Karlsruher Institut für Technologie

Collaborative Research Center TRR 257
Particle Physics Phenomenology after the Higgs Discovery

GeV scale strongly-interacting dark sectors at beam dump experiments

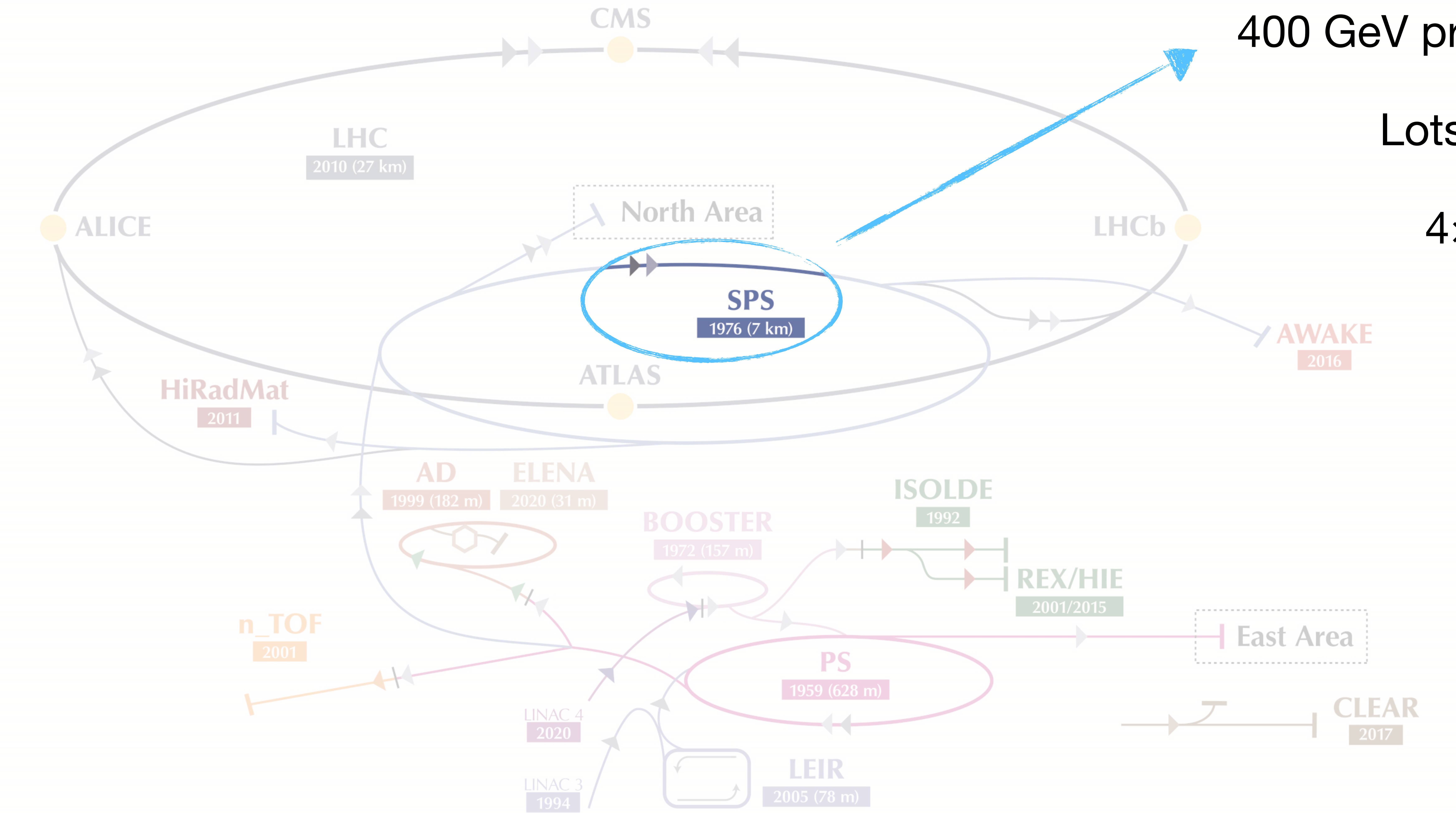
Nicoline Hemme (KIT, Germany)

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

EPS-HEP - Marseilles - July 9th 2025

The SHiP Experiment

The location



400 GeV proton beam extracted from SPS

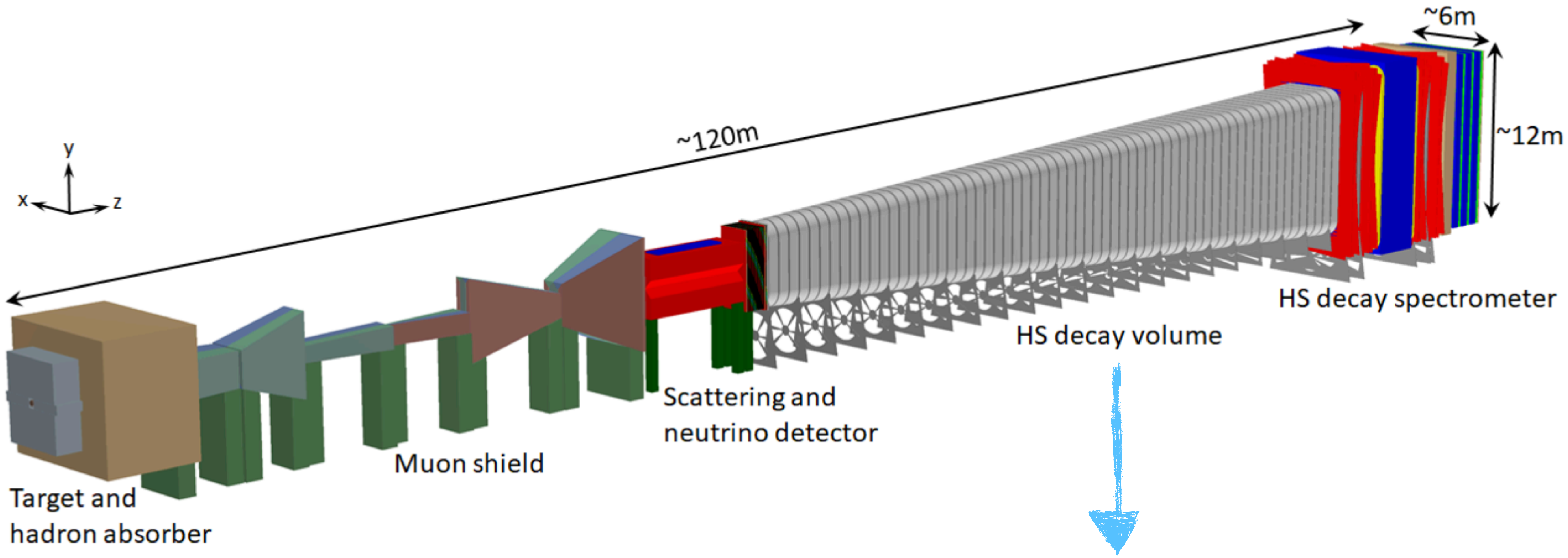
Lots of charm, beauty and photons

$4{\times}10^{19}$ proton-on-target annually

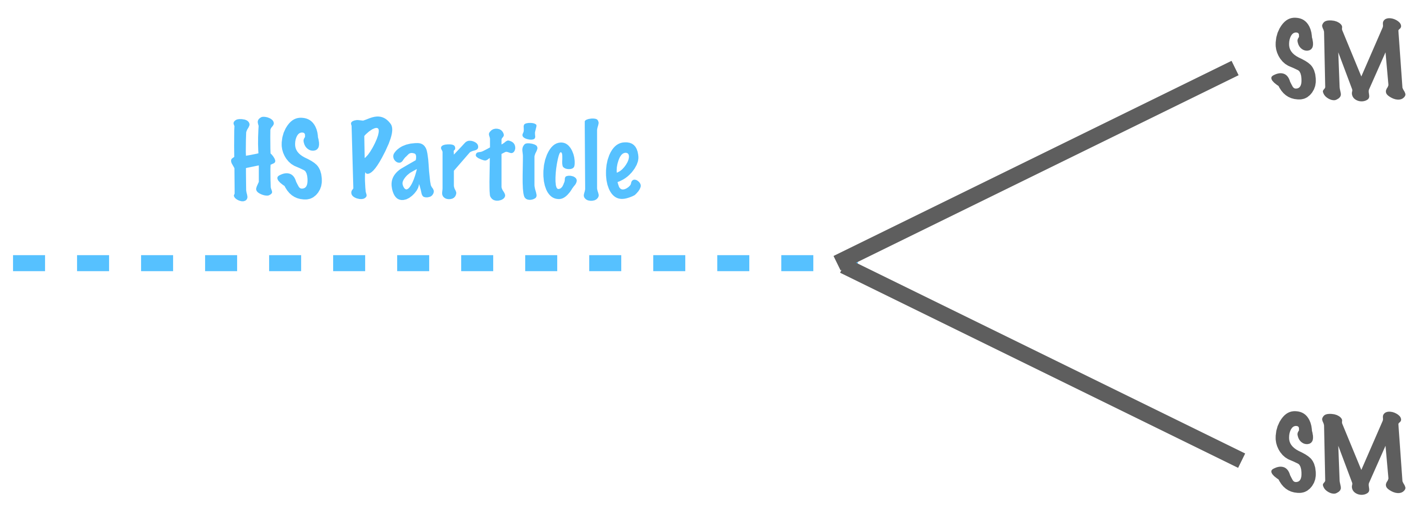
Image: *Configuration and Layouts section, Accelerator Coordination and Engineering group, Engineering department, CERN*

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

The layout



Designed for detection of LLPs



For more on SHiP: See Maksym Ovchynnikov's talk later today at **16.45 in the Main Auditorium**!

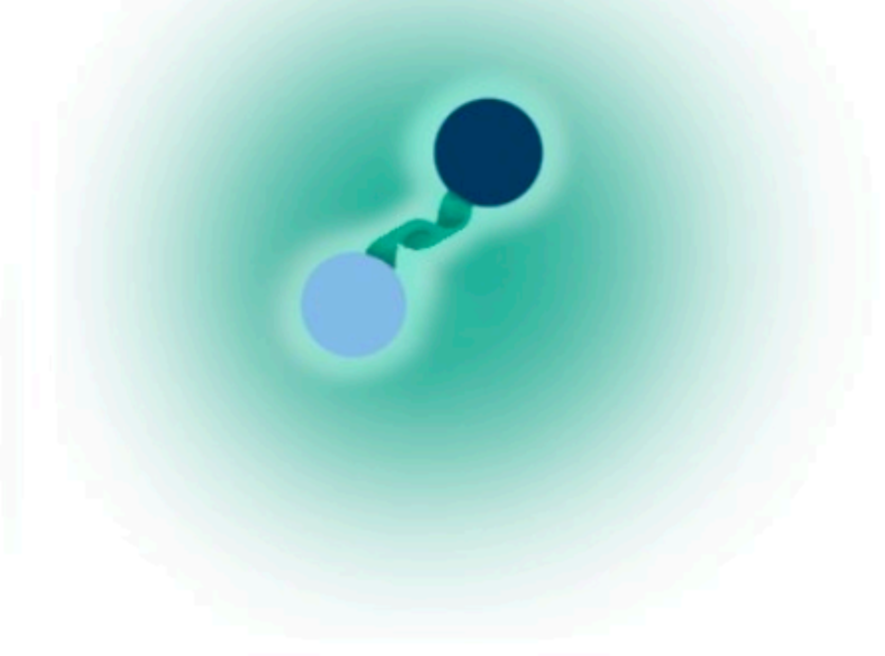
Ref: The SHiP Collaboration, *The SHiP experiment at the proposed CERN SPS Beam Dump Facility*, 2022

A strongly interacting dark sector

The theory

Particles of the theory
Dark quarks and dark gluons

Particles of the theory
Bound states



Confinement / breakdown of UV theory

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

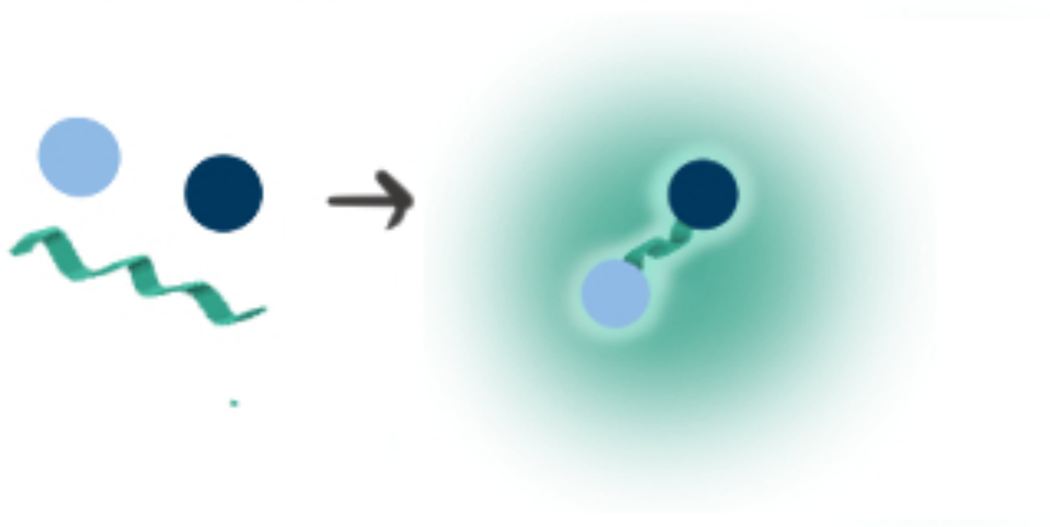
$$\mathcal{L}_{Ch} \supset \frac{f_{\pi_d}^2}{4} \mathrm{Tr}\left(D_{\mu} U D^{\mu} U\right) + \left[\frac{\mu_d^3}{2} \mathrm{Tr}\left(\mathrm{M}_q U^{\dagger}\right) + \mathrm{h.c.}\right]$$

High energy — $E \sim \Lambda_D$ — Low energy

The theory

N_{cd}
Number of dark colours

Λ_d
Dark confinement scale



N_{fd}
Number of dark flavours

m_d, m_{qd}
Mass spectra

The theory

N_{cd}

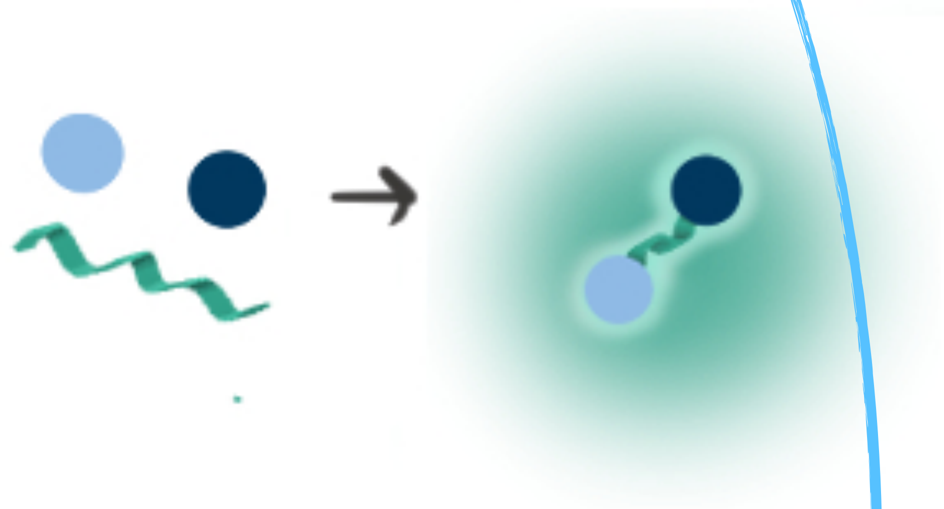
Number of dark colours

N_{fd}

Number of dark flavours

Λ_d

Dark confinement scale



m_d, m_{qd}

Mass spectra

Relate via Lattice QCD

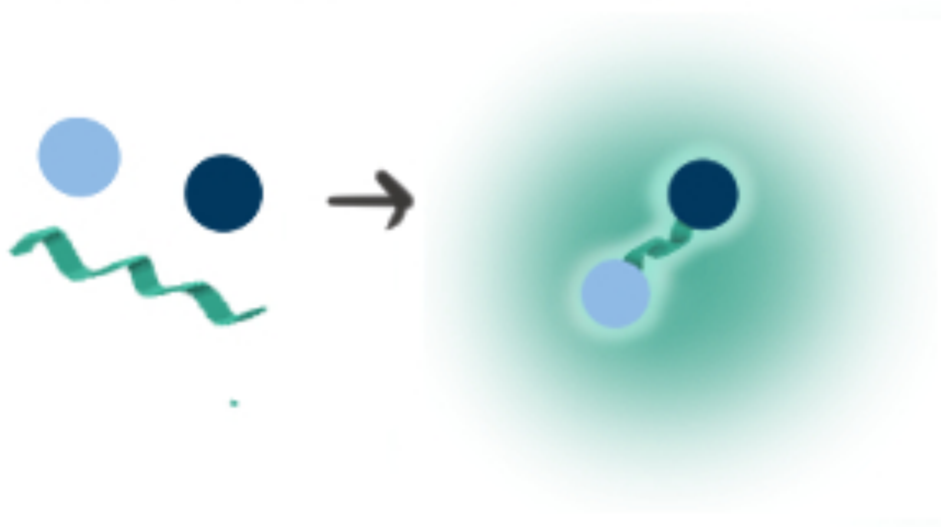
Ref: Theory, phenomenology, and experimental avenues for dark showers: a Snowmass 2021 report, 2022

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

The theory

N_{cd}
Number of dark colours

Λ_d
Dark confinement scale



Connection to SM
e.g. via Z' portal

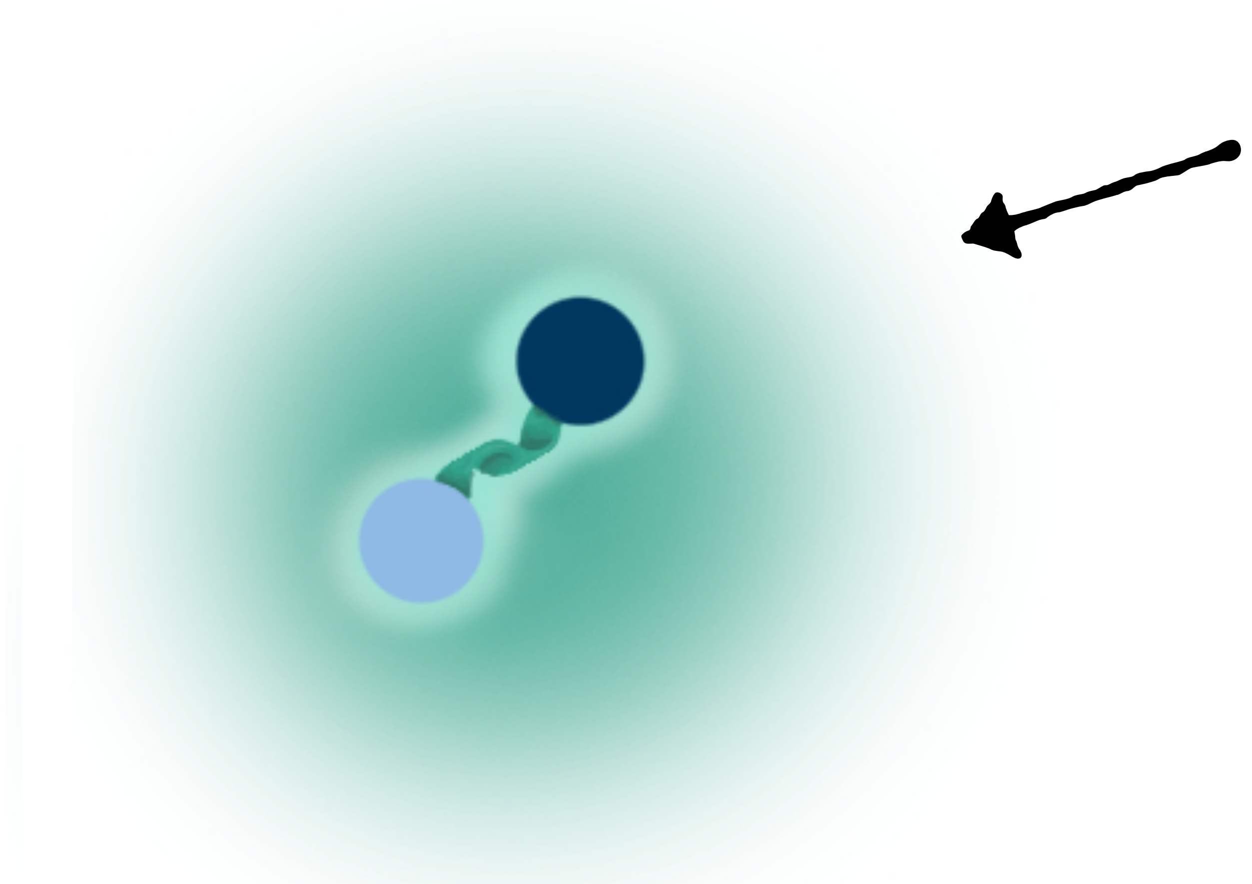
g, κ, e_d
Couplings

N_{fd}
Number of dark flavours

m_d, m_{qd}
Mass spectra

m_{med}
Mediator mass

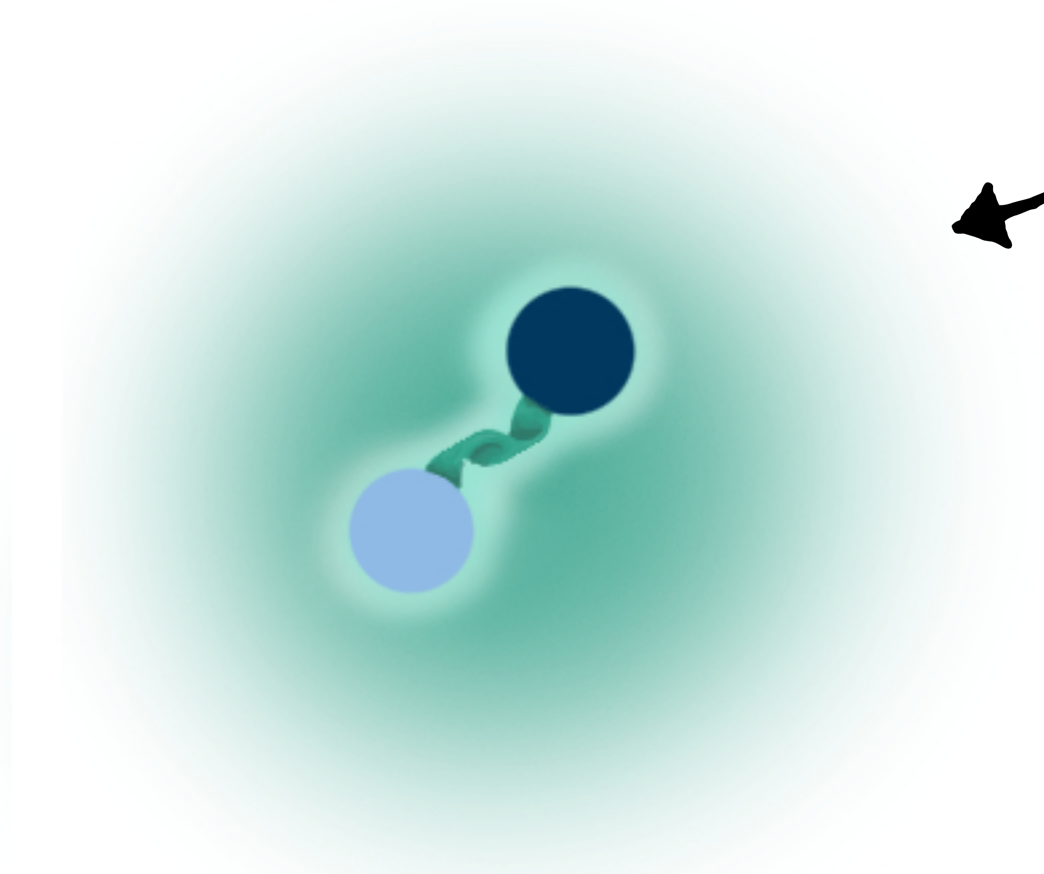
The bound states



Dark Matter candidate

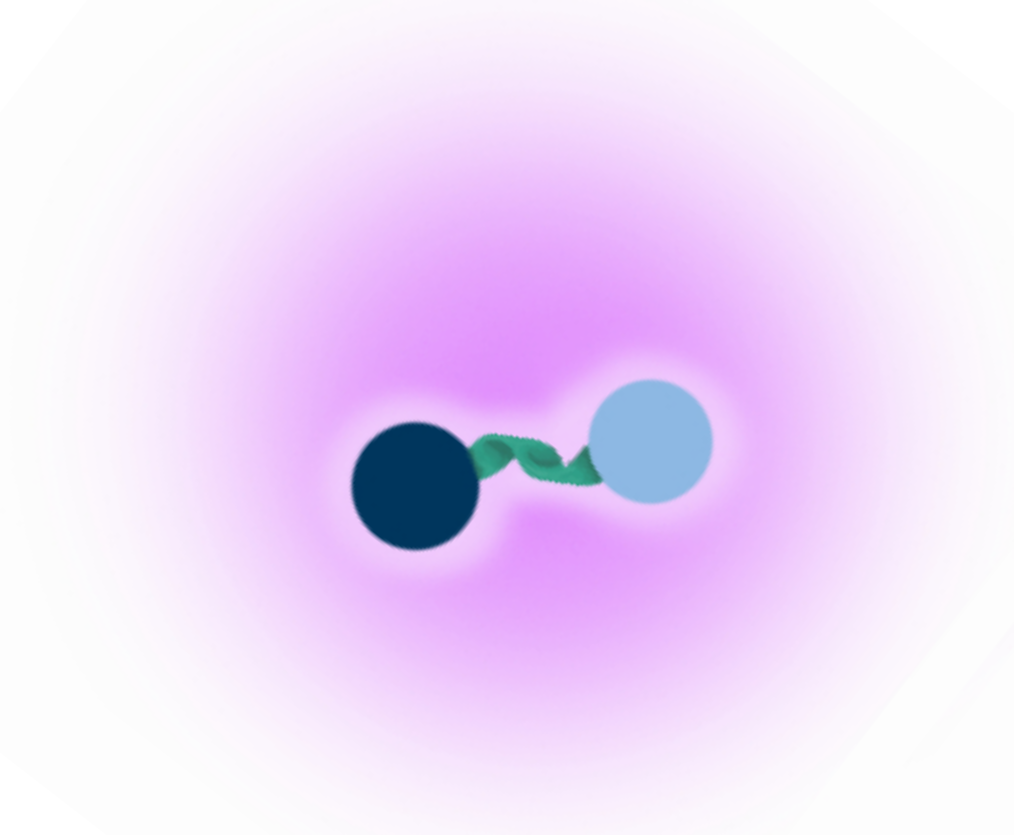
Dark pion π_D
(lightest bound state)

The bound states



Dark Matter candidate

Dark pion π_D
(lightest bound state)

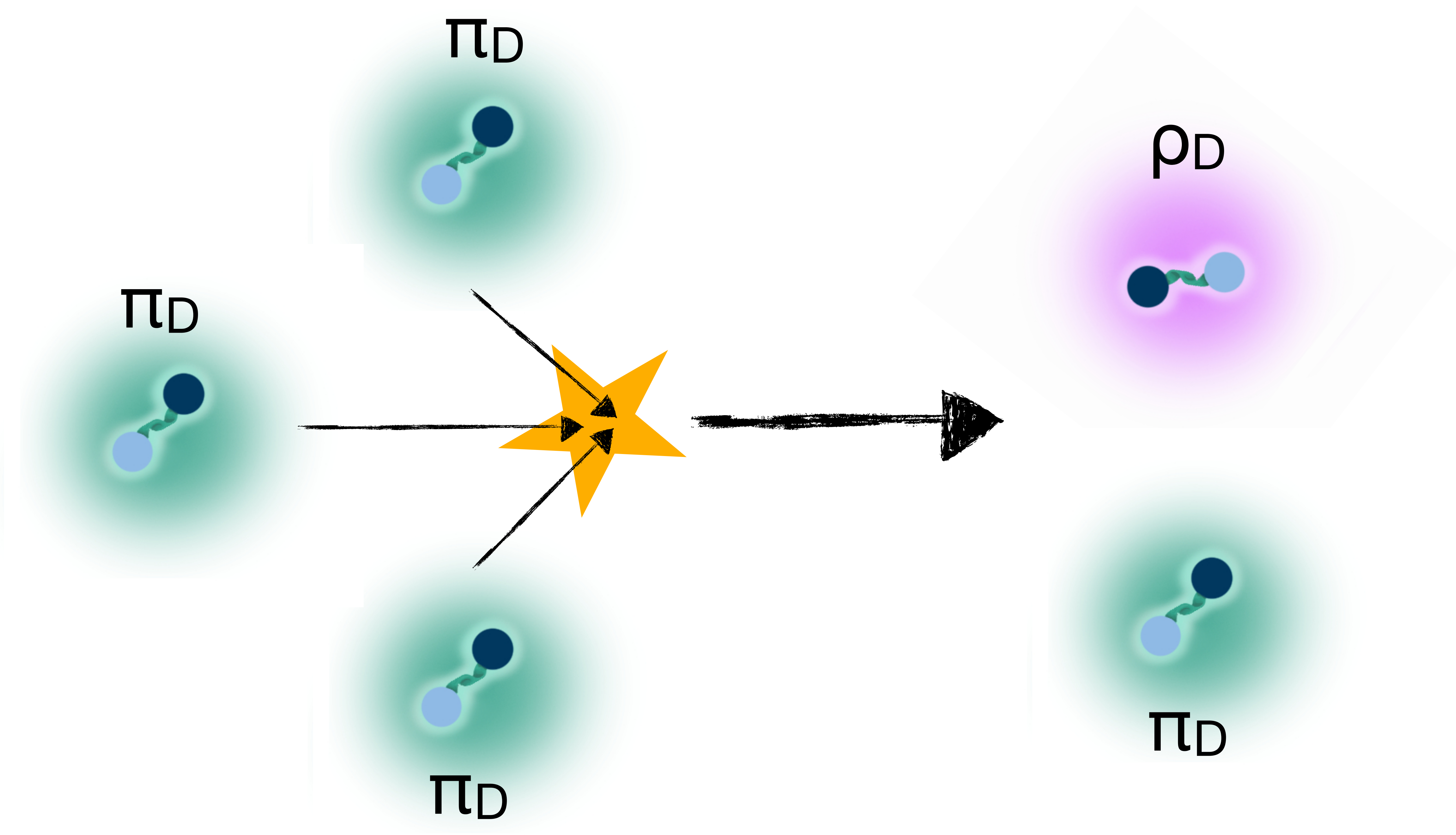


Dark rho meson ρ_D
(Second lightest bound state)

Candidate for SHiP signature

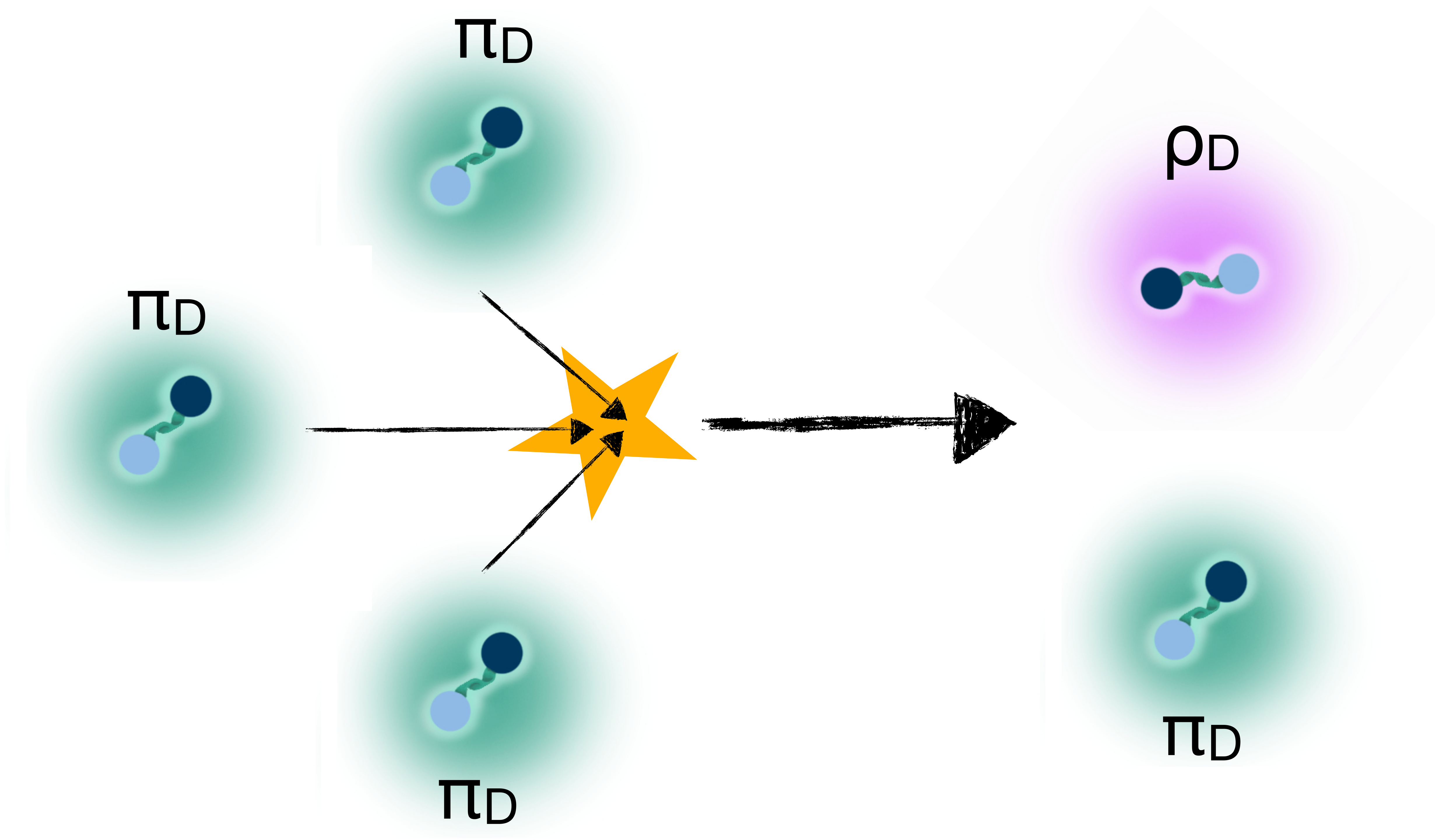
- Z' portal allows production at accelerators
- Kinetic mixing, κ, with SM photon

The light vector meson case: $m_{\rho_D} < 2m_{\pi_D}$



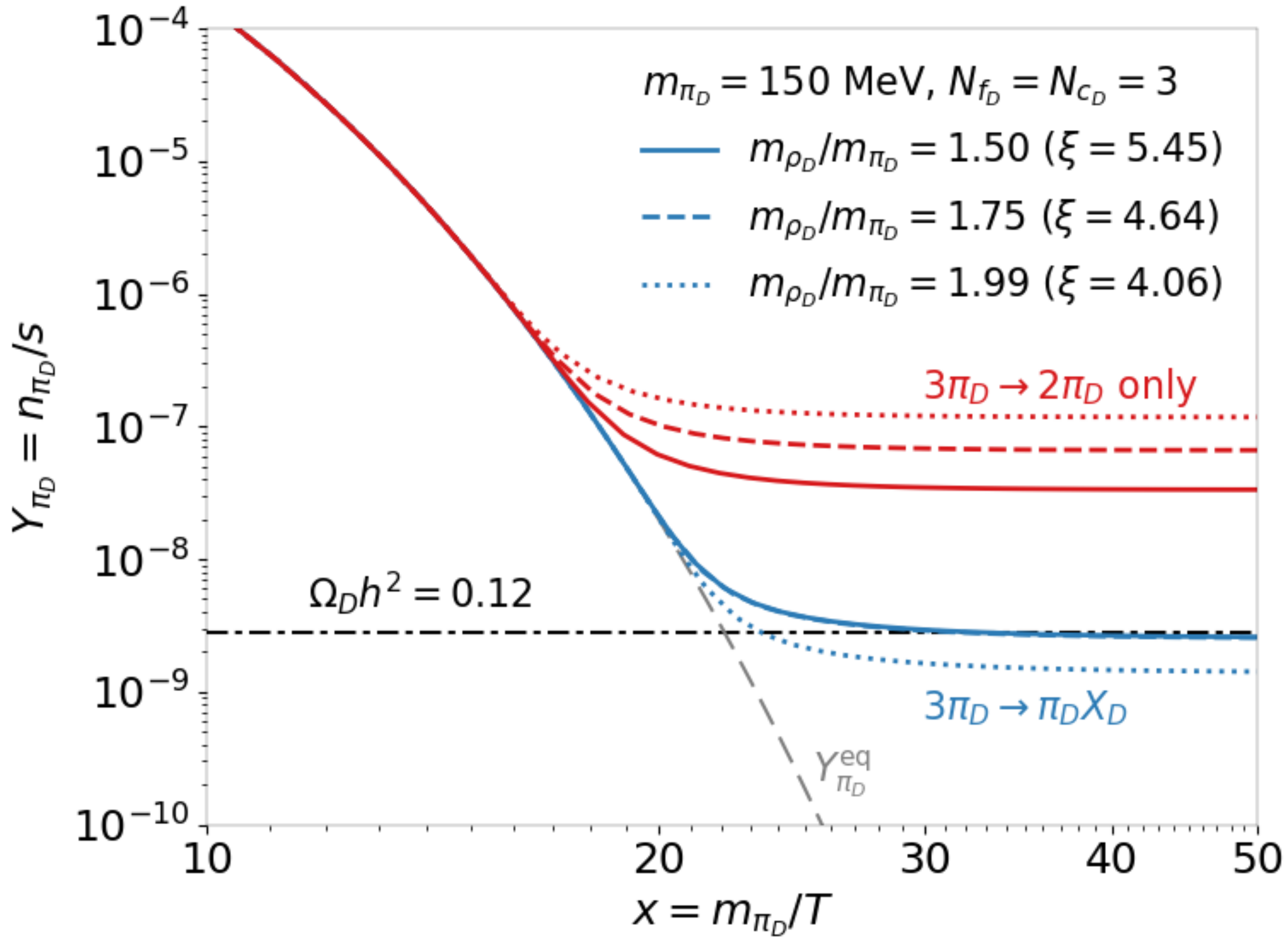
Allowed if $m_{\rho_D} < 2m_{\pi_D}$

The light vector meson case: $m_{\rho_D} < 2m_{\pi_D}$



Allowed if $m_{\rho_D} < 2m_{\pi_D}$

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



The light vector meson case: $m_{\rho_D} < 2m_{\pi_D}$

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

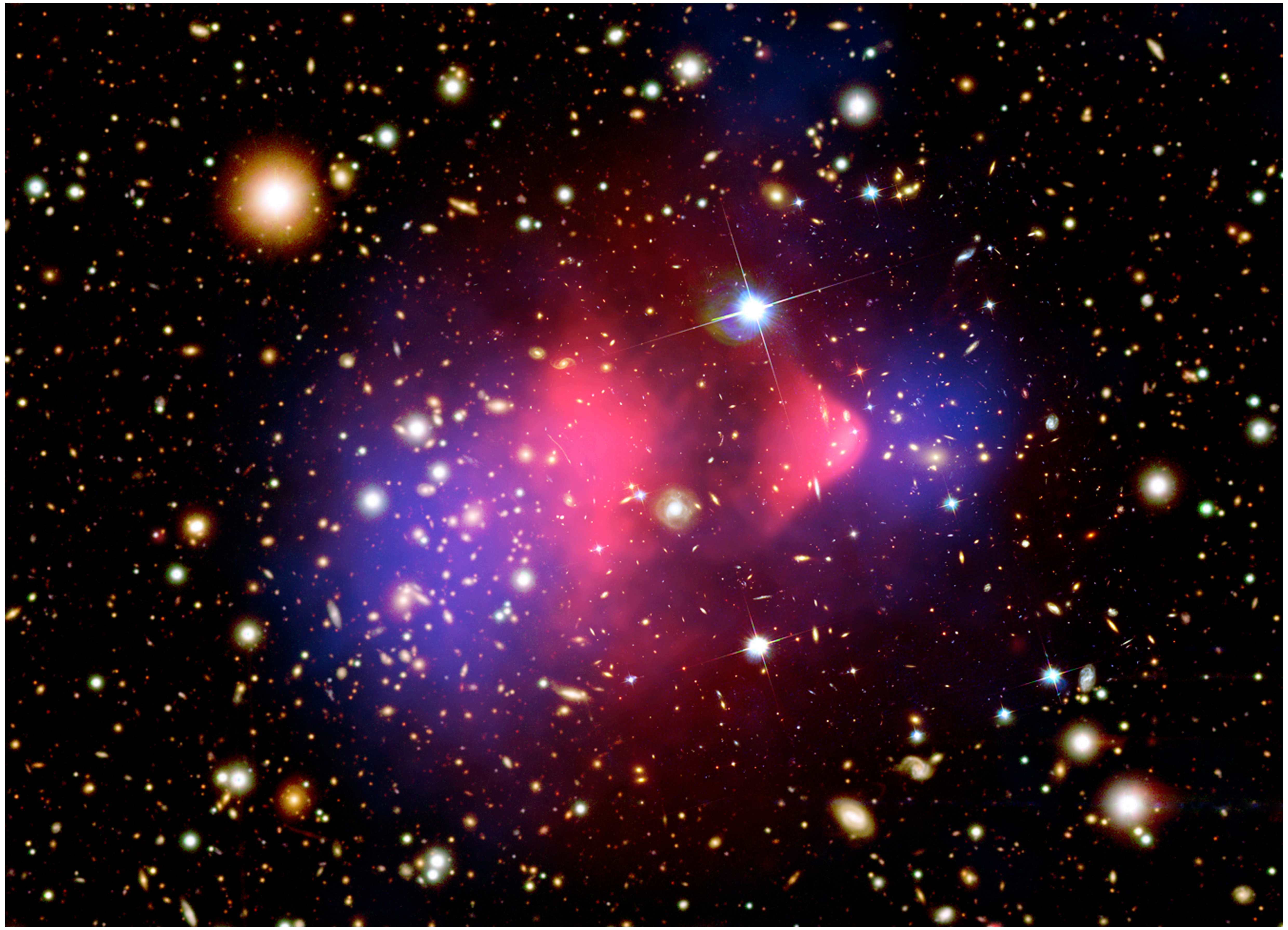
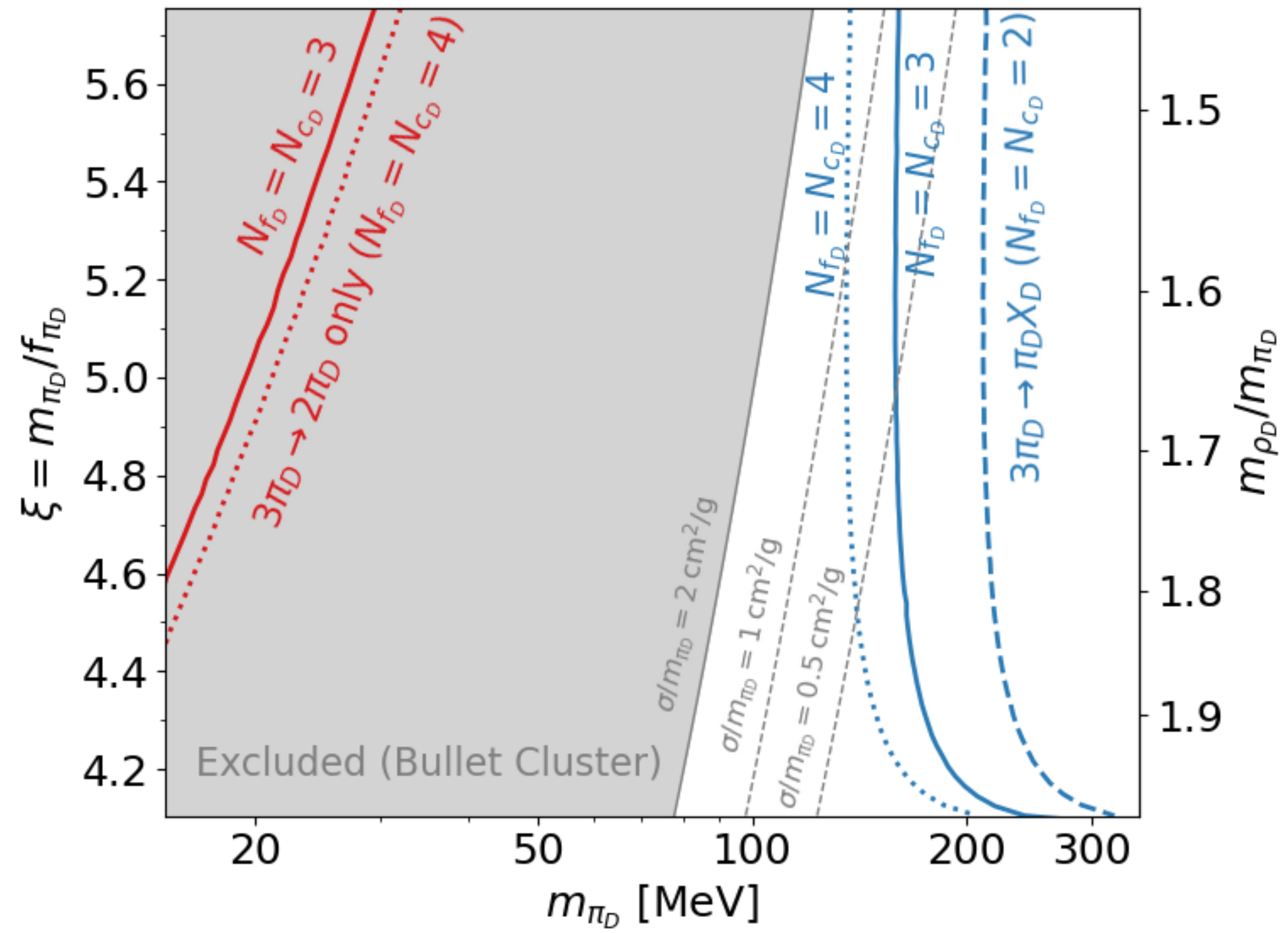


Image: *The Bullet Cluster,* ESA

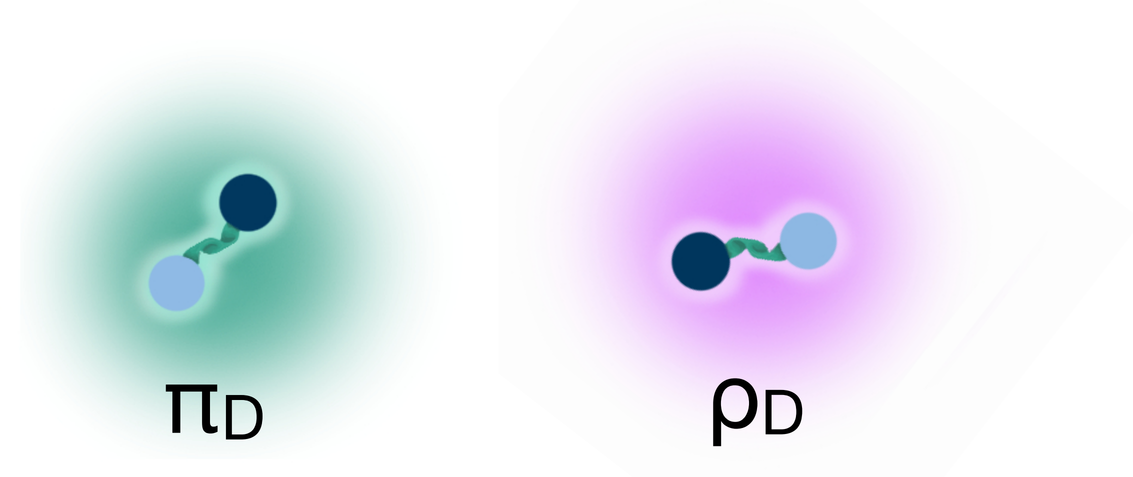
The light vector meson case: $m_{\rho_D} < 2m_{\pi_D}$

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

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



π_D and ρ_D better together!



Projected Sensitivity

ρ_D at SHiP

Simulation Chain

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

MadGraph

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

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

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

Simulation Chain

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

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

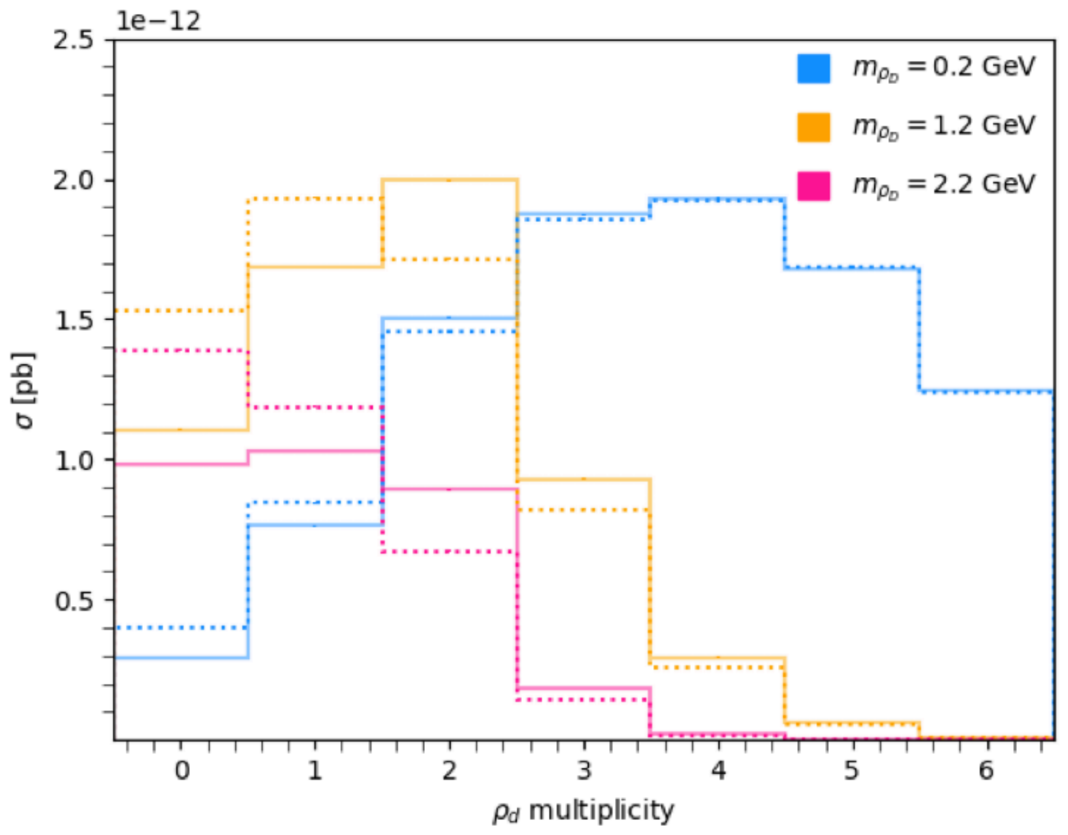
MadGraph

Pythia

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

$$\mathscr{L}_{\text{eff}} \supset \frac{2}{g_{\pi_D \rho_D}} \frac{m^2_{\rho_D}}{\Lambda^2} \rho^{\mu}_{D} \sum_f q_f \bar{f} \gamma_\mu f$$

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



Simulation Chain

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

$q_D + \bar{q}_D \to \pi_D s + \rho_D s$

ρ_Ds selected: $\vec{P} \to \frac{d^2 f}{d\theta dE}$

MadGraph

Pythia

Analysis

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

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

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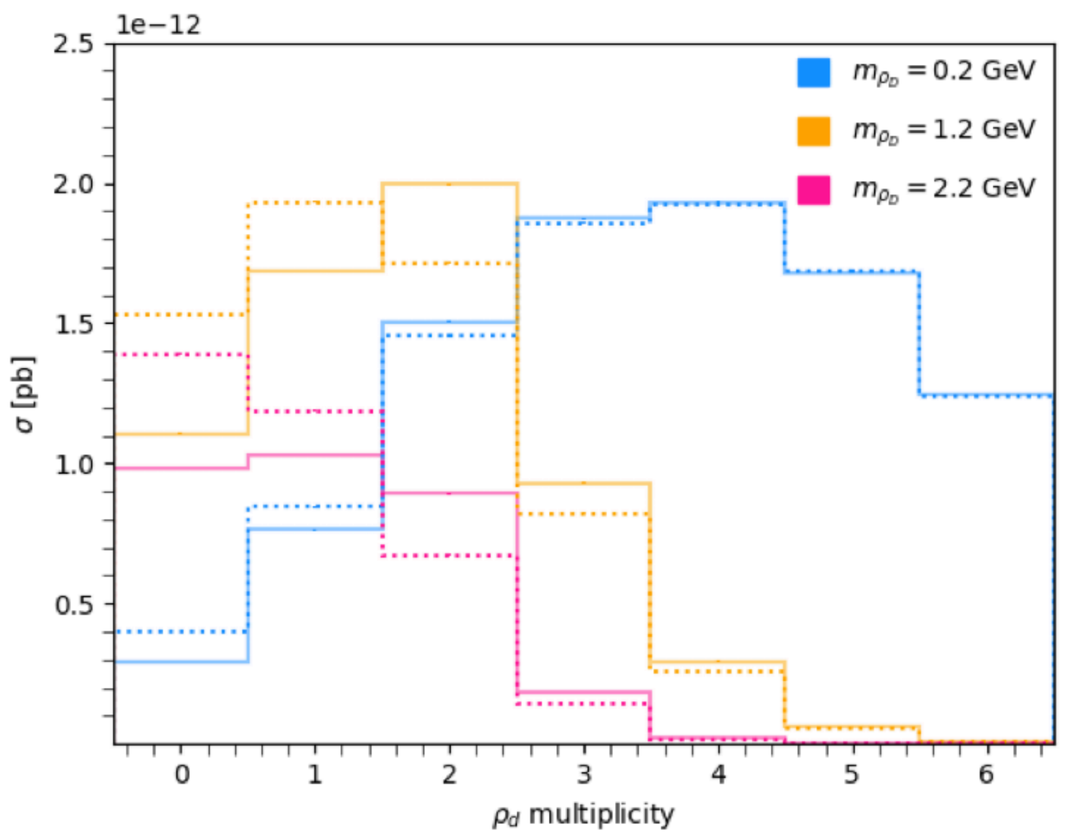
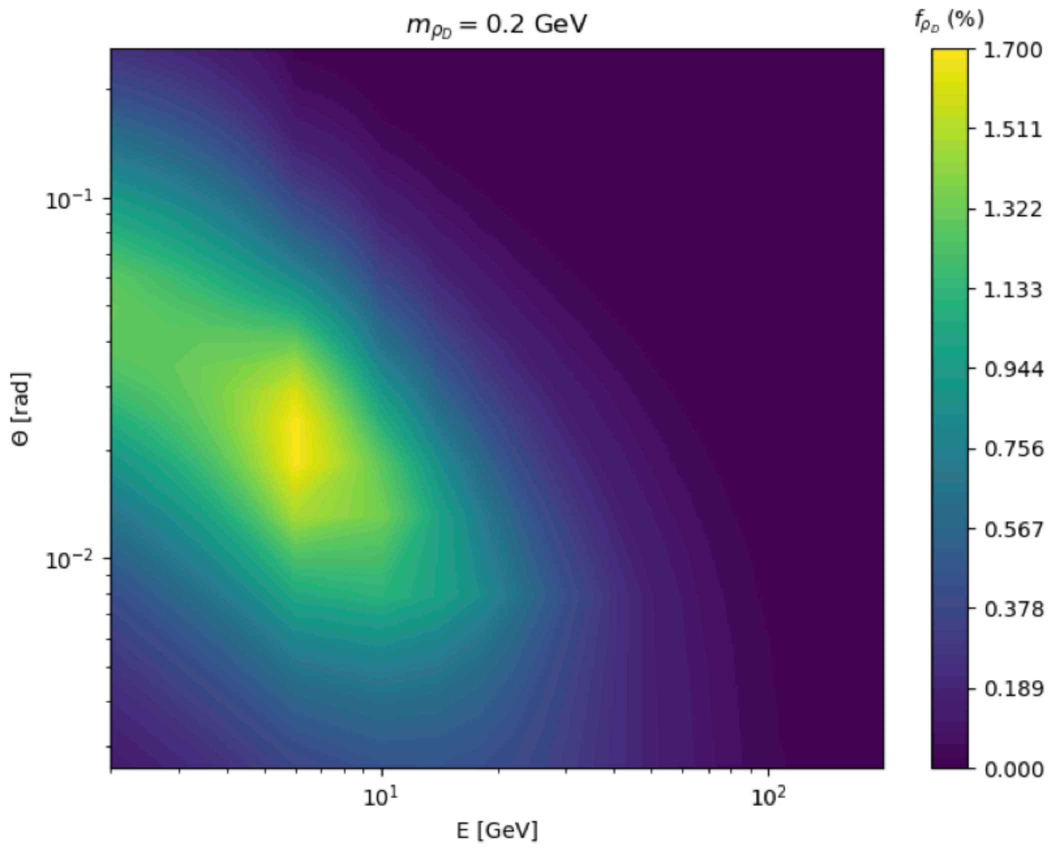




Simulation Chain

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

$$q_D + \bar{q}_D \to \pi_D s + \rho_D s$$

ρ_Ds selected: $\vec{P} \to \frac{d^2 f}{d\theta dE}$

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

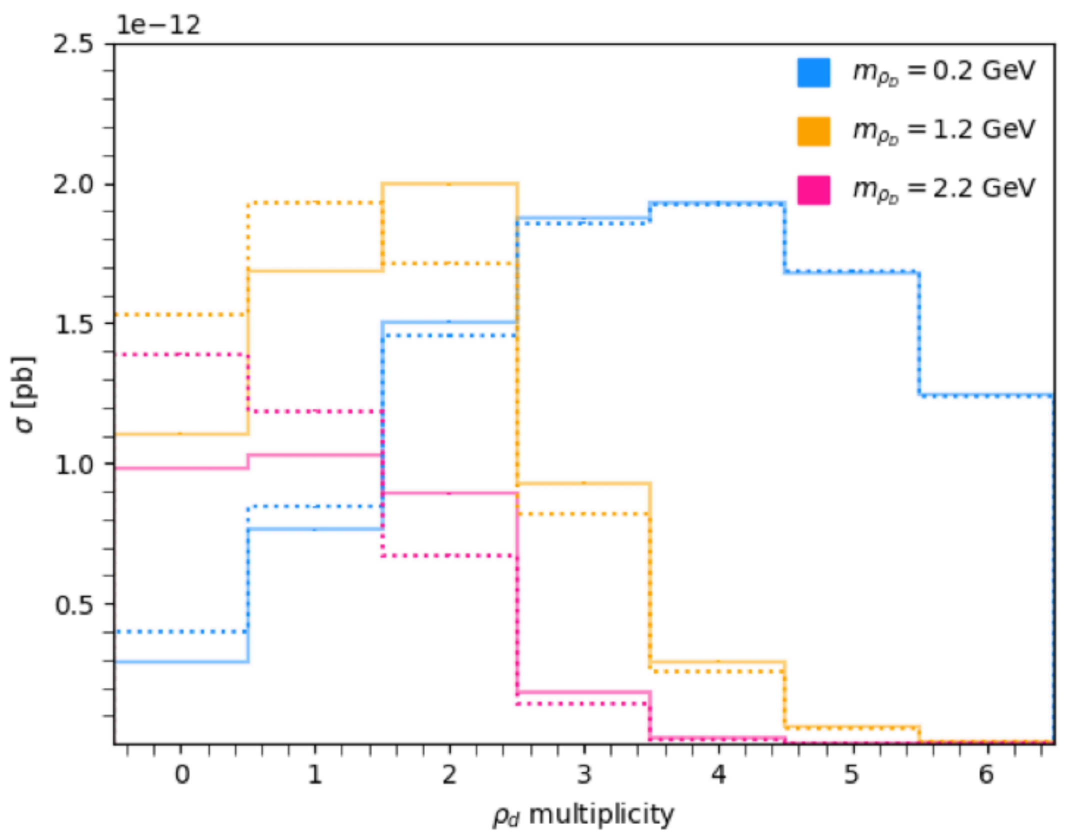
MadGraph

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

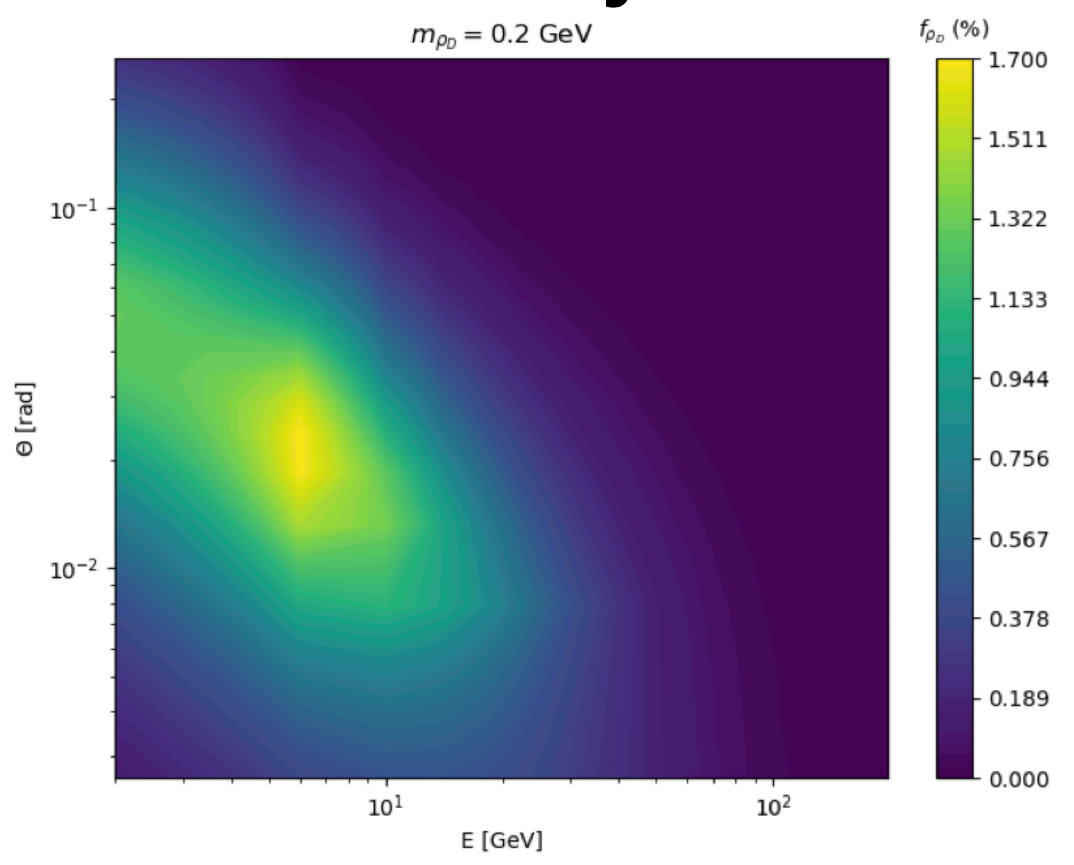
$$\mathscr{L}_{\text{eff}} \supset \frac{2}{g_{\pi_D \rho_D}} \frac{m^2_{\rho_D}}{\Lambda^2} \rho^{\mu}_D \sum_f q_f \bar{f} \gamma_\mu f$$

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

Pythia



Analysis



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

Parameters for simulation

Parameter	Value ($r = 1.5$)	Value ($r = 1.9$)	Setting in
$m_{Z'}$	1 TeV		MadGraph
$\Gamma_{Z'}$	1 GeV		MadGraph
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
$\Lambda_D = \frac{5}{12} \cdot m_{\pi_D} \cdot \sqrt{r^2 - 1.5}$	$0.36 m_{\pi_D}$	$0.61 m_{\pi_D}$	Pythia
$m_{q_D,\mathrm{curr}} = \frac{4}{121} \cdot \frac{m_{\pi_D}{}^2}{\Lambda_D}$	$0.09 m_{\pi_D}$	$0.05 m_{\pi_D}$	MadGraph
$m_{q_D,\mathrm{const}} = m_{q_D,\mathrm{curr}} + \Lambda_D$	$0.45 m_{\pi_D}$	$0.66 m_{\pi_D}$	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 $\sigma(\kappa) = \sigma(\kappa_{ref}) \cdot \kappa^2/\kappa_{ref}^2$

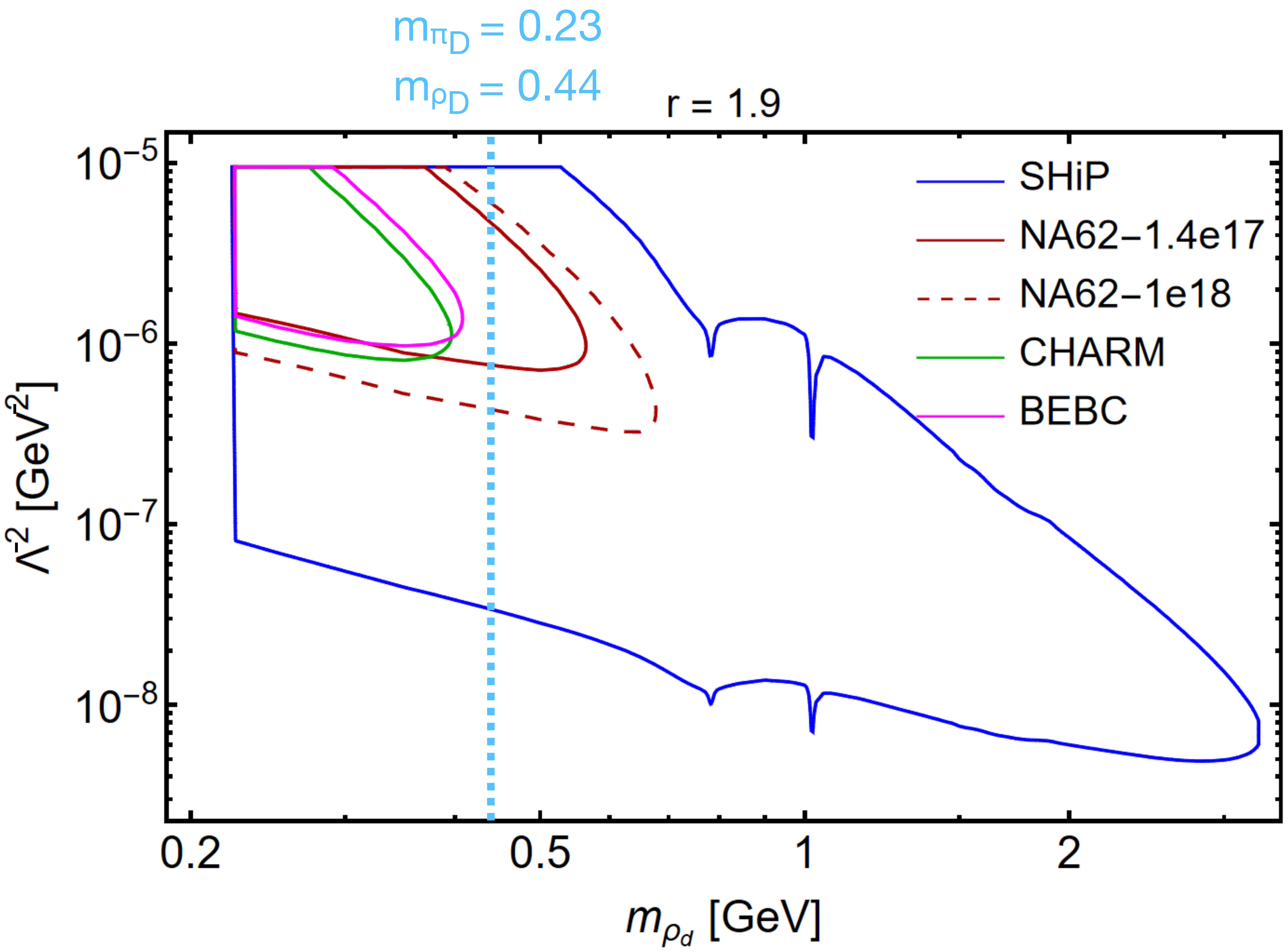
Relations derived from lattice QCD

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]

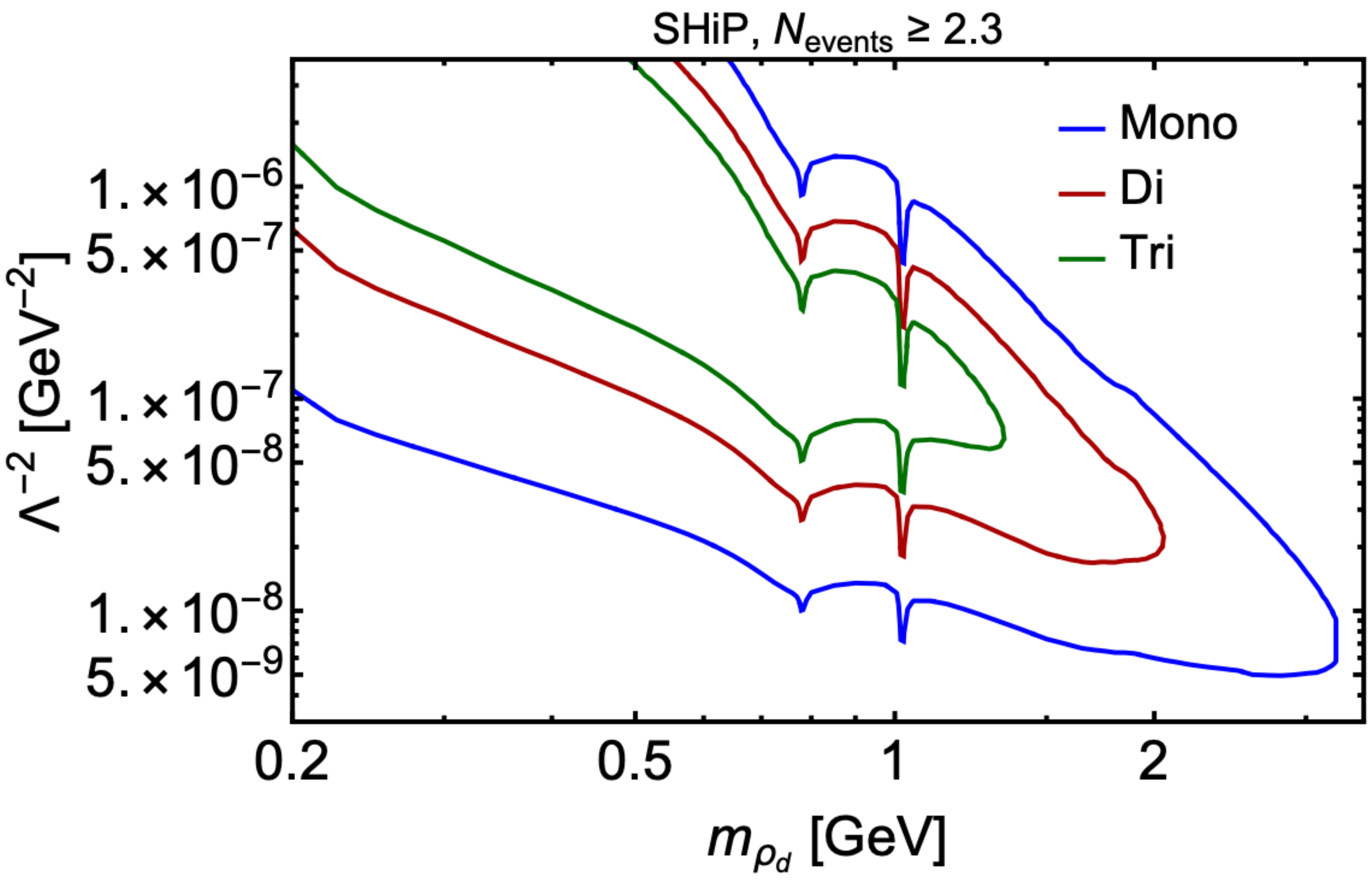
From fit derived by S. Kulkarni, J. Lockyer and W. Liu in [2505.03058]

ρ_D sensitivity at SHiP



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

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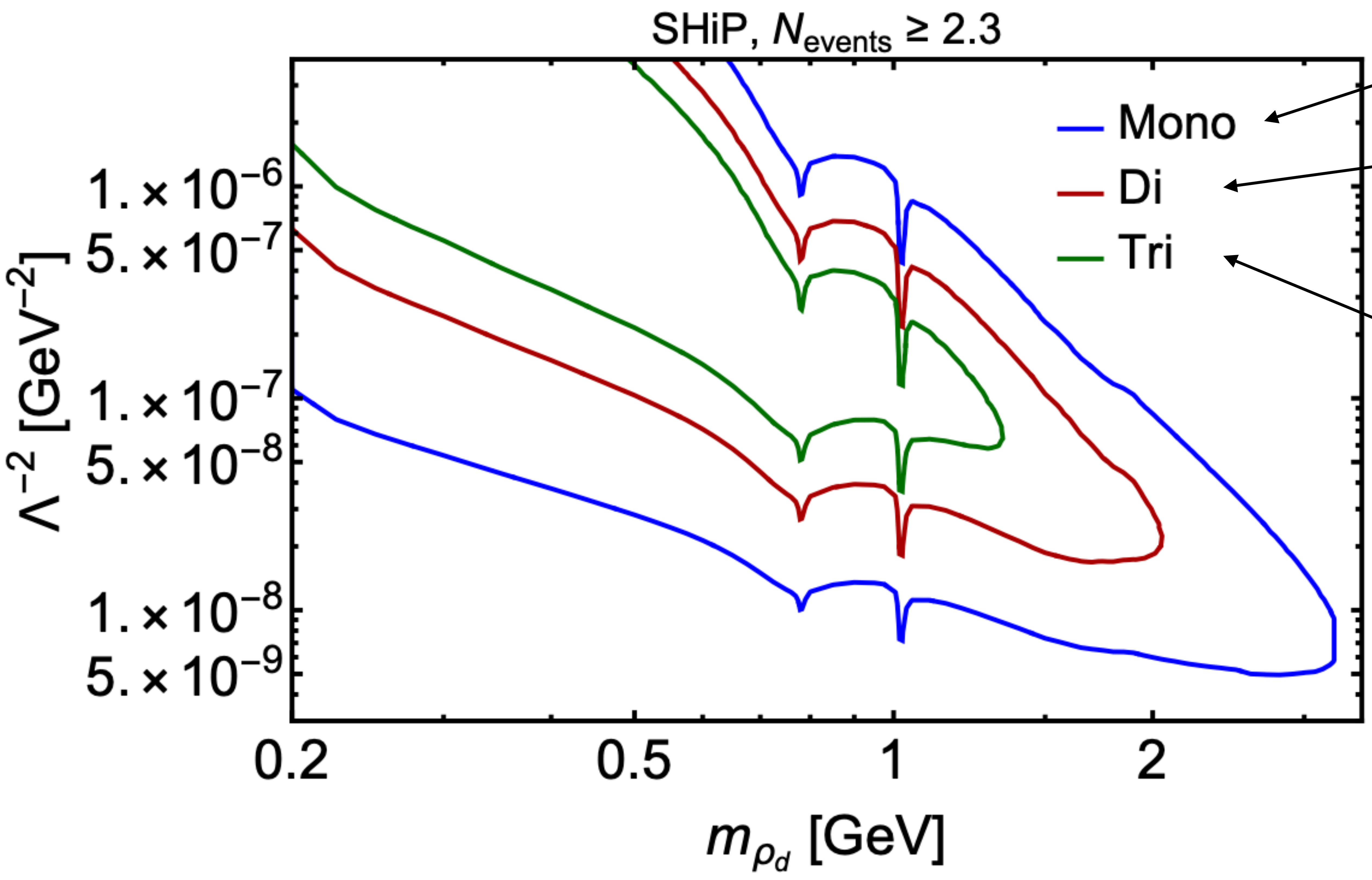


Could be DP: Cannot distinguish

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

Only expected for ρ_D

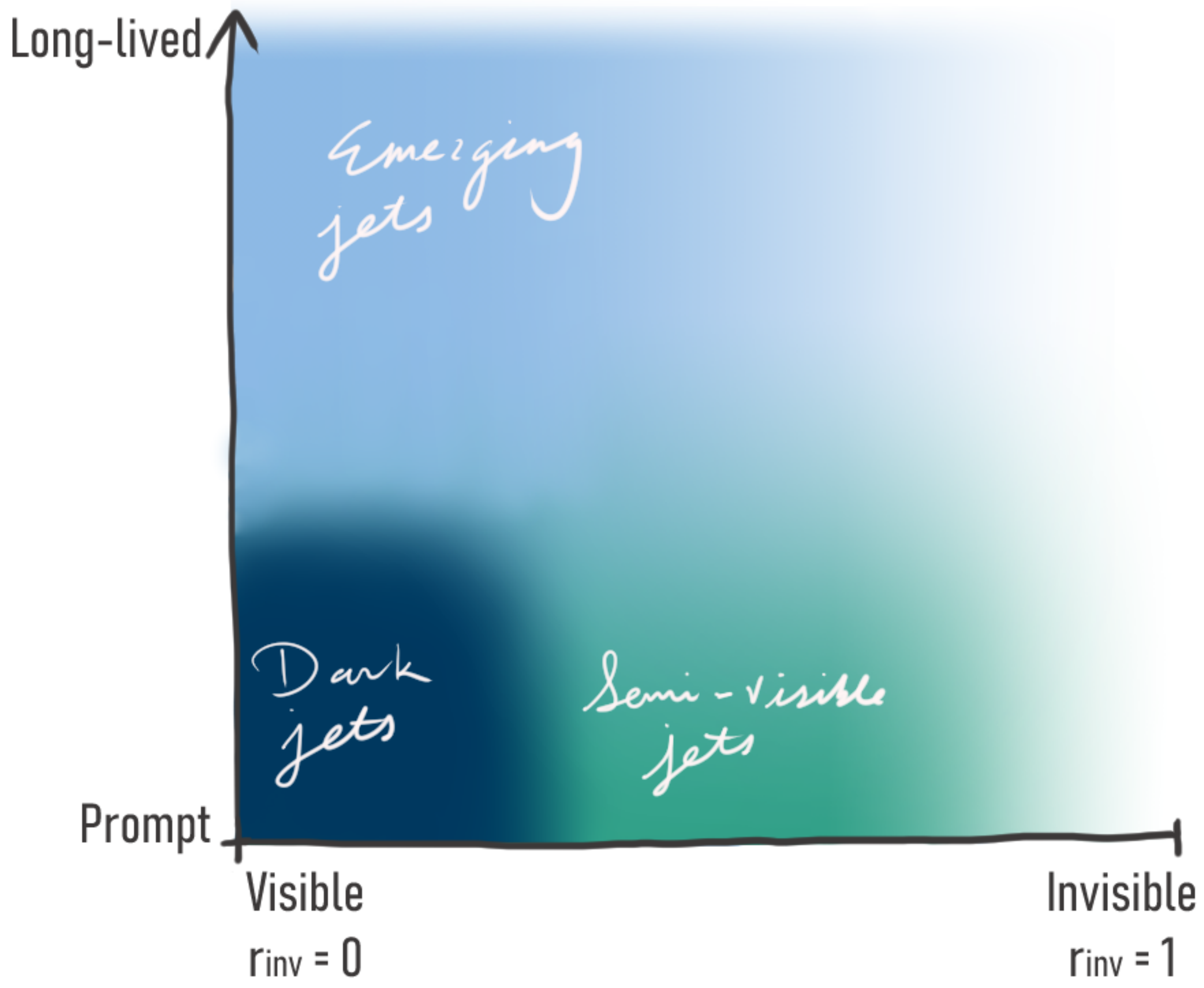
Summary

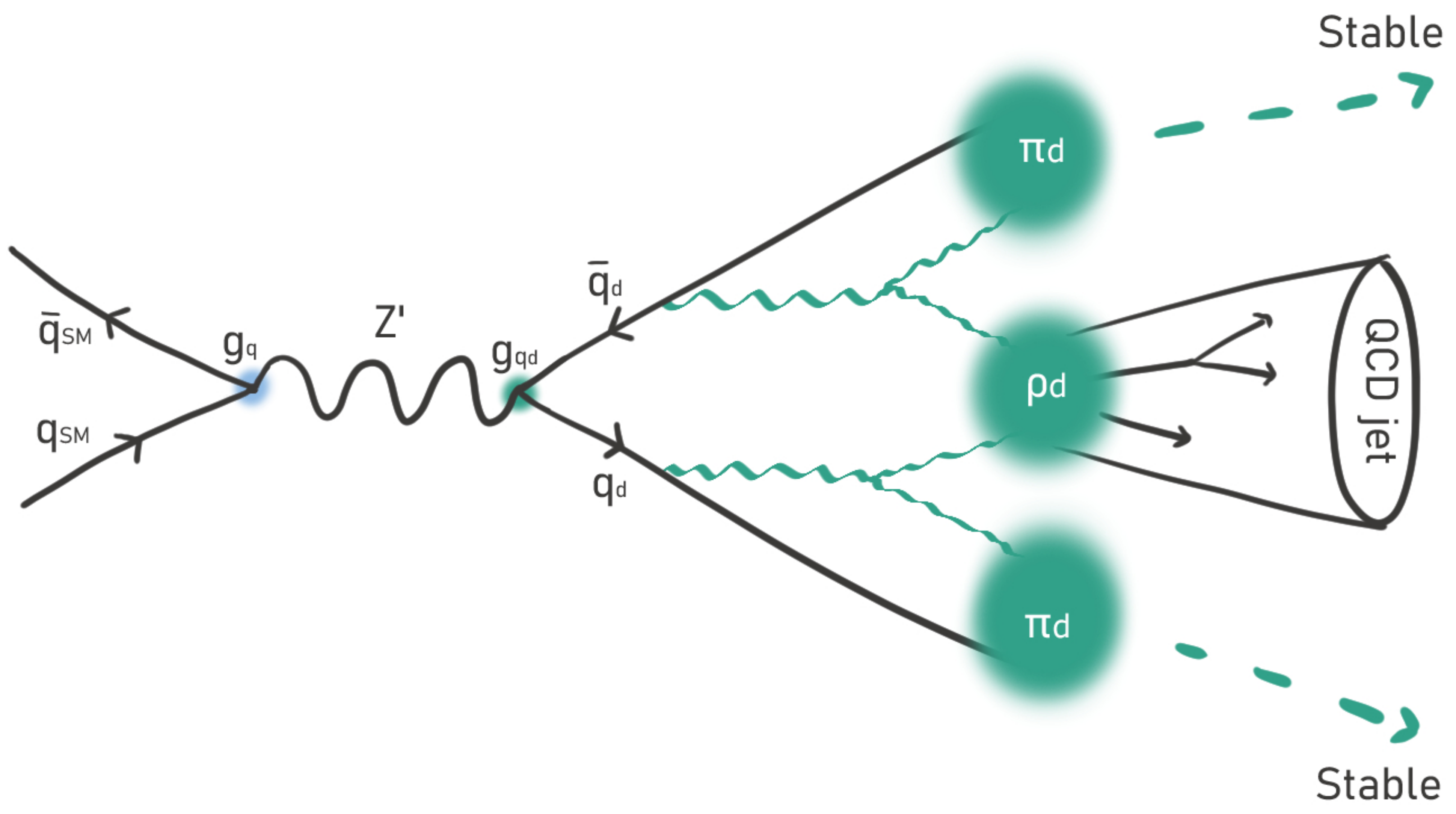
Light ρ_D ($m_{\rho_D} < 2m_{\pi_D}$) is a well-motivated scenario from a cosmological/astrophysical perspective

We can “easily” imagine models where ρ_D decays to SM particles

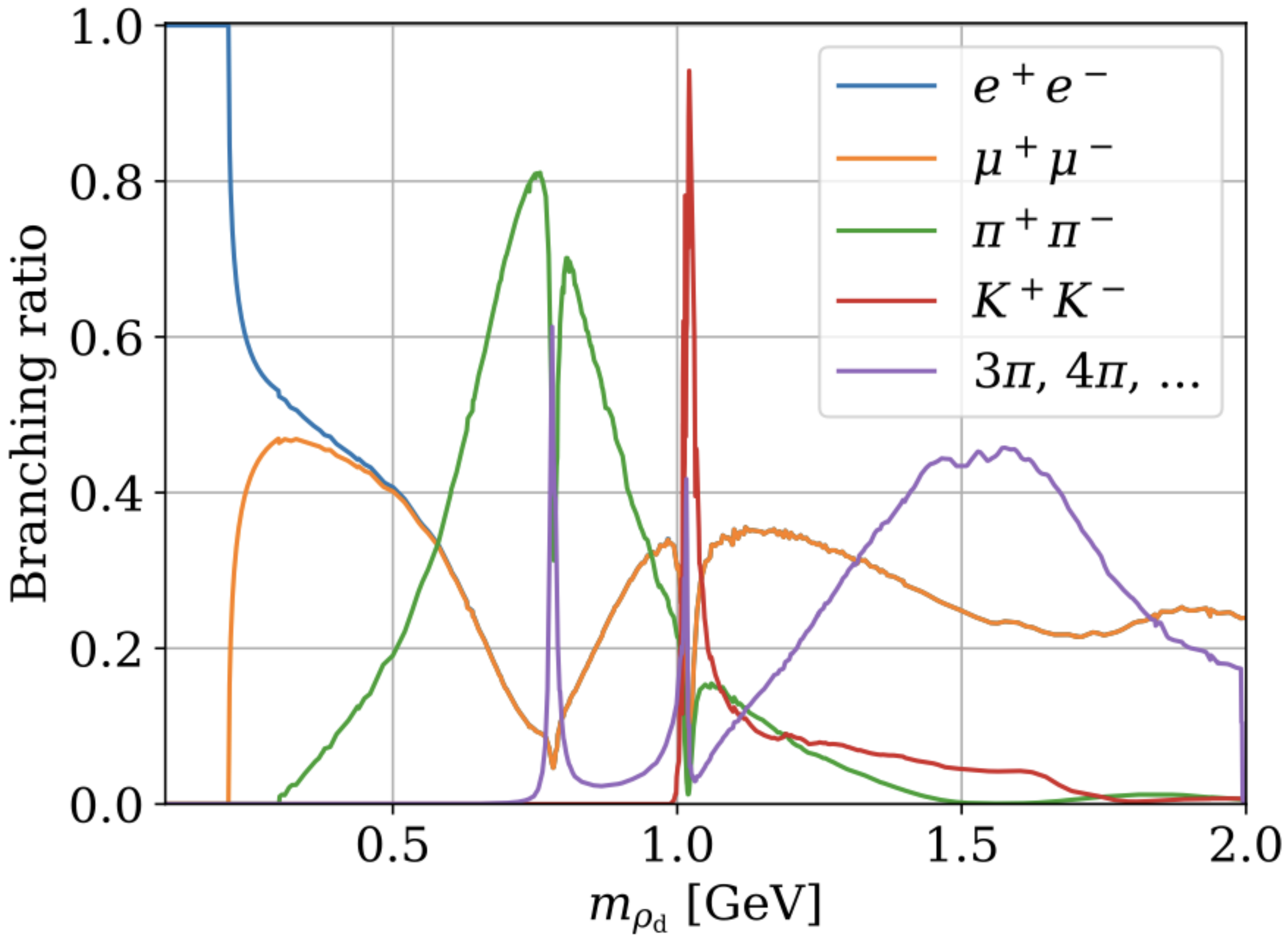
SHiP has good sensitivity to such a LLP in 0.2-3 GeV range, and may even be able to detect multi-decays to distinguish from DP

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)'

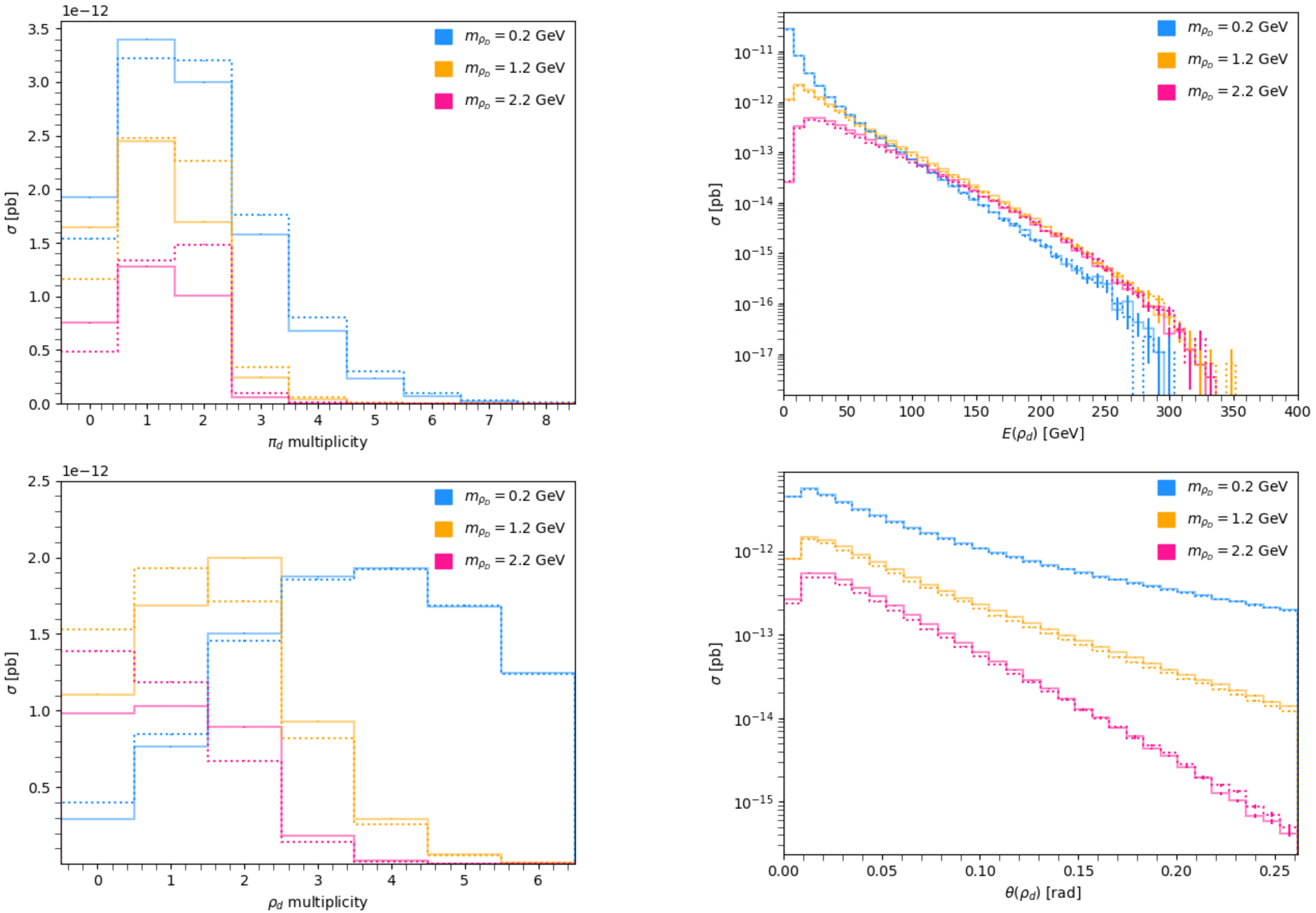
$$g_\ell = \frac{m_{\rho_D}^2}{m_{Z'}^2} \frac{2 e e_D \kappa}{g}$$

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

"*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. Kulkarini (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 - Lattice QCD Results

Infrared Properties of QCD from Dyson-Schwinger equations

Christian S. Fischer
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E-mail: `christian.fischer@physik.tu-darmstadt.de`

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]

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 $m_{\pi D}/\Lambda_D > 2.3$

$$\frac{m_{\pi_D}}{\tilde{\Lambda}_D} = 5.5\sqrt{\frac{m_{q_D}}{\tilde{\Lambda}_D}} \qquad \frac{m_{\rho_D}}{\tilde{\Lambda}_D} = \sqrt{5.76 + 1.5\frac{m_{\pi_D}^2}{\tilde{\Lambda}_D^2}}$$

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

QCD modeling of hadron physics

P. Maris[a,b] and P.C. Tandy[b]

[a]Dept. of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260

[b]Center 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.

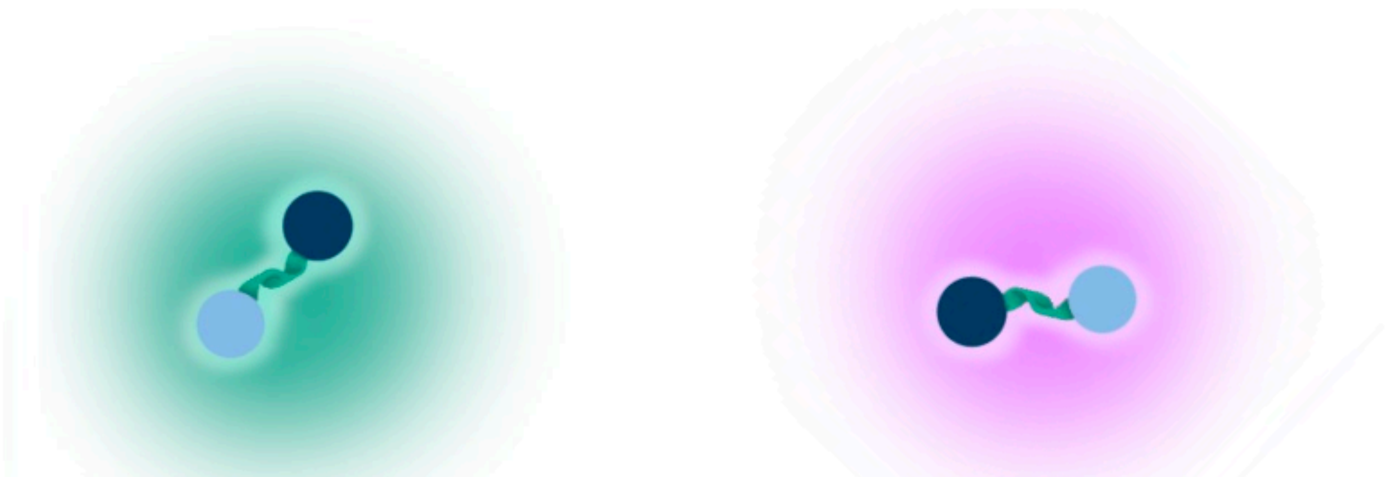
Ref: P. Maris and P. C. Tandy, Nucl. Phys. B Proc. Suppl. 161 (2006), 136–152, [nucl-th/0511017]

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. Kulkarini (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



Dark pion π_d
(the lightest)

Dark rho meson ρ_d
(the second lightest)

$\Downarrow$

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

Reminder :

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