

GeV scale strongly-interacting dark sectors at beam dump experiments

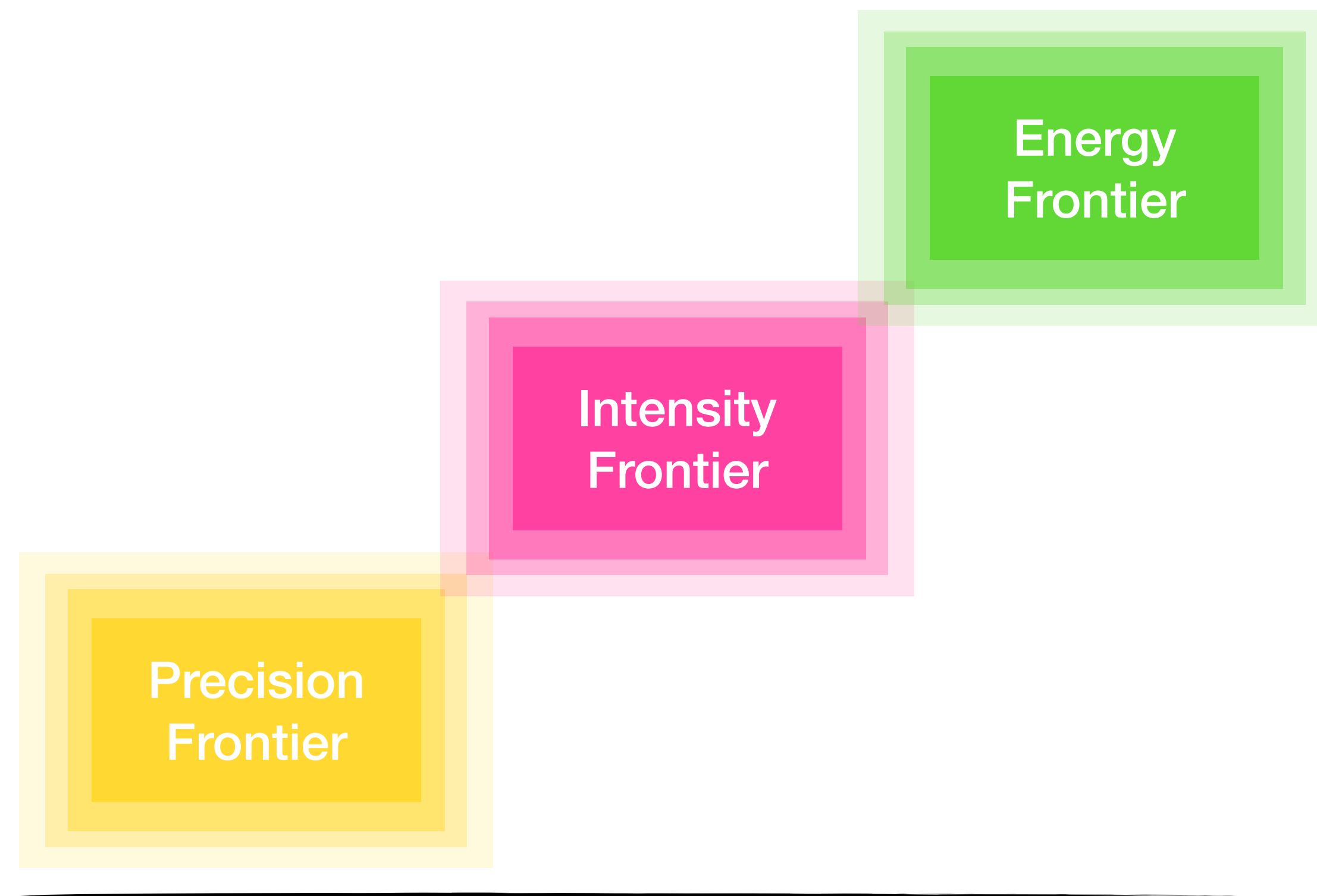
Nicoline Hemme (KIT, Germany)

Collaborators: Elias Bernreuther, Felix Kahlhoefer,
Suchita Kulkarni & Maksym Ovchinnikov

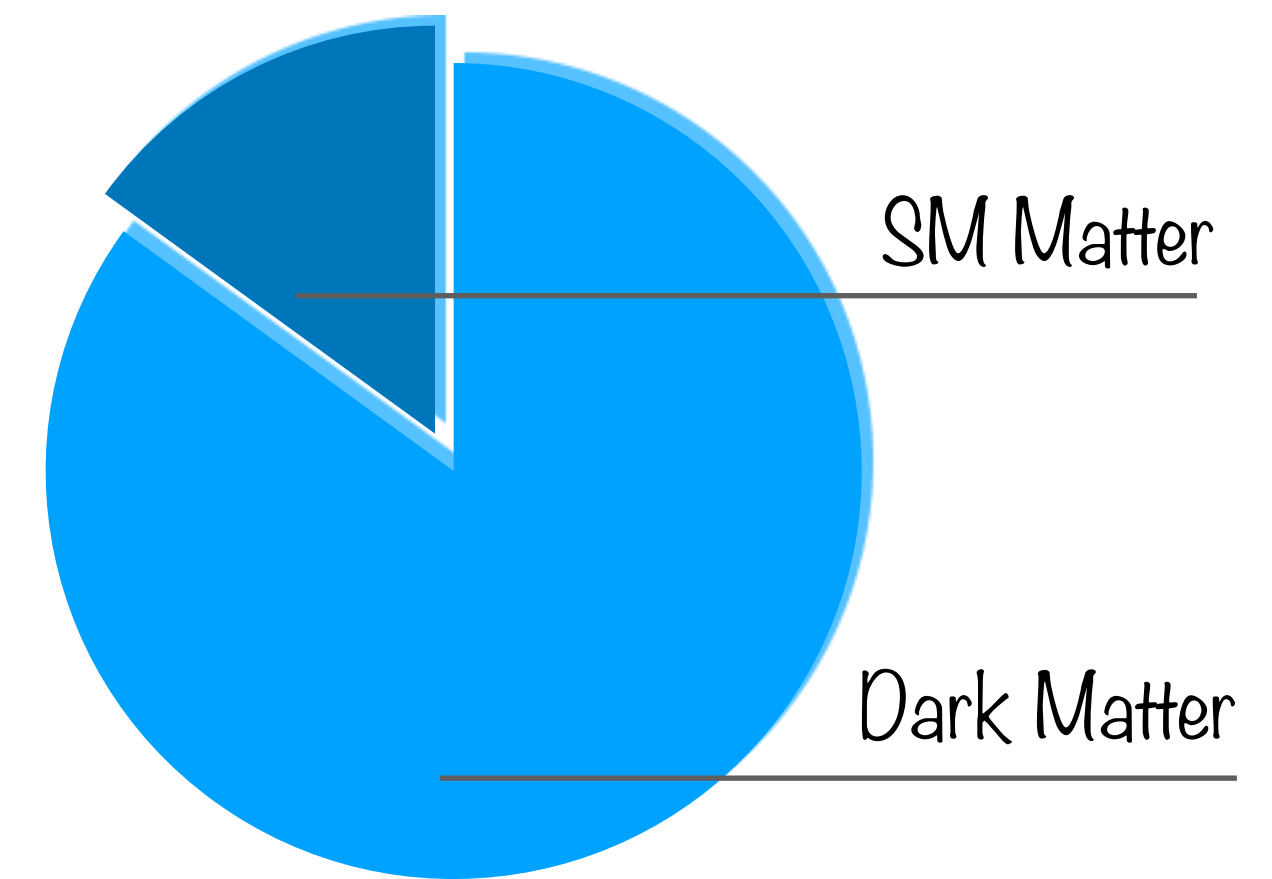
CRC Young Scientist Meeting @ Heidelberg - July 22nd

Searching for new physics

Coupling to SM



Mass of new particle



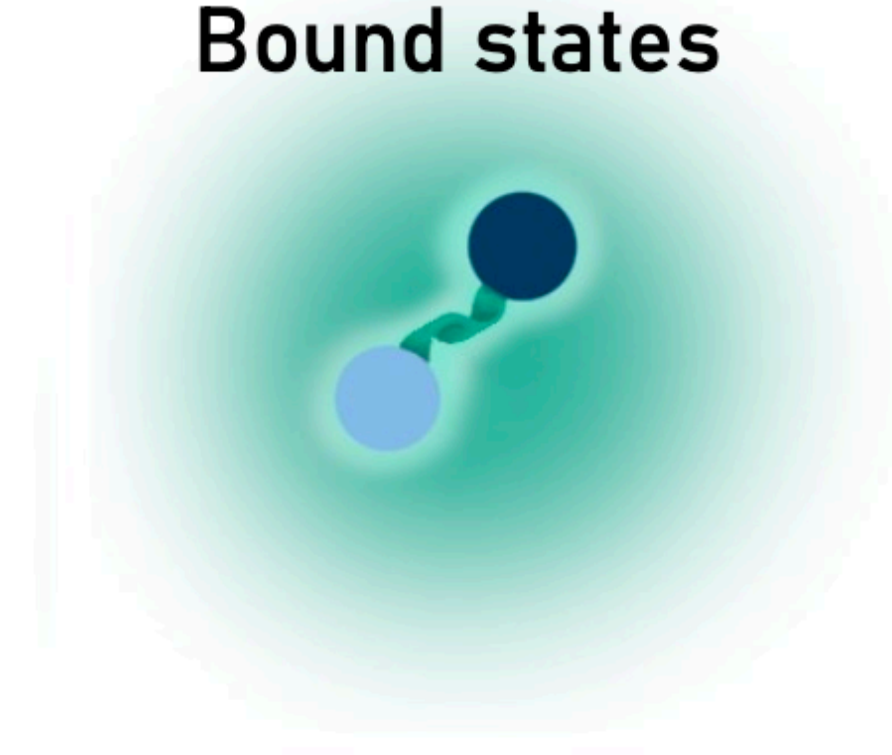
A strongly interacting dark sector

The theory - SU(N)

Particles of the theory
Dark quarks and dark gluons



Particles of the theory
Bound states



Confinement / breakdown of UV theory

$$\mathcal{L}_{UV} = -\frac{1}{4} G_{d\mu\nu}^a G_d^{a\mu\nu} + \bar{q}_d (i\gamma^\mu D_\mu - M_q) q_d$$

$$\mathcal{L}_{Ch} \supset \frac{f_{\pi_d}^2}{4} \text{Tr}(D_\mu U D^\mu U) + \left[\frac{\mu_d^3}{2} \text{Tr}(M_q U^\dagger) + \text{h.c.} \right]$$

High energy

$E \sim \Lambda_D$

Low energy

The theory - $SU(N)$

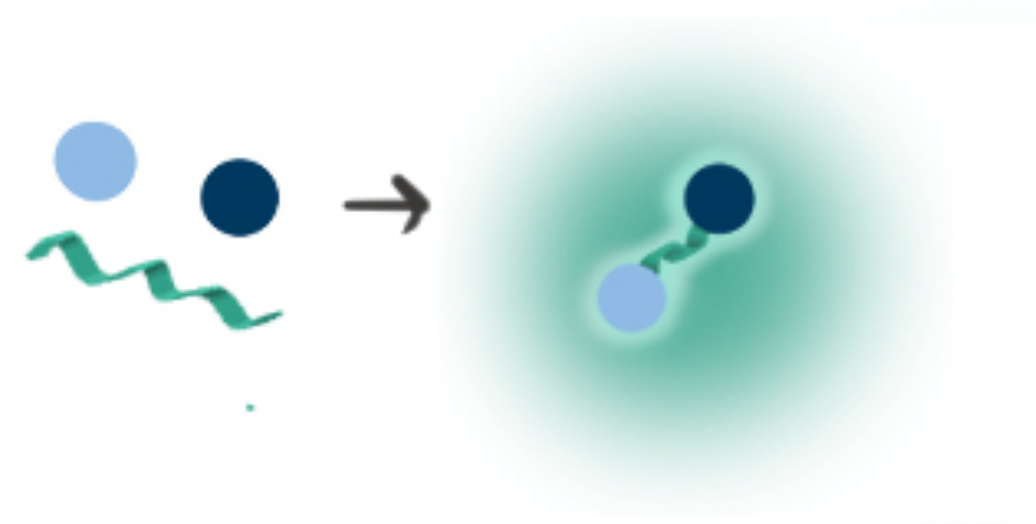
N_{cd}

Number of dark colours



Λ_d

Dark confinement scale



N_{fd}

Number of dark flavours



m_{qd}

Dark quark mass



The theory - $SU(N)$

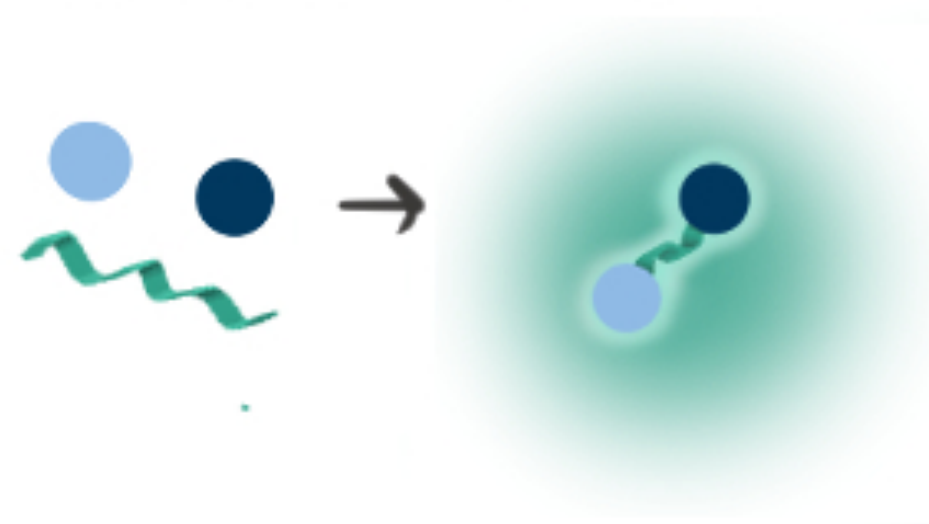
N_{cd}
Number of dark colours



N_{fd}
Number of dark flavours



Λ_d
Dark confinement scale



m_{qd}
Dark quark mass



Connection to SM
e.g. via Z' portal



g, κ, e_d
Couplings



m_{med}
Mediator mass



The theory - $SU(N)$

N_{cd}
Number of dark colours



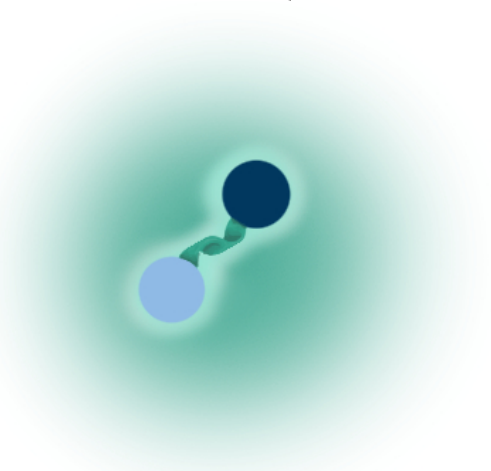
N_{fd}
Number of dark flavours



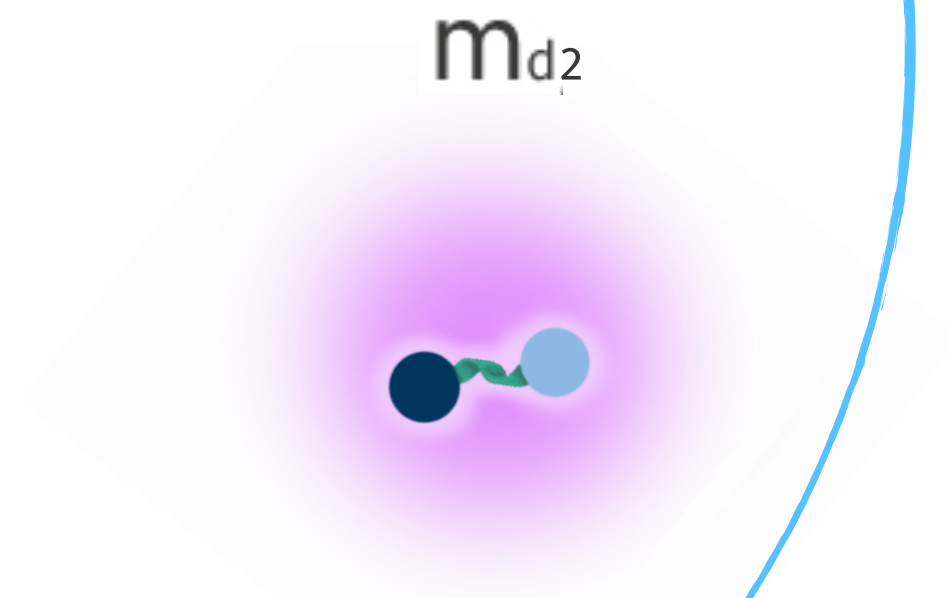
Λ_d
Dark confinement scale



m_{d1}



m_{d2}

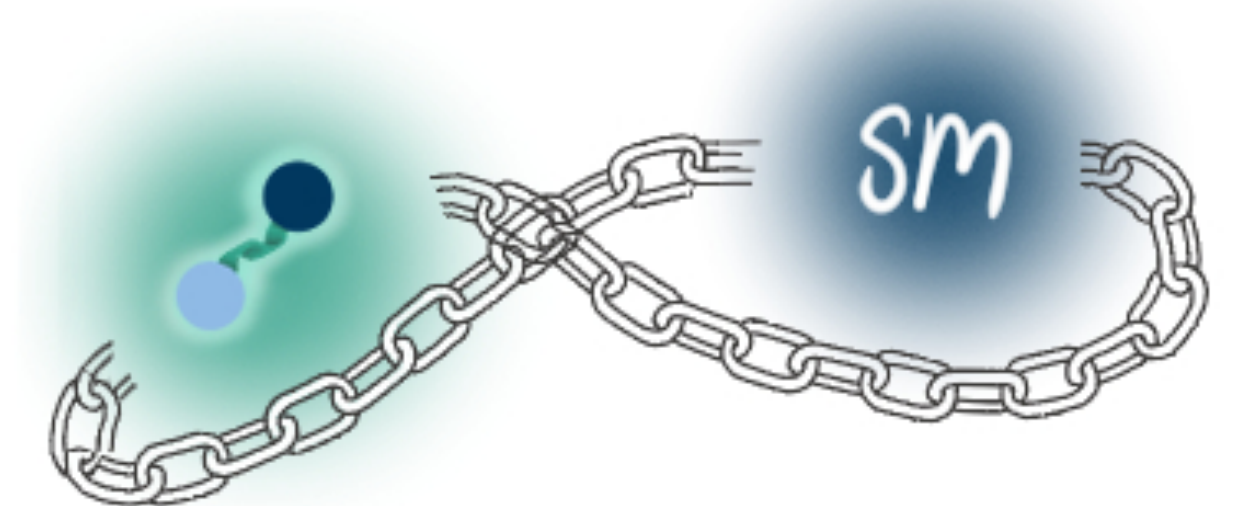


m_{qd}

Dark quark mass



g, κ, e_d
Couplings



m_{med}
Mediator mass

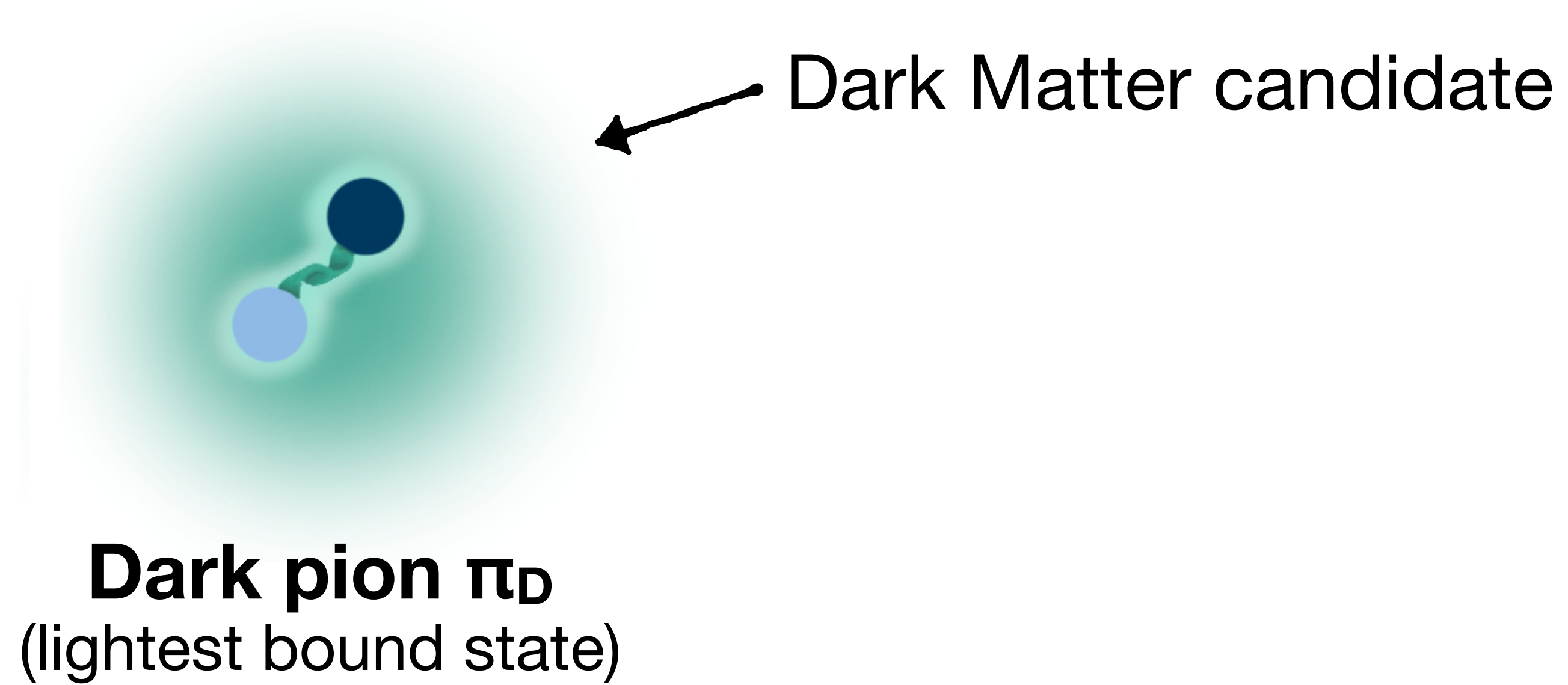


Exchange high-energy parameters for meson mass spectrum via Lattice QCD

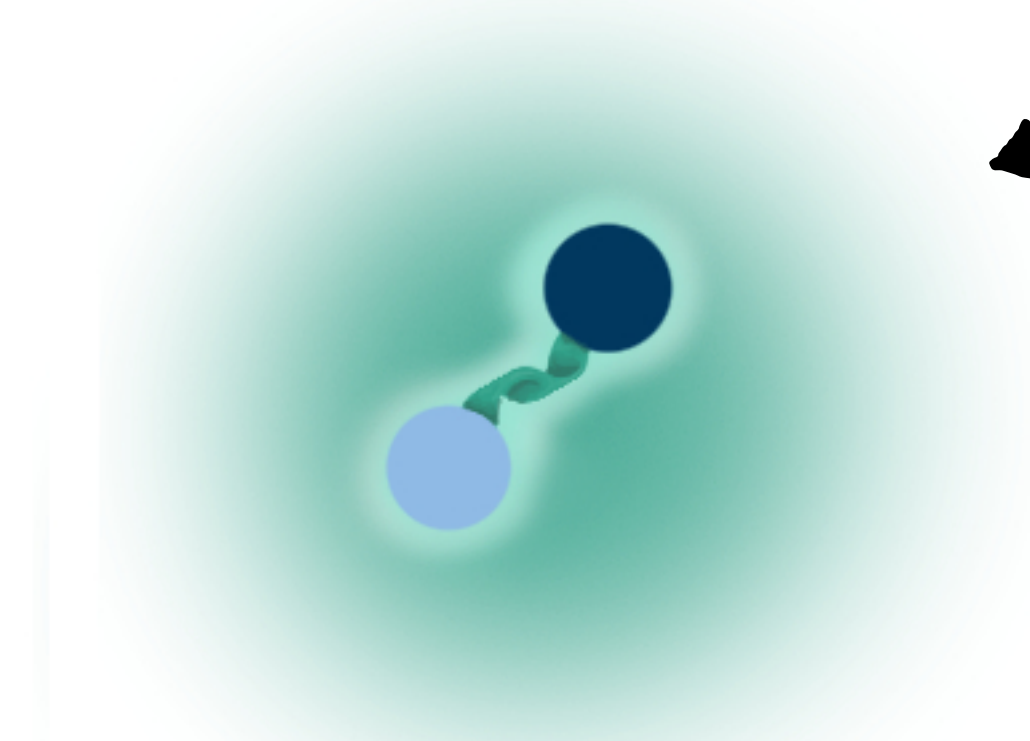
Ref: Theory, phenomenology, and experimental avenues for dark showers: a Snowmass 2021 report, 2022

Ref: C. S. Fischer, *Infrared properties of QCD from Dyson-Schwinger equations*, (2006), [hep-ph/0605173]

The bound states

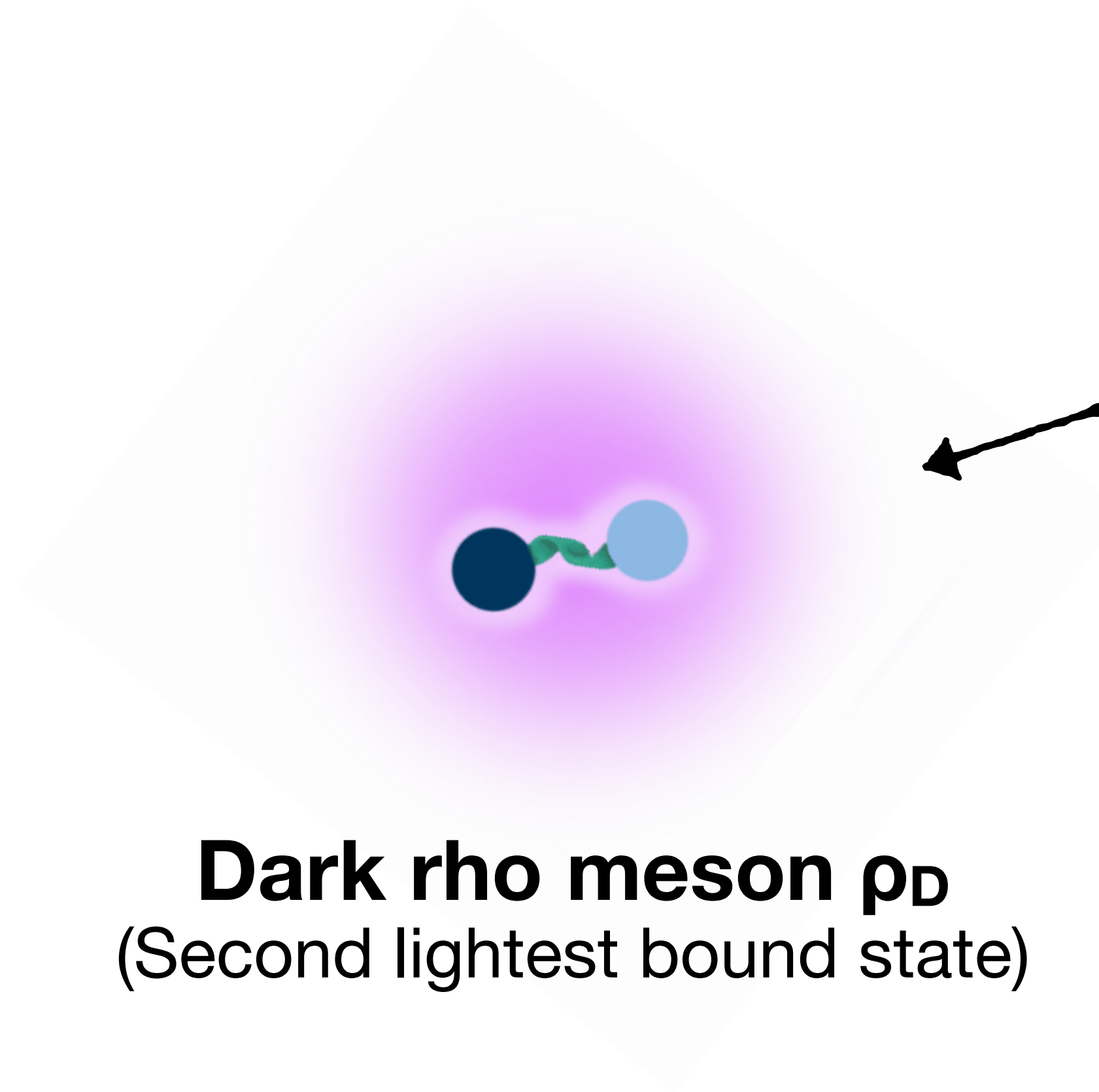


The bound states



Dark pion π_D
(lightest bound state)

Dark Matter candidate

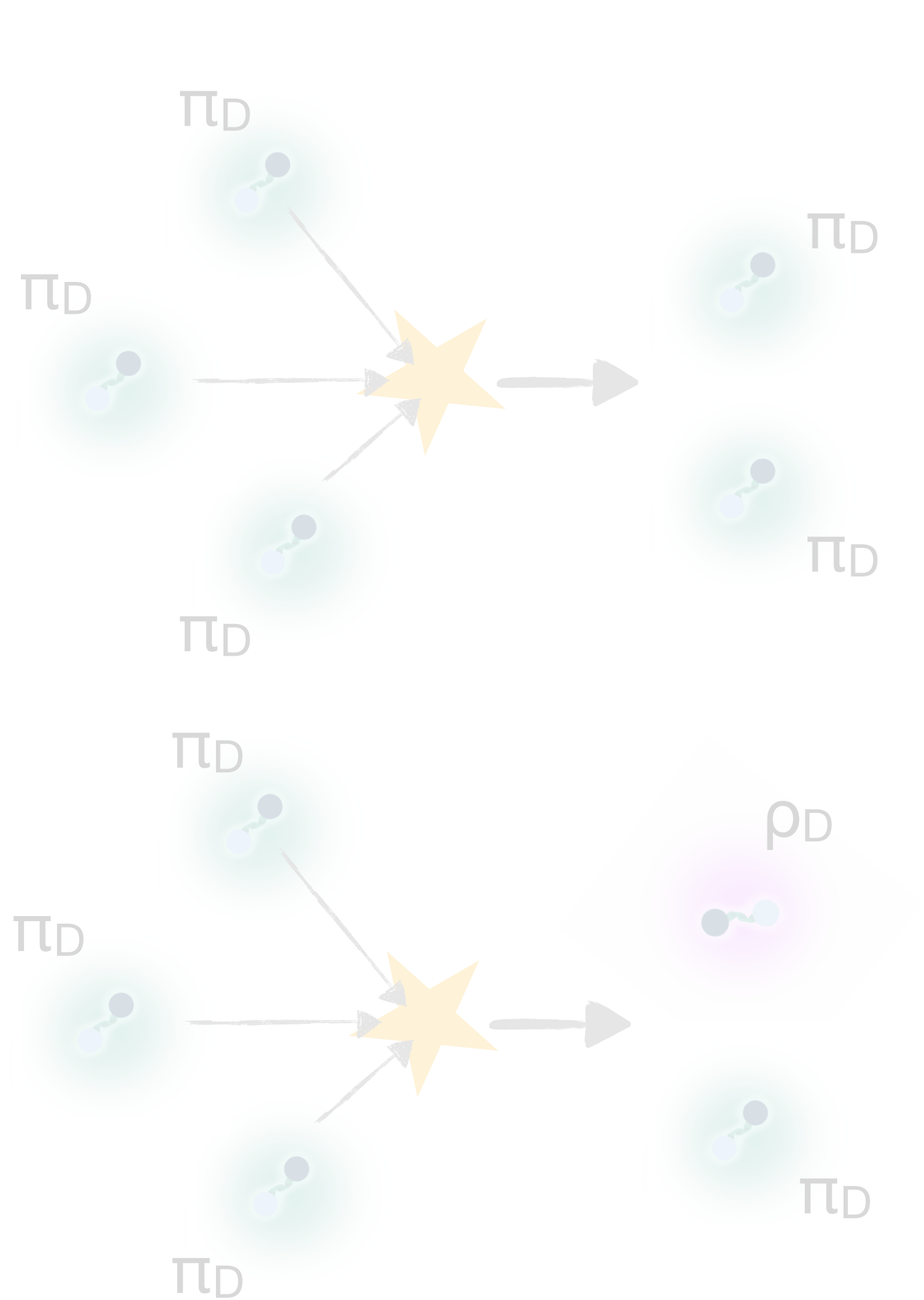


Dark rho meson ρ_D
(Second lightest bound state)

Candidate for
LLP signature

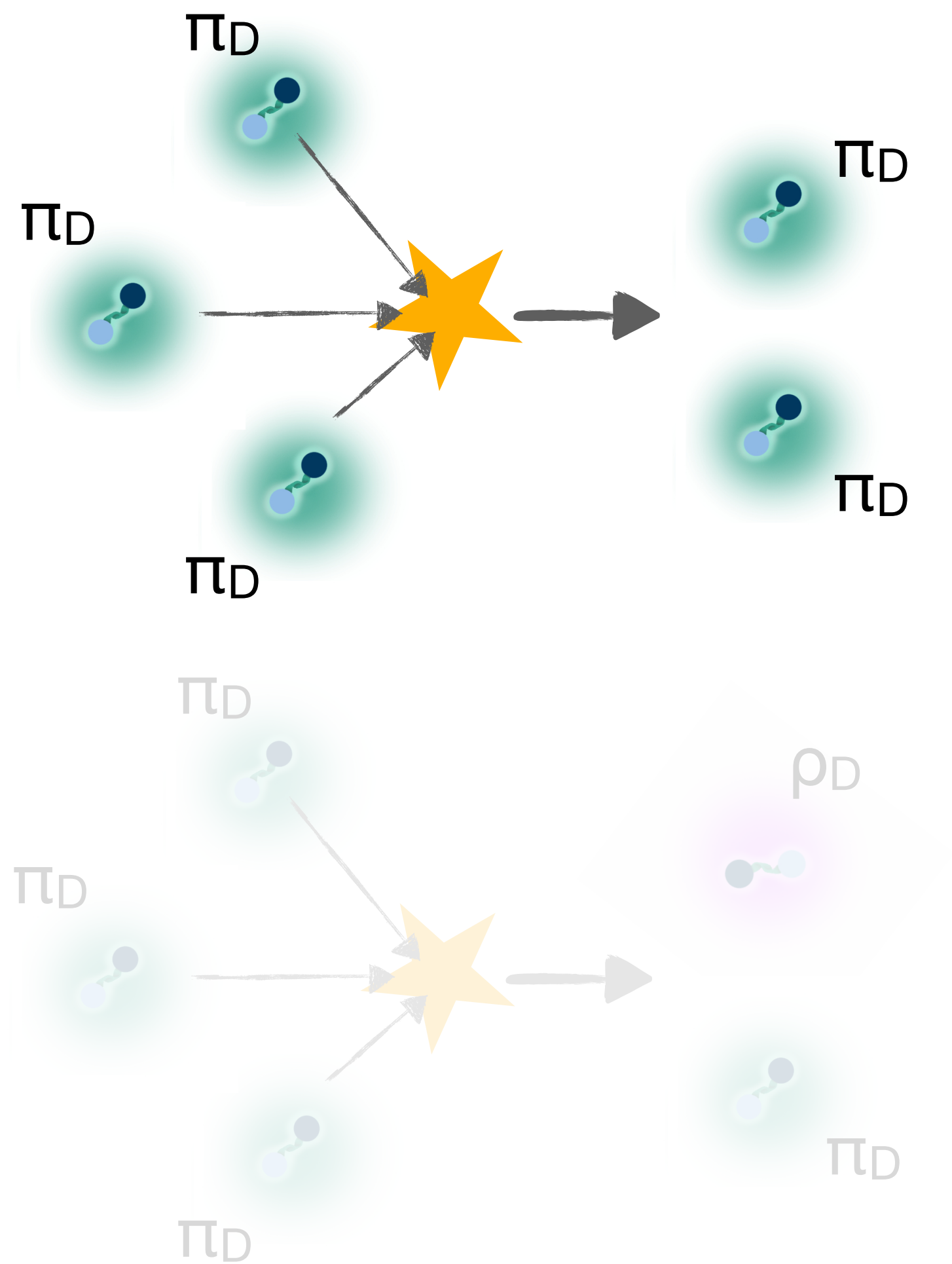
- Z' portal allows production at accelerators
- Kinetic mixing, κ , with SM photon

The freeze-out of pionic dark matter



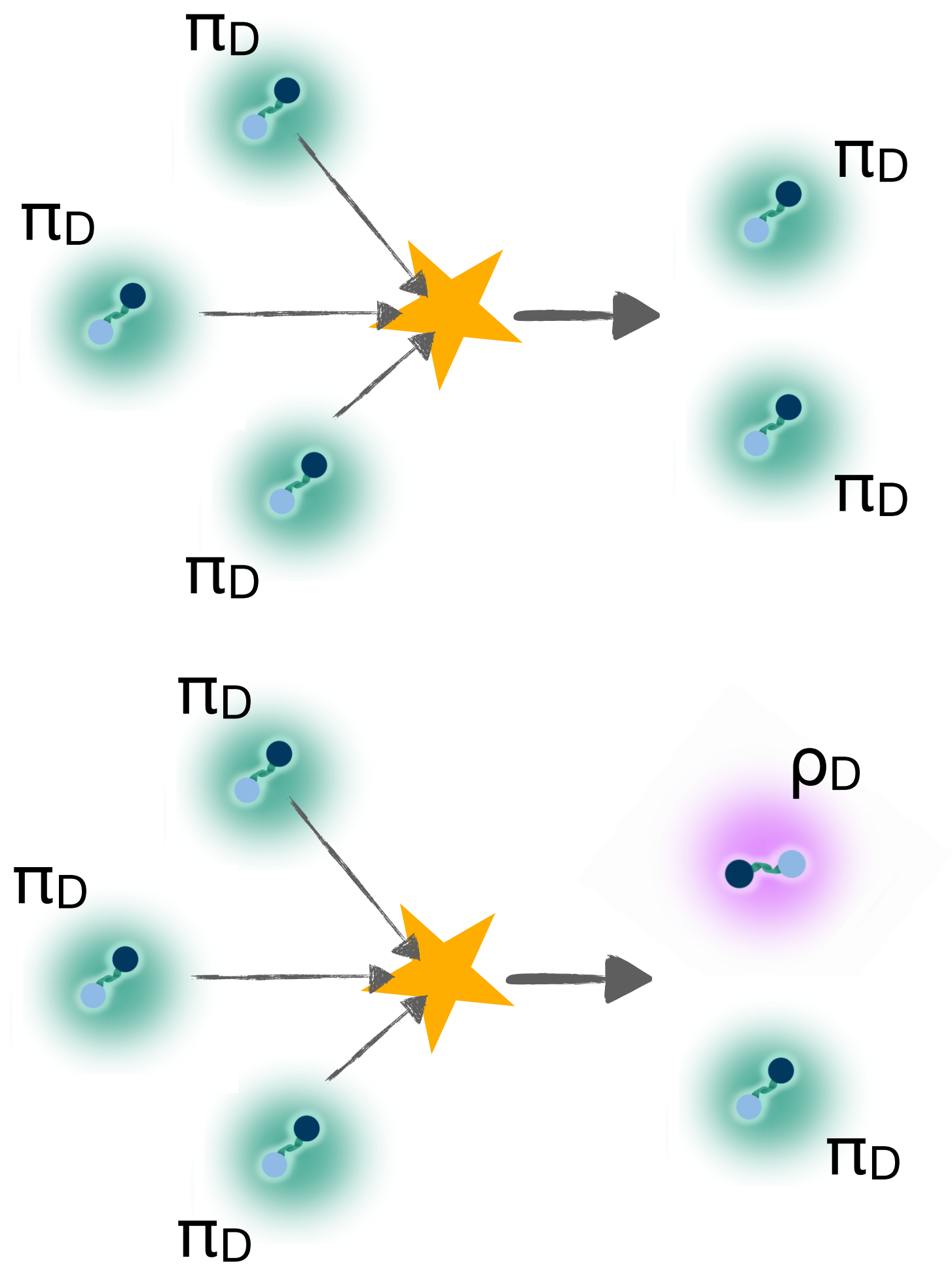
The freeze-out of pionic dark matter

If ρ_D is heavy ($m_{\rho_D} > 2m_{\pi_D}$)



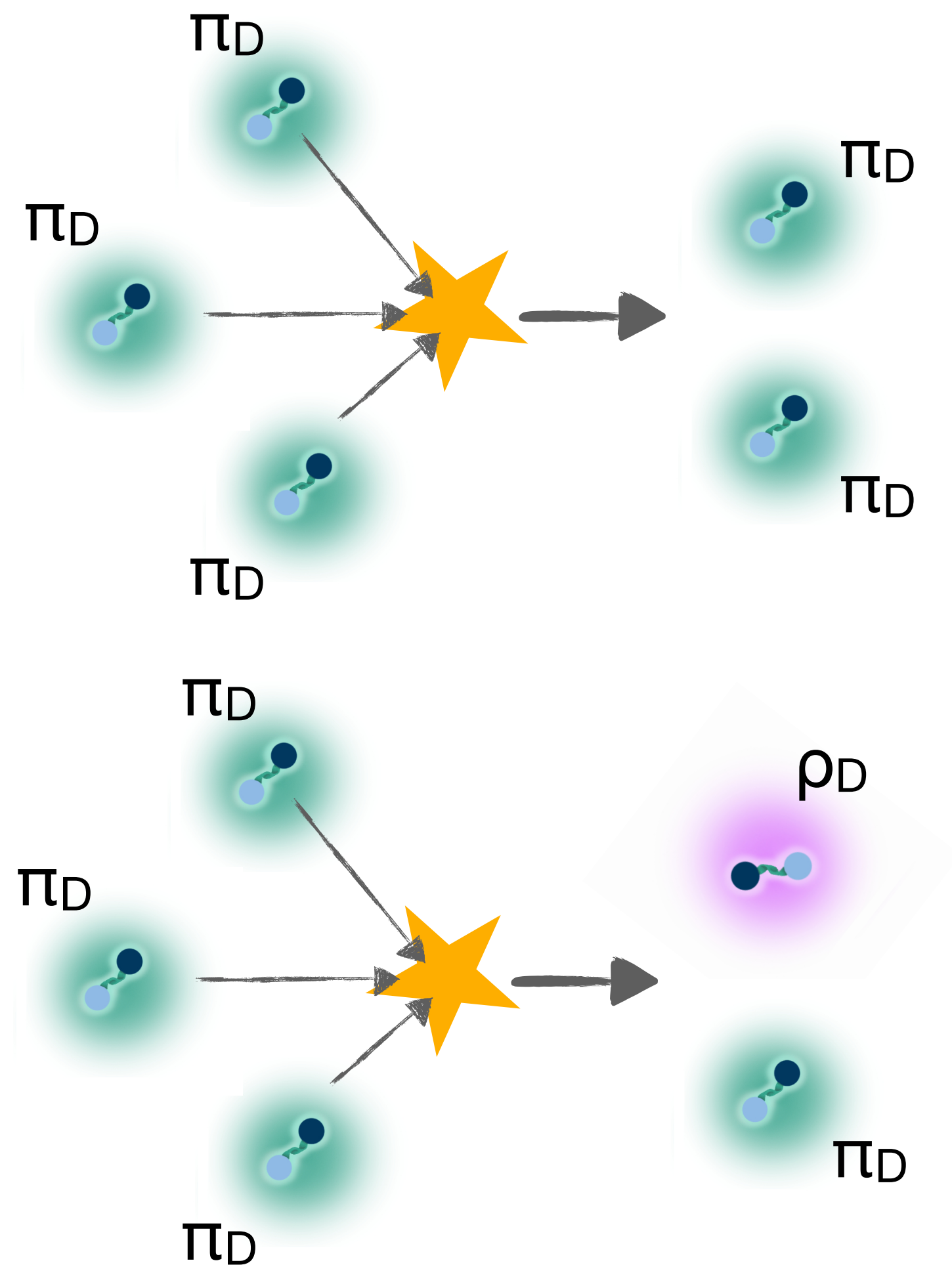
The freeze-out of pionic dark matter

If ρ_D is light ($m_{\rho_D} < 2m_{\pi_D}$)

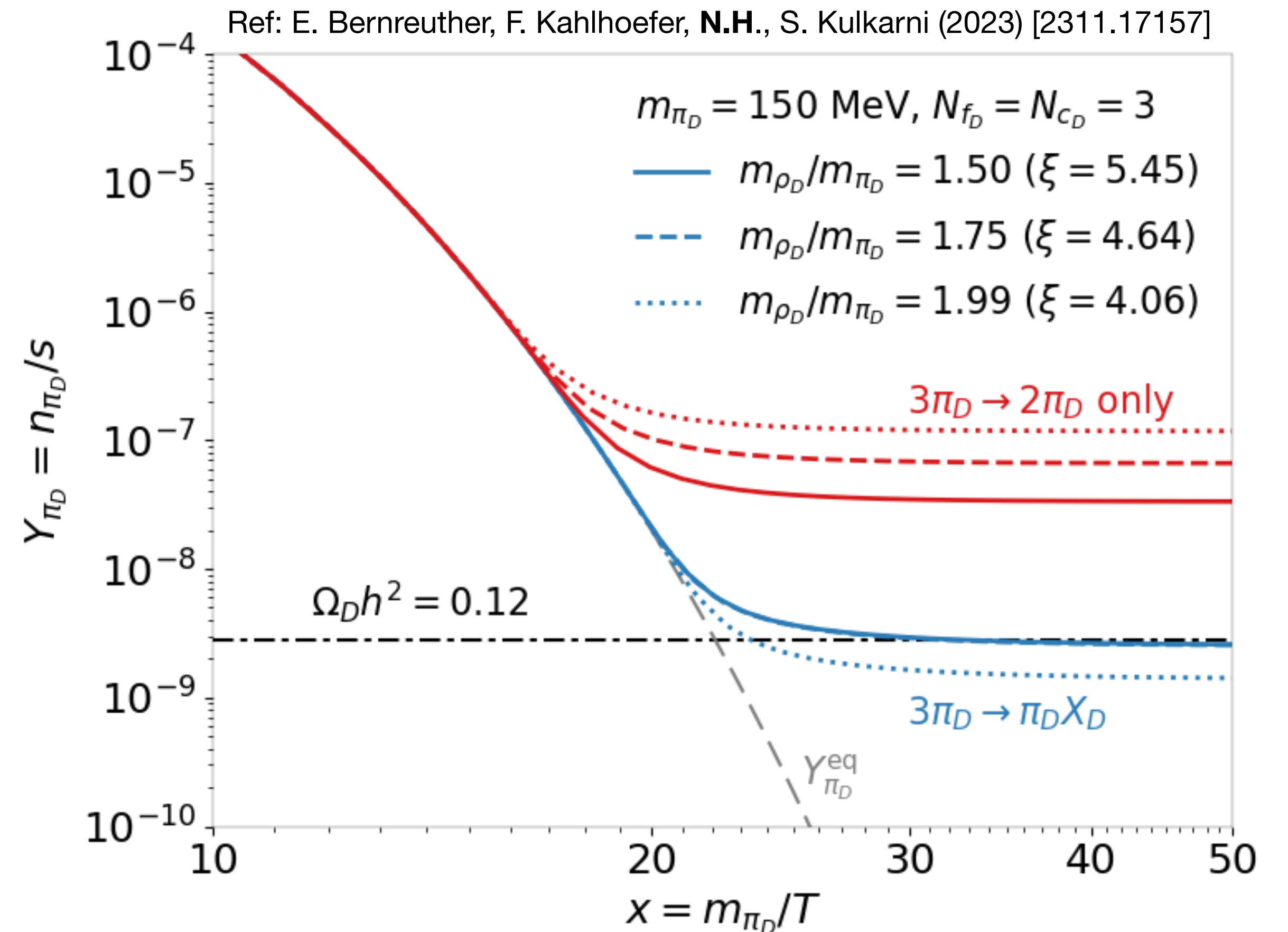


The freeze-out of pionic dark matter

If ρ_D is light ($m_{\rho_D} < 2m_{\pi_D}$)



Impact on the relic abundance of π_D



Pionic dark matter in astrophysical context

$\pi_D\pi_D$ scattering vs. Bullet Cluster self-interaction constraints

Ref: E. Bernreuther, F. Kahlhoefer, **N.H.**, S. Kulkarni (2023) [2311.17157]

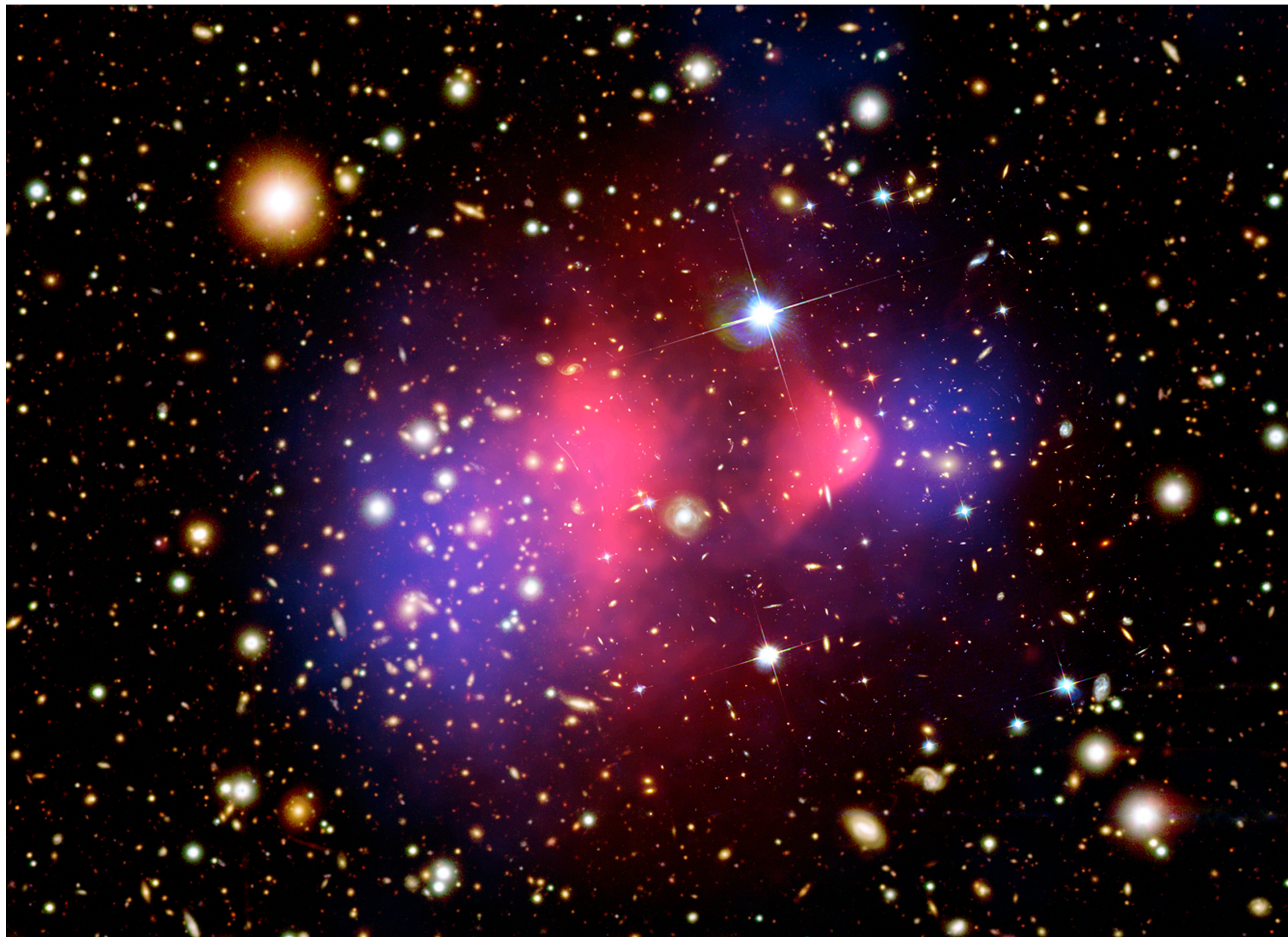
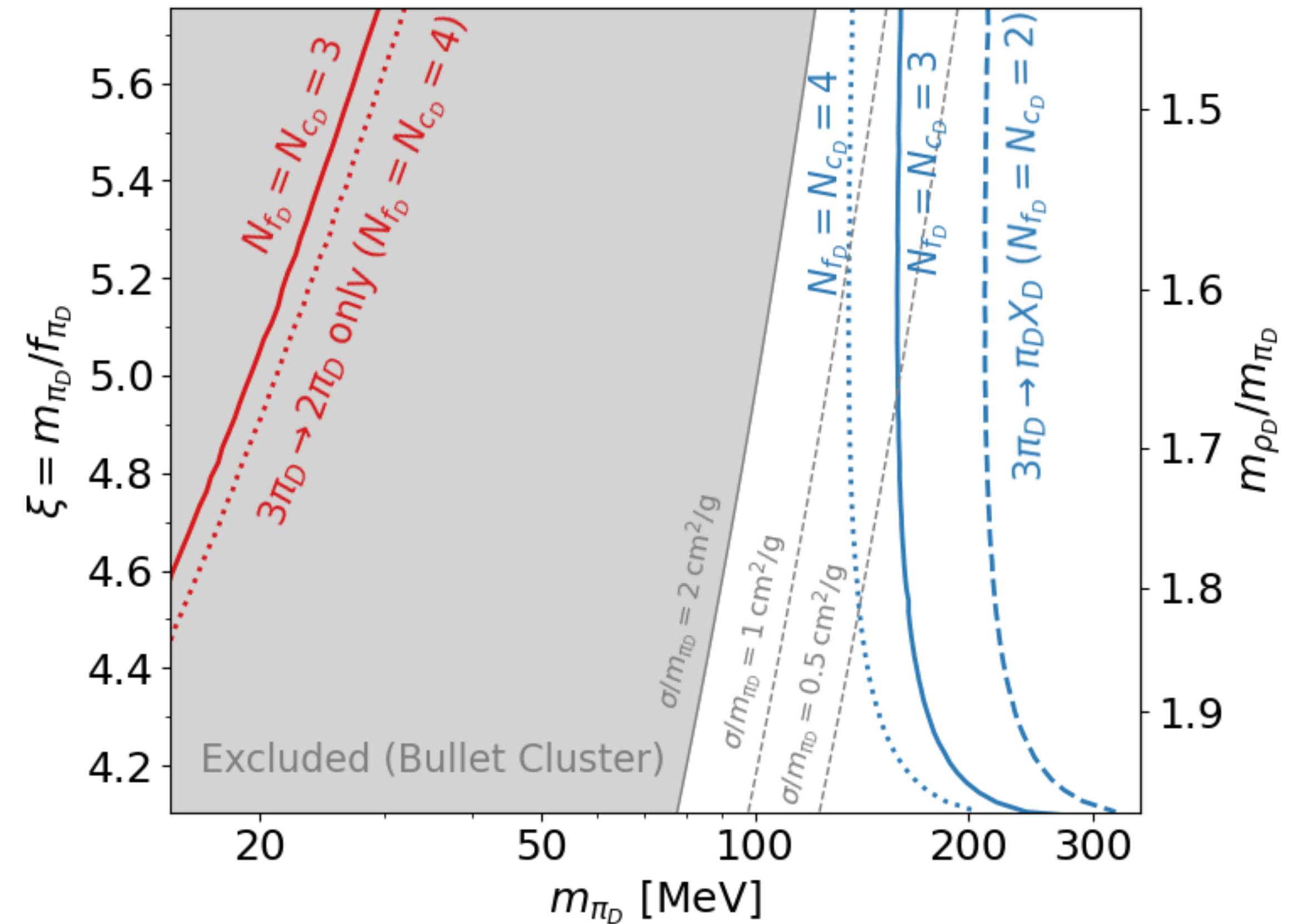


Image: *The Bullet Cluster*, ESA



Projected Sensitivity

ρ_D decays at SHiP

The SHiP Experiment

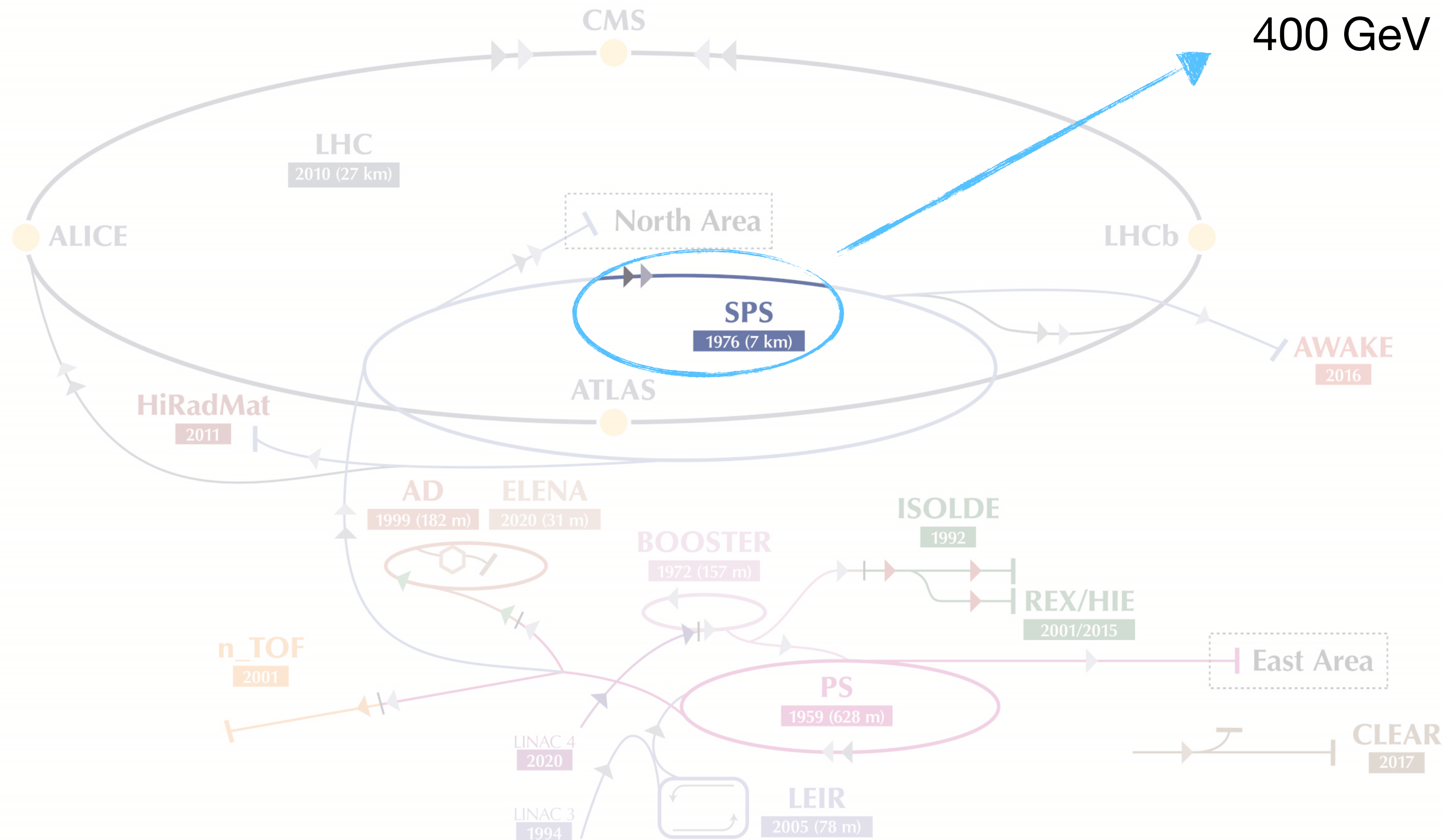
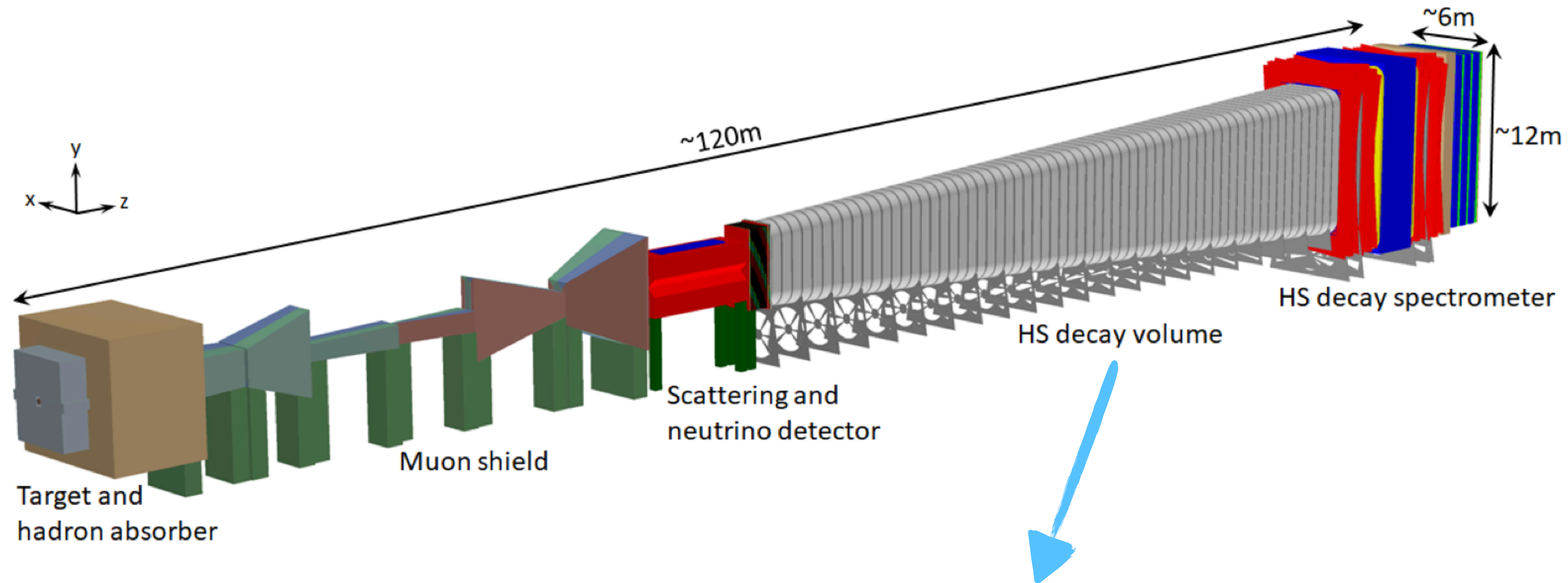


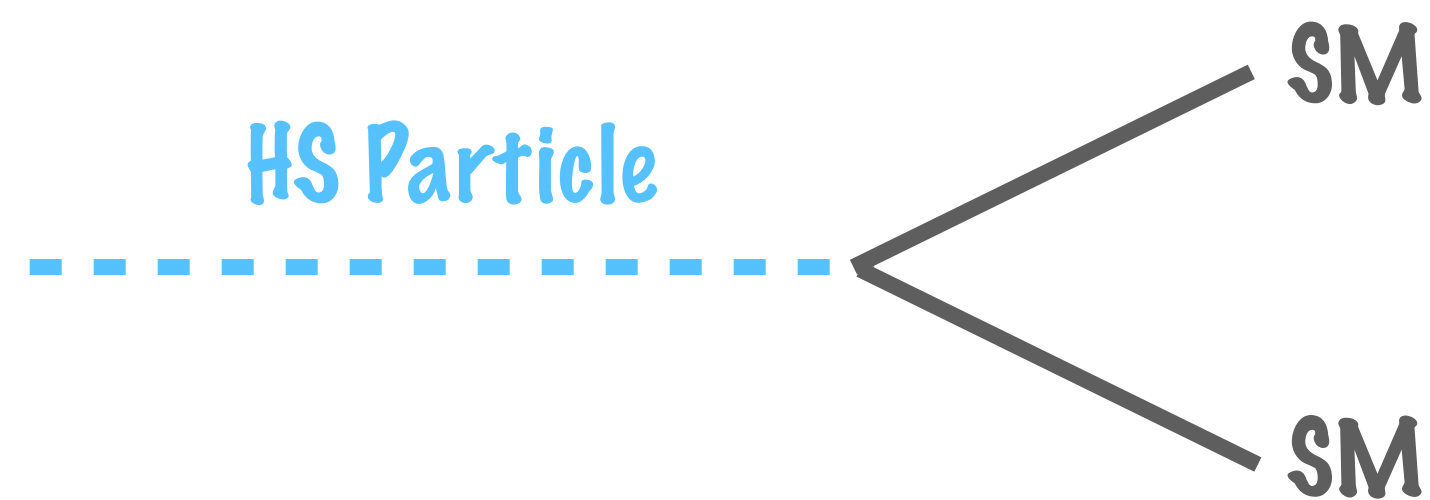
Image: Configuration and Layouts section, Accelerator Coordination and Engineering group, Engineering department, CERN

Ref: The SHiP Collaboration, *The SHiP experiment at the proposed CERN SPS Beam Dump Facility*, 2022

The SHiP Experiment

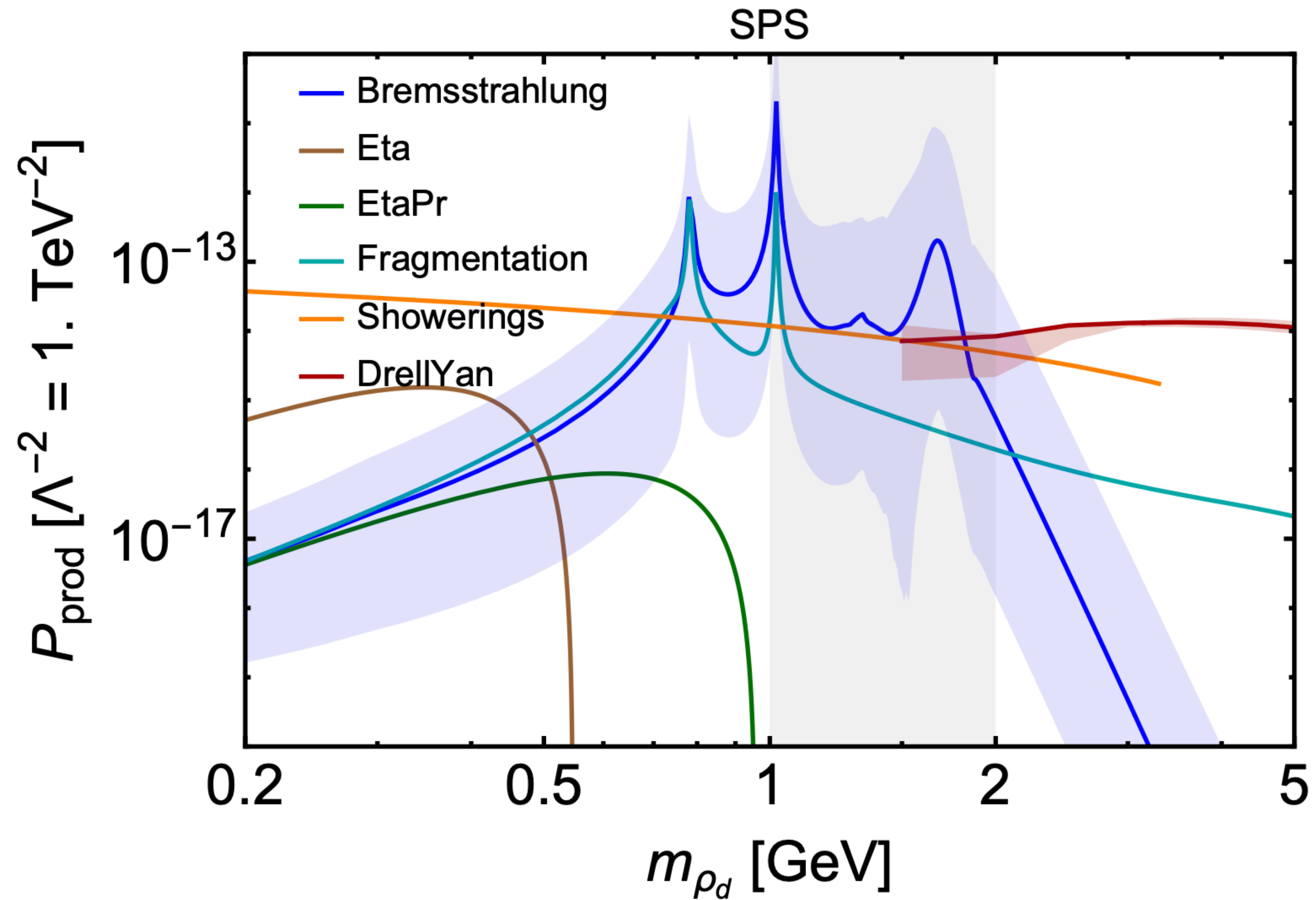


Designed for detection of LLPs



Ref: The SHiP Collaboration, *The SHiP experiment at the proposed CERN SPS Beam Dump Facility*, 2022

ρ_D production mechanisms at SPS



Simulation Chain

$$q_{SM} + \bar{q}_{SM} \rightarrow Z'^* \rightarrow q_D + \bar{q}_D$$

MadGraph

$$m_{Z'} \gg E_{cm} \gg \Lambda_D$$

$$\mathcal{L}_{\text{eff}} \supset \frac{2}{g_{\pi_D \rho_D}} \frac{m_{\rho_D}^2}{\Lambda^2} \rho_D^\mu \sum_f q_f \bar{f} \gamma_\mu f$$

$$\Lambda = m_{Z'} / \sqrt{k e e_D}$$

Simulation Chain

$$q_{SM} + \bar{q}_{SM} \rightarrow Z'^* \rightarrow q_D + \bar{q}_D$$

$$q_D + \bar{q}_D \rightarrow \pi_D^S + \rho_D^S$$

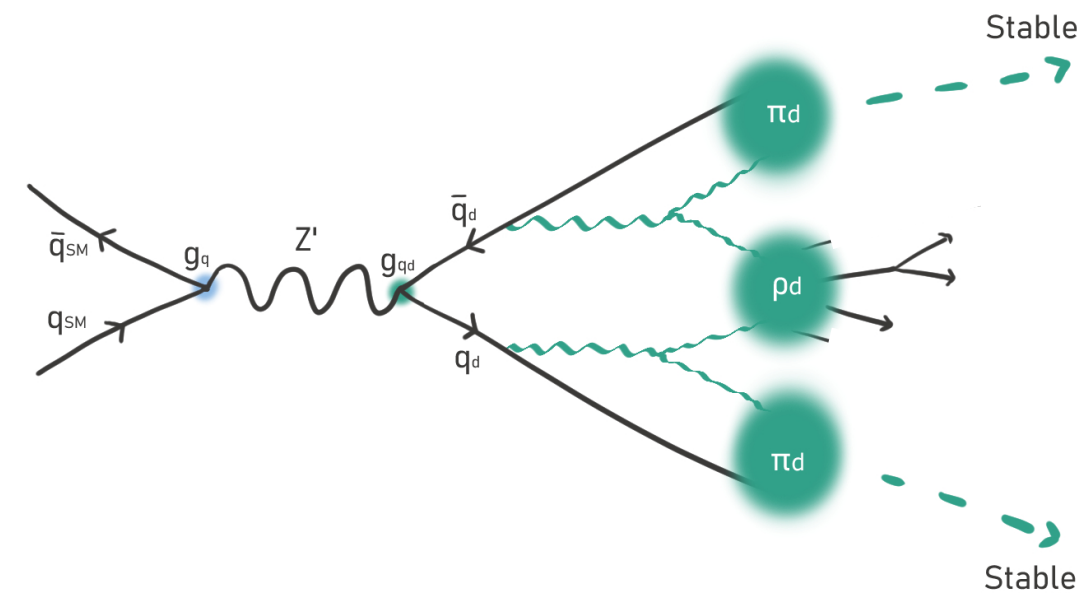
MadGraph

Pythia

$$m_{Z'} \gg E_{cm} \gg \Lambda_D$$

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Simulation Chain

$$q_{SM} + \bar{q}_{SM} \rightarrow Z'^* \rightarrow q_D + \bar{q}_D$$

$$q_D + \bar{q}_D \rightarrow \pi_D^S + \rho_D^S$$

$$\rho_{DS} \text{ selected: } \vec{P} \rightarrow \frac{d^2f}{d\theta dE}$$

MadGraph

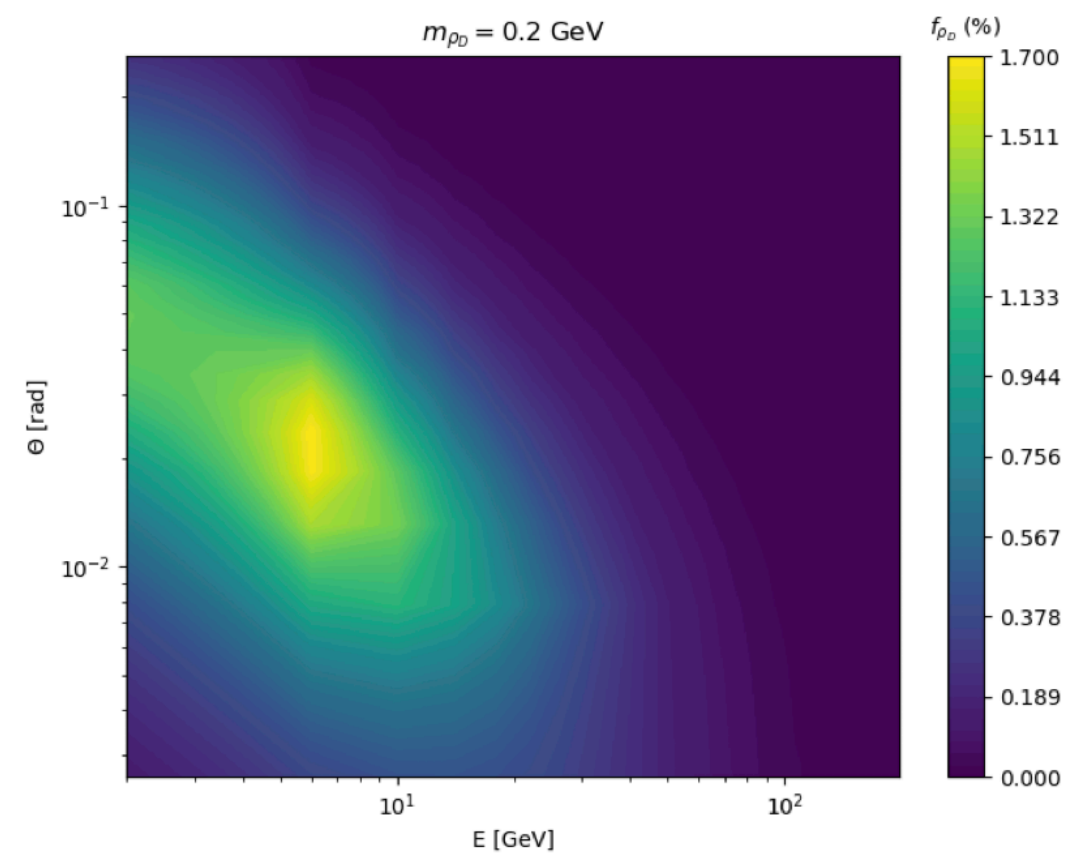
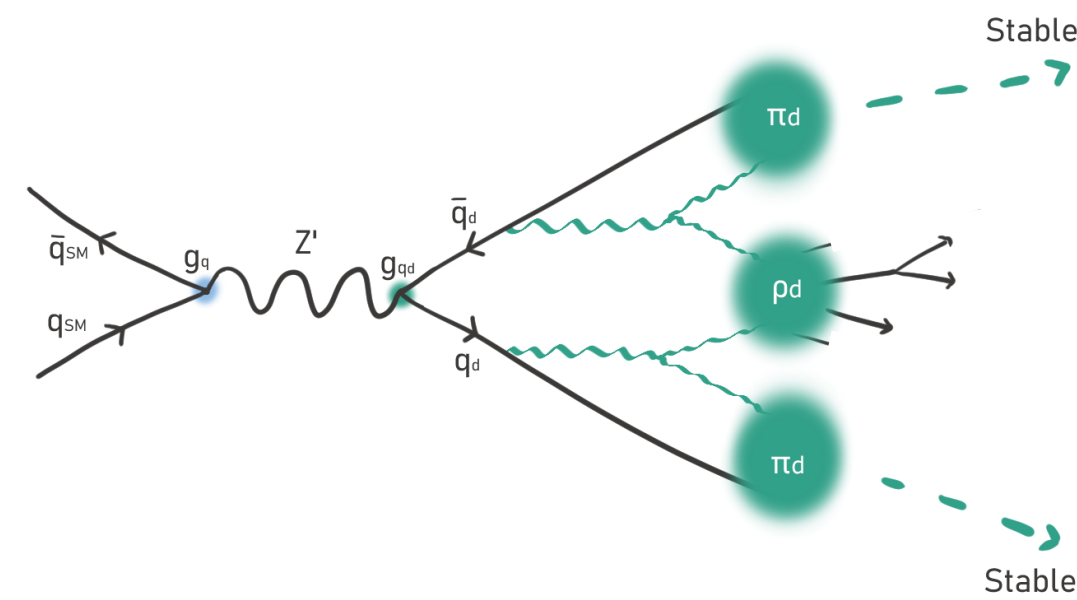
Pythia

Analysis

$$m_{Z'} \gg E_{cm} \gg \Lambda_D$$

$$\mathcal{L}_{eff} \supset \frac{2}{g_{\pi_D \rho_D}} \frac{m_{\rho_D}^2}{\Lambda^2} \rho_D^\mu \sum_f q_f \bar{f} \gamma_\mu f$$

$$\Lambda = m_{Z'} / \sqrt{k e e_D}$$



Simulation Chain

$$q_{SM} + \bar{q}_{SM} \rightarrow Z'^* \rightarrow q_D + \bar{q}_D$$

MadGraph

$$q_D + \bar{q}_D \rightarrow \pi_D^S + \rho_D^S$$

Pythia

$$\rho_{DS} \text{ selected: } \vec{P} \rightarrow \frac{d^2f}{d\theta dE}$$

Analysis

$$\frac{d^2f}{d\theta dE}, \tau_{\rho_D}, \epsilon_{geom}, \epsilon_{dec}$$

SensCalc/
EventCalc

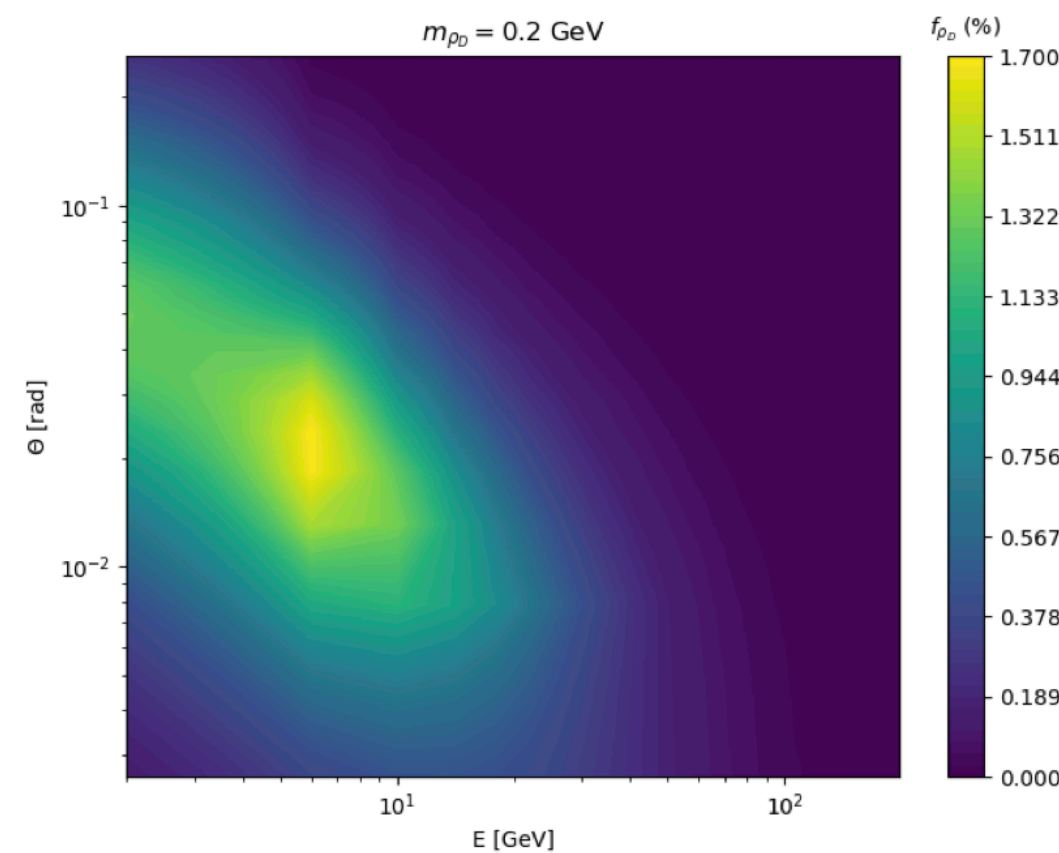
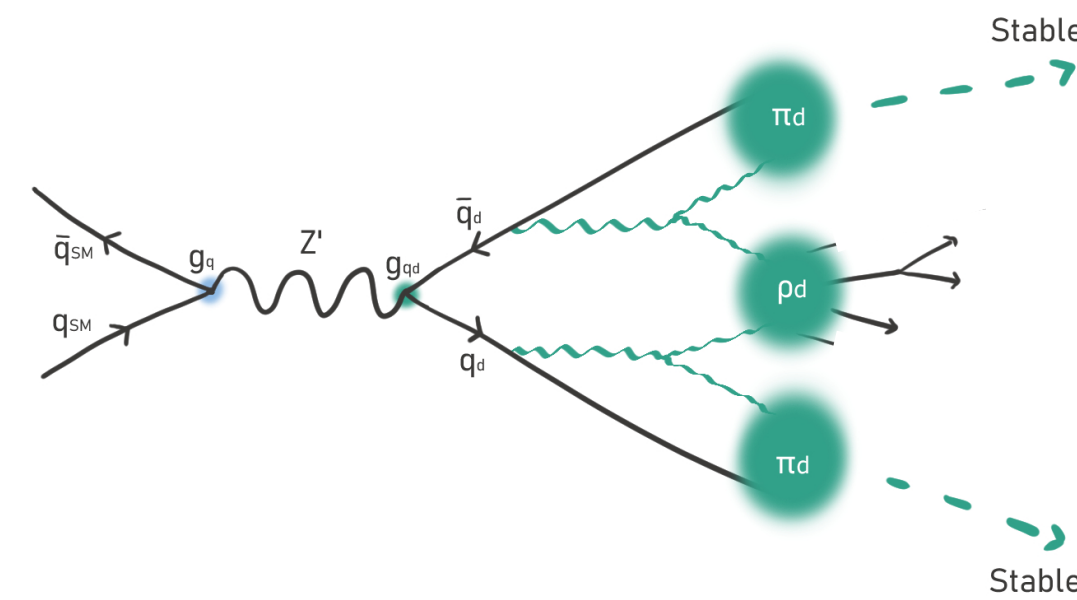
Calculates sensitivity at
several experiments

Developed by Maksym
Ovchynnikov et al. Ref:
[2305.13383] or find the code at
zenodo.org/records/15594401

$$m_{Z'} \gg E_{cm} \gg \Lambda_D$$

$$\mathcal{L}_{eff} \supset \frac{2}{g_{\pi_D \rho_D}} \frac{m_{\rho_D}^2}{\Lambda^2} \rho_D^\mu \sum_f q_f \bar{f} \gamma_\mu f$$

$$\Lambda = m_{Z'}/\sqrt{k e e_D}$$



Parameters for simulation

Parameter	Value ($r = 1.5$) Value ($r = 1.9$)		Setting in
$m_{Z'}$	1 TeV		MadGraph
$\Gamma_{Z'}$	1 GeV		MadGraph
$\text{dsqrt_q2fact}_{1,2}$	10 GeV		MadGraph
scalefact	1		MadGraph
dsqrt_shat	$2m_{\pi_D}$		MadGraph
κ	1×10^{-3}		MadGraph
e_d	1		MadGraph
m_{ρ_D}	0.2 – 3 GeV		Pythia, SensCalc
r	1.5	1.9	Pythia
$m_{\pi_D} = \frac{m_{\rho_D}}{r}$	0.134 – 1.5 GeV	0.1 – 1.58 GeV	Pythia
$\Lambda_D = \frac{5}{12} \cdot m_{\pi_D} \cdot \sqrt{r^2 - 1.5}$	$0.36m_{\pi_D}$	$0.61m_{\pi_D}$	Pythia
$m_{q_D, \text{curr}} = \frac{4}{121} \cdot \frac{m_{\pi_D}^2}{\Lambda_D}$	$0.09m_{\pi_D}$	$0.05m_{\pi_D}$	MadGraph
$m_{q_D, \text{const}} = m_{q_D, \text{curr}} + \Lambda_D$	$0.45m_{\pi_D}$	$0.66m_{\pi_D}$	Pythia
probVec	0.71	0.68	Pythia
N_{C_D}	3		Pythia
N_{f_D}	2		Pythia
aLund	0.3		Pythia
bLund	0.087		Pythia
separateFlav	On		Pythia
probKeepEta1	0 (suppressed)		Pythia
$g_{\pi\rho}$	~ 5.7 (KSRF)		SensCalc

SensCalc scans over $\Lambda = m_{Z'}/\sqrt{\kappa e e_d}$ and using the reference $\sigma(\kappa) = \sigma(\kappa_{ref}) \cdot \kappa^2/\kappa_{ref}^2$

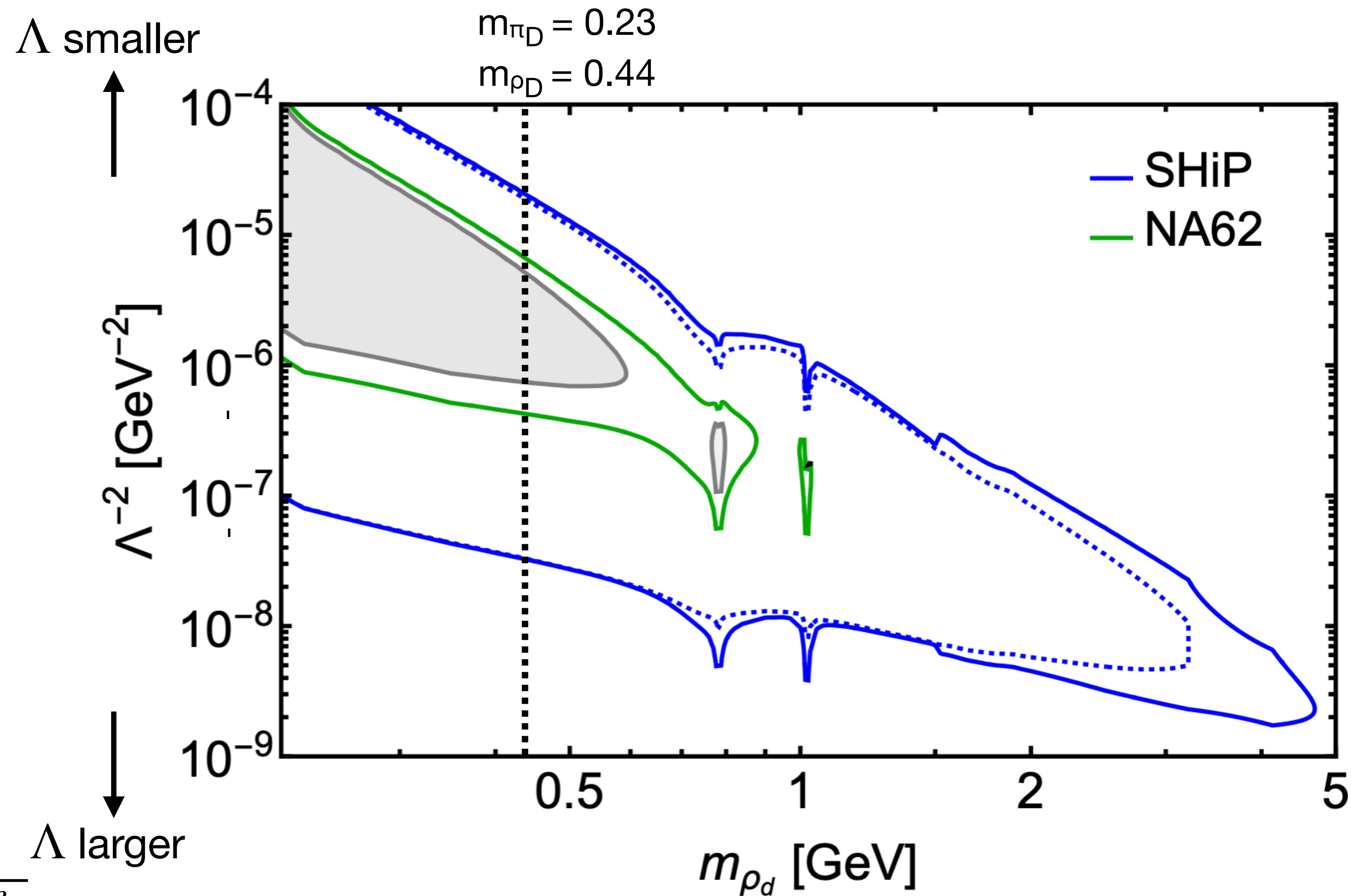
Relations derived from lattice QCD

Ref: E. Bernreuther, **N.H.**, S. Kulkarni et al., *Theory, phenomenology, and experimental avenues for dark showers: a Snowmass 2021 report*, 2022

Ref: C. S. Fischer, *Infrared properties of QCD from Dyson-Schwinger equations*, (2006), [hep-ph/0605173]

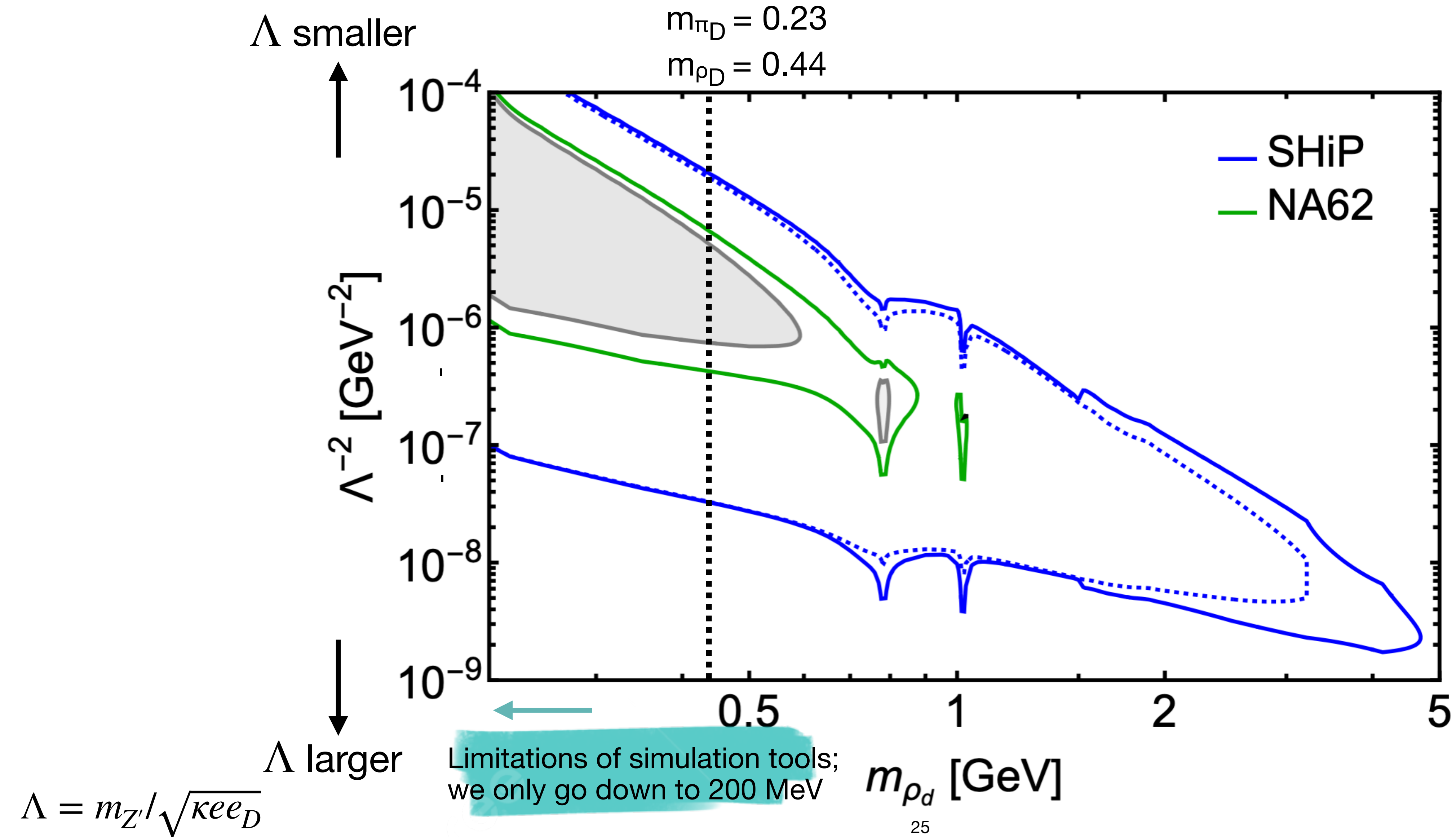
From fit derived by S. Kulkarni, J. Lockyer and W. Liu in [2505.03058]

ρ_D sensitivity at SHiP

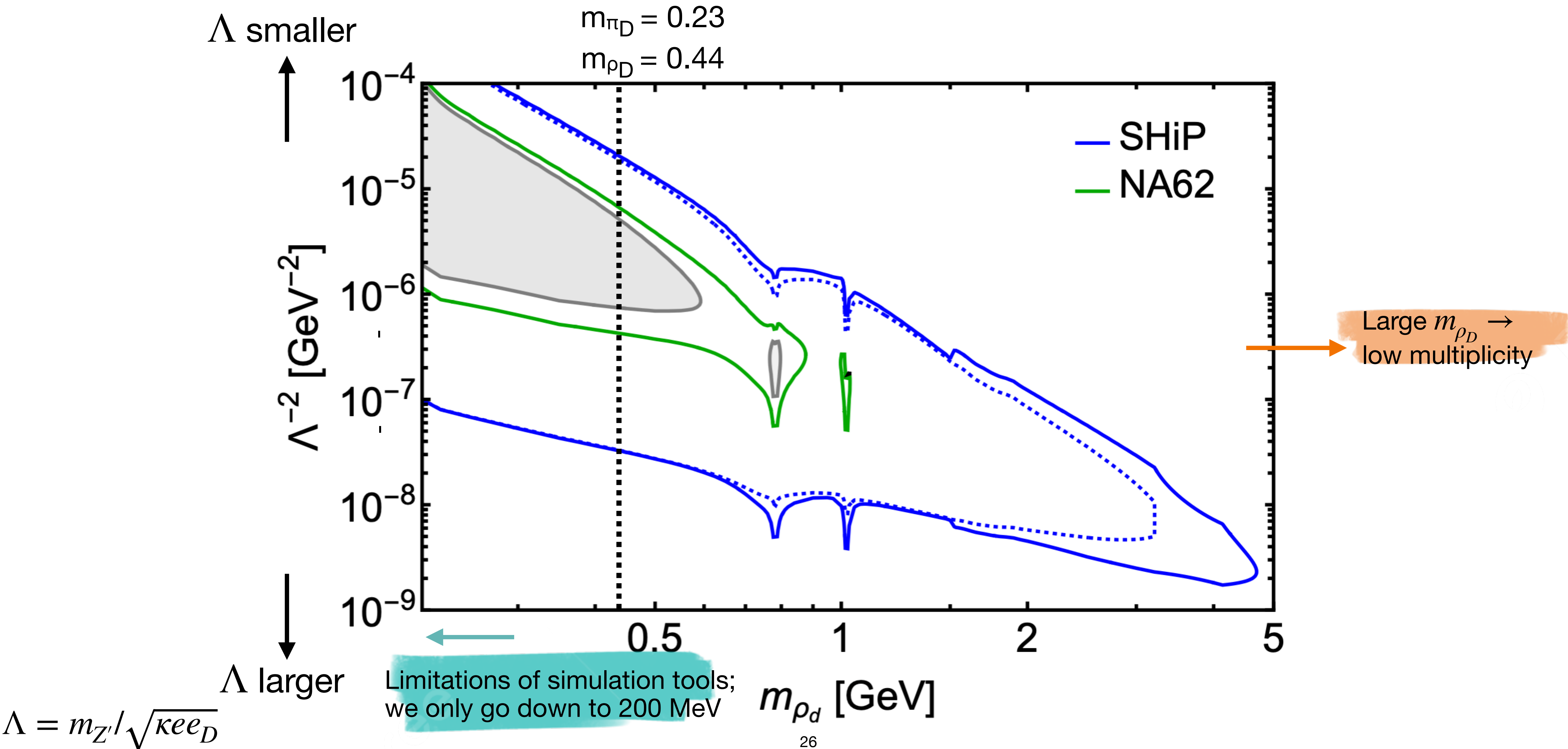


$$\Lambda = m_{Z'}/\sqrt{\kappa e e_D}$$

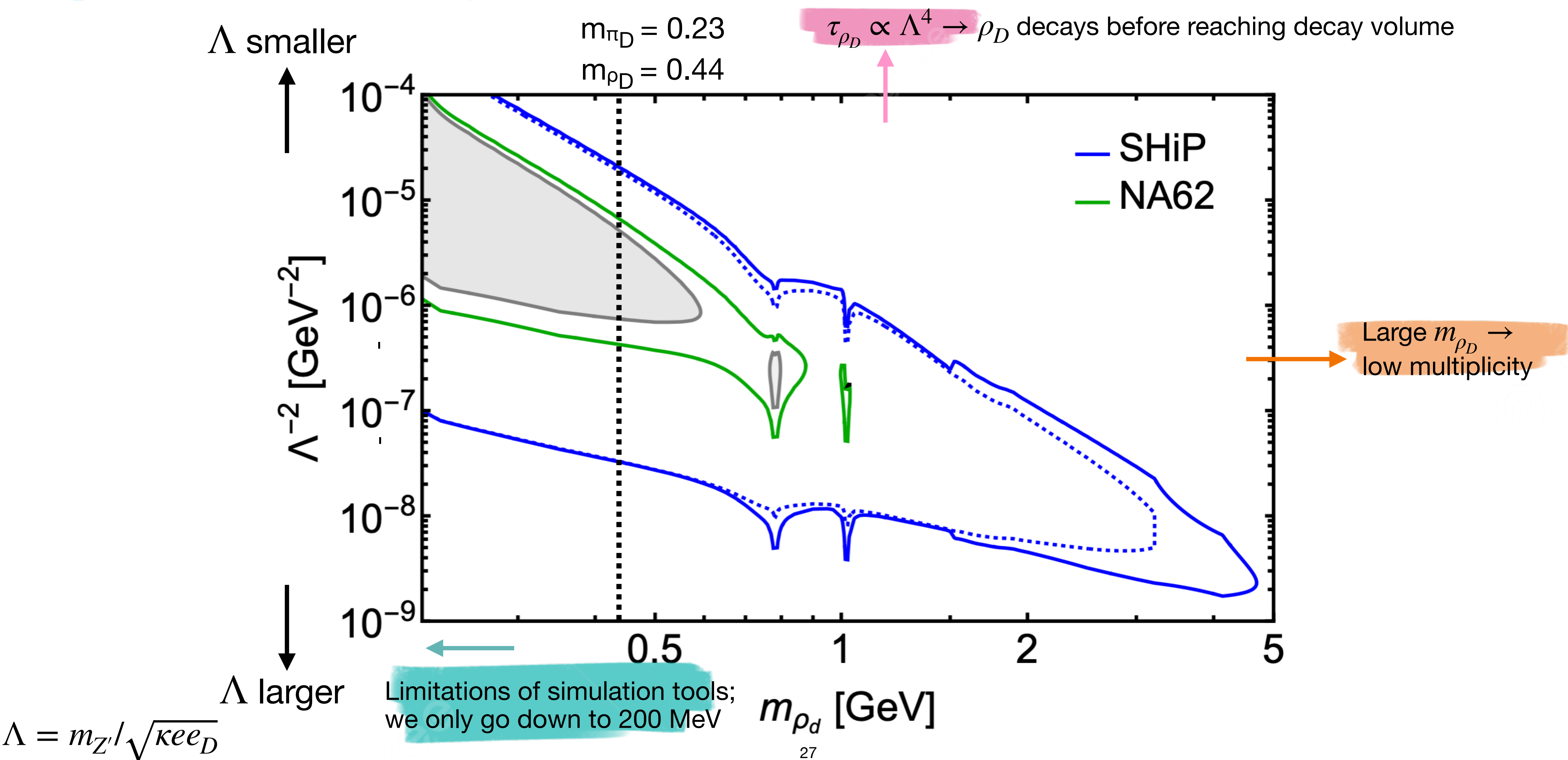
ρ_D sensitivity at SHiP



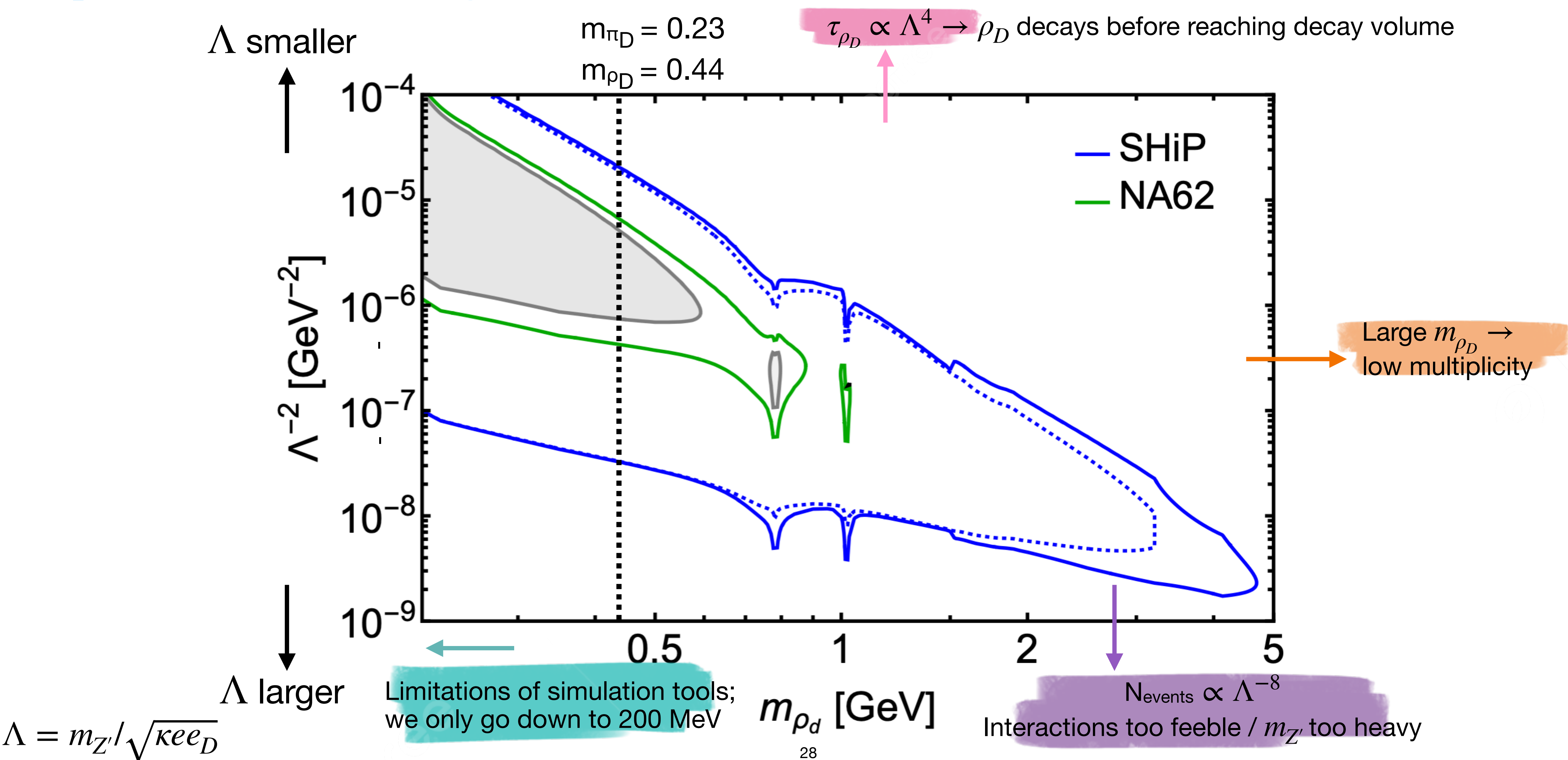
ρ_D sensitivity at SHiP



ρ_D sensitivity at SHiP

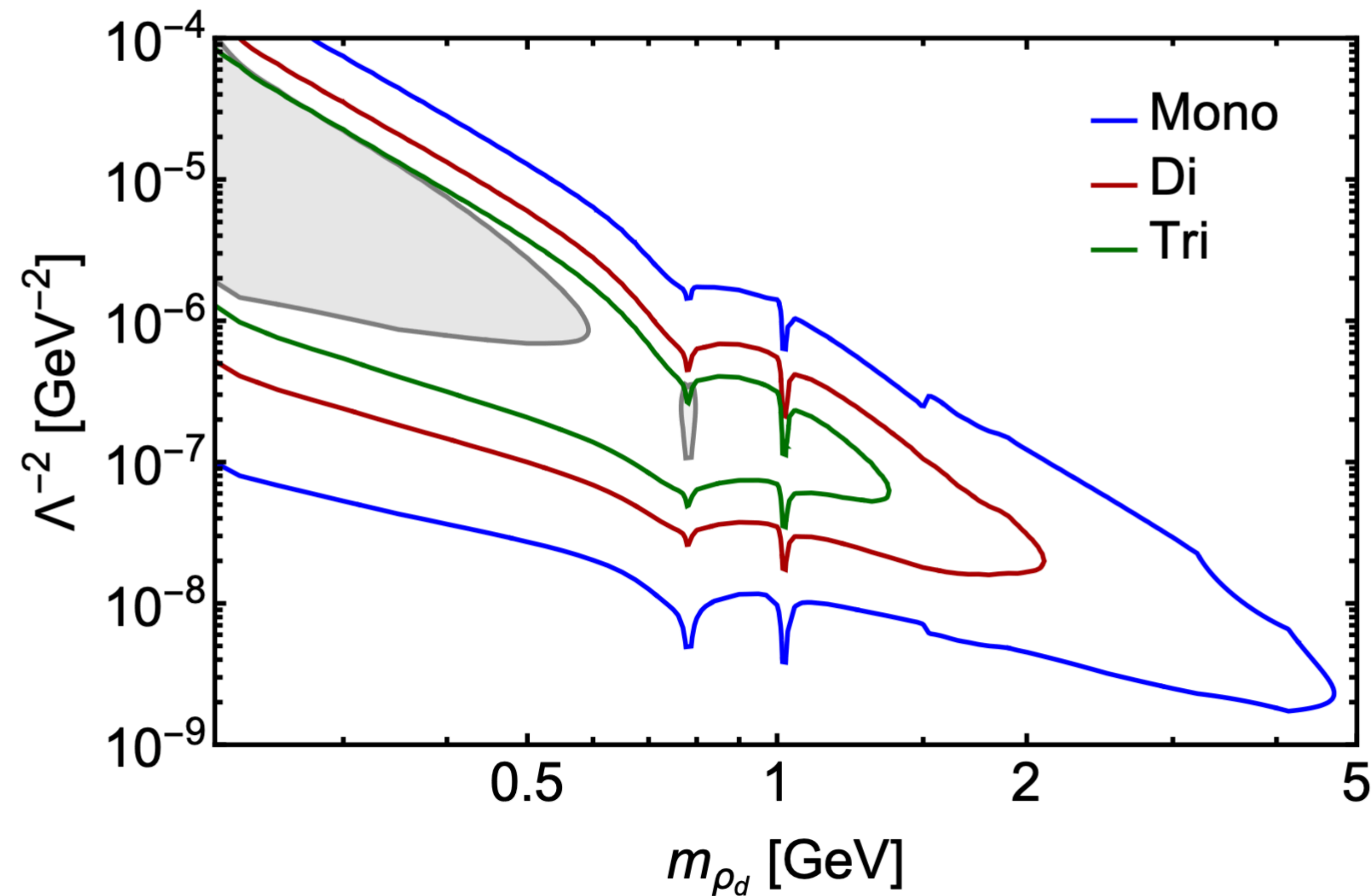


ρ_D sensitivity at SHiP



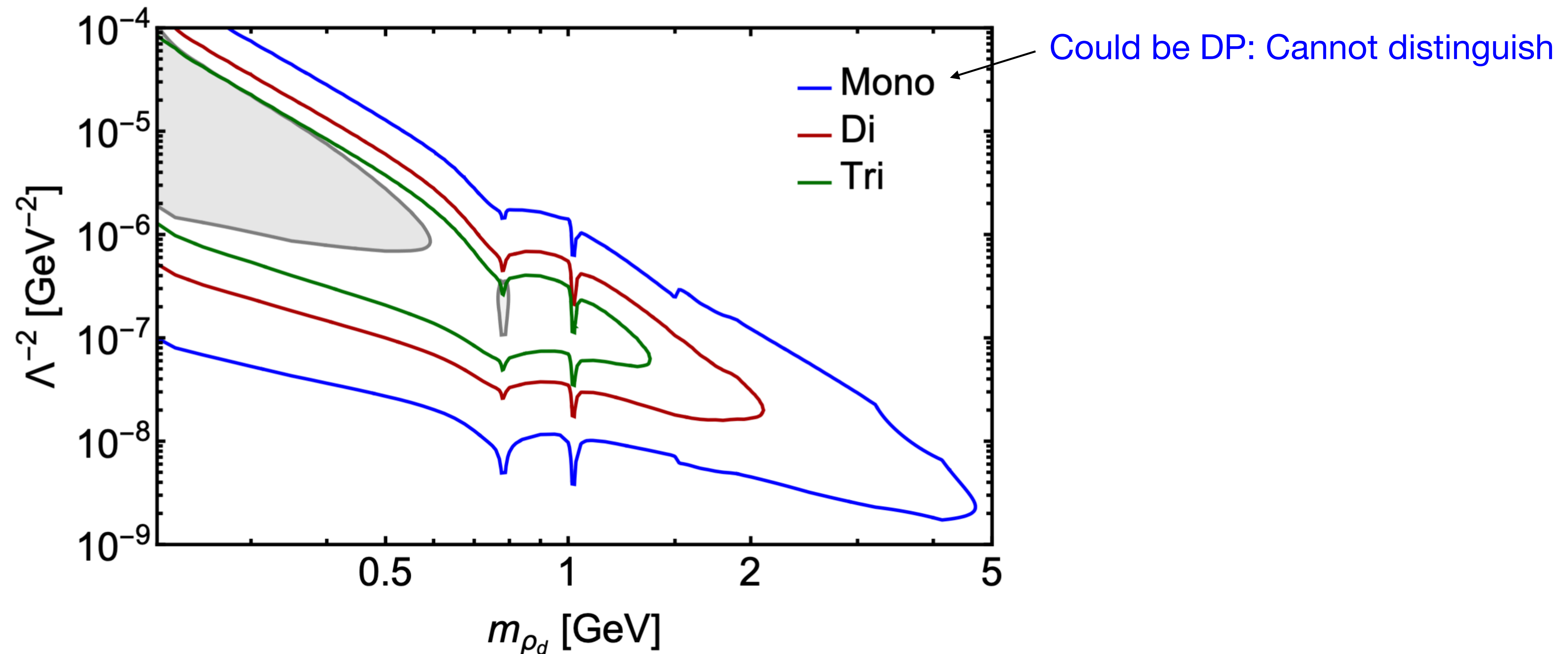
ρ_D sensitivity at SHiP

How can we tell if it is in fact a ρ_D or “just” a dark photon?



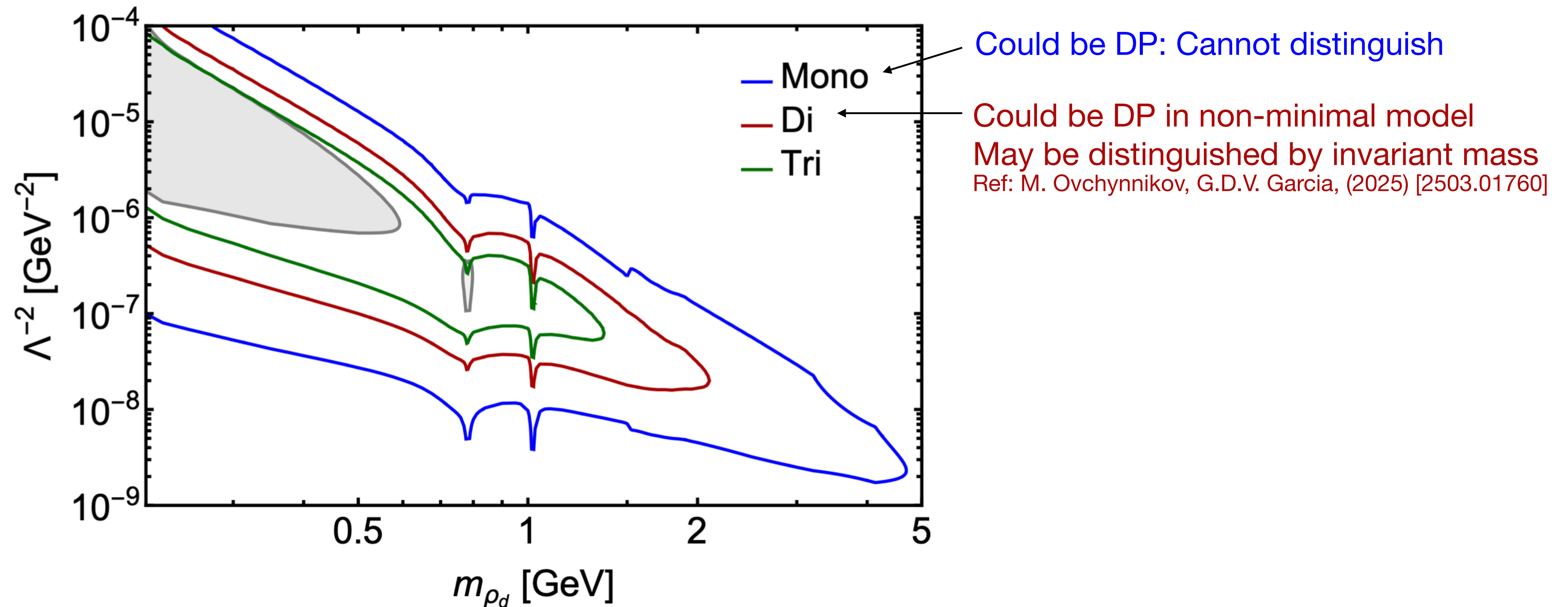
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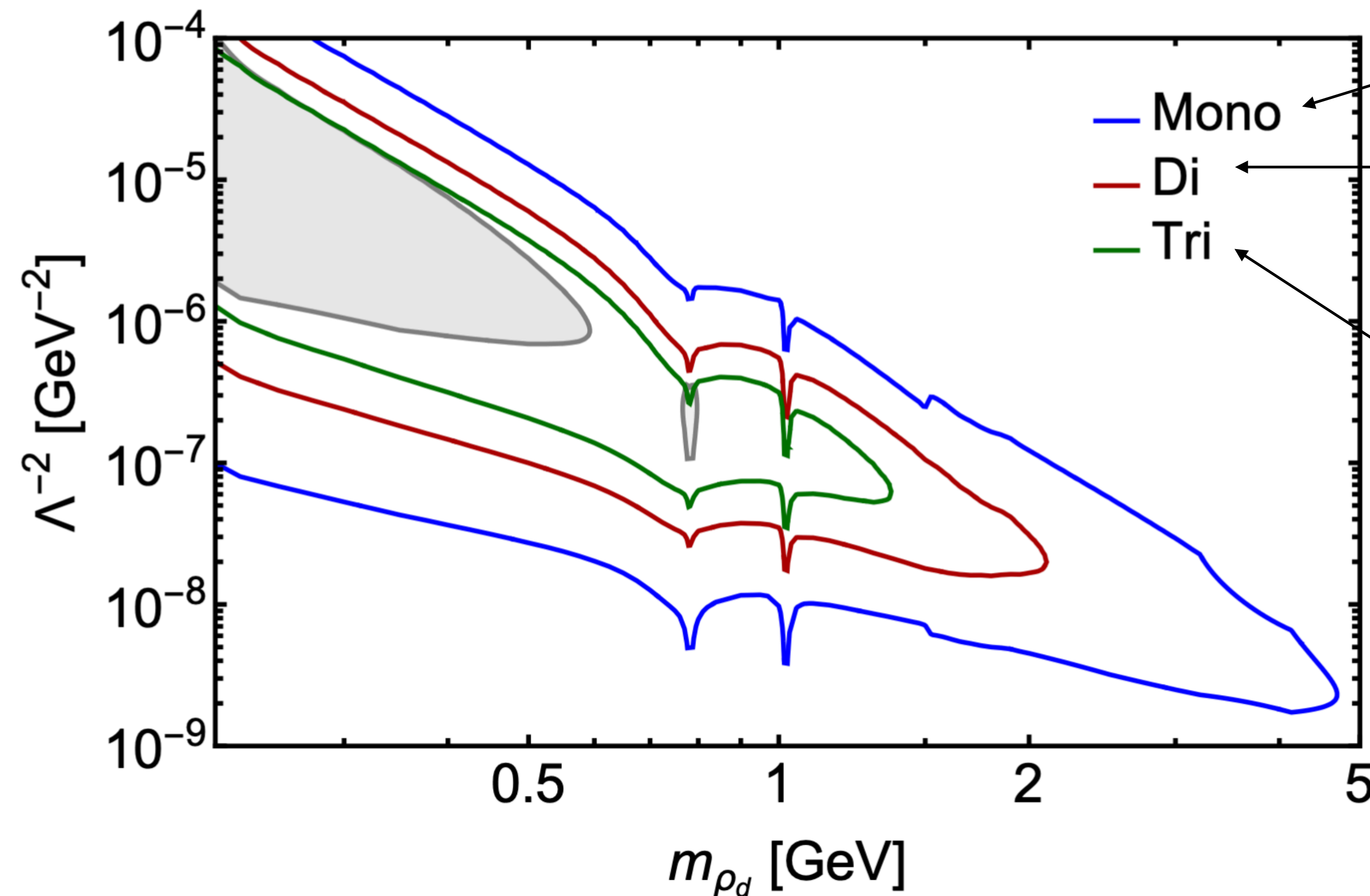
ρ_D sensitivity at SHiP

How can we tell if it is in fact a ρ_D or “just” a dark photon?



ρ_D sensitivity at SHiP

How can we tell if it is in fact a ρ_D or “just” a dark photon?



Could be DP: Cannot distinguish

Could be DP in non-minimal model
May be distinguished by invariant mass
Ref: M. Ovchinnikov, G.D.V. Garcia, (2025) [2503.01760]

Only expected for ρ_D



Summary

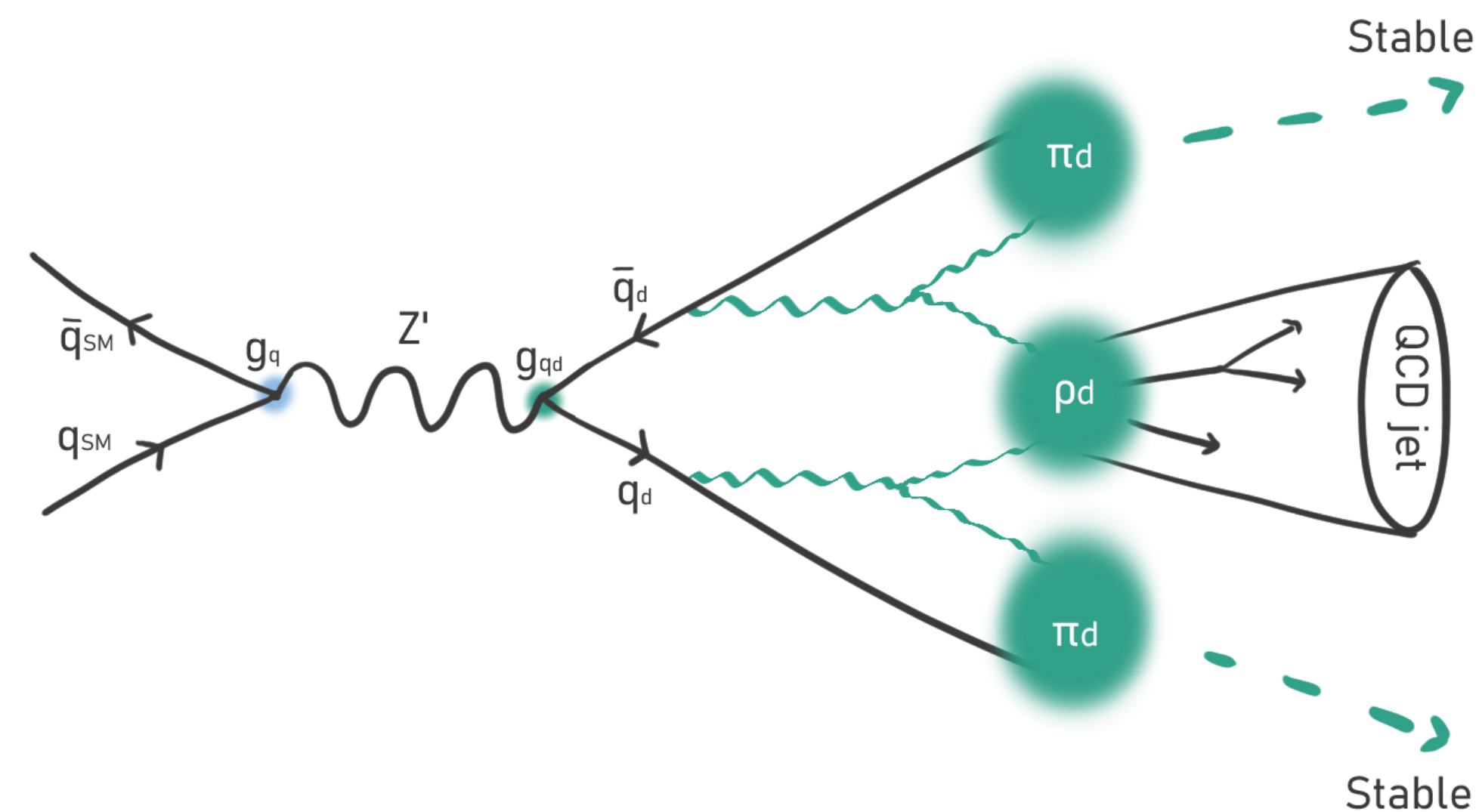
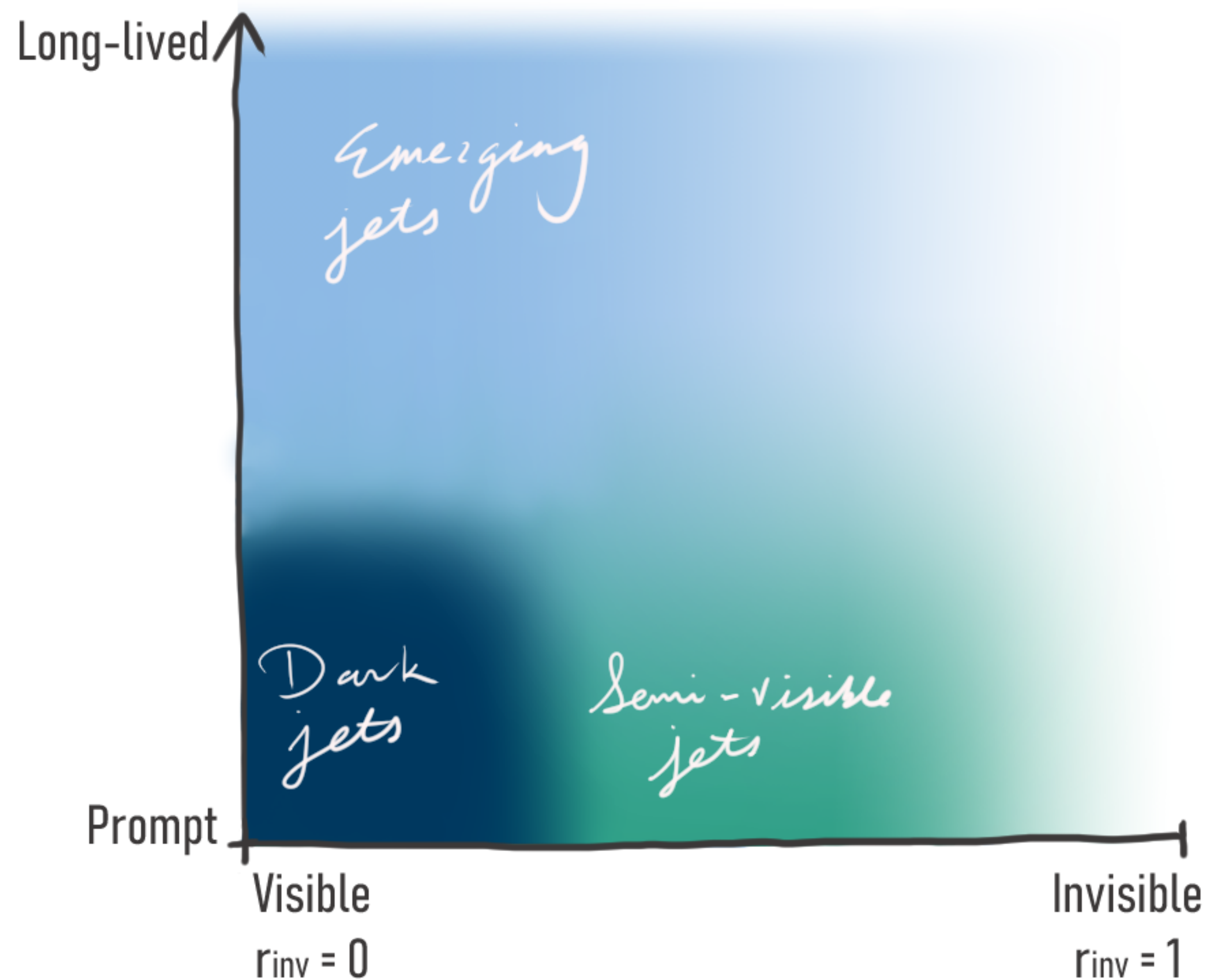
Light ρ_D ($m_{\rho_D} < 2m_{\pi_D}$) of $O(1 \text{ GeV})$ is a well-motivated scenario from a cosmological/astrophysical perspective

In this case, we can “easily” imagine models where ρ_D is long-lived with *dark photon like* decays to SM particles

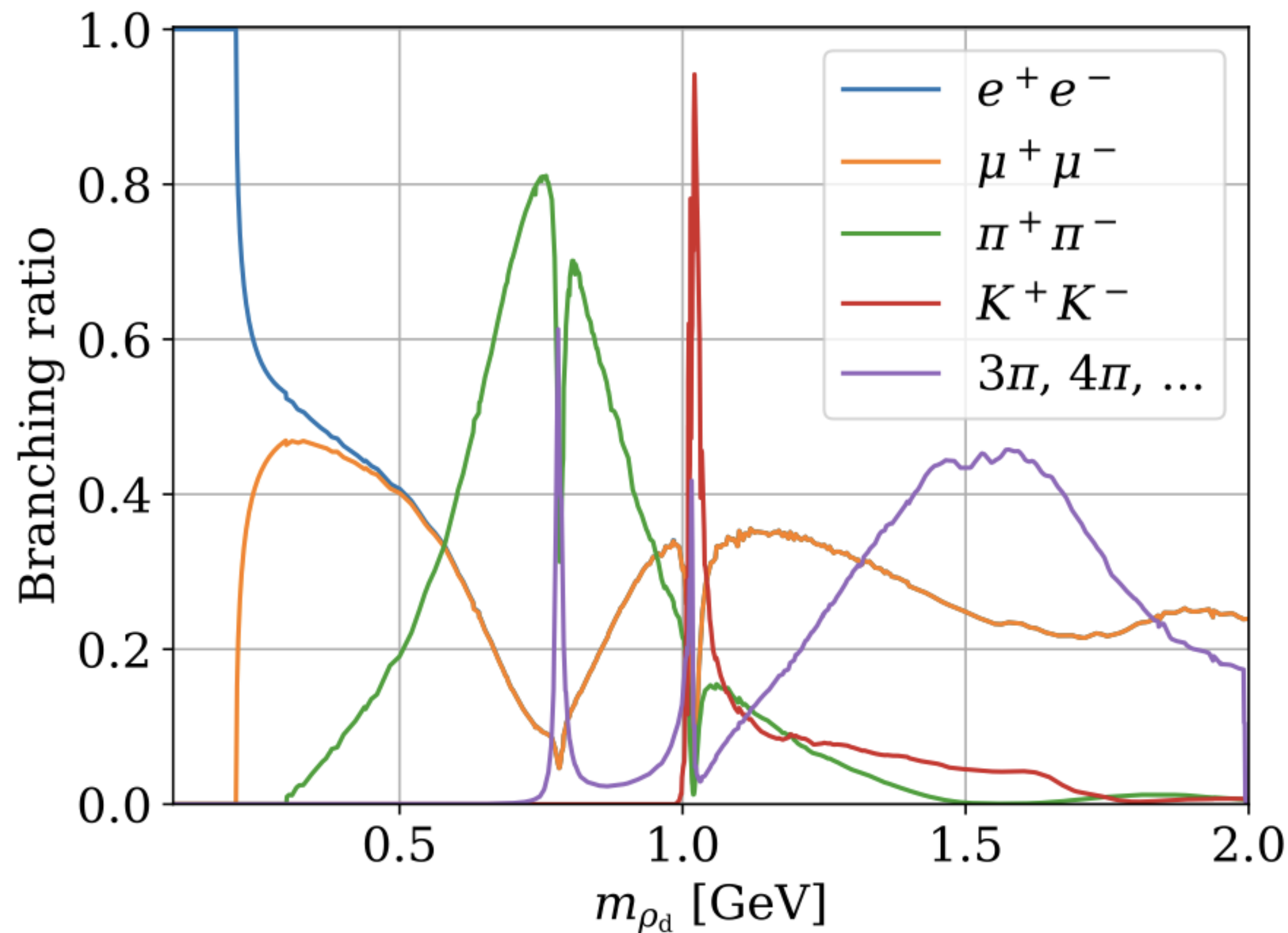
SHiP has sensitivity to such signatures at $<5 \text{ GeV}$ mass

A dark QCD origin of this signature will have a unique production mode and can “easily” give rise to multi-decays

Backup Slide - Dark Showers



Backup Slide - SM final states and $\pi_D \pi_D$ annihilations



Ref: E. Bernreuther, F. Kahlhoefer et al., (2022)
Forecasting dark showers at Belle II [2203.08824]

At small m_{ρ_D}

$$\mathcal{L}_{\text{mix}} = g_\ell \bar{e} \gamma_\mu e \rho_D^\mu$$

With new $U(1)'$

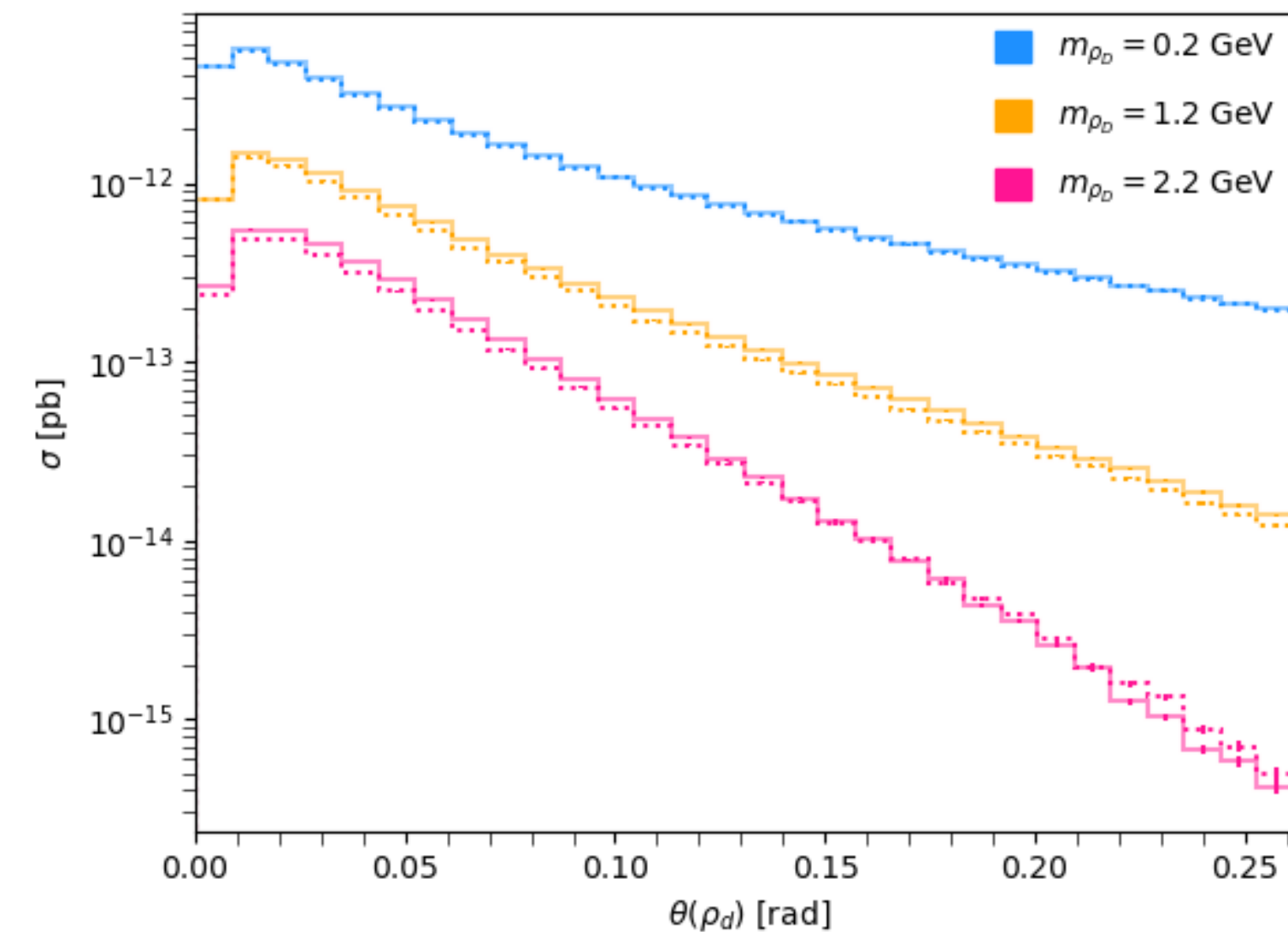
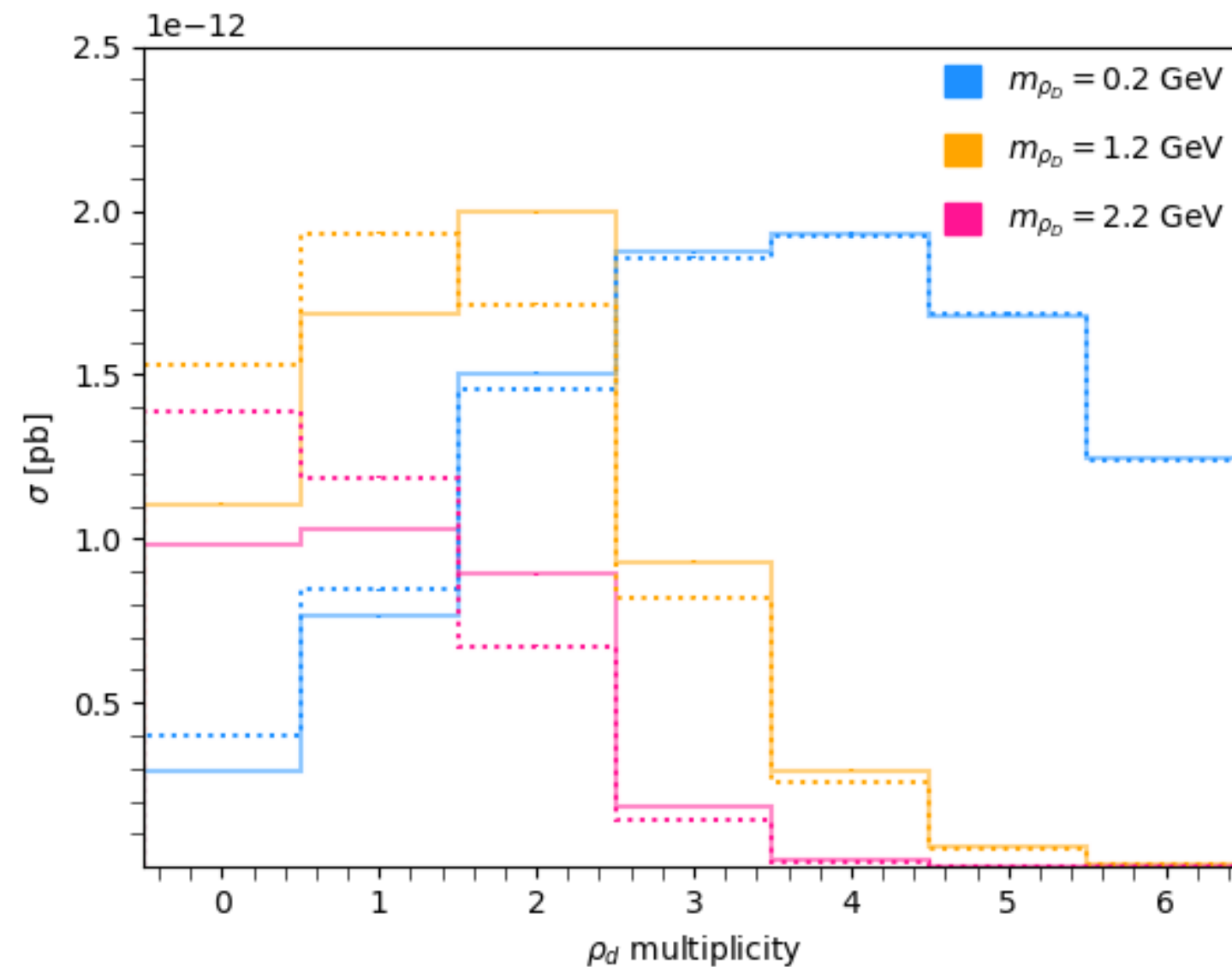
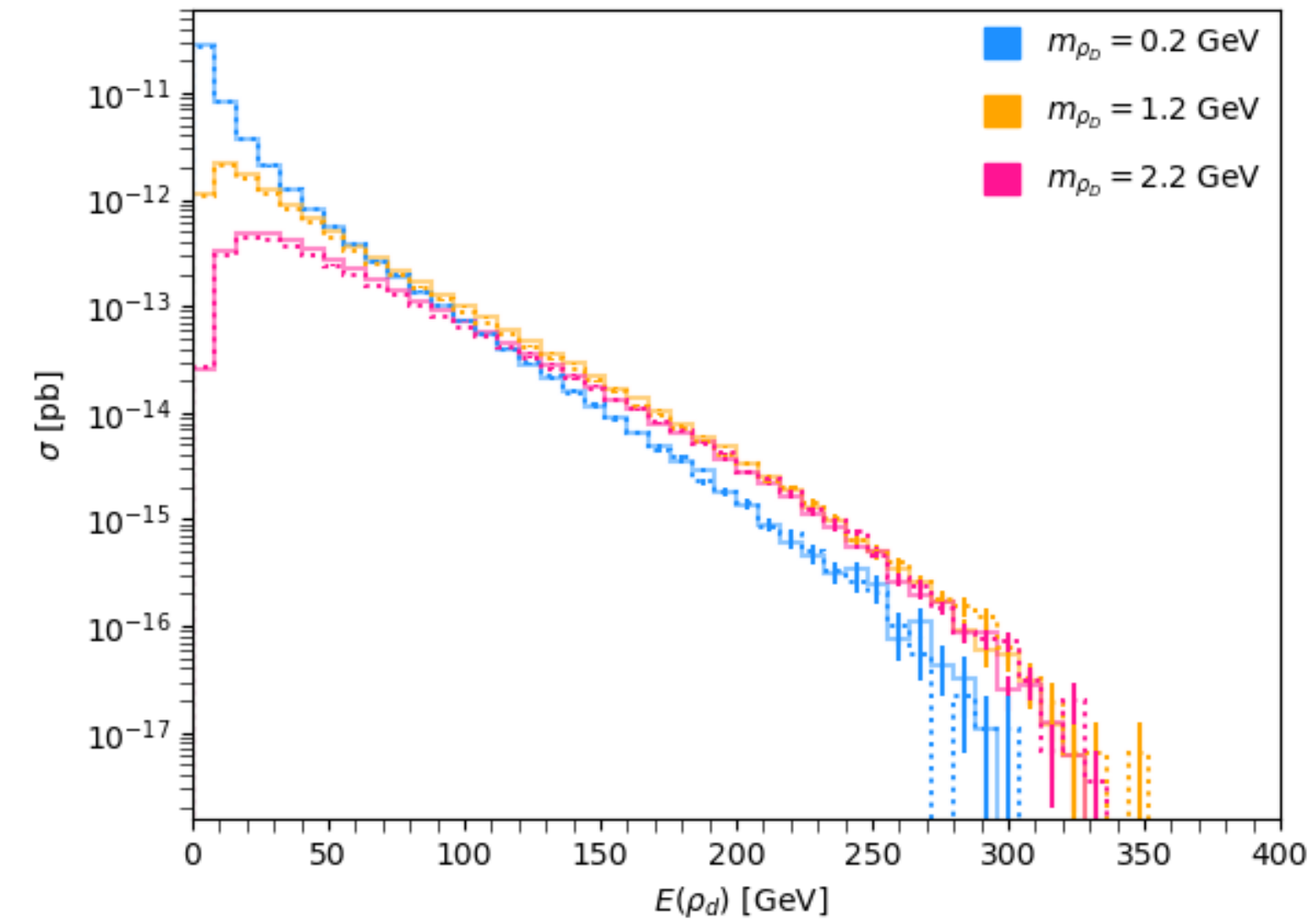
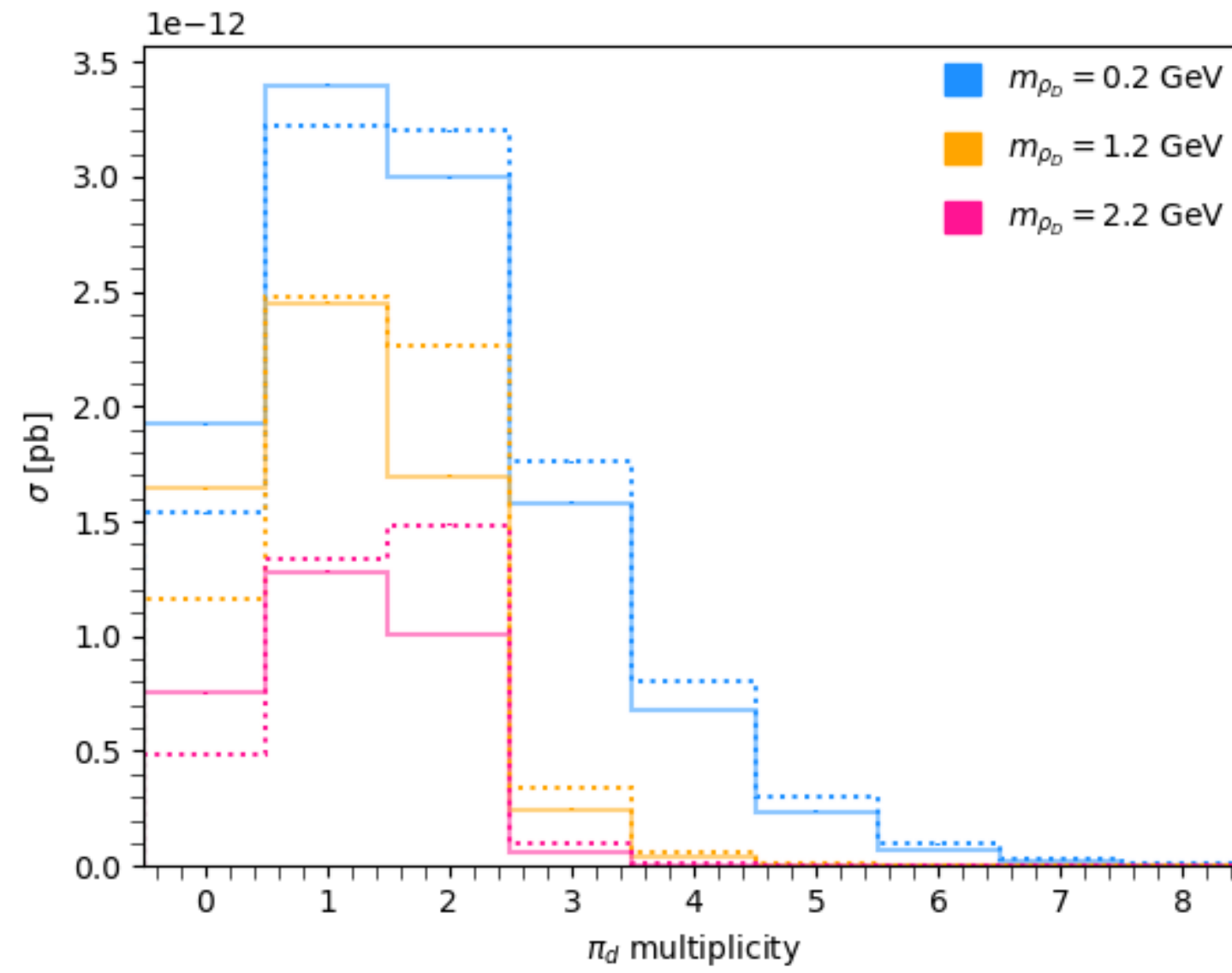
$$g_\ell = \frac{m_{\rho_D}^2}{m_{Z'}^2} \frac{2ee_D \kappa}{g}$$

$$g_\ell \lesssim 3 \times 10^{-5}$$

“We conclude that there is a wide region of parameter space, where the assumptions made in our analysis are satisfied, i .e . the decays of the dark rho meson maintain thermal equilibrium between the dark and visible sectors, but direct annihilations of dark pions into SM final states are negligible.”

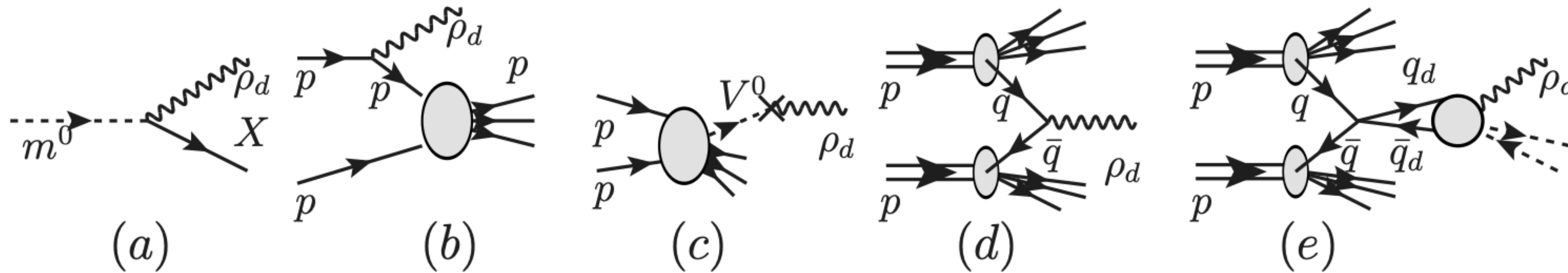
Ref: E. Bernreuther, F. Kahlhoefer, **N.H.**, S. Kulkarni
(2023) Dark matter relic density in strongly interacting dark sectors with light vector mesons [2311.17157]

Backup Slide - Kinematic distributions

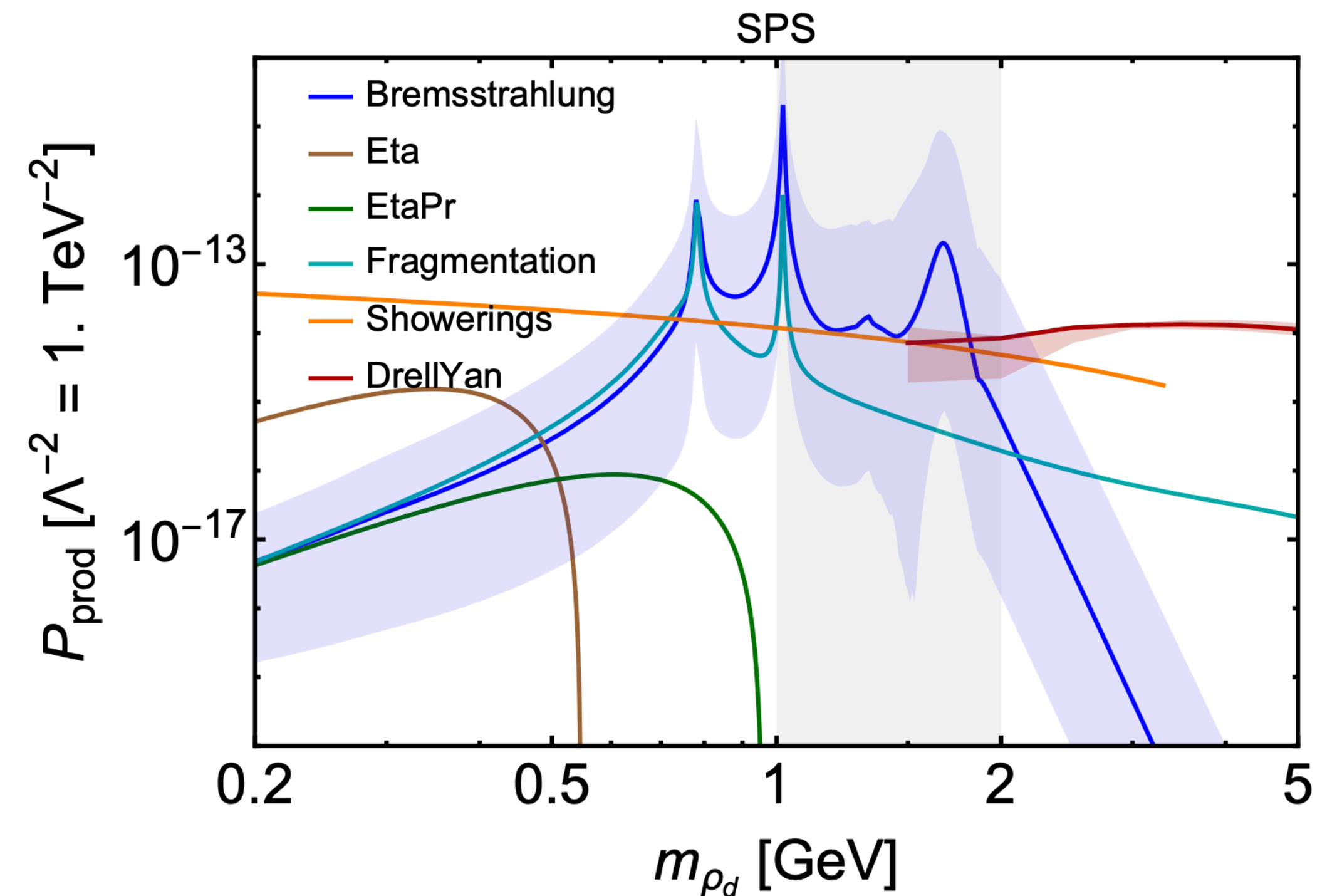


Solid line: $r=1.5$
Dotted line: $r=1.9$

Backup Slide - Production Mechanisms



- (a) Decays of neutral SM mesons
- (b) Proton Bremsstrahlung
- (c) Mixing with neutral SM mesons
- (d) Drell-Yan
- (e) Dark showers



Backup Slide - Non-perturbative Methods

Infrared Properties of QCD from Dyson-Schwinger equations

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Abstract. I review recent results on the infrared properties of QCD from Dyson-Schwinger equations. The topics include infrared exponents of one-particle irreducible Green's functions, the fixed point behaviour of the running coupling at zero momentum, the pattern of dynamical quark mass generation and properties of light mesons.

PACS numbers: 02.30.Rz, 11.10.St, 12.38.Aw, 12.38.Lg, 14.40.Aq, 14.65.Bt, 14.70.Dj

Ref: C. S. Fischer, *Infrared properties of QCD from Dyson-Schwinger equations*, (2006), [hep-ph/0605173]

QCD modeling of hadron physics

P. Maris^{ab} and P.C. Tandy^b

^aDept. of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260

^bCenter for Nuclear Research, Dept. of Physics, Kent State University, Kent OH 44242

We review recent developments in the understanding of meson properties as solutions of the Bethe-Salpeter equation in rainbow-ladder truncation. Included are recent results for the pseudoscalar and vector meson masses and leptonic decay constants, ranging from pions up to $c\bar{c}$ bound states; extrapolation to $b\bar{b}$ states is explored. We also present a new and improved calculation of $F_\pi(Q^2)$ and an analysis of the $\pi\gamma\gamma$ transition form factor for both $\pi(140)$ and $\pi(1330)$. Lattice-QCD results for propagators and the quark-gluon vertex are analyzed, and the effects of quark-gluon vertex dressing and the three-gluon coupling upon meson masses are considered.

Ref: P. Maris and P. C. Tandy, Nucl. Phys. B Proc. Suppl. 161 (2006), 136–152, [nucl-th/0511017]

Appropriate for small $m_{\pi D}/\Lambda_D$, though they work far beyond this expectation, and begin to differ from lattice computations by >10% only for $m_{\pi D}/\Lambda_D > 2.3$

$$\frac{m_{\pi D}}{\tilde{\Lambda}_D} = 5.5 \sqrt{\frac{m_{qD}}{\tilde{\Lambda}_D}} \qquad \frac{m_{\rho D}}{\tilde{\Lambda}_D} = \sqrt{5.76 + 1.5 \frac{m_{\pi D}^2}{\tilde{\Lambda}_D^2}}$$

Ref: E. Bernreuther, **N.H.**, S. Kulkarni et al., *Theory, phenomenology, and experimental avenues for dark showers: a Snowmass 2021 report*, 2022

Valid for $1 < m_{\rho D}/m_{\pi D} \lesssim 20$, where the lower limit on $m_{\rho D}/m_{\pi D}$ corresponds to $\xi \sim 8$:

$$\xi \equiv \frac{m_{\pi D}}{f_{\pi D}} = 7.79 \frac{m_{\pi D}}{m_{\rho D}} + 0.57 \left(\frac{m_{\pi D}}{m_{\rho D}} \right)^2$$

Ref: E. Bernreuther, F. Kahlhoefer, **N.H.**, S. Kulkarni (2023) *Dark matter relic density in strongly interacting dark sectors with light vector mesons* [2311.17157]

Backup Slide - $3\pi_D$ to $\pi_D + \rho_D$ interaction



$$D_\mu \pi_d = \partial_\mu \pi_d + ig[\pi_d, \rho_{d\mu}]$$

Reminder :

$$\mathcal{L}_{Ch} \supset \frac{f_{\pi_D}^2}{4} \text{Tr}(D_\mu U D^\mu U) + \left[\frac{\mu_D^3}{2} \text{Tr}(M_q U^\dagger) + \text{h.c.} \right]$$

