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Charting the Future of Hadronic Interaction Studies for High-Energy Cosmic Rays Toward the 2050s

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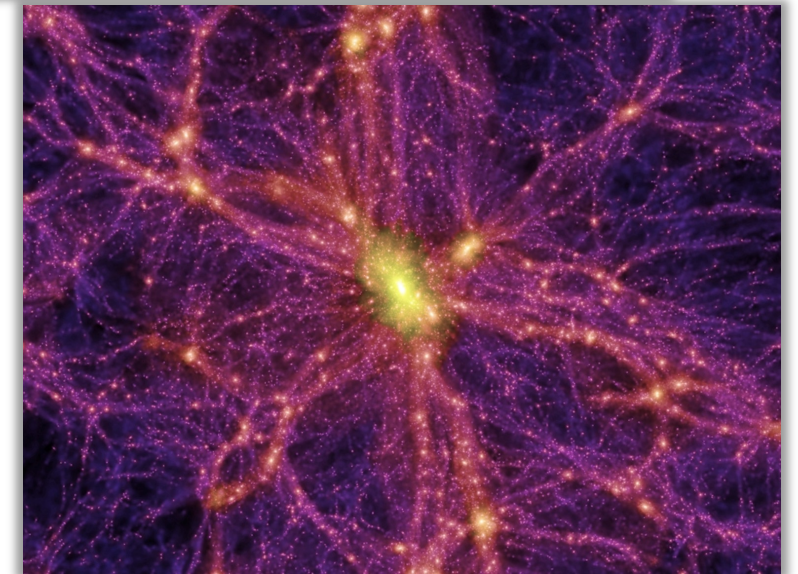
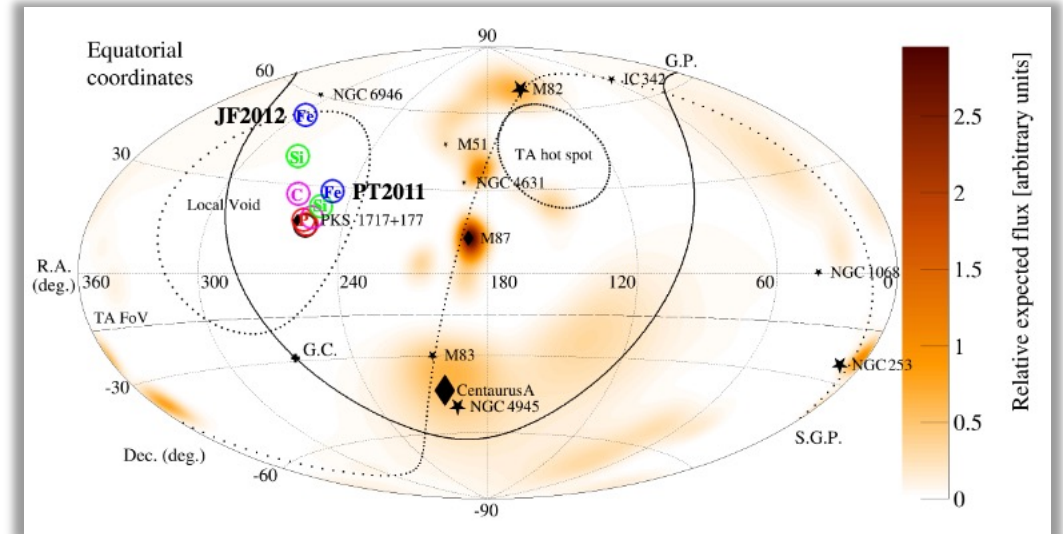
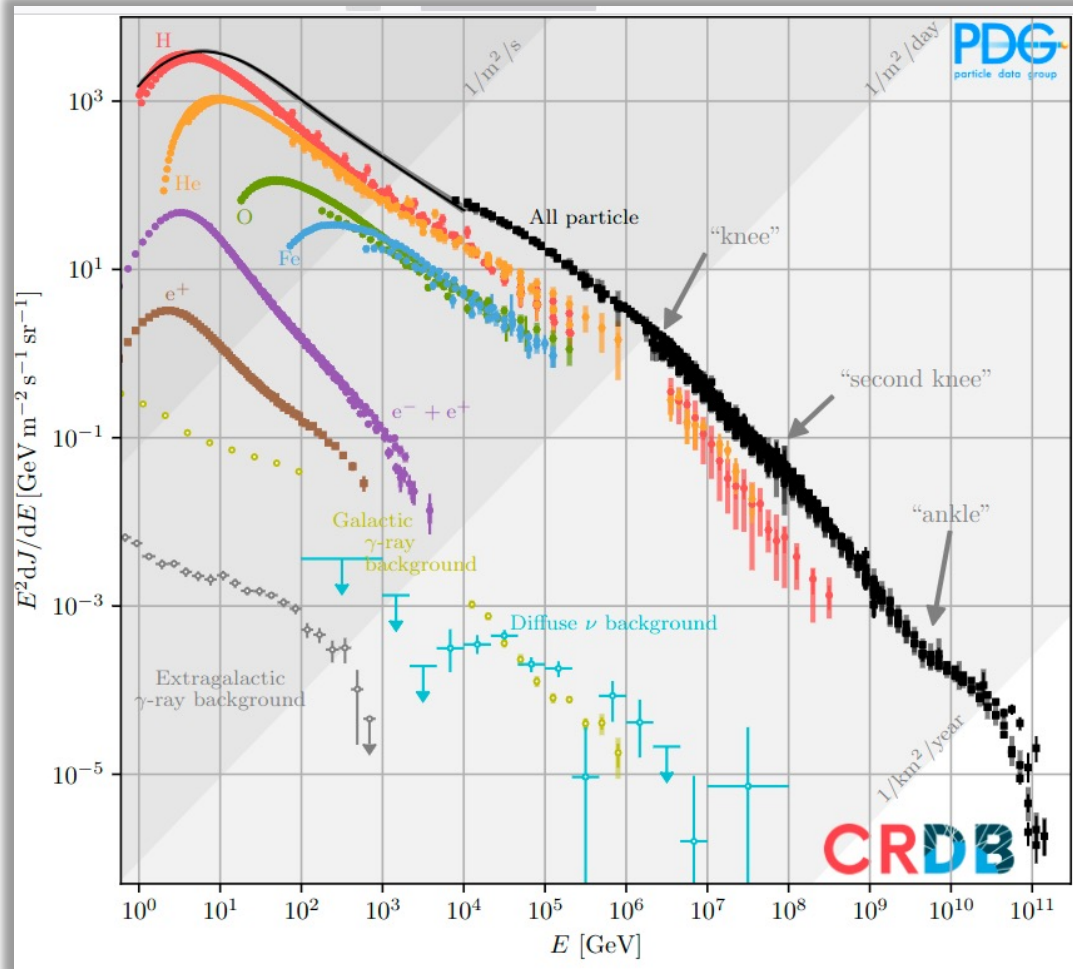
*Special thanks to K.Ohashi, H.Menjo,
and R. Higuchi for the discussion*



Remote talk

What we want to know?

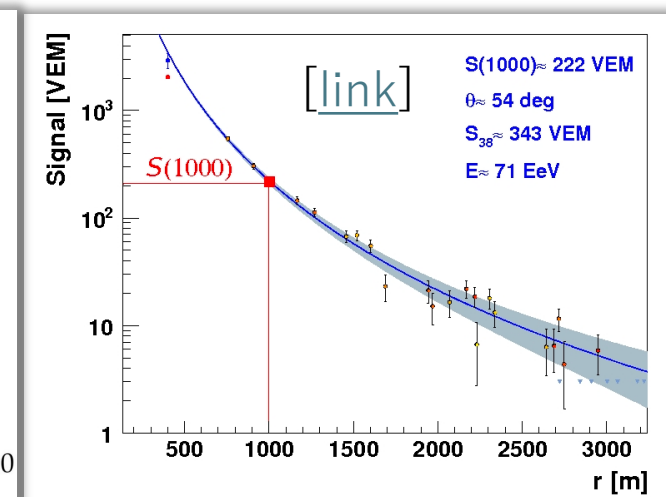
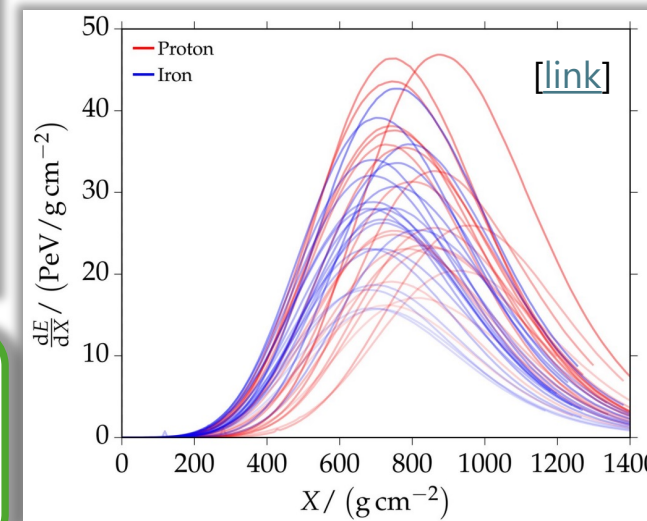
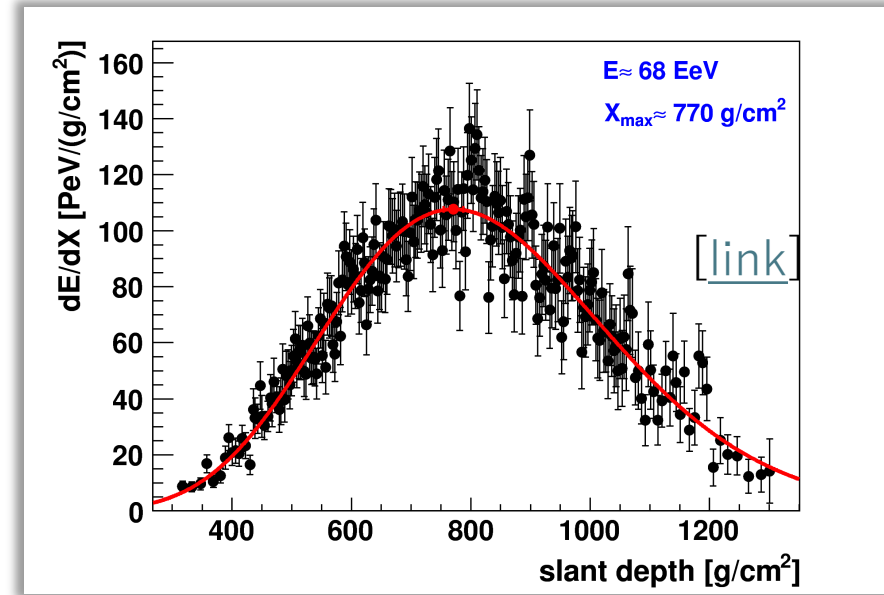
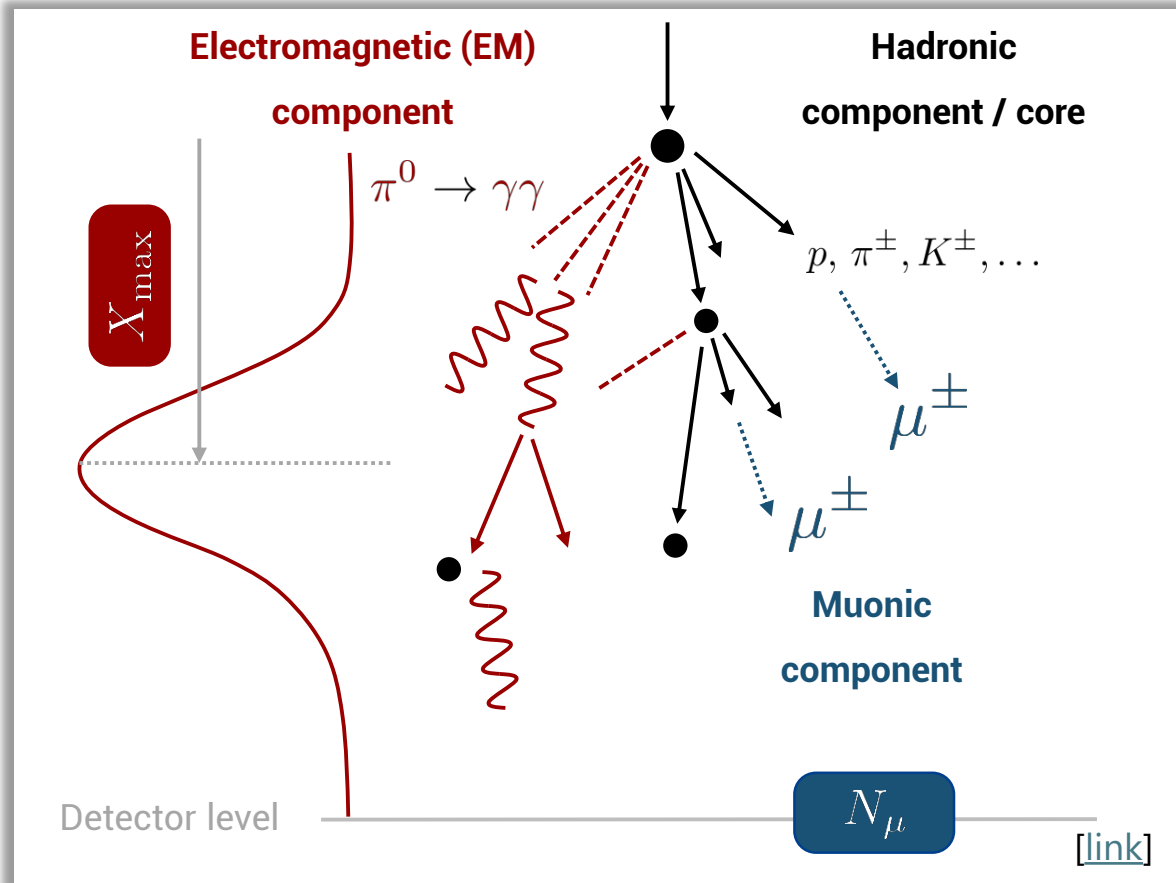
TA Collaboration, Science, 382, 903 (2023).



Dark Matter or
Beyond Standard
Models

Origin and nature of (ultra)-high-energy cosmic rays, acceleration mechanism etc...

Recap: how to measure HE cosmic-ray



Auger

Arrival direction, Energies, depth (mass/charge)

$N_{\max} \propto E,$ $\langle X_{\max} \rangle \propto \ln A,$ $\langle X_{\max} \rangle \propto \ln E$

How to approach the origin of cosmic-ray?

Current

- X_{\max} and N_{μ} average

Cosmic-ray skymap
+ mean mass

Arrival direction, Energies,
depth (mass/charge)

Focus on a specific
direction (e.g. weak
magnetic field)

Current+ α

- Event-by-event?
- Proton selection?

Proton skymap?

Correlation analysis
Proton Astronomy?

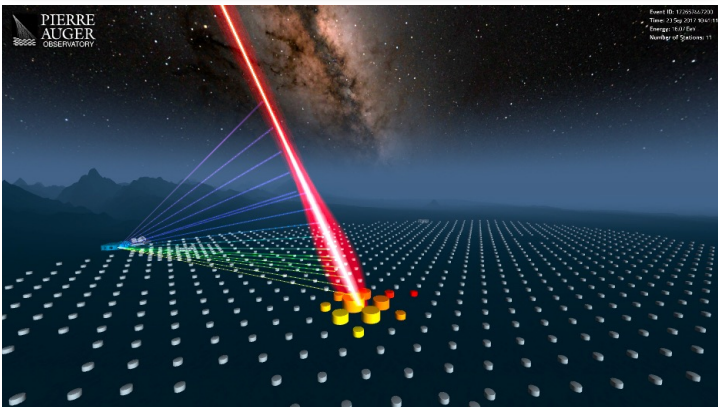
Future

- New measurement
technique ?
- New Observable?

Cosmic-ray Skymap
w/ mass
composition?
(e.g. P/He/CNO/Fe)

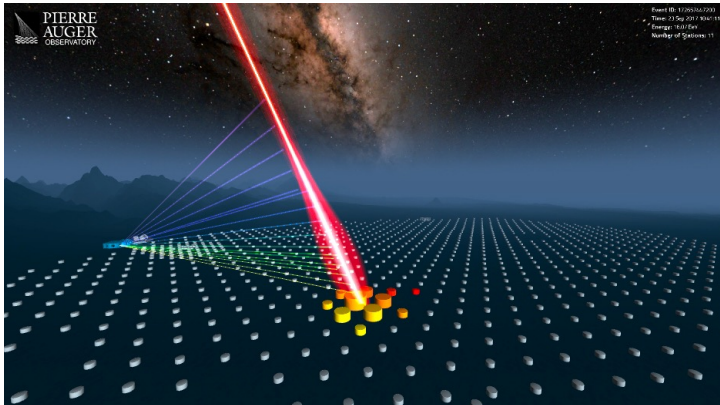
Correlation analysis
w/ sources and HE
CRs?

Derailed discussion in
K.Obashi's talk [\[link\]](#)



How to approach the origin of cosmic-ray?

Arrival direction, Energies,
depth (mass/charge)



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Hadron Interaction matters?

Derailed discussion in
K. Ohashi's talk [\[link\]](#)

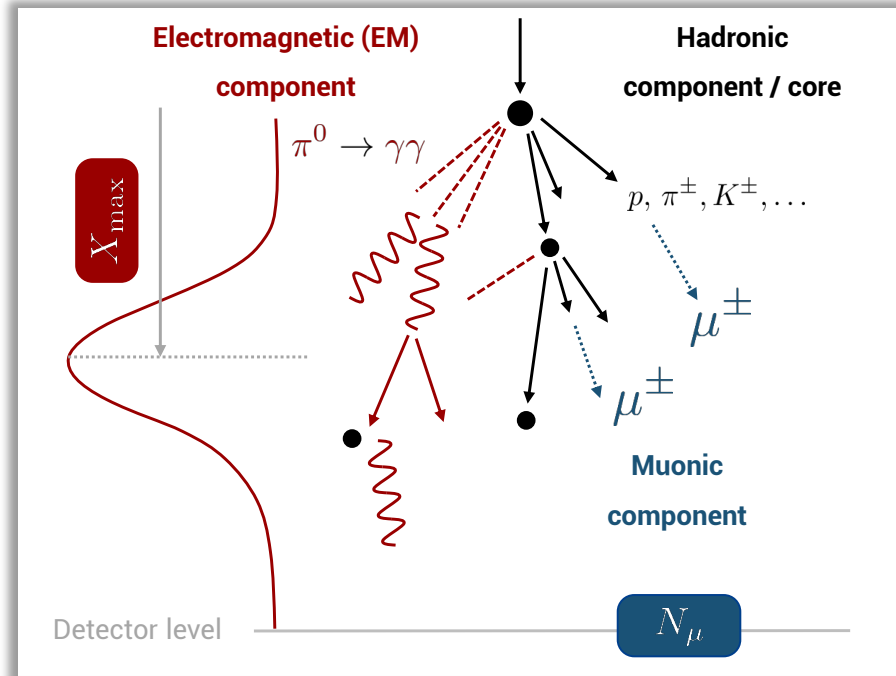
Hadron Shower Anatomy with X_{\max} and N_{μ}

X_{\max}

$$X_{\max} = X_{\text{first. int}} + X_0 \ln\left(\frac{E_0}{\epsilon_c N_{\text{multi}}}\right) / \ln 2$$

Probes the EM cascade

- Sensitive to **first interaction depth**
- Depends on **multiplicity N_{mult}** and **π^0 fraction r**
- Determines how fast energy flows into the EM shower



N_{μ}

$$N_{\mu} = \left(\frac{E_0}{\epsilon_d}\right)^{\beta}, \beta = 1 + \frac{\ln(1-r)}{\ln N_{\text{mult}}}$$

Probes the hadronic cascade

- Muons originate from **charged pion decays**
- Sensitive to **hadronic energy fraction $(1-r)$**
- Depends on **multiplicity and inelasticity**

What matters in hadronic interaction model

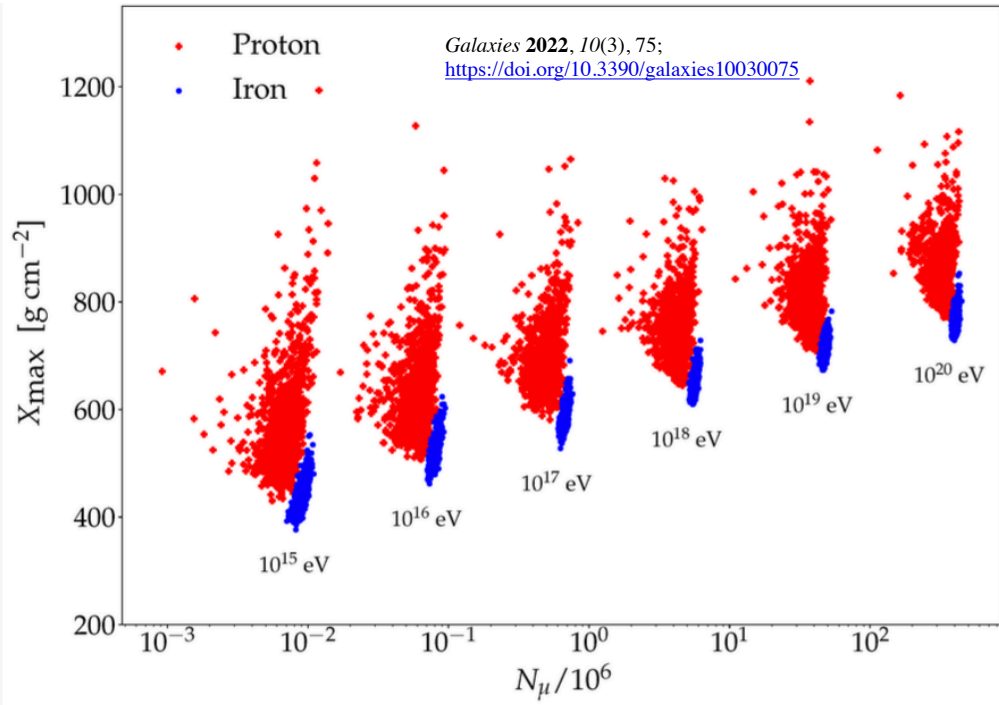
Affecting X_{\max}

- **p-air cross section** → first interaction depth
- **Multiplicity N_{mult}** → shower development speed
- **π^0 fraction r** → energy transfer to EM cascade

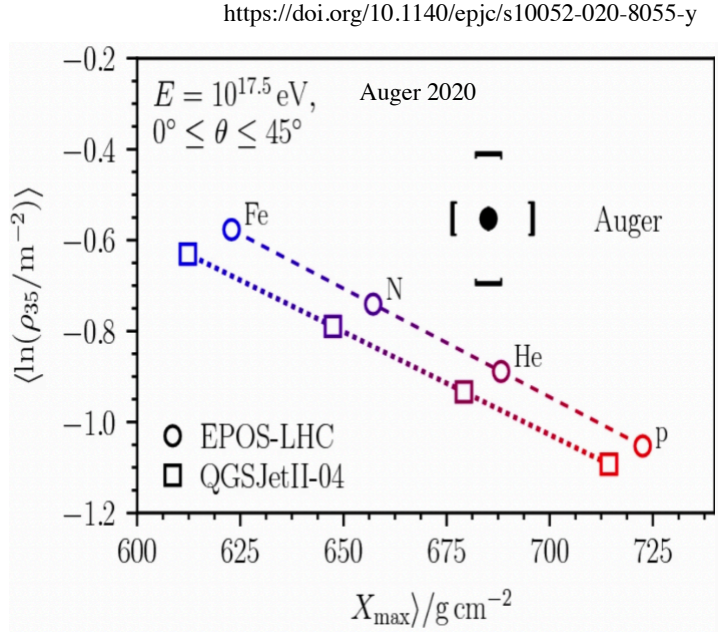
Affecting N_{μ}

- **Multiplicity N_{mult}** → # of hadrons in cascade
- **π^0 fraction r** → hadronic energy fraction $(1-r)$
- **Inelasticity K_{inel}** → energy retained in hadronic core

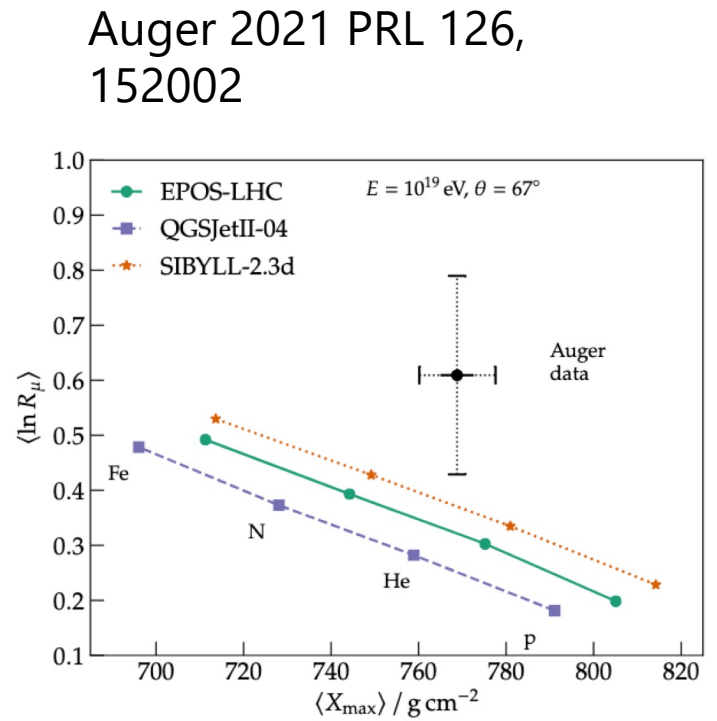
Mass composition with X_{\max} and N_{μ}



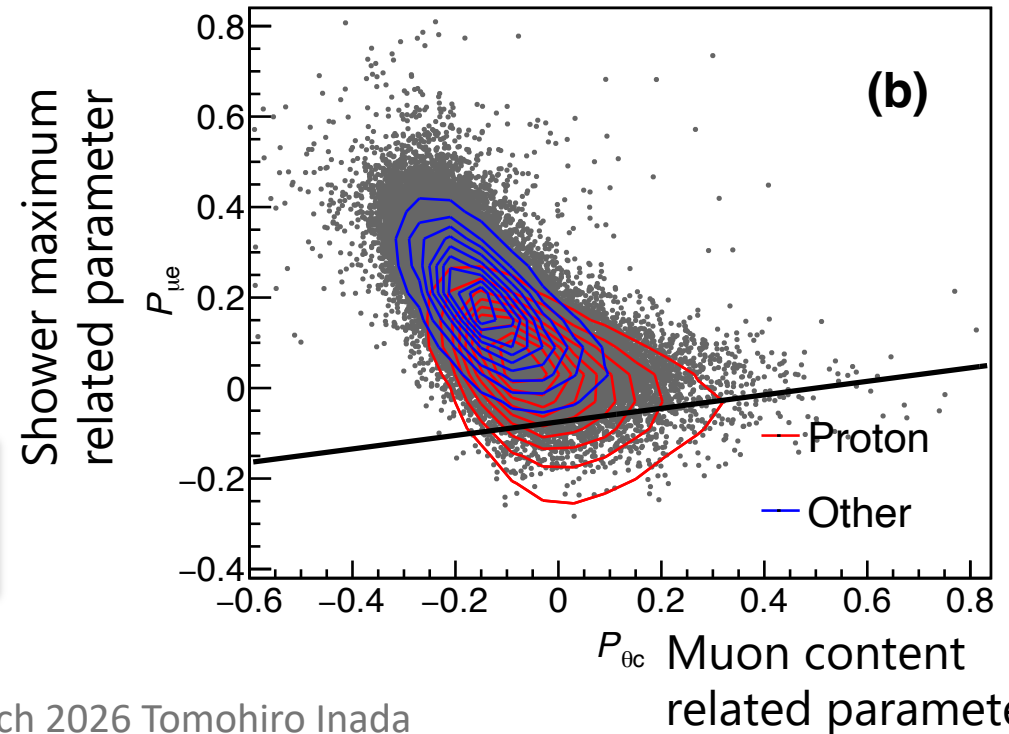
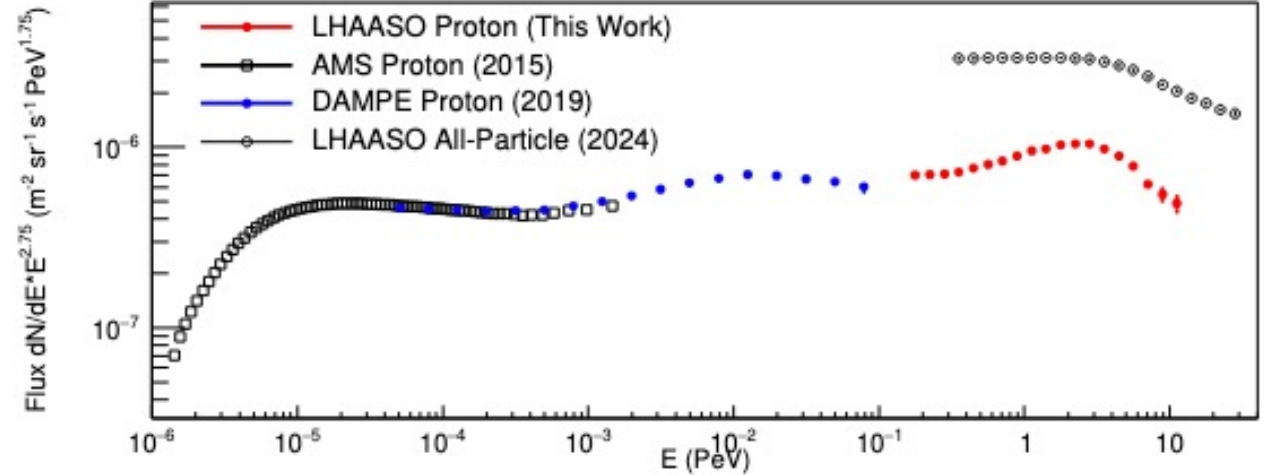
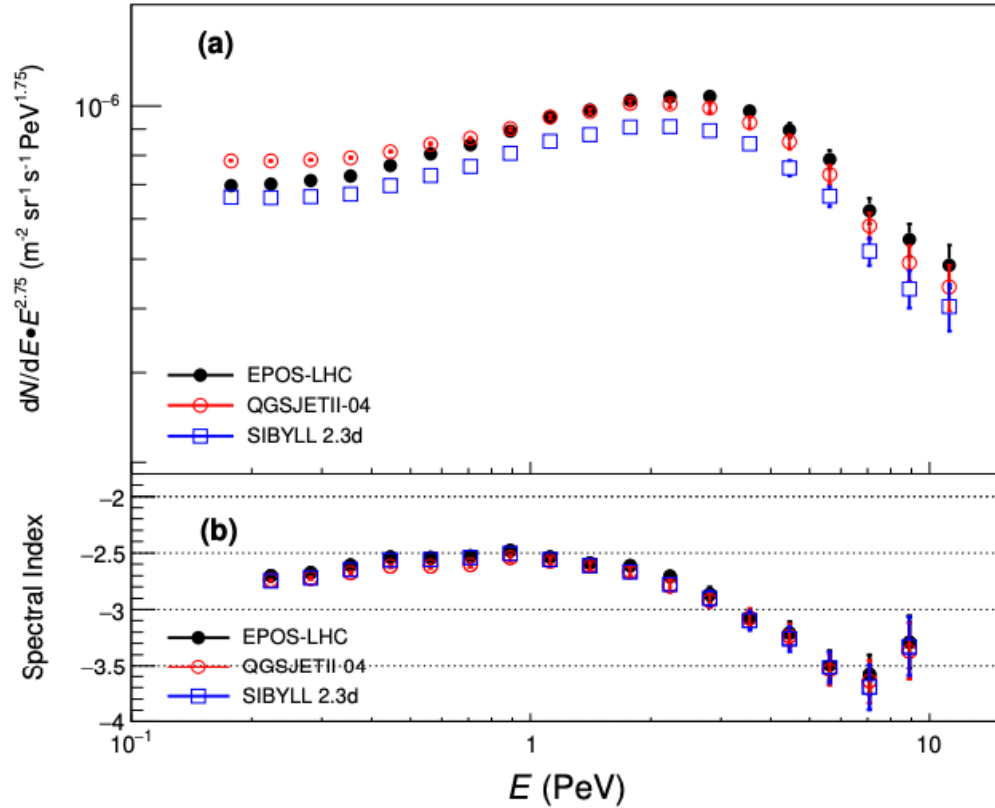
Using X_{\max} and N_{μ} , clearly separated between Proton and Iron



However, $E > 10^{17}$ eV, discrepancy between data and MC exists



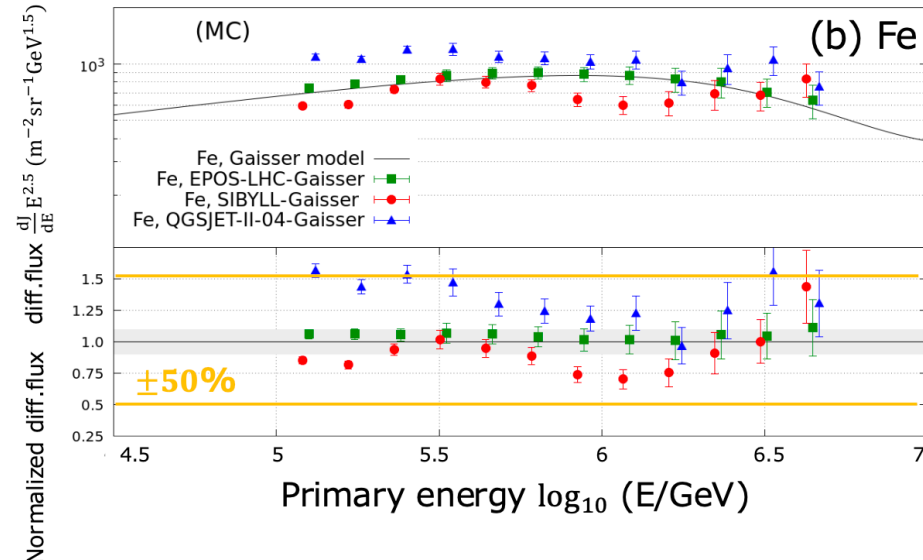
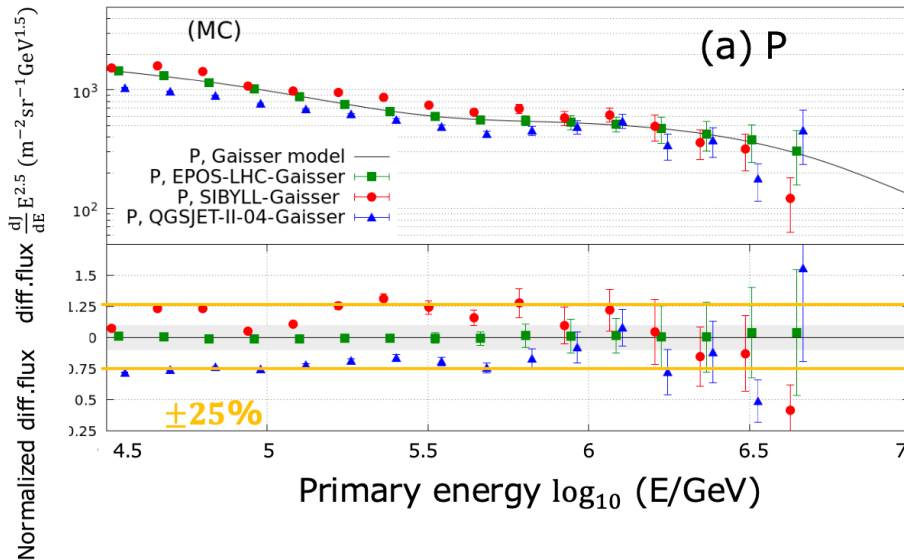
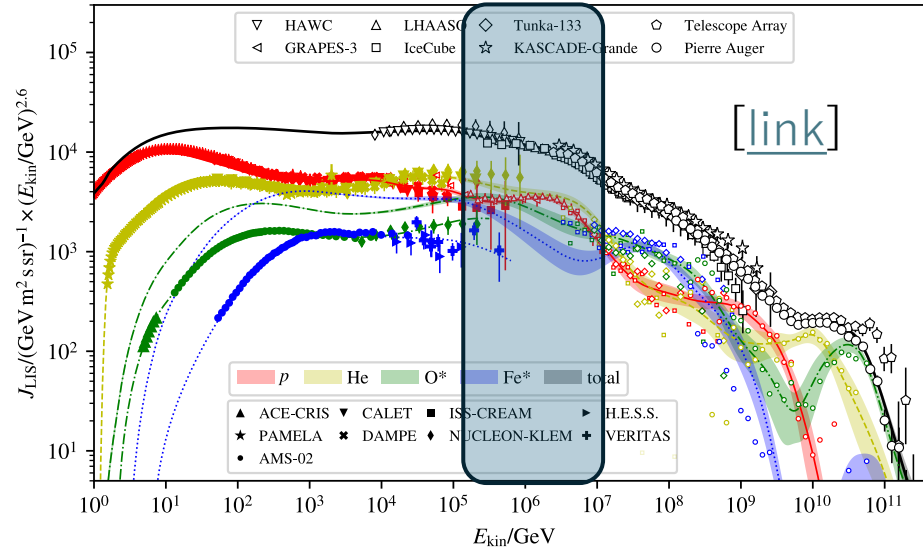
Proton selection?



PeV-scale seems Ok for proton selection?
Then, mass composition study in these energies?

Mass Composition at the PeV-scale

- PeV-scale is still relatively open for mass composition measurement
- Hadron interaction model still affects, but mildly
- Tune models with measurements
- Establish mass composition study?



G Imaizumi et al.,
PTEP 10 (2025)
[\[link\]](#)

The Era of "PeVatron Zoo"

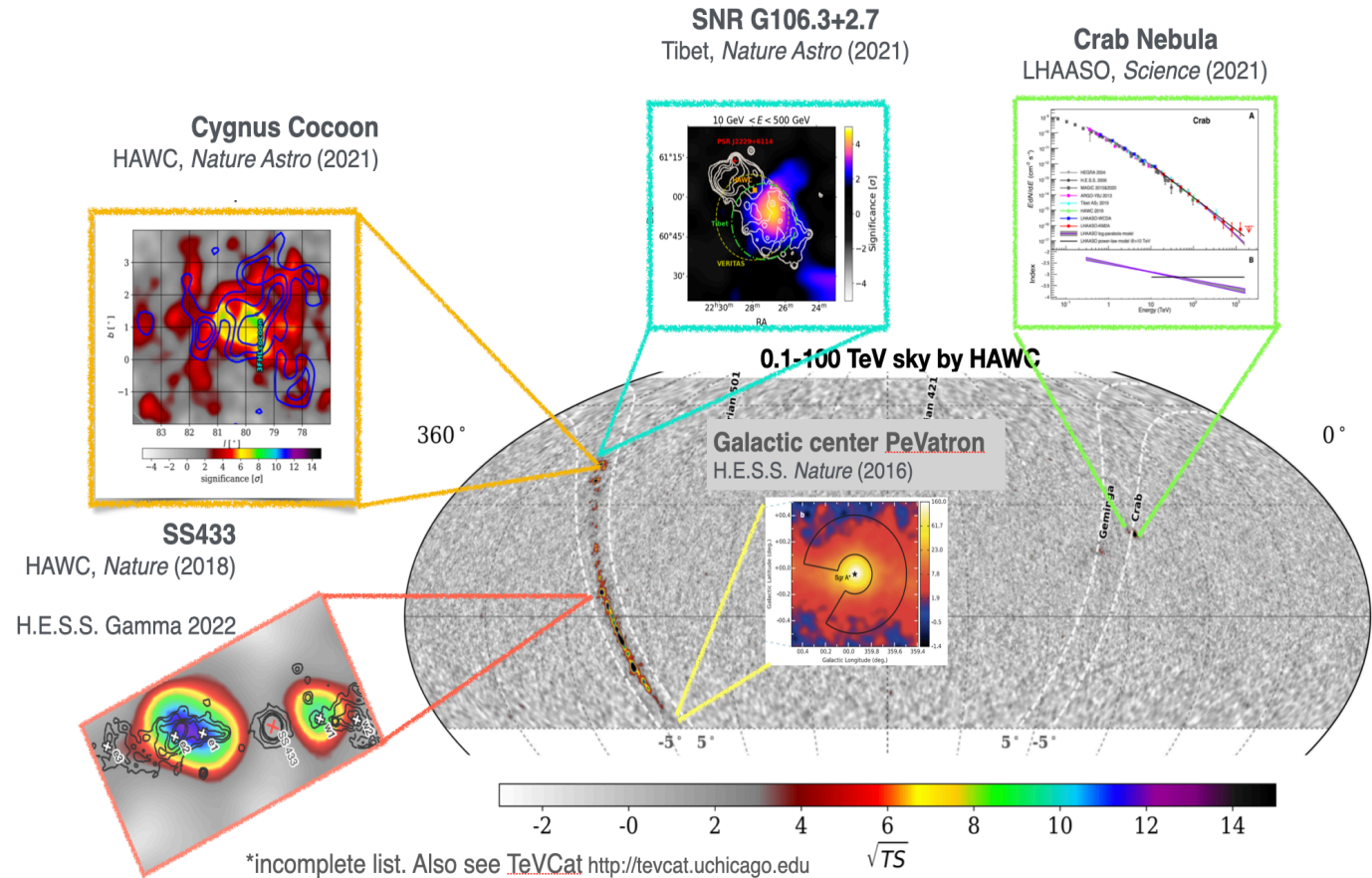
What open physics questions you think may be clarified before 2050

Maybe, source identification for PeVarons

What key problems you expect will still remain unresolved by 2050

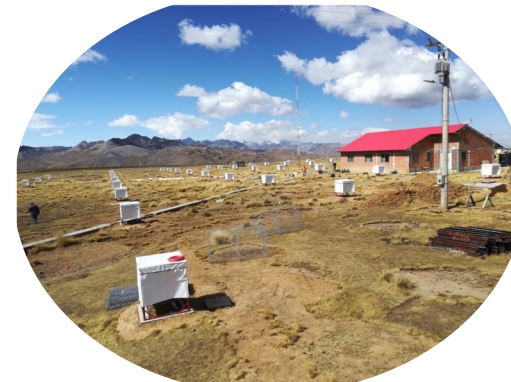
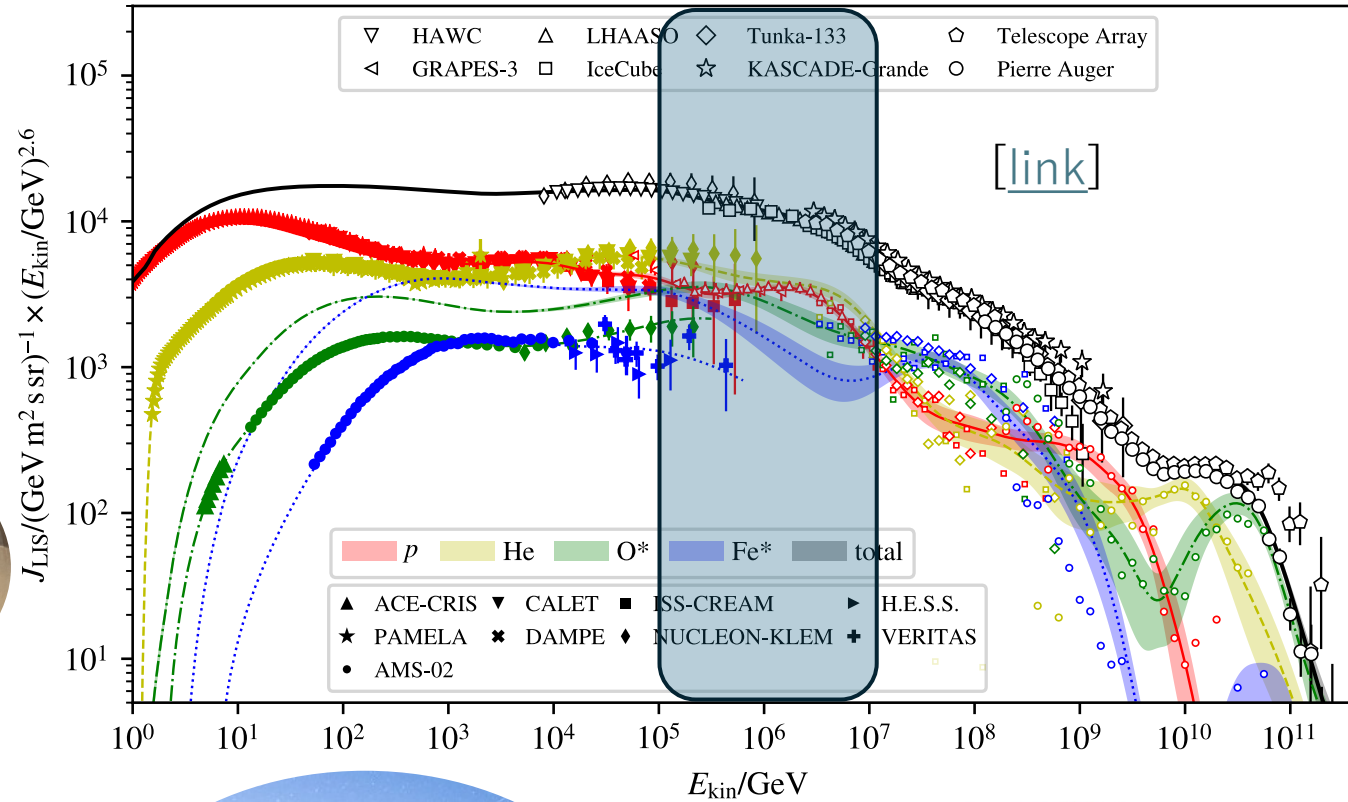
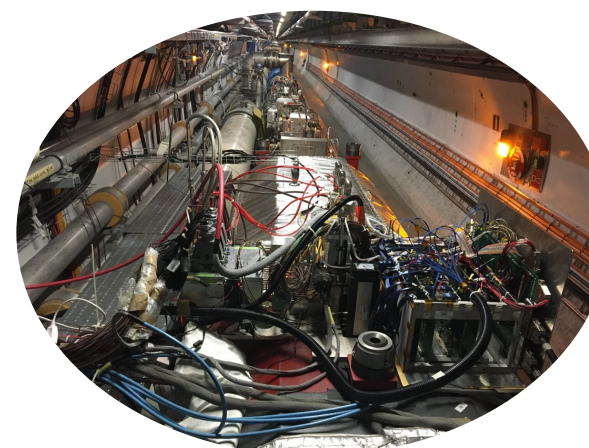
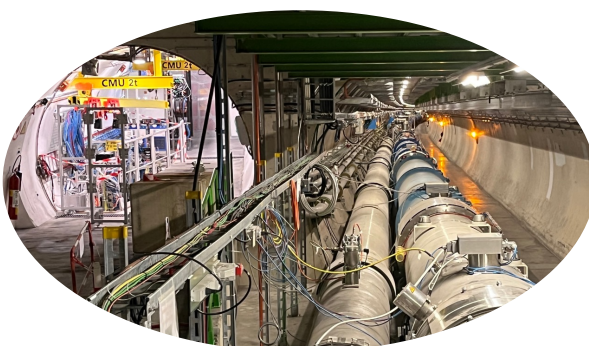
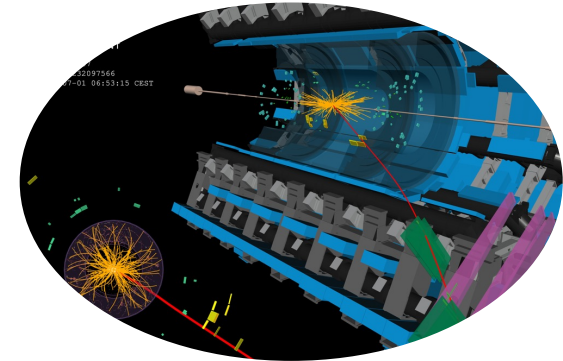
Then, the next question is if they could explain the amount of "Knee's fluxes"
 → The understanding of PeVatron Physics would be important

Multi-messenger, including CR mass composition?

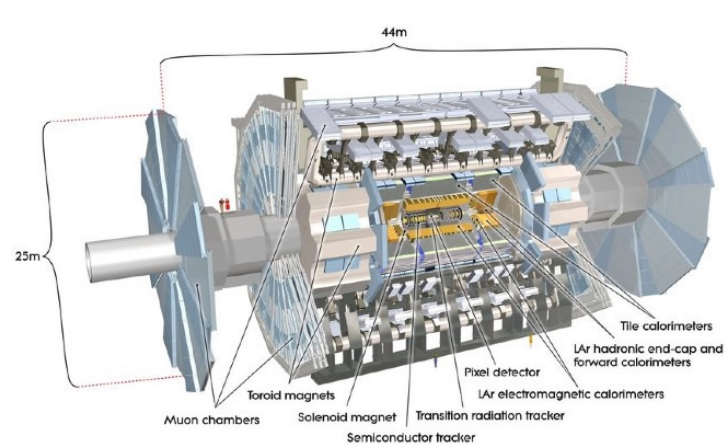


Adapted from K. Fang's slides

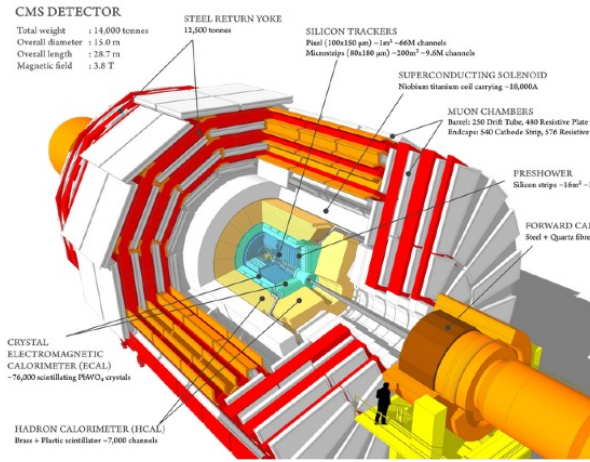
2030's: (sub) PeV-scale is intersection?



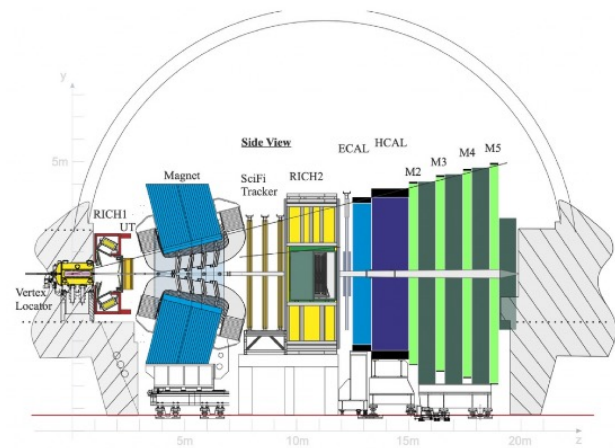
Hadron interaction studies at the LHC



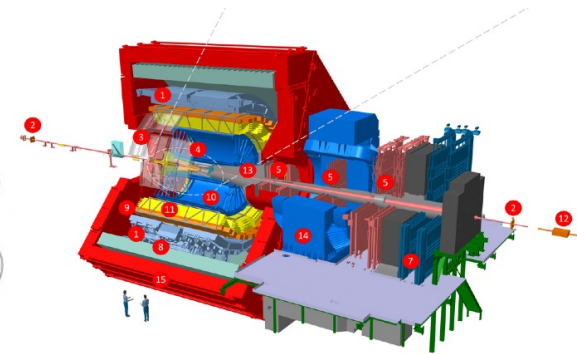
ATLAS [\[link\]](#)



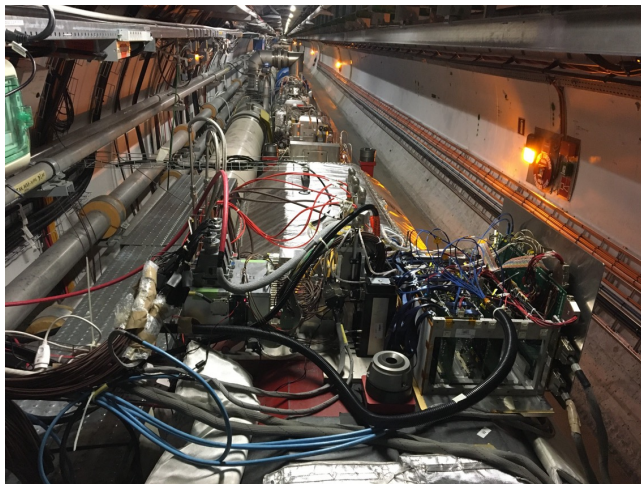
CMS [\[link\]](#)



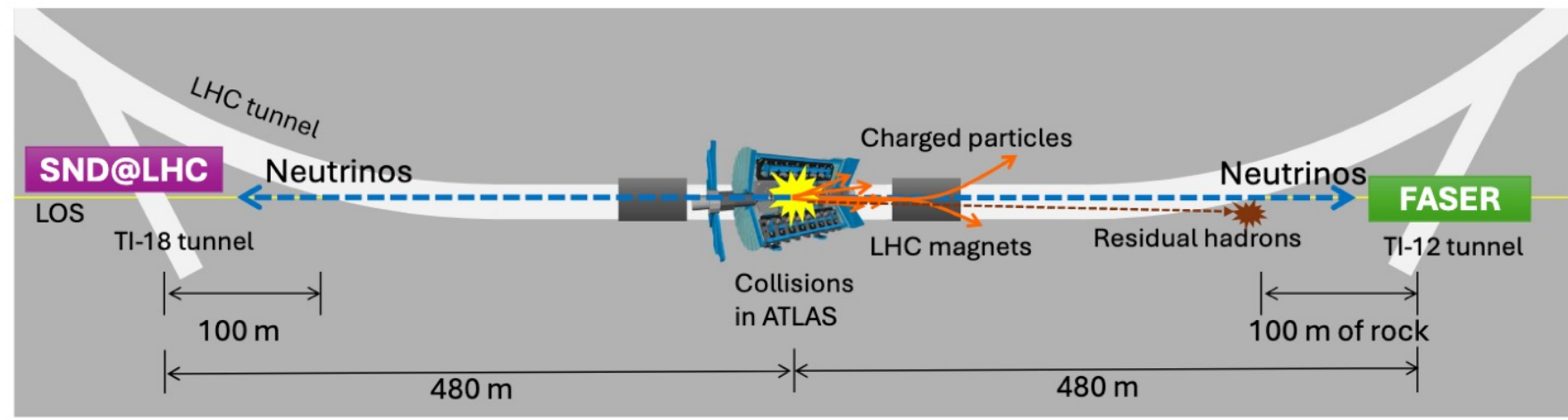
LHCb [\[link\]](#)



ALICE [\[link\]](#)

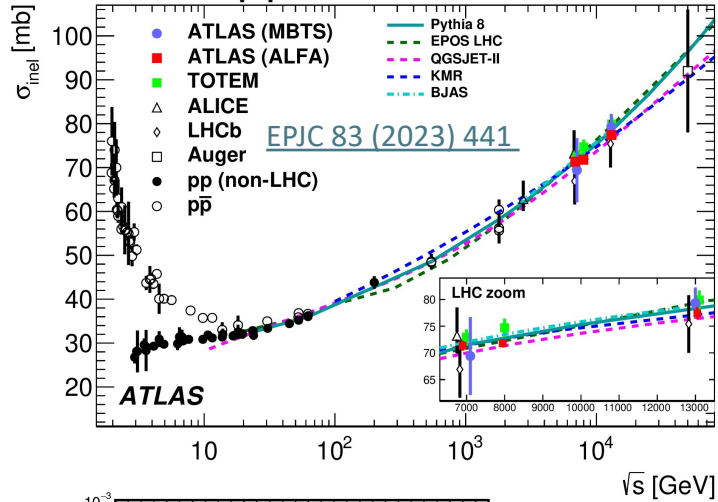


LHCf [\[link\]](#)

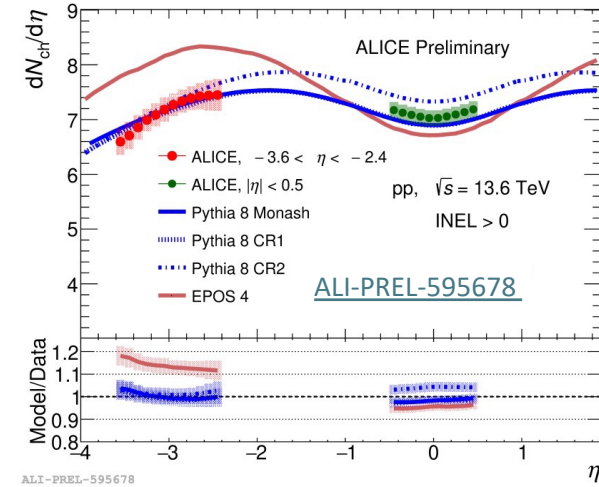
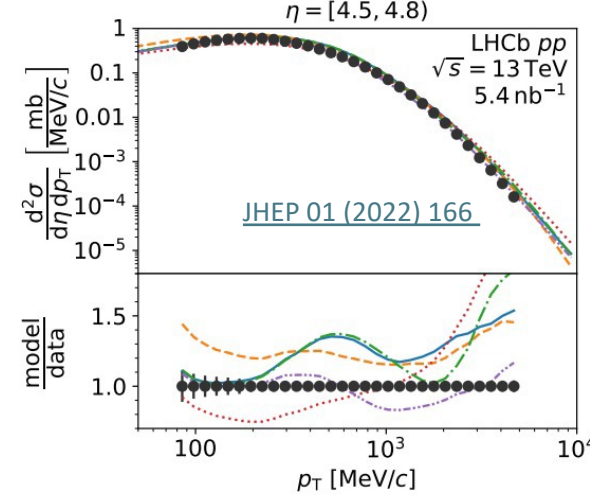
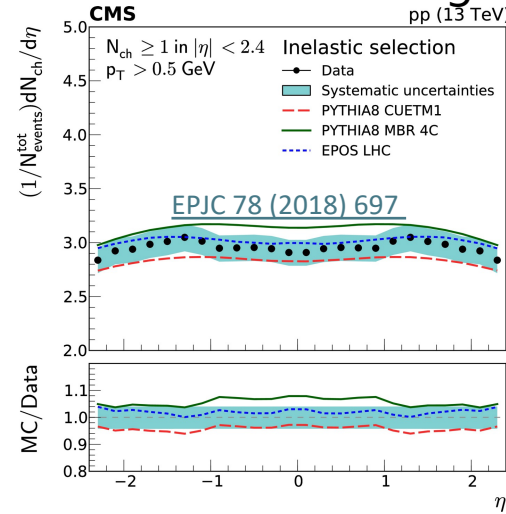


Hadron interaction studies at the LHC

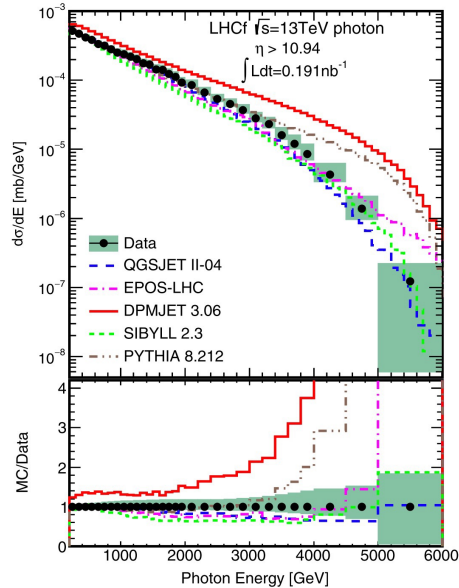
Inelastic pp cross section @ 13 TeV



Charge particle production @ 13 TeV / 13.6 TeV

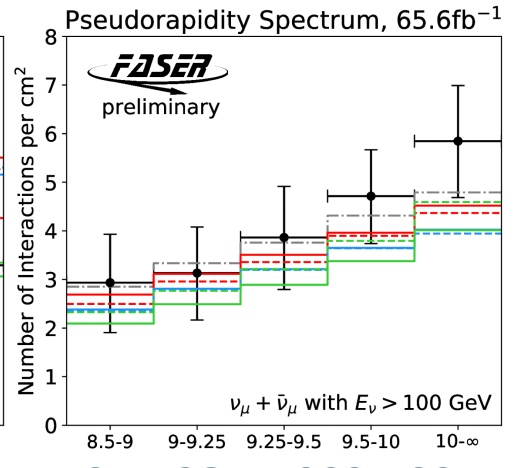
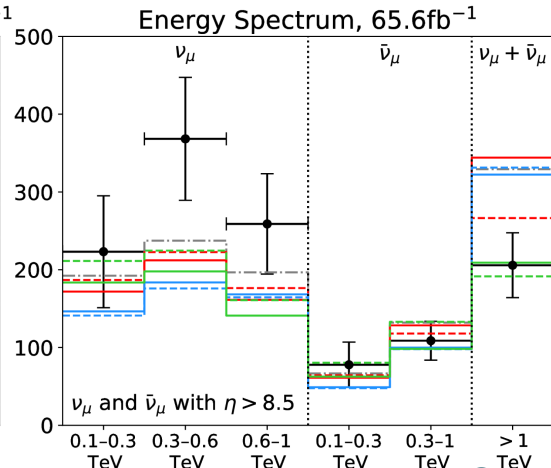
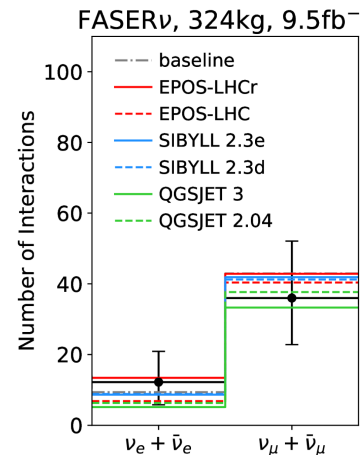


Forward Hadron production @ 13.6 TeV



PLB 780 (2018) 233-239

Forward photon
~ pi^0 production



CERN-FASER-CONF-2025-004

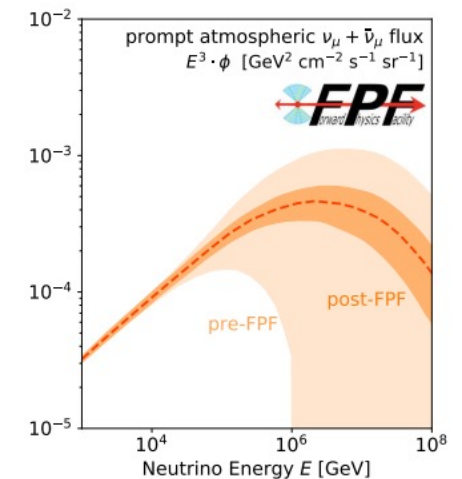
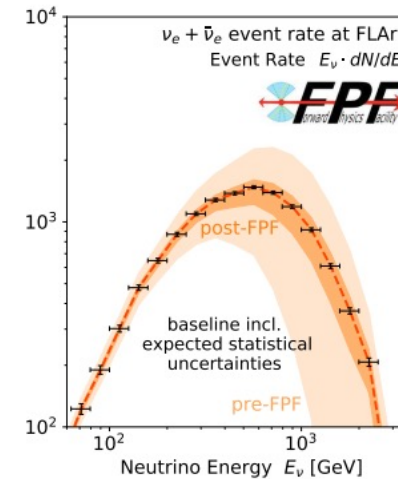
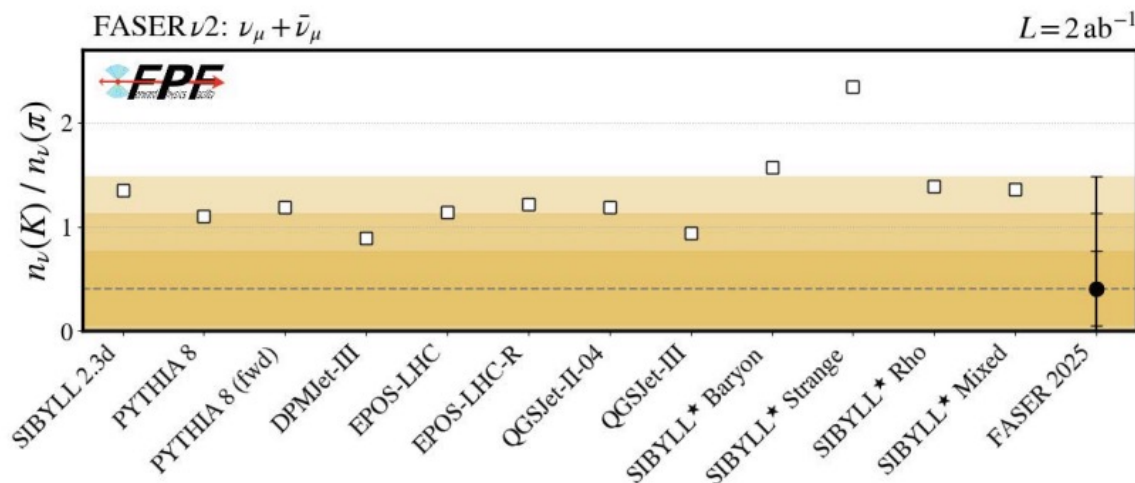
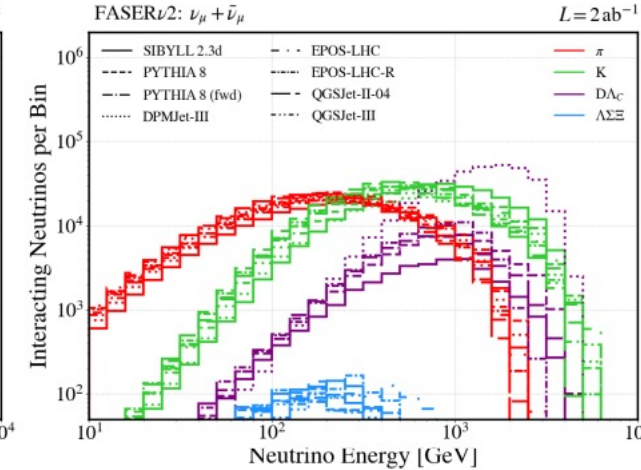
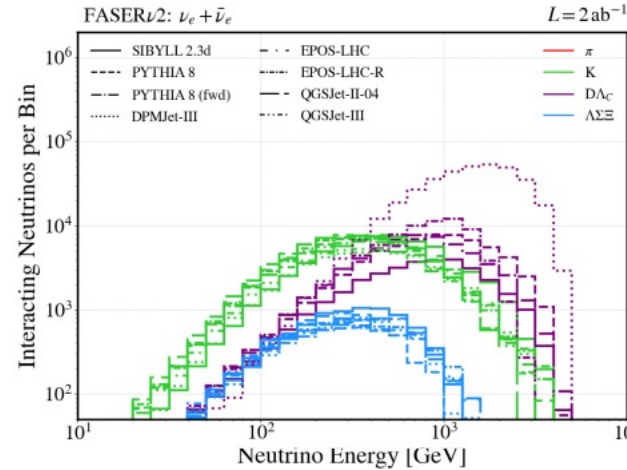
Collider Neutrino Inputs to Hadron Models

Ratio of electron and muon neutrinos is a proxy for the ratio of charged pions and kaons

Electron and muon neutrino fluxes populate different energy regions which will help to disentangle them

One of possible approach “muon excess”

Sensitive to measure a charm component, enable to constrain prompt neutrino for neutrino astronomy inputs



FPF LoI [\[link\]](#)

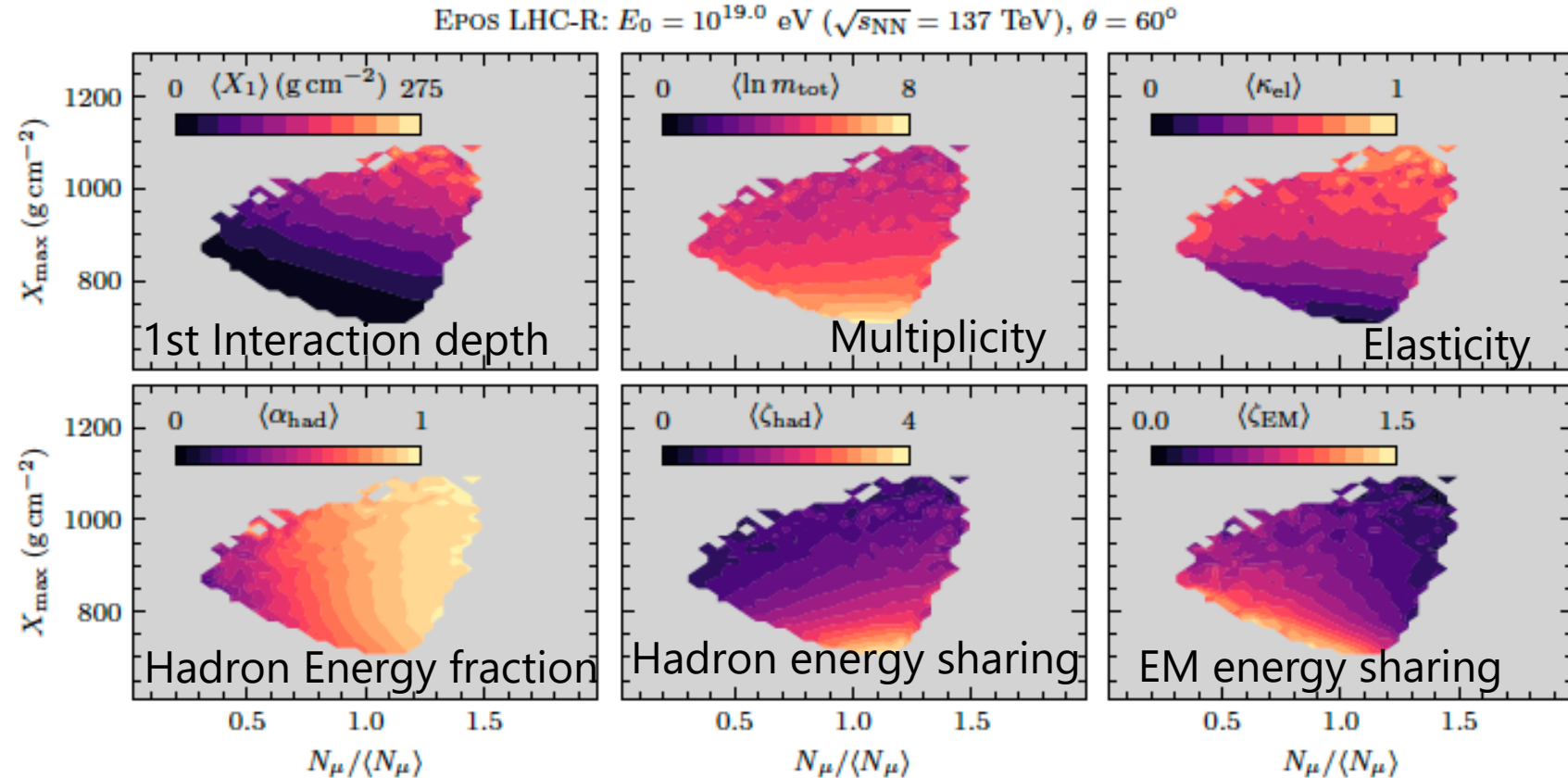
Cosmic-ray to Hadron Physics?

arXiv:2602.22105 [[link](#)]

Air shower observables (X_{\max} , N_{μ})
→ first interaction hadron physics

Enable to approach the forward
hadron production beyond the
LHC (100 PeV)

Different regions of the (X_{\max} , N_{μ})
plane correspond to
different properties of the first
proton–air interaction
→ sensitive to forward particle
production



This work does not directly compare with LHC data,, but provides a framework to interpret cosmic-ray air showers in terms of particle production in the first interaction, complementary to accelerator measurements.

Transition from Galactic to Ex-Galactic?

What open physics questions you think may be clarified before 2050

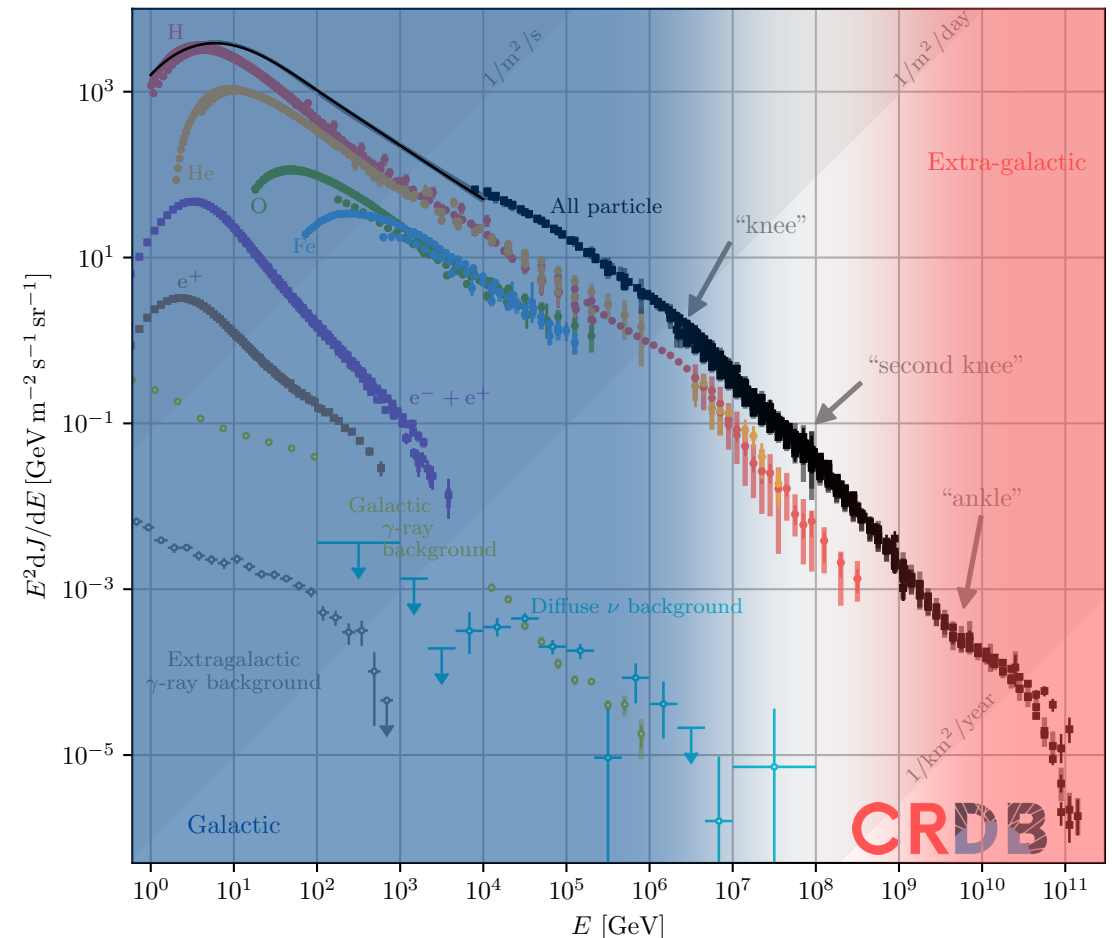
Proton extraction would work with hadron interaction model tuning and other technique improvement e.g. ML-based analysis: Auger PRL 2025 [\[link\]](#)

Hopefully, some mass composition studies are done.

Tuned hadron interaction model for UHECR study

What key problems you expect will still remain unresolved by 2050

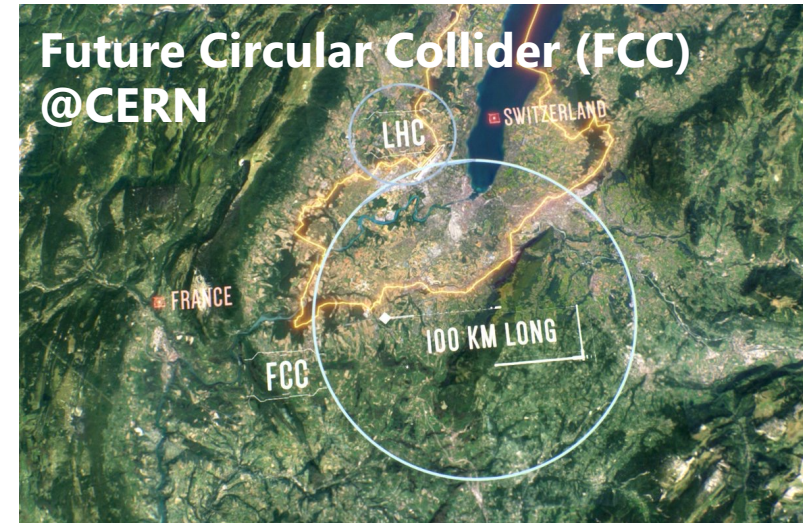
Maybe still, need to know the UHECR origin???



Details should be discussed in Keitaro and Max's talk

Cosmic-ray as a unique laboratory for fundamental physics

Your personal perspective and aspirations looking toward 2050



- **HL-LHC < 2040's and EIC ~ 2040's (?)**
No hadron collider for a few decades after 2040s – 50s.
The FCC-ee is a Higgs factory

Turns out we need to finish measurements for hadron interaction model before then (High priority!!)
(FASER upgrade by Menjo-san)

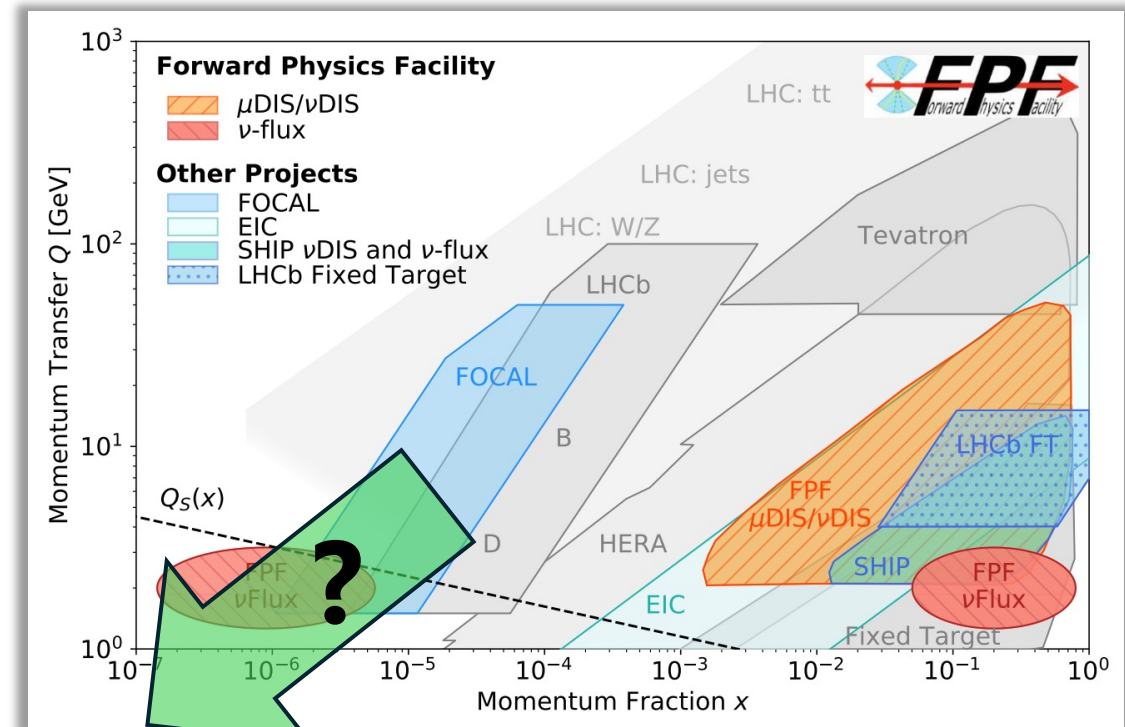
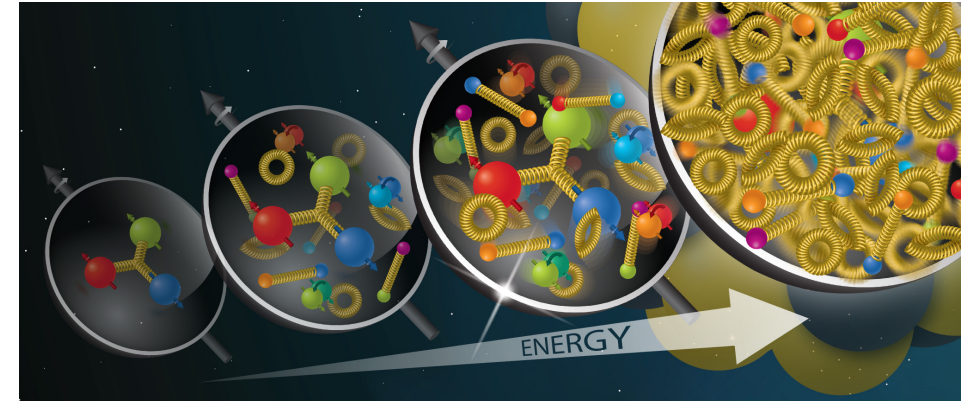
The tool for the direct measurement in the energy frontier (>TeV) might be only cosmic-ray

High-Energy Particle Interaction study with Cosmic-ray

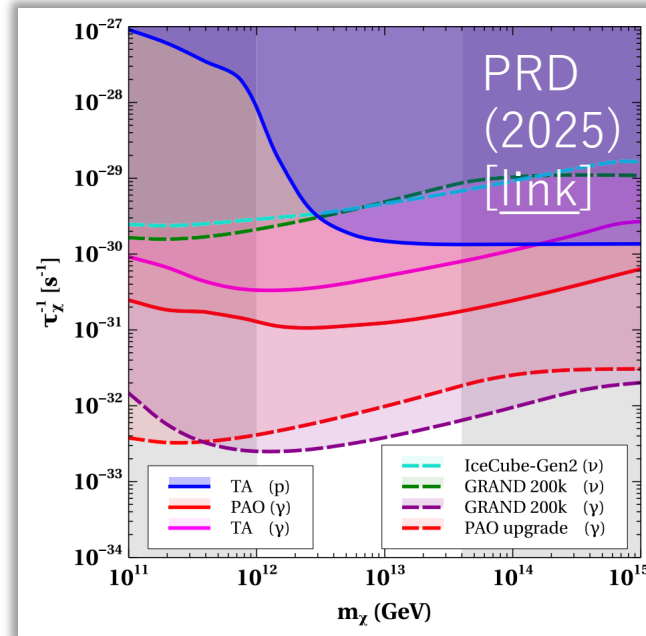
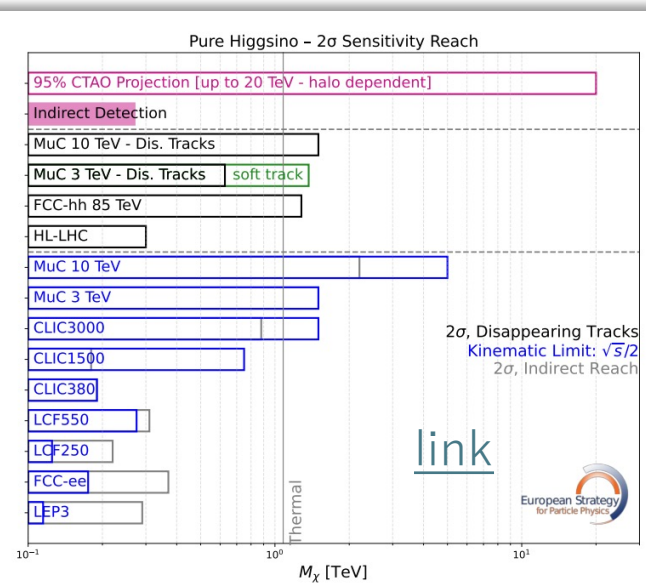
- **Precision Cosmic-ray measurement enables** Very small-x and dense QCD (gluon) frontier, hinting the origin of proton mass

Searches Dark matter or New Physics Beyond Standard Model in the energy frontier (like pion or muon discovery in the early time)

Would be good to cooperate with neighboring field



FPF Lol [\[link\]](#)



Summary

1. Cosmic-ray physics requires understanding of hadronic interactions

- Air-shower observables (X_{\max} , N_{μ}) depend on hadron interaction properties
- Current tension between **data and interaction models**

2. LHC and collider neutrinos provide key inputs

- Forward particle production measurements
- Neutrino measurements constrain **π/K production and muon excess**

3. Cosmic rays themselves probe hadron physics beyond accelerators

- Air showers access **> 100 PeV interactions**
- Complementary to accelerator experiments

4. Toward the 2030–2050 era

- Improve **proton extraction and mass composition**
- Tune hadron interaction models
- Enable light hadron **astronomy, and extend heavier nuclei for the future as well as PeVatron studies**



Take-home message

Cosmic rays are not only astrophysical messengers but also a unique laboratory for high-energy particle interactions.