Exploring neutrino compositeness

With invisible and displaced signals

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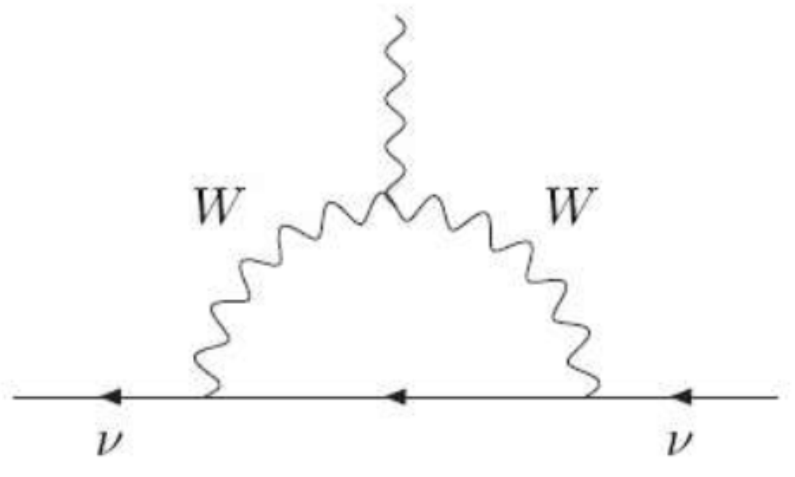
Motivation 1: neutrino structure

90. Searches for Quark and Lepton Compositeness

Neutrino Electromagnetic Properties

Giunti et al 2411.03122



Looking for non-dark structure

$$\mathcal{L}_{LL} = \frac{g^2_{\text{contact}}}{\Lambda^2} \sum_{i,j} \eta^{ij}_{LL} (\bar{q}^i_L \gamma_\mu q^i_L)(\bar{l}^j_L \gamma^\mu l^j_L),$$

$$\mathcal{L}_{RR} = \frac{g^2_{\text{contact}}}{\Lambda^2} \sum_{i,j} \eta^{ij}_{RR} (\bar{q}^i_R \gamma_\mu q^i_R)(\bar{l}^j_R \gamma^\mu l^j_R),$$

$$\mathcal{L}_{LR} = \frac{g^2_{\text{contact}}}{\Lambda^2} \sum_{i,j} \eta^{ij}_{LR} (\bar{q}^i_L \gamma_\mu q^i_L)(\bar{l}^j_R \gamma^\mu l^j_R),$$

$$\mathcal{L}_{RL} = \frac{g^2_{\text{contact}}}{\Lambda^2} \sum_{i,j} \eta^{ij}_{RL} (\bar{q}^i_R \gamma_\mu q^i_R)(\bar{l}^j_L \gamma^\mu l^j_L).$$

See for ex.
Peskin Eichten Lane PRL 1983
Falkowski et al. 2105.12136

$$\mathcal{L} = \frac{g^2_{\text{contact}}}{\Lambda^2} \left[\eta'_{LL} (\bar{\psi}_L \gamma_\mu \psi_L)(\bar{\psi}^*_L \gamma^\mu \psi^*_L) + \ldots\right.$$

Looking for heavy NP or heavy, single particle excitations

Motivation 2: neutrino masses

Standard Seesaw

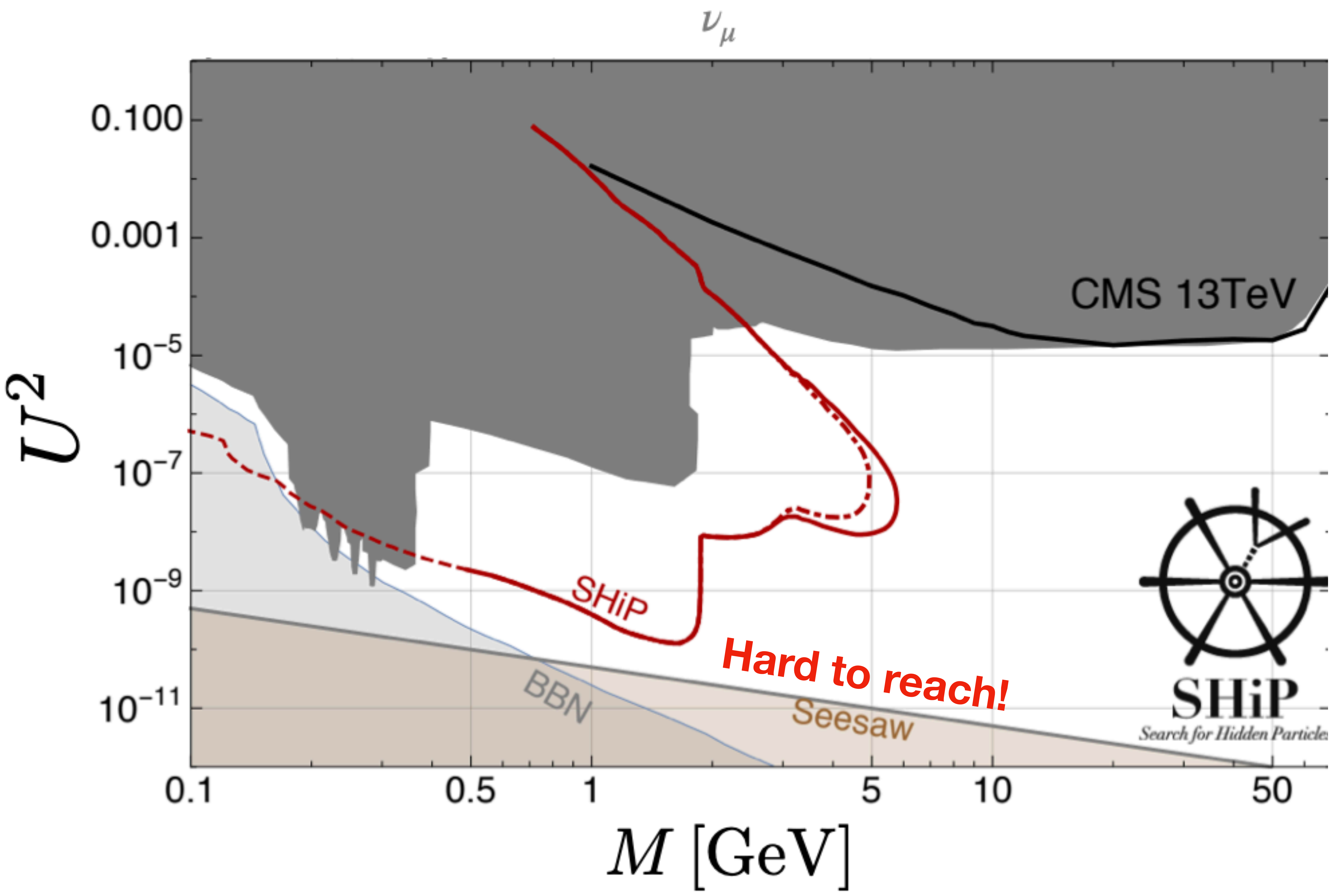
$$\mathscr{L} = y\bar{L}NH + \frac{1}{2}M\bar{N}^cN + \mathrm{h.c.}$$

N fermionic Majorana singlet

Active-Sterile mixing small!

$$|U|^2 \sim \left(\frac{yv}{M}\right)^2 \sim \frac{m_\nu}{M} \ll 1$$

Very hard to test phenomenologically!



SHIP collaboration[1811.00930v3]

Motivation 2: neutrino masses

Inverse Seesaw

Mohapatra and Valle, PRL 44, 912 (1980)

- Add N, S, fermion singlets

$$\mathscr{L} = y\bar{L}NH + M\bar{N}S + \frac{1}{2}\mu\bar{S}^c S + \mathrm{h.c.}$$

- Tiny breaking of $U(1)_L$
- Small mixing mass

$$\mu \ll yv \ll M$$

$$\mathscr{M} = \begin{pmatrix} 0 & yv & 0 \\ yv & 0 & M \\ 0 & M & \mu \end{pmatrix} \quad \begin{pmatrix} \nu \\ N \\ S \end{pmatrix}$$

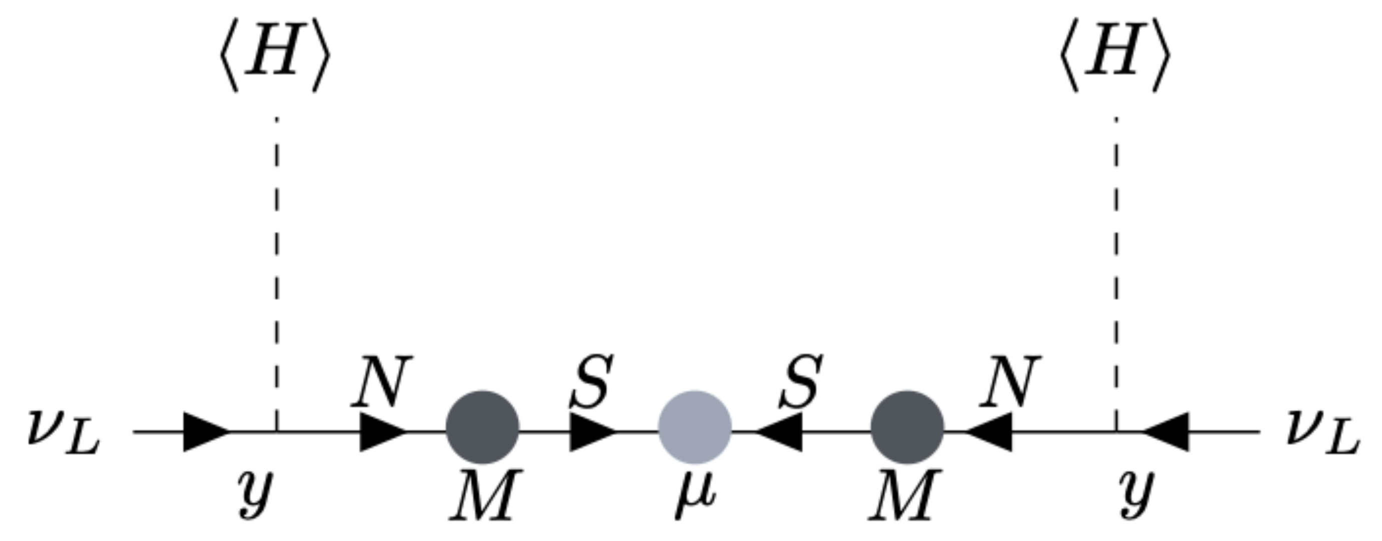
$\Downarrow$

Small neutrino mass…

$$m_\nu \sim \frac{y^2 v^2}{M^2}\mu$$

… but large mixing

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



How to generate the hierarchy?

Composite realization

Chacko Fox Harnik Liu 2012.01443

(Arkani-Hamed Grossman 9806223
Grossman Robinson 1009.2781)

Idea: generate hierarchy of scales from running of strongly coupled sector

$$O_N \sim N^3, N^5, N\Phi, \ldots$$

$[O_N] = \Delta$ Degree of compositeness: how many constituents

$\Lambda_{\rm UV}$ Cutoff: mediator size (~mutual interaction size)

$\Lambda_{\rm IR}$ Mass gap: size of compositeness

(y, c_O) (Coupling & dofs, degenerate with $\Lambda_{\rm UV}$)

$$\frac{O_{2N}}{\Lambda_{\rm UV}^{4-\Delta_{2N}}} \qquad \frac{y}{\Lambda_{\rm UV}^{\Delta-3/2}} LHO_N$$

"Dark quarks"
"Dark gluons"
$O_N \sim N^3$

$\Lambda_{\rm UV}$
$\gtrsim 10^3\,{\rm GeV}$

$$y\left(\frac{\Lambda_{\rm IR}}{\Lambda_{\rm UV}}\right)^{\Delta-3/2} \bar{L}H\psi + \ldots$$

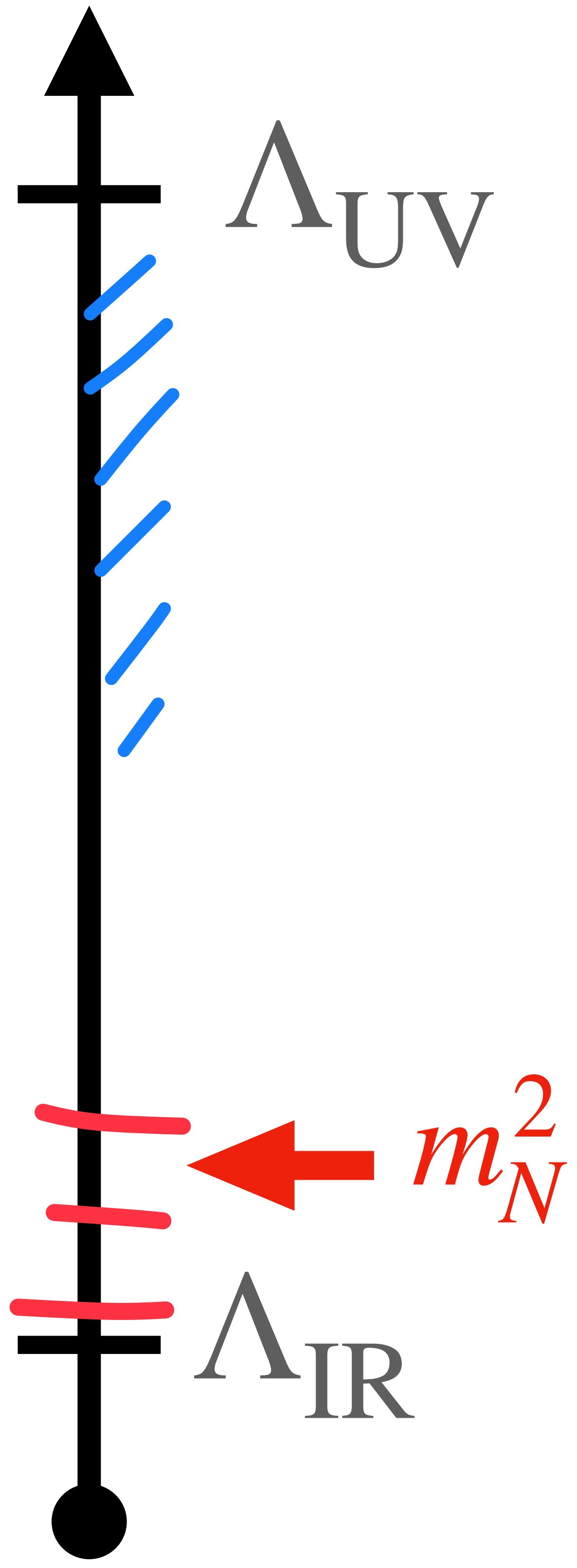
"Dark hadrons"
$O_N \sim \psi$

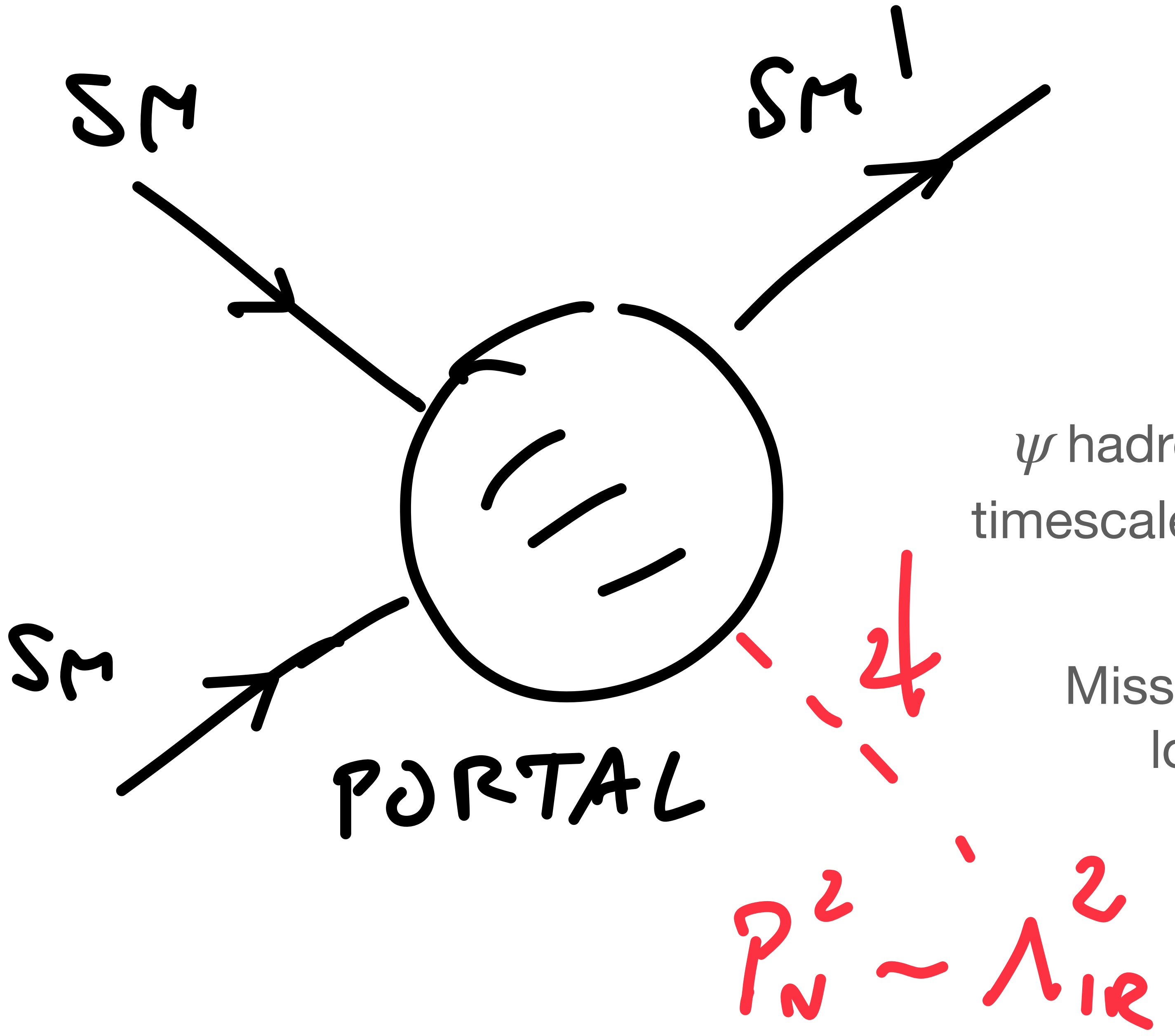
$\Lambda_{\rm IR}$
$\lesssim {\rm GeV}$

Typical production process

Contino Max Mishra 2012.08537

Arbitrary mass shell!
Integrate over all possible values of m_N^2 → **How are the events weighted in m_N^2?**



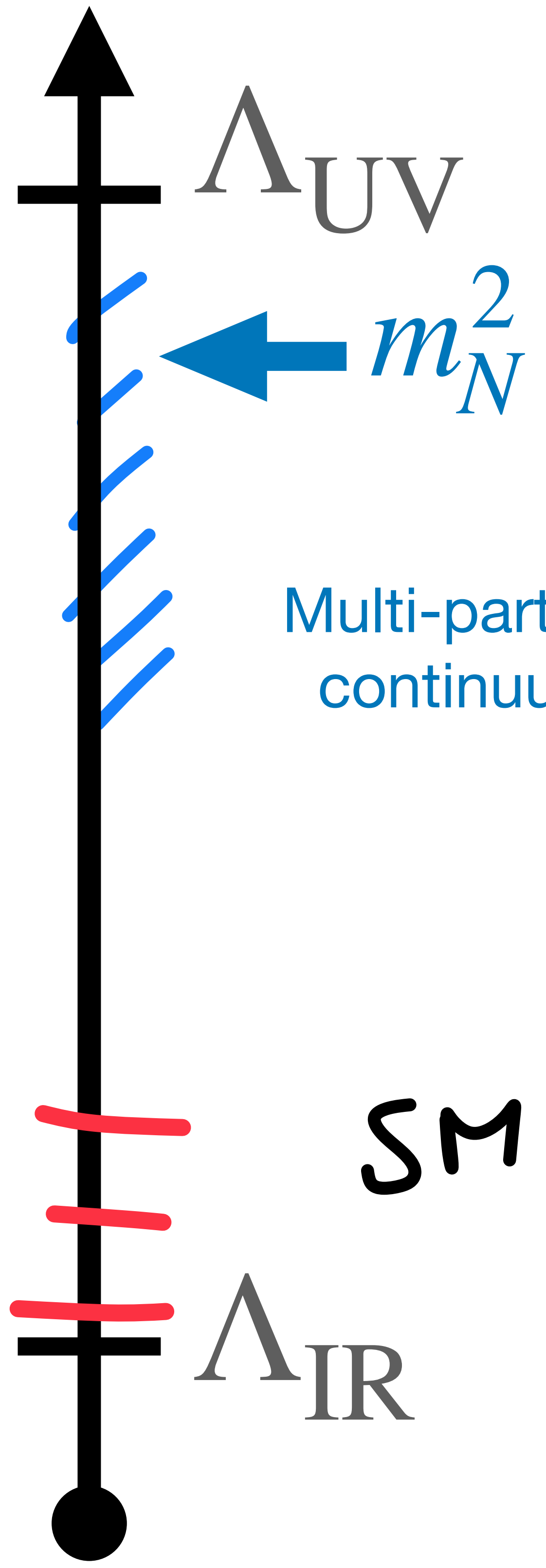


ψ hadronize on timescales ~$1/\Lambda_{\rm IR}$

Missing energy if long lived

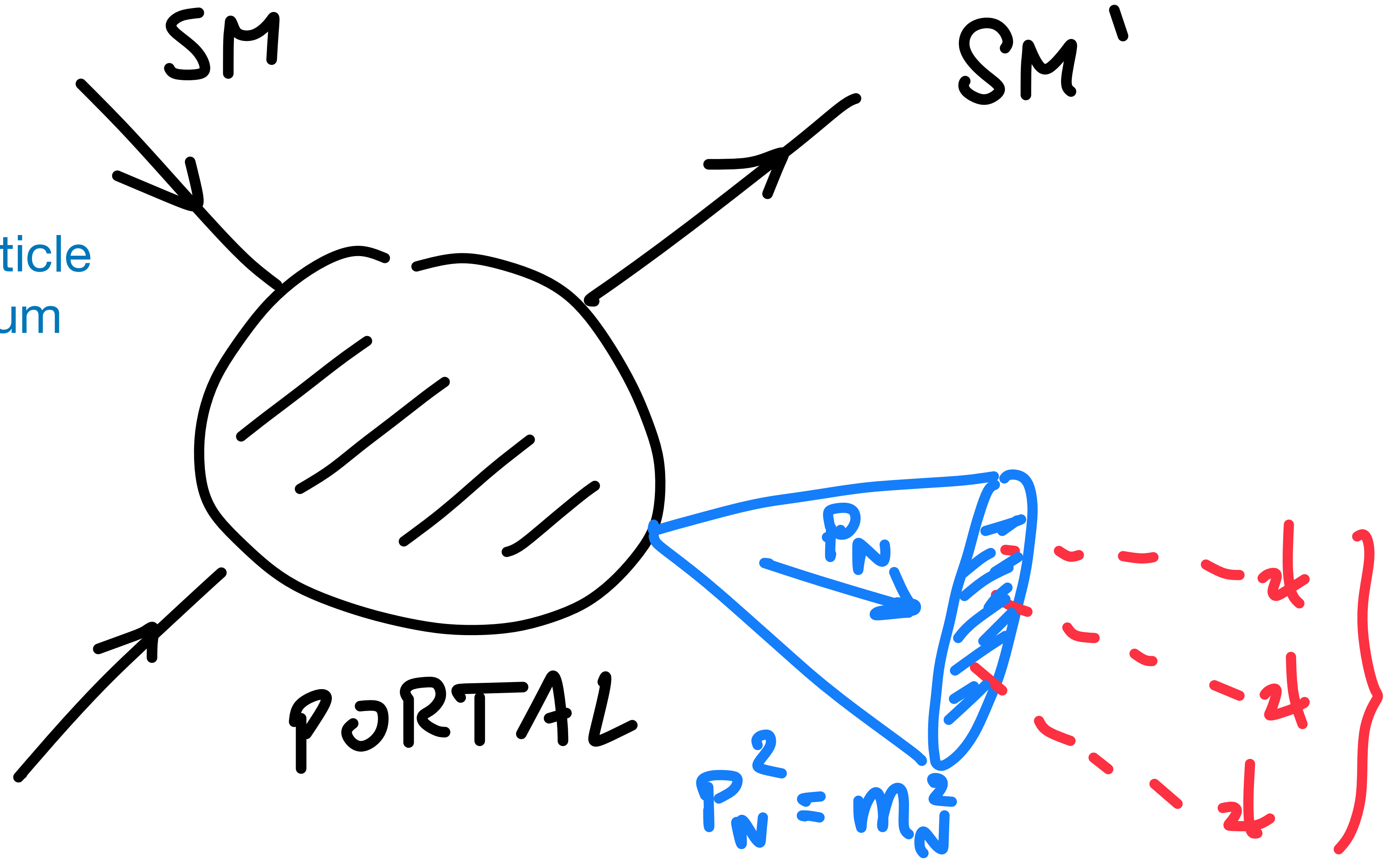
$$c\tau_\psi\Big|_{5/2} \approx y_\ell^2 \left(\frac{1.5\ \mathrm{GeV}}{\Lambda_{\rm IR}}\right)^5 \left(\frac{\Lambda_{\rm UV}}{10\ \mathrm{TeV}}\right)^2 \ \mathrm{m}$$

Resonant structure



Multi-particle continuum

"Conformal regime": Insensitive to resonance structure!

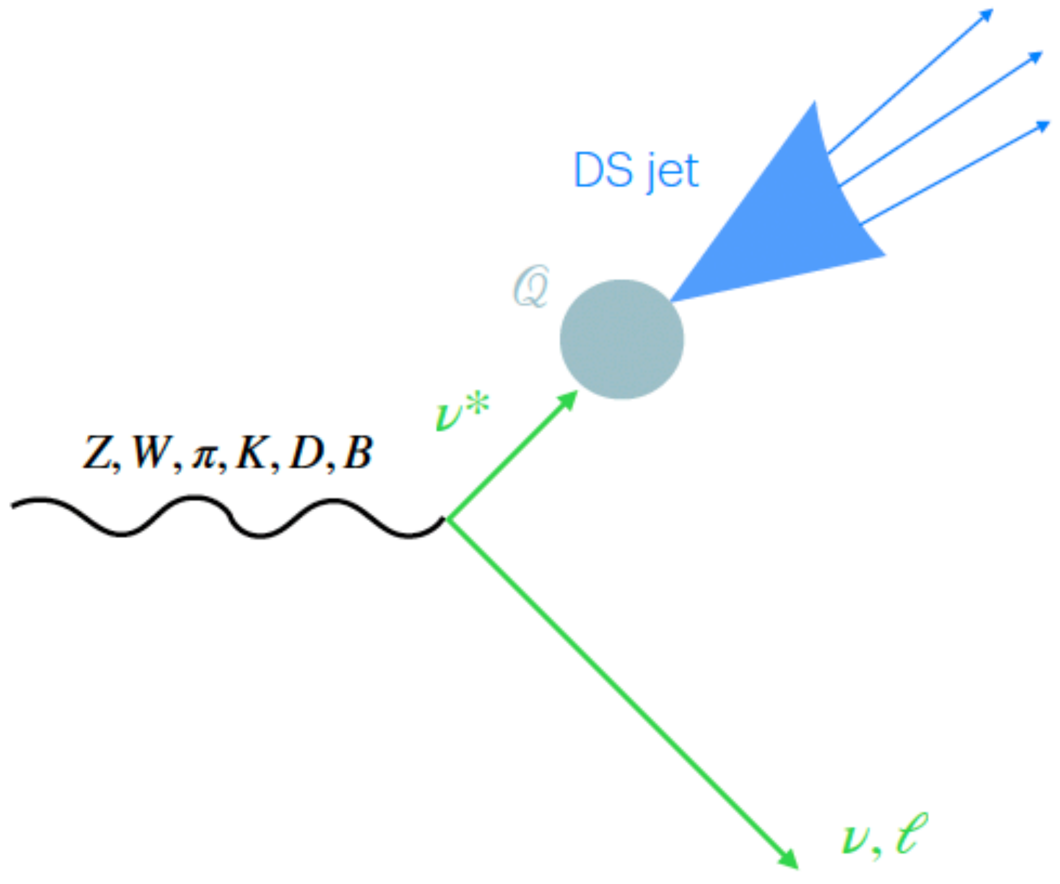


$$\frac{\mathrm{d}\sigma}{\mathrm{d}p_N^2} \propto \left(\frac{p_N^2}{s}\right)^\alpha$$

Invisible signatures

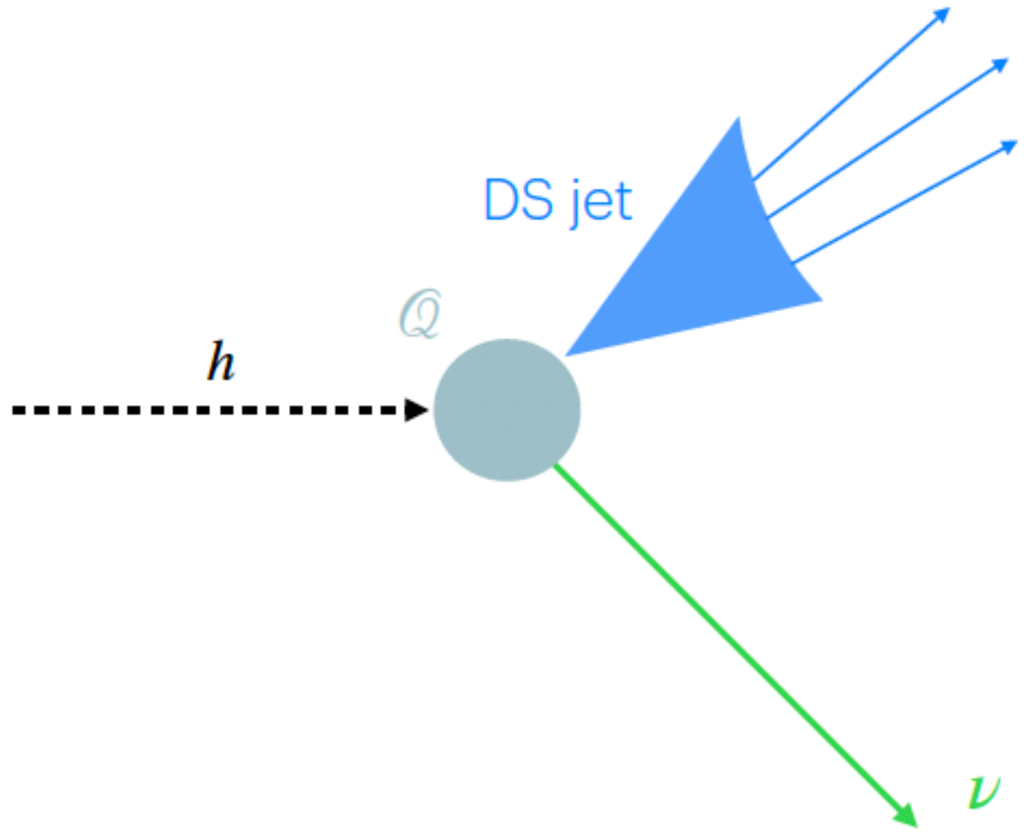
Inclusive production

Higgs, EW boson and meson invisible BR



$$\frac{\mathrm{d}\Gamma_X}{\mathrm{d}p_D^2} = \frac{A_N y_\ell^2 \Gamma_{\mathrm{SM,b}}}{4\pi p_D^2}\left(\frac{v^2}{p_D^2}\right)\left(\frac{p_D^2}{\Lambda_{\mathrm{UV}}^2}\right)^{\Delta_N - 3/2}$$

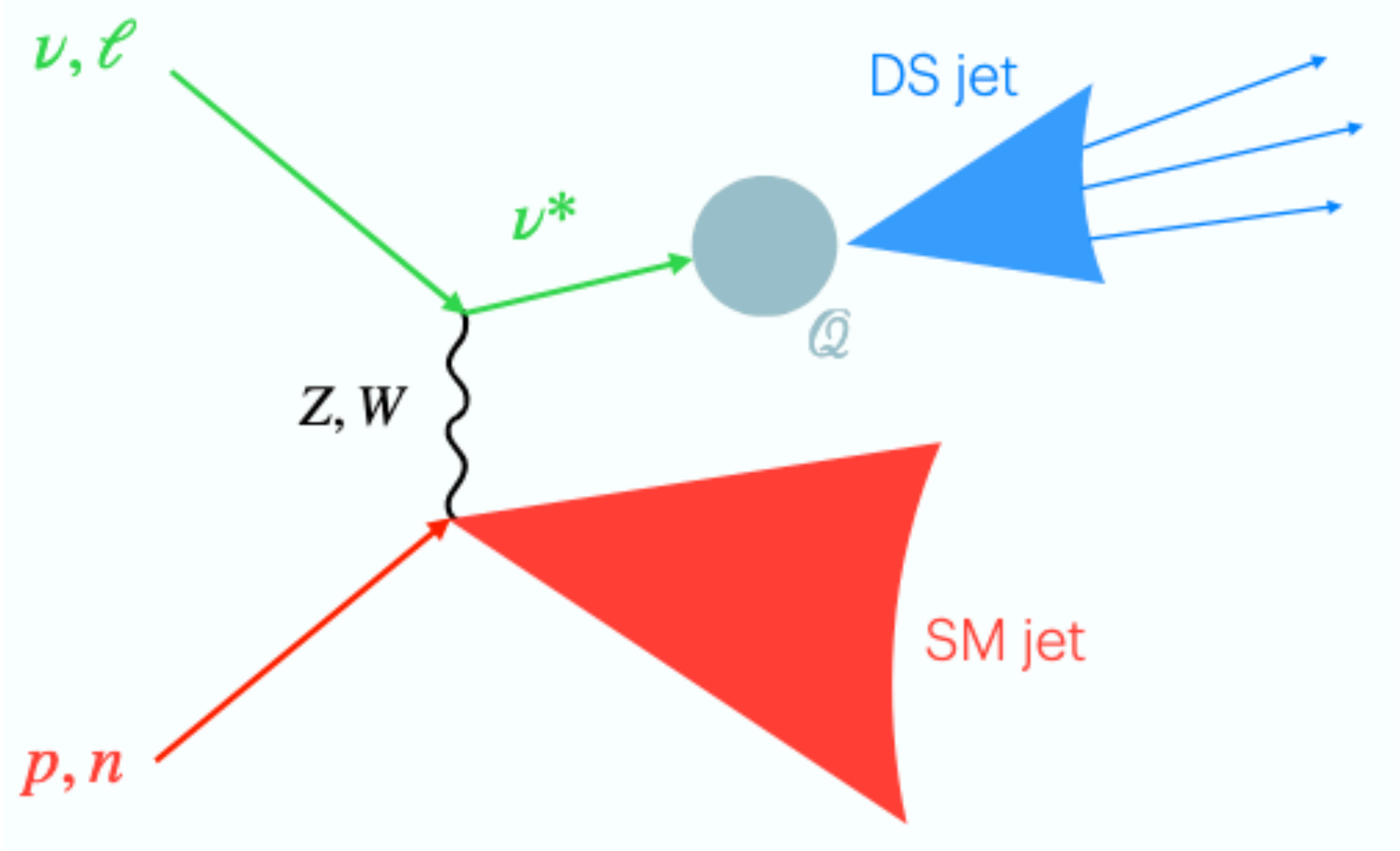
$$\frac{\mathrm{d}\Gamma_h}{\mathrm{d}p_D^2} = \frac{A_N y_\ell^2}{6 y_b^2}\frac{\Gamma_{\mathrm{SM,h}}}{4\pi p_D^2}\left(\frac{p_D^2}{\Lambda_{\mathrm{UV}}^2}\right)^{\Delta_N - 3/2}$$



$\mathcal{O}(1)$ UV coupling: Higgs to inv. potentially sensitive probe!

Bernal Deka Losada
2311.18033

Disintegration onto nuclei

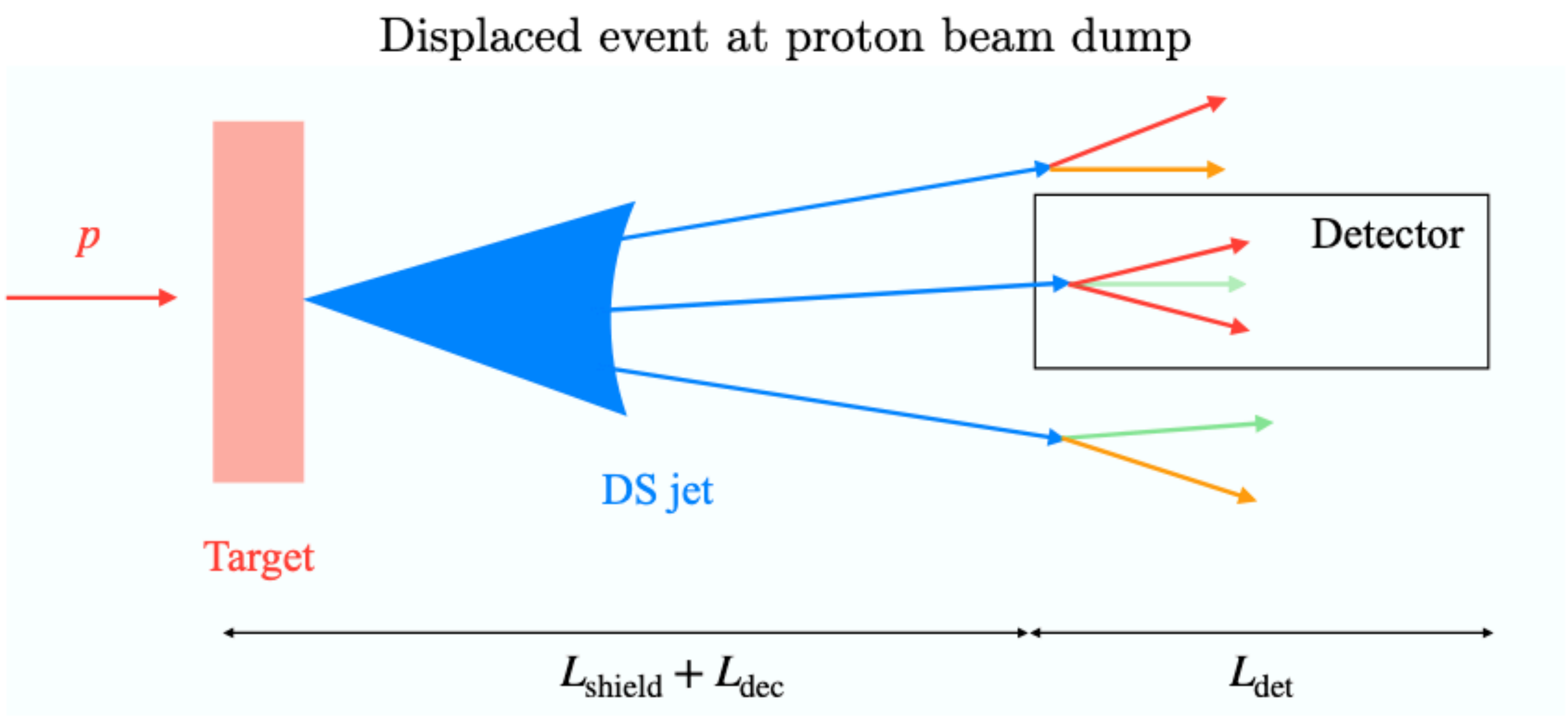


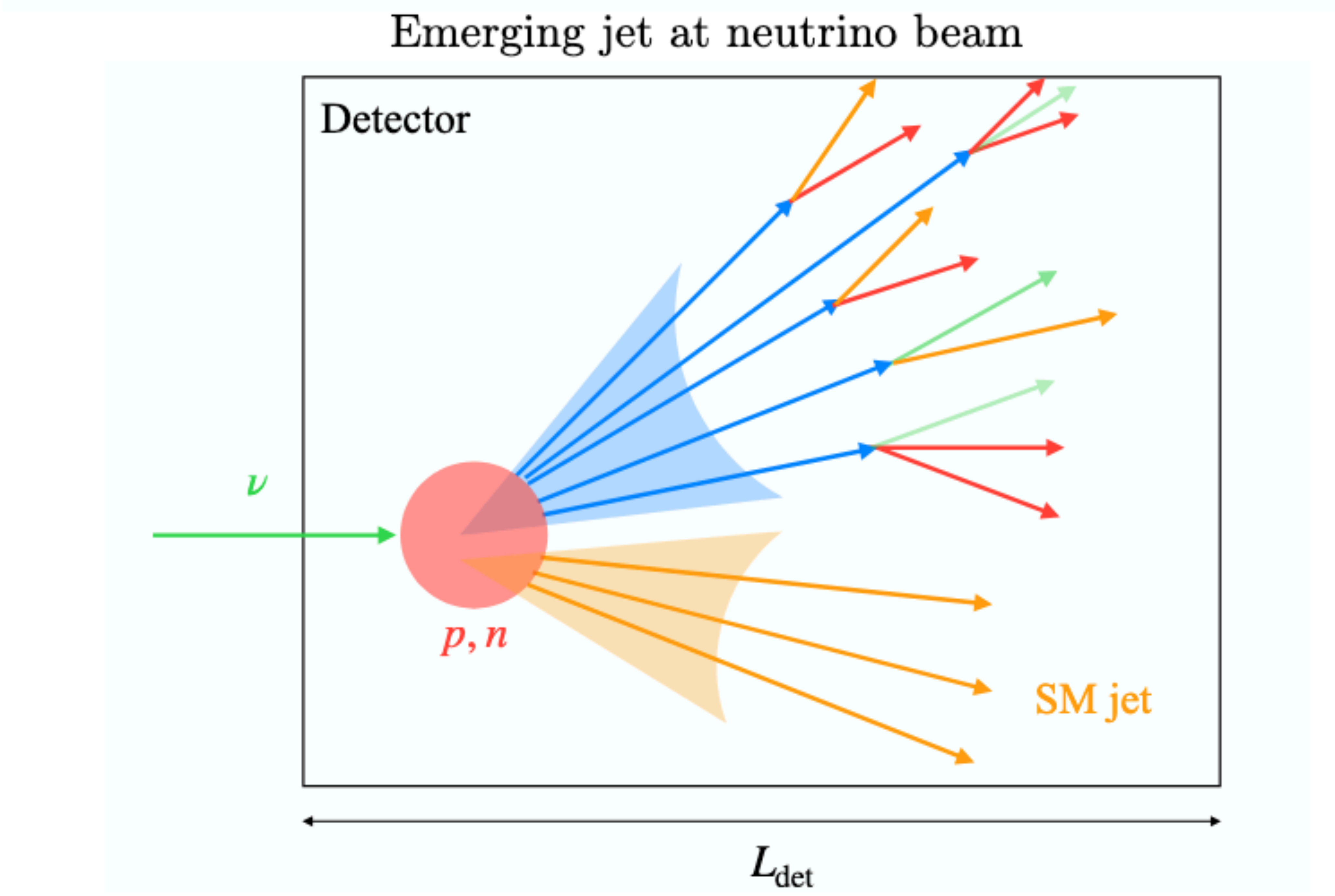
$$\frac{\mathrm{BSM\,NC's}}{\mathrm{CC's}} \sim \frac{\bar{s}\, v^2}{\Lambda_{\mathrm{UV}}^4}\left(\frac{\bar{s}}{\Lambda_{\mathrm{UV}}^2}\right)^{\Delta_N - \frac{7}{2}}$$

$$\frac{\mathrm{d}\sigma_{\mathrm{2DIS}}}{\mathrm{d}p_D^2} = \frac{A_N y_\ell^2 \sigma_{\mathrm{EW}}}{4\pi p_D^2}\left(\frac{v^2}{p_D^2}\right)\left(\frac{p_D^2}{\Lambda_{\mathrm{UV}}^2}\right)^{\Delta_N - 3/2}\mathcal{F}(p_D^2/s)$$

Visible signatures

Opportunity for beam dumps and neutrino experiments





$$S_{B\to \mathrm{vis}} = N_B \times \mathrm{Br}(B \to \mathcal{O}_N) \times P_{\rm dec}$$

$$S_{\rm displaced} \approx \left[B_{\rm NC}\, V_{\psi\nu}^2\, L_{\rm det}\, \Gamma_\psi\right] \times \left[\left(\frac{A_N m_p}{4\pi\Lambda_{\rm IR}}\right)\left(\frac{s}{\Lambda_{\rm IR}^2}\right)^{\Delta_N - 5/2} \tilde{\mathcal{F}}_{\Delta_N}(\Lambda_{\rm IR}^2, s)\right]$$

Collider version of this: displaced vertices

See also Jodlowski Trojanowski 2011.04751

Generic expectations

Before delving into mixing portal bounds…

- SN bounds: $\Lambda_{\rm IR} \gtrsim \mathcal{O}(100)\,\mathrm{MeV}$ Carenza et al. 2311.0003
- $\frac{1}{\Lambda_{\rm UV}^2}(HL)^\dagger \sigma^\mu \partial_\mu (HL) \to \frac{v^2}{\Lambda_{\rm UV}^2}\bar{\nu}\sigma^\mu\partial_\mu \nu \to \Lambda_{\rm UV} \gtrsim 10\,\mathrm{TeV}$, independent on Δ_N Antusch et al. 0607020 Blennow et al. 2306.01040, And others
- Other dark operators: $\frac{1}{\Lambda_{\rm UV}^{\Delta_S-2}} H^\dagger H O_S$: avoidable if $\Delta_S \gg \Delta_N$ (holography, chiral models,…)
- Other fermionic portals: $\frac{y}{\Lambda_{\rm UV}^{\Delta_N+1/2}} B_{\mu\nu} HL\sigma^{\mu\nu} O_N, \ \frac{1}{\Lambda_{\rm UV}^{\Delta_N+1/2}}(\bar{Q}u)(\bar{O}_N L).$ Higher dim. portals

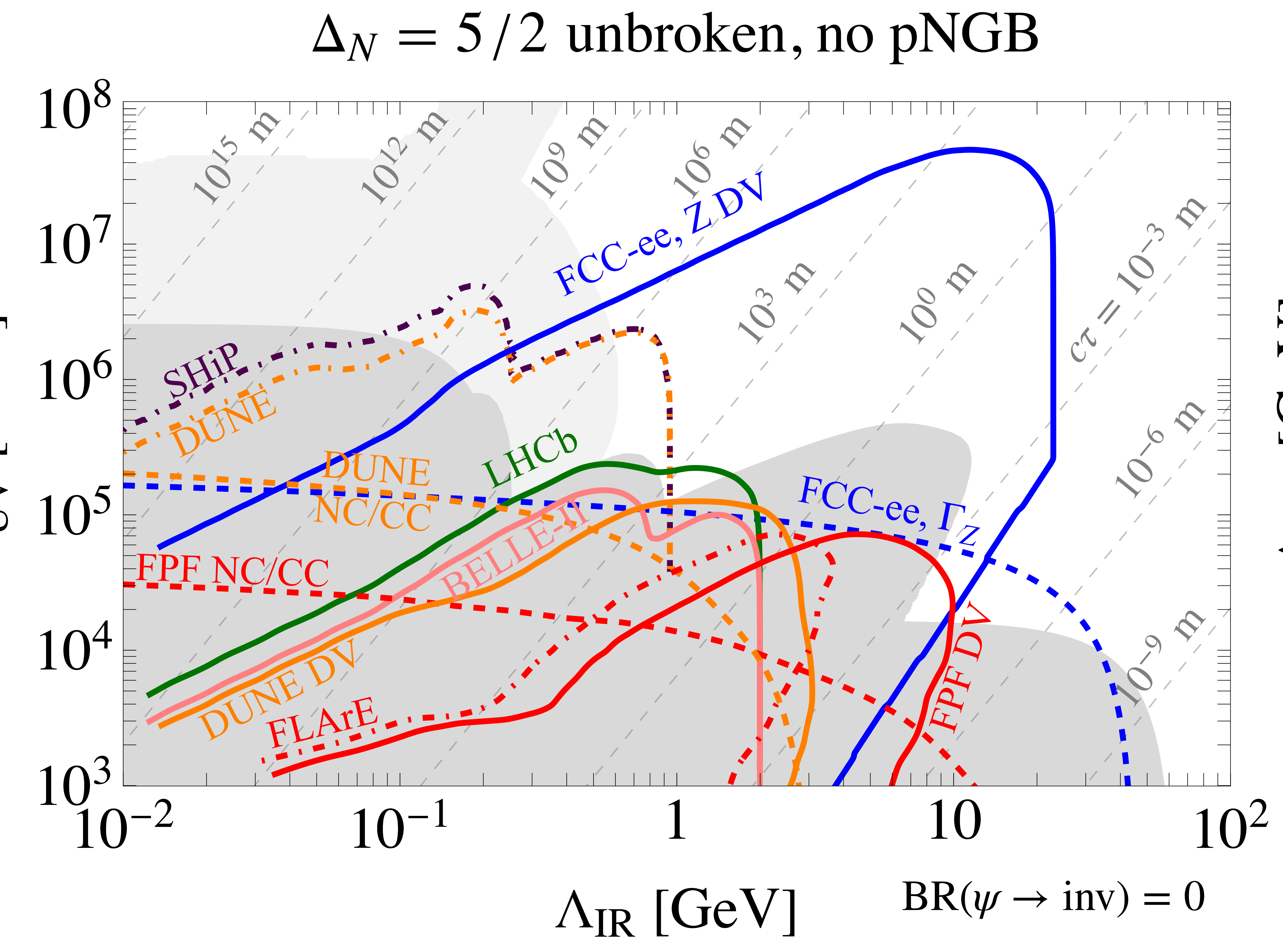
Results: vanilla scenario

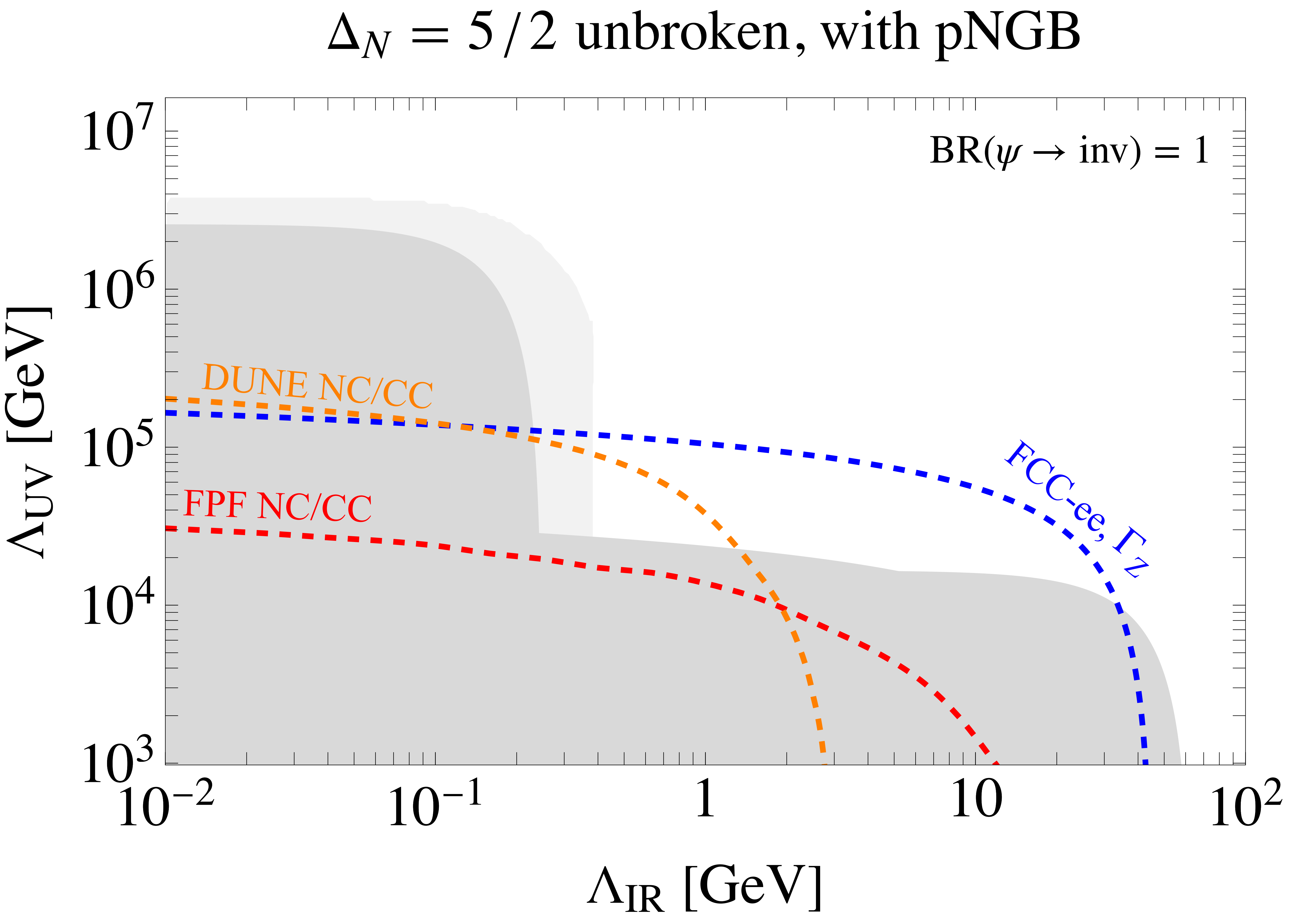
Projections

Visibile decay (prod. @ detector)

Visibile decay (prod. @ target)

Invisible signal





Conclusions

- Alternative m_ν generation mechanisms have large mixing with sterile sector
- (Even without a mass generation story, compositeness is a fundamental property of a particle, and should be tested)
- Simple DS parametrisation: $\Delta_N, \Lambda_{\rm IR}, \Lambda_{\rm UV}$
- Visible signature leading constraints: DS production at target or detector, ψ displaced decay. $\Lambda_{\rm UV} > 100$ TeV for $\Delta_N = 5/2$
- Invisible signatures can constrain $\mathrm{BR}(\psi \to \mathrm{inv}) = 1$: Higgs ,Z decays, NC/CC ratio.
- Lots of upcoming experiments!

Thanks for the attention!

Backup

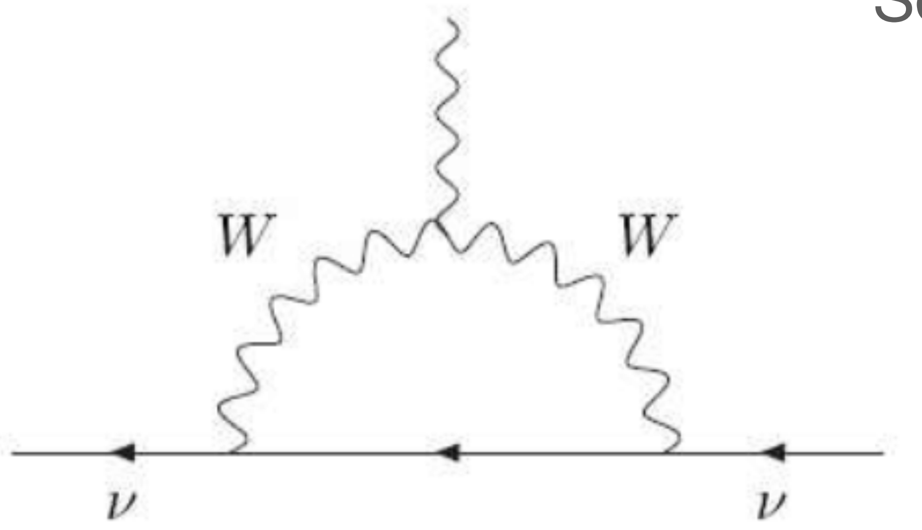
Modeling neutrino structure

See Giunti et al. 2411.03122

- Electromagnetic form factors

$d_\mu \bar{\nu} \sigma_{\mu\nu} \nu F^{\mu\nu}$

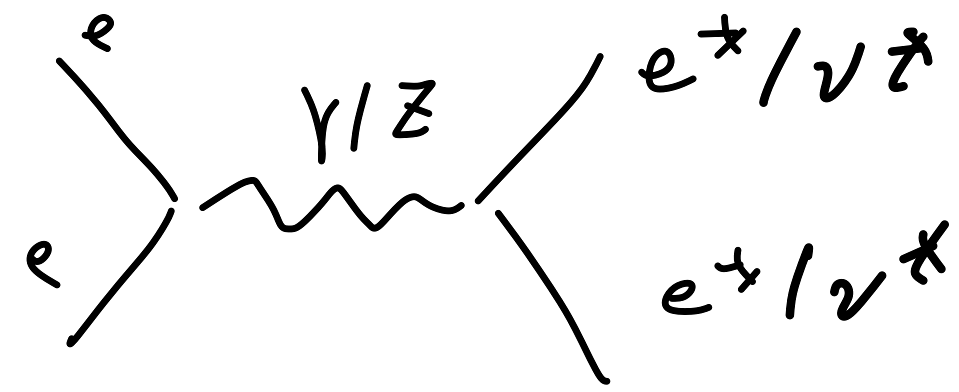
$r_\nu^2 \bar{\nu} \gamma^\mu \nu \partial_\mu F^{\mu\nu}$



$\mu_\nu \lesssim 10^{-24}\,\mathrm{cm}$

$r_\nu \lesssim 10^{-16}\,\mathrm{cm}$

- Excited states via EW process + decay



Peskin Eichten Lane PRL 1983

ATLAS: $\Lambda \lesssim 1.6\,\mathrm{TeV}$

- 4 fermions operator (SM interference)
  - $SU(2)_L$ compositeness

$\frac{1}{\Lambda_{\mathrm{UV}}^2} llll$ LEP: $\Lambda \lesssim 10\,\mathrm{TeV}$

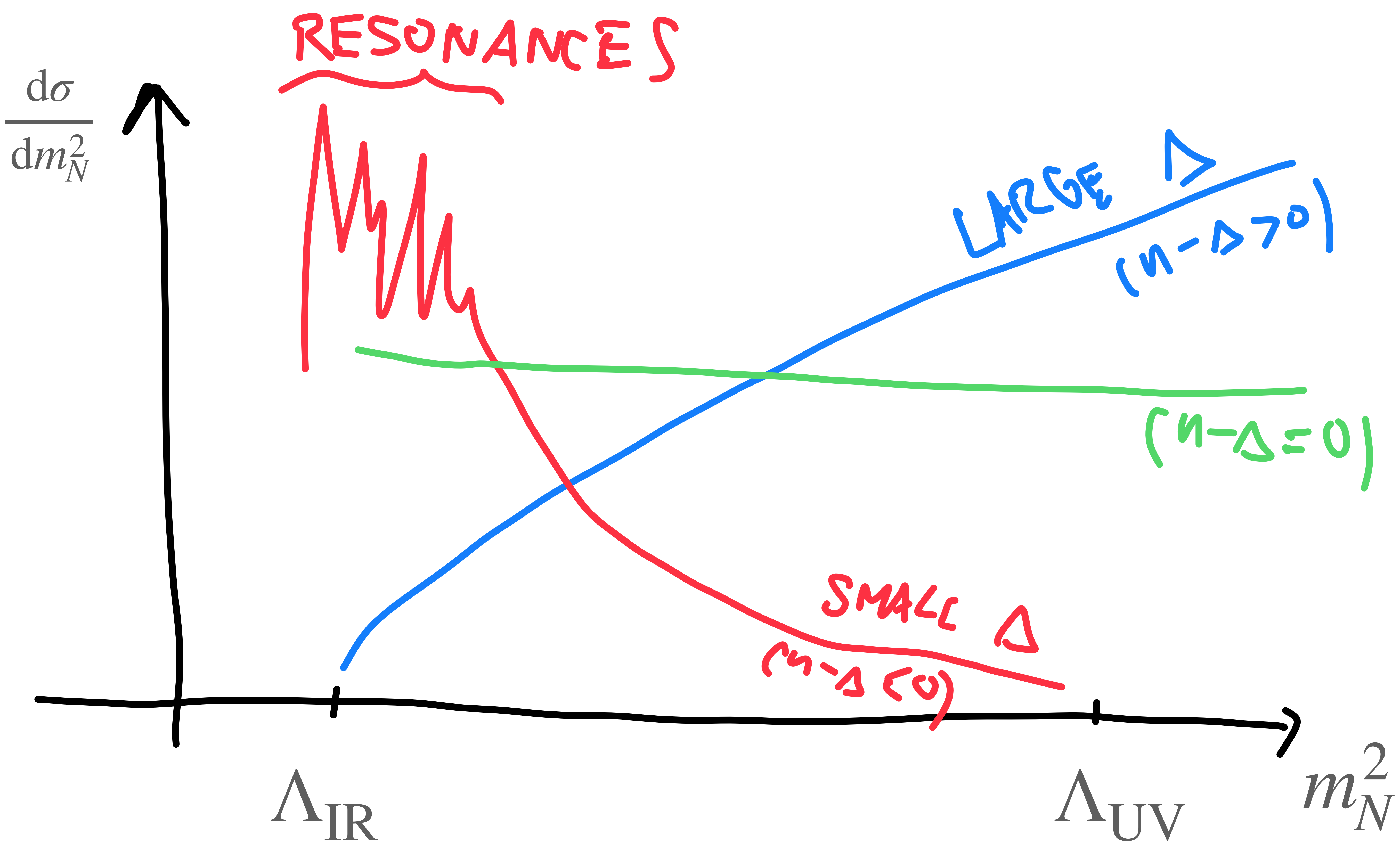
  - Neutrino Non-Standard Interactions

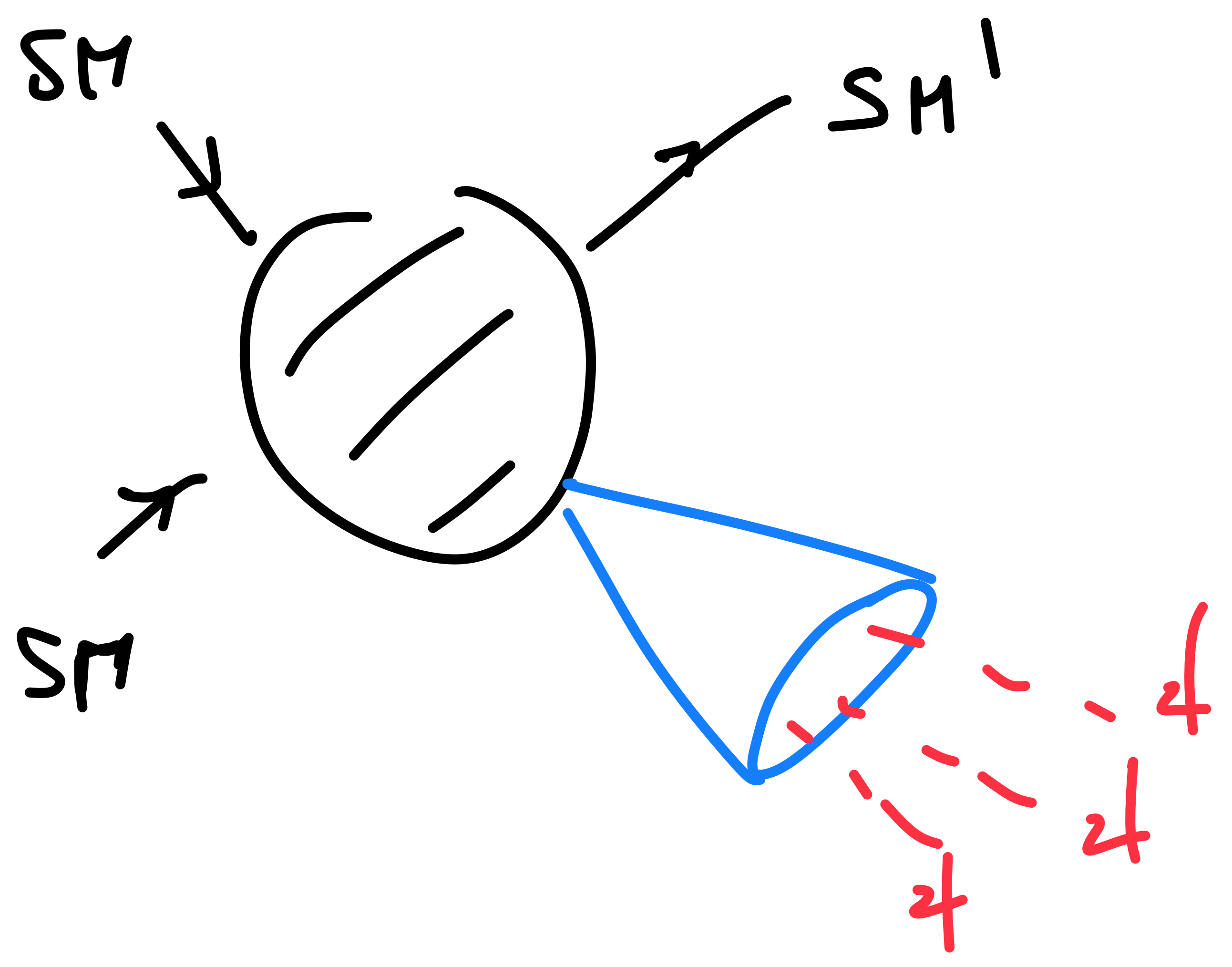
$\frac{1}{\Lambda_{\mathrm{UV}}^2}(\bar{\nu}\nu)(\bar{q}q)$ $\frac{1}{\Lambda_{\mathrm{UV}}^2}(\bar{\nu}l)(\bar{q}q')$ CCFR: $\Lambda \lesssim 5\,\mathrm{TeV}$

  - “Partial compositeness”

$$\frac{1}{\Lambda_{\mathrm{UV}}^2}\nu O_N \sim \frac{1}{\Lambda_{\mathrm{UV}}^2}\nu N^3 \to m_{\mathrm{mix}}\nu\psi$$

Production regimes





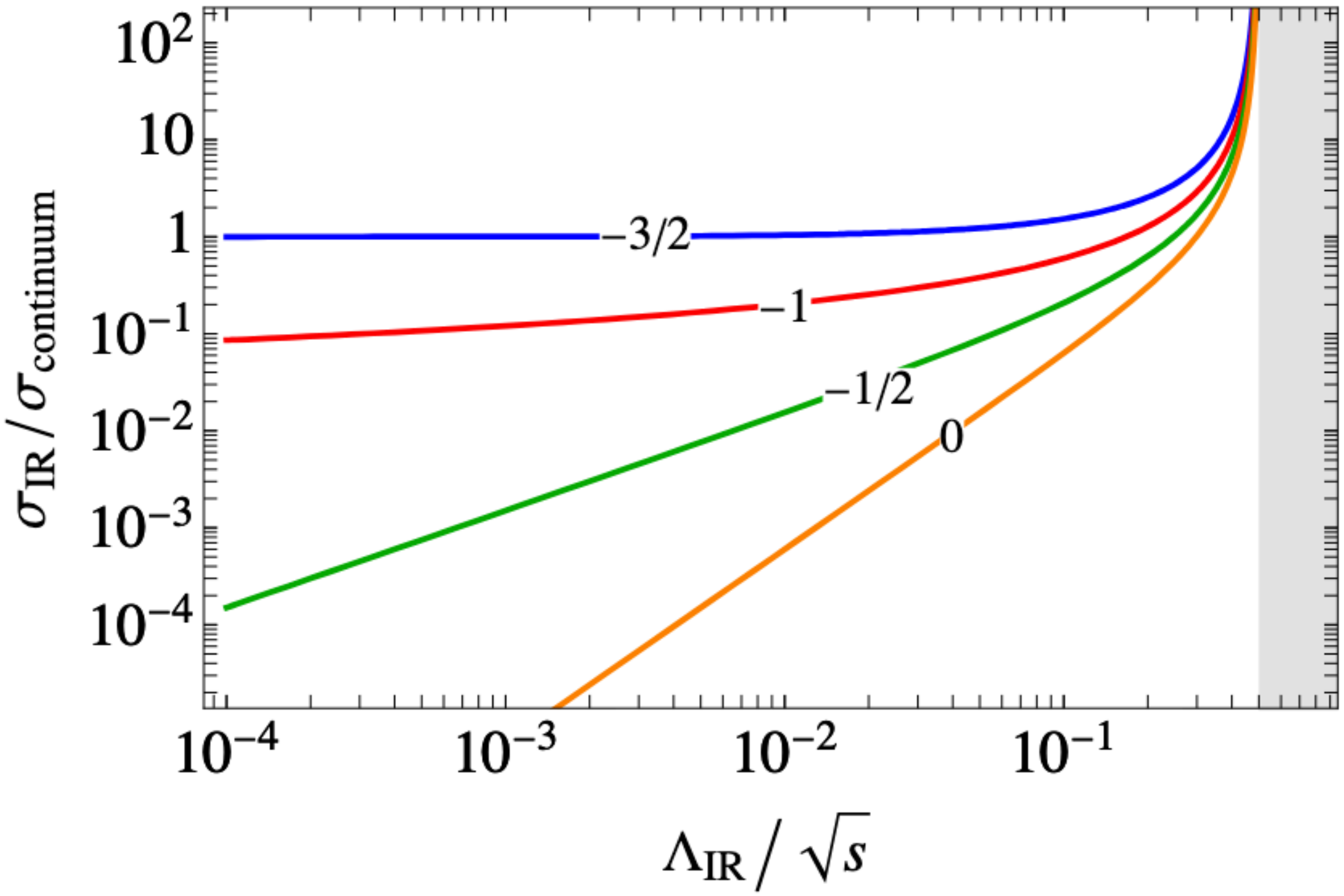
$$\tau_\psi \sim 10^{-10+4\Delta}\text{km}\left(\frac{10\,\text{MeV}}{\Lambda_{\rm IR}}\right)^{2\Delta}\left(\frac{\Lambda_{\rm UV}}{1\,\text{GeV}}\right)^{2\Delta-3}$$

Δ dictates which regime has more weighted in total σ

$$\frac{d\sigma}{dm_N^2} \propto \left(\frac{m_N^2}{\Lambda_{\rm UV}^2}\right)^{\Delta-n} \rightarrow \sigma \propto \left(\frac{m_N^2}{\Lambda_{\rm UV}^2}\right)^{\Delta-n+1}$$

Δ dictates lifetime of lightest resonance

UV dependency



$$\frac{d\sigma}{dp_D^2} \propto \left(\frac{p_D^2}{s}\right)^{\alpha} \left(1 - \frac{p_D^2}{s}\right)^2$$

DIS systematics

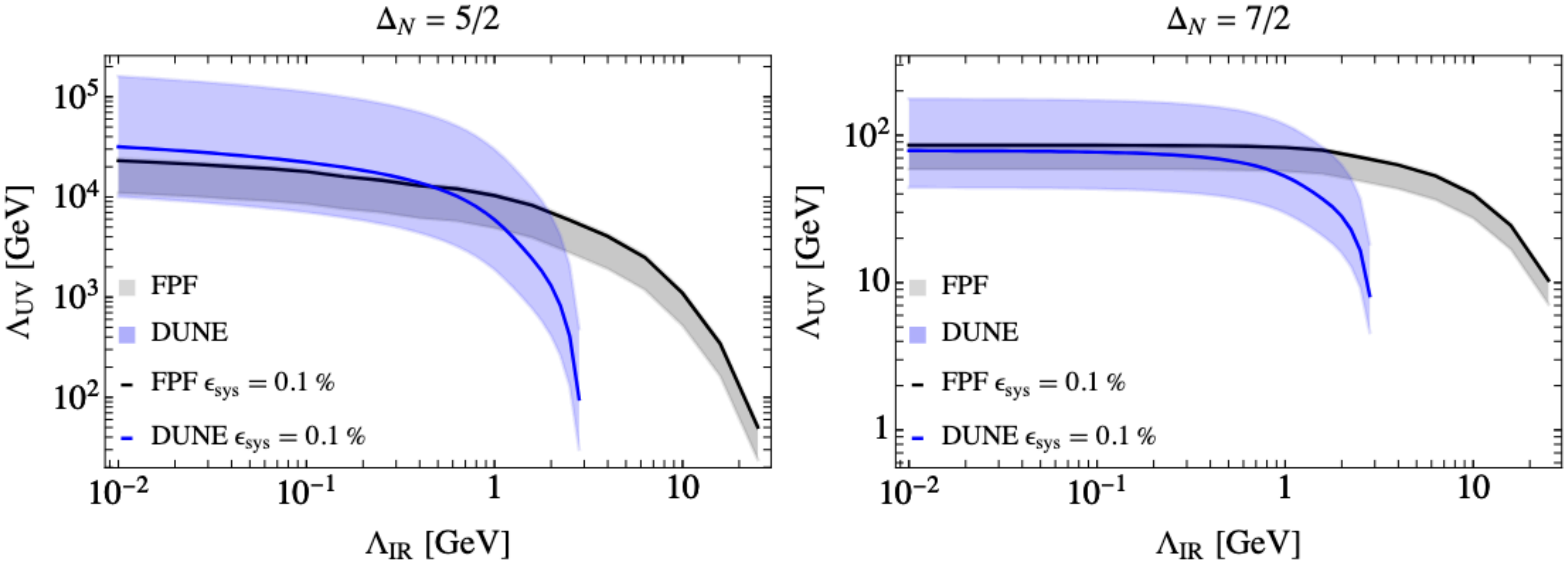
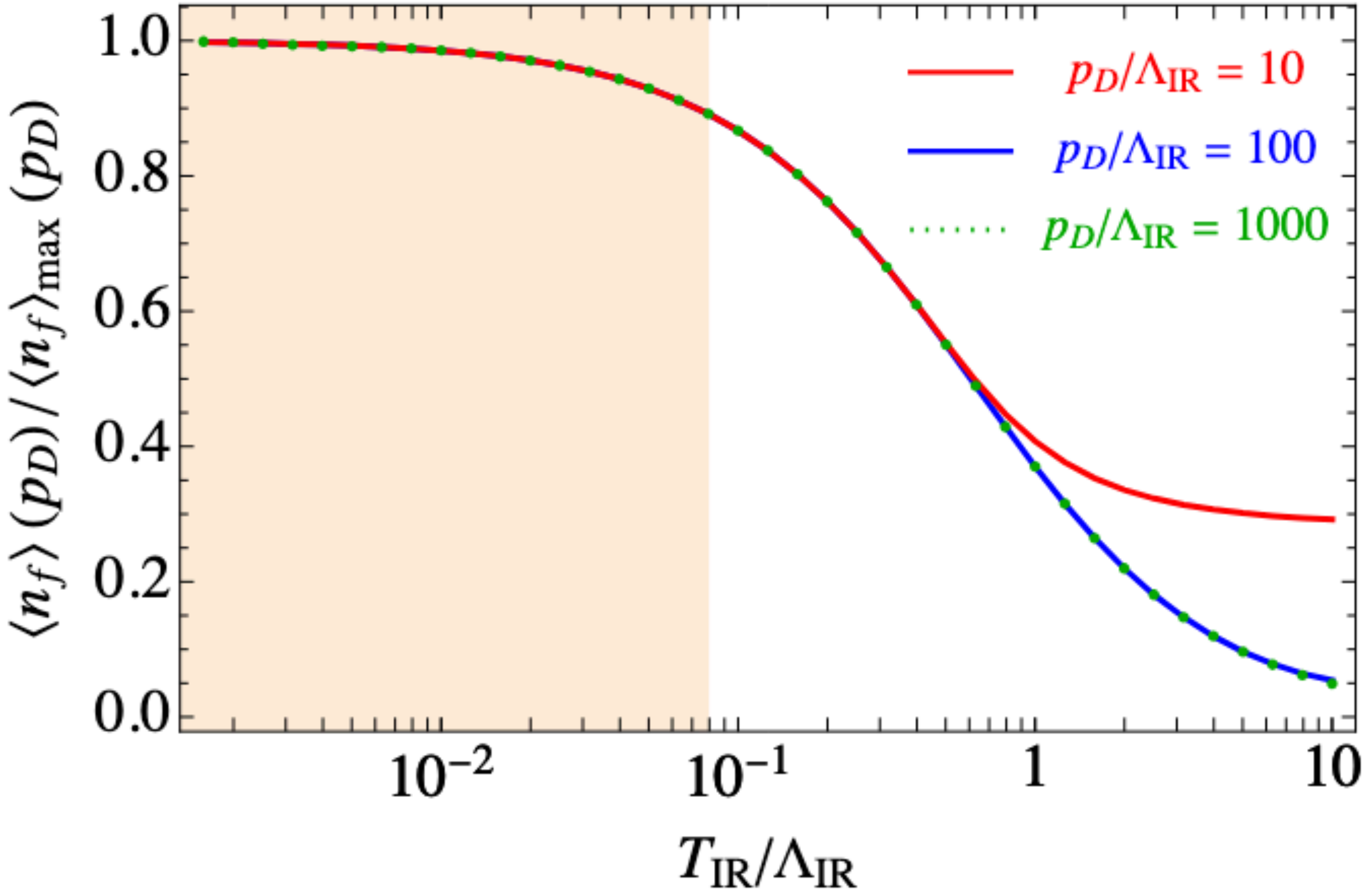


Figure 10: Effect of systematics uncertainties at DUNE (**blue**) and FPF (**black**). The colored region covers parameter space as ϵ_{sys} ranges from 0 to 0.01. Solid lines represent the level of systematic uncertainties obtained at NuTeV [18].

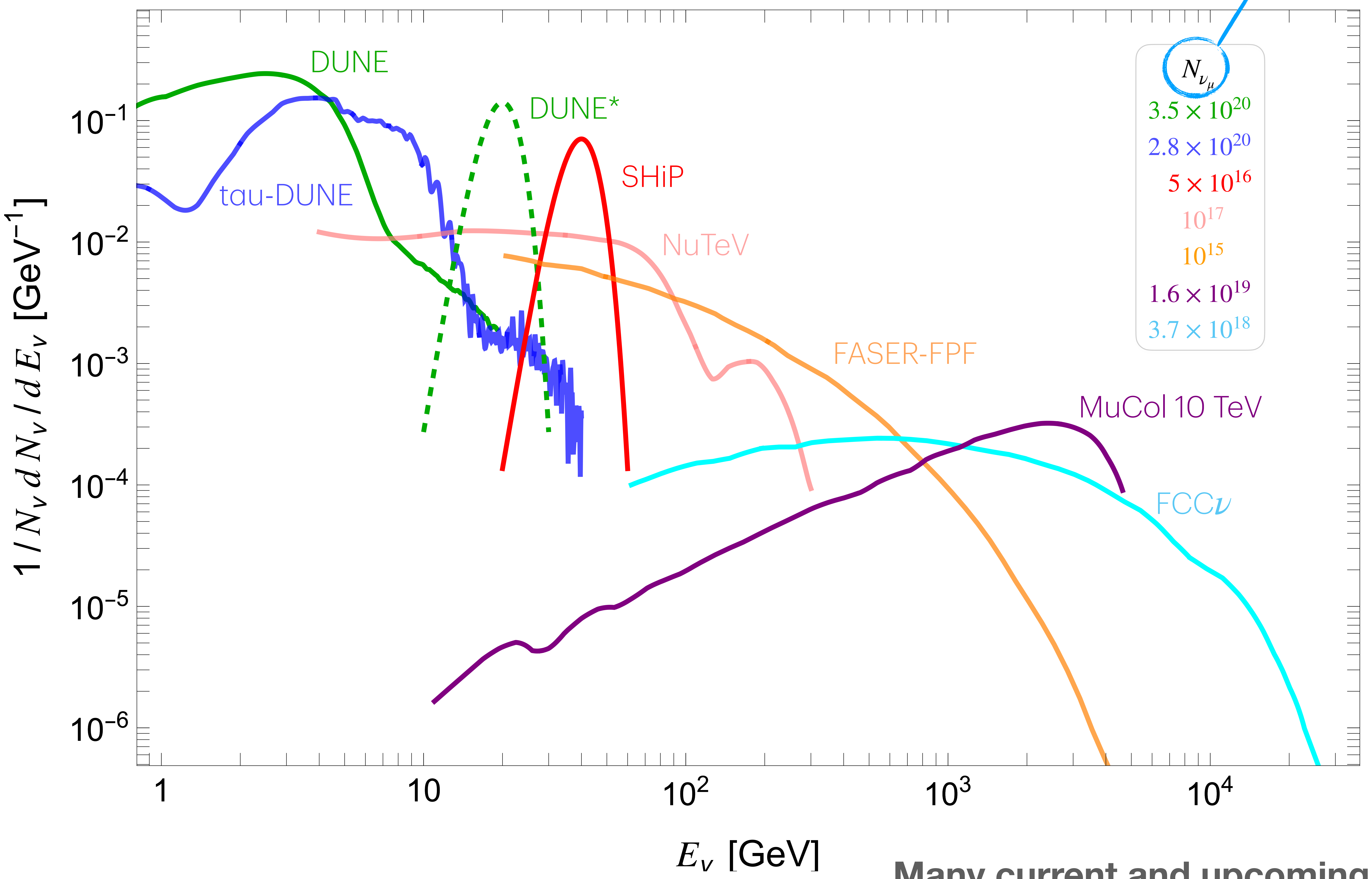
Number of fragments

$$\langle n_f(p_D^2)\rangle = \frac{1}{\mathcal{N}}\int_0^{\sqrt{p_D^2/4-\Lambda_{\rm IR}^2}} \frac{p_D}{\sqrt{\Lambda_{\rm IR}^2+\mathbf{p}^2}} \exp\left[-\frac{\sqrt{\Lambda_{\rm IR}^2+\mathbf{p}^2}}{T_{\rm IR}}\right]\mathbf{p}^2\,\mathrm{d}|\mathbf{p}|$$

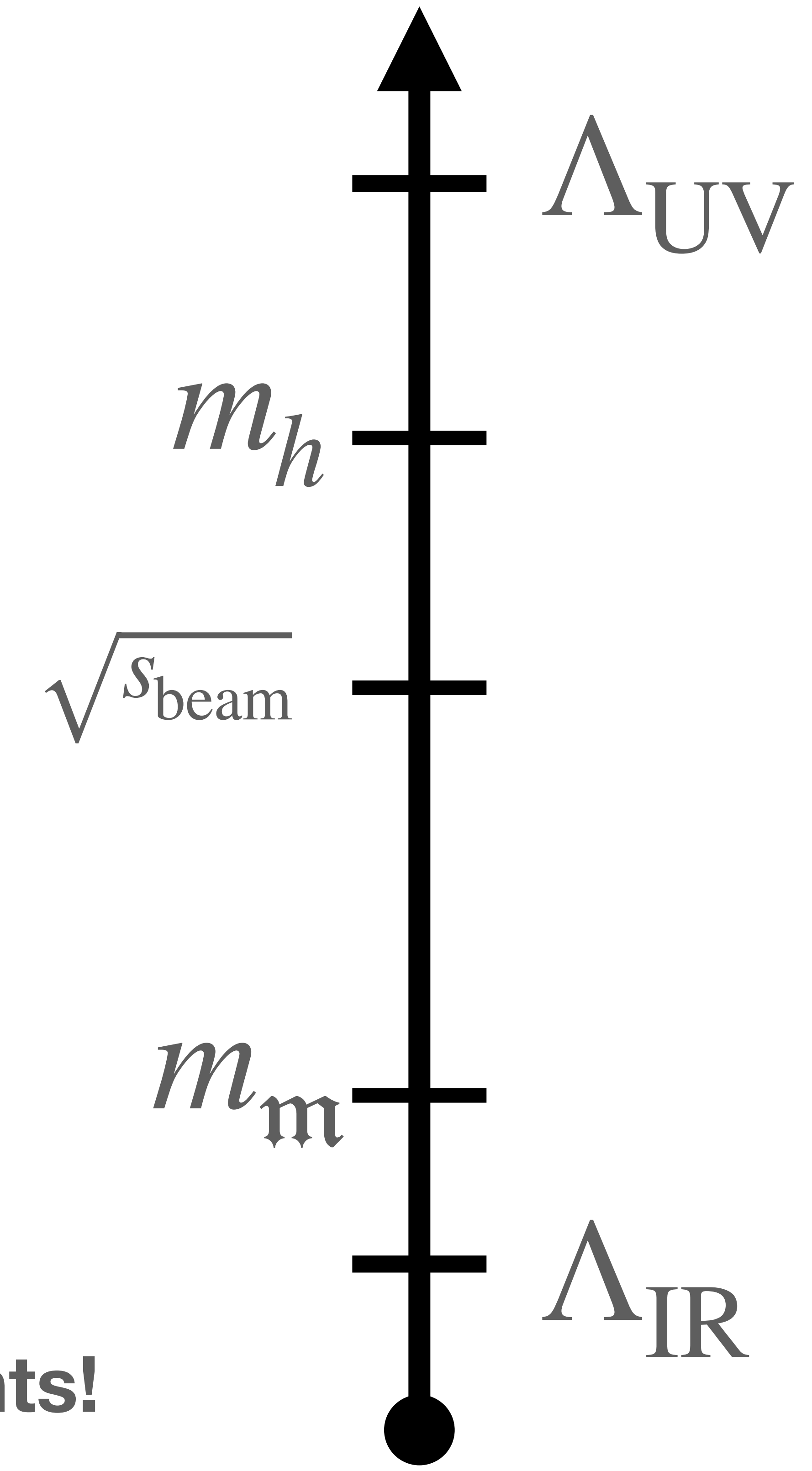


Beam landscape

Let's focus on muonic ν



Exp.	N_ν	$\langle E_\nu \rangle$ [GeV]	σ_E^2 [GeV^2]	$\sigma_{\text{target}}^{-1}$ [GeV^2]
DUNE	10^{20}	3	4	0.02
DUNE*	10^{20}	20	8	0.02
NuTeV	10^{17}	60	10^3	0.02
SHiP	5×10^{16}	40	32	0.2
FASERν	10^{12}	300	10^5	0.2
FASER-FPF	10^{15}	300	10^5	0.2
MuCol	10^{19}	2500	10^6	0.2
FCCν	10^{18}	4000	10^7	0.2

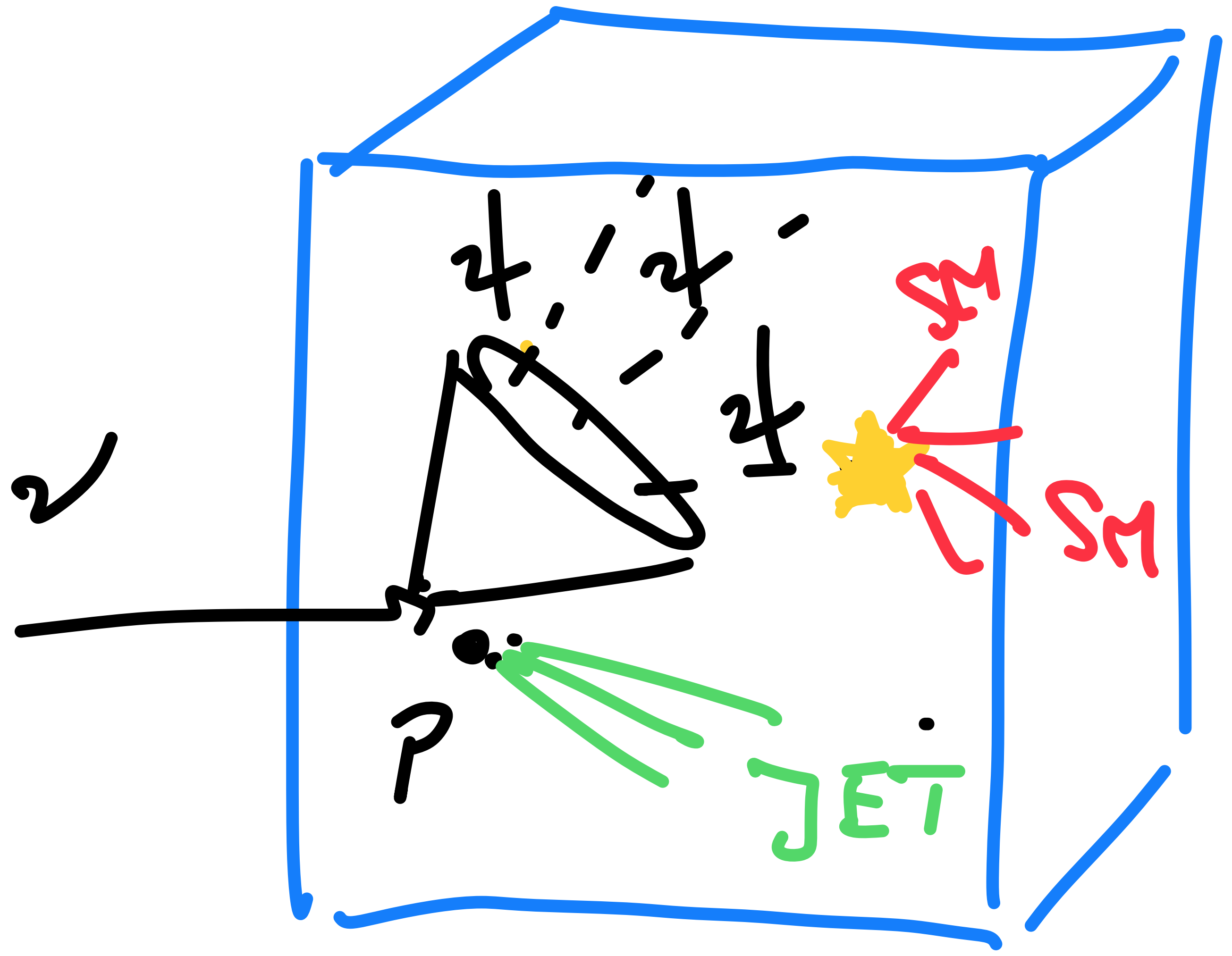


Many current and upcoming experiments!

Emerging jets

$$S_{B\to\text{vis}} = N_B \times \text{Br}(B \to \mathcal{O}_N) \times P_{\text{dec}}$$

- Hadronic activity in the primary vertex and visible tracks of SM particles in secondary displaced vertices
- Pile-up background negligible
- Neutral SM particle decays: can be killed with leptonic decays



Computing inclusive xsecs

- Look for inclusive x-secs in the dark sector!
- Model independent at high energy

Contino Max Mishra 2012.08537

Also: Hong Kurup Perelstein 1910.10160
Hong Kurup Perelstein 2207.10093
Hong Perelstein Youn 2412.00181

$$\frac{\mathrm{d}\sigma_S}{\mathrm{d}m_N^2} \propto \int \mathrm{d}\Phi_{\mathrm{DS}} \,|\langle \mathrm{DS}\,|\,O_N(p_{\mathrm{DS}})\,|\,0\rangle\,| = 2\mathrm{Im}\left[i\langle \bar{O}_N O_N\rangle\right]$$

Optical theorem

$$\mathrm{Im}\left[i\langle O_N(p)\bar{O}_N(-p)\rangle\right] = A_\Delta \gamma^\mu p_\mu p^{2\Delta-5}$$

Conformal invariance
(aka dimensional analysis)

$$\frac{\mathrm{d}\sigma_S}{\mathrm{d}m_N^2} \sim \left(\frac{m_N^2}{\Lambda_{\mathrm{UV}}^2}\right)^{\Delta-7/2}$$

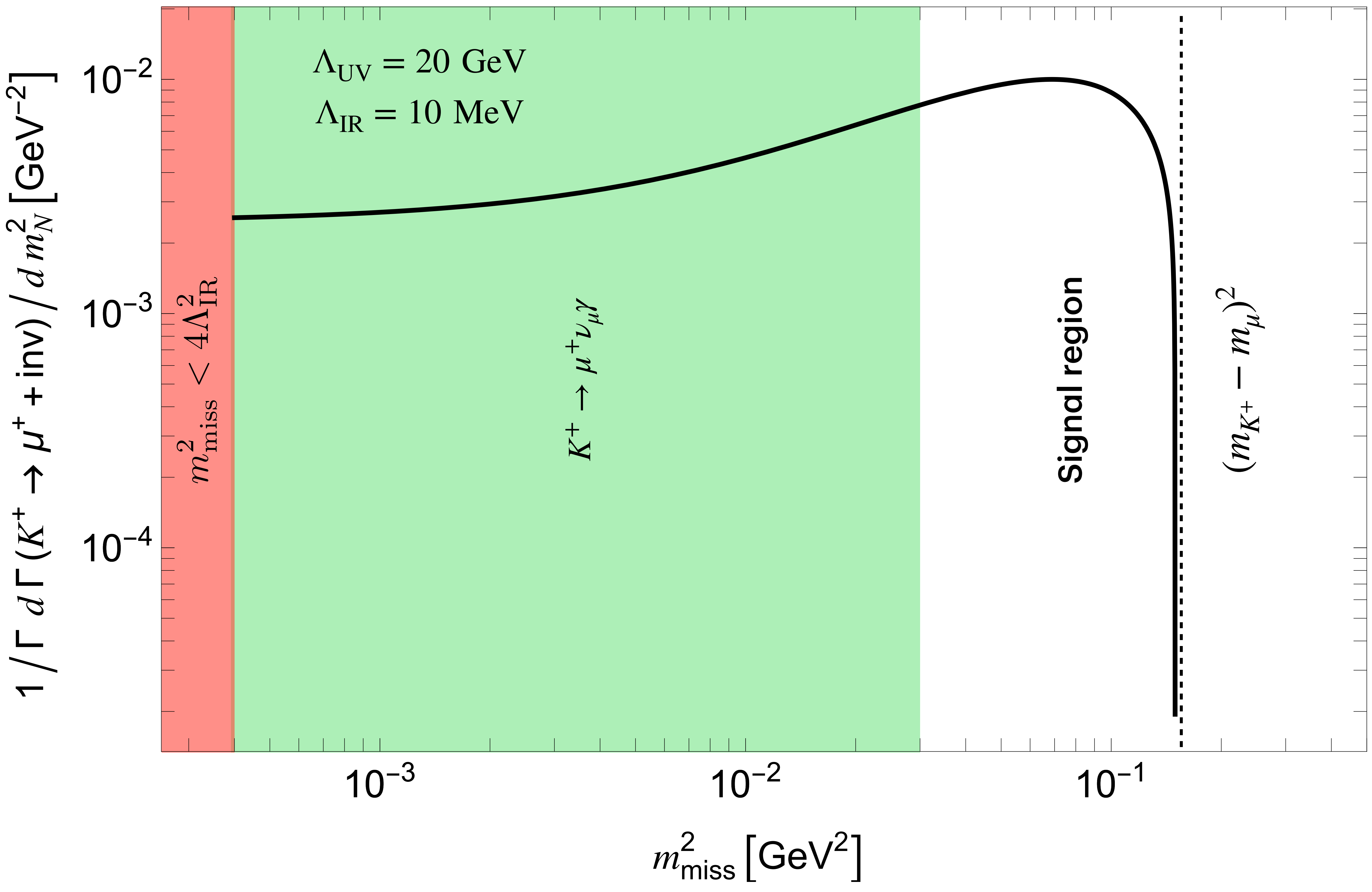
For large Δ total σ_S **UV dominated**: no need to model IR resonances

Disintegration UV dominated for $\Delta \geq 5/2$

Decay bounds

SM	$m_{\rm SM}$ [GeV]	$X_{\rm SM}$	Br (SM $\to \nu X_{\rm SM}$)	Invisible bound	Displaced bound
h	125	ν	$0.1 \times 10^{-2*}$	$10.7 \times 10^{-2\dagger}$	
W^+	80	μ^+	11×10^{-2}	0.3×10^{-2}	
Z	91	ν	20×10^{-2}	0.1×10^{-2}	10^{-6} [34]
π^+	0.140	μ^+	99.99×10^{-2}	0.8×10^{-6}	
		e^+	1.2×10^{-4}	0.8×10^{-6}	
K^+	0.494	μ^+	64×10^{-2}	0.2×10^{-2}	
		e^+	1.6×10^{-5}	1.4×10^{-7}	
D^+	1.9	μ^+	3.7×10^{-4}	0.3×10^{-4}	
		e^+		$9 \times 10^{-6\dagger}$	
		e^+X	16×10^{-2}	0.6×10^{-2}	
		μ^+X	18×10^{-2}	6×10^{-2}	
B^+	5.3	μ^+		$9 \times 10^{-7\dagger}$	
		e^+		$10 \times 10^{-7\dagger}$	
		e^+X	11×10^{-2}	5×10^{-2}	
		μ^+X	11×10^{-2}	7×10^{-2}	

Kaon decay spectrum



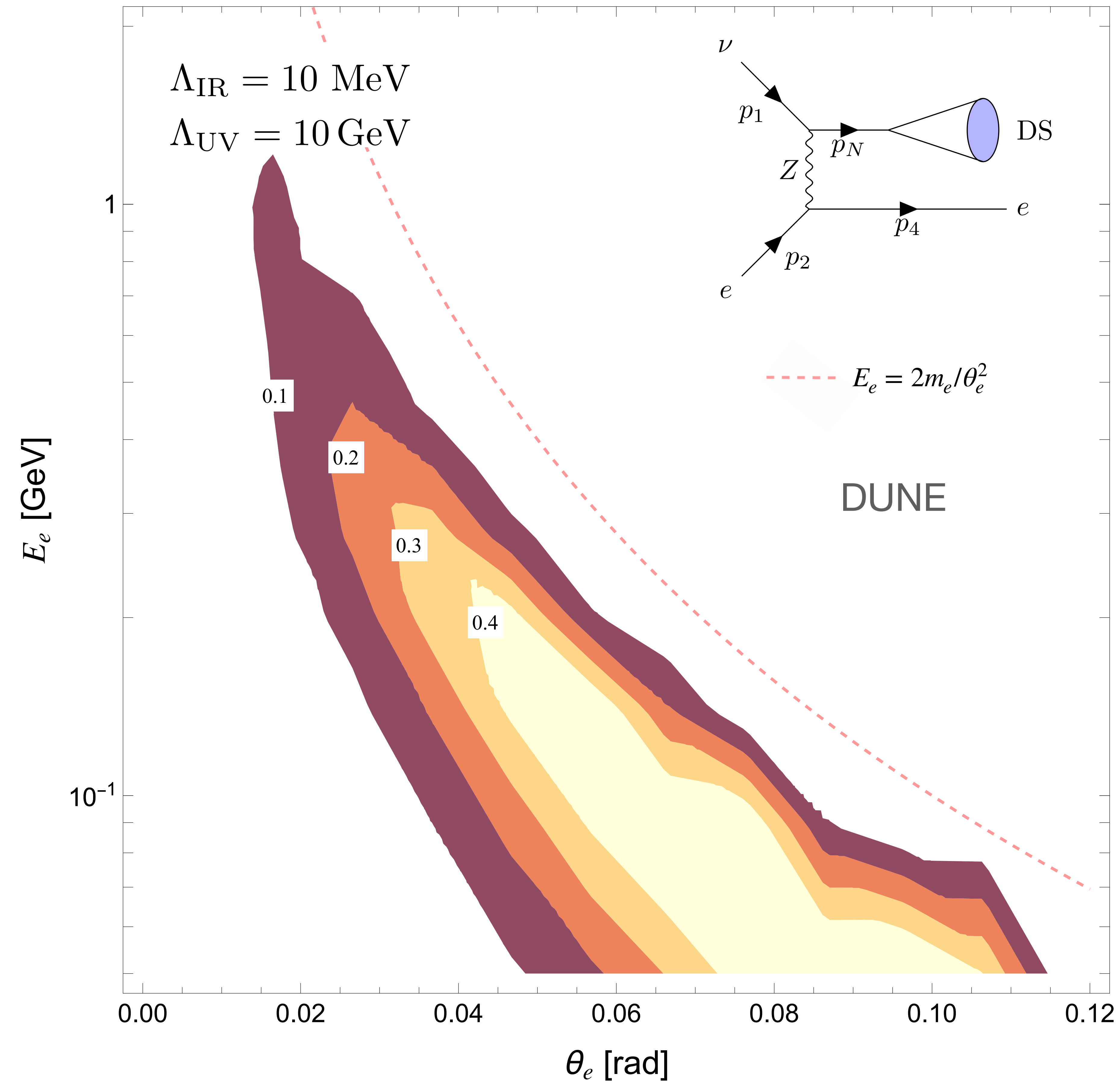
Disintegration on electrons

- Let's start with monochromatic beam
- SM NC: elastic, final electron with $E_e \sim \bar{E}_\nu;\ E_e(\theta_e)$
- Signal: inelastic, final electron with less energy

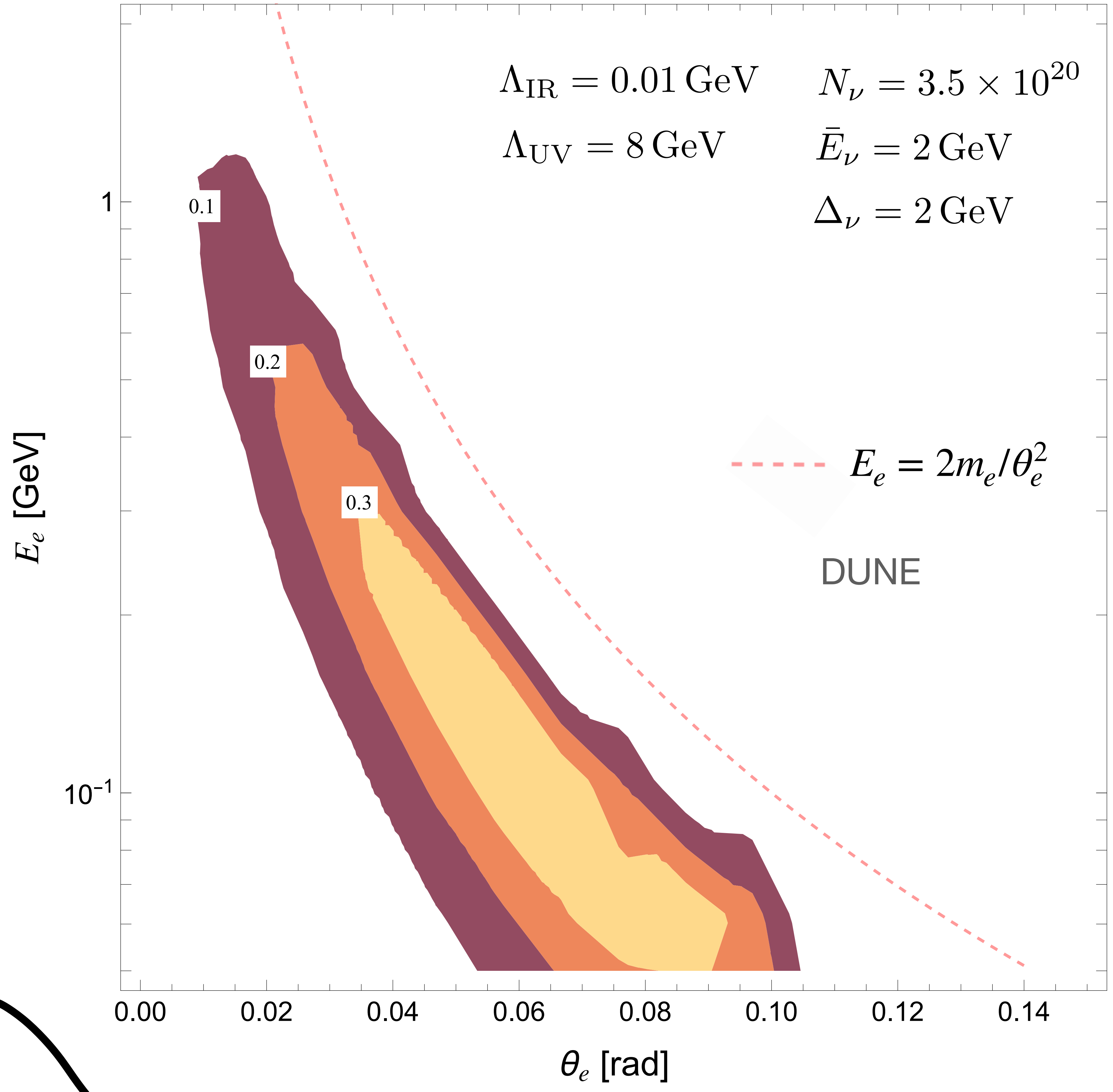
$$\frac{\mathrm{d}\sigma_L}{\mathrm{d}m_N^2} = \frac{A_N l_e^2 y_\mu^2}{96\pi^2} \frac{s_e}{v^2 \Lambda_{\mathrm{UV}}^4} \left[\frac{m_N^2}{\Lambda_{\mathrm{UV}}^2}\right]^{\Delta_N - 7/2} \left[1 - \frac{m_N^2}{s_e}\right]^2 \qquad s_e = 2E_\nu m_e$$

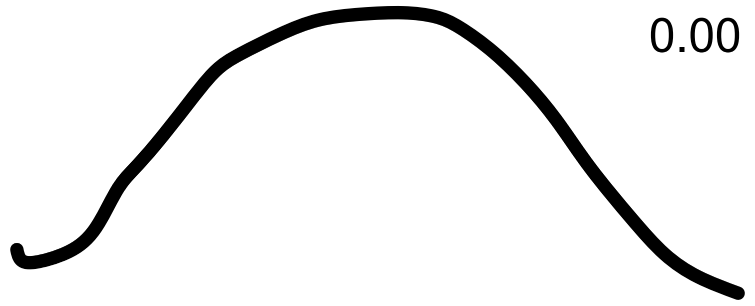
- Beam spread complicates…
- Binned analysis in (E_e, θ_e)

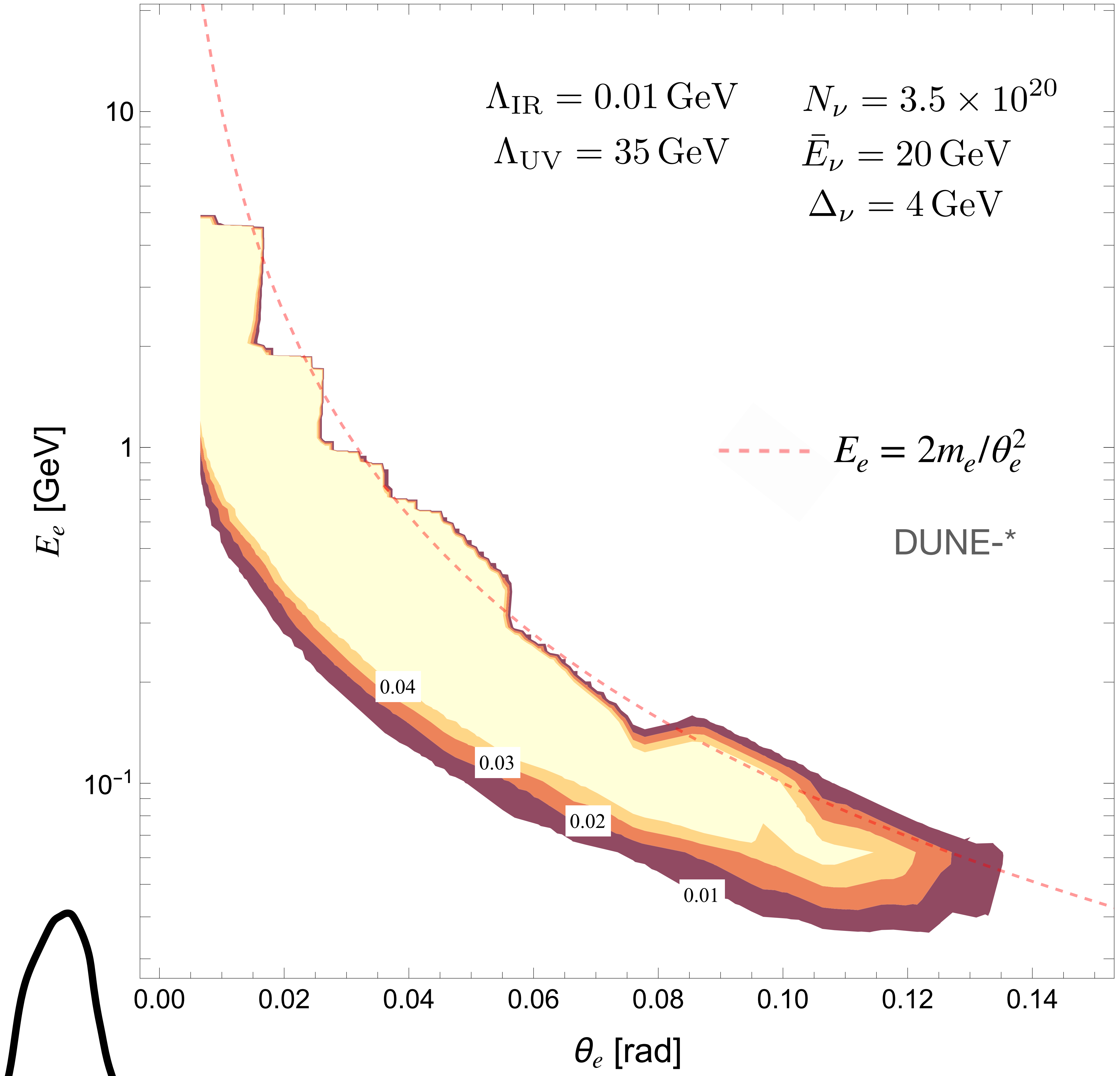
$$m_N^2 = p_N^2 = (p_1 + p_2 - p_4)^2$$

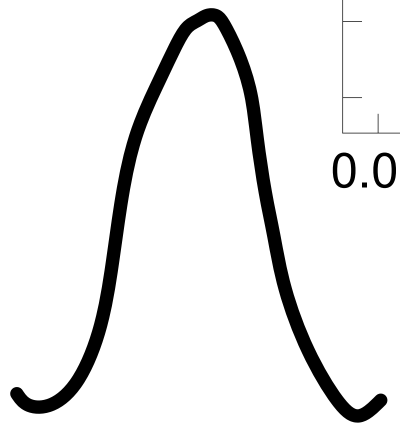


Disintegration on electrons





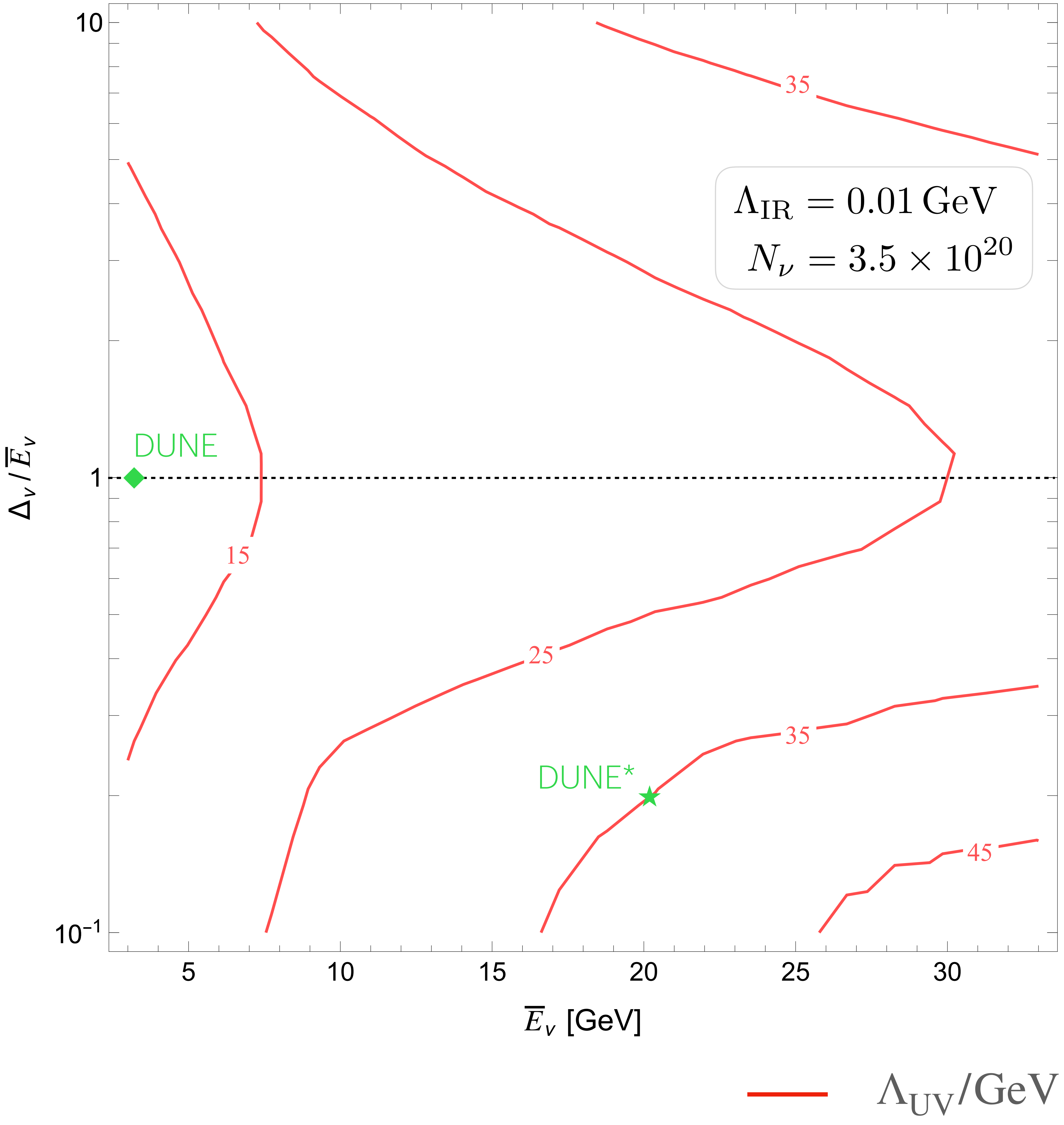




Disintegration on electrons

- Narrow flux: tail hunt high m_N^2
- Background free

- Large flux: spectrum distortion
- Both scenarios pay price of small $\sqrt{s}$



Disintegration on nucleons

Kinematics

- Larger s^2: $(m_p/m_e)^2$
- Even for monochromatic beam, m_j free
- At fixed (E_j, θ_j):

$$m^2_{\rm j,SM} \simeq 2 m_p E_j$$

$$m^2_{\rm j,BSM} \simeq m^2_{\rm j,SM} - \frac{m_N^2 E_j}{E_\nu - E_j}$$

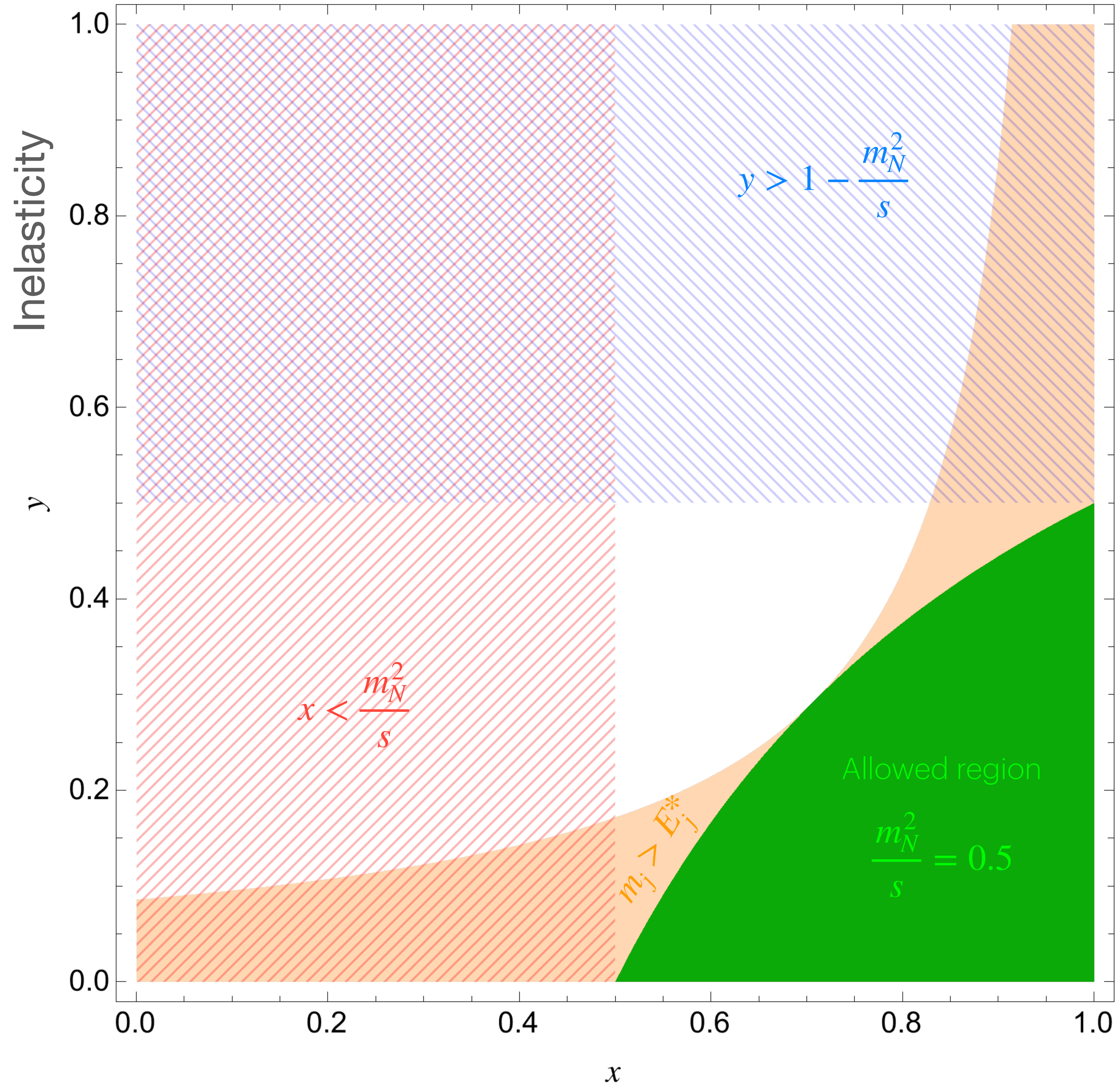
Number of tracks in jet

$$Q^2_{\rm SM} \simeq \frac{E_\nu E_j^2 \theta_j^2}{E_\nu - E_j}$$

$$Q^2_{\rm BSM} \simeq Q^2_{\rm SM} + \frac{m_N^2 E_j}{E_\nu - E_j}$$

Jet collimation

Kinematics much more complicated!

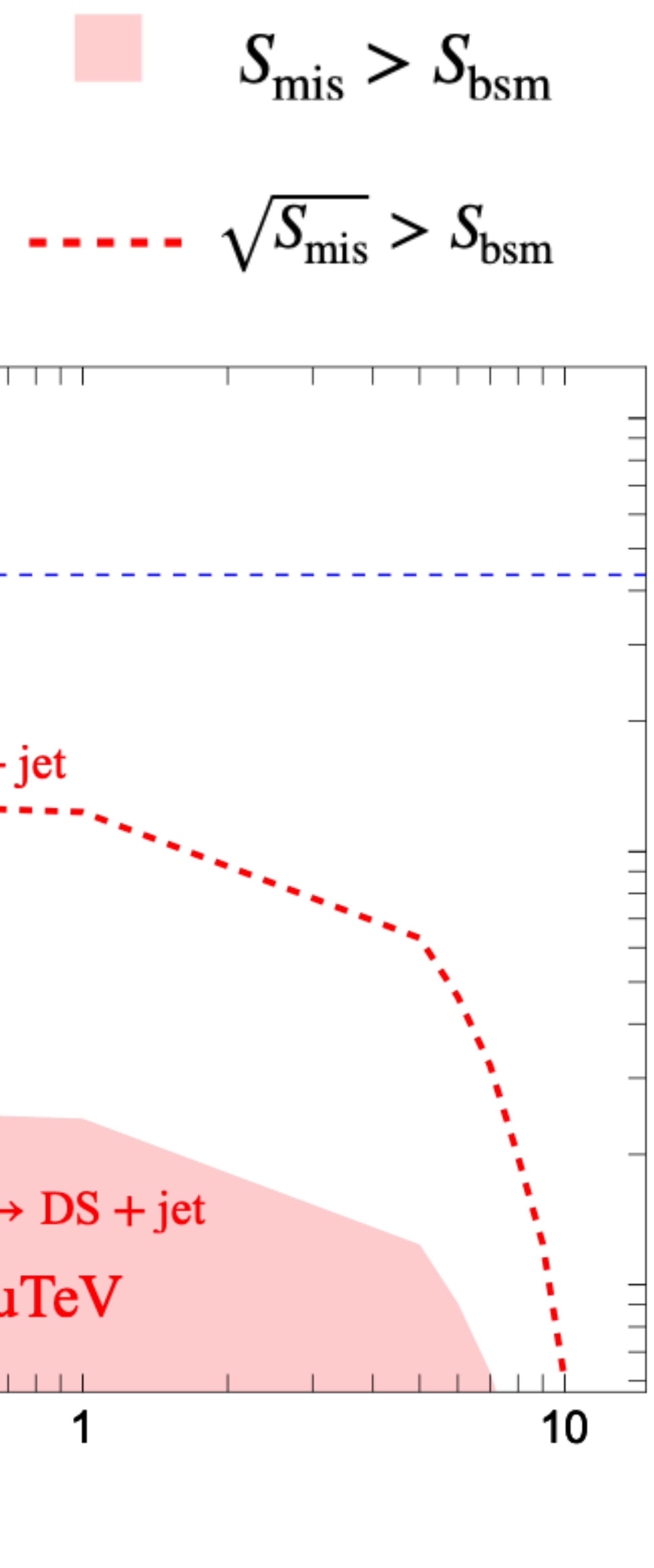


Parton momentum fraction

Disintegration on nucleons

NuTeV

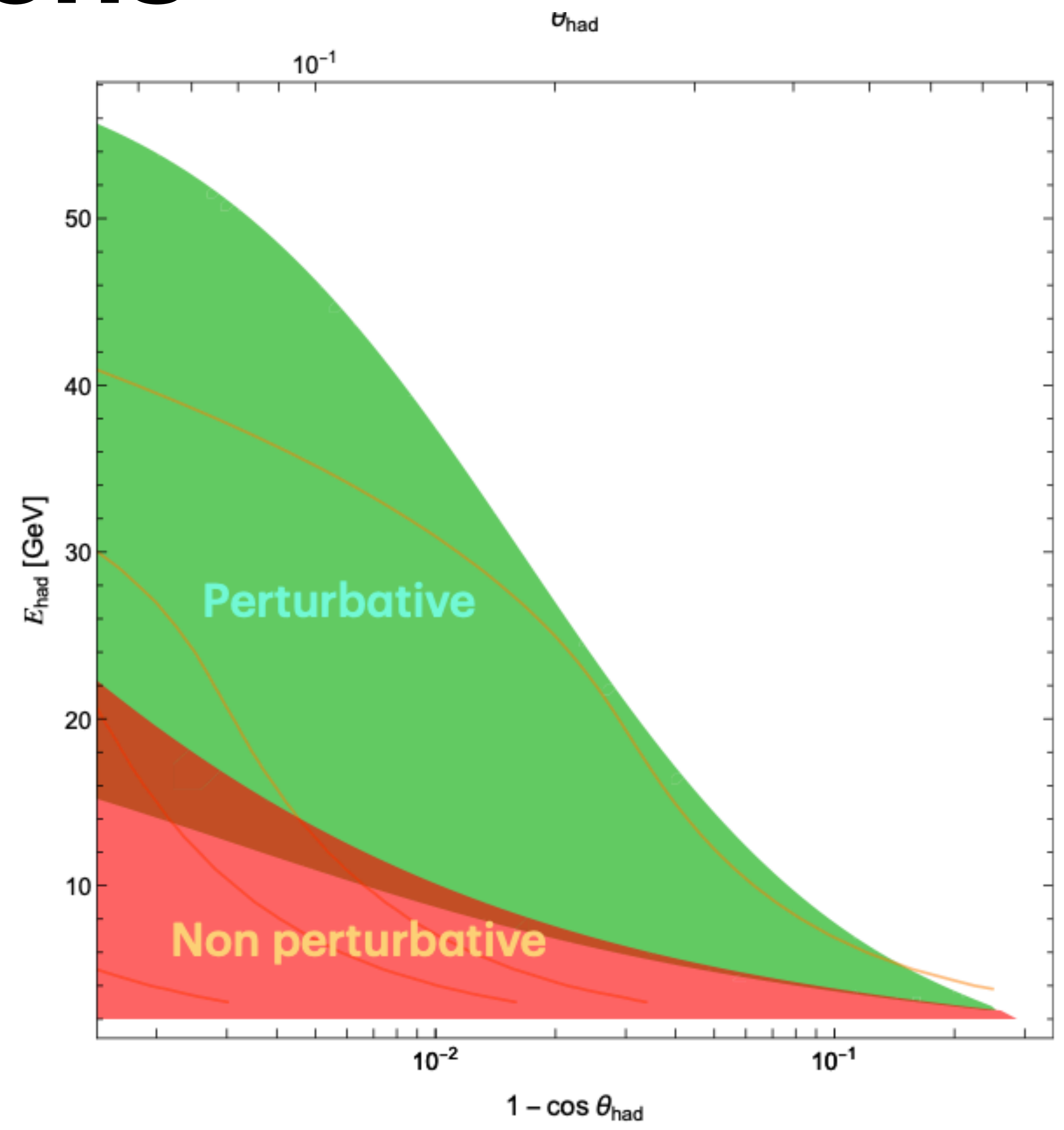
- Inclusive analysis
- $R = \frac{\text{short tracks}}{\text{long tracks}} = \frac{\text{NC}}{\text{CC}}$
- SM NC ~ 4.5×10^5
- Signal ~ $1.7 \times 10^3 \left(\frac{100\text{GeV}}{\Lambda_{UV}}\right)^4$



Disintegration on nucleons

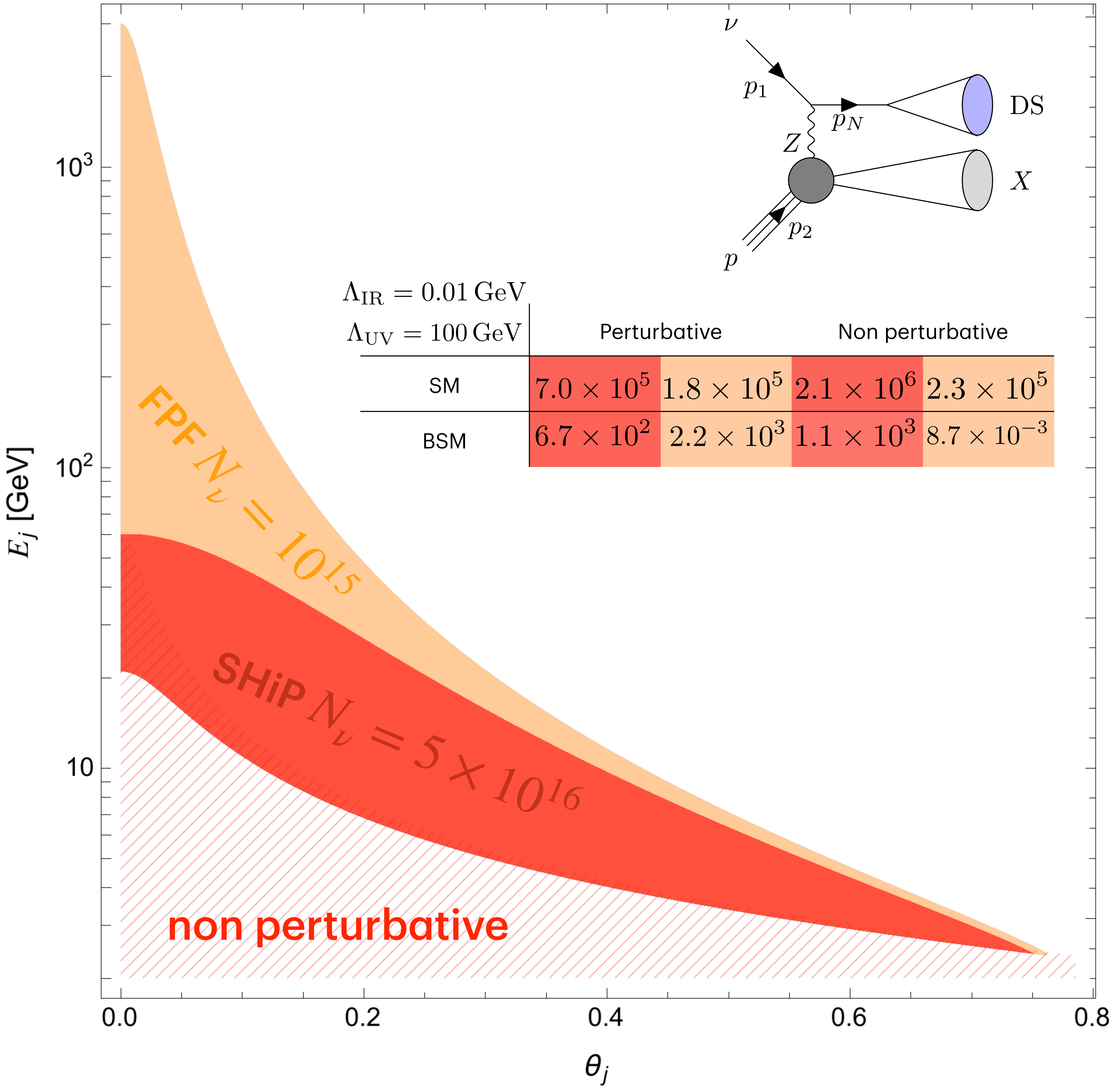
SHiP

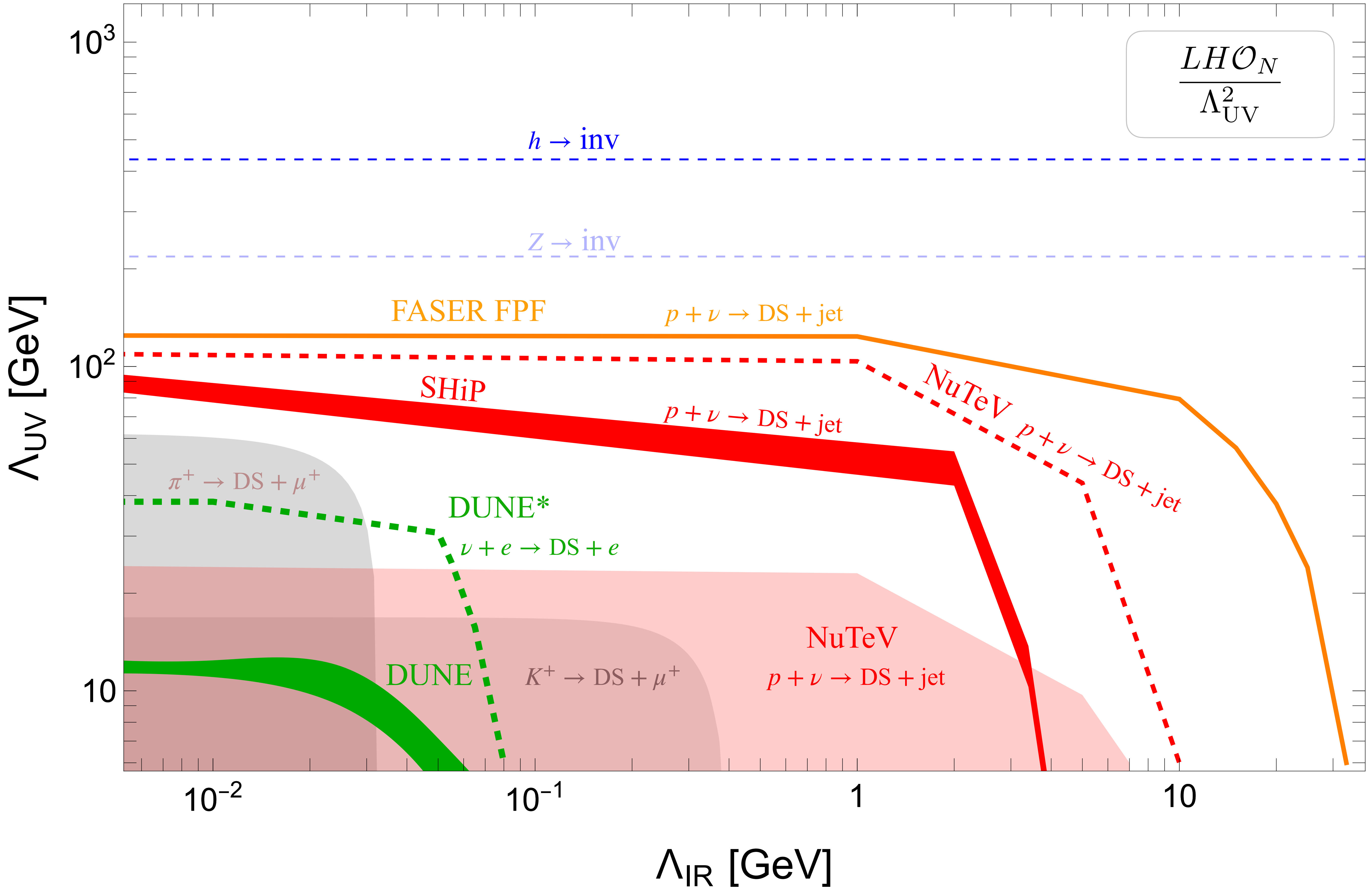
- We classify each bin (E_j, θ_j) as perturbative or not
- Then, merge into the two bins (pt or not)
- Conservative analysis: only pt.
- More aggressive: include also non-pt event bin, $\mathcal{O}(1)$ systematics



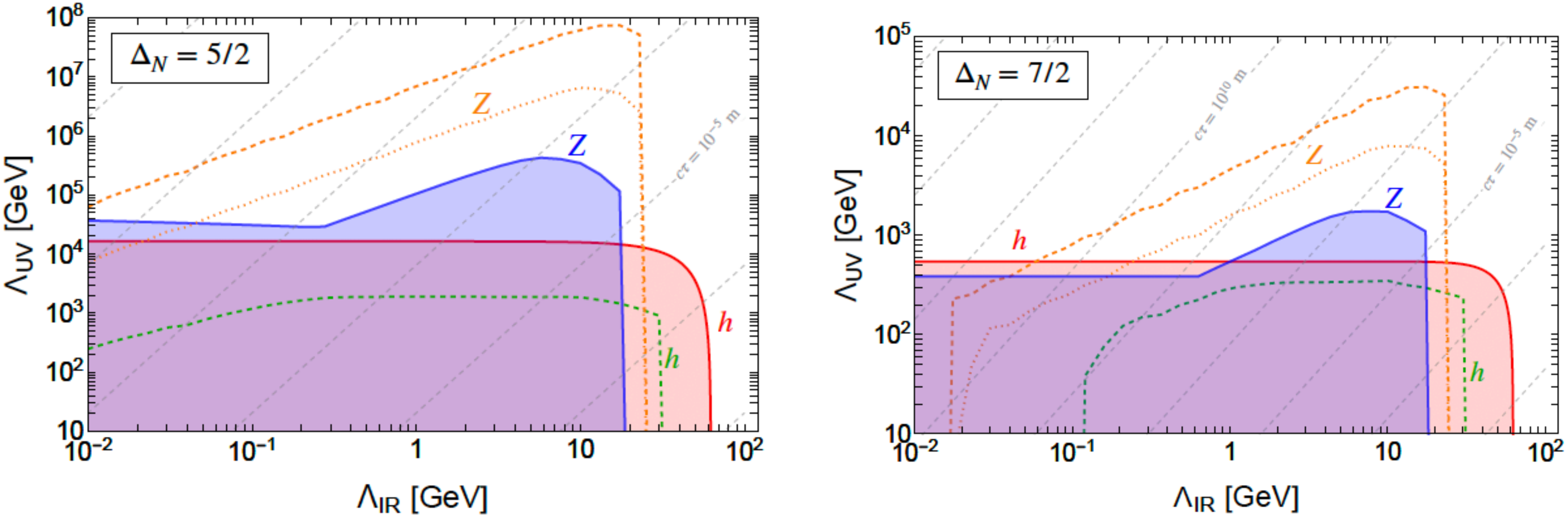
Disintegration on nucleons

SHiP/FPF

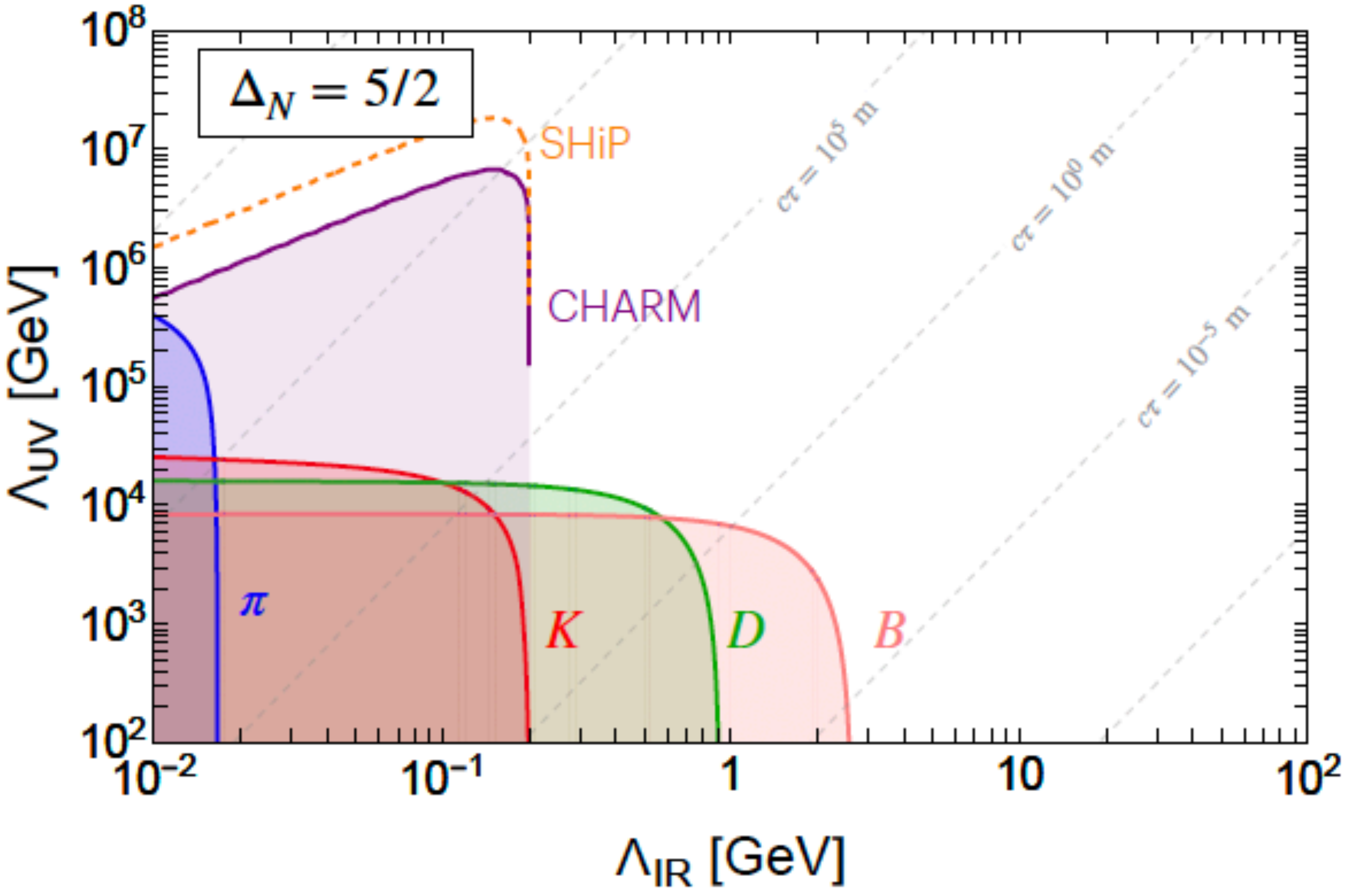


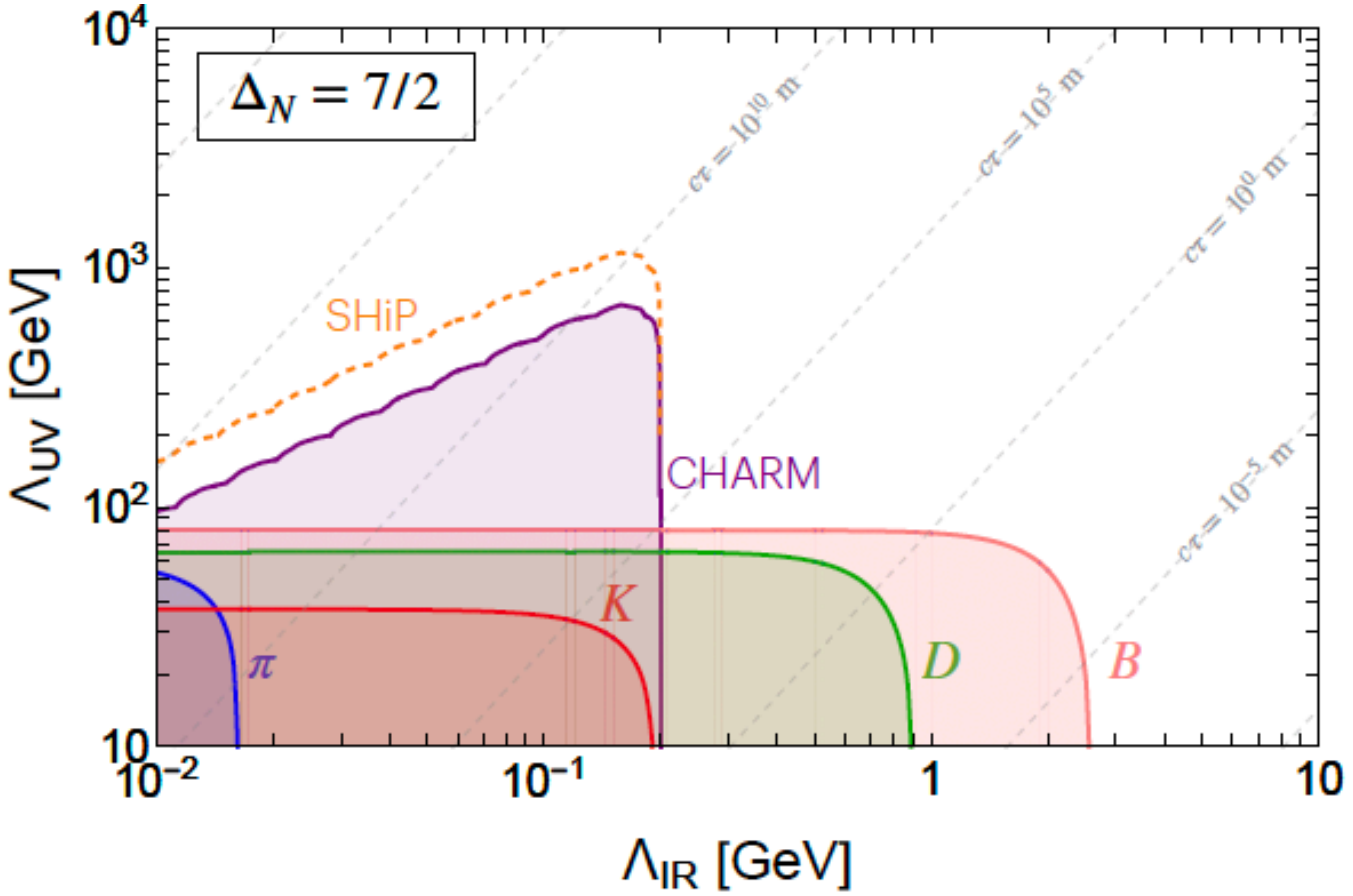


EW bounds


$\Delta_N = 5/2$
Z
Z
h
h
$c\tau = 10^{-5}$ m
Λ_{UV} [GeV]
Λ_{IR} [GeV]
$\Delta_N = 7/2$
Z
Z
h
h
$c\tau = 10^{10}$ m
$c\tau = 10^{-5}$ m
Λ_{UV} [GeV]
Λ_{IR} [GeV]

Meson decay bounds





Beyond the minimal assumptions

$\mathrm{BR_{inv}} = 1$ Extra dark states (e.g. NGBs)

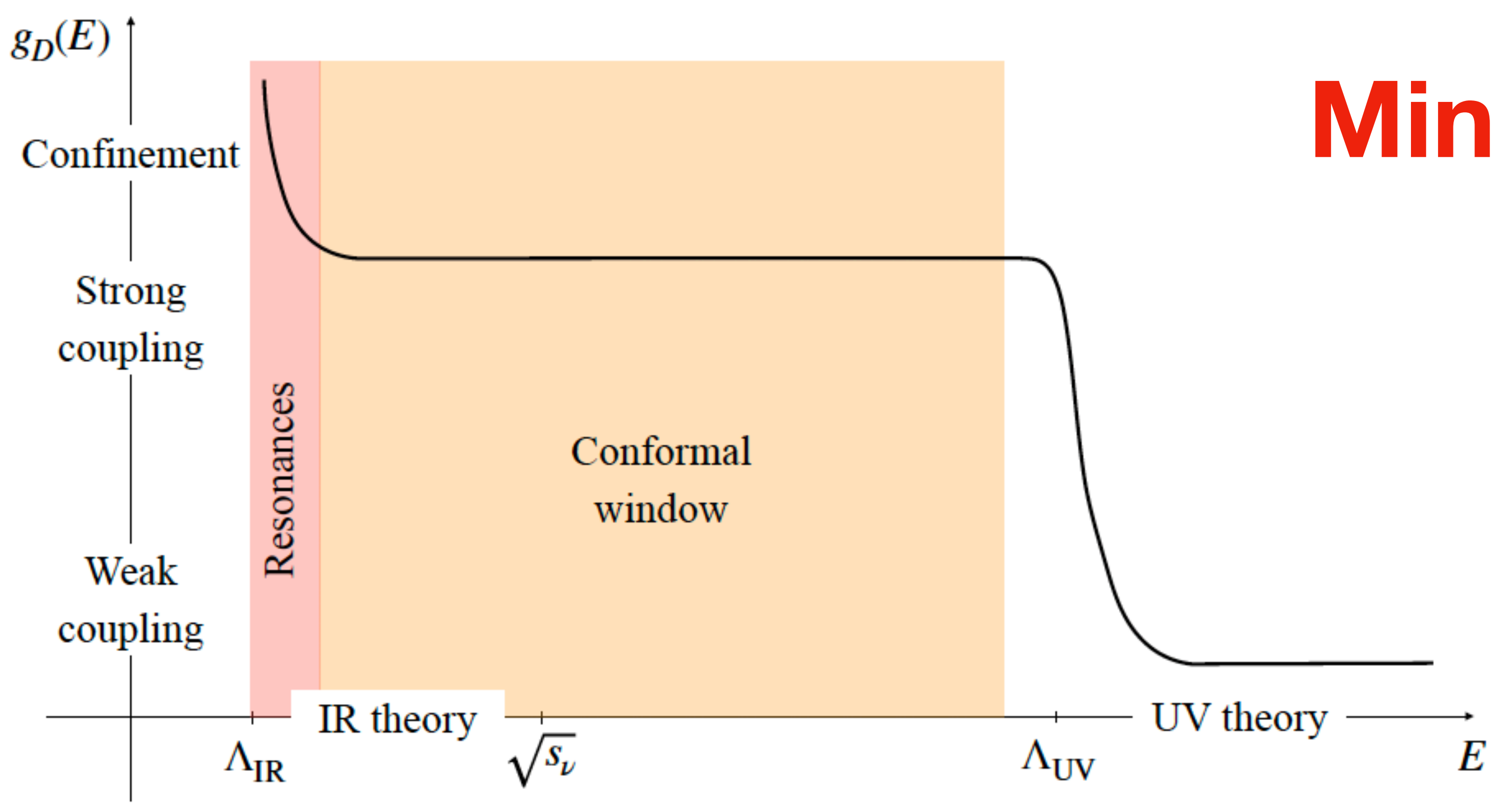
Favours high energy, invisible processes

Cuts contribution up to Λ_*, Invisibile processes

CFT up to EW

Broken CFT

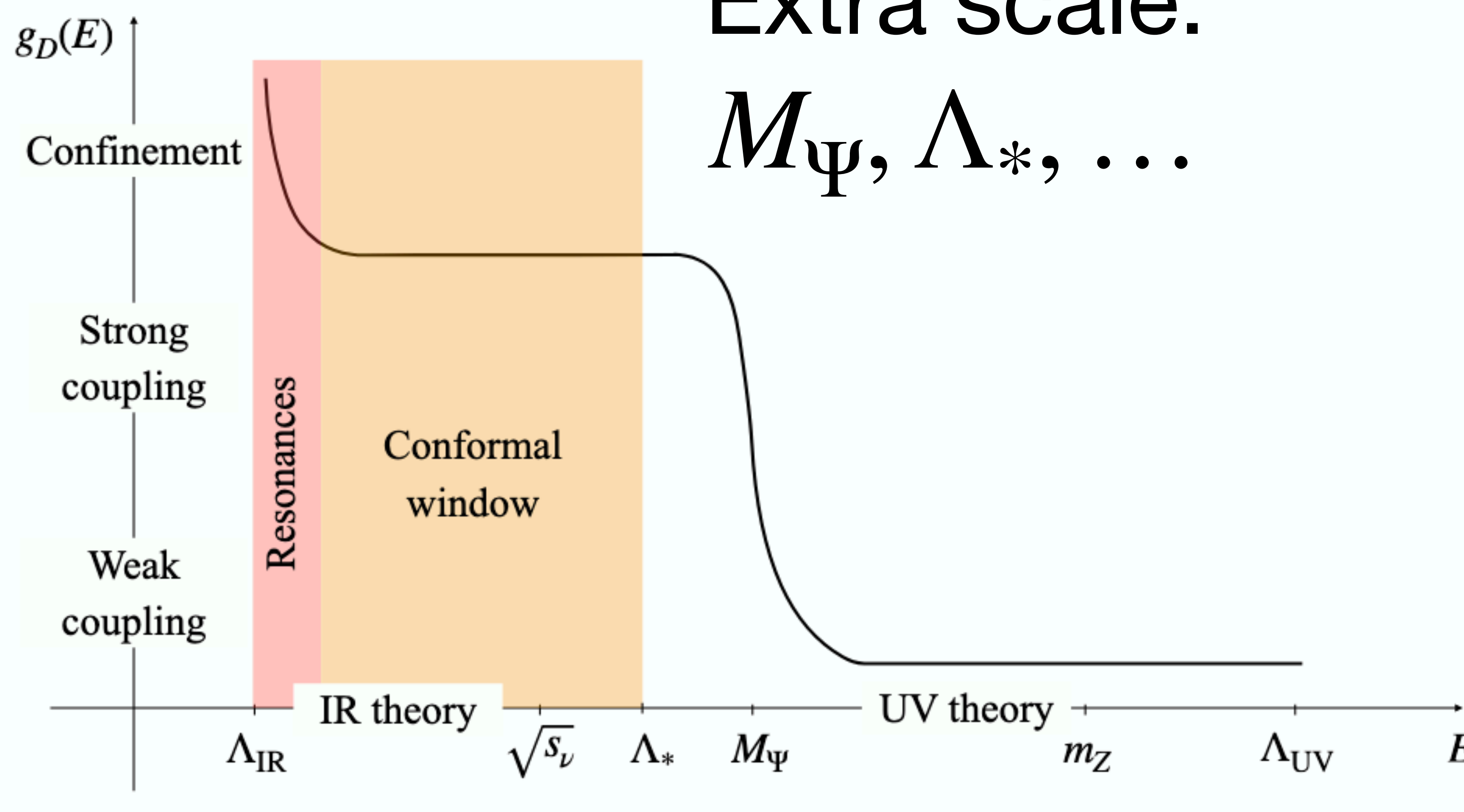
2 scale: $\Lambda_{\mathrm{IR}}, \Lambda_{\mathrm{UV}}$



Minimal models

Favours luminous displaced events

Extra scale: $M_\Psi, \Lambda_*, \ldots$



$\mathrm{BR_{inv}} \neq 1$

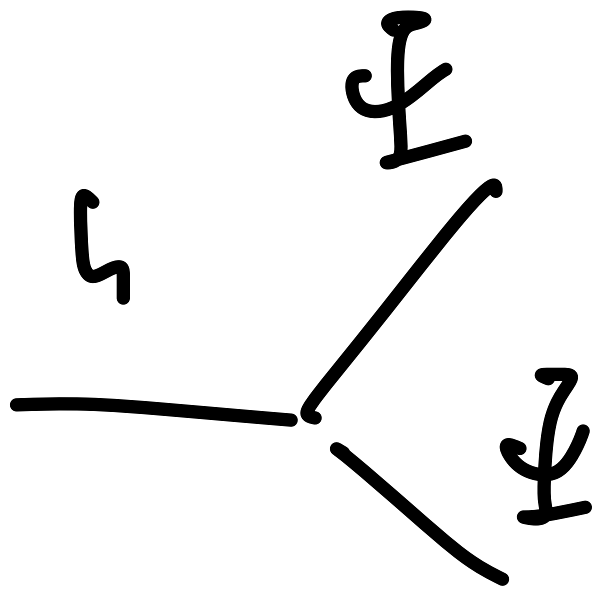
As in HNL

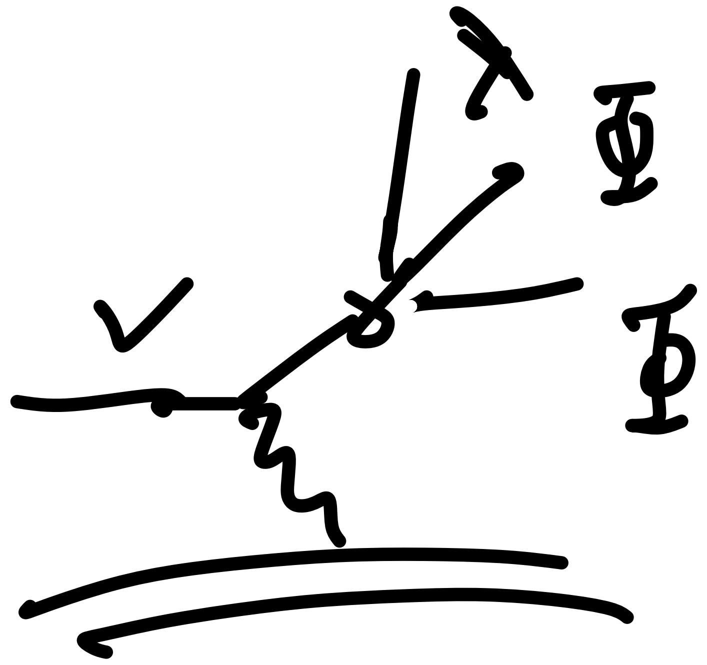
Evading Higgs constraints

Alternatively, think of
possible form factor
damping at v

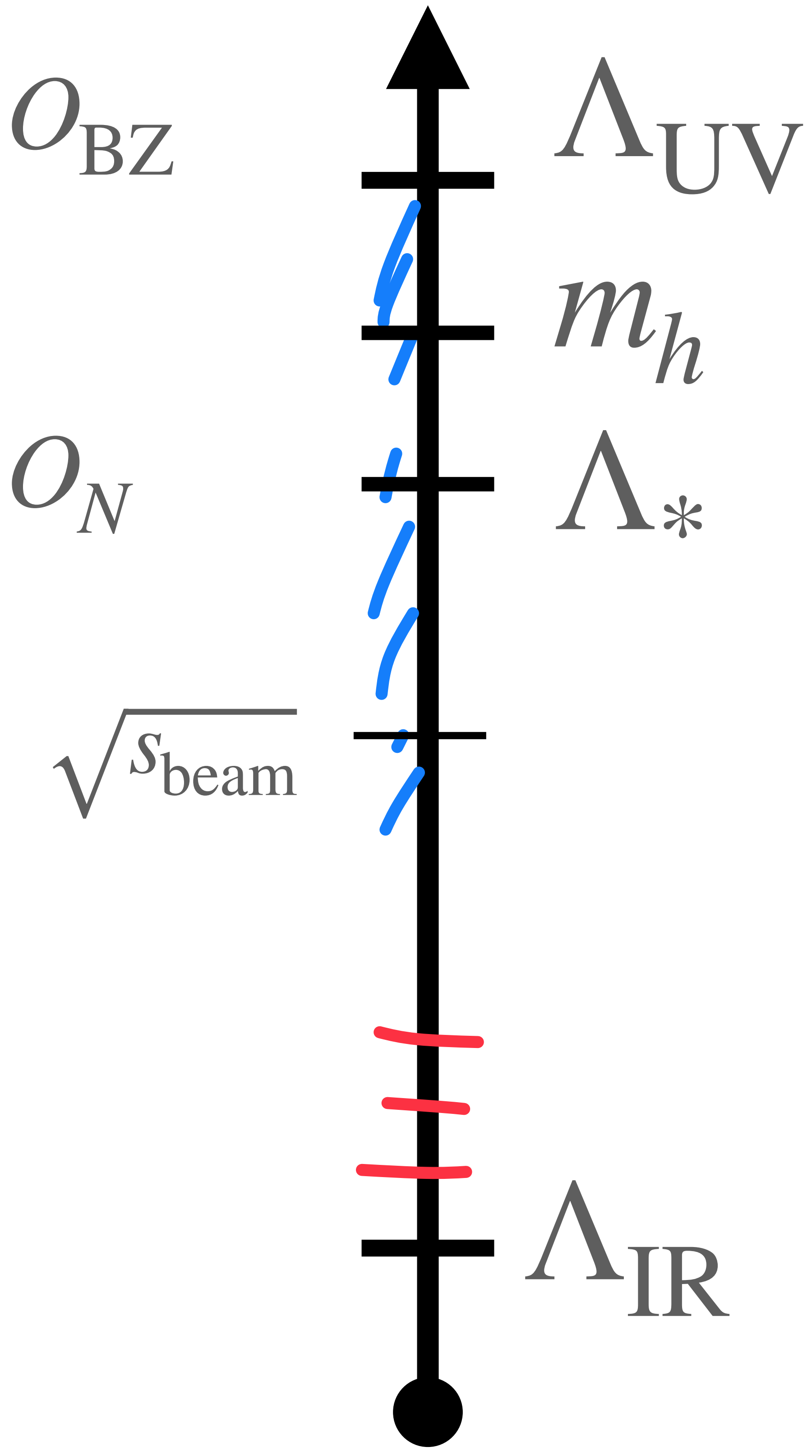
- Idea: make something happen at $\Lambda_{\mathrm{IR}} < \Lambda_* < m_h$
- Problem in general eased for $\Delta < 7/2$

$$\mathscr{L}_{\mathrm{UV}} = \tilde{y}HL\Psi + M_\Psi \bar{\Psi}\Psi + \frac{\bar{\Psi}\lambda\Phi^2}{\Lambda_*}$$



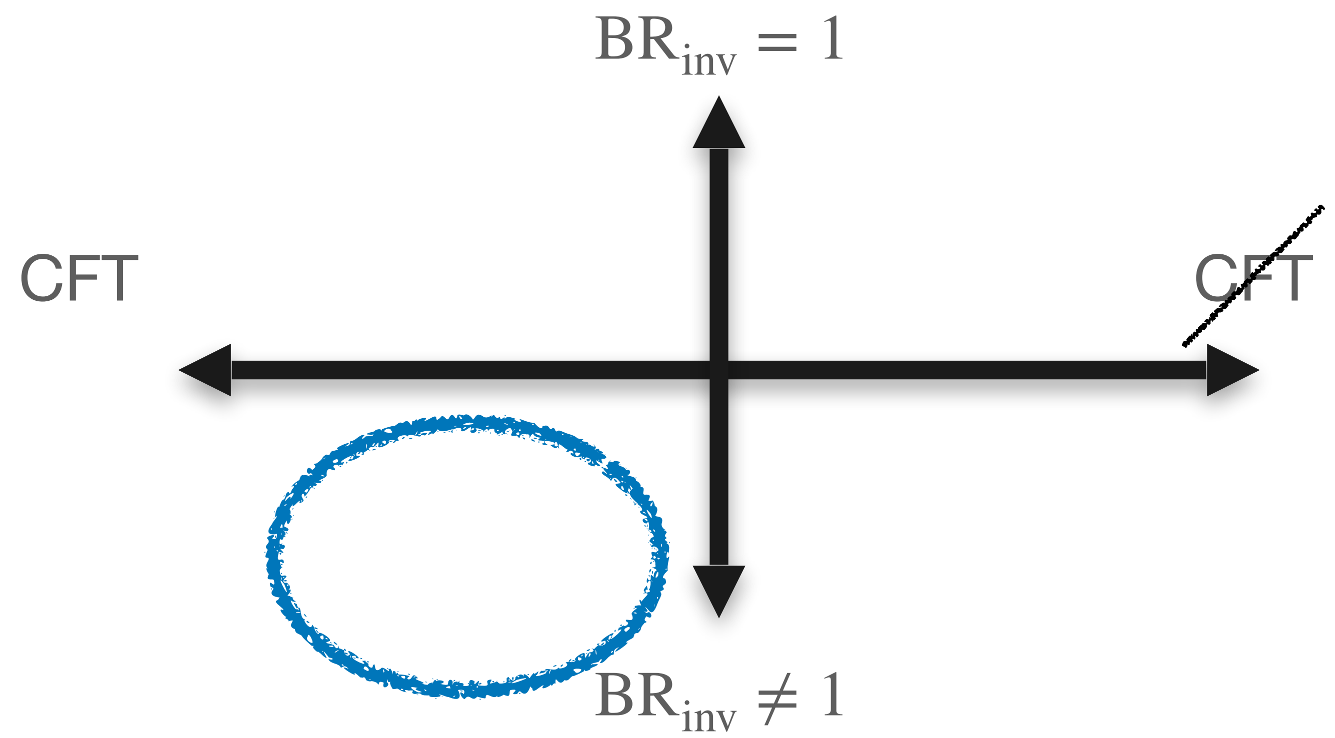


Decay bounds can be
made weaker if
"at Higgs scale sterile
sector is weakly
coupled"

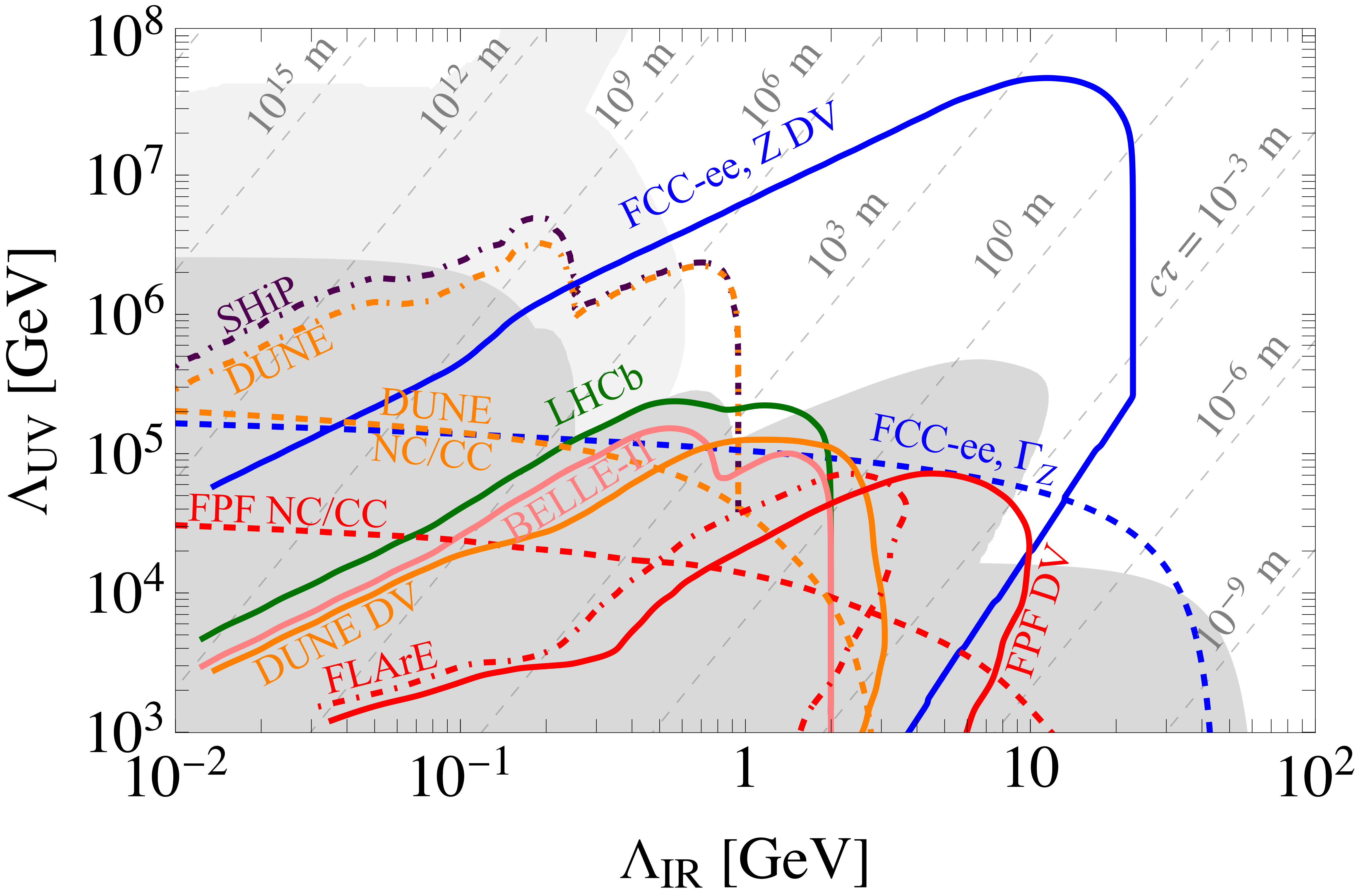


$\Delta_N = 7/2$ $\quad$ $5/2 > \Delta_{\mathrm{BZ}} > 3/2$

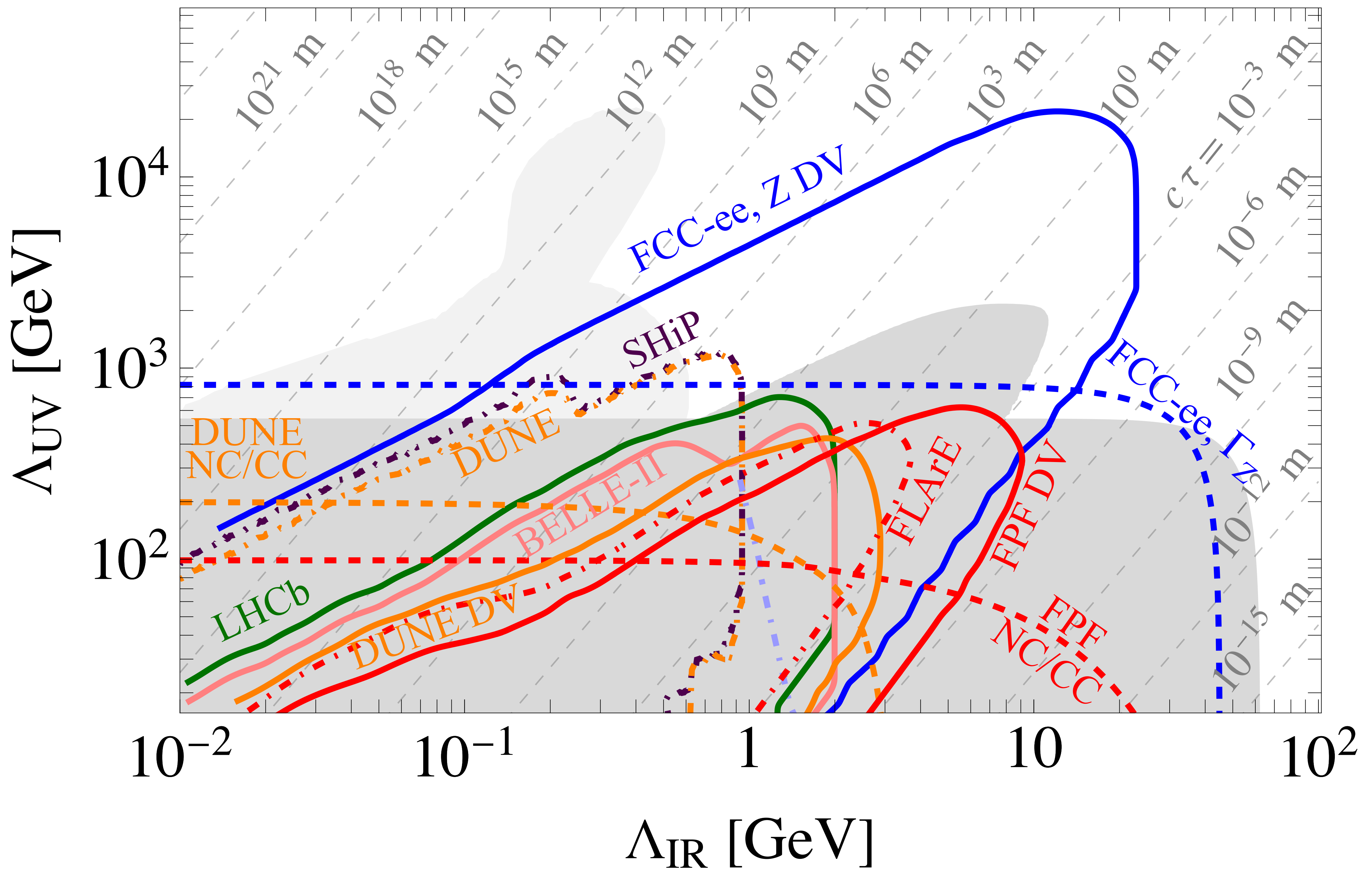
No GB, CFT all the way



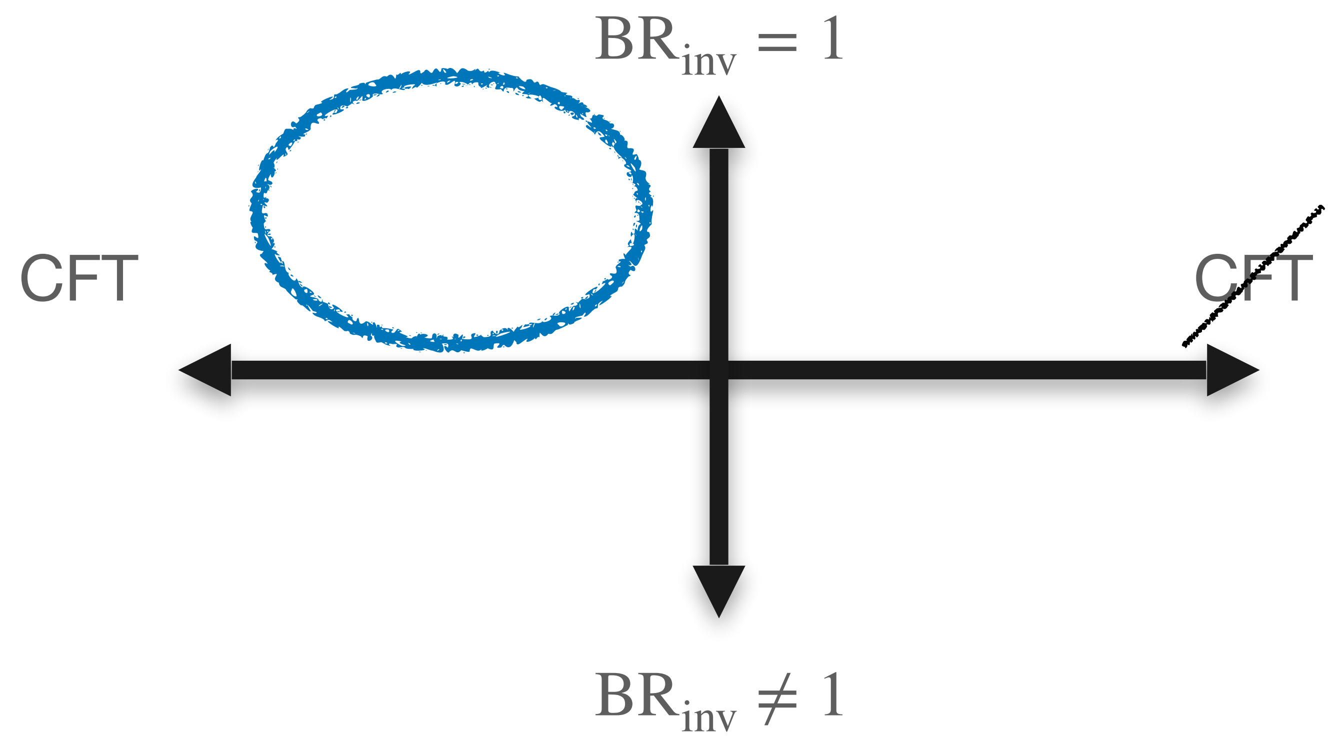
$\Delta_N = 5/2$ unbroken, no pNGB

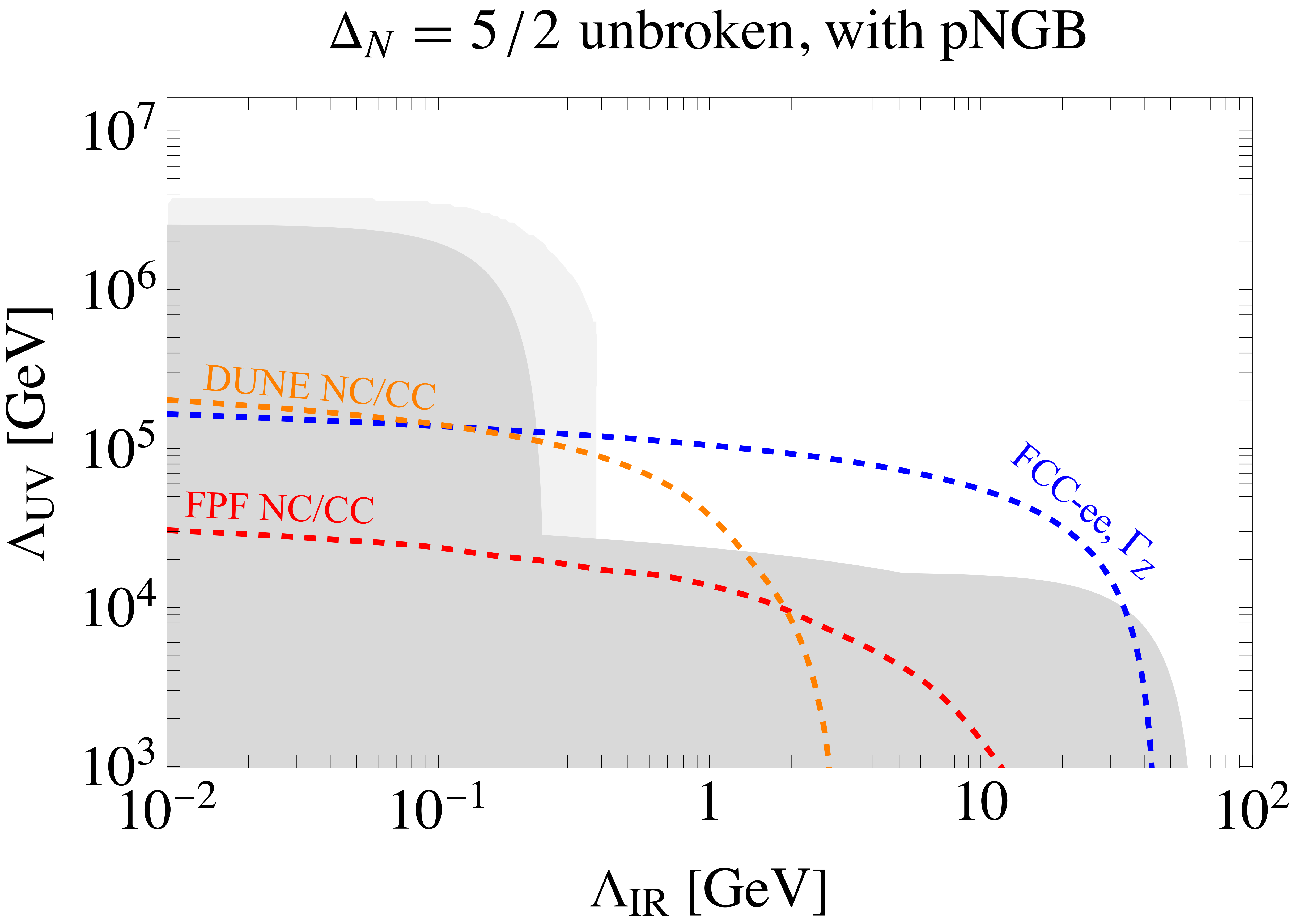


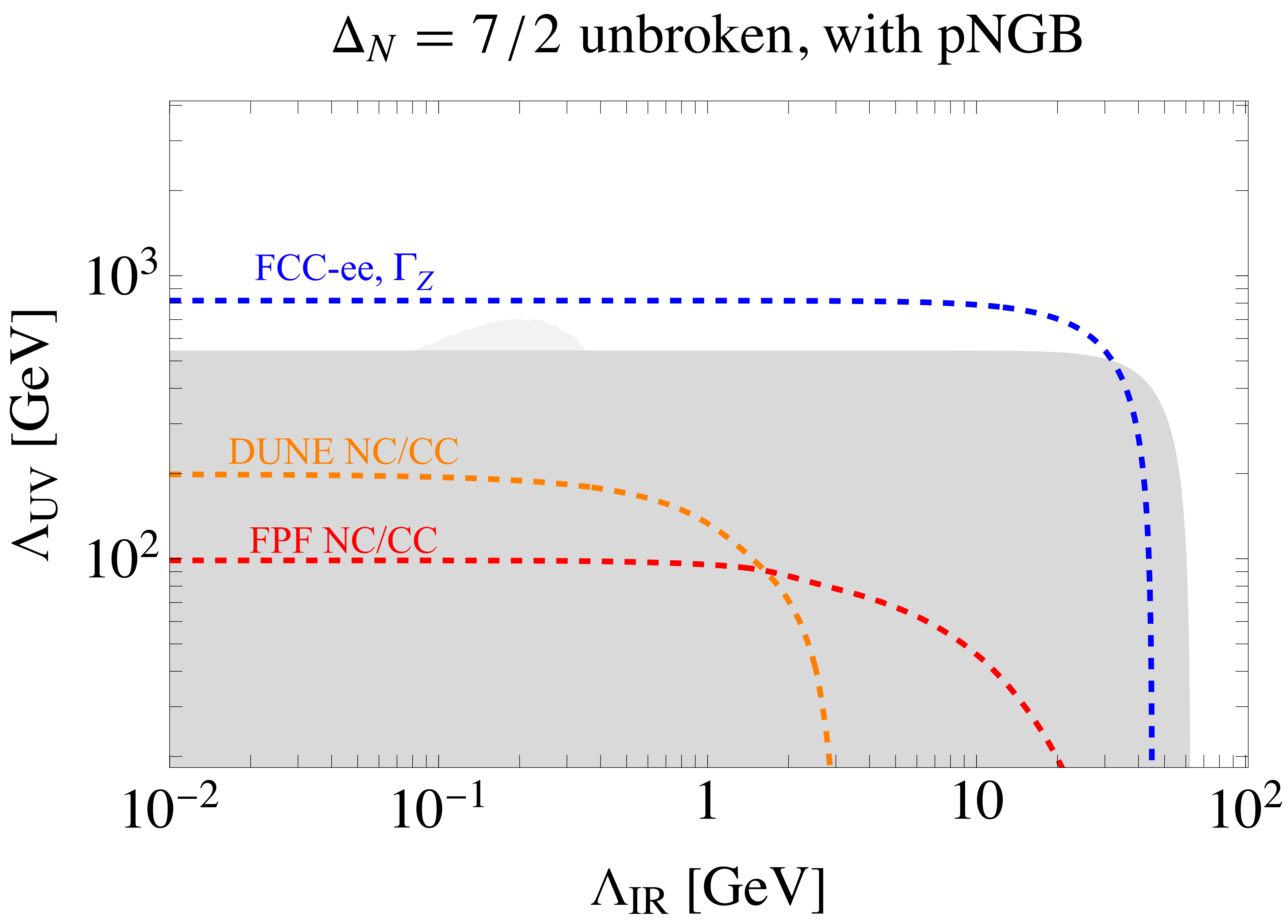
$\Delta_N = 7/2$ unbroken, no pNGB



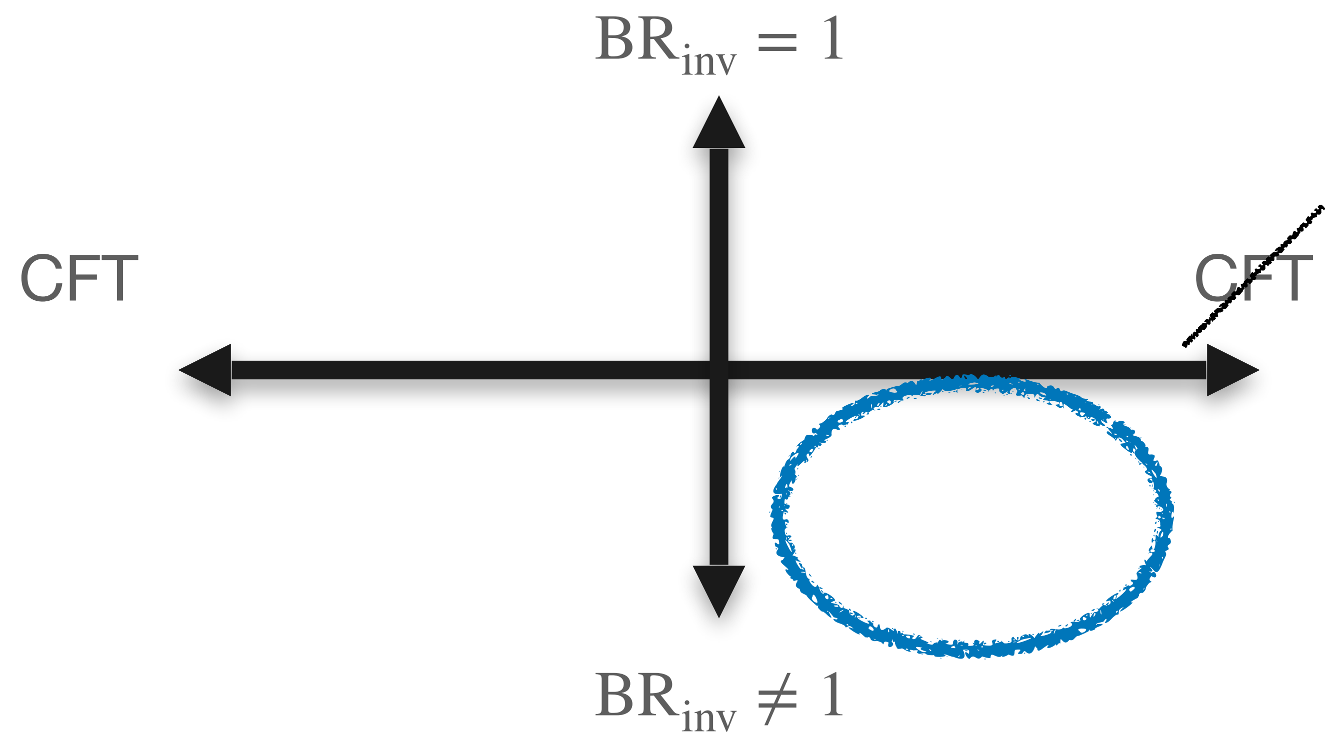
GB, CFT all the way

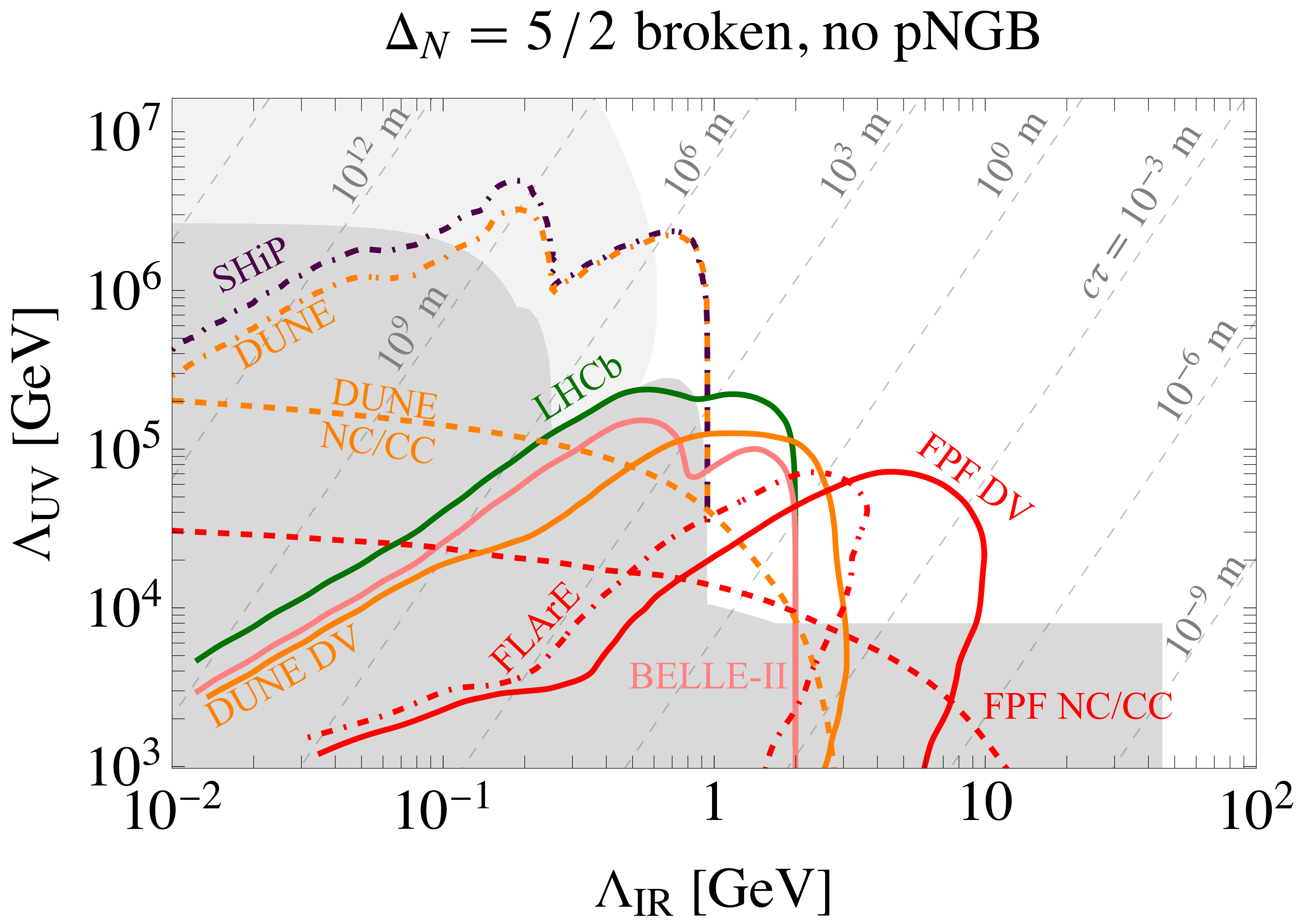


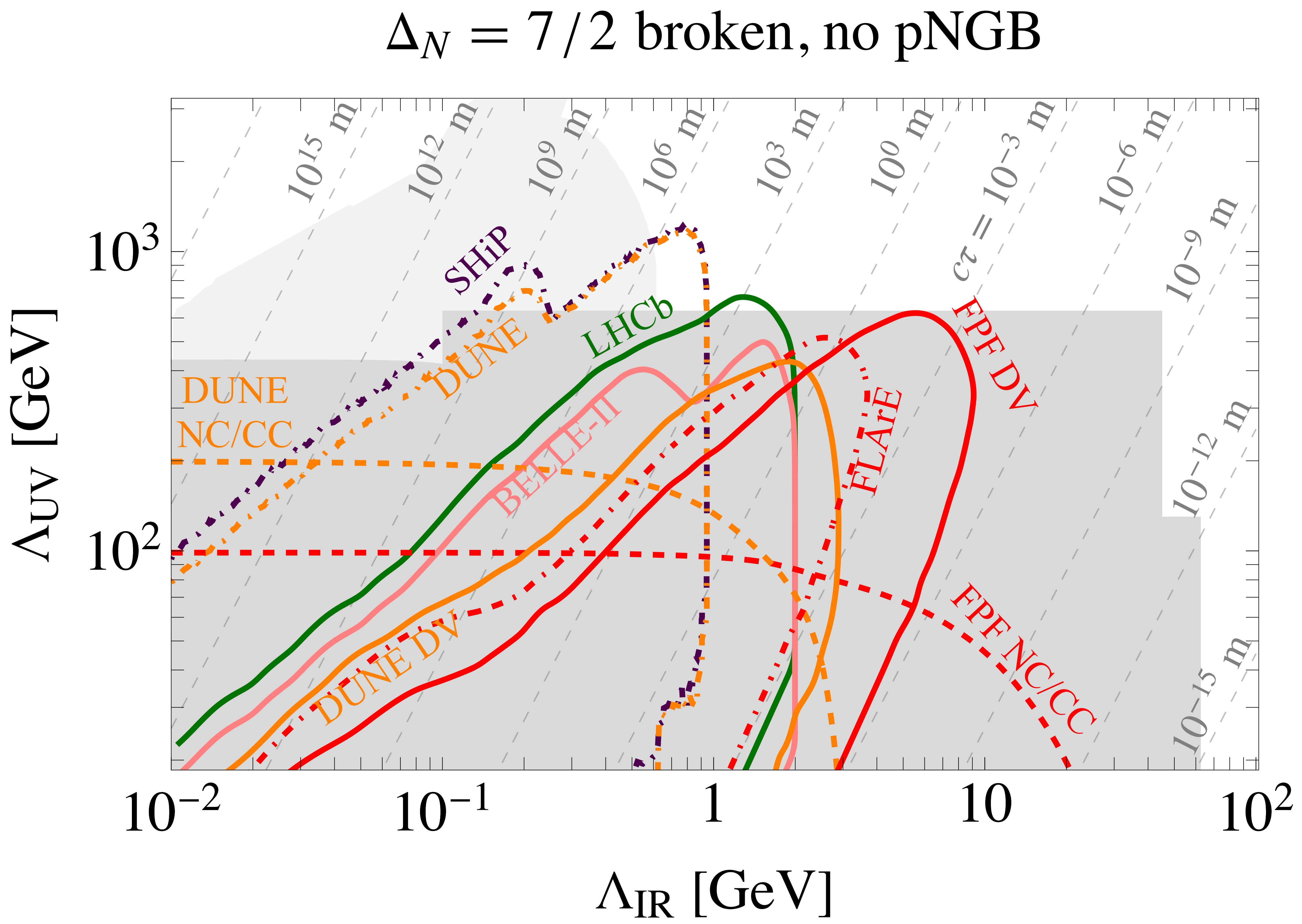




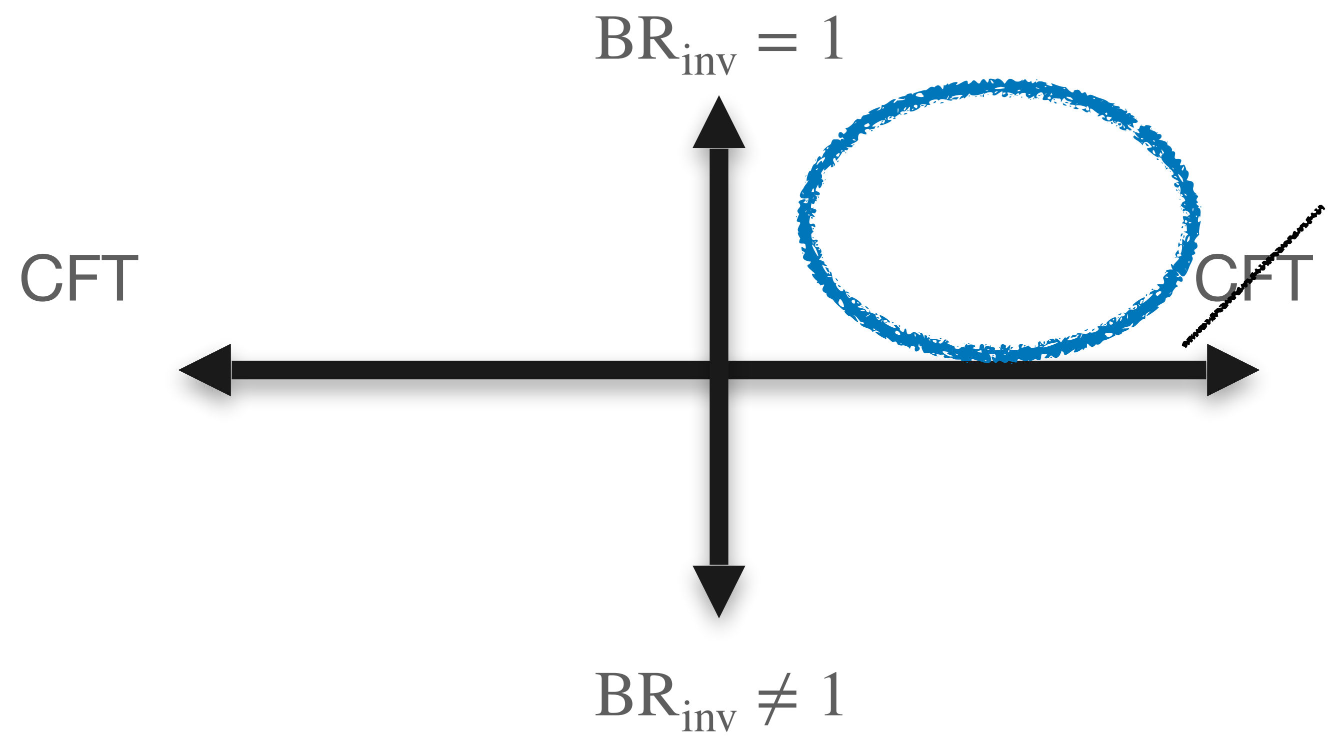
No GB, CFT breaking

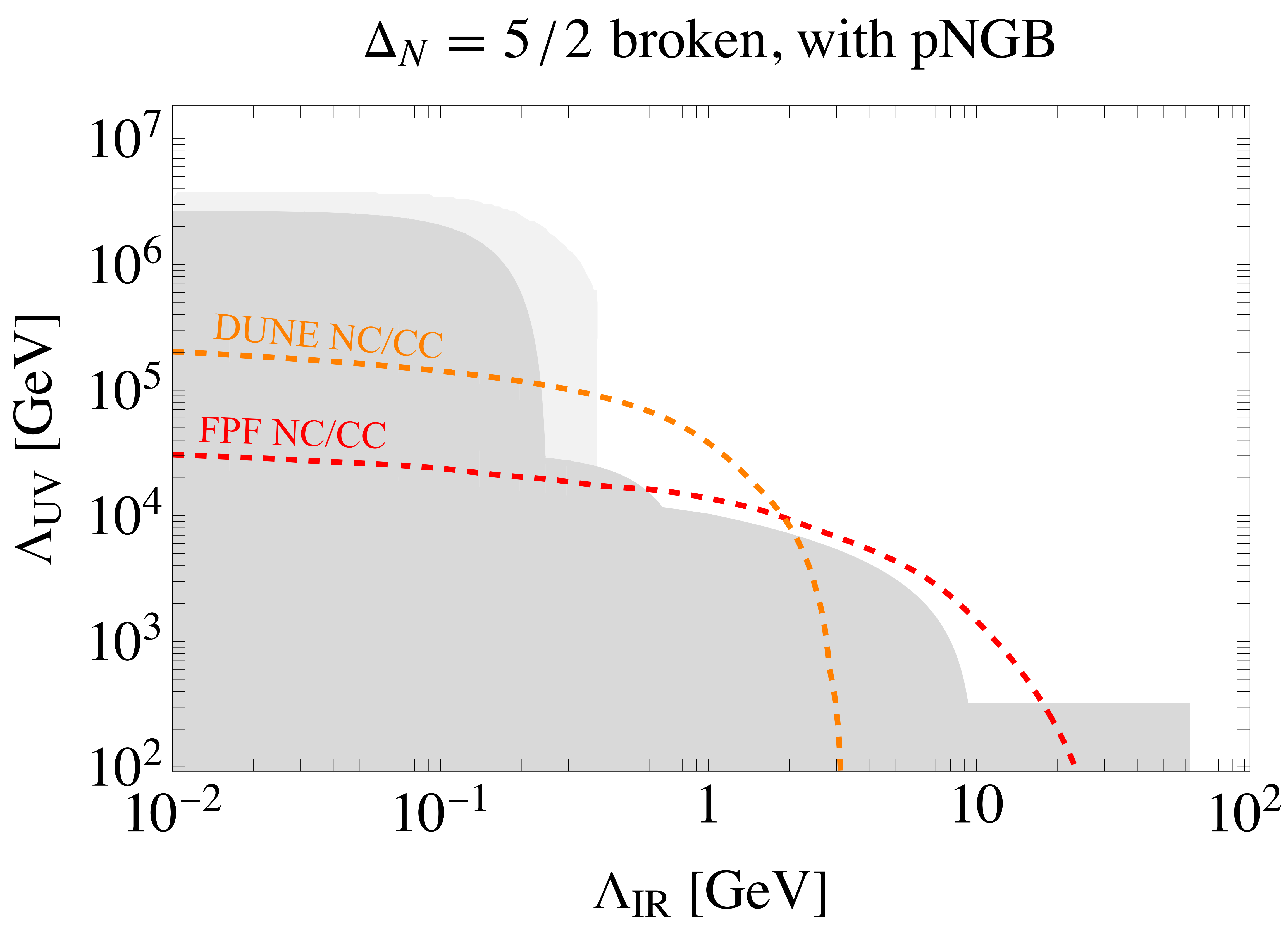


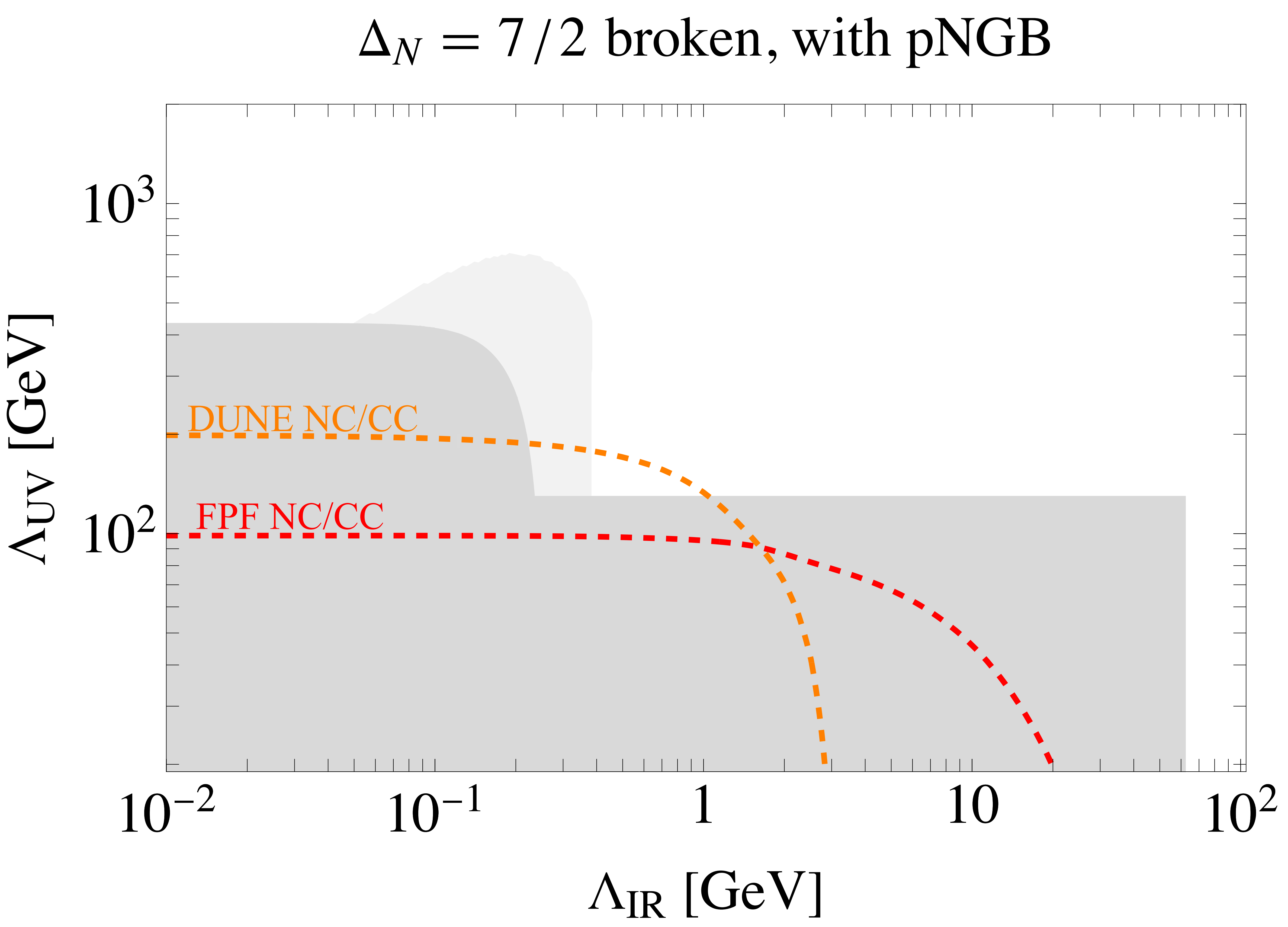




GB, CFT breaking

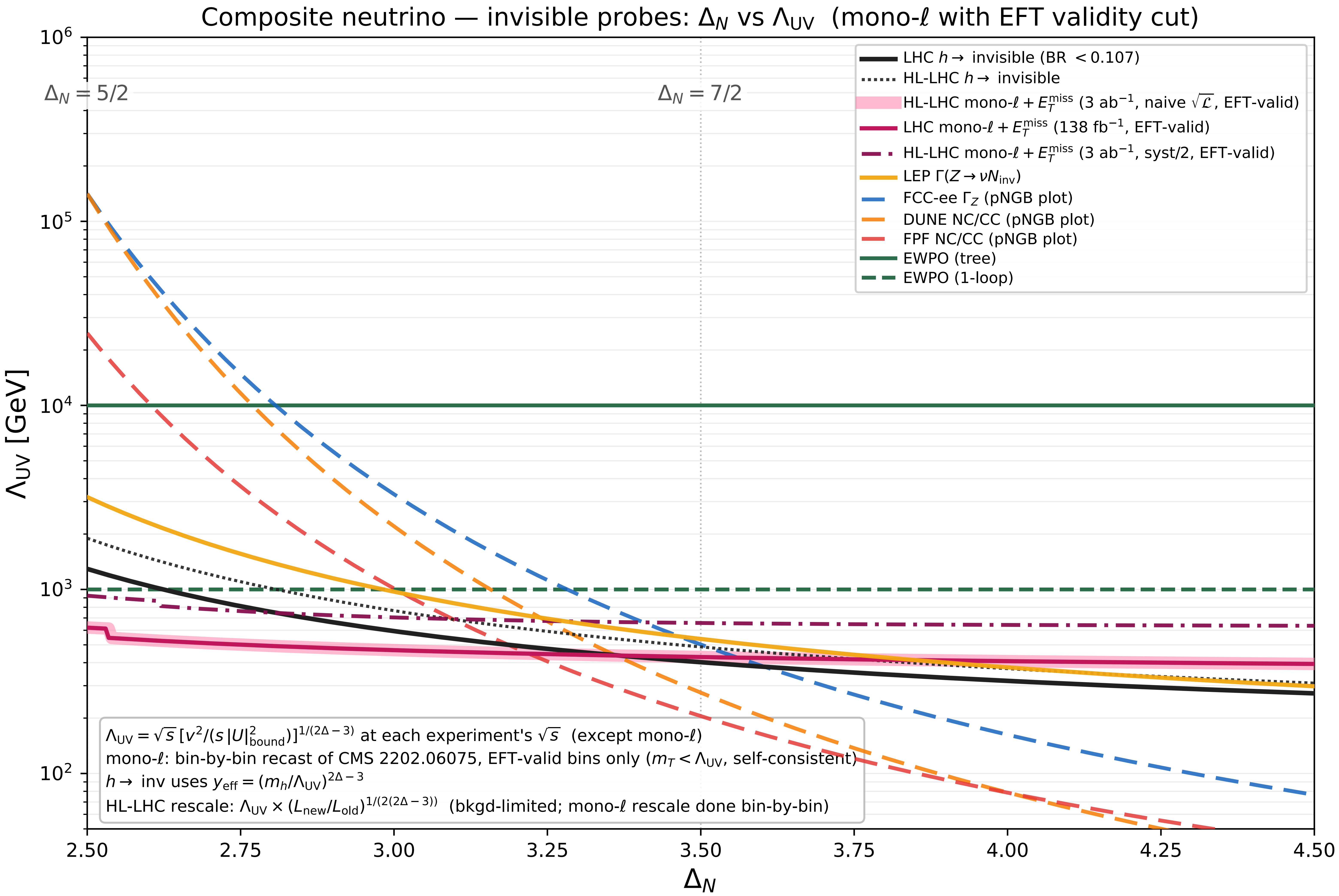




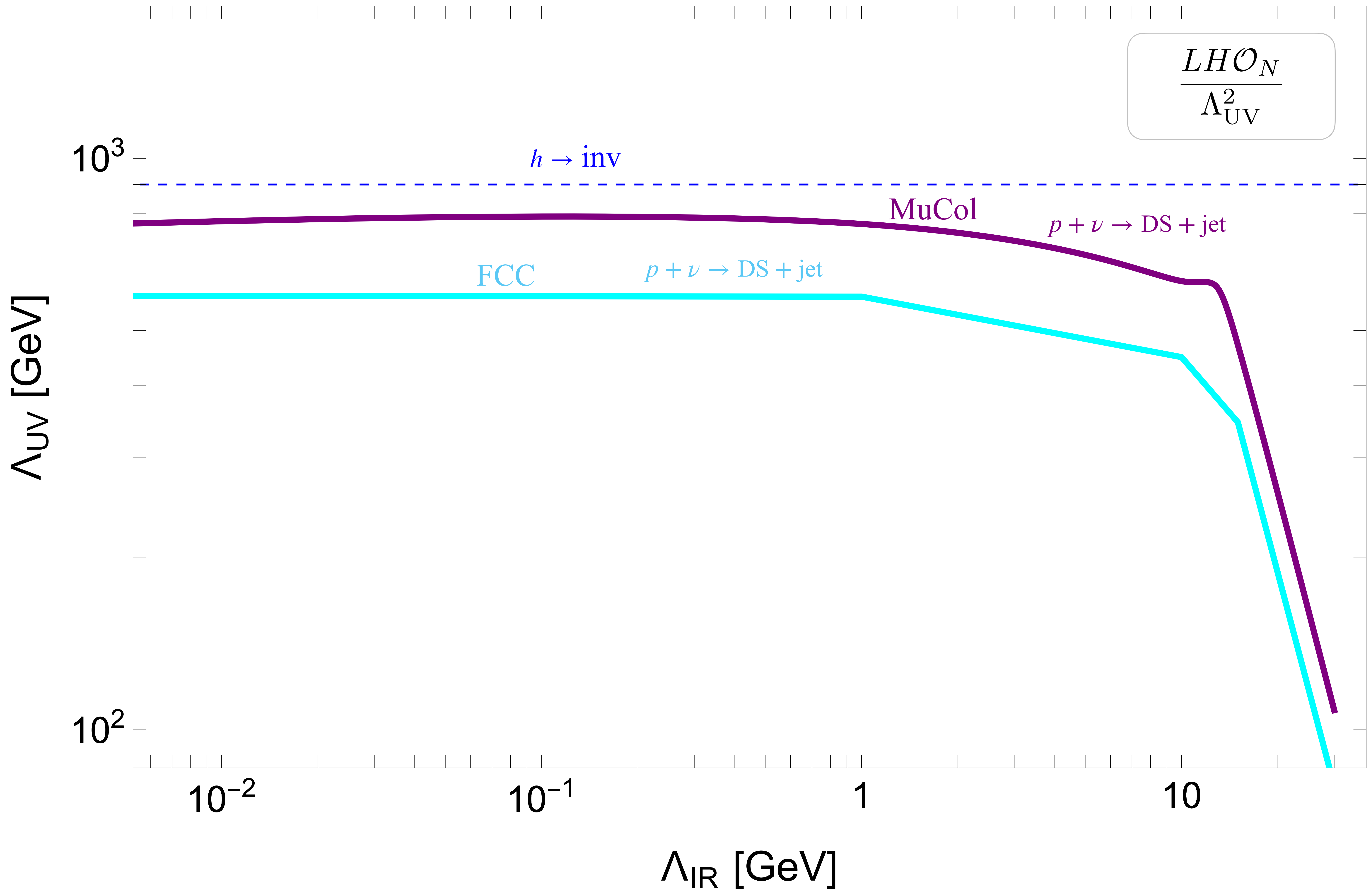


General expectations

PRELIMINARY



Future colliders



Composite dipole