UHECR measurements and physics at man-made accelerators: mutual constraints

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

PROSA
proton structure analyses in hadronic collisions

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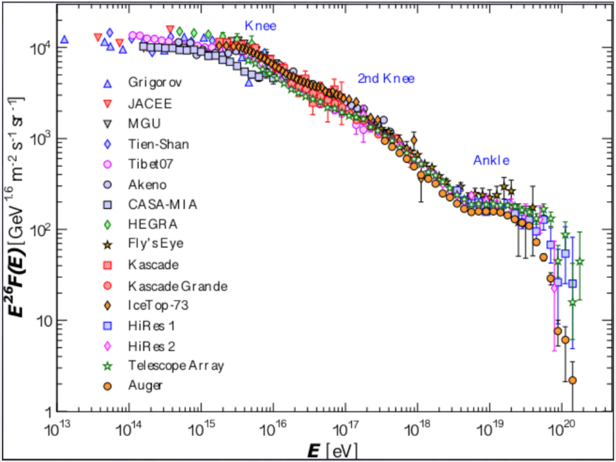
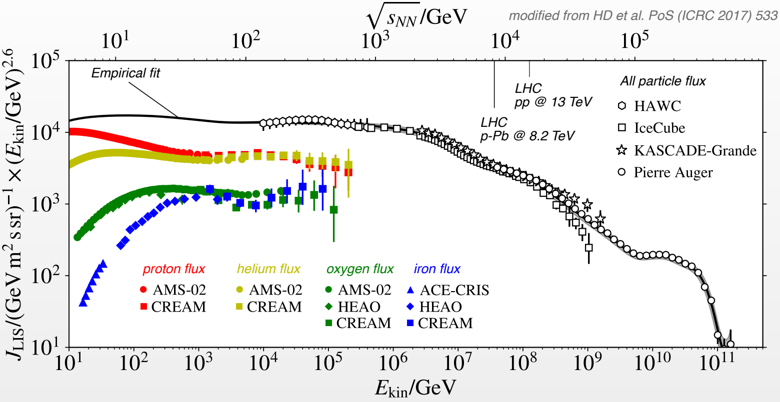
The all particle CR flux as a function of primary energy - I



- ∗ charged ions, detected by many different experiments (no evidence for γ or ν-initiated showers, at least so far).
- ∗ spectrum spans 11 orders in E and > 30 orders in flux intensity
- ∗ origin of the features ? (more precise measurements lead to additional ones: e.g. instep at $\sim 1.4\ 10^{19}$ eV)

The all particle CR flux as a function of primary energy - II

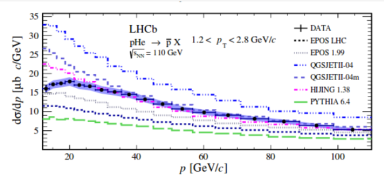


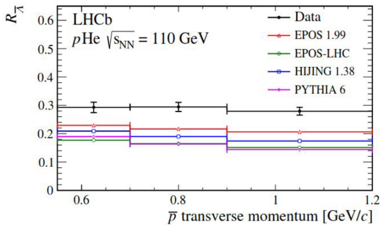
* we are interested in E, arrival direction, mass A, event-by-event to understand CR origin (multimessenger approach: γ, ν, GW signals can help)
* direct detection for $E < 100$ TeV
* indirect detection for $E > 100$ TeV (E, A reconstructed from EAS products: E from size of e, γ component, A from X_{max}, N_{μ}; direction from particle arrival times)
* tails with energy much larger than LHC

Low-energy CR: the antiprotons

* PAMELA, AMS02 measured e^+, $\bar{p}$, light-$\bar{A}$ fluxes: what's their origin ?
* Direct determination of $\sigma(pHe \rightarrow \bar{p} + X)$ at $\sqrt{s_{NN}} = 110$ GeV with LHCb-SMOG apparatus [PRL 121 (2018) 222001]

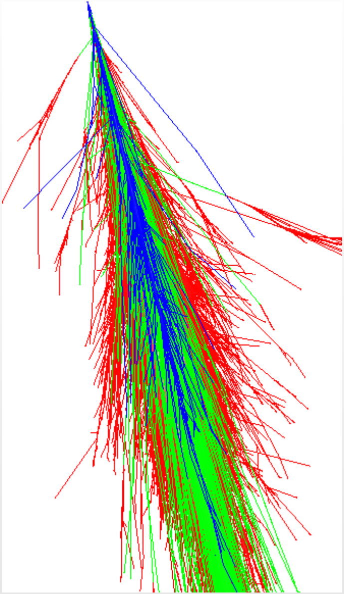
$\Rightarrow$ crucial for interpreting the precise $\bar{p}$ CR flux measurements because it allows to improve the precision of the secondary $\bar{p}$ CR flux predictions.





* ratio R of $\bar{p}$ detached and prompt production, the first via antihyperon decay: $\bar{\Omega}^+ \rightarrow \bar{\Lambda} K^+$, $\bar{\Xi}^0 \rightarrow \bar{\Lambda}\pi^0$, $\bar{\Xi}^+ \rightarrow \bar{\Lambda}\pi^+$, $\bar{\Sigma}^- \rightarrow \bar{p}\pi^0$, with $\bar{\Lambda} \rightarrow \bar{p}\pi^+$
* data show strangeness enhancement w.r.t. hadronic interaction models
* Possible forthcoming measurements thanks to H_2, D_2 injections: $\sigma(pD \rightarrow \bar{p} + X)$, $\sigma(pp \rightarrow \bar{p} + X)$ and their ratio: test isospin violation and constrain the $\bar{p}$ production from $\bar{n}$

UHECR Extended Air Showers



- Interaction of primary particle (proton, helium, iron ion. . .) with atmosphere
- Ordering parameter: atmospheric depth $X = \int d\vec{r}\,\rho(\vec{r})$ (top to bottom)
- Separate **hadronic interactions** from **propagation** through atmosphere
- Primary interaction creates π, K, n, p, $\Lambda\ldots$ which in turns propagate and interact with other nuclei of the atmosphere or decay ($\sim$ 10 generations).
- Heavier hadrons ($D\ldots$) are also produced, but do not propagate significantly, decaying immediately.
- μ's footprint of hadronic interactions

EAS: open problems

Soft hadronic interactions, dominating EAS formation, can not be described by pQCD.

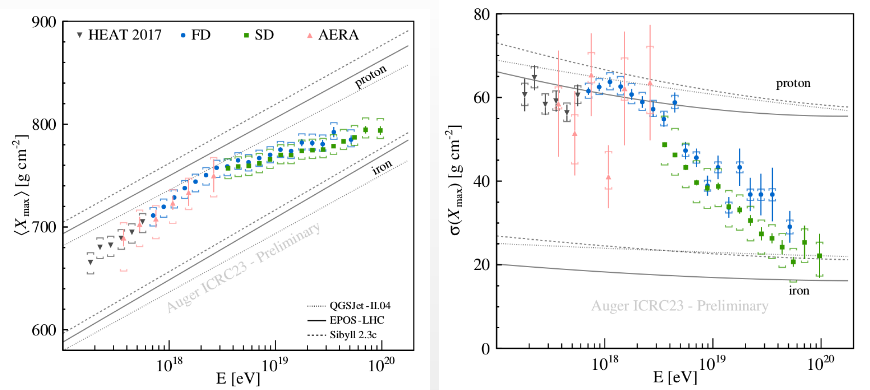
Although Monte Carlo generators for EAS have been tuned to LHC data (which has decreased the differences in their predictions), there is no way to describe simultaneously multiple EAS observables by a unique simulation:

$$< X_{max} >,\ \sigma(X_{max}),\ N_\mu,\ \sigma(N_\mu),\ < X^\mu_{max} >,\ ....$$

$\Rightarrow$ UHE CR composition (that unfortunately is inferred from comparison data/theory, instead of from just data) is still very uncerxtain !

Solving the composition problem would be important to understand the CR production mechanisms and the present composition uncertainty affects several other observables.

$< X_{max} >$ and $\sigma(X_{max})$ from Phase I at the PAO

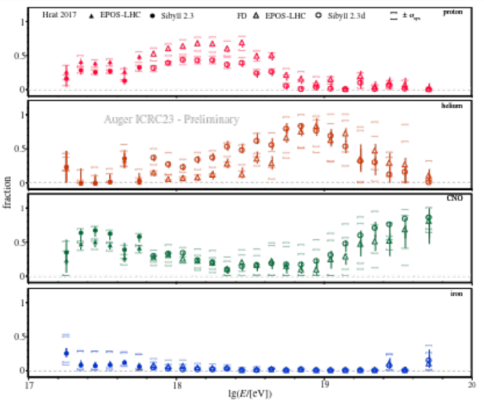


from PAO collaboration, PoS(ICRC 2023) 016

∗ SD allows to extend energy coverage (w.r.t. FD).

∗ Some systematics in the difference SD/FD still to be understood but measurements conducted with different techniques point to similar overall features concerning CR composition.

CR composition inferred at PAO from X_{max}



from PAO collab., PoS(ICRC 2023) 016

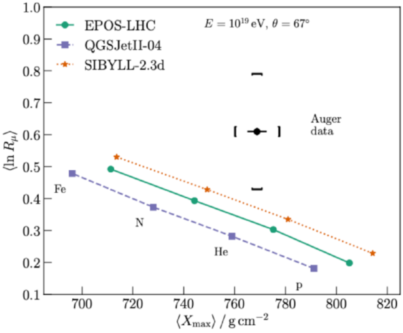
∗ Use of HEAT and FD data

∗ Composition more similar to p at $E \sim 3\ 10^{18}$ eV, becomes increasingly heavier at large energies, but the contribution of Fe is small.

∗ However the number of μ actually detected at Earth would correspond to an heavier composition!
$\rightarrow$ μ problem

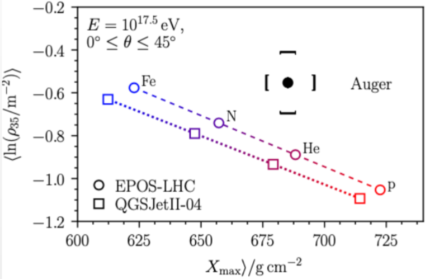
The μ problem at the PAO

Hybrid events and inclined showers



(Phys. Rev. Lett. 117 (2016) 192001,
Phys. Rev. D91 (2015) 032003)

Muon counters and vertical

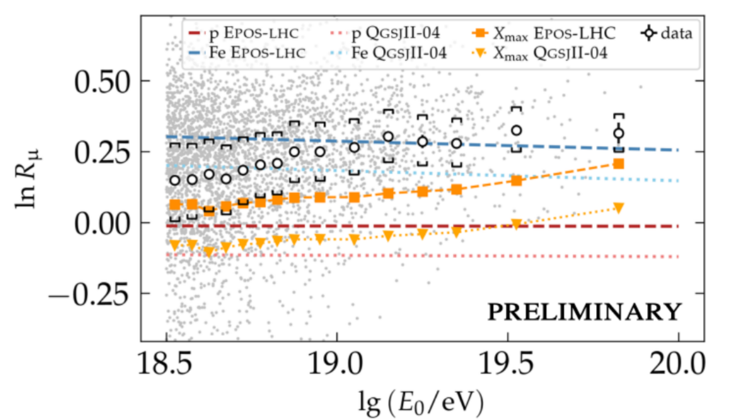


(Eur. Phys. J. C80 (2020) 751)

N_μ predictions from composition inferred from $\langle X_{max} \rangle$ at each primary energy E_0 are inconsistent with N_μ data.

N_μ is proportional to E_{had}, in turns proportional to $(1 - f_{\pi^0})^N$.
In case of perfect isospin symmetry $f_{\pi^0} = 1/3$.

The μ problem at the PAO: phase I results

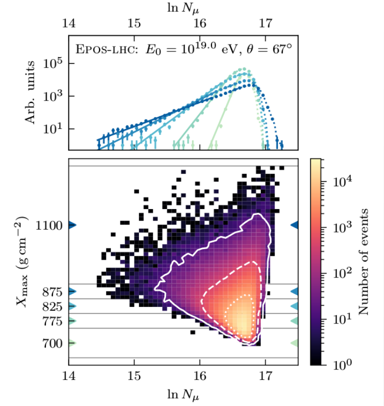


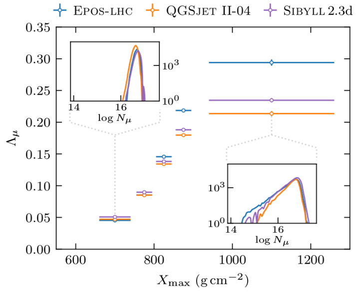
from PAO collaboration, PoS(ICRC 2023) 016

N_μ predictions from composition inferred from $\langle X_{max} \rangle$ are inconsistent with N_μ combined (FD+SD) data.

N_μ is proportional to E_{had}, in turns proportional to $(1 - f_{\pi^0})^N$.
In case of perfect isospin symmetry $f_{\pi^0} = 1/3$.

Two-dim ($\ln N_\mu$, $\langle X_{max} \rangle$) distribution and Λ_μ





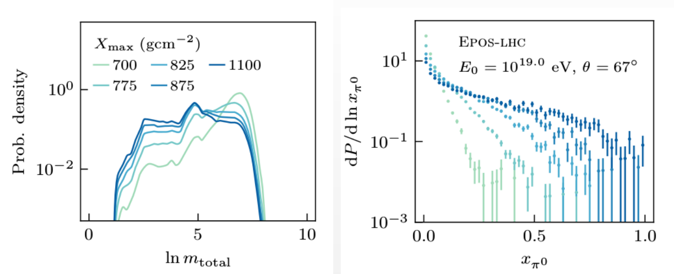
from L. Cazon et al., [arXiv:2406.08620]

∗ A wider range of N_μ values is possible for showers with larger $< X_{max} >$: 2-dim distri largely shaped by first interaction

∗ Λ_μ is the slope of the $\ln N_\mu$ distribution in the low $\ln N_\mu$ tail, in a fixed small bin of $\langle X_{max} \rangle$ values.

∗ Λ_μ increases with $\langle X_{max} \rangle$, with differences among generators increasing for showers characterized by less abundant, and then softer, hadronic activity.

Macroscopic quantities at first interaction and X_{max}



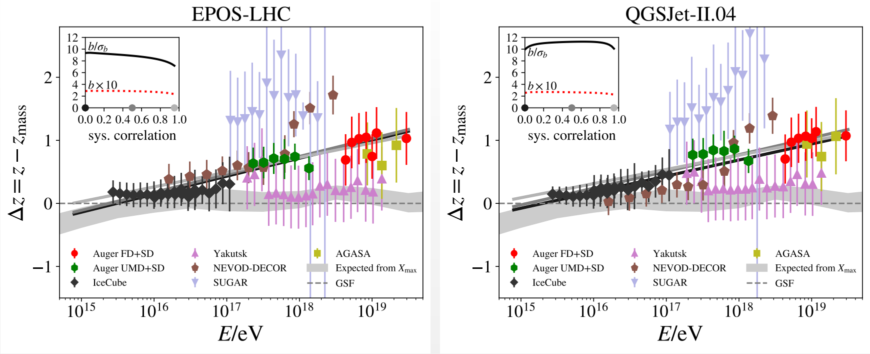
from L. Cazon et al., [arXiv:2406.08620]

∗ All-particle multiplicity distribution peaked towards larger multiplicities is connected to smaller $< X_{max} >$. ⇒ Larger hadronic Activity

∗ The x_E distribution of the π^0 spectrum reaches smaller x_E values for smaller $< X_{max} >$, corresponding to less energetic π^0's that can give rise to EM sub-showers. ⇒ Reduced EM activity

∗ Given that $\Lambda_\mu(X_{max})$ can be measured, it can be used to tune the hadronic interaction models and then we can constrain from this measurement the x_E spectrum of π^0's in regions hardly covered or not covered at man-made accelerators.

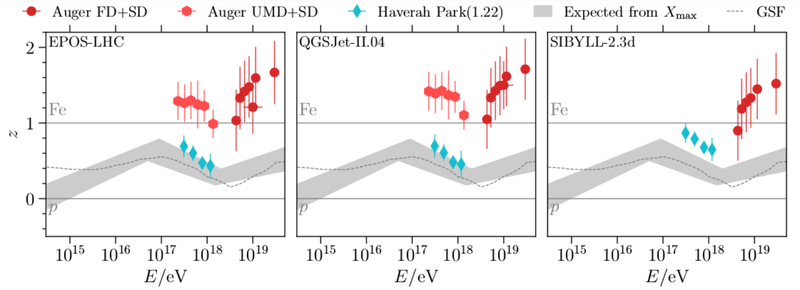
Universality of the μ problem



from J. Albrecht et al., [arXiv:2105.06148]

- ∗ issue for all generators and most of the UHE experiments, even within a same detector using different analysis techniques
- ∗ discrepancy theory/experiment gradually arising above $\sqrt{s_{NN}} > 8$ TeV
- ∗ within reach at LHC, unlikely from sudden BSM appearence above a fixed scale

Universality of the μ problem ???



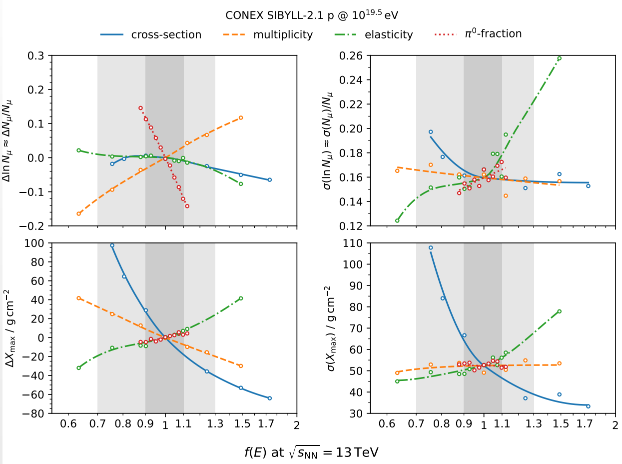
from L. Cazon et al., PoS(ICRC 2023), 431

∗ y-axis: $z = \frac{ln\langle N_\mu \rangle - ln\langle N_{\mu\ p} \rangle}{ln\langle N_{\mu,\ Fe} \rangle - ln\langle N_{\mu,\ p} \rangle}$

∗ The case of N_μ at Haverah Park Array: not all measurements seem to point towards a discrepancy between the number of μ inferred by ($\langle X_{max} \rangle$ measurements + hadronic event generators) and N_μ directly measured, even using the same techniques.....

∗ However, uncertainties in the absolute energy scale of the water-Cherenkov detectors at Haverah Park, derived from theoretical model.

Which modifications of the generators can solve the issue (keeping compatibility with other observables)?



from J. Albrecht et al., [arXiv:2105.06148]

The only reasonable change, considering that we do not want to affect too much $\sigma(N_\mu)$, X_{max}, $\sigma(X_{max})$ to avoid to create new incompatibilities with data, is reducing the fraction of particles originating the EM cascade (π^0).

Which mechanisms can effectively reduce the π^0 fraction ?

∗ $f_{\pi^0} = N(\pi^0)/N(all \pi's)$

∗ Breaking isospin symmetry by ρ^0 enhancement (breaking justified because mesons are massive), followed by $\rho^0 \to \pi^+\pi^-$ decay, inducing $N_\pi^0/(N_\pi^+ + N_\pi^-) < 1/2$

∗ enhance light baryon production (e.g. by replacing charged neutral combinations of two or three pions, with $p\bar{p}$, $n\bar{n}$) → may suggest need for different hadronization mechanism (more extreme hypothesis: chiral symmetry restoration).

∗ enhance strangeness (increase number of kaons and/or strange baryons)

- fireballs (extreme baryochemical potential, extreme temperature)
- strangeballs (no plasma)
- QGP
- CGC (+QGP)

∗ Parton Shower (in medium) followed by new hadronization mechanisms, going beyond the standard string mechanism (color reconnection, string shoving: enhance baryon production, not necessarily strange; string ropes: also enhance strangeness).

Strangeness enhancement at mid-rapidity: ALICE data

∗ Universality

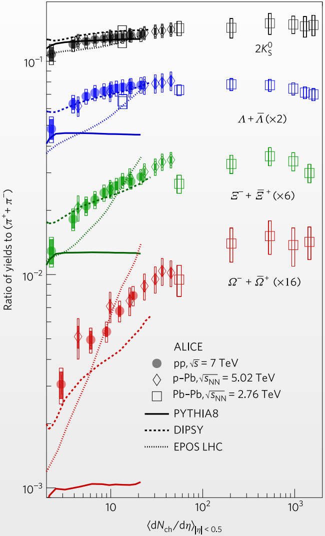
∗ signature of QGP or something else ?

∗ QGP even in small systems (also considering the discovery of correlations - ridge, flow - even there) ?

⇒ In this case, local temperature fluctuations can be large and QGP droplets with radius depending on the temperature, instead of a unique deconfined system of quarks and gluons, could be formed

→ practical realization: core-corona

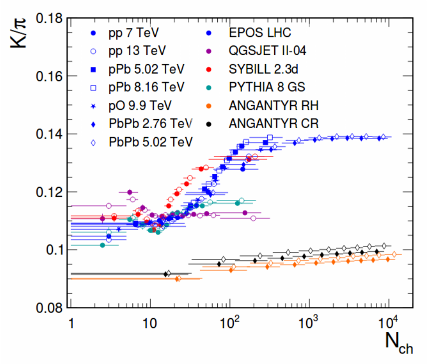
∗ Strangeness enhancement in forward direction ? LHCb results eagerly wanted.

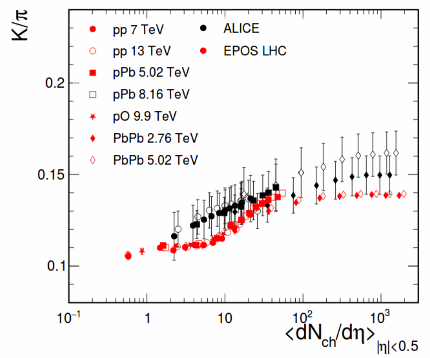


from ALICE collab., Nature Phys. 13 (2017) 535-539

Further measurements helpful to discriminate

between different mechanisms for strangeness enhancement





from R. Scaria et al. [arXiv:2304.00294]

∗ K/π ratios and correlation with charged particle multiplicity N_{ch}

∗ $R(\eta) = \langle dE_{em}/d\eta\rangle / \langle dE_{had}/d\eta\rangle$

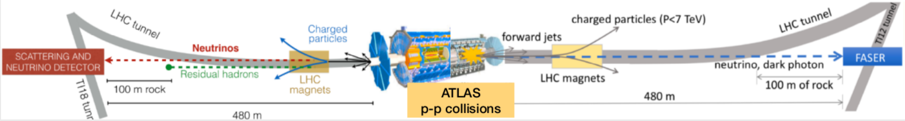
∗ $(R,\ N_{ch})$, $(K/\pi,\ R)$ correlations

Far-forward LHC experiments

* Various projects to exploit beams of particles produced in the interactions points at the LHC, propagating in the direction tangent to the accelerator arc.

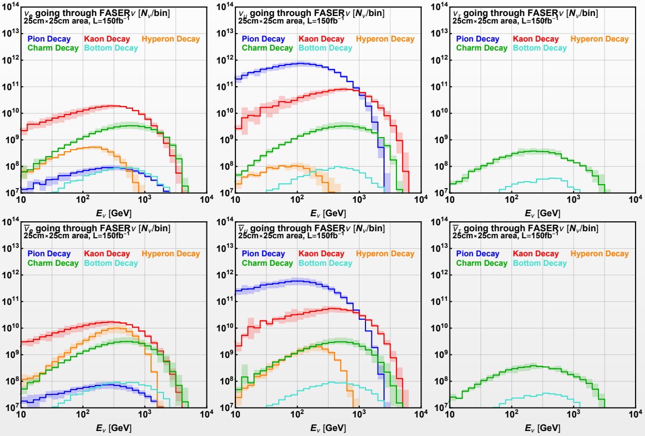
* Let these beams propagating for some distance: some particles will be deviated or stopped, some other will reach the detector.

* Pilot experiments, on the tangent to the LHC beam line, at $\sim$ 480 m from ATLAS IP:
  - FASER ($\eta > 9.2$), Faserν ($\eta > 8.5$) and SND@LHC ($7.2 < \eta < 8.4$), all active in taking data during Run 3.



* Detection mechanisms: CC and NC ν and $\bar{\nu}$ induced DIS, DM scatterings on e and A.

Examples of MC predictions of forward $(\nu + \bar{\nu})$ fluxes



from Faserν collab. [arXiv:1908.02310]

Estimated number of ν impinging on the transverse area of the FASERν detector.

* $\phi(\nu_e)/\phi(\nu_\mu)$ at $E_\nu < 200$ GeV proxy for K^+/π^+ ratio at forward rapidity (inaccessible at standard LHC detectors....)
* This measurement is made possible by the possibility of distinguishing ν_e and ν_μ on the basis of DIS signatures (showers vs. tracks), and ν from $\bar{\nu}$.

Even the strange content of protons and nuclei is quite uncertain....

∗ At present, one of the most uncertain partons in both proton and nuclear PDF fits. In some cases, results are consequences of strict assumptions: e.g. $u(x) = d(x) = s(x) = \bar{s}(x)$ or fixed values of $f_s = \bar{s}/(\bar{s} + \bar{d})$ or $R_s = (s(x) + \bar{s}(x))/(\bar{u}(x) + \bar{d}(x))$

∗ Big uncertainties and attitude partly motivated by the fact that data from different experiments seem to be partially incompatible among each other.

∗ Legacy data used in PDF fits to determine strange sea:

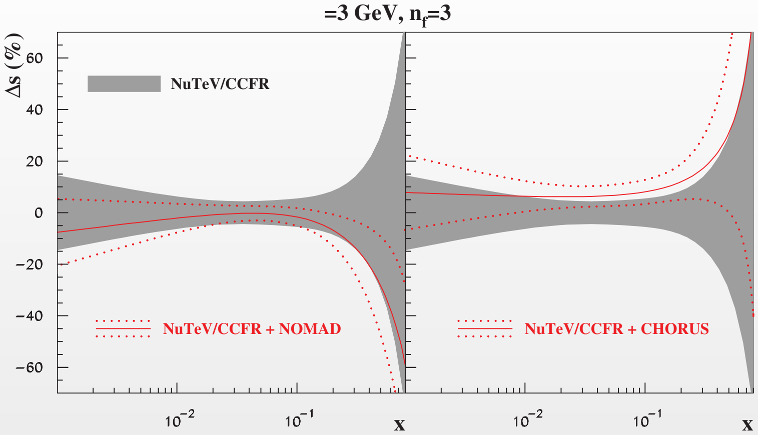
- massive high-density detectors providing dimuon data (CDHS, CDHSW, CCFR, CharmII, NuTeV, NOMAD)
- bubble chamber data (BEBC)
- nuclear emulsions (E531, CHORUS)

∗ The incapability of simultaneously obtaining a good fit of all previous ones has led the PDFs and nPDF collaborations to discard some datasets (e.g. NuTeV).

∗ Additionally, recent precise LHC data (in particular Drell-Yan) turn out to also be sensitive to strange quark distributions. They point to a larger strange component with respect to the dimuon data, generating some tension with the latter.

∗ Important to quantify strange sea in nPDF even to understand if the observed enhanced abundance of produced strange anti-barions in AA collisions can be ascribed to the onset of a QGP.

Strange sea from fixed-target data

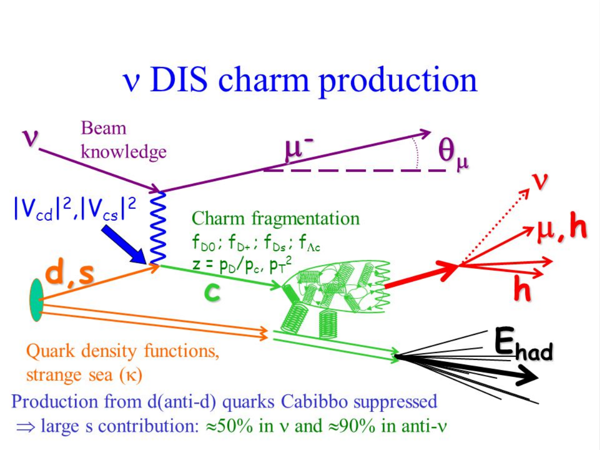


from S. Alekhin, ABM PDF fits

- ∗ NOMAD data (dimuon/inclusive CC DIS) pull down s for $x > 0.1$.
- ∗ CHORUS data pull up s.
- ∗ DY data (not shown) pull up s for $x \lesssim 0.1$.

Charm production in ν-induced CC DIS and strange sea

* Charm/Anticharm production in CC DIS has direct sensitivity to $s(x)$, $\bar{s}(x)$ at LO
* One can separate $s(x)$ and $\bar{s}(x)$ by disentangling ν and $\bar{\nu}$ events.



picture by G. De Lellis

The forthcoming pO, OO LHC runs

∗ All LHC experiments should take data.

∗ Measurements of rapidity distributions for π's, ρ's.....

∗ Measurements of degree of strangeness enhancement in inelastic collisions using a light target abundant in Air

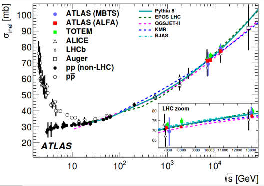
∗ Measurement of $\sigma_{TOT,inel}(pO)$, to which $\langle X_{max} \rangle$ is sensitive.

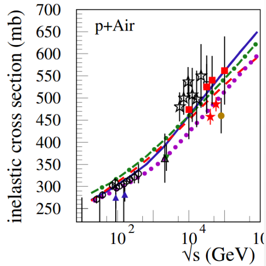
∗ Forward neutron production detected by ZDC allow to access single diffractive processes with π^0 exchange, and forward proton production detected by FPS allow to access single diffractive processes with pomeron exchange.

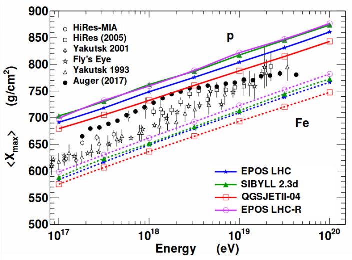
∗ + many other physics opportunities

Complementary measurement:
∗ p+O(gas) achievable with SMOG2 (lower $\sqrt{s}$, corresponding to intermediate generation in EAS)

$\sigma_{TOT,inel}$ at the LHC and $\langle X_{max} \rangle$







from ATLAS collaboration, [arXiv:2207.12246],
T. Pierog and K. Werner, PoS ICRC (2023) 230

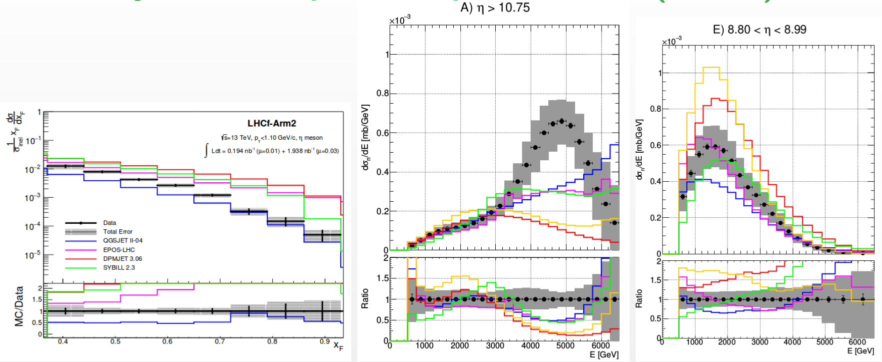
$*$ New measurement of $\sigma_{TOT,inel}$ in pp at $\sqrt{s} = 13$ TeV by ATLAS ALFA (a few mb below TOTEM one) propagates on

$\rightarrow$ $\sigma_{TOT,inel}(p - Air)$ smaller by about 10% at the highest E_p.

$\rightarrow$ shift in $\langle X_{max} \rangle$ (2% deeper than before, in EPOS-LHC-R)

$\rightarrow$ $< lnA >$ deduced by X_{max} $\sim$ 15% larger (muon deficit reduced)

Extremely-forward particle production (LHCf)



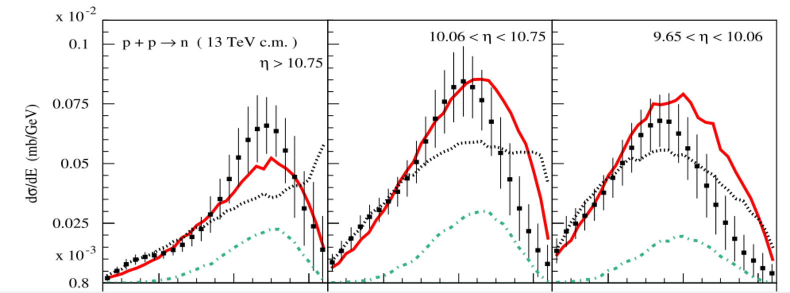
from LHCf collab., [arXiv:2305.06633], JHEP 20 (2020) 16

∗ Strangeness enhancement ? Too many η's at large x_F.

∗ in the past, no MC able to reproduce $d\sigma/dE$ of far-forward neutrons ($\eta > 10.75$),
but the agreement is qualitatively better for $\eta < 9$.

⇒ data useful for improving hadronic interaction models

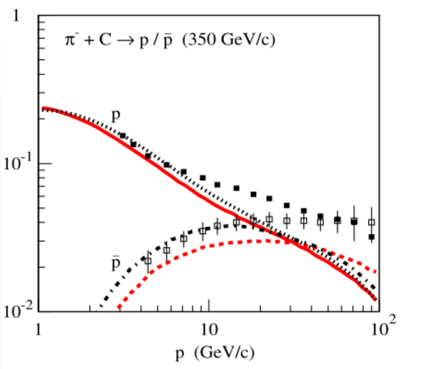
Extremely-forward neutron production vs. LHCf

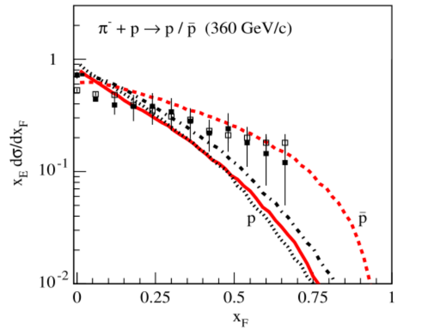


from S. Ostapchenko et al., PRD 109 (2024) 094019

In QGSJET-III the agreement of forward neutron production to LHCf experimental data improved with respect to QGSJET-II thanks to the incorporation of the pion exchange process.

Inconsistencies between data from different experiments ?





from S. Ostapchenko et al., PRD 109 (2024) 094019

$\ast$ proton/antiproton data from NA61 (left) and LEBC-EHS (right) are not reproduced equally well by QGSJET-II or III

$\ast$ Other possible inconsistencies for $K^{\pm}$ data from NA61 ($\pi^- C$) with NA49 (pp)

Take-home message

Global picture: μ puzzle can probably be solved by considering a sum of small effects.

Besides LHC measurements (with all possible detectors, including fixed-target and far-forward ν ones)

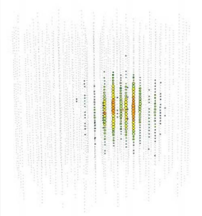
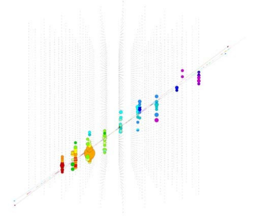
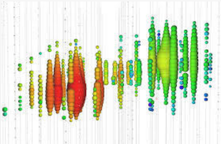
and studies at forthcoming EIC (initial conditions for QGP formation, how small a system can be and still show collectivity ?, radiation and hadronization in the nuclear medium ?),

even new measurements in astroparticle experiments (e.g. measurements of 2-dim distributions on a shower-by-shower basis, μ as a function of primary CR zenith angle, $\Lambda_\mu(X_{max})$, μ extraction from IceCube/IceTop.....)

will help to improve the hadronic-interaction generators and hopefully clarify the situation.

Experiments sensitive to high-energy astrophysical/atmospheric neutrinos

* Atmospheric neutrinos at ANTARES, IceCube, KM3NeT, Baikal-GVD... track / shower events from CC and NC $\nu + \bar{\nu}$ induced DIS in ice/water.

- lighter targets for DIS than in far-forward LHC experiments
- these experiments distinguish different flavour (like the LHC ones)
- these experiments do not distinguish ν and $\bar{\nu}$ (differently from LHC ones).
- these experiments do not have a ν and $\bar{\nu}$ pseudorapidity cut (differently from LHC ones).

Atmospheric neutrino fluxes

$CR + Air$ interactions:
- AA' interaction approximated as $A\ NA'$ interactions (super position);
- NA' approximated as $A'\ NN$ interactions: up to which extent is this valid ?

∗ conventional neutrino flux:

$$NN \rightarrow u, d, s, \bar{u}, \bar{d}, \bar{s} + X \rightarrow \pi^{\pm}, K^{\pm} + X' \rightarrow \nu_{\ell}(\bar{\nu}_{\ell}) + \ell^{\pm} + X',$$
$$NN \rightarrow u, d, s, \bar{u}, \bar{d}, \bar{s} + X \rightarrow K^0_S,\ K^0_L + X \rightarrow \pi^{\pm} + \ell^{\mp} + \overset{(-)}{\nu}_{\ell} + X$$
$$NN \rightarrow u, d, s, \bar{u}, \bar{d}, \bar{s} + X \rightarrow light\ hadron + X' \rightarrow \nu(\bar{\nu}) + X''$$

∗ prompt neutrino flux:

$$NN \rightarrow c, b, \bar{c}, \bar{b} + X \rightarrow heavy\text{-}hadron + X' \rightarrow \nu(\bar{\nu}) + X'' + X'$$

where the decay to neutrino occurs through semileptonic and leptonic decays:

$D^+ \rightarrow e^+ \nu_e X,\quad D^+ \rightarrow \mu^+ \nu_\mu X,$

$D_s^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + \tau^{\pm},$ with further decay $\tau^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + X$

proper decay lenghts: $c\tau_{0,\pi^{\pm}} = 780$ cm, $c\tau_{0,K^{\pm}} = 371$ cm, $c\tau_{0,D^{\pm}} = 0.031$ cm

Critical energy $\epsilon_h = m_h c^2 h_0 \,/\, (\mathrm{c}\ \tau_{0,h} \cos(\theta))$, above which hadron **decay** probability is suppressed with respect to its **interaction** probability:

$\epsilon_{\pi}^{\pm} < \epsilon_{K}^{\pm} << \epsilon_D \Rightarrow$ conventional flux is suppressed with respect to prompt one, for energies high enough, due to finite atmosphere height h_0.

Light flavour vs. heavy flavour

$*$ Light-flavoured hadrons include only light quarks as valence quarks in their composition.

$* \; m_u, \;\; m_d, \;\; m_s << \Lambda_{QCD}$

$\Rightarrow \alpha_S(m_u), \;\; \alpha_S(m_d), \;\; \alpha_S(m_s) \;\; > 1$

$\Rightarrow$ Light hadron production at low p_T is dominated by non-perturbative QCD effects.

$*$ Heavy-flavoured hadrons include at least one heavy-quark as valence quark in their composition.

$* \; m_c, \;\; m_b >> \Lambda_{QCD}$

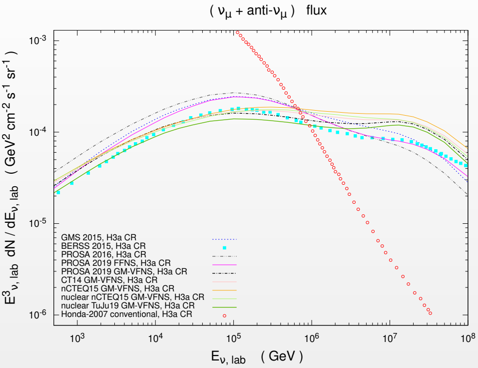
$\Rightarrow \alpha_s(m_c), \;\; \alpha_s(m_b), \;\; << 1$

$\Rightarrow$ At a scale $\sim m_Q$, QCD is still perturbative. At the LHC, charm is produced perturbatively (if one neglects possible intrinsic charm contributions) even at low p_T, but non-perturbative effects at such low scales may also play important roles. At the EIC, charm can also be produced by diffraction.

$* \; m_c, \;\; m_b <<$ LHC energies

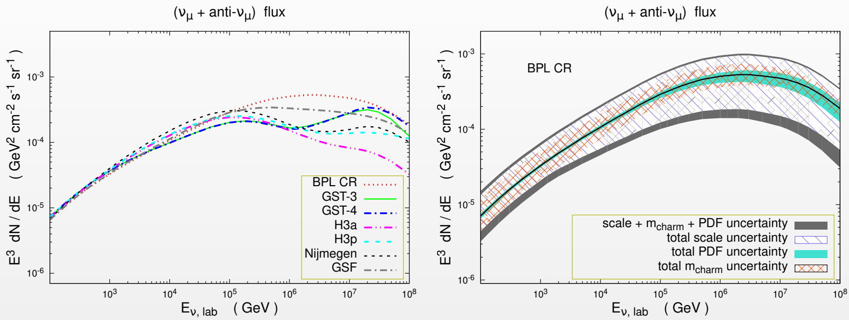
$\Rightarrow$ Multiscale issues, appearence of large logs.

$(\nu_\mu + \bar{\nu}_\mu)$ atmospheric fluxes: conventional $\to$ prompt transition



* Atmospheric ν from solving a system of coupled differential eqs. for the variation of fluxes of different particles as a function of the atmospheric depth.
* Honda-2007 conventional flux reweighted with respect to a more modern CR primary spectrum (H3a).
* central GM-VFNS, PROSA, BERSS and GMS flux predictions all yield to a very similar transition point $E_\nu \sim (6-9) \cdot 10^5$ GeV.
* Transition prompt conventional absent at colliders

Uncertainties on prompt neutrino fluxes

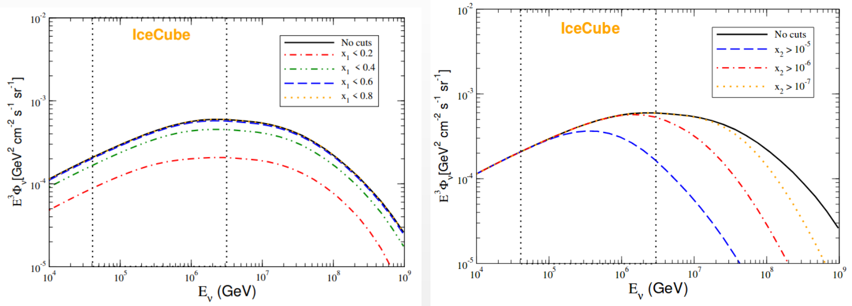


∗ Uncertainties in CR composition turn out to be smaller than QCD uncertainties. but still sizable ⇒ EAS CR experiments shall reduce them

∗ QCD uncertainties include here:

- renormalization and factorization scale variation
- charm mass
- parton distribution functions

Prompt atmospheric ν fluxes, small-x and large-x PDFs



, *from V. Goncalves et al. [arXiv:1708.03775]*

∗ A robust estimate of large x effects is important for determining the normalization of prompt atmospheric neutrino fluxes

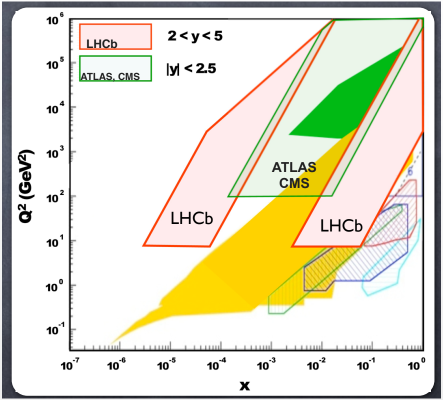
∗ Region particularly relevant: $0.2 < x < 0.8$, partly testable through ν experiments at the LHC.

∗ On the other hand, for ν at the PeV scale, knowledge of PDF down to $x > 10^{-6}$ is enough.

LHC heavy-flavour data coverage of the (x, Q^2) *plane*

- LHCb open-charm data ($2 < y < 4.5$)
- ATLAS (and CMS) open-charm data ($|y| < 2.5$)
- CDF open-charm data ($|y| < 1$)
- ALICE open-charm data ($|y| < 0.5$)

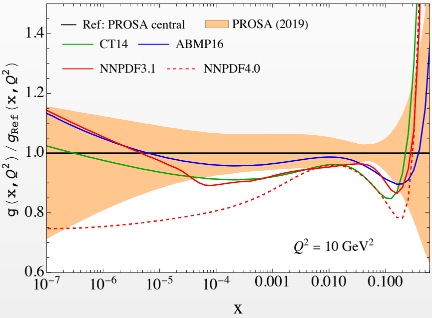
\+ further open-bottom data



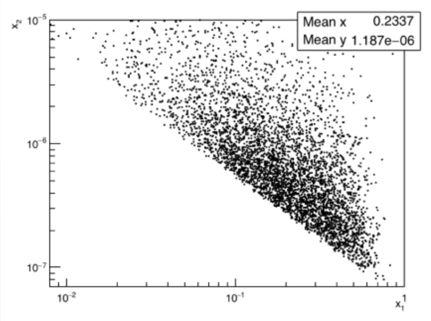
Different experiments span (Q^2, x) regions partially overlapping: good for verifying their compatibility and for cross-checking their theoretical description.

Description of similar quality for all these data so far.

PDFs uncertainties at low and large-x and x coverage of forward ν LHC exp.



W. Bai et al., [arXiv:2212.07865]



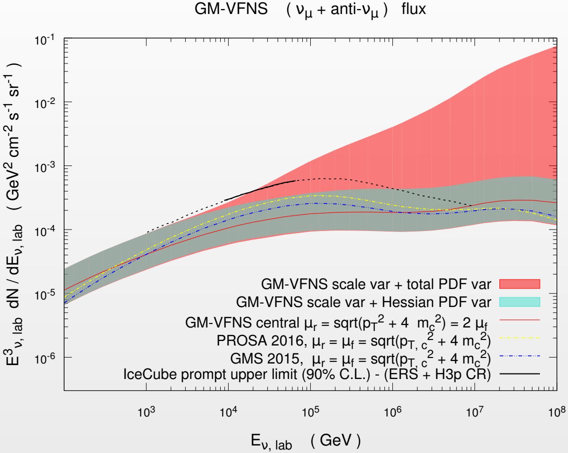
SND@LHC technical proposal (2021)

∗ Differences in gluon PDFs at large x are not covered by the uncertainties associated to each single PDF set.

∗ The coverage of forward ν experiments can help constraining PDFs at extreme x-values (actually more extreme than what is needed for atmospheric prompt ν at the PeV scale). Even measurement of prompt neutrino fluxes at IceCube/KM3NeT can help.

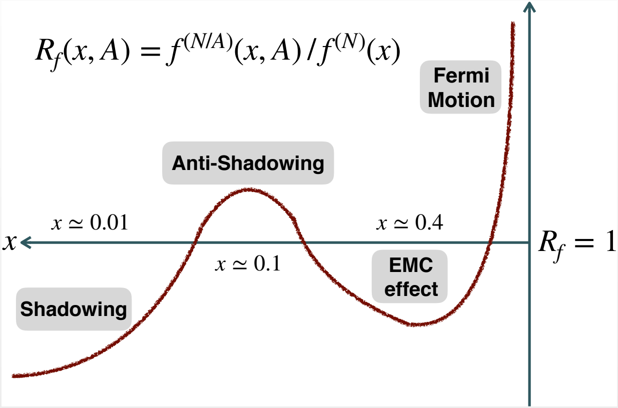
Prompt neutrino fluxes with GM-VFNS:

theoretical predictions from [arXiv:1705.10386] vs. IceCube upper limits



The extrapolation to high energy of IceCube results suggest that the CT14nlo gluon PDF uncertainty band at low x's is too large! ⇒ Constraints on PDFs complementary to those obtained at man-made experiments (fixed-target and HERA, LHC colliders)

Nuclear PDFs / p PDF: nuclear modification factors



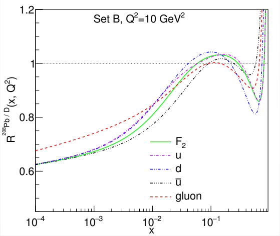
Schematic representation of different types of nuclear modifications that are expected to arise in nuclear PDFs, $f^{(N/A)}$, when presented as ratios to their free-nucleon counterparts, $R_f = f^{(N/A)} / f^{(N)}$.

from [arXiv:1904.00018]

Nuclear modification factors R_p^{Pb}

∗ Shadowing: $R < 1$ for $x \lesssim 0.1$ (a possible explanation: parton r ecombination/fusion process enhanced in nuclear target: partons with large spatial uncertainties (small x), can leak to a neighbor nucleon)

∗ Antishadowing: $R > 1$ for $0.1 \lesssim x \lesssim 0.3$, related to sha dowing.



from [arXiv:1611.03670]

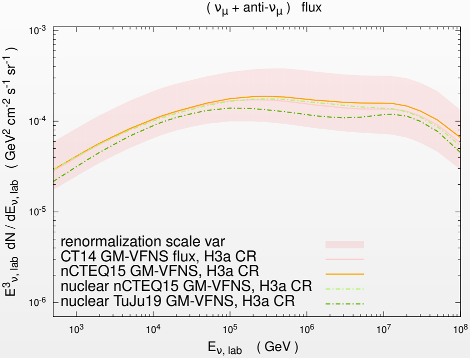
∗ EMC effect: $R < 1$ for $0.3 \lesssim x \lesssim 0.7$ (attributed to in-m edium nucleon swelling, nucleon-nucleon short range correlations, binding, ...).

∗ Fermi smearing: $R > 1$ for $0.7 \lesssim x < A$ short range nucleon correlations deform the nuclear structure functions mainly at large x.

No explicit modelization of nuclear effects occurs in most global fits of nPDFs. The modifications of the structure functions by nuclear effects are absorbed into the nPDF themselves.

⇒ Evergreen questions: how to write a parameterization for nPDFs ?

$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: cold nuclear matter effects



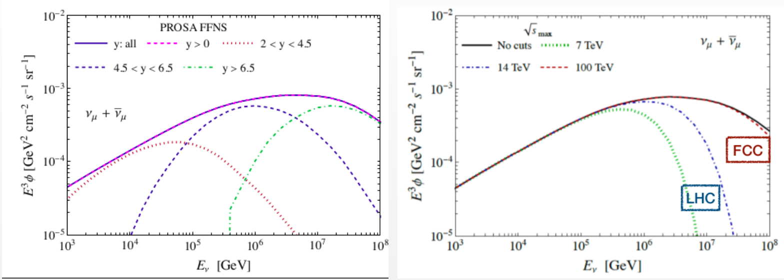
* Predictions using nuclear PDFs within scale uncertainty bands of those with proton PDFs and superposition model.

* Suppression of prompt fluxes due to CNM effects ? only moderate shadowing for low-mass nuclei....
  $\Rightarrow$ to be better tested at future colliders and in *pO* measurements at the LHC.

Wishlist useful measurements LHC, especially LHCb

* D-meson and B-meson spectra at 13.6 TeV, 14 TeV.
* if possible, more p_T bins in the region 0 - 5 GeV
* $\Lambda_c^\pm$ double-differential spectra in y, p_T.
* Additional focus on $D_s^\pm$ (main source of ν_τ and $\bar{\nu}_\tau$).
* Charge asymmetries with better statistics.
* All above in pp, pPb, pO standard collider modality
  + SMOG fxixed-target modality using various light targets.
* LHCb measurements of DY and $t\bar{t}$-pair production in pp.
* Measurements should be accompanied by detailed information concerning systematic uncertainties (correlation matrices).
* Further measurements of correlations between D-mesons from c and $\bar{c}$ help to stress-test theory predictions and to test predictions in factorization schemes beyond collinear one.

Prompt atmospheric ν fluxes and LHC phase-space coverage



∗ To connect to prompt ν fluxes at the PeV, LHC measurements of charm production should focus on the region $4 < y_c < 7$.

∗ The $\sqrt{s} = 14$ TeV at LHC is in any case a limitation, FCC would be better (see also analysis in V. Goncalves et al, [arXiv:1708.03775]).

∗ Exploring the connection between (E_ν, y_ν) and y_c reveals that there is some kinematic overlap between the heavy-flavour production region explored in far-forward ν experiments at the LHC and in the atmosphere.

Conclusions - prompt ν

* Prompt neutrino fluxes in the atmosphere are a background to neutrinos from far astrophysical sources.

* Theory uncertainties still large and constraints from VLVνT still loose. Computing higher-order corrections is an indispensable ingredient for reducing these uncertainties.

* Synergy collider experiments (LHC, EIC, ...) / astroparticle physics:

- EIC will help better constraining cold nuclear matter effects for light nuclei (closer to atmosphere), however for prompt neutrinos we need this at small x.

- EIC might help better understanding charm fragmentation.

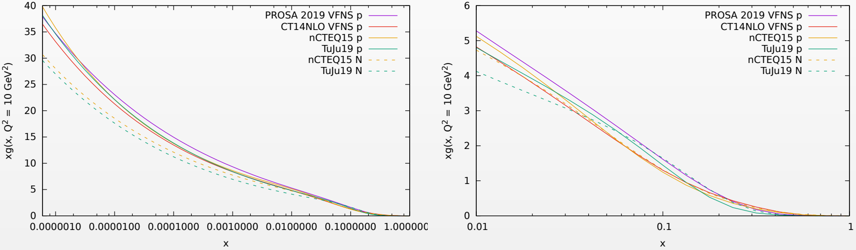
- There is some kinematical overlap between the charm hadron production region explorable in far-forward experiments at the LHC and the one explorable in VLVνT's.

- Atmospheric ν's with $E_{\nu,LAB} \sim \mathcal{O}(\text{PeV})$ mostly come from charm produced within LHC $\sqrt{s}$ in the rapidity range $4.5 < y_c < 7.2$, which in turn produce neutrinos even in the ν rapidity range of the SND@LHC detector $\eta_\nu > 7.2$ and future (like in the FPF).

Thank you for your attention!

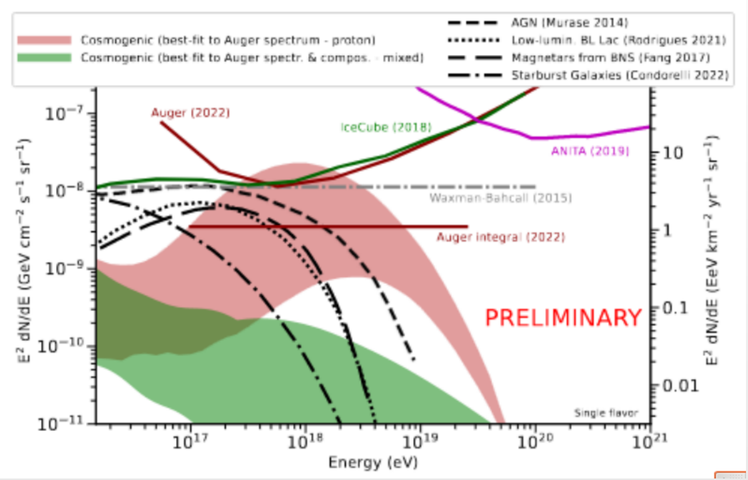
Back-up slides

gluon PDFs in Proton and Nitrogen



* N gluon PDFs at low x slightly suppressed w.r.t. p ones, but still in the uncertainty bands of the latter.
* N gluon PDFs at large x resemble the p ones: no antishadowing effects.

Limits on the neutrino diffuse flux from the PAO - Phase I



from PAO collaboration, PoS(ICRC 2023) 016