Emerging Jets

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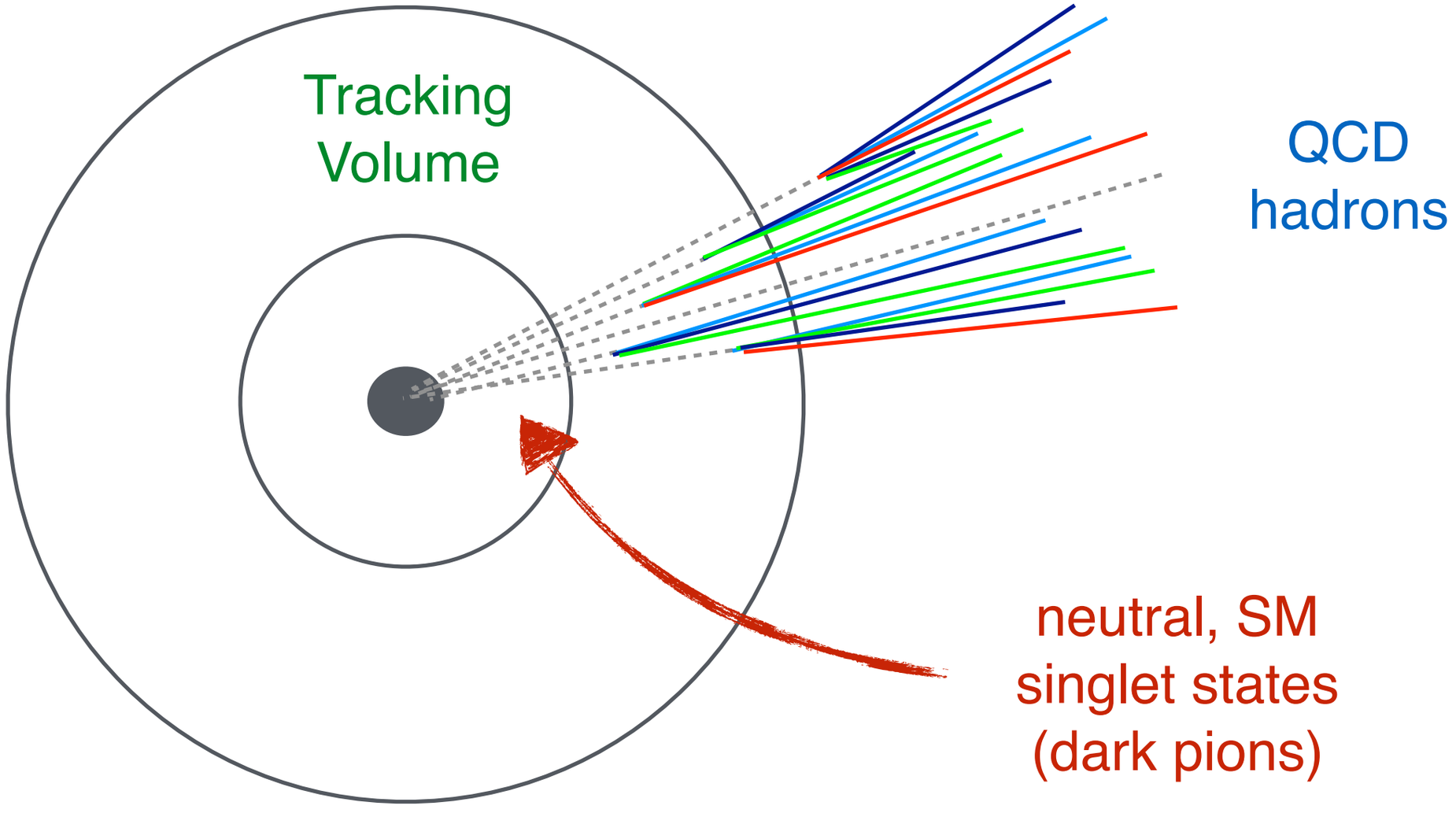
BOOST 2015
University of Chicago
12/8/15

Based on:
PS, Stolarski, Weiler, JHEP 1515 (2015)

What is an Emerging Jet?



What is an Emerging Jet?

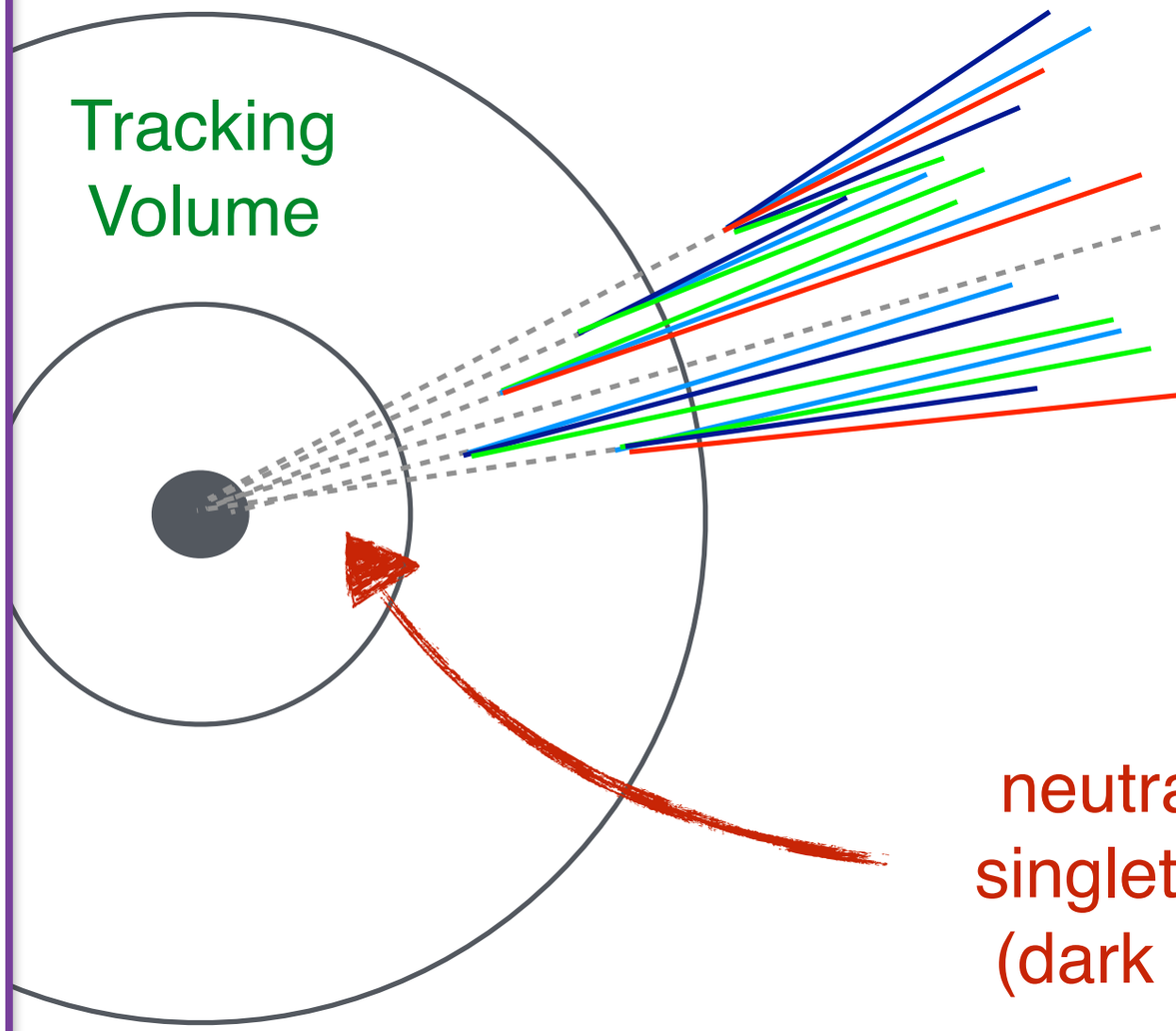
Possible origin:

Hidden sector with confining SU(N) gauge interactions

“dark QCD”

Bai, PS, PRD 2014
PS, Stolarksi, Weiler, JHEP 2015

Also in “Hidden Valleys”
Strassler, Zurek, 2006,2007
Han, Strassler, Zurek, 2007



Outline

- Why Emerging Jets
- Search Strategies
- Dark QCD and substructure

Dark QCD

- (Asymmetric) Dark Matter
  - Stability (dark baryon), relic density $\Omega_{\rm DM} \approx n_{\rm B} M_{\rm DM}$
  - Self interactions (small scale structure)
  - Efficient annihilation $p_D \bar{p}_D \to \pi_D \pi_D$
- Naturalness
  - Twin Higgs (top partners w/ dark color)
  - Relaxion (dark axion potential from dark QCD)

Dark QCD II

- DM/Naturalness motivates $\Lambda_{\rm Dark} \sim$ few GeV
  - e.g. $\dfrac{\Omega_{\rm DM}}{\Omega_{\rm B}} \sim \dfrac{M_{\rm DM}}{M_{\rm B}}$
- Dark pion lifetime possibly macroscopic

$$c\tau(\pi_D \to \mathrm{SM}) \sim \frac{M_X^4}{m_{\pi_D}^5} \sim \mathrm{cm} \times \left(\frac{\mathrm{M_X}}{\mathrm{TeV}}\right)^4 \left(\frac{\mathrm{GeV}}{\mathrm{m_{\pi_D}}}\right)^5$$

Also:

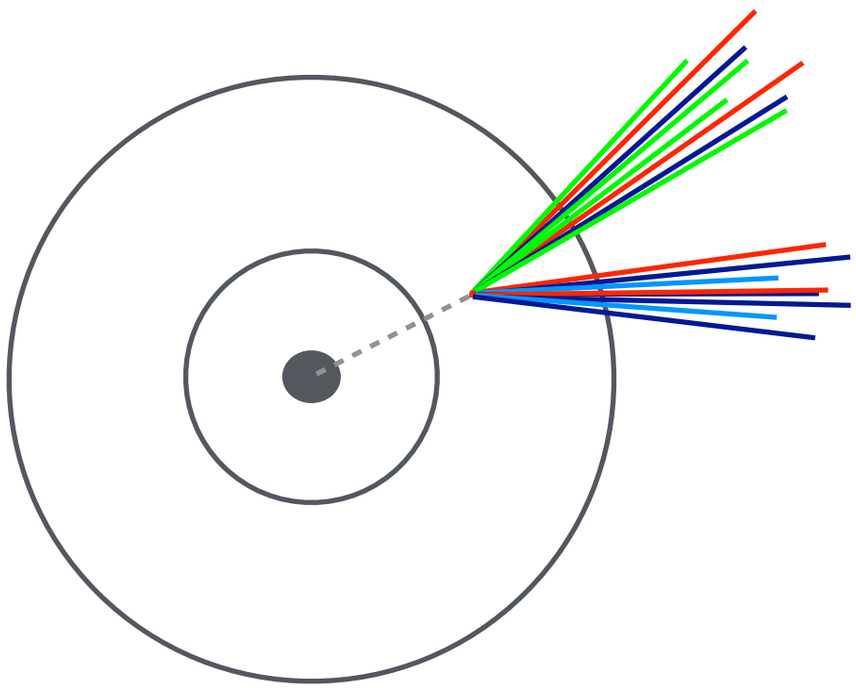
Important to close gap between prompt (multi-jet) and long lived (MET) searches for new physics

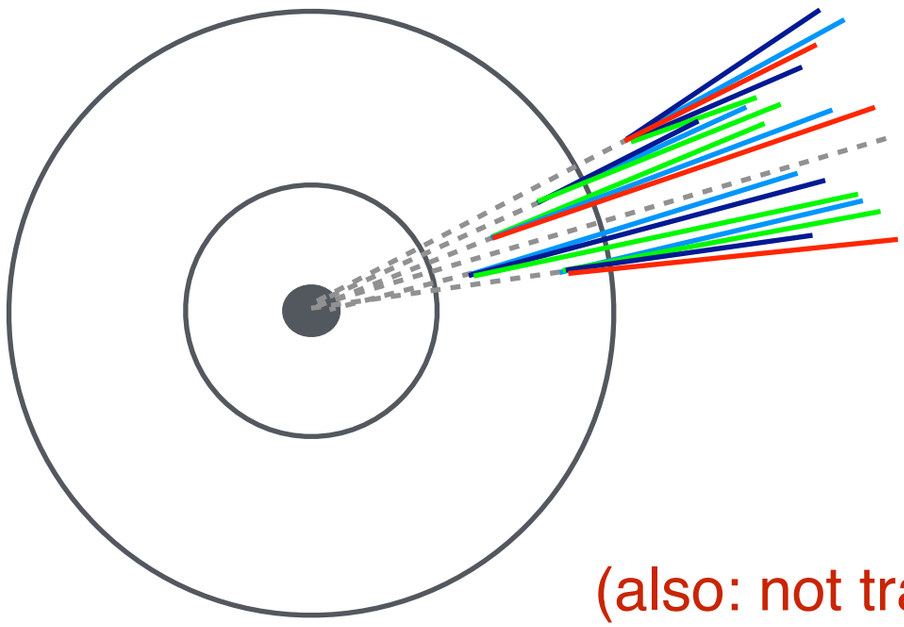
Should we have seen this already?

- 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





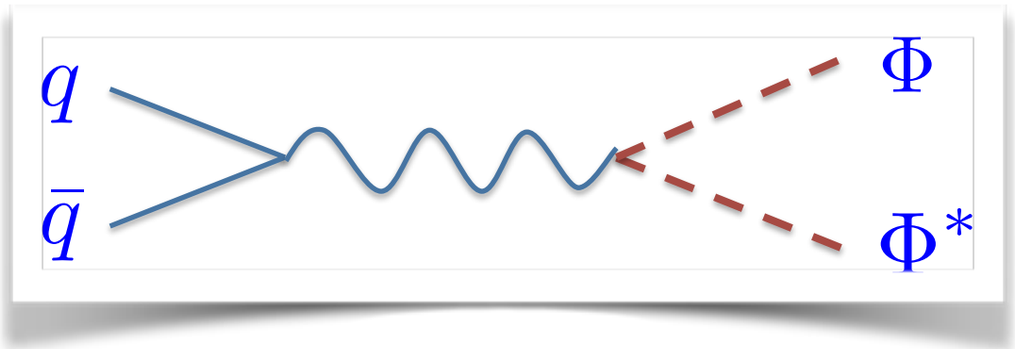
(also: not trackless!)

Model

- Mediators:
  - Bifundamental scalar Φ $\quad \mathcal{L} \supset \kappa \Phi \bar{Q}_D d_R$
  - or Z' (Hidden Valleys!)

$$\mathcal{L} \supset g' \bar{Q}_D \gamma^\mu Q_D Z'_\mu + \text{couplings to SM}$$

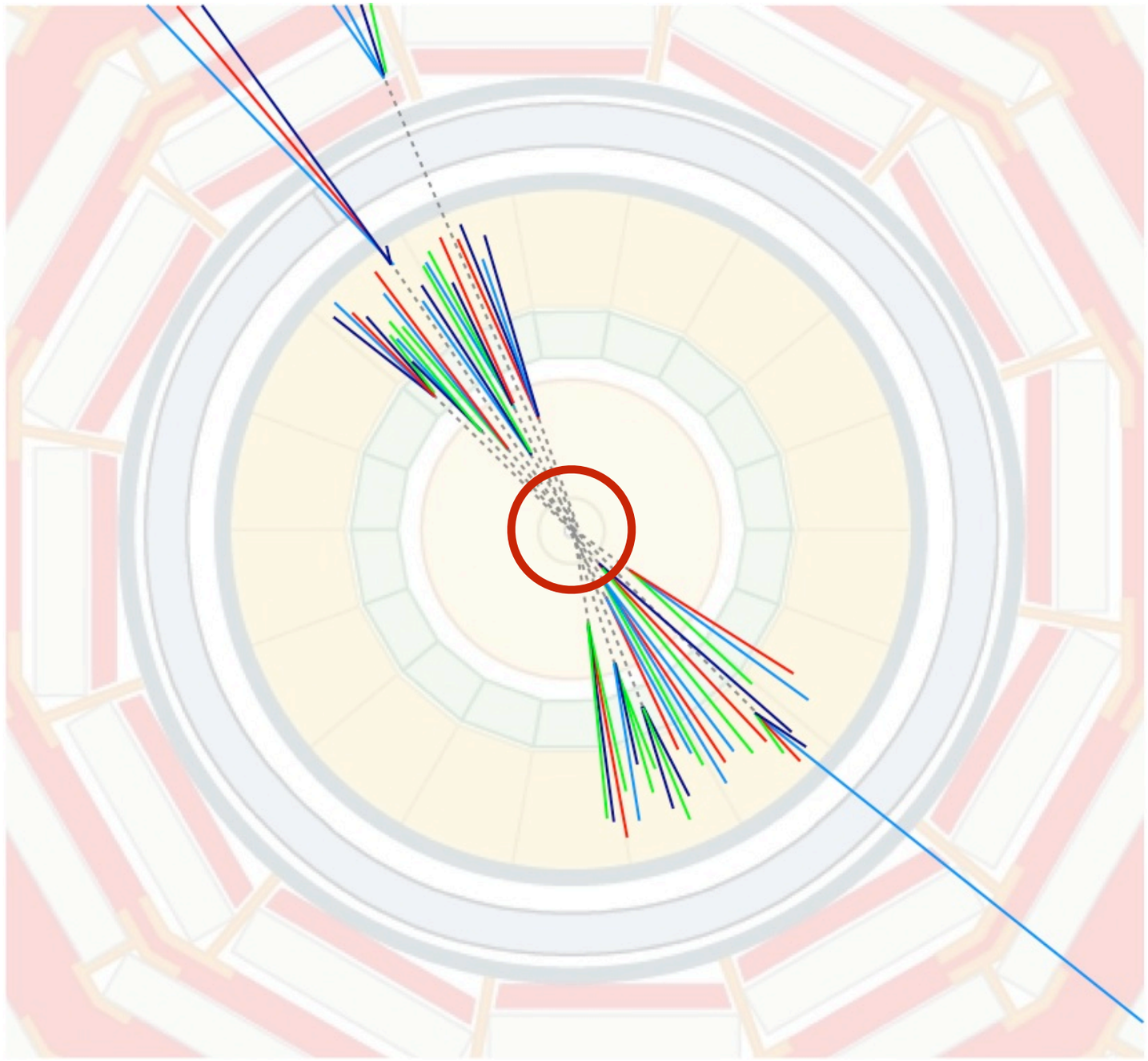
- Pair production of heavy bi-fundamental fields:



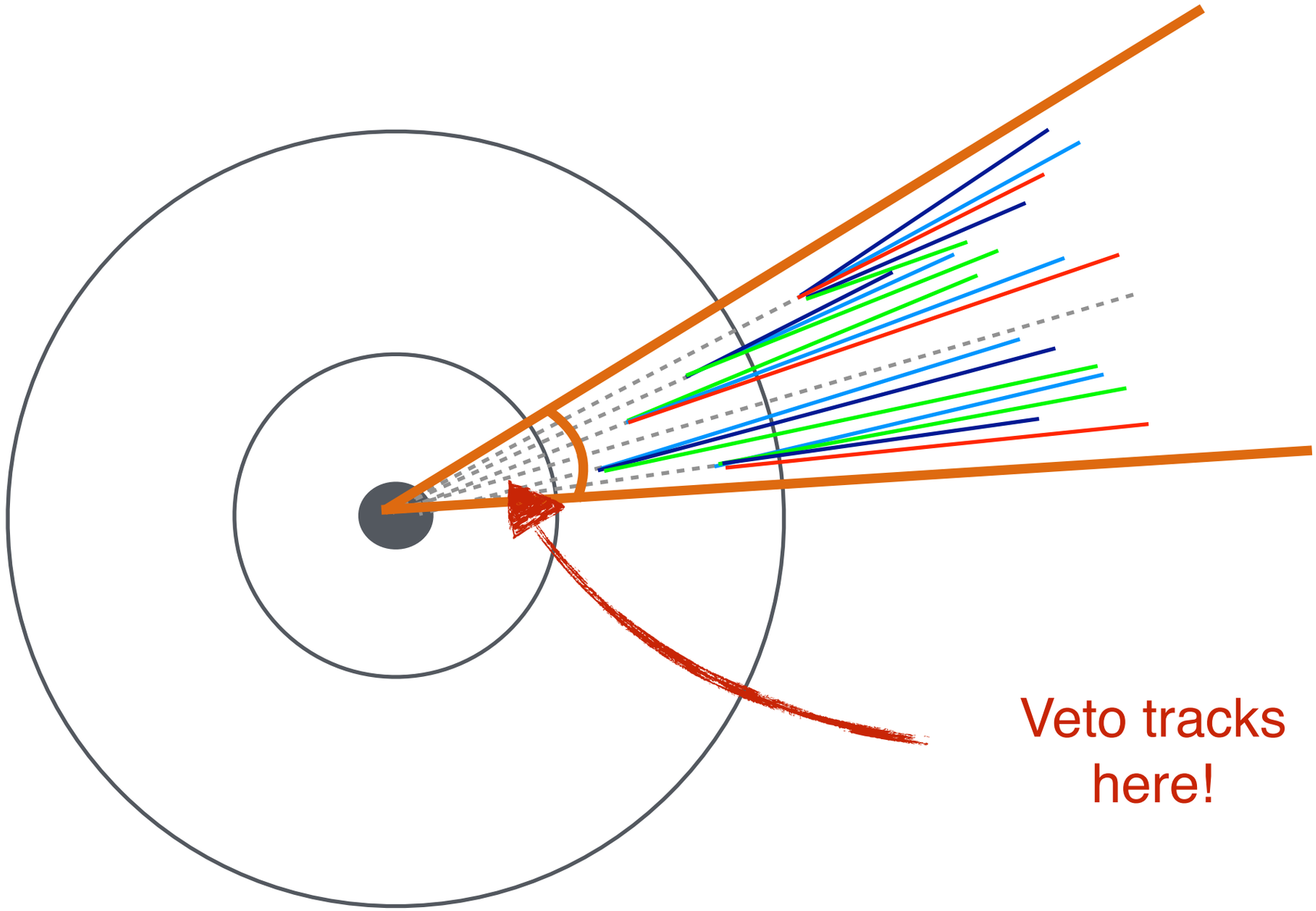
- Decay to quark - dark quark pairs: Two QCD jets, two Emerging Jets

Emerging Jets at the LHC

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



Strategy



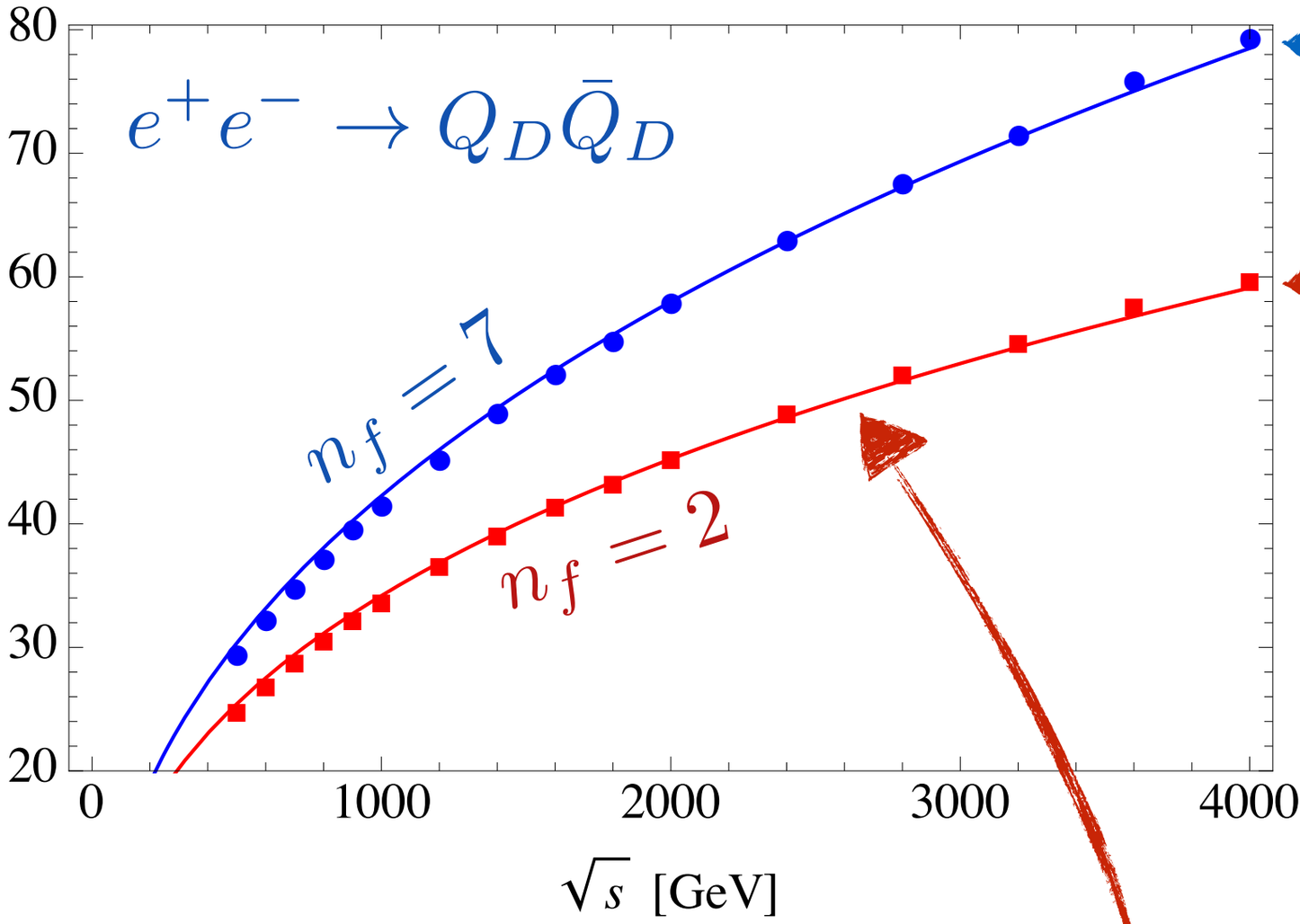
Benchmark Signal/Strategy

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

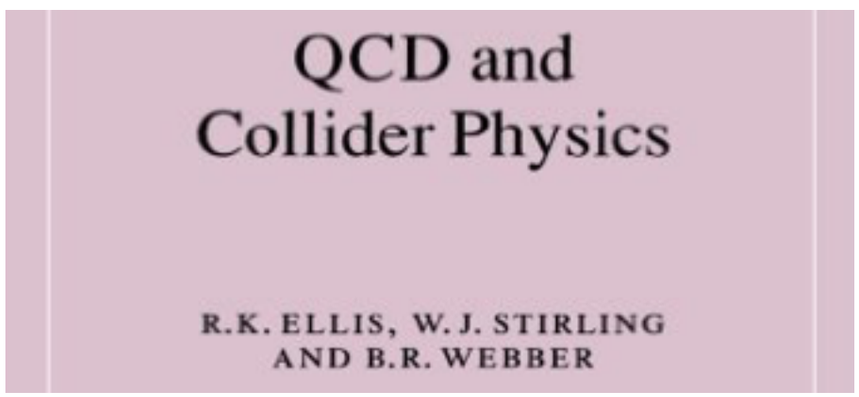
Dark Shower

dark meson multi-plicities



Pythia 8

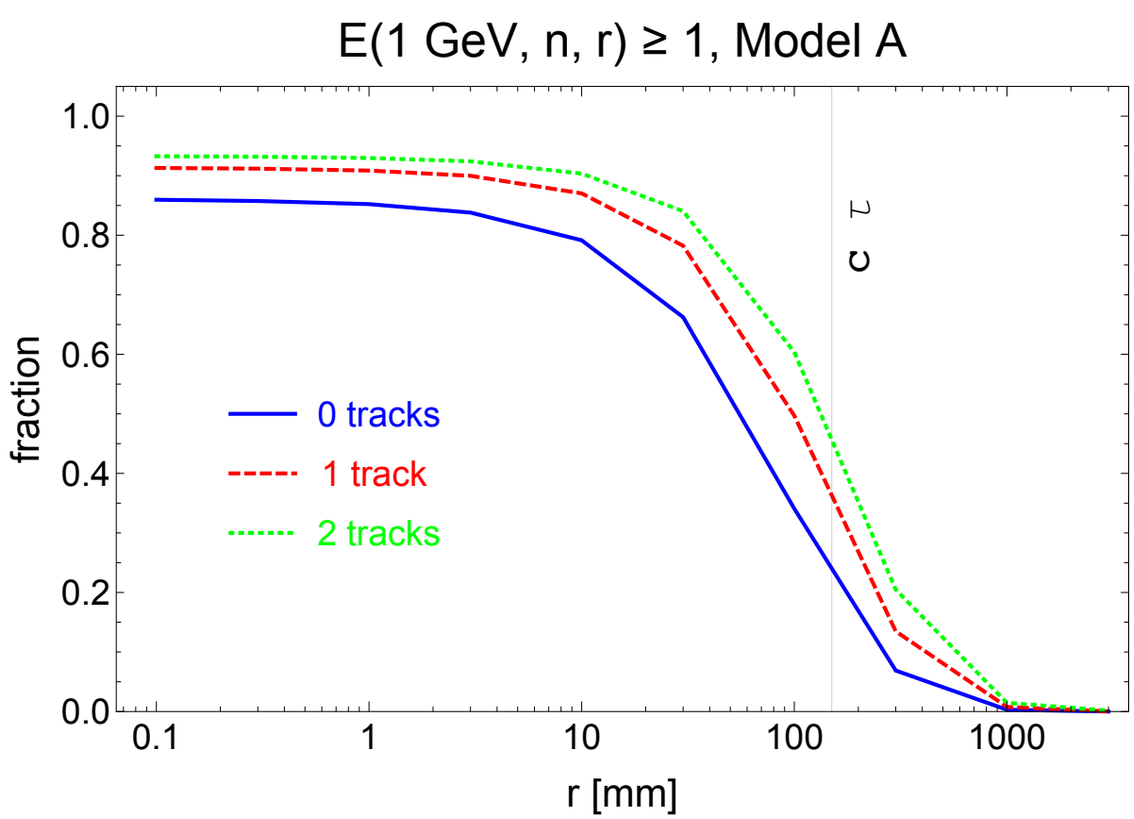
Carloni, Sjostrand, 2010
+ modifications
github.com/pedroschwaller/EmergingJets



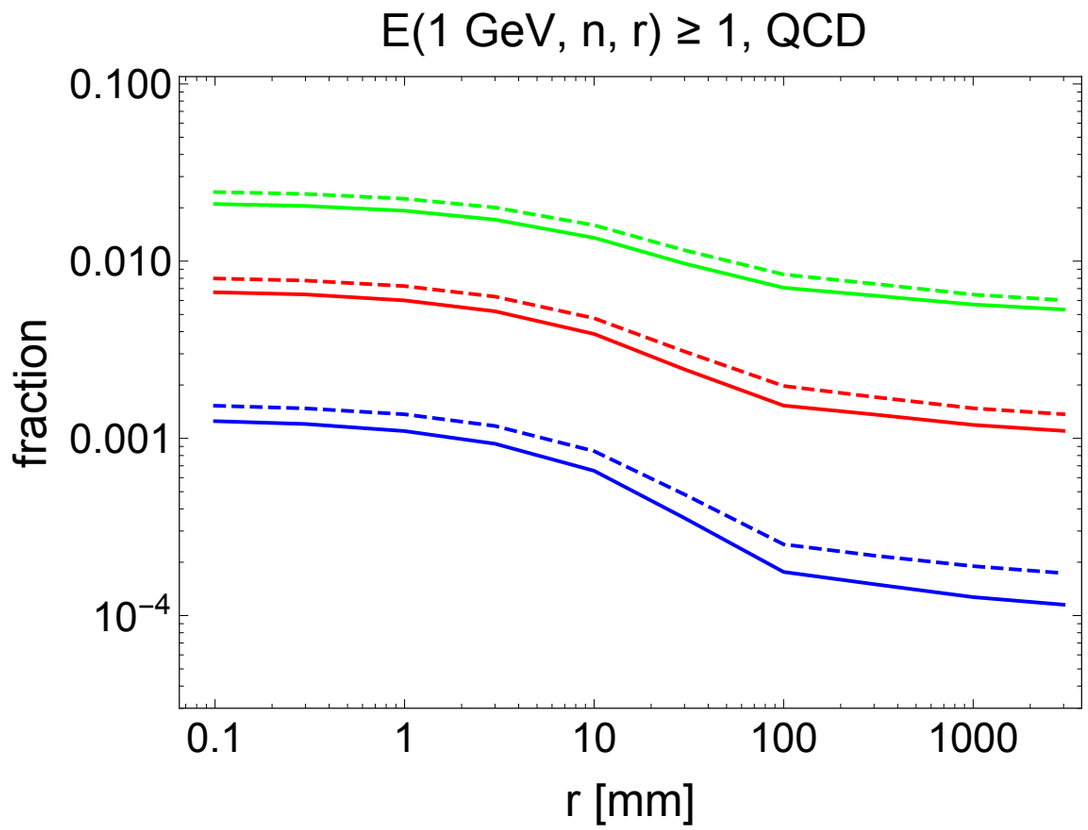
$$\langle N(\hat{s})\rangle \propto \exp\left(\frac{1}{b_1}\sqrt{\frac{6}{\pi\alpha_s(\hat{s})}} + \left(\frac{1}{4} + \frac{5n_f}{54\pi b_1}\right)\log\alpha_s(\hat{s})\right)$$

Cut Efficiencies

Signal



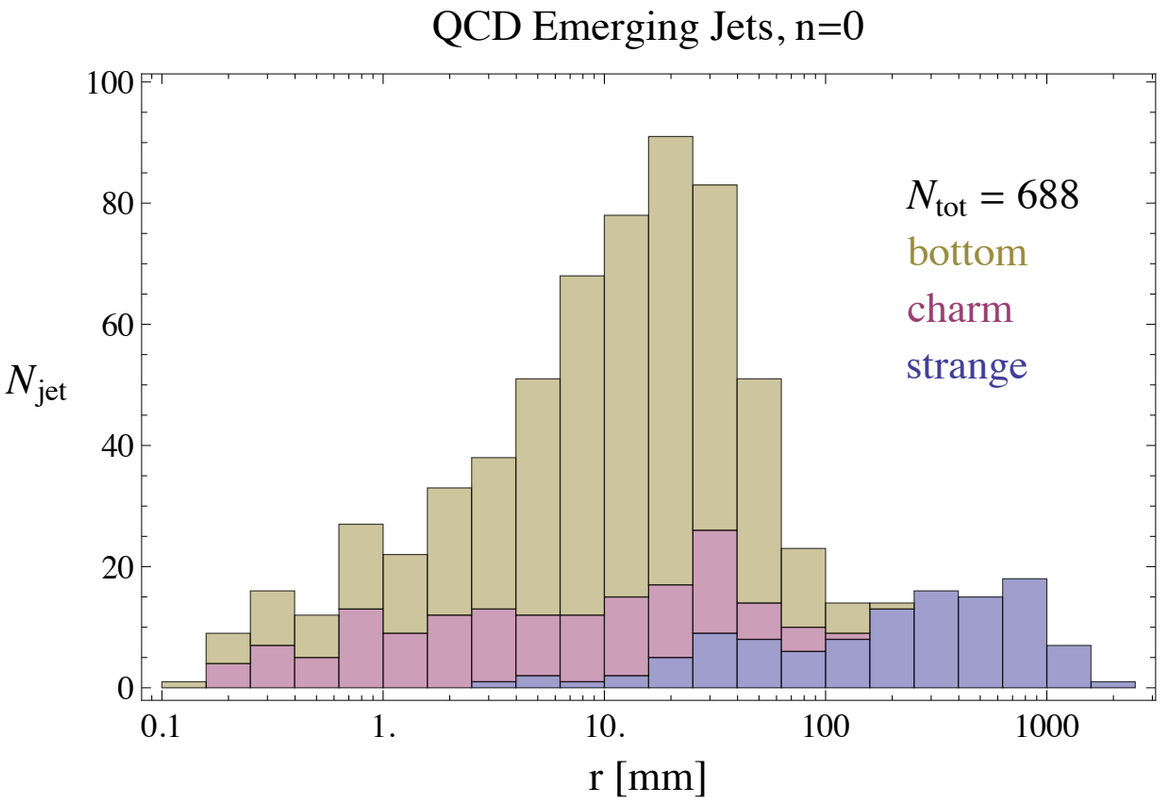
Background



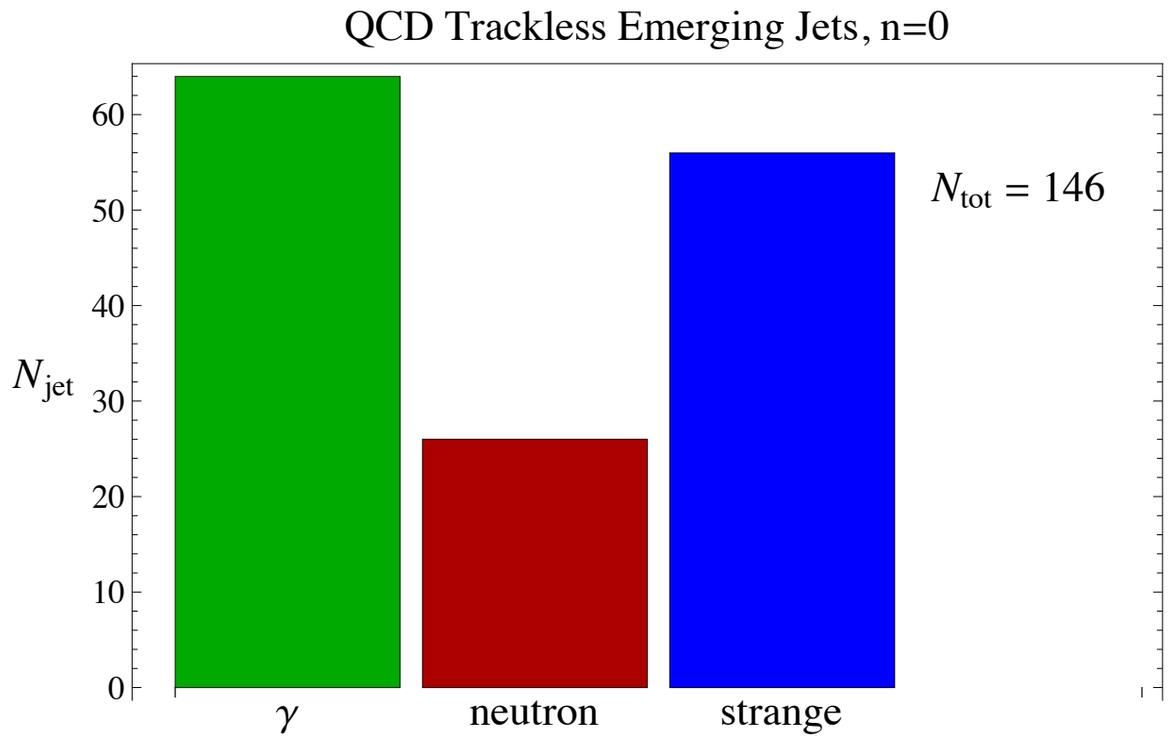
- Factor 100-1000 improved S/B per jet, compared to ordinary 4-jet search

Composition of QCD backgrounds

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



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



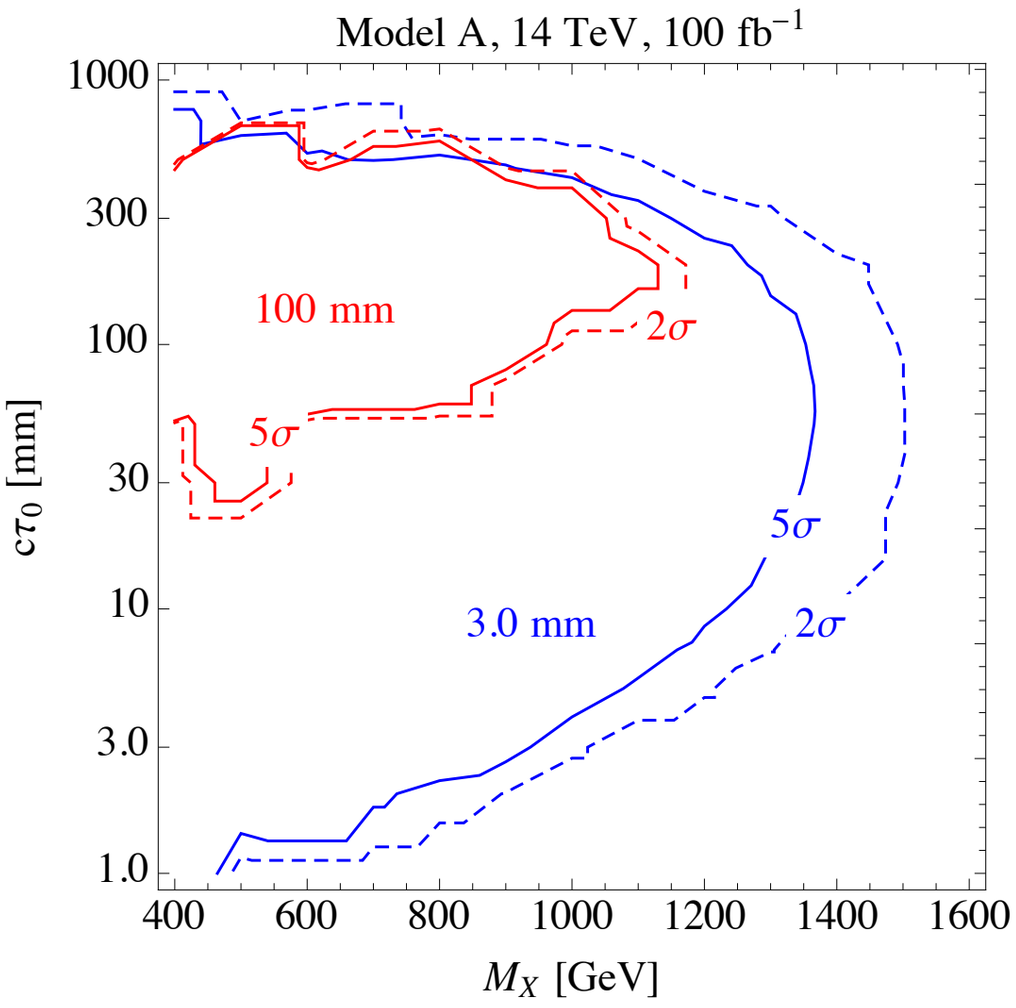
Purely trackless jets
identity of hardest particle

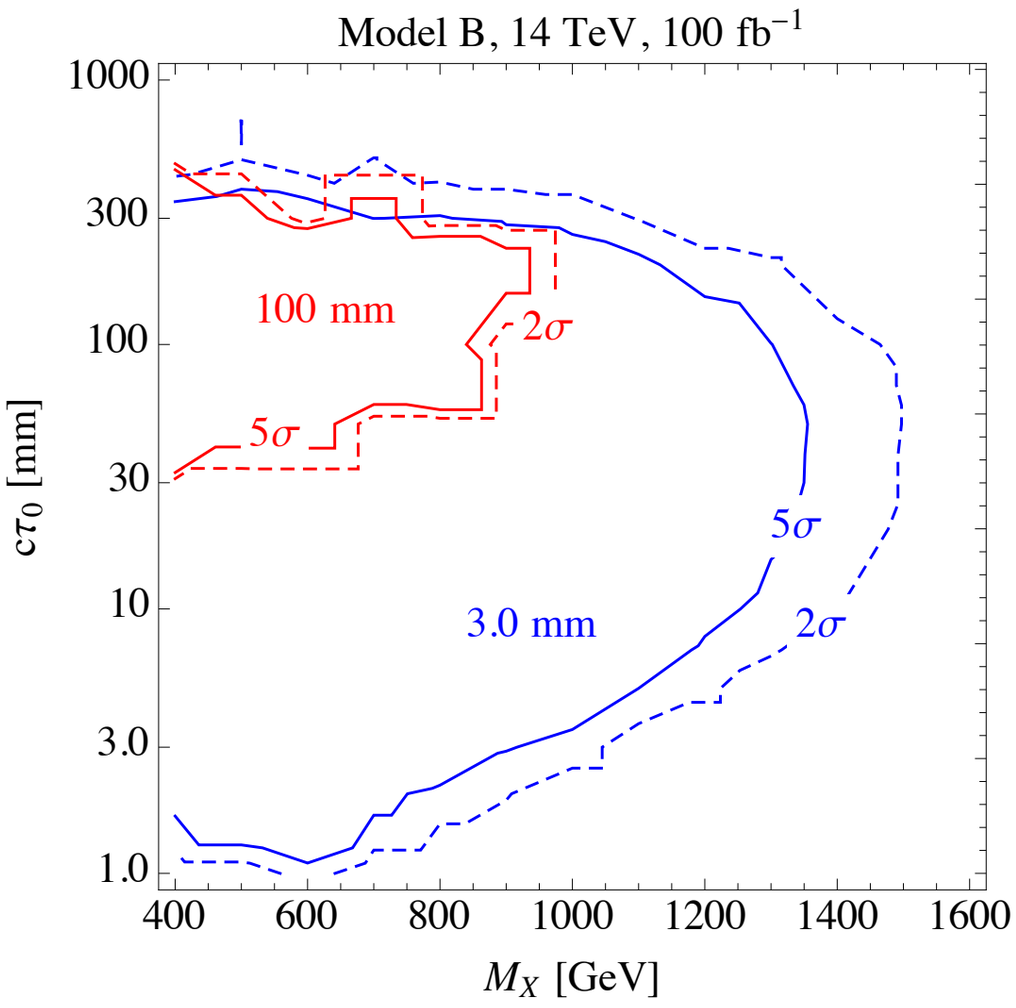
S/B

	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

Reach ATLAS/CMS





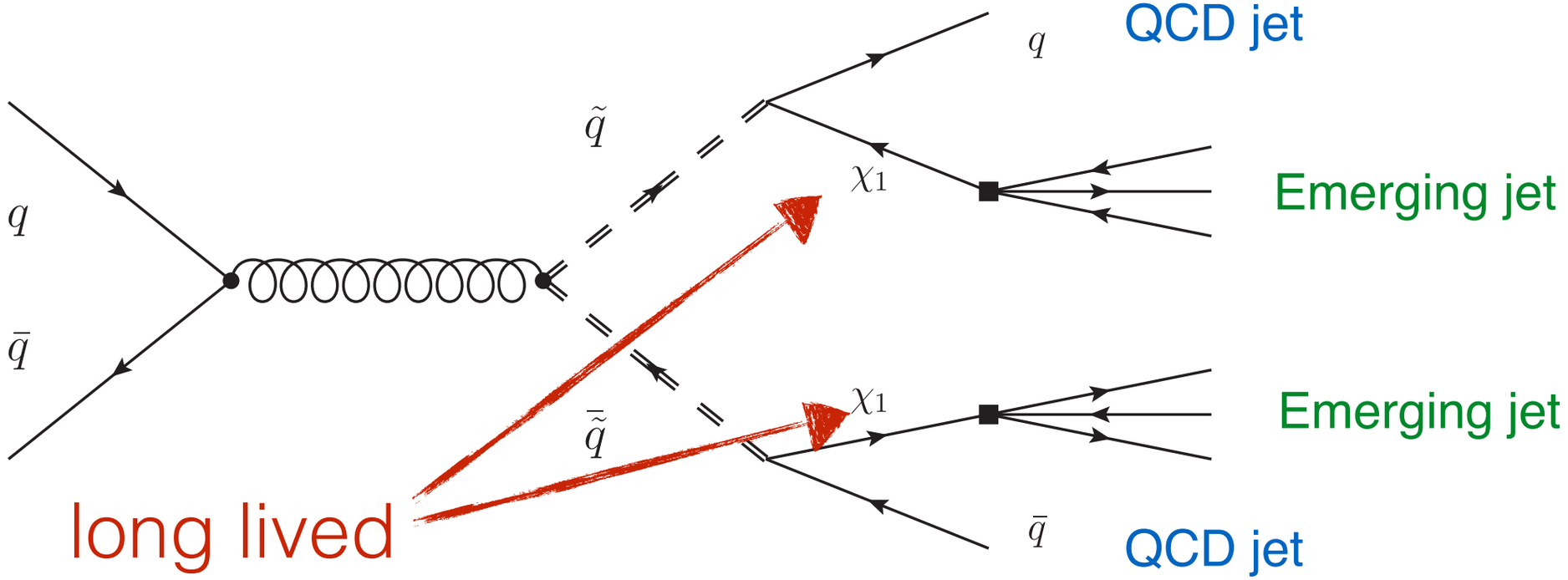
- Optimistic scenario (no non-collisional BGs)
- More realistic studies under way at CMS (ATLAS soon?)

Other New Physics

- RPV SUSY $\mathcal{W}_{\rm RPV} \supset \frac{1}{2}\lambda''_{ijk} U_i D_j D_k$

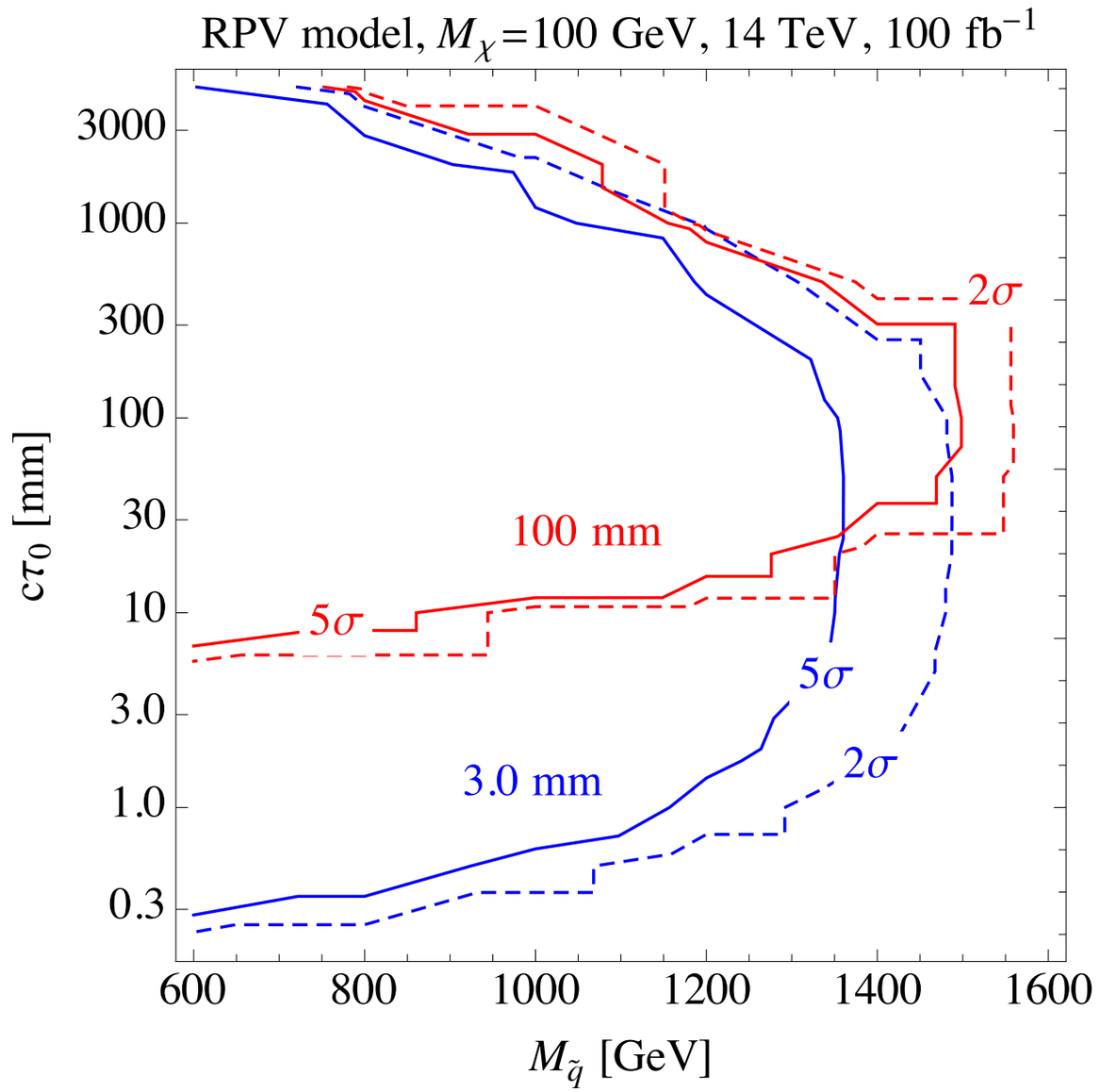
M. Kagan's talk (monday)

- One of the last "natural" MSSM scenarios



RPV SUSY sensitivity

- Competitive with displaced vertex searches
- Less model dependent
- “Natural SUSY” scenario with top jets to be done

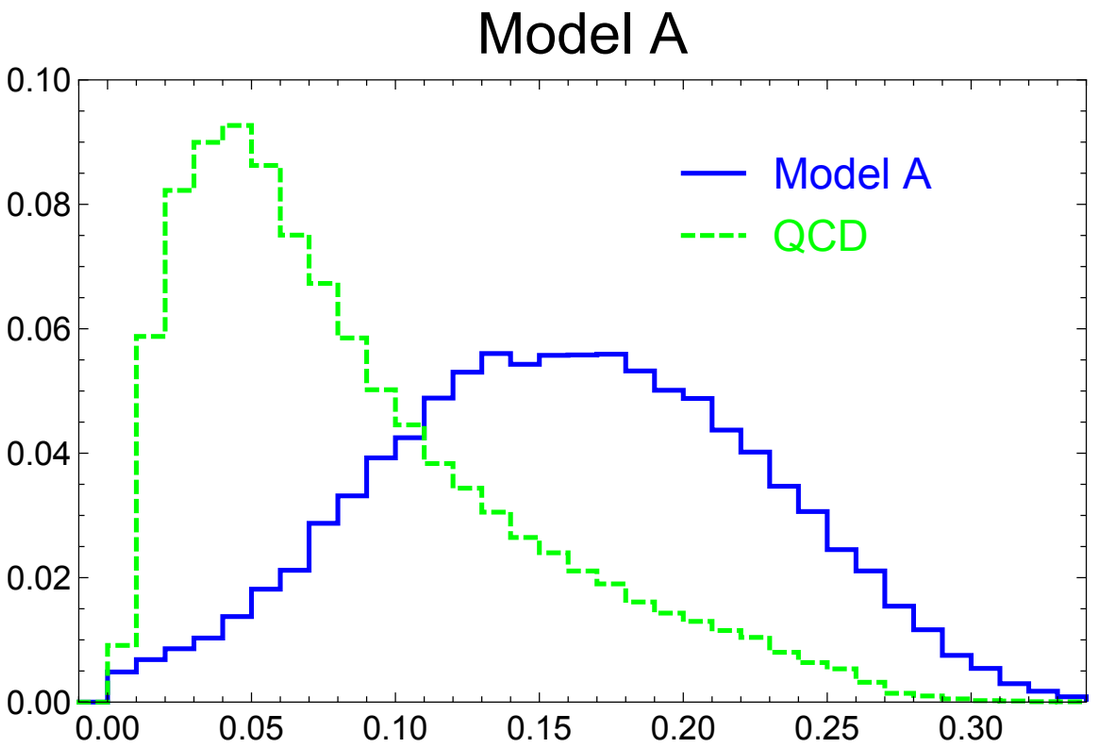


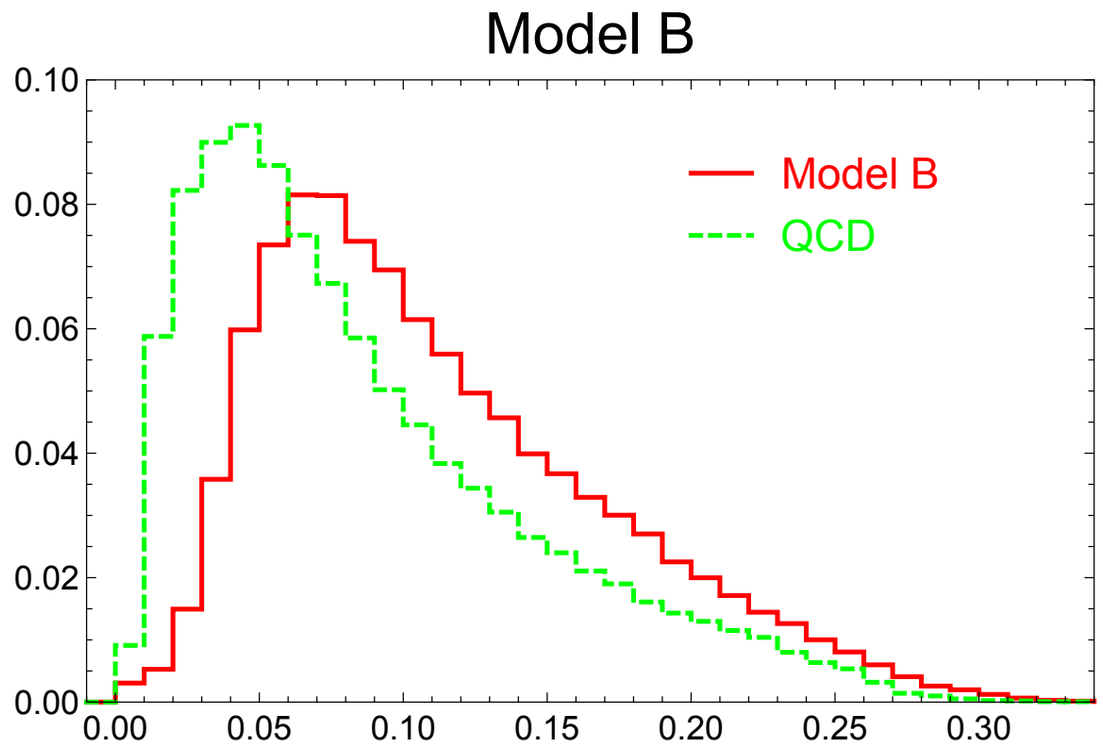
Shapes & Substructure?

Jet Shape(s)

- Girth

$$\frac{1}{p_T^{\text{jet}}} \sum_i p_T^i \, \Delta R_i$$





- Model discrimination (?)

- Subtleties: Might loose hardest dark meson, etc…

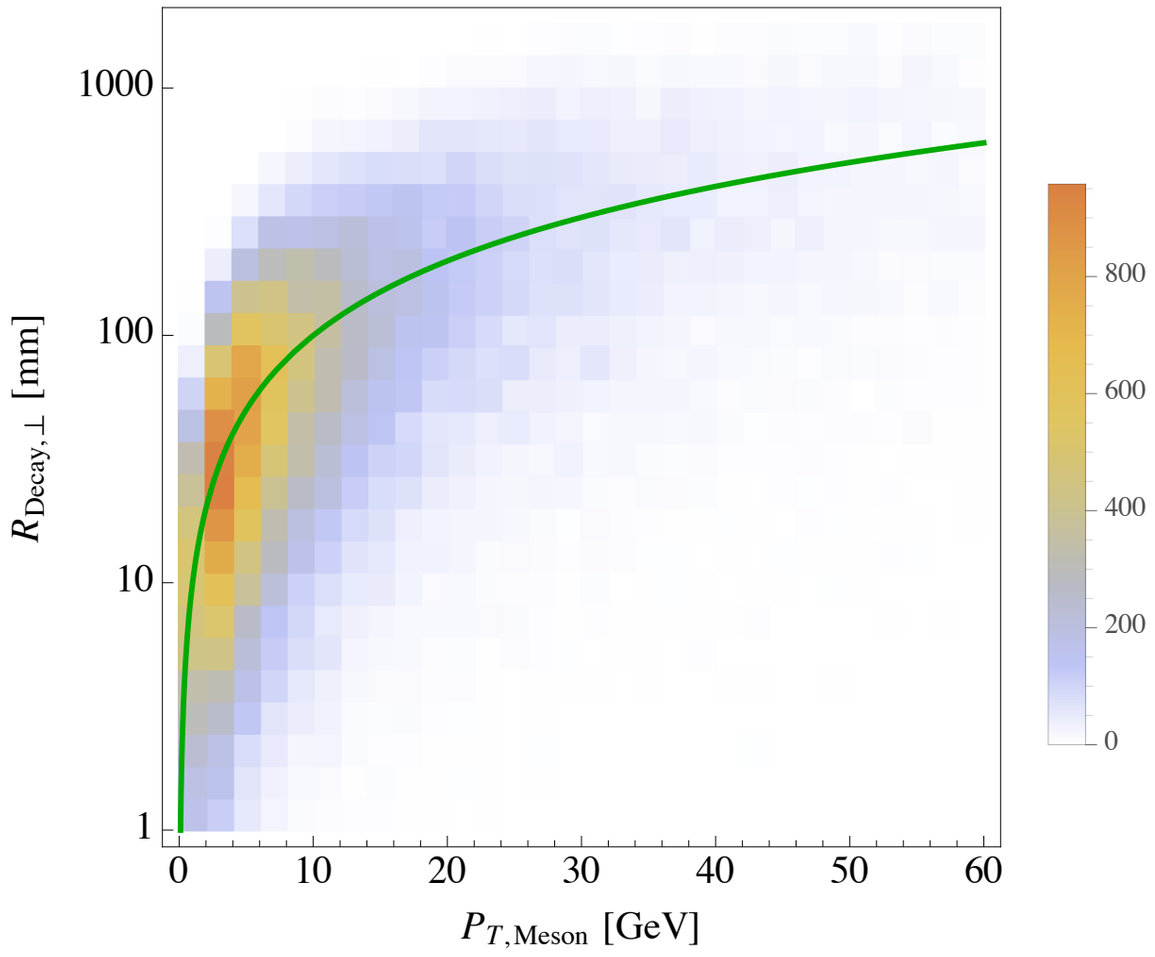
What if cτ « mm ?

- No displaced tracks. Can we still discriminate QCD and dark QCD jets?

- Sub-jets from individual dark pion decays

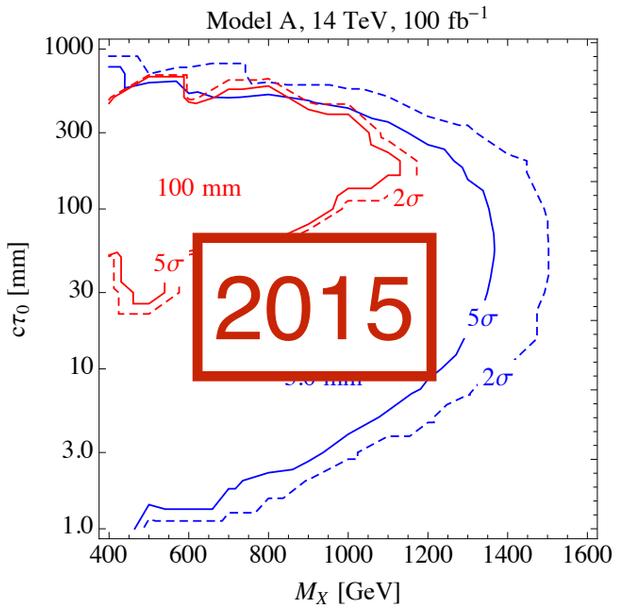
Probably discussed 8 years ago in context of Hidden Valleys

Much better tools now available!!!



Summary

- "Dark QCD" motivated in many BSM scenarios, in particular: DM and Naturalness
- Emerging jets are smoking gun, good prospects for ATLAS/CMS (LHCb in progress)
  Test TeV scale mediators without MET or Leptons
- New applications for substructure tools, fully exploit detectors capabilities



2015

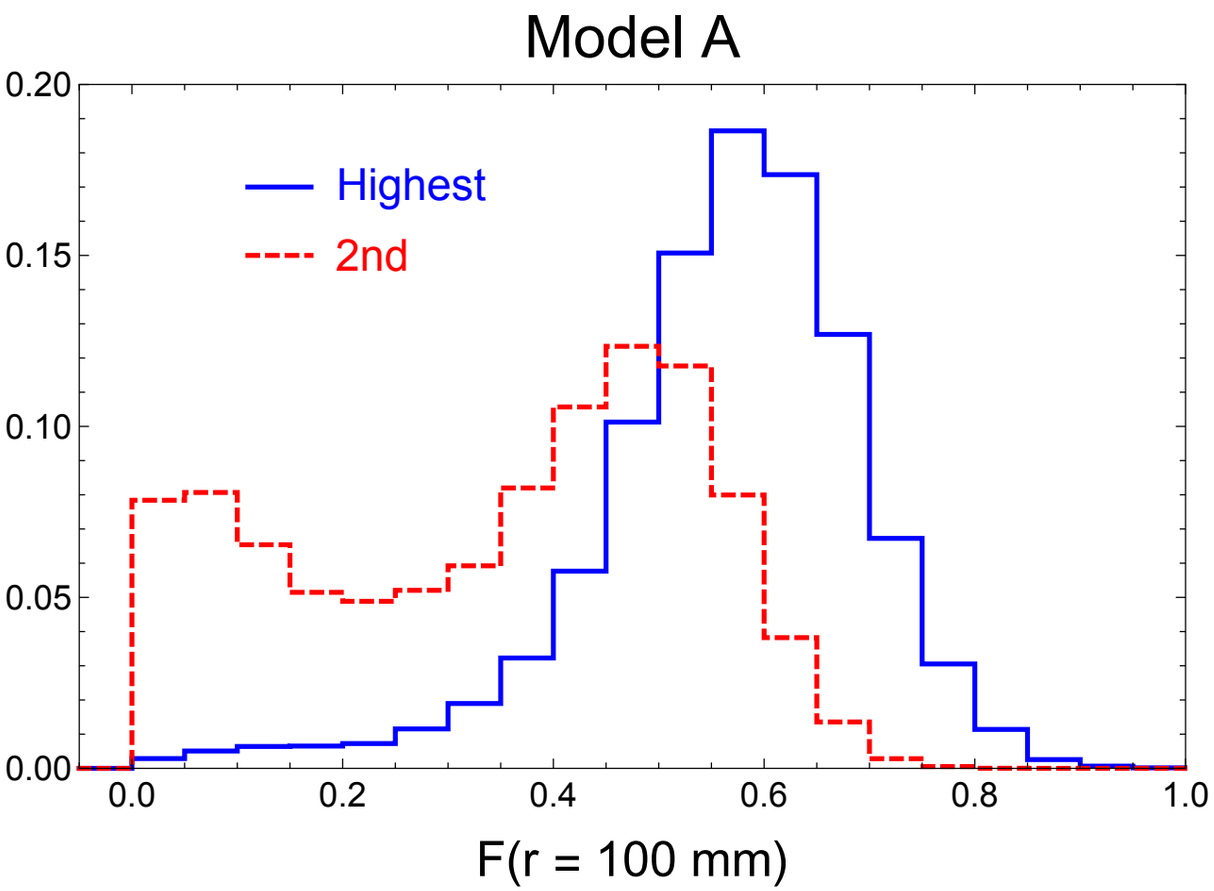
2016?

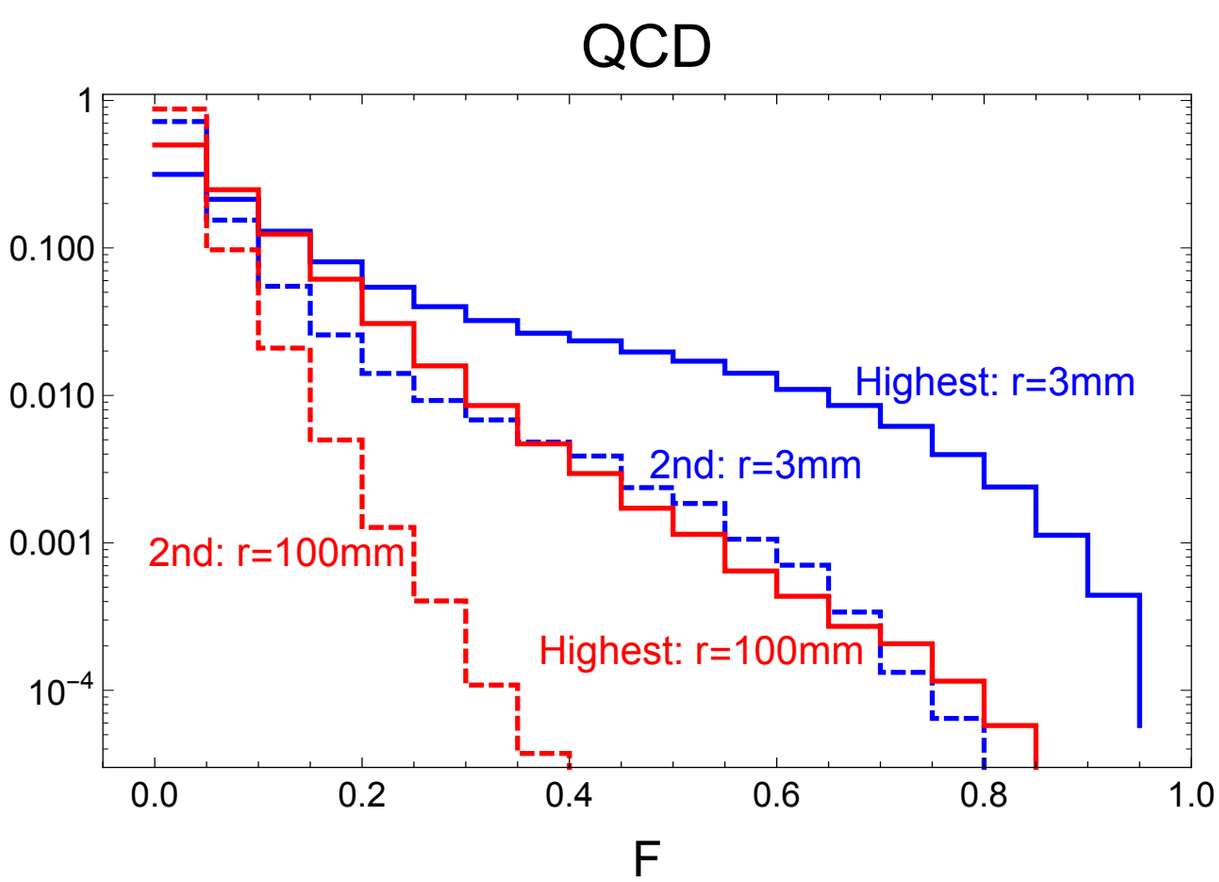
2017?

Supplemental Material

pT weighted strategy

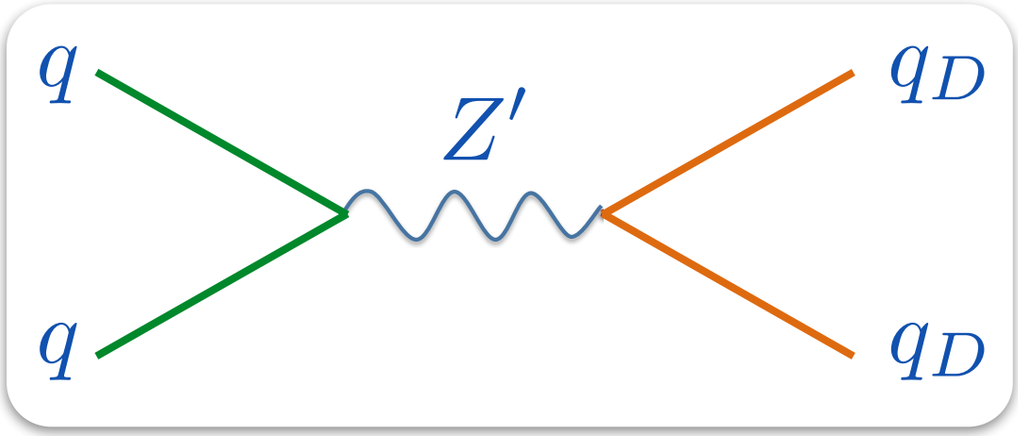
- Displaced fraction of jet $F(r) = \frac{1}{p_T^{\mathrm{calo-jet}}} \sum_{L_{xy}>r} p_T^i$

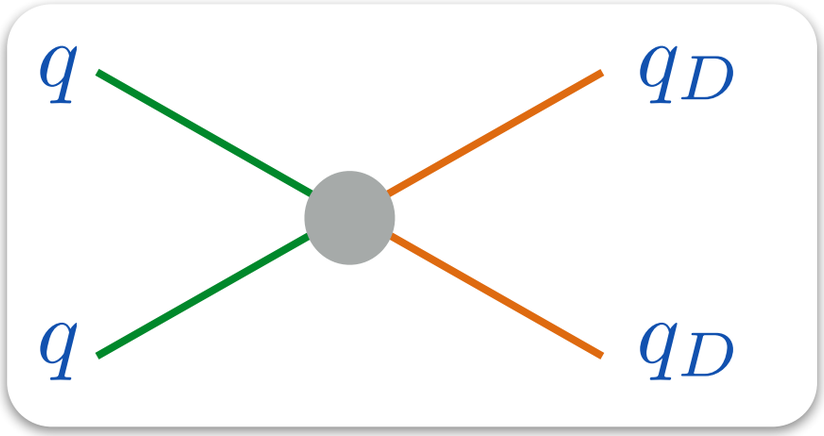




LHCb, SHIP, low energy

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

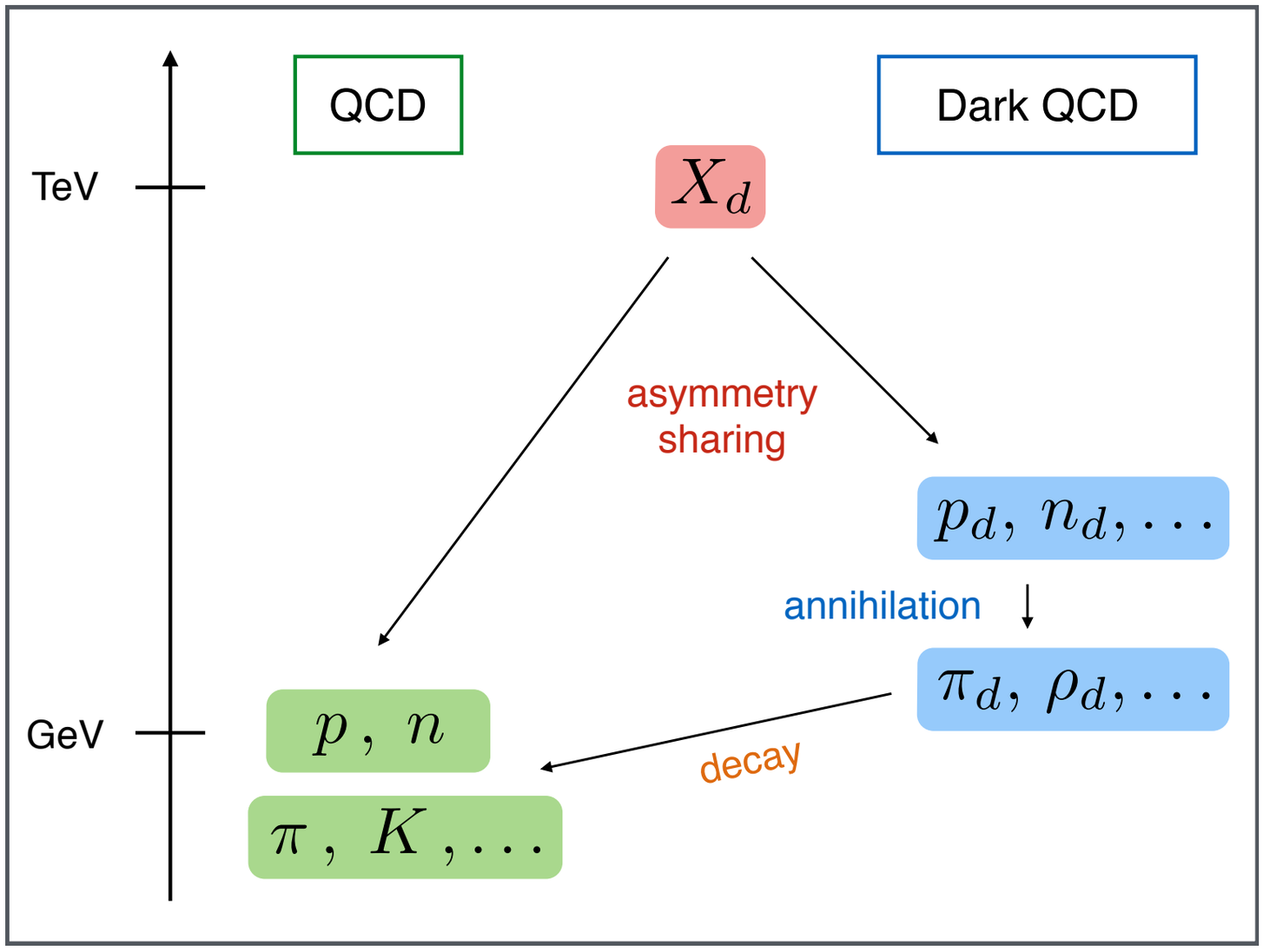




- Reconstruct individual dark pions, differentiate using lifetime, mass, decay products

- Depends on flavour structure → in progress

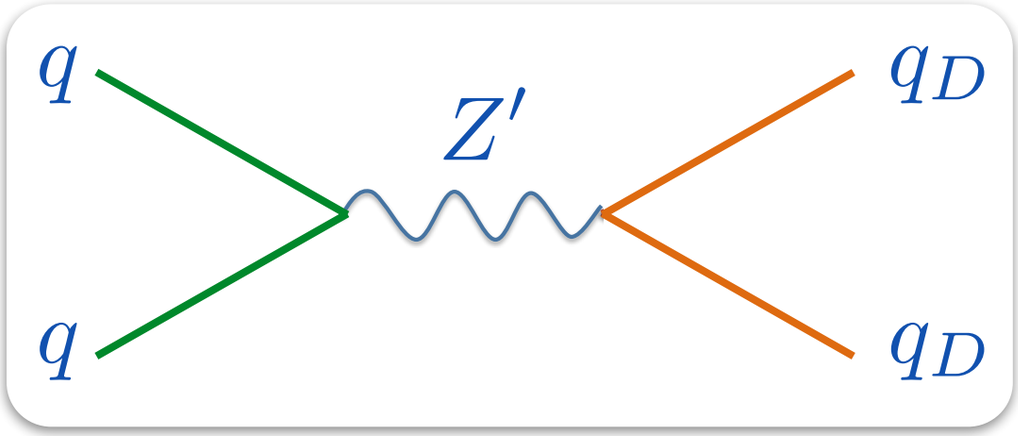
Model

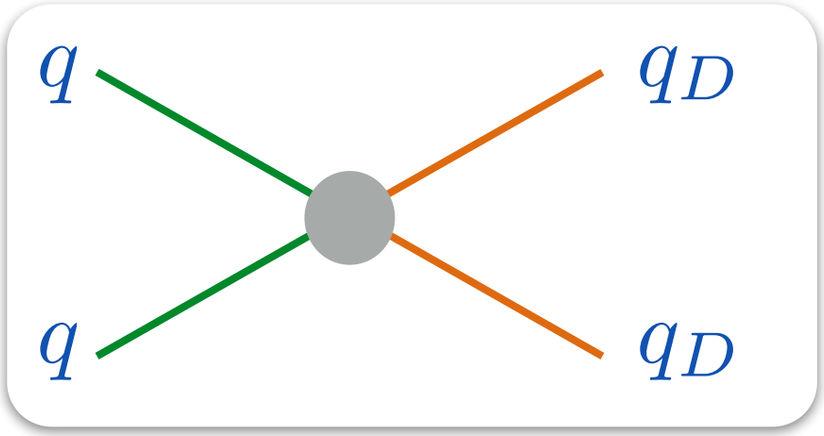


Field	$SU(3) \times SU(2) \times U(1)$	$SU(3)_{\text{dark}}$	Mass	Spin
Q_d	$(1, 1, 0)$	(3)	m_d $\mathcal{O}(\text{GeV})$	Dirac Fermion
X_d	$(3, 1, \frac{1}{3})$	(3)	M_{X_d} $\mathcal{O}(\text{TeV})$	Complex Scalar
Z_d	$(1, 1, 0)$	(1)	M_{Z_d} $\mathcal{O}(\text{TeV})$	Vector Boson

LHCb opportunities

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

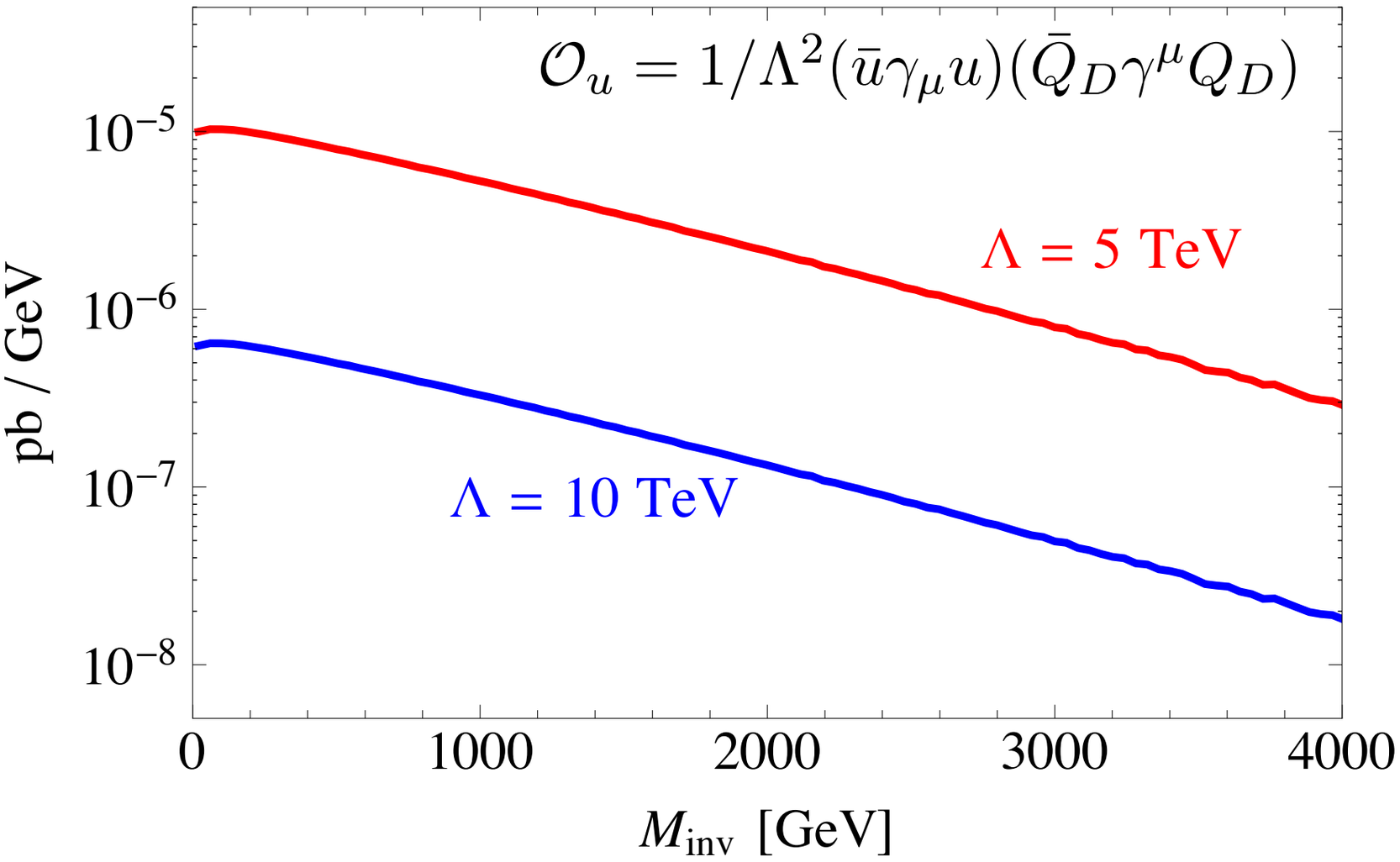




- Reconstruct individual dark pions, differentiate using lifetime, mass, decay products

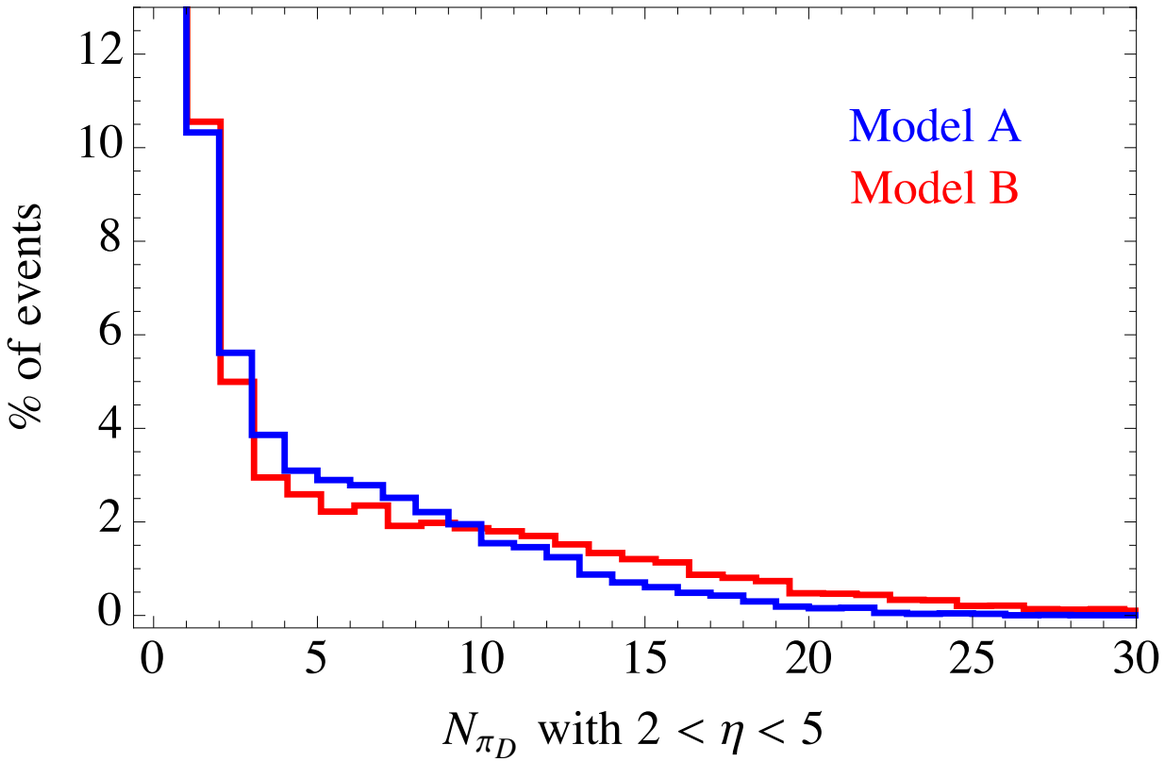
- Emerging jets without (hard) trigger requirements?

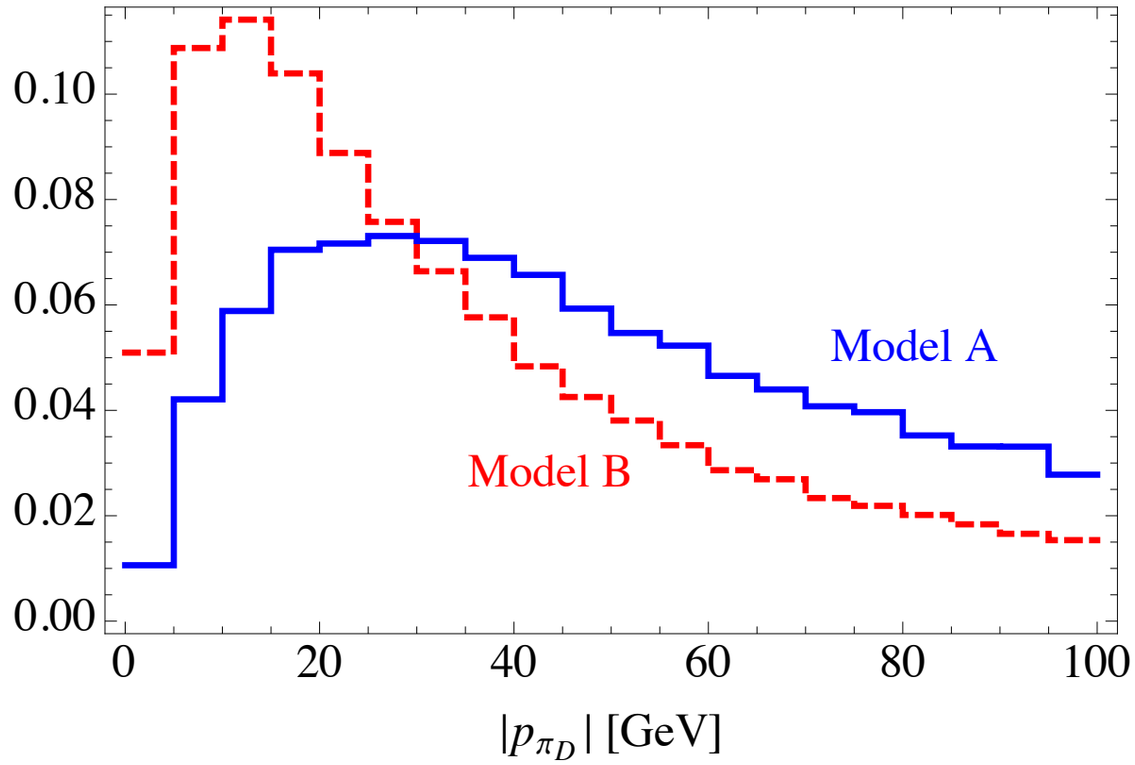
Off-shell production



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

Forward region

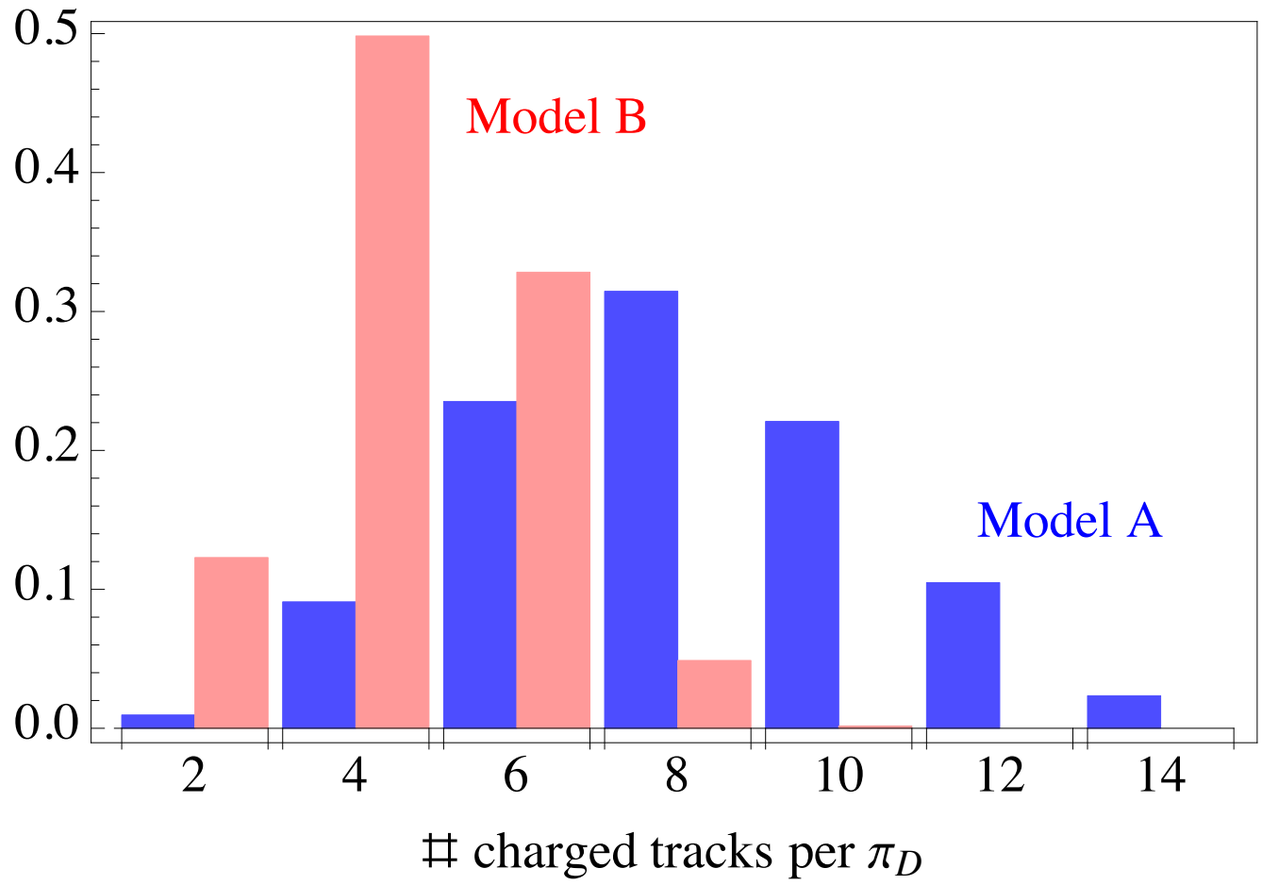




- Fraction of all signal events with N dark pions in $2 < \eta < 5$

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