EMERGING JETS

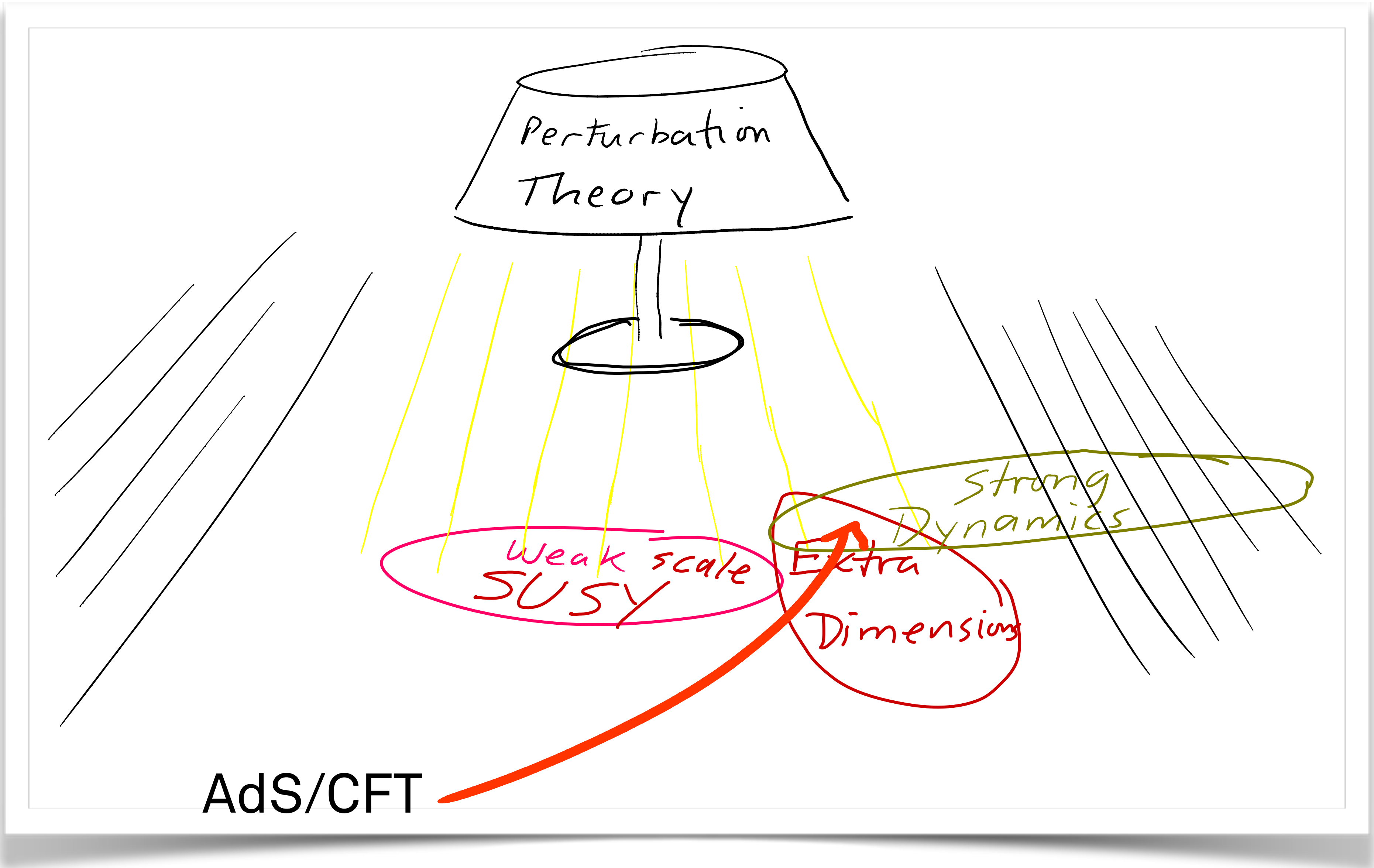
DANIEL STOLARSKI
WITH PEDRO SCHWALLER
AND ANDREAS WEILER

arXiv:141?.????

Warsaw University November 24, 2014

MOTIVATION 1

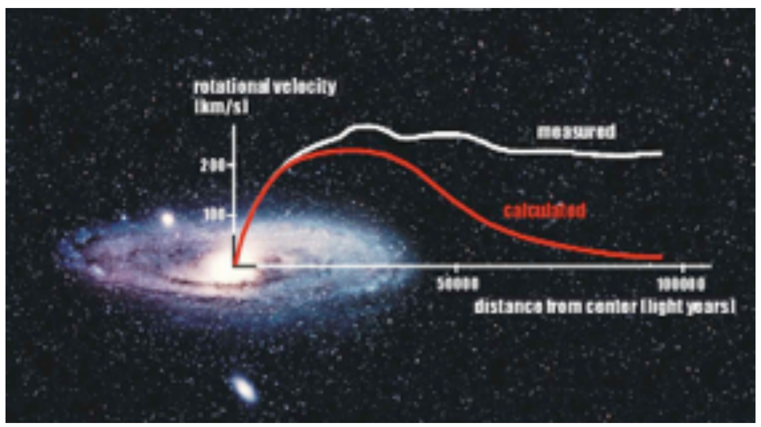
Getting away from the lamp post

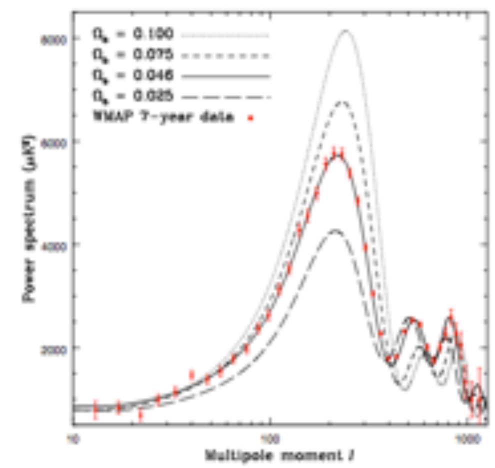


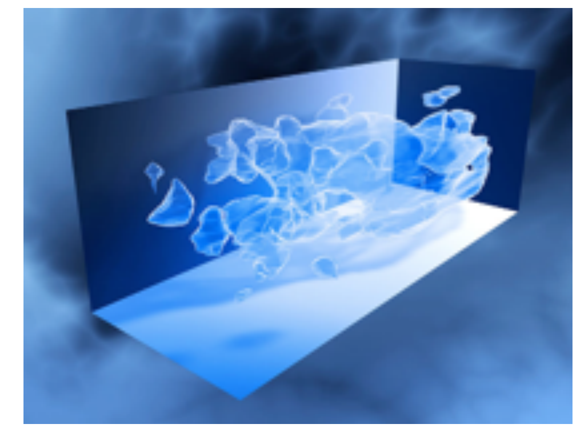
R. Sundrum

MOTIVATION 2

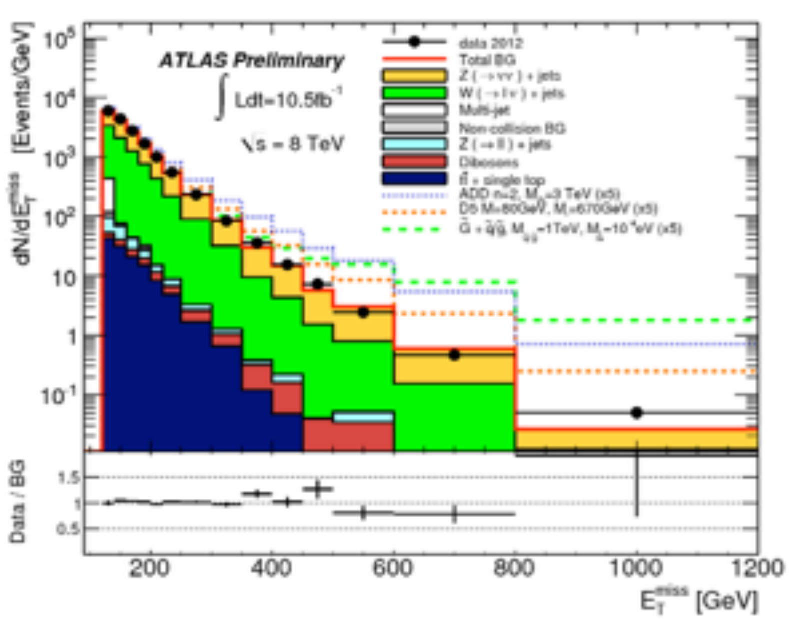
We have seen dark matter in the sky

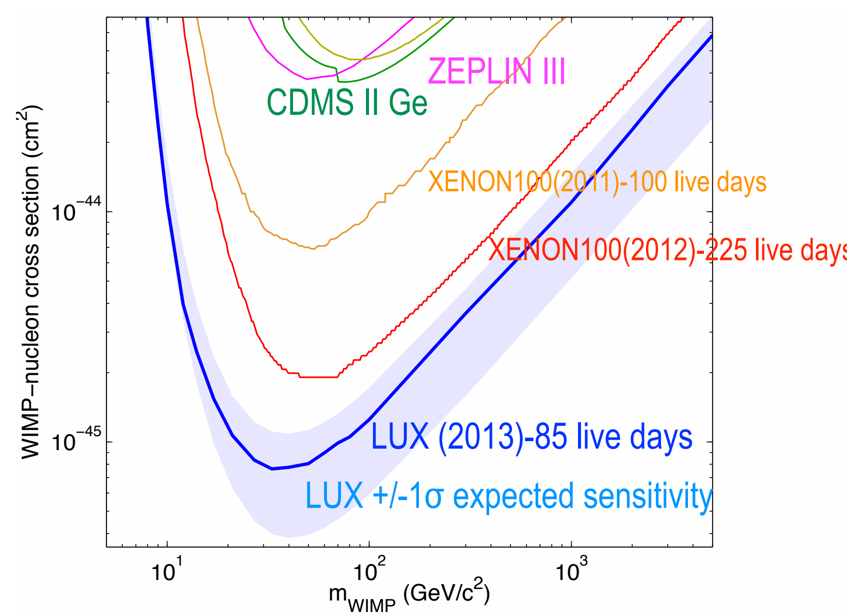






But not in the lab





ASYMMETRIC DARK MATTER

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

Controlled by complicated (known) QCD dynamics

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

?

Unknown dynamics of baryogenesis

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]].

ASYMMETRIC DARK MATTER

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

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

?

Unknown dynamics of baryogenesis

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

Can we get both?

GETTING THE MASS

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

QCD like

?

Controlled by complicated (known) QCD dynamics

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

$$\Omega_B = m_p n_B$$

?

Unknown dynamics of baryogenesis

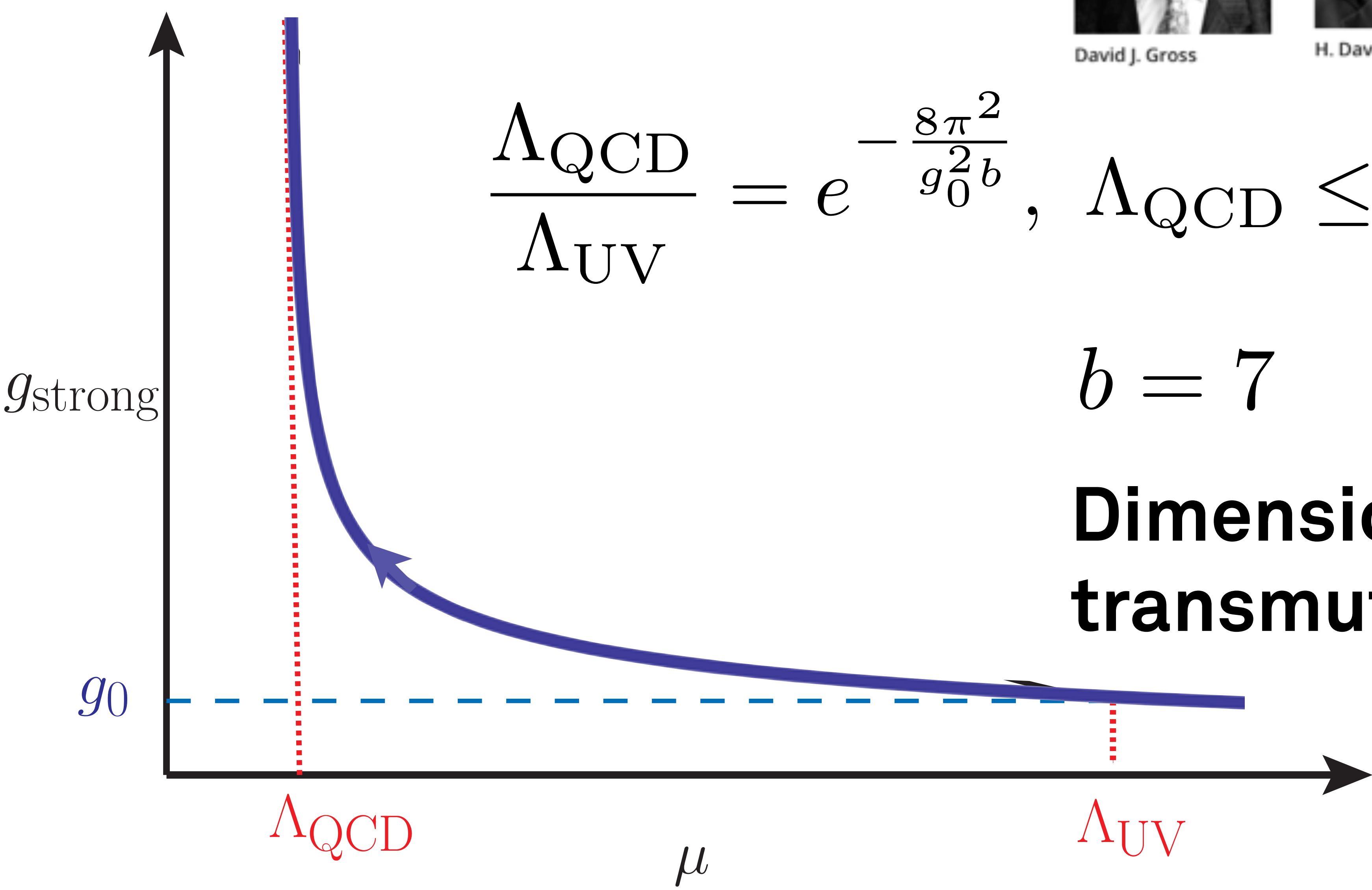
QCD SCALE

David J. Gross   H. David Politzer   Frank Wilczek

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

$$b = 7$$

Dimensional transmutation



DARK QCD

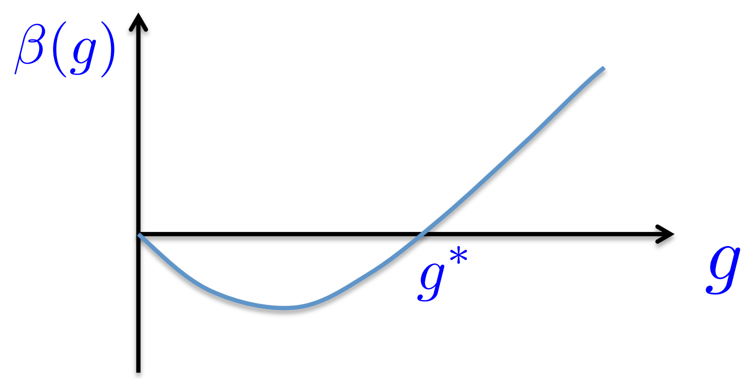
Propose new SU(N_d) "dark QCD," dark quarks
Bai, Schwaller, PRD 13.

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

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

Search for model with perturbative fixed point

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



SCALES ARE RELATED

Example

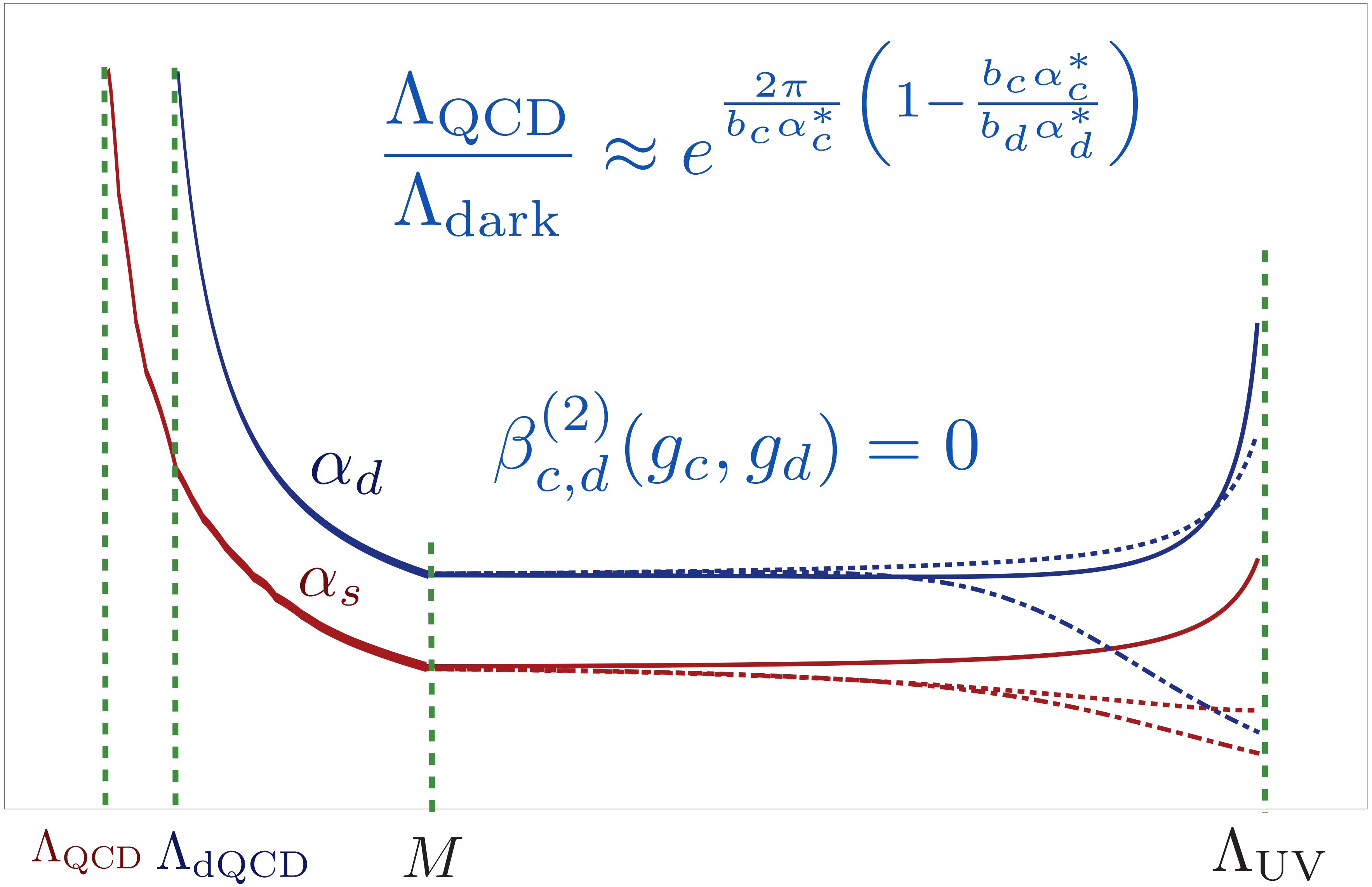
Fixed points:

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

$M = 870\ GeV$

DM mass:

$M_{DM} \approx 3.5\ GeV$



DARK MATTER

Can co-generate DM and baryon asymmetry

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

d_i → SM quark

Φ → bifundamental scalar

$\overline{Q}$ → dark quark

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

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

$$\boxed{p_d} \quad \boxed{\pi_d} \quad \text{Zoo}_d$$

Stable

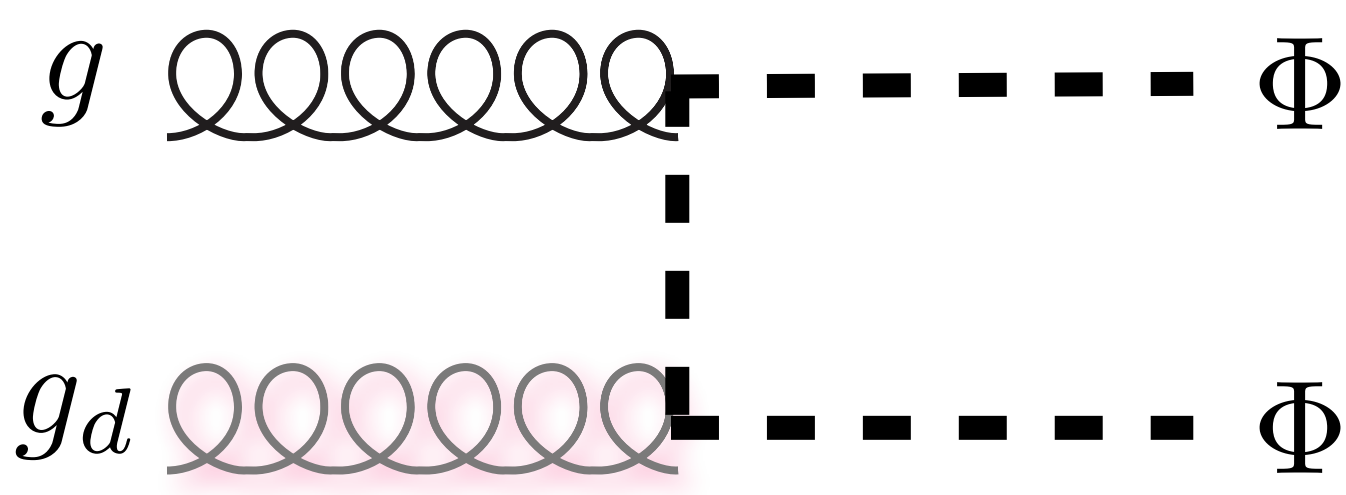
Decays to SM

MEDIATORS

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

$$M_\Phi \gg \Lambda_d$$

Example 1: Φ is a scalar charged under both color and dark color

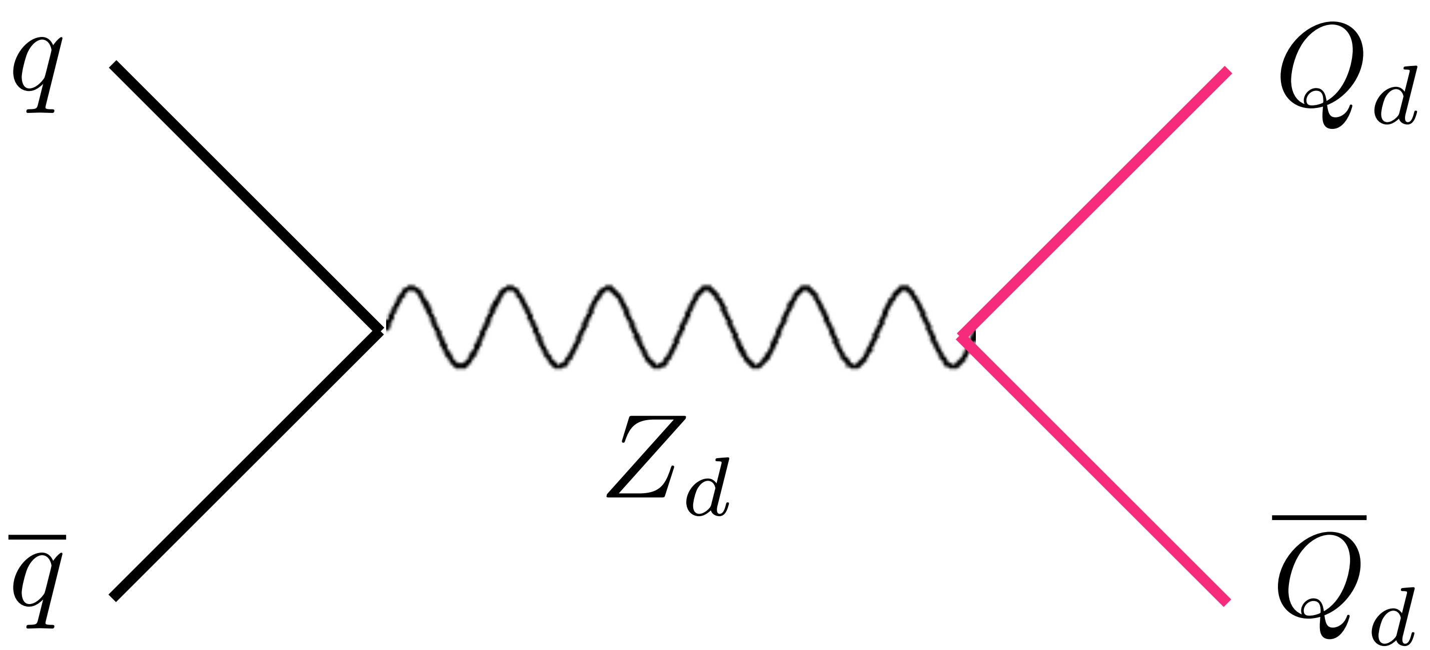


MEDIATORS

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

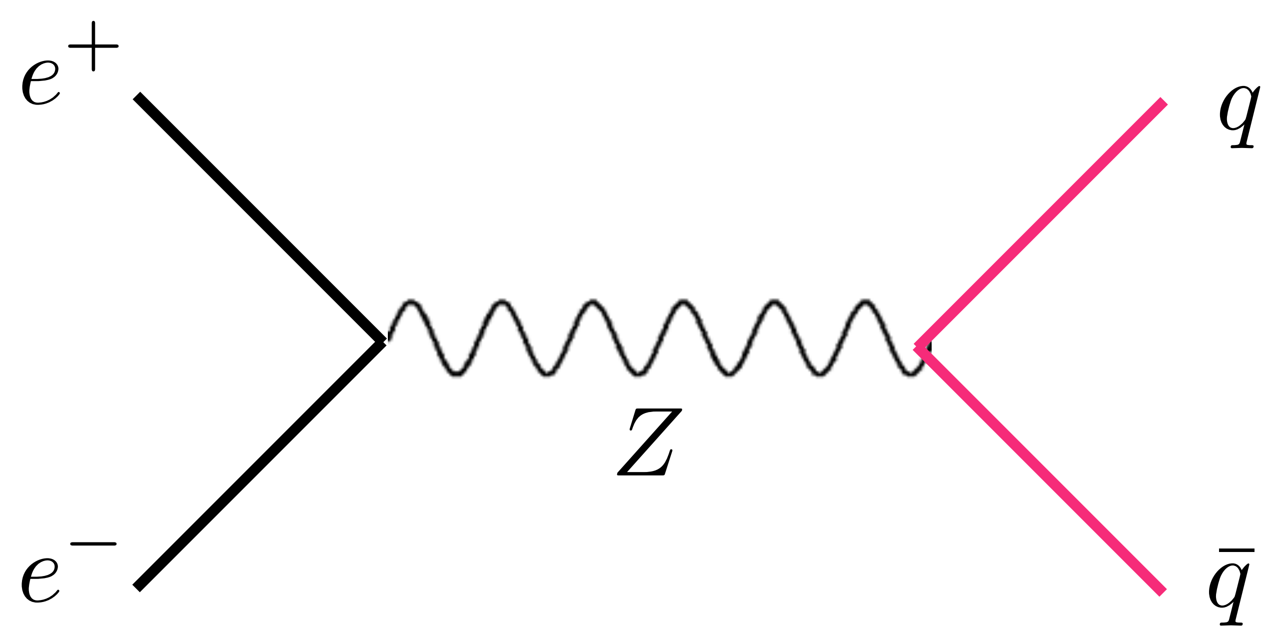
$$M_\Phi \gg \Lambda_d$$

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

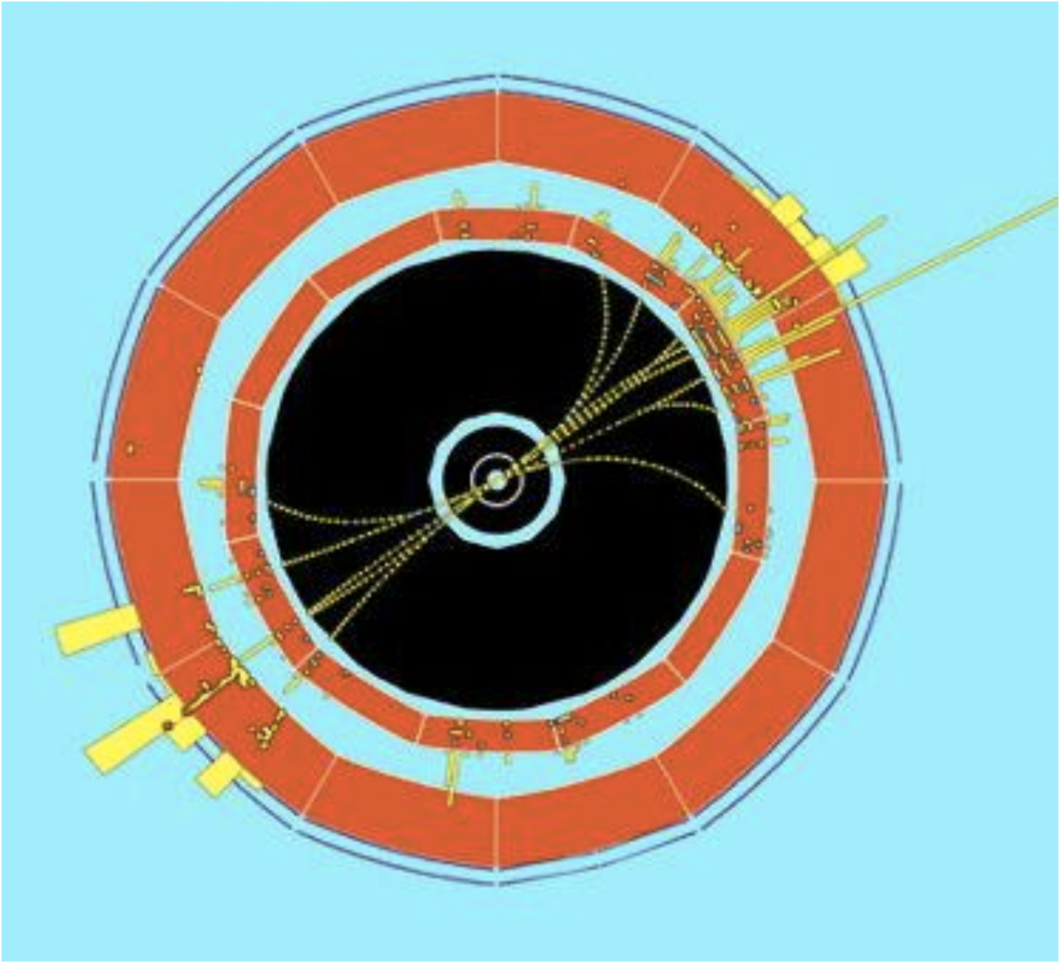


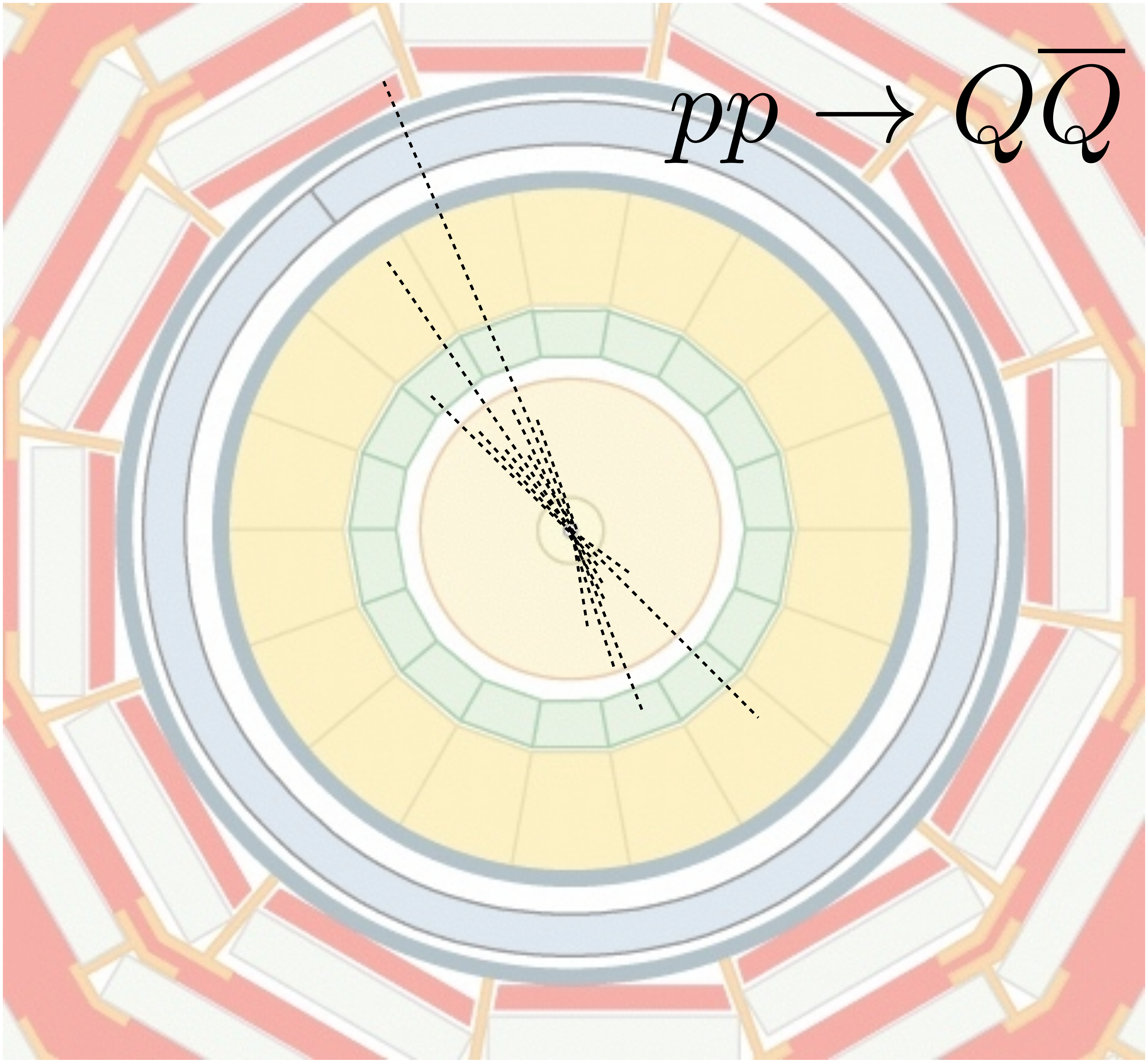
QCD JETS

Quark production at LEP



ALEPH event





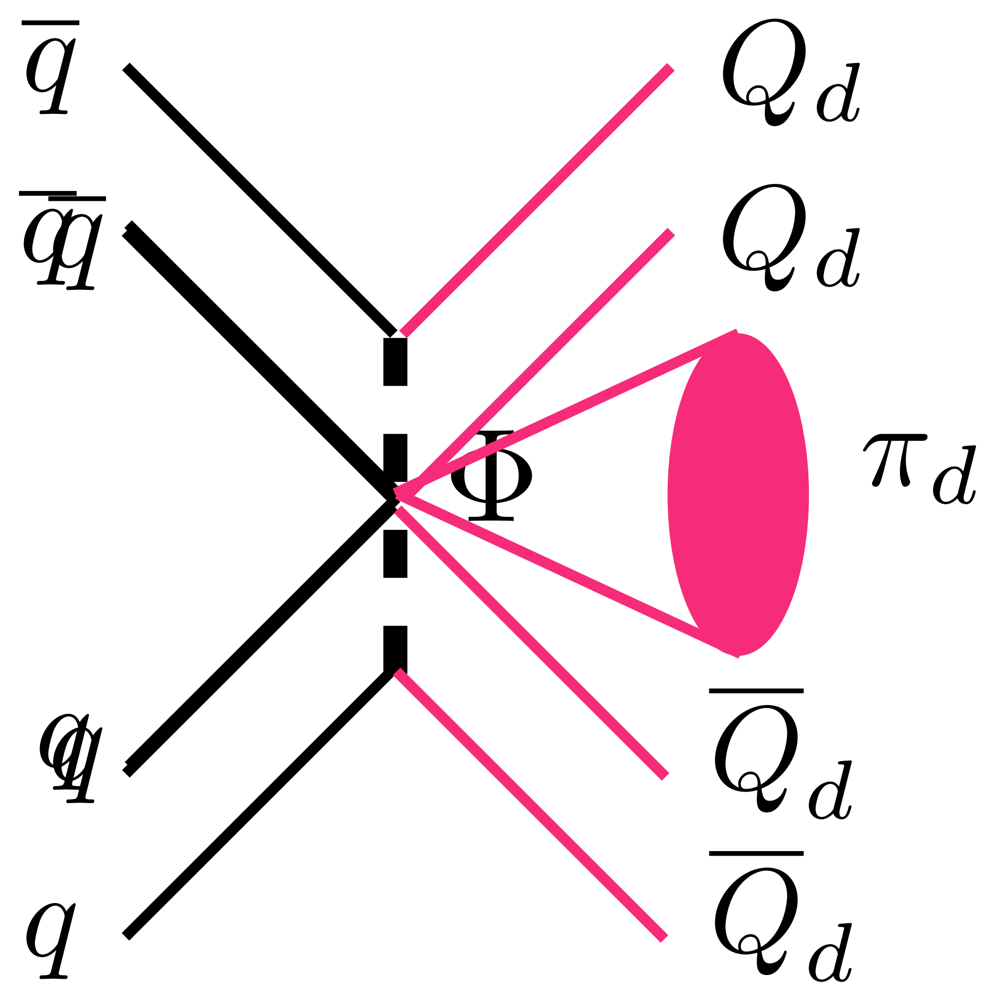
$$pp \to Q\overline{Q}$$

PION DECAY

Operator used to generate asymmetry mediates decay

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

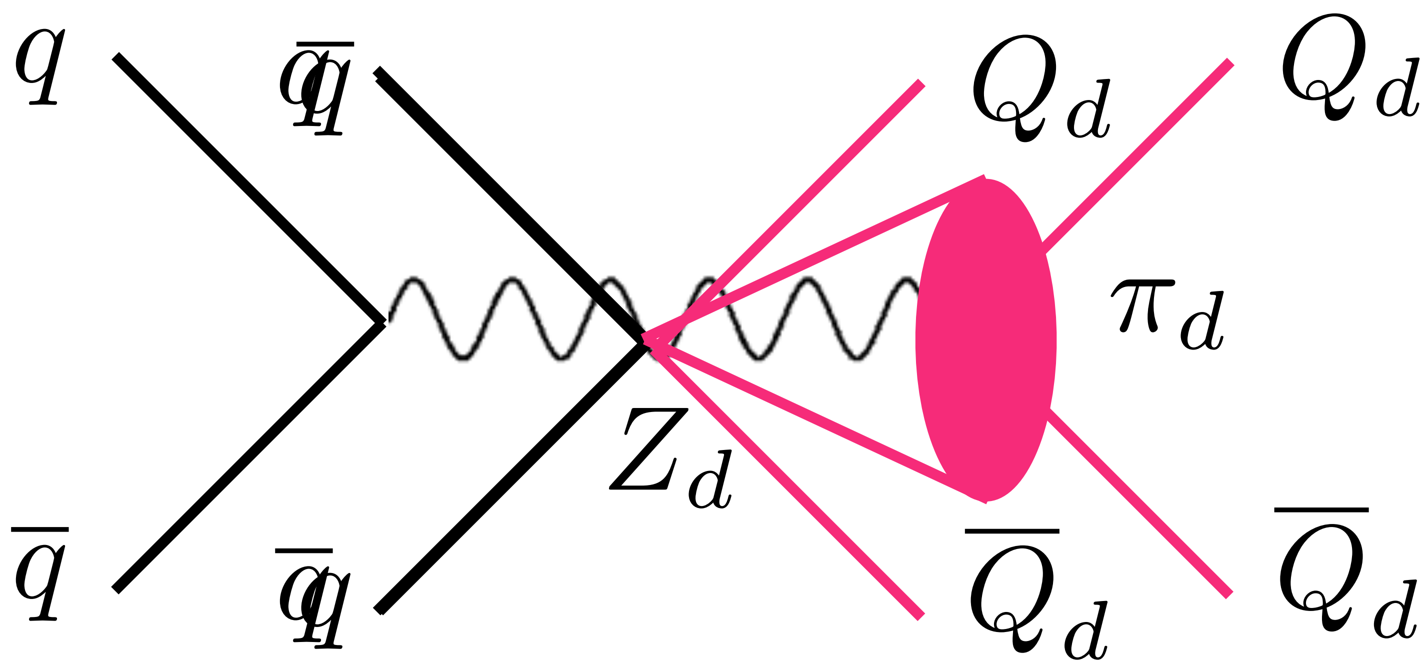
Integrate out Φ



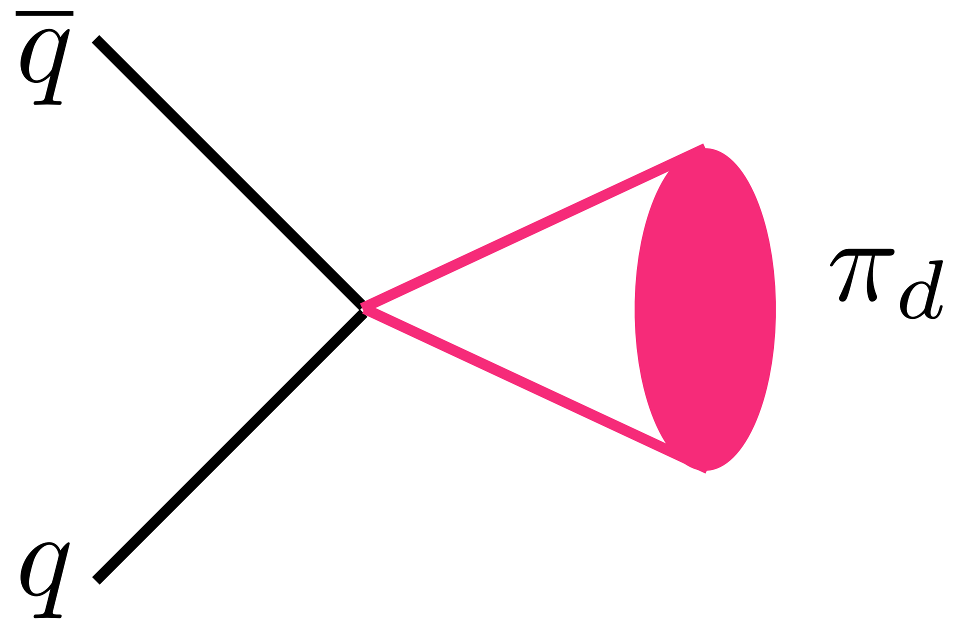
Dark pion decays to quarks

PION DECAY

Same story for Z_d model:



DECAY LENGTH



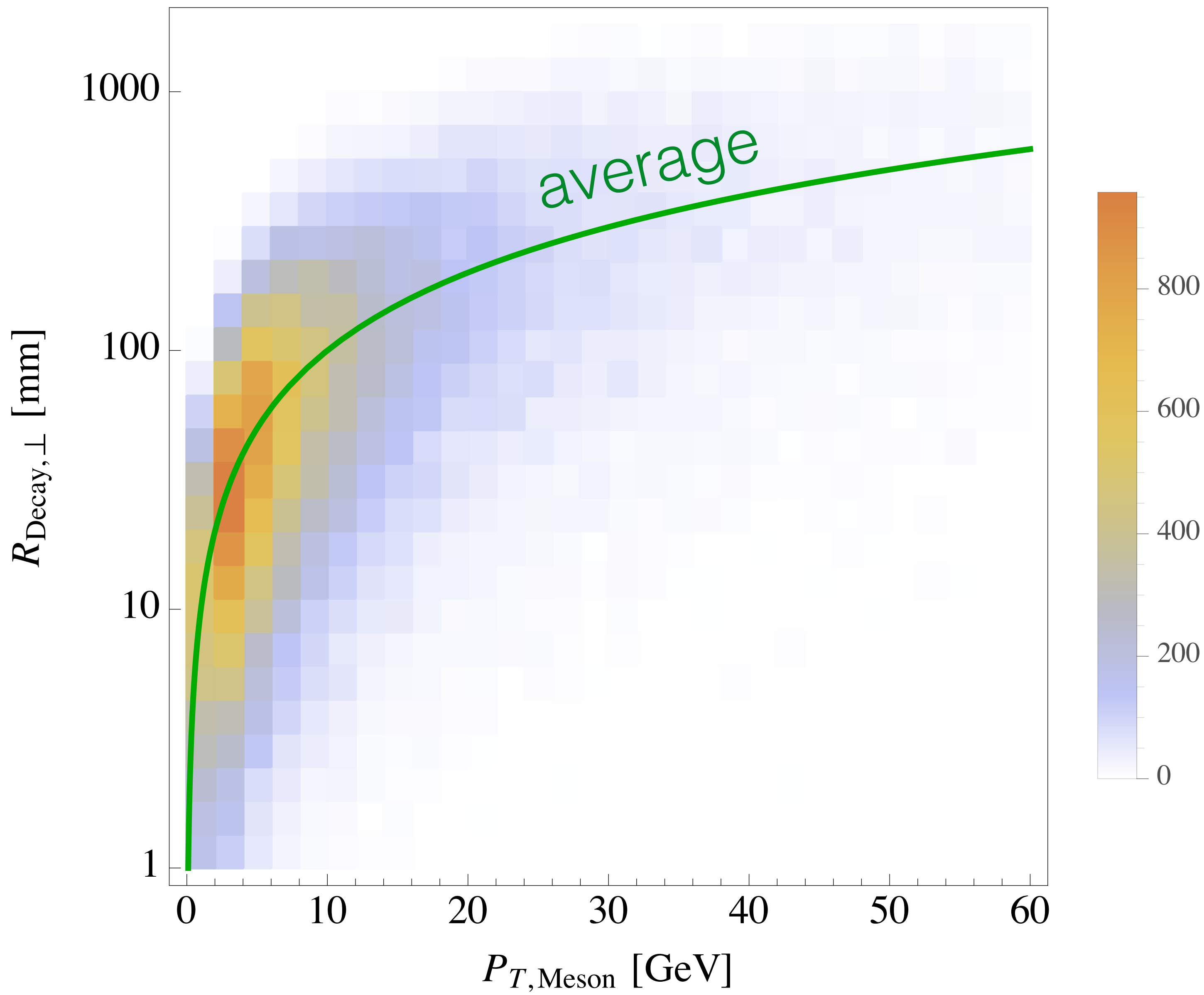
$$\frac{1}{M_X^2}\overline{Q}\gamma_\mu Q\,\bar{d}_R\gamma^\mu d_R$$

Can use (dark) chiral Lagrangian to estimate:

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

$$c\tau \approx 5\,\mathrm{cm} \times \left(\frac{1\ \mathrm{GeV}}{f_{\pi_d}}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_{\mathrm{d}}}\right)^2 \left(\frac{1\ \mathrm{GeV}}{m_{\pi_d}}\right) \left(\frac{M_{X_d}}{1\ \mathrm{TeV}}\right)^4$$

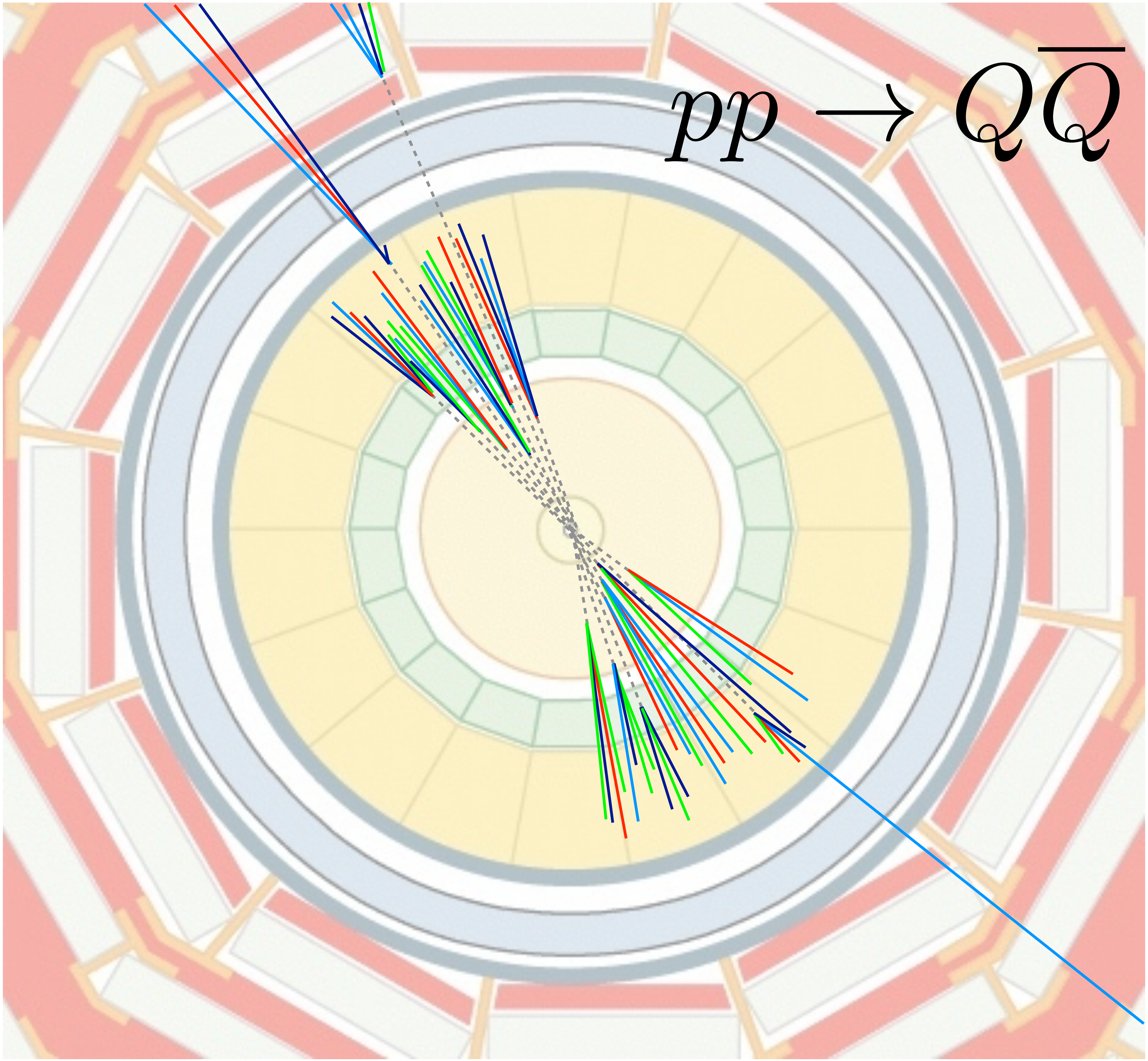
DECAY LENGTH



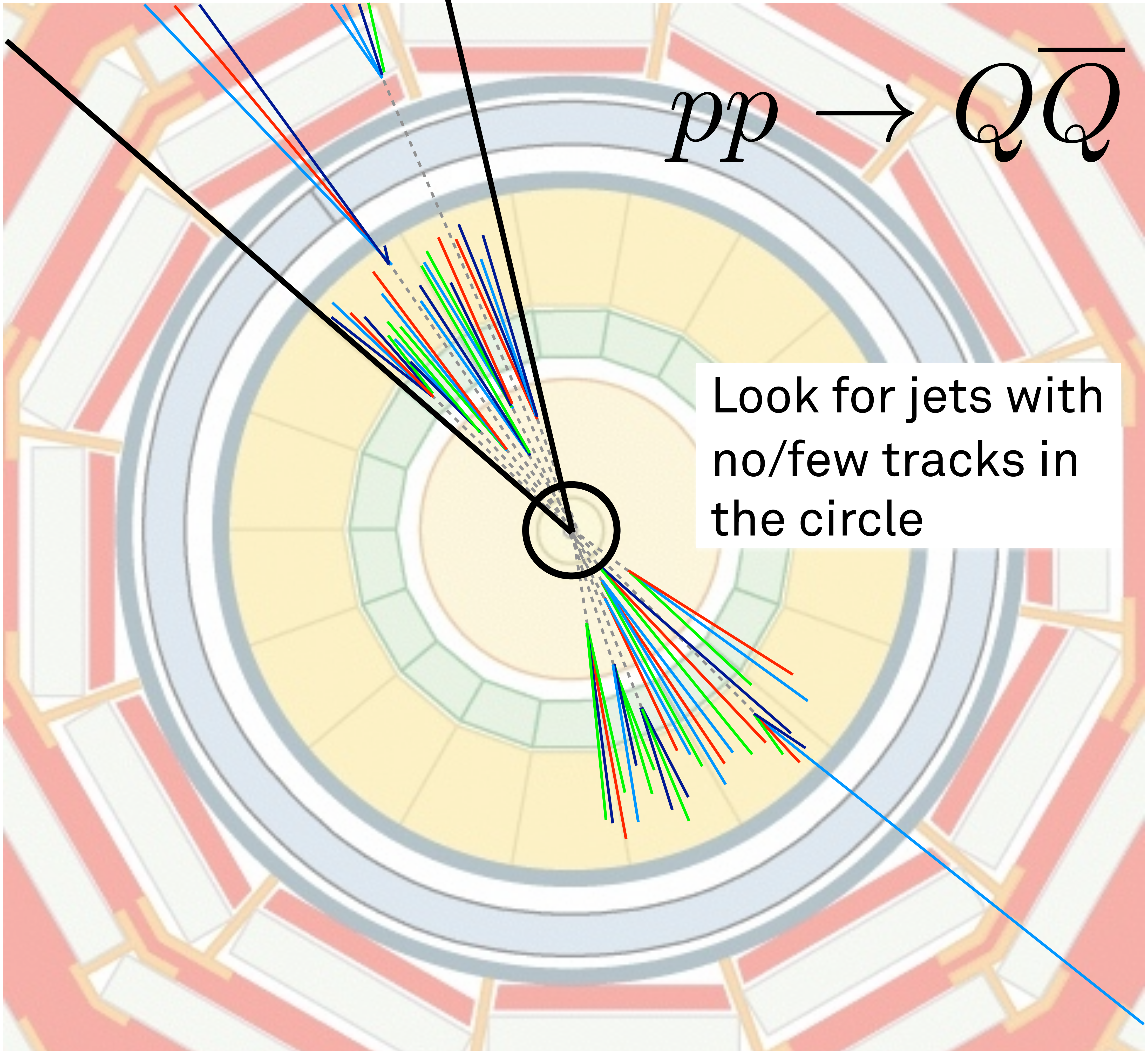
	Model **A**	Model **B**
Λ_d	10 GeV	4 GeV
m_V	20 GeV	8 GeV
m_{π_d}	5 GeV	2 GeV
$c\,\tau_{\pi_d}$	50 mm	5 mm

$$c\tau \approx 5\,\mathrm{cm} \times \left(\frac{1\ \mathrm{GeV}}{f_{\pi_d}}\right)^2 \left(\frac{100\ \mathrm{MeV}}{m_{\mathrm{d}}}\right)^2 \left(\frac{1\ \mathrm{GeV}}{m_{\pi_d}}\right) \left(\frac{M_{X_d}}{1\ \mathrm{TeV}}\right)^4$$

$$pp \to Q\overline{Q}$$

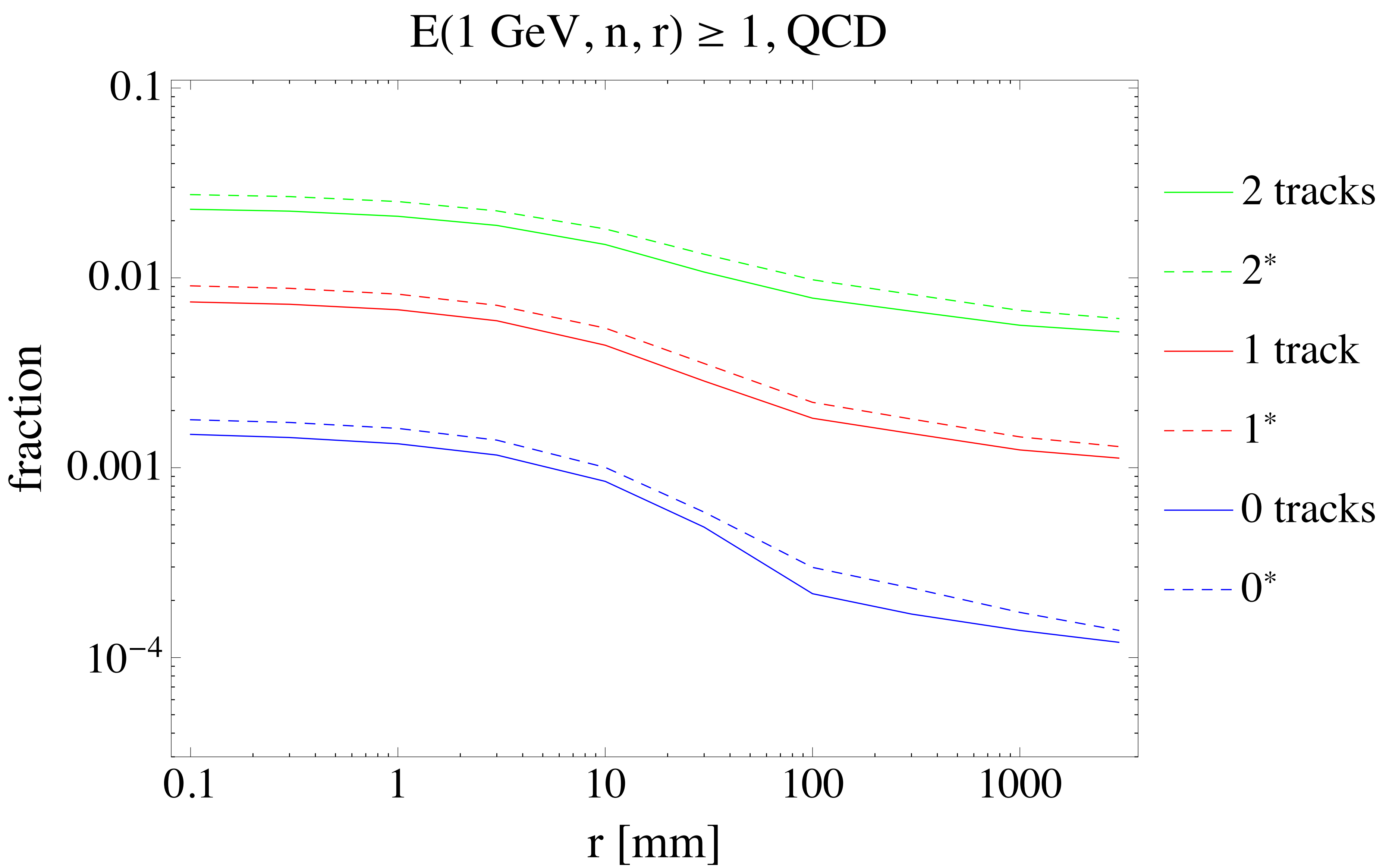


~ 2 m (CMS)


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

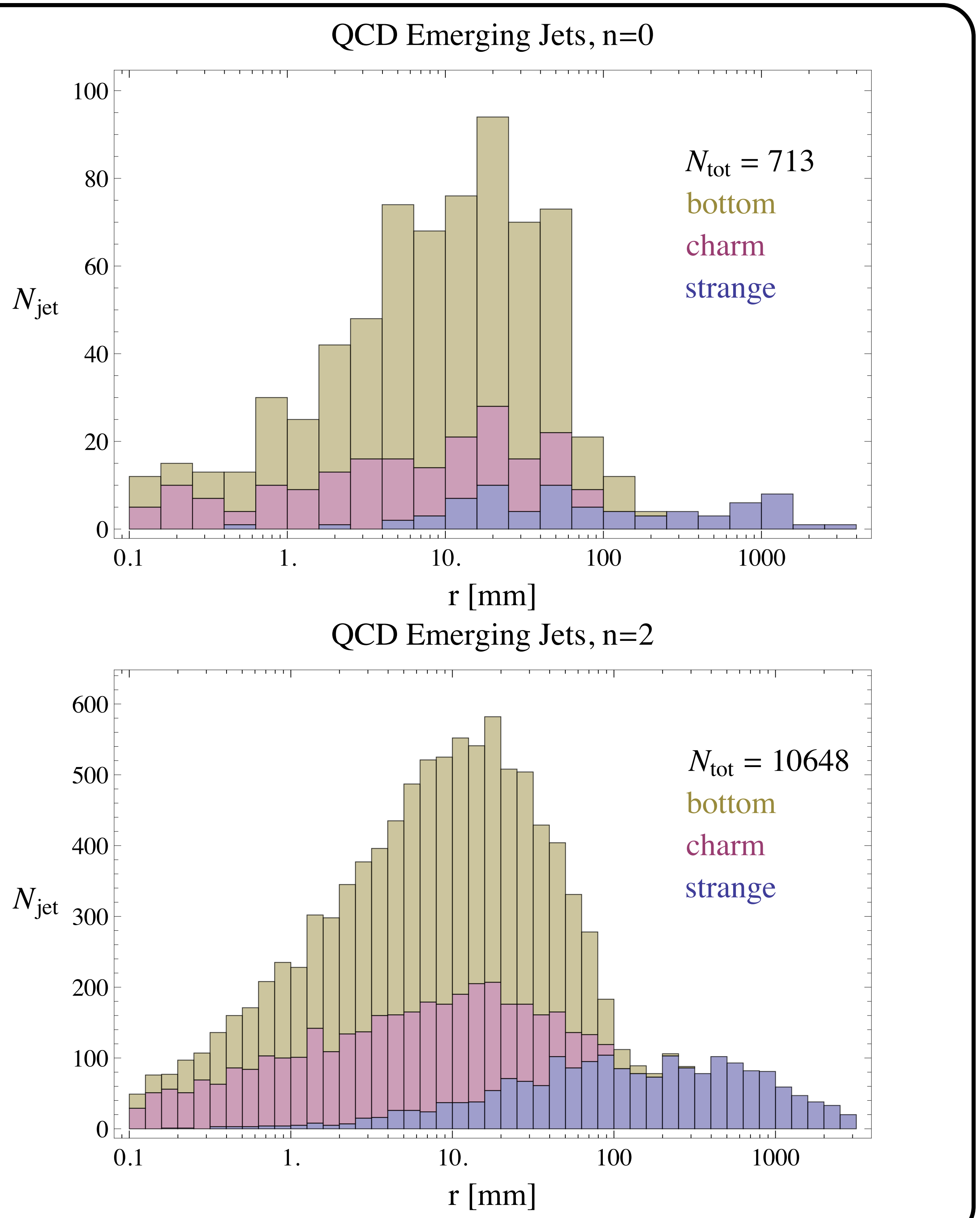
BACKGROUND?

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



* - modified Pythia tune to increase QCD contribution

BACKGROUND COMPOSITION

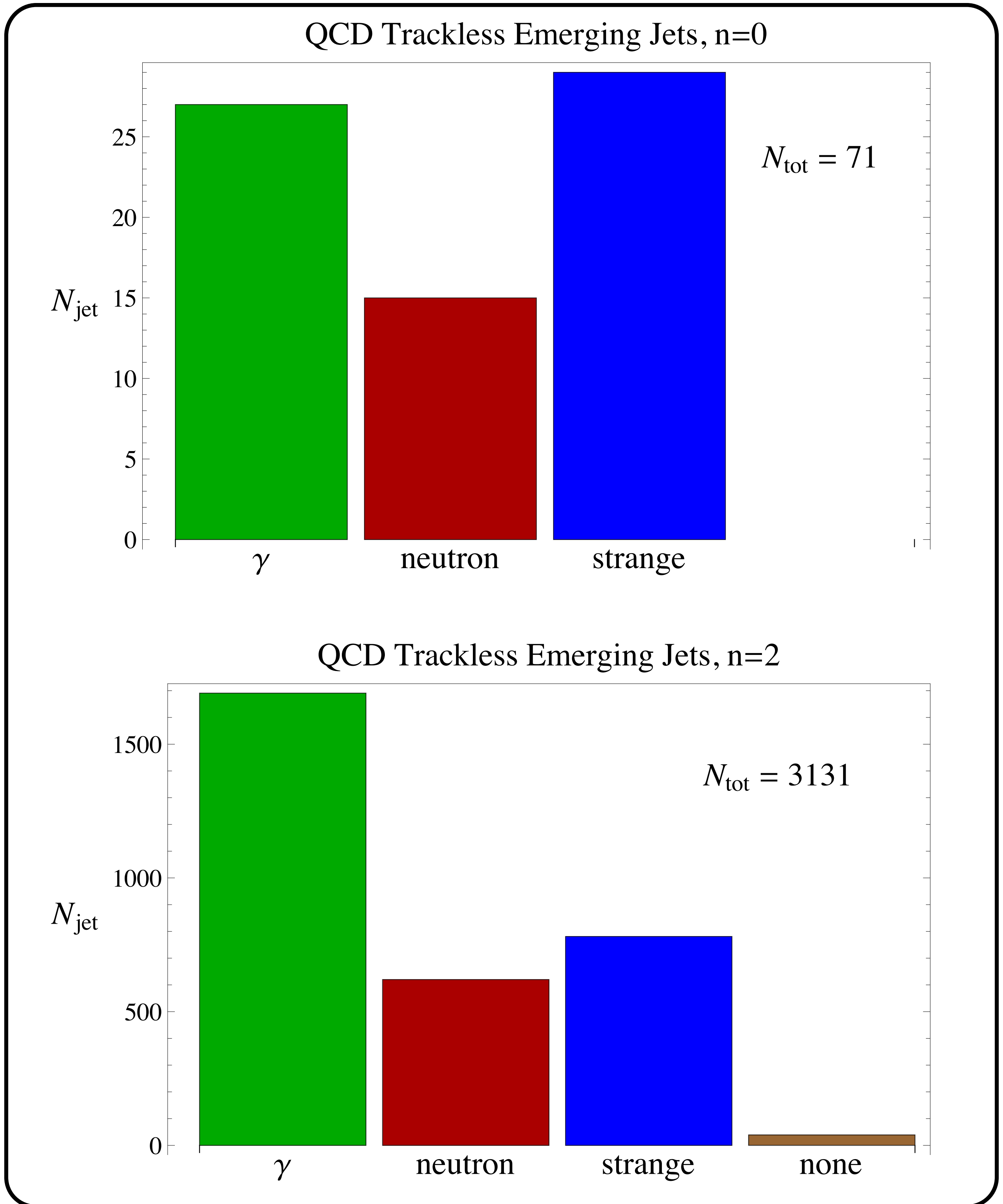


Flavor of earliest decaying track

track $p_T > 1$ GeV

jet $p_T > 200$ GeV

TRACKLESS BACKGROUND



Composition of completely trackless background

track $p_T > 1 \text{ GeV}$

jet $p_T > 200 \text{ GeV}$

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!

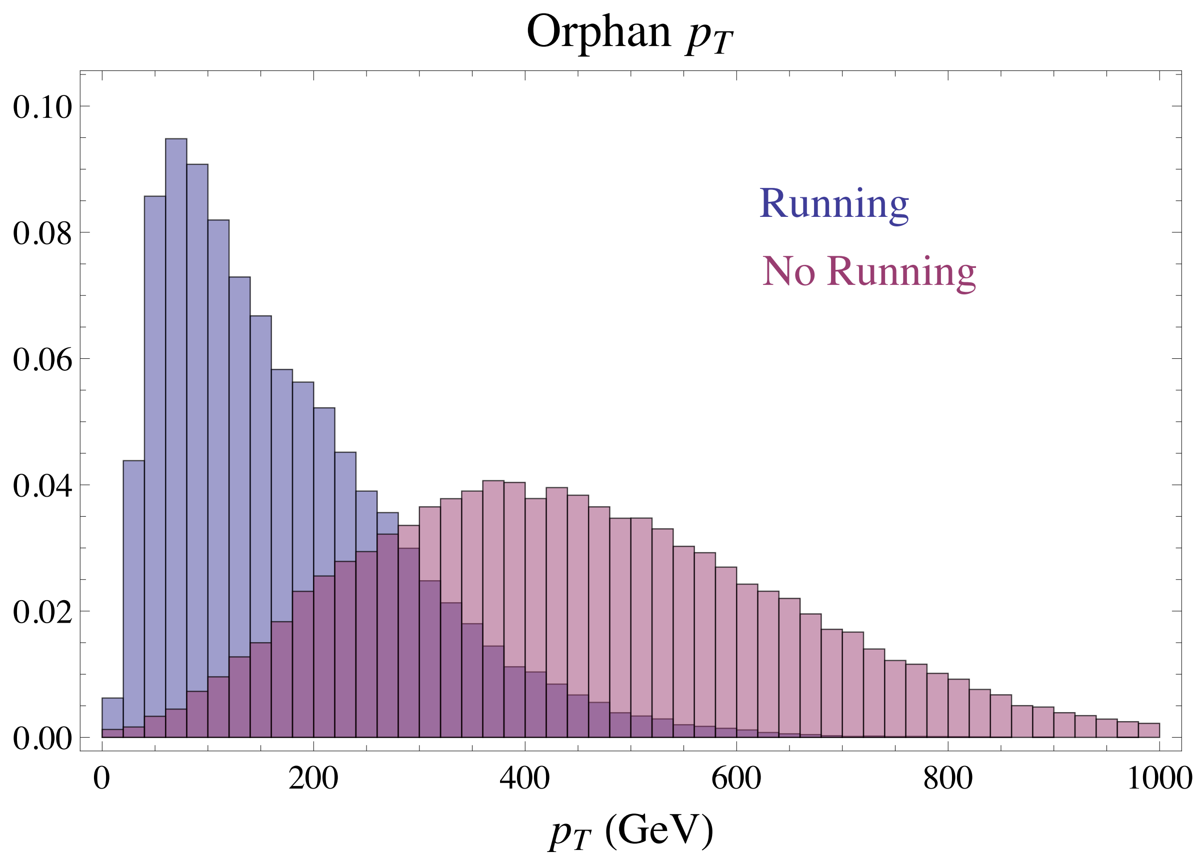
Carloni, Sjorstrand, 2010.

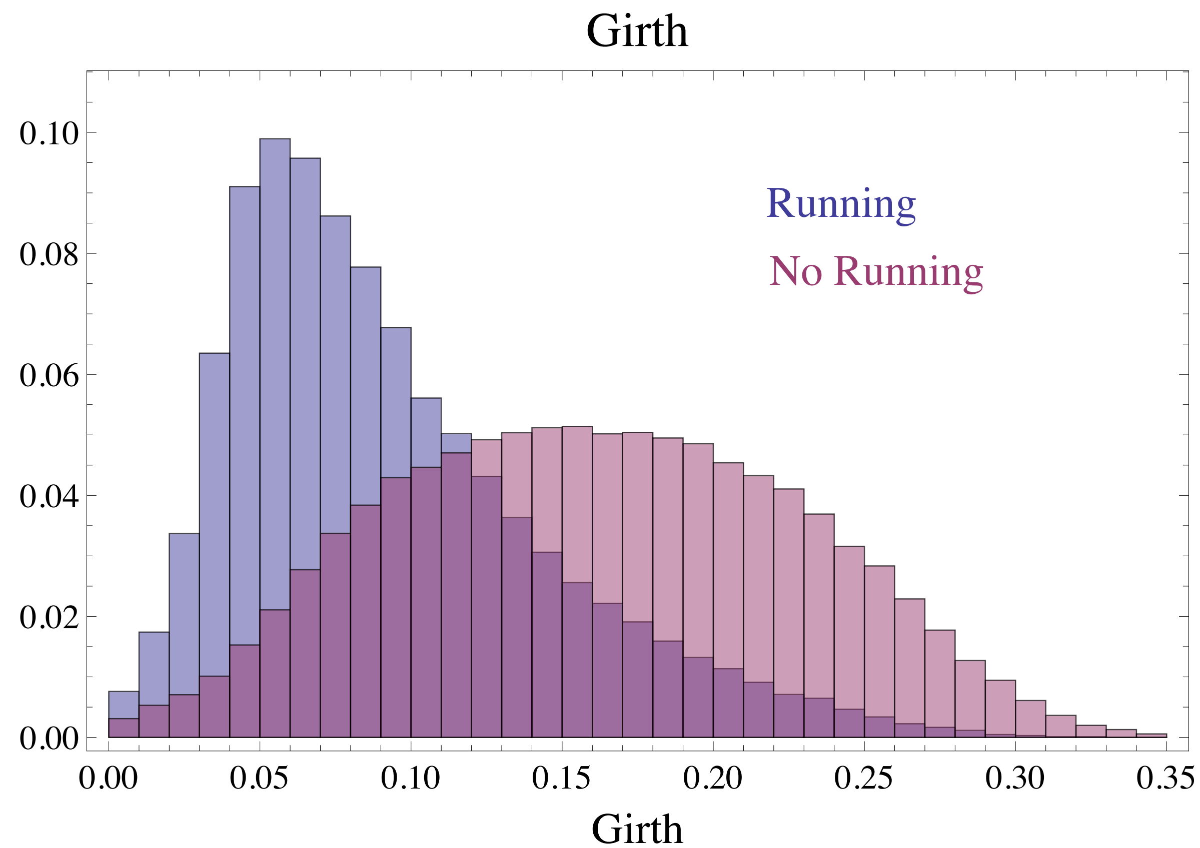
Carloni, Rathsman, Sjorstrand, 2011.

Run modified version with running

COUPLING RUNNING

Modify PYTHIA to include gauge coupling running





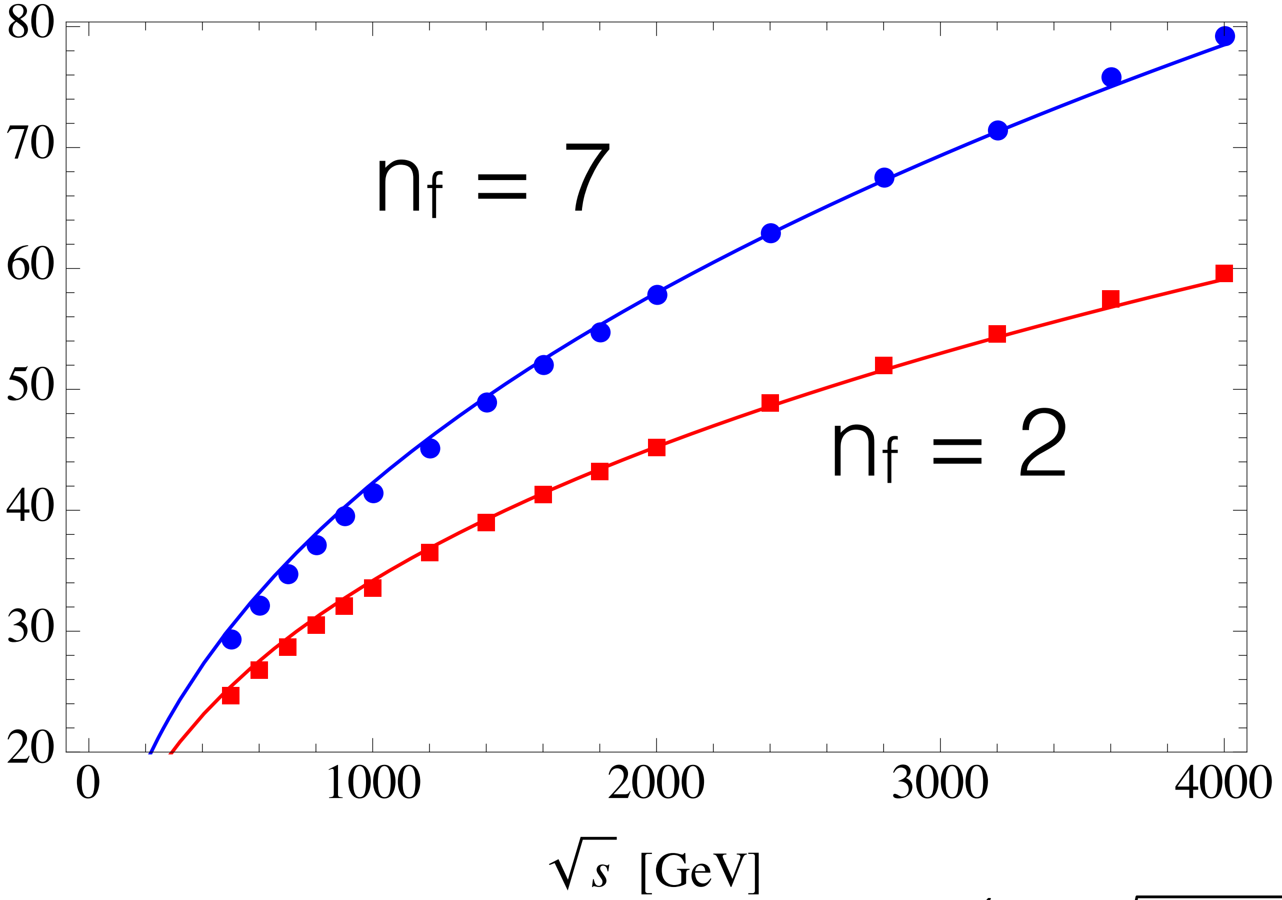
p_T not in jets with

$p_T > 200$ GeV

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

SIMULATION

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

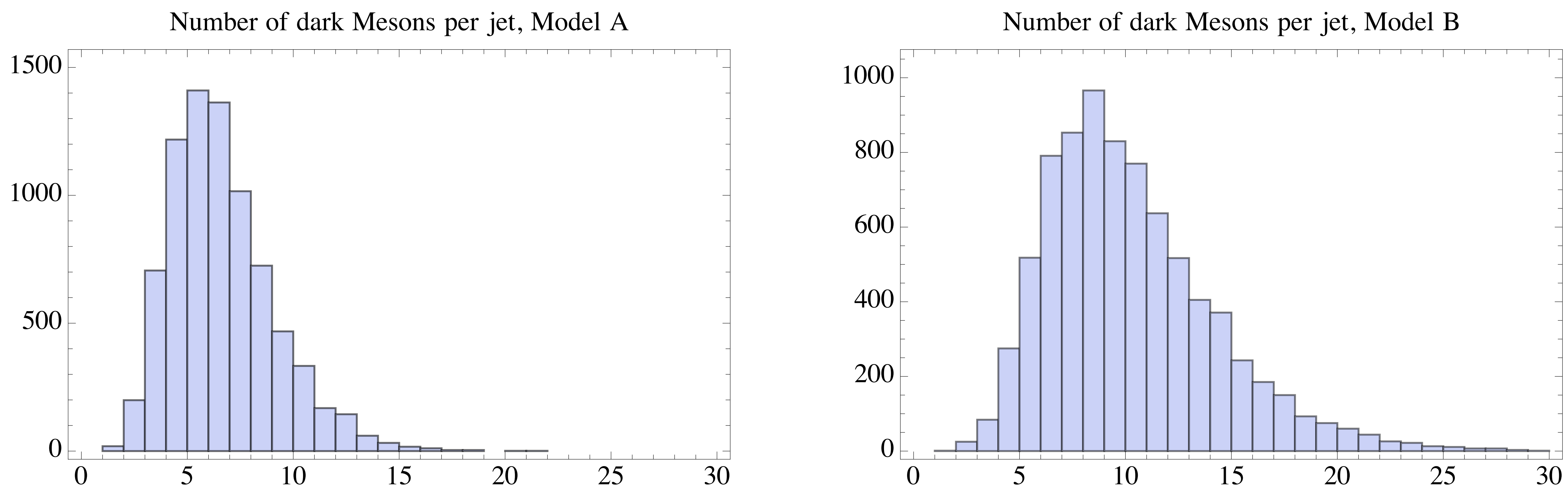


Ellis, Stirling, and Weber, 1996.

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

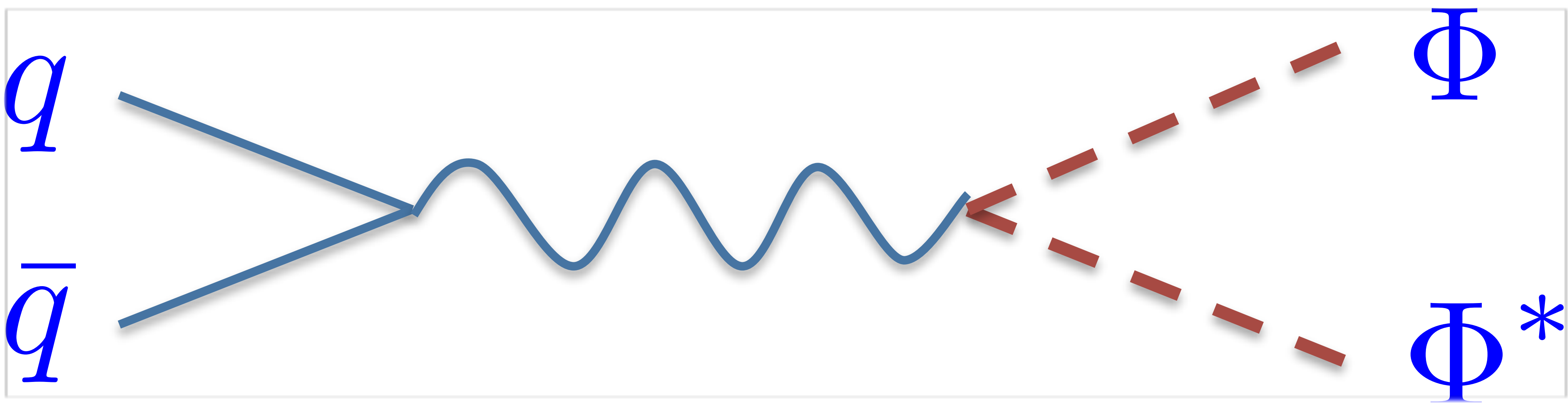
MESON MULTIPLICITY

Number of dark mesons in a jet



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

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

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

@ LHC14

BENCHMARK MEDIATOR 2

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

Final state is

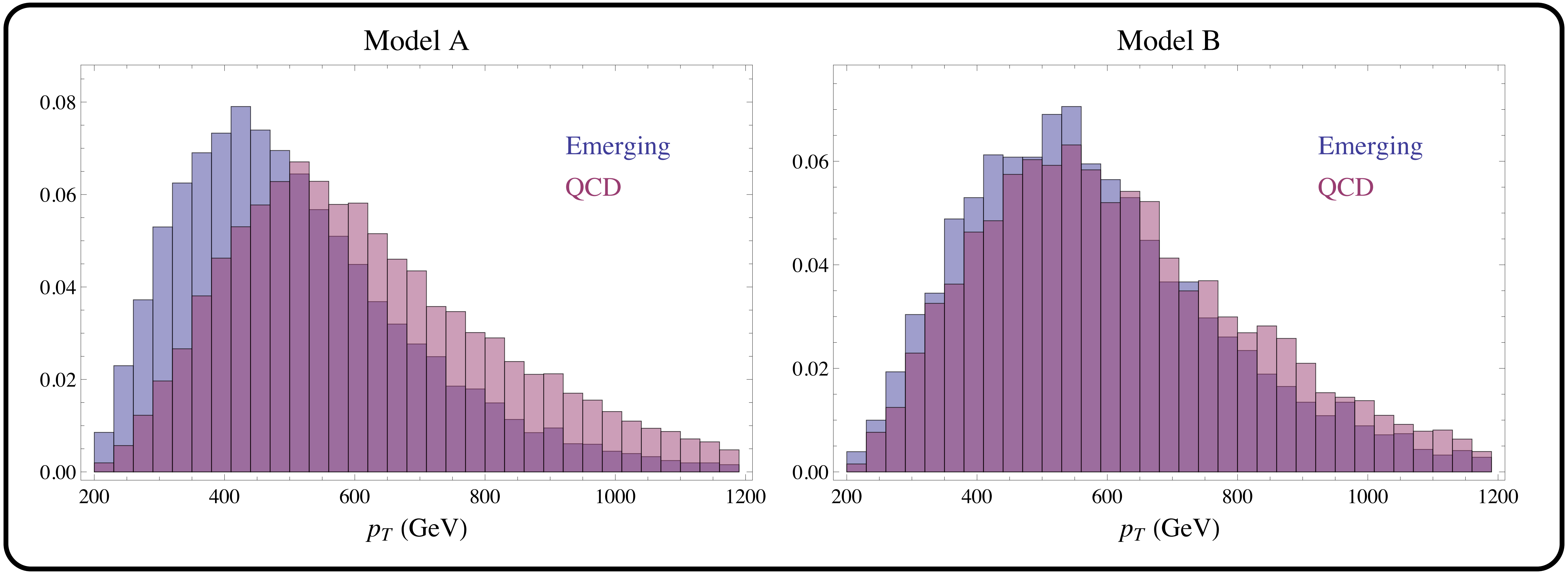
- 2 emerging jets

Cross section depends on couplings

Work in progress

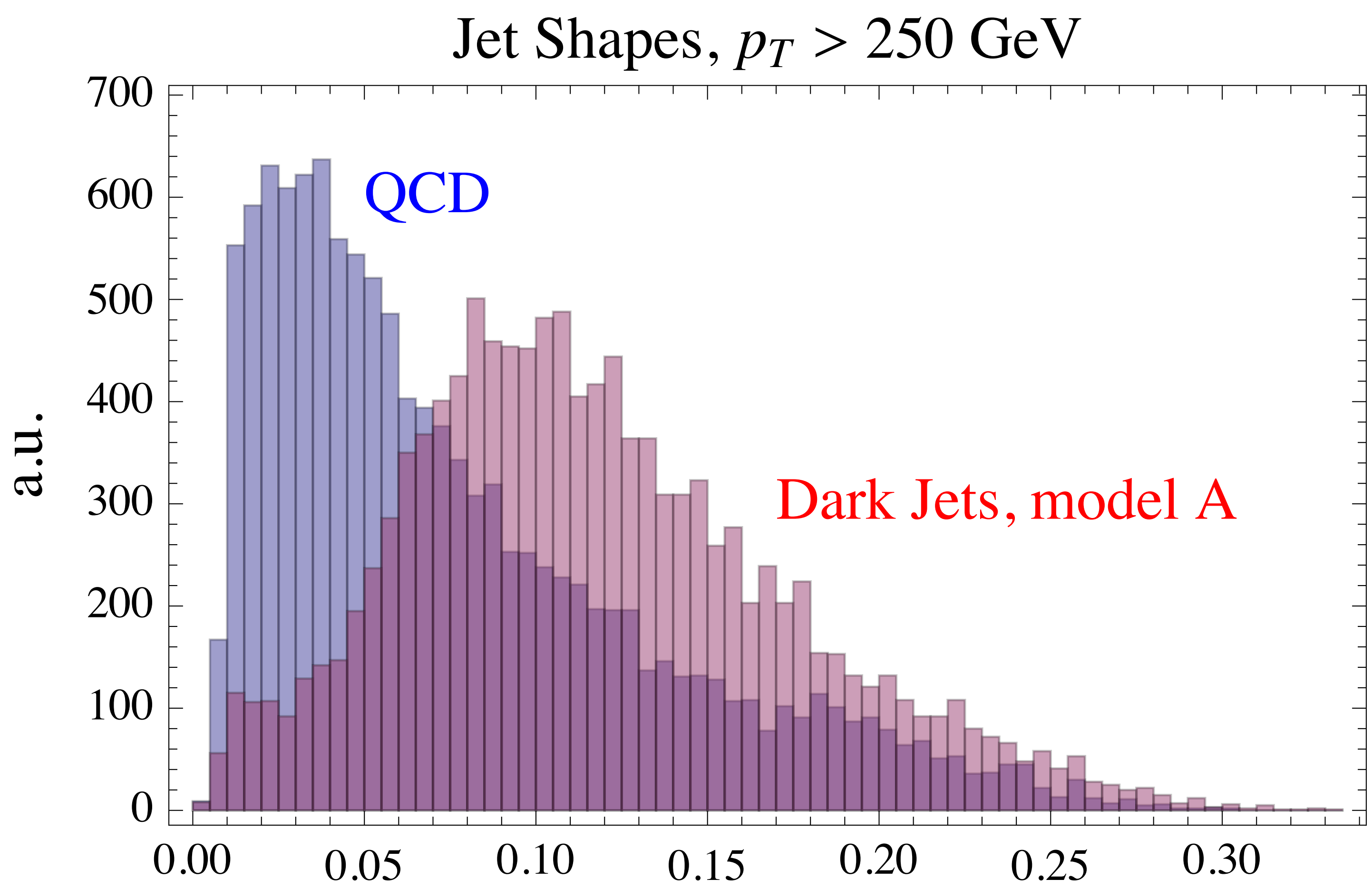
JET MOMENTA

Hardest jet p_T



Four hard jets is enough to pass trigger

JET SHAPES



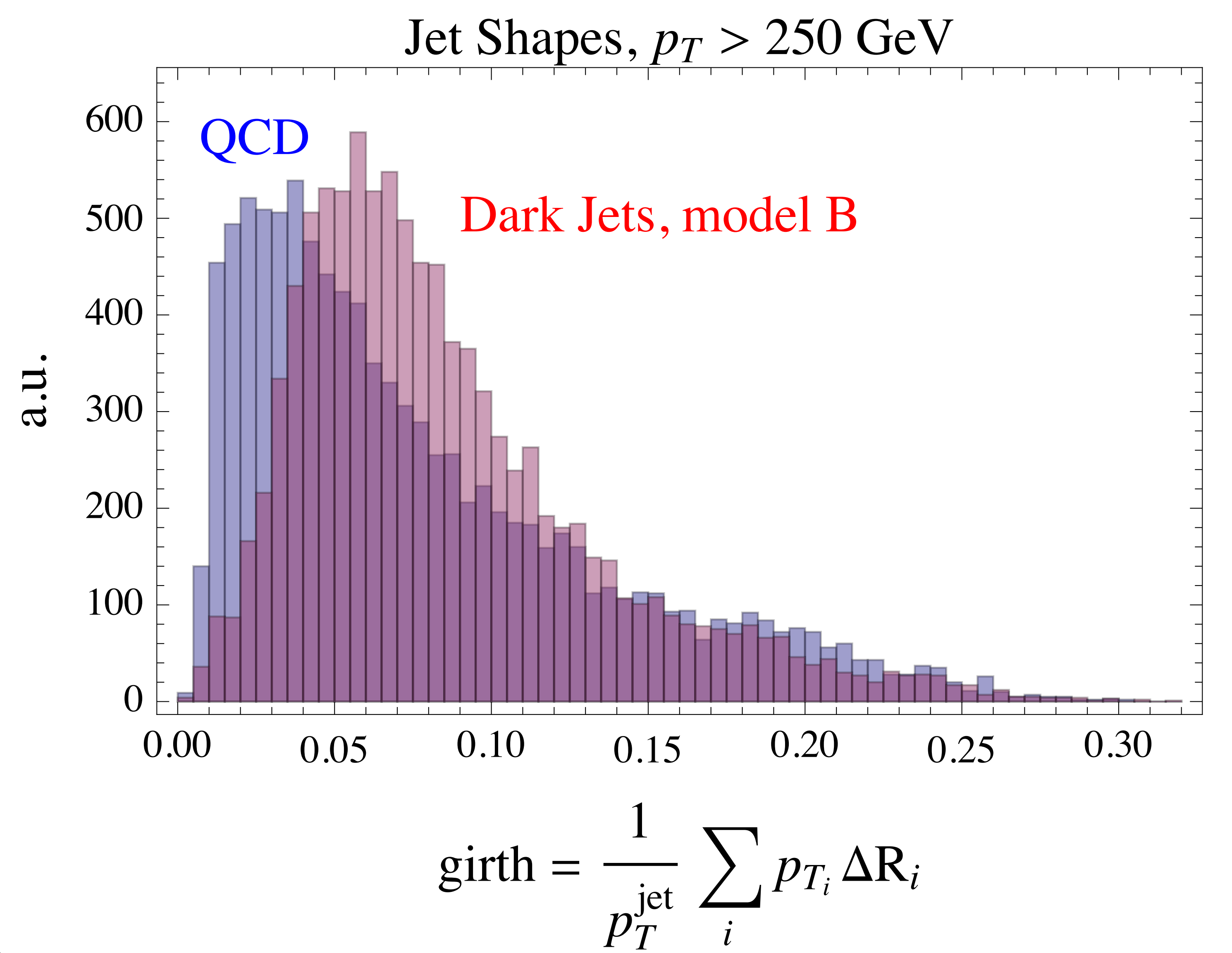
$$\text{girth} = \frac{1}{p_T^{\text{jet}}} \sum_i p_{T_i} \Delta R_i$$

Measure girth to get a sense of jet width

<u>Model A:</u>

$$m_\Phi = 1\,\text{TeV}$$
$$\Lambda_d = 10\,\text{GeV}$$
$$m_{\pi_d} = 5\,\text{GeV}$$
$$c\tau_{\pi_d} = 50\,\text{mm}$$

JET SHAPES



Quite sensitive to dark sector params.

<u>Model B:</u>

$$m_\Phi = 1\,\text{TeV}$$

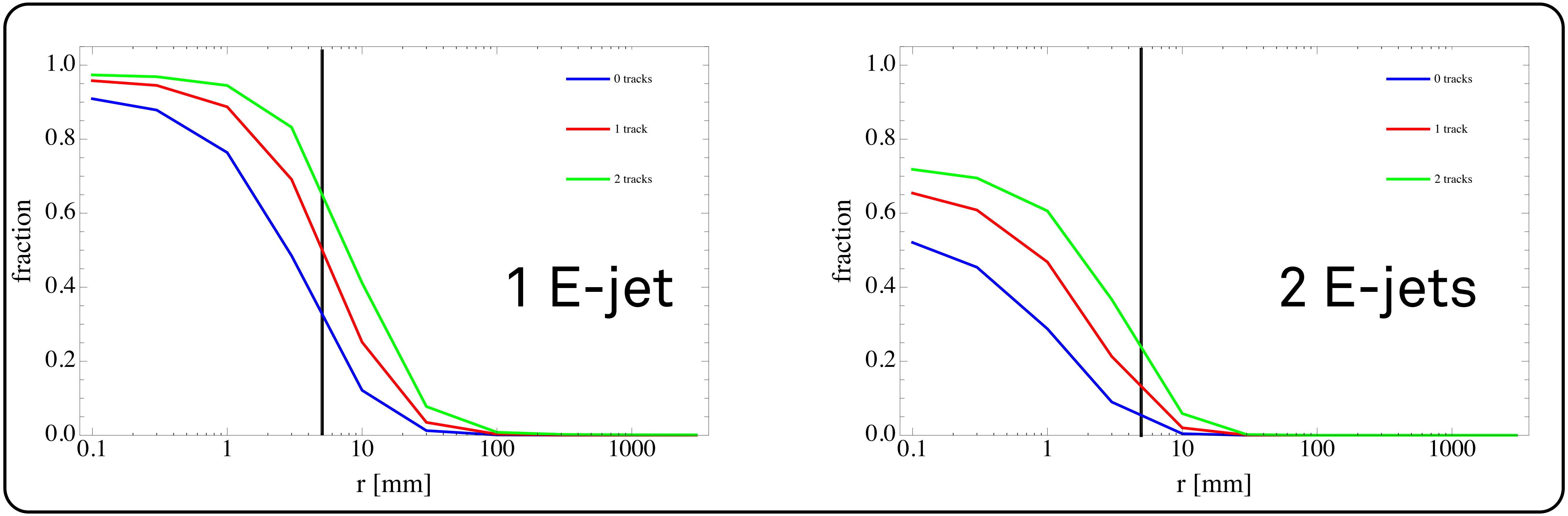
$$\Lambda_d = 4\,\text{GeV}$$

$$m_{\pi_d} = 2\,\text{GeV}$$

$$c\tau_{\pi_d} = 20\,\text{mm}$$

SEARCH STRATEGY

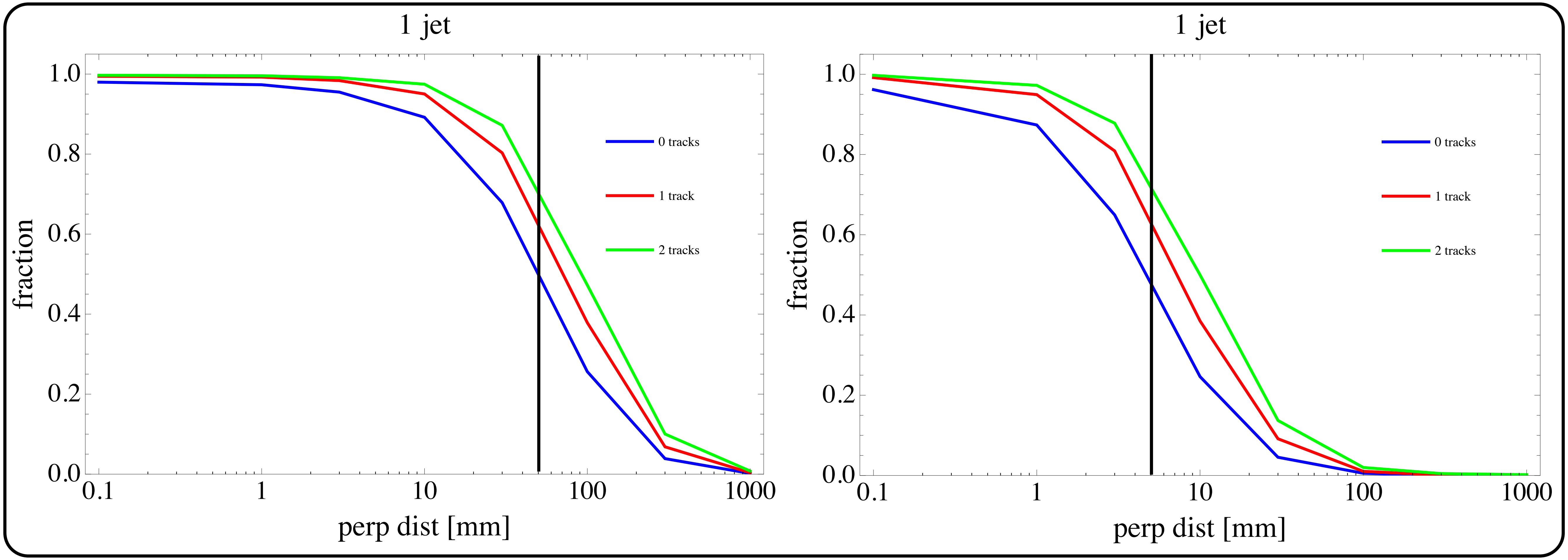
$$pp \to \Phi\Phi^\dagger \to \bar{q}\,Q_d\,\bar{Q}_d\,q$$



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

DIFFERENT MODEL POINTS

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



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

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

CUT FLOW

PRELIMINARY

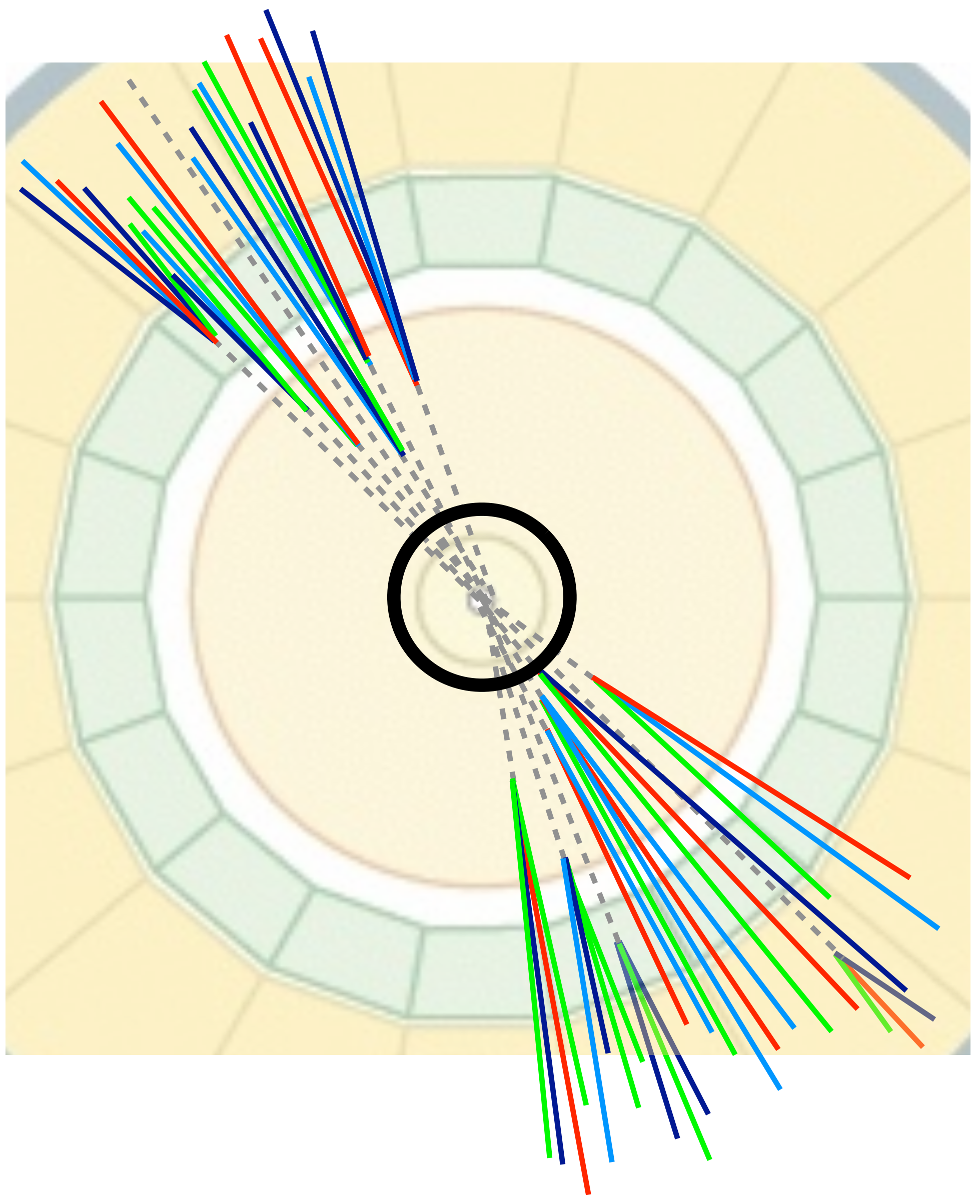
Cross sections in fb at LHC14:

	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!

Requiring emerging jets changes the game.

ALTERNATIVE STRATEGY



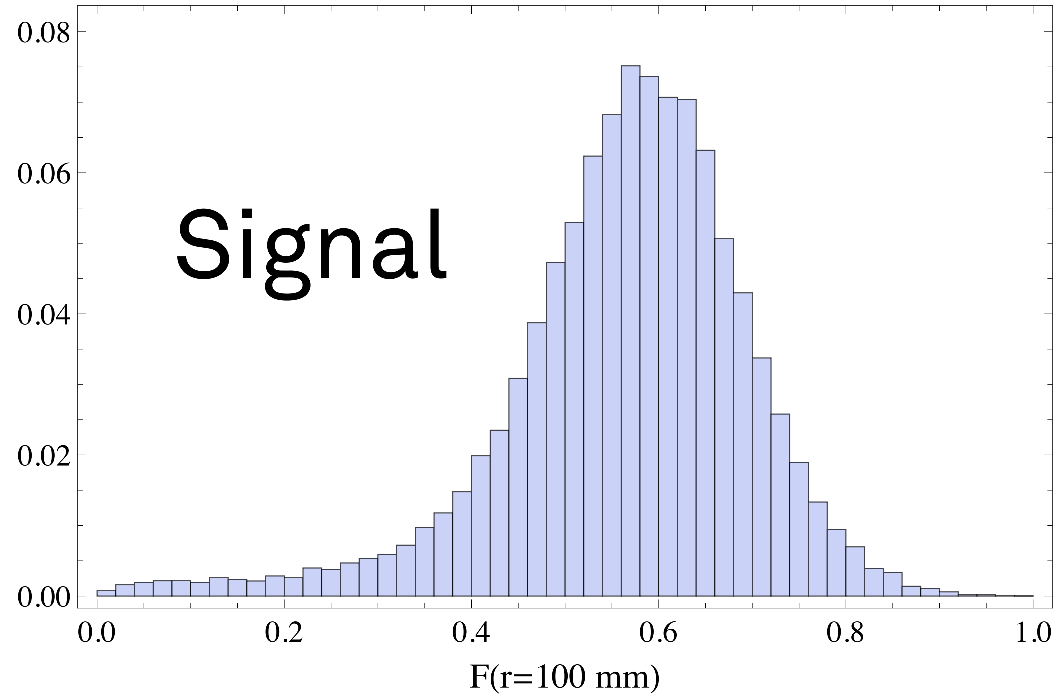
Fraction of jet energy reconstructing outside of circle

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

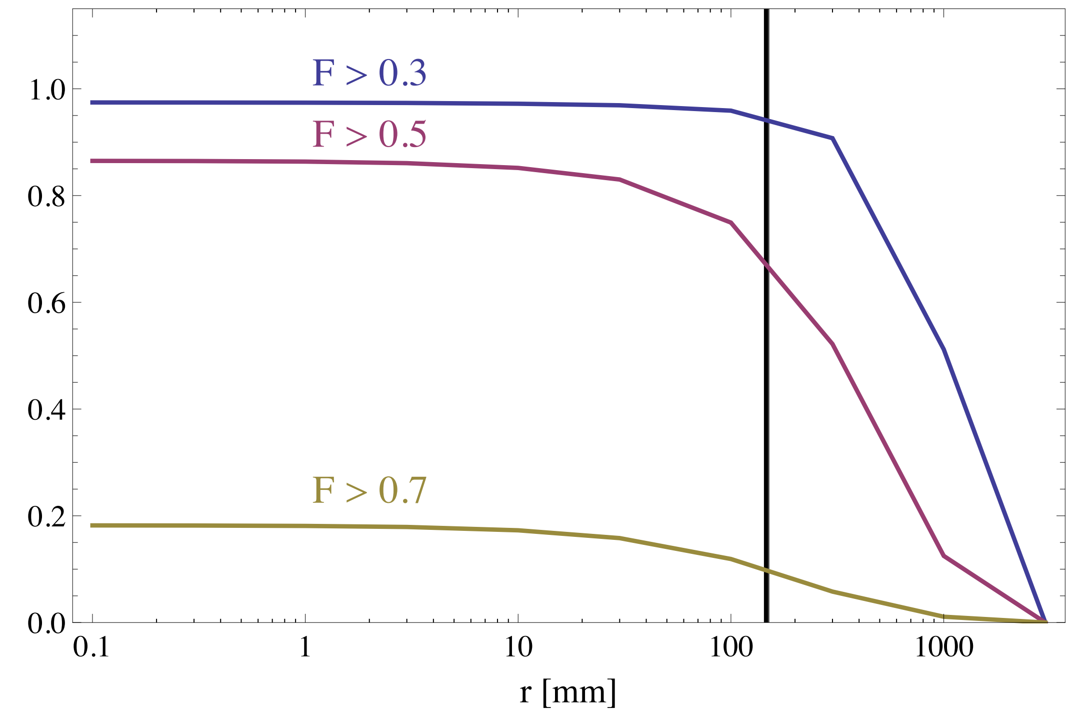
Much more robust to pile-up

F DISTRIBUTIONS

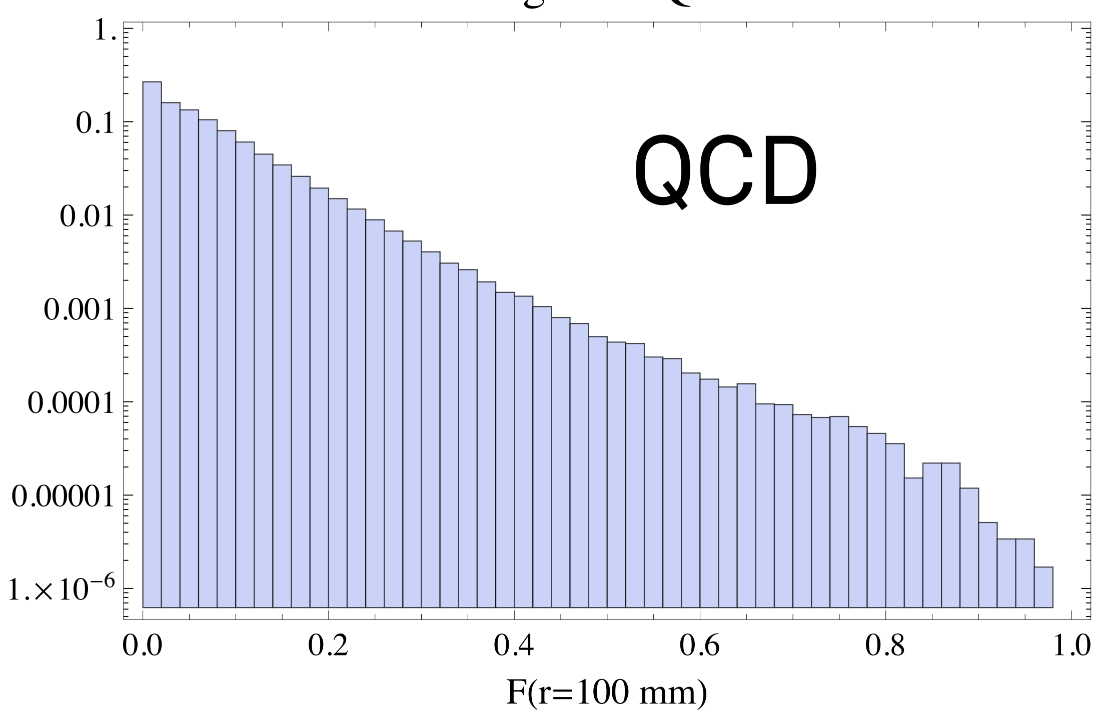
Largest F: Model A



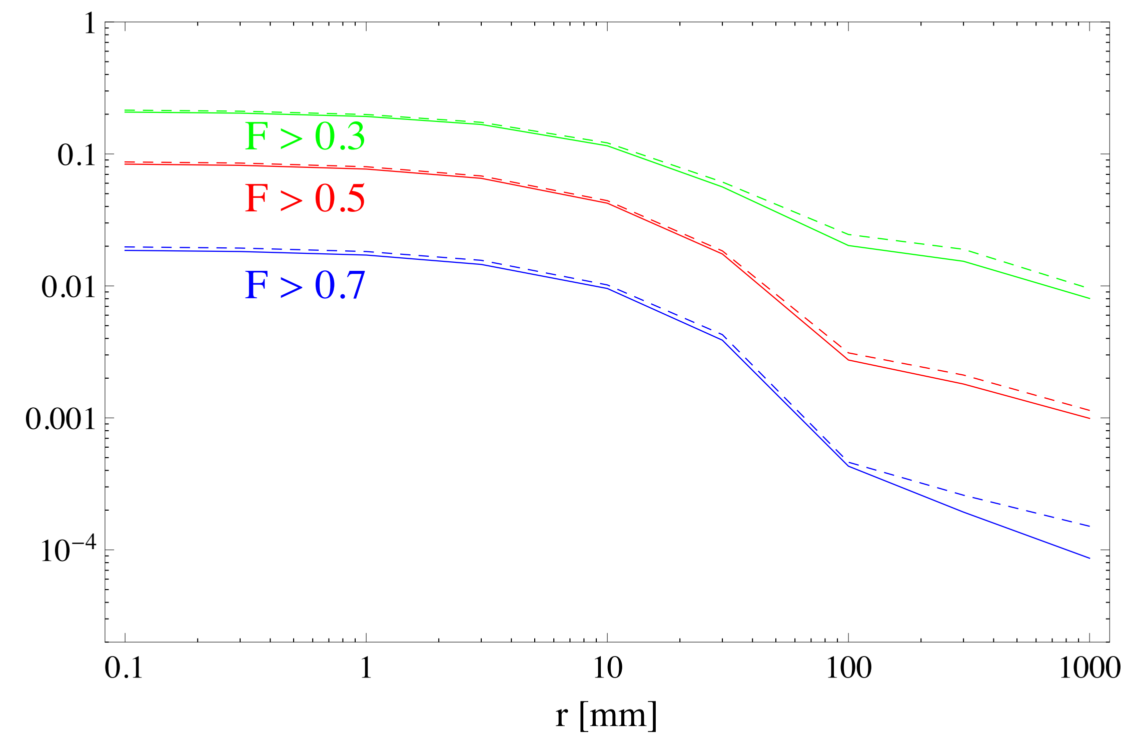
≥ 1 jet: Model A



Largest F: QCD



≥ 1 jet: QCD



ALTERNATIVE CUT FLOW

PRELIMINARY

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	8.4	48,000	48,000
1 jet $F(100\text{ mm}) > 0.5$	3.7	1.8	130	150
2 jets $F(100\text{ mm}) > 0.5$	1.3	0.1	0.3	0.2

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

Works pretty well at *r*=100 mm even for short lifetime model

CMS SEARCH

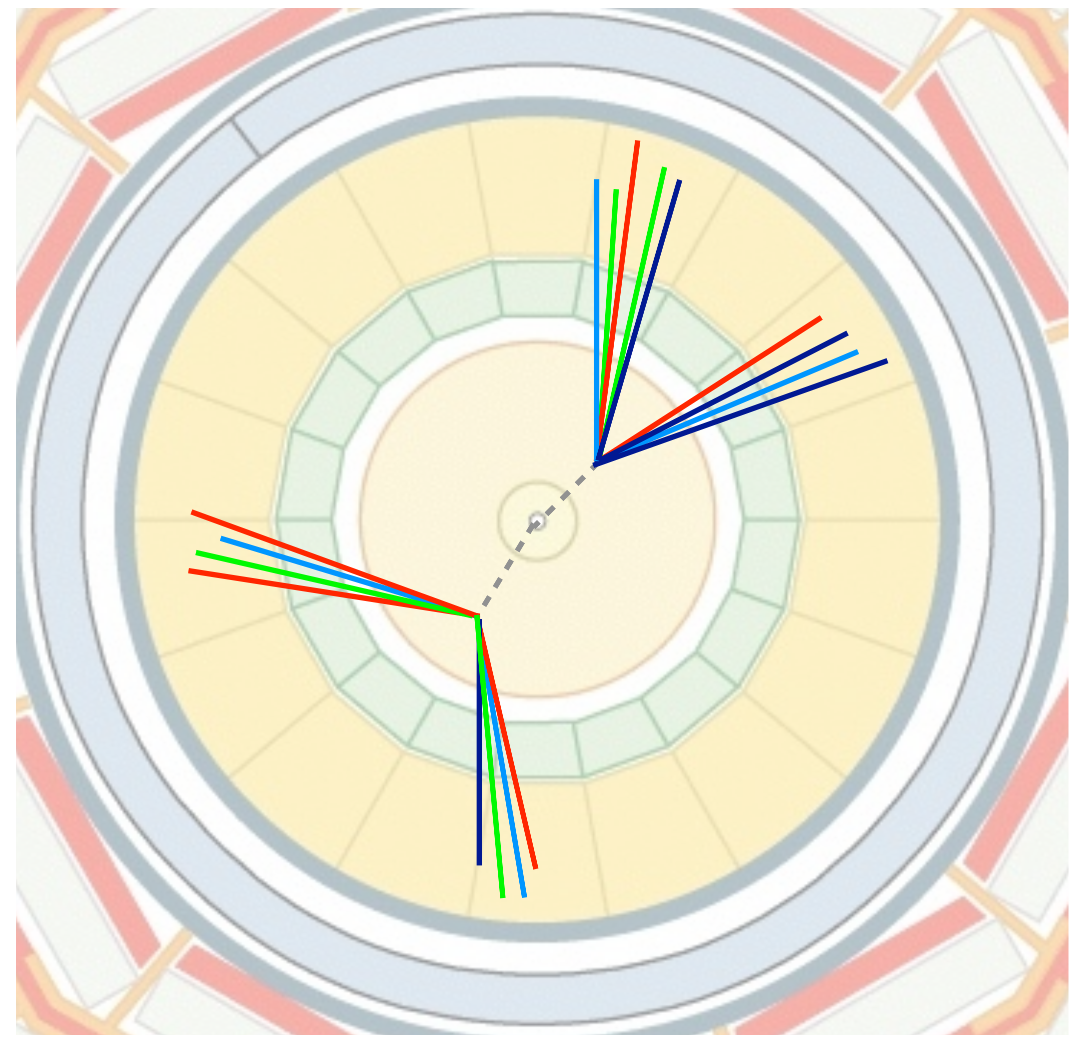
Search for long-lived neutral particles decaying to dijets

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 PAS EXO-12-038



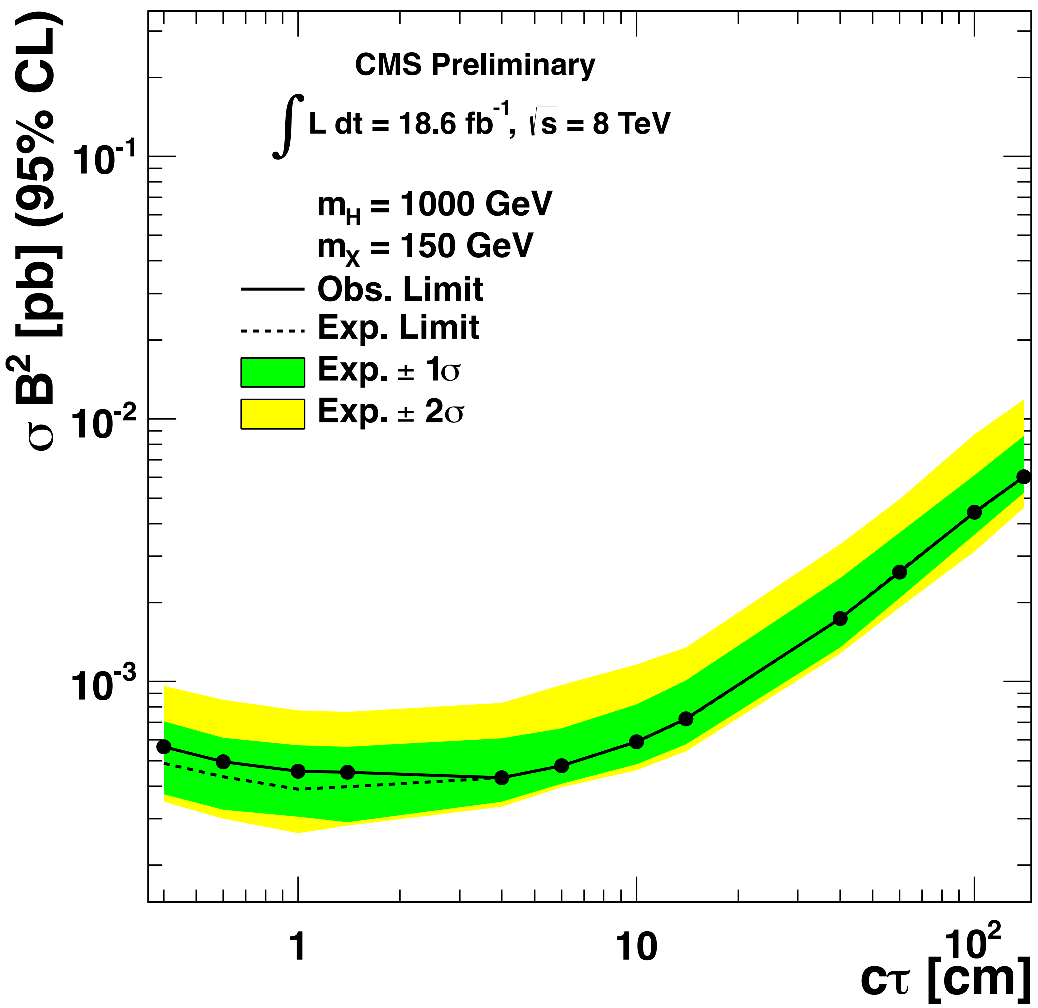
CMS SEARCH

CMS PAS EXO-12-038

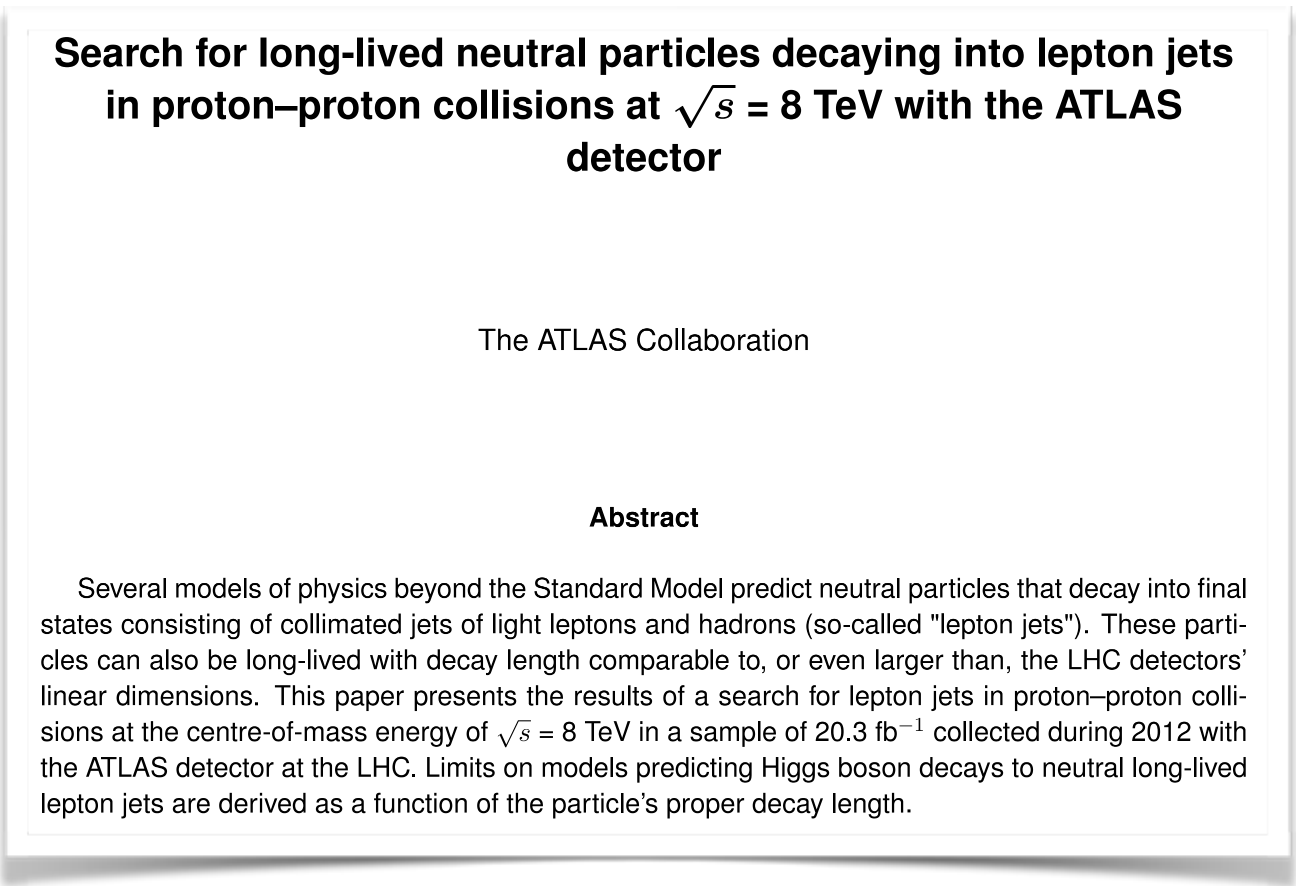
Require di-jets all coming from a single displaced vertex

Throw away energy of tracks not reconstructed from vertex

Unlikely to be sensitive to emerging phenomenology



ATLAS SEARCH



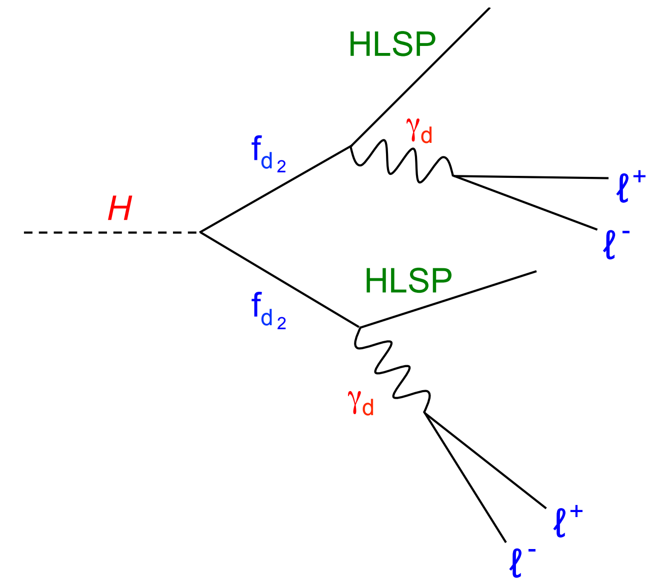
Search for long-lived neutral particles decaying into lepton jets in proton–proton collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector

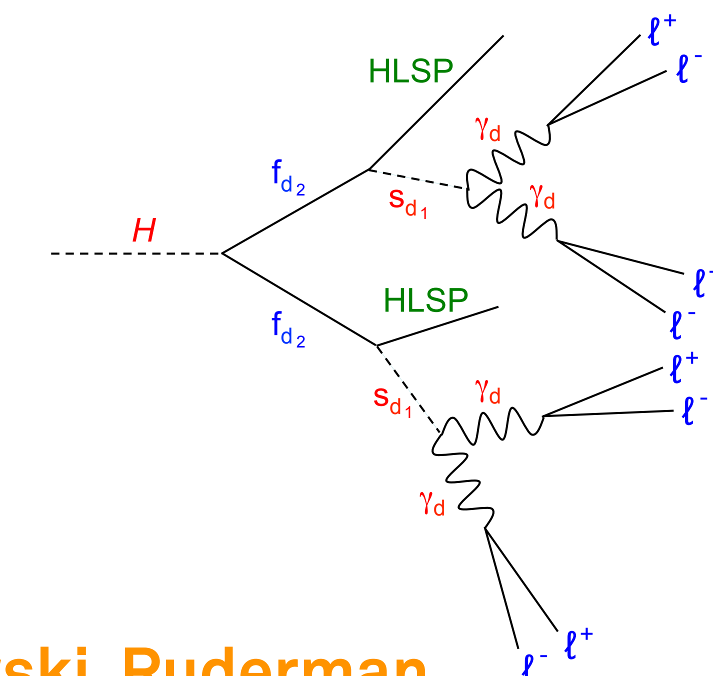
The ATLAS Collaboration

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.

arXiv:1409.0746v2 [hep-ex]





Falkowski, Ruderman, Volansky, Zupan '10

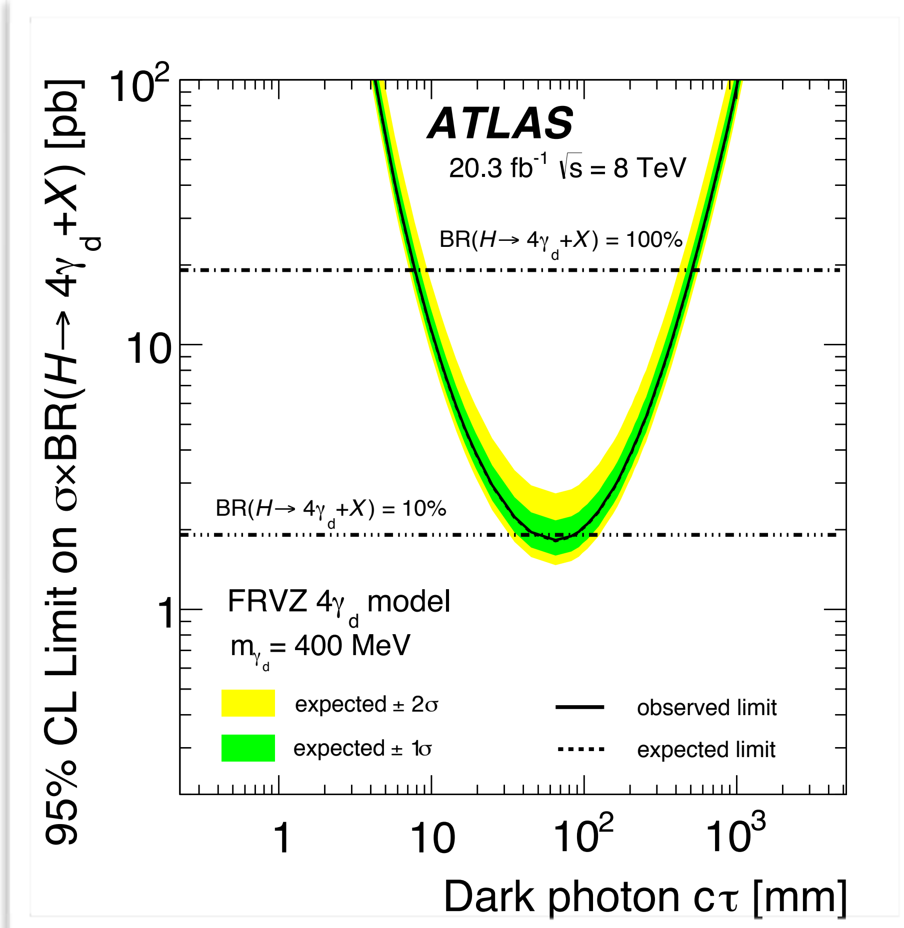
ATLAS SEARCH

arXiv:1409.0746v2 [hep-ex]

Only one category that doesn't require muons

Requires ECAL/HCAL < 0.1

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

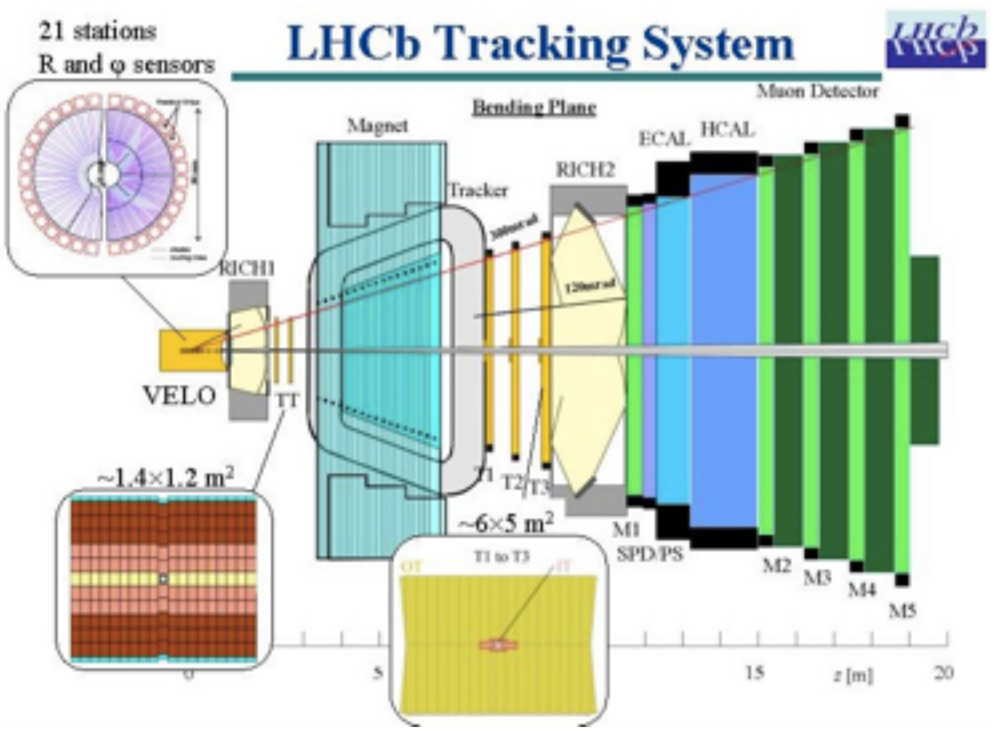


See also ATLAS trigger paper: arXiv:1305.2204 [hep-ex].

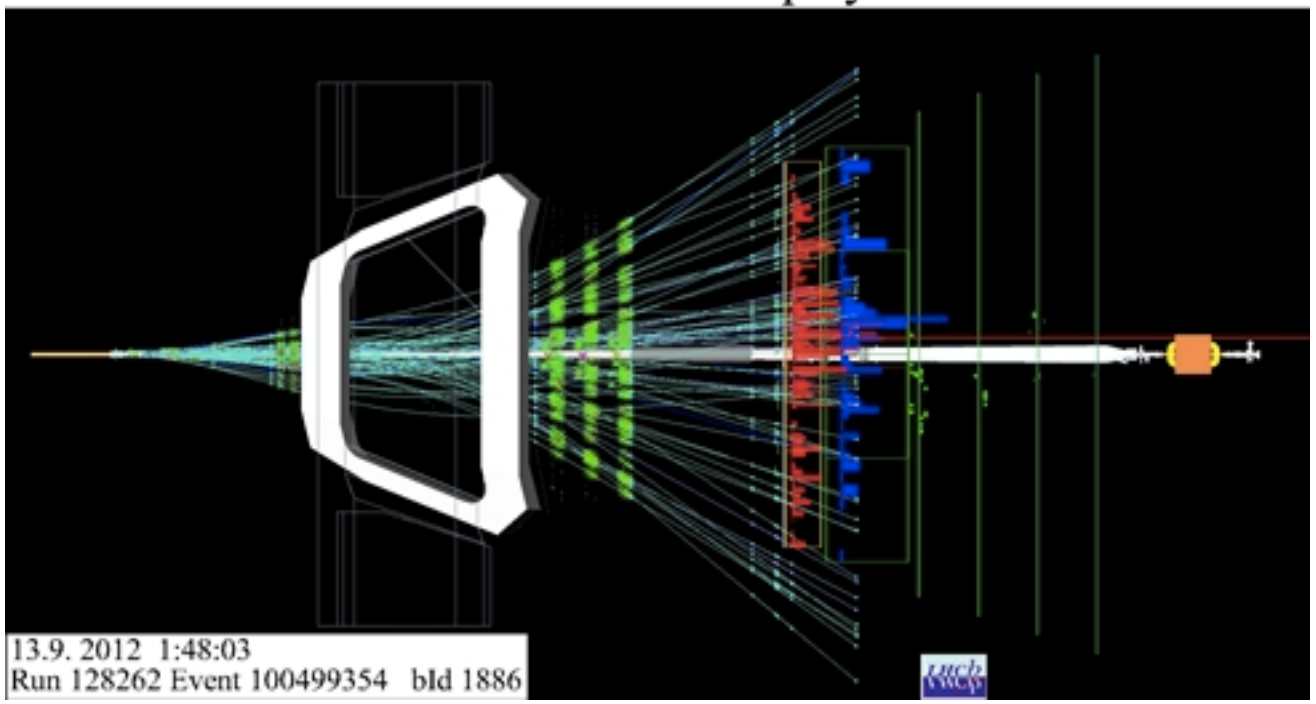
LHCb

LHCb has excellent tracking

Limited coverage of event



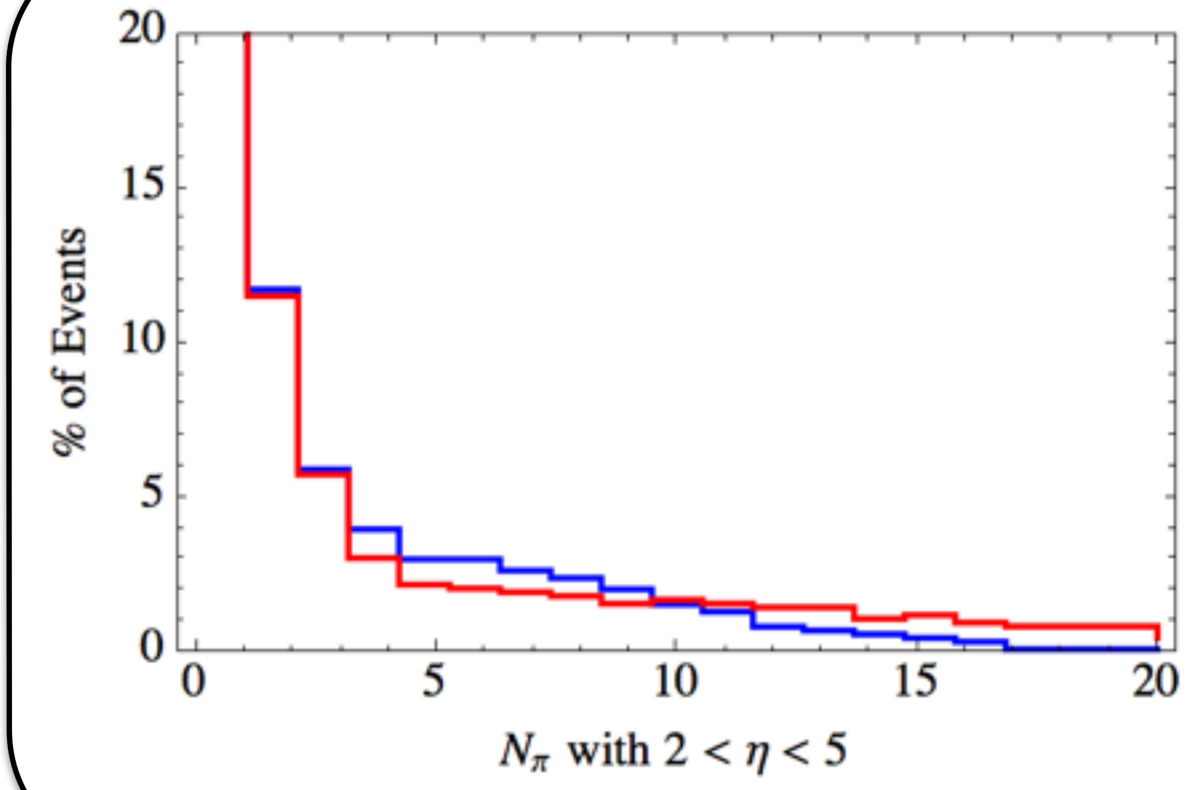
LHCb Event Display



LHCb

Still get a good fraction of events with dark pions in LHCb

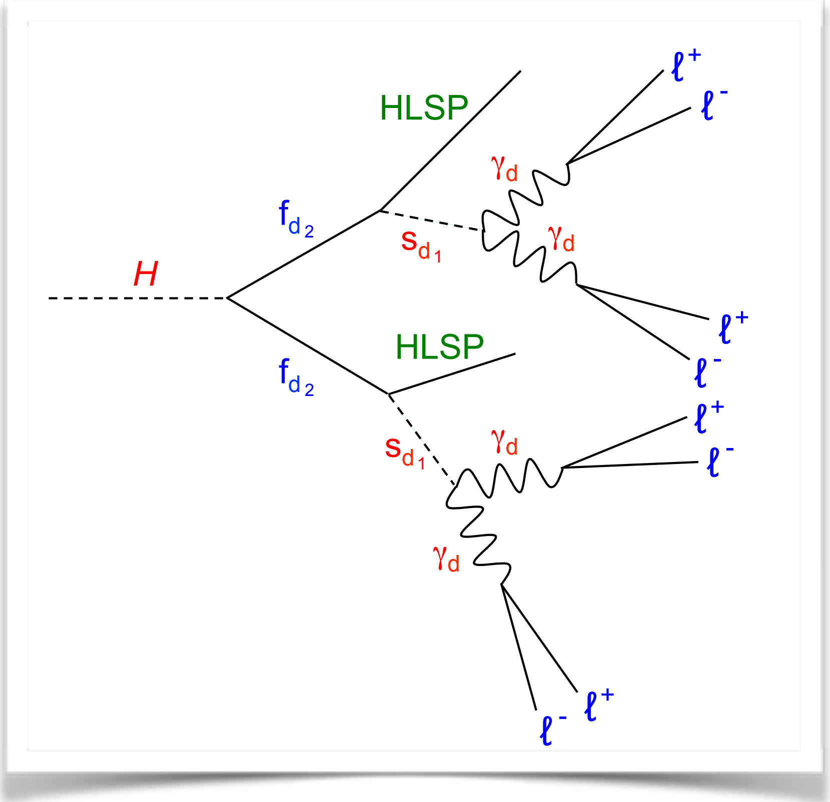
Discussions with collaboration ongoing



POWER OF EMERGING JET

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

- Lepton jets
- RPV neutralinos decay to jets
- …



Work in progress

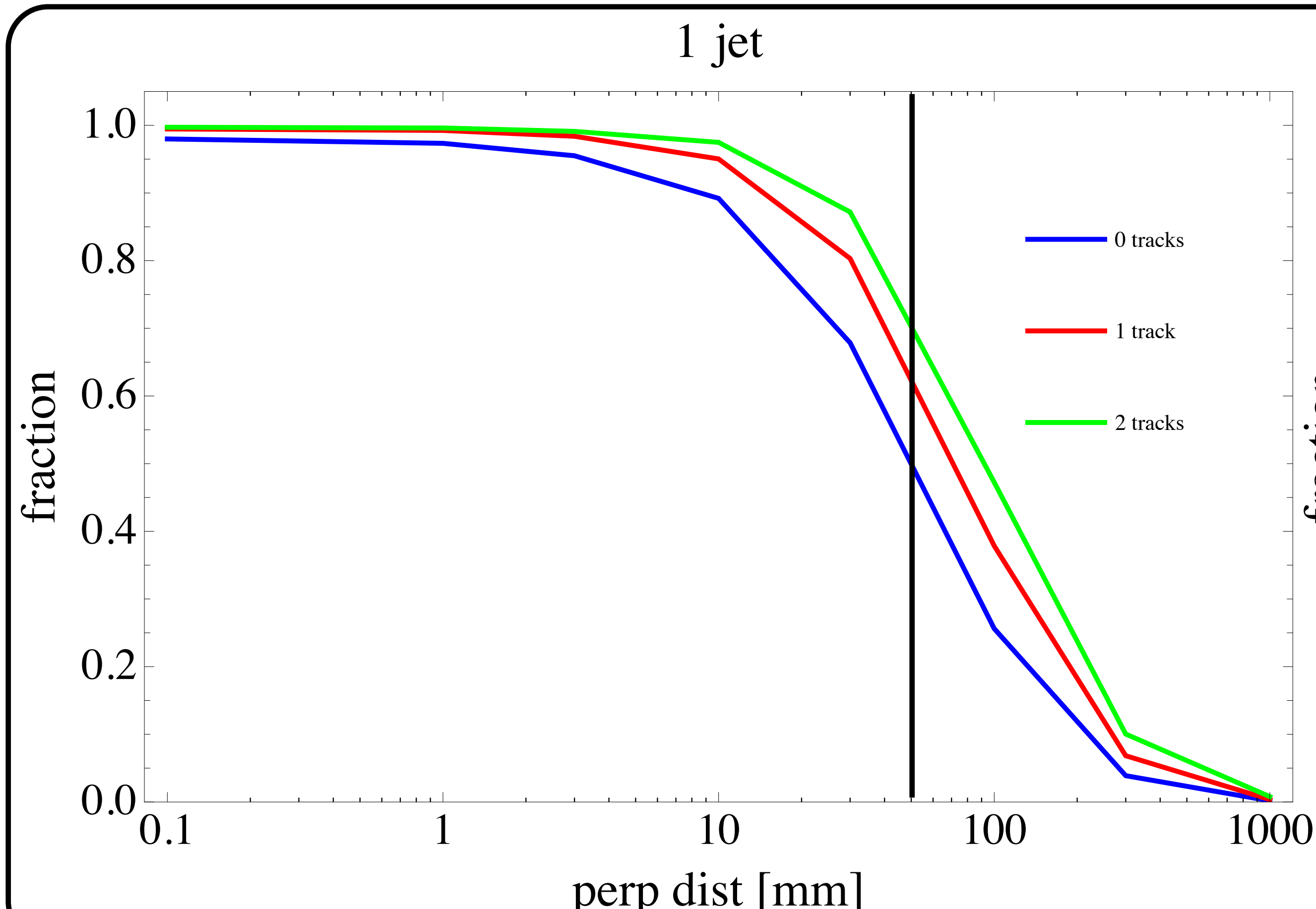
CONCLUSIONS

- Important to explore different ways LHC can search for NP
- DM exists, exhaustively search for different classes of models
- 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
- ATLAS and CMS exotics groups are investigating

THANK YOU

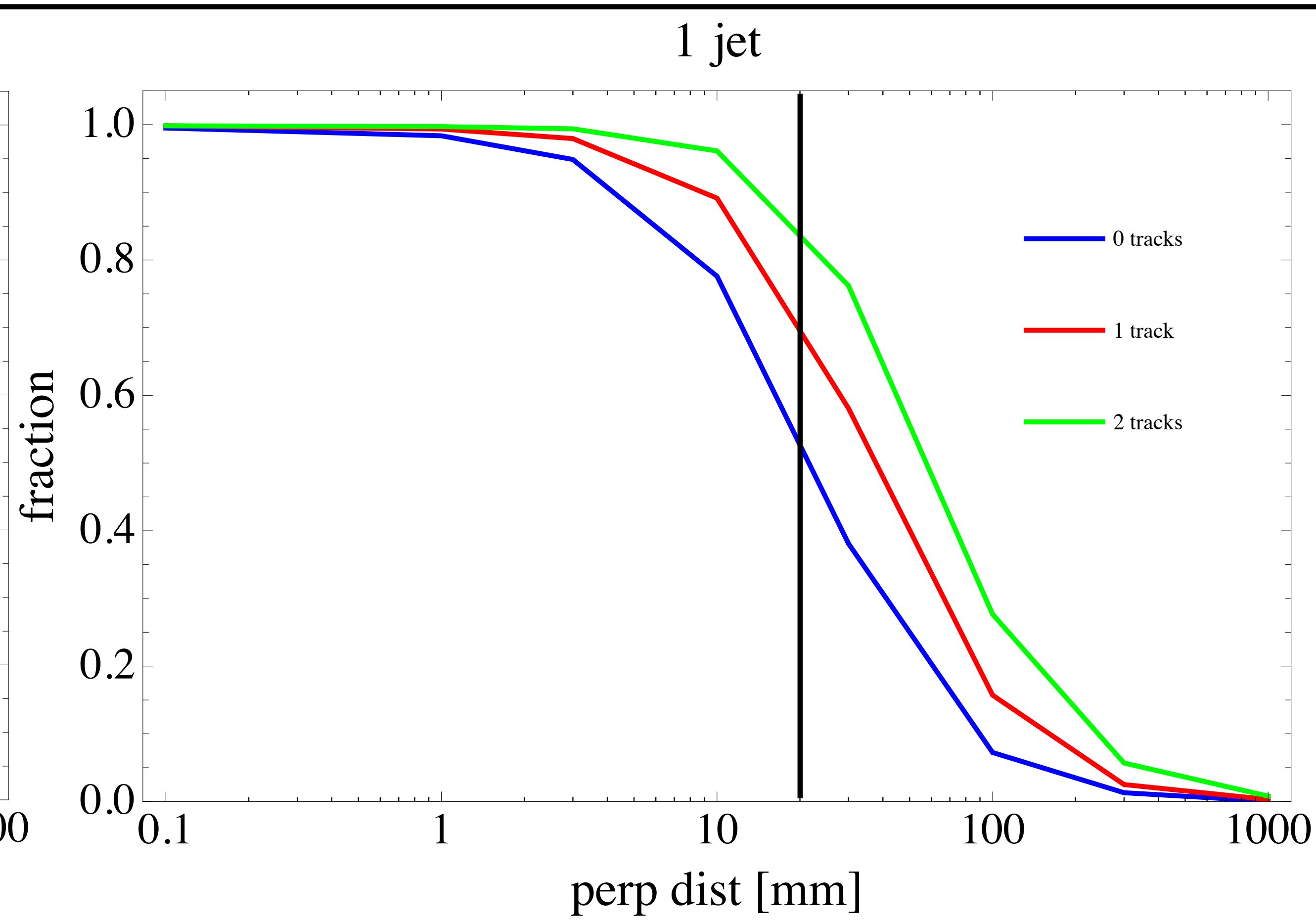
DIFFERENT MODEL POINTS

Model **A**



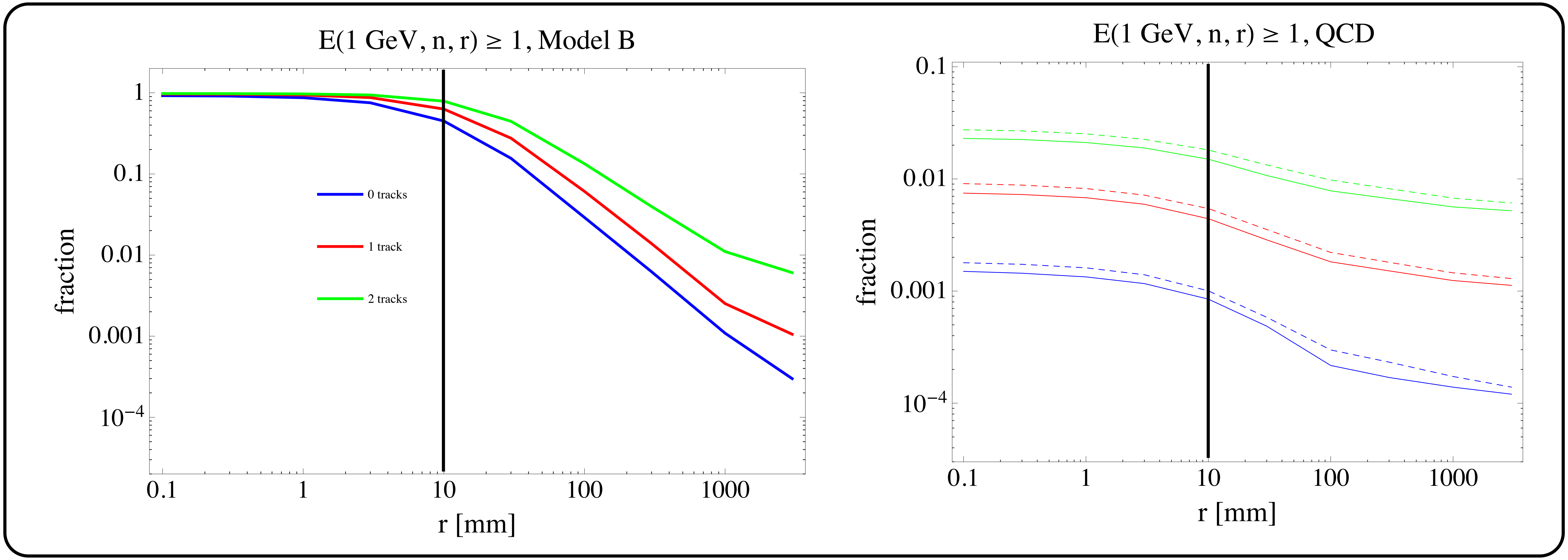
$$m_{\pi_d} = 5\,\mathrm{GeV}$$
$$c\tau_{\pi_d} = 50\,\mathrm{mm}$$

Model **B**



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

SIGNAL VS BG



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

MESON MOMENTUM FRACTION

Fraction of jet momentum carried by any individual dark meson