EMERGING JETS

Carleton UNIVERSITY

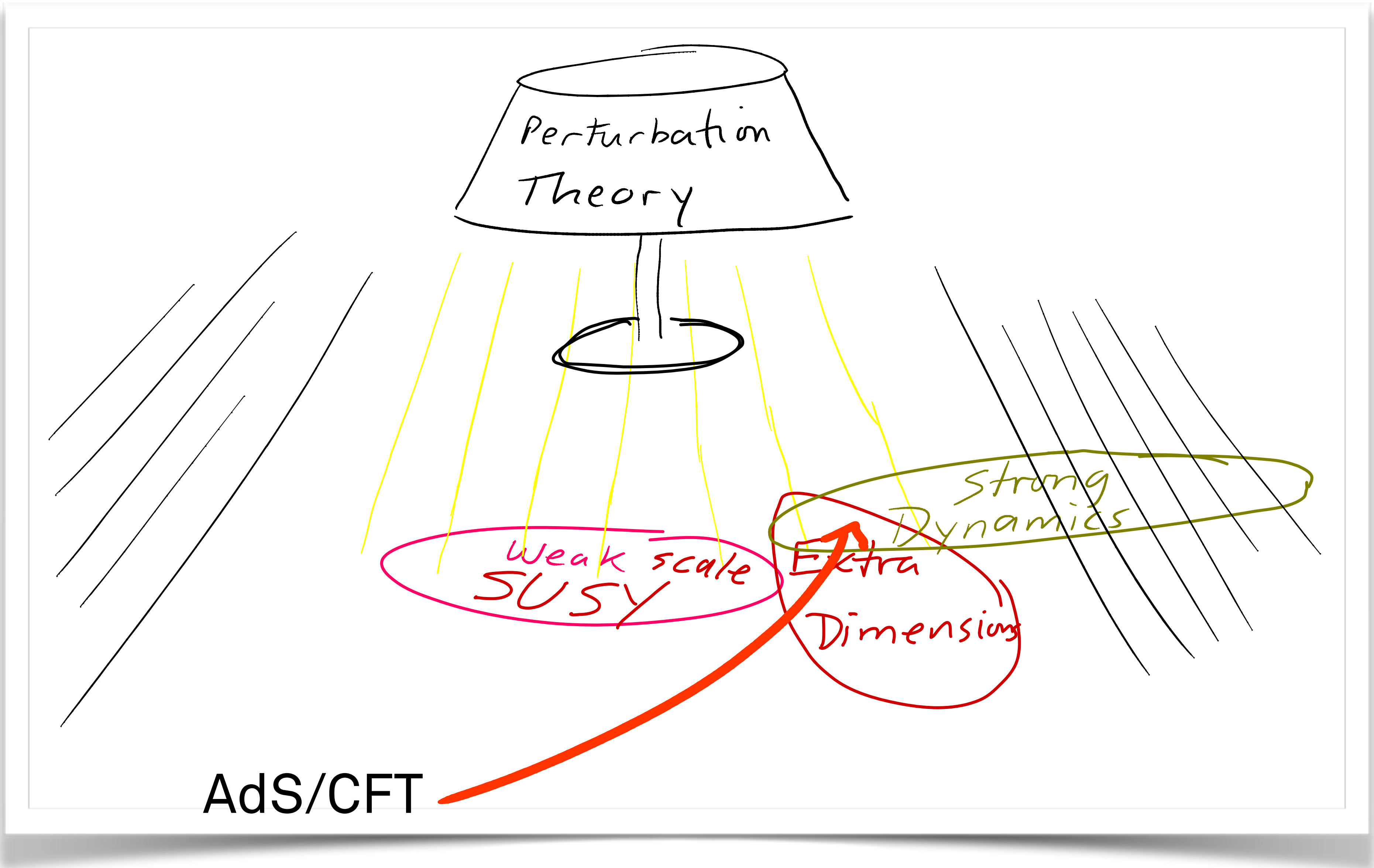
DANIEL STOLARSKI
WITH PEDRO SCHWALLER
AND ANDREAS WEILER

JHEP 1505, 059 (2015)
[arXiv:1502.0409].

Wisconsin May 23, 2017

MOTIVATION 1

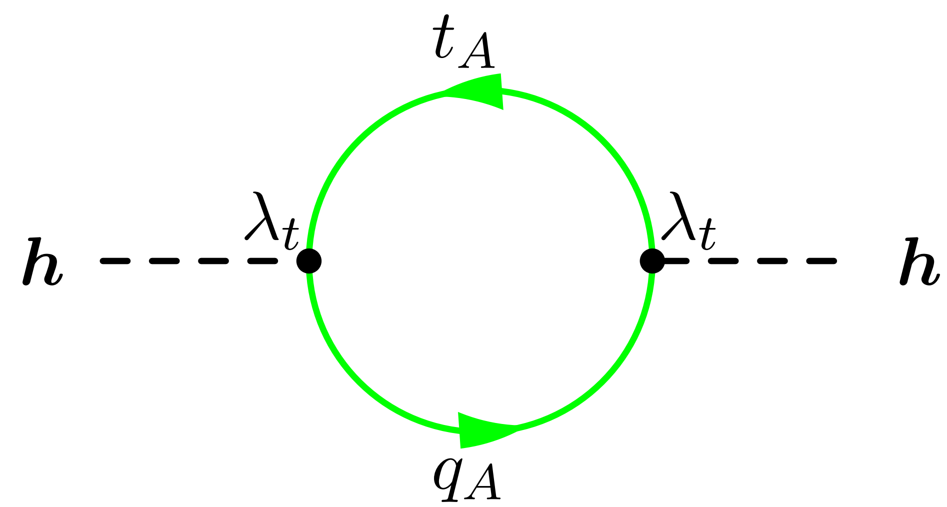
Getting away from the lamp post



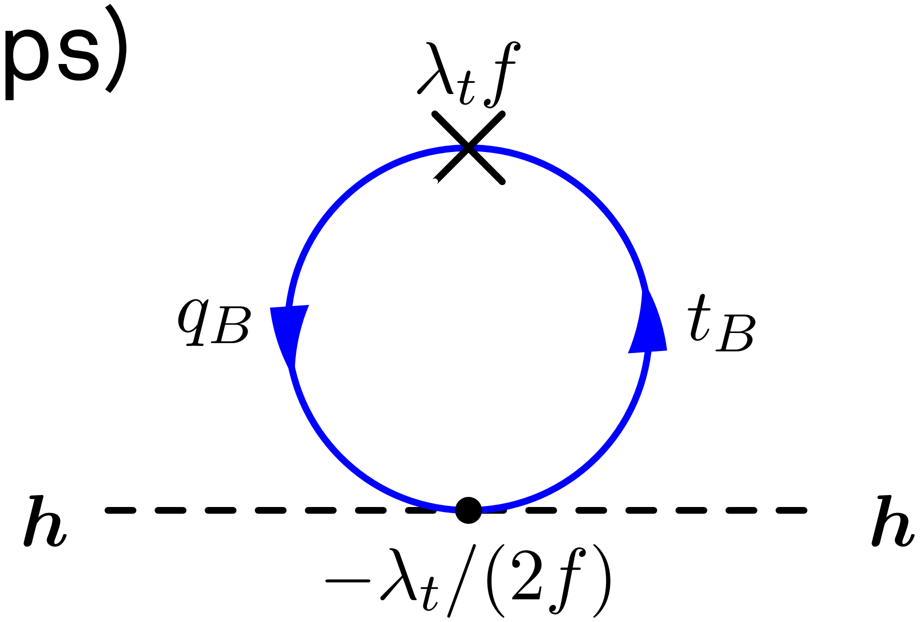
R. Sundrum

MOTIVATION 2

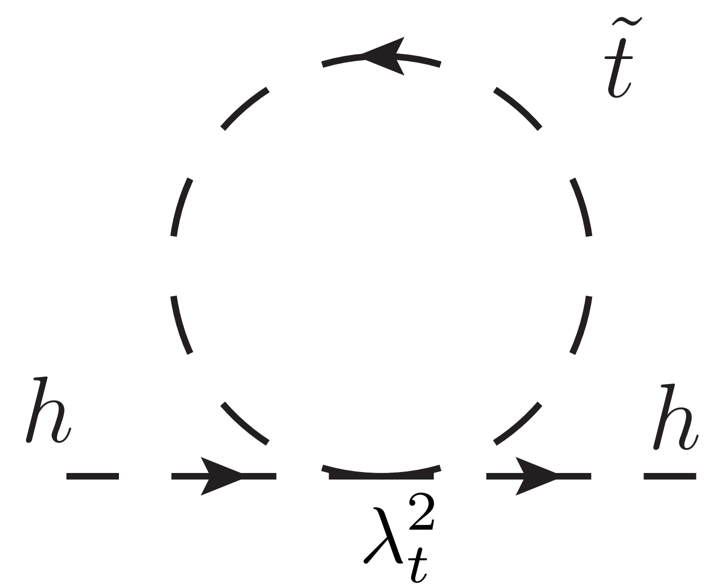
Gauge hierarchy problem:



Solved in composite Higgs (SUSY) with top-partners (stops)



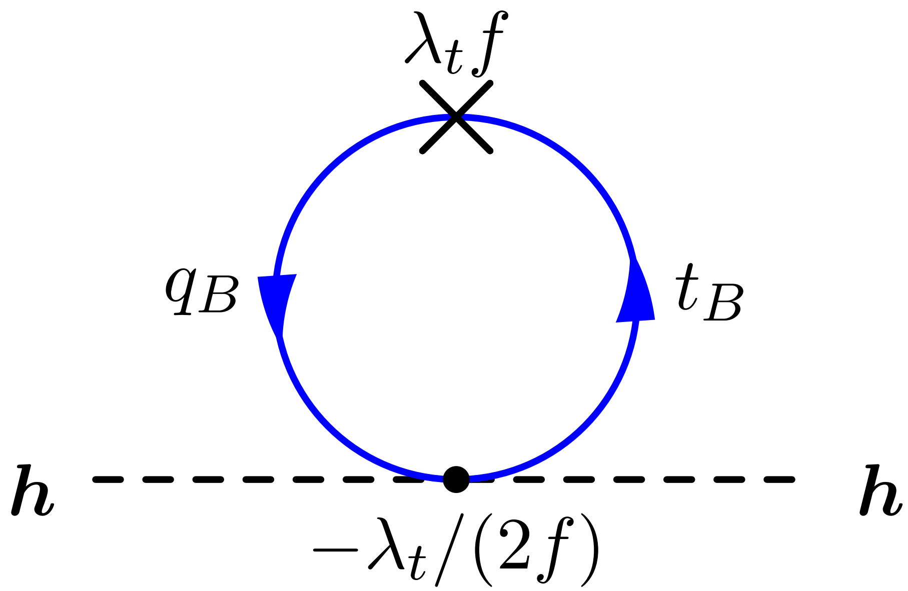
or

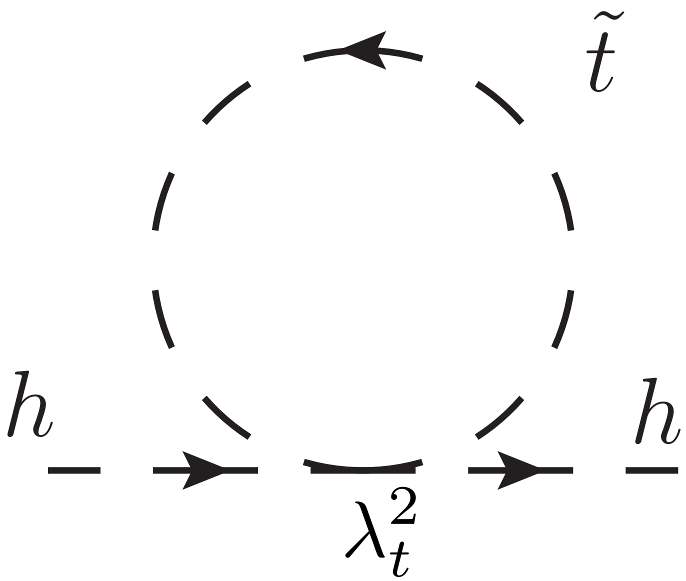


Do these partners need to be colored?

TWIN HIGGS/FOLDED SUSY

No! But still need factor of 3.



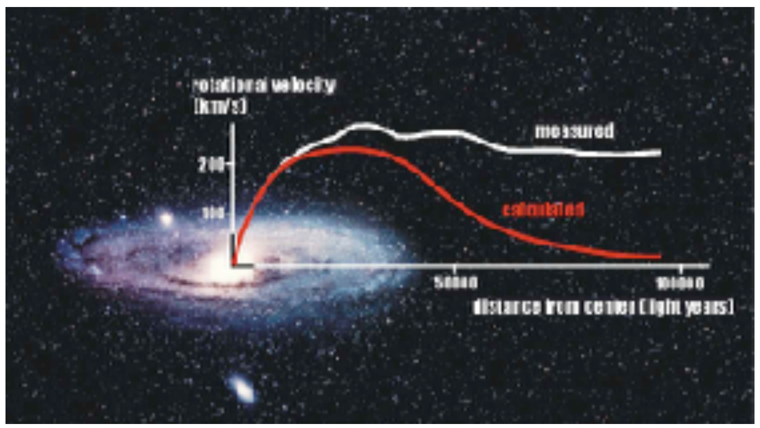


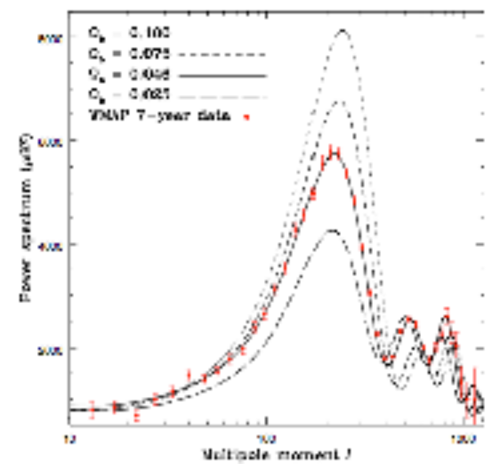
Chacko, Goh, Harnik, hep-ph/0506256.
Burdman, Chacko, Goh, Harnik, hep-ph/0609152.

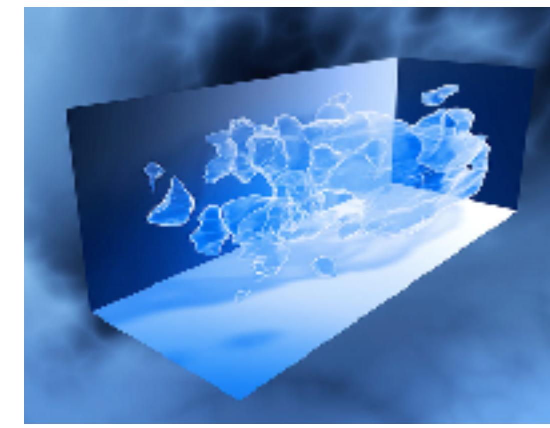
Most models have twin color which confines around GeV scale (or slightly higher).

MOTIVATION 3

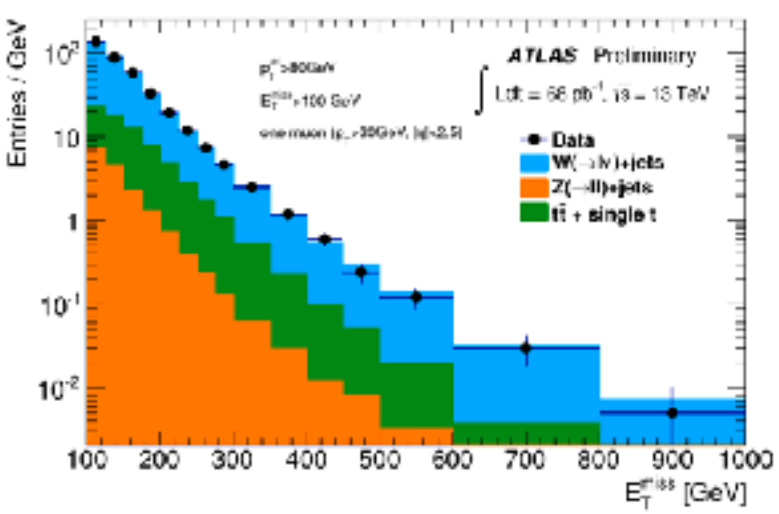
We have seen dark matter in the sky.

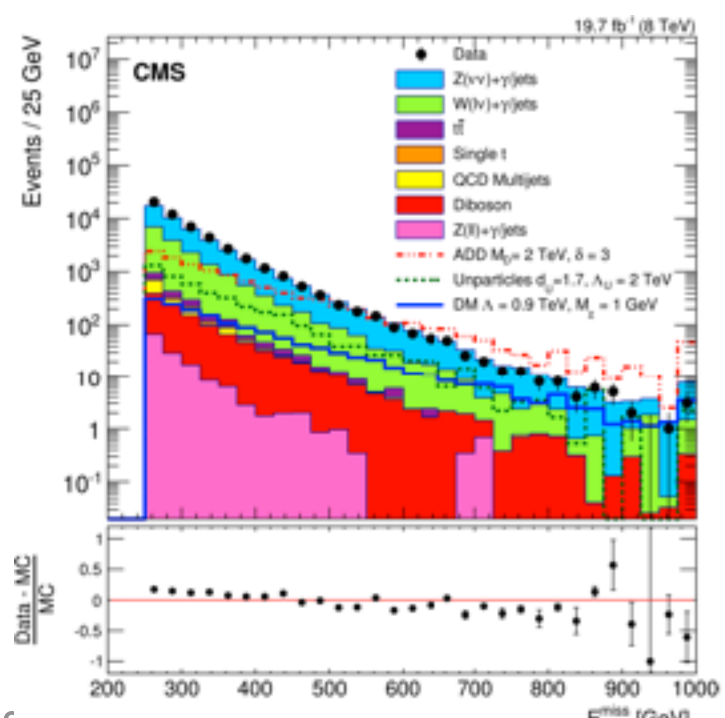


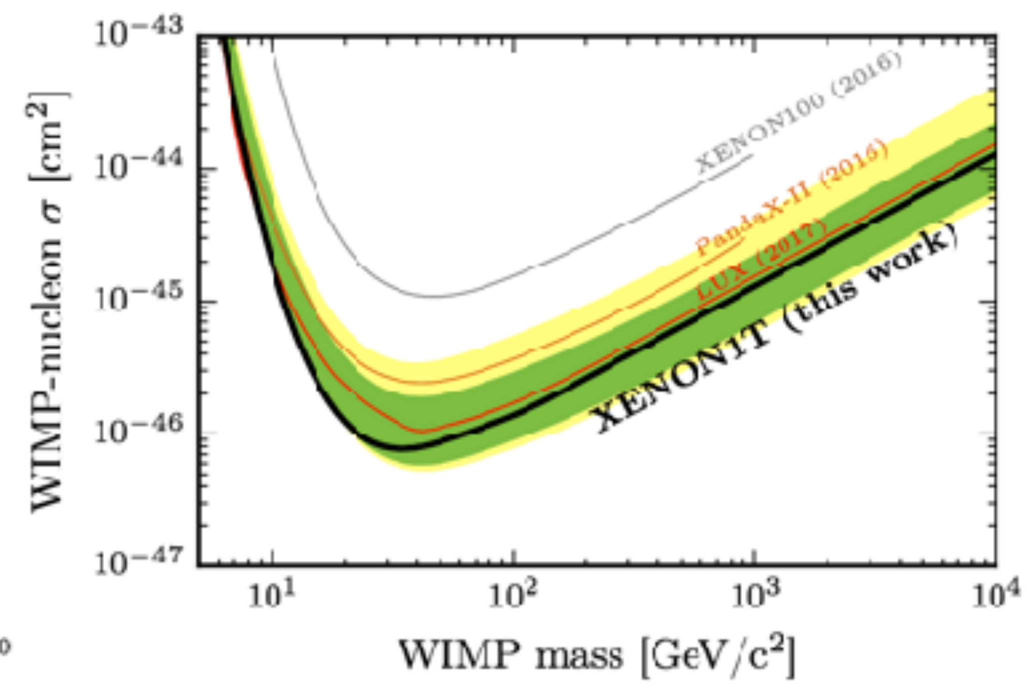




But not in the lab.







ASYMMETRIC DARK MATTER

$$\Omega_{DM} \simeq 5\Omega_B$$

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$$\Omega_{DM} = m_{DM} n_{DM}$$

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Controlled by complicated (known) QCD dynamics

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Unknown dynamics of baryogenesis

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?

Unknown dynamics of baryogenesis

MANY PAPERS

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]].

K. K. Boddy, J. L. Feng, M. Kaplinghat, and T. M. P. Tait, Phys. Rev. D. **89** 11, 115017 (2014) [arXiv:1402.3629 [hep-ph]].

For a review see K. Petraki and R. R. Volkas, Int.J.Mod.Phys.A 28, 1330028 (2013) [arXiv:1305.4939 [hep-ph]].

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$$\Omega_{DM} = m_{DM} n_{DM} \qquad \Omega_B = m_p n_B$$

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Unknown dynamics of baryogenesis

Can get $n_{DM} \sim n_B$, usually have to assume $m_{DM} \sim m_B$.

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Can get $n_{DM} \sim n_B$, usually have to assume $m_{DM} \sim m_B$.

Can we get both?

GETTING THE MASS

$$\Omega_{DM} \simeq 5\Omega_B$$

Controlled by complicated (known) QCD dynamics

$$\Omega_{DM} = m_{DM} n_{DM} \qquad \Omega_B = m_p n_B$$

?

Unknown dynamics of baryogenesis

GETTING THE MASS

$$\Omega_{DM} \simeq 5\Omega_B$$

QCD like

?

Controlled by complicated (known) QCD dynamics

$$\Omega_{DM} = m_{DM} n_{DM} \qquad \Omega_B = m_p n_B$$

?

Unknown dynamics of baryogenesis

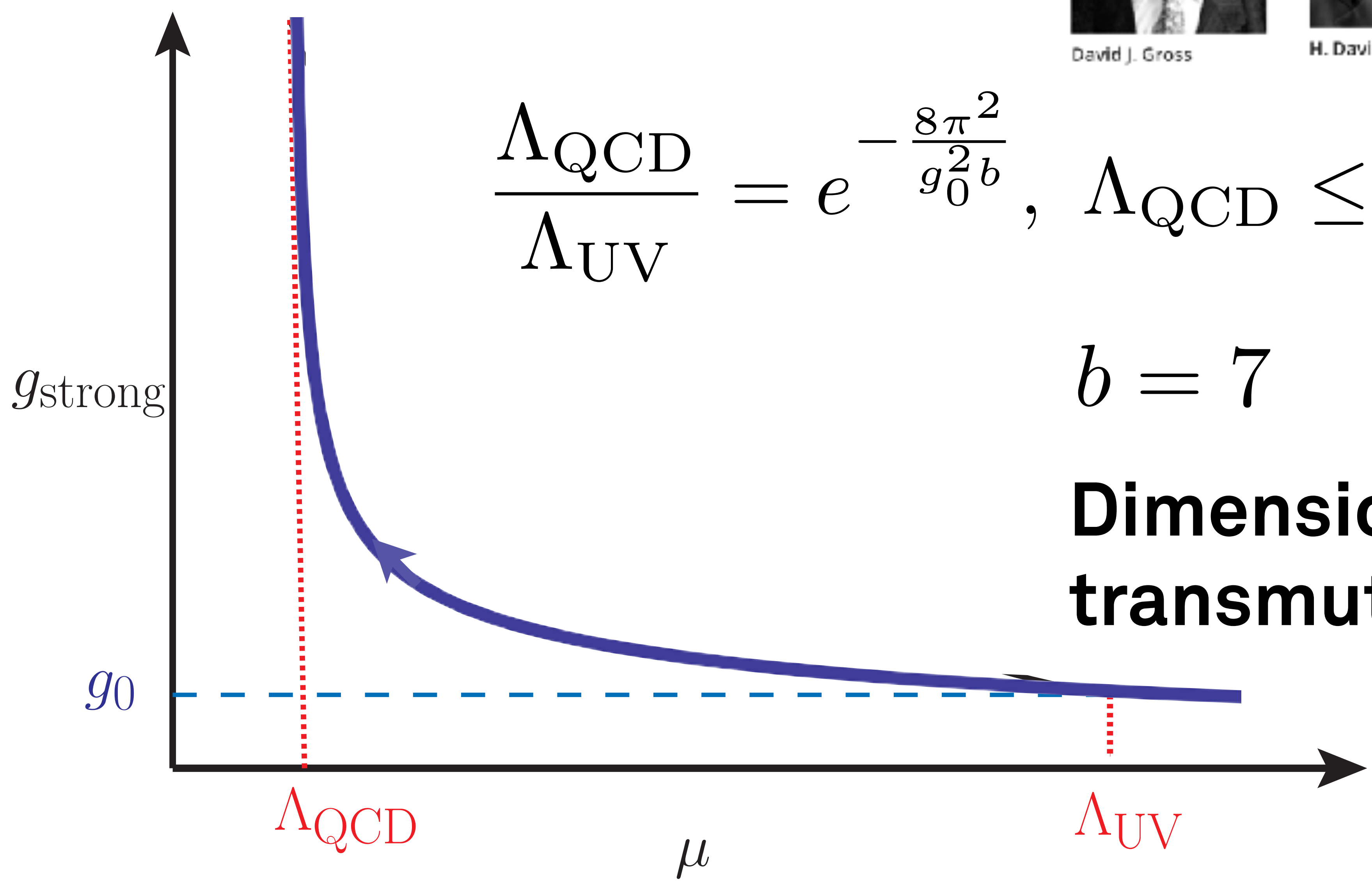
QCD SCALE

David J. Gross   H. David Politzer   Frank Wilczek

$$\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm UV}} = e^{-\frac{8\pi^2}{g_0^2 b}}, \quad \Lambda_{\rm QCD} \leq \ \text{GeV}$$

$$b = 7$$

Dimensional transmutation



DARK QCD

Propose new SU(N_d) "dark QCD," dark quarks.
Bai, Schwaller, PRD 13.

Dark matter is dark sector baryons with mass ~ $\Lambda_{\rm dQCD}$.

Massive bifundamental fields decouple at mass $M \gg \Lambda_{\rm dQCD}$.

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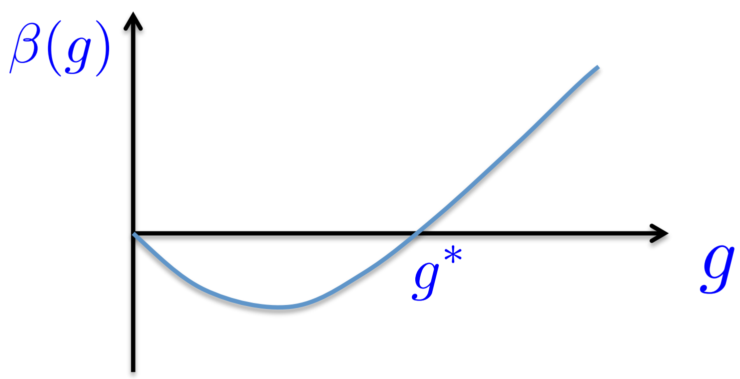
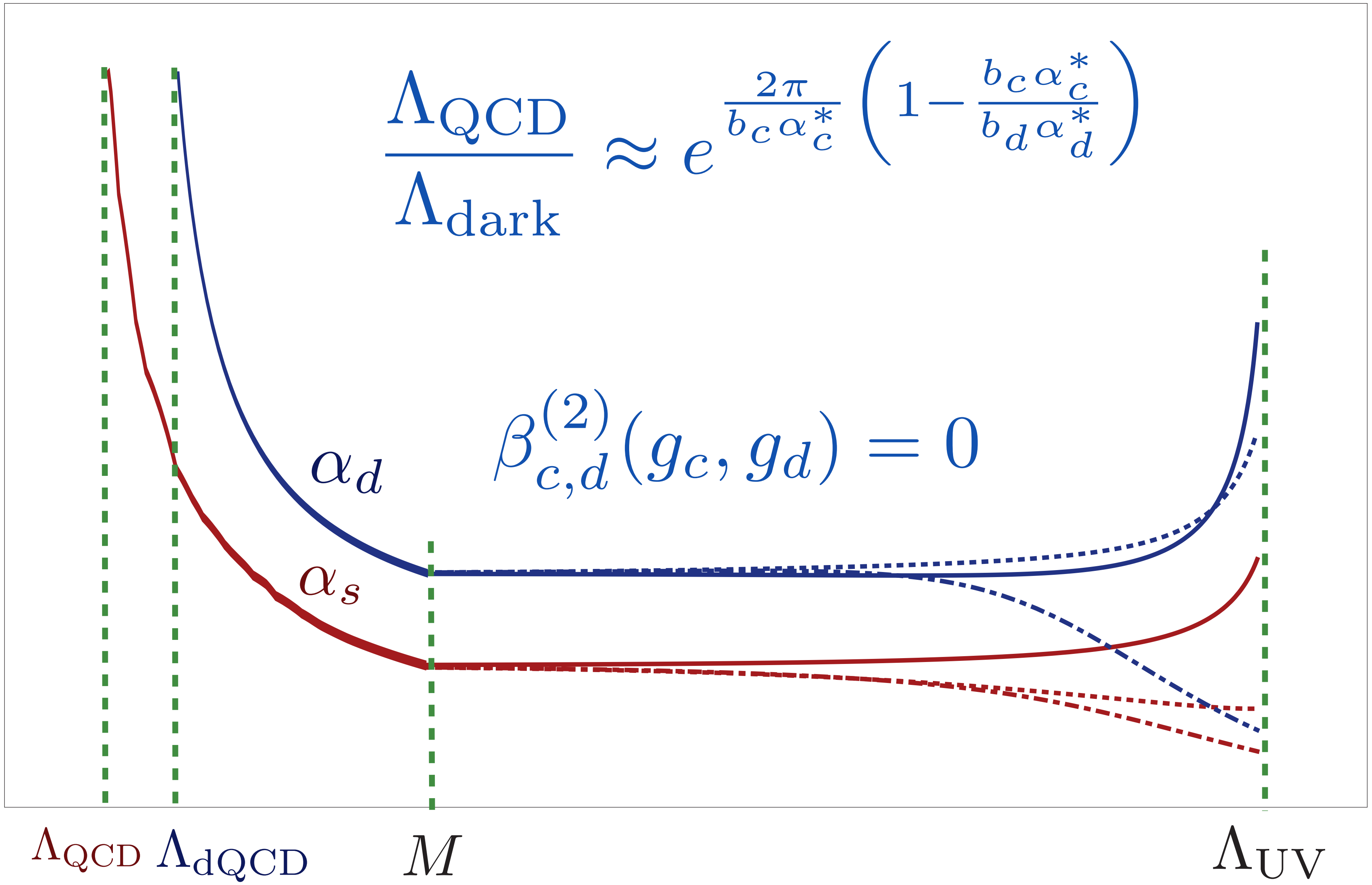
Search for model with perturbative fixed point.

$$\frac{dg}{dt} = \beta(g) = 0 \text{ for } g = g^*$$



SCALES ARE RELATED



SCALES ARE RELATED

Example

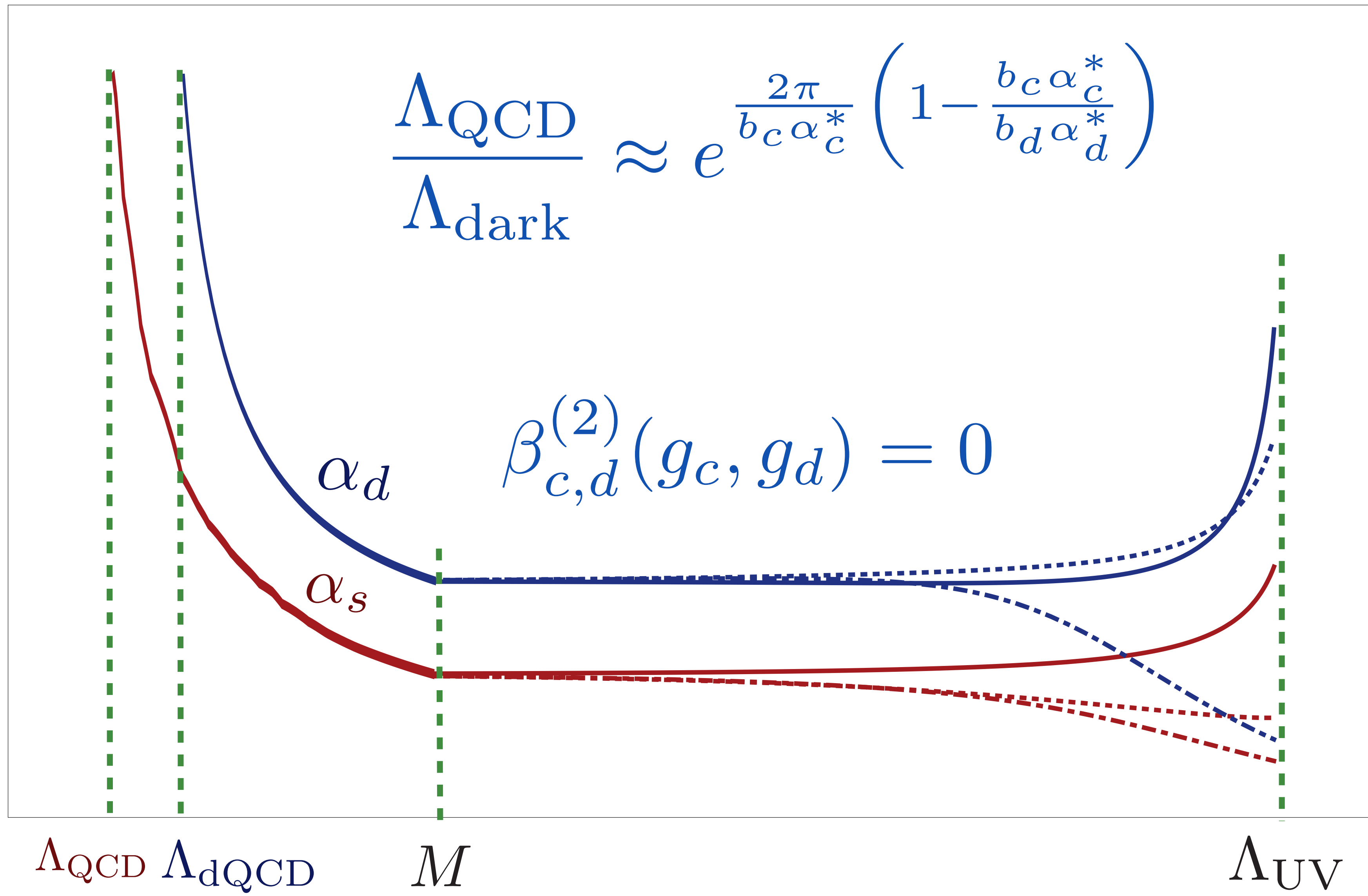
Fixed points:

$\alpha_c^* = 0.090 \quad \alpha_d^* = 0.168$

$M = 870\ GeV$

DM mass:

$M_{DM} \approx 3.5\ GeV$



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Can co-generate DM and baryon asymmetry.

$$\overline{Q}\,\Phi\,d_i$$

- d_i → SM quark
- Φ → bifundamental scalar
- $\overline{Q}$ → dark quark

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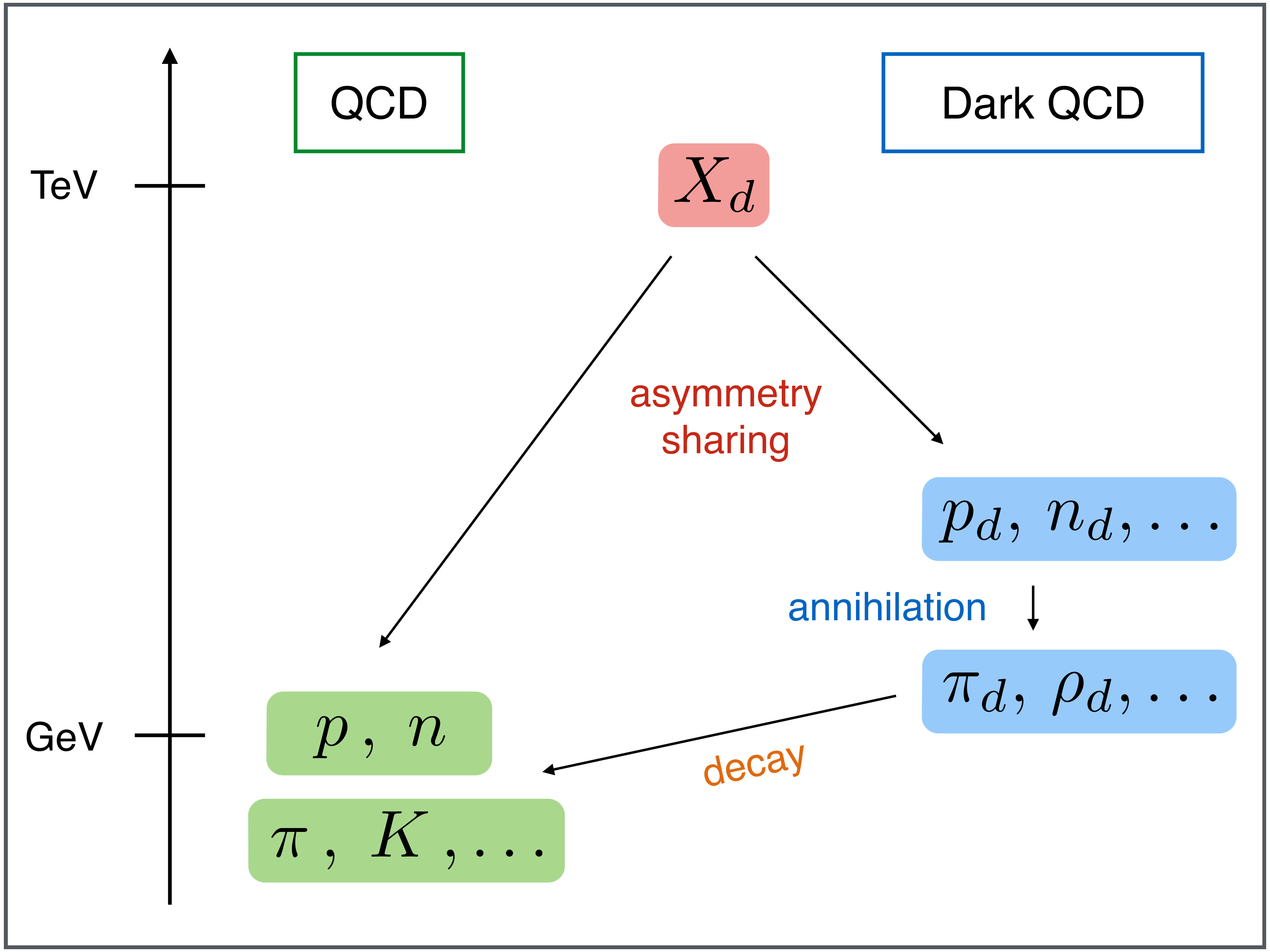
Dark matter is strongly self interacting — potentially solves various problems of cold dark matter.

- Cusp vs core

  Rocha et. al. '12. Peter et. al. '12.
  Vogelsberger, Zavala, Loeb, '12.
  Zavala, Vogelsberger, Walker '12.

- Missing satellites
- Too big to fail

GENERAL PICTURE



PHENOMENOLOGY

DARK QCD

Confining SU(N_c) gauge group with N_f flavors.

$$Q_i \quad \overline{Q}_j \quad G_d^{\mu\nu}$$

This sector is QCD like, and it confines at a scale.

$$\Lambda_d \sim 1 - 10 \text{ GeV}$$

At the confining scale we have all the usual states.

$$p_d \qquad \pi_d \qquad \text{Zoo}_d$$

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Stable

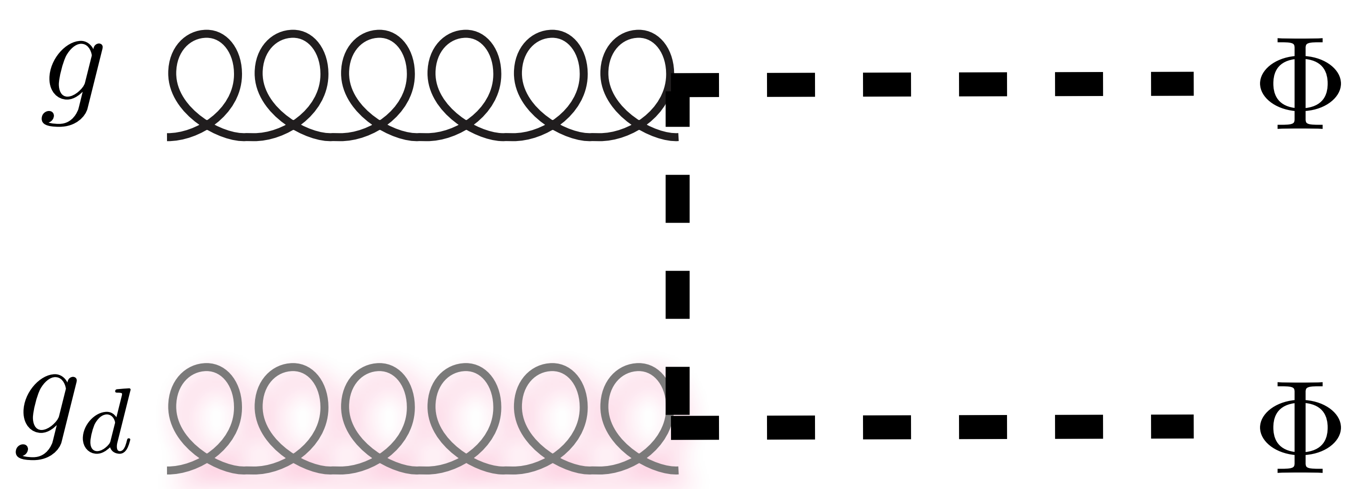
Decays to SM

MEDIATORS

Motivated by getting comparable asymmetries, put in heavy mediator which couples to SM and dark sector.

$$M_\Phi \gg \Lambda_d$$

<u>Example 1:</u> Φ is a scalar charged under both color and dark color.



MEDIATORS

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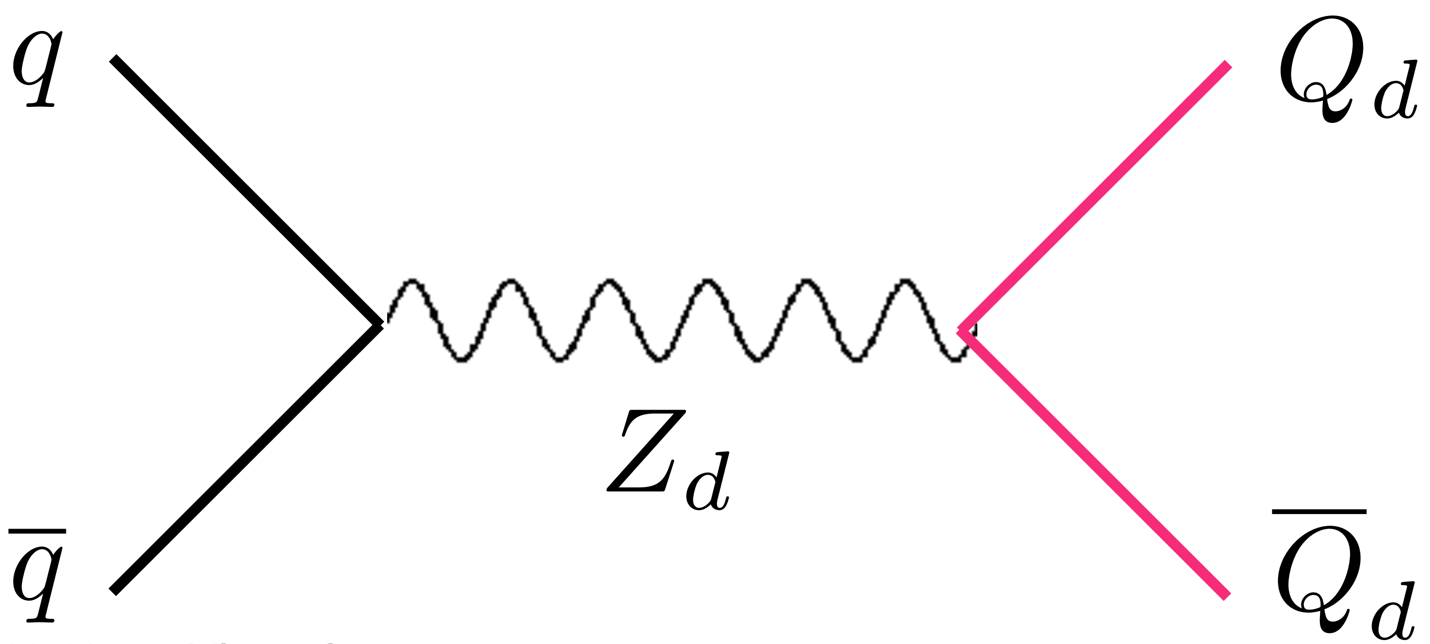
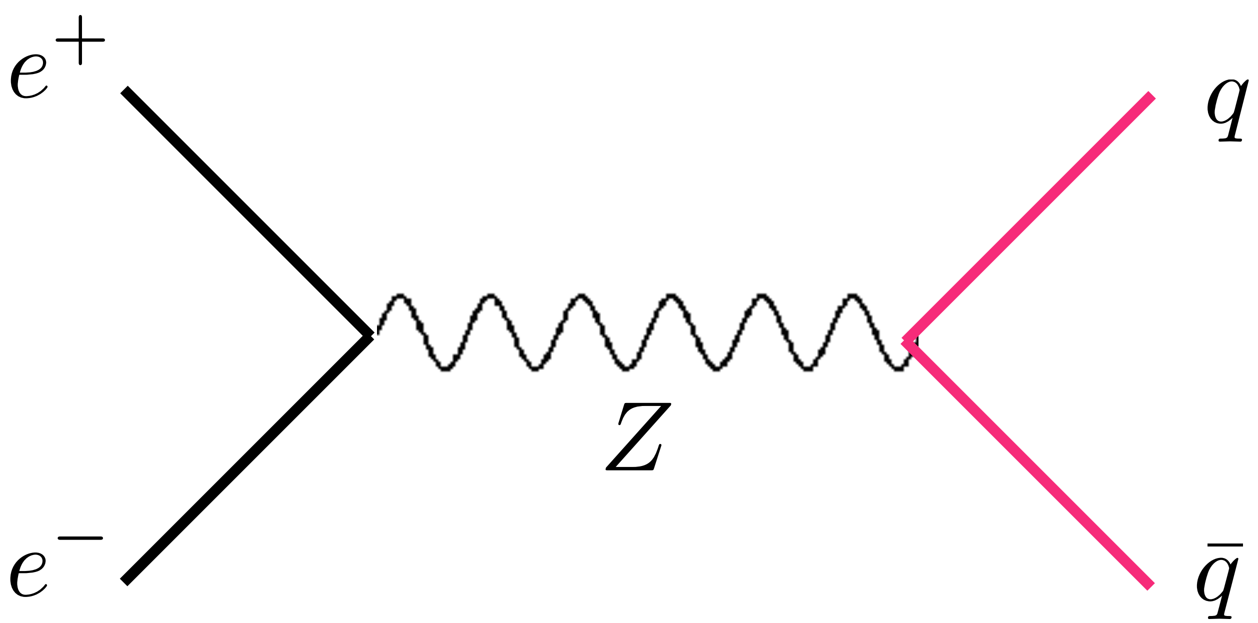
Example 2: Z_d is a vector that couples to quarks and dark quarks. Strassler, Zurek, PLB 07.

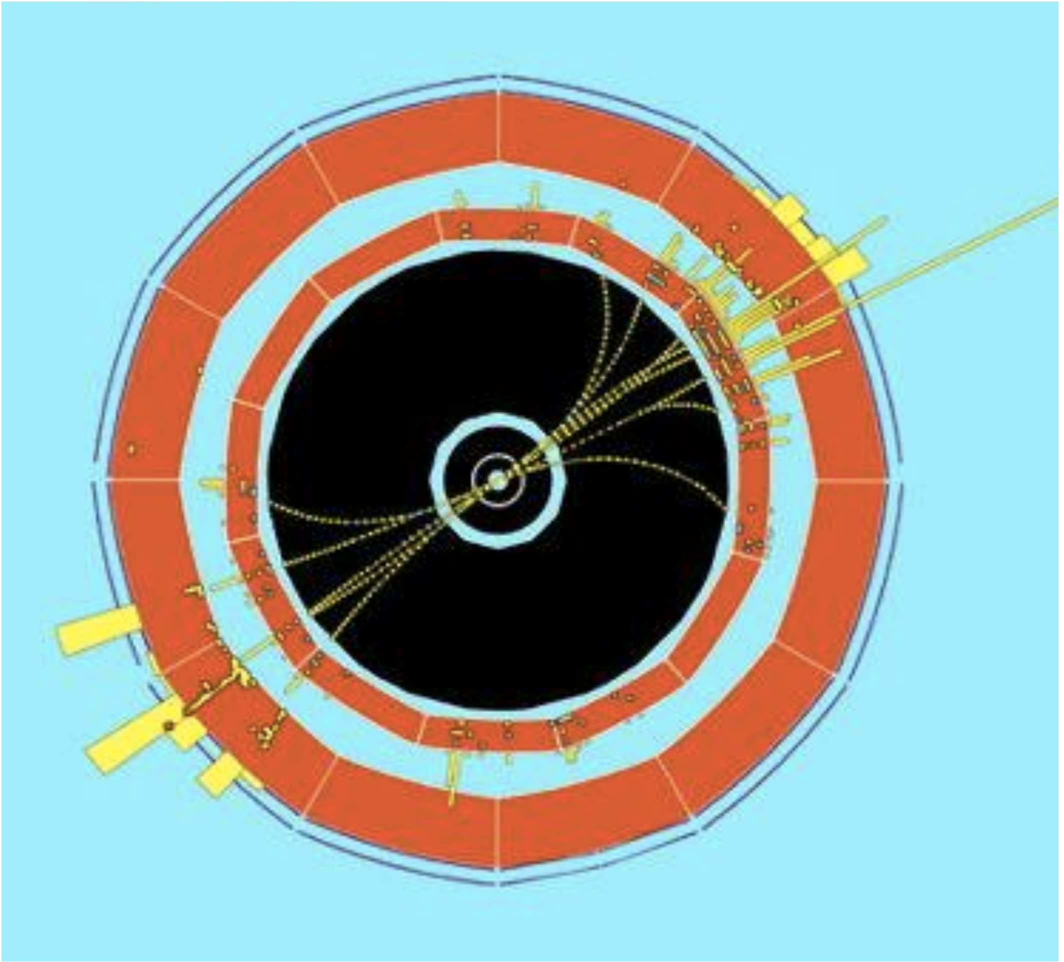


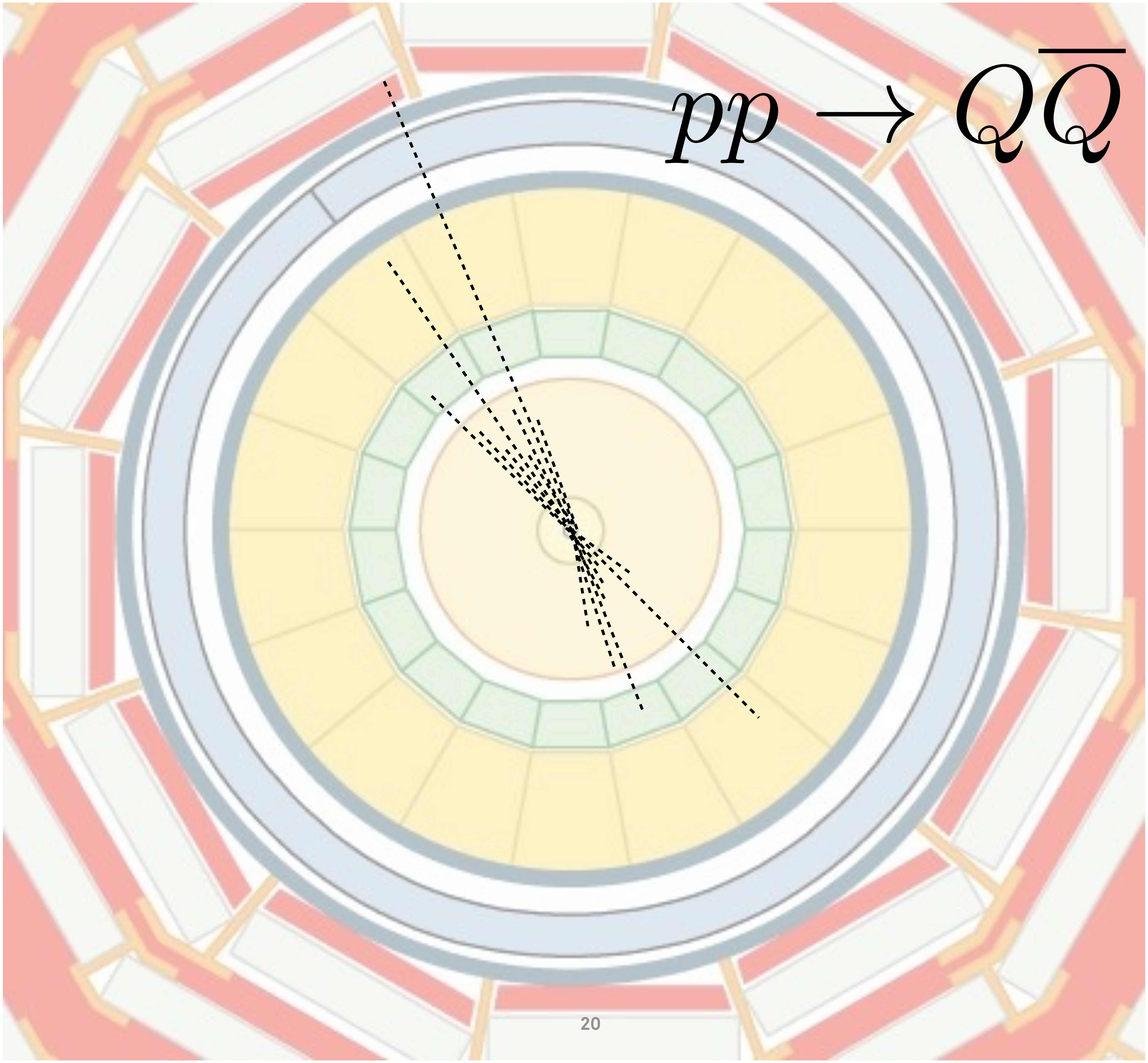
QCD JETS

Quark production at LEP:



ALEPH event

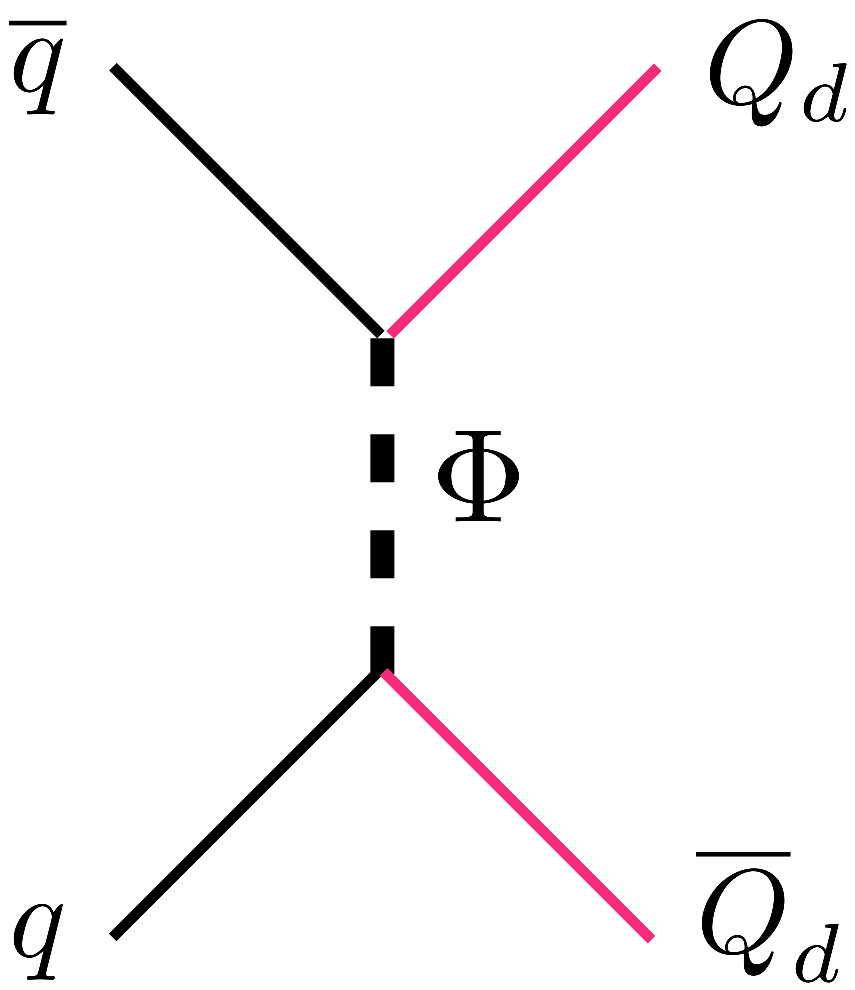



$pp \to Q\overline{Q}$

PION DECAY

Operator used to generate asymmetry mediates decay:

$$\overline{Q}\,\Phi\,d_i$$



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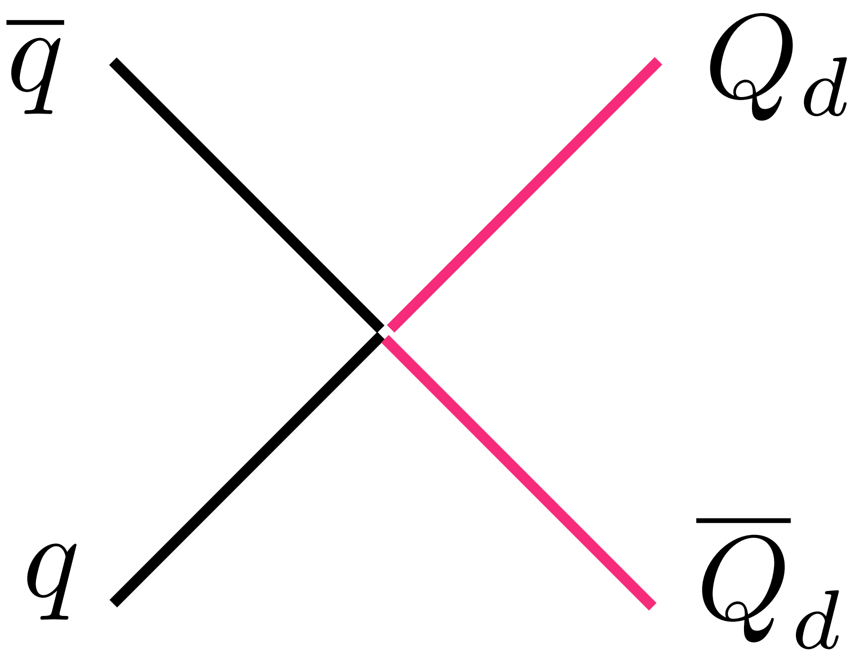
Integrate out Φ



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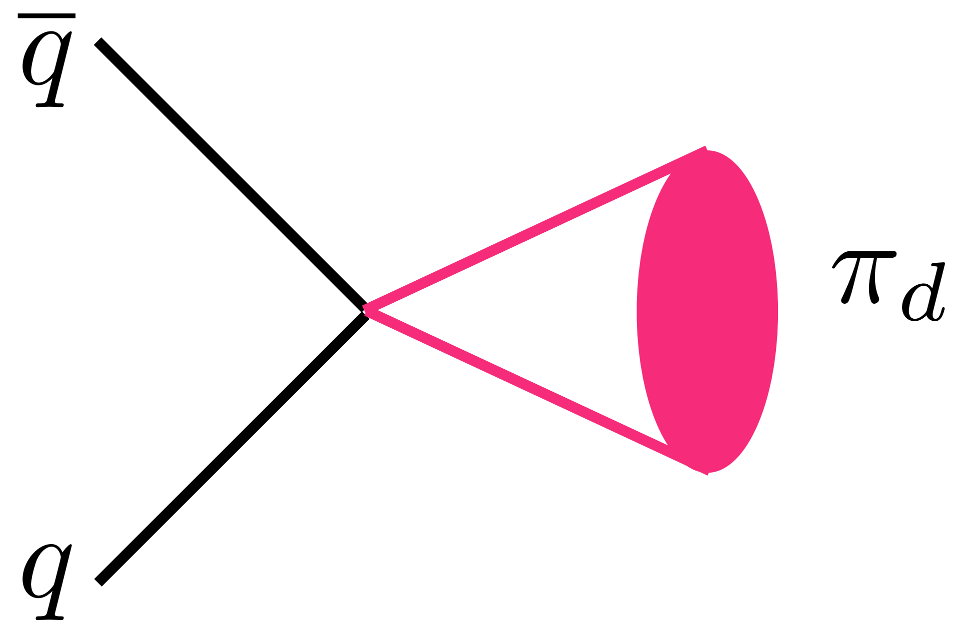
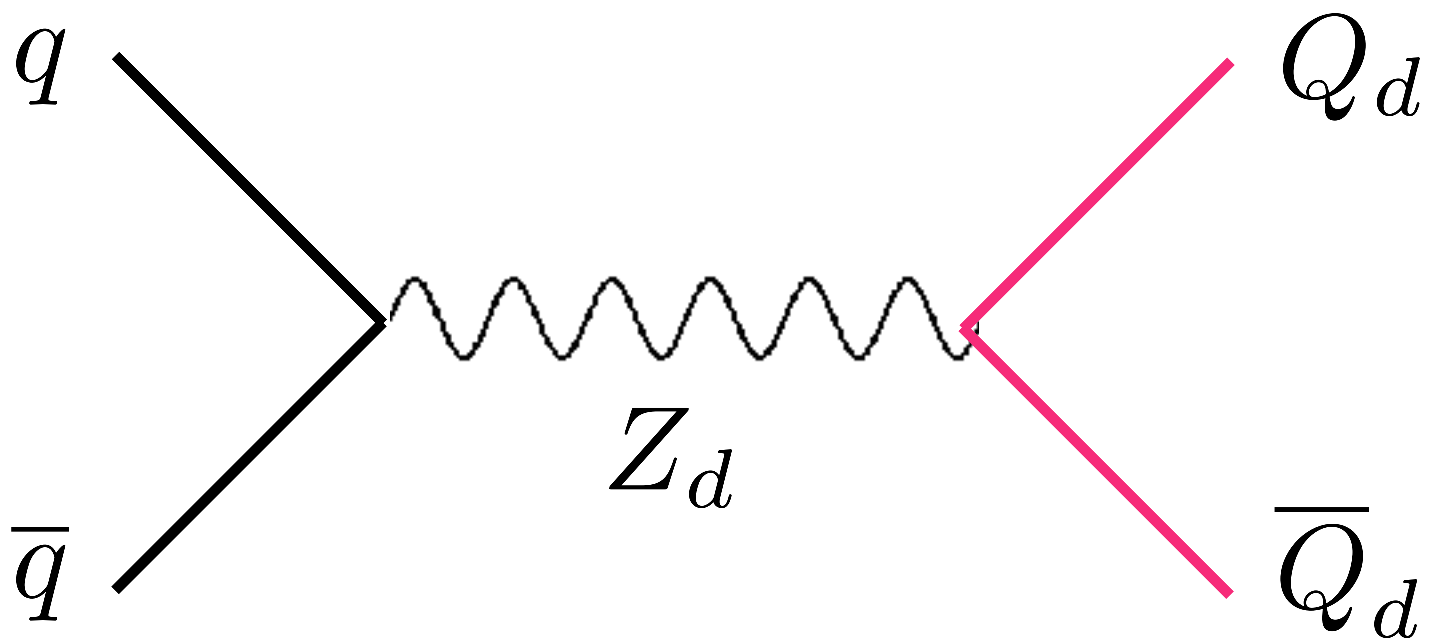


Dark pion decays to quarks

PION DECAY

Same story for Z_d model:



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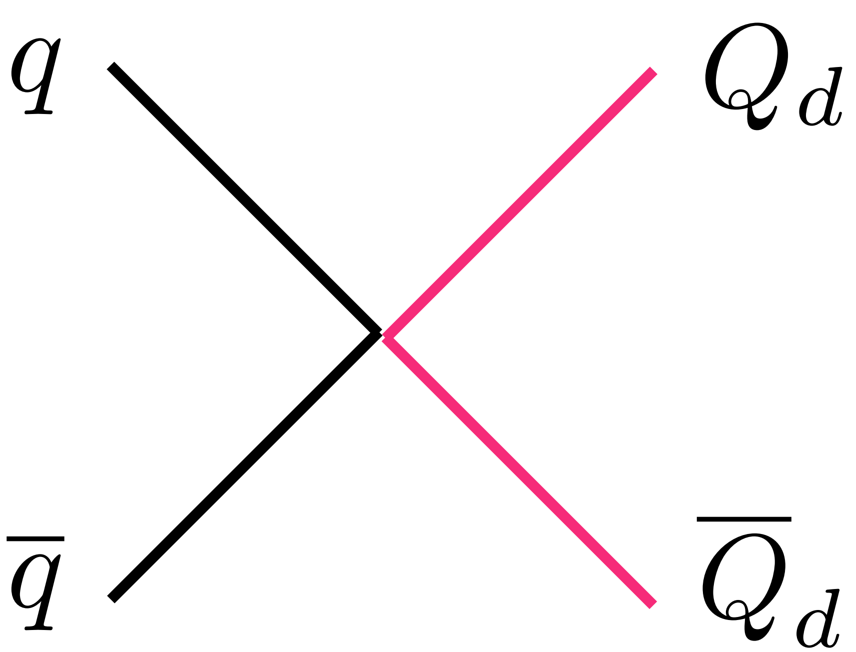

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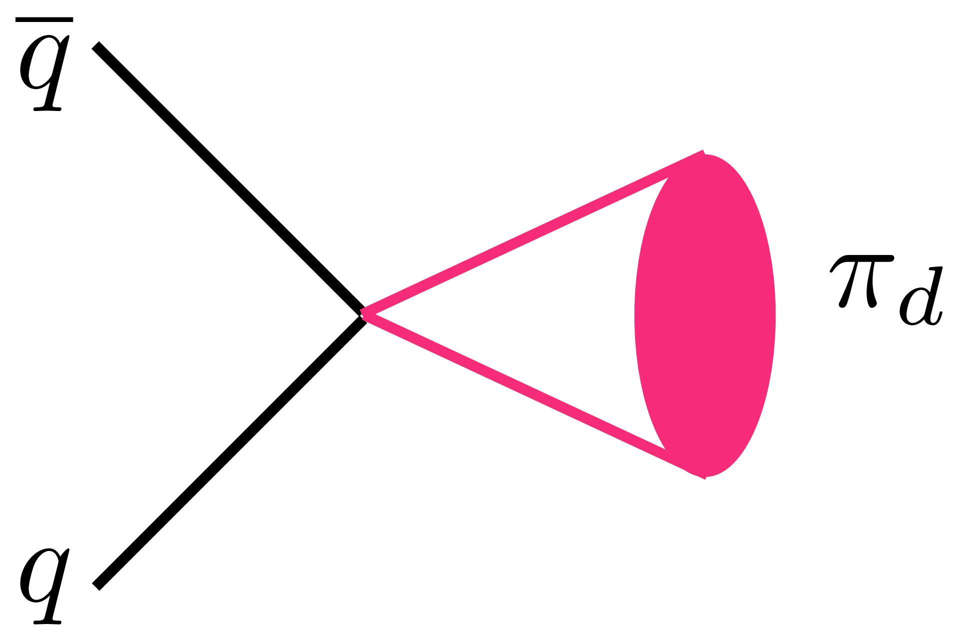
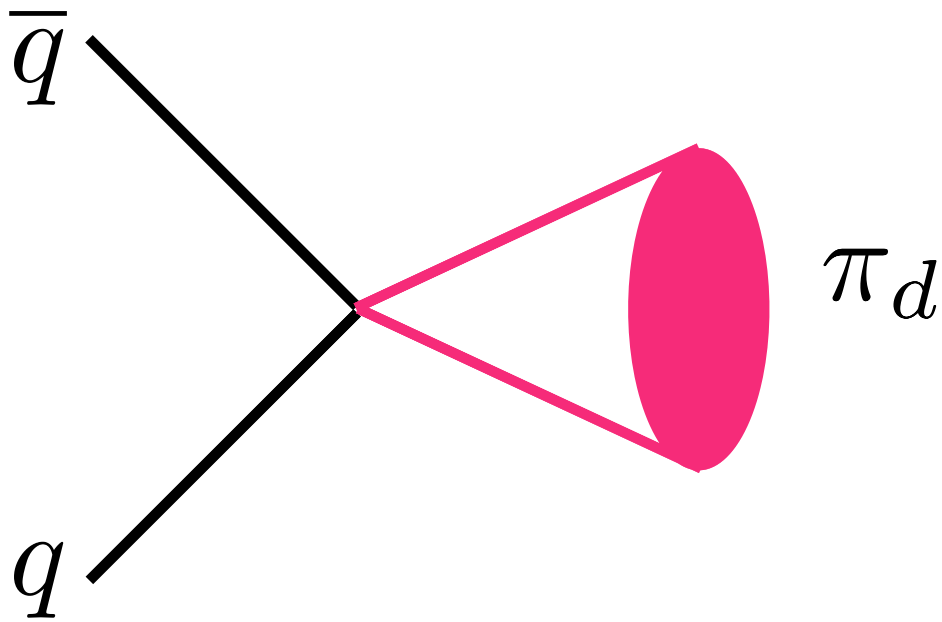


DECAY LENGTH



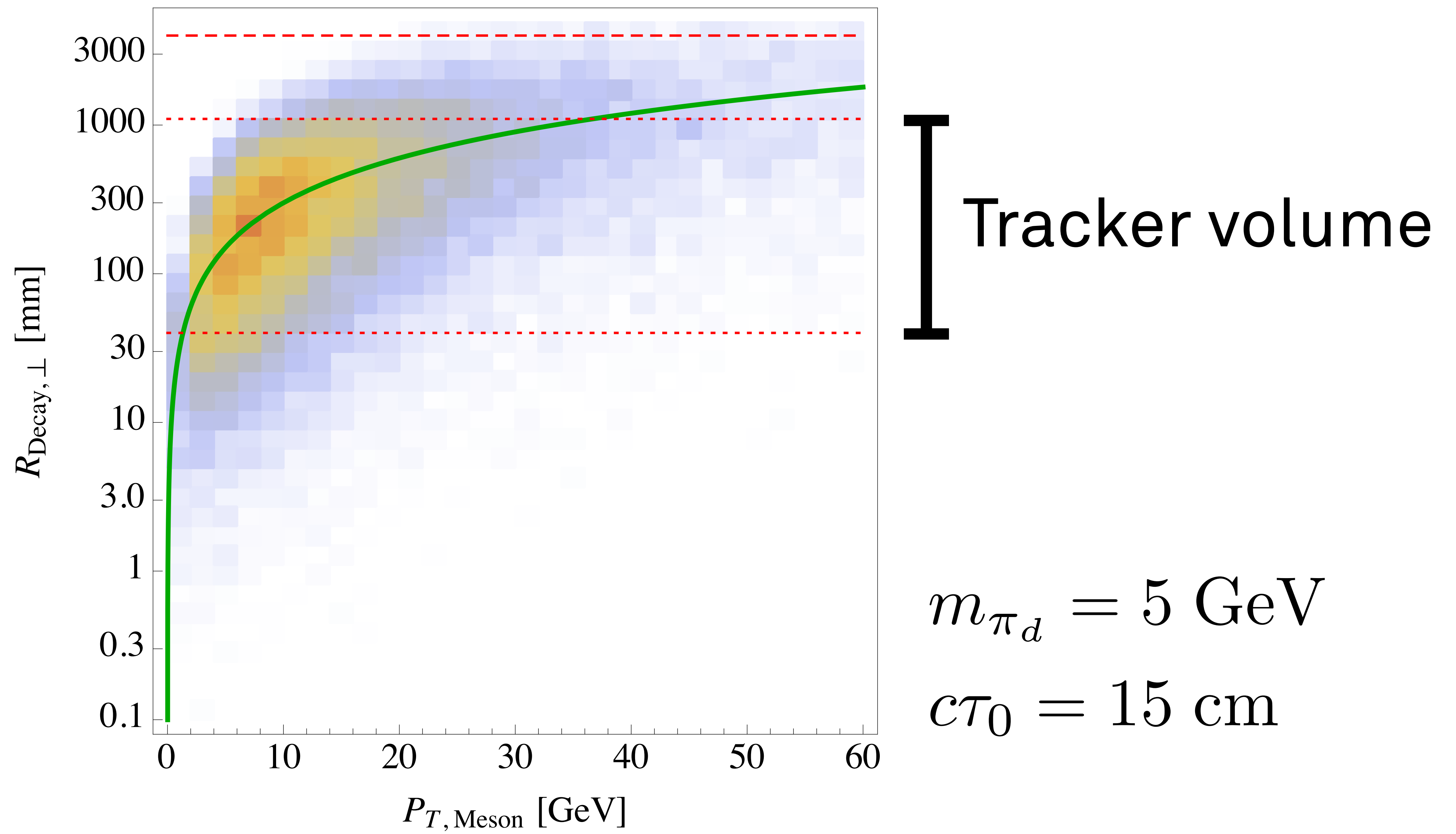
$$\frac{1}{M_X^2}\overline{Q}\gamma_\mu Q\,\bar{d}_R\gamma^\mu d_R$$

Can use (dark) chiral Lagrangian to estimate:

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

$$c\tau_0 \approx 10\,\mathrm{cm} \times \left(\frac{2\ \mathrm{GeV}}{f_{\pi_d}}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_{\mathrm{down}}}\right)^2 \left(\frac{2\ \mathrm{GeV}}{m_{\pi_d}}\right) \left(\frac{M_{X_d}}{1\ \mathrm{TeV}}\right)^4$$

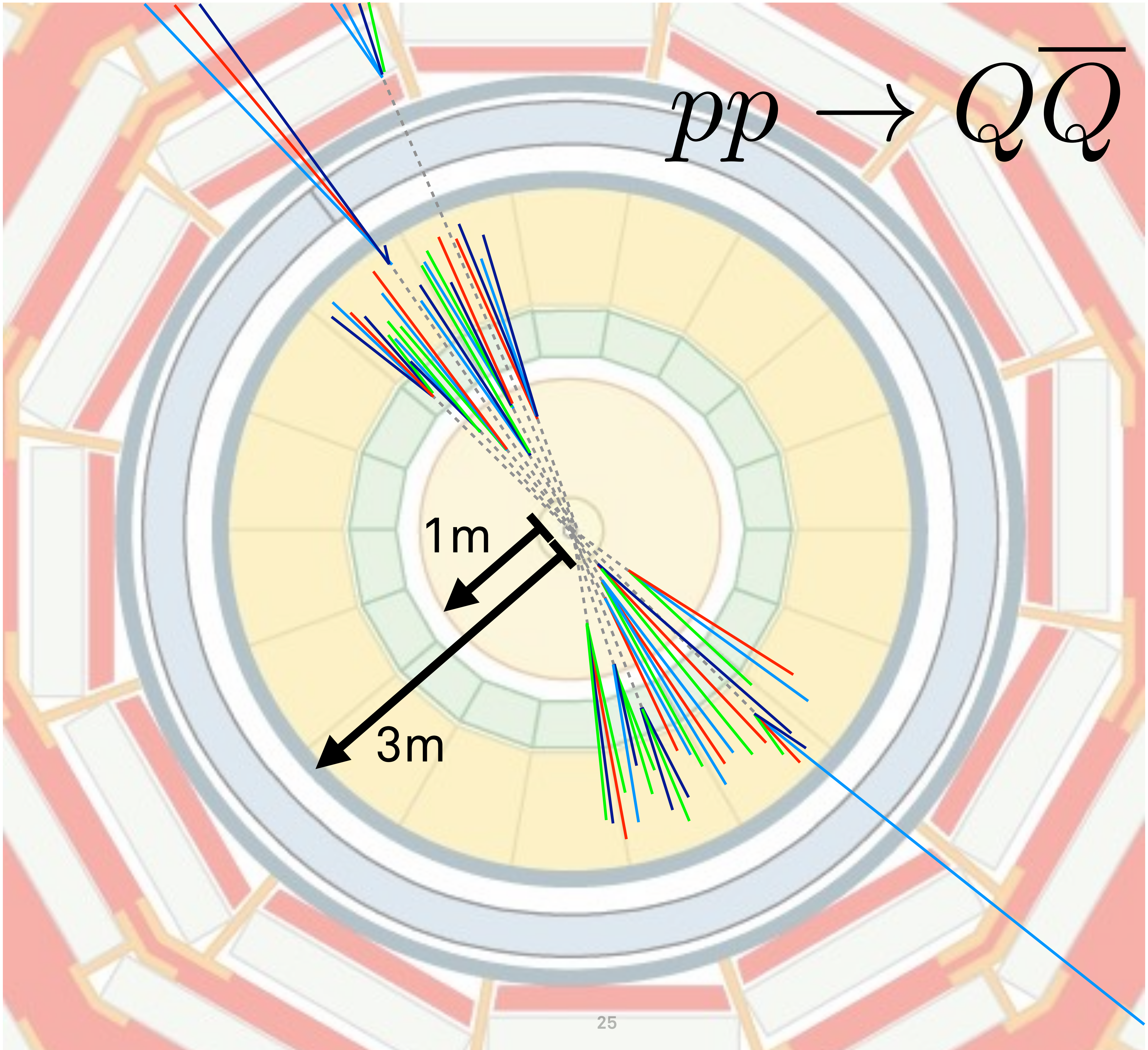
DECAY LENGTH

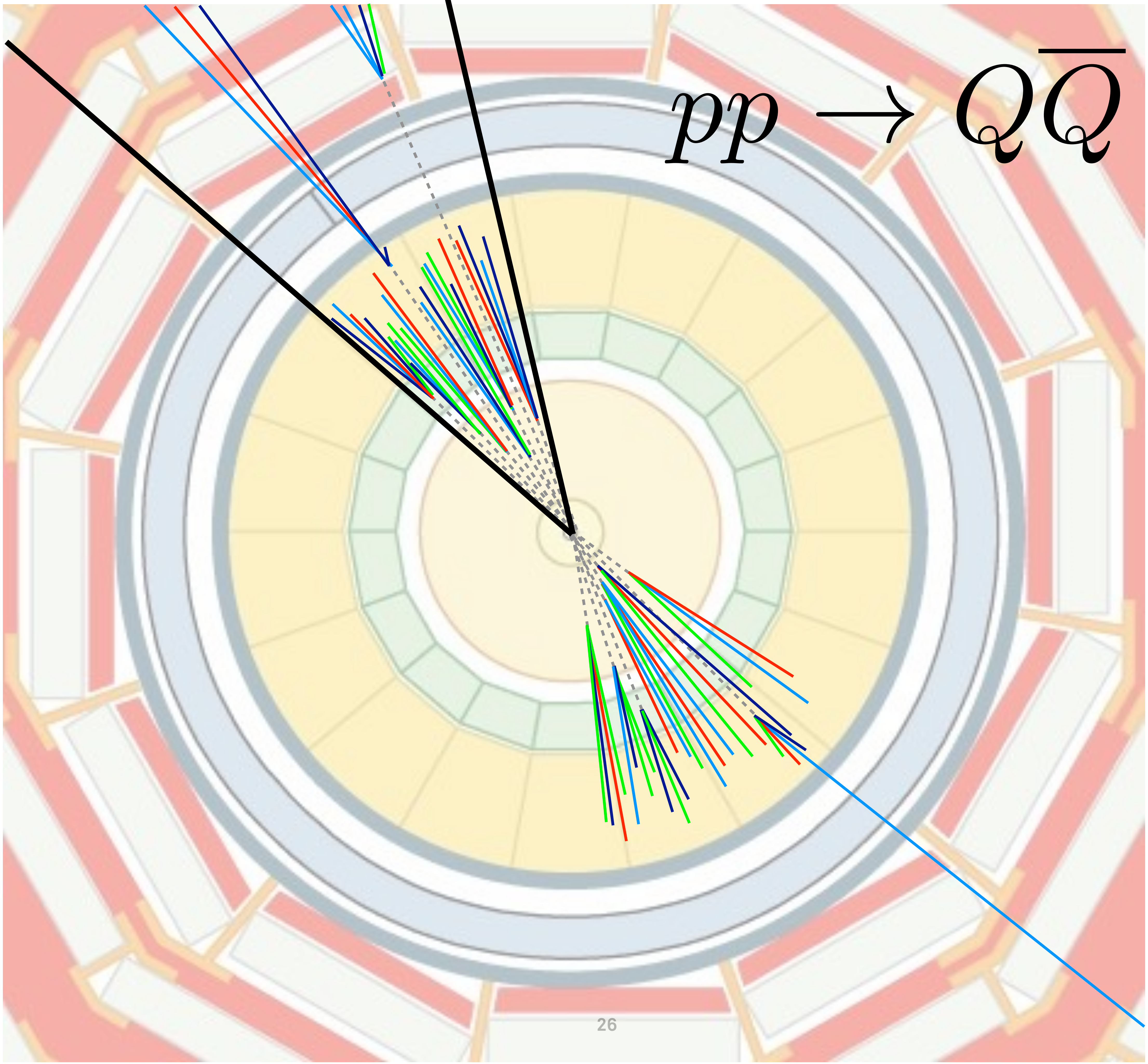


$m_{\pi_d} = 5$ GeV

$c\tau_0 = 15$ cm

$$c\tau_0 \approx 10\,\text{cm} \times \left(\frac{2\ \text{GeV}}{f_{\pi_d}}\right)^2 \left(\frac{100\ \text{MeV}}{m_{\text{down}}}\right)^2 \left(\frac{2\ \text{GeV}}{m_{\pi_d}}\right) \left(\frac{M_{X_d}}{1\ \text{TeV}}\right)^4$$


$pp \to Q\overline{Q}$
1m
3m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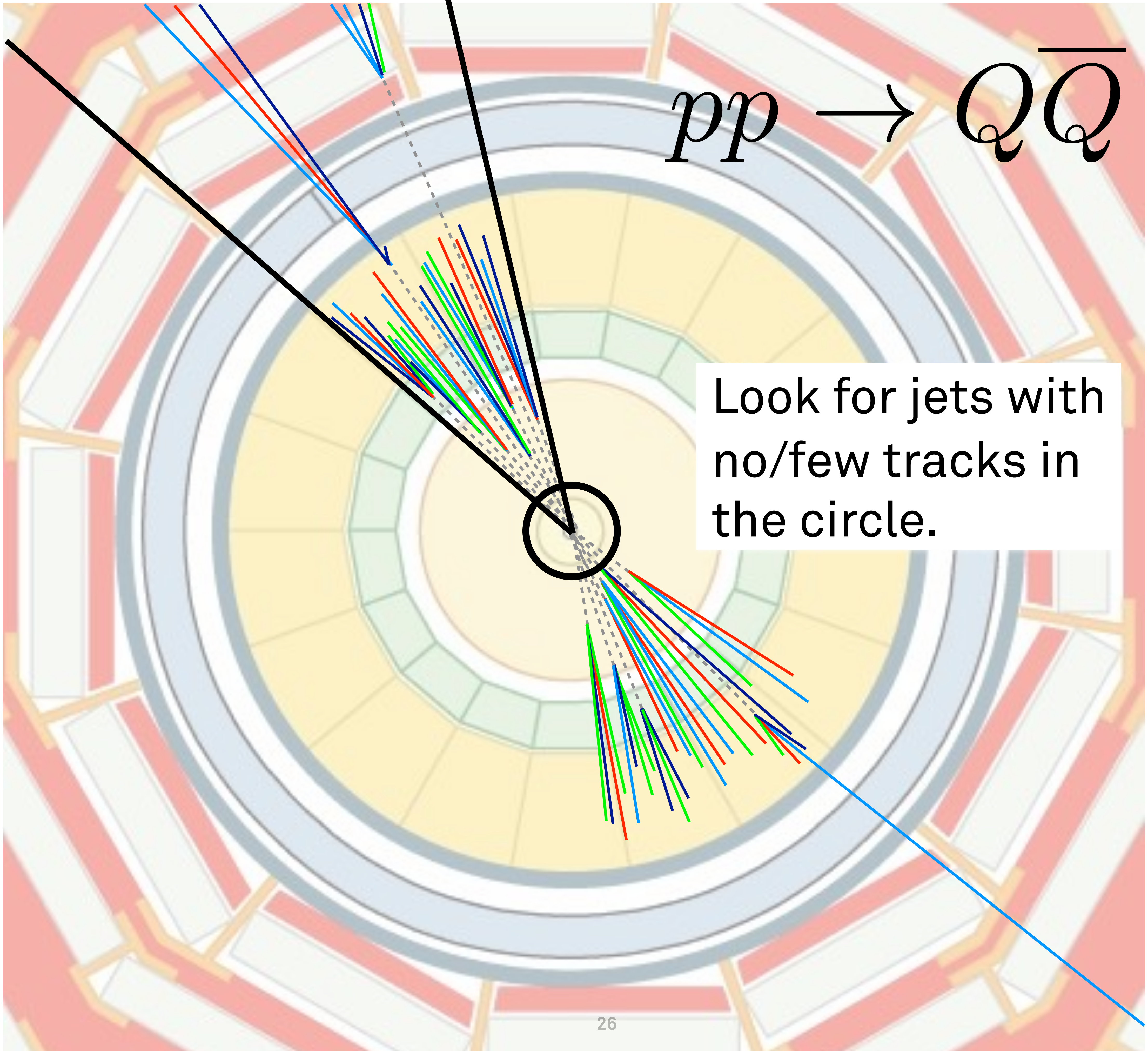
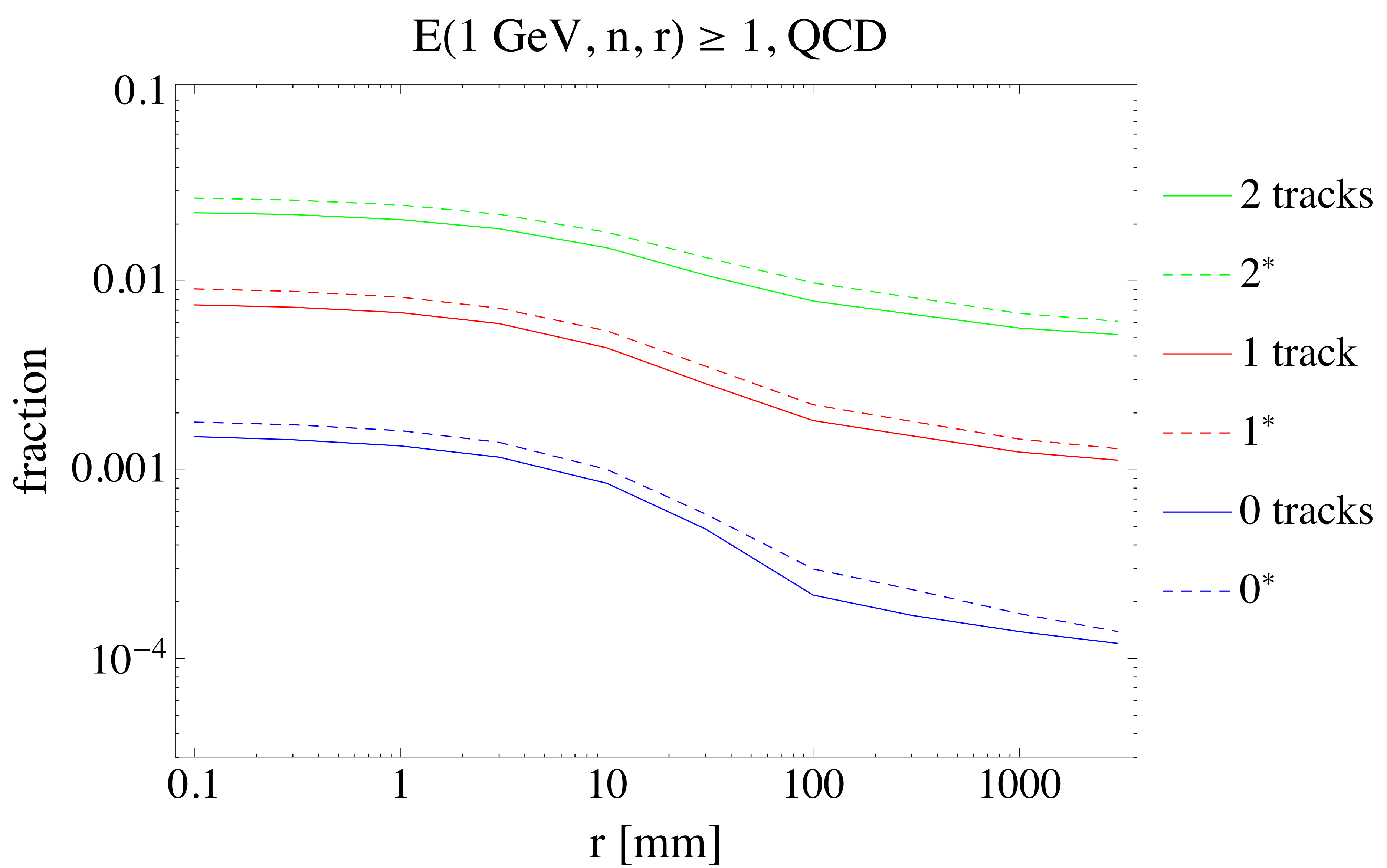

$pp \to Q\overline{Q}$
Look for jets with no/few tracks in the circle.

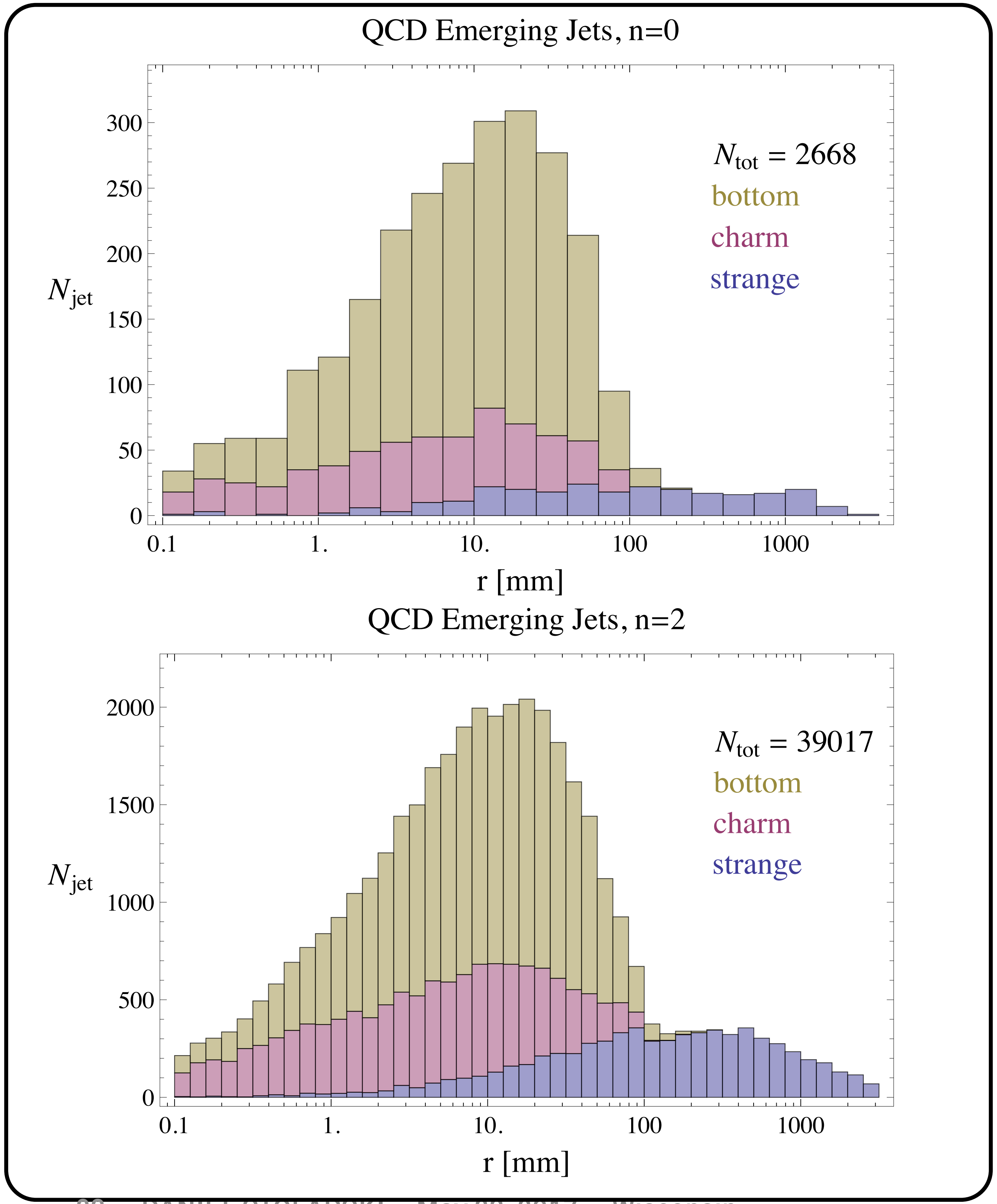
BACKGROUND?

QCD 4-jet production in PYTHIA 8 $p_T > 200\ \mathrm{GeV}$



* - modified Pythia tune to increase QCD contribution

BACKGROUND COMPOSITION

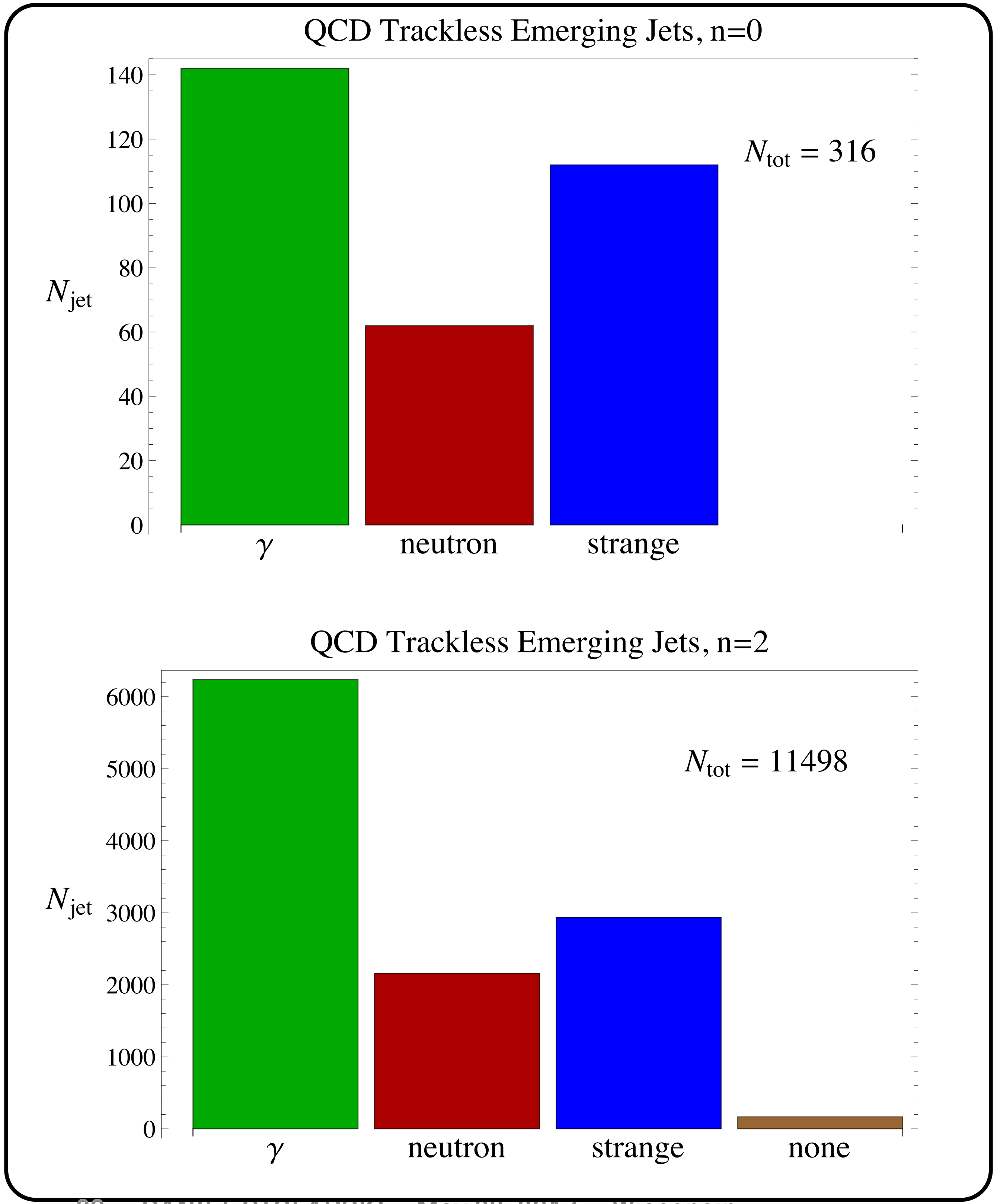


Flavor of earliest decaying track.

track $p_T > 1$ GeV

jet $p_T > 200$ GeV

TRACKLESS BACKGROUND



Composition of completely trackless background.

track $p_T > 1$ GeV

jet $p_T > 200$ GeV

DARK SECTOR

Choose two benchmarks:

	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

$$N_c = 3 \text{ and } n_f = 7$$

Dark QCD already in PYTHIA!

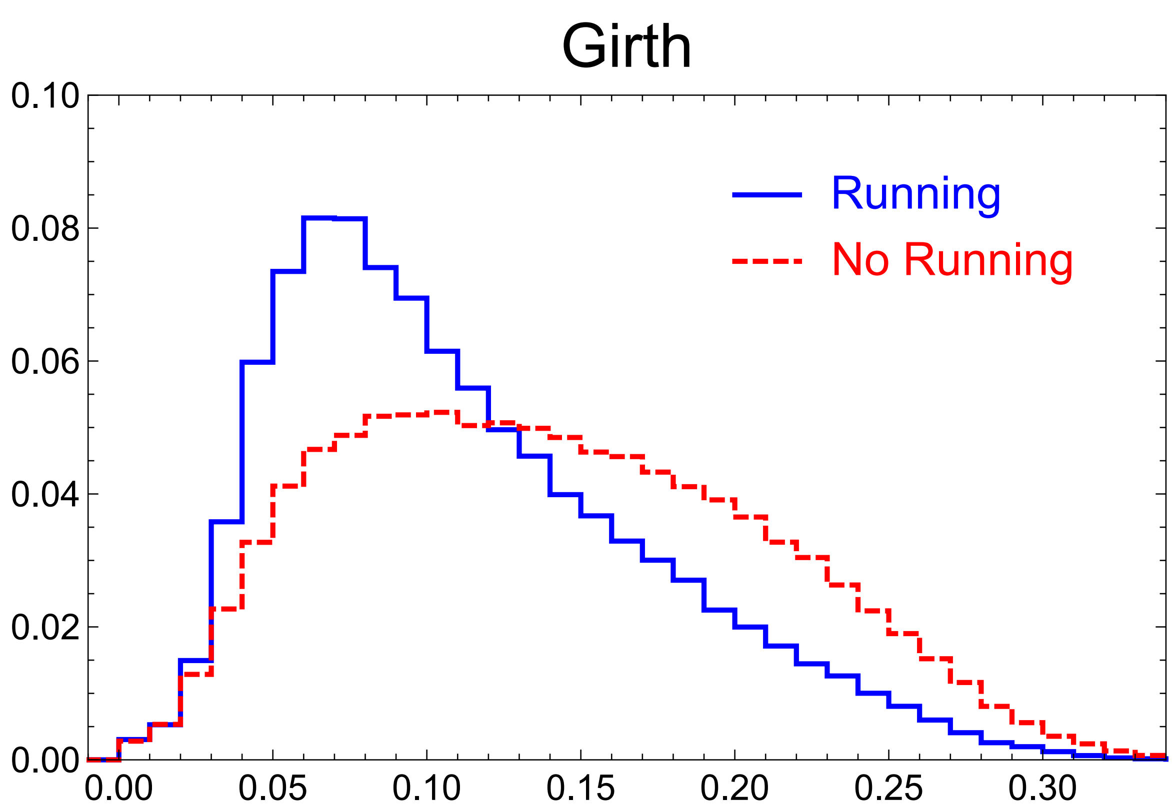
Carloni, Sjorstrand, 2010.

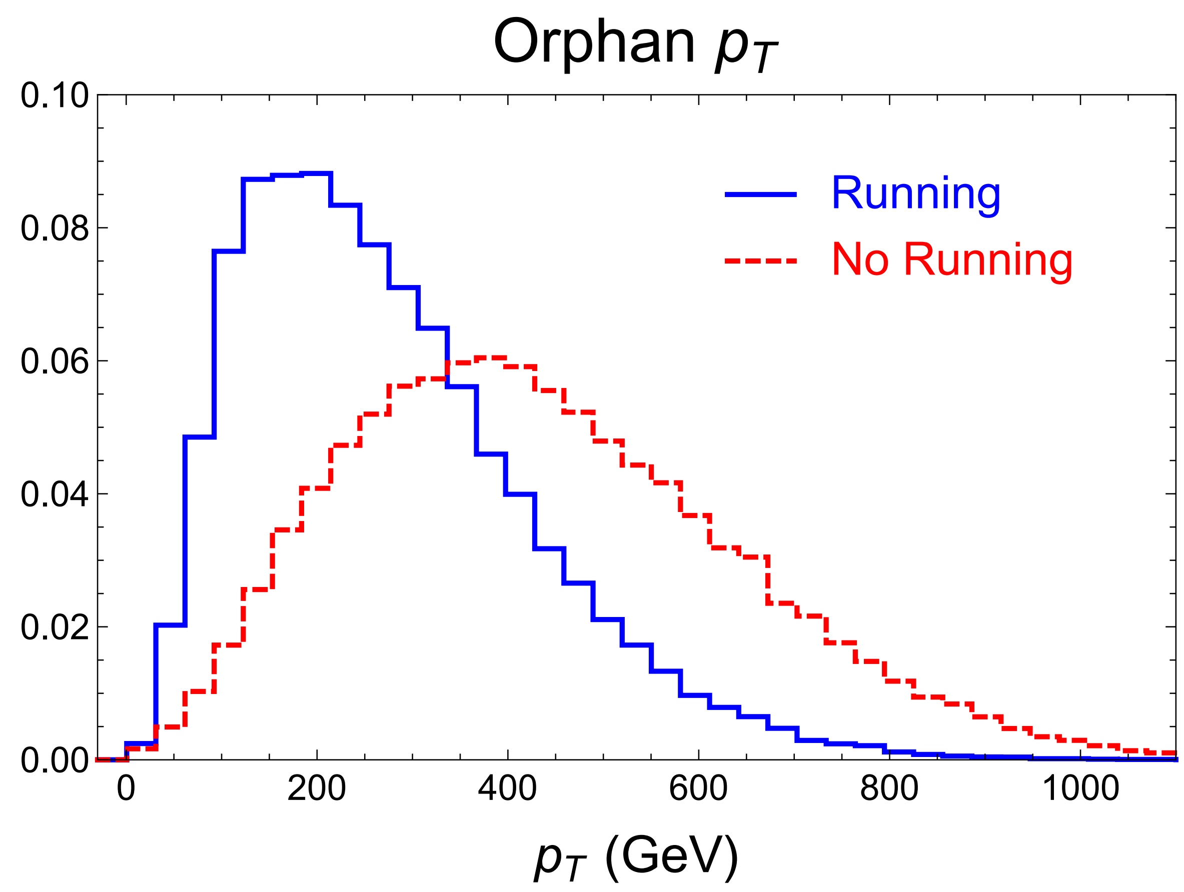
Carloni, Rathsman, Sjorstrand, 2011.

Run modified version with running.

COUPLING RUNNING

Modify PYTHIA to include gauge coupling running (current version now includes running).



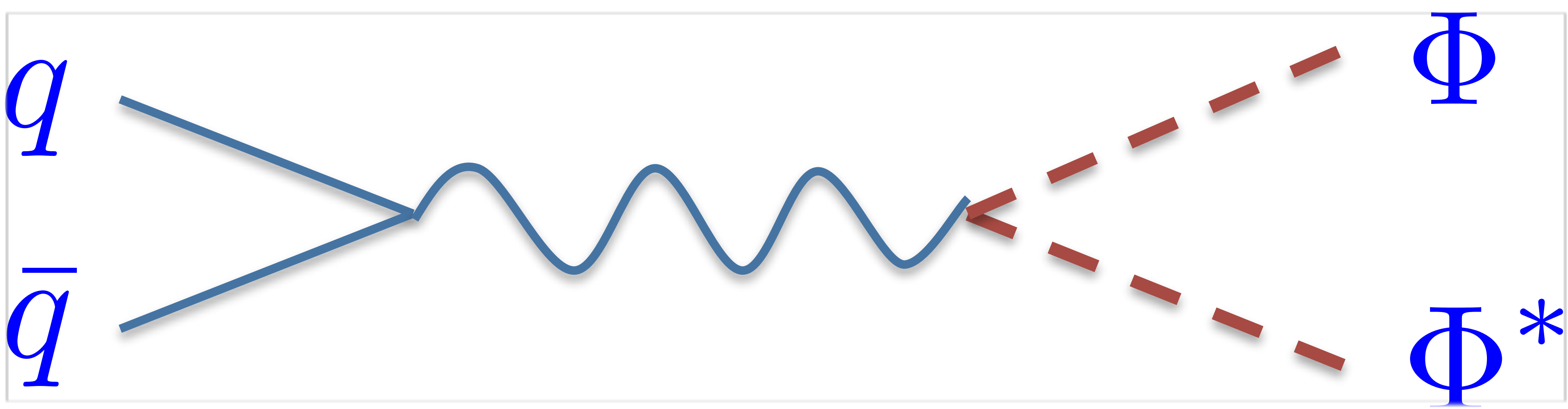


$$\text{girth} = \frac{1}{p_T^{\text{jet}}} \sum_i p_T^i \, \Delta R_i$$

p_T not in jets with $p_T > 200$ GeV

BENCHMARK MEDIATOR 1

$$pp \to \Phi\Phi^\dagger \to \bar{q}\, Q_d\, \overline{Q}_d\, q$$



BENCHMARK MEDIATOR 1

$$pp \to \Phi\Phi^\dagger \to \bar{q}\, Q_d\, \overline{Q}_d\, q$$

Final state is

- 2 QCD jets
- 2 emerging jets

Cross section is stop-like

$$\sigma \approx \text{ few} \times \sigma(pp \to \tilde{t}_1 \tilde{t}_1)$$

$$\sigma(M_\Phi = 1\,\text{TeV}) \approx 10\,\text{fb}$$

@ LHC14

BENCHMARK MEDIATOR 2

$$pp \to Z_d \to Q_d \, \overline{Q}_d$$

Final state is

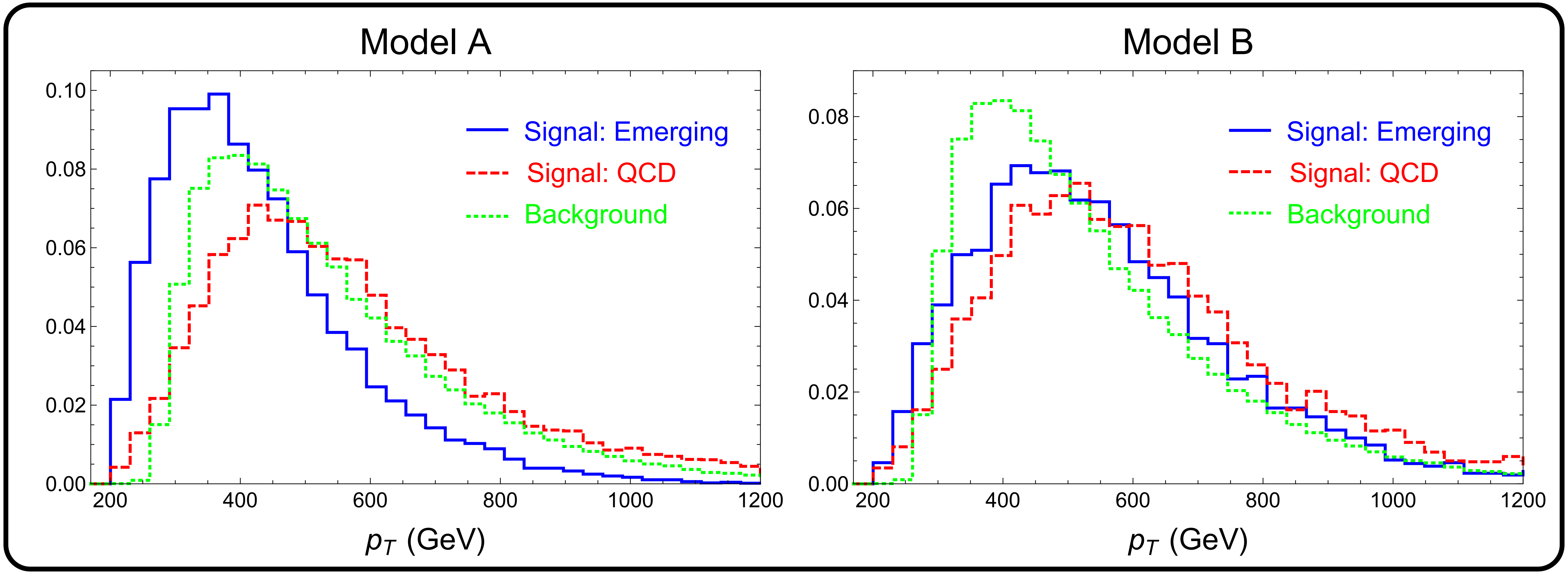
- 2 emerging jets

Cross section depends on couplings.

Work in progress.

JET MOMENTA

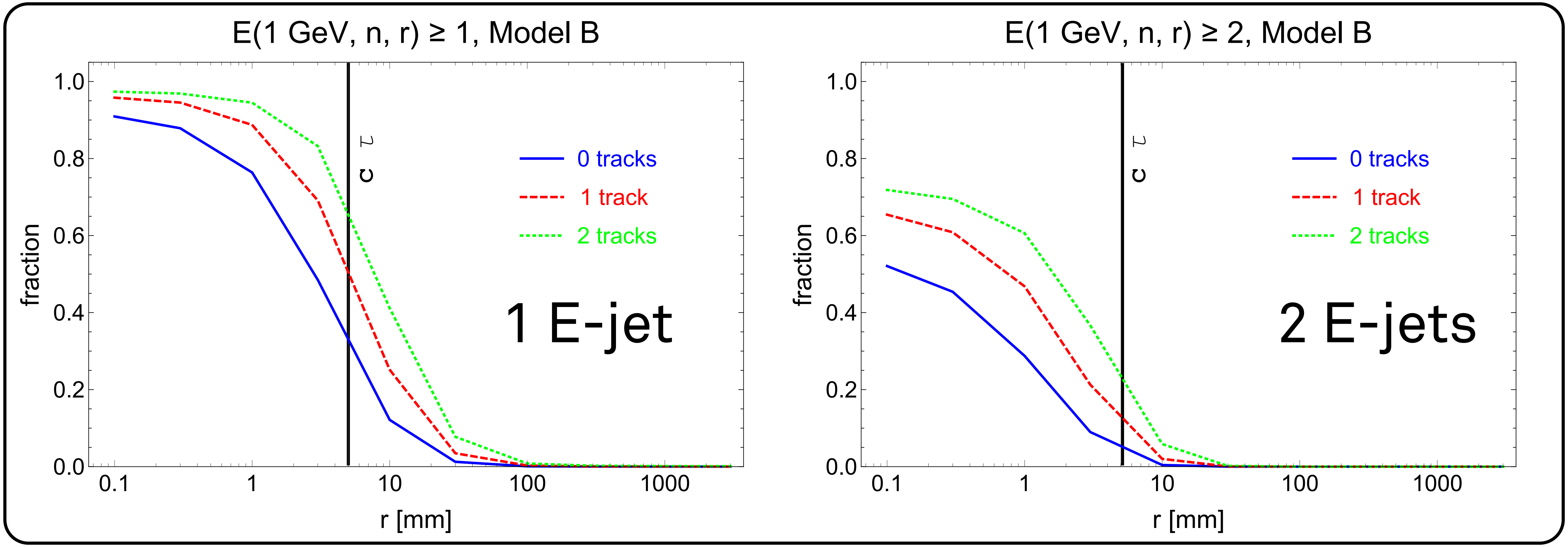
Hardest jet p_T



Four hard jets is enough to pass trigger for high mass mediator. (What about low mass?)

SEARCH STRATEGY

$$pp \to \Phi\Phi^\dagger \to \bar{q}\, Q_d\, \bar{Q}_d\, q$$



$$m_{\pi_d} = 2\ \mathrm{GeV} \qquad c\tau_{\pi_d} = 5\ \mathrm{mm}$$

CUT FLOW

Cross sections in fb at LHC14:

	Model **A**	Model **B**	QCD 4-jet	Modified PYTHIA
Tree level	14.6	14.6	410,000	410,000
≥ 4 jets, $\lvert\eta\rvert < 2.5$ $p_T(\text{jet}) > 200$ GeV $H_T > 1000$ GeV	4.9	8.4	48,000	48,000

Paired di-jet resonance search very difficult!

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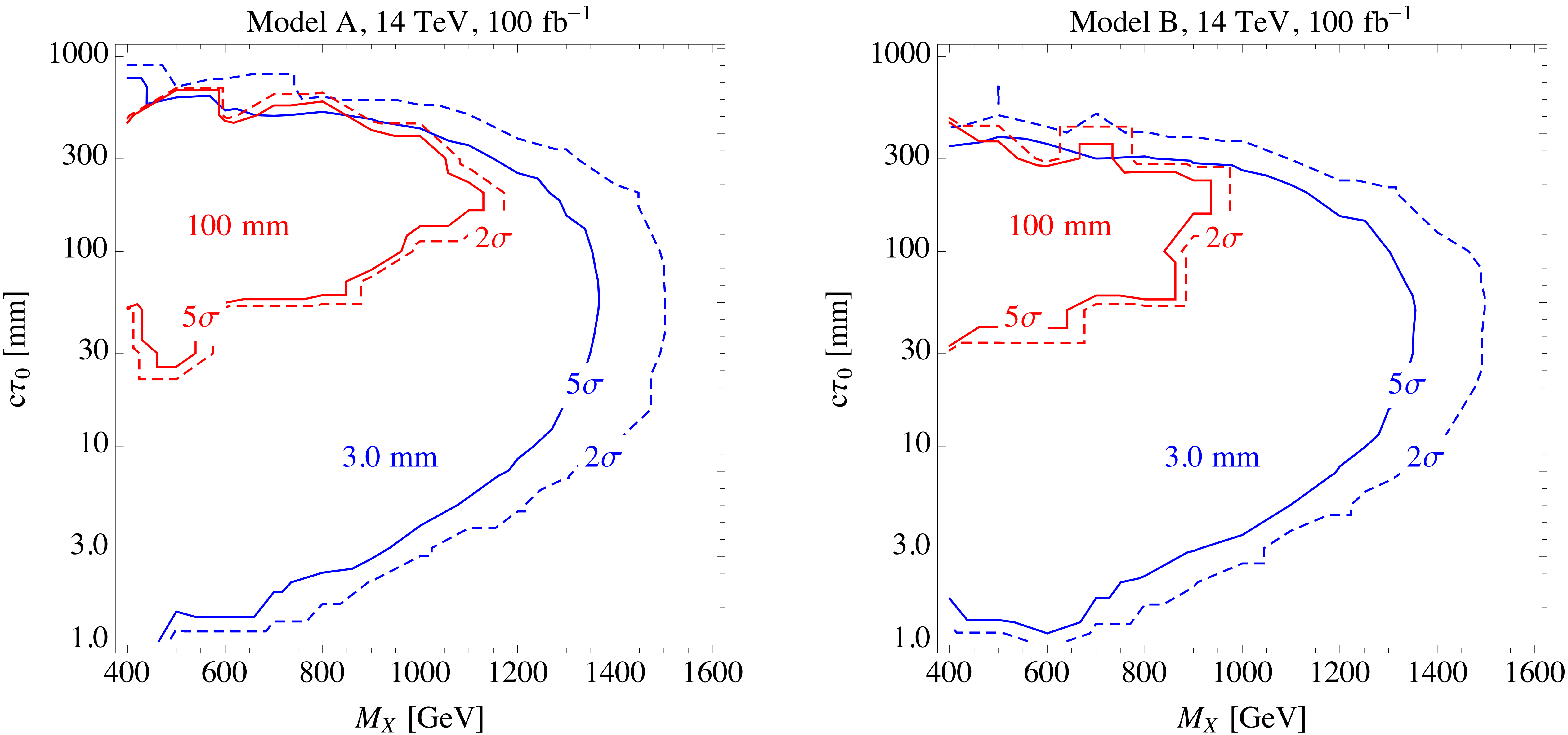
$E(1\,\text{GeV}, 0, 3\,\text{mm}) \geq 1$	4.1	4.1	54	67
$E(1\,\text{GeV}, 0, 3\,\text{mm}) \geq 2$	1.8	0.8	~ 0.08	~ 0.04
$E(1\,\text{GeV}, 0, 100\,\text{mm}) \geq 1$	1.7	$\lesssim 0.01$	11	15
$E(1\,\text{GeV}, 0, 100\,\text{mm}) \geq 2$	0.2	$\lesssim 0.01$	$\lesssim 0.02$	$\lesssim 0.02$

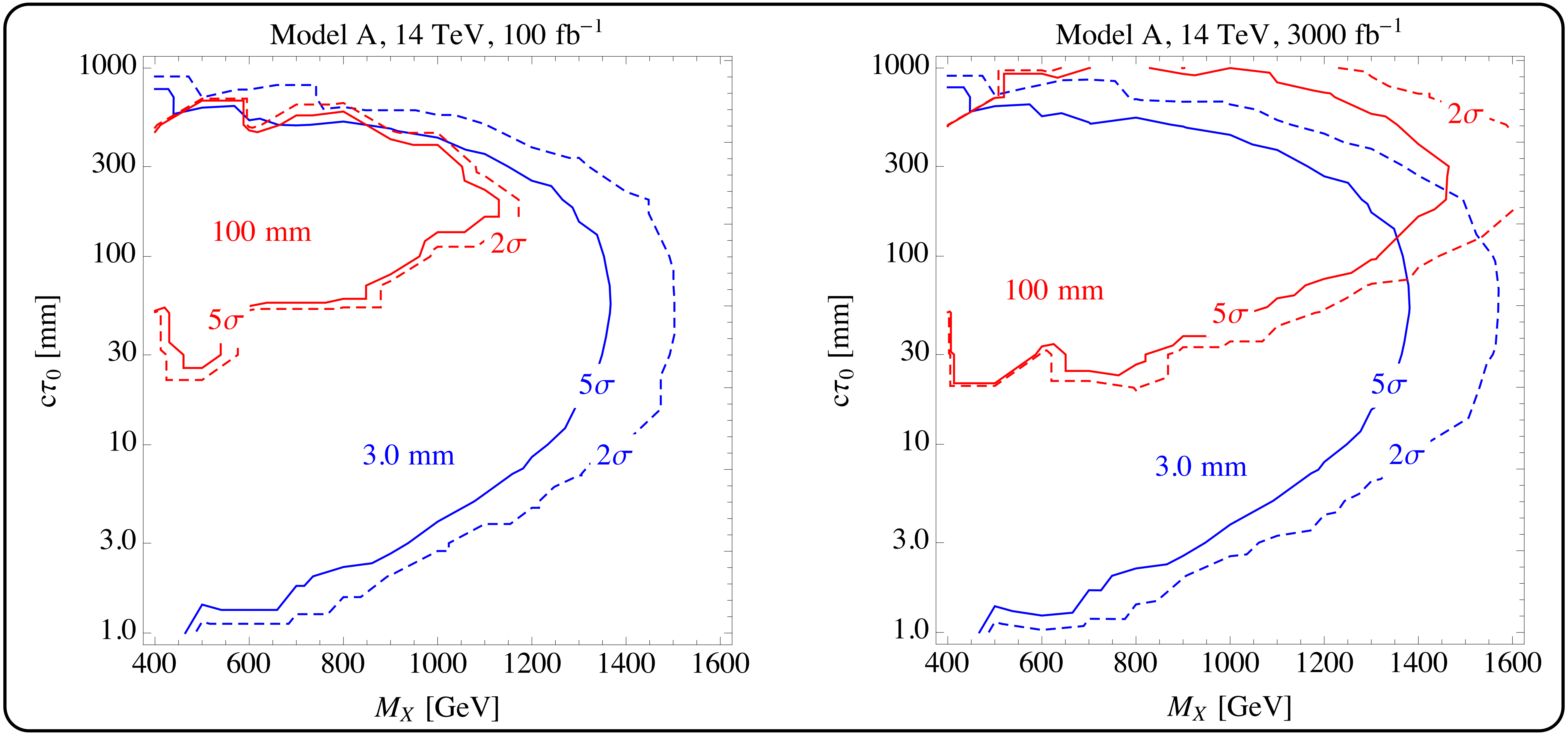
Requiring emerging jets changes the game.

REACH



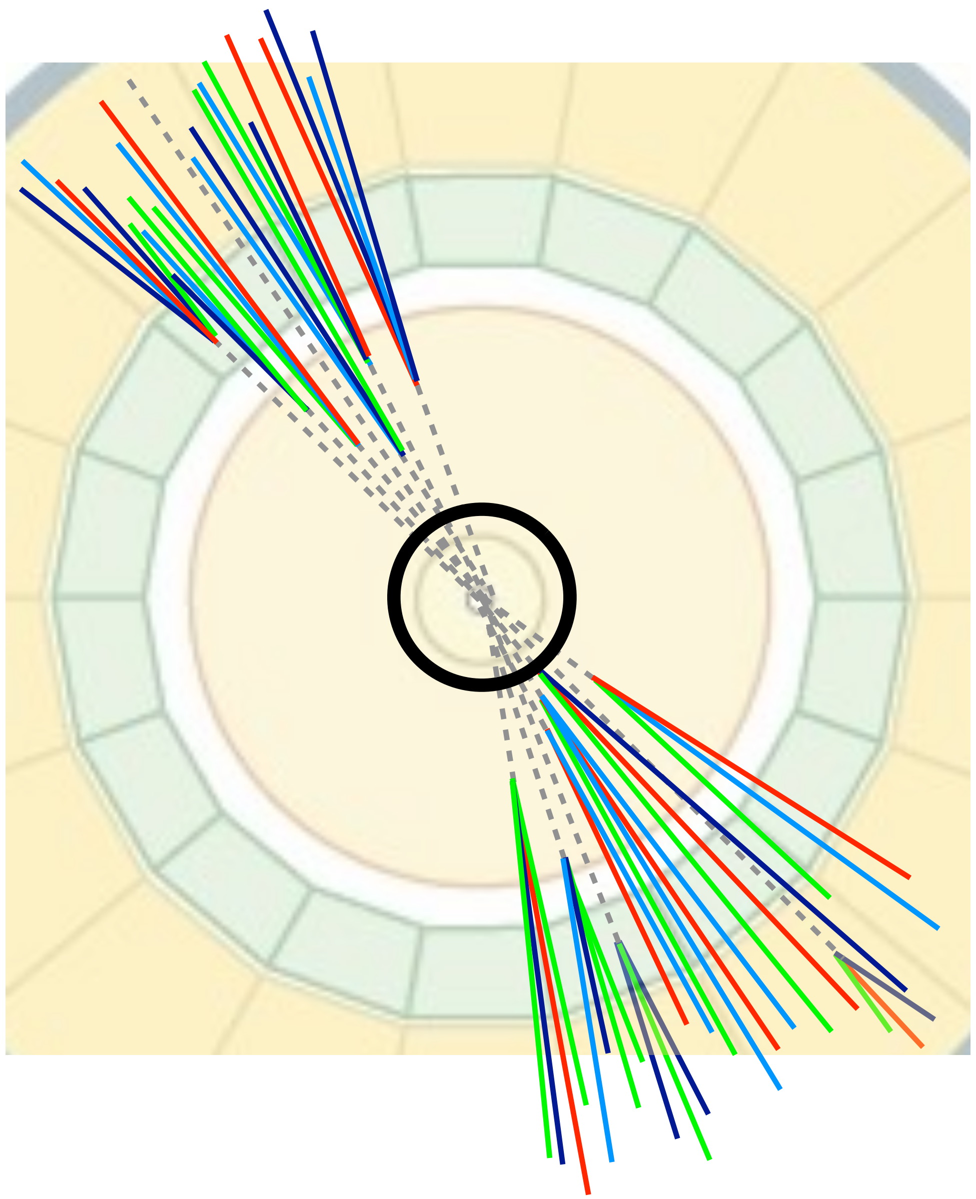
Assume 100% systematic error on background.

HIGH LUMI-LHC



Better reach with high luminosity.

ALTERNATIVE STRATEGY

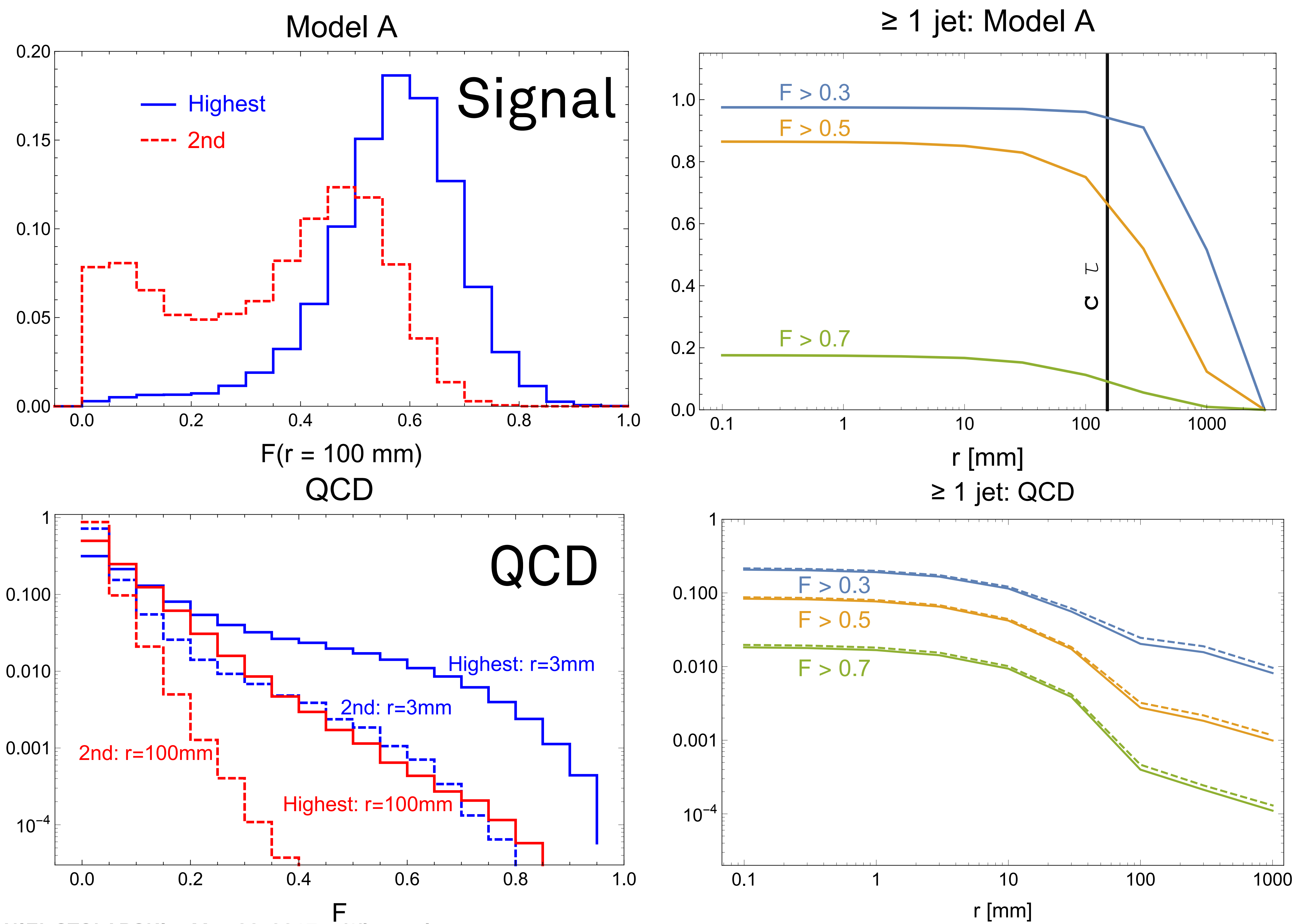


Fraction of jet energy reconstructing outside of circle.

Neutrals (photon, neutron) do not contribute, hard to get F=1.

Much more robust to pile-up.

F DISTRIBUTIONS



ALTERNATIVE CUT FLOW

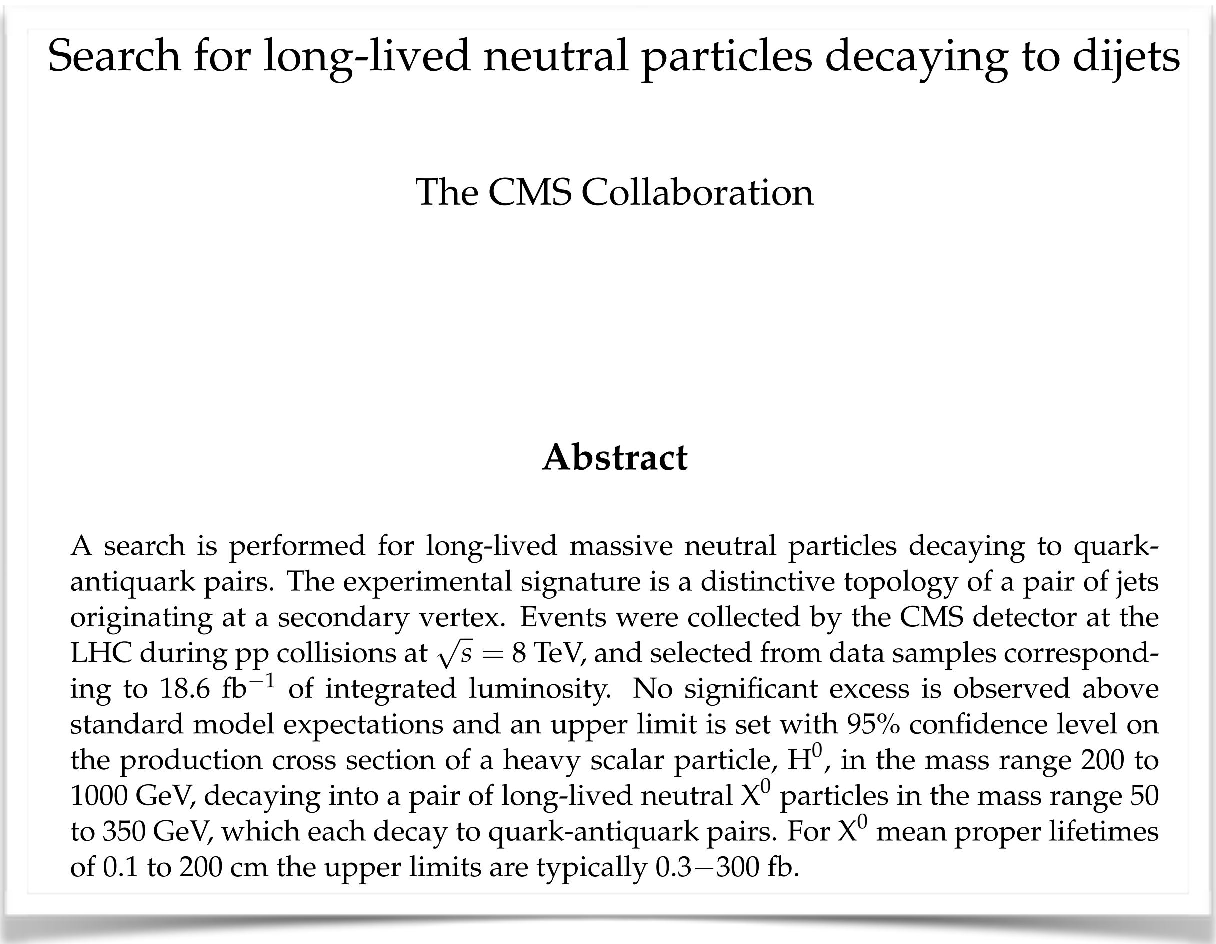
Cross sections in fb:

	Model **A**	Model **B**	QCD 4-jet	Modified PYTHIA
≥ 4 jets, $\lvert\eta\rvert < 2.5$ $p_T(\text{jet}) > 200$ GeV $H_T > 1000$ GeV	4.9	8.5	48,000	48,000
1 jet $F(100\text{ mm}) > 0.5$	3.7	1.9	130	150
2 jets $F(100\text{ mm}) > 0.5$	1.2	0.1	0.2	0.2
$\sigma(100\,\text{fb}^{-1})$	5.9	0.5	-	-

b-jet background too large at *r*=10 mm.

Works pretty well at *r*=100 mm.

CMS SEARCH



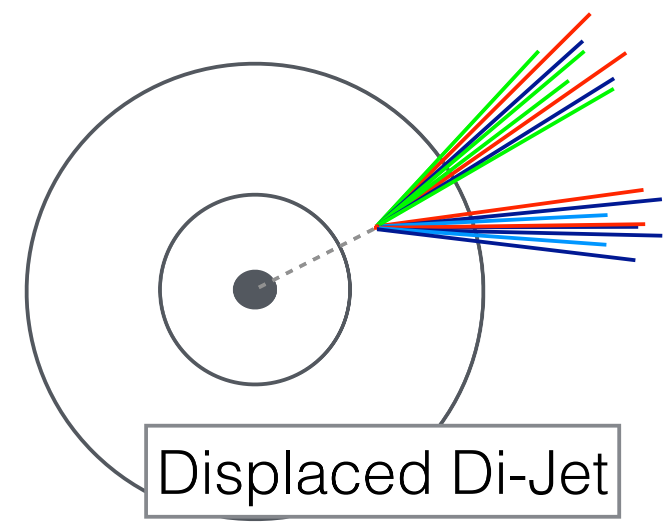
Search for long-lived neutral particles decaying to dijets

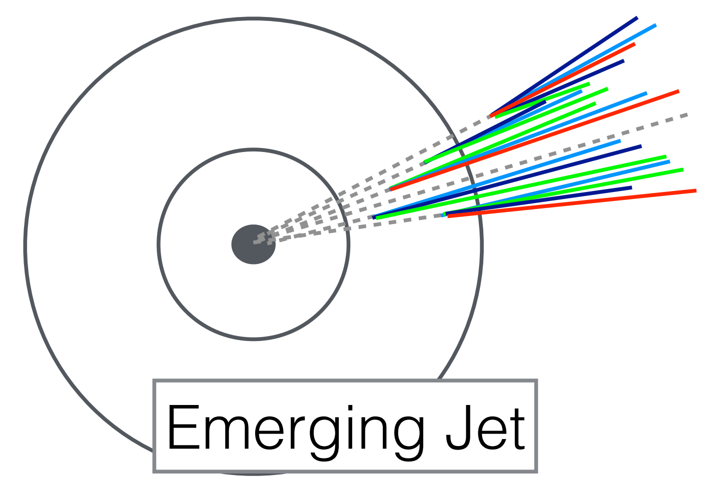
The CMS Collaboration

Abstract

A search is performed for long-lived massive neutral particles decaying to quark-antiquark pairs. The experimental signature is a distinctive topology of a pair of jets originating at a secondary vertex. Events were collected by the CMS detector at the LHC during pp collisions at $\sqrt{s} = 8$ TeV, and selected from data samples corresponding to 18.6 fb^{-1} of integrated luminosity. No significant excess is observed above standard model expectations and an upper limit is set with 95% confidence level on the production cross section of a heavy scalar particle, H^0, in the mass range 200 to 1000 GeV, decaying into a pair of long-lived neutral X^0 particles in the mass range 50 to 350 GeV, which each decay to quark-antiquark pairs. For X^0 mean proper lifetimes of 0.1 to 200 cm the upper limits are typically 0.3−300 fb.

CMS Collaboration, Phys.Rev.D.91, 012017 (2015) [arXiv:1411.6530].





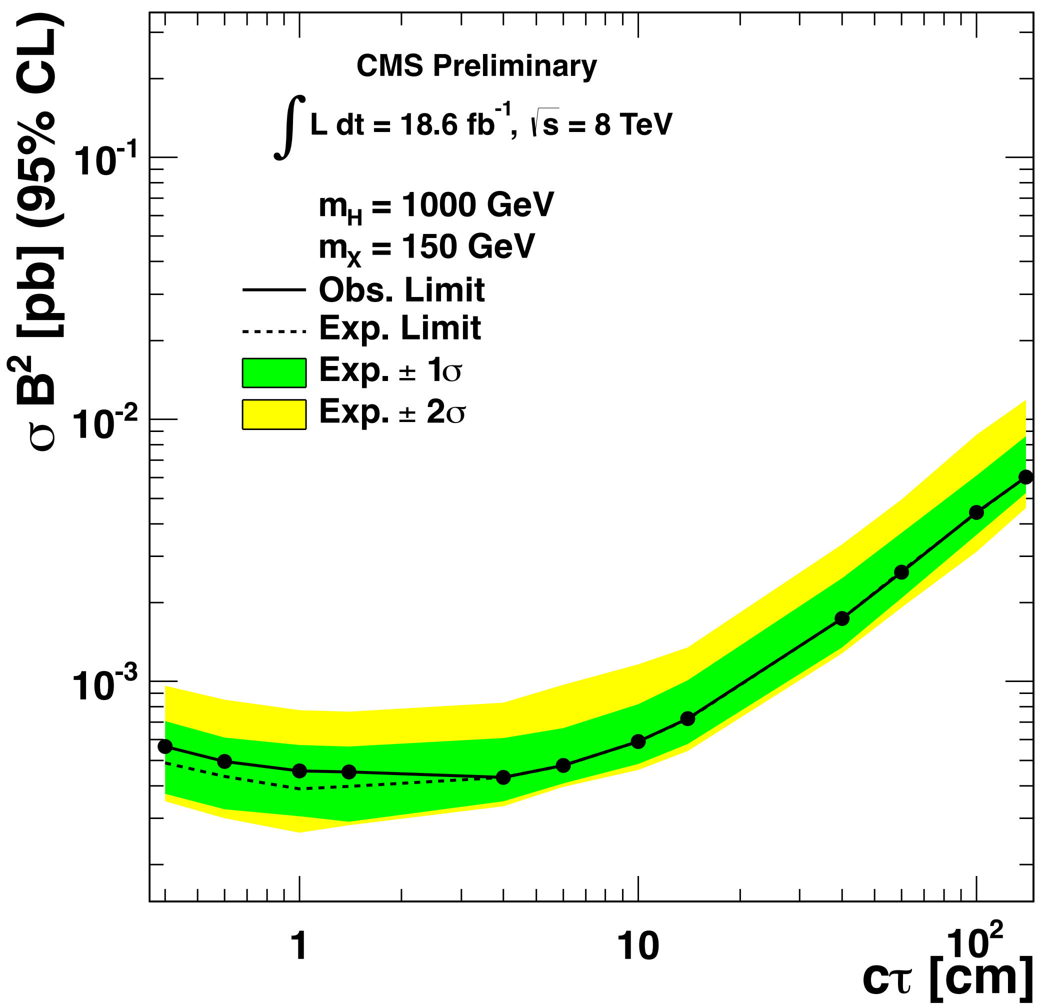
CMS SEARCH

CMS PAS EXO-12-038

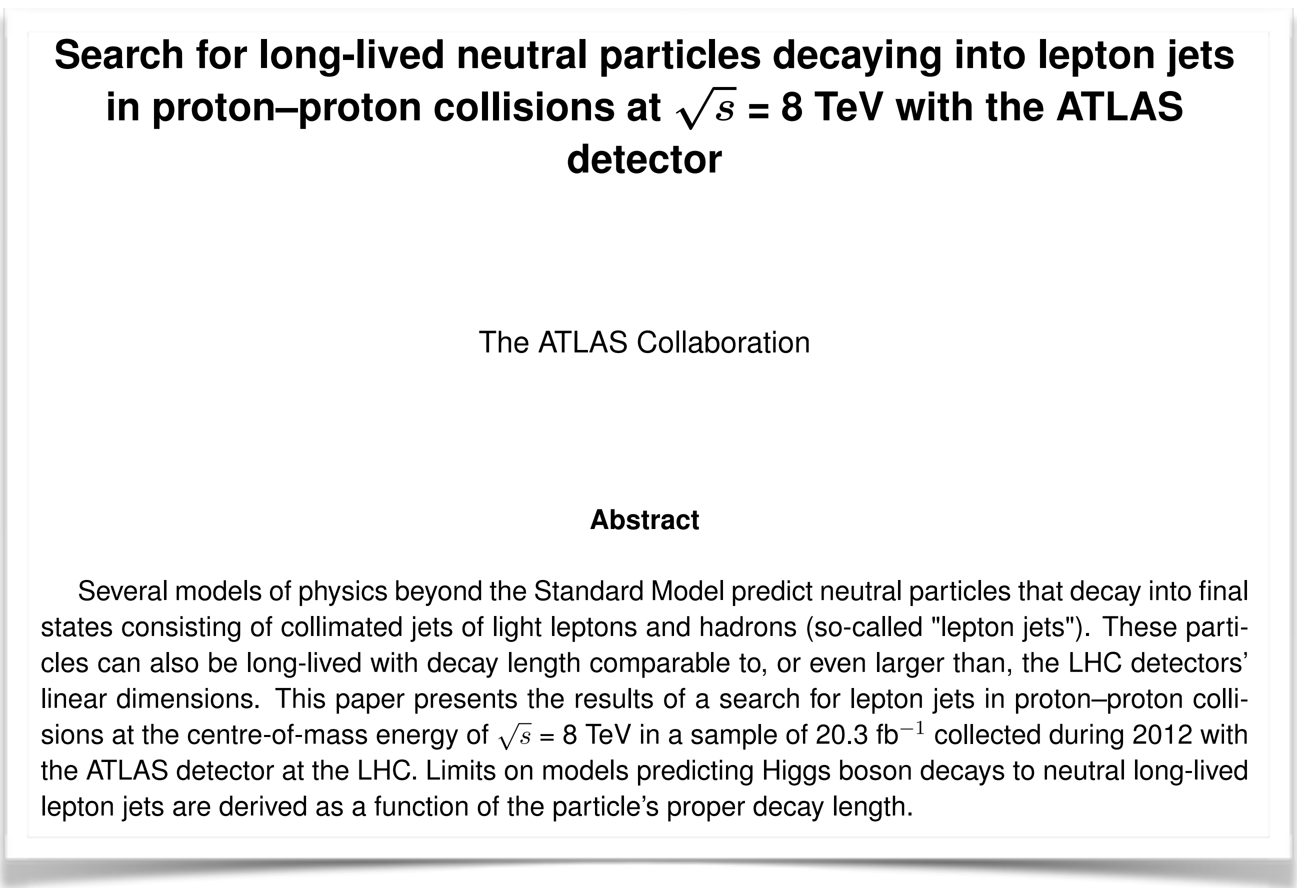
Require di-jets all coming from a single displaced vertex.

Throw away energy of tracks not reconstructed from vertex.

Unlikely to be sensitive to emerging phenomenology.



ATLAS SEARCH 1



Search for long-lived neutral particles decaying into lepton jets in proton–proton collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector

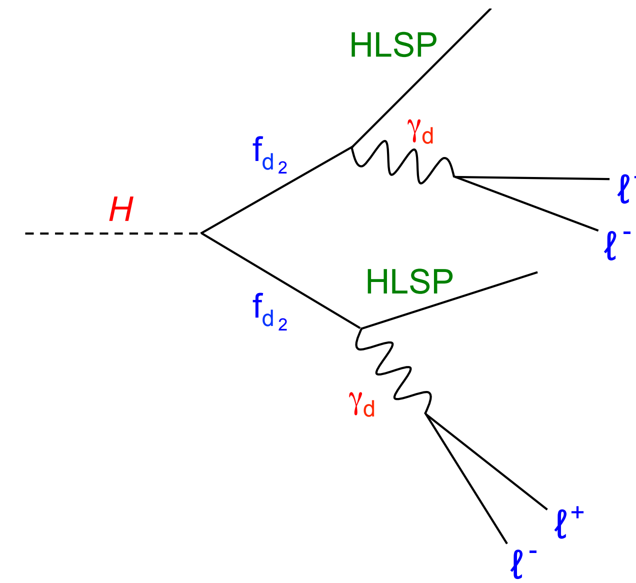
The ATLAS Collaboration

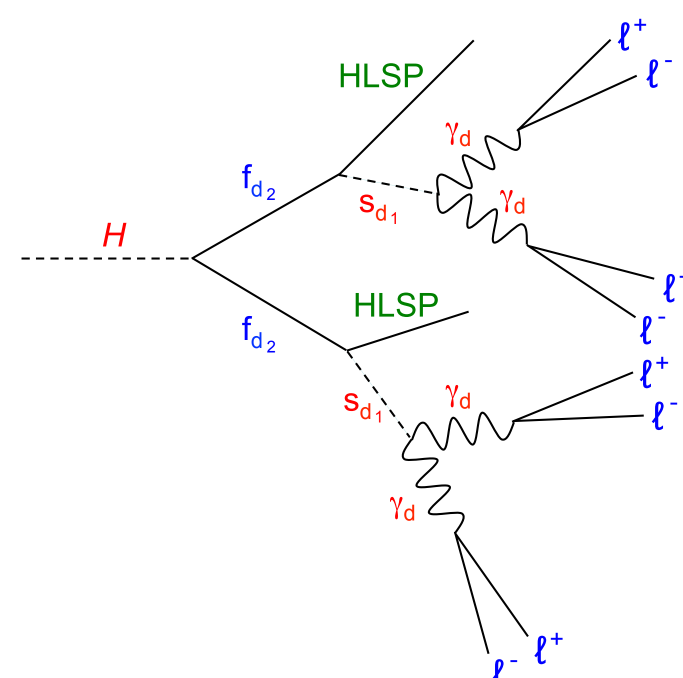
Abstract

Several models of physics beyond the Standard Model predict neutral particles that decay into final states consisting of collimated jets of light leptons and hadrons (so-called "lepton jets"). These particles can also be long-lived with decay length comparable to, or even larger than, the LHC detectors' linear dimensions. This paper presents the results of a search for lepton jets in proton–proton collisions at the centre-of-mass energy of $\sqrt{s}$ = 8 TeV in a sample of 20.3 fb^{-1} collected during 2012 with the ATLAS detector at the LHC. Limits on models predicting Higgs boson decays to neutral long-lived lepton jets are derived as a function of the particle's proper decay length.

ATLAS Collaboration, JHEP.1411,88 (2014) [arXiv:1409.0746].

ATLAS Collaboration, [arXiv:1501.04020].





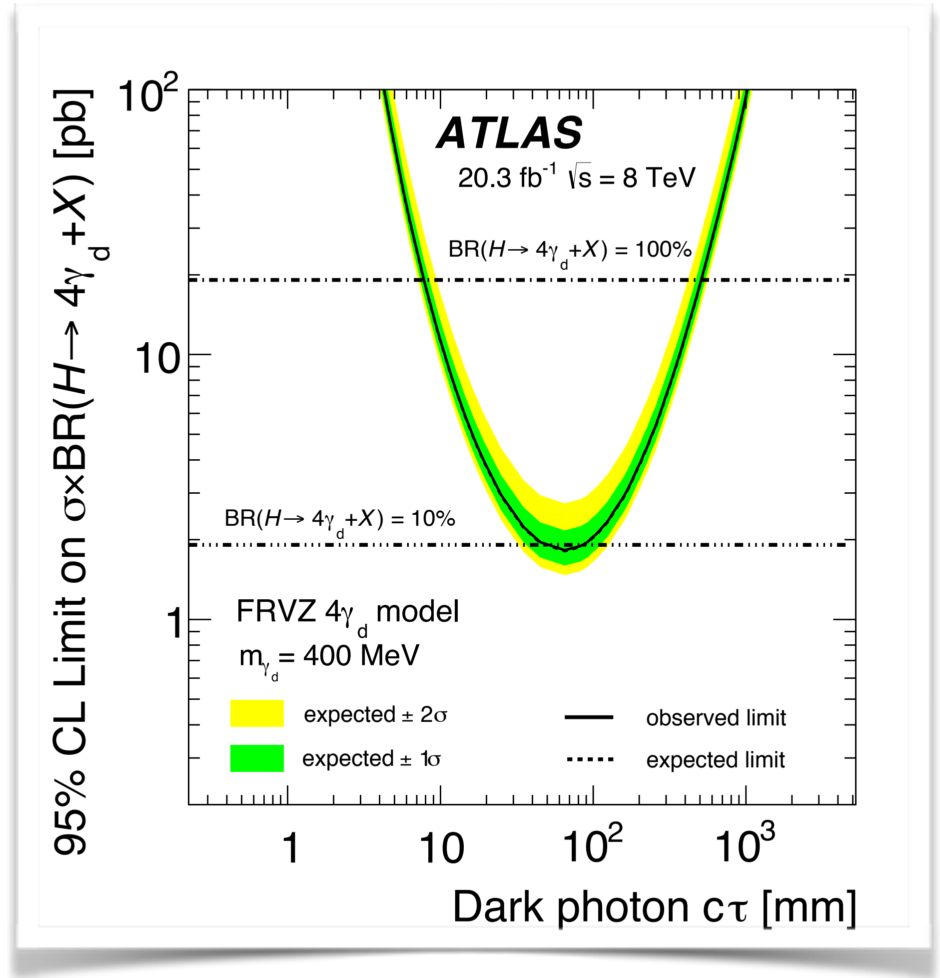
Falkowski, Ruderman, Volansky, Zupan '10

ATLAS SEARCH 1

arXiv:1409.0746v2 [hep-ex]

Requires ECAL/HCAL < 0.1.

Optimized for decays within HCAL, extremely low efficiency except possibly for long lifetimes.



See also ATLAS trigger paper: arXiv:1305.2204 [hep-ex].

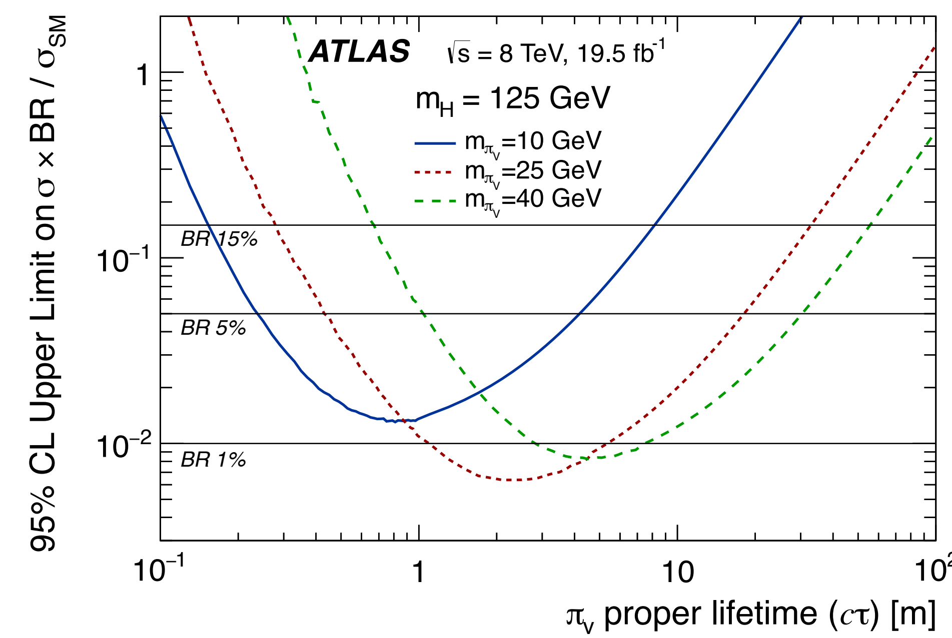
ATLAS SEARCH 2

Search for long-lived, weakly interacting particles that decay to displaced hadronic jets in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

A search for the decay of neutral, weakly interacting, long-lived particles using data collected by the ATLAS detector at the LHC is presented. This analysis uses the full dataset recorded in 2012: 20.3 fb^{-1} of proton–proton collision data at $\sqrt{s} = 8$ TeV. The search employs techniques for reconstructing decay vertices of long-lived particles decaying to jets in the inner tracking detector and muon spectrometer. Signal events require at least two reconstructed vertices. No significant excess of events over the expected background is found, and limits as a function of proper lifetime are reported for the decay of the Higgs boson and other scalar bosons to long-lived particles and for Hidden Valley $Z'$and Stealth SUSY benchmark models. The first search results for displaced decays in $Z'$and Stealth SUSY models are presented. The upper bounds of the excluded proper lifetimes are the most stringent to date.



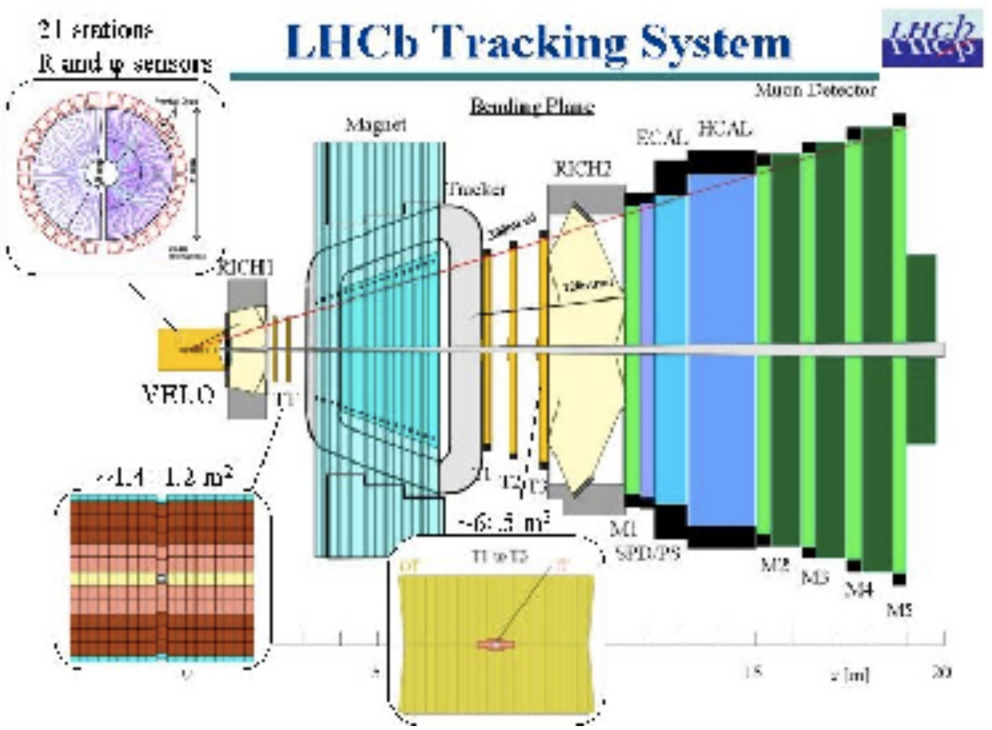
ATLAS Collaboration, Phys.Rev.D.92 (2015) [arXiv:1504.03634].
See also ATLAS [arXiv:1501.04020].

Similar isolation requirements as CMS search.

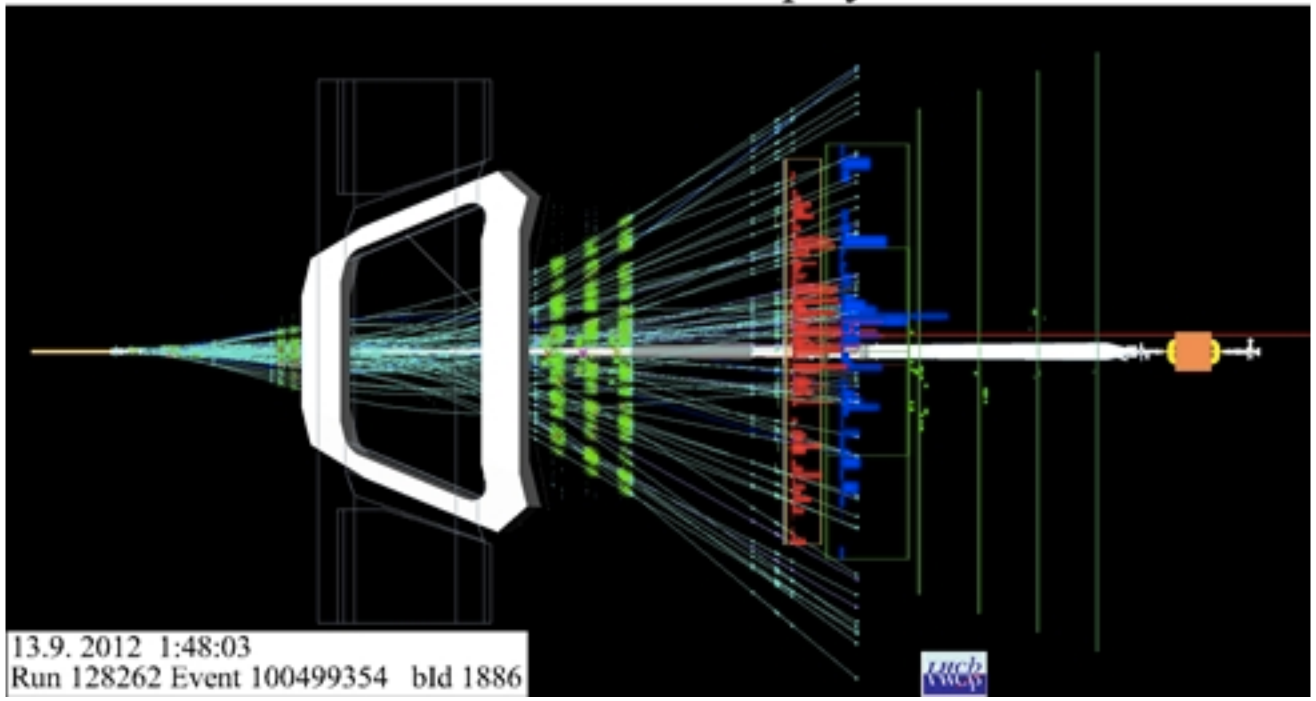
LHCb

LHCb has excellent tracking.

Limited coverage of event.



LHCb Event Display



LHCb SEARCH

Search for long-lived particles decaying to jet pairs

The LHCb collaboration†

Abstract

A search is presented for long-lived particles with a mass between 25 and 50 GeV/c^2 and a lifetime between 1 and 200 ps in a sample of proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 7\,\text{TeV}$, corresponding to an integrated luminosity of $0.62\,\text{fb}^{-1}$, collected by the LHCb detector. The particles are assumed to be pair-produced by the decay of a Standard Model-like Higgs boson. The experimental signature of the long-lived particle is a displaced vertex with two associated jets. No excess above the background is observed and limits are set on the production cross-section as a function of the long-lived particle mass and lifetime.

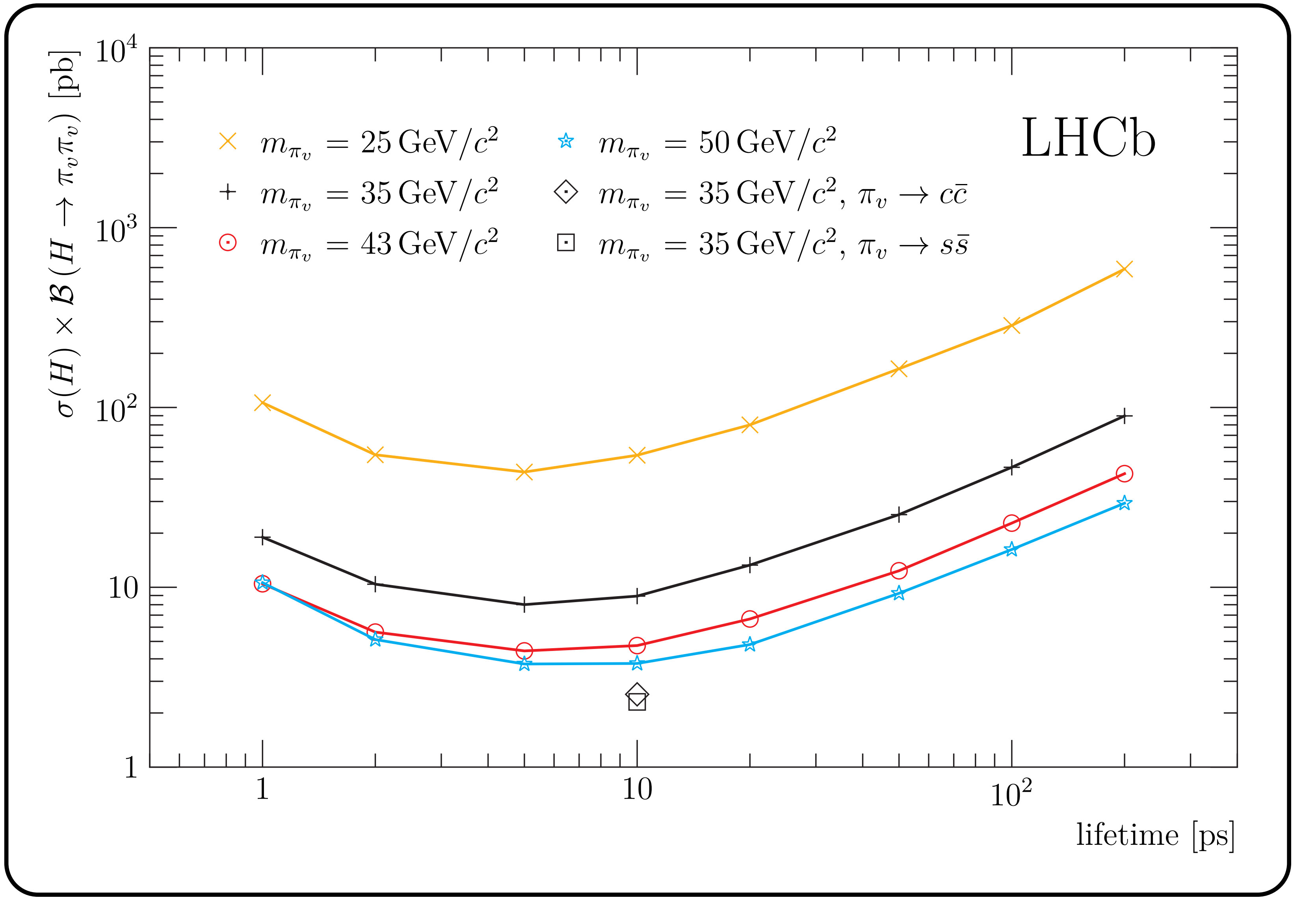
arXiv:1412.3021v1

Similar model to CMS search.

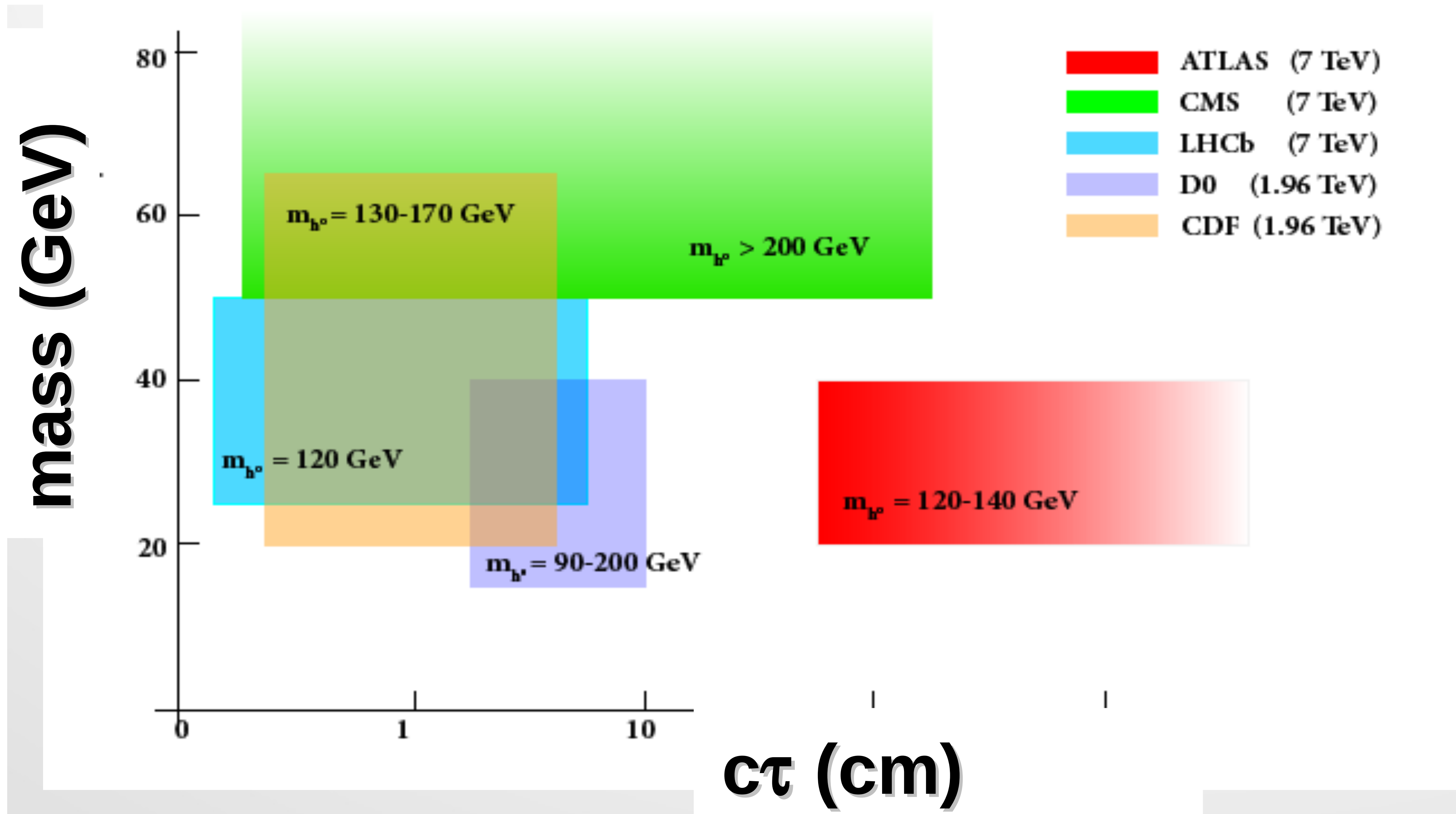
LHCb SEARCH

Again require to distinct jets with single vertex.

Insensitive to emerging pheno.

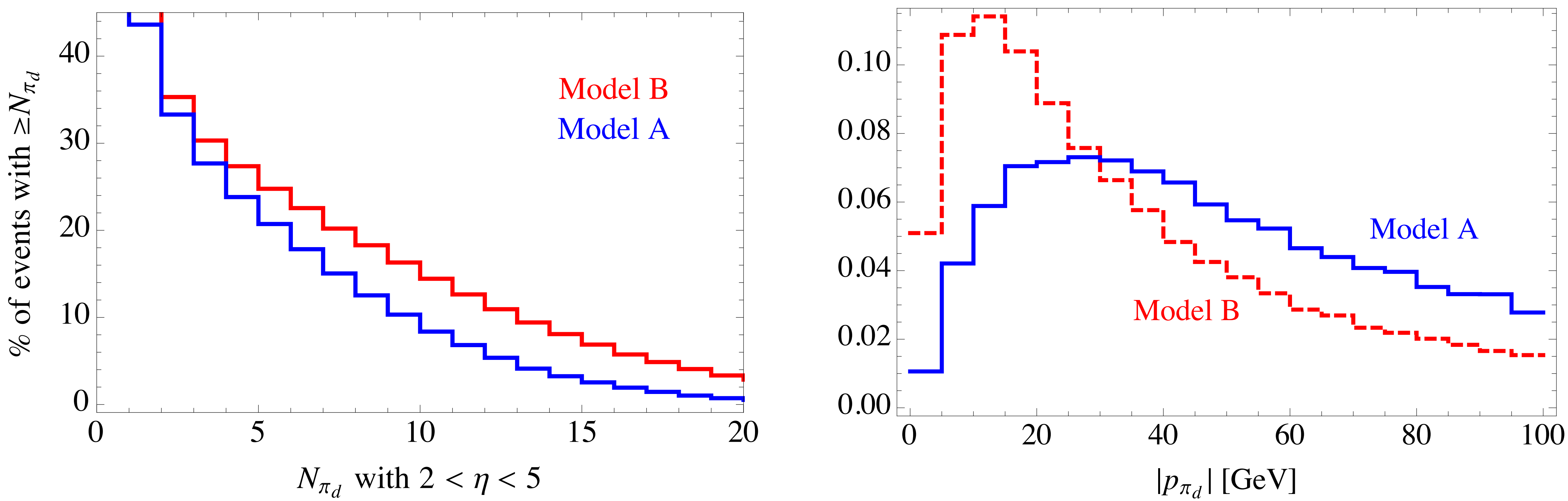


COMPLEMENTARITY



Talk by A. Hicheur, SILAFAE 2014

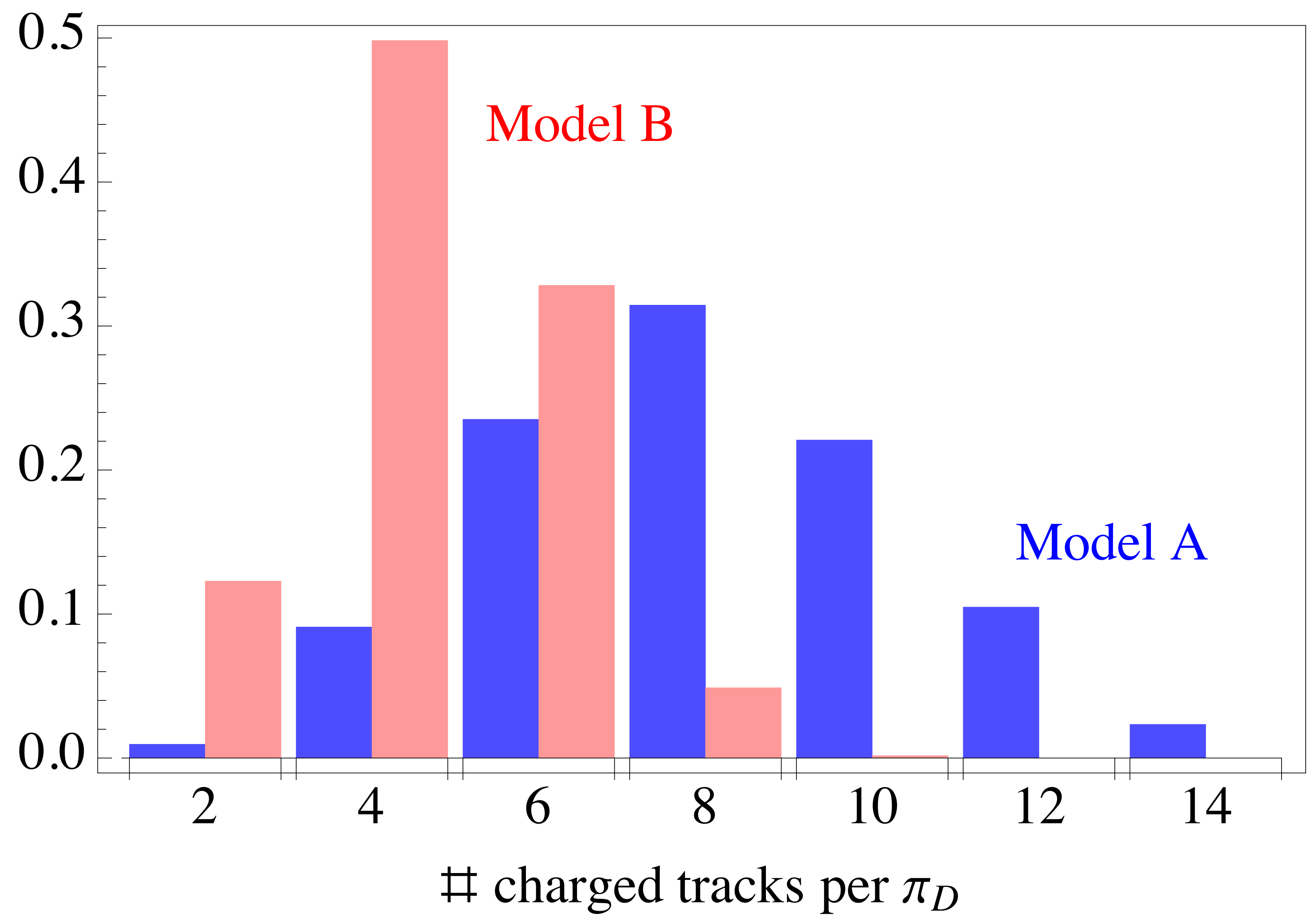
LHCb SENSITIVITY



~45% of events have > 0 pions in LHCb.

~30% have > 2.

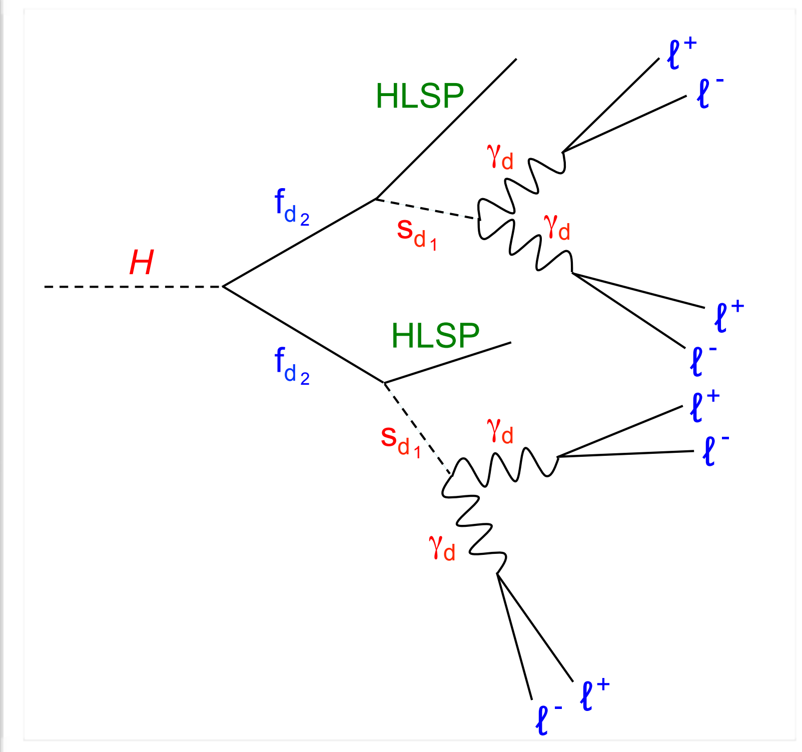
TRACK MULTIPLICTY



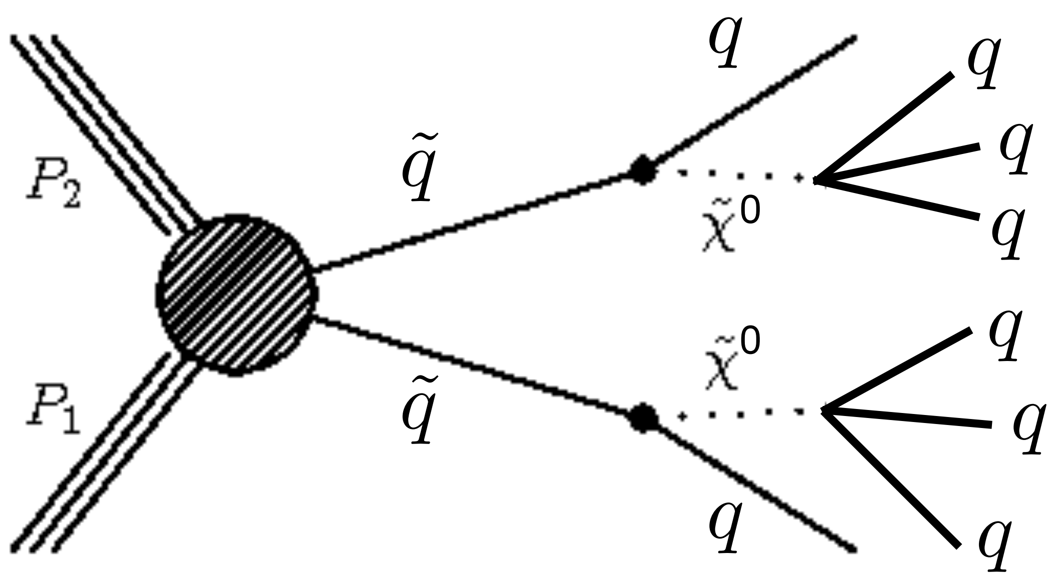
POWER OF EMERGING JET

Emerging jet search would be sensitive to other long-lived scenarios

- Lepton jets
- RPV neutralinos decay to jets
- …

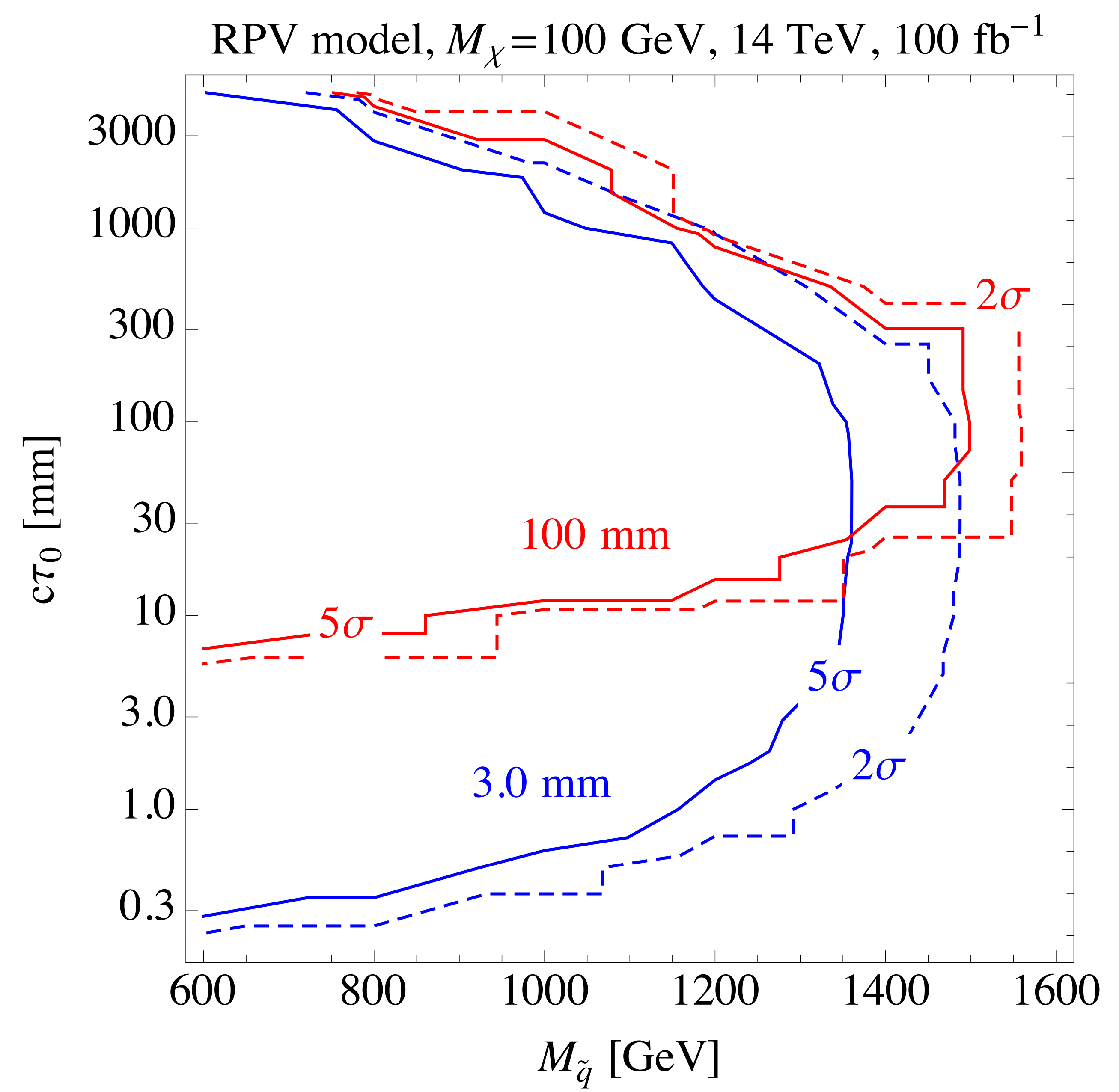


RPV NEUTRALINO

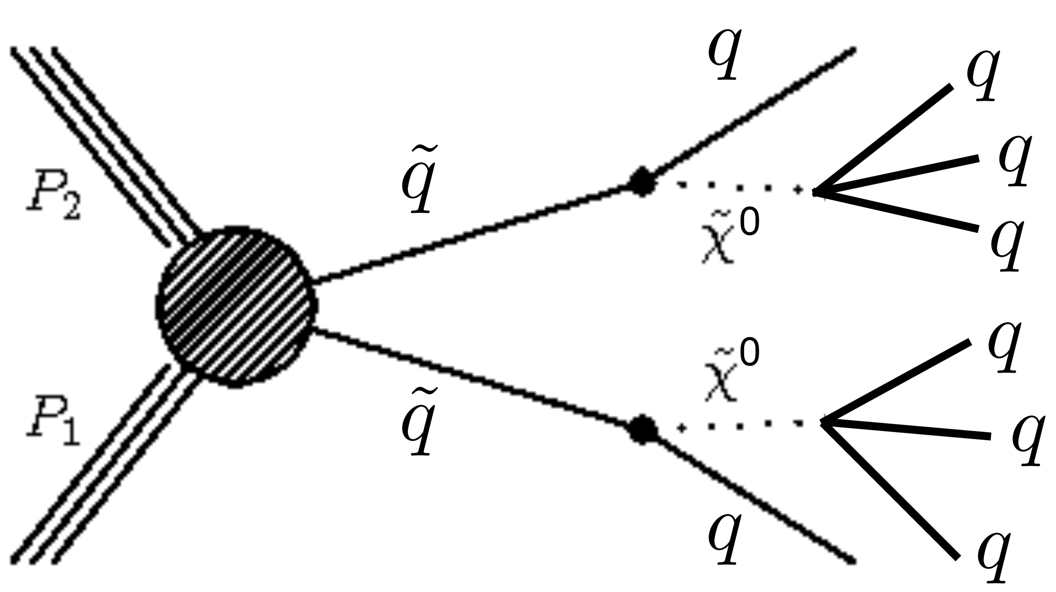


Squark pair production

Neutralino decay to 3 jets

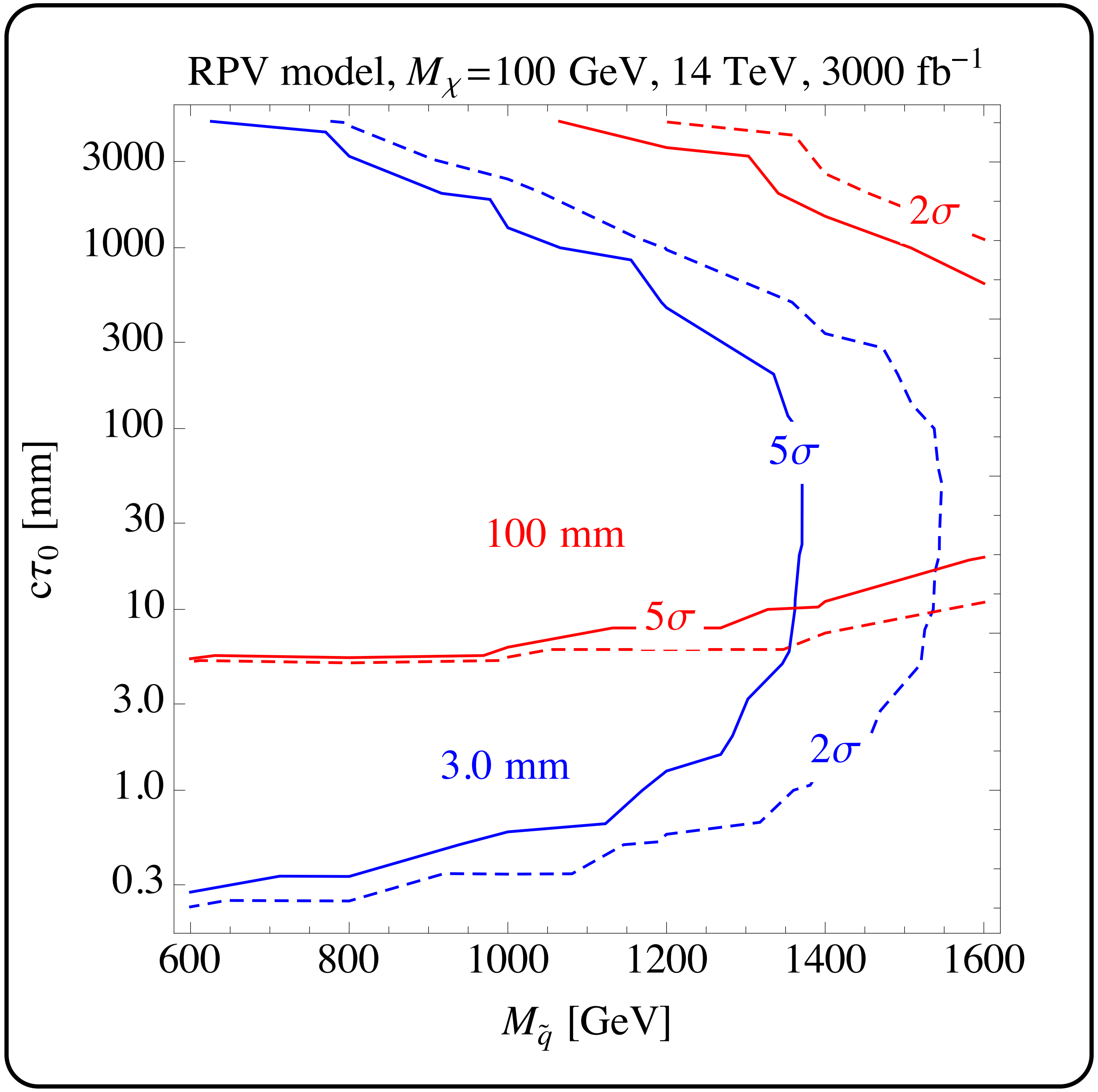


HIGH LUMINOSITY



Squark pair production

Neutralino decay to 3 jets



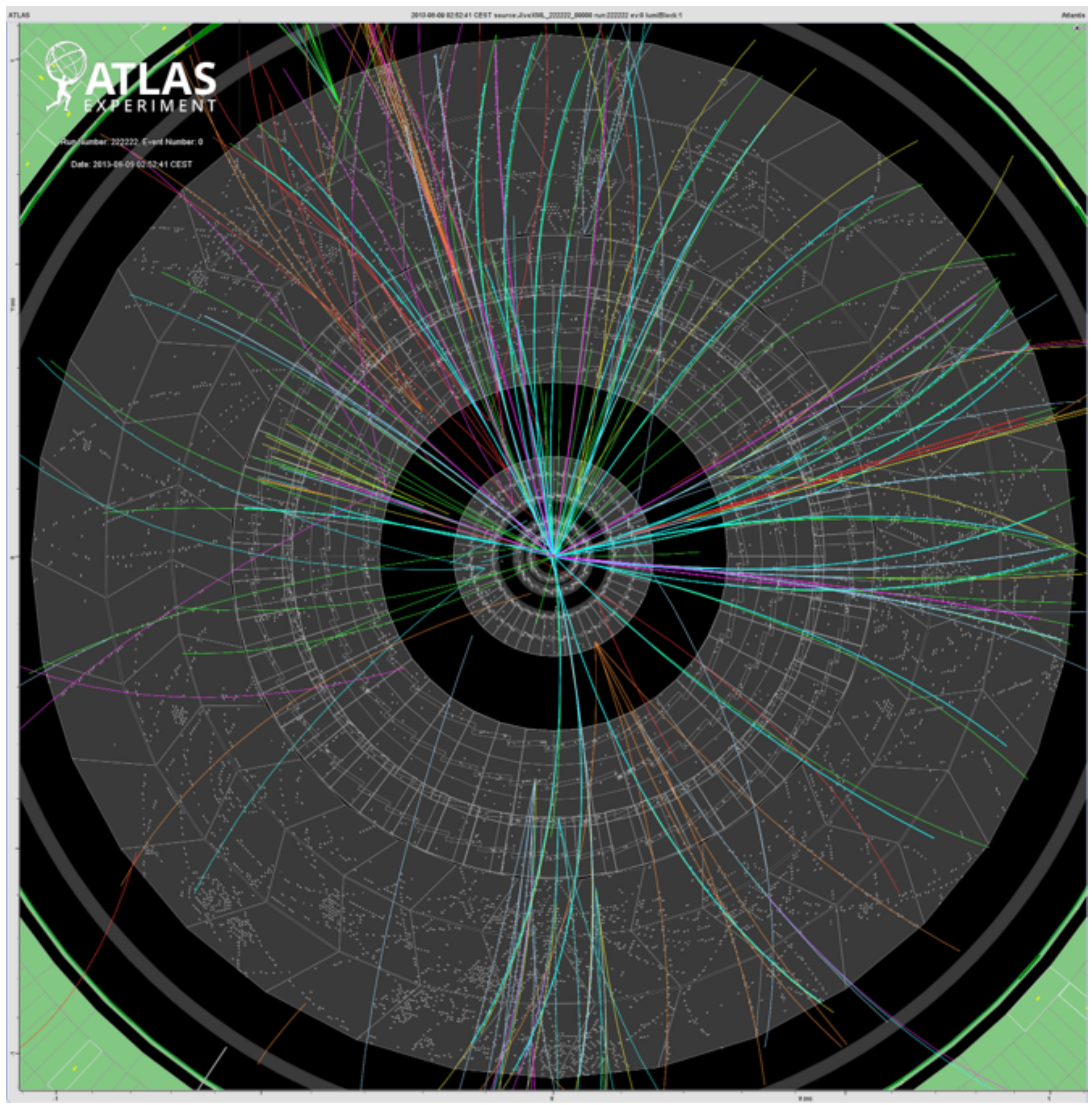
EXPERIMENTAL WORK

Ongoing work in 3 different collaborations:

- ATLAS (Ohio State, NYU)
- CMS (Florida St., Maryland)
- LHCb (Cincinnati, Santiago de Compostela)

ATLAS MONTE CARLO

Emerging Jets at 13 TeV



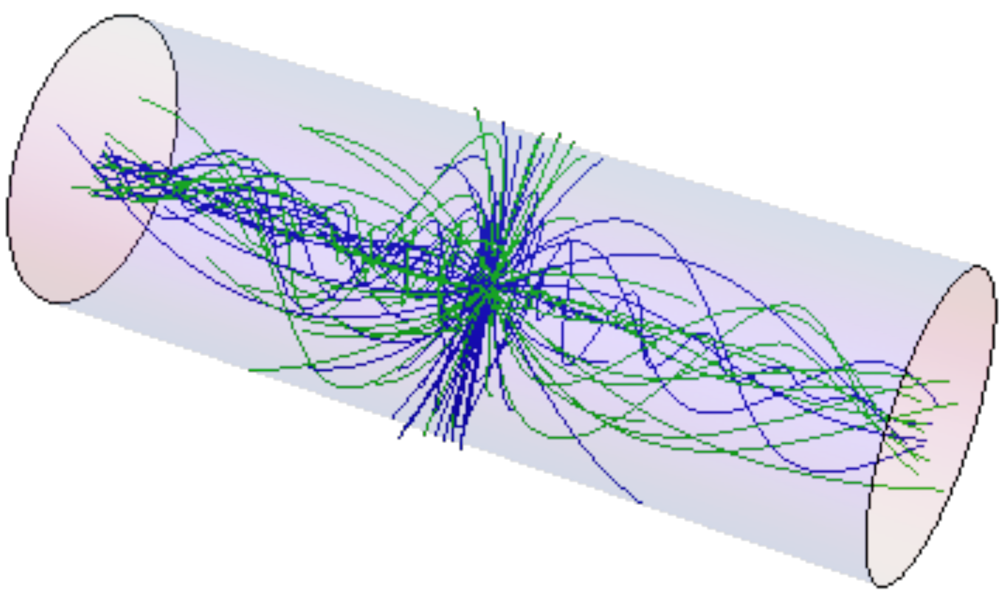
James Beacham (Ohio State) ATLAS Dark Sector Workshop — Cosenza, Italy — 10 Feb. 2016 9

SOFT BOMBS

If dark sector is approximately conformal instead of QCD-like, hadrons will generate soft bombs instead of jets.

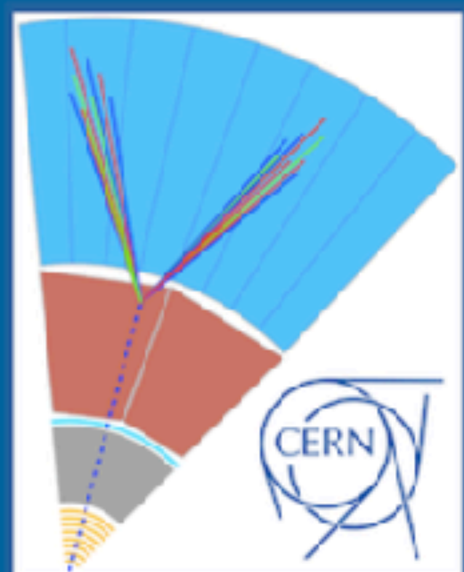
Knapen, Griso, Papucci, Robinson, arXiv:1612.00850.

Unclear what the best strategies are for this.



Also called Soft Unclustered Energy Patterns (SUEP).

WORK IS ONGOING



Searches for long-lived particles at the LHC: Workshop of the LHC LLP Community

24-26 April 2017
CERN
Europe/Zurich timezone

Search...

14:00 **WG 4: Dark showers** 2h 50m 14-4-030 Join

Speakers: Andrew Haas (New York University), Devin Walker, Jakub Scholtz (UW Seattle), James Beacham (Ohio State University (US)), Dr. Julia Shelton, Pedro Klaus Schwaller (DESY)

WG4.pdf

DARK SHOWERS

P. Schwaller

DARK SHOWERS

Tasks for the theorists

- Vary particle multiplicity in existing MCs and check effect
- Benchmark models <= can we populate the classifications we have outlined above
- What gives us wide jets? (Nf, Kinematics -- How to MC this?): (how to interpolate between Emergent Pencil jets and SUEP)
- Pedro and Dan add multiple lifetimes for dark pions
- Doodle a meeting for theorist discussion of these things

Tasks for the experimentalists

- Secondary vertex efficiency in ATLAS and CMS
- How Jet cleaning cuts (or a MET cut, if we were to do one) affect emerging jet efficiencies cuts
- Get SUEP lhe files from Simon Knapen, et al., and simulate, estimate efficiencies
- Investigate dedicated triggers (ATLAS: FTK, photon-jets, inner tracker hit multiplicity, etc.)

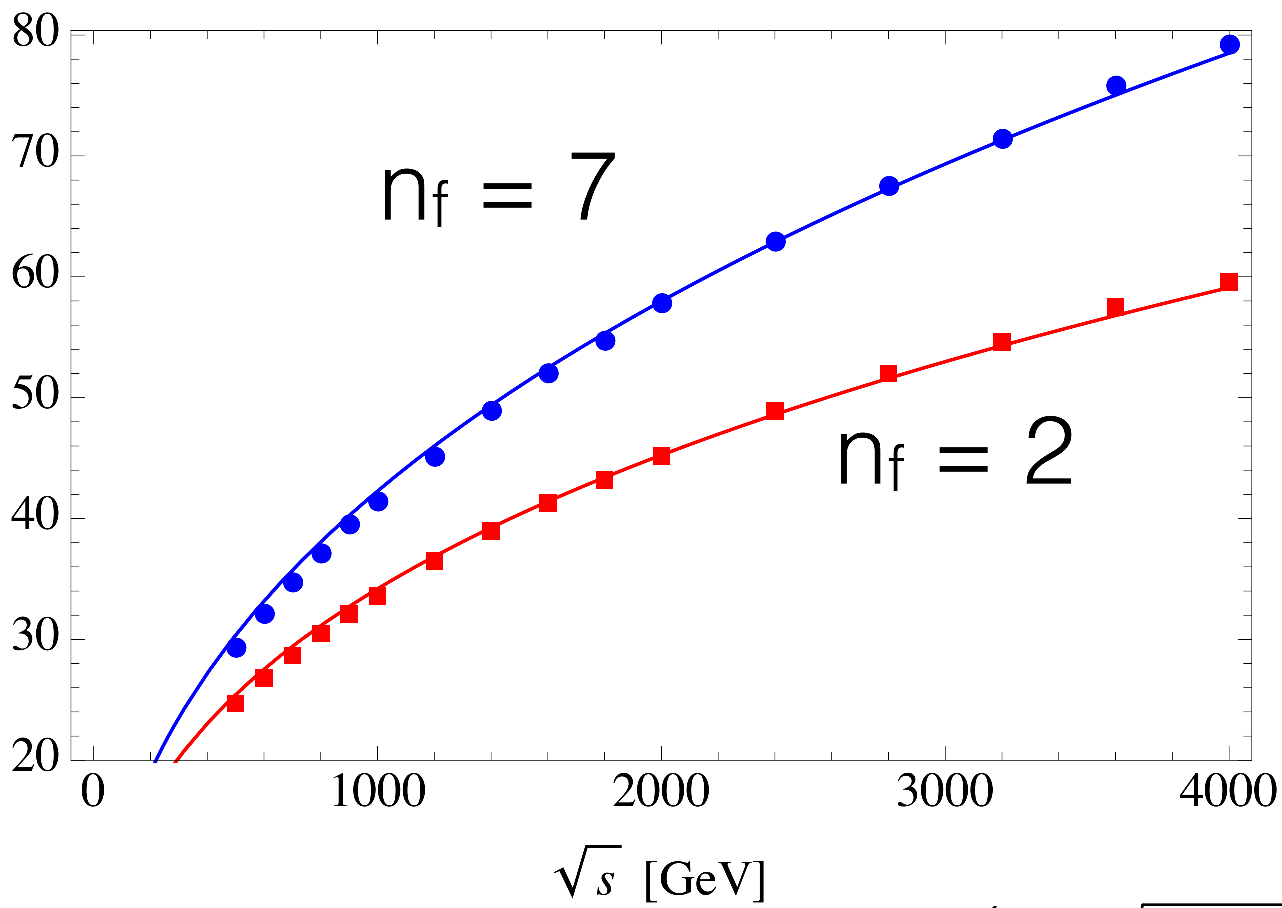
CONCLUSIONS

- Important to explore different ways LHC can search for NP.
- Emerging jets are novel and motivated, no current searches are sensitive.
- Strategies presented here can reach very low cross sections, sensitive to broad class of displaced models.
- Now clear that this is part of a broader class of signatures that the LHC is only beginning to explore.
- Opportunities for ATLAS, CMS, and LHCb. Collaboration between theorists and experimentalists is essential to maximize discovery potential.

THANK YOU

SIMULATION

Check to see if simulation makes sense by looking at average particle multiplicity.

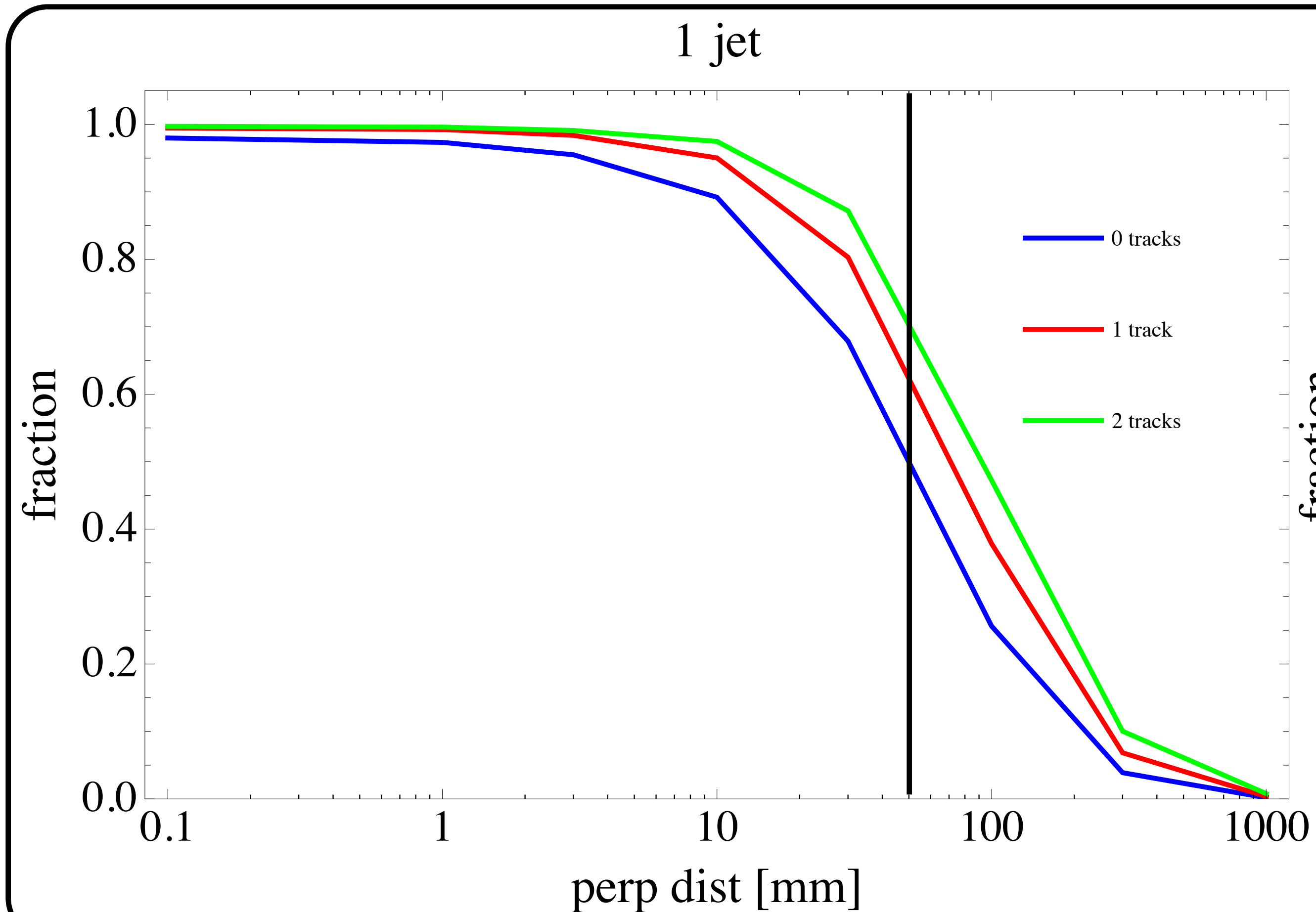


Ellis, Stirling, and Weber, 1996.

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

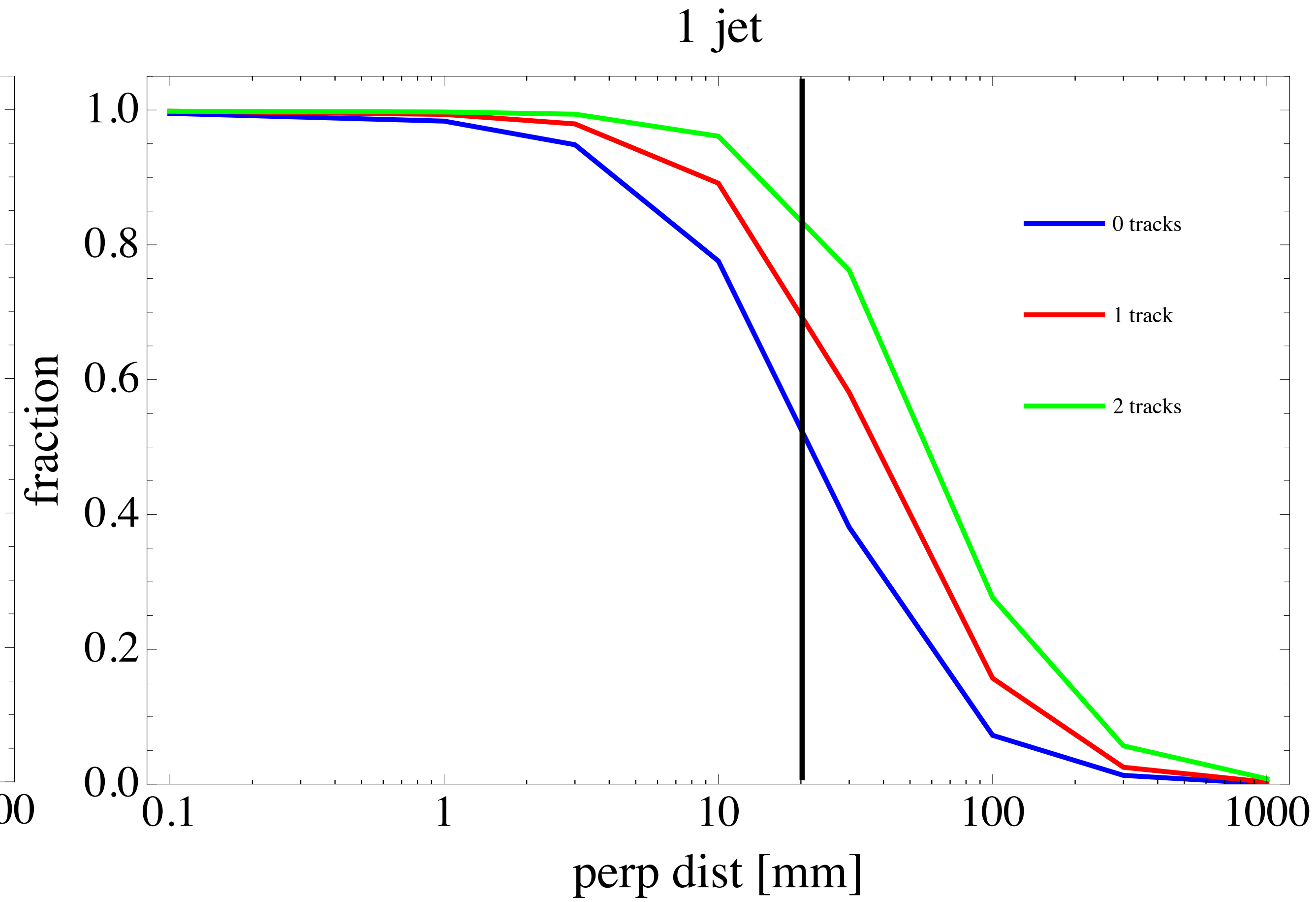
DIFFERENT MODEL POINTS

Model **A**



$$m_{\pi_d} = 5\,\mathrm{GeV}$$
$$c\tau_{\pi_d} = 50\,\mathrm{mm}$$

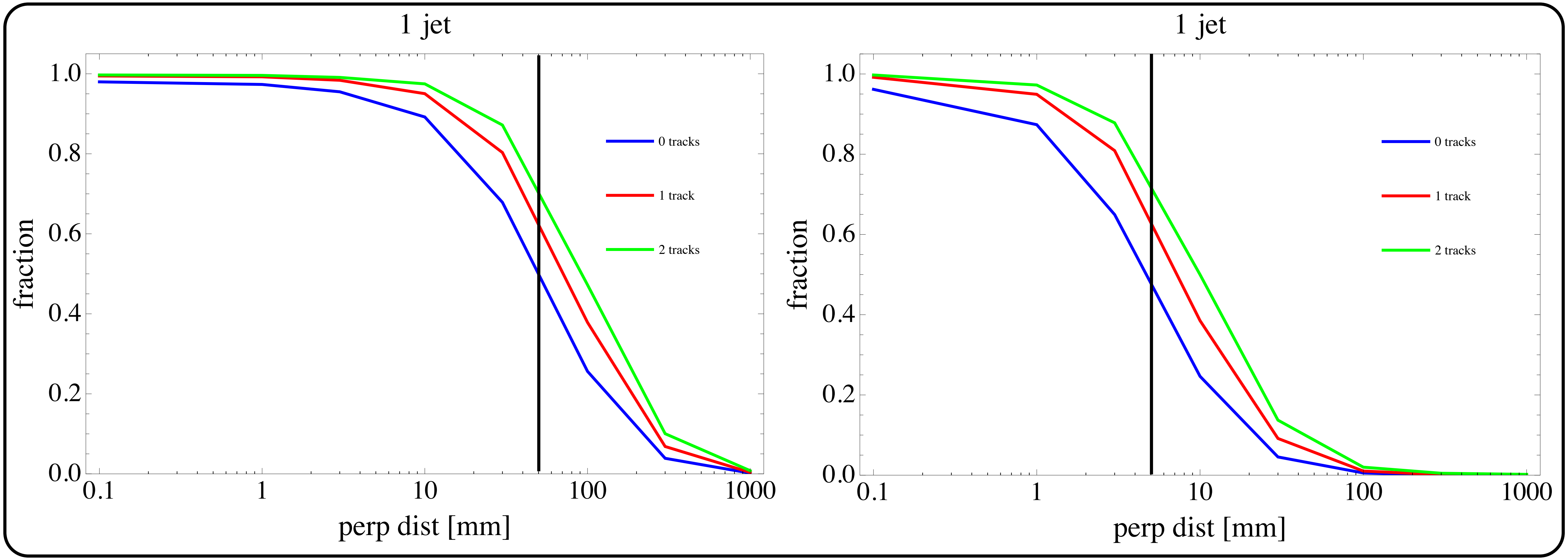
Model **B**



$$m_{\pi_d} = 2\,\mathrm{GeV}$$
$$c\tau_{\pi_d} = 20\,\mathrm{mm}$$

DIFFERENT MODEL POINTS

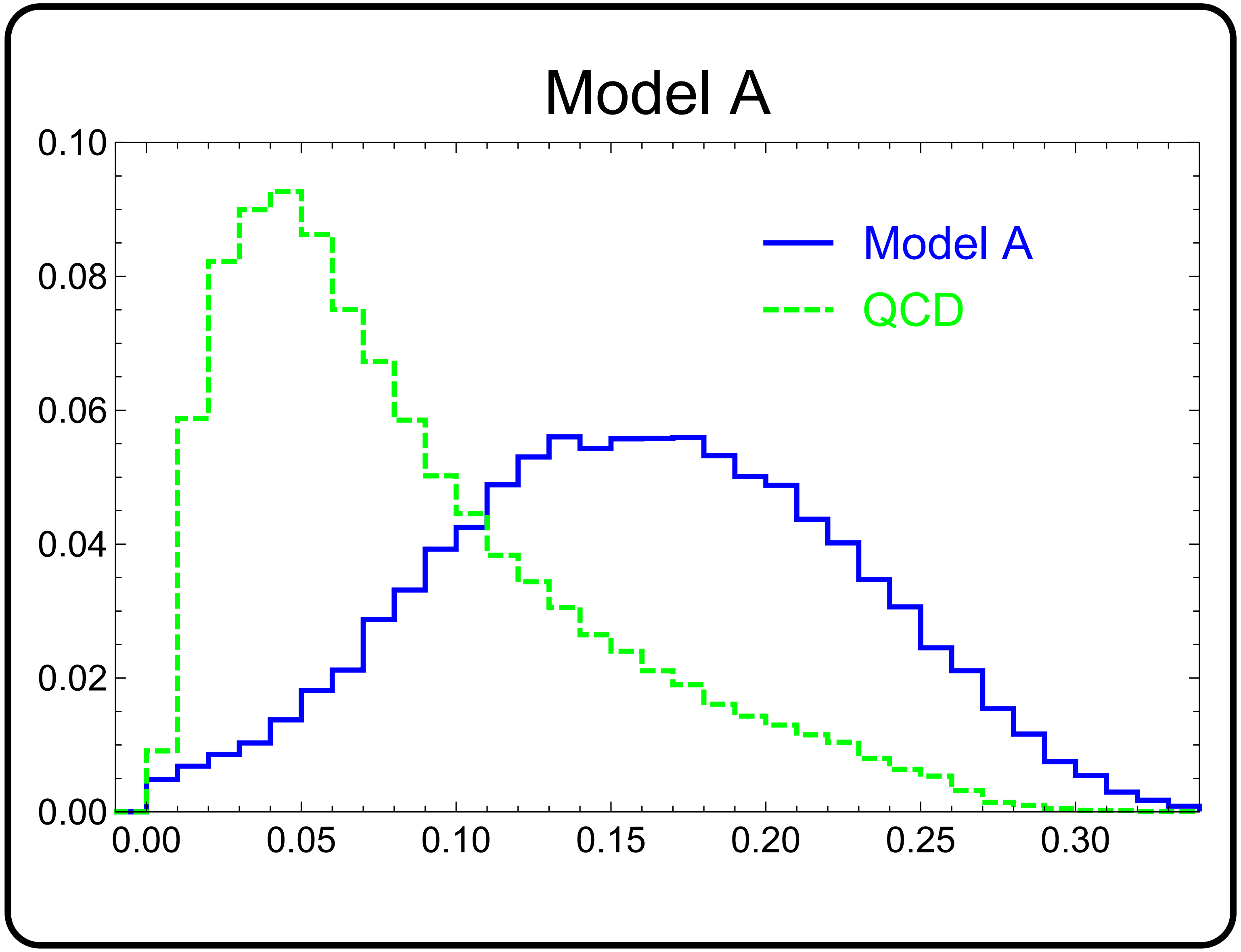
Model **A'** Model **A''**



$$m_{\pi_d} = 5\,\mathrm{GeV}$$
$$c\tau_{\pi_d} = 50\,\mathrm{mm}$$

$$m_{\pi_d} = 5\,\mathrm{GeV}$$
$$c\tau_{\pi_d} = 5\,\mathrm{mm}$$

JET SHAPES



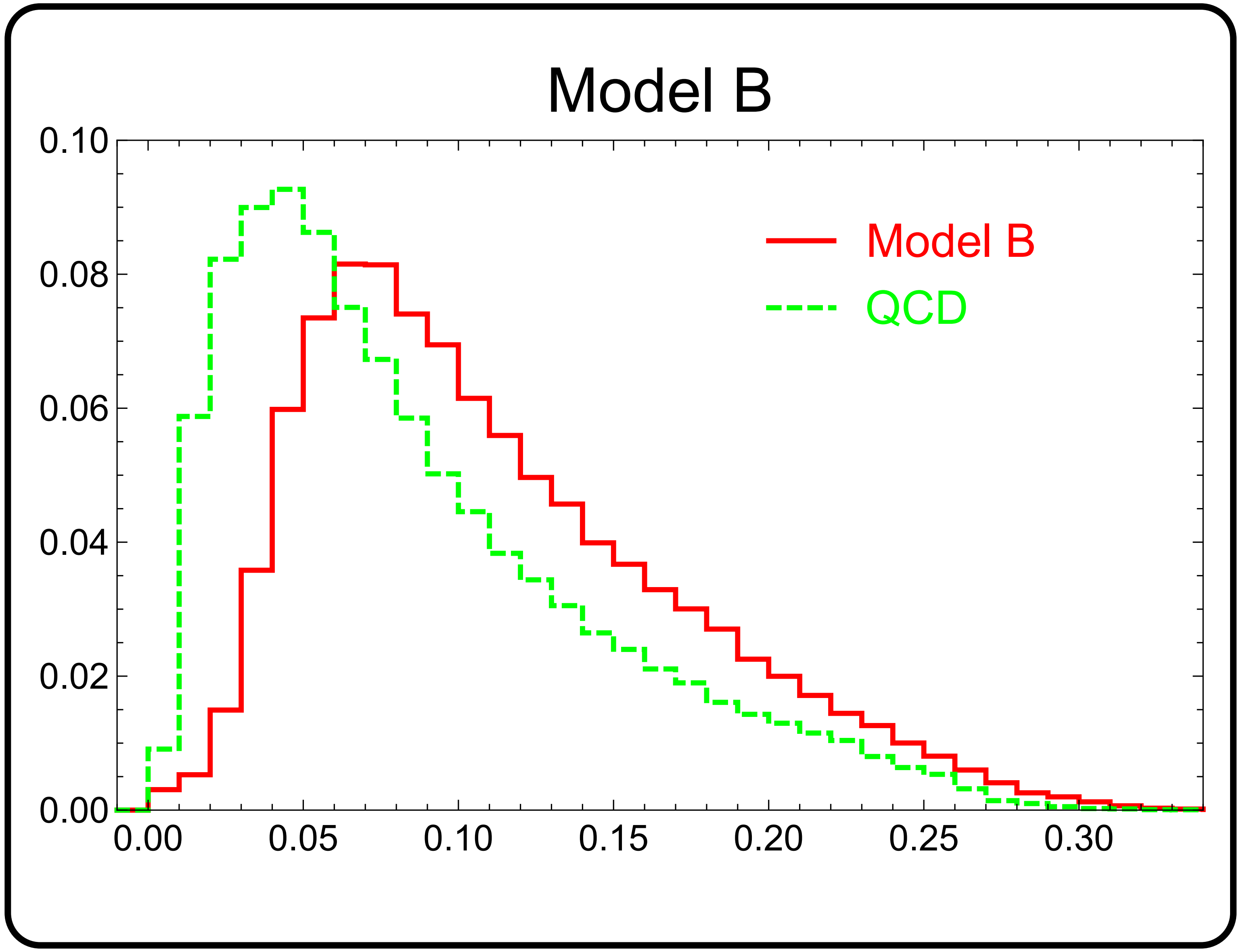
$$\text{girth} = \frac{1}{p_T^{\text{jet}}} \sum_i p_T^i \, \Delta R_i$$

Measure girth to get a sense of jet width

<u>Model A:</u>

$$m_\Phi = 1\,\text{TeV}$$
$$\Lambda_d = 10\,\text{GeV}$$
$$m_{\pi_d} = 5\,\text{GeV}$$
$$c\tau_{\pi_d} = 150\,\text{mm}$$

JET SHAPES



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

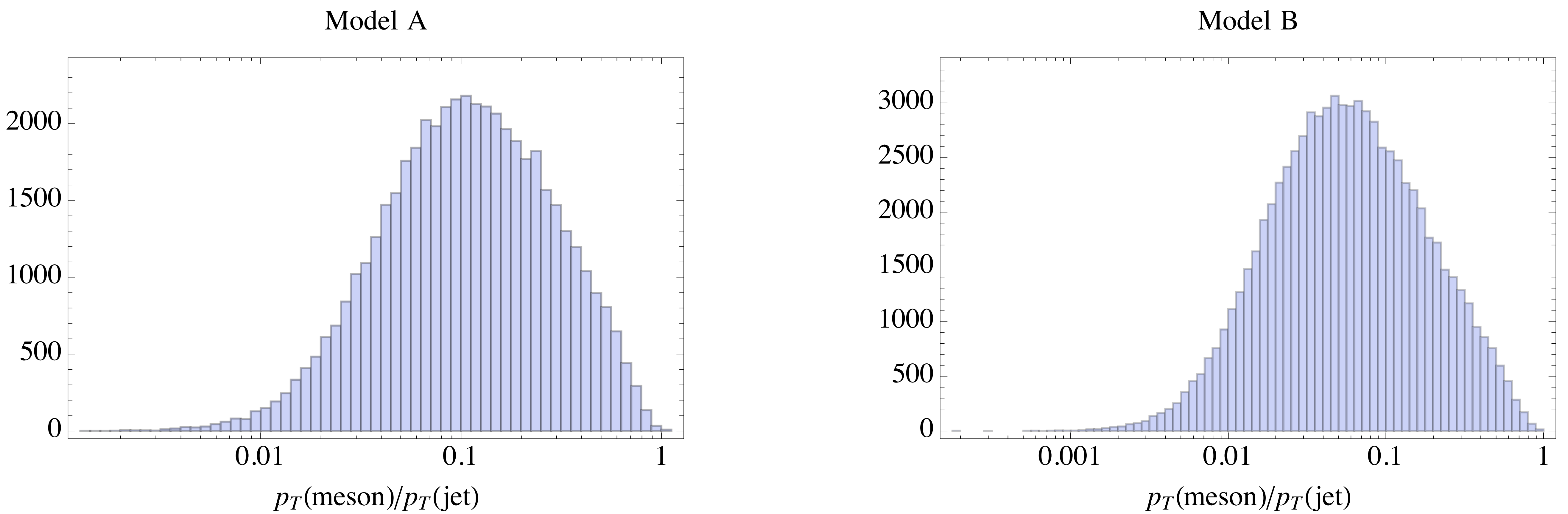
Quite sensitive to dark sector params.

<u>Model B:</u>

$$m_\Phi = 1\,\text{TeV}$$
$$\Lambda_d = 4\,\text{GeV}$$
$$m_{\pi_d} = 2\,\text{GeV}$$
$$c\tau_{\pi_d} = 5\,\text{mm}$$

MESON MOMENTUM FRACTION

Fraction of jet momentum carried by any individual dark meson



MESON MULTIPLICITY

Number of dark mesons in a jet.