Sub-GeV dark matter and dark showers at beam-dump experiments

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SLAC Theory Seminar

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Phys.Rev.D 110 (2024) 3, arXiv:2311.17157
with Nicoline Hemme, Felix Kahlhoefer and Suchita Kulkarni

Phys.Rev.D 113 (2026) 7, 075002, arXiv:2510.23696
with Nicoline Hemme, Felix Kahlhoefer, Suchita Kulkarni and Maksym Ovchynnikov

Why (strongly) interacting dark matter?

All evidence for dark matter so far relies only on gravity, including our one measurement:

$$\Omega_\chi h^2 = 0.12$$

Planck, arXiv:1807.06209

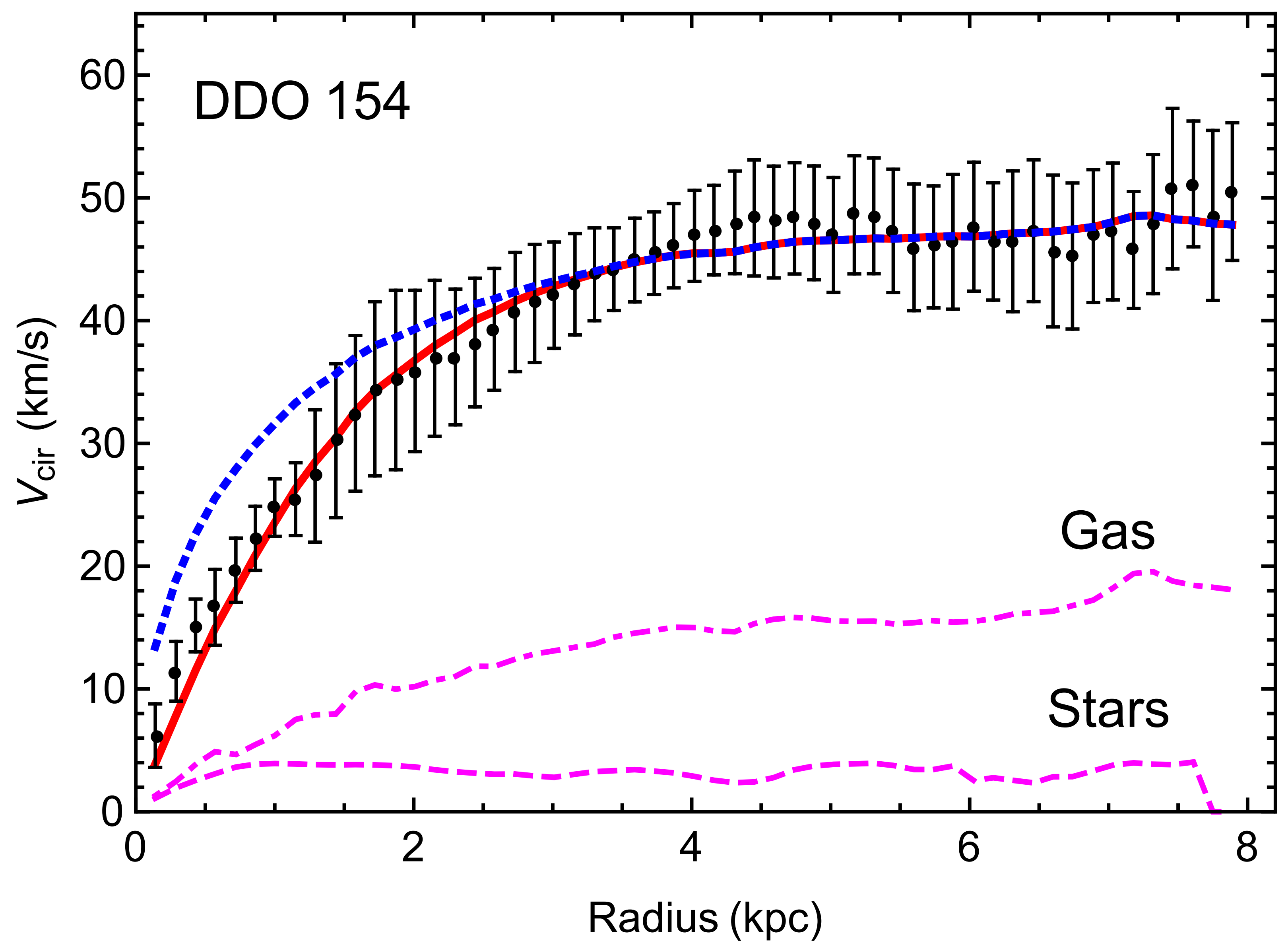
ΛCDM with **cold collisionless DM** (interacting only gravitationally) describes **large structures** in our universe extremely well

But **discrepancies** between cold collisionless DM and observations **at galaxy scales**

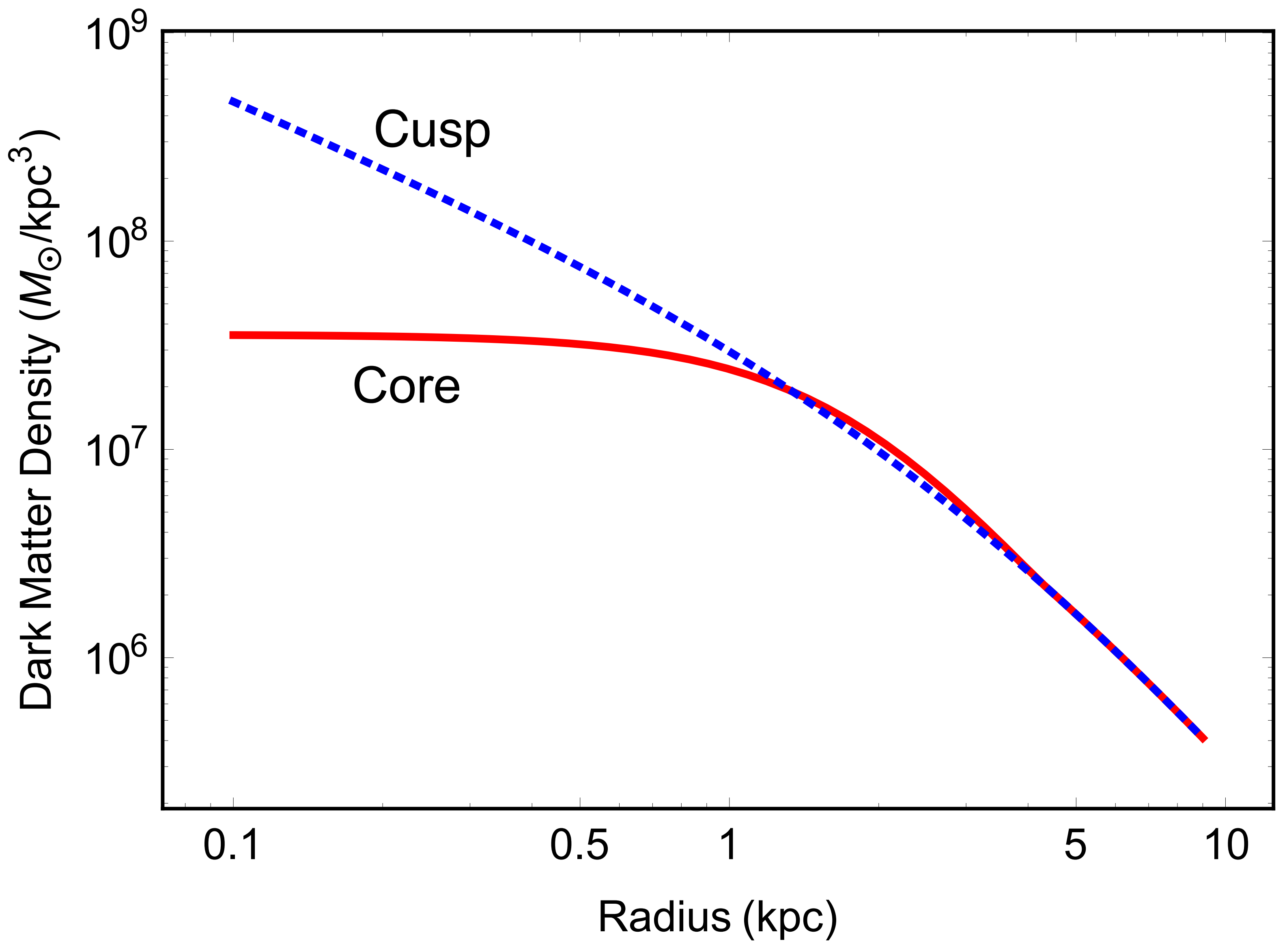
Small-scale problems of ΛCDM

Example: **Core-cusp problem**

Discrepancy between predicted and measured circular velocities at small radii



Points towards density profile with core instead of cusp



Other small-scale tensions: diversity problem, too-big-to-fail

Tulin & Yu, 1705.02358

Strongly self-interacting dark matter

Structures at galaxy scales are sensitive to DM self-interactions

➡ One possible resolution of discrepancies: self-interacting DM

Required strength of DM self-interactions:

$$\frac{\sigma_{SI}}{m_{DM}} \gtrsim 1\ \text{cm}^2/\text{g}$$
$$\approx 1\ \text{barn}/\text{GeV}$$
$$\approx \Lambda_{QCD}^{-3}\ !$$

similar to hadronic interactions in QCD

➡ **Motivates QCD-like dark sector at sub-GeV scale, i.e.** $\sim \Lambda_{QCD}$

Strongly interacting dark sectors

Dark sector resembling QCD

$$\mathscr{L} \supset -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu,a} + \overline{q_\mathrm{D}}i\not{D}q_\mathrm{D} - \overline{q_\mathrm{D}}M_{q_D}q_\mathrm{D}$$

Dark quarks q_d in fundamental representation of new non-abelian gauge group

If dark sector exhibits confinement below some scale Λ_D:

- **Dark mesons, baryons or glueballs** can be dark matter candidates

  Bai & Hill, 1005.0008; Buckley & Neil, 1209.6054; Cline et al, 1312.3325; see e.g. Kribs & Neal, 1604.04627 for a review

- If coupled to SM, **dark mesons and glueballs** can be produced and decay visibly at accelerators

  Strassler & Zurek, hep-ph/0604261; Daci et al. 1503.05505; Pierce et al., 1708.05389; Kribs et al., 1809.10184; Cheng et al., 1906.02198; Butterworth et al., 2105.08494; Knapen et al., 2103.01238; Cheng et al., 2401.08785

Dark matter candidates

Dark baryons:

- stabilized by dark baryon number
- typically looser connection between DM and collider pheno

Dark pions π_D

- massive pseudo-Goldstone bosons if $m_q > 0$
- can be stabilized by $U(1)'$ symmetry or dark G-parity

Bai & Hill, arXiv:1005.0008

In this talk: focus on dark pion DM in $SU(N_{c_D})$ sector with N_{f_D} light(ish) dark quarks ($m_{q_D} \lesssim \Lambda_D$)

How do they attain their relic abundance?

Part 1:
Dark matter relic density in strongly interacting dark sectors

Constraints on sub-GeV DM

Standard freeze-out via 2-to-2 annihilations into SM particles requires

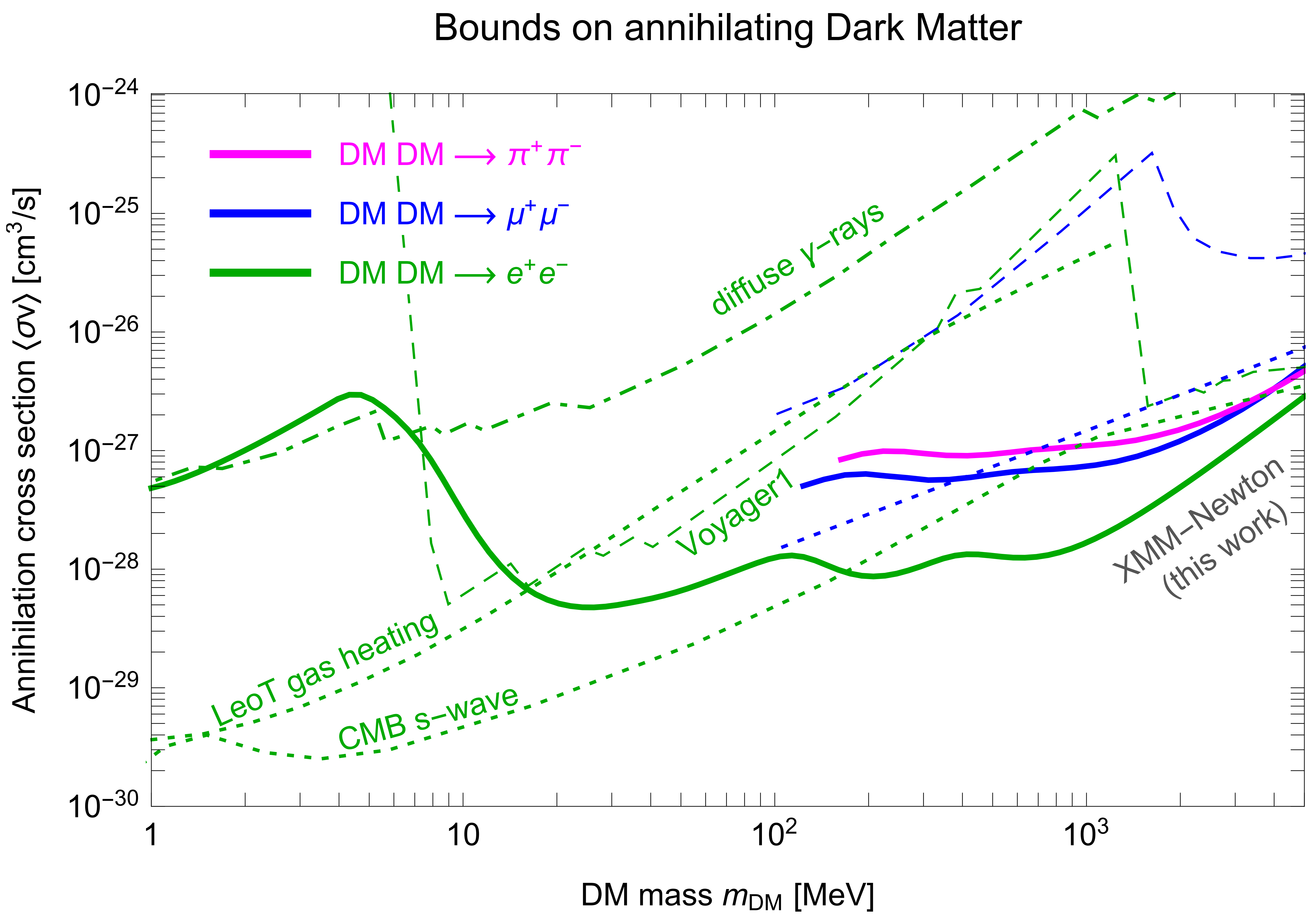
$$\sigma_{\mathrm{ann}} v \sim 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

Prohibitive direct detection constraints for DM at GeV scale and above

Problem for sub-GeV DM:

Small fraction of DM still annihilating at later times

X-ray observations and CMB rule out σ_{ann} for sub-GeV DM



Cirelli et al., arXiv:2303.08854

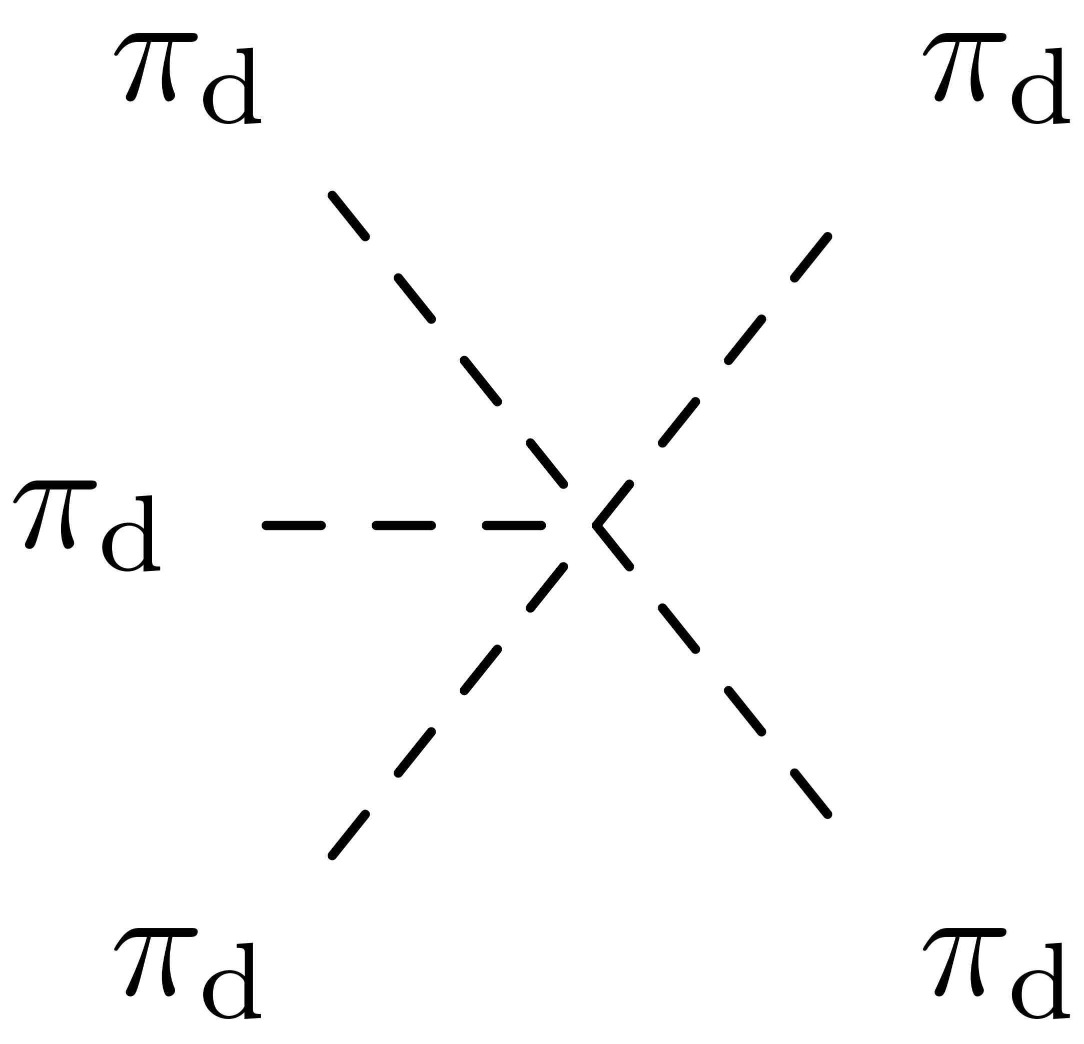
SIMP mechanism

X-ray/CMB constraints rely on annihilations into SM particles

→ avoided by freeze-out via interactions ***within* the dark sector***

* still requires (much weaker) interaction with SM to exchange entropy

SIMP mechanism: $3\,\pi_D \to 2\,\pi_D$ **annihilations** Hochberg et al., arXiv:1402.5143
Hochberg et al., arXiv:1411.3727



From Wess-Zumino-Witten term

$$\mathscr{L}_\mathrm{WZW} = \frac{2N_{c_D}}{15\pi^2 f_{\pi_D}^5}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}\left(\pi_D\partial_\mu\pi_D\partial_\nu\pi_D\partial_\rho\pi_D\partial_\sigma\pi_D\right)$$

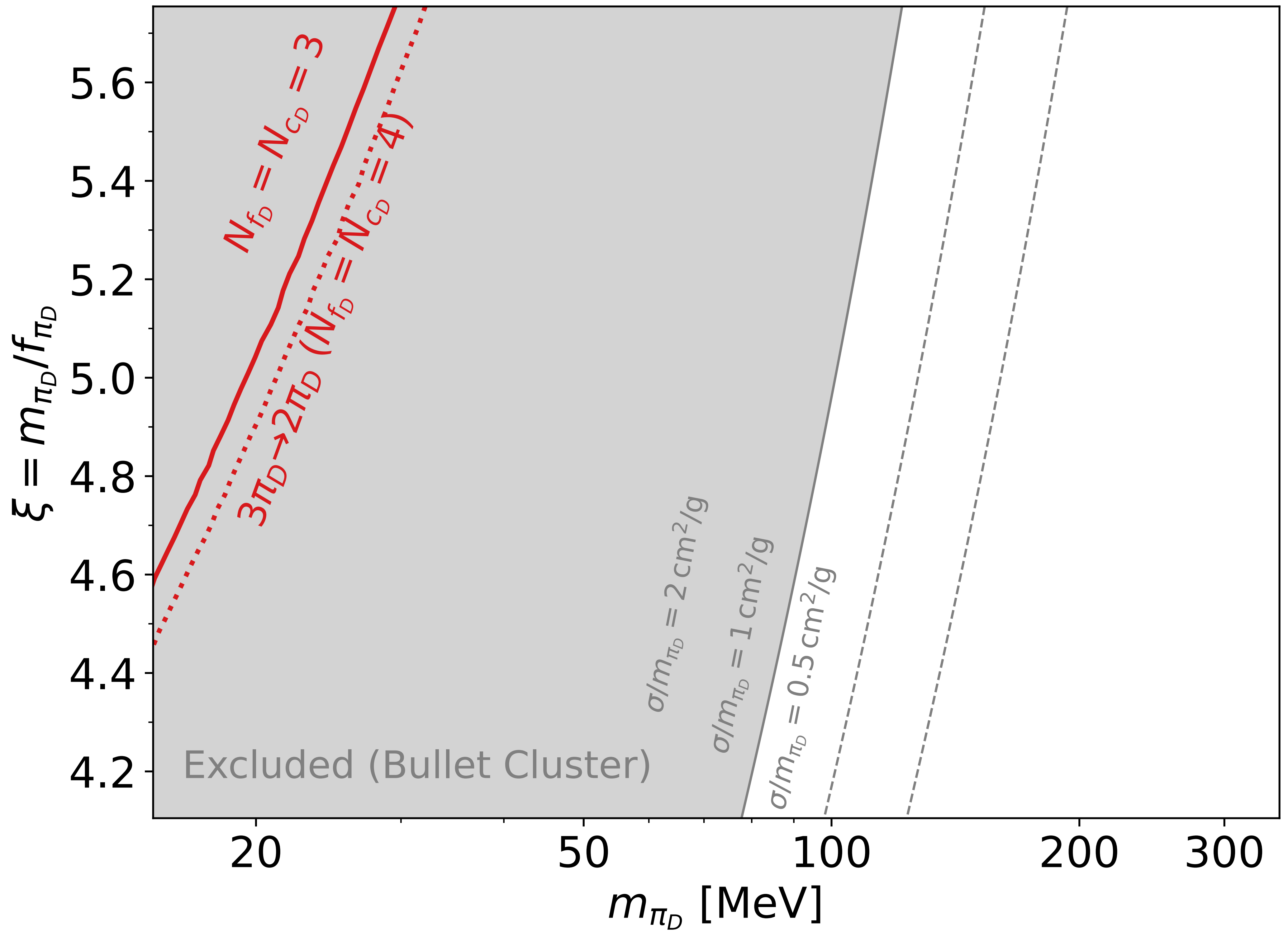
in chiral Lagrangian describing dark pions

parameters: $m_{\pi_D}\,,\ \xi \equiv m_{\pi_D}/f_{\pi_D} \ll 4\pi$

SIMPs vs the bullet cluster

SIMP mechanism produces correct relic density for MeV-scale DM

Chiral EFT not reliable at larger ξ



Problem:

$\pi_D\pi_D \to \pi_D\pi_D$ **self-interactions**

$$\sigma_{SI}/m_{\pi_D} \gtrsim 40\ \mathrm{cm}^2/\mathrm{g}$$

along relic density line

Very robustly excluded by bullet cluster limit

$$\sigma_{SI}/m_{\pi_D} \lesssim 2\ \mathrm{cm}^2/\mathrm{g}$$

Satisfying SI constraint requires $\xi \approx 14$ → **outside ChiralEFT validity**

Dark vector mesons

Issues with $3\pi_D \to 2\pi_D$ SIMP mechanism strongly motivate number-changing processes with other dark mesons

In particular **dark vector mesons** ρ_D Berlin et al., 1801.05805, Choi et al, 1801.07726, Li & Tsai, 1901.09936, EB et al., 1907.04346

generically unstable, can couple to SM particles via mixing

Mass predicted by lattice calculations given m_{π_D} and ξ

e.g. Maris & Tandy, nucl-th/0511017
Fischer, hep-ph/0605173

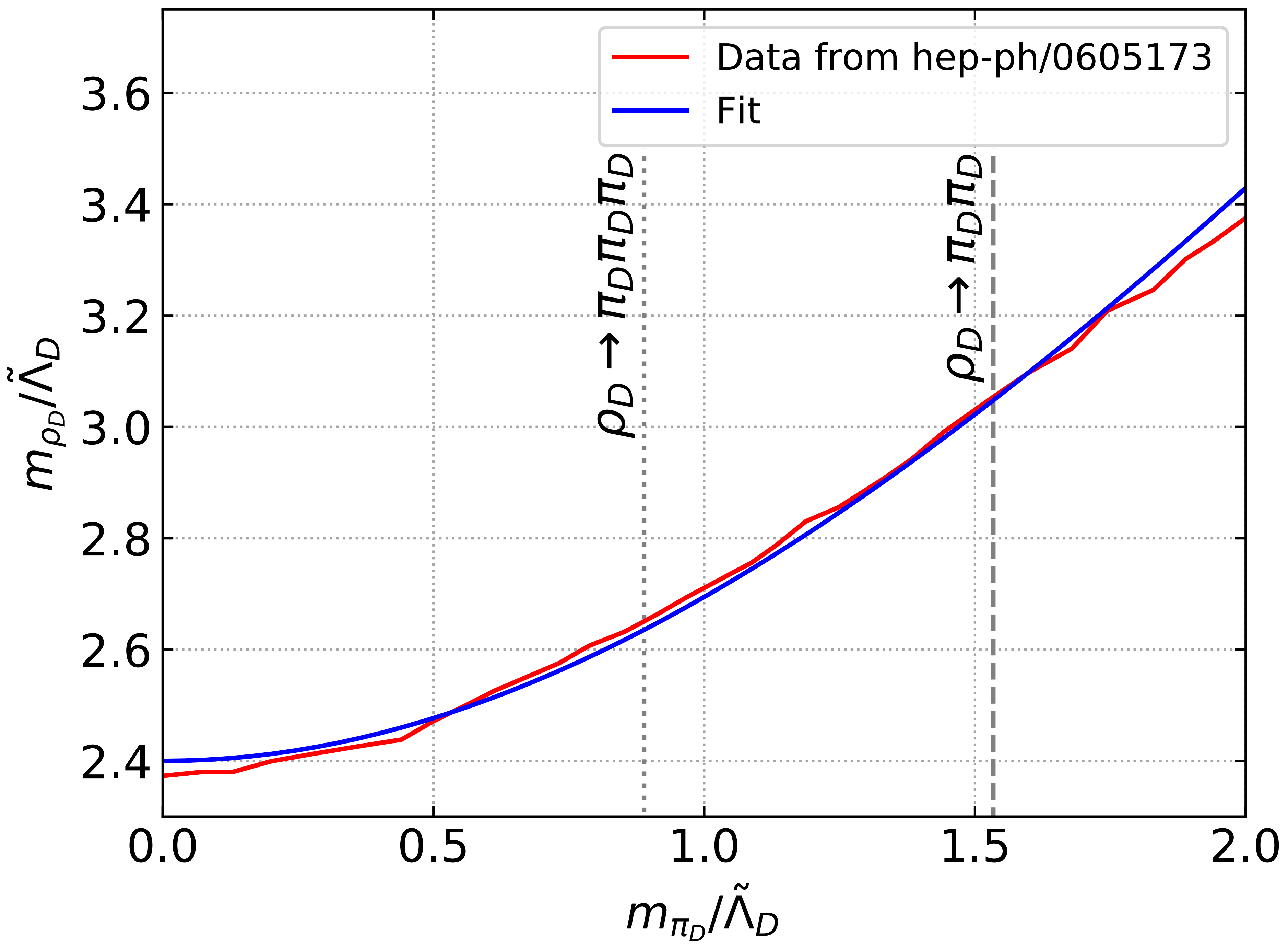
Fitted relation:

$$\xi \equiv \frac{m_{\pi_D}}{f_{\pi_D}} = 7.79\,\frac{m_{\pi_D}}{m_{\rho_D}} + 0.57\left(\frac{m_{\pi_D}}{m_{\rho_D}}\right)^2$$

Example:

$$\xi = 5 \quad \Longleftrightarrow \quad m_{\rho_D} = 1.6\, m_{\pi_D}$$

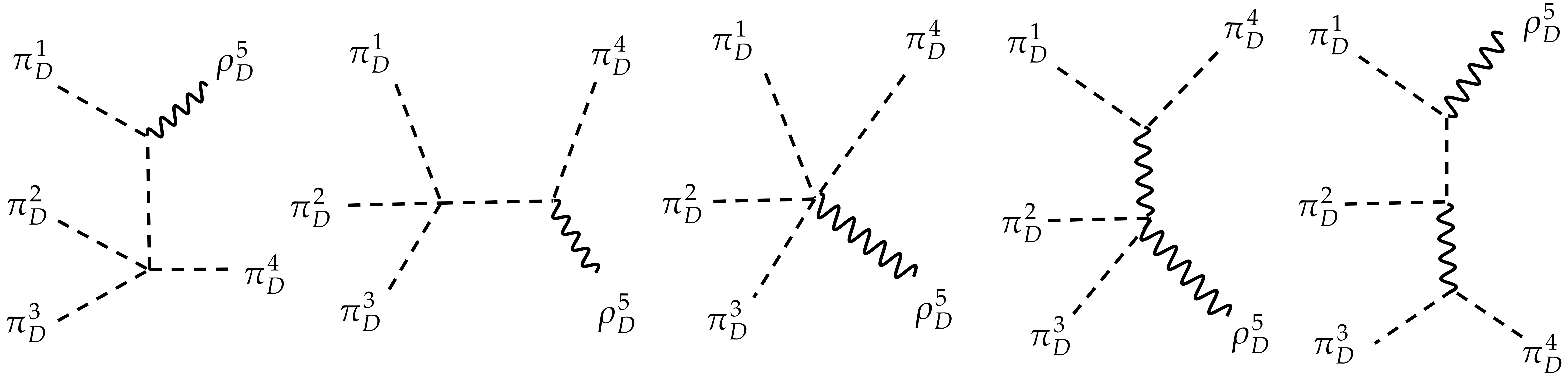
$m_{\rho_D} < 2m_{\pi_D}$ **in most interesting parameter space**



Albouy et al., arXiv:2203.09503

DM annihilations to dark rho mesons

If $m_{\rho_D} < 2\, m_{\pi_D}$, dark rho final states contribute to dark pion annihilations



$3\,\pi_D \to 2\,\pi_D$ is d-wave while $3\,\pi_D \to \pi_D\,\rho_D$ **is s-wave**

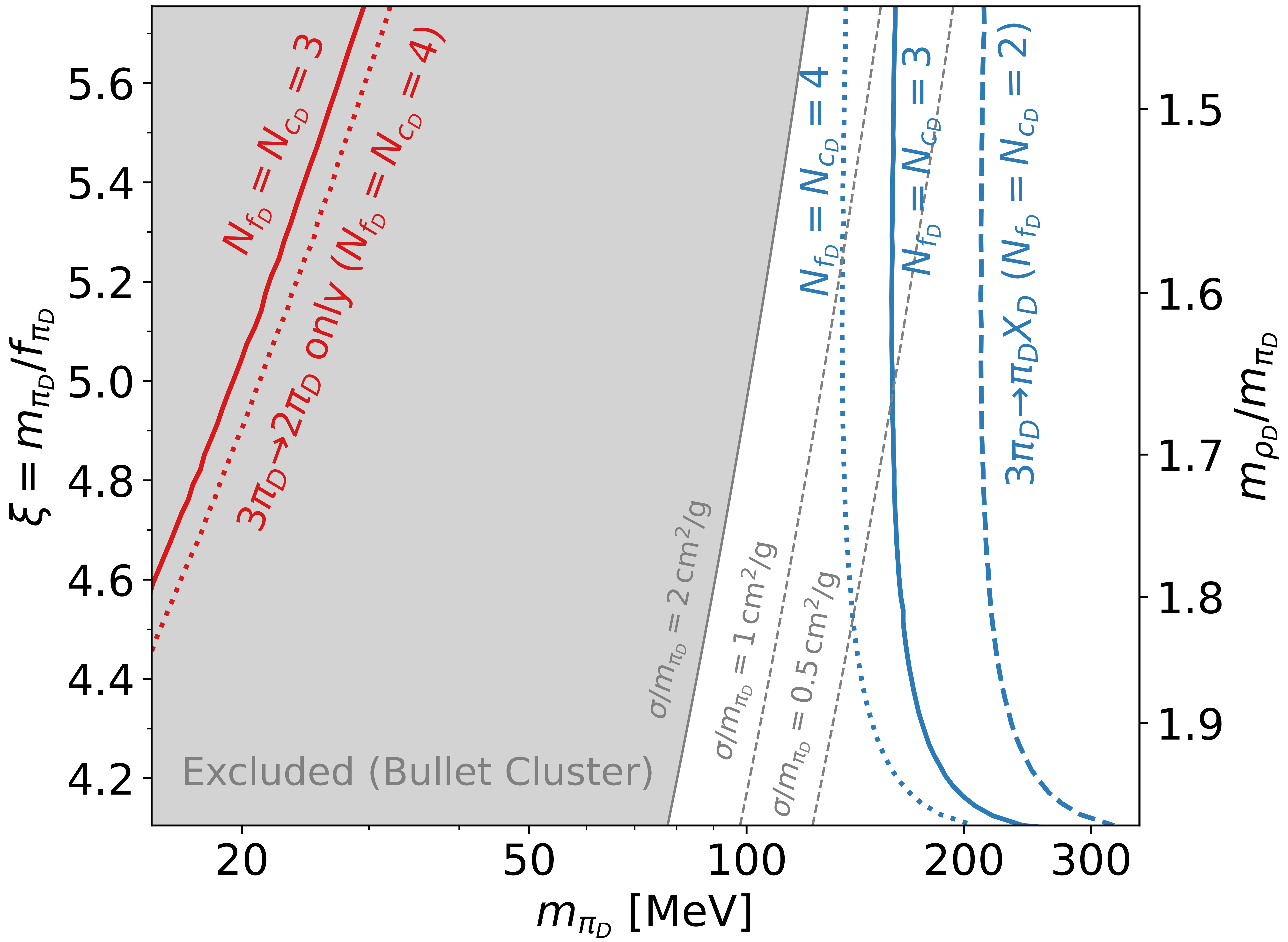
$3\,\pi_D \to \pi_D\,\rho_D$ **dominates**

$$\frac{\langle \sigma v^2 \rangle_{3\pi_D \to \pi_D \rho_D}}{\langle \sigma v^2 \rangle_{3\pi_D \to 2\pi_D}} \approx (1800 - 8500) \times \frac{1}{N_{c_D}^2 \xi^4} \frac{x^2}{\sqrt{1-y}}$$

$x \equiv m_{\pi_D}/T \qquad y \equiv m_{\rho_D}^2 / 4 m_{\pi_D}^2$

DM freeze-out with dark rho mesons

$3\pi_D \to \pi_D \rho_D$ **freeze-out consistent with bullet cluster and theoretically well controlled**



With rho mesons, preferred dark pion mass scale increases by factor 3 to 10

Prediction:

$$m_{\pi_D} \approx 330\ \mathrm{MeV} \times N_{f_D}^{-2/3}$$

Condition: ρ_D **is in equilibrium** with SM bath

Part 2:
Dark showers at beam dumps

Prediction of visible decays from relic density

Predictions of freeze-out scenario:

- ρ_D requires interactions with SM to be in thermal equilibrium
- $m_{\rho_D} < 2m_{\pi_D}$ implies that $\rho_D \to \pi_D \pi_D$ is not allowed

→ **Dominant ρ_D decay is to SM**

Possible signal at accelerator experiments

For concreteness specify e.g. effective interaction

$$\mathscr{L}_{\text{eff}} \supset \frac{1}{\Lambda_{\text{eff}}^2} \sum_f q_f \bar{f} \gamma^\mu f \bar{q}_{\text{d}} \gamma_\mu q_{\text{d}}$$

→ dark-photon-like coupling of dark vector meson

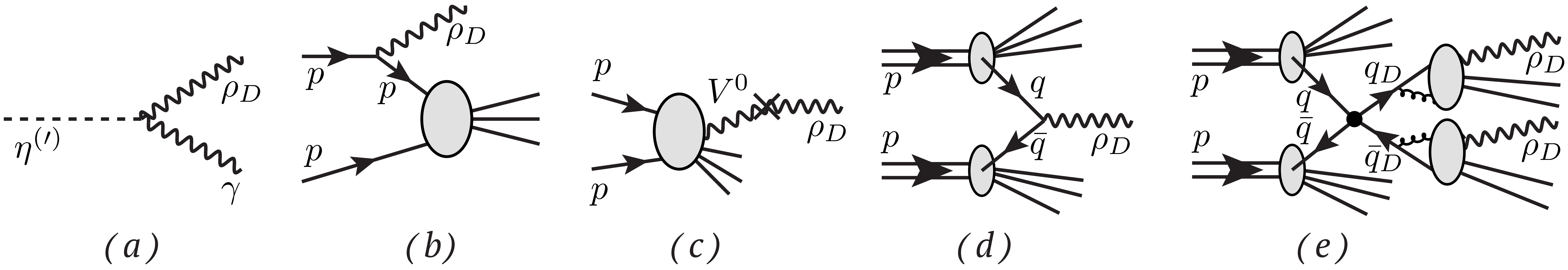
$$\frac{2m_{\rho_D}^2}{\Lambda_{\text{eff}}^2 \, g_{\pi\rho}} \rho_D^\mu J_{\mu,\text{EM}}$$

Decay $\rho_D \to f\bar{f}$ with **decay length** $c\tau_{\rho_D} \sim \Lambda_{\text{eff}}^4 / m_{\rho_D}^5$ **typically macroscopic** for sub-GeV ρ_D

Dark rho meson production

ρ_D **is sub-GeV long-lived particle** → motivates search at beam dump experiments

Dark vector meson production processes at proton beam dumps



meson decay | bremsstrahlung | meson mixing | Drell-Yan | **dark shower**

standard dark-photon-like production

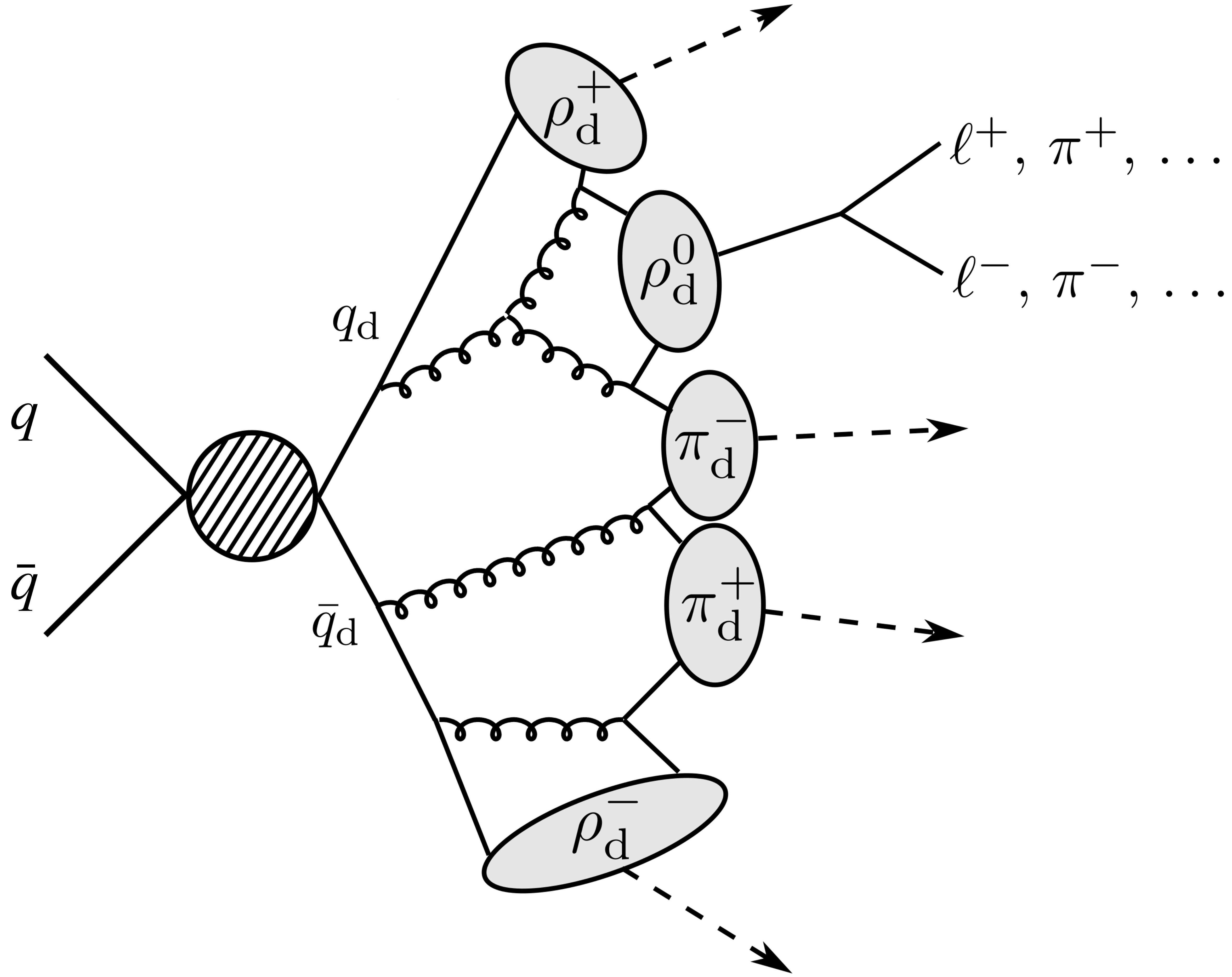
with effective mixing $\epsilon = \frac{2m_{\rho_D}^2}{\Lambda_{\text{eff}}^2 \, g_{\pi\rho} e}$

see also Berlin et al, 1801.05805

NEW

Dark showers

If $\sqrt{s} \gg \Lambda_D,\ m_{q_D}$: dark shower producing dark mesons



Simulation with Pythia 8 Hidden Valley Module

Potentially large number of dark mesons

Multiplicity varies event by event

In recent years, establishment of extensive search program for dark shower signatures at LHC

see e.g. Snowmass white paper, Albouy et al., arXiv:2203.09503

So far no dark shower predictions at beam dump experiments

The SHiP experiment

Particularly promising experiment for MeV- to GeV-scale LLPs with decay length $\sim \mathcal{O}(m)$:

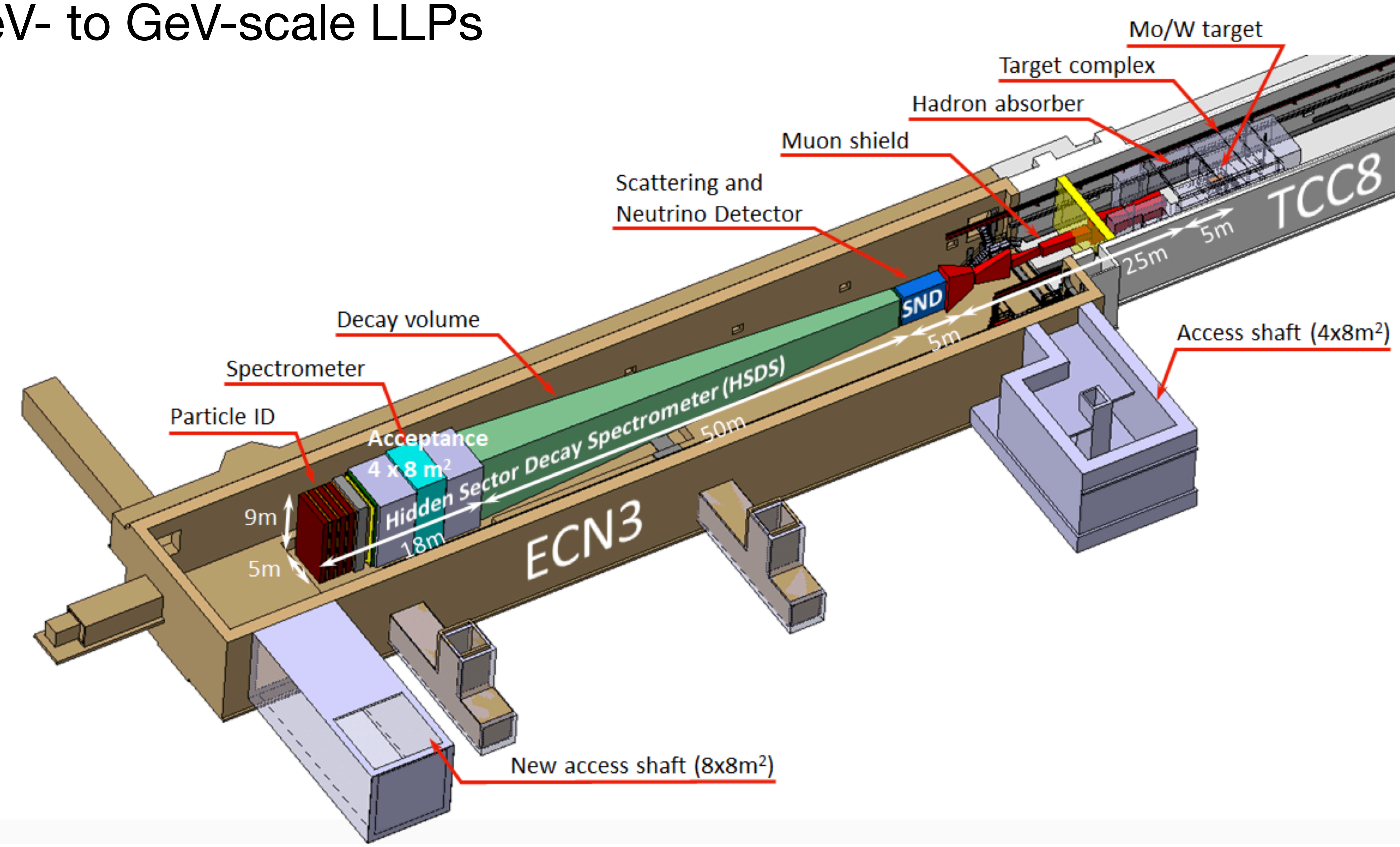
SHiP experiment at CERN SPS

Start of operation ~ 2034

$400~\mathrm{GeV}$ proton beam on fixed target

➡ $\sqrt{s} = 27.4~\mathrm{GeV}$

$50~\mathrm{m}$ long decay volume
$32~\mathrm{m}$ downstream from target

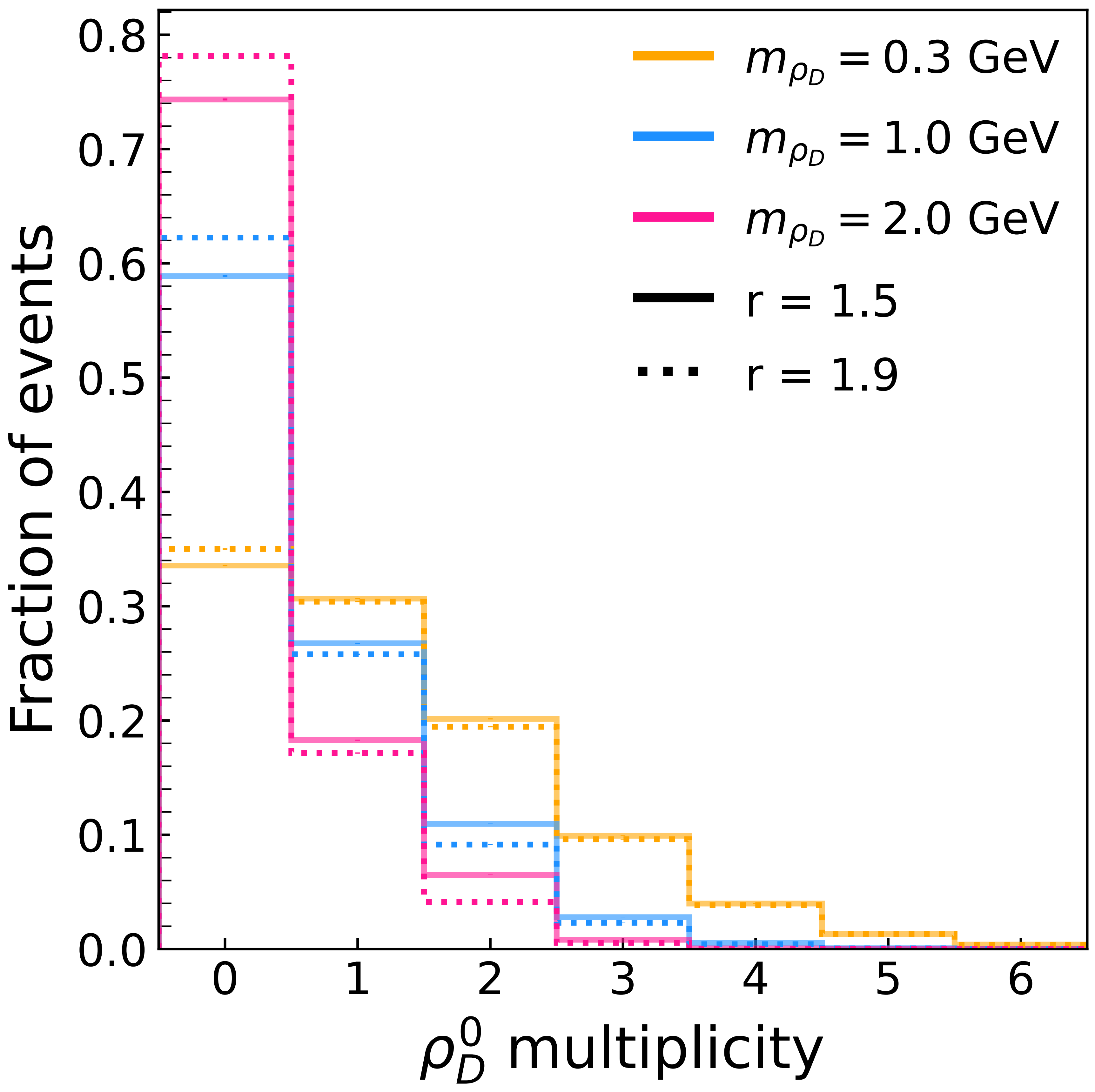


SHiP collaboration,
CERN-SPSC-2022-032 ; SPSC-I-258

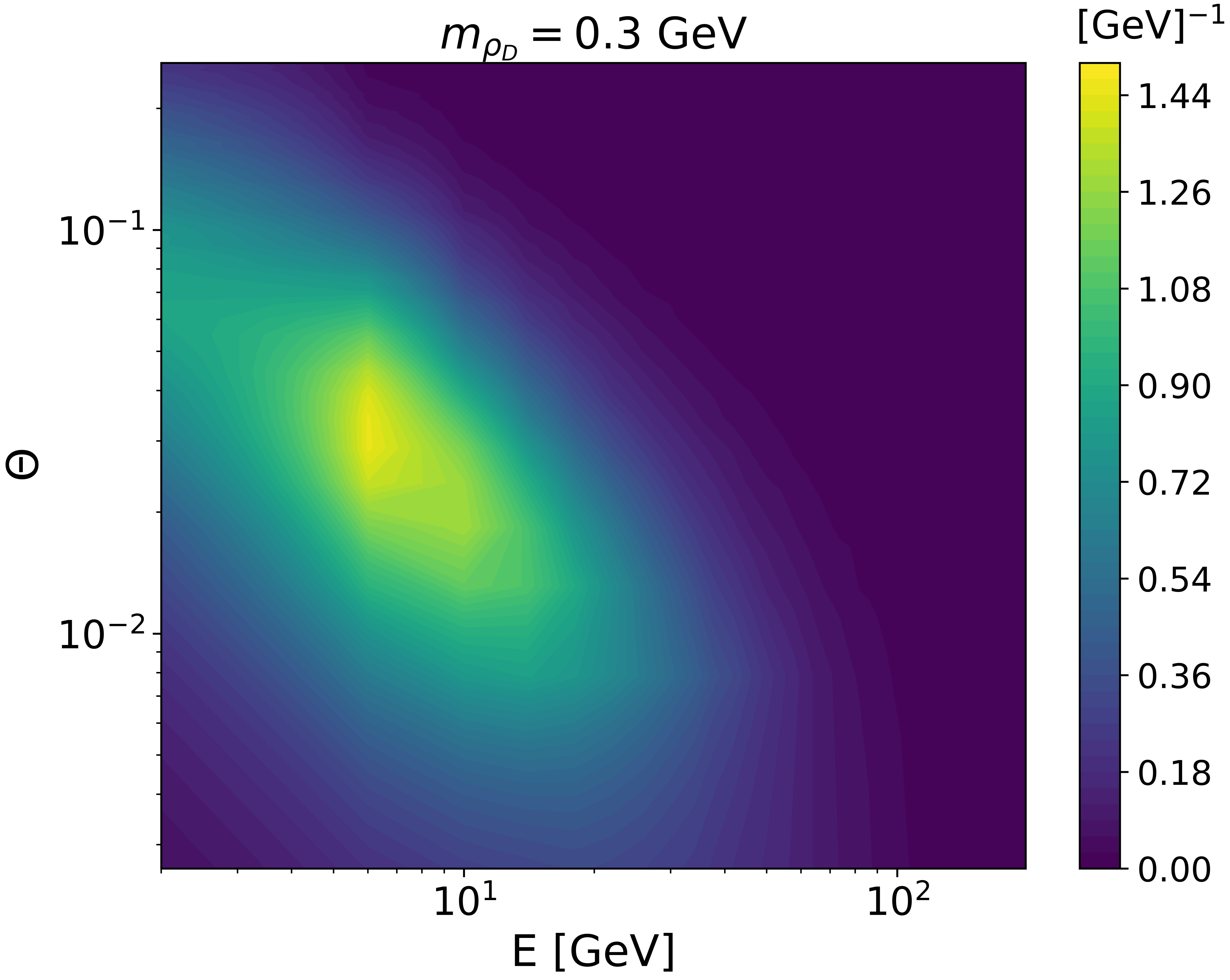
Dark showers at SHiP

Dark shower simulation with Pythia 8, setting dark QCD parameters consistently based on lattice results

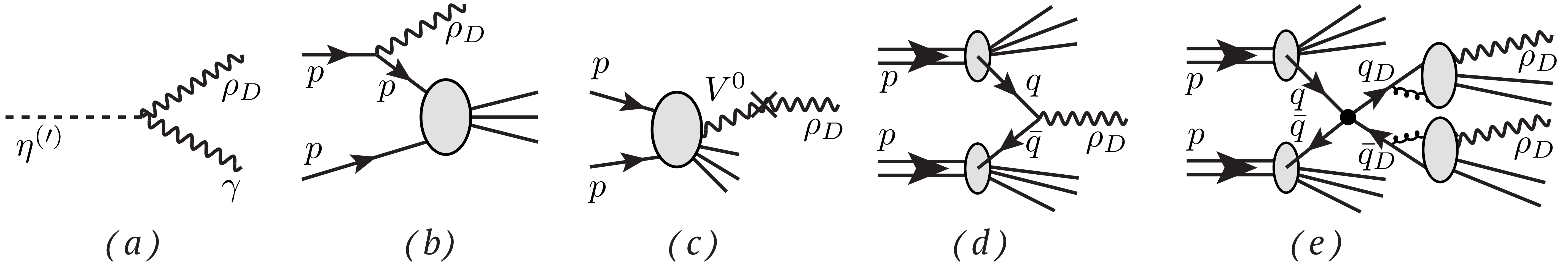
Multiplicity of unstable dark mesons ρ_D^0

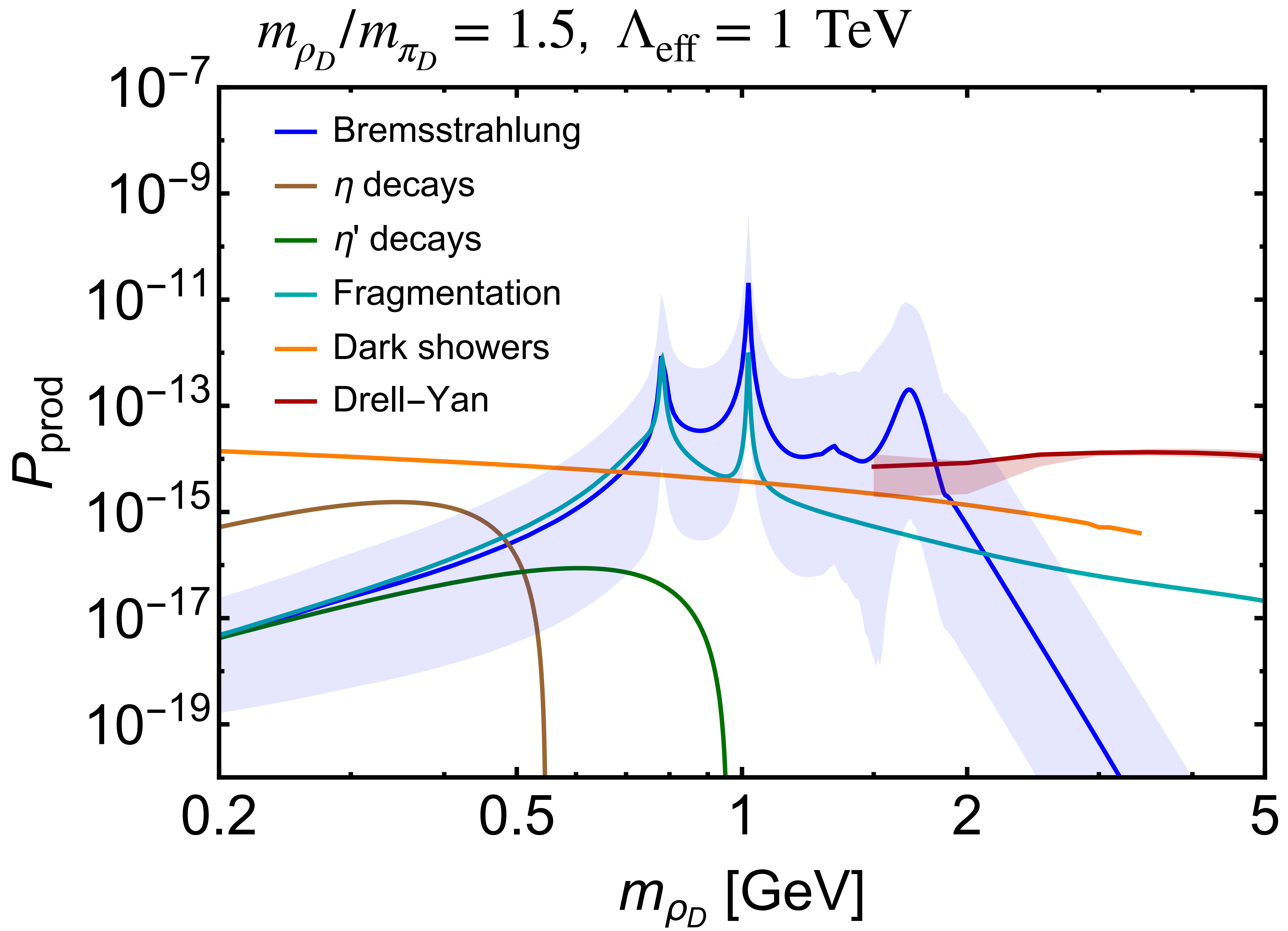


ρ_D^0 kinematics



Comparison of production modes





- $m_{\rho_D} \lesssim 0.8$ GeV:

  Dark shower production dominates
  (other production modes suppressed by $\epsilon \sim m_{\rho_D}^2$)

- $m_{\rho_D} \gtrsim 2$ GeV:

  Drell-Yan dominates

- Intermediate m_{ρ_D}:

  Combination of different production modes

Displaced decay analysis at SHiP

Cuts require each reconstructed displaced vertex to have ≥ 2 decay products with

- zero net charge
- $E > 1\ \mathrm{GeV}$
- transverse impact parameter $< 2.5\ \mathrm{m}$

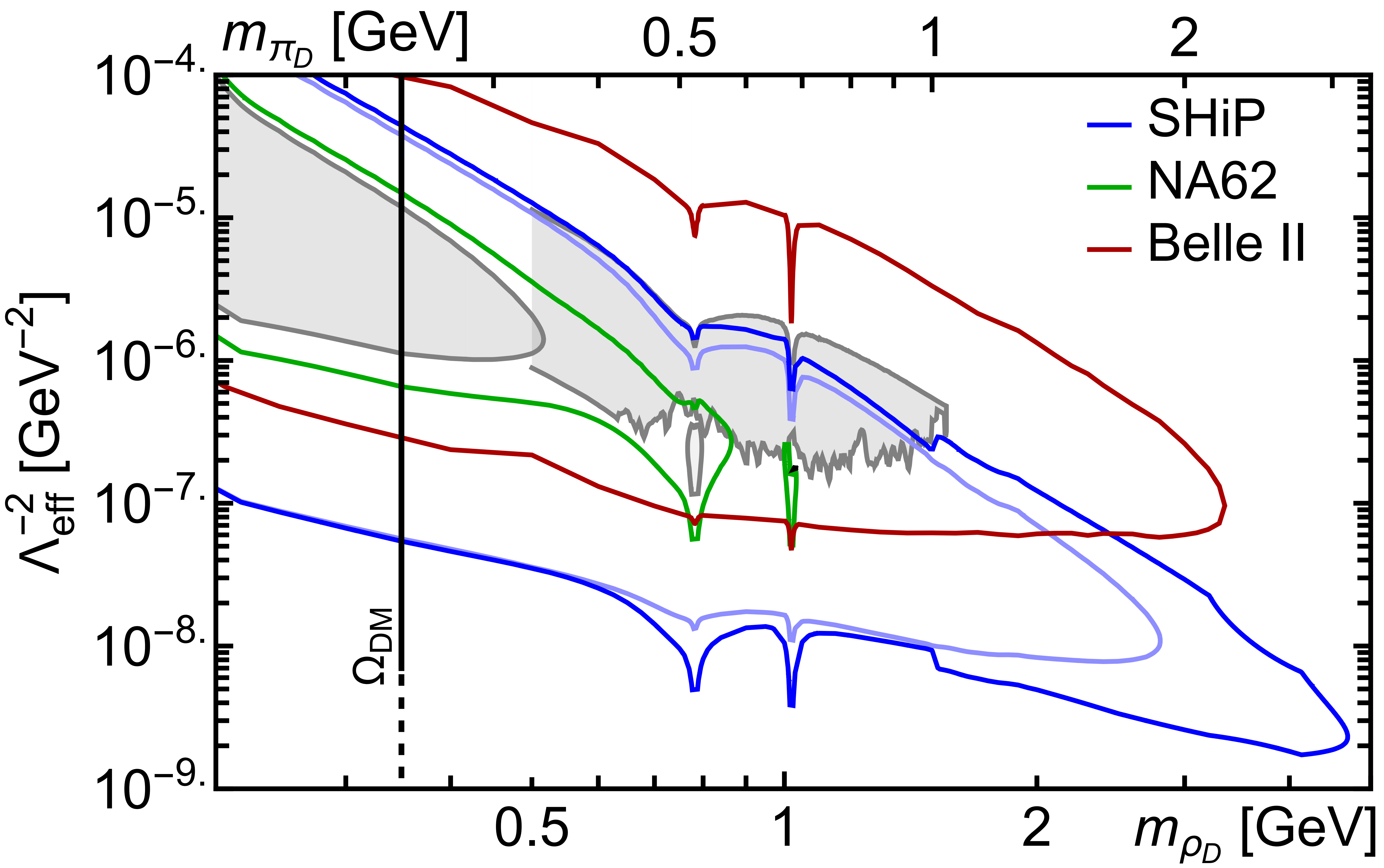
Search for signal events with at least one such reconstructed vertex

(sufficient in background-free environment)

$N_{\mathrm{PoT}} = 6 \times 10^{20}$ protons on target

Sensitivity projections with public code SensCalc Ovchynnikov et al., 2305.13383

Projected sensitivities and constraints



Existing constraints:

- BEBC, CHARM, NA62 probe $m_{\rho_D} \lesssim 0.5$ GeV
- BaBar probes $0.5 \text{ GeV} < m_{\rho_D} \lesssim 1.6$ GeV

SHiP projection:

- **Reach up to $m_{\rho_D} \approx 5$ GeV**
- Dark showers contribute up to $m_{\rho_D} \approx 3$ GeV

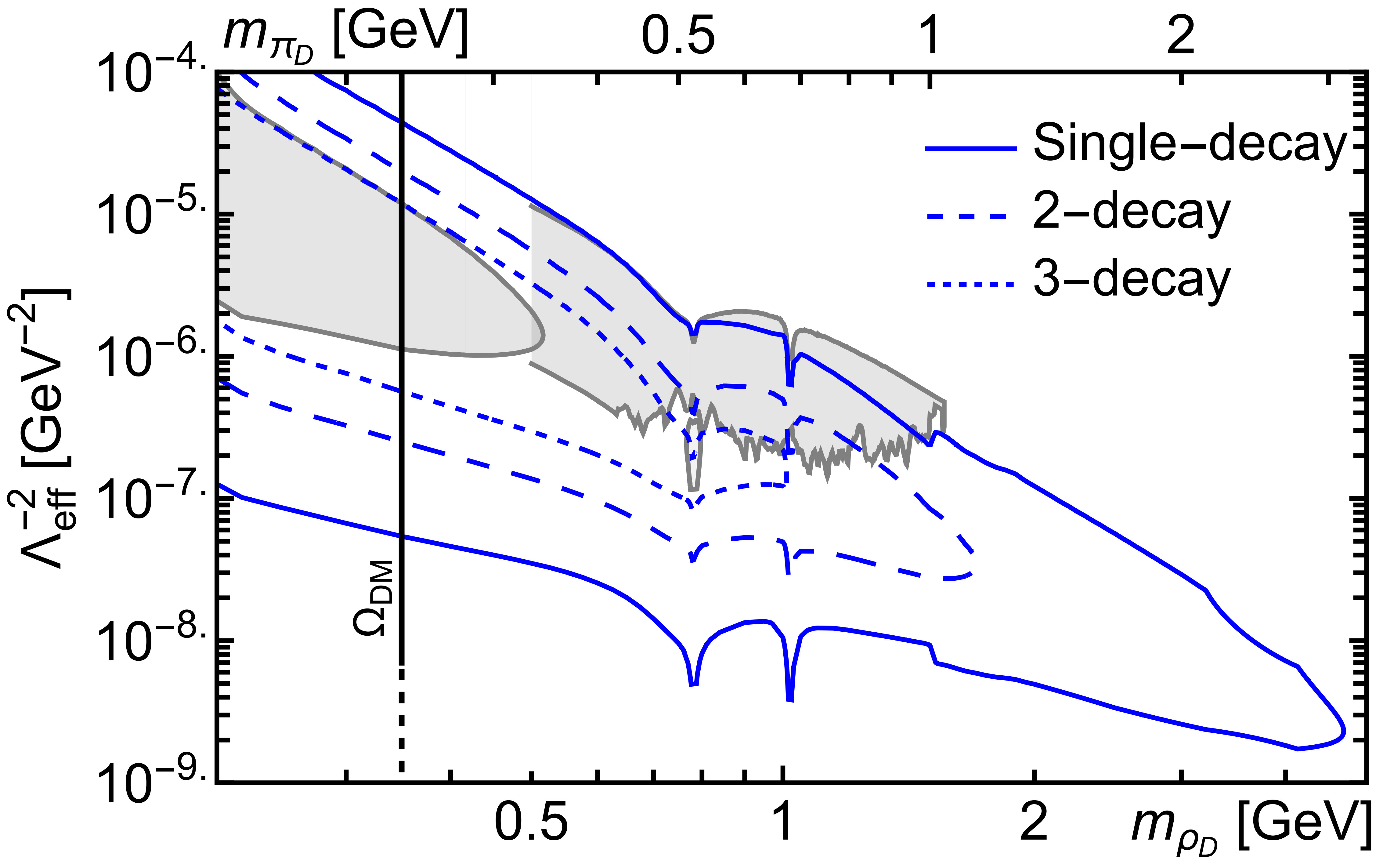
Belle II projection:

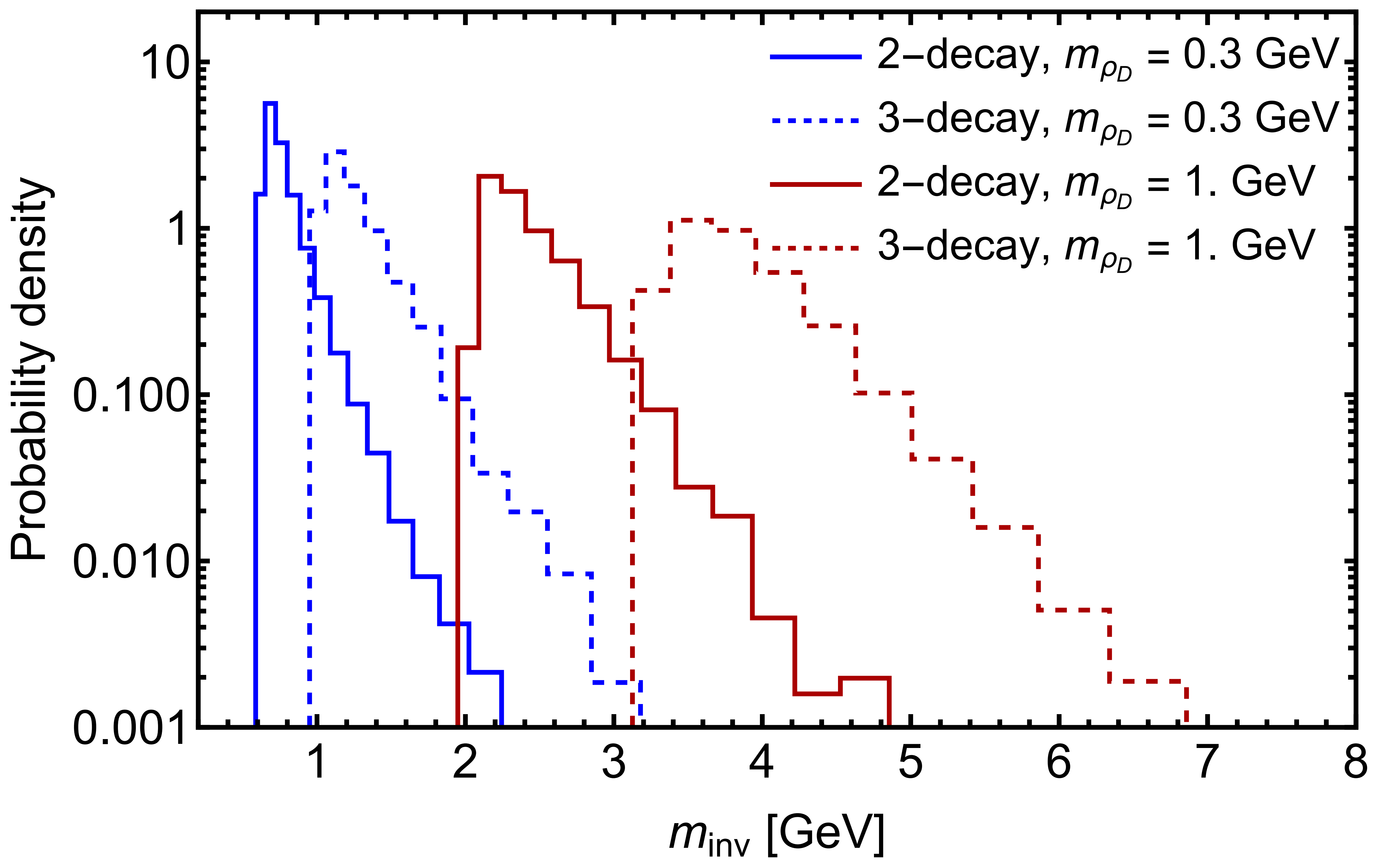
- Complementary to SHiP
- updated based on EB et al., 2203.08824

SHiP + Belle II probe almost entire relic density target
(where ρ_D's are in equilibrium in the early Universe)

Multi-decay events for model discrimination

In case of a discovery, **observation and analysis of multi-decay events helps with model discrimination**





Dark showers can be **distinguished from minimal dark photon** models by observing 2- or 3-decay events

and from **non-minimal dark photon** models via **relative multiplicities and shape of total** $m_{\rm inv}$

Conclusions

- A strongly interacting dark sector (dark QCD) is well motivated
- Dark pions are excellent DM candidates
- Standard SIMP mechanism for relic density, based on $3\pi_D \to 2\pi_D$ annihilations, faces prohibitive self-interaction constraints
- Taking into account dark vector mesons in calculation via $3\pi_D \to \pi_D\rho_D$ increases preferred dark pion mass and evades constraints
- SIMP mechanism with dark rho mesons predicts visible signals at accelerator experiments from displaced decays
- SHiP can probe dark shower signal in sub-GeV to GeV range, including relic density target
- Complementary sensitivity at SHiP and Belle II

Backup

Chiral Lagrangian

$$\mathscr{L}_{\rm Ch} = \frac{f_{\pi_D}^2}{4}\mathrm{Tr}\left(\partial_\mu U \partial^\mu U^\dagger\right) + \left[\frac{\mu_D^3}{2}\mathrm{Tr}\left(M_{q_D}U^\dagger\right) + \mathrm{h.c.}\right]$$

with $U \equiv \exp\left(2i\pi_D/f_{pi_D}\right)$

$$\mathscr{L}_{\rm Ch} \supset \mathrm{Tr}\left(D_\mu \pi_D D^\mu \pi_D\right) + m_{\pi_D}^2 \mathrm{Tr}\left(\pi_D^2\right) + \frac{m_{\pi_D}^2}{3f_{\pi_D}^2}\mathrm{Tr}\left(\pi_D^4\right) - \frac{2}{3f_{\pi_D}^2}\mathrm{Tr}\left(\pi_D^2 D_\mu \pi_D D^\mu \pi_D - \pi_D D_\mu \pi_D \pi_D D^\mu \pi_D\right)$$

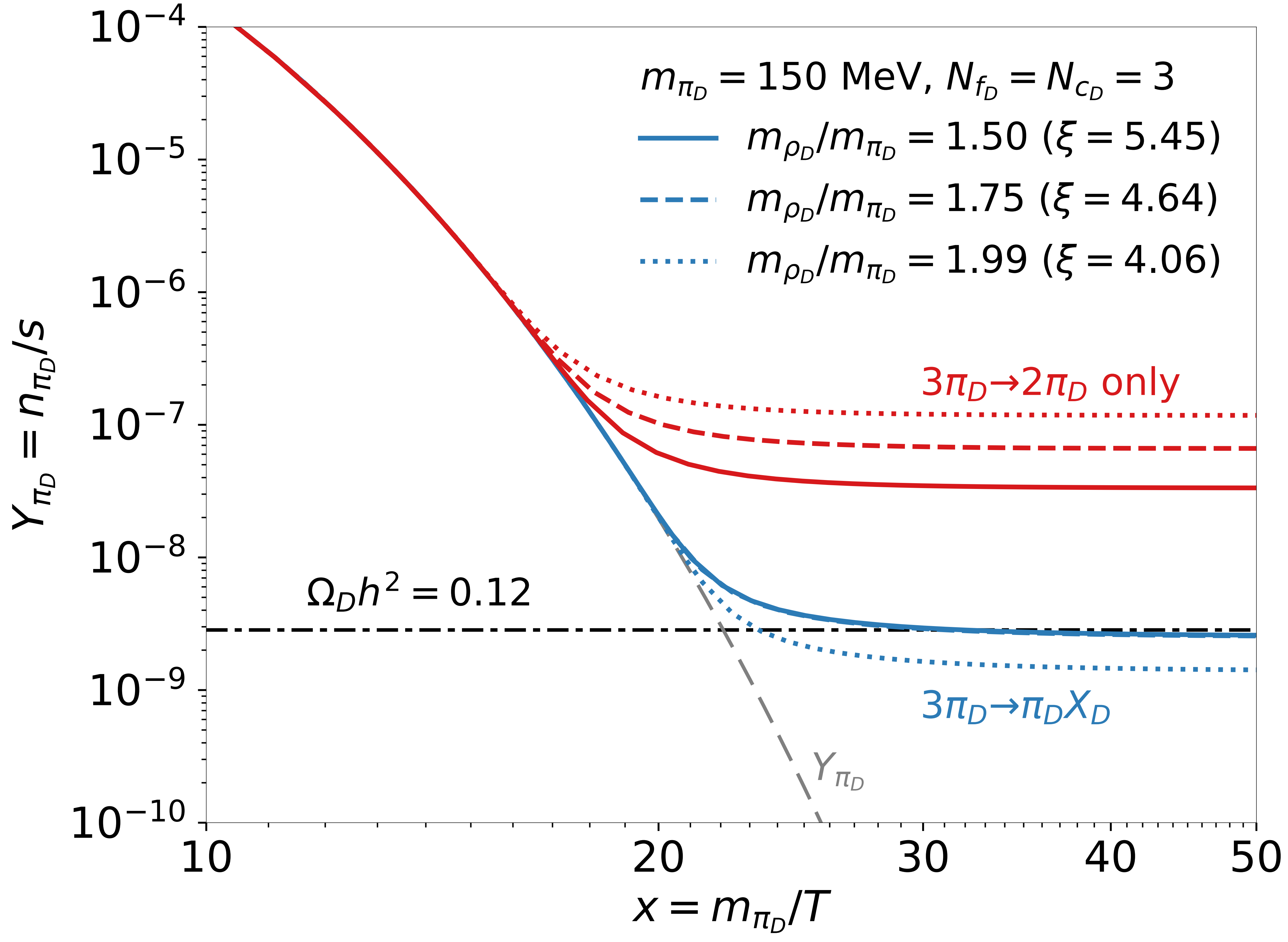
$$D^\mu U = \partial^\mu U + ig[U, \rho_D^\mu] \qquad D^\mu \pi_D = \partial^\mu \pi_D + ig[\pi_D, \rho_D^\mu] \qquad g \approx m_{\rho_D}/(\sqrt{2}f_{\pi_D})$$

$$\mathscr{L}_{\rm WZW} = \frac{2N_{c_D}}{15\pi^2 f_{\pi_D}^5}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}\left(\pi_D \partial_\mu \pi_D \partial_\nu \pi_D \partial_\rho \pi_D \partial_\sigma \pi_D\right)$$

DM freeze-out with dark rho mesons

Assumption: ρ_D is in equilibrium with SM bath, e.g. via mixing

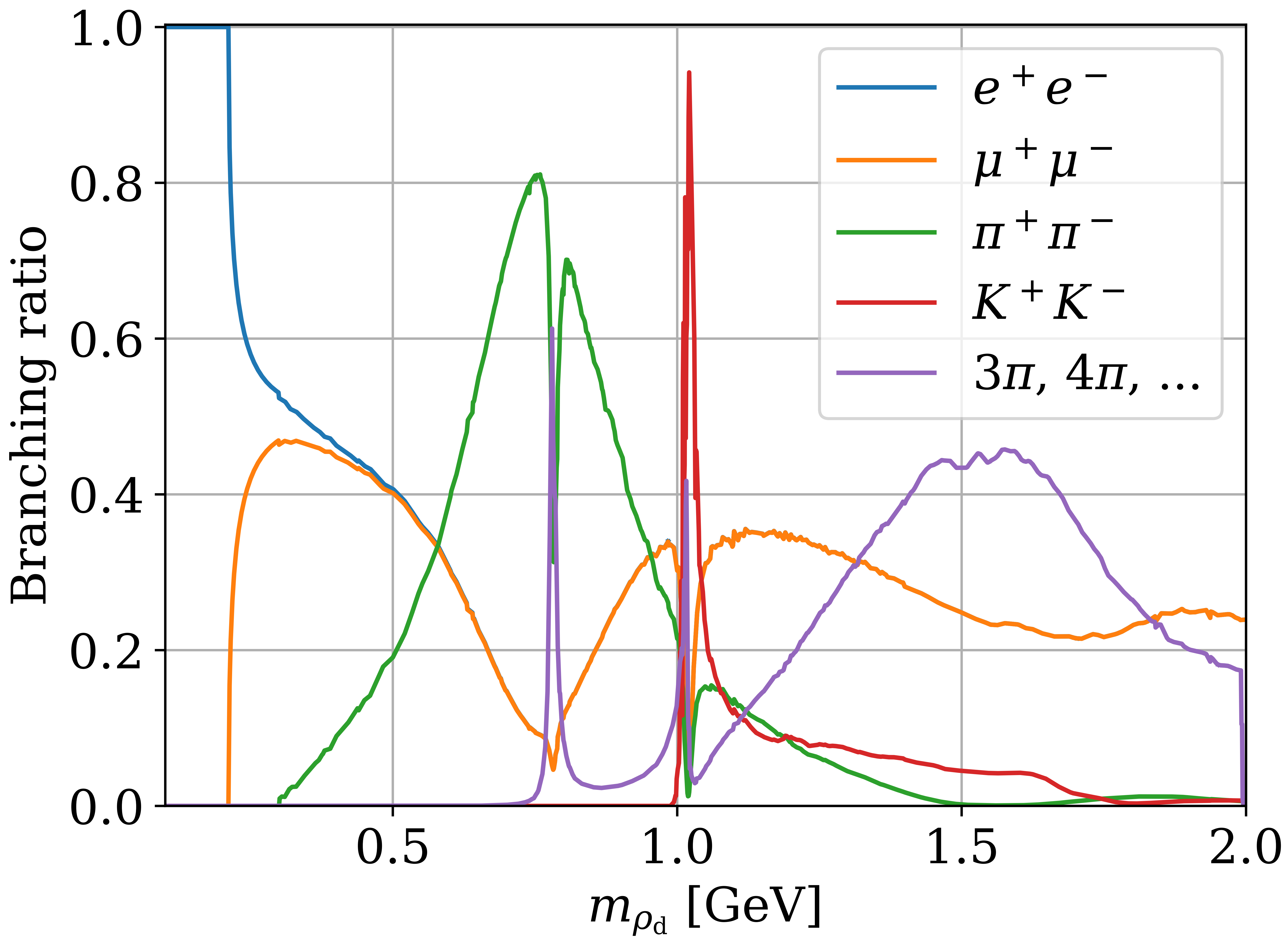
Comoving DM number density



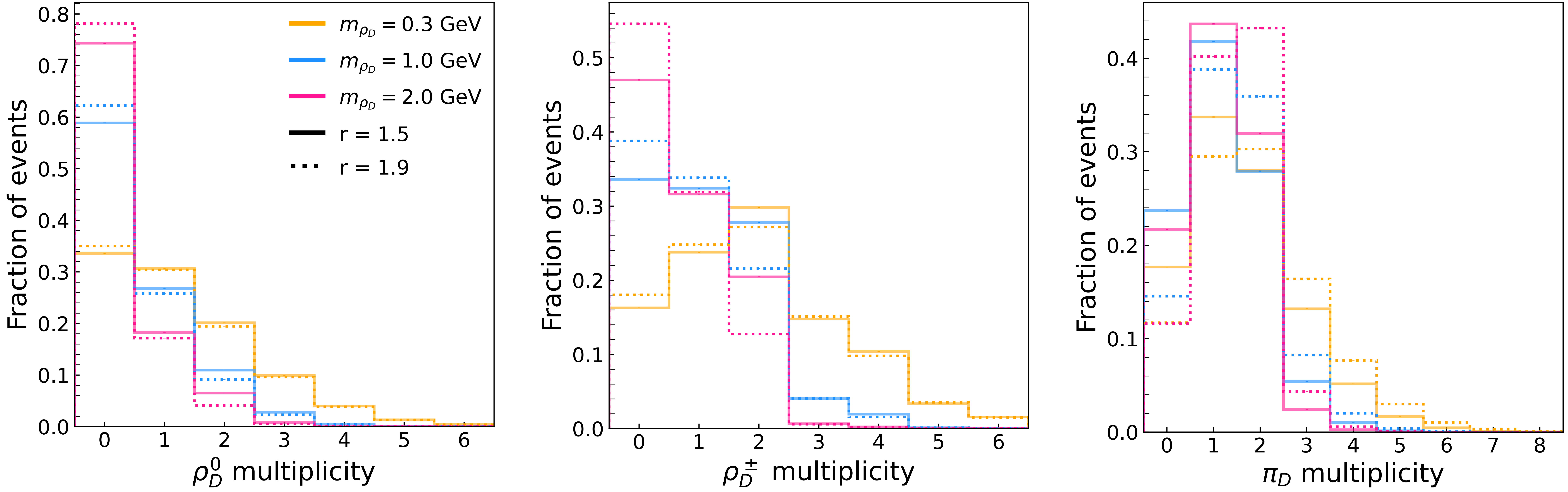
Without rho mesons, DM overproduction by an order of magnitude

With rho mesons, correct DM relic abundance

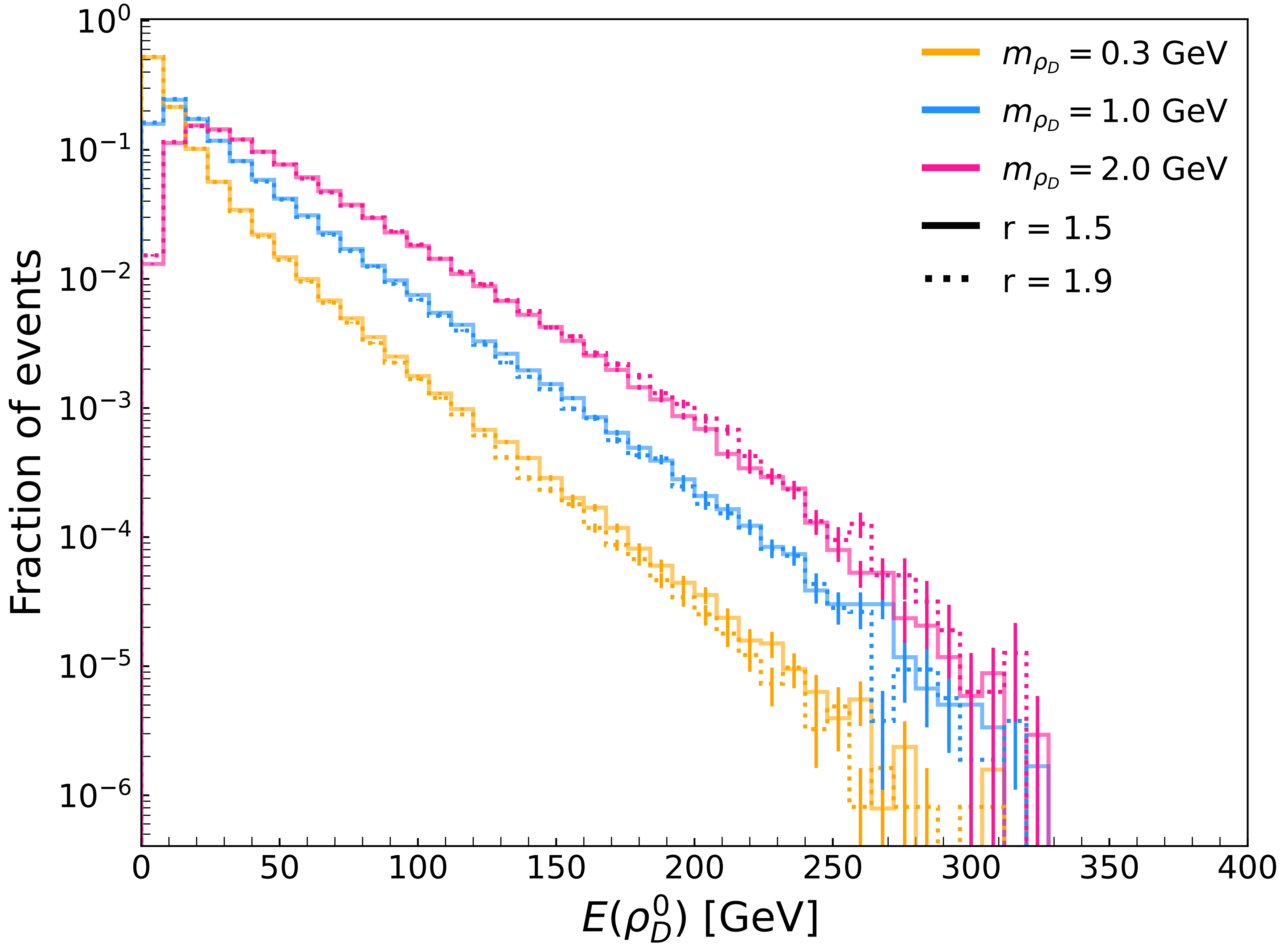
Dark rho branching fractions

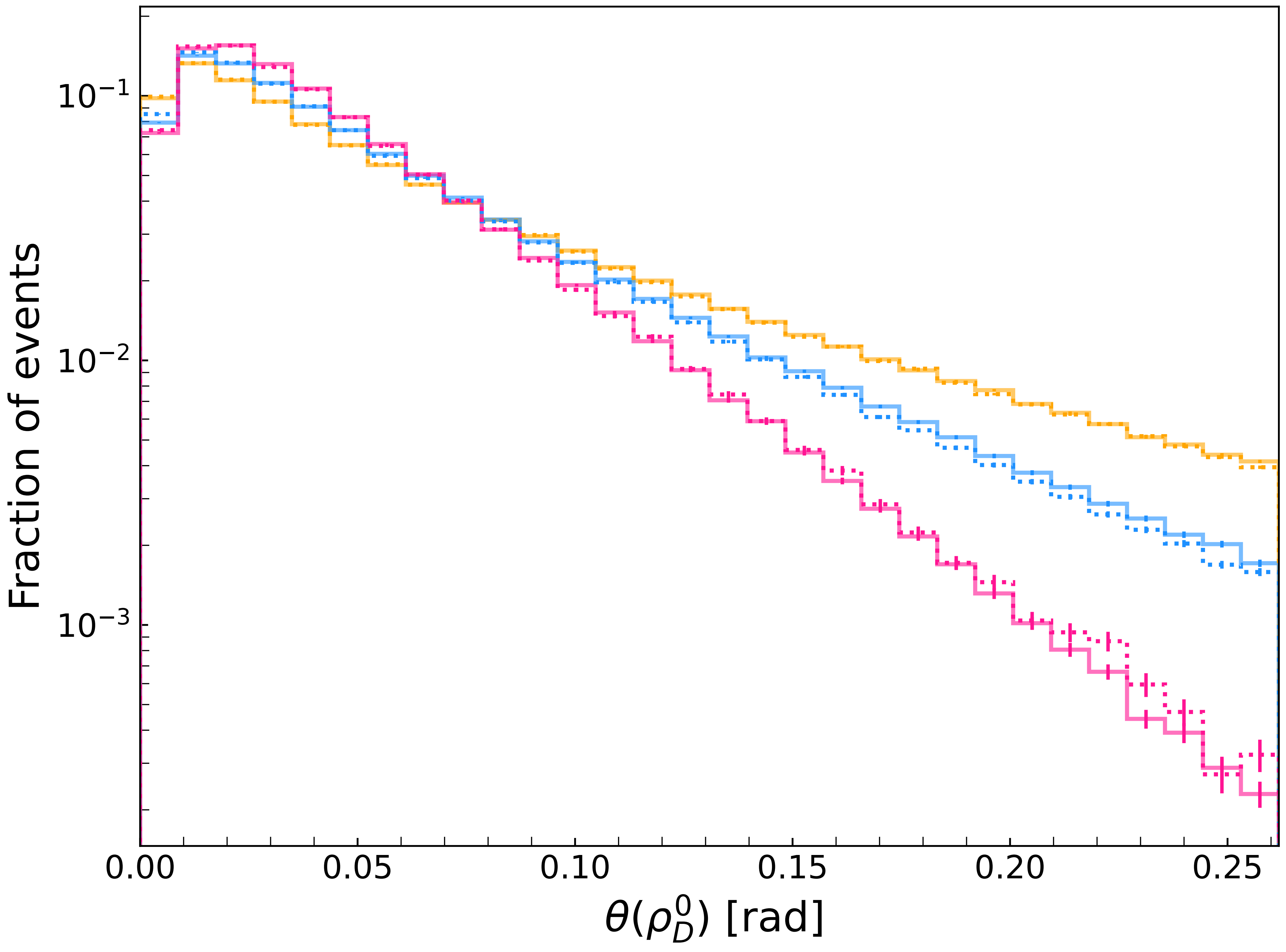


Dark meson multiplicities in dark showers at SHiP

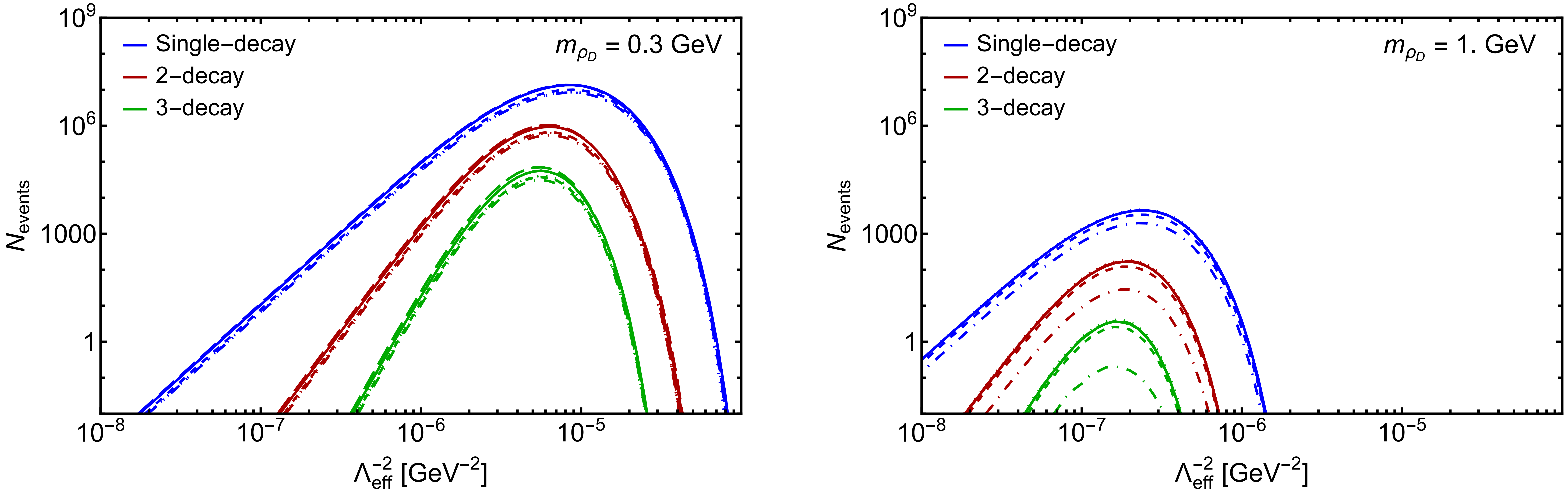


Dark meson kinematics in dark showers at SHiP





Dark shower uncertainty



solid: baseline parameters, short dash: $\Lambda_D = \Lambda_{D,0}/3$, long dash: $\Lambda_D = 3\Lambda_{D,0}$,
dash-dot: $\mathrm{probVec} = 0.33$, dotted: $\mathrm{probVec} = 0.75$,
long dash-dot: $r = m_{\rho_D}/m_{\pi_D} = 1.9$