FPF Connection to Astro-Particle Physics

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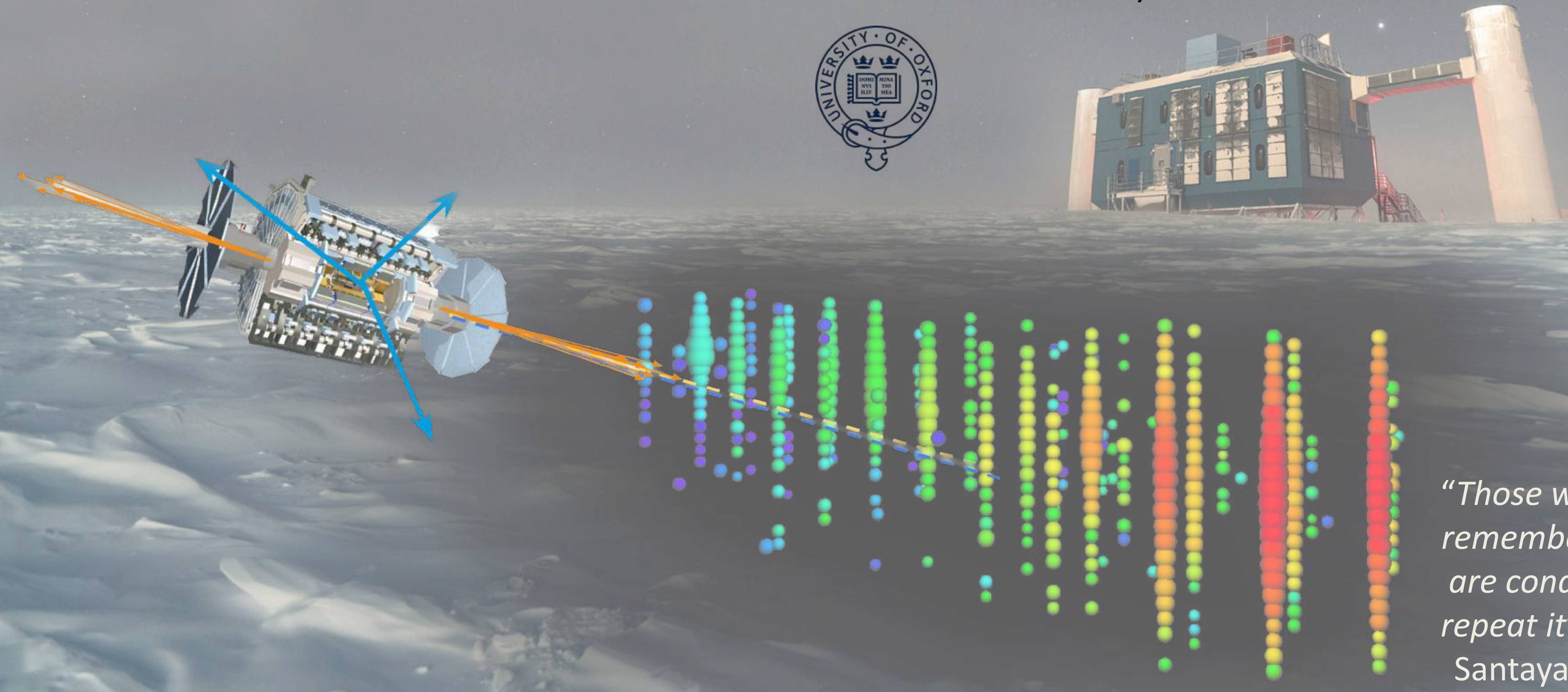


"Those who cannot remember the past are condemned to repeat it" – George Santayana (1905)

Forward Physics Facility: Theory Workshop, CERN, 18-19 September 2023

NEUTRINO AND MUON PHYSICS IN THE COLLIDER MODE OF FUTURE ACCELERATORS*)

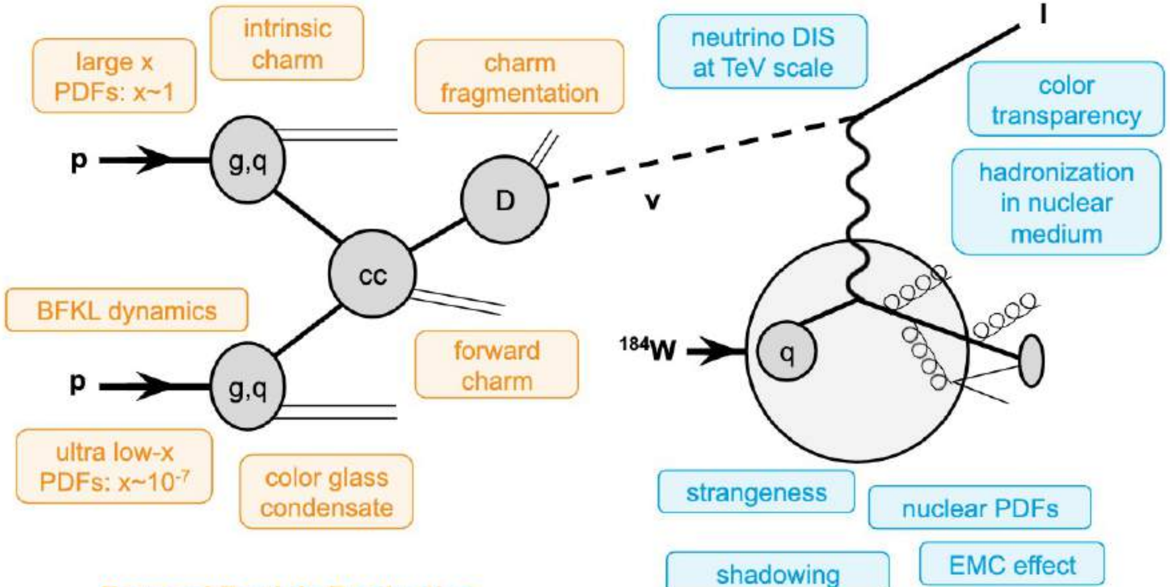
A. De Rújula and R. Rückl

CERN, Geneva, Switzerland

[Proc. ECFA-CERN Workshop on large hadron collider in the LEP tunnel: 21-27 Mar 1984]

ABSTRACT

Extracted beams and fixed target facilities at future colliders (the SSC and the LHC) may be (respectively) impaired by economic and "ecological" considerations. Neutrino and muon physics in the multi-TeV range would appear not to be an option for these machines. We partially reverse this conclusion by estimating the characteristics of the "prompt" ν_μ, ν_e, ν_τ and μ beams necessarily produced (for free) at the pp or $\bar{p}p$ intersections. The neutrino beams from a high luminosity (pp) collider are not much less intense than the neutrino beam from the collider's dump, but require no muon shielding. The muon beams from the same intersections are intense and energetic enough to study μp and μN interactions with considerable statistics and a Q^2-coverage well beyond the presently available one. The physics program allowed by these lepton beams is a strong advocate of machines with the highest possible luminosity: pp (not $\bar{p}p$) colliders.



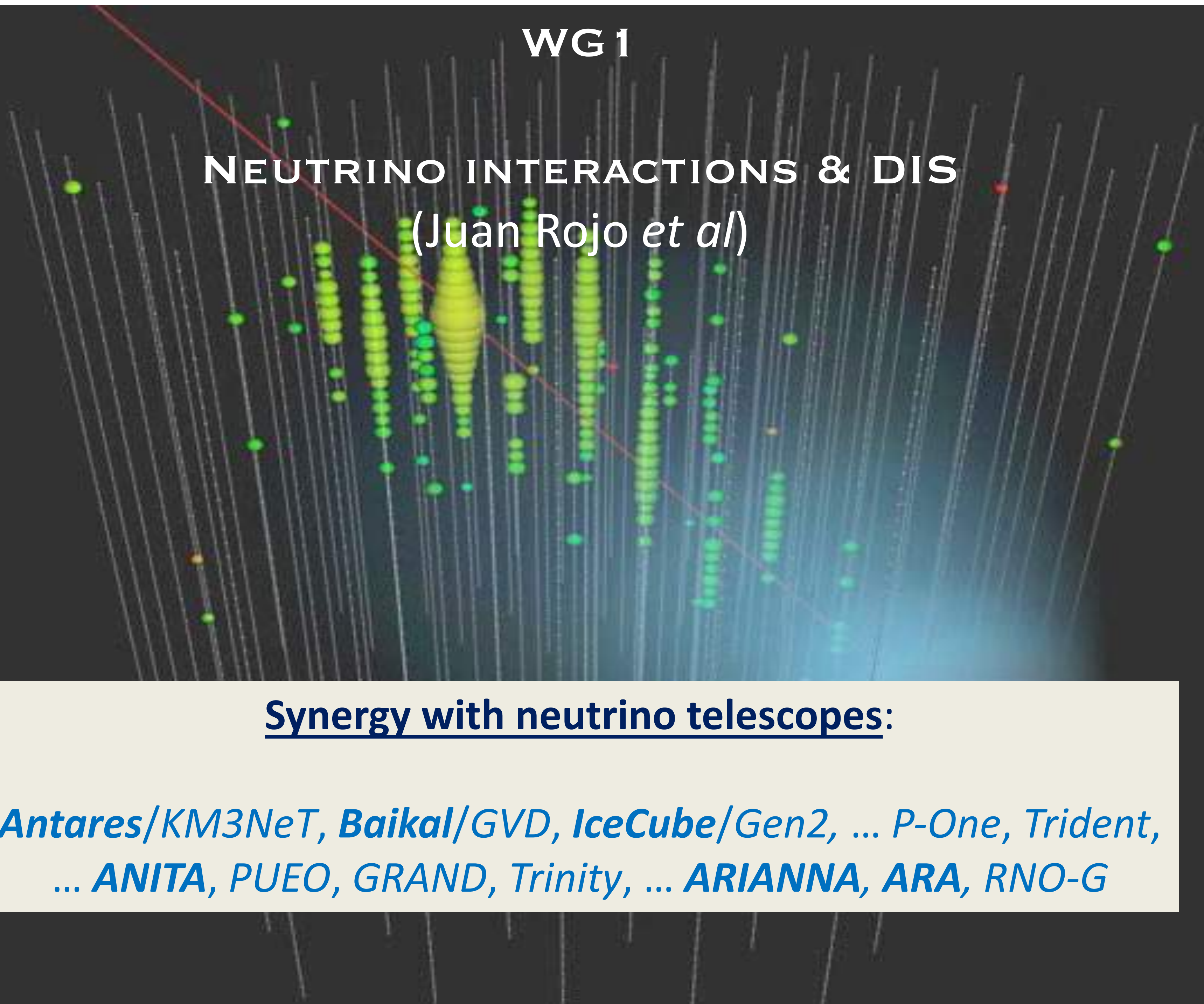
Forward Particle Production

This provides the means to study interesting open issues in QCD – of relevance to **neutrino telescopes**; to study forward production of light hadrons – of relevance to **cosmic ray air shower arrays;** and enables searches for long-lived particles arising in BSM physics (axions, dark photons, heavy neutral leptons, milli-charged particles, scalar dark matter *etc*) – of relevance to various **dark matter experiments** (both direct and indirect searches).
(FPF collab., *Phys.Rep.* **968**:1,2022, *J.Phys.*G**50**:030501,2023)

WG1

Neutrino interactions & DIS

(Juan Rojo *et al*)



Synergy with neutrino telescopes:

Antares/*KM3NeT*, ***Baikal***/*GVD*, ***IceCube***/*Gen2*, … *P-One*, *Trident*, … ***ANITA***, *PUEO*, *GRAND*, *Trinity*, … ***ARIANNA***, ***ARA***, *RNO-G*

Neutrino telescopes like IceCube detect very high energy neutrinos – to interpret the event rate in terms of the incident flux, we must know the Deep Inelastic Scattering #-secn (using known PDFs)

ν-N deep inelastic scattering is well-understood in the Standard Model

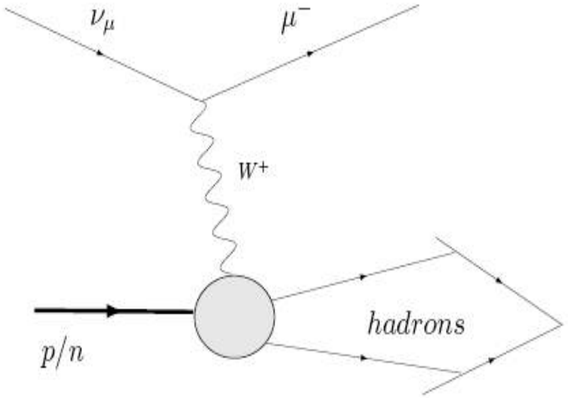
$$\frac{\partial^2 \sigma^{CC,NC}_{\nu,\bar{\nu}}}{\partial x \partial y} = \frac{G_F^2 M E}{\pi} \left(\frac{M_i^2}{Q^2 + M_i^2} \right)$$

$Q^2 \uparrow \Rightarrow$ propagator $\downarrow$

$$[\frac{1+(1-y)^2}{2} F_2^{CC,NC}(x,Q^2) - \frac{y^2}{2} F_L^{CC,NC}(x,Q^2)$$

$Q^2 \uparrow \Rightarrow$ parton distribution functions $\uparrow$

$$\pm y \left(1 - \frac{y}{2}\right) x F_3^{CC,NC}(x,Q^2)]$$



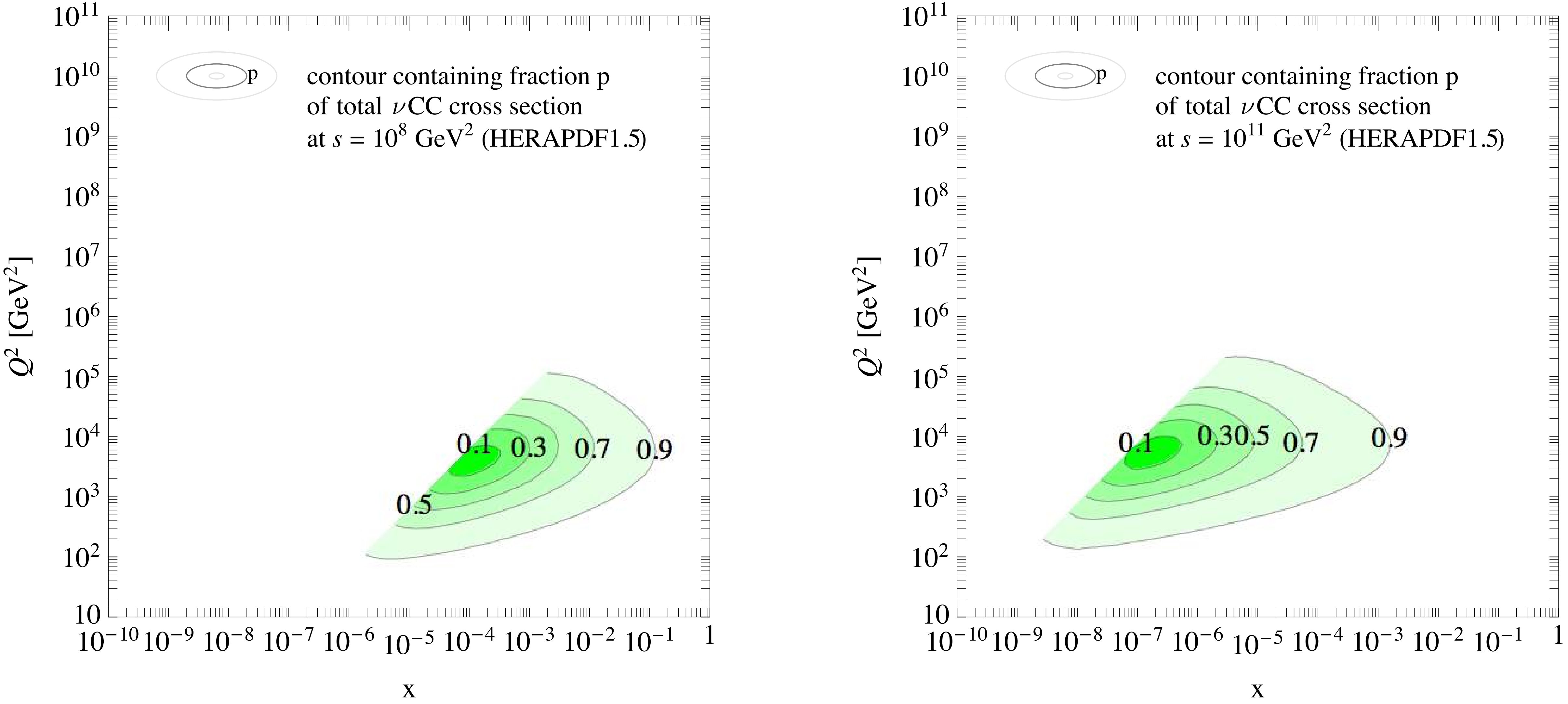
Most of the contribution to #-secn comes from: $Q^2 \sim M_W^2$ and $x \sim \frac{M_W^2}{M_N E_\nu}$

$$\text{At leading order (LO)}: F_L = 0, \quad F_2 = x(u_v + d_v + 2s + 2b + \bar{u} + \bar{d} + 2\bar{c}),$$
$$xF_3 = x(u_v + d_v + 2s + 2b - \bar{u} - \bar{d} - 2\bar{c}) = x(u_v + d_v + 2s + 2b - 2\bar{c})$$

Can calculate numerically at Next-to-Leading-Order (NLO) … *no* significant further change at NNLO

For UHE neutrinos, perform DGLAP evolution of PDFs to low-*x* (heavy flavour thresholds, nuclear targets, …)

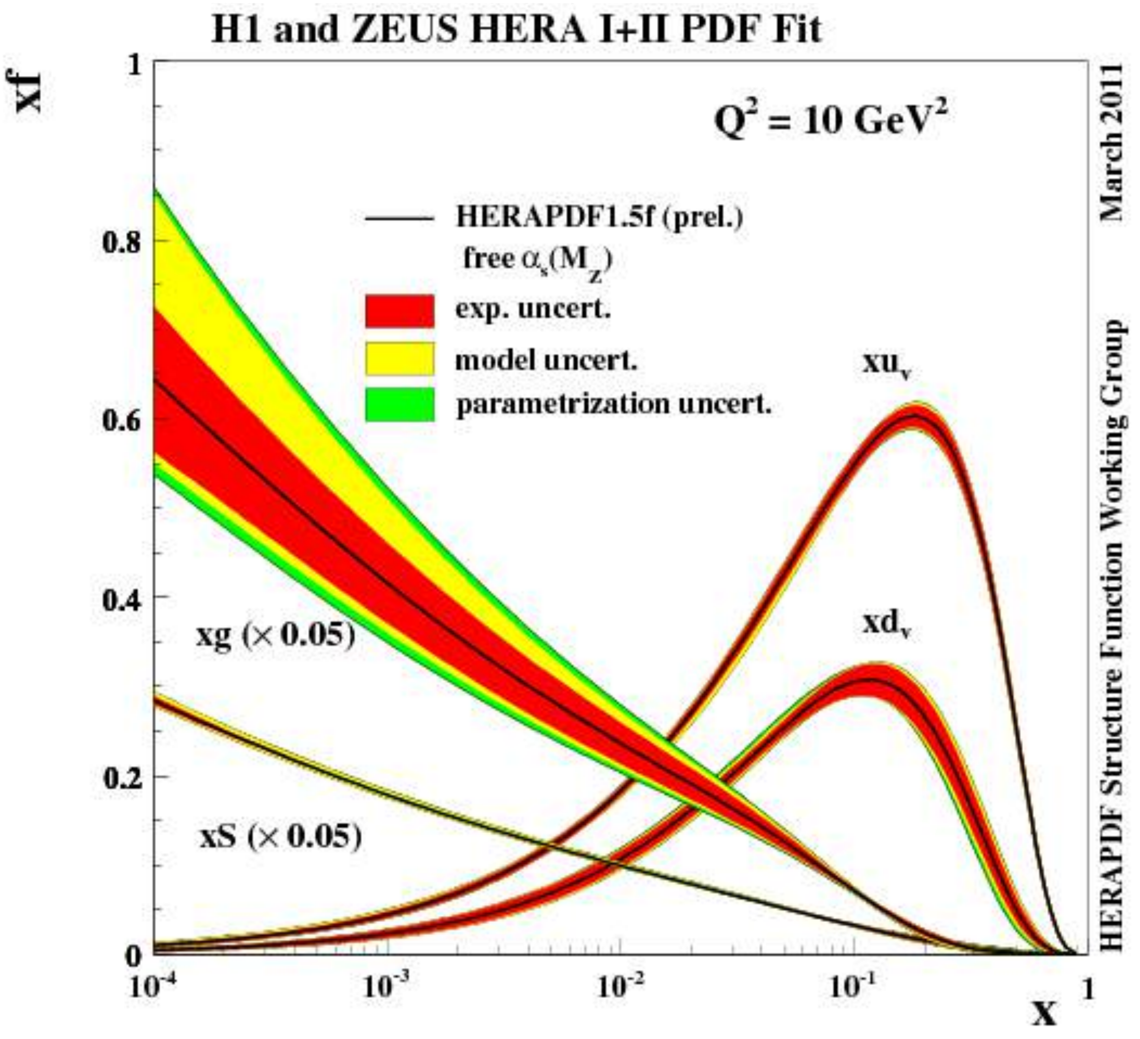
As the neutrino energy increases, lower values of x are being probed

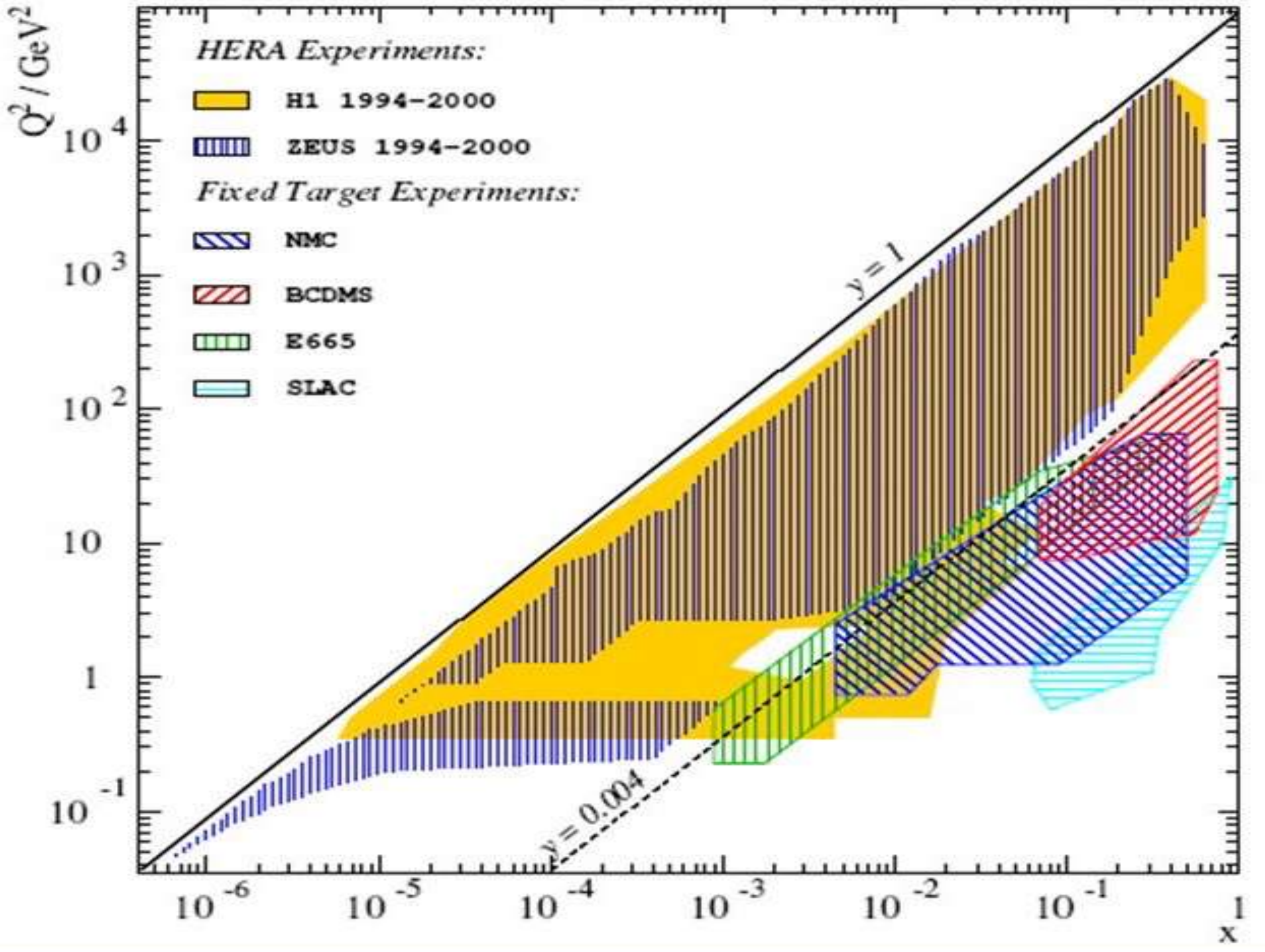


Mertsch, Cooper-Sarkar, S.S., *JHEP* **08**:042,2011

To determine the DIS cross-section accurately it is thus essential to have PDF measurements down to as *low* Bjorken-*x* as is possible (NB: for E_ν over ~10^3 TeV we have to evolve these further (using the DGLAP/BFKL formalism)

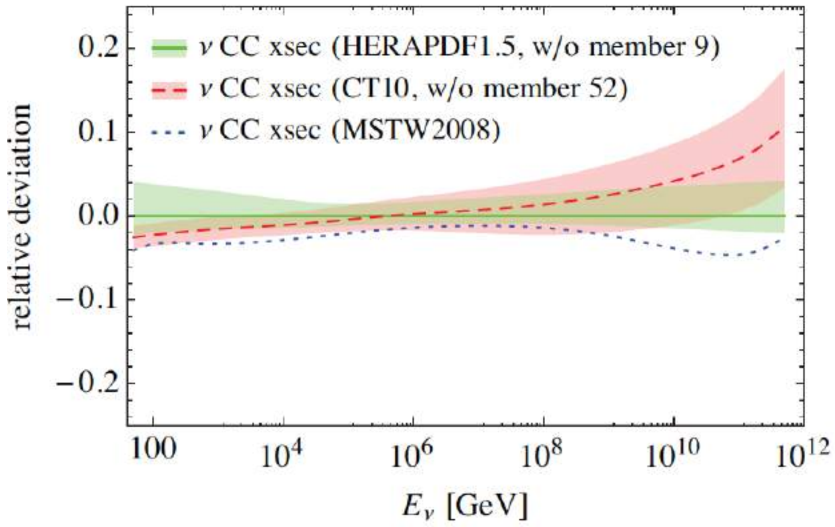
The H1 & ZEUS experiments at HERA were the first to measure DIS at high Q^2 and low Bjorken-x – an unexpected finding was the *steep* rise of the gluon PDF at low x which is particularly relevant for HE neutrino interactions

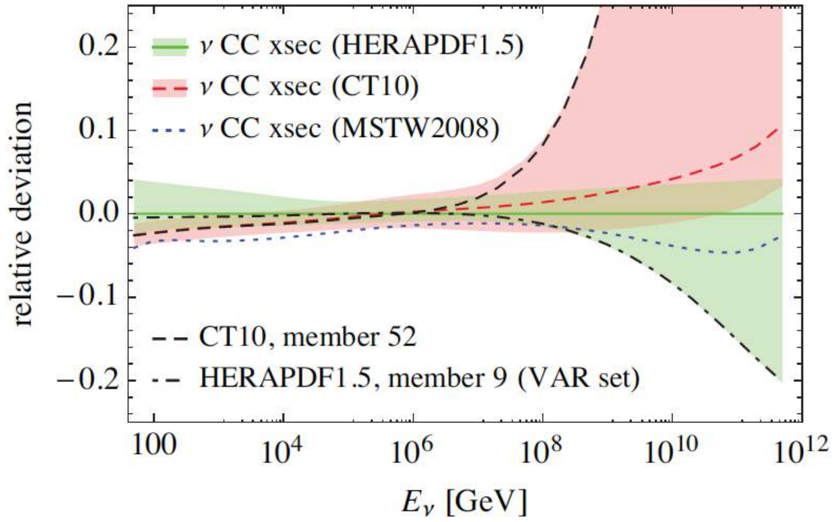


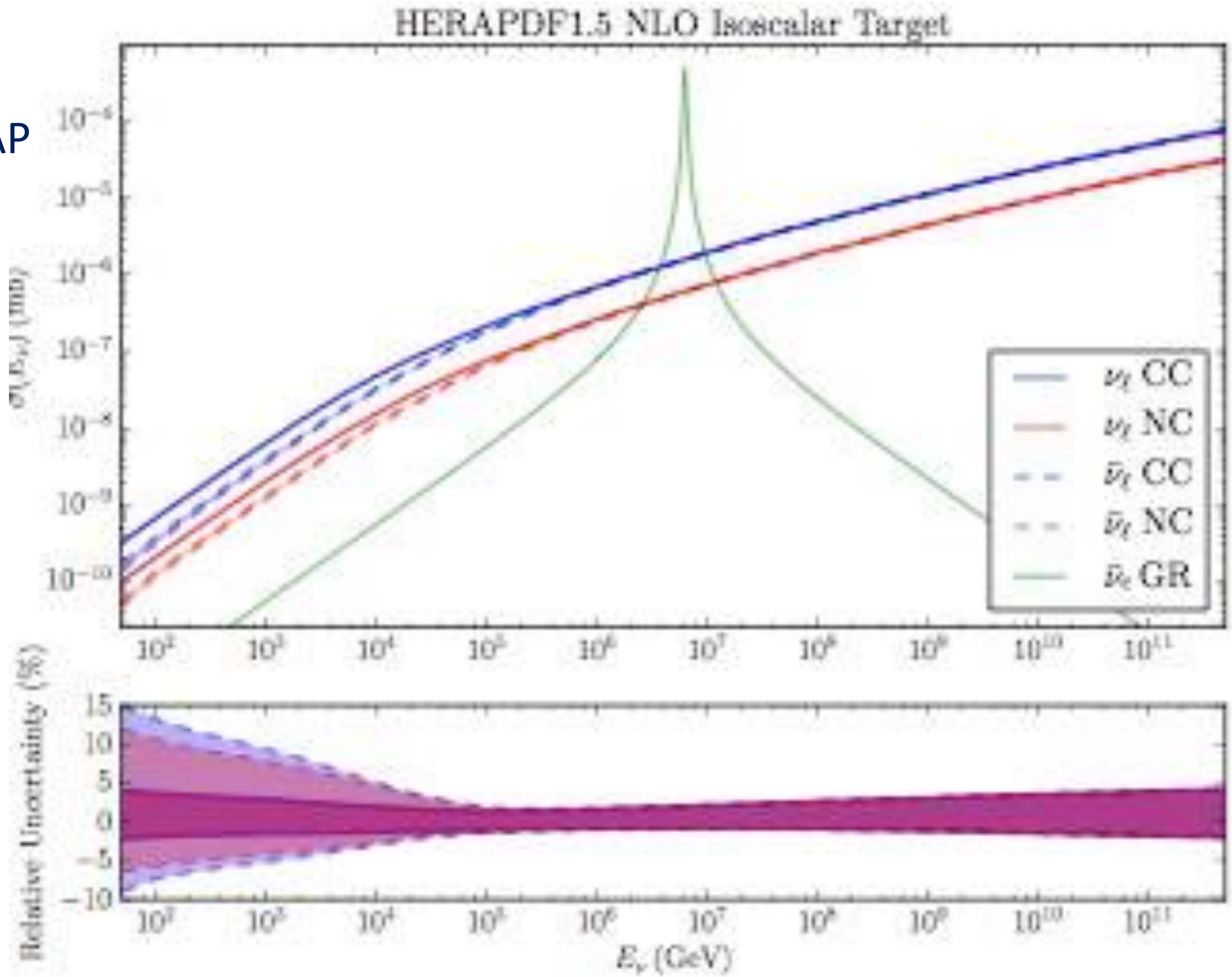


Subsequently data from the LHC (*W*, *Z*, *tt*bar, jets …) have led to more accurate PDFs and some new findings (low-x strange sea *less* suppressed than believed earlier, a hint of intrinsic charm …)

Neutrino telescopes like *IceCube* use NuGeN which incorporates our NLO calculation using HERAPDF1.5, incl. effect of heavy quarks on DGLAP evolution (Code: https://dispred.hepforge.org/)



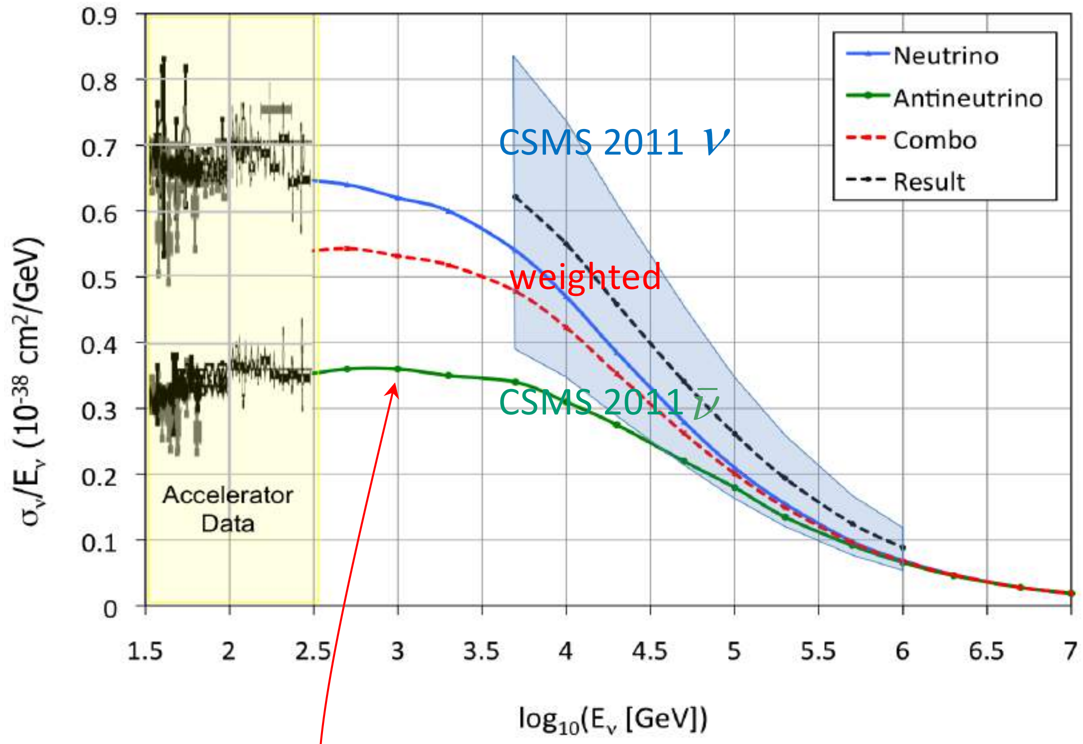


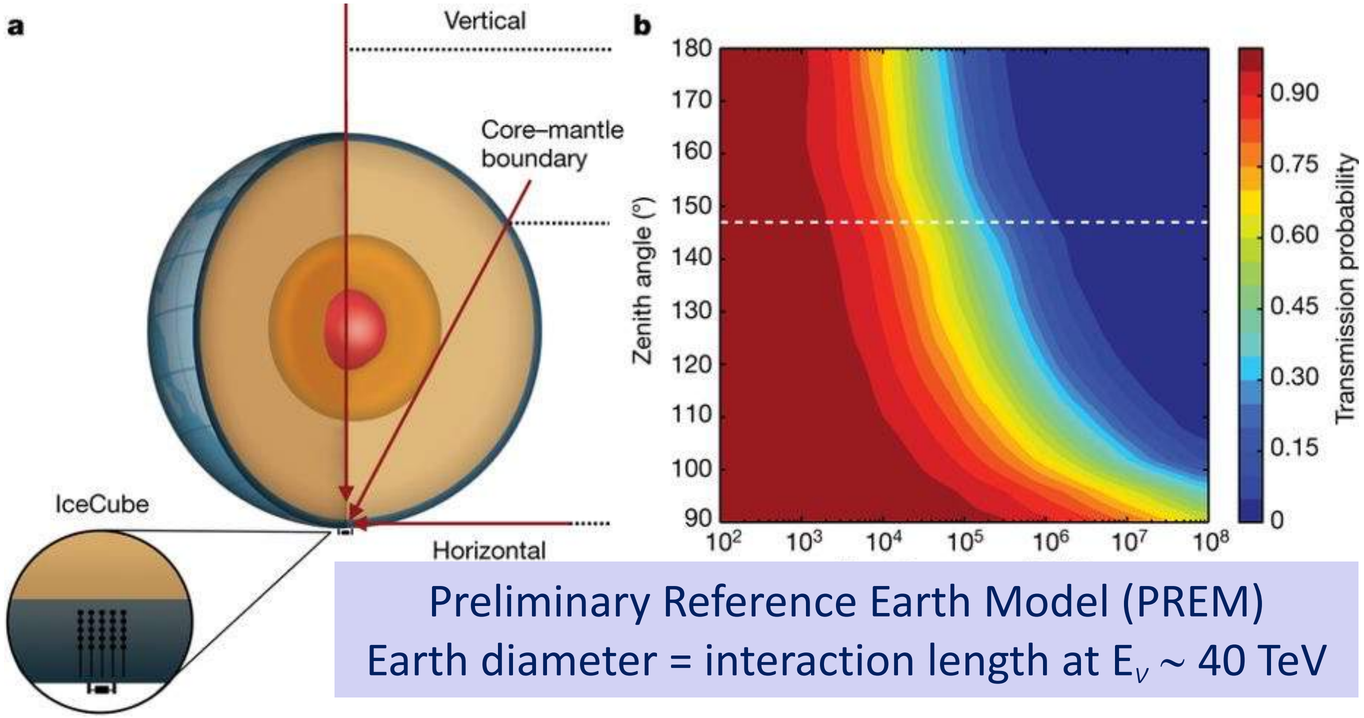


Mertsch, Cooper-Sarkar, S.S., *JHEP* **08**:042,2011 ⇒ CSMS

We found good agreement between different PDF sets after rejecting *unphysical* members which would have yielded negative values for the structure function F_L (or violated the Froissart bound)

Our predicted UHE ν-N cross-section has been verified using ν absorption in the Earth





Preliminary Reference Earth Model (PREM)
Earth diameter = interaction length at $E_\nu \sim$ 40 TeV

IceCube Collaboration, *Nature* **551**:596,2017

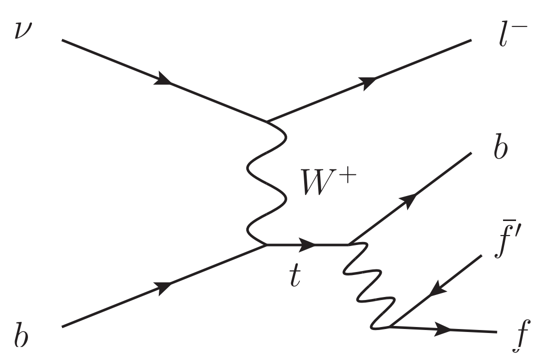
(Can *invert* the argument to perform tomography of the Earth, Donnini *et al*, *Nature Phys.* **15**:37,2019)

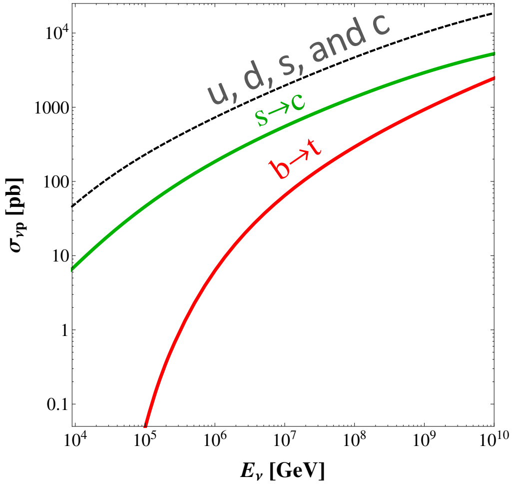
However the measurement uncertainty is large (~30%) and the Earth absorption method works only above ~10 TeV

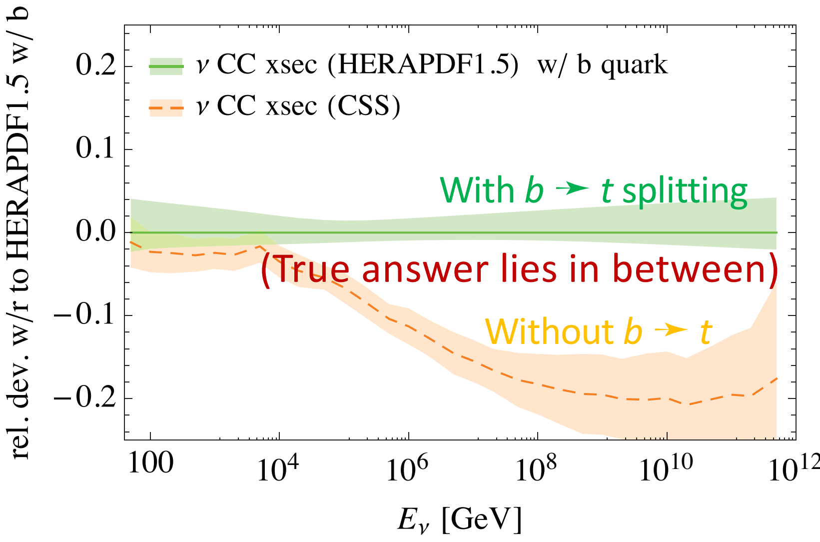
The FPF is well suited to bridge the gap down to laboratory measurements (upto ~300 GeV) at fixed-target experiments

* Heavy quark effects on DGLAP evolution:

Barger *et al*, *PR* **D95**:093002,2017





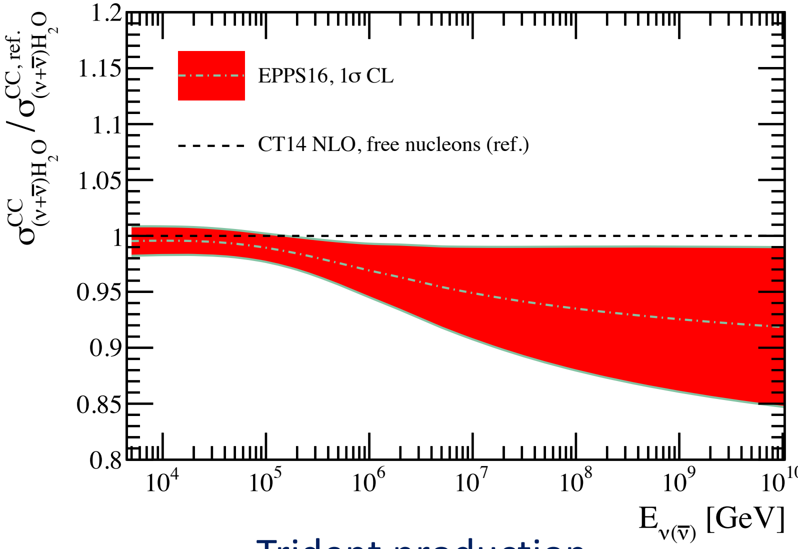


CSMS, *JHEP* **08**:042,2011

The exact way the b ➛ t contribution turns on ⇒ ~10% syst. uncertainty

* Nuclear binding effects:

There is *no* experimental evidence for 'shadowing' but theory suggests it may depress the cross-section by ~5-10% at UHE

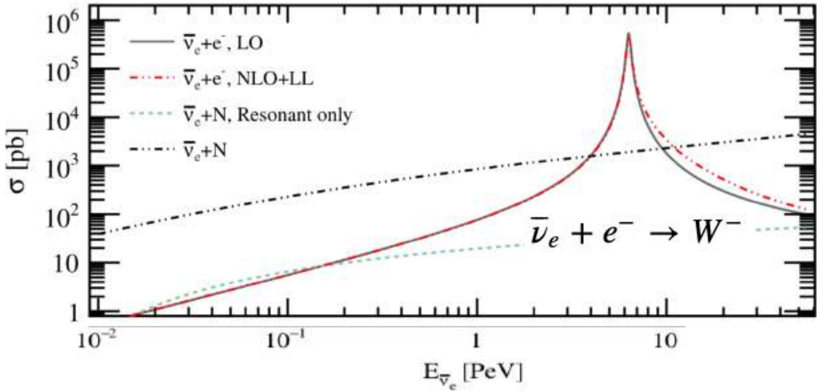


Bertone *et al*, *JHEP* **01**:217,2019

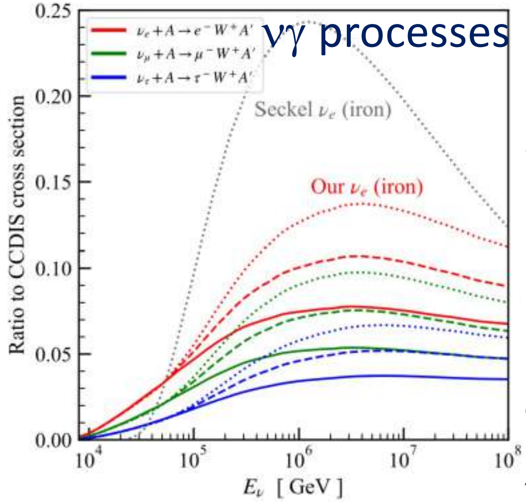
* Other contributions:

Glashow resonance @ 6.3 PeV

Gauld, *PR* D**100**:091301,2019

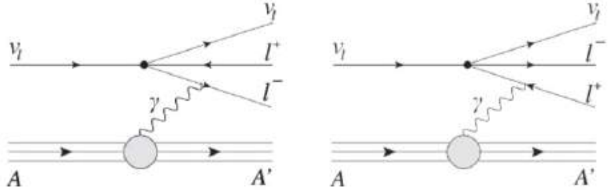


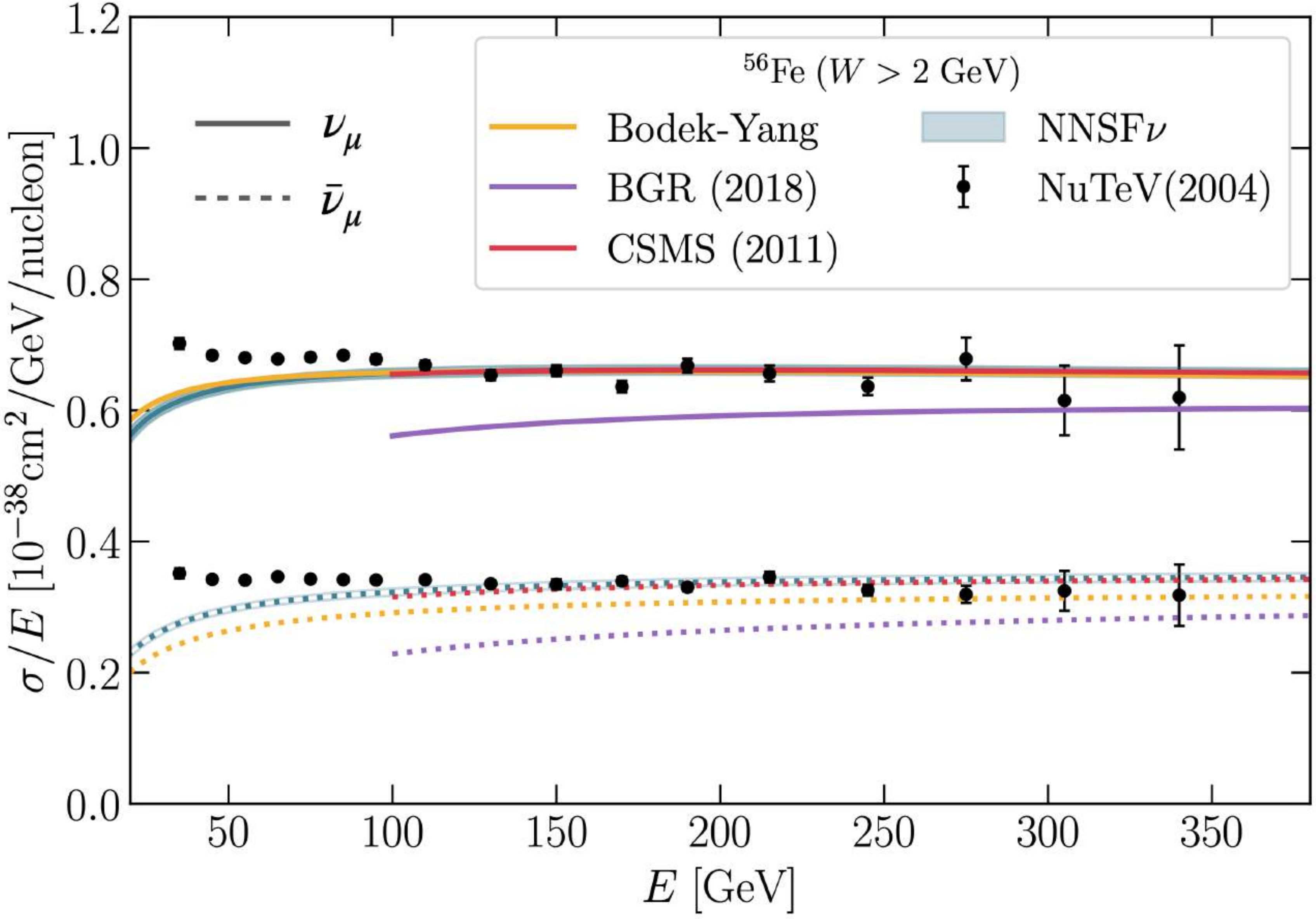
νγ processes



Zhou & Beacom, *PR* D**101**:036001,2019

Trident production



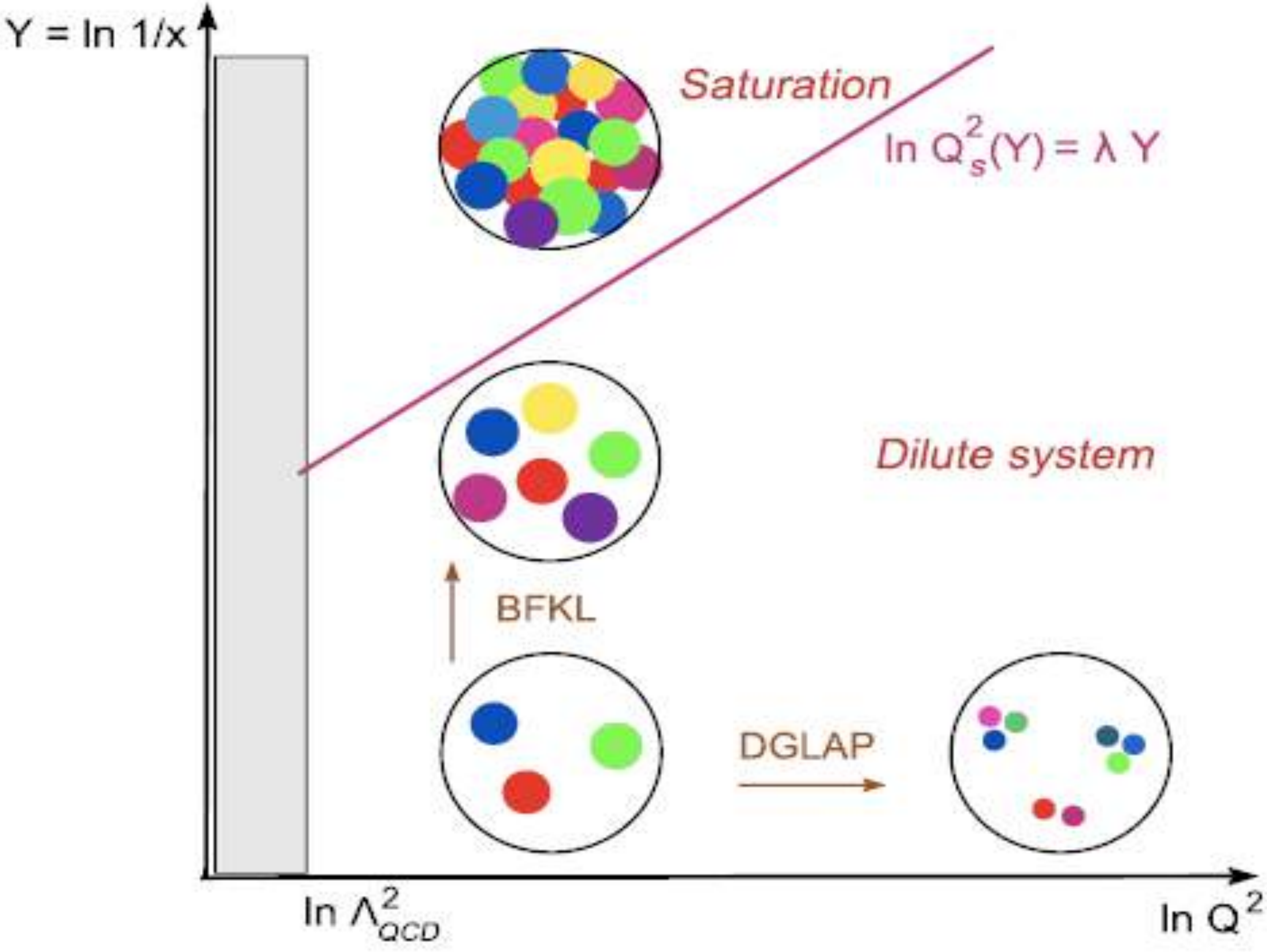


Candido *et al.*, JHEP 05:149,2023

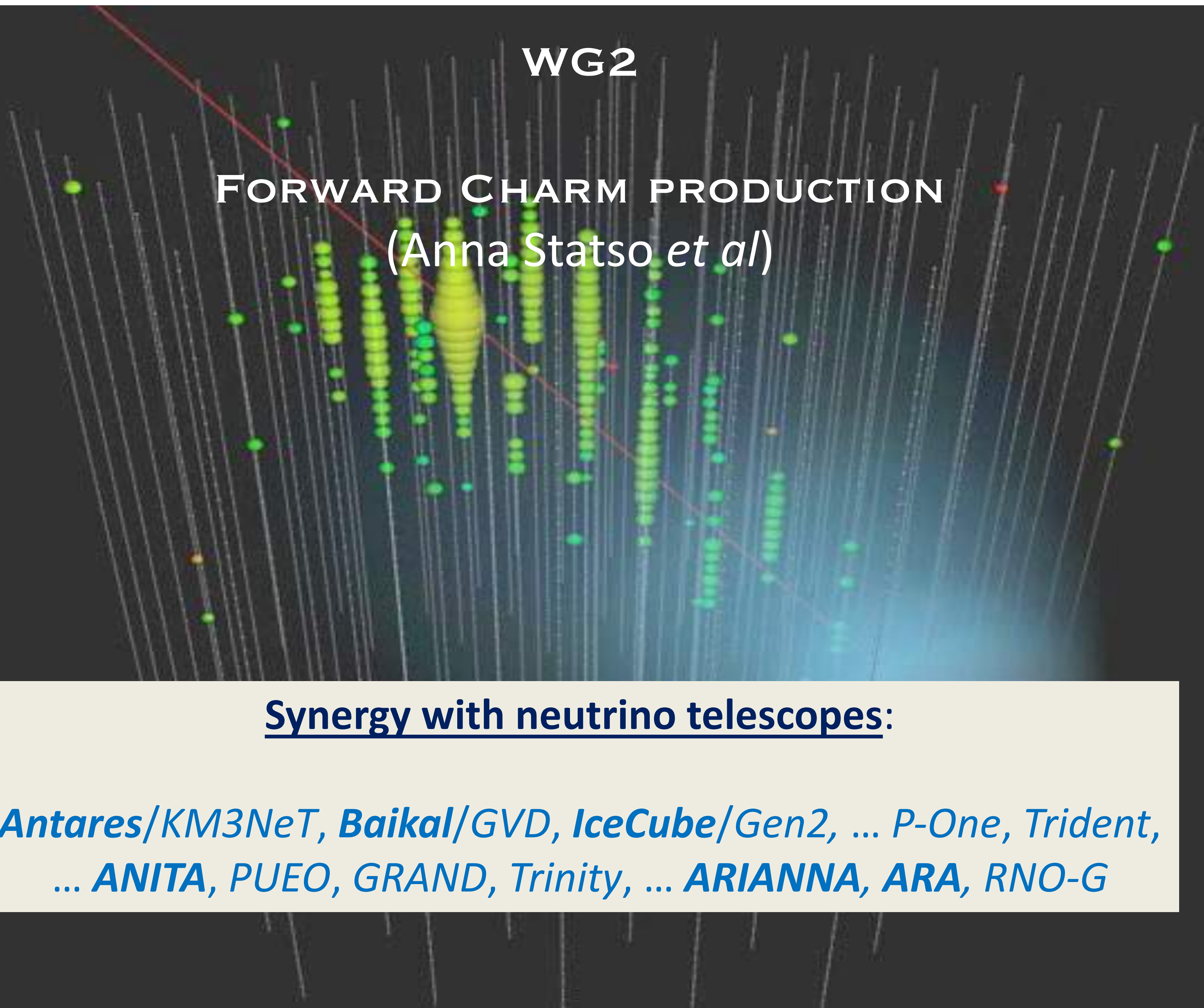
https://nnpdf.github.io/nnusf/index.html

This is being used to predict inclusive cross sections for a range of energies and target nuclei relevant for the FPF

As the gluon density rises at low x, a new phase of QCD – the Colour Glass Condensate - has been postulated to exist (and has some support from RHIC and ALICE data)



Would be interesting to explore using neutrino deep inelastic scattering …



WG2

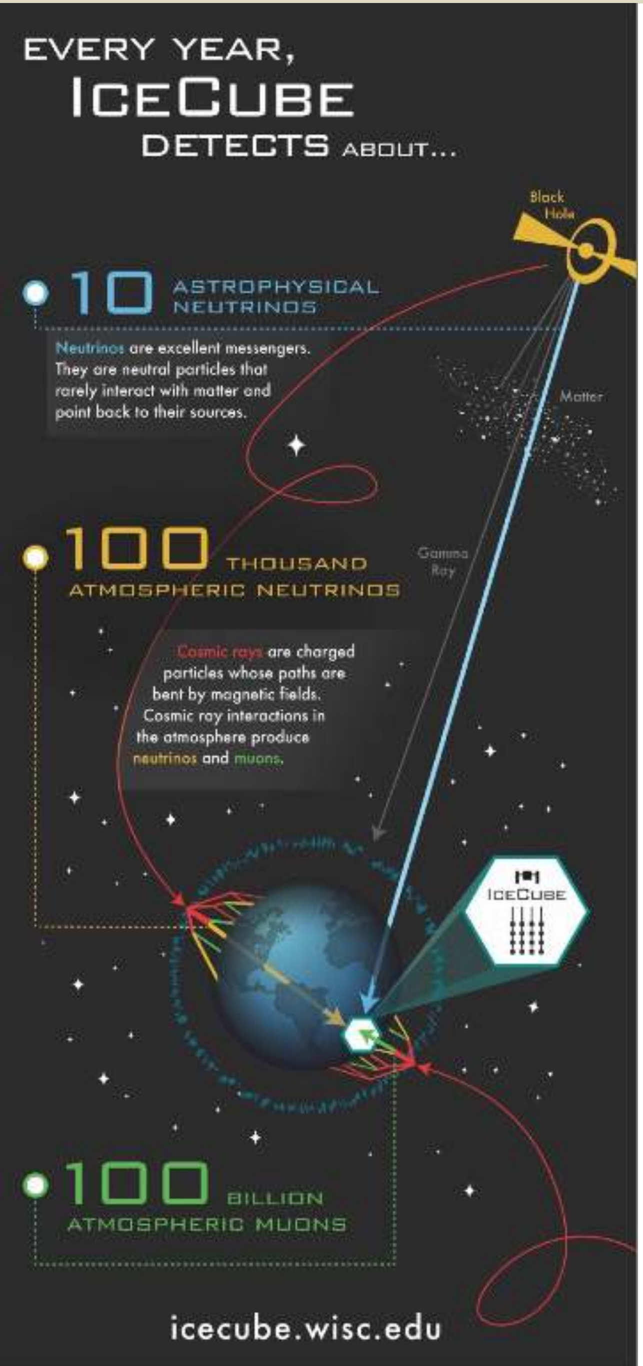
Forward Charm production

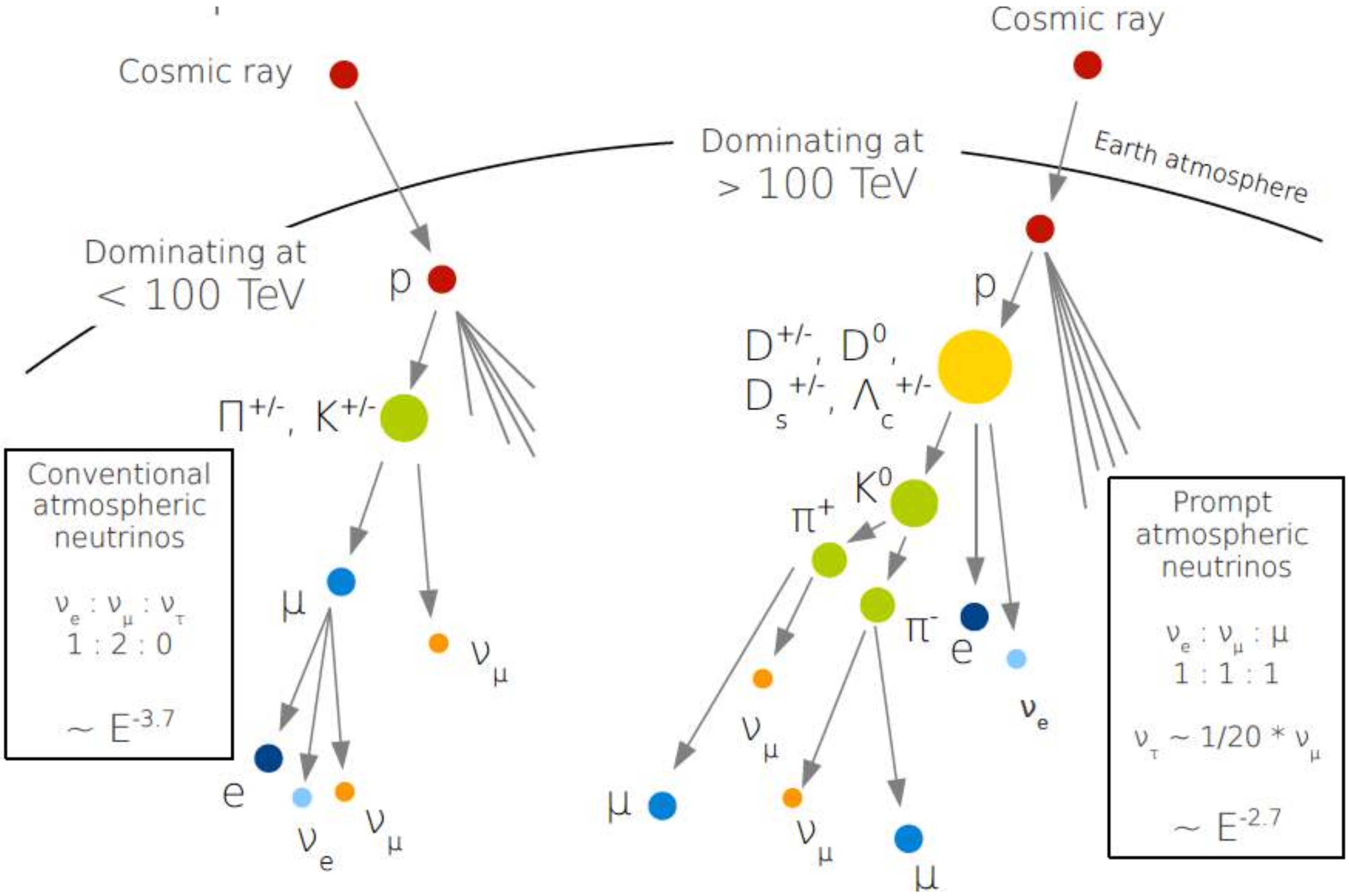
(Anna Statso *et al*)

Synergy with neutrino telescopes:

Antares/*KM3NeT*, ***Baikal***/*GVD*, ***IceCube***/*Gen2, … P-One, Trident,*
… ***ANITA***, *PUEO, GRAND, Trinity, …* ***ARIANNA***, ***ARA***, *RNO-G*

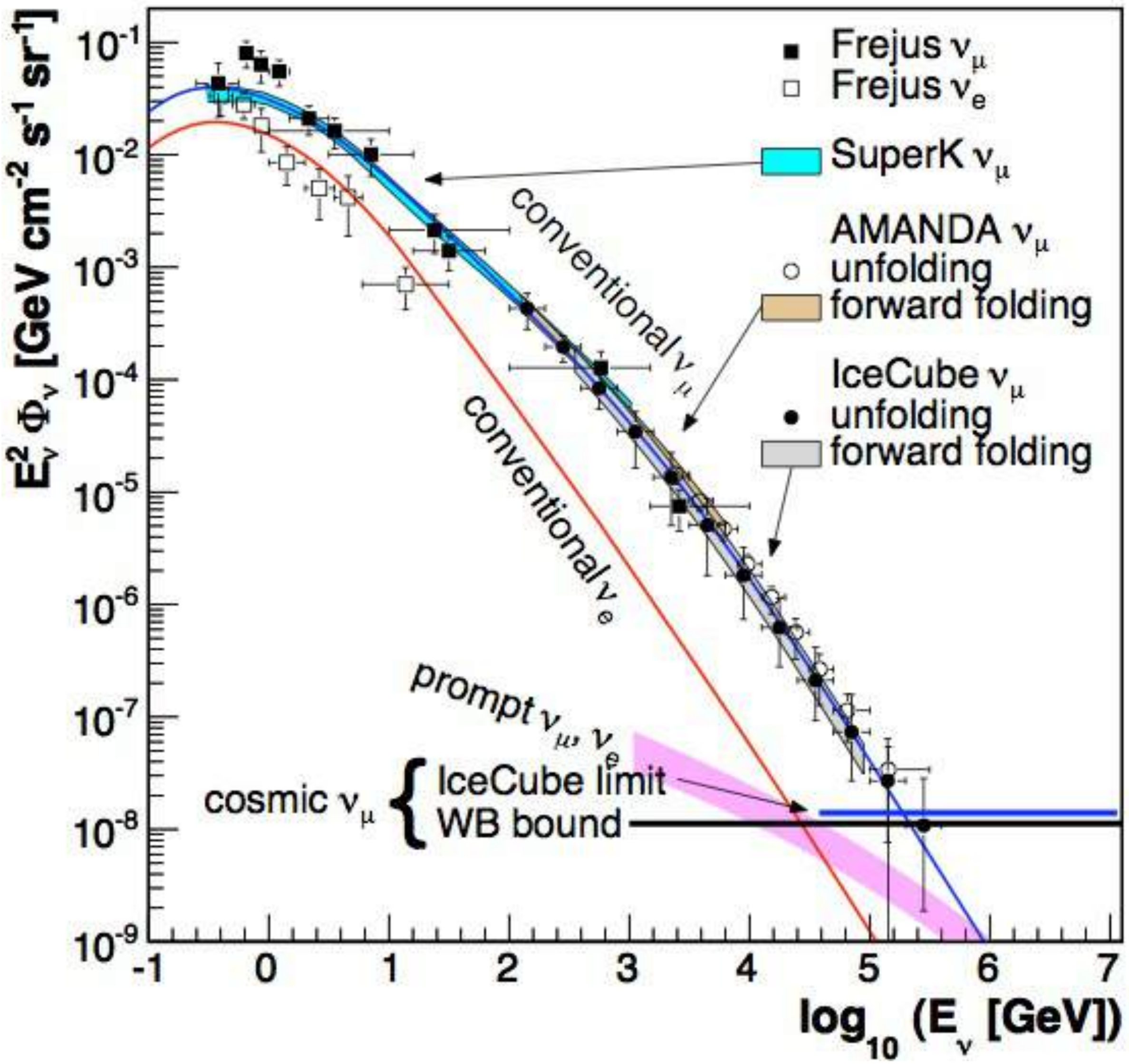
Neutrino telescopes look for a cosmic signal buried in a huge background of atmospheric neutrinos

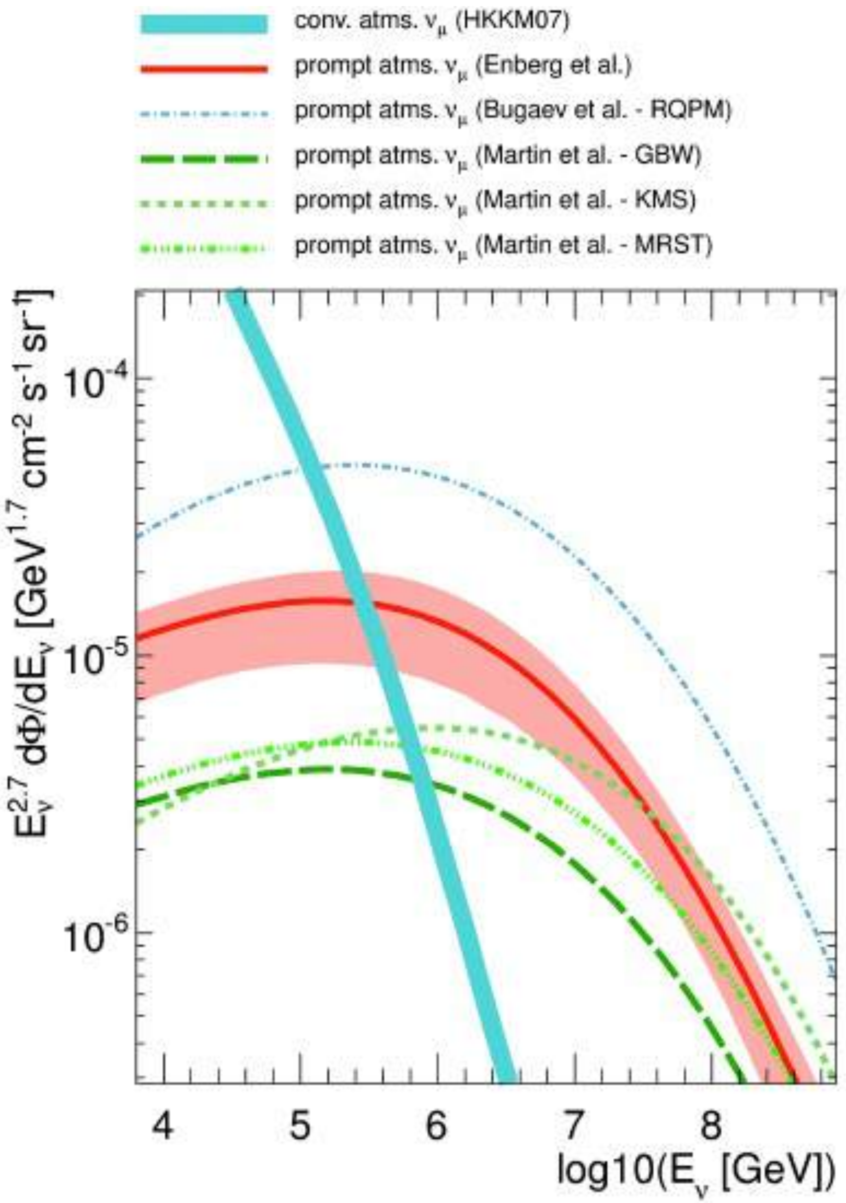




Courtesy: Anne Schukraft

The 'conventional flux' is well understood as it is calibrated against many observations but uncertainties in charm production make the prompt flux less so although it is the most important background for the astrophysical flux!





The prompt flux is *harder* than the conventional flux, and was predicted to *dominate* the total flux at E > 10^{5-6} GeV

The quantity needed to determine charm production in cosmic ray air showers is:

$$Z_{ph} = \int_E^\infty dE' \frac{\phi_p(E')}{\phi_p(E)} \frac{A}{\sigma_{pA}(E)} \frac{d\sigma(pp \to c\bar{c}Y; E', E)}{dE}$$

- The **differential cross-section** can be calculated in a variety of formalisms, e.g. the 'colour dipole model' of ERS which is empirical (hard to estimate uncertainties)

  However, **perturbative QCD (with DGLAP evolution)** *can* describe charm production data for the entire kinematical region of interest, hence can calculate with **NLO+PS MC event generators**

- Boosting from CM to the rest frame of the (atmospheric) fixed target:

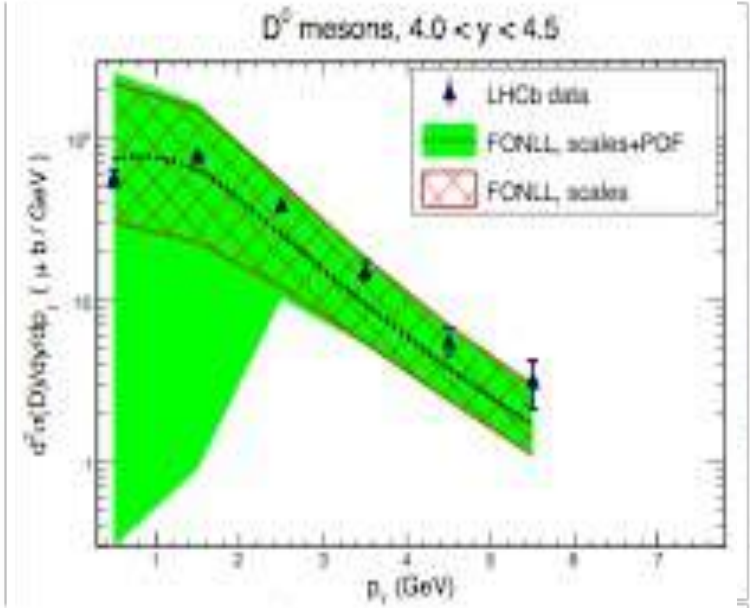
$$\sqrt{s} = 7\ [TeV] \longleftrightarrow E_b = 2.6 \times 10^7\ [GeV]$$

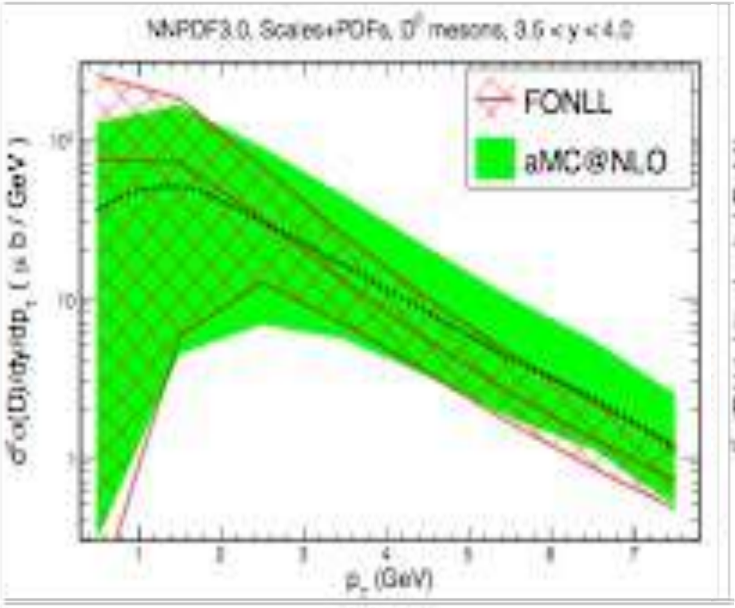
We can thus predict the prompt neutrino flux at energies **up to 10^7 GeV** … at these energies, charm production is dominated by **gluon fusion**, hence sensitive to the behaviour of the **gluon PDF at small-*x***

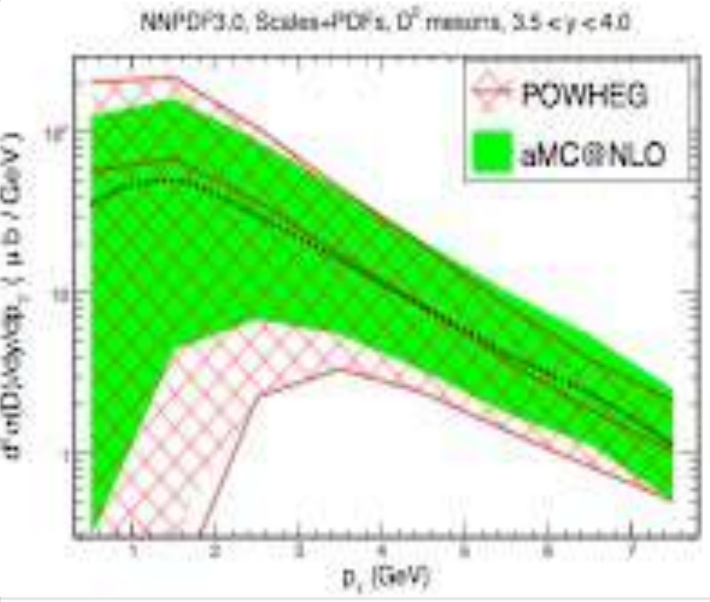
Gauld *et al*, *JHEP* **02**:130,2016

Forward Charm Production & LHCb

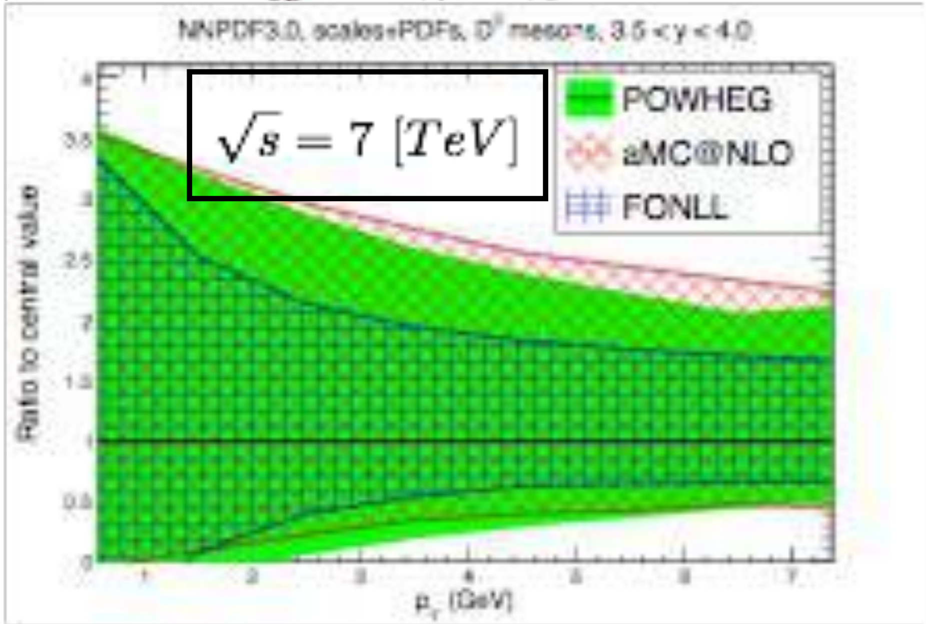
LHCb collab. *Nucl.Phys.***B871**:1,2013



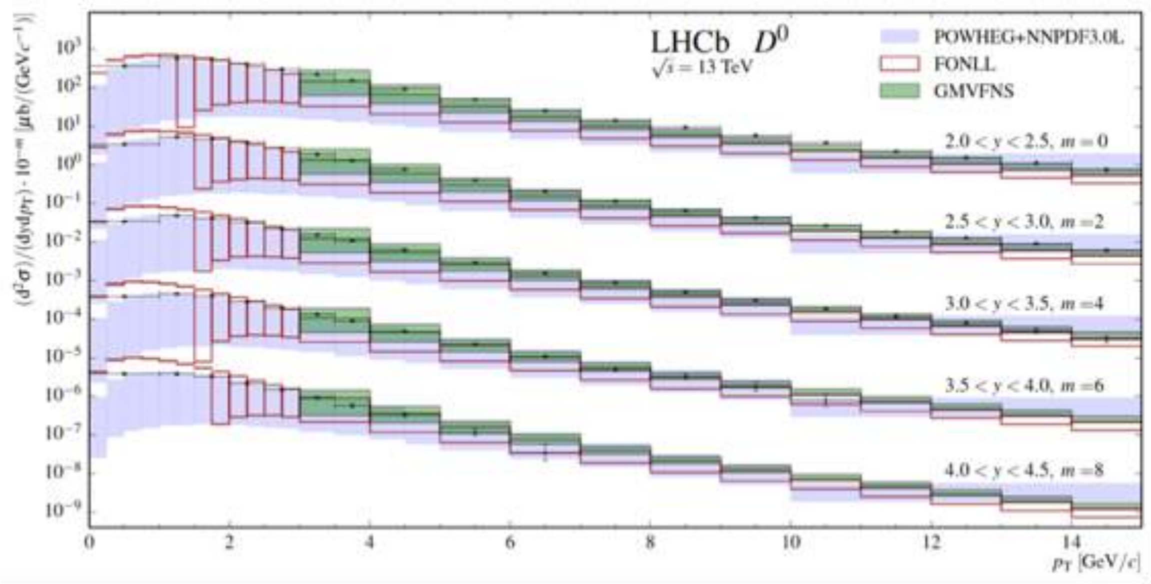




Gauld *et al*, *JHEP* **11**:009,2015

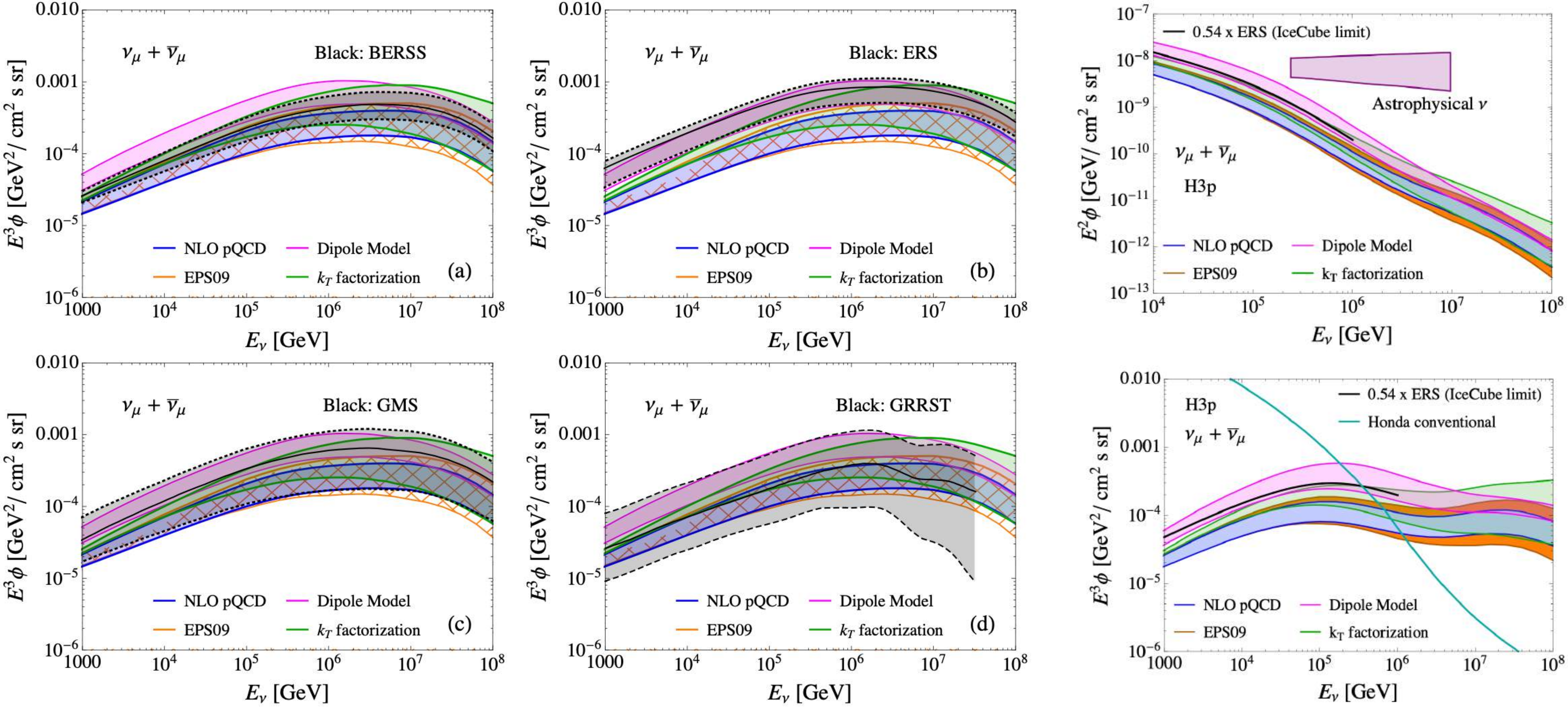


Prediction for 13 TeV matched the data!



NLO predictions for forward charm production validated with LHCb data

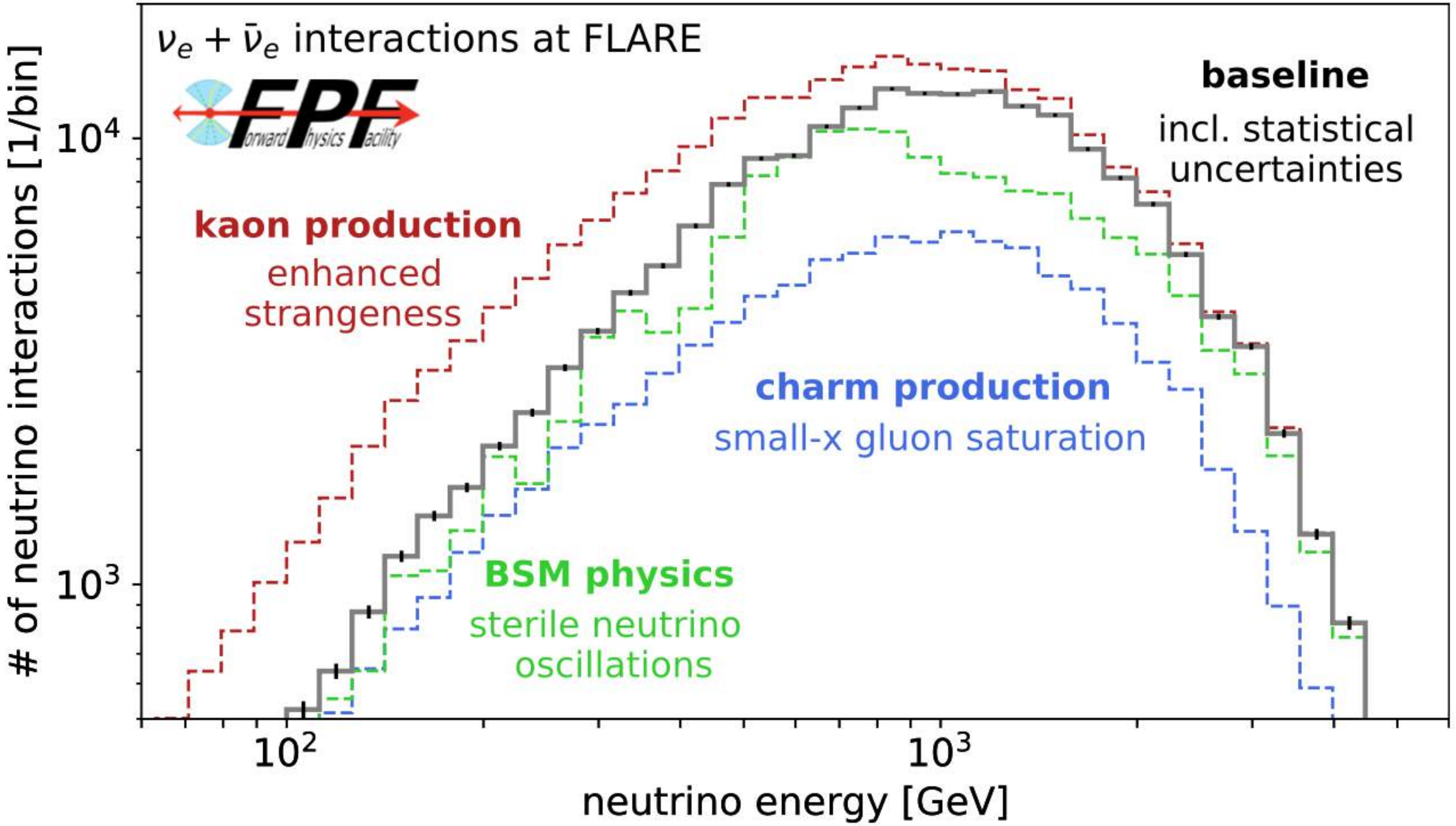
Range of predictions narrowed with input from *LHCb* data



Bhattacharya *et al*, *JHEP* 11:167,2016

FASERν and *SND@LHC* will measure the prompt neutrinos in a more forward region (y > 7.2) than *LHCb* can access

- FLArE measurements of neutrino flux can probe both very high-x and very low-x regions of colliding protons
- Gluon recombination $(gg \to g)$ is expected to be relevante for $x \sim 10^{-7}$ and would tame growth of gluon PDF in this region



Courtesy: Luis Anchordoqui

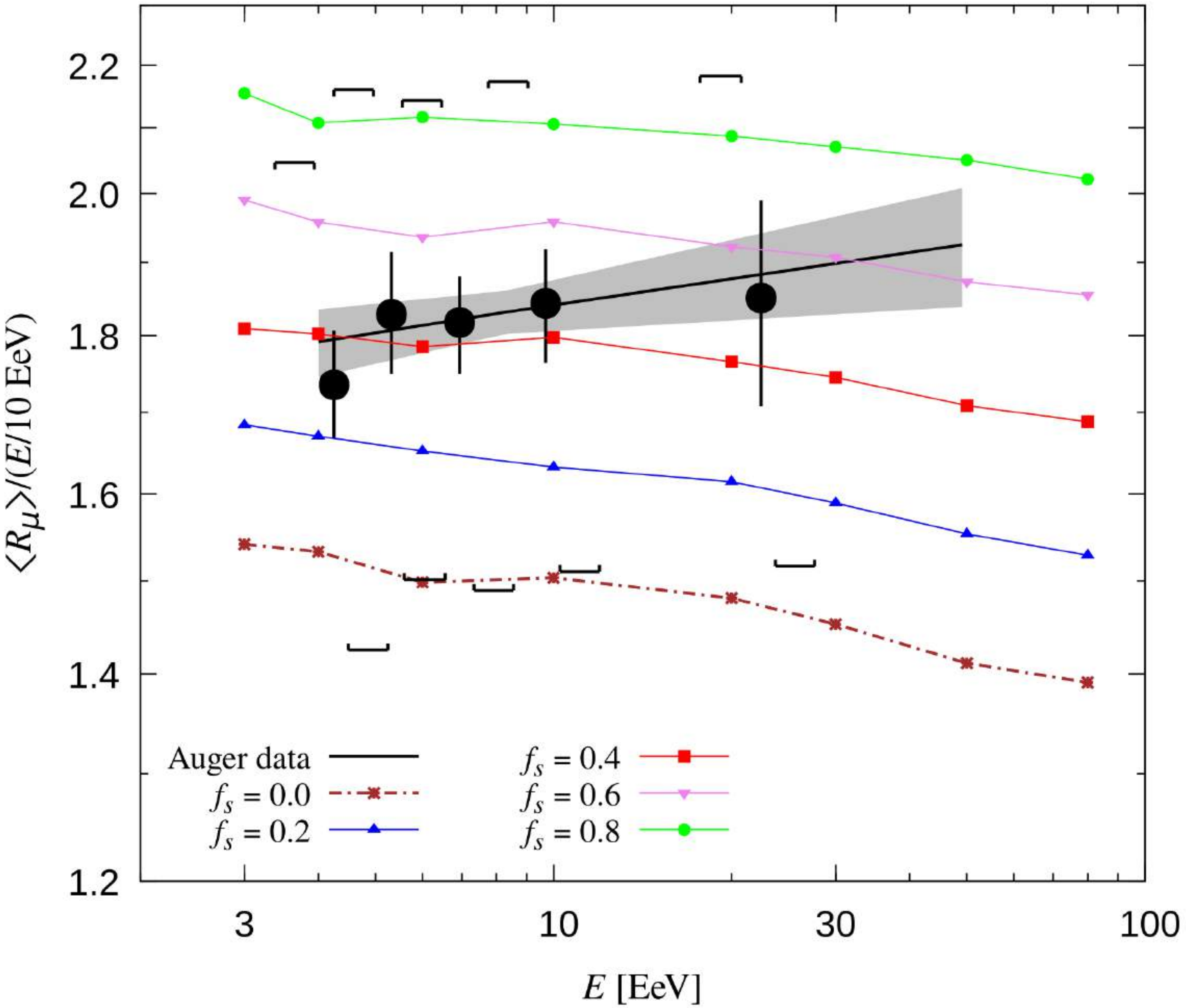
WG3

Light hadron production

(Dennis Soldin *et al*)

Synergy with Cosmic Ray Air Shower arrays:

Pierre Auger Observatory, ***IceTop***, *KASCADE-GRANDE*, ***NEVOD-DECOR …***



Anchordoqui *et al*, *JHEAp* **34**:19,2022

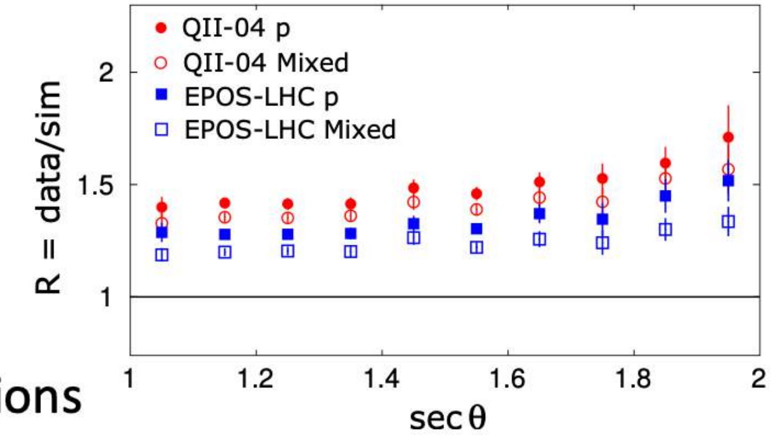
- Hints in ALICE data

arXiv:1606.07424

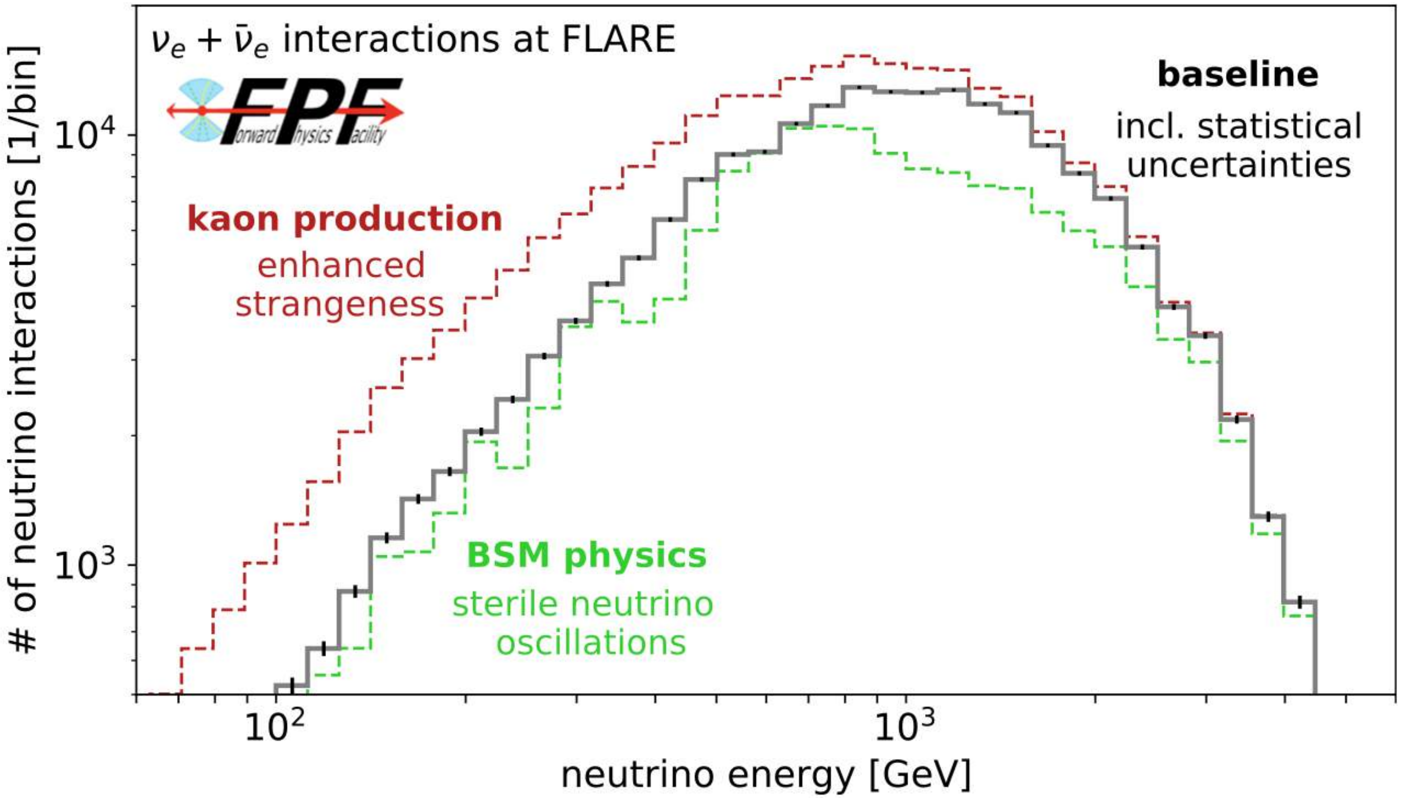
- Hadronic component of showers

with $10^{9.8} < E/\mathrm{GeV} < 10^{10.2}$

contains more muons than expected from simulations



arXiv:1610.08509



Whether the muon excess is simply due to enhanced strangeness production in the forward direction can easily be tested at the FPF …

Courtesy: Luis Anchordoqui

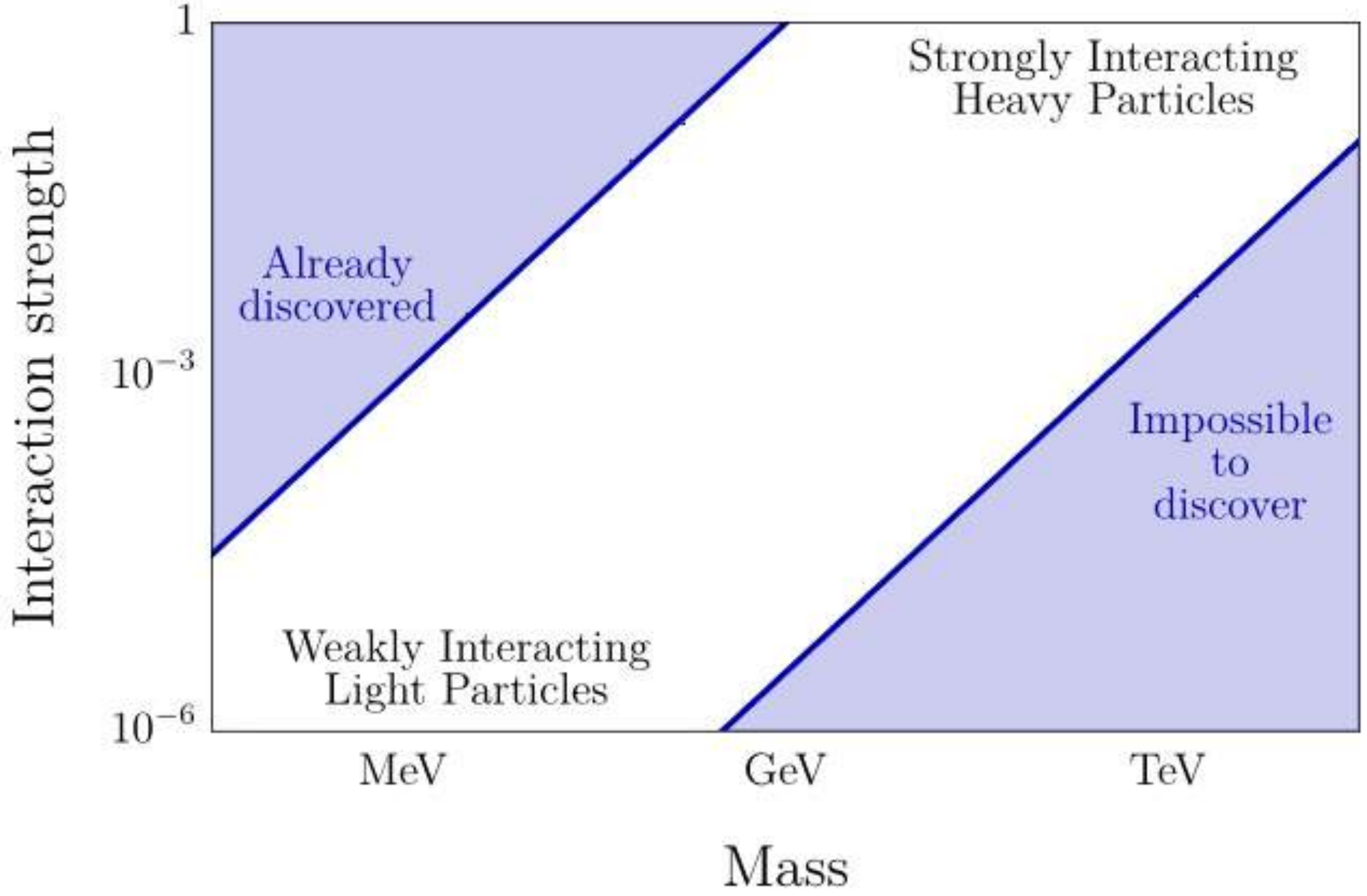
WG4

BSM physics

(Sebastian Trojanowski *et al*)

Synergy with neutrino telescopes & dark matter experiments

The new particle landscape

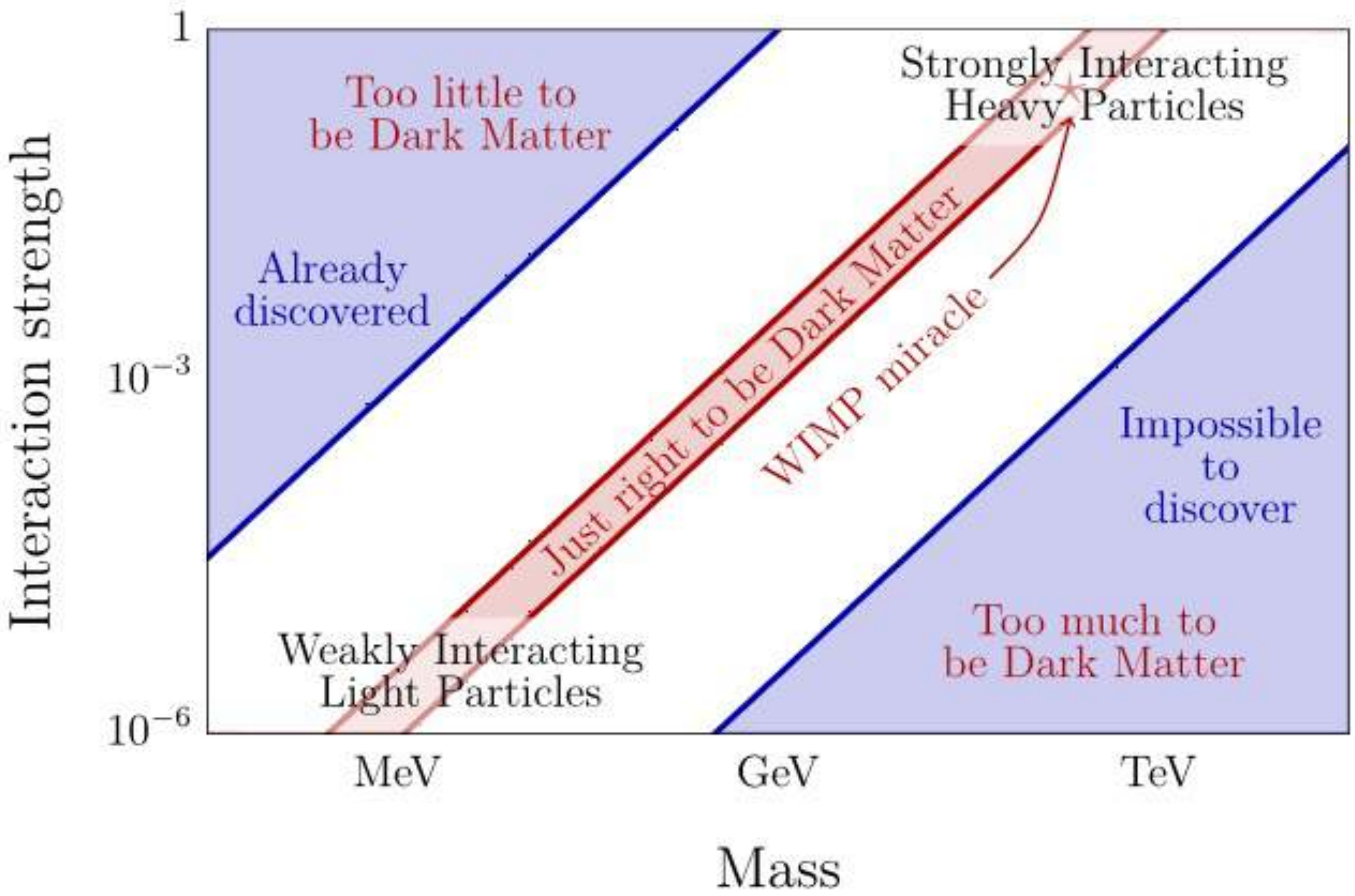


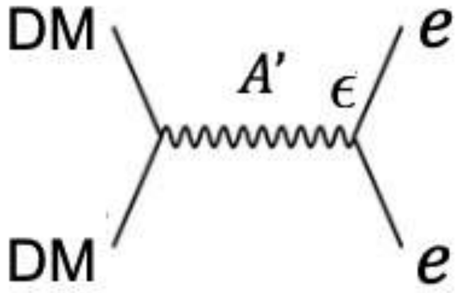
Courtesey: Luis Anchordoqui

- ATLAS and CMS detectors are designed to find new heavy particles which are produced almost at rest and decay isotropically
- New light particles are mainly produced along the beamline and so new particles disappear through the holes that let the beams in
- We need a detector to cover the blind spots in the forward region *

* Or do a beam dump experiment!

THE 'WIMP-LESS MIRACLE'





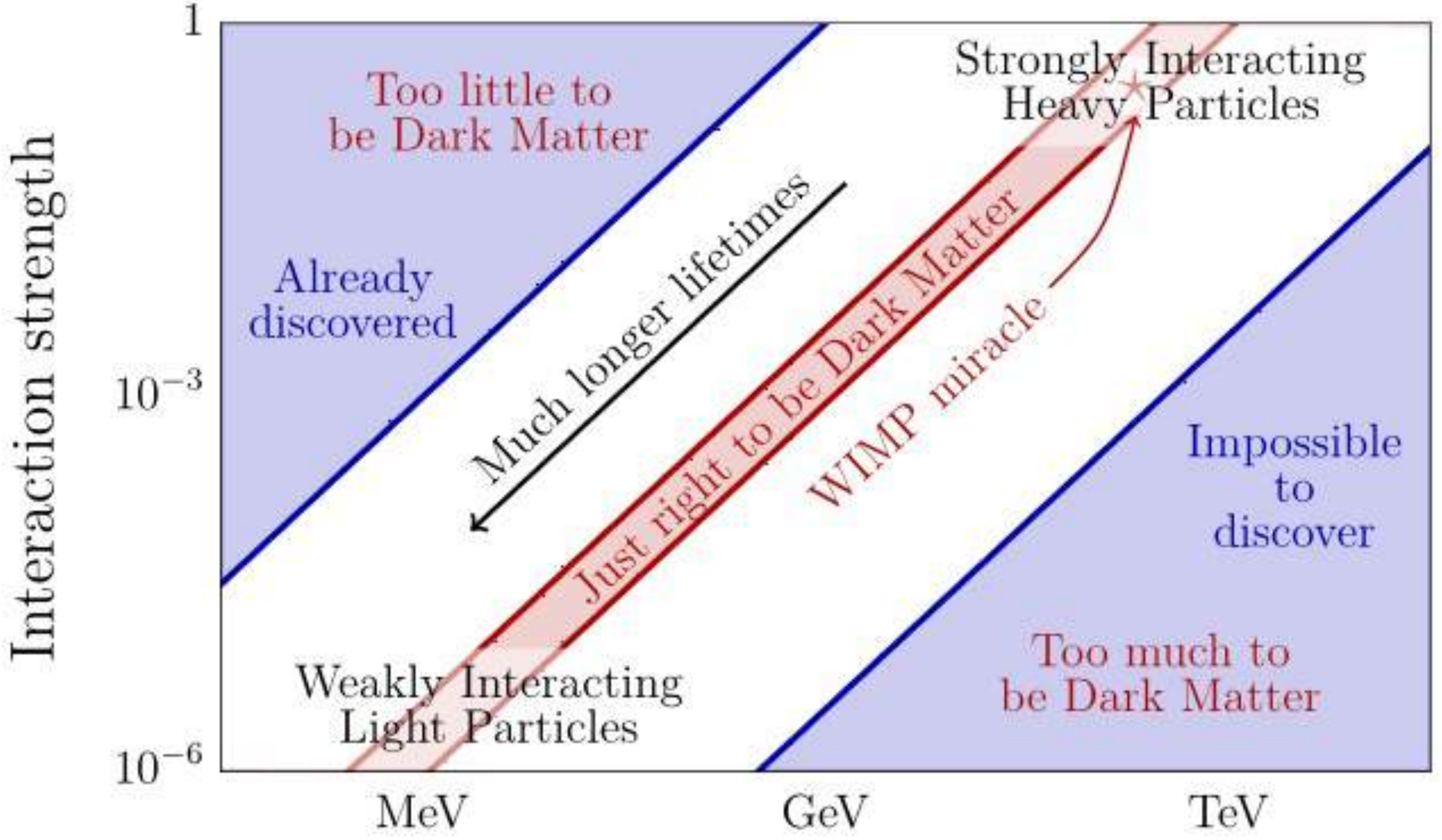
$$\langle \sigma v \rangle \sim \epsilon^2 / m_{A'}^2$$

Feng & Kumar, PRL **101:231301**,2008

$$\Omega_{DM} \propto 1/\langle \sigma v \rangle \sim m_{A'}^2/\epsilon^2$$

Courtesey: Luis Anchordoqui

Long-lived particles



Velocity near the speed of light

$v \sim 1$

Rest lifetime enhanced by small mass, small ε

$\tau \propto \frac{1}{\epsilon^2 m_{A'}}$

Lifetime further enhanced by time dilation

$\gamma \propto \frac{E}{m_{A'}}$

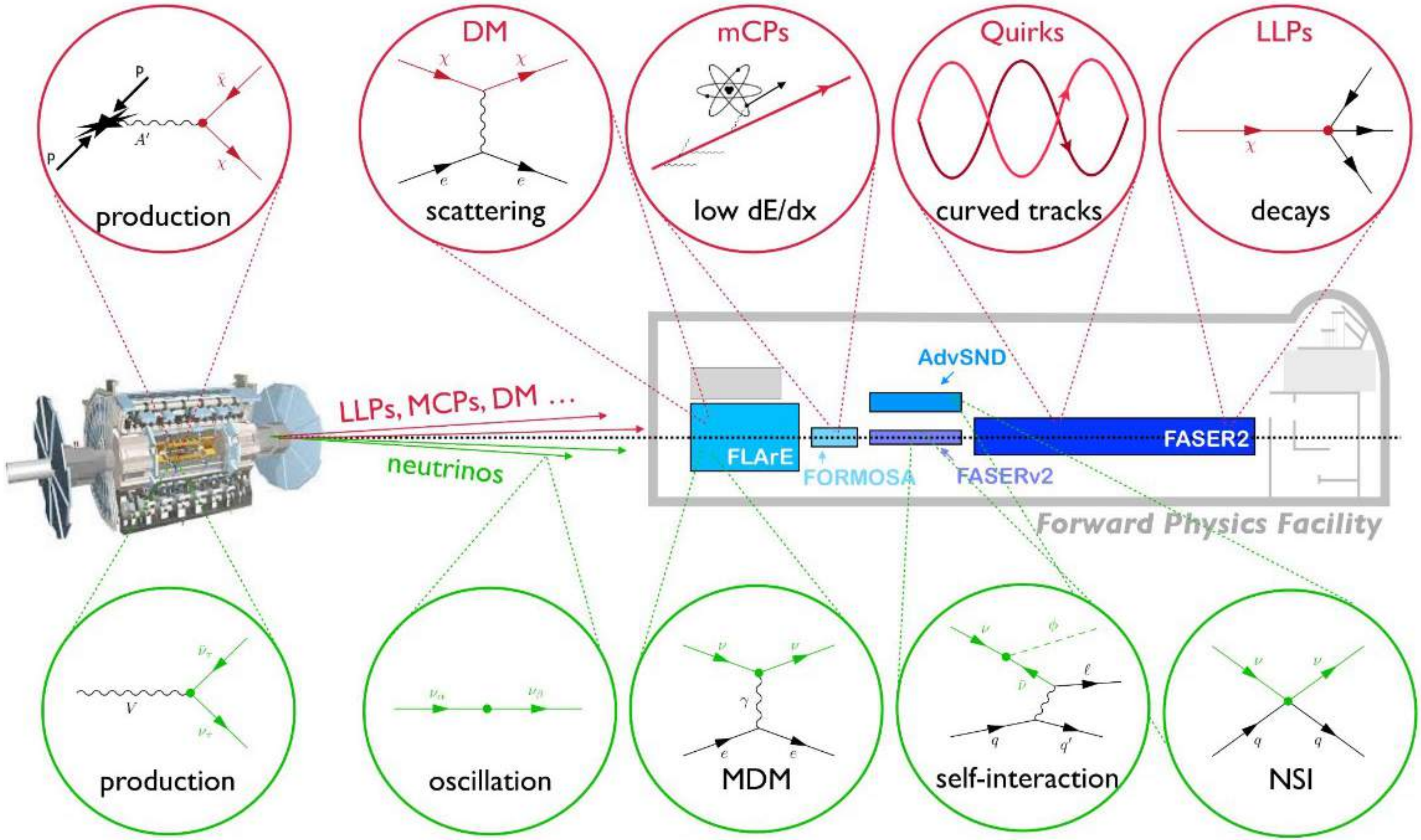
$$L = v\tau\gamma \sim 100\ \text{m} \left(\frac{10^{-5}}{\epsilon}\right)^2 \left(\frac{100\ \text{MeV}}{m_{A'}}\right)^2 \left(\frac{E}{\text{TeV}}\right)$$

Courtesey: Luis Anchordoqui

The Portal Formalism

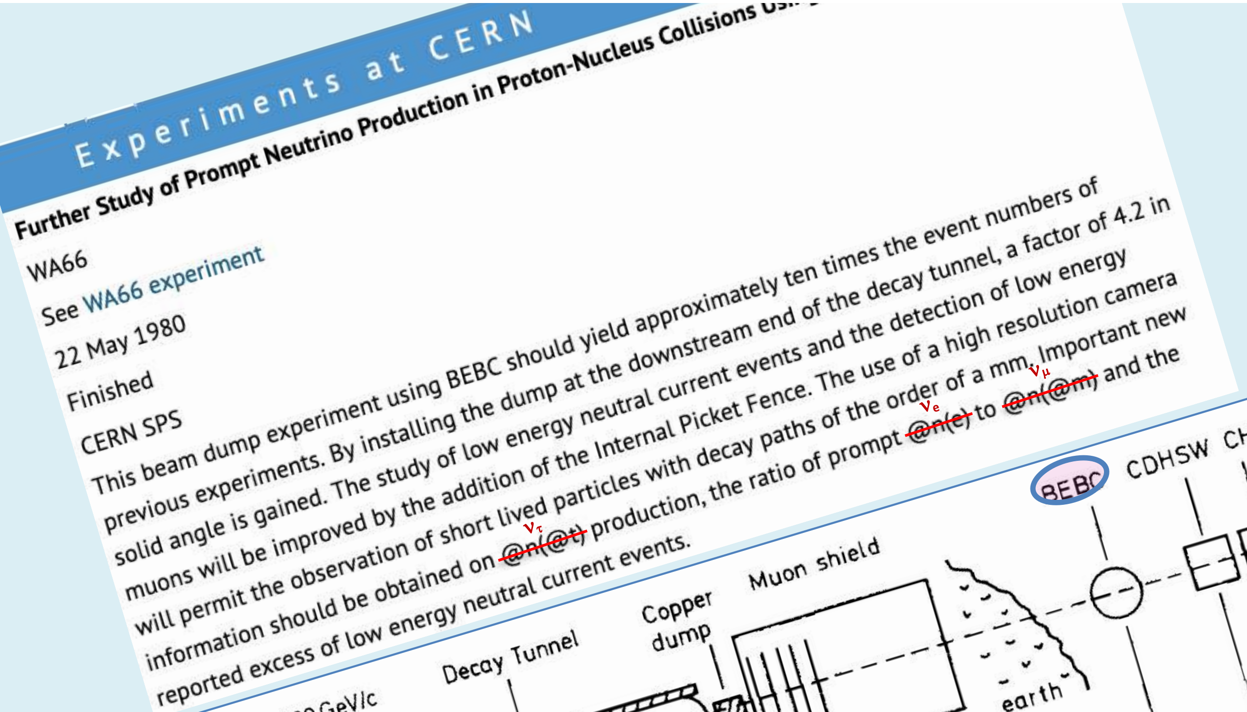
$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$$

Vector portal	$F'_{\mu\nu} F^{\mu\nu}$	
Scalar portal	$\phi H^\dagger H$	$\phi^2 H^\dagger H$
Neutrino portal	$L H N$	
Axion portal	$\frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$	



Courtesey: Felix Kling

Such searches were carried out ~40 years ago at CERN by the neutrino beam dump experiments at the SPS – I will focus on BEBC WA66 which searched for light neutralinos, heavy neutral leptons, neutrino magnetic moments *etc*



Experiments at CERN

Further Study of Prompt Neutrino Production in Proton-Nucleus Collisions Usi...

WA66

See WA66 experiment

22 May 1980

Finished

CERN SPS

This beam dump experiment using BEBC should yield approximately ten times the event numbers of previous experiments. By installing the dump at the downstream end of the decay tunnel, a factor of 4.2 in solid angle is gained. The study of low energy neutral current events and the detection of low energy muons will be improved by the addition of the Internal Picket Fence. The use of a high resolution camera will permit the observation of short lived particles with decay paths of the order of a mm. Important new information should be obtained on ~~@n(@t)~~ ν_τ production, the ratio of prompt ~~@n(e)~~ ν_e to ~~@n(@m)~~ ν_μ and the reported excess of low energy neutral current events.

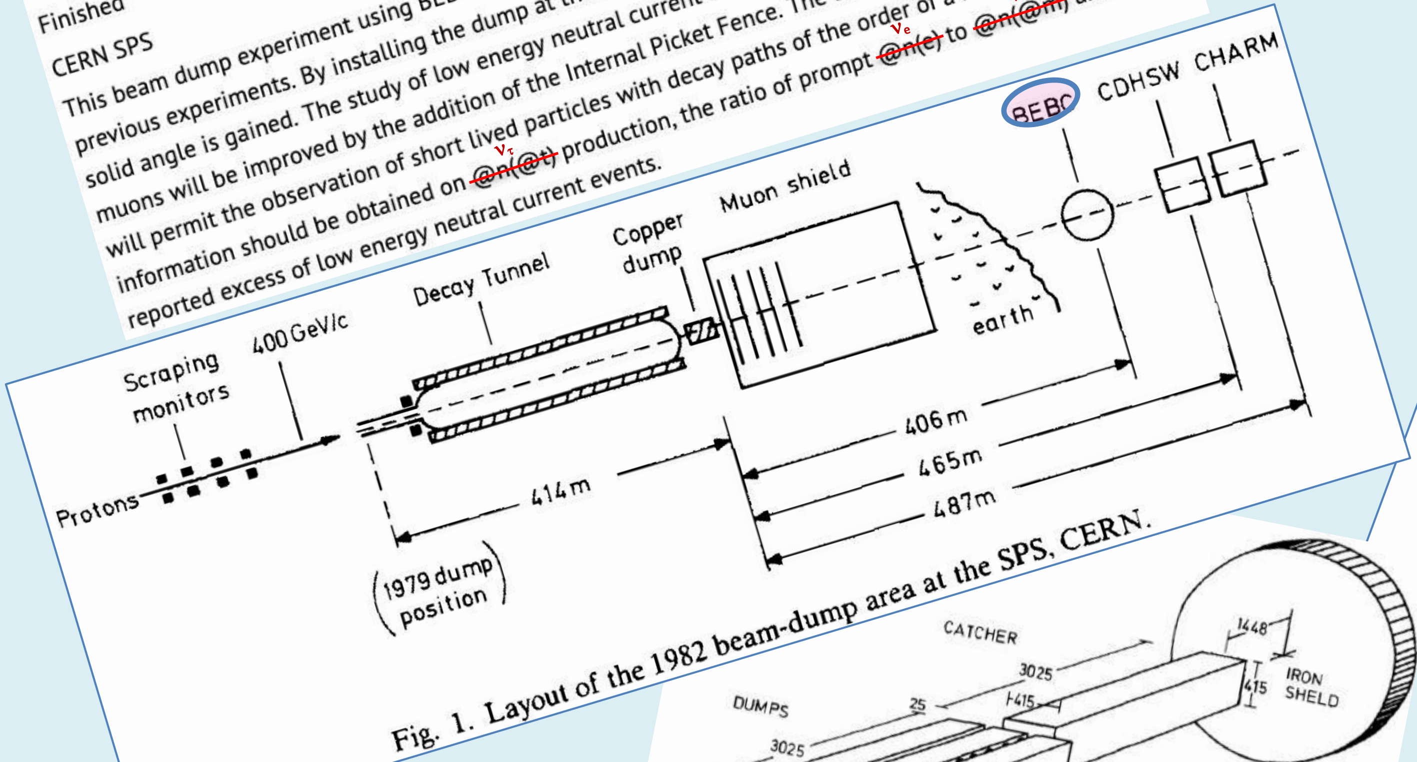
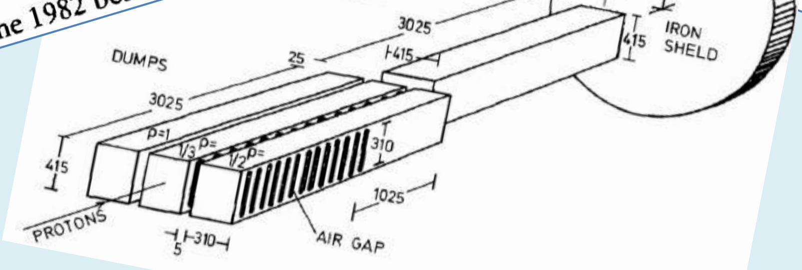
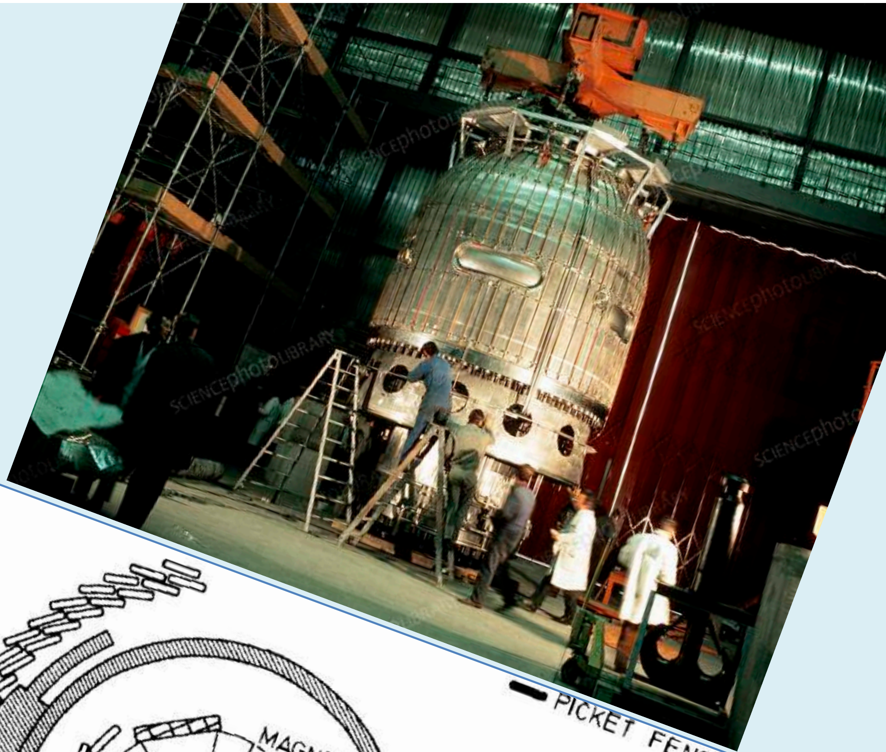
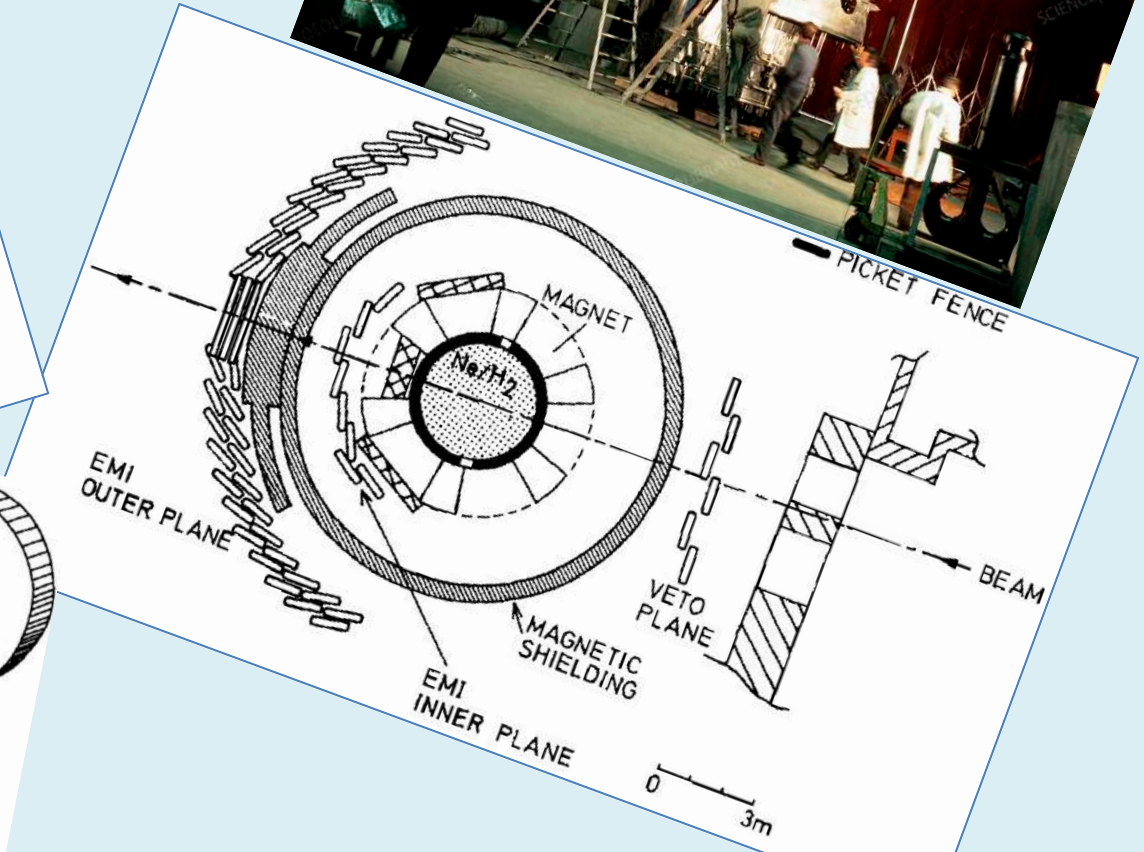


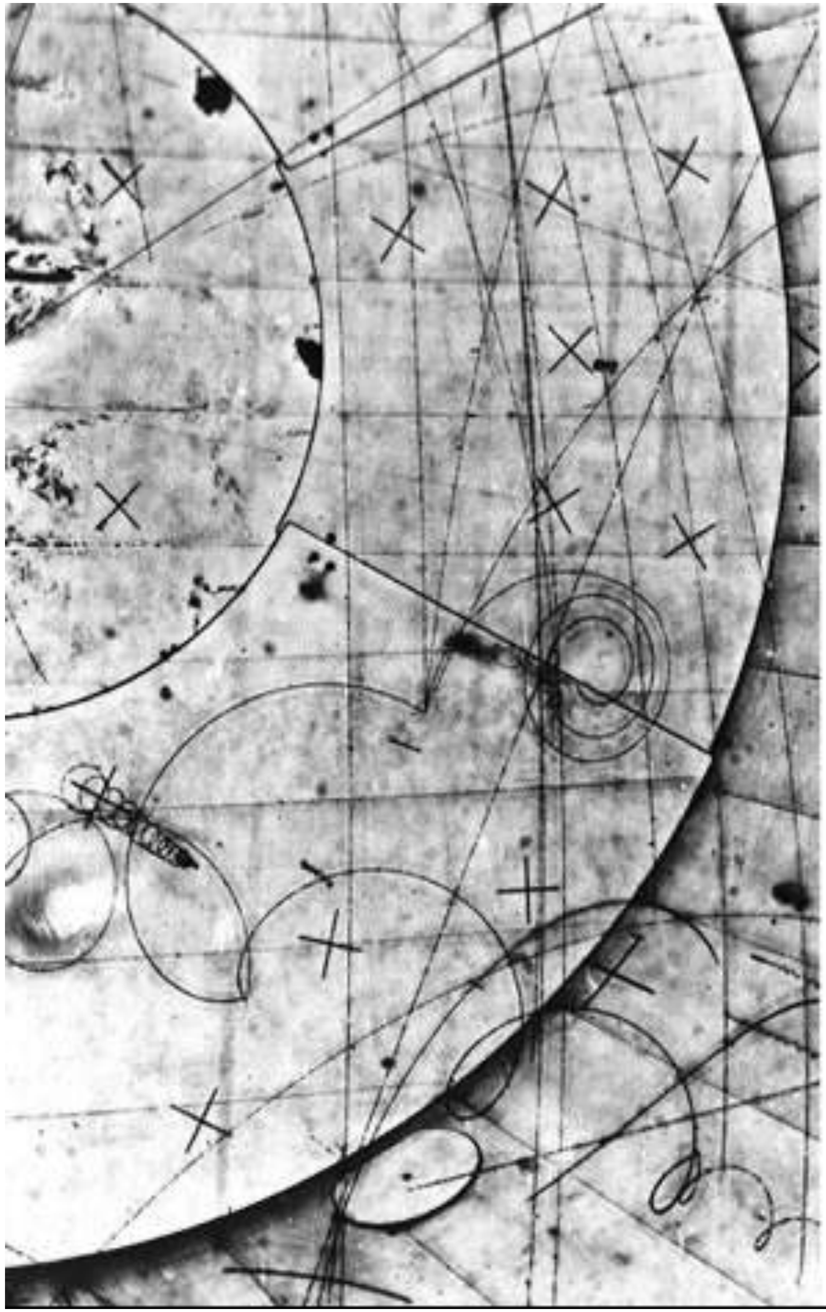
Fig. 1. Layout of the 1982 beam-dump area at the SPS, CERN.

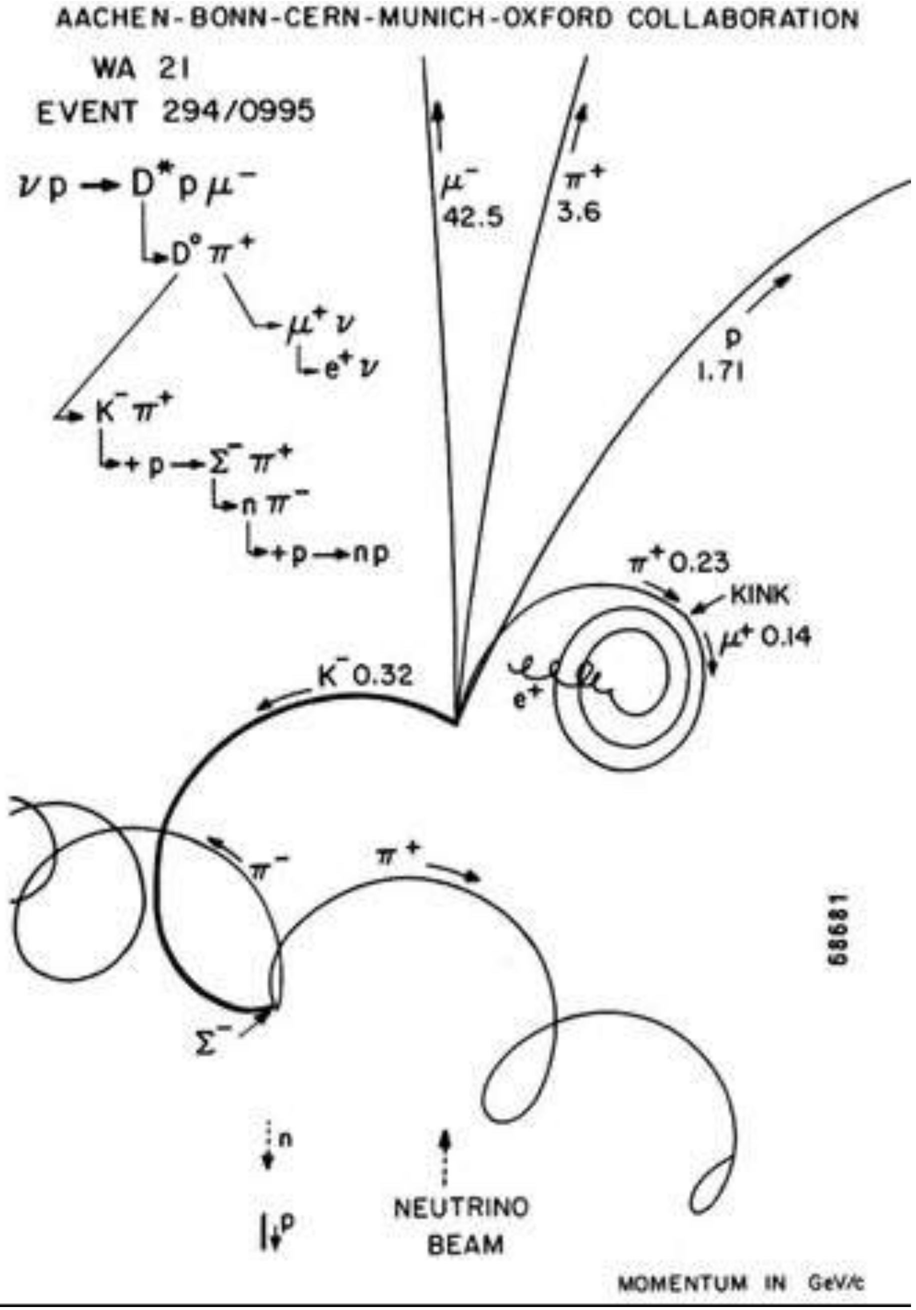






Fully reconstructed neutrino interaction event in BEBC





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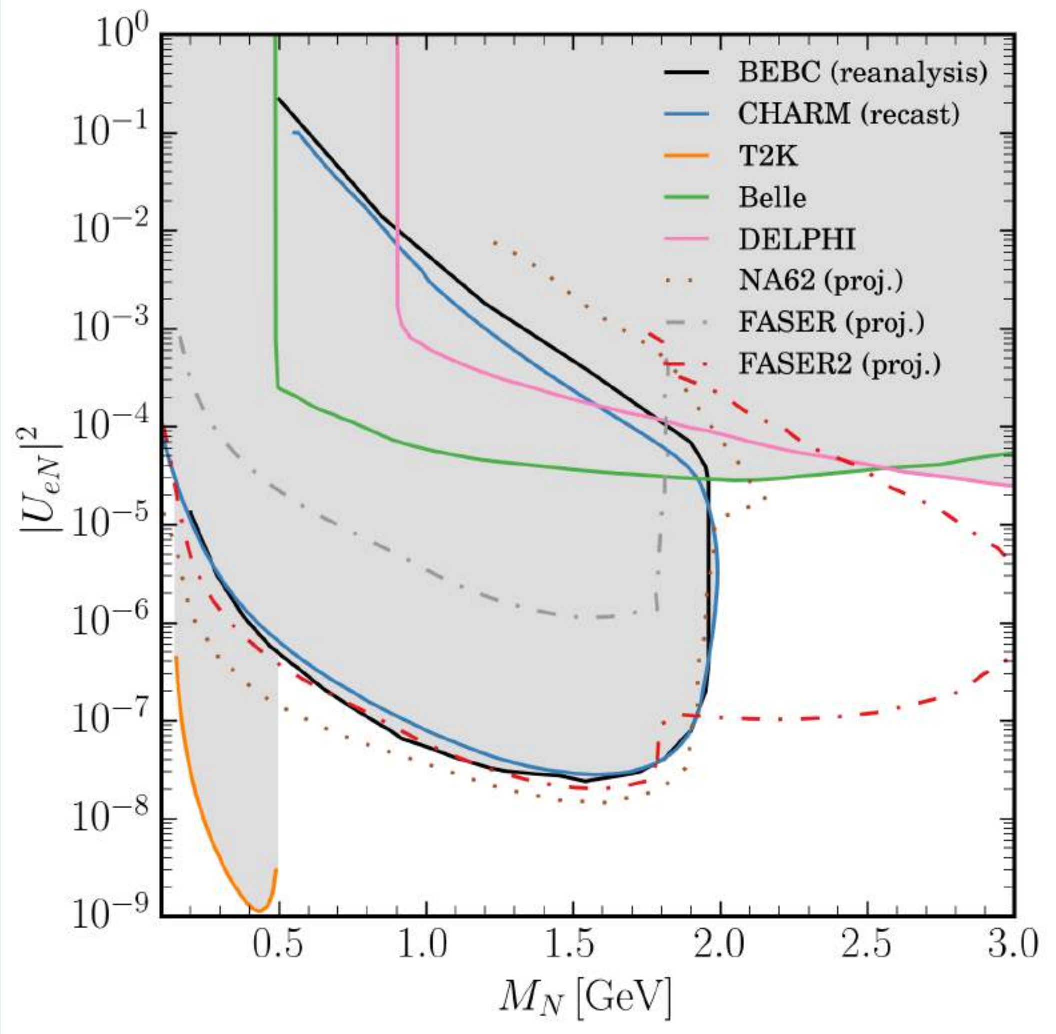
Blast from the past II: Constraints on heavy neutral leptons from the BEBC WA66 beam dump experiment

Ryan Barouki, Giacomo Marocco* and Subir Sarkar

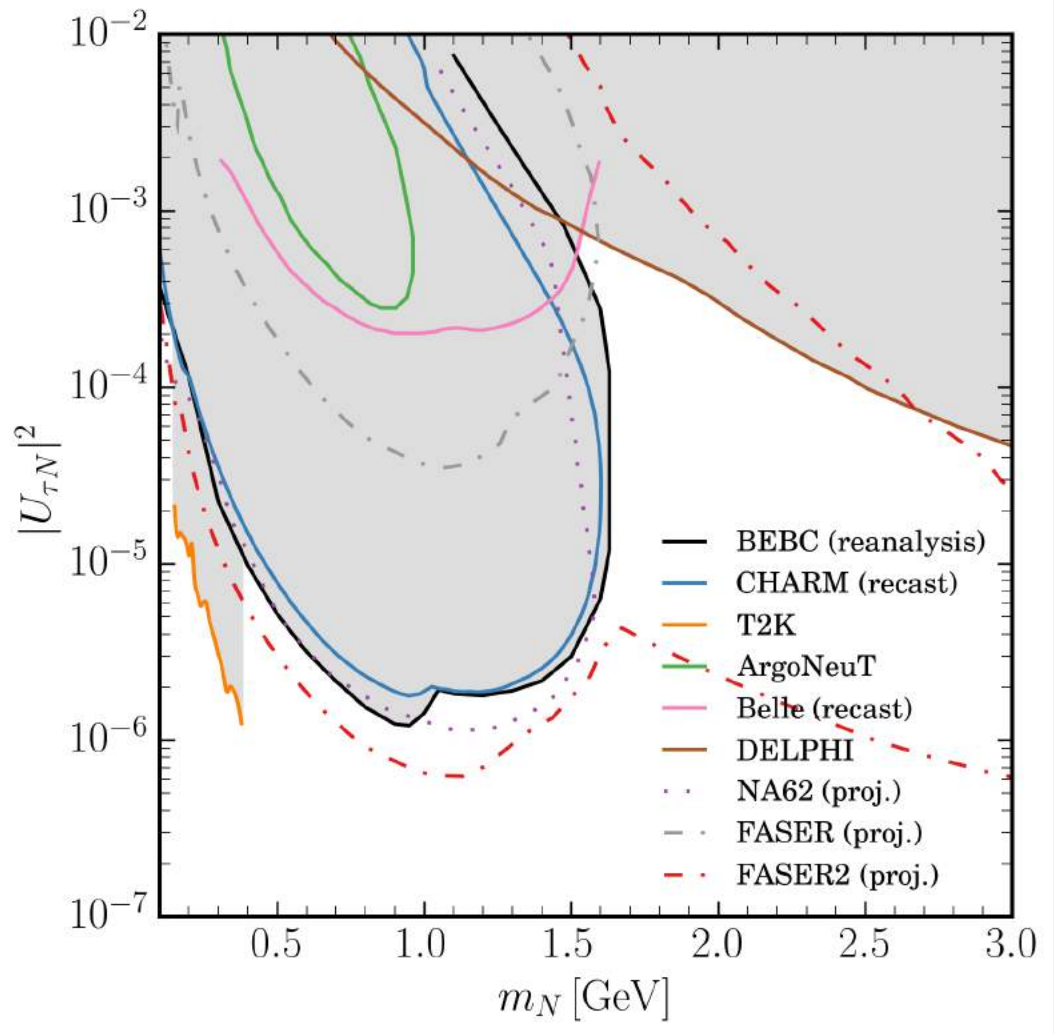
Rudolf Peierls Centre for Theoretical Physics, University of Oxford,
Parks Road, Oxford OX1 3PU, United Kingdom

We revisit the search for heavy neutral leptons with the Big European Bubble Chamber in the 1982 proton beam dump experiment at CERN, focussing on those heavier than the kaon and mixing only with the tau neutrino, as these are far less constrained than their counterparts with smaller mass or other mixings. Recasting the previous search in terms of this model and including additional production and decay channels yields the strongest bounds to date, up to the tau mass. This applies also to our updated bounds on the mixing of heavy neutral leptons with the electron neutrino.



This turns out to still be the most sensitive bound on the mixings of HNLs with active neutrinos …

FASER2 will do a factor of ~5 better upto m_c and a factor of ~100 better upto m_b



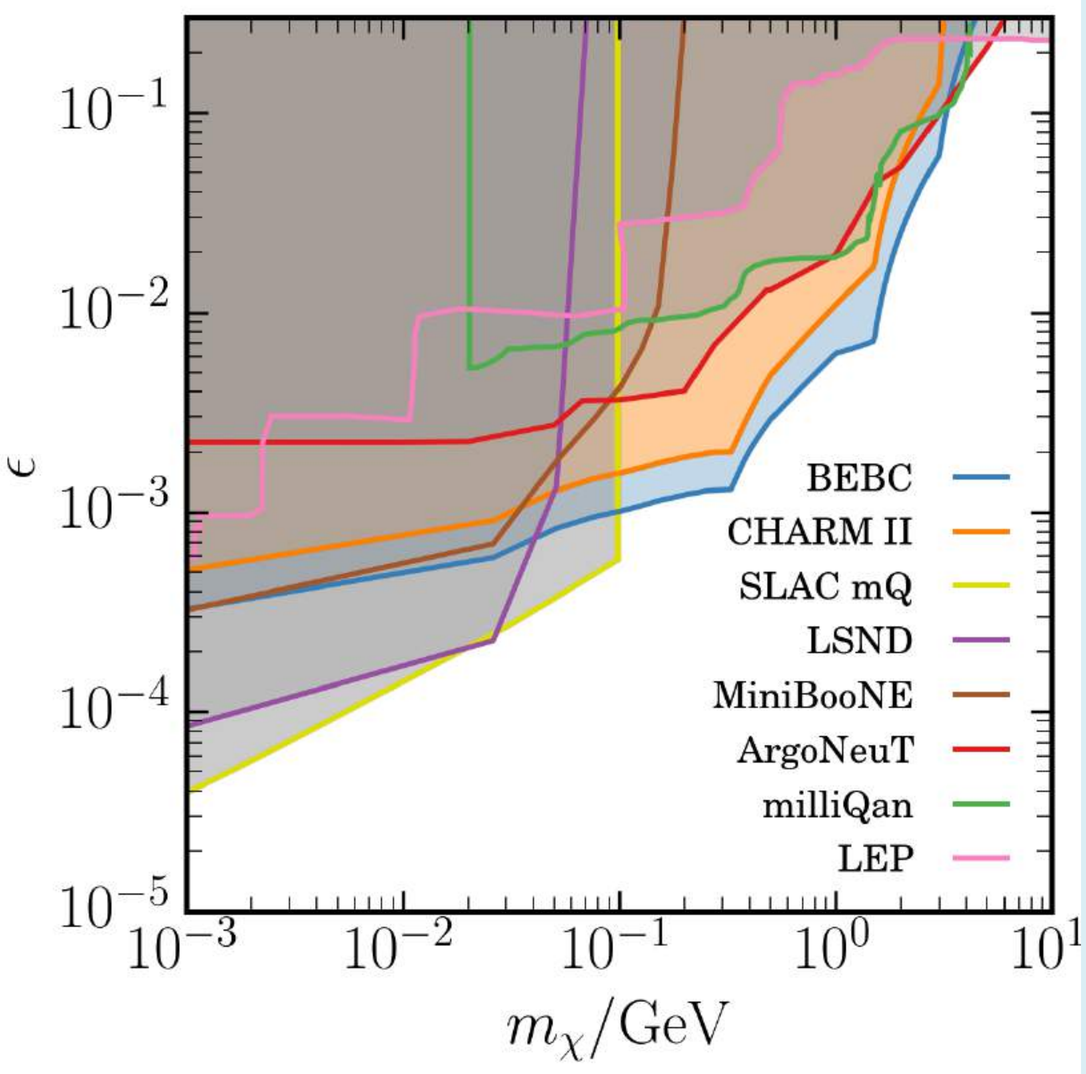
SciPost
SciPost Phys. 10, 043 (2021)

Blast from the past: Constraints on the dark sector from the BEBC WA66 beam dump experiment

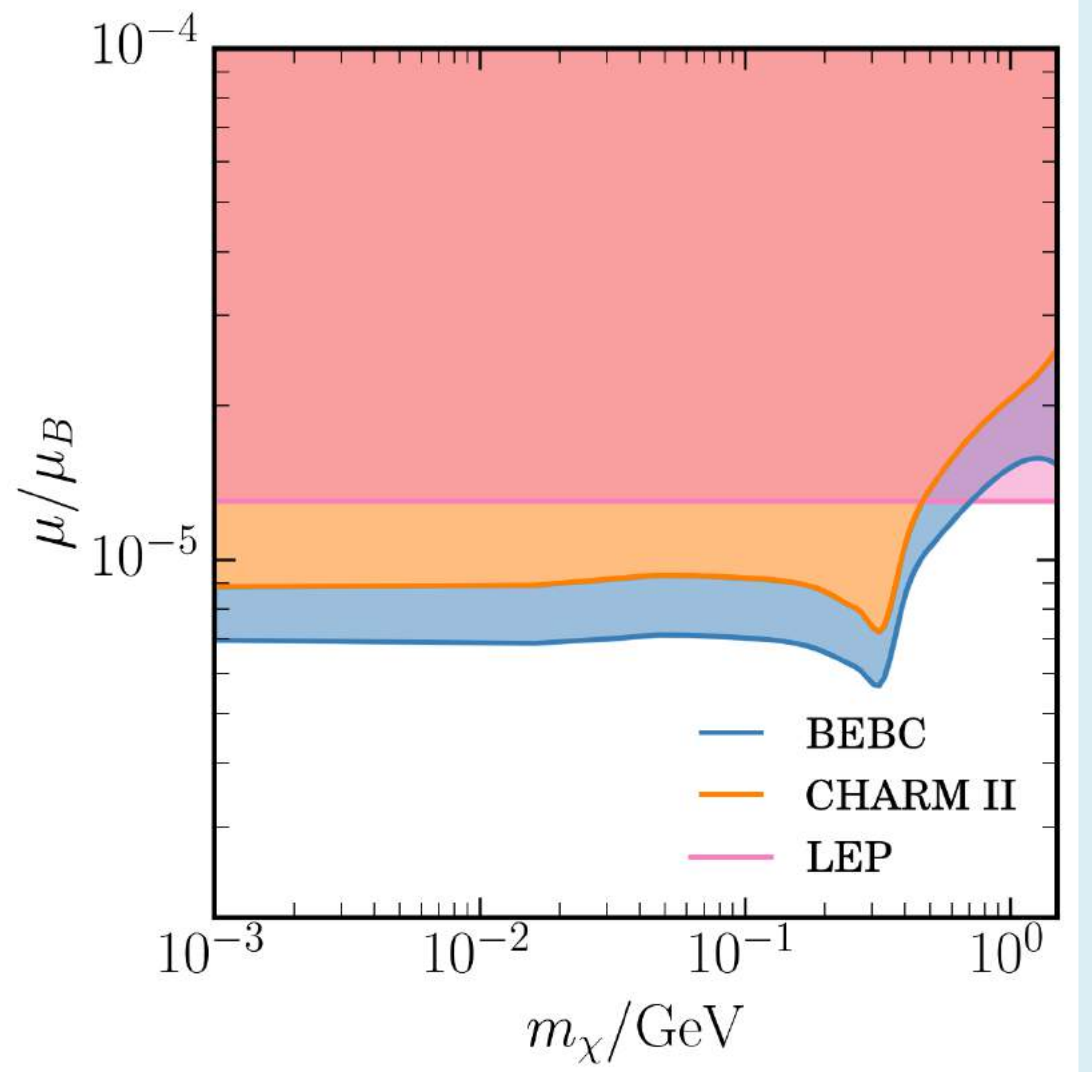
Giacomo Marocco * and Subir Sarkar

Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom

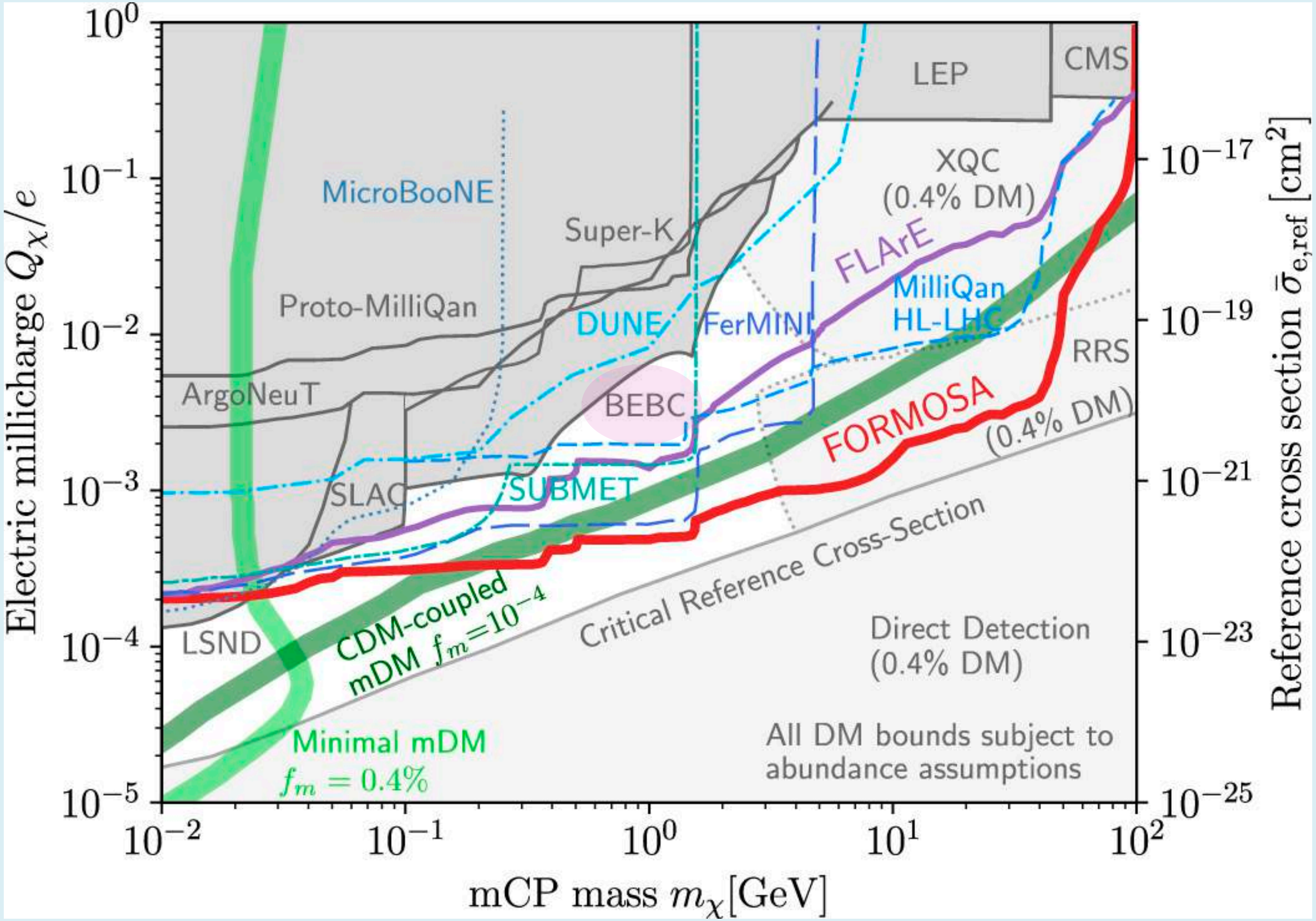
We derive limits on millicharged dark states, as well as particles with electric or magnetic dipole moments, from the number of observed forward electron scattering events at the Big European Bubble Chamber in the 1982 CERN-WA-066 beam dump experiment. The dark states are produced by the 400 GeV proton beam primarily through the decays of mesons produced in the beam dump, and the lack of excess events places bounds extending up to GeV masses. These improve on bounds from all other experiments, in particular CHARM II.



… this recast turns out to still be the most sensitive bound on milli-charged particles and on neutrino magnetic moments

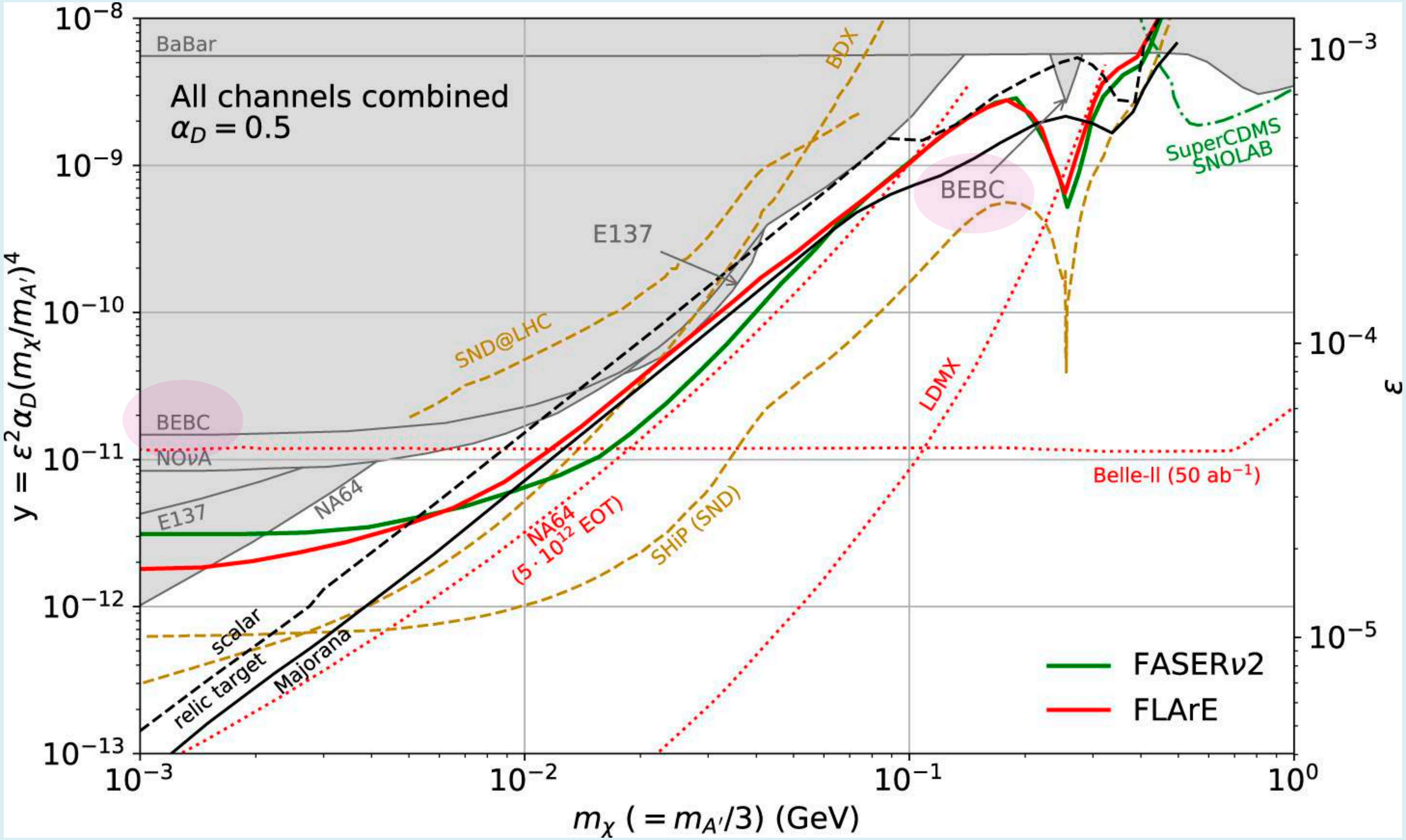


The reach will improve with FLArE & FORMOSA at the FPF [arXiv:2109.10905]



Present bounds on mCPs (grey): LSND, ArgoNeuT, SLAC, Super-K (limit on diffuse SN ν bkgd), LEP, CMS, BEBC

Expected sensitivities for FORMOSA, FLArE; **Projections** for SUBMET, FerMINI, MilliQan @ HL-LHC, DUNE, The WA66 constraint on forward scattered electrons also translates into a competetive bound on scattering of ~MeV-GeV scalar dark matter (Buonocore *et al*, PR D102 (2020) 035006)



Projected exclusion bounds for **FASERν2** & **FLArE-10** detectors @ HL-LHC with 3 ab^{-1} integrated luminosity. Existing constraints (grey) & projected reaches from other expts [arXiv:2107.00666]

Conclusion


SNACK BAR
Ἐὰν μὴ ἔλπηται
ἀνέλπιστον, οὐκ ἐξευ-
ρήσε. If you do not
hope for the unexpected,
you will not find it!
HERACLITUS
Healthy greek snacks
Organic coffee-cocoa
-chocolate-