A model independent probe for dark sectors at neutrino experiments

SCUOLA NORMALE SUPERIORE

Sonali Verma

Planck 2022

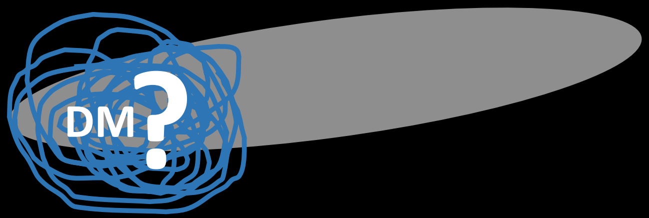
02 June 2022

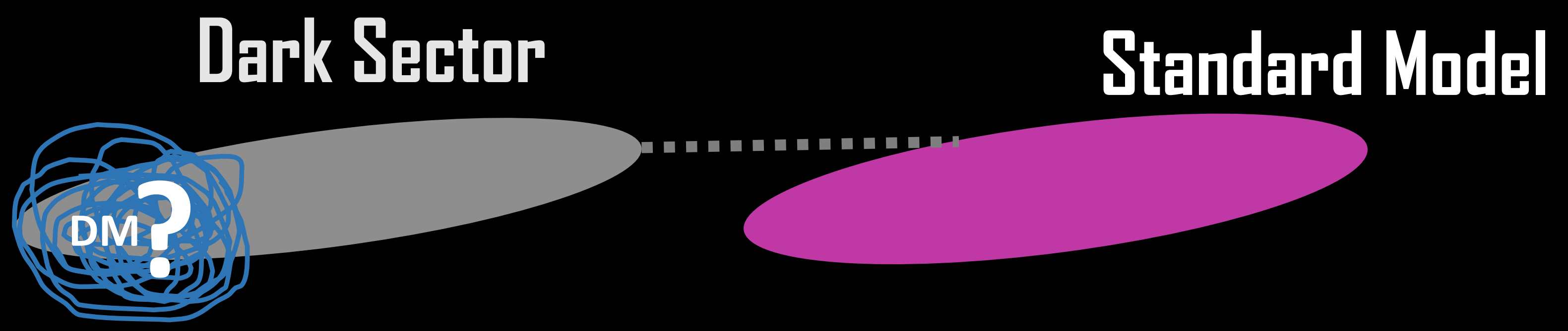
Work in progress

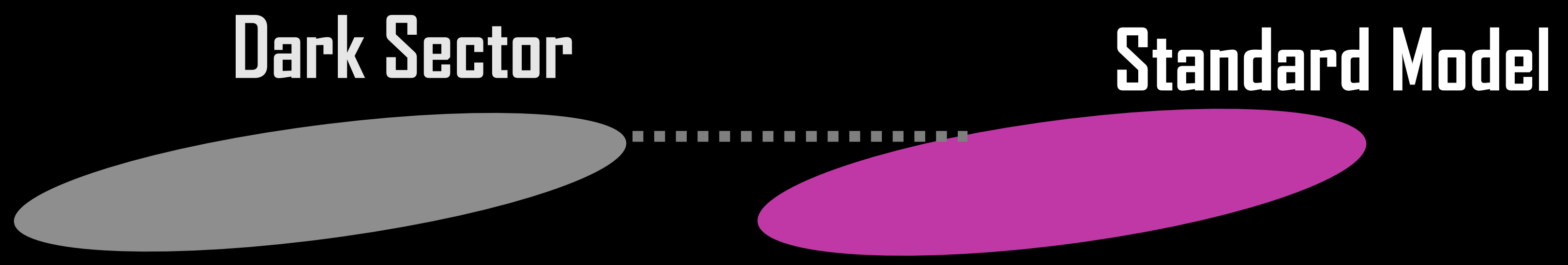
with Marco Costa, Rashmish K. Mishra.

INFN
Istituto Nazionale di Fisica Nucleare

Dark Sector



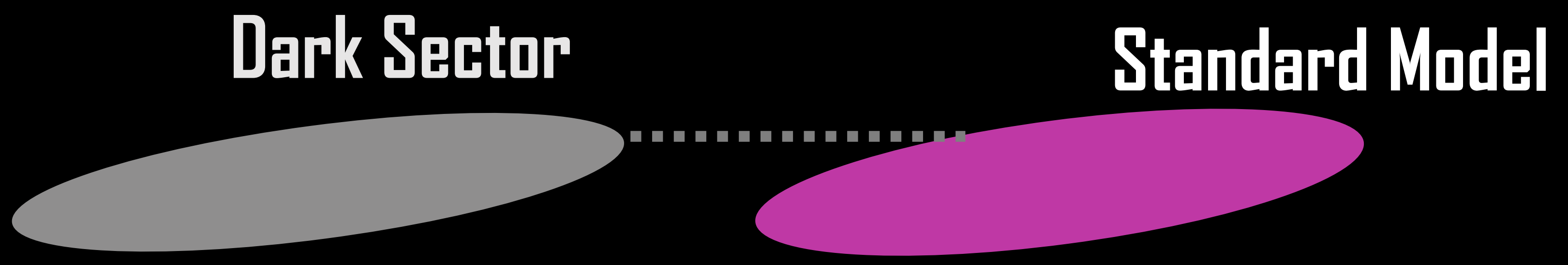

Dark Sector
Standard Model
DM?



$$\mathcal{L}_{\rm portal} = \mathcal{O}_{DS}\mathcal{O}_{SM}$$

Dark sector Singlet operator

SM Singlet operator

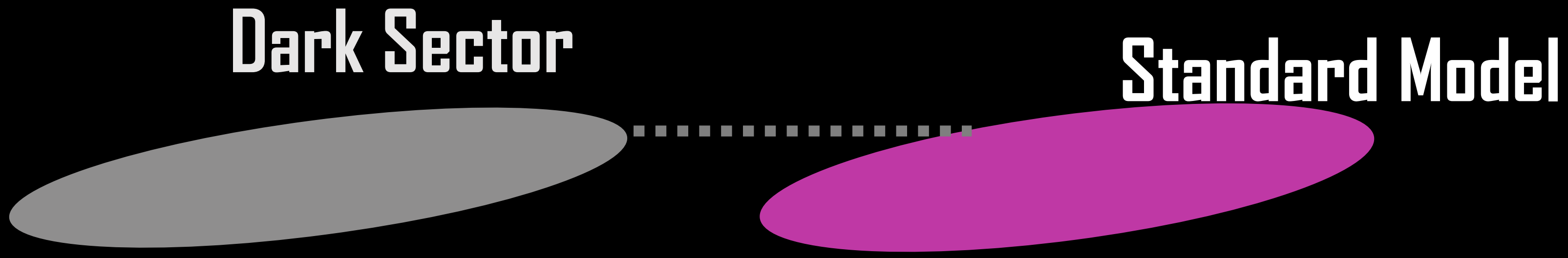


$$\mathcal{L}_{\text{portal}} = \mathcal{O}_{DS}\mathcal{O}_{SM}$$

$$\text{dim} = [\mathcal{O}_{\text{SM}}] + [\mathcal{O}_{\text{DS}}] \leq 4$$

Marginal + Relevant Portals

Dark higgs, dark photon, unparticle etc.



$$L_{\text{portal}} = \frac{\kappa}{\Lambda_{\text{UV}}^{D-4}} \mathcal{O}_{\text{DS}} \mathcal{O}_{\text{SM}}$$

Very elusive DS!

$$\text{dim} = [\mathcal{O}_{\text{SM}}] + [\mathcal{O}_{\text{DS}}] > 4$$

THIS TALK:

Irrelevant Portals

[Contino, Max, Mishra '20],
[Darme, Ellis, You '20],
[Cheng, Li, Salvioni '21]...

A **model independent probe** for dark sectors at neutrino experiments

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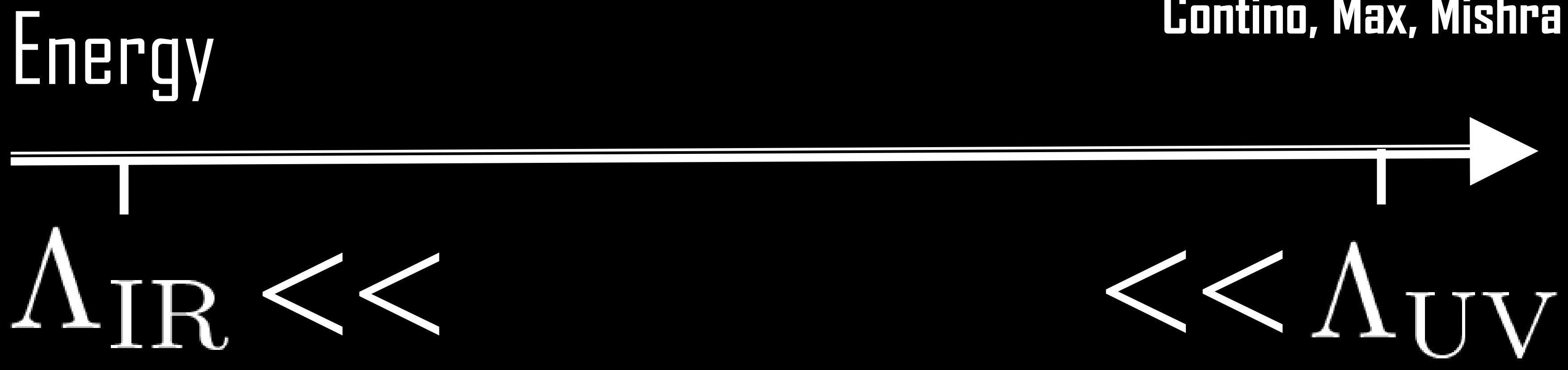
Minimal Assumptions?

Contino, Max, Mishra JHEP 06 (2021) 127



Minimal Assumptions?

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Minimal Assumptions?

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Energy

$$\Lambda_{IR} << p_{DS} << \Lambda_{UV}$$

Lightest state | Energy at which DS is probed | Mediator

Minimal Assumptions?

Energy

$$\Lambda_{\rm IR} << p_{DS} << \Lambda_{\rm UV}$$

Lightest state

Dark sector is conformal here!

Mediator

Minimal Assumptions?

Energy

$$\Lambda_{\mathrm{IR}} << p_{DS} << \Lambda_{\mathrm{UV}}$$

Lightest state | Dark sector is conformal here! | Mediator

Let's us be model independent!

Model Independence?

Energy

$$\Lambda_{\rm IR} << p_{DS} << \Lambda_{\rm UV}$$

Lightest state — Dark sector is conformal here! — Mediator

Let's us be model independent!

Inclusive cross section
for DS production

$$\sigma \propto \sum_n \int d\Phi_{\rm DS} |\langle 0|\mathcal{O}_{\rm DS}|n\rangle|^2 = 2\ {\rm Im}[i\langle 0|\mathcal{O}_{\rm DS}\mathcal{O}_{\rm DS}|0\rangle]$$

Model Independence?

Energy

$$\Lambda_{\rm IR} << p_{DS} << \Lambda_{\rm UV}$$

Lightest state

Dark sector is conformal here!

Mediator

Inclusive cross section for DS production

DS phase space

$$\sigma \propto \sum_n \int d\Phi_{\rm DS} |\langle 0|\mathcal{O}_{\rm DS}|n\rangle|^2 = 2\,{\rm Im}[i\langle 0|\mathcal{O}_{\rm DS}\mathcal{O}_{\rm DS}|0\rangle]$$

Model Independence?

Energy

$$\Lambda_{\rm IR} << p_{DS} << \Lambda_{\rm UV}$$

Lightest state — Dark sector is conformal here! — Mediator

Inclusive cross section for DS production

DS operator interpolating DS state $|n\rangle$ from vacuum

$$\sigma \propto \sum_n \int d\Phi_{\rm DS} |\langle 0|\mathcal{O}_{\rm DS}|n\rangle|^2 = 2\,{\rm Im}[i\langle 0|\mathcal{O}_{\rm DS}\mathcal{O}_{\rm DS}|0\rangle]$$

Model Independence?

Energy

$\Lambda_{\text{IR}} << p_{DS} << \Lambda_{\text{UV}}$

Lightest state

Dark sector is conformal here!

Mediator

Inclusive cross section for DS production

From conformal invariance

Optical Theorem

$$\sigma \propto \sum_n \int d\Phi_{\text{DS}} |\langle 0|\mathcal{O}_{\text{DS}}|n\rangle|^2 = 2\ \text{Im}[i\langle 0|\mathcal{O}_{\text{DS}}\mathcal{O}_{\text{DS}}|0\rangle]$$

Model Independence?

Approximate inclusive DS production cross section in a model independent way when well above threshold!

Inclusive cross section for DS production

From conformal invariance

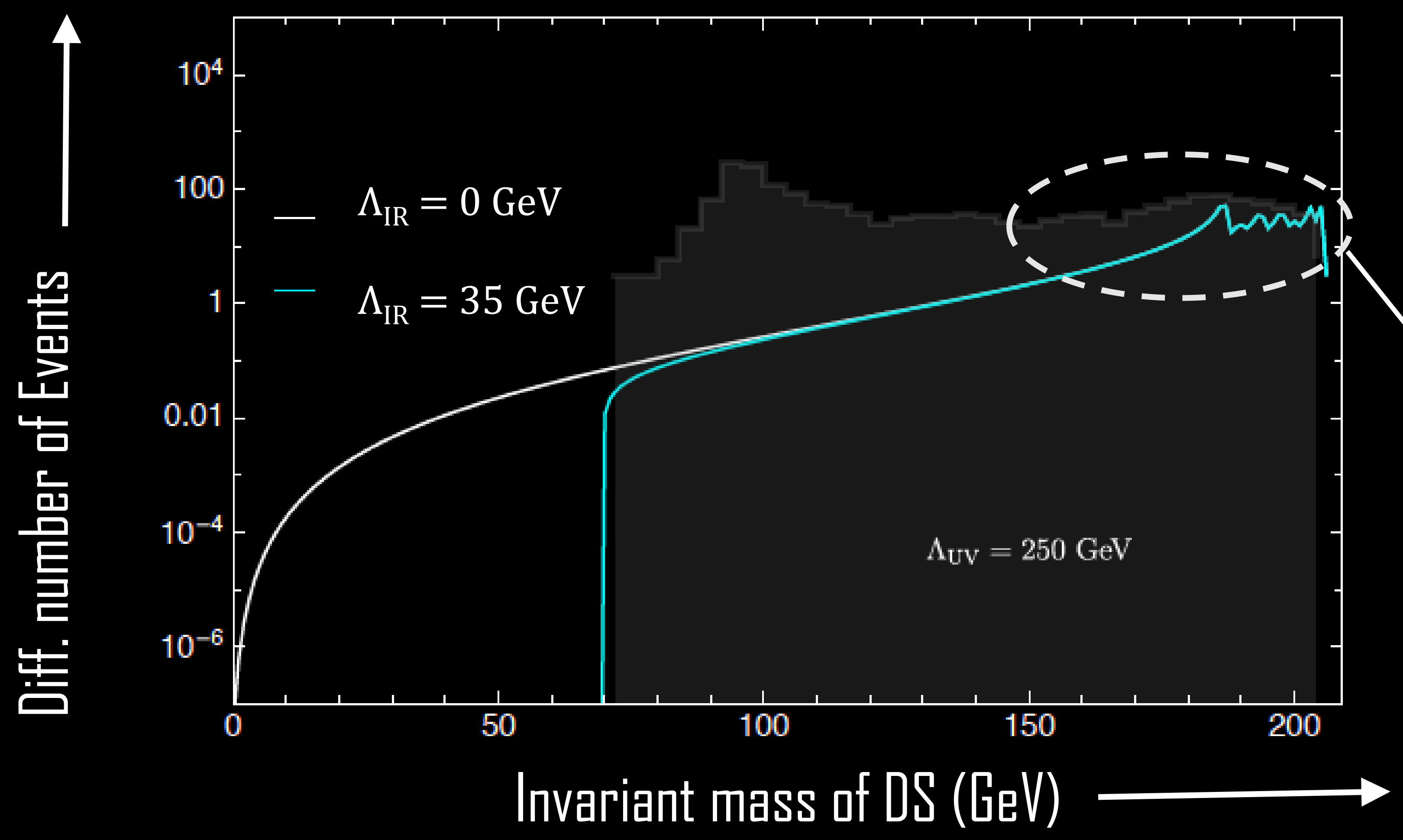
Optical Theorem

$$\sigma \propto \sum_n \int d\Phi_{\rm DS} |\langle 0|\mathcal{O}_{\rm DS}|n\rangle|^2 = 2\ {\rm Im}[i\langle 0|\mathcal{O}_{\rm DS}\mathcal{O}_{\rm DS}|0\rangle]$$

How good is the approximation?

Contino, Max, Mishra 2012.08537

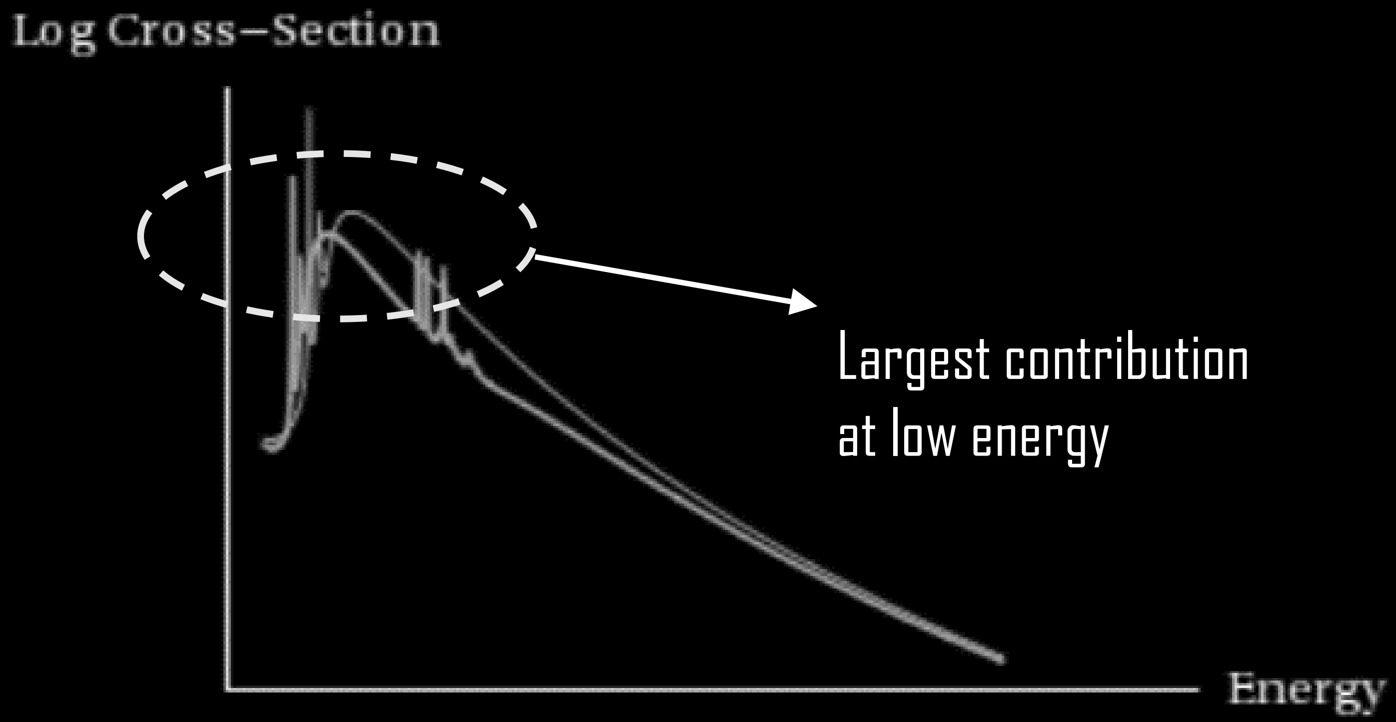
Free Fermion DS: 1 Majorana fermion + 1 scalar (integrated out)



Largest contribution at high p_{DS}^2 away from threshold

For relevant portals: See Strassler arXiv:0801.0629

$$\mathcal{O}_{\mathrm{DS}} H^\dagger H \qquad \Delta_{\mathcal{O}} < 2$$

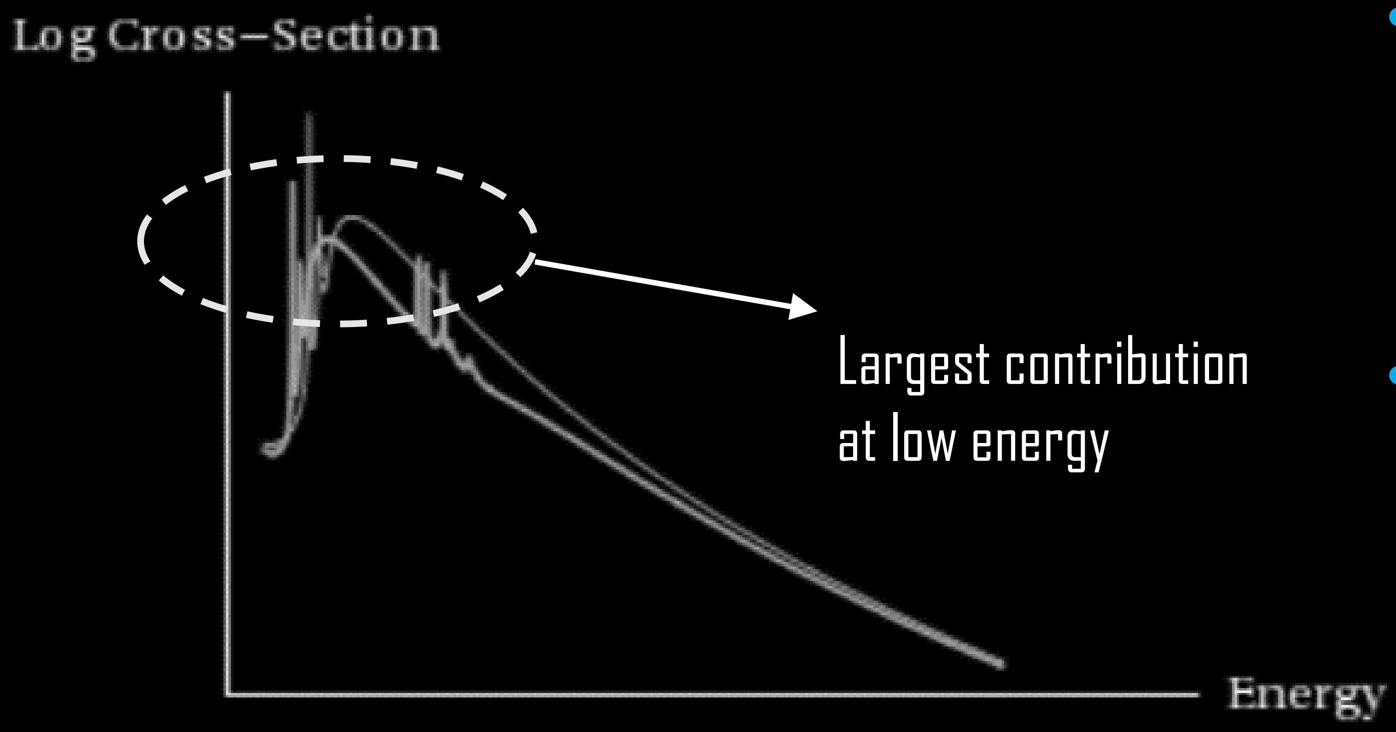


Largest contribution at low energy

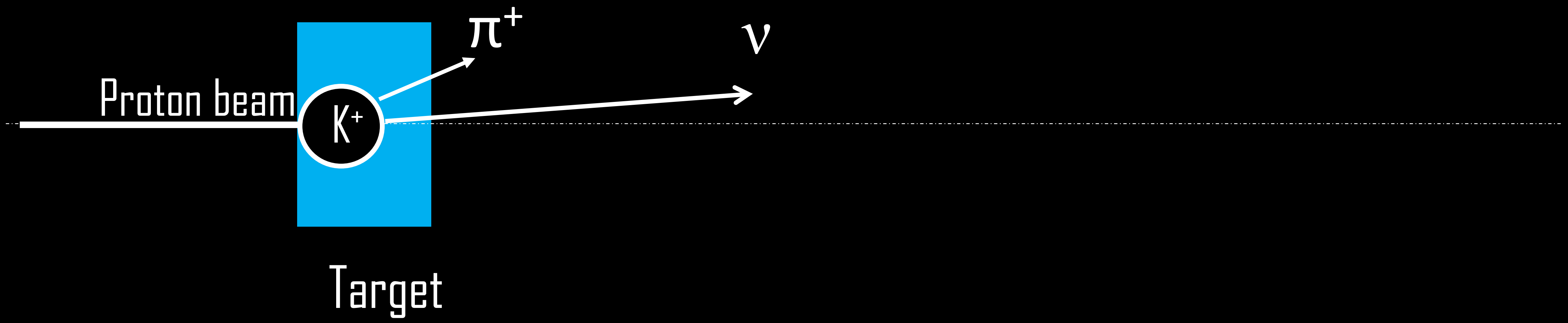
For relevant portals:

See Strassler arXiv:0801.0629

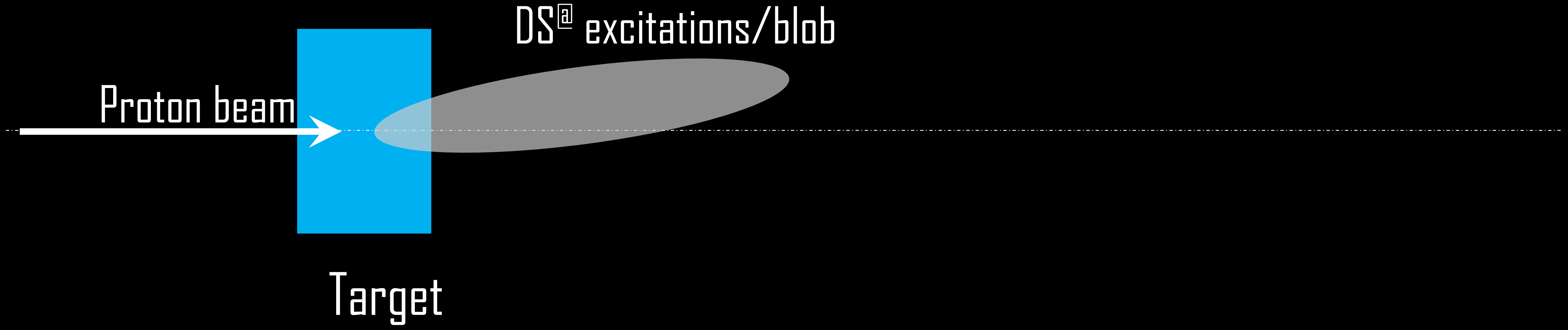
$$\mathcal{O}_{\rm DS} H^\dagger H \qquad \Delta_{\mathcal{O}} < 2$$



- Threshold contributions depend on dimensionality of portals
- For D > 4, cross section grows with energy, bulk of events are in the conformal regime.
- Our approximation works v well for irrelevant portals!



π^+
ν
Proton beam
K^+
Target

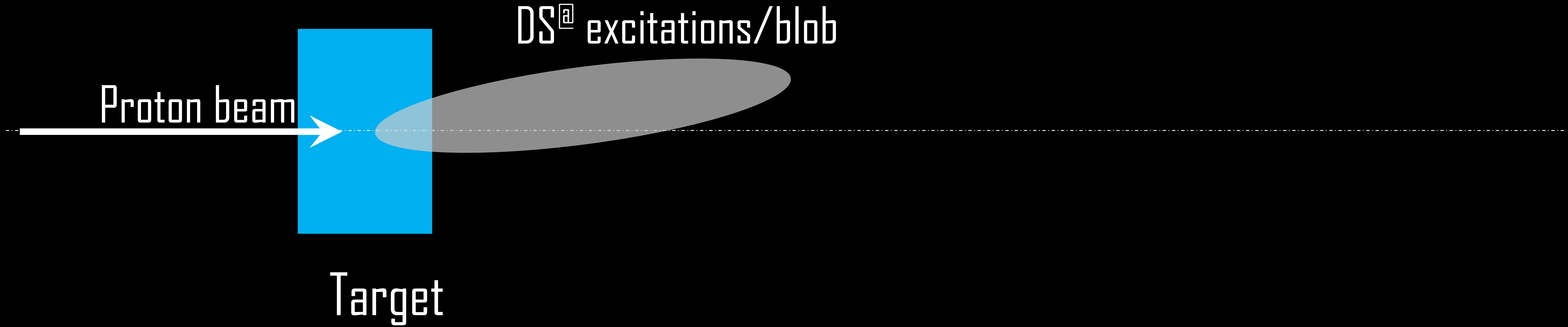


@Dark Sector

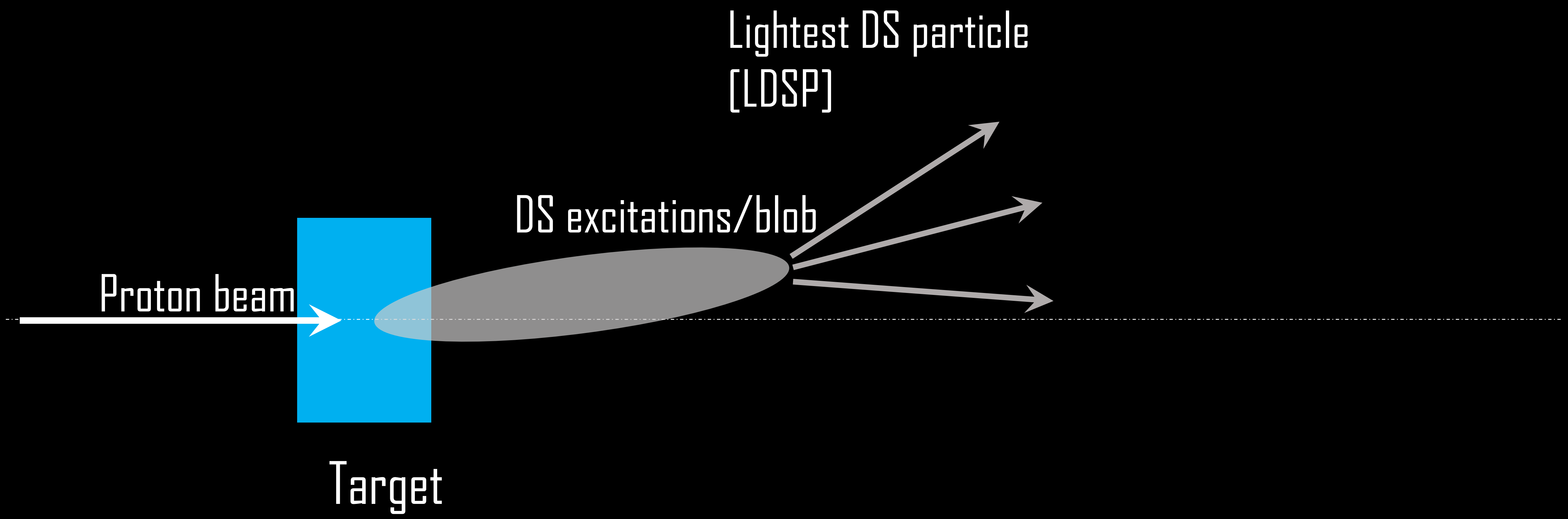
$K \longrightarrow \pi + DS$

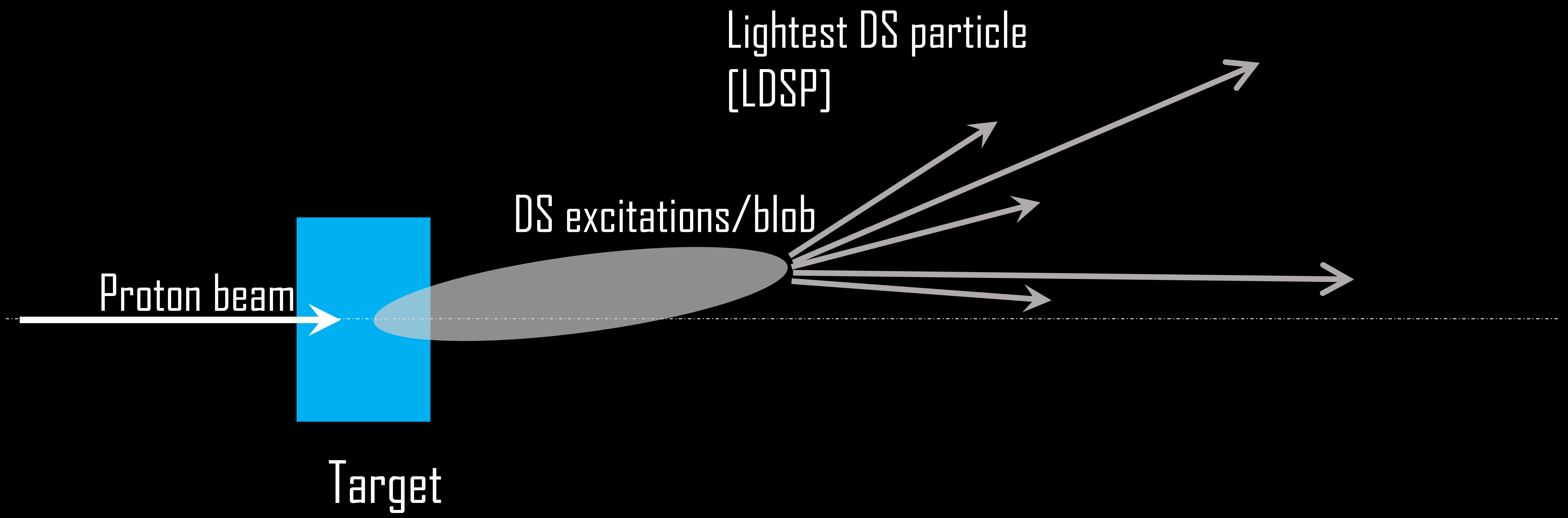
$\text{partons} \longrightarrow DS$

$p + p \longrightarrow DS\ [ISR] + X$

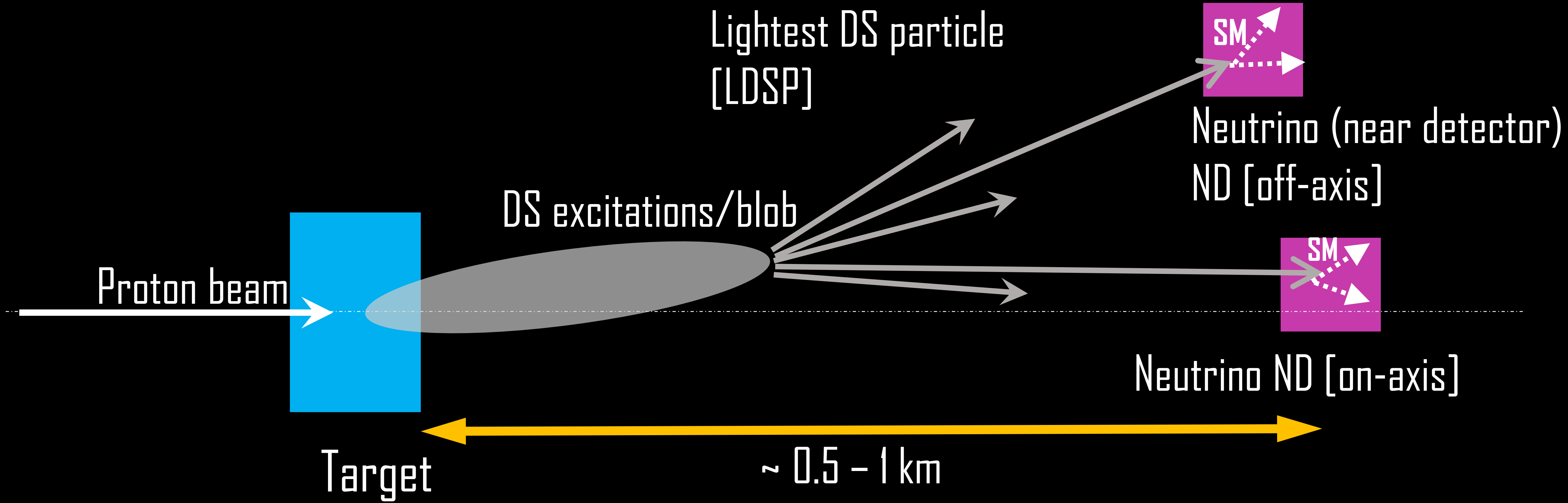


@Dark Sector

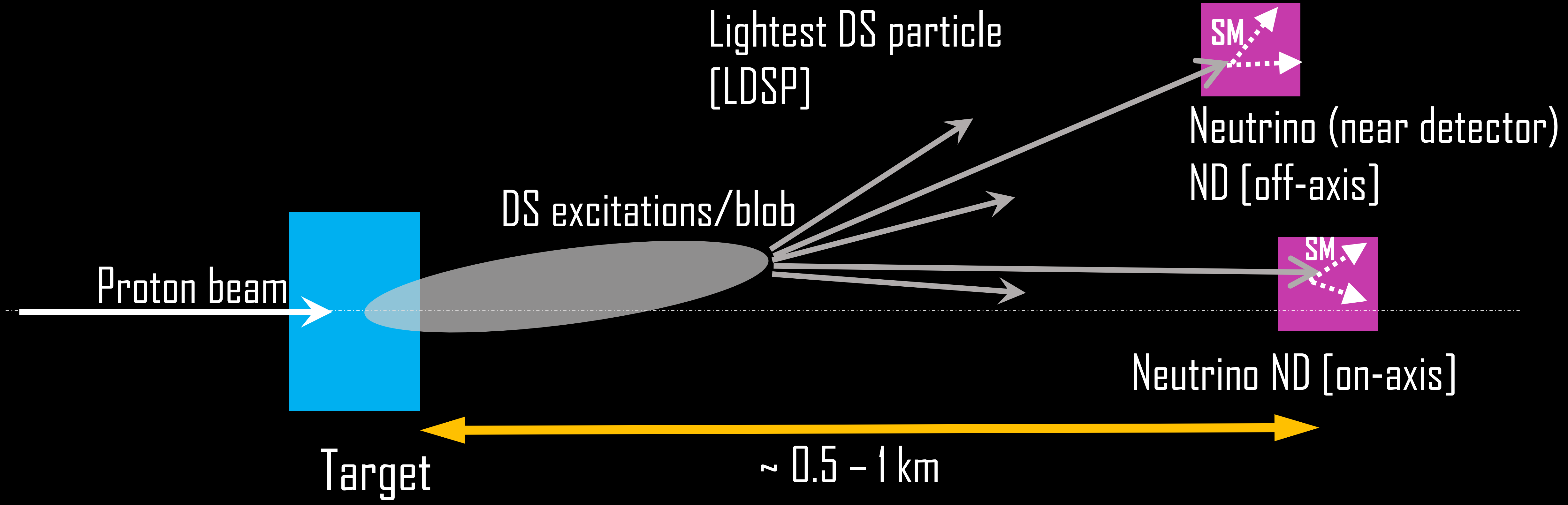

Lightest DS particle
[LDSP]
DS excitations/blob
Proton beam
Target



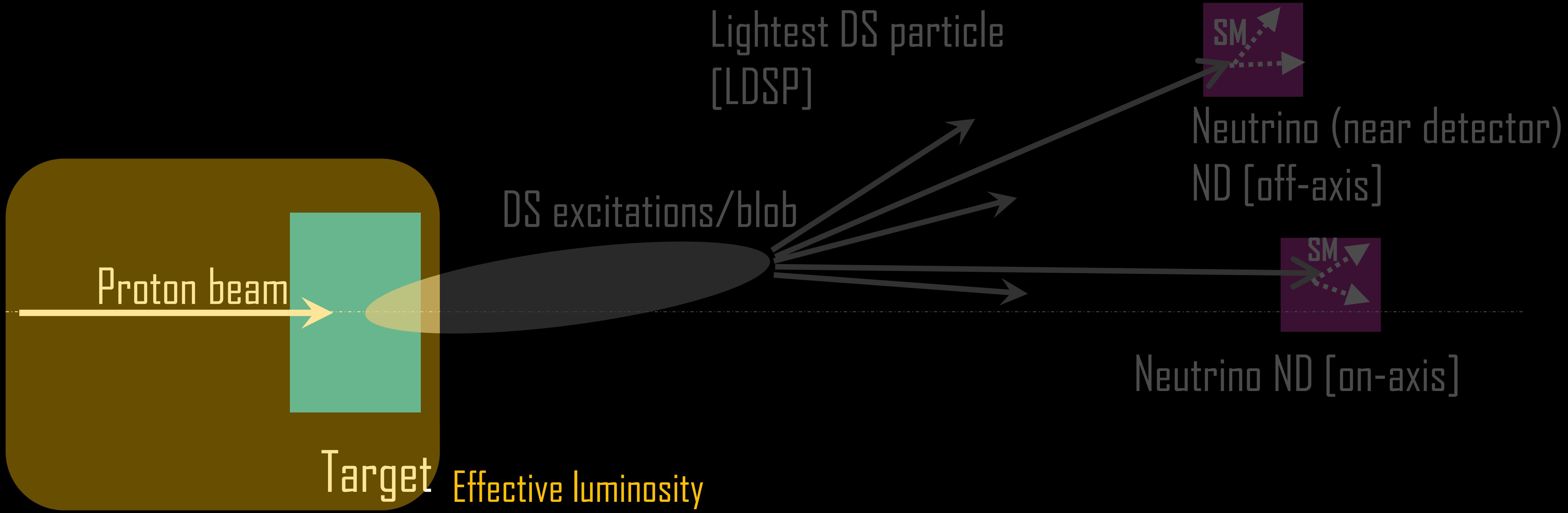
Lightest DS particle
(LDSP)
DS excitations/blob
Proton beam
Target



Lightest DS particle
[LDSP]
SM
Neutrino (near detector)
ND [off-axis]
DS excitations/blob
SM
Proton beam
Neutrino ND [on-axis]
Target
~ 0.5 – 1 km



$$\text{Signal} = \frac{N_{\text{POT}}}{\sigma_{\text{pN}}} \times \sigma_{\text{prod}} \times P_{\text{decay}} \times \epsilon_{\text{geo}}$$

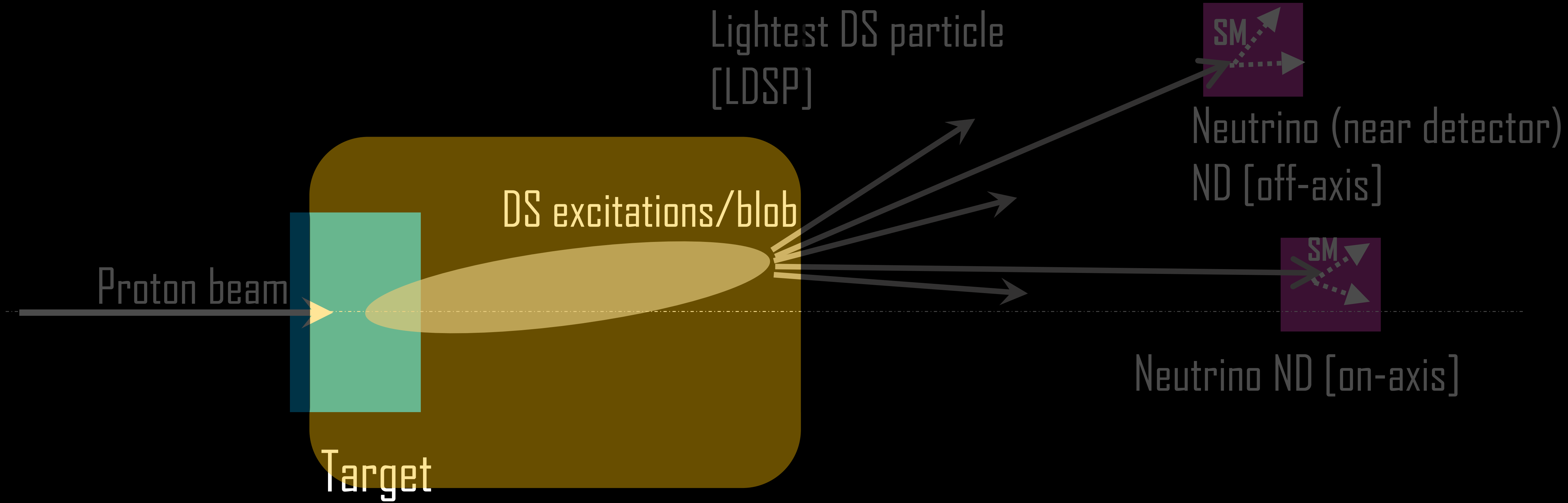


Effective luminosity

$$\text{Signal} = \frac{N_{\text{POT}}}{\sigma_{\text{pN}}} \times \sigma_{\text{prod}} \times P_{\text{decay}} \times \epsilon_{\text{geo}}$$

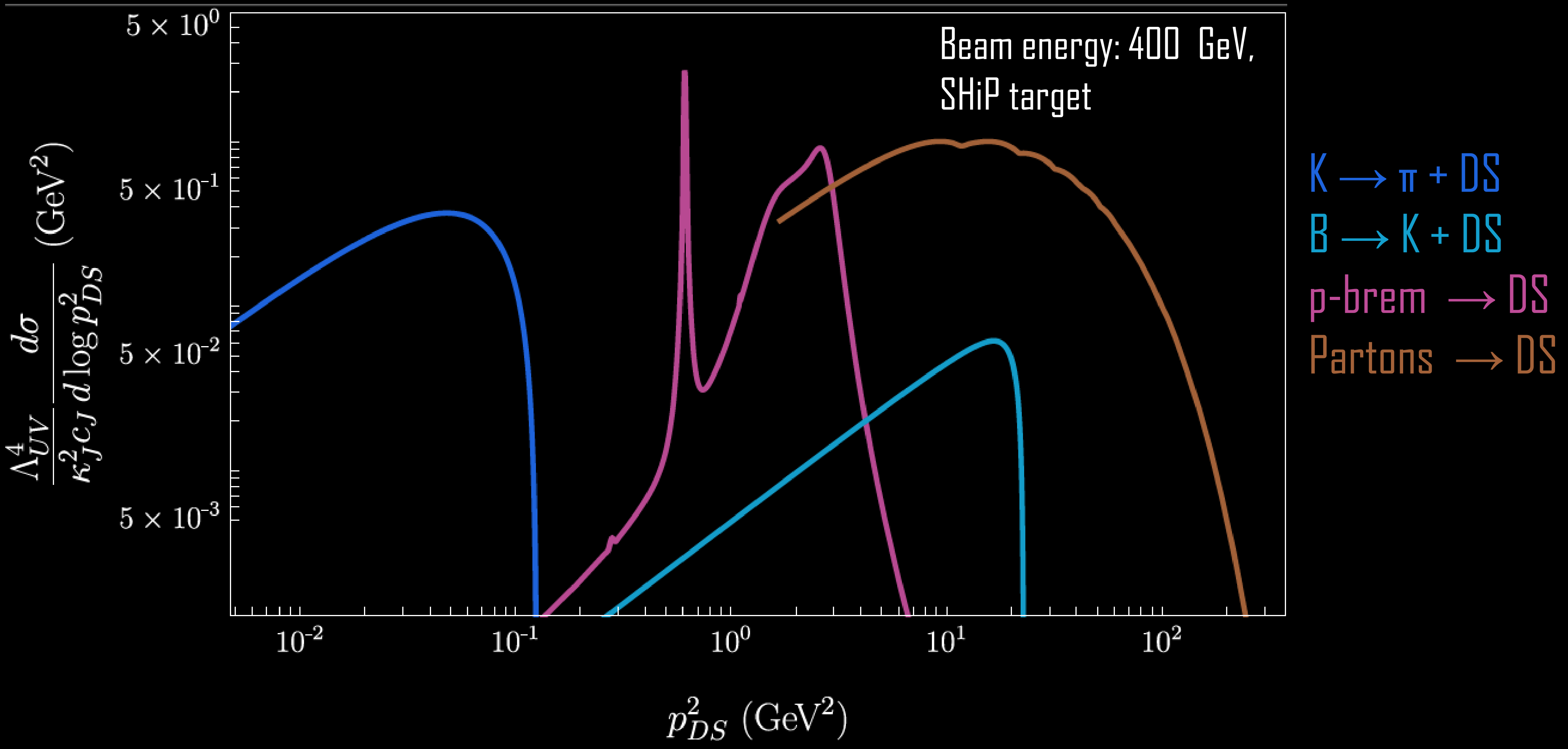
protons on target

cross section p on target



DS production cross section

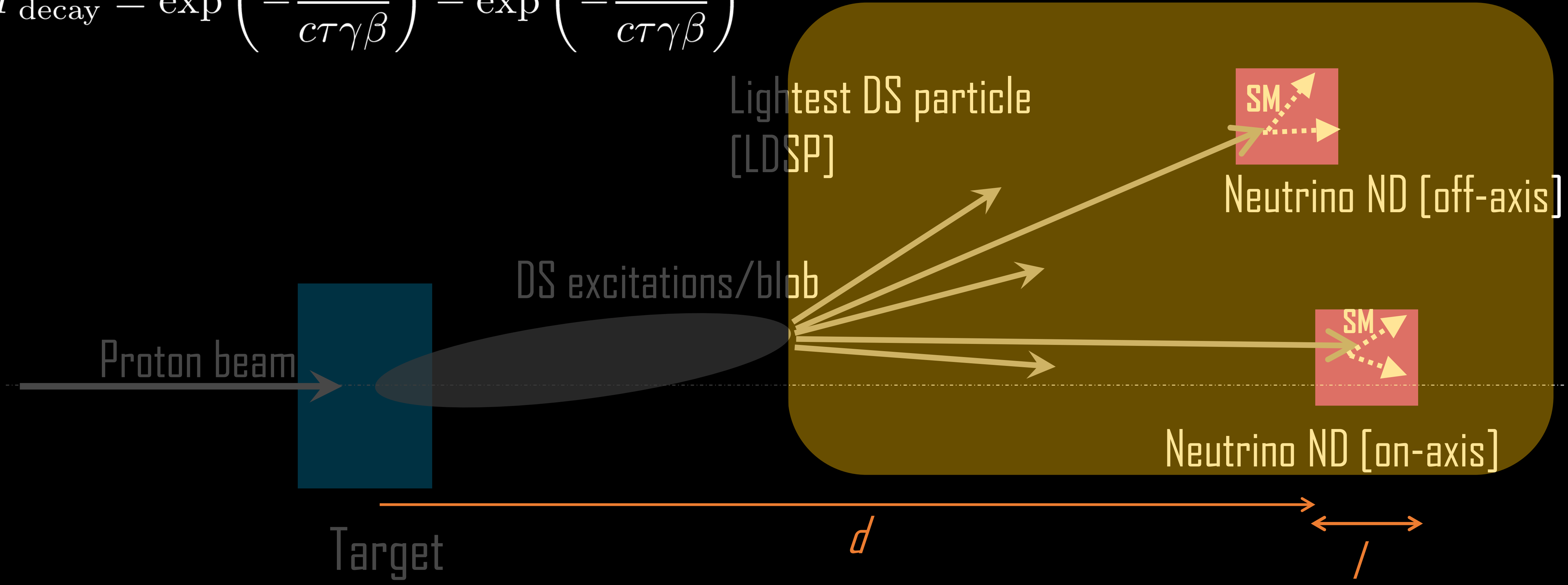
$$\text{Signal} = \frac{N_{\text{POT}}}{\sigma_{\text{pN}}} \times \sigma_{\text{prod}} \times P_{\text{decay}} \times \epsilon_{\text{geo}}$$



DS production cross section

$$\text{Signal} = \frac{N_{\text{POT}}}{\sigma_{\text{pN}}} \times \sigma_{\text{prod}} \times P_{\text{decay}} \times \epsilon_{\text{geo}}$$

$$P_{\rm decay} = \exp\left(-\frac{d}{c\tau\gamma\beta}\right) - \exp\left(-\frac{d+l}{c\tau\gamma\beta}\right)$$



Probability of LDSP decaying inside detector

$$\text{Signal} = \frac{N_{\rm POT}}{\sigma_{\rm pN}} \times \sigma_{\rm prod} \times P_{\rm decay} \times \epsilon_{\rm geo}$$

$$P_{\rm decay} = \exp\left(-\frac{d}{c\tau\gamma\beta}\right) - \exp\left(-\frac{d+l}{c\tau\gamma\beta}\right)$$

Average boost factor

DS 3-momentum lab

$$\langle\gamma\beta\rangle = \frac{\langle\vec{p}_{\rm DS}^{\,\rm lab}\rangle}{n_{\rm LDSP}\Lambda_{\rm IR}}$$

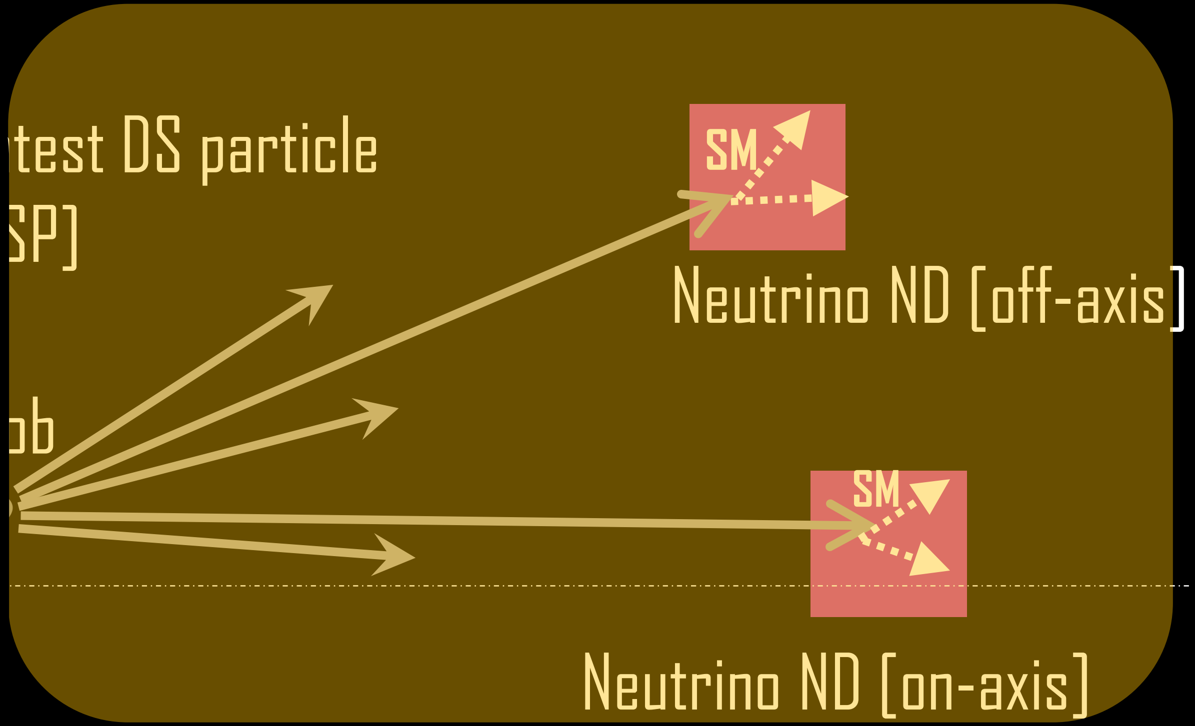
LDSPs

$$(\tau_{\rm LDSP})^{-1} \sim \Lambda_{\rm IR}\frac{\kappa^2}{8\pi}\frac{f^2}{\Lambda_{\rm IR}^2}\left(\frac{\Lambda_{\rm IR}^2}{\Lambda_{\rm UV}^2}\right)^{D-4}$$

c = # dark d.o.f.

D = dimension of portal

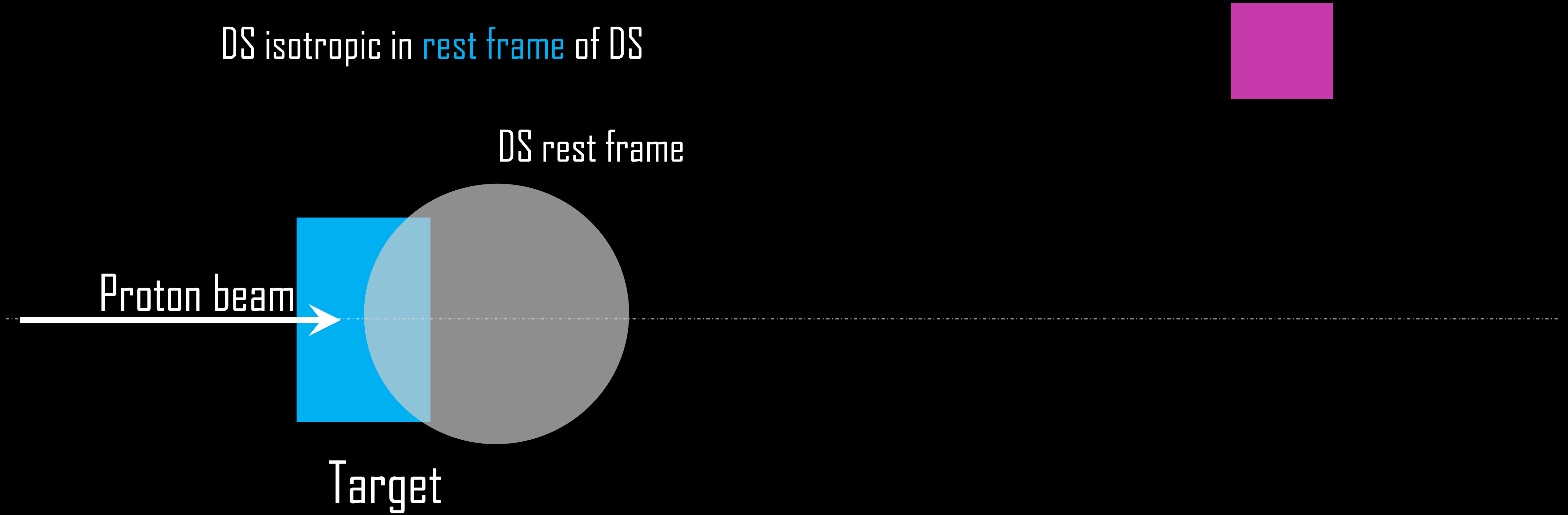
$$f = \sqrt{c}\Lambda_{\rm IR}/4\pi$$



Probability of LDSP decaying inside detector

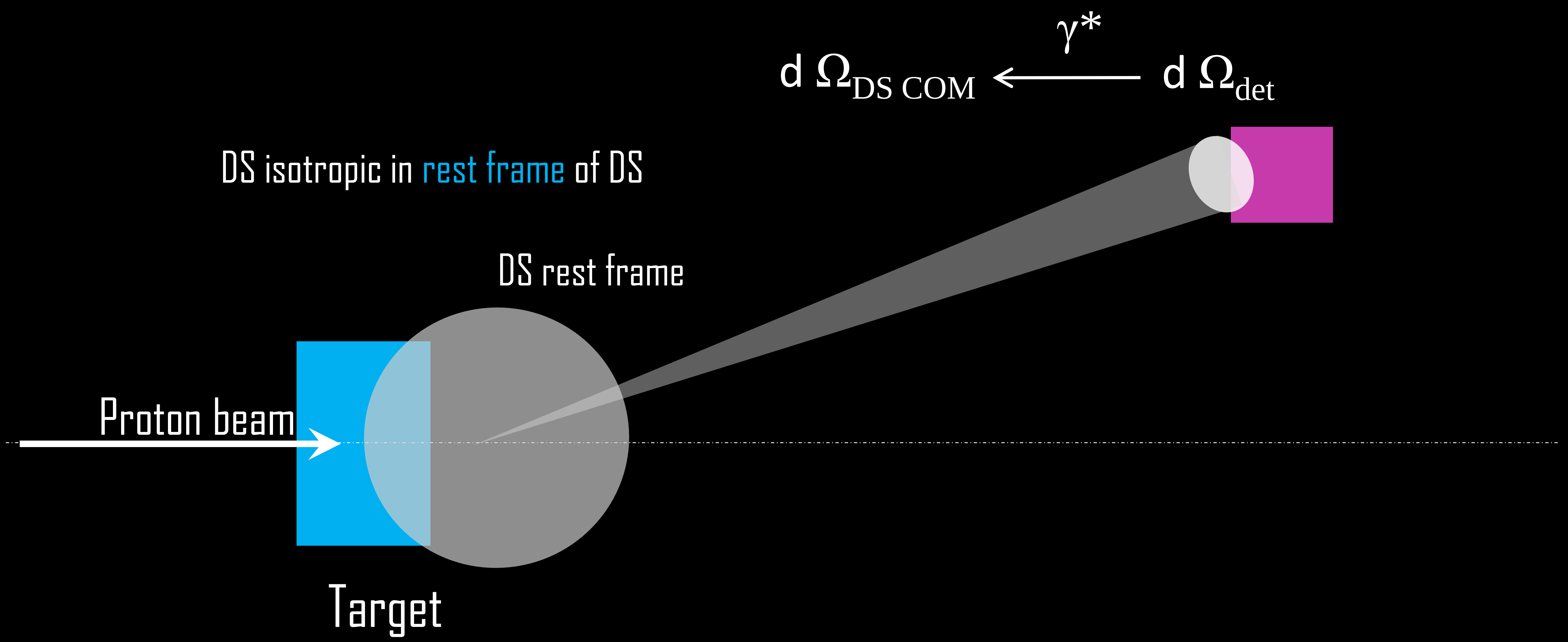
$$\text{Signal} = \frac{N_{\rm POT}}{\sigma_{\rm pN}} \times \sigma_{\rm prod} \times P_{\rm decay} \times \epsilon_{\rm geo}$$

DS isotropic in rest frame of DS



Geometric acceptance

$$\text{Signal} = \frac{N_{\text{POT}}}{\sigma_{\text{pN}}} \times \sigma_{\text{prod}} \times P_{\text{decay}} \times \epsilon_{\text{geo}}$$



Geometric acceptance

$$\text{Signal} = \frac{N_{\text{POT}}}{\sigma_{\text{pN}}} \times \sigma_{\text{prod}} \times P_{\text{decay}} \times \epsilon_{\text{geo}}$$

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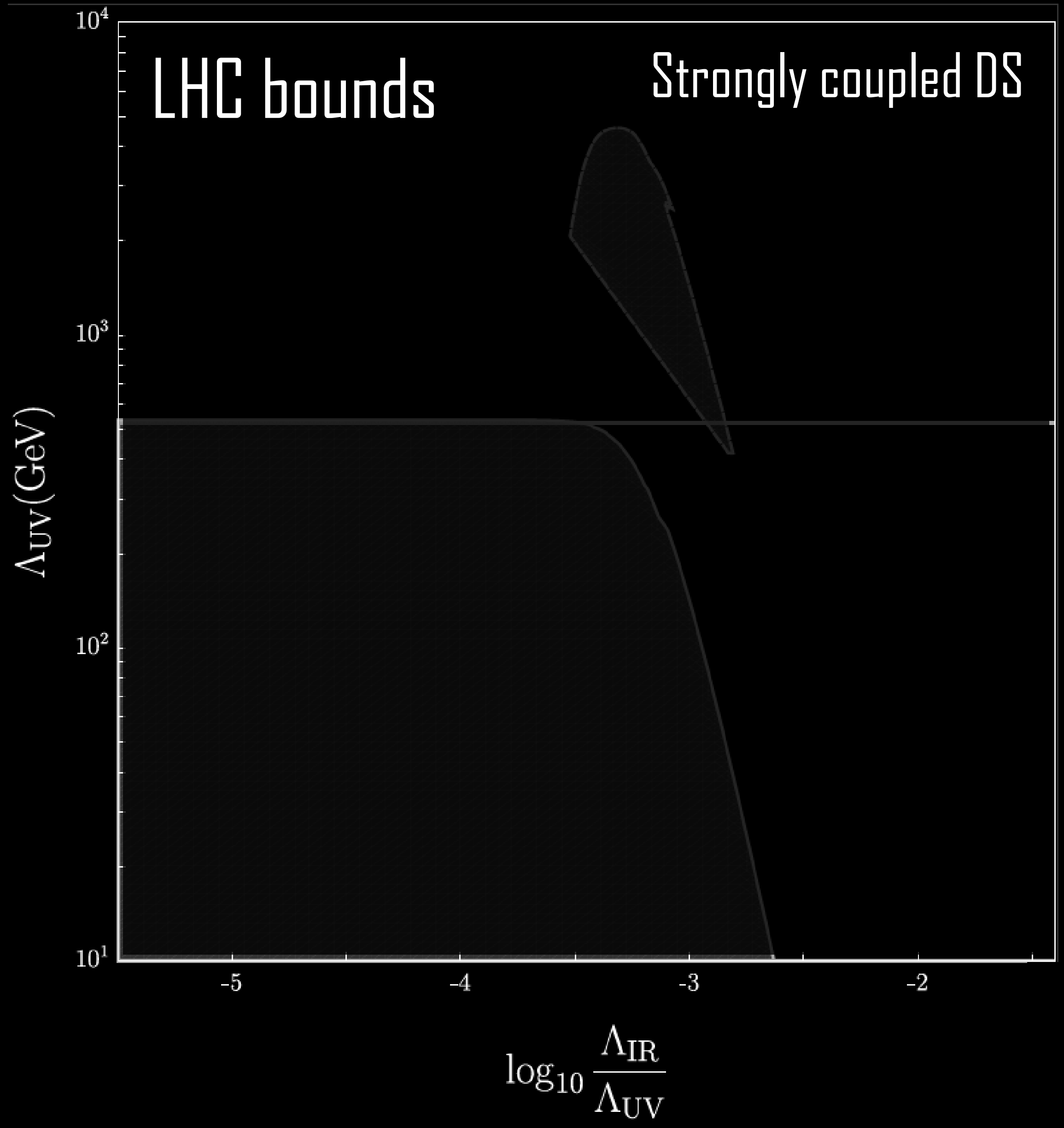

Portal: $H^\dagger i D_\mu H J^\mu_{\rm DS}$

$\downarrow$

$v m_z Z_\mu J^\mu_{\rm DS}$

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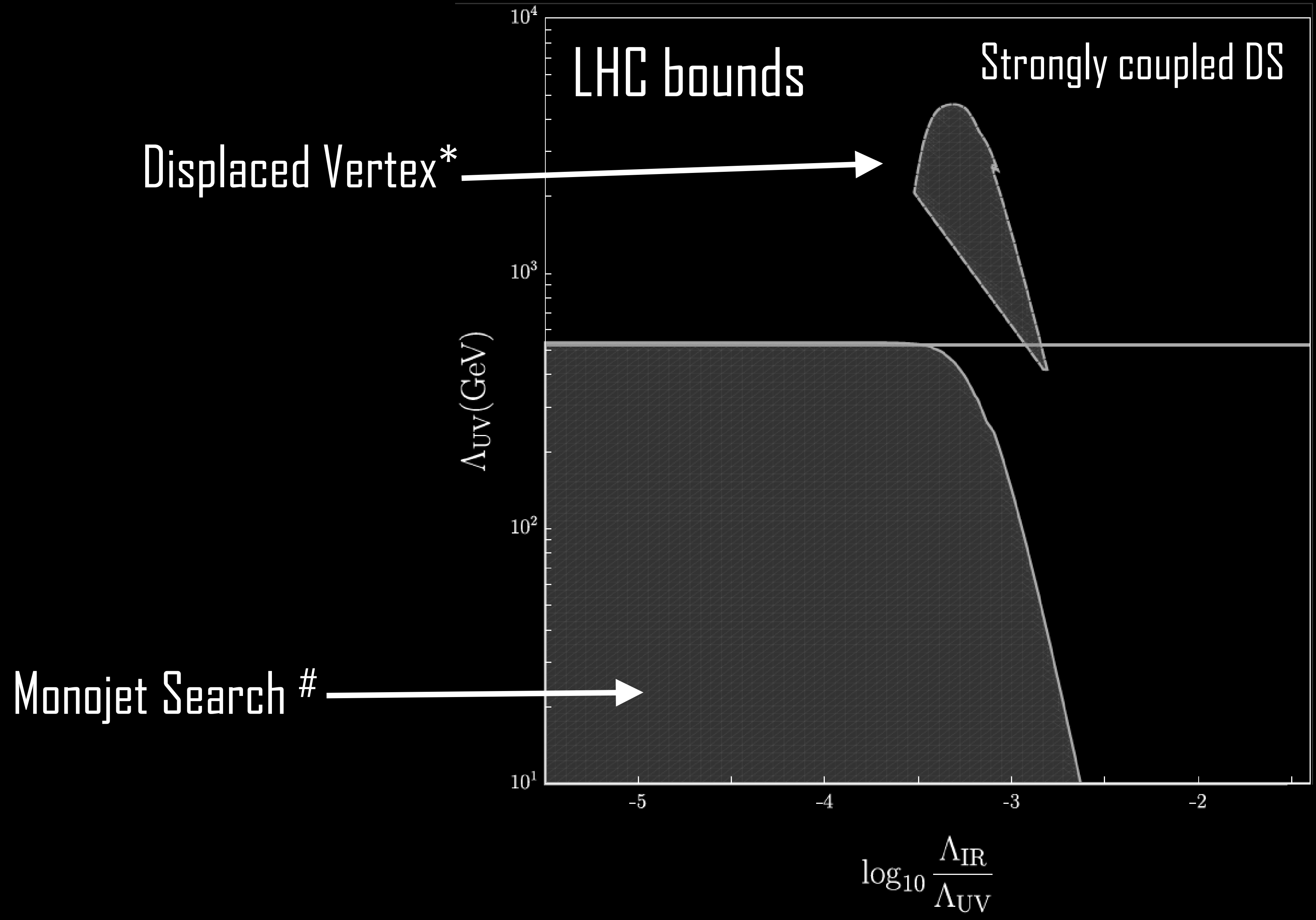

Portal: $H^\dagger i D_\mu H J^\mu_{\rm DS}$

↓

$v m_z Z_\mu J^\mu_{\rm DS}$

*ATLAS search for Displaced Vertex PRD (2019)(2020)

#ATLAS JHEP 01 (2018) 126

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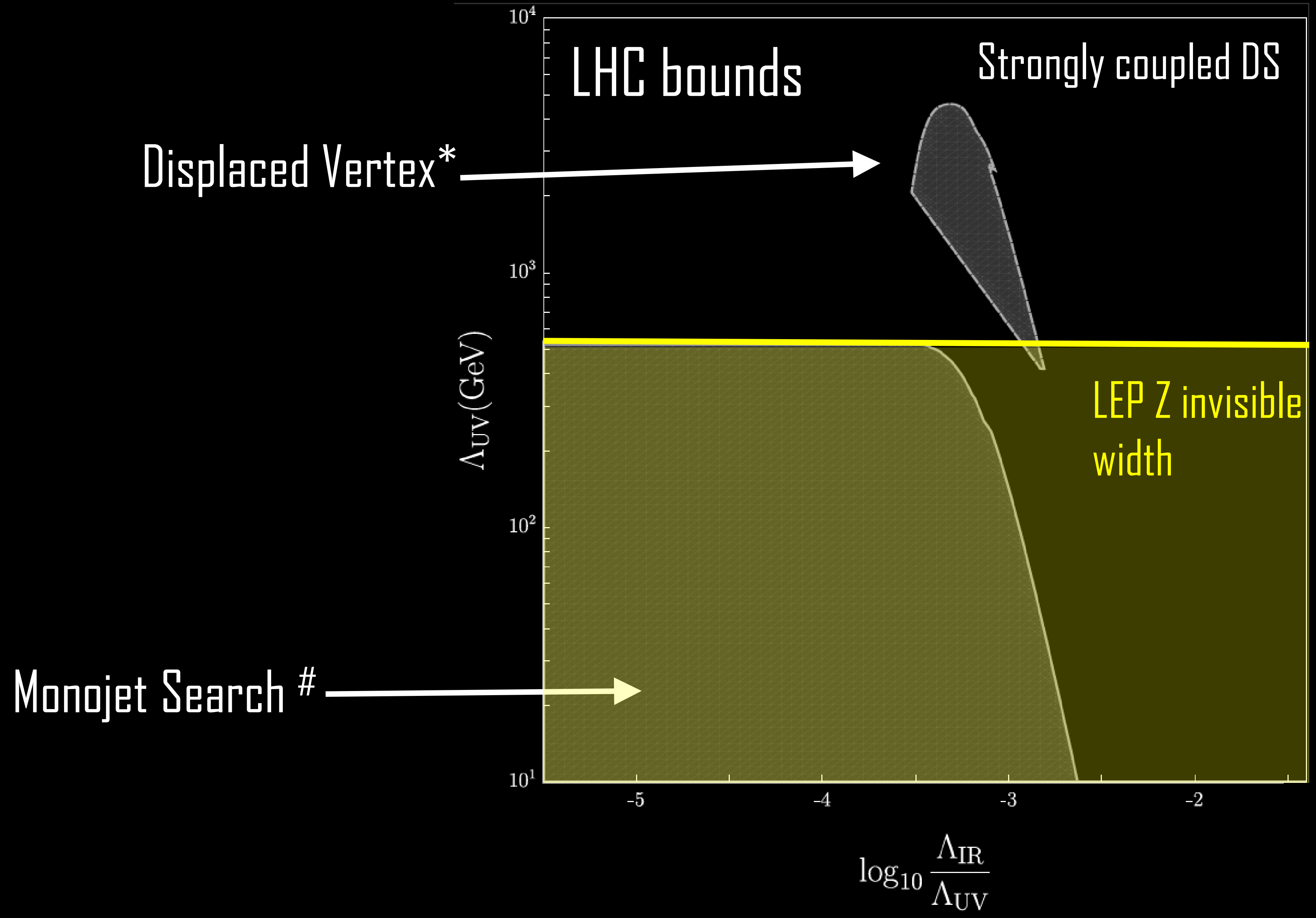

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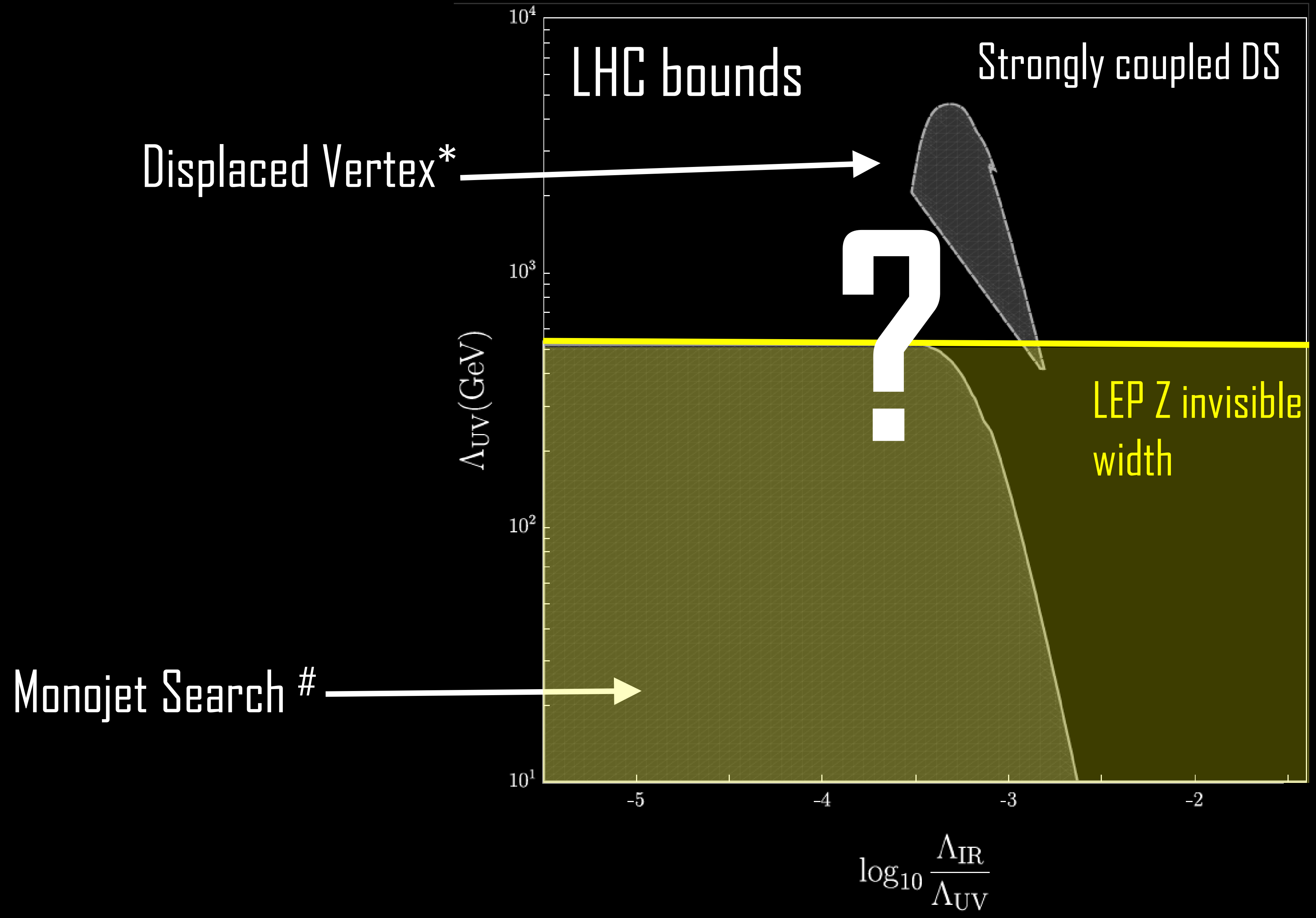

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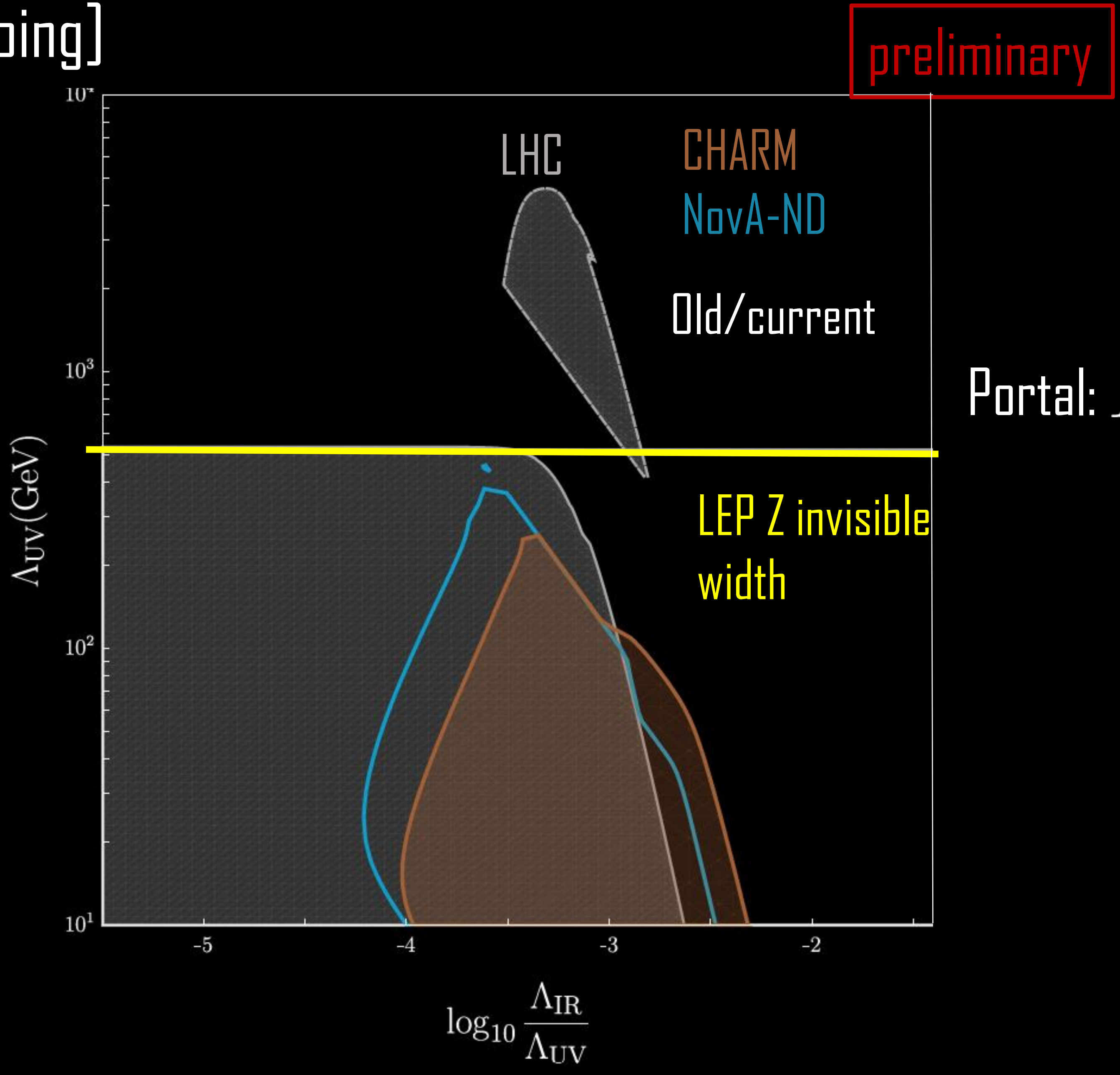
#ATLAS JHEP 01 (2018) 126

Costa, Mishra, SV [ongoing]

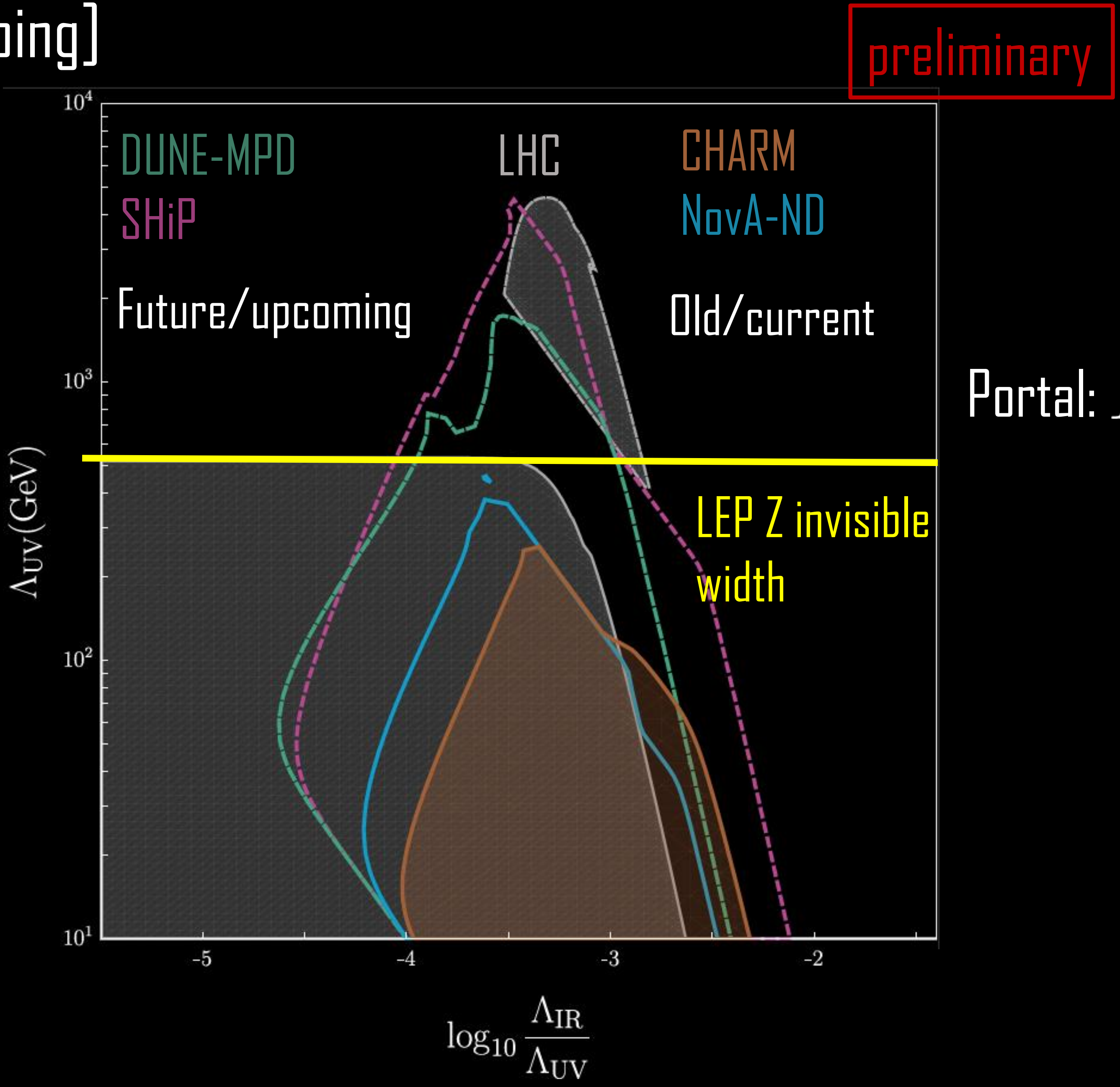


Portal: $H^\dagger i D_\mu H J^\mu_{\text{DS}}$

$\downarrow$

$v m_z Z_\mu J^\mu_{\text{DS}}$

Costa, Mishra, SV [ongoing]

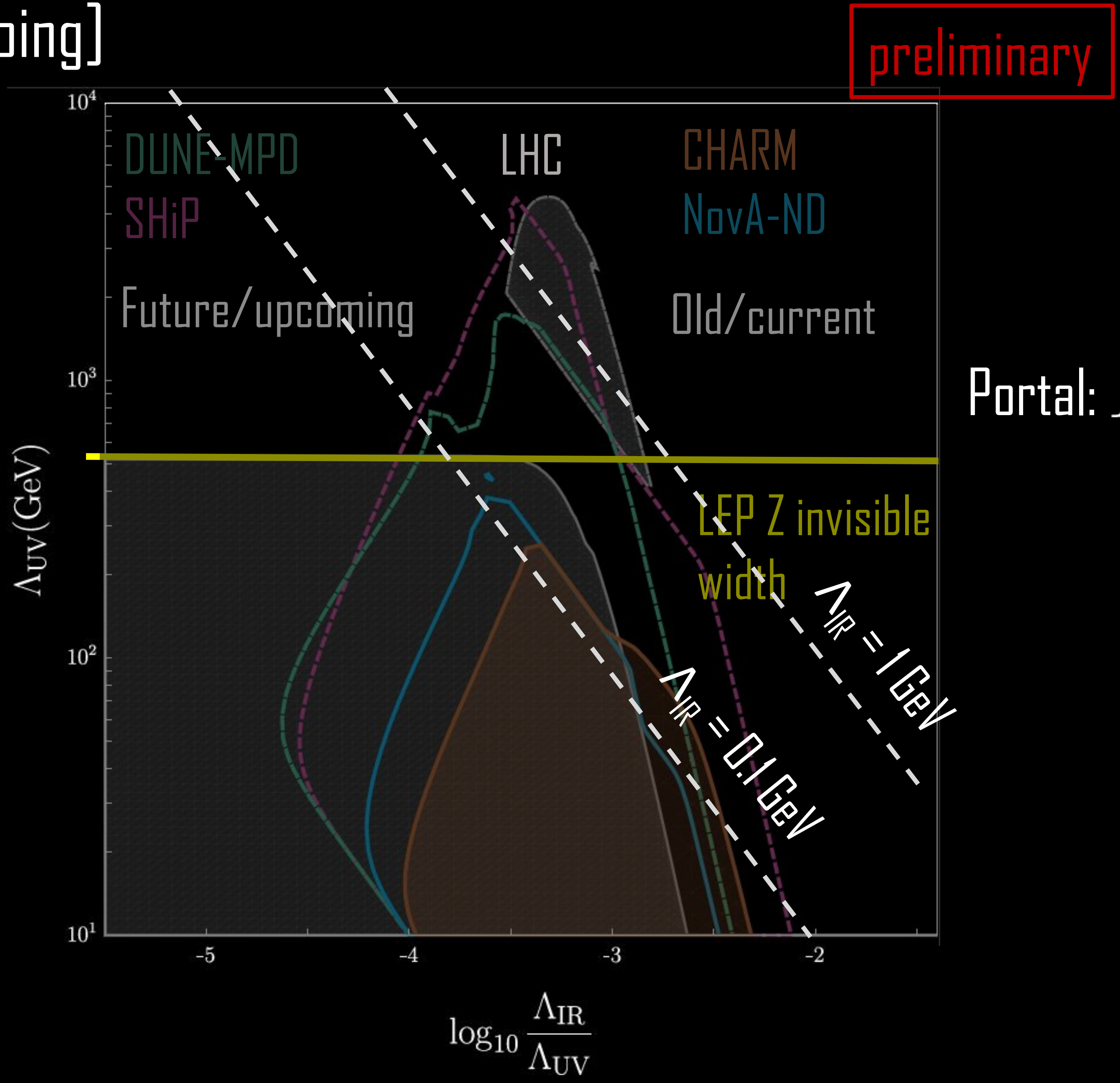


Portal: $H^\dagger i D_\mu H J^\mu_{\mathrm{DS}}$

↓

$v m_z Z_\mu J^\mu_{\mathrm{DS}}$

Costa, Mishra, SV [ongoing]



Portal: $H^\dagger i D_\mu H J^\mu_{\rm DS}$

$\downarrow$

$v m_z Z_\mu J^\mu_{\rm DS}$

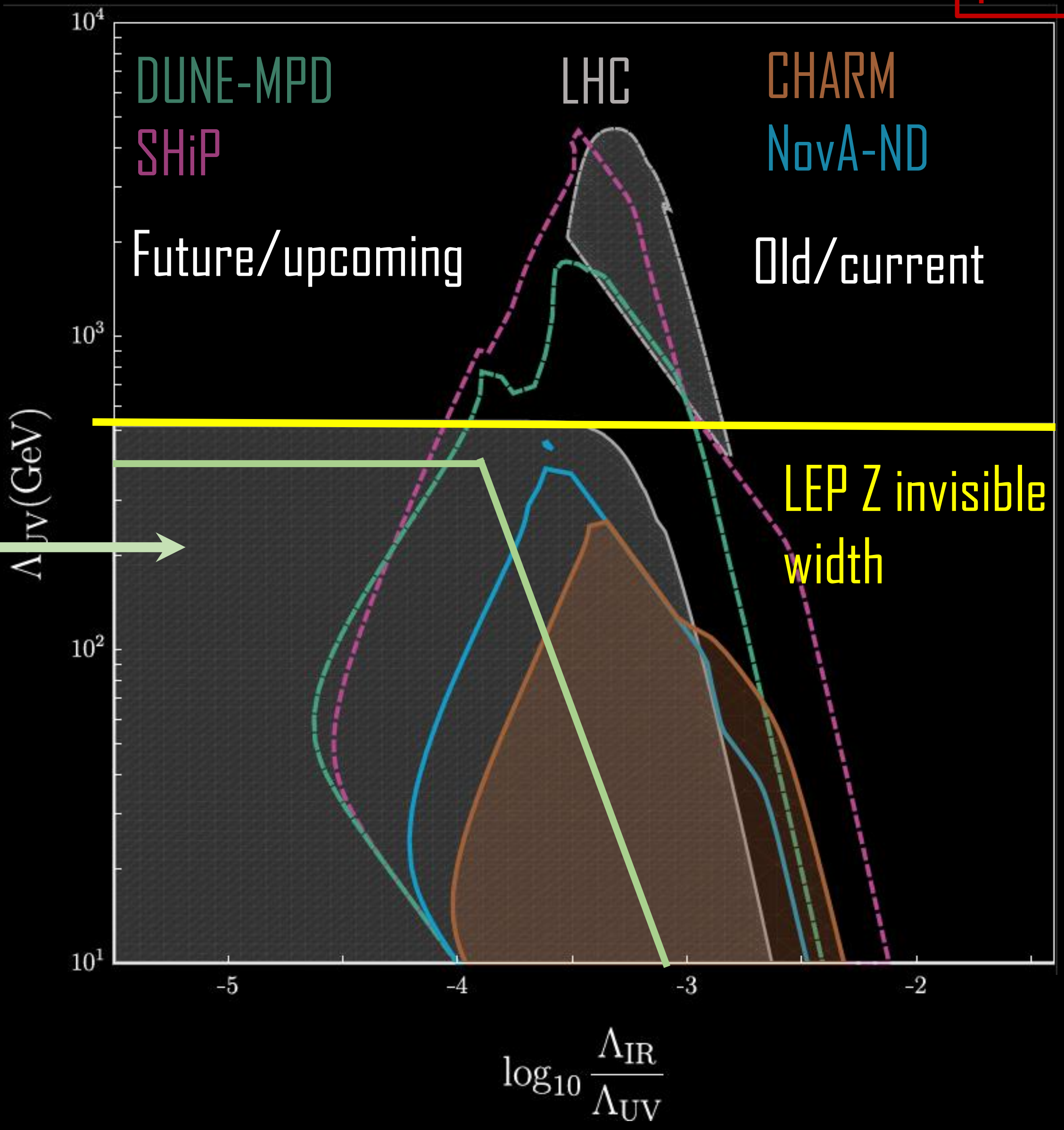
Conclusions

- We can use constrain elusive DS using a model independent framework.
- Interplay of various DS production mechanisms at neutrino experiments.
- Future neutrino experiments and LLP search experiments like SHiP will be important probes.
- Will complement LHC searches as elusive DS probes in a short timescale.

BACK UP

Costa, Mishra, SV [ongoing]

preliminary



SN1987A bound
Λ_{UV} < 400 GeV,
Λ_{IR} << 100 MeV

Portal: $H^\dagger i D_\mu H J^\mu_{\rm DS}$

↓

$v m_z Z_\mu J^\mu_{\rm DS}$

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Searching DS at Neutrino Experiments?

Previous works:

- For relevant portals

[Batell, Pospelov, Ritz '09],
[Batell, Berger, Ismail '19],
[Berryman et. al. '20]...

- For Irrelevant portals

[Darme, Ellis, You '20]

$$(\mu S + \lambda S^2) H^\dagger H$$ Dark higgs or scalar portal

$$\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}$$ Vector portal

$$\frac{1}{\Lambda^2} (\bar{\chi} \Gamma \chi) \mathcal{O}^{(3)}_{\rm SM}$$ Fermion portal

Searching DS at Neutrino Experiments?

Previous works:

- For relevant portals

[Batell, Pospelov, Ritz '09],
[Batell, Berger, Ismail '19],
[Berryman et. al. '20]...

- For Irrelevant portals

[Darme, Ellis, You '20]

This Work

D = 6 $$J_\mu^{\mathrm{DS}} J^\mu_{\mathrm{SM}} \begin{cases} \bar{\psi}\gamma_\mu\psi \\ H^\dagger i D_\mu H \end{cases}$$

$\Delta_{\mathcal{O}} = 4$

$\Delta_{\mathcal{O}} = 3$

$$\mathcal{O}_{\mathrm{DS}} H^\dagger H$$

See Contino, Max, Mishra '20

Benchmark Models

- **Pure Yang Mills DS** (See Mitridate et. al. arxiv: 1707.05380)

L + N model, L : Dirac fermion and N: majorana fermion under SO(N)
Masses of L+N>> dark confinement scale, (DM in UV sector)
pure YM DS with long lived dark glueballs.

- **Free Fermion DS** with 1 majorana fermion + 1 scalar

(similar to SUSY with neutralino + selectron)
(DM is fermion)

....

2 benchmark cases of n or number of LDSPs (lightest dark sector particle)

- <n> = 2 for weakly coupled dynamics

- $$\langle n \rangle = A \left(\frac{1}{\log(\langle E \rangle^2 / \bar{\Lambda}^2)} \right)^B \exp\left(\frac{C}{\sqrt{\log(\langle E \rangle^2 / \bar{\Lambda}^2)}} \right), \quad \begin{array}{ll} A = 0.06 & C = 1.8 \\ B = 0.5 & \bar{\Lambda} = 0.1\,\Lambda_{\rm IR} \end{array}$$

  for strongly coupled dynamics*

  *Same as QCD prediction (c.f. Webber, Phys. Lett. B 143 (1984) 501-504.)

See Contino, Max, Mishra '20

RS model dim 8 case