Emerging Jets:

Invisibles becoming Visible

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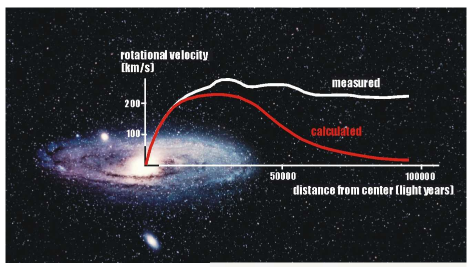
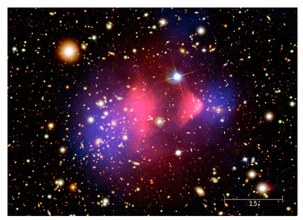
Invisibles Workshop
IFT, Madrid
June 23, 2015

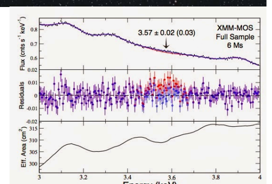
Based on:
Bai, PS, PRD 89 (2014)
PS, Stolarski, Weiler, JHEP 1515 (2015)

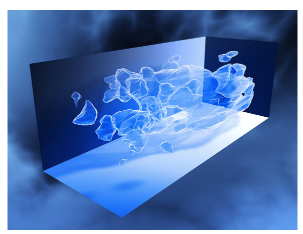
Motivation

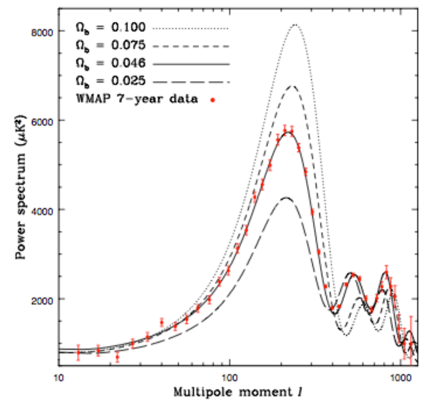
We have seen DM in the sky:



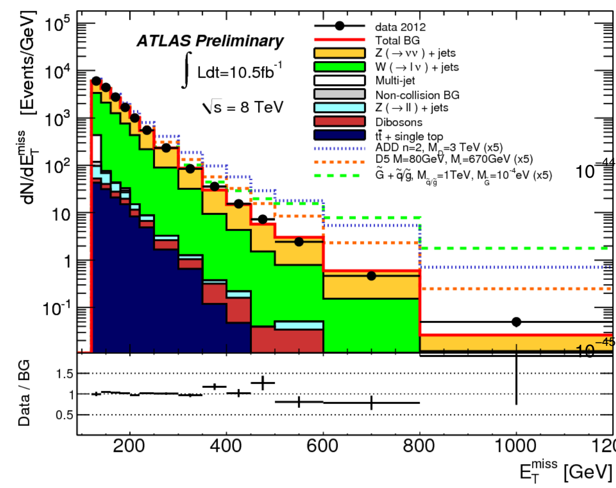


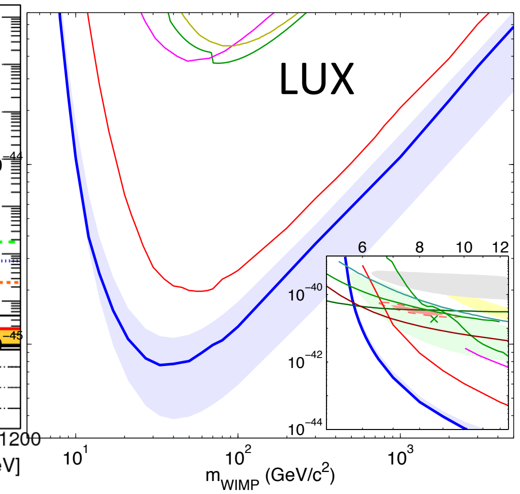






But no direct observation



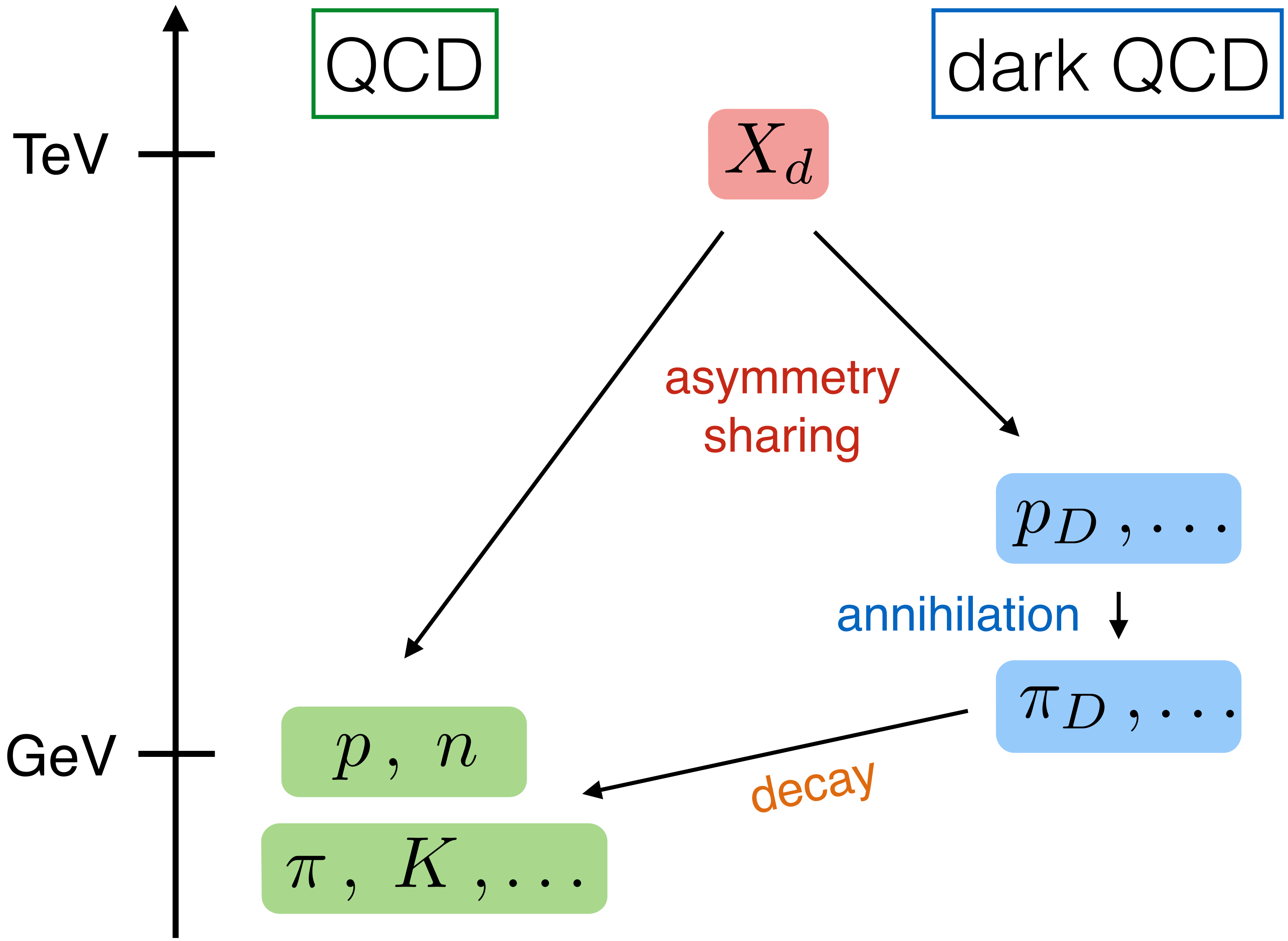


Maybe DM is just part of a larger dark sector

- Example: Proton is massive, stable, composite state
- DM self interactions solve structure formation problems
- New signals, new search strategies!

Bai, PS, PRD 89, 2014

Dark QCD



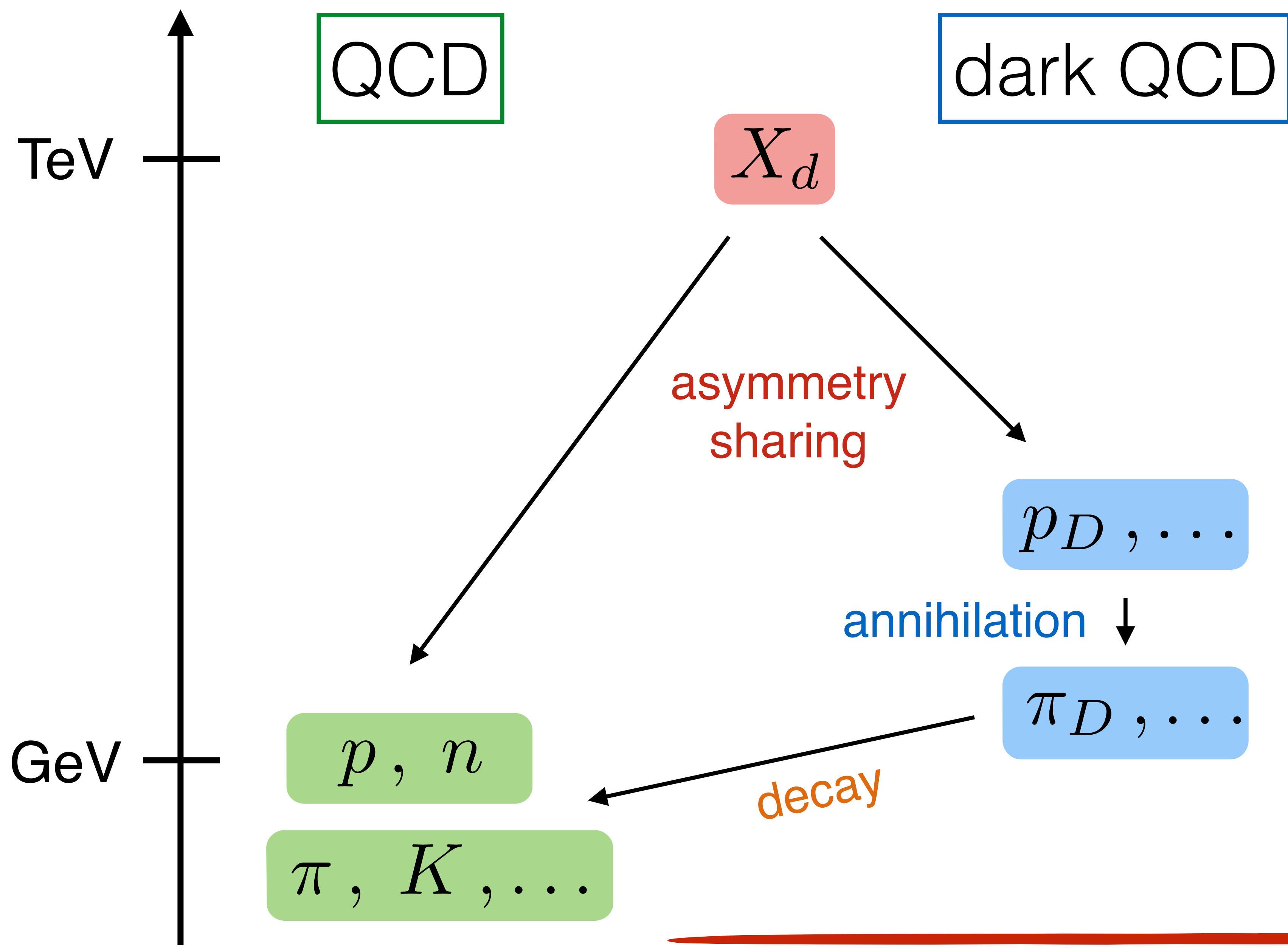
- SU(N) dark sector with neutral "dark quarks"
- Confinement scale

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

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

Bai, PS, PRD 89, 2014

Dark QCD



Advantages:

- Alternative explanation of relic density
- Avoids stringent direct/indirect detection limits
- Self interaction solves small scale structure problems

New Phenomenology!

Related Work

S. Nussinov, Phys.Lett.B.165 (1985) 55.

D. B. Kaplan, Phys.Rev.Lett.B.68 (1992) 741-3.

...

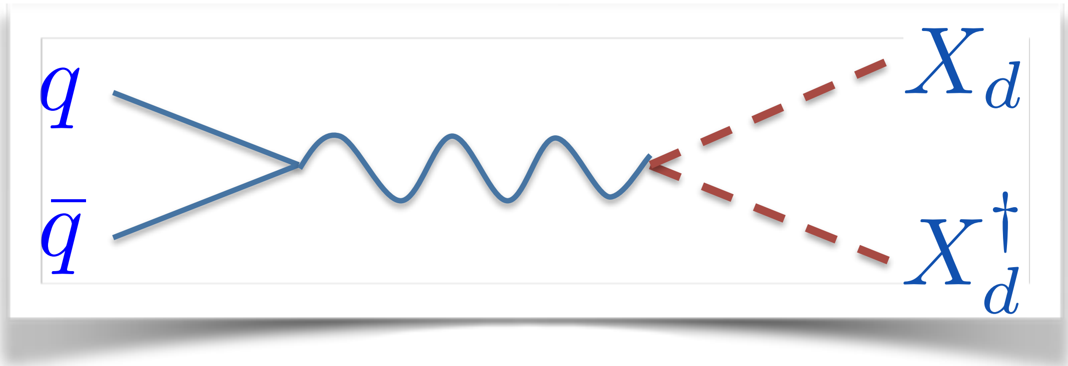
D. E. Kaplan, M. A. Luty, K. M. Zurek, Phys.Rev.D **79** 115016 (2009) [arXiv:0901.4117 [hep-ph]].

Large number of papers. Recent reviews:

Petraki, Volkas, IJMPA 28, 2013.
Zurek, Phys. Rept. 537, 2014.

Collider Signature

- Production of mediator, e.g.:



- 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

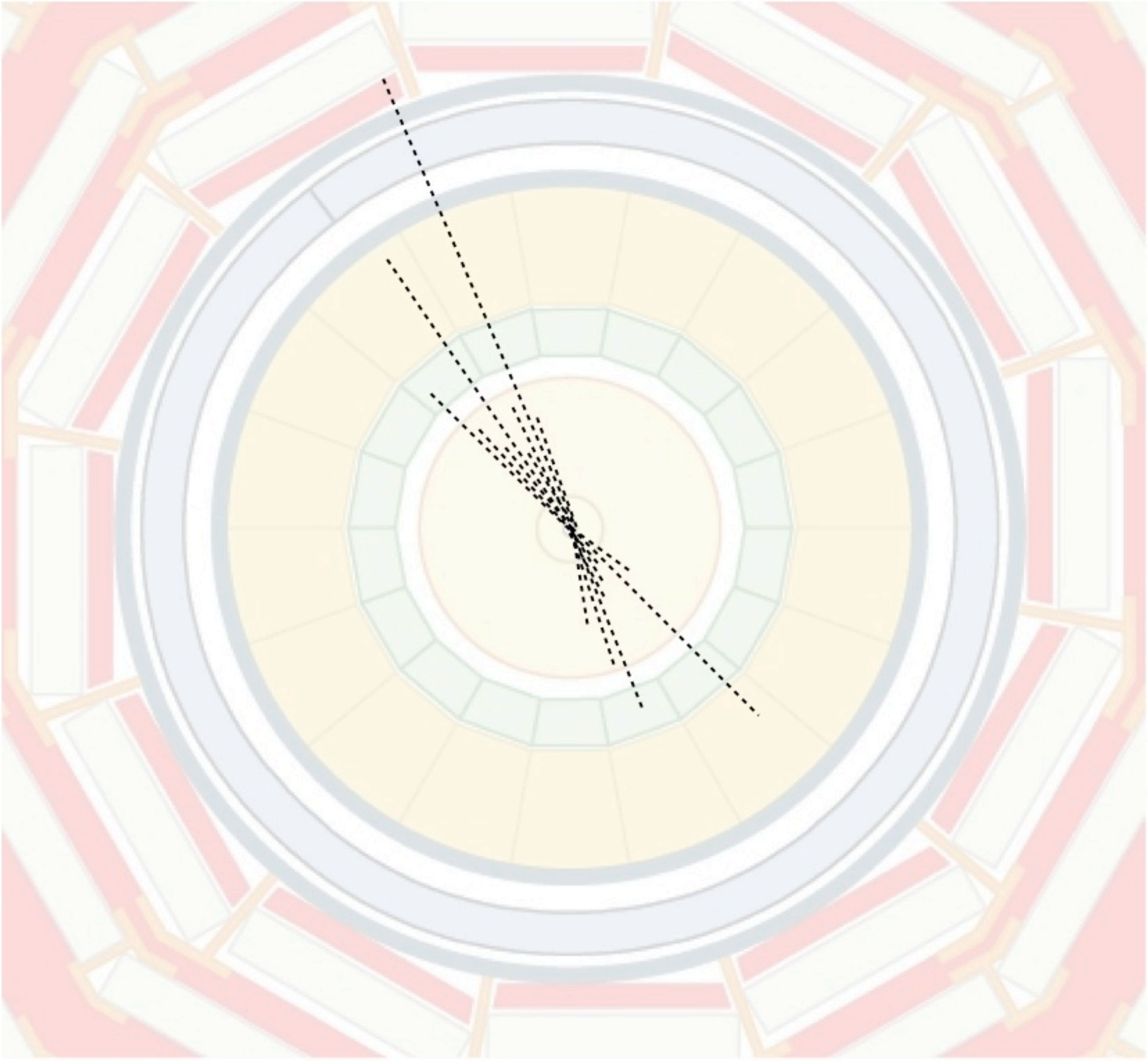
Also “Hidden Valley” signature
Strassler, Zurek, 2007; …

Emerging Jets at the LHC

- Dark meson jets from dark parton shower

- Macroscopic lifetime for

$m_{\pi_d} \sim \text{few GeV}$



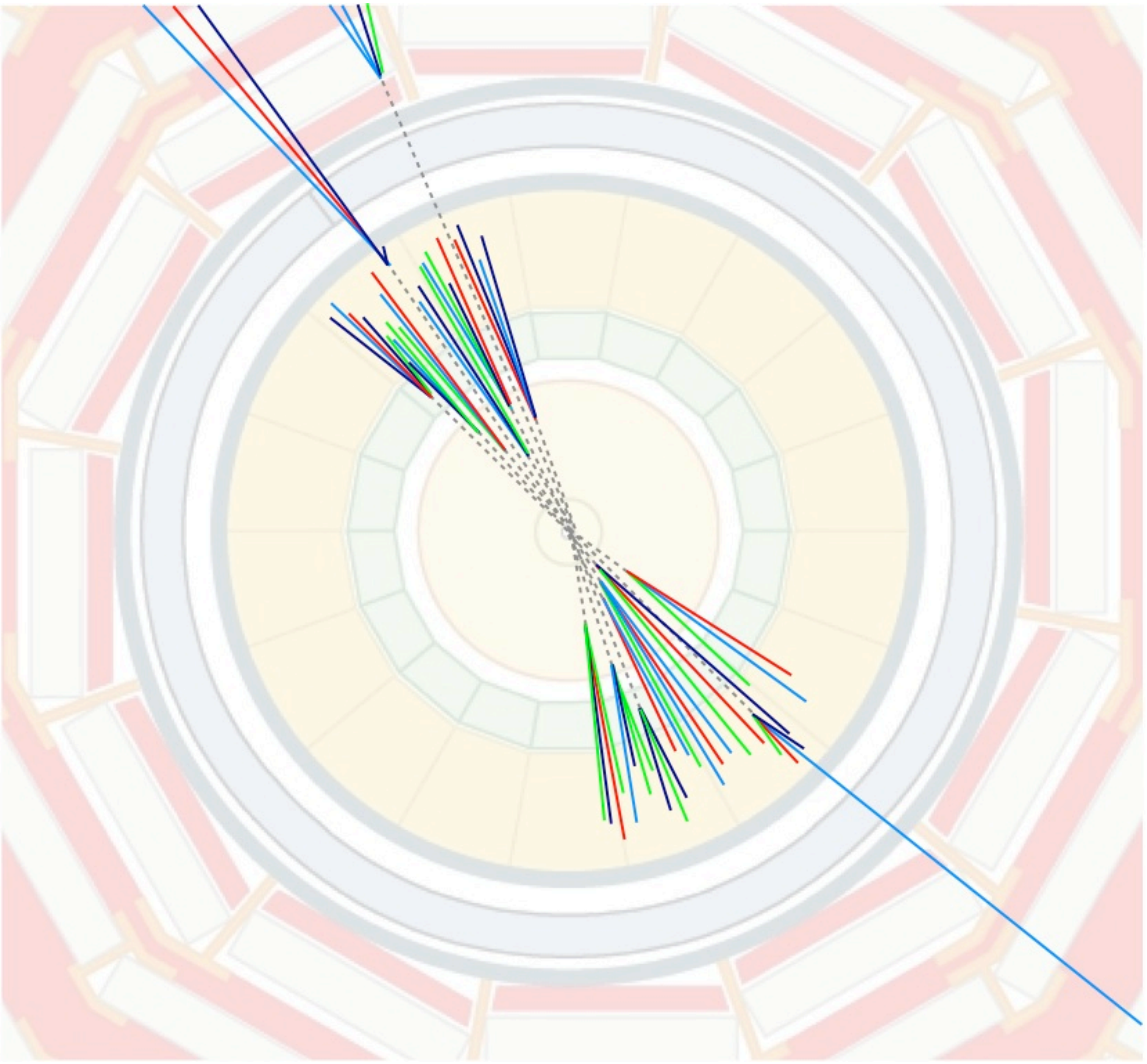
Emerging Jets at the LHC

- Decay back to SM quarks

- Jets emerge at distance

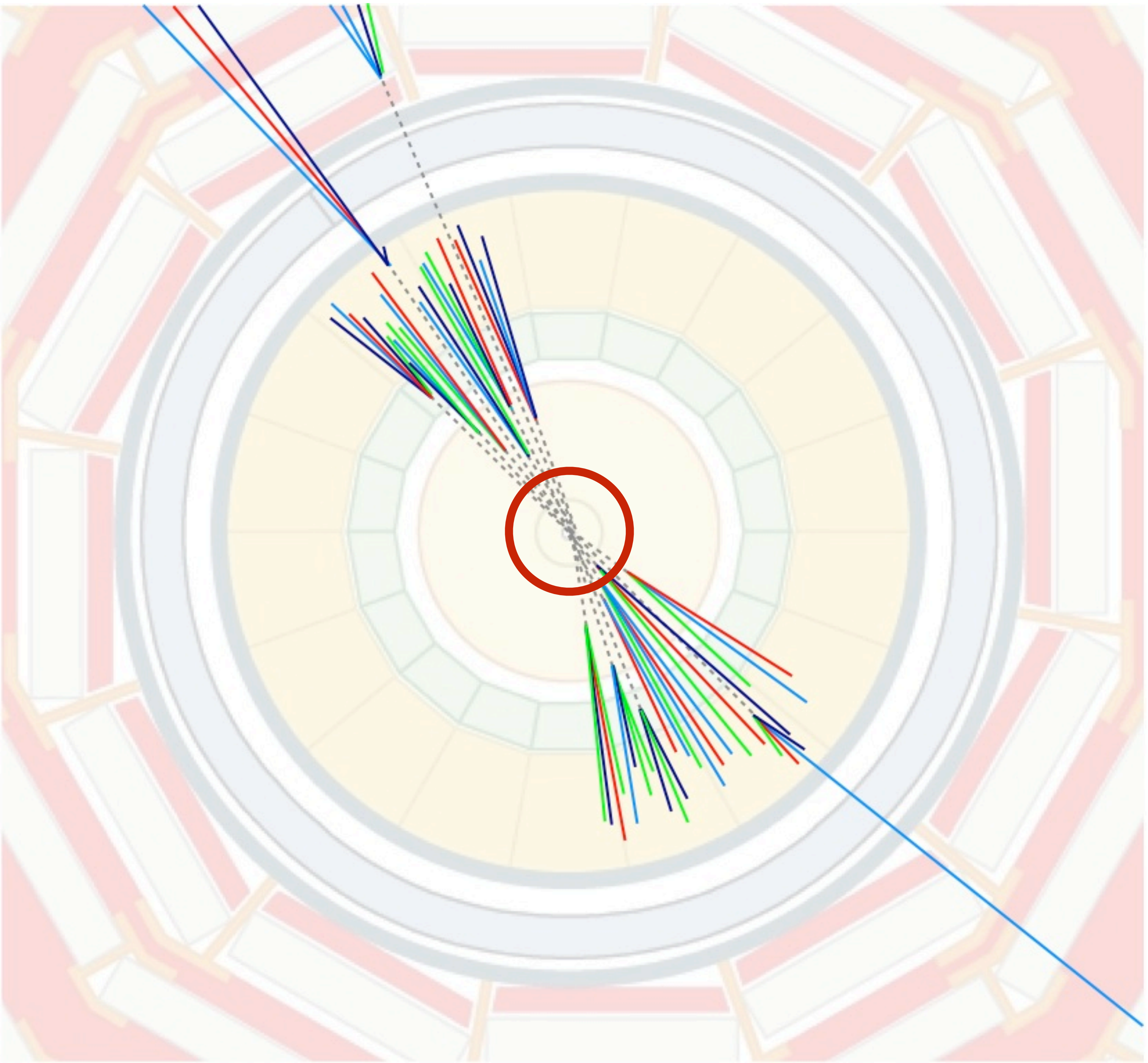
$$c\tau$$

- Several displaced vertices inside a jet “cone”



Emerging Jets at the LHC

- Characteristic:
  - few/no tracks in inner tracker
- New "emerging" jet signature
- Universal for large class of composite DM models!

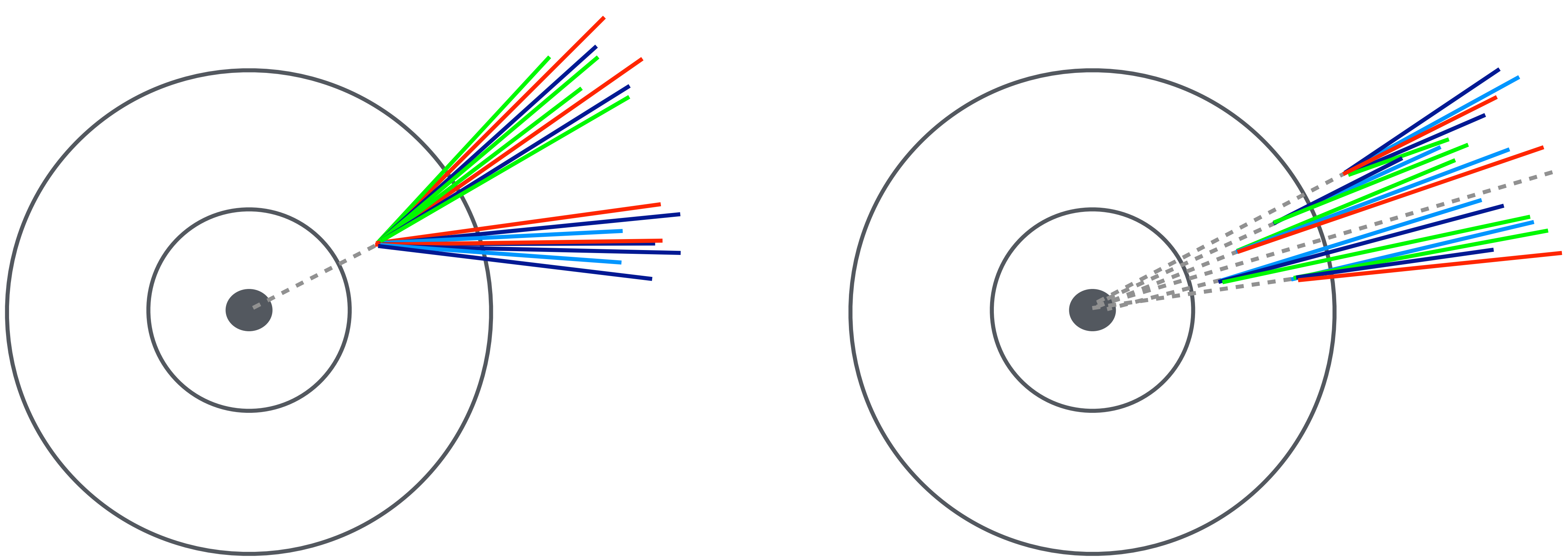


Existing displaced jet searches

- ATLAS (arXiv:1409.0746)
- CMS (arxiv:1411.6530)
- LHCb (arxiv:1412.3021)

Main differences:

- Lower mass
- Lower track multiplicities from individual vertices
- Multiple displaced vertices in same cone



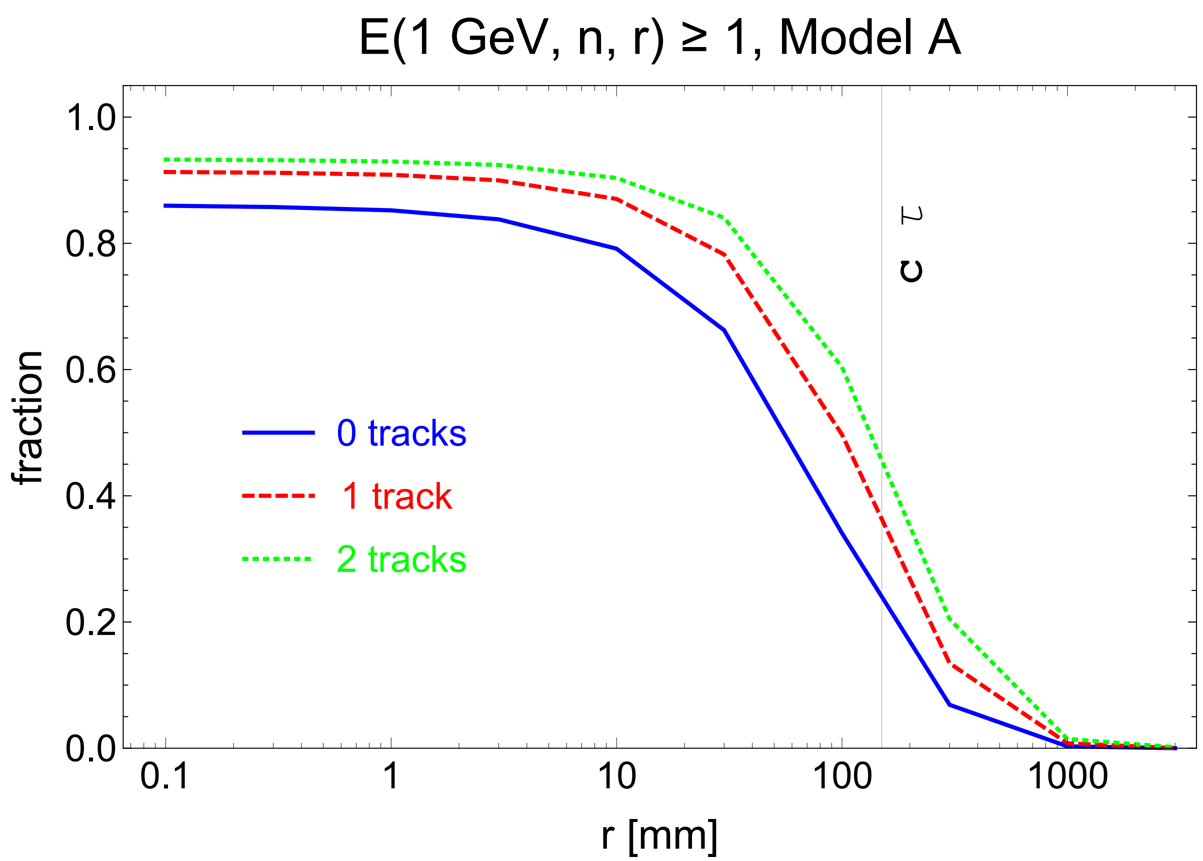
Benchmark Signal/Strategy

- Pair production of 1 TeV bi-fundamental scalars
- Trigger on 4 HCAL jets $p_T > 200$ GeV
- Require one or two "emerging jets:"
  Jets with at most 0/1/2 tracks originating from a distance $r < r_{\rm cut}$
- Two scenarios:

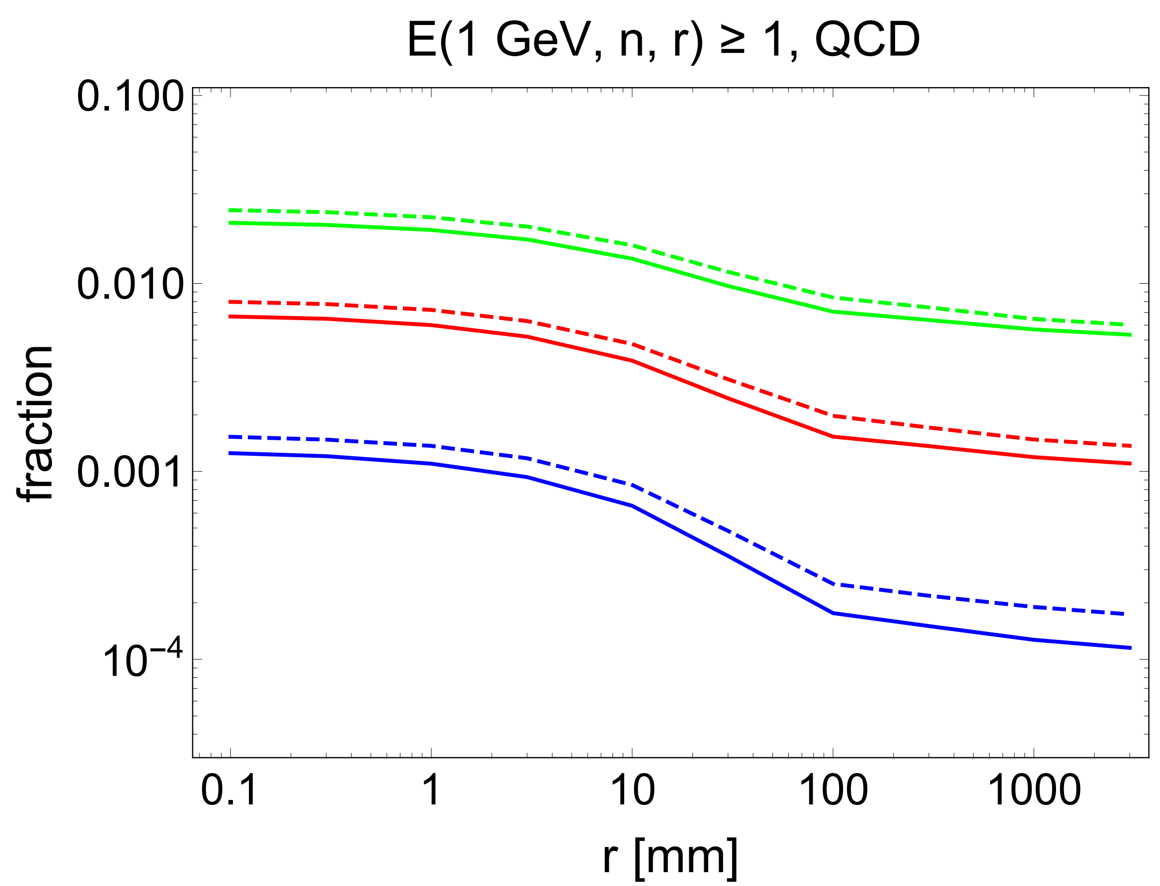
	Model **A**	Model **B**
Λ_d	10 GeV	4 GeV
m_V	20 GeV	8 GeV
m_{π_d}	5 GeV	2 GeV
$c\tau_{\pi_d}$	150 mm	5 mm

Cut Efficiencies

Signal

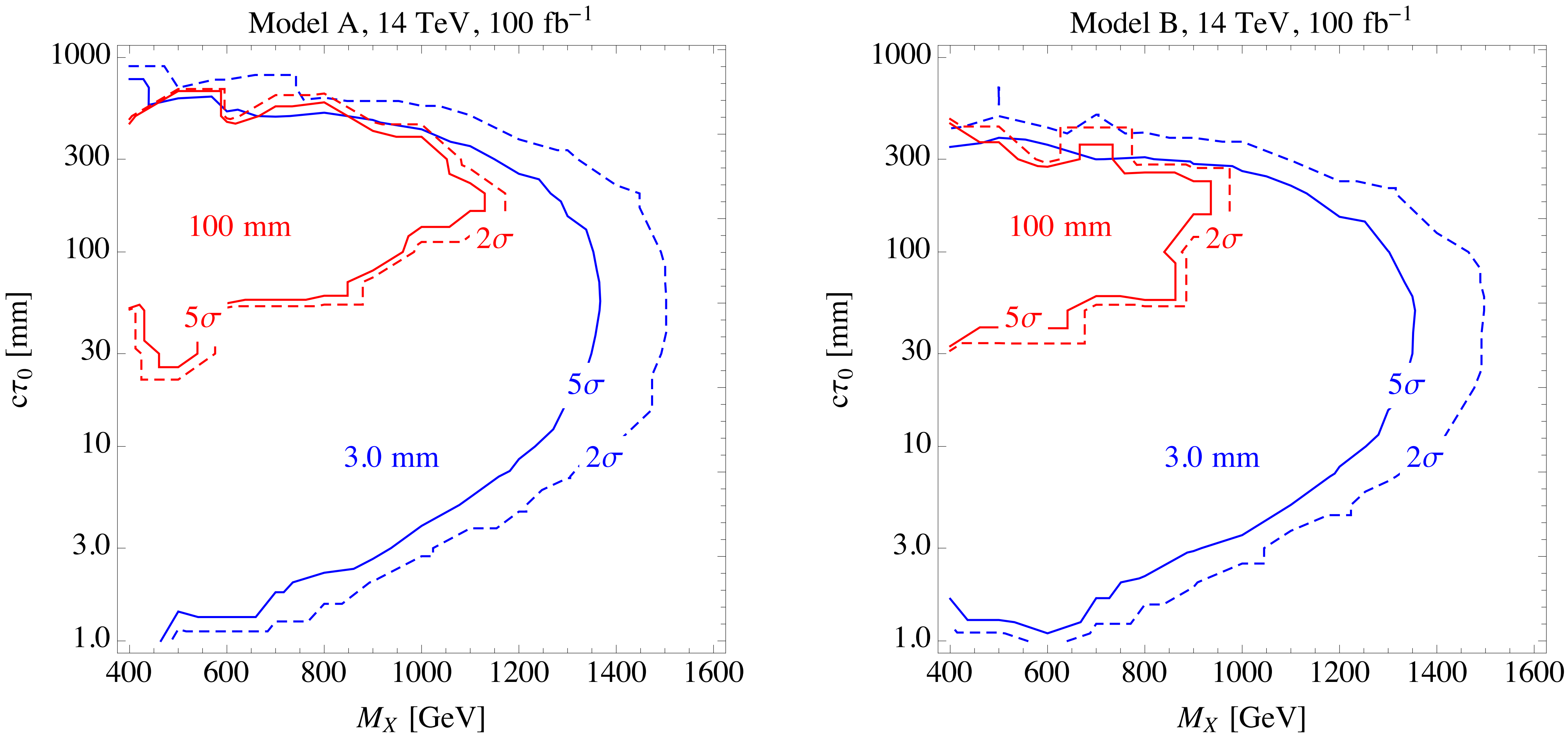


Background



- Factor 1000^2 improved S/B compared to ordinary 4-jet search

Reach ATLAS/CMS

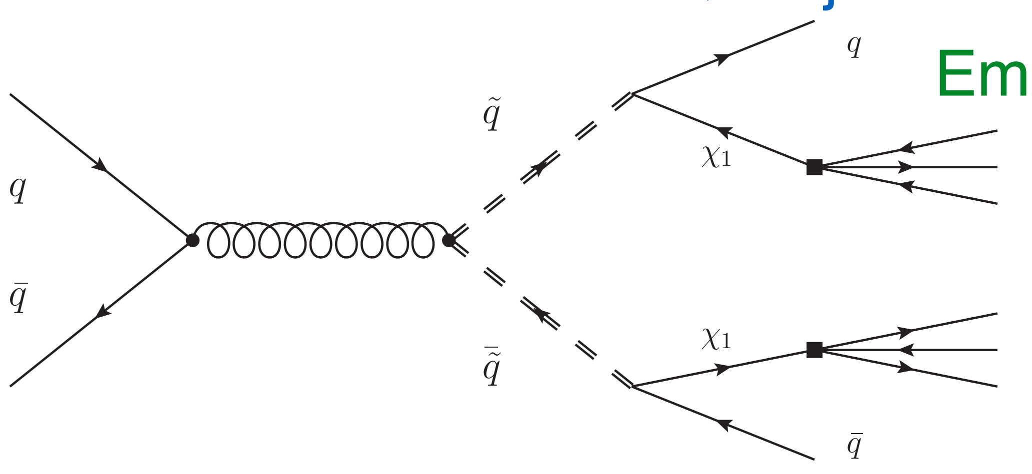


- More realistic studies under way at CMS
- Will also catch some displaced vertex & SIMP signals, possibly photon jets

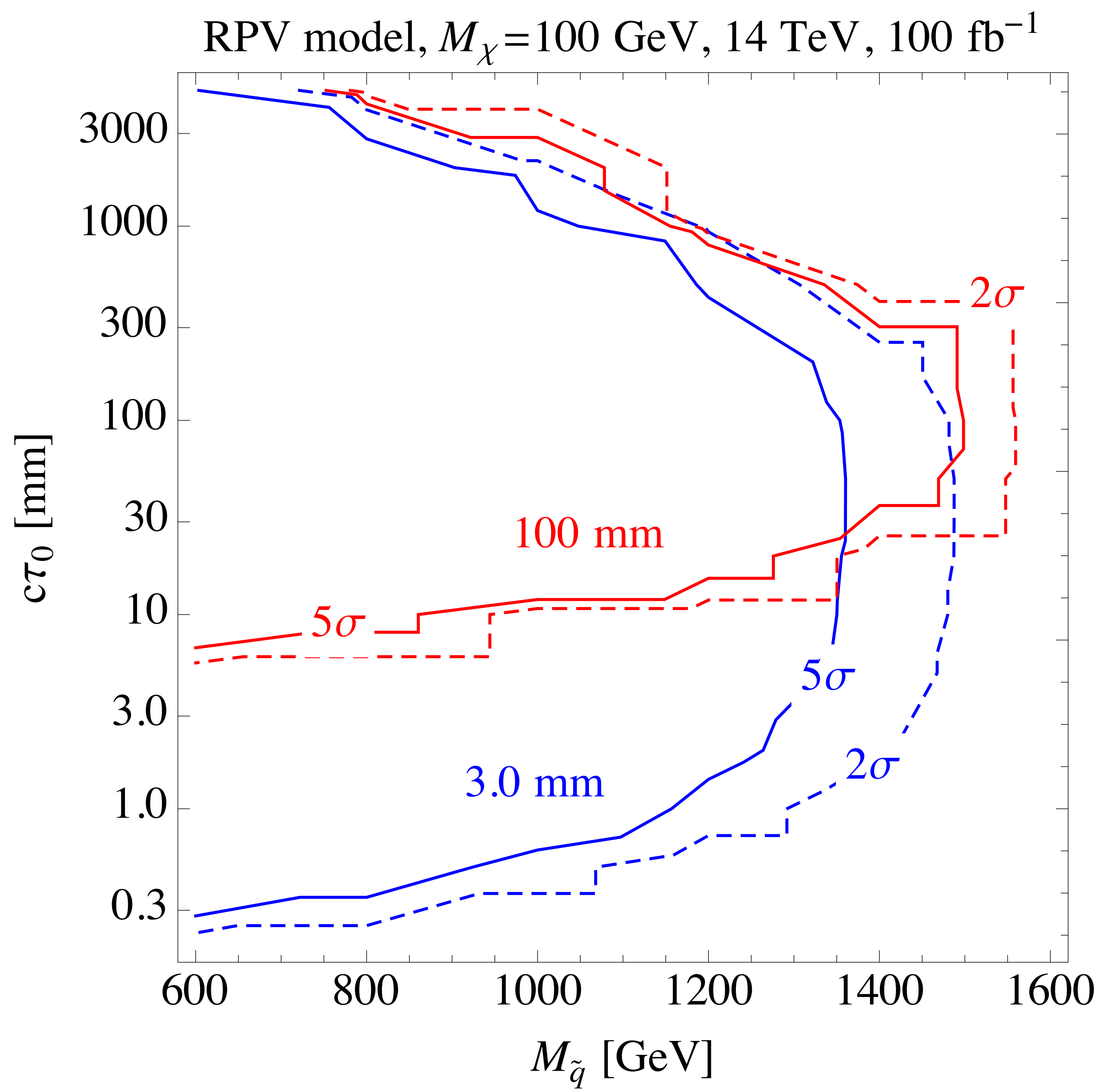
RPV SUSY sensitivity

QCD jet

Emerging jet

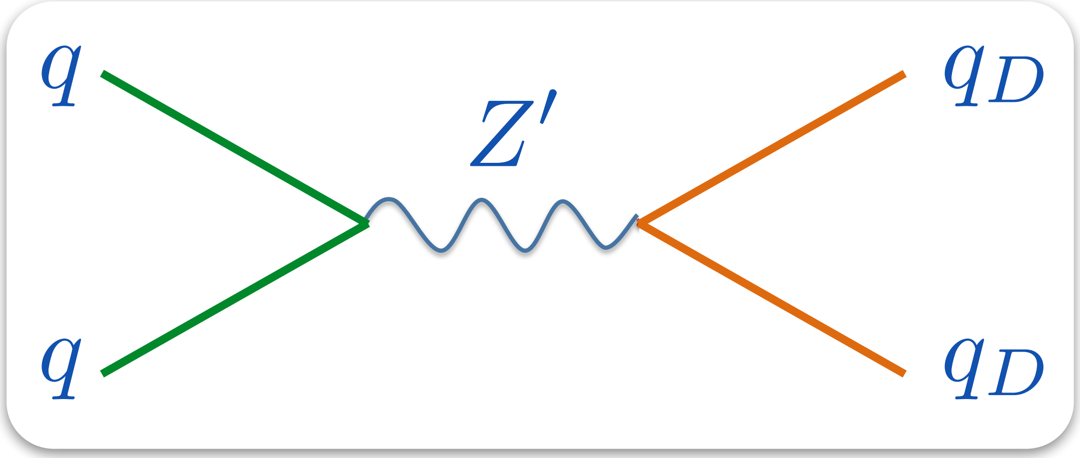


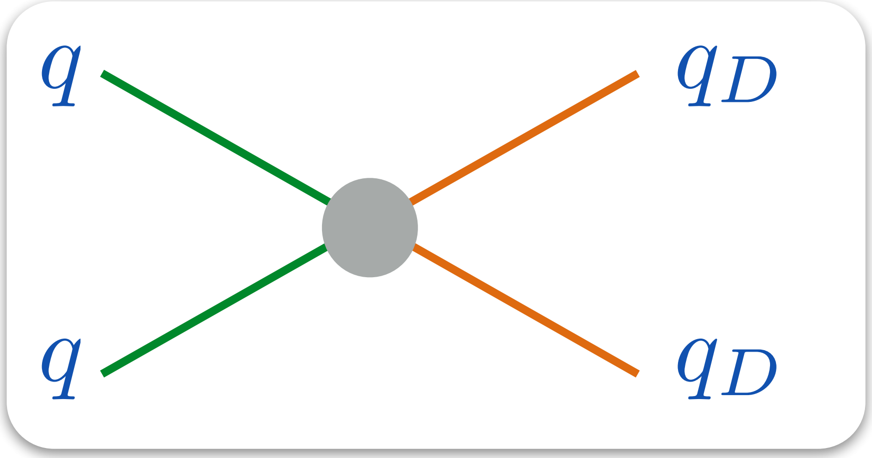
- Competitive with displaced vertex searches
- Less model dependent



LHCb, SHIP, low energy

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



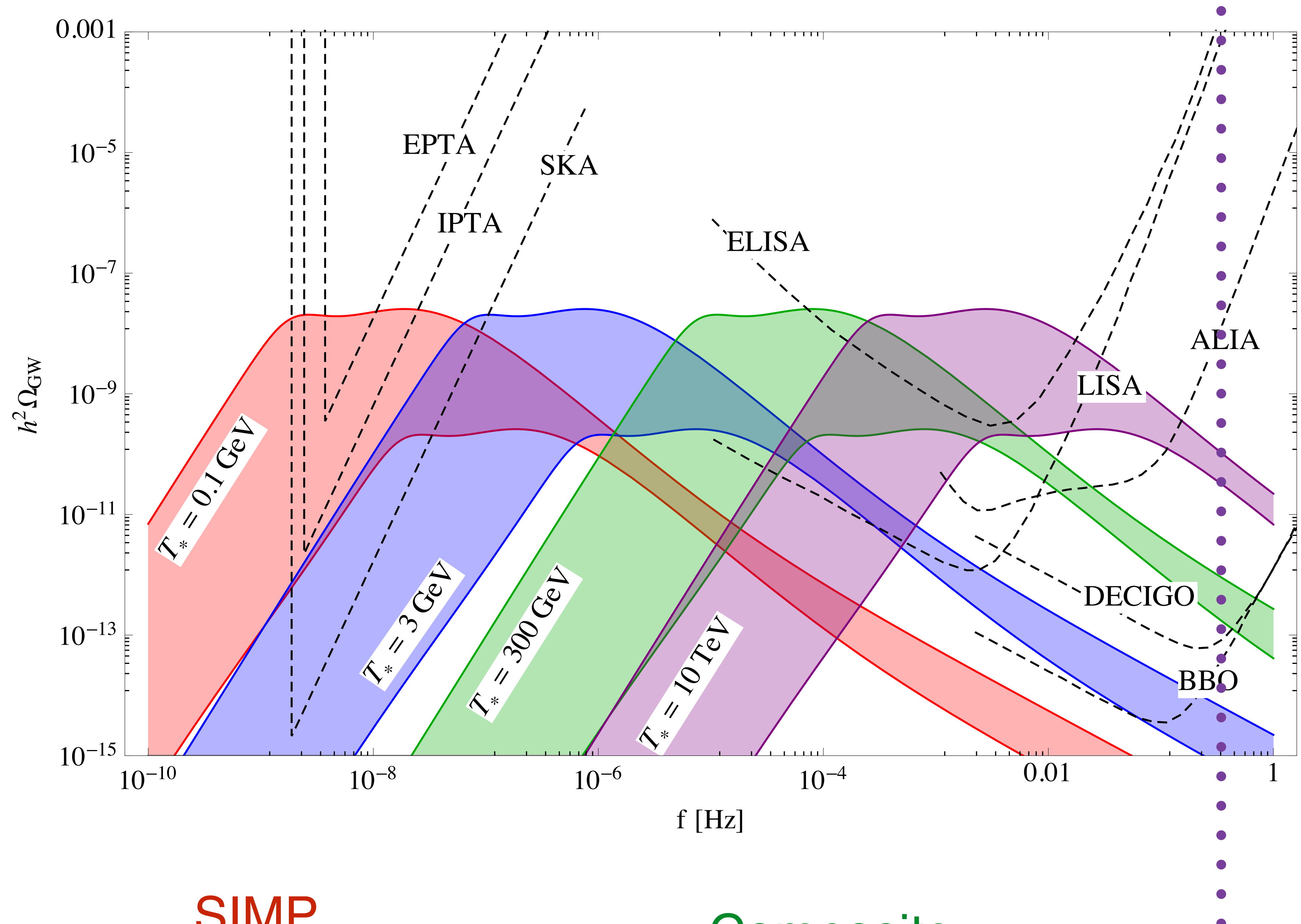


- Reconstruct individual dark pions, differentiate using lifetime, mass, decay products

- Depends on flavour structure → in progress

Gravitational Wave Signal

- Dark QCD PT can be strong first order
- GW signal detectable
- New frontier for DM/dark sector searches!!!



SIMP

Composite ADM
Twin Higgs

Composite
WIMP-y

DM
Unitarity

Summary

- Important to explore DM beyond WIMPs
- QCD like dark sectors appears in many models
- Emerging jets are “smoking gun”, good prospects for ATLAS/CMS
- Can probe TeV scale mediators at LHC, without MET or Leptons
- Gravitational waves are independent probe of dark sector phase transition

Thank You

Supplemental Material

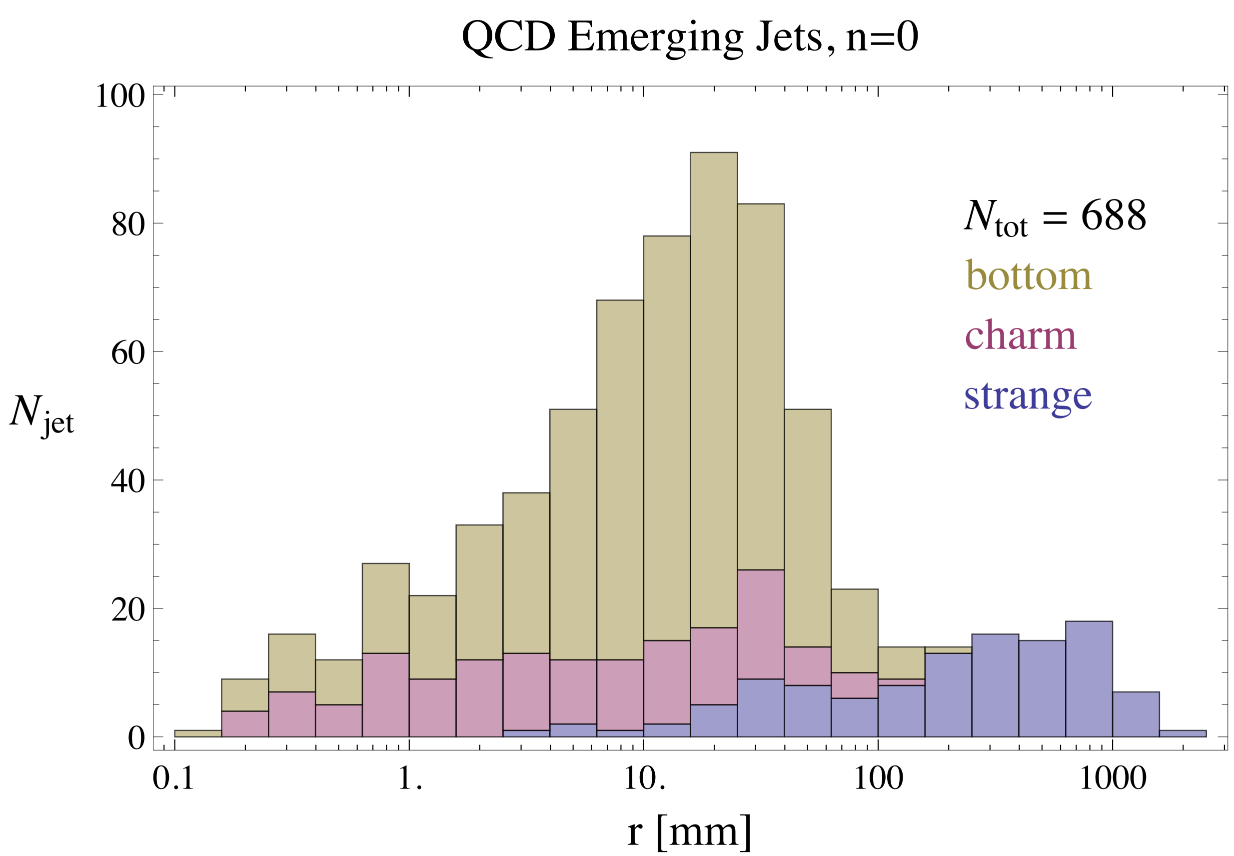
S/B

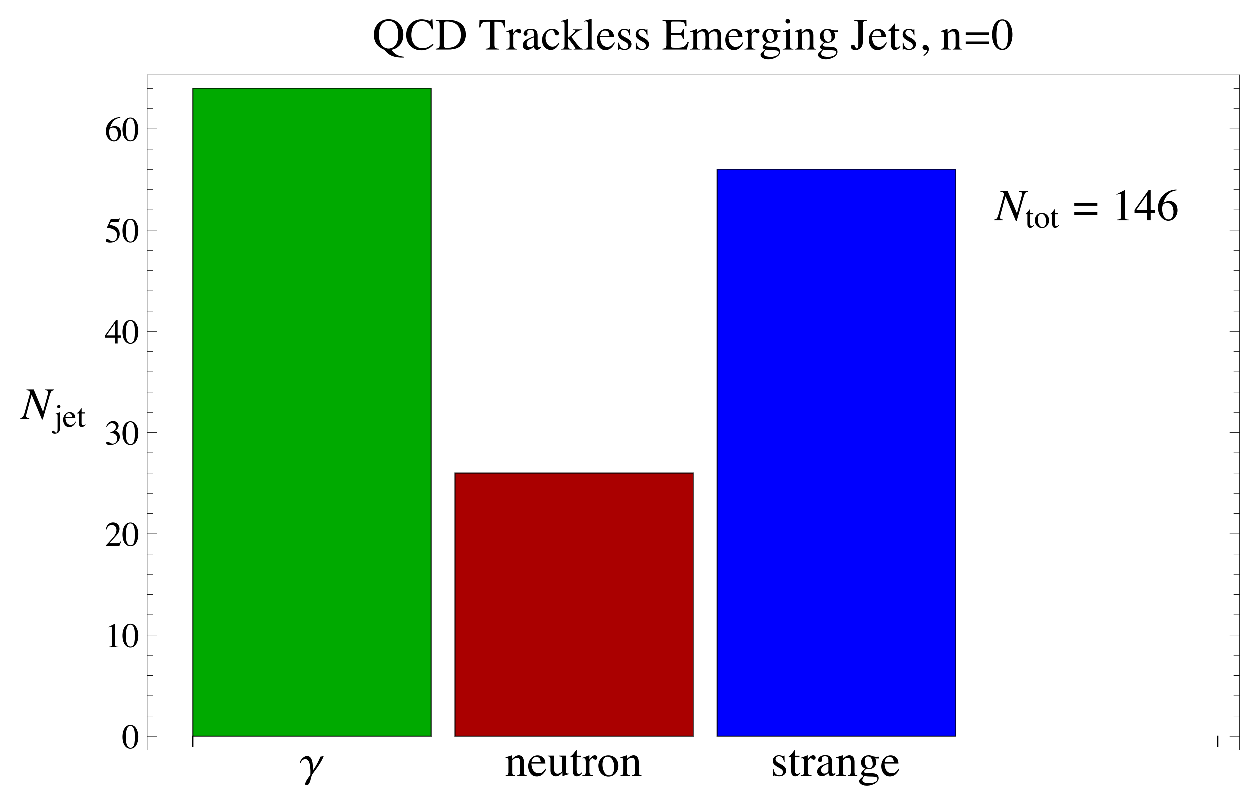
	Model **A**	Model **B**	QCD 4-jet	
Tree level	14.6	14.6	410,000	fb
≥ 4 jets, $\lvert\eta\rvert < 2.5$ $p_T(\text{jet}) > 200$ GeV $H_T > 1000$ GeV	4.9	8.4	48,000	fb
$E(1\,\text{GeV}, 0, 3\,\text{mm}) \geq 1$	4.1	4.1	45	fb
$E(1\,\text{GeV}, 0, 3\,\text{mm}) \geq 2$	1.8	0.8	~ 0.08	fb
$E(1\,\text{GeV}, 0, 100\,\text{mm}) \geq 1$	1.7	$\lesssim 0.01$	8.5	fb
$E(1\,\text{GeV}, 0, 100\,\text{mm}) \geq 2$	0.2	$\lesssim 0.01$	$\lesssim 0.02$	fb

- Can still add paired di-jet cuts
- Will also catch some displaced vertex & SIMP signals, possibly photon jets

Composition of QCD backgrounds

- QCD jets with $p_{T,j} > 200\ \text{GeV}$





Track(s) appears at distance *r*
Flavour of long lived state

Purely trackless jets
identity of hardest particle

Check dark shower w/ meson multiplicity

e.g. Ellis, Stirling, Webber

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

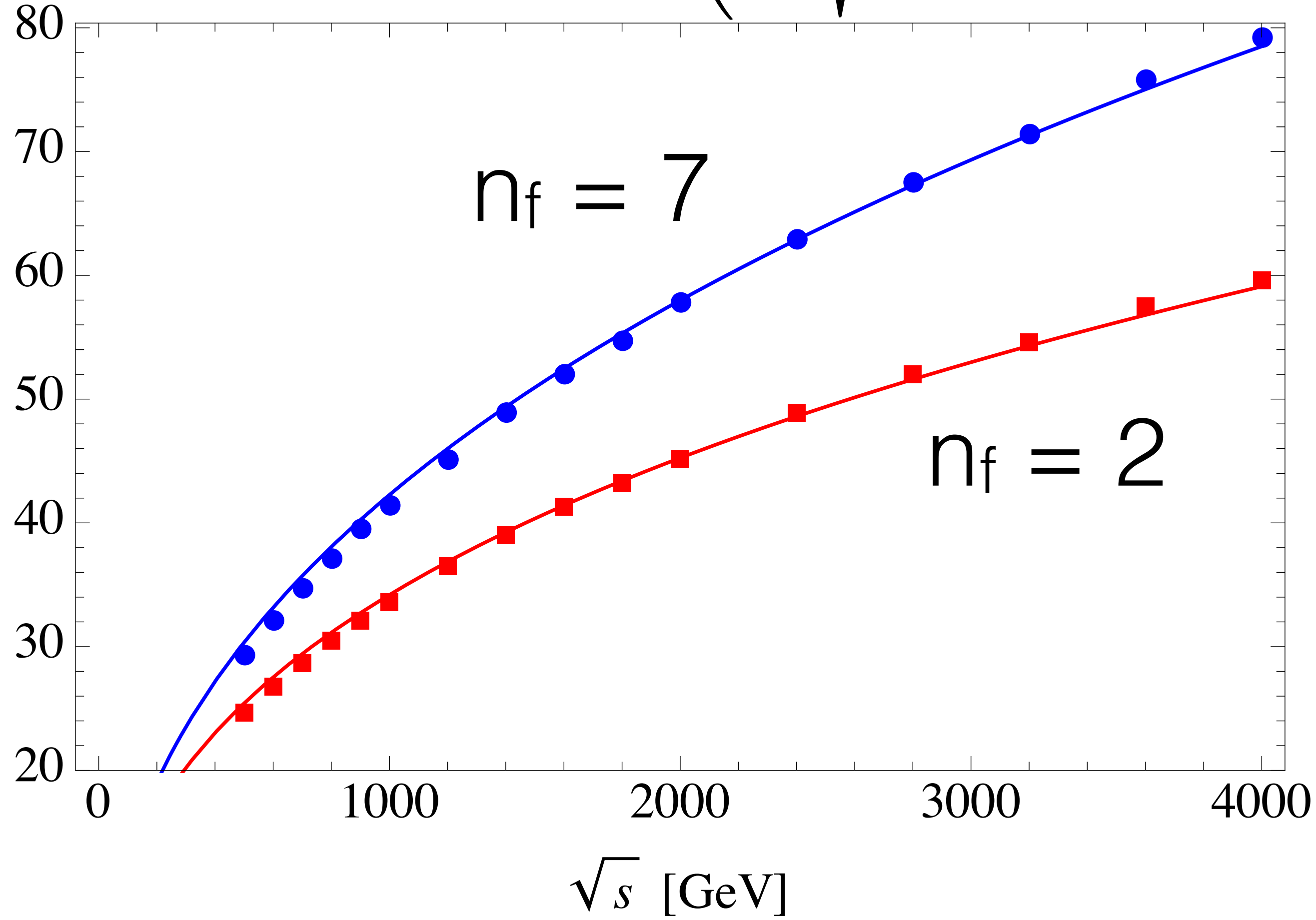
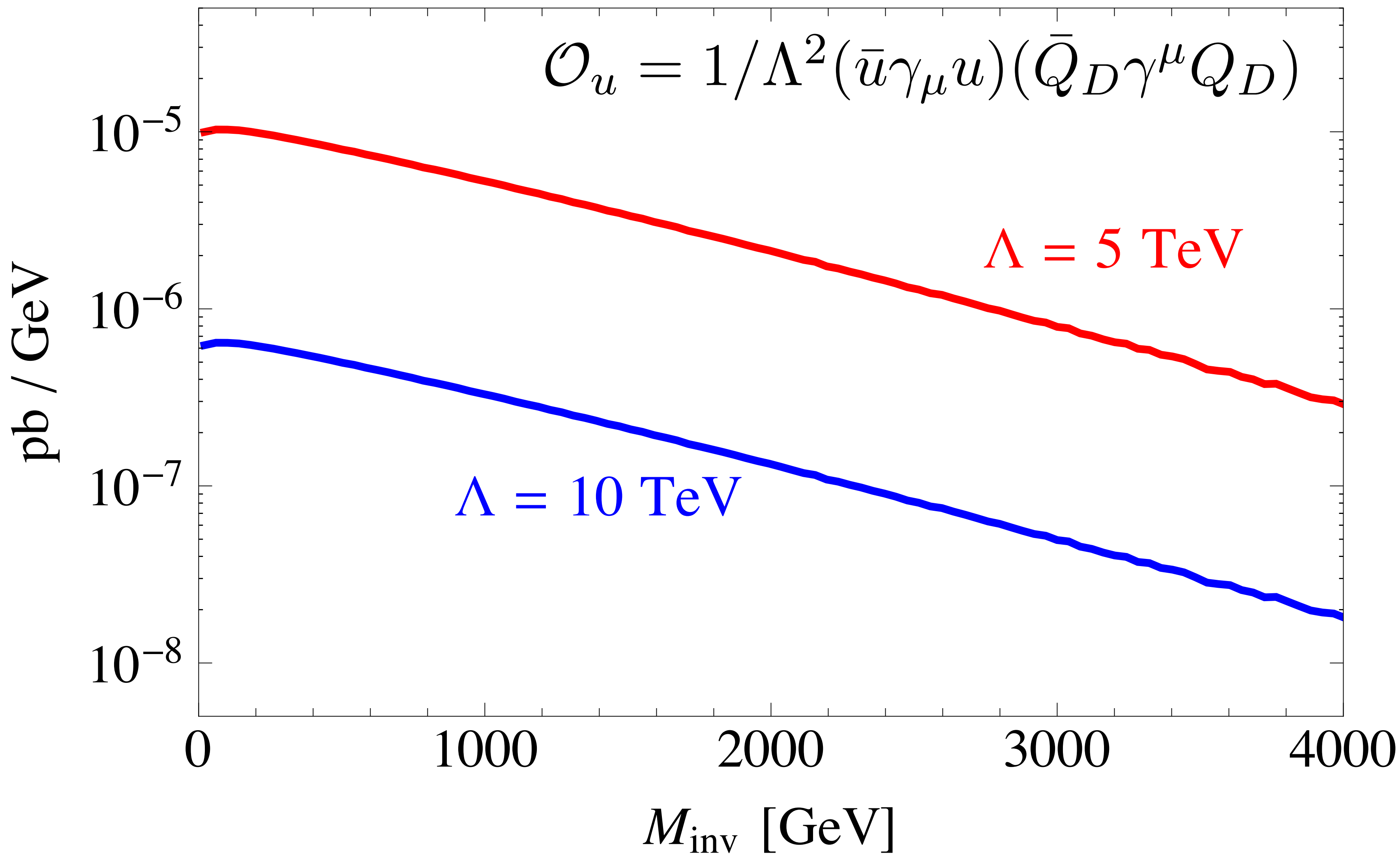


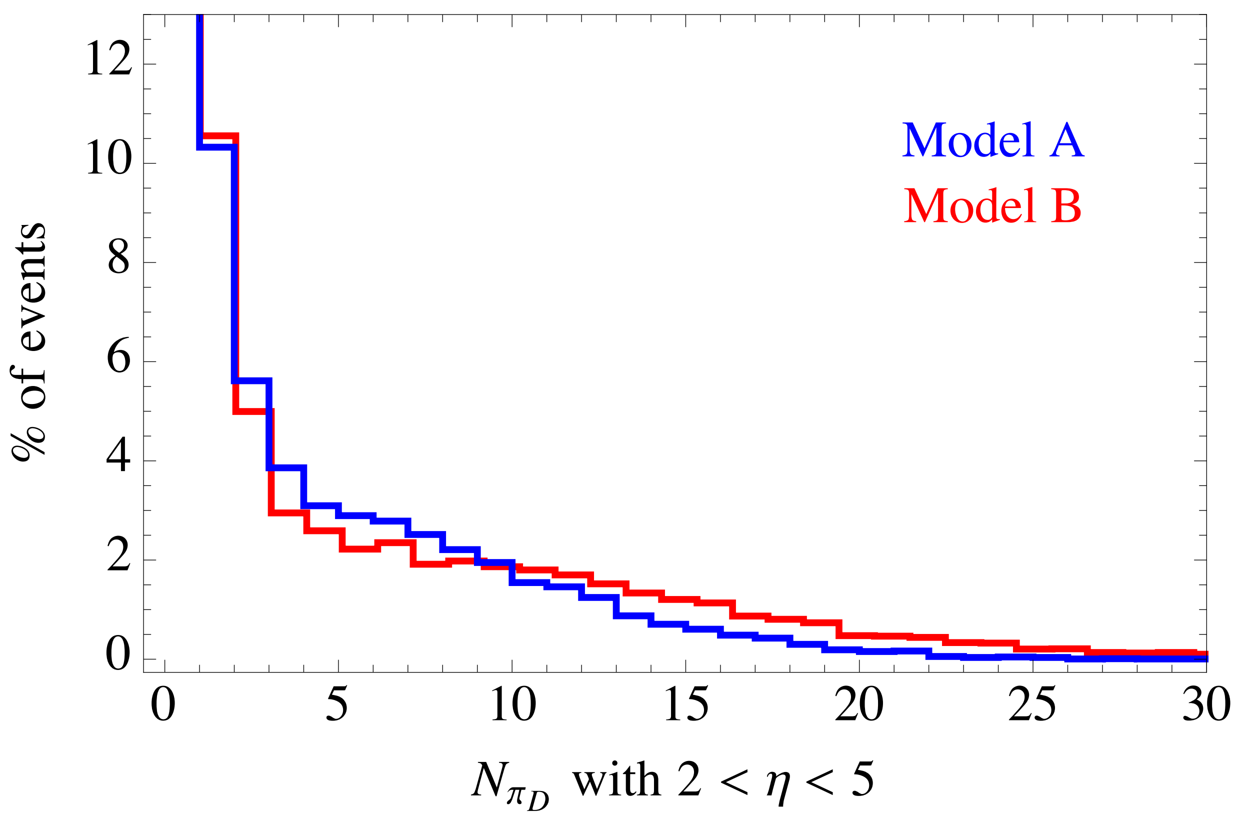
Figure 11: Average dark meson multiplicity in $e^+e^- \to Z'^* \to \bar{Q}_d Q_d$ as a function of the centre-of-mass energy $\sqrt{s}$. We compare the output of the modified PYTHIA implementation for $n_f = 7$ (blue circles) and $n_f = 2$ (red squares) to the theory prediction Eqn. (15), where we only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

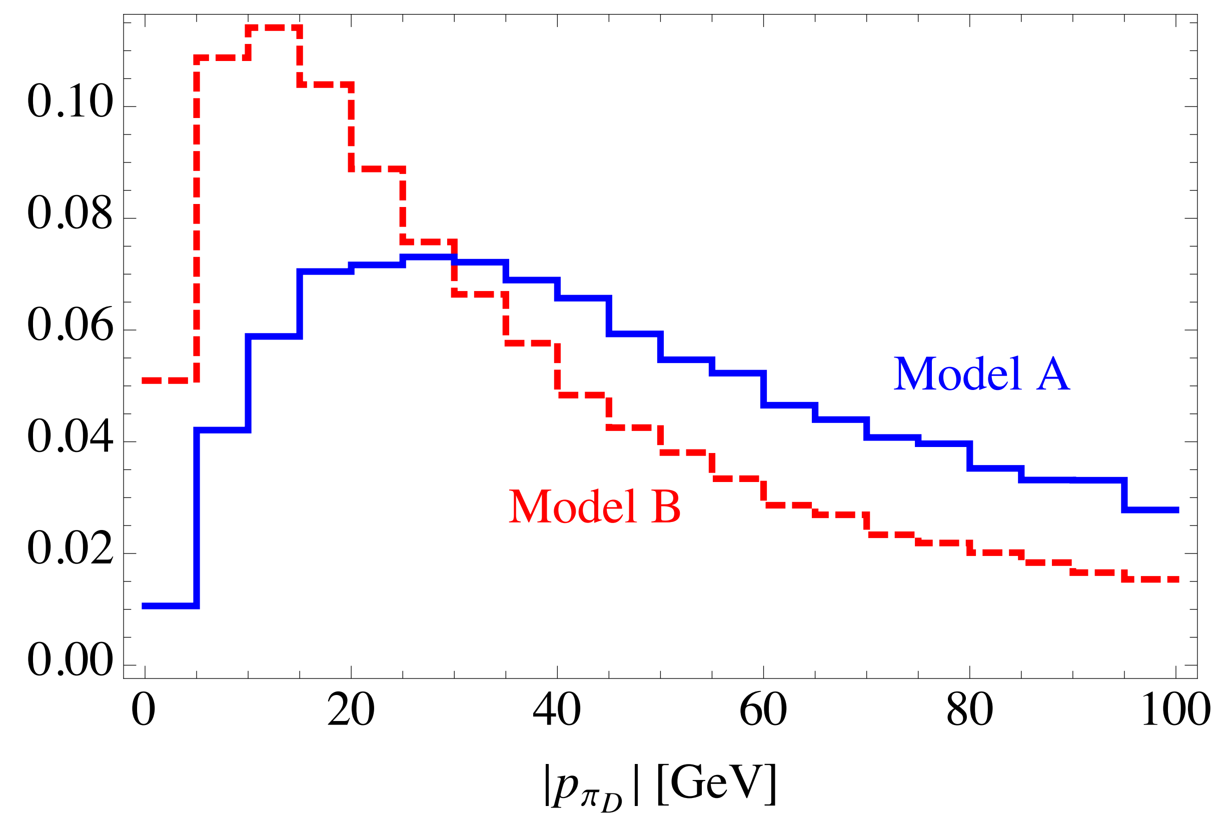
Off-shell production



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

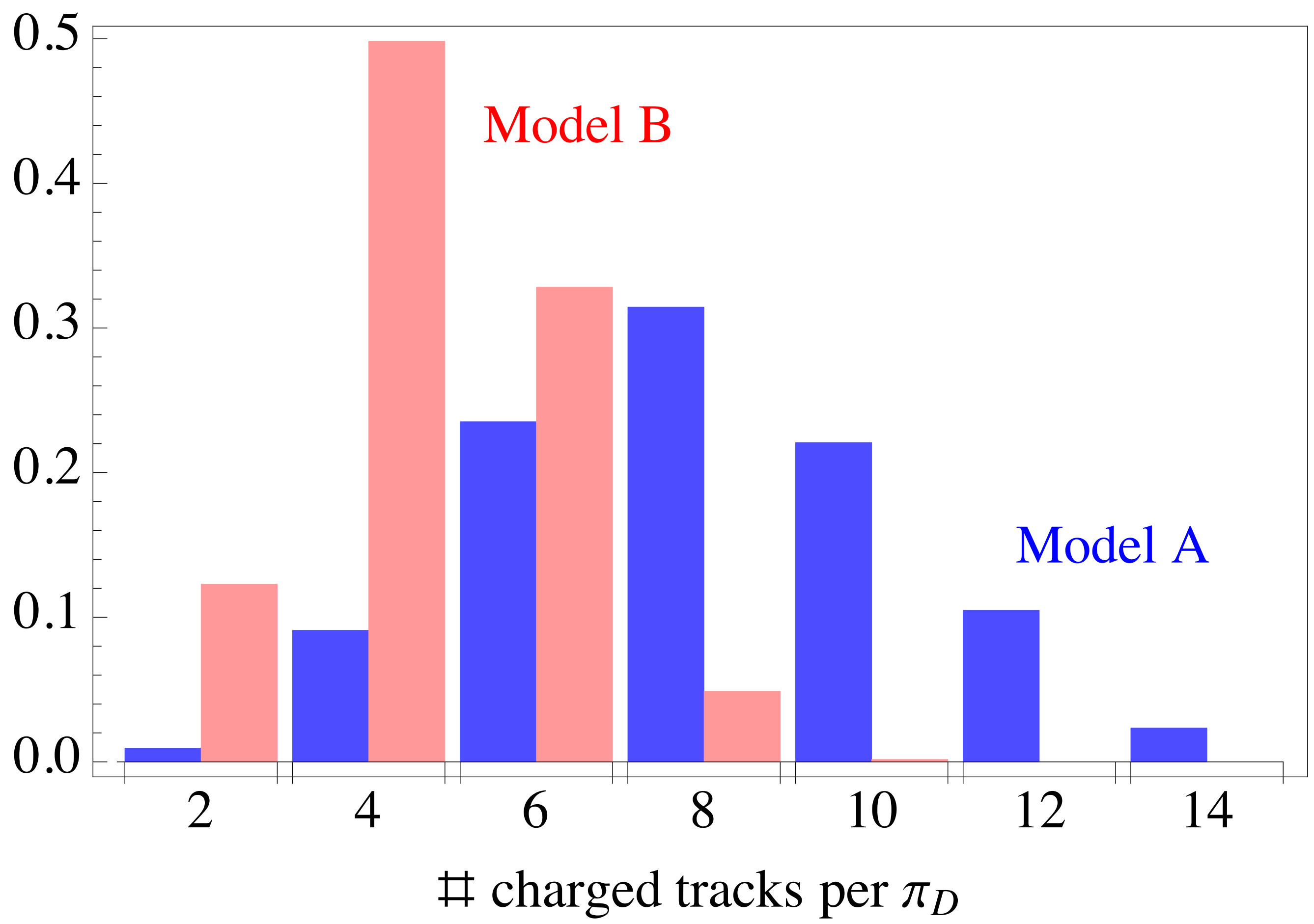
Forward region





- 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!

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