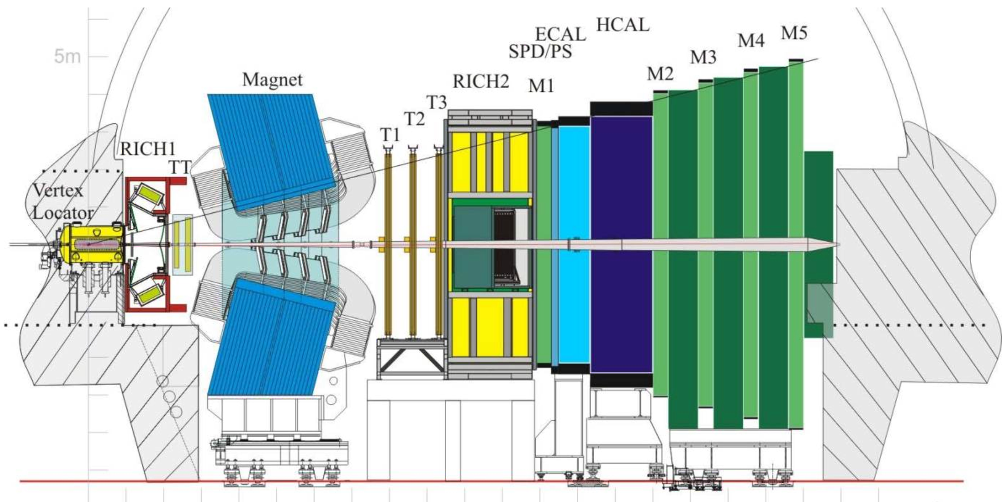
+ 3 high-elevation telescopes

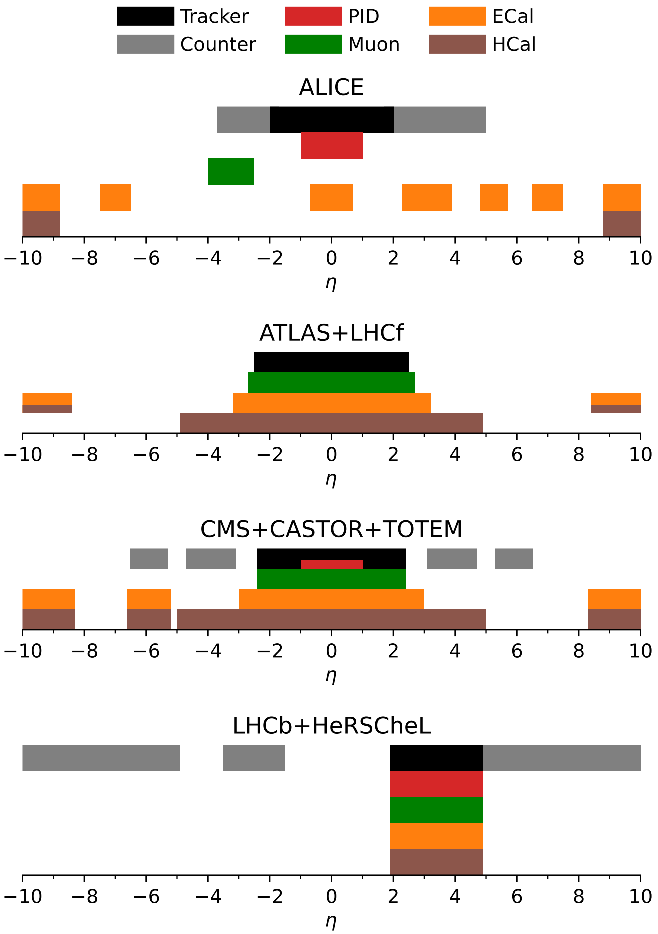
Surface Detector Array
charged particle + photon detector
1500 m grid: 1660 stations (3000 km^2)

+ 750 m grid: 71 stations, (25 km^2)

LHCb detector

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



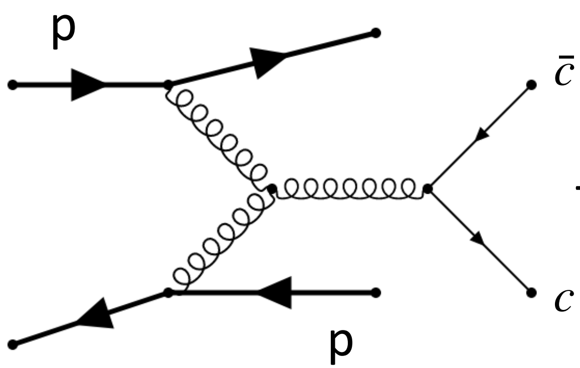


General-purpose forward spectrometer

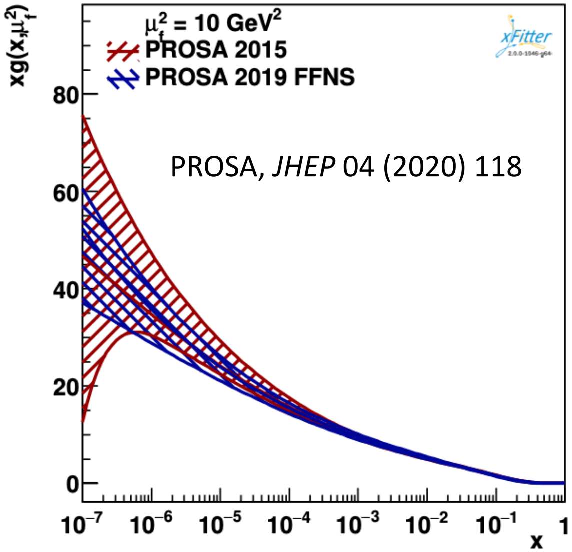
- Forward acceptance $2 < \eta < 5$
- Very good momentum and vertex resolution
  - Acceptance down to $p_T \sim 0.1\,\mathrm{GeV}/c$
- Particle identification: essential to measure $\pi^{\pm}, K^{\pm}, p, \bar{p}$ production cross-sections

Hans Dembinski

PROSA approach



+ hadronization of $c, \bar{c}$



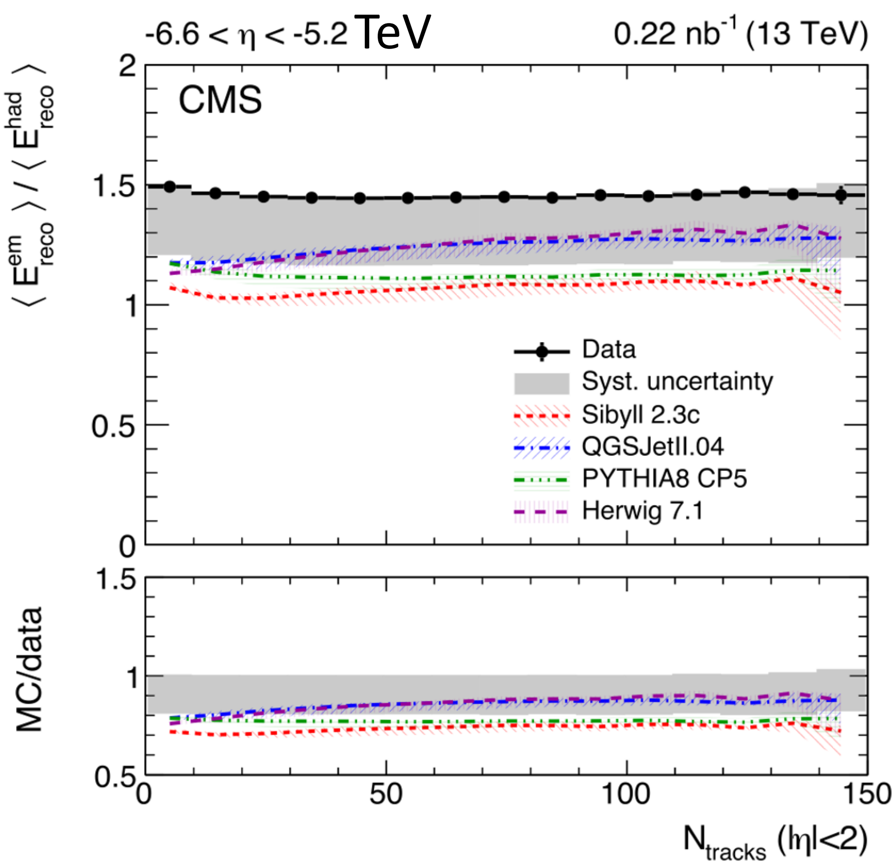
- SIBYLL: direct constraints from LHCb charm production cross-sections
  - Caveat: phase-space $x_{\rm lab} > 0.1$ not covered
- PROSA: indirect constraints from LHCb and other experiments
  - Calculate charm production using QCD factorisation theorem, ingredients:
    - Gluon PDF
    - Perturbative QCD cross-section $gg \to c\bar{c}$
    - Hadronization model
  - Caveat: model-dependent gluon PDF and hadronization
  - **Tightest constrains from LHCb** for gluon PDF at small x, down to 5×10^{-6}

Direct forward measurement of R

CMS, Eur.Phys.J. C79 (2019) no.11, 893

p-p @ 13 TeV

R_{reco}



$\propto dN_{ch}/d\eta$

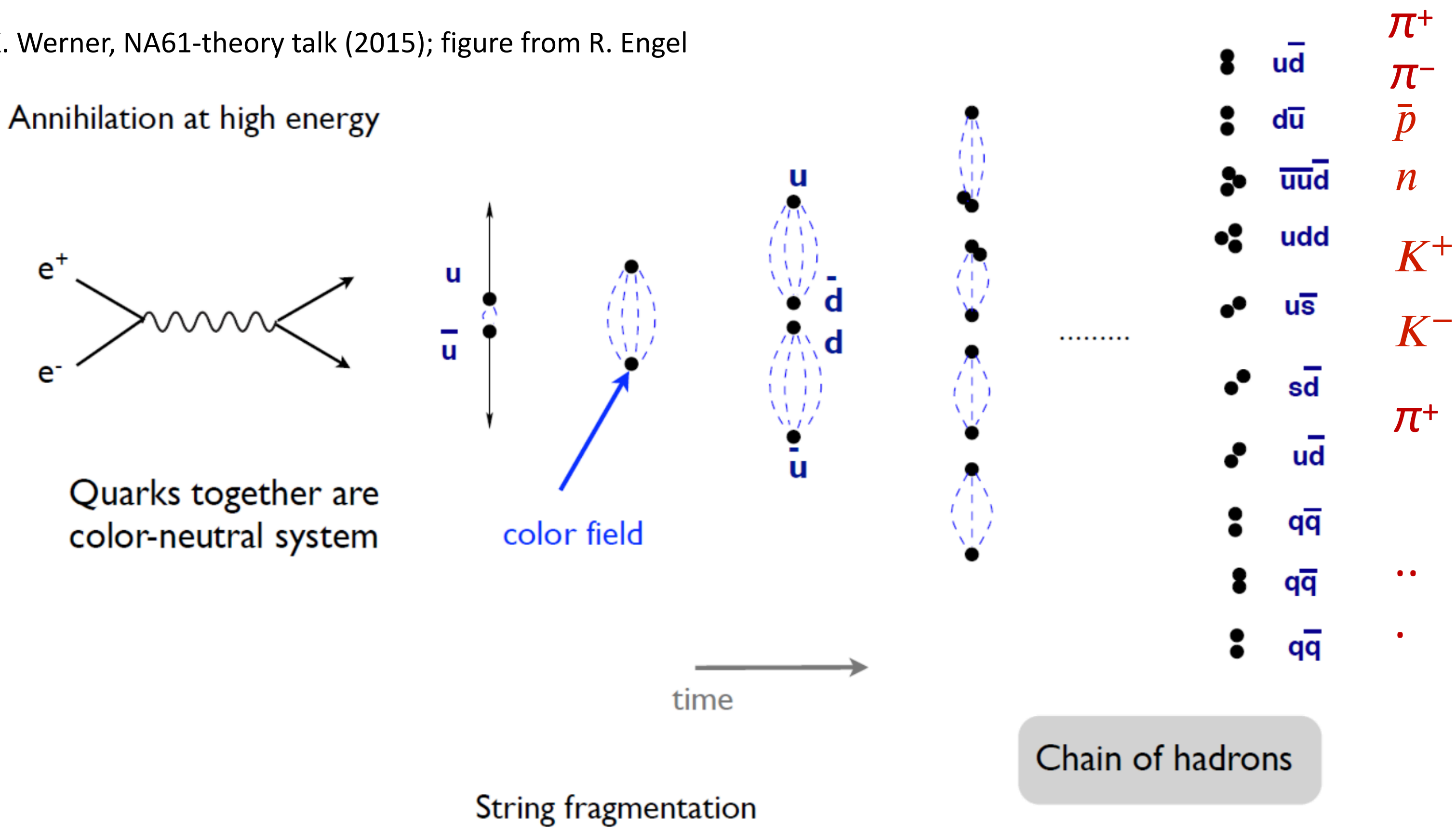
- Double surprise
  - R_{reco} higher than predicted in p-p
  - No dependence on event multiplicity
- Data inconclusive due to large systematic uncertainties

$R_{reco} > R$ here, because of detector effects

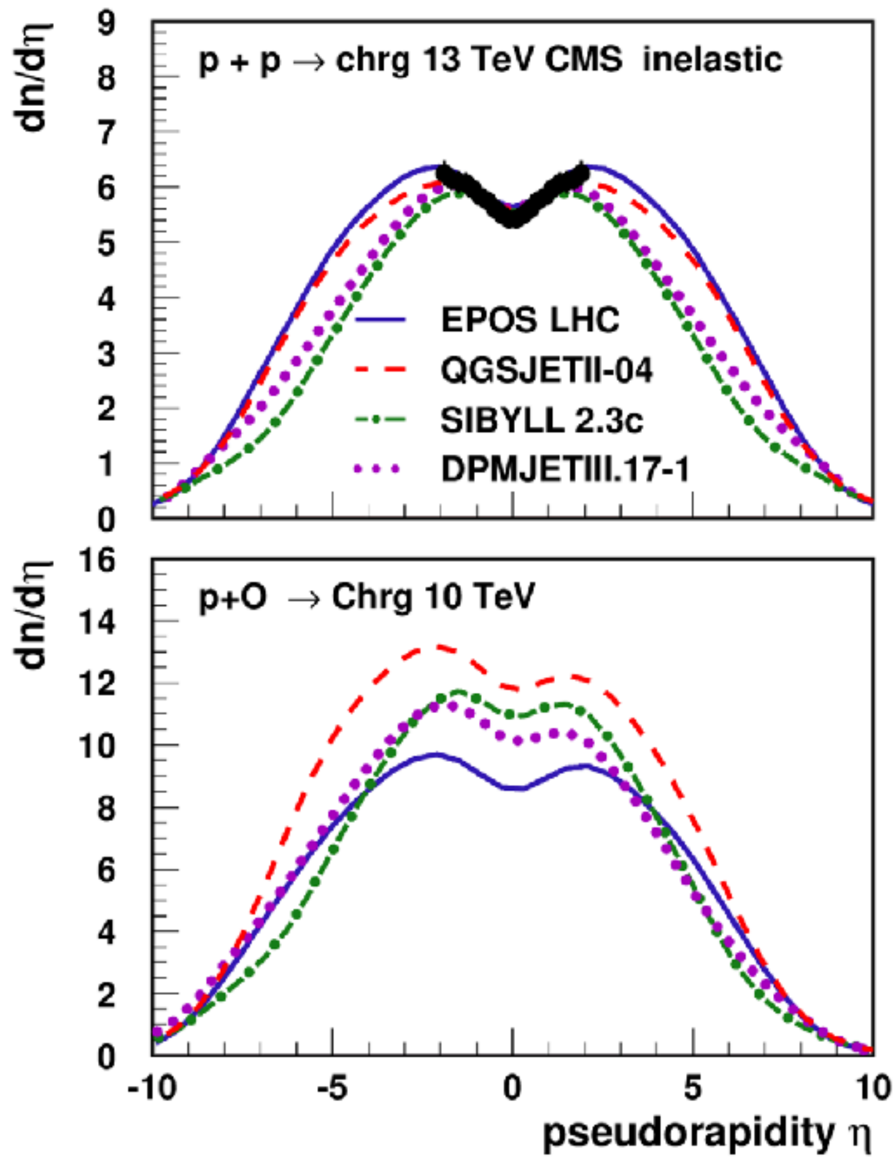
Possibilities to reduce energy ratio R

- Difficult to change *R* within standard QCD
  - Standard theory: hadron composition **independent** of initial state
  - Iso-spin symmetry: $\pi^+ : \pi^- : \pi^0 \sim 1:1:1$

T. Pierog, K. Werner, NA61-theory talk (2015); figure from R. Engel

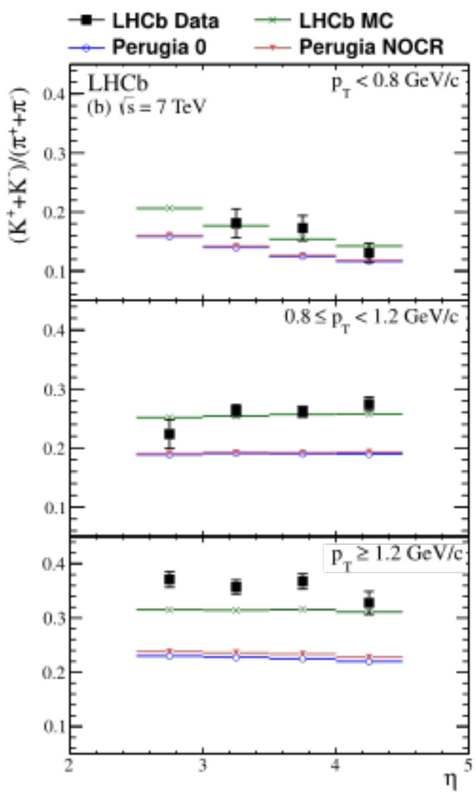


Proton+oxygen collisions at the LHC



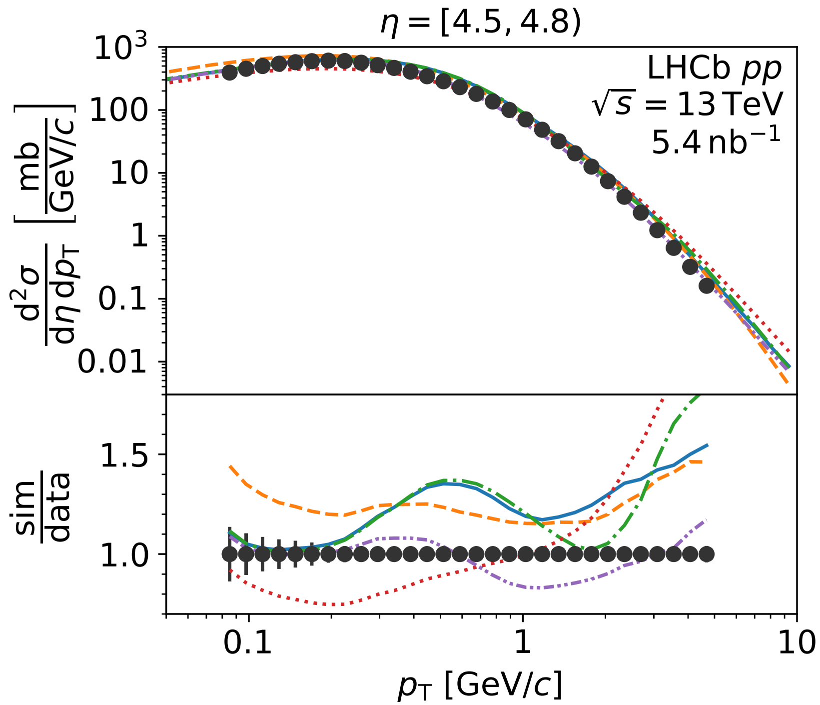
Forward identified hadron spectra

LHCb, EPJC (2012) 72:2168
p-p @ 0.9, 7 TeV



LHCb-PAPER-2021-015,
arXiv:2107.10090
p-p, p-Pb @ 5 TeV

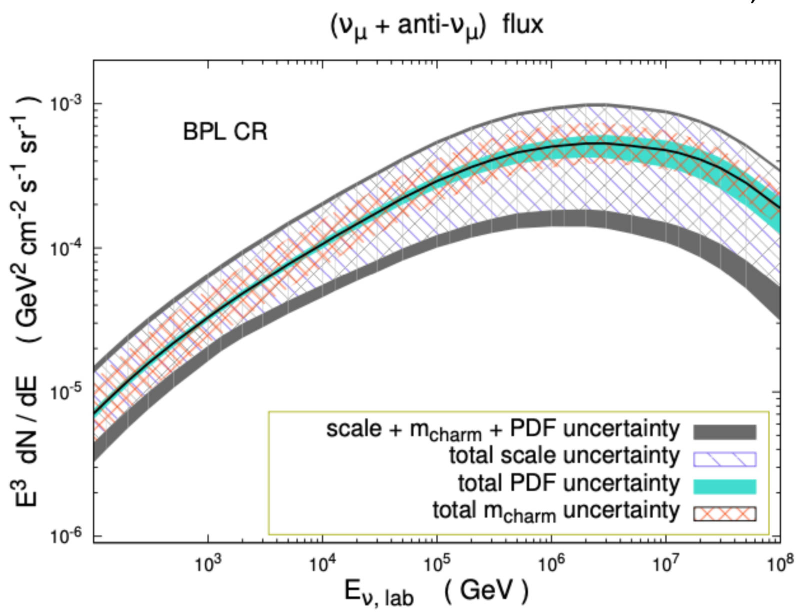
LHCb-PAPER-2021-010,
arXiv:2107.10090
p-p @ 13 TeV

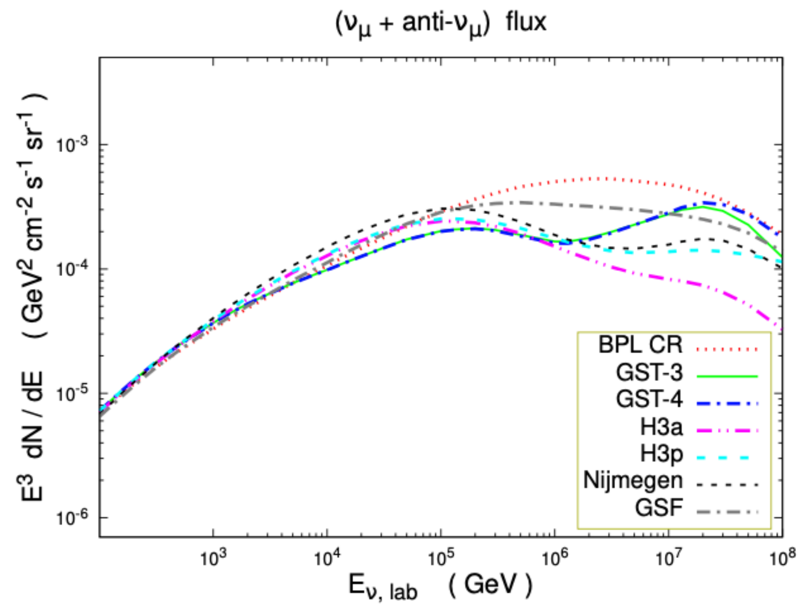


- *R* constrained by **π, K, p ratios** measured in **p-p at 0.9 and 7 TeV** by LHCb
- **In progress**: analysis of identified hadrons in **p-p @ 13 TeV, p-Pb @ 8.16 TeV, p-He(gas), p-Ne(gas)**

Systematic uncertainties

PROSA, *JHEP* 04 (2020) 118



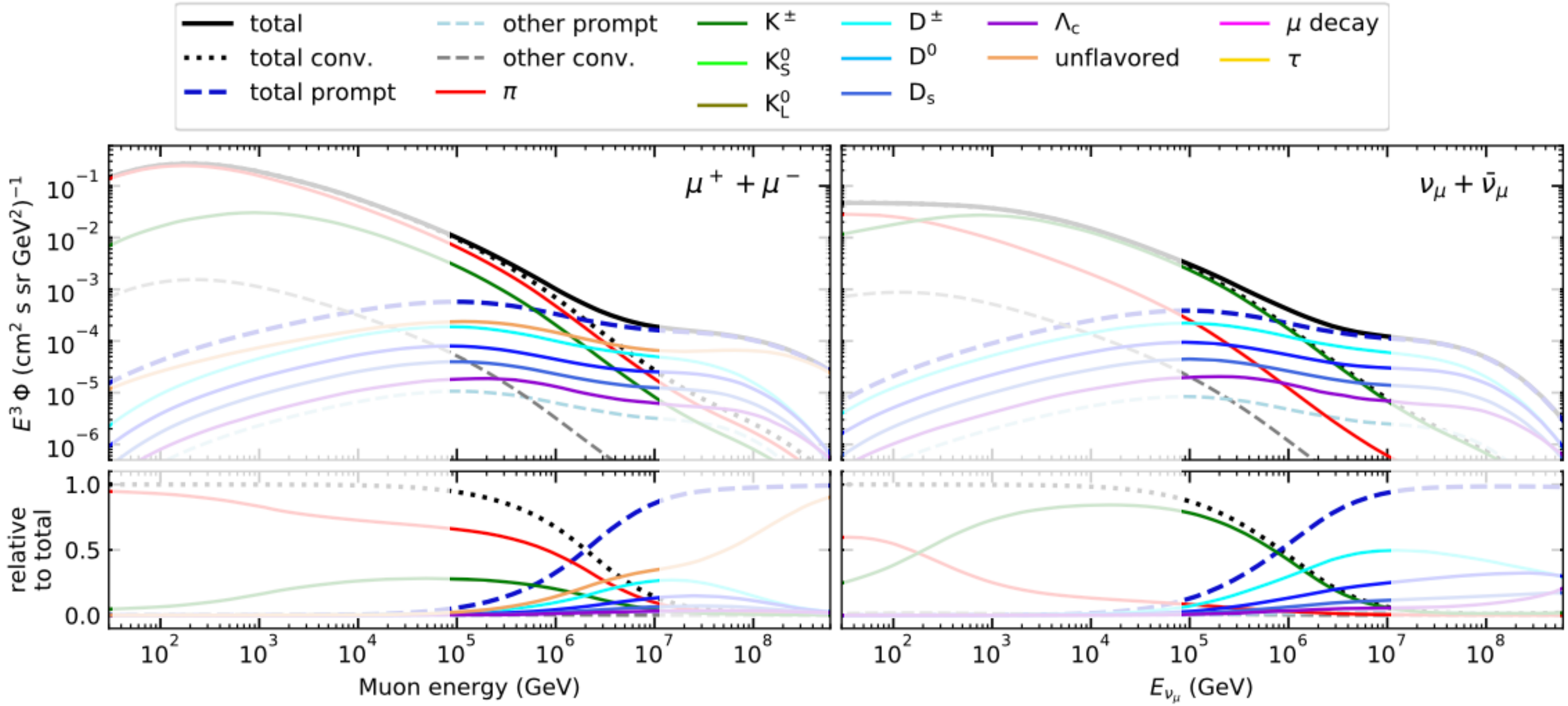


SFB F3 + F4

Constrain sources of uncertainties with global fits of IceCube + LHCb data

Leading contributions to prompt atm. flux

A. Fedynitch et al., Phys.Rev.D 100 (2019) 103018



- μ flux
  - conventional: π, K±
  - prompt: unflavoured $(\eta, \omega, \eta', \rho^0, \ldots)$, D mesons
- ν_μ flux
  - conventional: K±
  - prompt: D mesons