Long-Lived Particles at Spallation Sources

In collaboration with C. Argüelles (Harvard) & S. Urrea (IFIC, Valencia)

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The Magnificent CEvNS 2024
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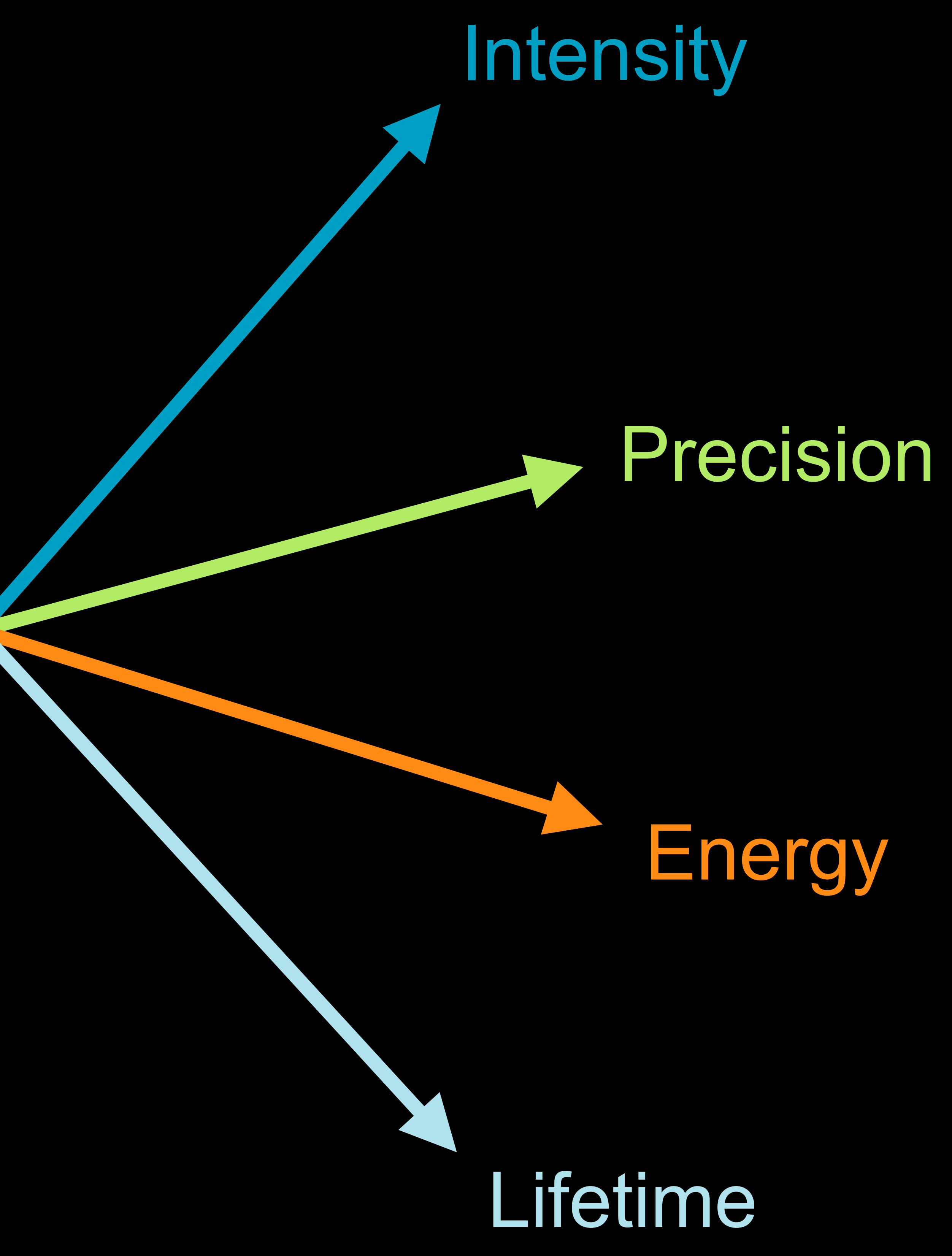
BSM in the laboratory



Intensity

Precision

Energy

Lifetime

Long-lived particles at Spallation sources (Intensity & Lifetime)

Neutrino masses, dark matter, the flavor pattern, strong CP problem, …

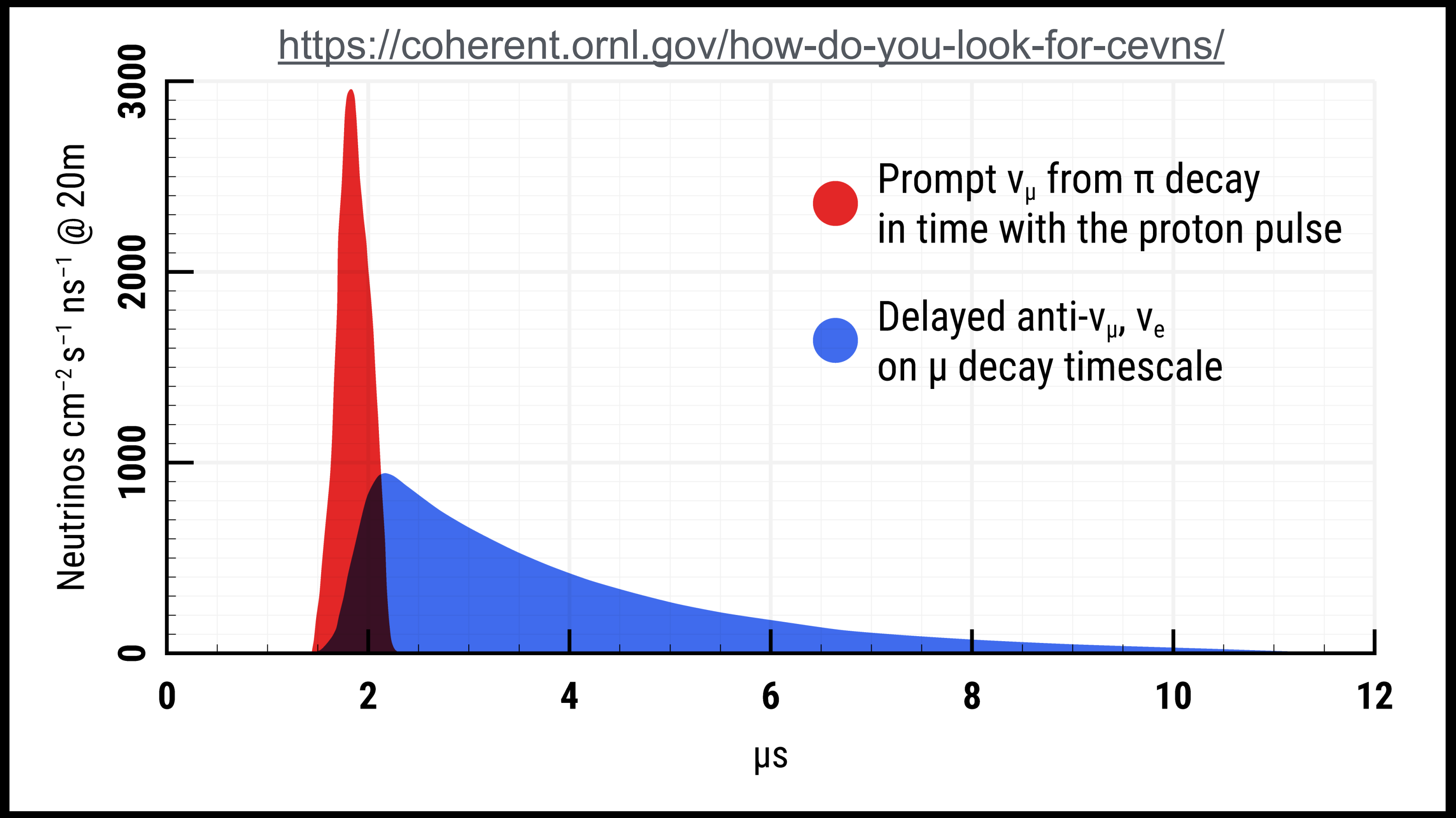
The existence of new light particles is not *mandatory* for solving
the predictivity and incompleteness issues of the Standard Model.

But it sure would provide major hints of the direction forward.

Searching for new light “dark sectors” is cheap
and could bring a new revolution to our field.

Long-lived particles at Spallation sources (Intensity & Lifetime)

$10^{20} - 10^{22}$ π^+, K^+, and μ^+ decays at rest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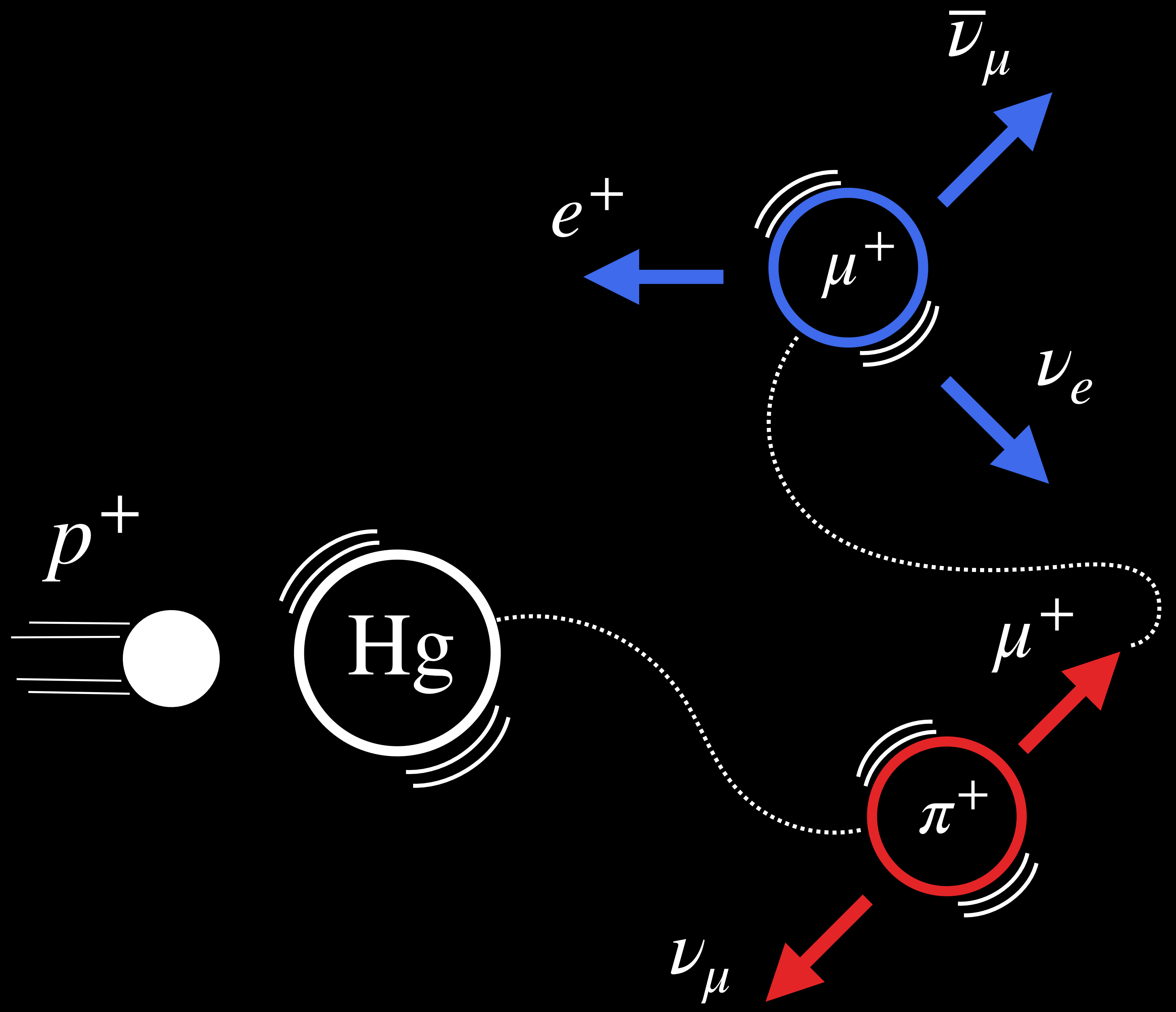
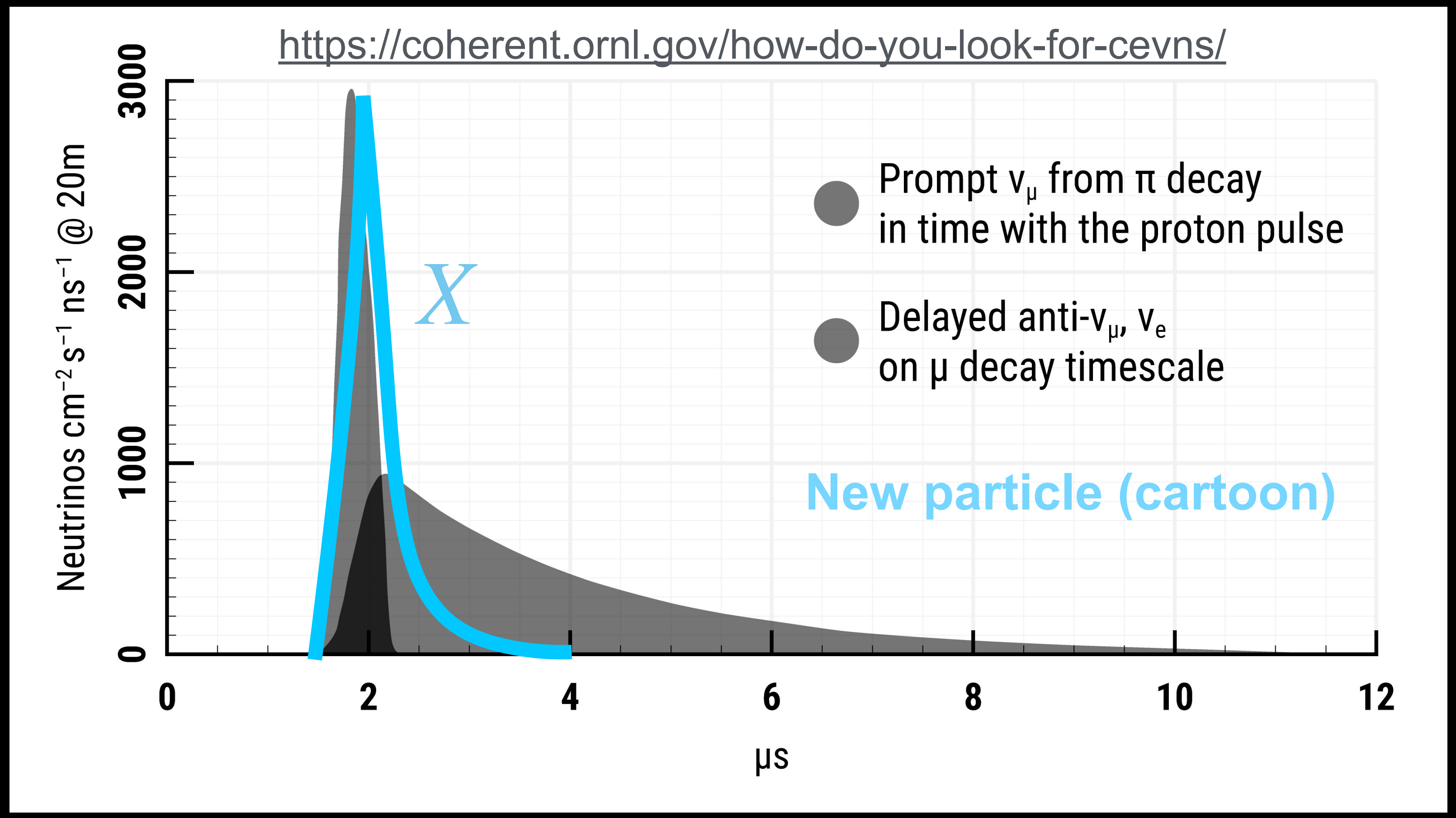


Long-lived particles at Spallation sources (Intensity & Lifetime)

$10^{20} - 10^{22}$ π^+, K^+, and μ^+ decays at rest

Close to *medium*-sized neutrino detectors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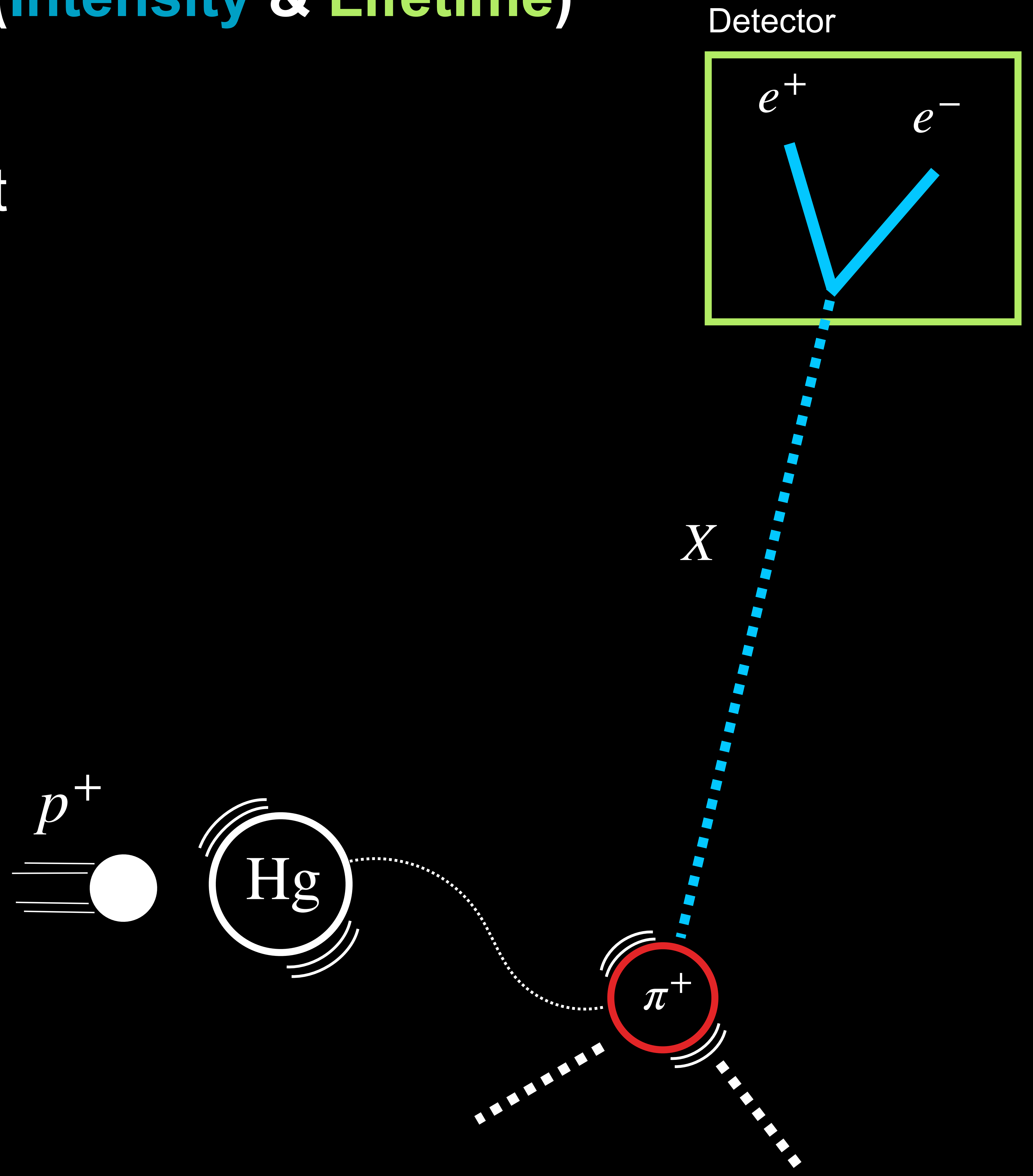

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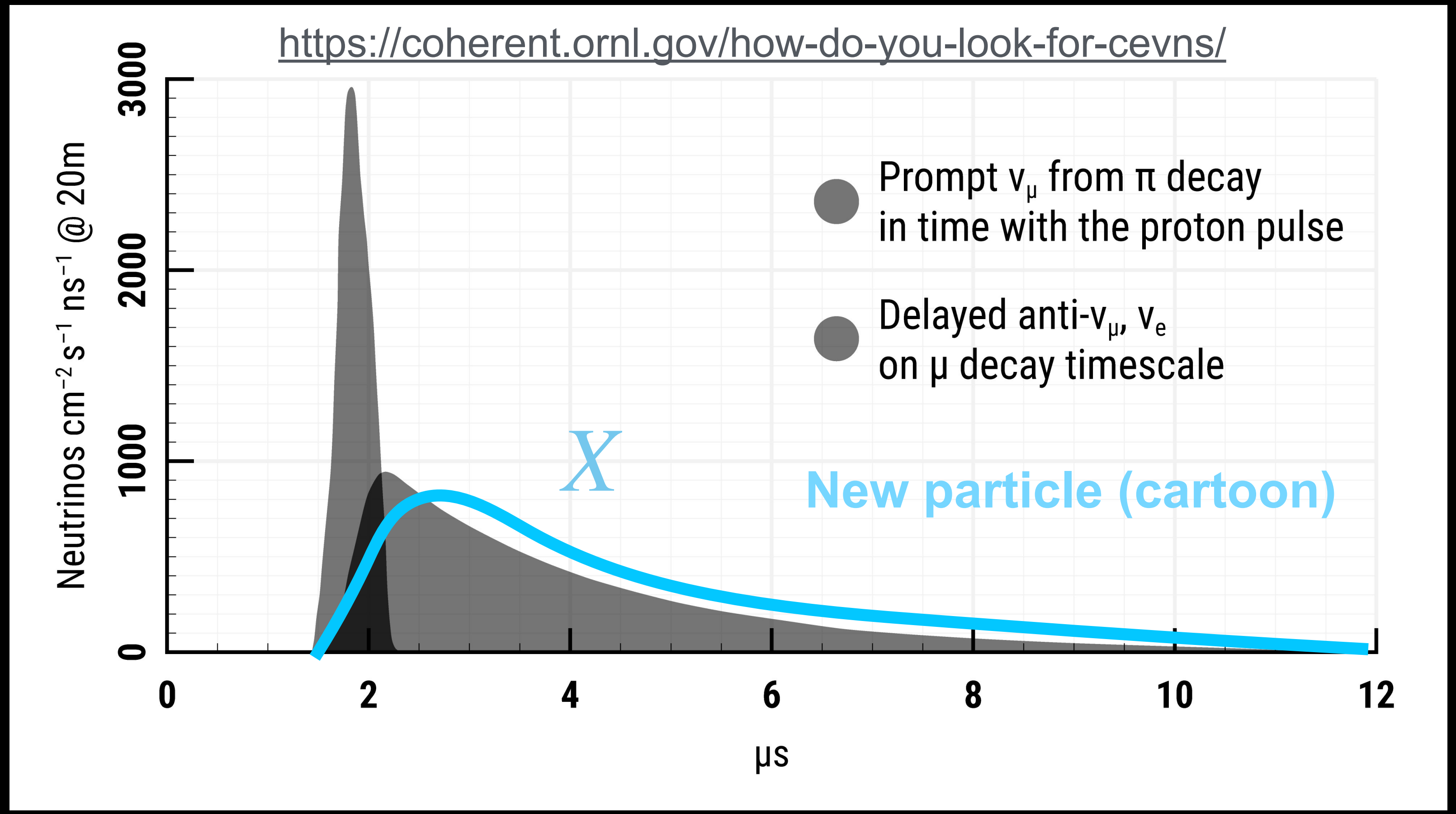
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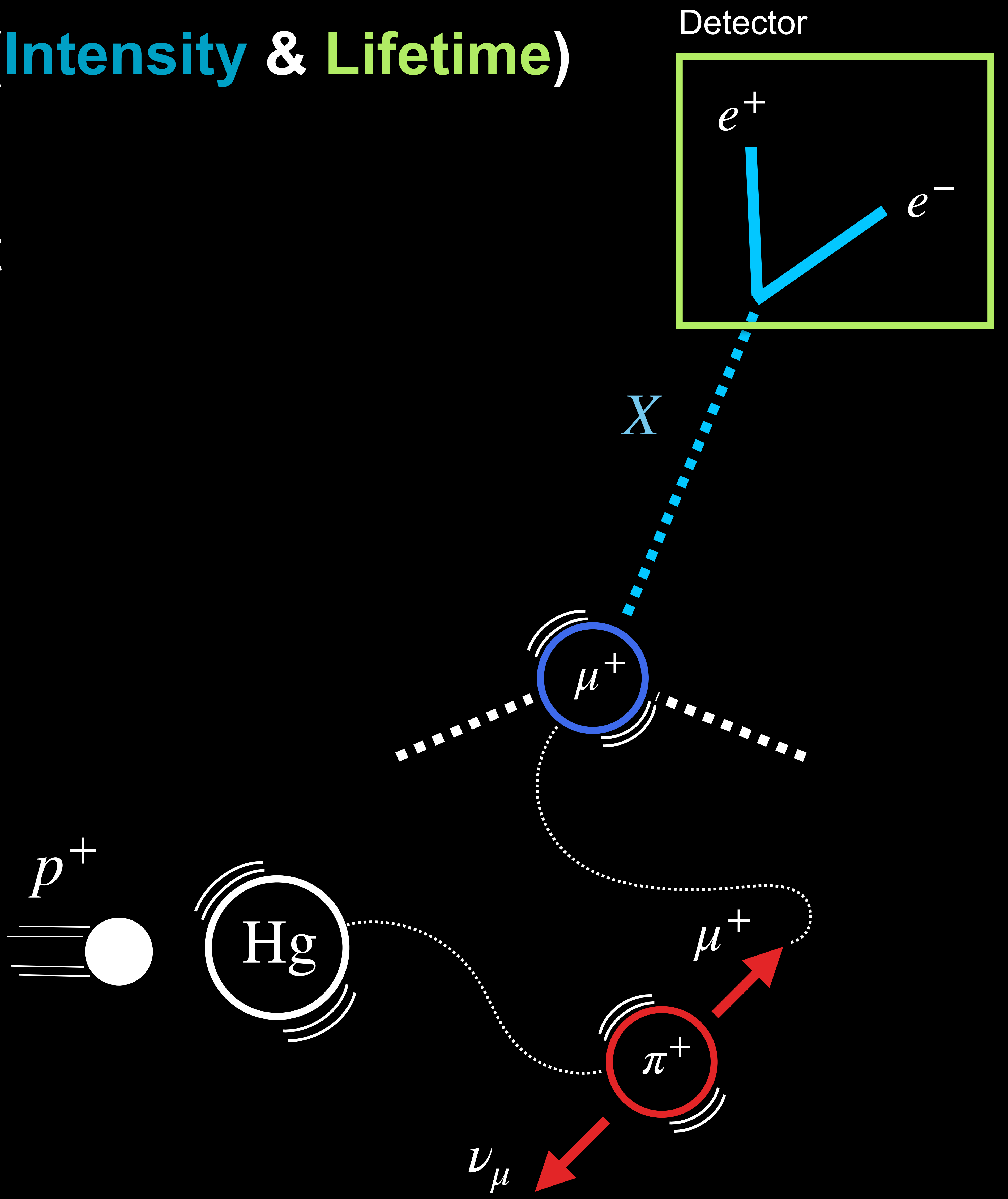


For the impatient:

1) There is plenty of room for new long-lived particles below the pion and muon mass.

2) Can lead to e^+e^-, γ, and $\gamma\gamma$ inside the fiducial volume with several 10’s of MeV energy.* Because of the DAR kinematics, this becomes a bump hunt in some models.

*great synergy with plans to measure ν_e CC @ SNS: D_2O, LAr, NaIvETe.

3) Ideal detector: a fast, well-shielded, *large-volume and low-density* detector.

$\pi^+/\mu^+/K^+$ DAR sources

ISIS (Rutherford, UK)
- 0.8 GeV p^+
- 0.16 MW and 0.2 mA
- 50 Hz
- 200 ns double-pulse (total 700 ns)
- About 4% πDAR/POT

SNS (Oak Ridge, USA)
- 1 GeV p^+
- 1.4 MW and 1.1 mA
- 60 Hz
- 400 ns single-pulse
- About 9% πDAR/POT

SINQ (PSI, Switzerland)
- 0.59 GeV p^+
- 1.4 MW and 2.4 mA
- Continuous
- Total of (—) πDAR/POT

LANSCE current (Los Alamos, USA)
- 0.8 GeV p^+
- 0.1 MW and 0.125 mA
- 20 Hz
- 290 ns single-pulse
- Total of 4.6% πDAR/POT

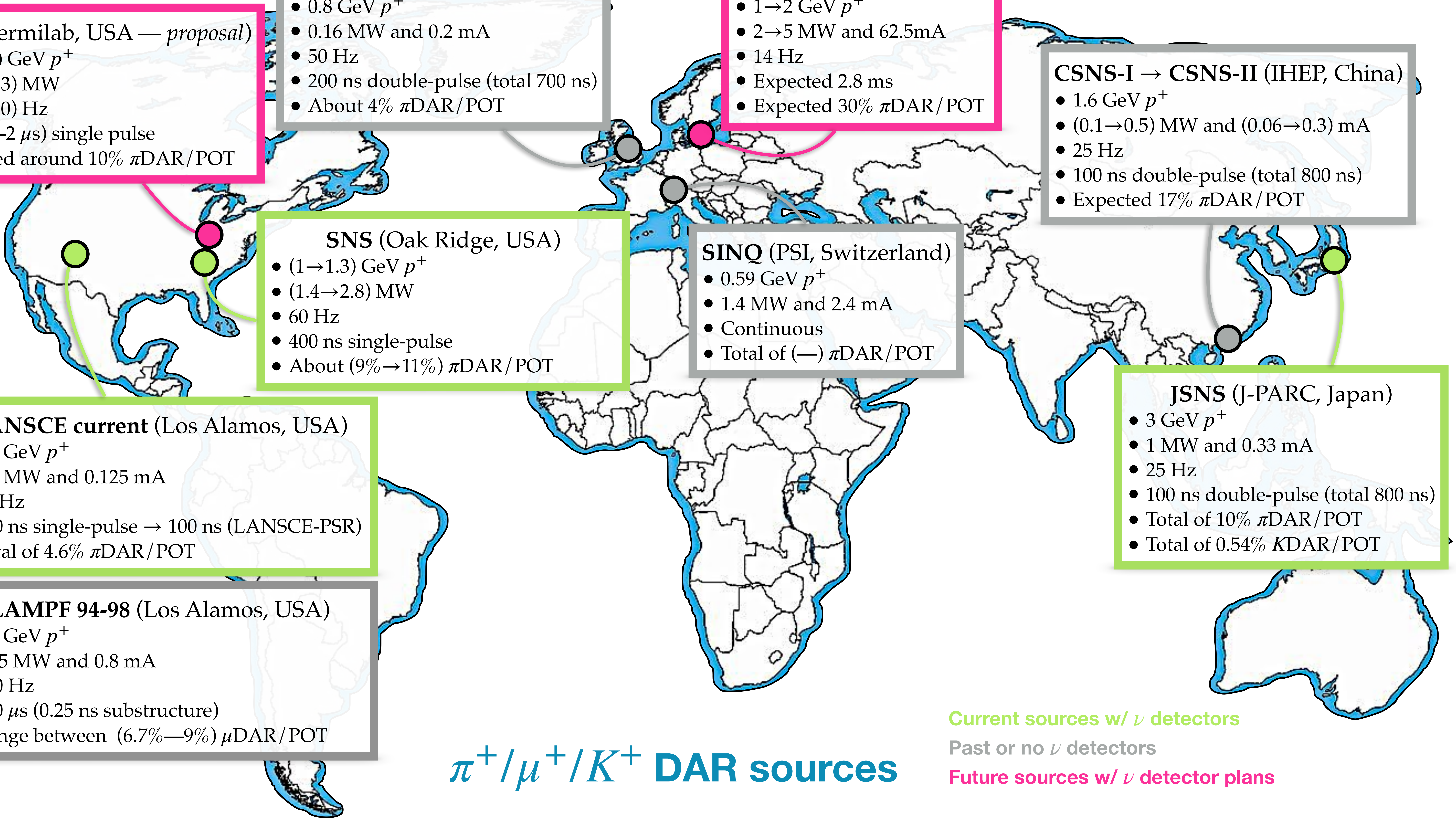
LAMPF 94-98 (Los Alamos, USA)
- 0.8 GeV p^+
- 0.65 MW and 0.8 mA
- 120 Hz
- 600 μs (0.25 ns substructure)
- Range between (6.7%—9%) μDAR/POT

JSNS (J-PARC, Japan)
- 3 GeV p^+
- 1 MW and 0.33 mA
- 25 Hz
- 100 ns double-pulse (total 800 ns)
- Total of 10% πDAR/POT
- Total of 0.54% KDAR/POT

Current sources w/ ν detectors

Past or no ν detectors

$\pi^+/\mu^+/K^+$ DAR sources



F2D2 (Fermilab, USA — *proposal*)
- $(0.8$—$2)$ GeV p^+
- (0.1—1.3) MW
- (60—120) Hz
- (20 ns—2 μs) single pulse
- Expected around 10% πDAR/POT

ISIS (Rutherford, UK)
- 0.8 GeV p^+
- 0.16 MW and 0.2 mA
- 50 Hz
- 200 ns double-pulse (total 700 ns)
- About 4% πDAR/POT

ESS (Lund, Sweden)
- $1 \rightarrow 2$ GeV p^+
- $2 \rightarrow 5$ MW and 62.5mA
- 14 Hz
- Expected 2.8 ms
- Expected 30% πDAR/POT

CSNS-I → CSNS-II (IHEP, China)
- 1.6 GeV p^+
- $(0.1 \rightarrow 0.5)$ MW and $(0.06 \rightarrow 0.3)$ mA
- 25 Hz
- 100 ns double-pulse (total 800 ns)
- Expected 17% πDAR/POT

SNS (Oak Ridge, USA)
- $(1 \rightarrow 1.3)$ GeV p^+
- $(1.4 \rightarrow 2.8)$ MW
- 60 Hz
- 400 ns single-pulse
- About $(9\% \rightarrow 11\%)$ πDAR/POT

SINQ (PSI, Switzerland)
- 0.59 GeV p^+
- 1.4 MW and 2.4 mA
- Continuous
- Total of (—) πDAR/POT

JSNS (J-PARC, Japan)
- 3 GeV p^+
- 1 MW and 0.33 mA
- 25 Hz
- 100 ns double-pulse (total 800 ns)
- Total of 10% πDAR/POT
- Total of 0.54% KDAR/POT

LANSCE current (Los Alamos, USA)
- 0.8 GeV p^+
- 0.1 MW and 0.125 mA
- 20 Hz
- 290 ns single-pulse → 100 ns (LANSCE-PSR)
- Total of 4.6% πDAR/POT

LAMPF 94-98 (Los Alamos, USA)
- 0.8 GeV p^+
- 0.65 MW and 0.8 mA
- 120 Hz
- 600 μs (0.25 ns substructure)
- Range between (6.7%—9%) μDAR/POT

Current sources w/ ν detectors
Past or no ν detectors
Future sources w/ ν detector plans

What do we already have?

The LSND $\nu - e$ scattering measurement

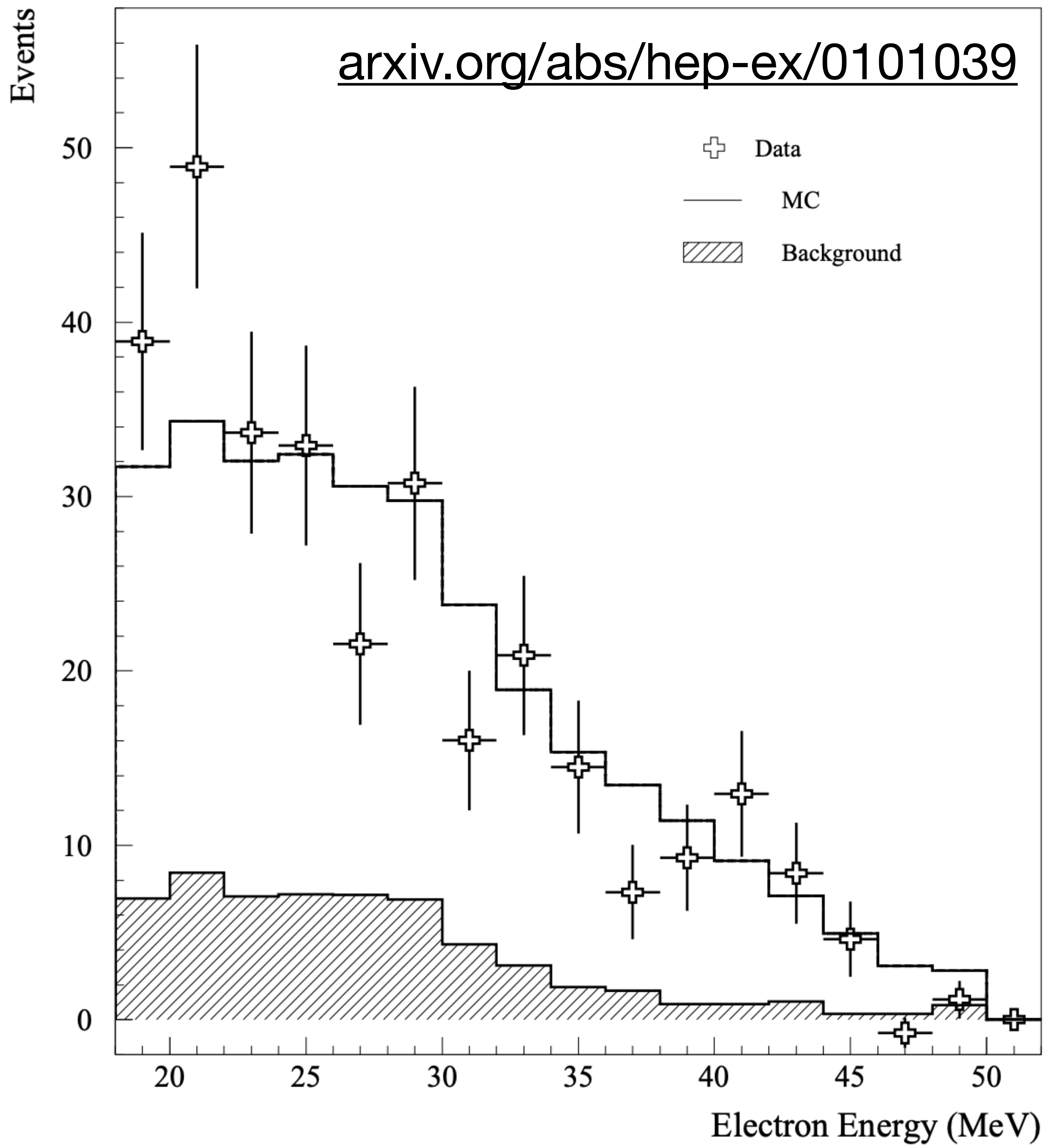
LSND: $\nu + e \to \nu + e$ scattering
(*not the same channel as the LSND anomaly.)

Has been very useful for a **large number** of BSM applications.

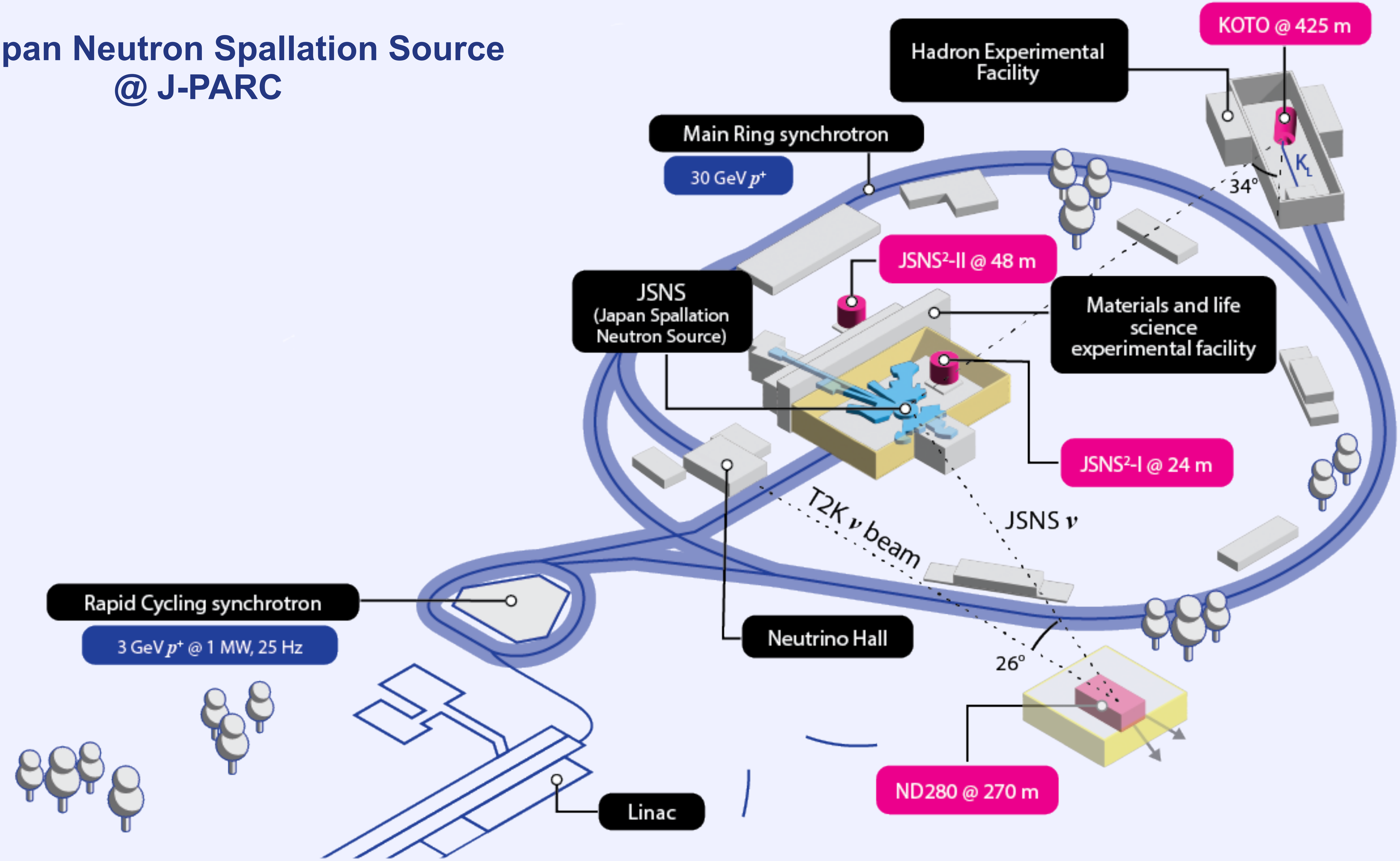
But is has its limitations:

1) Can only constrain $\mu^+ \to X$ decays (no π or K DAR)
2) Only single showers (how to account for misID of e^+e^-?)
3) Limited energy range: 18 MeV $< E_{\rm vis} <$ 50 MeV
4) Only the most forward electrons: $\cos\theta_{\rm vis} > 0.9$

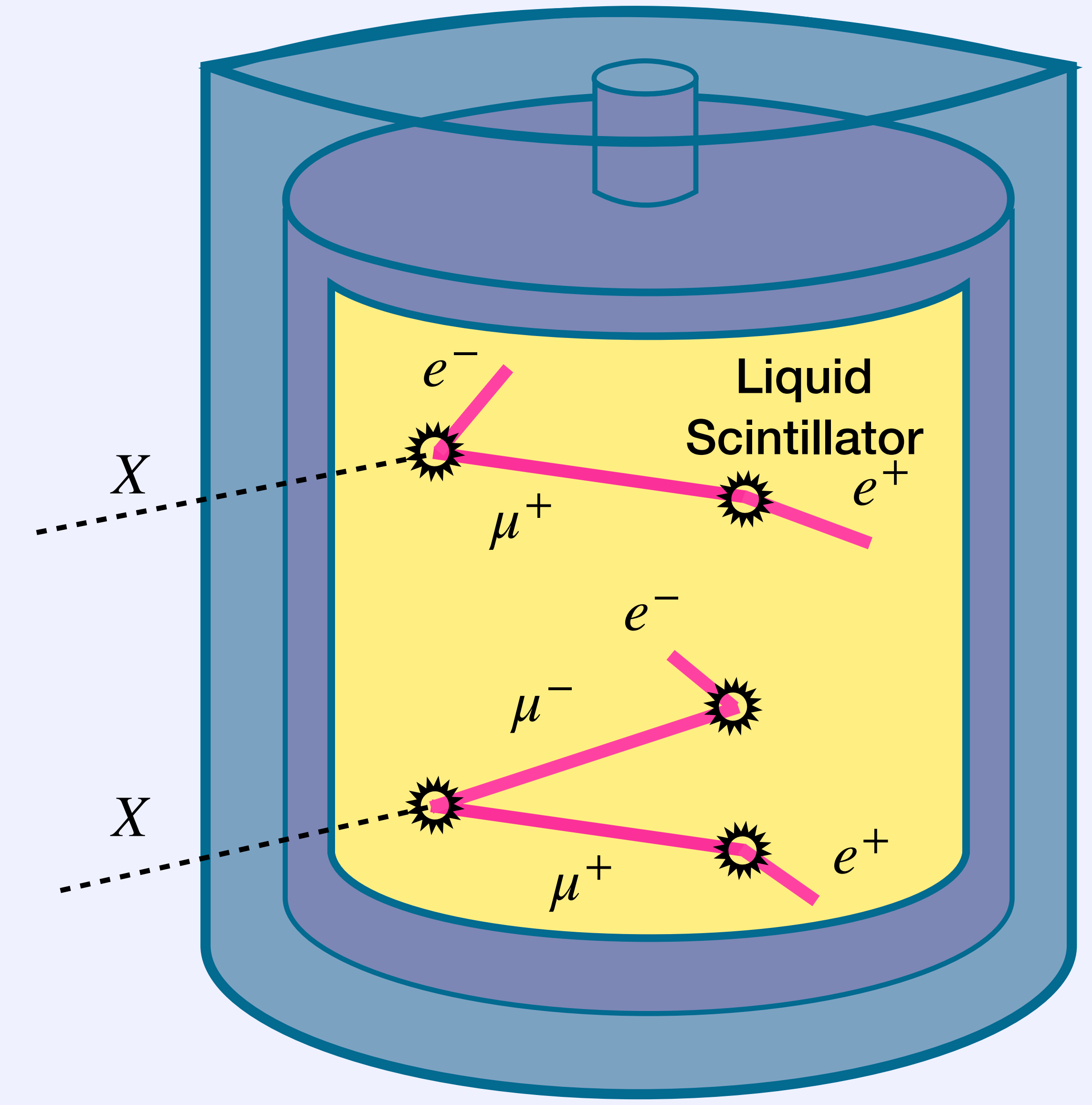
No data release… how to model efficiencies?
All bounds come from theorists digitizing this one plot →


arxiv.org/abs/hep-ex/0101039

The Japan Neutron Spallation Source @ J-PARC



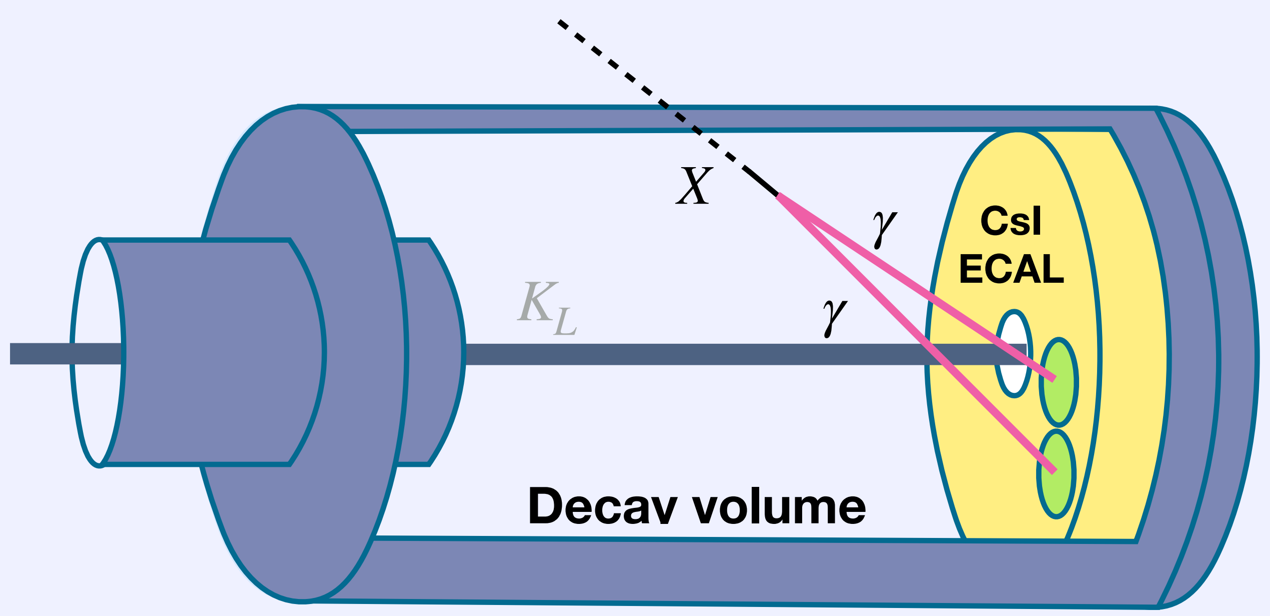
by J. Pairin

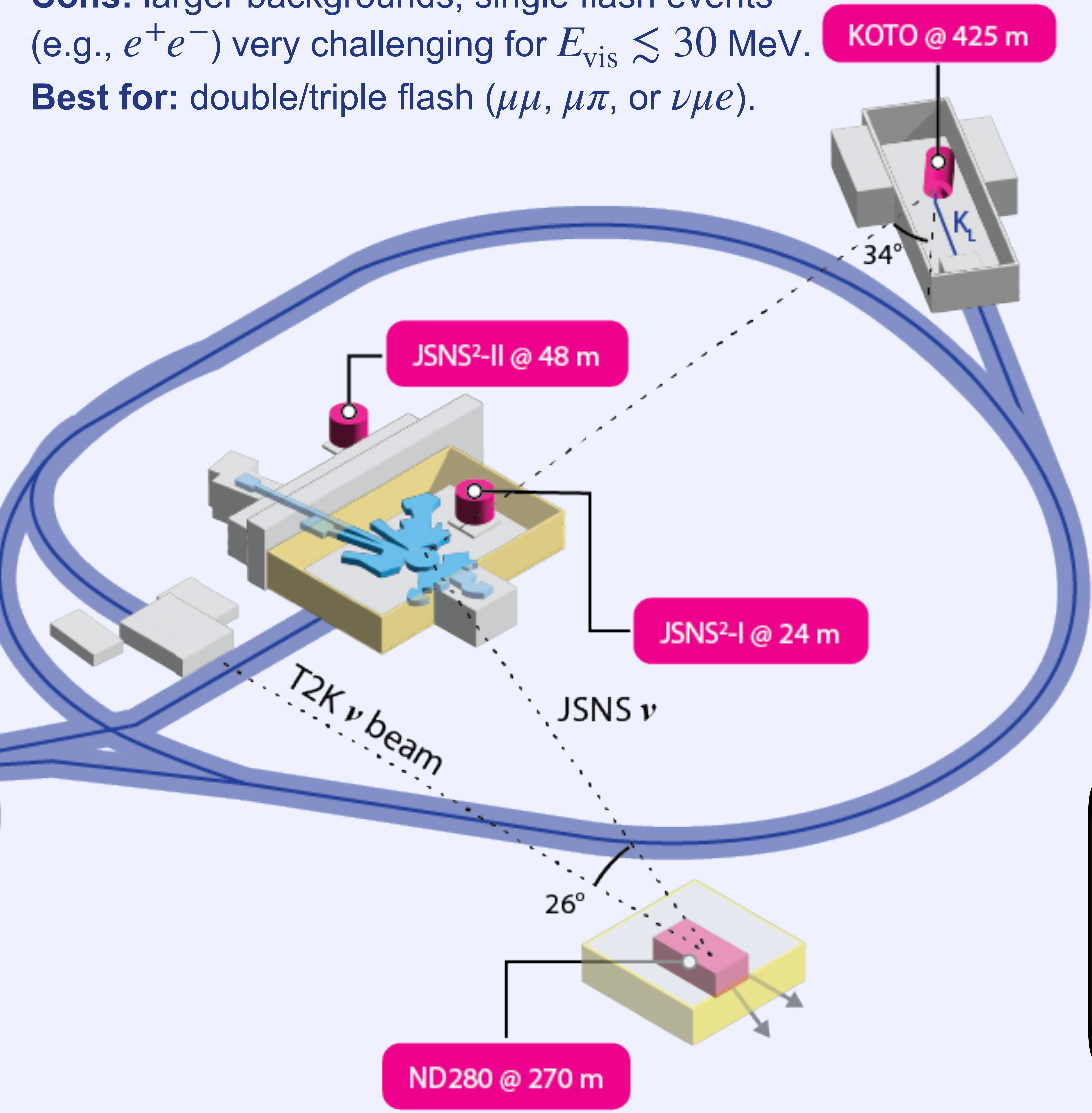


JSNS^2 (I and II):

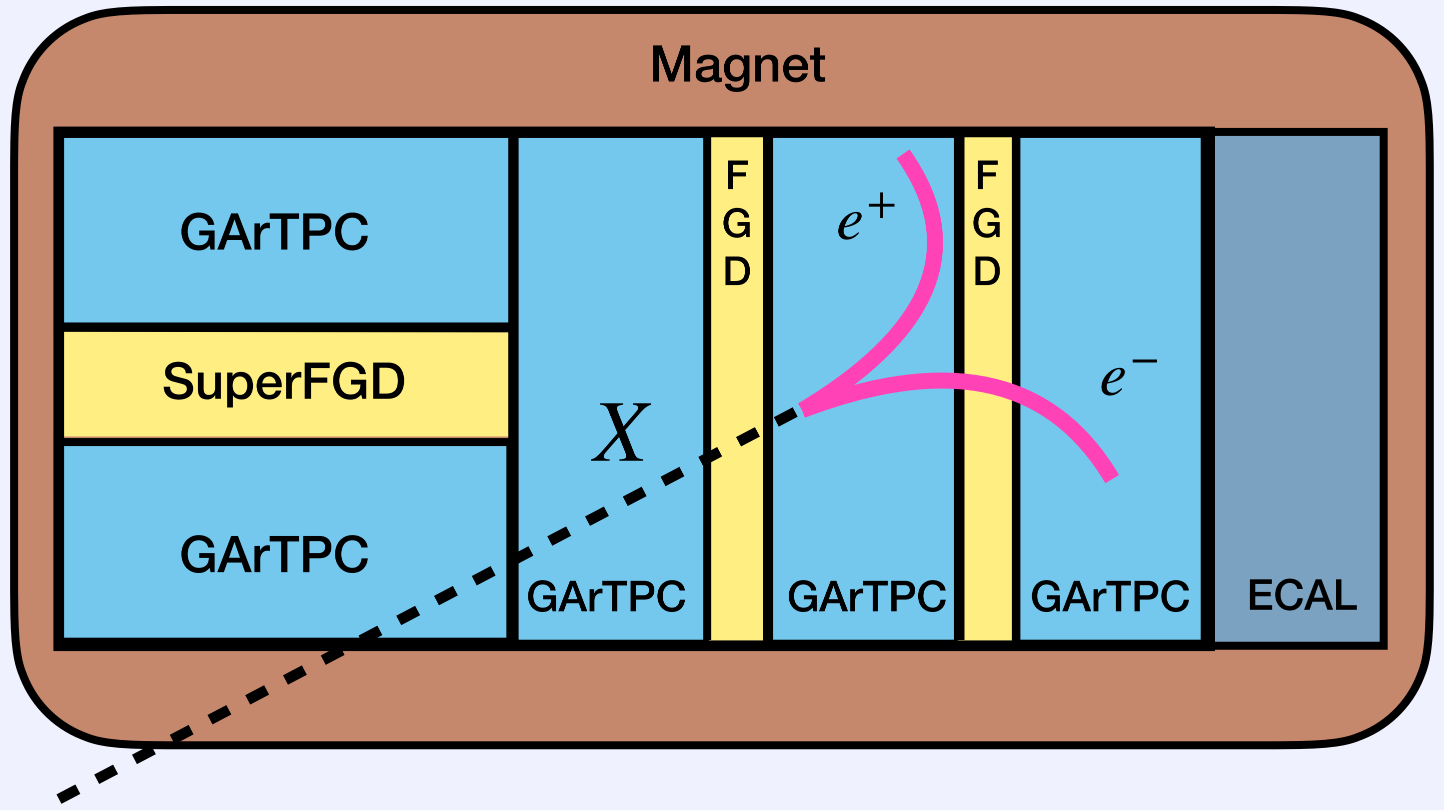
Pros: Closest to the source and largest vol
Cons: larger backgrounds, single flash events (e.g., e^+e^-) very challenging for $E_{\text{vis}} \lesssim 30$ MeV.
Best for: double/triple flash ($\mu\mu$, $\mu\pi$, or $\nu\mu e$).

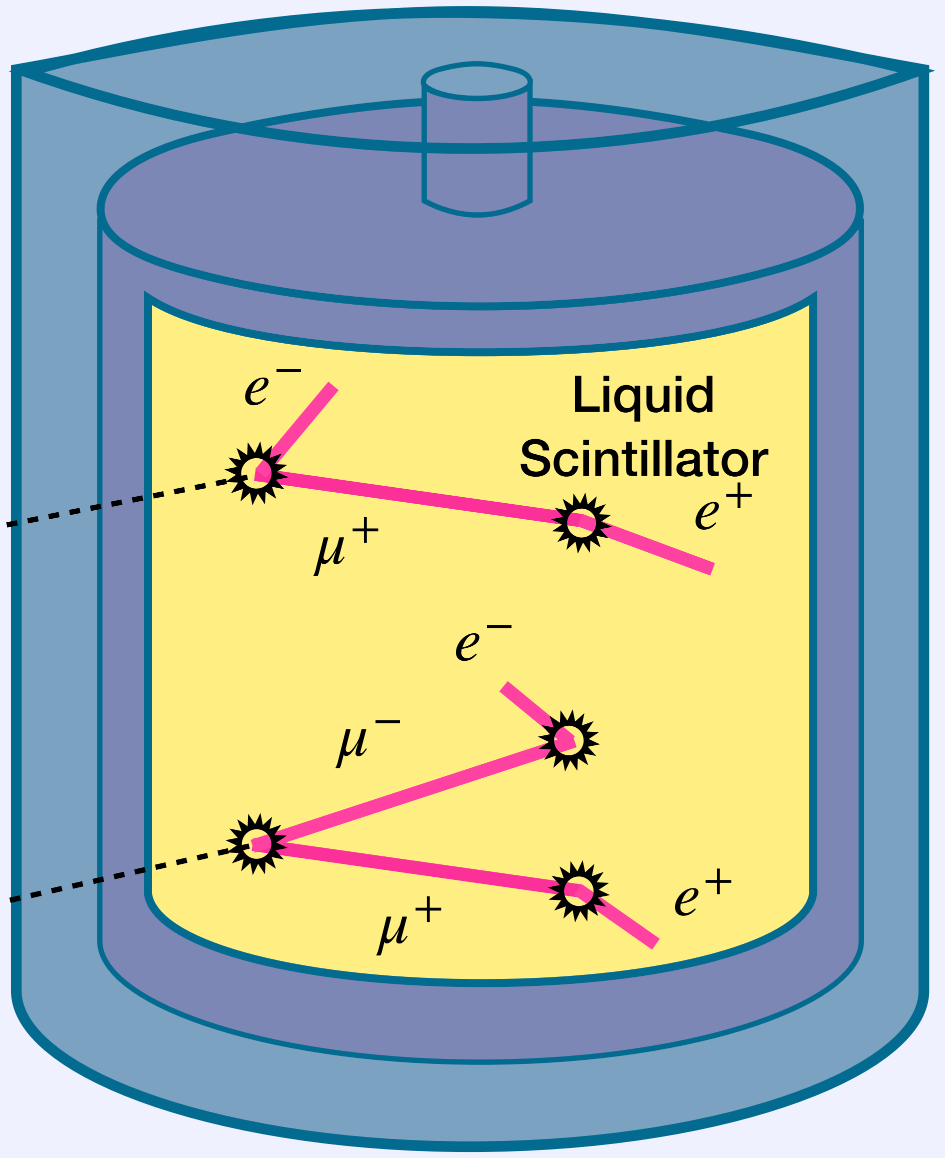
KOTO:
Pros: Low-density vol and low bkg
Cons: Further away
Best for: π^0 and $\gamma\gamma$





ND280:
Pros: Low-density and magnetized
Cons: Further away
Best for: any charged final state





JSNS^2 (I and II):

Pros: Closest to the source and largest vol

Cons: larger backgrounds, single flash events (e.g., e^+e^-) very challenging for $E_{\text{vis}} \lesssim 30$ MeV.

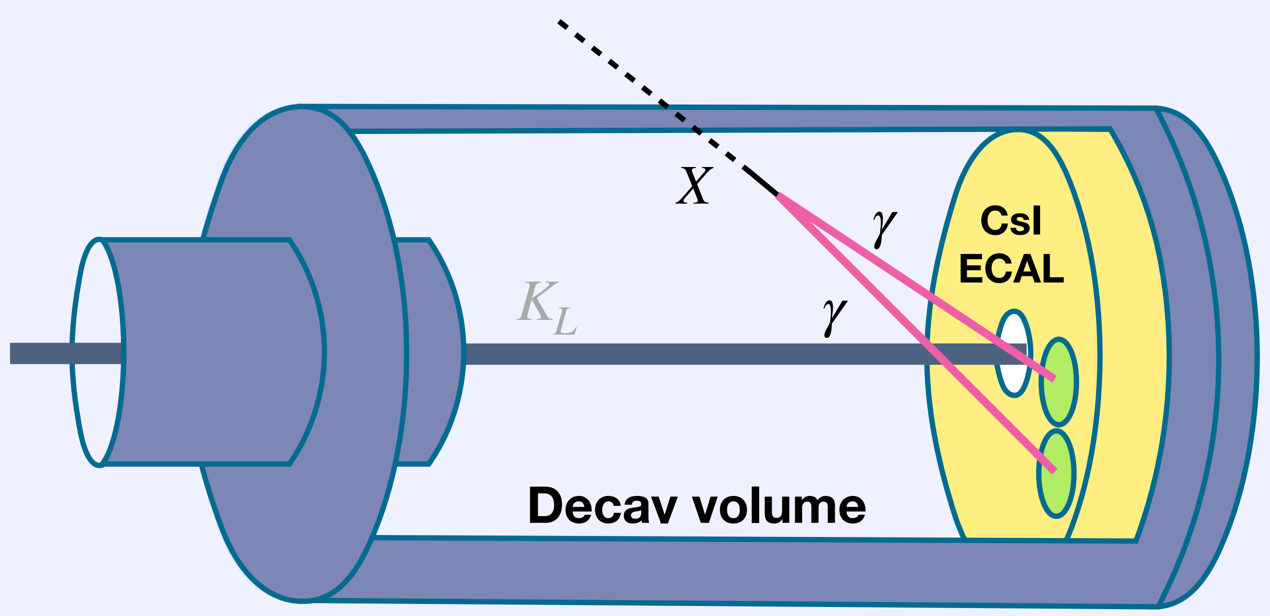
Best for: double

KOTO:

Pros: Low-density vol and low bkg

Cons: Further away

Best for: π^0 and $\gamma\gamma$



KOTO @ 425 m

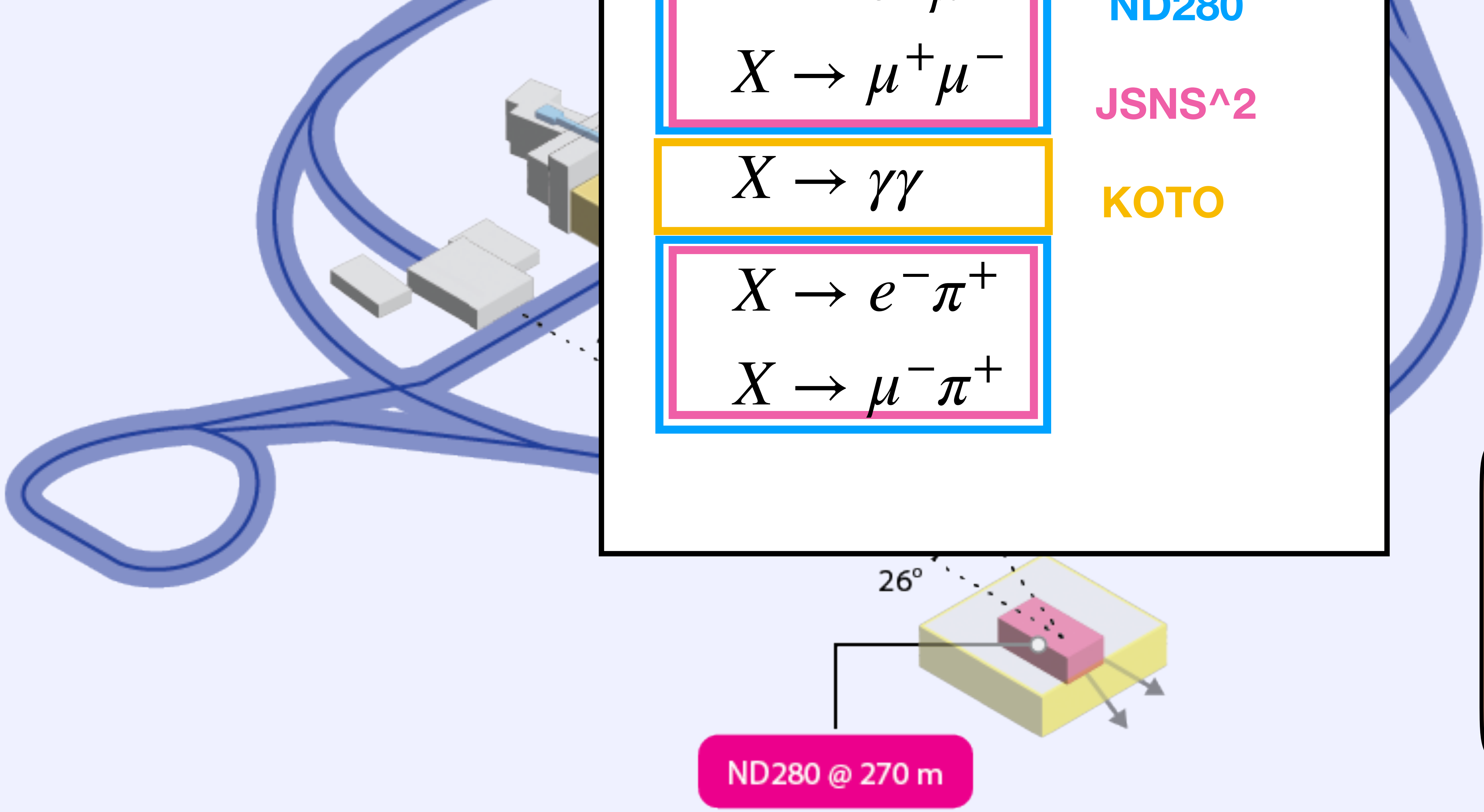
Decay modes

- $X \to e^+e^-$
- $X \to e^+\mu^-$
- $X \to \mu^+\mu^-$
- $X \to \gamma\gamma$
- $X \to e^-\pi^+$
- $X \to \mu^-\pi^+$

ND280

JSNS^2

KOTO

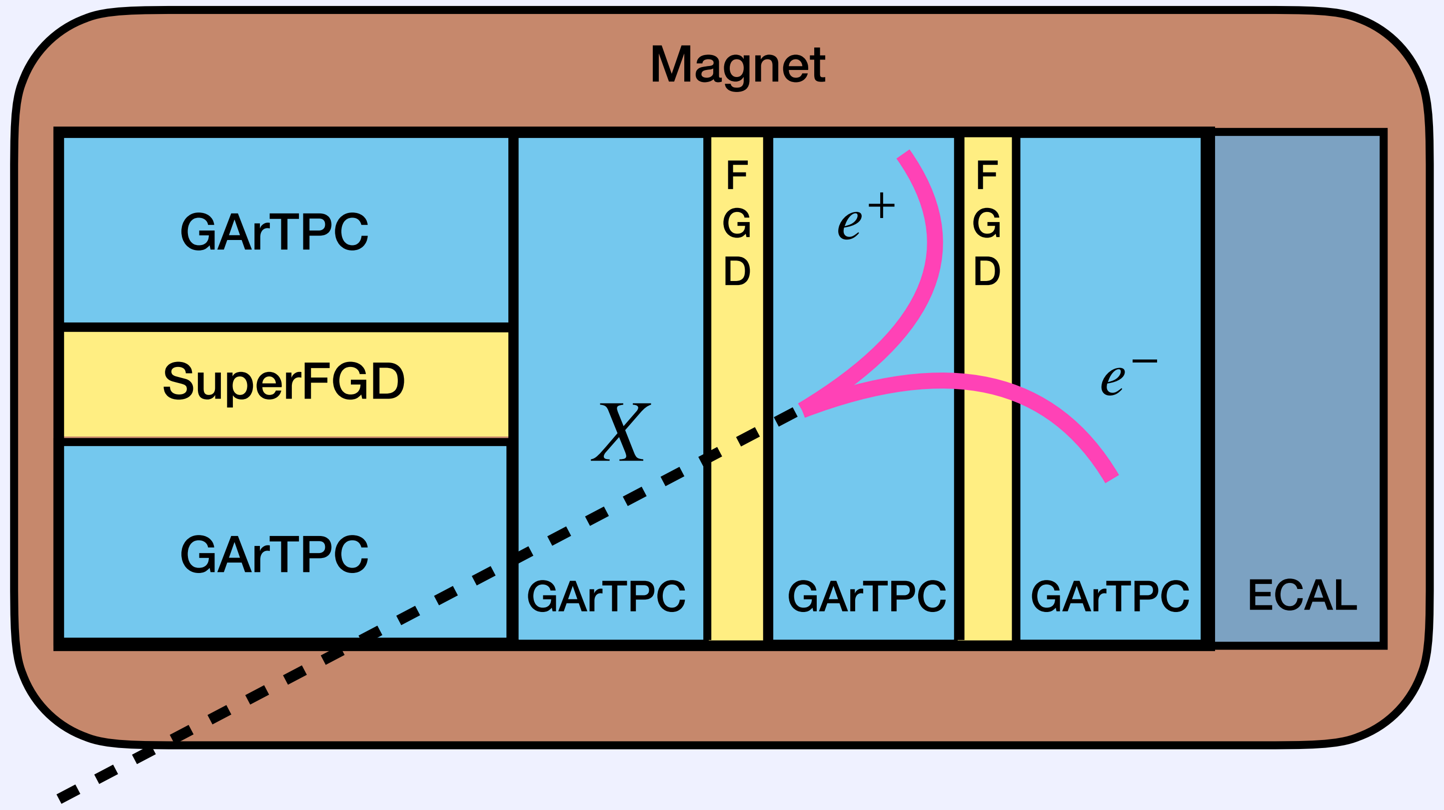


ND280:

Pros: Low-density and magnetized

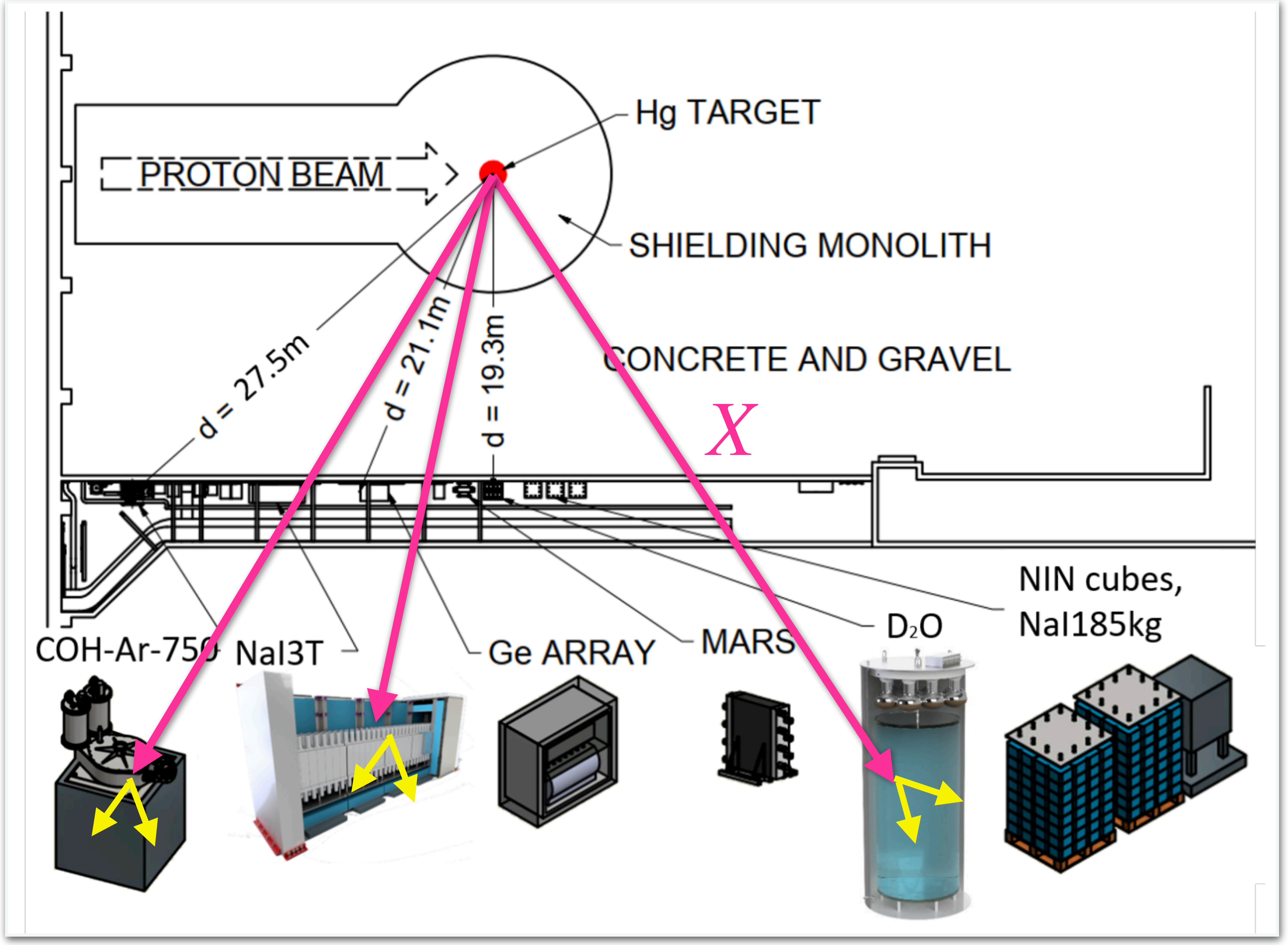
Cons: Further away

Best for: any charged final state



Opportunities at SNS and LANSCE

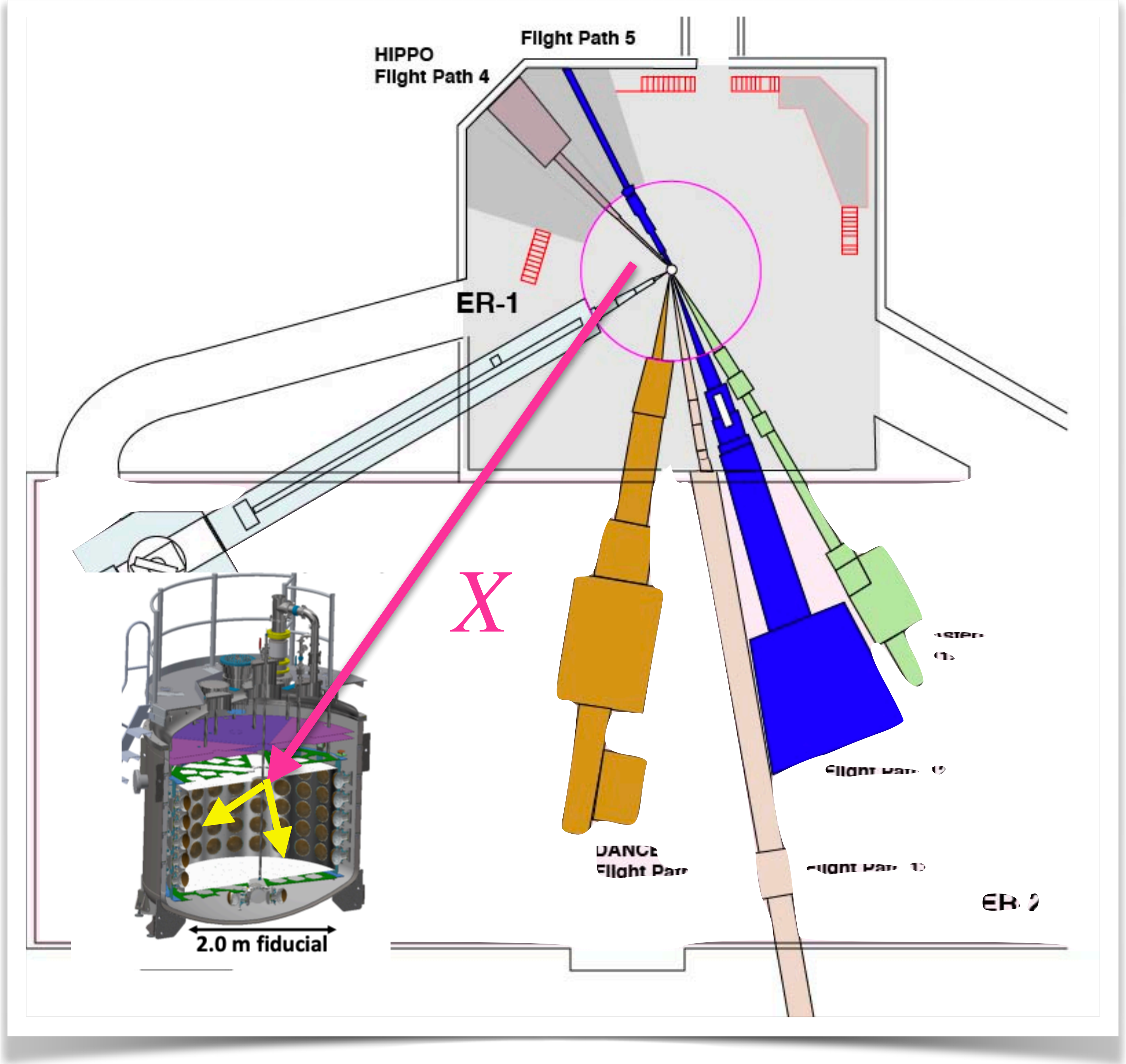
SNS COHERENT detectors



750 kg (LAr) + 590 kg (H2O) + 590 kg (D2O) [+ possibly NaIVeTe?]

Requiring 50 events/3 years of operation

LANSCE Coherent-Captain-Mills (CCM)



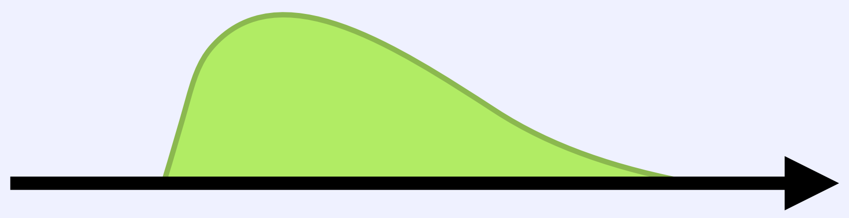
CCM: 7 tons of LAr

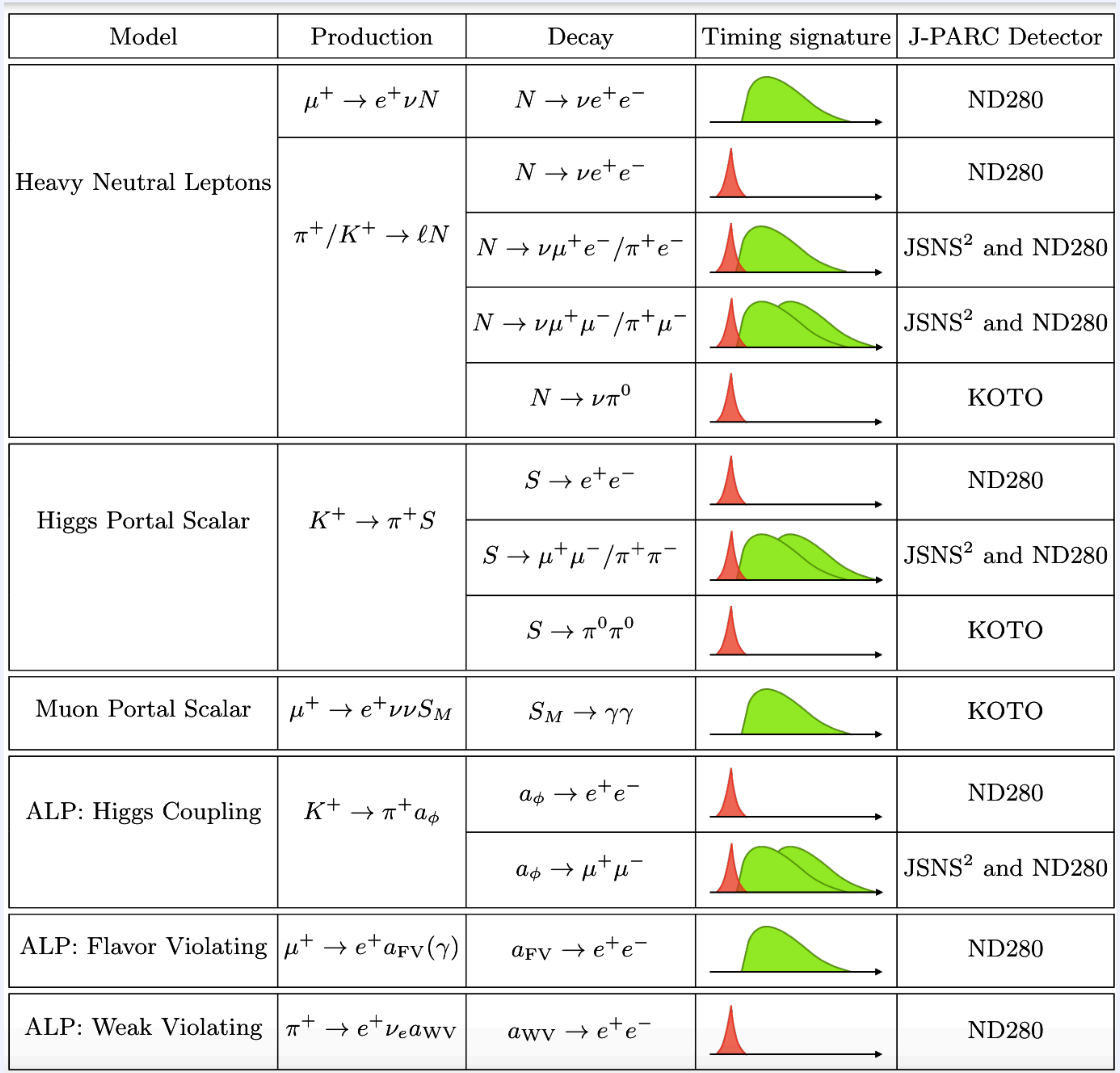
Requiring 40 events/3 years of operation

Timing profile of LLP signatures

Prompt $\mathcal{O}(100)$ ns (on time from π^+/K^+ decay)

$\mathcal{O}(2)$ μs delayed (μ^+ time)



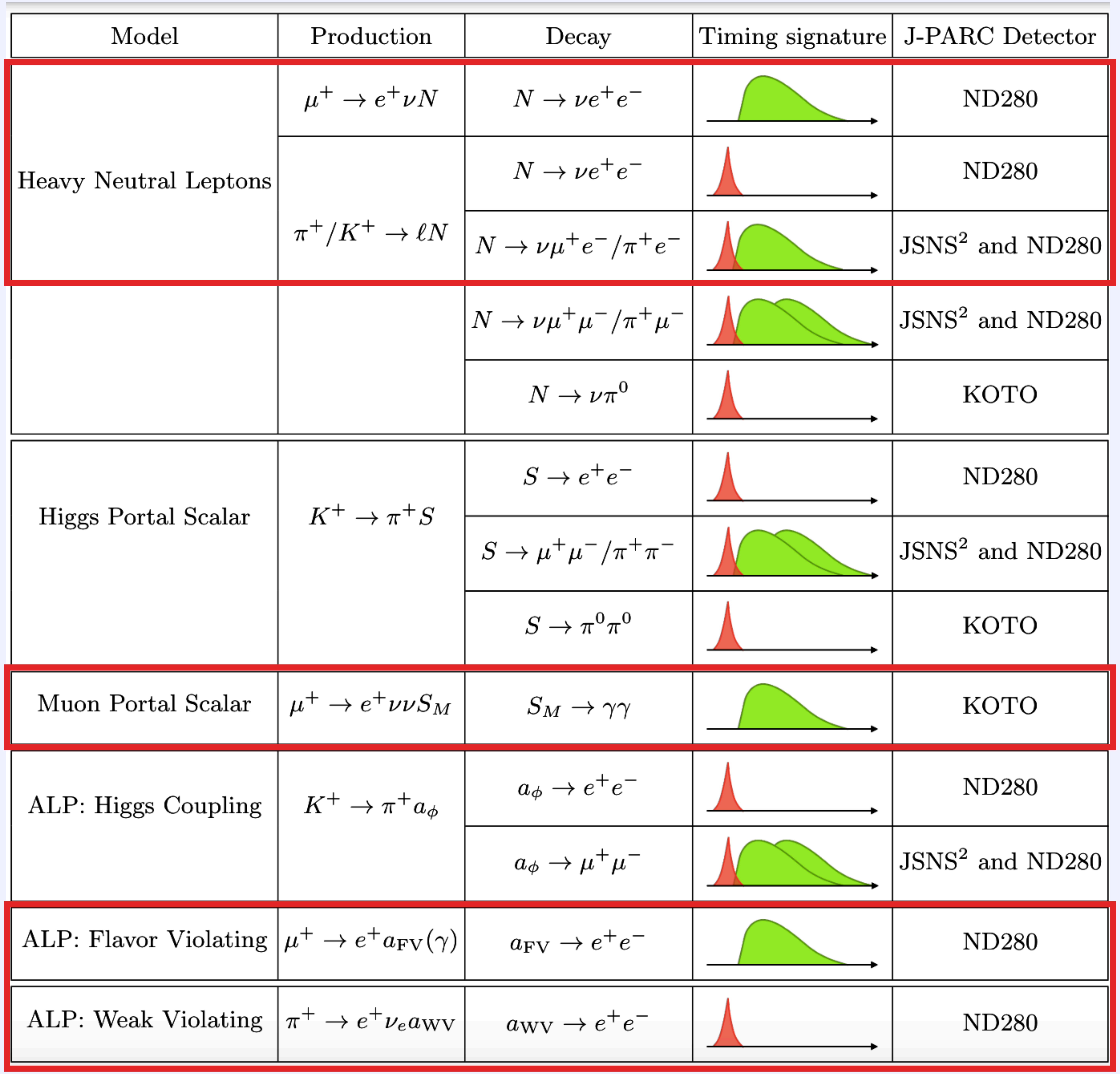


Model	Production	Decay	Timing signature	J-PARC Detector
Heavy Neutral Leptons	$\mu^+ \to e^+ \nu N$	$N \to \nu e^+ e^-$	🟩	ND280
	$\pi^+/K^+ \to \ell N$	$N \to \nu e^+ e^-$	🟥	ND280
		$N \to \nu \mu^+ e^- / \pi^+ e^-$	🟥🟩	JSNS^2 and ND280
		$N \to \nu \mu^+ \mu^- / \pi^+ \mu^-$	🟥🟩	JSNS^2 and ND280
		$N \to \nu \pi^0$	🟥	KOTO
Higgs Portal Scalar	$K^+ \to \pi^+ S$	$S \to e^+ e^-$	🟥	ND280
		$S \to \mu^+ \mu^- / \pi^+ \pi^-$	🟥🟩	JSNS^2 and ND280
		$S \to \pi^0 \pi^0$	🟥	KOTO
Muon Portal Scalar	$\mu^+ \to e^+ \nu \nu S_M$	$S_M \to \gamma\gamma$	🟩	KOTO
ALP: Higgs Coupling	$K^+ \to \pi^+ a_\phi$	$a_\phi \to e^+ e^-$	🟥	ND280
		$a_\phi \to \mu^+ \mu^-$	🟥🟩	JSNS^2 and ND280
ALP: Flavor Violating	$\mu^+ \to e^+ a_{\mathrm{FV}} (\gamma)$	$a_{\mathrm{FV}} \to e^+ e^-$	🟩	ND280
ALP: Weak Violating	$\pi^+ \to e^+ \nu_e a_{\mathrm{WV}}$	$a_{\mathrm{WV}} \to e^+ e^-$	🟥	ND280

Timing profile of LLP signatures

A lot of these come from μ^+ and π^+ decays.

~1 GeV p^+ beams are in the game.



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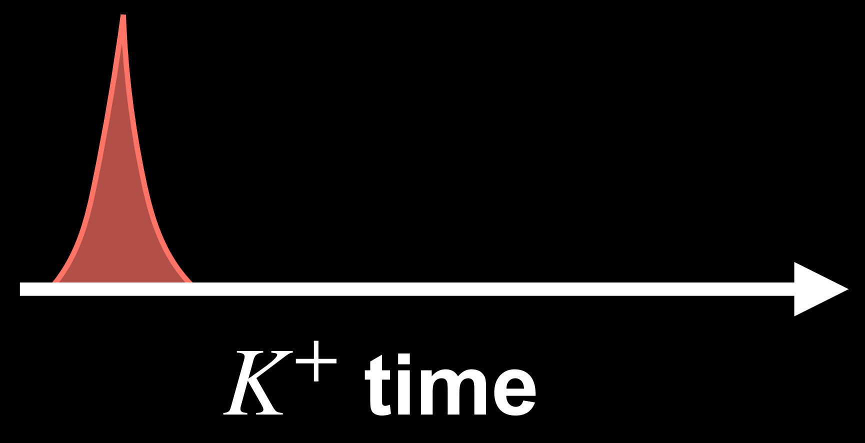
Long-lived particles at spallation sources

Higgs portal scalar



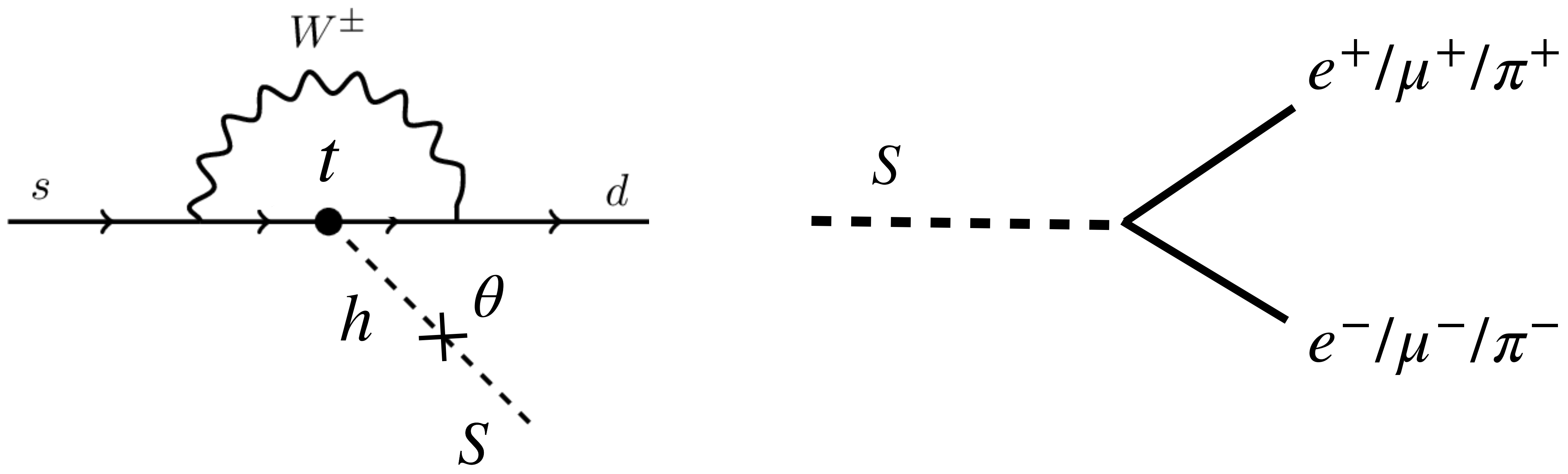
Arguably the simplest extension of the SM:

Singlet scalar particle S that mixes with the Higgs boson
a.k.a. Higgs Portal Scalar (HPS).

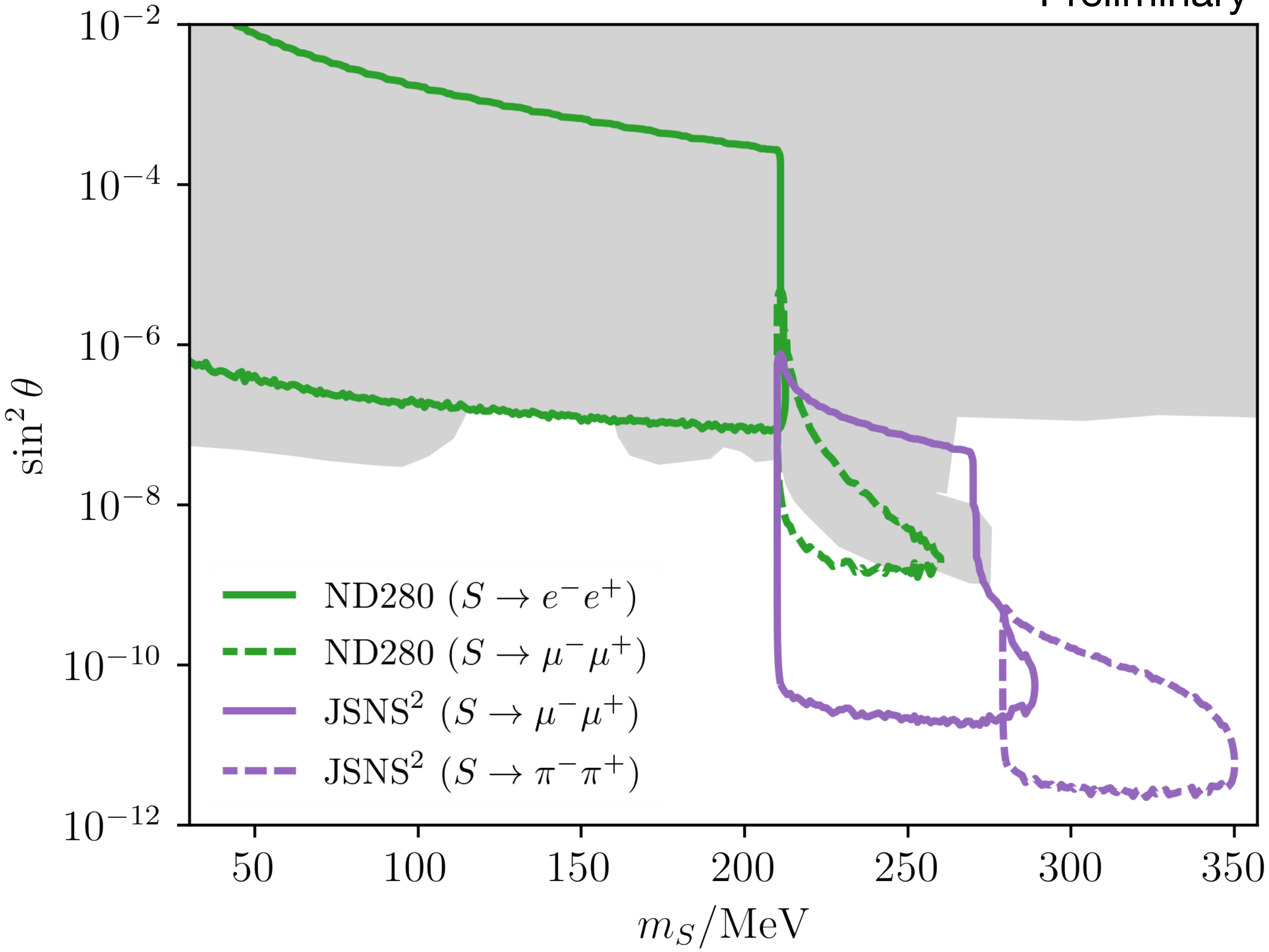
Production exclusively through K decays.

J-PARC is most well suited for this.
(+ accelerators like T2K and FNAL's SBN program)

$$K^+ \to \pi^+ S$$

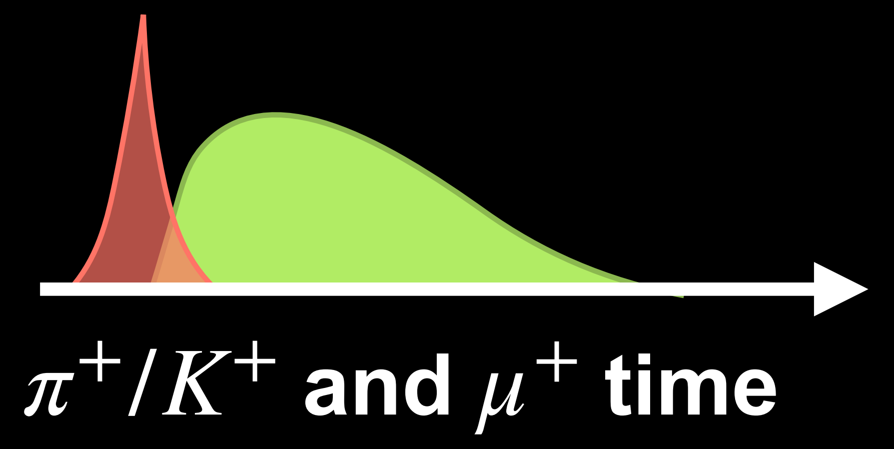


Preliminary



Long-lived particles at spallation sources

Heavy neutral leptons



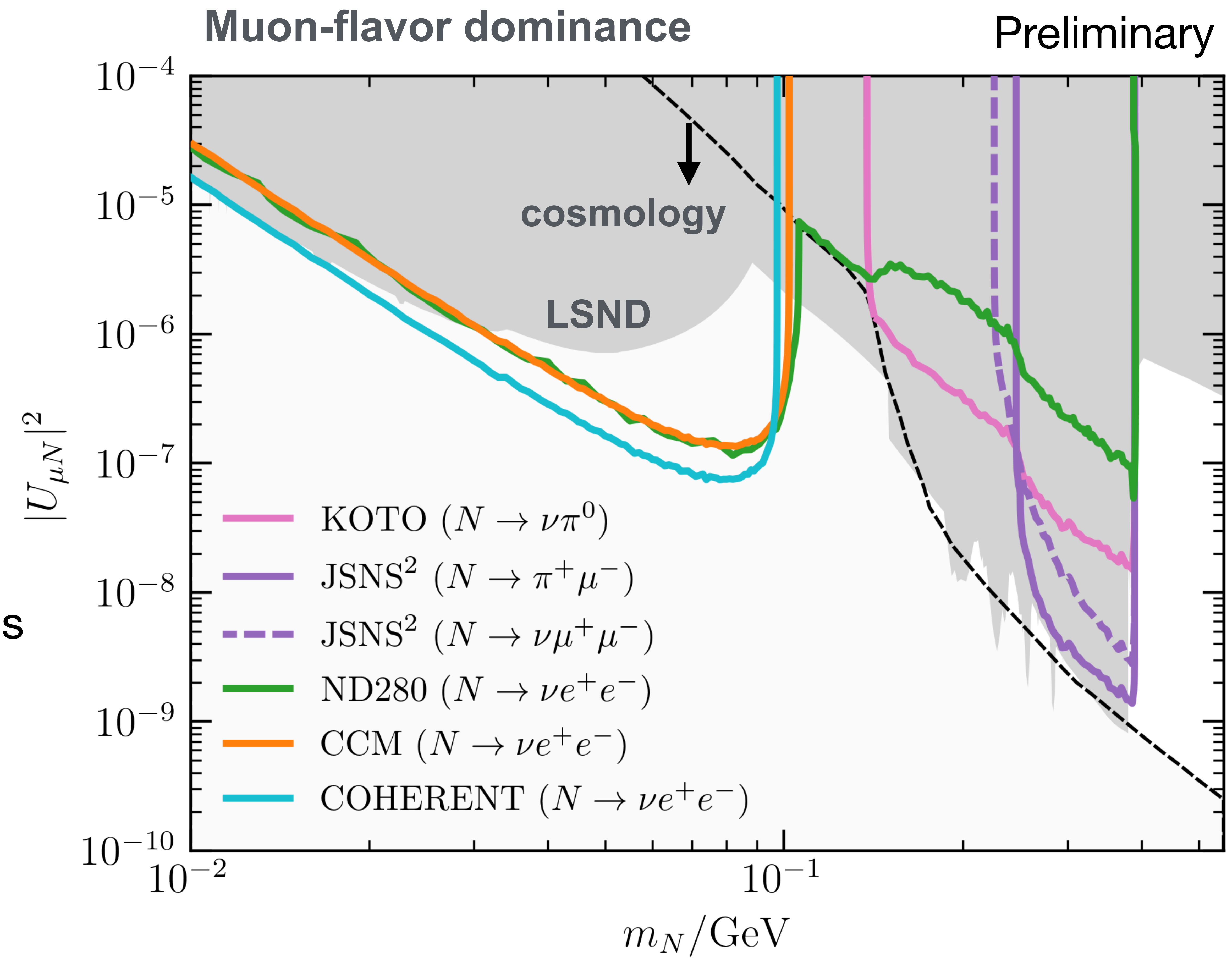
Low-scale neutrino mass model

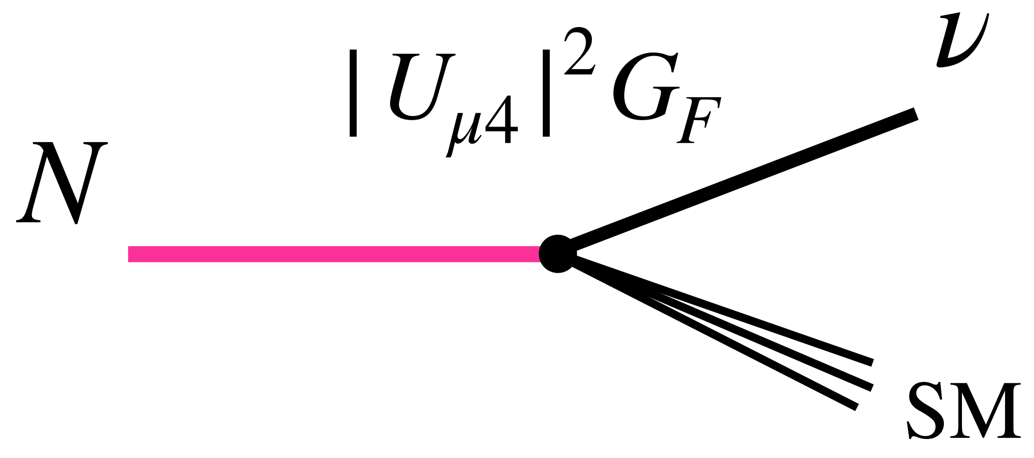
Improvement over LSND because of the stringent signal selection criterion to fake $\nu - e$ scattering.

Note: Cosmological limits typically make the sub-100 MeV region less interesting in minimal HNL models.

Showing minimal case here, but if new forces exist (e.g., magnetic moments or dark photons), lab limits on LLPs quickly become the most important.

C. Argüelles, N. Foppiani, MH 2109.03831





LSND limit derived in Y. Ema, Z. Liu, K. Lyu, M. Pospelov, arXiv:2306.07315

See E. Fernández-Martínez, M.González-López, J. Hernández-García, MH, J. Lópes-Pavón, 10.1007/JHEP09(2023)001

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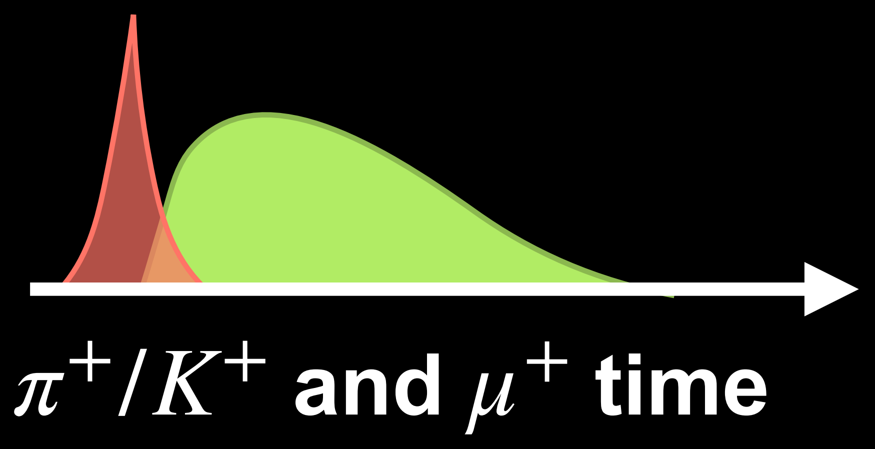

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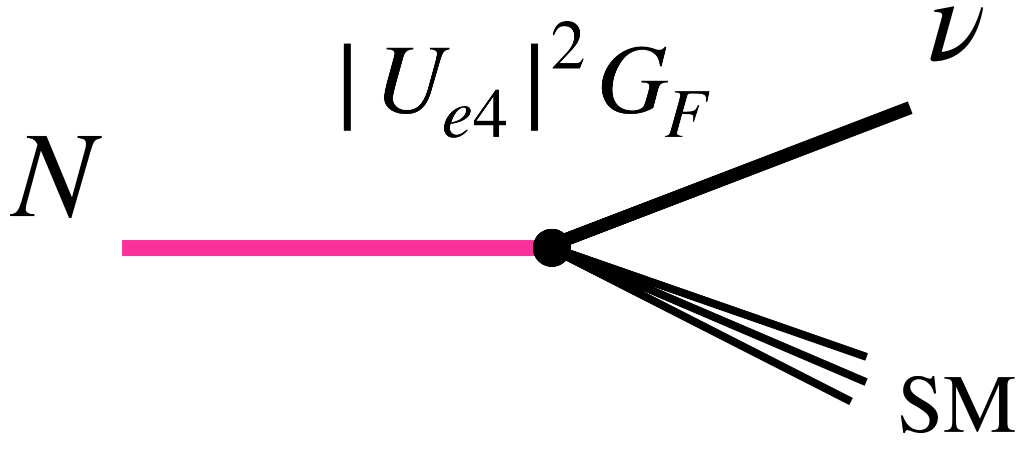
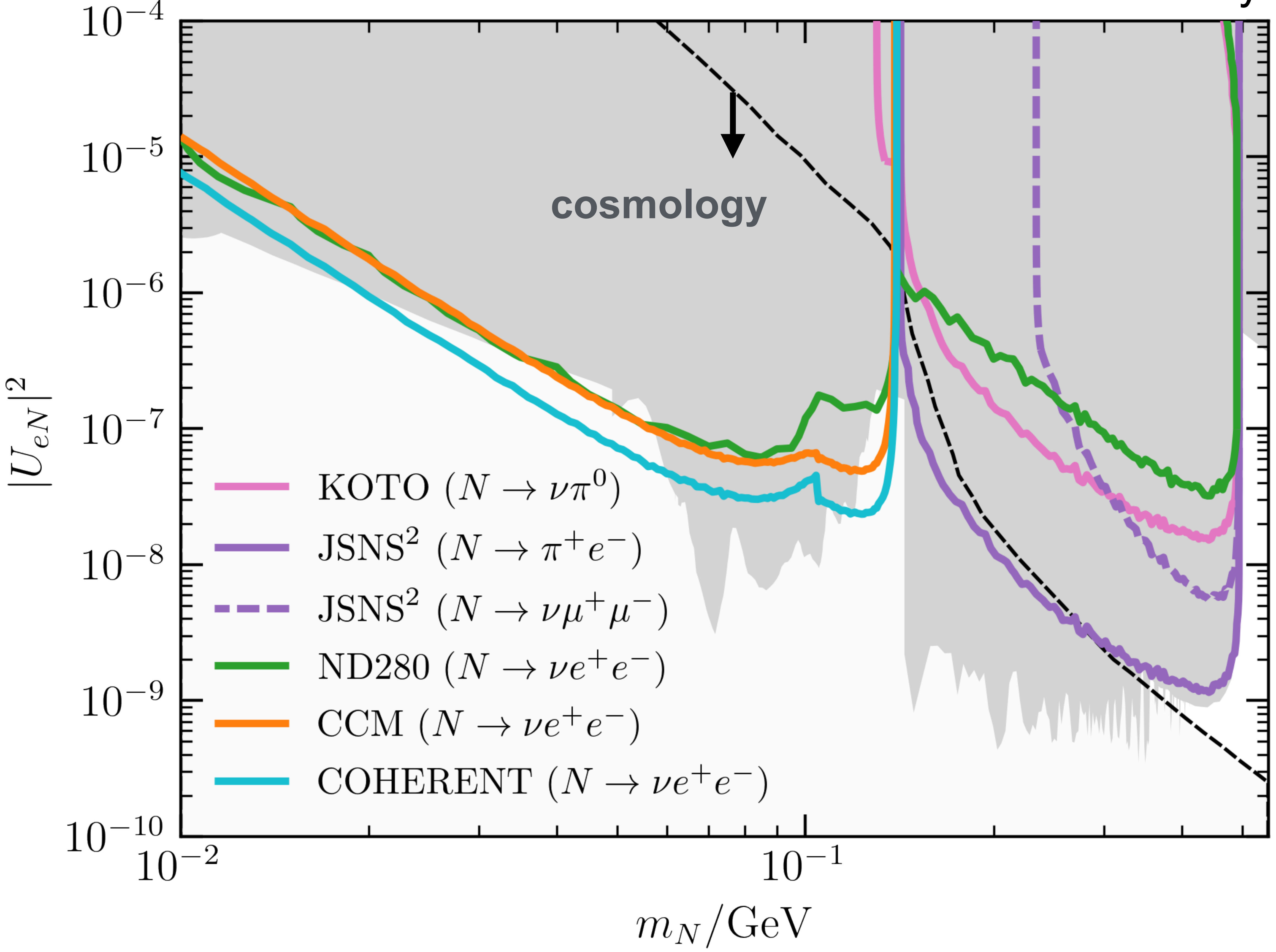


Electron-flavor dominance

Preliminary



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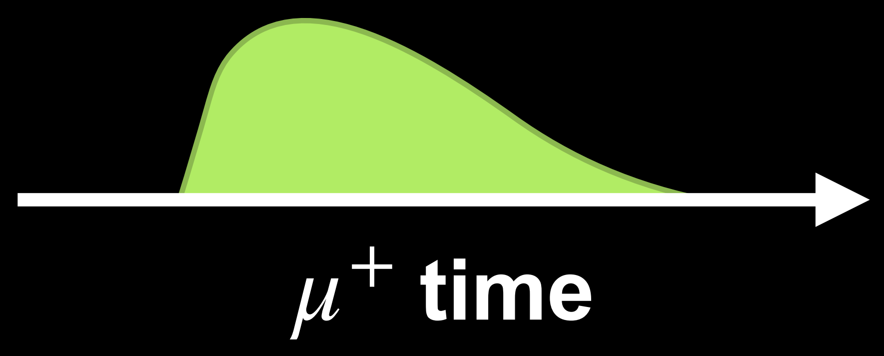
Long-lived particles at spallation sources

Muonphilic scalar

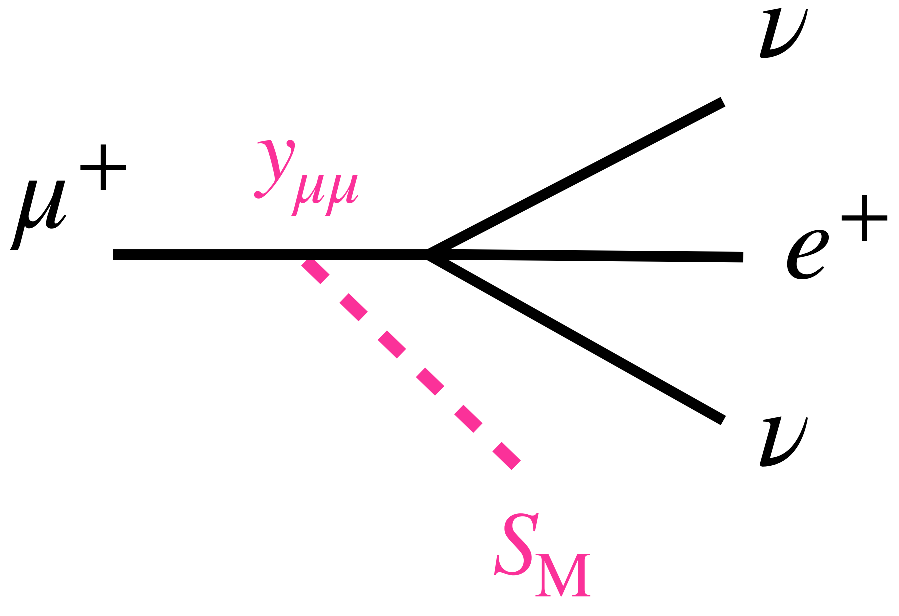


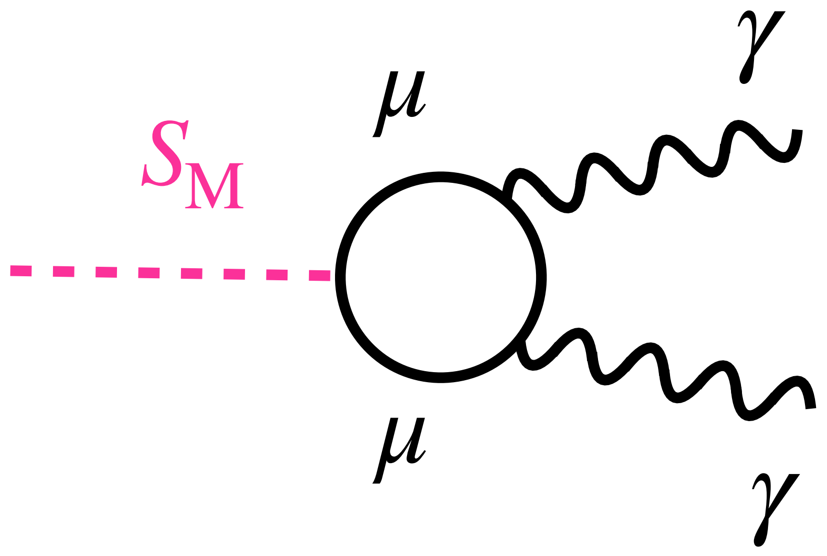
Exotic force that couples only to muons

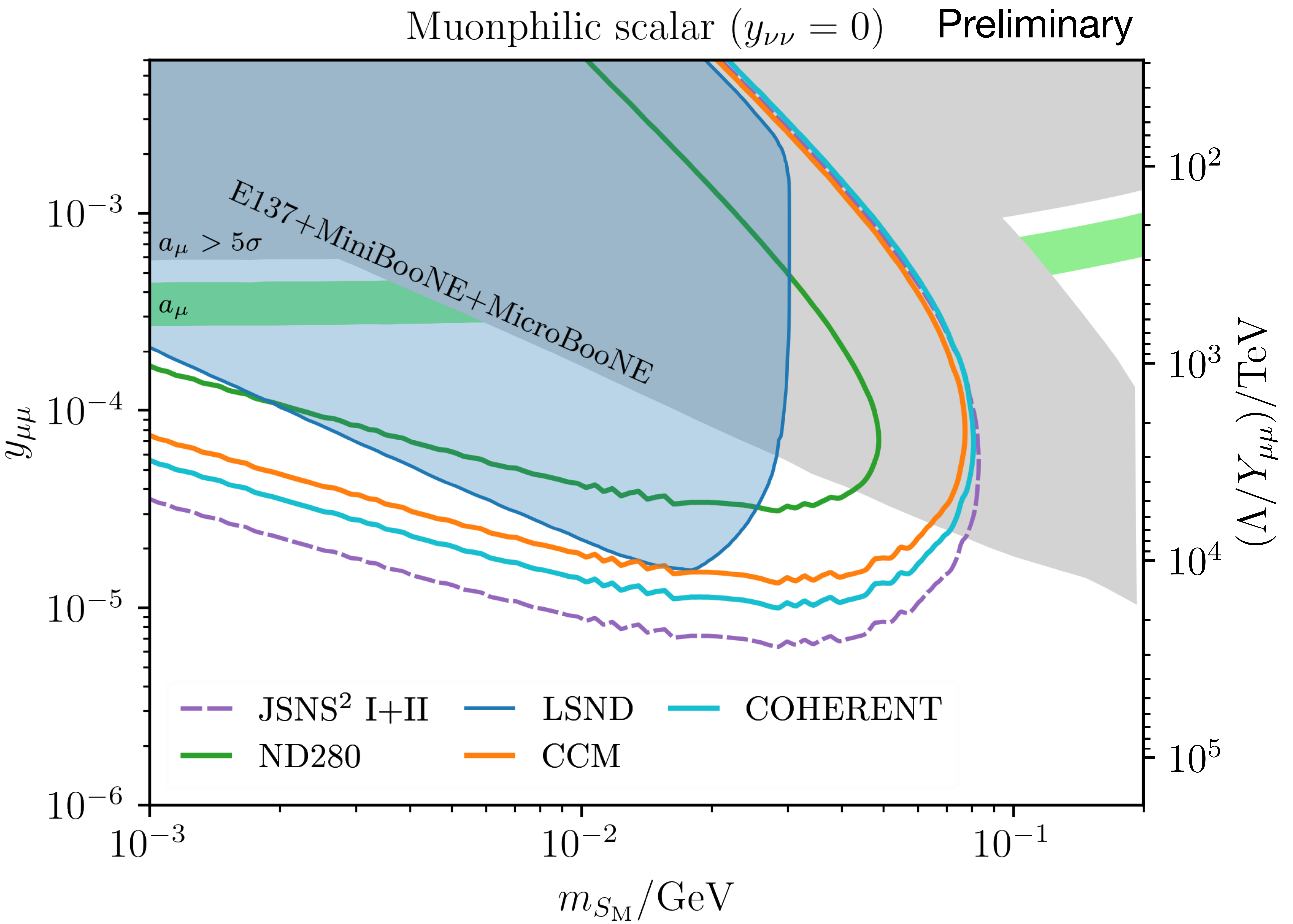
Effective model of that has been a popular extension to explain the apparent discrepancy in $(g-2)_\mu$.

Very hard to constrain — no coupling to neutrinos.

Below dimuon threshold ($m_S < 2m_\mu$), the scalar is long-lived:

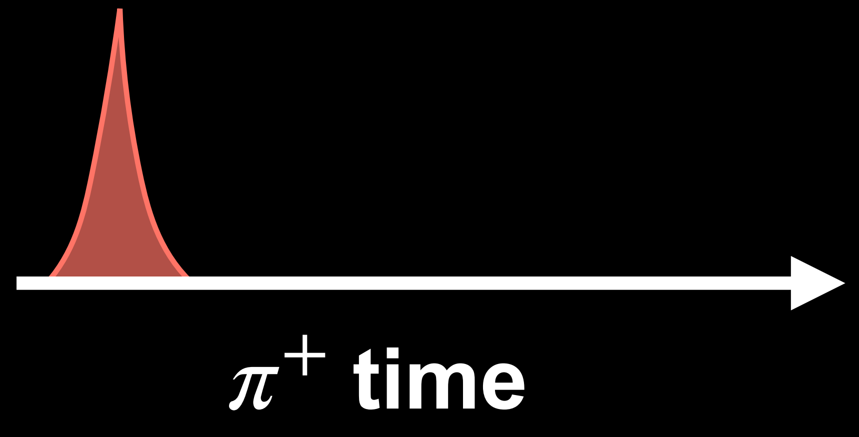






Long-lived particles at spallation sources

Weak-violating axion-like-particle (WV ALP)

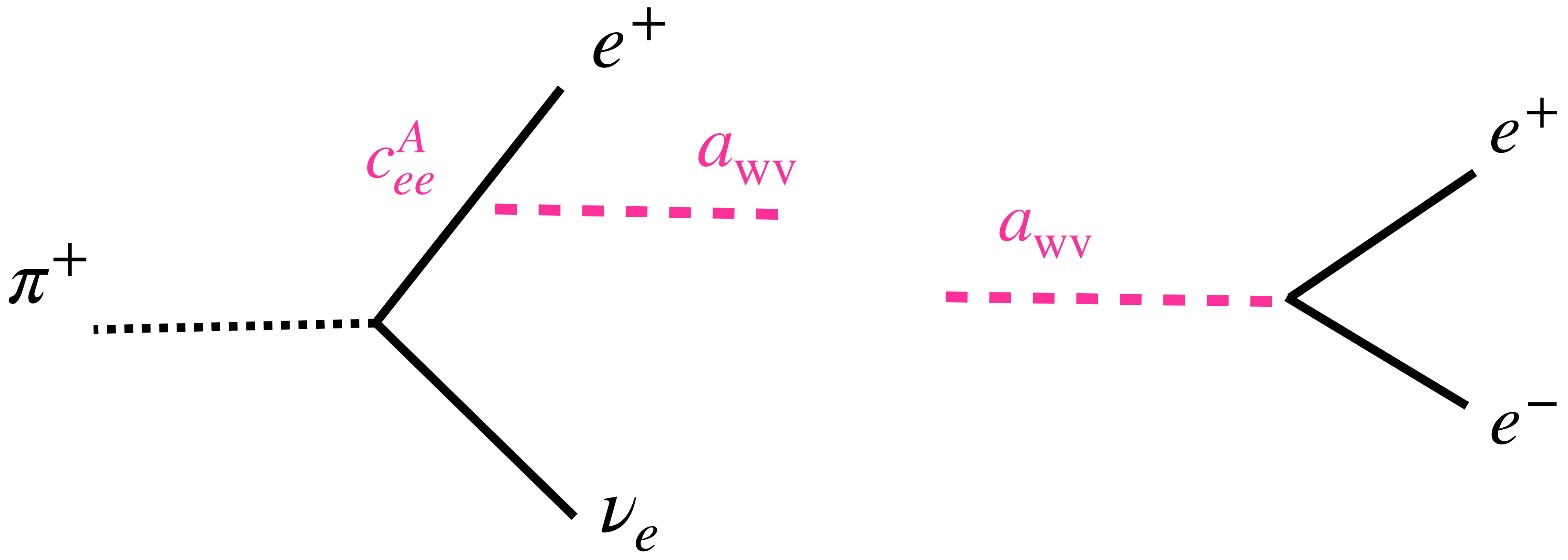


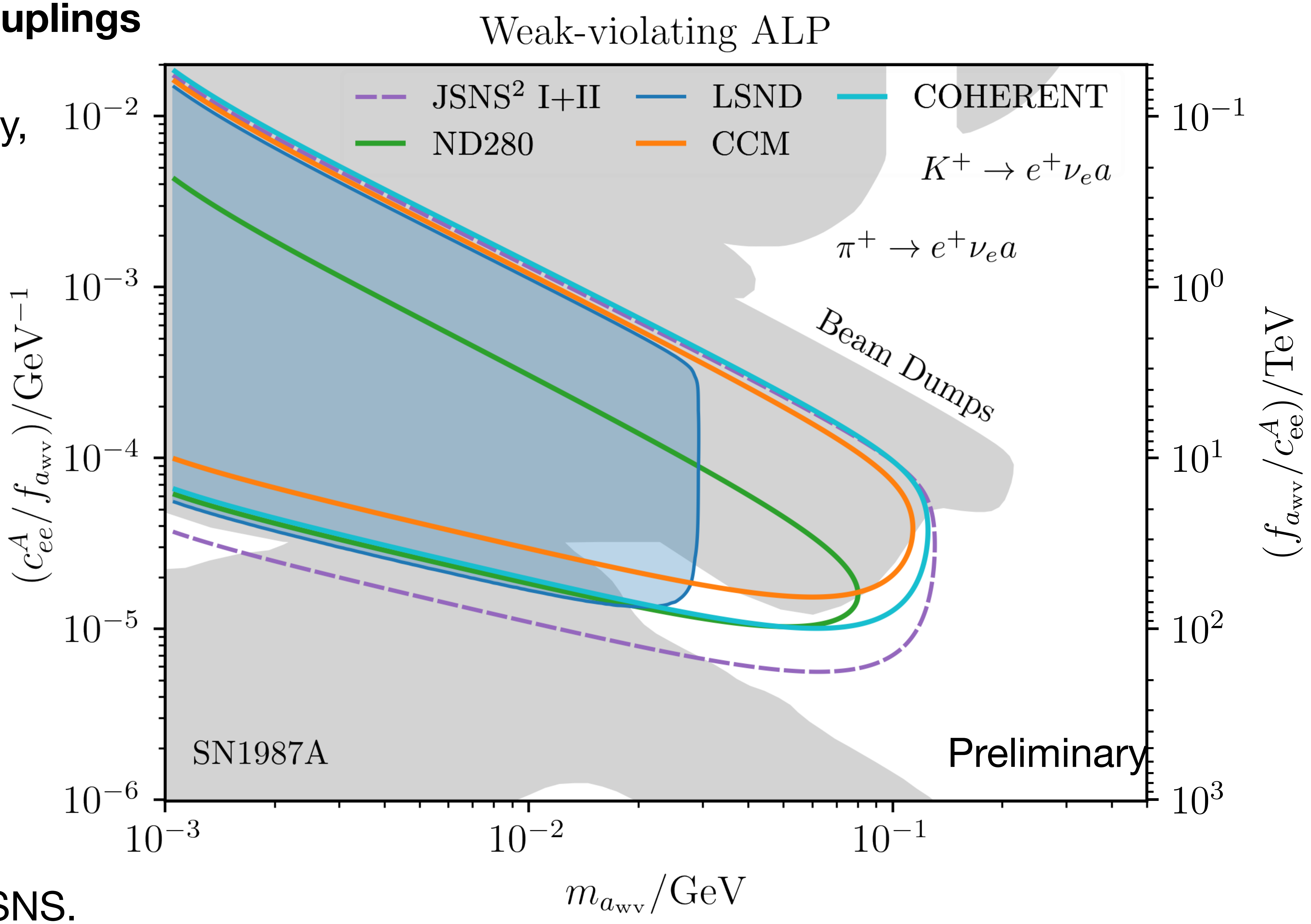
Light goldstone boson that probes exotic electron couplings

Lifting helicity suppression in 3-body π^+ decay is not easy, but can be done in a class of ALP models with "weak-violating" (SU$(2)_L$-violating) couplings.

W. Altmannshoffer et al, arXiv:2209.00665

In this case, three-body decays of the pion are the dominant source of these ALPs at accelerators.



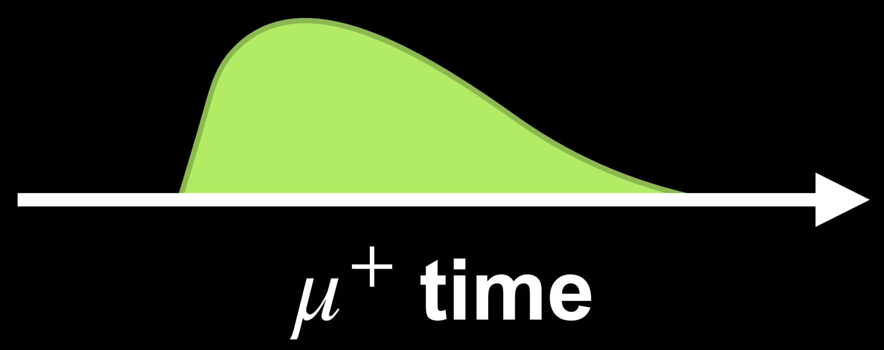


Very complementary coverage by JSNS, LANSCE, and SNS.

See also CCM collaboration, arXiv:2309.02599

Long-lived particles at spallation sources

A lepton-flavor-violating axion-like particle (LFV ALP)



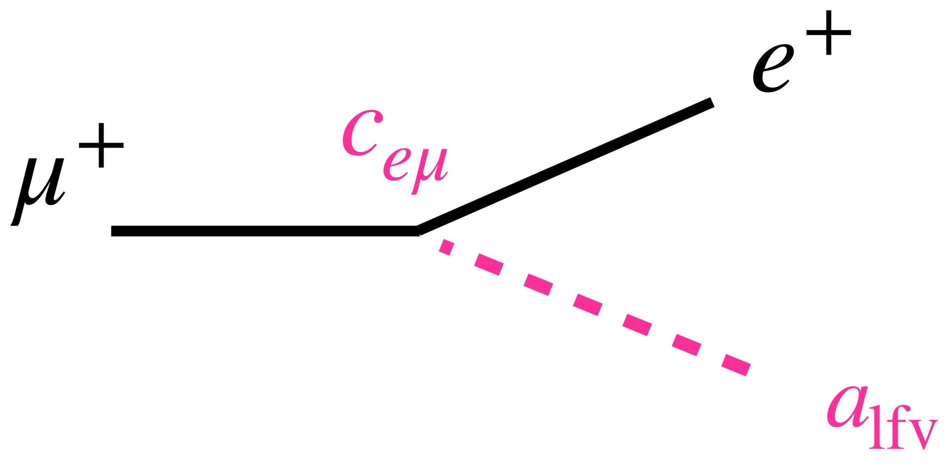
Light goldstone boson to probe lepton flavor violation

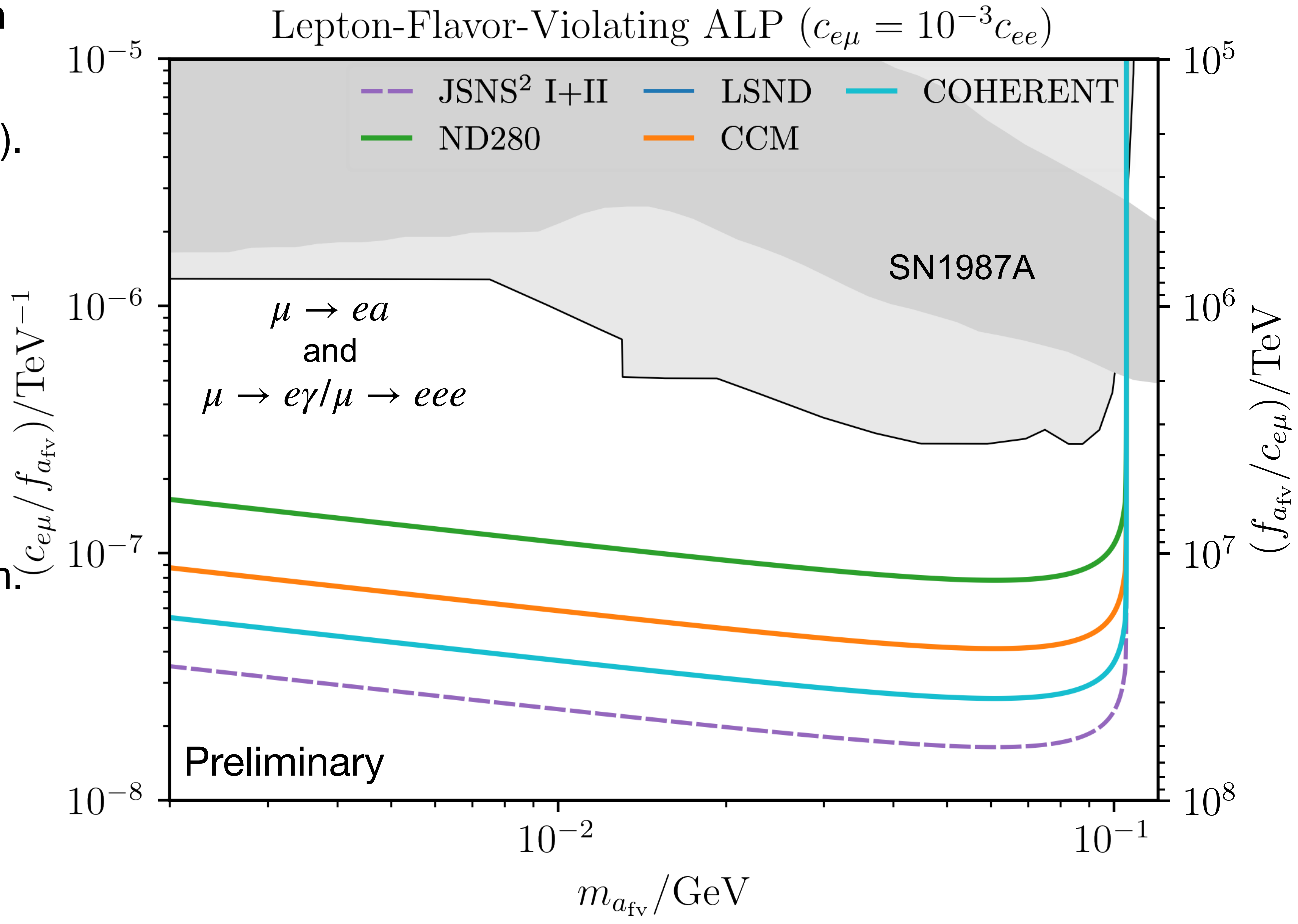
Complementary to $\mu \to e$ program (Mu2e, Mu3e, MEG-II).

Direct limit: $\mathscr{B}(\mu^+ \to e^+ a) \lesssim 10^{-5}$ if a is long-lived.

That would lead to about $10^{14} - 10^{16}$ a in typical spallation sources…

Obvious target for LLP search if $a \to e^+ e^-$ decay is open.





L. Calibbi et al 2006.04795 and M. Bauer et al, 2110.10698

Summary

Thank you for listening!

Matheus Hostert (mhostert@g.harvard.edu)

1) Spallation targets are a very messy environment… but move a bit further out and build sufficiently large-volume detectors, and *extremely rare processes* from LLPs could appear.

2) Shown a non-exhaustive list of long-lived particle (LLP) models that can be constrained with existing spallation sources and detectors. Many more scenarios could be studied.

*See A. Schneider's & B. Dutta's talks

3) A clear application for a well-shielded, low-density, large-volume, and fast detector close to the source.

Not all about POTs and volume: background rejection, timing, and people-power.

Lots of stones are left unturned.

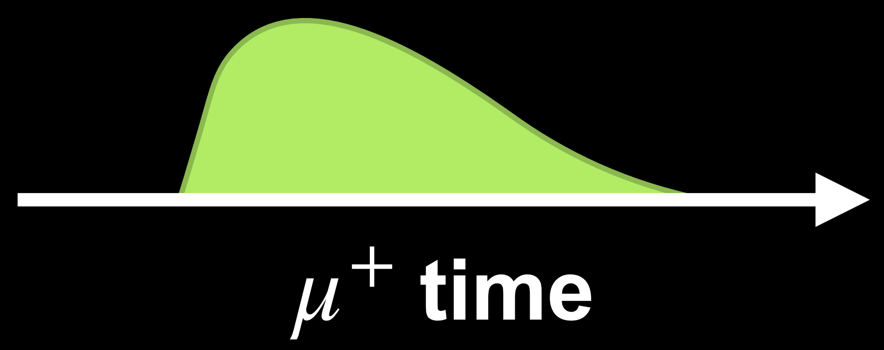
Build bigger and away from the neutrino alley? Lower density CCM? Beam upgrades?

The future is bright and I look forward to the new ideas in this space!

Back-up slides

Long-lived particles at spallation sources

Muonphilic scalar

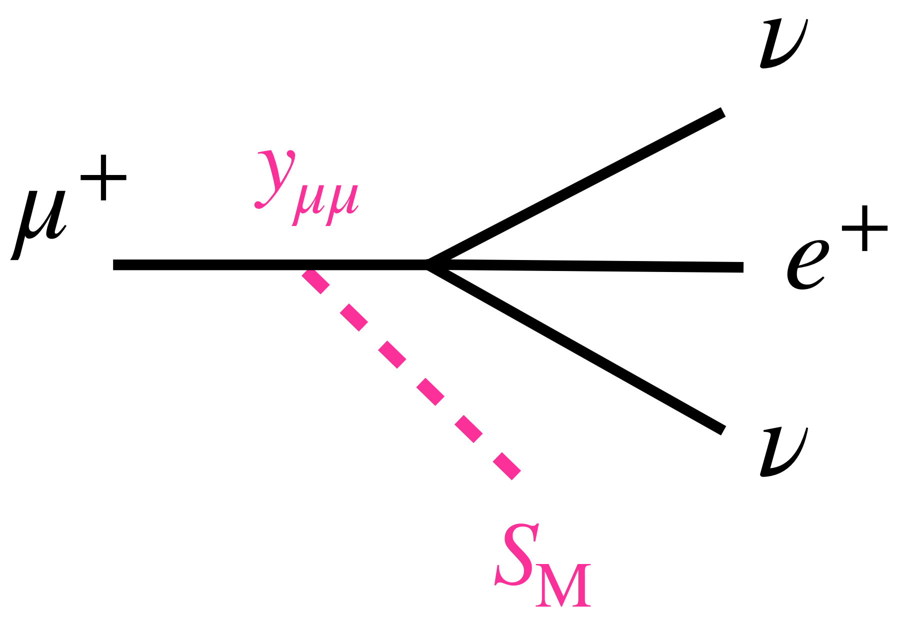


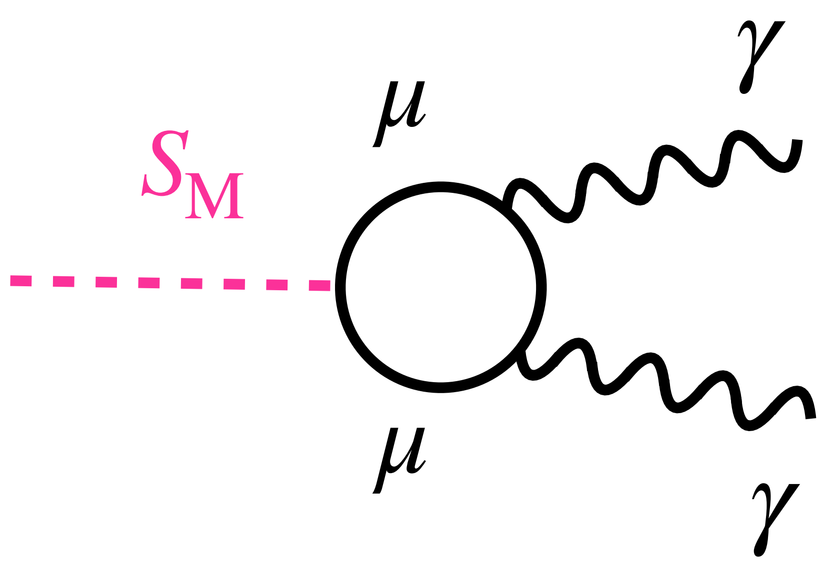
Exotic force that couples only to muons

Effective model of that has been a popular extension to explain the apparent discrepancy in $(g-2)_\mu$.

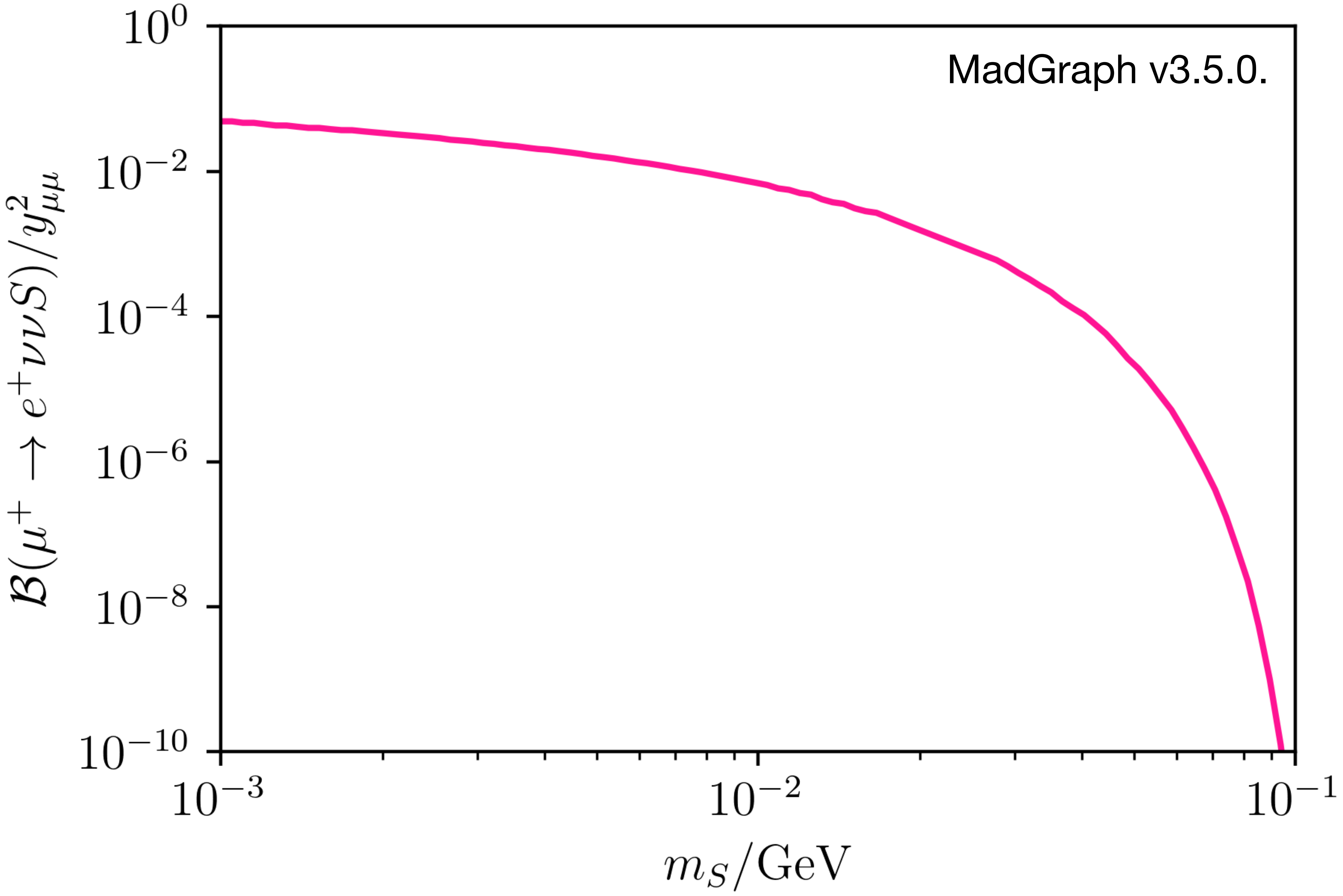
Very hard to constrain — no coupling to neutrinos.

Below dimuon threshold ($m_S < 2m_\mu$), the scalar is long-lived:



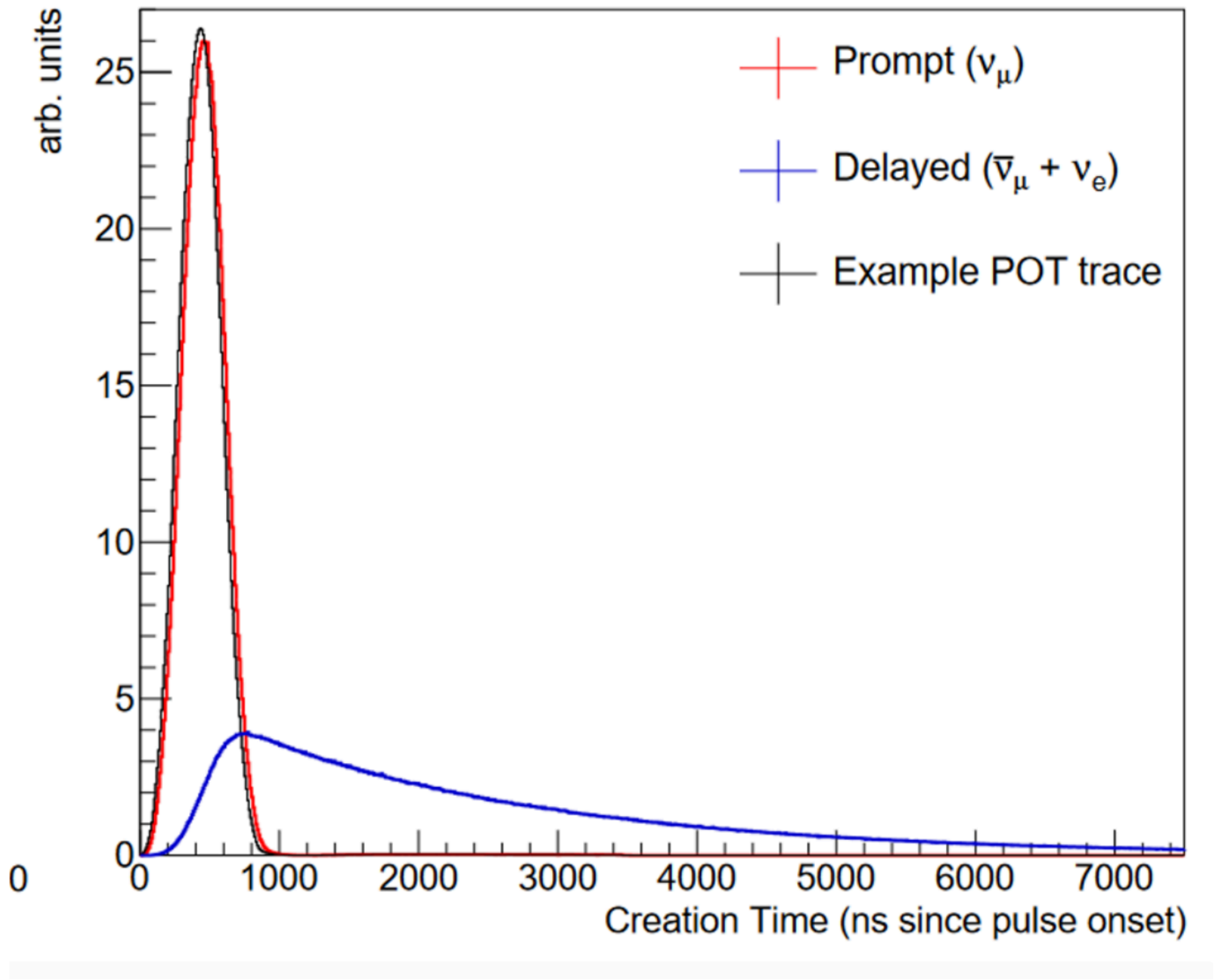


Scalar production in 4-body muon decays:

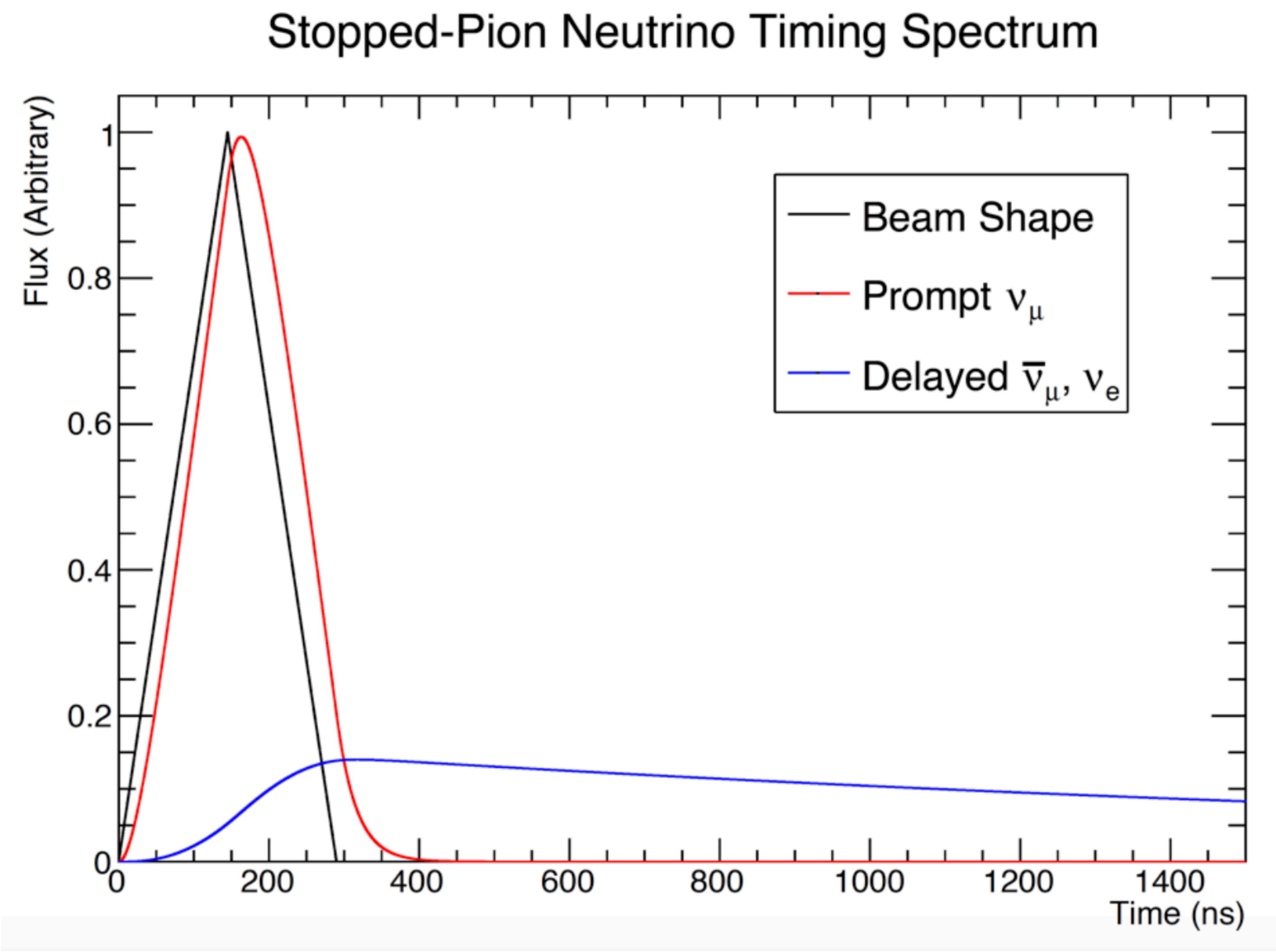


Timing

SNS



LANSCE



JSNS