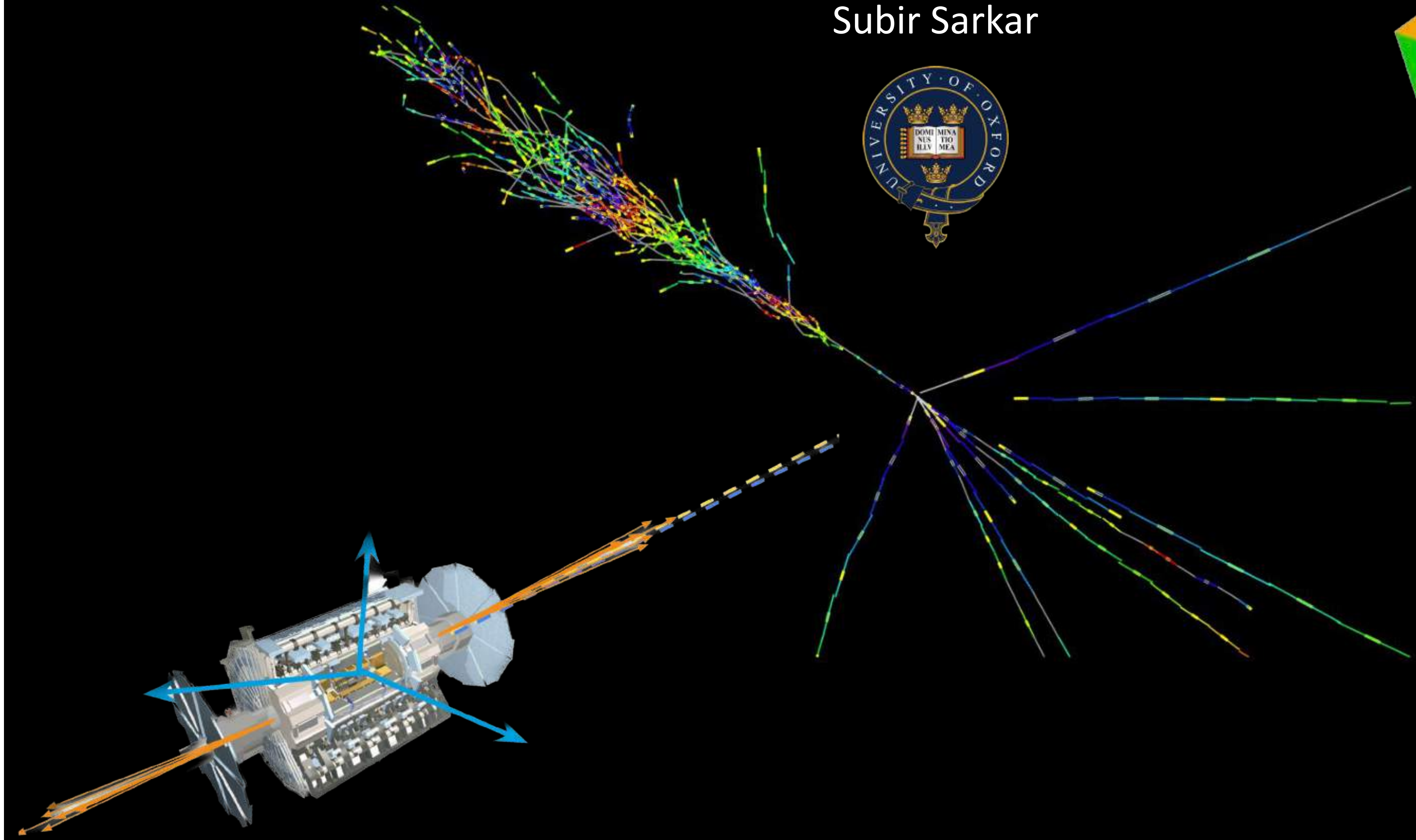
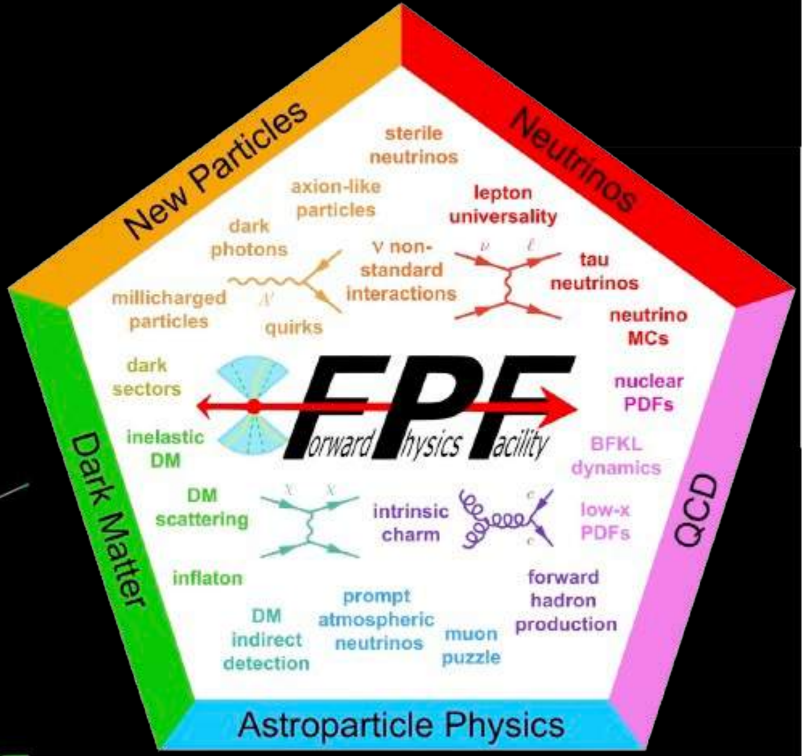
FPF: Physics Opportunities

(Neutrino, QCD, BSM, Astroparticle)

Subir Sarkar





7th Forward Physics Facility Meeting, CERN, 29 Feb–1 Mar2024

LHC PROVIDES A COLLIMATED BEAM OF TEV ENERGY NEUTRINOS IN THE FAR FORWARD DIRECTION

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

A. De Rújula and R. Rückl

CERN, Geneva, Switzerland

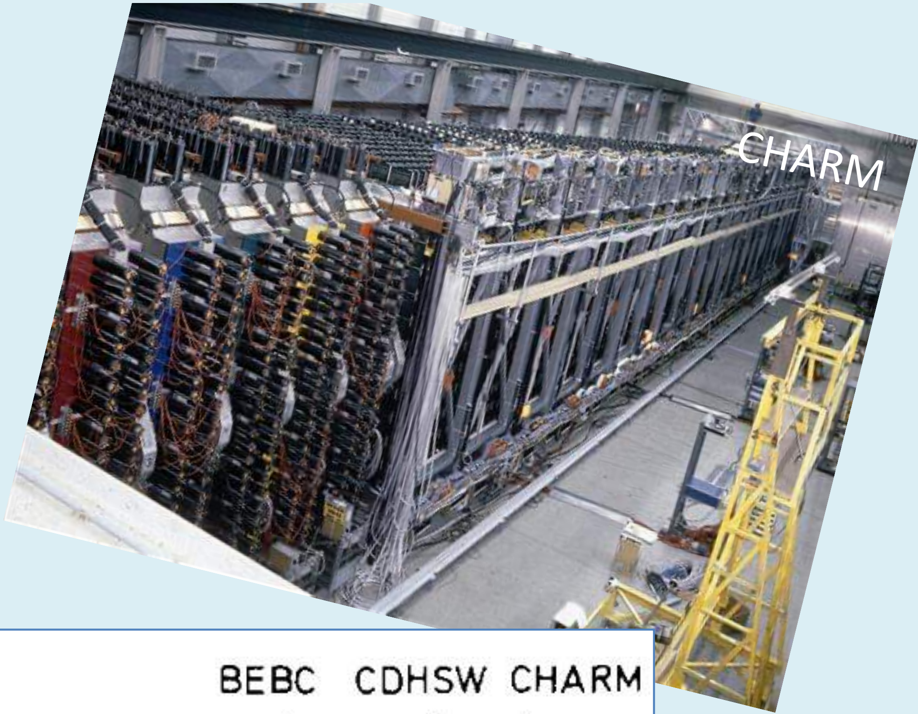
Proc. ECFA-CERN Workshop on large hadron collider in the LEP tunnel: 21-27 Mar 1984

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.

Forty years later, this vision is being realized …

Recall this was following a glorious era of pioneering neutrino experiments @ CERN



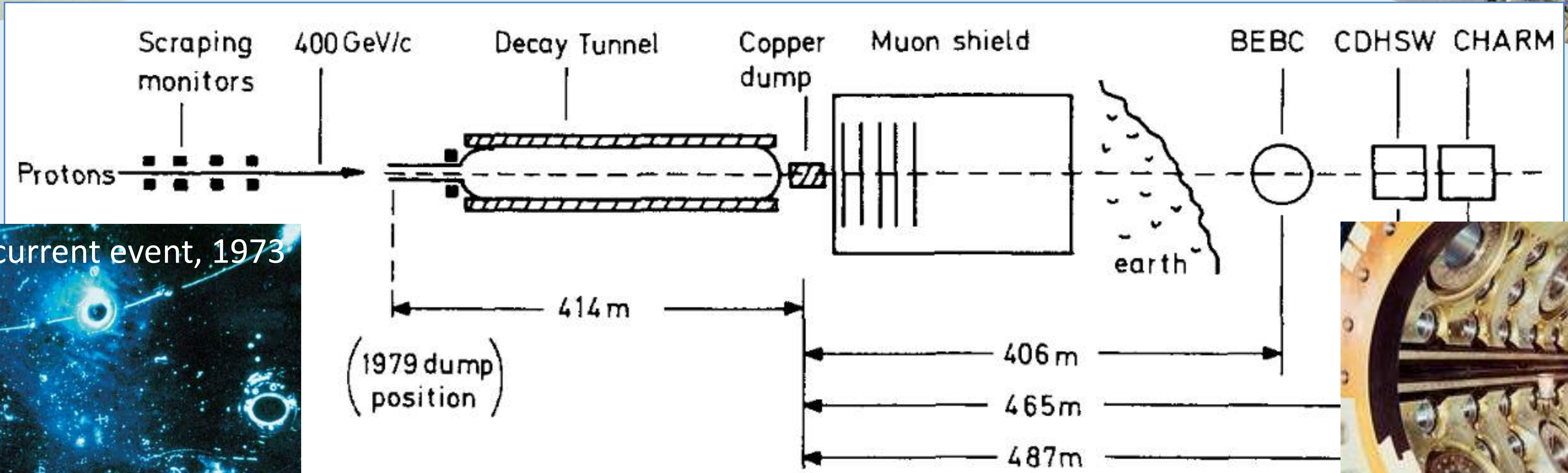
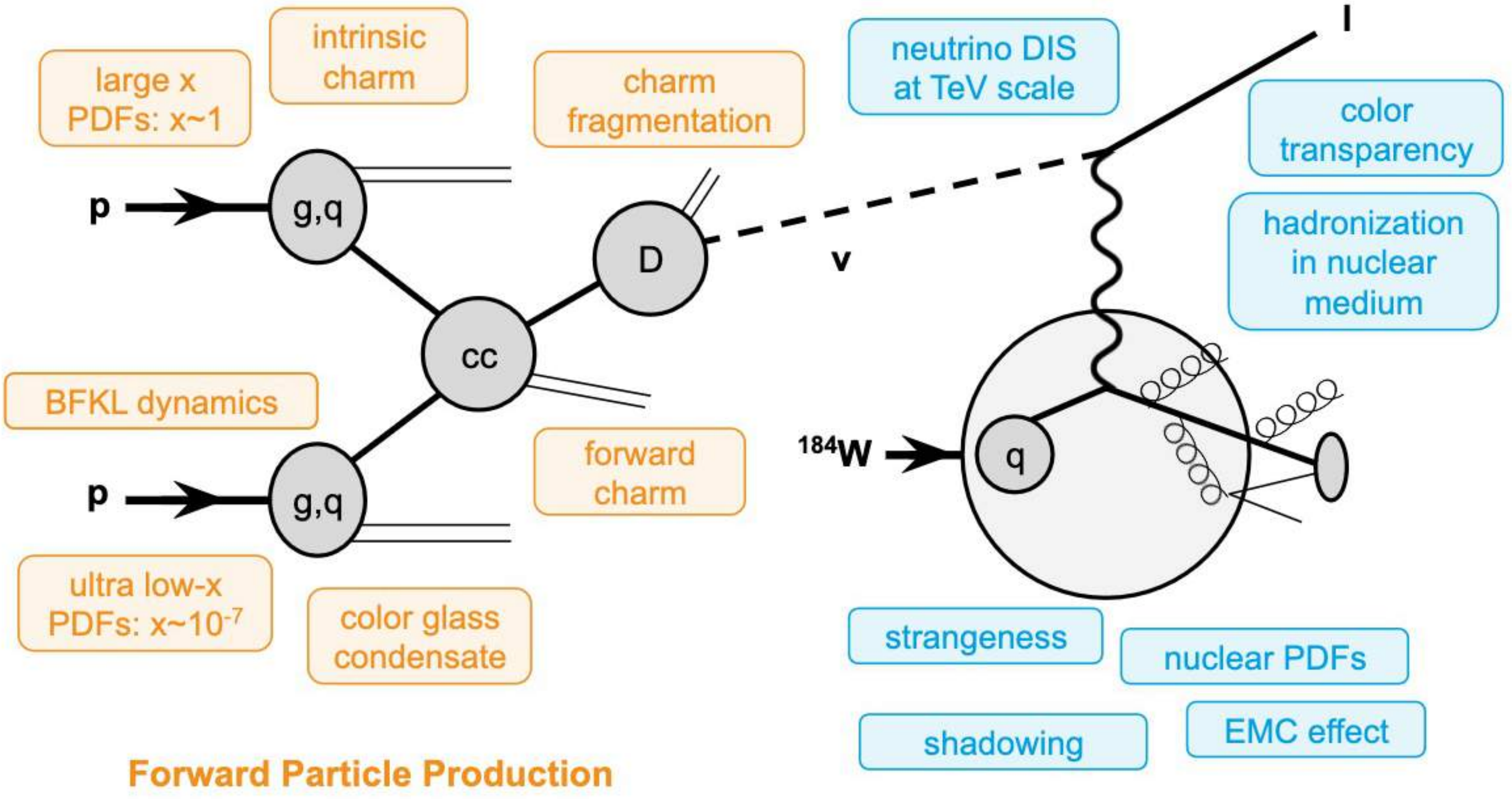


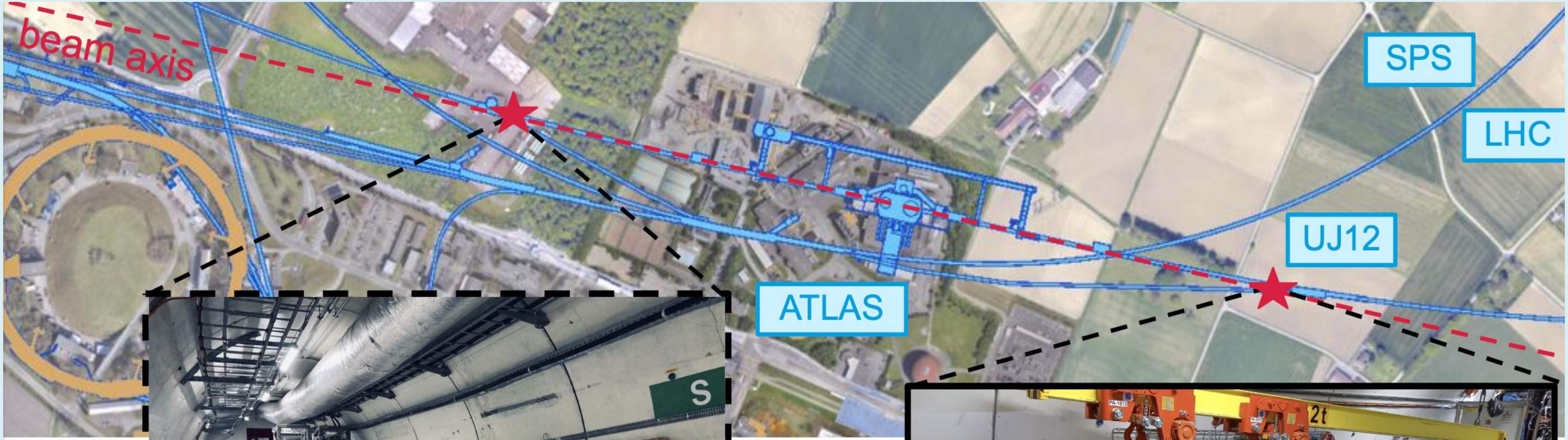
Fig. 1. Layout of the 1982 beam-dump area at the SPS, CERN.

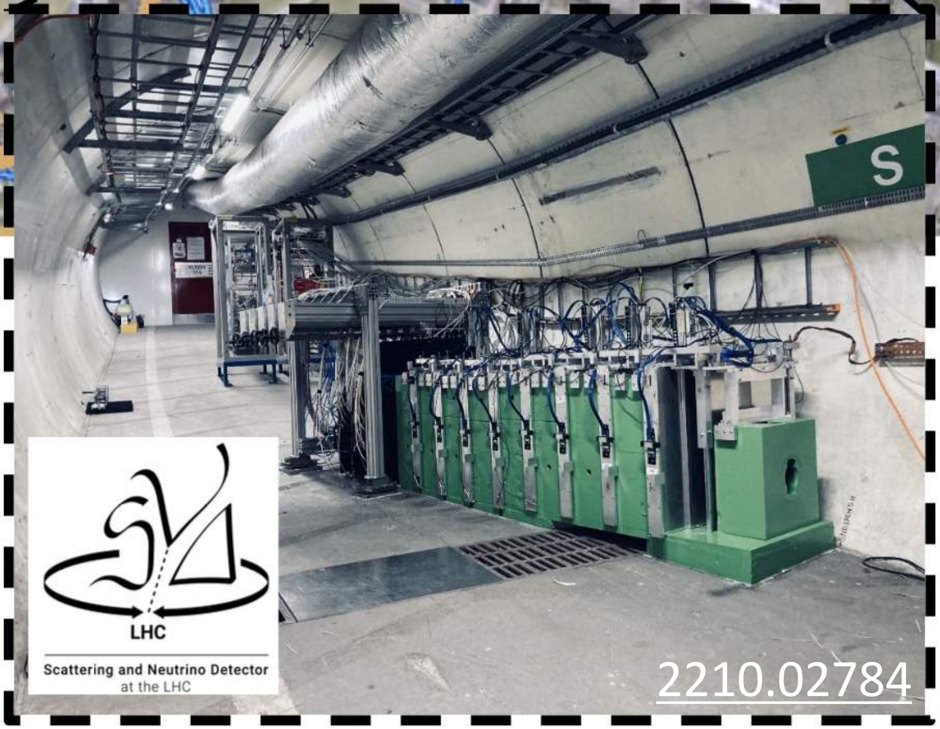
WHAT CAN WE DO WITH AN INTENSE BEAM OF TEV ENERGY NEUTRINOS?



Study interesting open issues in **QCD** – of relevance to **neutrino telescopes**; Study forward production of light hadrons – of relevance to **cosmic ray air shower arrays;** Search for **Beyond-Standard-Model** long-lived particles (axions, dark photons, heavy neutral leptons, milli-charged particles, scalar dark matter, quirks *etc*) – of relevance to **dark matter experiments.** Feng *et al*, J.Phys.G**50**:030501,2023

‘Proof-of-principle’ in 2022 - when 2 new experiments started operation @ CERN

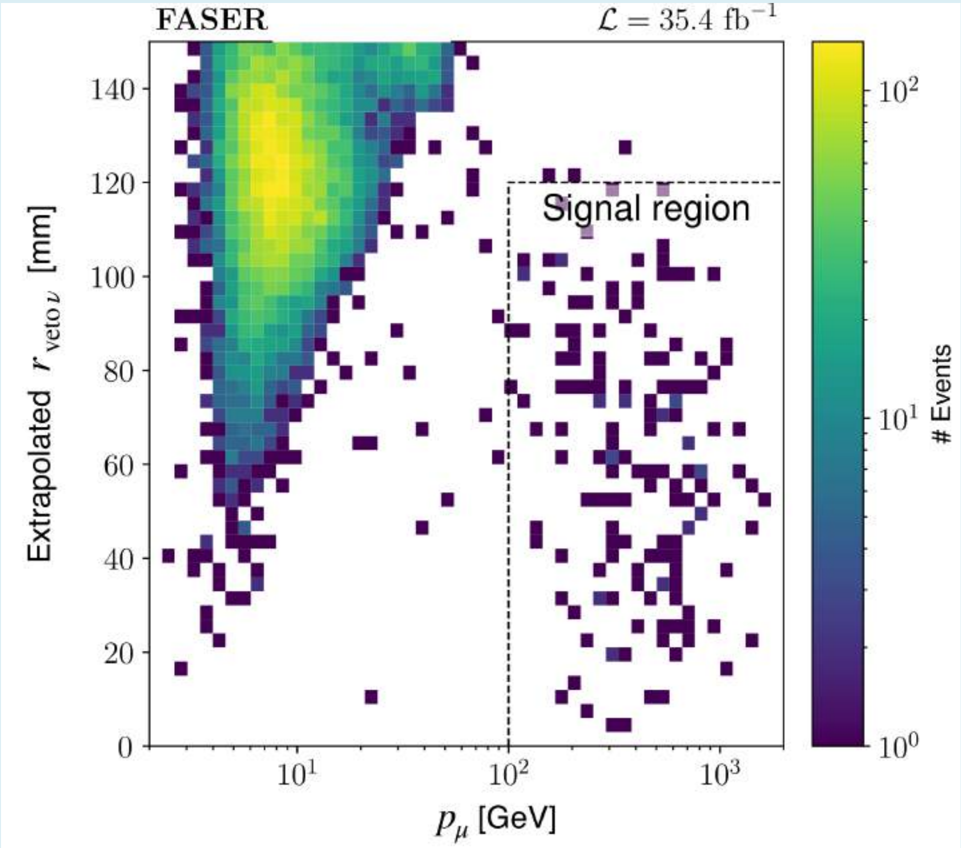


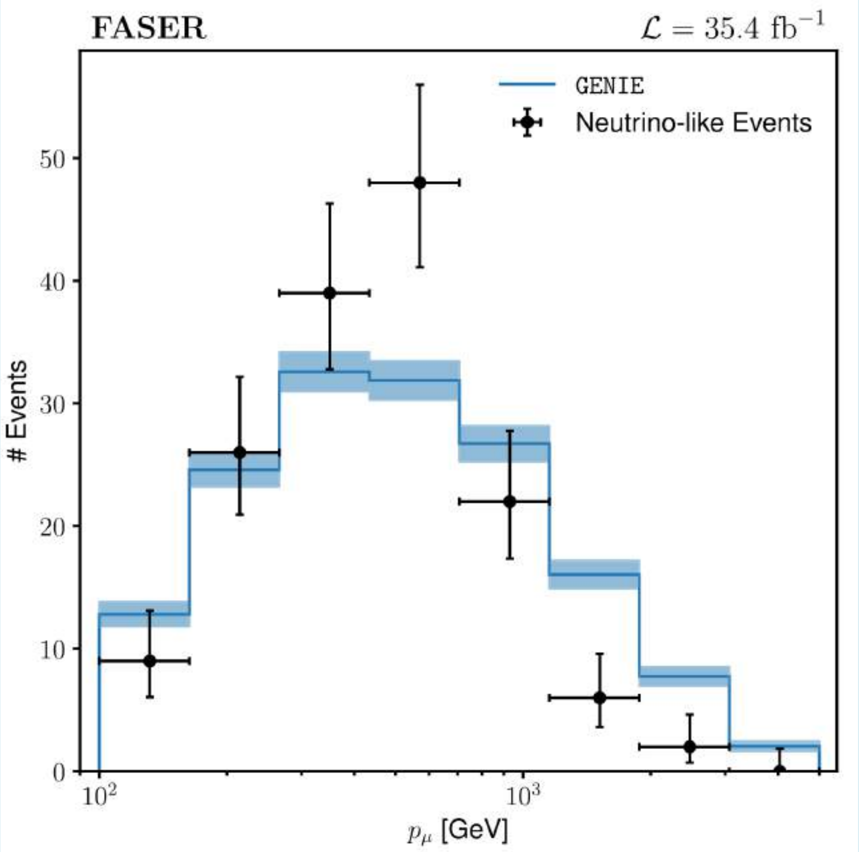


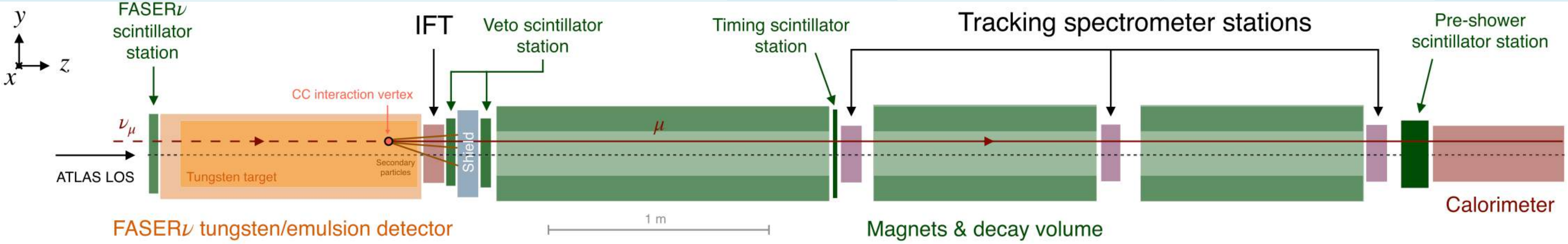
“Until now, no neutrino produced at a particle collider has ever been directly detected”

The dawn of collider neutrino physics

~0.2 background events expected in signal region … upon unblinding find 153 events with *no* veto







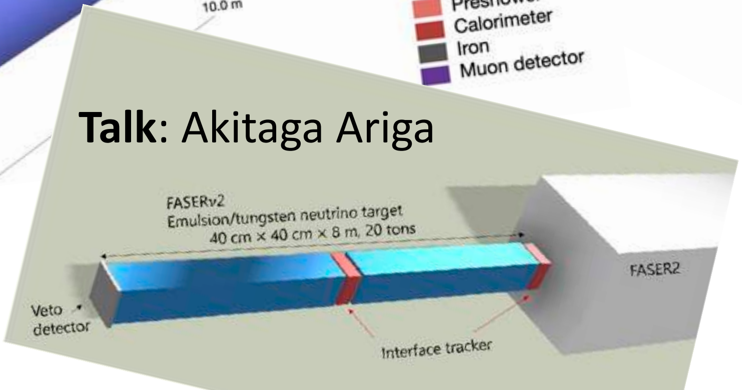
FASER collab., *PRL* **131**;031801,2023

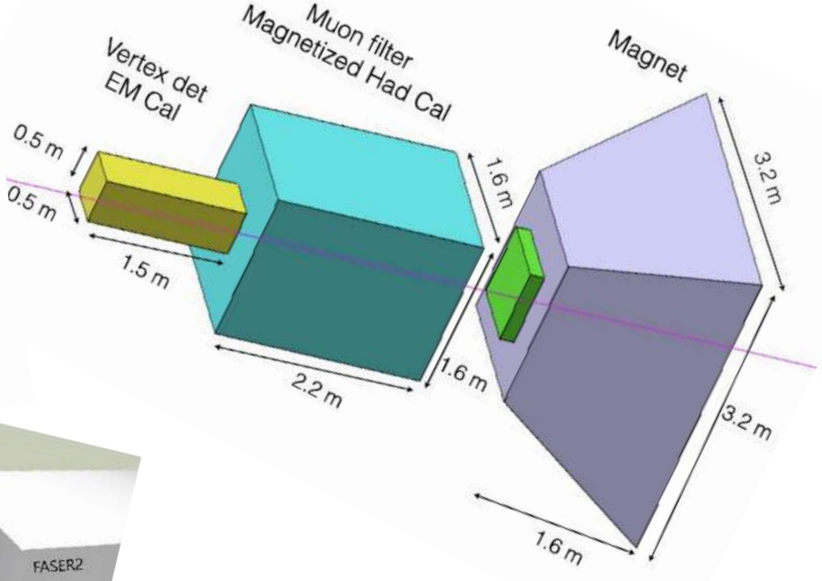
Expected Neutrino Fluxes at Forward Physics Facility experiments

Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754

Talk: Oliver Salin

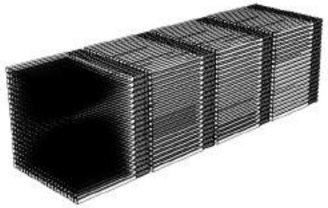
Talk: Akitaga Ariga

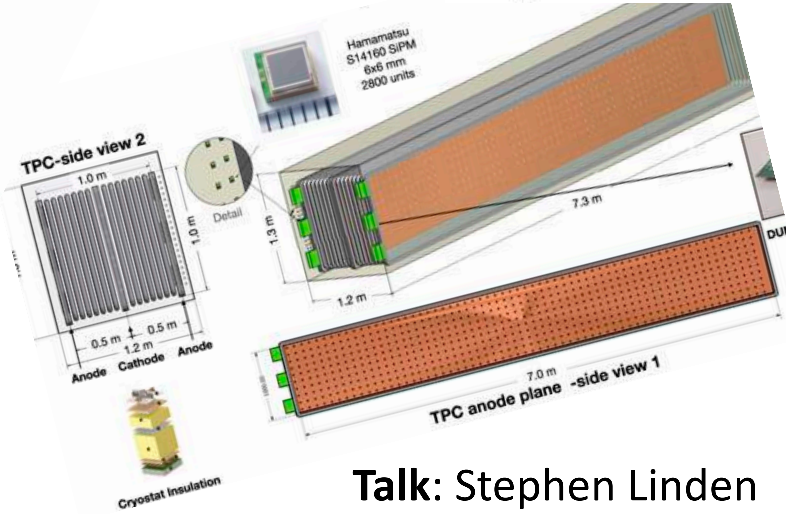




Talk: Giovanni De Lellis

Talk: Juan Salvador Tafoya Vargas

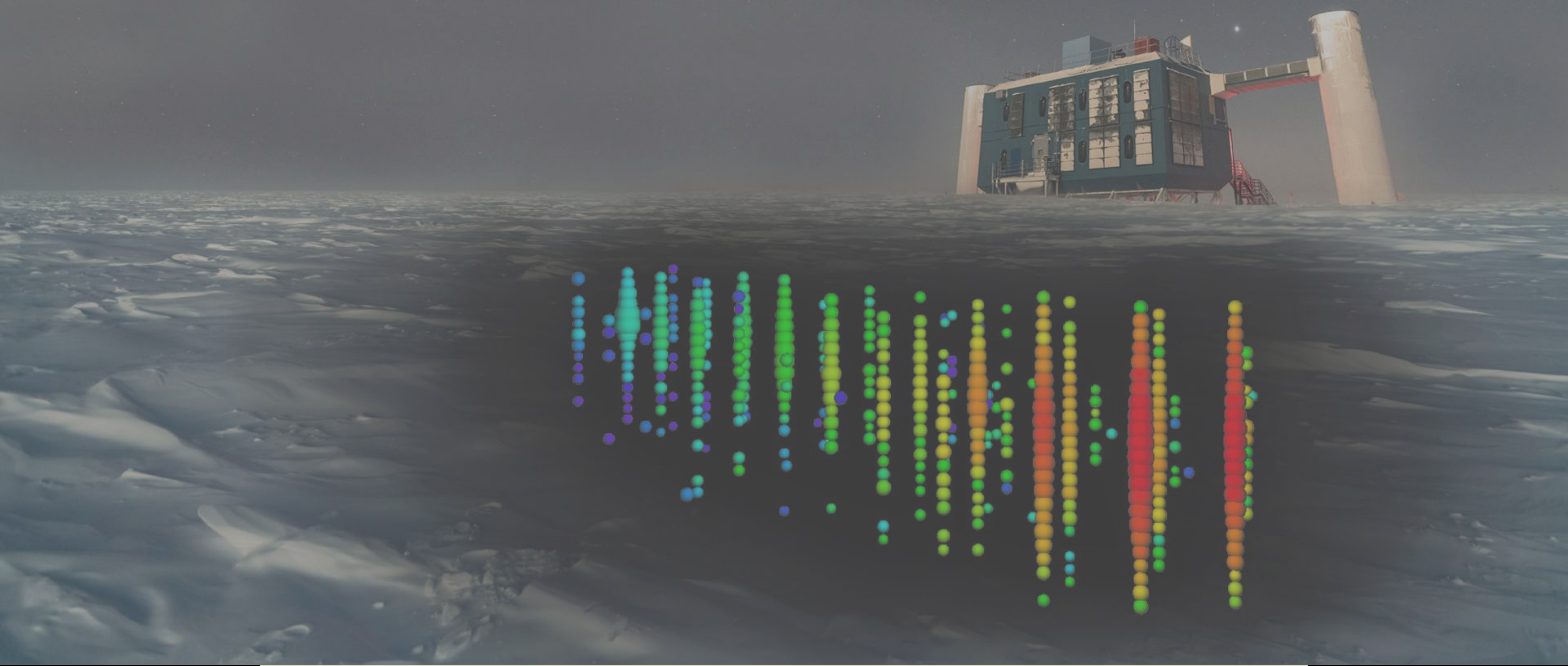




Talk: Stephen Linden

Feng *et al*, *J.Phys.***G50**:030501,2023

Neutrino interactions



Synergy with Neutrino Telescopes

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

WG1 : Juan Rojo
+ 124 members

Talks: Max Fieg,
Toni Makela, …

Neutrino telescopes detect very high energy neutrinos – to obtain the incident flux from the event rate requires knowledge of the ν-N Deep Inelastic Scattering #-secn

This is calculable in the (perturbative) Standard Model, if the parton distribution functions (PDFs) are known

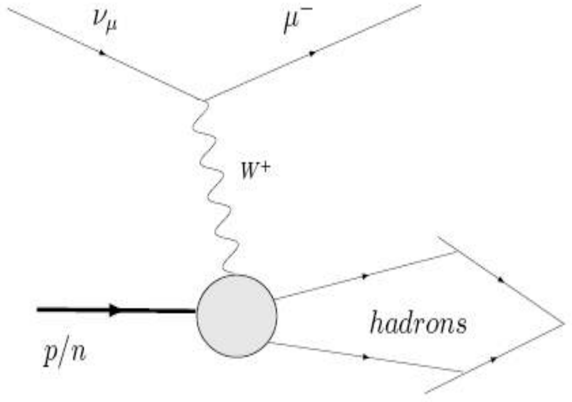
$$\frac{\partial^2 \sigma_{\nu,\bar{\nu}}^{CC,NC}}{\partial x \partial y} = \frac{G_F^2 M E}{\pi} \left(\frac{M_i^2}{Q^2 + M_i^2} \right)$$

$Q^2 \uparrow \Rightarrow$ 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 $x \sim \frac{M_W^2}{M_N E_\nu}$

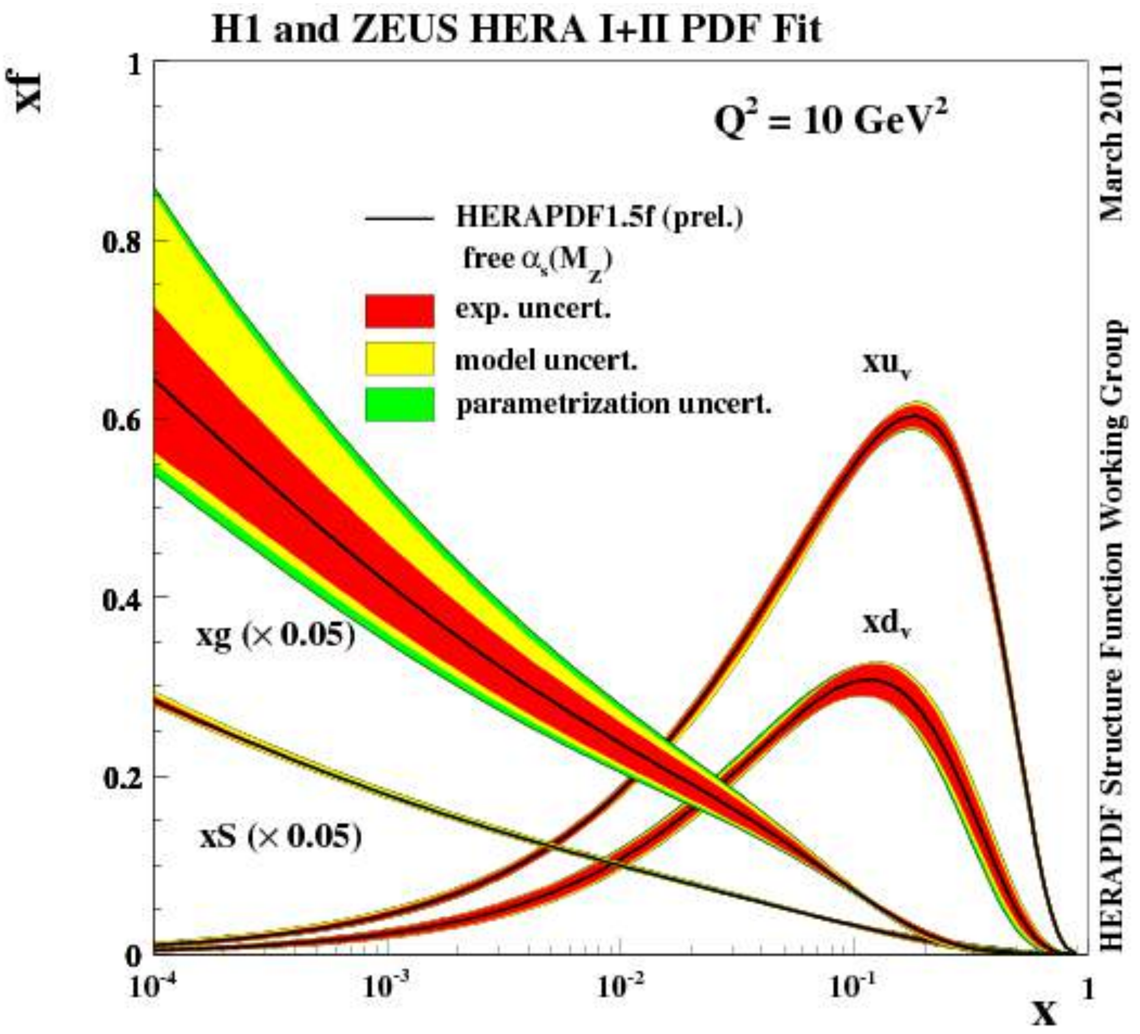
$$\text{At leading order (LO)}: F_L = 0, \quad F_2 = x(u_v + d_v + 2s + 2b + \bar{u} + \bar{d} + 2\bar{c}),$$

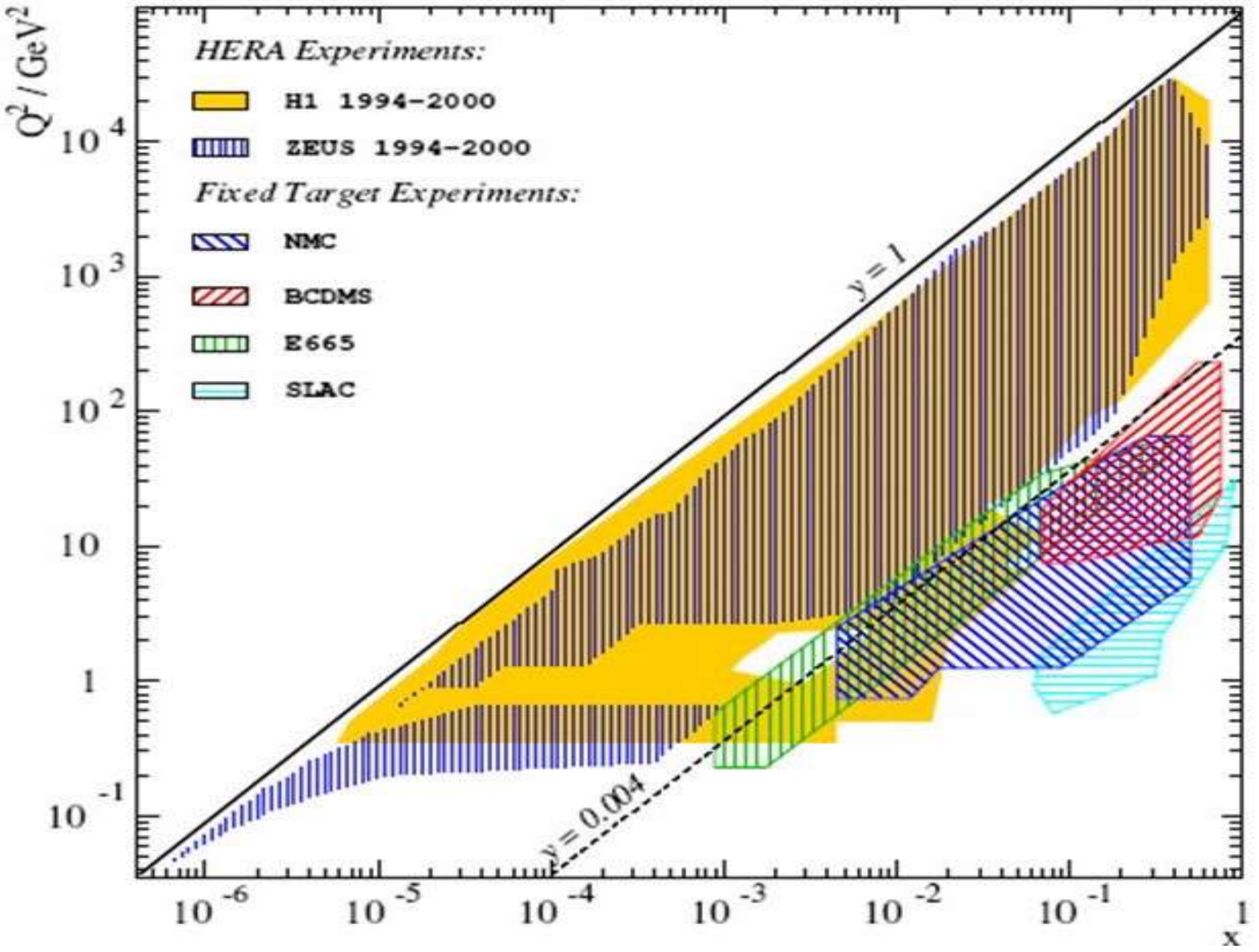
$$xF_3 = x(u_v + d_v + 2s + 2b - \bar{u} - \bar{d} - 2\bar{c}) = x(u_v + d_v + 2s + 2b - 2\bar{c})$$

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

For UHE neutrinos, need to perform DGLAP evolution of measured PDFs to (high) Q^2 and (low) Bjorken-x
(subtleties: heavy flavour thresholds, BFKL resummation, nuclear targets, …)

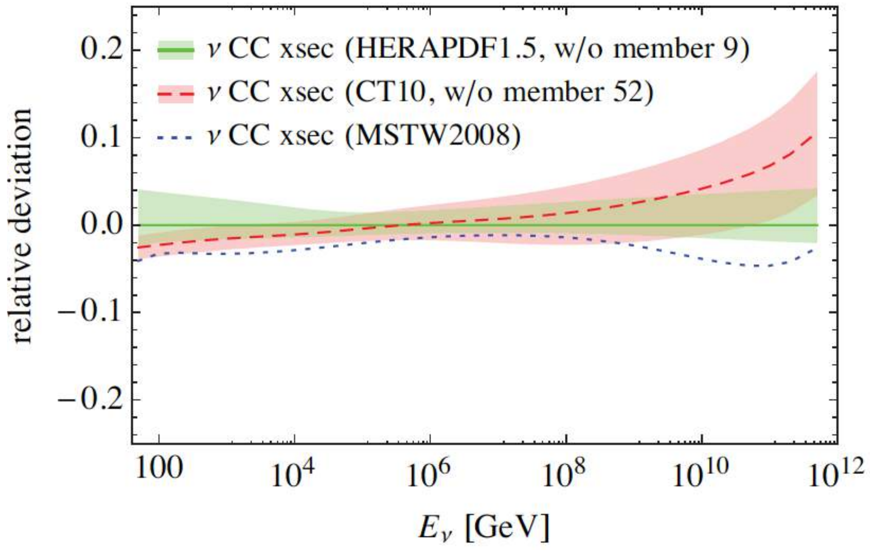
The H1 & ZEUS experiments at HERA were the first to measure DIS at high Q^2 and low Bjorken-x – an unexpected finding was the *steep* rise of the gluon PDF at low x which is particularly relevant for HE neutrino interactions

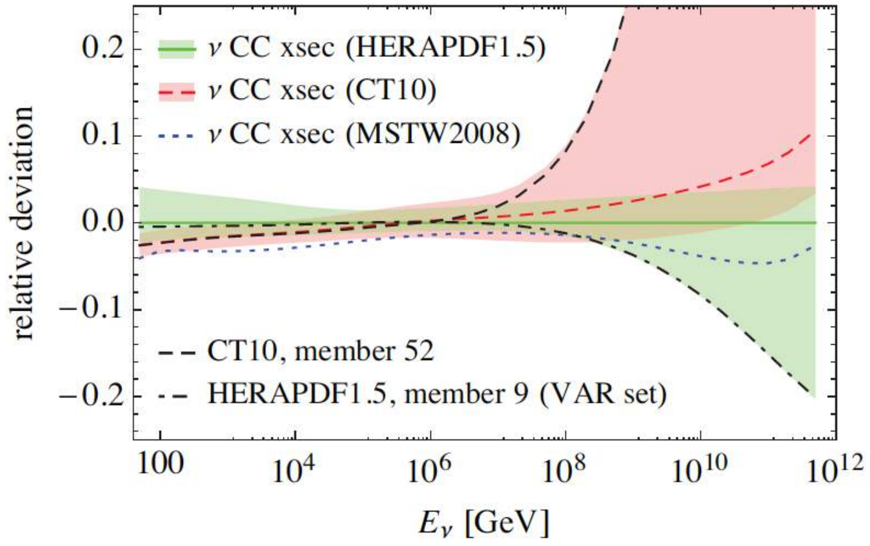


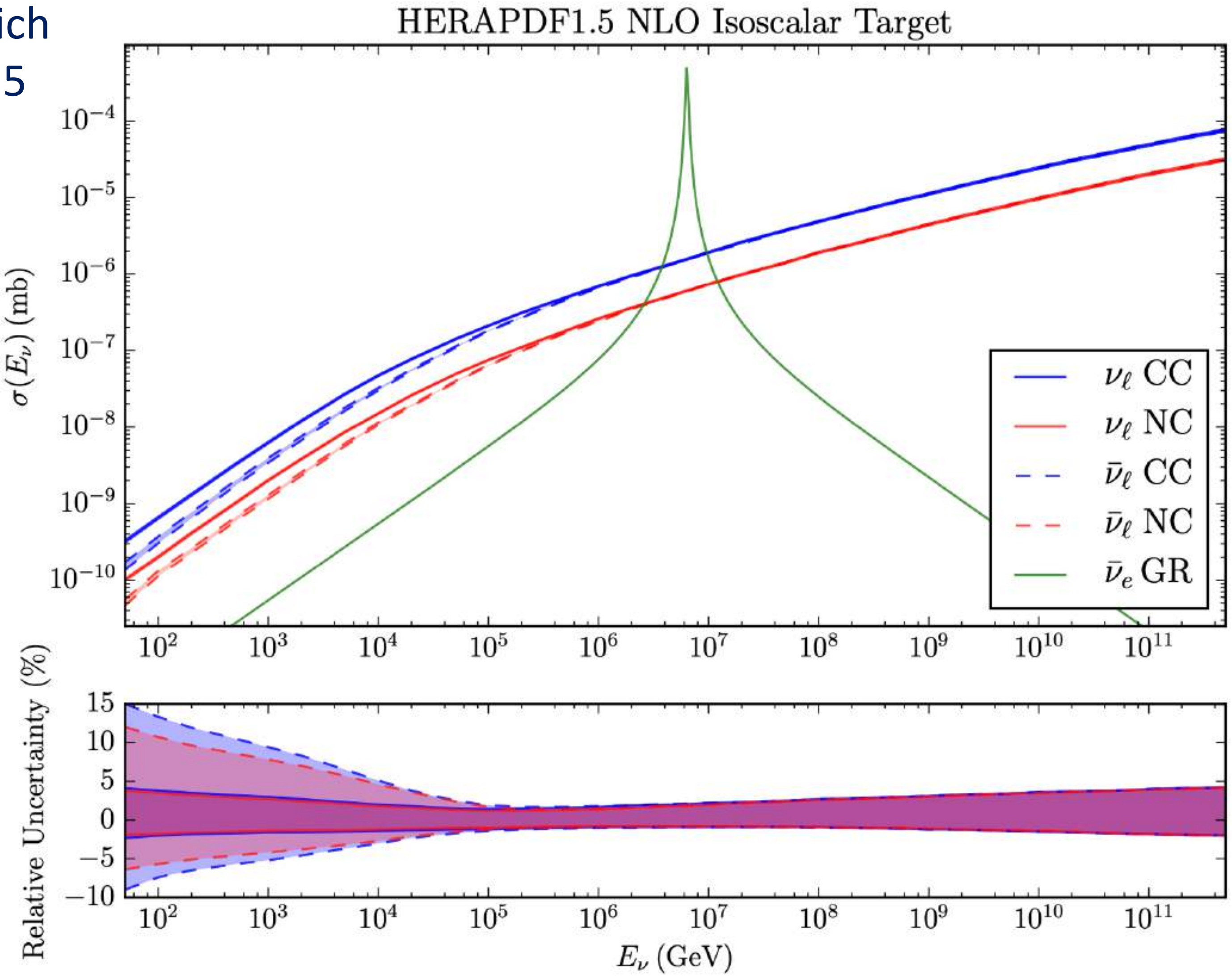


Subsequently data from the LHC (*W*, *Z*, *tt*bar, jets …) have led to more accurate PDFs and new findings (low-*x* strange sea *less* suppressed than believed earlier, a hint of intrinsic charm …)

Neutrino telescopes like *IceCube* use NuGeN which incorporates a NLO calculation using HERAPDF1.5 (Code: https://dispred.hepforge.org/)



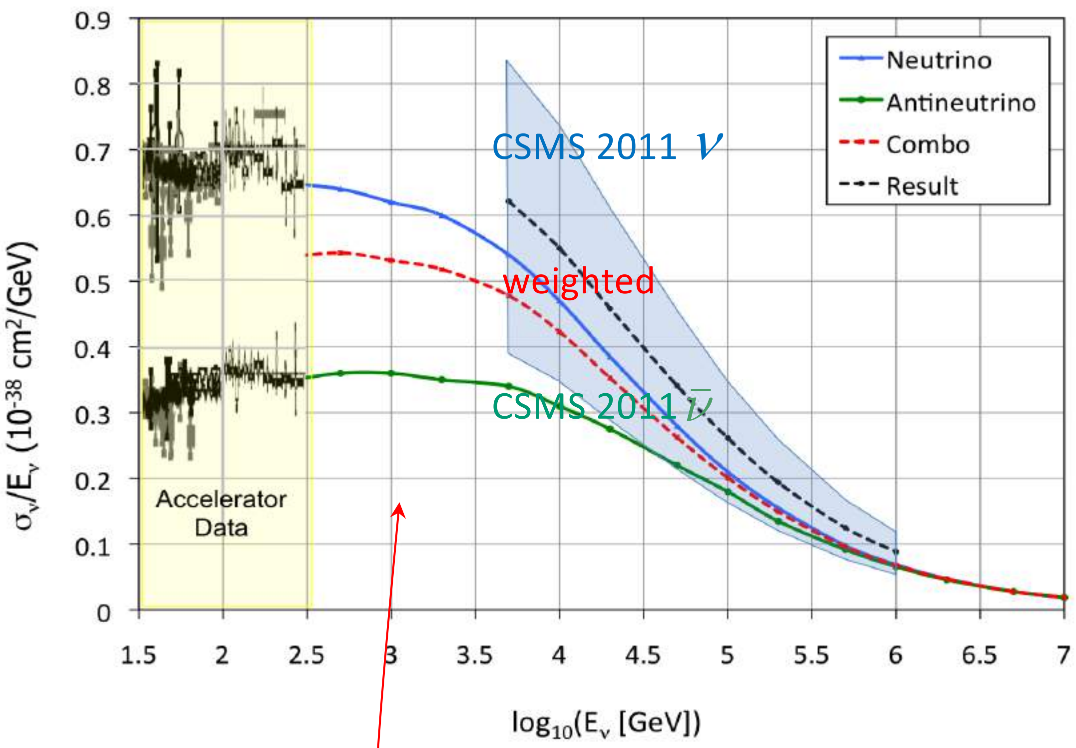


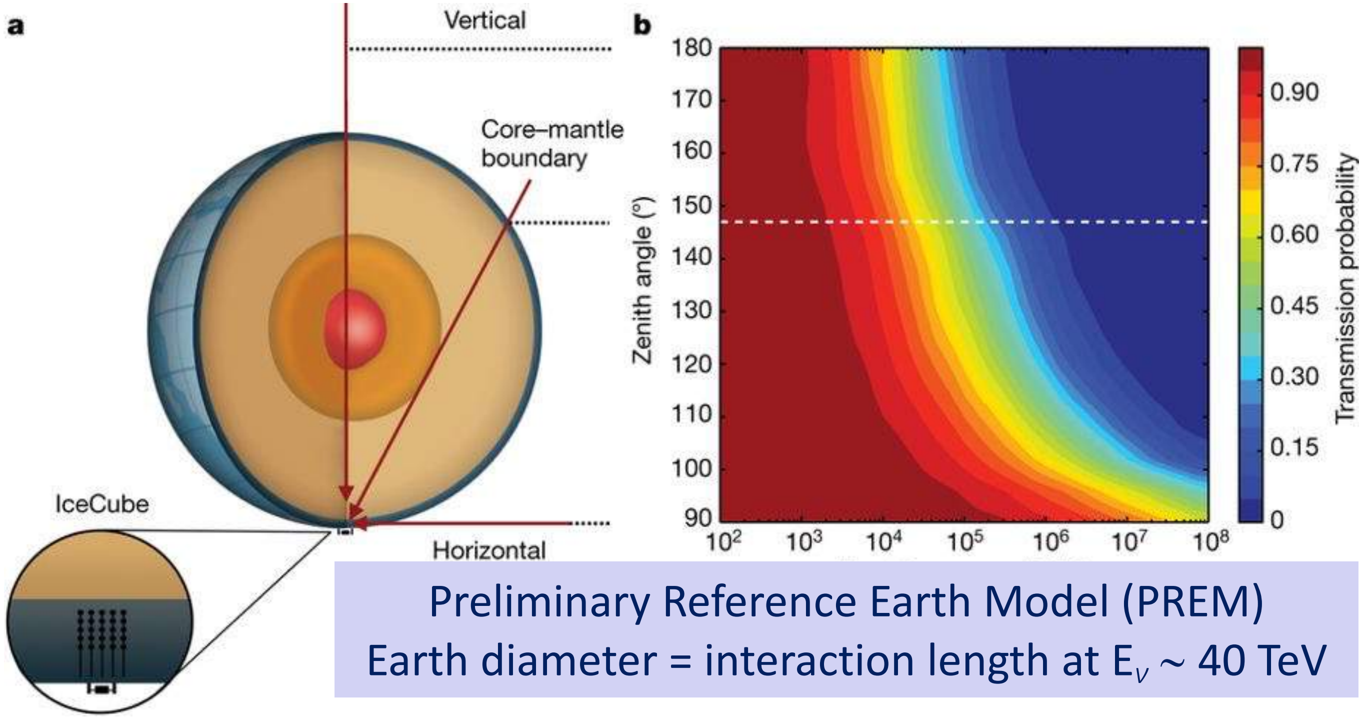


Mertsch, Cooper-Sarkar, S.S., *JHEP* **08**:042,2011 ⇒ **CSMS**

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)

THE PREDICTED ν-N CROSS-SECTION HAS BEEN VERIFIED UPTO 10^3 TEV BY ν ABSORPTION IN THE EARTH





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

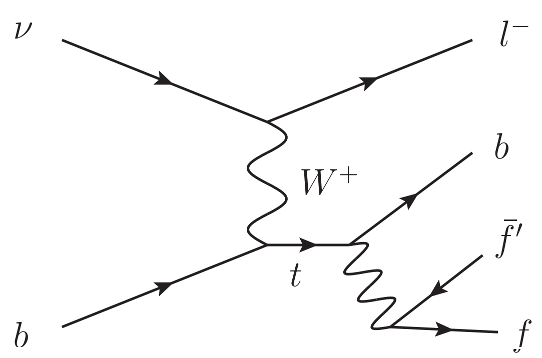
(Can also *invert* the argument to perform tomography of the Earth: Donnini *et al*, *Nature Phys.* **15**:37,2019)

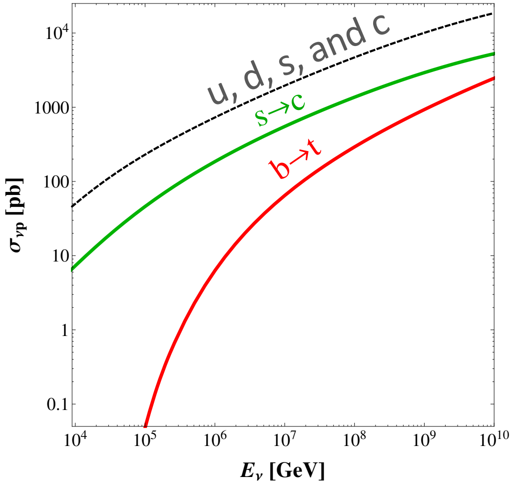
However, the measurement uncertainty is large (~30%) and the Earth absorption method works only above ~40 TeV

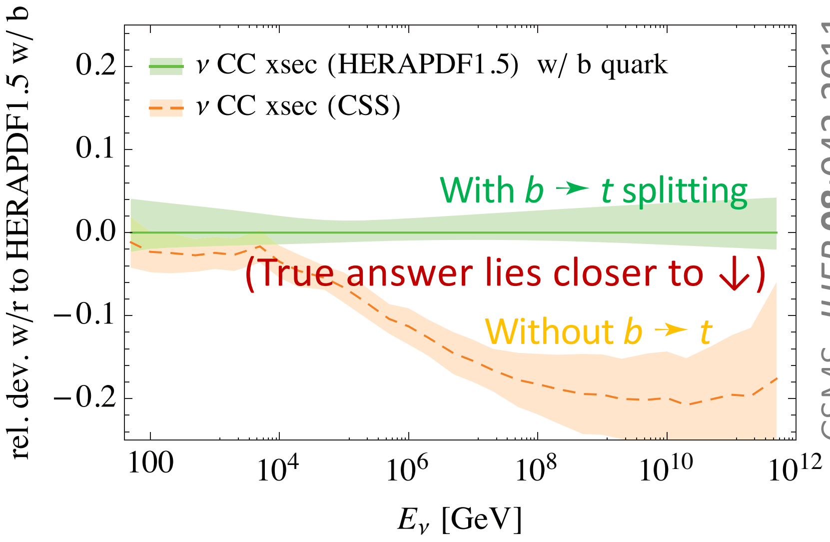
The FPF is well suited to bridge the gap between neutrino telescopes and measurements (upto ~350 GeV) at fixed-target experiments

* Heavy quark effects on DGLAP evolution:

Barger *et al*, *PRD* **95**:093002,2017





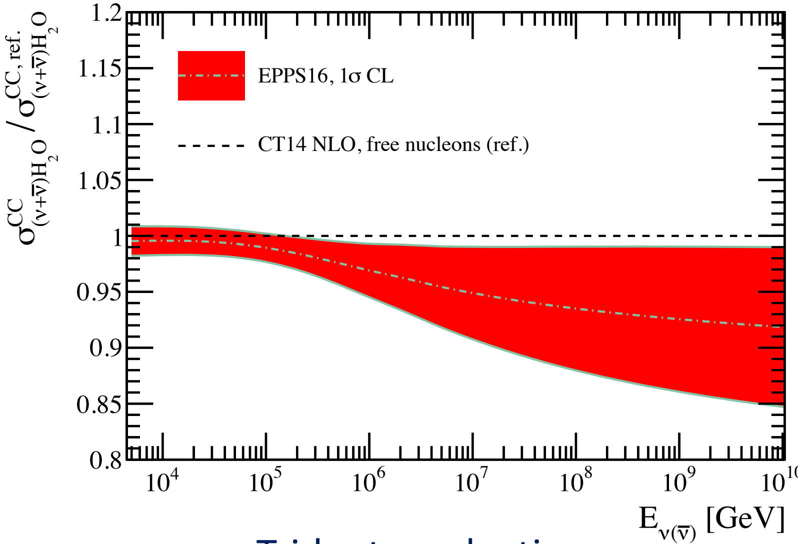


CSMS, *JHEP* **08**:042,2011

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

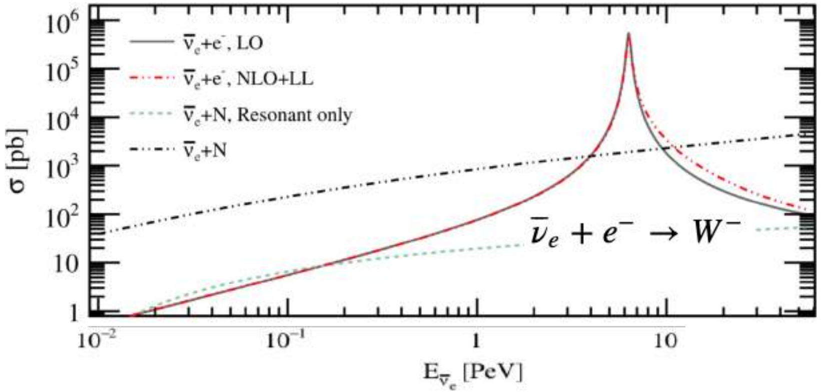


Bertone *et al*, *JHEP* **01**:217,2019

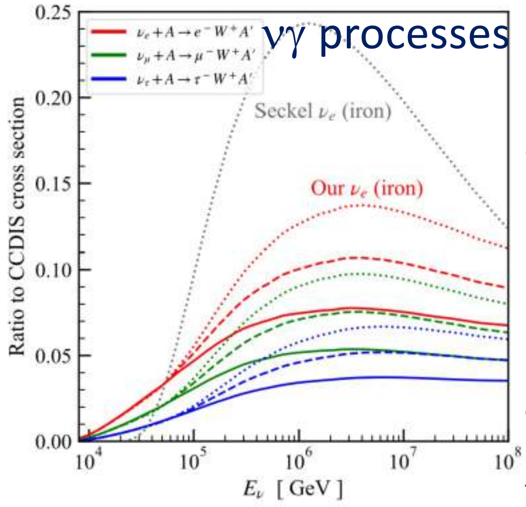
* Other contributions:

Glashow resonance @ 6.3 PeV

Gauld, *PRD* **100**:091301,2019

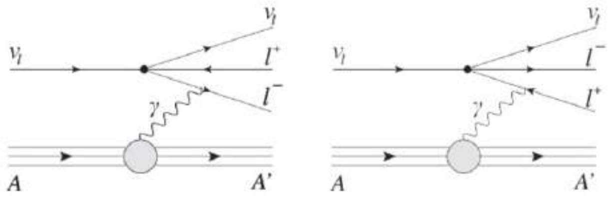


νγ processes



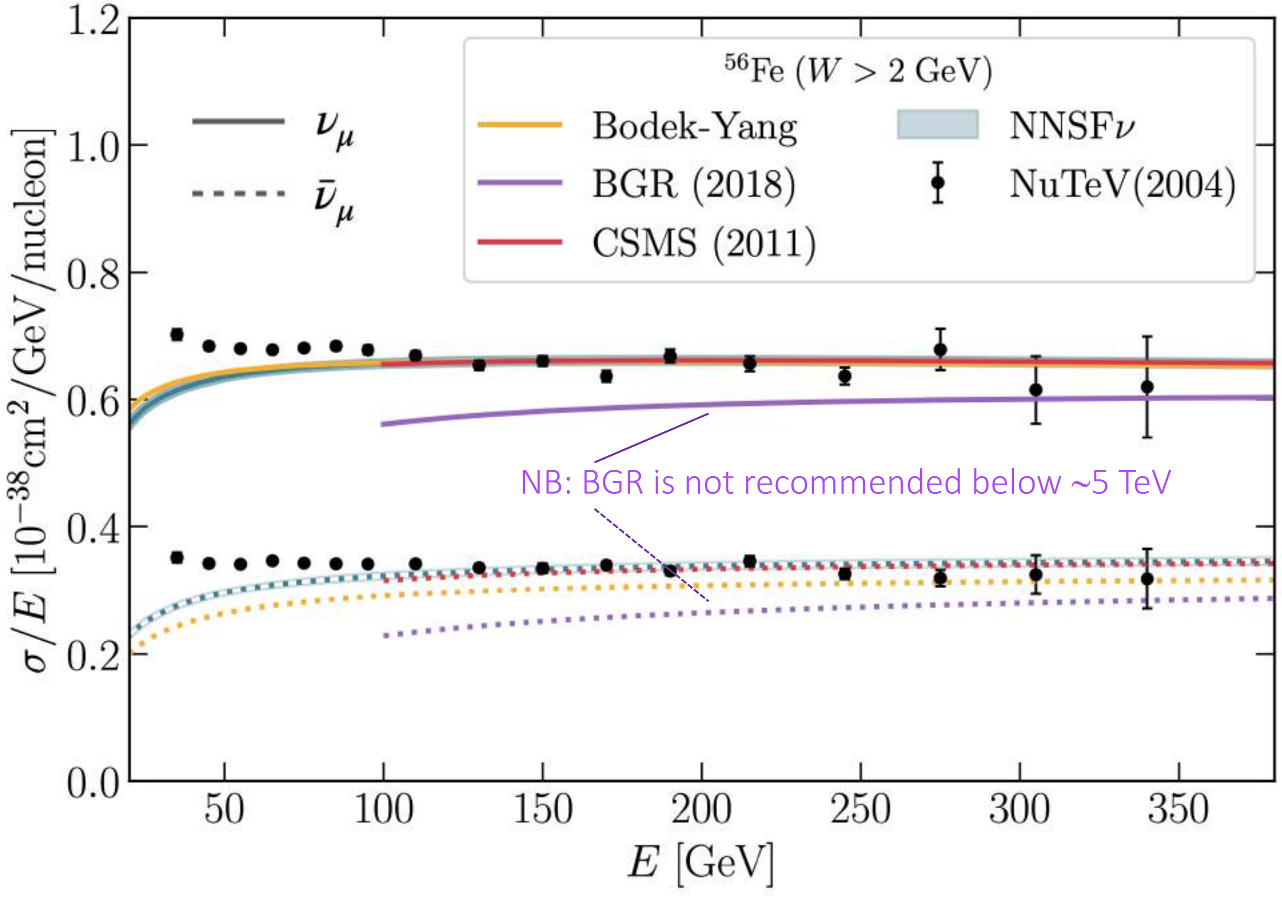
Zhou & Beacom, *PRD* **101**:036001,2019

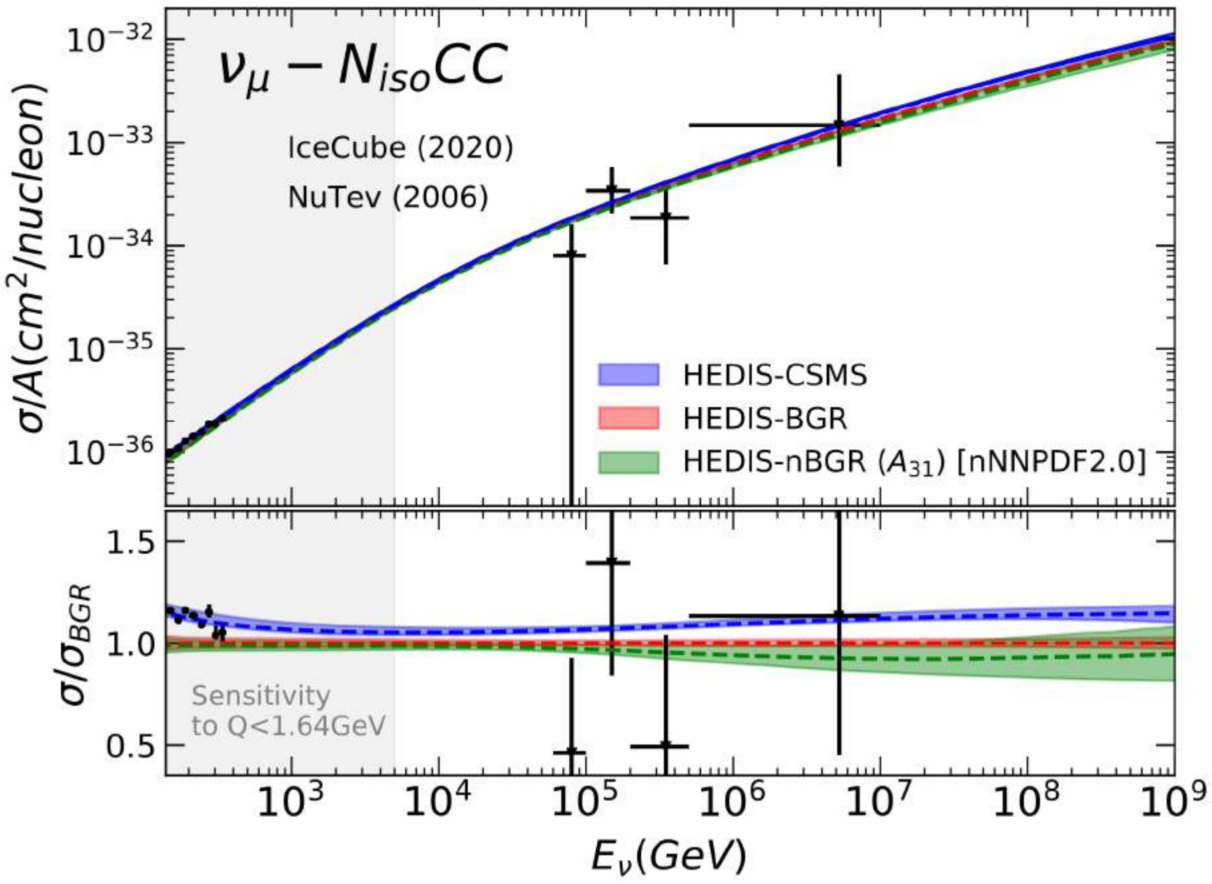
Trident production



NNSFν provides structure functions from GeV to multi-EeV energies

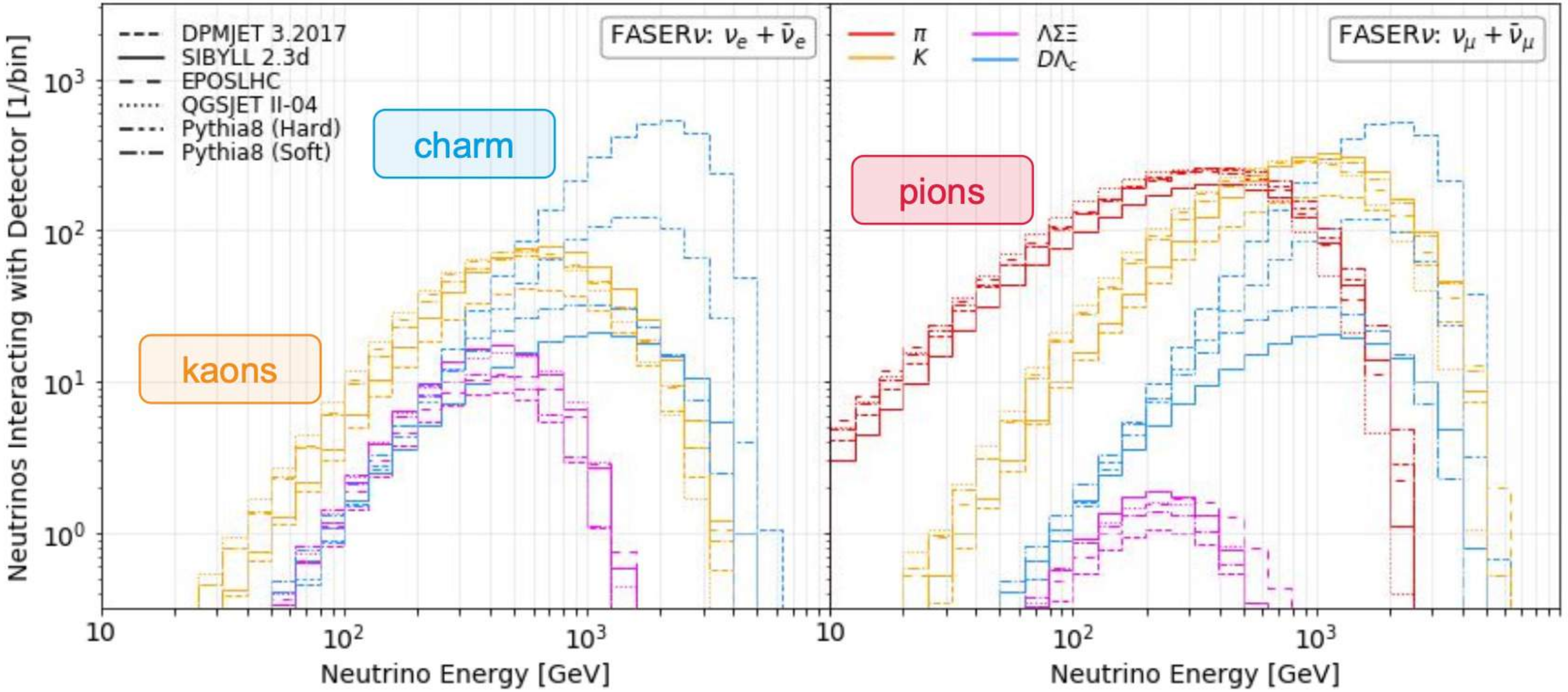
… being used to predict inclusive cross sections relevant for the FPF (Candido *et al*., *JHEP* **05**:149,2023)





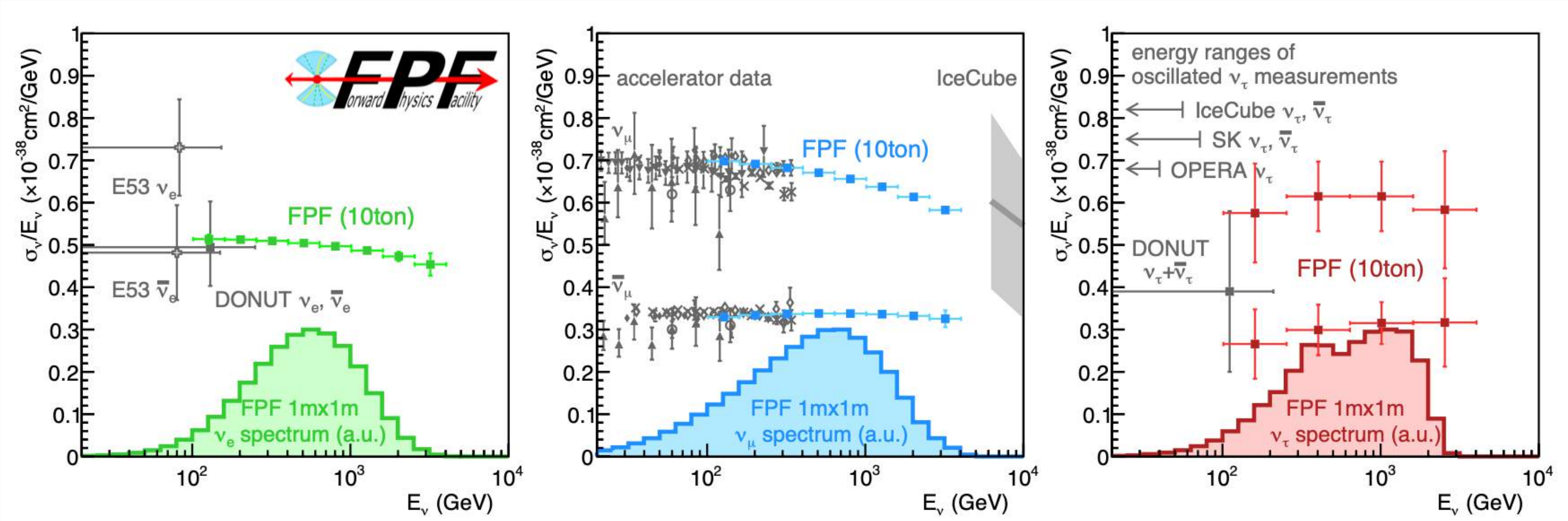
GENIEv3 has a HEDIS module offering a choice of UHE #-section calculations (*Eur.Phys.J.ST* **230**:4449,2021)

Expected spectrum of LHC neutrinos

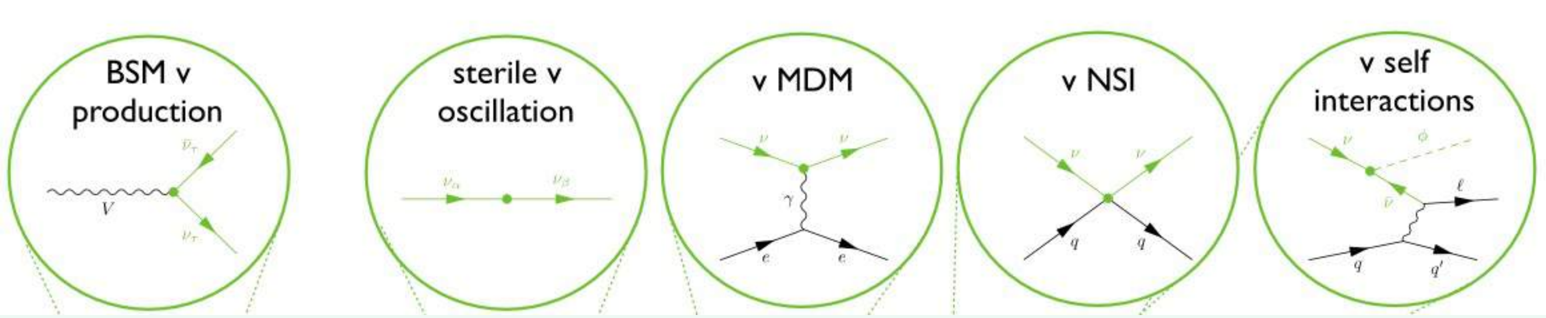


Also a probe of forward particle production …

Neutrino flux as a function of energy for e neutrinos (left), μ neutrinos (middle), and τ neutrinos (right), with expected precision of FPF measurements (statistical uncertainties only)

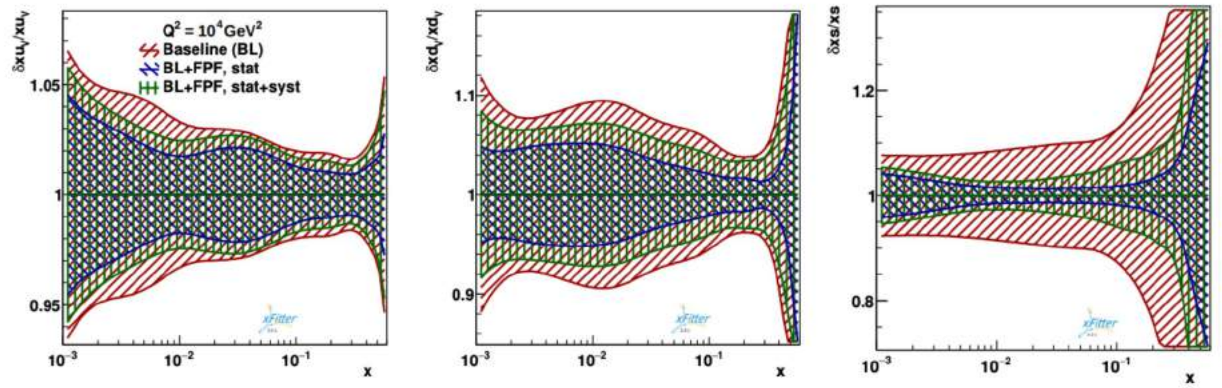


Feng *et al*, *J.Phys.G* **50**:030501,2023

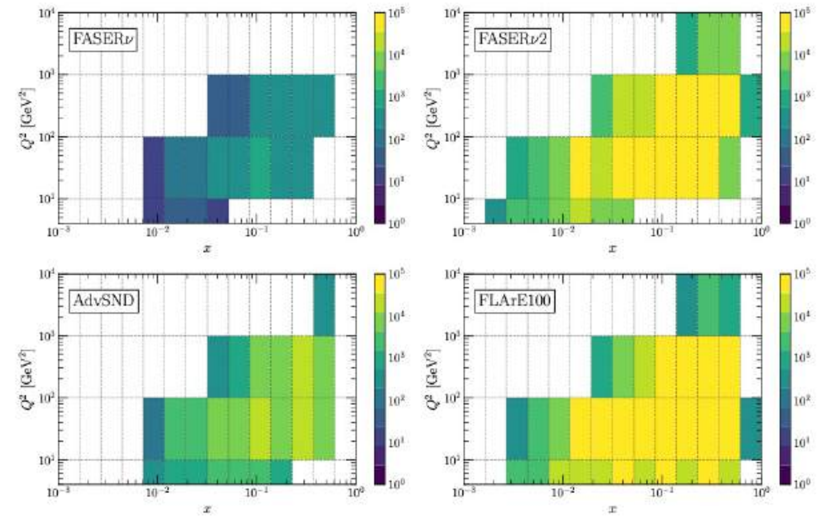


Can investigate many interesting BSM neutrino signatures too …

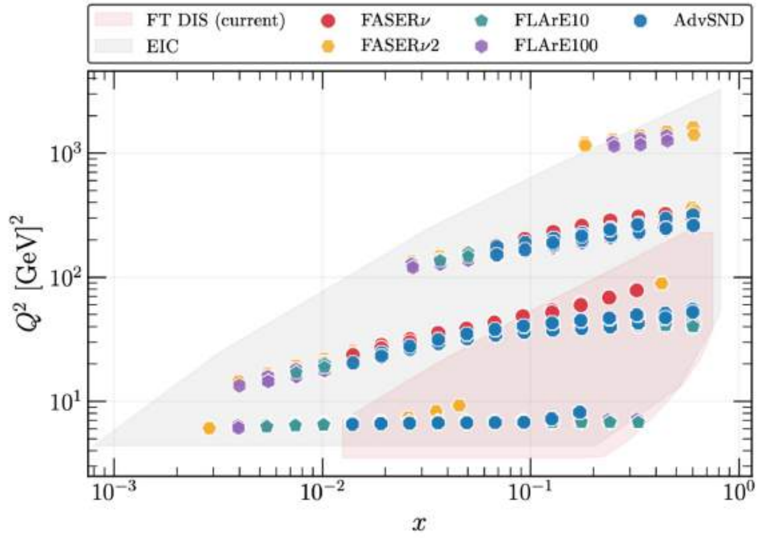
Impact on proton PDFs



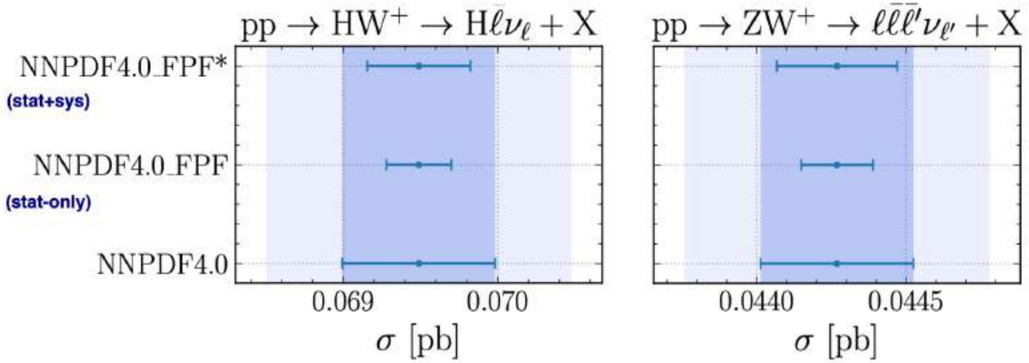
- Impact on proton PDFs quantified by the **Hessian profiling of PDF4LHC21** (xFitter) and by direct inclusion in the **global NNPDF4.0 fit**
- Most impact on **up and down valence quarks** as well as in **strangeness,** ultimately limited by systematics, but
- PDFs improved with LHC neutrino data **enhance precision HL-LHC measurements like *W* mass**

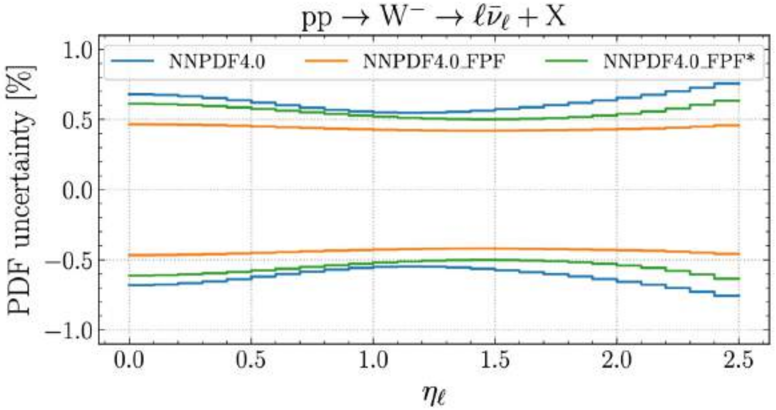


Cruz-Martinez *et al*, 2309.09581



Implications for the HL-LHC





- Impact on **core HL-LHC processes** i.e. single and double weak boson production and Higgs production (VH, VBF)
- Also relevant for **BSM searches at large-mass** (via large-*x* PDFs)

Talk: Juan Rojo

CHARM PRODUCTION

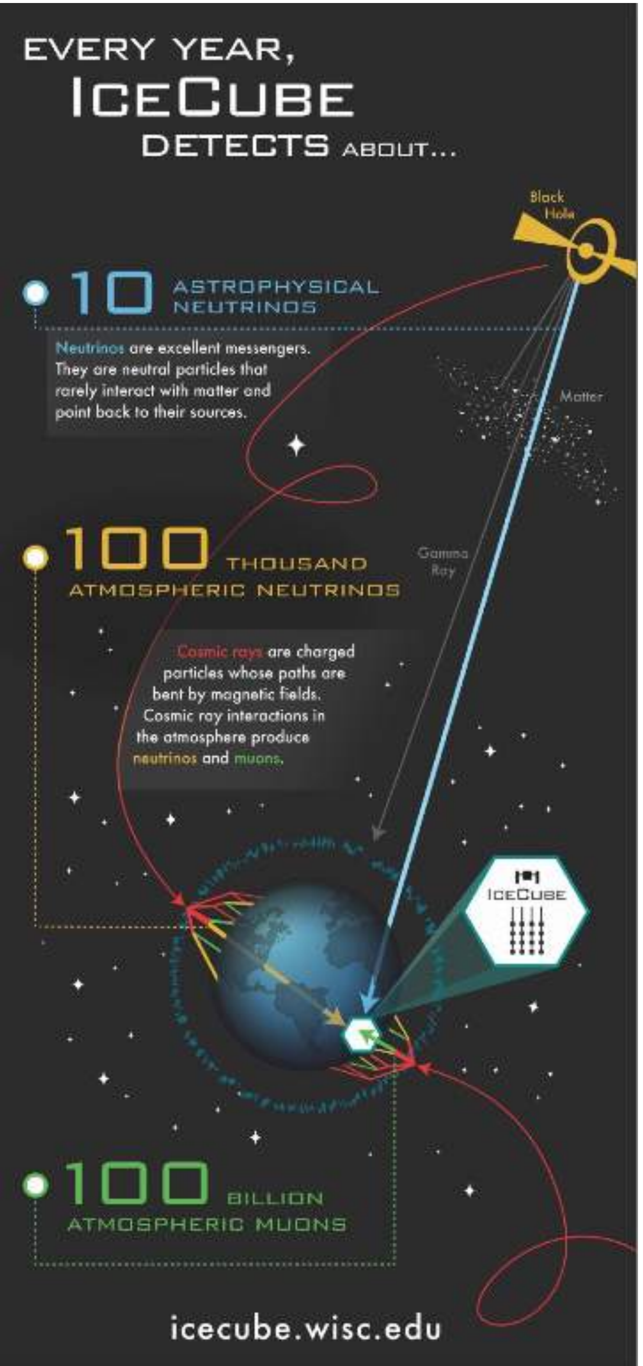
WG2 : Ana Stasto
+ 95 members

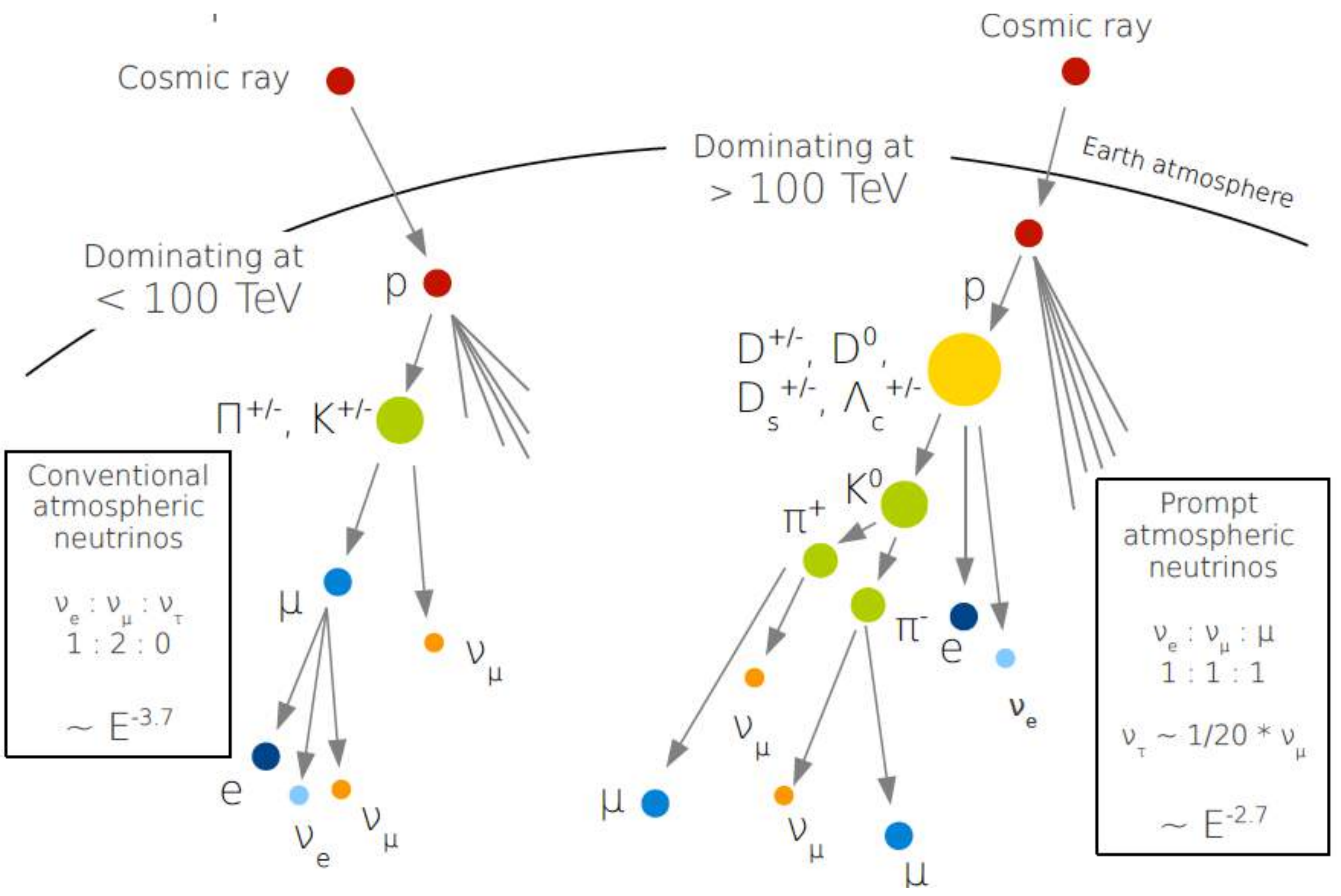
Synergy with Neutrino Telescopes:

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

Talks: Lu Lu,
Anatoli Fedynitch

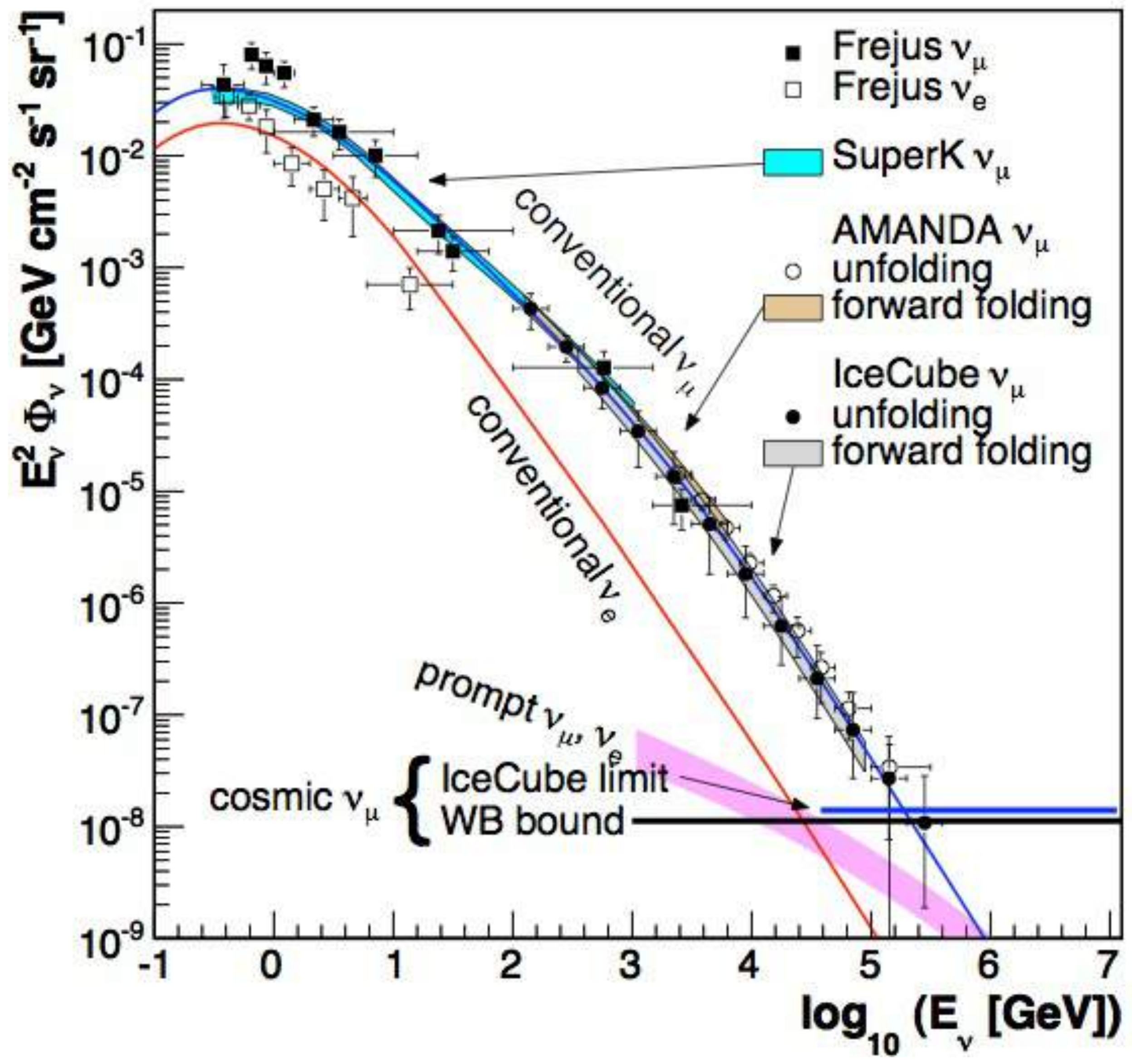
Neutrino telescopes look for a cosmic signal buried in a huge background of atmospheric neutrinos

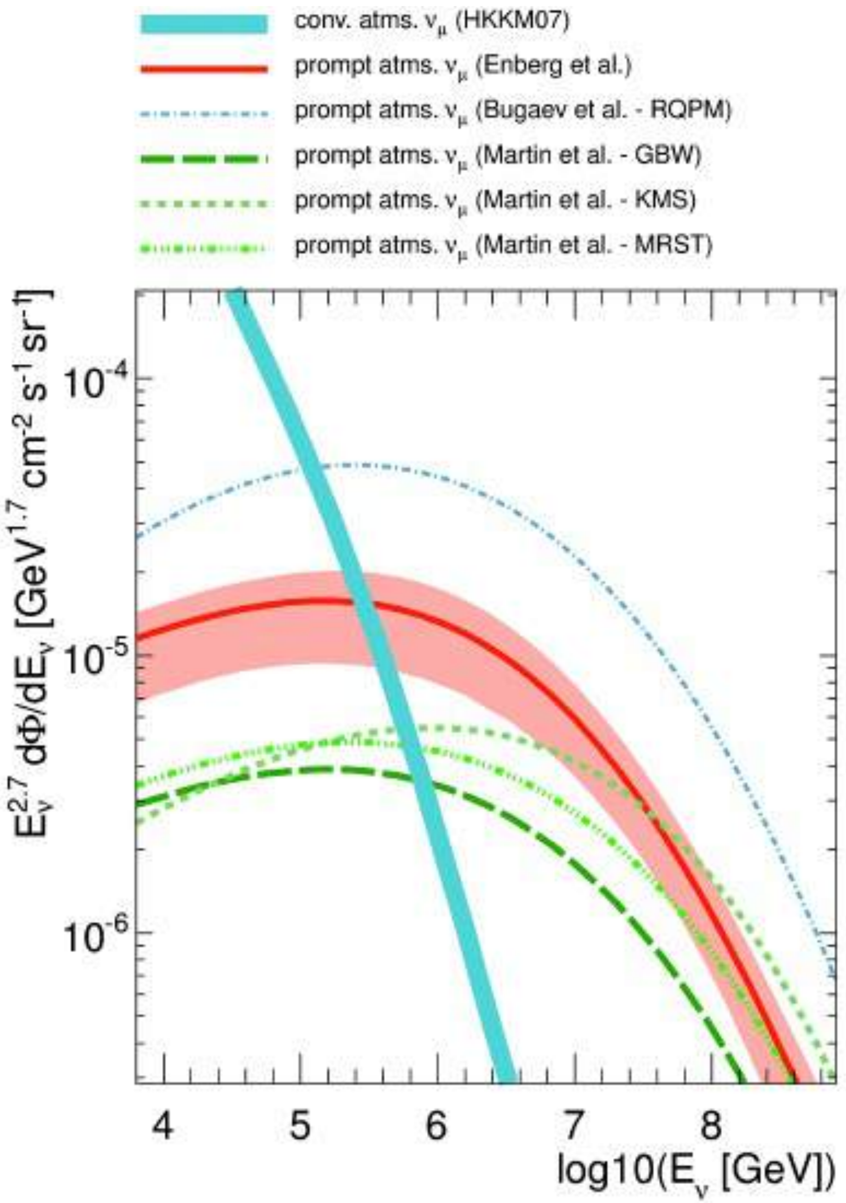




Courtesy: Anne Schukraft

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. using the 'colour dipole model' of Enberg, Reno & Sarcevic (*PRD* **78**:043005,2008) which is empirical … so 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 Monte Carlo event generators** (*modulo* theoretical uncertainties re. validity of factorisation theorem, choice of starting scale *etc*)

- Can use LHCb hadroproduction data … conversion from CM to rest frame of the (atmospheric) fixed target:

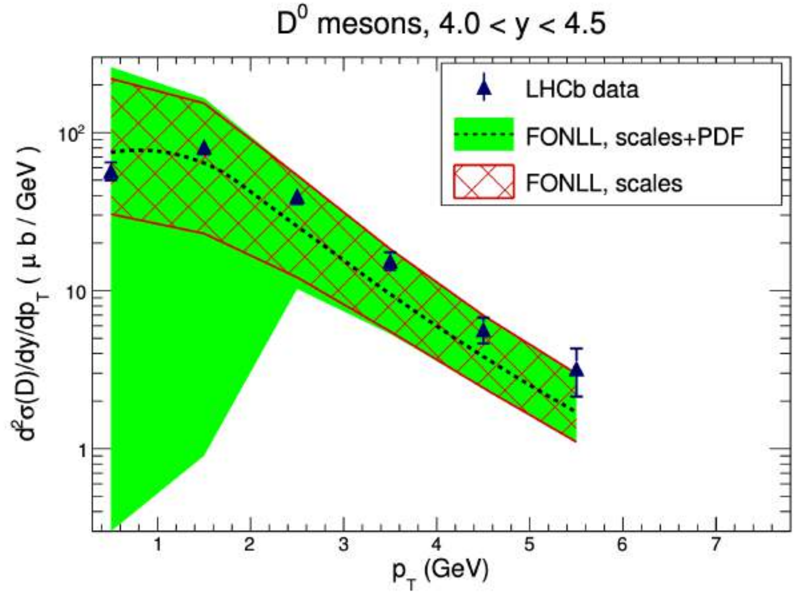
$$\sqrt{s} = 7\ [TeV] \longleftrightarrow E_b = 2.6 \times 10^7\ [GeV]$$

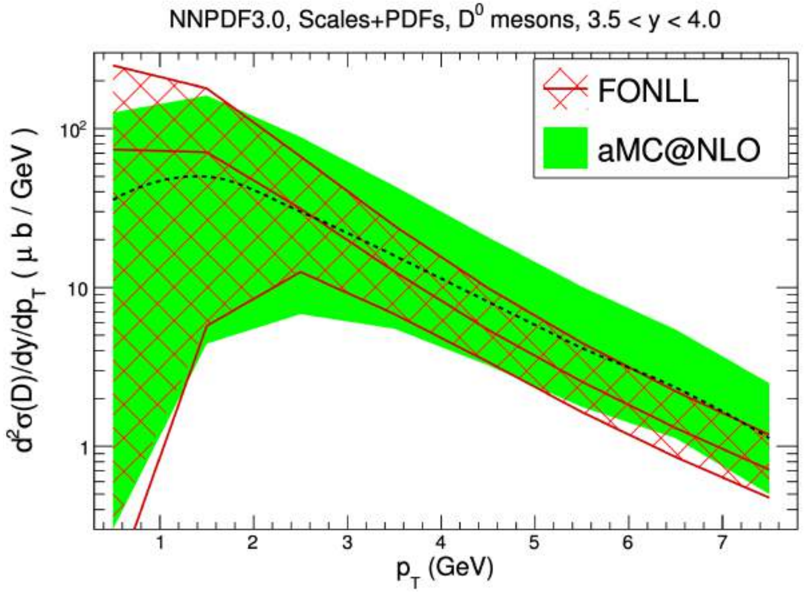
We can therefore predict the prompt neutrino flux at energies **up to 10^7 GeV** … at these energies, charm production is dominated by **gluon fusion**, hence sensitive to the behaviour of the **gluon PDF at small-*x***

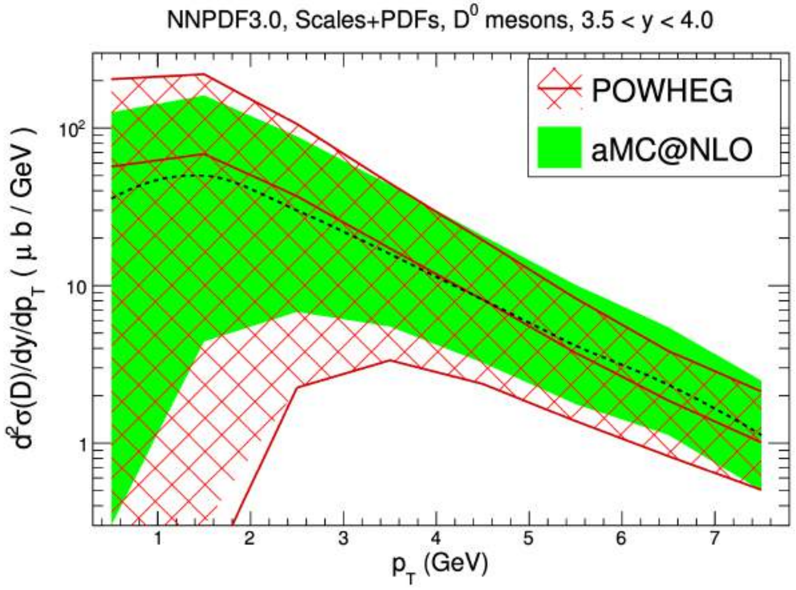
Gauld *et al*, *JHEP* **02**:130,2016

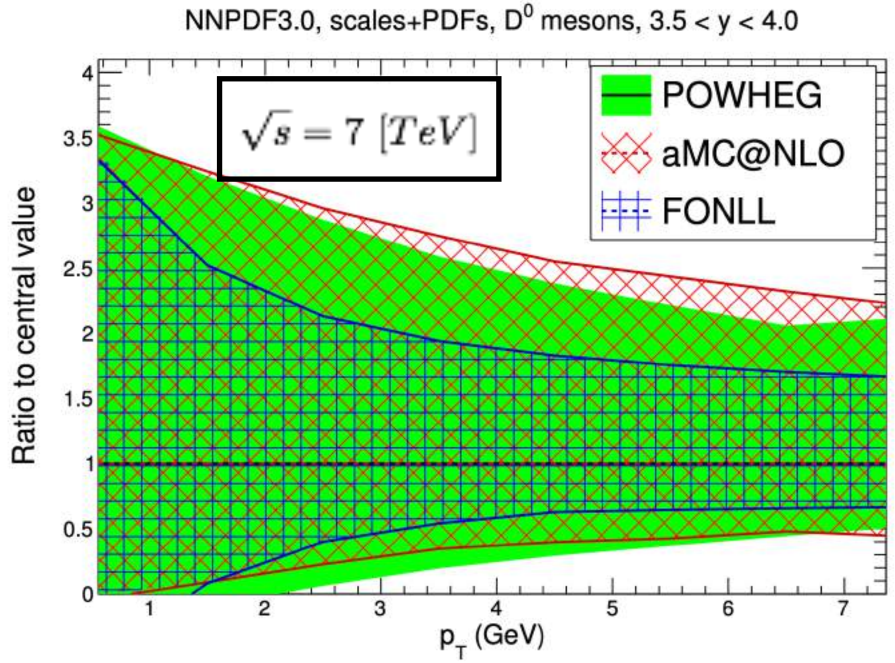
Forward Charm Production & LHCb

LHCb collab. *NPB* **871**:1,2013

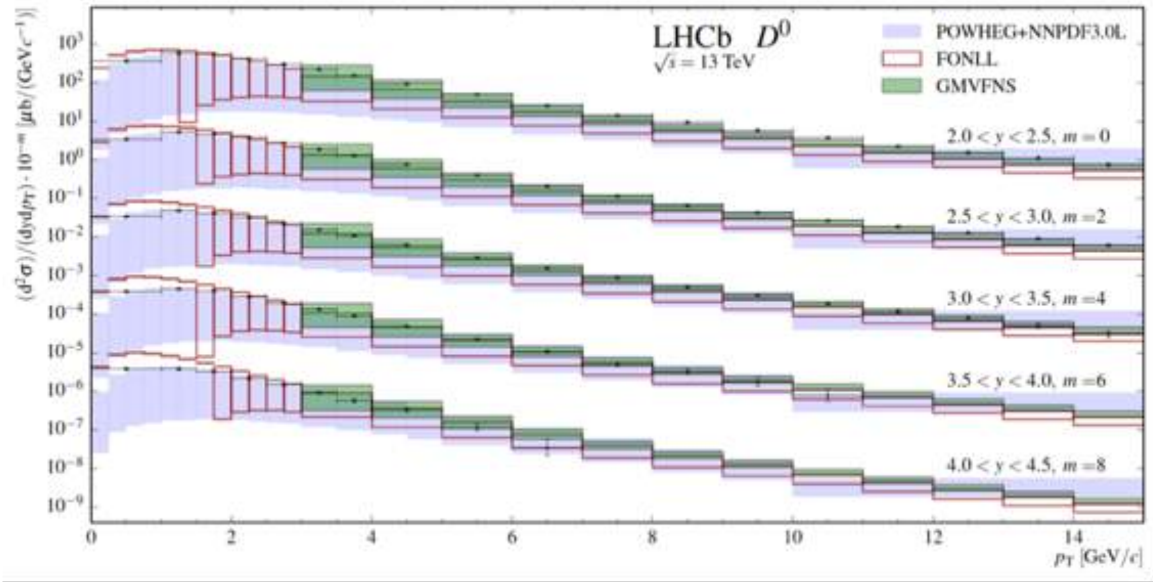








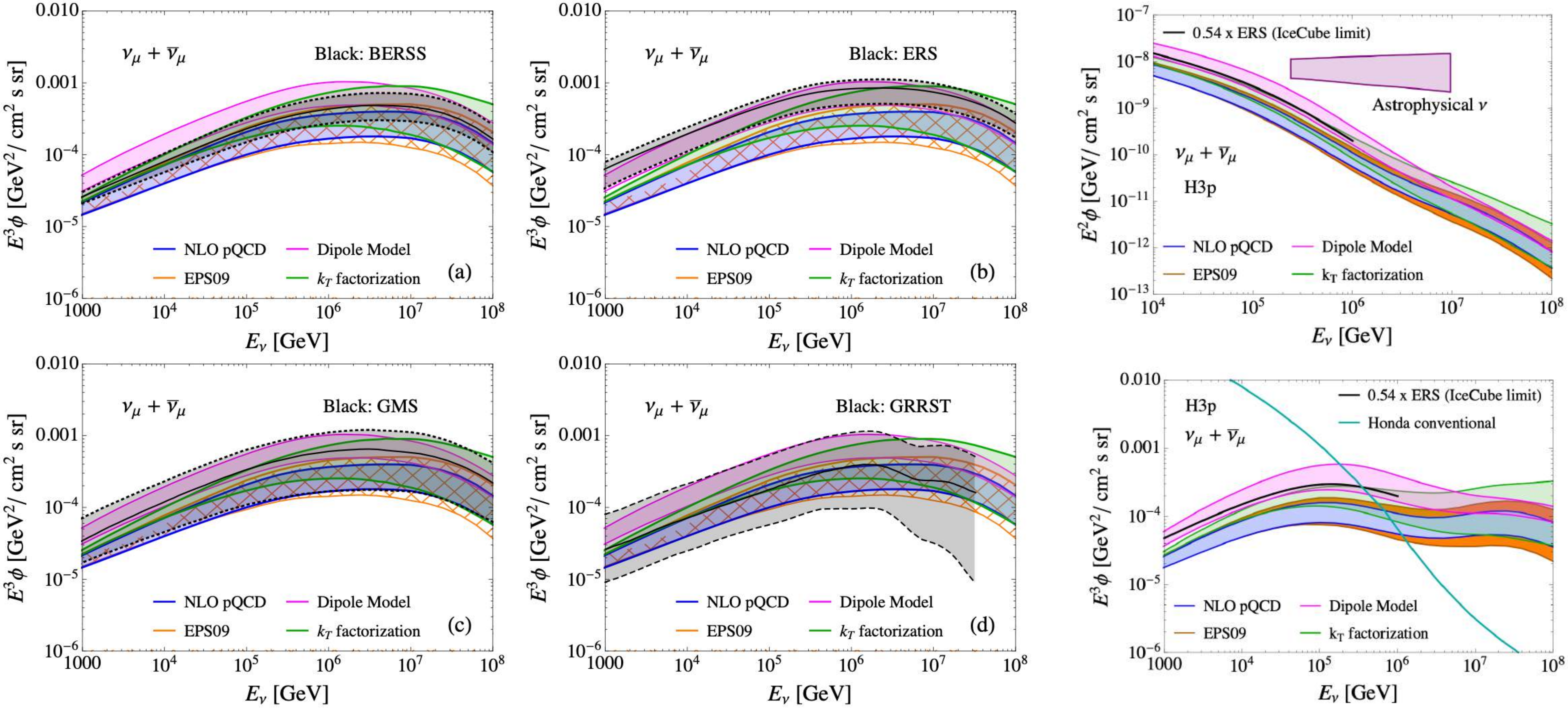
Prediction for 13 TeV matched the data!



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

NLO predictions for forward charm production validated with LHCb data

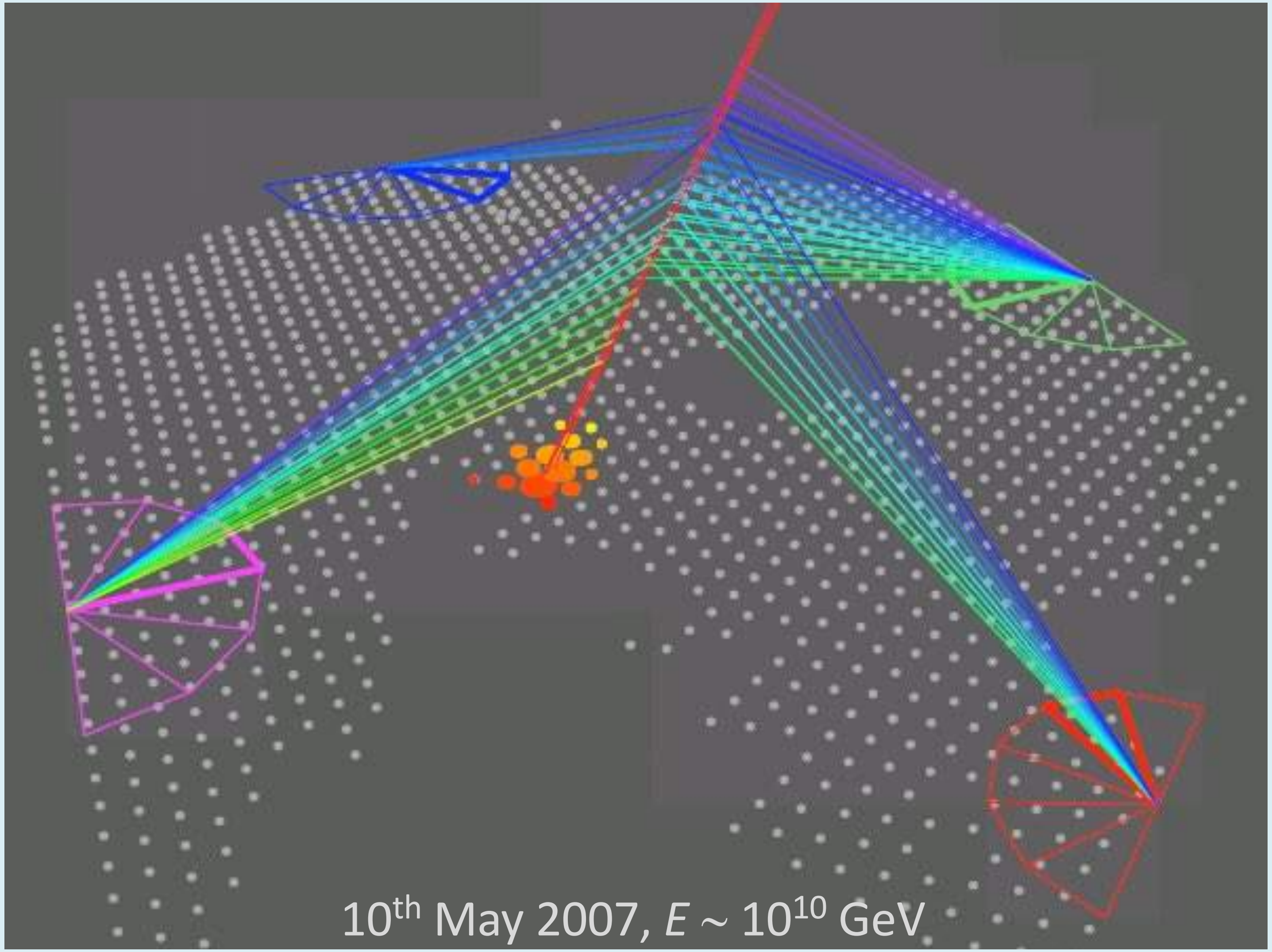
Range of predictions narrowed further with input from LHCb



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

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

Light hadron production



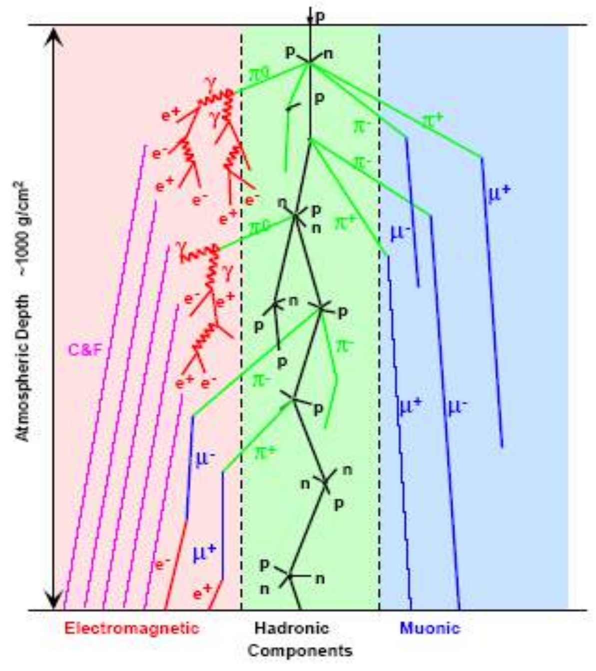
WG3: Luis Anchordoqui, Denis Soldin + 89 members

Synergy with Cosmic Ray Air Shower arrays:

Pierre Auger Observatory, ***IceTop***, *KASCADE-GRANDE*, ***NEVOD-DECOR***, *SUGAR*, ***Telescope Array***, *TUNKA*, *Yakutsk* **…**

Talk: Ralph Engel

Schematic Shower Development



Fluorescence & Cherenkov-Light (isotropic) (forward peaked)

p, n, π : near shower axis
μ, e, γ : widely spread

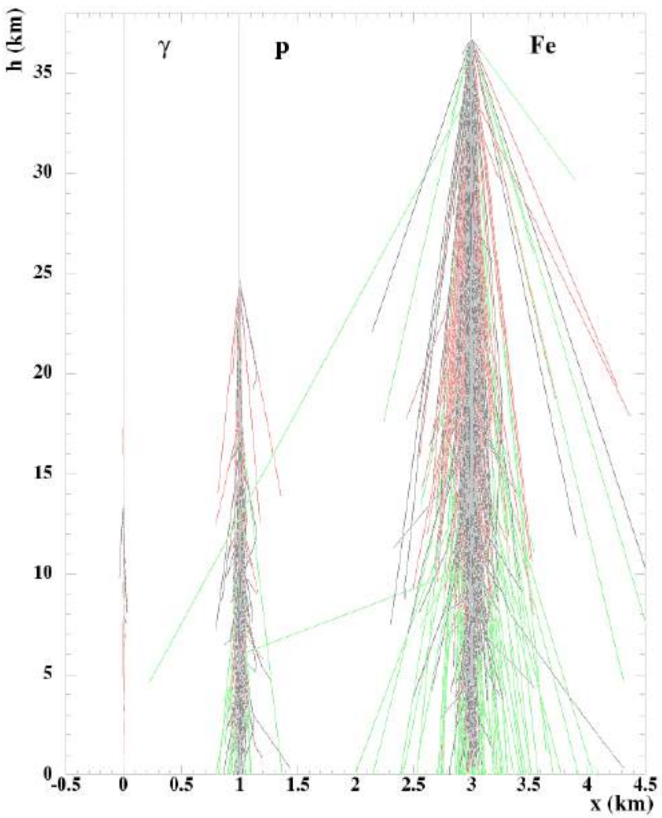
e, γ : from π^0, μ decays ~ 10 MeV
μ : from $\pi^{\pm}$, K, ... decays ~ 1 GeV

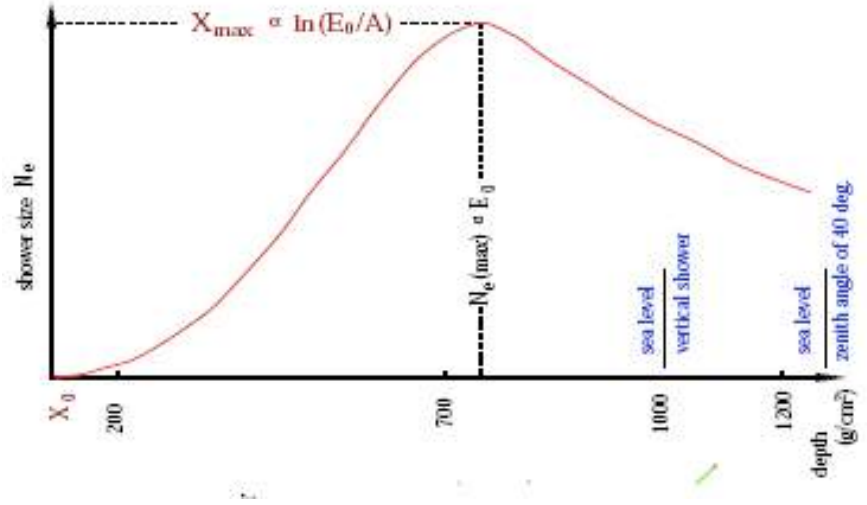
$N_{e,\gamma} : N_{\mu}$ ~ 10 ... 100 varying with core distance, energy, mass, Θ, ...

Details depend on:
interaction cross-sections,
hadronic and el.mag. particle production,
decays, transport, ...
at energies well above man-made accelerators

Complex interplay with many correlations
requires MC simulations

Courtesy: Johannes Knapp





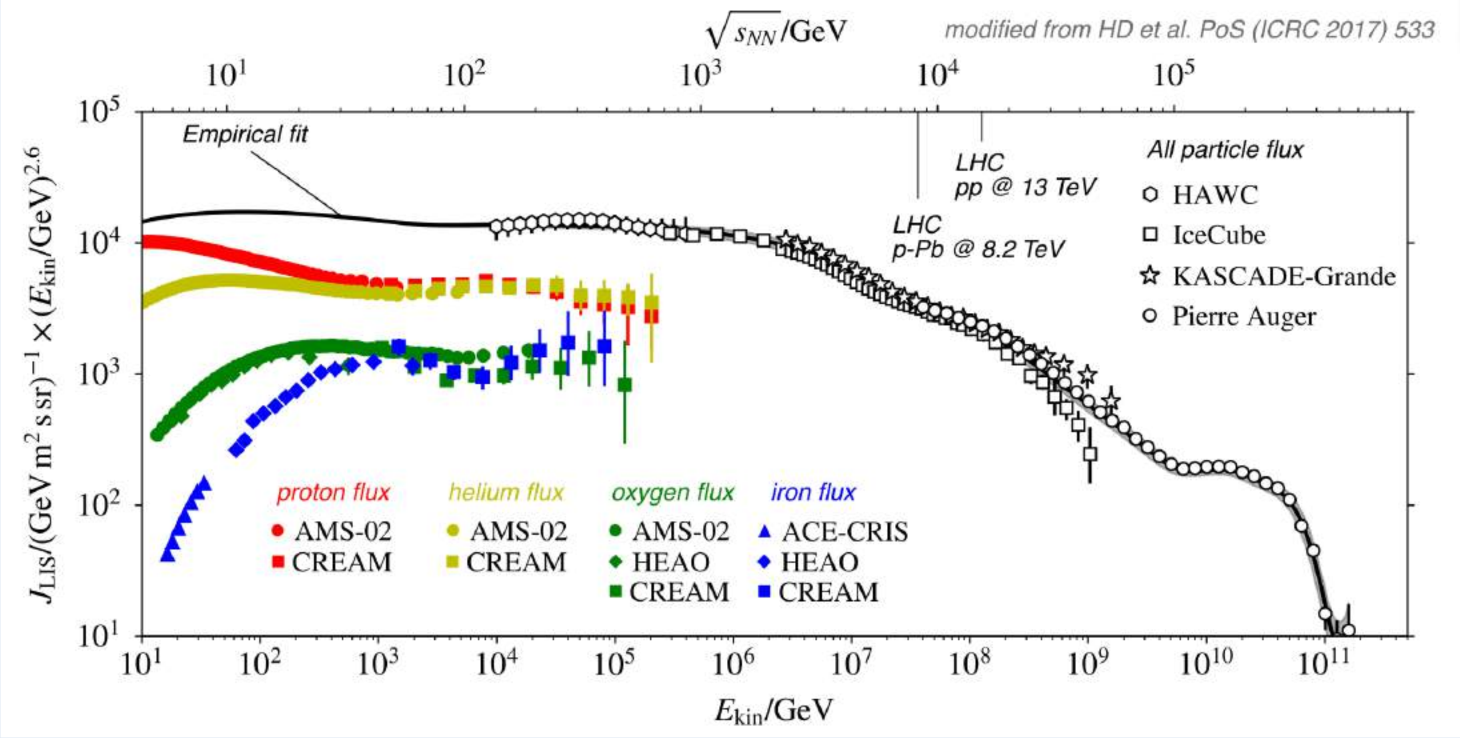
Main sources of uncertainty

- Minijet cross-section (parton densities, range of applicability)
- Transverse profile function (total #-secn, multiplicity distribution)
- Energy dependence of leading particle production
- Role of nuclear effects (saturation, stopping power, QGP)

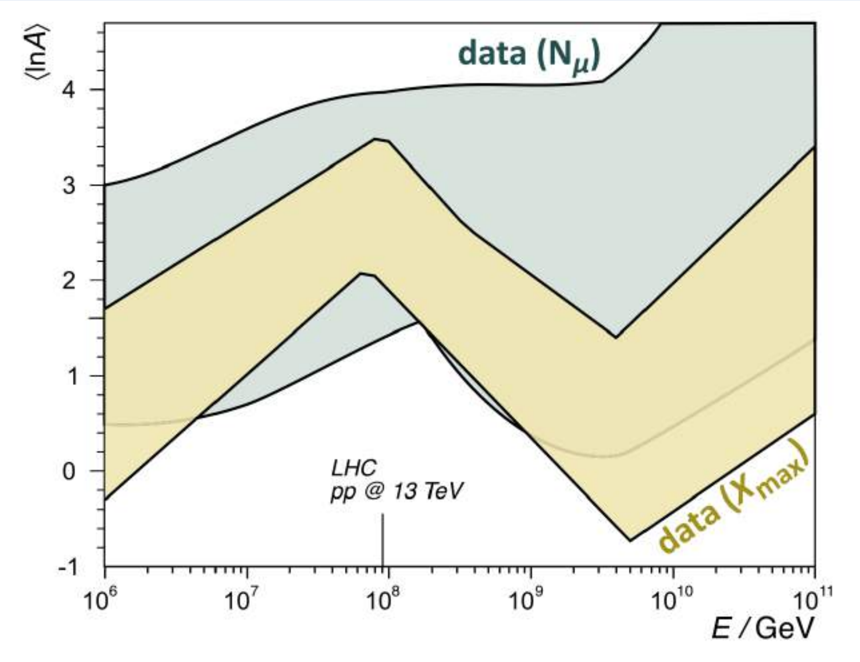
Need input from forward physics experiments

The Cosmic ray muon anomaly

There is a ~30-60% mismatch between the observed muon flux and that expected from simulations

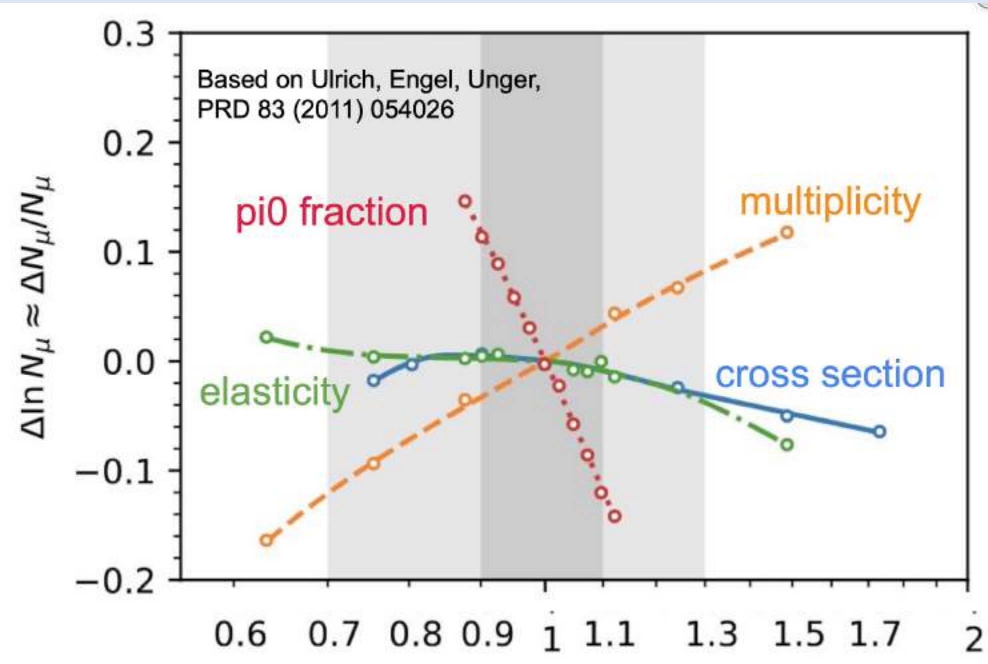


Albrecht *et al*, *Ap.Sp.Sci.* **367**:27,2022

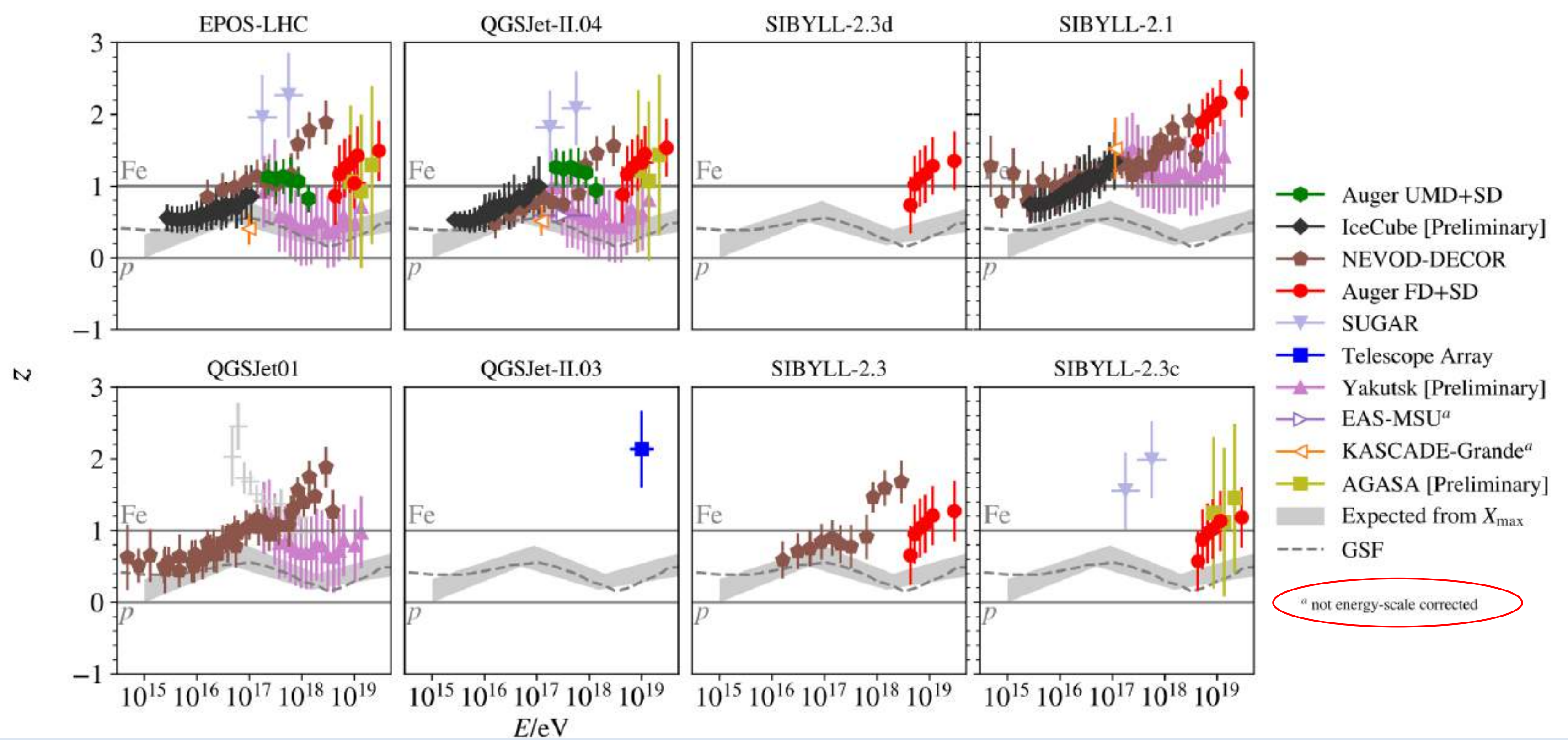


Kampert & Unger, *AP* **35**:660,2012

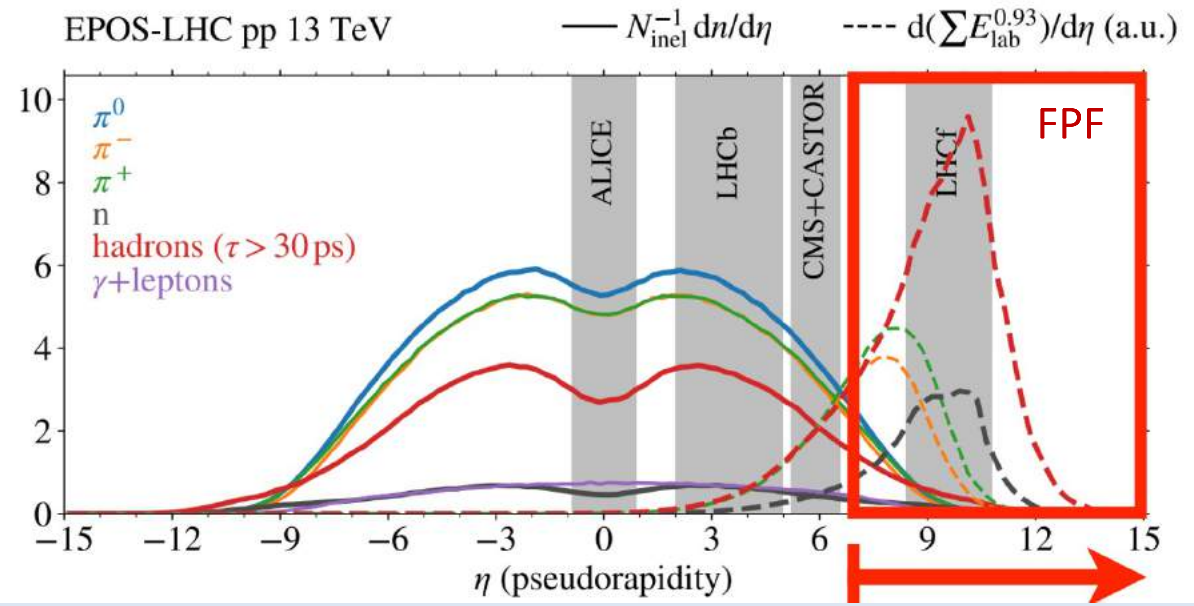
Difficult to explain away by tuning parameters without introducing other discrepancies with cosmic ray data



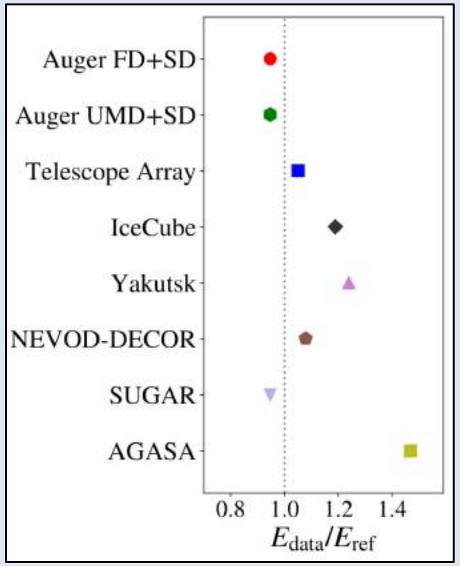
Comparison of muon flux measurements with predictions from air shower simulations + X_{max} measurements (grey band)



The FPF will measure forward light hadron production in a kinematic range never before explored

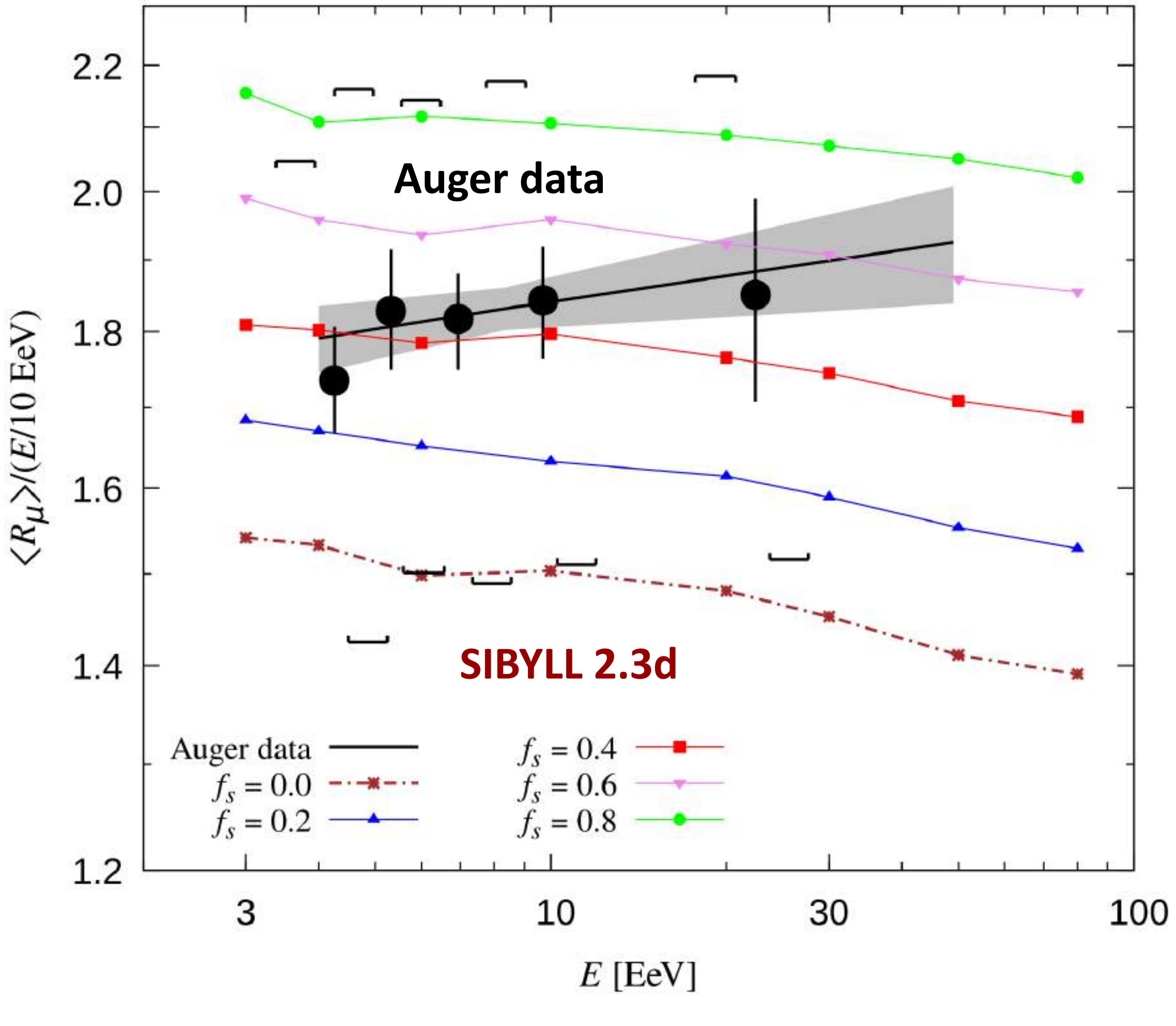


Energy scale corrections



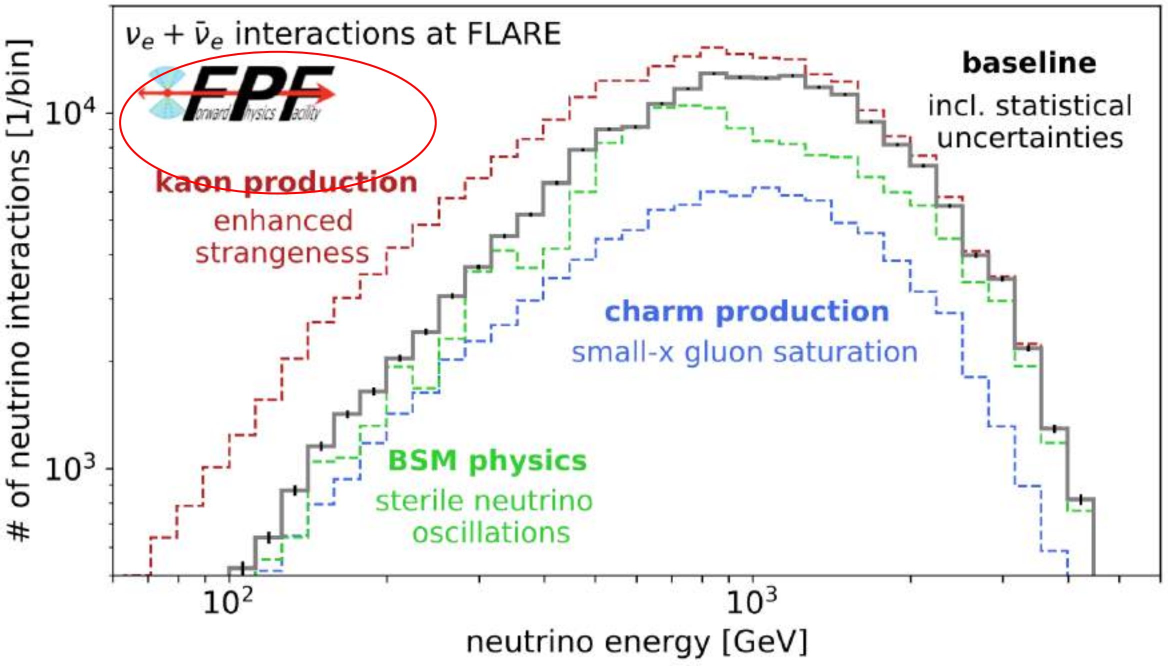
Albrecht et al, *Astrophys.Space.Sci.* **367**:27,2022

Is the muon deficit in simulations wrt UHECR data due to enhanced strange production?



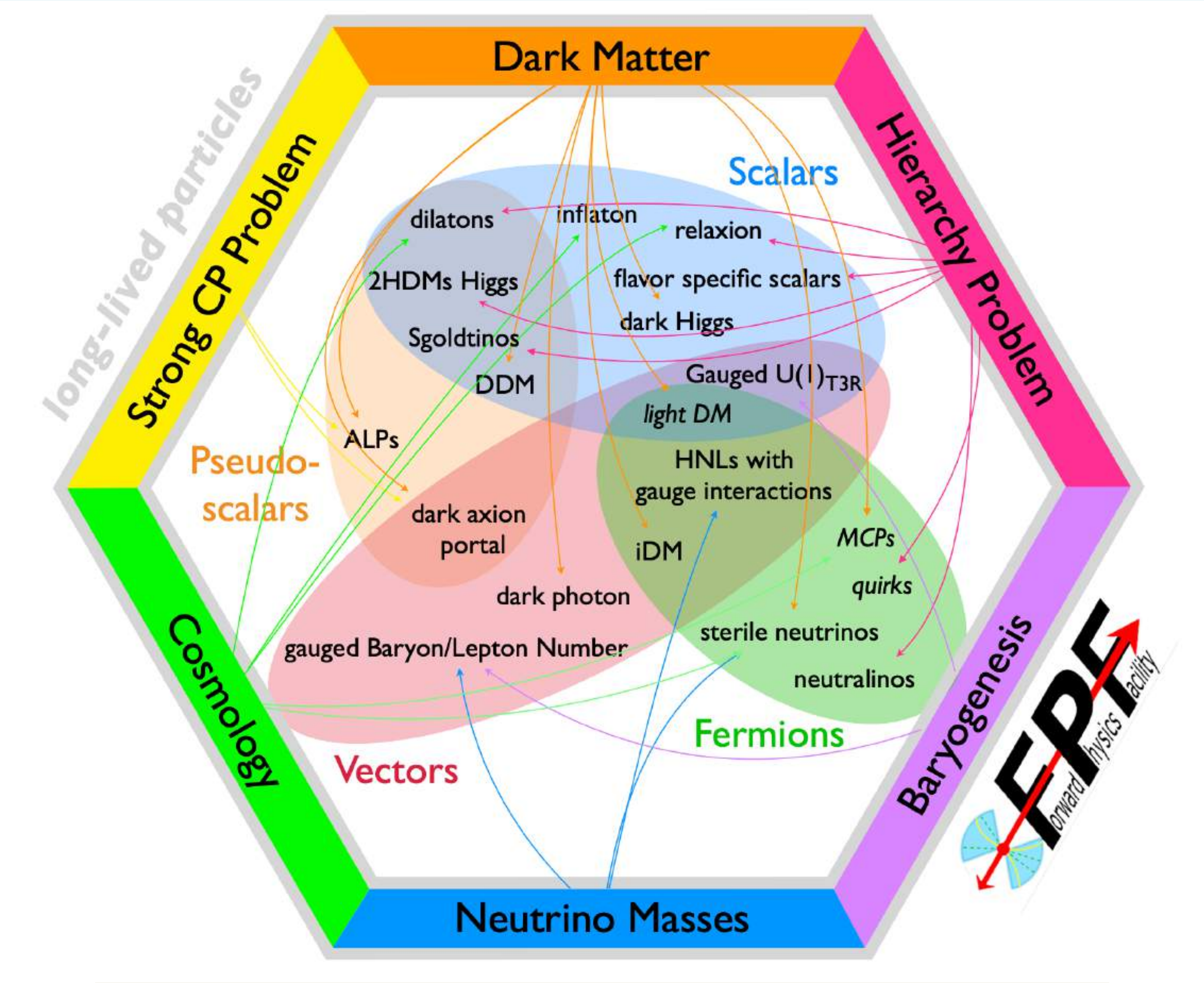
Turning a fraction *fs* of forward pions into kaons … can solve muon puzzle!
Anchordoqui *et al*, *JHEAp* **34**:19,2022

There is a suggestion of this in ALICE data …
(*Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions*, ALICE collaboration, *Nature Phys.* 13:535,2017)



This can be tested directly at the FPF

New physics



Synergy with dark matter search experiments

WG4: Brian Batell
Sebastian Trojanowski
+ 98 members

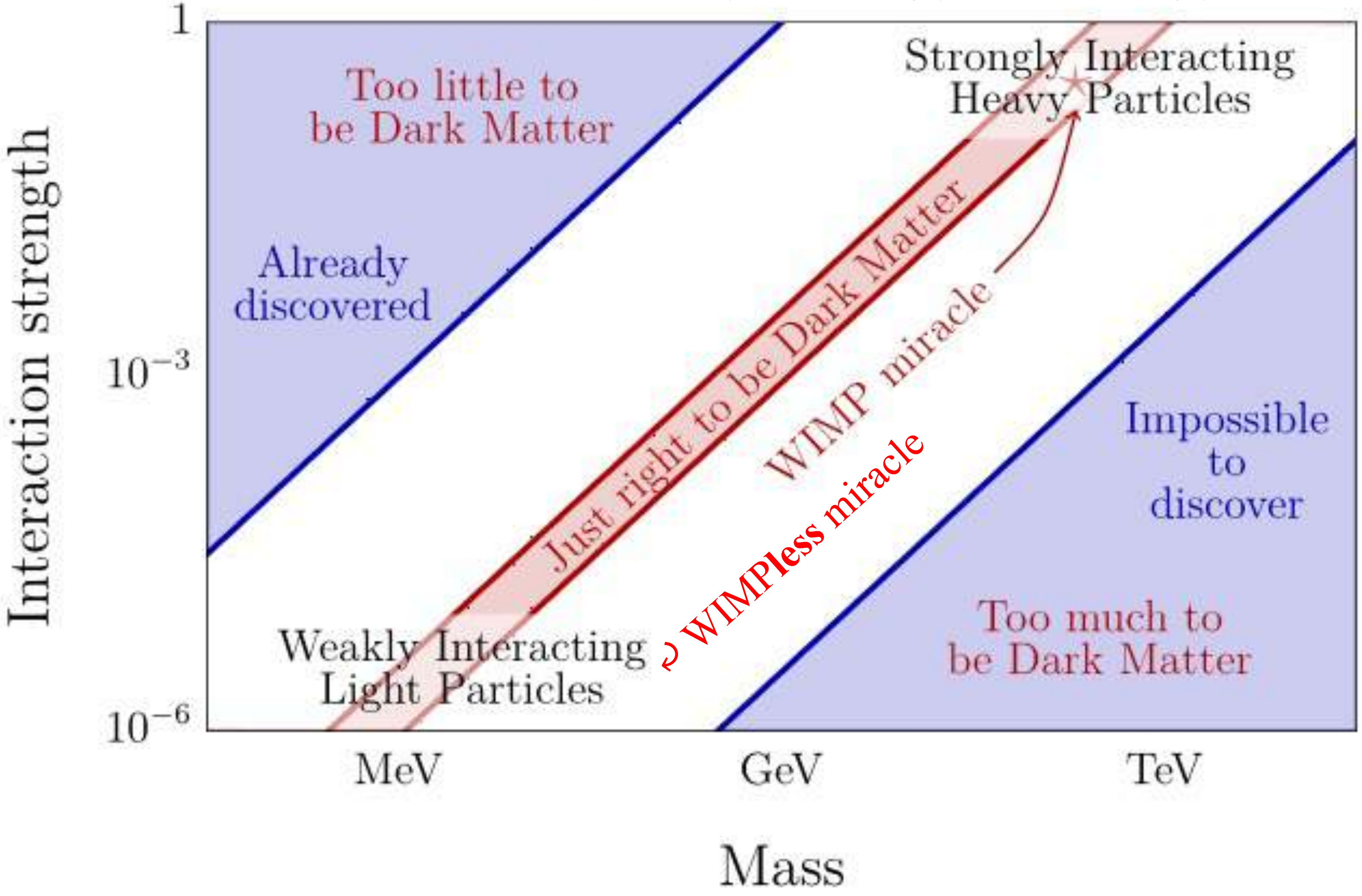
Talks: Jyotismita Adhikary, Reuven Balkin, Nicolás Bernal, Maksym Ovchynnikov, Roman Macarelli, Aparajitha Karthikeyan, Lingfeng Li, …

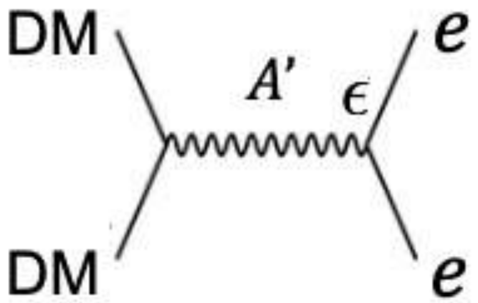
Theoretical motivations for New Light Feebly Interacting/Long-Lived Particles

- SM
  - Abelian, unbroken: Electromagnetism $U(1)_{EM}$
  - Abelian, spontaneously broken: Hypercharge $U(1)_Y$
  - Non-Abelian, spontaneously broken: Weak SU(2)
  - Non-Abelian, dynamically broken: QCD SU(3)
- BSM
  - Abelian, unbroken: millicharged particles (FORMOSA)
  - Abelian, spontaneously broken: dark photon, $B - L$, $L_\mu - L_\tau$ gauge bosons (FASER2, FASERν2, AdvSND, FLArE)
  - Non-Abelian, spontaneously broken: ?
  - Non-Abelian, dynamically broken: quirks (FASER2, FLArE, and others?)

Courtesy: Jonathan Feng

Dark Matter: the 'WIMP-less miracle'



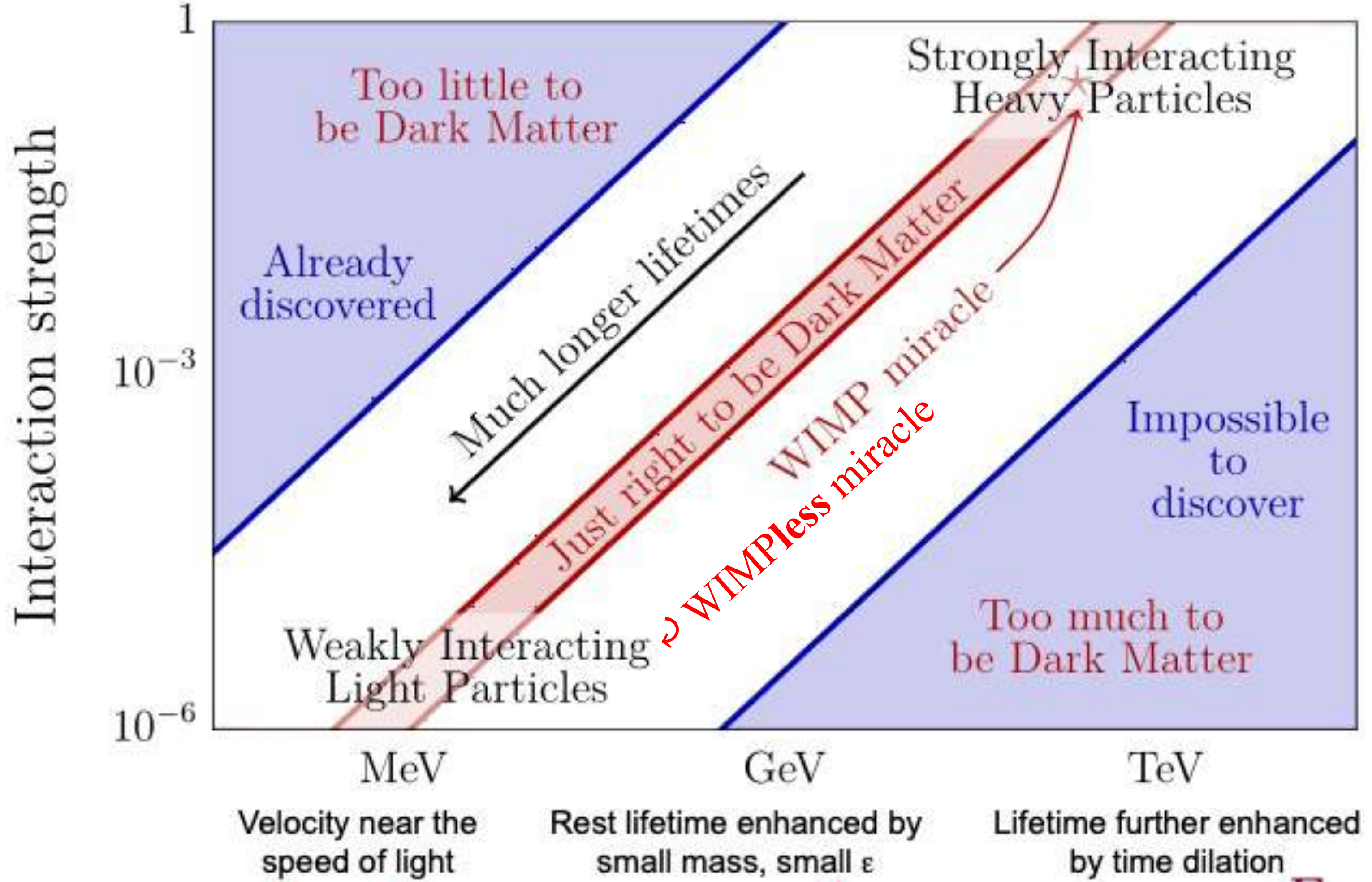


$$\langle \sigma v \rangle \sim \epsilon^2 / m_{A'}^2$$

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

Courtesy: Luis Anchordoqui

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



$$v \sim 1 \qquad \tau \propto \frac{1}{\epsilon^2 m_{A'}} \qquad \gamma \propto \frac{E}{m_{A'}}$$

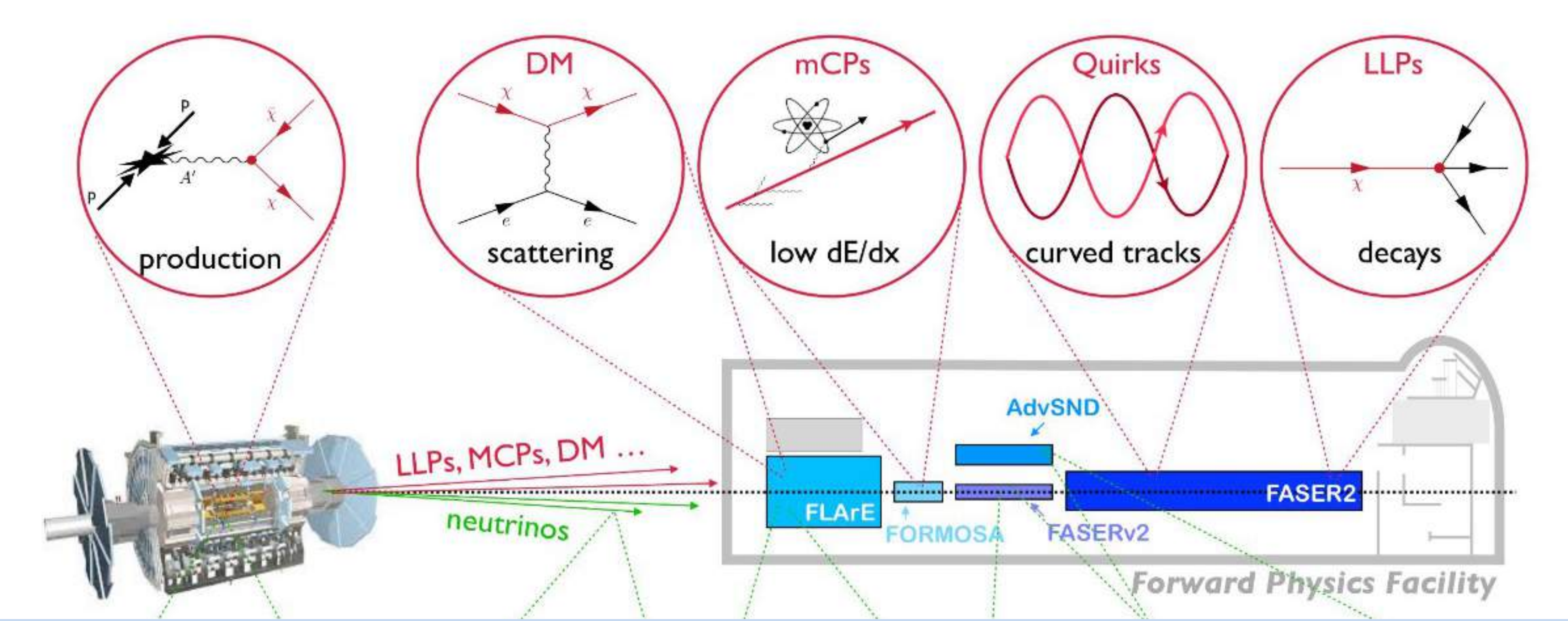
$$L = v\tau\gamma \sim 100\ \text{m} \left(\frac{10^{-5}}{\epsilon}\right)^2 \left(\frac{100\ \text{MeV}}{m_{A'}}\right)^2 \left(\frac{E}{\text{TeV}}\right)$$

Courtesy: Luis Anchordoqui

The Portal Formalism

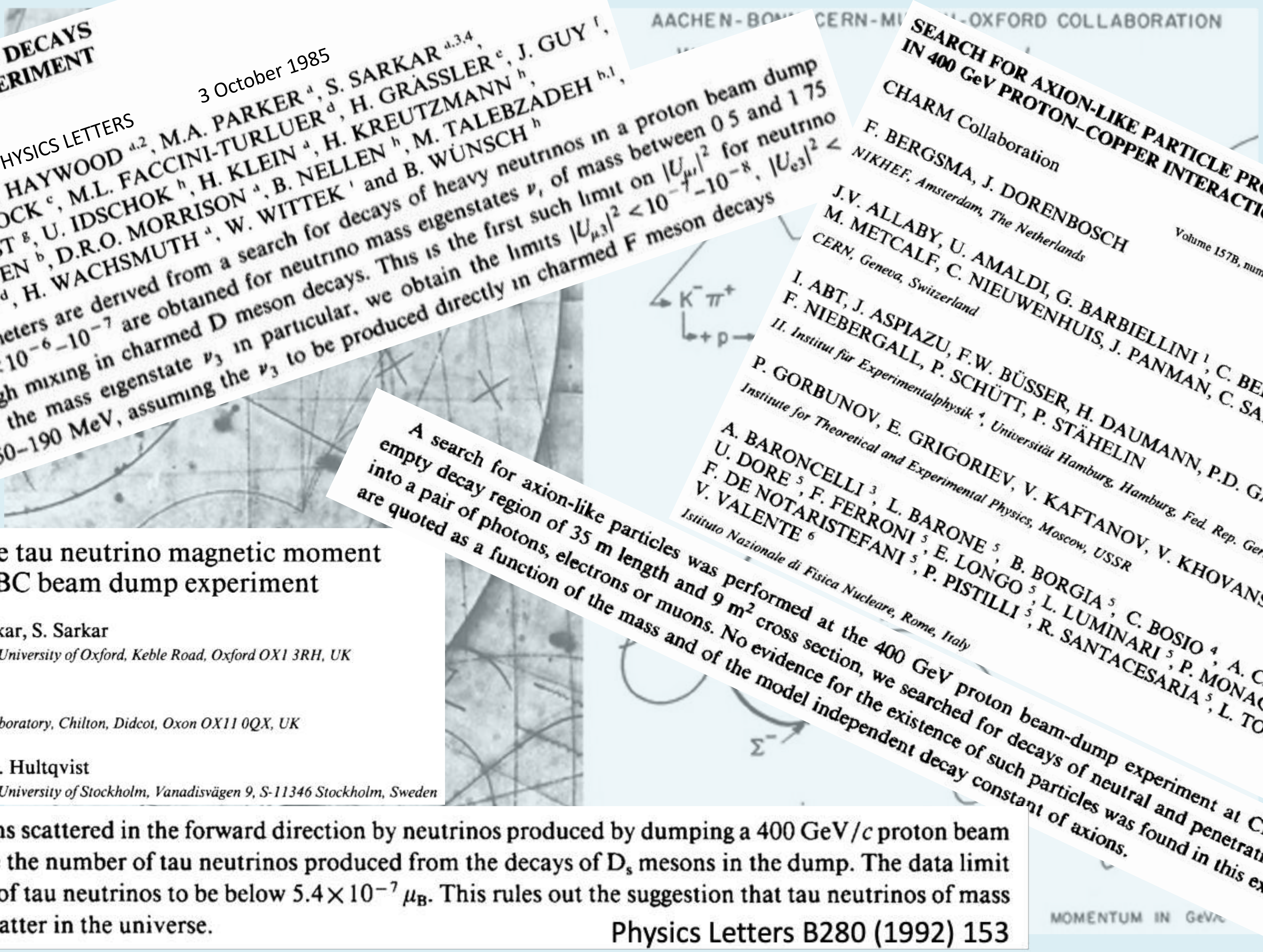
$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$$

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 e.g. using BEBC we searched for light neutralinos, heavy neutral leptons, neutrino magnetic moments *etc*



PHYSICS LETTERS
Volume 160B, number 1, 2, 3
3 October 1985

SEARCH FOR HEAVY NEUTRINO DECAYS IN THE BEBC BEAM DUMP EXPERIMENT

WA66 Collaboration
A.M. COOPER-SARKAR [a,1], S.J. HAYWOOD [d,2], M.A. PARKER [a], S. SARKAR [a,3,4], K.W.J. BARNHAM [b], P. BOSTOCK [c], M.L. FACCINI-TURLUER [d], H. GRÄSSLER [e], J. GUY [f], P.O. HULTH [g], K. HULTQVIST [g], U. IDSCHOK [h], H. KLEIN [a], H. KREUTZMANN [h], J. KRSTIC [c], M.M. MOBAYYEN [b], D.R.O. MORRISON [a], B. NELLEN [h], M. TALEBZADEH [b,1], W. VENUS [f], D. VIGNAUD [d], H. WACHSMUTH [a], W. WITTEK [i] and B. WÜNSCH [h]

New limits on lepton mixing parameters are derived from a search for decays of heavy neutrinos in a proton beam dump experiment. The limits $|U_{\mu i}|^2$, $|U_{ei}|^2 < 10^{-6}-10^{-7}$ are obtained for neutrino mass eigenstates ν_i of mass between 0.5 and 1.75 GeV, which can be produced through mixing in charmed D meson decays. This is the first such limit on $|U_{\mu i}|^2$ for neutrino masses greater than 0.5 GeV. For the mass eigenstate ν_3 in particular, we obtain the limits $|U_{\mu 3}|^2 < 10^{-7}-10^{-8}$, $|U_{e3}|^2 < 10^{-9}-10^{-10}$ for the mass range 150–190 MeV, assuming the ν_3 to be produced directly in charmed F meson decays.

Bound on the tau neutrino magnetic moment from the BEBC beam dump experiment

A.M. Cooper-Sarkar, S. Sarkar
Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK

J. Guy, W. Venus
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, UK

P.O. Hulth and K. Hultqvist
Department of Physics, University of Stockholm, Vanadisvägen 9, S-11346 Stockholm, Sweden

We have searched for electrons scattered in the forward direction by neutrinos produced by dumping a 400 GeV/c proton beam on a copper target. We estimate the number of tau neutrinos produced from the decays of D_s mesons in the dump. The data limit the possible magnetic moment of tau neutrinos to be below $5.4\times10^{-7}\,\mu_B$. This rules out the suggestion that tau neutrinos of mass O(MeV) constitute the dark matter in the universe.

Physics Letters B280 (1992) 153

PHYSICS LETTERS
Volume 157B, number 5,6

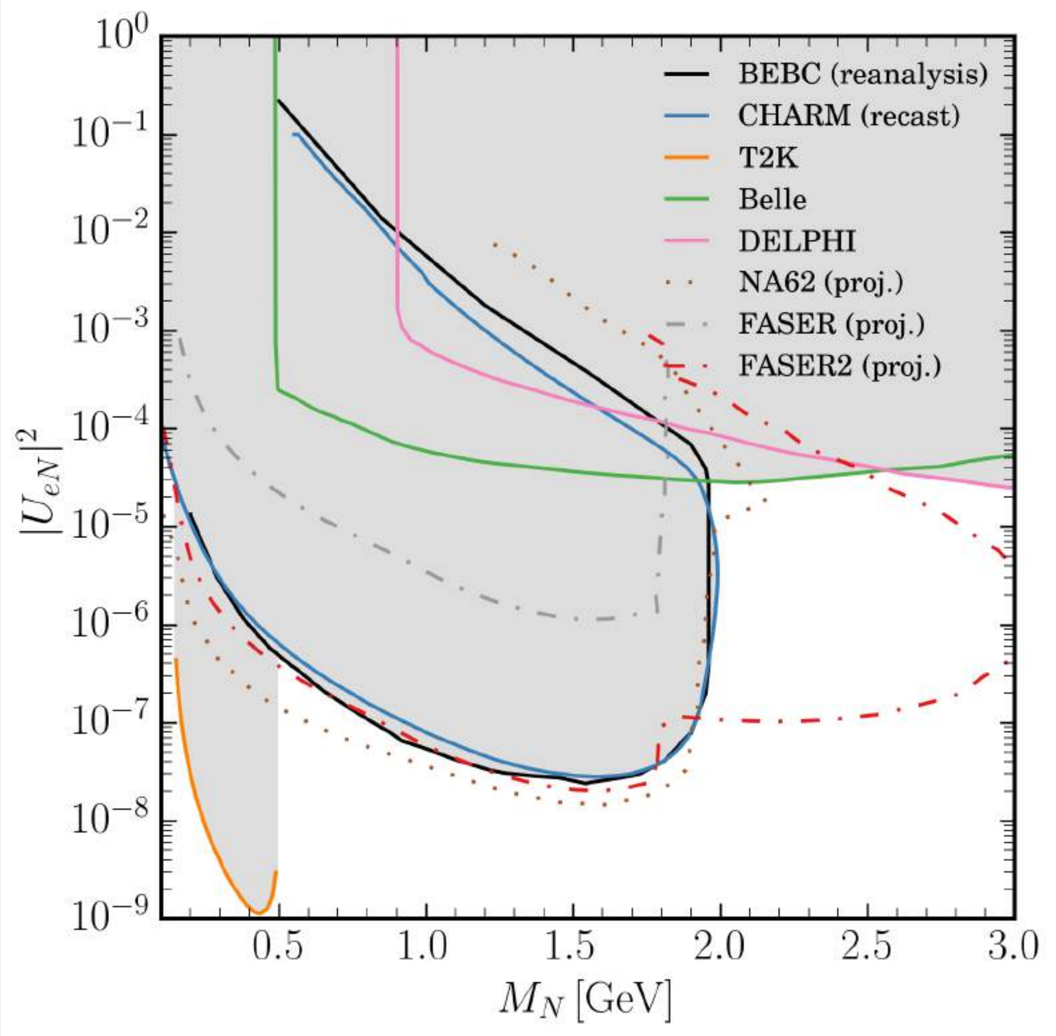
SEARCH FOR AXION-LIKE PARTICLE PRODUCTION IN 400 GeV PROTON–COPPER INTERACTIONS

CHARM Collaboration
F. BERGSMA, J. DORENBOSCH
NIKHEF, Amsterdam, The Netherlands
J.V. ALLABY, U. AMALDI, G. BARBIELLINI [1], C. BERGER [2], W. FLEGEL, L. LANCERI, M. METCALF, C. NIEUWENHUIS, J. PANMAN, C. SANTONI [3], K. WINTER
CERN, Geneva, Switzerland
I. ABT, J. ASPIAZU, F.W. BÜSSER, H. DAUMANN, P.D. GALL, T. HEBBEKER, F. NIEBERGALL, P. SCHÜTT, P. STÄHELIN
II. Institut für Experimentalphysik [4], Universität Hamburg, Hamburg, Fed. Rep. Germany
P. GORBUNOV, E. GRIGORIEV, V. KAFTANOV, V. KHOVANSKY, A. ROSANOV
Institute for Theoretical and Experimental Physics, Moscow, USSR
A. BARONCELLI [3], L. BARONE [5], B. BORGIA [5], C. BOSIO [4], A. CAPONE [5], M. DIEMOZ [5], U. DORE [5], F. FERRONI [5], E. LONGO [5], L. LUMINARI [5], P. MONACELLI [5], F. DE NOTARISTEFANI [5], P. PISTILLI [5], R. SANTACESARIA [5], L. TORTORA [3] and V. VALENTE [6]
Istituto Nazionale di Fisica Nucleare, Rome, Italy

A search for axion-like particles was performed at the 400 GeV proton beam-dump experiment at CERN. Exploring an empty decay region of 35 m length and 9 m² cross section, we searched for decays of neutral and penetrating scalar particles into a pair of photons, electrons or muons. No evidence for the existence of such particles was found in this experiment. Limits are quoted as a function of the mass and of the model independent decay constant of axions.

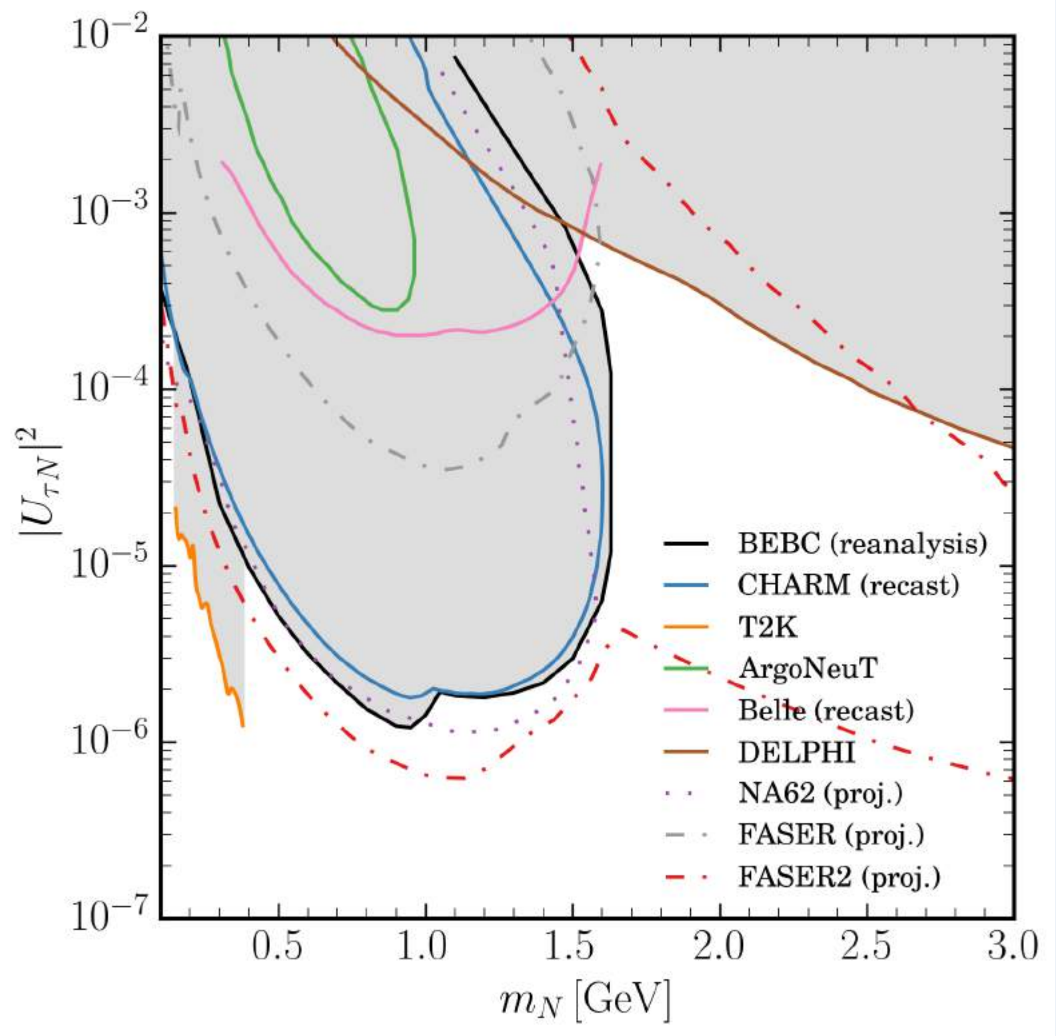
The 40+ year old Fixed target experiments @ CERN still provide world-leading sensitivity to LLPs

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. Barouki, Marocco, S.S., *SciPost Phys.* **13**:118,2020

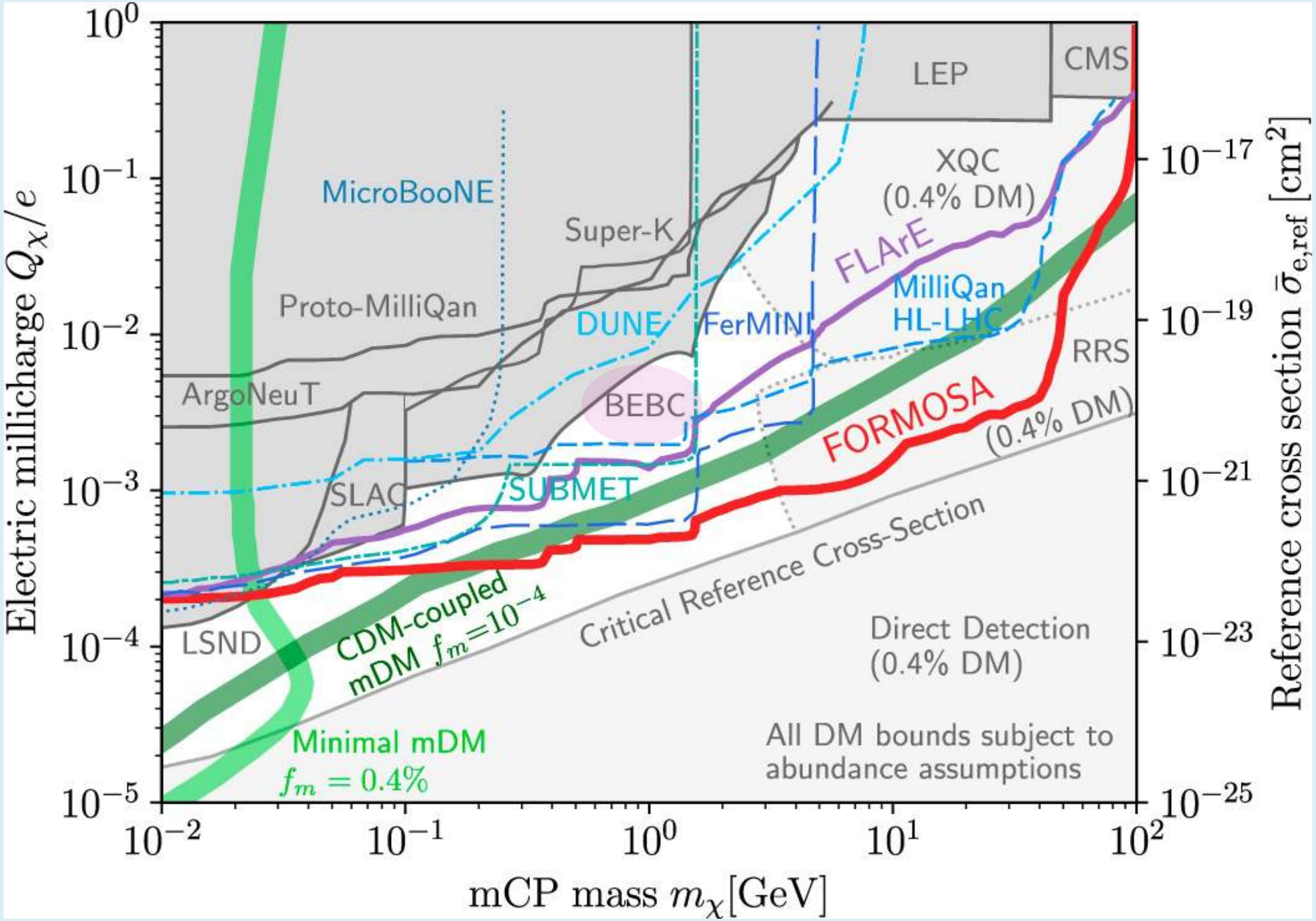


Blast from the past: Constraints on heavy neutral leptons from the BEBC WA66 beam dump experiment

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



The reach for milli-charged particles at the FPF



Anchordoqui *et al*, *Phys.Rep.* **968**:1,2020

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

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