Summary/Highlights: Experimental searches for direct evidence of sterile neutrinos

Marcin Chrzaszcz (CERN, IFJ PAN)

LEP

- LEP start-up advertised for 14 July 1989
  - July 14, First turn
  - August 13, First Collisions
  - August 13-18, Physics pilot run
  - August 21-Sept.11, Machine studies
  - Sept. 20-Nov. 5, Physics

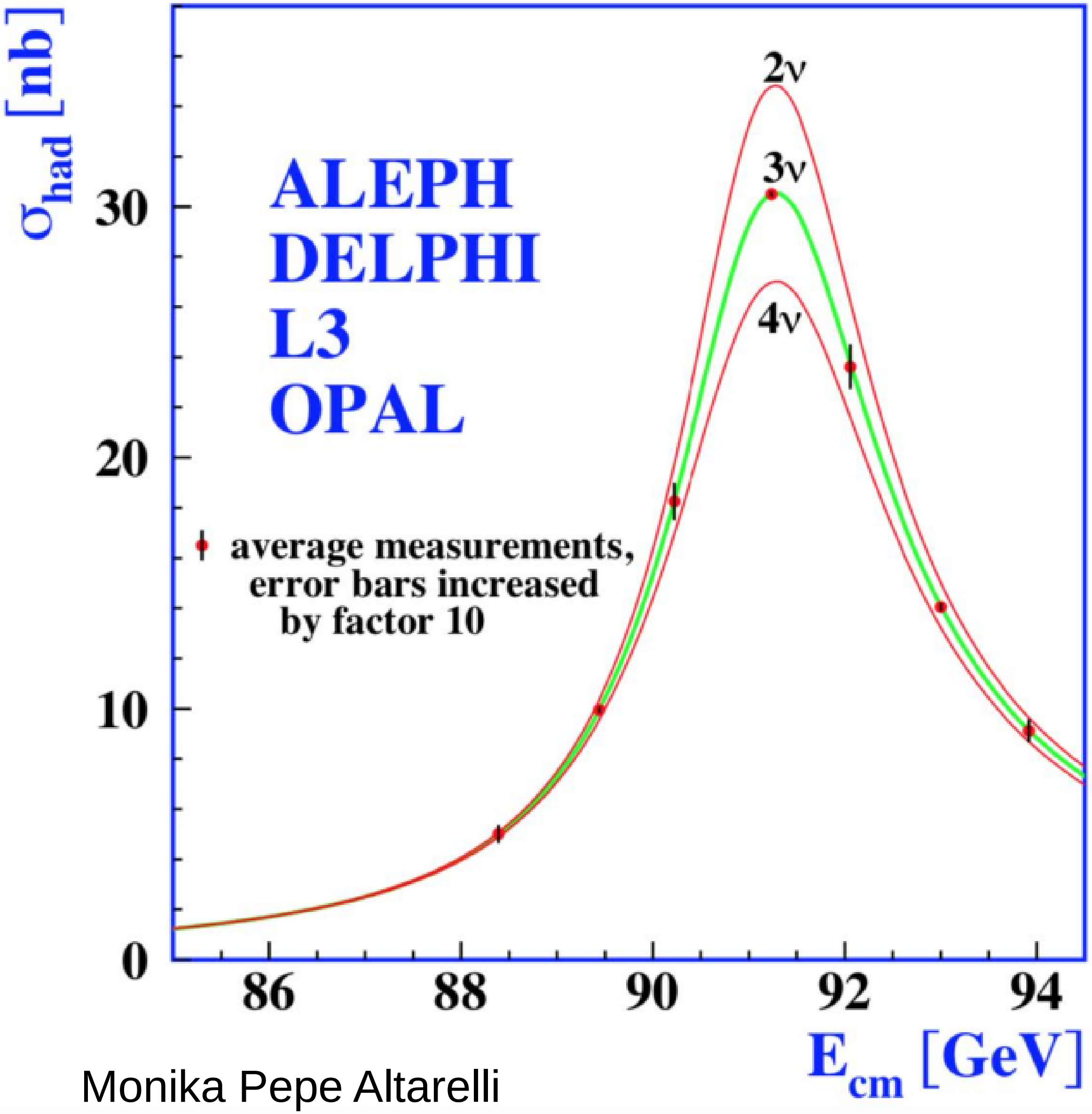
- The Economist August 19, 1989

"The results from California are impressive, especially as they come from a new and unique type of machine. They may provide a sure answer to the generation problem before LEP does. This explains the haste with which the finishing touches have been applied to LEP. The 27km-long device, six years in the making was transformed from inert hardware to working machine in just four weeks--- a prodigous feat, unthinkable anywhere but at CERN..............

........Even so, it was still not as quick as Dr. Carlo Rubbia, CERN's domineering director-general might have liked".

[S.Meyers, CERN's 50th anniversary]

Final combined result



$$N_\nu = 2.9840 \pm 0.0082$$

- Based on 17 million Z decays
- Less than 3 per mille uncertainty
- ~ half of it from theoretical uncertainty on low-angle Bhabha scattering cross-section

LEP EW WG:
Phys. Rept. 427 (2006)

- First paper ever signed by over 2500 authors !

from: ALEPH collaboration 'determination of the number of light neutrino species'
Physics Letters B Volume 231, Issue 4, 16 November 1989, Pages 519-529

$$N_\nu = 3.27 \pm 0.30. \quad (5)$$

The hypothesis $N_\nu = 4$ is ruled out at 98% confidence level. This measurement improves in a decisive way upon previous determinations of the number of neutrino species from the UA1 [16] and UA2 [17] experiments, from PEP [18] and PETRA [19], from cosmological [20] or astrophysical [21] arguments, as well as from a similar determination at the Z peak [22].

The demonstration that there is a third neutrino confirms that the τ neutrino is distinct from the e and μ neutrinos. The absence of a fourth light neutrino indicates that the quark-lepton families are closed with the three which are already known, except for the possibility that higher order families have neutrinos with masses in excess of $\sim$ 30GeV.

by 1989 (and before the measurement at LEP)
the first three families of neutrinos (ν_e ν_μ ν_τ) were «already known»

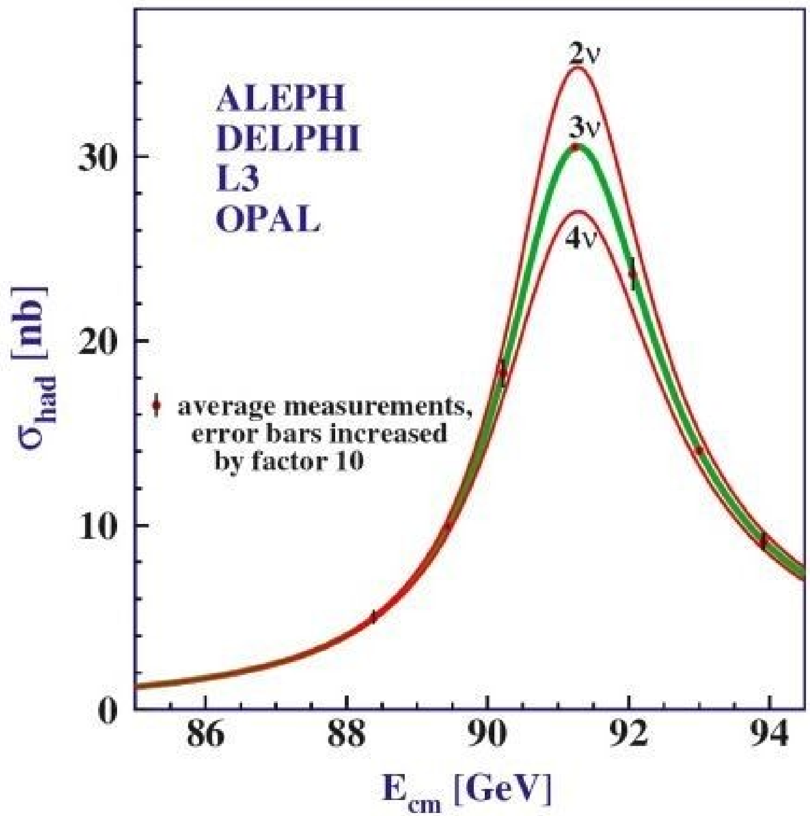
Alain Blondel

At the end of LEP:

Phys.Rept.427:257-454,2006

N_ν = 2.984 ±0.008

- 2 σ :^) !!



This is determined from the Z line shape scan and dominated by the measurement of the hadronic cross-section at the Z peak maximum

The dominant systematic error is the theoretical uncertainty on the Bhabha cross-section (0.06%) which represents an error of ±0.0046 on N_ν

NB PDG >2017 using the then known top and Higgs masses and full two loop gives N_ν = 2.991 ±0.007.

Alain Blondel

Alain Blondel

The explanation was provided by an electrician from the Swiss electricity company EOS: he knew that effect well !

Vagabond currents from trains and subways

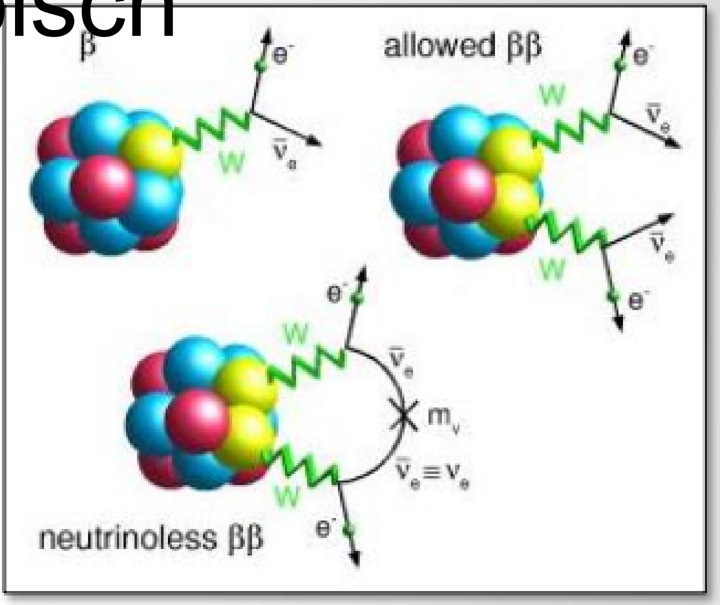
Source of electrical noise and corrosion (first discussed in 1898)

Beta Decays and ν Mass

University College London

Frank Deppisch

- Single beta decay
  $$(A,Z) \to (A,Z+1) + e^- + \bar{\nu}_e$$
  - Tritium decay, KATRIN: $m_\beta \approx 0.2$ eV
  - Project 8: Atomic Tritium + Cyclotron Radiation Spectroscopy: $m_\beta \approx 0.05$ eV
  - HOLMES: e^- capture in ^{163}Ho: $m_\beta \approx 0.1$ eV?
- Allowed double beta ($2\nu\beta\beta$) decay
  $$(A,Z) \to (A,Z+2) + 2e^- + 2\bar{\nu}_e$$
- Neutrinoless double beta ($0\nu\beta\beta$) decay
  $$(A,Z) \to (A,Z+2) + 2e^-$$
  - Violation of lepton number
  - Mediated by Majorana neutrinos

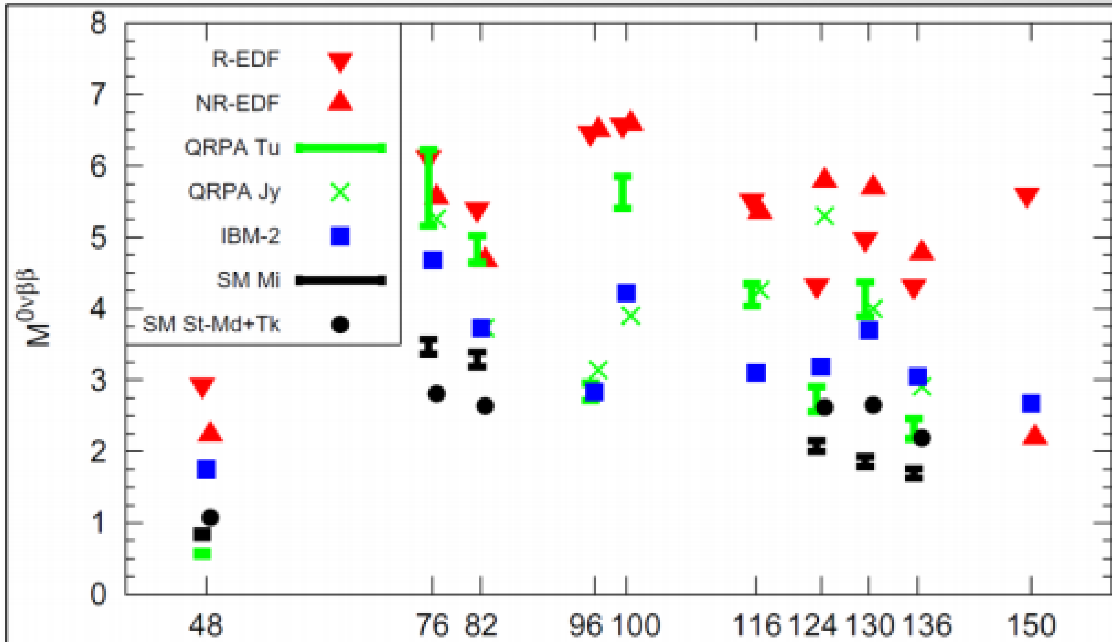


Nuclear Matrix Elements

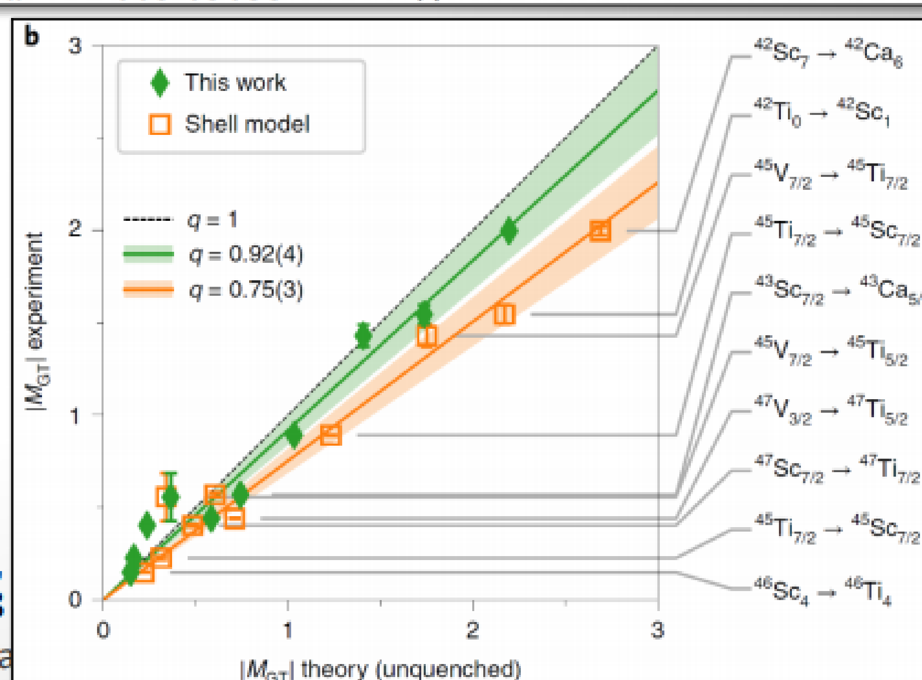
- Nuclear Matrix Element

$$M^{0\nu} = g_A^2\left(M_{GT} - \frac{g_V^2}{g_A^2}M_F + M_T\right)$$

  - Factor 2 – 3 uncertainty between nuclear models
  - "Quenching" of axial nucleon coupling g_A?
    - Restricted model space
    - Missing effect of two-body currents



Menendez, arXiv:1605.05059

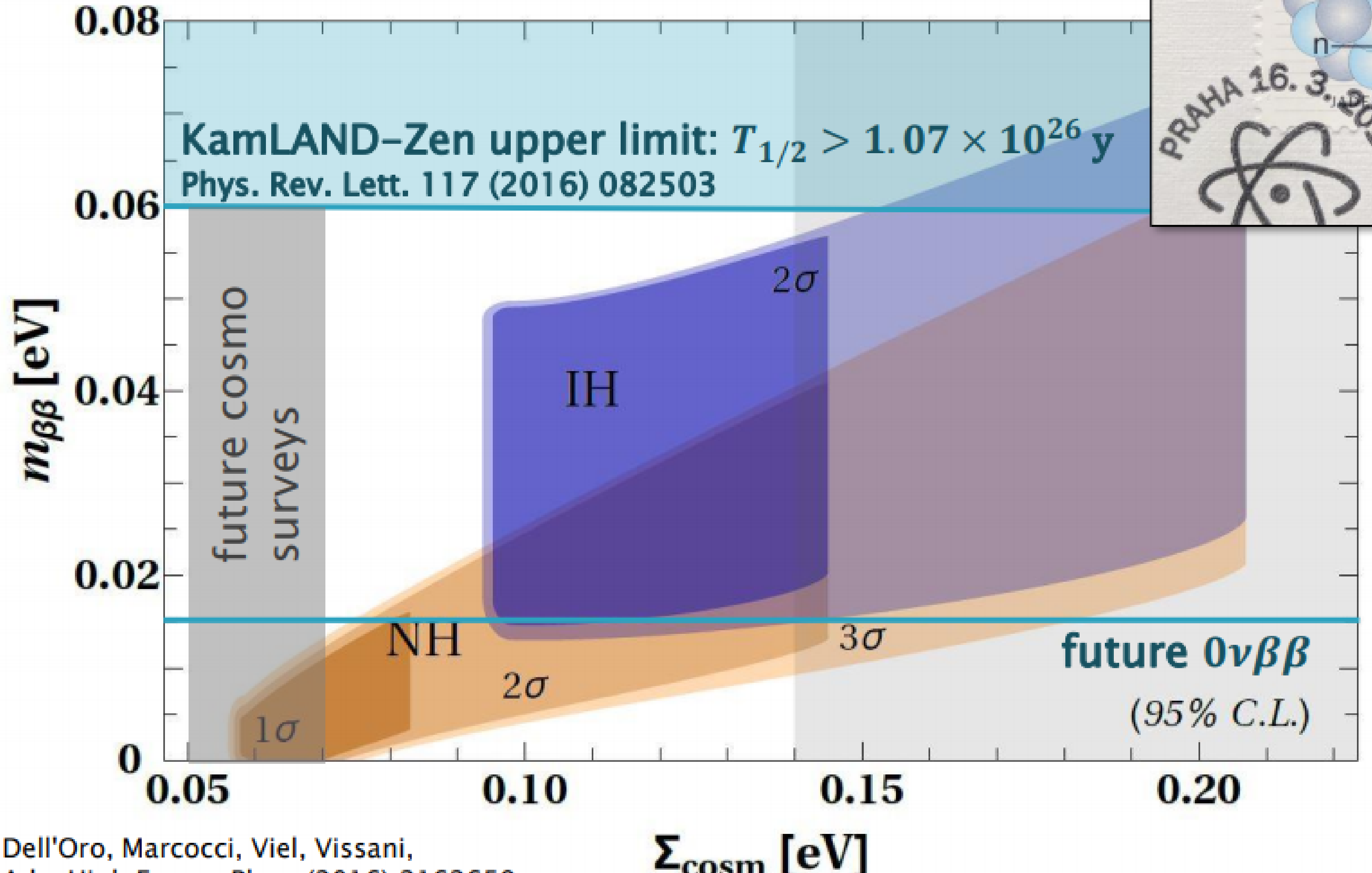


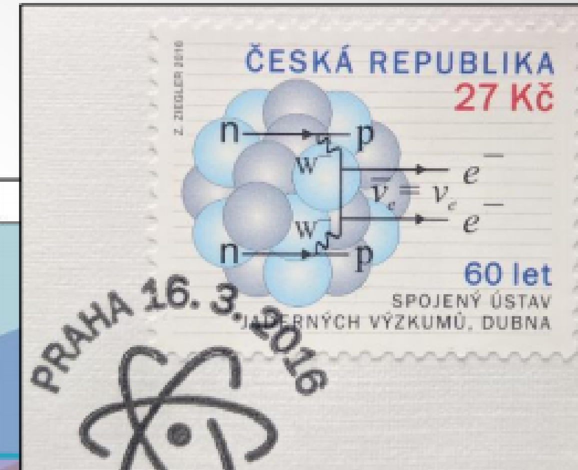
Gysbers et al.,
Nature Physics 15 (2019) 428

Fra

Experimental Sensitivity

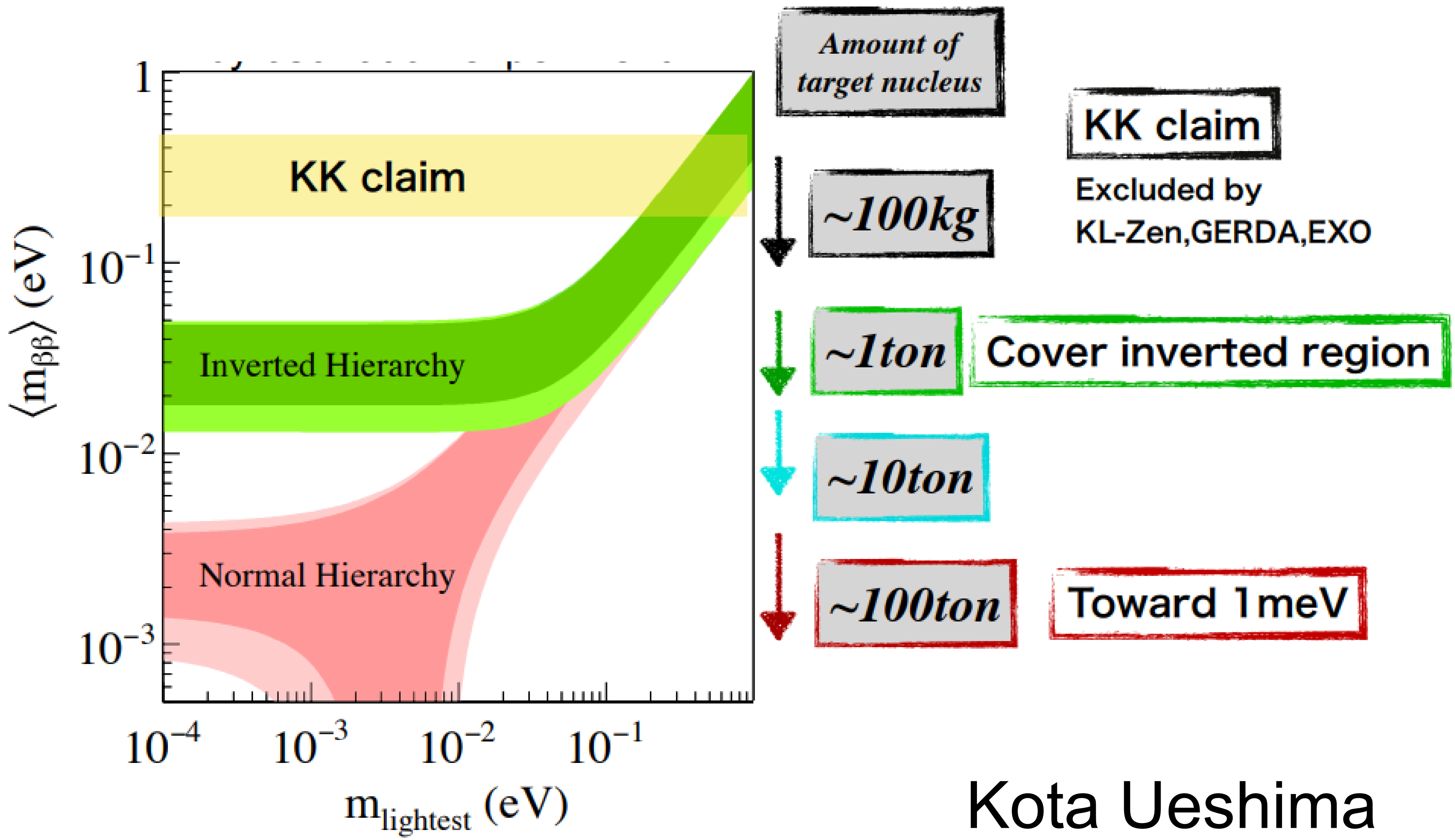
- Effective $0\nu\beta\beta$ Mass





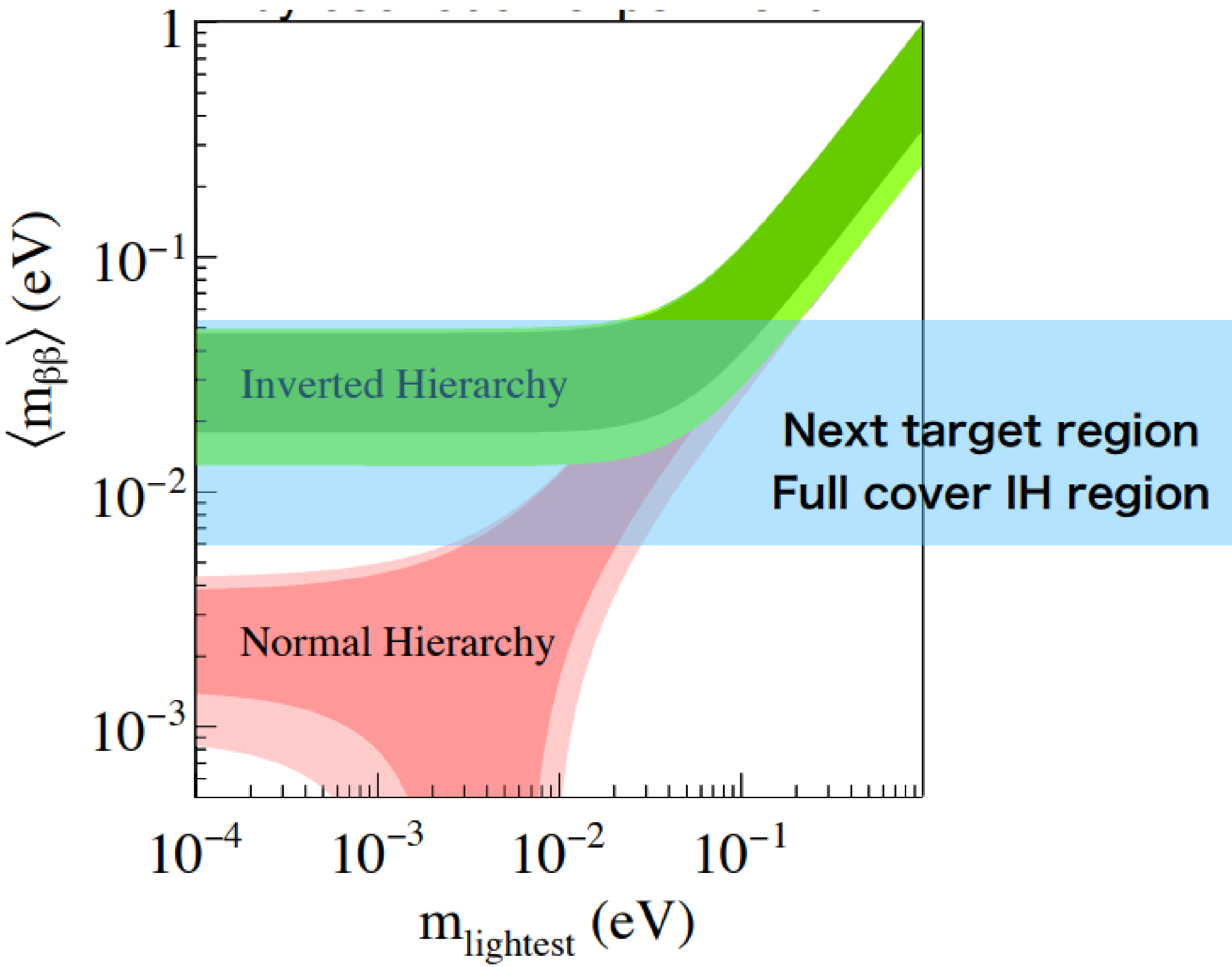
Dell'Oro, Marcocci, Viel, Vissani,
Adv. High Energy Phys. (2016) 2162659

Milestones of $0\nu 2\beta$ search



Kota Ueshima

Future experiments



- SuperNEMO
- AMoRE
- NEXT
- PandaX-III
- SNO+
- KL2-Zen
- LEGEND
- CUPID
- nEXO

Kota Ueshima

Background Index in BW

GERDA

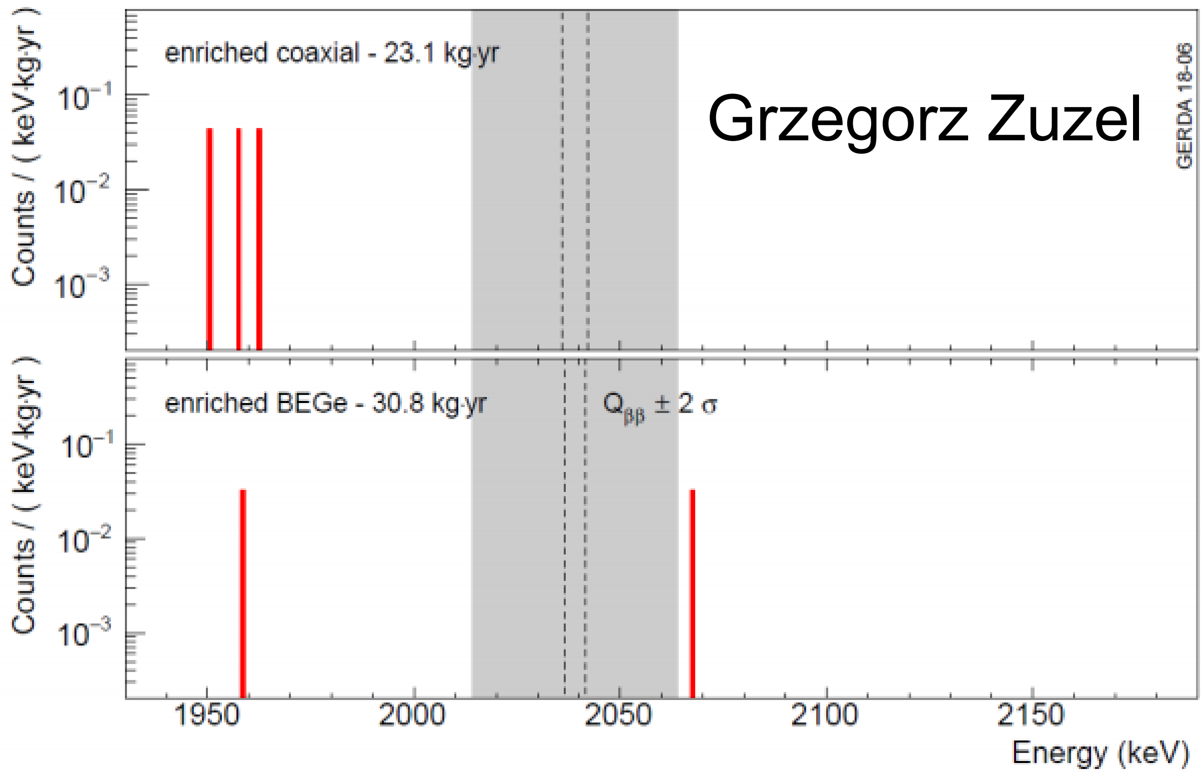
ββ decay

GERDA design

Bkg reduction

Latest results

Summary



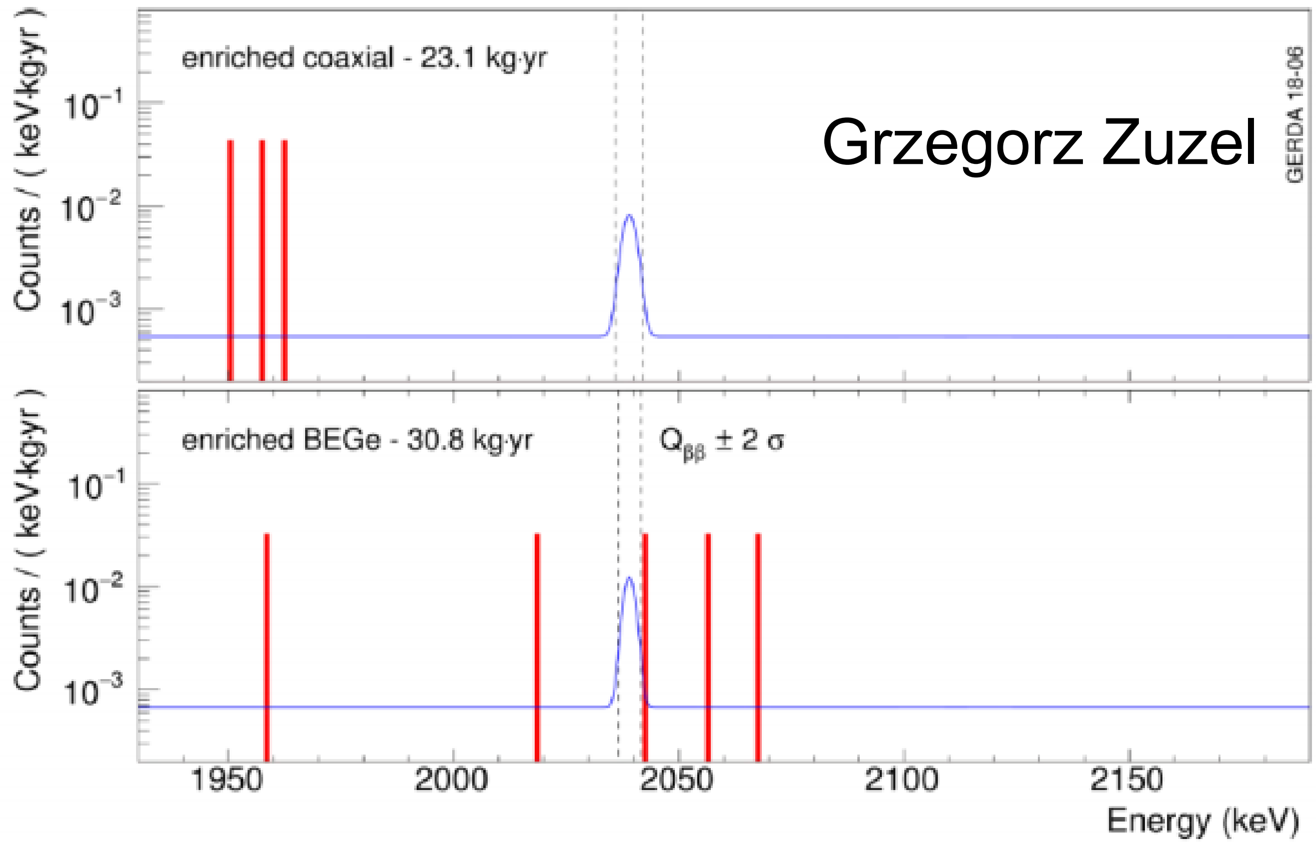
BW: [1930, 2190] keV, excl. ±5 keV around ^{208}Tl (SEP), ^{214}Bi (FEP) and $Q_{\beta\beta}$

Coax: $BI = 5.7^{+4.1}_{-2.6} \cdot 10^{-4}$ cts/(keV·kg·yr)

BEGe: $BI = 5.6^{+3.4}_{-2.4} \cdot 10^{-4}$ cts/(keV·kg·yr)

Less than 1 background event expected in ROI → background-free operation

Statistical Analysis



Frequentist:

– best fit $N_{0\nu} = 0$

– $T_{1/2}$ ($0\nu\beta\beta$) > 0.9×10^{26} yr, median sensitivity $T_{1/2}$ ($0\nu\beta\beta$) > 1.1×10^{26} yr at 90% C.L.

Bayesian:

– $T_{1/2}$ ($0\nu\beta\beta$) > 0.8×10^{26} yr, median sensitivity $T_{1/2}$ ($0\nu\beta\beta$) > 0.8×10^{26} yr at 90% C.I.

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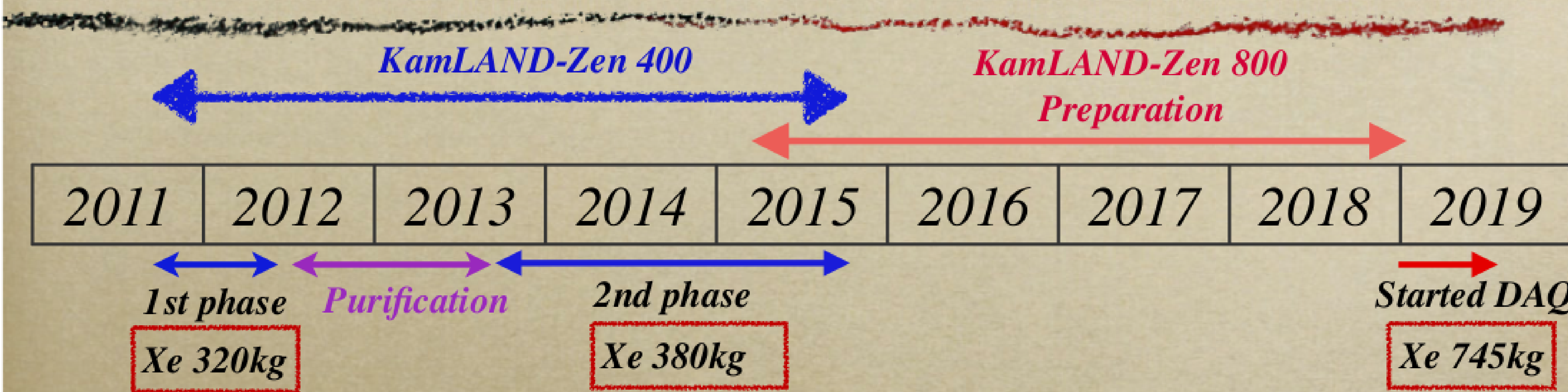
History



- *1st phase (Oct.2011- Jun.2012)* ***PRL 110, 062502(2013)***
- *Purification (Jun.2012-Nov.2013) Xe extraction, Xe purification, LS purification.*
- *2nd phase (Dec.2013- Oct.2015)*
  Latest 0ν2β result was released in 2016. ***PRL 117, 082503(2016)***
- *Preparation for KamLAND-Zen 800 phase was started in 2015*
  (Zen 400 mini-balloon extraction, new mini-balloon production, extracted xenon & new xenon purification)
- *KamLAND-Zen 800 phase was started. Jan.2019 -*

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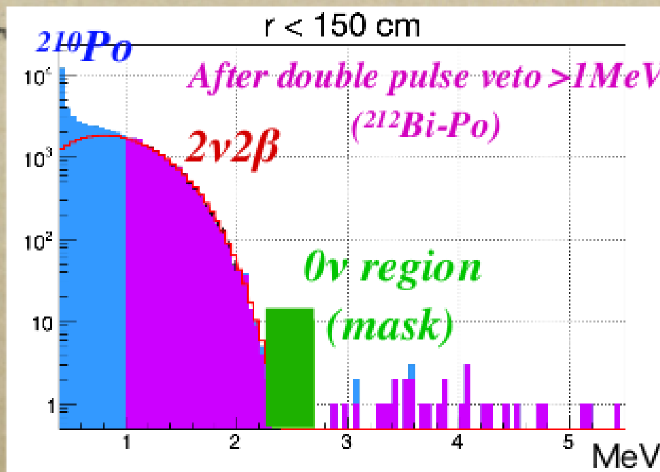
0ν2β search status

Energy spectrum after ^{214}Bi-Po veto



No strange BG!!

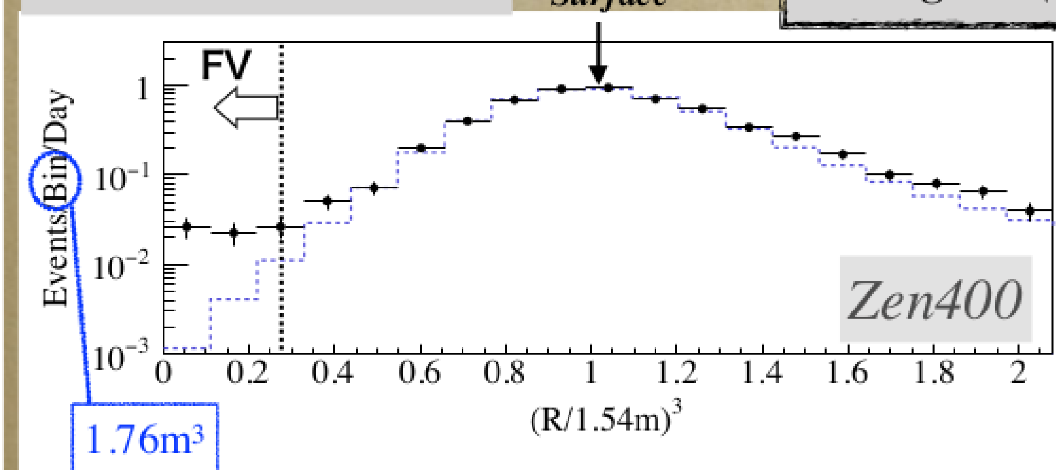
Mini-balloon was clean!!   ~1/10 low BG

FV will be increased to 3~4 times of Zen400.

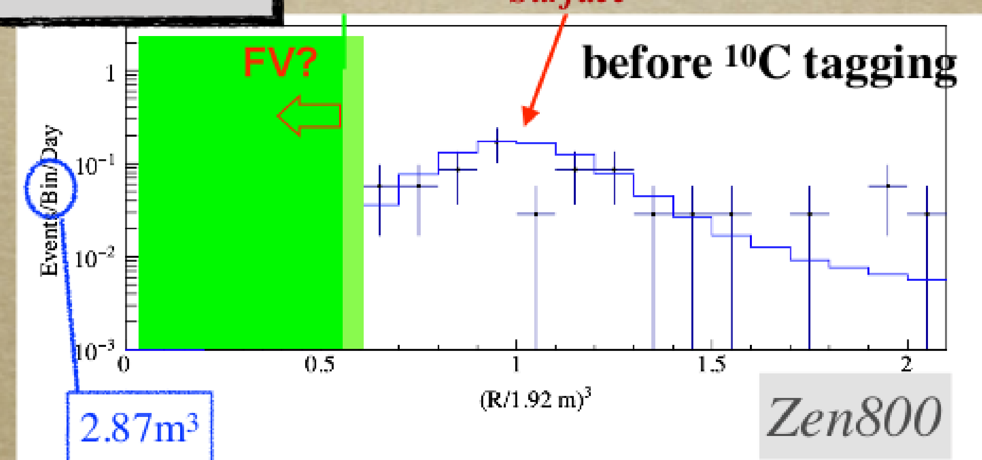
r^3 event distribution

Surface

0ν region (2.3~2.7MeV)



Surface



Target Sensitivity : $\langle m_{\beta\beta} \rangle$ ~ 40meV   (5yr data taking)

DISCUSSION

Is there a right-handed (‘sterile’) neutrino in the eV range?

Alain Blondel. My views and a few others

Conclusions

- Neutrinos can be powerful messengers of new physics beyond the SM as the existence of light sterile neutrinos indicated by the reactor, Gallium and LSND anomalies.
- Exciting 2018 model-independent indication of light sterile neutrinos at the eV scale from the NEOS and DANSS experiments in approximate agreement with the reactor and Gallium anomalies.
- 2019 DANSS data do not confirm the 2018 indication and the reactor indications in favor of SBL oscillations seem to be fadind away.
- Important checks in the near future by the reactor experiments PROSPECT, STEREO, SoLid. (Neutrino-4?)
- Independent tests through the effect of m_4 in β-decay (KATRIN), electron-capture (ECHo, HOLMES) and $\beta\beta_{0\nu}$-decay experiments.
- The MINOS+ bound (if correct) disfavors the LSND and MiniBooNE short-baseline $\nu_\mu \to \nu_e$ signals.

?

- Status of Light Sterile Neutrinos? They do not seem to feel well.

Alain Blondel

Right Handed Neutrinos

Sin Kyu Kang (Seoul Tech.)
August 4-10, 2019, Quy Nhon, Vietnam

15th Recontres du Vietnam

How do we find ν_R ?

- Introduction of ν_R leads to a modification of the leptonic C.C. Lagrangian

$$\frac{g}{\sqrt{2}}\mathbf{U}^{ji}\bar{\ell}_j\gamma^\mu P_L\nu_i W_\mu^- + \text{c.c.}$$

j=physical neutrino states, i=1,2,3 (charged lepton flavor)

-For SM, U corresponds to the 3x3 unitary matrix $U_{\rm PMNS}$

-For SM+ν_R : U is deviated from unitarity

- The overall 6x6 mass matrix can be diagonalized by a unitary matrix

$$\begin{pmatrix} V & R \\ S & U \end{pmatrix}^\dagger \begin{pmatrix} M_{\rm L} & M_{\rm D} \\ M_{\rm D}^T & M_{\rm R} \end{pmatrix} \begin{pmatrix} V & R \\ S & U \end{pmatrix}^* = \begin{pmatrix} \widehat{M}_\nu & \mathbf{0} \\ \mathbf{0} & \widehat{M}_{\rm N} \end{pmatrix}$$

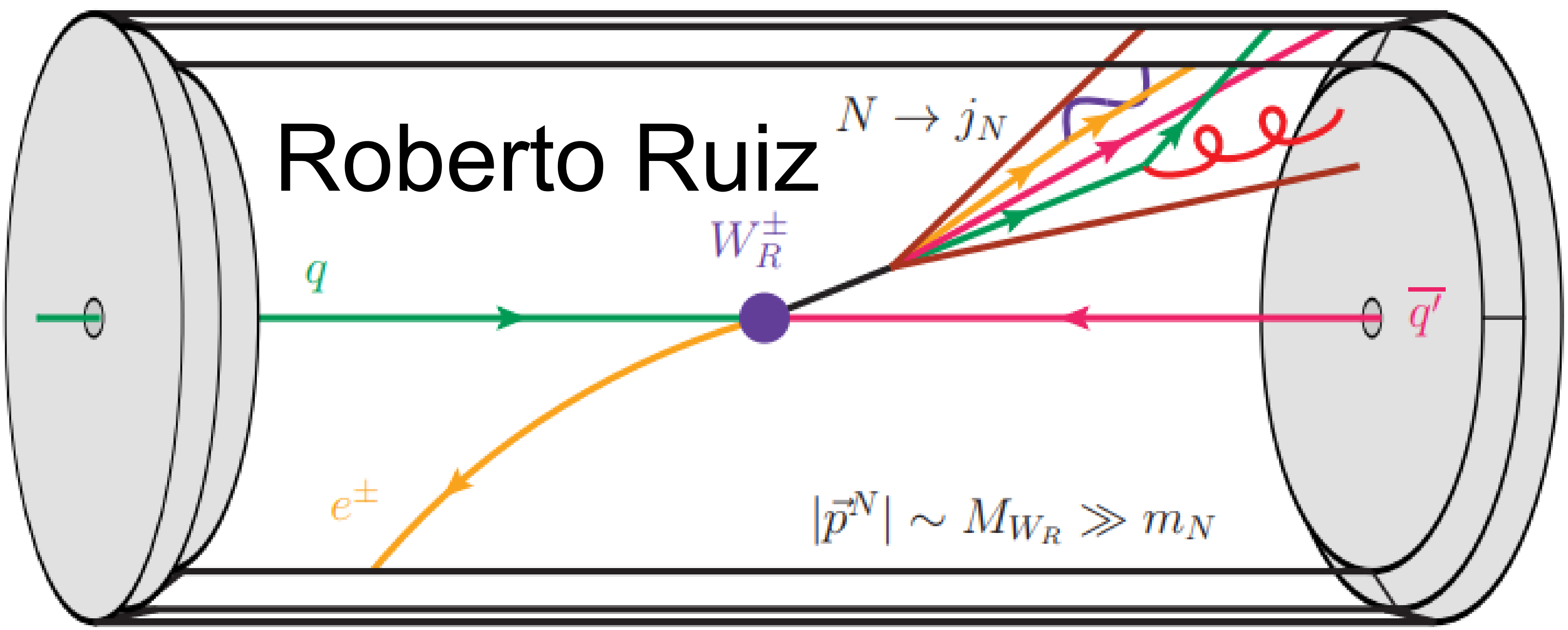
Sin Kyu Kang

For a $1 \to 2$ decay, $m_{ij}^2 = (p_i + p_j)^2 \approx 2E_iE_j(1 - \cos\theta_{ij}) \approx E_iE_j\theta_{ij}^2$

$$\Rightarrow \text{Angle between } e \text{ and } (q\overline{q'})\text{-system} = \theta_{e(q\overline{q'})} \sim \frac{m_N}{\sqrt{E_iE_j}} \sim \frac{4m_N}{M_{W_R}}$$

As (m_N/M_{W_R}) shrinks, N is more boosted, and its decay *more collimated:*

For $\left(\frac{m_N}{M_{W_R}}\right) < 0.1, \theta_{e(q\overline{q'})}$ falls below det. isolation threshold, $\theta_{\ell X}^{\min} = 0.4$

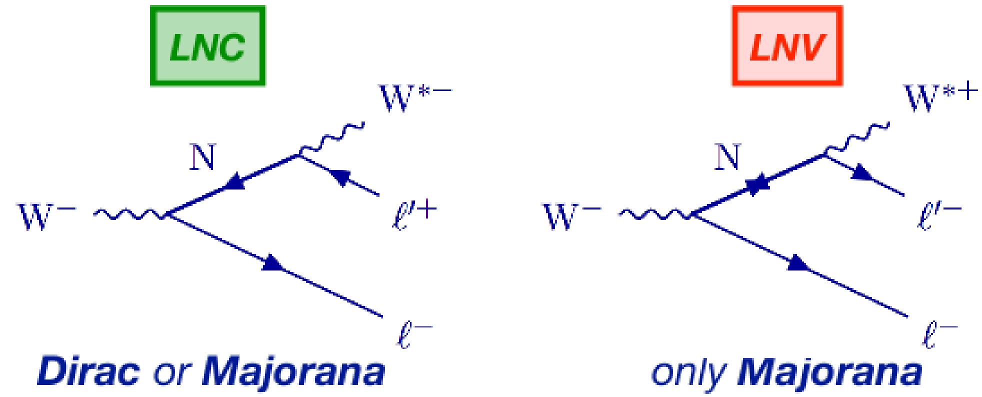


Fun Idea: Why not treat second $e^\pm$ like any other poorly isolated particle bathed in QCD radiation and label it as constituent of a jet?

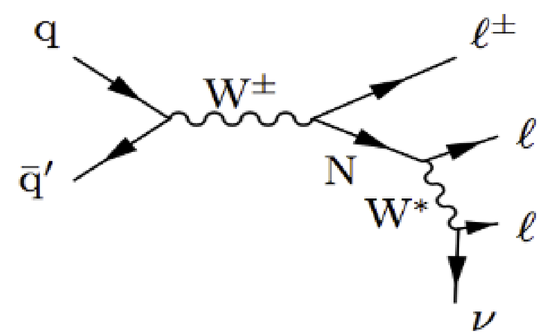
w/ Mitra, Scott, Spannowsky, PRD ('17) [1607.03504], w/ Mitra, Mattelaer [1607.03504]

Type-I: HNL production & decay

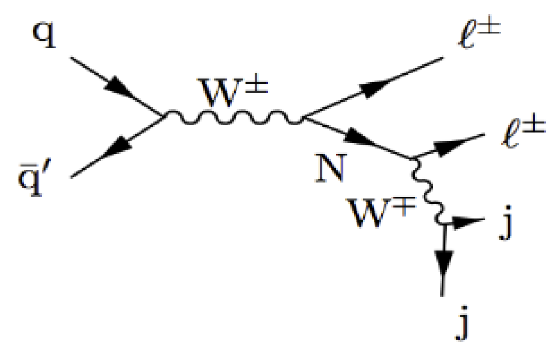
- Two parameters: HNL mass m_N and ν_ℓ-N mixing angle $|V_\ell|^2$
- Produced from W boson decays
- **Conserving** or **violating** lepton number



- Possible final states
  - $3\ell + \nu$: lower background, but no m_N peak



  - $2\ell + 2q$: large background, m_N measurable



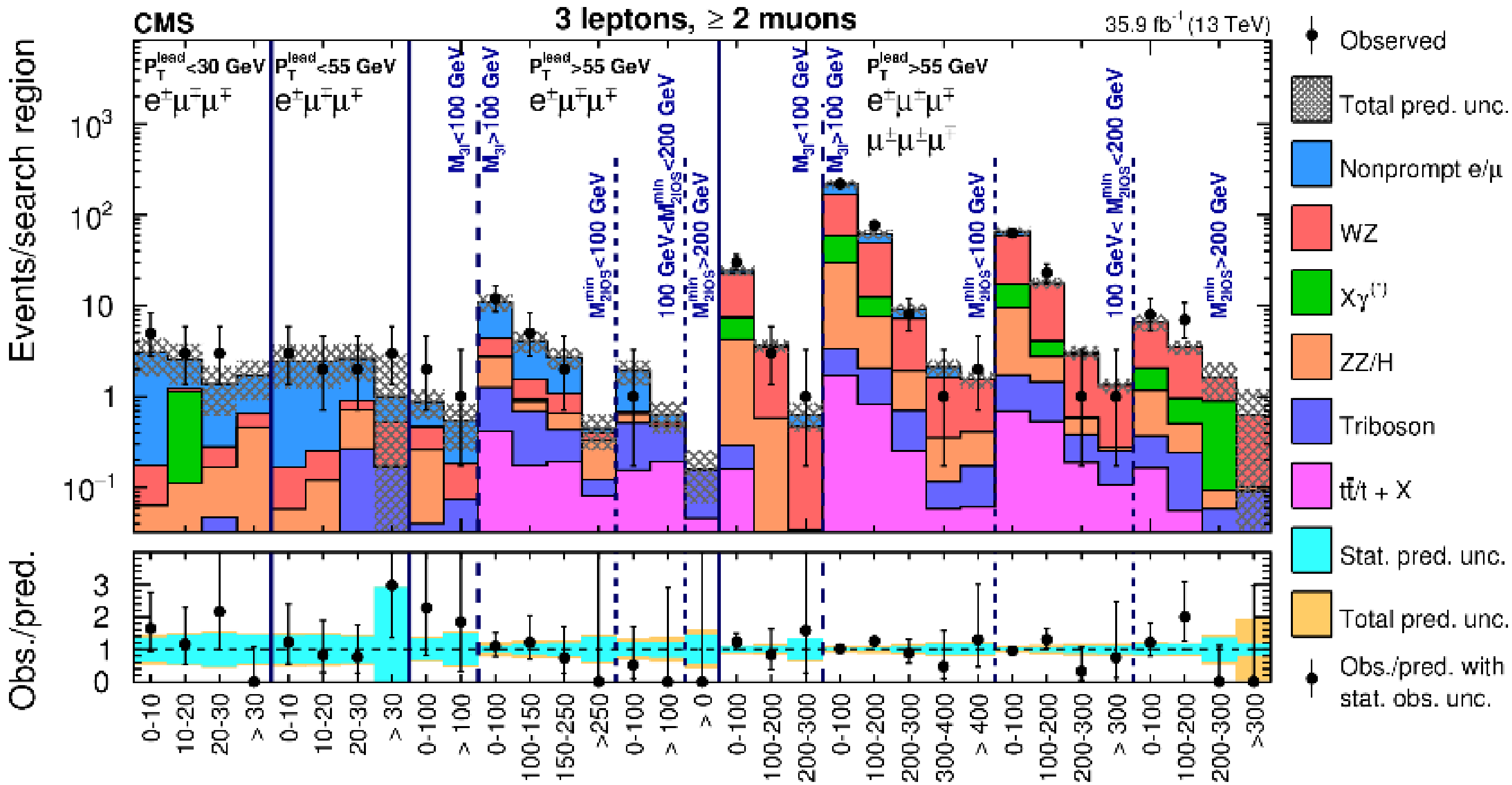
Daniele Torcino

Type-I: trilepton channel (CMS)

Phys. Rev. Lett. 120, 221801 (2018)

- Search for Majorana HNLs mixing with e and μ, with $m_N = 1$ GeV–1.2 TeV
  - 33 search categories to target a large variety of kinematics ($m_N < m_W$ or $m_N > m_W$)
  - categorize by lepton p_T, 2ℓ and 3ℓ invariant mass, MET, presence of a lepton pair with opposite sign and same flavor (OSSF)

$\int L = 36\ \mathrm{fb}^{-1}$

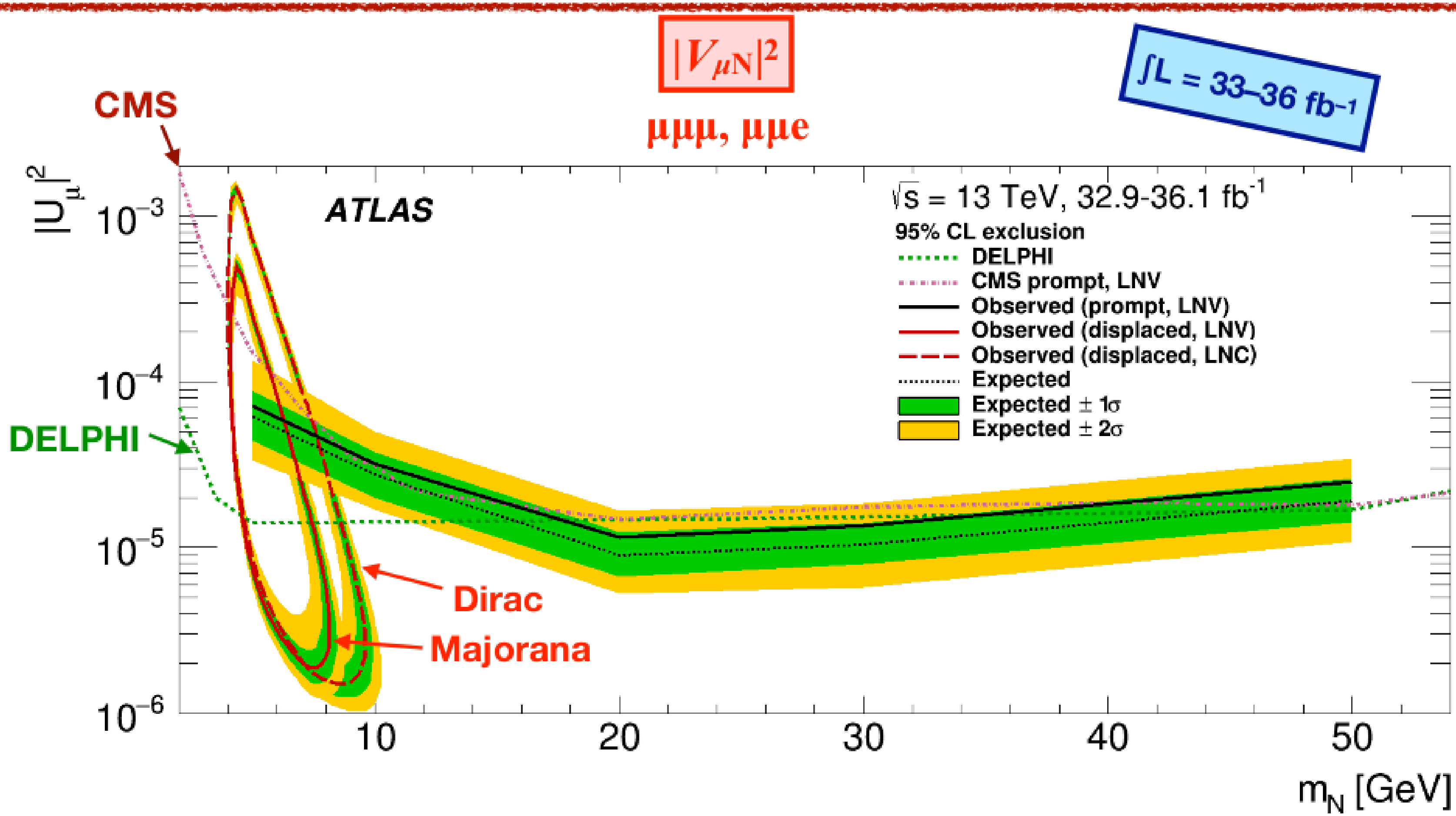


$m_N < m_W$ $m_N < m_W$

no-OSSF OSSF

Daniele Torcino

Type-I: trilepton channel (ATLAS)



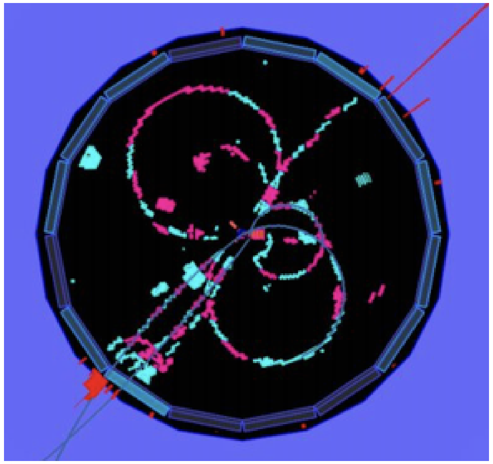
- First HNL search at ATLAS+CMS using displaced vertices!
- Majorana HNL has 1/2 lifetime than Dirac HNL ⇒ weaker limits
- Width of the limit contour corresponds to decay lengths of 1–30 mm

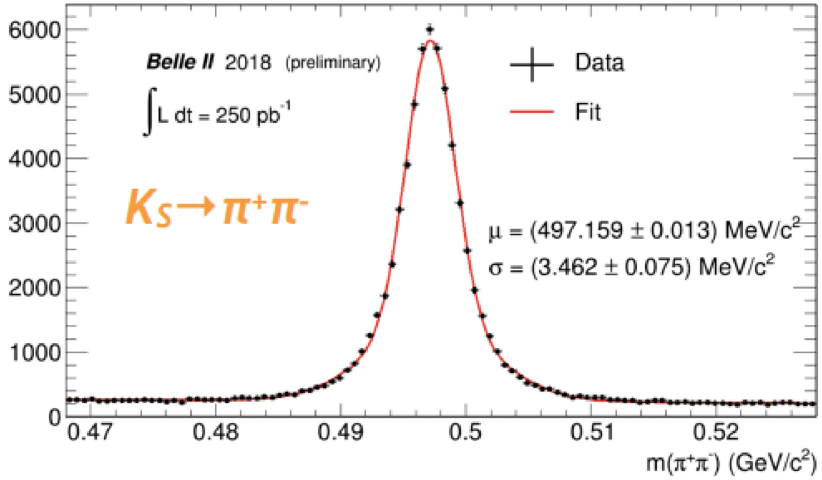
arXiv:1905.09787v1 [hep-ex]

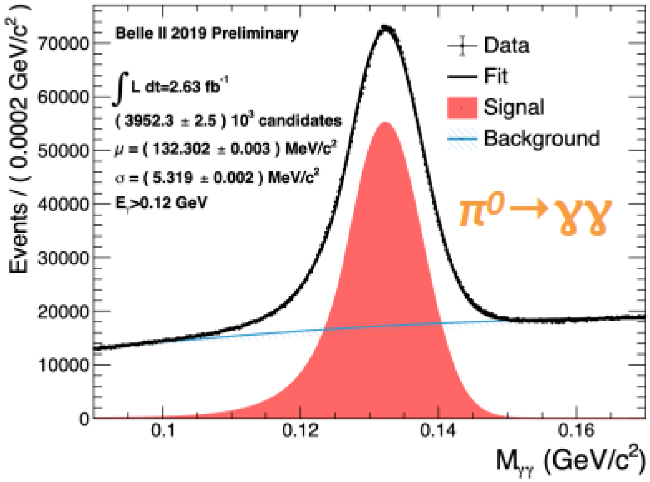
Daniele Torcino

First collisions @ Belle II

- First collisions recorded by Belle II on 26th April 2018
- During **Phase 2** (April-July 2018) about ~**0.5 fb^{-1}** of data was recorded
- **Phase 3** since March 2019 with ~**6.5 fb^{-1}** so far
- Good performance of the subsystems. Clear mass peaks observed from both tracks and photons.







Peter Rados

Limits on $N \leftrightarrow \nu_{e,\mu}$ mixing

- Number of HNL decays detected by Belle:

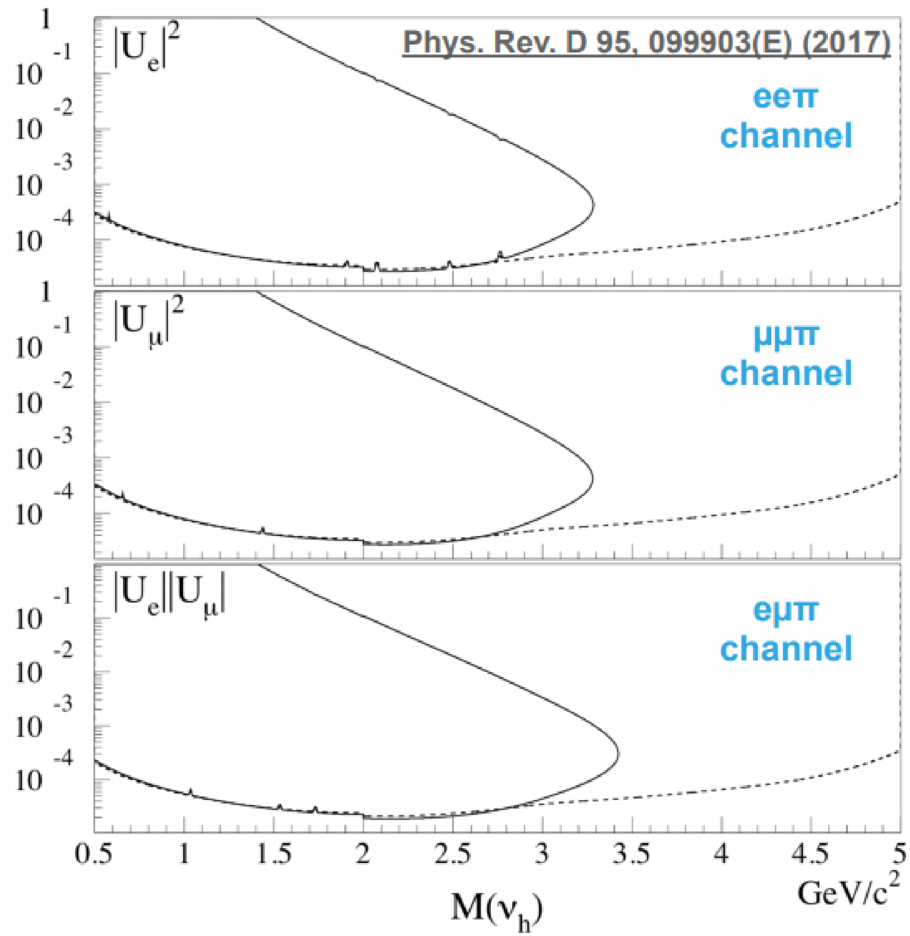
$$n(\nu_h) = 2N_{BB}\,\mathcal{B}(B \to \nu_h)\,\mathcal{B}(\nu_h \to \ell\pi) \int \frac{m\Gamma}{p} \exp\left(-\frac{m\Gamma R}{p}\right)\varepsilon(R)dR$$
$$= |U_\alpha|^2|U_\beta|^2\,2N_{BB}\,f_1(m)\,f_2(m)\,\frac{m}{p}\int \exp\left(-\frac{m\Gamma R}{p}\right)\varepsilon(R)dR$$

⇒ solved for $|U|^2$ to obtain upper limits

- Total systematic uncertainty of **25.0%** and **25.4%** for small and large-mass regimes. Largest contributions:
  - χ^2/ndof and dz vertex cuts (10.1%, 10.0%)
  - tracking of HNL daughter particles (8.7% per-track)

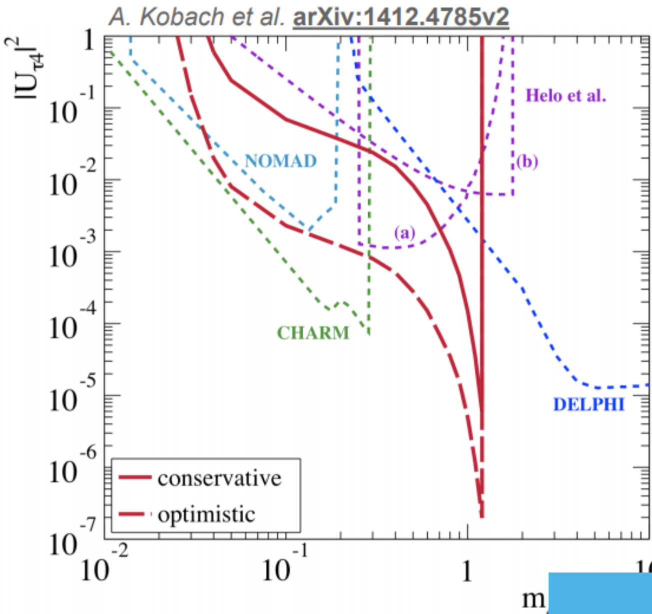
- Maximum sensitivity at $M_N \simeq 2$ GeV
  - **3.0×10^{-5}** for $|U_{eN}|^2$ and $|U_{\mu N}|^2$
  - **2.1×10^{-5}** for $|U_{eN}|\,|U_{\mu N}|$

$$\mathcal{B}(B \to X\ell\nu_h) \times \mathcal{B}(\nu_h \to \ell\pi^+) < 7.2 \times 10^{-7}$$



Peter Rados

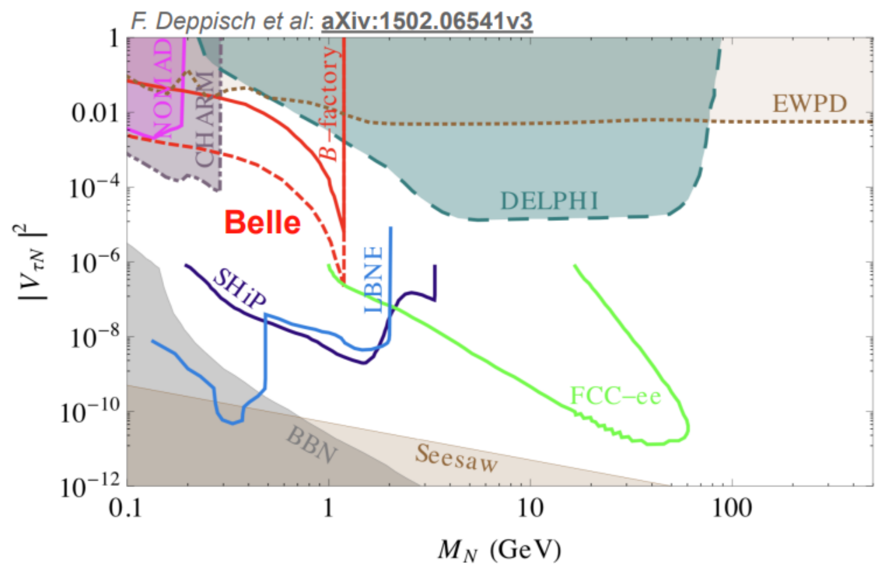
HNL in τ decay kinematics



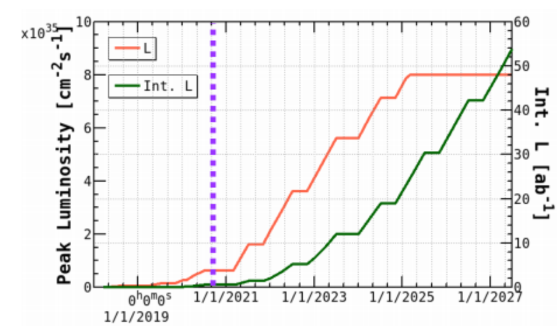
- Sensitivity estimate based on pseudo-data study
- MC sample of ee→ττ with τ→3πν decay(s)
  - assuming Belle lumi, √s=11 GeV
  - smearing to mimic typical Belle resolution
  - both optimistic and conservative scenarios wrt systematics
- **Belle** may be able to place stringent limits on $|U_{\tau N}|^2$ as low as $\mathcal{O}$(**10^{-7} - 10^{-3}**) for **100 MeV ≲ M_N ≲ 1.2 GeV**

Peter Rados

Belle vs upcoming experiments



- **Belle** (1 ab^{-1}) compared to future experiments (**SHiP**, **LBNE**, **FCC-ee**)



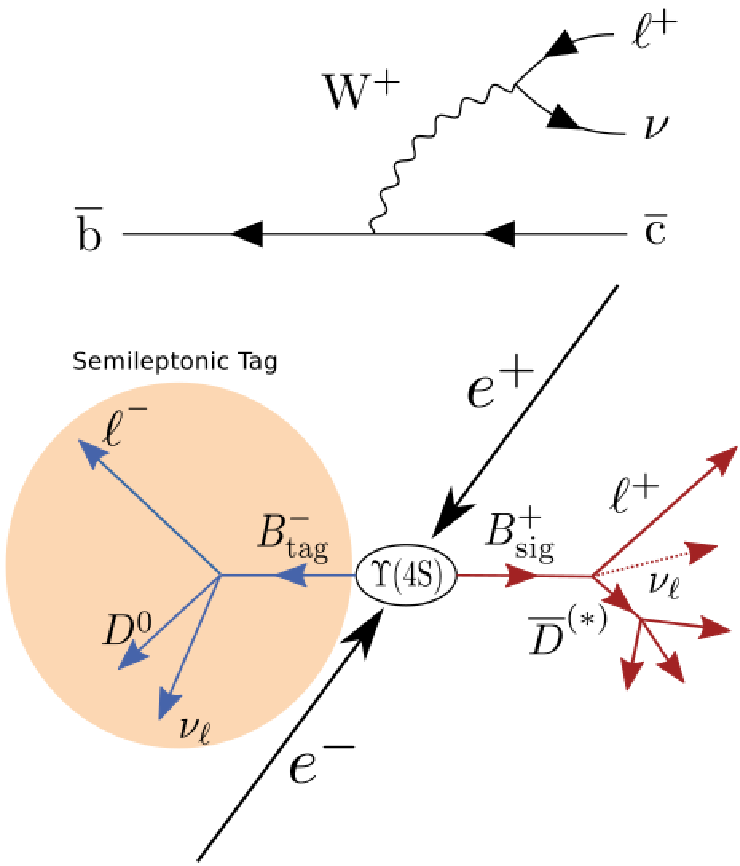
- **Belle II should exceed Belle in 2020** (50x statistics by 2027)

Tag-Side Reconstruction and Selection

- B_{tag} is reconstructed in $D\ell\nu$ and $D^*\ell\nu$ decay chains (semileptonic tag).
- Good tags identified by classifier output.
- Veto for $B \to D^*\tau(\to \ell\nu\nu)\nu$ via

$$\cos\theta_{B,D^{(*)}\ell} = \frac{2E_{\mathrm{beam}}E_{D^{(*)}\ell} - m_B^2 - m_{D^{(*)}\ell}^2}{2|\vec{p}_B||\vec{p}_{D^{(*)}\ell}|}.$$

- Correctly reconstructed B candidates are found in $\cos\theta_{B,D^{(*)}\ell} = [-1, 1]$.
- Mis-reconstructed $B \to D^*\tau(\to \ell\nu\nu)\nu$ decays have larger negative values.

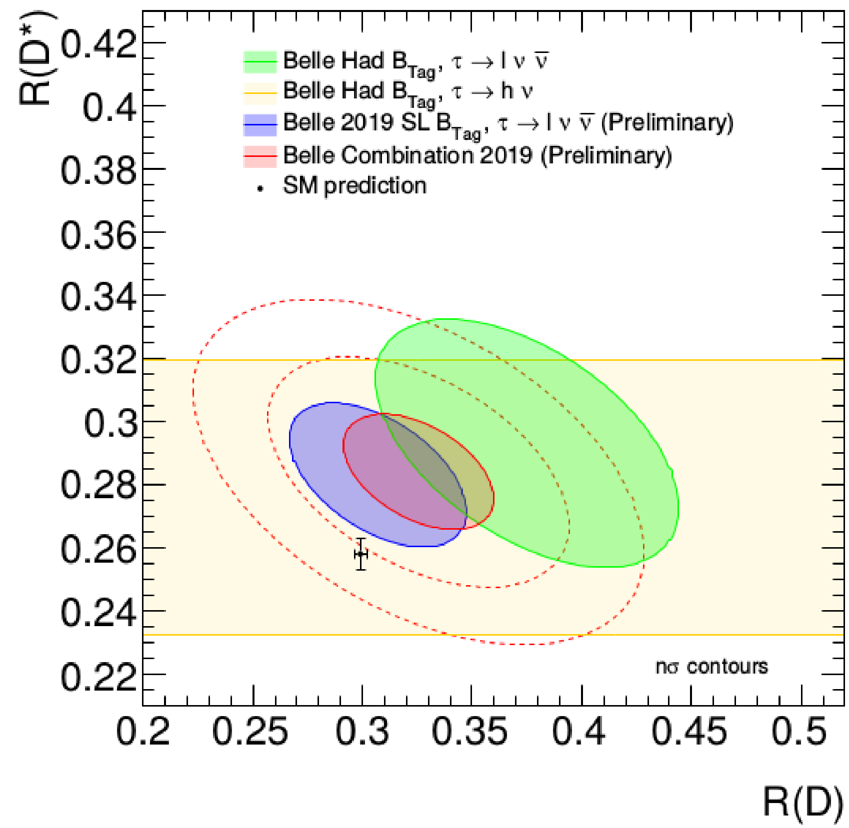


Markus Prim

Results

$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

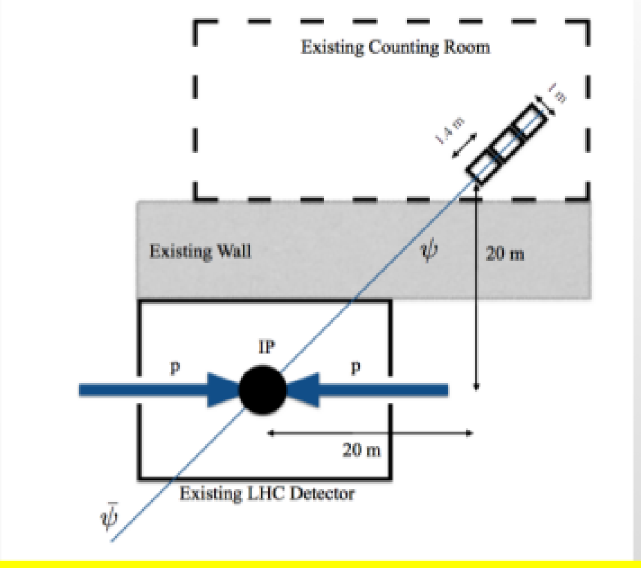
- SM agreement: $1.2\,\sigma$.
- **First result for $\mathcal{R}(D)$ with semileptonic tagging.**
- **Most precise determination of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ to date.**



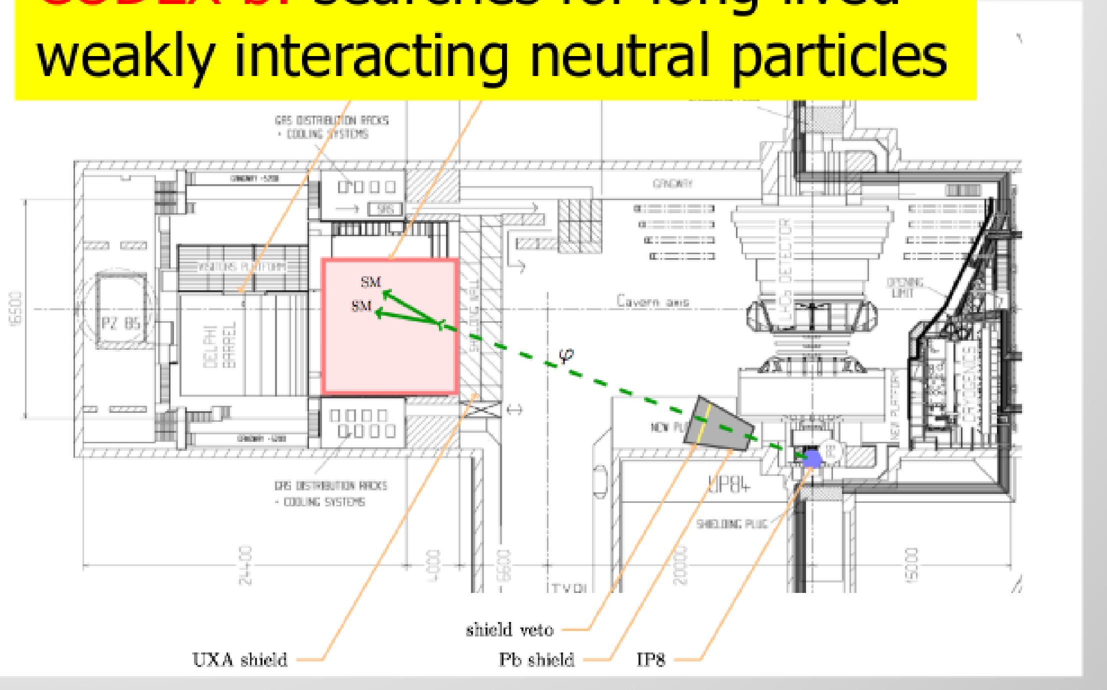
Markus Prim

Proposals for New Experiments @LHC

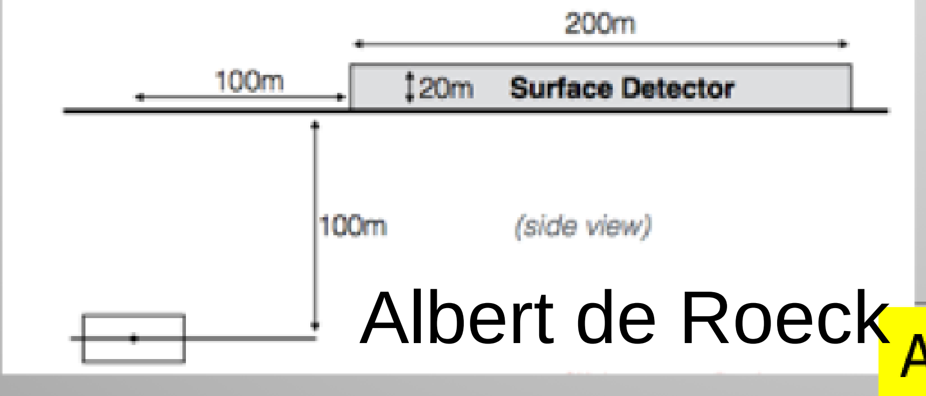
MilliQan: searches for milli-charged particles
MAPP: Same from MoEDAL



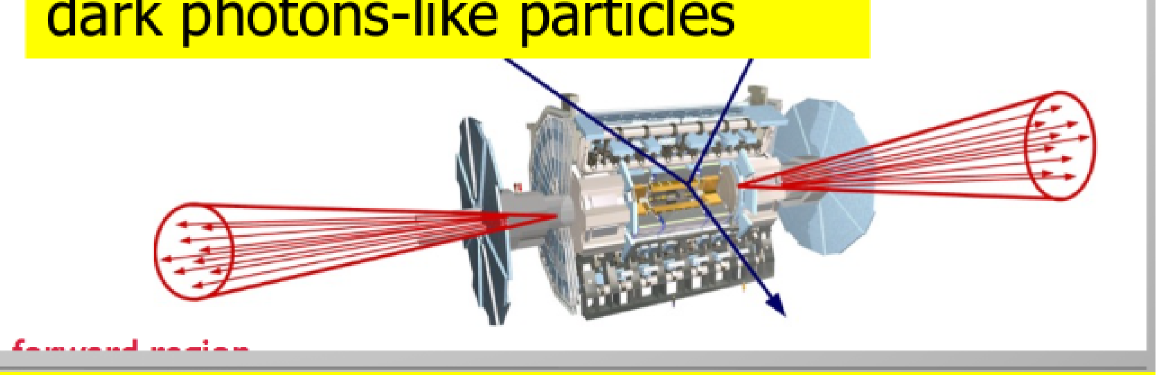
CODEX-b: searches for long lived weakly interacting neutral particles



MATHUSLA: searches for long lived weakly interacting neutral particles



FASER: searches for long lived dark photons-like particles



Albert de Roeck

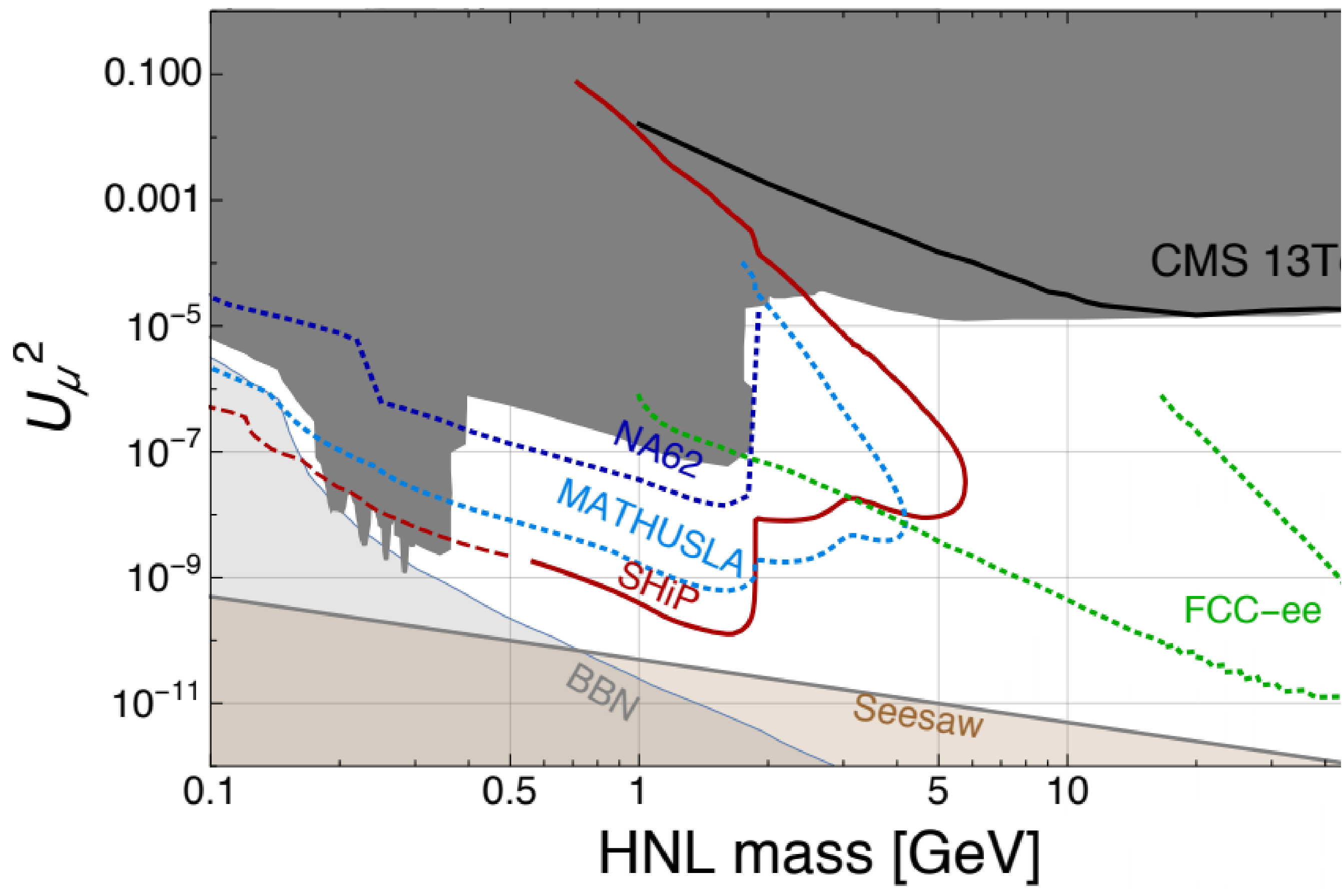
Also: AL3X ('ALICE' for LLP arXiv.1810.03636)...

Sensitivity

- Showing case

$$U_e^2 : U_\mu^2 : U_\tau^2 = 0 : 1 : 0$$

- B_c-contribution not knownat SHiP energy → showing upper and lower limits
- Covering large parts of the cosmologically interesting parameter space up to B threshold
- Complementary to



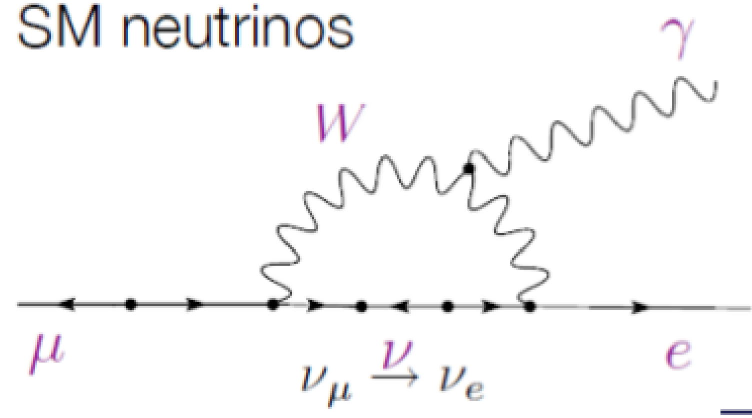
Dedicated paper: [JHEP 1904 (2019) 077]

Oliver Lantwin

Why are these processes so sensitive to BSM ?
First: cLFV in the SM are NOT observable

In pre-ν oscillations SM cLFV (charged Lepton Flavor Violating) amplitudes are 0 due to the fact that neutrino masses are 0

SM neutrinos



$\mu \to e\gamma$ rate in the standard model after neutrino oscillations

$$P_{osc} \approx \sin^2\left(\delta m_\nu^2 \frac{L}{E}\right); L \approx \frac{1}{M_W}; E \approx M_W$$

$$BR \sim \alpha P_{osc} \sim \alpha\left(\frac{\delta m_\nu^2}{M_W^2}\right)^2 \quad ; \delta m_\nu^2 \sim 10^{-5} eV^2 \Rightarrow BR \sim 10^{-55}$$

$$\frac{3\alpha}{32\pi}\left|\sum_{k=1,3}\frac{U_{\mu k}U^*_{ek}m^2_{\nu_k}}{M_W^2}\right|^2.$$

cLFV are VERY clean channels for new physics searches

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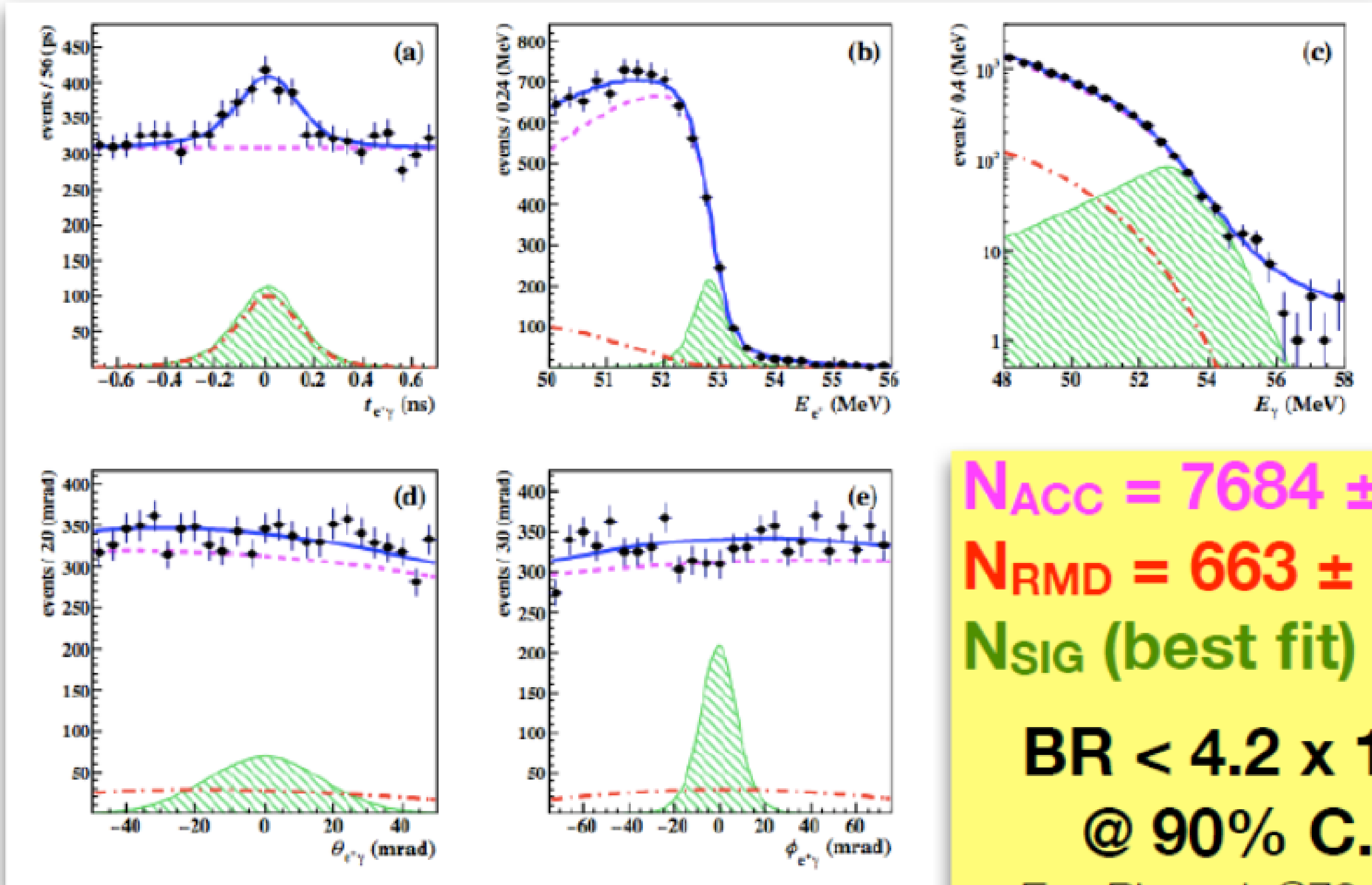
A more quantitative comparison...



N_{ACC} = 7684 ± 103

N_{RMD} = 663 ± 59

N_{SIG} (best fit) = -2.2

BR < 4.2 x 10^{-13}

@ 90% C.L.

Eur. Phys. J. C76 (2016)

Magnified signal (BR = 4 x 10^{-11})

The relative angle is split into zenith and azimuth

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Final sensitivity of 6×10^{-14}

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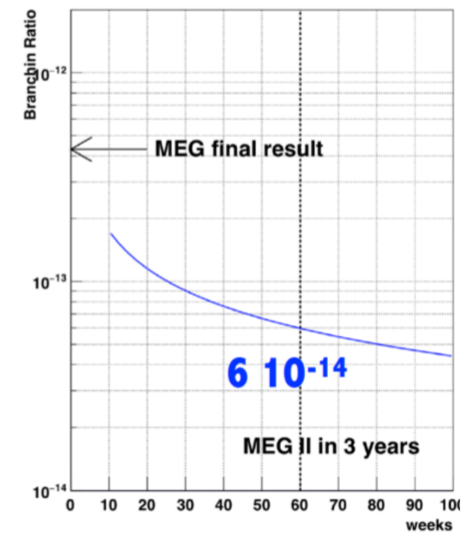
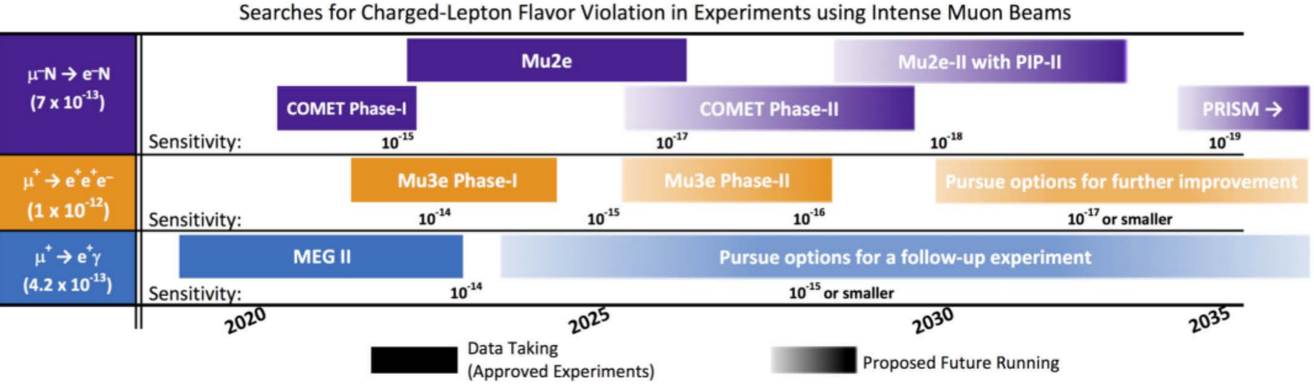
PDF parameters	MEG	MEG II
E_{e^+} (keV)	380	130
θ_{e^+} (mrad)	9.4	5.3
ϕ_{e^+} (mrad)	8.7	3.7
z_{e^+}/y_{e^+} (mm) core	2.4/1.2	1.6/0.7
$E_\gamma(\%)$ (w>2 cm)/(w<2 cm)	2.4/1.7	1.1/1.0
$u_\gamma, v_\gamma, w_\gamma$ (mm)	5/5/6	2.6/2.2/5
$t_{e^+\gamma}$ (ps)	122	84
Efficiency (%)		
Trigger	≈ 99	≈ 99
Photon	63	69
e^+(tracking × matching)	30	70

$$B_{acc} \propto R_\mu \Delta E_e \Delta E_\gamma^2 \Delta\Theta_{e\gamma}^2 \Delta t_{e\gamma}$$



Schedule of the muon LFV experiments

Searches for Charged-Lepton Flavor Violation in Experiments using Intense Muon Beams



Input to Eur. Particle Physics Strategy
"Charged Lepton Flavour Violation using Intense Muon Beams at Future Facilities"

Thank you all for coming!!!