Emerging Jets at Neutrinos and Charged Leptons High-Energy Beams

Borrello, Costa, Redigolo [2507.12527]
Borrello, Costa, Redigolo, Tammaro, *to appear*

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Neutrino masses: seesaw framework

Standard seesaw

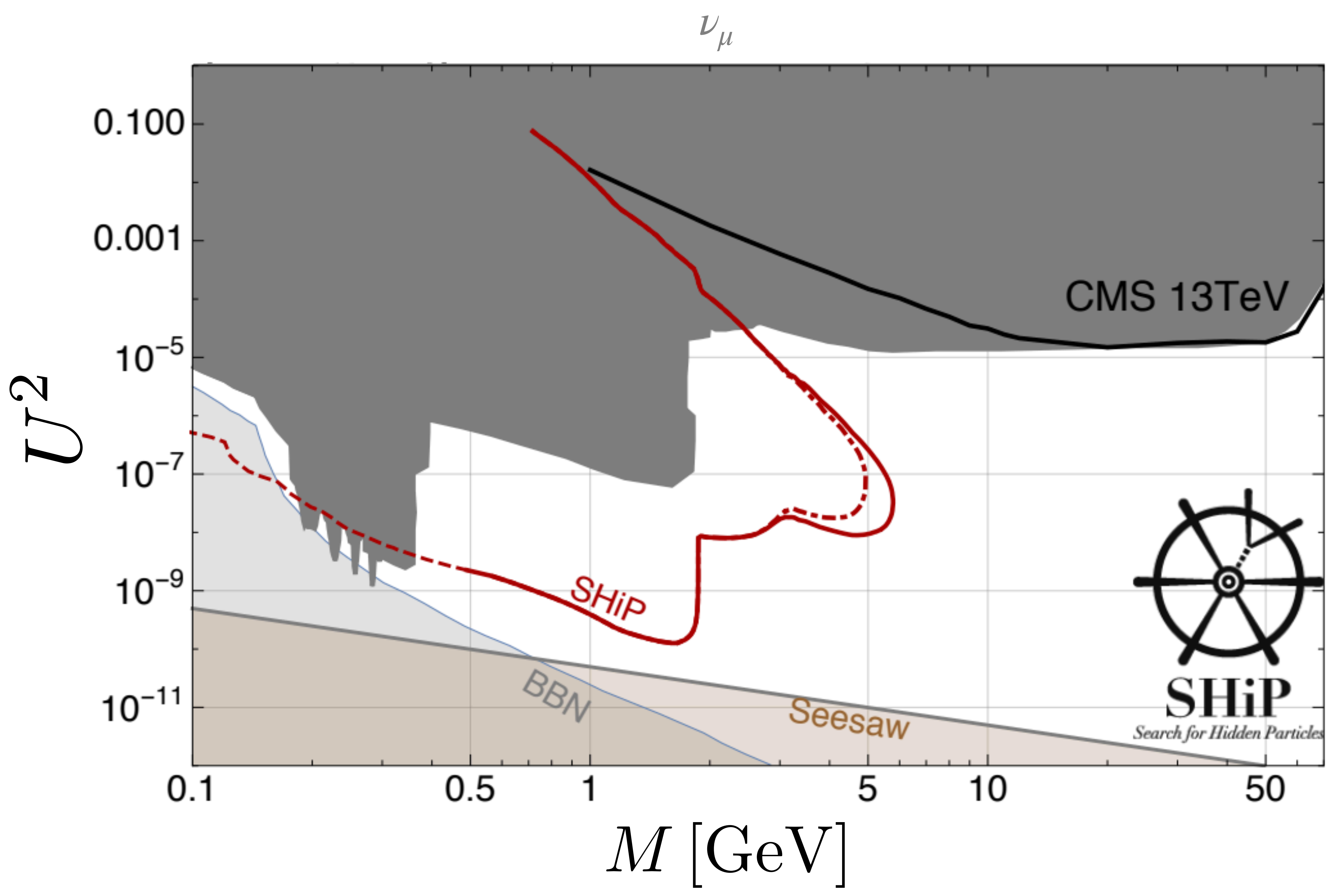
$$\mathcal{L} = y\overline{L}NH + \frac{1}{2}M\overline{N^c}N + \text{h.c.}$$

N SM singlet

active - sterile mixing

$$|U|^2 = \left(\frac{yv}{M}\right)^2 = \frac{m_\nu}{M}$$

Poor phenomenology: small mixing



SHIP collaboration[1811.00930v3]

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Inverse seesaw

$$\mathcal{L} = y\overline{L}NH + M\overline{N}S + \frac{1}{2}\mu\overline{S^c}S + \text{h.c.}$$

N, S SM singlets

μ Majorana mass

Mohapatra and Valle, Phys. Rev. Lett. 44, 912 (1980)

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μ is very small $\Longrightarrow$ Richer phenomenology

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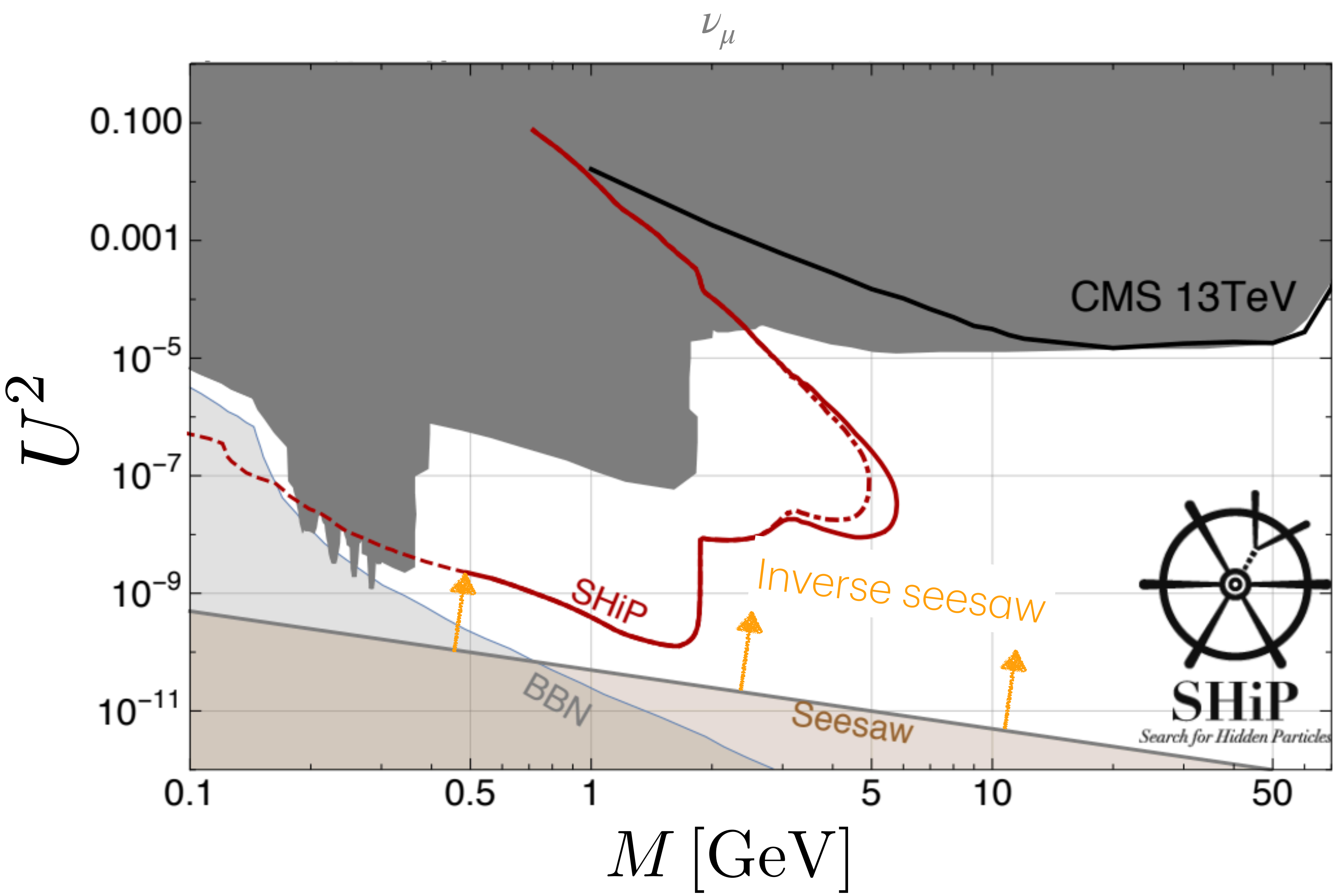

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Strongly coupled sectors

$$\mathcal{L} = y\overline{L}NH$$

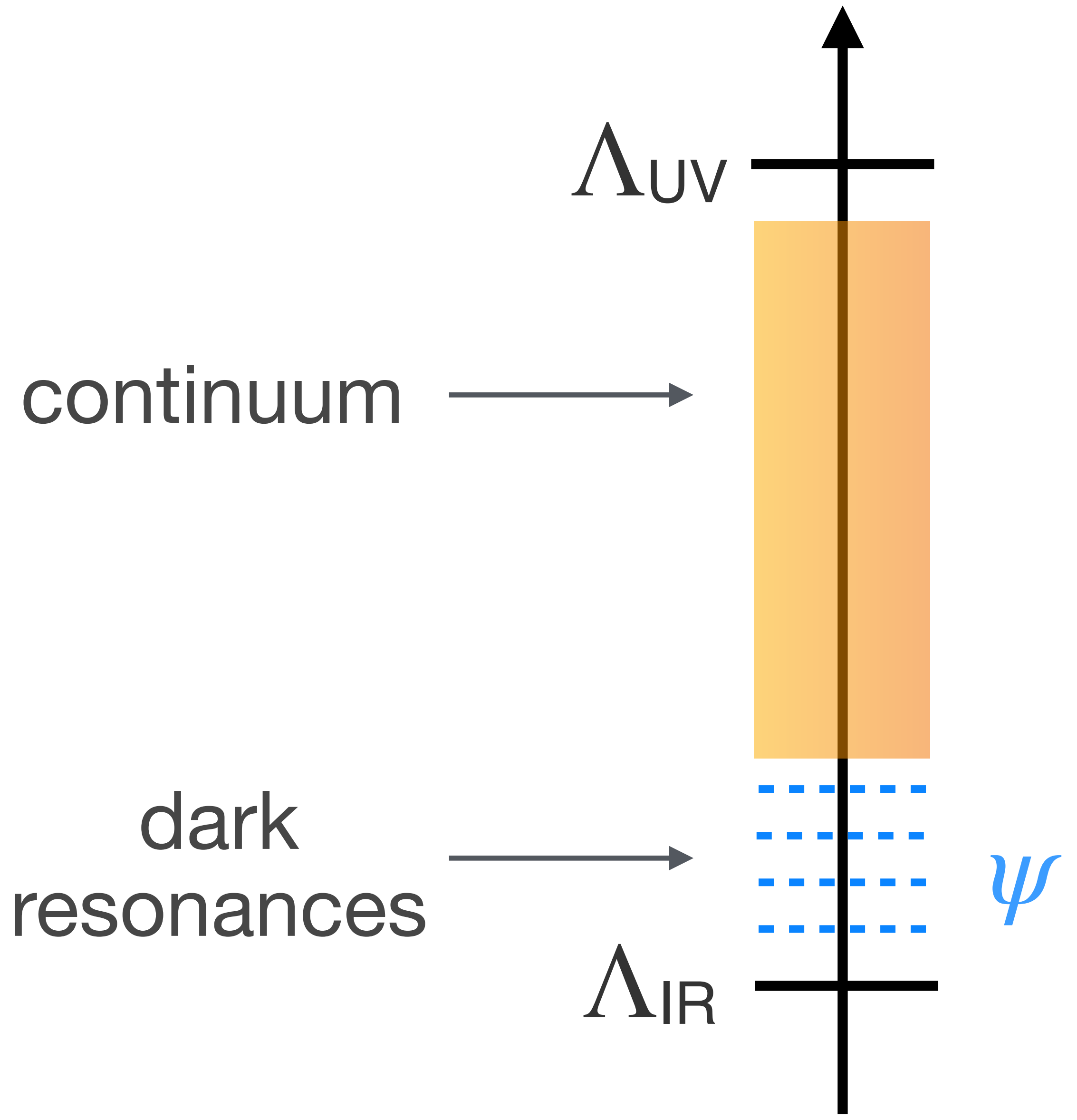
Single particle state

$\mathcal{O}_N$ Composite operator of disimension Δ_N

$$\Delta\mathcal{L}_{5/2} = \frac{y_\mu \tilde{H} L \mathcal{O}_N}{\Lambda_{\rm UV}^{\Delta_N - 3/2}}$$

Chacko at al. [2012.01443]

Large hierarchy $\Lambda_{\rm IR} \ll \Lambda_{\rm UV} \implies$ approximately scale invariance



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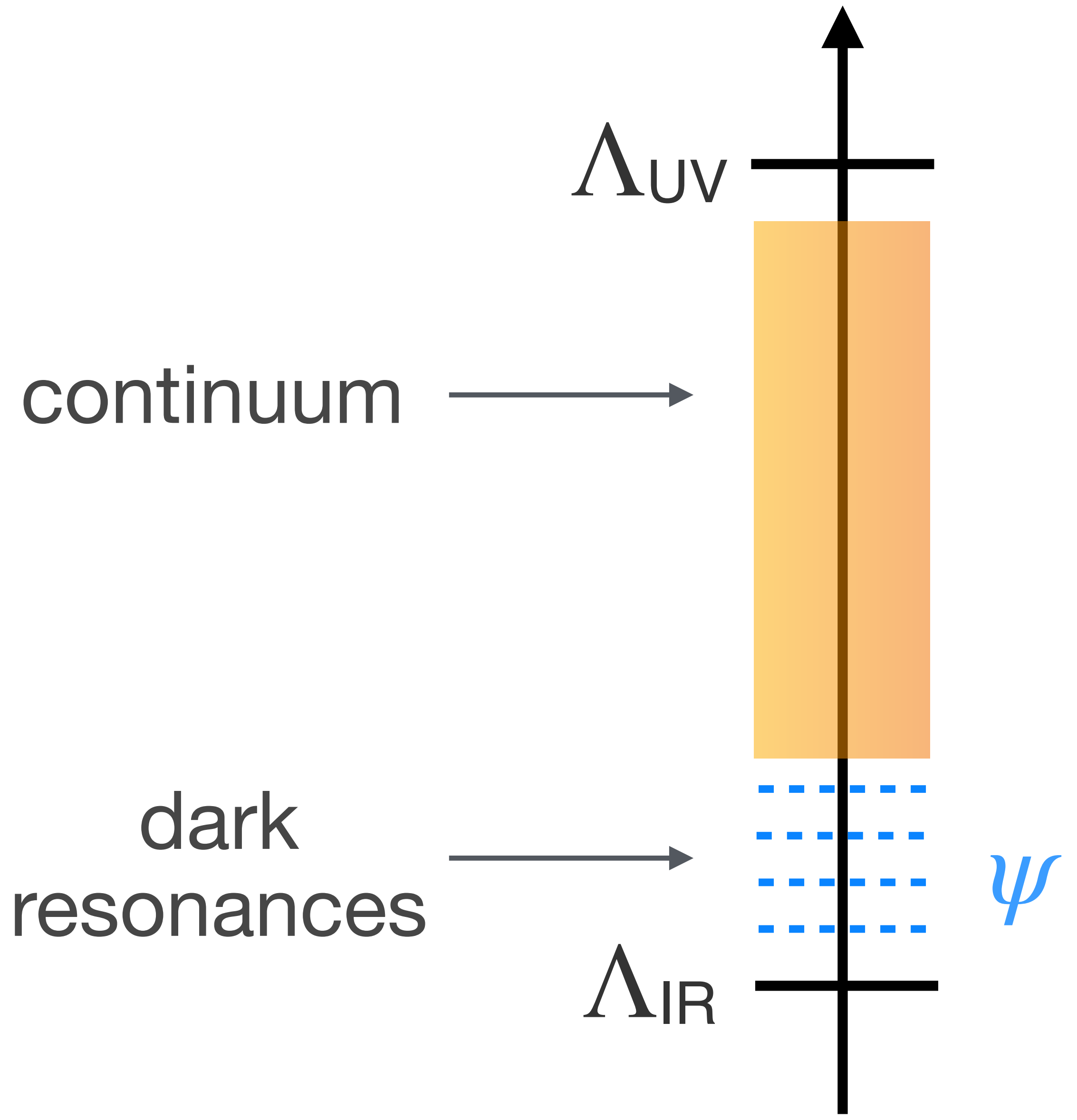

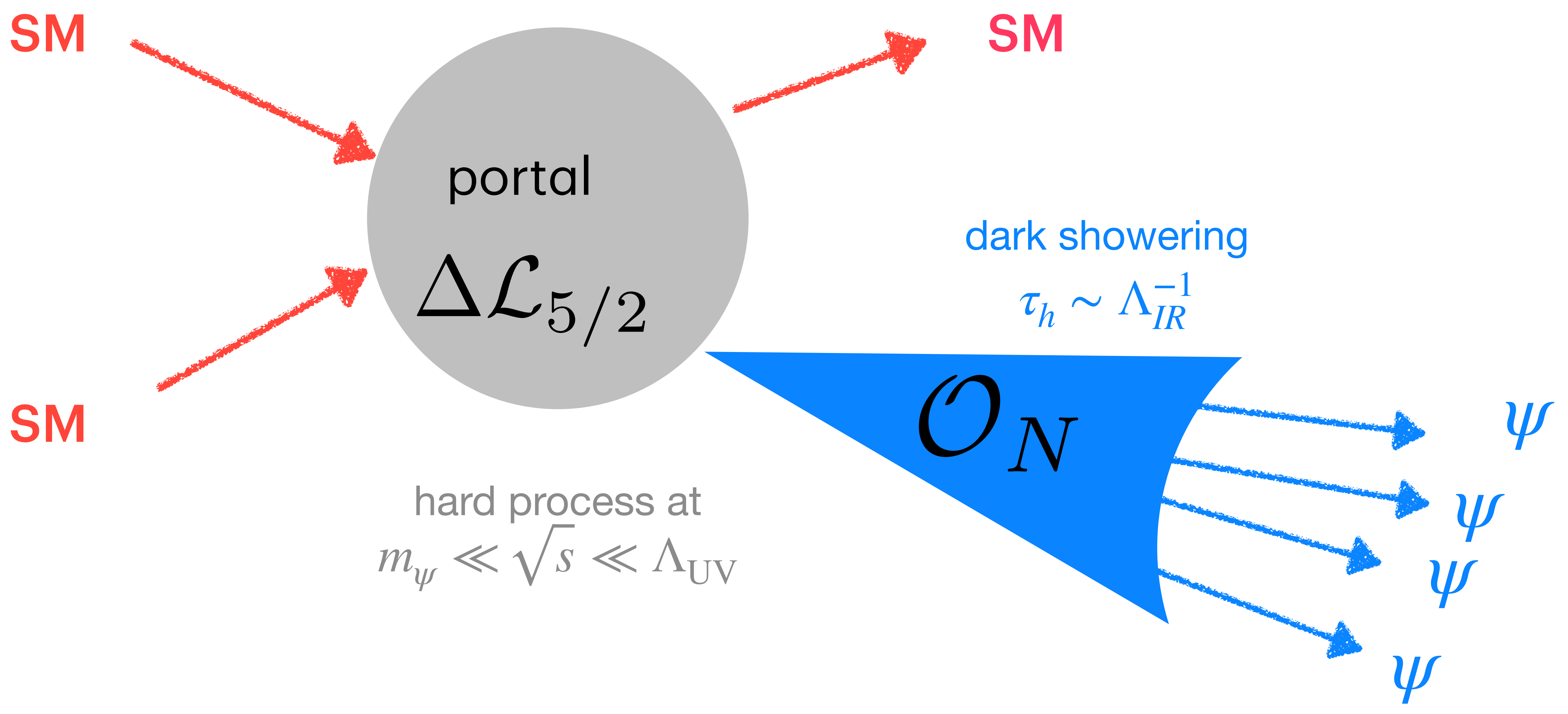

Many portals...

$\Delta_{\mathrm{SM}} = 5/2$

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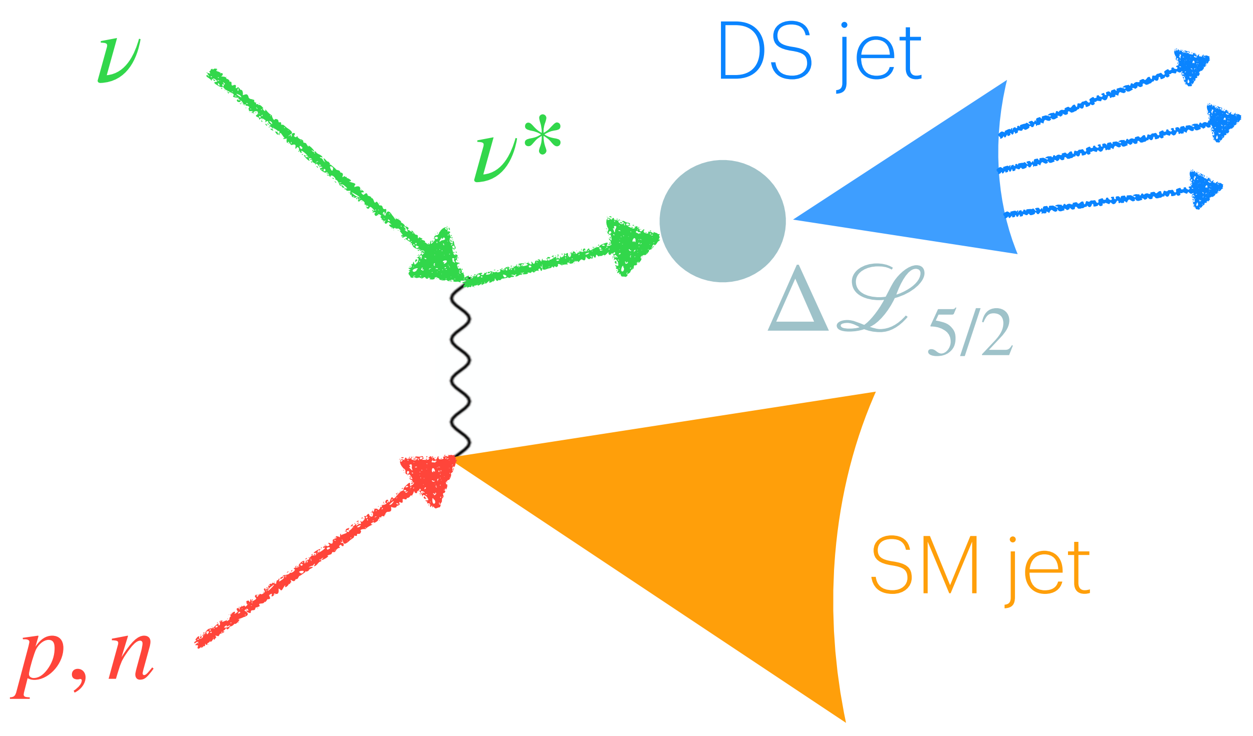

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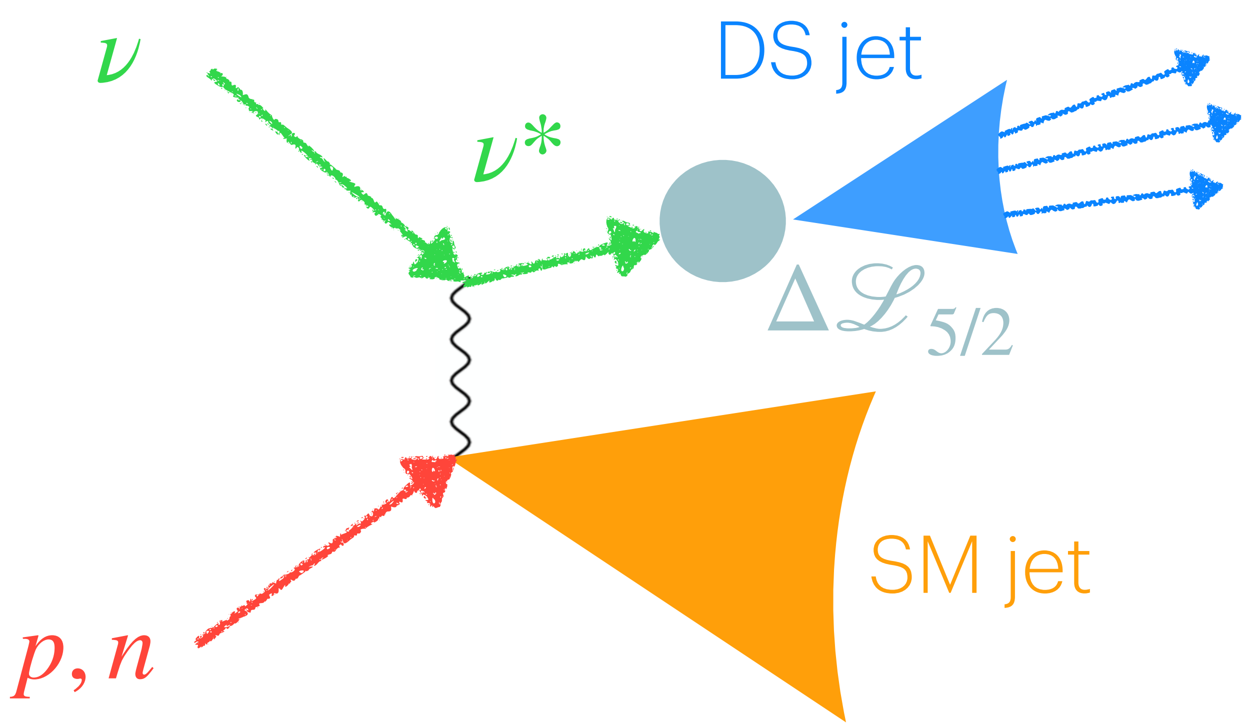

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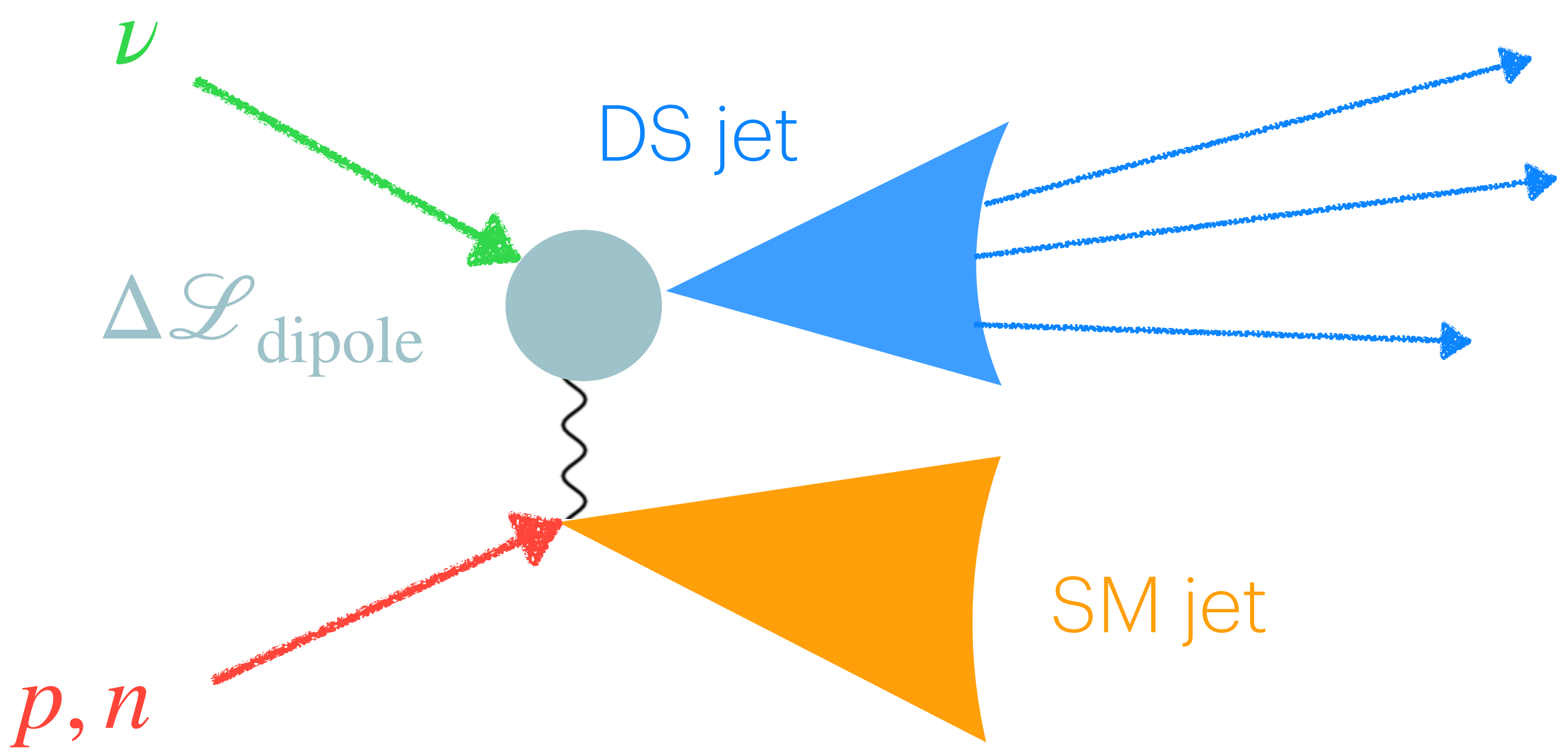

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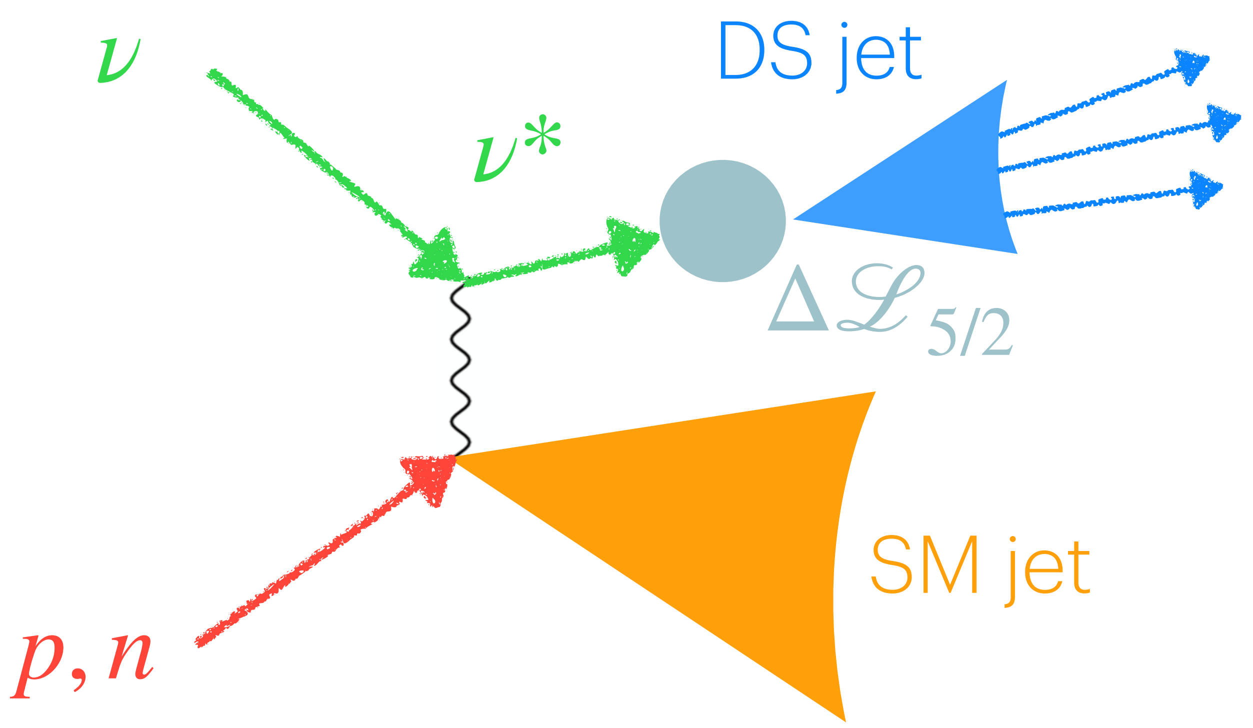

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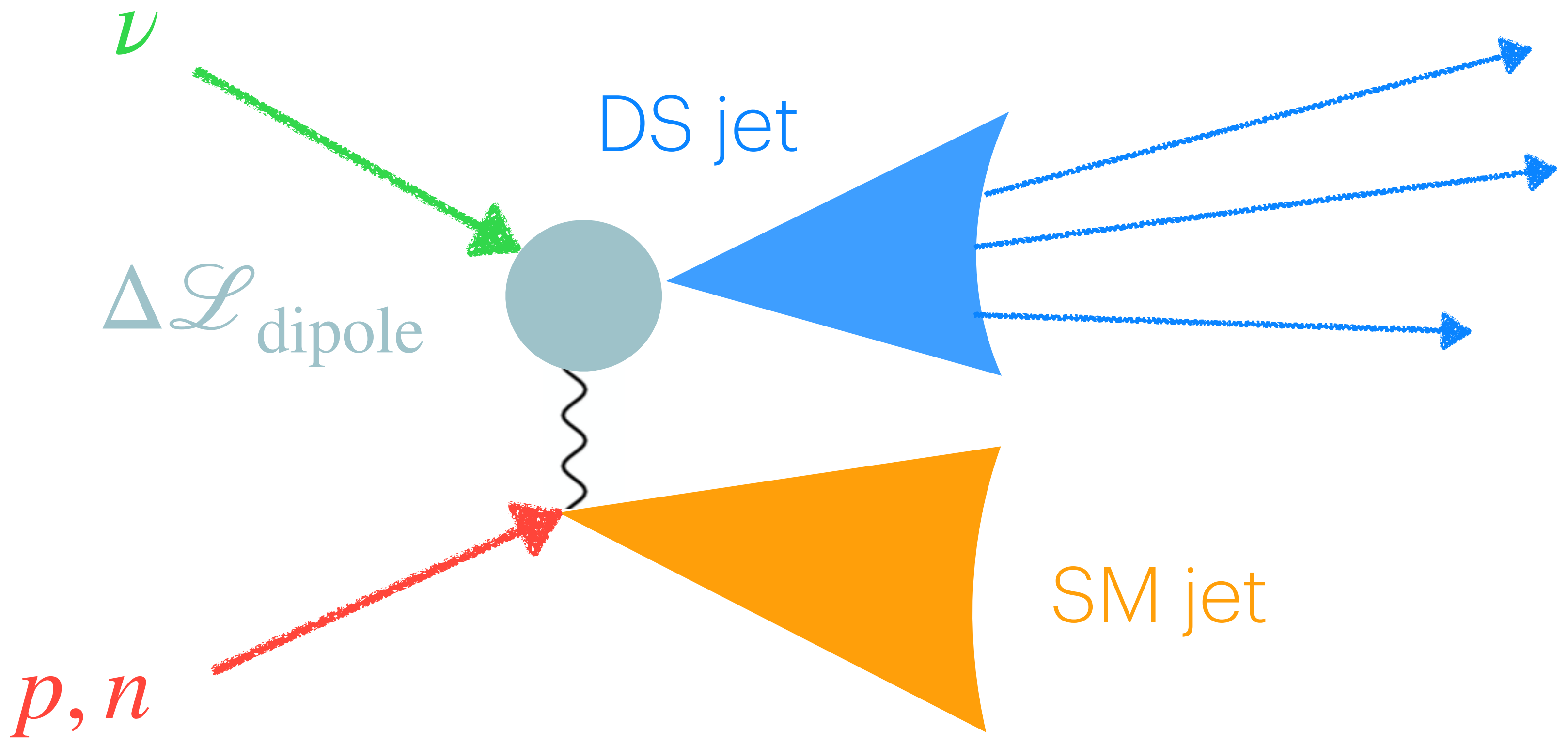
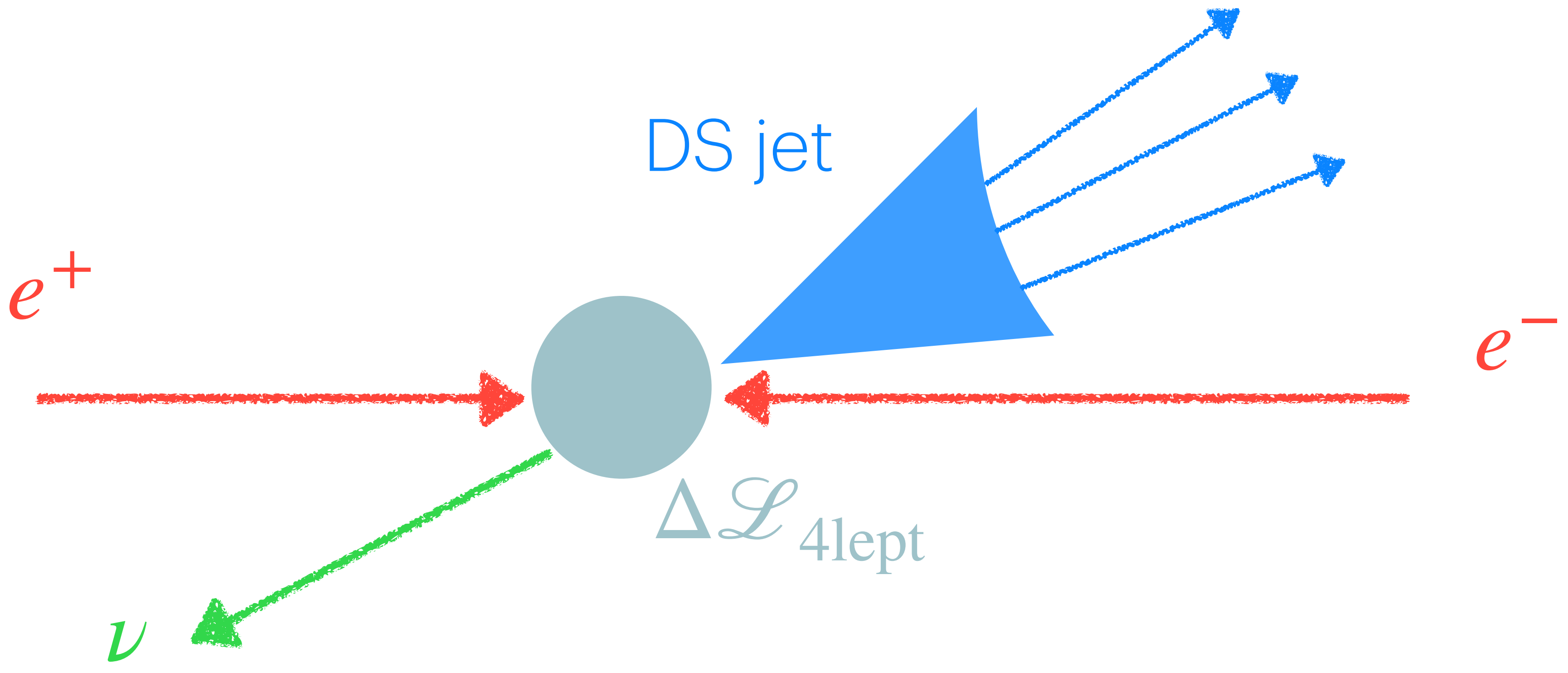
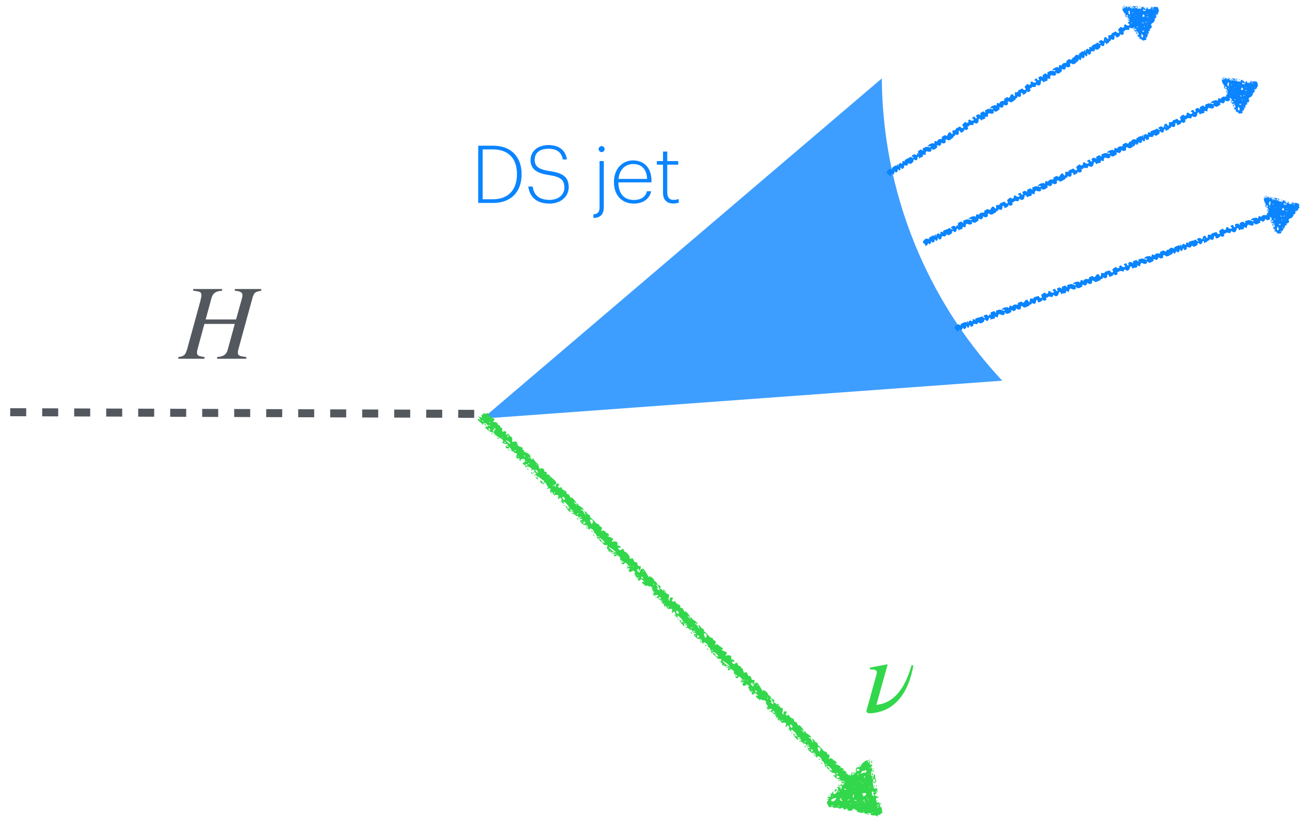


$$\Delta\mathcal{L}_{4F} = \frac{1}{\Lambda_{\rm UV}^{\Delta_N + 1/2}} \left[\left(\bar{L} \; \Gamma \; \mathcal{O}_N \right) \left(\bar{F} \; \Gamma \; F \right) \right]$$

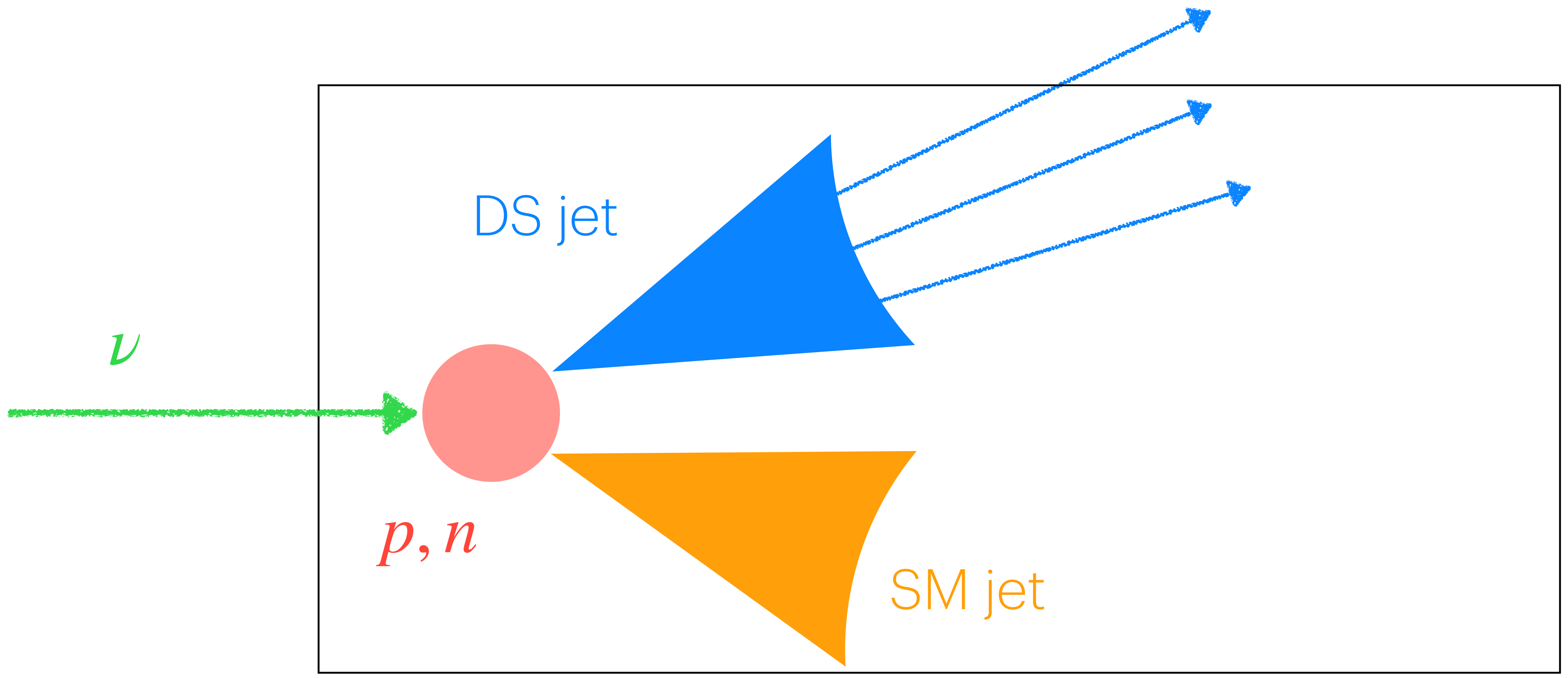


...and many signals!

Weak bosons and SM Higgs branching ratios

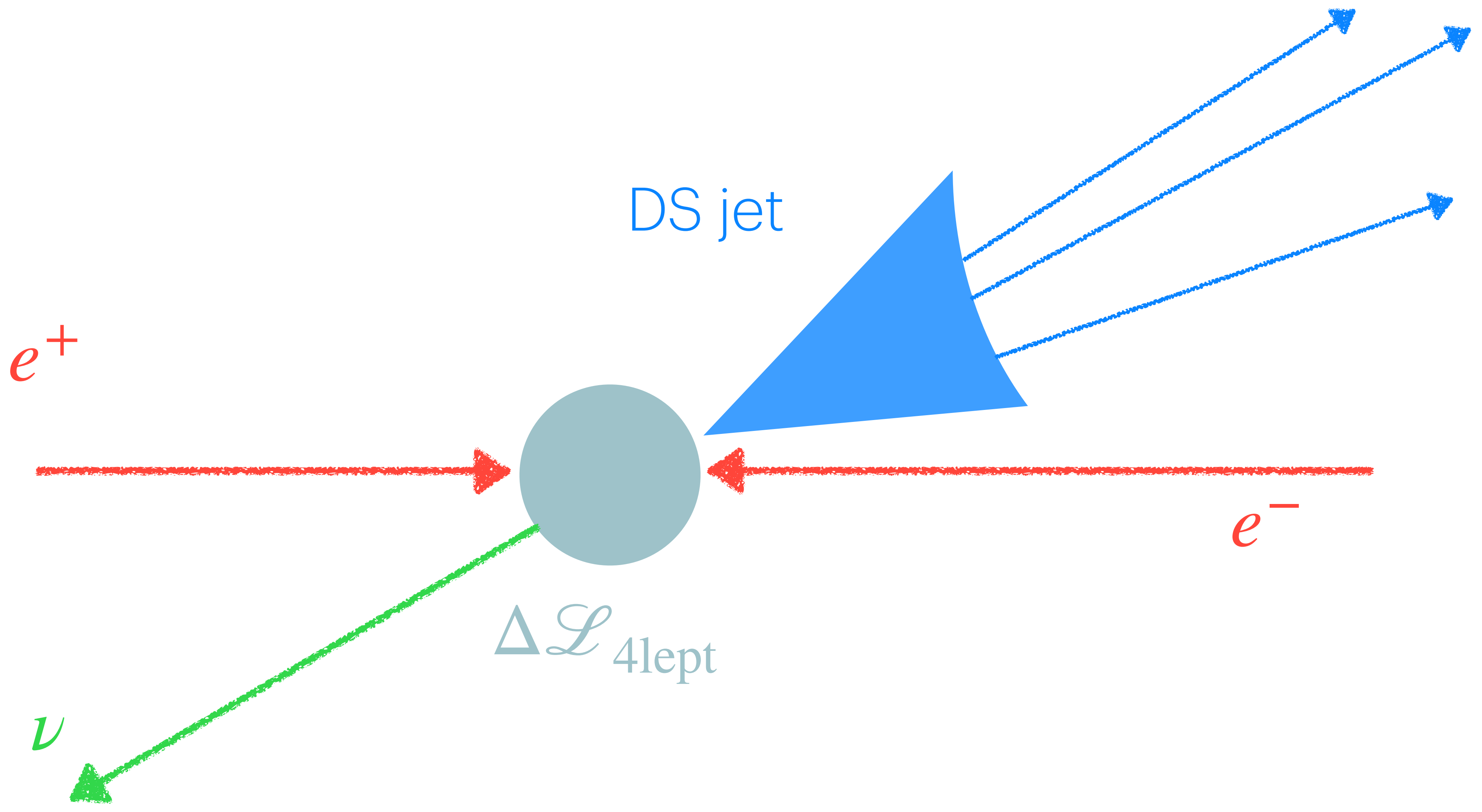


Neutrino disintegration at neutrino beams



Detector

Production at lepton/hadron colliders



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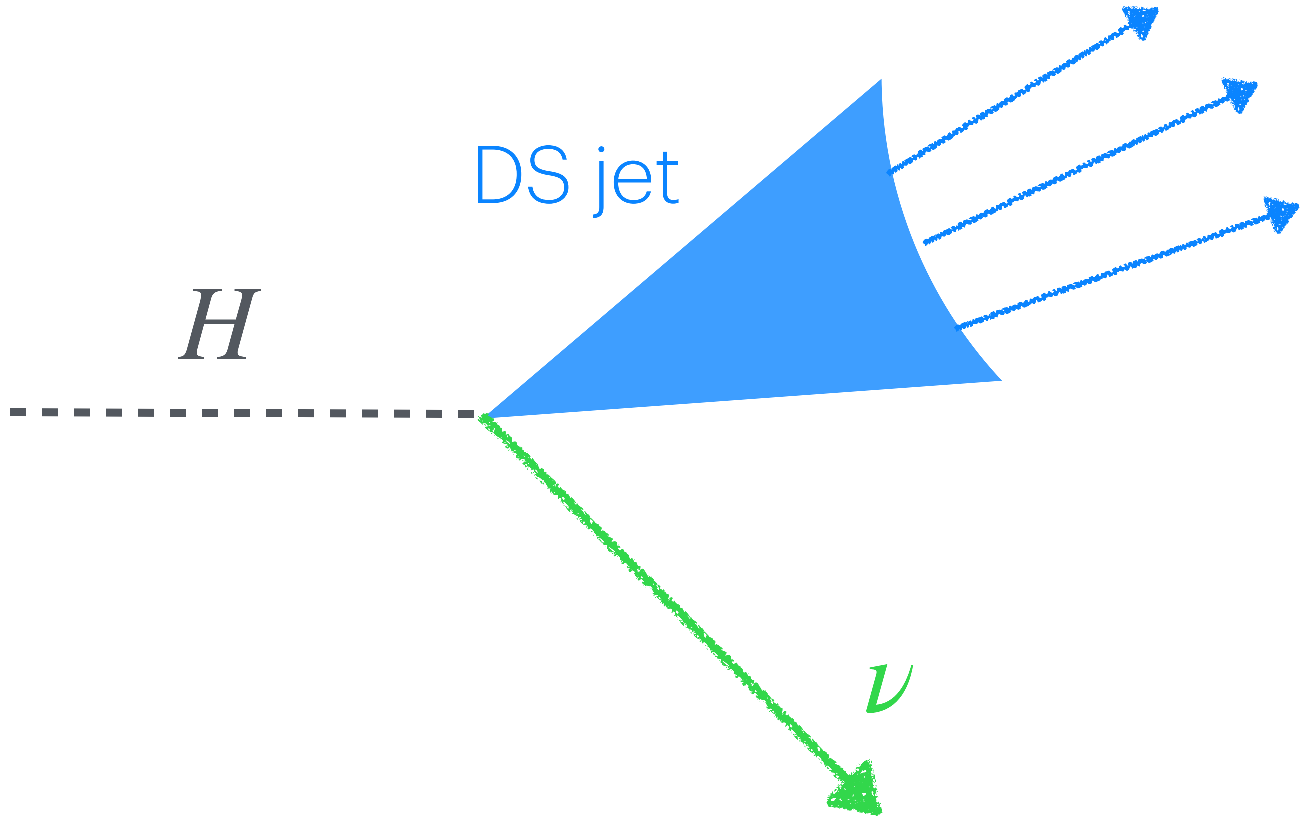

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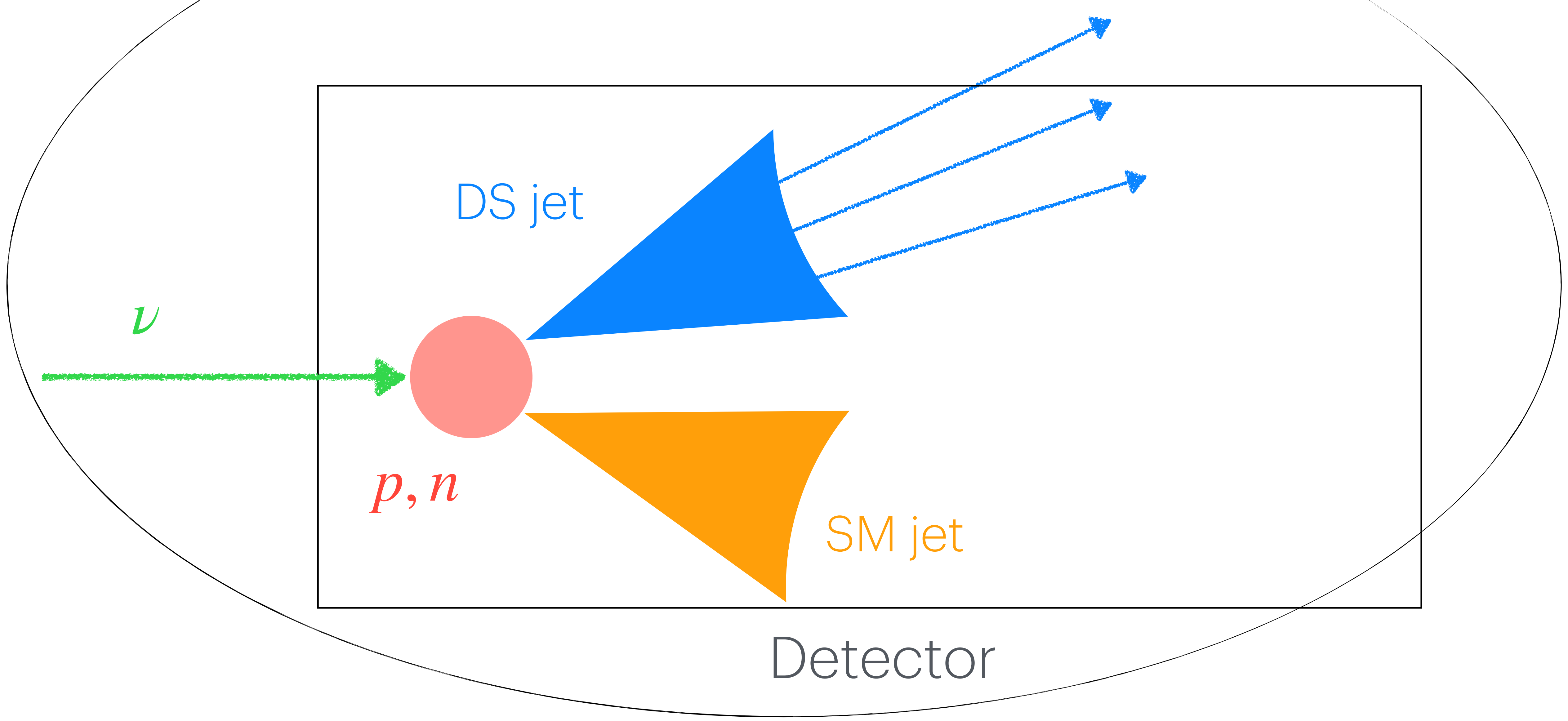

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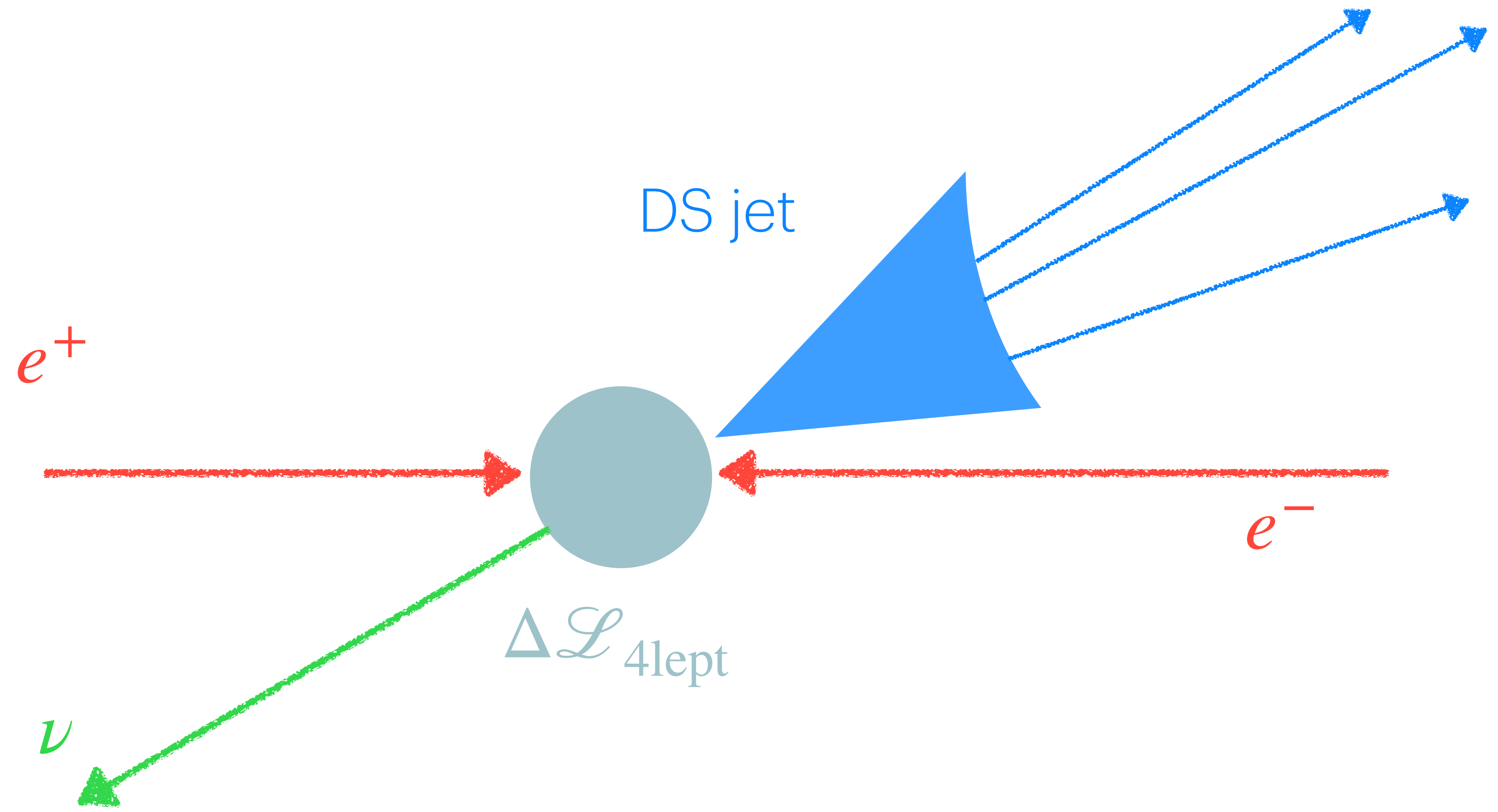
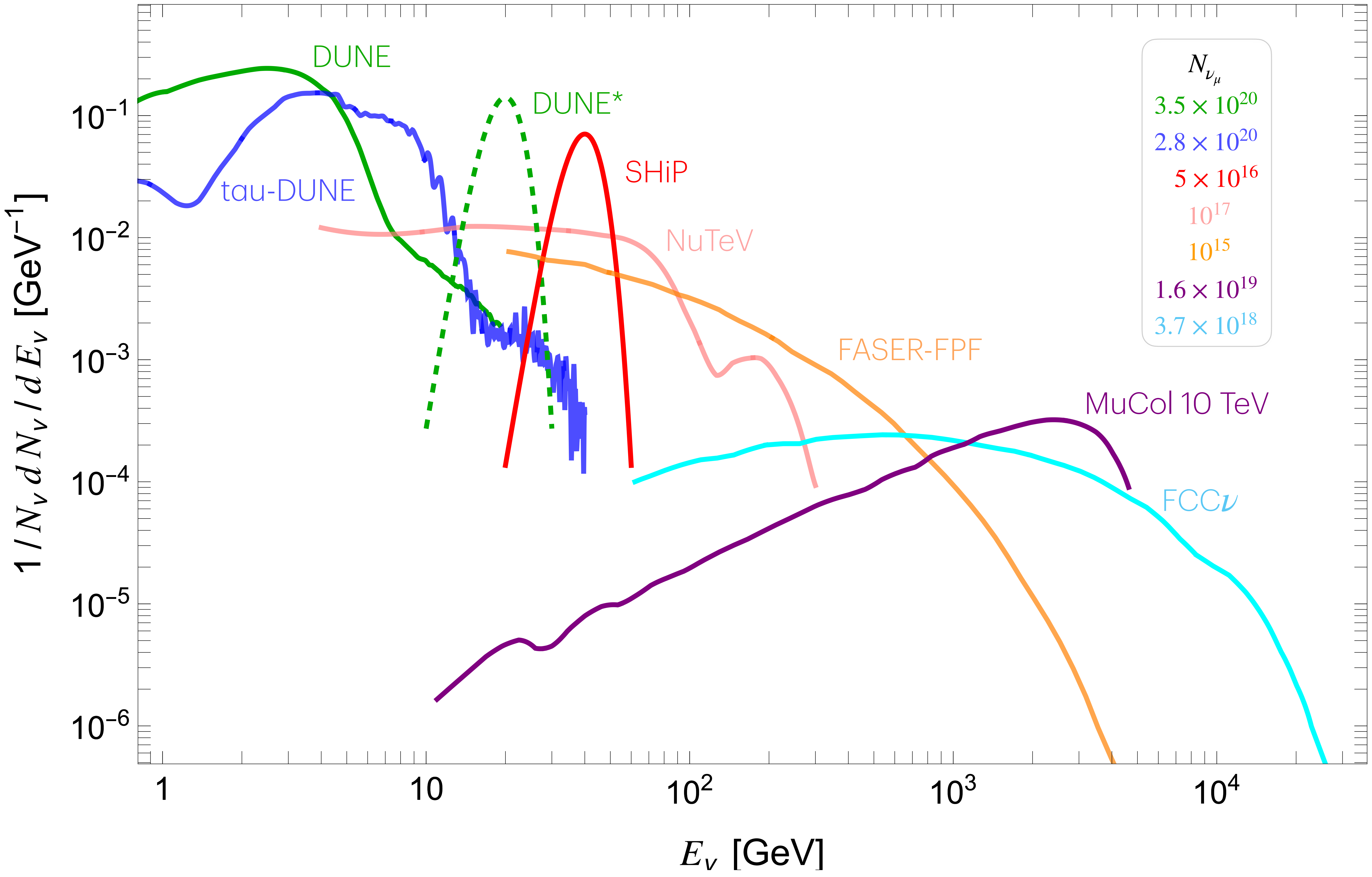


Why higher dimensional portals now?



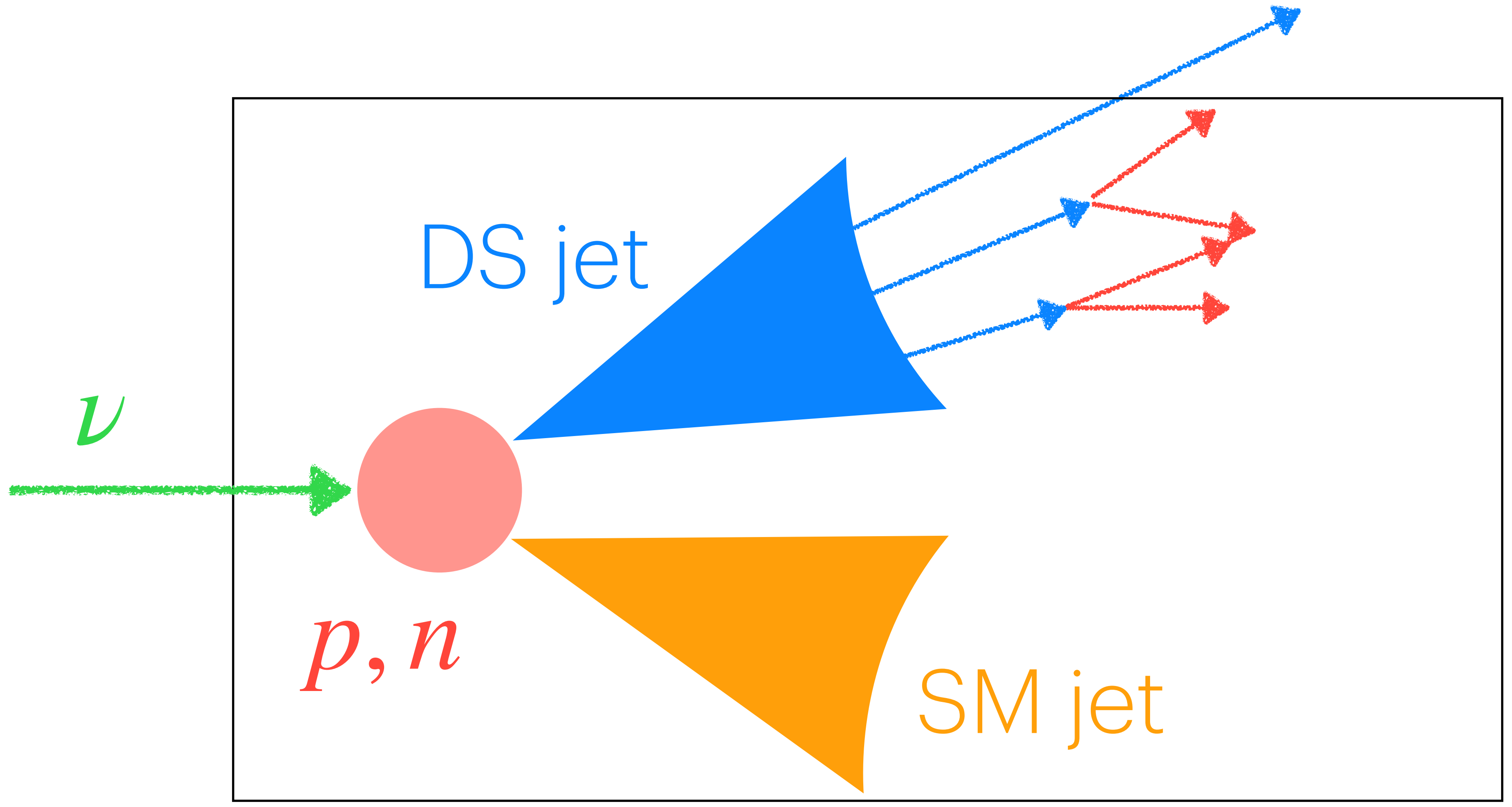
Higher dimension $D > 5 \rightarrow$ signal increases with energy

$$s = 2 m_p \bar{E}_\nu$$

$$\sigma \sim \frac{1}{s} \left(\frac{s}{\Lambda_{\mathrm{UV}}^2} \right)^{D-4}$$

Unique opportunity: soon available neutrino beam with **high energy and intensity**

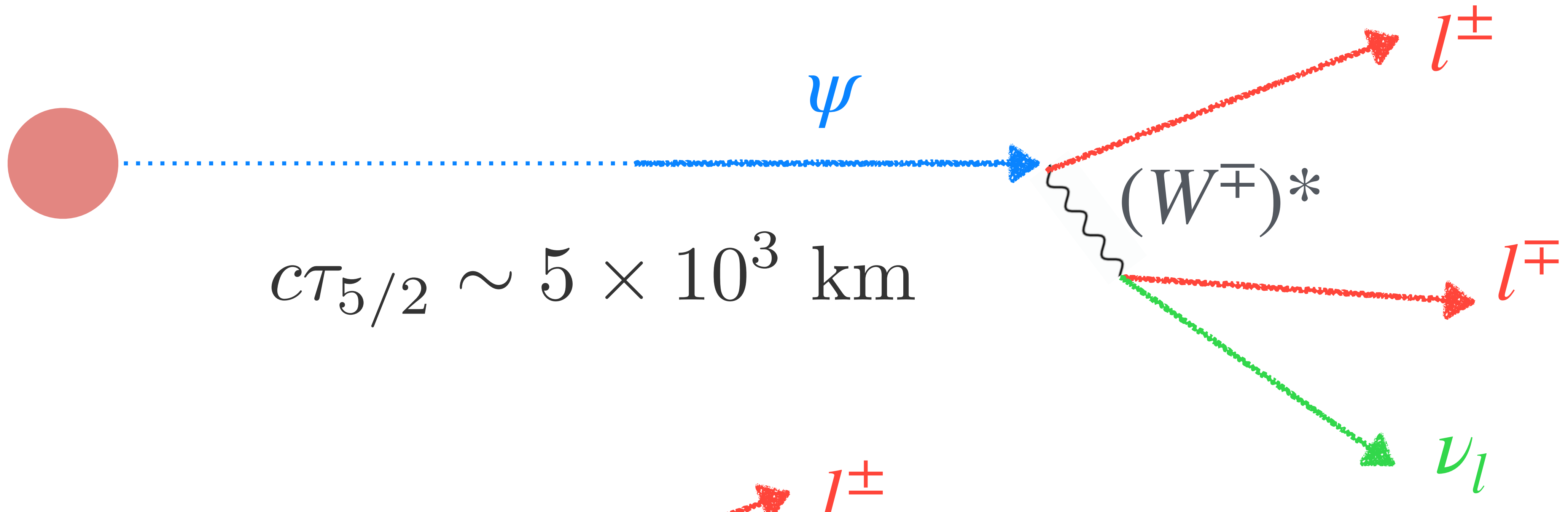
Looking for unstable light states



$$\Delta\mathcal{L}_{5/2} = \frac{y_\mu \tilde{H} L \mathcal{O}_N}{\Lambda_{\mathrm{UV}}^{\Delta_N - 3/2}}$$

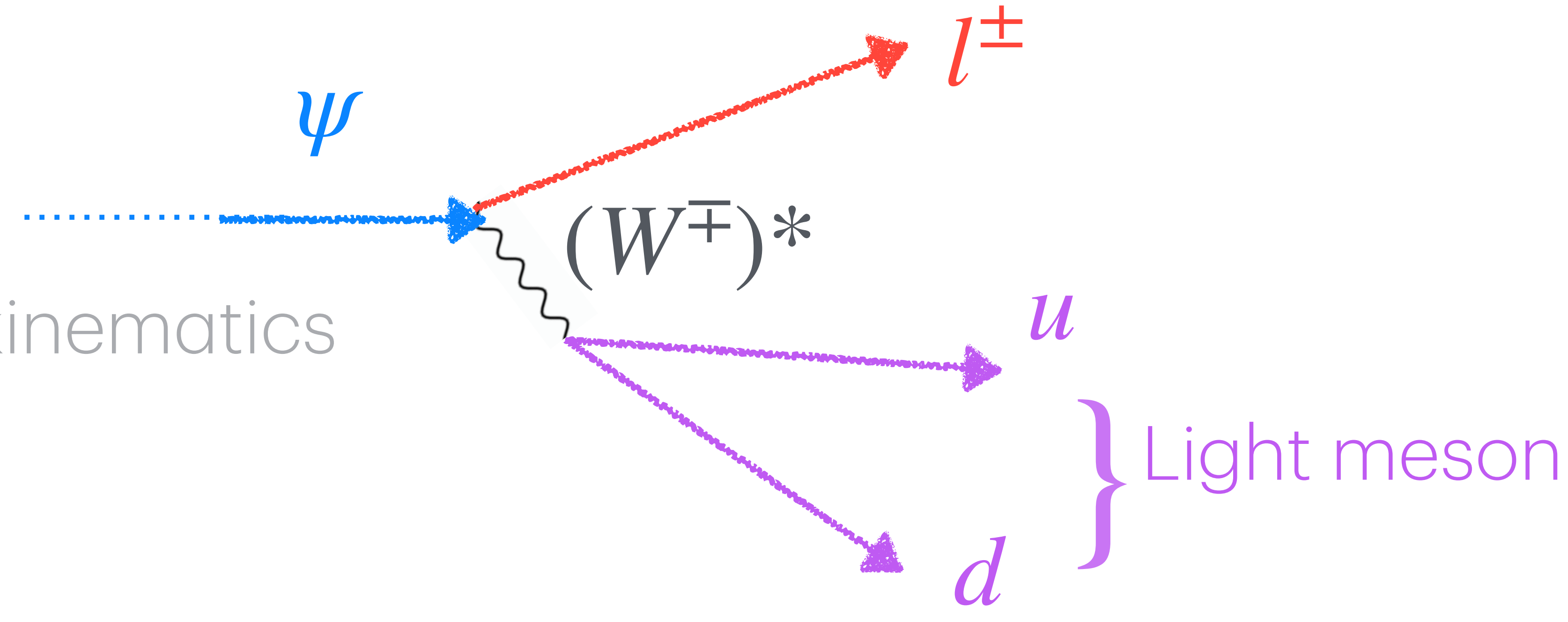
Charged leptons + Missing energy

Primary vertex:
hadronic activity



$$c\tau_{5/2} \sim 5 \times 10^3 \ \mathrm{km}$$

Semi-leptonic



W branching ratios + kinematics

+ Z mediated decays

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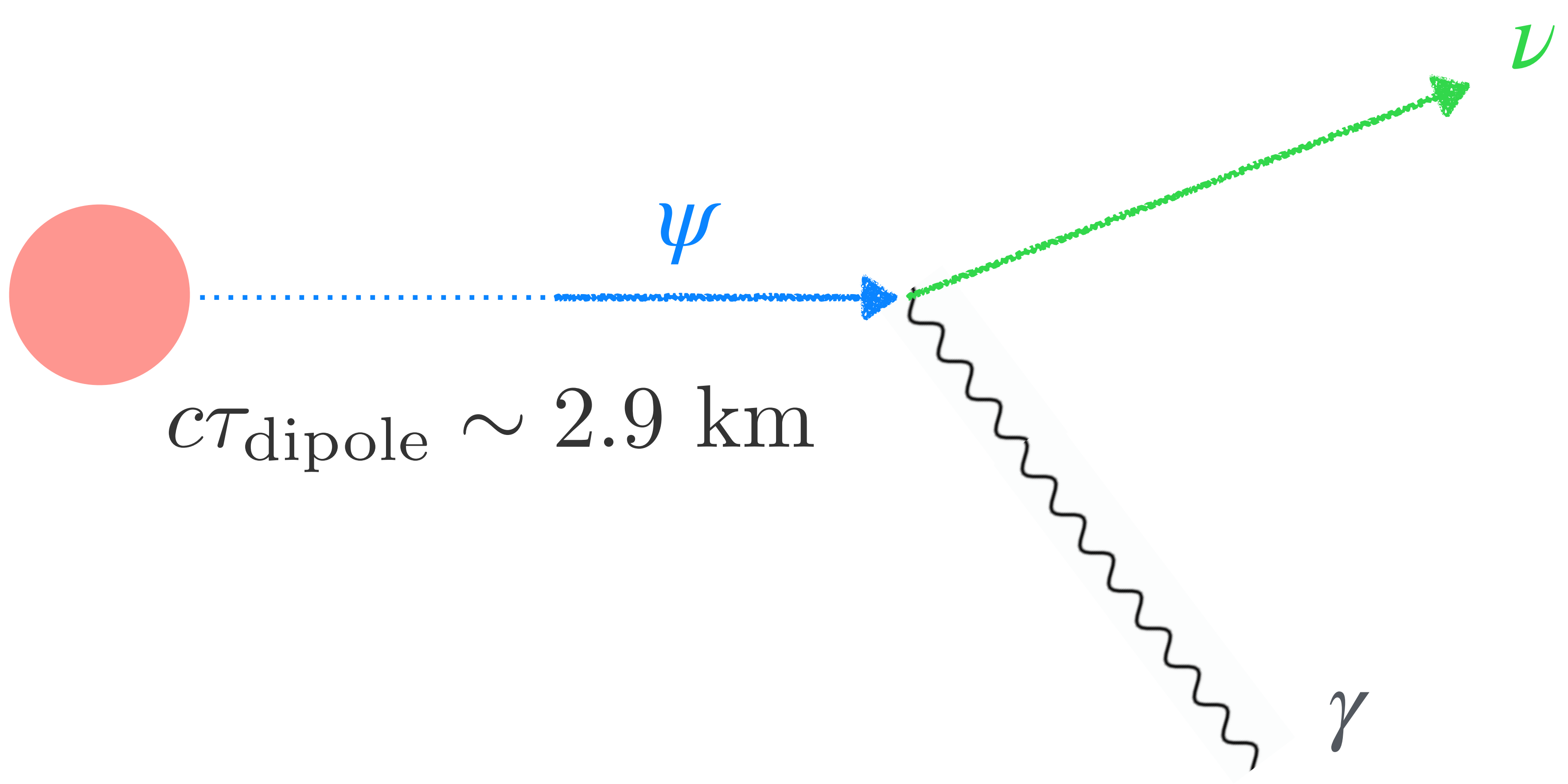

Photon + Missing energy

Charged leptons + Missing energy

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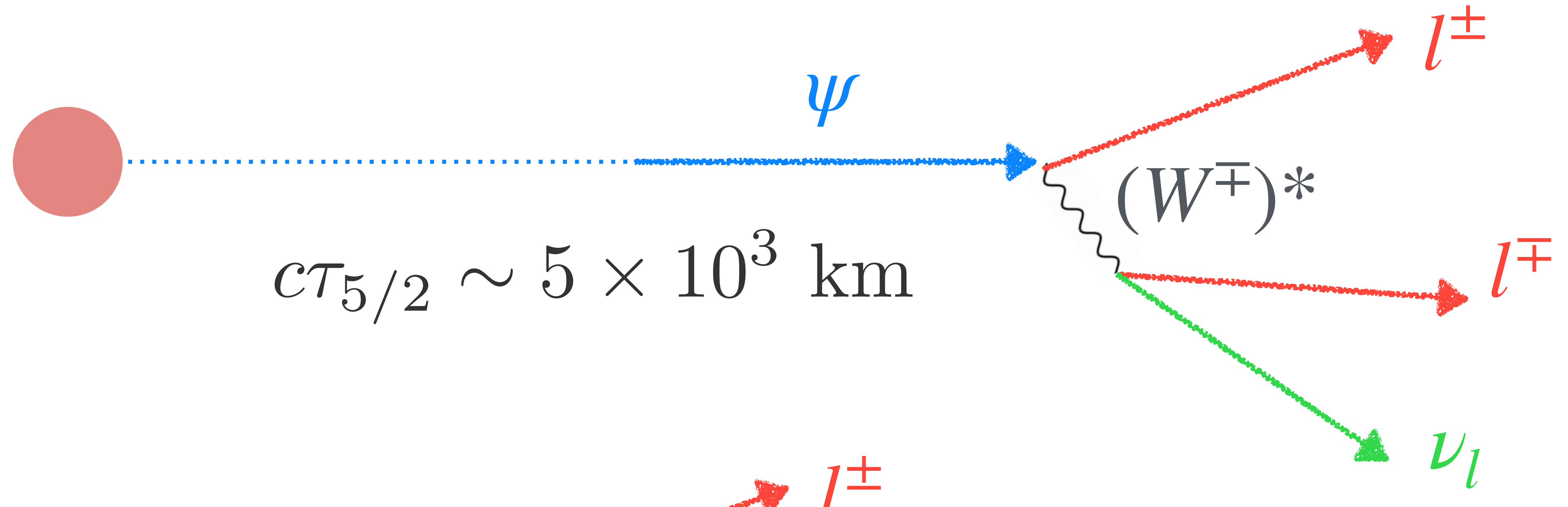

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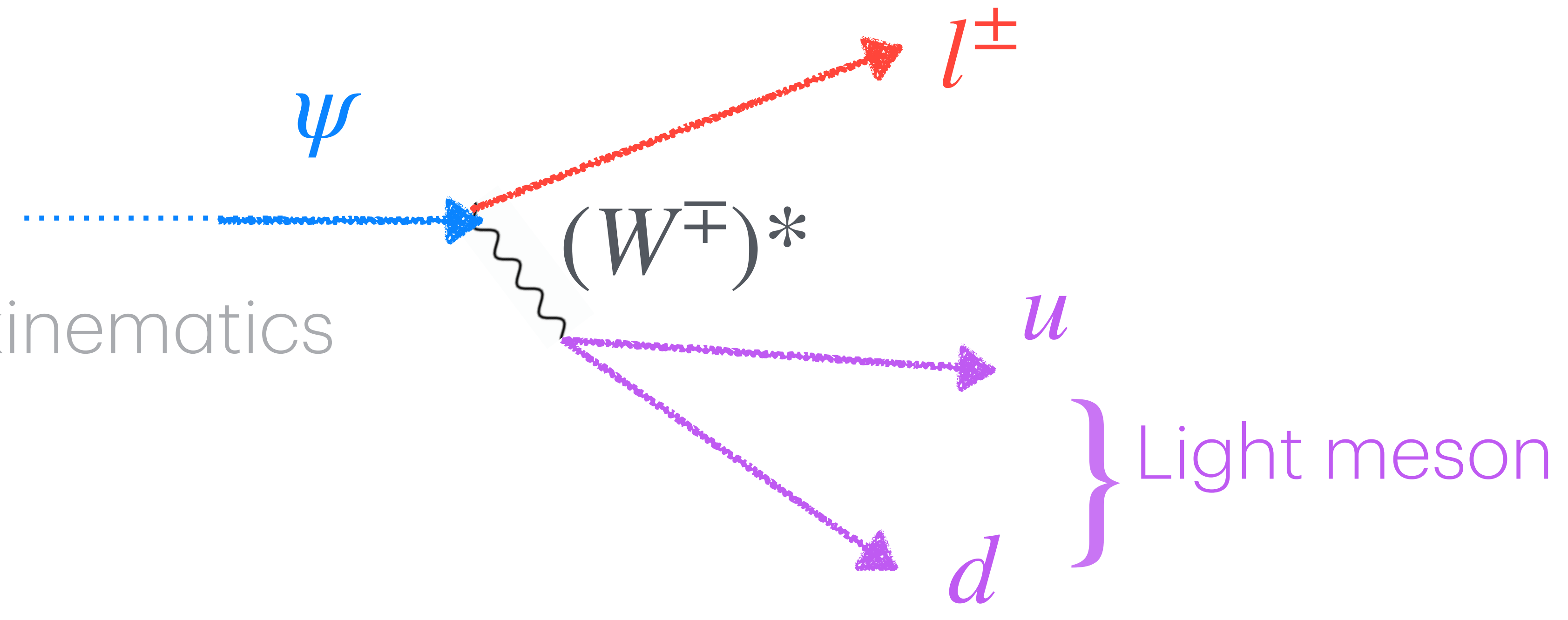

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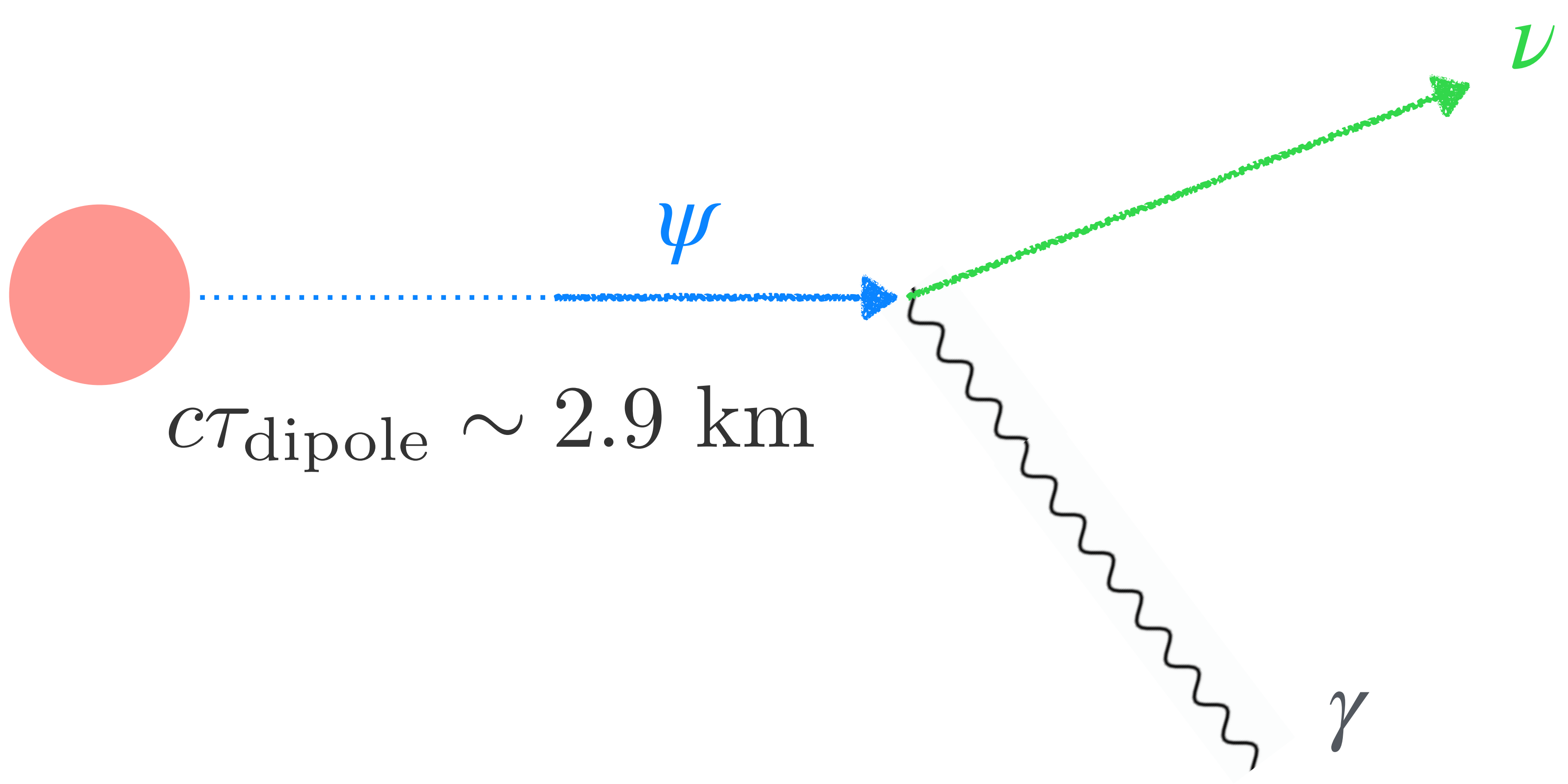

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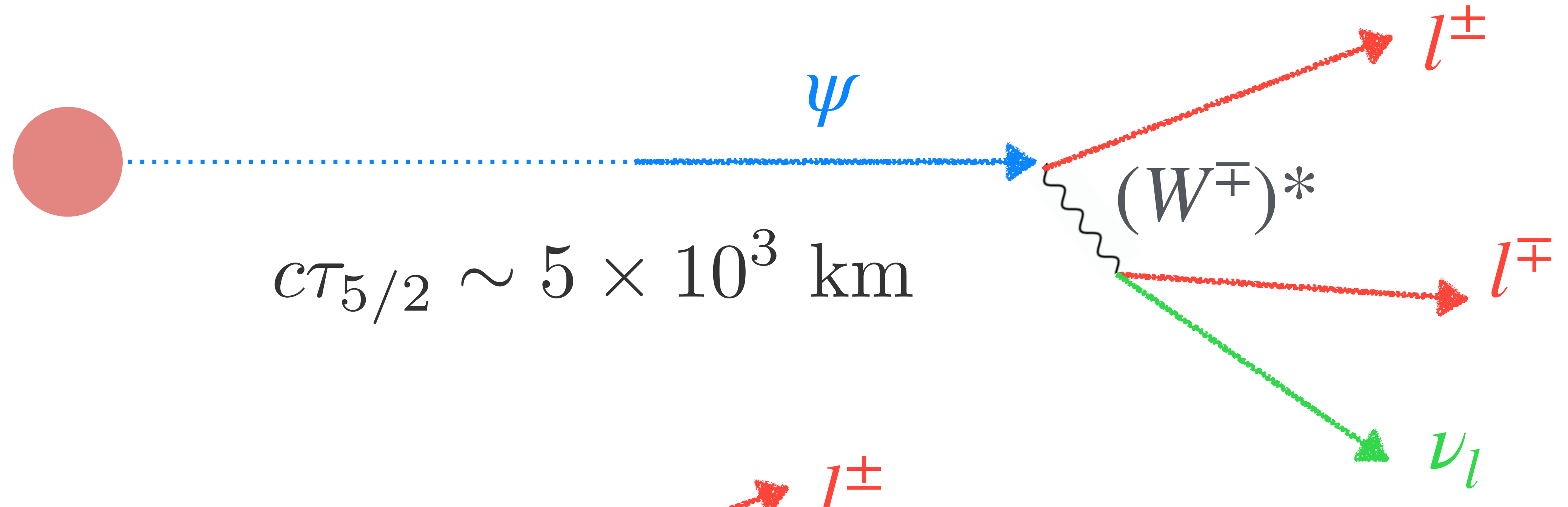

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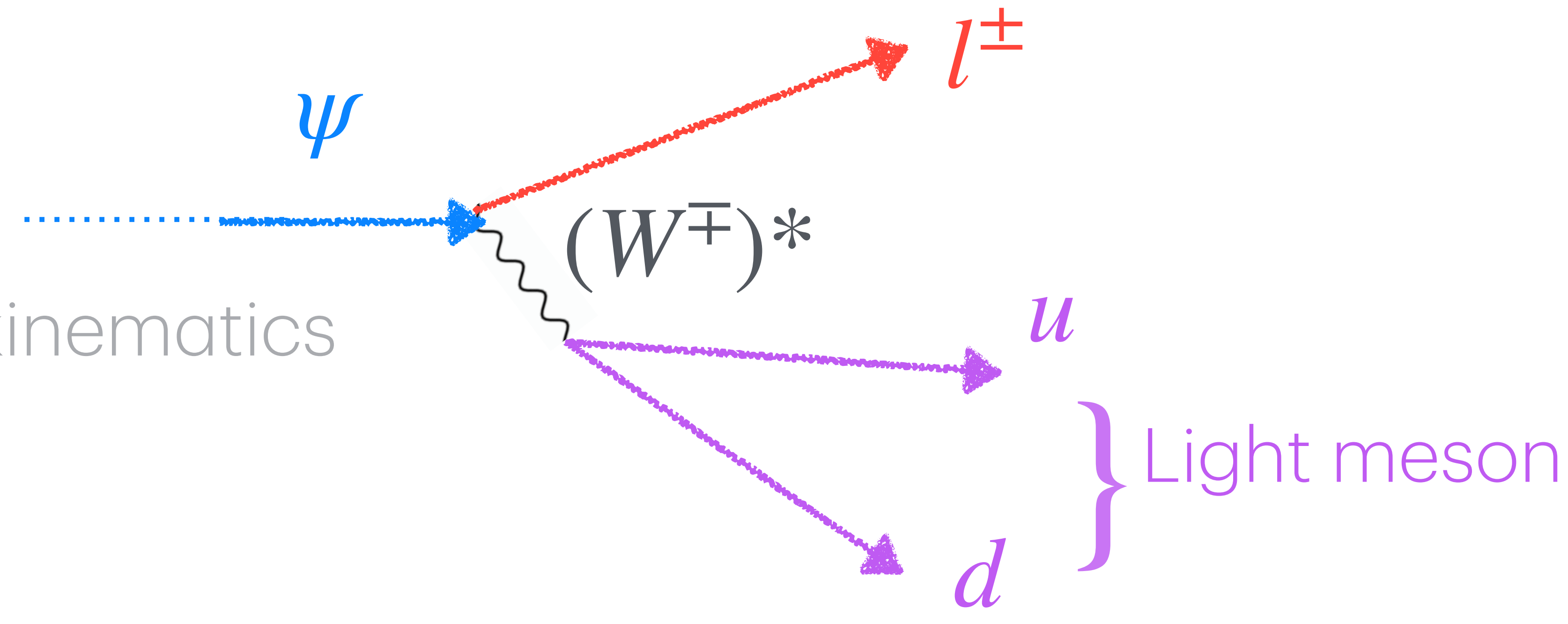
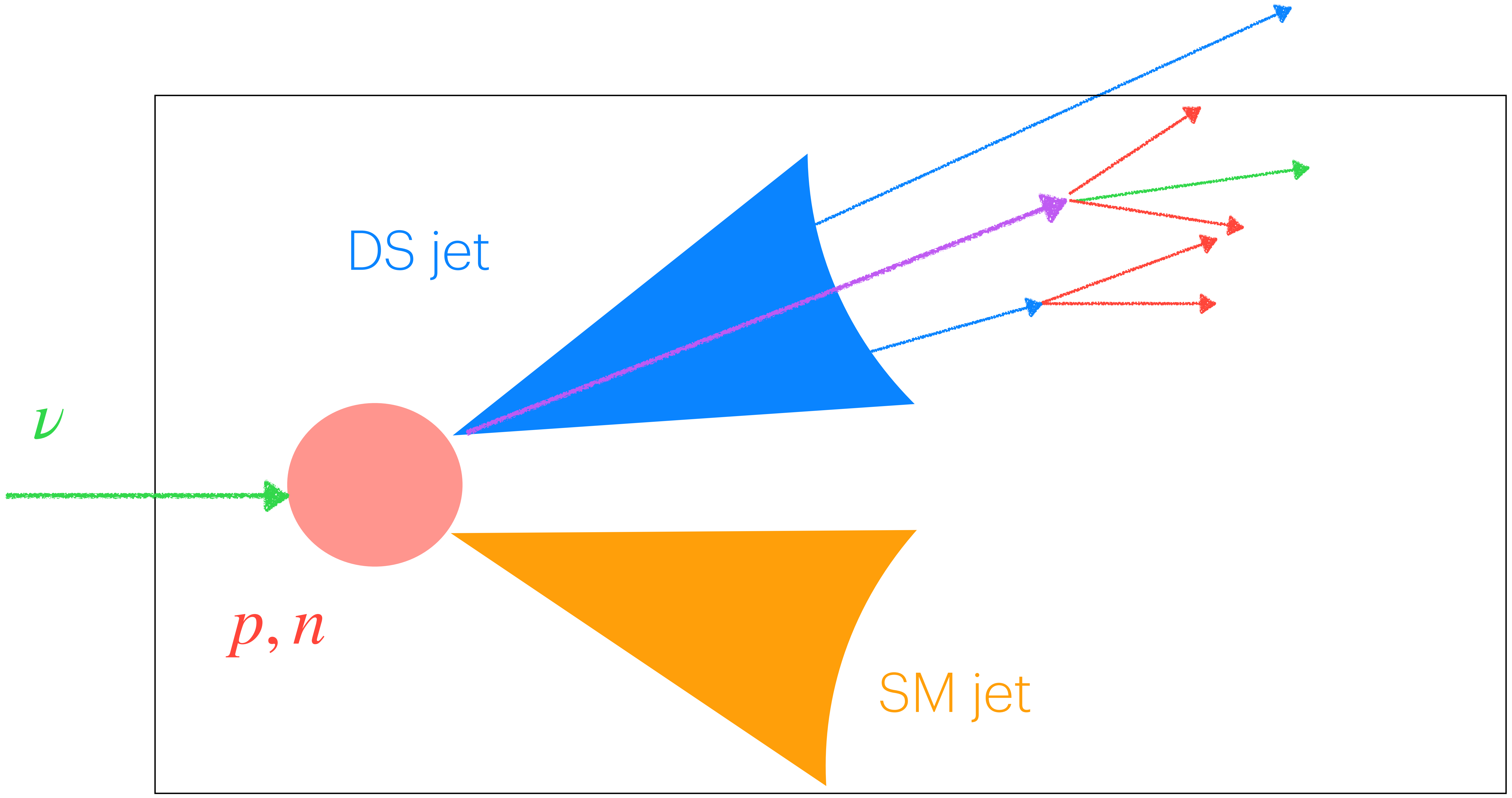


+ Z mediated decays

Looking for unstable light states

Interesting signal with both **theoretical and experimental challenges!**

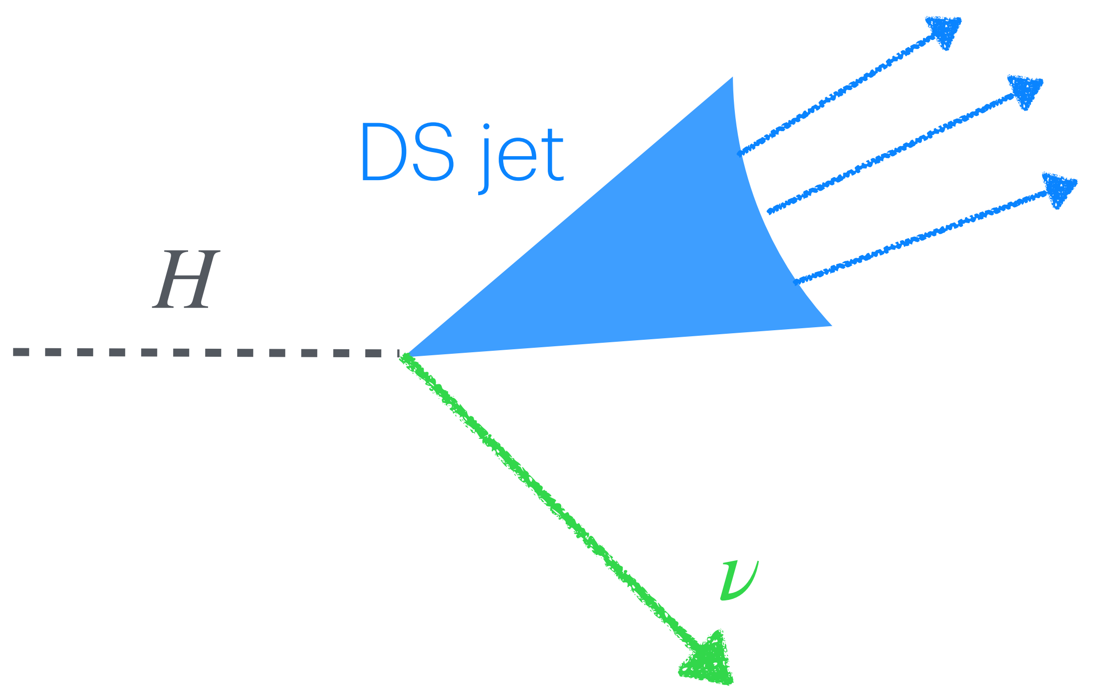


Challenges

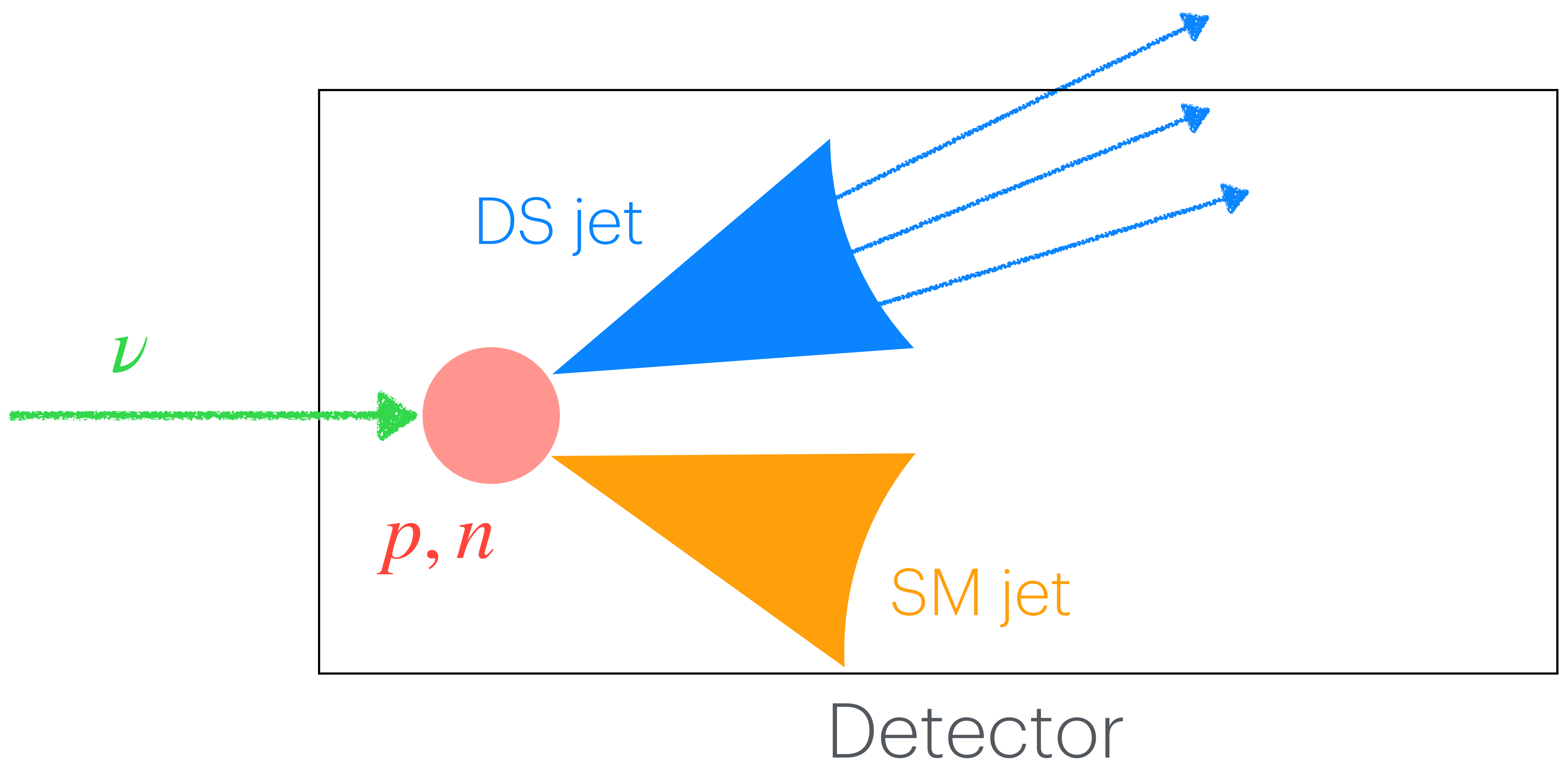
- Minimum energy to identify the primary vertex
- Minimum observable displacement
- Trigger threshold in amount of missing energy in the SM emerging jet
- Minimum energy in SM jet
- Emerging jet of SM particles displaced from hadronic activity…**backgrounds**?

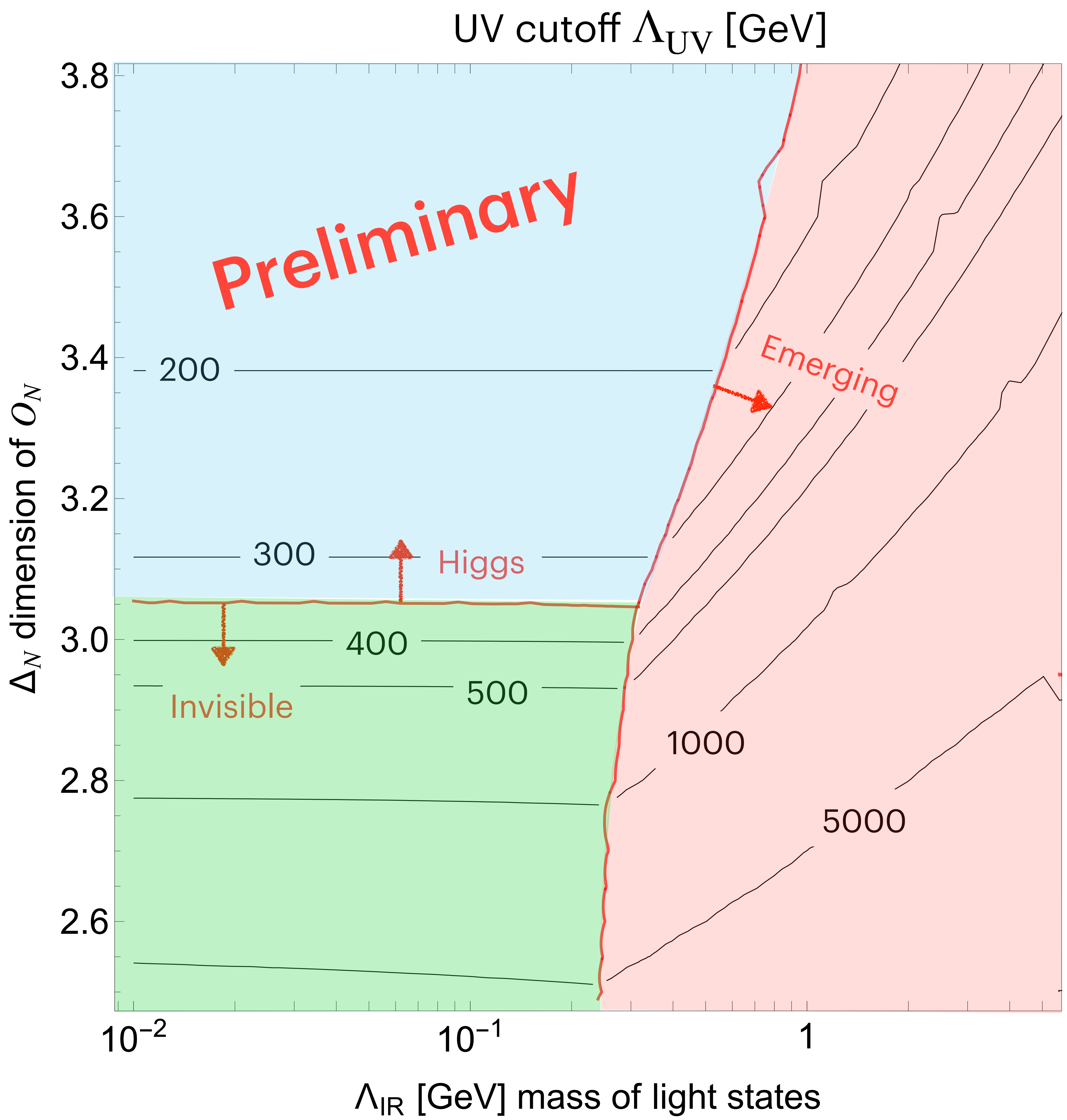
Results

$$\Delta\mathcal{L}_{5/2} = \frac{y_\mu \tilde{H} L \mathcal{O}_N}{\Lambda_{\rm UV}^{\Delta_N - 3/2}}$$



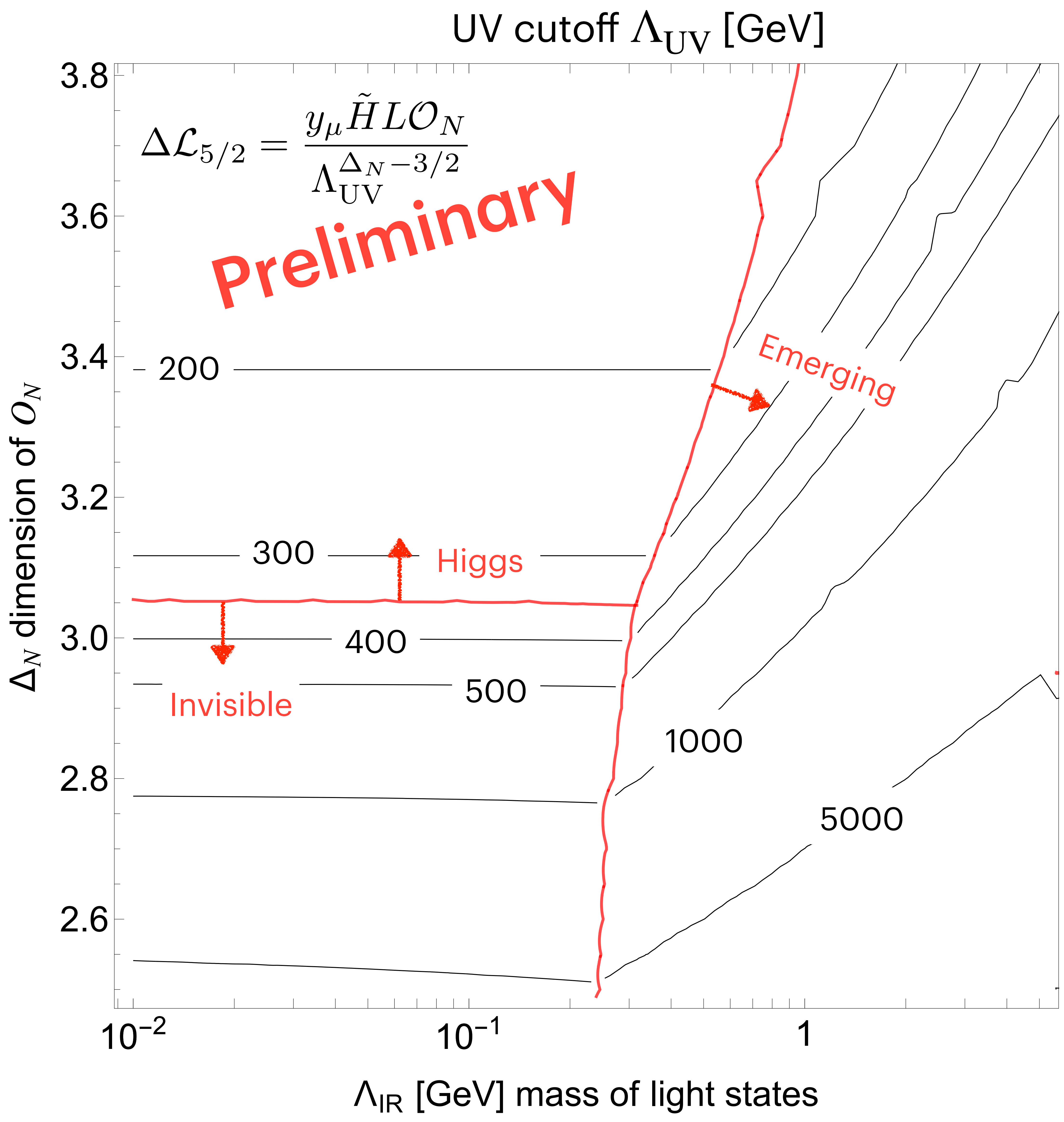
- Emerging jets leading probe of heavy (→ unstable) IR states
- Stable states tested through precision SM measures (Higgs BR) and enhancement in neutral current





Summary

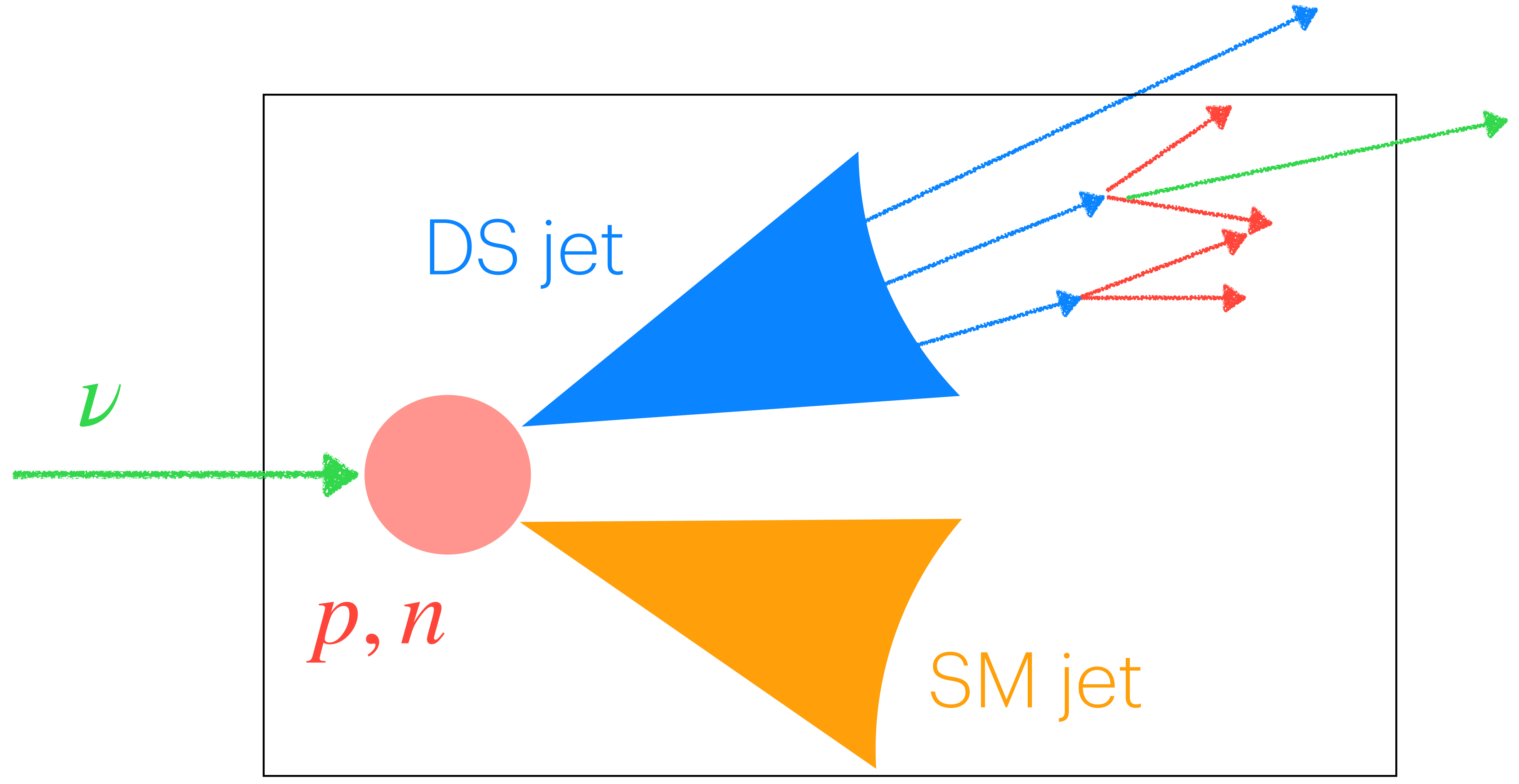
- Next generation neutrino beams test interaction at unprecedented **energy and intensity** → probing higher dimensions
- Emerging jet leading probe for **unstable** light states
- Stable states probed via **precision measurements** or neutral current **neutrino scattering**



Thank you for your attention and stay tuned!

Emerging dark jets

Hadronic activity (primary vertex) + displaced jet of SM particles



$$s = 2 m_p \bar{E}_\nu$$

$$S_{\text{emerging}} \sim \boxed{\frac{N_\nu}{\sigma_t} \frac{s^2}{\Lambda_{\text{UV}}^4 v^2} \left(\frac{s}{\Lambda_{\text{UV}}^2} \right)^{\Delta_N - 7/2}} \boxed{\frac{L_{\text{det}}}{\gamma \beta c \tau} n_{\text{fragments}}} \sim 1$$

Production of DS jet

Probability of decaying inside the detector

Invisible dark jets at neutrino beams

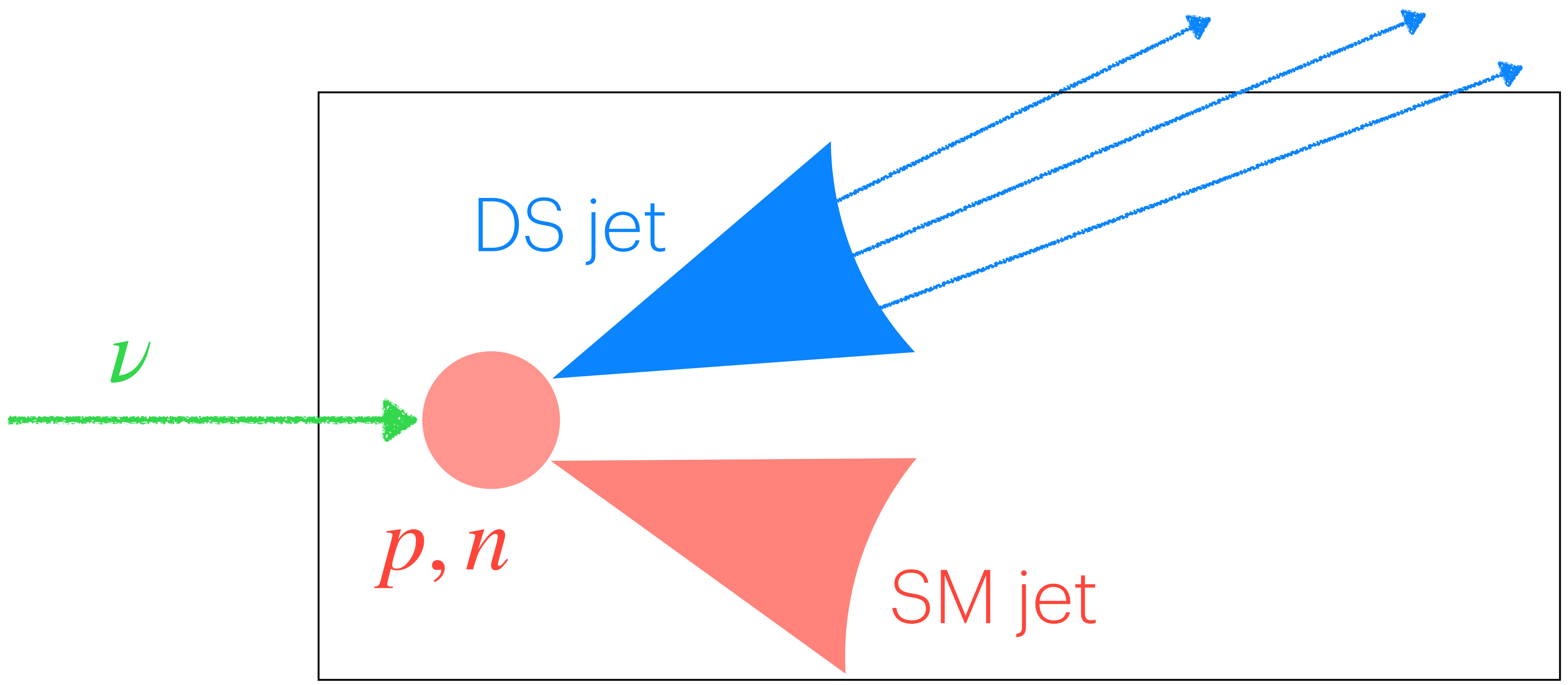
ψ long lived: only hadronic activity → background from SM neutral current

$s = 2m_p\bar{E}_\nu$

$$S^{HL}_{\rm inv} \sim \frac{N_\nu}{\sigma_t}\frac{s^2}{\Lambda^4_{\rm UV}v^2}\left(\frac{s}{\Lambda^2_{\rm UV}}\right)^{\Delta_N-7/2}$$

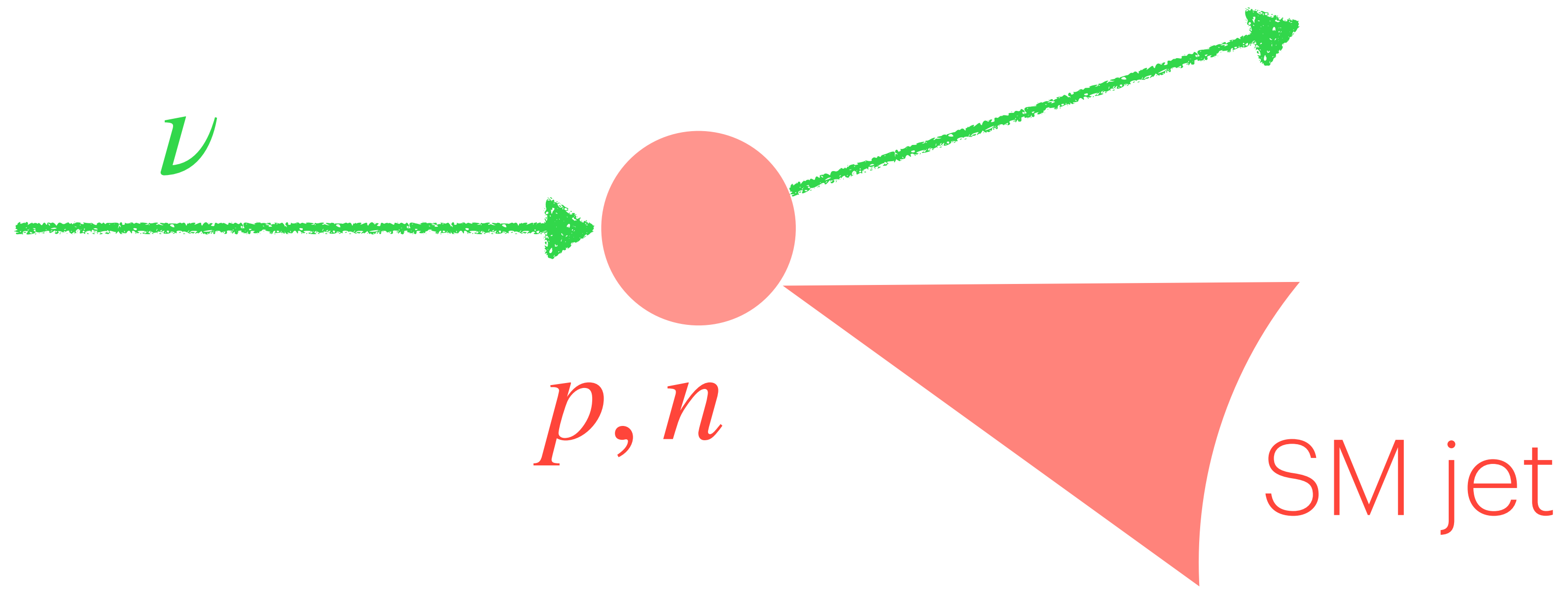
$$B \sim \frac{s}{8v^4\pi}\sigma_t^{-1}N_\nu$$

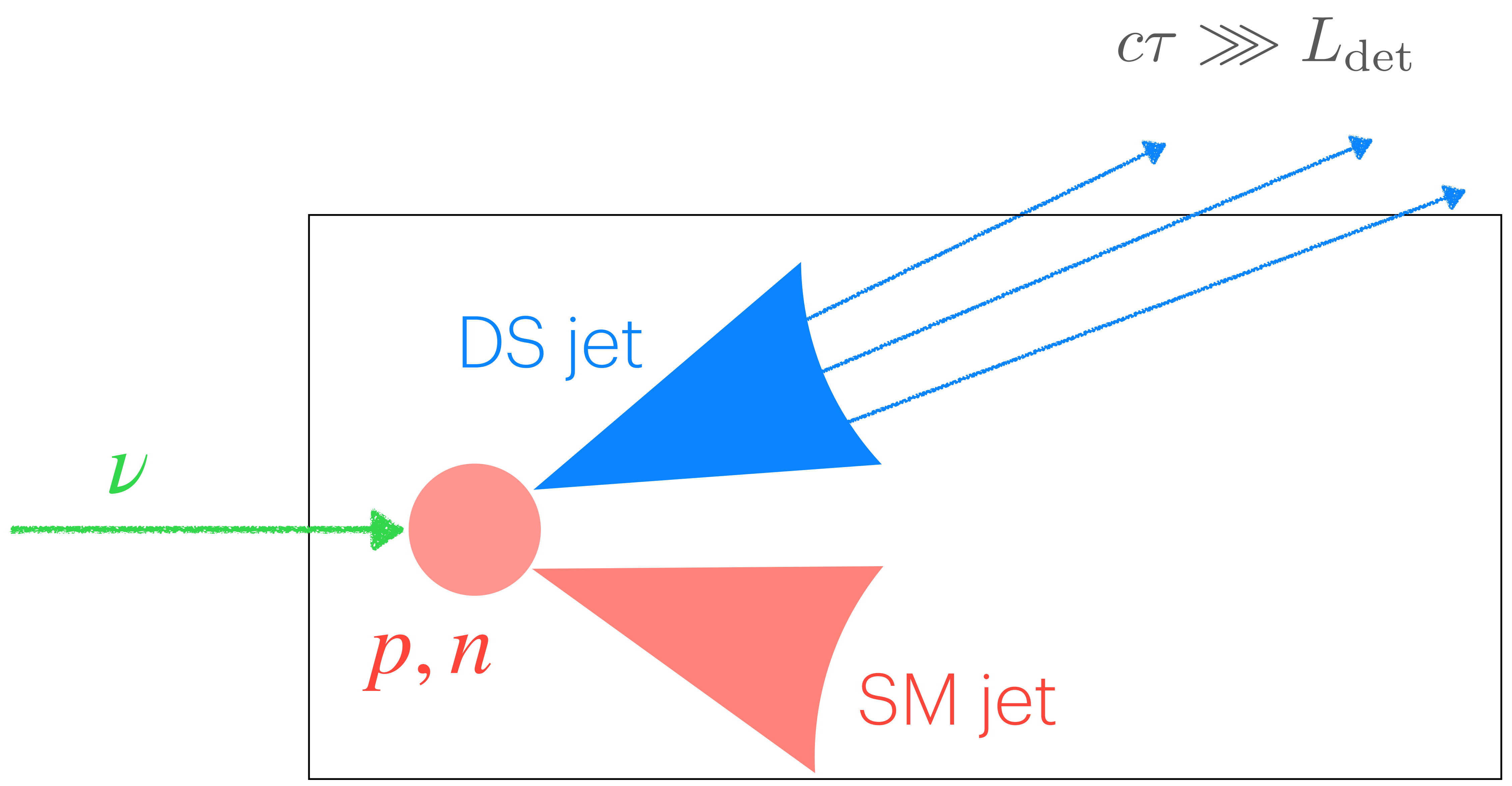
$c\tau \ggg L_{\rm det}$



Prefered higher energy experiment and scattering over nucleons

Invisible dark jets at neutrino beams





- $S_{\rm inv}$ is softer (slower SM jet) than B
- $S_{\rm inv}$ remains perturbative $Q^2_{\rm DS} > m_p^2$ where B is not

Challenges

- Is there any experimental observable to distinguish perturbative vs non perturbative SM hadronic jets?
- Monochromatic neutrino beams?

The magnetic dipole portal

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