LHC/EIC impact on Cosmic Ray physics

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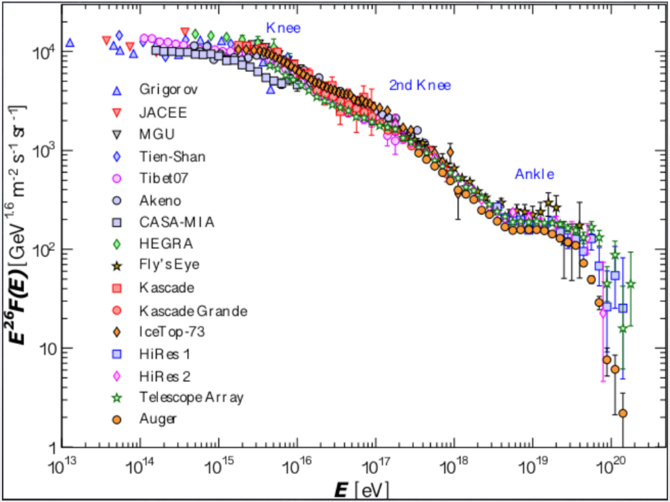
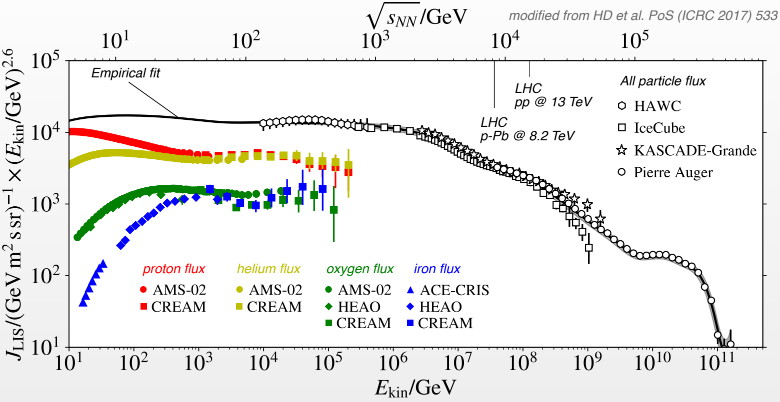
The all particle CR flux as a function of primary energy - I



* charged ions, detected by many different experiments
* spectrum spans 11 orders in E and > 30 orders in flux intensity
* origin of the features ?

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

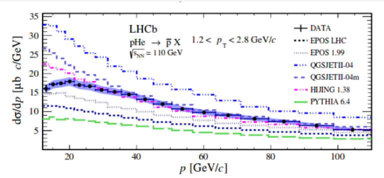


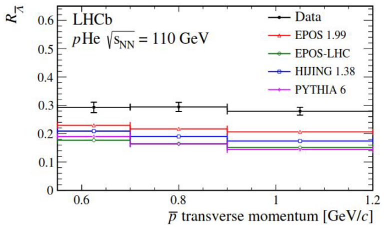
* we are interested in E, arrival direction, mass A, event-by-event to understand CR origin (multimessenger approach: γ, μ, GW signals can help)
* direct detection for $E <$ 100 TeV
* indirect detection for $E >$ 100 TeV (E, A reconstructed from EAS products: E from size of e, γ component, A from X_{max}, 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]
⇒ 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.



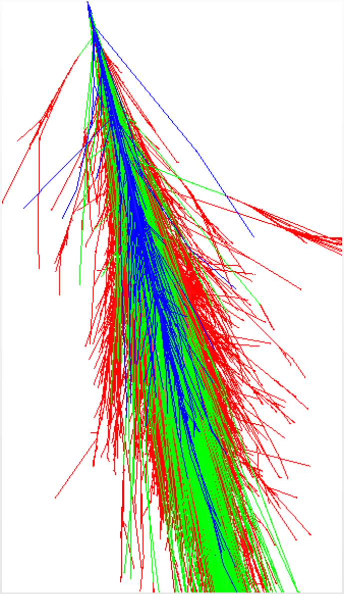


∗ prompt and detached production, via antihyperon decay:
$\bar{\Omega}^+ \rightarrow \bar{\Lambda} K^+$, $\bar{\Xi}^0 \rightarrow \bar{\Lambda}\pi^0$, $\bar{\Xi}^+ \rightarrow \bar{\Lambda}\pi^+$, $\bar{\Sigma}^- \rightarrow \bar{p}\pi^0$, with $\Lambda \rightarrow \bar{p}\pi^+$

∗ 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 $\bar{n}$ production

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.

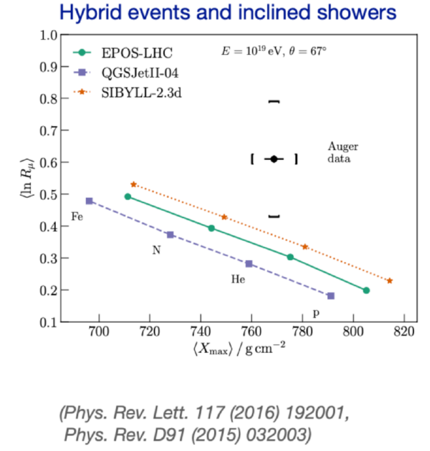
Although Monte Carlo generators for EAS have been tuned to LHC data (which has decreased the differences in their predictions), there is no way to describe simultaneously multiple EAS observables by a unique simulation:

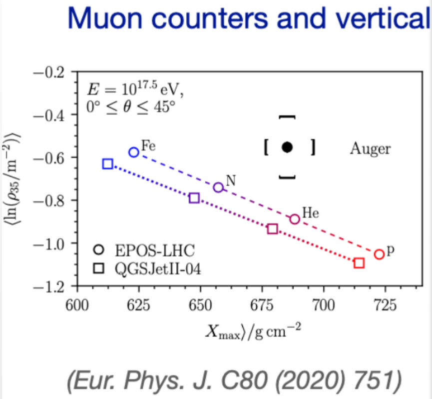
$$< X_{max} >, \sigma(X_{max}), N_\mu, \sigma(N_\mu), < X_{max}^\mu >, ...$$

$\Rightarrow$ 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.

The μ problem

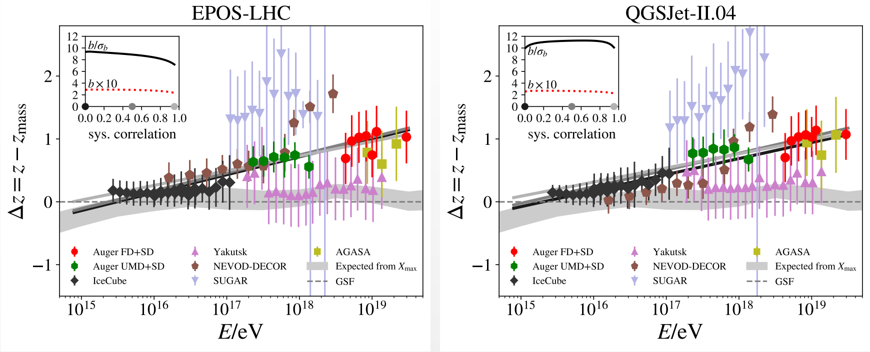




N_μ predictions from composition inferred from $\langle X_{max} \rangle$ are inconsistent with N_μ data.

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

Universality of the μ problem



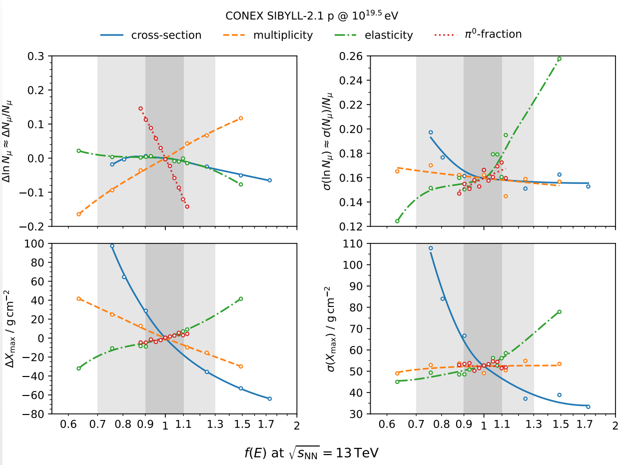
from J. Albrecht et al., [arXiv:2105.06148]

∗ issue for all generators and all 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

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 xsymmetry 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

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

- chiral symmetry restoration
- fireballs
- strangeballs
- QGP
- CGC

∗ 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

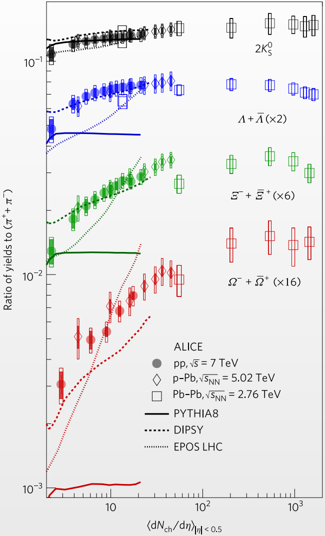
∗ signature of QGP or something else ?

∗ 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 inversely proportional to the temperature, instead of a unique deconfined system of quarks and gluons, could be formed

→ practical realization: core-corona

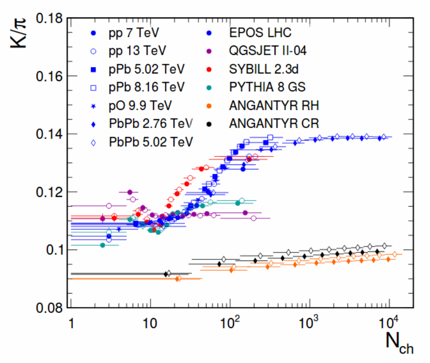
∗ Strangeness enhancement in forward direction ? LHCb results eagerly wanted.

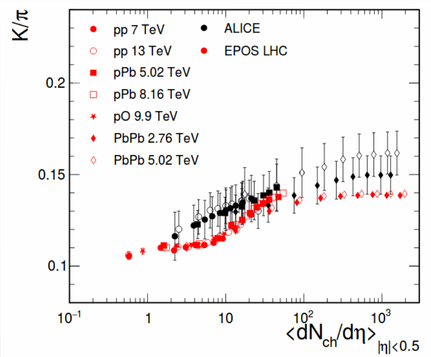


from ALICE collab., Nature Phys. 13 (2017) 535-539

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}

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

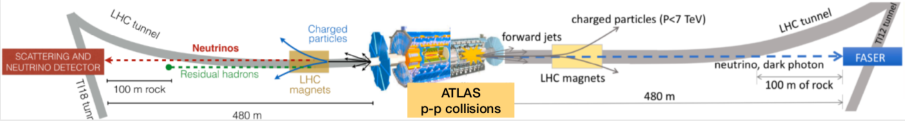
$*$ (R, N_{ch}), $(K/\pi, R)$ correlations

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.

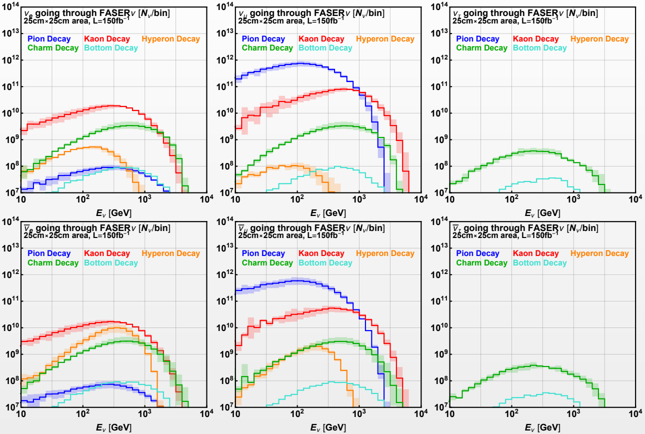
* Let these beams propagating for some distance: some particles will be deviated or stopped, some other will reach the detector.

* 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 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:

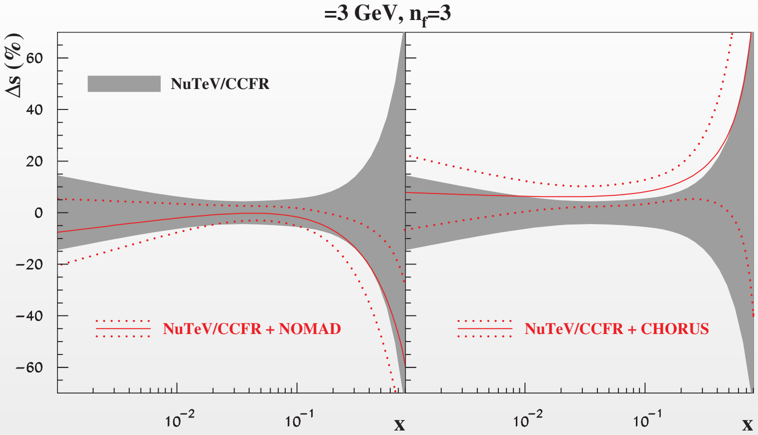
- massive high-density detectors providing dimuon data (CDHS, CDHSW, CCFR, CharmII, NuTeV, NOMAD)
- bubble chamber data (BEBC)
- nuclear emulsions (E531, CHORUS)

∗ The incapability of simultaneously obtaining a good fit of all previous ones has led the PDFs and nPDF collaborations to discharge some data (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

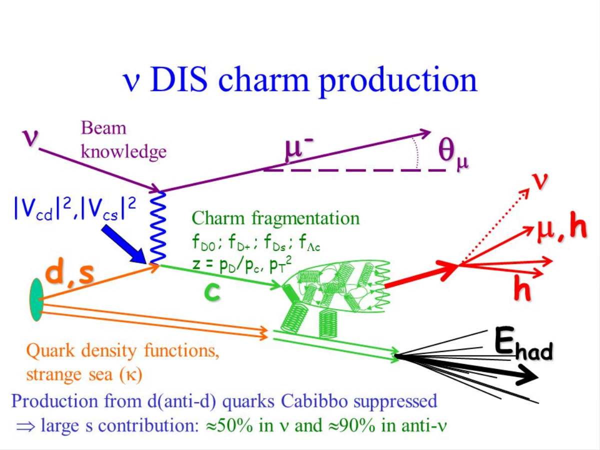
∗ NOMAD data (dimuon/inclusive CC DIS) pull down s for $x > 0.1$.

∗ 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 pO, OO LHC runs in 2024

$*$ 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

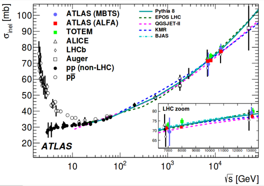
$*$ Measurement of $\sigma_{TOT,inel}(pO)$, to which $\langle X_{max} \rangle$ is sensitive.

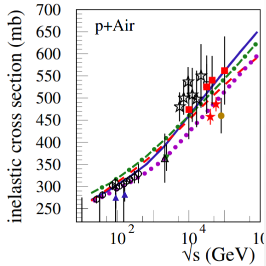
$*$ Forward neutron production detected by ZDC allow to access single diffractive processes with π^0 exchange, and forward proton production detected by FPS allow to access single diffractive processes with pomeron exchange.

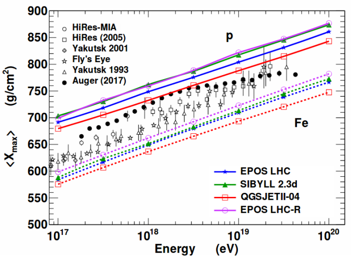
$*$ $+$ many other physics opportunities

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

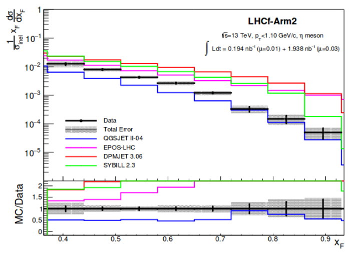
$*$ New measurement of $\sigma_{TOT,inel}$ in pp at $\sqrt{s} = 13$ TeV by ATLAS ALFA (a few mb below TOTEM one) propagates on

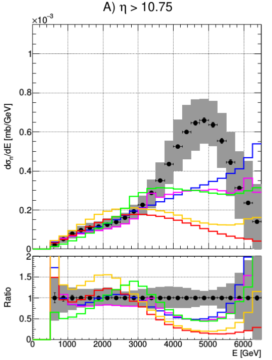
$\rightarrow$ $\sigma_{TOT,inel}(p - Air)$ smaller by about 10% at the highest E_p.

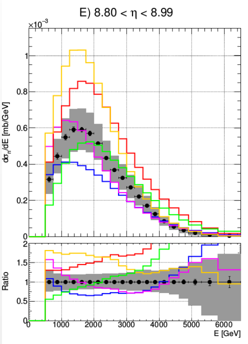
$\rightarrow$ shift in $\langle X_{max} \rangle$ (2% deeper than before, in EPOS-LHC-R)

$\rightarrow$ $< lnA >$ 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.
* 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

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 far-forward ν ones)

and studies at 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. μ as a function of primary CR zenith angle, μ extraction from IceCube/IceTop.....)

will help to clarify the situation.

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 $\epsilon_h = m_h c^2 h_0\ /\ (c\ \tau_{0,h} \cos(\theta))$, 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.

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

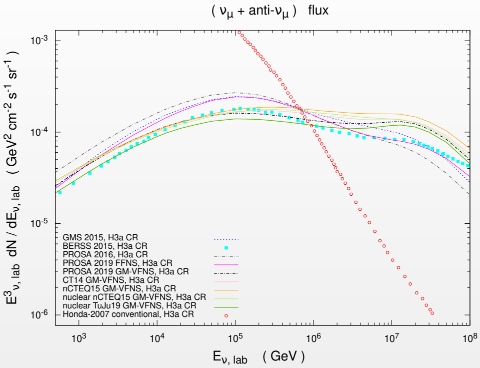
$\Rightarrow \alpha_s(m_c), \;\; \alpha_s(m_b), \;\; << 1$

$\Rightarrow$ 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

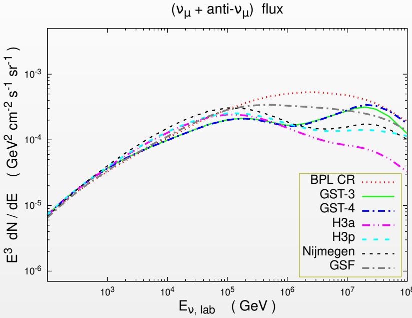
$\Rightarrow$ Multiscale issues, appearence of large logs.

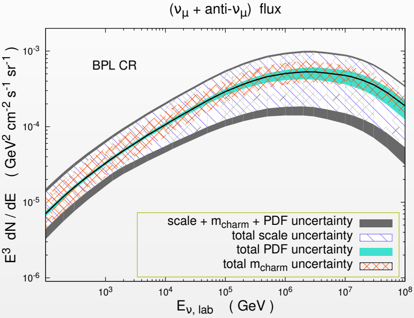
$(\nu_\mu + \bar{\nu}_\mu)$ atmospheric fluxes: conventional $\rightarrow$ prompt transition



* 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

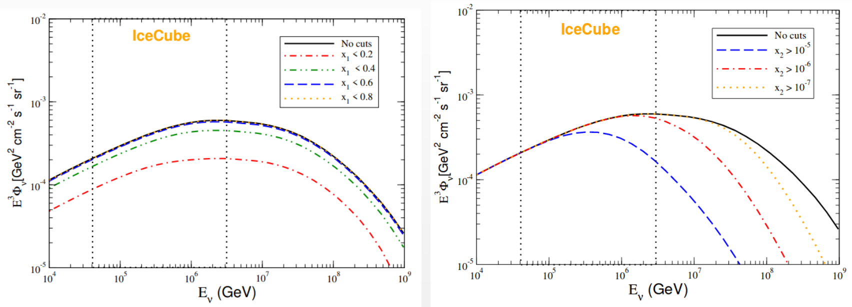
Uncertainties on prompt neutrino fluxes





- Uncertainties in CR composition turn out to be smaller than QCD uncertainties.
- 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]*

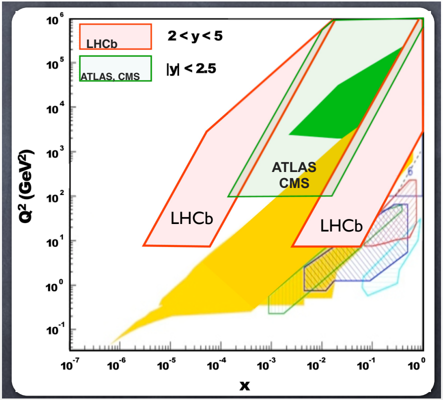
$*$ A robust estimate of large x effects is important for determining the normalization of prompt atmospheric neutrino fluxes

$*$ 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

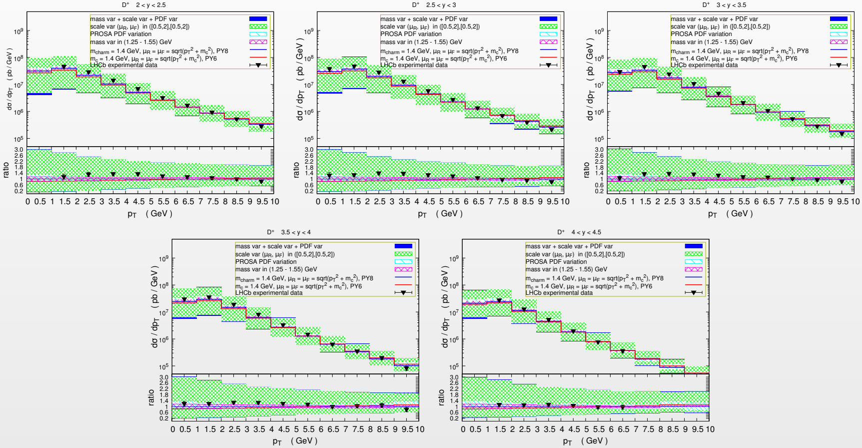


Different experiments span (Q^2, x) regions partially overlapping: good for verifying their compatibility and for cross-checking their theoretical description.

Description of similar quality for all these data so far.

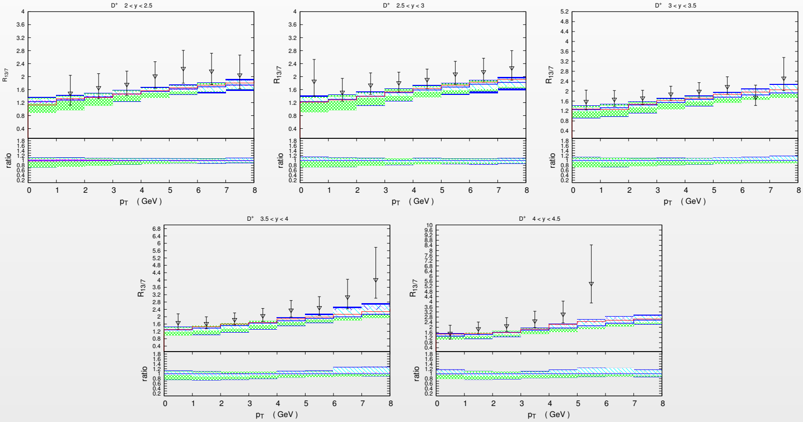
NLO+PS differential σ vs experimental data

for differential cross-sections for $pp \to D^{\pm} + X$ at LHCb at 5 TeV



* agreement theory/experiment within large (μ_R, μ_F) uncertainty bands.
* theory uncertainties much larger than the experimental ones.

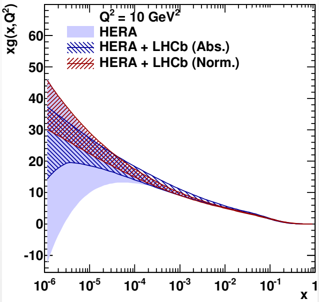
Ratios of theory predictions at different energies vs. 13/7 LHCb experimental data - $pp \rightarrow D^{\pm} + X$

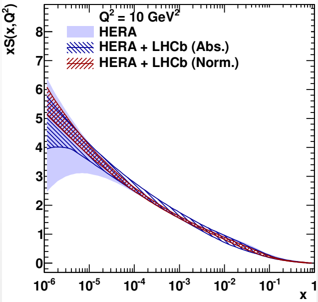


- ∗ Uncertainty shrinks in ratios.
- ∗ Also observe that predictions of very different methodologies (NLO+PS+hadronization) vs. (GM-VFNS NLO + FF) are compatible within present uncertainty bands.

PROSA 2015 PDF fit: comparison between three variants

from PROSA collab., EPJC 75 (2015) 471





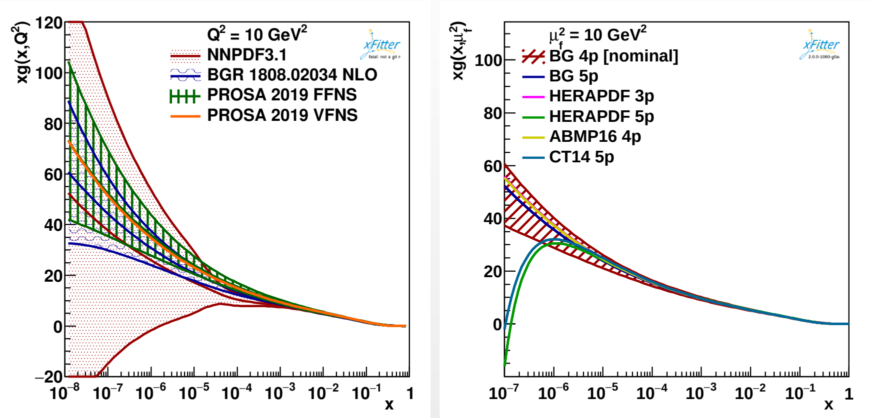
Three variants of the PDF fit:

1) one with HERA data only (behaviour at low (x, Q^2) driven by parameterization and sum rules);

2) one also including LHCb absolute differential cross-sections;

3) another one with reduced uncertainties: for each fixed LHCb p_T bin, use the ratios of distributions $(d\sigma/dy)/(d\sigma/dy_0)$ considering different rapidity intervals (i.e. normalized to the central bin $3 < y_0 < 3.5$):
in the ratios theoretical uncertainties partly cancel.
Shapes of rapidity distributions are fitted.

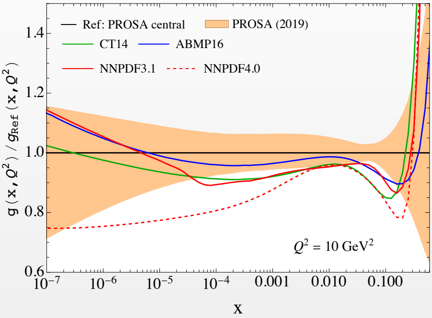
gluon PDF: comparison between different PDF fits, parameterizations



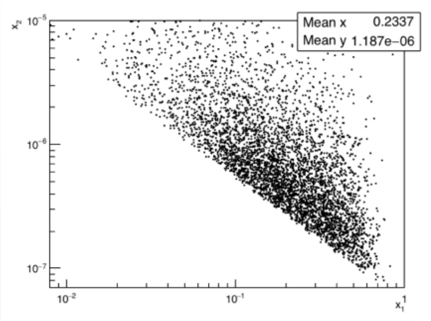
∗ Compatibility of indipendent PDF fits including *D*-meson data.

∗ However, sensitivity to the parameterization, as soon as one exits the region covered by data.

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



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

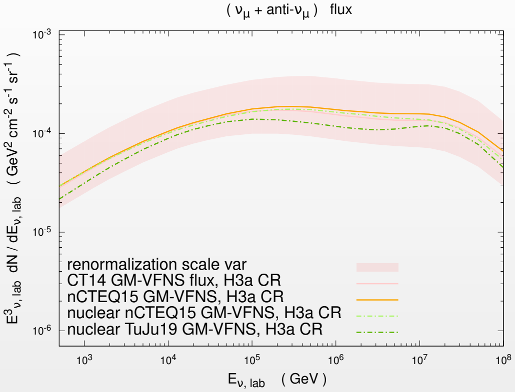


SND@LHC technical proposal (2021)

∗ 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).

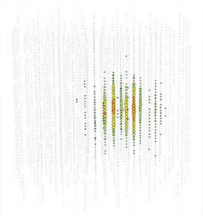
$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: cold nuclear matter effects

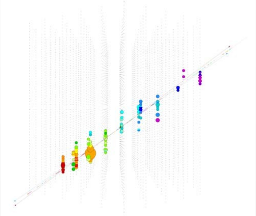


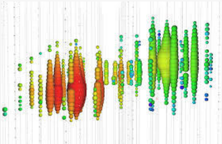
- ∗ Predictions using nuclear PDFs within scale uncertainty bands of those with proton PDFs and superposition model.
- ∗ Suppression of prompt fluxes due to CNM effects ?
  only moderate shadowing for low-mass nuclei....
  ⇒ to be better tested at future colliders.

Experiments sensitive to high-energy 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.

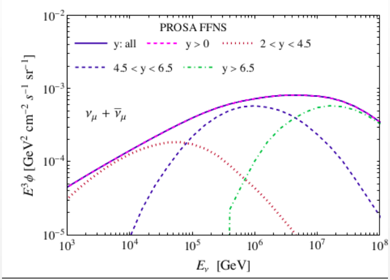


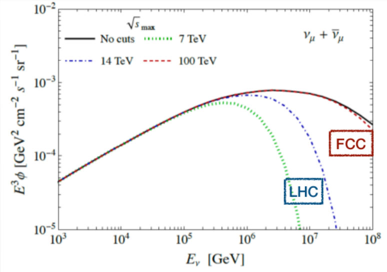




- lighter targets for DIS than in far-forward LHC experiments
- these experiments distinguish different flavour (like the LHC ones)
- these experiments do not distinguish ν and $\bar{\nu}$
  (differently from LHC ones).
- these experiments do not have a ν and $\bar{\nu}$ pseudorapidity cut
  (differently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

Prompt atmospheric ν fluxes and LHC phase-space coverage



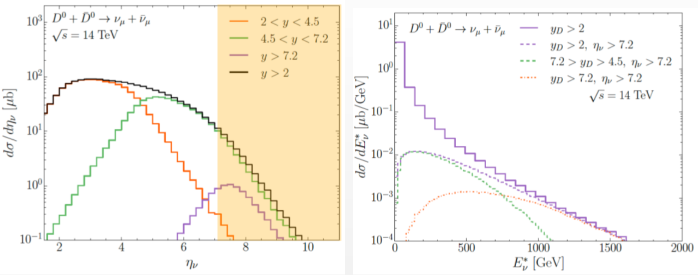


* To connect to prompt ν fluxes at the PeV, LHC measurements of charm production should focus on the region $4 < y_c < 7$.

* 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.

Prompt ν fluxes at the LHC



$*$ At the LHC, charmed mesons with $4 < y_c < 7$ give rise to neutrino populating a wide rapidity spectrum, with a maximum around $\eta_\nu \sim 5$.

$*$ These neutrinos constitutes the majority of neutrinos for $\eta_\nu \gtrsim 7.2$ (region probed by SND@LHC, and at future FPF).

$*$ The energy spectrum of these neutrinos is peaked at $\sim$ 100 GeV in CM frame, but extends also to the TeV. For $E_\nu \sim 700$ GeV half neutrinos at the LHC come from charm with $4.5 < y_c < 7.2$, whereas another half come from charm with $y_c > 7.2$. On the other hand, most energetic neutrinos at the LHC come from charmed mesons with higher rapidities.

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 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!