Prompt neutrinos in the atmosphere vs. LHC where do we stand ?

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based on work in collaboration with
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Hamburg Universität, II Institut für Theoretische Physik

Seminar at the Eötvös Loránd TudományEgyetem, Budapest, March 19th, 2024

Measured or Predicted Neutrino fluxes

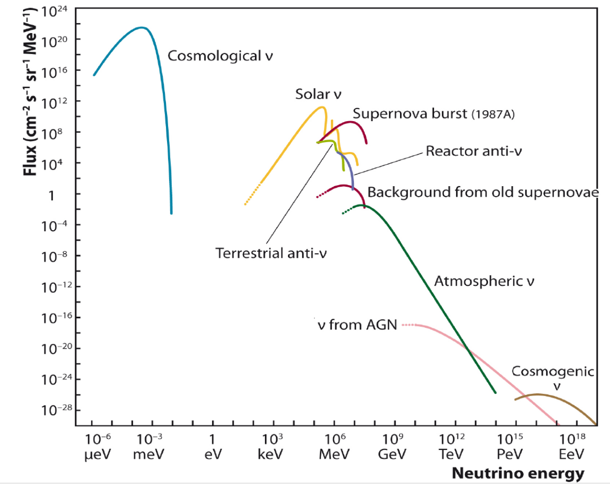
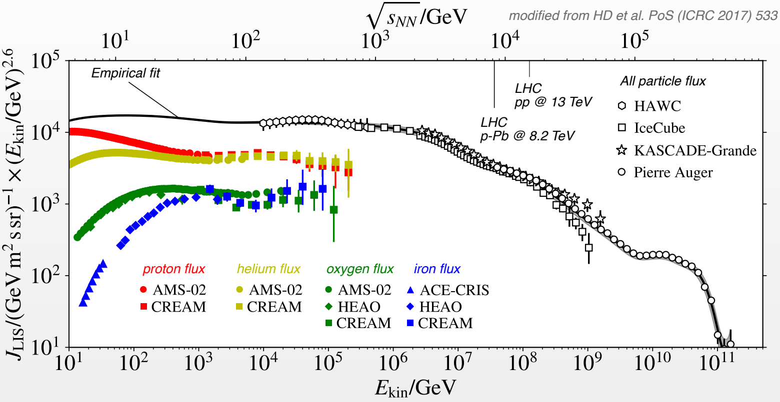


figure from U. Katz and C. Spiering Prog. Part. Nucl. Phys. 67 (2012) 651-704

- ∗ Detected: solar, Supernovae, atmospheric, geoneutrinos, astrophysical
- ∗ Not yet detected with certainty or directly: cosmological CνB, cosmogenic (UHECR + CMB γ's and UHECR + EBL γ's)
- ∗ Created in the laboratory: reactors, accelerators

The all particle CR flux as a function of primary energy



* 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

Neutrino Astronomy

- Observation of high-energy ν's by large volume neutrino telescopes, as a window to better understand the high-energy Universe, in particular the relation between these ν and high-energy Cosmic Rays, and particle acceleration in possible galactic and/or extragalactic sources (AGNs, etc....).
- This is possible thanks to
  - ν weak interactions only ($\neq$ Cosmic Rays)
  - ν propagation not bended by galactic and extra-galactic magnetic fields ($\neq$ Cosmic Rays)

Very Large Volume Neutrino Telescopes

$*$ First idea to use lake or sea water as an extended target for ν interactions was suggested by Markov in $\sim$ 1960 $\Rightarrow$ Neutrino Telescopes.

$*$ ν_l / $\bar{\nu}_l + N \rightarrow \ell^\pm + X$, with $\ell^\pm$ emitting Cherenkov light detected by PMTs in water:

- time, position and amplitude of the photon signal allow to reconstuct $\ell^\pm$ trajectory;
- total amount of light allows to reconstruct the energy of the event.

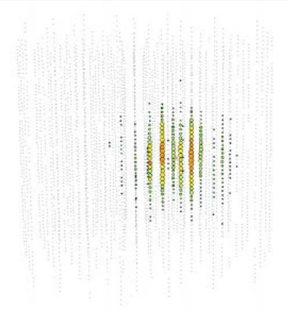
$*$ under-water neutrino telescopes: Baikal, upgraded to Baikal-GVD and ANTARES/NEMO/NESTOR, now working in a joint effort towards a full KM3NeT Mediterranean Neutrino Observatory, with an instrumented volume similar to that of IceCube.

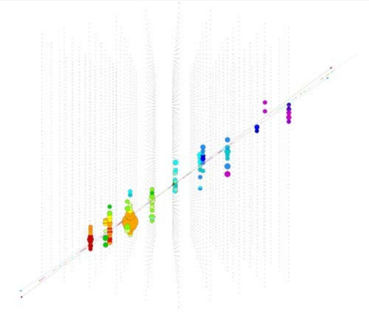
$*$ in-ice neutrino telescopes: IceCube 1 km^3 instrumented volume already allowed for the actual detection of a high-energy ν flux

Event topologies @ VLVνTs

Events @ VLVνTs are classified according to the following topologies in the Optical Modules:

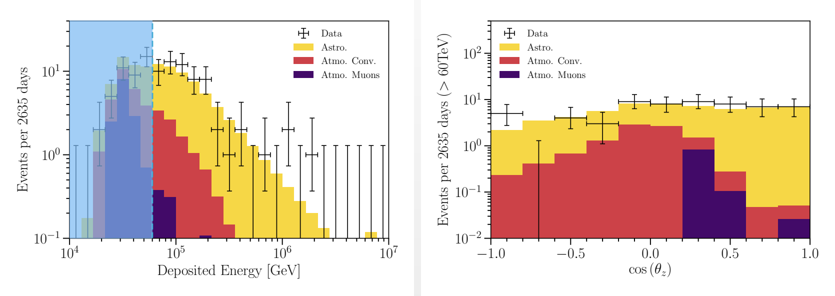
- shower events: produced by ν_e
- track events: produced by ν_μ
- double-bang events: two showers, one from ν_τ interaction products (except τ) and the second, displaced, from τ decay.
- sizable background due to atmospheric μ: only from the Northern Hemisphere, smaller for horizontal events than for vertical ones.





IceCube HESE analysis

∗ **2020**: 2635-day analysis, with a total of **102** events (42 with $E < 60$ TeV and 60 with $E > 60$ TeV).
The last ones are compatible with a single power spectrum with spectral index $\Gamma = -2.87^{+0.20}_{-0.19}$.
No new events with deposited energy above 450 TeV with respect to the previous analyses !



2020 best fit of the (astrophysical + atmospheric) components vs. experimental data

from IceCube collaboration, [arXiv:2011.03545 [astro-ph]]

* high-energy diffuse flux further tested by ANTARES and testable by KM3NeT/ARCA

* HESE analysis, extended in **2023** to MESE one (lower energies, down to $E_\nu > 1$ TeV) *[arXiv:2307.15183]*

Candidate sources for HESE considered in literature

1) Astrophysical Sources:

extragalactic: AGNs (Quasars, Blazars, also including BL Lacs), GRBs, Starburst galaxies, galaxy clusters...

galactic: SNRs, pulsars, microquasars, Fermi bubbles, Galactic halo

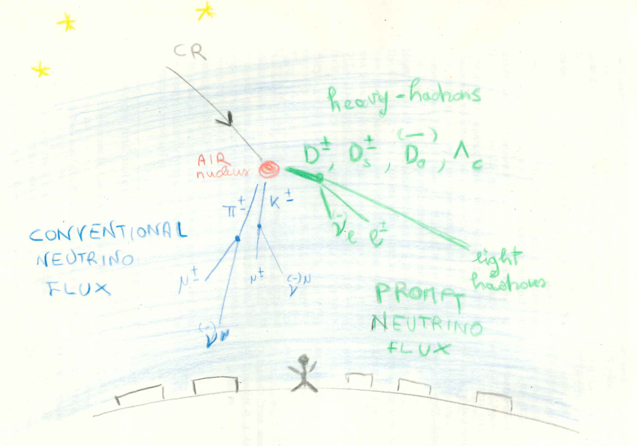
2) Heavy DM decay, DM-DM annihilation

3) Atmospheric leptons

May be a combination of some of the previous ones ?

For sure, precise predictions/measurements of the atmospheric ν fluxes have to be taken into account in the analyses, because they represent a "background" for any astrophysical or BSM hypothesis.

Atmospheric ν flux: conventional and prompt components



Cosmic Rays + Atmospheric Nuclei → hadrons → neutrinos + X

* Two contributing mechanisms, following two different power-law regimes:
  - **conventional** ν flux from the decay of $\pi^{\pm}$ and $K^{\pm}$
  - **prompt** ν flux from charmed and heavier hadrons (D's, $\Lambda_c^{\pm}$'s.....)
* **Transition point**: still subject of investigation......

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:
$D^+ \rightarrow e^+\nu_e X$, $D^+ \rightarrow \mu^+\nu_\mu X$,
$D_s^{\pm} \rightarrow \nu_\tau(\bar{\nu}_\tau) + \tau^{\pm}$, 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.

Conventional $\rightarrow$ prompt transition

Prompt fluxes expected to dominate above $E_{lab,\nu} > 10^5$ - 10^6 GeV, depending of the flavour and zenith angle.

Investigating the transition requires accurate computation of both fluxes:

– predictions for conventional fluxes at high energies are more uncertain than at lower ones.

– same applies to prompt fluxes.

– characterizing the transition point is important for an explicit detection of prompt fluxes.

– Possible computation of both fluxes in a consistent framework. But the physics of the interactions at the core of the two fluxes differs.

Light flavour vs. heavy flavour

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

∗ m_u, m_d, $m_s << \Lambda_{QCD}$
⇒ $\alpha_S(m_u)$, $\alpha_S(m_d)$, $\alpha_S(m_s) > 1$
⇒ 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, $m_b >> \Lambda_{QCD}$
⇒ $\alpha_s(m_c)$, $\alpha_s(m_b)$, $<< 1$
⇒ At a scale $\sim m_Q$, QCD is still perturbative. At the LHC, charm is produced perturbatively even at low p_T, but non-perturbative effects at such low scales may also play important roles.

∗ m_c, $m_b <<$ LHC energies
⇒ Multiscale issues, appearence of large logs.

How to get atmospheric fluxes? From cascade equations to Z-moments [*review in Gaisser, 1990; Lipari, 1993*]

Solve a system of coupled differential equations regulating particle evolution in the atmosphere (interaction/decay/(re)generation):

$$\frac{d\phi_j(E_j,X)}{dX} = -\frac{\phi_j(E_j,X)}{\lambda_{j,int}(E_j)} - \frac{\phi_j(E_j,X)}{\lambda_{j,dec}(E_j)} + \sum_{k\neq j} S_{prod}^{k\to j}(E_j,X) + \sum_{k\neq j} S_{decay}^{k\to j}(E_j,X) + S_{reg}^{j\to j}(E_j,X)$$

Under assumption that X dependence of fluxes factorizes from E dependence, analytical approximated solutions in terms of Z-moments:

– Particle Production:

$$S_{prod}^{k\to j}(E_j,X) = \int_{E_j}^{\infty} dE_k \frac{\phi_k(E_k,X)}{\lambda_k(E_k)} \frac{1}{\sigma_k} \frac{d\sigma_{k\to j}(E_k,E_j)}{dE_j} \sim \frac{\phi_k(E_j,X)}{\lambda_k(E_j)} Z_{kj}(E_j)$$

– Particle Decay:

$$S_{decay}^{j\to l}(E_l,X) = \int_{E_l}^{\infty} dE_j \frac{\phi_j(E_j,X)}{\lambda_j(E_j)} \frac{1}{\Gamma_j} \frac{d\Gamma_{j\to l}(E_j,E_l)}{dE_l} \sim \frac{\phi_j(E_l,X)}{\lambda_j(E_l)} Z_{jl}(E_l)$$

Solutions for $E_j >> E_{crit,j}$ and for $E_j << E_{crit,j}$, respectively, are interpolated geometrically.

Z-moments for heavy hadron production and decay

- CR + Air interactions producing heavy hadrons (in particular including charm) parameterized in terms of p-p collisions
- Integration variable: $x_E = E_h/E_p$
- Z-moments for intermediate hadron production:

$$Z_{ph}(E_h) = \int_0^1 \frac{dx_E}{x_E} \frac{\phi_p(E_h/x_E)}{\phi_p(E_h)} \frac{A_{air}}{\sigma^{tot,inel}_{p-Air}(E_h)} \frac{d\sigma_{pp\to c\bar{c}\to h+X}}{dx_E}(E_h/x_E)$$

- These hadrons are then decayed semileptonically, producing leptons $(+X)$
- Integration variable: $x'_E = E_l/E_h$
- Z-moments for intermediate hadron decay:

$$Z_{hl}(E_l) = \int dx'_E \frac{\phi_h(E_l/x_{E'})}{\phi_h(E_l)} F_{h\to l}(x'_E)$$

Heavy-quark production in hadronic collisions

* Heavy quarks are mostly produced in pairs in the Standard Model.
  This process is dominated by QCD effects.

* Collinear factorization theorem is assumed:

$$d\sigma(N_1 N_2 \to Q\bar{Q} + X) = \sum_{ab} PDF_a^{N_1}(x_a, \mu_F) PDF_b^{N_2}(x_b, \mu_F) \otimes \\ \otimes \; d\hat{\sigma}_{ab \to Q\bar{Q}X'}(x_a, x_b, \mu_F, \mu_R, m_Q) \quad + \quad \text{P.C.}$$

$\mathrm{d}\hat{\sigma}$: differential perturbative partonic hard-scattering cross-section,

μ_F, μ_R reabsorb IR and UV divergences,

PDFs: perturbative evolution with factorization scale μ_F,
non-perturbative dependence on $x = p^+/P_N^+$.

QCD uncertainties

* μ_F and μ_R choice: no univocal recipe.
* Approximate knowledge of heavy-quark mass values m_Q (SM input parameters).
* Choice of the Flavour Number Scheme (several possibilities).
* PDF ($+\ \alpha_S(M_Z)$) fits to experimental data.

Flavour Number Schemes for heavy-flavour production

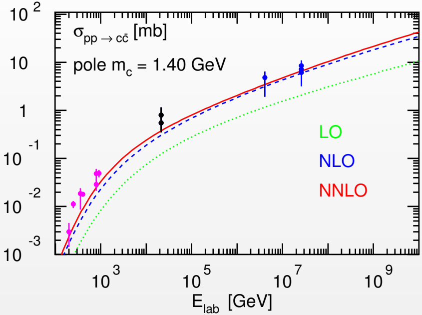
$m_l = m_u,\ m_d,\ m_s < \Lambda_{QCD} \rightarrow$ assumed massless always,
$m_{HQ} = m_c,\ m_b,\ m_t > \Lambda_{QCD}$ treatment depends on scheme
and, depending on the kinematics and $\sqrt{s}$, it may happen $p_{T,HQ} >> m_Q$ or $Q >> m_Q$

∗ **Decoupling scheme with a fixed flavour number** (FFNS):
- The mass of at least one (or more) HQ is retained at all scales
- HQ can be produced as final states and circulate in loops.
- They are excluded from initial states.
- Divergences due to light quark loops contributing to α_S renormalization are subtracted at zero mass (like in the $\overline{\mathrm{MS}}$ scheme), those due to heavy-quark loops are subtracted at zero momentum.
- **issue** at high p_T or Q: $\log\,(p^2_{T,HQ}/m^2_{HQ})$ or $\log\,(Q^2/m^2_{HQ})$ may become so big that they may spoil the convergence of the perturbative series!

∗ **Zero-mass variable flavour number scheme** (ZM-VFNS):
- HQ massless quarks at all scales in all components of the calculation.
- These quarks are present in the initial state above fixed thresholds.
- They contribute to α_S running (in the $\overline{\mathrm{MS}}$ scheme) above the same thresholds.
- **issue** at low p_T or Q: powers of $(m^2_{HQ}/p^2_{T,HQ})$ or of (m^2_{HQ}/Q^2_{HQ}) missing!

∗ **General-mass variable flavour number schemes** (GM-VFNS):
- HQ mass retained in part of the calculation; meant to combine optimal features of FFNS and ZM-VFNS at different p_T or Q.
- **advantage**: logs resummed and powers (at least the leading ones) present.
- **problem**: some arbitrariness in the combination (different variants possible)

Total $\sigma(pp \to c\bar{c}(+X))$ at LO, NLO, NNLO QCD



$(E_{lab} \simeq 400 \text{ GeV} \sim E_{cm} = 27 \text{ GeV})$

$(E_{lab} \simeq 7000 \text{ GeV} \sim E_{cm} = 114.6 \text{ GeV})$

$(E_{lab} = 10^6 \text{ GeV} \sim E_{cm} = 1.37 \text{ TeV})$
$(E_{lab} = 10^8 \text{ GeV} \sim E_{cm} = 13.7 \text{ TeV})$
$(E_{lab} = 10^{10} \text{ GeV} \sim E_{cm} = 137 \text{ TeV})$

data from fixed target exp (E769, LEBC-EHS, LEBC-MPS, HERA-B)
+ colliders (STAR, PHENIX, ALICE, ATLAS, LHCb)
are extrapolated from fiducial measurements.

* LHC fixed-target program make measurements in the region between old fixed-target experiments and RHIC (not covered by other exp.).
* Sizable QCD uncertainty bands not included in the figure.
* Leading order is not accurate enough for this process!

From parton production at NLO to heavy-flavour hadrons

Different descriptions of the transition are possible:

1) fixed-order QCD + Parton Shower + hadronization:
match the fixed-order calculation with a parton-shower algorithm (resummation of part of the logarithms related to soft and collinear emissions on top of the hard-scattering process), followed by hadronization (phenomenological model).

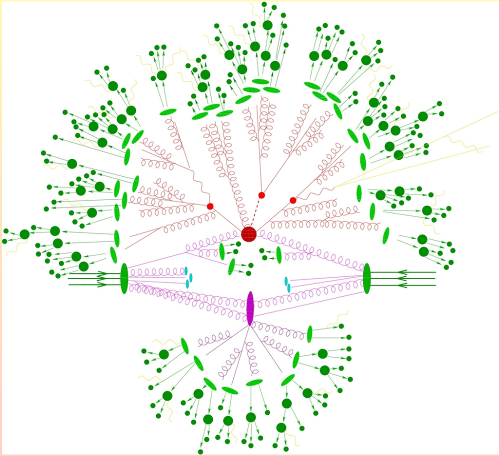
Advantage: fully exclusive event generation, correlations between final state particles/hadrons are kept.

Problem: accuracy not exactly known, differently from the case of conventional analytical resummation procedures to all orders in P. T.

2) Convolution of partonic cross-sections with Fragmentation Functions (see the following).

Both methods 1) and 2) are used in the following.

p-p and p-$\bar{\mathrm{p}}$ collision overview (LHC and Tevatron)



$Q = a \ few \ TeV$

- hard scattering
- parton shower
- QED shower

$\Lambda_{QCD} = 200 \ MeV$

- hadronization
- hadron decay
- underlying event
- pile-up (overlap of different collisions).

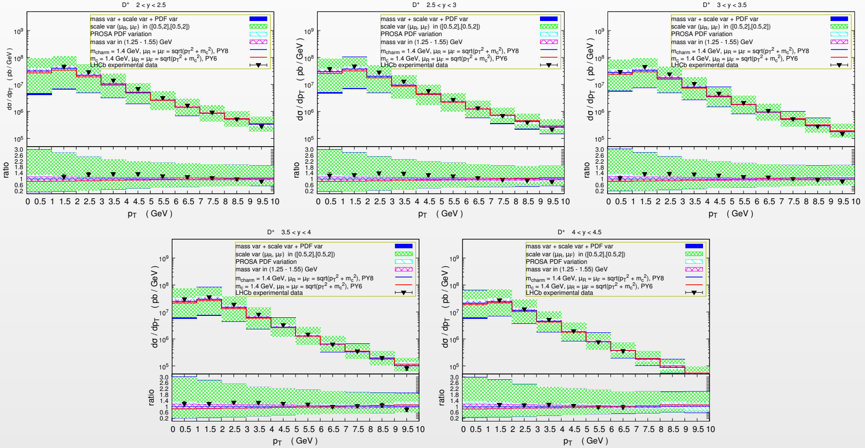
DECREASING ENERGY SCALE

PERTURBATIVE AND NON-PERTURBATIVE COMPONENTS

Monday, December 9, 13

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.

QCD factorization

for 1-particle inclusive heavy-hadron hadroproduction

$$d\sigma(N_1 N_2 \to H + X) = \sum_{abc} PDF_a^{N_1}(x_a, \mu_{F,i}) PDF_b^{N_2}(x_b, \mu_{F,i}) \otimes$$
$$\otimes\ d\hat{\sigma}_{ab\to cX'}(x_a, x_b, z, \mu_{F,i}, \mu_{F,f}, \mu_R) \otimes FF_c^H(z, \mu_{F,f})$$

$d\hat{\sigma}$: differential perturbative partonic cross-section,
its m_Q dependence, neglected in ZM-VFNS, is instead kept in GM-VFNS.

μ_F, μ_R reabsorb IR and UV divergences (truncation of P.T. series).

PDFs: perturbative evolution with factorization scale $\mu_{F,i}$,
non-perturbative dependence on $x{=}p^+/P_N^+$.

FFs: perturbative evolution with factorization scale $\mu_{F,f}$,
non perturbative parameterization in terms of $z = P_H^+/p_c^+$ frequently used.

QCD uncertainties

* $\mu_{F,i}$, $\mu_{F,f}$ and μ_R choice: no univocal recipe.
* Choice of Variable Flavour Number Scheme (several possibilities!)
* PDF (+ $\alpha_S(M_Z)$) fits to experimental data
* Fits to experimental data of the non-perturbative parameters of the FF

GM-VFNS partonic and hadronic pp cross-sections

$*$ Taking the limit $m \to 0$ of the massive cross-section does not reduce to the masslese one obtained in dimensional regularization for $\epsilon \to 0$ (finite mass regulators and dimensional regularization of collinear divergences yield different finite terms):

$$d\hat{\sigma}^{sub} = \lim_{m\to 0} d\hat{\sigma}^{FFNS}(m) - d\hat{\sigma}^{ZM-VFNS}$$

$*$ Subtraction of overlapping terms:

$$d\hat{\sigma}^{GM-VFNS}(m) = d\hat{\sigma}^{FFNS}(m) - a\, d\hat{\sigma}^{sub}$$

with $a = 1$ in the S-ACOT scheme,
$a = a(p_T, m, ...)$ for other schemes (e.g. FONLL).

$*$ S-ACOT GM-VFNS hadronic σ for single inclusive heavy-hadron production obeys a factorization formula which generalizes the CSS factorization theorem in the ZM-VFNS:

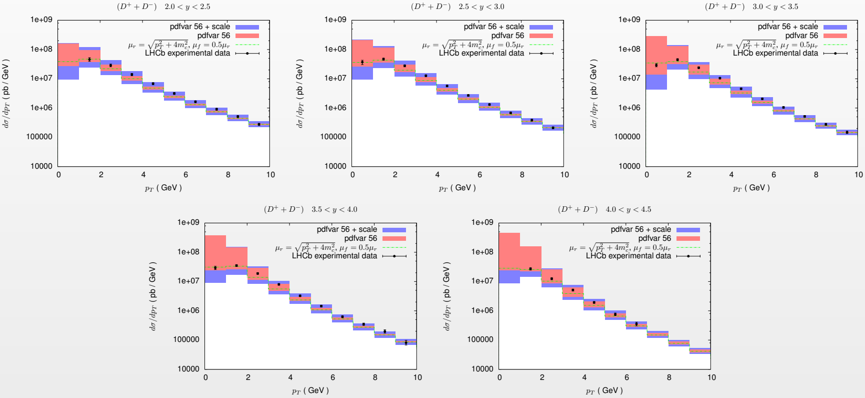
$$d\sigma^{ZM}_{pp\to hX}(P,S) = F_{i/p}(x_1,\mu_i)F_{j/p}(x_2,\mu_i) \otimes d\hat{\sigma}_{ij\to kX}(p,s,\mu_r,\mu_i,\mu_f) \otimes D_{h/k}(z,\mu_f)$$

$$\frac{1}{p_T}\frac{d\sigma^{ZM}_{pp\to hX}}{dp_T dy}(S,p_T,y) = \frac{2}{S}\sum_{i,j,k}\int_{1-V+VW}^{1}\frac{dz}{z^2}\int_{\frac{VW}{z}}^{1-\frac{1-V}{z}}\frac{dv}{1-v}\int_{\frac{VW}{vz}}^{1}\frac{dw}{w}$$
$$F_{i/p}(x_1,\mu_i)F_{j/p}(x_2,\mu_i)\,\frac{1}{v}\frac{d\hat{\sigma}^{\mathrm{ZM}}_{ij\to kX}}{dvdw}(s,v,w,z,\mu_r,\mu_i,\mu_f)\,D_{h/k}(z,\mu_f)\,,$$

with proper replacement of massless kinematics and integration limits
with massive kinematics and integration limits where needed.

GM-VFNS predictions vs experimental data

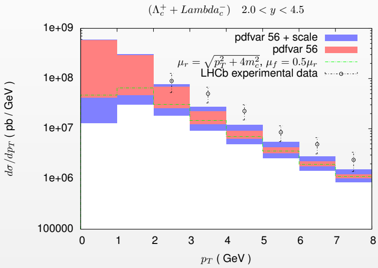
for differential cross-sections for $pp \to D^{\pm} + X$ at LHCb at 5 TeV



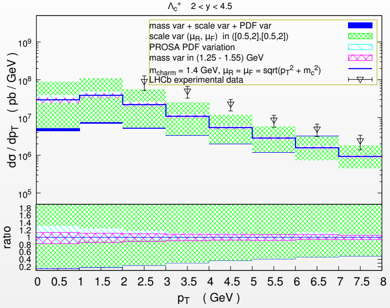
∗ Scale uncertainties larger than experimental ones.

∗ Large PDF uncertainties (CT14nlo), increasing at low p_T / large y, can be mitigated by using other PDF fits.

Forward Λ_c hadroproduction in pp collisions



GM-VFNS + FF



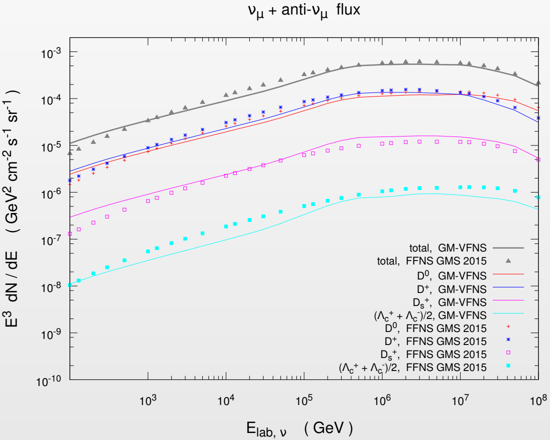
NLO + PS + had

* LHCb experimental data at $\sqrt{s} = 7$ TeV above the theory bands (differences within 2σ).
* Update of branching ratios and fragmentation fractions needed: big uncertainties on these elements ($\sim 25\%$ and 8%).
* What happens at 13 and 5 TeV ?
* LHCb has measured Λ_c/D^0 ratios in $p-Pb$ collisions.

$\Rightarrow$ Extension to pp would be important for assessing fragmentation/hadronization mechanisms

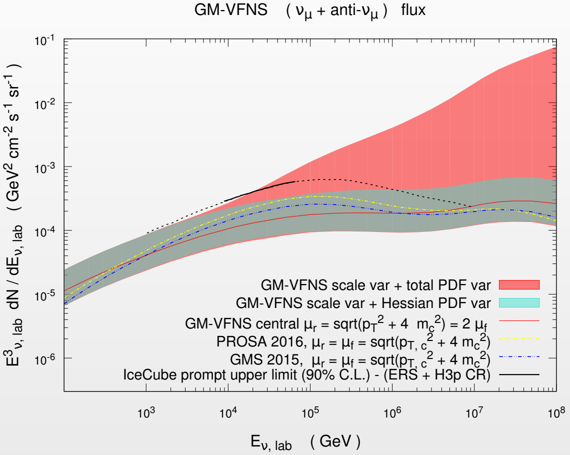
* A rapidity dependence might be expected/should be experimentally checked.

Prompt $(\nu_\mu + \bar{\nu}_\mu)$ fluxes in the GM-VFNS and in GMS (i.e. NLO + PYTHIA) approach: contribution of different charmed hadrons



Prompt neutrino fluxes with GM-VFNS:

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

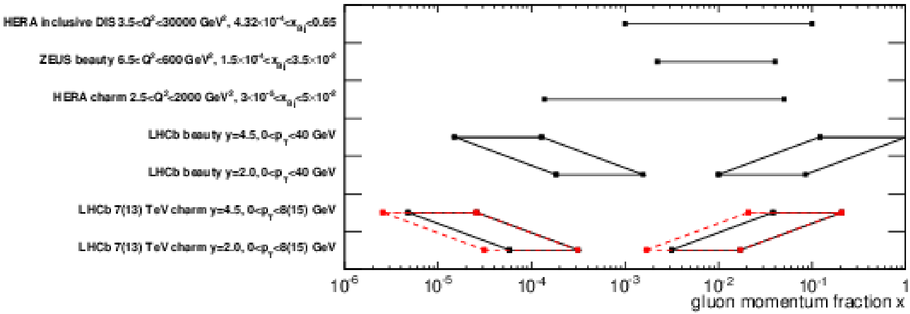


The extrapolation to high energy of IceCube results suggest that the CT14nlo gluon PDF uncertainty band at low x's is too large!

Important ingredient of these calculations: PDF fits

* x-dependence of PDFs is fitted to experimental data.
* HERA data (core of all PDF fits) offer good coverage in the range $10^{-4} < x < 10^{-1}$.
* Prompt ν fluxes sensitive to a wider range of x values, due to the fact that
  - The $\sqrt{s}$ for the relevant collisions involve a wide range of energies (from $\sqrt{s} \sim 100$ GeV to $\sqrt{s} \sim 150$ TeV).
  - The relevant rapidities extend to values much larger than those accessible in traditional experiments at human-made colliders.

x coverage of HERA and LHCb experiments



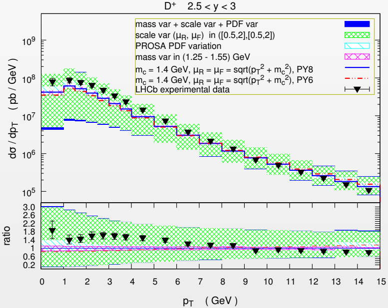
LHCb data allow to cover x regions uncovered by HERA data,
both at low x's (especially open charm data)
and at large x's (especially open bottom data).

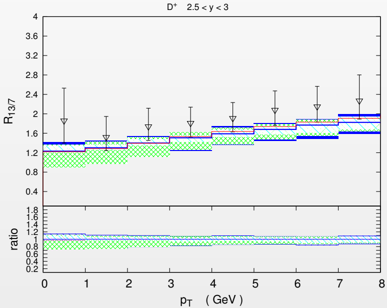
For LHCb, LO formula $x_{1,2} = (\sqrt{p_T^2 + m_Q^2}/E_p)\ \exp(\pm y)$ $\Rightarrow$ Larger rapidities of the emitted quark correspond to more extreme x's; large $\sqrt{s} \leftrightarrow$ small x 's

charm production in DIS at EIC extends HERA charm coverage even to $x > 0.1$.

How to use charm production data for inferring other quantities, if scale uncertainties are so big ?

- Issue already seen in the comparison with LHCb data on charmed meson production



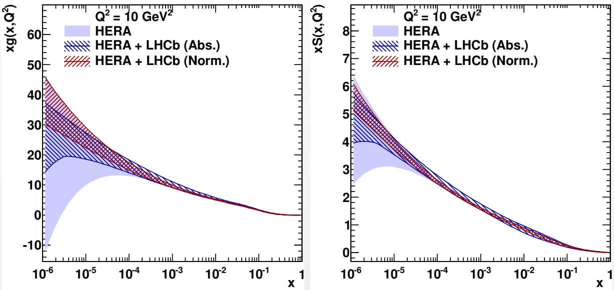


- Solution: use ratios.
- When considering LHCb, it is possible to use data in two different rapidity ranges: e.g. ($4 < y < 4.5$) and ($3 < y < 3.5$).
- One can also use ratios of data at two different center-of-mass energies.

The power of LHCb data ratios in constraining PDFs

PROSA 2015 PDF fit: comparison between three variants

from PROSA collab., EPJC 75 (2015) 471



Three <u>variants</u> 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.

PROSA 2015 PDF fit: methodology

* Fit entirely performed with `xFitter` - publicly available framework (see next talk).
* Methodology inspired by the HERAPDF1.0 PDF fit.
* Ab-initio fit. All data (HERA DIS + LHCb open heavy flavour at $\sqrt{s} = 7$ TeV) included from the very beginning.
* NLO QCD predictions for heavy-quark production (FFNS).
* Fragmentation functions: c as measured at HERA [EPJC 59 (2009) 589, JHEP 04 (2009) 082], b as measured at LEP [NPB 566 (2000) 245].
* Fragmentation fractions: combination of LEP and HERA measurements [arXiv:1112.3757]
* m_c^{pole}, m_b^{pole} left as free parameters in the fit.

PROSA 2019 PDF fit:

what is new w.r.t. PROSA 2015 ?

∗ central (μ_R, μ_F) scale choice

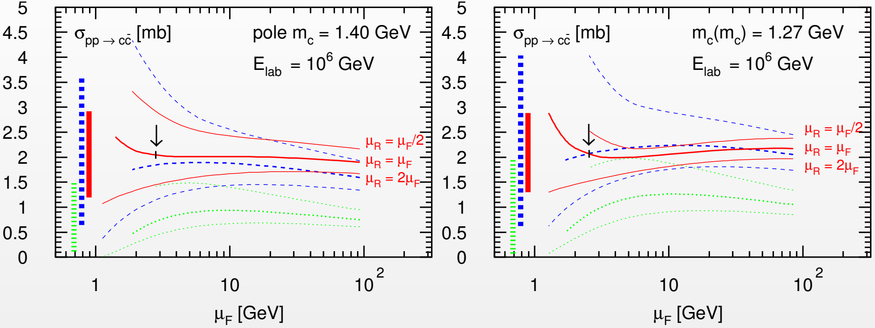
∗ Together with the PDF dependence on x, we fit the values of $m_c(m_c)$ and $m_b(m_b)$ in the MSbar scheme, consistently used for all theoretical predictions at NLO in the FFNS. We find
$m_c(m_c) = 1.23 \pm 0.03$ (exp) GeV,
$m_b(m_b) = 3.98 \pm 0.010$ (exp) GeV.

∗ PDF parameterization modified/extended with additional terms.

∗ FFNS and VFNS versions

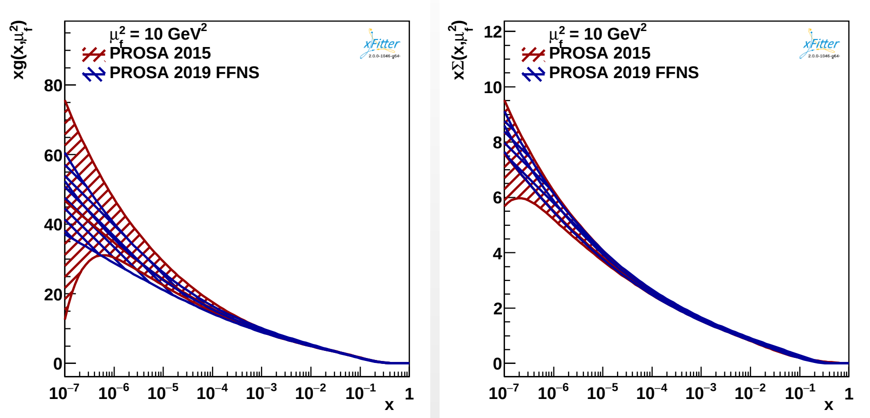
from O. Zenaiev et al., [arXiv:1911.13164]

$\sigma(pp \to c\bar{c})$: scale dependence at LO, NLO, NNLO



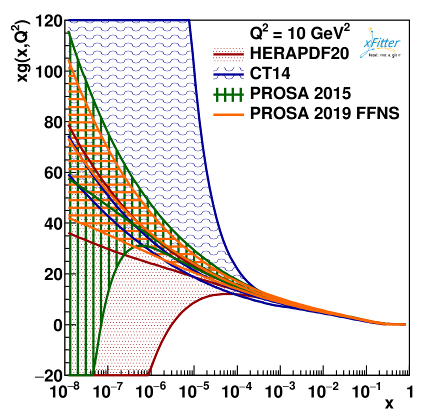
- ∗ Perturbative convergence when mass is renormalized in $\overline{\mathrm{MS}}$ scheme is reached slightly faster than in pole mass scheme.
- ∗ Sensitivity to radiative corrections is smaller at a scale $\mu_R \sim \mu_F \sim 2m_c$ than at the scale $\mu_R \sim \mu_F \sim m_c$.
- ∗ This translates into a dynamical scale $\sqrt{p_{T,c}^2 + 4m_c^2}$ to better catch dynamics in differential distributions.

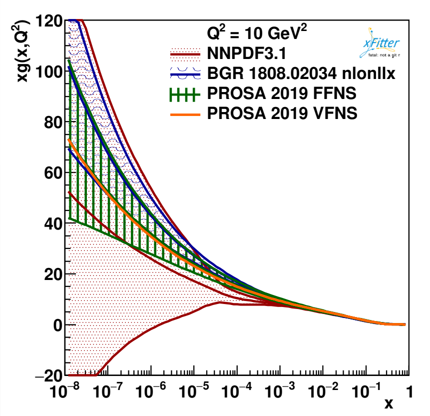
PROSA 2019 vs PROSA 2015: gluons & sea quarks



* new gluon and sea quark PDFs consistent with the old ones
* reduced uncertainties for $x < 10^{-4}$

gluon PDF: comparison between different PDF fits

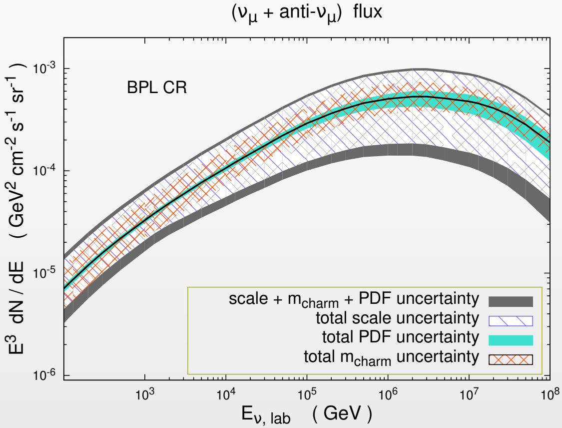




$*$ PROSA2019 better constrained than PROSA2015 due to inclusion of data at $\sqrt{s} = 13$ and 5 TeV, besides 7 TeV.

$*$ Compatibility between different PDF sets including D-meson LHCb data.

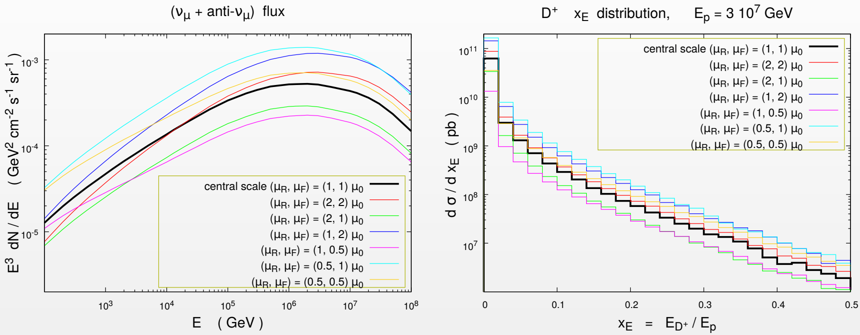
PROSA 2019 atmospheric prompt $(\nu_\mu + \bar{\nu}_\mu)$ flux: QCD scale, mass and PDF uncertainties



from [arXiv:1911.13164]

∗ PDF uncertainty subdominant,
assuming extrapolation at $x < 10^{-6}$ works.

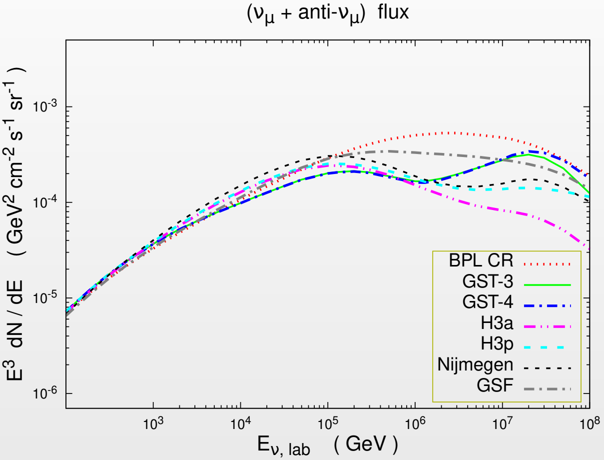
μ_R and μ_F scale uncertainties



* Scale uncertainties are evaluated by making an envelope over different variations.

* Predictions have a <u>shape</u> uncertainty, not only a <u>normalization</u> uncertainty!

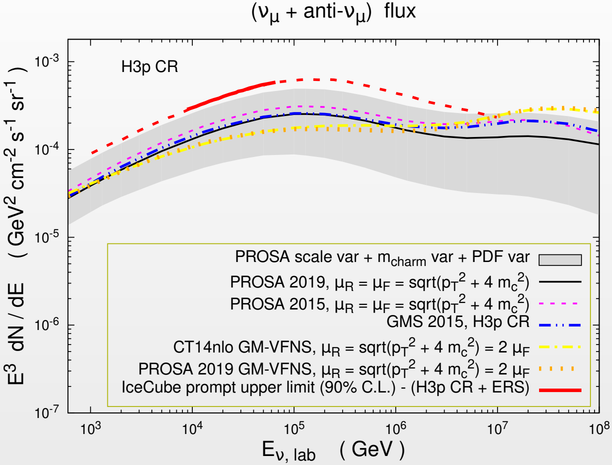
PROSA prompt ($\nu_\mu + \bar{\nu}_\mu$) fluxes with different CR primary all-nucleon fluxes



∗ Uncertainty in CR composition turns out to be smaller than QCD scale uncertainties.

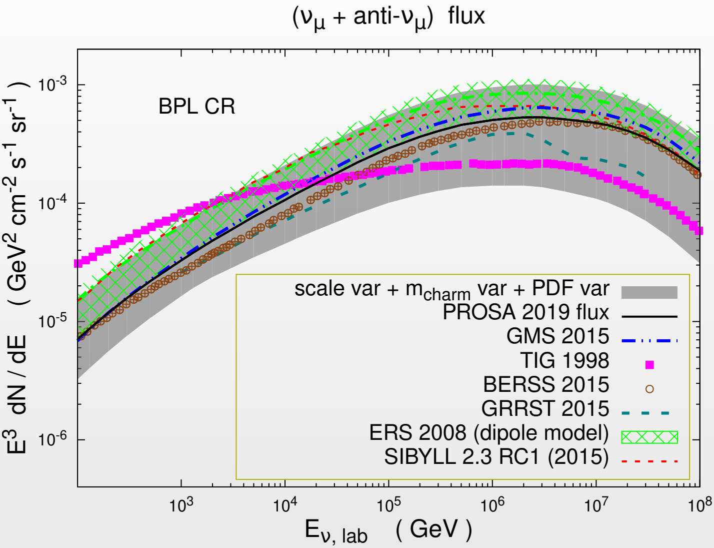
Prompt neutrino fluxes:

theoretical predictions vs. IceCube upper limits



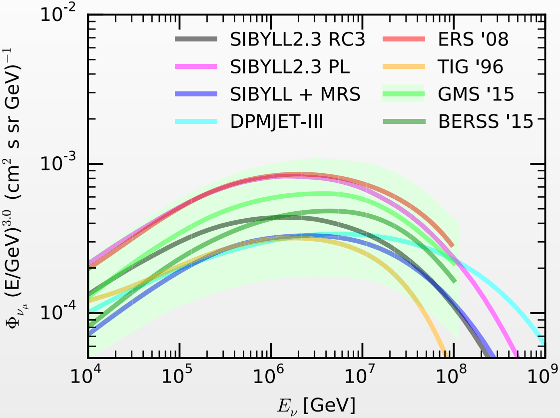
IceCube upper limit on prompt fluxes from the 6-year analysis of thoroughgoing μ tracks from the Northest Hemisphere [arXiv:1607.08006] assumed the ERS flux as a basis for modelling prompt neutrinos (reweighted to the H3p CR flux).

Comparison of predictions by different groups



Different predictions compatible within the uncertainty band

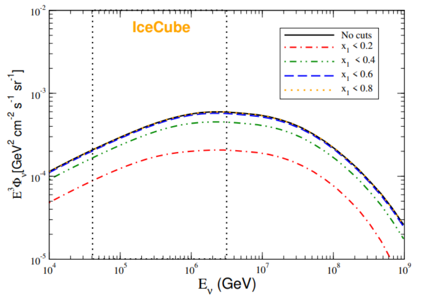
$(\nu_\mu + \bar{\nu}_\mu)$ fluxes: comparison with predictions of hadronic models used in EAS physics

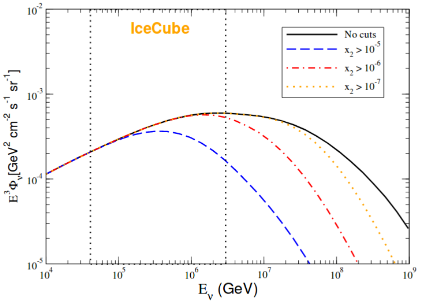


from A. Fedynitch, EPJ Web of Conferences 116, 11010 (2016)

All recent central predictions, both those on the basis of pQCD and those on the basis of hadronic models used in EAS physics (like SIBYLL, DPMJET), turn out to lie within our uncertainty band.

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





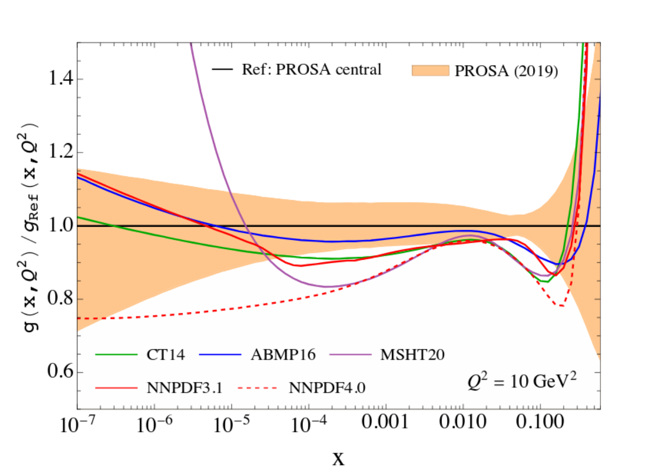
, *from V. Goncalves et al. [arXiv:1708.03775]*

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

∗ Region particularly relevant: $0.2 < x < 0.6$, 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.

PDFs uncertainties at low and large-x



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

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

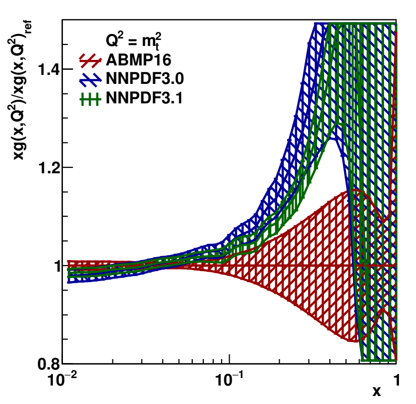
PDF uncertainties at large x

- PDF uncertainties are often estimated by considering a single PDF set.
- However, the differences between different PDF sets might be not covered by the uncertainty of a single set.

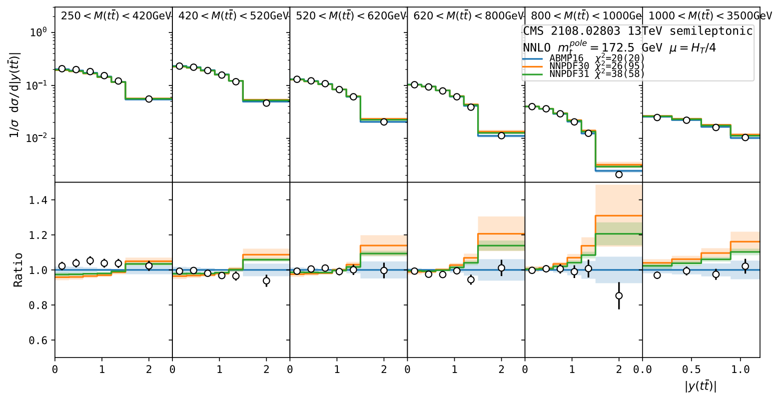
$\Rightarrow$ A more comprehensive estimate would be recommended.

- g PDF at large x play an important role in the predictions.

$\Rightarrow$ data on $t\bar{t} + X$ and jet production at the LHC are important for constraining g PDF in this region.



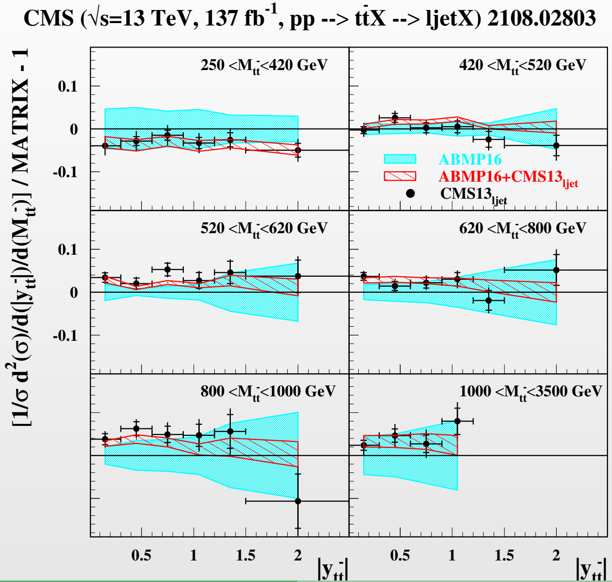
NNLO predictions on $d^2\sigma/dM(t\bar{t})dy(t\bar{t})$ for $t\bar{t}+X$ with different PDF sets vs. experimental data



* The NNPDF central sets shows
  a poor description of these data, in the high-energy tails.

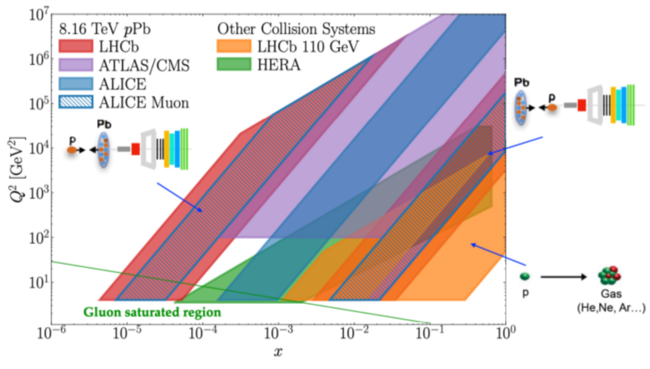
* The uncertainty bands, although large, do not encompass data
  in all bins

Pulls of CMS TOP-20-001 data with respect to ABMP predictions



- ABMP PDF fit variant incorporating this specific dataset, w.r.t. published ABMP16 PDF fit
- Still to be investigated: what happens when incorporating these data into PROSA2019 PDF fit ?

Fixed-target experiments at the LHC: increased large x coverage and sensitivity to nuclear matter effects

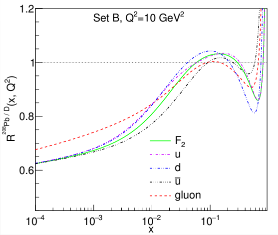


from LHCb collaboration

- ∗ LHCb-FT coverage at scale $Q^2 \sim 4$ GeV^2:

  $2 \cdot 10^{-4} \lesssim x \lesssim 4 \cdot 10^{-1} \Rightarrow$ gluon, sea quarks
- ∗ Light targets: probe NM effects in pA collisions in A range different from Pb
- ∗ Cold and Hot Nuclear Matter effects (at small x) can be compared by using p or Pb beams impinging on the nuclear targets (He, Ne, Ar, ...).

Nuclear modification factors R_p^{Pb}



from [arXiv:1611.03670]

$*$ Shadowing: $R < 1$ for $x \lesssim 0.1$ (a possible explanation: parton recombination/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 shadowing.

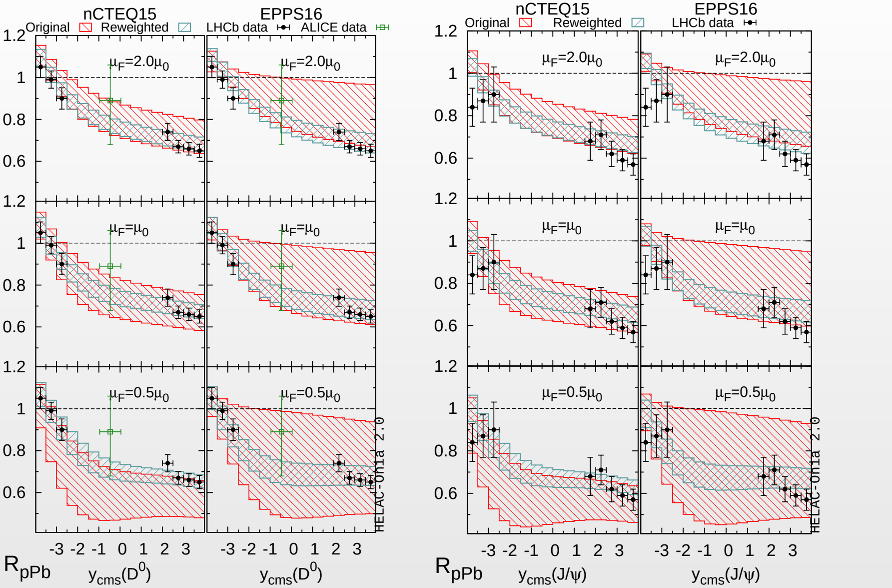
$*$ EMC effect: $R < 1$ for $0.3 \lesssim x \lesssim 0.7$ (attributed to in-medium nucleon swelling, nucleon-nucleon short range correlations, binding, ...).

$*$ 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.

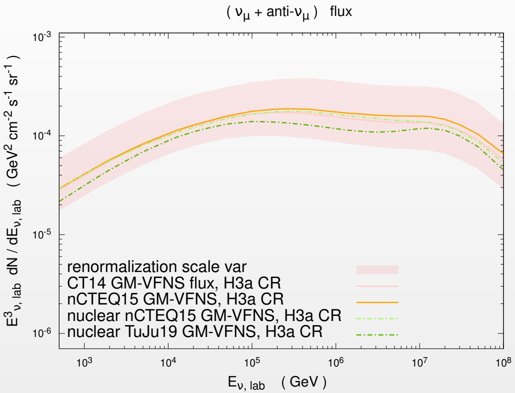
$\Rightarrow$ Evergreen questions: how to write a parameterization for nPDFs ?

nPDF fits and D^0 and J/ψ data in p-Pb / pp collisions



from A. Kusina, J.-P. Lansberg, I. Schienbein, H.-S. Shao, [arXiv:1712.07024v2]

$(\nu_\mu + \bar{\nu}_\mu)$ 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 ? Large shadowing effects do not emerge for all nuclear PDF fits, especially for low-mass nuclei

Wishlist useful measurements LHC, especially LHCb

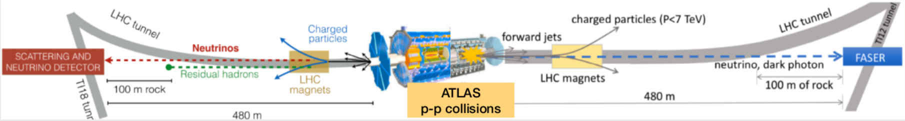
* D-meson and B-meson spectra at 13.6 TeV, 14 TeV.
* if possible, more p_T bins in the region 0 - 5 GeV
* $\Lambda_c^\pm$ double-differential spectra in y, p_T.
* Additional focus on $D_s^\pm$ (main source of ν_τ and $\bar{\nu}_\tau$).
* Charge asymmetries with better statistics.
* All above in pp, pPb, 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.

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.

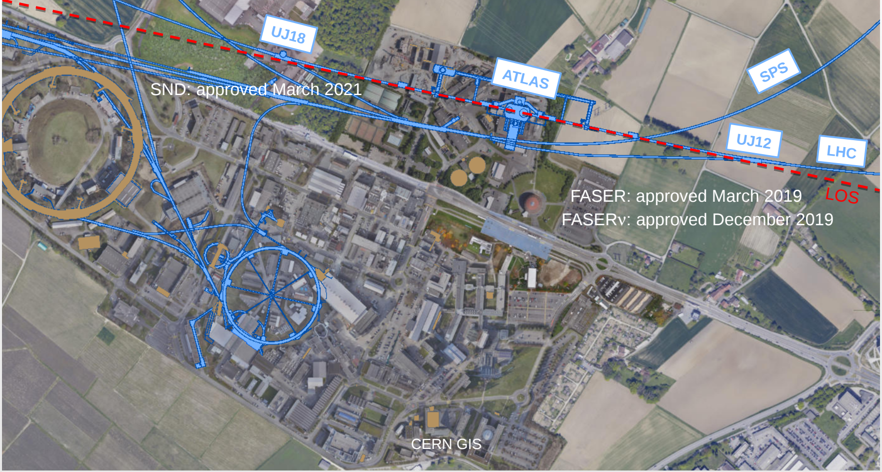
* Pilot experiments, on the tangent to the LHC beam line, at $\sim$ 480 m from ATLAS IP:
  - FASER ($\eta > 9.2$), Faserν ($\eta > 8.5$) and SND@LHC ($7.2 < \eta < 8.4$), all active in taking data during Run 3.



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

FAR FORWARD LHC EXPERIMENTS

The existing caverns UJ12 and UJ18 and adjacent tunnels are good locations for experiments along the LOS: 480 m from ATLAS and shielded from the ATLAS IP by ~100 m of rock.



First observations of far-forward LHC neutrinos

∗ FASER collab., [arXiv:2105.06197]:

A search for neutrino interactions is presented based on a small emulsion detector installed at the LHC in 2018. We observe the first candidate vertices consistent with neutrino interactions at the LHC. A 2.7σ excess of neutrino-like signal above muon-induced backgrounds is measured. These results demonstrate FASERν's ability to detect neutrinos at the LHC and pave the way for future collider neutrino experiments.

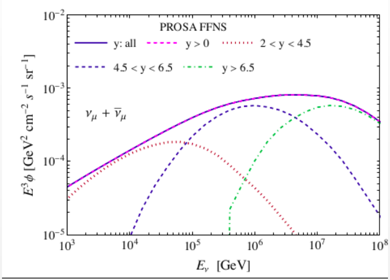
∗ FASER collab., [arXiv:2303.14185]:

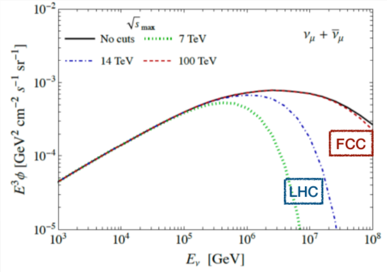
Summary We report the first direct detection of neutrinos produced at a collider experiment using the active electronic components of the FASER detector. We observe 153^{+12}_{-13} neutrino events from CC interactions from ν_μ and $\bar{\nu}_\mu$ taking place in the tungsten-emulsion detector of FASERν. The spatial distribution and properties of the observed signal events are consistent with neutrino interactions, and the chosen analysis strategy does not depend on the quality of the modeling of detector effects in the simulation. For the signal events, the reconstructed charge shows the presence of anti-neutrinos, and the reconstructed momentum implies that neutrino candidates have energies significantly above 200 GeV. This

∗ SND@LHC collab., [arXiv:2305.09383]:

Conclusions - A search for high energy neutrinos originating from *pp* collisions at $\sqrt{s} = 13.6$ TeV is presented using data taken by the electronic detectors of SND@LHC. We observe 8 candidate events consistent with ν_μ CC interactions. Our muon-induced and neutral-hadron backgrounds for the analysed data set amount to $(7.6 \pm 3.1) \times 10^{-2}$ events, which implies an excess of ν_μ CC signal events over the background-only hypothesis of seven standard deviations.

Prompt atmospheric ν fluxes and LHC phase-space coverage



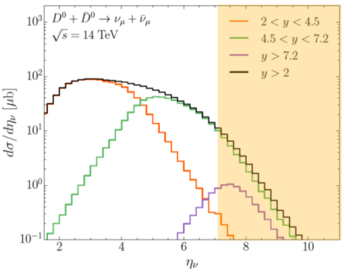


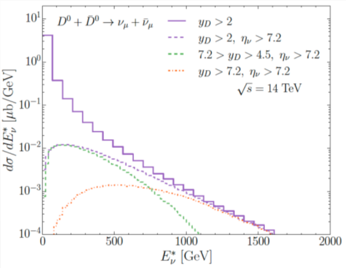
∗ To connect to prompt ν fluxes at the PeV, LHC measurements of charm production should focus on the region $4.5 < y_c < 7$.

∗ 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 $4 < y_c < 7.2$ 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 neutrinos

* 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/FCC-hh)-(HERA/EIC/FCC-eh)-astroparticle physics

* 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!