Blast from the past

Subir Sarkar

Rudolf Peierls Centre for Theoretical Physics

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

Herbi-Fest: *Pursuing physics beyond the Standard Model*, Bonn, 27-28 March 2023

Herbi and I have happy memories of our time in the Oxford Particle Theory Group at 1 Keble Road … mainly due to our mentor Graham Ross – an inspiration to us all!

GrahamFest , 30 September 2011

Herbi & I didn't write any papers together then, but he did thank me for discussions in papers written with others … and in later years we did collaborate on several projects

PHYSICAL REVIEW D, VOLUME 61, 095009

Supersymmetric solution to the KARMEN time anomaly

Debajyoti Choudhury,[1] Herbi Dreiner,[2] Peter Richardson,[3] and Subir Sarkar[3]
[1]*Mehta Research Institute, Chhatnag Road, Jhusi, Allahabad 211019, India*
[2]*Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, United Kingdom*
[3]*Theoretical Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, United Kingdom*
(Received 16 November 1999; published 10 April 2000)

We interpret the KARMEN time anomaly as being due to the production of a (domina… with mass 33.9 MeV, which is the lightest supersymmetric particle but decays into… violation of *R* parity. For independent gaugino masses M_1 and M_2 we find regions i… parameter space where such a light neutralino is consistent with all experiments,… are outlined.

Physics of the Dark Universe 9–10 (2015) 8–23

Contents lists available at ScienceDirect

ELSEVIER

Physics of the Dark Universe

journal homepage: www.elsevier.com/locate/dark

Simplified models for dark matter searches at the LHC

PHYSICAL REVIEW D 85, 065027 (2012)

Gravitino cosmology with a very light neutralino

Herbi K. Dreiner* and Marja Hanussek†
Bethe Center for Theoretical Physics and Physikalisches Institut, University of Bonn, Bonn, Germany
Jong Soo Kim‡
Institut für Physik, Technische Universität Dortmund, Dortmund, Germany, and ARC Centre of Excellence for Particle Physics at the Terascale, School of Chemistry and Physics, University of Adelaide, Adelaide, Australia
Subir Sarkar§
Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford OX1 3NP, UK
(Received 9 December 2011; published 30 March 2012)

It has been shown that very light or even massless neutralinos are consistent with all current experiments, given nonuniversal gaugino masses. Furthermore, a very light neutralino is consistent with astrophysical bounds from supernovae and cosmological bounds on dark matter. Here we study the cosmological constraints on this scenario from big bang nucleosynthesis (taking gravitinos into account) and find that a very light neutralino is even favored by current observations.

Chinese Physics C Vol. 40, No. 10 (2016) 100001

REVIEW OF PARTICLE PHYSICS

Particle Data Group

OPEN ACCESS
IOP Publishing

J. Phys. G: Nucl. Part. Phys. 50 (2023) 030501 (413pp)

Journal of Physics G: Nuclear and Particle Physics

https://doi.org/10.1088/1361-6471/ac865e

Major Report

The Forward Physics Facility at the High-Luminosity LHC

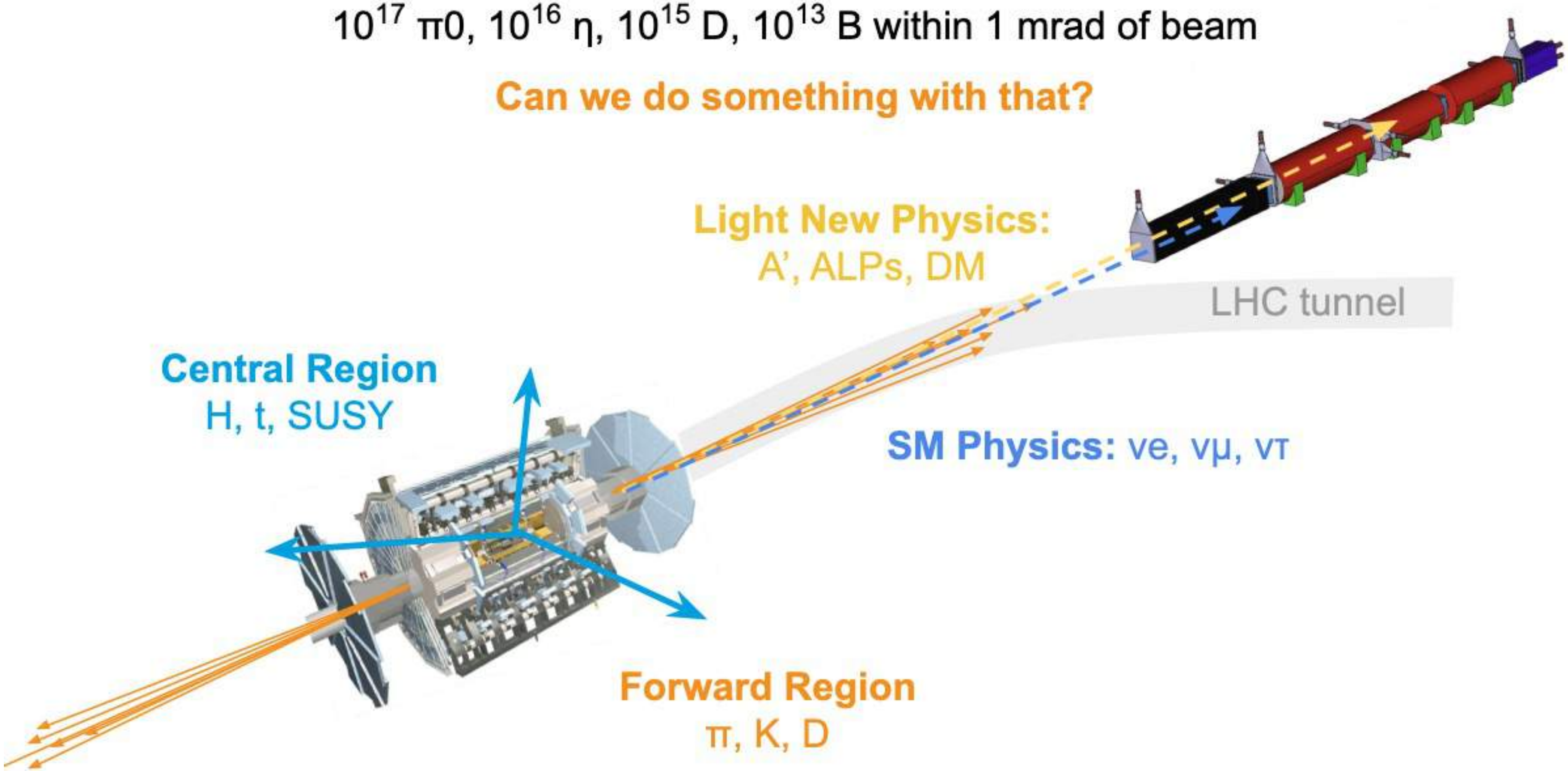
I'll focus today on the forthcoming FPF

While waiting for new physics to be discovered at the energy frontier, can we also explore the intensity frontier for free*?

The LHC produces an intense and strongly collimated beam of highly energetic particles in the forward direction.

10^{17} π0, 10^{16} η, 10^{15} D, 10^{13} B within 1 mrad of beam

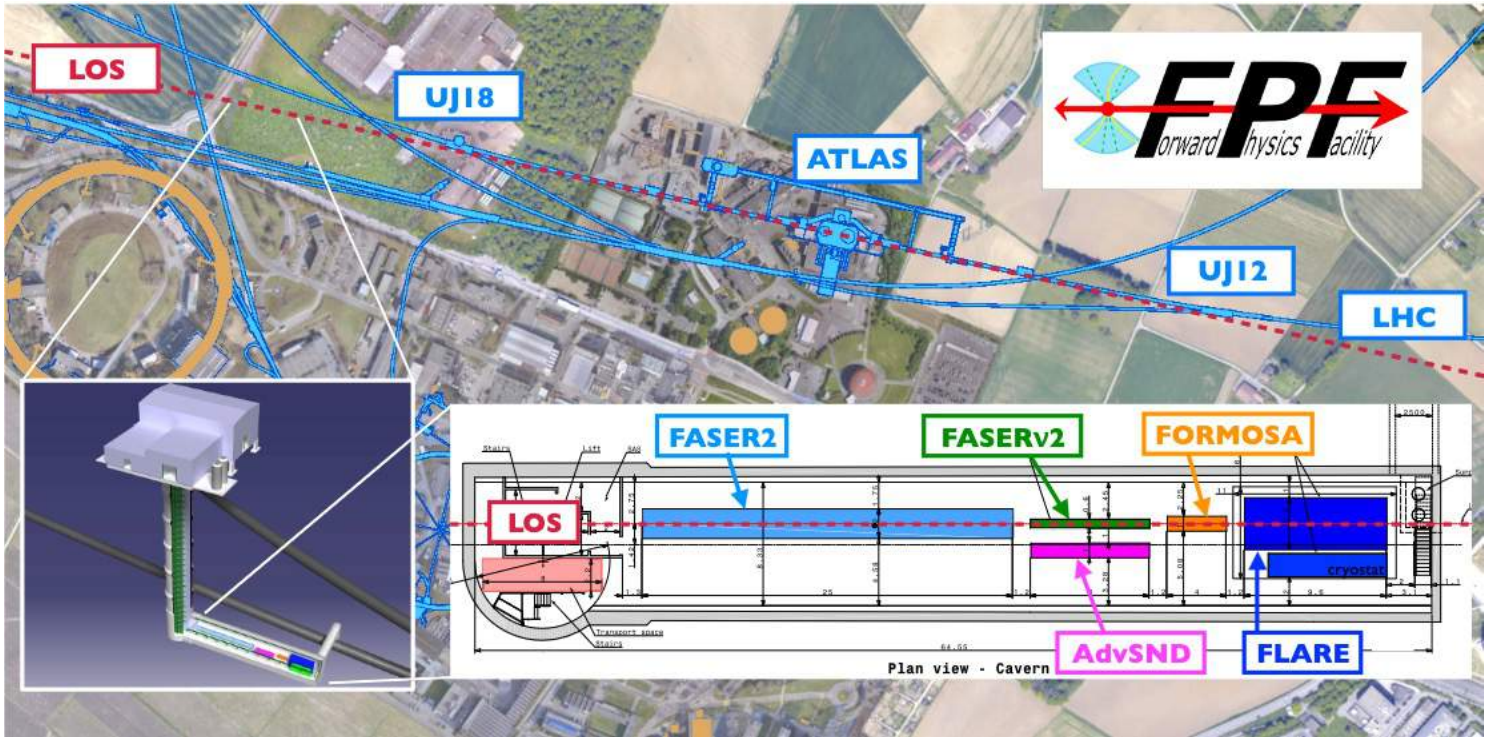
Can we do something with that?



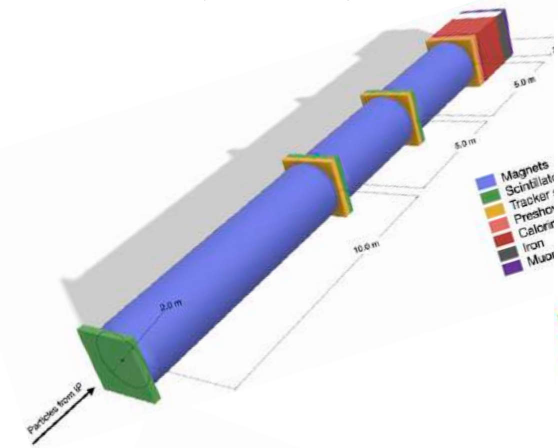
*Preliminary cost estimate: 25 + 13 MCHF

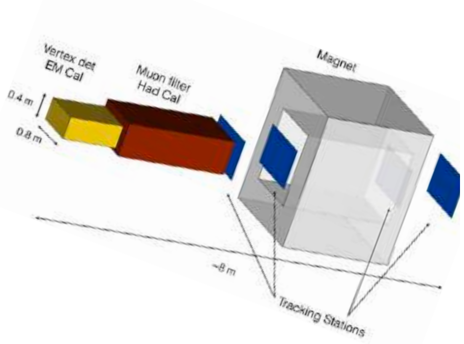
Courtesey: Felix Kling

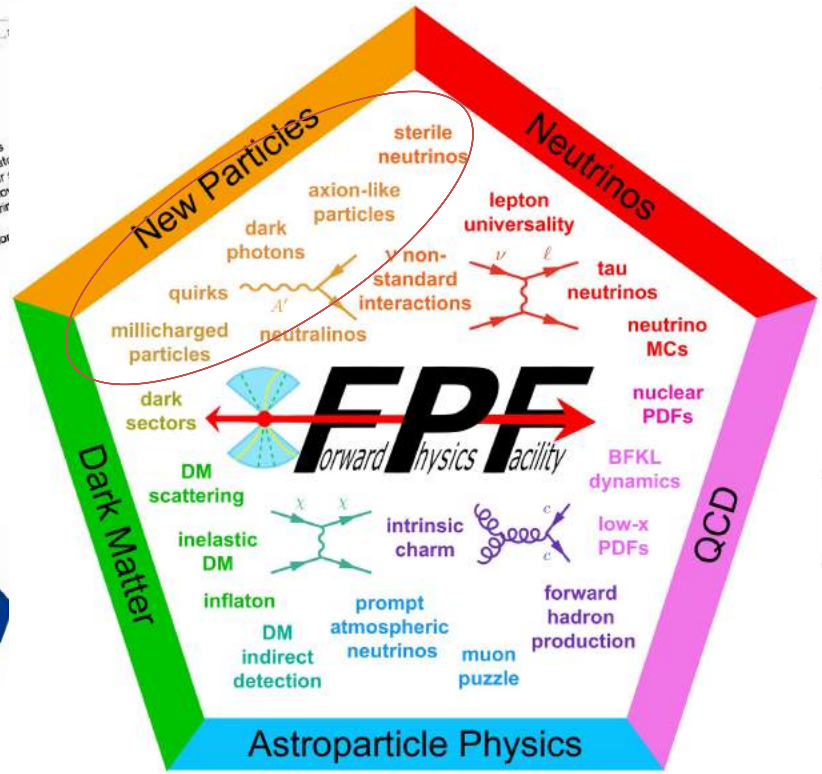
The Forward Physics Facility (FPF) is a proposal to create a cavern with the space and infrastructure to support a suite of far-forward experiments at the Large Hadron Collider during the High Luminosity era. Located along the beam collision axis and shielded from the interaction point by at least 100 m of concrete and rock, the FPF will house experiments that will detect particles outside the acceptance of all existing LHC experiments and will observe rare and exotic processes in an extremely low-background environment. In this work, we summarize the current status of plans for the FPF, including recent progress in civil engineering in identifying promising sites for the FPF; the FPF experiments currently envisioned to realize the FPF's physics potential; and the many Standard Model and new physics topics that will be advanced by the FPF, including searches for long-lived particles, probes of dark matter and dark sectors, high-statistics studies of TeV neutrinos of all three flavors, aspects of perturbative and non-perturbative QCD, and high-energy astroparticle physics. [*Phys. Rep.* 968 (2022) 1, *J. Phys. G* 50 (2023) 030501]

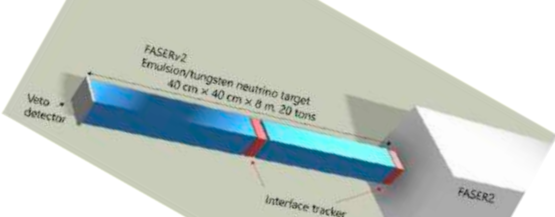


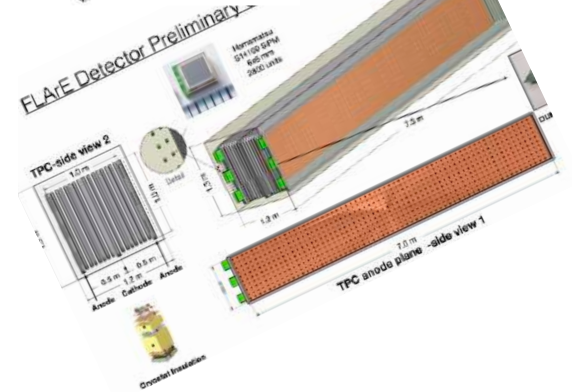
The FPF is uniquely suited to exploit physics opportunities in the far-forward region, because it will house a diverse set of experiments, each optimized for particular physics goals. The envisioned experiments and their physics targets are: (1) **FASER2**, a magnetic spectrometer and tracker, will search for light and weakly-interacting states, including long-lived particles, new force carriers, axion-like particles, light neutralinos, and dark sector particles. (2) **FASERnu2** and (3) **Advanced SND**, proposed emulsion and electronic detectors, respectively, will detect roughly one million neutrinos and anti-neutrinos at TeV energies, including one thousand tau neutrinos, the least well-understood of all known particles. (4) **FLArE**, a proposed 10-tonne-scale noble liquid detector, will detect neutrinos and also search for light dark matter. And (5) **FORMOSA**, a detector composed of scintillating bars, will provide world-leading sensitivity to millicharged particles and other very weakly-interacting particles across a large range of masses.



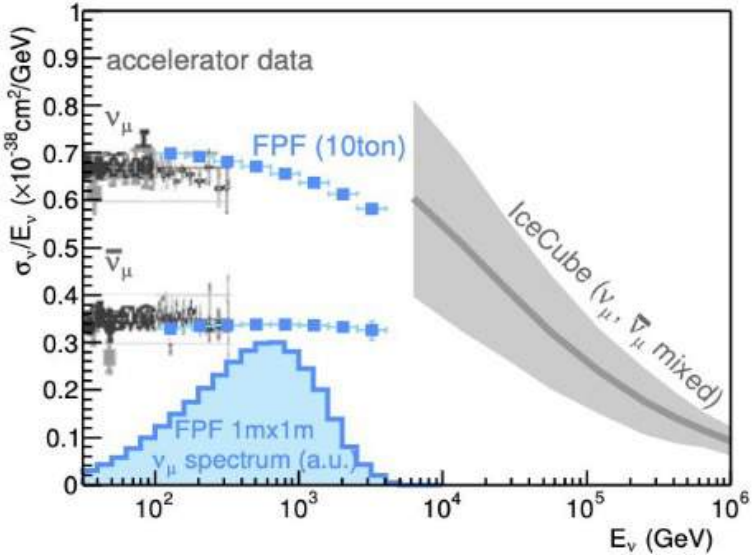








LHC provides a collimated beam of TeV energy neutrinos in the far forward direction



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

A. De Rújula and R. Rückl

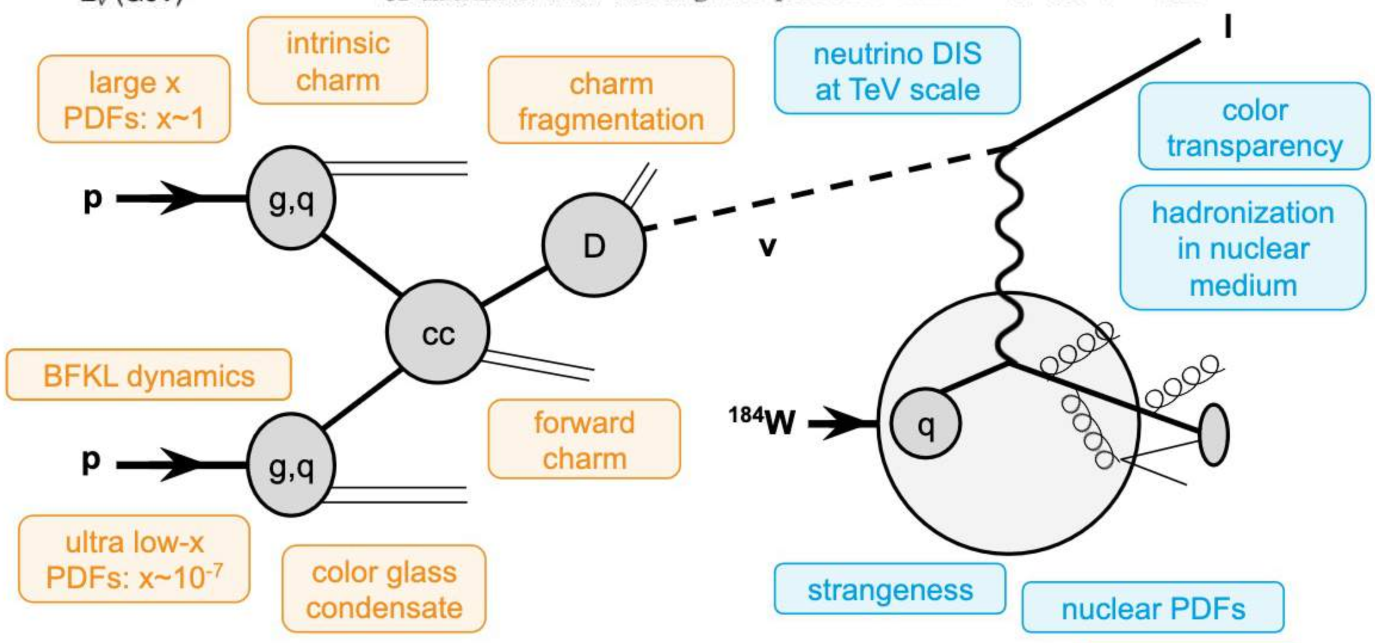
CERN, Geneva, Switzerland

[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.

Provides the means to study a number of open issues in QCD (at low Bjorken-x) … which are also of relevance to astroparticle experiments such as *IceCube*



Forward Particle Production

The Portal Formalism

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

(1) Vector: Dark Photon, A'	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
(2) Scalar: Dark Higgs, S	$(\mu S + \lambda_{\text{HS}} S^2) H^\dagger H$
(3) Pseudo-scalar: Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
(4) Fermion: Heavy Neutral Lepton, N	$y_N LHN$

Dark photon/milli-charged particles

$$\mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - \frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B_{\mu\nu},\ \mathcal{L}_{\text{DS}} = -\frac{1}{4}(F'_{\mu\nu})^2 + \frac{1}{2} m^2_{A'} (A'_\mu)^2 + |(\partial_\mu + i g_D A'_\mu)\chi|^2 + \ldots$$

Scalar DM

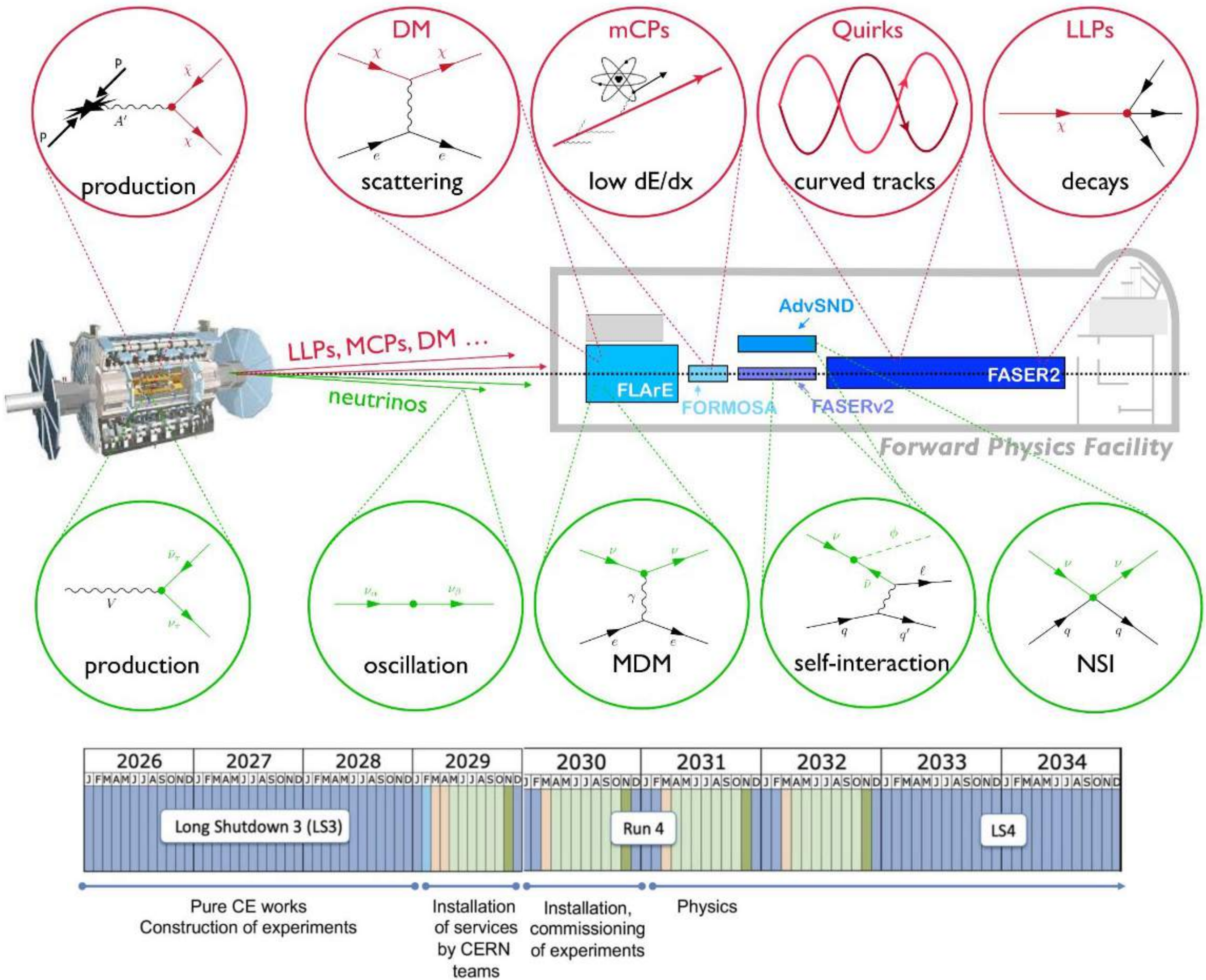
$$\mathcal{L}_{\text{scalar}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - (\mu S + \lambda S^2) H^\dagger H$$

Axions

$$\mathcal{L}_{\text{axion}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \frac{a}{4f_\gamma} F_{\mu\nu}\tilde{F}_{\mu\nu} + \frac{a}{4f_G} \text{Tr} G_{\mu\nu}\tilde{G}_{\mu\nu} + \frac{\partial_\mu a}{f_l} \sum_\alpha \bar{l}_\alpha \gamma_\mu \gamma_5 l_\alpha + \frac{\partial_\mu a}{f_q} \sum_\beta \bar{q}_\beta \gamma_\mu \gamma_5 q_\beta$$

Heavy neutral leptons

$$\mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \sum F_{\alpha I} (\bar{L}_\alpha H) N_I \qquad \nu_\alpha \to \sum_I U_{\alpha I} N_I$$



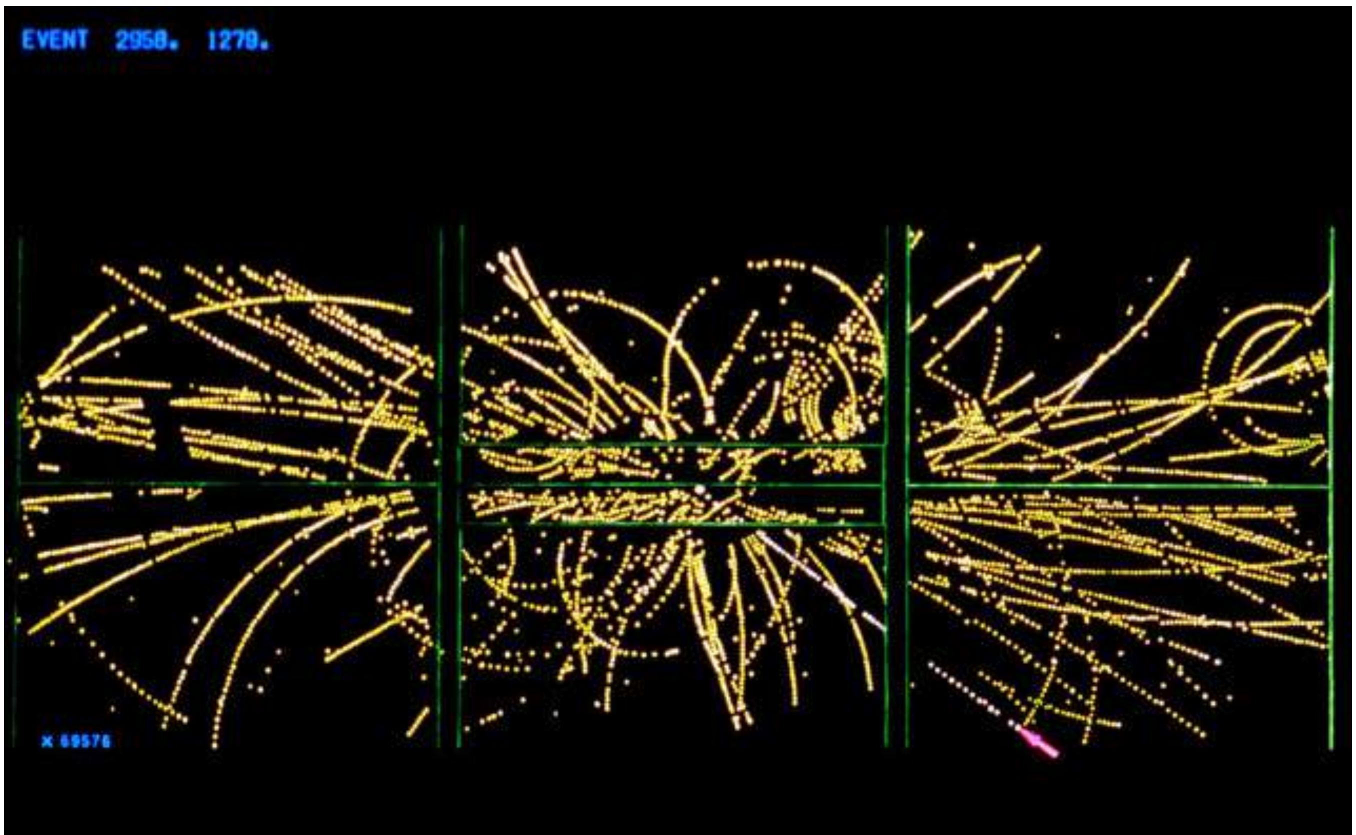
Courtesey: Felix Kling

Herbi is first and foremost a phenomenologist (although he did flirt briefly with string theory) and I would like to pay homage to that today by talking about work I've done recently with students … which has a bearing on the proposed BSM searches at FPF

W boson turns 40

25 January 2023

Forty years ago today, physicists at CERN announced to the world that they had discovered the electrically charged carrier of the weak force, one of nature's four fundamental forces



First direct production of the W boson in the UA1 experiment in late 1982. (Image: CERN)

I was at CERN during 1983-85 – a glorious time during which the *W* and *Z* were found …
along with lots of `new physics' (monojets, anomalous $Z \to \ell^+ \ell^- \gamma$, top @ 43 GeV, …)!

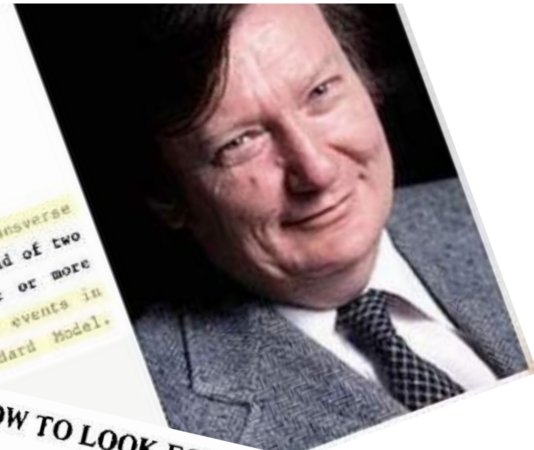
EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON(S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV

[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(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 $\bar{p}p \to (W \to e\bar{\nu})$ + 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 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

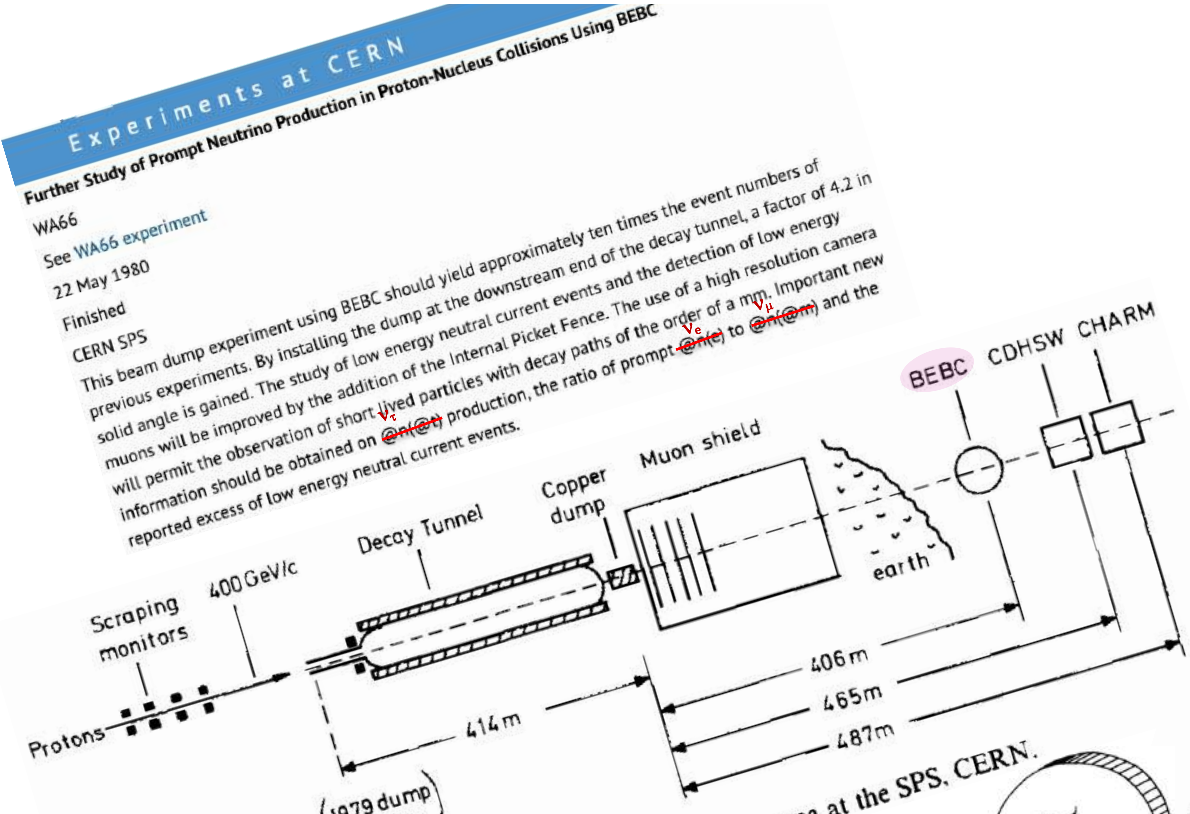
SCALAR QUARK SIGNATURES AT THE $\bar{p}p$ COLLIDER

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.

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



Experiments at CERN

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

WA66

See WA66 experiment

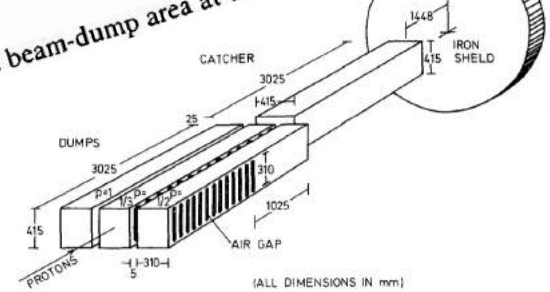
22 May 1980

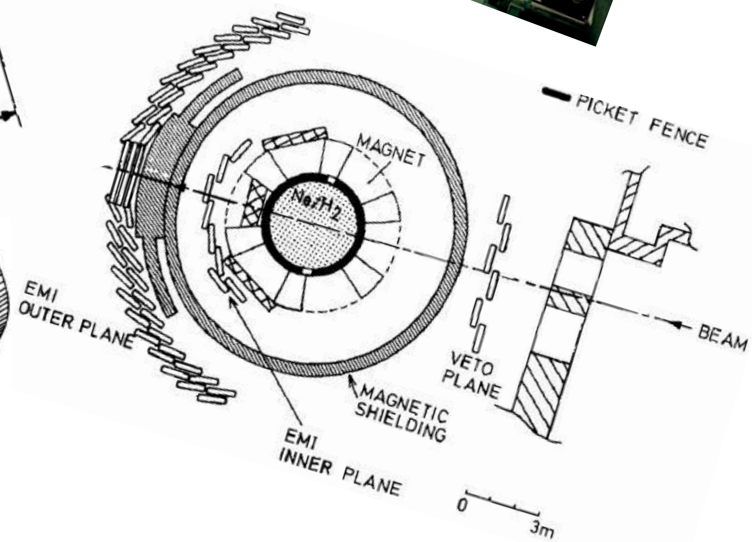
Finished

CERN SPS

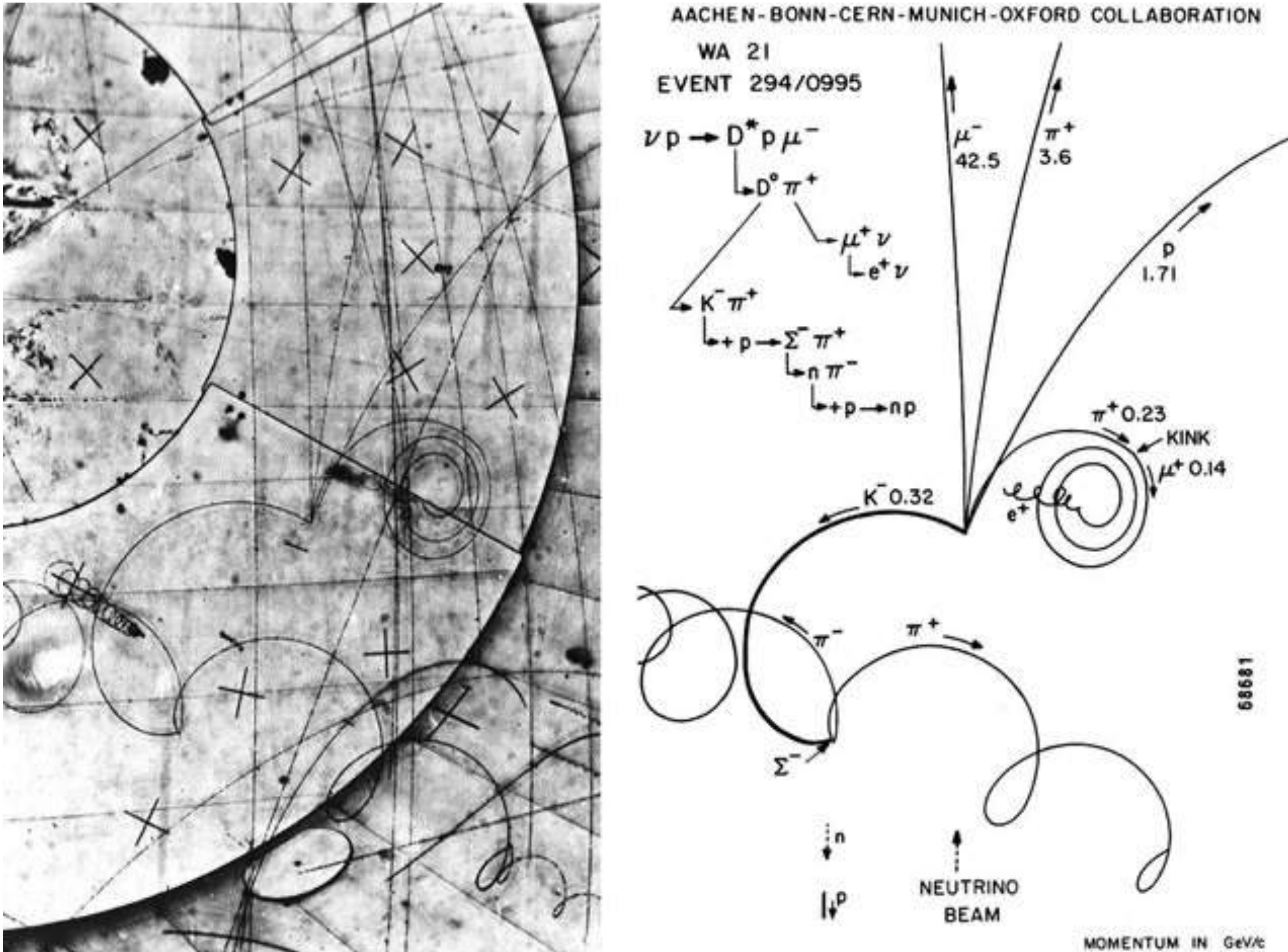
This beam dump experiment using BEBC should yield approximately ten times the event numbers of previous experiments. By installing the dump at the downstream end of the decay tunnel, a factor of 4.2 in solid angle is gained. The study of low energy neutral current events and the detection of low energy 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 ~~@n(@)~~ 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



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

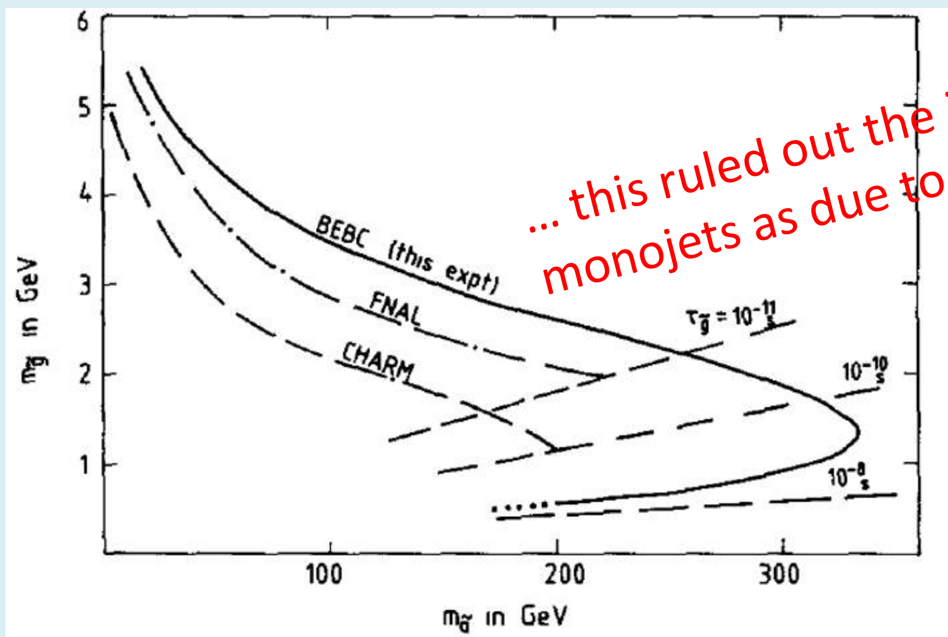
BOUNDS ON LIGHT GLUINOS FROM THE BEBC BEAM DUMP EXPERIMENT

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 [h], 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 $m_{\tilde{g}} \geq 4$ 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

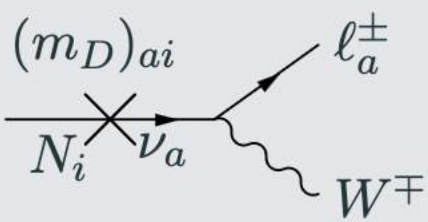


... this ruled out the interpretation of the monojets as due to light gluinos/squarks

Active neutrino masses

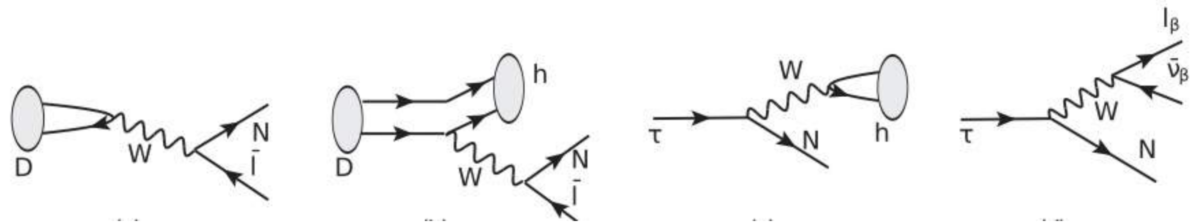
$$m_\nu = -m_D M_M^{-1} m_D^T$$

HNL mixing

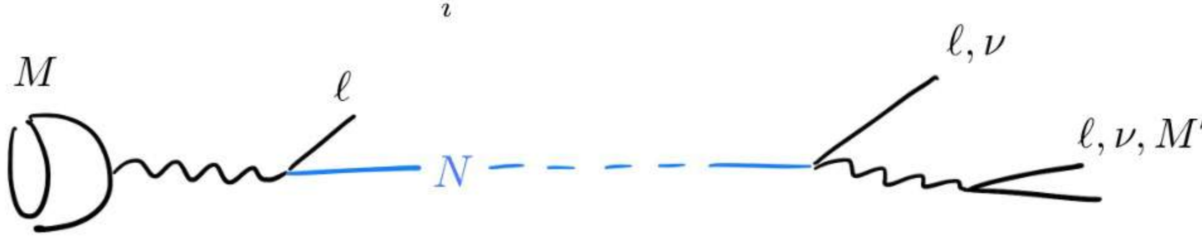


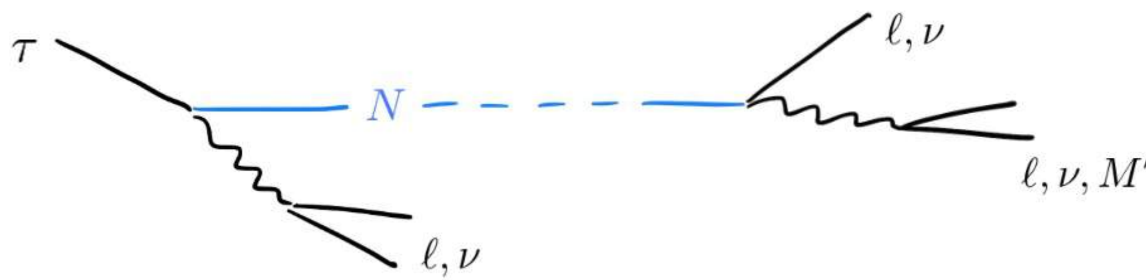
$$U_{ai}^2 \equiv \left|\left(m_D M_M^{-1}\right)_{ai}\right|^2$$

$$U^2 = \sum_{a,i} U_{ai}^2$$



$$\nu_\alpha = \sum_i U_{\alpha i}\nu_i + U_{\alpha 4} N$$





$$L_{lab,N} \simeq 30 \left(\frac{10^{-3}}{|U_{\tau 4}|^2}\right)\left(\frac{E_N}{10\ \mathrm{GeV}}\right)\ \mathrm{m}$$

For $\begin{cases} m_N \sim 1\ \mathrm{GeV} \\ |U_{e4}| = |U_{\mu 4}| = 0 \end{cases}$

We considered production in the beam dump of charmed particles – which decay promptly to neutrinos ... whose mixings create a collimated HNL beam that decay in the downstream 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 [h,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

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 *eeν*, *eμν* or *μμν*, or for *eπ*, and only 1 candidate for $\mu^+\pi^-$, *cf.* estimated background of 0.6 ± 0.2 ⇒ upper limit of 3.5 events @ 90% CL

We specifically considered production of tau neutrinos ... and looked for forward scattered electrons that would be a signature of their 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 $10^{-6}\,\mu_B$ … 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

Physics Letters B280 (1992) 153-158

We 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 $5.4\times10^{-7}\,\mu_B$. This rules out the suggestion that tau neutrinos of mass O(MeV) constitute the dark matter in the universe.

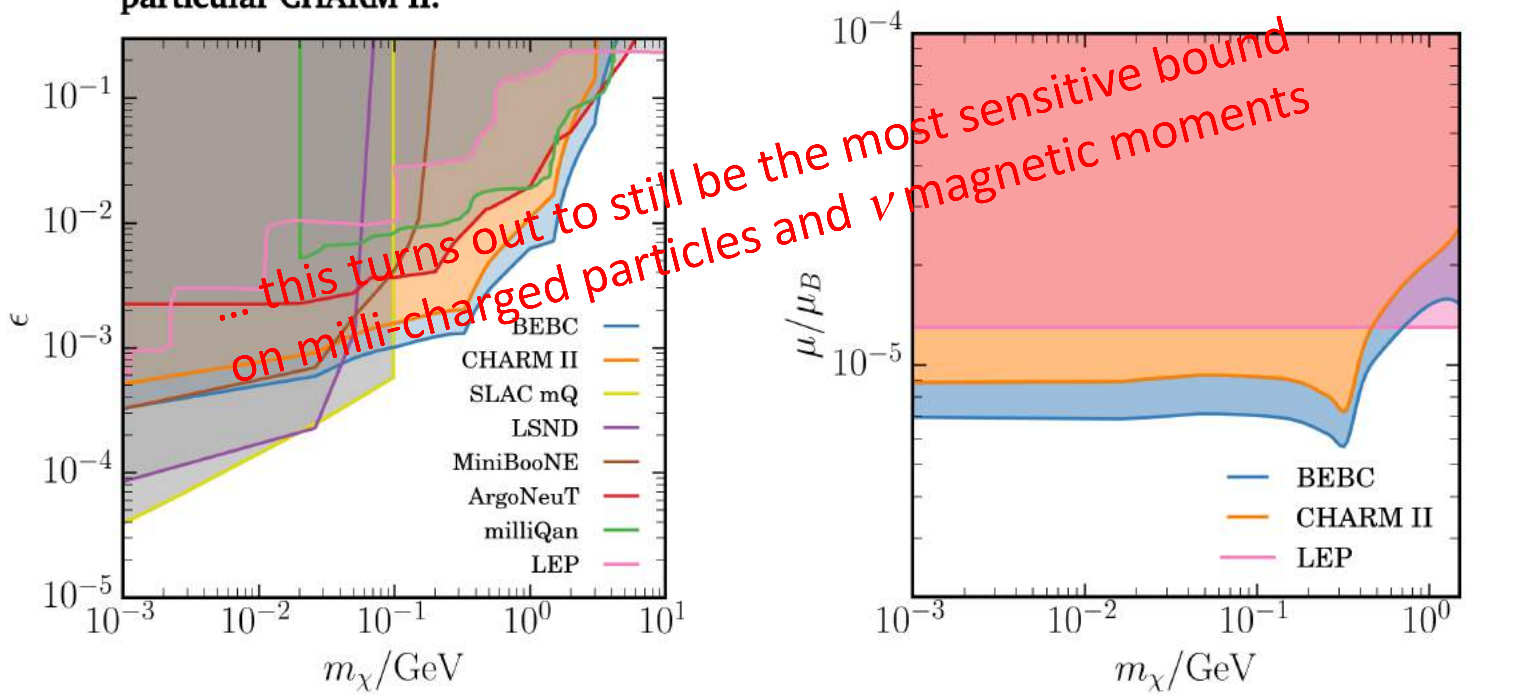
SciPost Phys. 10, 043 (2021)

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

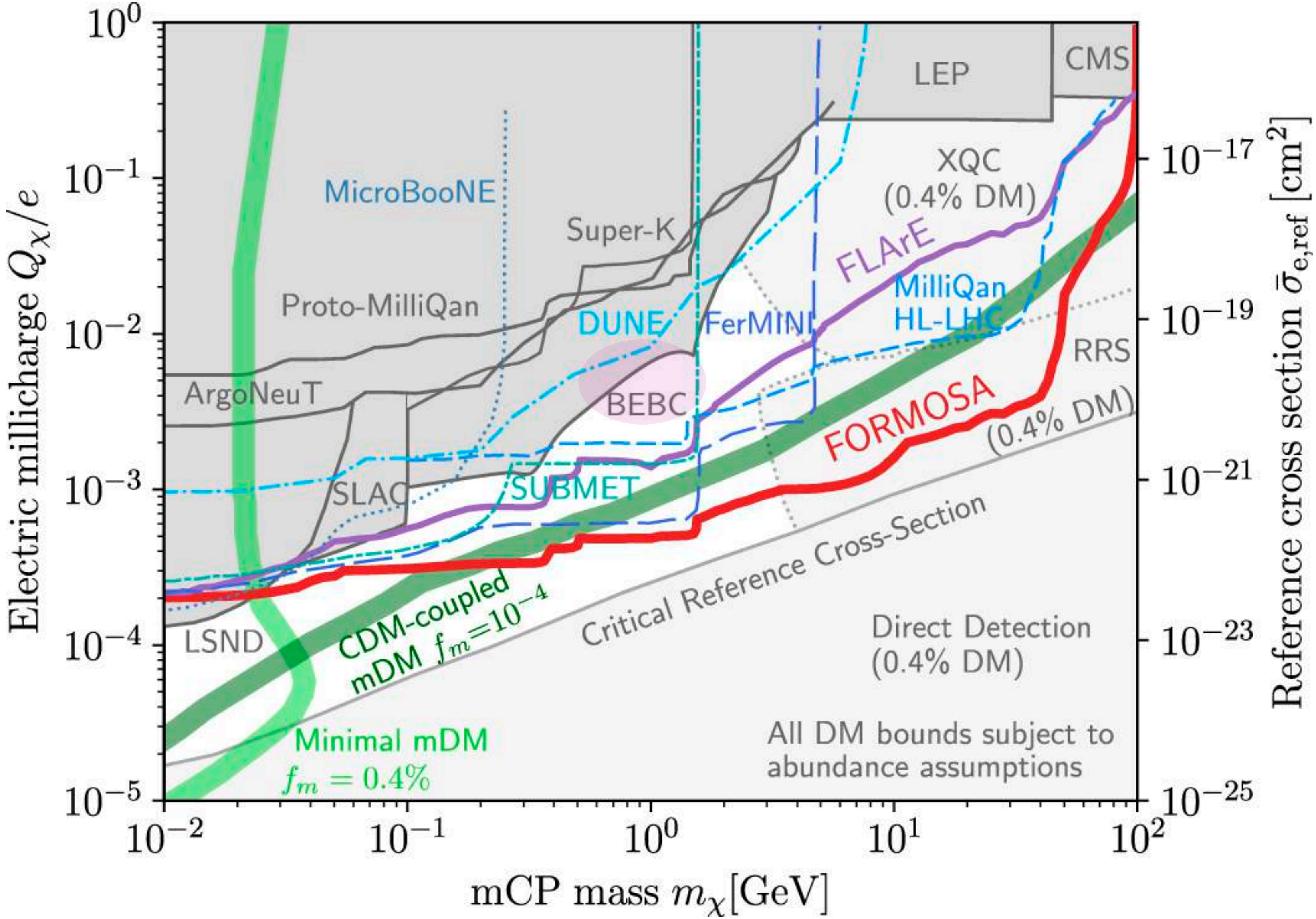
Giacomo Marocco ⋆ **and Subir Sarkar**

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.



The reach will improve with the proposed experiments at the FPF …



Bounds on mCPs from previous searches (grey): SLAC, LEP, CMS, LSND, ArgoNeuT, BEBC, Super-K (limit on diffuse SN ν background). **Expected sensitivities** for **FORMOSA** (red) and **FLArE** (purple) and **projections** for **milliQan @ HL-LHC**, **FerMINI** and **SUBMET** (dashed). [arXiv:2109.10905]

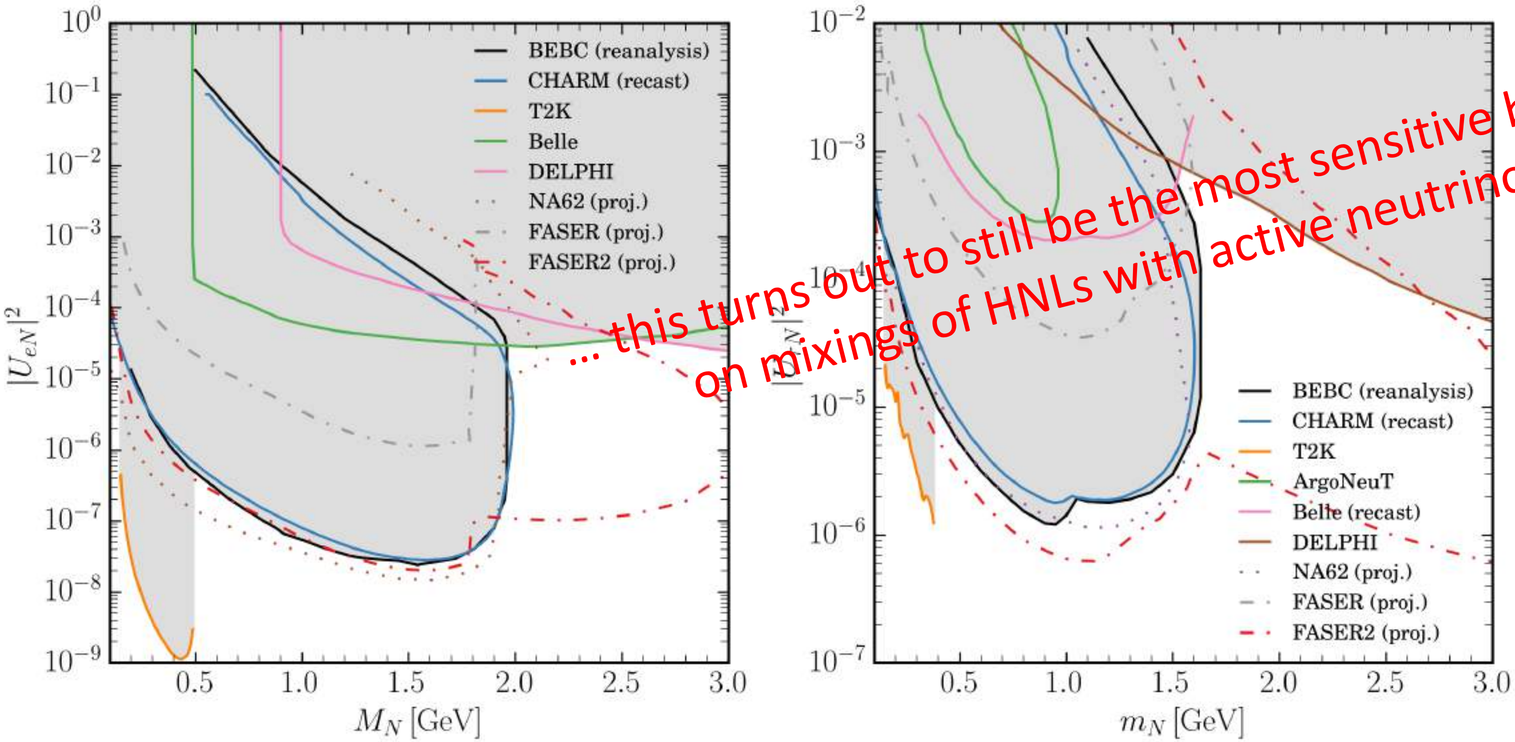
SciPost Phys. 13, 118 (2022)

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

Ryan Barouki, Giacomo Marocco⋆ and Subir Sarkar

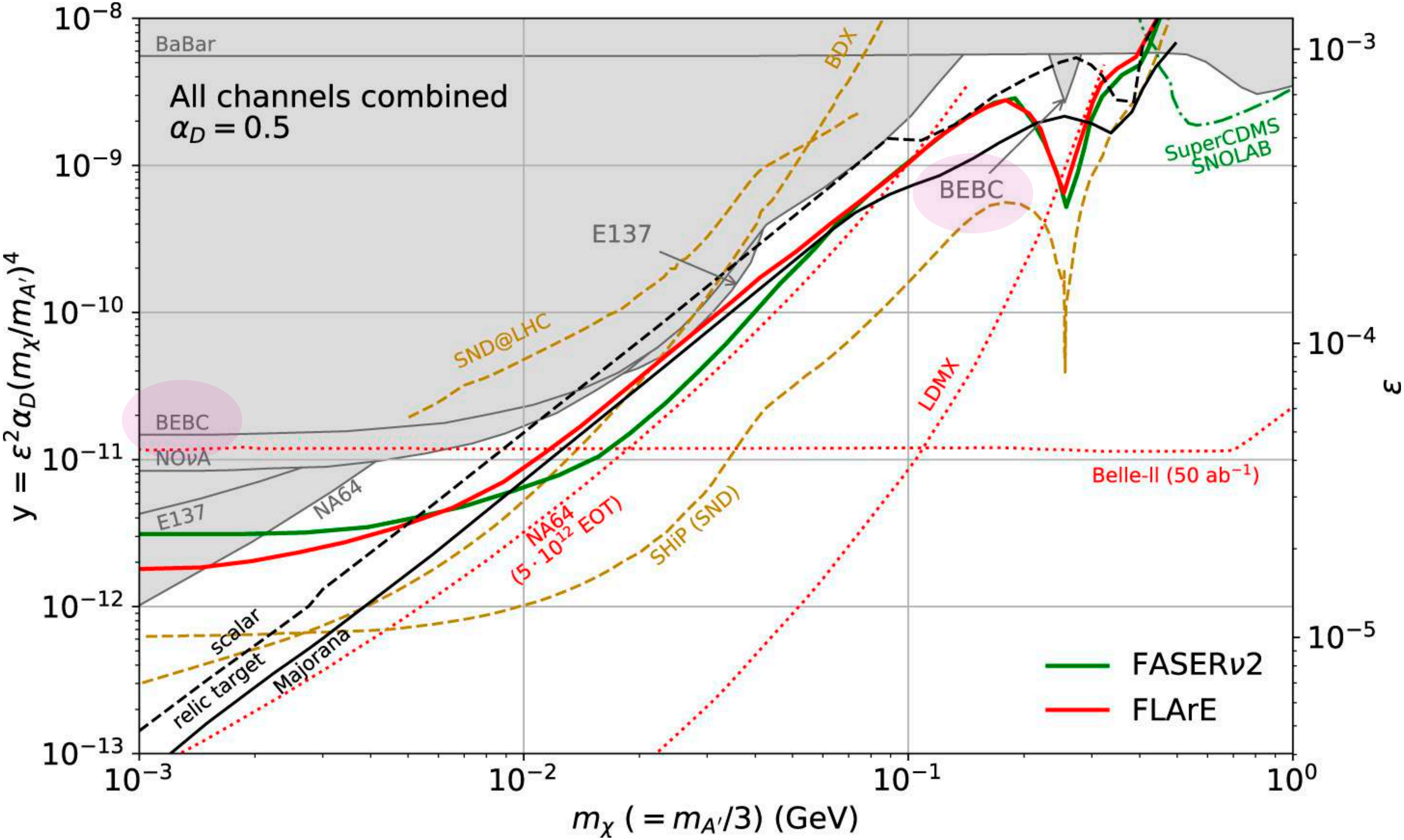
Rudolf Peierls Centre for Theoretical Physics, University of Oxford,
Parks Road, Oxford OX1 3PU, United Kingdom

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.



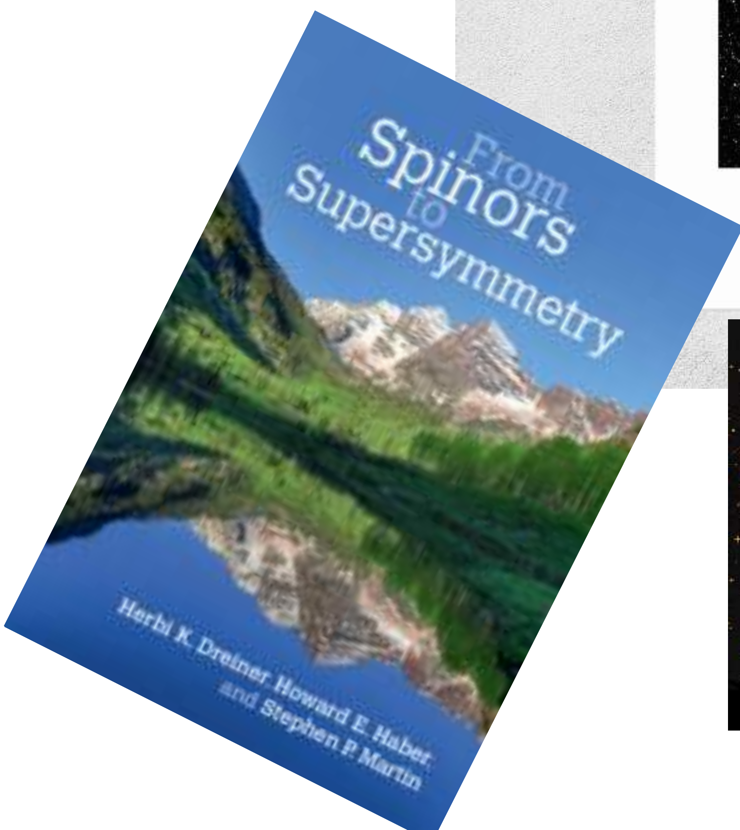
… this turns out to still be the most sensitive bound on mixings of HNLs with active neutrinos

The WA66 constraint on forward scattered electrons also translates into a leading bound on scattering of ~MeV-GeV scalar dark matter (Buonocore *et al*, Phys.Rev. 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



dear Herbi!