New Signals from Dark Sectors

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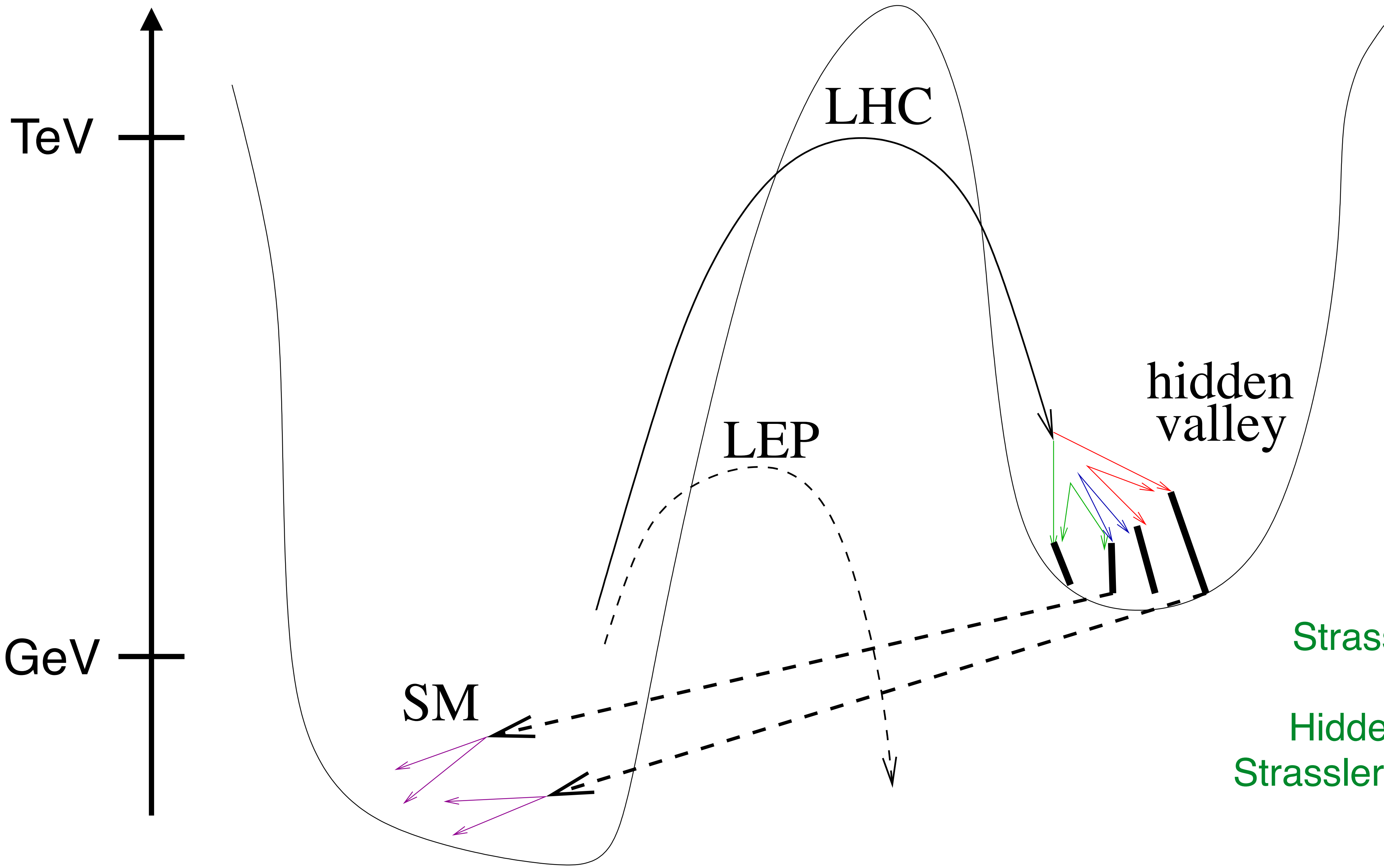
Dark Sector?

Dark Sector, also stylized as darkSector, is a third-person shooter video game developed by Digital Extremes for the Xbox 360, PlayStation 3 and Microsoft Windows. Wikipedia

Dark Sector!



Strassler, 2006

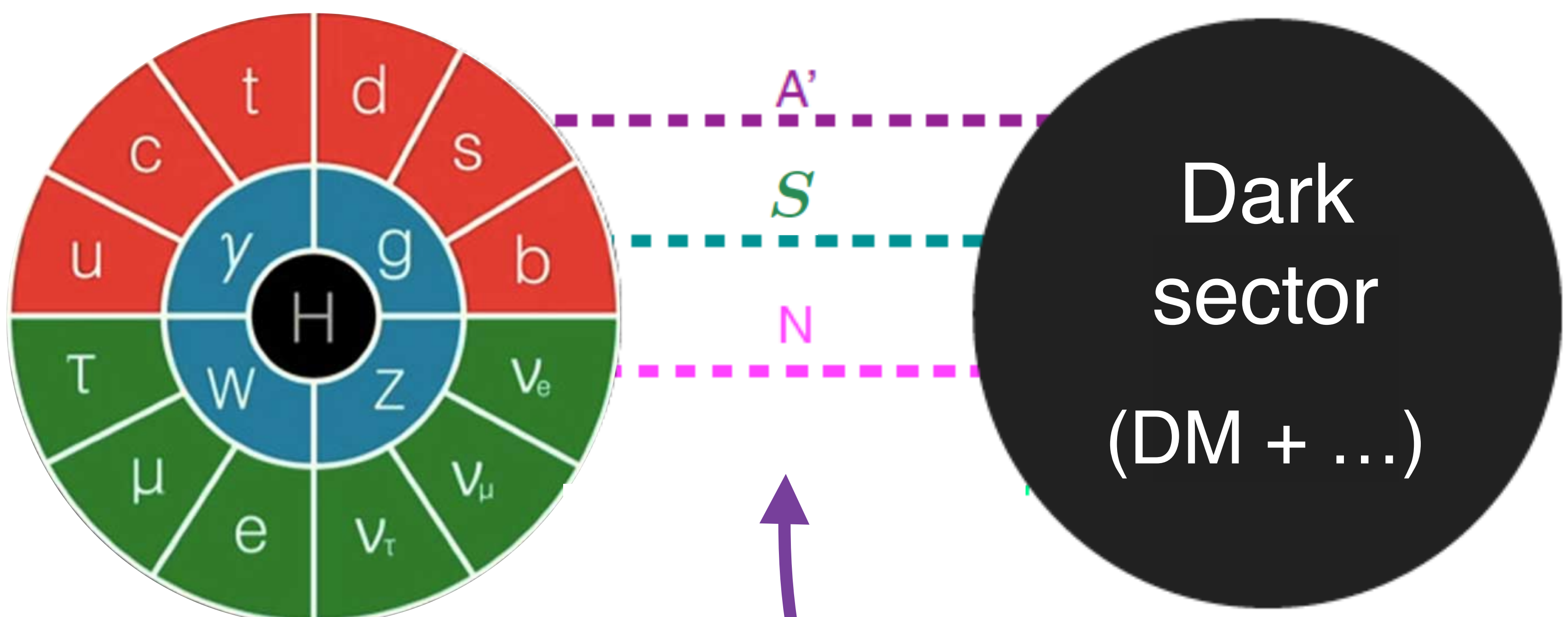
Hidden Valleys:
Strassler, Zurek, 2006
…

An extension of the SM with its own dynamics

with weak/suppressed couplings to SM particles

hopefully contains a DM candidate

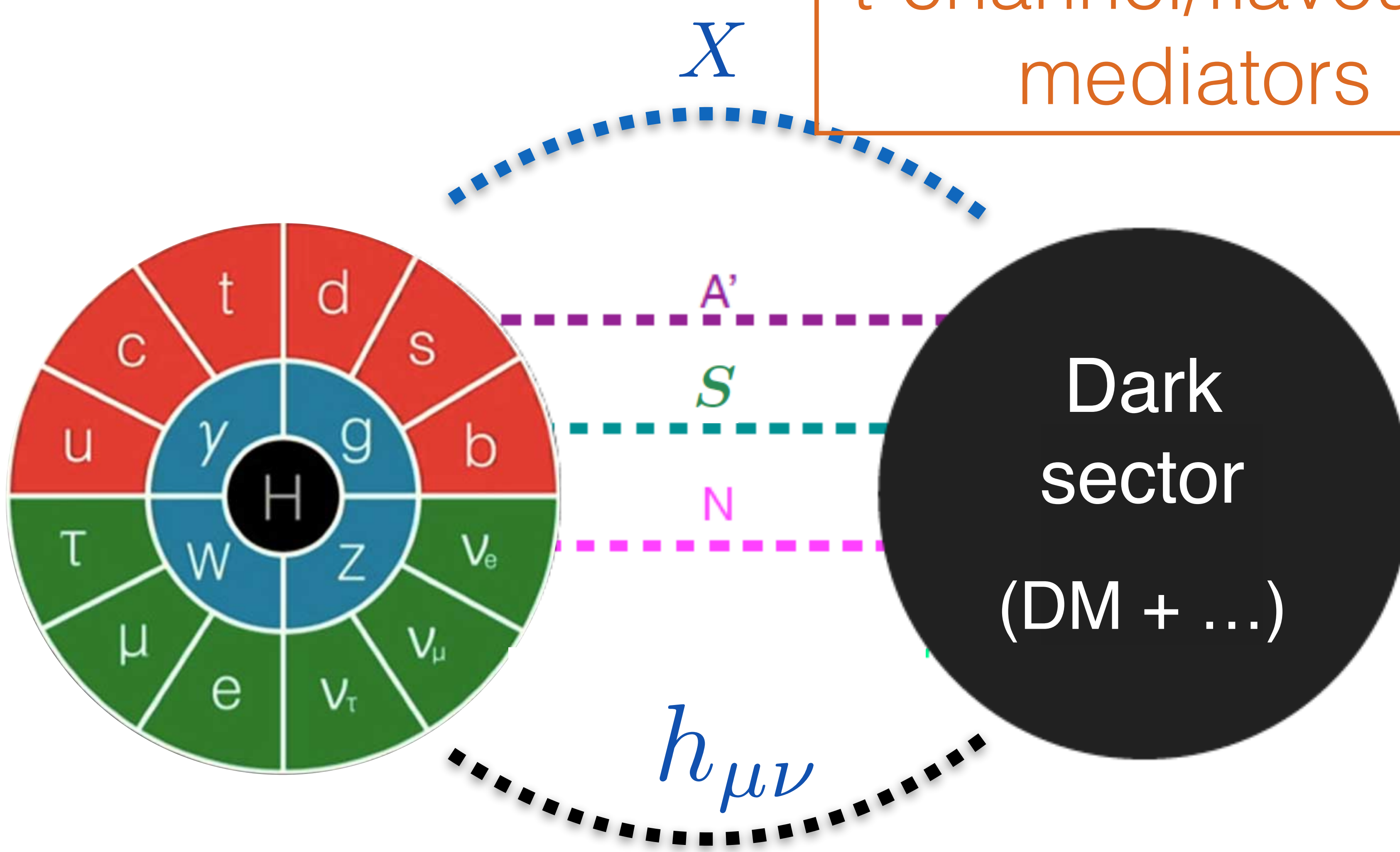
Dark sectors and mediators



Pheno depends on how we talk to the dark sector

Dark sectors and mediators

t-channel/flavoured mediators



Often will consider composite QCD like dark sector → emerging mediators

Gravitational Waves

Long lived particles/ dark showers

Dark Sectors

- Consider a dark sector with SU(N) symmetry and confinement scale Λ
- A portal interaction with $M \gg \Lambda$
- e.g. a QCD like dark sector with a Z' mediator

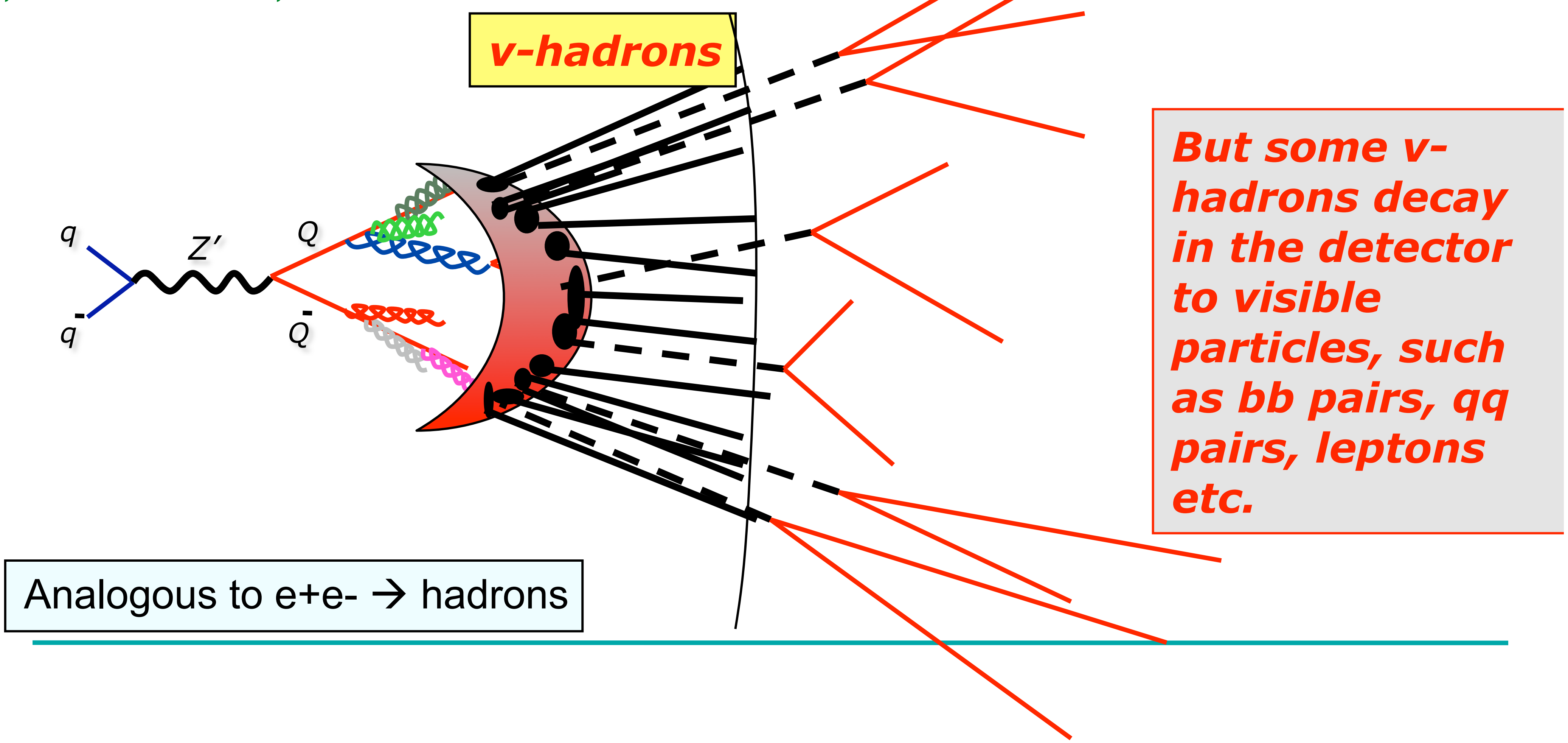
- Then you can expect something like this:

$q\,\bar{q} \rightarrow Q\,\bar{Q}$

hep-ph/0604261

From M. Strasslers slides, 2006
Pioneering papers by
Strassler, Zurek 2006, 2007
…

Some v-hadrons are stable and therefore invisible



Why?

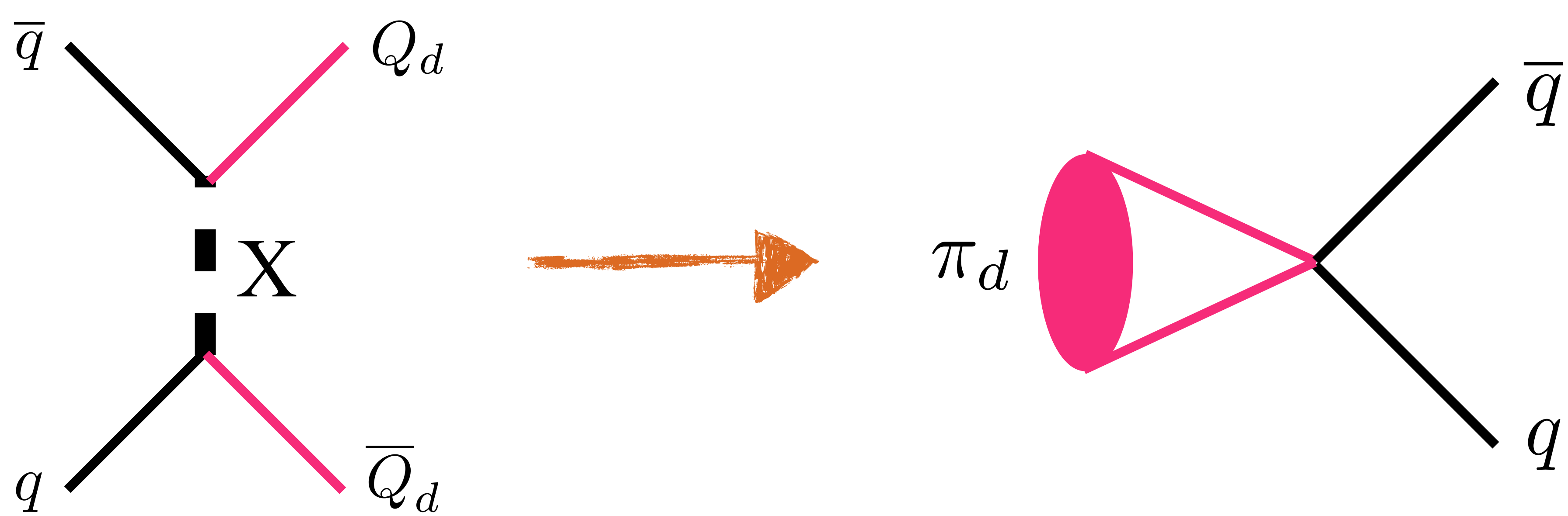
- Hidden valleys generic in string theory
- Dark QCD e.g. in Twin Higgs models, SIMP DM
- Asymmetric DM provides strong motivation for

  see Kathryn's talk!
  - ~ 5 GeV scale in hidden sector
  - TeV scale mediator for asymmetry transfer e.g. Bai, PS, 2014

$$\frac{\Lambda}{M} \sim \mathcal{O}(10^2)$$ → rich shower!

Dark Pion Lifetime

- Integrate out mediator, match to dark pion current



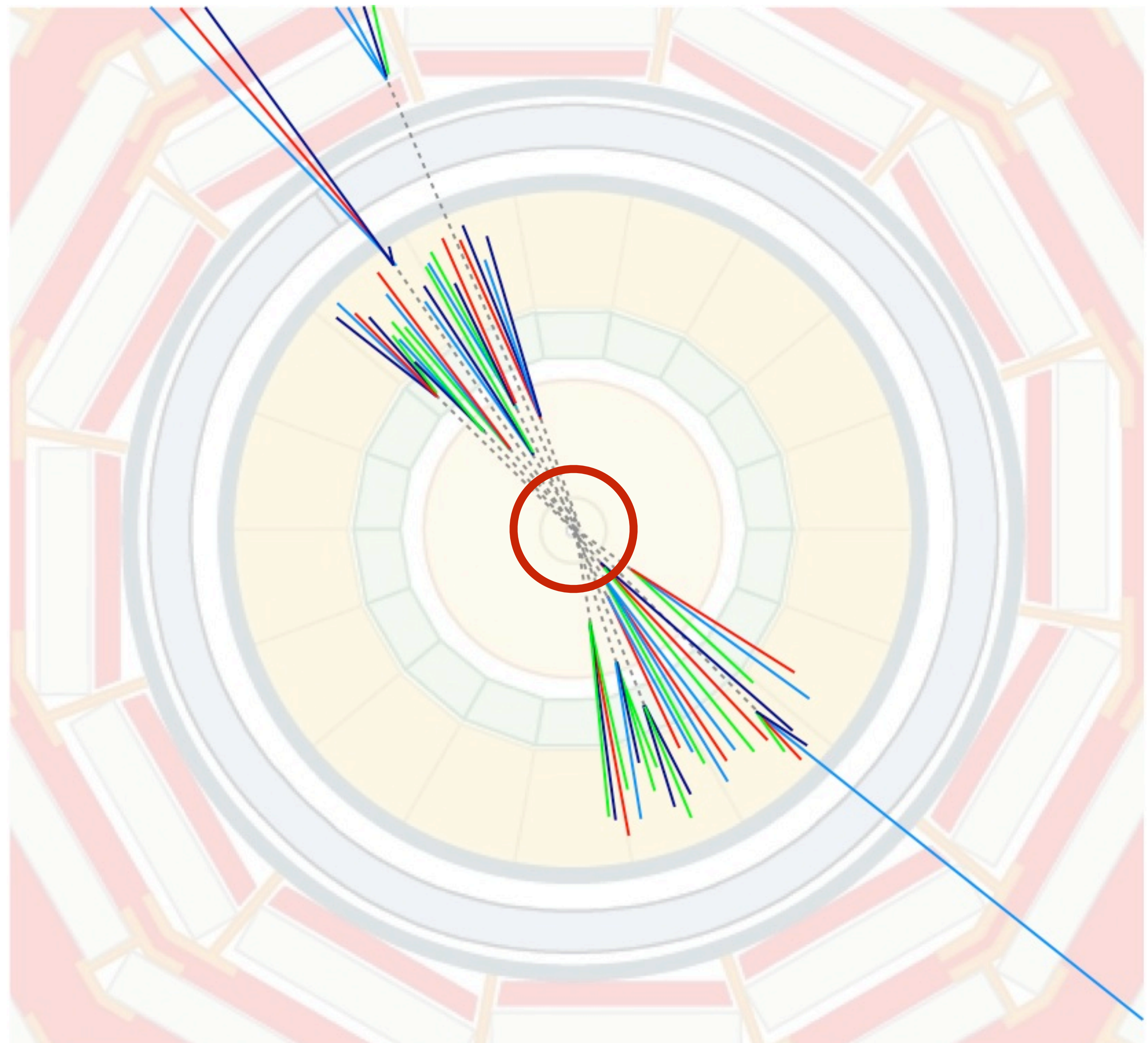
- Decay to SM jets (pions)

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

Decay in LHC detectors!

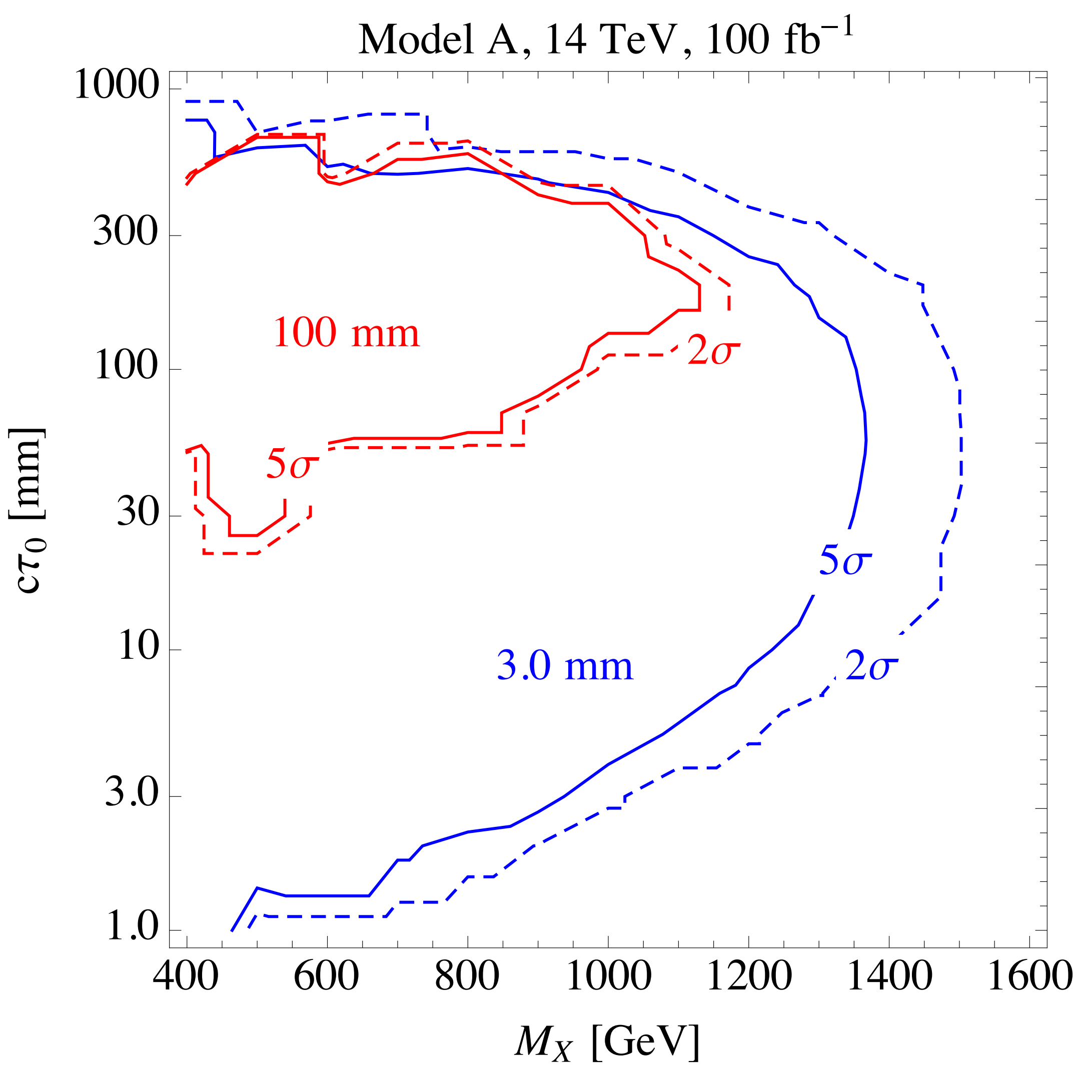
Emerging Jets at the LHC

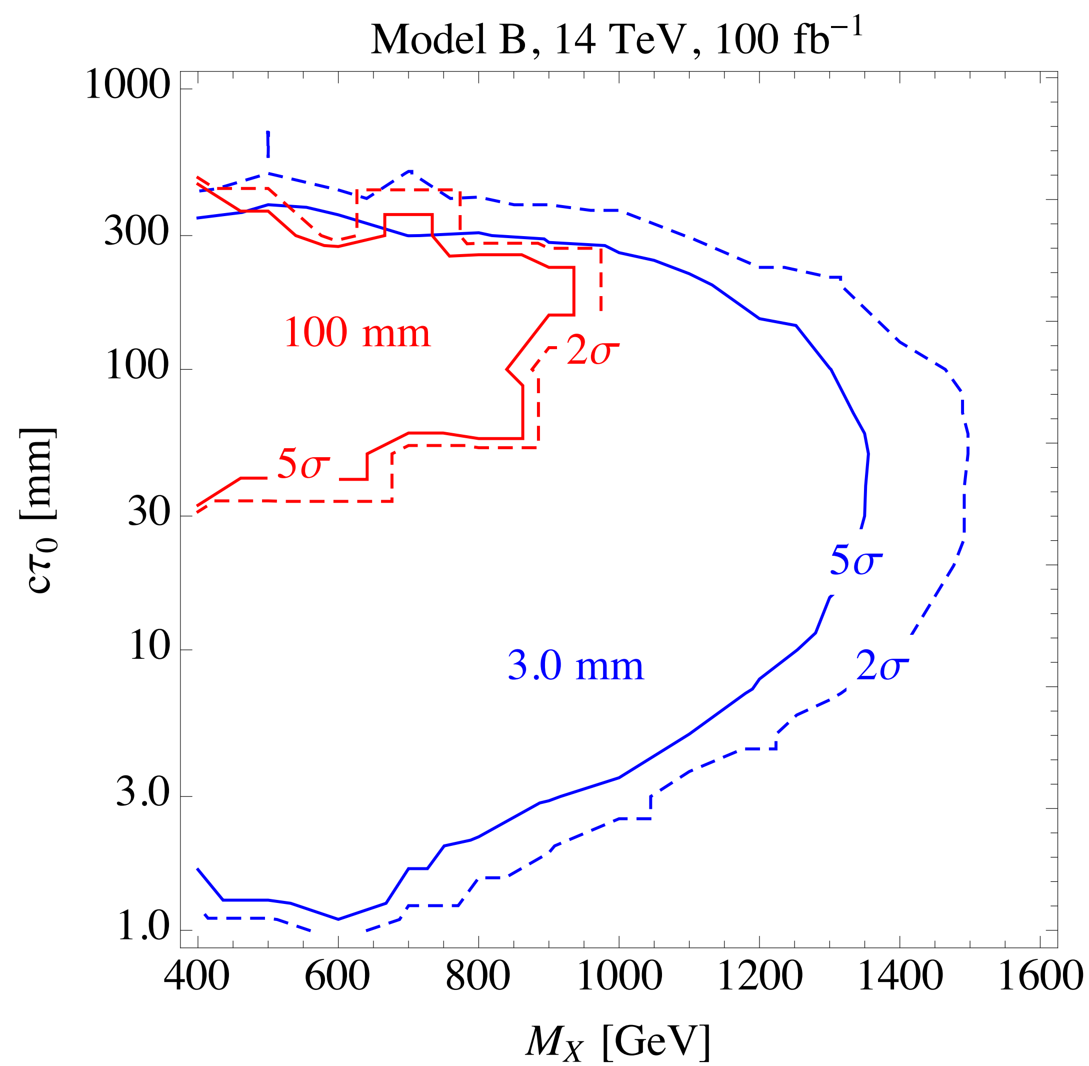
- Production of mediator, decay to dark quarks
- Characteristic:
  - few/no tracks in inner tracker
- New “emerging” jet signature
- Smoking gun of composite hidden sectors



PS, Stolarski, Weiler, 2015

Reach ATLAS/CMS





- Using simple strategy (veto on prompt tracks)
- More refined searches ongoing (ATLAS, CMS)

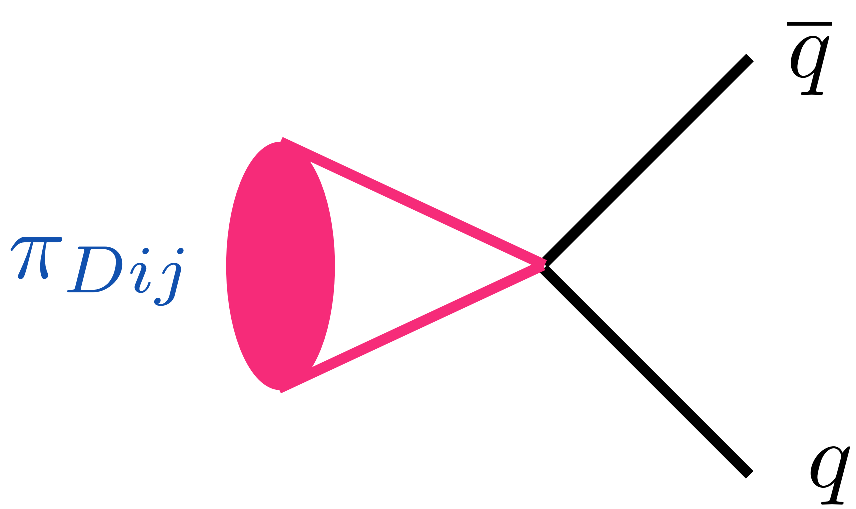
PS, Stolarski, Weiler, 2015

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:

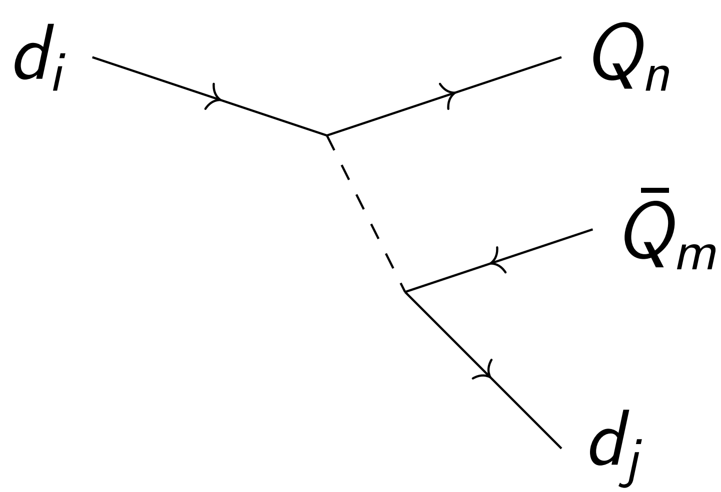


$$\propto \sum_{q,q'} |\lambda_{qi} \lambda^*_{q'j}|^2$$

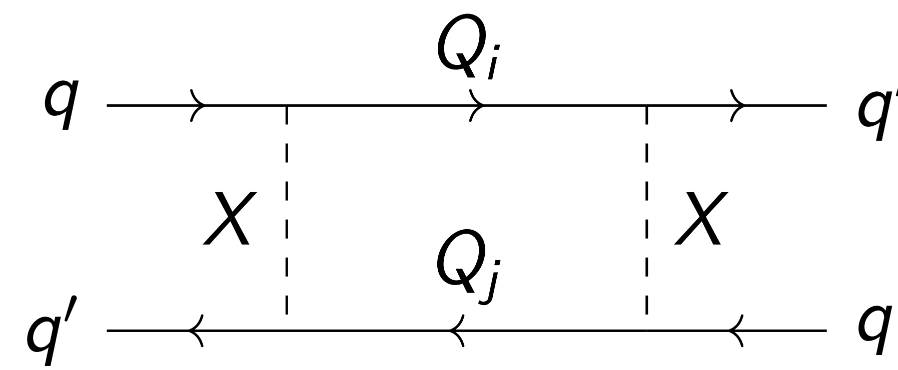
S. Renner, PS, 1803.08080

S. Renner, PS, 1803.08080

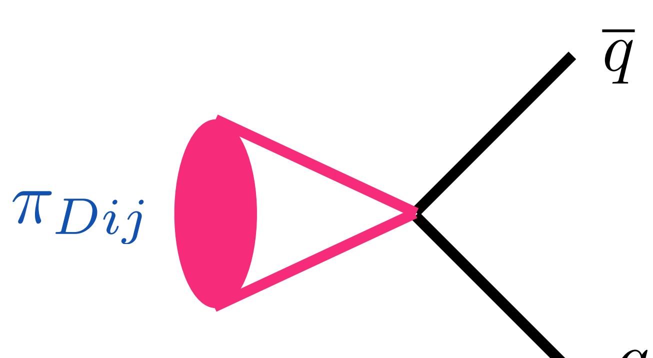
Flavour matters



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



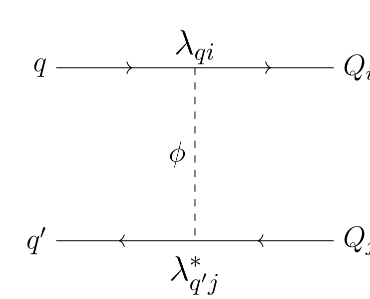
$$\lambda_{ij}\bar{d}_{Ri}Q_{Lj}\Phi$$



dark pion properties

fixed target experiments

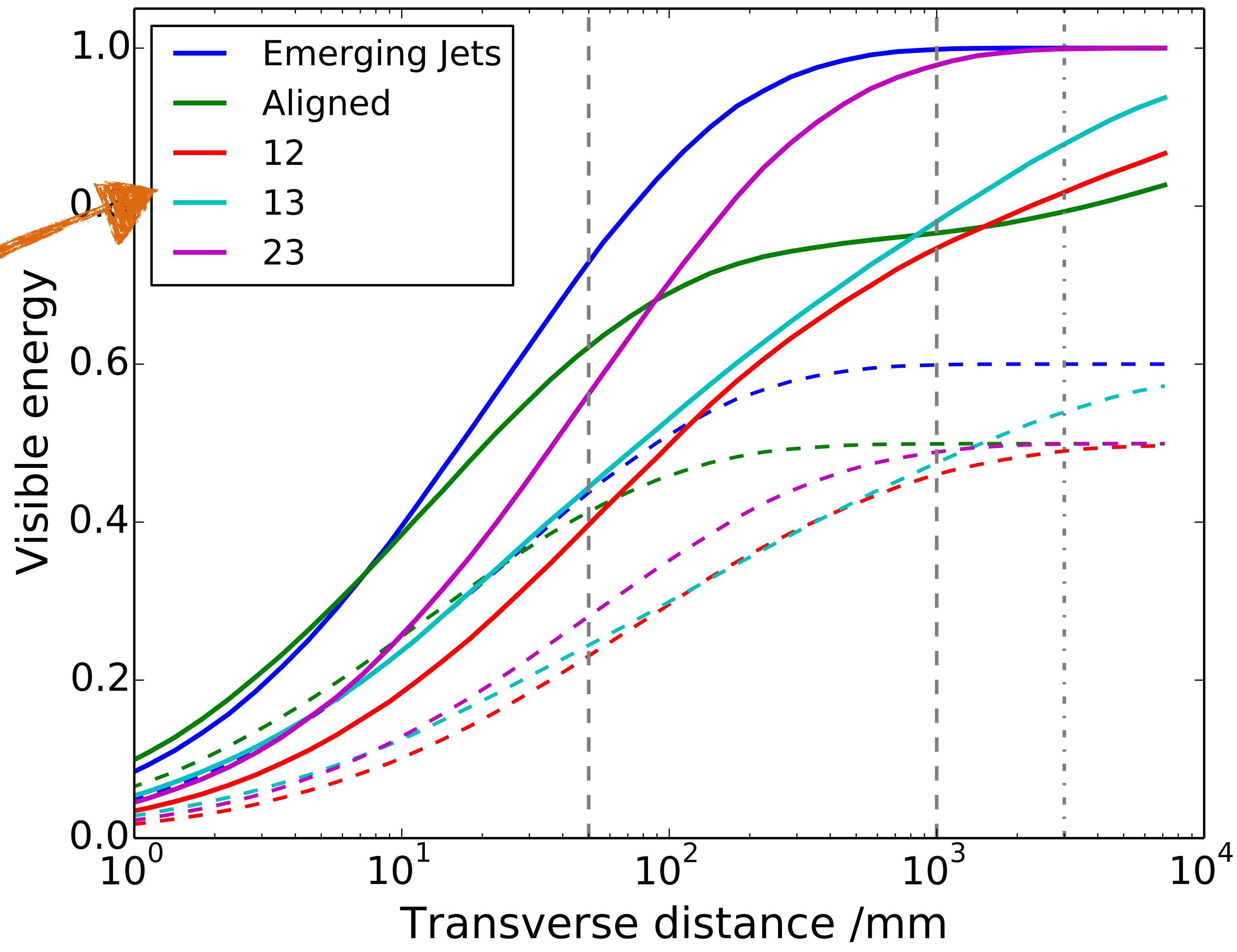
NA62



SHiP
Search for Hidden Particles

Emerging Jets revisited

different flavour scenarios



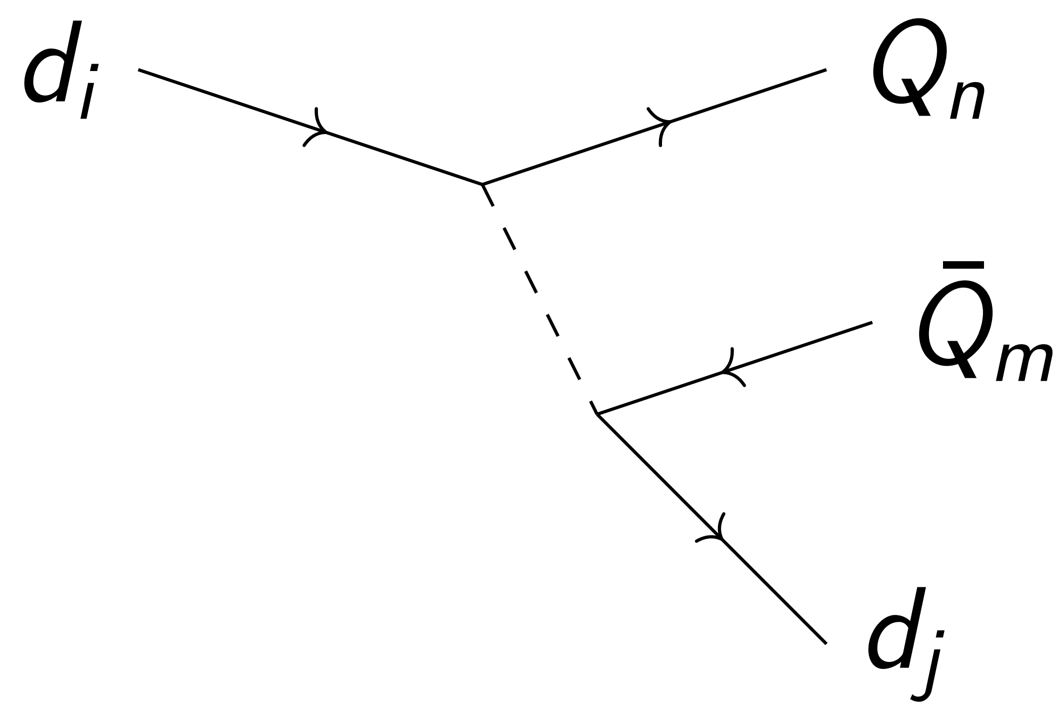
heavy flavours

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!

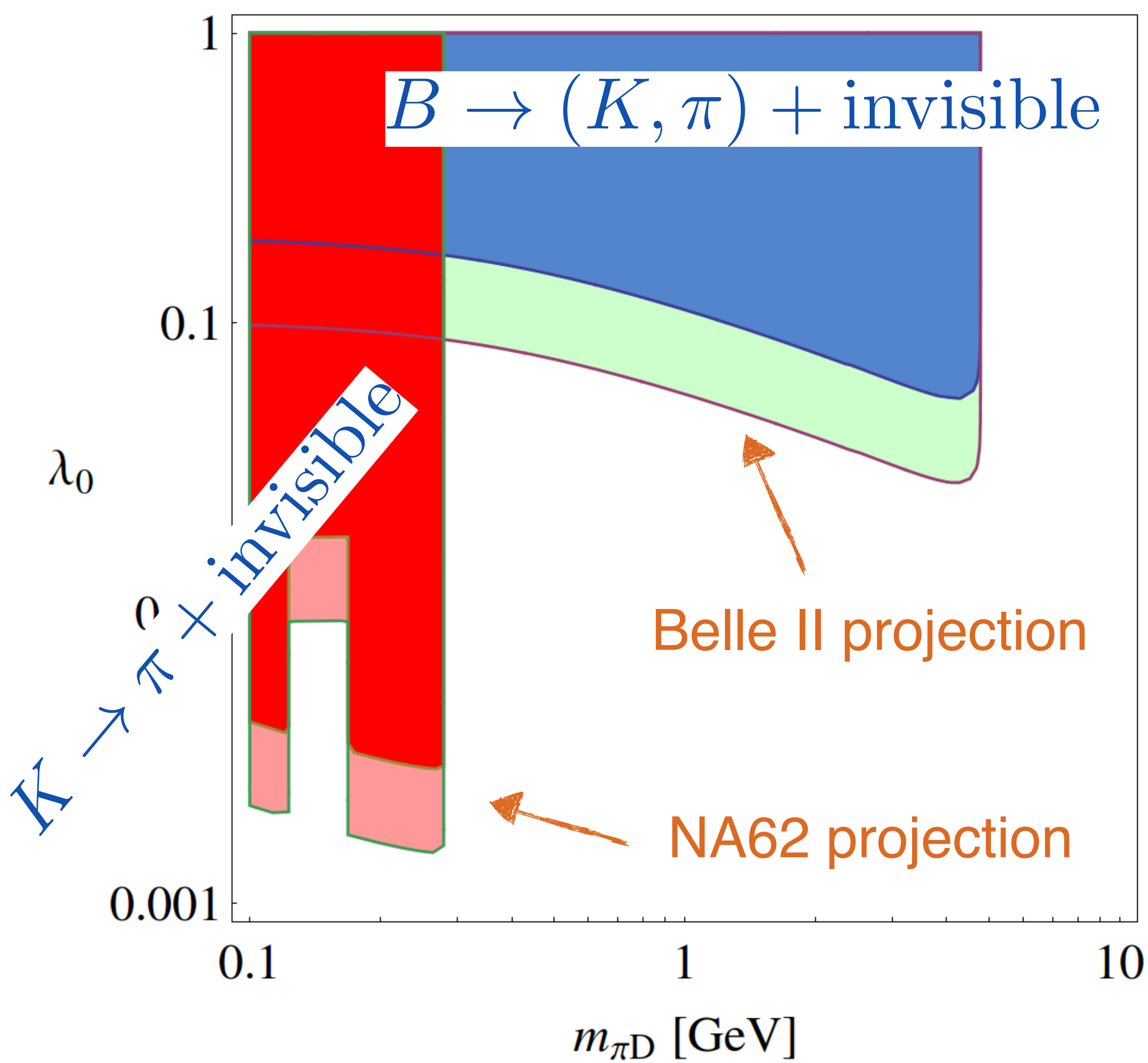
great resource:
Kamenik, Smith, 2011

S. Renner, PS, 1803.08080

Bounds from rare decays

- Best bound on couplings for very light dark pions

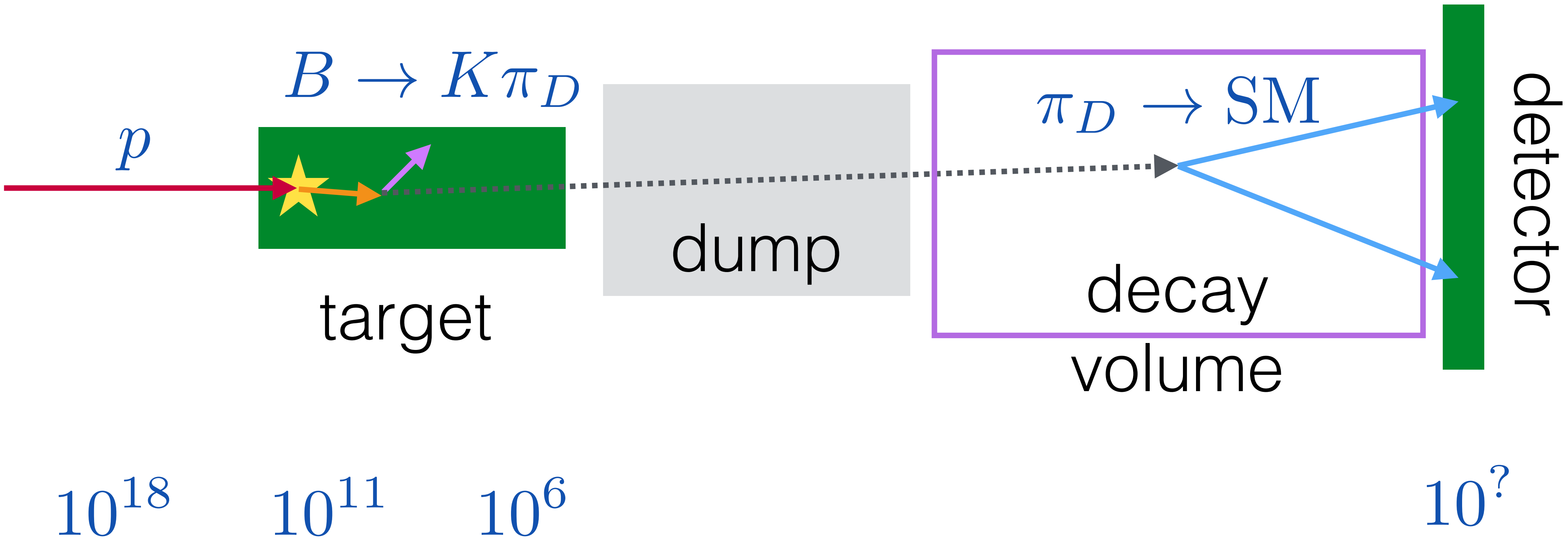
- Dark pion production in fixed target expts!



S. Renner, PS, 1803.08080

Fixed target

- My simplified NA62/SHiP:

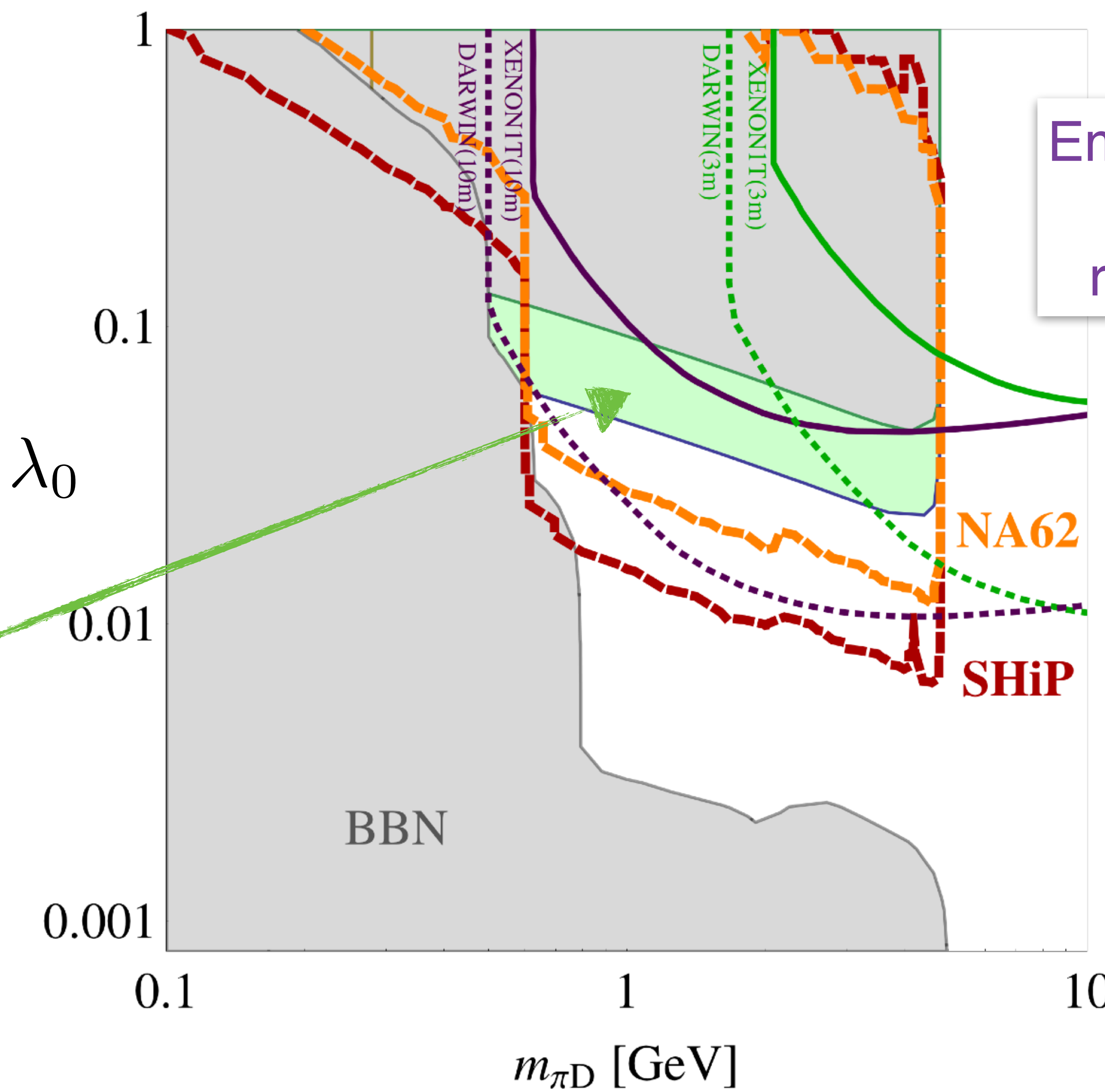


- Leading channels: $\pi_D \to \pi K$, $\pi_D \to \pi^+\pi^-\pi^0$
- No $\pi\pi$, probe of CP nature of π_D

S. Renner, PS, 1803.08080

Fixed target reach

- Including bounds from cosmology



Emerging jets region

Belle II reach

S. Renner, PS, 1803.08080

GWs from the dark sector

Consider simple DS model

- Kinetically mixed dark photon (or Z'):

$$\epsilon Z^{\mu\nu} A'_{\mu\nu}$$

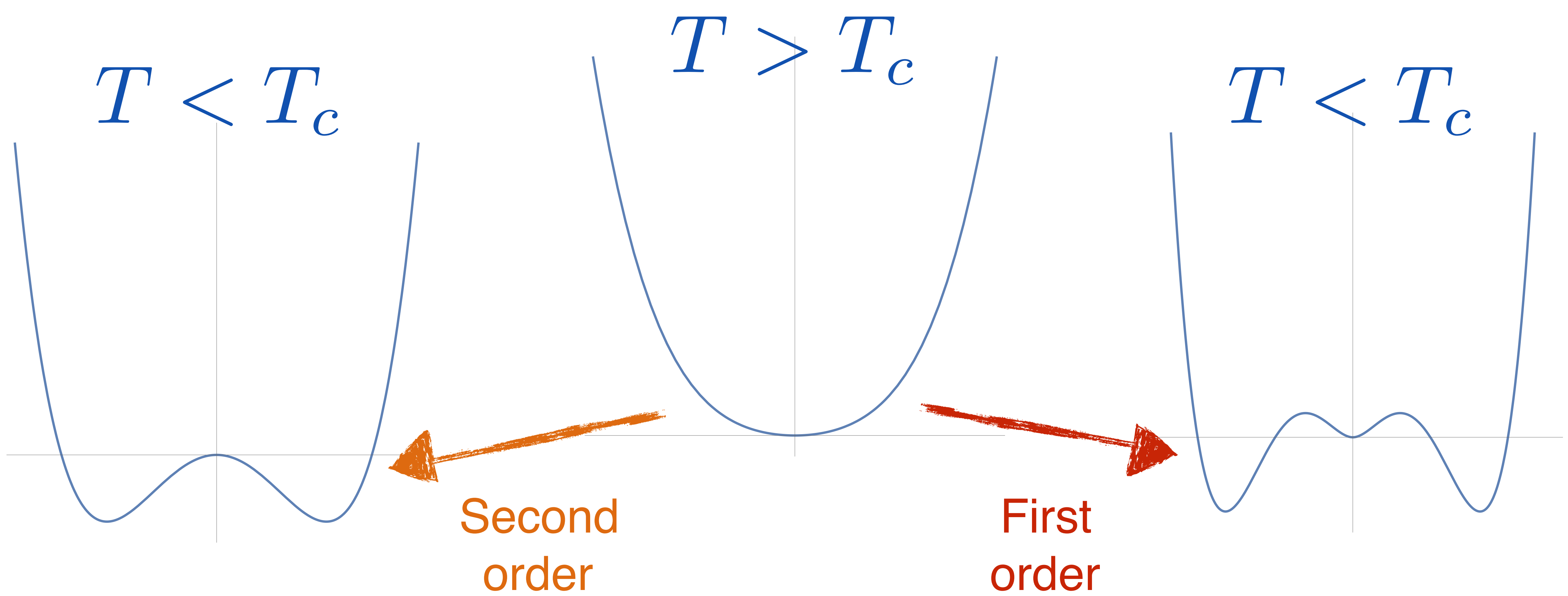
- Not massless ➞ probably some dark Higgs boson involved

- Symmetry breaking phase transition in the early universe

$$T_c \sim m_{A'}$$

Cosmological Phase Transitions

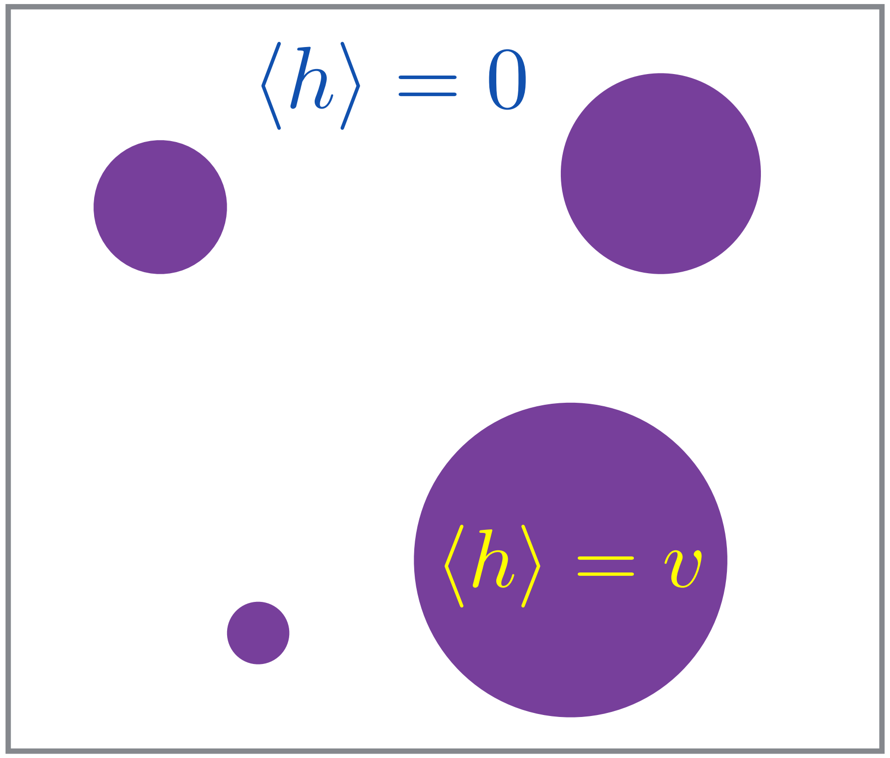
- Early Universe in symmetric phase (e.g. unbroken electroweak symmetry)

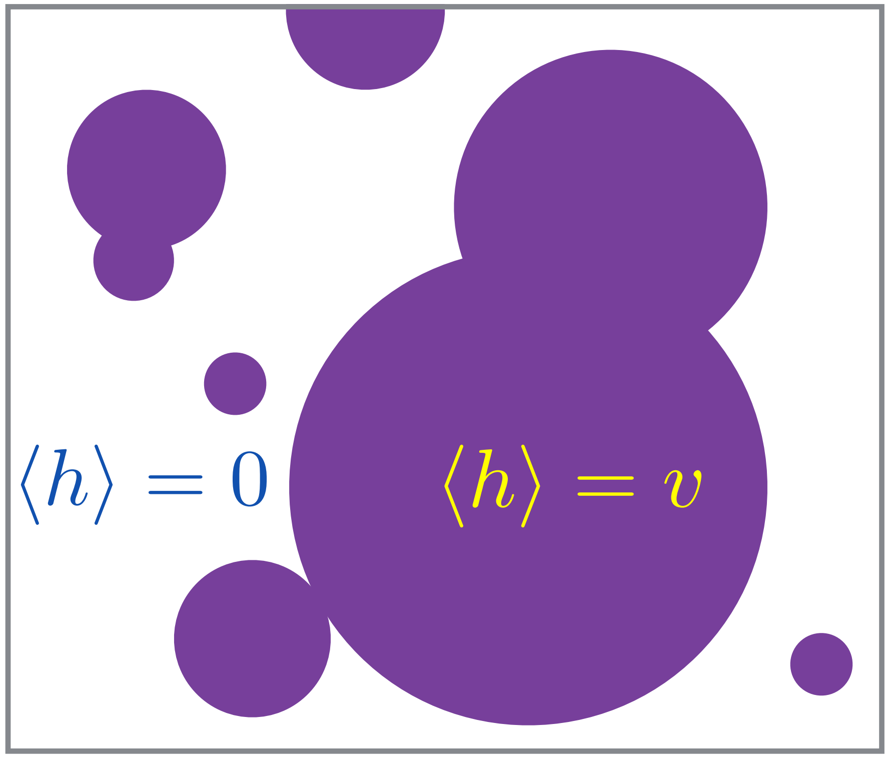


GWs from PTs

First order PT ➞ Bubbles nucleate, expand

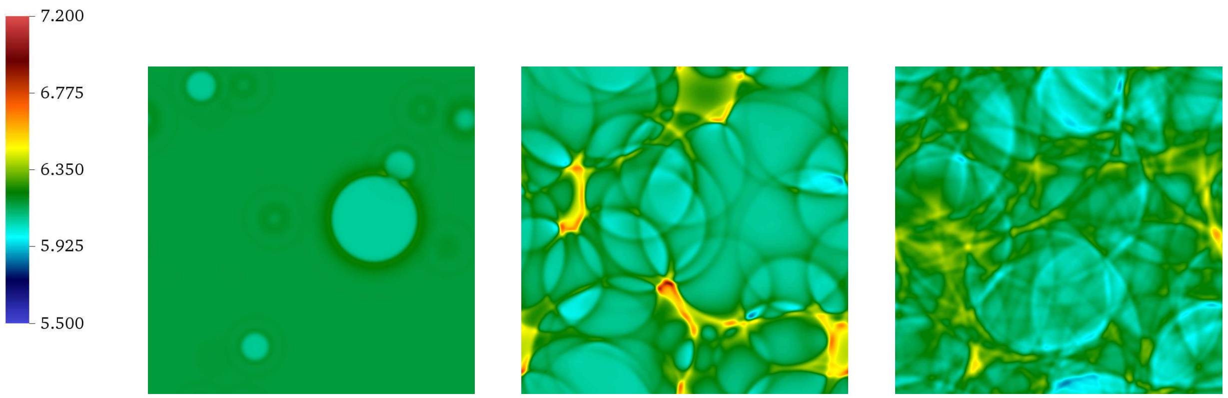
Bubble collisions ➞ Gravitational Waves





Stochastic GW "background"

- PT characterised by few parameters, calculable in QFT:
  - Latent heat $\alpha \approx \frac{\Omega_{\text{vacuum}}}{\Omega_{\text{rad}}}$
  - Bubble wall velocity v
  - Bubble nucleation rate β
  - PT temperature T_*
- GW spectra from simulations:
  - Bubble wall collisions
  - Turbulence
  - Sound waves



Hindmarsh et al, 2015

Phenomenological Parameterisations:
Caprini et al, 1512.06239

Peak Frequency

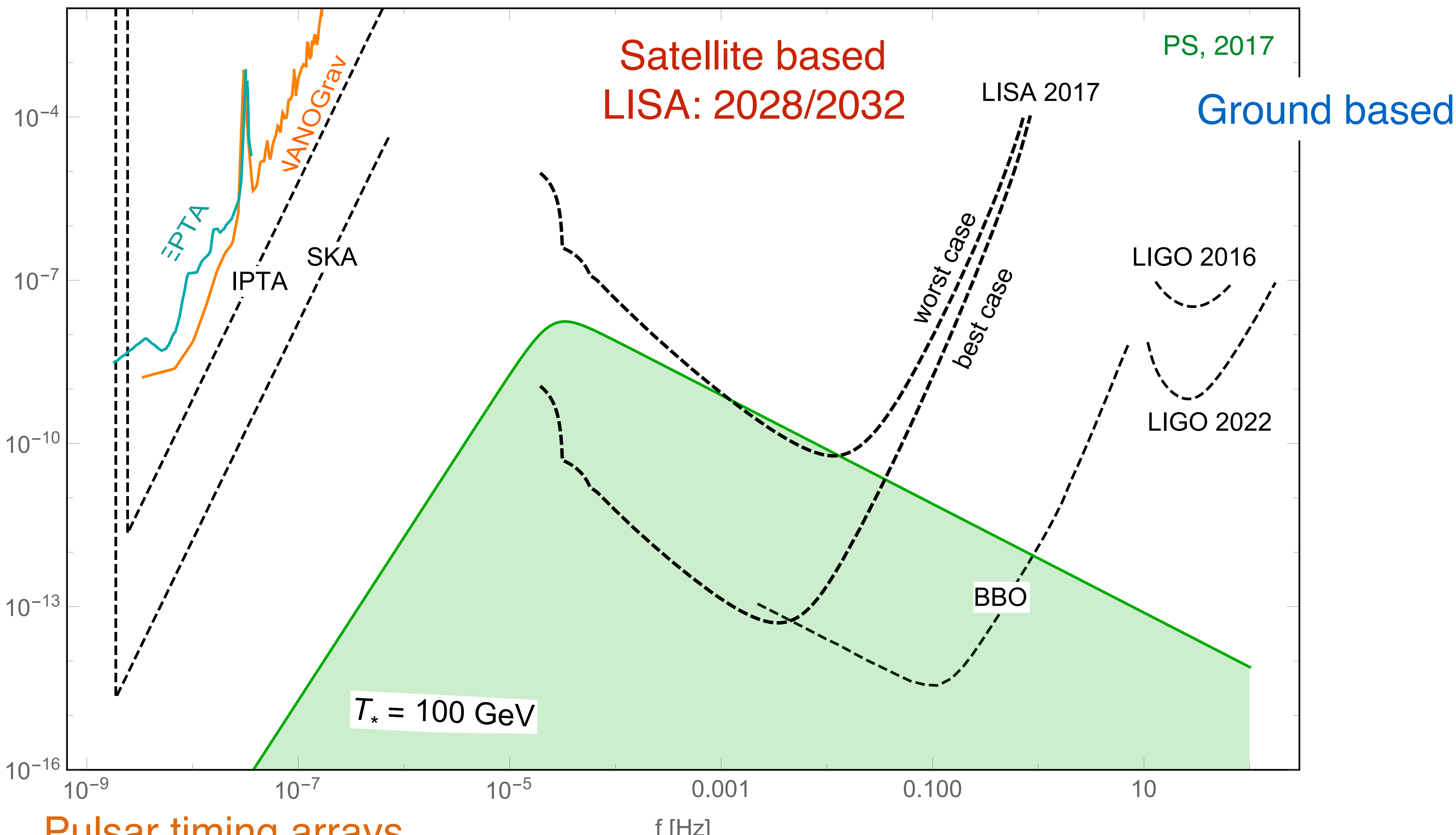
- Set by Hubble rate at time of production

$$H \sim \frac{T_c^2}{M_{\mathrm{Pl}}} \sim \frac{v^2}{M_{\mathrm{Pl}}}$$

- and redshift

$$f_p \sim 10^{-6}\ \mathrm{Hz} \left(\frac{T_c}{100\ \mathrm{GeV}} \right)$$

Example: Strong EWPT



Pulsar timing arrays
Data already available

Dark sector

- Rough relation:

$$T_c \sim m_{DM} \quad \text{or} \quad T_c \sim m_{\rm mediator}$$

- Viable models span large range of masses from
  - MeV (SIMP, dark photon etc…)
  - $\sim$100 TeV (strongly coupled thermal relics)

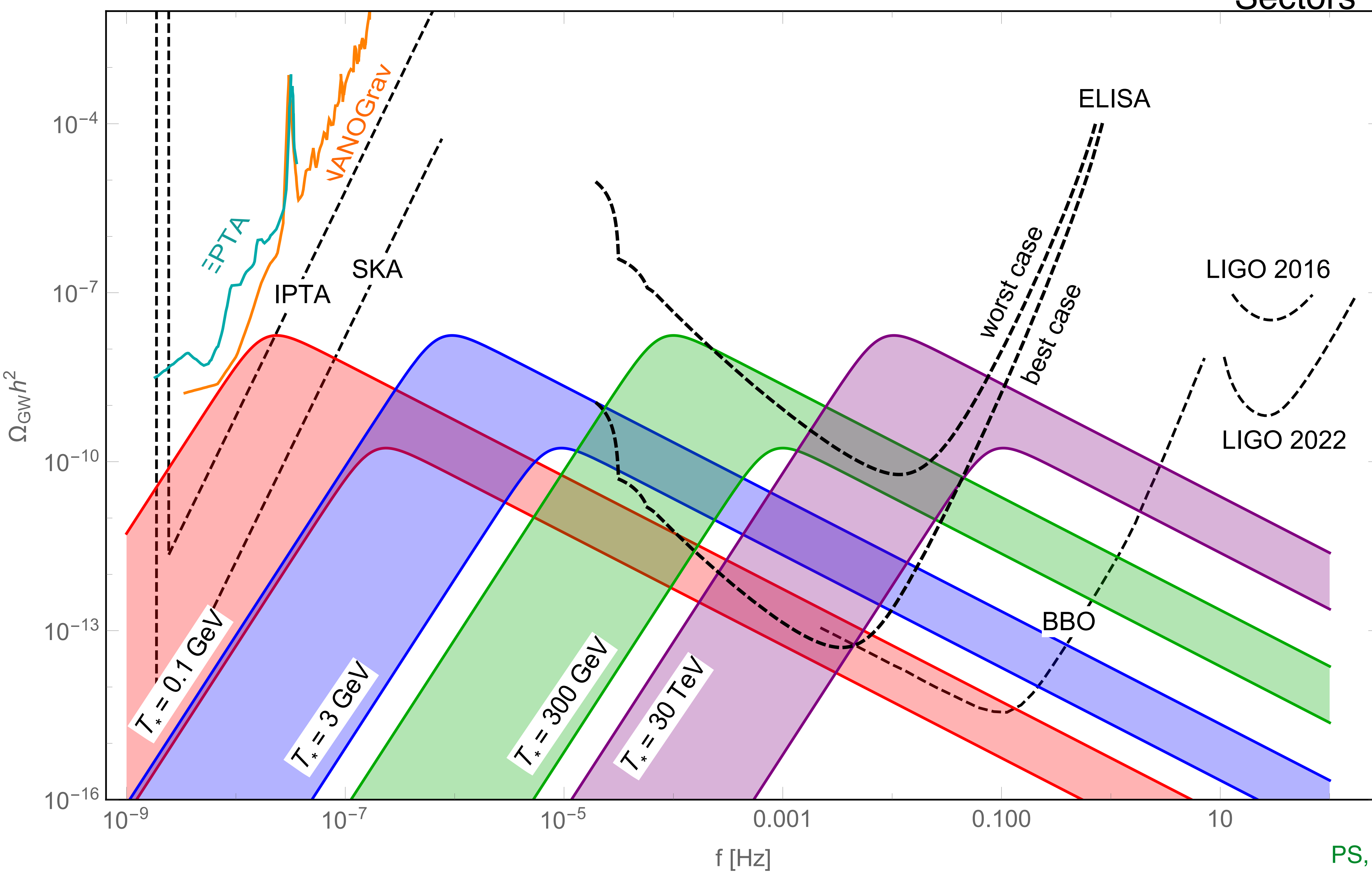
sub-GeV DM

Composite ADM Twin Higgs

Composite WIMP-y

DM Unitarity

B-L breaking, Hidden Sectors

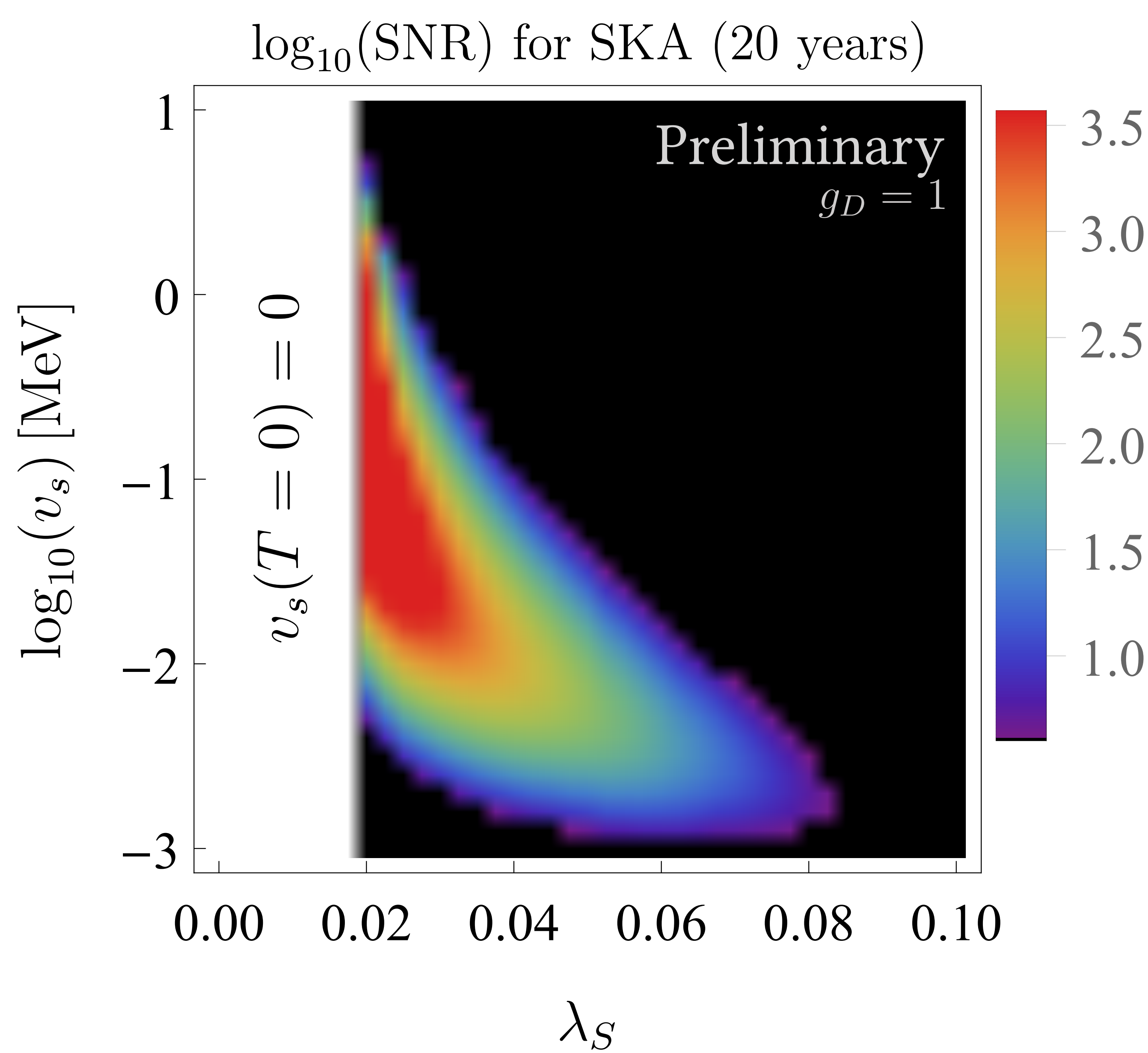


PS, 2017

Higgsed dark photon model

- $A'_\mu \ , \ S$
- PTAs probe very low DS scale
- Constraints from BBN, N_{eff}
- More details:

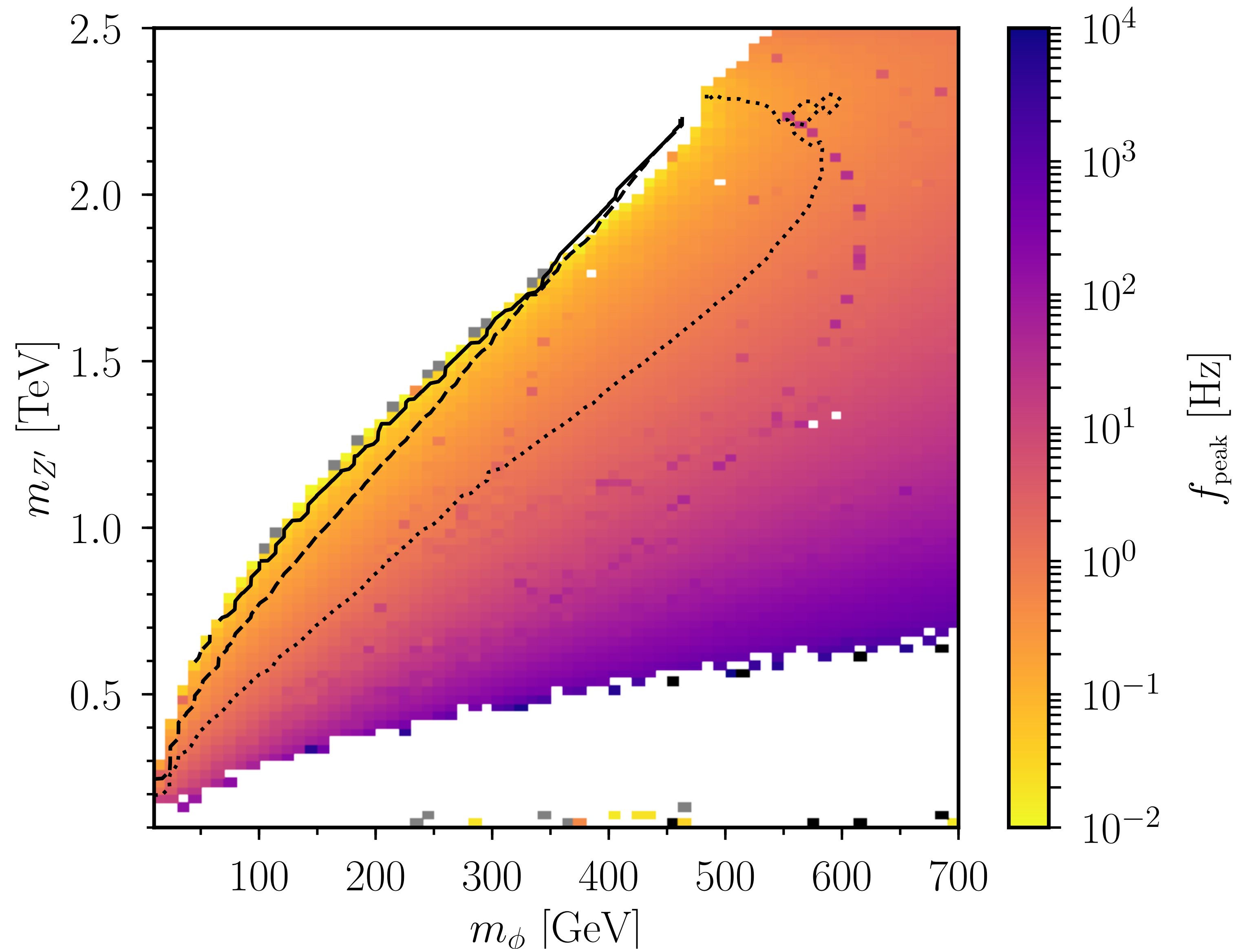
Toby Opferkuch's talk!



Leptophilic DM

- SM + RH ν + $U(1)_\ell$
- Vectorlike leptons to cancel gauge anomalies
  ➞ DM candidate
- GWs from $U(1)_L$ breaking
- More details:

  Eric Madge's talk!



(De)confinement PT

- QCD "like" dark sectors
- Nonabelian SU(N) dark sector, confinement scale Λ_d
- n_f light/massless flavours
- First order PT for
  - $N_d \geq 3 \qquad n_f = 0$
  - $N_d \geq 3 \qquad 3 \leq n_f < 4N_d$

Non-perturbative
Quantitative prediction of GW signal difficult

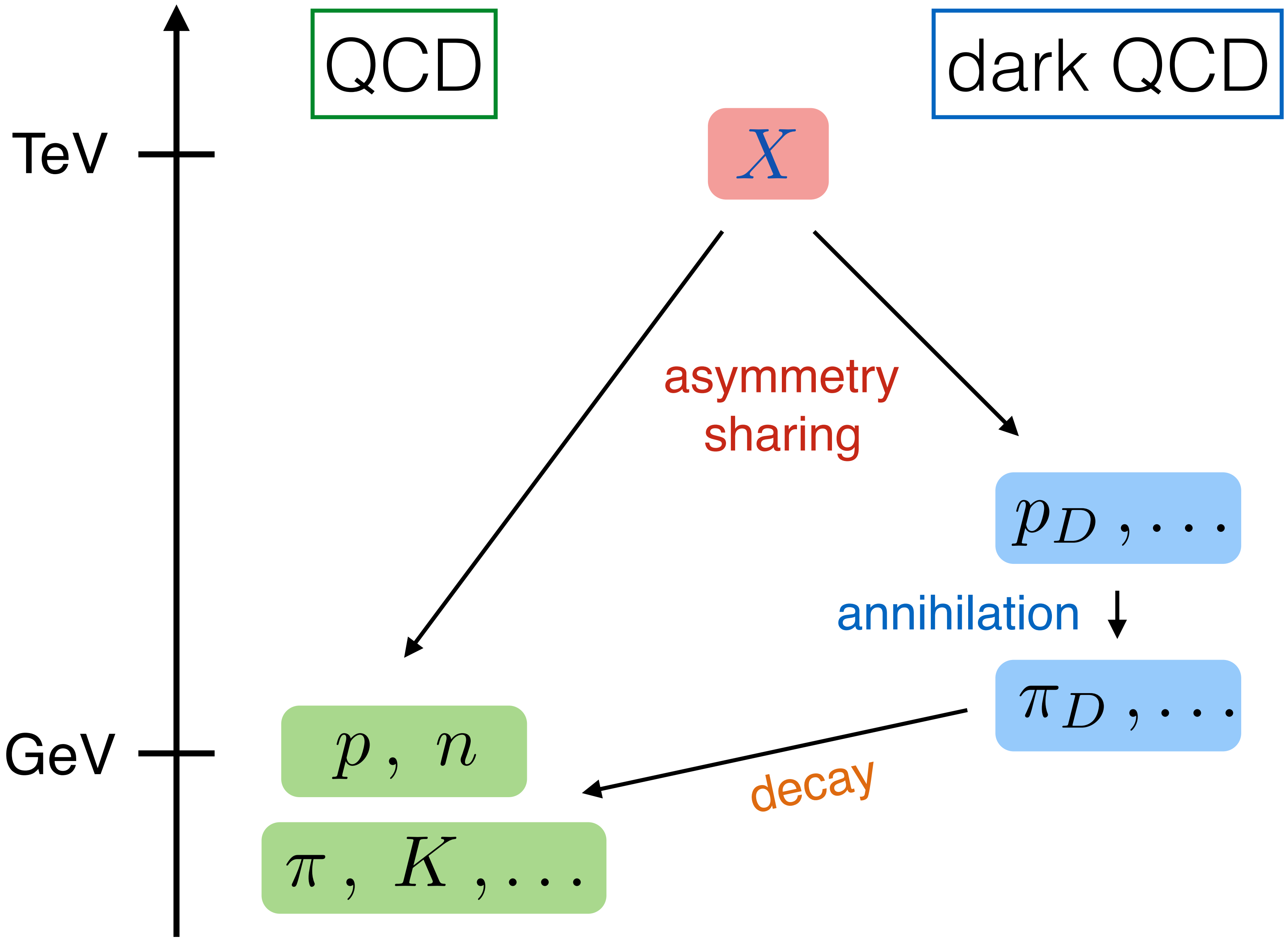
PS, 2017

Summary

- Search for the dark sector is ongoing, activity on many fronts
  - Gravitational wave signals from early universe phase transition in the dark sector
  - Long lived particle searches at colliders (and beyond!)
- For composite dark sectors:
  - Emerging jets at ATLAS/CMS (searched for!)
  - Flavour adds new dimension to emerging jets phenomenology
  - Interesting opportunity for fixed target, LHCb

Thank You

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

Flavour constraints

- Parameterise

Parameterisation from Agrawal, Blanke, Gemmler, 2014

unitary

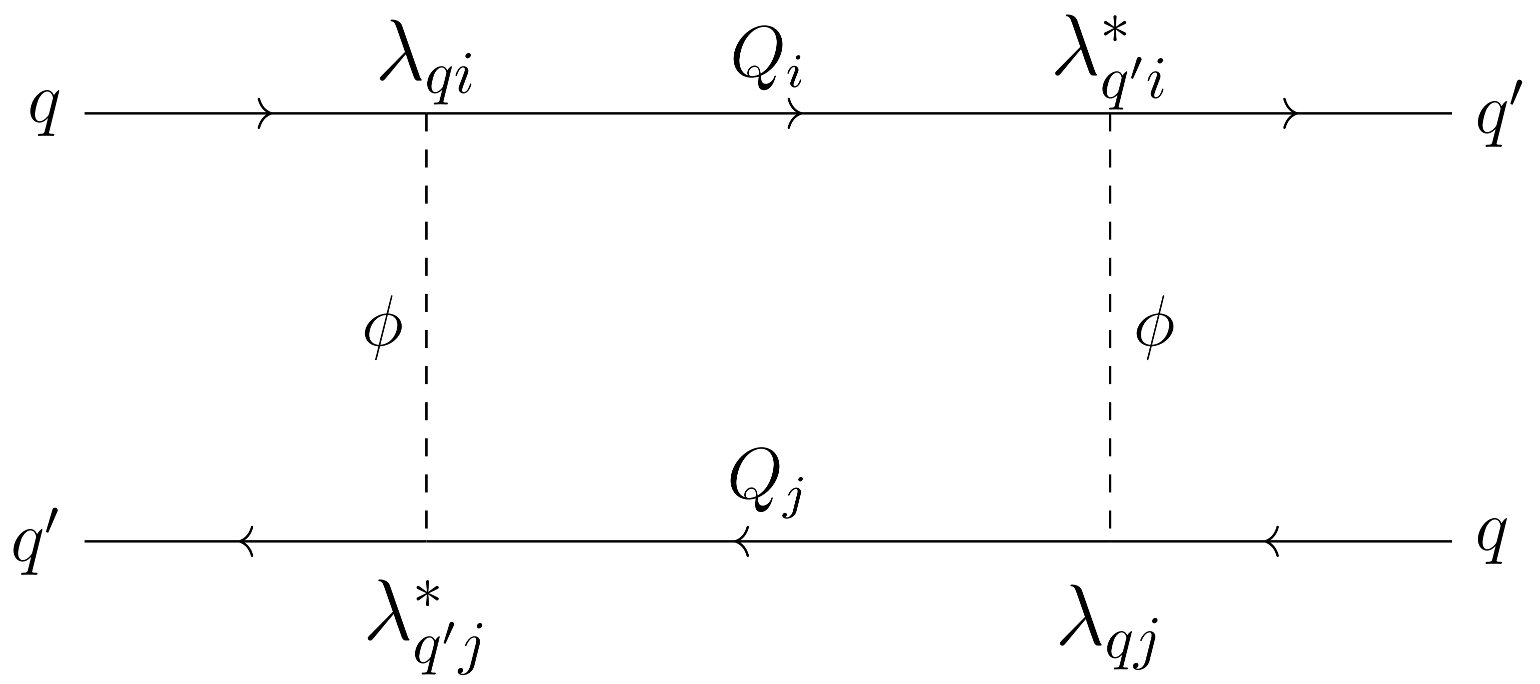
$$\lambda = UDV$$

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



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

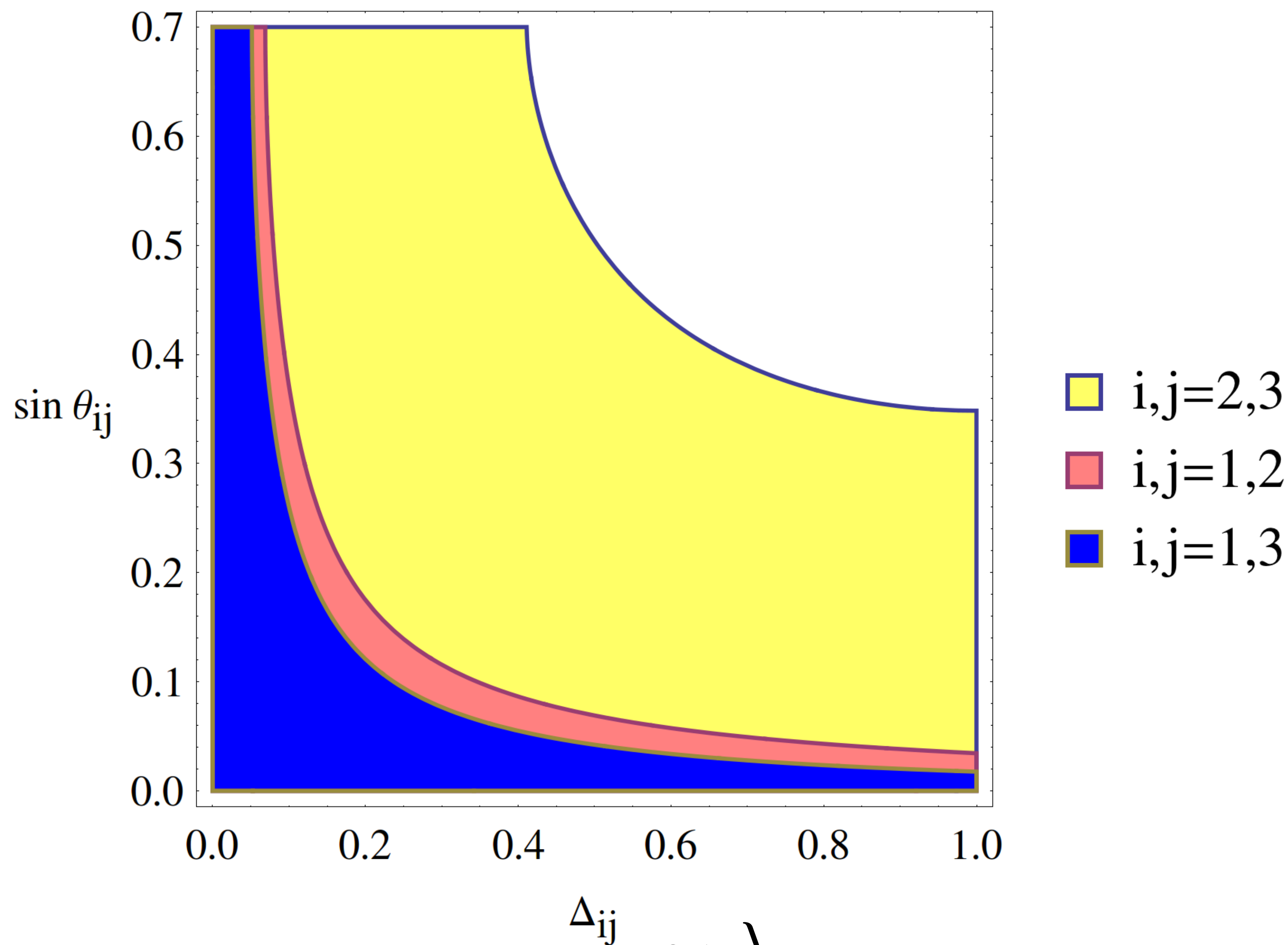
$$\left(\sum_{i=1}^{3} \lambda_{qi}\lambda^*_{q'i}\right)^2 = \left([UD(UD)^\dagger]_{qq'}\right)^2 = \lambda_0^4 \left([UU^\dagger]_{qq'}\right)^2 = 0$$

S. Renner, PS, in progress

ΔF=2

- Otherwise bounds on mixing matrix

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



$\sim \lambda_{1,2}$

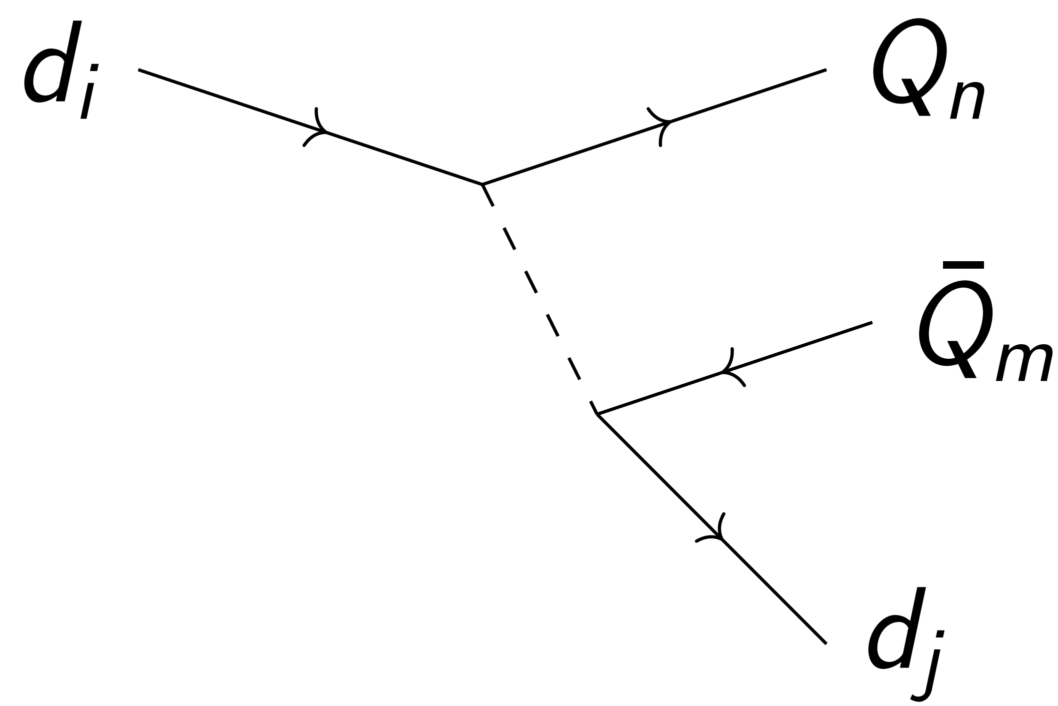
S. Renner, PS, in progress

ΔF=1

- 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, in progress

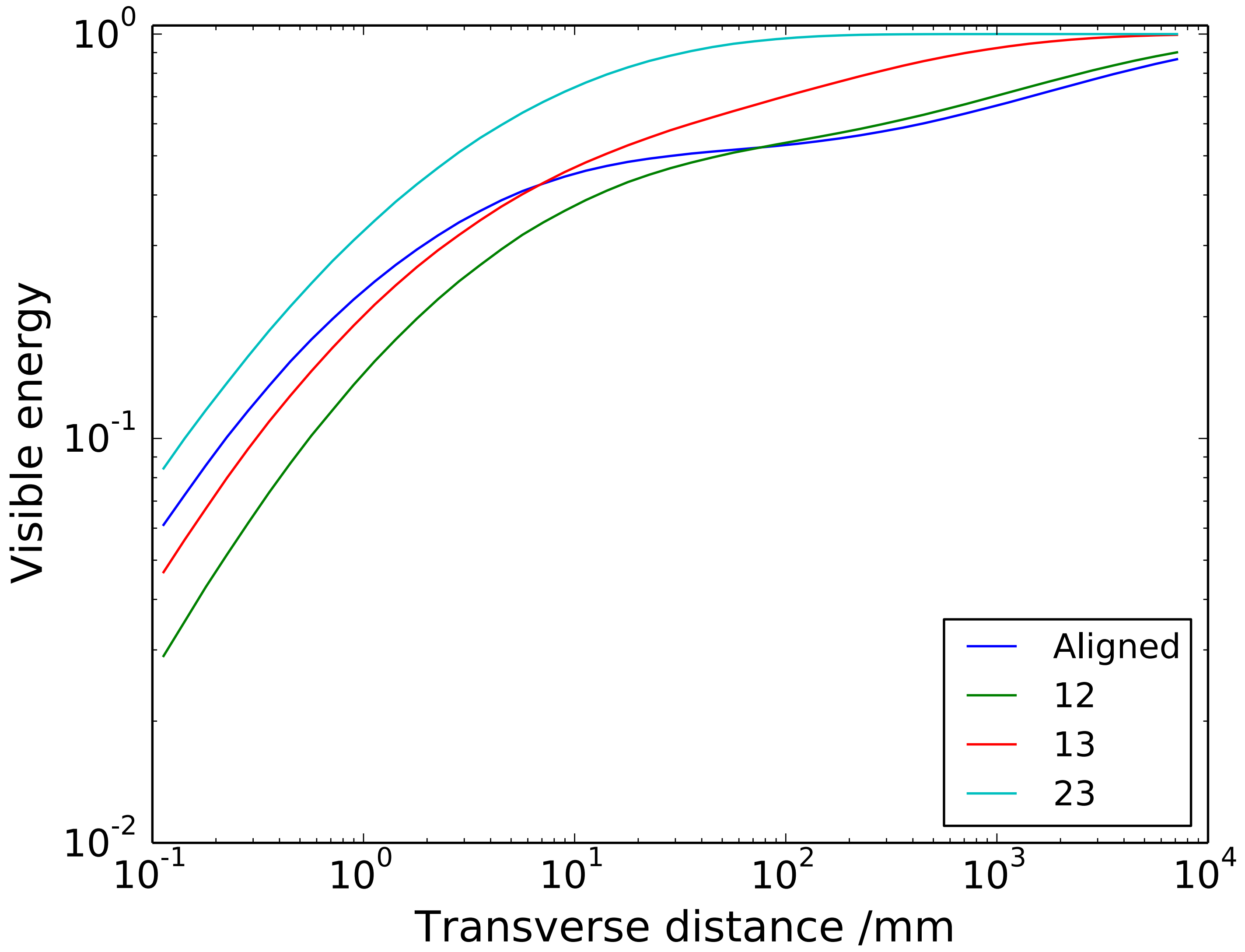
Emerging jets revisited

- Range of dark pion lifetimes

Scenario	Flavour composition	$c\tau_0\lambda_0^4$ /mm ($m_{\pi_D} = f_{\pi_D} = 2$GeV)	$c\tau_0\lambda_0^4$ /mm ($m_{\pi_D} = f_{\pi_D} = 15$GeV)
Aligned	Diagonal	88.6	1.08×10^{-4}
	$\bar{Q}_1 Q_2$	88.6	0.210
	$\bar{Q}_1 Q_3$	Long-lived	1.08×10^{-4}
	$\bar{Q}_2 Q_3$	Long-lived	1.08×10^{-4}
$\sin\theta_{12} = 0.1$, $\Delta_{12} = 0.5$	Diagonal	86.5	1.72×10^{-3}
	$\bar{Q}_1 Q_2$	40.0	9.48×10^{-2}
	$\bar{Q}_1 Q_3$	Long-lived	1.92×10^{-4}
	$\bar{Q}_2 Q_3$	Long-lived	4.25×10^{-4}
$\sin\theta_{13} = 0.05$, $\Delta_{13} = 0.5$	Diagonal	88.6	3.37×10^{-4}
	$\bar{Q}_1 Q_2$	56.9	2.29×10^{-2}
	$\bar{Q}_1 Q_3$	5.7×10^{6}	1.23×10^{-4}
	$\bar{Q}_2 Q_3$	2.27×10^{5}	1.91×10^{-4}

S. Renner, PS, in progress

Emerging jets revisited

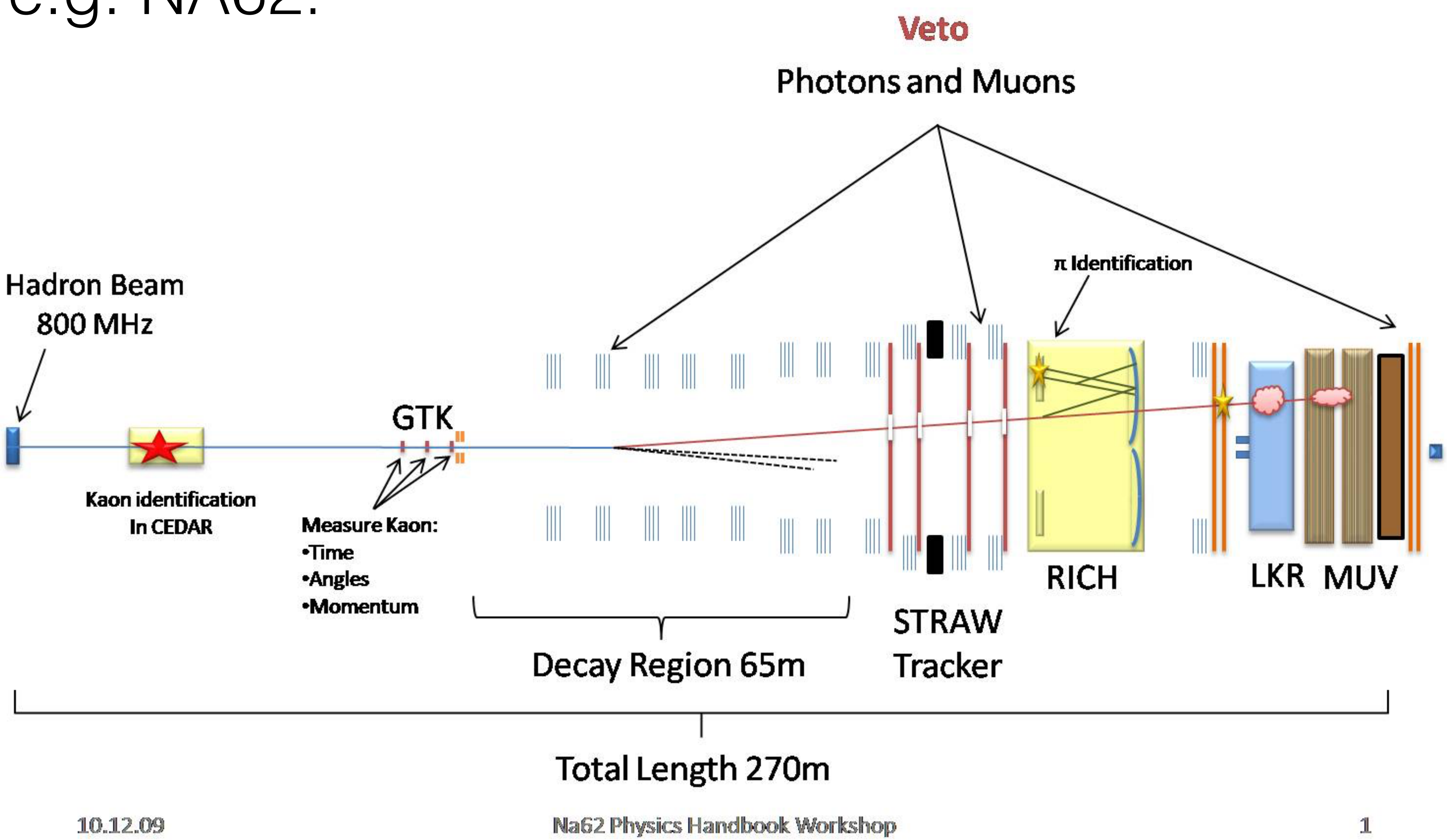


$$\lambda_0 = 0.25$$
$$m_\pi = 10\ \text{GeV}$$

S. Renner, PS, in progress

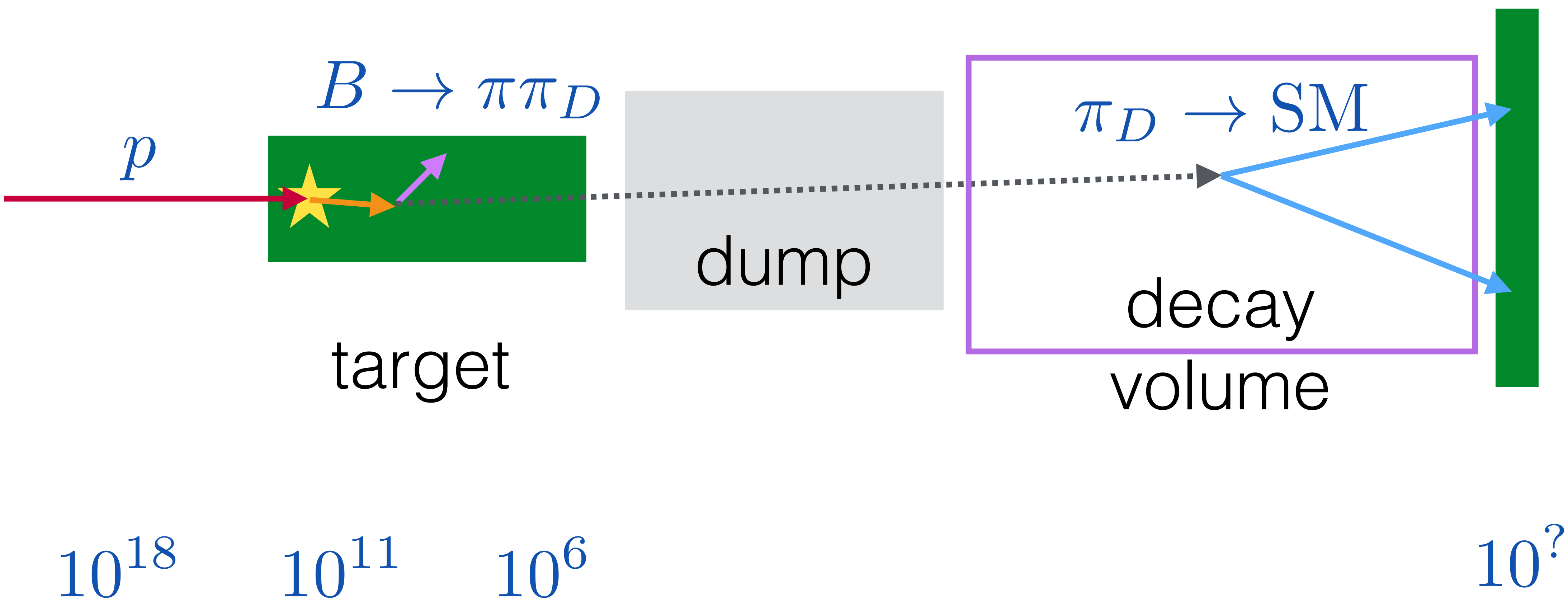
Fixed target

- e.g. NA62:



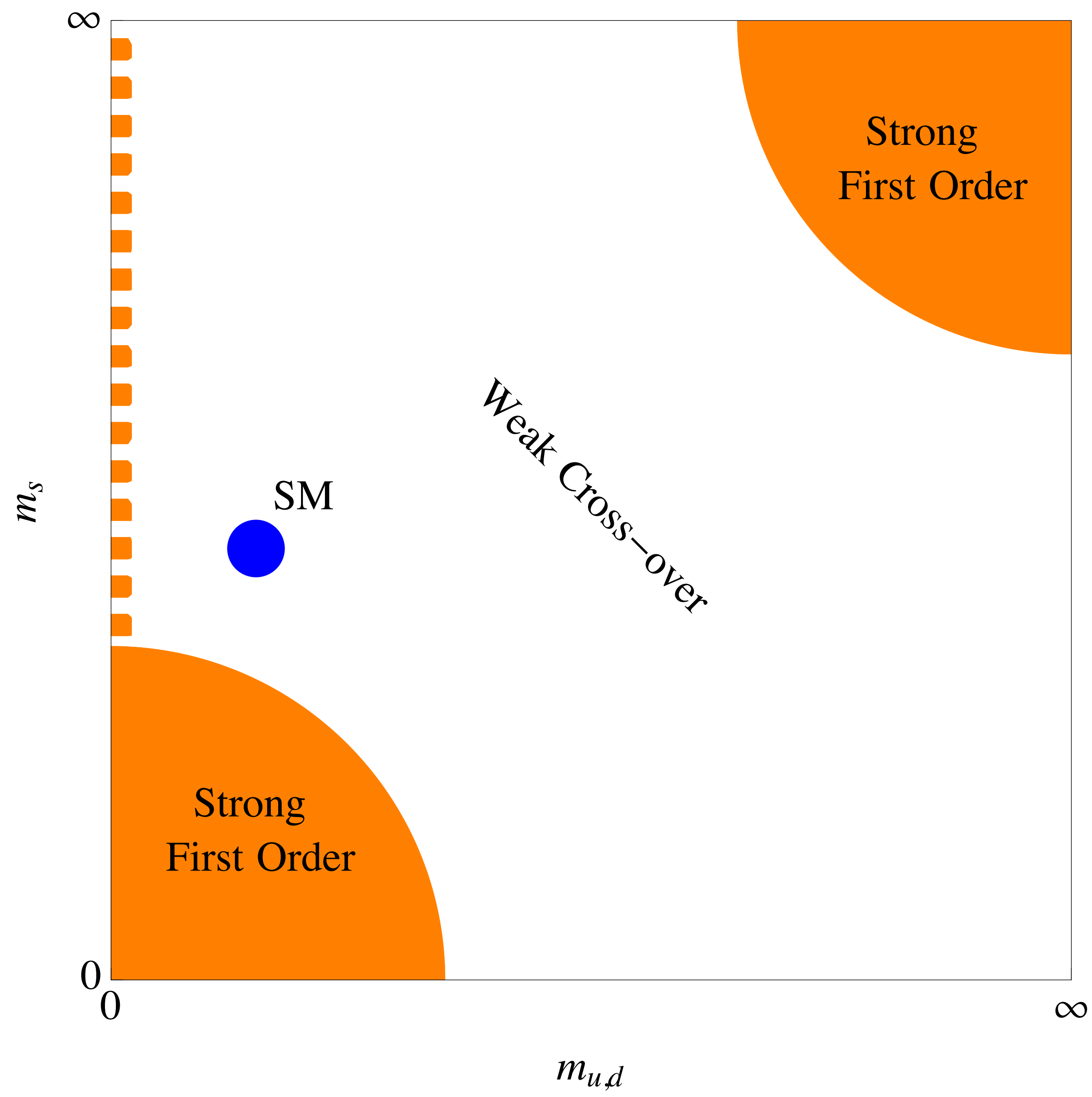
Fixed target

- my cartoon :)

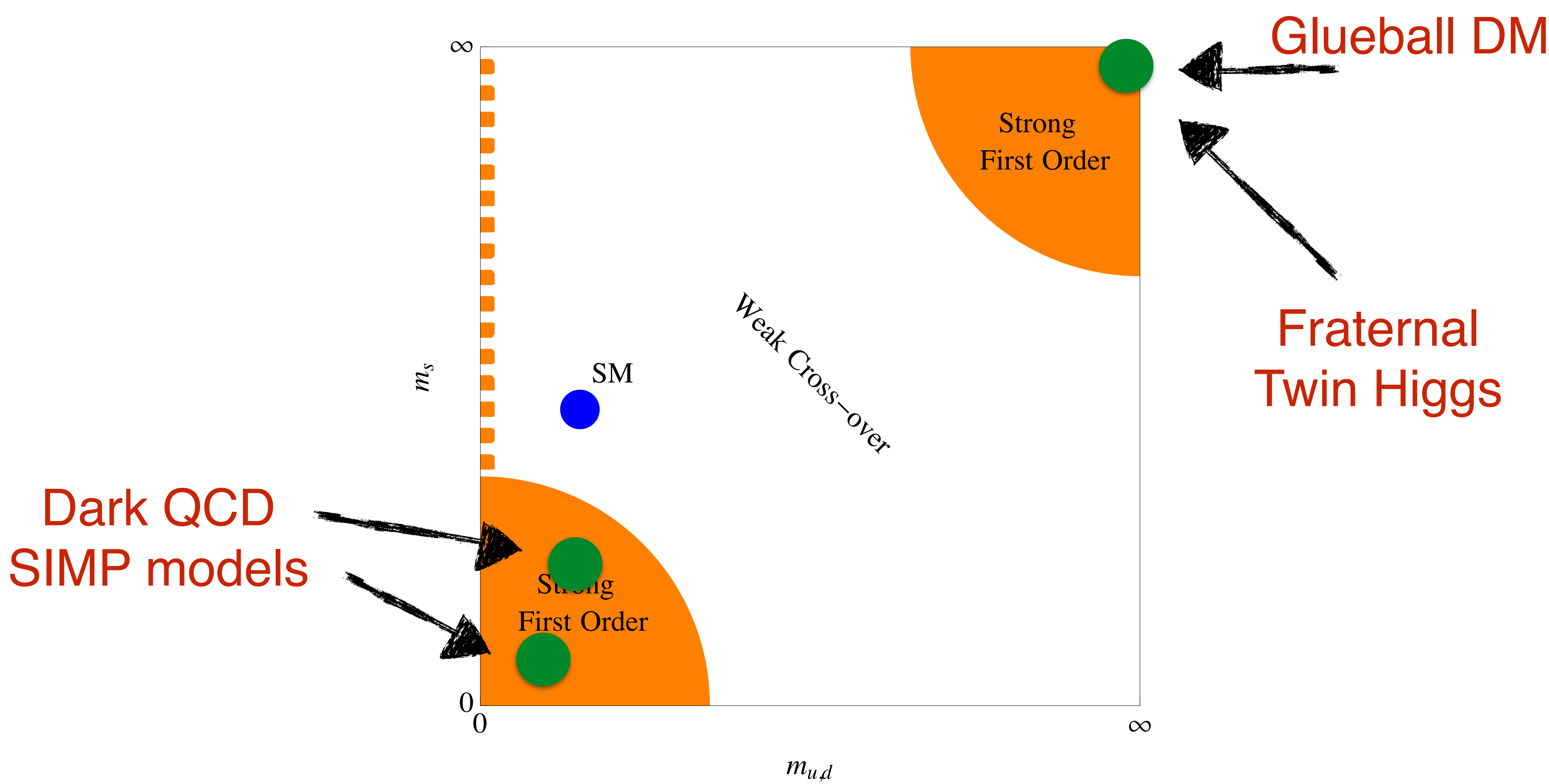


in progress…

QCD Phase Diagram



Phase Diagram II



Check dark shower w/ meson multiplicity

e.g. Ellis, Stirling, Webber

$$\langle N(\hat{s})\rangle \propto \exp\left(\frac{1}{b_1}\sqrt{\frac{6}{\pi\alpha_s(\hat{s})}}+\left(\frac{1}{4}+\frac{5n_f}{54\pi b_1}\right)\log\alpha_s(\hat{s})\right)$$

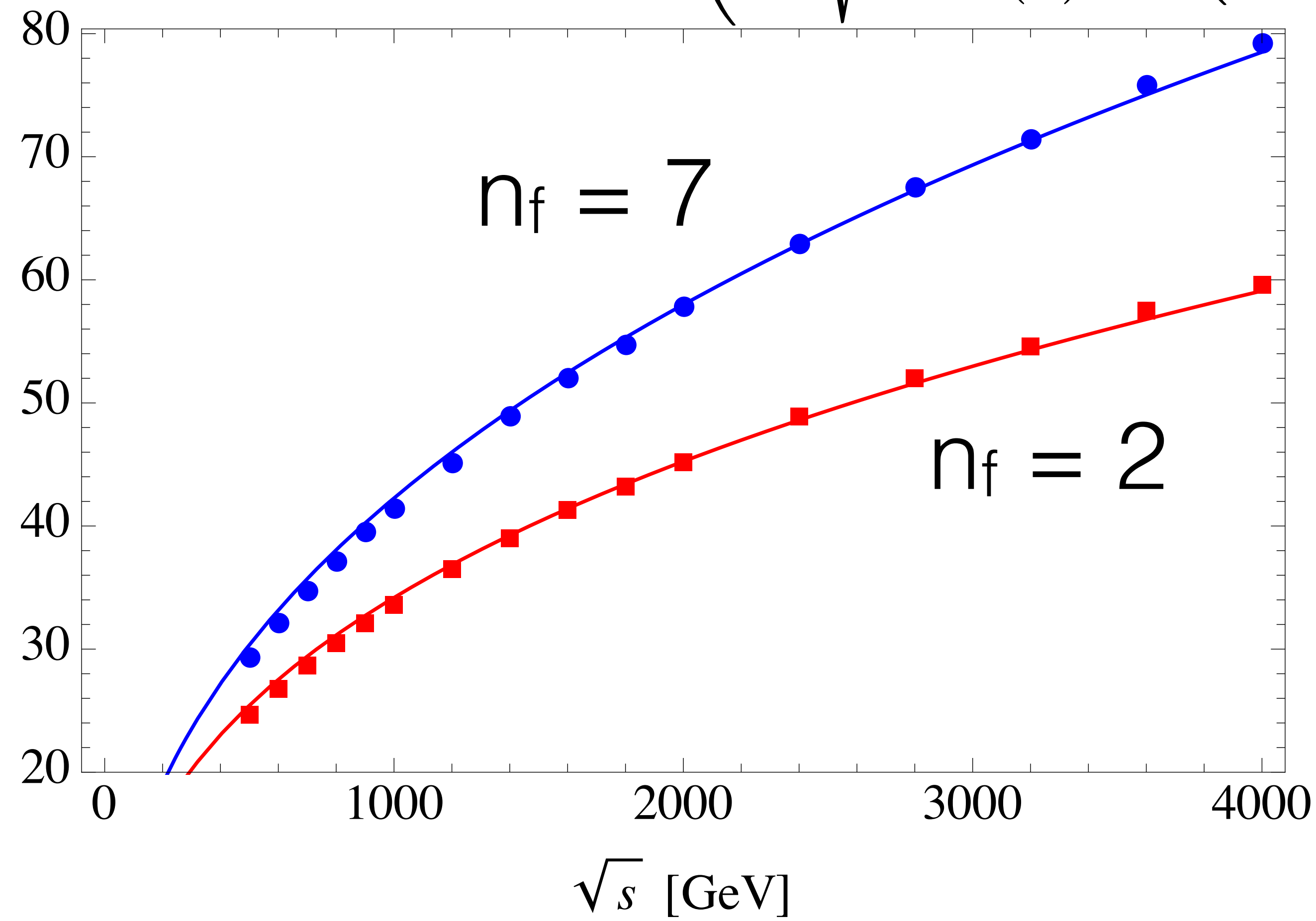
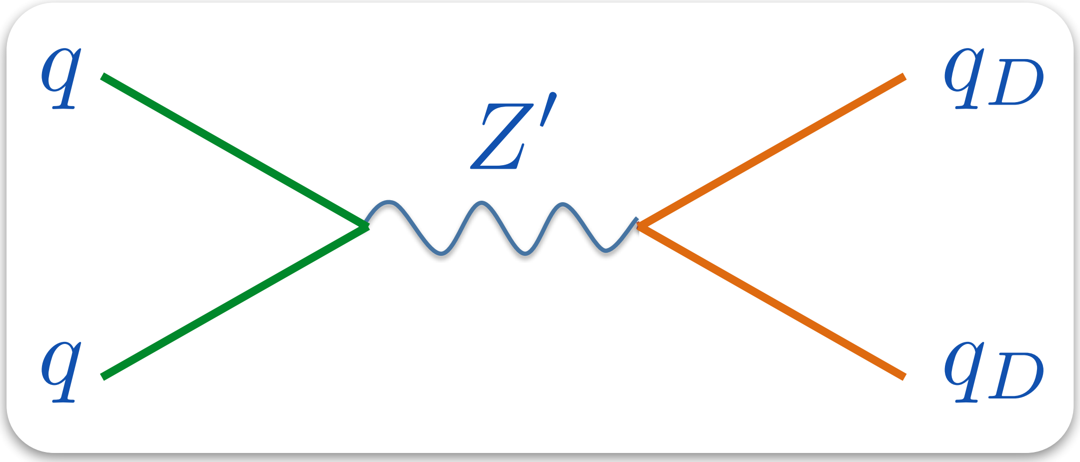


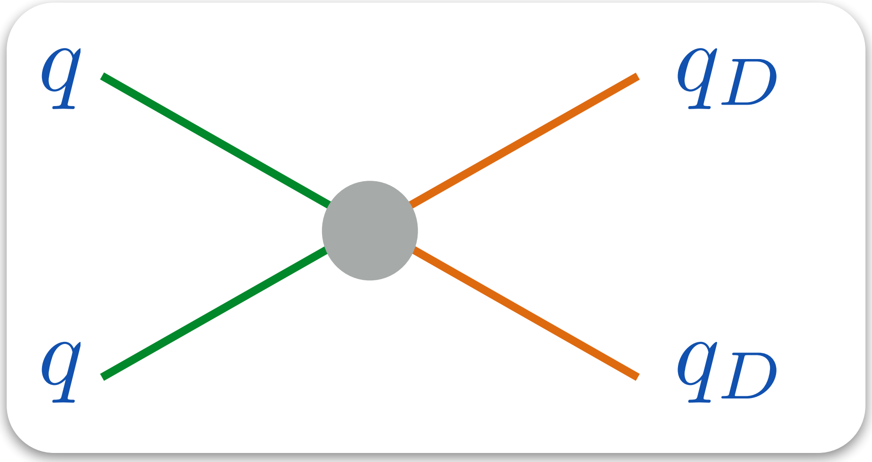
Figure 11: Average dark meson multiplicity in $e^+e^- \to Z'^* \to \bar{Q}_d Q_d$ as a function of the centre-of-mass energy $\sqrt{s}$. We compare the output of the modified PYTHIA implementation for $n_f = 7$ (blue circles) and $n_f = 2$ (red squares) to the theory prediction Eqn. (15), where we only float the normalisation. The dark QCD scale and dark meson spectrum corresponds to benchmark model B.

PS, Stolarski, Weiler, in progress

LHCb opportunities

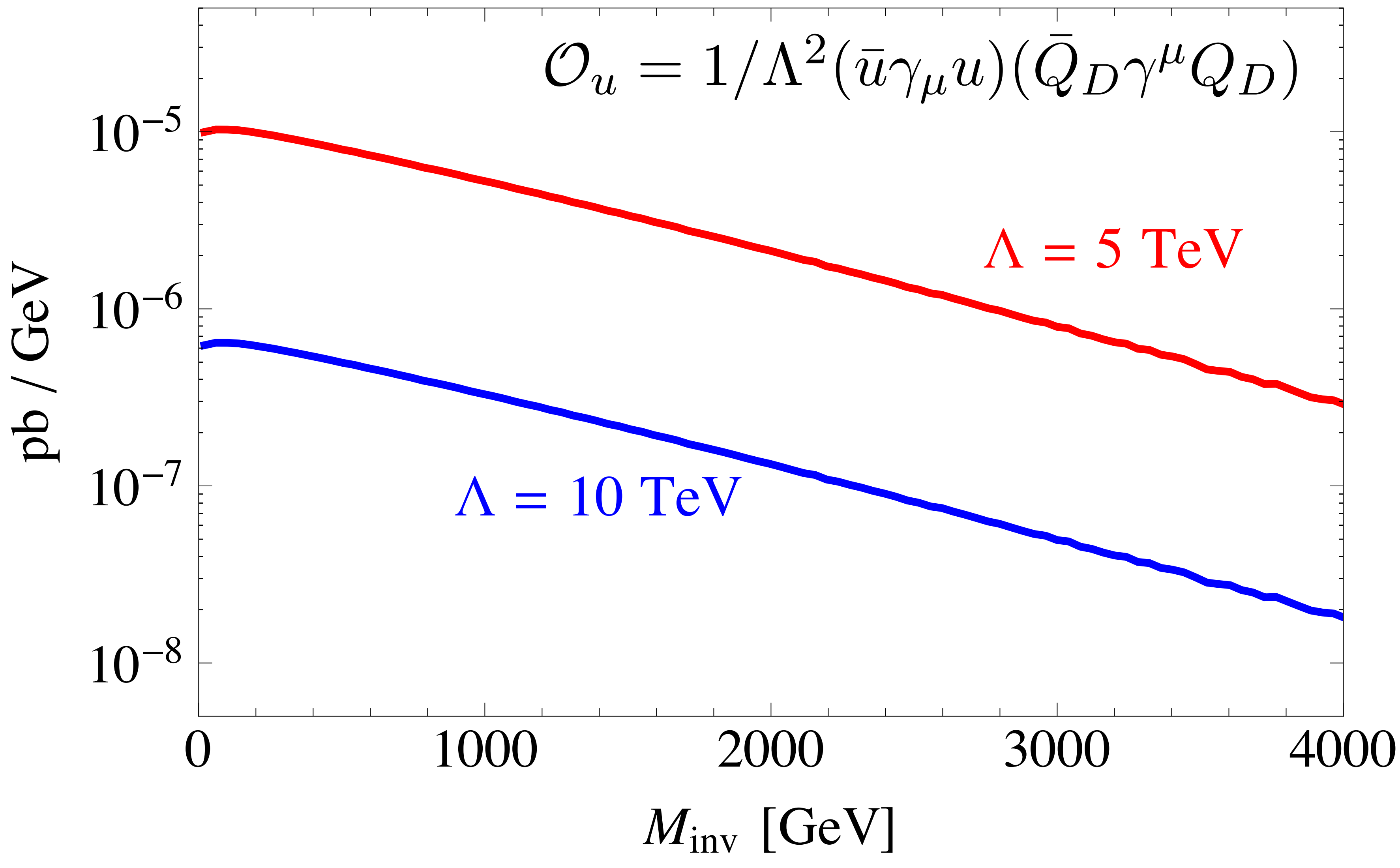
- Z' mediator is difficult to trigger at ATLAS/CMS
  Same if dominant production is off-shell





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

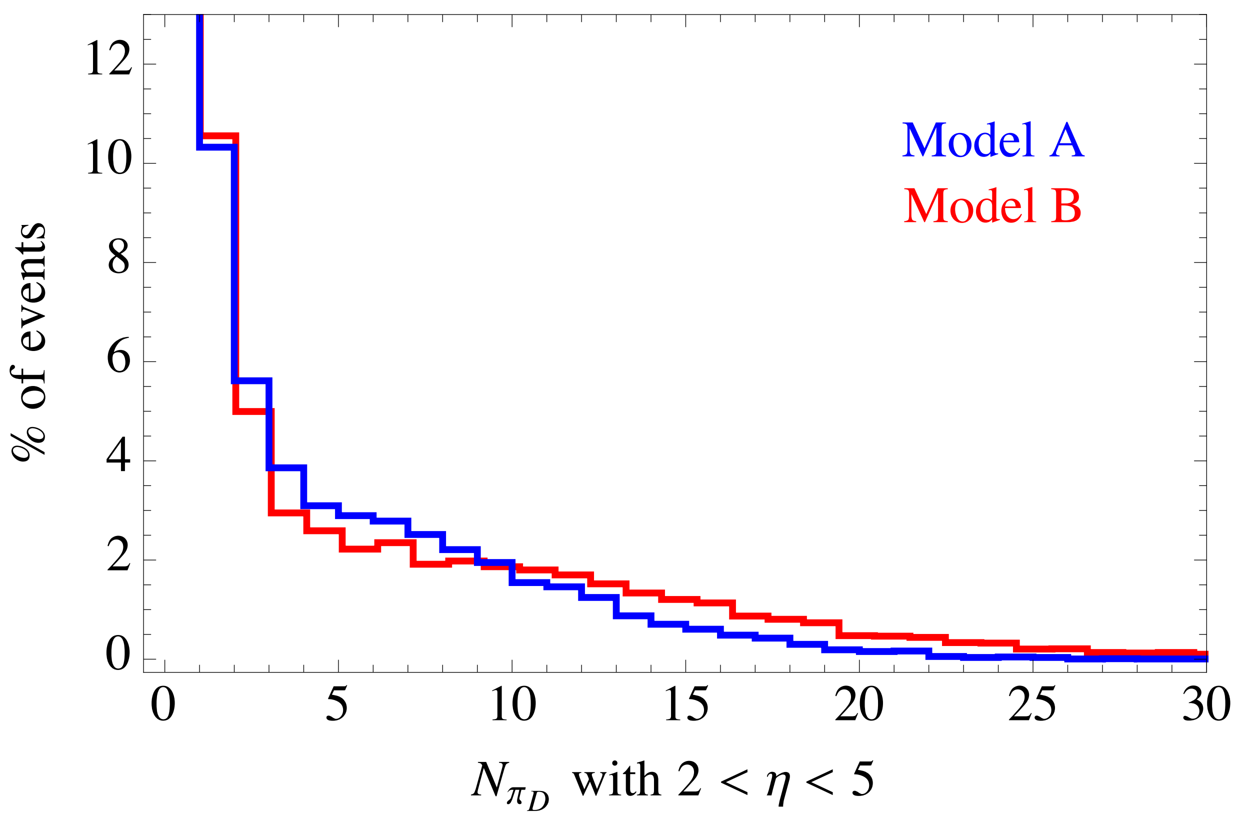
Off-shell production

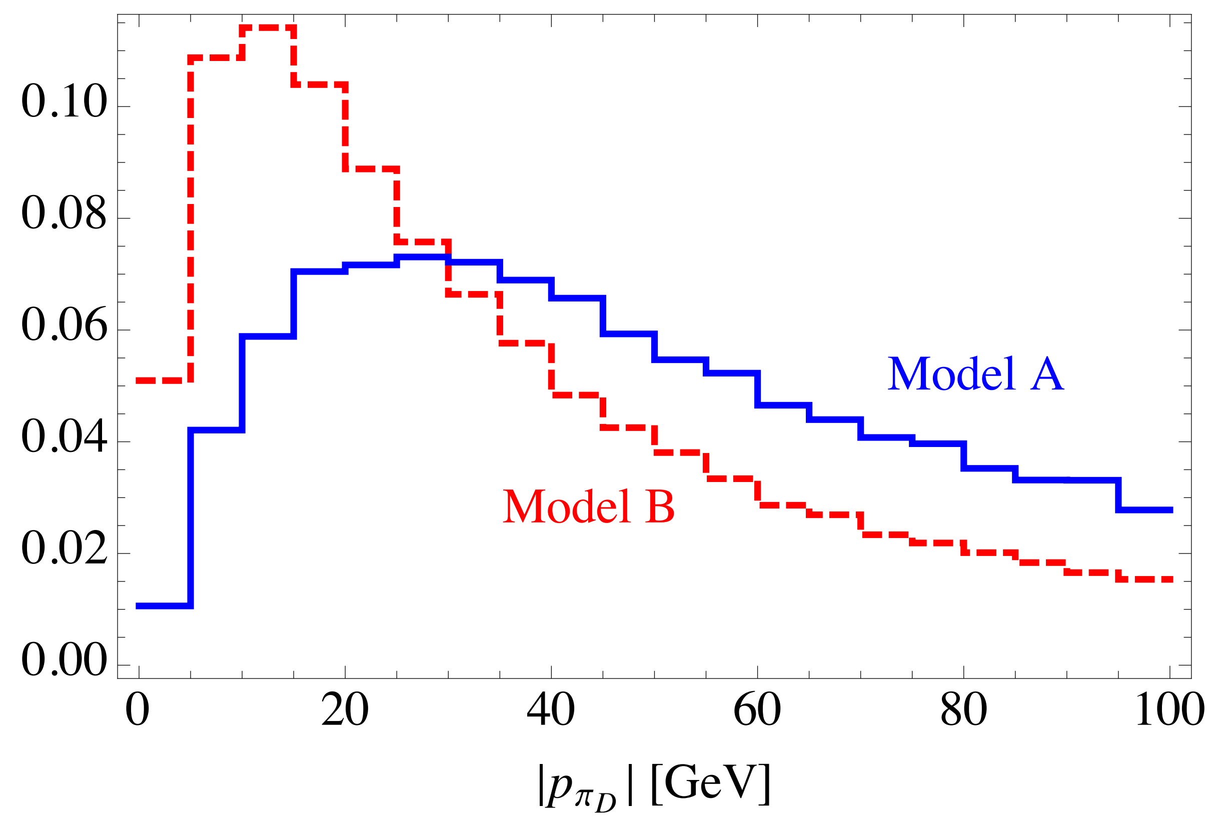


- Total rate: $\sigma(pp \to \bar{Q}_D Q_D) \approx 8.2 \text{ pb} \times \left(\frac{\text{TeV}}{\Lambda}\right)^4 \times N_d \times N_F$

PS, Stolarski, Weiler, in progress

Forward region

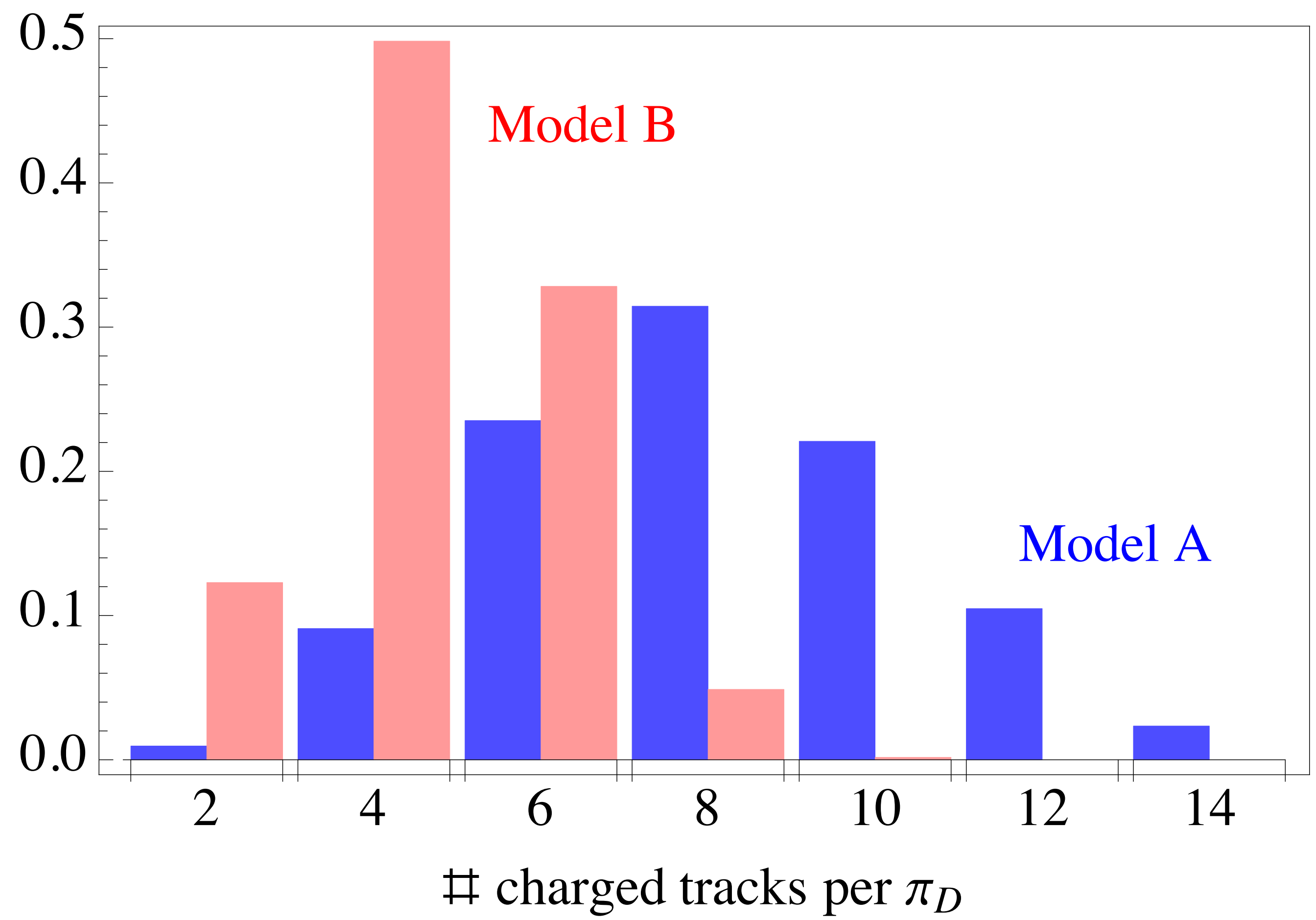




- Fraction of all signal events with N dark pions in $2 < \eta < 5$
- Momentum (not pT) distribution of dark pions in $2 < \eta < 5$

PS, Stolarski, Weiler, in progress

Decay characteristics



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

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 $\Lambda \approx 5\ \mathrm{TeV}$