Emerging jets

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Amsterdam, LLP@LHC workshop
October 23, 2018

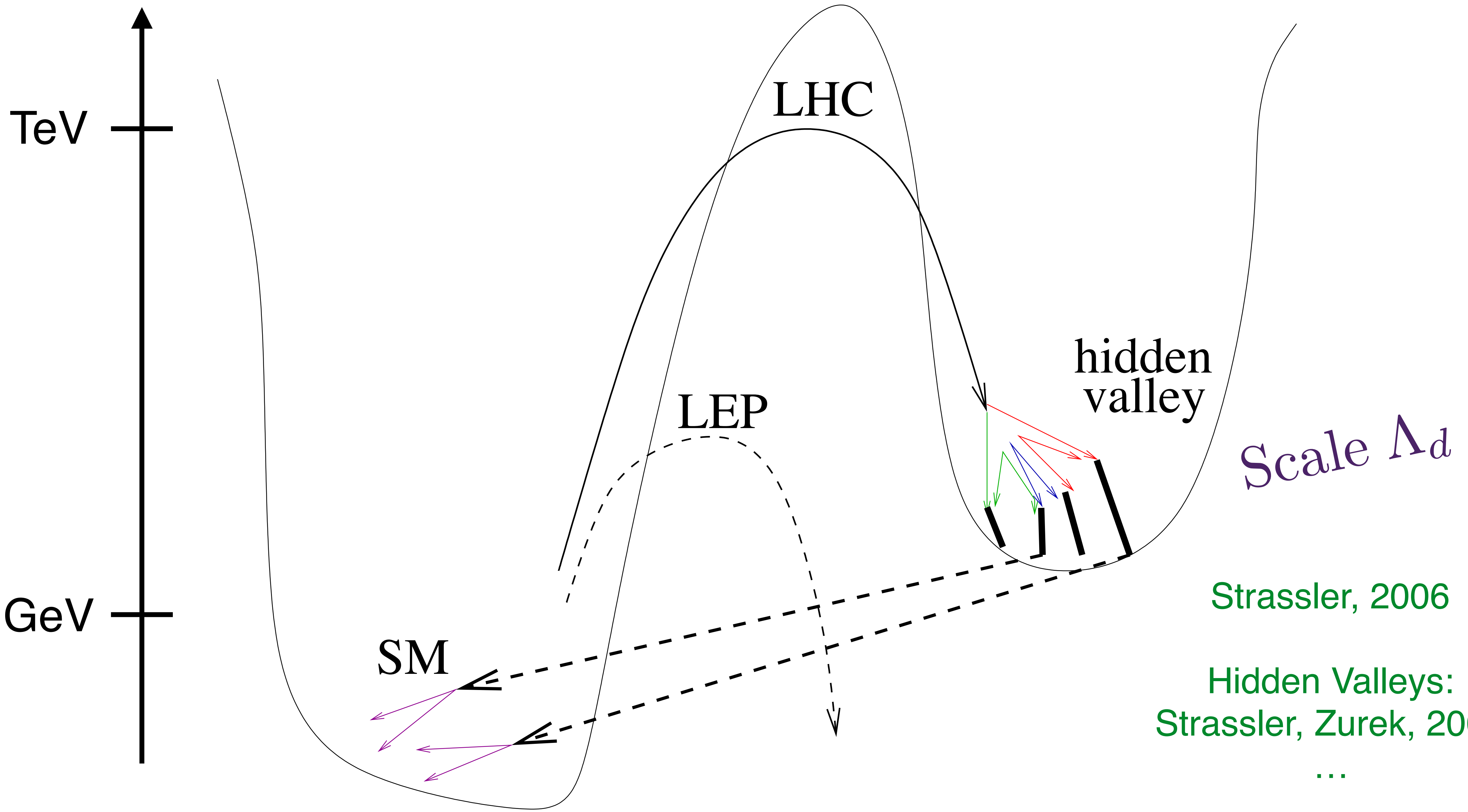
based on:

Bai, PS, 2013
PS, Stolarski, Weiler, 2015
Renner, PS, 2018

Plan

- Motivation: Light dark sectors
- Emerging jets
- … with flavour
- … everywhere

Dark Sector!



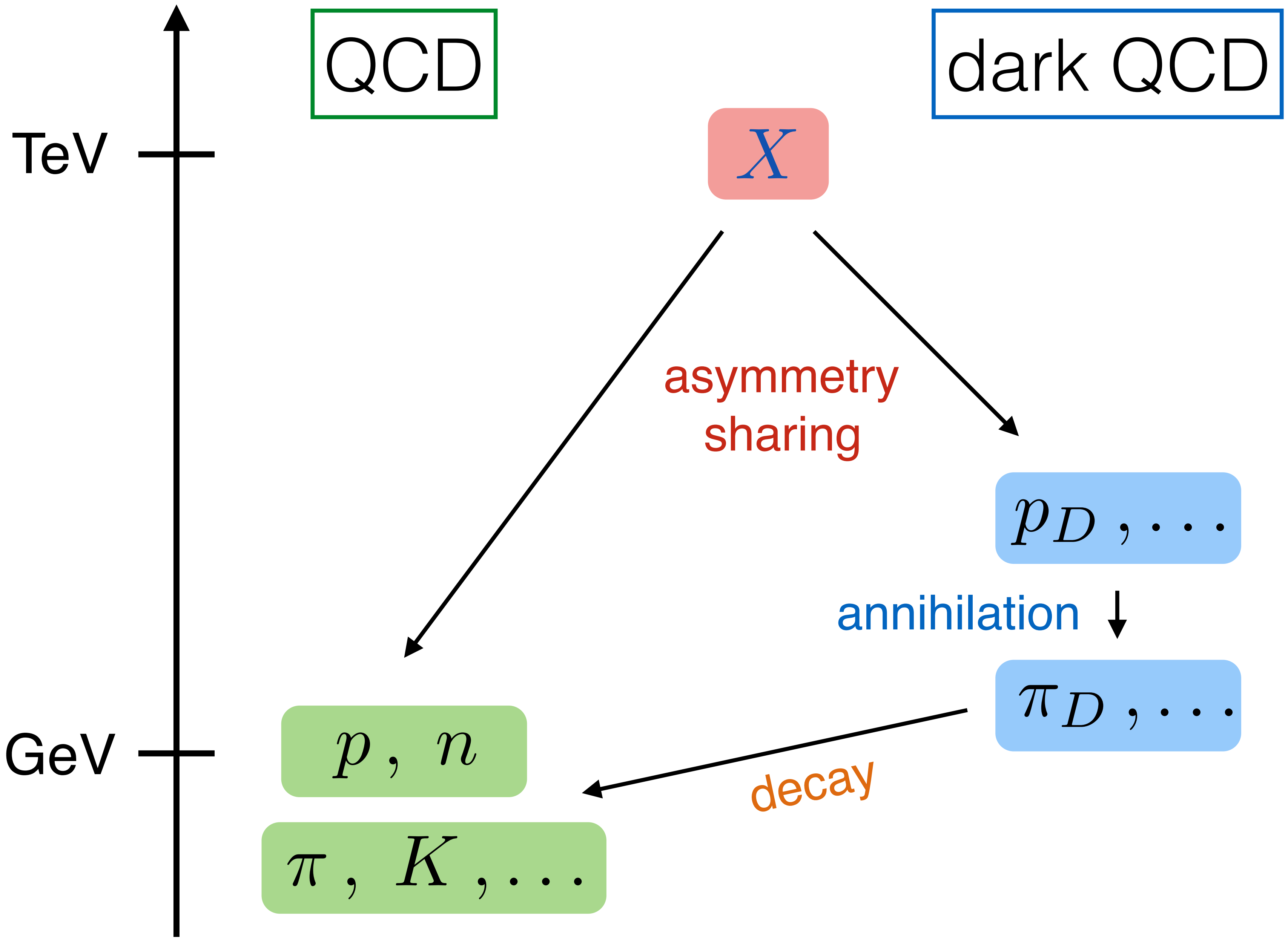
Strassler, 2006

Hidden Valleys:
Strassler, Zurek, 2006
…

Sub-weak scale motivation

- Dark baryons good (asymmetric) DM candidates
  - Relic abundance → $\Lambda_d \sim \mathcal{O}(10 \text{ GeV})$
- Twin Higgs
  - Twin QCD with $\Lambda_d \gtrsim \Lambda_{QCD}$
- SIMP DM
  - $3\pi_d \to 2\pi_d$ annihilations for $m_{\pi_D} \sim \text{GeV}$
- Pheno: Only started looking there!

Dark QCD



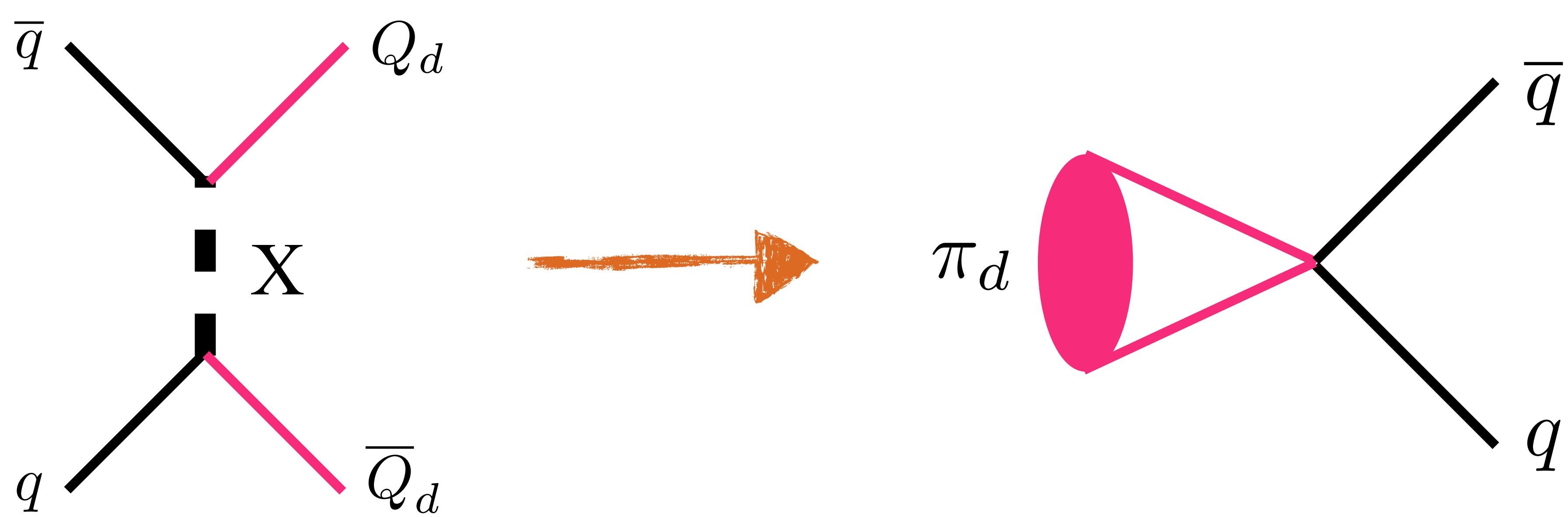
- SU(N) dark sector with neutral "dark quarks"
- Confinement scale

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

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

Dark Pion Lifetime

- Integrate out mediator, match to dark pion current

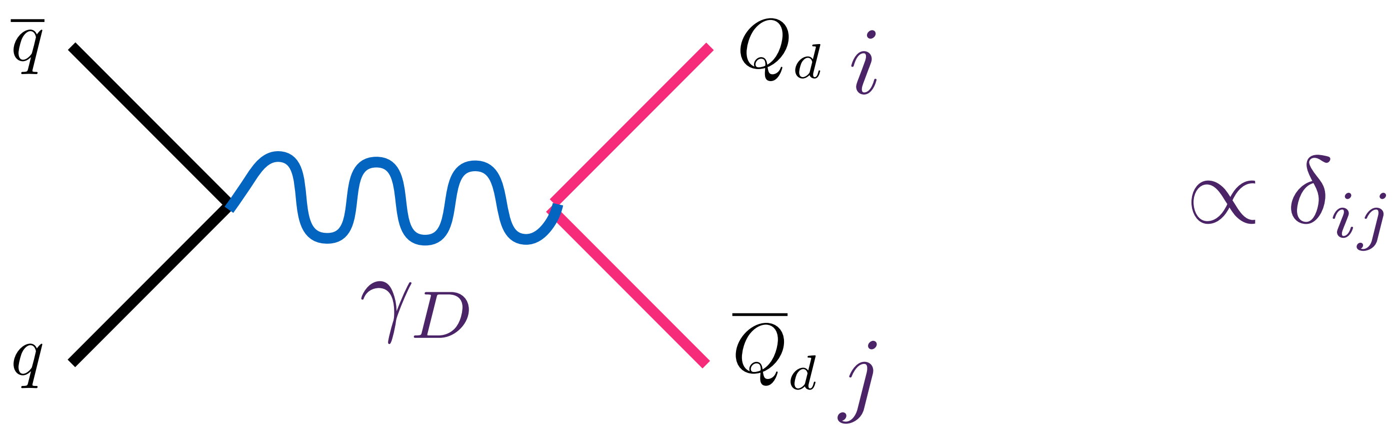


- Decay to SM jets (pions)

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

Decay in LHC detectors!

With s-channel mediator



- Unbroken flavour symmetries
  - some stable dark pions → undercover jets

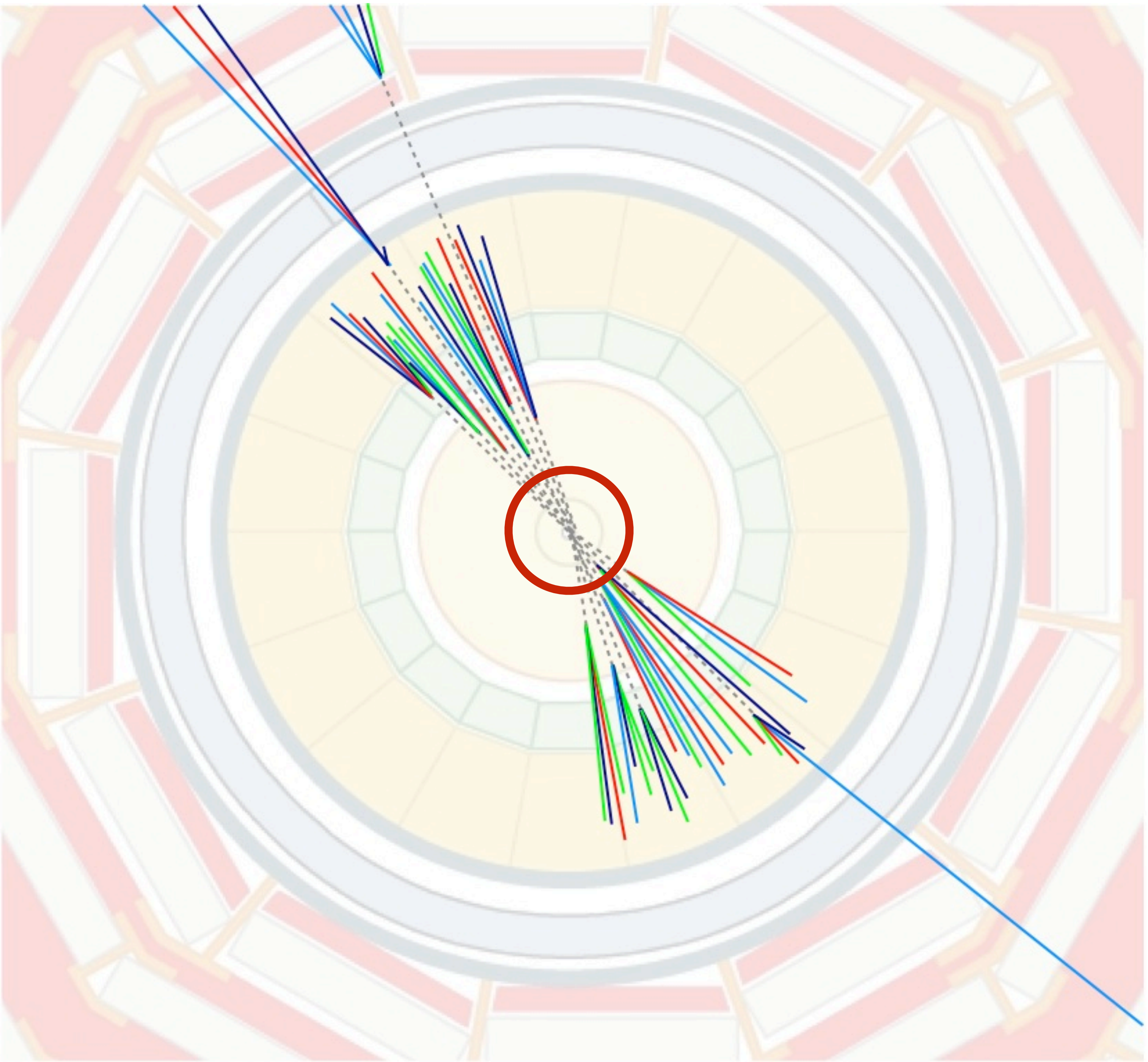
Cohen, Lisanti, Lou, 2015

- Flavour also for t-channel mediator → later

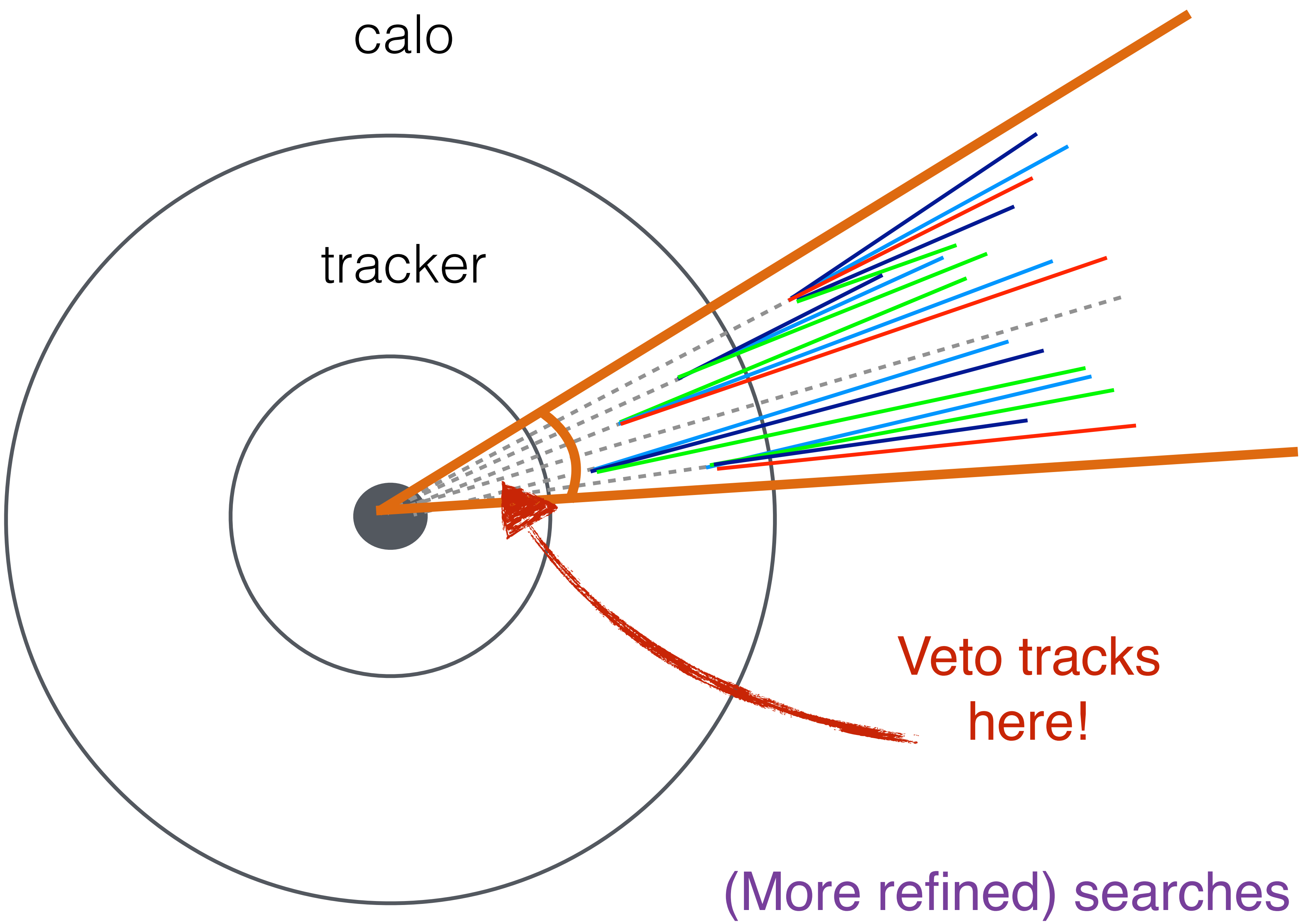
Emerging Jets at the LHC

- 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



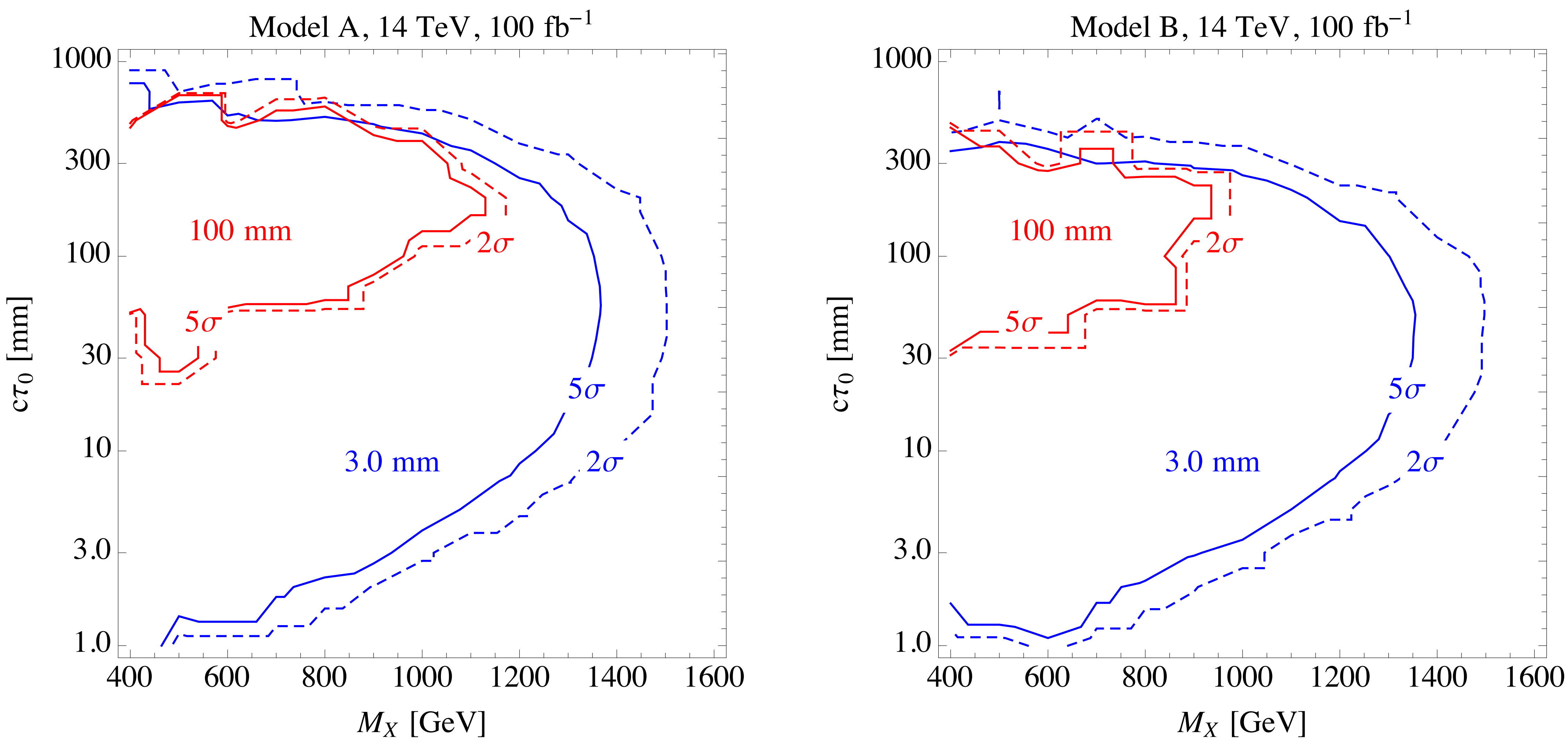
Strategy



(More refined) searches ongoing at ATLAS/CMS

PS, Stolarski, Weiler, 2015

Reach ATLAS/CMS



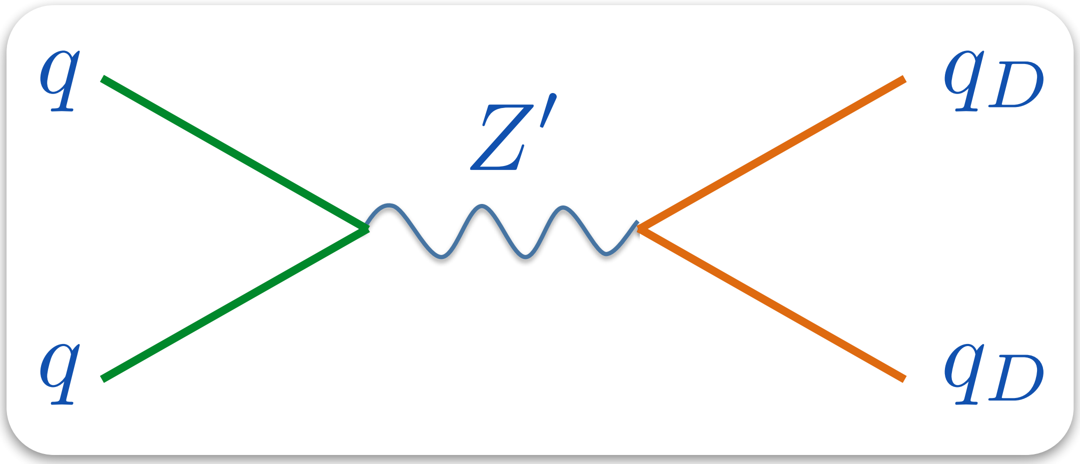
- Seems our estimates where not so bad. Thanks CMS, waiting for ATLAS ;)
- Also sensitive to some RPV SUSY models etc

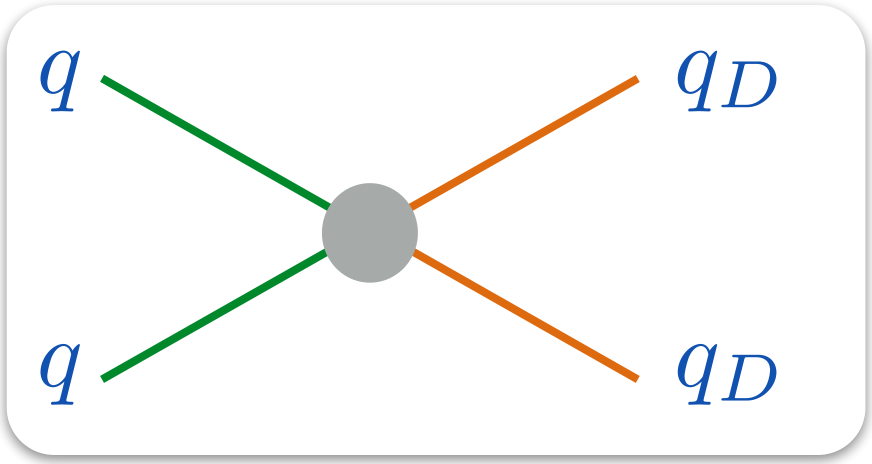
PS, Stolarski, Weiler, 2015

PS, Stolarski, Weiler, 2015

LHCb opportunities

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



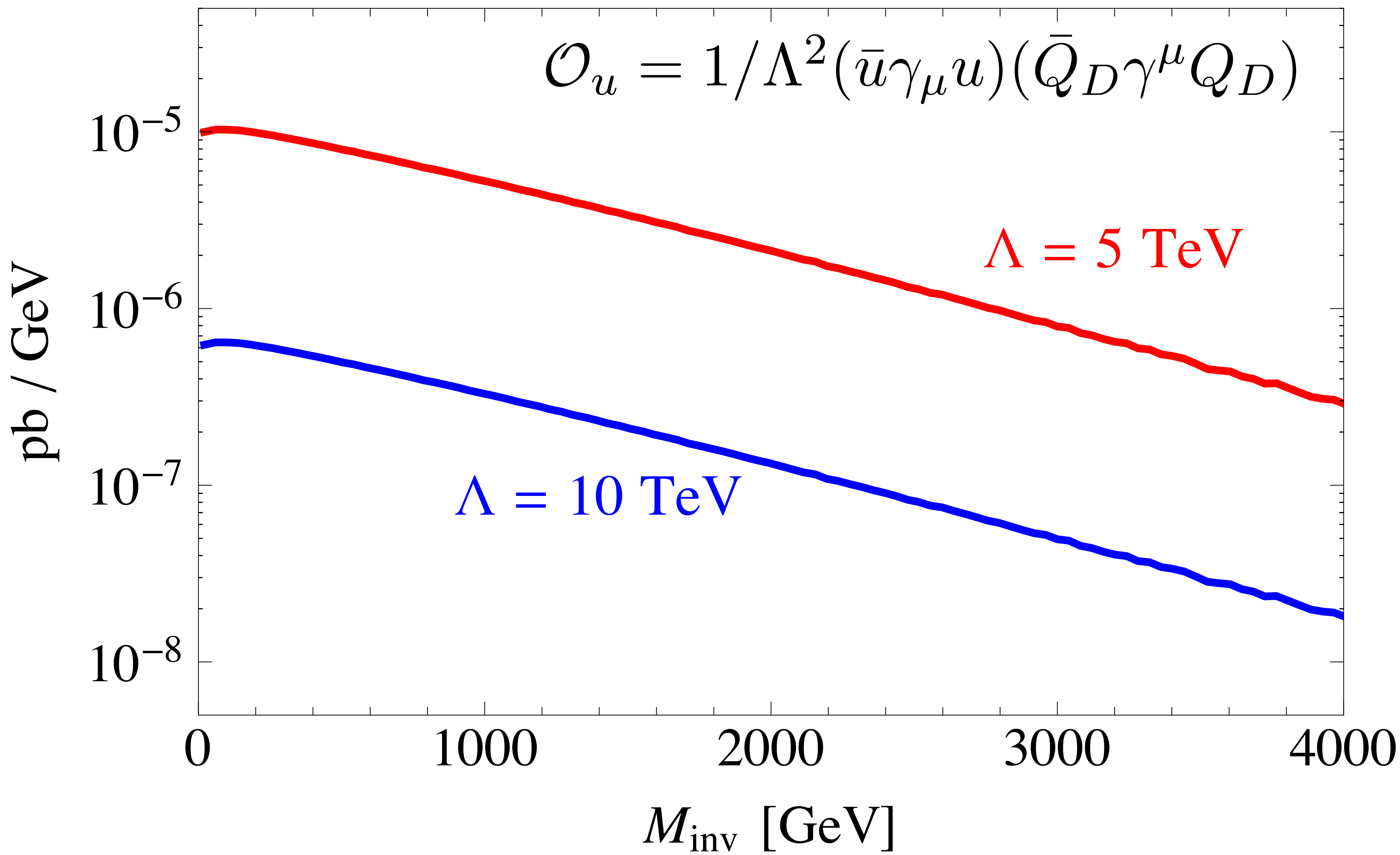


- Reconstruct individual dark pions, differentiate using lifetime, mass, decay products

- Emerging jets without (hard) trigger requirements?

PS, Stolarski, Weiler, 2015

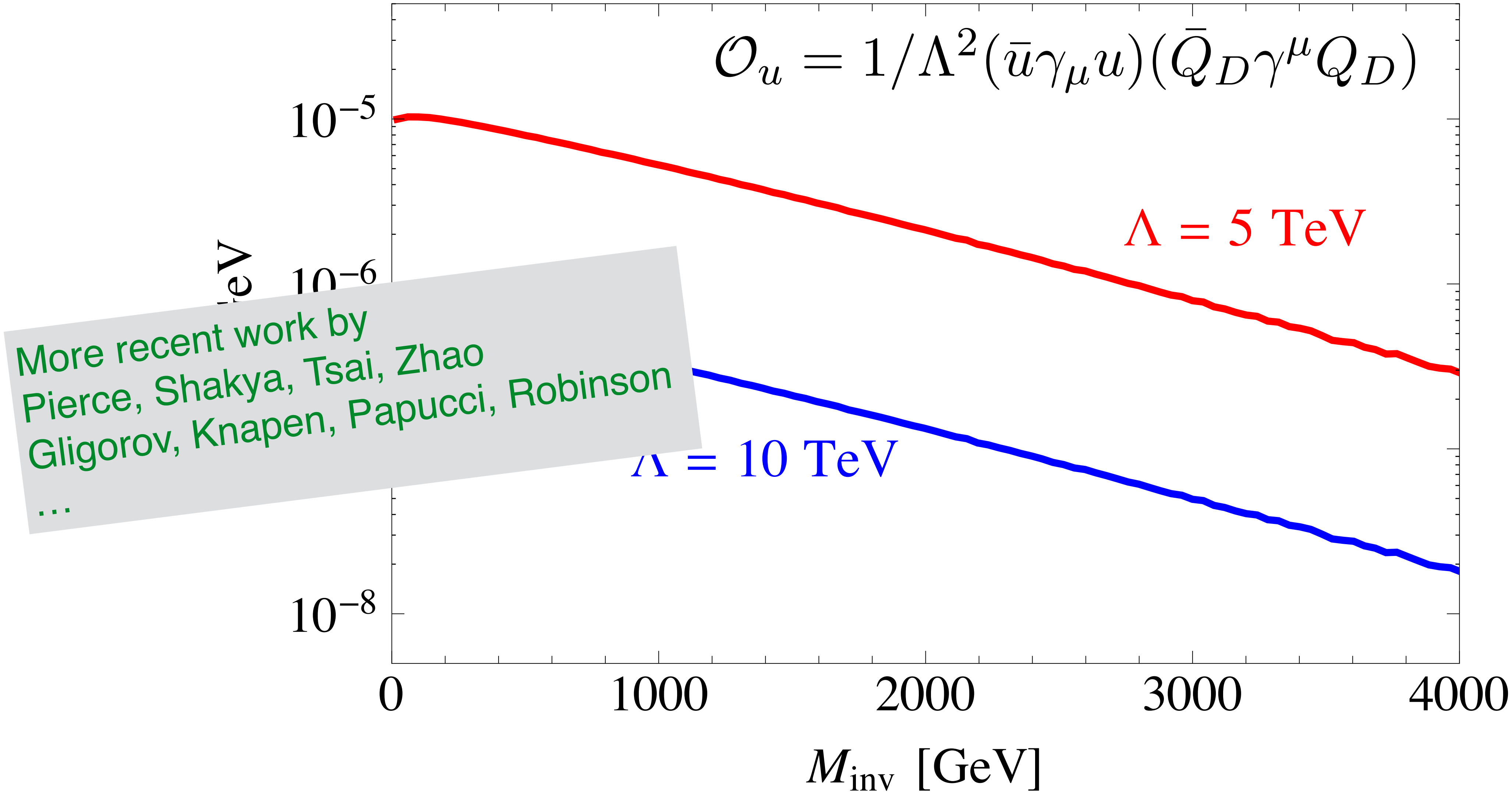
Off-shell production



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

PS, Stolarski, Weiler, 2015

Off-shell production



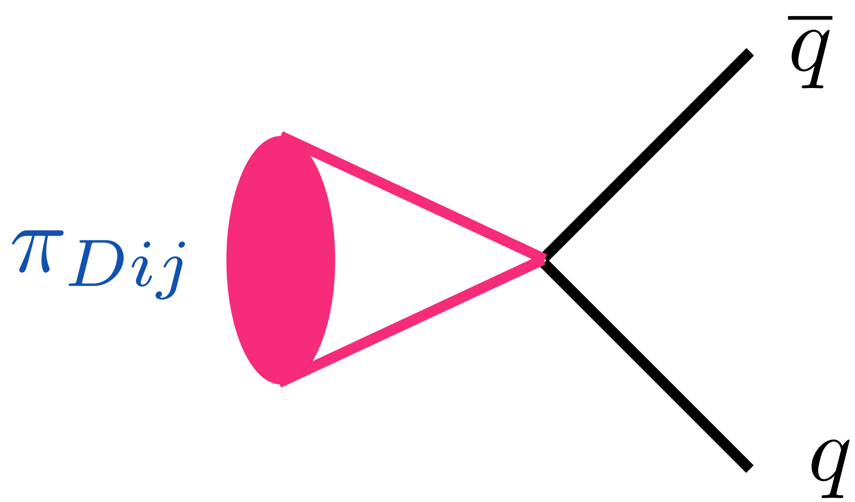
- Total rate: $\sigma(pp \to \bar{Q}_D Q_D) \approx 8.2\ \text{pb} \times \left(\frac{\text{TeV}}{\Lambda}\right)^4 \times N_d \times N_F$

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, JHEP 2018

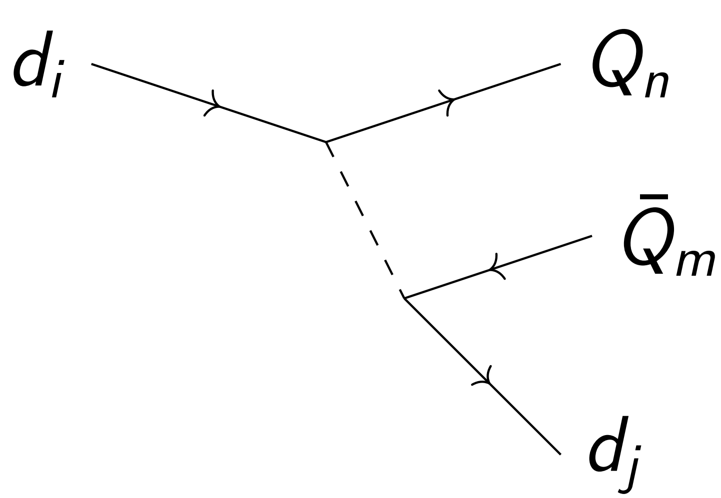
Note:

This is a flavour violating ALP!

With a UV story!

S. Renner, PS, JHEP 2018

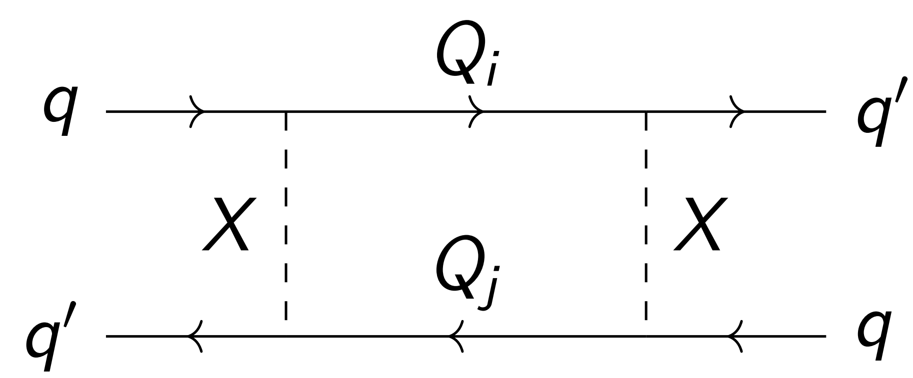
Flavour matters



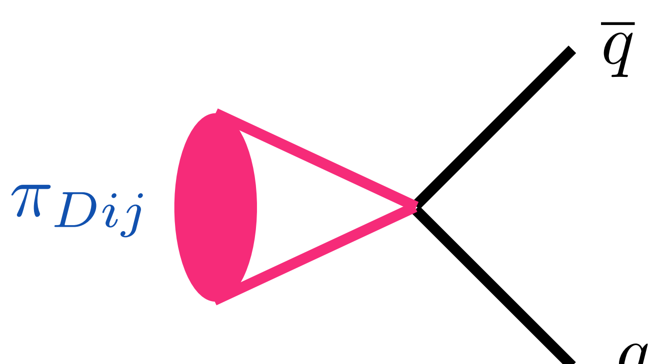
$\Delta F = 1$

$\Delta F = 2$

constraints

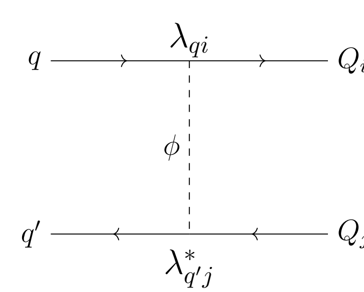


$$\lambda_{ij} \bar{d}_{Ri} Q_{Lj} \Phi$$



dark pion properties

fixed target experiments



Rare decays

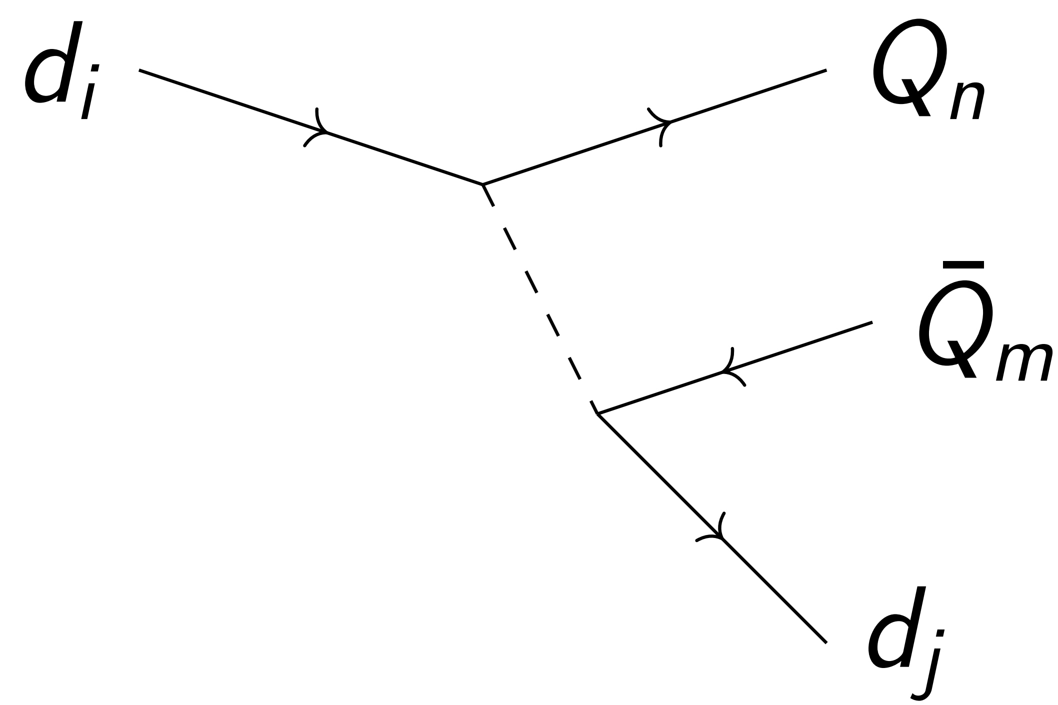
- Allows rare decays

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

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

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

- Don't vanish in flavour symmetric limit!



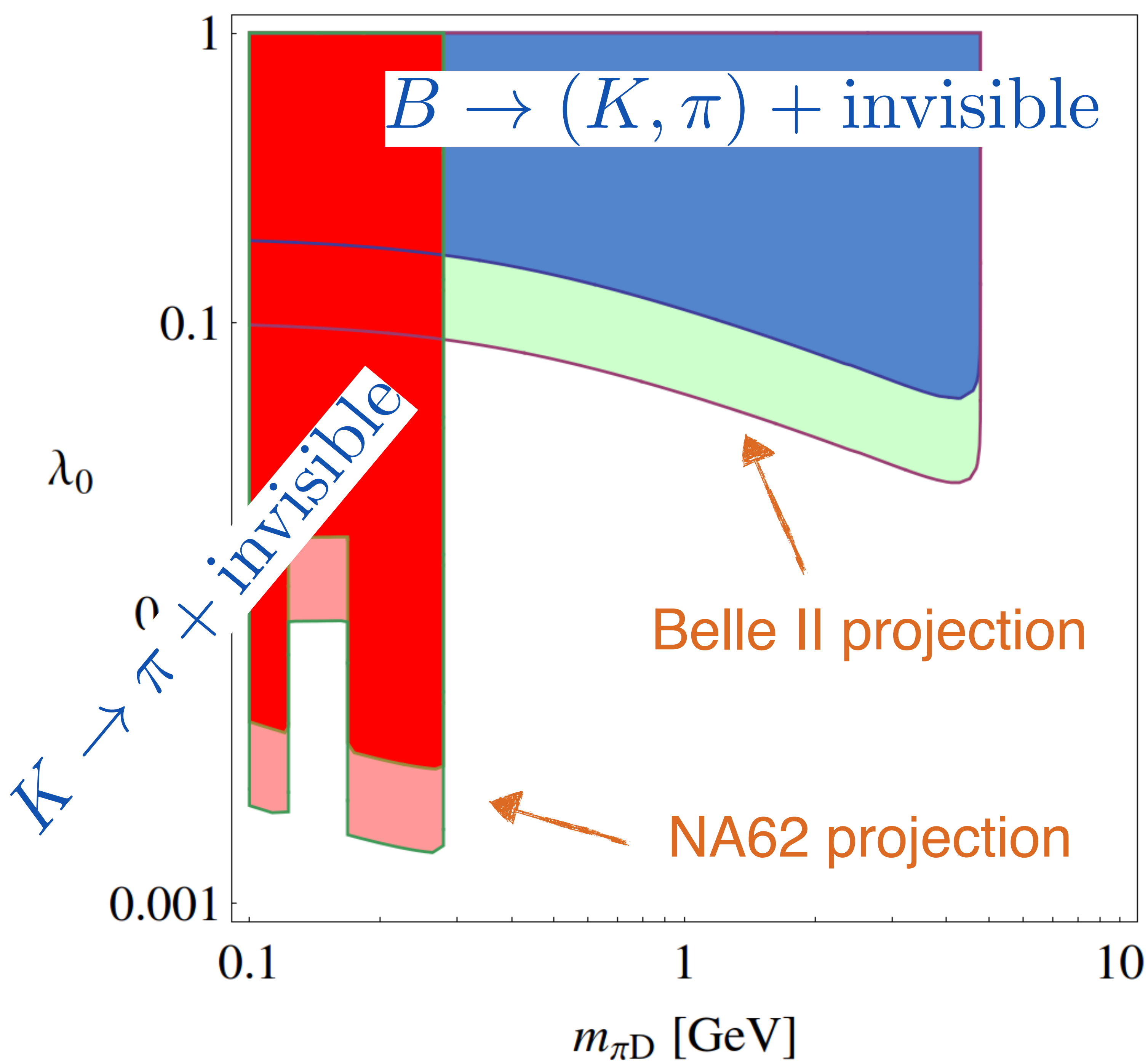
great resource:
Kamenik, Smith, 2011

S. Renner, PS, JHEP 2018

Bounds from rare decays

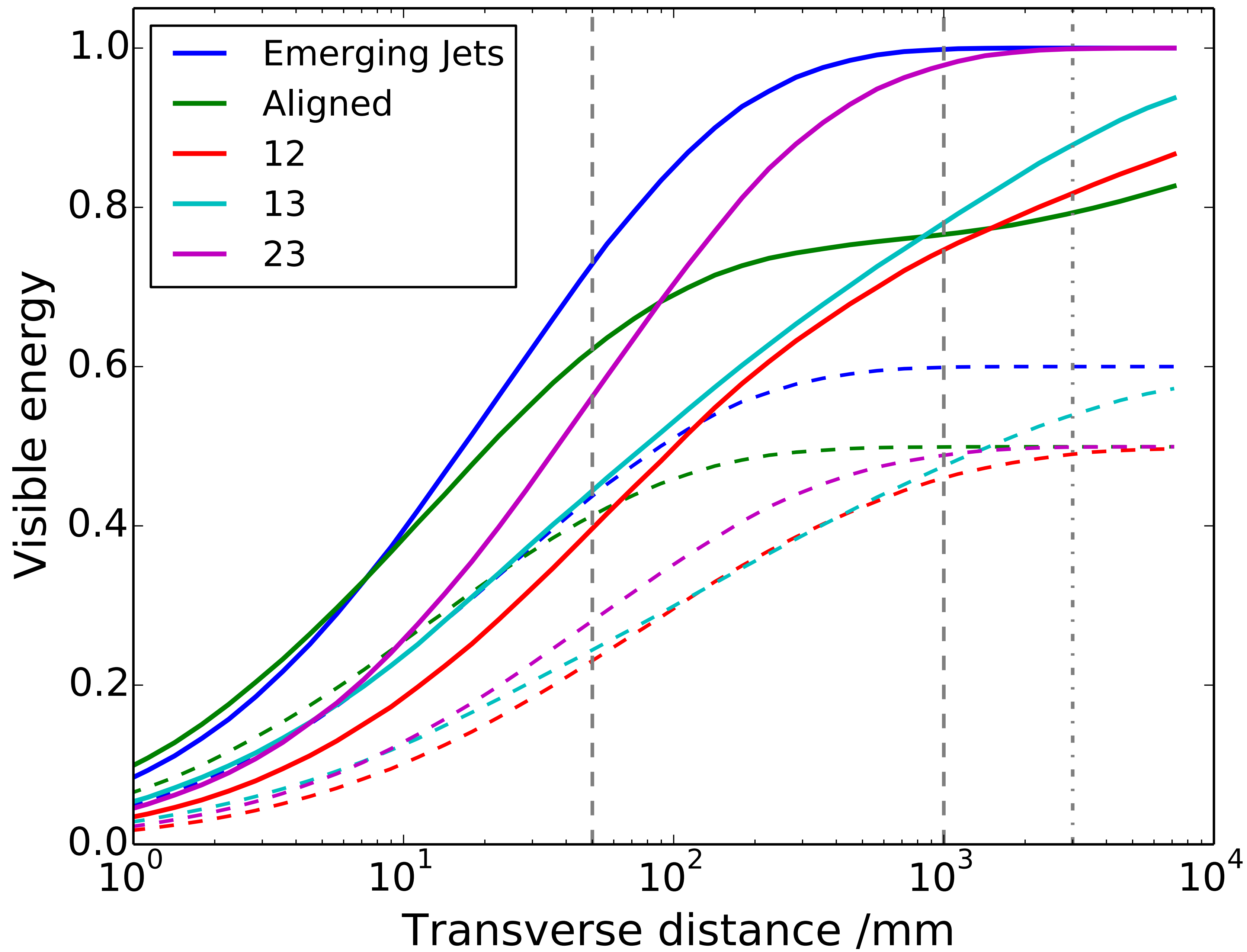
- Best bound on couplings for very light dark pions

- Dark pion production in fixed target expts!



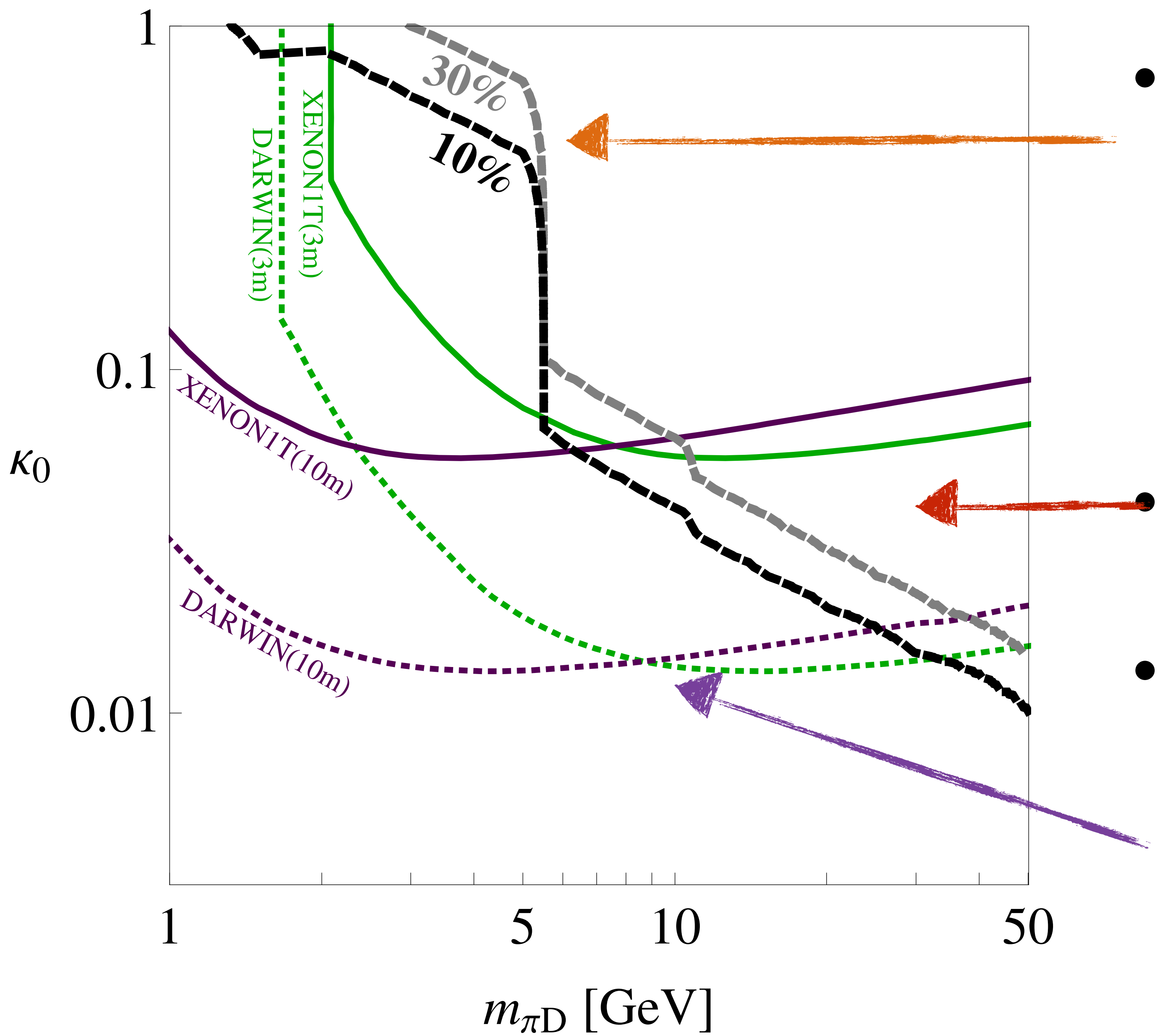
S. Renner, PS, JHEP 2018

Emerging Jets v2



S. Renner, PS, JHEP 2018

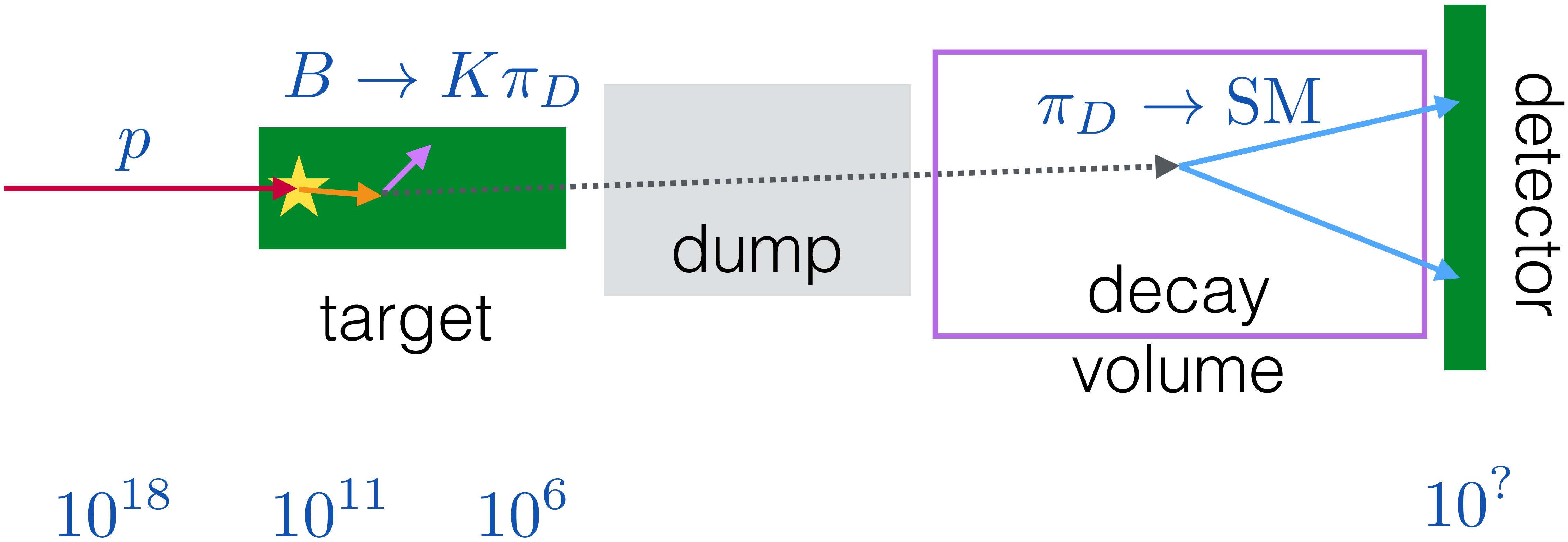
DM/EJ region



- Percentage of energy deposited in Calos (avg, large fluctuations)
- EJ best region
- Direct detection bounds and future reach

Fixed target

- My simplified NA62/SHiP:

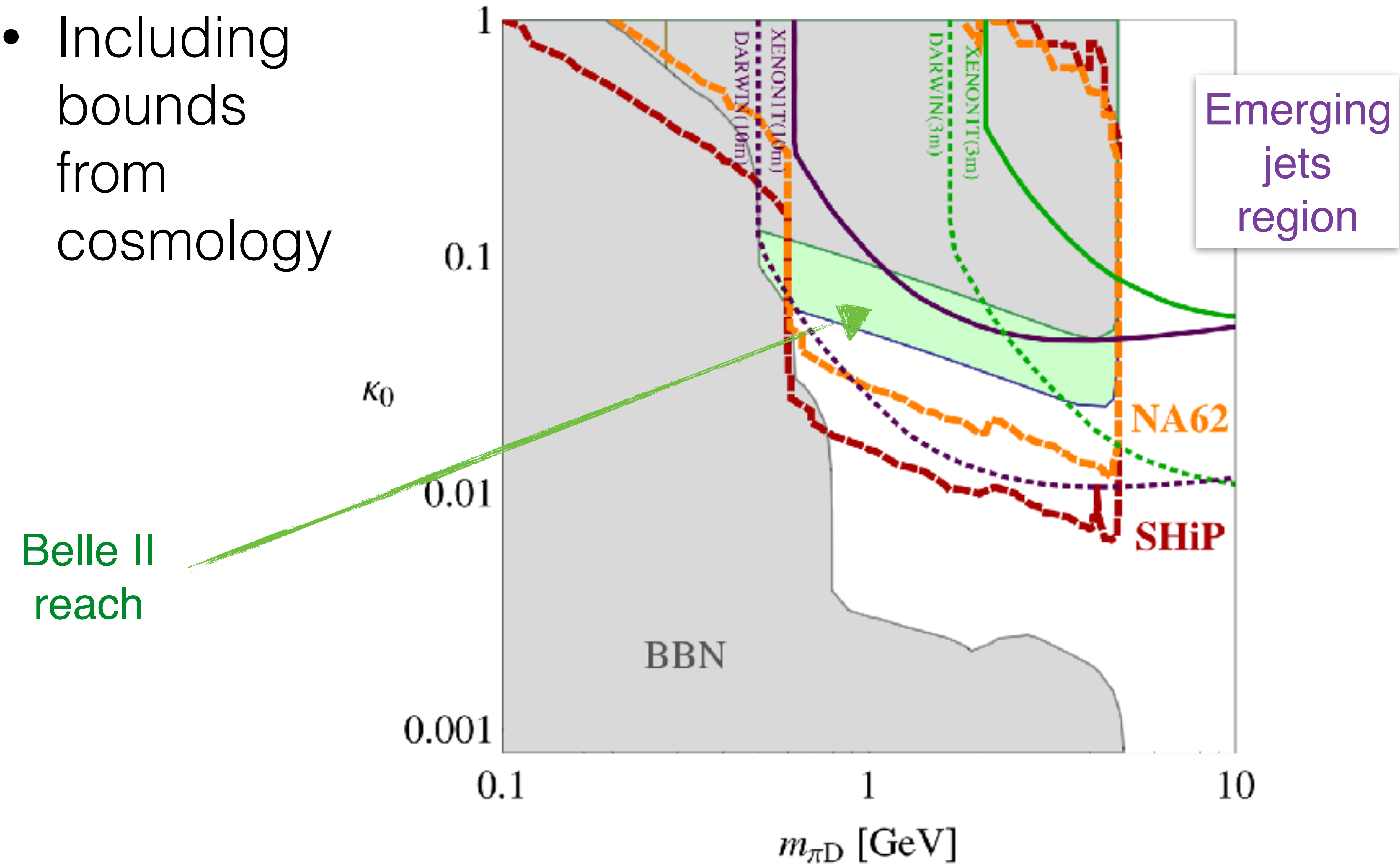


- Leading channels: $\pi_D \to \pi K$, $\pi_D \to \pi^+\pi^-\pi^0$
- No $\pi\pi$, probe of CP nature of π_D

S. Renner, PS, JHEP 2018

Fixed target reach

- Including bounds from cosmology



Summary

- “Dark QCD” motivated in many BSM scenarios, in particular: DM and Naturalness
- Emerging jets are smoking gun, good prospects for ATLAS/CMS
  - Test TeV scale mediators without MET or Leptons
- Flavour adds new dimension to emerging jets phenomenology
- Interesting opportunity for fixed target experiments
- More studies of dark showers to understand what can be learned?

Thank You

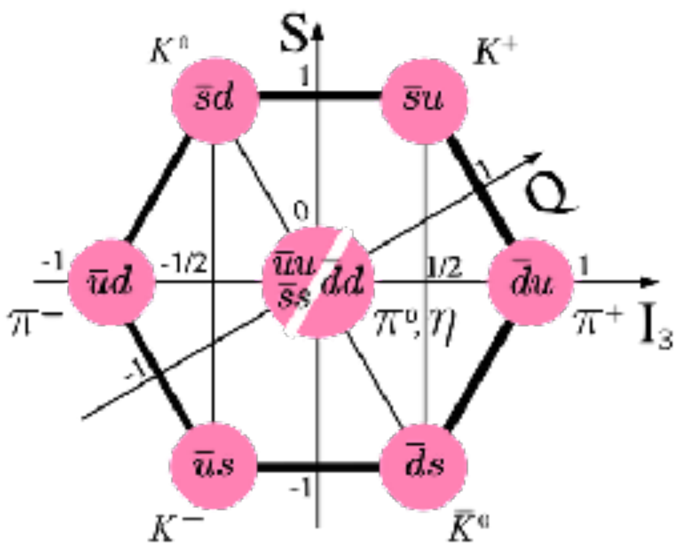
Particles and symmetries

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

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

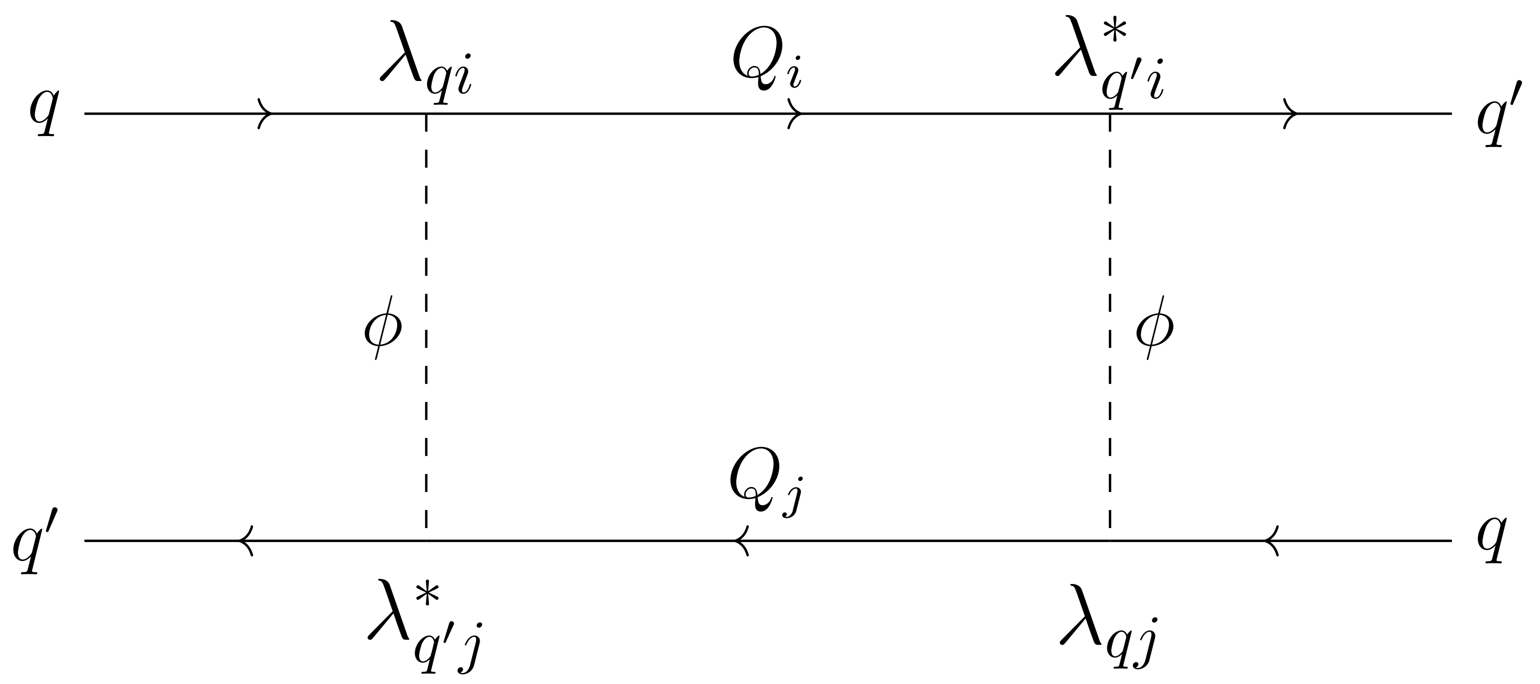
$$\lambda = U D V$$

unitary (U, V); diagonal (D)

- 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



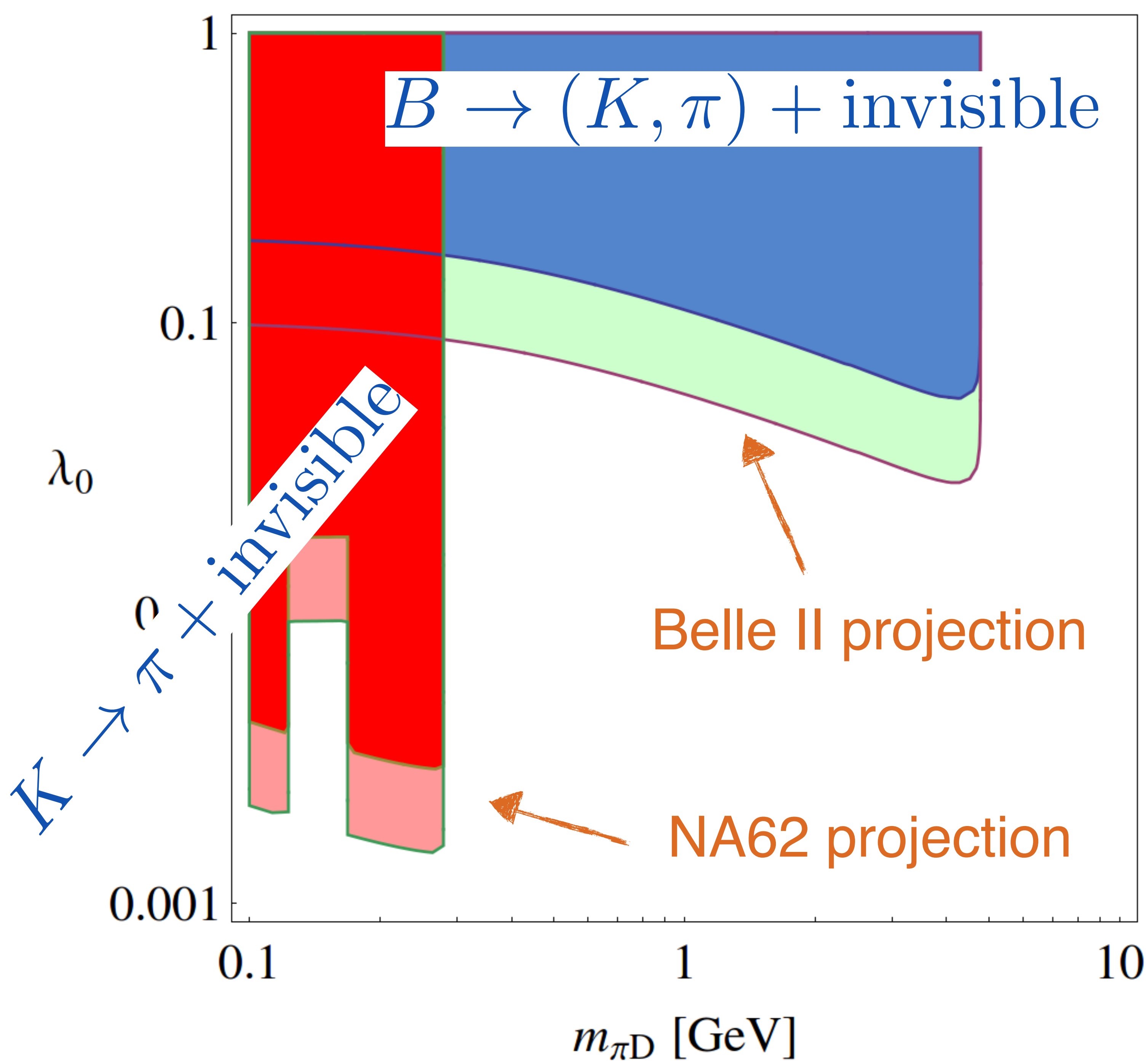
- Absent in $D = \lambda_0 \cdot \mathbb{1}$ limit!

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

S. Renner, PS, in progress

ΔF=1

- Best bound on couplings for very light dark pions



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LHCb opportunities

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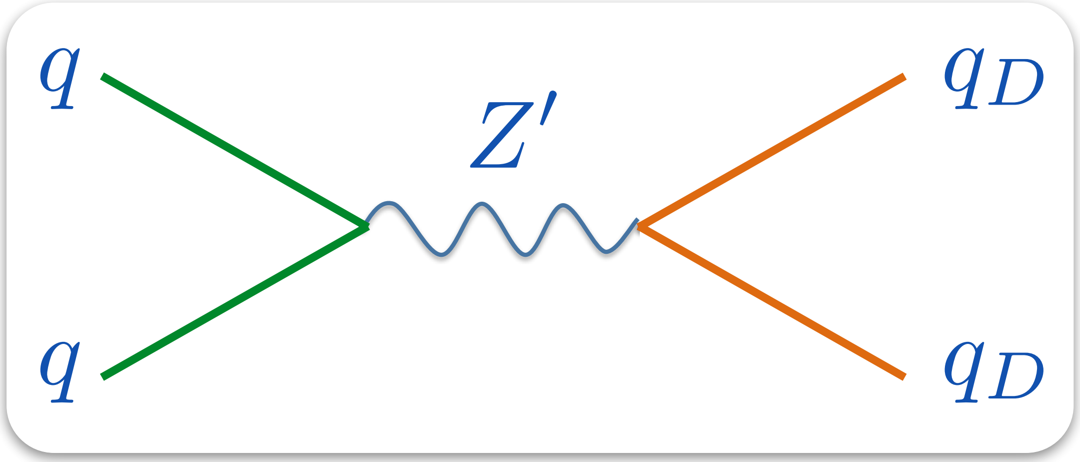
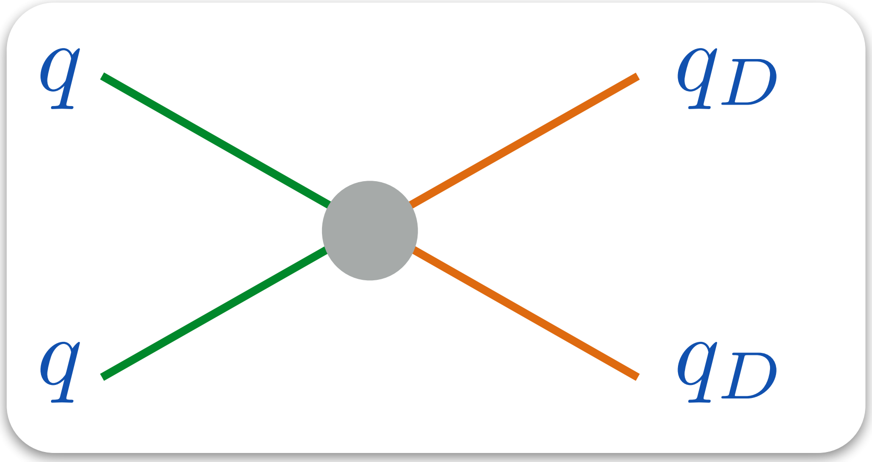
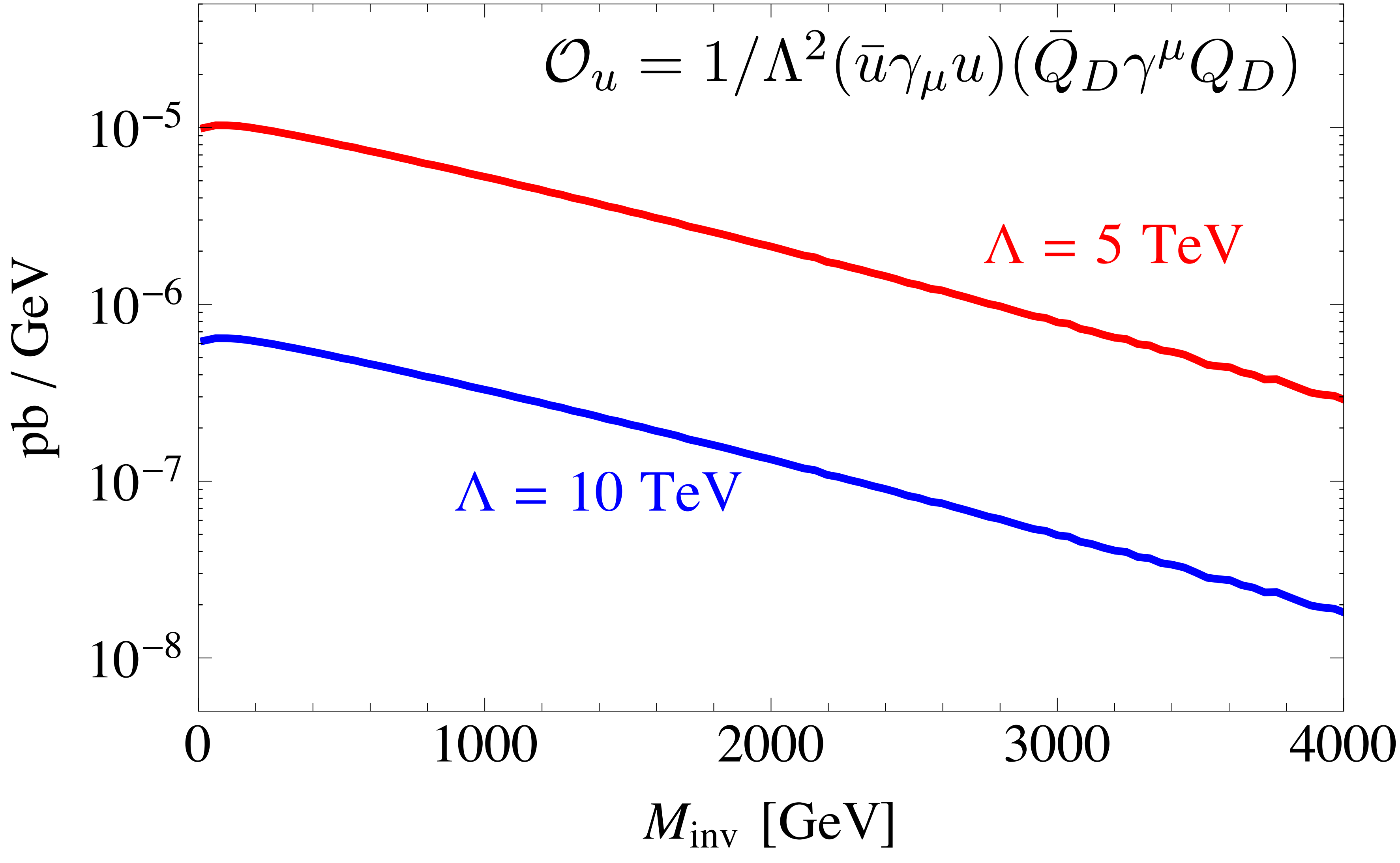




- Reconstruct individual dark pions, differentiate using lifetime, mass, decay products

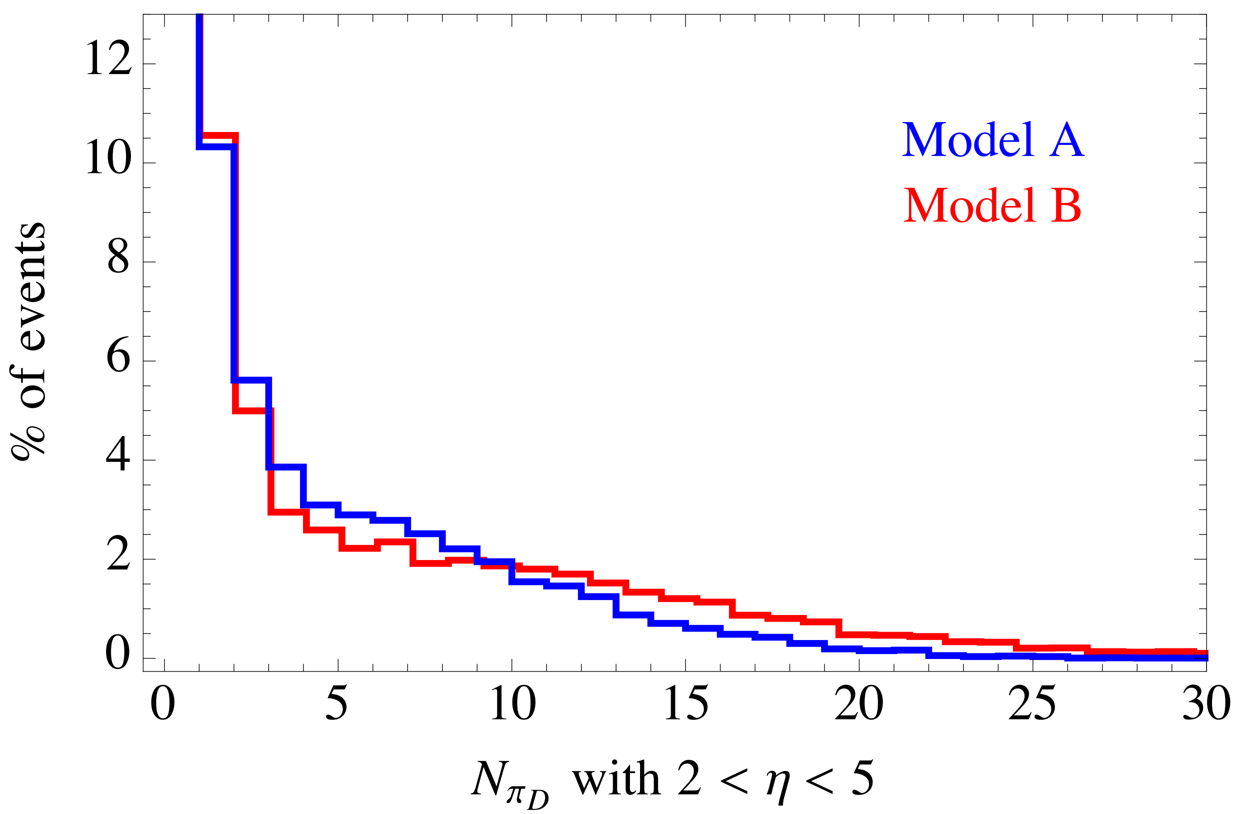
- Emerging jets without (hard) trigger requirements?

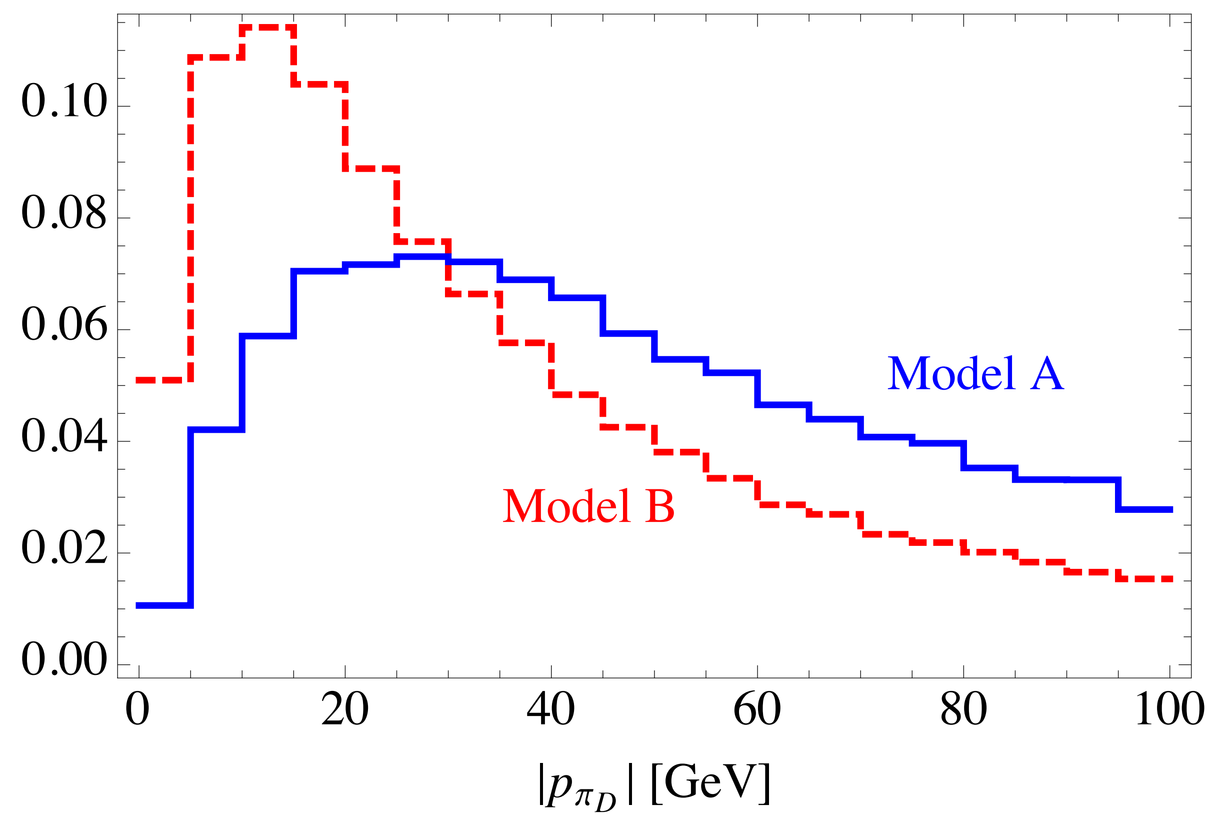
Off-shell production



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

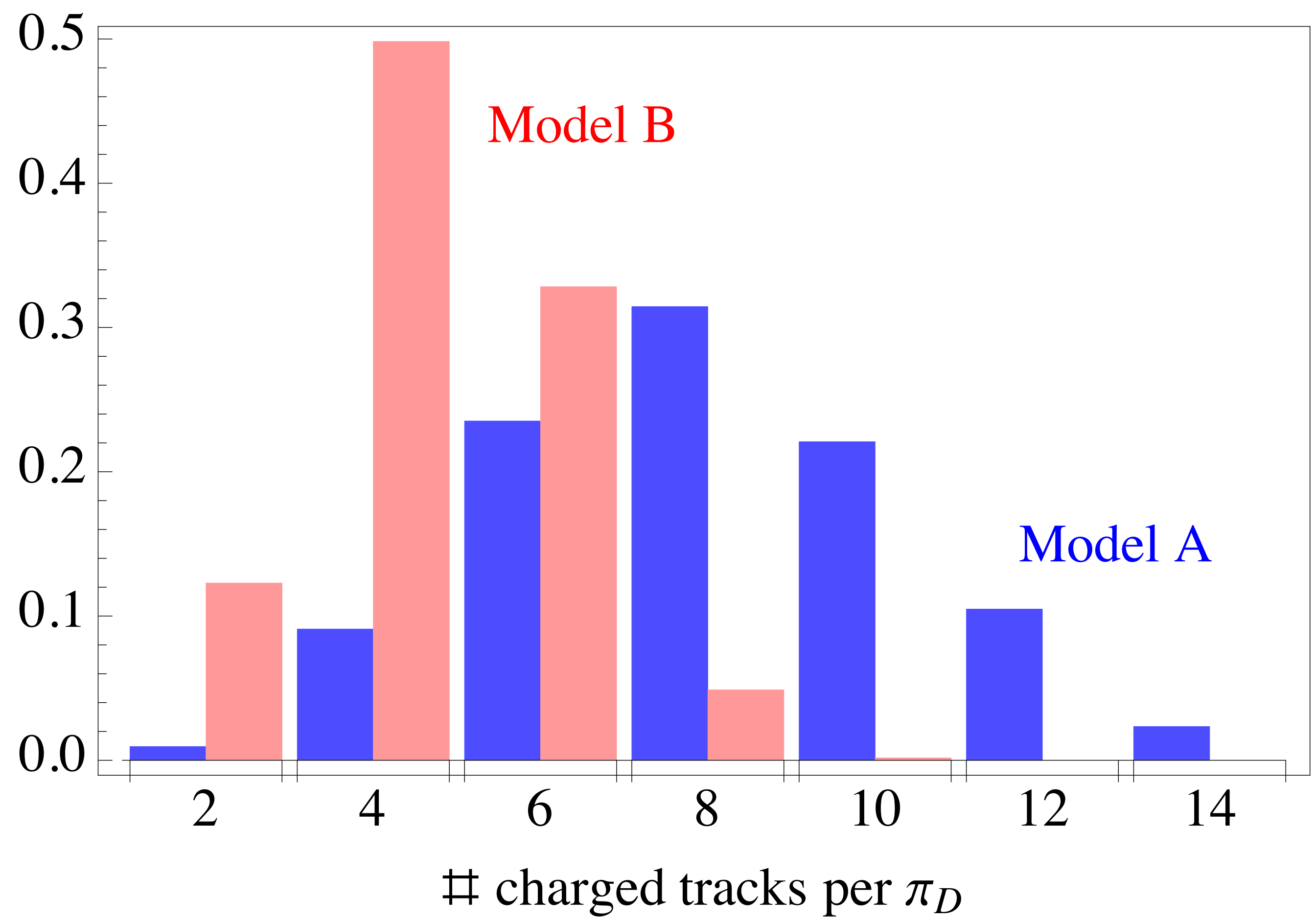
Forward region





- 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!

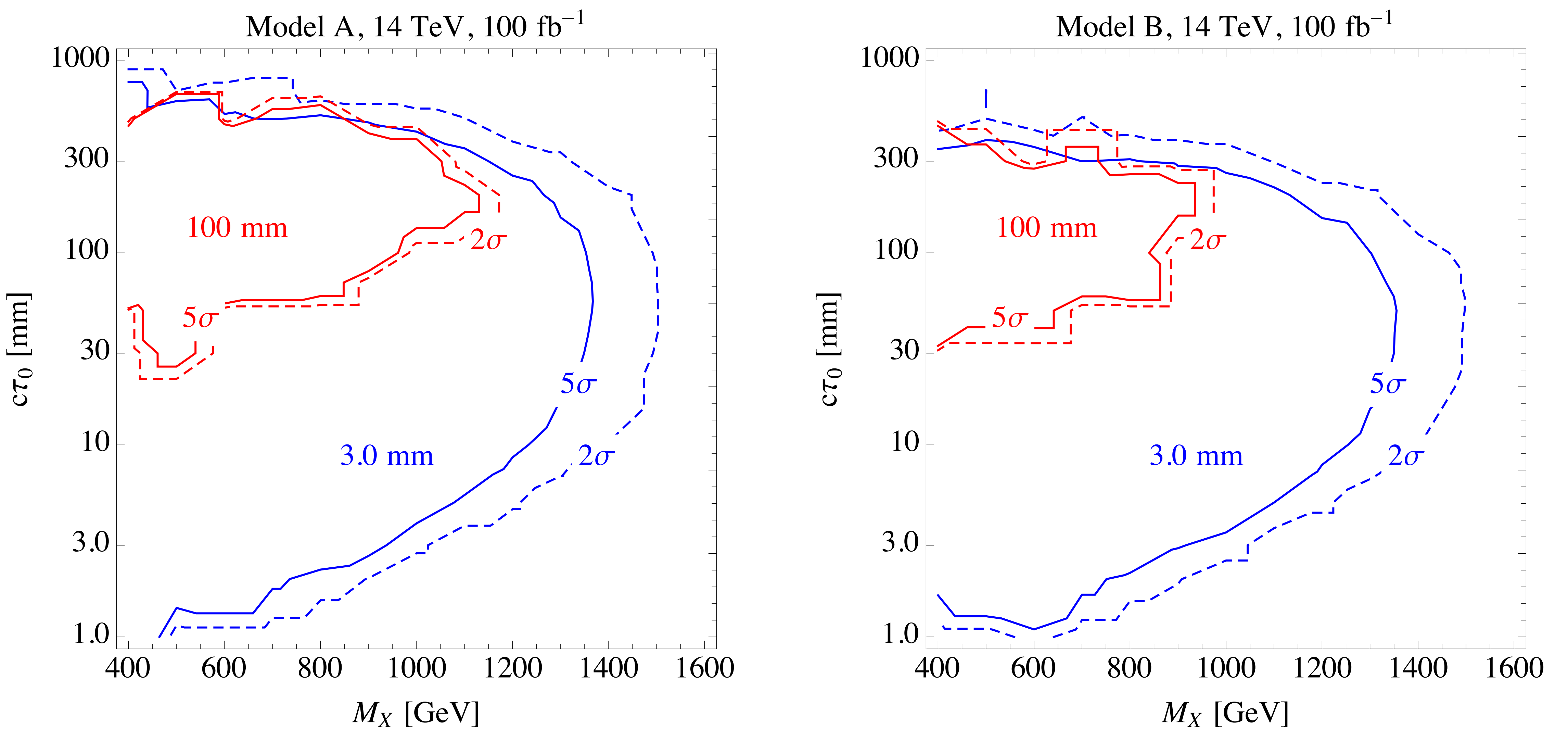
PS, Stolarski, Weiler, in progress

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

PS, Stolarski, Weiler, 2015

Models

- High scale (above M):
  - Bifundamental scalars Φ and fermions Y
  - Quarks q and dark quarks Q_D
  - Also allow (dark) coloured scalars
- Below M: Only q and Q_D
- Example (with $N_{F,d} = 7$):

$$\alpha_c^* = 0.090 \quad \alpha_d^* = 0.168$$
$$M = 870\ GeV$$

$$M_{\mathrm{DM}} \approx 3.5\ \mathrm{GeV}$$

Asymmetry

- Produce asymmetry in bi-fundamentals from heavy particle decay (à la Leptogenesis)
- Decay to quarks and dark quarks (color conservation) → equal B and D
- Including sphalerons: $\frac{|n_D|}{n_B} = \frac{79}{56} \approx \frac{7}{5}$
- For example model:

$$\frac{\rho_{DM}}{\rho_B} = \frac{7}{5} \frac{3.5 \text{ GeV}}{0.94 \text{ GeV}} \approx 5$$

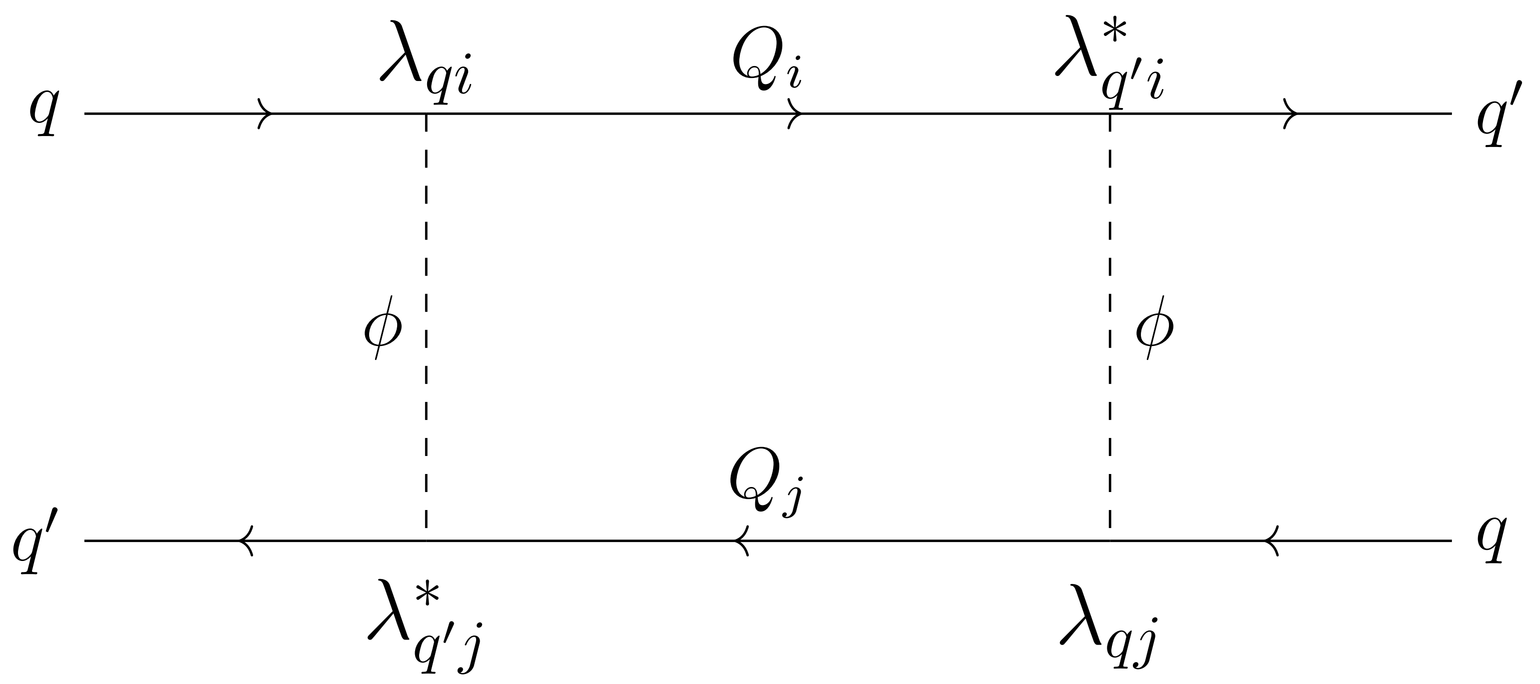
"naturally"

Features

- Relic density fine, without direct detection trouble
- Symmetric component annihilation:
  - $p_D \bar{p}_D \to \pi_D \pi_D$ very efficient
  - $\pi_D \to SM$ transfers entropy back to SM
- DM self interaction mediated by dark pions, might help with structure formation issues

Generic properties of "dark QCD" models worth studying their phenomenology!

ΔF=2



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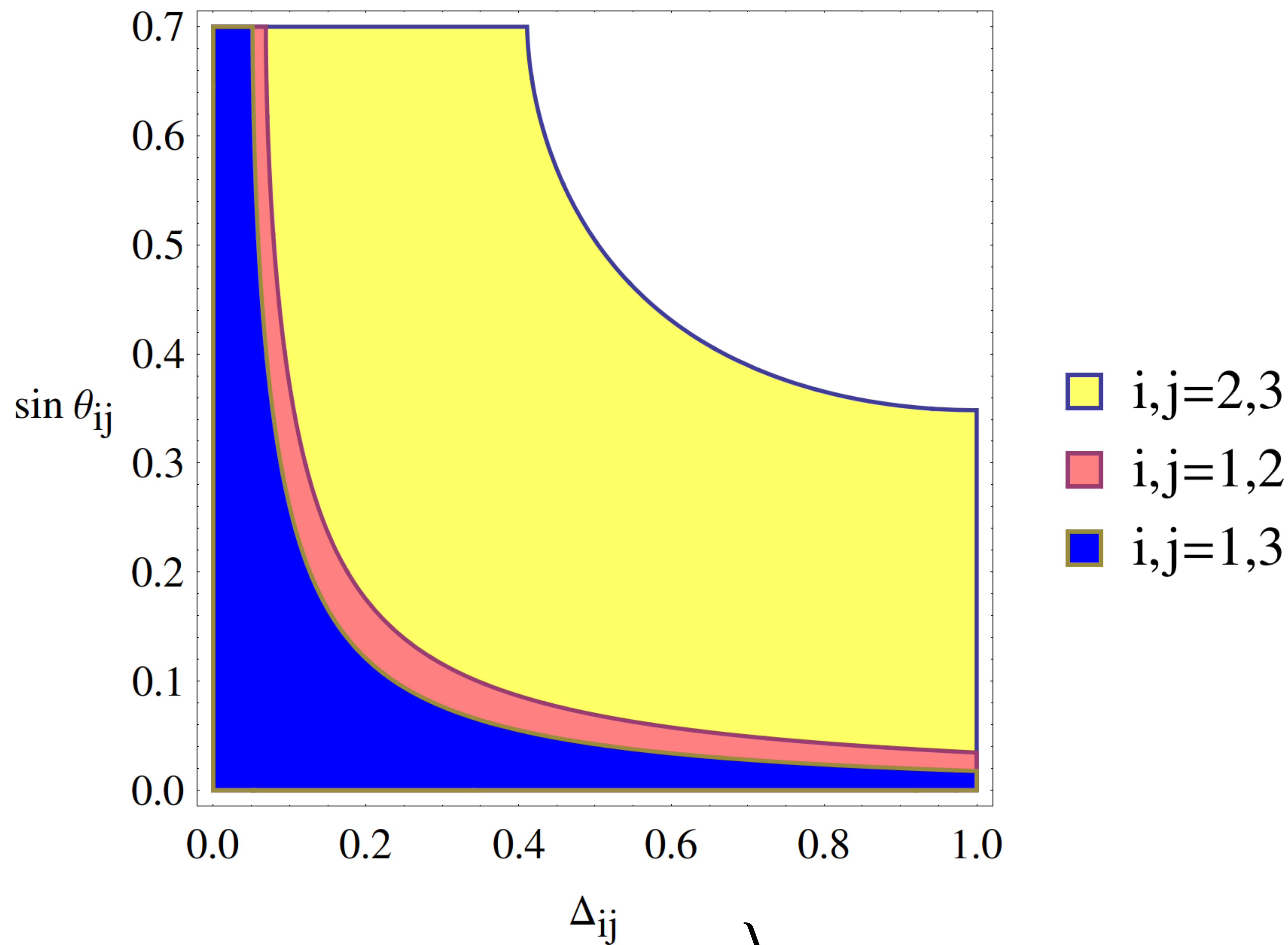
S. Renner, PS, JHEP 2018

ΔF=2

- Otherwise bounds on mixing matrix

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



$\sim \lambda_{1,2}$

S. Renner, PS, JHEP 2018