A flavoured dark sector

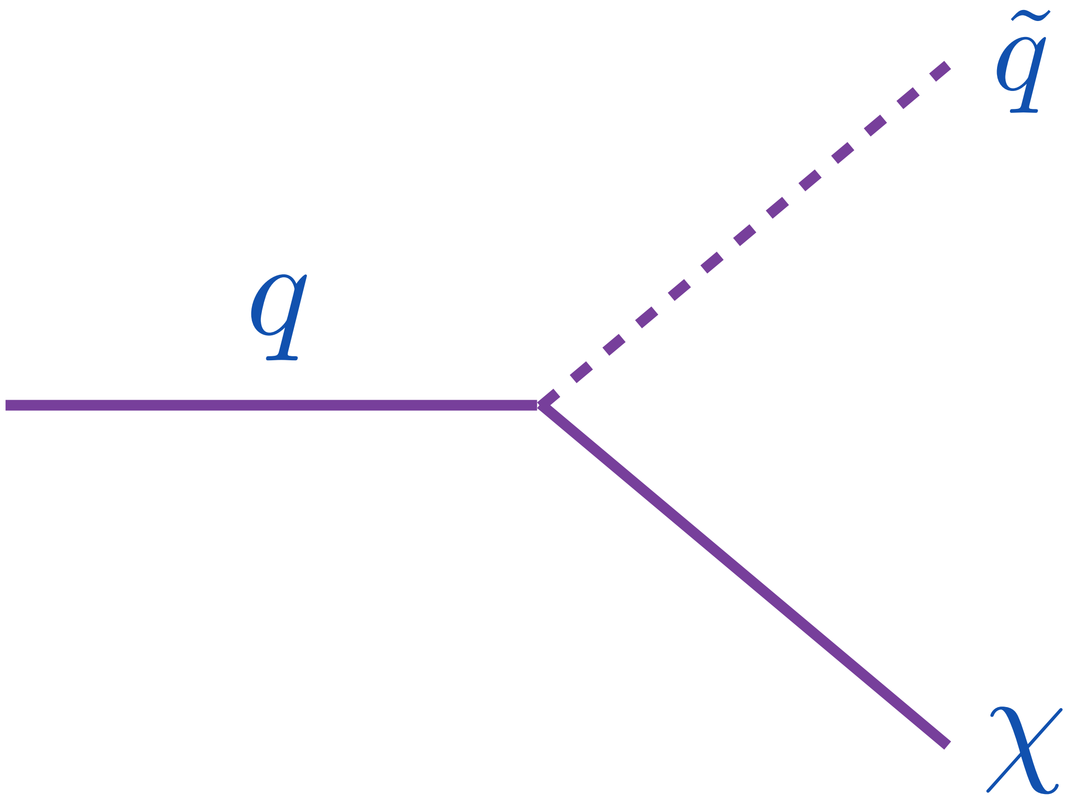
Pedro Schwaller (Mainz University)

Zurich Physics Workshop
January 10, 2019

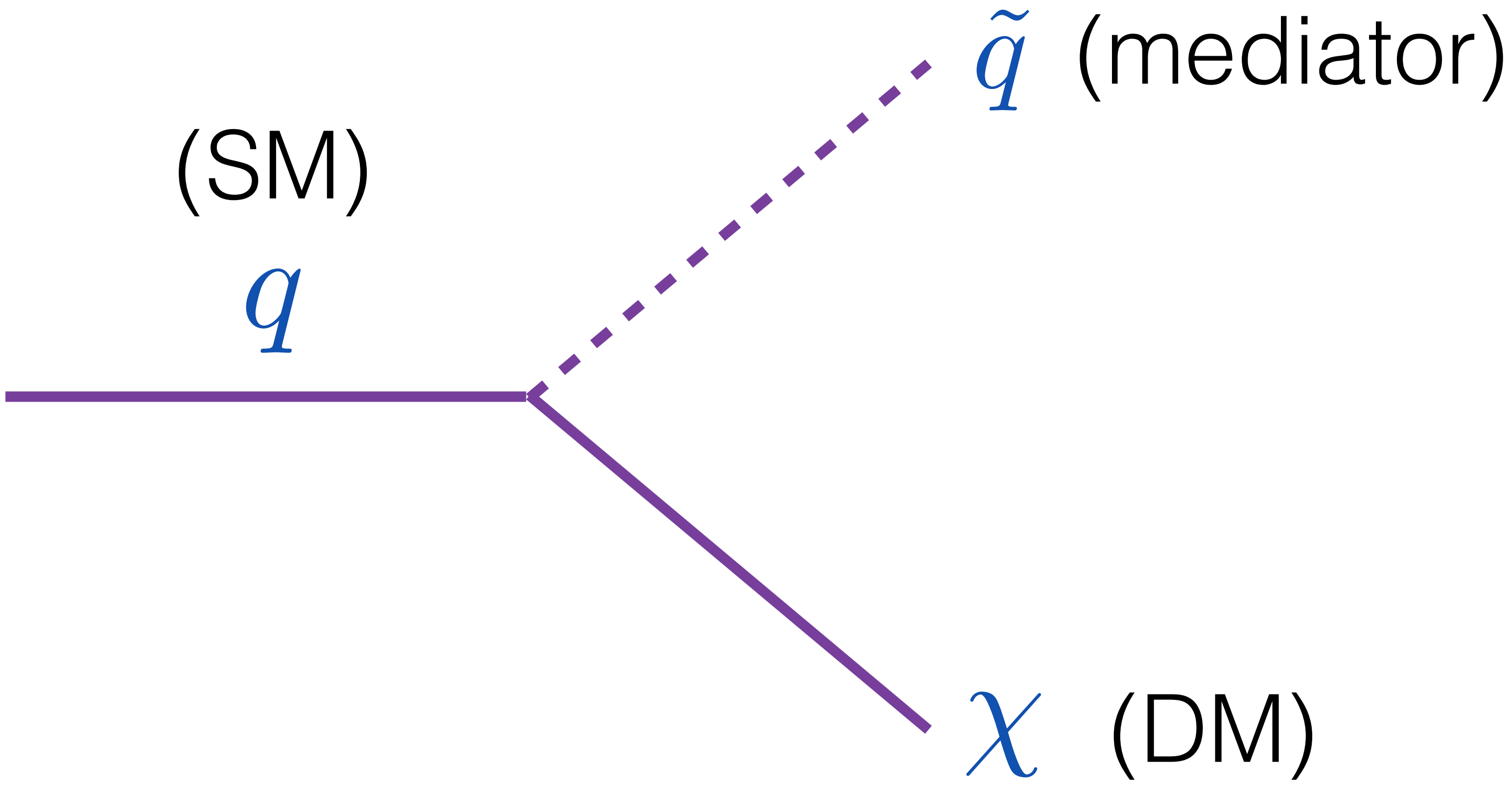
based on:

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

Flavoured Dark Matter



Flavoured Dark Matter



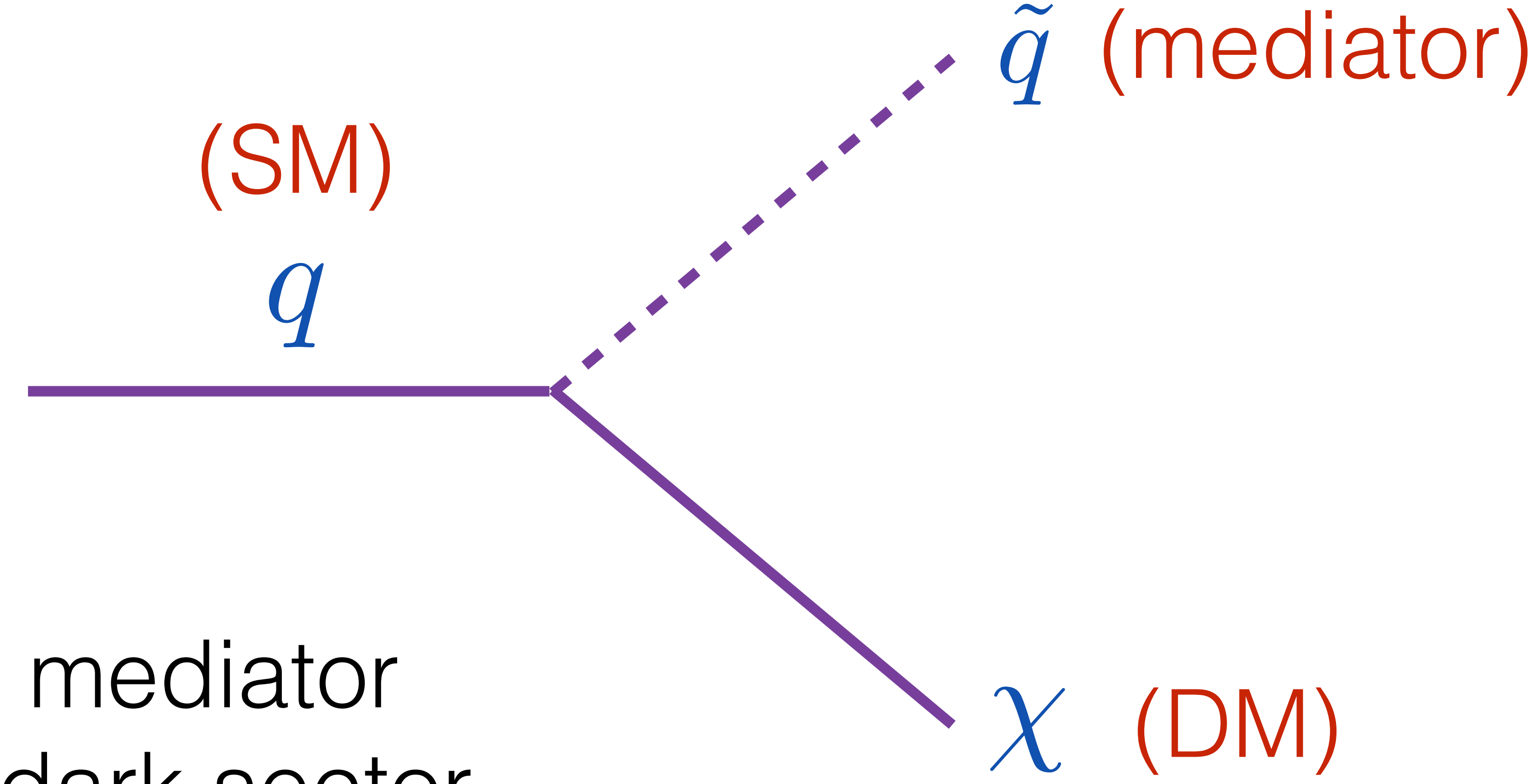
(SM)

q

$\tilde{q}$ (mediator)

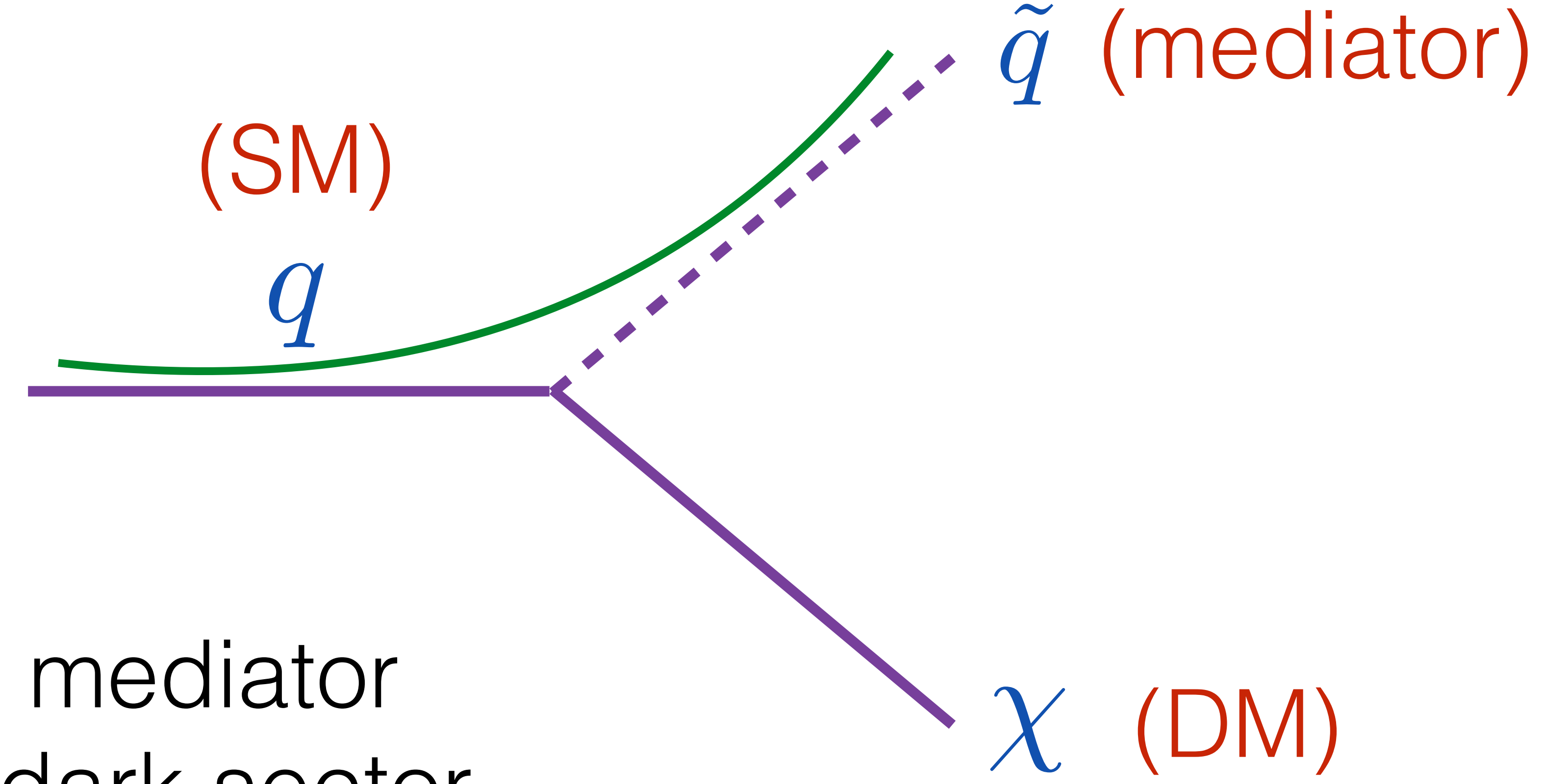
χ (DM)

Flavoured Dark Matter



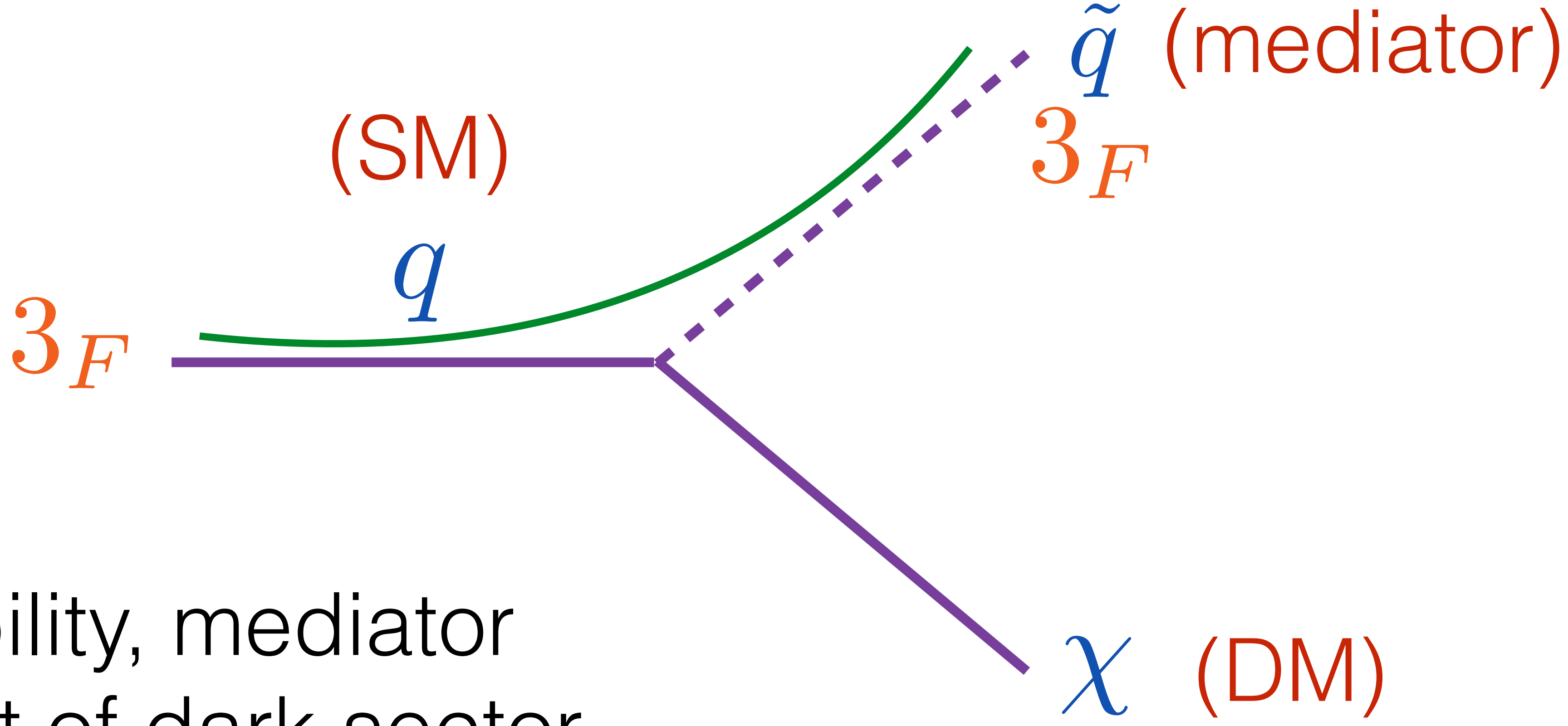
- For DM stability, mediator must be part of dark sector
- Mediator inherits SM charges

Flavoured Dark Matter



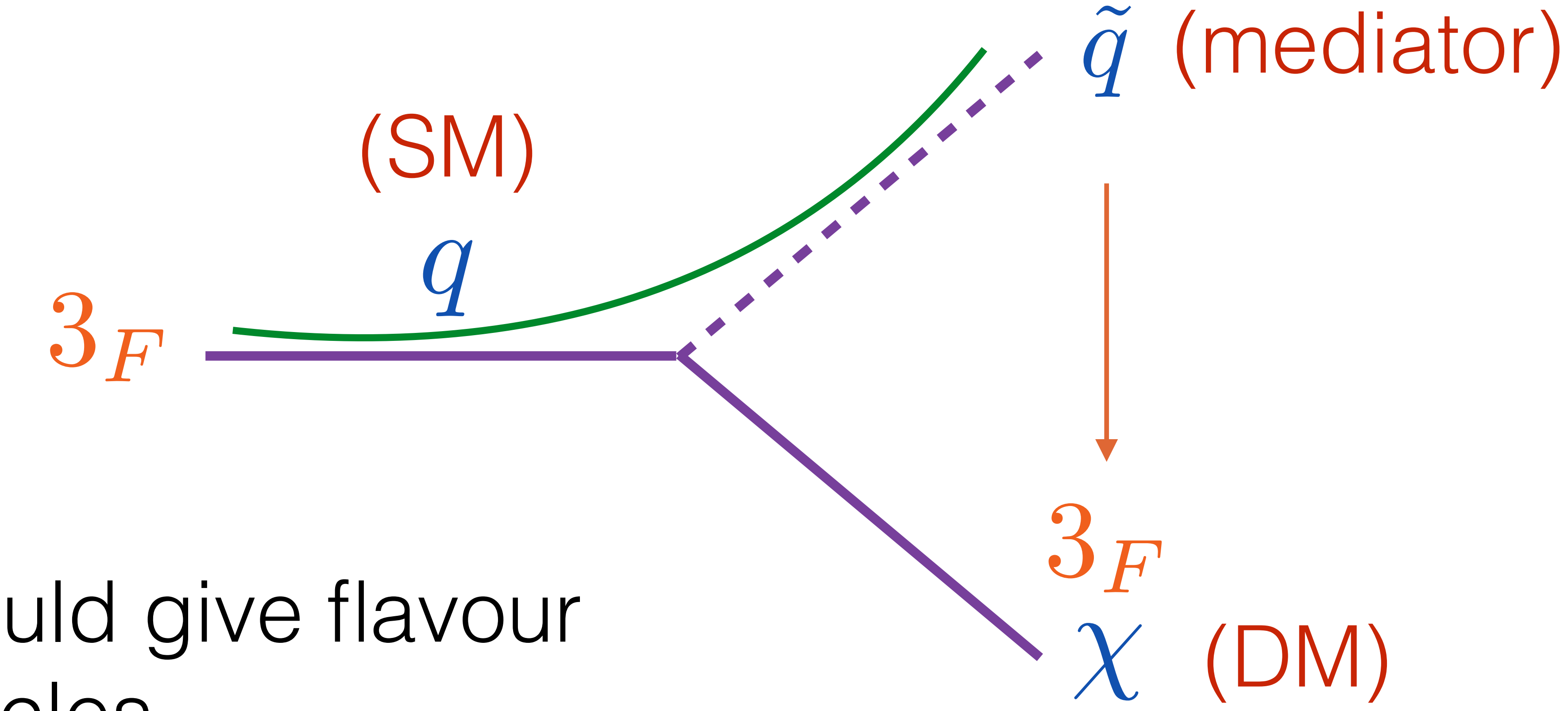
- For DM stability, mediator must be part of dark sector
- Mediator inherits SM charges
  - Colour

Flavoured Dark Matter



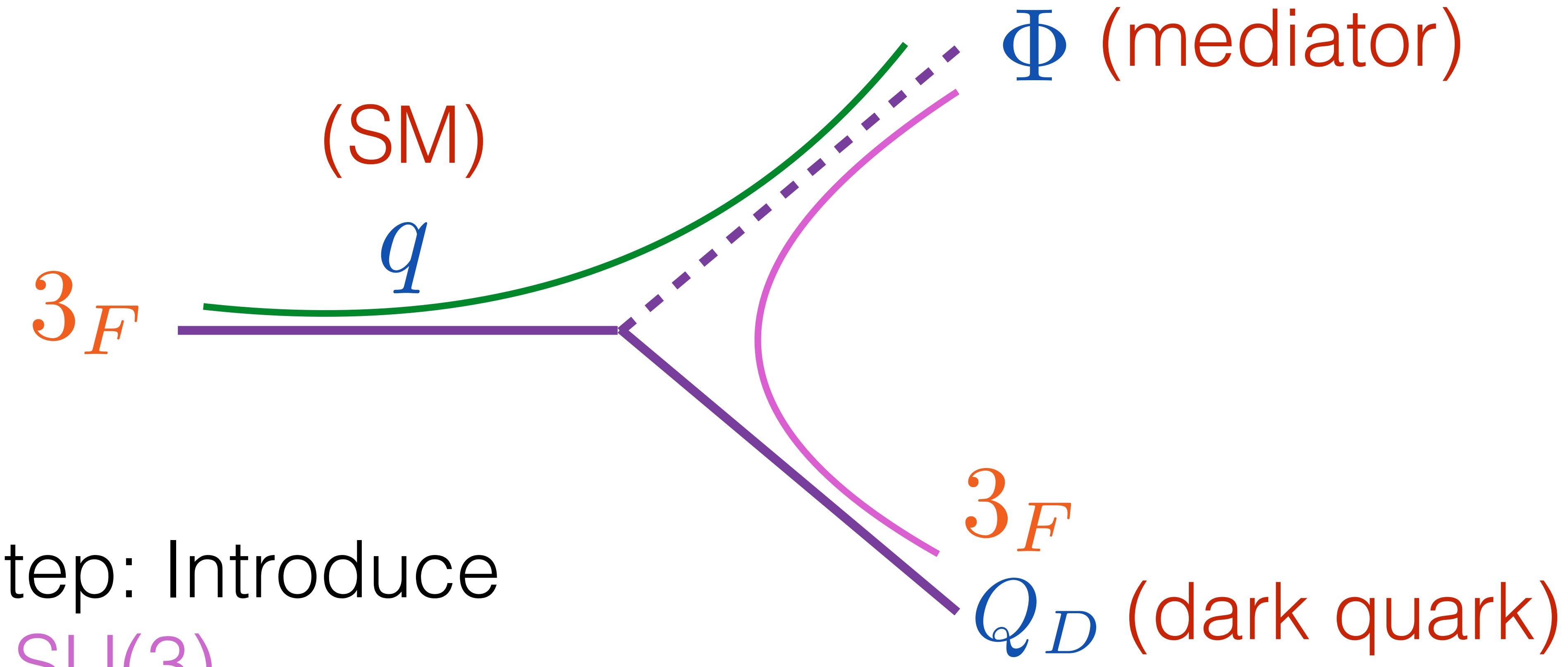
- For DM stability, mediator must be part of dark sector
- Mediator inherits SM charges
    - Colour
    - Flavour

Flavoured Dark Matter



- Instead, could give flavour to DM particles
- flavoured DM
  (Agrawal,Blachet,Chacko,Kilic)

Flavoured Dark Sector

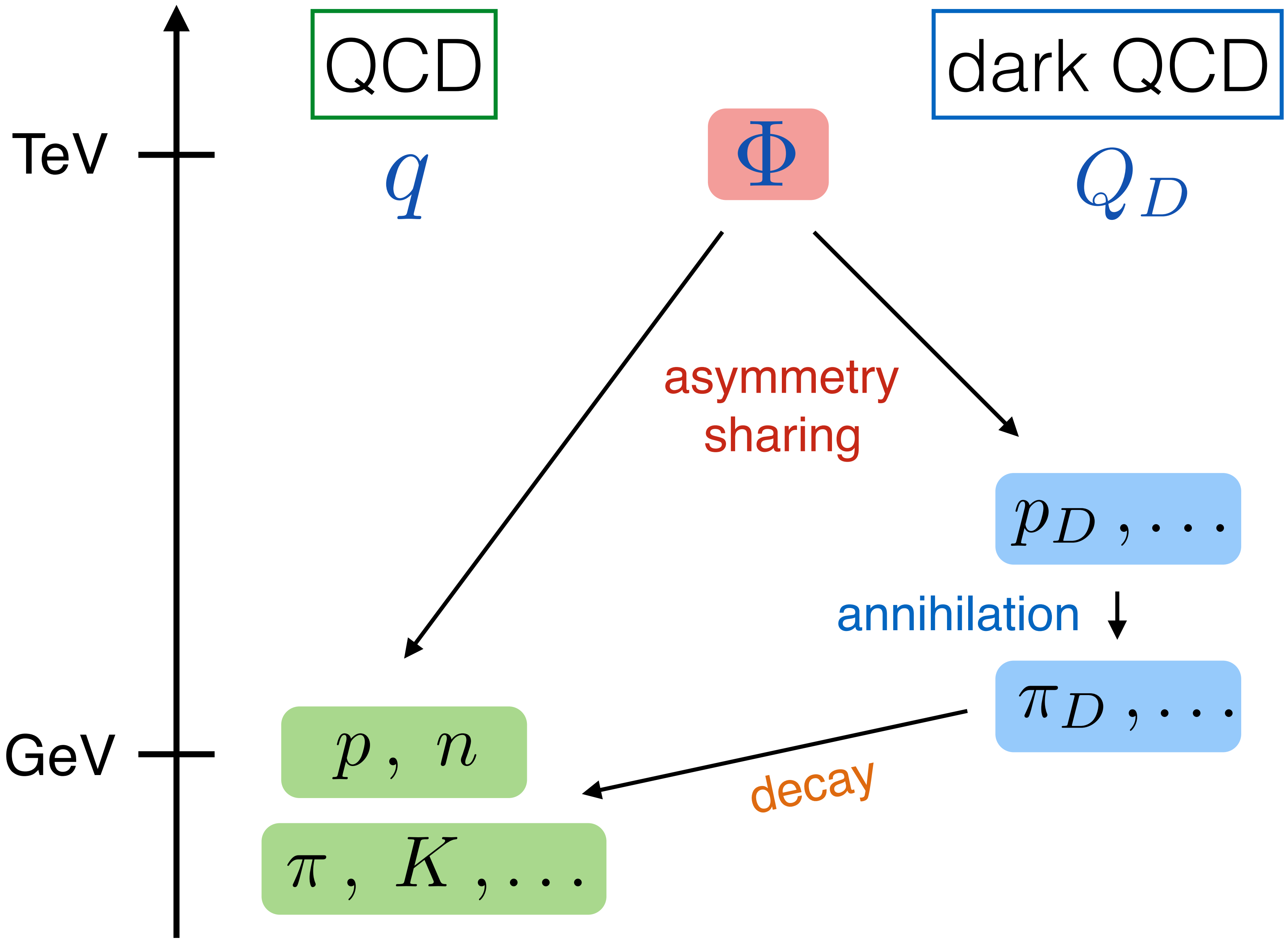


- One more step: Introduce dark colour SU(3)
- DM stability from dark gauge inv.
- Mediator heavy (colour!), dark quarks may be light → QCD like dark sector

Outline

- Collider pheno of QCD like dark sectors
- The flavour portal and consequences

Dark QCD



TeV

GeV

QCD

dark QCD

q

Φ

Q_D

asymmetry sharing

$p_D\,, \ldots$

annihilation ↓

$\pi_D\,, \ldots$

decay

$p\,,\ n$

$\pi\,,\ K\,, \ldots$

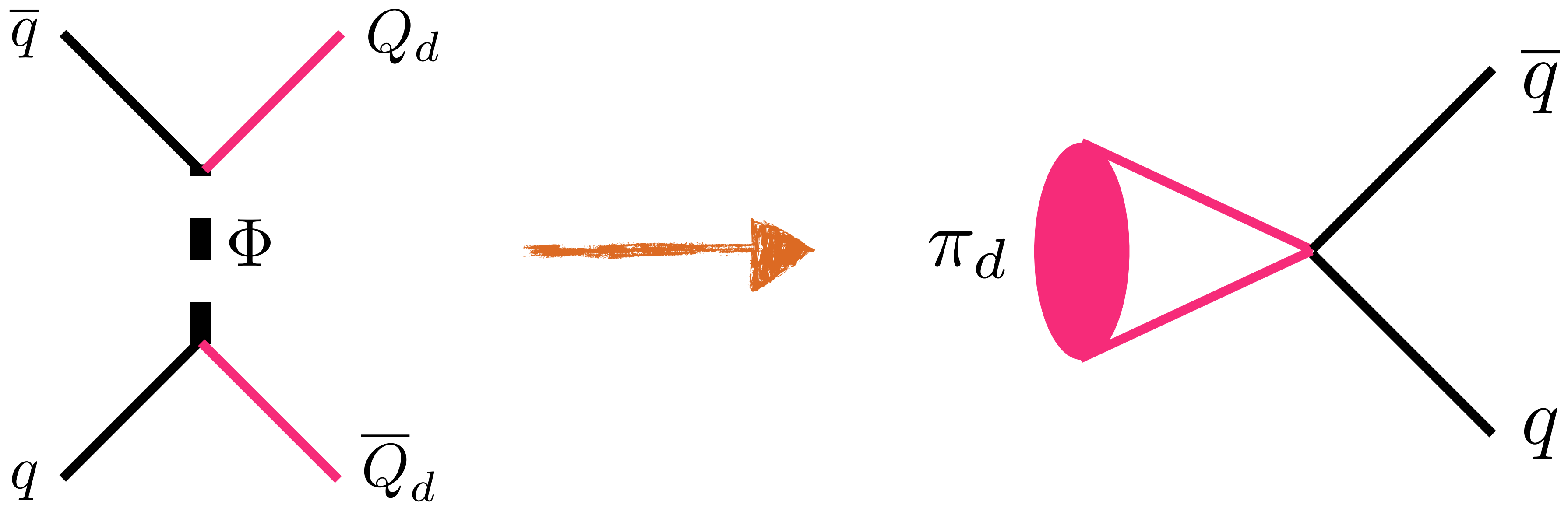
- SU(N) dark sector with neutral “dark quarks”
- Confinement scale

  $\Lambda_{\mathrm{darkQCD}}$

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

Dark Pion Lifetime

- Integrate out mediator, match to dark pion current



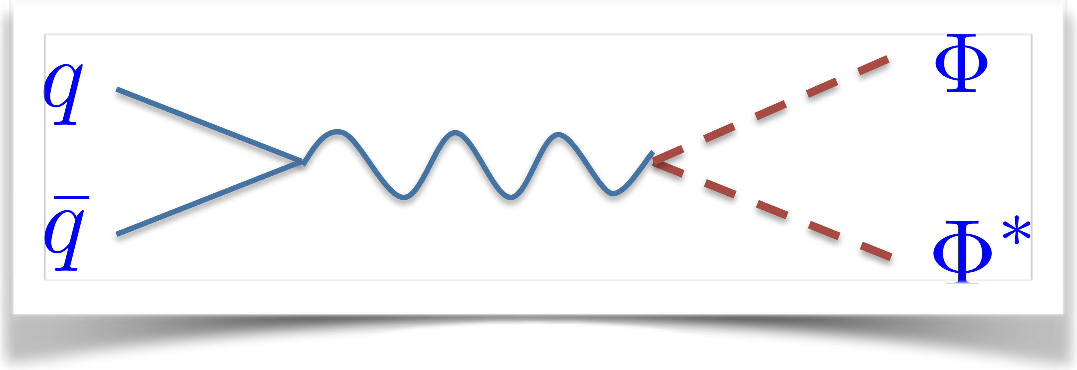
- Decay to SM jets (pions)

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

Decay in LHC detectors!

Collider Signature

- Pair production of heavy bi-fundamental fields:



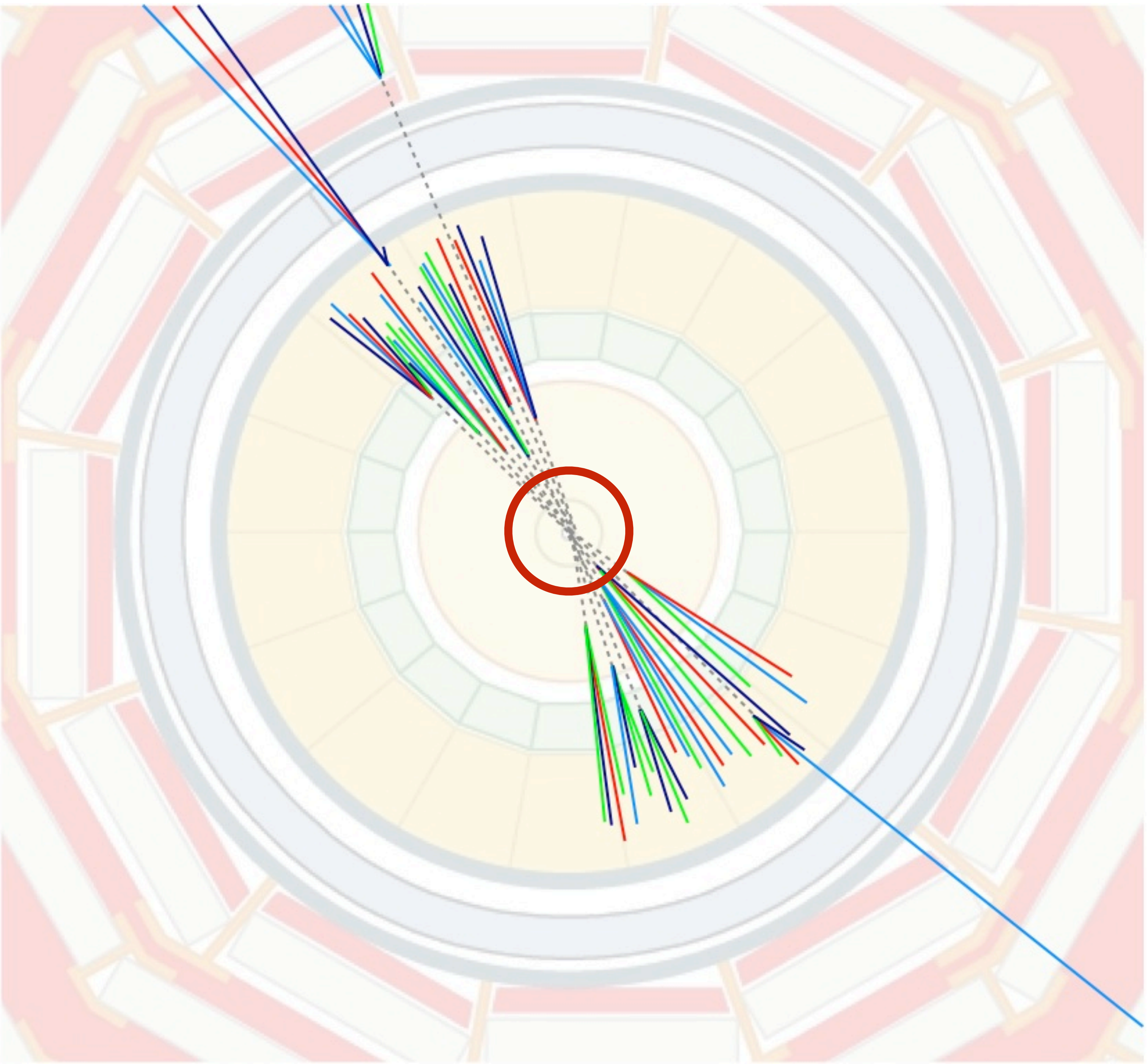
- Decay to quark - dark quark pairs
  - two QCD-jets
  - two "Emerging Jets":
    dark quarks shower and hadronize in dark sector
    decay back to SM jets with displaced vertices

Also "Hidden Valley" signature
Strassler, Zurek, 2007; …
related: SIMP dark matter
Bai, Rajaraman, 2011

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

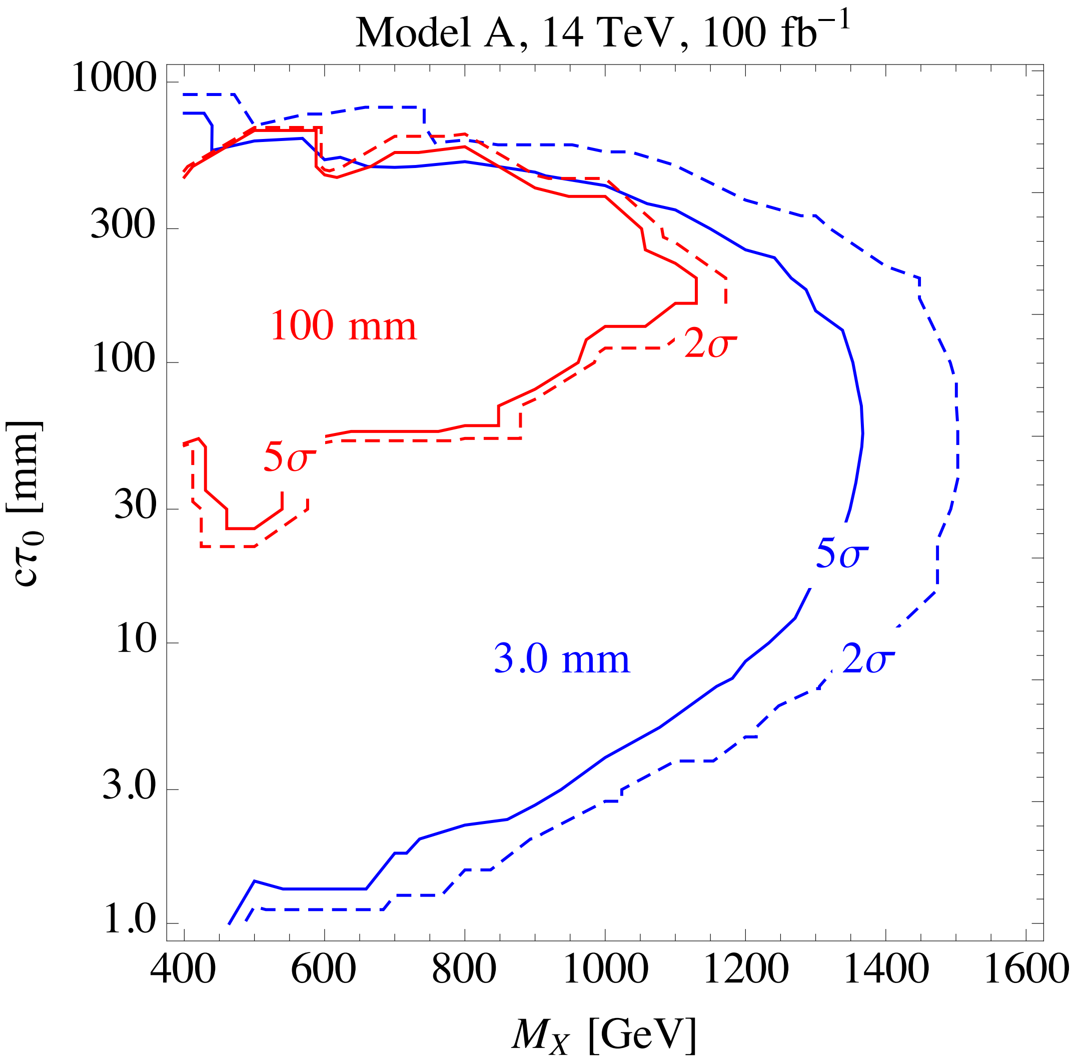
PS, Stolarski, Weiler, 2015

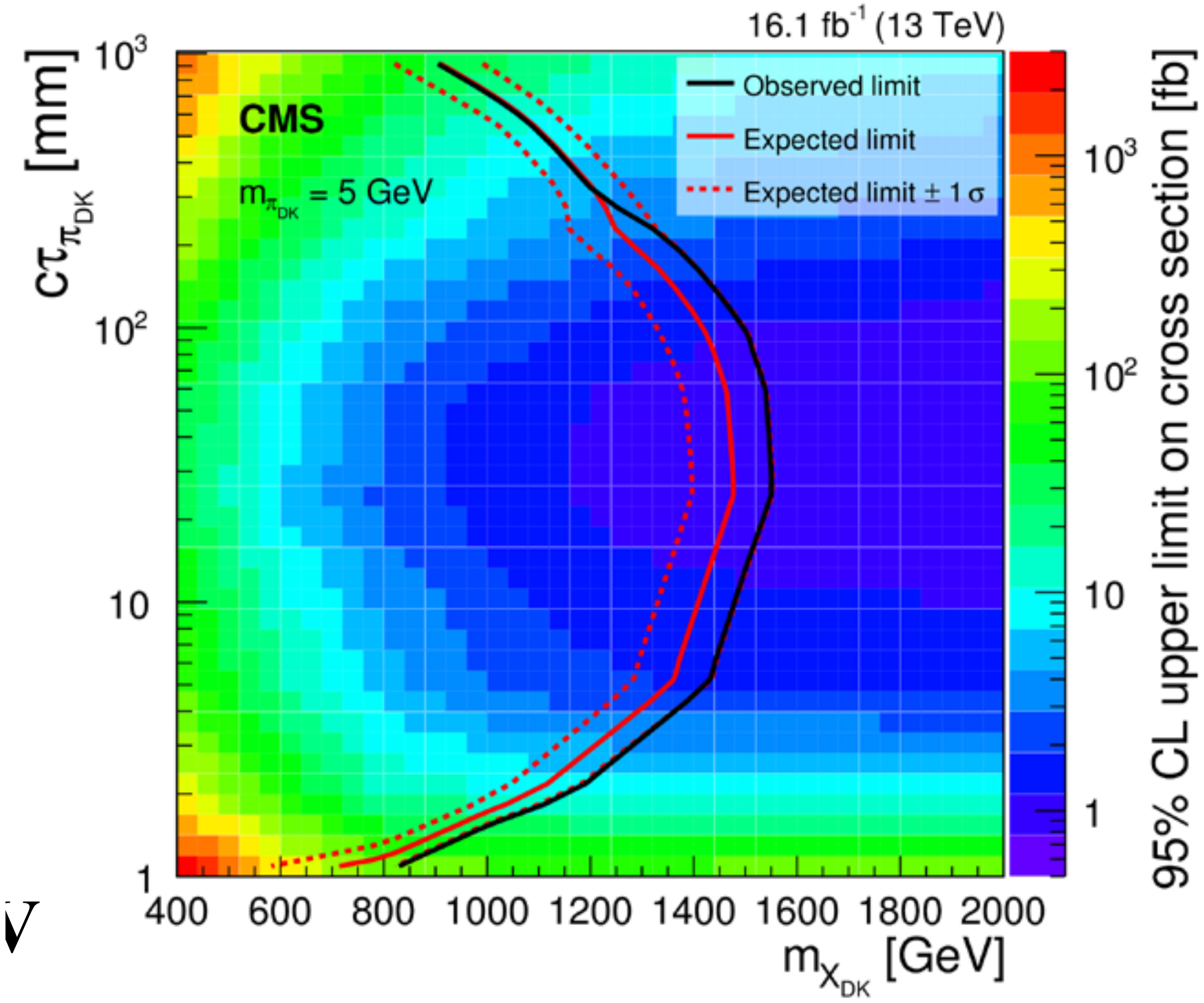


First search published!

PS, Stolarksi, Weiler, 2015

CMS 2018!





Talk by Kevin Pedro,
LLP workshop Amsterdam, 2018

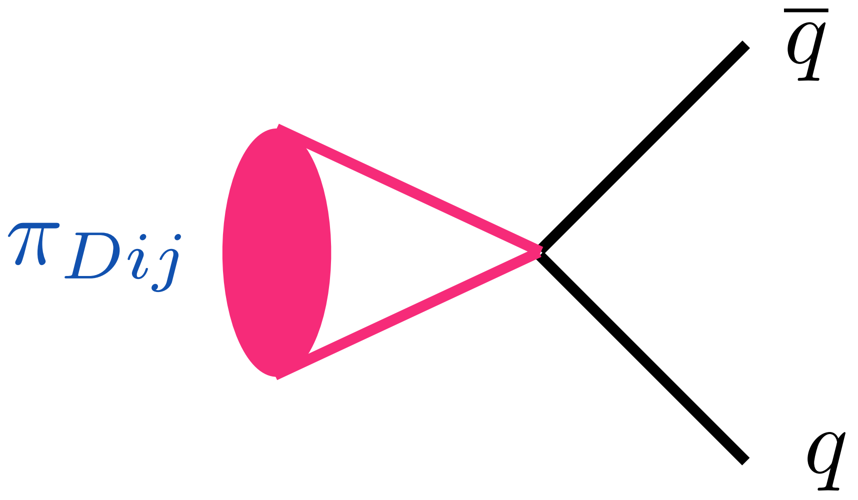
With extra flavour

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:

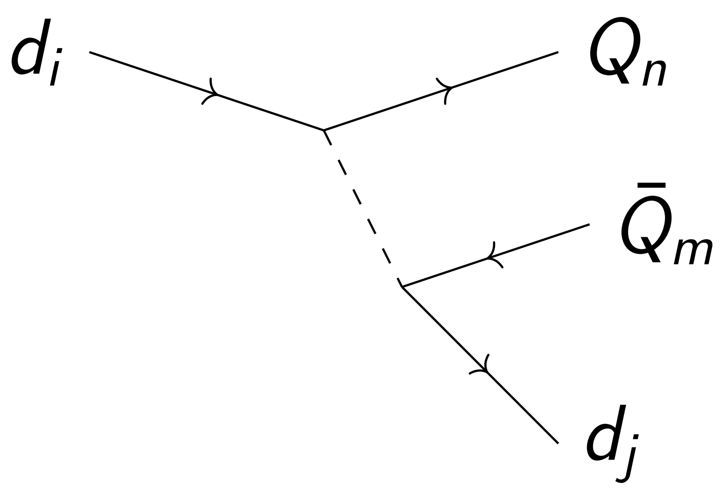


$$\propto \sum_{q,q'} |\lambda_{qi} \lambda^*_{q'j}|^2$$

S. Renner, PS, 2018

S. Renner, PS, 2018

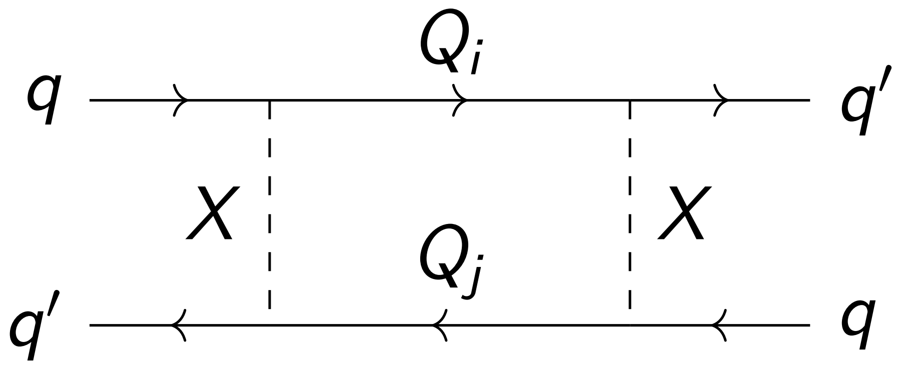
Flavour matters



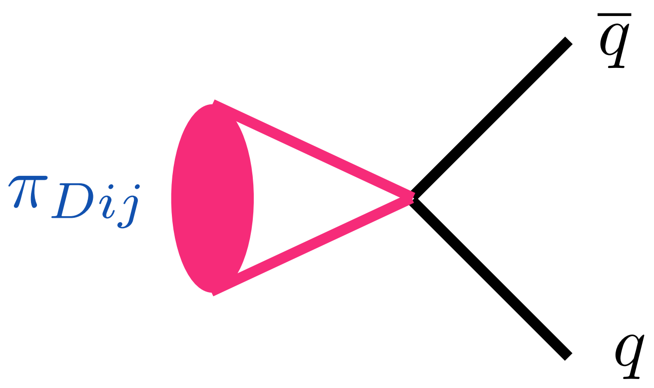
$\Delta F = 1$

$\Delta F = 2$

constraints



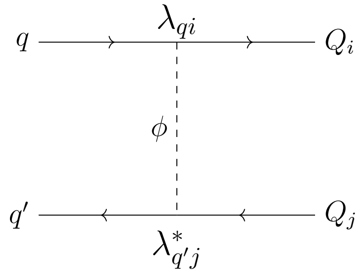
$$\lambda_{ij}\bar{d}_{Ri}Q_{Lj}\Phi$$



dark pion properties

fixed target experiments

NA62



SHiP

Search for Hidden Particles

Flavour constraints

Parameterisation from Agrawal, Blanke, Gemmler, 2014

- Parameterise

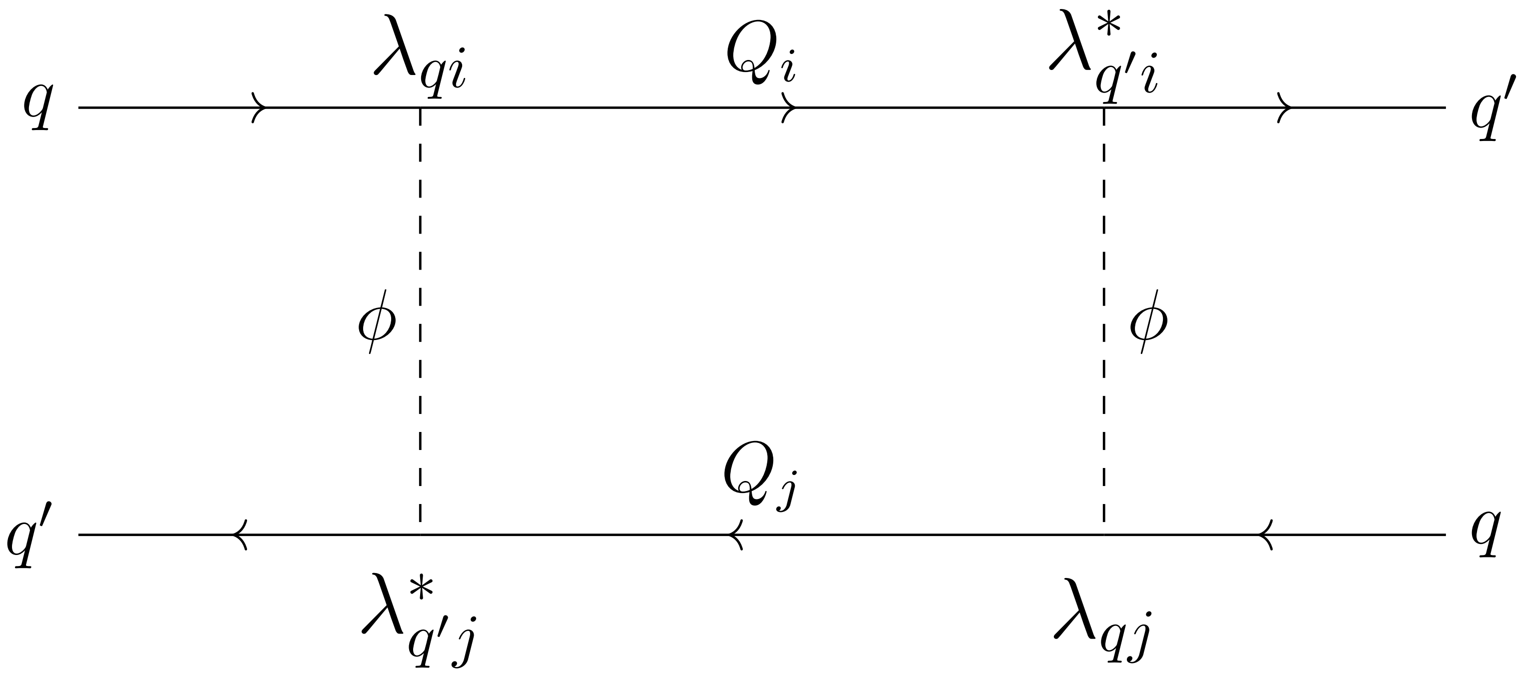
unitary

$$\lambda = UDV$$

diagonal

- For degenerate dark quark masses, can absorb V
- If $D \propto \mathbb{1}$, SM & dark flavours aligned
- Write $D = \Big(\lambda_0 \cdot \mathbb{1} + \mathrm{diag}(\lambda_1, \lambda_2, -(\lambda_1 + \lambda_2))\Big)$

ΔF=2



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

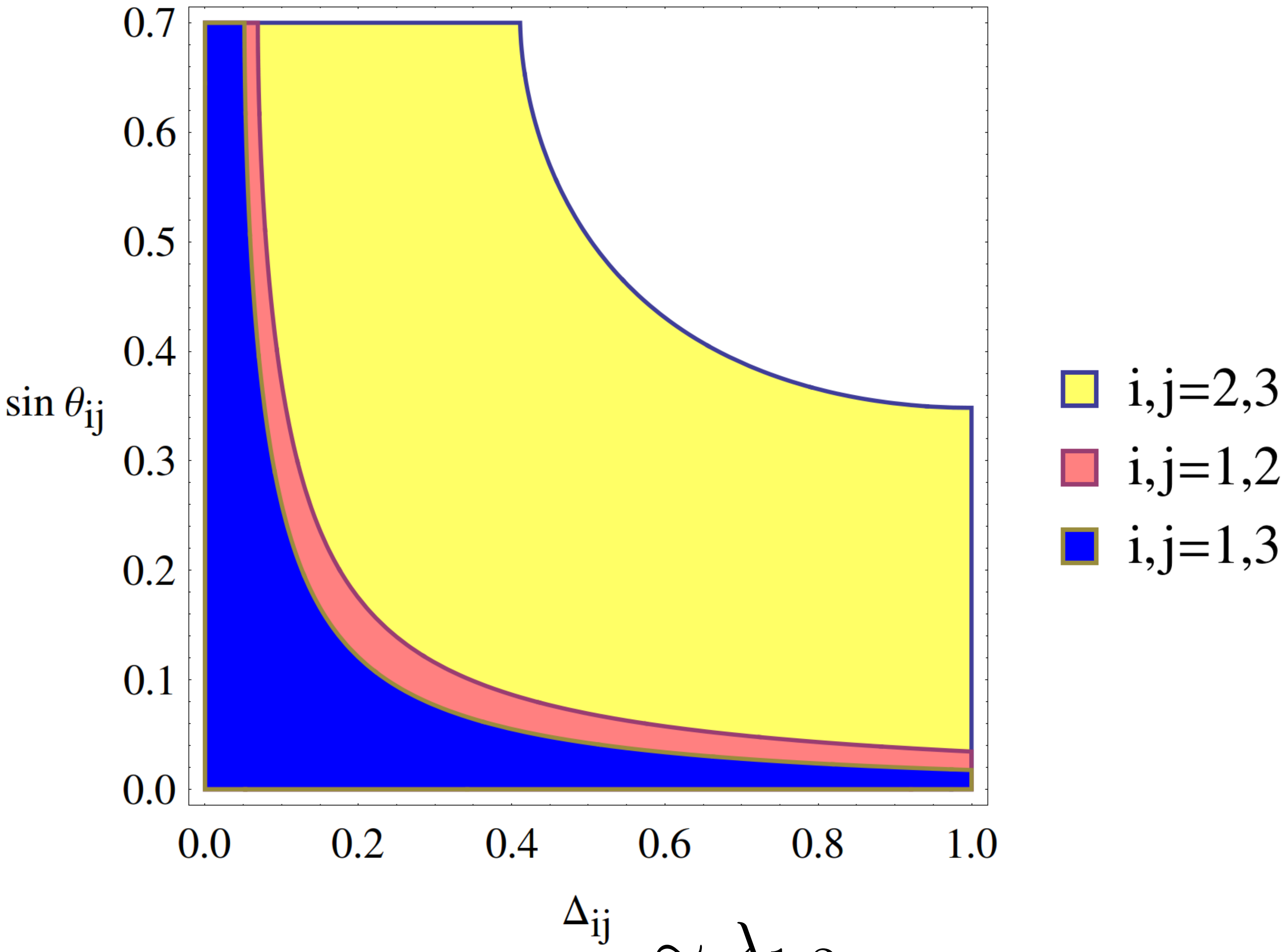
$$\left(\sum_{i=1}^{3} \lambda_{qi}\lambda^*_{q'i}\right)^2 = \left([UD(UD)^\dagger]_{qq'}\right)^2 = \lambda_0^4 \left([UU^\dagger]_{qq'}\right)^2 = 0$$

S. Renner, PS, 2018

ΔF=2

- Otherwise bounds on mixing matrix

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



$\sim \lambda_{1,2}$

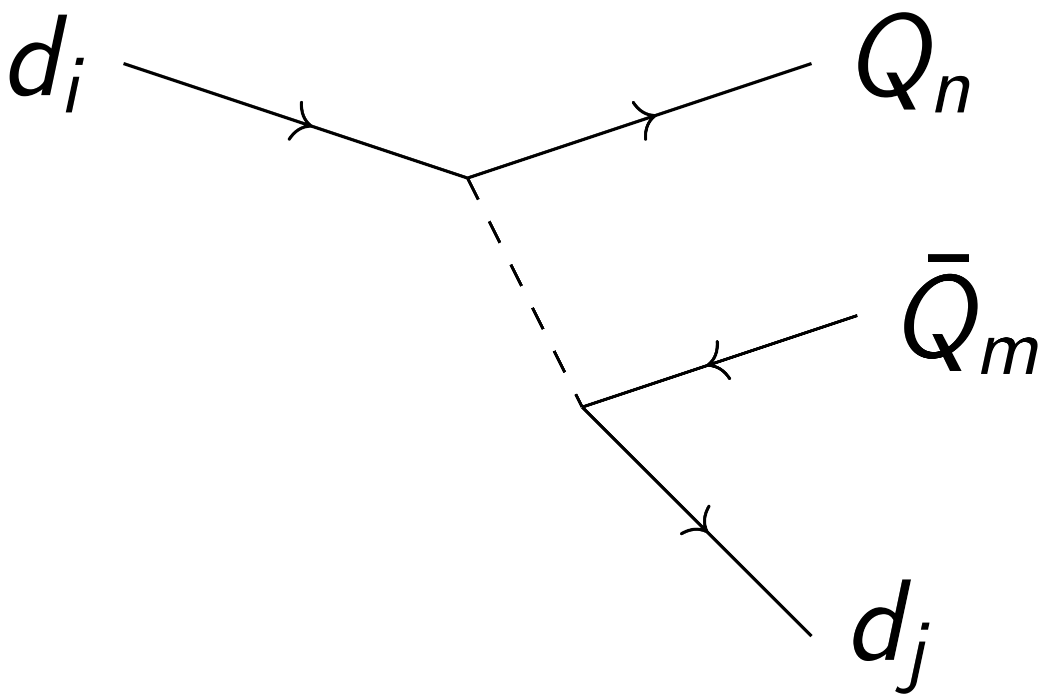
S. Renner, PS, 2018

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 aligned limit!

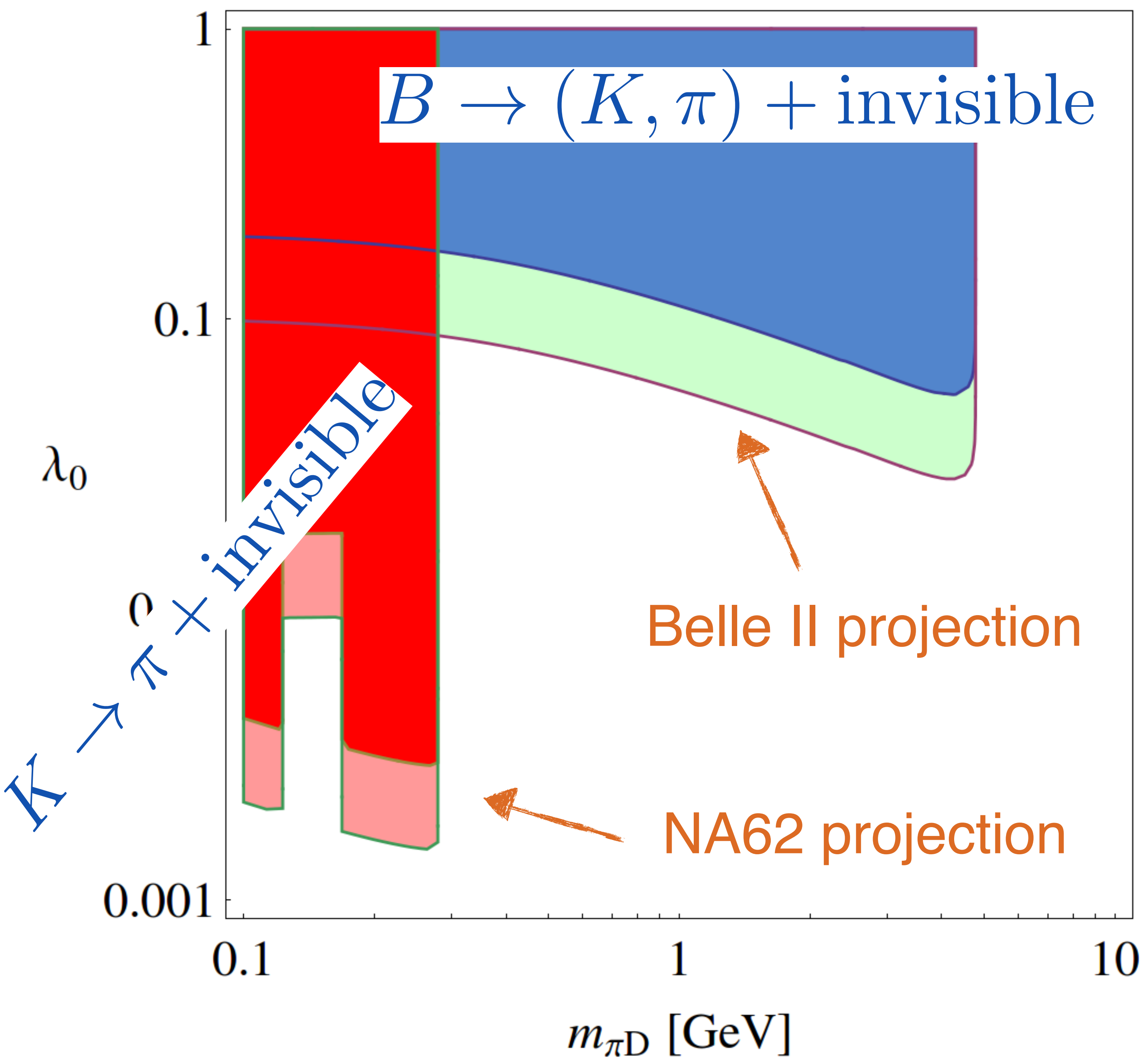
great resource:
Kamenik, Smith, 2011

S. Renner, PS, 2018

Bounds from rare decays

- Best bound on couplings for very light dark pions

- Dark pion production in fixed target expts!



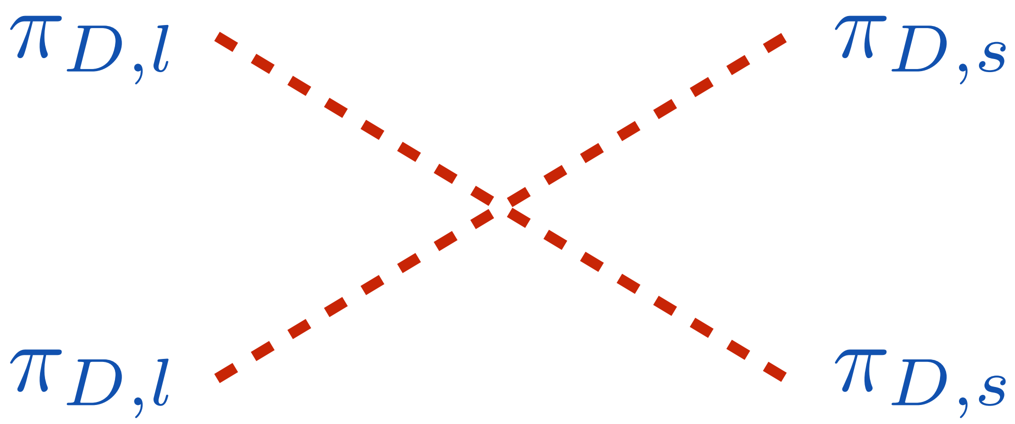
S. Renner, PS, 2018

BBN

- Energy injection during/after BBN is bad
- Usual constraint:

$$\Gamma(X \to \mathrm{SM}) > (1\ \mathrm{s})^{-1} \quad \forall \quad X$$

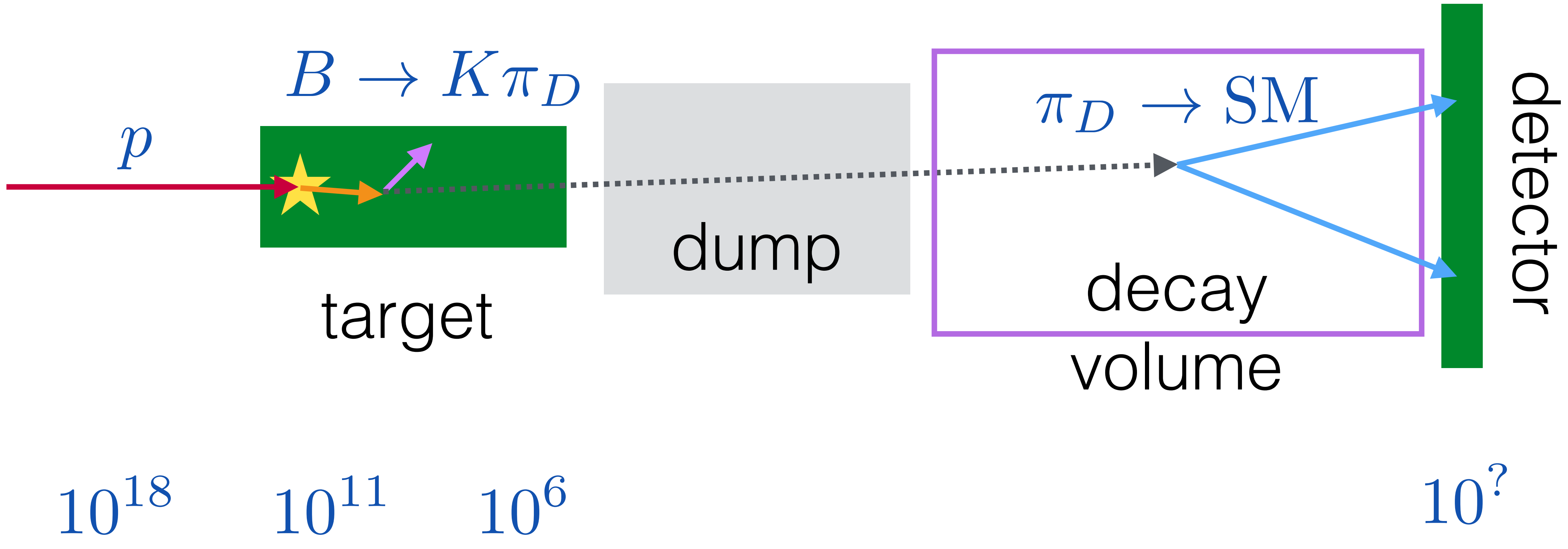
- Here:



- Only need one sufficiently short lived dark pion

Fixed target

- My simplified NA62/SHiP:

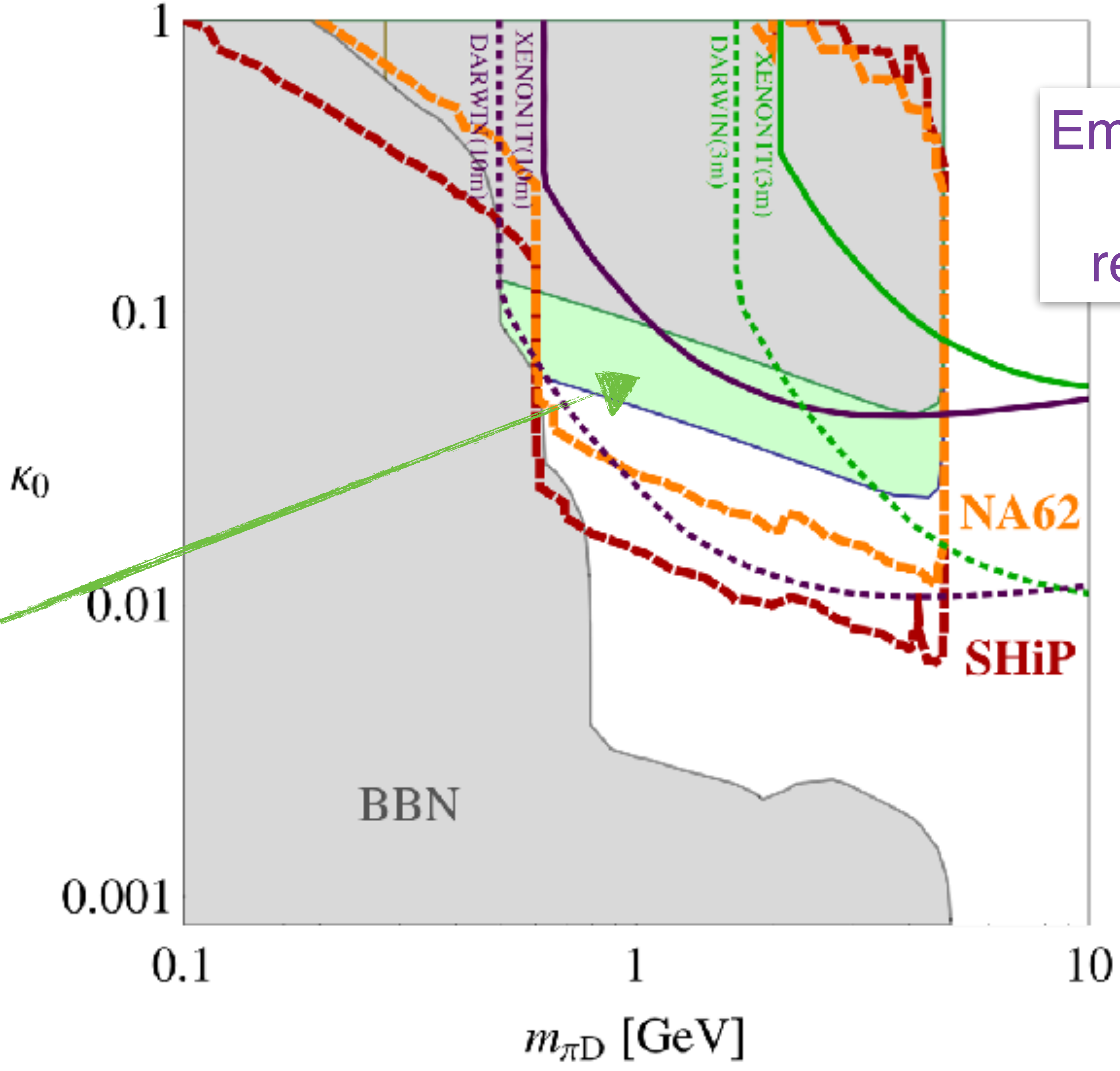


- Leading channels: $\pi_D \to \pi K$, $\pi_D \to \pi^+\pi^-\pi^0$
- No $\pi\pi$, probe of CP nature of π_D

S. Renner, PS, 2018

Fixed target reach

- Including bounds from cosmology



Emerging jets region

Belle II reach

S. Renner, PS, 2018

Summary

Flavoured dark sectors have rich phenomenology, many experiments are sensitive

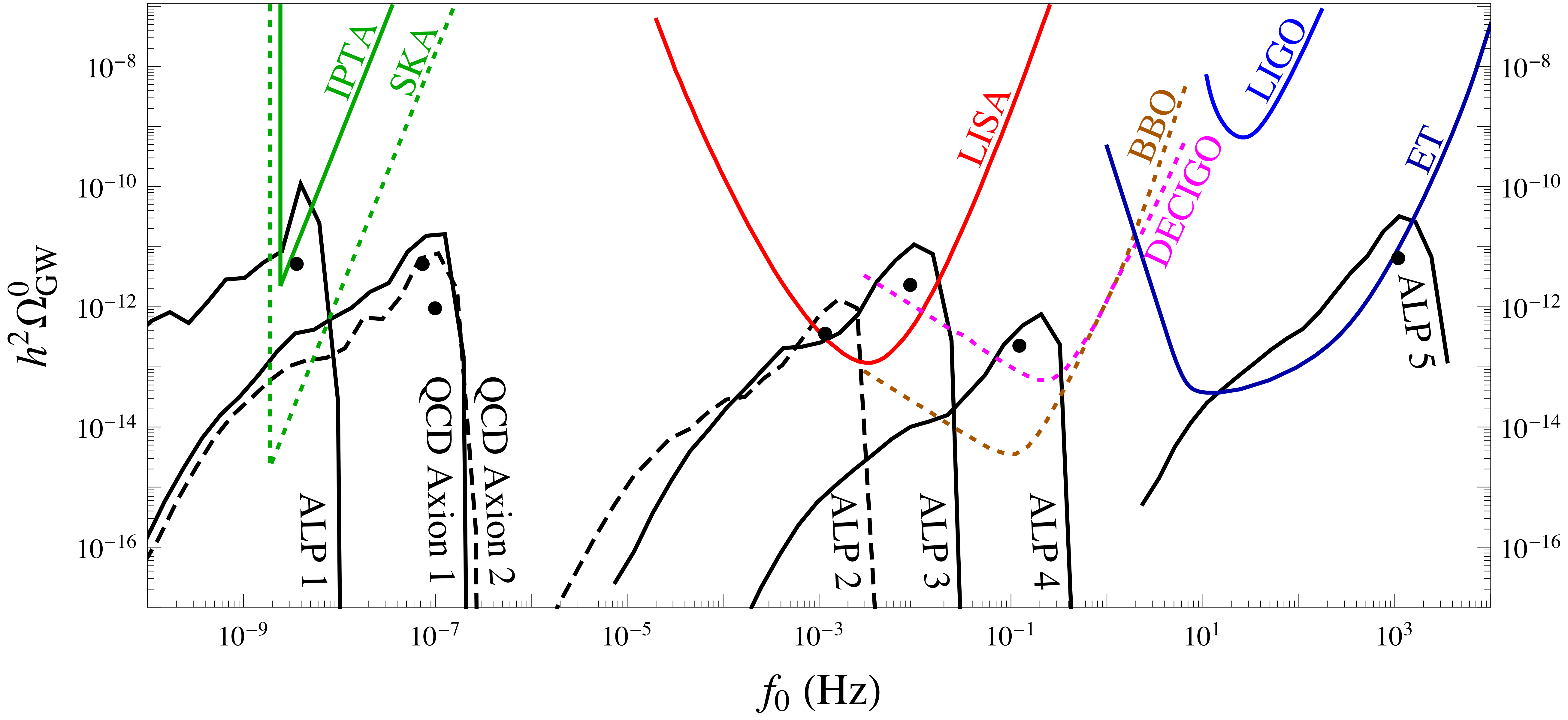
- First Emerging Jets search at CMS
- Invisible $\Delta F=1$ processes at NA62, Belle II
- Dark pion decays at NA62, SHiP
  (also LHCb, Mathusala probably)
- Direct detection & cosmological probes
- Broader range of emerging jets signatures

Outlook

- Comparison of conventional and dedicated LLP searches
- Up-flavoured and leptonic dark sectors
- Connection with B anomalies
- Dark baryon DM properties

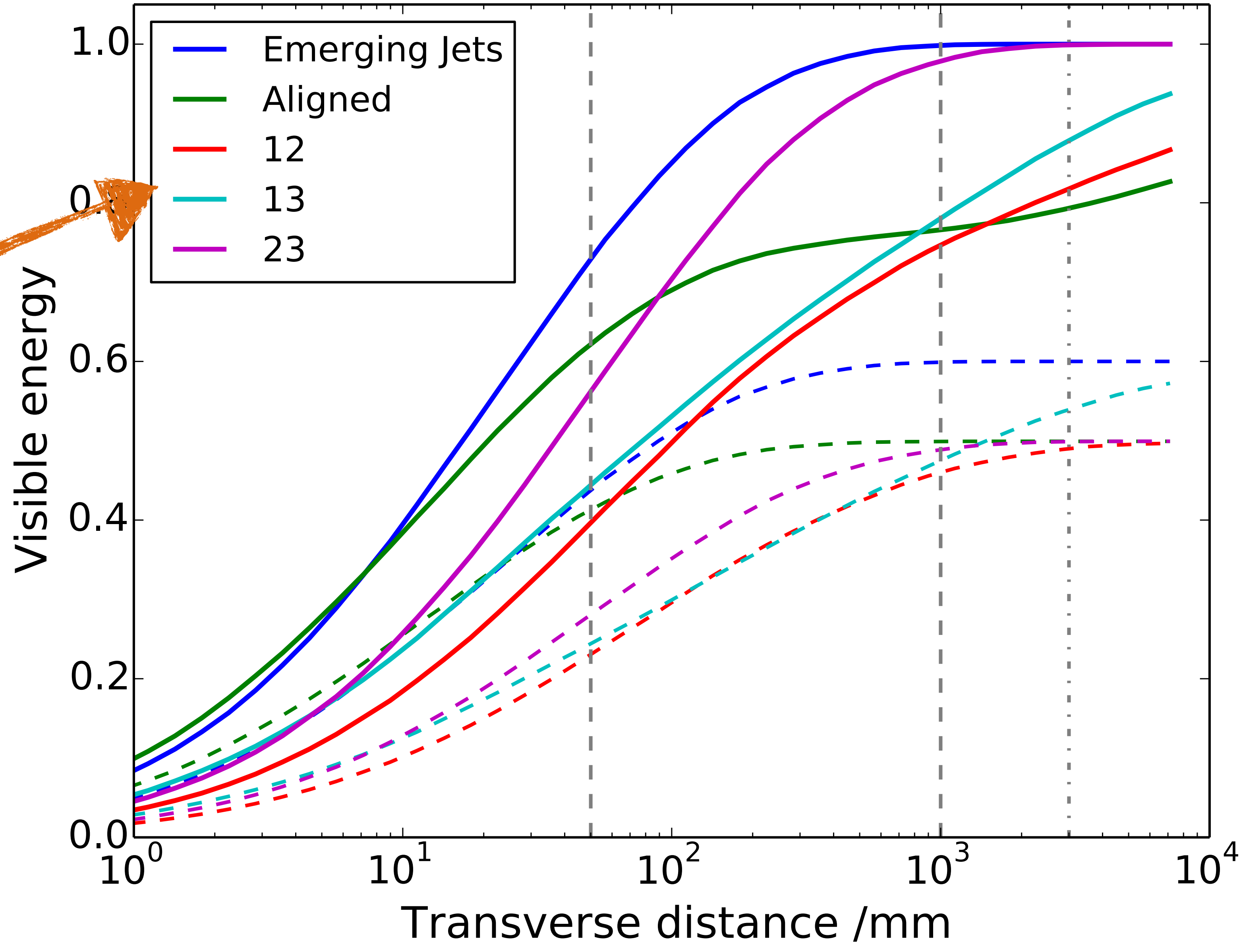
For Gilad

- If instead, you are interested in GWs from axion dark matter in the early universe: **arXiv:1811.01950**



Thank You

Emerging Jets revisited



different flavour scenarios

heavy flavours

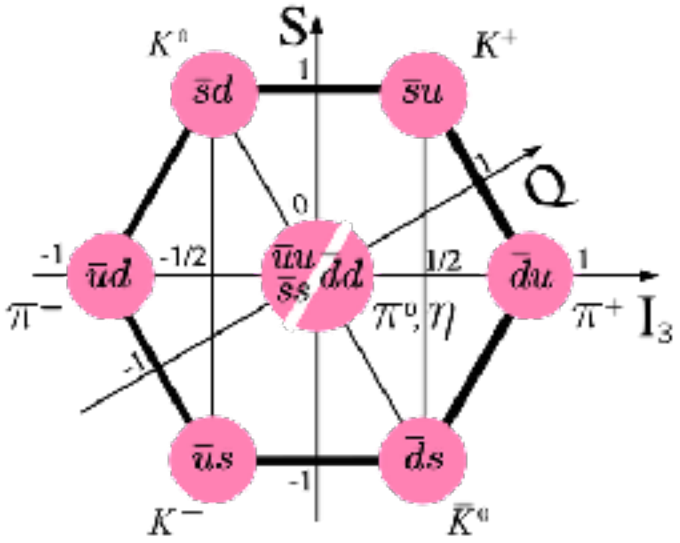
Particles and symmetries

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

Ansatz: 3 dark quark flavours Q_i

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

$\Longrightarrow$ 8 DARK PIONS



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

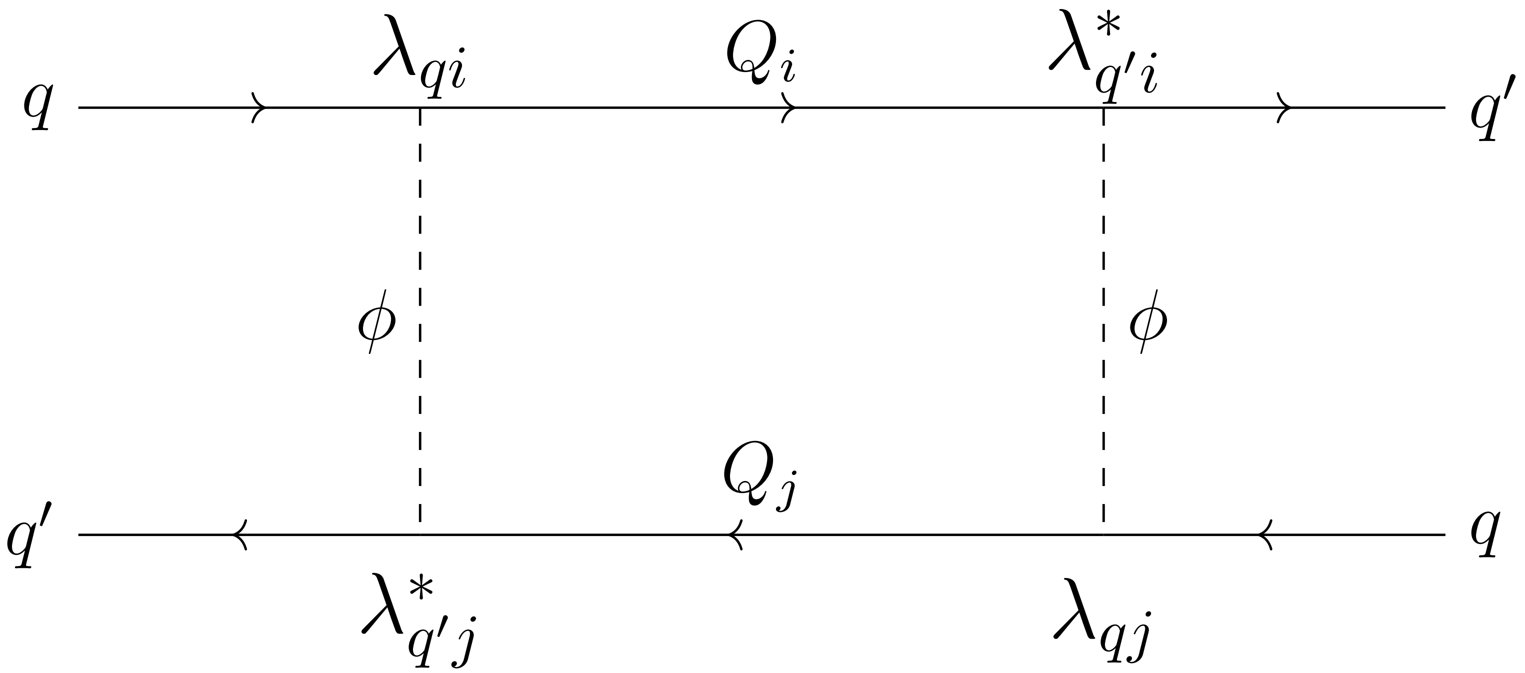
$$\lambda = UDV$$

diagonal

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

S. Renner, PS, in progress

ΔF=2



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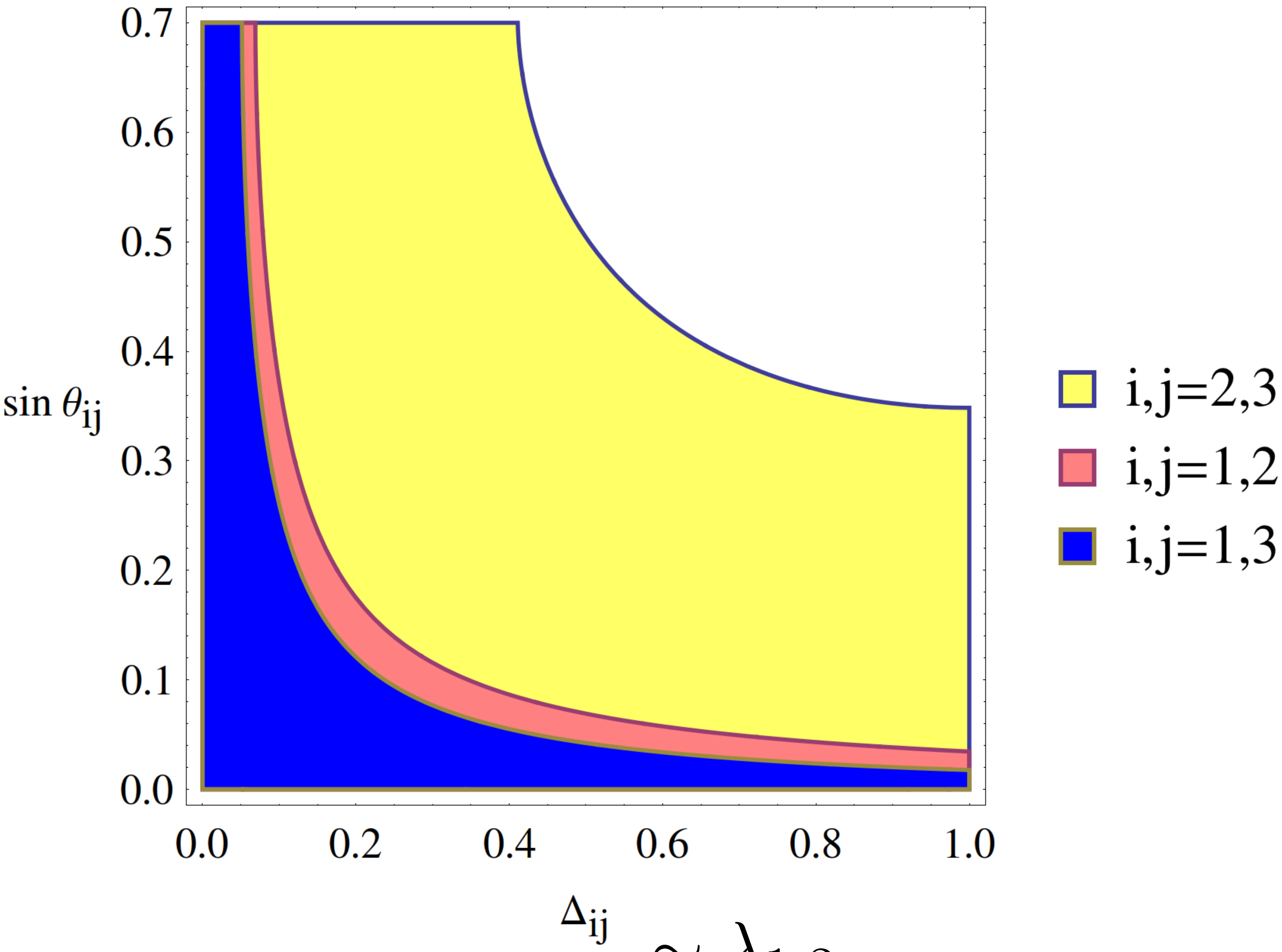
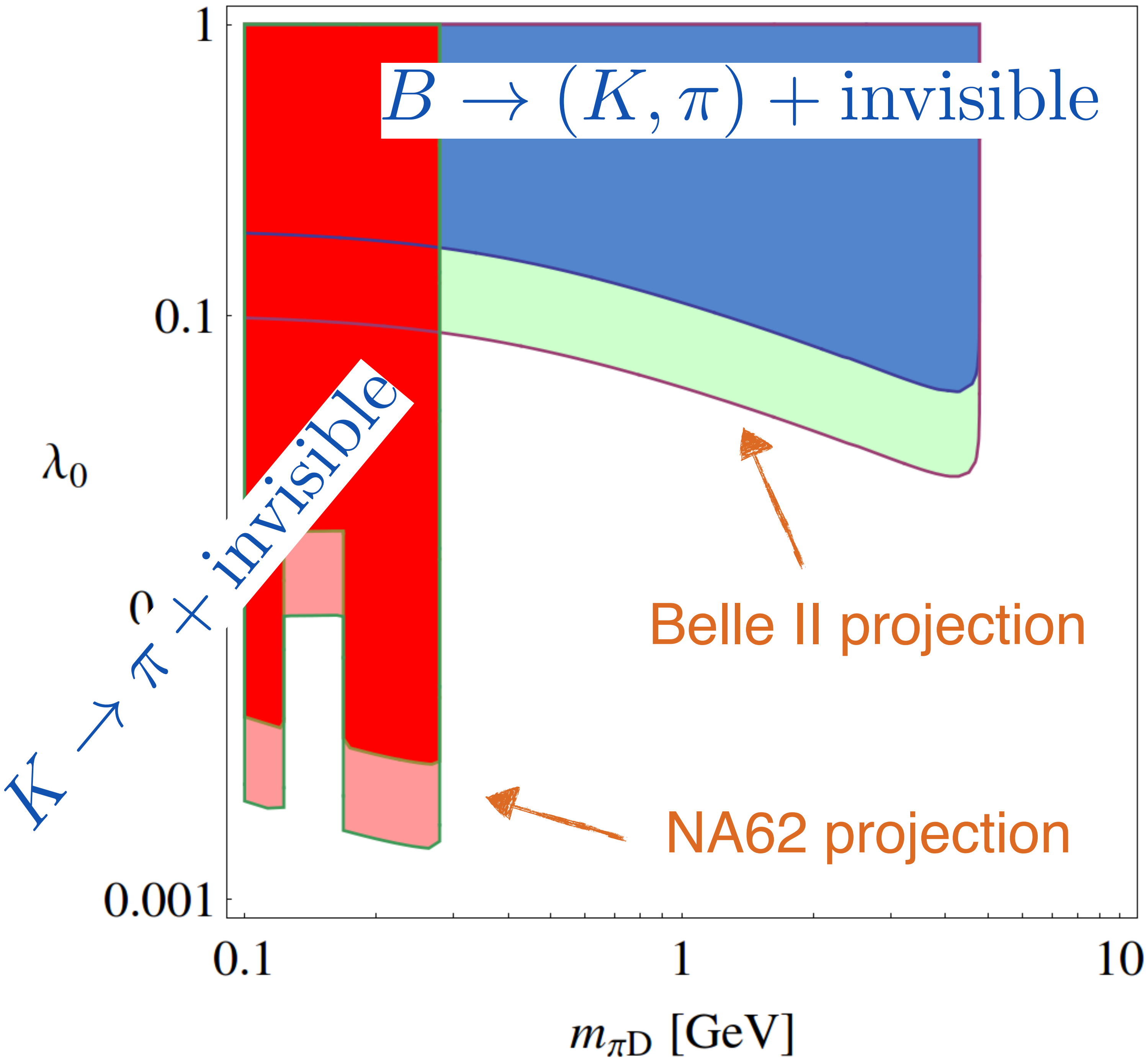


$\sim \lambda_{1,2}$

S. Renner, PS, in progress

ΔF=1

- Best bound on couplings for very light dark pions



Belle II projection

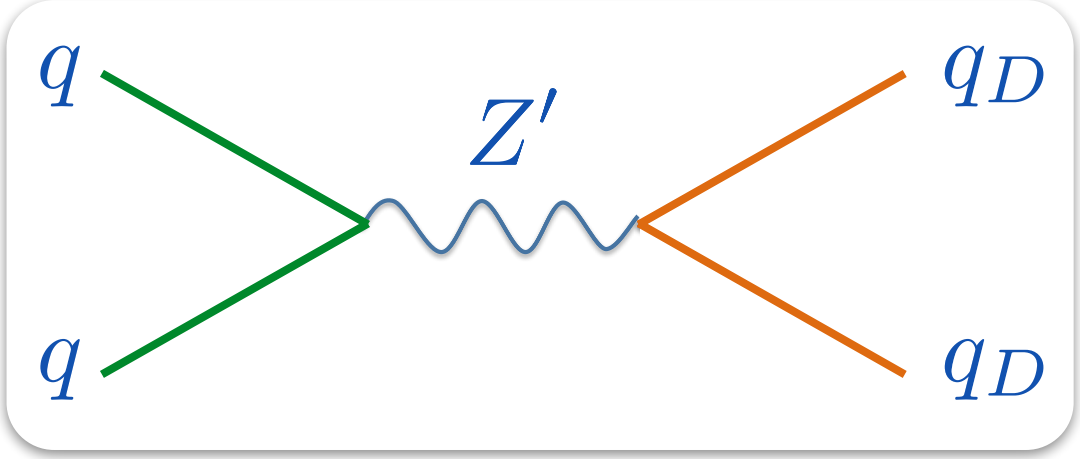
NA62 projection

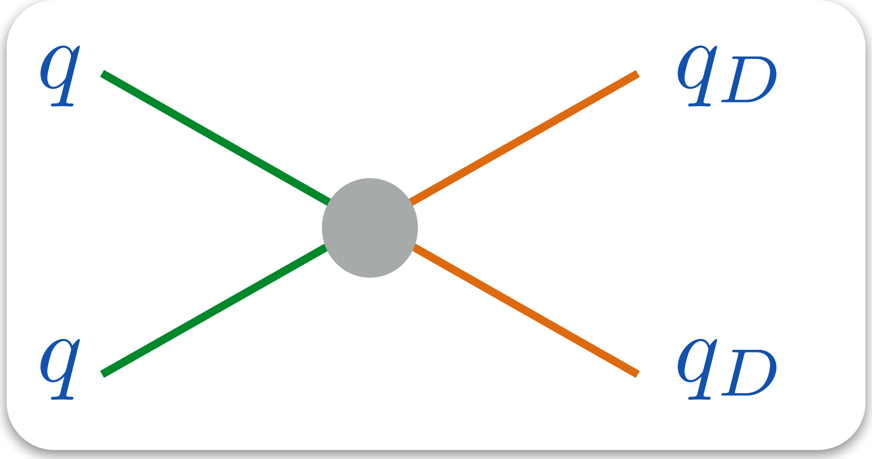
S. Renner, PS, in progress

PS, Stolarski, Weiler, in progress

LHCb opportunities

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



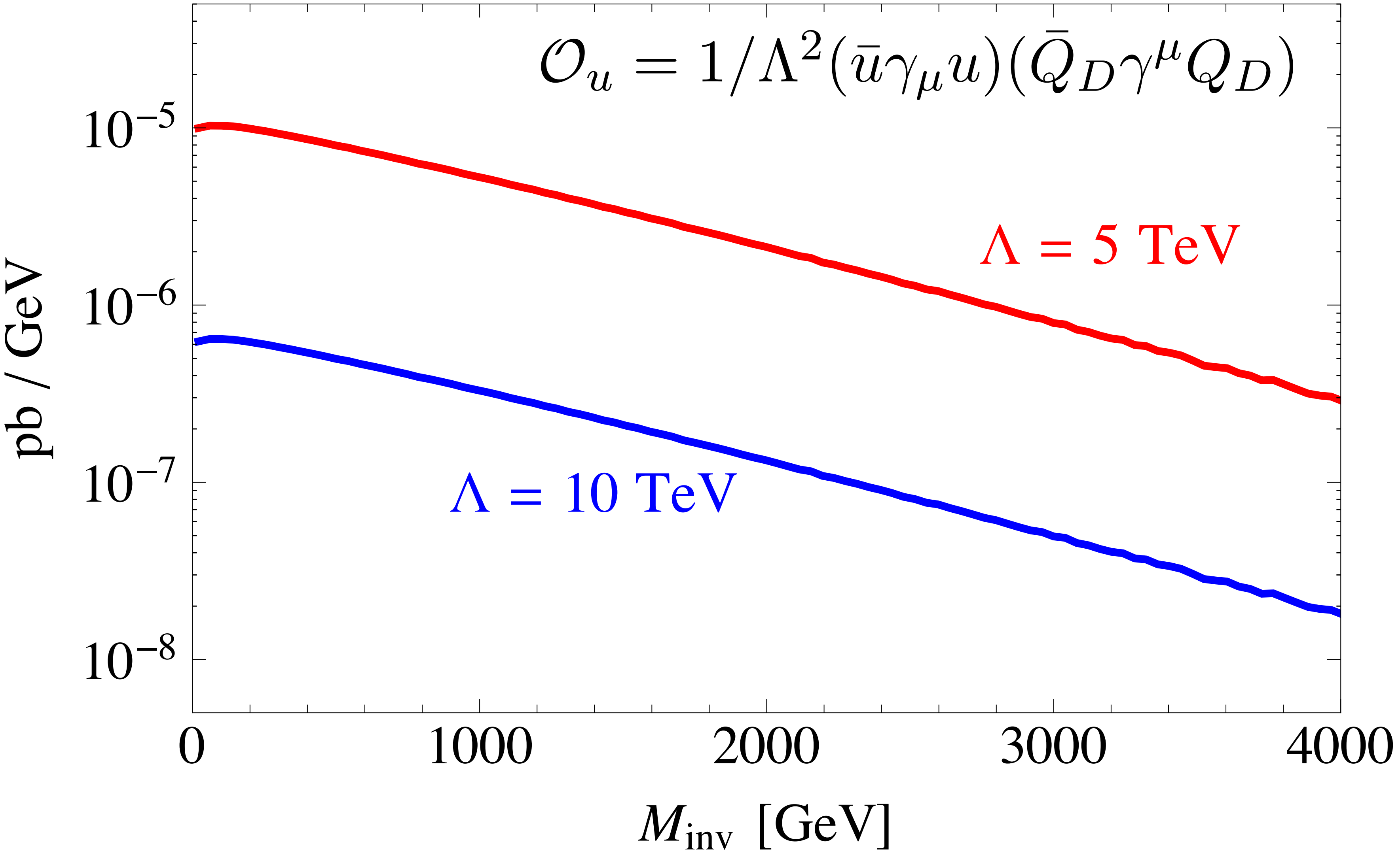


- Reconstruct individual dark pions, differentiate using lifetime, mass, decay products

- Emerging jets without (hard) trigger requirements?

PS, Stolarski, Weiler, in progress

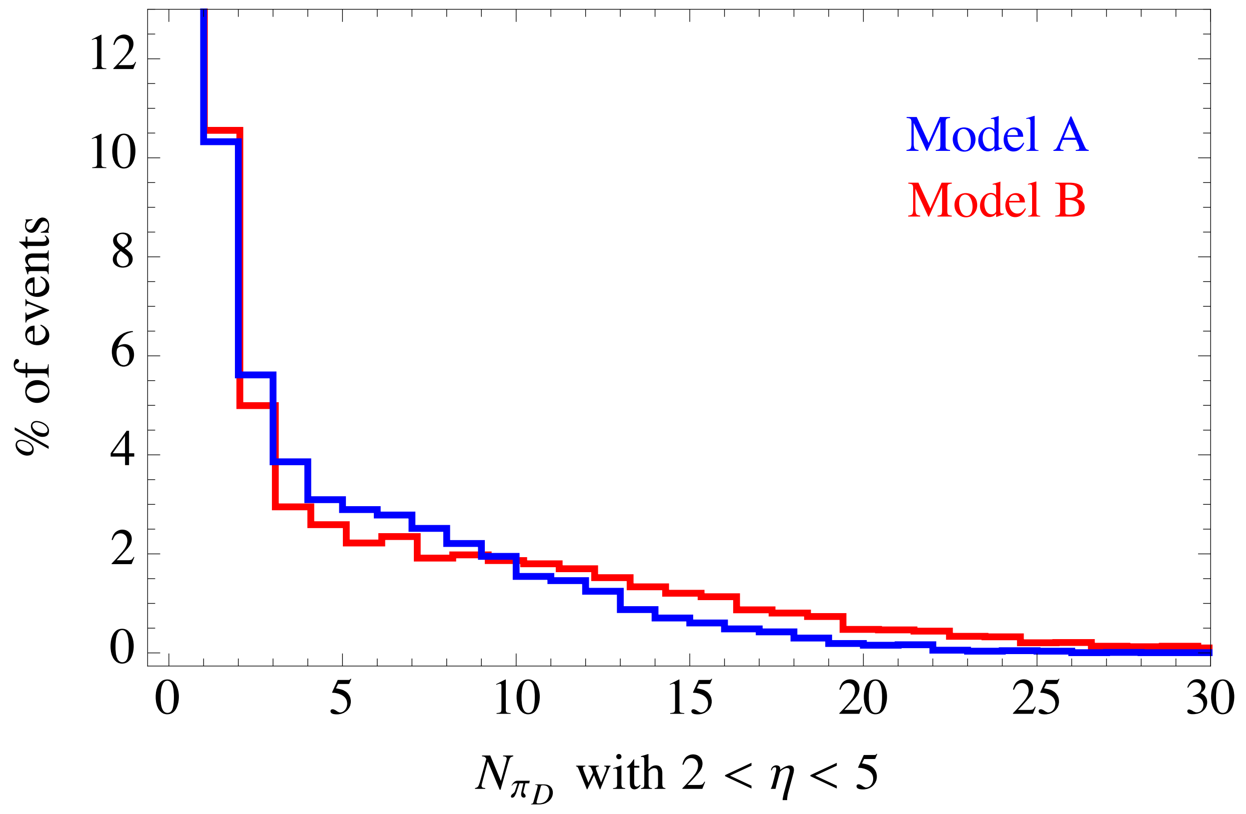
Off-shell production

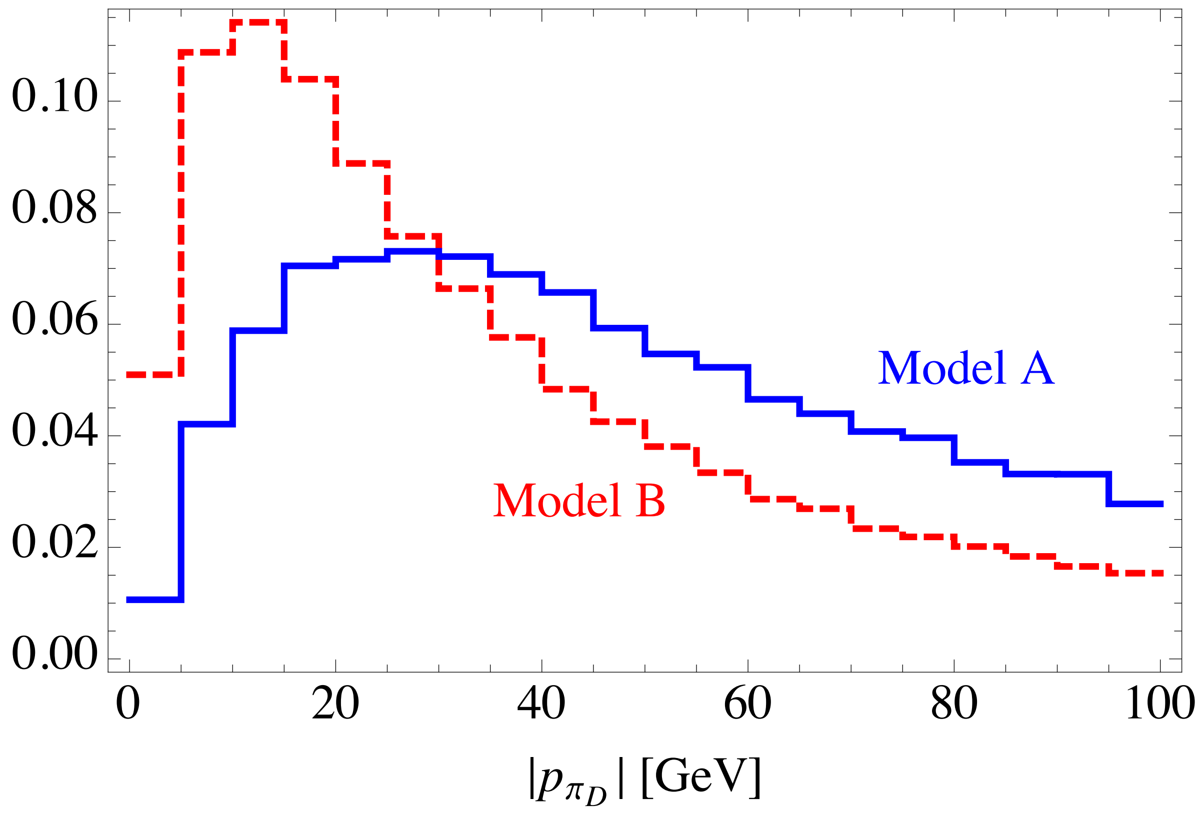


- Total rate: $\sigma(pp \to \bar{Q}_D Q_D) \approx 8.2\ \text{pb} \times \left(\frac{\text{TeV}}{\Lambda}\right)^4 \times N_d \times N_F$

PS, Stolarski, Weiler, in progress

Forward region

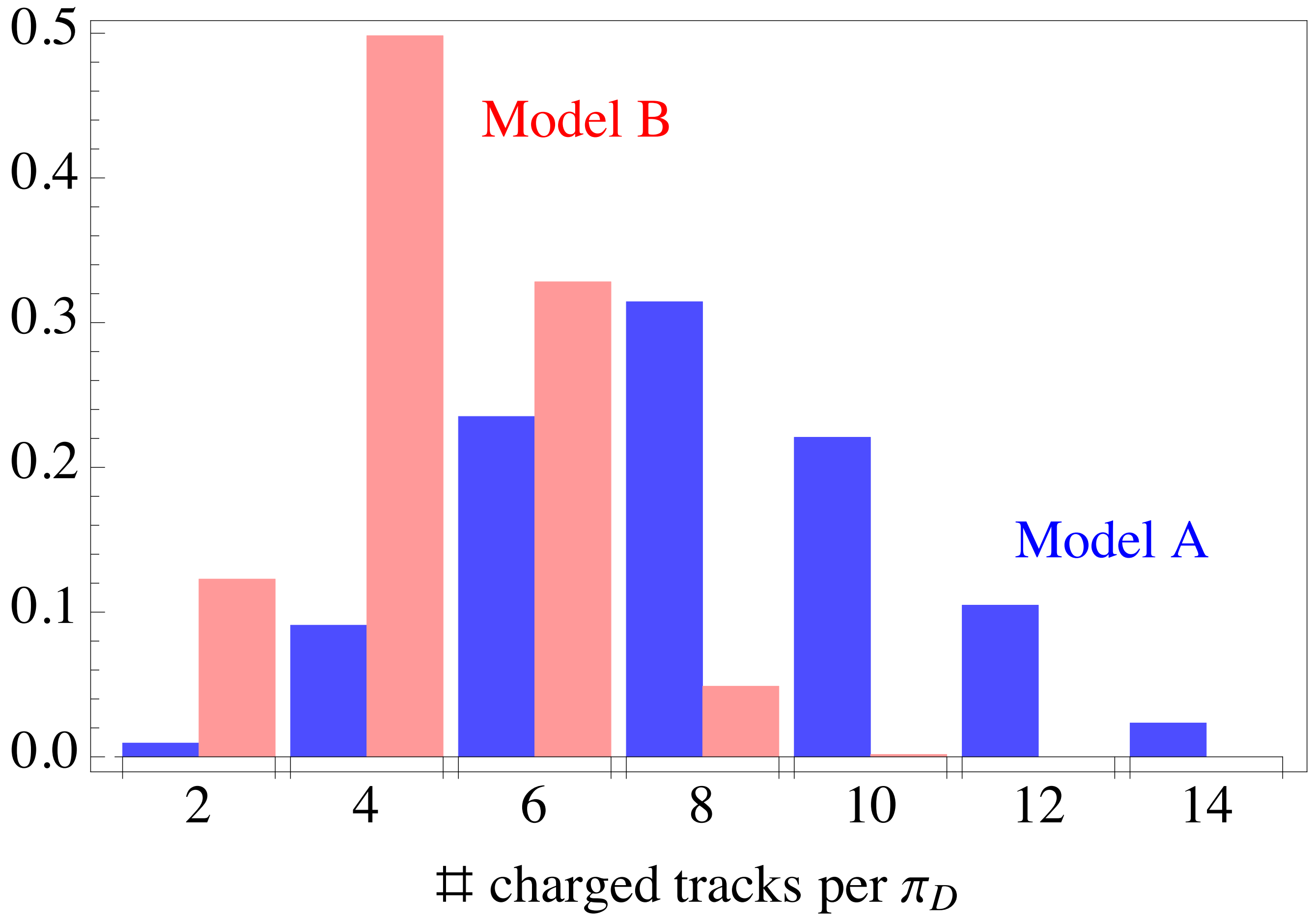




- Fraction of all signal events with N dark pions in $2 < \eta < 5$
- Momentum (not pT) distribution of dark pions in $2 < \eta < 5$

PS, Stolarski, Weiler, in progress

Decay characteristics



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

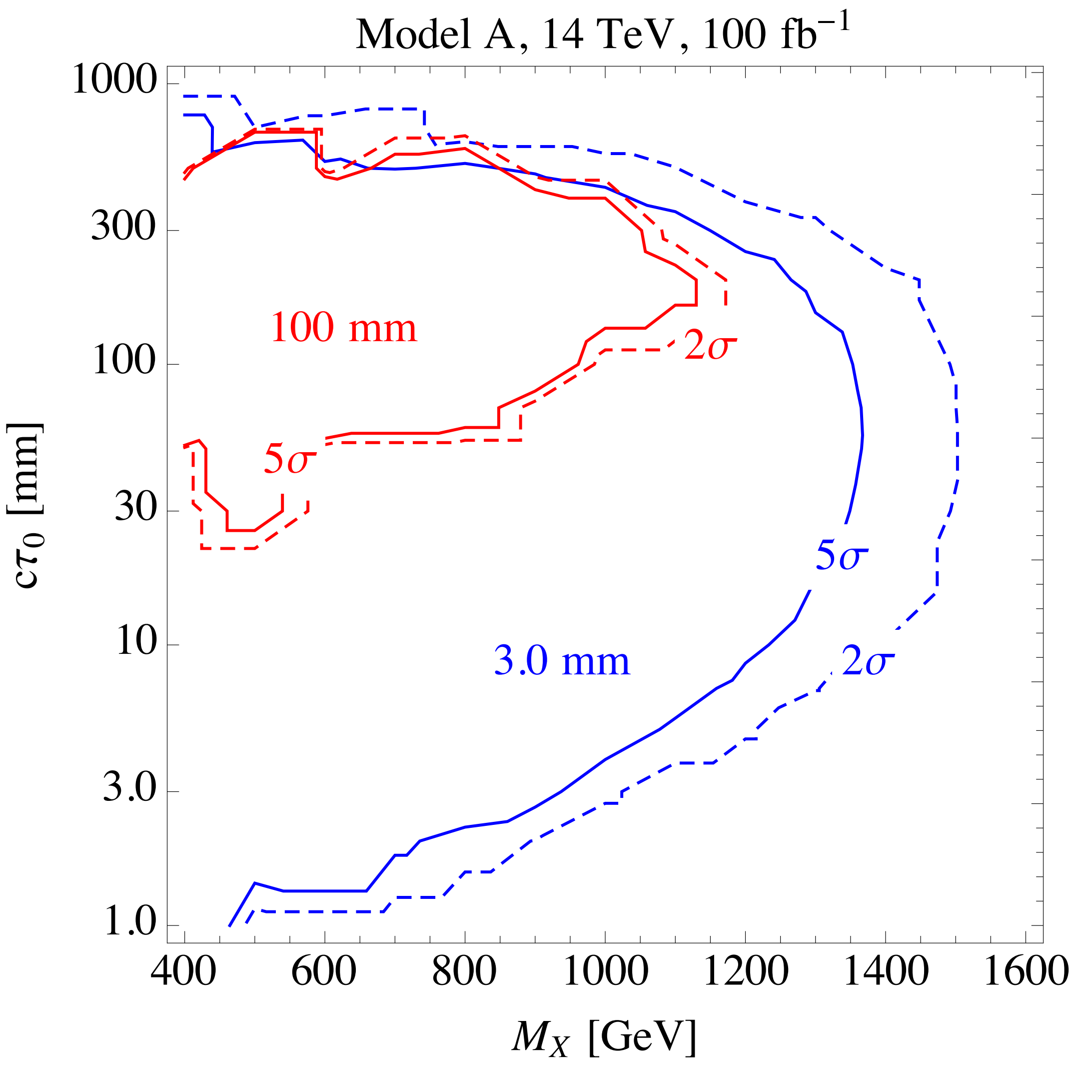
PS, Stolarski, Weiler, in progress

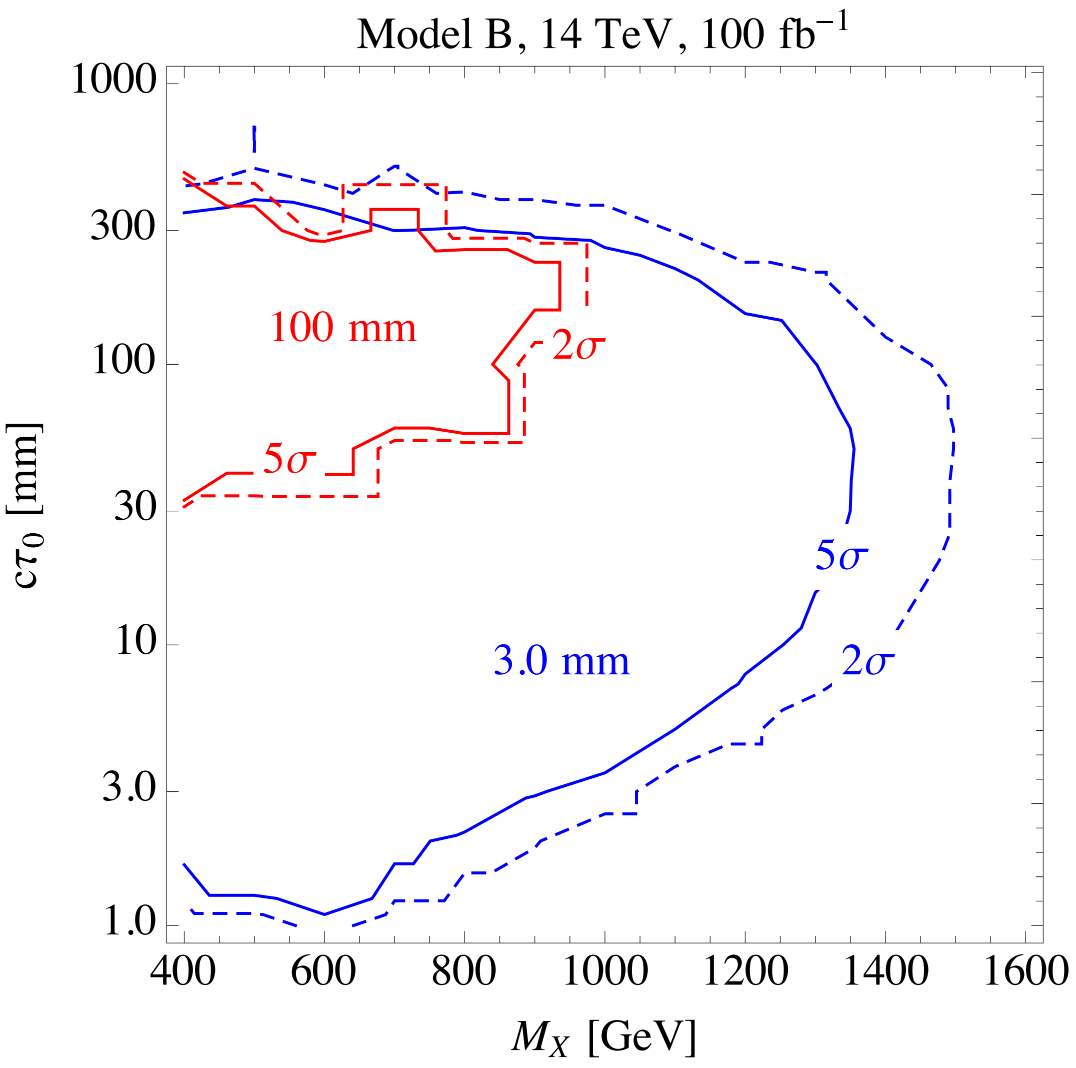
Very very (very) rough estimate

- 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 $N_{F,d} = 7$):

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

$$\boxed{M_{\rm DM} \approx 3.5\ {\rm GeV}}$$

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:

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

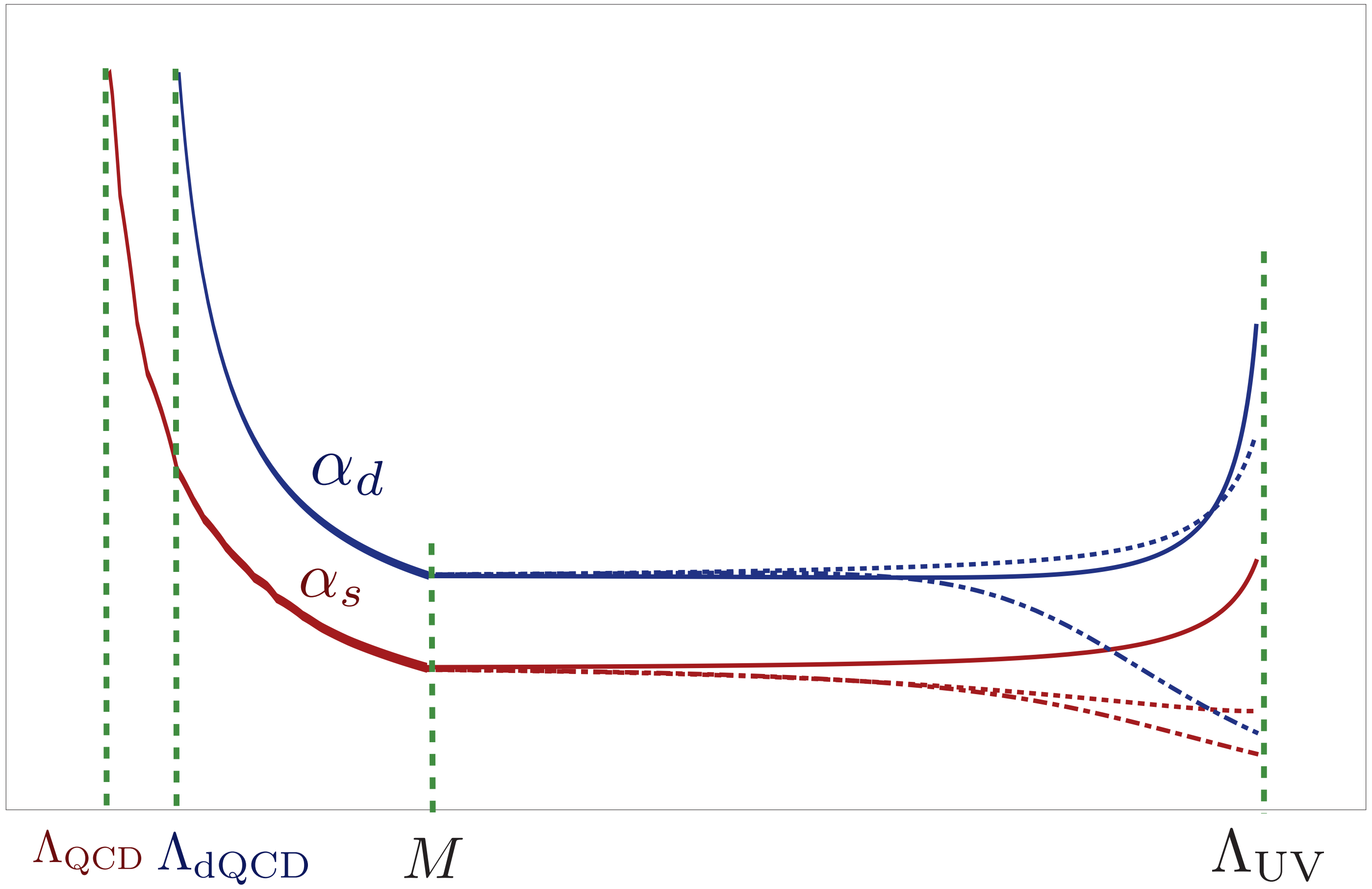
"naturally"

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!

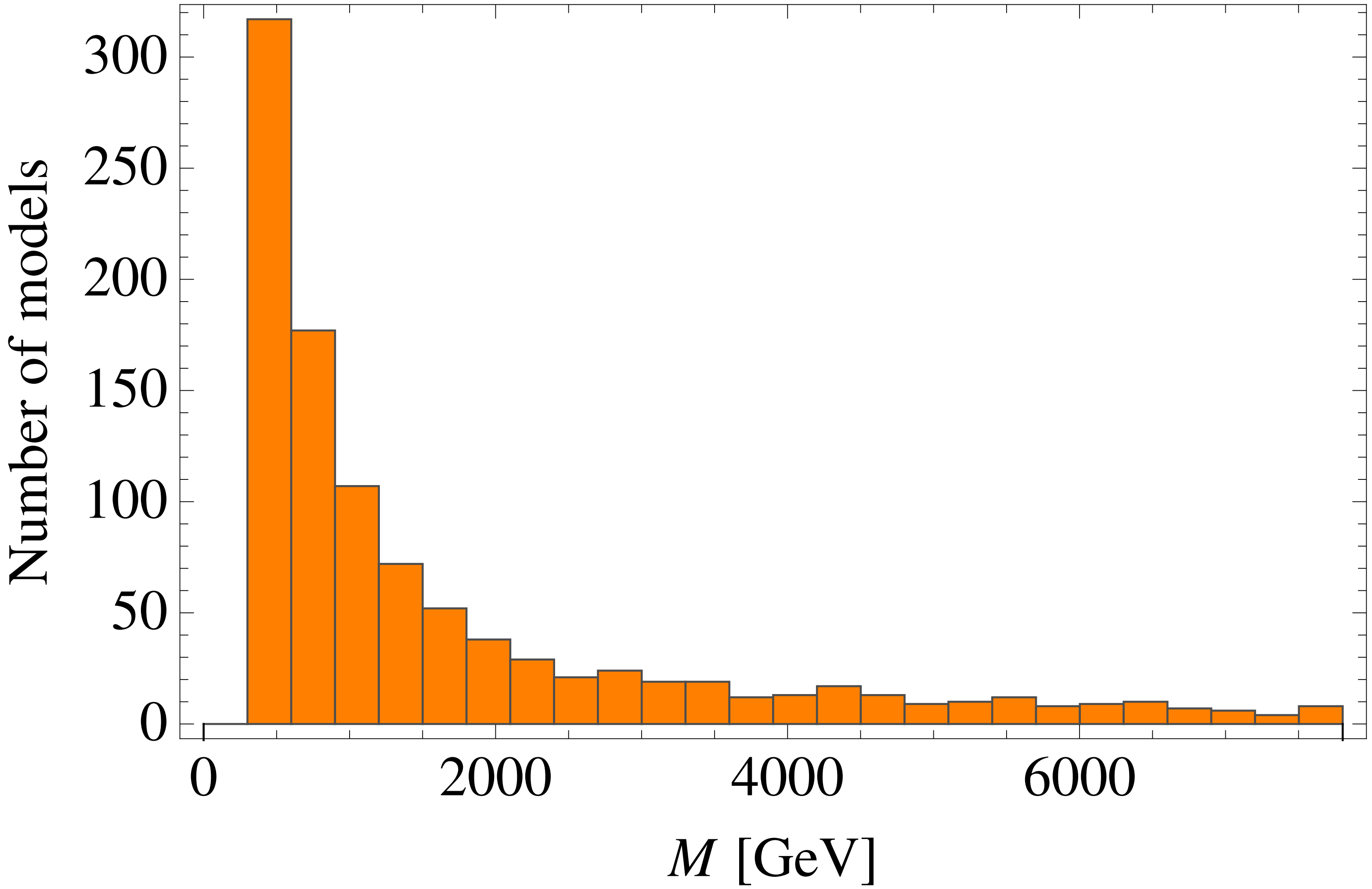
IRFP & running



- Bi-fundamental fields decouple at scale M

$$\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm dark}} \approx e^{\frac{2\pi}{b_c\alpha_c^*}\left(1-\frac{b_c\alpha_c^*}{b_d\alpha_d^*}\right)}$$

Model distribution



- Models with DM mass close to proton mass