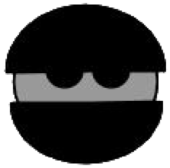
The hidden side of particle physics

Philippe Mermod
University of Geneva, 11 January 2018

The most conspicuous mysteries of the Universe

- What is dark matter made of?



- Where do neutrino masses come from?

- Where is the antimatter gone?

The neutrino

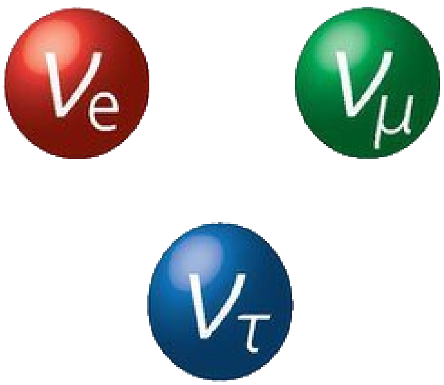
- Neutral lepton, produced in weak decays
- More than 1’000’000 times lighter than the electron
- Different neutrino species mix with each other

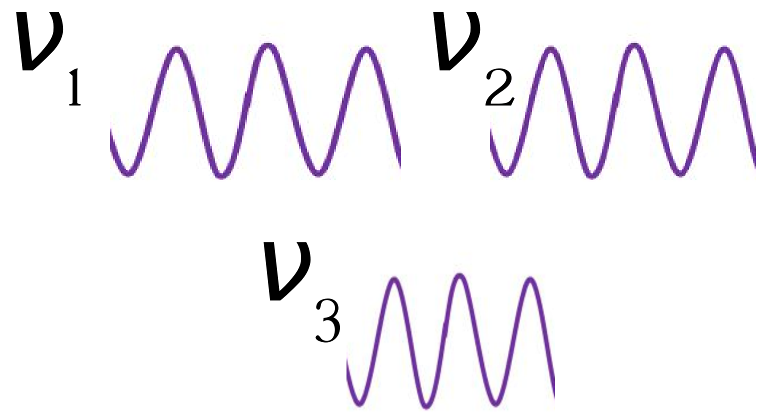
Flavour (α = e,μ,τ) and mass (k = 1,2,3) states

While interacting

(production/detection)

While propagating





$$| \nu_\alpha \rangle = \sum_k U_{\alpha k} \, | \nu_k \rangle$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

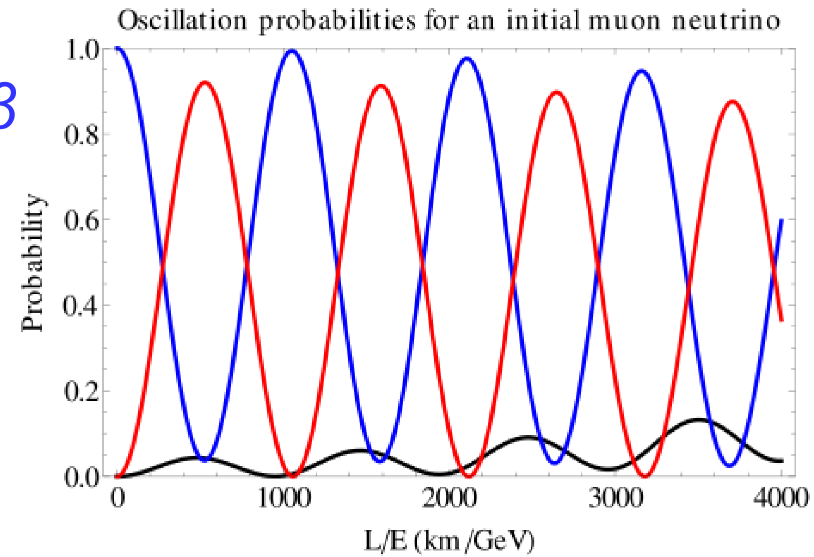
U: PMNS matrix or neutrino mixing matrix

Neutrino oscillations

- Transition probability from α to β

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha \rangle|^2$$

$$\approx \left| \sum_k U^*_{\alpha k} U_{\beta k} e^{-i m_k^2 L/(2E)} \right|^2$$



$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin(\theta_{13})e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin(\theta_{13})e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Solar neutrinos $\nu_e \to \nu_\mu$ $\to \theta_{12}$
- Atmospheric neutrinos $\nu_\mu \to \nu_\tau$ $\to \theta_{23}$
- Reactor neutrinos $\bar{\nu}_e \to \bar{\nu}_\tau$ $\to \theta_{13}$
- Accelerator neutrinos $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ $\to \delta$

Neutrino masses

The Nobel Prize in Physics 2015

Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2

Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

How do we know that neutrinos have masses?

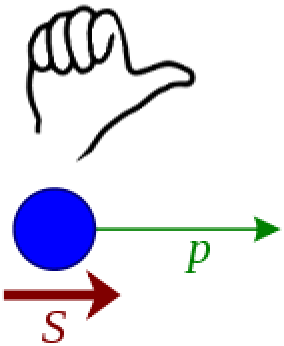
➔ They oscillate!

Why is this so important?

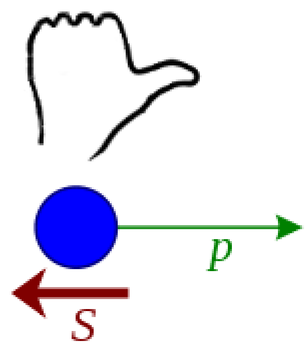
➔ It implies new physics!

Reminder: helicity and chirality of fermions

- Helicity: spin direction with respect to movement



"right handed"
(R)



"left handed"
(L)

  - If $v < c$, the helicity depends on the frame of reference
- Chirality: intrinsic property of a particle, equivalent to helicity in the relativistic limit
- Quirk of physics: weak interactions act only on particles with "left-handed" chiralities!
  - Hence one can only produce left-handed neutrinos
  - Right-handed neutrinos do not exist in the Standard Model

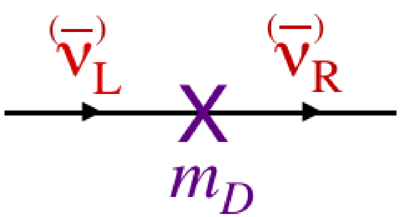
Dirac mass
⇕
Coupling to Higgs field

- Like for other fermions, one can give a Dirac mass to the neutrino with a term that couples it to the Higgs field and relates left- and right-handed chiralities:

Vacuum expectation value

$$yH\bar{\nu}_R\nu_L \Rightarrow y\langle H\rangle_0\bar{\nu}_R\nu_L \equiv m_D\bar{\nu}_R\nu_L$$

Yukawa coupling constant   Dirac Mass



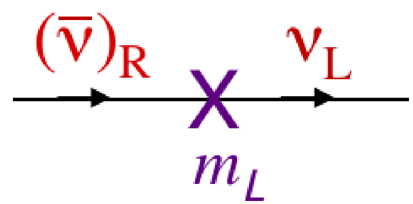
- Effect: chirality inversion
- Implication: existence of right-handed neutrino
  - New physics!

Majorana mass

- Being electrically neutral, the neutrino is the only fermion which can possess a term which relates particle and anti-particle:

$$m_L \overline{\nu_L} \nu_L^c$$

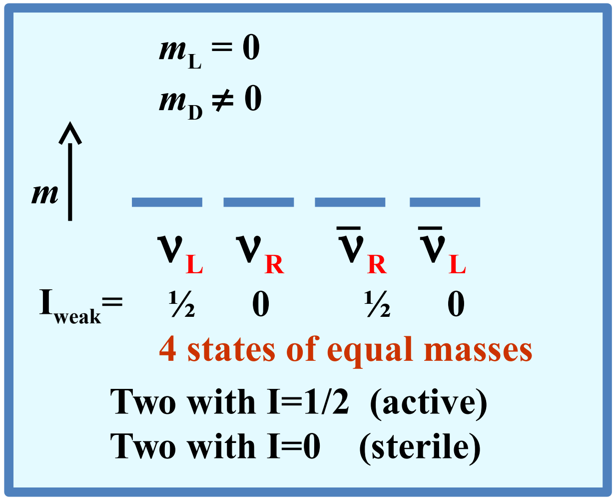
Majorana mass



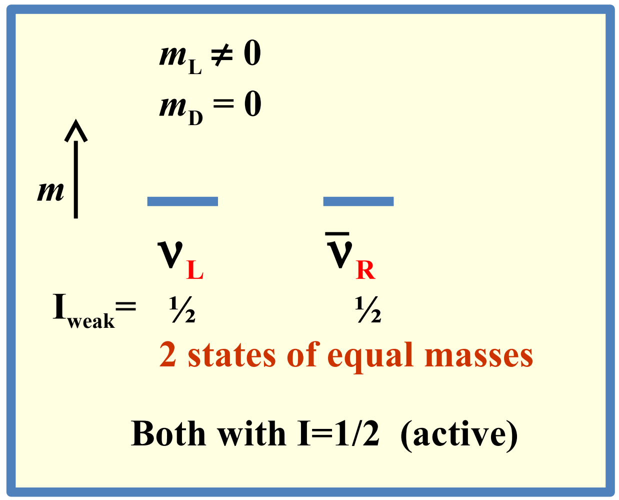
- Effect: the neutrino is its own anti-particle, and leptonic number is violated
- Implication: mass generation mechanism which does not involve the Higgs field
  - New physics!

The seesaw mechanism

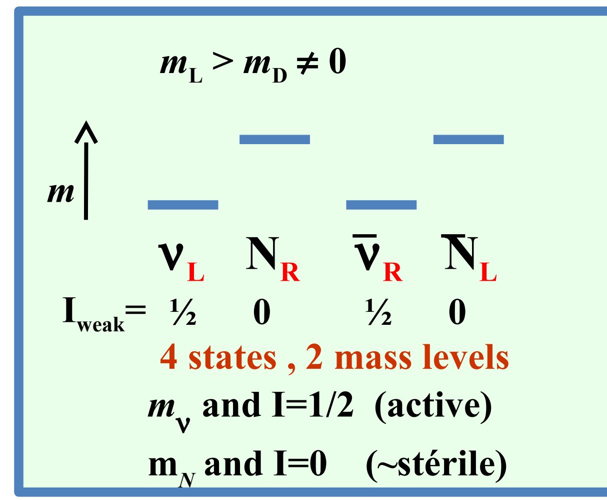
Only Dirac



Only Majorana



Dirac + Majorana (seesaw)



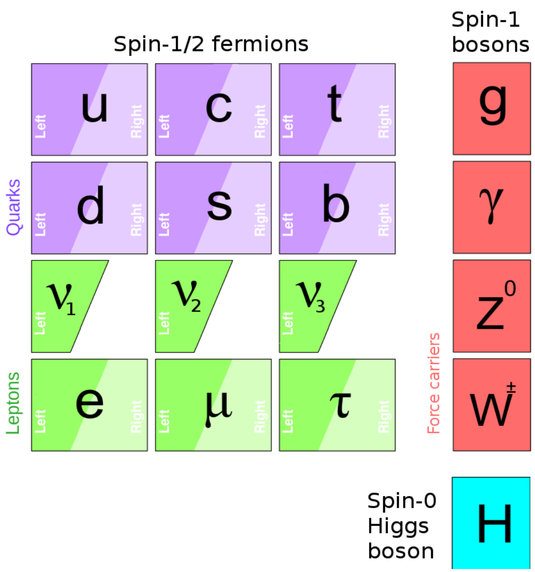
- Adding a Majorana mass (m_L) to the Dirac mass (m_D) causes a splitting of left (ν) and right (N) chiralities
- If $m_L >> m_D$ one gets

$$m_N \simeq m_L \qquad m_\nu \simeq \frac{m_D^2}{m_L}$$

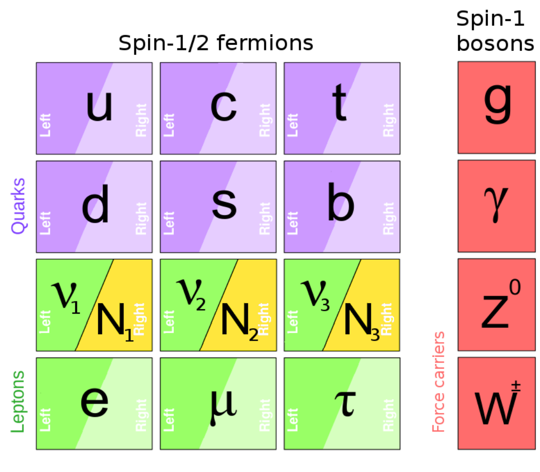
- A “natural” explanation, why active neutrino masses are over 1 million times lighter than the electron mass

Heavy neutrinos: Three missing pieces

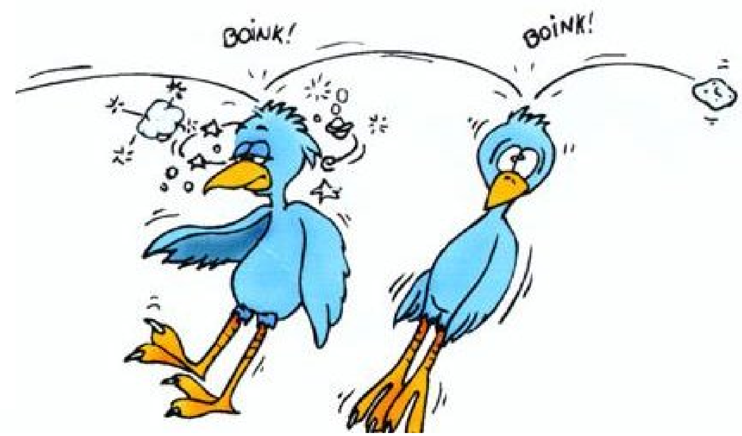
SM



νMSM

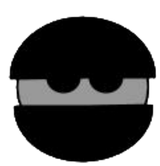


Ann. Rev. Nucl. Part. Sci. 59, 191 (2009)



N_1 mass ~keV

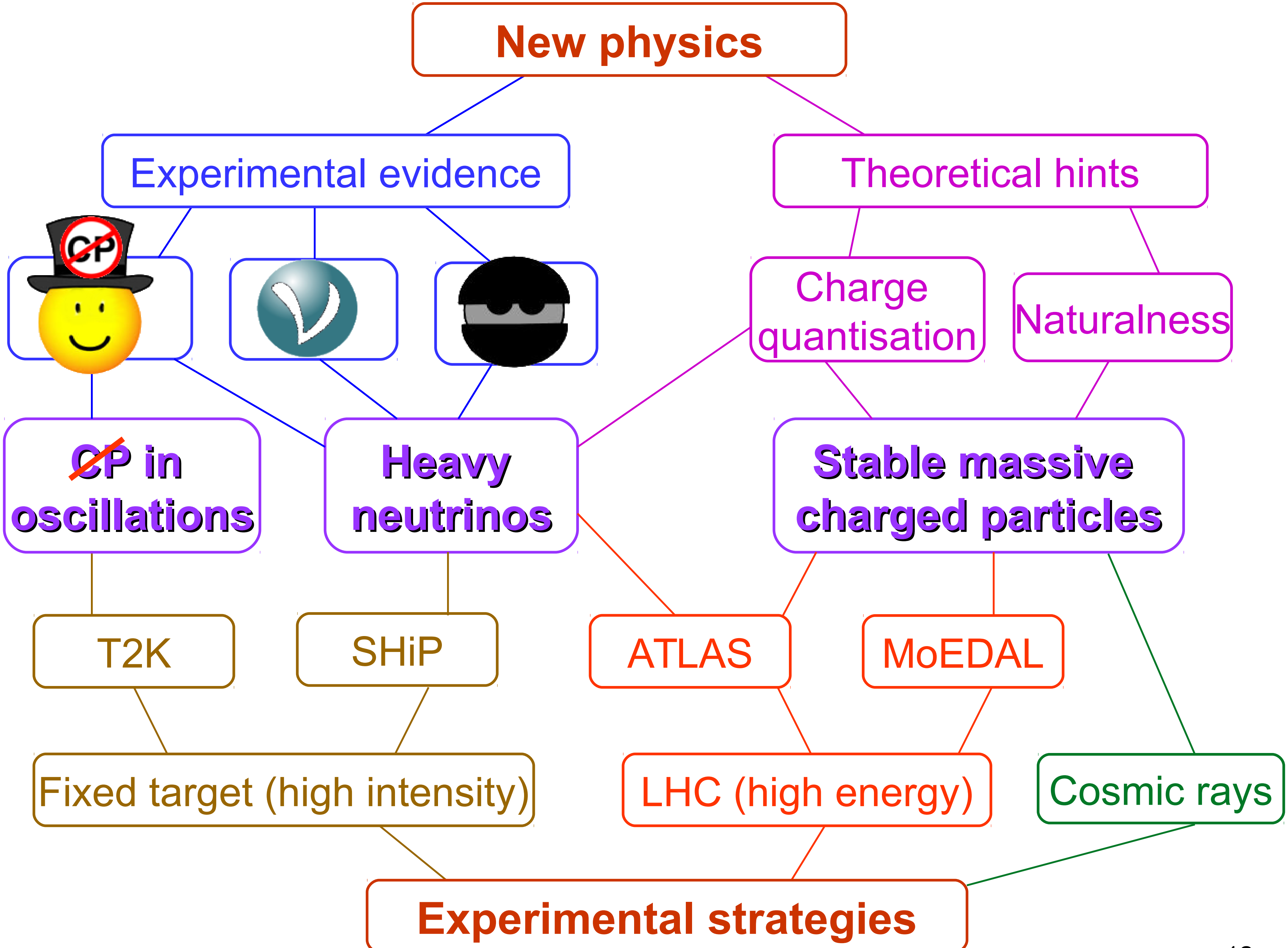
→ **dark matter**



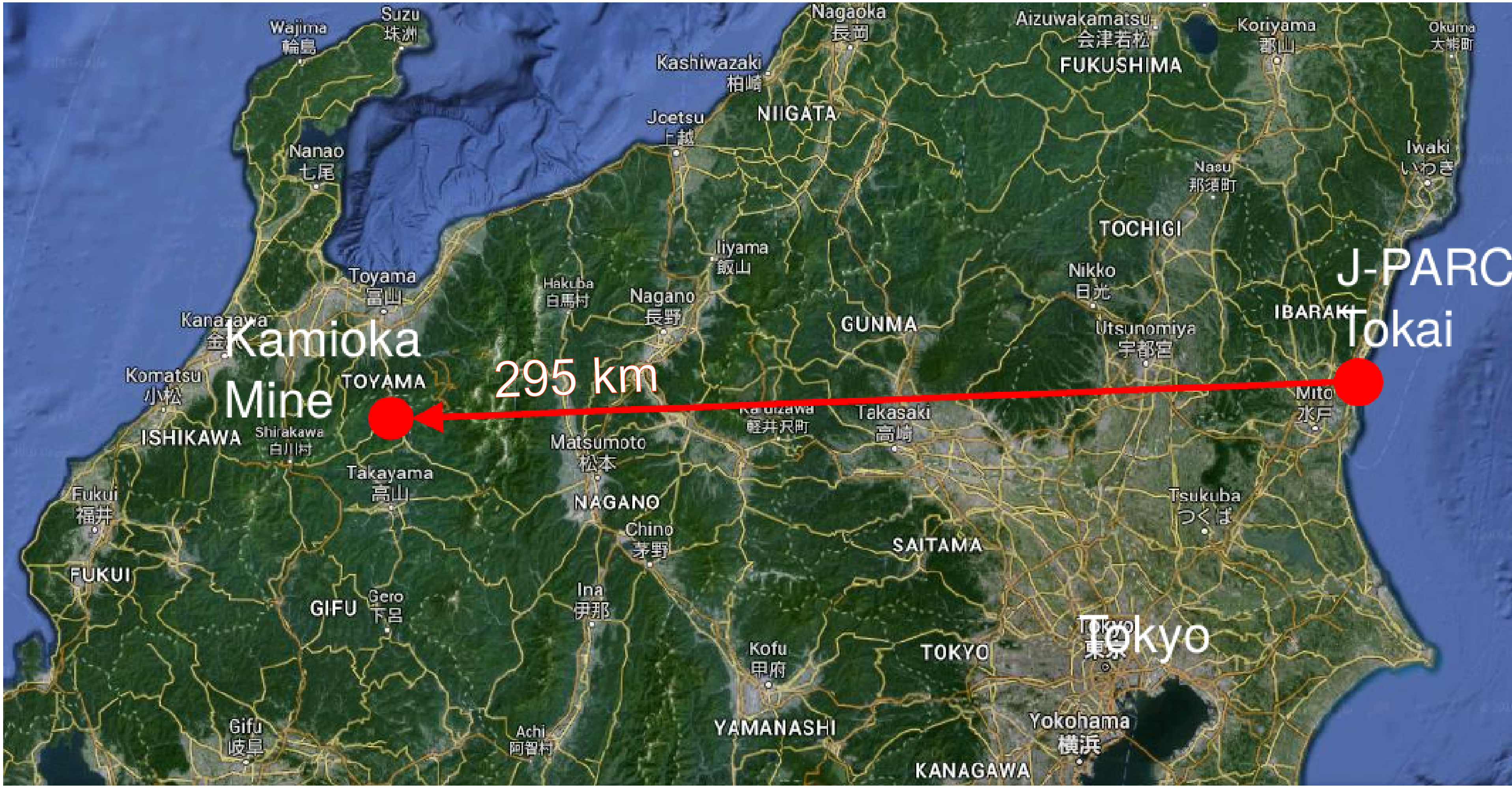
$N_{2,3}$ masses ~GeV

→ **seesaw**

→ **leptogenesis**

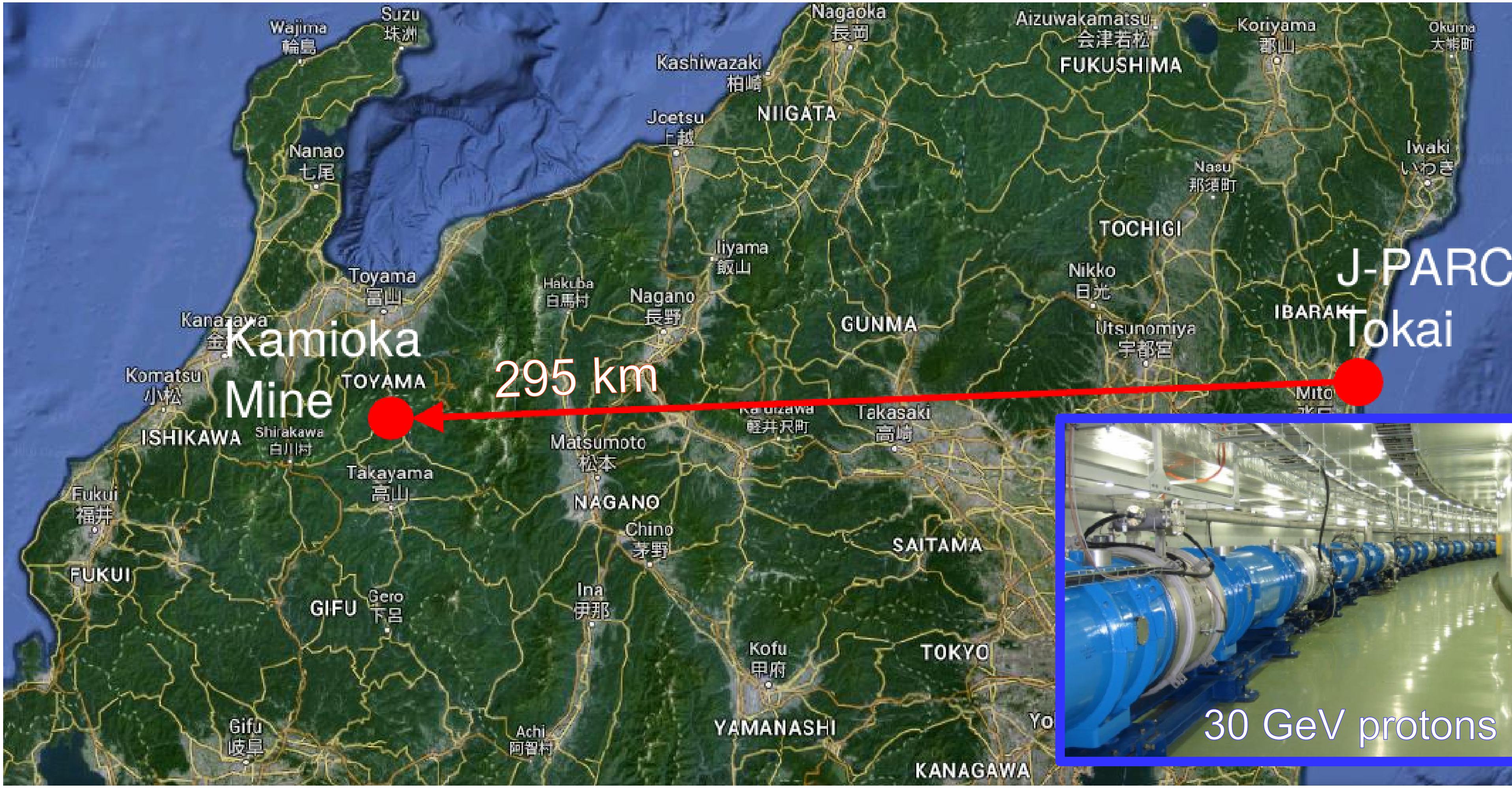

New physics
Experimental evidence
Theoretical hints
CP
Charge quantisation
Naturalness
CP in oscillations
Heavy neutrinos
Stable massive charged particles
T2K
SHiP
ATLAS
MoEDAL
Fixed target (high intensity)
LHC (high energy)
Cosmic rays
Experimental strategies

T2K experiment



- Energy and distance correspond to ν_{μ} oscillation maximum
- Muons and electrons reconstructed in ND280 et Super-K

T2K experiment



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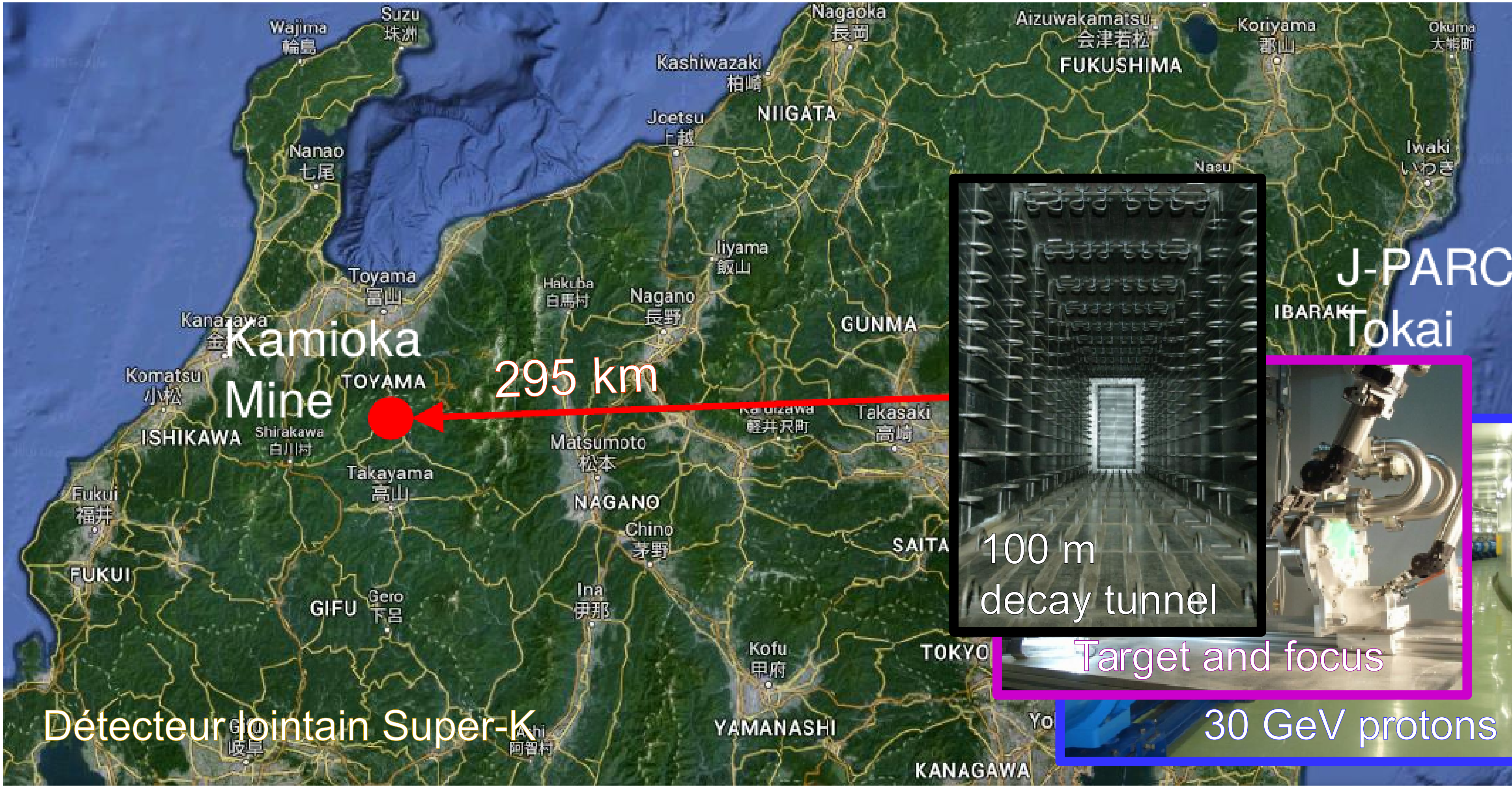

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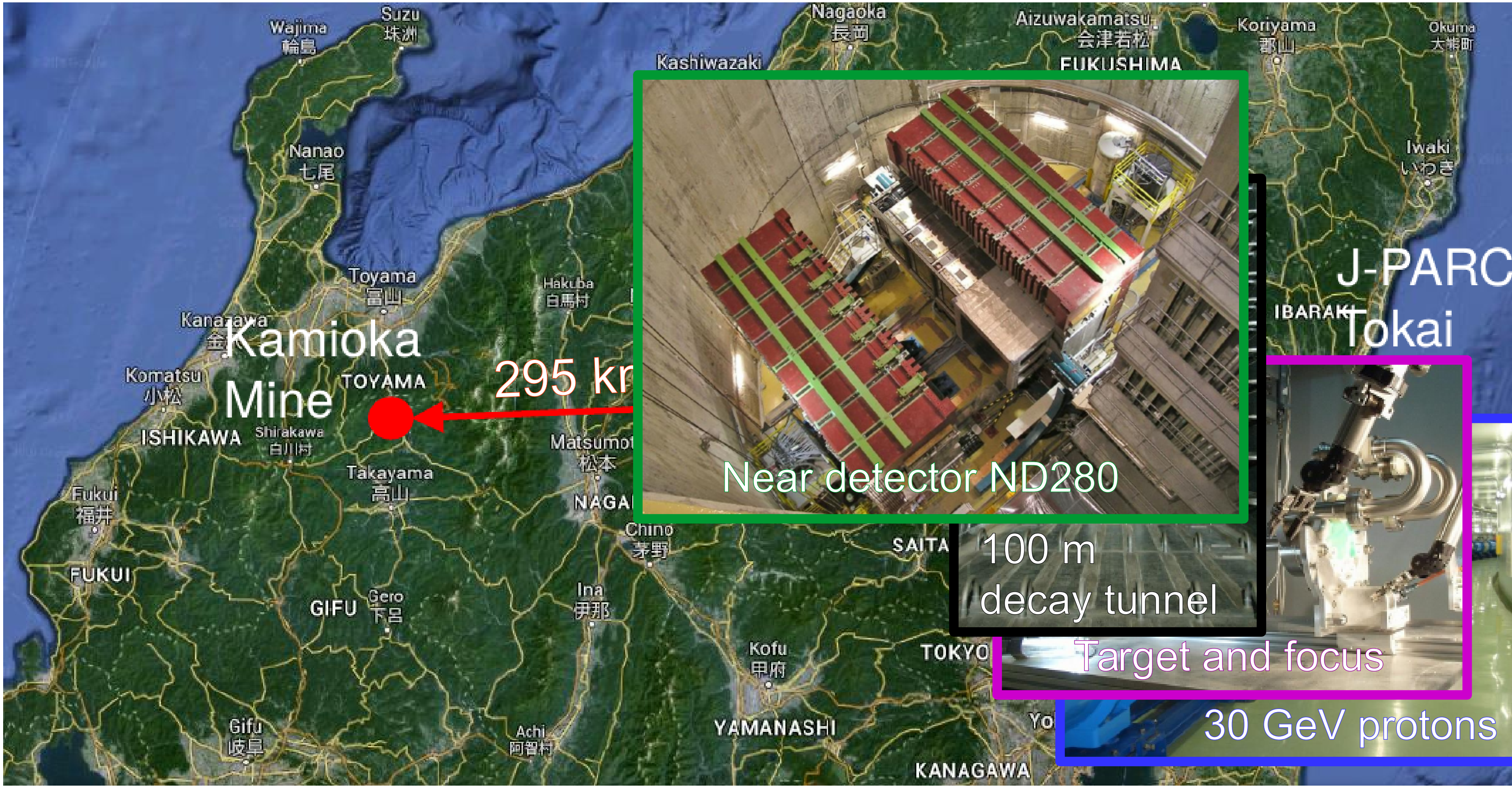

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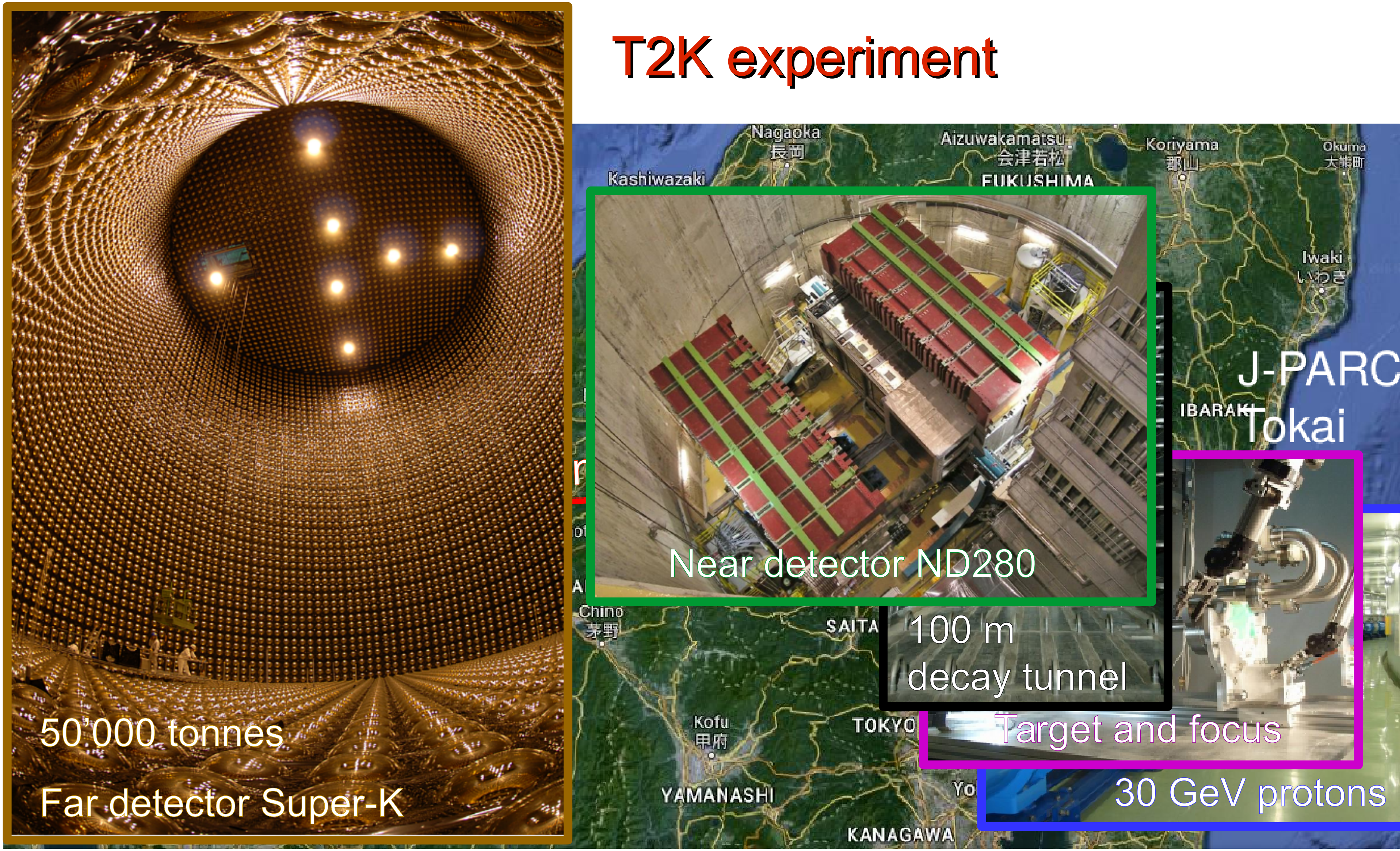

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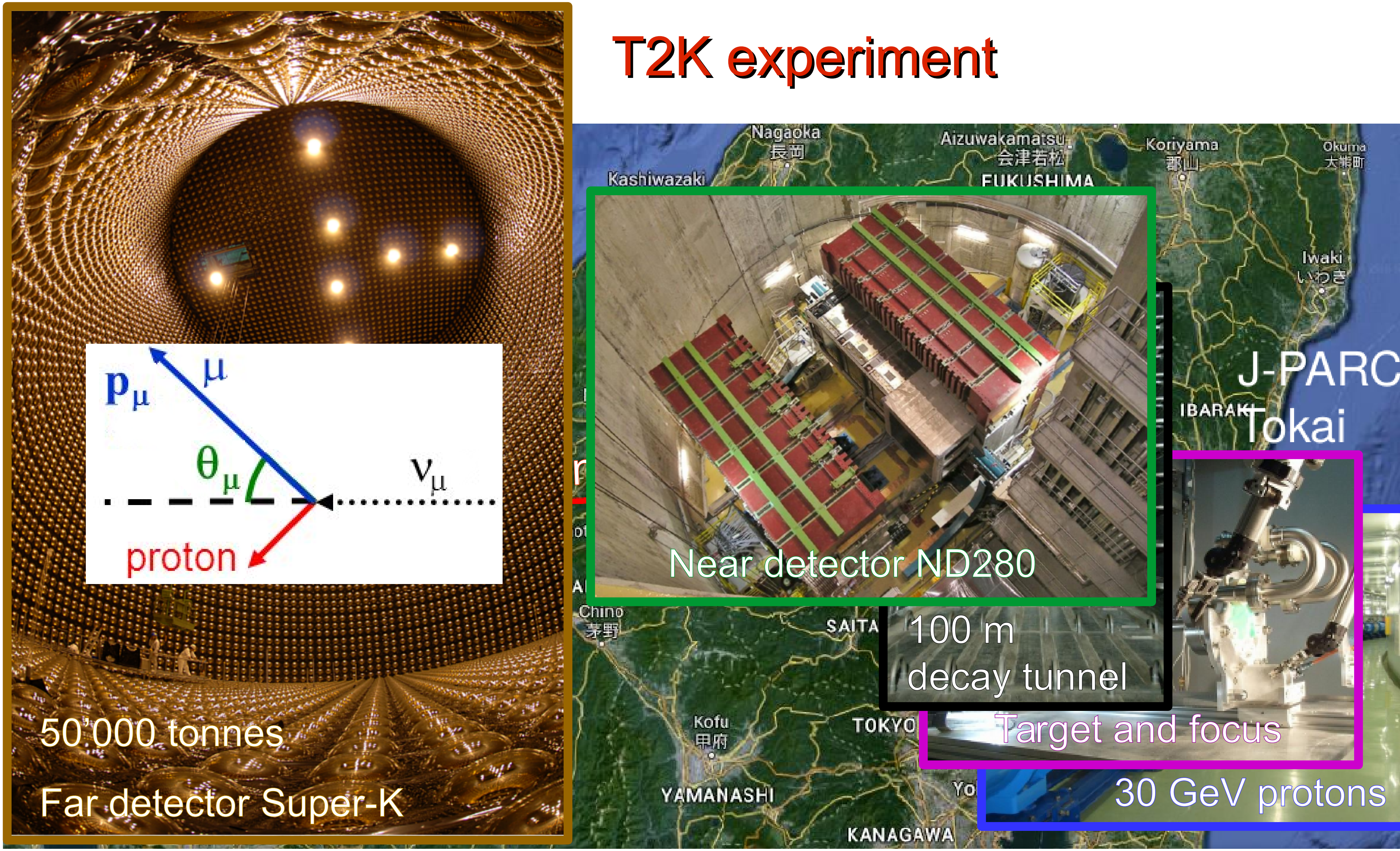

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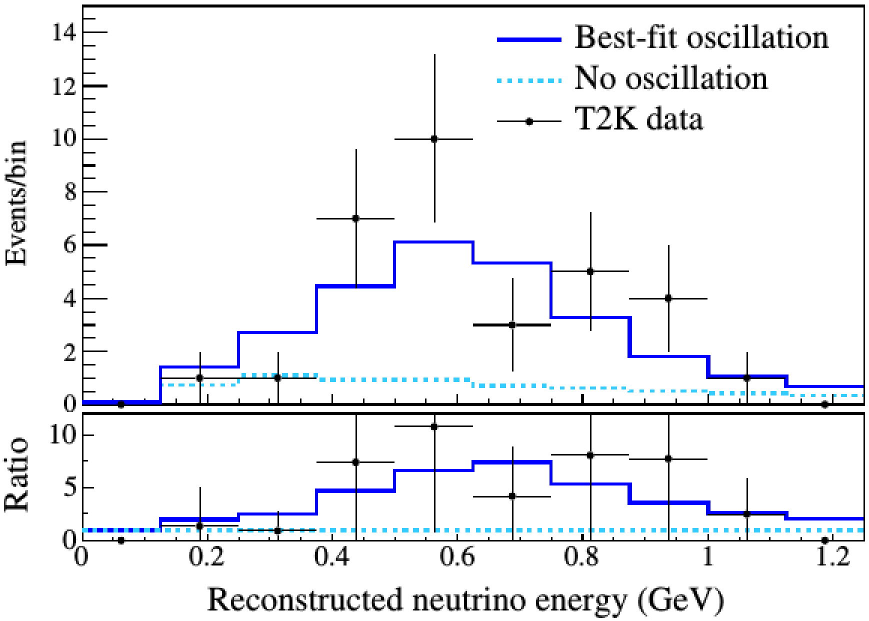
Latest news from T2K

$\nu_\mu \rightarrow \nu_e$

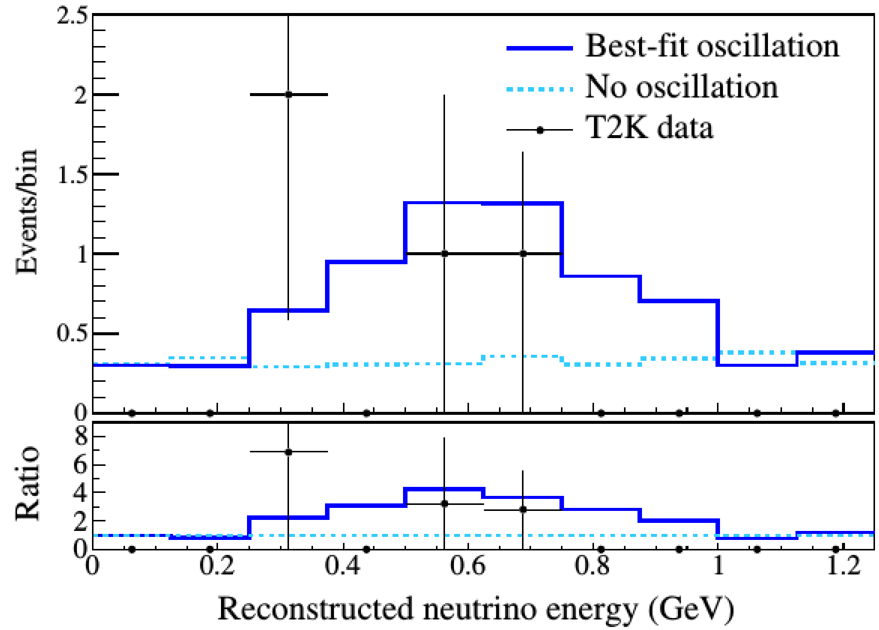


32 observed events

One expects 24.2 if δ = 0
28.7 if δ = -π/2

$\overline{\nu_\mu} \rightarrow \overline{\nu_e}$

PRD 96, 092006 (2017)



4 observed events

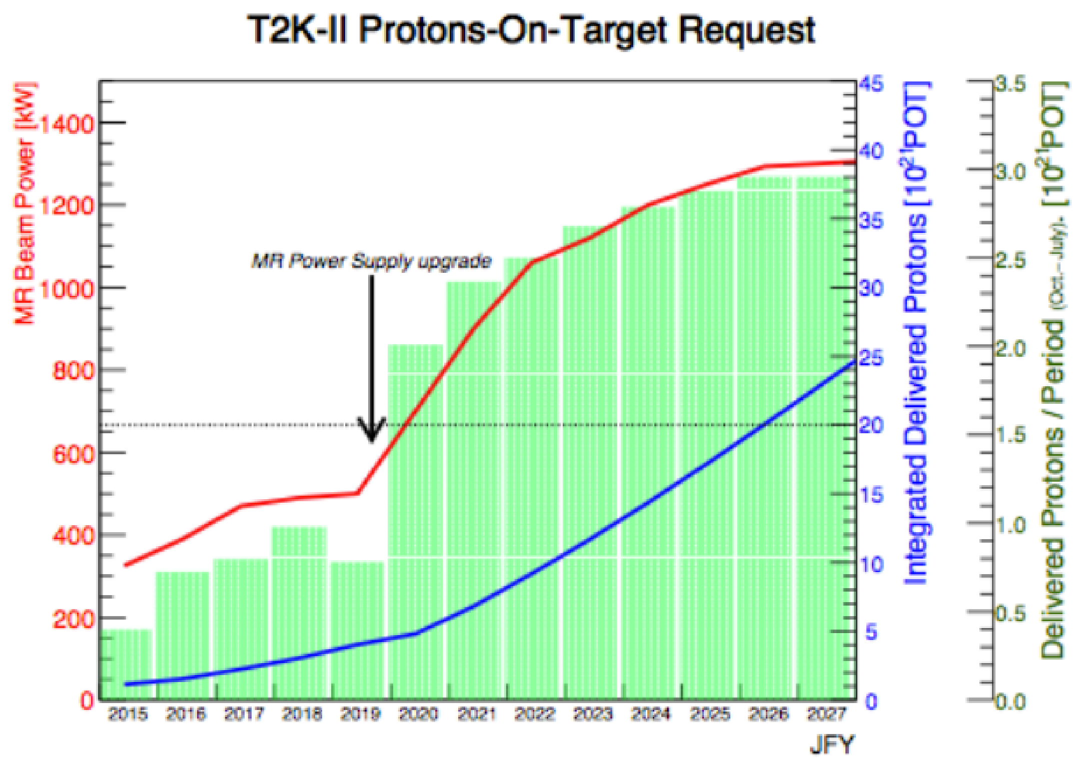
One expects 6.9 if δ = 0
6.0 if δ = -π/2

- Strong indication of ~~CP~~!
- Consistent with recent results from NOvA experiment

Towards T2K-II

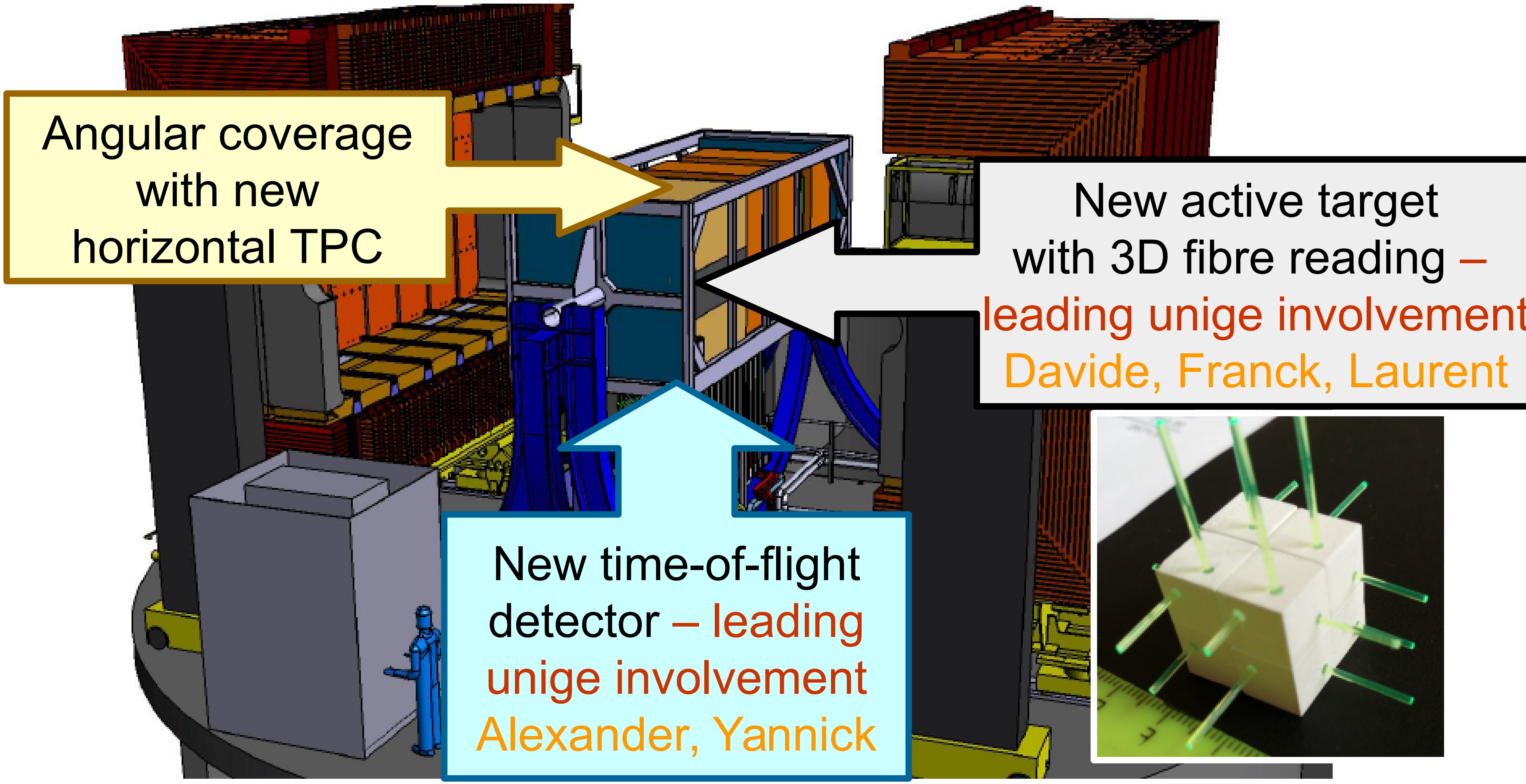
Beam intensity to be doubled by 2020

- Extended run – phase 2 (2020-2026) to collect 3 times more events than originally planned
- Super-K to be upgraded with Gadolinium



- ND280 to be upgraded for reduction of model-independent systematic uncertainty down to < 4%

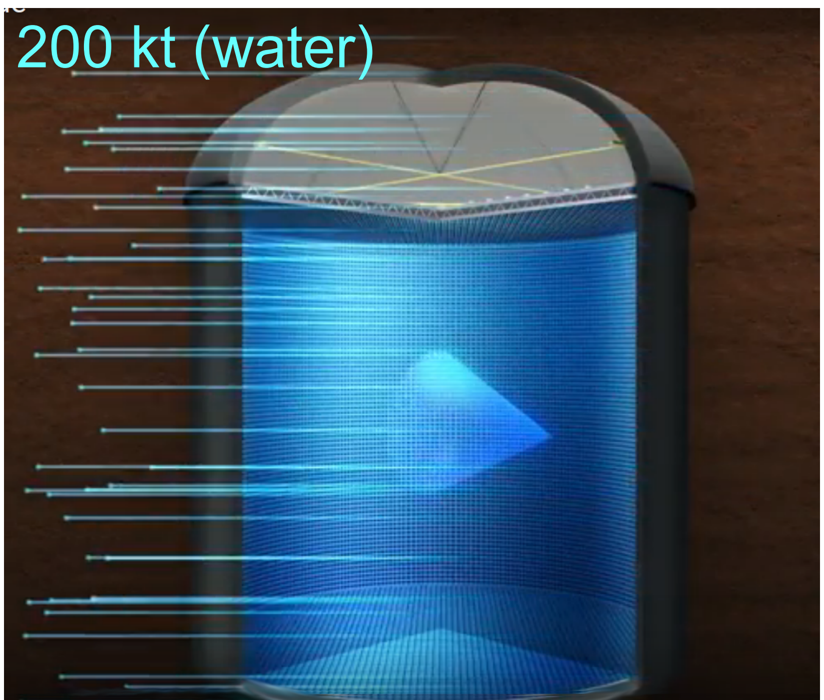
T2K ND280 upgrade



Future projects: Hyper-K and DUNE (~2026)

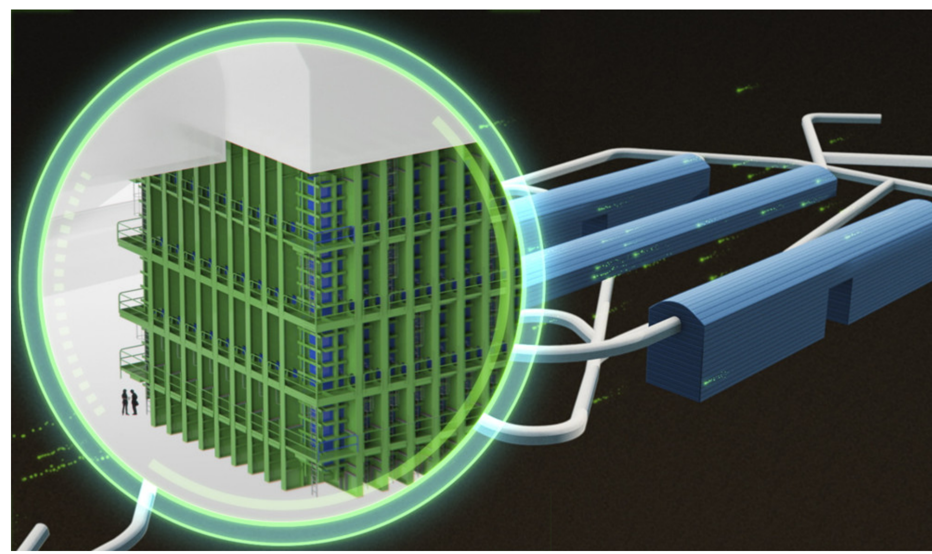
- Even more powerful beams at J-Parc et Fermilab
- Even bigger far detectors
- Ultra-precise oscillation measurements – ~~CP~~

Hyper-K (Japan)

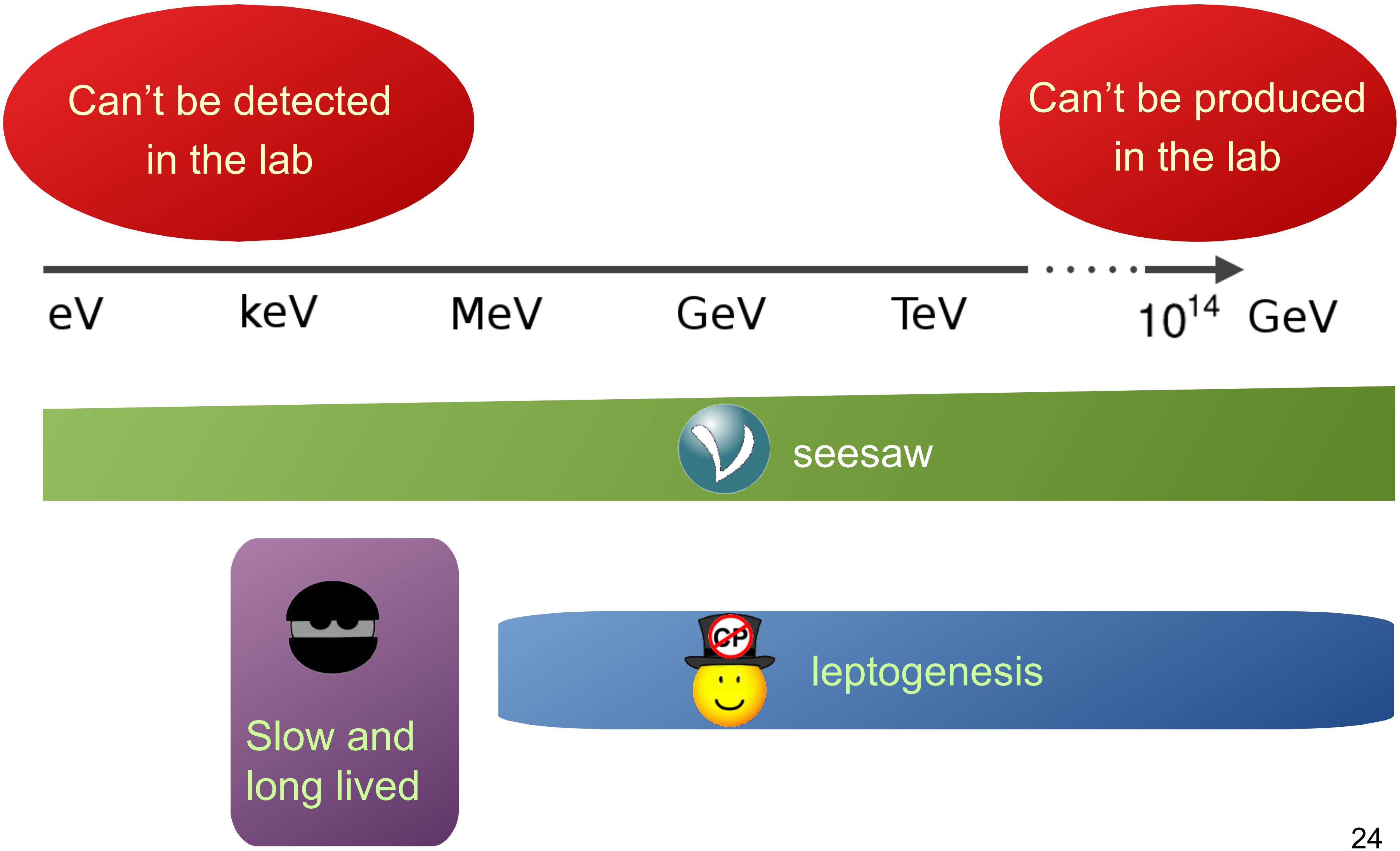


DUNE (USA)

40 kt (liquid argon)



Heavy neutrinos (N)?



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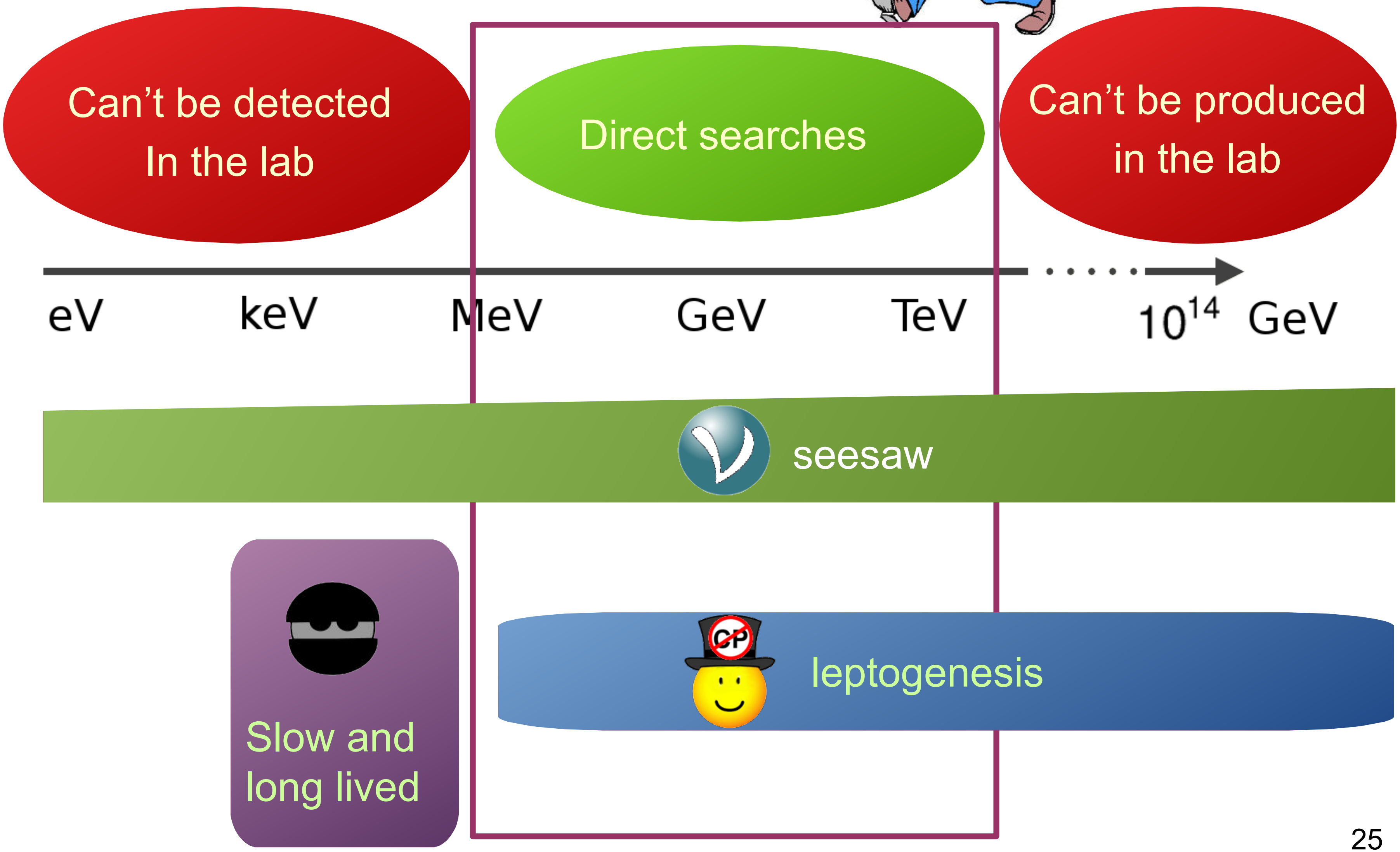
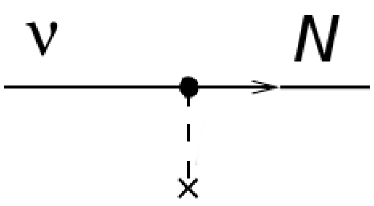
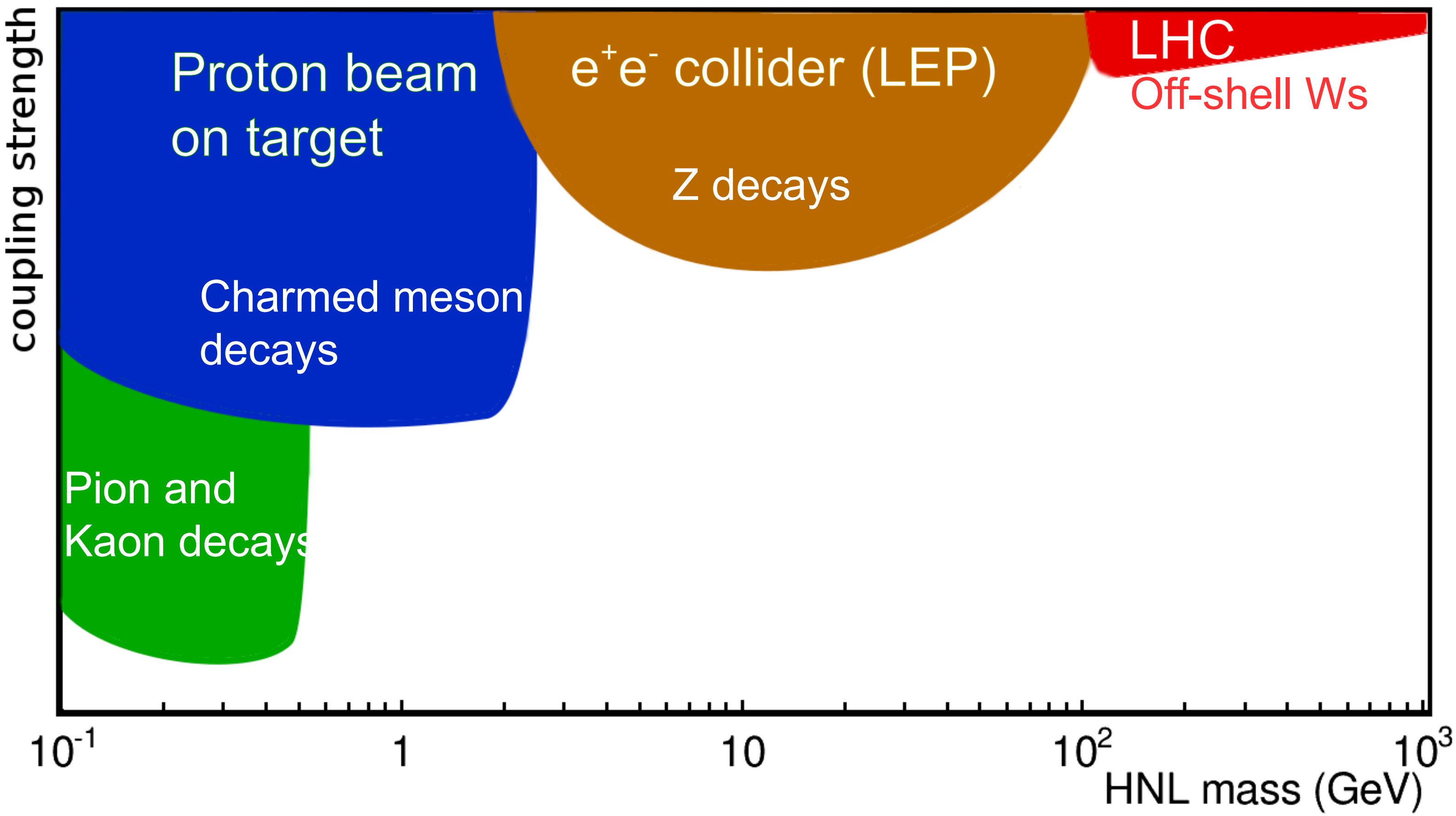


N production and detection in the lab



Very weak coupling →

- **High intensity**
- **Long lifetime**



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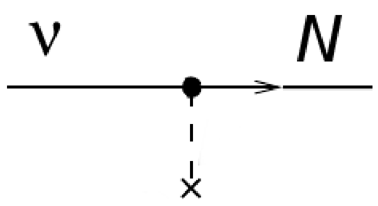

Very weak coupling ➡

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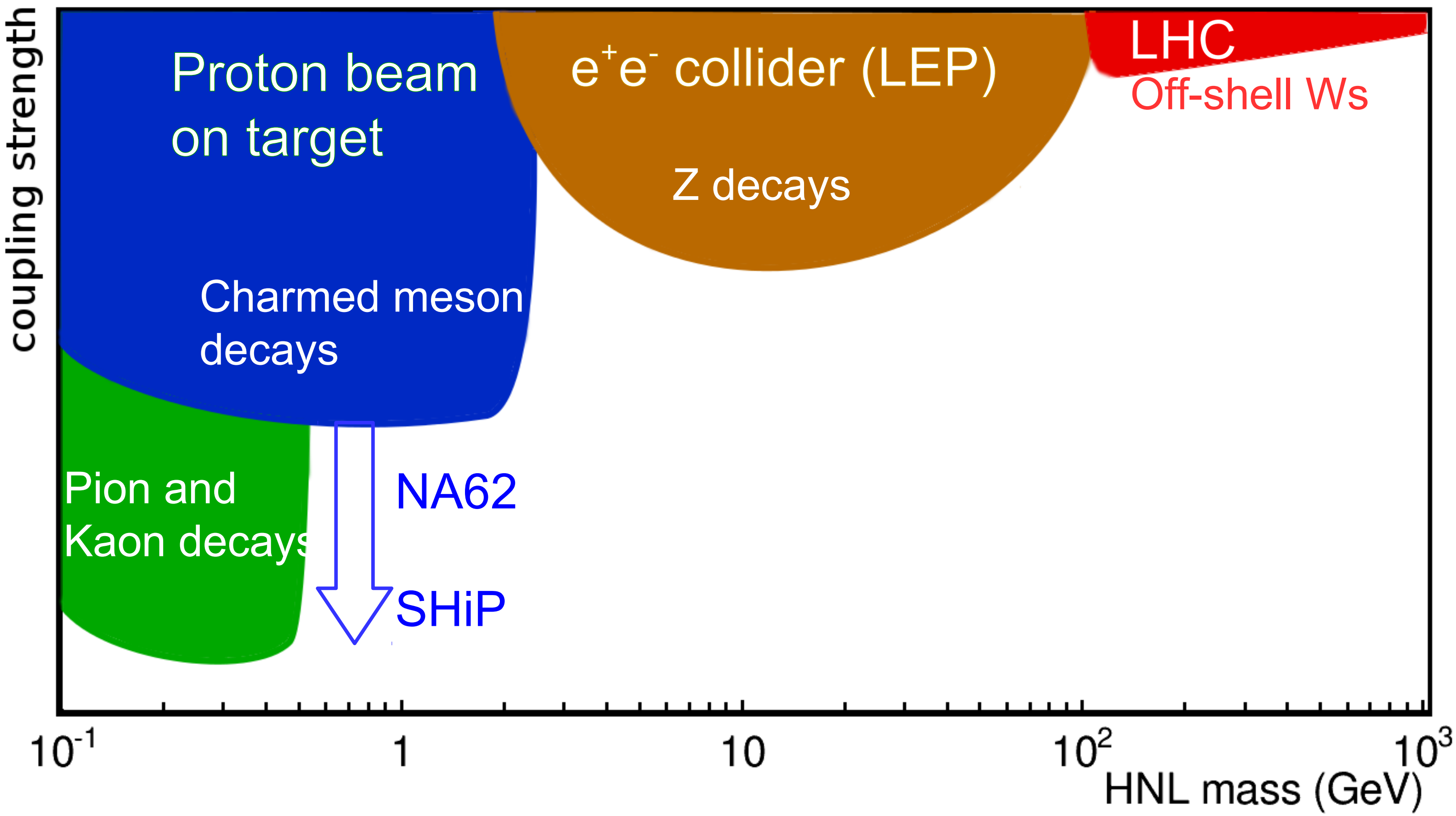

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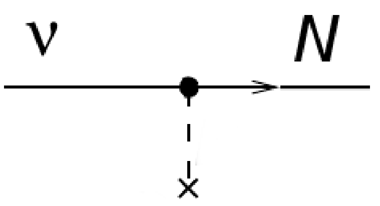

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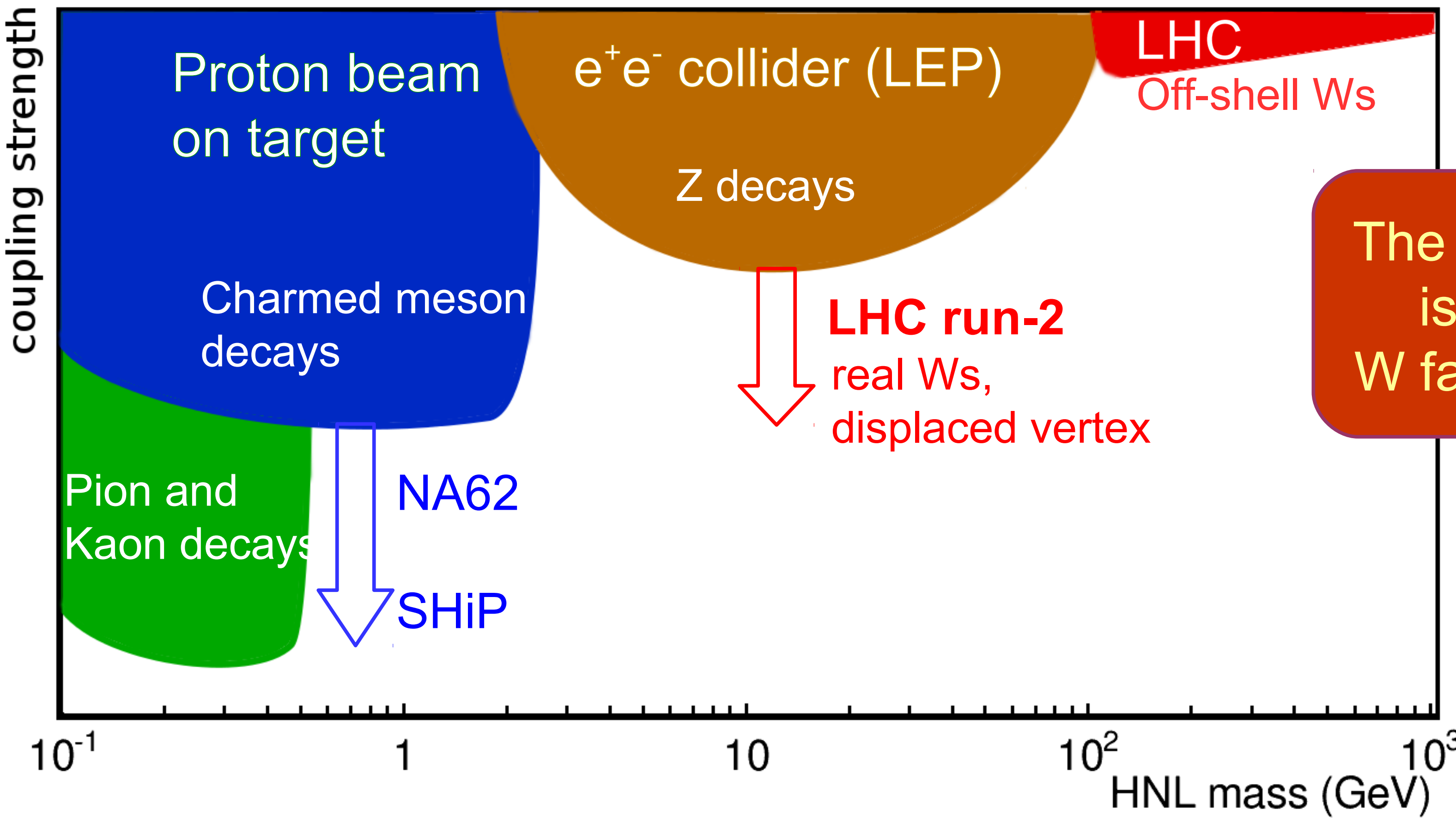
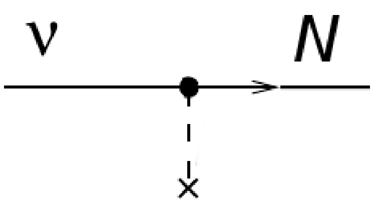


The LHC
is a
W factory

N production and detection in the lab



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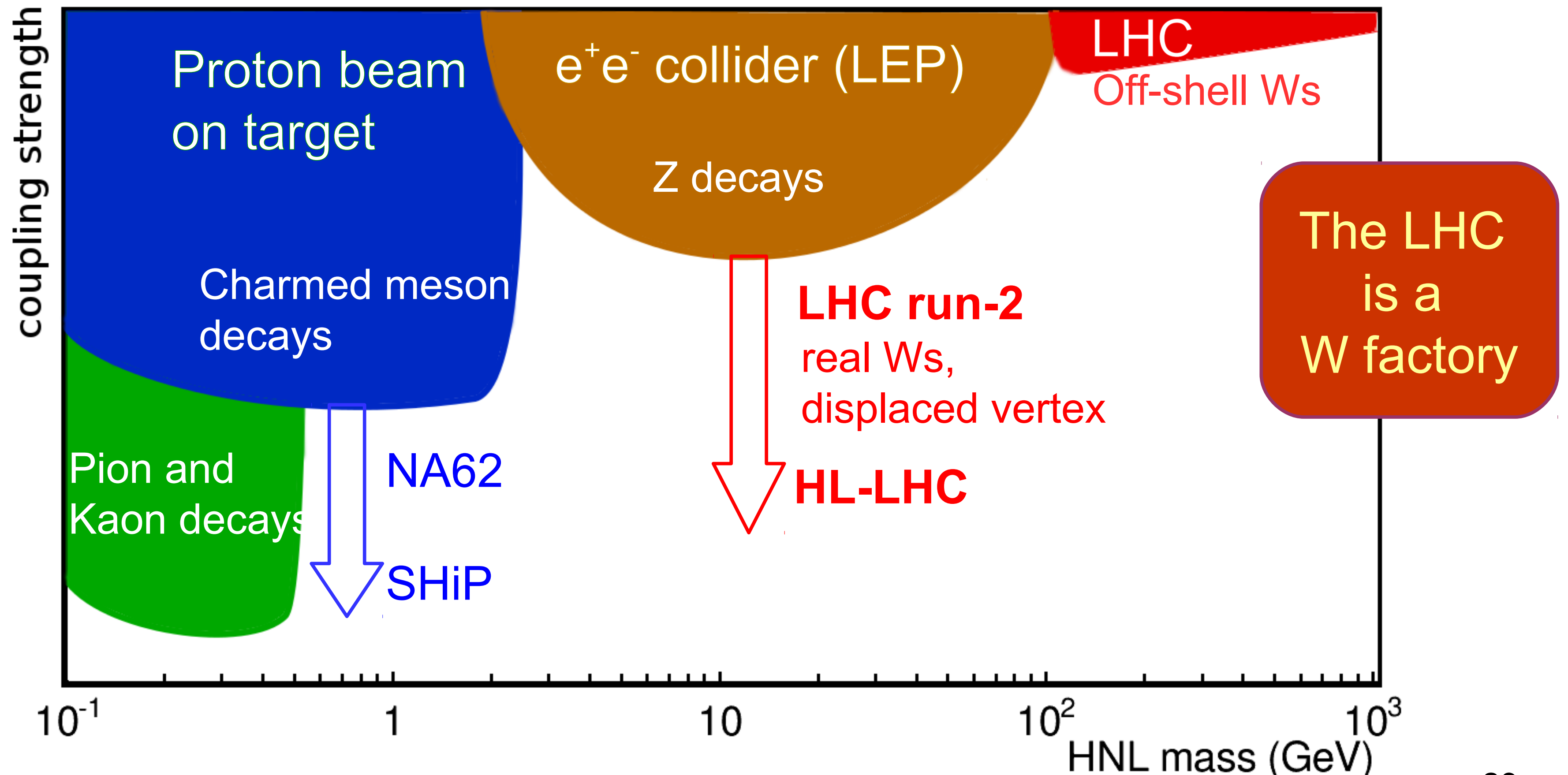
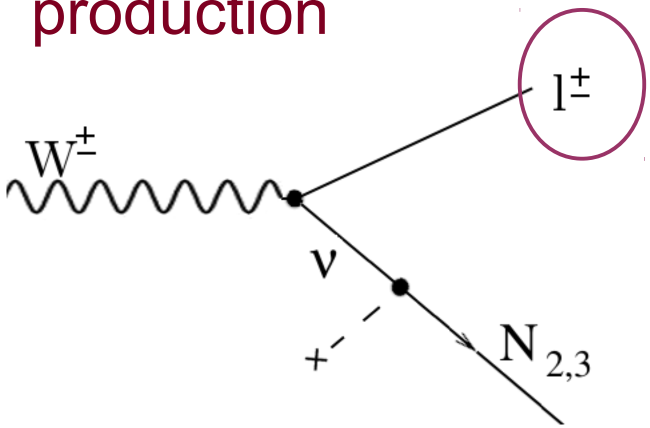


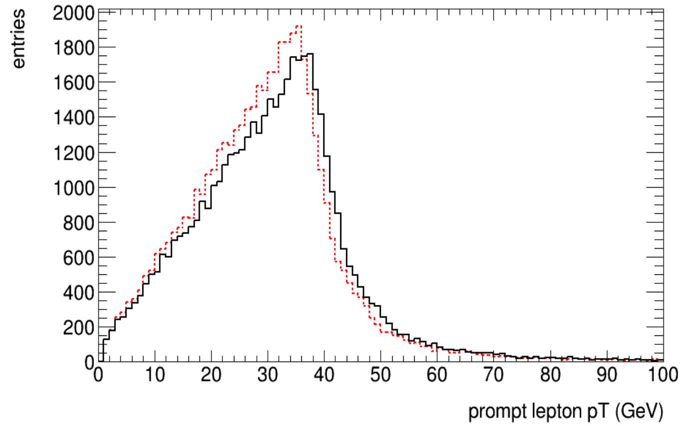
N from real Ws at the LHC

production

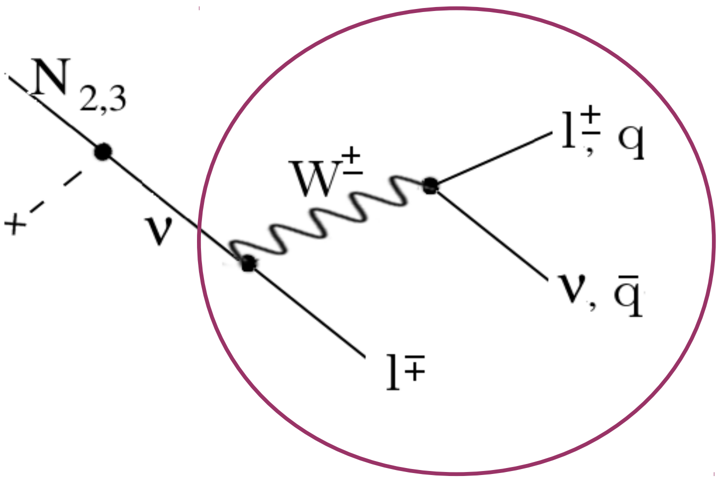


charged lepton essential for triggering

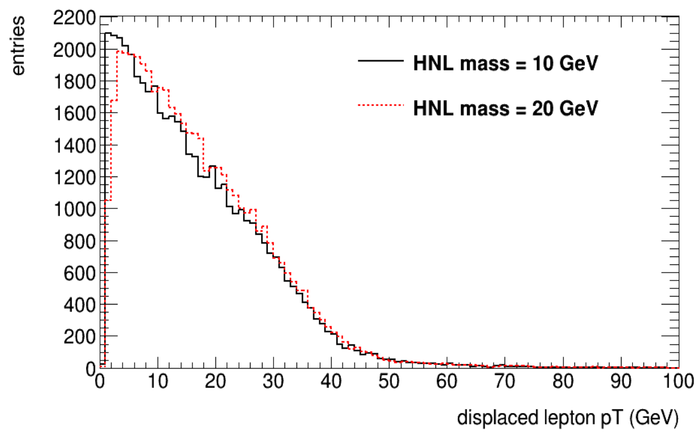
p_T distributions



decay



Displaced vertex (DV) essential for background rejection



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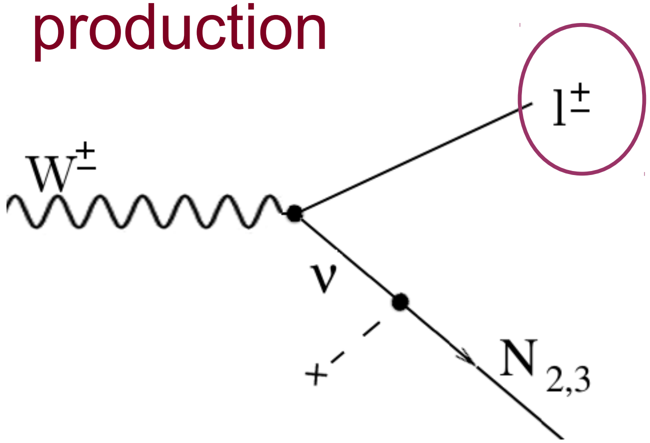

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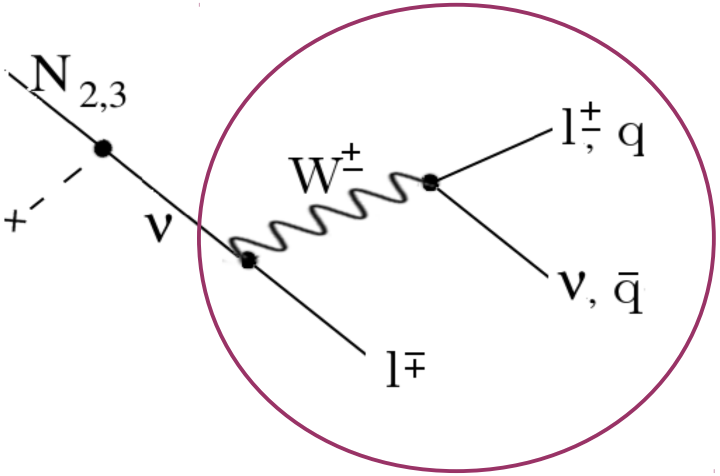

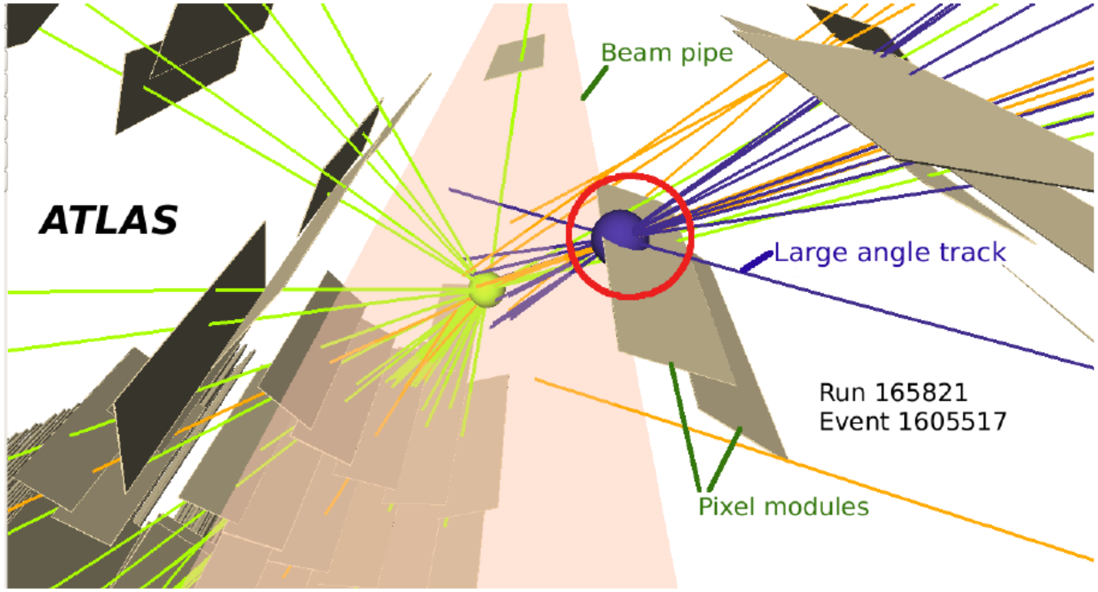

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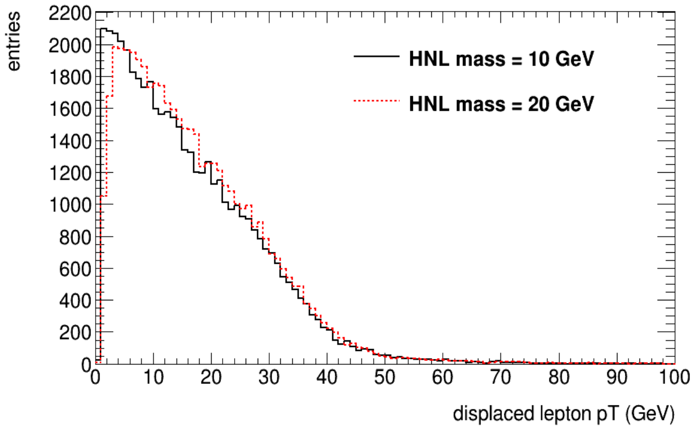


N at ATLAS: current and next challenges

First N search with DV at LHC (2016 data)

- Analysis finalised – Arnaud's thesis
- probes mixing with ν_μ beyond LEP for the first time for m_N ~ 10 GeV

Full run-2 dataset

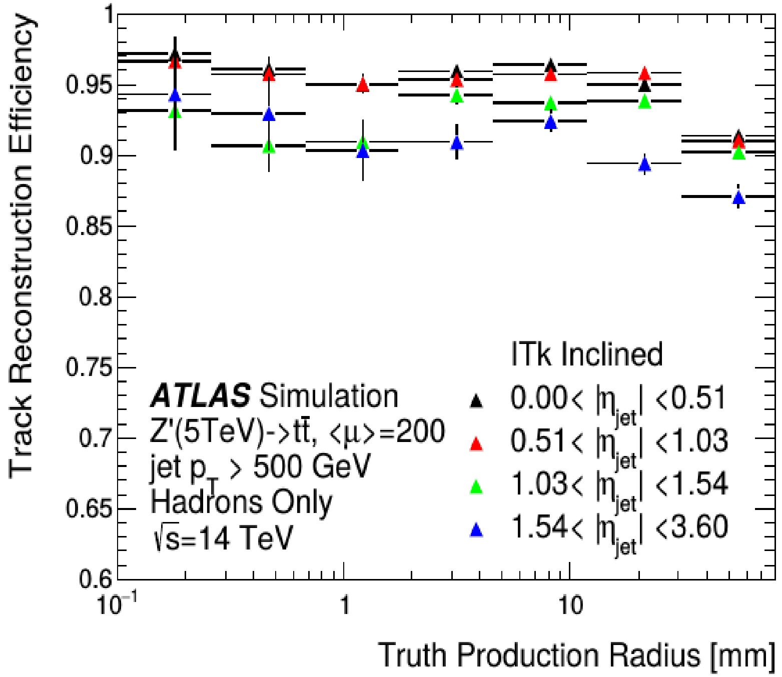
- Also probe mixing with ν_e, also hadronic N decay channel

Run-3

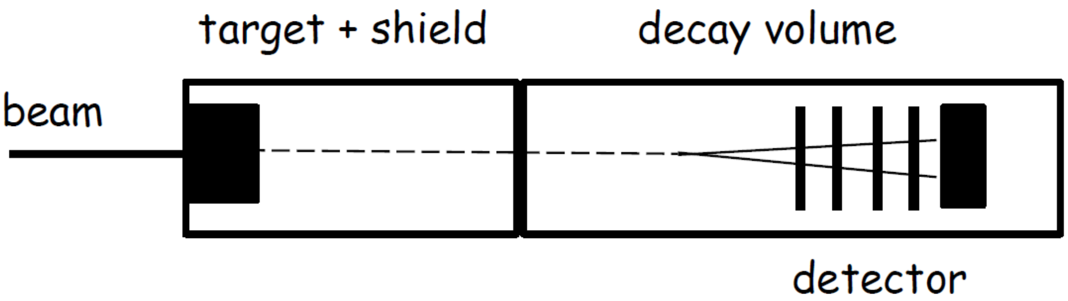
- Dedicated triggers
- Probe mixing with ν_τ

HL-LHC

- Advanced triggers
- DVs after ITk upgrade
- Sensitivity to most interesting regions of parameter space



N at fixed-target facilities

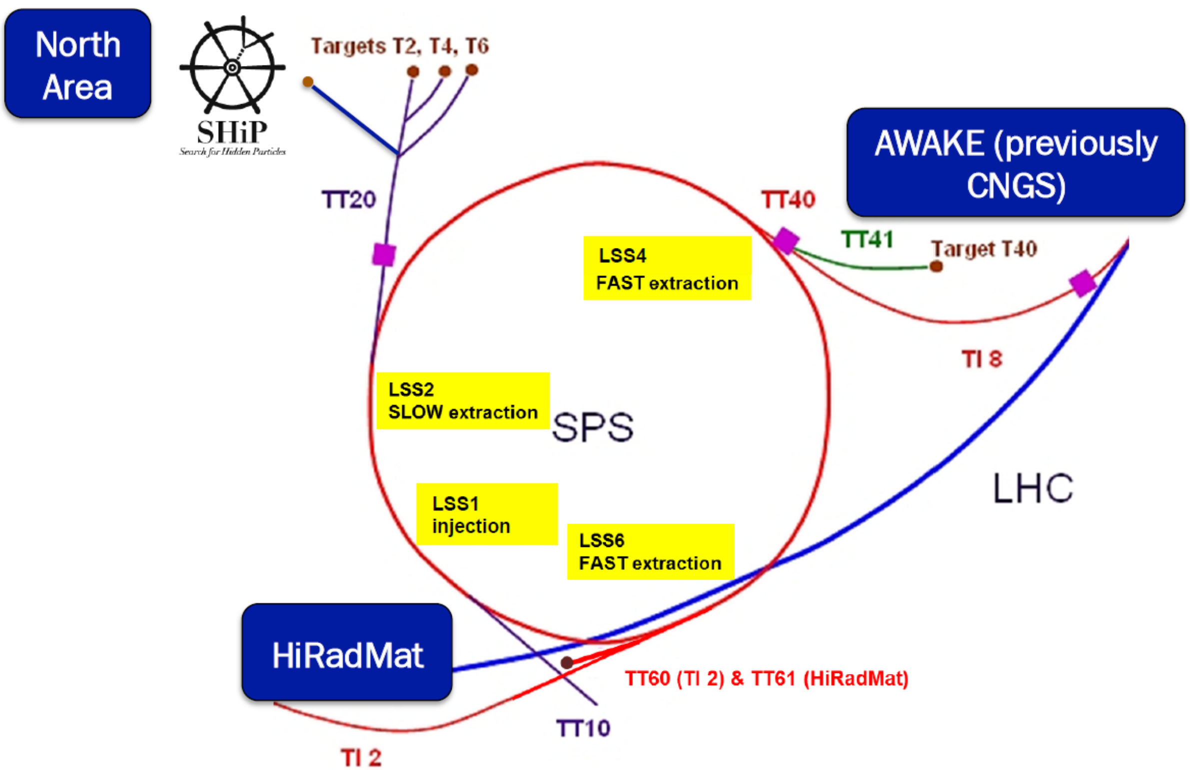


Strategy

- high-intensity proton beam on a target
- decay volume as close as possible to target
- highly efficient background rejection systems

Search for hidden particles – SHiP

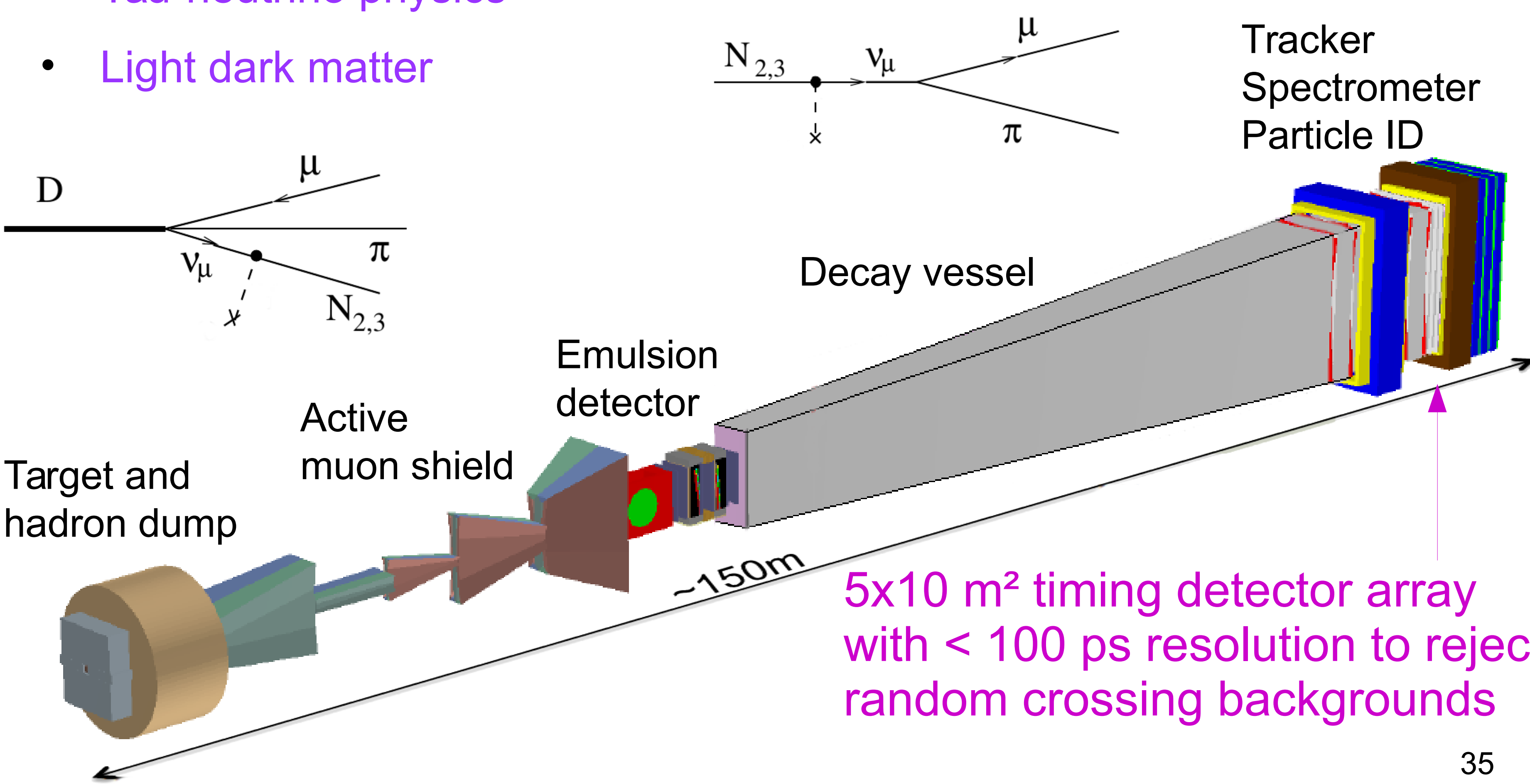
- Proposed facility: 400 GeV protons from the CERN SPS
- Collaboration of 250 members from 46 institutes
- Major actor in CERN Physics Beyond Colliders study group
    - Approval ~2020
    - Physics runs ~2026, aim at $2 \cdot 10^{20}$ protons on target in 5 years



The SHiP experiment

Wide physics programme

- Variety of possible decay modes – N, dark photon, dark scalar...
- Tau-neutrino physics
- Light dark matter

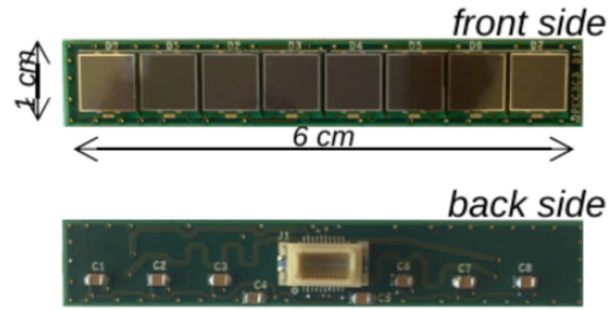


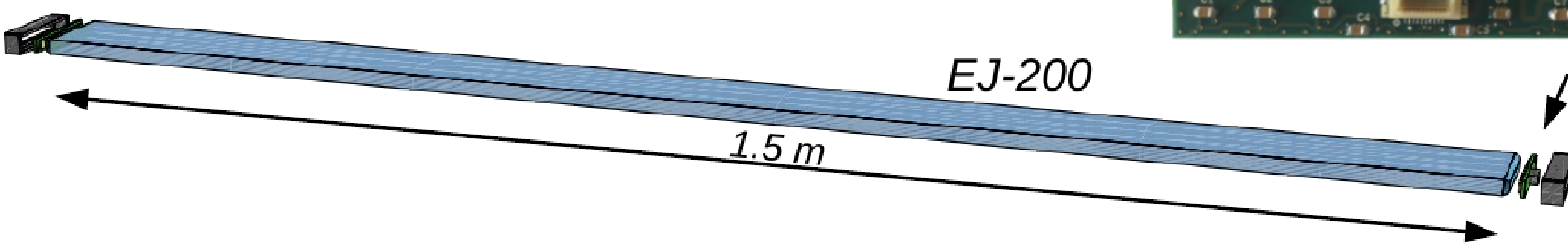
A timing detector for SHiP and ND280 upgrade

Novel concept: bulk plastic scintillators read out by large-area SiPM arrays

- High photon detection efficiency, especially for green light
- Low bias voltage (~60 V)
- Compact – no need for lightguides
- Tolerates magnetic fields
- Getting cheaper every year

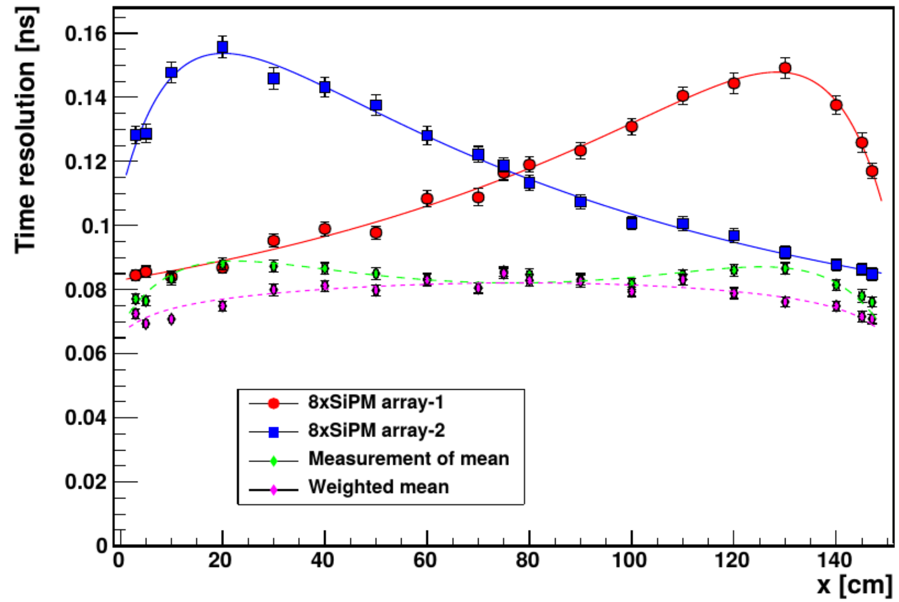
In-house made PCBs – Yannick





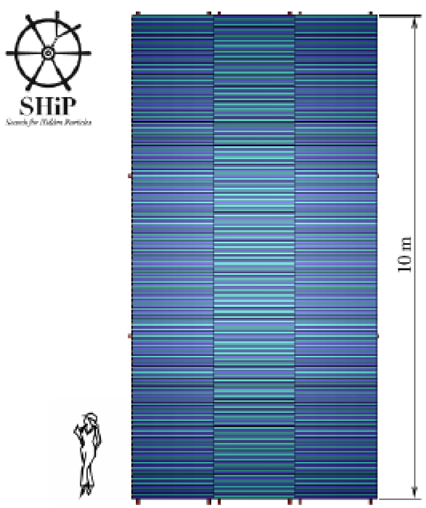
Plastic scintillator R&D

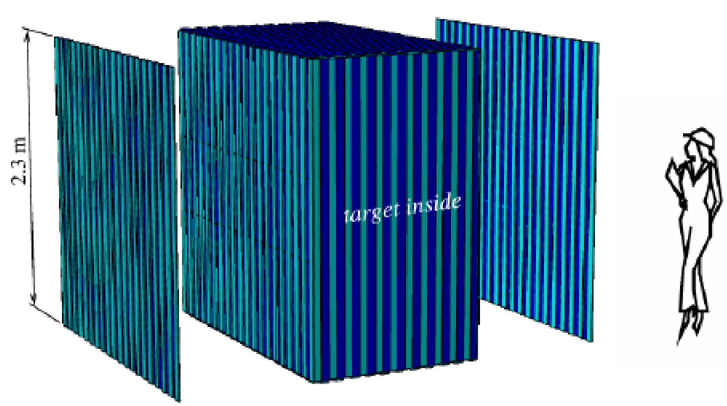
JINST 12, P11023 (2017)



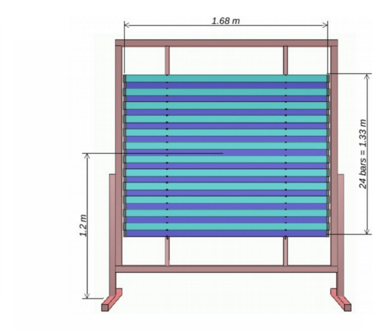
Very promising results from test beams this Summer – Alexander's work

- 80 ps resolution along 1.5 m bar
- 24-bar prototype to be built and tested this year

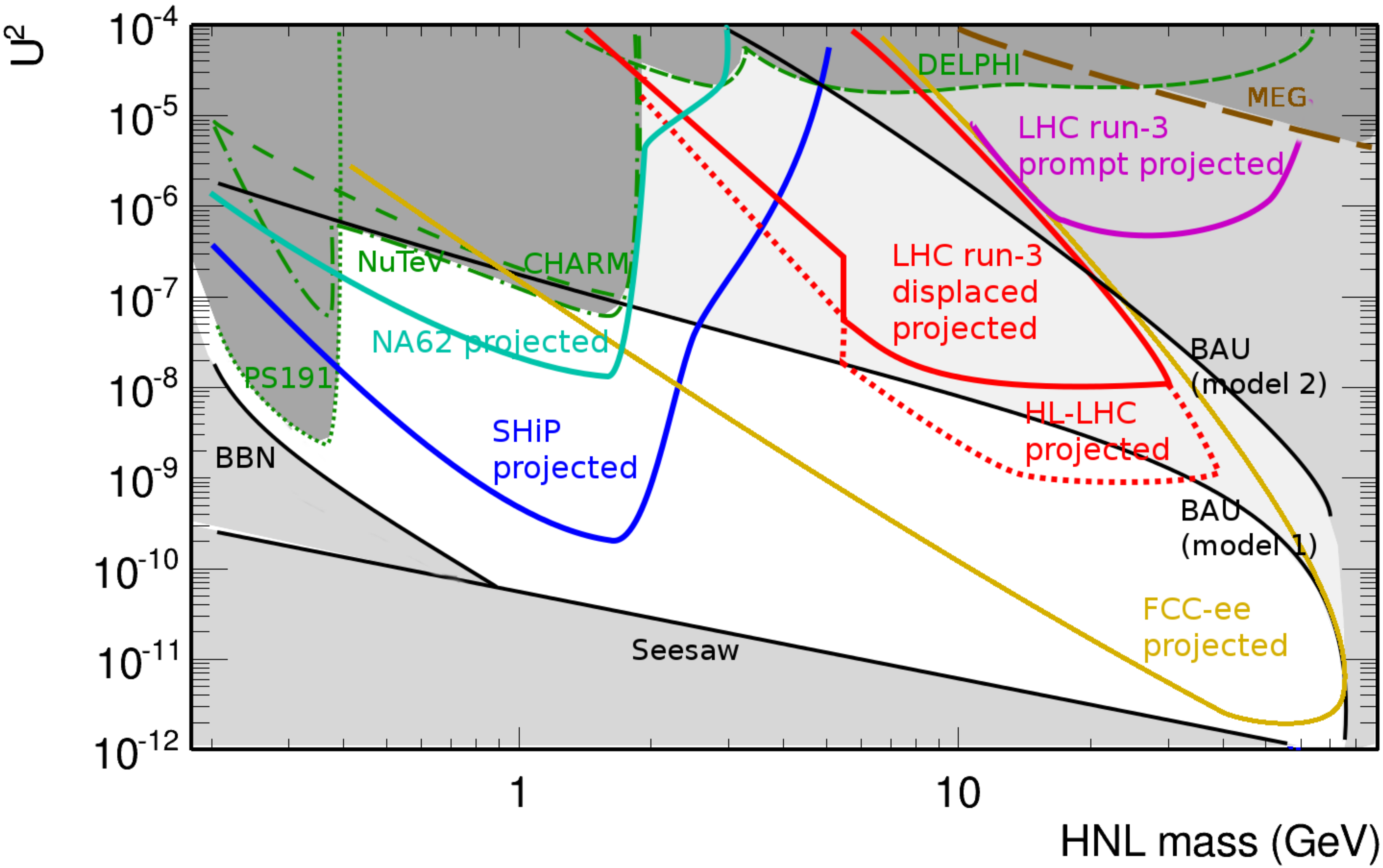




prototype



N at CERN in the next 10 years, and beyond



Summary and outlook

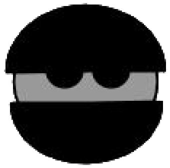
Measuring CP violation in neutrino oscillations

- T2K and NOvA, T2K upgrade
- Hyper-K and DUNE

Probing the existence of heavy neutrinos

- Complementary approaches with displaced vertices at high-intensity beams – LHC and SHiP

Possibly key to explaining Universe’s most blatant mysteries

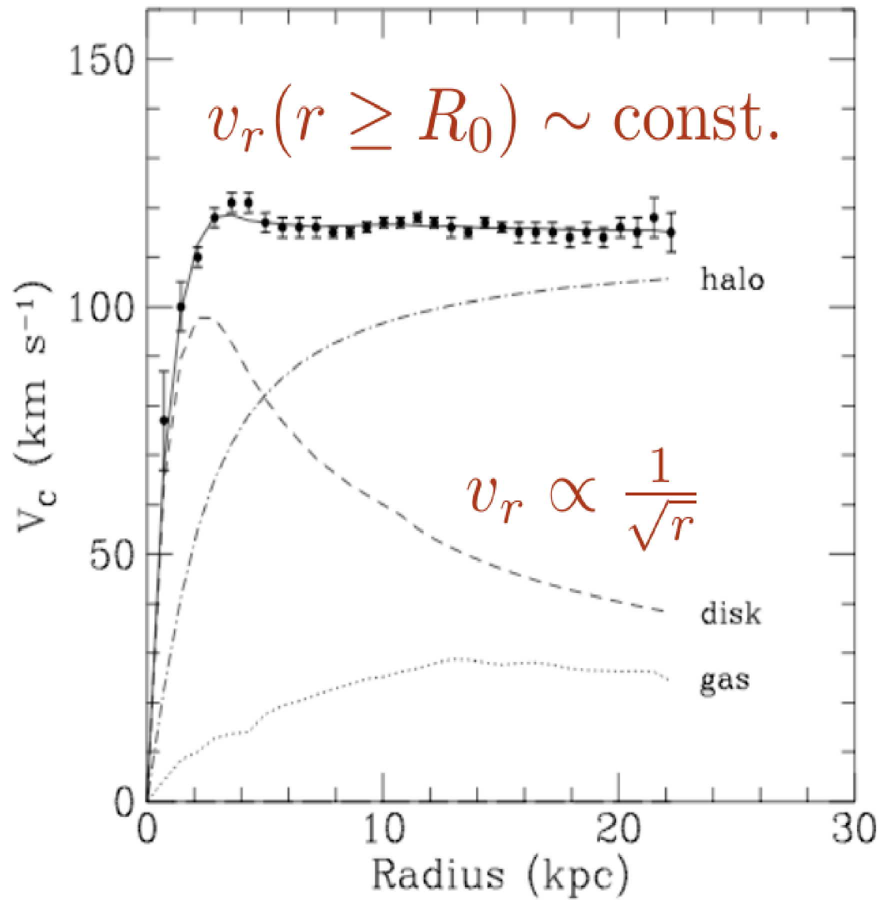



Extras

Dark matter

84% of the mass of the Universe is invisible

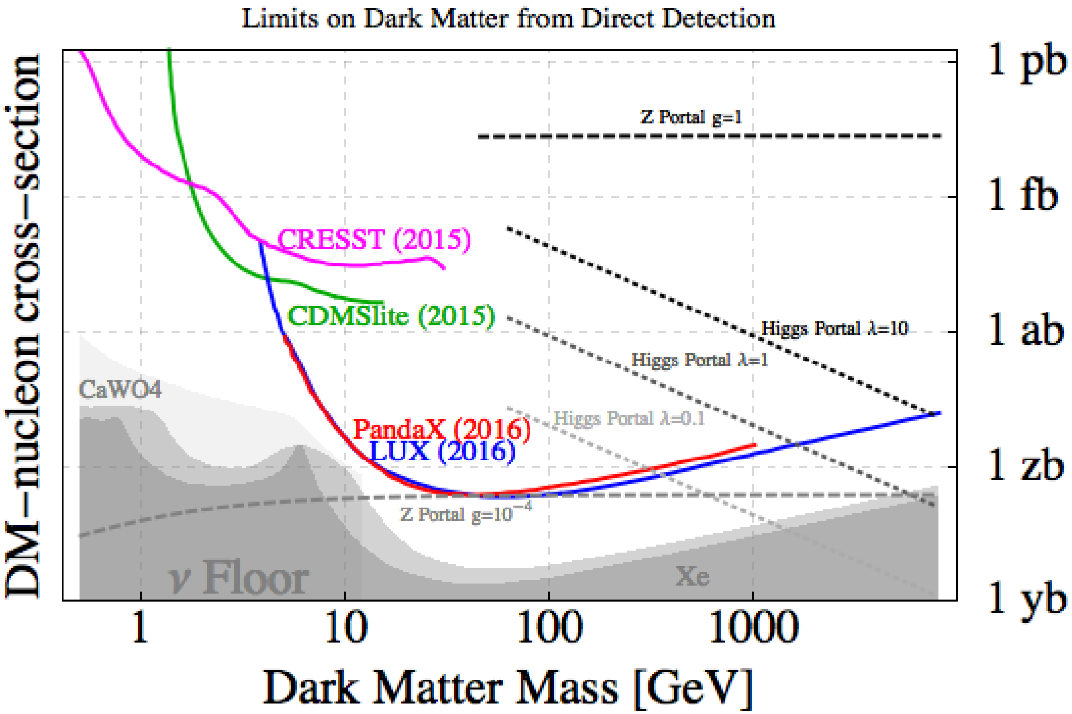
- Motion of stars and galaxies
- Gravitational lenses
- Anisotropies of cosmic microwave backround
- Large-scale structure formation



Possible candidates

- New neutral stable particle
- New dense state of matter
- Modified gravitational law

Dark-matter particles



Nuclear recoil detection with various techniques

- Very low backgrounds
- Very large target mass
- Exclusion for masses exceeding ~1 GeV even for extremely weak interactions

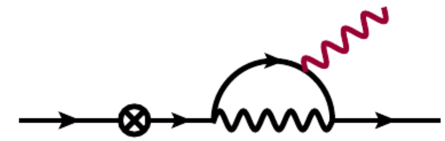
The LHC also probes masses of order GeV–TeV.

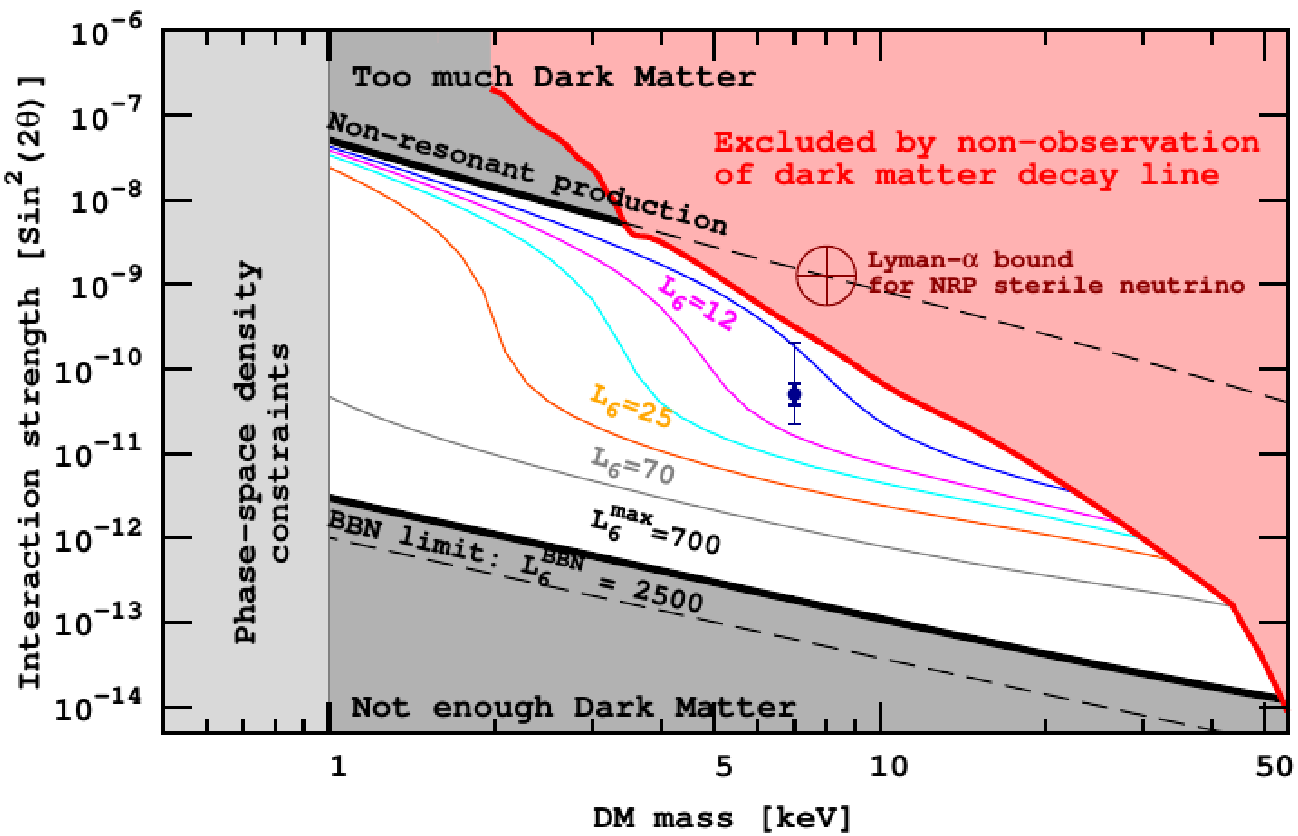
If dark matter is a particle:

- Either it has quasi no interactions with known particles
- Or its mass is << GeV
- Or its mass is >> TeV.

Heavy neutrino dark matter

- Mass in keV range – warm, very long ligetime, but occasionally decaying ($N \rightarrow \nu\gamma$)
- Look at decay line in galaxy clusters





~~CP~~ in neutrino oscillations

- Do neutrinos behave the same as antineutrinos?

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

$$= -2\sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})\boldsymbol{\sin(\delta)}\sin\left(\frac{\Delta m^2_{21}L}{4E}\right)\sin\left(\frac{\Delta m^2_{32}L}{4E}\right)\sin\left(\frac{\Delta m^2_{31}L}{4E}\right)$$

- Measuring δ is a challenge, it requires
  - Chosing *L* et *E* such as to maximise this difference
  - Controlling neutrino and antineutrino fluxes
  - Observing the appearance of neutrinos and antineutrinos
  - Controlling backgrounds which can mimic this appearance
  - ➔ Accelerator neutrinos

$$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$$

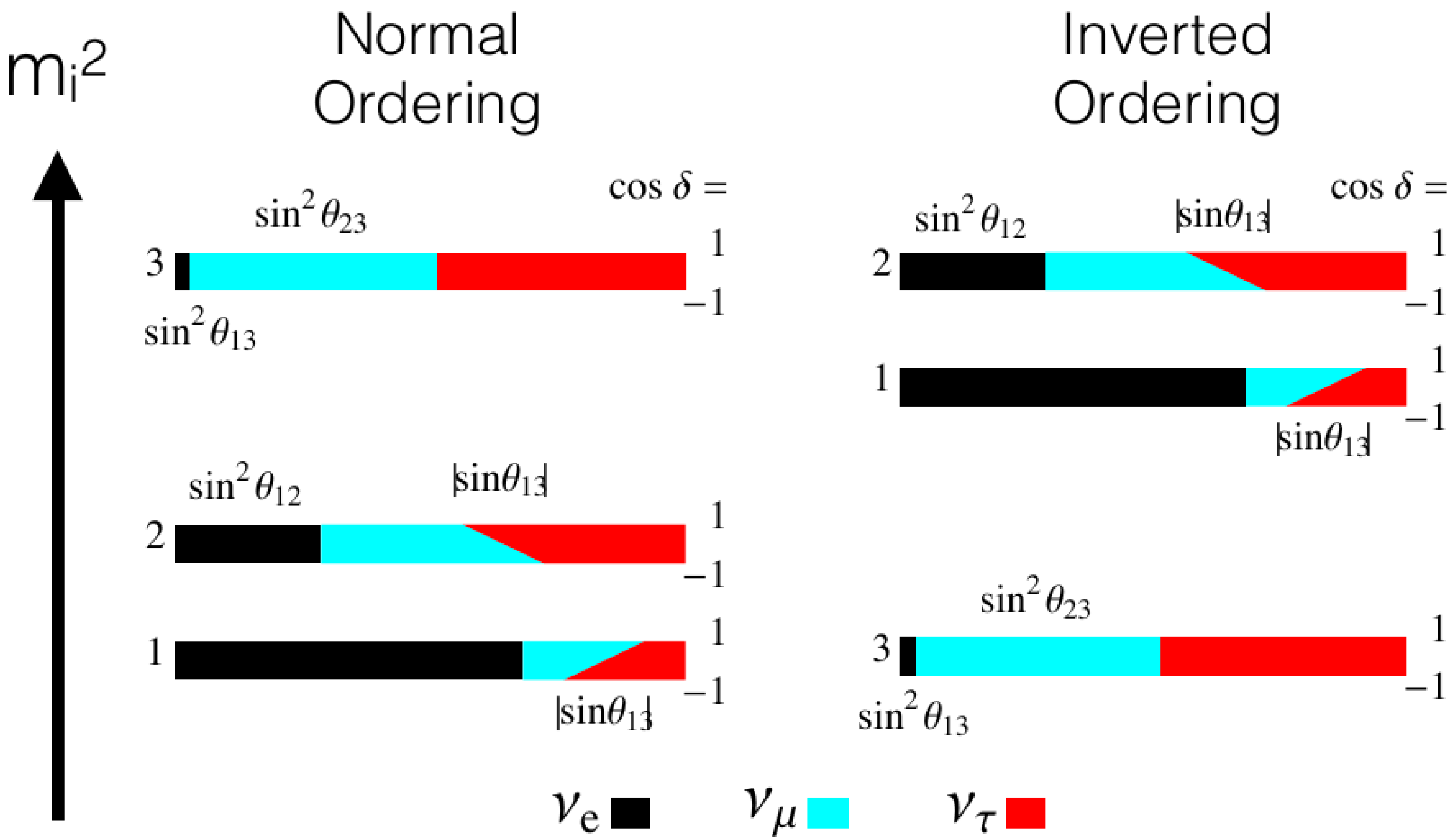
Leptogenesis

- Postulate right-handed neutrino N (Dirac+Majorana)
  - Copiously produced in primordial soup
  - Capable of ~~CP~~
- Step 1: asymmetric production of leptons and anti-leptons

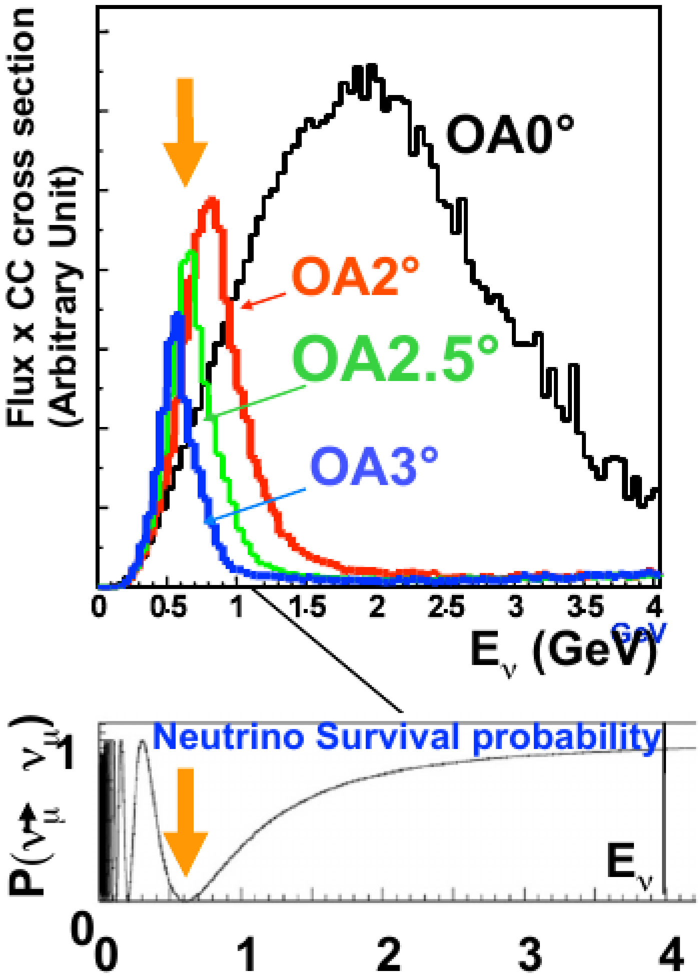
$$\mathrm{BR}(N \to \ell^+ + W^-) \neq \mathrm{BR}(N \to \ell^- + W^+)$$

- Step 2: action of sphaleron
  - Standard Model process which does not conserve baryonic (B) and leptonic (L) numbers (but conserves B-L)
  - Lepton-antilepton asymmetry converted into baryon-antibaryon asymmetry
- Postulating N is sufficient to explain matter-antimatter asymmetry in the Universe!

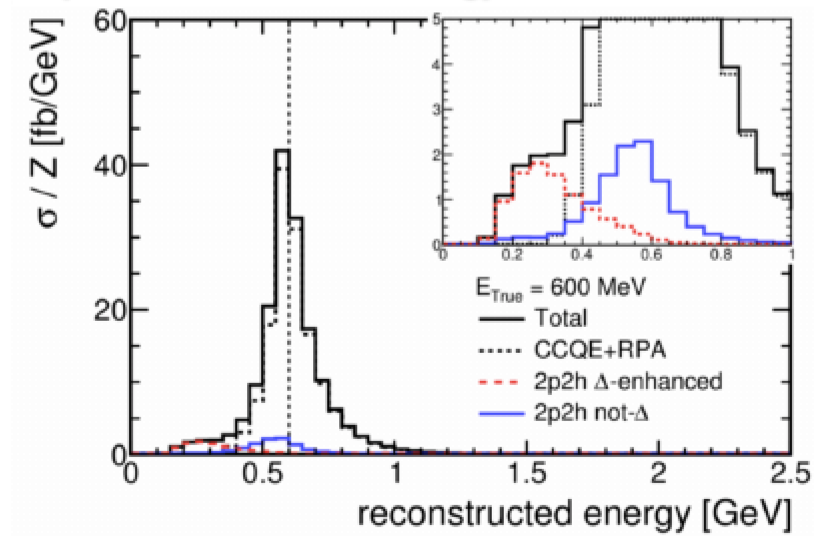
Neutrino flavour contents



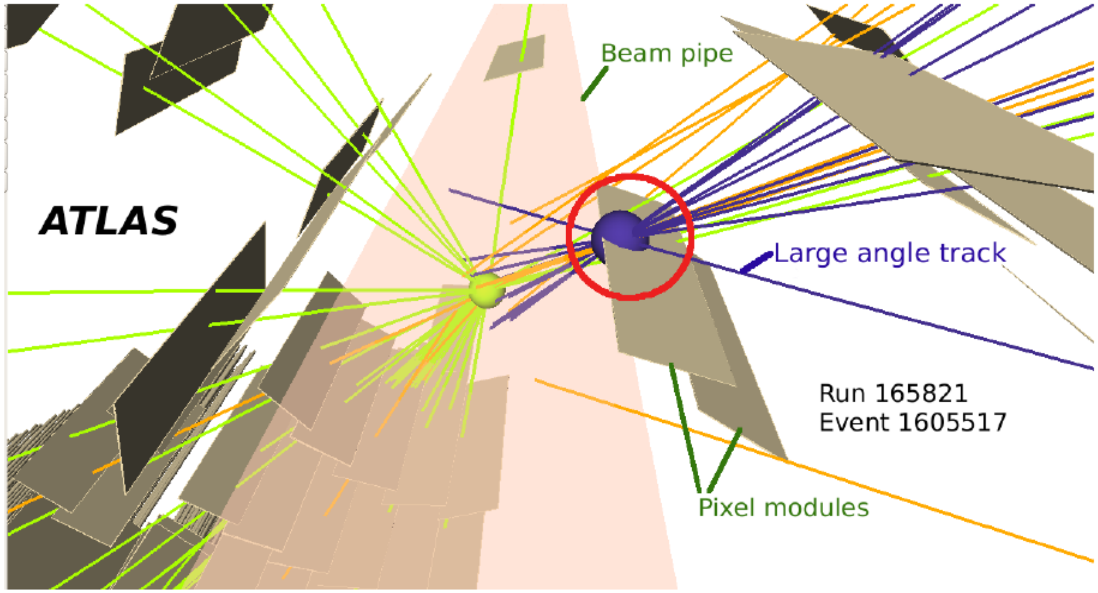
T2K neutrino beam spectrum

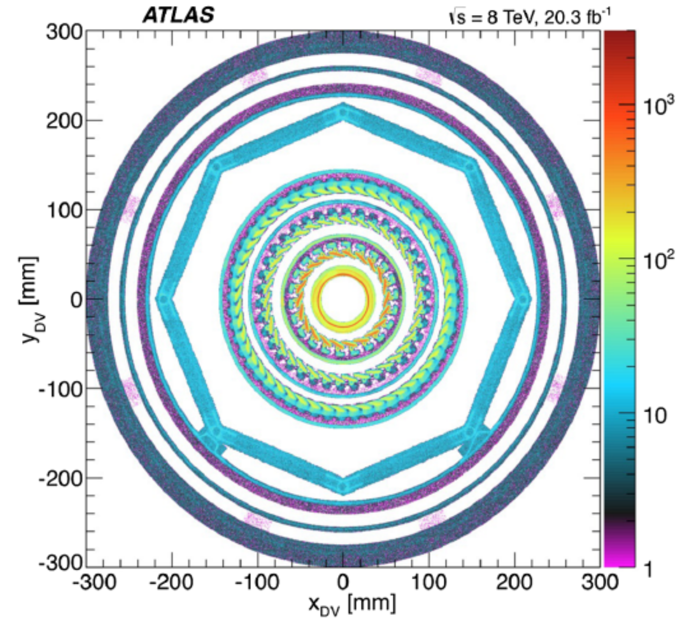


2p2h → bias the energy reconstruction

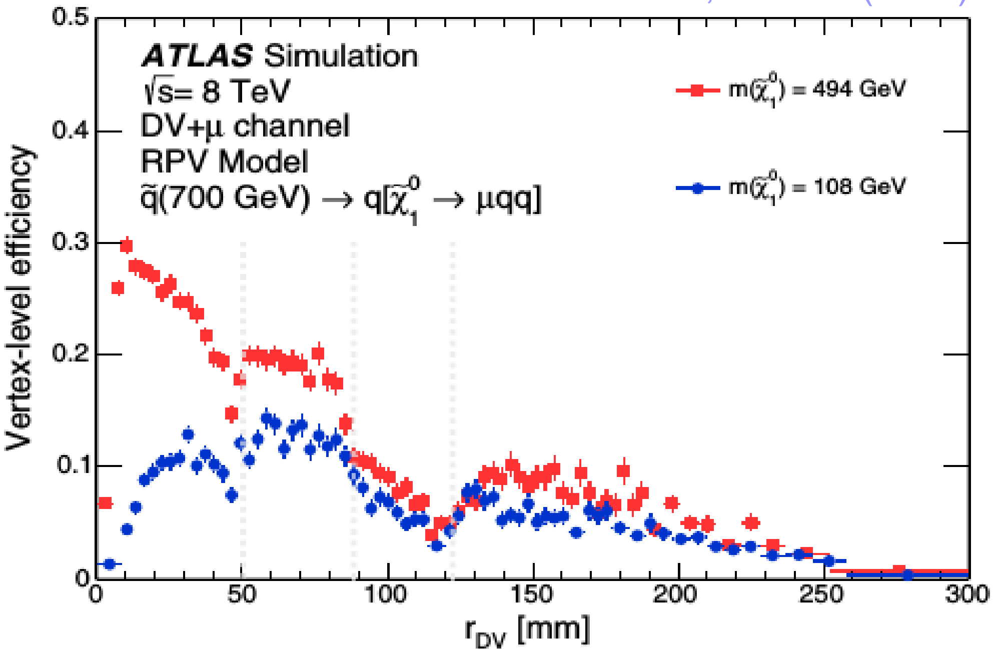


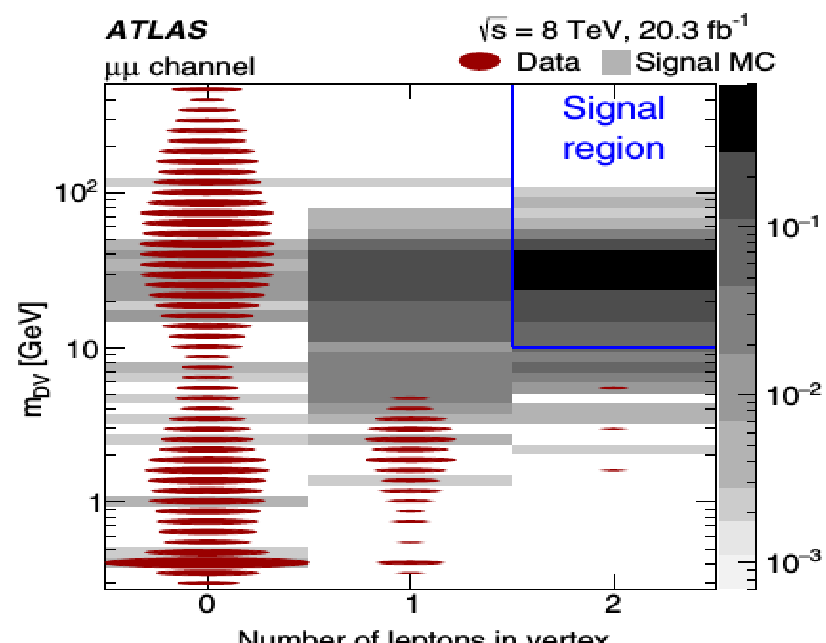
DV signatures at ATLAS





PRD 92, 072004 (2015)

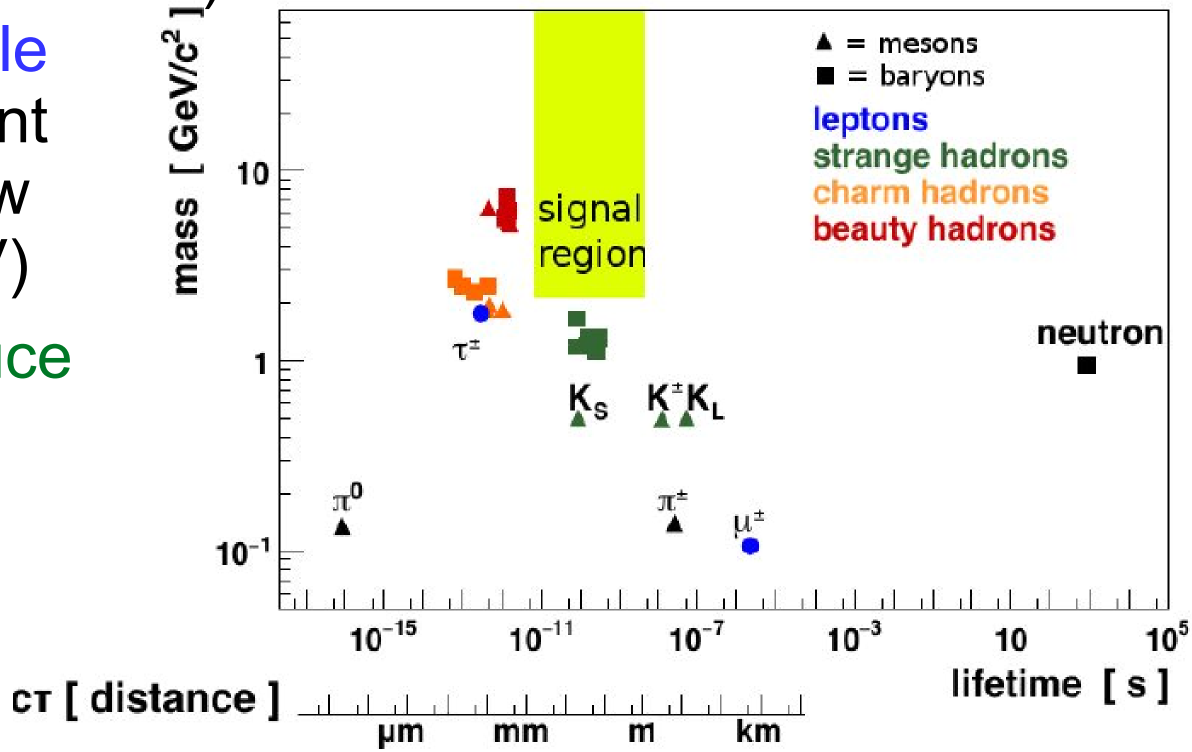




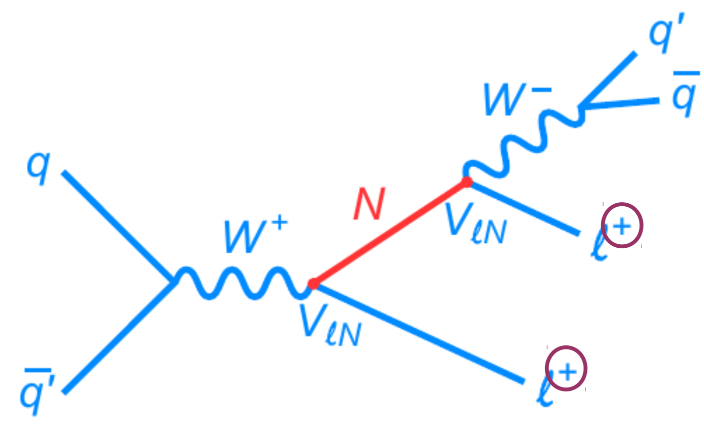
Backgrounds

- Random crossings of pile-up tracks
- Hadronic interactions with detector material (reduced by material map veto
- Cosmics producing back-to-back displaced muons (rejected by cosmic veto)
- Metastable particle decays – dominant background at low masses (< 5 GeV)

Most of these produce hadrons, hence the “tight” lepton ID requirements to reduce fakes



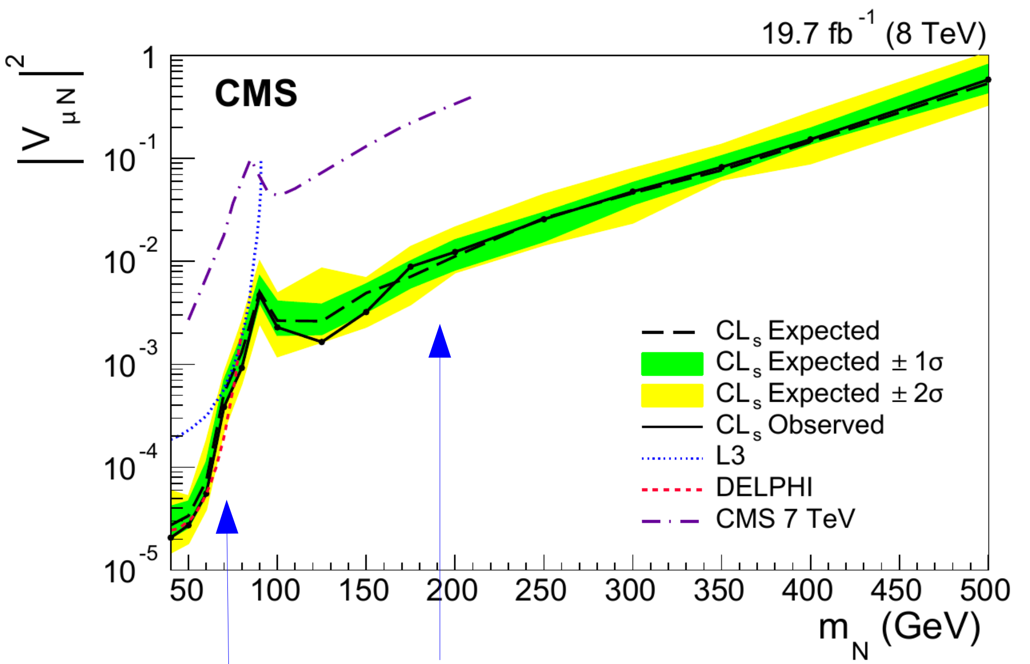
LHC – prompt high-pT signature



Same-sign leptons + two jets

- Exploit Majorana nature of the neutrino
- Investigated in both ATLAS and CMS

  PLB 717, 109 (2012); JHEP 07, 162 (2015); PLB 748, 144 (2015)



on-shell *W*

off-shell *W*

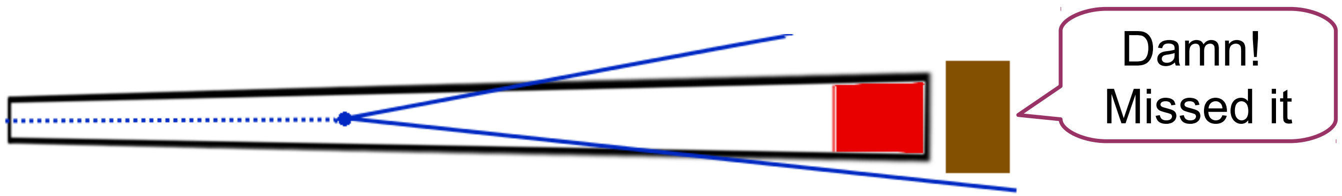
- Models of leptogenesis point to lower mass, lower mixing

  → on-shell W

Example of typical SHiP event selection

Start with two high-quality tracks in spectrometer

– Typically 6% probability once N decays inside the vessel



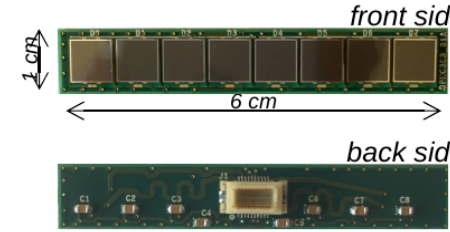
For these require:

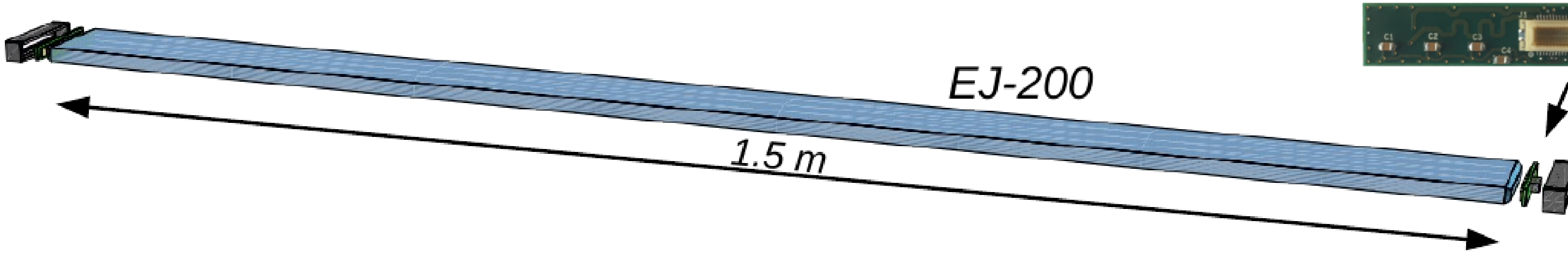
- Vertex with DOCA < 30 cm inside the decay volume
- Identify one muon and one pion
- Matched hits in timing detector within 200 ps window
- No hit in the upstream veto tagger and in surround veto near the vertex
- Reconstructed parent pointing to target within 2.5 m distance

~70% efficiency for $N \rightarrow \mu\pi$ once both tracks are reconstructed

< 0.1 background events remaining

Test module

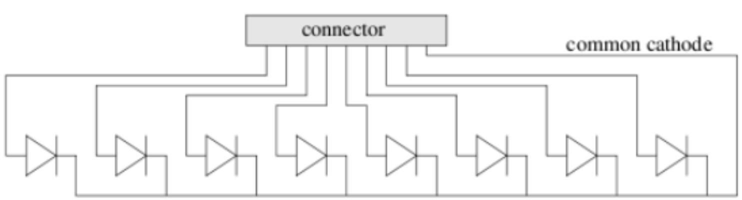


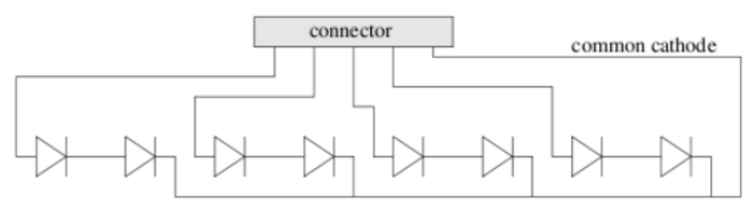


- EJ-200 plastic bars, 6 cm x 1 cm x 1.5 m
- Customised external PCBs with large-area SiPM arrays applied directly to bar surface on both ends

"parallel" connection:
8 6x6 mm² sensors in parallel → 8 signals

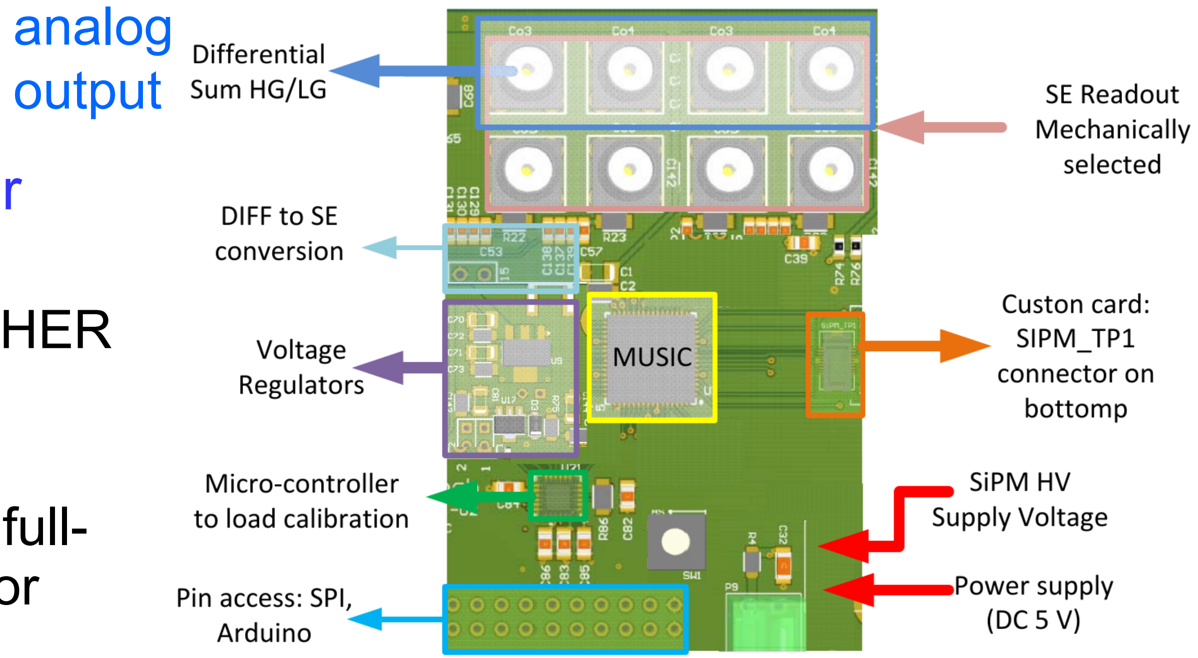
"series" connection:
4 pairs of 6x6 mm² sensors in parallel with each pair connected in series → 4 signals





Electronics

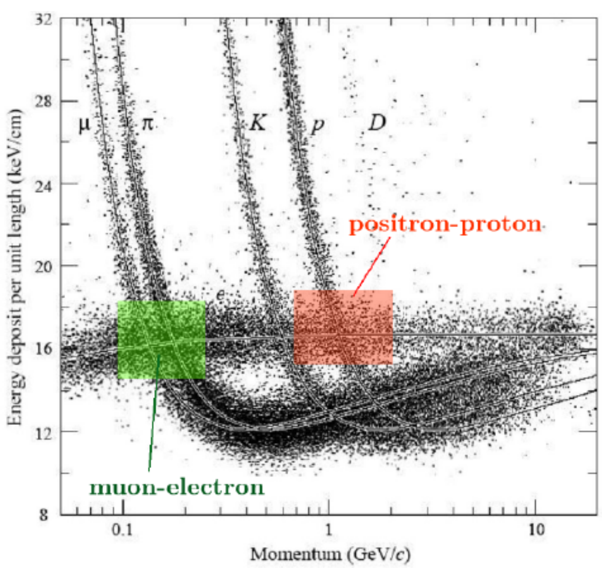
- SiPM anode readout ASIC (MUSIC R1)
  - read, amplify and sum up to 8 SiPM output signals
- Highly customisable board used for tests
  - But we do not need all its functions
- Simpler, cheaper board being developed



- Waveform digitiser
  - 16-channel WAVECATCHER for tests
  - 64-channel SAMPIC for full-scale detector

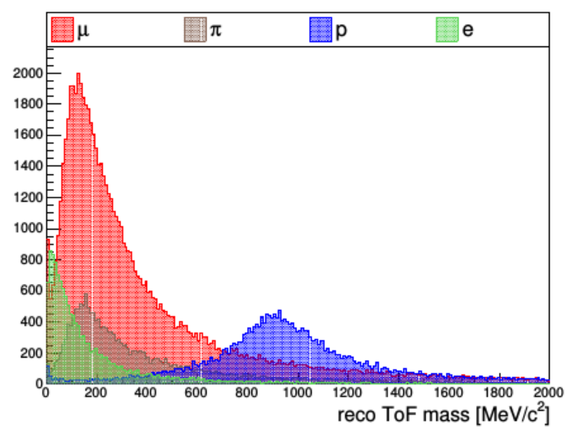
Timing improves signal identification

- Measure track sense – reject OOFV backgrounds
  - Two planes 600 ps resolution 75 cm apart: 3σ separation
  - Two planes 150 ps resolution 75 cm apart: 11σ separation
- Help with particle identification
  - Muon-electron confusion zone ~0.2 GeV
  - Proton-positron confusion zone ~1 GeV

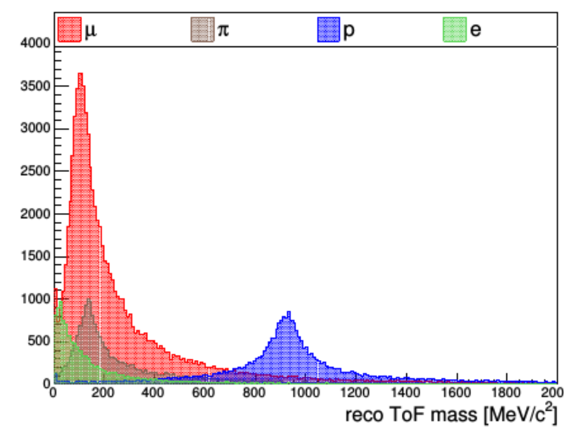


(from study by M. Lamoureux)

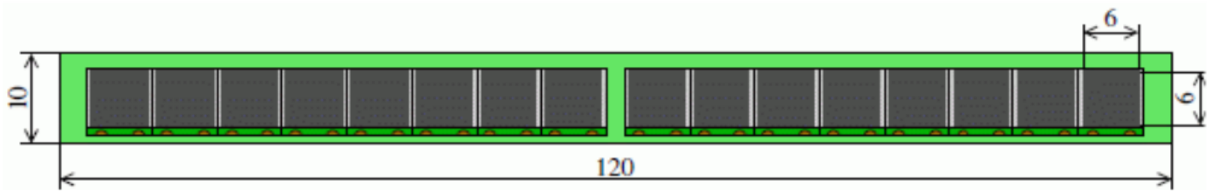
$\sigma = 600$ **ps**

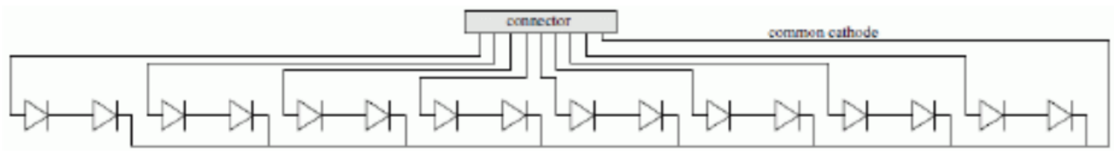


$\sigma = 150$ **ps**



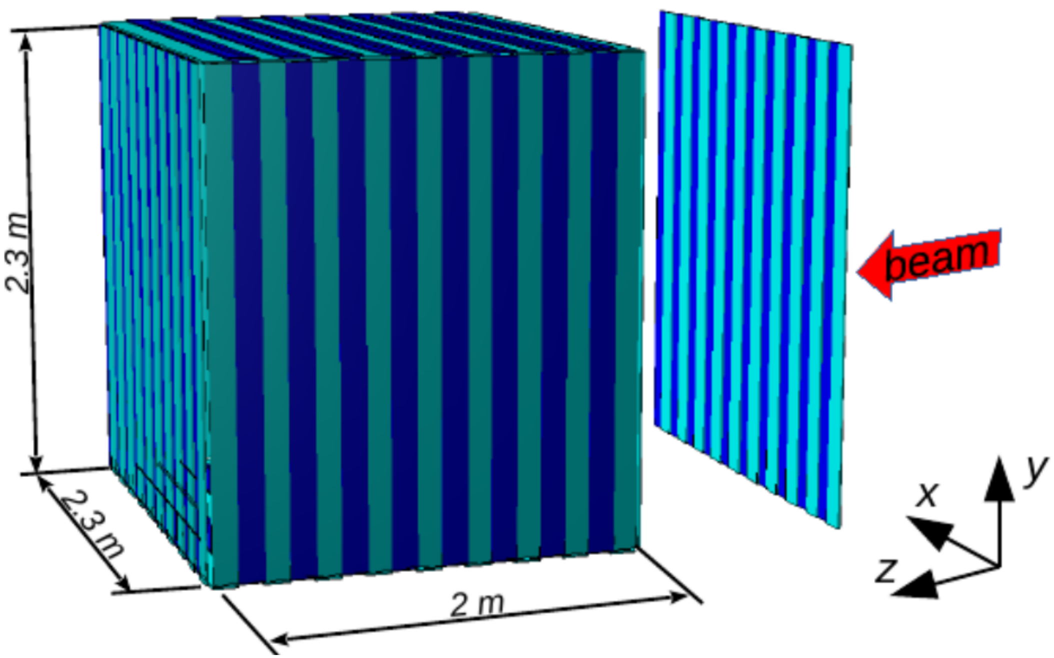
Proposed design for ND280 upgrade





Pairs of SiPMs in series

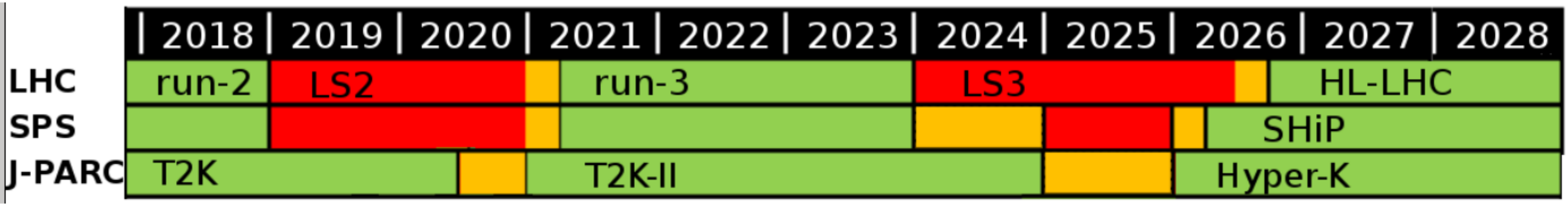
- 12 cm width
- 16 SiPMs per channel



- XY module: 20 bars
- XZ, YZ modules: 17 bars
- 3x20 + 4x17 = 128 bars
- 2 x 128 = 256 channels
- 16 x 256 = 4096 SiPMs

Estimated cost 200 kEUR

Timeline



1st ATLAS N search

Timing det. prorotype

Super-FGD prototype

ND280 upgrade construction commissioning

T2K-II operation

Hyper-K operation

Hyper-K R&D

Hyper-K construction and commissioning

SHiP CDS

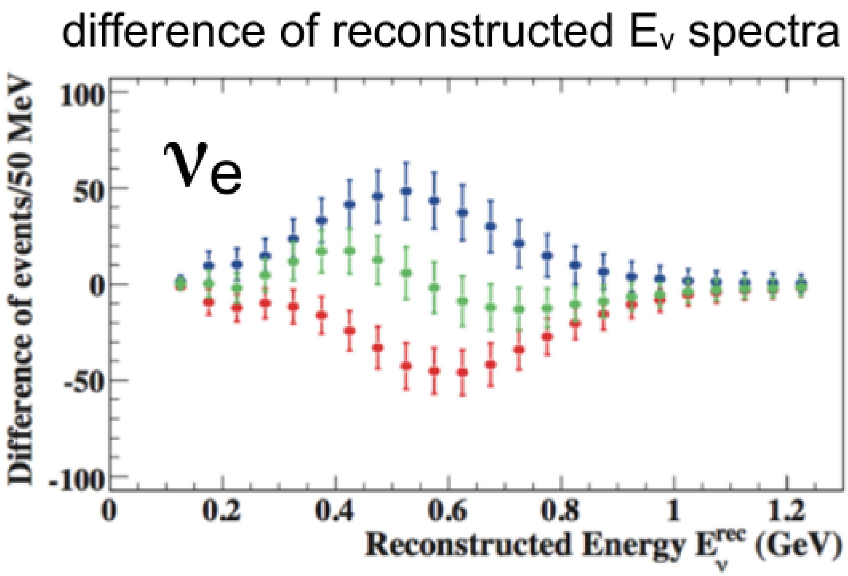
SHiP approval

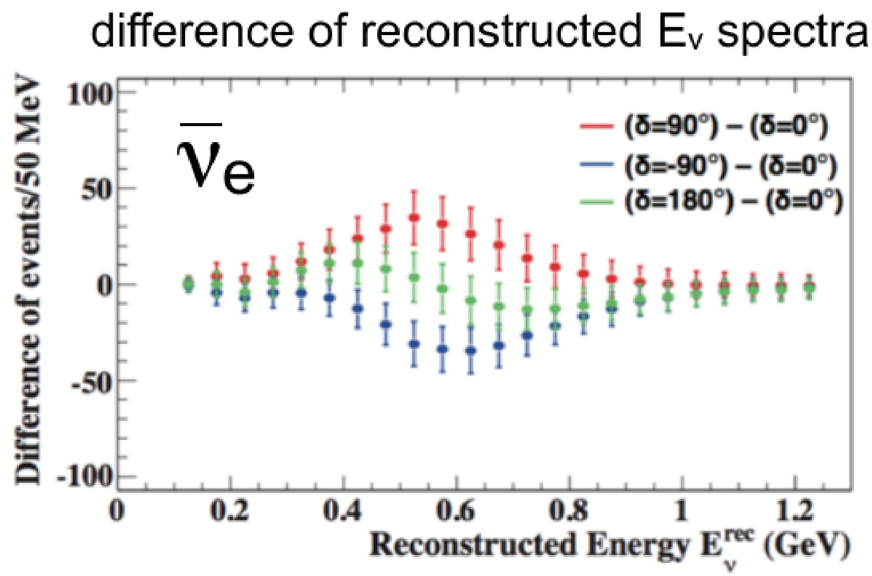
SHiP TDR

SHiP construction and commissioning

SHiP operation

Hyper-K expected performance





Possibility of using shape information in energy to distinguish different values for δ (CP)

- 1.3 MW for JPARC proton beam
- ~ 40% PMT coverage in HK
- 3-4% systematic uncertainties