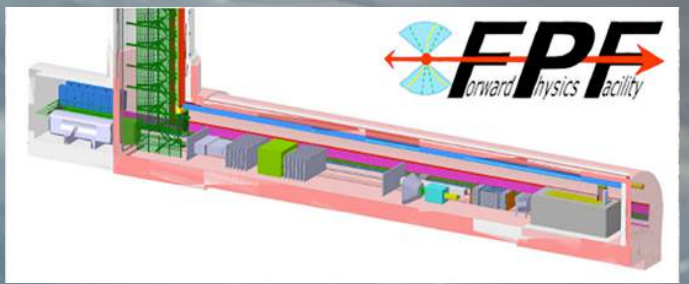
Adventures of a theorist with neutrino experiments, old & new

Subir Sarkar

IceCube (2002–)

BEBC (1983-85)



9th Forward Physics Facility Meeting, CERN, 5-6 March 2026

As Urs Weidemann commented yesterday, **theorists** have shown great interest in the rich physics programme of the **FPF** (and contributed to the 'White Paper') … here are just those who signed the LoI:

arXiv:2510.26260v1 [hep-ex] 30 Oct 2025

LETTER OF INTENT:

THE FORWARD PHYSICS FACILITY

Luis A. Anchordoqui,[1] John Kenneth Anders,[2] Akitaka Ariga,[3,4] Tomoko Ariga,[5] David Asner,[6] Jeremy Atkinson,[3] Alan J. Barr,[7] Larry Bartoszek,[8] Brian Batell,[9] Hans Peter Beck,[3,10] Florian U. Bernlochner,[11] Bipul Bhuyan,[12] Jianming Bian,[13] Aleksey Bolotnikov,[14] Silas Bosco,[3] Jamie Boyd,[15,*] Nick Callaghan,[7] Gabriella Carini,[14] Michael Carrigan,[16] Kohei Chinone,[4] Matthew Citron,[17] Isabella Coronado,[18] Peter Denton,[14] Albert De Roeck,[15] Milind V. Diwan,[14] Sergey Dmitrievsky,[19] Radu Dobre,[20] Monica D'Onofrio,[2] Jonathan L. Feng,[13] Max Fieg,[13,21] Elena Firu,[20] Reinaldo Francener,[22,23,24] Haruhi Fujimori,[4] Frank Golf,[25] Yury Gornushkin,[19] Kranti Gunthoti,[26] Claire Gwenlan,[7] Carl Gwilliam,[2] Andrew Haas,[27] Elie Hammou,[28] Daiki Hayakawa,[4] Christopher S. Hill,[16] Dariush Imani,[29] Tomohiro Inada,[5] Sune Jakobsen,[15] Yu Seon Jeong,[30] Kevin J. Kelly,[31] Samantha Kelly,[17] Luke Kennedy,[7] Felix Kling,[13,32,†] Umut Kose,[33] Peter Krack,[23,24] Jinmian Li,[34] Yichen Li,[14] Steven Linden,[14] Ming Liu,[26] Kristin Lohwasser,[35] Adam Lowe,[7] Steven Lowette,[36] Toni Mäkelä,[13] Roshan Mammen Abraham,[13] Christopher Mauger,[37] Konstantinos Mavrokoridis,[38] Josh McFayden,[39] Hiroaki Menjo,[40] Connor Miraval,[14] Keiko Moriyama,[5] Toshiyuki Nakano,[40] Ken Ohashi,[3] Toranosuke Okumura,[4] Hidetoshi Otono,[5] Vittorio Paolone,[41] Saba Parsa,[3] Junle Pei,[42] Michaela Queitsch-Maitland,[43] Mary Hall Reno,[44] Sergio Rescia,[14] Filippo Resnati,[15] Adam Roberts,[38] Juan Rojo,[23,24] Hiroki Rokujo,[5] Olivier Salin,[45] Jack Sander,[7] Sai Neha Santpur,[29] Osamu Sato,[40] Paola Scampoli,[3,46] Ryan Schmitz,[29] Matthias Schott,[11] Anna Sfyrla,[47] Dennis Soldin,[18] Albert Sotnikov,[19] Anna Stasto,[48] George Stavrakis,[38] Jacob Steenis,[17] David Stuart,[29] Juan Salvador Tafoya Vargas,[17] Yosuke Takubo,[49] Simon Thor,[50] Sebastian Trojanowski,[51] Yu Dai Tsai,[26] Serhan Tufanli,[3] Svetlana Vasina,[19] Matteo Vicenzi,[14] Iacopo Vivarelli,[52] Nenad Vranjes,[53] Marija Vranjes Milosavljevic,[53] Kazuhiro Watanabe,[54] Michele Weber,[3] Benjamin Wilson,[43] Wenjie Wu,[55] Tiepolo Wybouw,[36] Kin Yip,[14] Jaehyeok Yoo,[56] and Jonghee Yoo[57]

People sometimes wonder what the role of a theorist can be in a high energy physics experiment?

As Paul Dirac said: "Theory names the vasiables"

So allow me to recount my personal experience of such interactions over the past ~42 years

I WAS LUCKY ENOUGH TO BE AT CERN DURING 1983-85 – WHEN THE W AND Z WERE FOUND ... ALONG WITH MUCH `NEW PHYSICS' (MONOJETS, ANOMALOUS Z → $\ell^+ \ell^-$ G , TOP QUARK @ 43 GeV, ETC)

EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON(S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV

[PL, 139B, 115 (1984)]

UA1 Collaboration, CERN, Geneva, Switzerland

Abstract

We report the observation of five events in which a missing transverse energy larger than 40 GeV is associated with a narrow hadronic jet and of two similar events with a neutral electromagnetic cluster (either one or more closely spaced photons). We cannot find an explanation for such events in terms of backgrounds or within the expectations of the Standard Model.

HOW TO LOOK FOR SQUARKS WITH THE $\bar{p}p$ COLLIDER ☆

M.J. HERRERO, L.E. IBÁÑEZ, C. LÓPEZ and F.J. YNDURÁIN
Departamento de Física Teórica, Universidad Autónoma de Madrid, Canto Blanco, Madrid-34, Spain

Received 9 July 1983
Volume 132B, number 1, 2, 3
PHYSICS LETTERS
24 November 1983

We consider Drell–Yan-like production of squarks $\tilde{q}$ from $\bar{p}p$, starting with a valence quark and a gluino from the sea. The signal would be a highly energetic jet, $E_{jet} \sim \frac{1}{2} m_{\tilde{q}}$, and the same amount of missing energy back to back with it. If $m(\text{gluino}) \lesssim 16$ GeV, $m_{\tilde{q}} \sim 60$–160 GeV. The amount of such signals would be some 14 to 1 times that of the signal for $\bar{p}p \to (W \to e\nu) +$ all.

IS SUPERSYMMETRY FOUND? ☆

John ELLIS
CERN, Geneva, Switzerland
Marc SHER [1]
University of California, Irvine, CA, USA

Monojet events seen recently by the UA1 collaboration at the CERN $p\bar{p}$ collider may be due to squarks or gluinos with masses O(40) GeV. The thinness of the observed jets favours the squark interpretation. In this case, we predict that sleptons should have masses between 20 and 30 GeV and that the photino should have a mass between 5 and 10 GeV. Such masses are close to the experimental lower limits and sparticles could soon be detectable in $e^+e^- \to (\tilde{\gamma}\tilde{\gamma})\gamma$ experiments and $W^\pm$ and Z^0 decay. We demonstrate that such light sparticle masses are consistent with models whose weak gauge symmetry breaking is driven by a t quark weighing O(40) GeV as recently reported, and even with no-scale models in which the supersymmetry breaking scale is also determined dynamically.

Volume 148B, number 4,5
PHYSICS LETTERS
29 November 1984

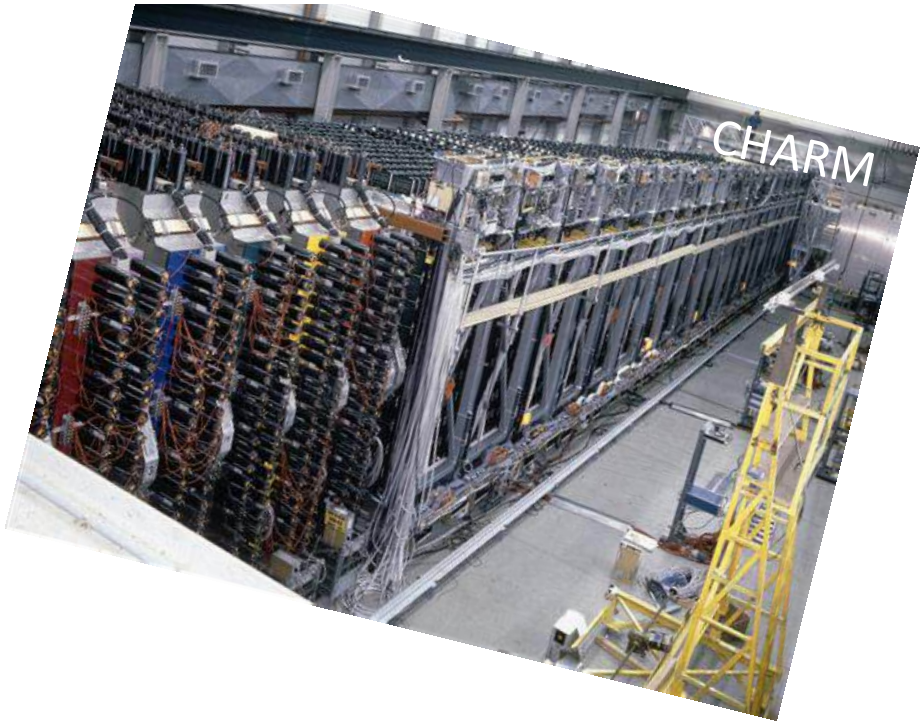
SCALAR QUARK SIGNATURES AT THE $\bar{p}p$ COLLIDER

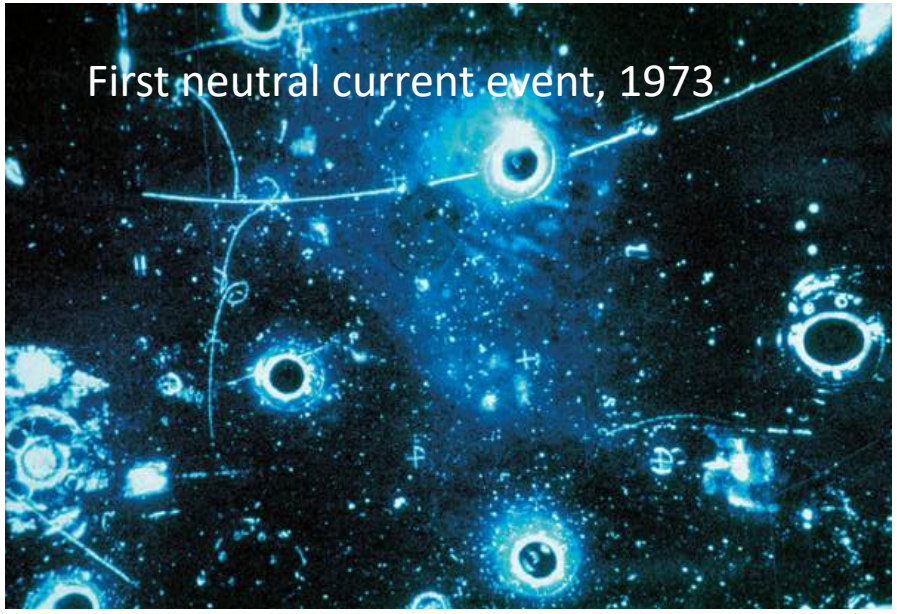
A.R. ALLAN, E.W.N. GLOVER and A.D. MARTIN
Department of Physics, University of Durham, England

Received 20 June 1984
Volume 146B, number 3, 4
PHYSICS LETTERS
11 October 1984

The recently observed $\bar{p}p$ collider events with large missing p_T are studied in terms of scalar quark–antiquark production and decay. This mechanism can account for the observed event rate and the relative number of visible one-jet to two-jet events if the mass of the scalar quark is in the range 20–35 GeV.

The 1970's-80's were a glorious era of pioneering neutrino experiments @ CERN





I had got to know the BEBC WA66 beam dump collaboration – an experiment my wife Amanda was involved with. It seemed to provide an excellent test bed for some explanations proposed for the anomalies e.g. a light gluino which everyone was talking about in TH as possibly responsible for the 'monojet' events seen by UA1 (… which turned out to be QCD background – as was shown by Stephen Ellis, Robert Kleiss & James Stirling)

Experiments at CERN

Further Study of Prompt Neutrino Production in Proton-Nucleus Collisions Using BEBC

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 ν_τ production, the ratio of prompt ν_e to ν_μ and the reported excess of low energy neutral current events.

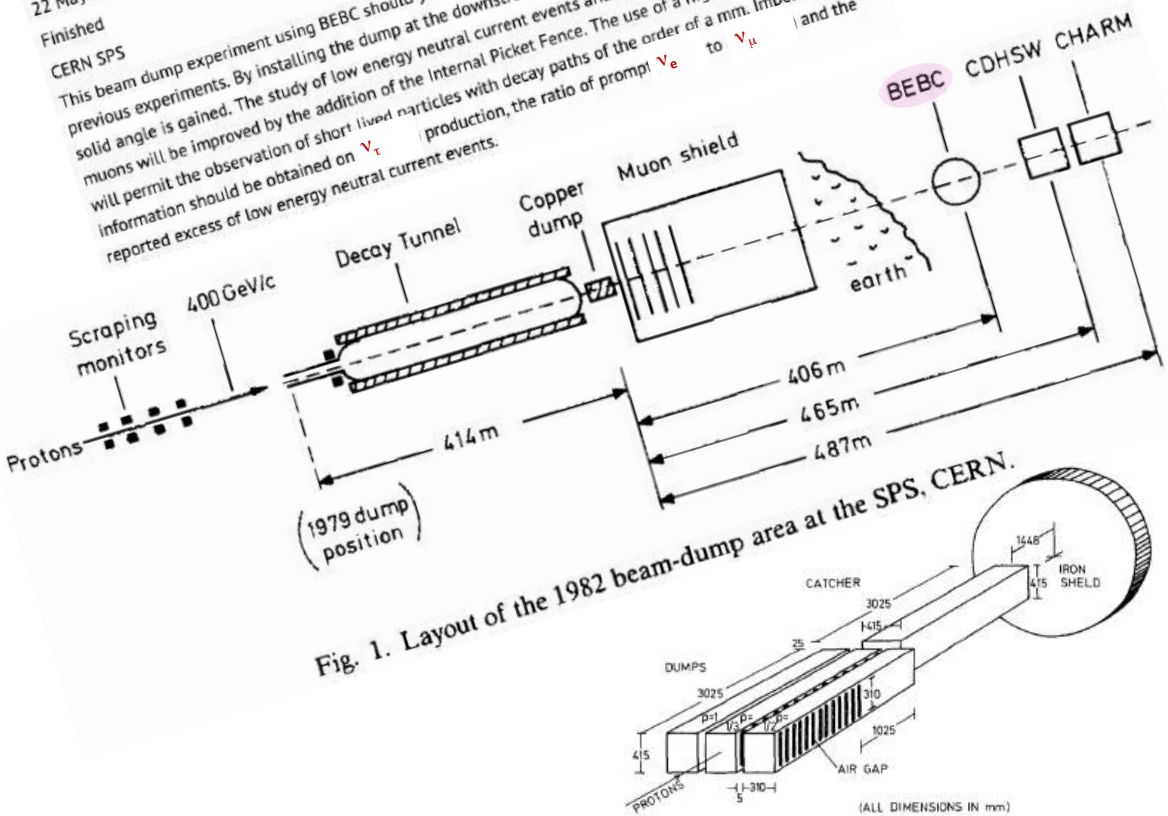
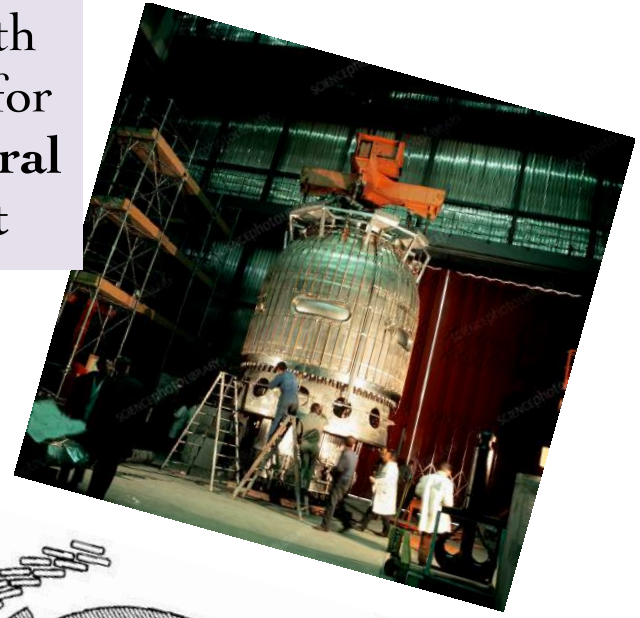
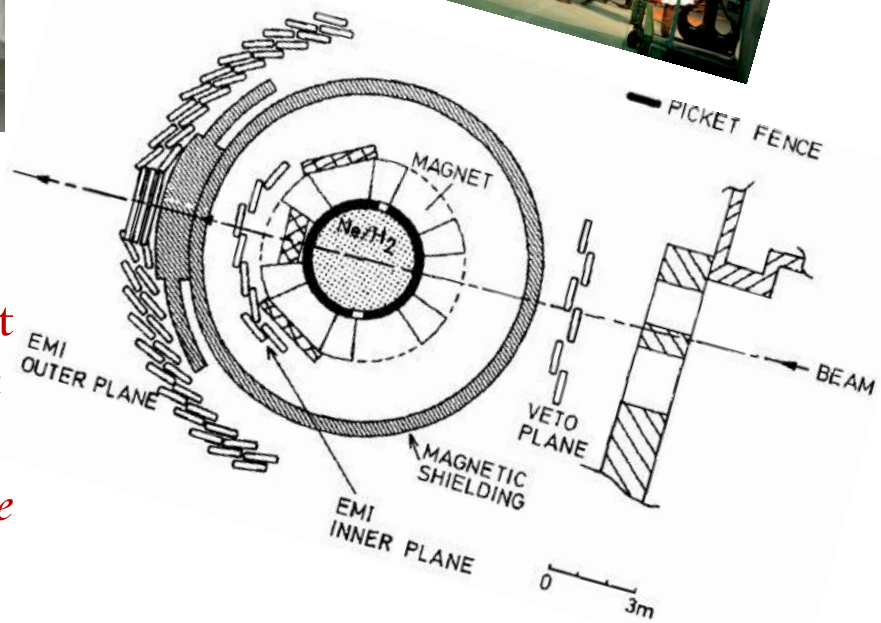


Fig. 1. Layout of the 1982 beam-dump area at the SPS, CERN.

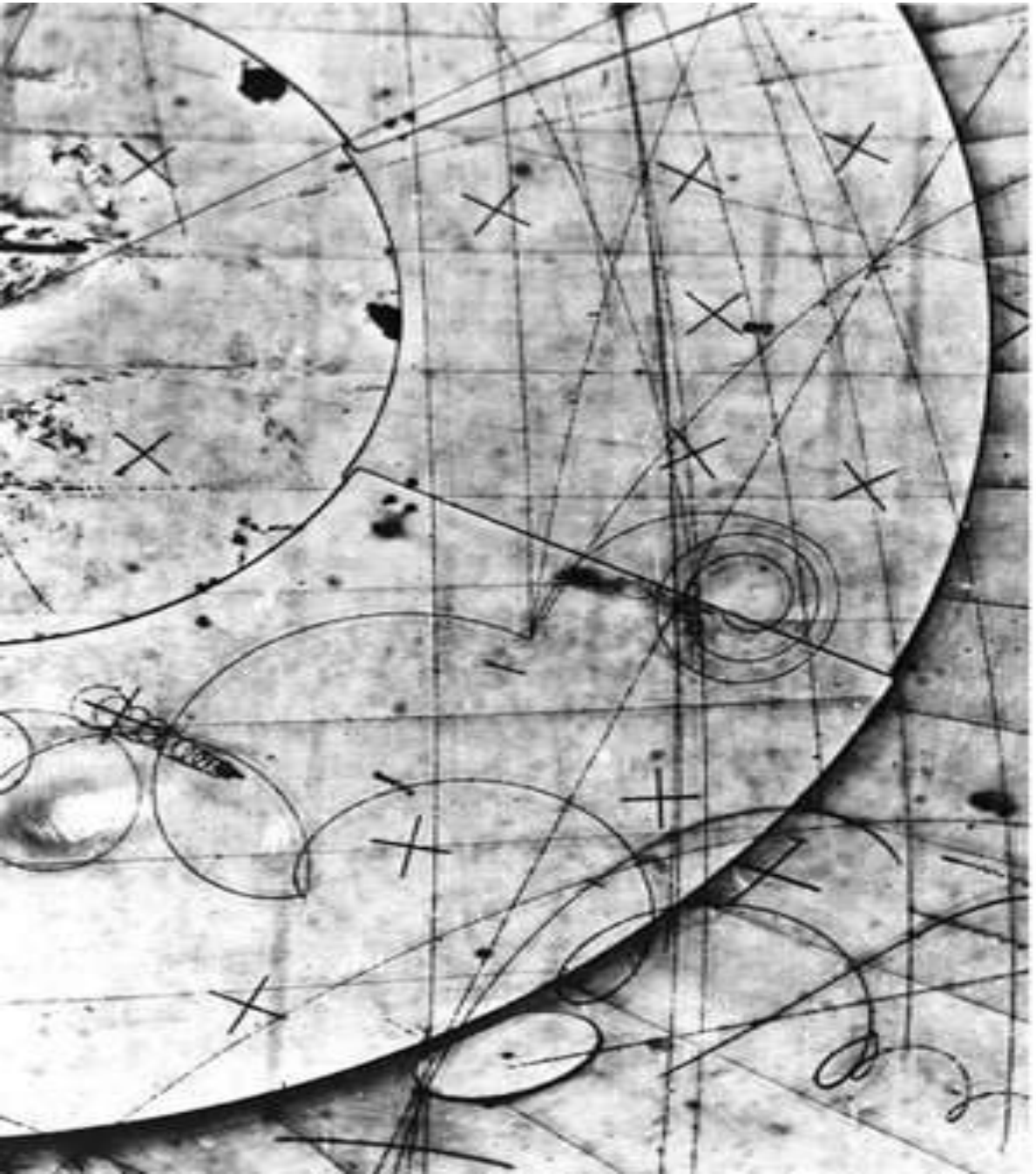
The WA66 Spokesperson Per-Olaf Hulth took a chance on my proposal to search for **supersymmetry** and for new **heavy neutral leptons** … and for a ν_τ **dipole moment**

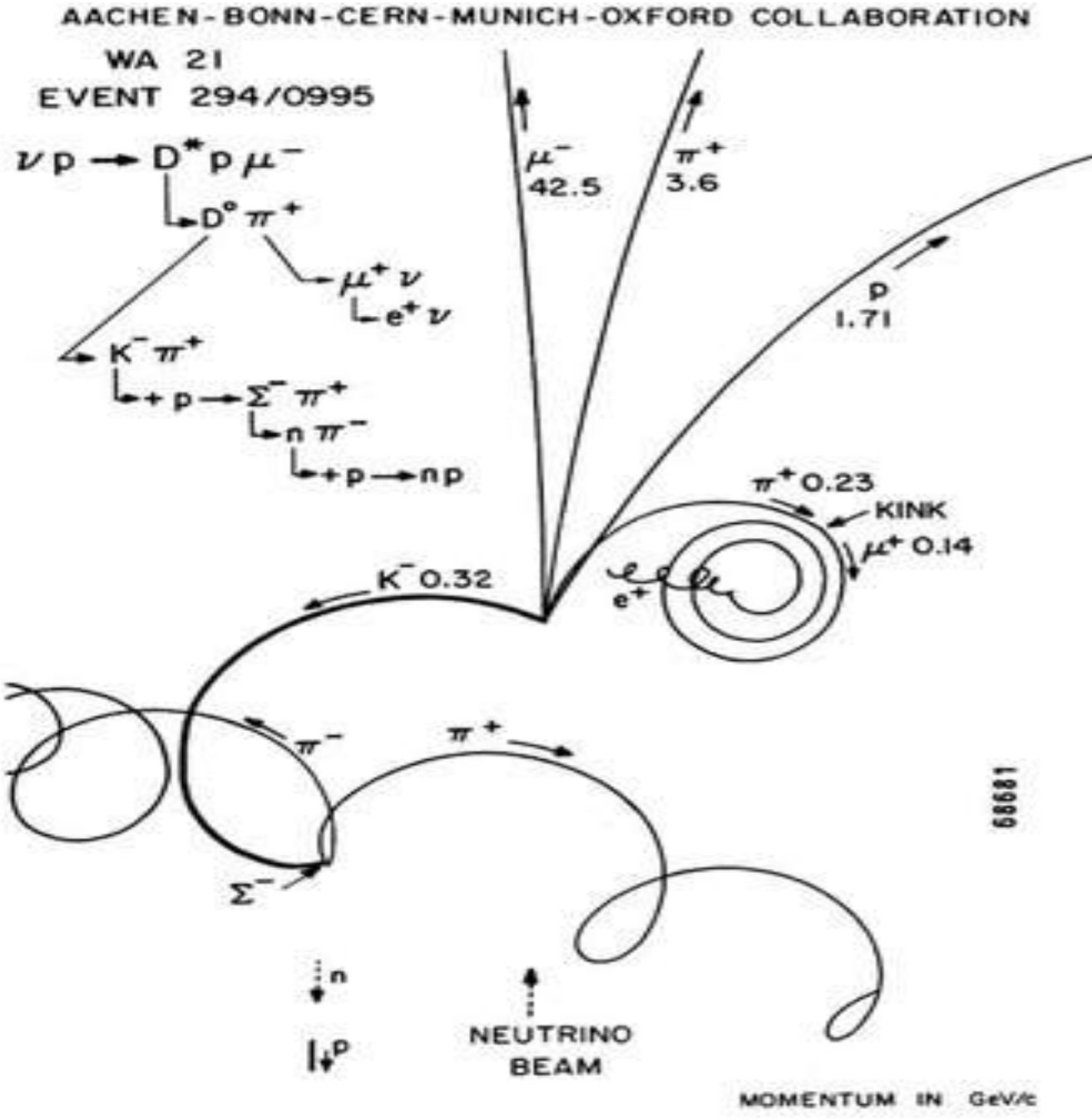


The WA66 experimentalists were sceptical but relished the hunt for new physics (they had only *one* ν_τ candidate)

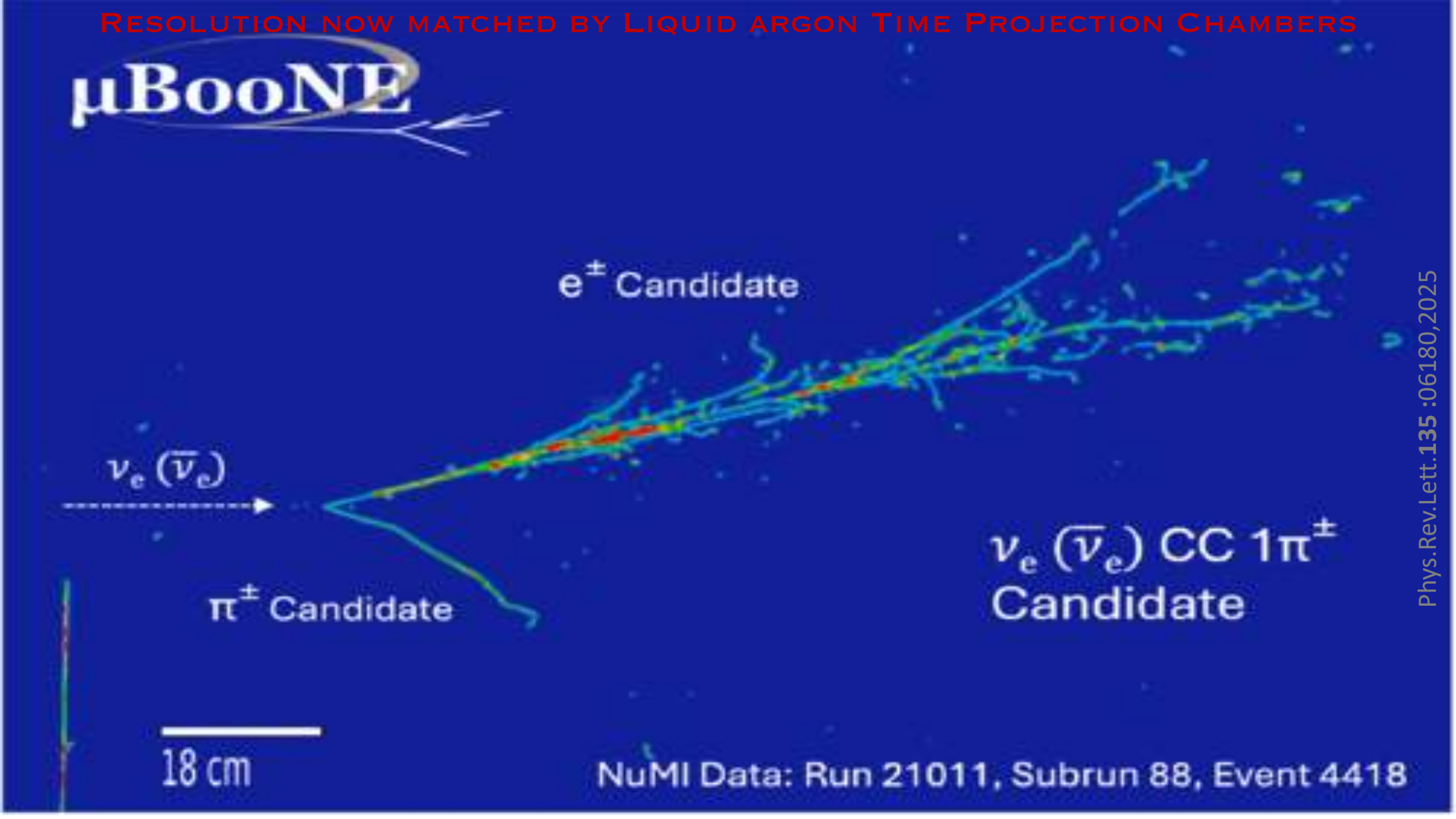


Fully reconstructed neutrino interaction event in BEBC



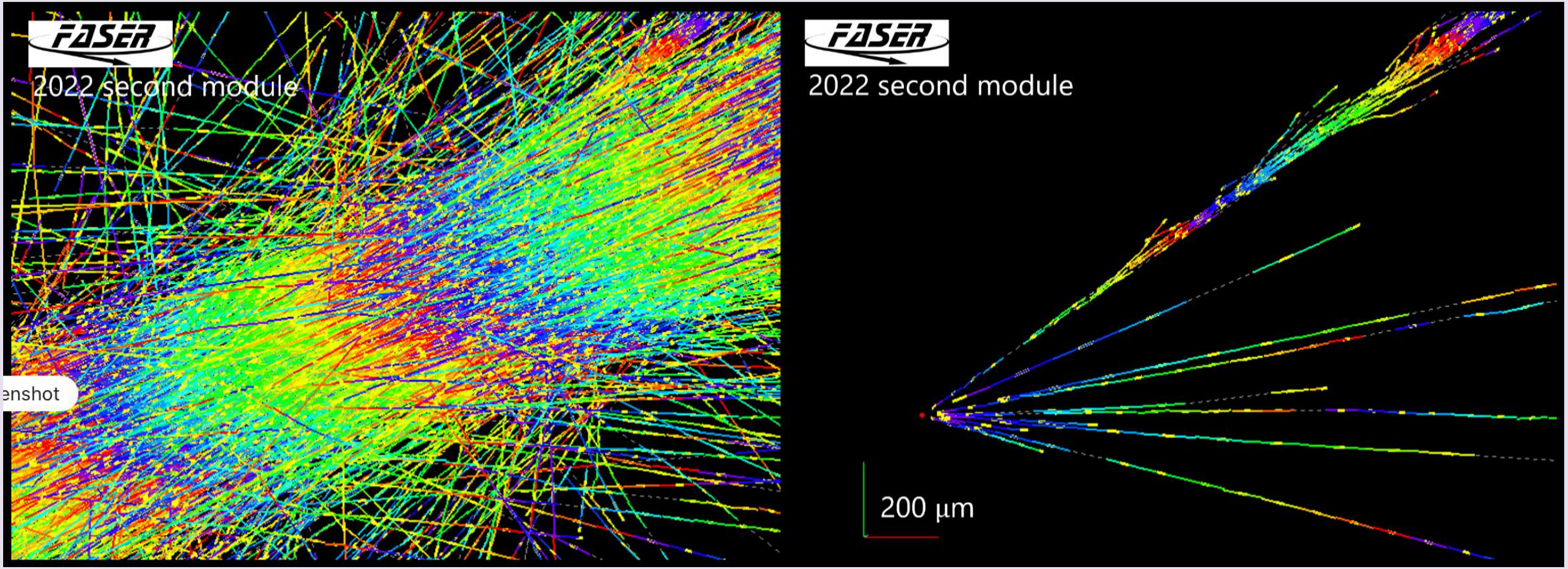


Resolution now matched by Liquid argon Time Projection Chambers



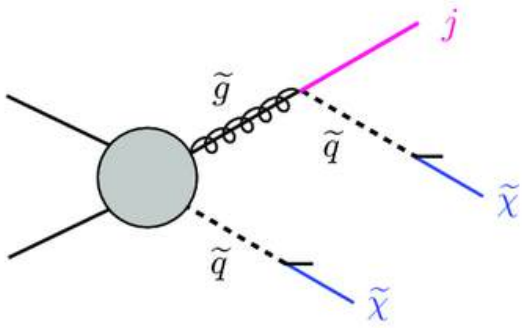
Phys.Rev.Lett.135 :06180,2025

Although still not as good as nuclear emulsions (which I had began my career with in cosmic rays)



FASER collab. *JINST* **20**:P12018(2025)

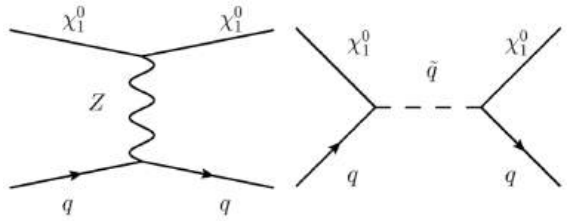
We considered production in the beam dump of light gluinos – which decay promptly to **neutralinos** ... whose interactions we searched for in the downstream **BEBC** detector as an **excess of neutral current-like events**



BOUNDS ON LIGHT GLUINOS FROM THE BEBC BEAM DUMP EXPERIMENT

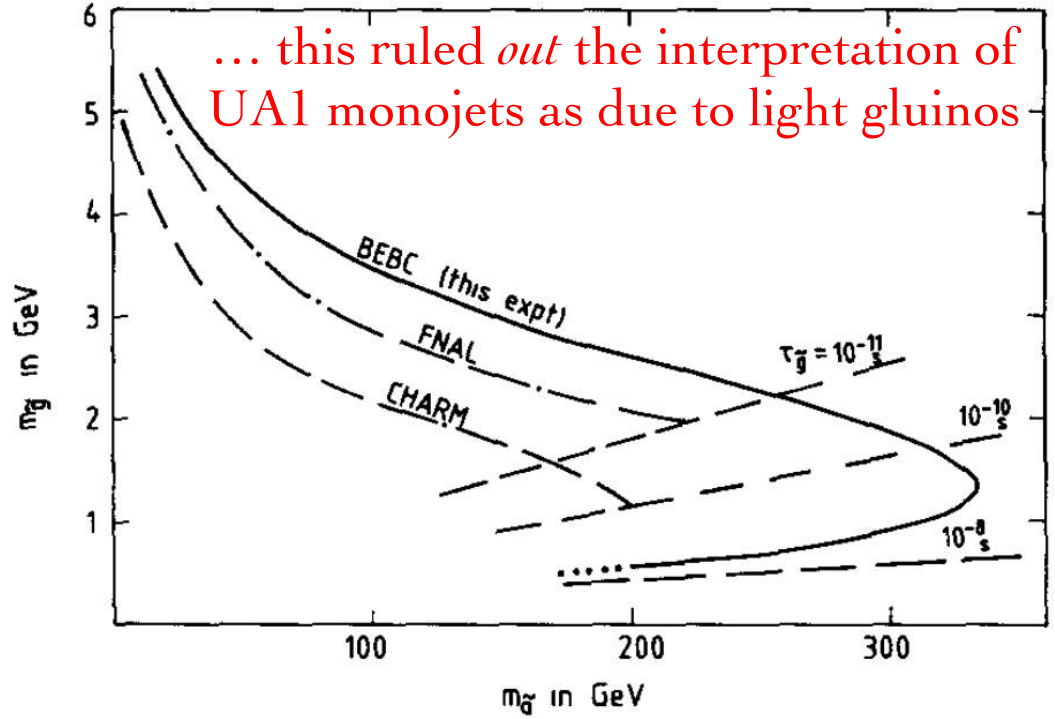
WA66 Collaboration Volume 160B, number 1, 2, 3 PHYSICS LETTERS 3 October 1985

A.M. COOPER-SARKAR [a,1], M.A. PARKER [a], S. SARKAR [a,2,3], M. ADERHOLZ [b], P. BOSTOCK [c], E.F. CLAYTON [d], M.L. FACCINI-TURLUER [e], H. GRÄSSLER [f], J. GUY [g], P.O. HULTH [h], K. HULTQVIST [h], U. IDSCHOK [i], H. KLEIN [a], H. KREUTZMANN [i], J. KRSTIC [c], M.M. MOBAYYEN [d], D.R.O. MORRISON [a], B. NELLEN [i], P. SCHMID [a], N. SCHMITZ [b], M. TALEBZADEH [d,1], W. VENUS [g], D. VIGNAUD [e], Ch. WALCK [h], H. WACHSMUTH [a] and B. WÜNSCH [i]



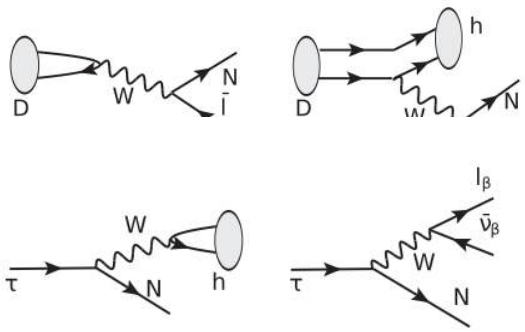
Observational upper limits on anomalous neutral-current events in a proton beam dump experiment are used to constrain the possible hadroproduction and decay of light gluinos. These results require $m_{\tilde{g}} \gtrsim 4$ GeV for $m_{\tilde{q}} \simeq m_W$

We found 5 candidate events, *cf.* background of 10.1 ± 2.7 events ⇒ < 5.4 events @ 90% CL



Advised re. stats. by Fred James!

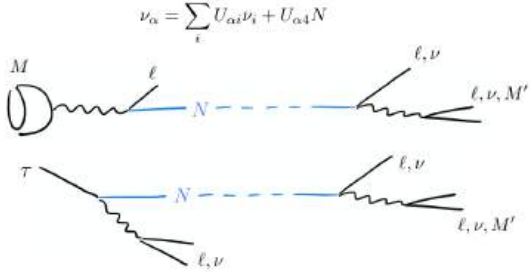
We considered production in the beam dump of charmed particles – decaying promptly to neutrinos ... whose mixings create a HNL beam that decay in the BEBC detector into opposite sign particles



SEARCH FOR HEAVY NEUTRINO DECAYS IN THE BEBC BEAM DUMP EXPERIMENT

WA66 Collaboration Volume 160B, number 1, 2, 3 PHYSICS LETTERS 3 October 1985

A.M. COOPER-SARKAR [a,1], S.J. HAYWOOD [a,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 [1] 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

The number of HNLs produced, $\mathcal{N}_N$ can be *directly* related to the total number of detected active neutrinos of a particular species $\mathcal{N}_{\nu_\ell}$ via:

$$\frac{\mathcal{N}_N}{\mathcal{N}_{\nu_\ell}} \simeq \frac{\sum_i \sigma(pN \to P_i + X)\mathrm{Br}(P_i \to N + Y)}{\sigma(pN \to D^+D^- + X)\mathrm{Br}(D^\pm \to \ell\,\nu_\ell + X) + \sigma(pN \to D^0\bar{D}^0 + X)\mathrm{Br}(D^0 \to \ell\,\nu_\ell + X)}$$

There were 0 candidates for the HNL decay channels $ee\nu$, $e\mu\nu$ or $\mu\mu\nu$, or for $e\pi$, and only 1 candidate for $\mu^+\pi^-$, *cf.* estimated background of 0.6 ± 0.2 ⇒ upper limit of 3.5 events @ 90% CL

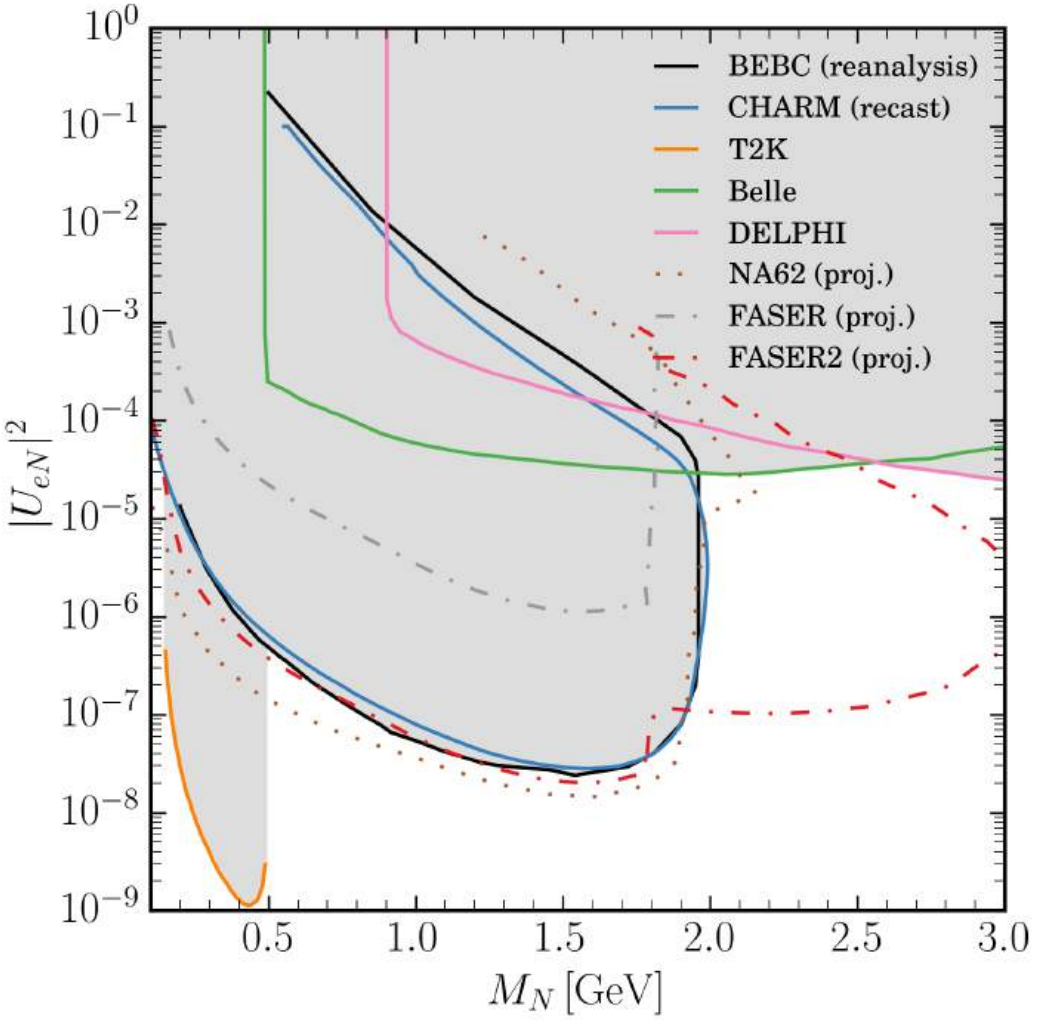
SciPost Phys. 13, 118 (2022)

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

Ryan Barouki, Giacomo Marocco* and Subir Sarkar

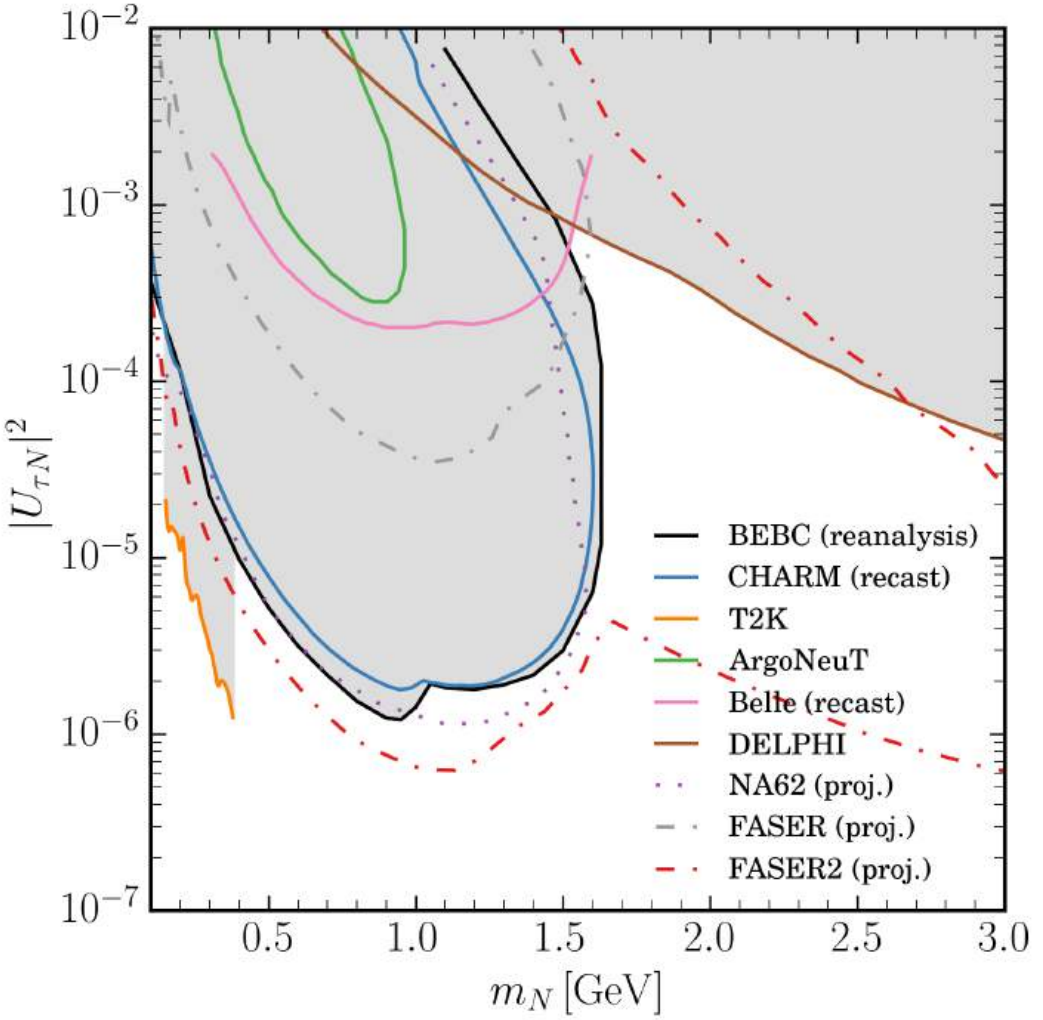
Rudolf Peierls Centre for Theoretical Physics, University of Oxford,
Parks Road, Oxford OX1 3PU, United Kingdom

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.



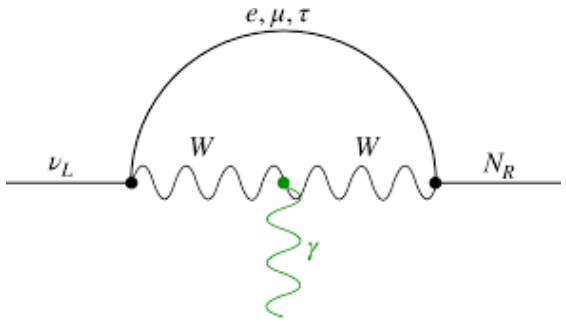
This turns out to still be the most sensitive bound on the mixings of HNLs with active neutrinos

FASER2 will do ⊗5 better upto m_c and ⊗100 better upto m_b … and SHiP will do even better (exploring parameter space of leptogenesis with HNLs)



We considered production of tau neutrinos … and looked for forward scattered electrons that are a signature of electromagnetic properties

The motivation was to test the proposal by Giudice (1990, 1991) that ~MeV mass tau neutrinos could have a magnetic moment of order $10^{-6}\, m_B$ … and thus annihilate sufficiently to become DM



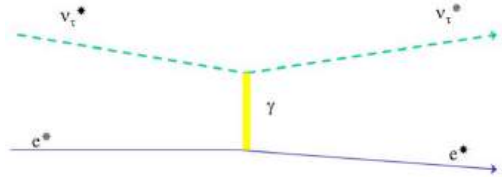
Bound on the tau neutrino magnetic moment from the BEBC beam dump experiment

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

Phys.Lett.B**280**:153,1992



Found 1 candidate event, *cf.* expected background of 0.5 ± 0.1 ⇒ < 3.5 events @ 90% CL

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 $5.4 \times 10^{-7}\ \mu_B$. This rules out the suggestion that tau neutrinos of mass O(MeV) constitute the dark matter in the universe.

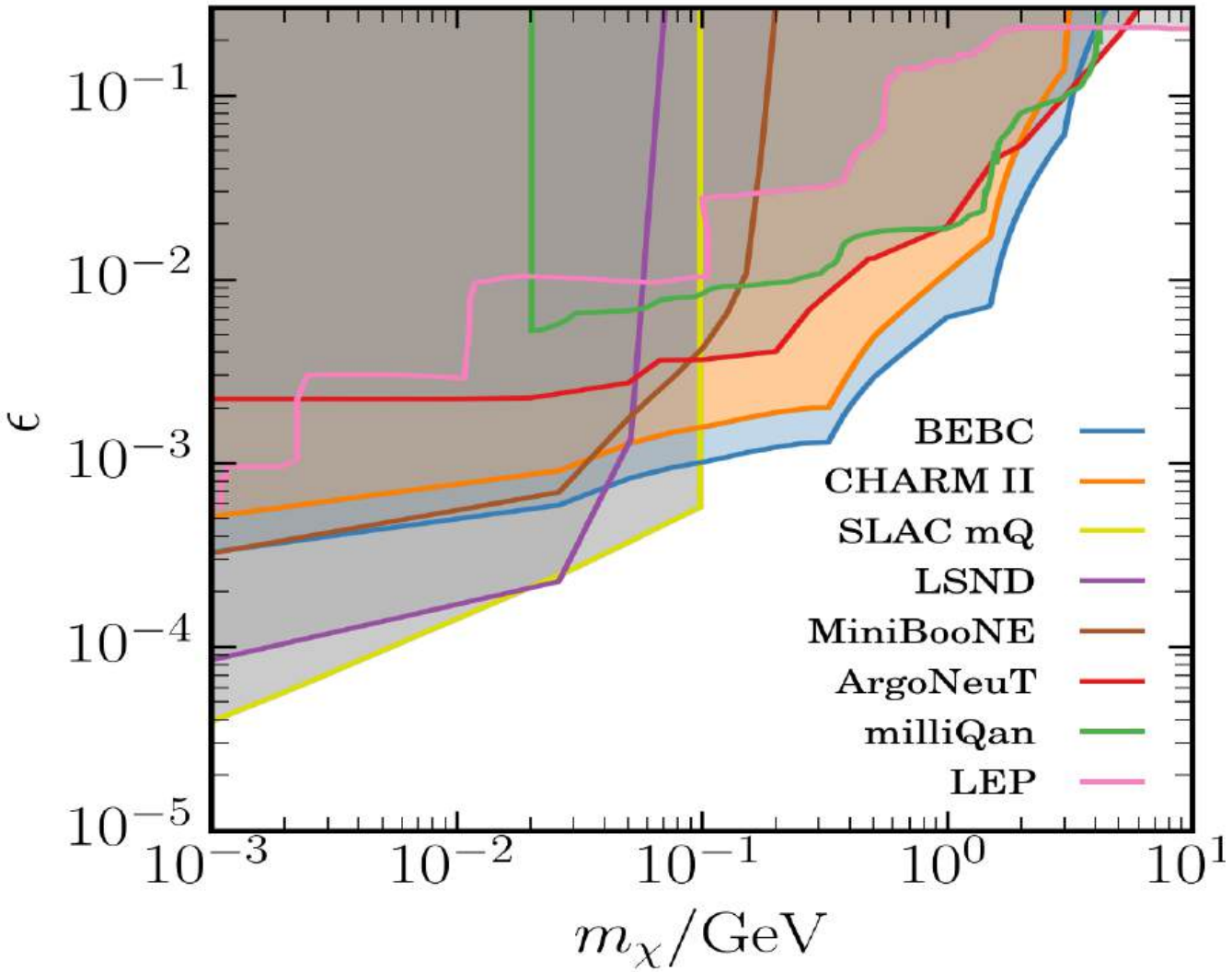
SciPost Phys. 10, 043 (2021)

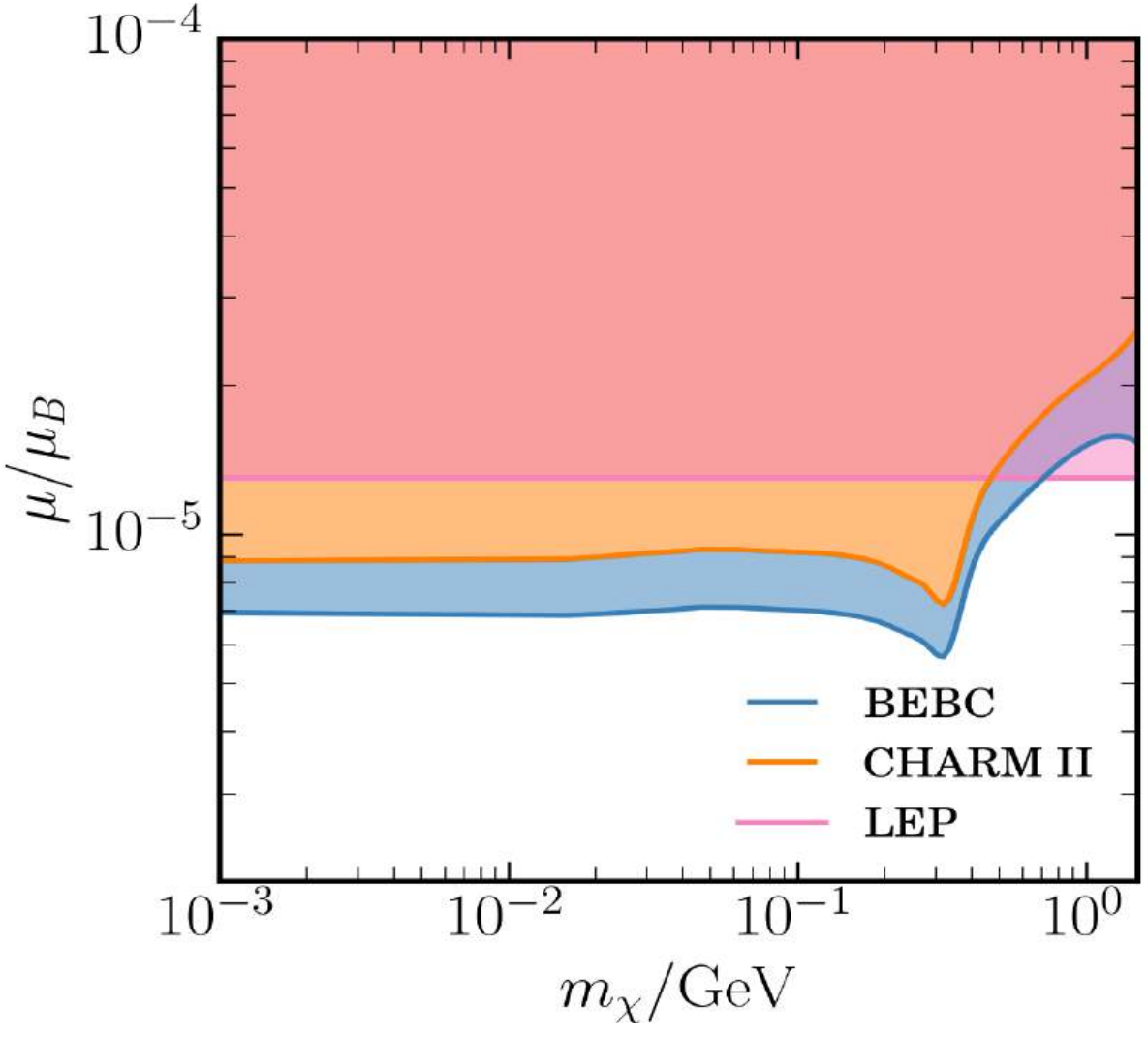
Blast from the past: Constraints on the dark sector from the BEBC WA66 beam dump experiment

Giacomo Marocco * **and Subir Sarkar**

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

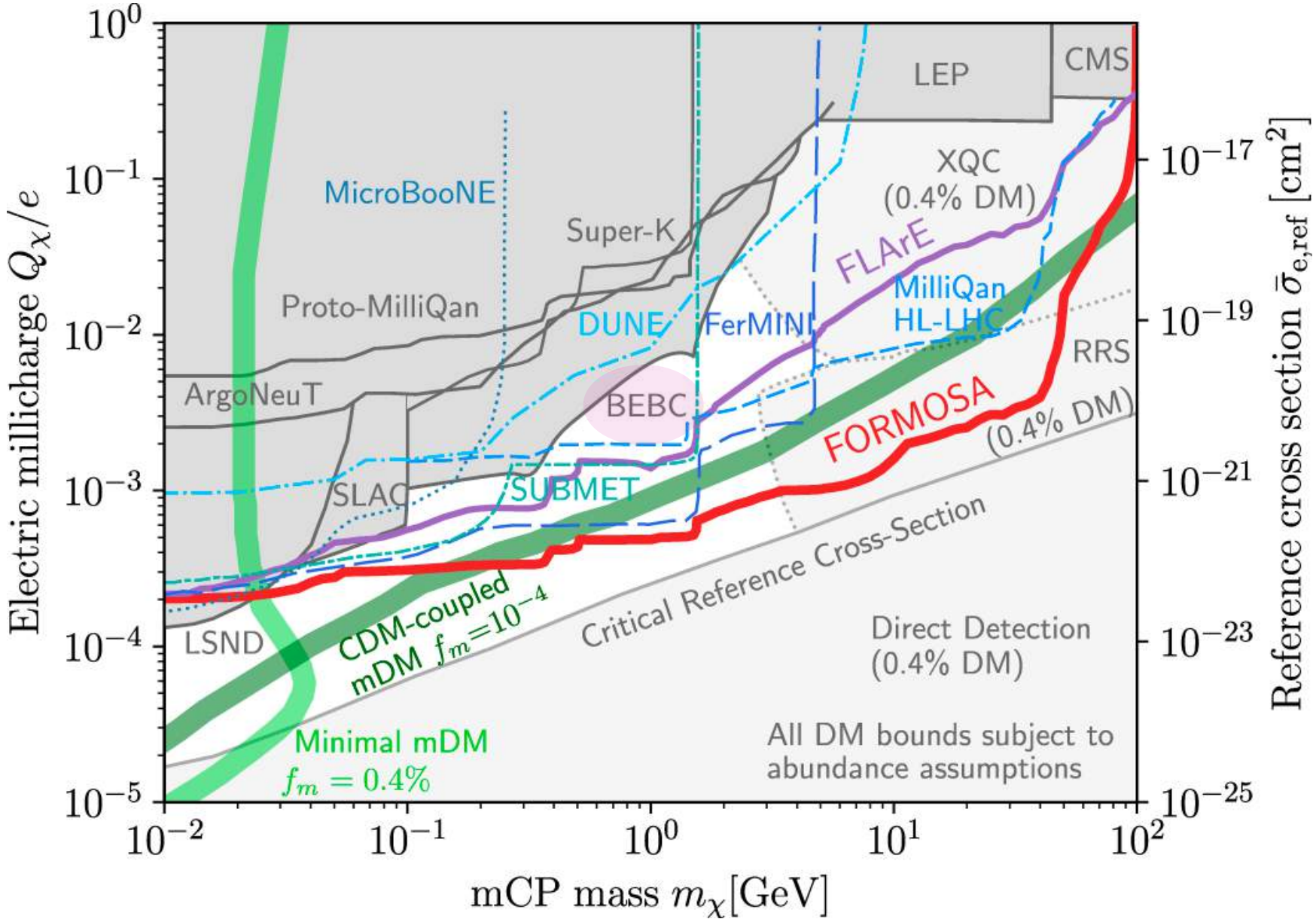
We derive limits on millicharged dark states, as well as particles with electric or magnetic dipole moments, from the number of observed forward electron scattering events at the Big European Bubble Chamber in the 1982 CERN-WA-066 beam dump experiment. The dark states are produced by the 400 GeV proton 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 is still the most sensitive bound on milli-charged particles

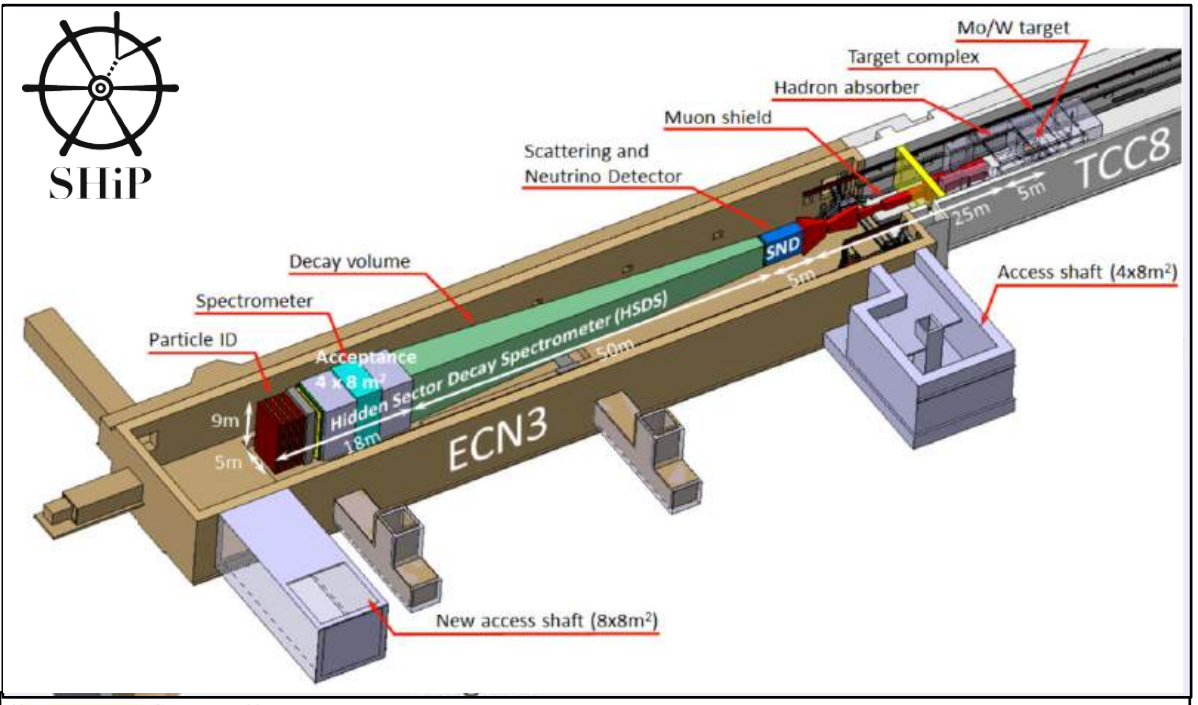
The reach will improve with MilliQan@HL-LHC and FLArE & FORMOSA at the FPF

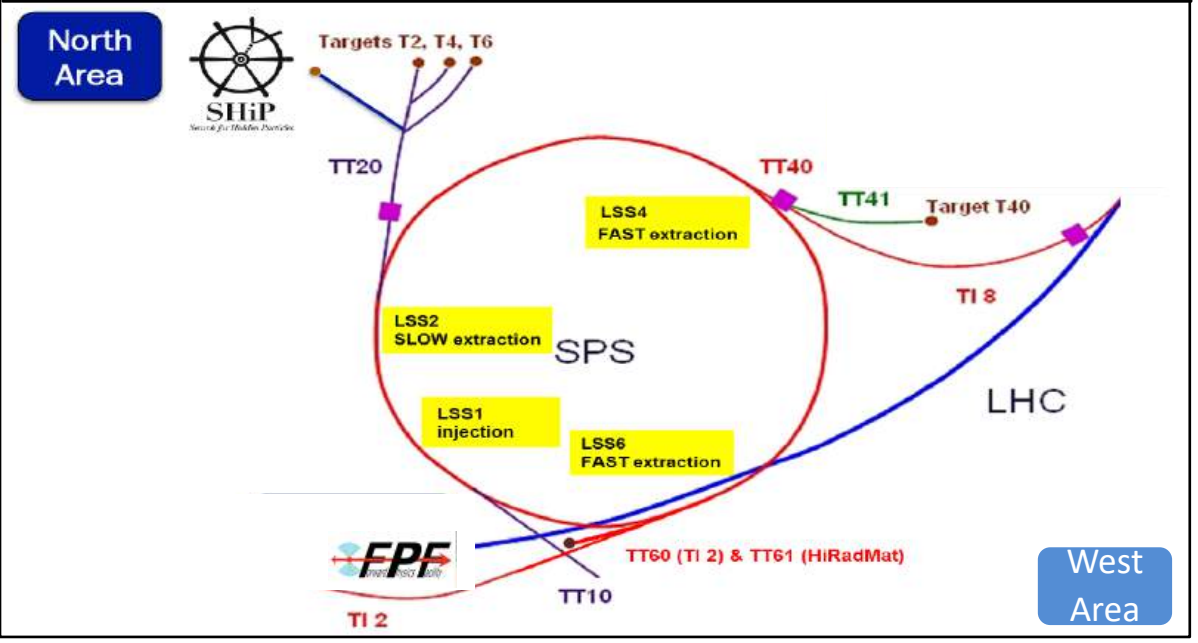


Phys.Rept.968:1(2022)

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

Expected sensitivities: FORMOSA, FLArE; **Projections:** SUBMET, FerMINI, MilliQan @ HL-LHC, DUNE





2016

- ➢ Proposal for 'Search for hidden particles' (SHiP) @SPS
- ➢ Physics Beyond Colliders (PBC) initiative launched

2018

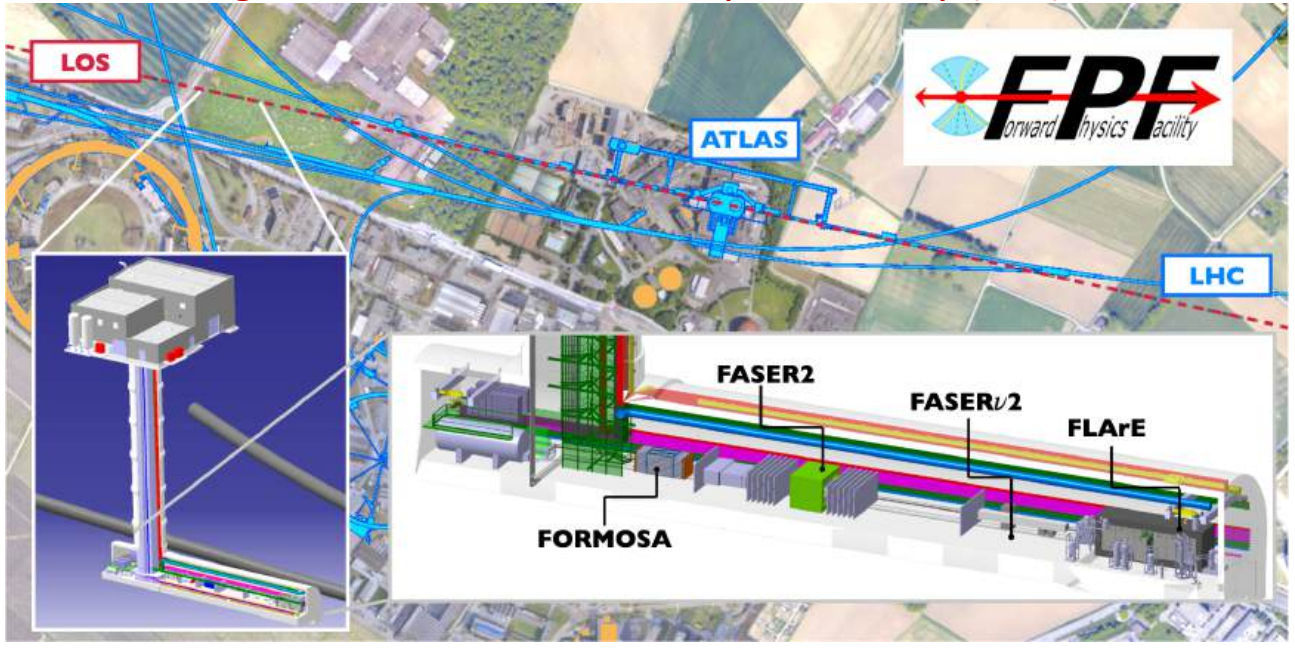
- ➢ FASER proposed to detect neutrinos from LHC P1

2023

- ➢ Detection of collider neutrinos by FASERν & SND@LHC

2024

- ➢ SHiP approved for construction
- ➢ Awaiting decision on Forward Physics Facility (FPF) @ LHC



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

A. De Rújula and R. Rückl

CERN, Geneva, Switzerland

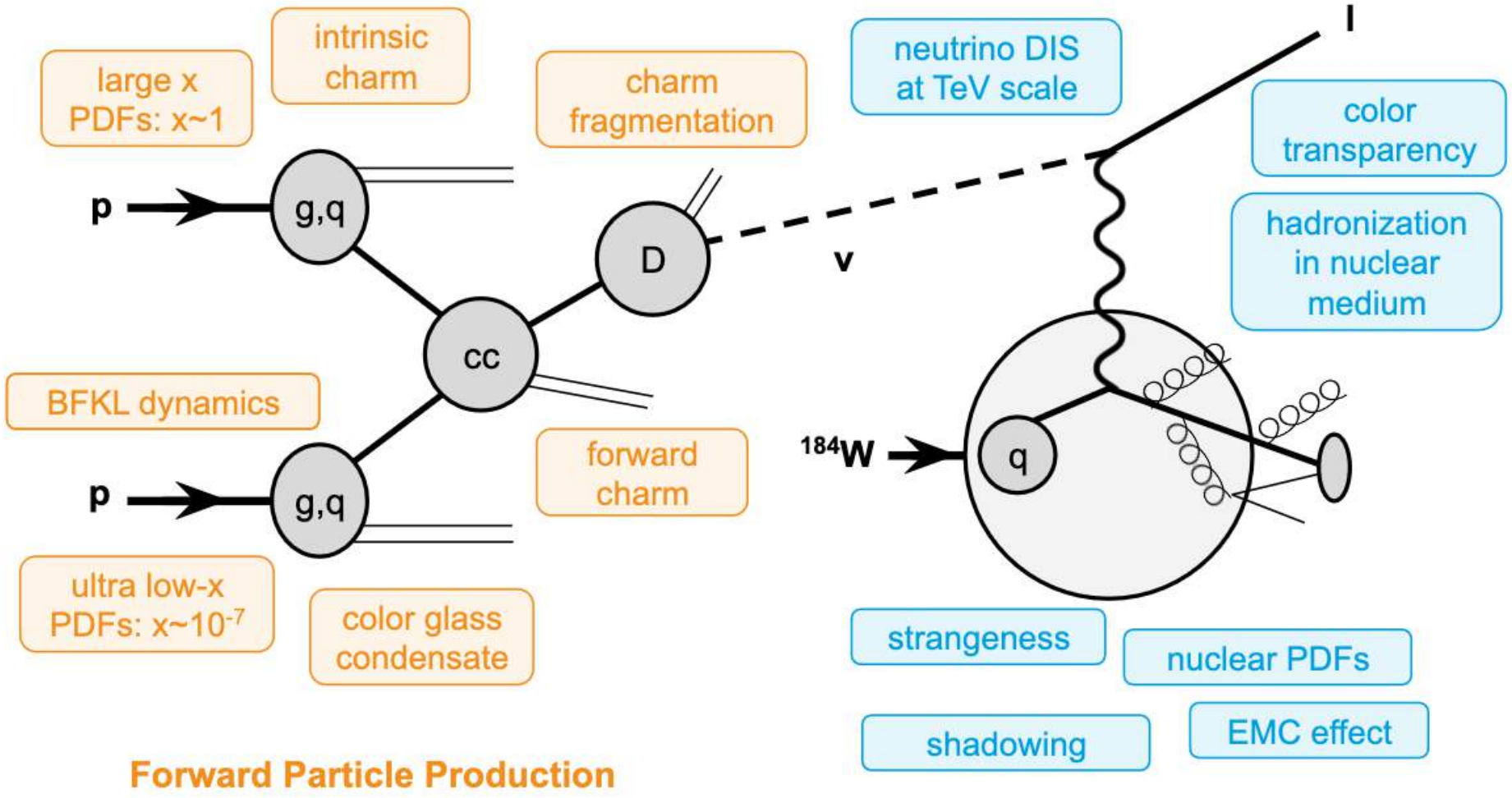
Proc. ECFA-CERN Workshop on large hadron collider in the LEP tunnel: 21-27 Mar 1984

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

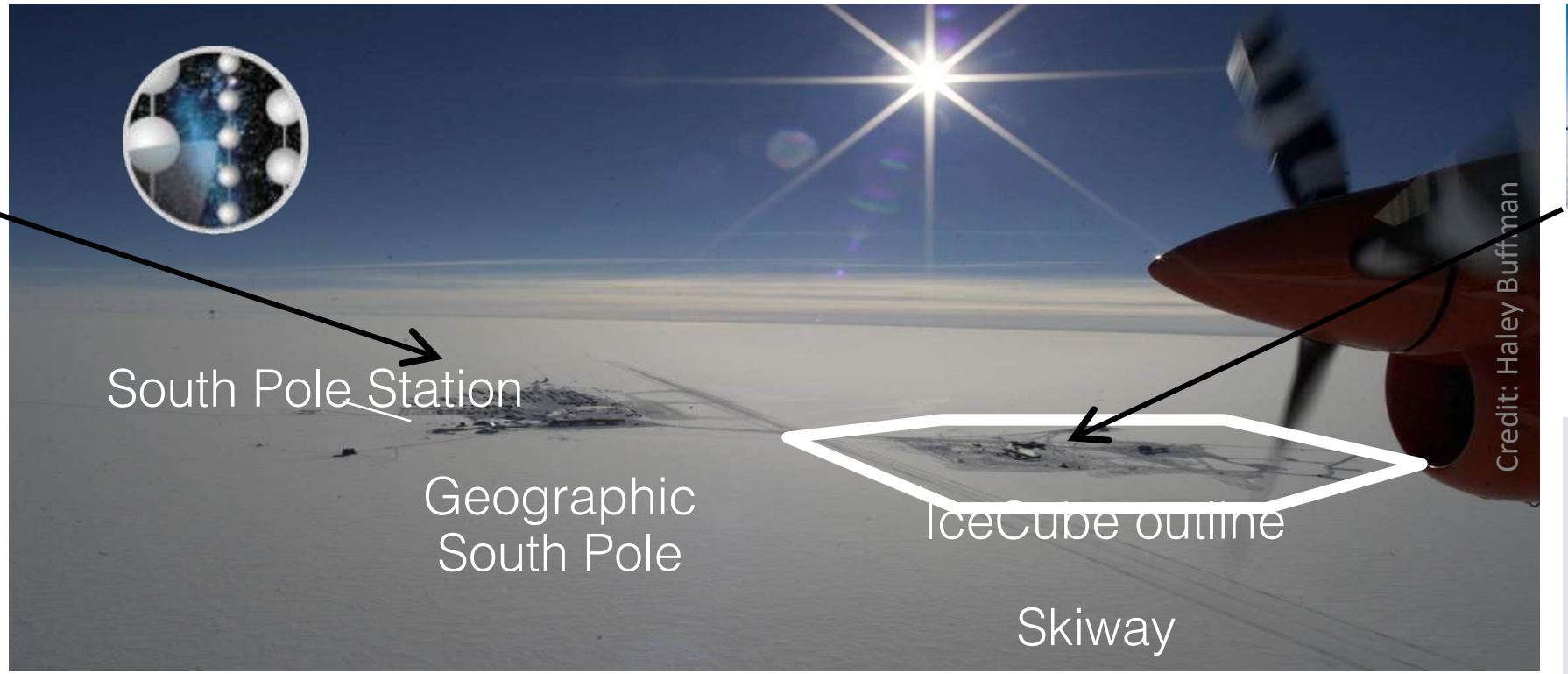
What can we do with an intense beam of TeV energy neutrinos?



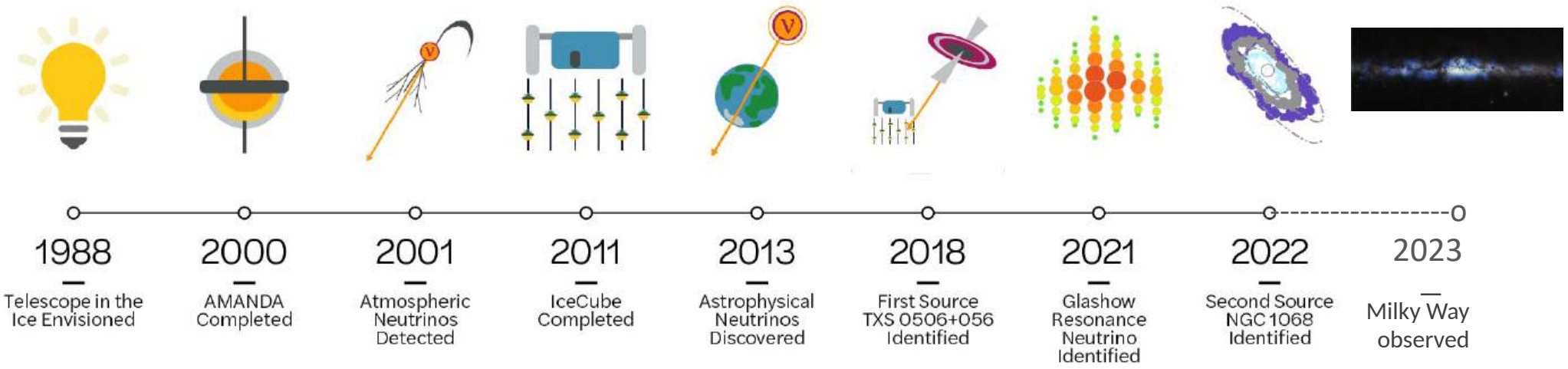
Study interesting open issues in **QCD** – of relevance to **neutrino telescopes**; Study forward production of light hadrons – of relevance to **cosmic ray air shower arrays;** Search for **Beyond-Standard-Model** long-lived particles (axions, dark photons, heavy neutral leptons, milli-charged particles,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

The IceCube Neutrino Observatory

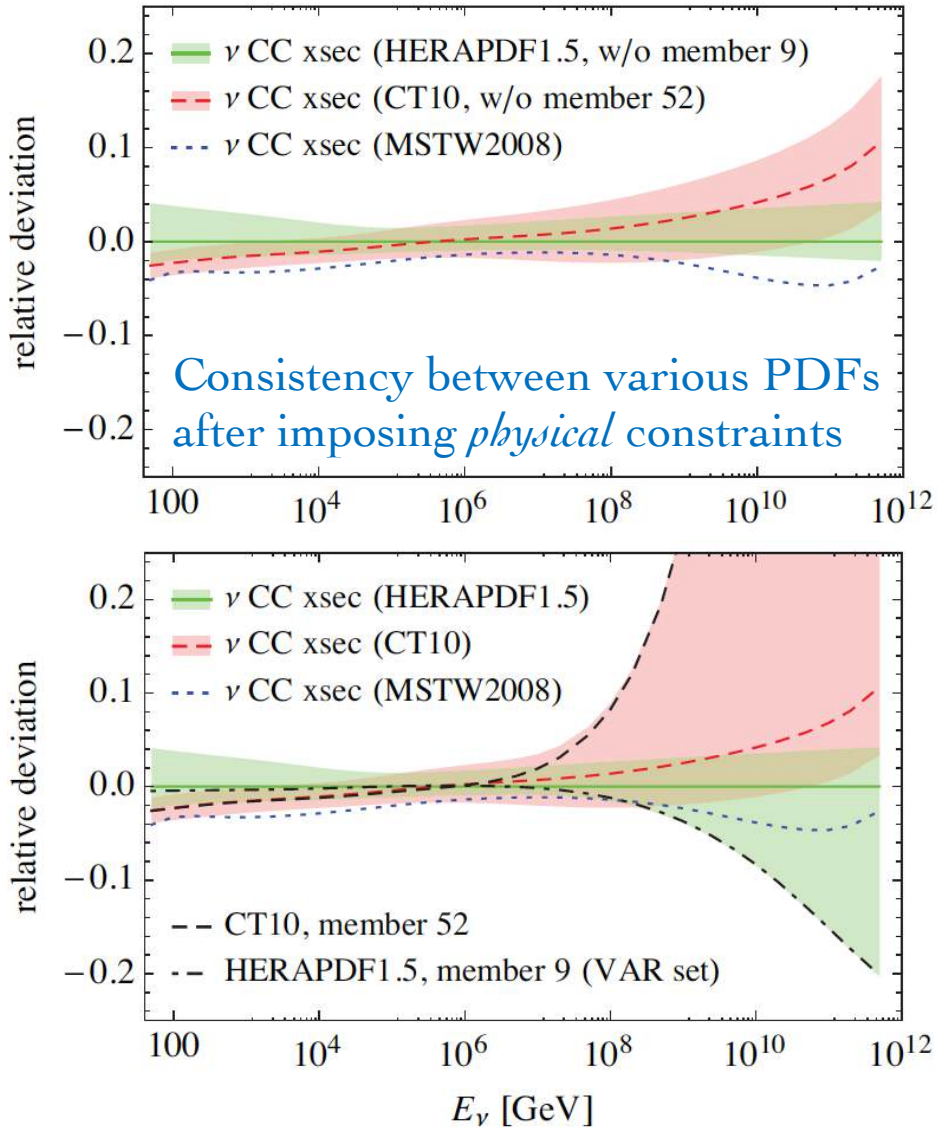
In 2004, Per-Olof Hulth, who was then Spokesperson of **IceCube Neutrino Observatory** invited me to join this expt.

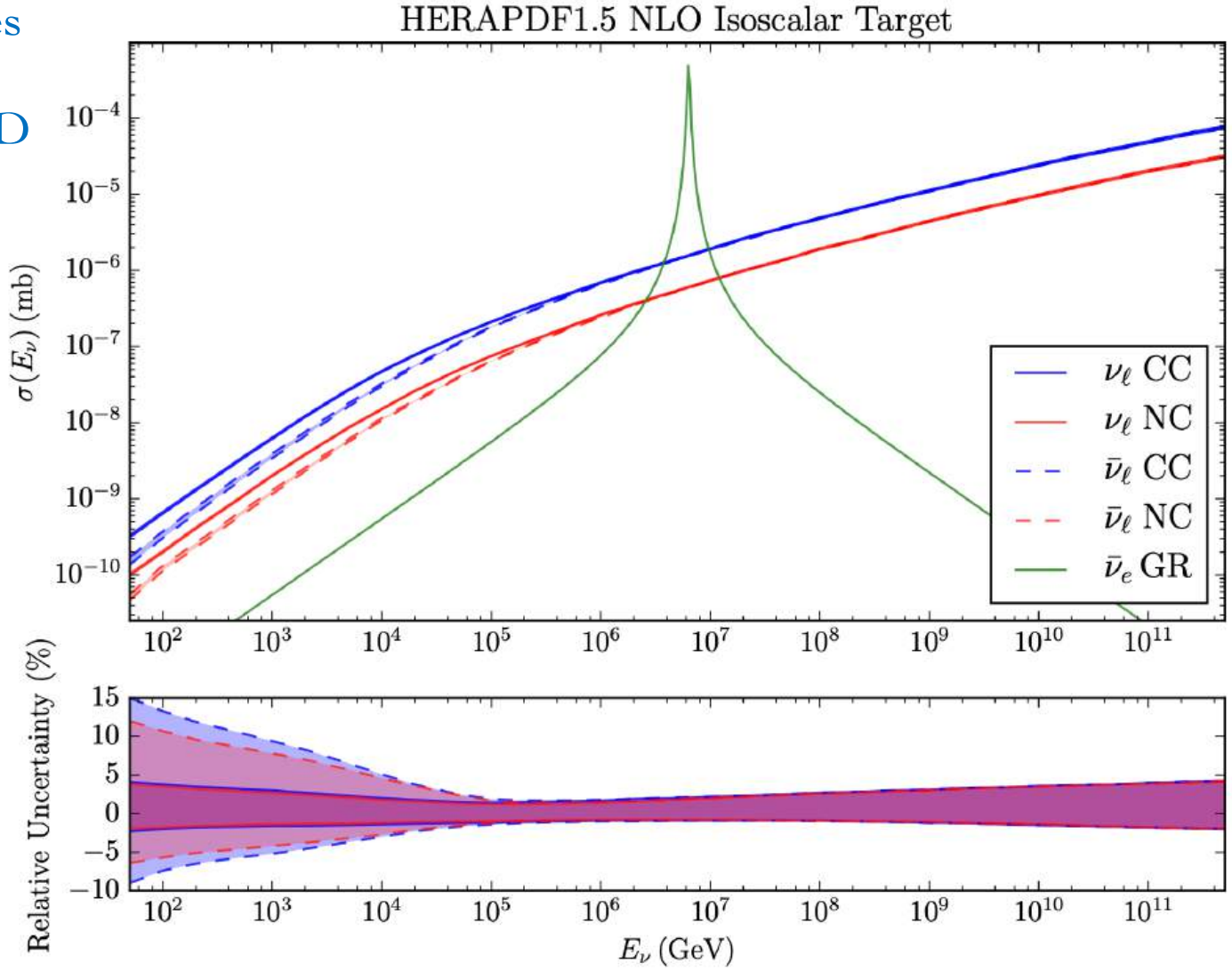


… it helped that IceCube PI (Francis Halzen) was also a theorist!



Neutrino telescopes like *IceCube* explore energies where there is no direct knowledge of the DIS cross section, so this must be estimated in pQCD from measured parton distribution functions

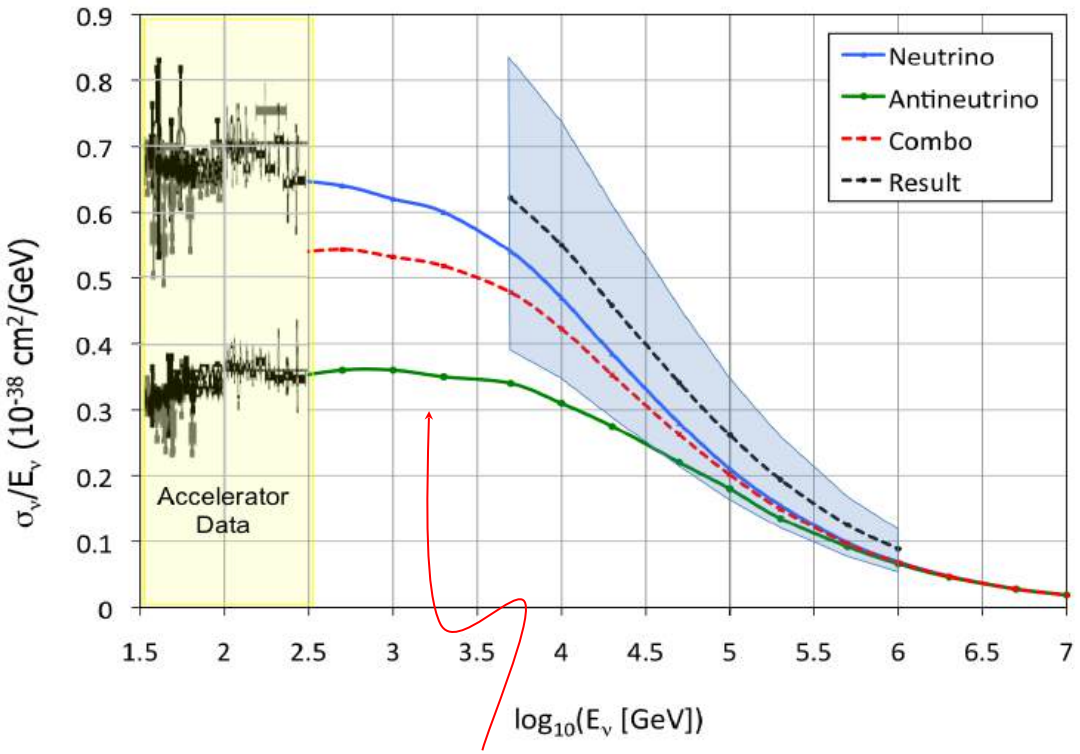


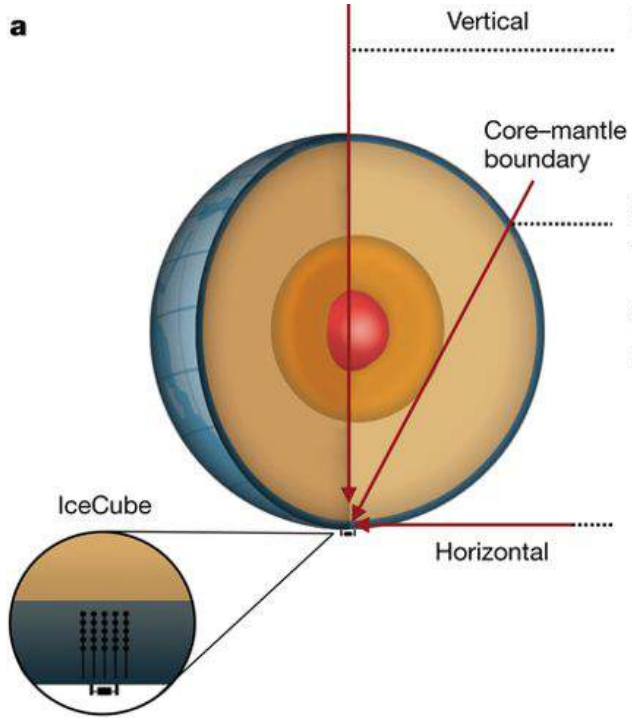


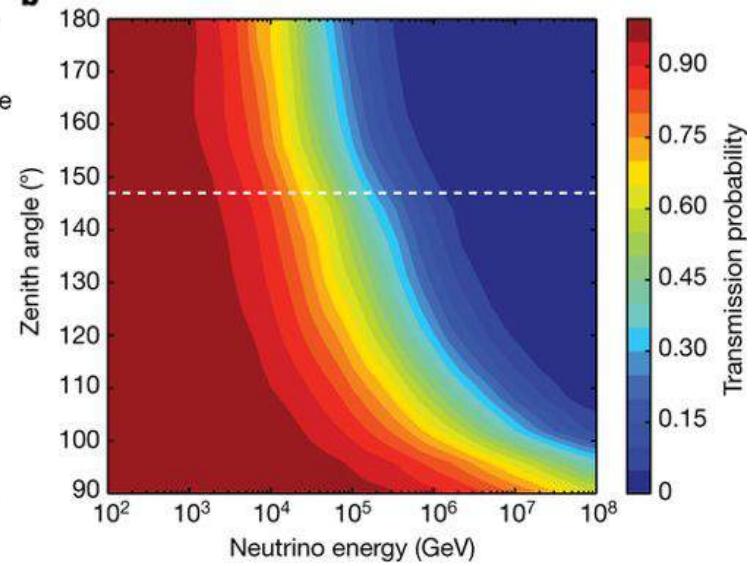
Our calculation @NLO using HERAPDF1.5 and incl.effect of heavy quarks on DGLAP evolution is incorporated in the neutrino event generator NuGeN (and in GENIEv3 via the HEDIS plugin module)

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

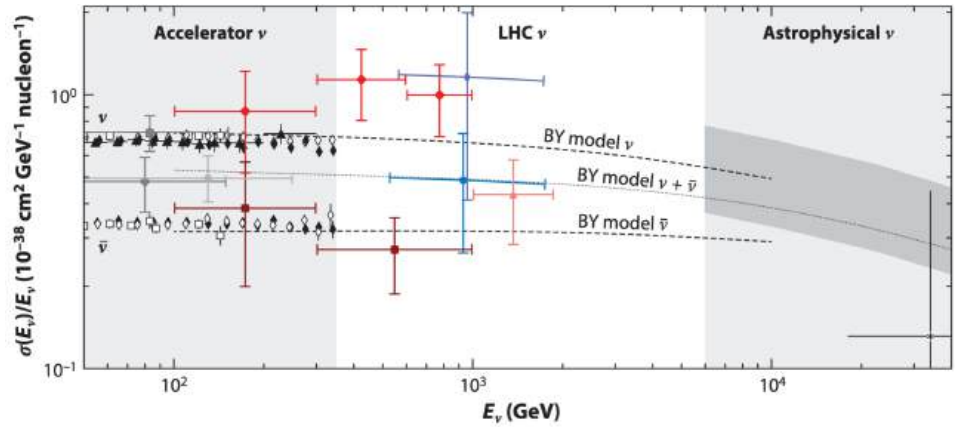
Our predicted UHE ν-N cross-section has been verified using ν absorption in the Earth

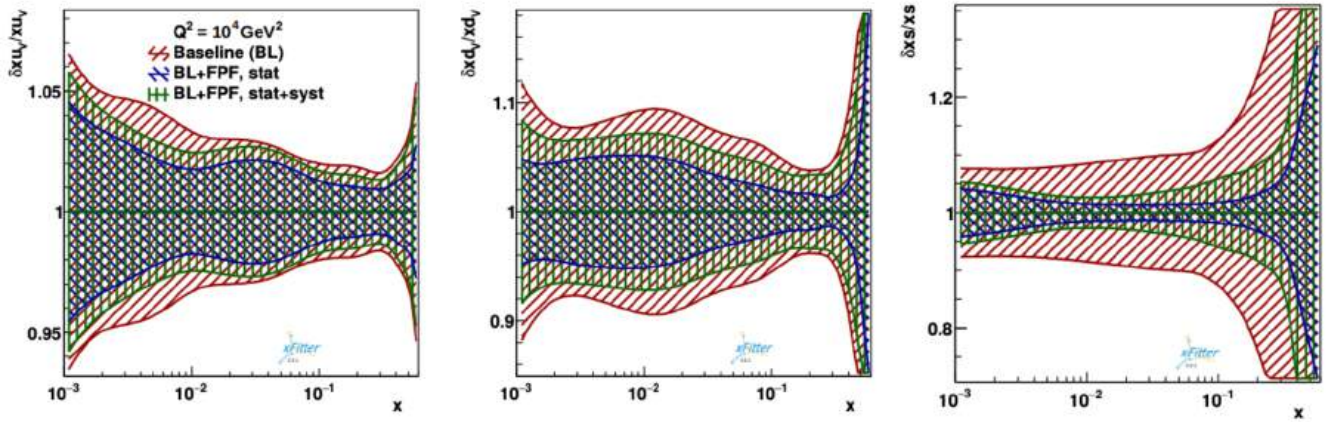






IceCube Collaboration, *Nature* **551**:596,2017





FASER is exploring the gap down to measurements at fixed-target experiments

The FPF will make *precision* measurements, thus lowering PDF uncertainties

Detection of a particle shower at the Glashow resonance with IceCube

Nature | Vol591 | 11March2021

Predicted in 1959
... observed 42 years later

PHYSICAL REVIEW VOLUME 118, NUMBER 1 APRIL 1960

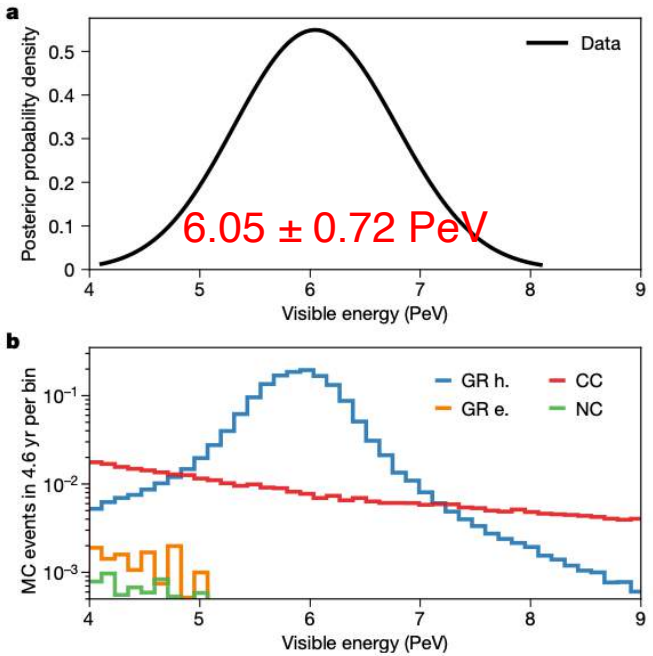
Resonant Scattering of Antineutrinos

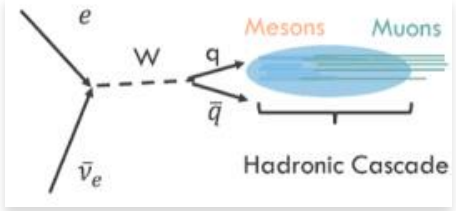
SHELDON L. GLASHOW*
Institute for Theoretical Physics, Copenhagen, Denmark
(Received October 26, 1959)

The hypothesis of an unstable charged boson to mediate muon decay radically affects the cross section for the process $\bar{\nu}+e \to \bar{\nu}+\mu^-$ near the energy at which the intermediary may be produced. If the boson is assumed to have K-meson mass, the resonance occurs at an incident antineutrino energy of $\sim 2\times 10^{23}$ ev. The flux of energetic antineutrinos produced in association with cosmic-ray muons will then produce two muon counts per day per square meter of detector, independently of the depth and the orientation at which the experiment is performed.

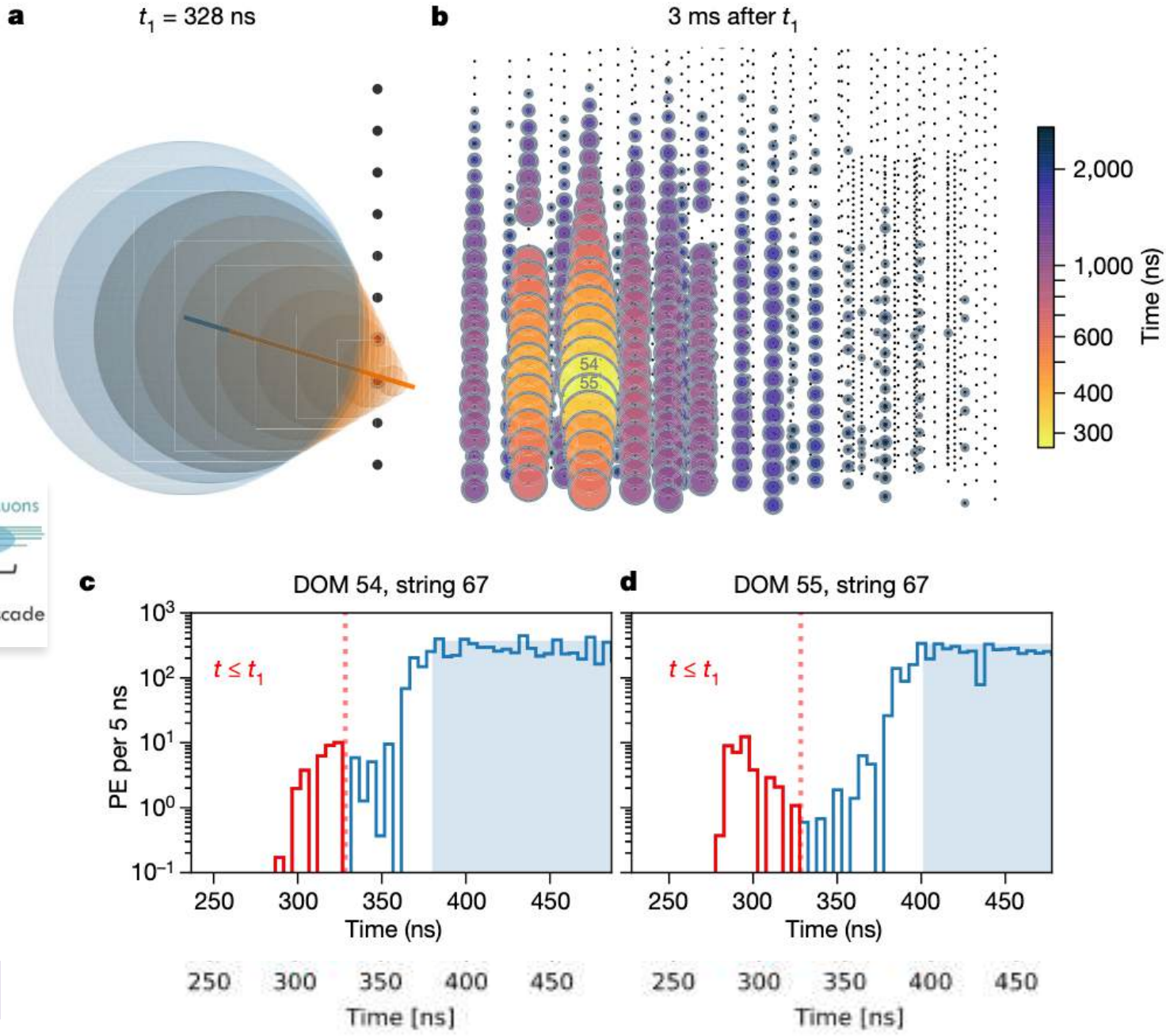
$$\sigma(s) = 24\pi\Gamma_W^2 B_{W^-\to\bar{\nu}_e+e^-} \frac{s/M_W^2}{(s-M_W^2)^2+\Gamma_W^2 M_W^2}$$

$$E_R = M_W^2/(2m_e) = 6.32\text{PeV}.$$

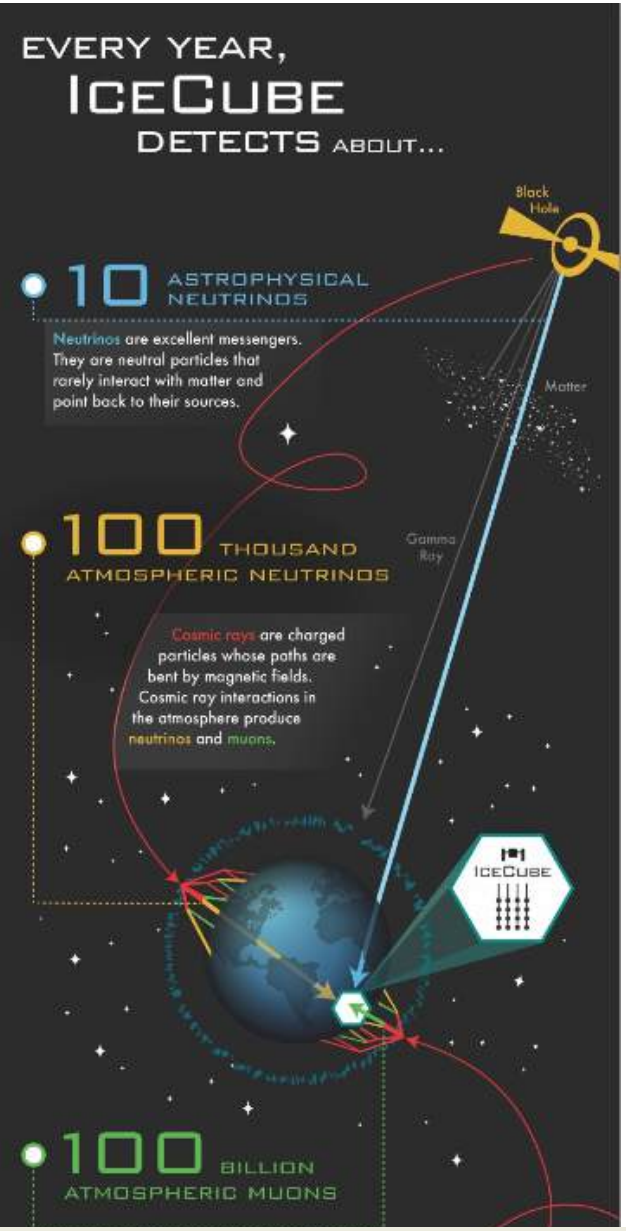


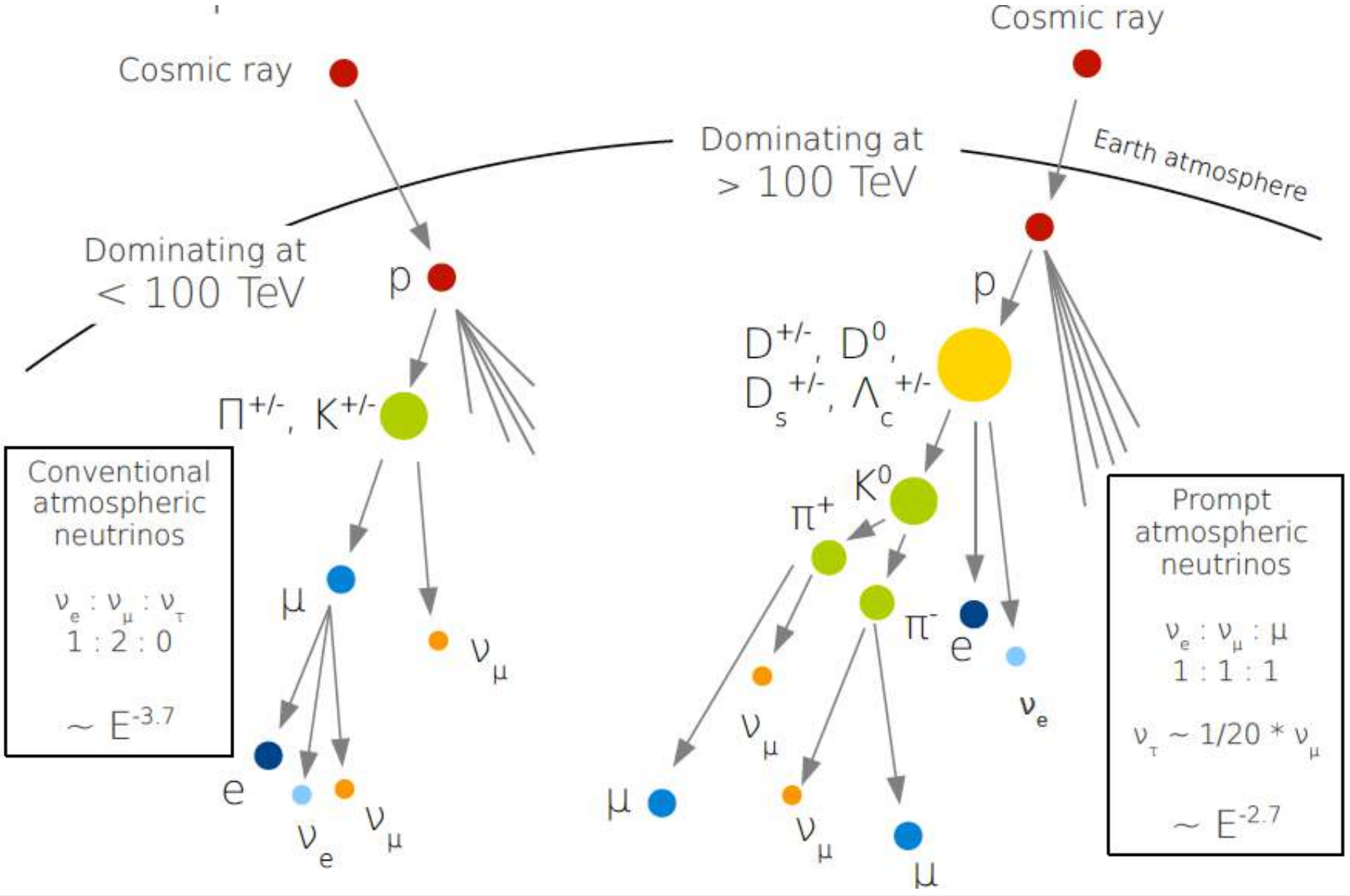


The precision with which the DIS #-secn can be predicted determines the C.L. of the GR identification



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



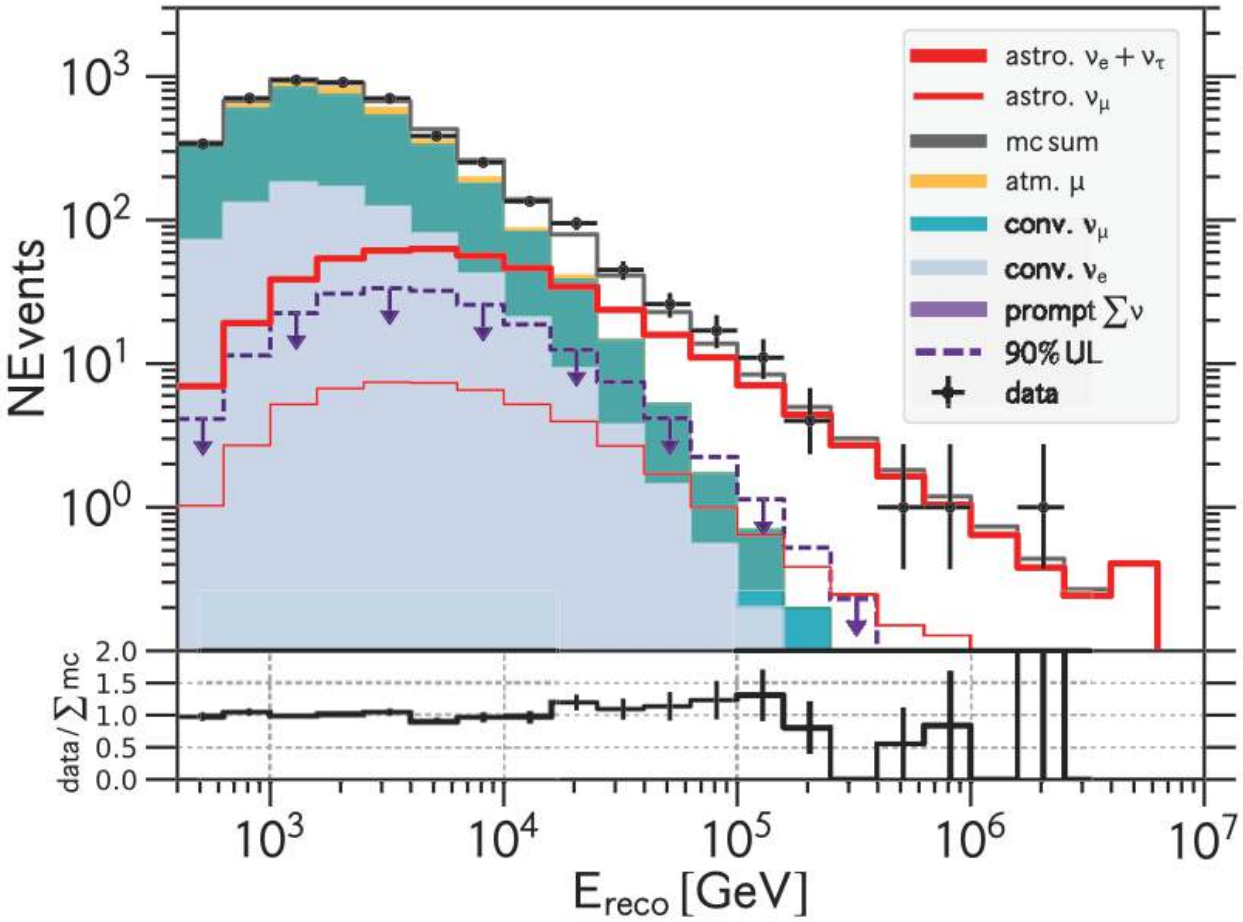


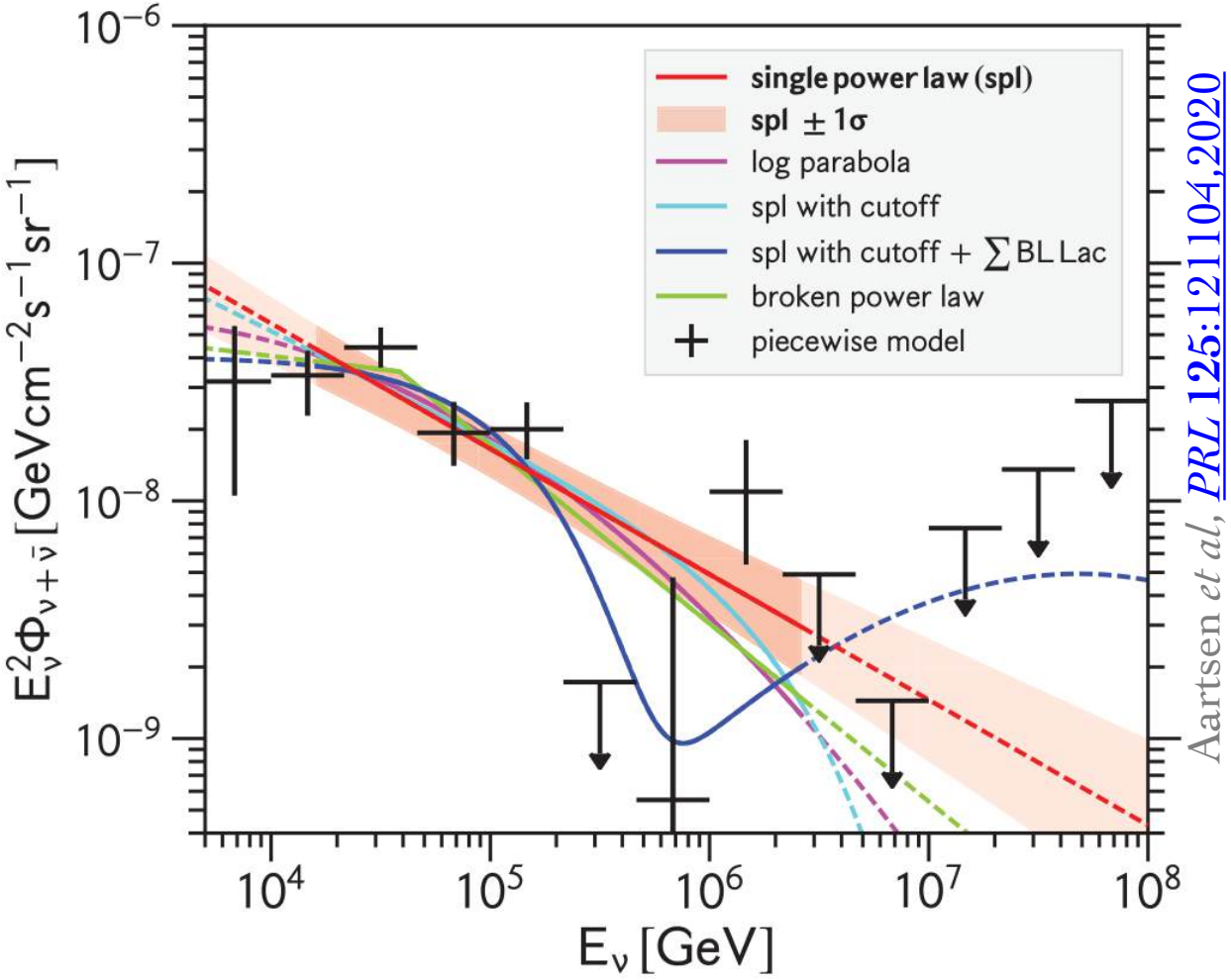
Courtesy: Anne Schukraft

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 astrophysical ν flux can be fitted by a power-law, broken power-law, spline with a cut-off, log-parabola …

Need to discriminate between these in order to identify the source(s) – but this requires better estimate of atmospheric prompt ν background



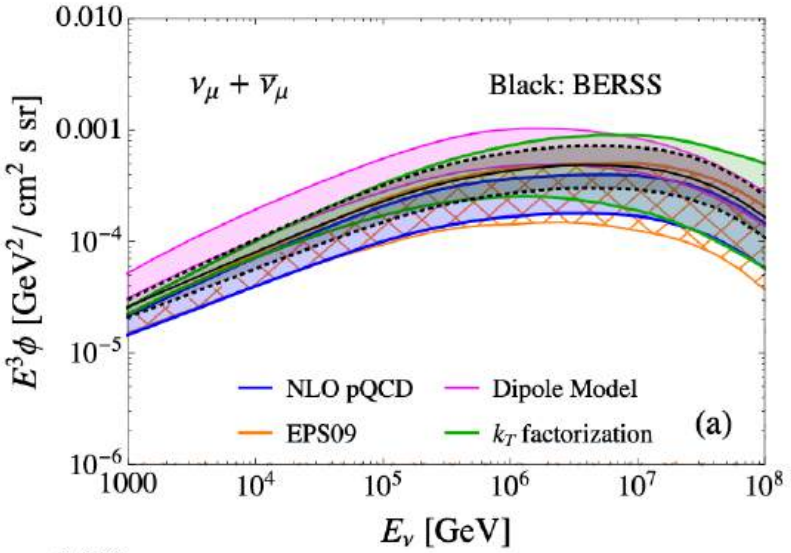


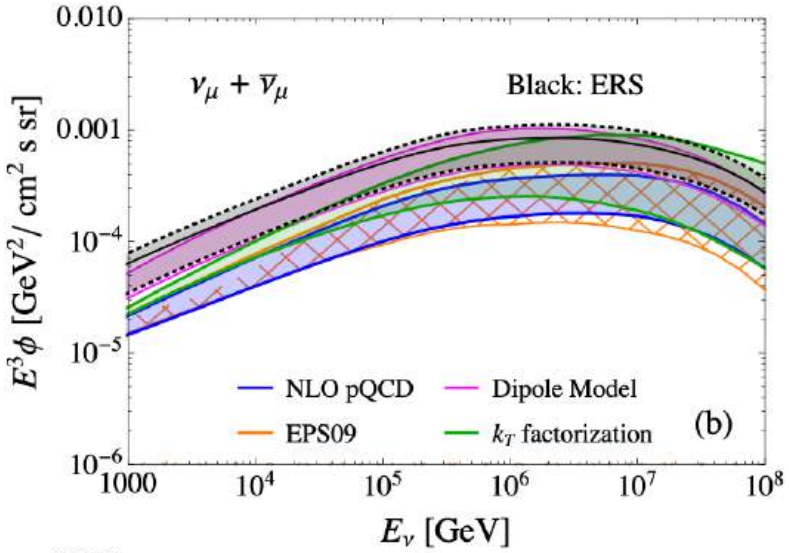
To measure this at an accelerator requires:

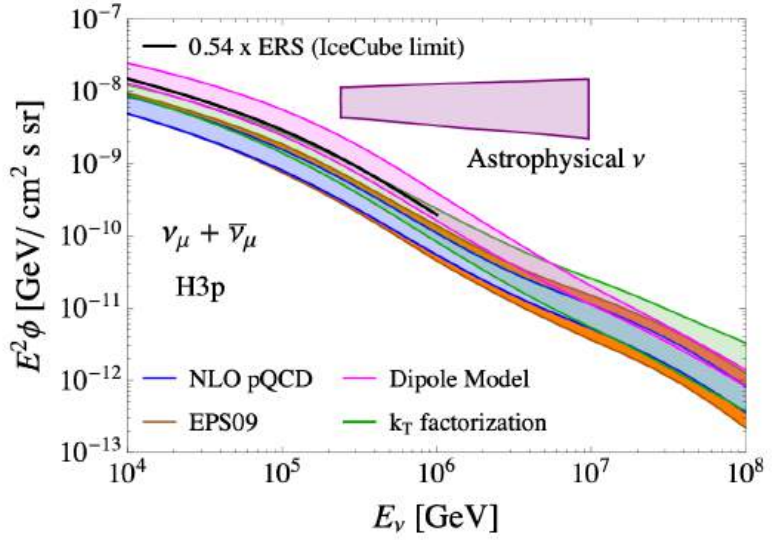
$\sqrt{s} = \sqrt{2 E_\nu m_p} \simeq 10$ TeV, for $E_\nu \sim 10^7$ GeV: **LHCb**

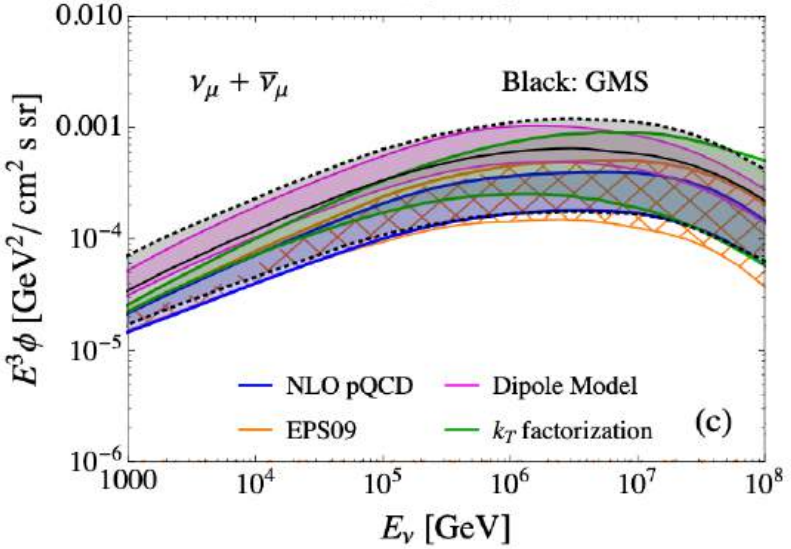
and $x_{1,2} \sim (m_c/\sqrt{s})\, e^{\pm\eta} \Rightarrow \eta \sim 7$-9: requires **FPF**

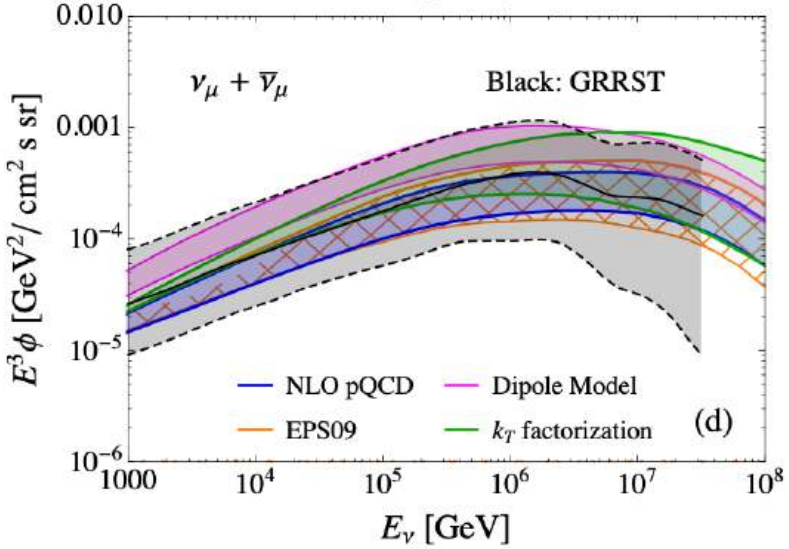
Range of predictions improved with input from LHCb

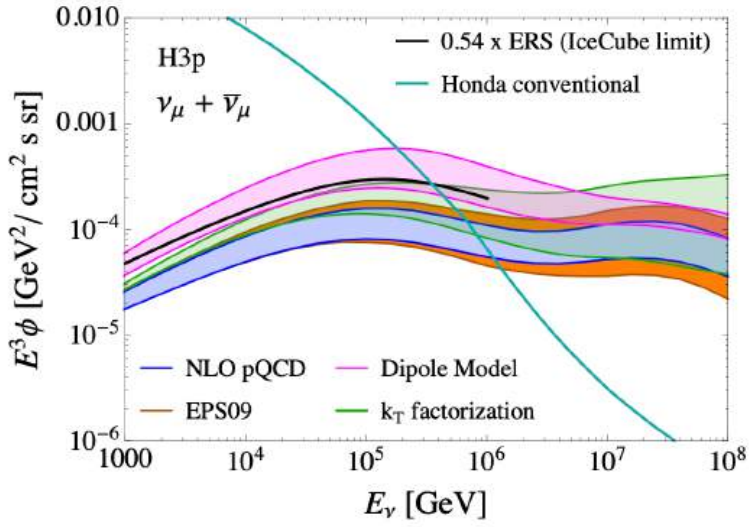












Bhattacharya *et al*, *JHEP* 11:167(2016)

FPF will measure the prompt neutrinos in a *more* forward region ($|y| > 7.2$) than LHCb can access

CONCLUSIONS

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

… and my message to the decision makers