

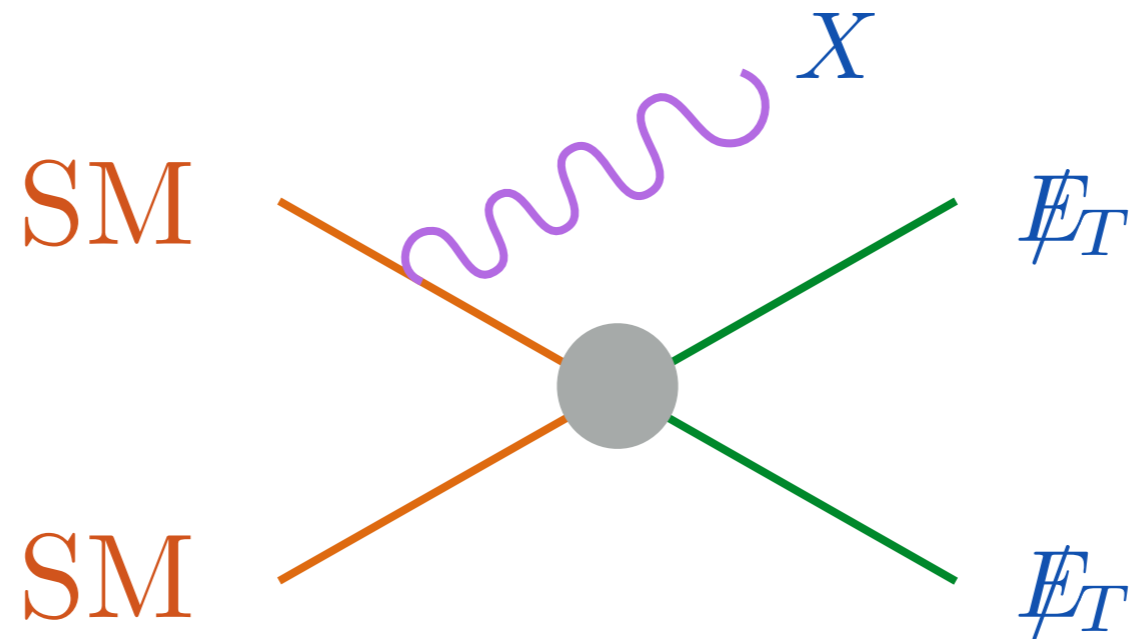
Dark Matter at Colliders

Pedro Schwaller (Mainz University)

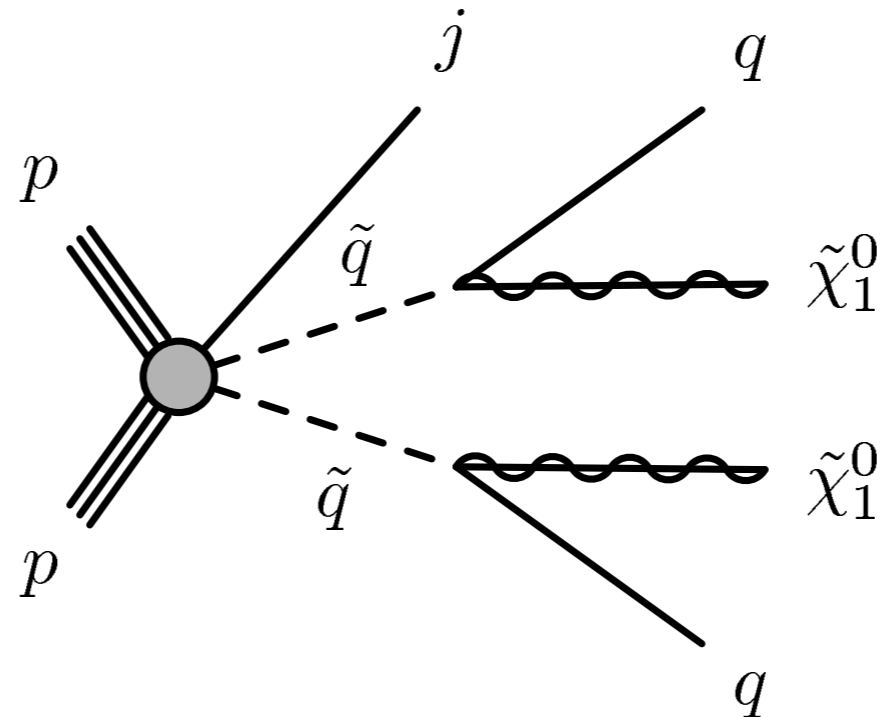
Les Rencontres de Physique de la Vallée d'Aoste
March 2, 2018

DM Production

- Direct

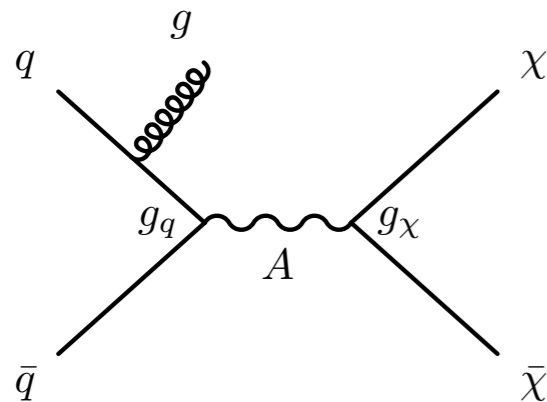


- As decay product

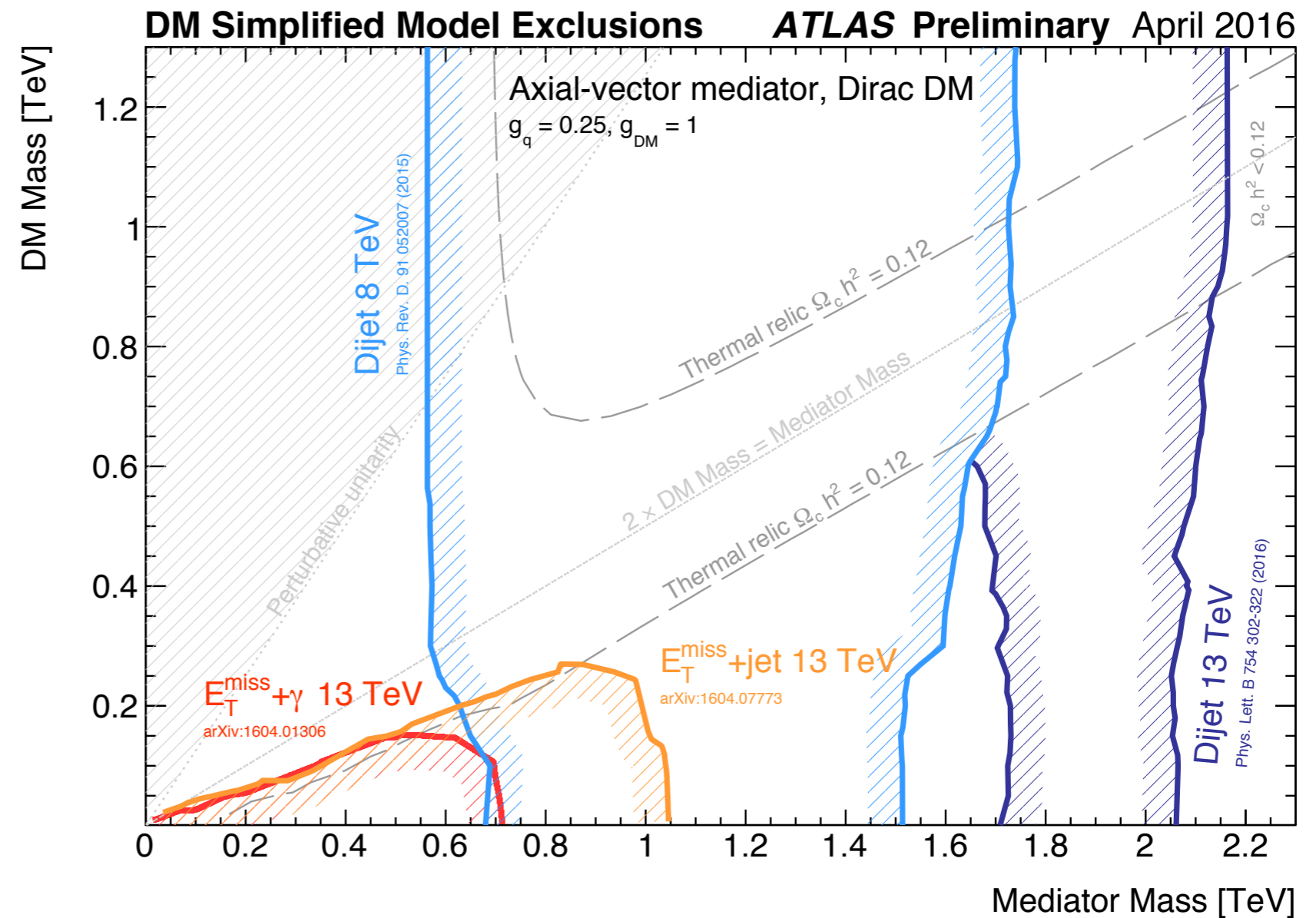


Direct DM production

- Mono-X searches



- Interpretation in simplified models



Indirect DM production

- DM stability usually from parity symmetry
- Other parity odd states might be easier to produce at collider
- DM is produced in cascade decays

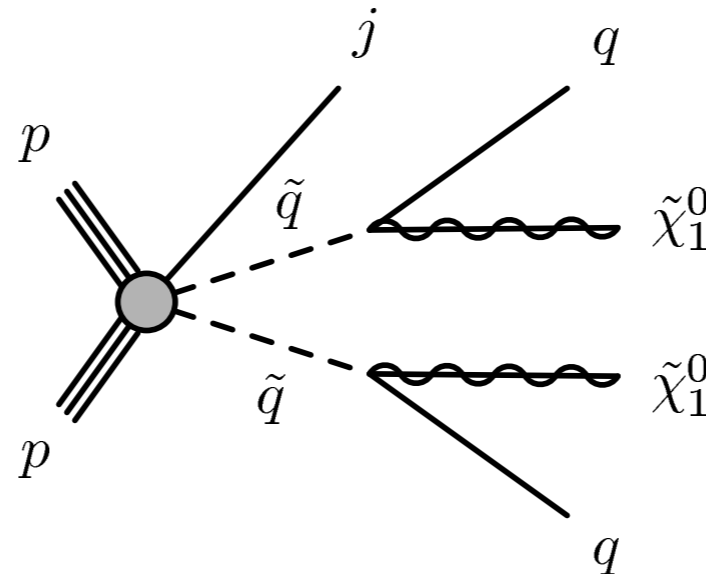


diagram from
1604.07773

SUSY DM Searches

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13$ TeV

Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L} d[\text{fb}^{-1}]$	Mass limit	$\sqrt{s} = 7, 8$ TeV	$\sqrt{s} = 13$ TeV	Reference	
Inclusive Searches	MSUGRA/CMSSM	0-3 e, μ /1-2 τ	2-10 jets/3 b	Yes	20.3	\tilde{q}, \tilde{g}	1.85 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	\tilde{q}	1.35 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV, $m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$	ATLAS-CONF-2016-078
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	\tilde{q}	608 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0) < 5$ GeV	1604.07773
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	\tilde{g}	1.86 TeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^\pm \rightarrow q\tilde{q}W^\pm\tilde{\chi}_1^0$	0	2-6 jets	Yes	13.3	\tilde{g}	1.83 TeV	$m(\tilde{\chi}_1^0) < 400$ GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	13.2	\tilde{g}	1.7 TeV	$m(\tilde{\chi}_1^0) < 400$ GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	2 e, μ (SS)	0-3 jets	Yes	13.2	\tilde{g}	1.6 TeV	$m(\tilde{\chi}_1^0) < 500$ GeV	ATLAS-CONF-2016-037
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	\tilde{g}	2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	\tilde{g}	1.65 TeV	$c\tau(\text{NLSP}) < 0.1$ mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	\tilde{g}	1.37 TeV	$m(\tilde{\chi}_1^0) < 950$ GeV, $c\tau(\text{NLSP}) < 0.1$ mm, $\mu < 0$	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	\tilde{g}	1.8 TeV	$m(\tilde{\chi}_1^0) > 680$ GeV, $c\tau(\text{NLSP}) < 0.1$ mm, $\mu > 0$	ATLAS-CONF-2016-066
GGM (higgsino NLSP)	2 e, μ (Z)	2 jets	Yes	20.3	\tilde{g}	900 GeV	$m(\text{NLSP}) > 430$ GeV	1503.03290	
Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	865 GeV	$m(\tilde{G}) > 1.8 \times 10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})=1.5$ TeV	1502.01518	
3 rd gen. \tilde{g} med.	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	14.8	\tilde{g}	1.89 TeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	14.8	\tilde{g}	1.89 TeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	\tilde{g}	1.37 TeV	$m(\tilde{\chi}_1^0) < 300$ GeV	1407.0600
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	3.2	\tilde{b}_1	840 GeV	$m(\tilde{\chi}_1^0) < 100$ GeV	1606.08772
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{\chi}_1^\pm$	2 e, μ (SS)	1 b	Yes	13.2	\tilde{b}_1	325-685 GeV	$m(\tilde{\chi}_1^0) < 150$ GeV, $m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_1^0)+100$ GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$	0-2 e, μ	1-2 b	Yes	4.7/13.3	\tilde{t}_1	117-170 GeV	$m(\tilde{\chi}_1^\pm)=2m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)=55$ GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	4.7/13.3	\tilde{t}_1	90-198 GeV	$m(\tilde{\chi}_1^0)=1$ GeV	1506.08616, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	\tilde{t}_1	90-323 GeV		1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_1	150-600 GeV	$m(\tilde{\chi}_1^0) > 150$ GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	13.3	\tilde{t}_2	290-700 GeV	$m(\tilde{\chi}_1^0) < 300$ GeV	ATLAS-CONF-2016-038
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1 e, μ	6 jets + 2 b	Yes	20.3	\tilde{t}_2	320-620 GeV	$m(\tilde{\chi}_1^0)=0$ GeV	1506.08616
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$	90-335 GeV	$m(\tilde{\chi}_1^0)=0$ GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^\pm \rightarrow \tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	13.3	$\tilde{\chi}_1^\pm$	640 GeV	$m(\tilde{\chi}_1^0)=0$ GeV, $m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2016-096
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	14.8	$\tilde{\chi}_1^\pm$	580 GeV	$m(\tilde{\chi}_1^0)=0$ GeV, $m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2016-093
	$\tilde{\chi}_1^+\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_L\nu\tilde{\ell}_L(\tilde{\ell}\tilde{\nu}), \tilde{\ell}\tilde{\nu}\tilde{\ell}_L(\tilde{\ell}\tilde{\nu})$	3 e, μ	0	Yes	13.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	1.0 TeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)=0$, $m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2016-096
	$\tilde{\chi}_1^+\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	425 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)=0$, $\tilde{\ell}$ decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^+\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h \rightarrow b\bar{b}/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	270 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)=0$, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_2^0 \rightarrow \tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	635 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)=0$, $m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086
	GGM (wino NLSP) weak prod.	1 $e, \mu + \gamma$	-	Yes	20.3	\tilde{W}	115-370 GeV	$c\tau < 1$ mm	1507.05493
	GGM (bino NLSP) weak prod.	2 γ	-	Yes	20.3	\tilde{W}	590 GeV	$c\tau < 1$ mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	270 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0) \sim 160$ MeV, $\tau(\tilde{\chi}_1^\pm)=0.2$ ns	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^\pm$	495 GeV	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0) \sim 160$ MeV, $\tau(\tilde{\chi}_1^\pm) < 15$ ns	1506.05332
	Stable, stopped \tilde{g} R-hadron	0	1-5 jets	Yes	27.9	\tilde{g}	850 GeV	$m(\tilde{\chi}_1^0)=100$ GeV, $10 \mu\text{s} < \tau(\tilde{g}) < 1000$ s	1310.6584
	Stable \tilde{g} R-hadron	trk	-	-	3.2	\tilde{g}	1.58 TeV		1606.05129
	Metastable \tilde{g} R-hadron	dE/dx trk	-	-	3.2	\tilde{g}	1.57 TeV		1604.04520
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	$m(\tilde{\chi}_1^0)=100$ GeV, $\tau > 10$ ns	1411.6795
	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	440 GeV	$1 < \tau(\tilde{\chi}_1^0) < 3$ ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow e\bar{e}\nu/\mu\bar{\mu}\nu$	displ. $e\bar{e}/\mu\bar{\mu}$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$7 < c\tau(\tilde{\chi}_1^0) < 740$ mm, $m(\tilde{g})=1.3$ TeV	1504.05162
	GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0 \rightarrow Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	$6 < c\tau(\tilde{\chi}_1^0) < 480$ mm, $m(\tilde{g})=1.1$ TeV	1504.05162
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e\mu/\tau\mu$	$e\mu, \tau\mu$	-	-	3.2	$\tilde{\nu}_\tau$	1.9 TeV	$\lambda_{311}^2=0.11, \lambda_{132/133/233}=0.07$	1607.08079
	Bilinear RPV/CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{q}, \tilde{g}	1.45 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{\text{LSP}} < 1$ mm	1404.05525
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow e\bar{\nu}, e\mu\nu, \mu\bar{\nu}$	1 μ	-	Yes	13.3	$\tilde{\chi}_1^\pm$	1.14 TeV	$m(\tilde{\chi}_1^0) > 400$ GeV, $\lambda_{12k} \neq 0$ ($k=1, 2$)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \rightarrow \tau\nu_e, e\tau\nu_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^\pm$	450 GeV	$\lambda_{111}^2 > 0.2 \times m(\tilde{\chi}_1^0), \lambda_{133} \neq 0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{q}$	0	4-5 large- R jets	-	14.8	\tilde{g}	1.55 TeV	$\text{BR}(\tilde{g})=\text{BR}(\tilde{b})=\text{BR}(\tilde{c})=0\%$	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\tilde{q}$	0	4-5 large- R jets	-	14.8	\tilde{g}	1.55 TeV	$m(\tilde{\chi}_1^0)=800$ GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\tilde{q}$	1 e, μ	8-10 jets/0-4 b	-	14.8	\tilde{g}	1.75 TeV	$m(\tilde{\chi}_1^0)=800$ GeV	ATLAS-CONF-2016-094
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow \tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{s}$	1 μ	8-10 jets/0-4 b	-	14.8	\tilde{g}	1.4 TeV	$625 \text{ GeV} < m(\tilde{t}_1) < 850 \text{ GeV}$	ATLAS-CONF-2016-094
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\ell}$	0	2 jets + 2 b	-	15.4	\tilde{t}_1	410 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{\ell}$	2 e, μ	2 b	-	20.3	\tilde{t}_1	0.4-1.0 TeV	$\text{BR}(\tilde{t}_1 \rightarrow b\ell/\mu) > 20\%$	ATLAS-CONF-2015-015	
Other	Scalar charm, $\tilde{c} \rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	\tilde{c}	510 GeV	$m(\tilde{\chi}_1^0) < 200$ GeV	1501.01325

*Only a selection of the available mass limits on new

10^{-1}

1

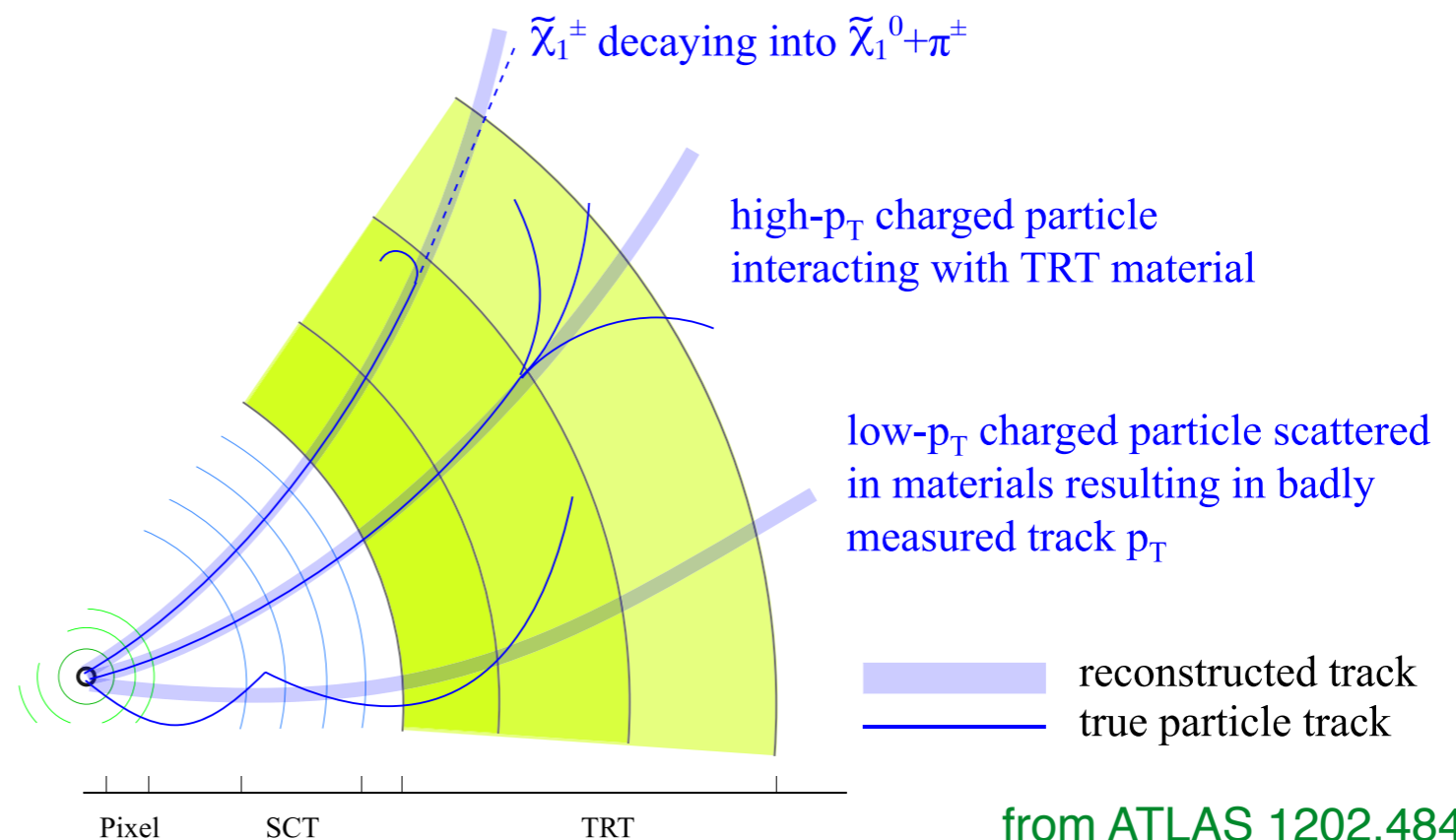
Mass scale [TeV]

Indirect DM production

- Sometimes need to go beyond the usual “energetic SM states + MET” searches, e.g.
- Squeezed spectra
 - minimal models, co-annihilation
 - freeze-in scenarios
- Extended dark sectors, with states below M_{DM}
 - dark photons
 - confining hidden sectors

Higgsino/Wino DM

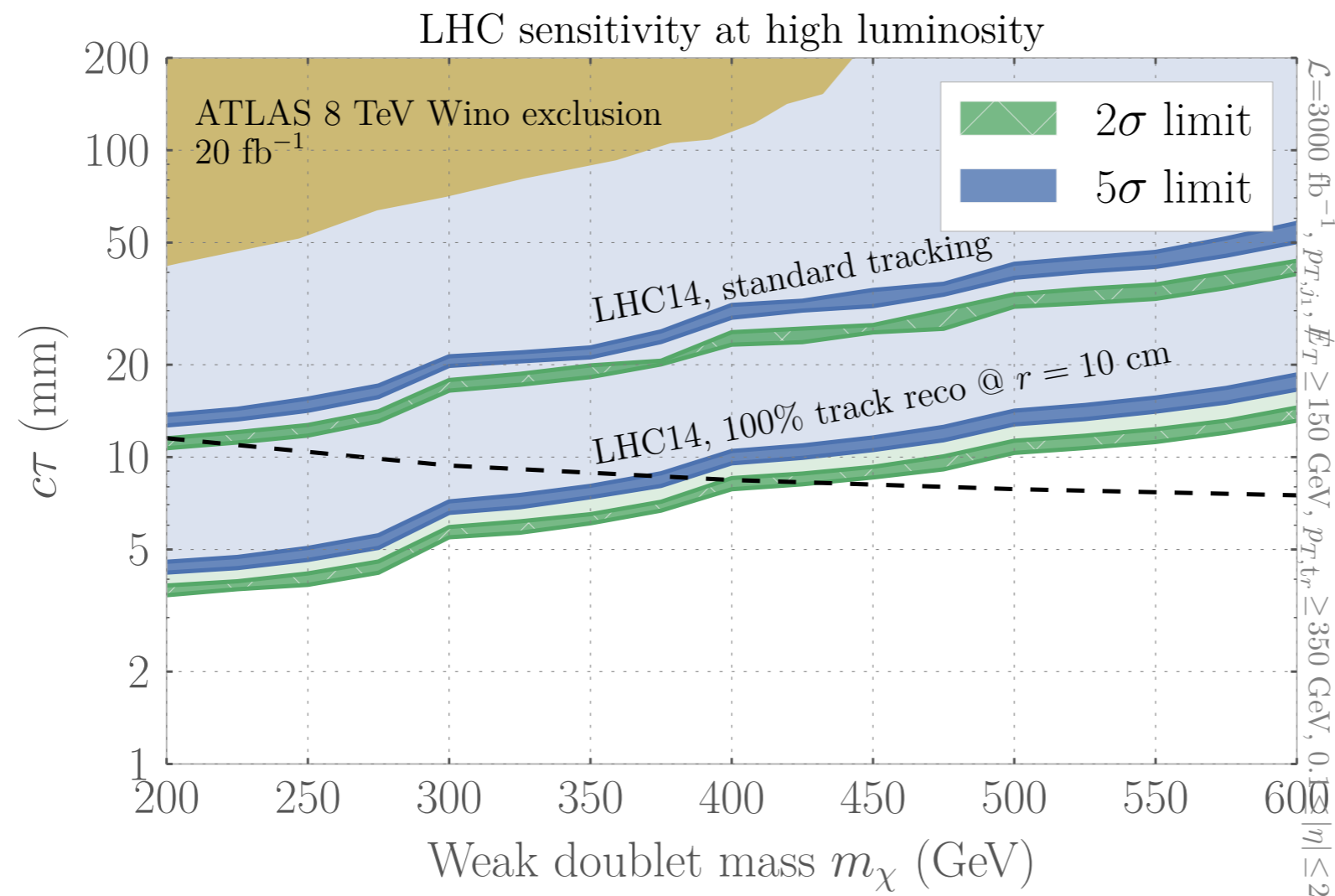
- Minimal SU(2) **doublet** or **triplet** DM (Wino/Higgsino)
- DM state accompanied with nearly **degenerate** charged state (chargino)
- Lifetime few cm
→ disappearing charged track
- Strongest limit on Wino DM



from ATLAS 1202.4847

Fig. 2 Origins of disappearing high- p_T tracks.

Higgsino DM



Higgsino

- Assumption: 100% track efficiency at 10cm
Moriond a week later: 12 cm is possible!

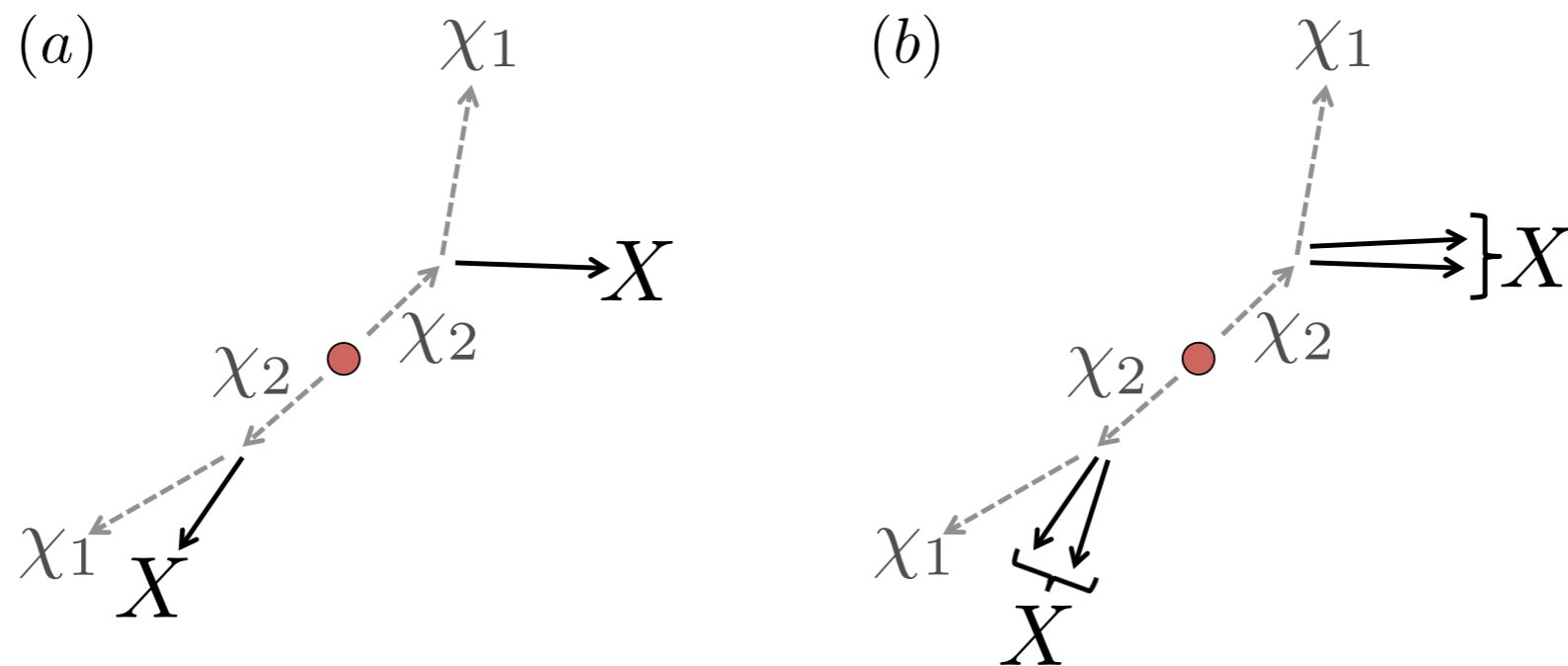
Example of lifetime frontier!

Explore with simplified models

Simplified models for LLPs

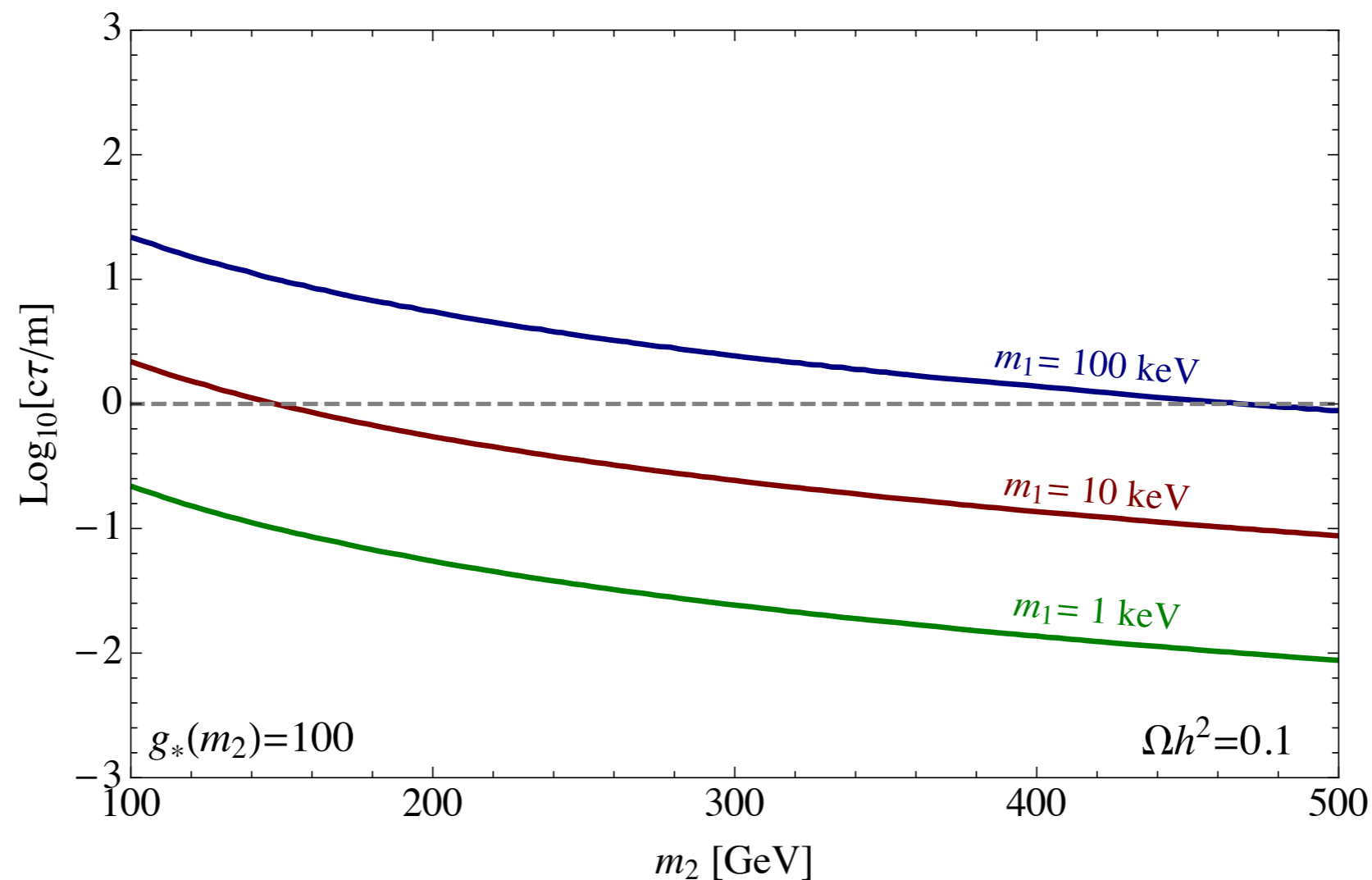
- Successful way to present collider searches in a less model dependent way
 - Two masses (DM & mediator) and two couplings
- Minimal extension to include displaced decays
 - Add second “dark” state with mass $m_2 > m_{\text{DM}}$
 - Lifetime $\Gamma(\chi_2 \rightarrow \chi_1 X)$
- Underlying models e.g. “GMSB SUSY”, freeze-in DM, twin Higgs dark sectors

Signatures



- X can be any set of SM particles
- Can also imagine SM charged χ_2 Aoude, Madge, PS, Shepherd in progress
- UFO files available in Buchmuller, De Roeck, Hahn, McCullough, PS, Sung, Yu, 2017

Freeze-in DM connection

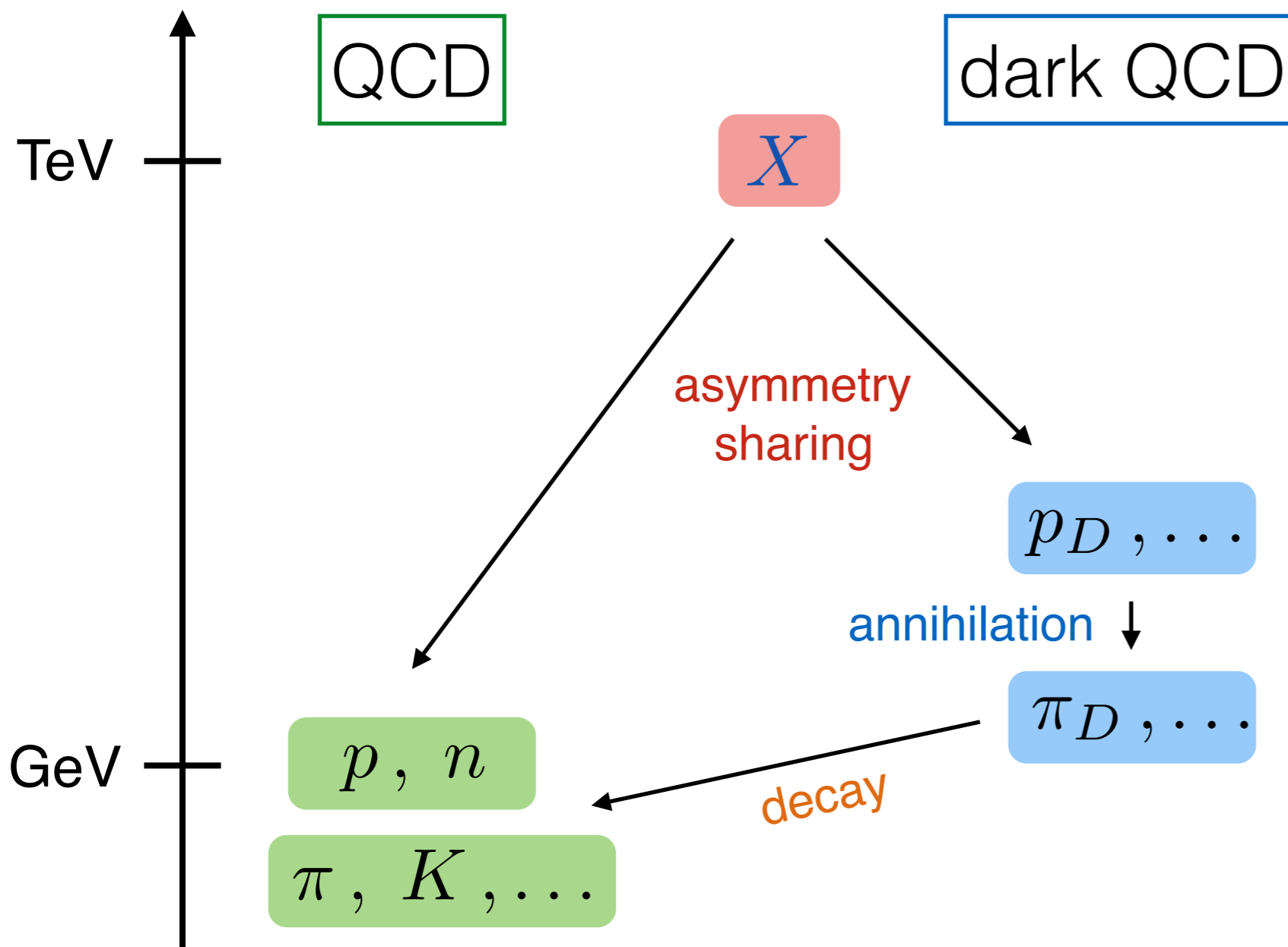


- Centimetre to metre lifetimes consistent with freeze-in DM relic abundance (solid lines)

Buchmuller, De Roeck, Hahn,
McCullough, PS, Sung, Yu, 2017

Composite dark sectors

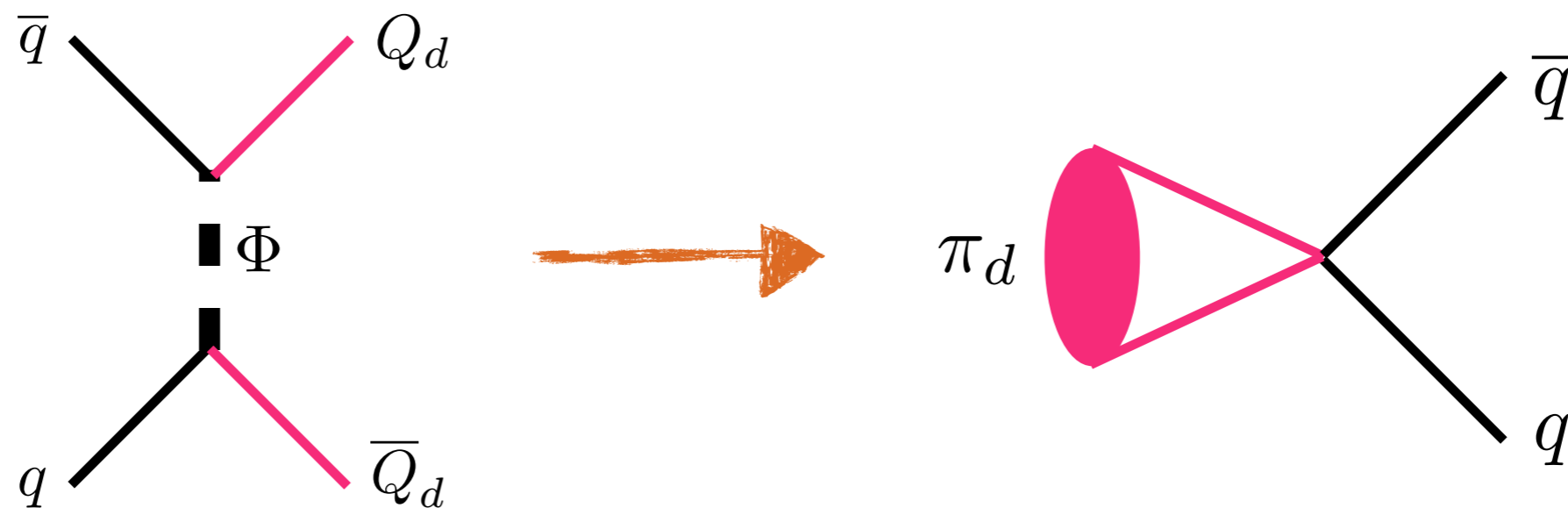
Dark QCD



- SU(N) dark sector with neutral “dark quarks”
- Confinement scale Λ_{darkQCD}
- DM is composite “dark proton”
- “Dark pions” unstable, long lived

Dark Pion Lifetime

- Integrate out mediator, match to dark pion current



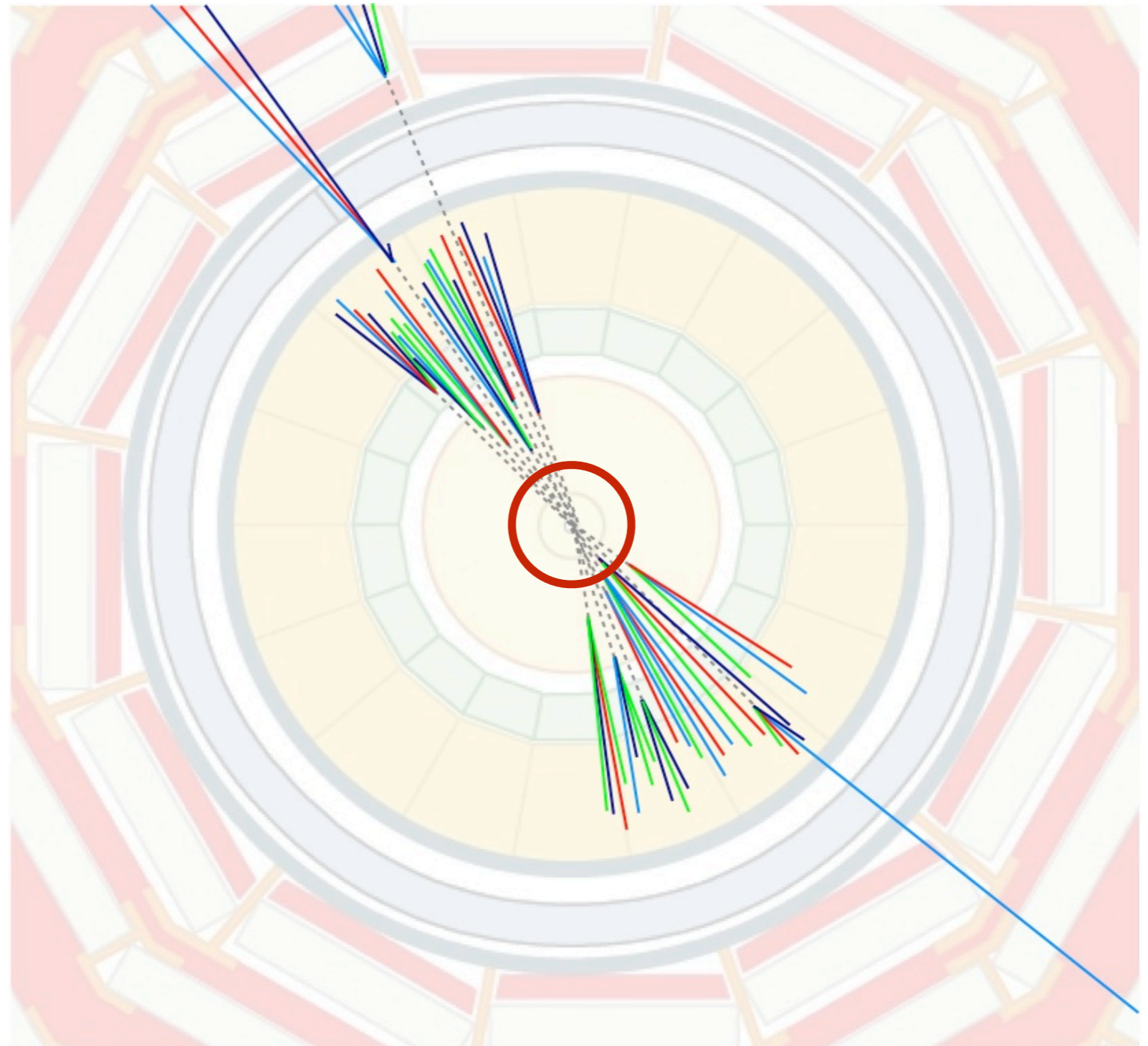
- Decay to SM jets (pions)

$$\Gamma(\pi_d \rightarrow \bar{d}d) \approx \frac{f_{\pi_d}^2 m_d^2}{32\pi M_{X_d}^4} m_{\pi_d} \sim \text{cm}$$

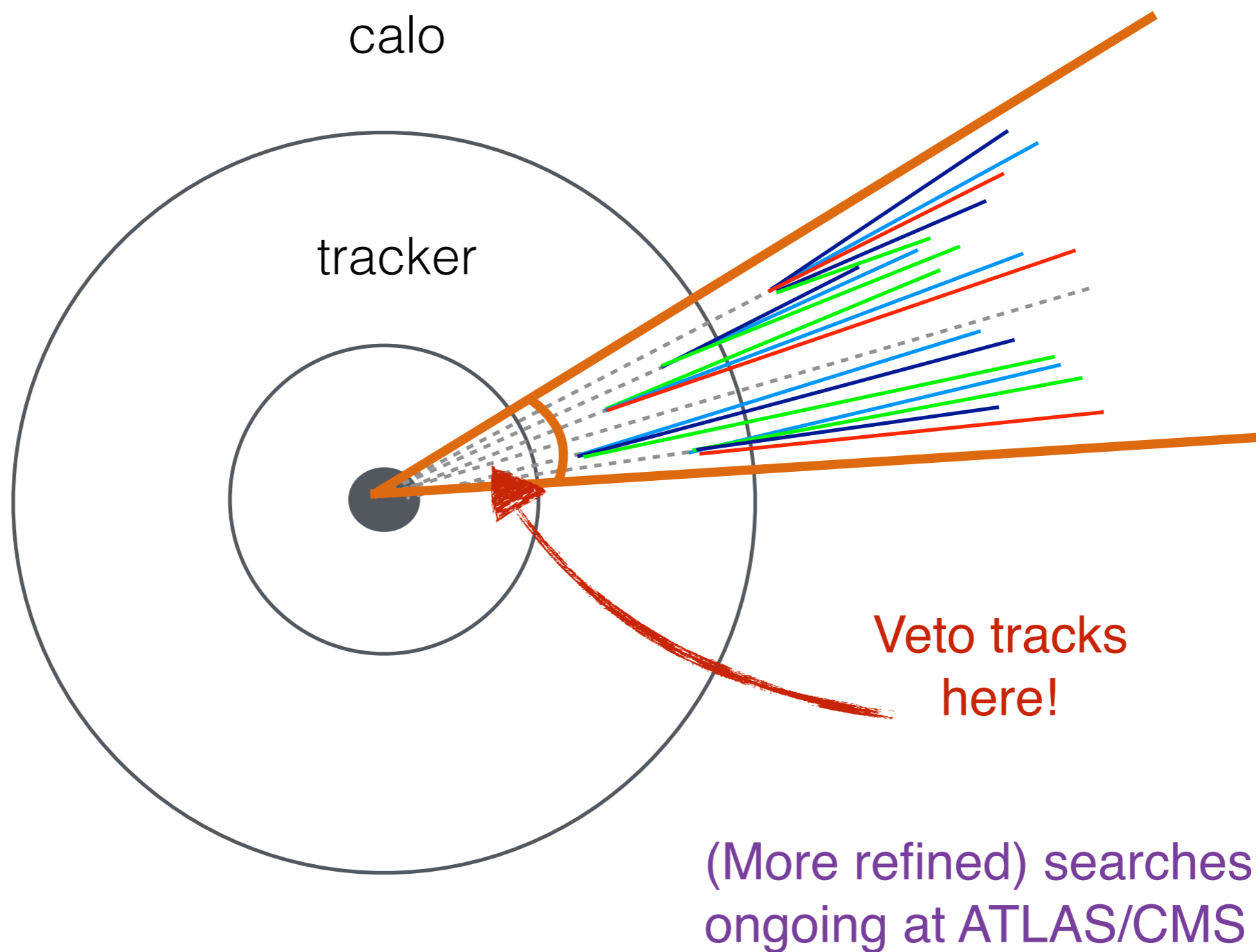
Decay in LHC
detectors!

Emerging Jets at the LHC

- Production of mediator, decay to dark quarks
- Characteristic:
 - few/no tracks in inner tracker
- New “**emerging**” **jet** signature
- Smoking gun of composite hidden sectors



Strategy

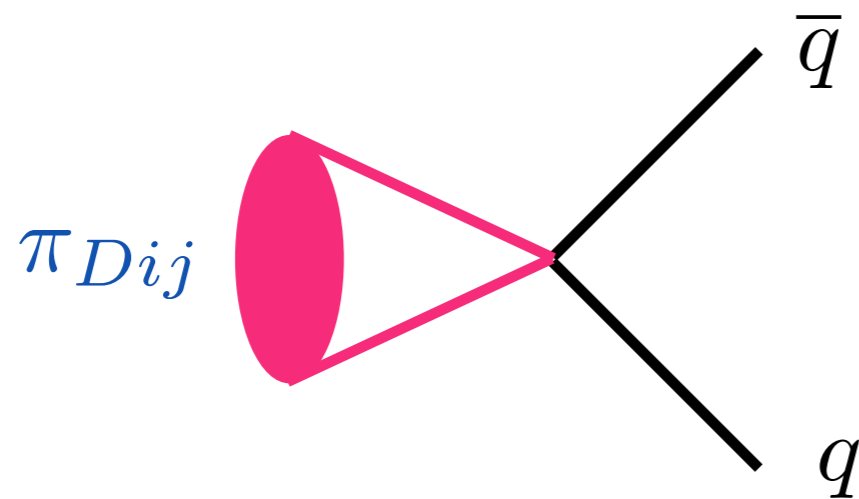


Adding flavour

- So far, assumed universal lifetime for dark pions
- Actually

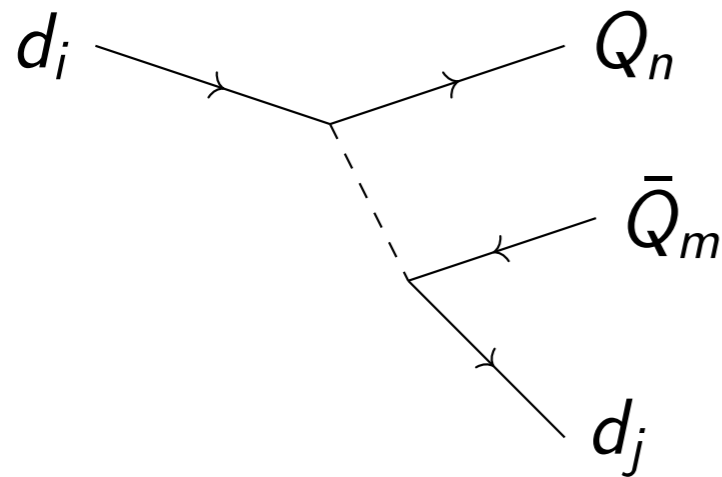
$$\lambda \bar{d}_R Q_L \Phi = \lambda_{ij} \bar{d}_{Ri} Q_{Lj} \Phi$$

- Not all pions are equal:

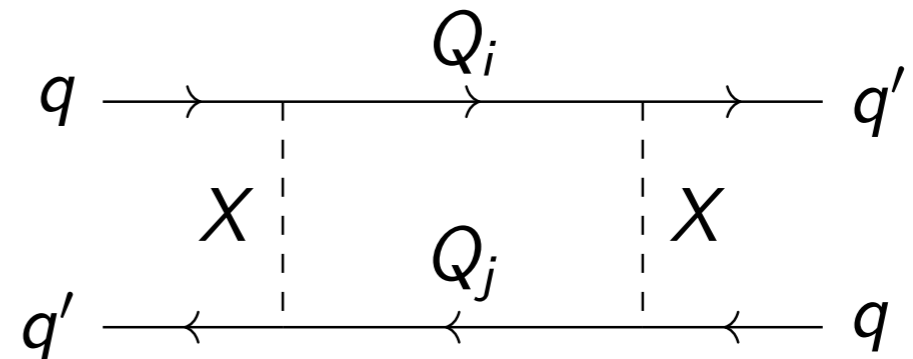


$$\propto \sum_{q,q'} |\lambda_{qi} \lambda_{q'j}^*|^2$$

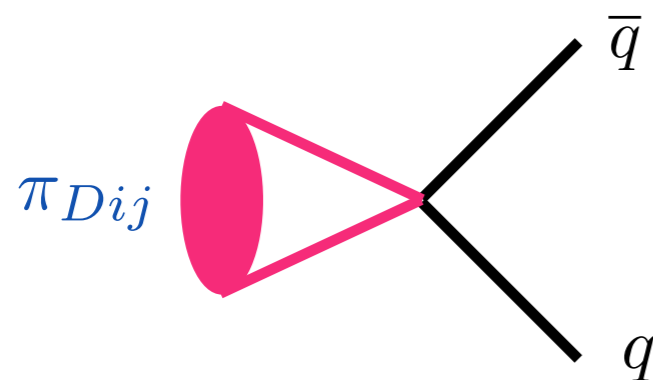
Flavour matters



$\Delta F = 1$
 $\Delta F = 2$
 constraints

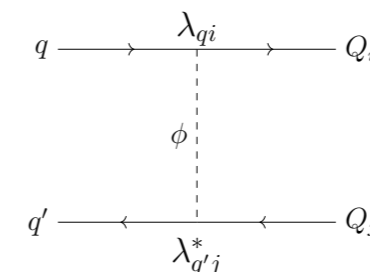


$$\lambda_{ij} \bar{d}_{Ri} Q_{Lj} \Phi$$



dark pion properties

fixed target experiments



Rare decays

- Allows rare decays

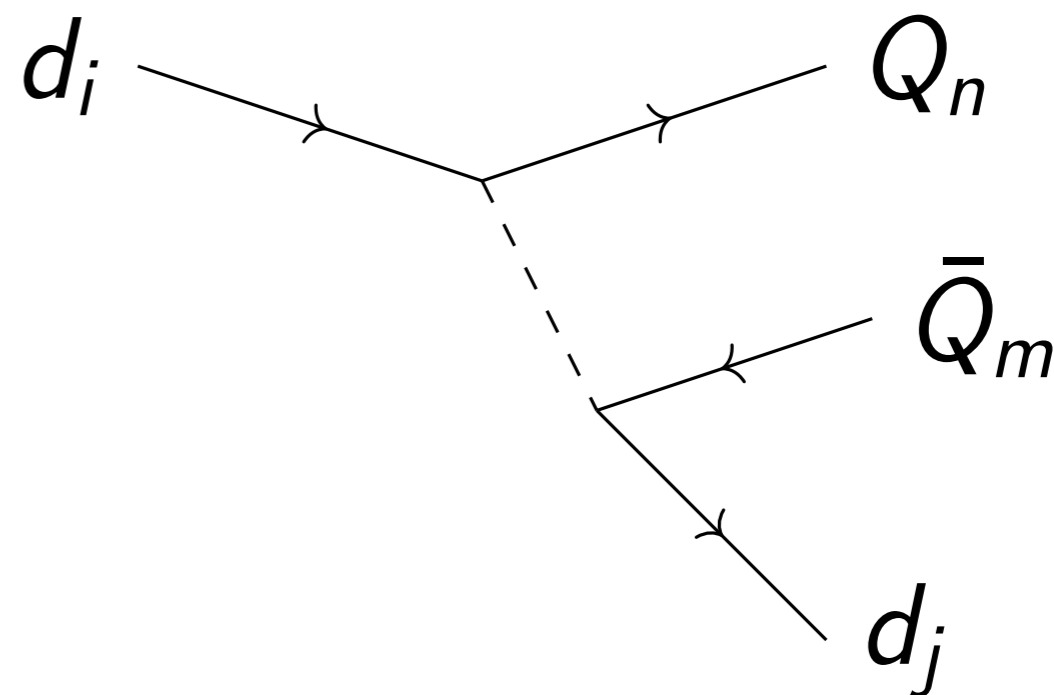
$$B \rightarrow (K, \pi) + \text{invisible}$$

$$K \rightarrow \pi + \text{invisible}$$

- Strongest close to thresholds:

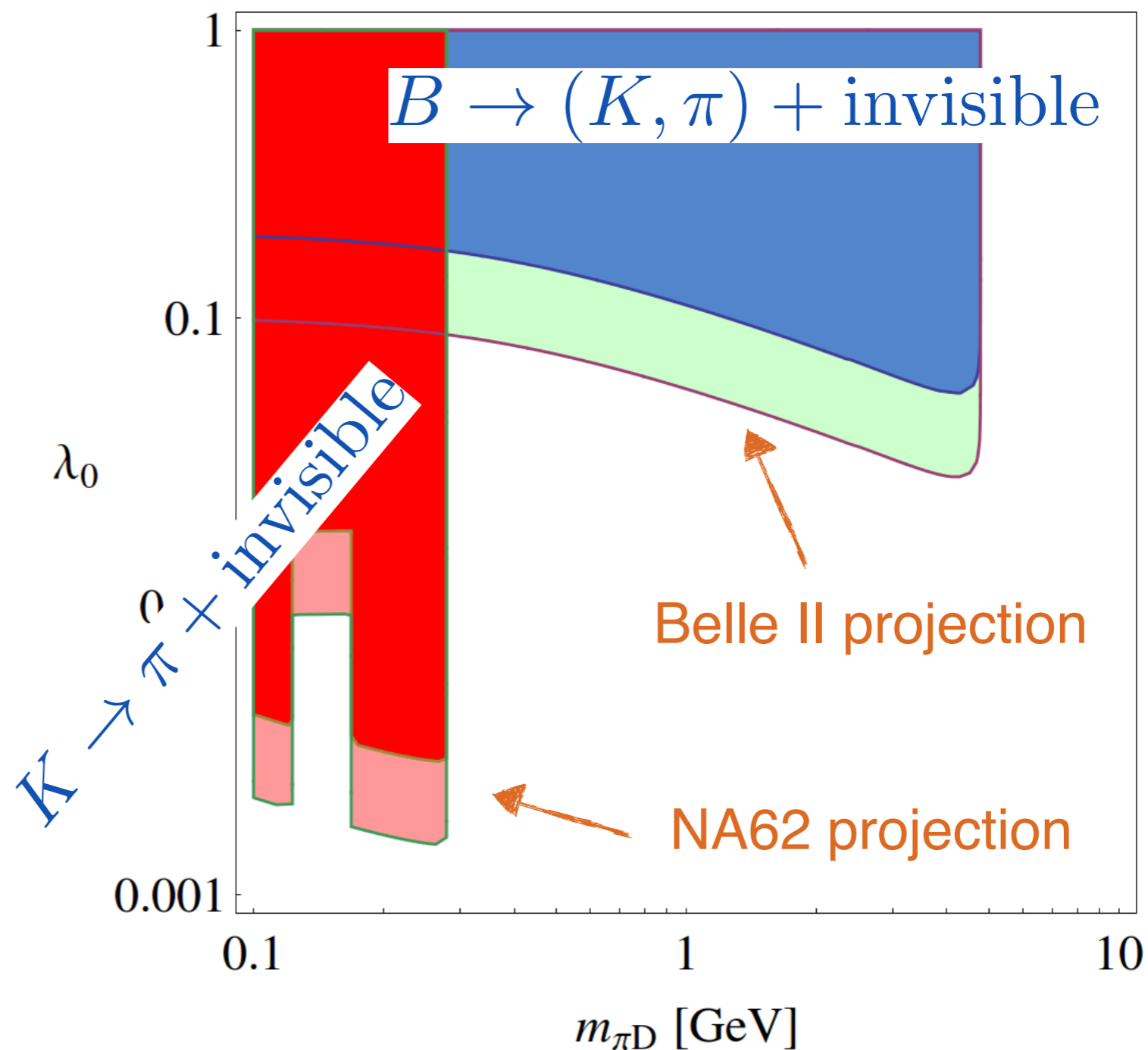
$$K \rightarrow \pi \pi_D \text{ wins over } K \rightarrow \pi Q \bar{Q}$$

- Don't vanish in flavour symmetric limit!



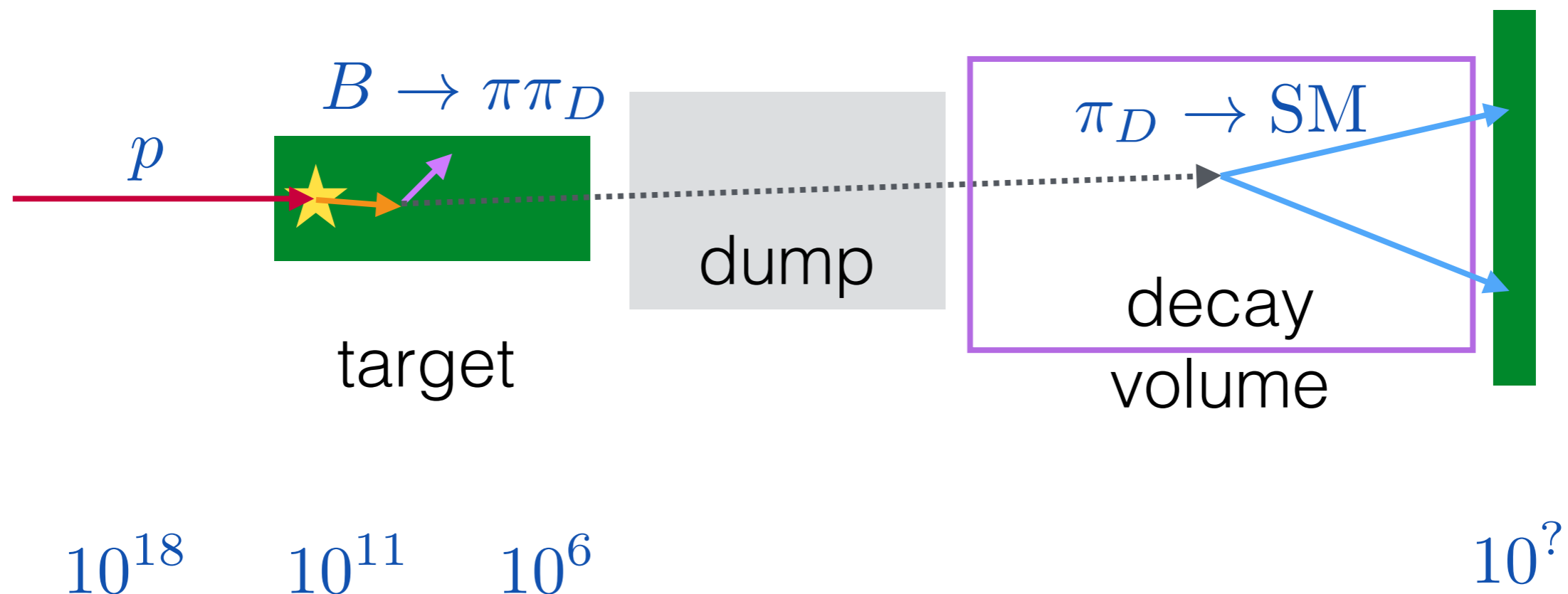
Bounds from rare decays

- Best bound on couplings for very light dark pions
- Dark pion production in fixed target expts!



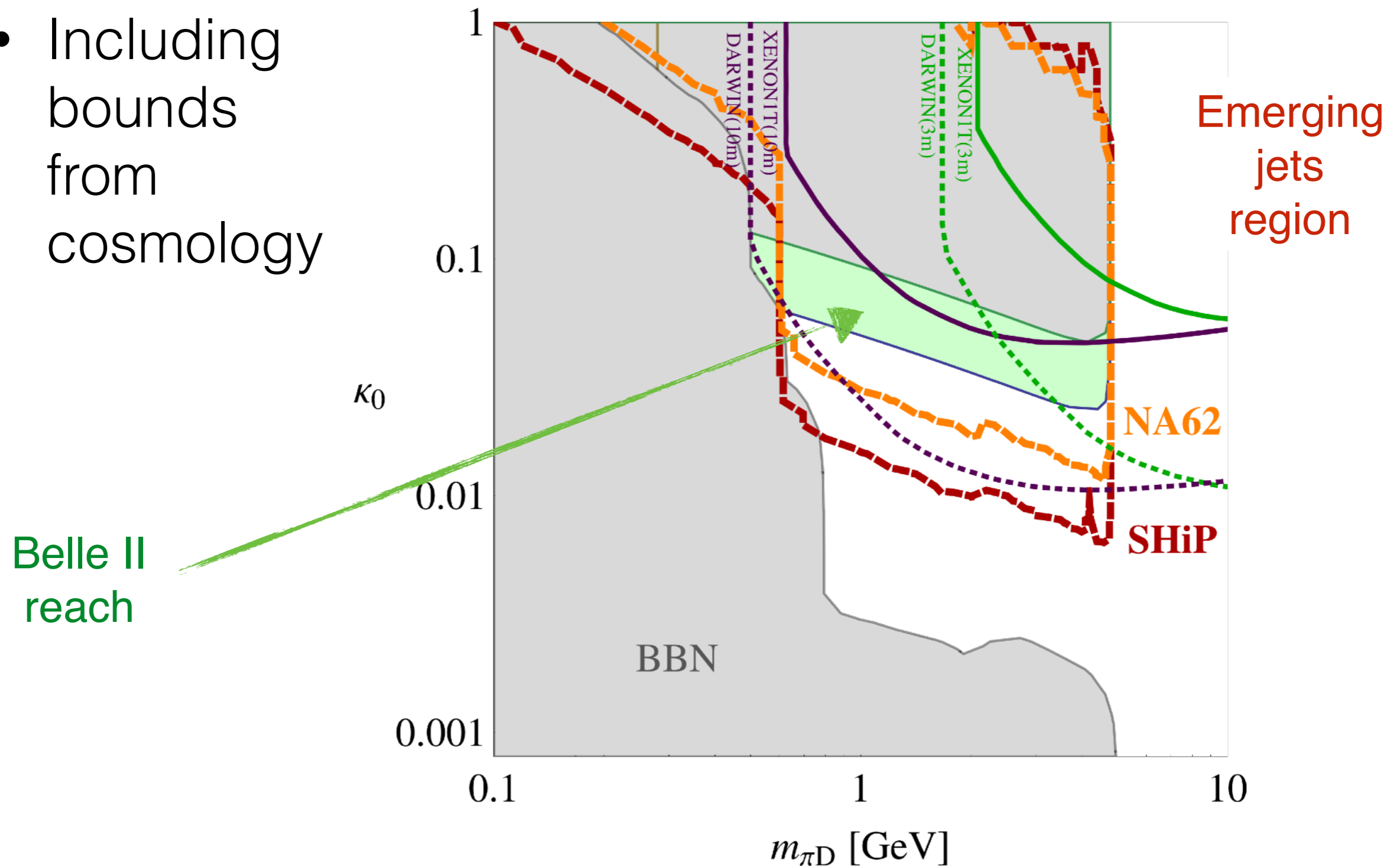
Fixed target

- My simplified NA62/SHiP:



Fixed target reach

- Including bounds from cosmology



Summary

- Search for the dark matter is ongoing, activity on many fronts
 - Direct/indirect production at colliders well covered
 - New(er) frontier: Long lived particle searches
- New signatures from richer dark sectors:
 - Emerging jets at ATLAS/CMS (searched for!)
 - Long lived mediators at NA62/SHiP

Thank You

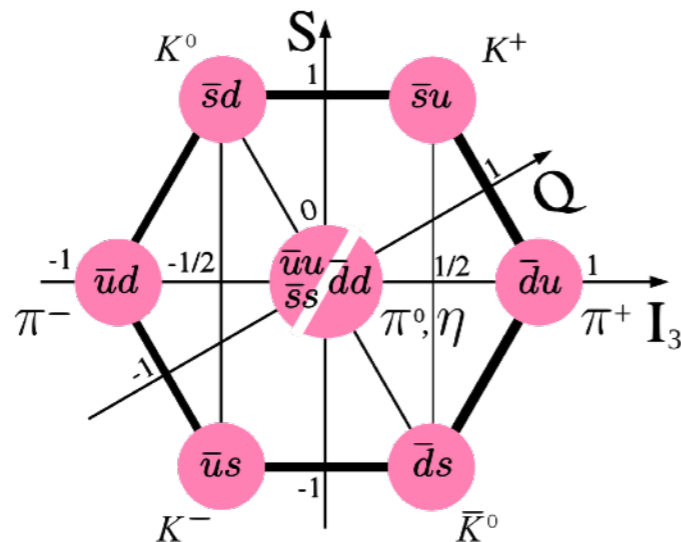
Particles and symmetries

$$\mathcal{L}_{dark} \supset i\bar{Q}_i \not{\partial} Q_i + M^2 \bar{Q}_i Q_i + \lambda_{ij} \bar{Q}_i P_R d_j X$$

Ansatz: 3 dark quark flavours Q_i

$$U(3)_L \times U(3)_R \rightarrow SU(3)_V \times U(1)_B$$

\Rightarrow 8 DARK PIONS



Lightest baryon “dark proton”
Charged under $U(1)_B \Rightarrow$ stable

Dark quark flavour symmetry broken only by λ_{ij}

Dark Pion Lifetime

$$\Gamma(\pi_d \rightarrow \bar{d}d) \approx \frac{f_{\pi_d}^2 m_d^2}{32\pi M_{X_d}^4} m_{\pi_d}$$

$$c\tau \approx 5 \text{ cm} \times \left(\frac{1 \text{ GeV}}{f_{\pi_d}} \right)^2 \left(\frac{100 \text{ MeV}}{m_d} \right)^2 \left(\frac{1 \text{ GeV}}{m_{\pi_d}} \right) \left(\frac{M_{X_d}}{1 \text{ TeV}} \right)^4$$

Decay in LHC detectors!

Flavour constraints

- Parameterise

$$\lambda = U D V$$

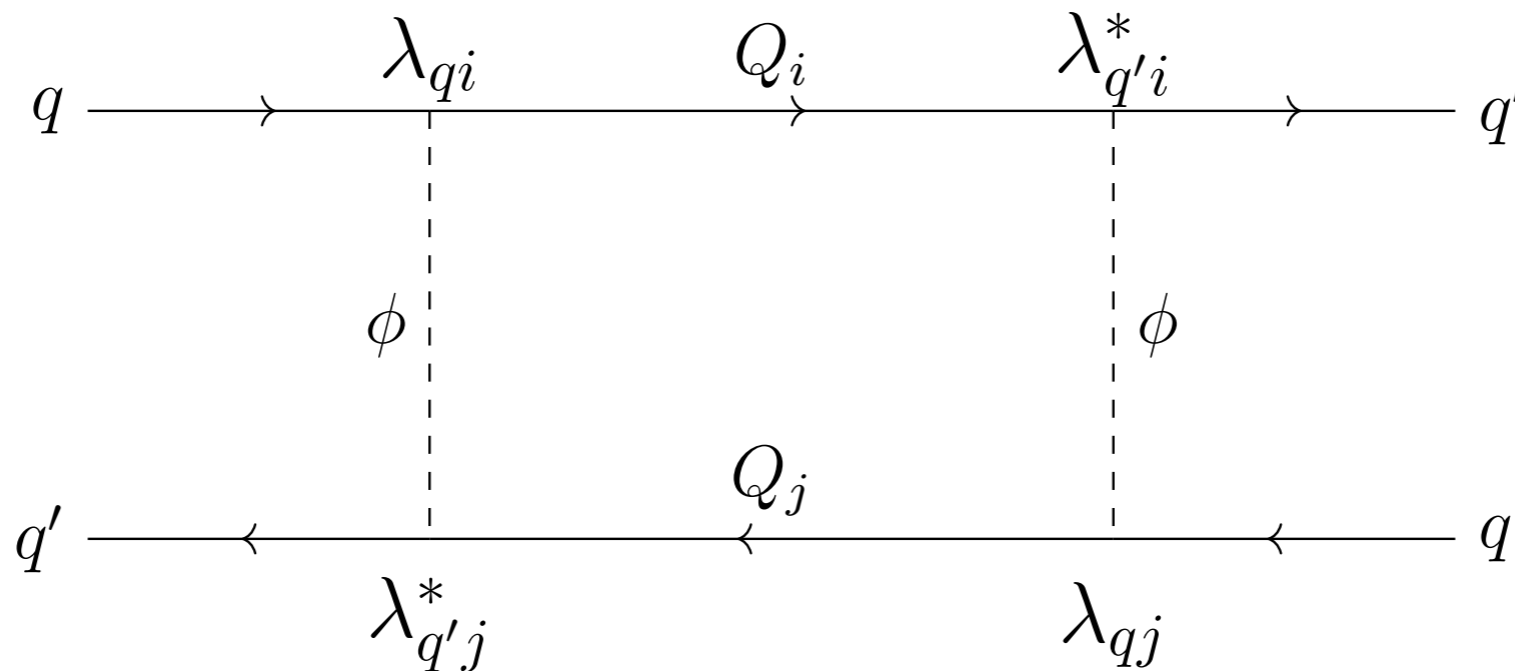
unitary

diagonal

Parameterisation from
Agrawal, Blanke,
Gemmler, 2014

- For degenerate dark quark masses, can absorb V
- If $D \propto \mathbb{1}$, SM flavour symmetry unbroken
- Write $D = \left(\lambda_0 \cdot \mathbb{1} + \text{diag}(\lambda_1, \lambda_2, -(\lambda_1 + \lambda_2)) \right)$

$$\Delta F=2$$



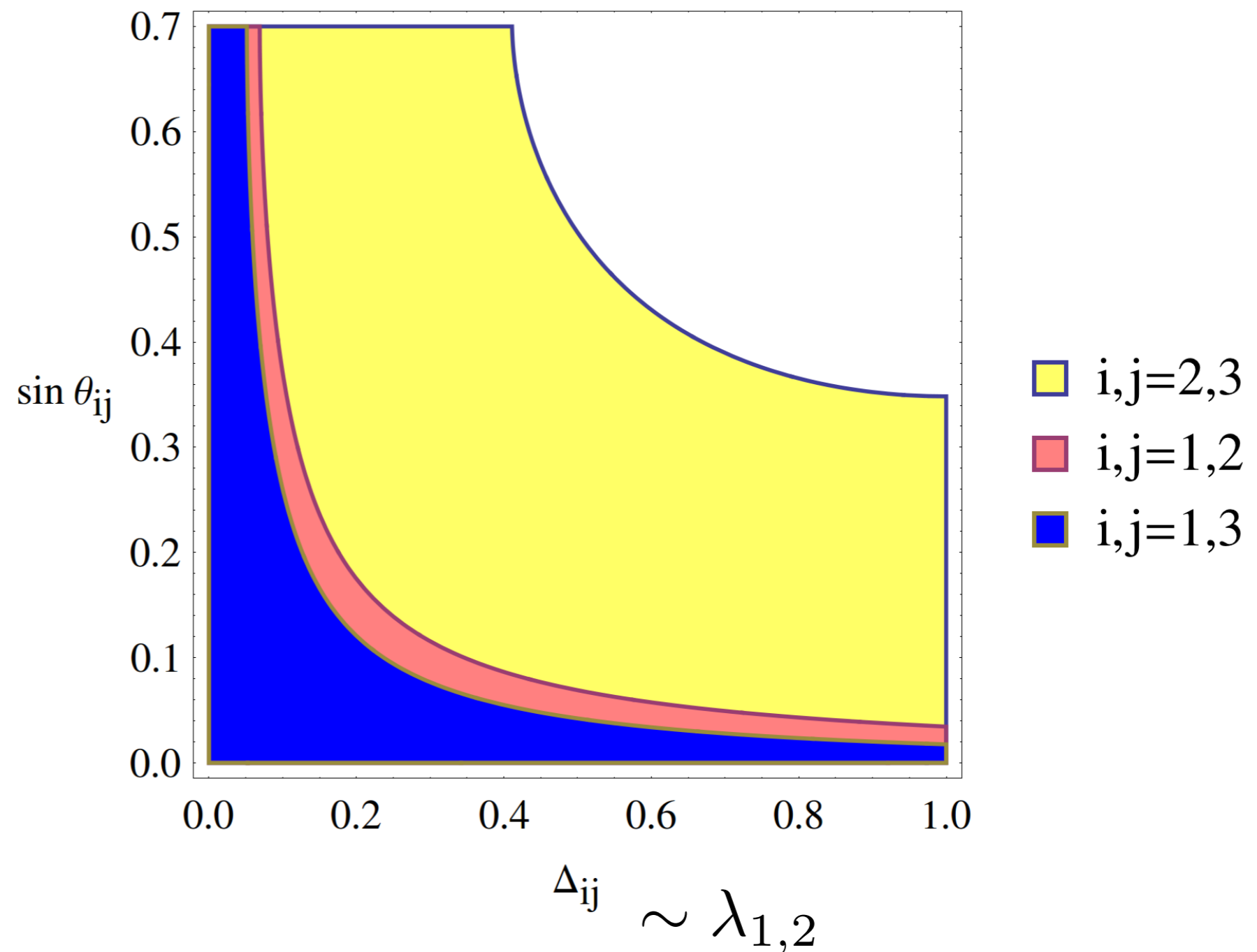
- Absent in $D = \lambda_0 \cdot \mathbb{1}$ limit!

$$\left(\sum_{i=1}^3 \lambda_{qi} \lambda_{q'i}^* \right)^2 = \left([UD(UD)^\dagger]_{qq'} \right)^2 = \lambda_0^4 \left([UU^\dagger]_{qq'} \right)^2 = 0$$

$$\Delta F=2$$

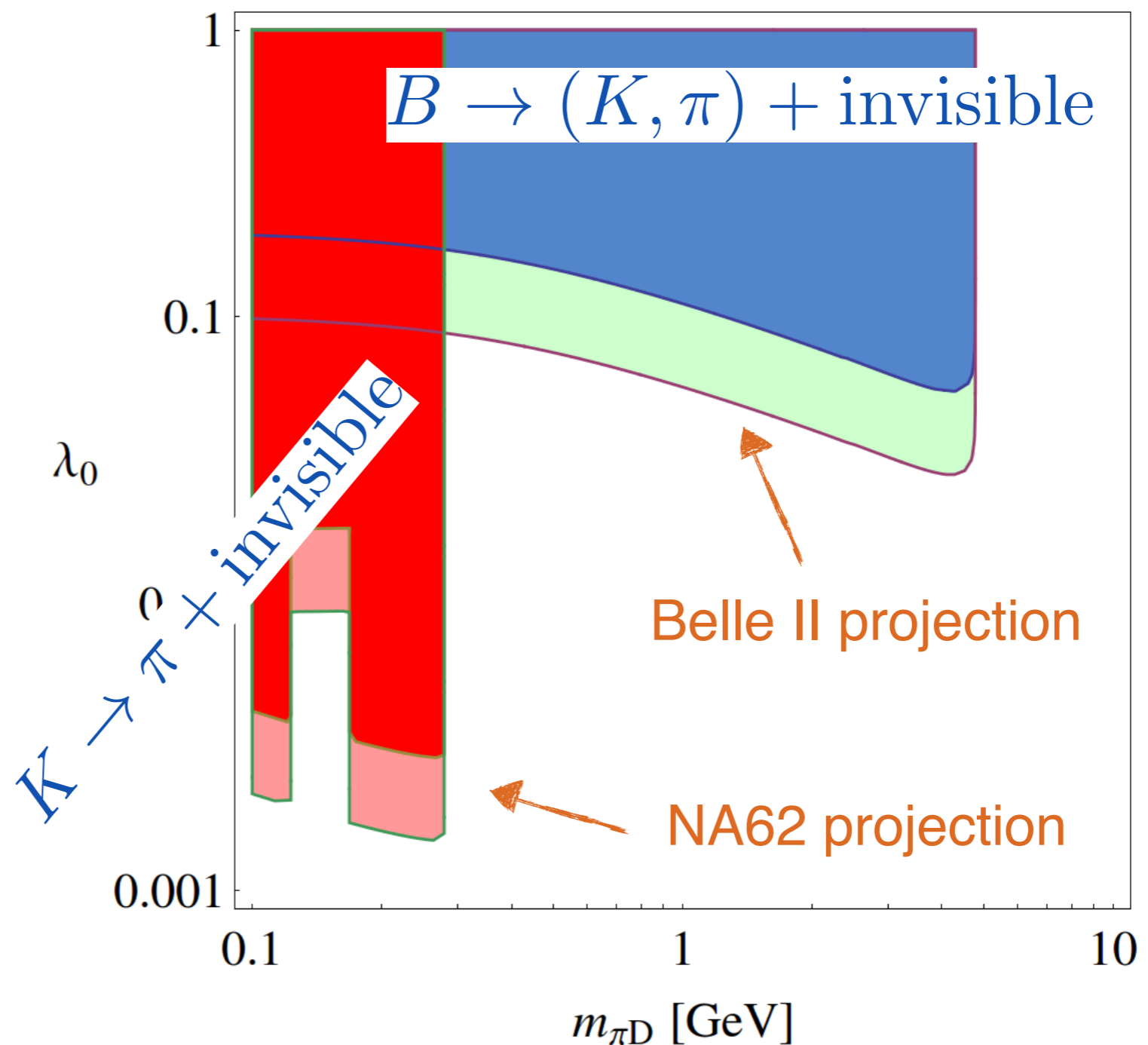
- Otherwise bounds on mixing matrix

$$U = U_{12}U_{13}U_{23}$$



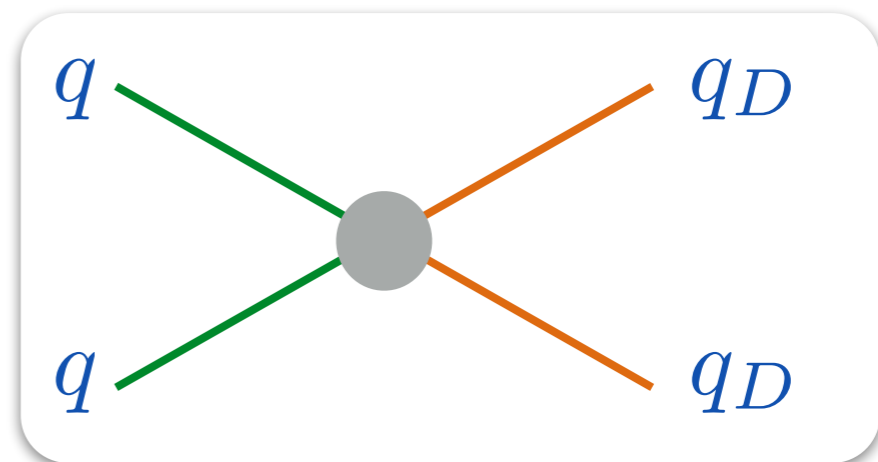
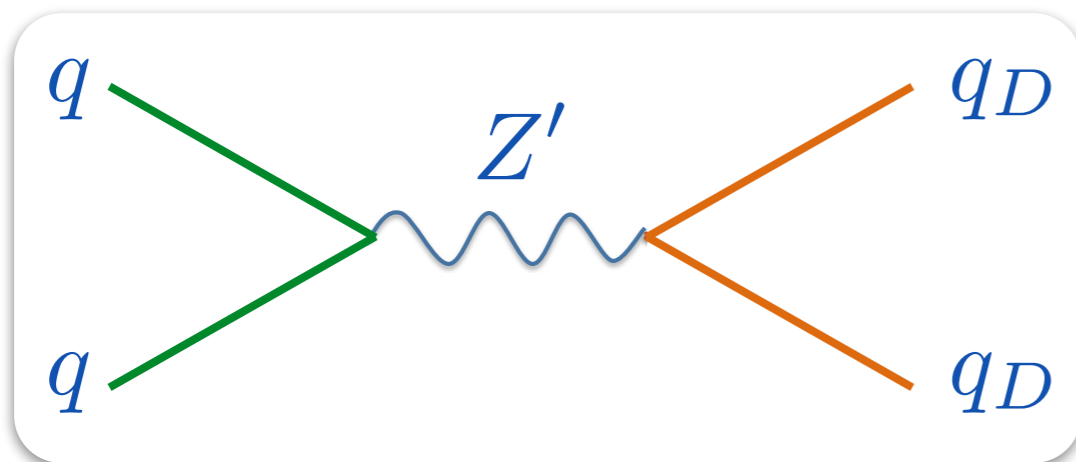
$$\Delta F = 1$$

- Best bound on couplings for very light dark pions



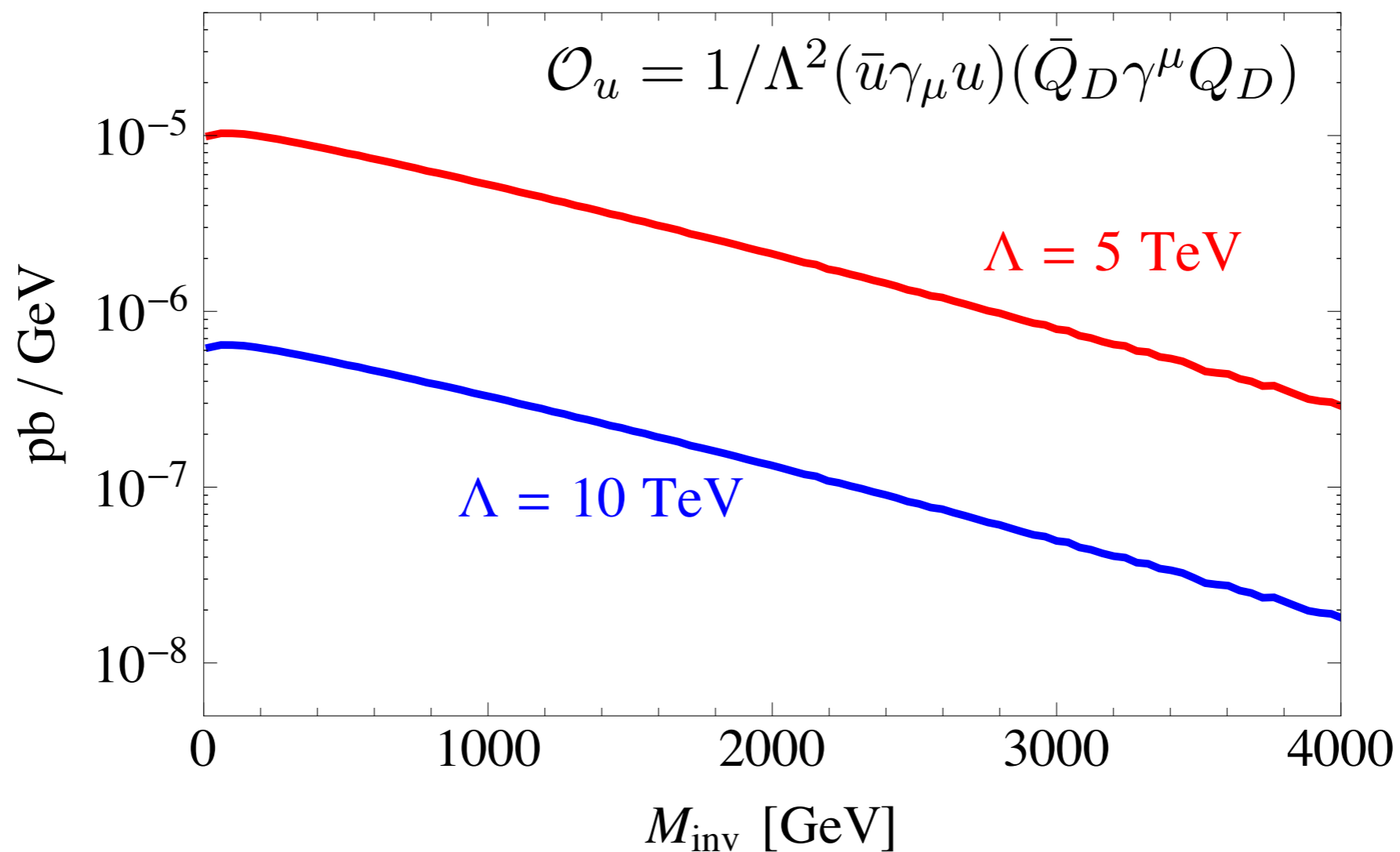
LHCb opportunities

- Z' mediator is difficult to trigger at ATLAS/CMS
Same if dominant production is off-shell



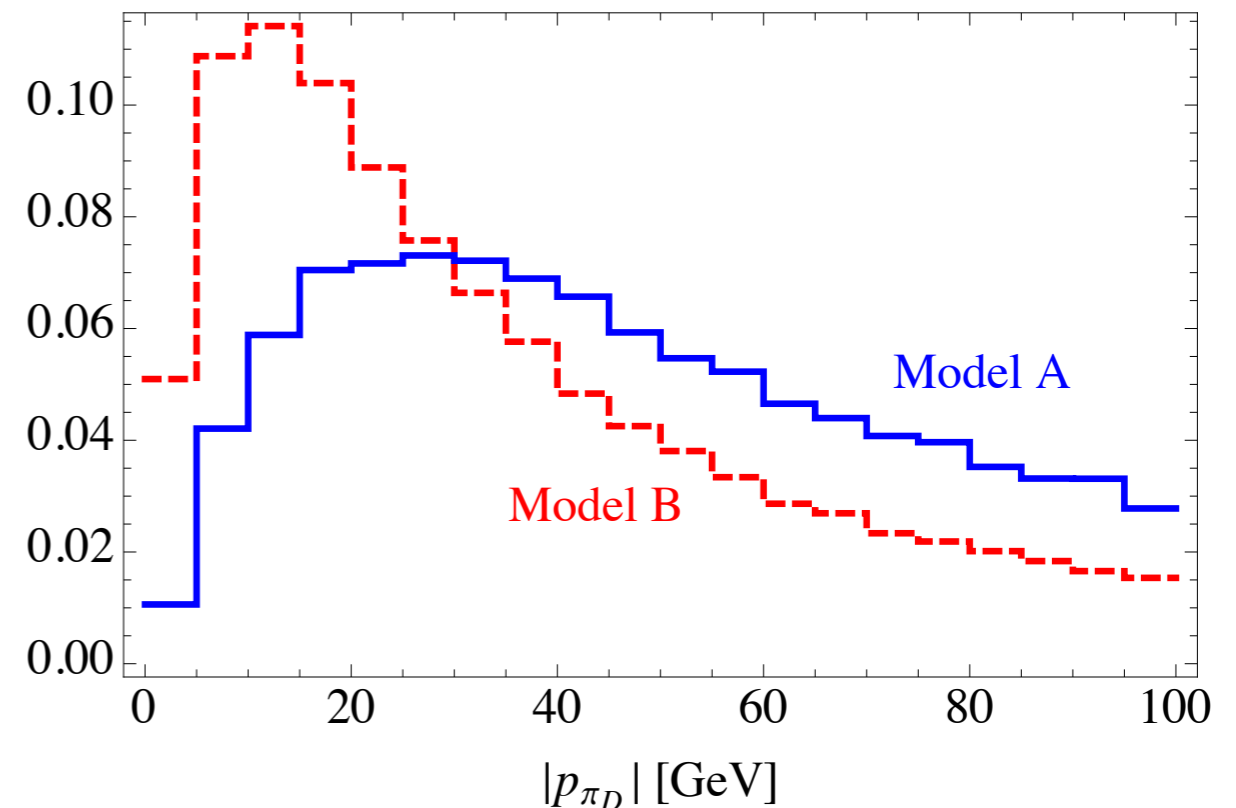
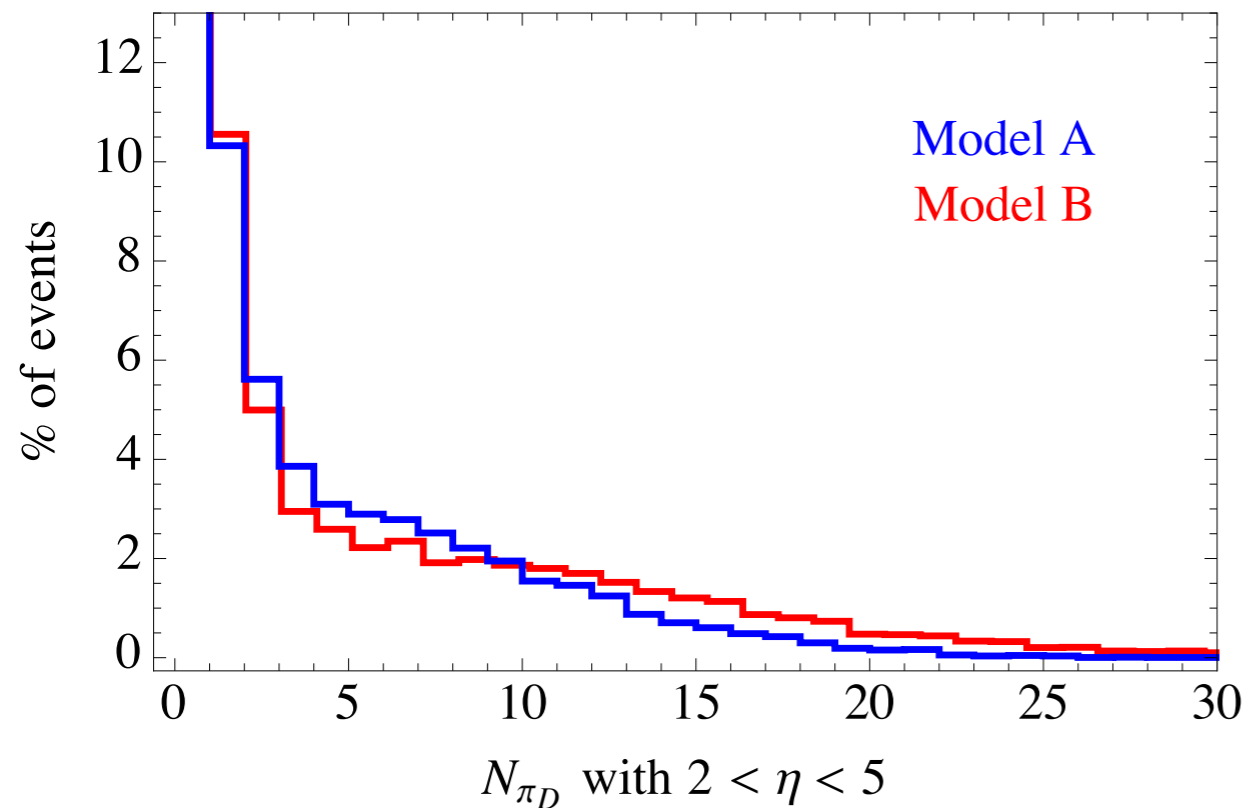
- **Reconstruct individual dark pions**, differentiate using lifetime, mass, decay products
- Emerging jets without (hard) trigger requirements?

Off-shell production



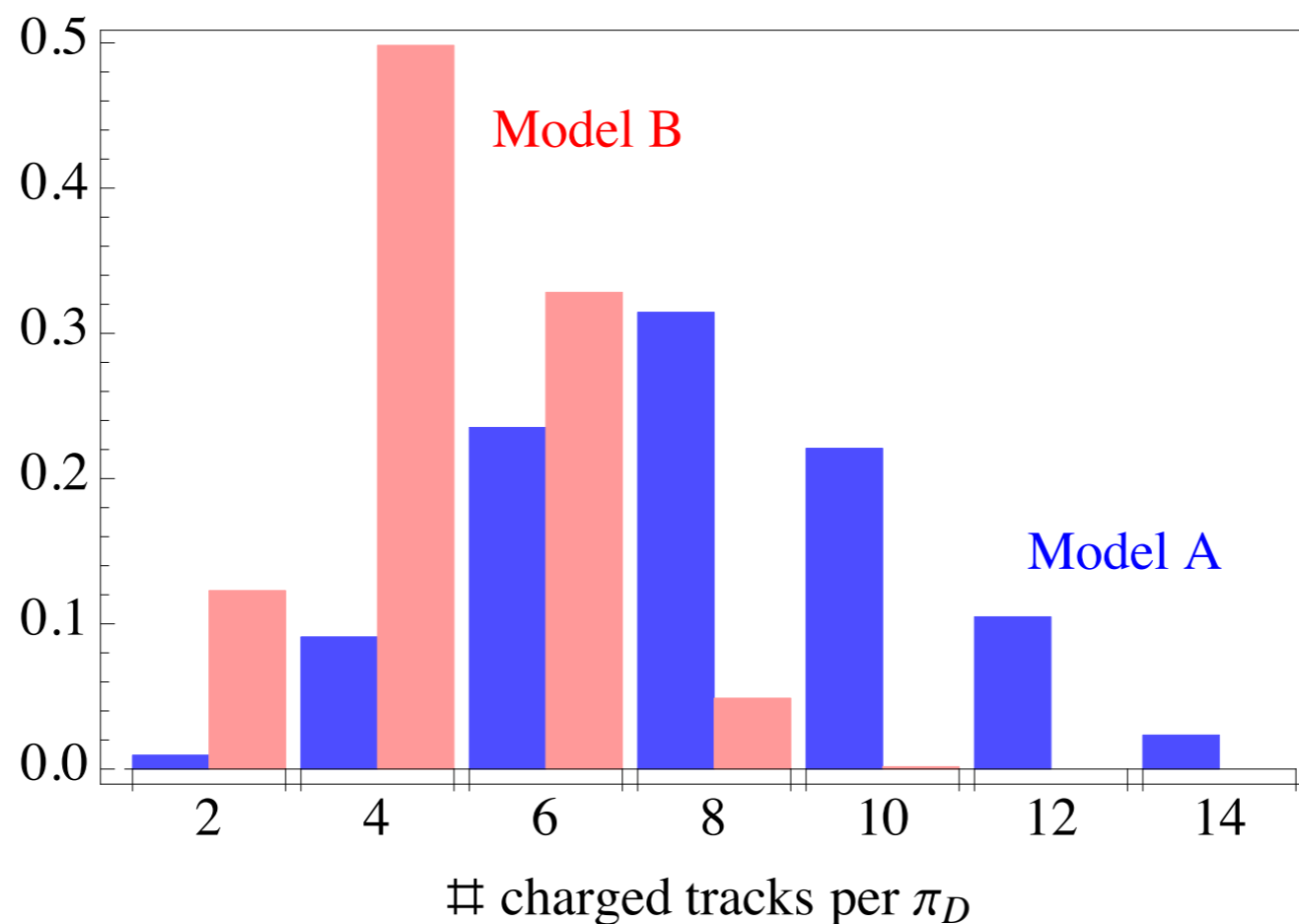
- Total rate: $\sigma(pp \rightarrow \bar{Q}_D Q_D) \approx 8.2 \text{ pb} \times \left(\frac{\text{TeV}}{\Lambda}\right)^4 \times N_d \times N_F$

Forward region



- Fraction of all signal events with N dark pions in $2 < \eta < 5$
- Momentum (not pT) distribution of dark pions in $2 < \eta < 5$

Decay characteristics

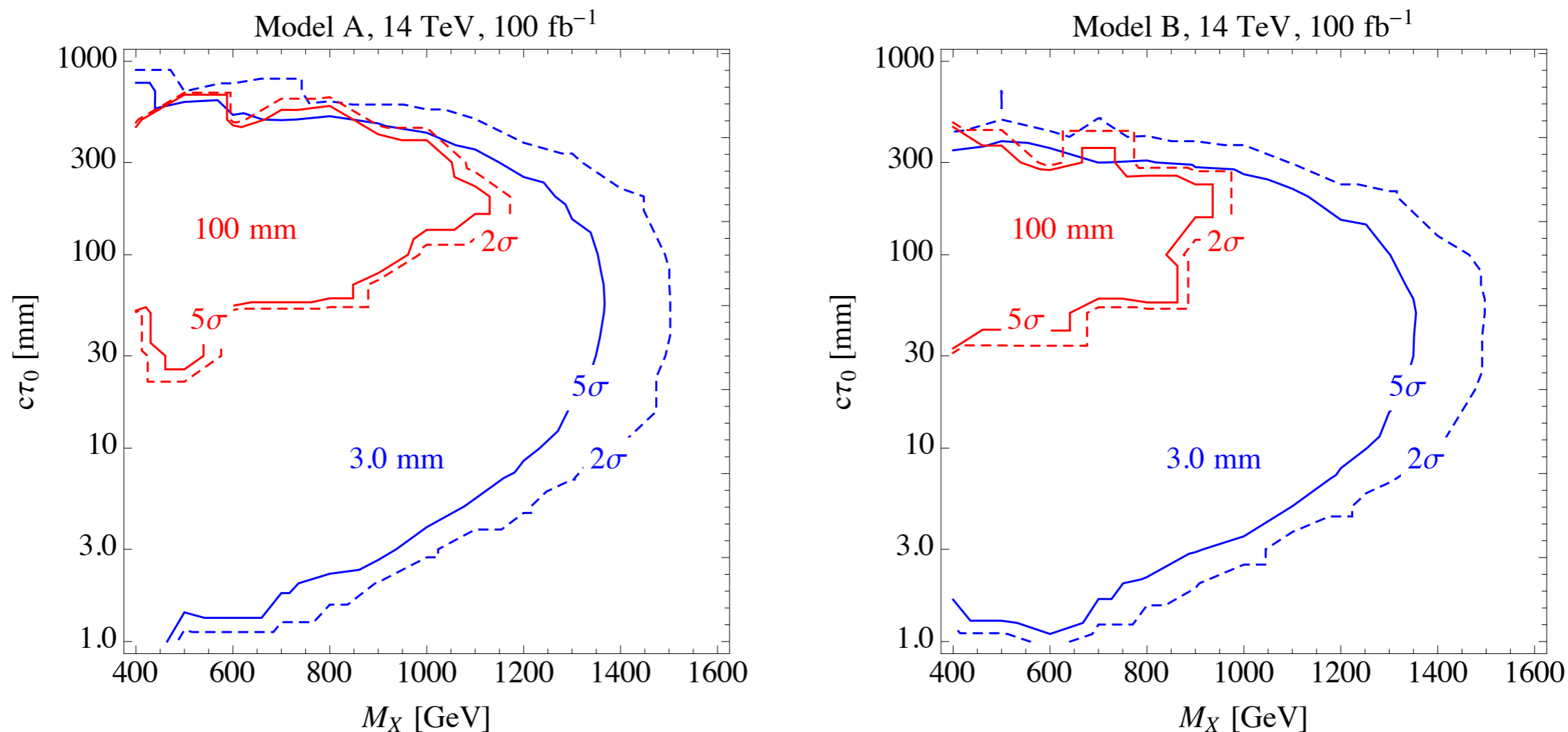


- Number of charged tracks from dark pion decays
- Also depend on flavour structure - some more work!

Very very (very) rough estimate

- 20 inverse fb
 - Assume that events with 3 or more reconstructed dark pions are significantly different from QCD (i.e. no background)
 - 10% reconstruction efficiency
- ➔ Sensitivity to $\sigma = 8 \text{ fb}$, corresponds to $\Lambda \approx 5 \text{ TeV}$

Reach ATLAS/CMS



- Optimistic scenario (no non-collisional BGs)
- Also sensitive to some RPV SUSY models etc