Co-decaying Dark Matter in a Hidden Valley

based on 240X.XXXX with Adrian Carmona, Fatemeh Elahi, Pedro Schwaller
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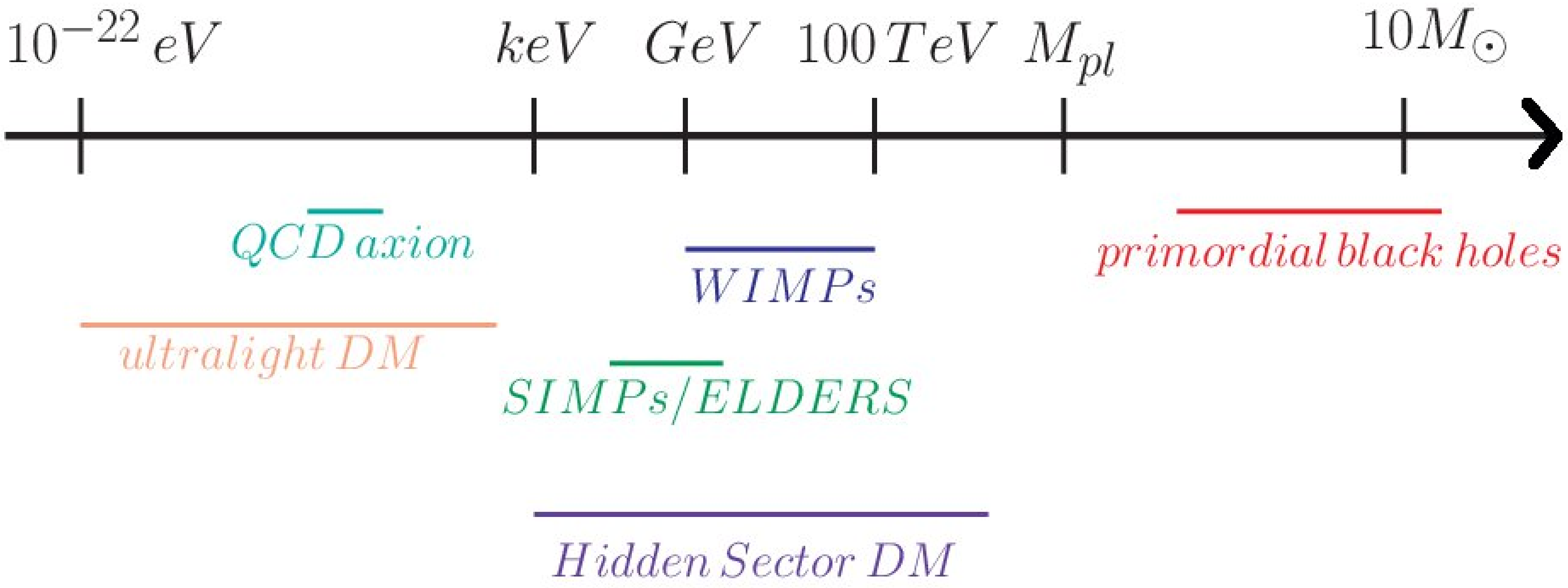
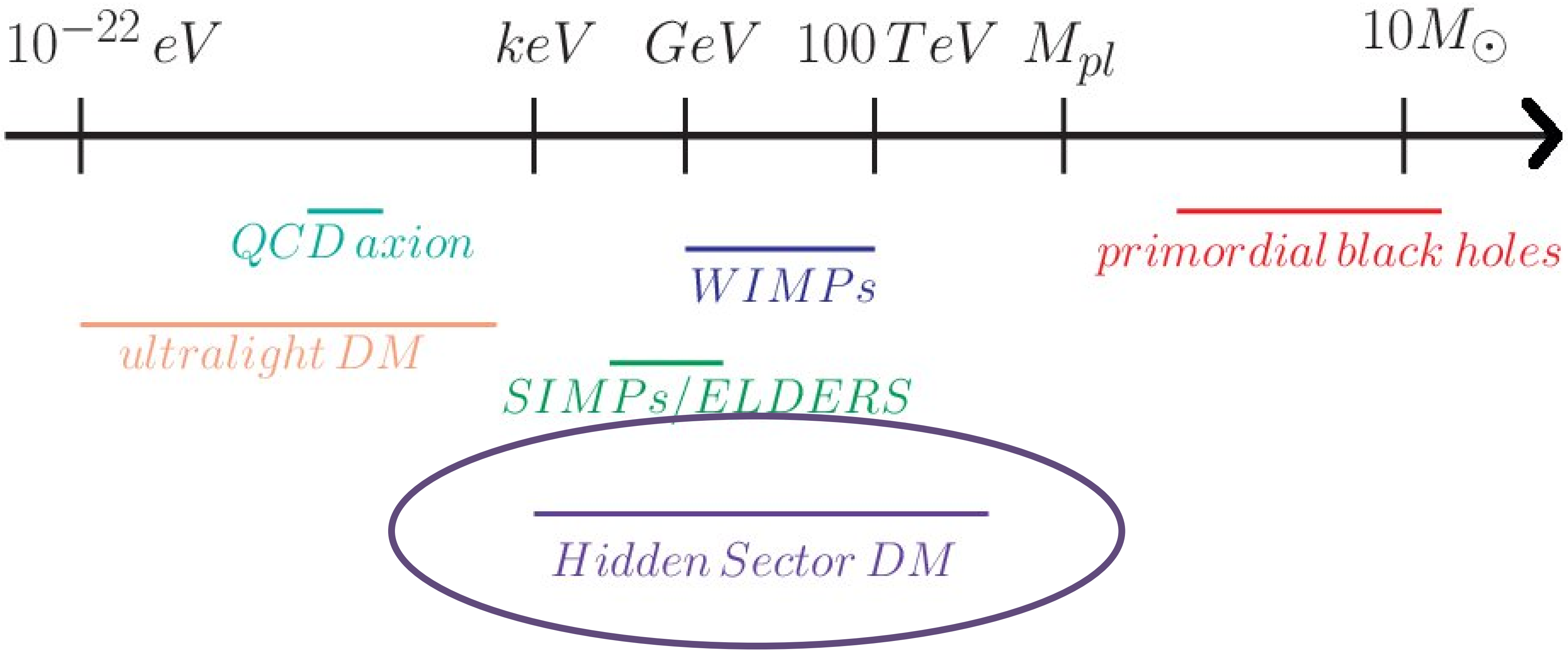
04/22/2024

Dark Matter



10^-22 eV
keV
GeV
100 TeV
M_pl
10M_⊙
QCD axion
ultralight DM
WIMPs
SIMPs/ELDERS
Hidden Sector DM
primordial black holes

Dark Matter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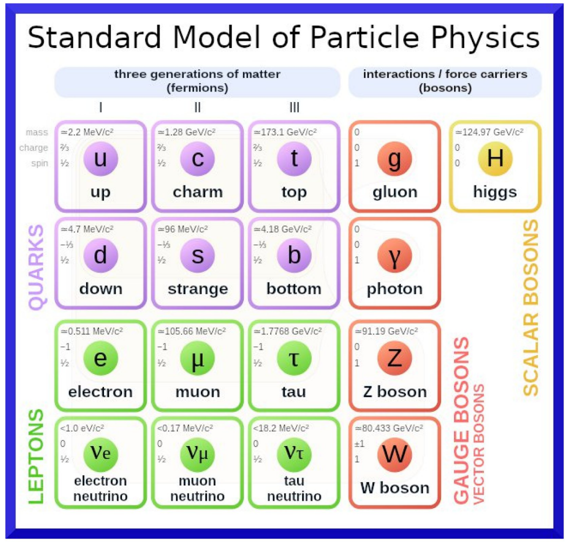
Hidden Valley Models



QCD-like Dark Sector

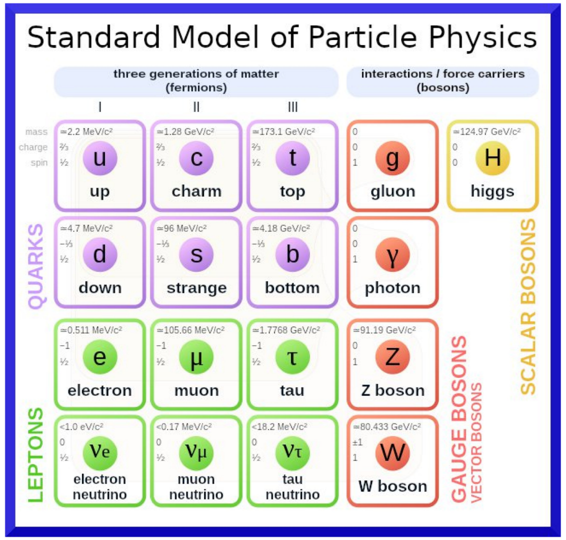
$$\mathcal{G}_{SM} \times SU(N_D)_D$$

n_D dark quarks Q_D

N_D dark colours

Portal

Hidden Valley Models: t-channel mediator



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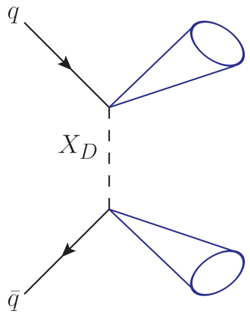


$$\text{Mediator } X_D: \; (3, \bar{3}) \sim SU(3)_c \times SU(3)_D$$

$$\mathcal{L}_D = -\frac{1}{4} G_{D,\mu\nu} G_D^{\mu\nu} + i \bar{Q}_D \not{D} Q_D - m_{Q_D} \bar{Q}_D Q_D + D_\mu X_D^\dagger D^\mu X_D + m_X |X_D|^2 - (\kappa_{\alpha i} \bar{q}_{R_i} Q_{D_{L\alpha}} X_D + h.c.)$$

Hidden Valley Models: t-channel mediator

$$\mathcal{L}_{dQCD} = \bar{Q}_\alpha \left(i\not{D} - m_{Q_D}\delta_{\alpha,\beta} \right) Q_\beta - \frac{1}{4} G^A_{D_{\mu\nu}} \tilde{G}^{\mu\nu A}_D$$

for small m_Q: approximate $SU(3)_{d_L} \times SU(3)_{d_R}$

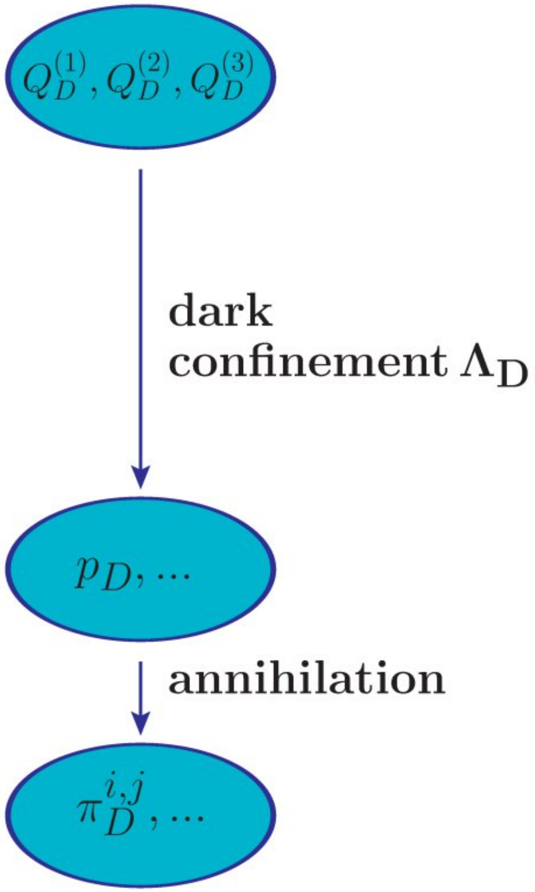
$\downarrow$

broken by dark quark condensate to $SU(3)_V$

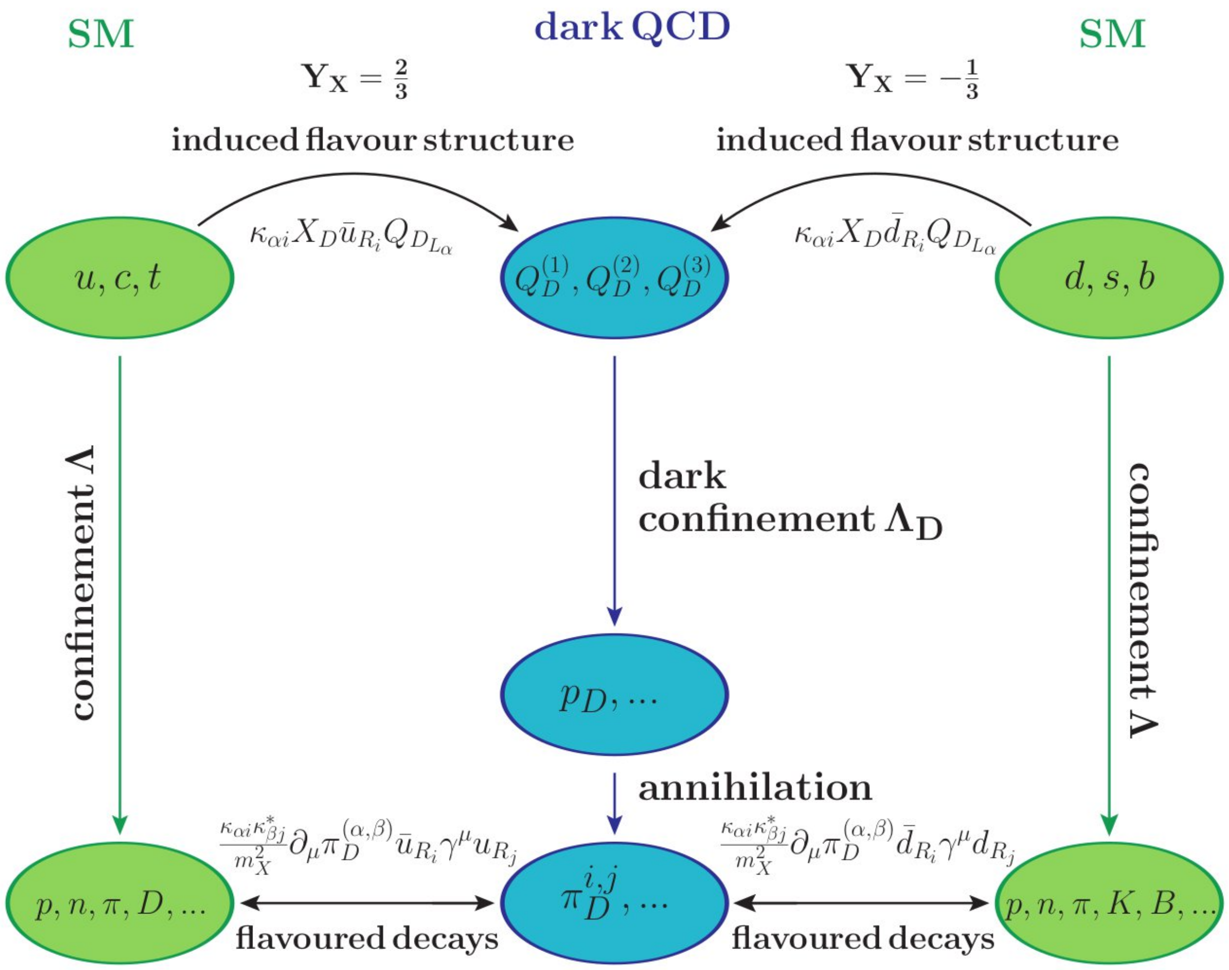
$\downarrow$

8 pseudo-Nambu-Goldstone bosons

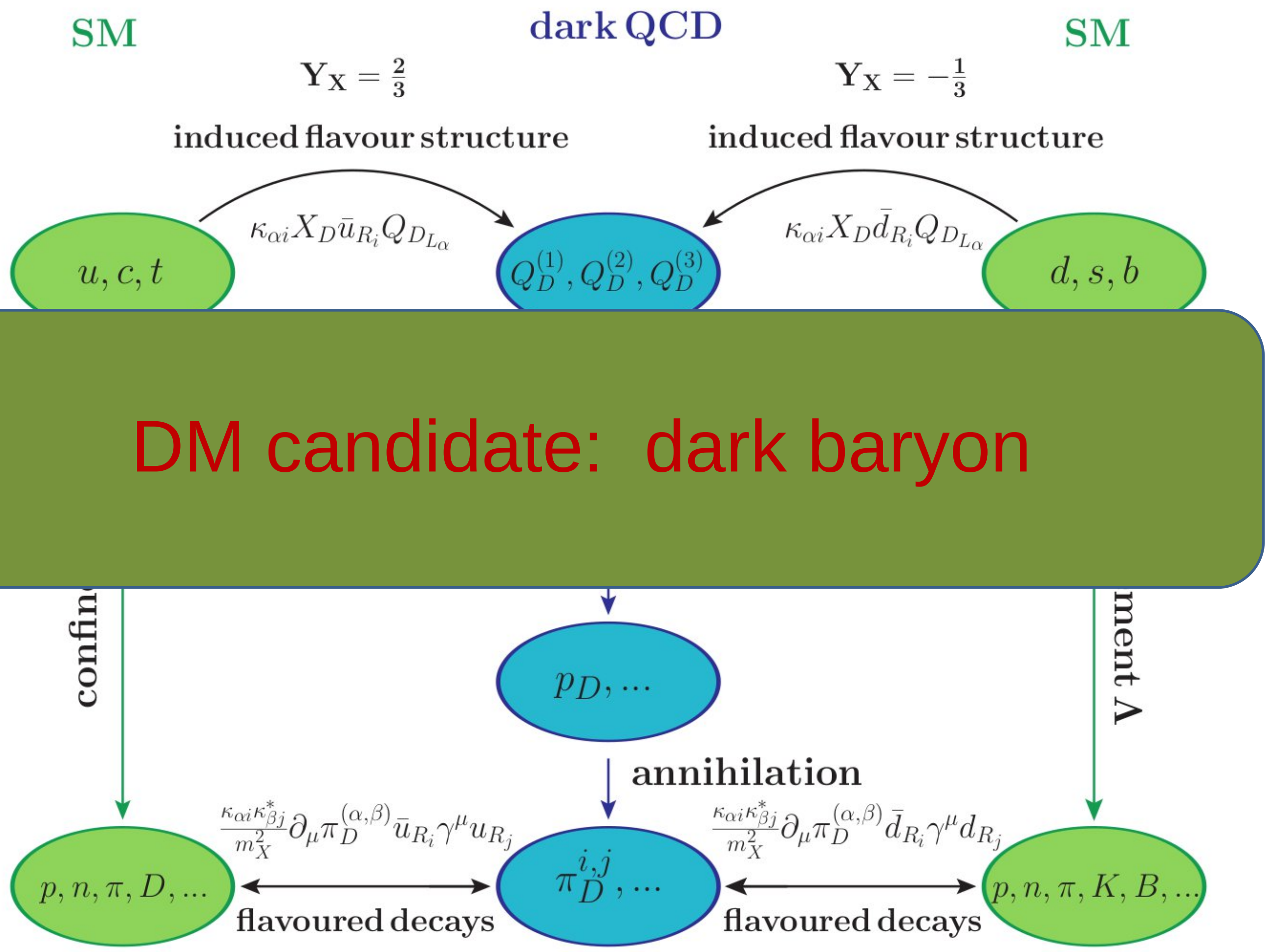
Dark Pion	Dark Quark Content
$\pi_D^{(1,2)}$	$\bar{Q}_{D2} Q_{D1}$
$\pi_D^{(1,3)}$	$\bar{Q}_{D3} Q_{D1}$
$\pi_D^{(2,3)}$	$\bar{Q}_{D3} Q_{D2}$
π_D^3	$\frac{1}{\sqrt{2}} \left[\bar{Q}_{D1} Q_{D1} - \bar{Q}_{D2} Q_{D2} \right]$
π_D^8	$\frac{1}{\sqrt{6}} \left[\bar{Q}_{D1} Q_{D1} + \bar{Q}_{D2} Q_{D2} - 2\bar{Q}_{D3} Q_{D3} \right]$



Hidden Valley Models: t-channel mediator

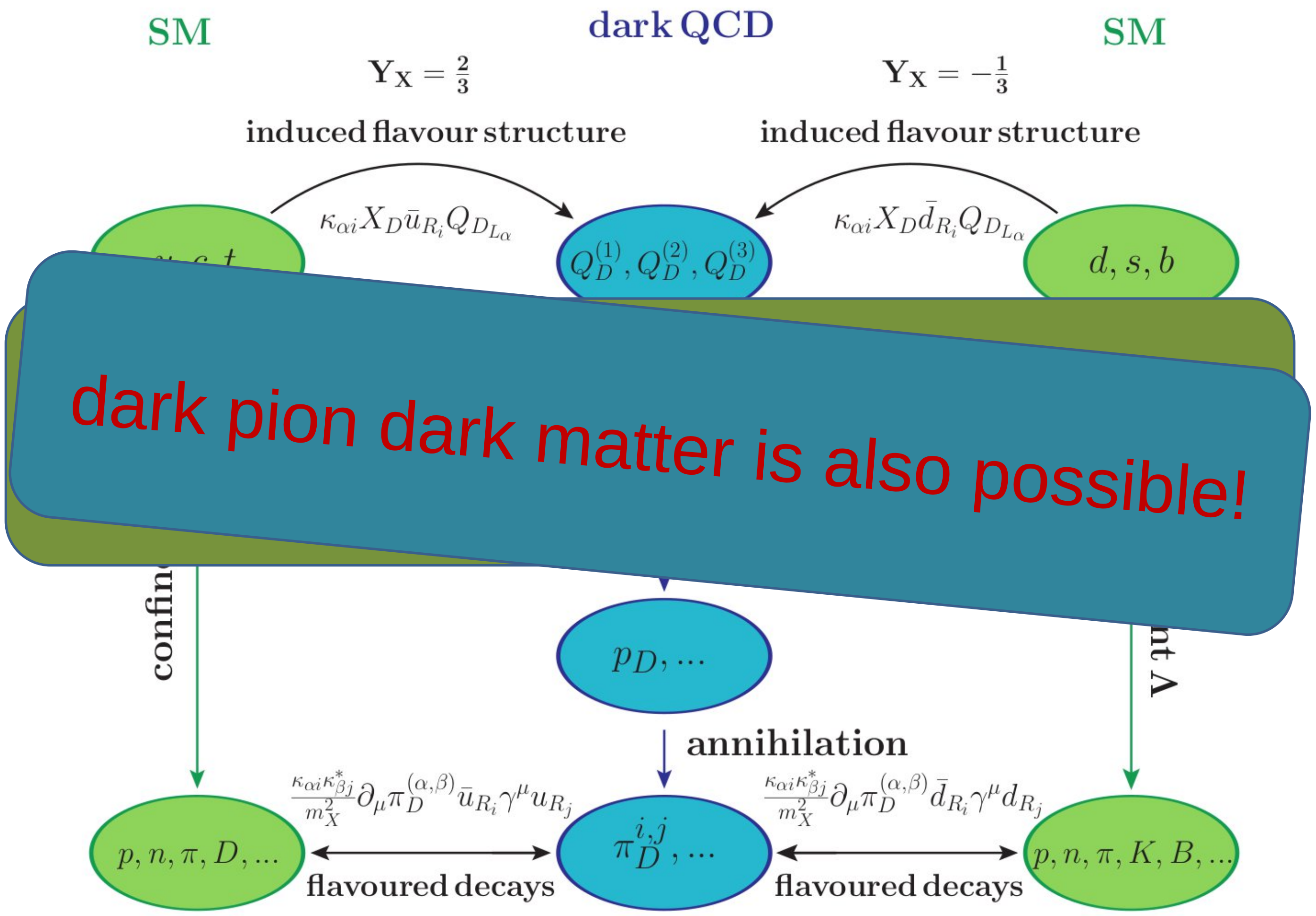


Hidden Valley Models: t-channel mediator



DM candidate: dark baryon

Hidden Valley Models: t-channel mediator



dark pion dark matter is also possible!

Dark pion dark matter in Hidden Valleys

expand SM by:

- $G_{SM} \times SU(3)_D$
- **n_f > 3** dark quarks charged under $SU(3)_D$

$\Longrightarrow n_f^2 - 1$ dark pions

flavour symmetry breaking now:

$$SU(n_f) \times SU(3) \rightarrow U(1)^{n_f - 3}$$

Dark pion dark matter in Hidden Valleys

$$(\kappa_{\alpha i}\bar{q}_{R_i}Q_{D_{L_\alpha}}X_D + h.c.)$$

$$\kappa = VDU$$

V is unitary $n_f \times n_f$ matrix

U is unitary 3×3 matrix

D is diagonal $n_f \times 3$ matrix

Dark pion dark matter in Hidden Valleys

$$(\kappa_{\alpha i}\bar{q}_{R_i}Q_{D_{L_\alpha}}X_D + h.c.)$$

$$\kappa = VDU$$

V is unitary $n_f \times n_f$ matrix, **n_f = 4**

U is unitary 3×3 matrix $\Longrightarrow$

D is diagonal $n_f \times 3$ matrix

$$\kappa = \begin{pmatrix} \kappa_{11} & \kappa_{12} & \kappa_{13} \\ \kappa_{21} & \kappa_{22} & \kappa_{23} \\ \kappa_{31} & \kappa_{32} & \kappa_{33} \\ 0 & 0 & 0 \end{pmatrix}$$

Dark pion dark matter in Hidden Valleys

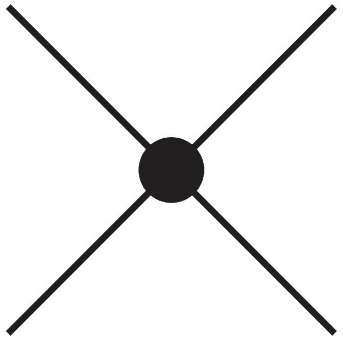
$$\kappa = \begin{pmatrix} \kappa_{11} & \kappa_{12} & \kappa_{13} \\ \kappa_{21} & \kappa_{22} & \kappa_{23} \\ \kappa_{31} & \kappa_{32} & \kappa_{33} \\ 0 & 0 & 0 \end{pmatrix} \quad \Longrightarrow \quad \pi_{D_{4i}} \, (i = 1, 2, 3)$$

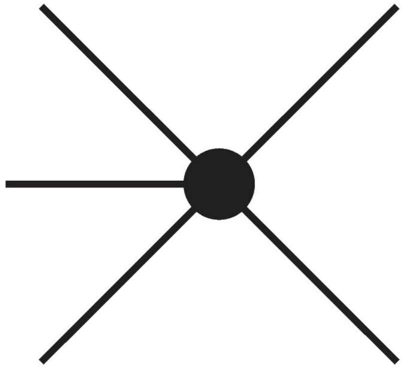
$\longrightarrow$ **3 decaying** diagonal dark pions

$\longrightarrow$ **6 decaying** off-diagonal dark pions

$\longrightarrow$ **6 stable** off-diagonal dark pions

Dark pion interactions





$$\mathcal{L}_{\rm SI}^{(4)} = -\frac{2}{3f_D^2}\pi_D^a\pi_D^b\partial_\mu\pi_D^c\partial^\mu\pi_D^d\left[\frac{1}{4}f^{acm}f^{bdm}\right]$$

$$\mathcal{L}_{\rm SI}^{(5)} = \frac{2N_d}{15\pi^2 f_D^5}\epsilon^{\mu\nu\rho\sigma}\pi^a\partial_\mu\pi^b\partial_\nu\pi^c\partial_\rho\pi^d\partial_\sigma\pi^e\left[-\frac{1}{16}\left(f^{abf}f^{cdg}d^{efg}\right)\right]$$

Boltzmann Equations

$$\frac{1}{a^3}\frac{d}{dt}(n_{\rm DM}a^3) =$$
$$-\langle\sigma v\rangle_{2_{\rm DM}\to 2_{\rm dec}}\left[n_{\rm DM}^2 - (n_{\rm DM}^2)_{\rm eq}^2\right]$$
$$-2\langle\sigma v^2\rangle_{3_{\rm DM}\to 1_{\rm DM}1_{\rm dec}}\left[n_{\rm DM}^3 - \left(\frac{n_{\rm DM}^2}{n_{\rm dec}}\right)_{\rm eq} n_{\rm DM}n_{\rm dec}\right]$$
$$-2\langle\sigma v^2\rangle_{2_{\rm DM}1_{\rm dec}\to 2_{\rm dec}}\left[n_{\rm DM}^2 n_{\rm dec} - \left(\frac{n_{\rm DM}^2}{n_{\rm dec}}\right)_{\rm eq} n_{\rm dec}^2\right]$$
$$+2\langle\sigma v^2\rangle_{3_{\rm dec}\to 2_{\rm DM}}\left[n_{\rm dec}^3 - \left(\frac{n_{\rm dec}^3}{n_{\rm DM}^2}\right)_{\rm eq} n_{\rm DM}^2\right]$$

$$\frac{1}{a^3}\frac{d}{dt}(n_{\rm dec}a^3) =$$
$$+\langle\sigma v\rangle_{2_{\rm DM}\to 2_{\rm dec}}\left[n_{\rm DM}^2 - (n_{\rm DM}^2)_{\rm eq}\right]$$
$$-\langle\sigma v^2\rangle_{3_{\rm dec}\to 2_{\rm dec}}\left[n_{\rm dec}^3 - (n_{\rm dec})_{\rm eq} n_{\rm dec}^2\right]$$
$$-3\langle\sigma v^2\rangle_{3_{\rm dec}\to 2_{\rm DM}}\left[n_{\rm dec}^3 - \left(\frac{n_{\rm dec}^3}{n_{\rm DM}^2}\right)_{\rm eq} n_{\rm DM}^2\right]$$
$$-\langle\sigma v^2\rangle_{1_{\rm DM}2_{\rm dec}\to 1_{\rm DM}1_{\rm dec}}\left[n_{\rm dec}^2 n_{\rm DM} - (n_{\rm dec})_{\rm eq} n_{\rm dec}n_{\rm DM}\right]$$
$$+\langle\sigma v^2\rangle_{2_{\rm DM}1_{\rm dec}\to 2_{\rm dec}}\left[n_{\rm dec}n_{\rm DM}^2 - \left(\frac{n_{\rm DM}}{n_{\rm dec}}\right)_{\rm eq} n_{\rm dec}^2\right]$$
$$-\langle\sigma v^2\rangle_{2_{\rm DM}1_{\rm dec}\to 2_{\rm DM}}\left[n_{\rm DM}^2 n_{\rm dec} - (n_{\rm dec})_{\rm eq} n_{\rm DM}^2\right]$$
$$+\langle\sigma v^2\rangle_{3_{\rm DM}\to 1_{\rm DM}1_{\rm dec}}\left[n_{\rm DM}^3 - \left(\frac{n_{\rm DM}^2}{n_{\rm dec}}\right)_{\rm eq} n_{\rm DM}n_{\rm dec}\right] - \Gamma(\pi_{\rm dec})n_{\rm dec}$$

Boltzmann Equations

$$
\begin{aligned}
\frac{1}{a^3}\frac{d}{dt}(n_{\mathrm{DM}}a^3) = &- \langle\sigma v\rangle_{2_{\mathrm{DM}}\to 2_{\mathrm{dec}}}\left[n_{\mathrm{DM}}^2 - (n_{\mathrm{DM}}^2)_{\mathrm{eq}}^2\right] \\
&- 2\langle\sigma v^2\rangle_{3_{\mathrm{DM}}\to 1_{\mathrm{DM}}1_{\mathrm{dec}}}\left[n_{\mathrm{DM}}^3 - \left(\frac{n_{\mathrm{DM}}^2}{n_{\mathrm{dec}}}\right)_{\mathrm{eq}} n_{\mathrm{DM}}n_{\mathrm{dec}}\right] \\
&- 2\langle\sigma v^2\rangle_{2_{\mathrm{DM}}1_{\mathrm{dec}}\to 2_{\mathrm{dec}}}\left[n_{\mathrm{DM}}^2 n_{\mathrm{dec}} - \left(\frac{n_{\mathrm{DM}}^2}{n_{\mathrm{dec}}}\right)_{\mathrm{eq}} n_{\mathrm{dec}}^2\right] \\
&+ 2\langle\sigma v^2\rangle_{3_{\mathrm{dec}}\to 2_{\mathrm{DM}}}\left[n_{\mathrm{dec}}^3 - \left(\frac{n_{\mathrm{dec}}^3}{n_{\mathrm{DM}}^2}\right)_{\mathrm{eq}} n_{\mathrm{DM}}^2\right]
\end{aligned}
$$

$$
\begin{aligned}
\frac{1}{a^3}\frac{d}{dt}(n_{\mathrm{dec}}a^3) = &+ \langle\sigma v\rangle_{2_{\mathrm{DM}}\to 2_{\mathrm{dec}}}\left[n_{\mathrm{DM}}^2 - (n_{\mathrm{DM}}^2)_{\mathrm{eq}}\right] \\
&- \langle\sigma v^2\rangle_{3_{\mathrm{dec}}\to 2_{\mathrm{dec}}}\left[n_{\mathrm{dec}}^3 - (n_{\mathrm{dec}})_{\mathrm{eq}} n_{\mathrm{dec}}^2\right] \\
&- 3\langle\sigma v^2\rangle_{3_{\mathrm{dec}}\to 2_{\mathrm{DM}}}\left[n_{\mathrm{dec}}^3 - \left(\frac{n_{\mathrm{dec}}^3}{n_{\mathrm{DM}}^2}\right)_{\mathrm{eq}} n_{\mathrm{DM}}^2\right] \\
&- \langle\sigma v^2\rangle_{1_{\mathrm{DM}}2_{\mathrm{dec}}\to 1_{\mathrm{DM}}1_{\mathrm{dec}}}\left[n_{\mathrm{dec}}^2 n_{\mathrm{DM}} - (n_{\mathrm{dec}})_{\mathrm{eq}} n_{\mathrm{dec}} n_{\mathrm{DM}}\right] \\
&+ \langle\sigma v^2\rangle_{2_{\mathrm{DM}}1_{\mathrm{dec}}\to 2_{\mathrm{dec}}}\left[n_{\mathrm{dec}} n_{\mathrm{DM}}^2 - \left(\frac{n_{\mathrm{DM}}}{n_{\mathrm{dec}}}\right)_{\mathrm{eq}} n_{\mathrm{dec}}^2\right] \\
&- \langle\sigma v^2\rangle_{2_{\mathrm{DM}}1_{\mathrm{dec}}\to 2_{\mathrm{DM}}}\left[n_{\mathrm{DM}}^2 n_{\mathrm{dec}} - (n_{\mathrm{dec}})_{\mathrm{eq}} n_{\mathrm{DM}}^2\right] \\
&+ \langle\sigma v^2\rangle_{3_{\mathrm{DM}}\to 1_{\mathrm{DM}}1_{\mathrm{dec}}}\left[n_{\mathrm{DM}}^3 - \left(\frac{n_{\mathrm{DM}}^2}{n_{\mathrm{dec}}}\right)_{\mathrm{eq}} n_{\mathrm{DM}} n_{\mathrm{dec}}\right] - \Gamma(\pi_{\mathrm{dec}})n_{\mathrm{dec}}
\end{aligned}
$$

Boltzman equations

Assumptions:

1. kinetic equilibrium: $f_D^4/m_{\pi_D}^3 < 10^{16}\ \mathrm{GeV}$

2. thermal equilibrium: $C_q \equiv \frac{(\kappa^\star_{\alpha q}\kappa^\star_{\beta q}c_{\alpha\beta})\mathrm{Max}(f_D, m_{\pi_D})^2}{m_\chi^2} > 10^{-5}$

3. decaying dark pions decay instantly

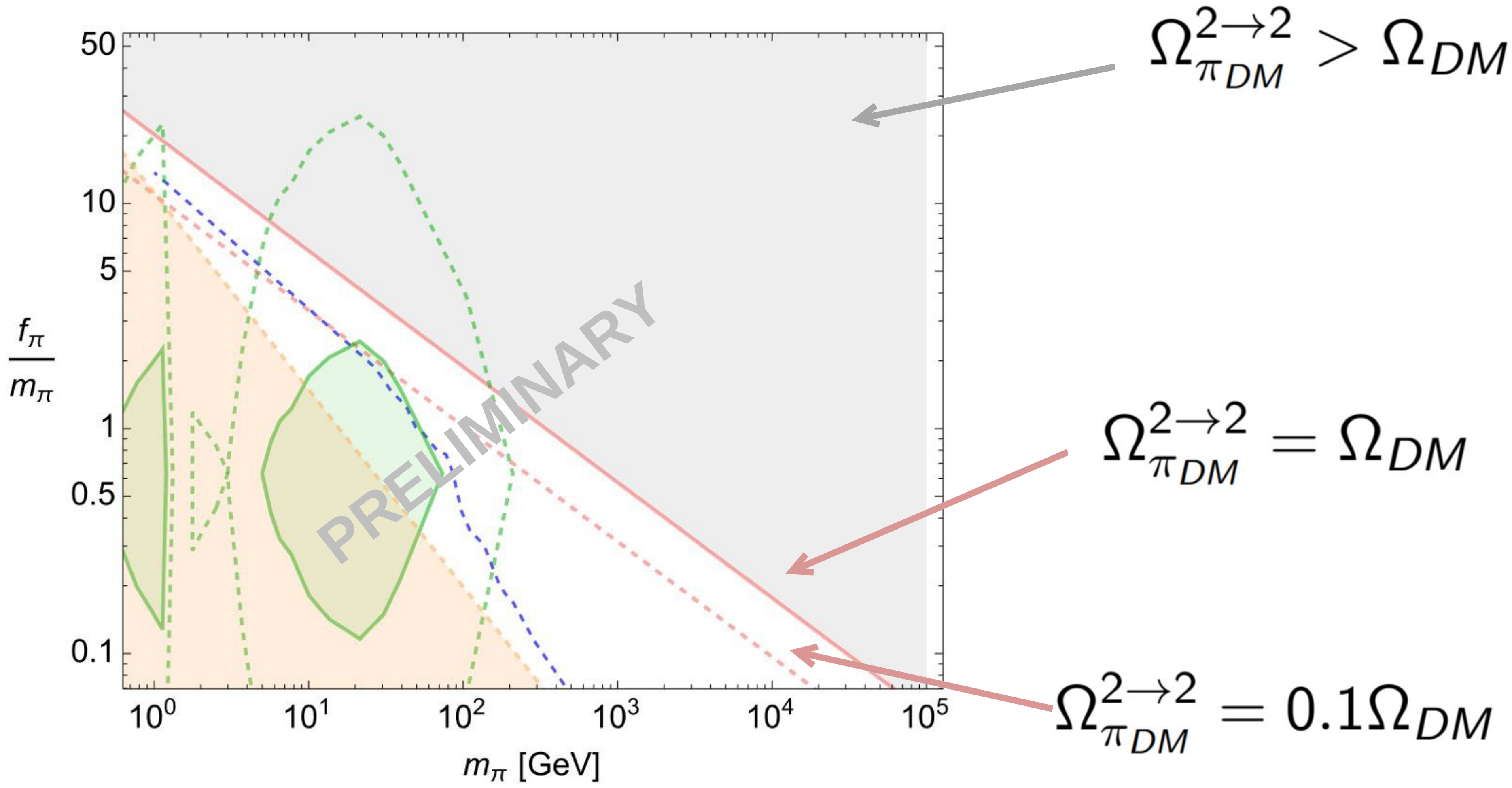
Boltzman equations

$$\frac{1}{a^3}\frac{d}{dt}(n_{\rm DM}a^3) = -\langle\sigma v\rangle_{2_{\rm DM}\to 2_{\rm dec}}\left[n_{\rm DM}^2 - (n_{\rm DM}^2)_{\rm eq}^2\right] + 2\langle\sigma v^2\rangle_{3_{\rm dec}\to 2_{\rm DM}}\left[n_{\rm dec}^3 - \left(\frac{n_{\rm dec}^3}{n_{\rm DM}^2}\right)_{\rm eq} n_{\rm DM}^2\right]$$

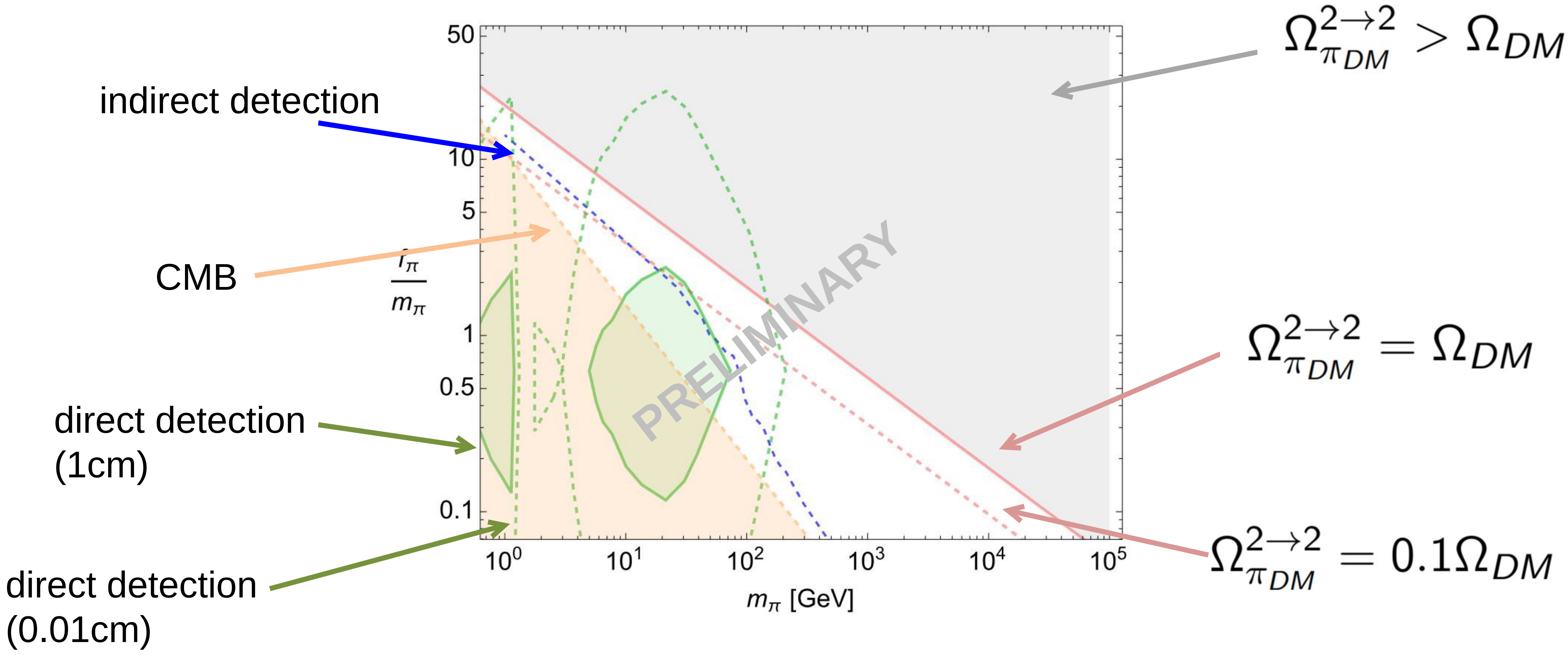
$$\frac{1}{a^3}\frac{d}{dt}(n_{\rm dec}a^3) = \langle\sigma v\rangle_{2_{\rm DM}\to 2_{\rm dec}}\left[n_{\rm DM}^2 - (n_{\rm DM}^2)_{\rm eq}\right] - 3\langle\sigma v^2\rangle_{3_{\rm dec}\to 2_{\rm DM}}\left[n_{\rm dec}^3 - \left(\frac{n_{\rm dec}^3}{n_{\rm DM}^2}\right)_{\rm eq} n_{\rm DM}^2\right] - \Gamma(\pi_{\rm dec})n_{\rm dec}$$

see also Kopp et al ‘16

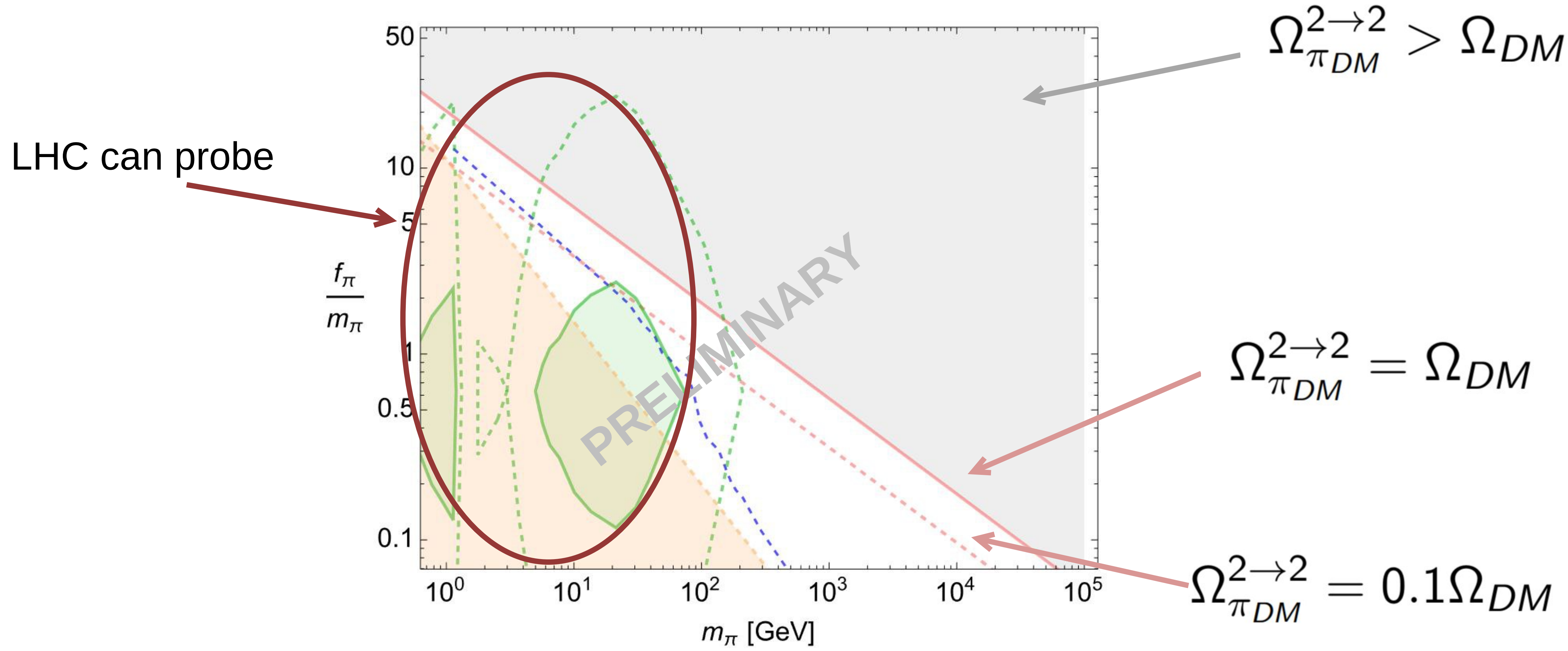
Dark Matter parameter space



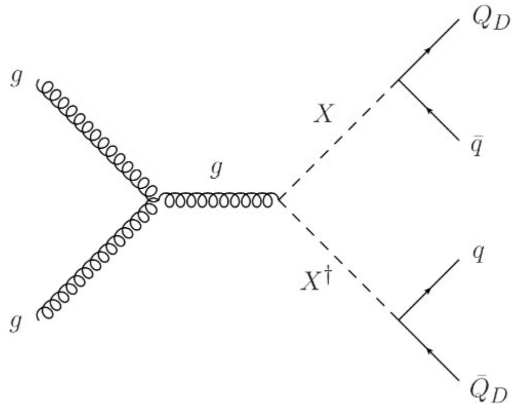
Dark Matter parameter space

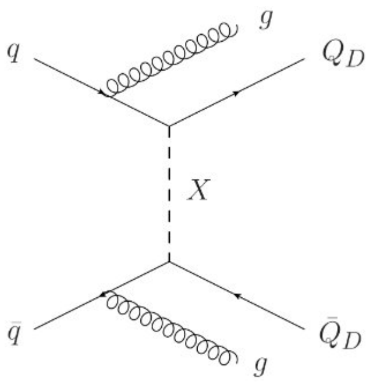


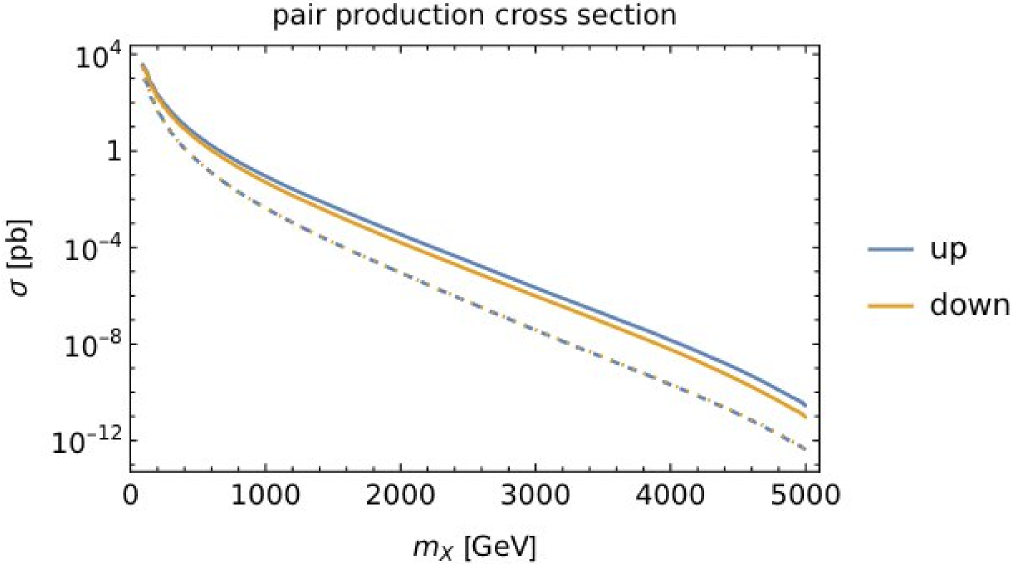
Dark Matter parameter space

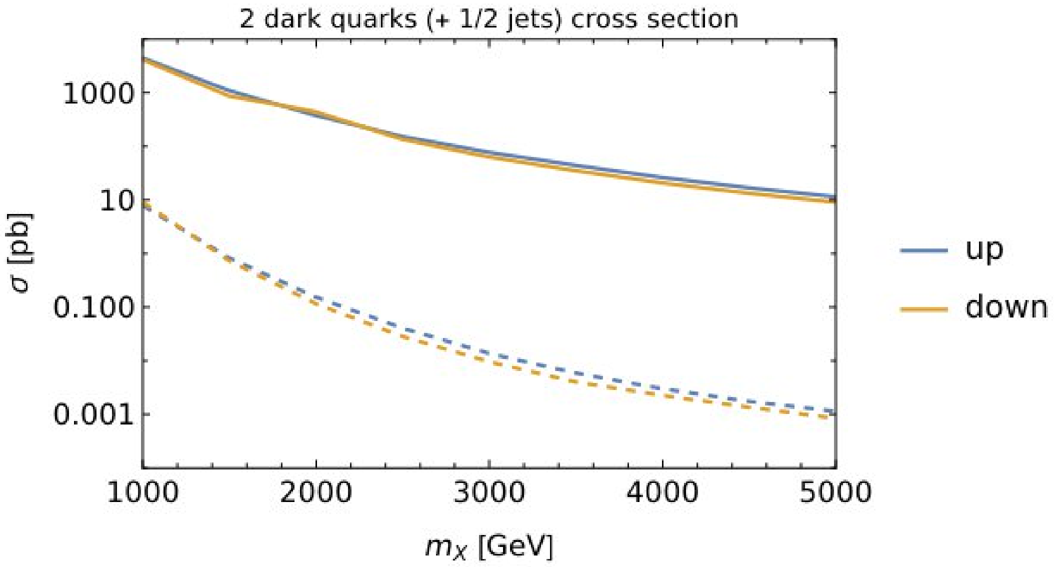


Dark pion production at LHC



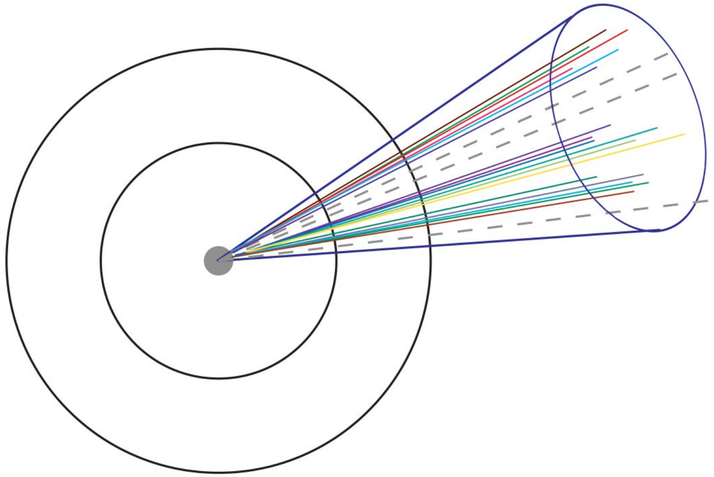






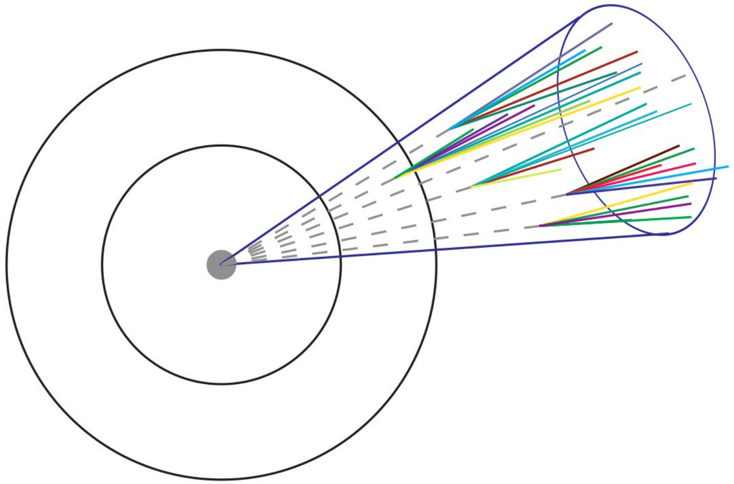
Signatures

1. decaying dark pions decay **promptly** $\longrightarrow$ four jets/semi-visible jets



Signatures

1. decaying dark pions decay **promptly** $\longrightarrow$ four jets/semi-visible jets
2. decaying dark pions **long-lived** $\longrightarrow$ emerging jets/jets plus MET



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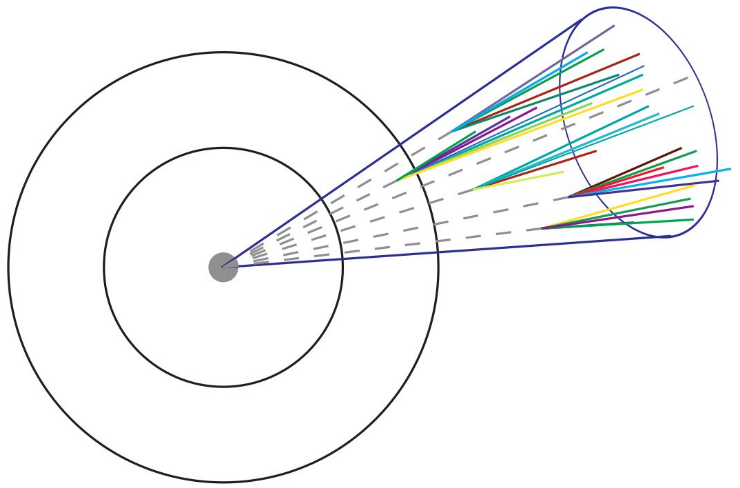
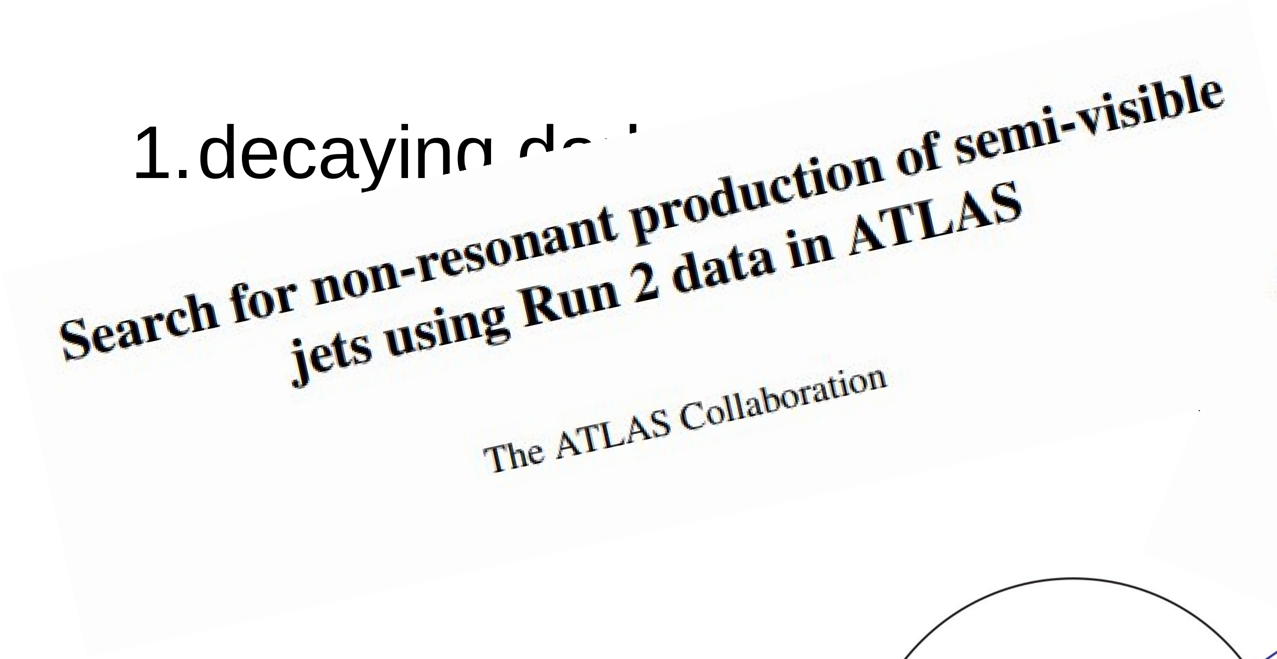


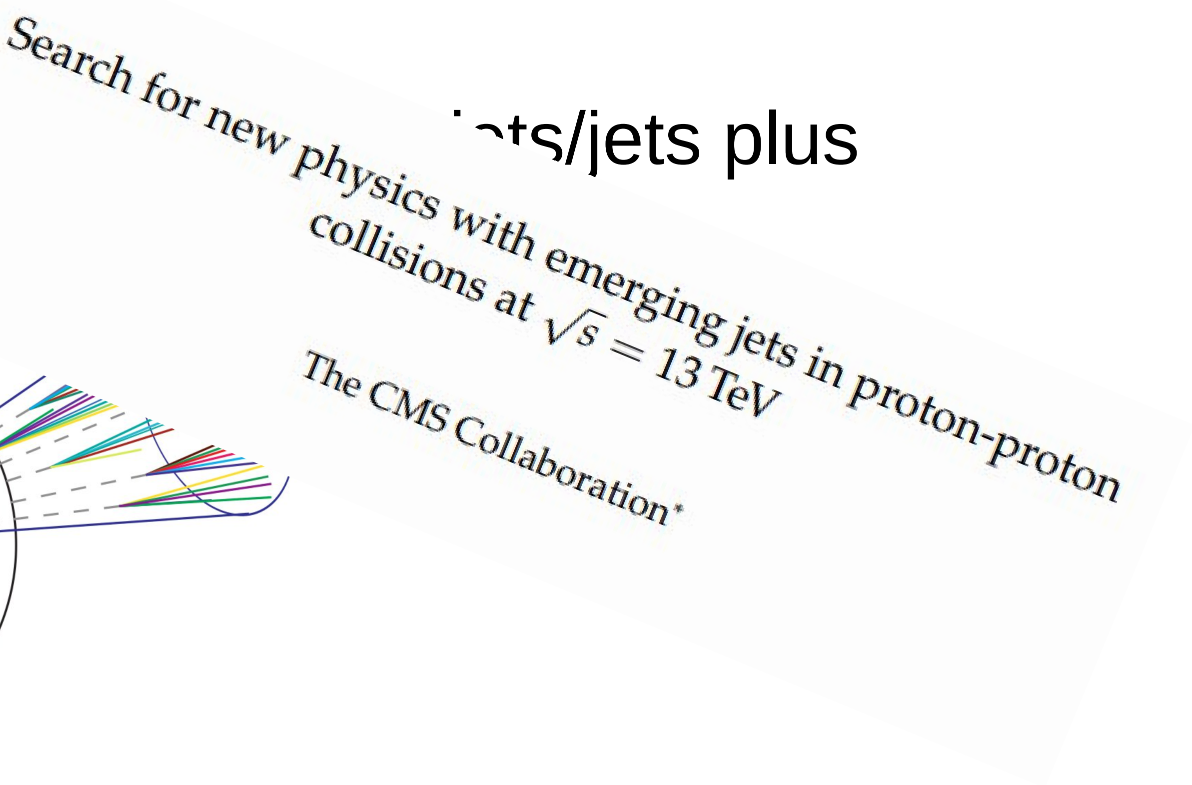
Signatures

1. decaying da... **...ptly** ⟶ four jets/semi-visible

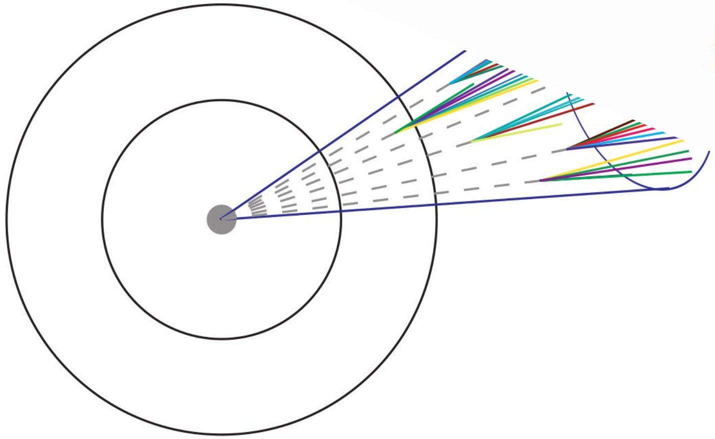
...jets/jets plus


Search for non-resonant production of semi-visible jets using Run 2 data in ATLAS

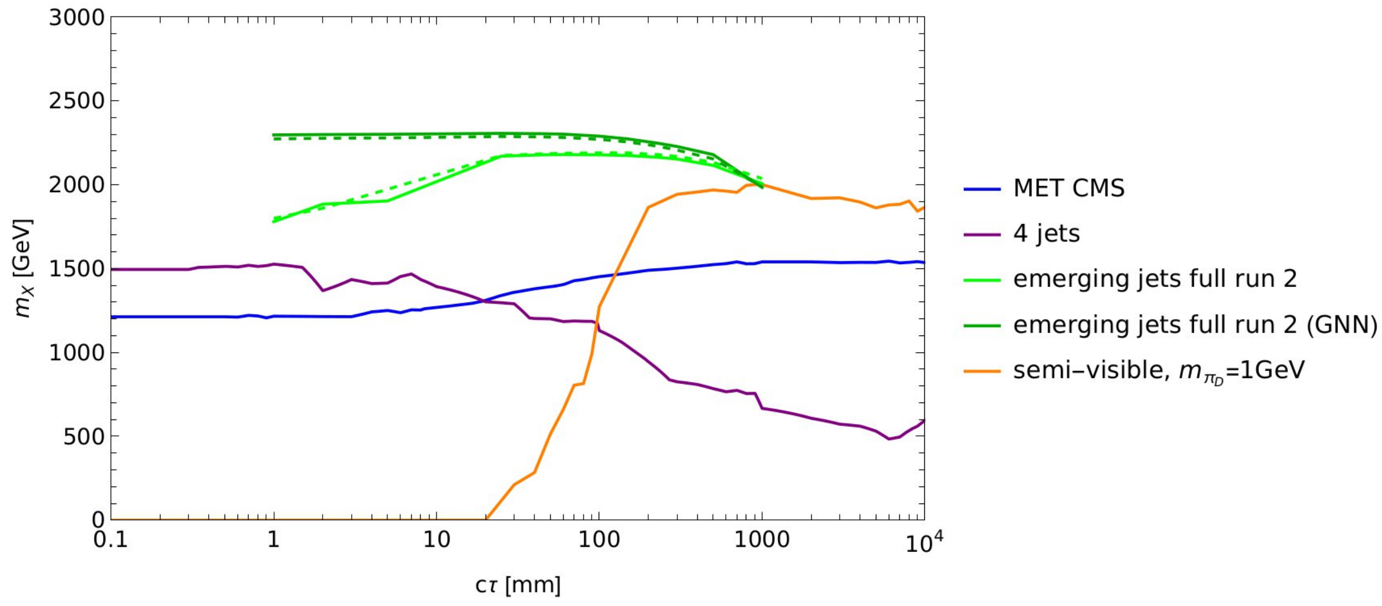
The ATLAS Collaboration


Search for new physics with emerging jets in proton-proton collisions at $\sqrt{s} = 13$ TeV

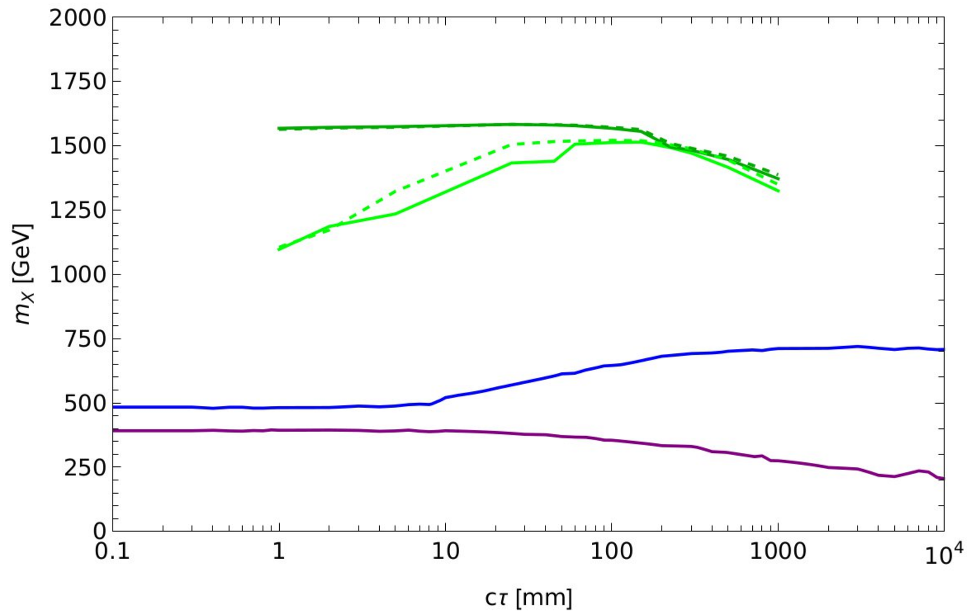
The CMS Collaboration*



Couplings to up-type quarks

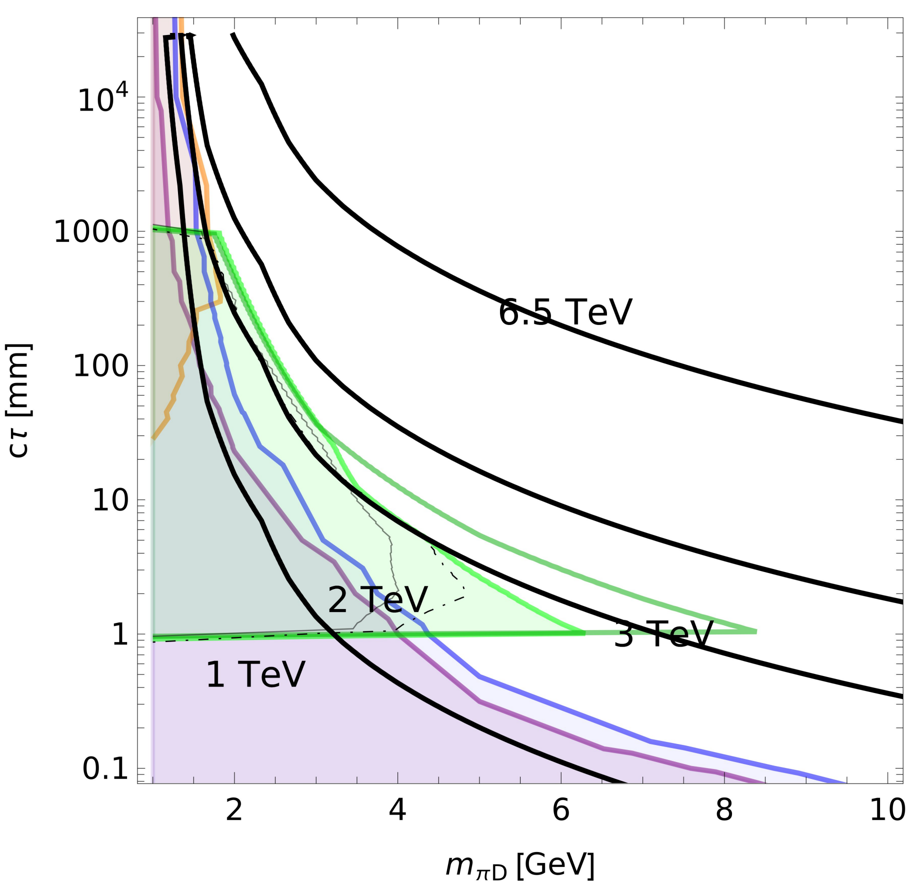


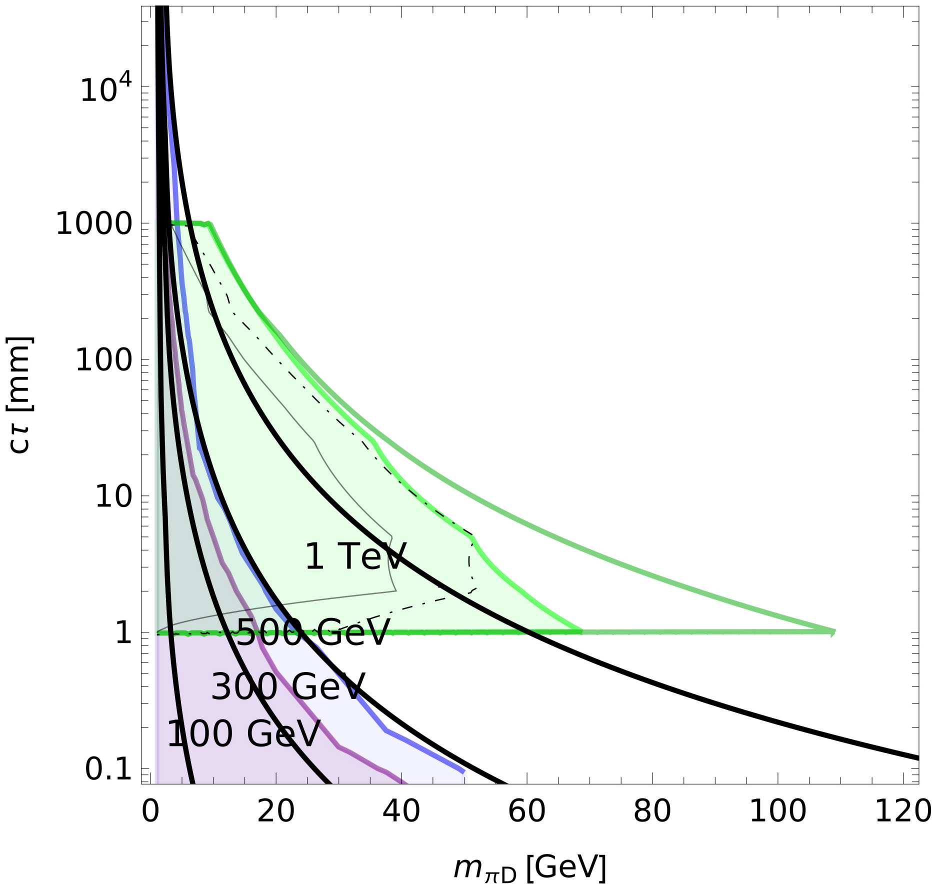
$\kappa = 1$



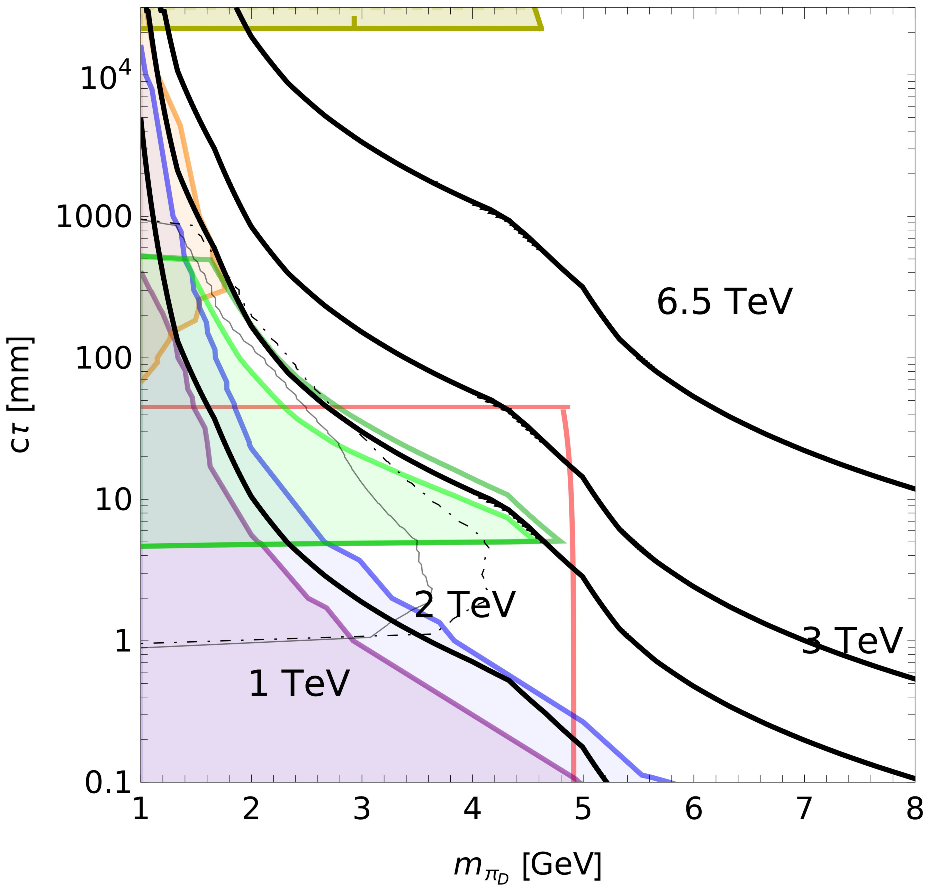
$\kappa = 0.1$

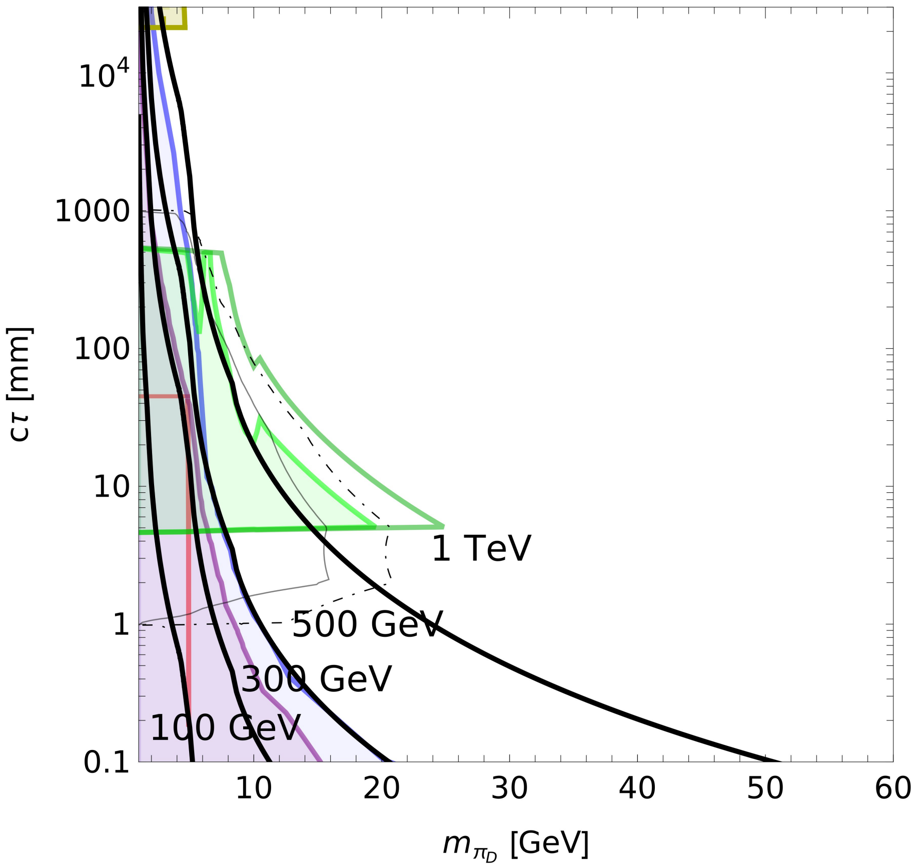
Coupling to up-type quarks



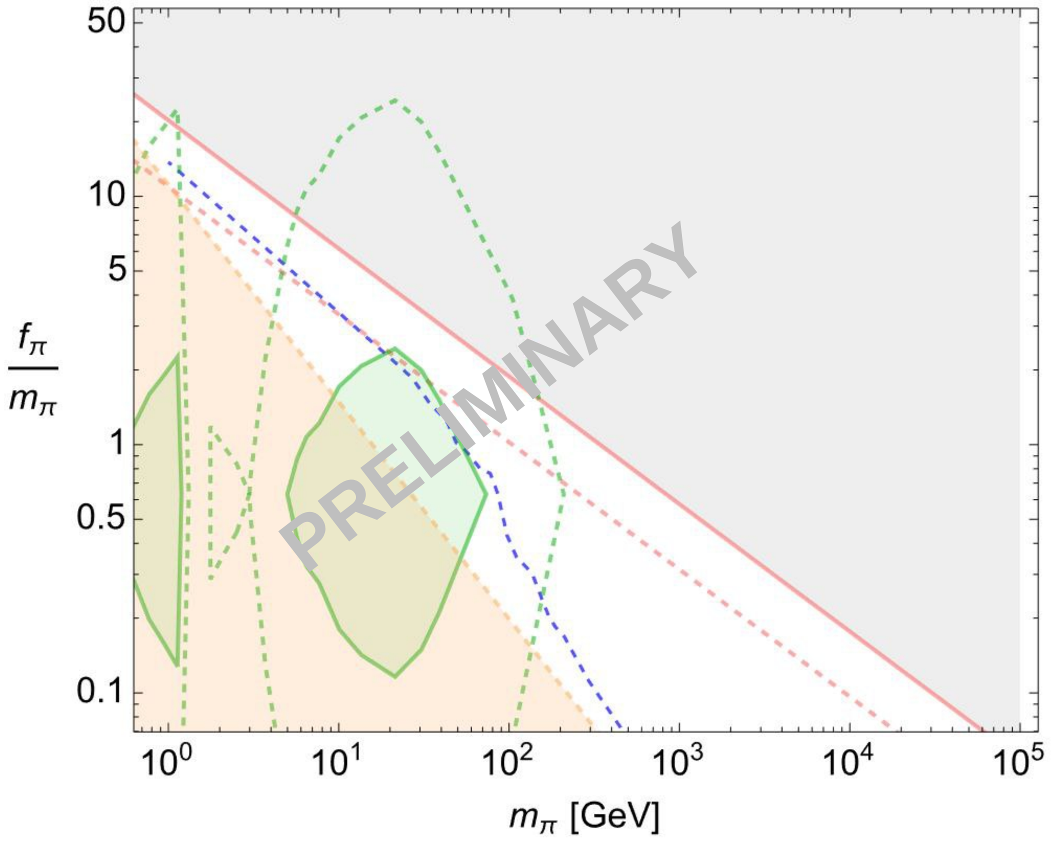


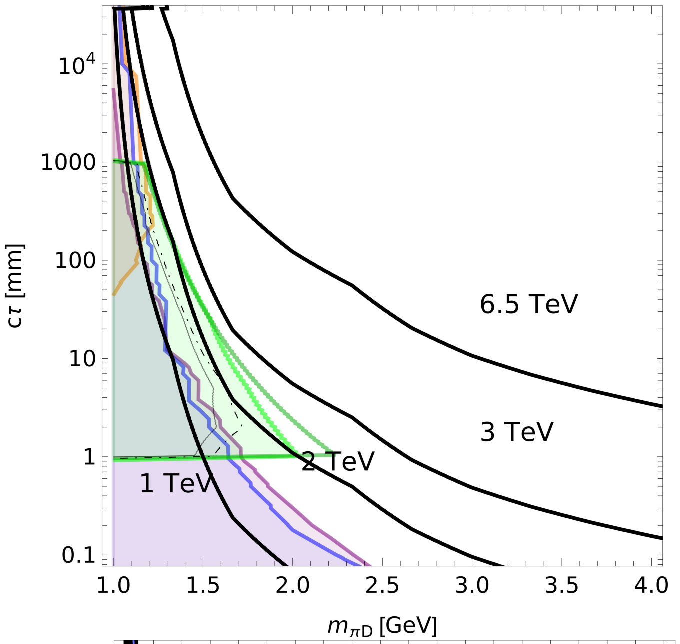
Couplings to down-type quarks

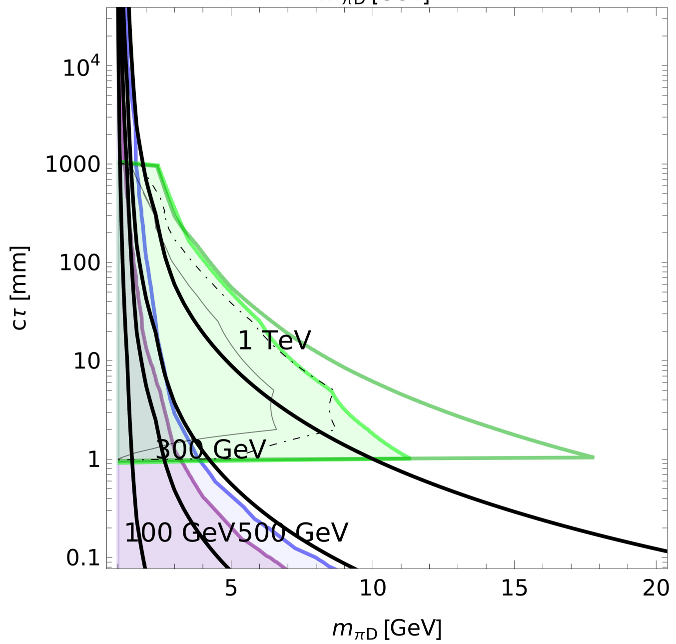




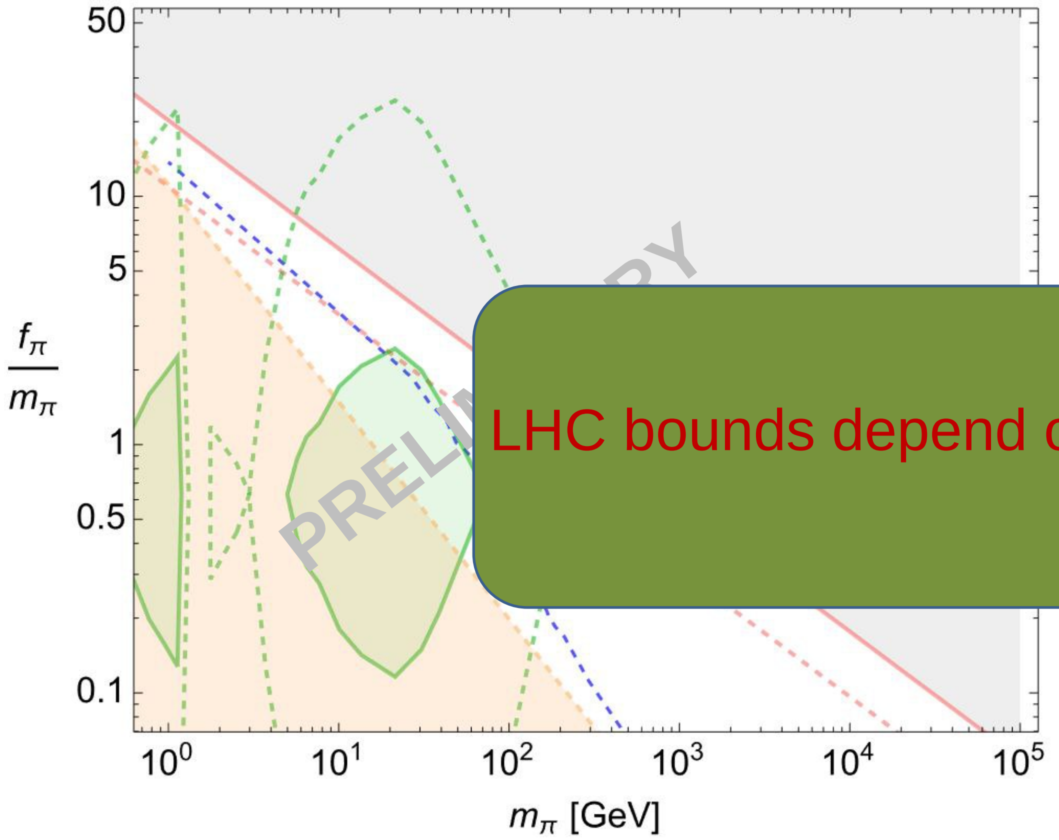
Parameter space

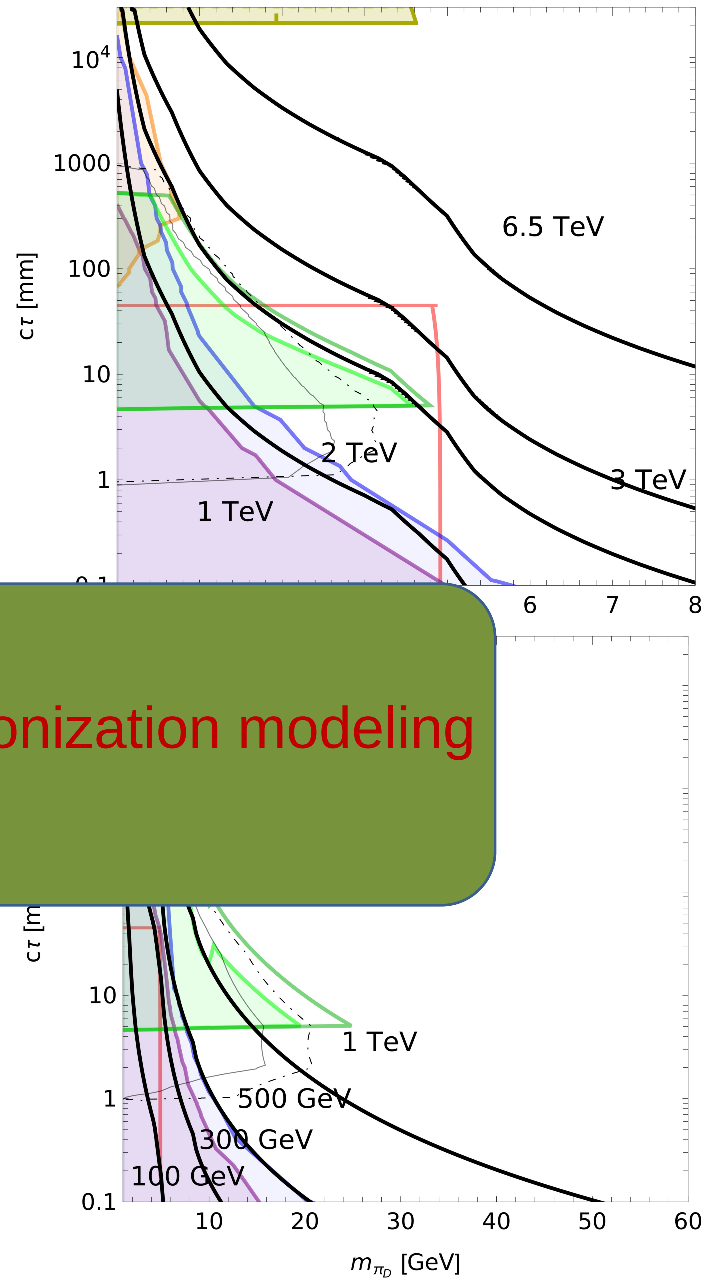






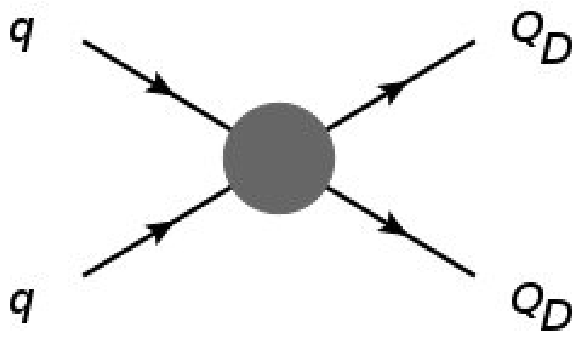
Parameter space





LHC bounds depend on dark hadronization modeling

Dark jets



→

dark sector shower

↓

dark sector hadronization

↓

dark hadron decay

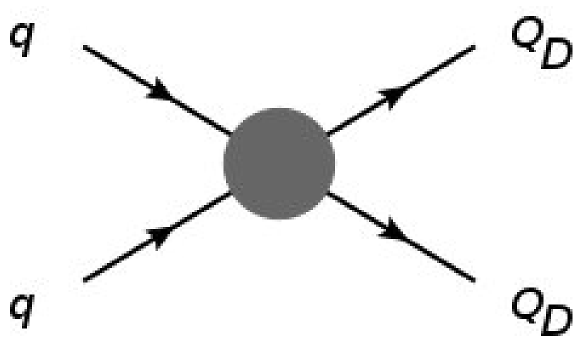
↓

SM shower

↓

SM hadronization

Dark jets



dark sector shower

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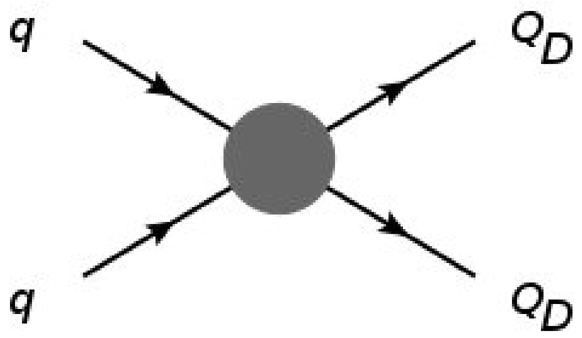
Dark jets



dark sector shower

↓

dark sector hadronization

↓

dark hadron decay

↓

SM shower

↓

SM hadronization

Lund String Fragmentation

In particle physics, the **Lund string model** is a phenomenological model of hadronization. It treats all but the highest-energy gluons as field lines, which are attracted to each other due to the gluon self-interaction and so form a narrow tube (or string) of strong color field. Compared to electric or magnetic field lines, which are spread out because the carrier of the electromagnetic force, the photon, does not interact with itself.

String fragmentation is one of the parton fragmentation models used in the PYTHIA/Jetset and UCLA event generators, and explains many features of hadronization quite well. In particular, the model predicts that in addition to the particle jets formed along the original paths of two separating quarks, there will be a spray of hadrons produced between the jets by the string itself—which is precisely what is observed.

This use of "string" is not the same as in string theory, in which strings are the fundamental objects of nature rather than collections of field lines.

Lund String Fragmentation

- when quarks separate force between them increases forming string-like potential
- for large enough potential energy string breaks

$\longrightarrow$ creates new quark-antiquark pair

$\longrightarrow$ continues until only hadrons remain

- fragmentation function gives probability of hadron with momentum z being created

$$f(z) = \frac{1}{z^{1+r_{Q_D} b_{m^2_{Q_D}}}} (1-z)^{a_L} \exp\left(\frac{-b^2_{m^2_{Q_D}}}{z}\right)$$

Thoughts on hadronization

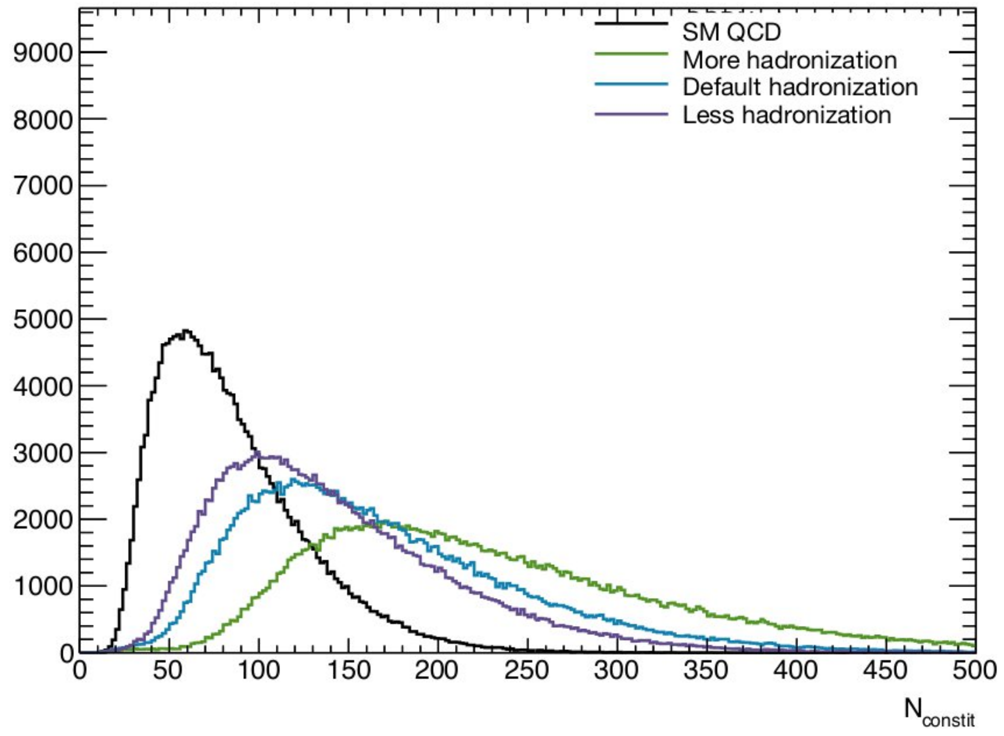
- number of constituents in jet is very susceptible to hadronization model

⟶ analyses with cuts on that hard to interpret

- QCD fewer constituents than dark jets

⟶ makes sense since they have secondary shower and hadronization

⟶ even that is model dependent!



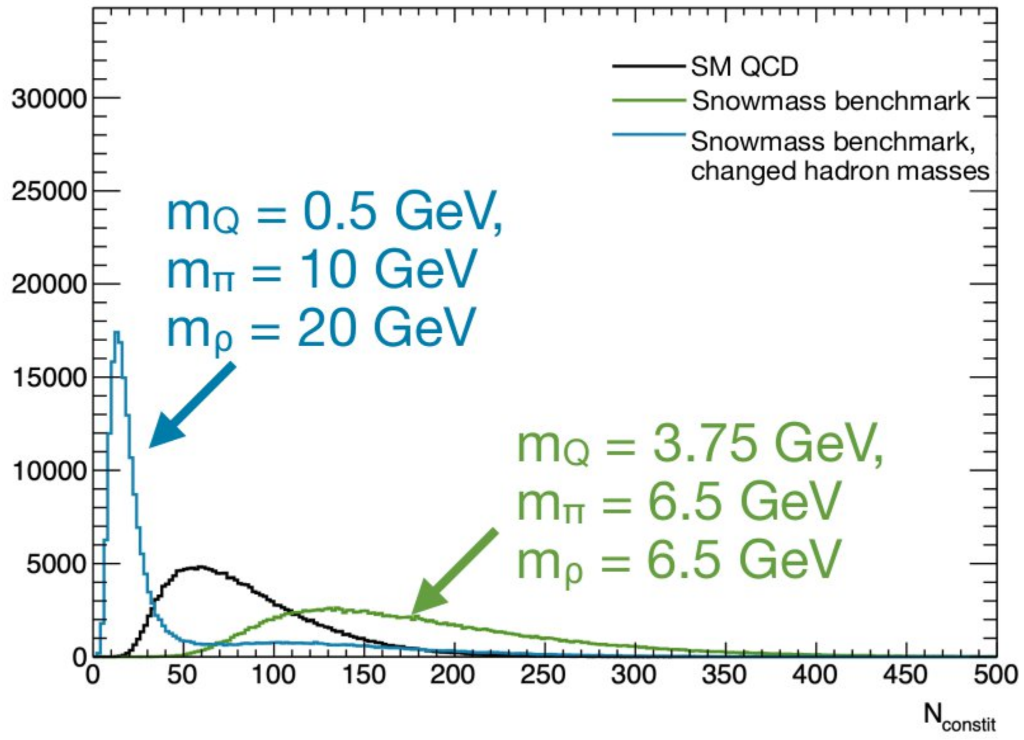
Thoughts on hadronization

depending on parameters to scan over, the behavior can become very problematic

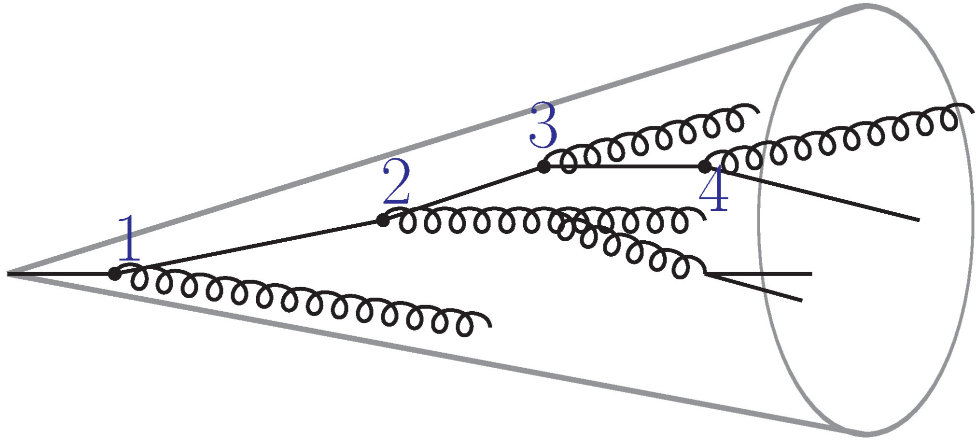
⟶ e.g. just changing the dark hadron masses can result in major changes to the jet substructure

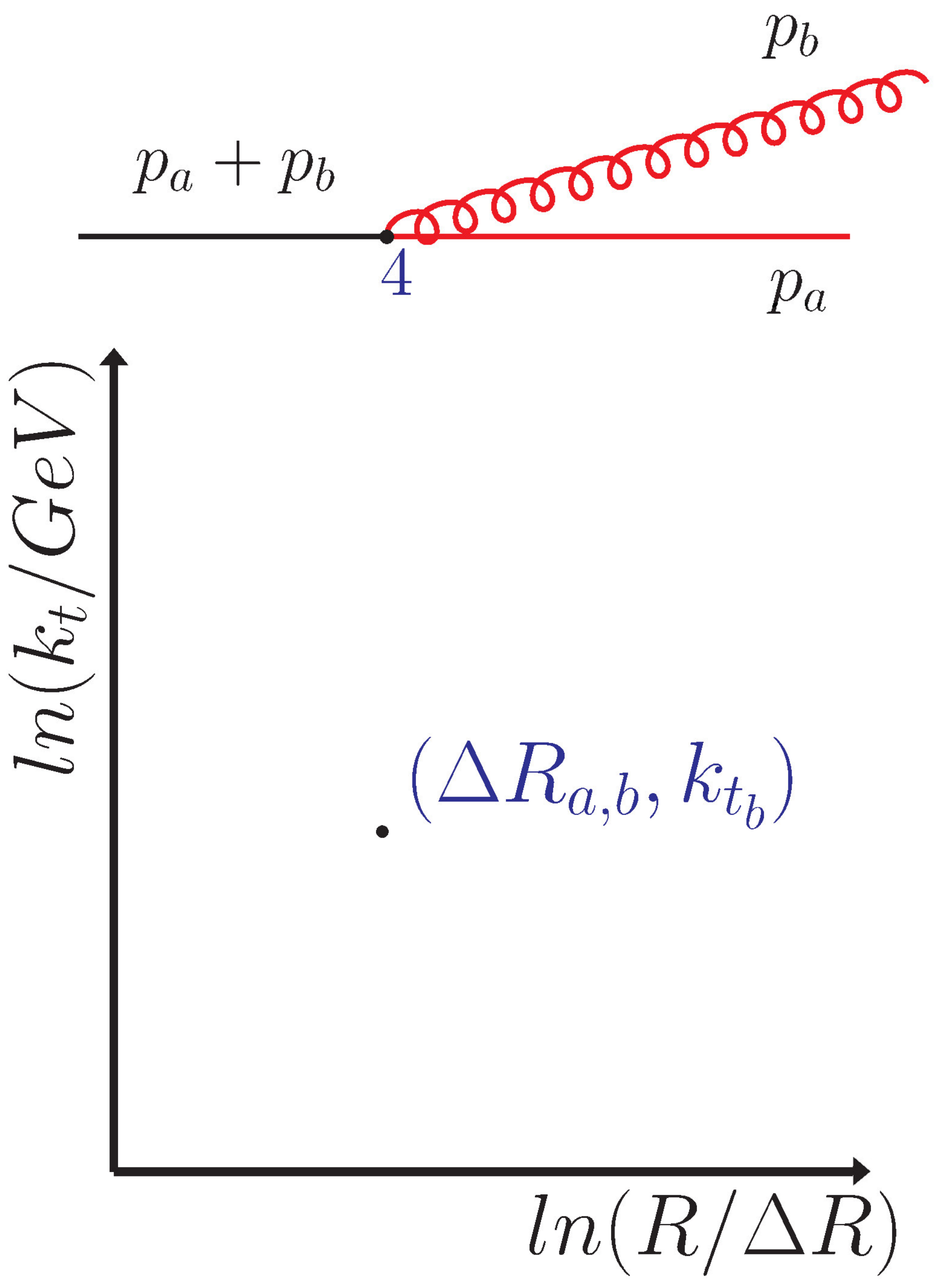
⟶ Lund Jet Plane separates different jet regions

(Dreyer, Salam, Soyez ‘18)

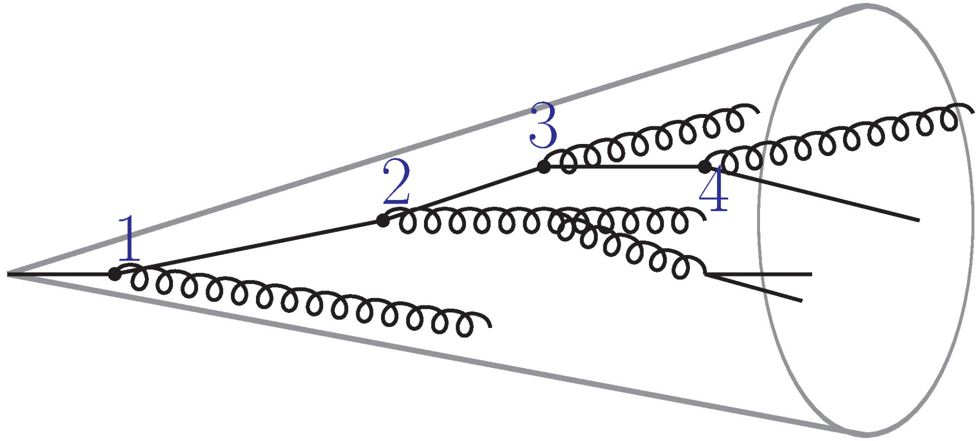


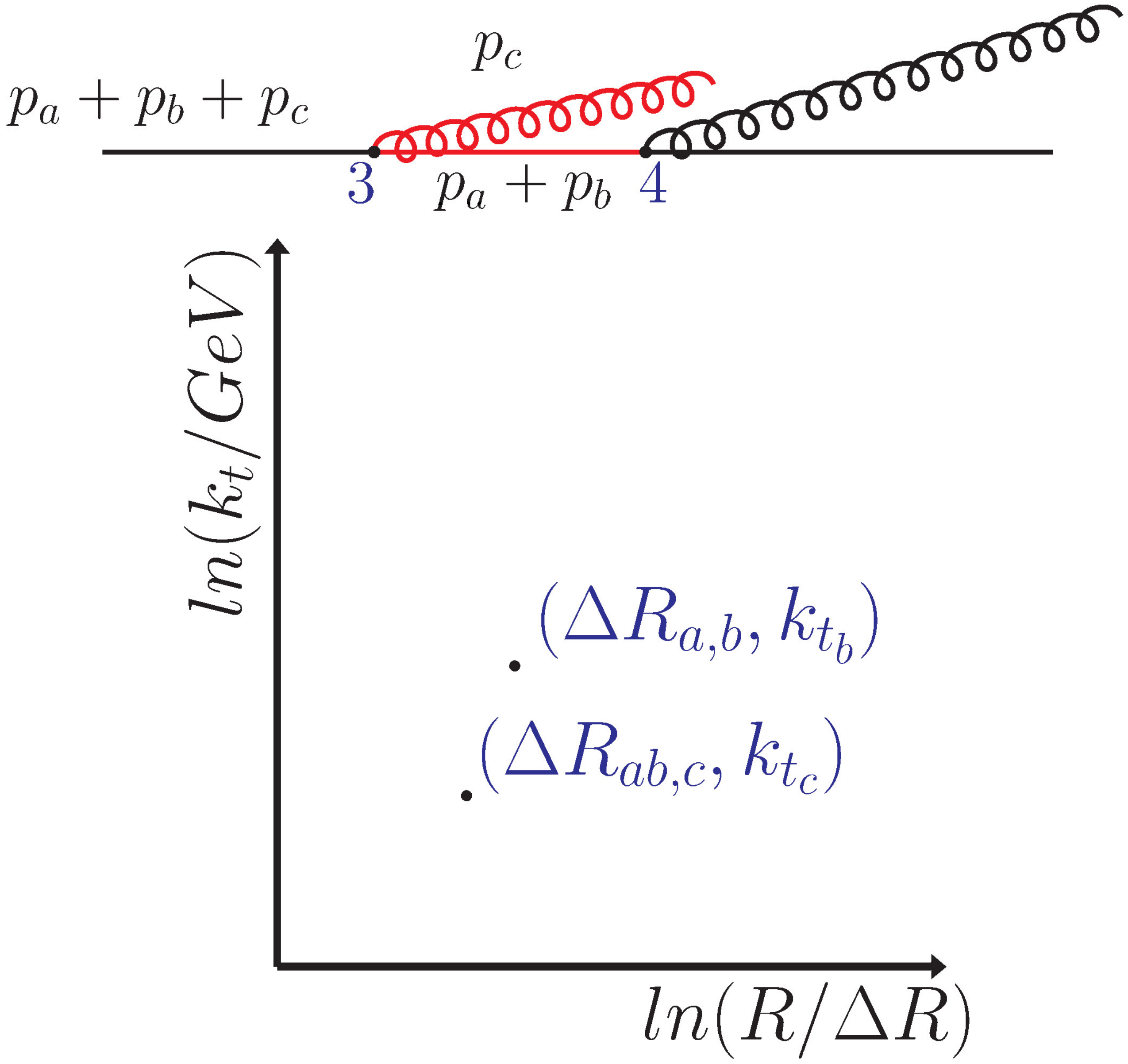
Lund Jet Plane



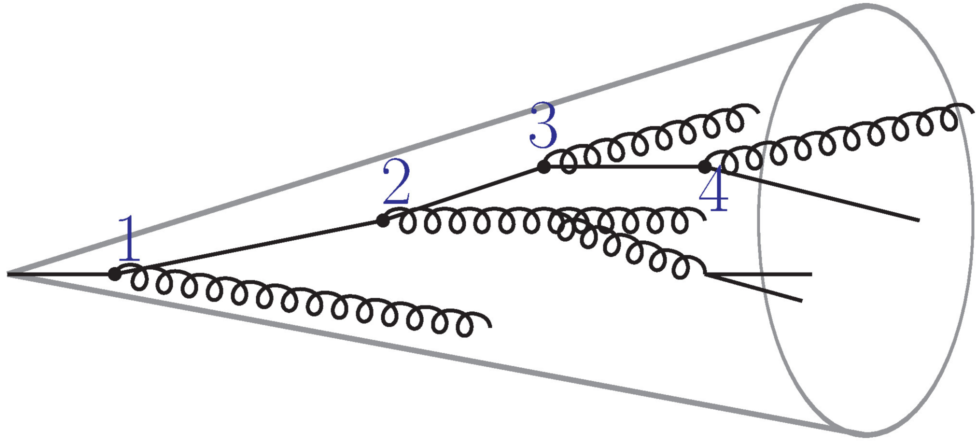


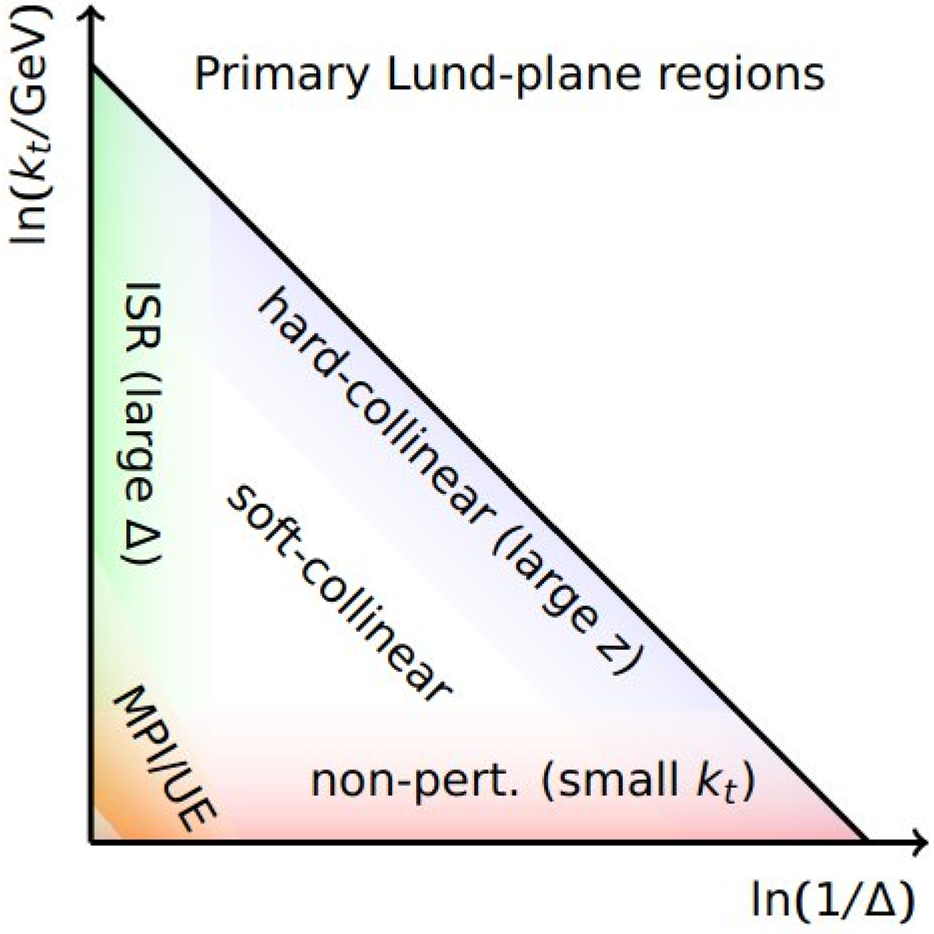
Lund Jet Plane





Lund Jet Plane





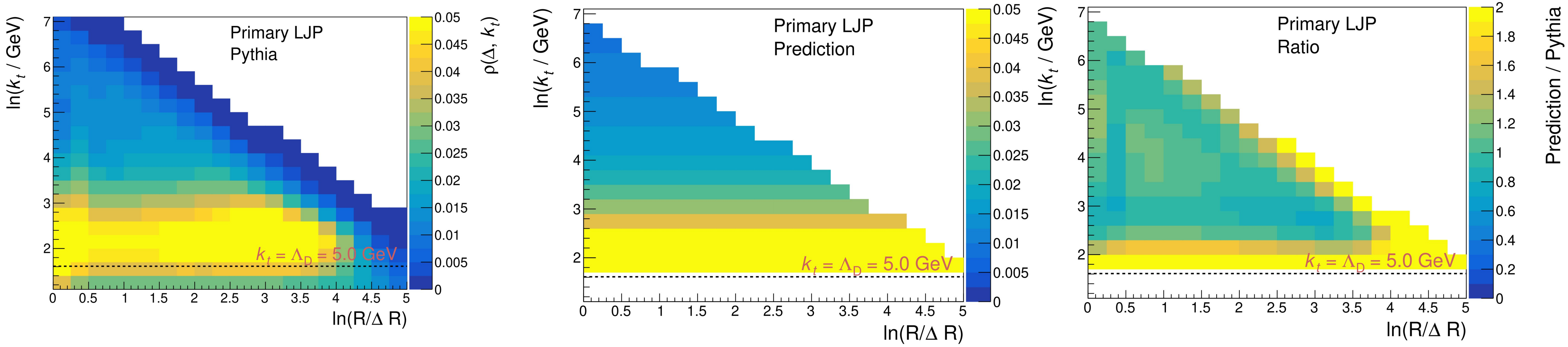
(1807.04758, 2007.06578)

Dark sector jets in the Lund Jet Plane

first check that MC predictions reproduce expected behavior

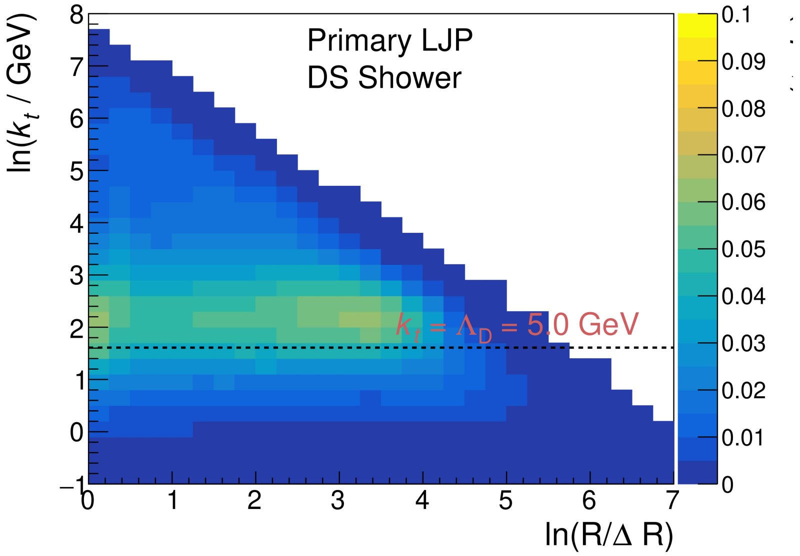
Expected density:

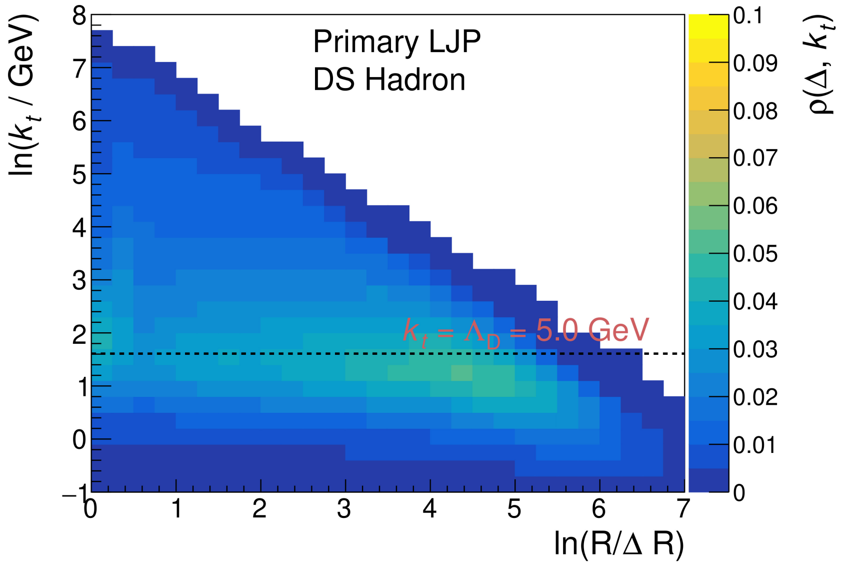
$$\frac{2\alpha_{\mathrm{D}}(k_t)C_F}{\pi}$$

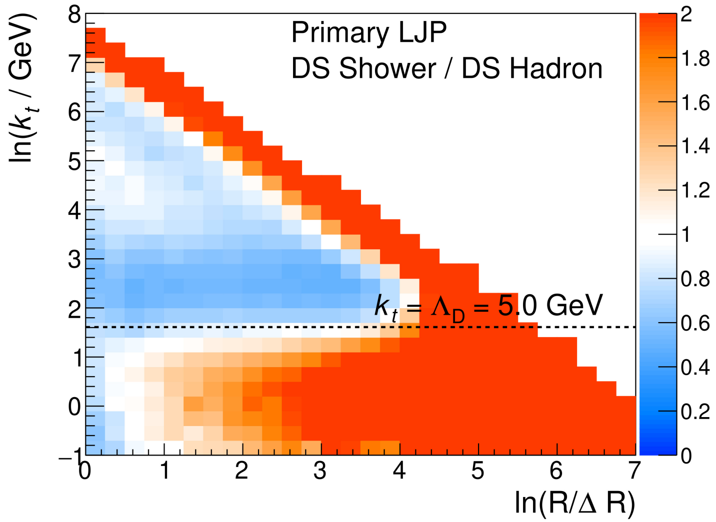


Dark sector jets in the Lund Jet Plane

look at Lund Jet Plane at various stages of event generation



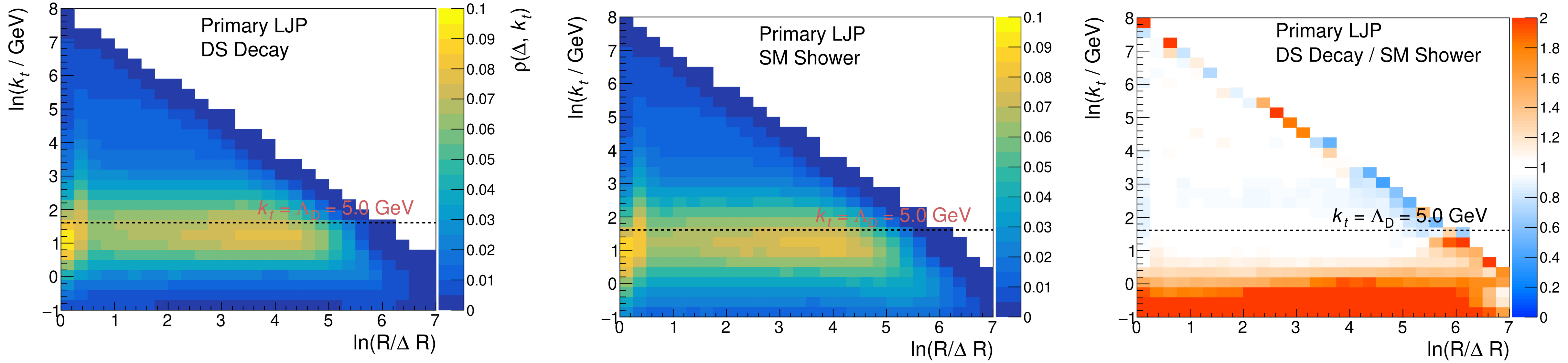




dark hadronization has largest impact on low-kt region

Dark sector jets in the Lund Jet Plane

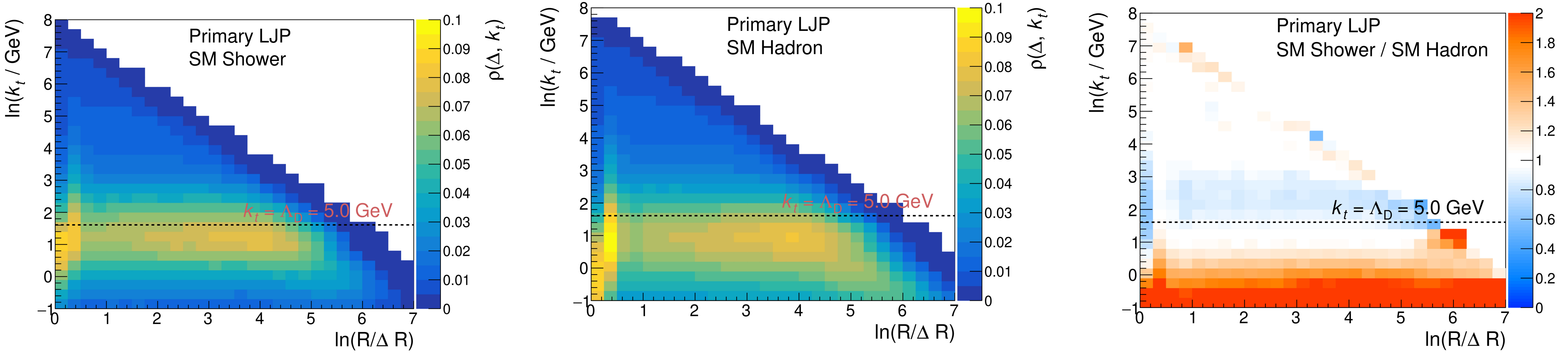
look at Lund Jet Plane at various stages of event generation



SM shower doesn’t have strong impact due to small dark hadron mass

Dark sector jets in the Lund Jet Plane

look at Lund Jet Plane at various stages of event generation

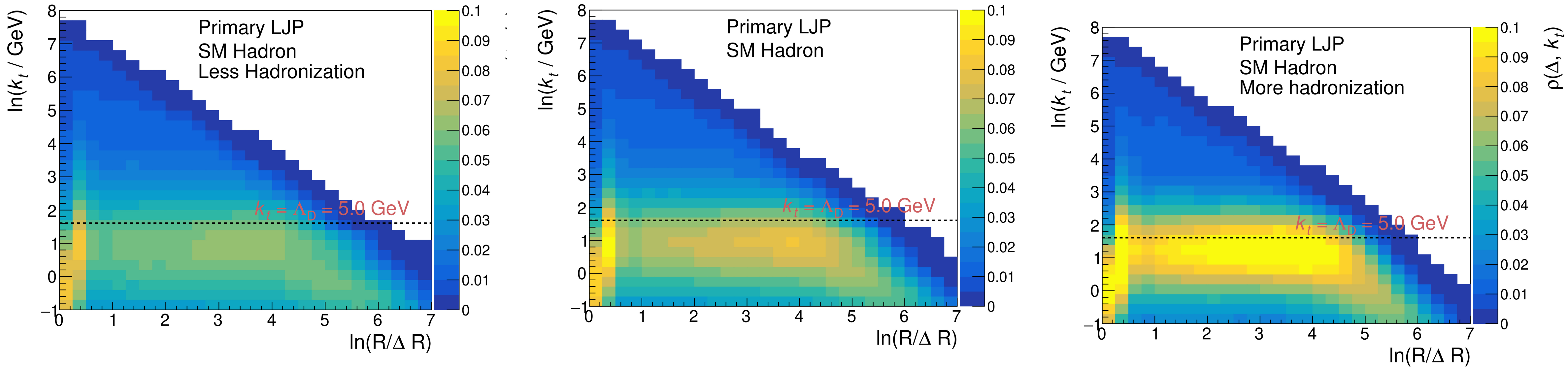


SM hadronization shows small changes in low-kt region

Using Lund Jet Plane for searches

different hadronization parameter choices give very different Lund Jet Planes

⟶ can translate into large differences in variables, e.g. number of tracks



Impact of Hadronization

define new observable:

 # emissions above k_t cut

compare to

- jet energy sharing D_{p_t}
- # jet constituents $N_{constit}$
- jet mass

using

- background rejection $p = \frac{\epsilon_D}{\sqrt{\epsilon_{QCD}}}$
- resilience against hadronization

$$\zeta = \left(\frac{\Delta\epsilon_D}{\langle\epsilon_D\rangle}\right)^2$$

with

- $\Delta\epsilon = \epsilon - \epsilon'$,
- $\langle\epsilon\rangle = (\epsilon + \epsilon')/2$
- ϵ_D dark sector jet efficiency
- ϵ_{QCD} QCD jet efficiency
- ϵ efficiency for default hadronization
- ϵ' efficiency for larger hadronization

Impact of Hadronization

- define new observable:

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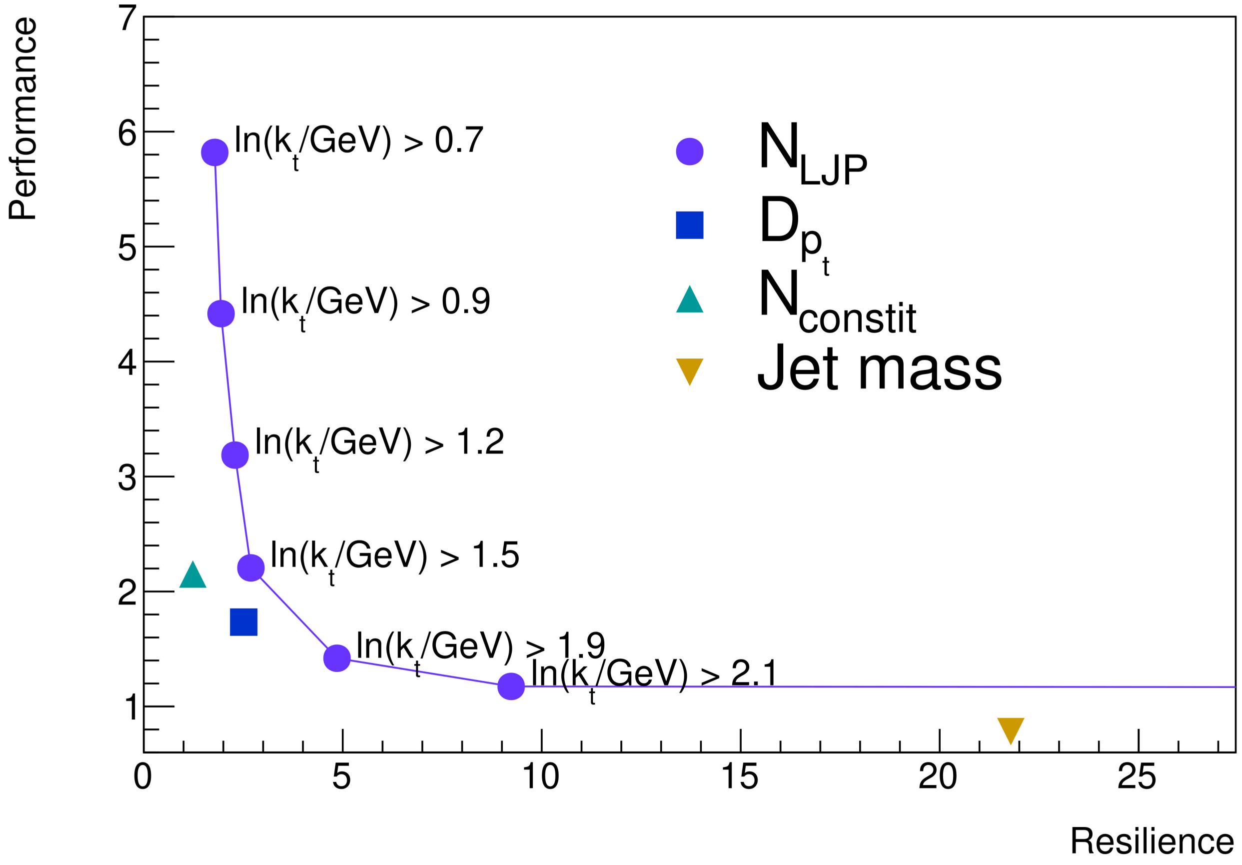

Summary & Outlook

- QCD-like dark sectors are an interesting dark matter scenario
- n_f > 3 allows dark pion dark matter

$\longrightarrow$ full Boltzmann equations need to be studied

- low mass dark matter region can be probed by LHC and flavor
- collider analysis can be dependent on hadronization model
- Lund Jet Plane can be used to construct hadronization independent variables

$\longrightarrow$ optimal transport might allow to decorrelate hadronization parameters

Back-up

Direct Detection

Scattering of dark pions on nuclei via

$$\mathcal{L}_{\rm dChPT}^{\rm portal} = i\frac{f_D^2}{4m_X^2}\kappa_{\alpha i}\kappa_{\beta j}^* {\rm Tr}(c_{\beta\alpha}U_D^\dagger\partial_\mu U_D)(\bar{\psi}_i\gamma^\mu\psi_j)$$

both $(\bar{q}\gamma^\mu q)$ and $(\bar{q}\gamma^\mu\gamma^5 q)$ interactions leading to

$$\frac{d\sigma_{DD}}{dE_R} \simeq \frac{m_A}{8\pi v^2 {\rm Max}(f_D, m_{\pi_D})^4}\left[f(C_{ud}) + 2|v_T^\perp|^2 f(C_{ud})\right]\left(J_n(A-Z)^2 + J_p Z^2\right)$$

$$f(C_{ud}) = (13|C_u|^2 + 7|C_d|^2 + 4|C_u C_d|)$$

Anand, Fitzpatrick, Haxton ‘13
Bishara, Brod, Grinstein, Zupan ‘17

Indirect detection

DM self-annihilation to SM particles
$\longrightarrow$ in our case cascade via decaying dark pions

gamma-ray flux:

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{dE}_\gamma} = \underbrace{\frac{1}{8\pi m_{\mathrm{DM}}^2} \sum_f \langle \sigma_{\mathrm{ann}} v \rangle_{DMDM \to ff} \frac{\mathrm{dN}_\gamma^f}{\mathrm{dE}_\gamma}}_{\text{DM model}} \times \underbrace{\int_{\Delta\Omega} \mathrm{d}\Omega' \int_{\mathrm{los}} \rho^2 \mathrm{d}l(r, \theta')}_{\text{Astrophysics part}}$$

LHC searches

four jets	two jets plus MET	semi-visible
$N_j \geq 4$ with $p_T > 80$ GeV, $\|\eta\| < 2.5$	$N_{jet} \geq 2$ with $p_T > 30$ GeV, $\|\eta\| < 2.4$	$N_{jet} \geq 2$ with $p_T > 30$ GeV, $\|\eta\| < 2.8$
$H_T < 1050$ GeV or ≥ 1 jet with $p_T > 550$ GeV	$H_T > 300$ GeV in $\|\eta\| < 2.4$ and $H_T^{miss} > H_T$	$H_T > 600$ GeV and leading jet $p_T > 250$ GeV
	$H_T^{miss} > 300$ GeV in $\|\eta\| < 5$	$H_T^{miss} > 600$ GeV
	no isolated leptons with $p_T > 10$ GeV	no leptons with $p_T > 7$ GeV
		≤ 1 b-jet
	$\Delta\phi(\vec{H}_T^{miss}, j_{1,2}) > 0.5$ and p_T jets $\Delta\phi(\vec{H}_T^{miss}, j_{>2}) > 0.3$	as least one jet with $\Delta\phi(\vec{H}_T^{miss}, j) = 2$
$\Delta R_{1,2} < 2$, $\Delta\eta < 1.1$ and asymmetry < 0.1		