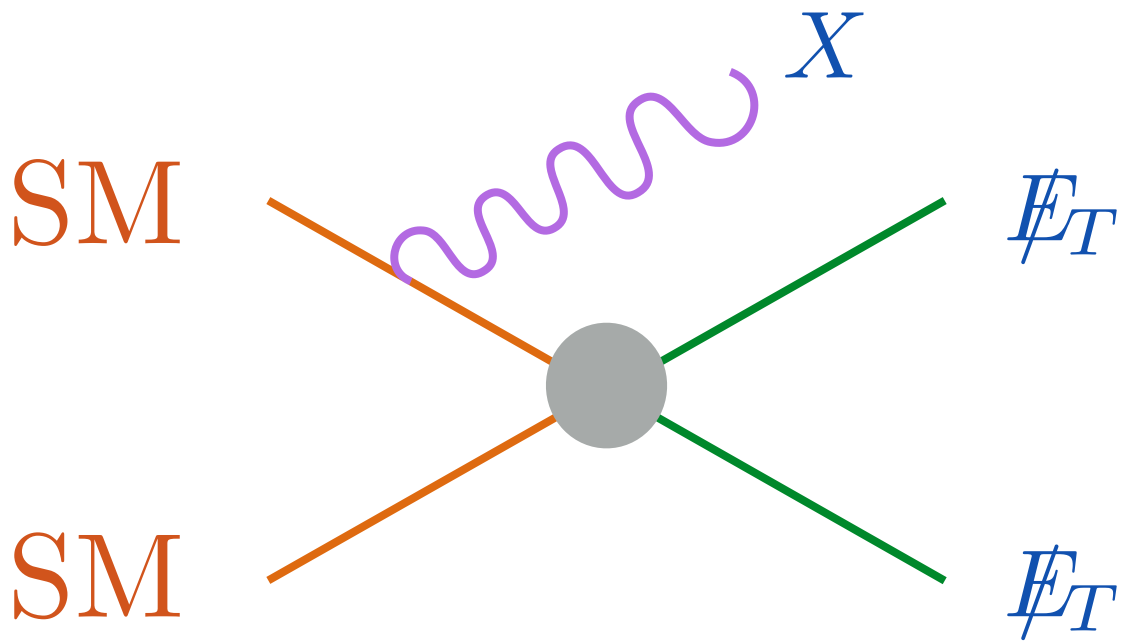
Dark Matter at Colliders

Pedro Schwaller (Mainz University)

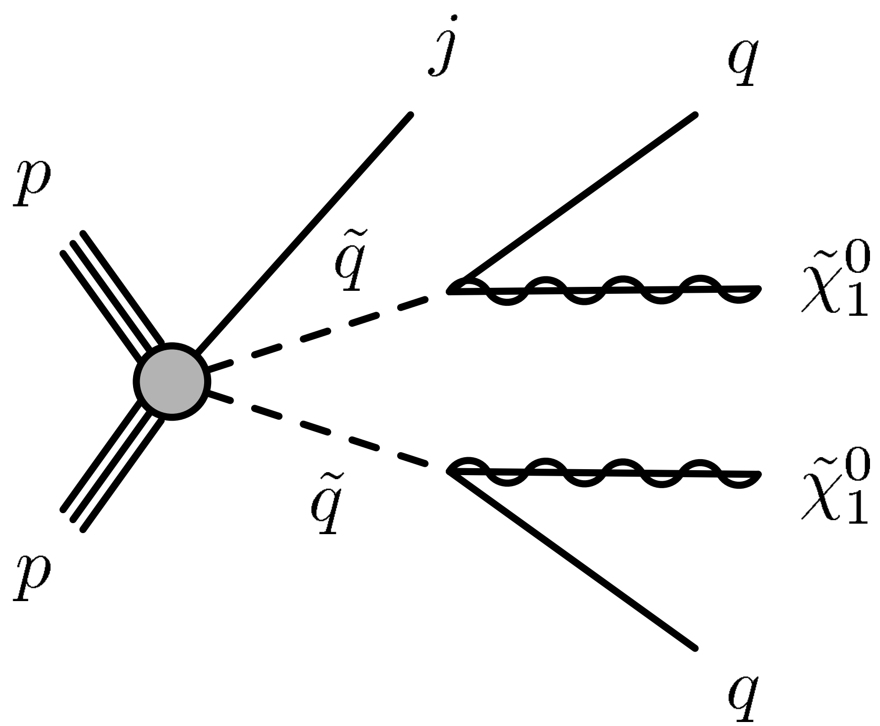
Les Rencontres de Physique de la Vallée d'Aoste
March 2, 2018

DM Production

- Direct

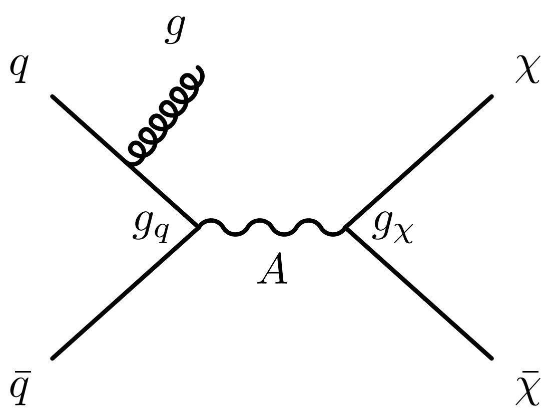


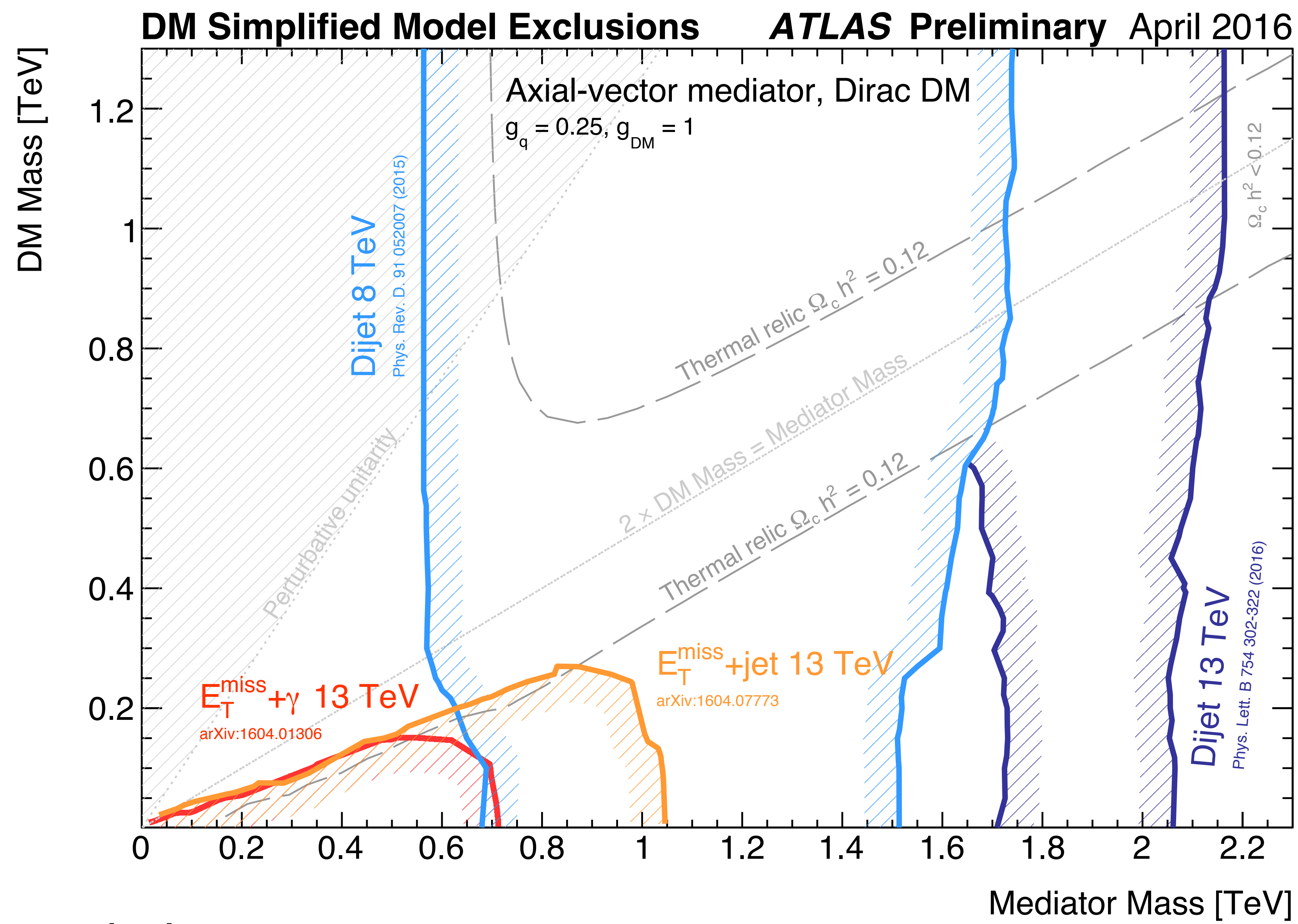
- As decay product



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

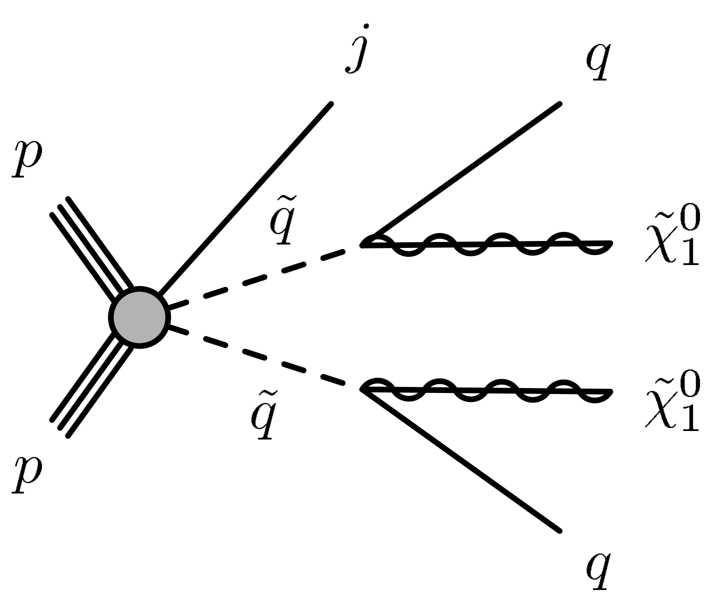
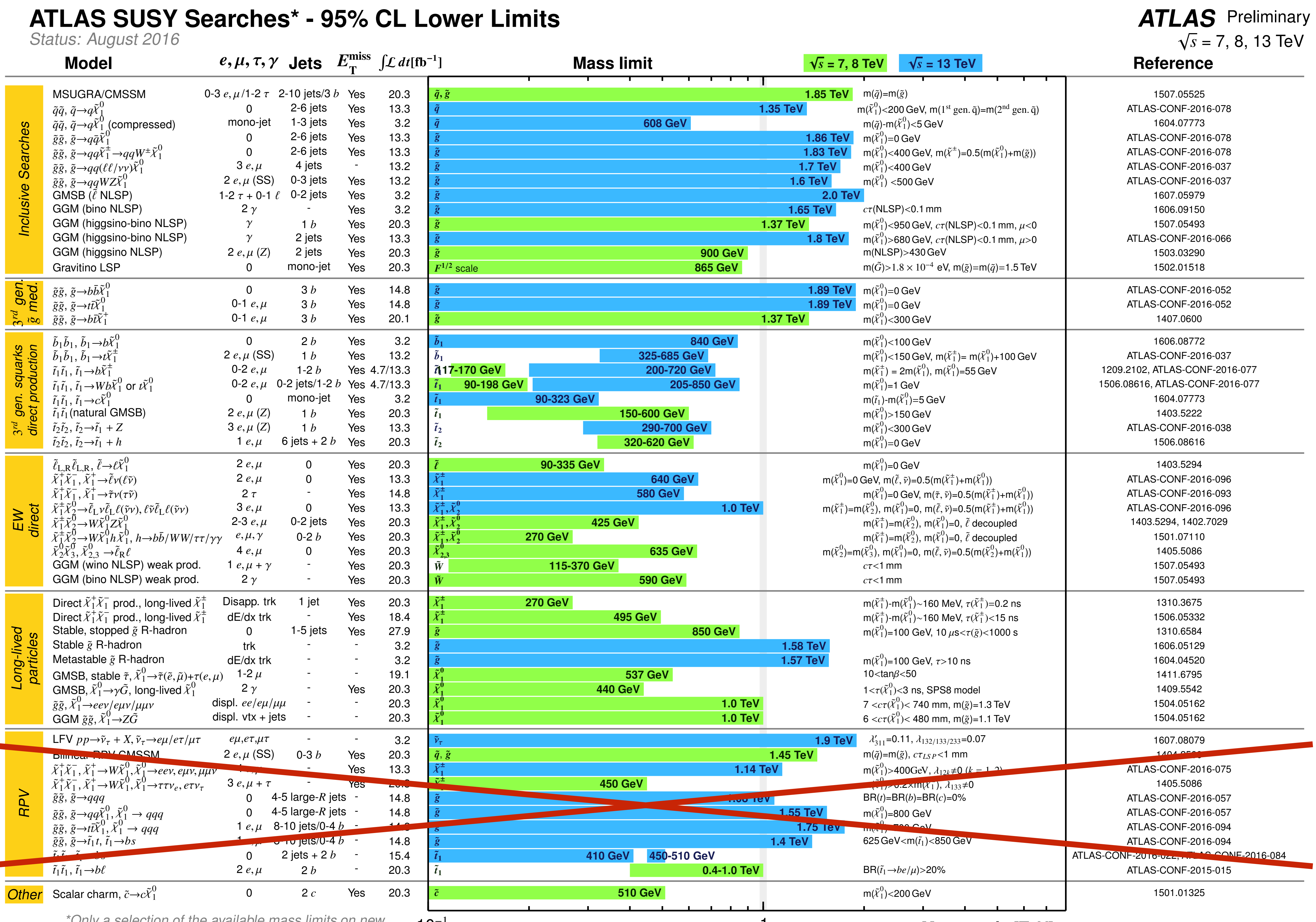


diagram from 1604.07773

SUSY DM Searches

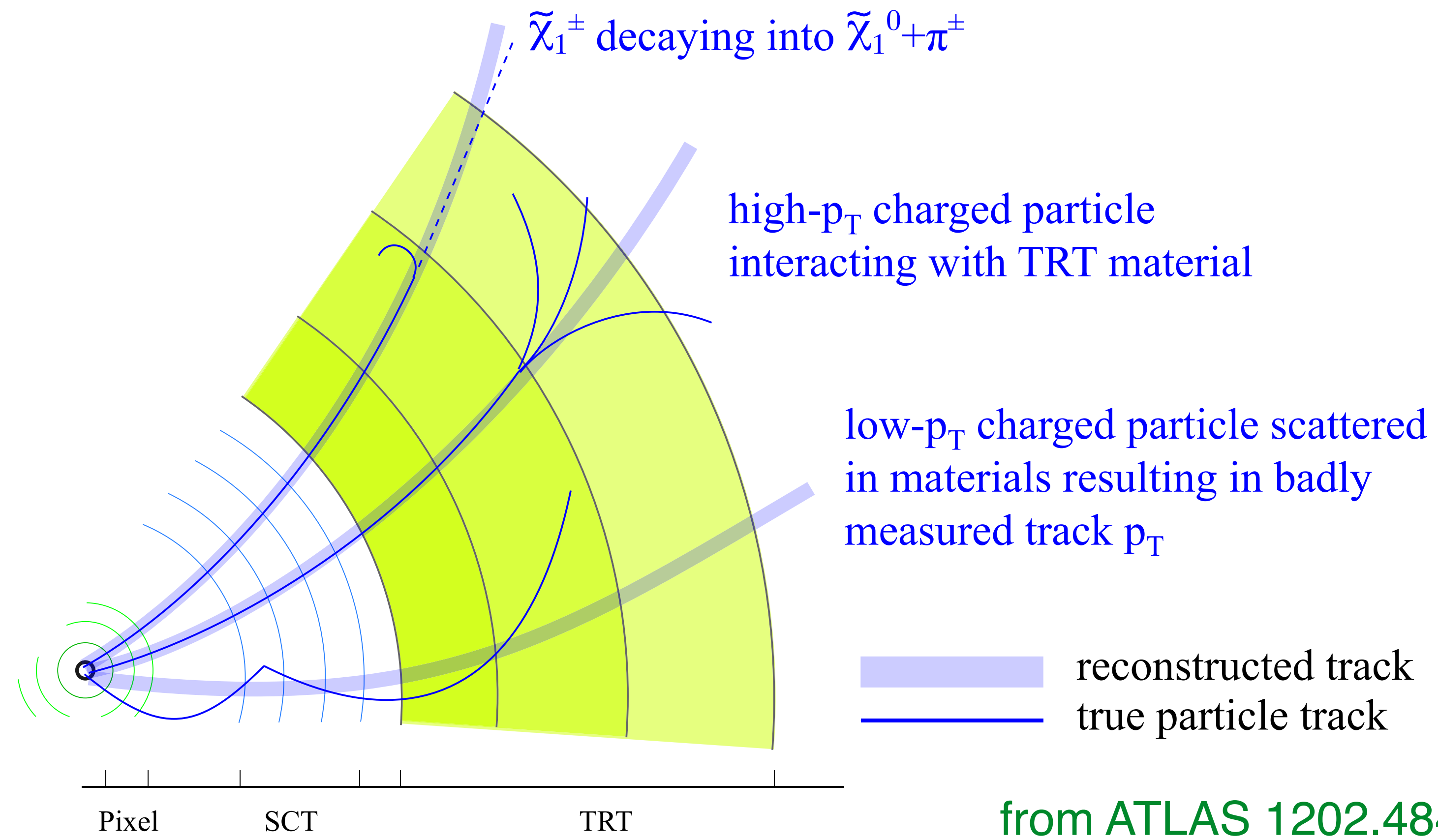


Indirect DM production

- 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

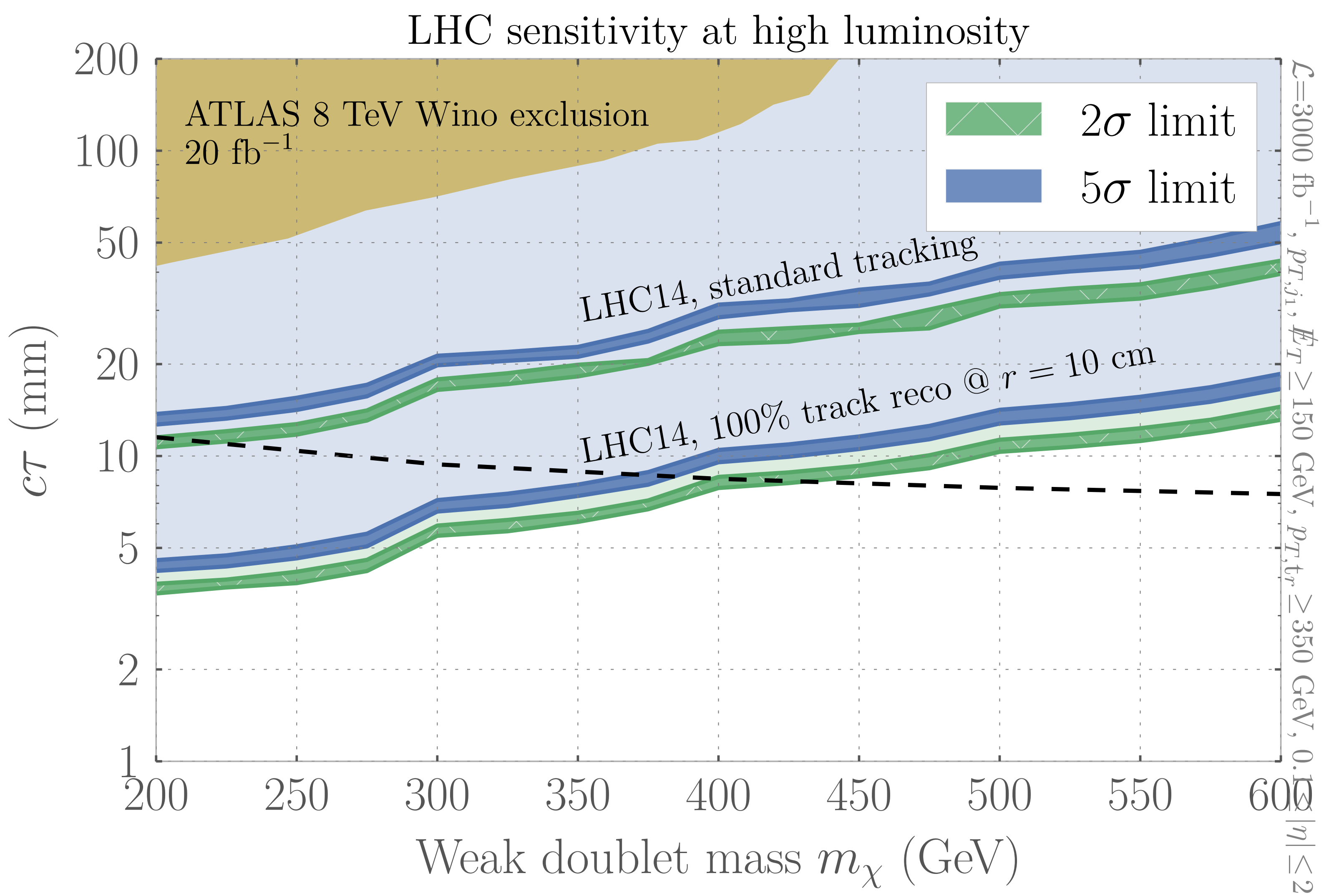
- Minimal SU(2) doublet or triplet DM (Wino/Higgsino)
- DM state accompanied with nearly degenerate charged state (chargino)
- Lifetime few cm → disappearing charged track
- Strongest limit on Wino DM



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!

Mahbubani, PS, Zurita, 2017

Example of lifetime frontier!

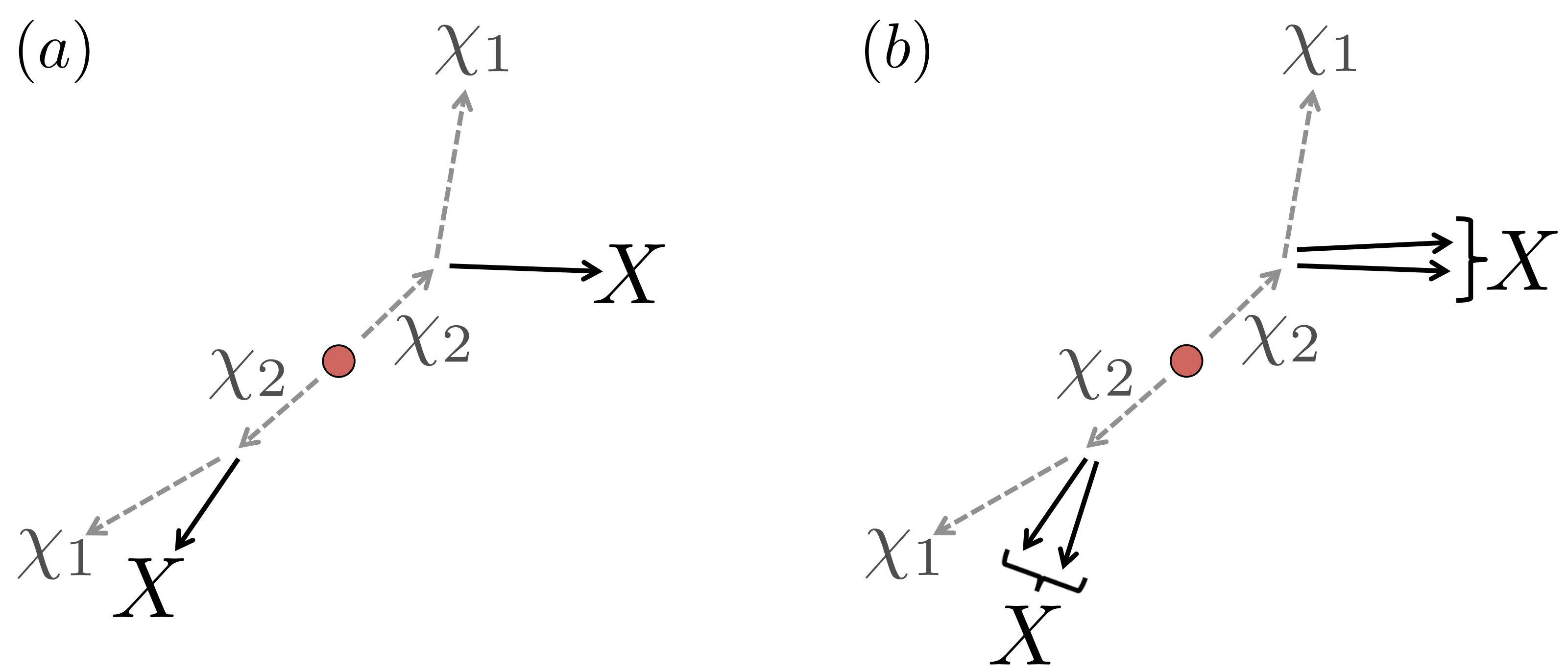
Explore with simplified models

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 $m_2 > m_{\rm DM}$
  - Lifetime $\Gamma(\chi_2 \to \chi_1 X)$
- Underlying models e.g. “GMSB SUSY”, freeze-in DM, twin Higgs dark sectors

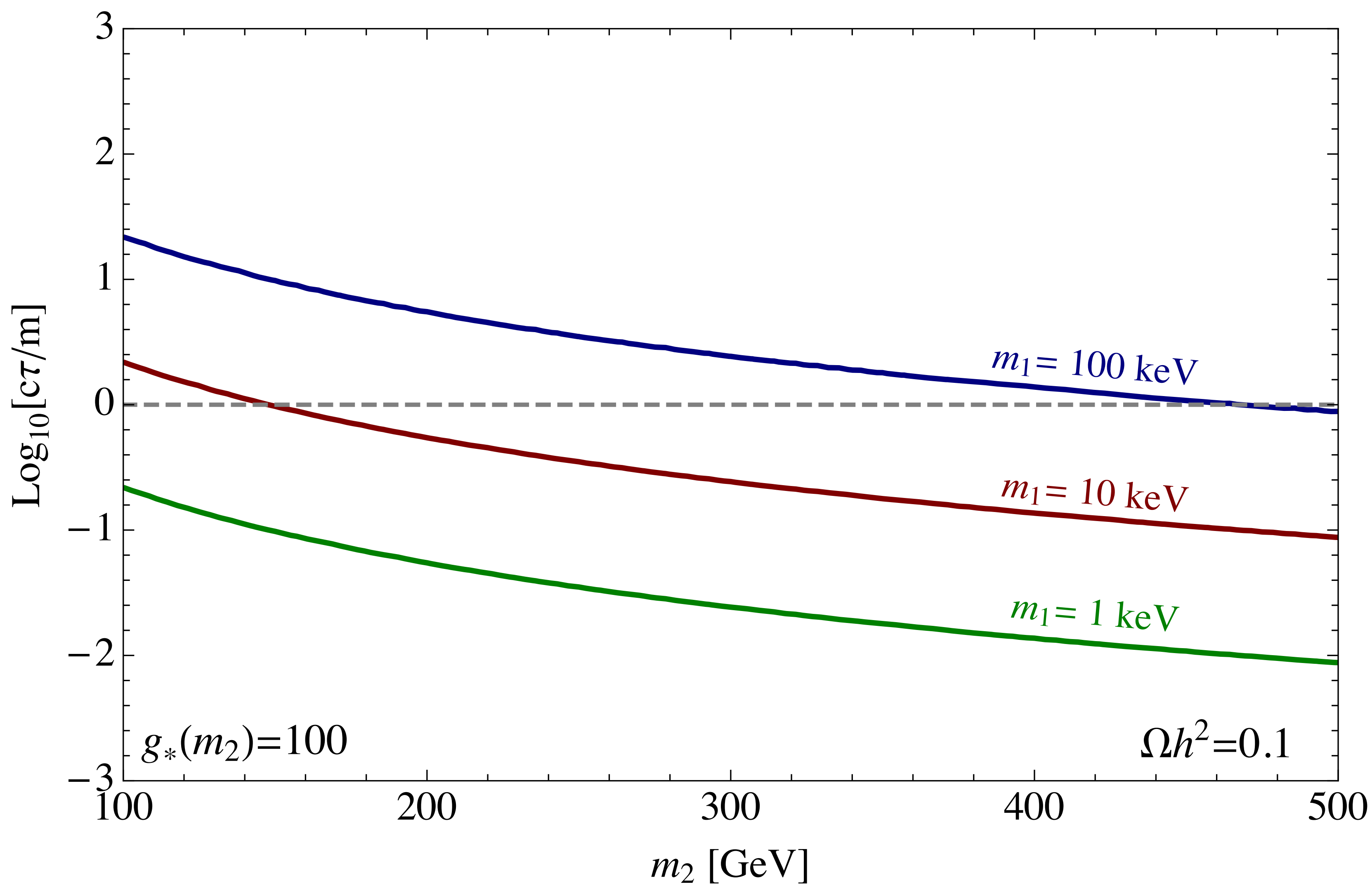
Buchmuller, De Roeck, Hahn, McCullough, PS, Sung, Yu, 2017

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

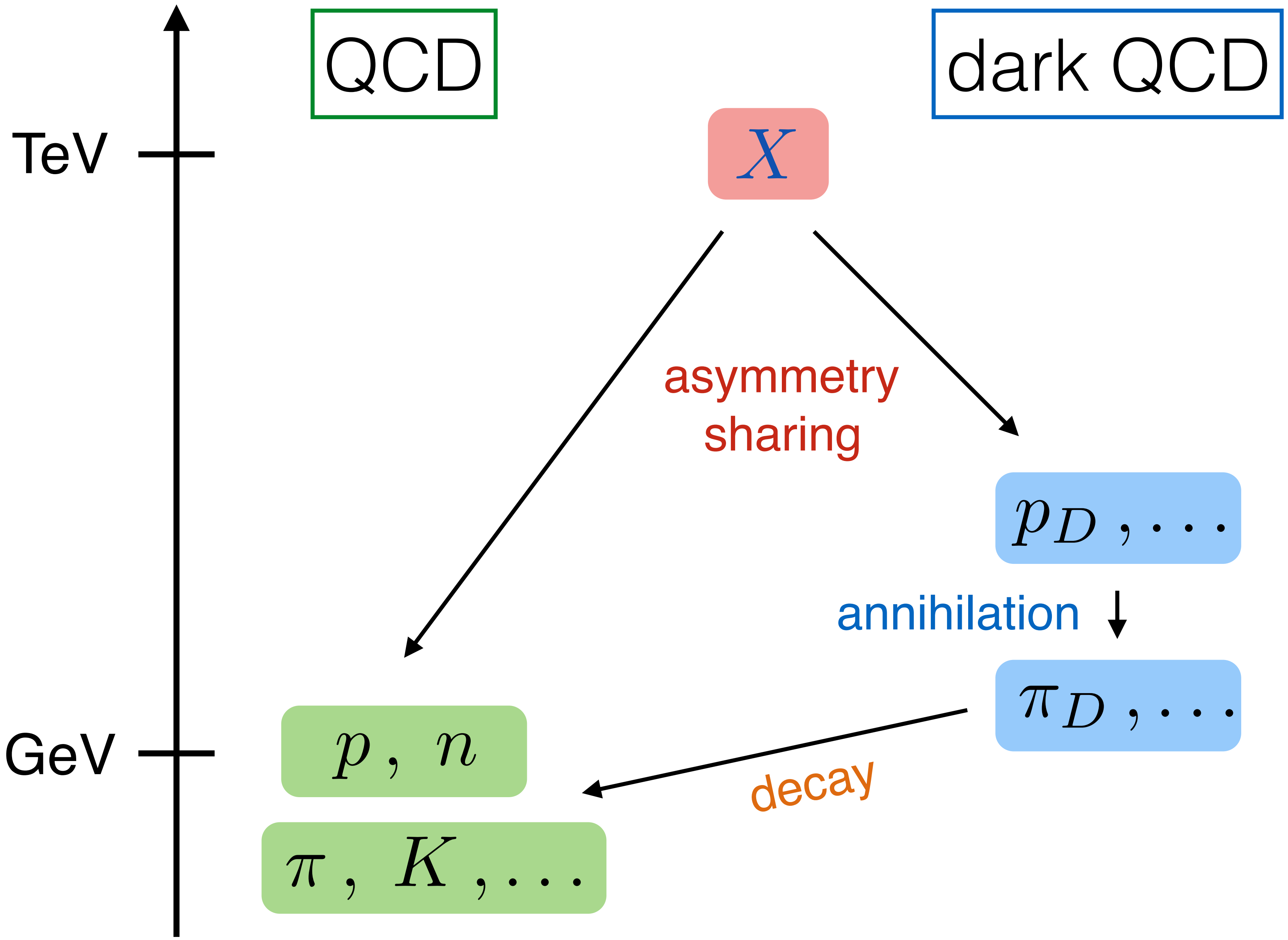


- Centimetre to metre lifetimes consistent with freeze-in DM relic abundance (solid lines)

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

Composite dark sectors

Dark QCD



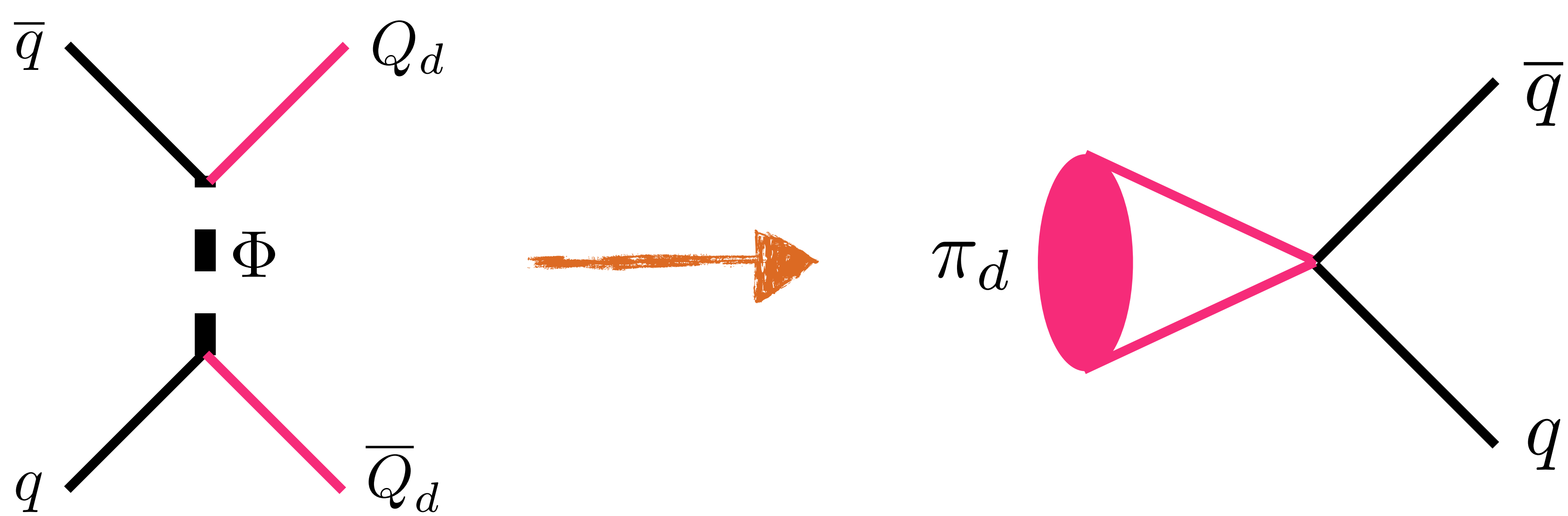
- SU(N) dark sector with neutral "dark quarks"
- Confinement scale

$$\Lambda_{\mathrm{darkQCD}}$$

- DM is composite "dark proton"
- "Dark pions" unstable, long lived

Dark Pion Lifetime

- Integrate out mediator, match to dark pion current



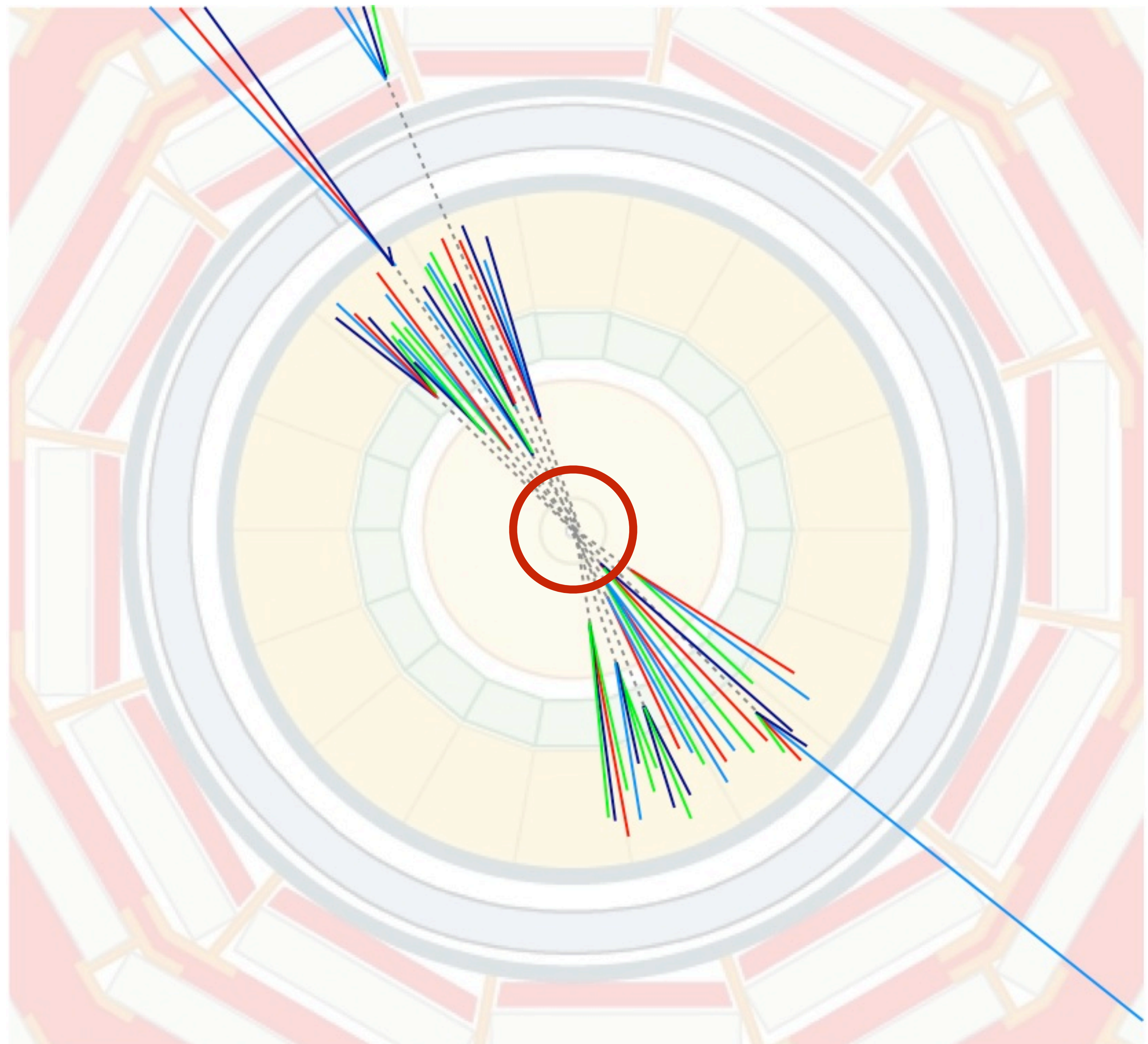
- Decay to SM jets (pions)

$$\Gamma(\pi_d \to \bar{d}d) \approx \frac{f_{\pi_d}^2 m_{\mathrm{d}}^2}{32\pi M_{X_d}^4} m_{\pi_d}$$ ~ cm

Decay in LHC detectors!

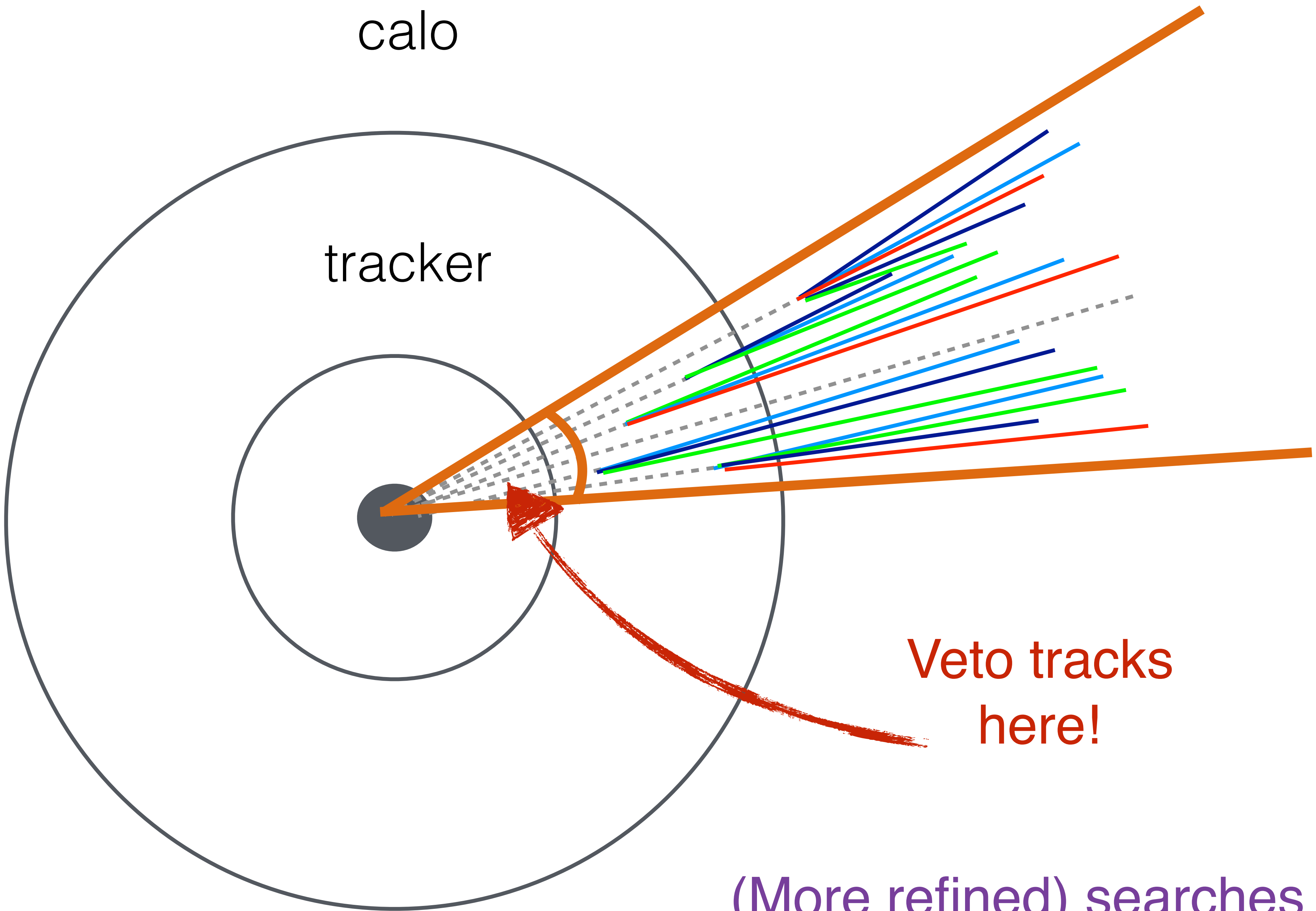
Emerging Jets at the LHC

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



PS, Stolarski, Weiler, 2015

Strategy



(More refined) searches ongoing at ATLAS/CMS

PS, Stolarski, Weiler, 2015

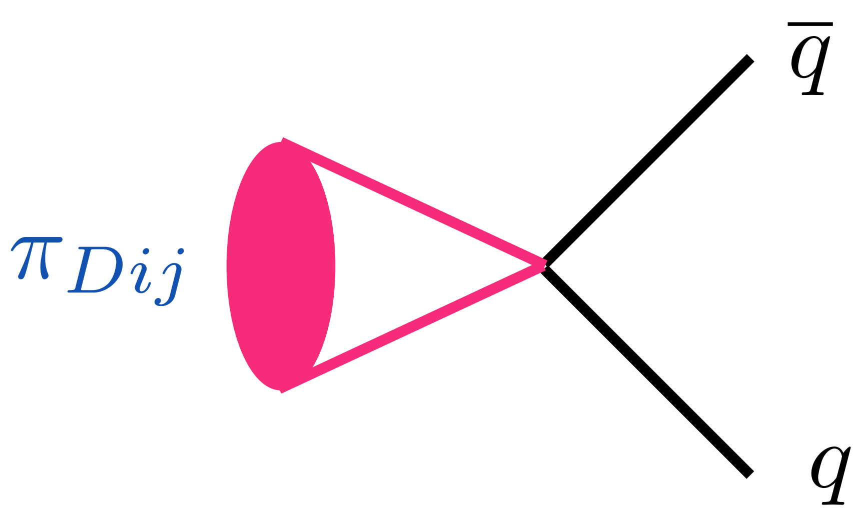
Adding flavour

- 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:

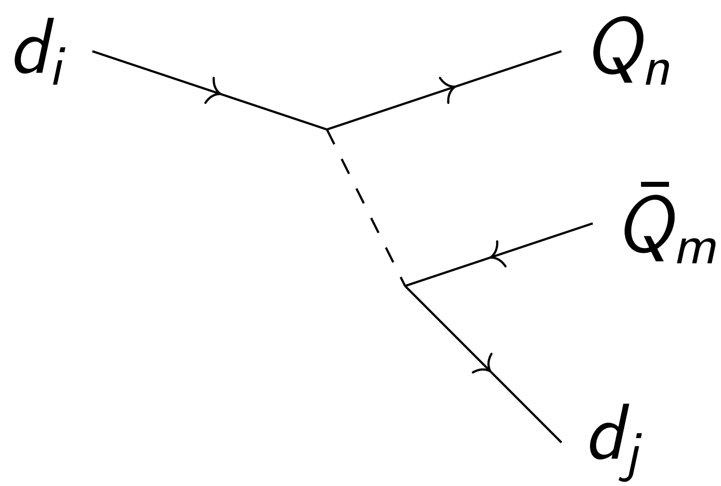


$$\propto \sum_{q,q'} |\lambda_{qi} \lambda^*_{q'j}|^2$$

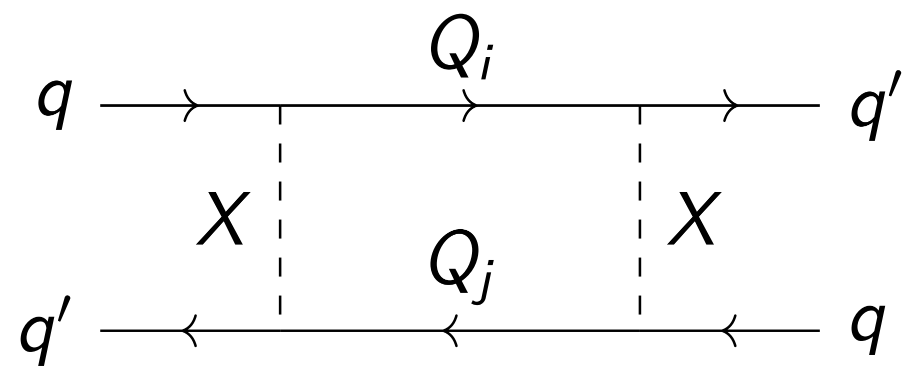
S. Renner, PS, in progress

S. Renner, PS, in progress

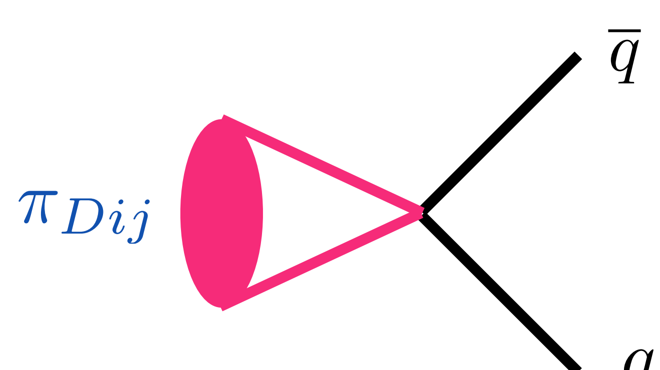
Flavour matters



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



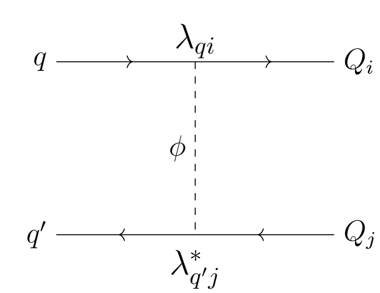
$$\lambda_{ij}\bar{d}_{Ri}Q_{Lj}\Phi$$



dark pion properties

fixed target experiments

NA62



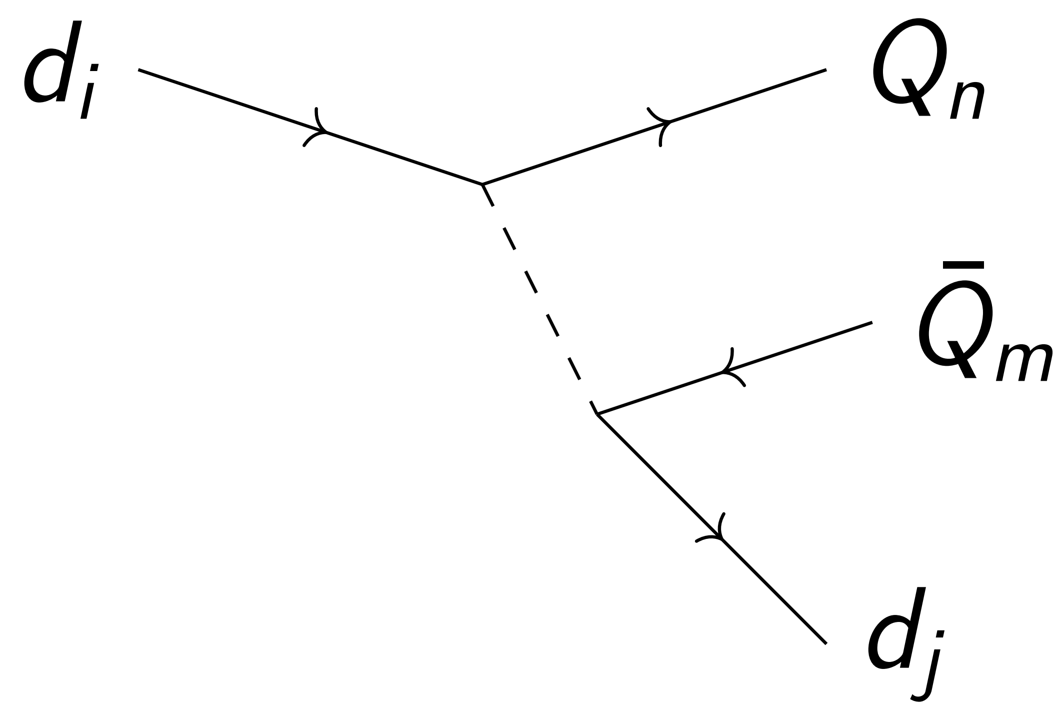
SHiP
Search for Hidden Particles

Rare decays

- Allows rare decays

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

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



- Strongest close to thresholds:
  $K \to \pi\,\pi_D$ wins over $K \to \pi\, Q\bar{Q}$

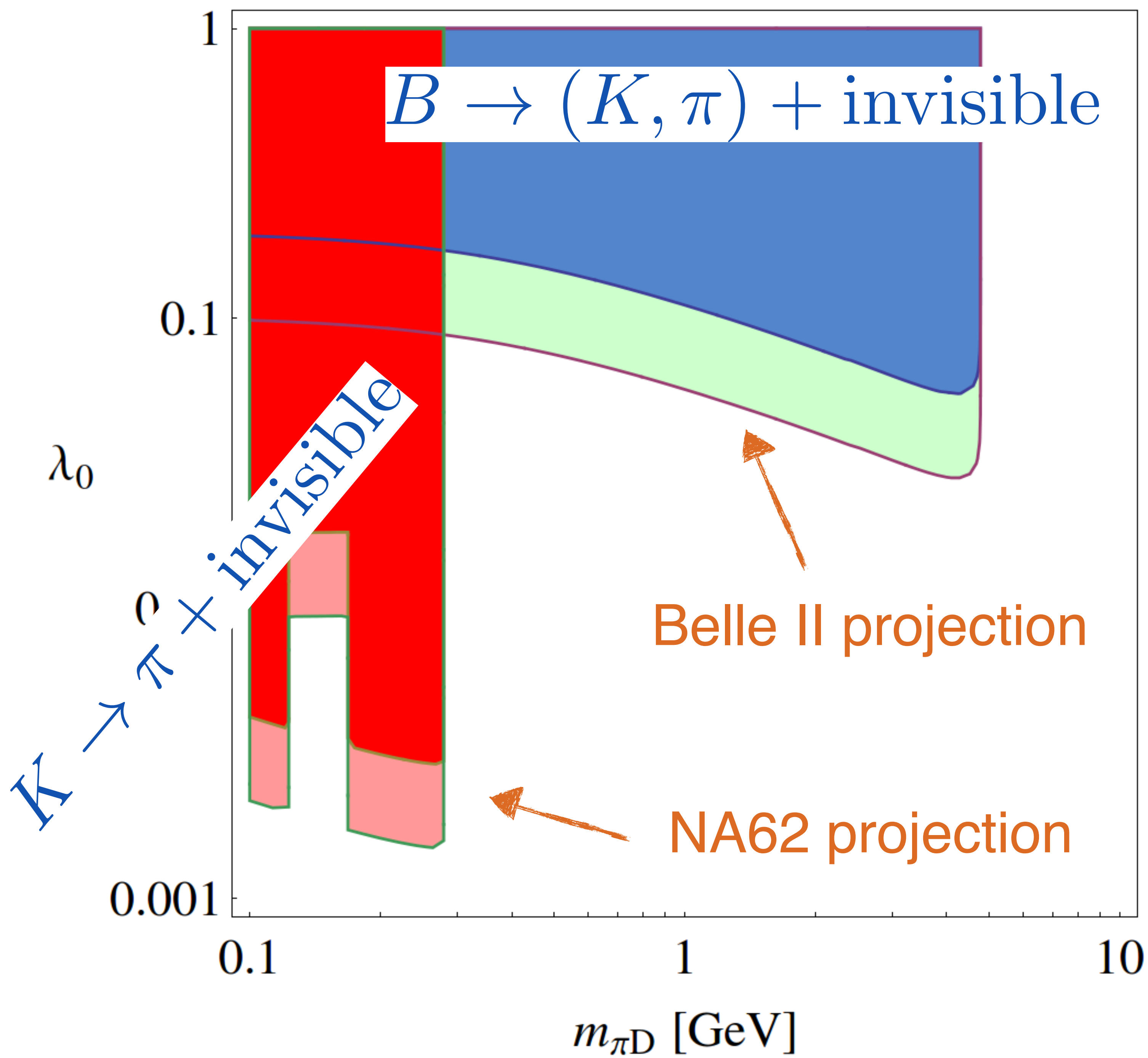
- Don't vanish in flavour symmetric limit!

S. Renner, PS, in progress

great resource:
Kamenik, Smith, 2011

Bounds from rare decays

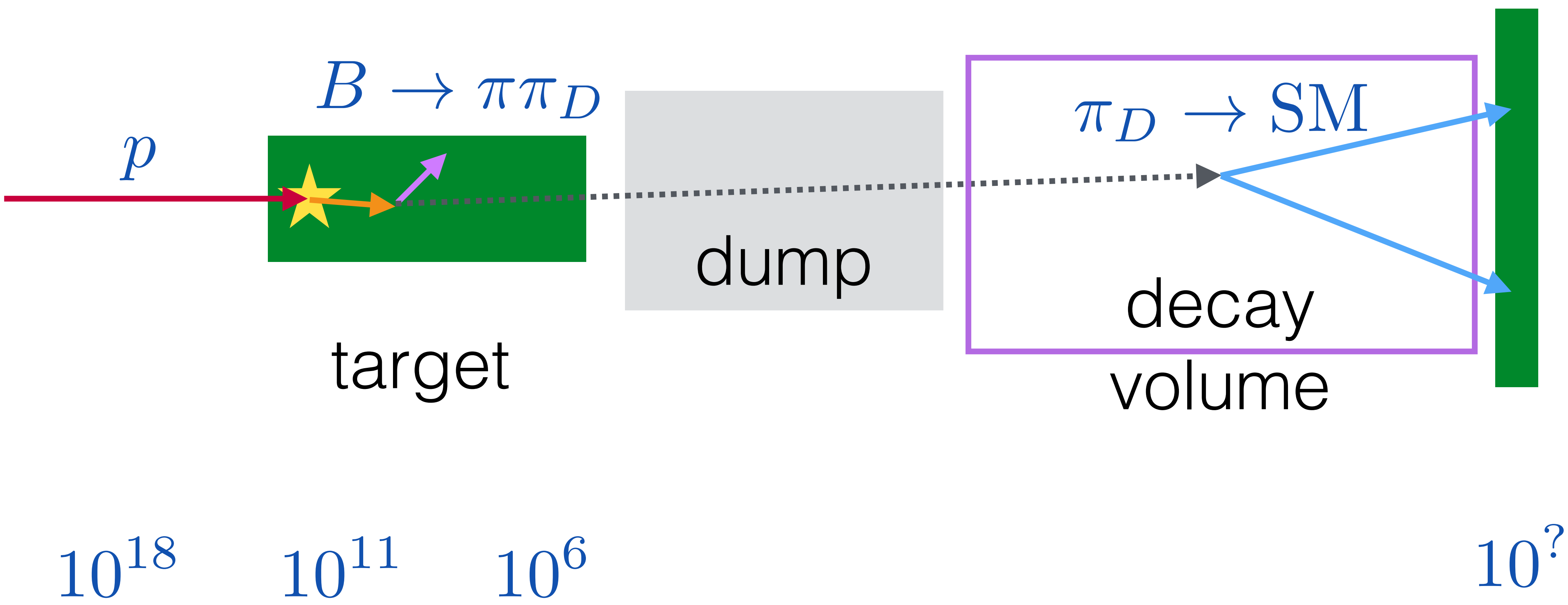
- Best bound on couplings for very light dark pions
- Dark pion production in fixed target expts!



S. Renner, PS, in progress

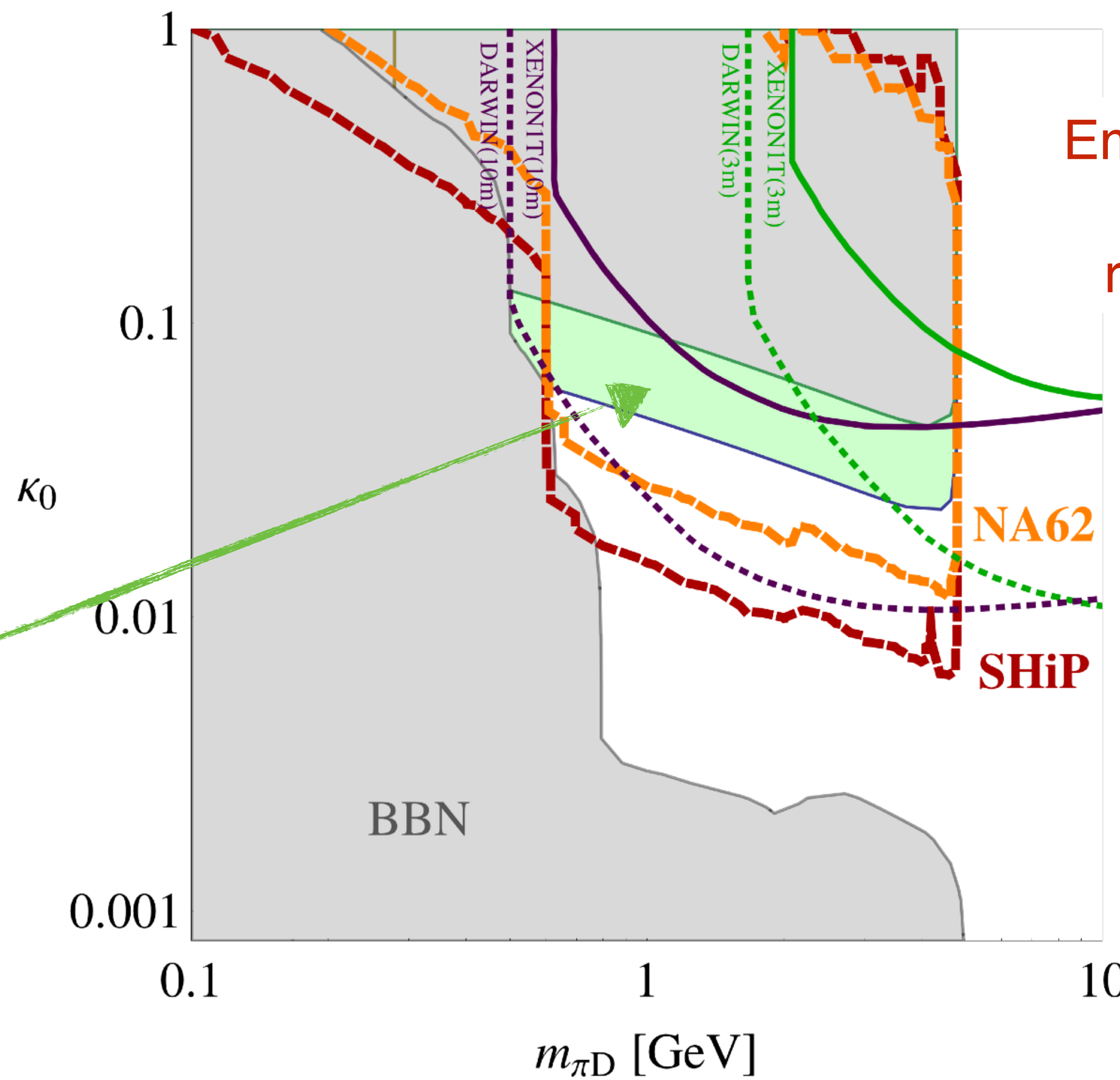
Fixed target

- My simplified NA62/SHiP:



Fixed target reach

- Including bounds from cosmology



Emerging jets region

Belle II reach

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

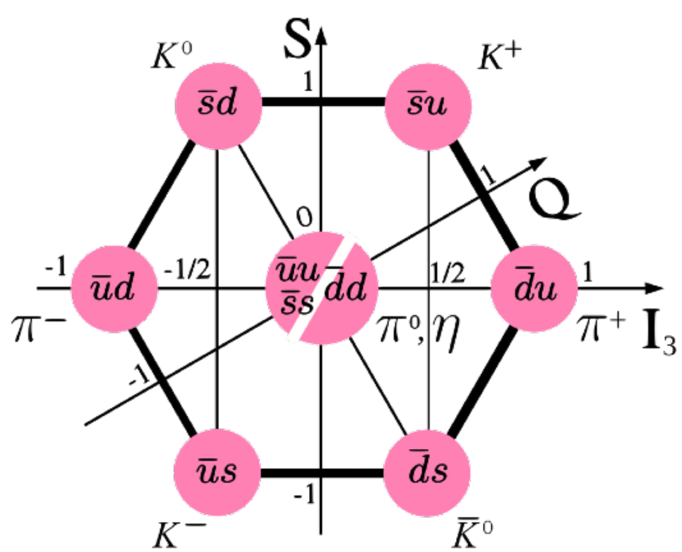
Particles and symmetries

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

Ansatz: 3 dark quark flavours Q_i

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

$\implies$ 8 DARK PIONS



Lightest baryon "dark proton"
Charged under $U(1)_B \implies$ stable

Dark quark flavour symmetry broken only by λ_{ij}

Dark Pion Lifetime

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

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

Decay in LHC detectors!

Flavour constraints

- Parameterise

Parameterisation from Agrawal, Blanke, Gemmler, 2014

unitary

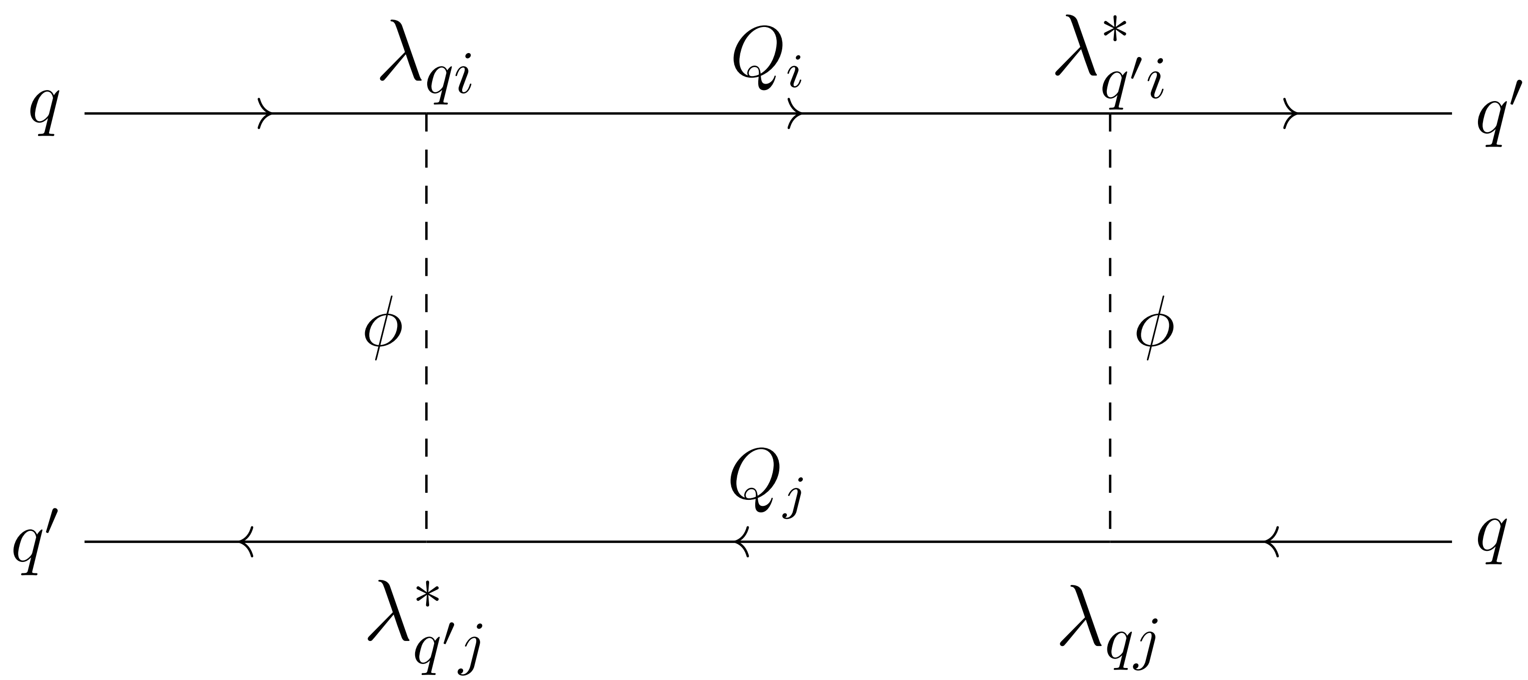
$$\lambda = UDV$$

diagonal

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

S. Renner, PS, in progress

ΔF=2



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

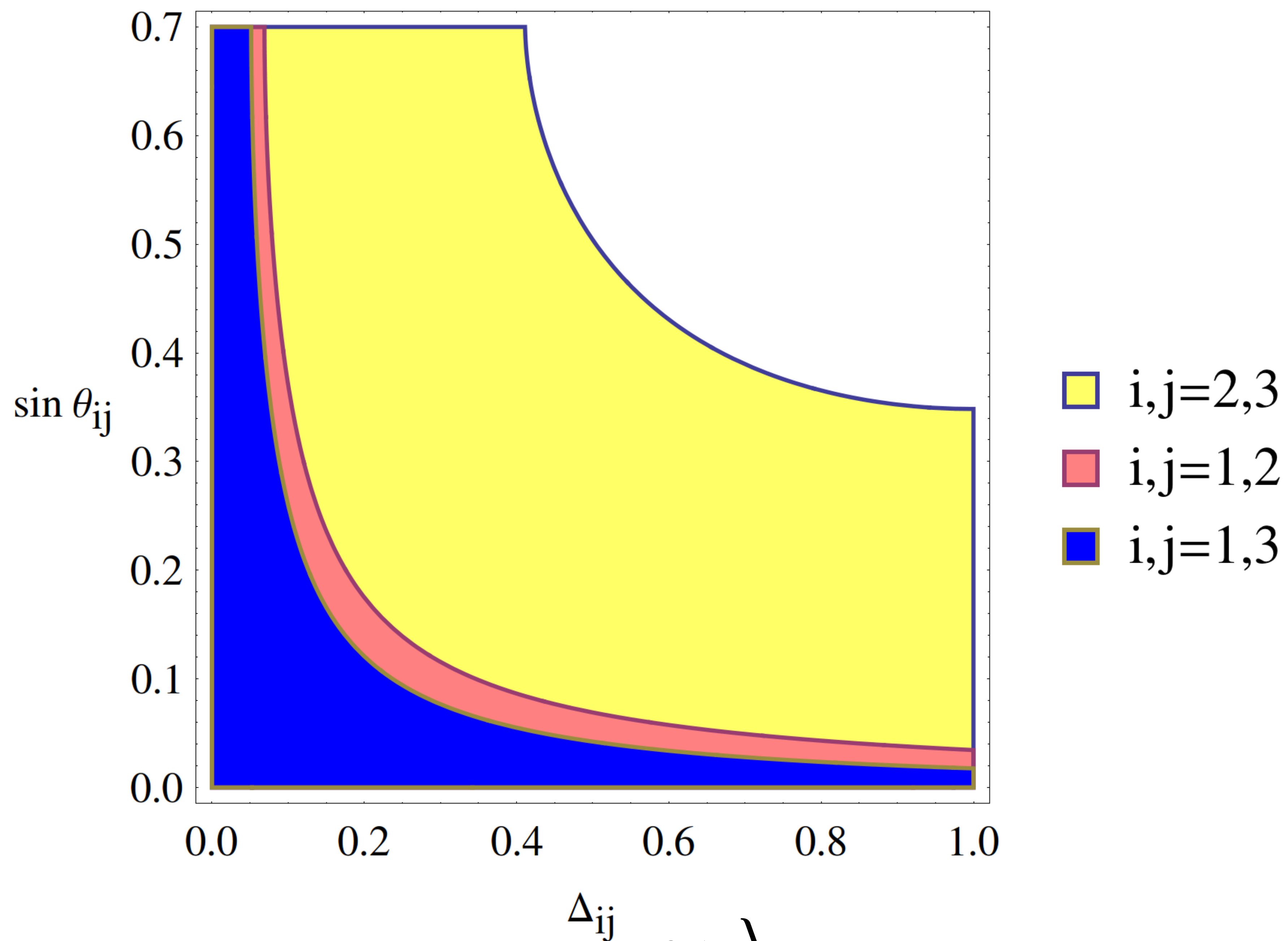
$$\left(\sum_{i=1}^{3} \lambda_{qi}\lambda^*_{q'i}\right)^2 = \left([UD(UD)^\dagger]_{qq'}\right)^2 = \lambda_0^4\left([UU^\dagger]_{qq'}\right)^2 = 0$$

S. Renner, PS, in progress

ΔF=2

- Otherwise bounds on mixing matrix

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

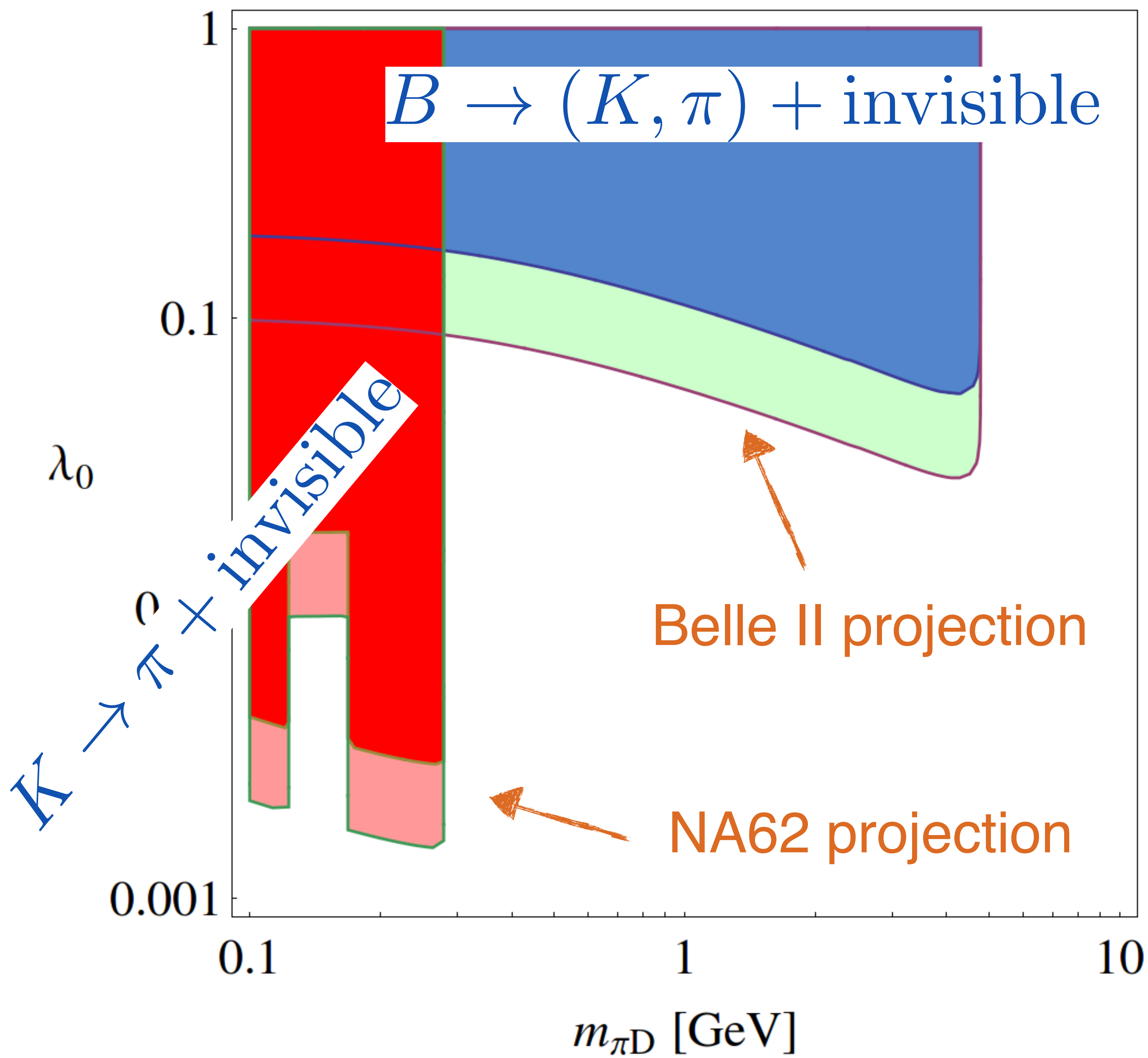


$\sim \lambda_{1,2}$

S. Renner, PS, in progress

ΔF=1

- Best bound on couplings for very light dark pions

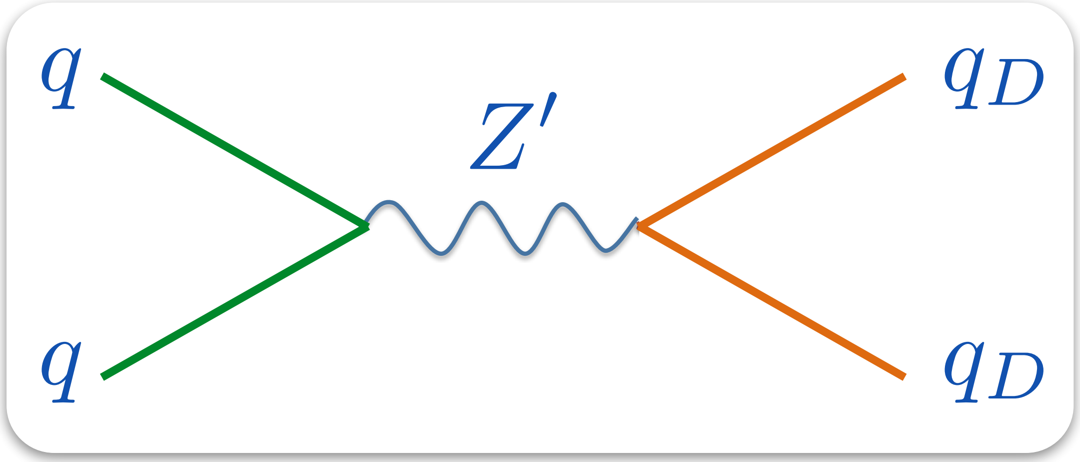


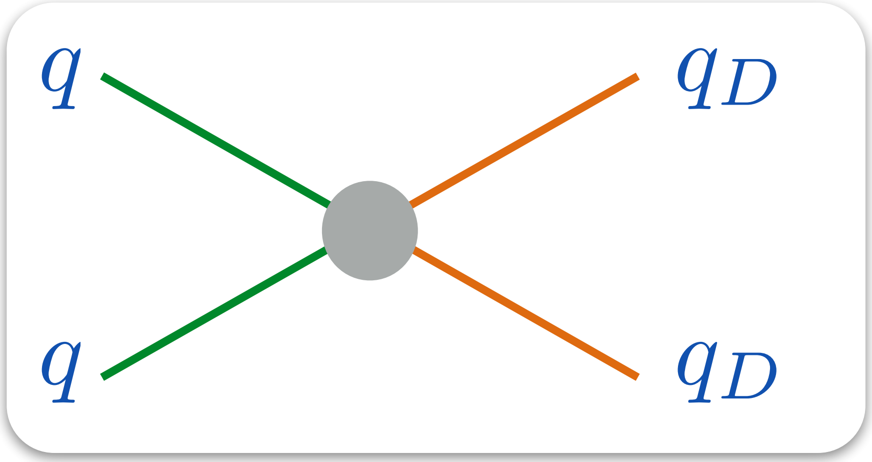
S. Renner, PS, in progress

PS, Stolarski, Weiler, in progress

LHCb opportunities

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

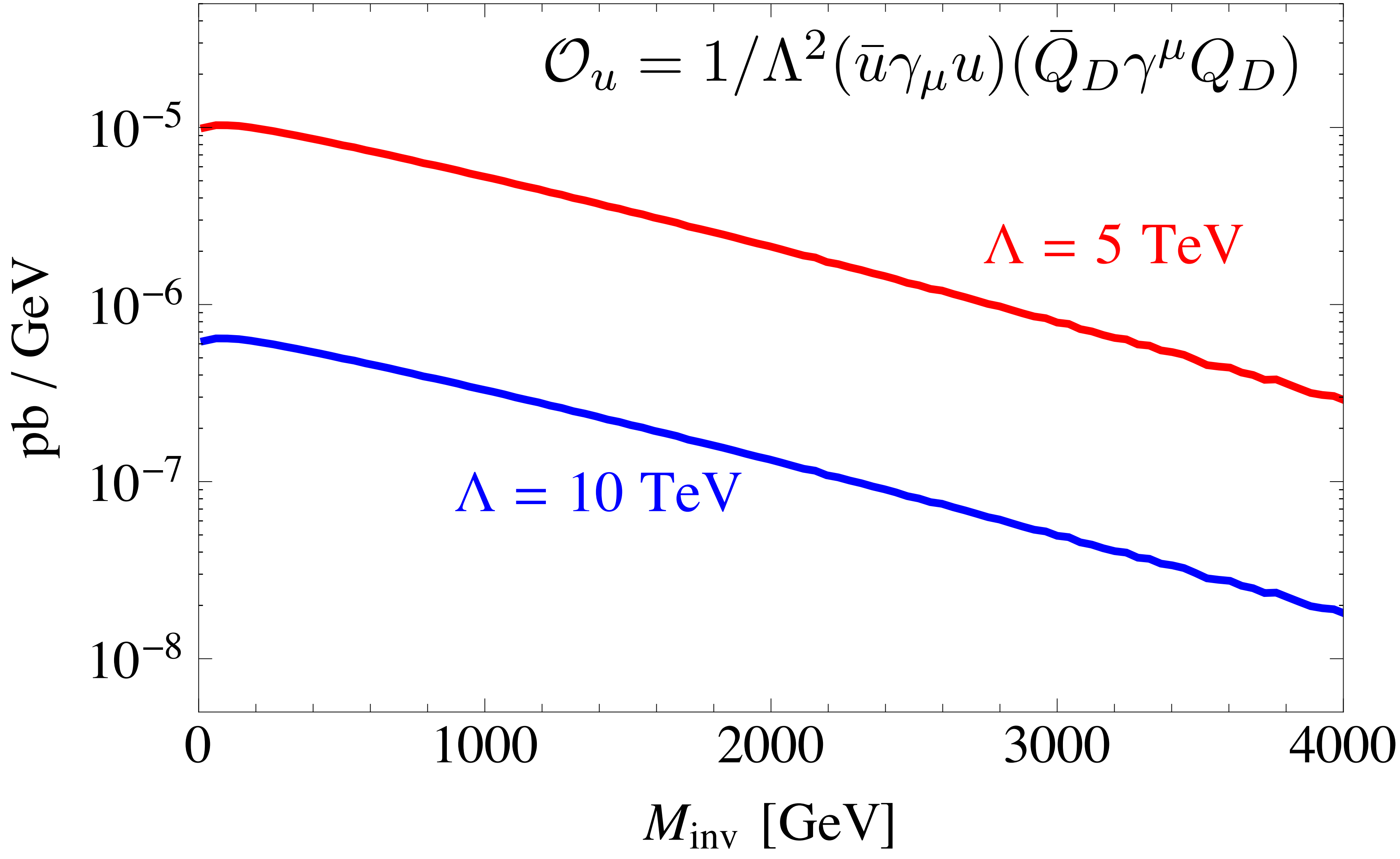




- Reconstruct individual dark pions, differentiate using lifetime, mass, decay products

- Emerging jets without (hard) trigger requirements?

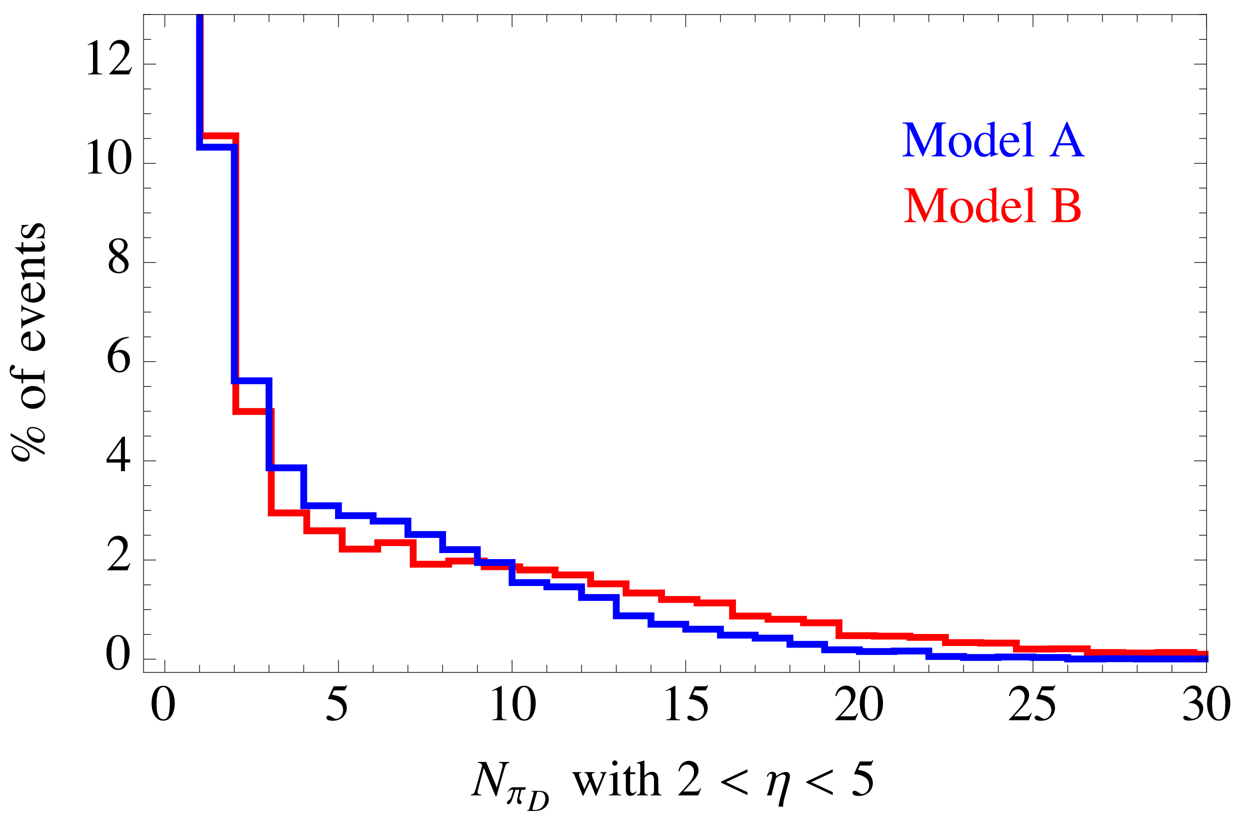
Off-shell production

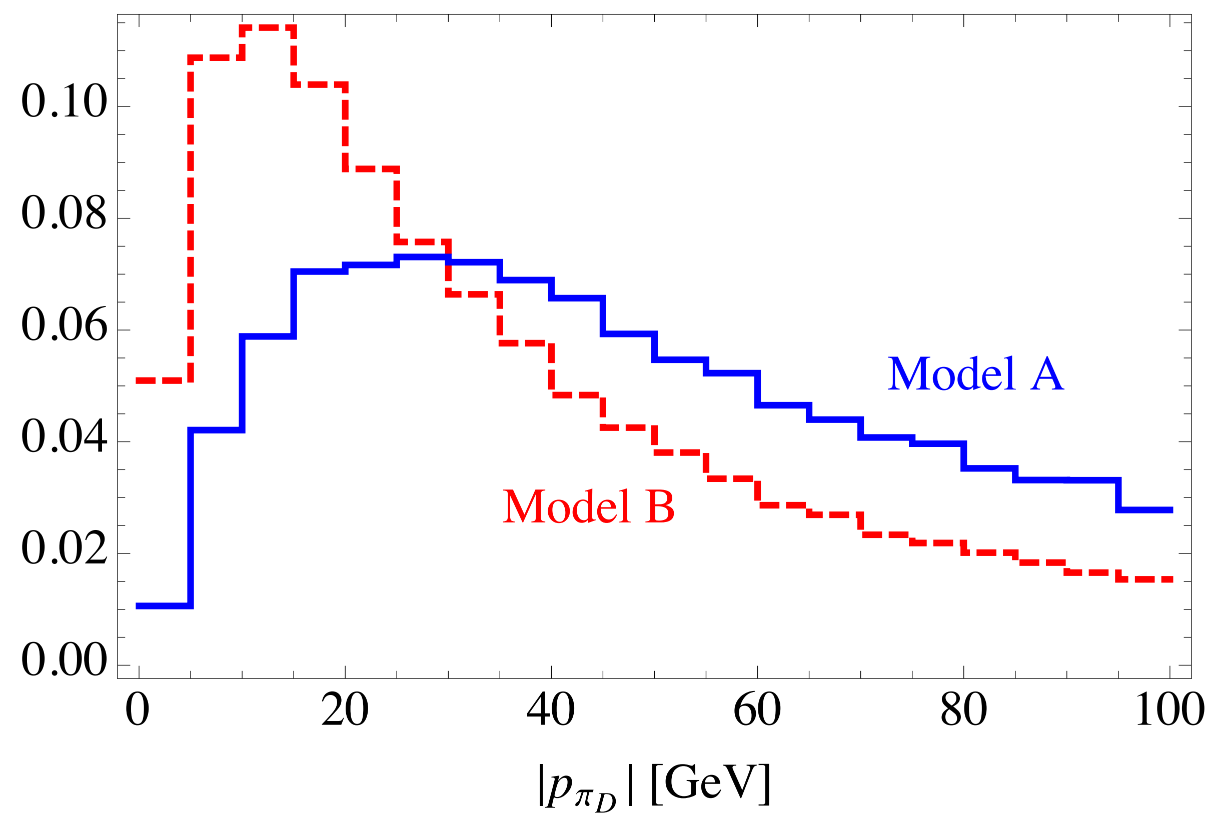


- Total rate: $\sigma(pp \to \bar{Q}_D Q_D) \approx 8.2\ \mathrm{pb} \times \left(\frac{\mathrm{TeV}}{\Lambda}\right)^4 \times N_d \times N_F$

PS, Stolarski, Weiler, in progress

Forward region

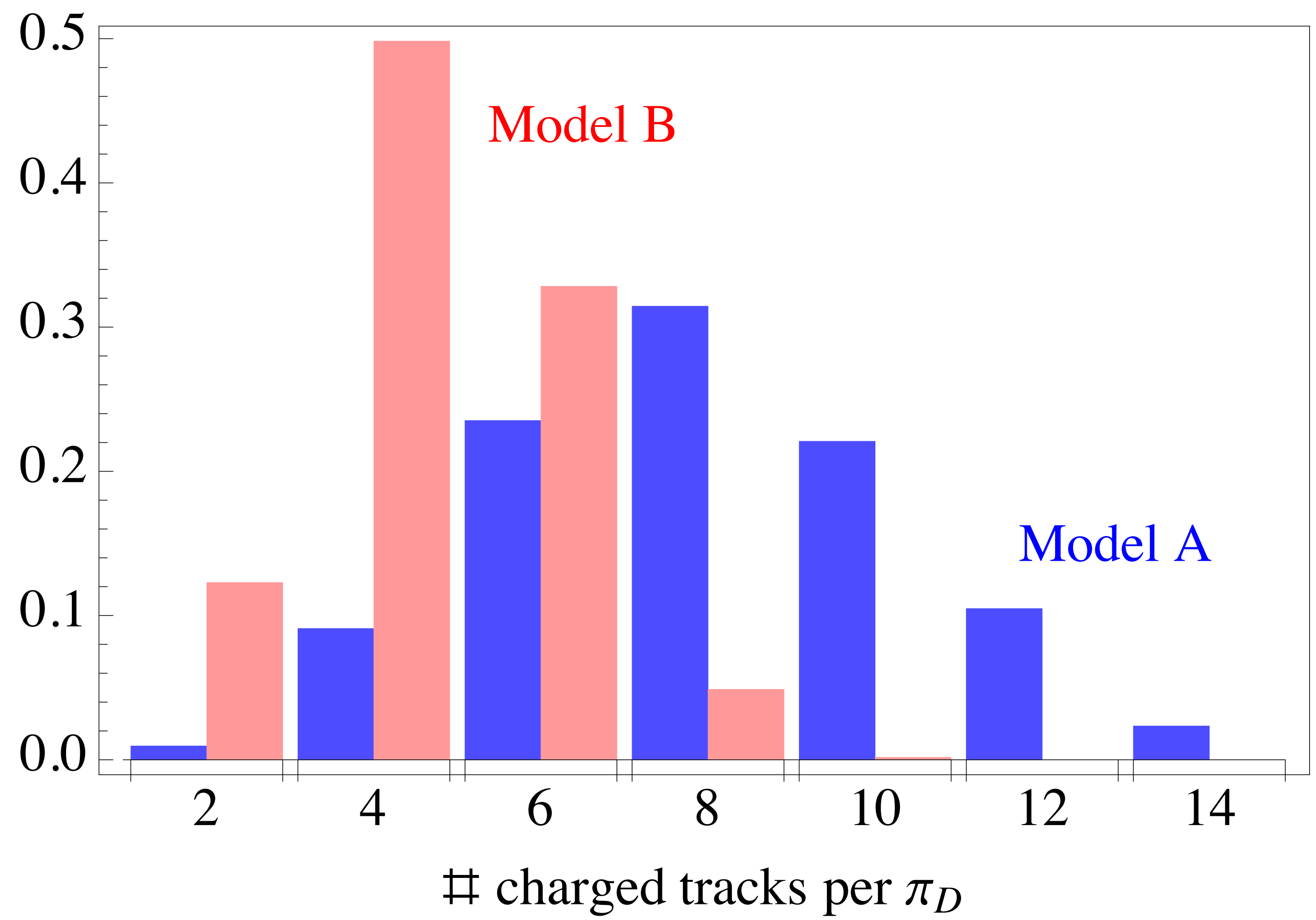




- Fraction of all signal events with N dark pions in $2 < \eta < 5$
- Momentum (not pT) distribution of dark pions in $2 < \eta < 5$

PS, Stolarski, Weiler, in progress

Decay characteristics



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

Very very (very) rough estimate

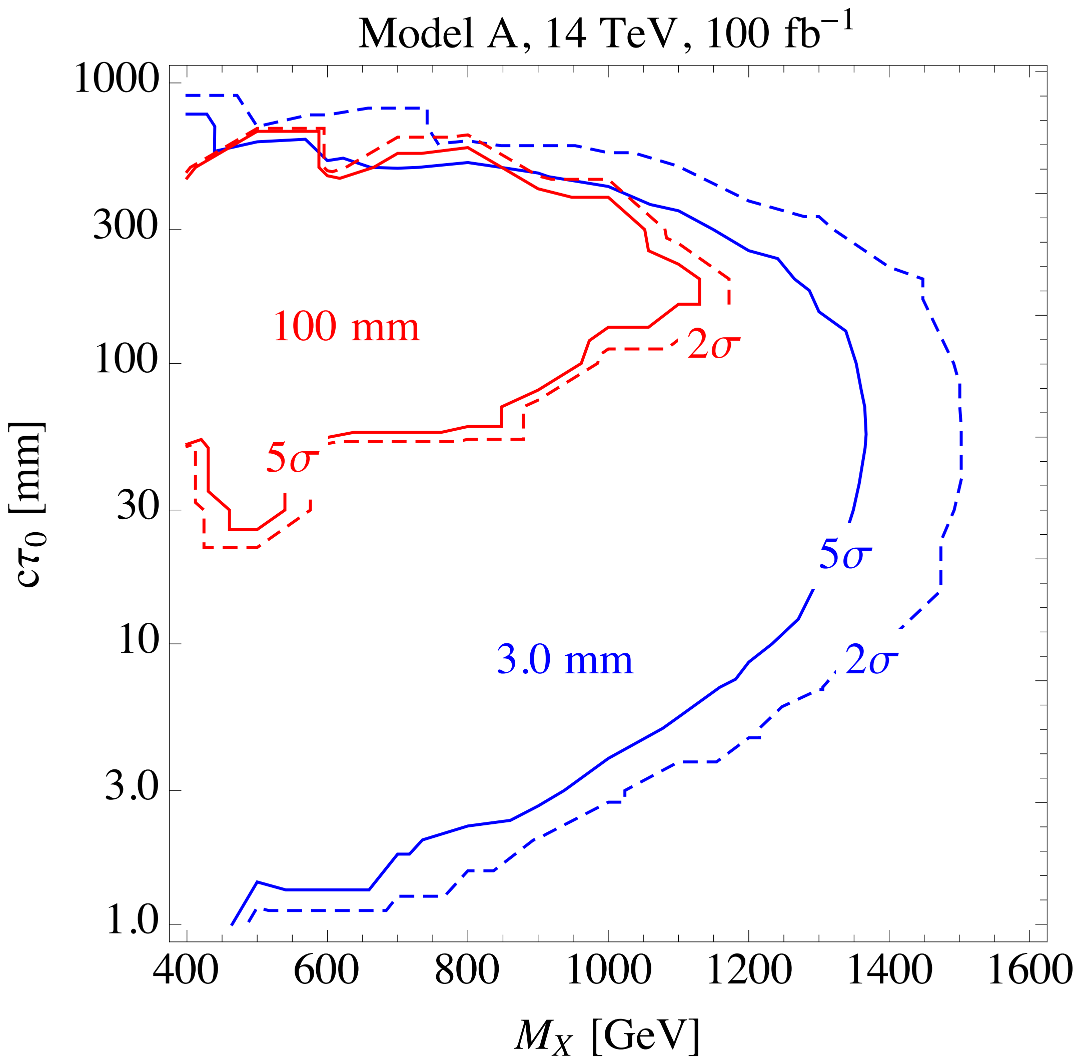
- 20 inverse fb

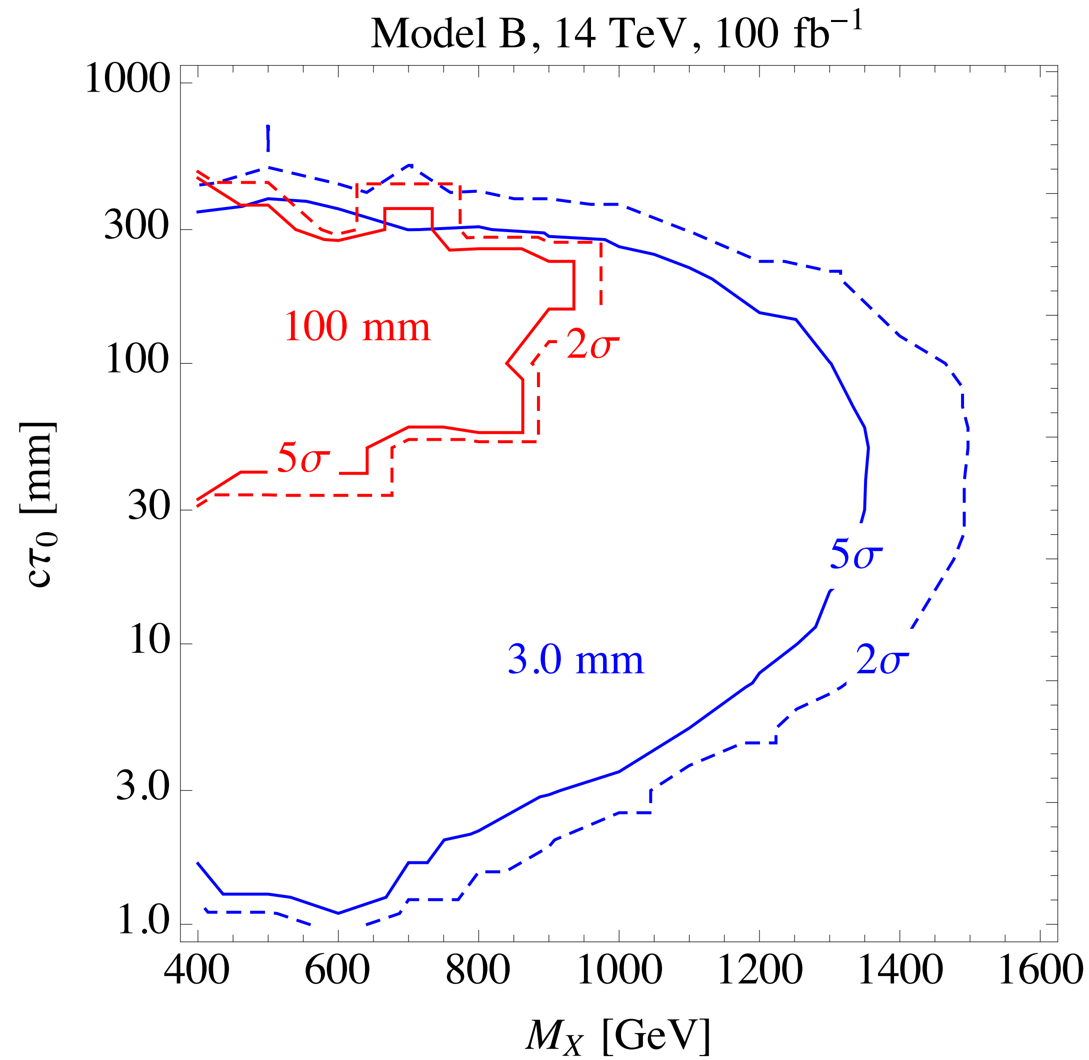
- Assume that events with 3 or more reconstructed dark pions are significantly different from QCD (i.e. no background)

- 10% reconstruction efficiency

➡ Sensitivity to $\sigma = 8\ \mathrm{fb}$, corresponds to $\Lambda \approx 5\ \mathrm{TeV}$

Reach ATLAS/CMS





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

PS, Stolarski, Weiler, 2015