Emerging Jets

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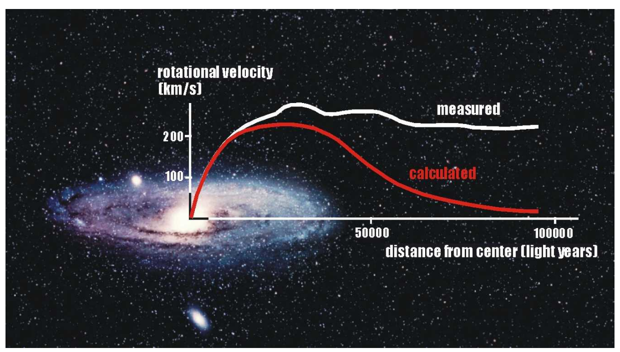
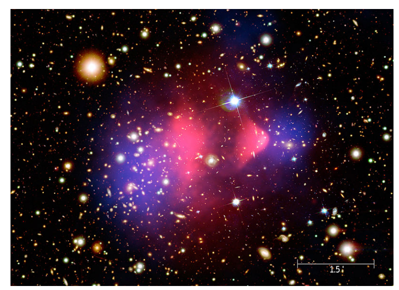
9/4/2015
Portoroz

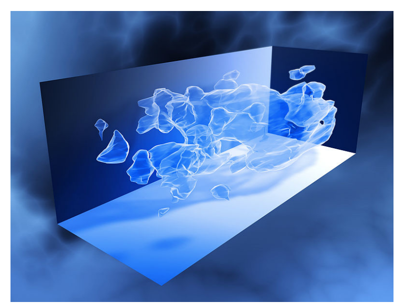
with Dan Stolarski and Pedro Schwaller
arXiv:1502.05409

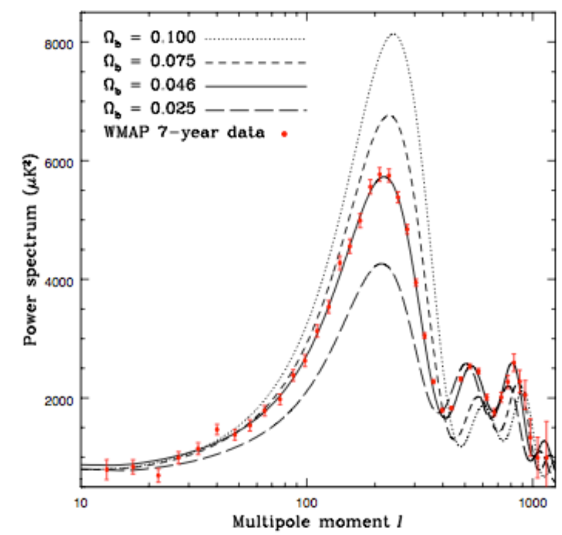
Dark matter

- We have seen dark matter in the sky

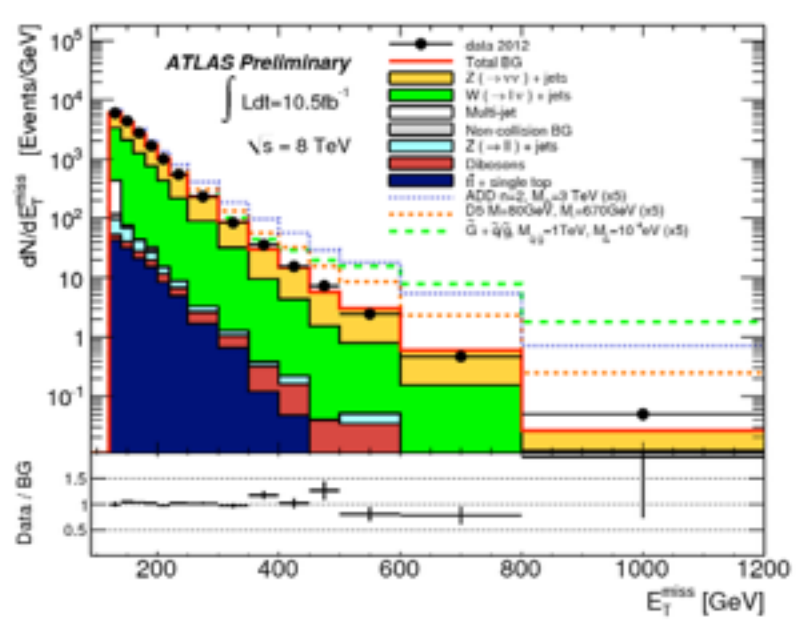


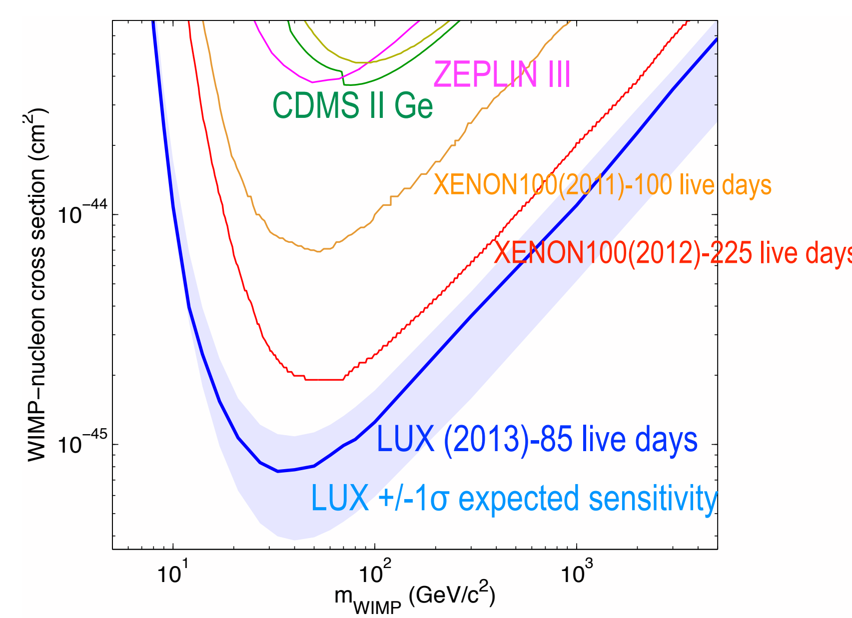


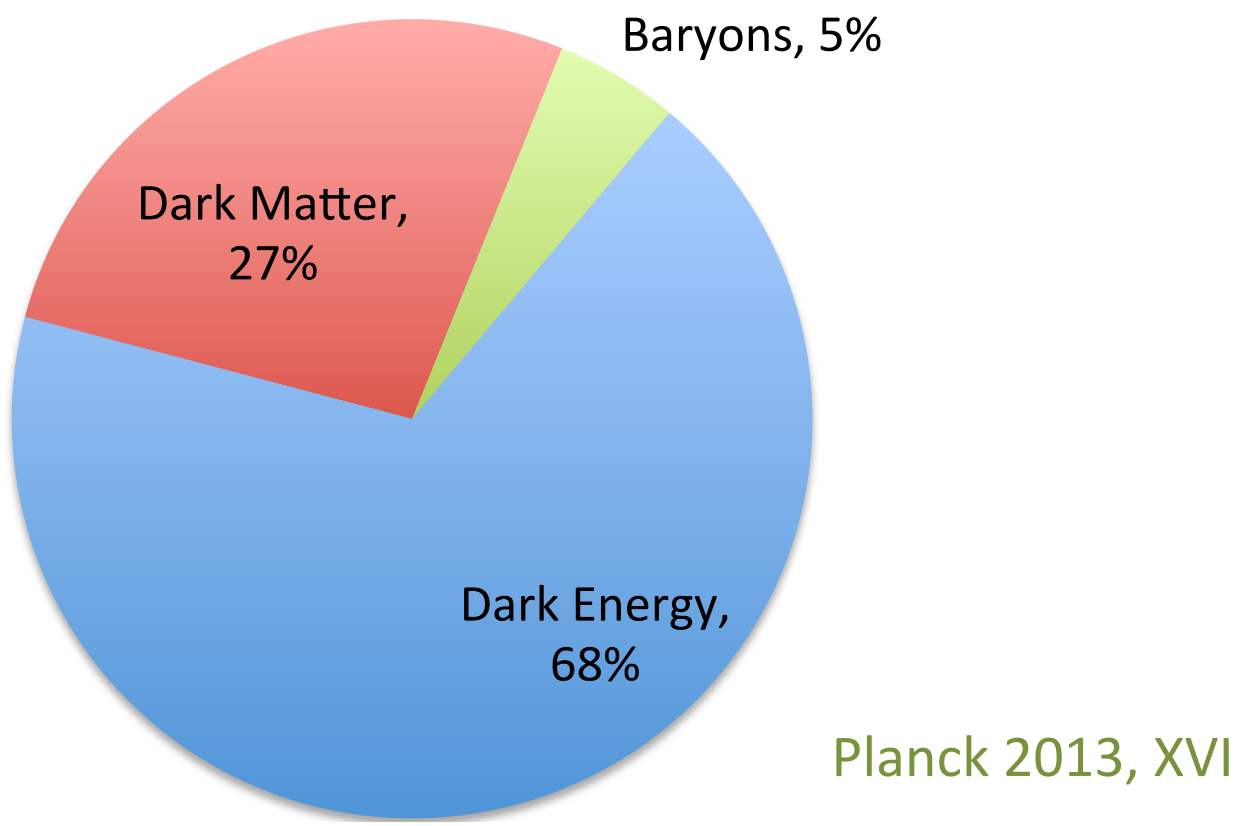




- But not in the lab







We don’t understand these numbers…

Wimp DM

Baryon mass

$$M_p = 938 \text{ MeV}$$

Baryonic matter density

$$\eta = \frac{n_B}{n_\gamma} \approx 6 \times 10^{-10}$$

DM mass

$$M_{\rm DM} \sim 100 \text{ GeV}$$

DM matter density

$$n_{\rm DM} \text{ from thermal freeze-out}$$

Asymmetric DM

Nussinov '85, D.B. Kaplan '92,
D.E.Kaplan, Luty, Zurek '09, …
many people (incl. audience members)

$$\frac{\Omega_{\rm DM}}{\Omega_B} \approx 5$$ Maybe a hint?

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DM matter density

$$n_{\rm DM} \sim n_B$$

$$M_{DM} \approx 5 M_p$$ usually unexplained

Coincidence?

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

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Controlled by complicated (known) QCD dynamics

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Unknown dynamics of baryogenesis

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QCD like?

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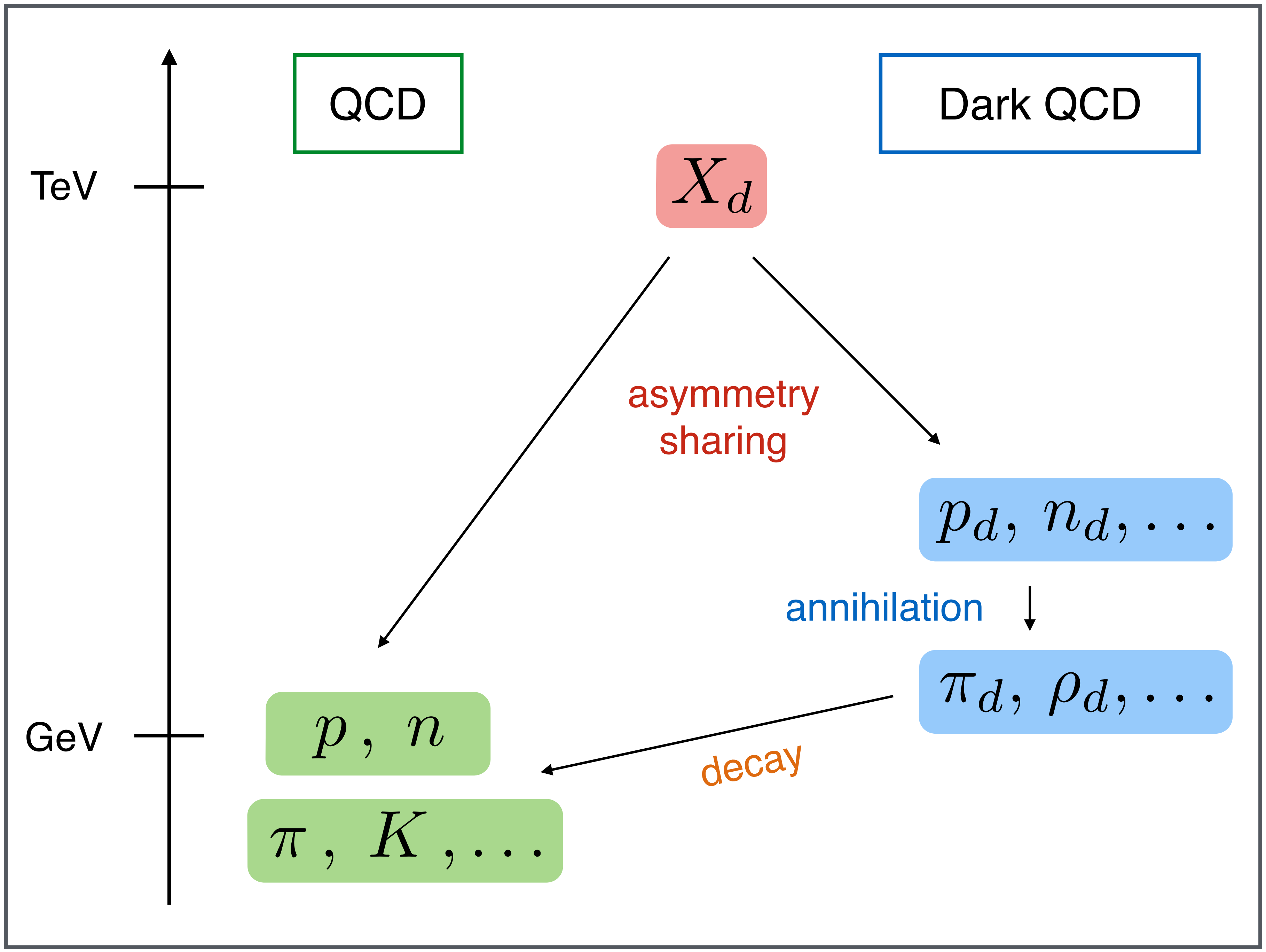
General Picture



QCD

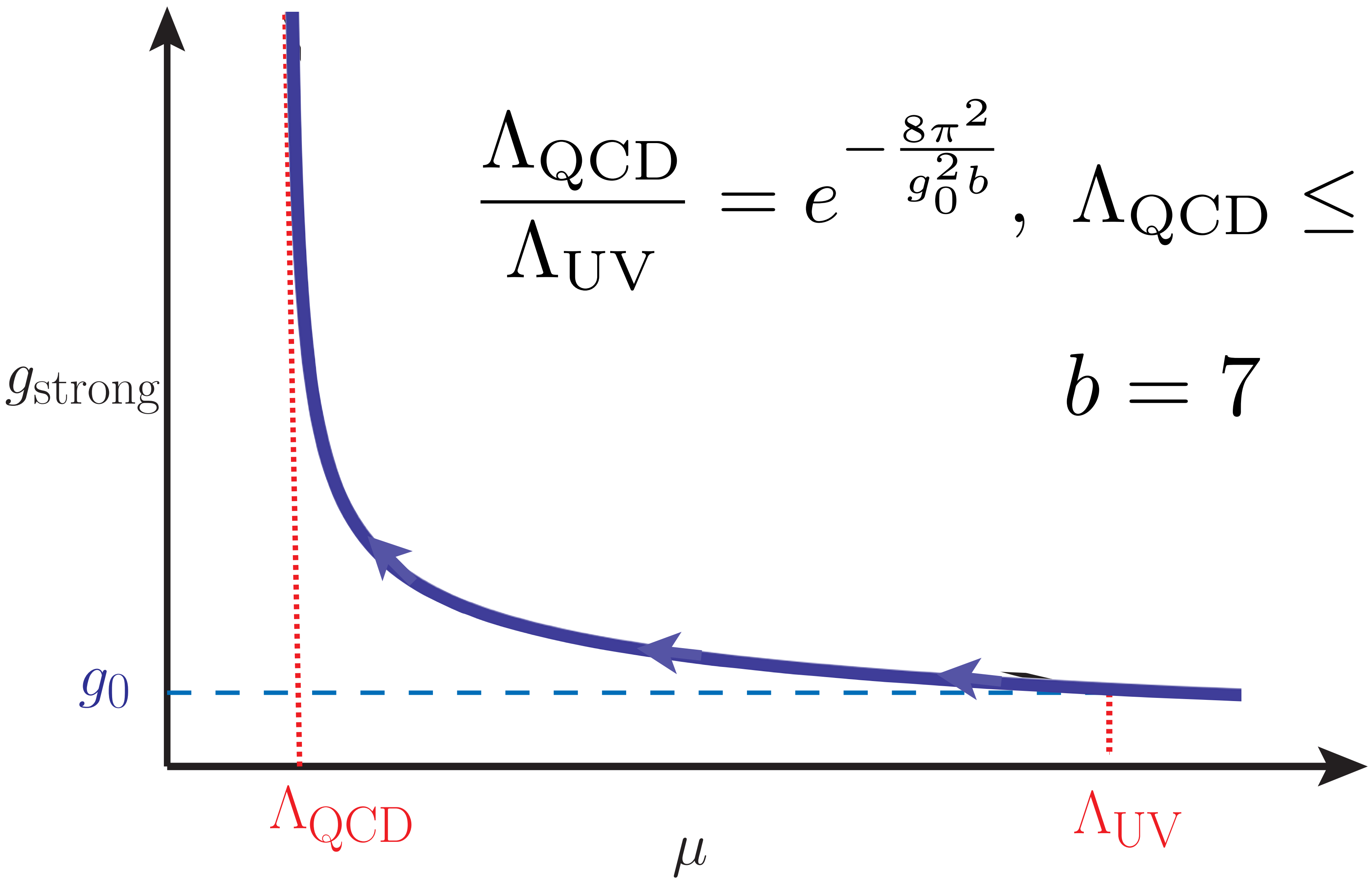

David J. Gross


H. David Politzer


Frank Wilczek

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

$$b = 7$$



Asymptotic freedom

QCD scale ~ mass scale of QCD composites

Dark-QCD

Bai, Schwaller '13

- New SU(N_d) 'dark QCD', dark quarks
- Dark matter is a dark-baryon with mass $\sim \Lambda_{\mathrm{dark\,QCD}}$
- Massive bi-fundamental fields decouple at M
- Perturbative IR fixed points explains coincidence of scales

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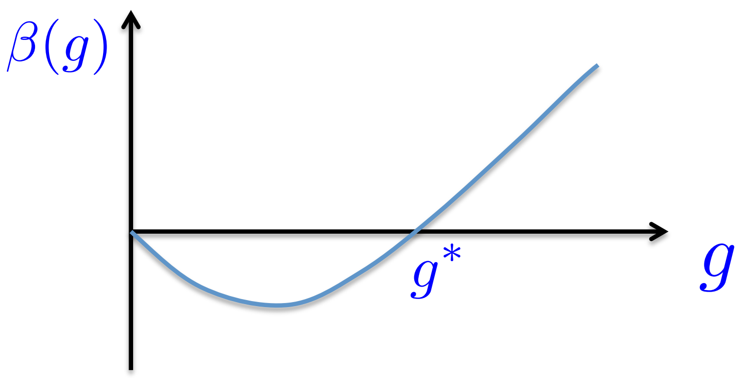
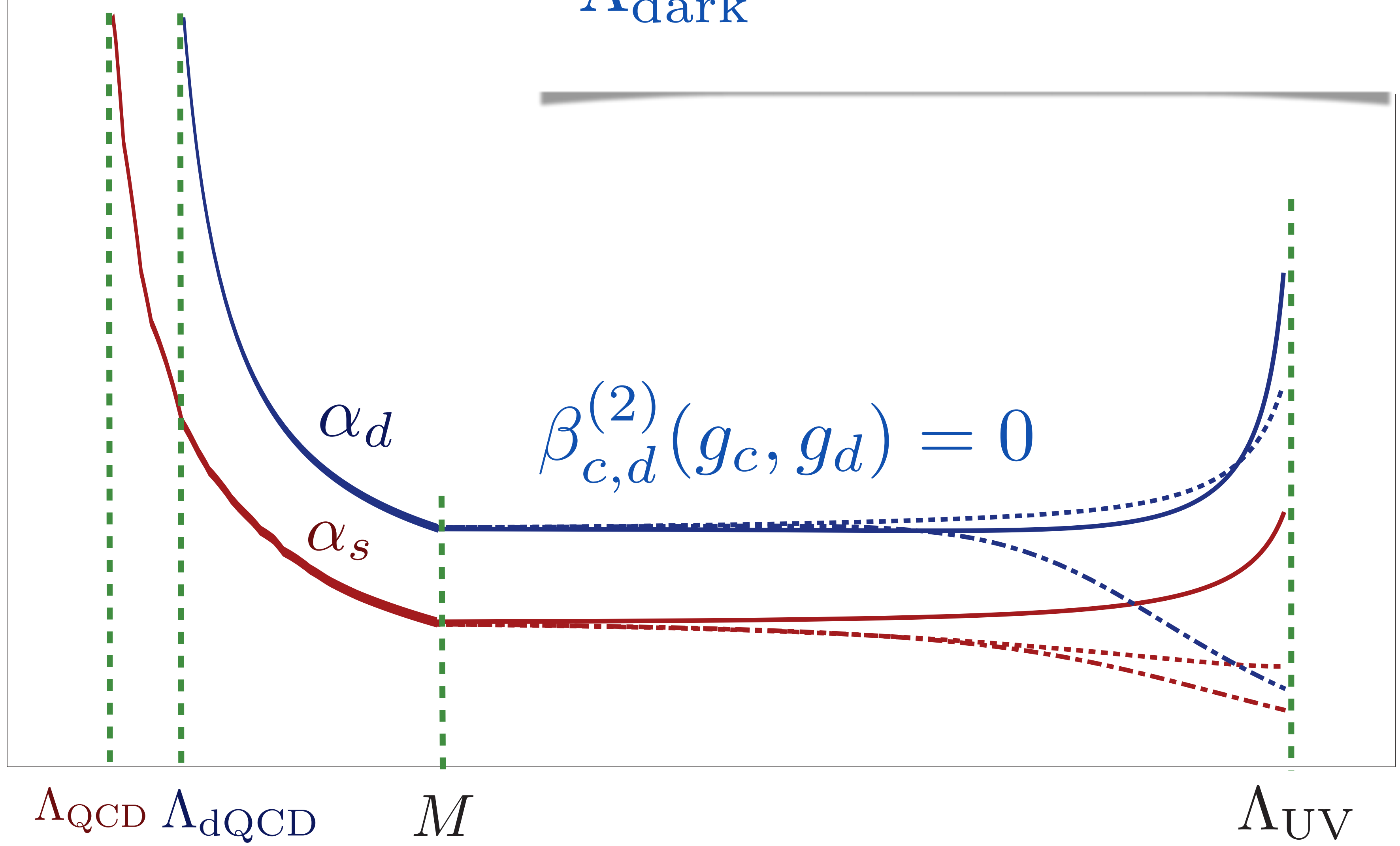
$$\frac{dg}{dt} = \beta(g) = 0 \text{ for } g = g^*$$



Relate QCD/dQCD scale

$$\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm dark}} \approx e^{\frac{2\pi}{b_c \alpha_c^*}\left(1-\frac{b_c\alpha_c^*}{b_d\alpha_d^*}\right)}$$



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Example

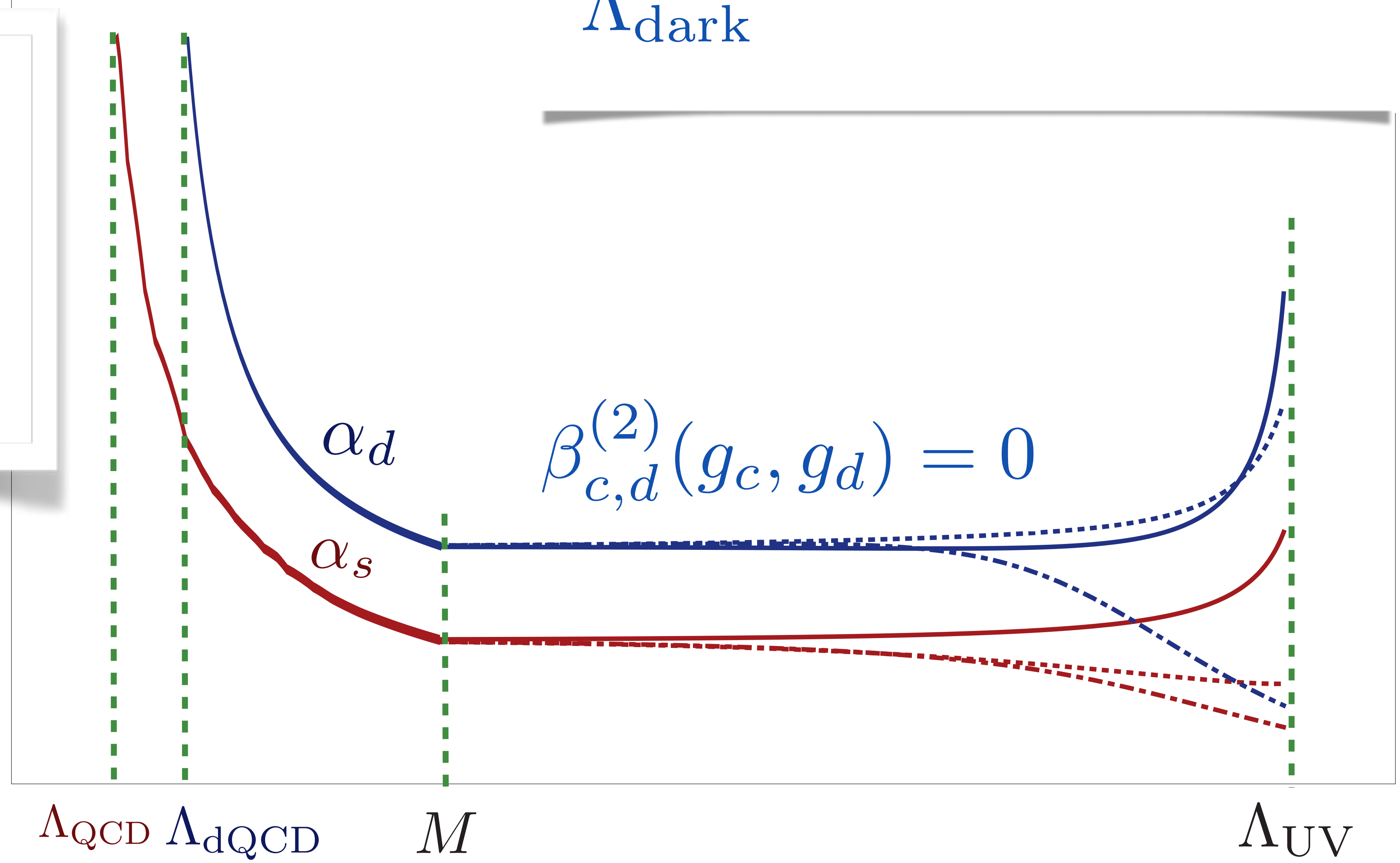
Fixed points:

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

$M = 870\ GeV$

DM mass:

$M_{DM} \approx 3.5\ GeV$



Bai, Schwaller '13

Asymmetric dark matter

- Asymmetric decay, asymmetry in bi-fundamentals (à la leptogenesis), decay to quarks and dark-quarks
- Relic density predicted: $\rho_{\mathrm{DM}} \approx 5 \times \rho_B$ "naturally"
- DM self-interaction mediated by dark-pion (might help with structure formation)

Phenomenology

Dark QCD

QCD like SU(N_c) with N_f flavors, confines at a scale

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

At the confining scale we have

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

Mediators: - bi-fundamental Φ $\qquad \mathcal{L} \supset \kappa \Phi \bar{Q}_D d_R$

- Z' (hidden valley) $\qquad \mathcal{L} \supset g' \bar{Q}_D \gamma^\mu Q_D Z'_\mu$

$+$ couplings to SM

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p_d: stable

π_d: decay to SM

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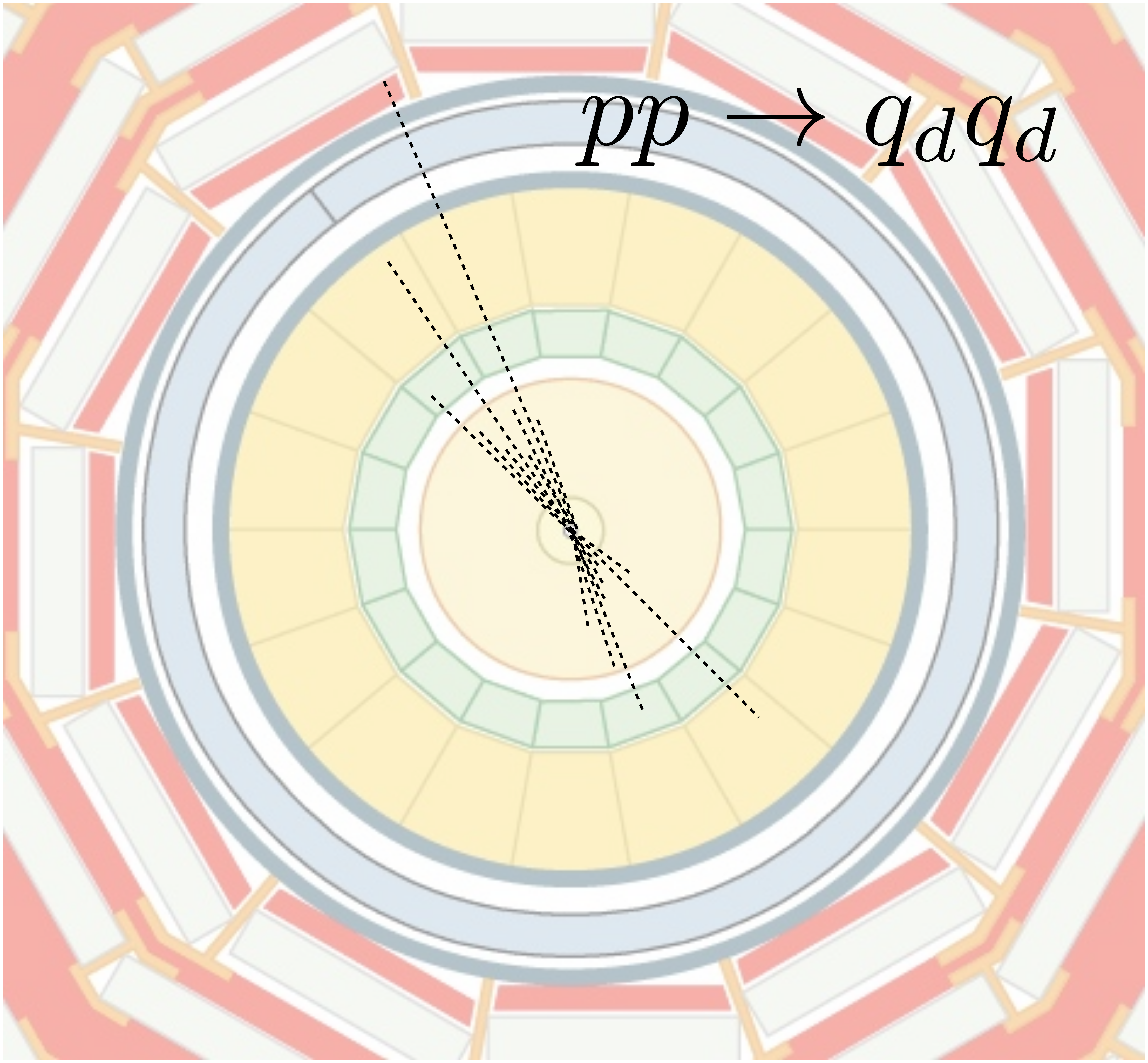
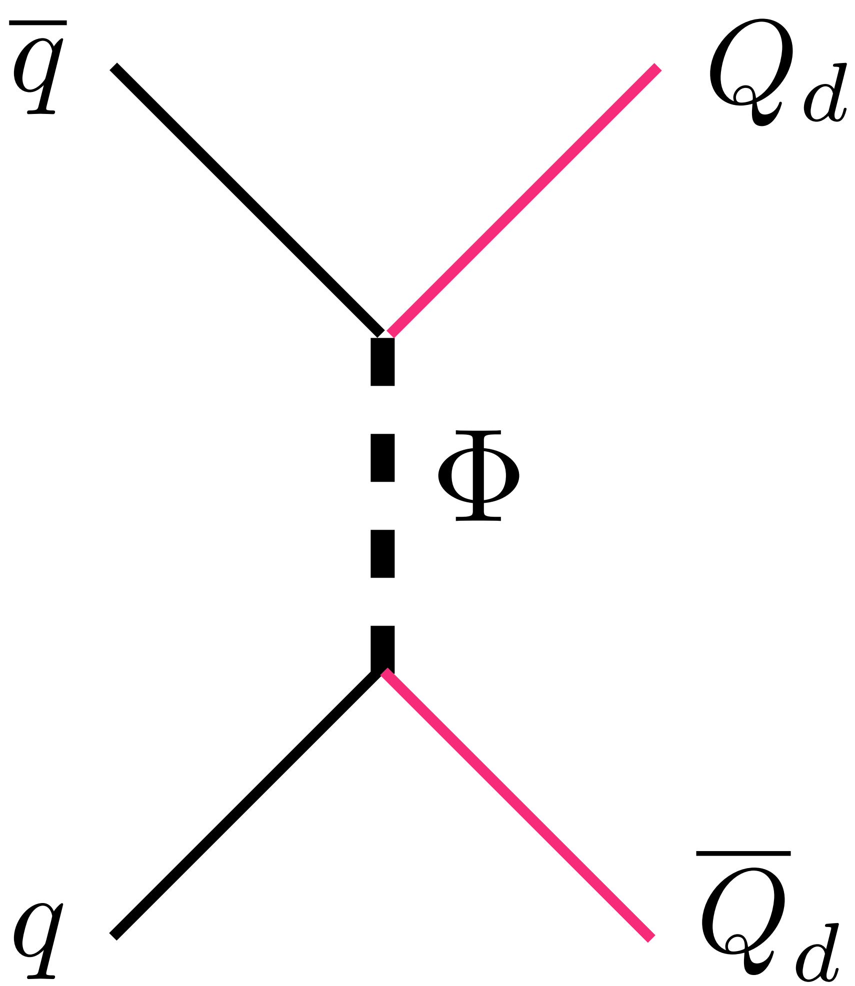

$pp \to q_d q_d$

Co-generate asymmetries with additional operator:

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



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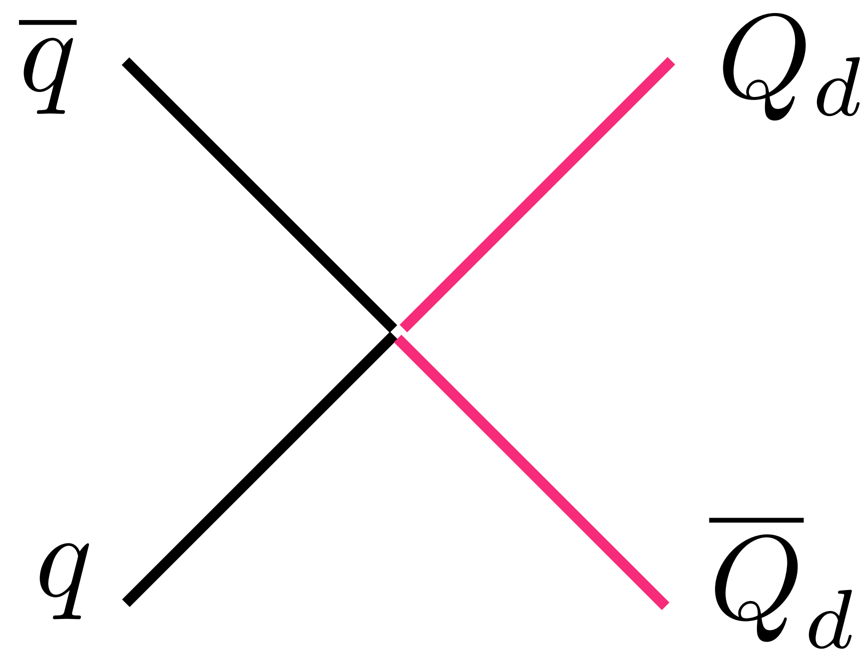
Integrate out Φ



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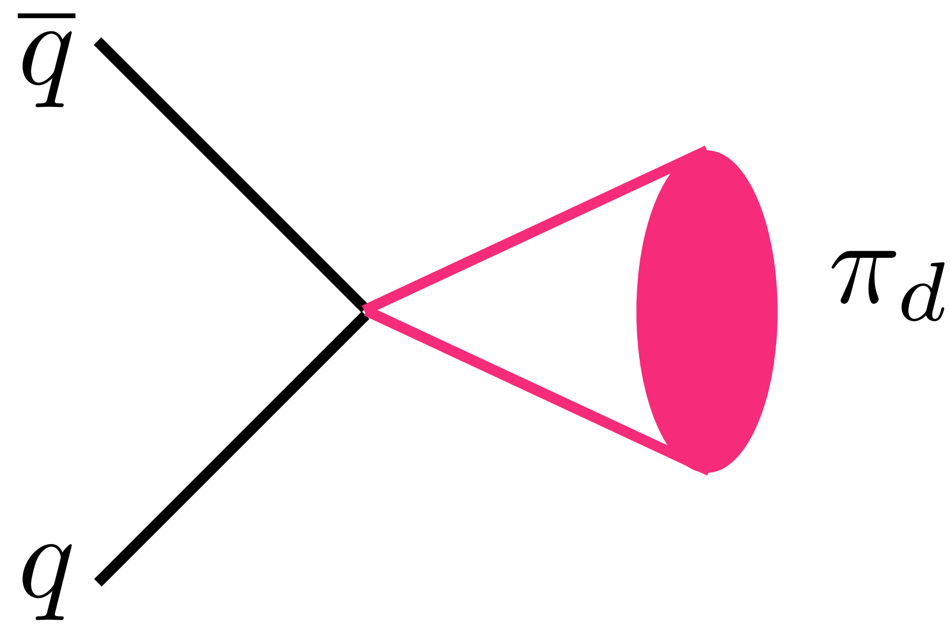
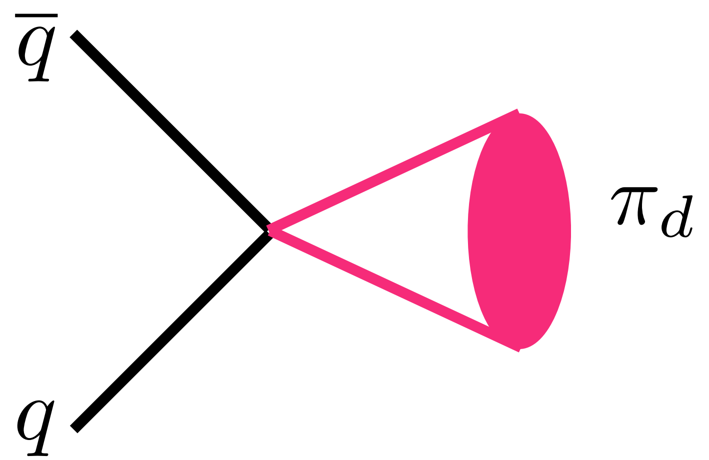


Dark pion decays to quarks

Dark Pion Lifetime



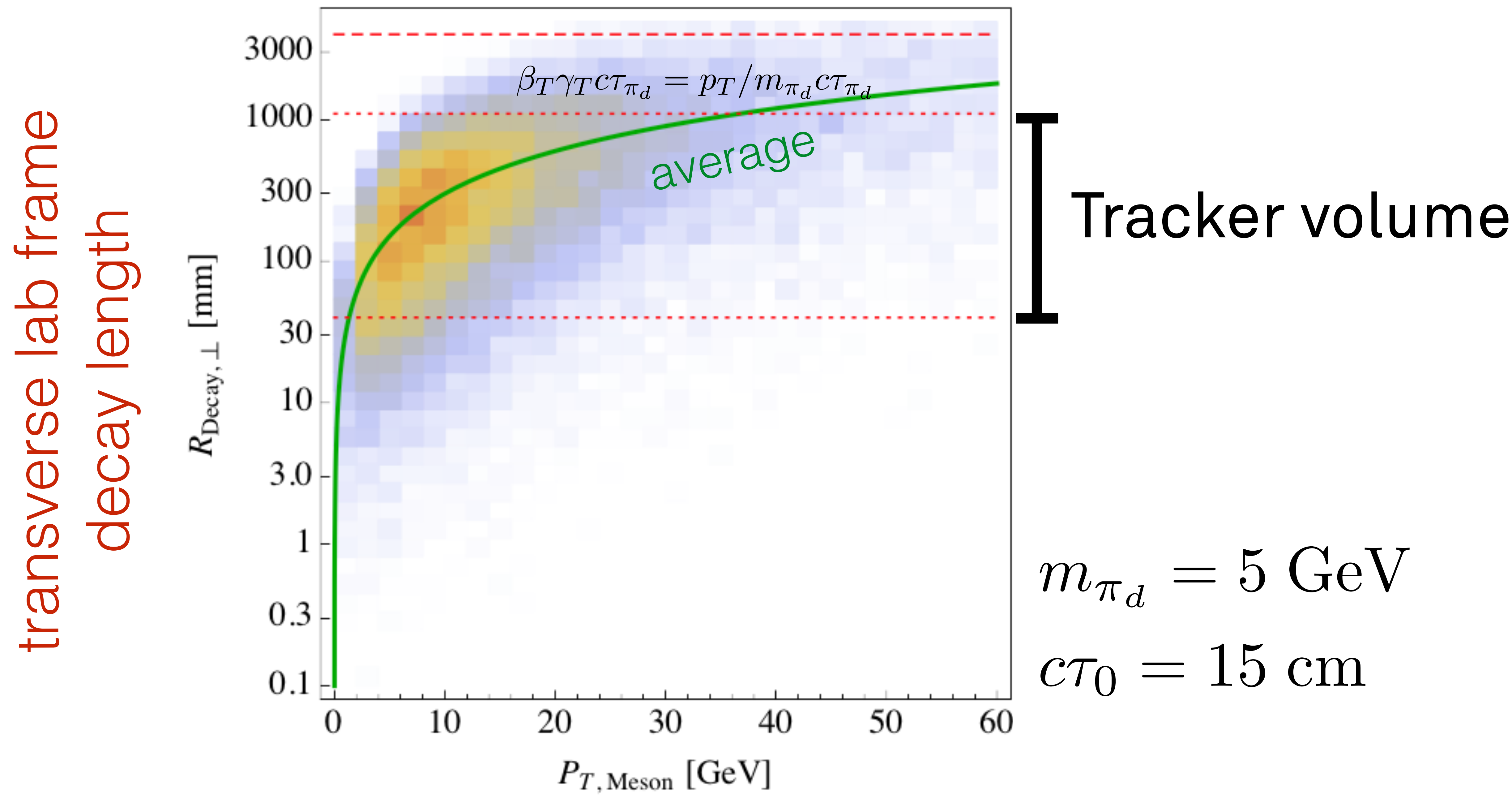
$$\frac{1}{M_X^2}\overline{Q}\gamma_\mu Q\,\bar{d}_R\gamma^\mu d_R$$

Use chiral Lagrangian to estimate

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

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

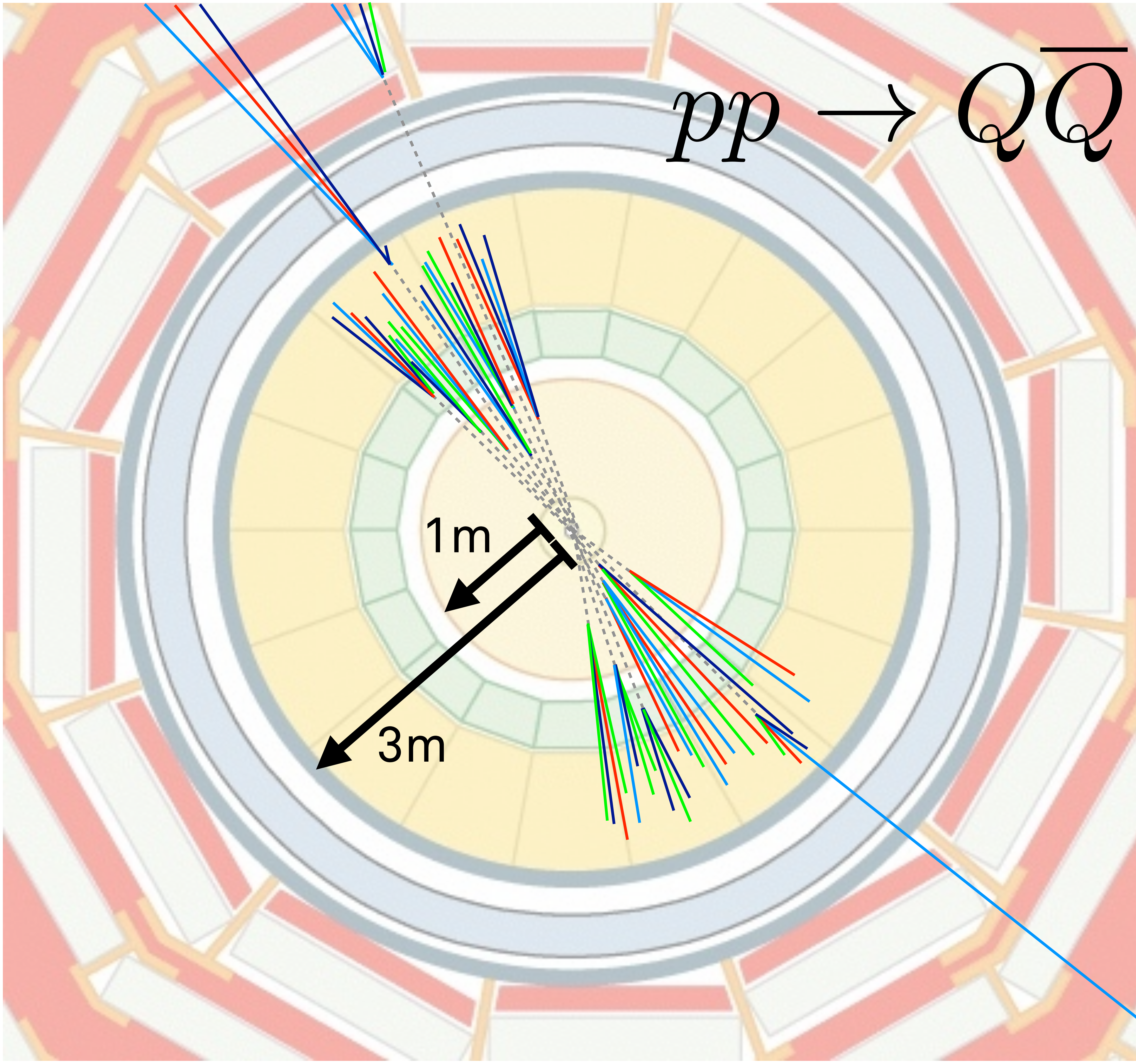
Dark pion decay distances

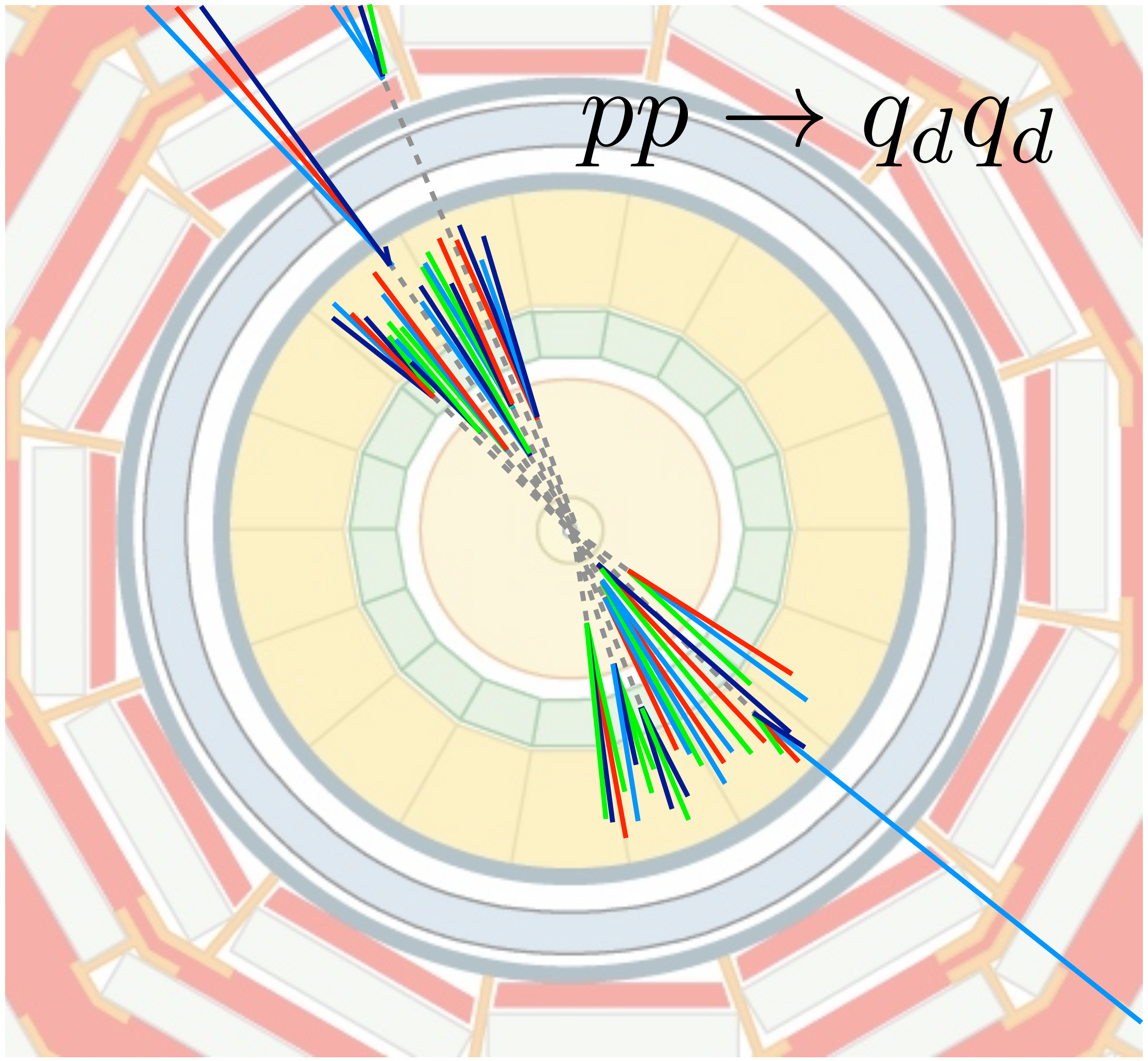


$m_{\pi_d} = 5$ GeV

$c\tau_0 = 15$ cm

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

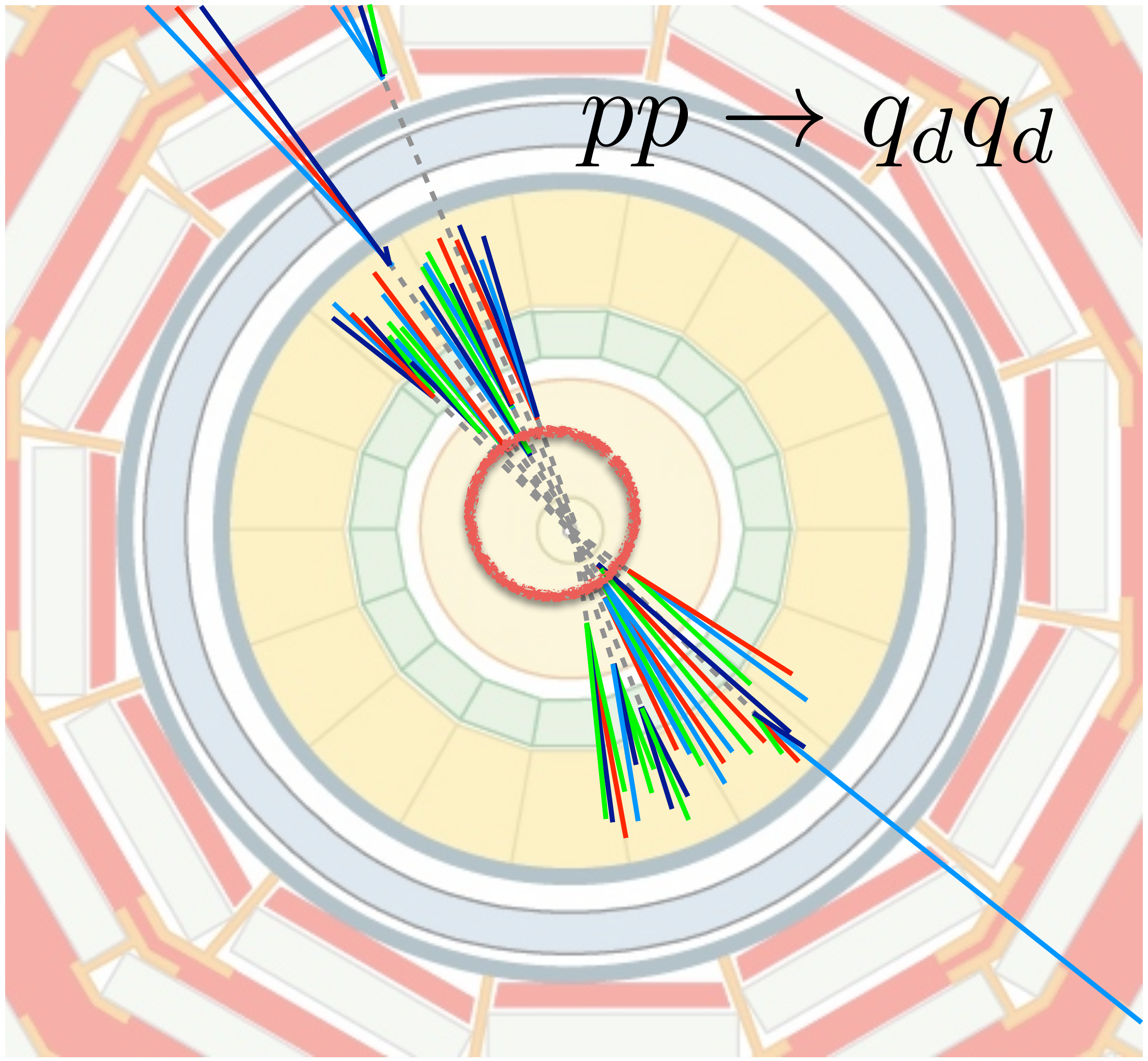

$pp \to Q\overline{Q}$
1m
3m



Decay lifetime of ~ cm

Exponential decay profile: Several displaced vertices inside a jet “cone” (or calo-jet)

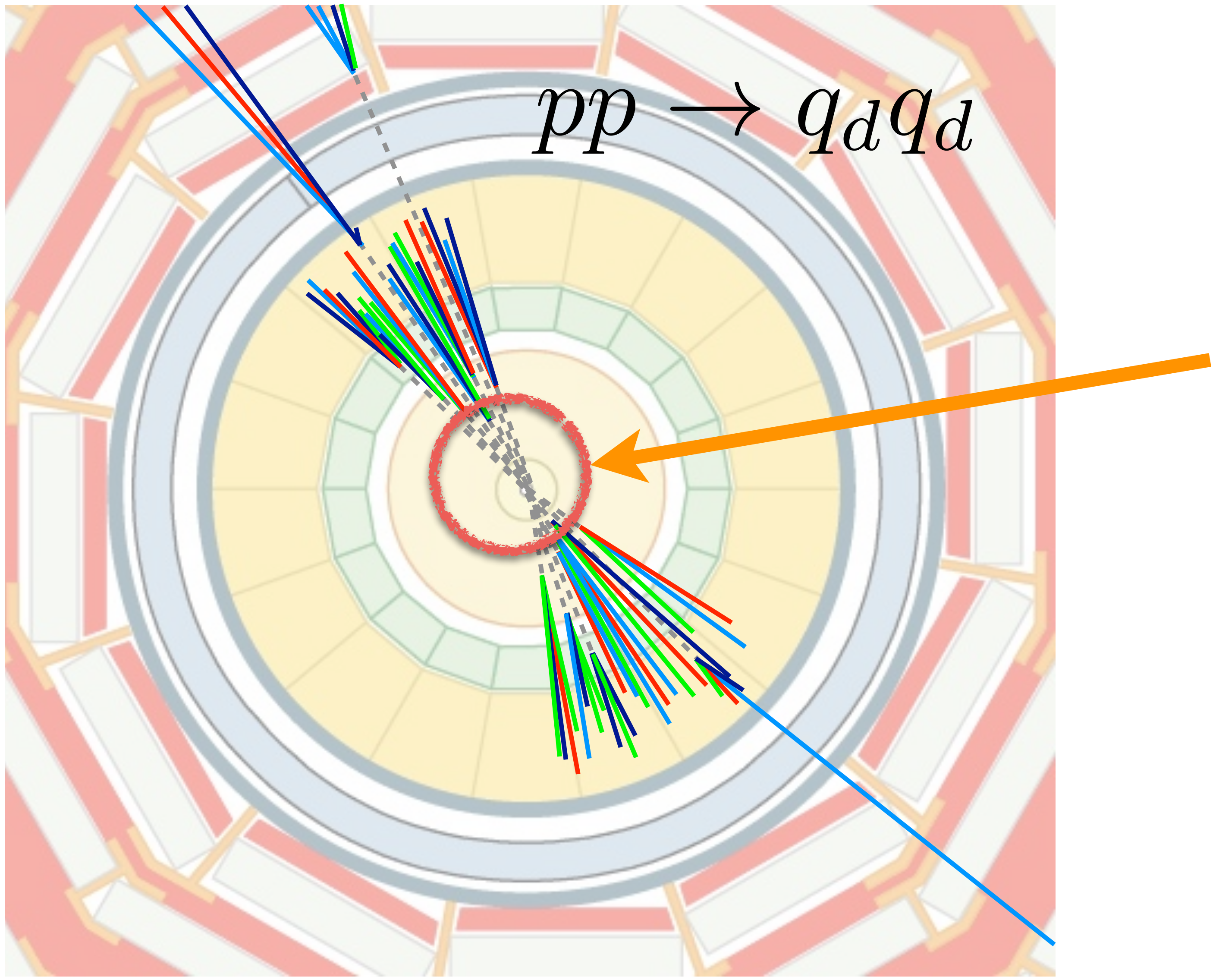
No/few tracks originating from interaction point



Look for Hcal-jets with no/few tracks below distance to interaction point (inside circle)

New 'track-less' signature

Universal for a large class of displaced physics



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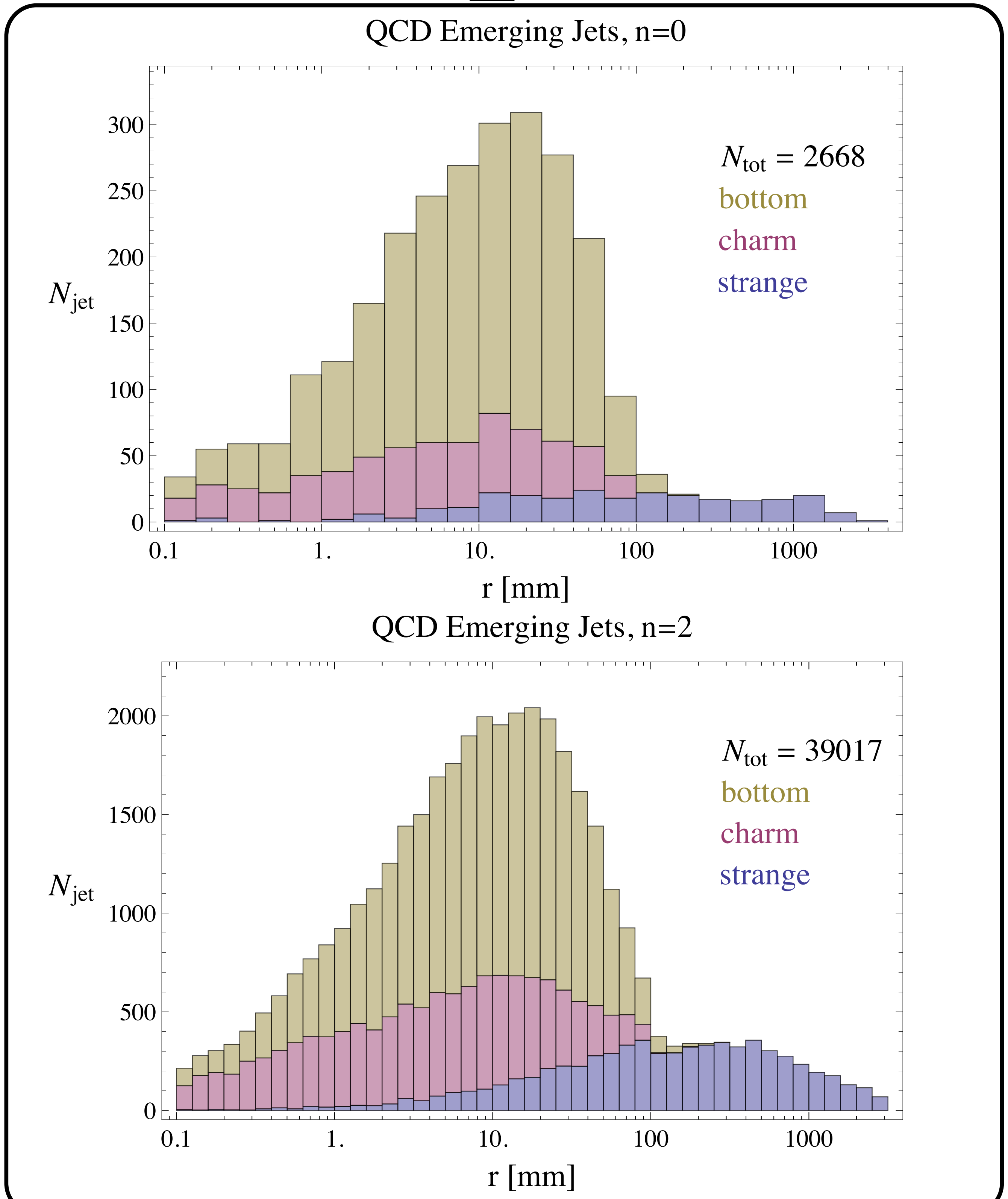
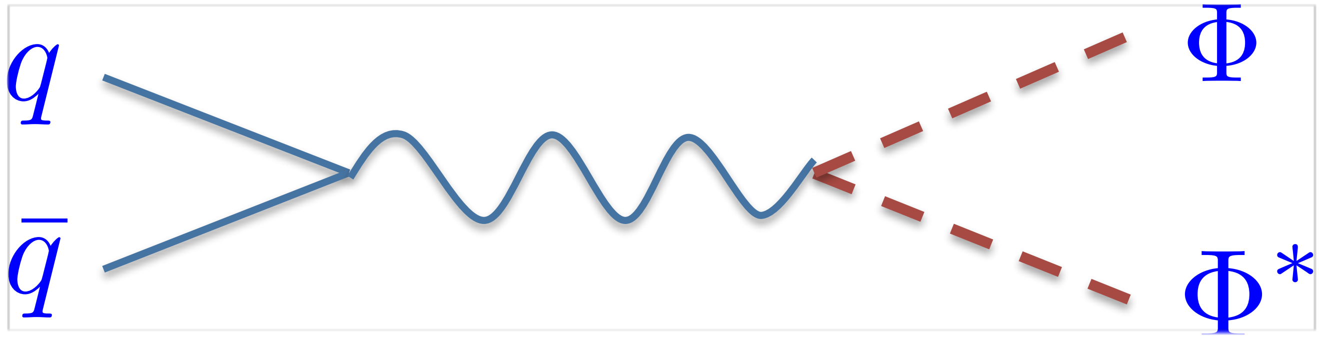
Background composition



Flavor of earliest decaying track.

track $p_T > 1$ GeV

jet $p_T > 200$ GeV



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

Final state is
- 2 QCD jets
- 2 emerging jets

Cross section is stop-like

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

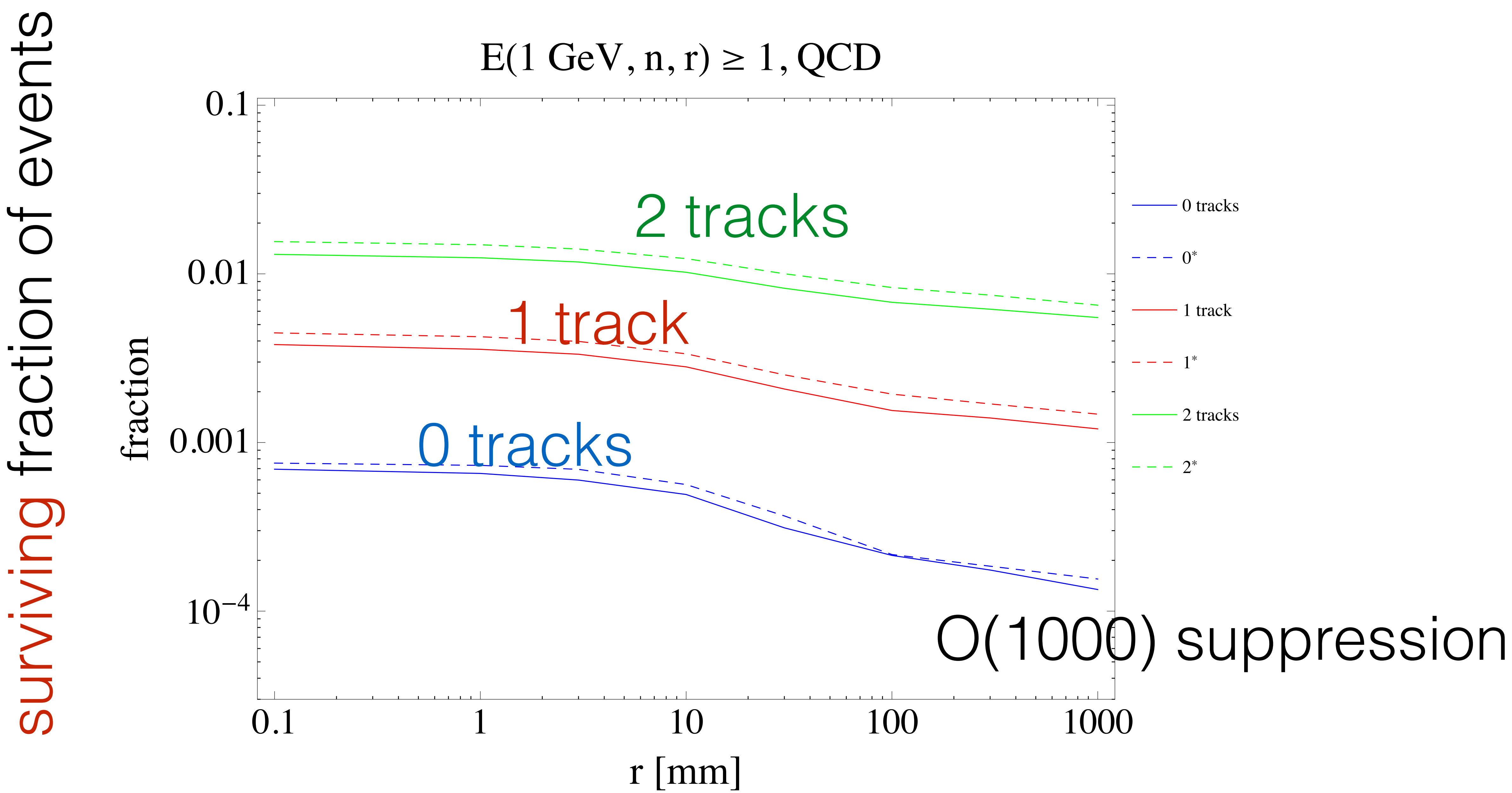
$$\sigma(M_\Phi = 1\,\text{TeV}) \approx 10\,\text{fb}$$

@ LHC14

Dark QCD prototype implemented in Pythia (we changed the shower to include α_{dark} running)

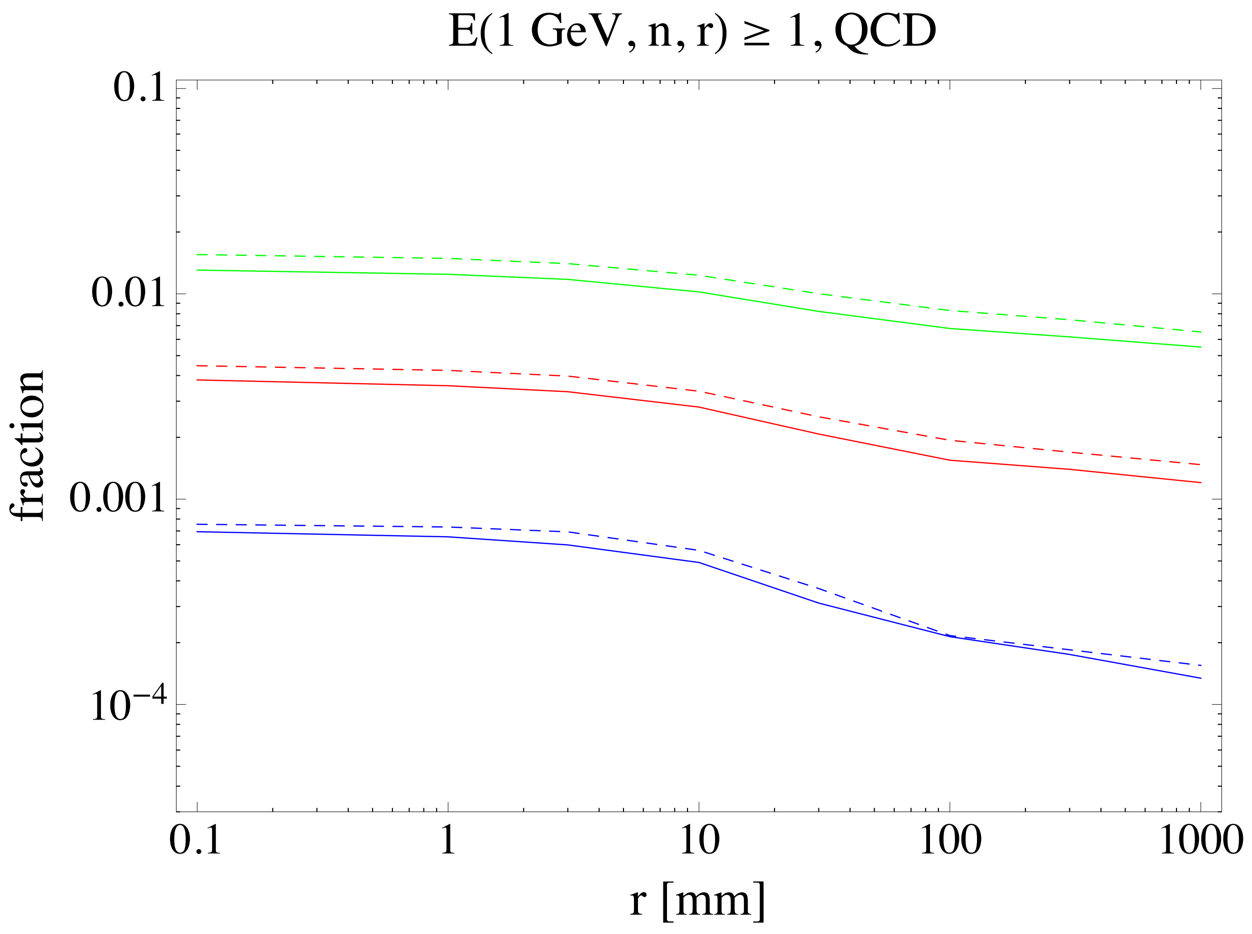
Backgrounds

QCD 4-jet production in Pythia8

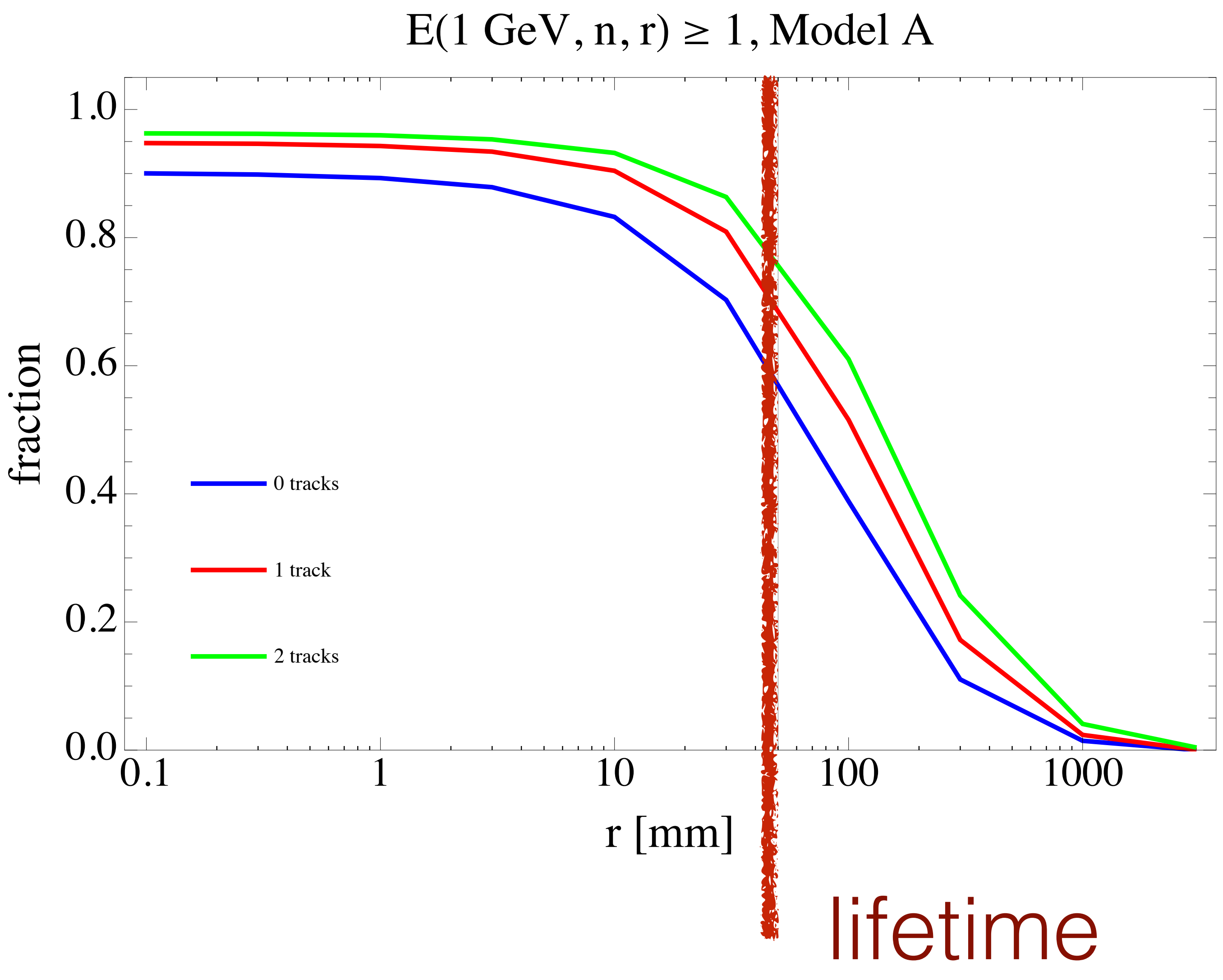


* - modified Pythia tune to increase QCD contribution

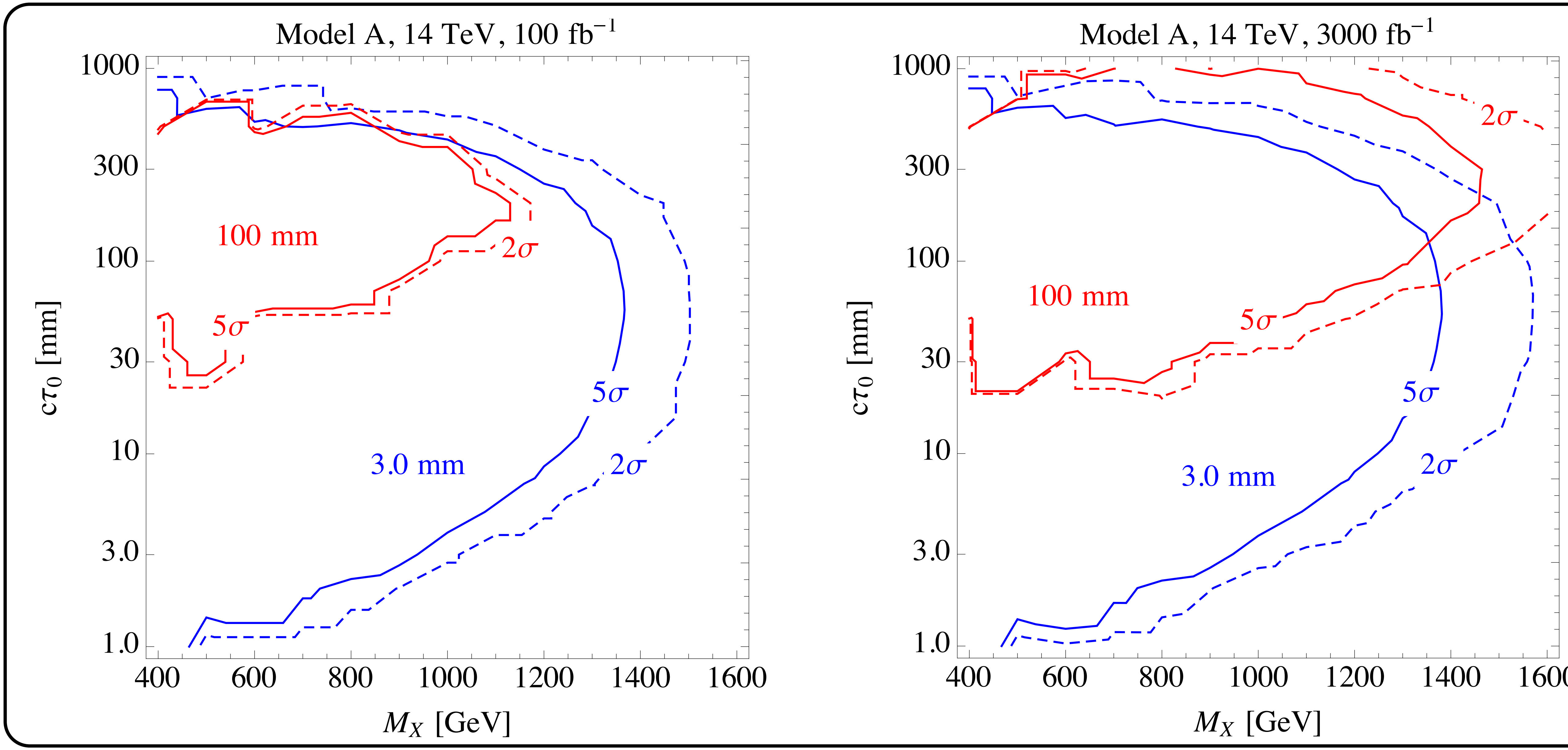
Background



Signal



Reach



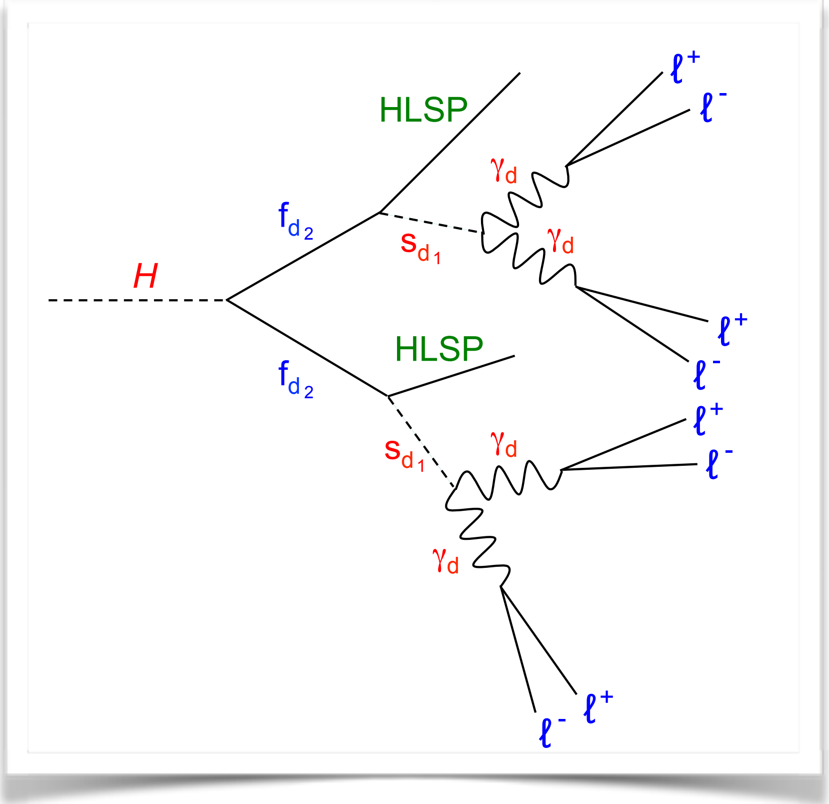
Assume 100% systematic error on background.

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

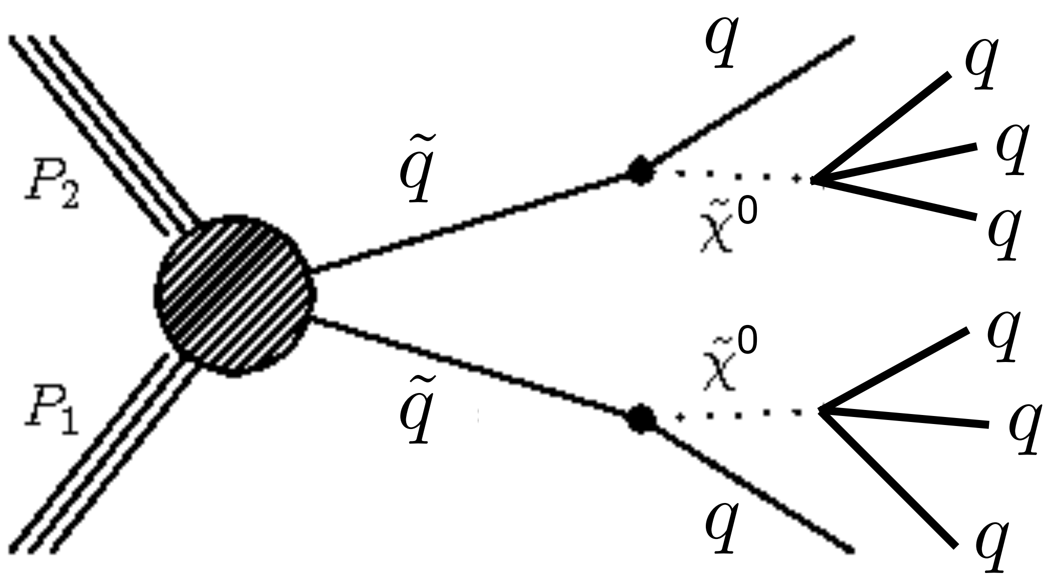
Power of emerging jets

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

- Lepton jets
- RPV neutralinos decay to jets
- ...

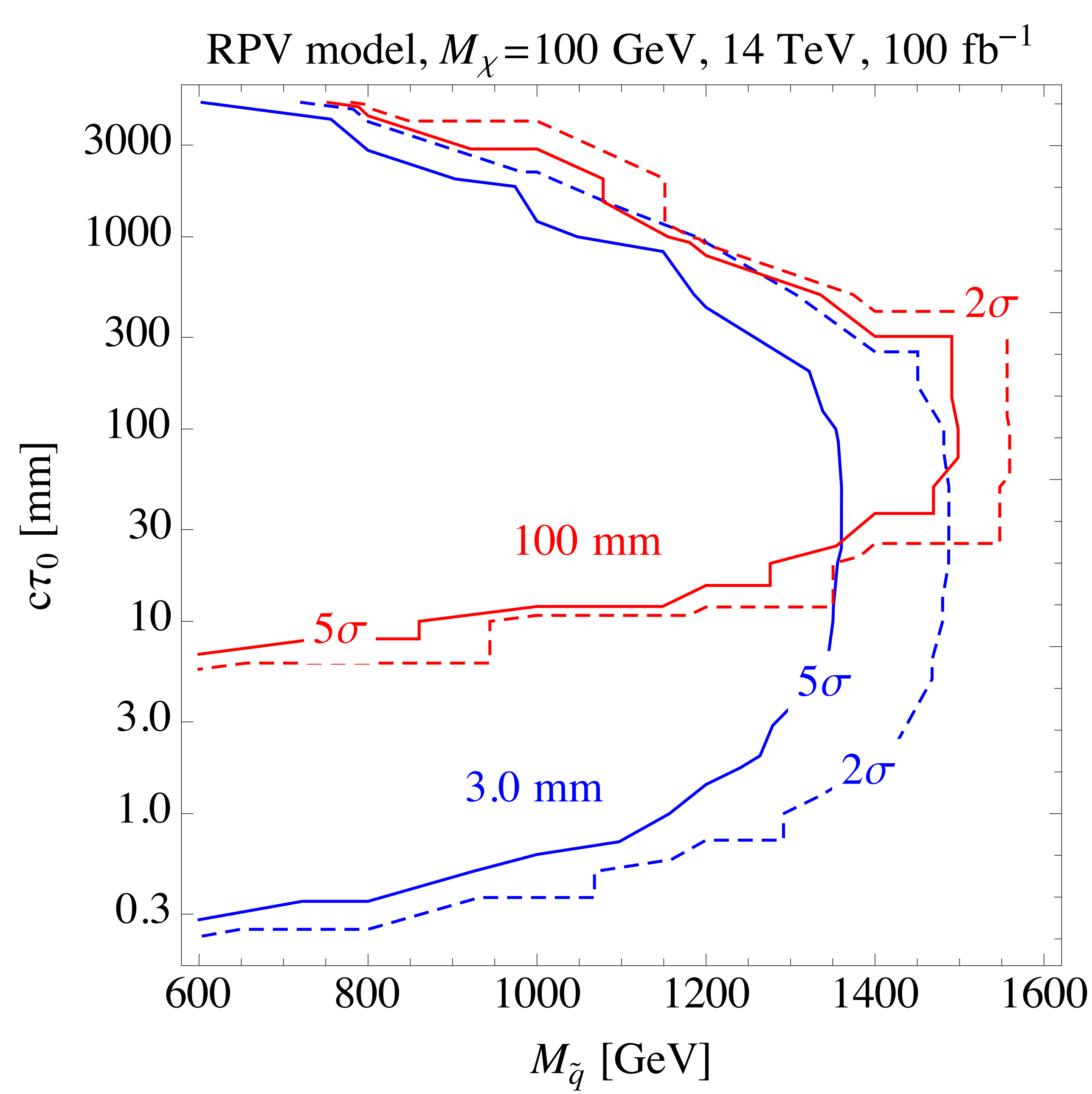


RPV neutralino

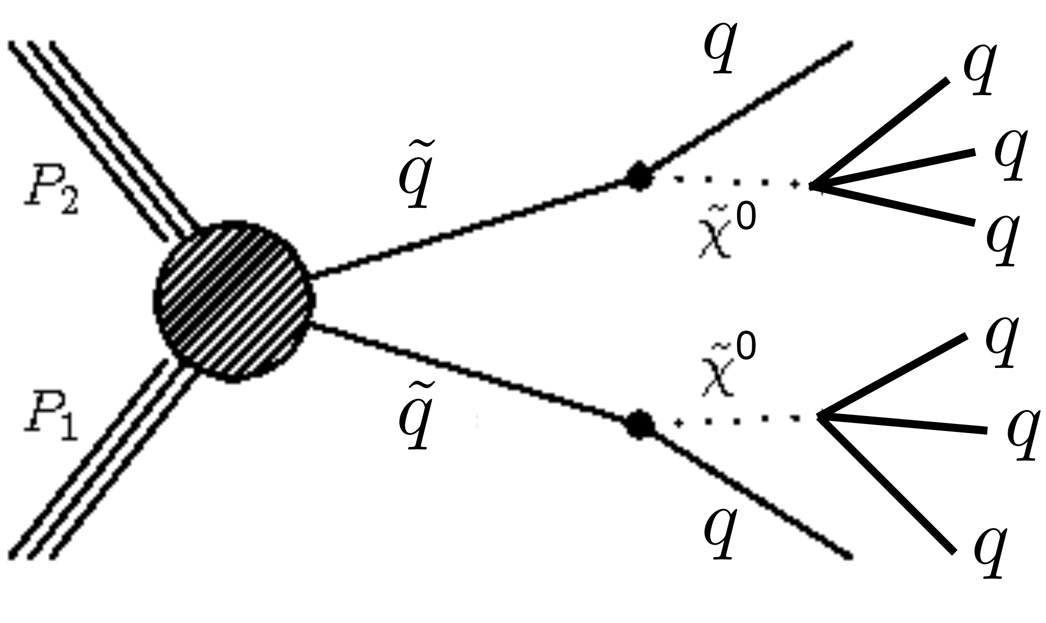


Squark pair production

Neutralino decay to 3 jets



RPV neutralino @ **HL-LHC**



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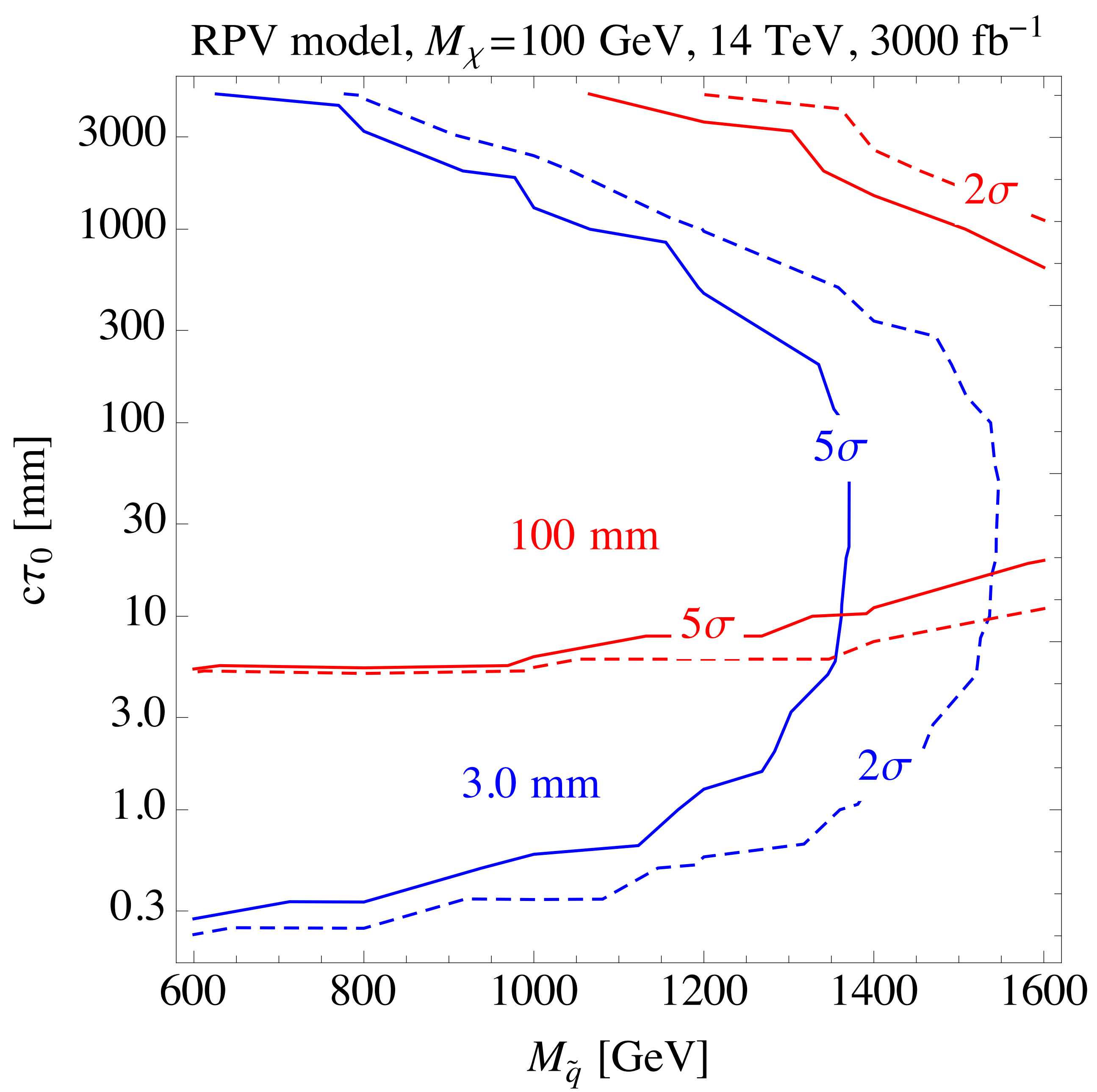
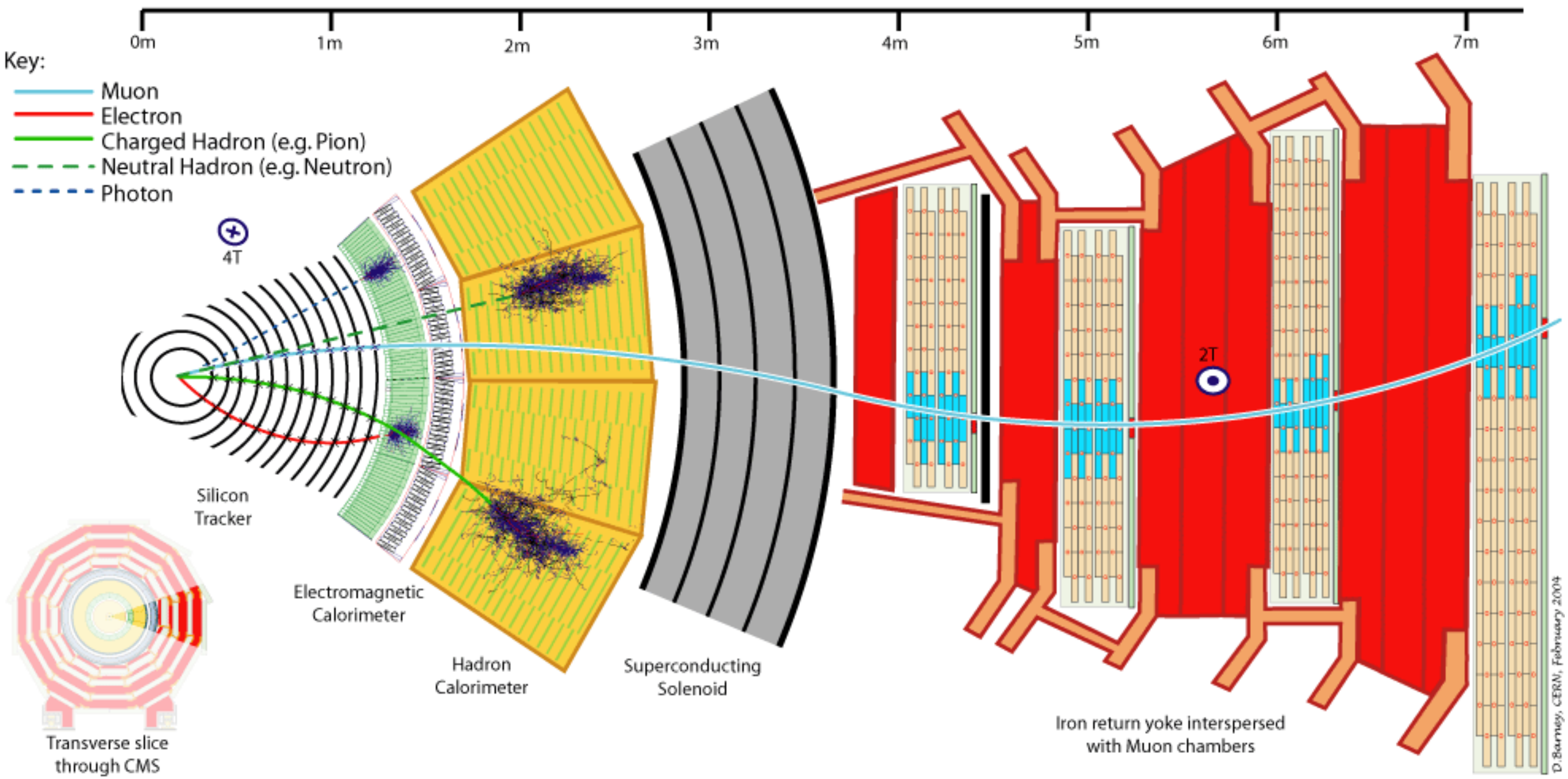


Conclusions

- DM exists, important to explore beyond-WIMP dark matter
- 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.
- Opportunities for ATLAS, CMS, and LHCb. Exotics groups are investigating.



0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

Check dark shower w/ meson multiplicity

e.g. Ellis, Stirling, Webber

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

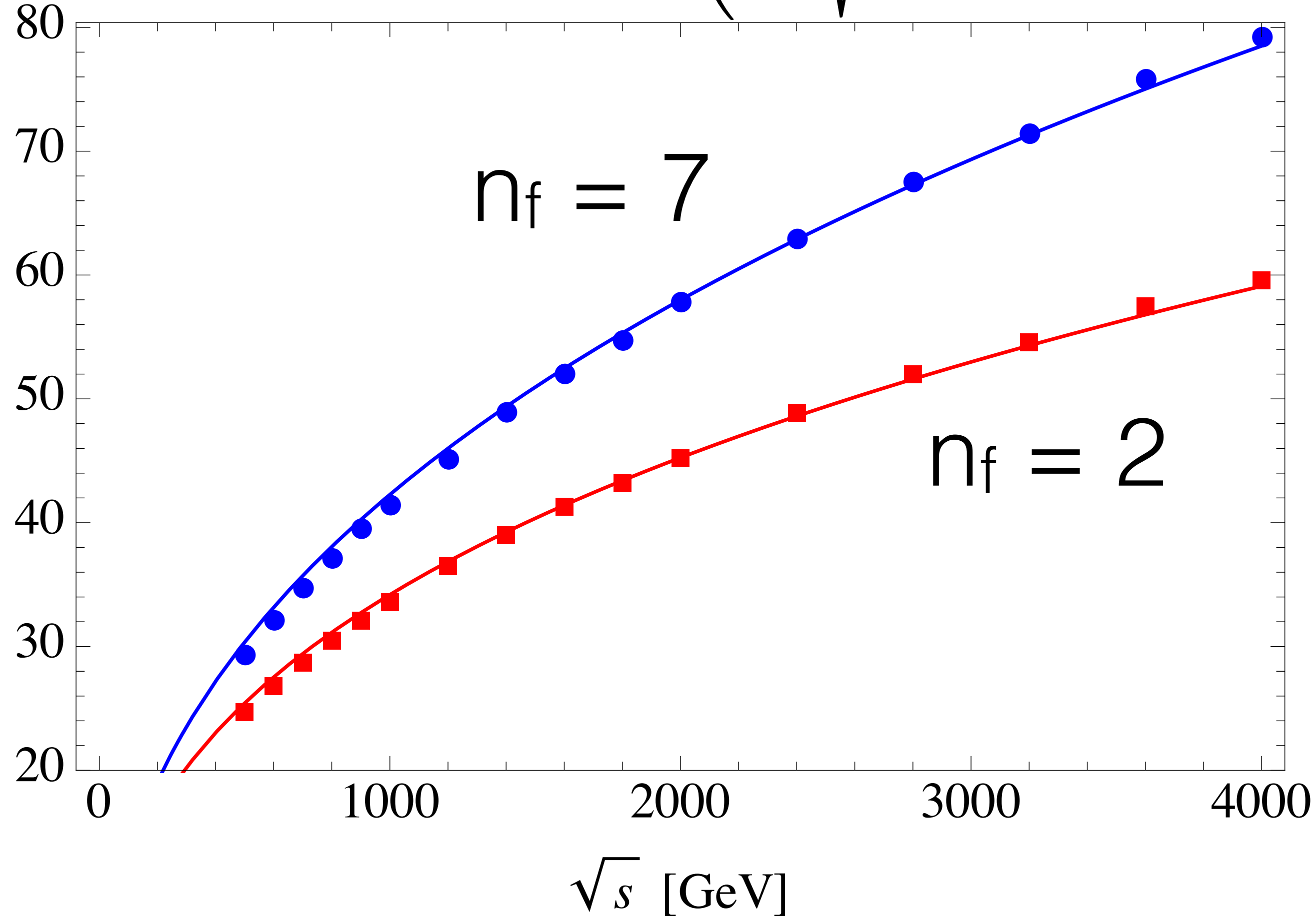


Figure 11: Average dark meson multiplicity in $e^+e^- \to Z'^* \to \bar{Q}_d Q_d$ as a function of the centre-of-mass energy $\sqrt{s}$. We compare the output of the modified PYTHIA implementation for $n_f = 7$ (blue circles) and $n_f = 2$ (red squares) to the theory prediction Eqn. (15), where we only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

cut flows

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.

Benchmarks

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

$N_c = 3$ and $n_f = 7$

Dark QCD already in PYTHIA!

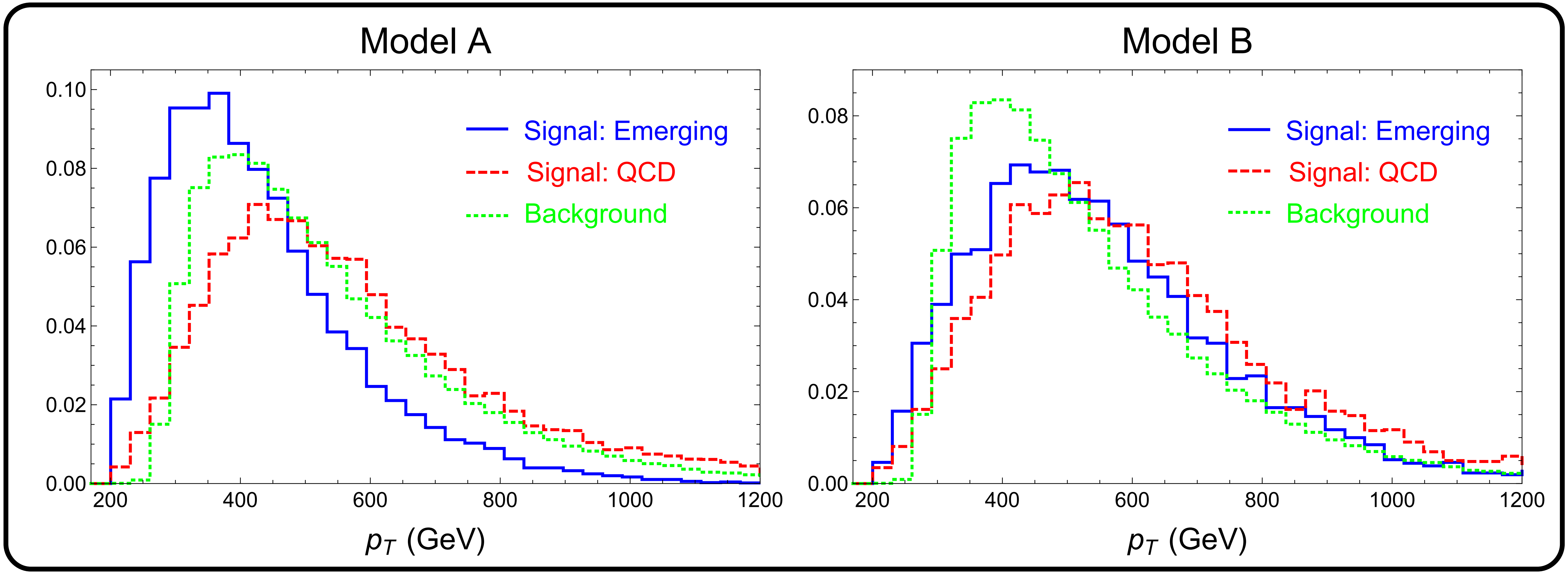
Carloni, Sjorstrand, 2010.

Carloni, Rathsman, Sjorstrand, 2011.

Run modified version with running.

jet momenta

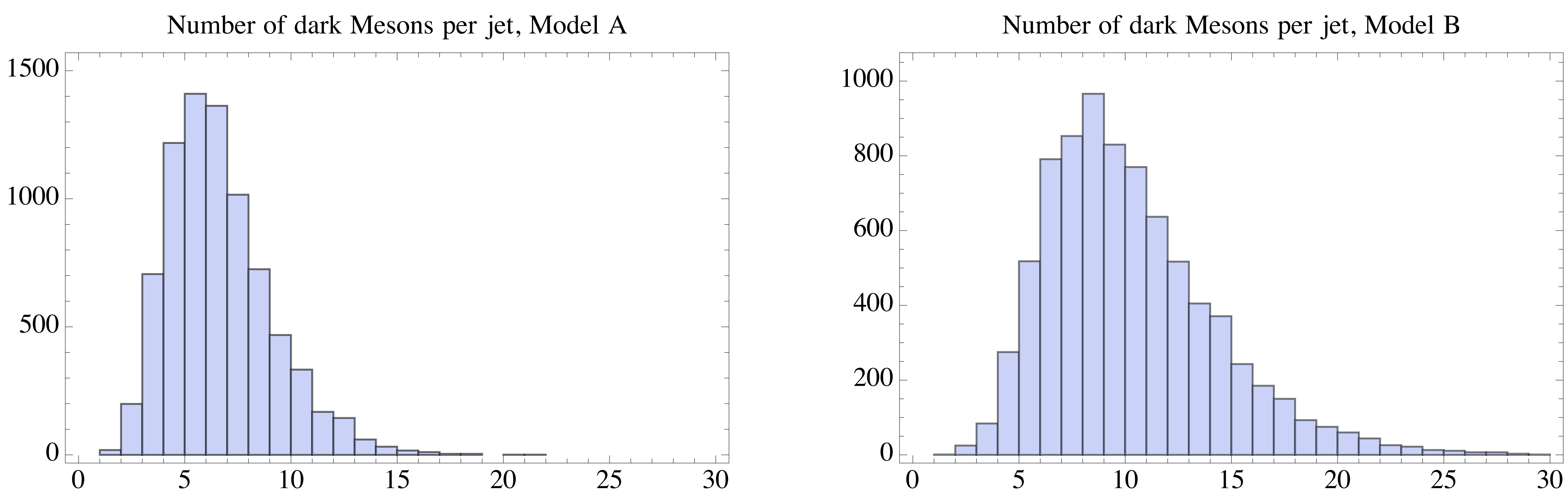
Hardest jet p_T



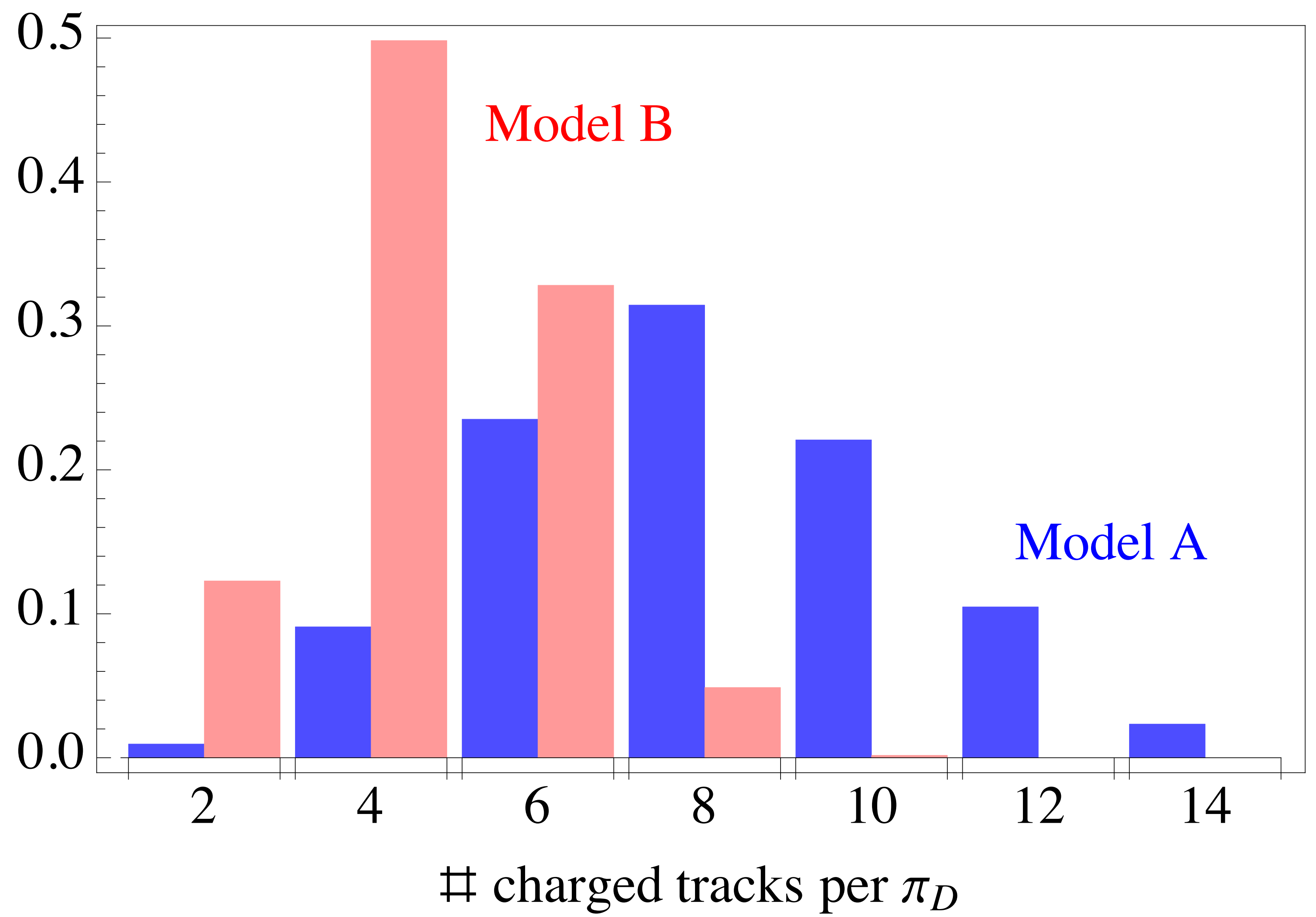
Four hard jets is enough to pass trigger.

meson multiplicity

Number of dark mesons in a jet.

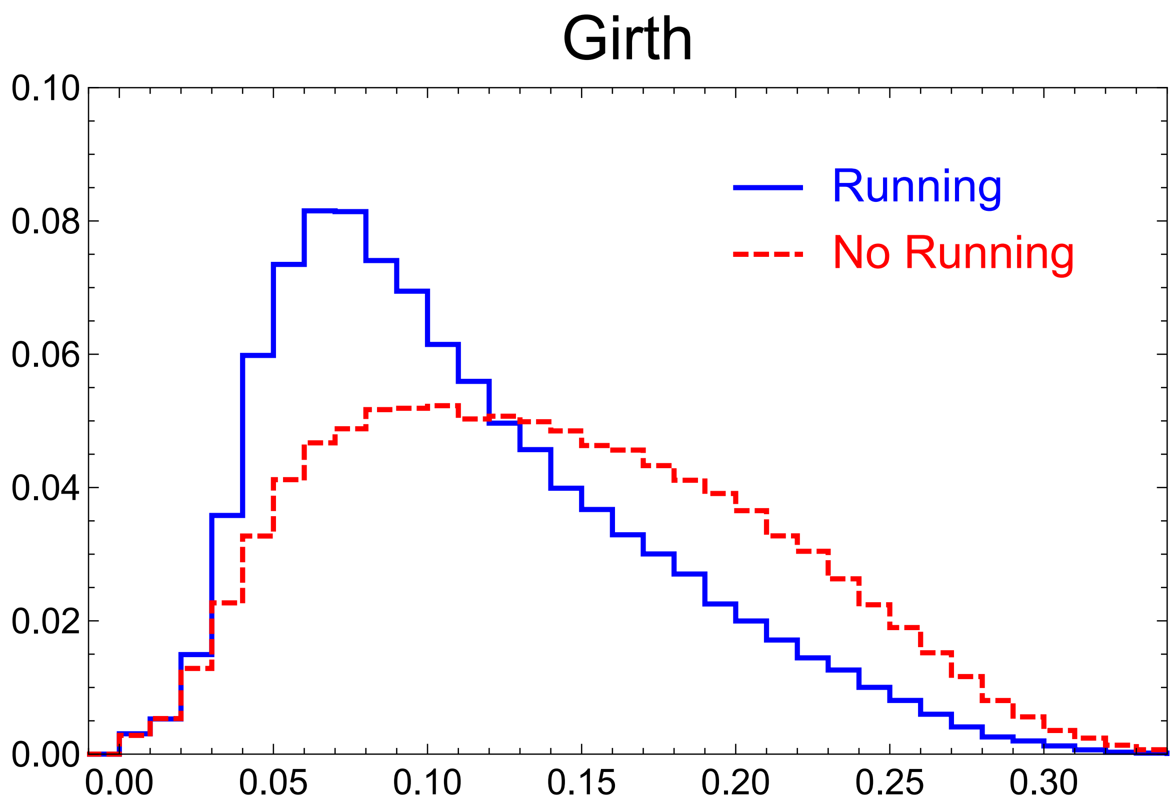


track multiplicity

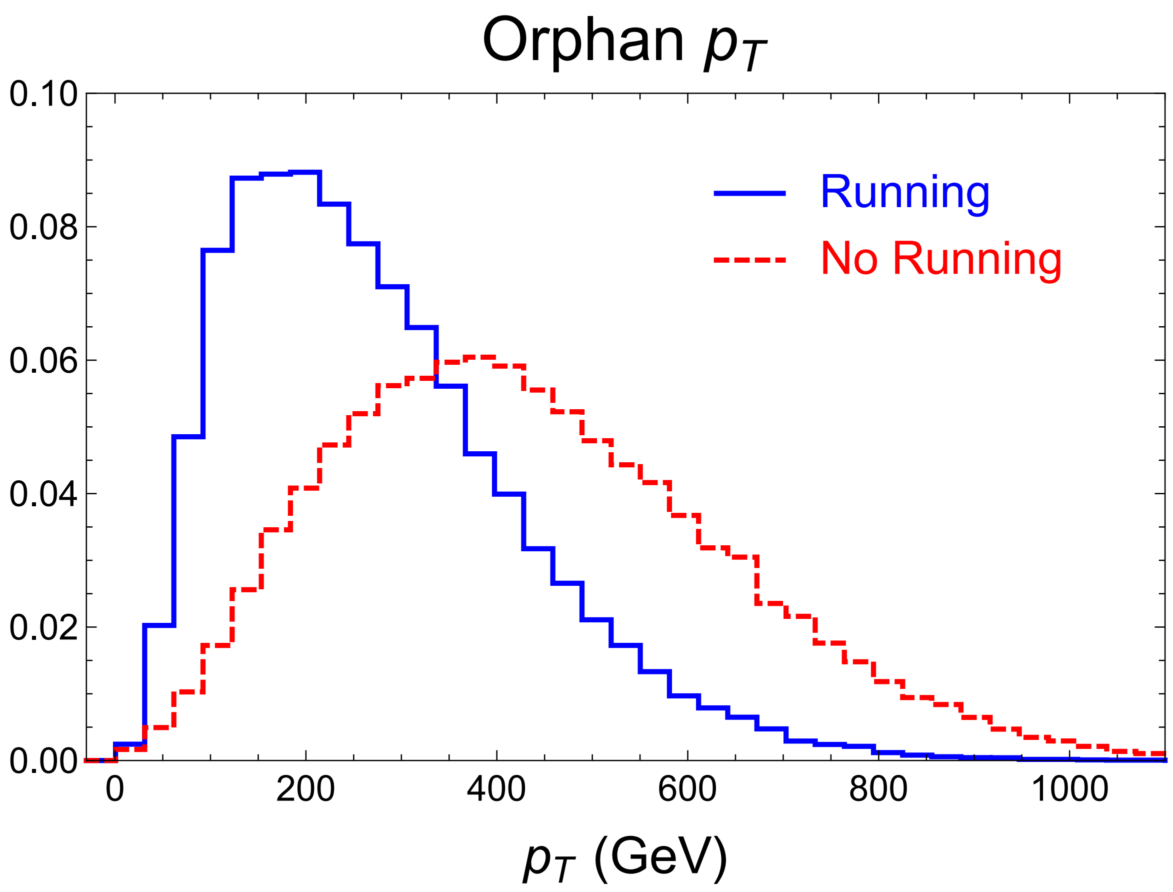


Running of dark coupling

Modify PYTHIA to include gauge coupling running.

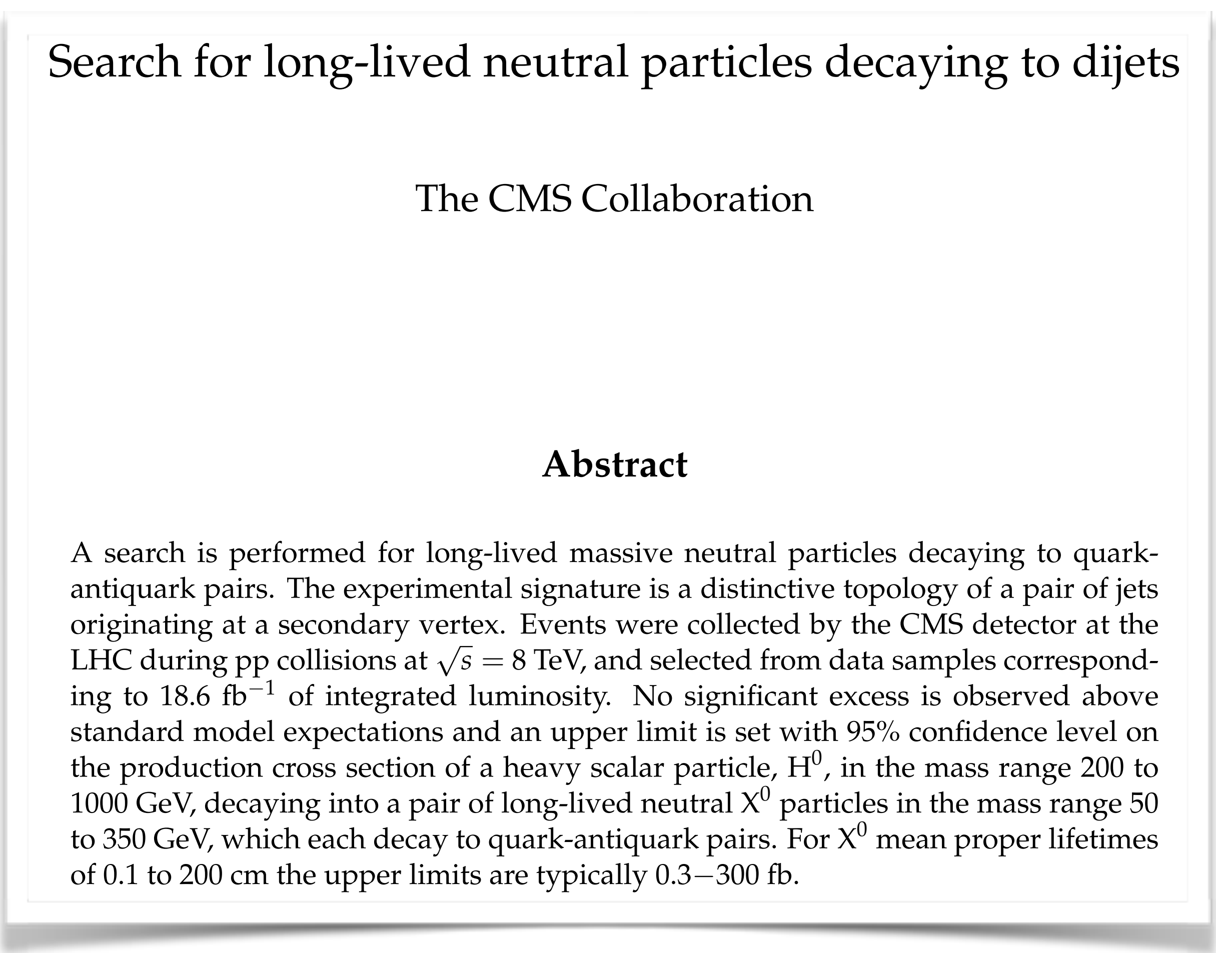


$$\text{girth} = \frac{1}{p_T^{\text{jet}}} \sum_i p_T^i \, \Delta R_i$$



p_T not in jets with $p_T > 200$ GeV

CMS search

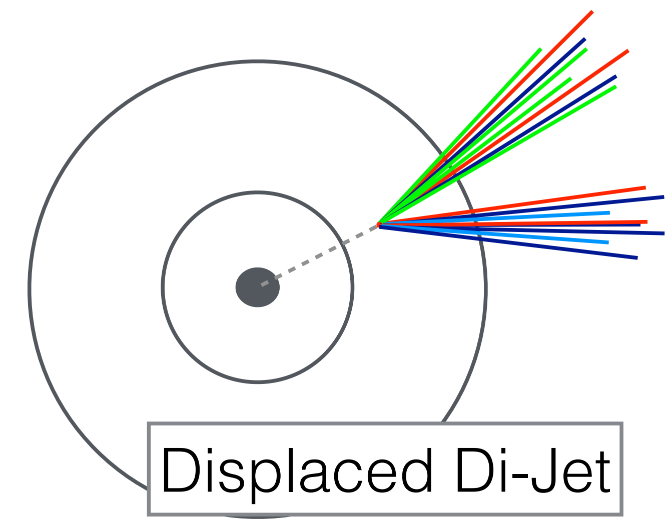

Search for long-lived neutral particles decaying to dijets

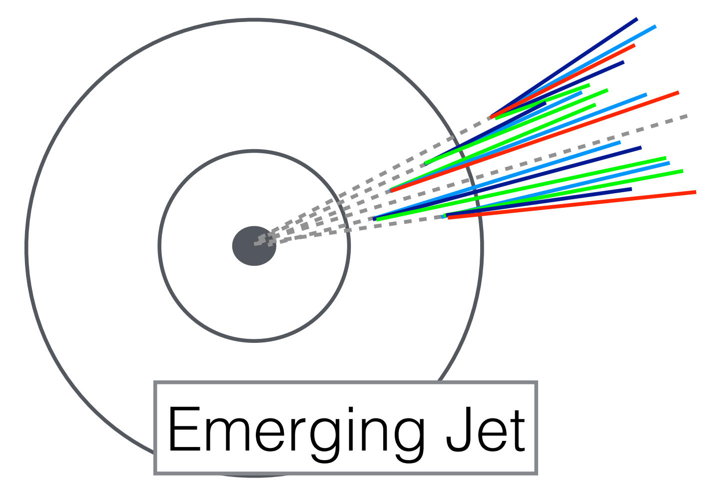
The CMS Collaboration

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].





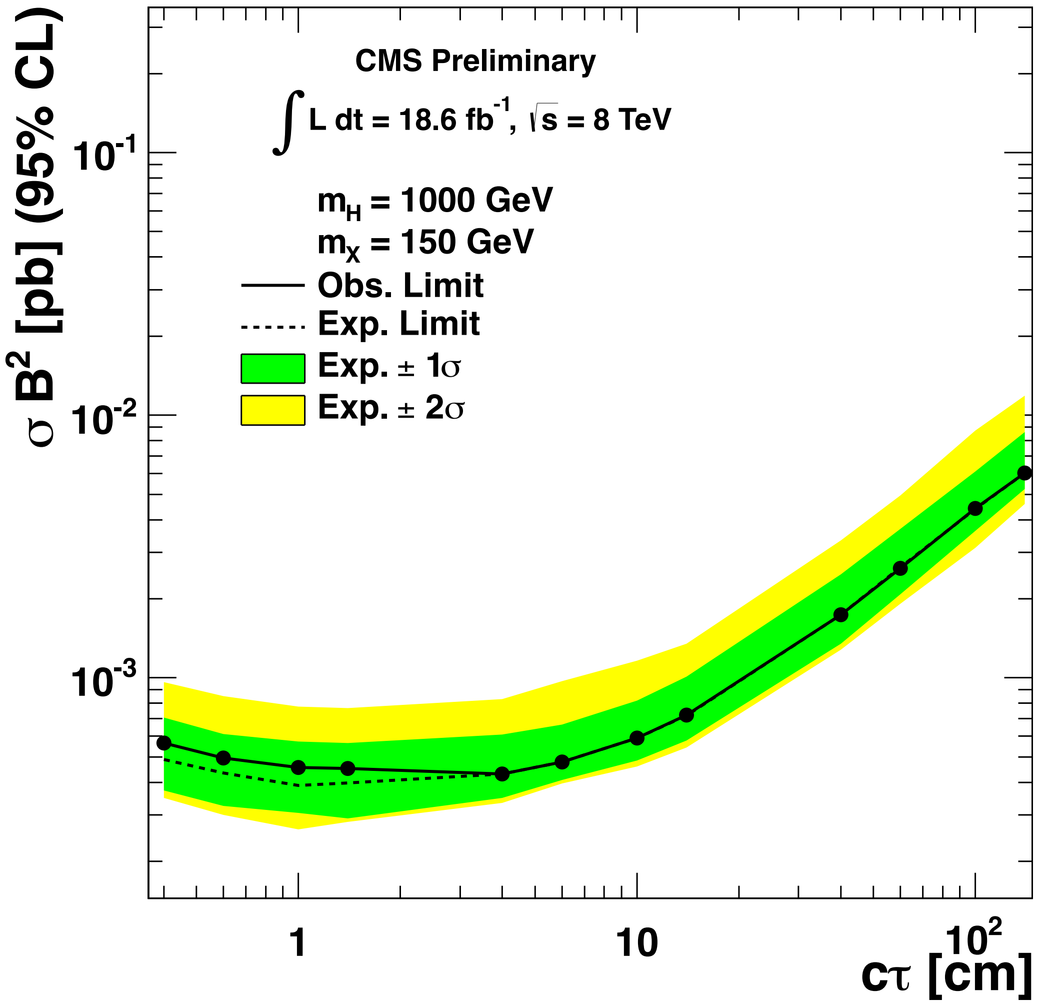
CMS search

CMS PAS EXO-12-038

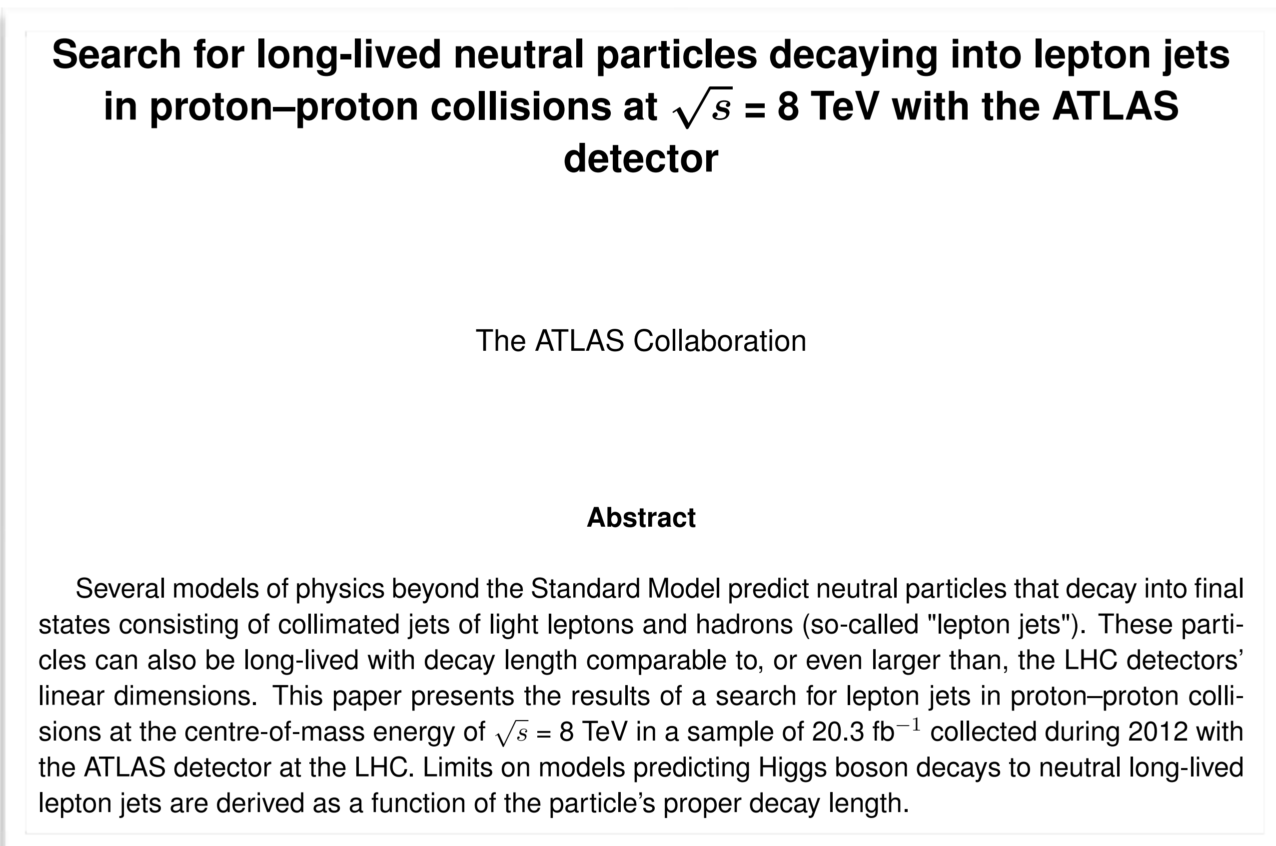
Require di-jets all coming from a single displaced vertex.

Throw away energy of tracks not reconstructed from vertex.

Unlikely to be sensitive to emerging phenomenology.



ATLAS search



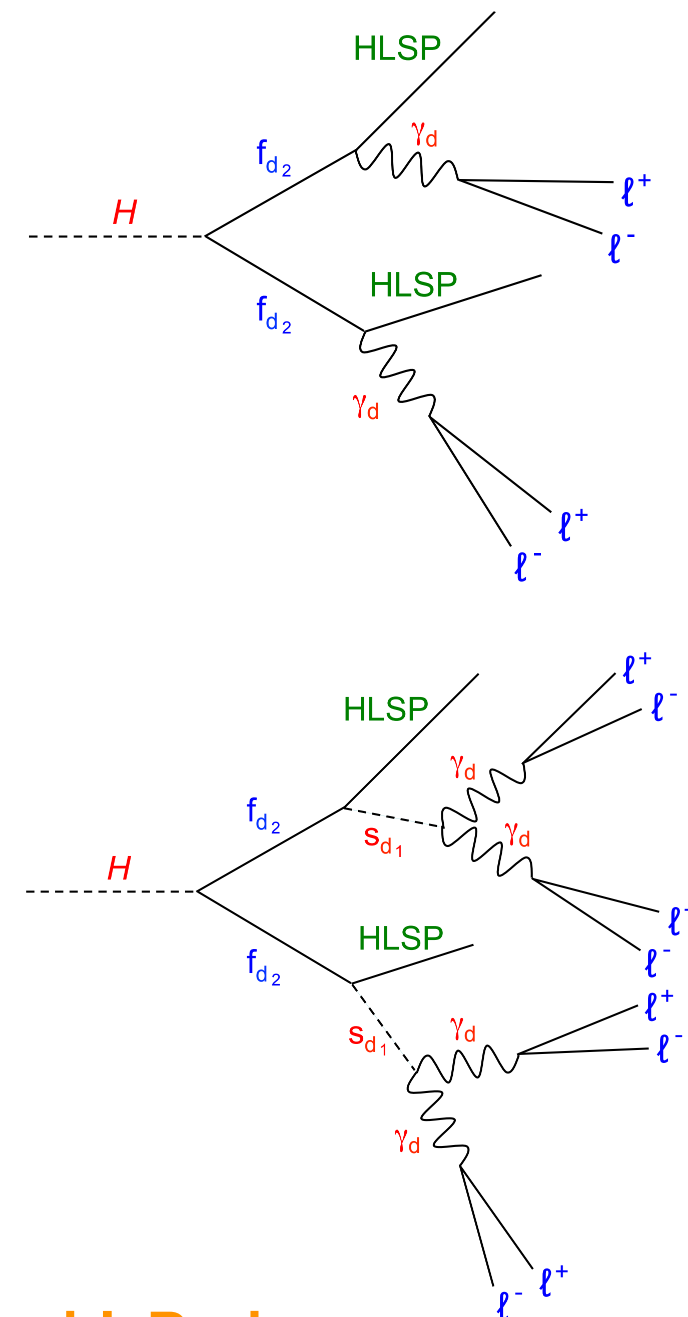
Search for long-lived neutral particles decaying into lepton jets in proton–proton collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector

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].



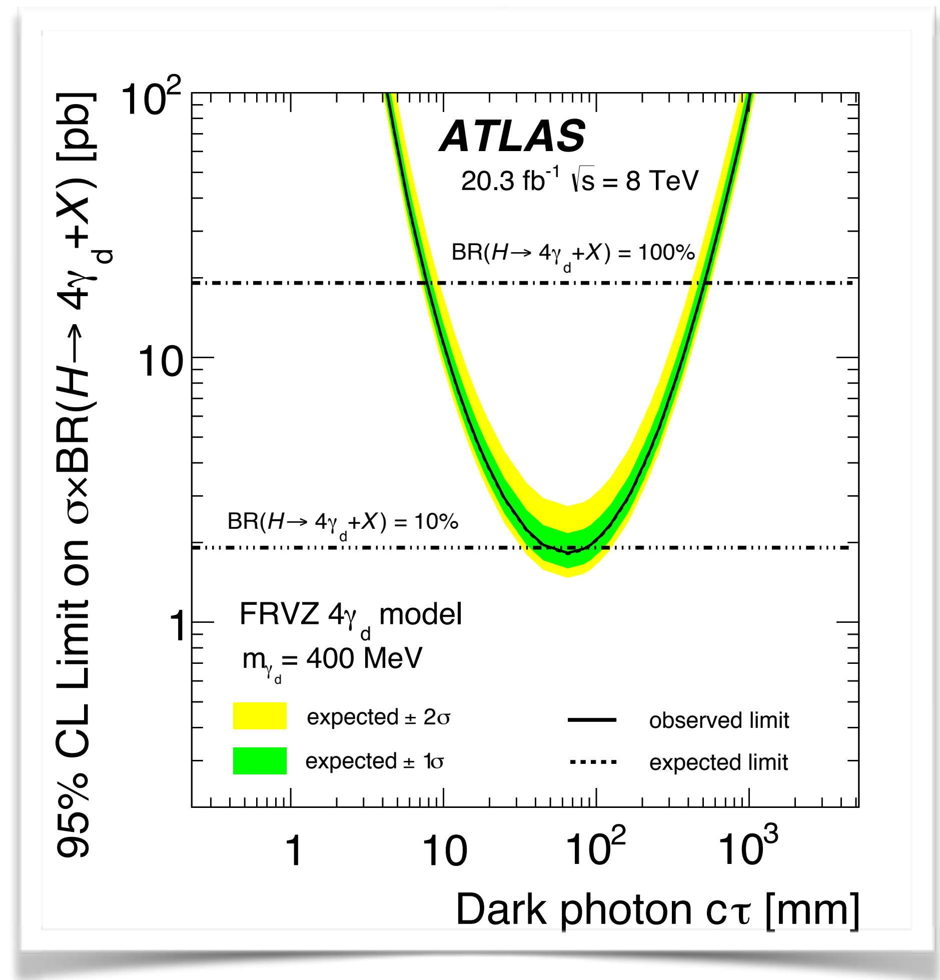
Falkowski, Ruderman, Volansky, Zupan '10

ATLAS search

arXiv:1409.0746v2 [hep-ex]

Requires ECAL/HCAL < 0.1.

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

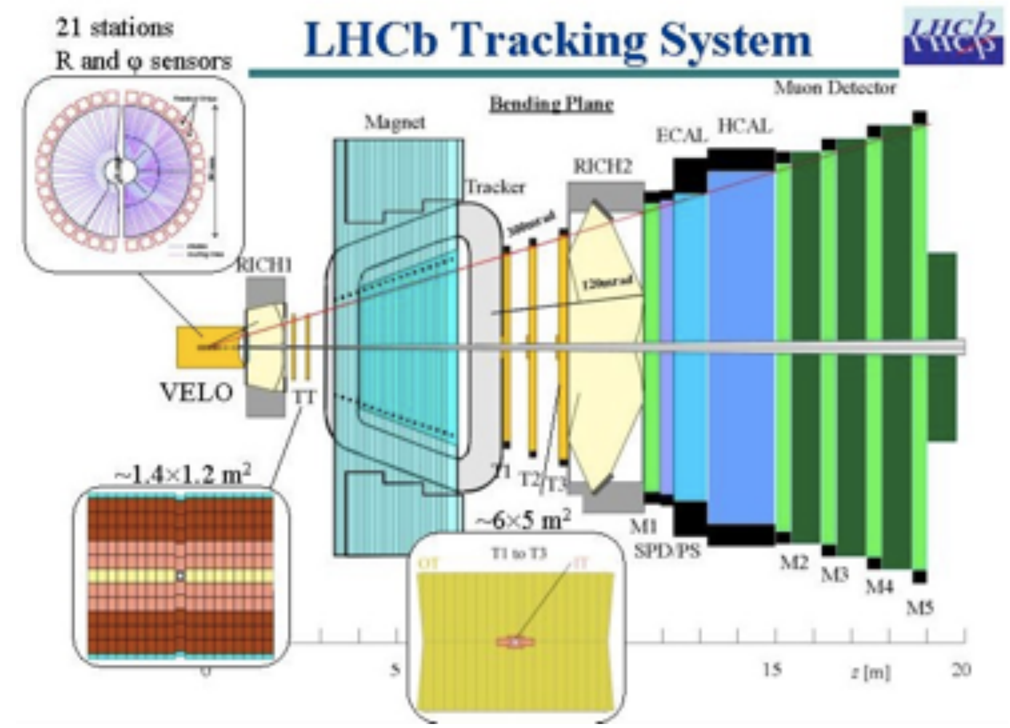


See also ATLAS trigger paper: arXiv:1305.2204 [hep-ex].

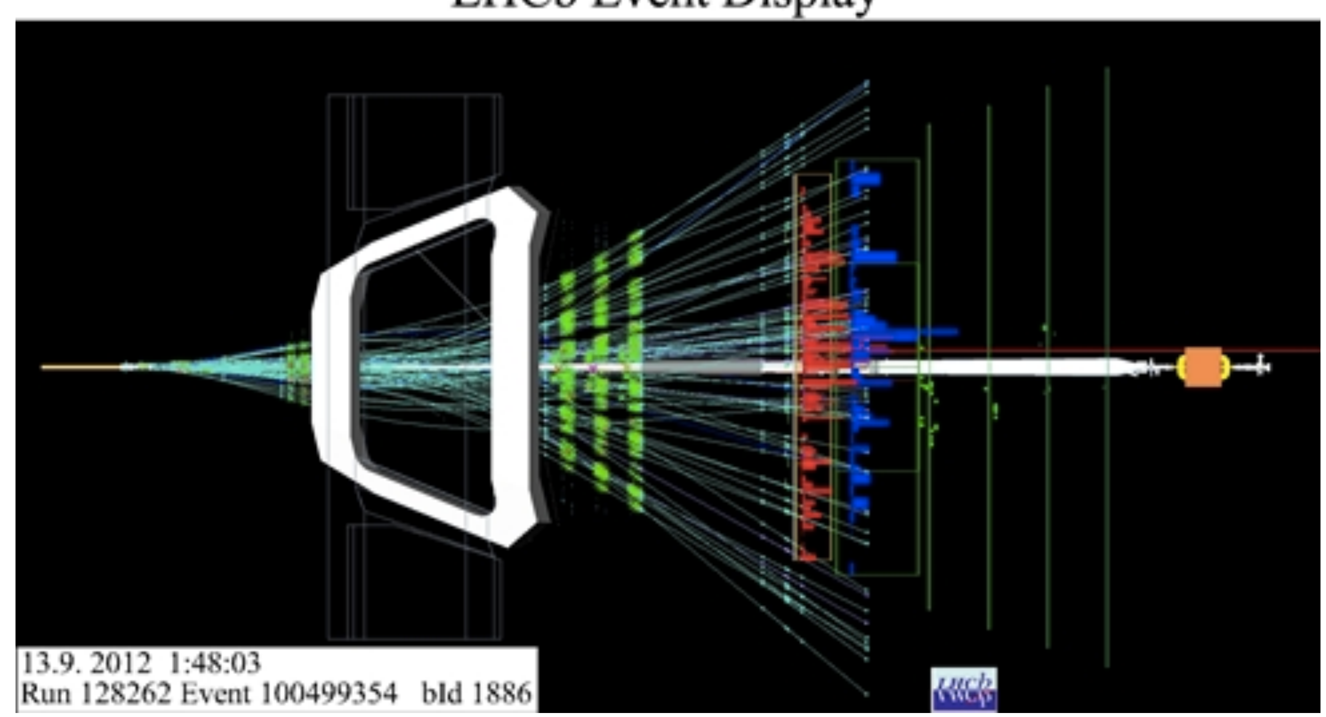
LHCb

LHCb has excellent tracking.

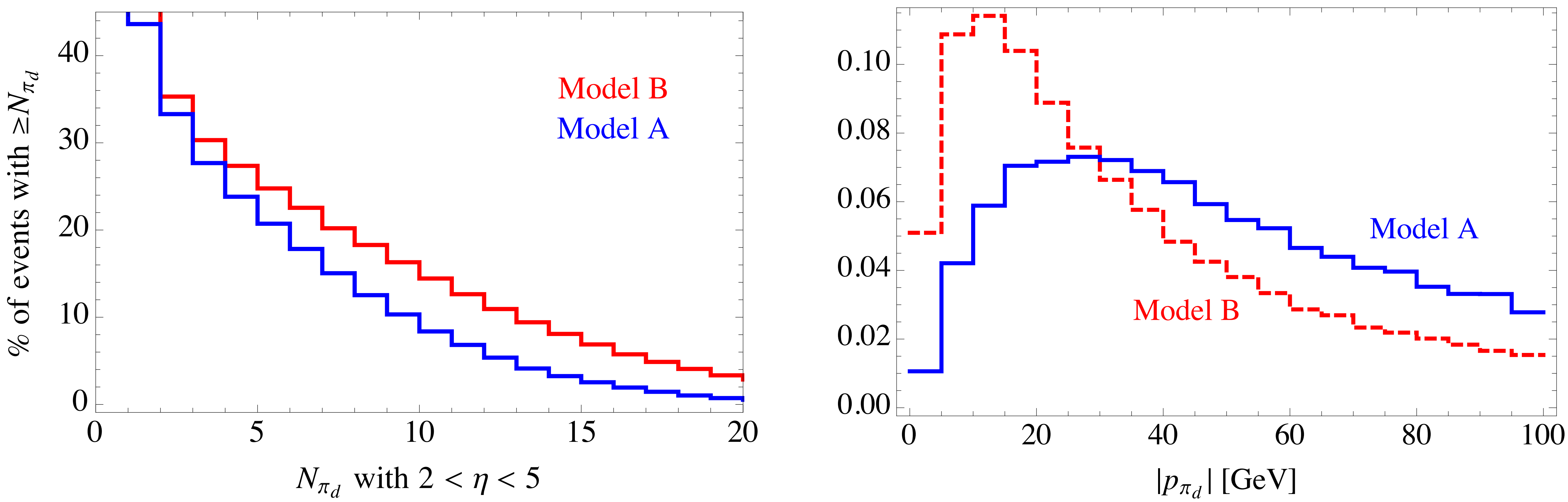
Limited coverage of event.



LHCb Event Display



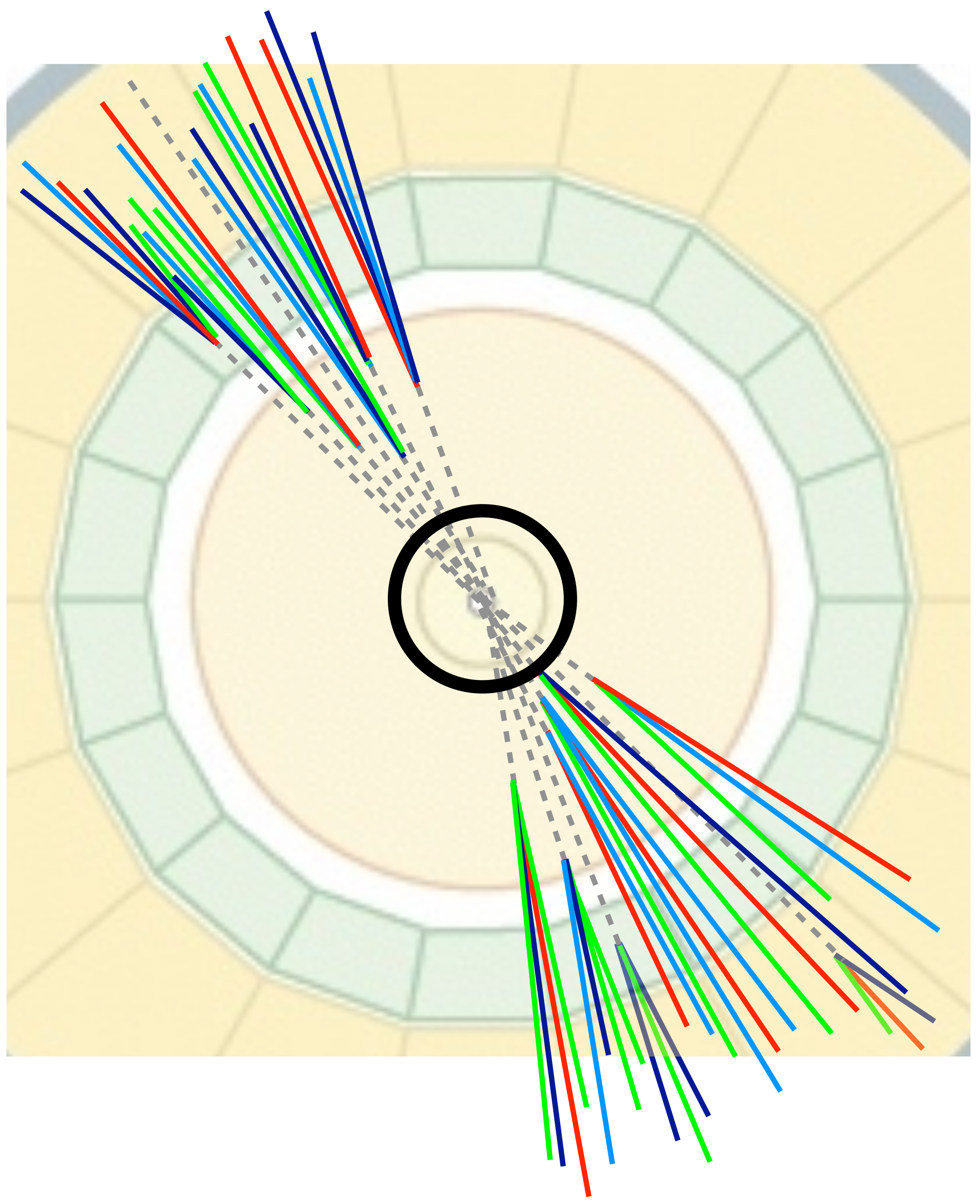
LHCb



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

~30% have > 2.

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.

Distributions