The 5th International Symposium on Cosmic Rays and Astrophysics (ISCRA-2025)

The systematics of the theoretical studies of the muon excess in UHECR

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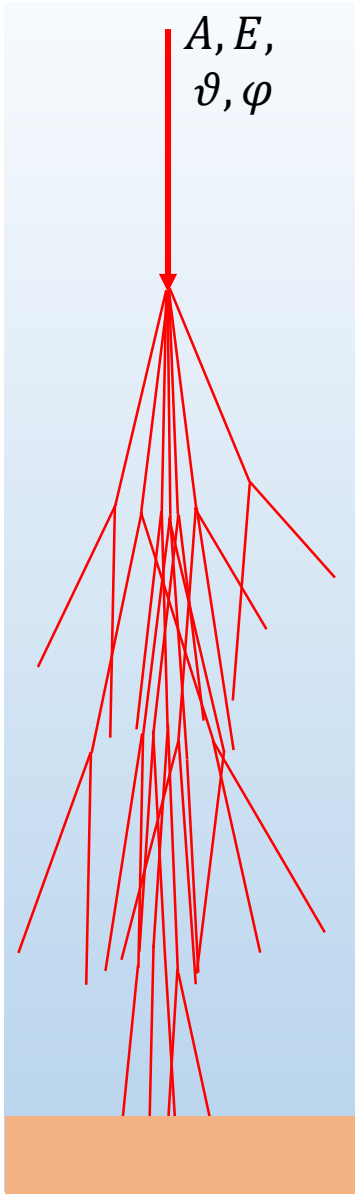
Moscow, 24-26 June 2025

Unknown functions in UHECR physics



PCR input

Mass composition
$f_1(E) \leftrightarrow \langle \ln A \rangle (E)$

Energy spectrum
$f_2(E) \equiv dN/dE\ (E)$

EAS development simulation

Hadronic interaction model (high energies)

$f_3(E) \equiv (\sigma, N_{\mathrm{ch}}, p_\perp, \dots)(E)$

+

VHE electromagnetic model?

$f_1(E), f_2(E)$ and $f_3(E)$ are, de-facto, unknown functions!

Output

Particle list: N_μ, N_e, E_μ

Longitudinal profile, lateral profile

Cherenkov, fluorescence, radio …

EAS measurements (for details see Dembinski et al., DOI: https://doi.org/10.1051/epjconf/201921002004)

EM component measurements

Note: strongly influenced by hadronic cascade model

Measurement	Agree with models
Proton-air cross-section (PAO, TA)	+
Longitudinal shape (CC) + $X_{\max}$	+*
Moments of $X_{\max}$-distribution (PAO)	+
Lateral density profile (IceCube)	+/-**
Attenuation with zenith angle (TA, KASCADE-Grande)	+

* Some unphysical second moments for QGSJET-II-04
** SIBYLL-2.1 and EPOS LHC inconsistent with combined measurements with muons

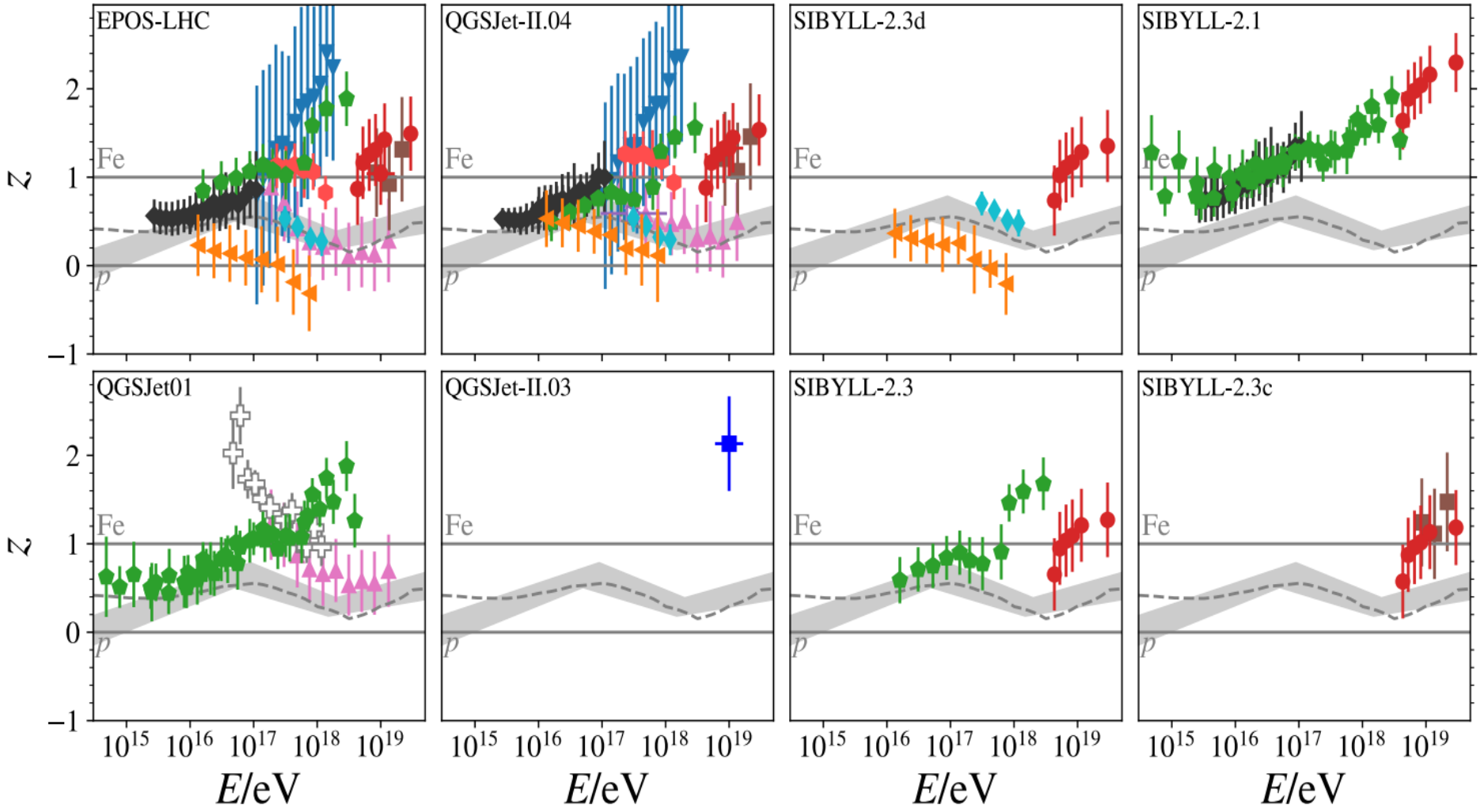
Muon measurements

Measurement	Agree with models
Lateral density (WHISP Collaboration)	-
Production depth (height) (PAO, KASCADE-Grande)	-/+
Attenuation with zenith angle (KASCADE-Grande)	-
Multiplicity in muon bundles (ALICE, DECOR)	-*
Mean muon energy in bundles (NEVOD-DECOR)	-
Atmospheric flux of TeV muons (IceCube)	+/-
Lateral separation of TeV muons (IceCube)	-**
Rise-time of shower front (PAO)	-

* The relative abundance is well reproduced by QGSJET-II-04
** Partial agreement only for SIBYLL-2.1

The Muon Puzzle: current status

From J.C. Arteaga, ISVHECRI-2024, WHISP's combined muon analysis



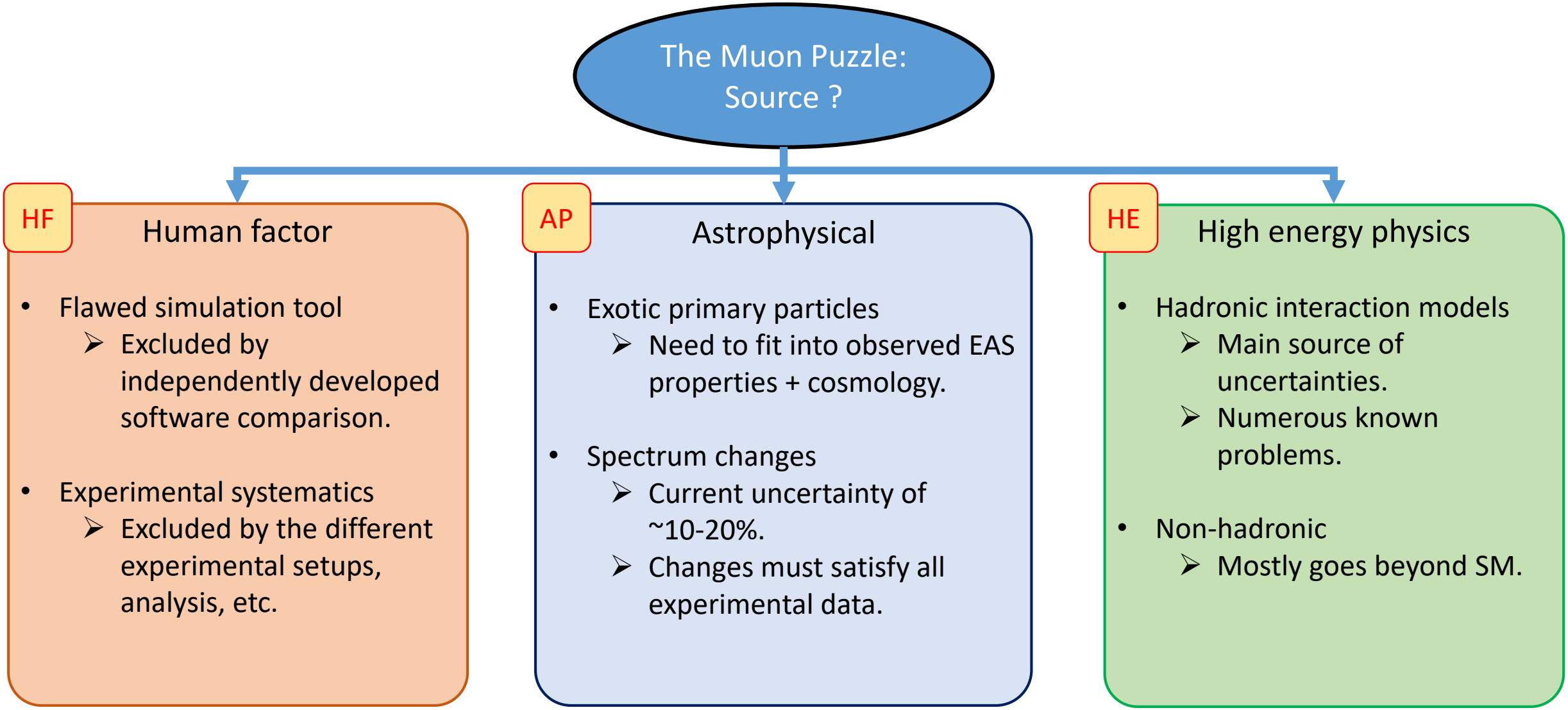
$$z = \frac{\ln N_\mu^{\mathrm{det}} - \ln N_\mu^{\mathrm{sim,p}}}{\ln N_\mu^{\mathrm{sim,Fe}} - \ln N_\mu^{\mathrm{sim,p}}}$$

- Auger FD+SD
- Auger UMD+SD
- Telescope Array
- IceCube
- Yakutsk
- NEVOD-DECOR
- SUGAR
- KASCADE-Grande
- EAS-MSU[a]
- AGASA
- HiRes-MIA[a]
- Haverah Park
- Expected from $X_{\max}$
- GSF

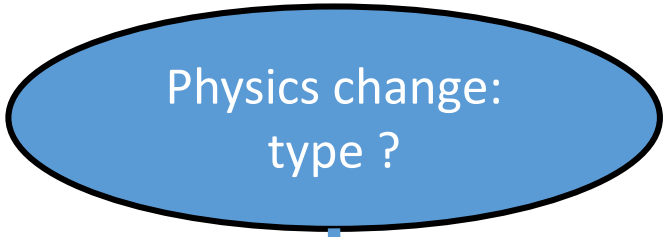
[a] not energy-scale corrected

- After energy cross-calibration

The hypotheses classification: by source



The hypotheses classification: by physics change type



PT Known physics: tuning

- Cross-sections, PDF, diffraction, …
  - Non-linear effects for Pomeron, saturation, MPI, NNLO PDF, etc.
- Change global properties: $X_{\max}$, $N_\mu + N_e$, LDF, …
- Small impact on exclusive particle production.

NE Known physics: New effects

- Collective effects + EPM
  - QGP, QGC, glasma, string shoving, rope hadronization, color reconnection, etc.
- String fragmentation
  - Isospin asymmetry, heavy flavor, spin physics, angular momentum, etc.
- Certain type of particle enhancement (baryon, strangeness, vector meson, heavy flavors)

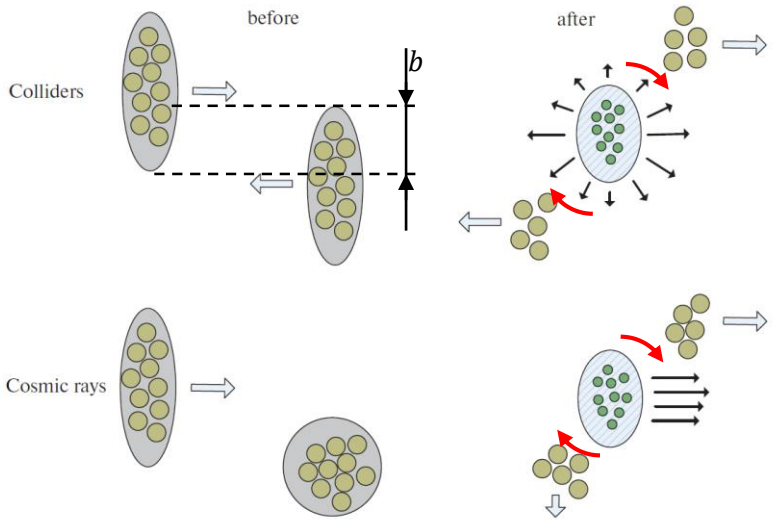
NP New physics (Beyond SM)

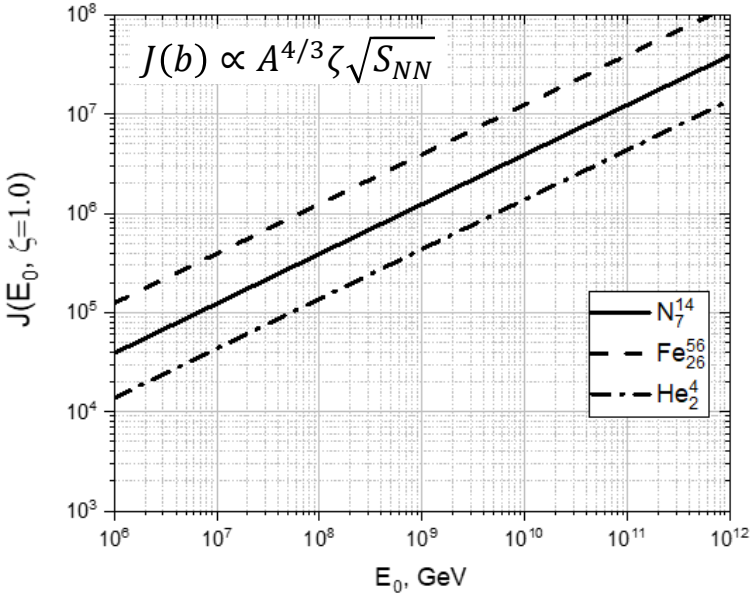
- New matter
  - Dark matter, stranglets, etc.
- Symmetries restoration / breaking
- Super exotics
  - Supersymmetry, mirror dimensions, extra dimensions / dimension reduction, Branes, Domain walls, etc.
- How to produce a (relatively) normal EAS?

Light particle retention (1/2): High-Rotation Quark-Gluon Matter (HR-QGM) model

HE NE

A.A. Petrukhin, 2012, DOI: 10.1016/j.nima.2011.12.074





- High-energy non-central nuclei collisions produce a QGP fireball with huge angular momentum
- In the assumption of the system elasticity and continuous lifespan, a centrifugal barrier for particle of mass m appears:

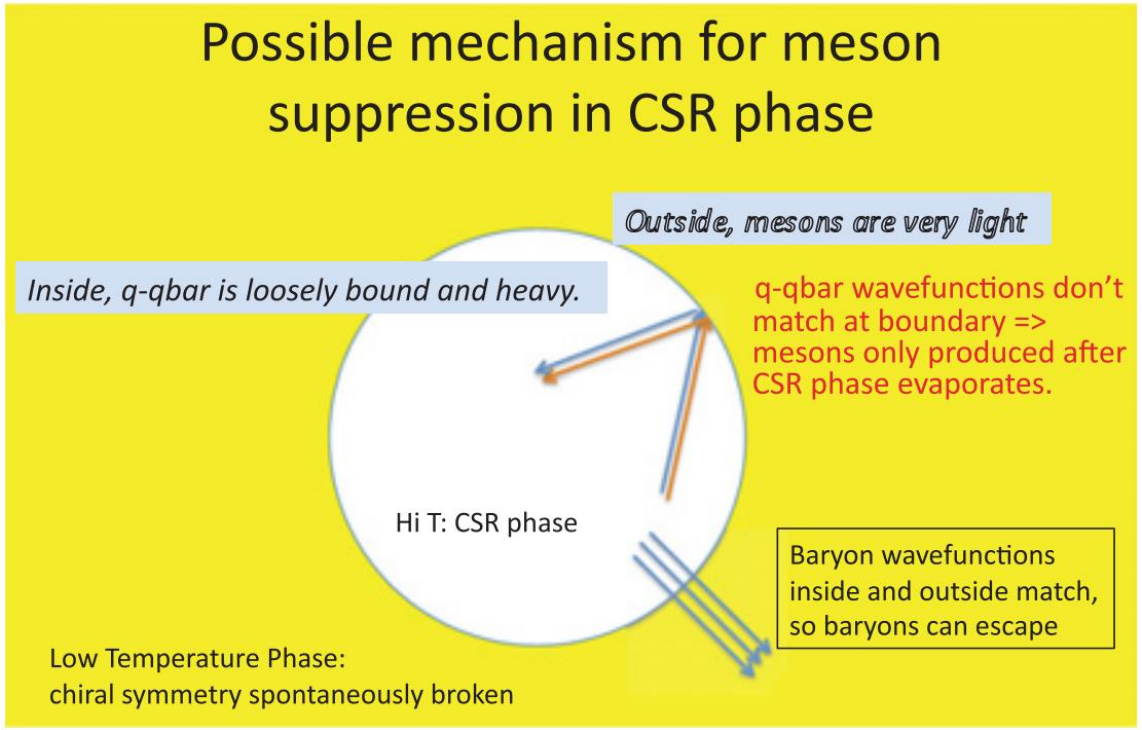
$$V_{\mathrm{cb}} = \frac{J(J+1)}{2mb^2}.$$

- The centrifugal barrier prevents lightest hadrons to escape the QGP fireball.
- Targeted scenario – strange mesons and baryons enhancement.

➢ Hard to distinguish from regular QGP scenario
➢ Does it affect particle production at freeze-out?
➢ Contribution in the case of light CR systems?
➢ Should be well observed in PbPb at the LHC

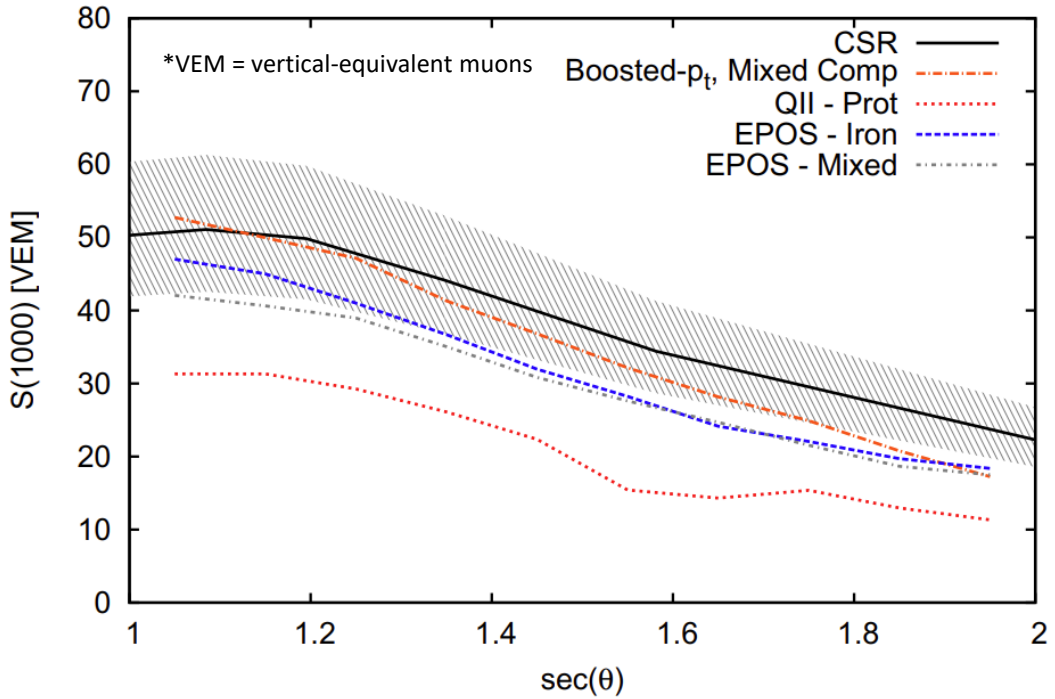
Light particle retention (2/2): Chiral Symmetry Restoration (CSR) model

HE NP



- Based on the Nambu-Goldstone CSR model
- When chiral symmetry is broken, pions (pseudo-Goldstone bosons) with $m_\pi < \Lambda_{\mathrm{QCD}} \approx 200$ MeV can be produced
- Nuclei collisions in UHECR create a very high temperature phase -> chiral symmetry could be restored

G.R. Farrar and J.D. Allen, 2013, DOI: 10.1051/epjconf/20135307007

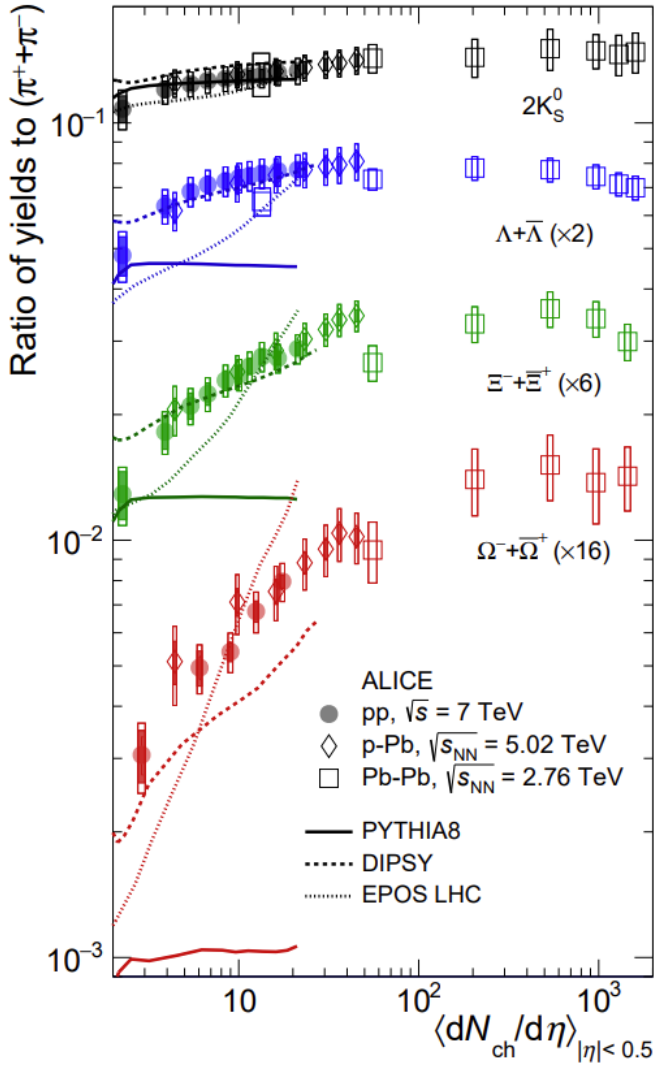


- With CSR light mesons (with $m \lesssim 500$ MeV) cannot be produced -> light pion suppression
- No rigorous calculations of the effect
  - Initial conditions?
  - Impact?
  - Why not observed in PbPb at LHC?

Quark-gluon plasma in small systems: EPOS LHC model and core-corona approach

by K. Werner and T. Pierog

HE NE

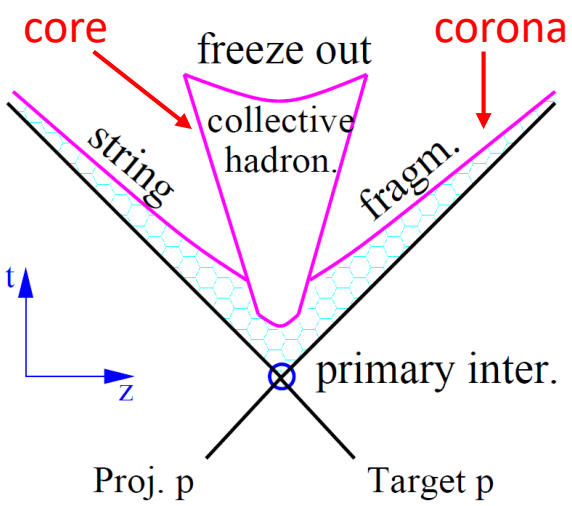


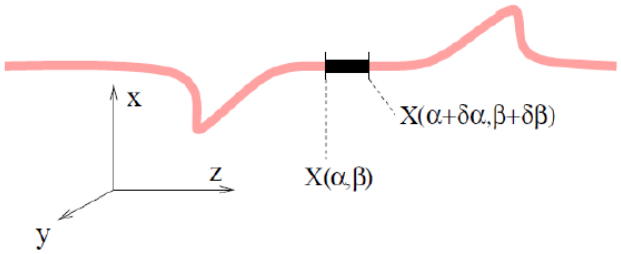
ALICE Collaboration, 2017, DOI: 10.1038/nphys4111

Strangeness enhancement in pp collisions: QGP in small systems?

$s\bar{s}$-pair mass is of QCD phase transition temperature: $m_{s\bar{s}} \approx 200$ MeV

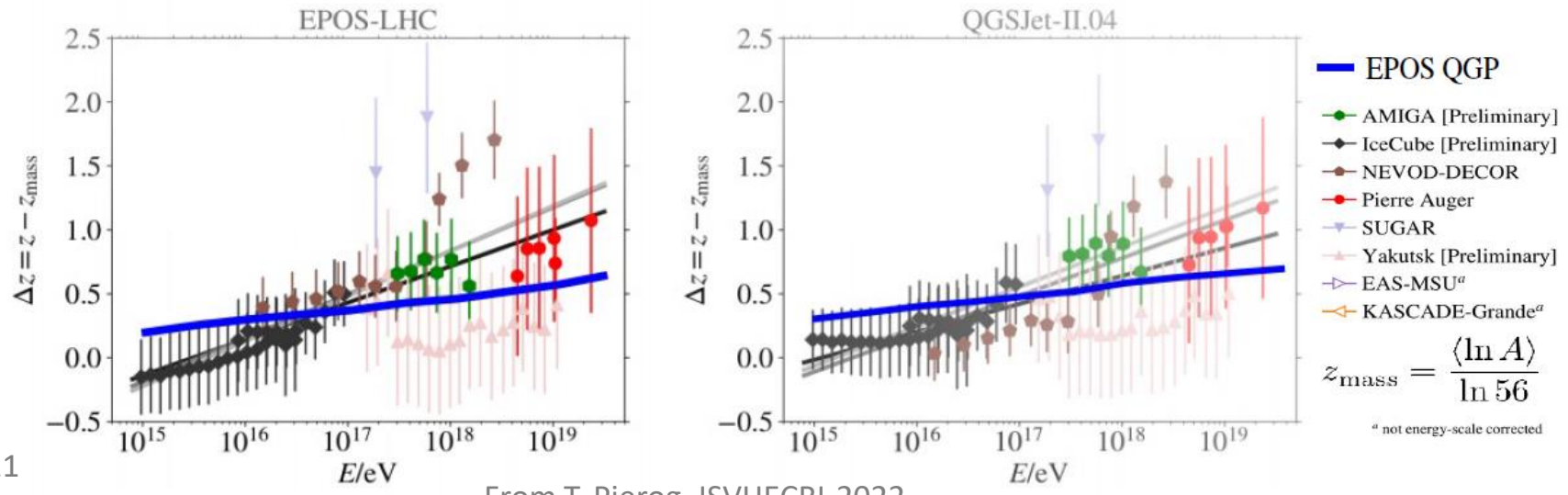
- Enhanced $s\bar{s}$ production in QGP phase
- Suppress light particles.





The core-corona approach: fuse string pieces in dense regions into QGP "core", fragment strings in low-density region normally – "corona"

Both mechanisms are universal – but the contribution is parameterized

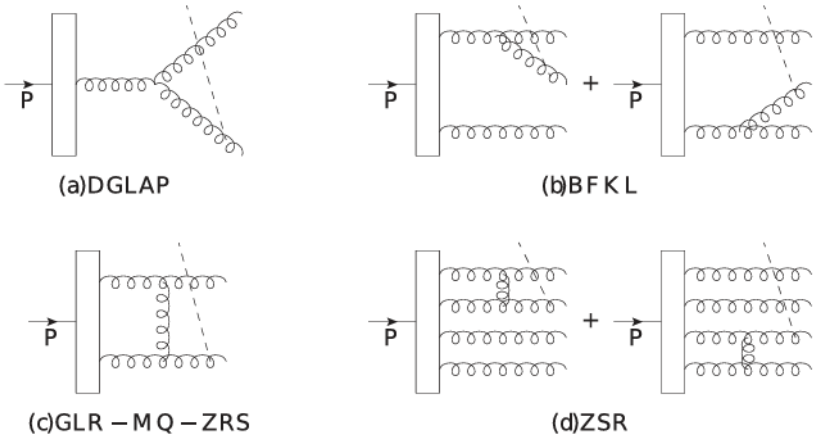


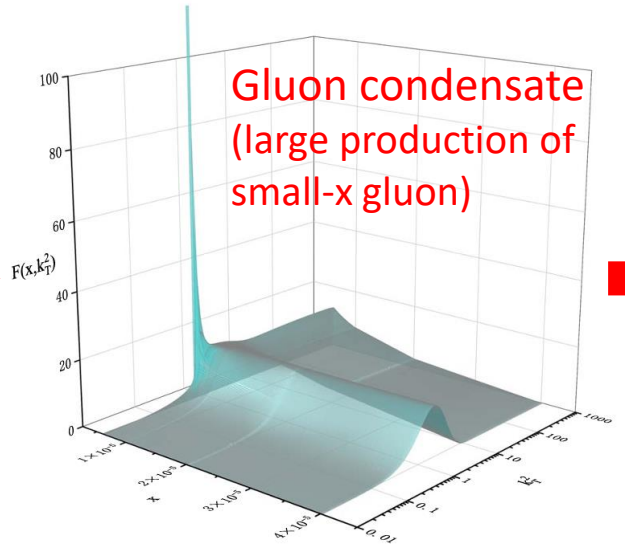
From T. Pierog, ISVHECRI-2022

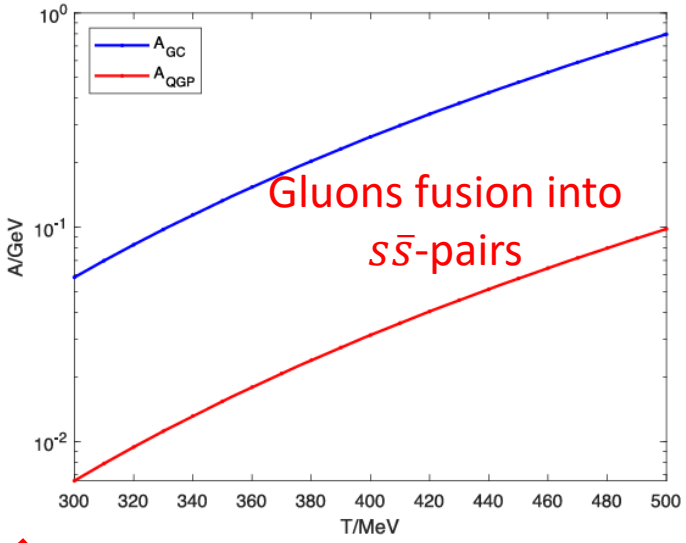
Color Glass Condensate (CGC) and Glasma models

HE NE

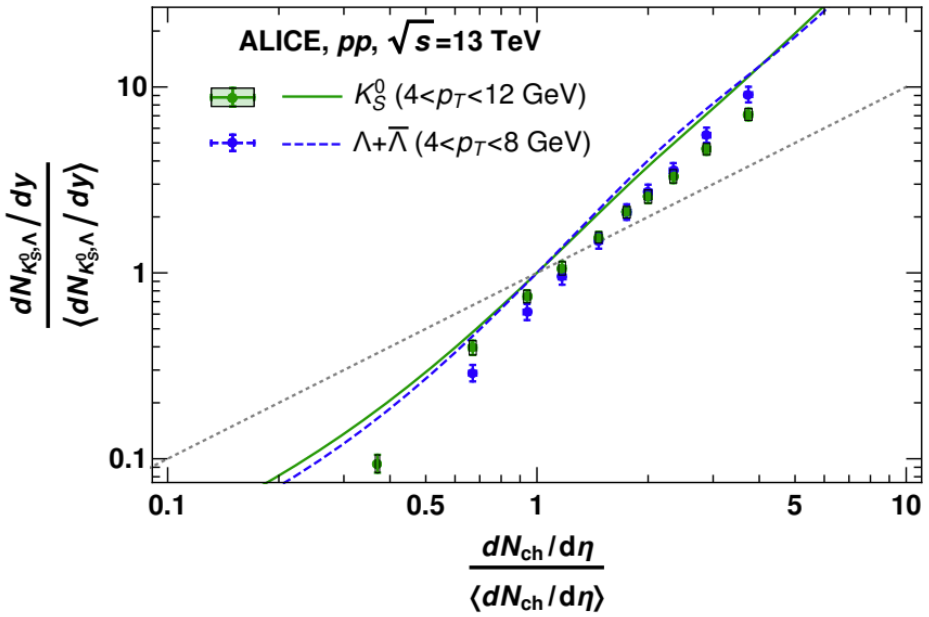
Next-order gluon PDF calculation in comparison to standard DGLAP



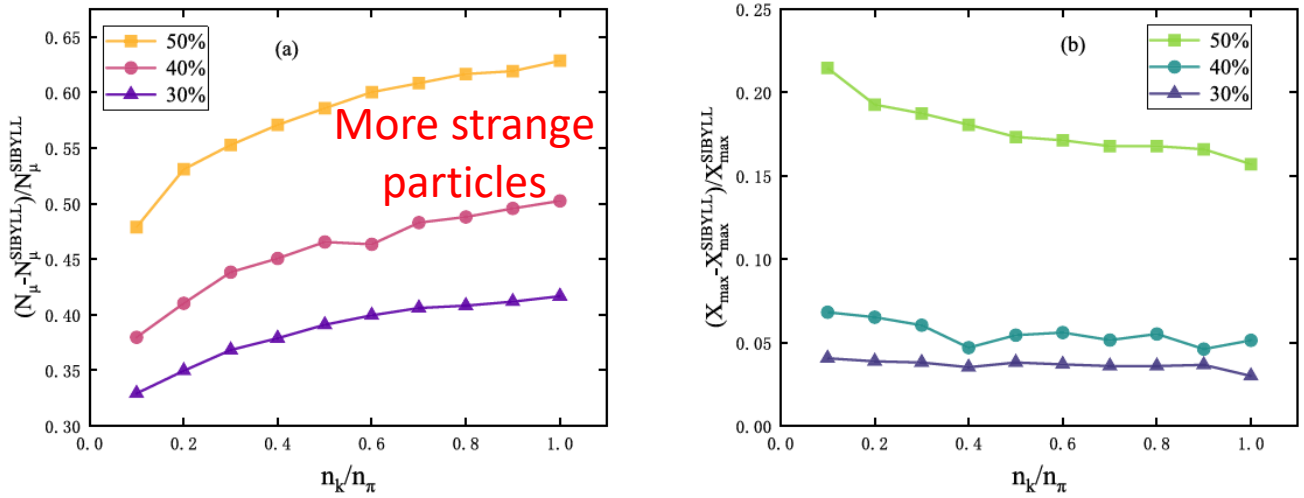




From M. Siddikov, I. Schmidt, DOI: 10.1103/PhysRevD.104.016024



- Hard to estimate the real contribution in CR – only as free parameter



From B. Liu, Zh. Yang, DOI: 10.3847/1538-4357/ad6b9a

Enhanced Parton Models (EMP) + string interactions

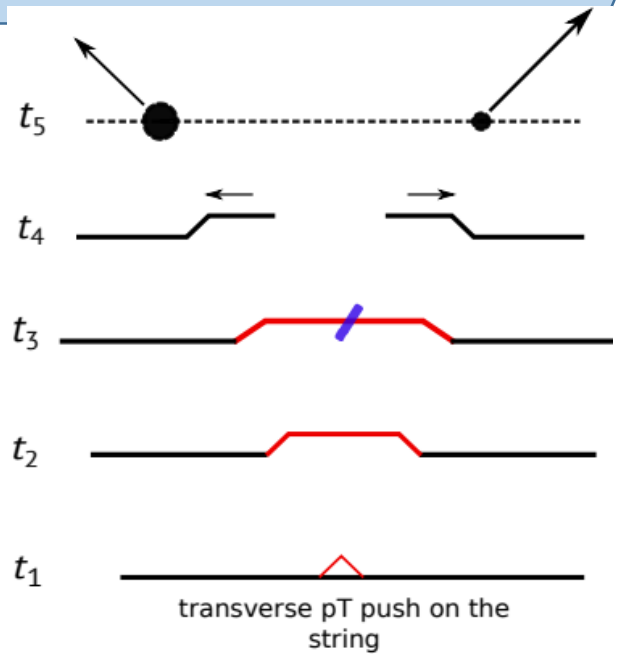
HE NE

Enhanced parton models:

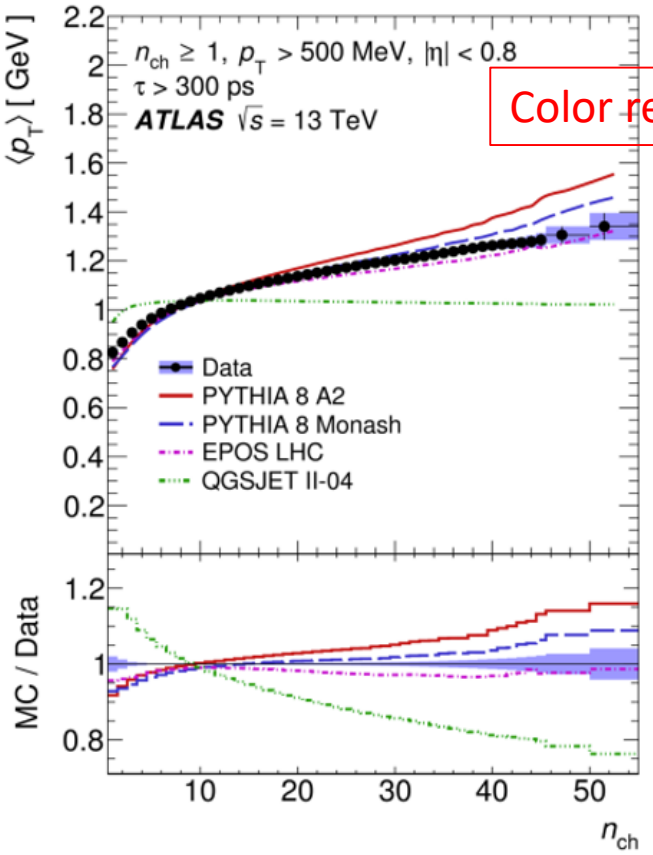
- Use complex parton-parton interaction techniques to calculate the parton shower evolution in dense medium
  -> **QGP-like hydrodynamics.**
- BAMPS (Z. Xu, C. Greiner, 2005, 10.1103/PhysRevC.71.064901), AMPT (Z.-W. Lin, et al., 2005, 10.1103/PhysRevC.72.064901)

- No clear impact for EAS physics.

String shoving

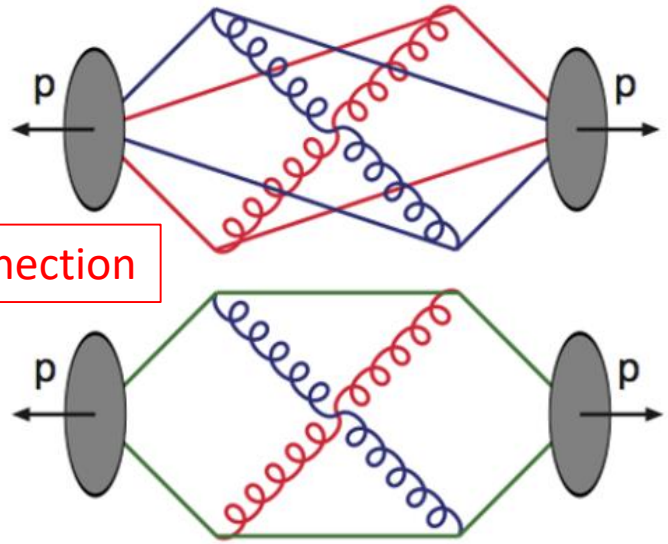


String interaction scenarios

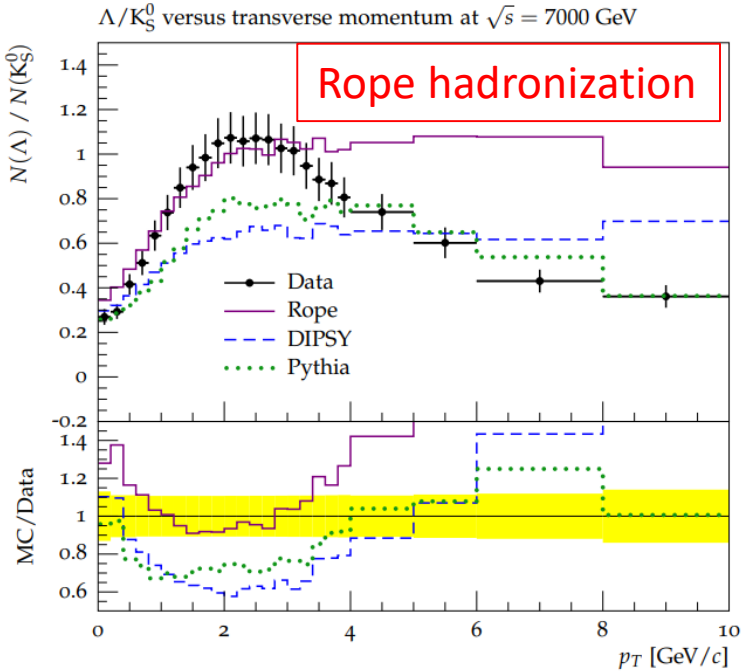


See C. Bierlich, G. Gustafson, J.R. Christiansen, et al. – String Shoving, Color Reconnection, Rope hadronization in Pythia and DIPSY.

Color reconnection



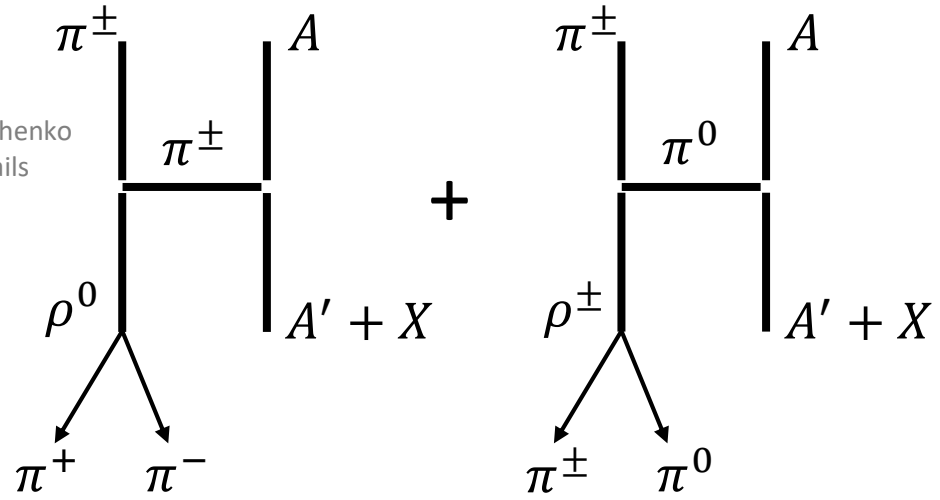
Rope hadronization



Enhanced Fragmentation Model (EFM): PICCO and SIBYLL

HE NE

See S. Ostapchenko for more details

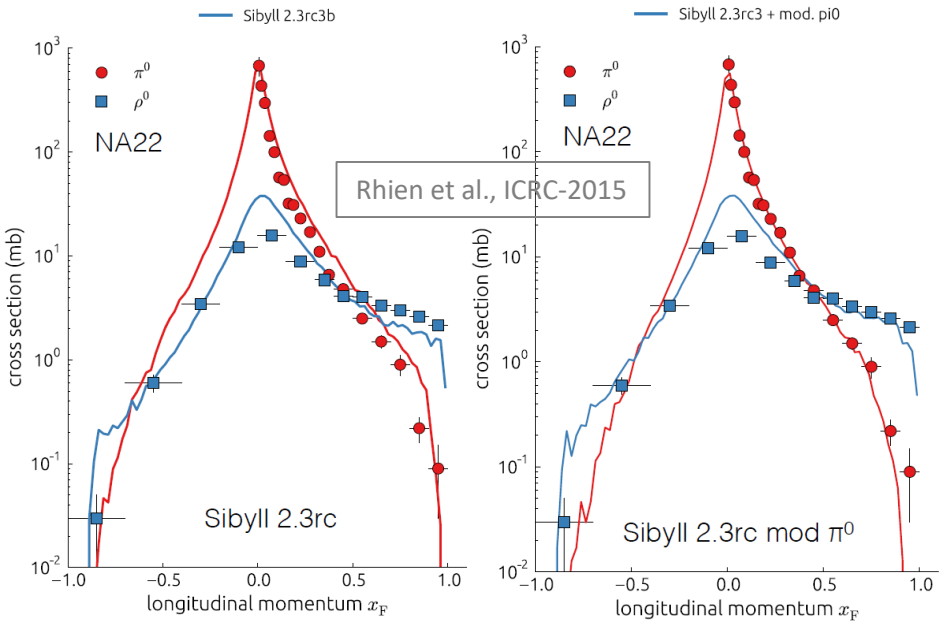


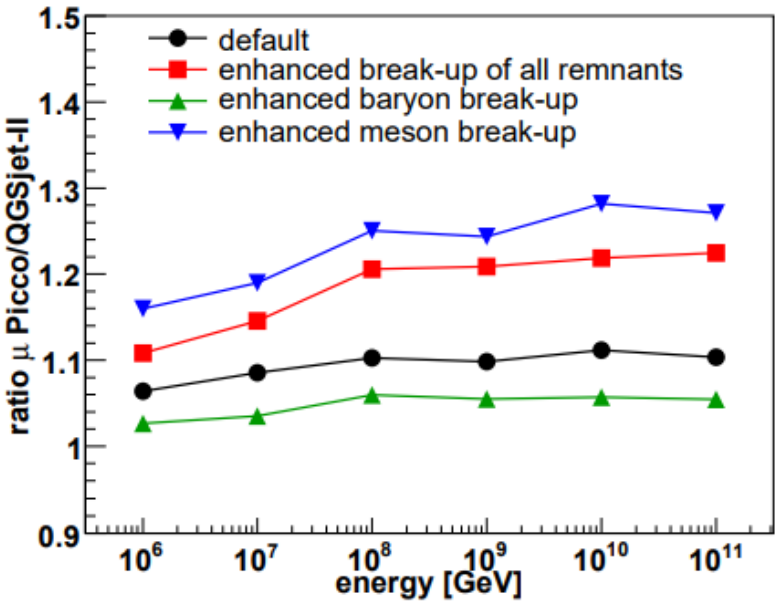
3:1 charged-to-neutral pions ratio

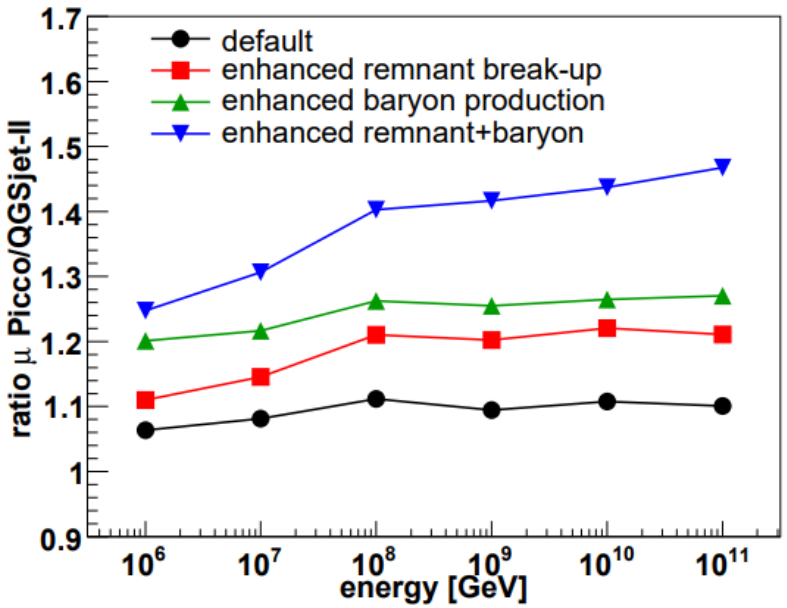
Forward region particle production

- Enhance ρ-meson production in π-exchange -> more hadronic energy in leading particles
- Enhance remnant break-up: instead of creating leading π^0 from remnant force it to fragment
- Enhance baryon production -> baryon remnant remains baryon

H.-J. Drescher, 2008, DOI: 10.1103/PhysRevD.77.056003







Lorentz Invariance Violation (LIV) models

HE NP

Add an effective term to the dispersion relation:

$$E^2 - p^2 = m^2 + f(\vec{p}, M_{\mathrm{Pl}}, \eta)$$

Expand to leading order:

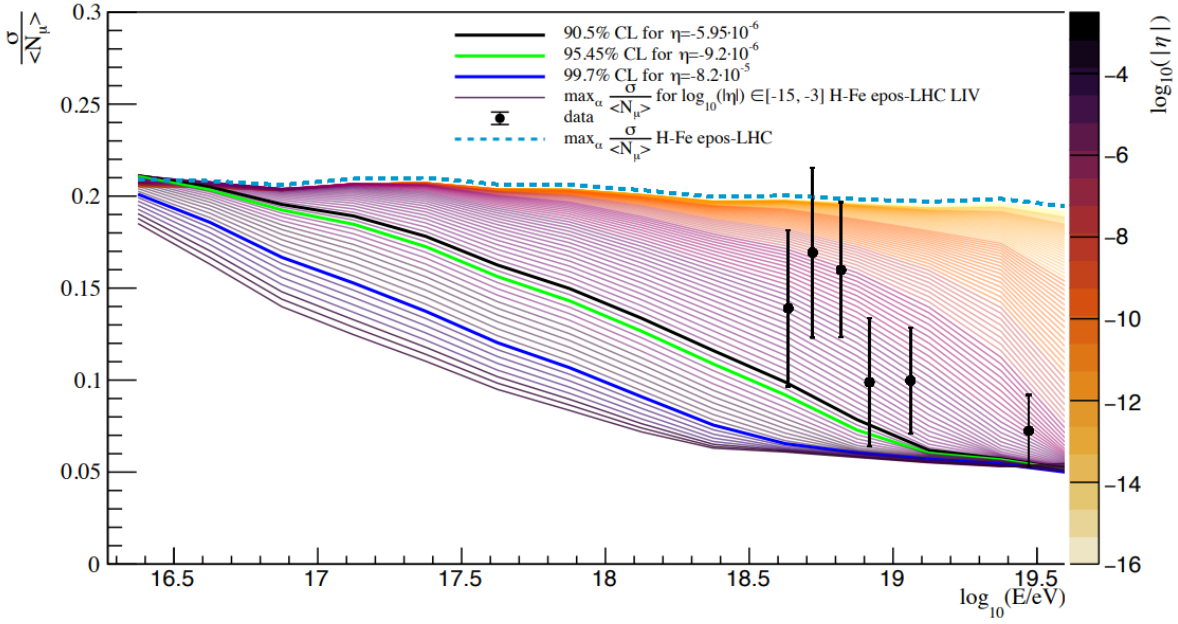
$$E^2 - p^2 = m^2 + \eta^{(n)} \frac{p^{n+2}}{M_{\mathrm{Pl}}^n} \equiv m_{\mathrm{LIV}}^2$$

η - LIV parameter

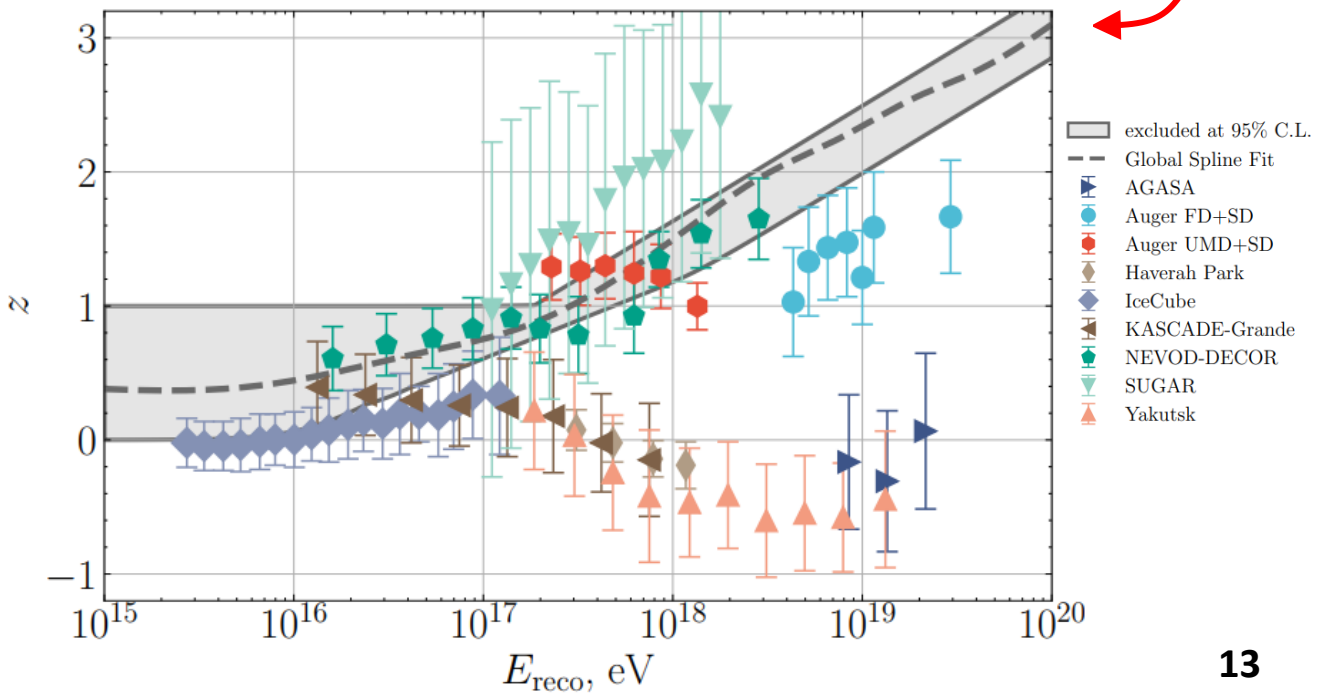
Different LIV scenarios:

- γ_{VHE} decay
- π^0_{VHE} “stability” -> more energy to the hadronic channel in first interactions
- Suppressed e^+e^- pair production by γ_{VHE} -> reconstructed E_0 shift

C. Trimarelli, 2021, DOI: 10.22323/1.395.0340



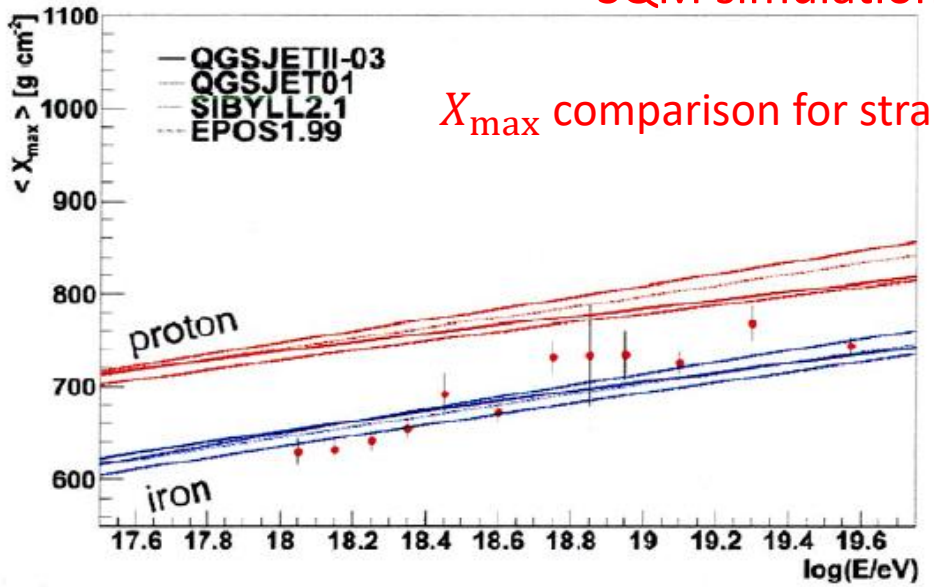
N.S. Martynenko et al., 2025, DOI: 10.1103/PhysRevD.111.063010



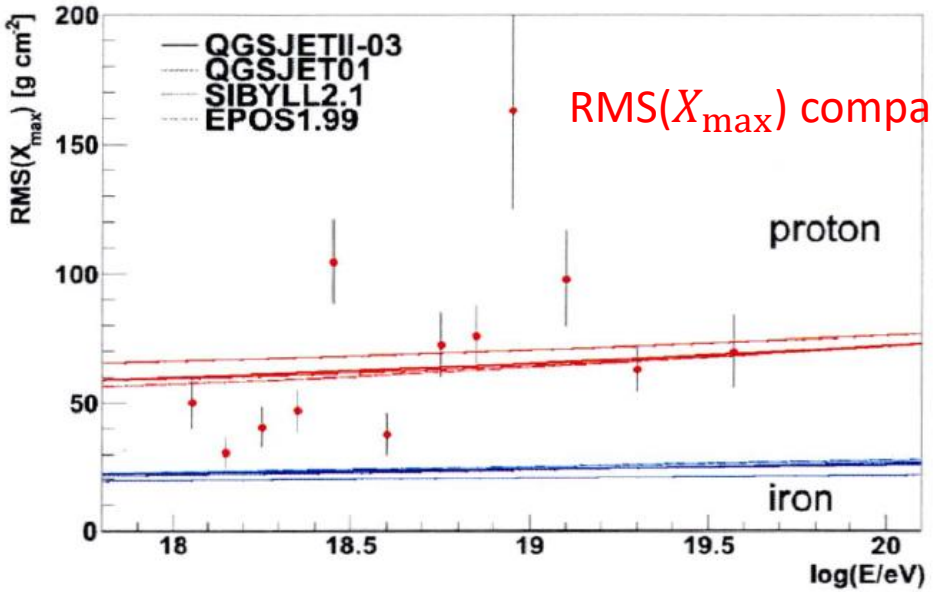
Strange quark matter in PCR

AP NP

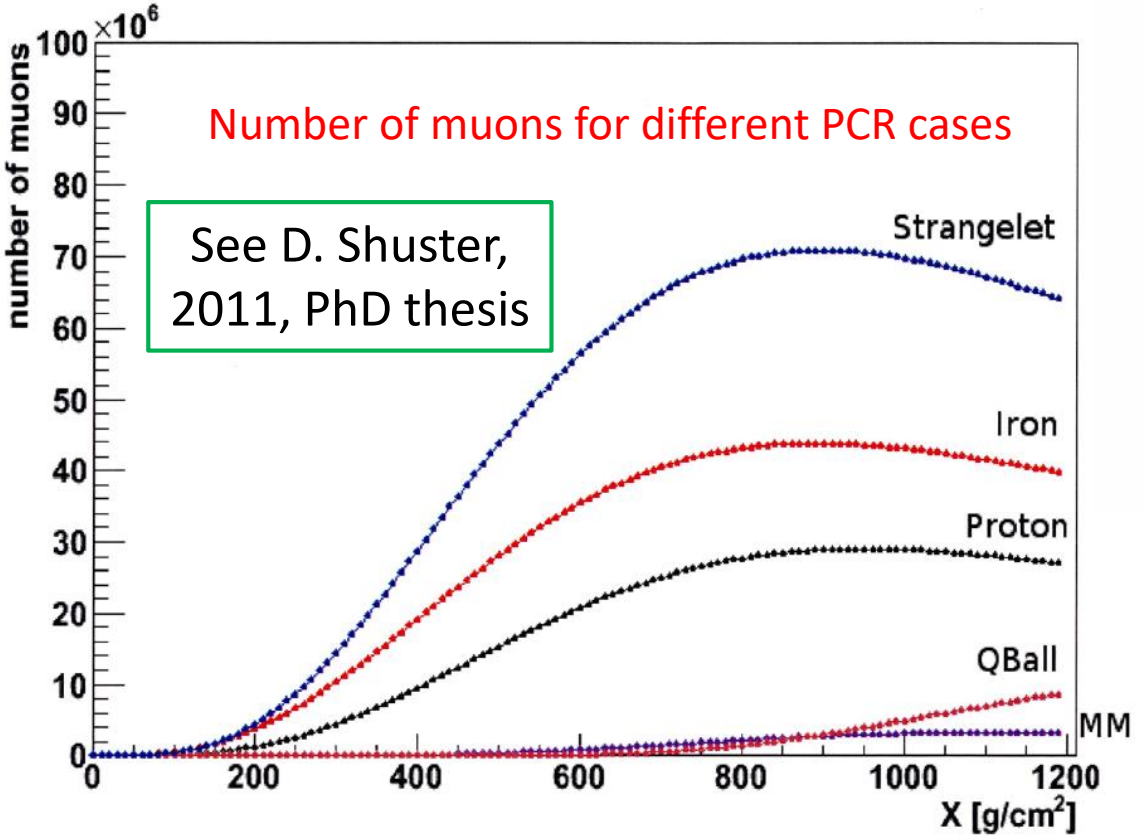
SQM simulation with EPOS: A=500, hypernucleus compressed of Λ_0



$X_{\max}$ comparison for stranglets



RMS($X_{\max}$) comparison

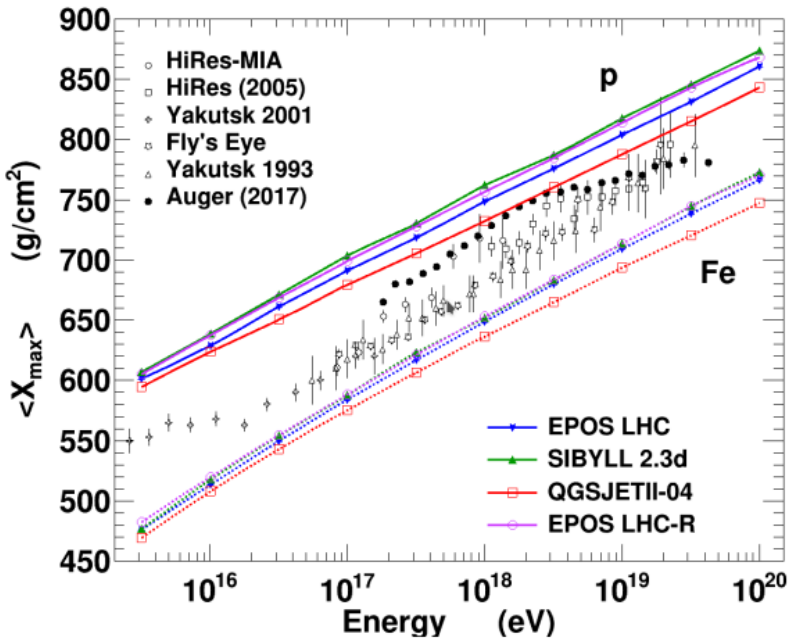


- Need to calculate cross-sections, PDF, fragmentation, etc. for SQM – but not clear, how.
- Requires very fine tuning of SQM parameters (mass, bounding energy, composition) to produce “normal” EAS.

EPOS LHC-R

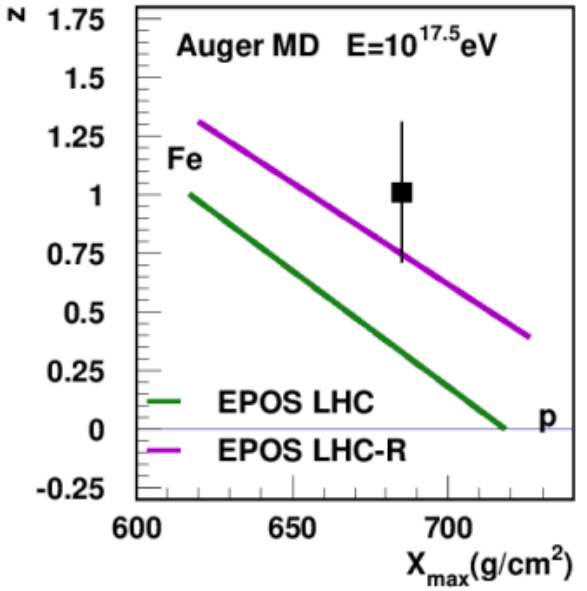
T. Pierog, ISVHECRI-2024

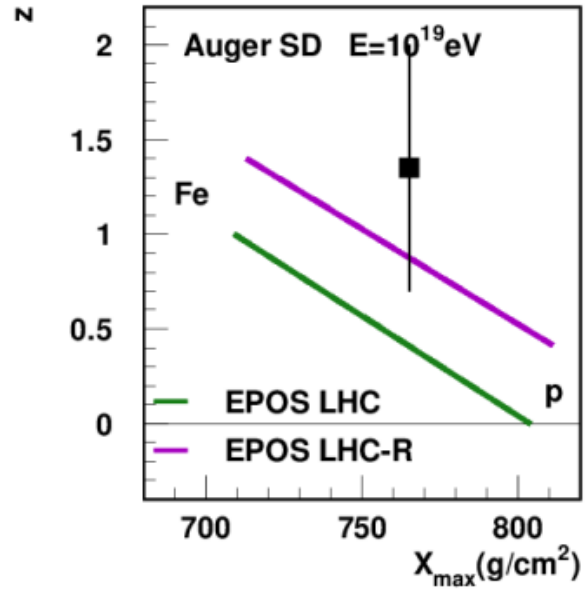
HE PT NE



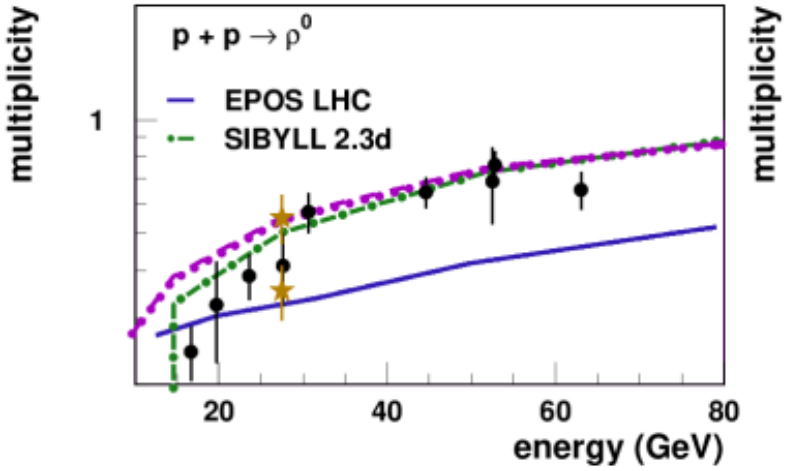
Larger $\langle \ln A \rangle$

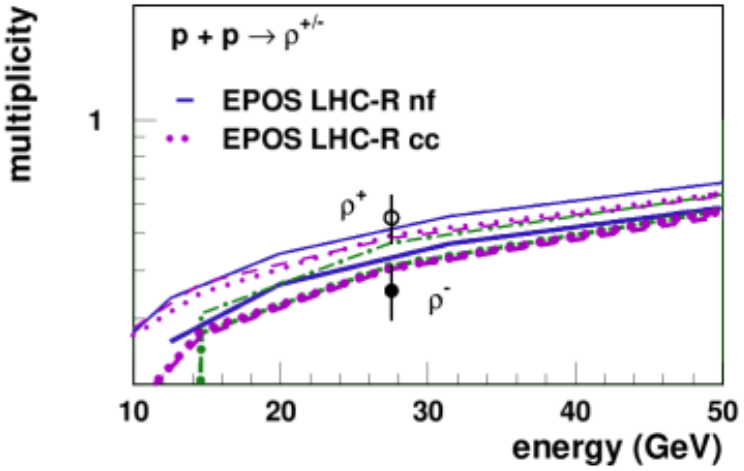
Correction of nuclear fragmentation in EPOS :
X_{max} RMS Fe
LHC=20g/cm2
LHC-R=24g/cm2
SIB=25g/cm2
QII=25g/cm2

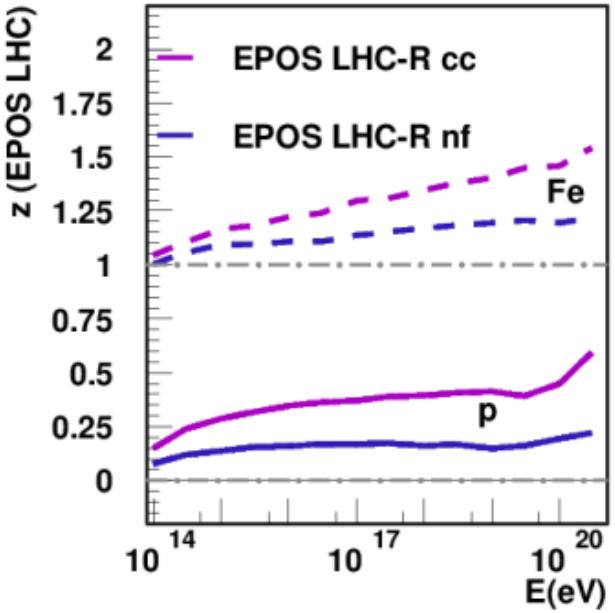




Isospin symmetry: enhance ρ^0 production







Muon Puzzle solved?

Summary

- The Muon Puzzle remains a challenging problem after more than 10 years of its study.

- Many models have been proposed in order to resolve the puzzle.
  - Most hypotheses focus on the models of high-energy physics;
  - Hadronic interaction models offer most space for improvement and changes;
  - Alternative approaches appear -> more tests required!

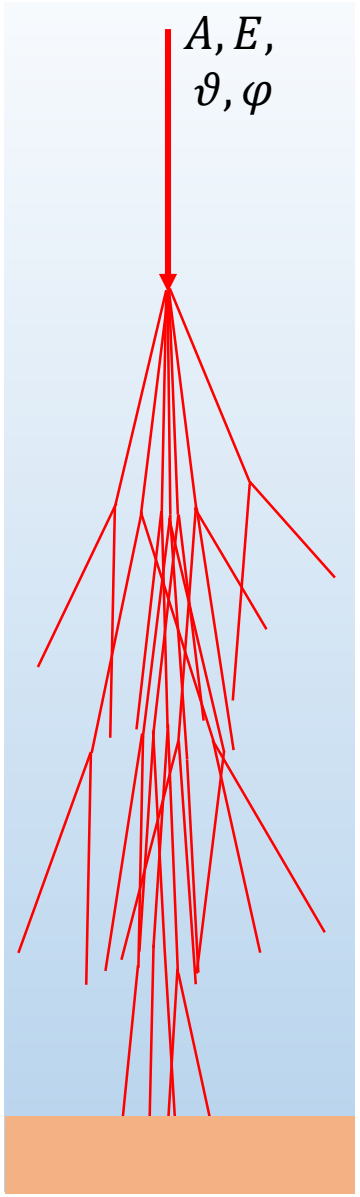
- The main challenge is to perform a complete calculation within the framework of the proposed changes
  - Only EPOS LHC-R model stays within its basic physics from PCR to EAS properties.
  - The exotic scenarios are usually hard to quantify rigorously.

- The most probable explanation includes **both** collective effects and single-string modifications in hadronic models.

Thank you for your attention!

BACK UP SLIDES

Simulations in UHECR physics: a main source of uncertainties



PCR input

- Mass composition $f_1(E) \equiv \langle \ln A \rangle (E)$
- Energy spectrum $f_2(E) \equiv dN/dE\ (E)$
- Arrival direction ϑ, φ - isotropic

EAS development simulation

Hadronic interaction model (HE / LE)

$f_3(E) \equiv (\sigma, N_{\mathrm{ch}}, p_\perp, \dots)(E)$

E/m model

- Pair production
- Ionization
- Bremsstrahlung
- Photonuclear
- Coulomb, Moller, Bhabha, …
- VHE behavior ??

Tracking and decays

- Magnetic field
- Atmosphere model
- Mean free path
- Decay length
- Curved atmosphere

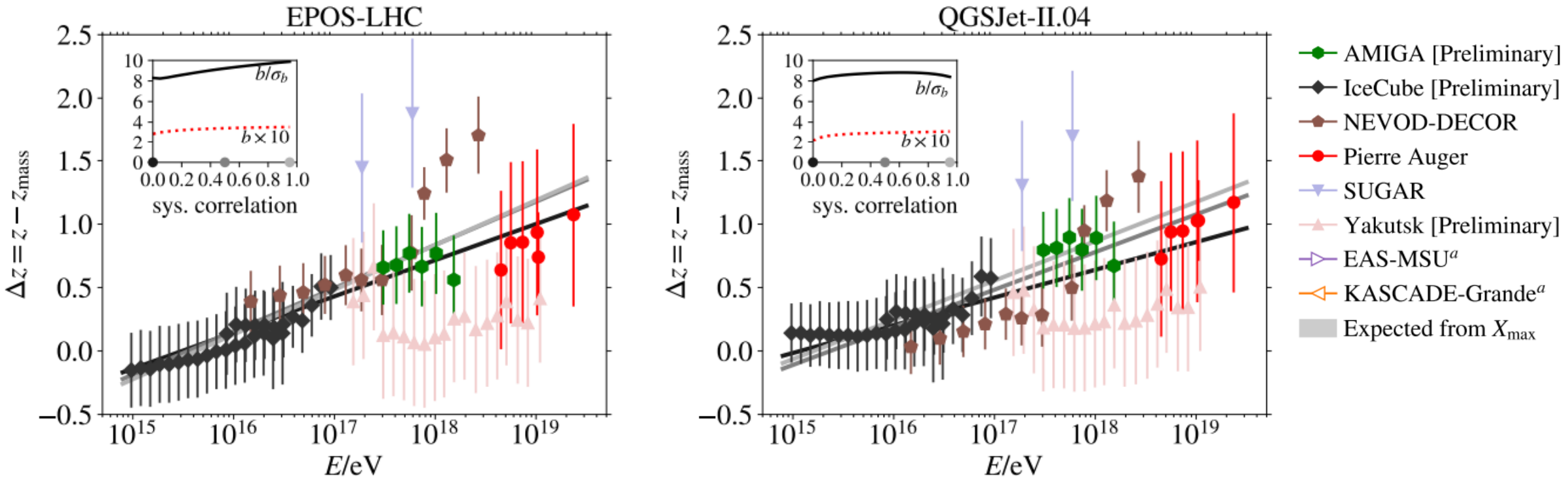
Output

- Particle list: position, momentum, type, time
- Longitudinal profile, lateral profile
- Cherenkov, fluorescence, radio …

$f_1(E), f_2(E)$ and $f_3(E)$ are, de-facto, unknown functions!

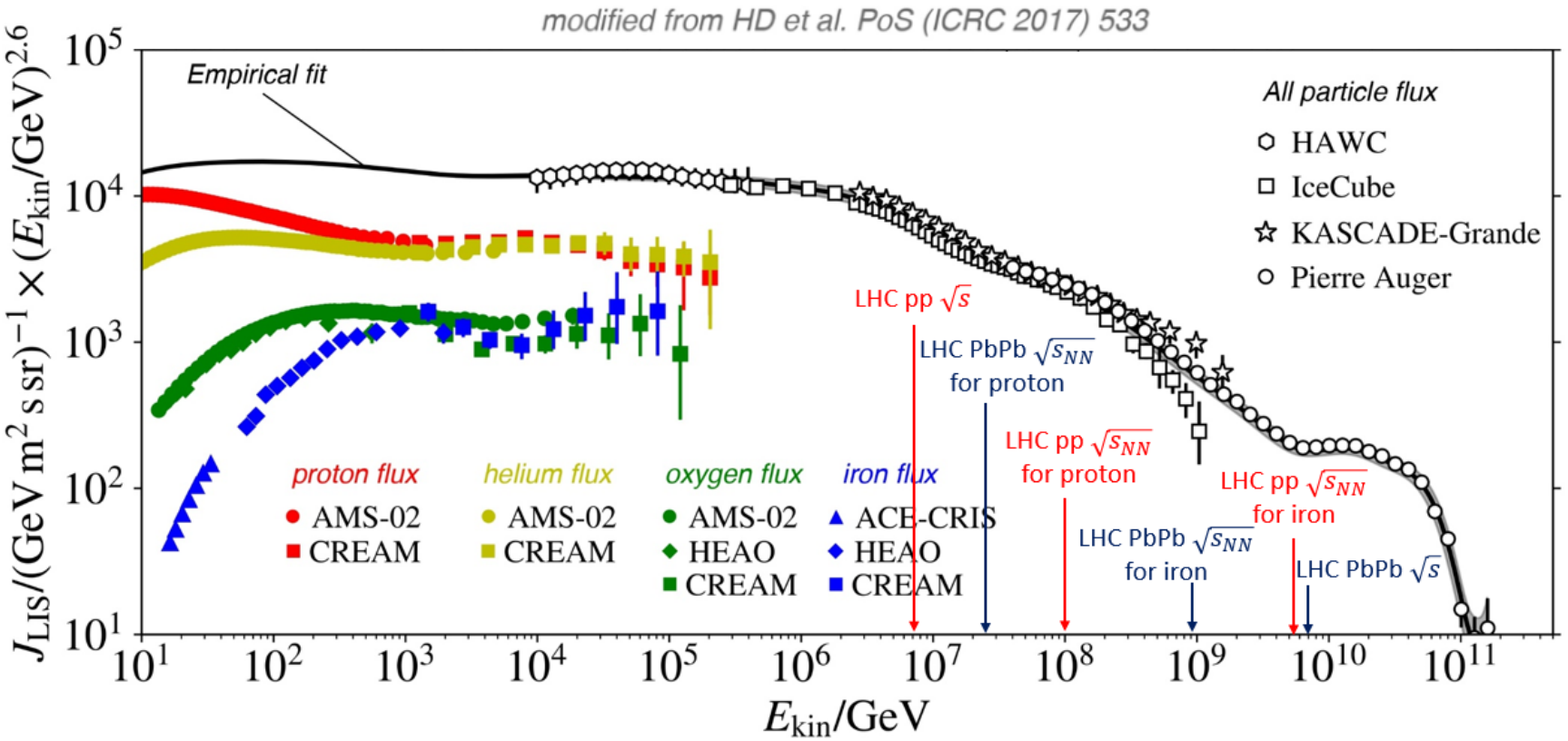
The Muon Puzzle: current status

From H. Dembinski et al., DOI: https://doi.org/10.1051/epjconf/201921002004



- Non-zero slope independent of assumed correlations in uncertainties.
- The trend is clearly seen starting with $\sim 10^{17}$ eV, so the physics nature of the muon puzzle should be seen at LHC energies.

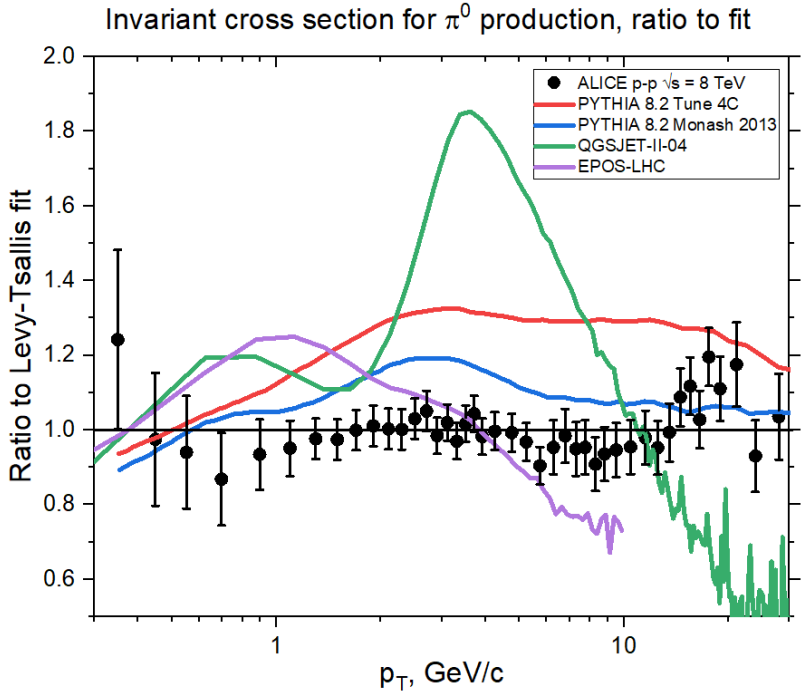
Equivalent energy in cosmic rays: $\sqrt{s}$ vs $\sqrt{s_{NN}}$ and proton vs iron primary



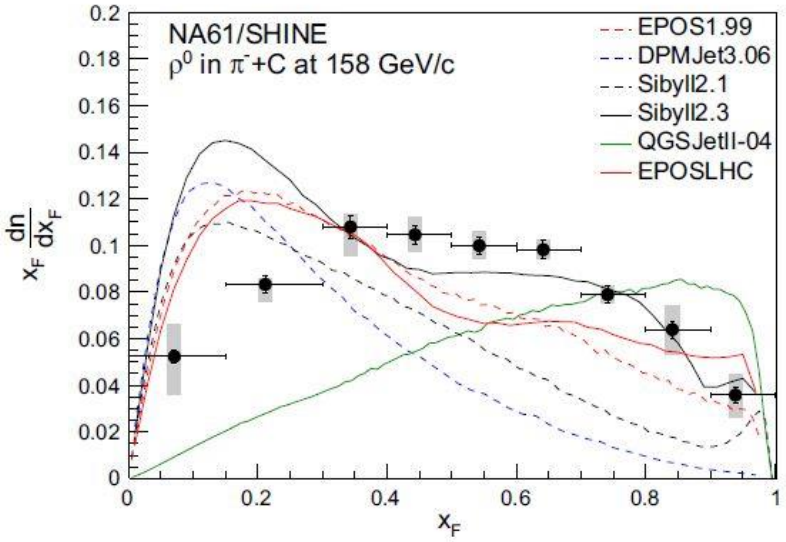
- $\sqrt{s}$-transition as if colliding particles have no inner structure – only total CM energy matters
- $\sqrt{s_{NN}}$-transitions is based on assumption that physics is defined by binary N-N collision energy

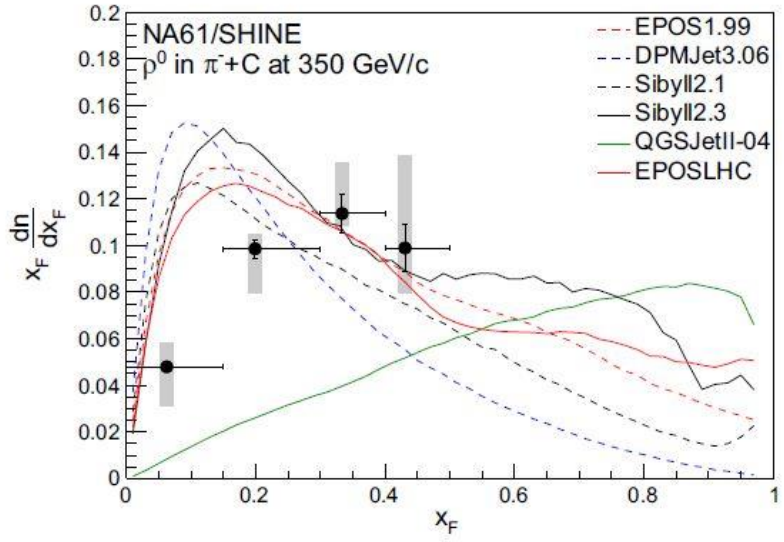
- Equivalent energy depends on the assumed primary particle mass – higher heavy PCR nuclei energy corresponds to LHC.
- $\sqrt{s}$-transition undermines inner structure of hadrons and is incorrect – not all collision energy is transferred into hard processes.
- But $\sqrt{s_{NN}}$-transition does not cover the full picture either: hadronization process deals with the total energy of the entire fragmenting parton system.

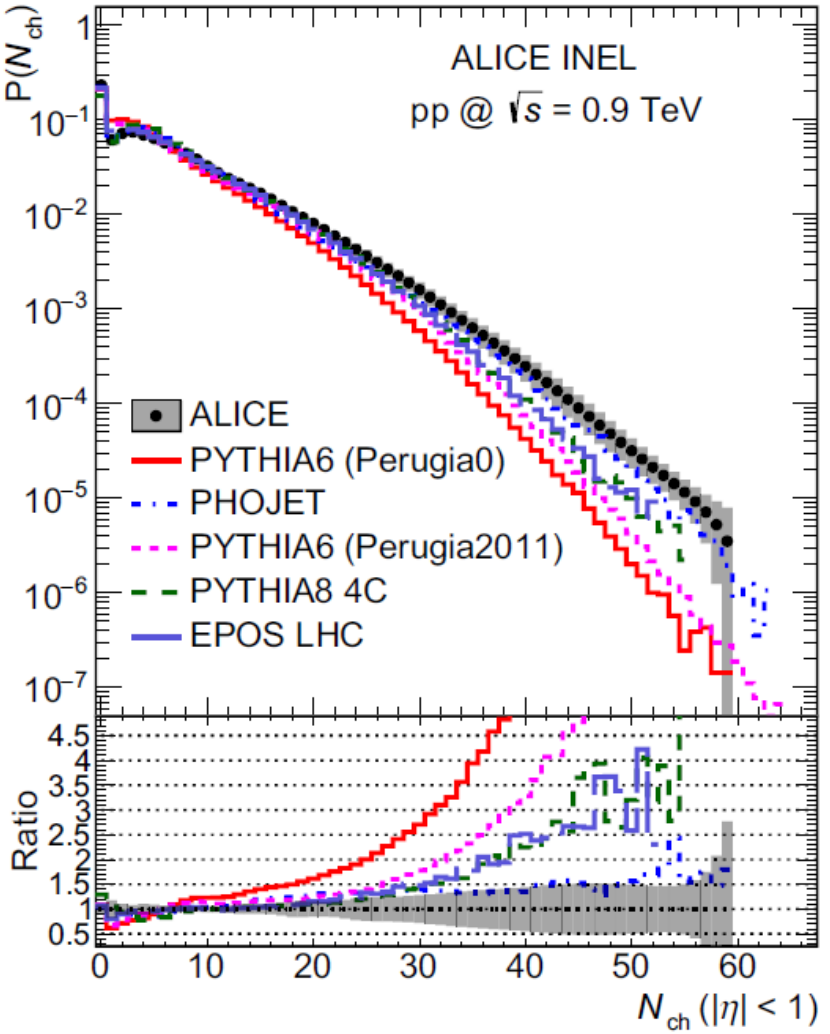
Problems with hadron production



- Just some examples, out of many…
- Note that models face difficulties with the description of the ***typical*** particle production (mostly light mesons).
- Forward region is of great importance.







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