Title: Emerging Jets

Date: Feb 27, 2015 02:00 PM

URL: http://pirsa.org/15020132

Abstract: <p>I will describe a new collider object we have termed emerging jets.
These can arise when there is a confining dark sector connected to the
Standard Model by a TeV scale mediator, a scenario that is well
motivated by dark matter considerations. The signature of an emerging
jet is O(10) displaced vertices inside the jet each with different
impact parameter, and a small number of prompt tracks. I will describe
strategies that can be used to discover emerging jets even if they
have very small cross sections.</p>

EMERGING JETS

DANIEL STOLARSKI

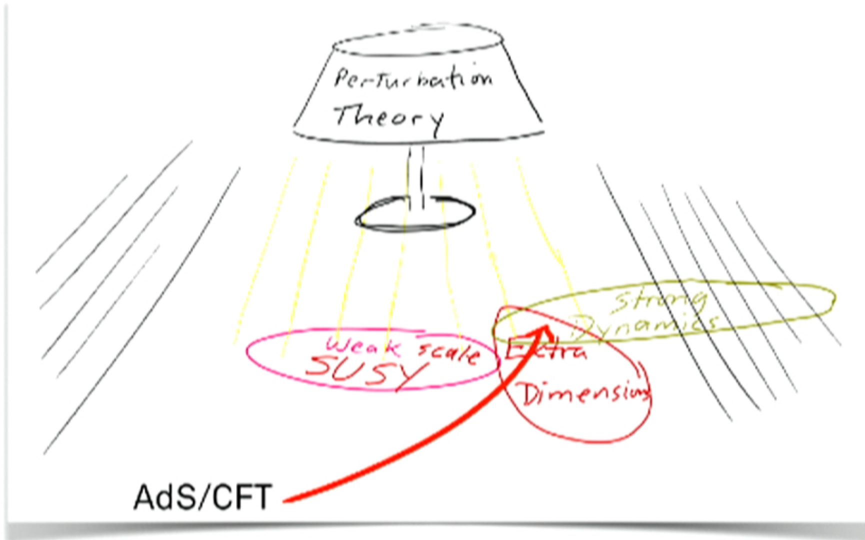
WITH PEDRO SCHWALLER
AND ANDREAS WEILER

arXiv:1502.05409

Perimeter Institute   February 27, 2015

MOTIVATION 1

Getting away from the lamp post



R. Sundrum

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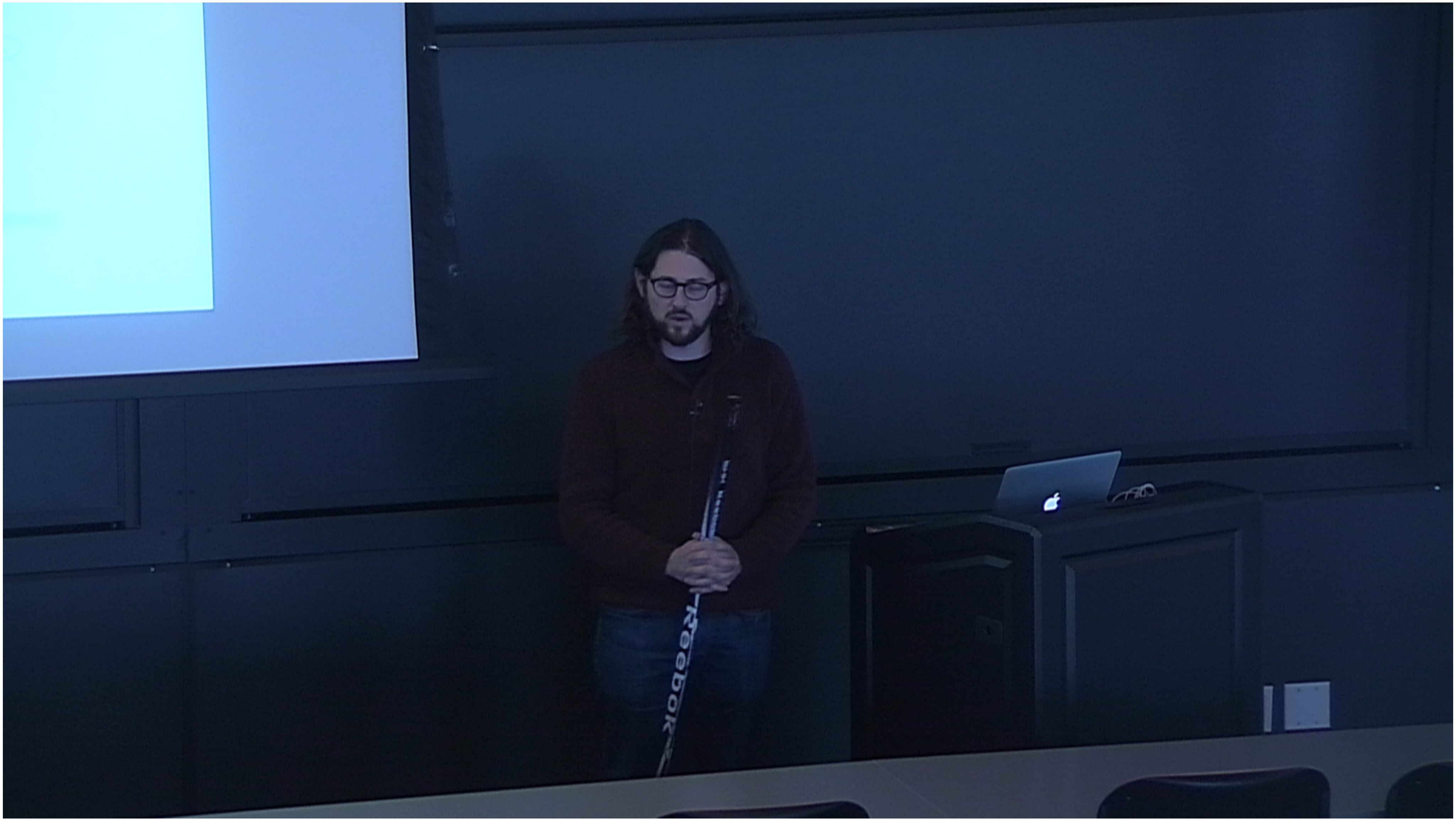
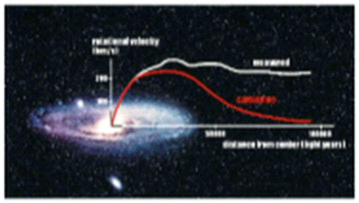
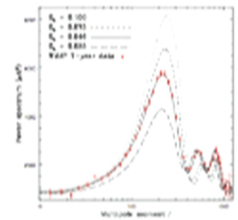

Reebok

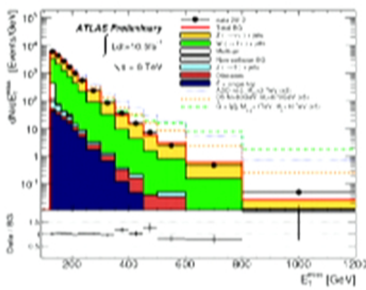
MOTIVATION 2

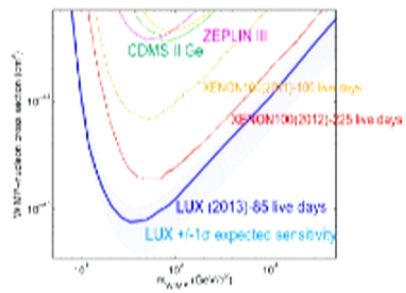
We have seen dark matter in the sky.





But not in the lab.





ASYMMETRIC DARK MATTER

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

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Controlled by complicated (known) QCD dynamics

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

?

Unknown dynamics of baryogenesis

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

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

?

Unknown dynamics of baryogenesis

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

GETTING THE MASS

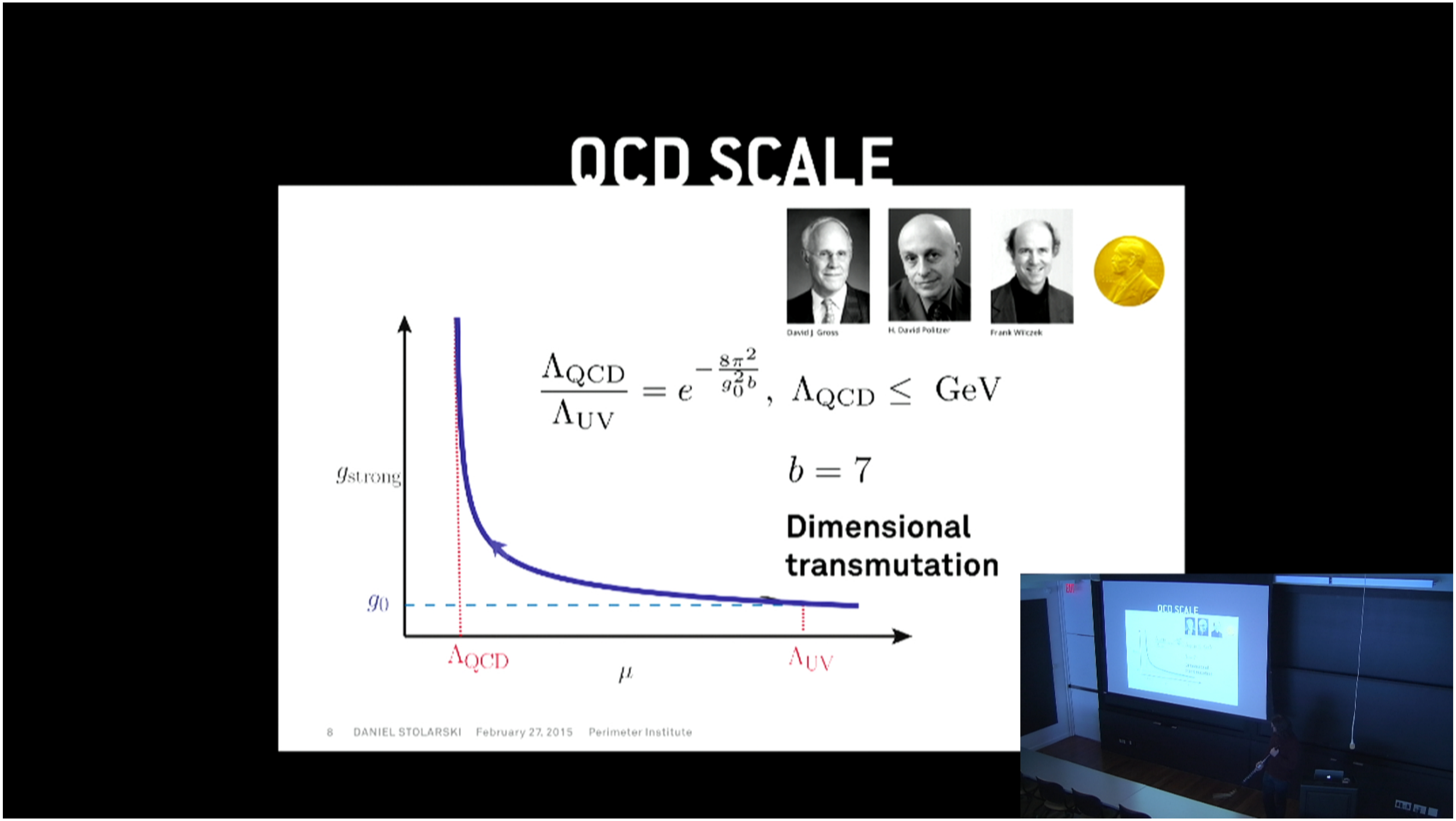
$$\Omega_{DM} \simeq 5\Omega_B$$

Controlled by complicated (known) QCD dynamics

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

?

Unknown dynamics of baryogenesis


QCD SCALE
David J. Gross
H. David Politzer
Frank Wilczek
$\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm UV}} = e^{-\frac{8\pi^2}{g_0^2 b}}, \ \Lambda_{\rm QCD} \leq \ {\rm GeV}$
$b = 7$
Dimensional transmutation
$g_{\rm strong}$
g_0
$\Lambda_{\rm QCD}$
μ
$\Lambda_{\rm UV}$
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DARK QCD

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

Dark matter is dark sector baryons with mass ~ Λ_{dQCD}.

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

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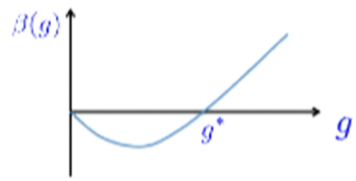
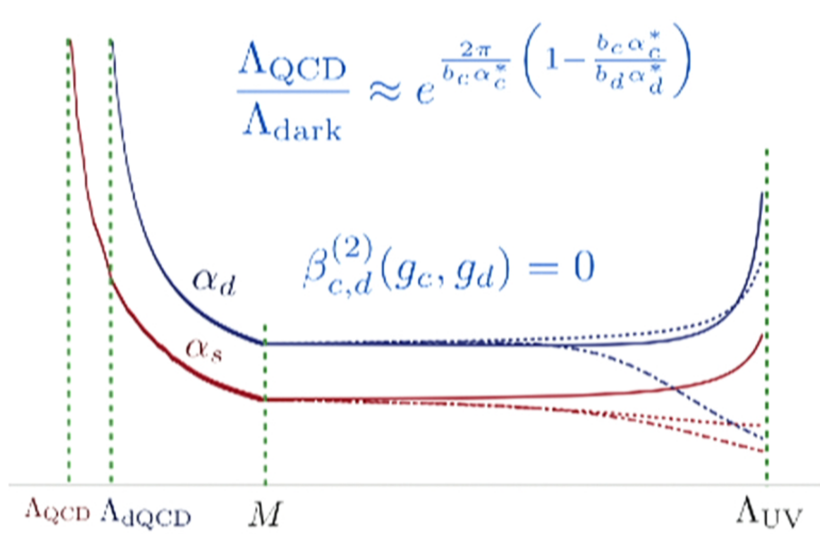
Search for model with perturbative fixed point

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



SCALES ARE RELATED



DARK MATTER

Can co-generate DM and baryon asymmetry.

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

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

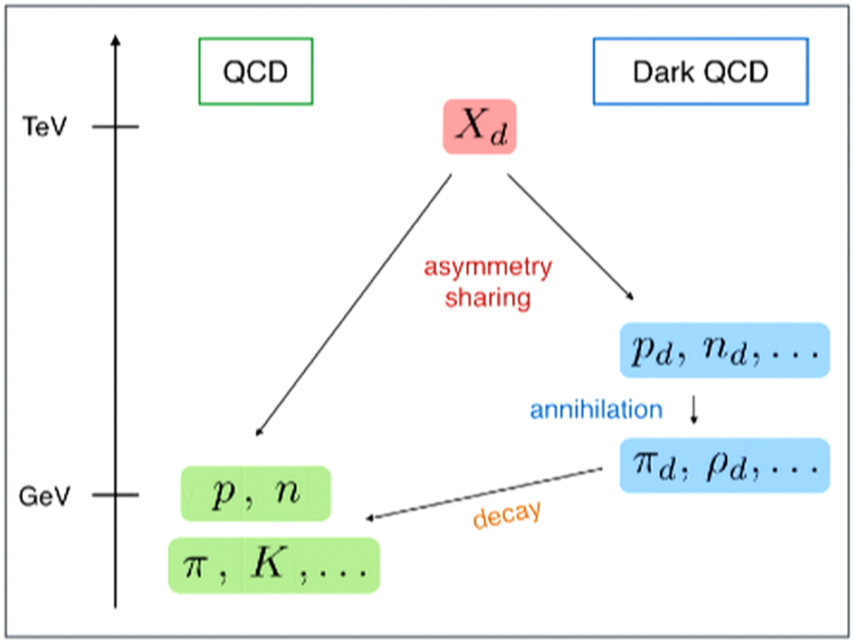
Dark matter is strongly self interacting — potentially solves various problems of cold dark matter.

- 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

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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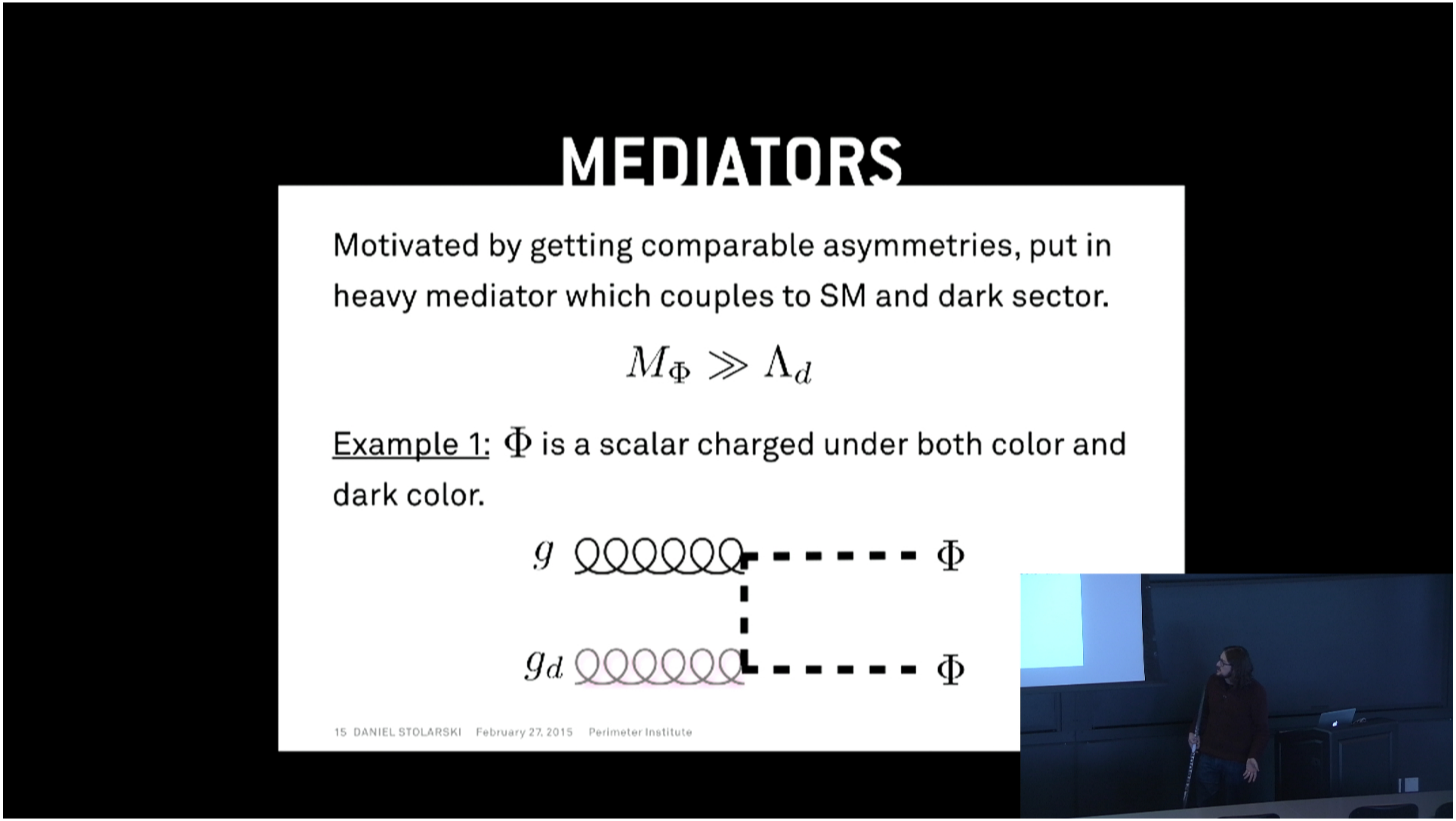
Stable — Decays to SM


MEDIATORS
Motivated by getting comparable asymmetries, put in heavy mediator which couples to SM and dark sector.
$M_\Phi \gg \Lambda_d$
Example 1: Φ is a scalar charged under both color and dark color.
g
g_d
Φ
Φ
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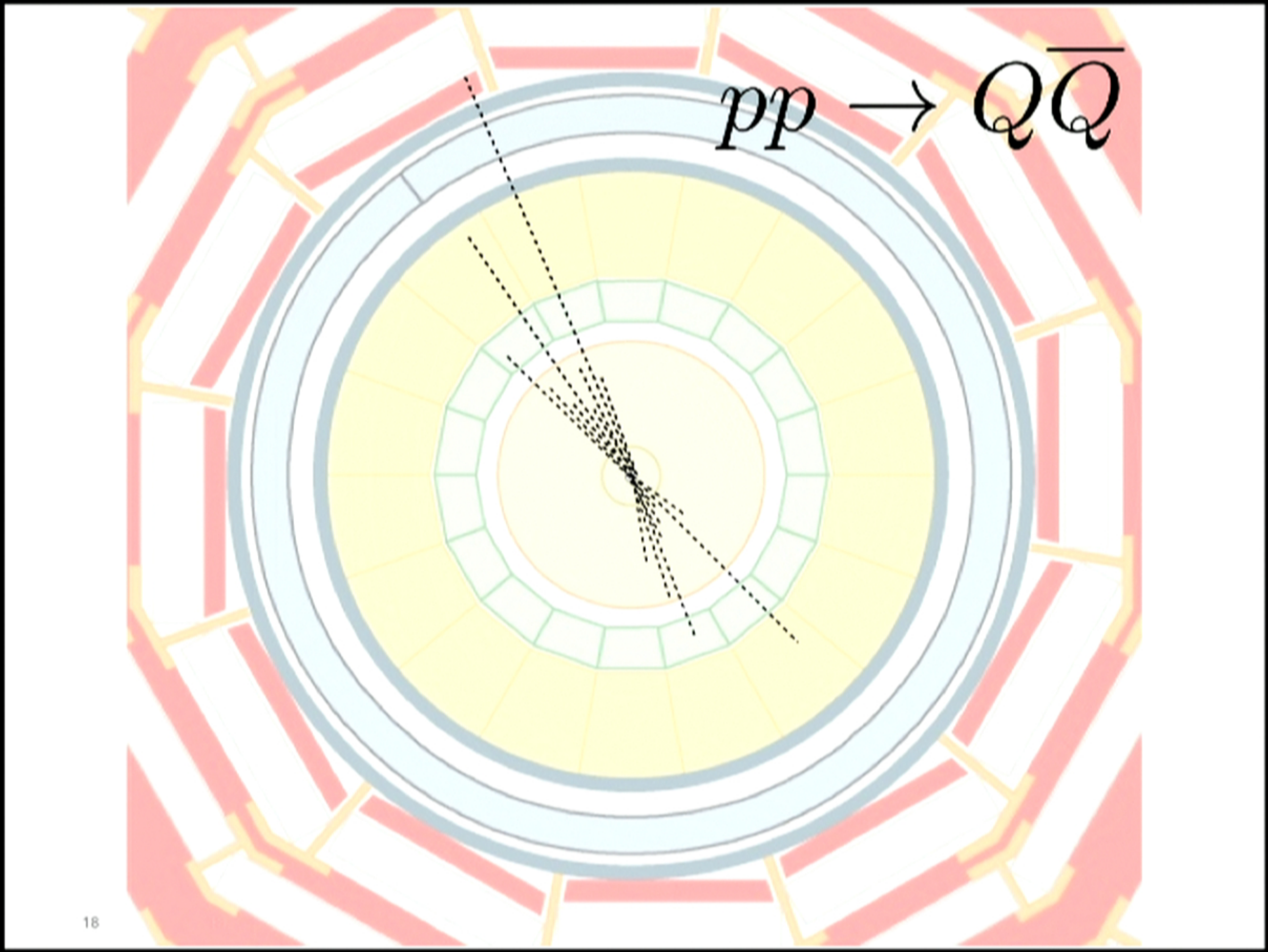
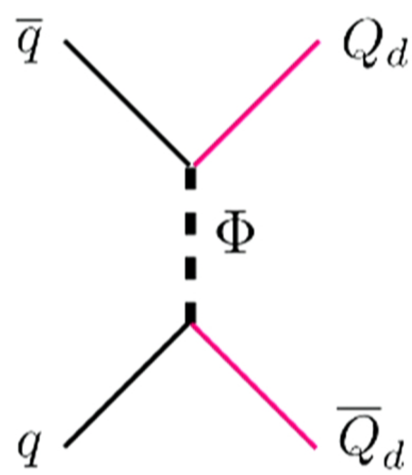

$pp \to Q\overline{Q}$
18

PION DECAY

Operator used to generate asymmetry mediates decay:

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



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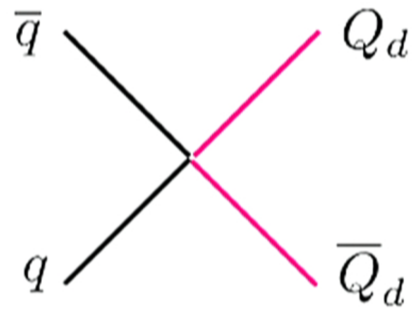
Integrate out Φ



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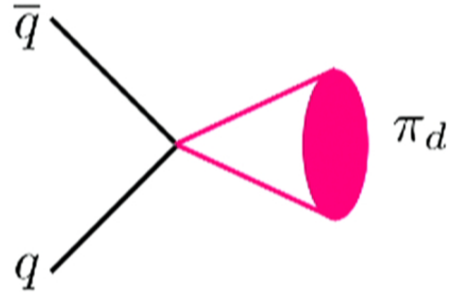

Dark pion decays to quarks

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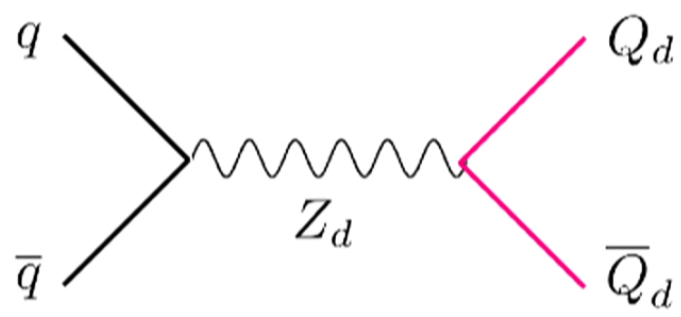
PION DECAY

Same story for Z_d model:



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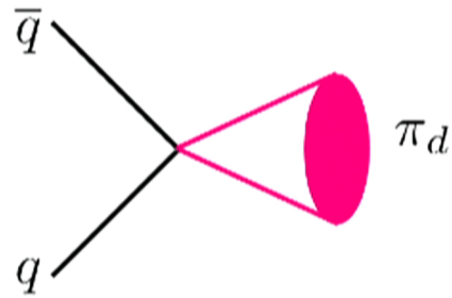
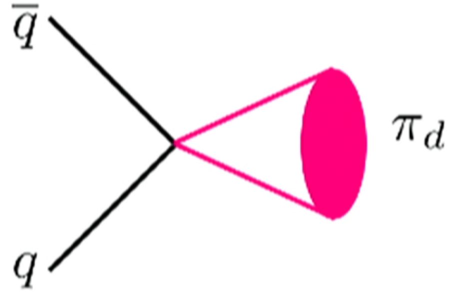


DECAY LENGTH



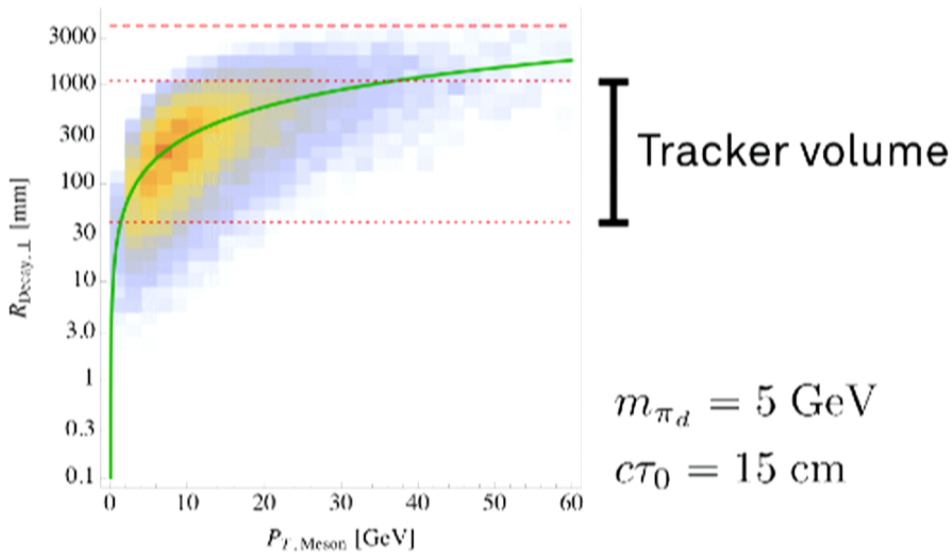
$$\frac{1}{M_X^2}\overline{Q}\gamma_\mu Q\,\bar{d}_R\gamma^\mu d_R$$

Can use (dark) chiral Lagrangian to estimate:

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

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

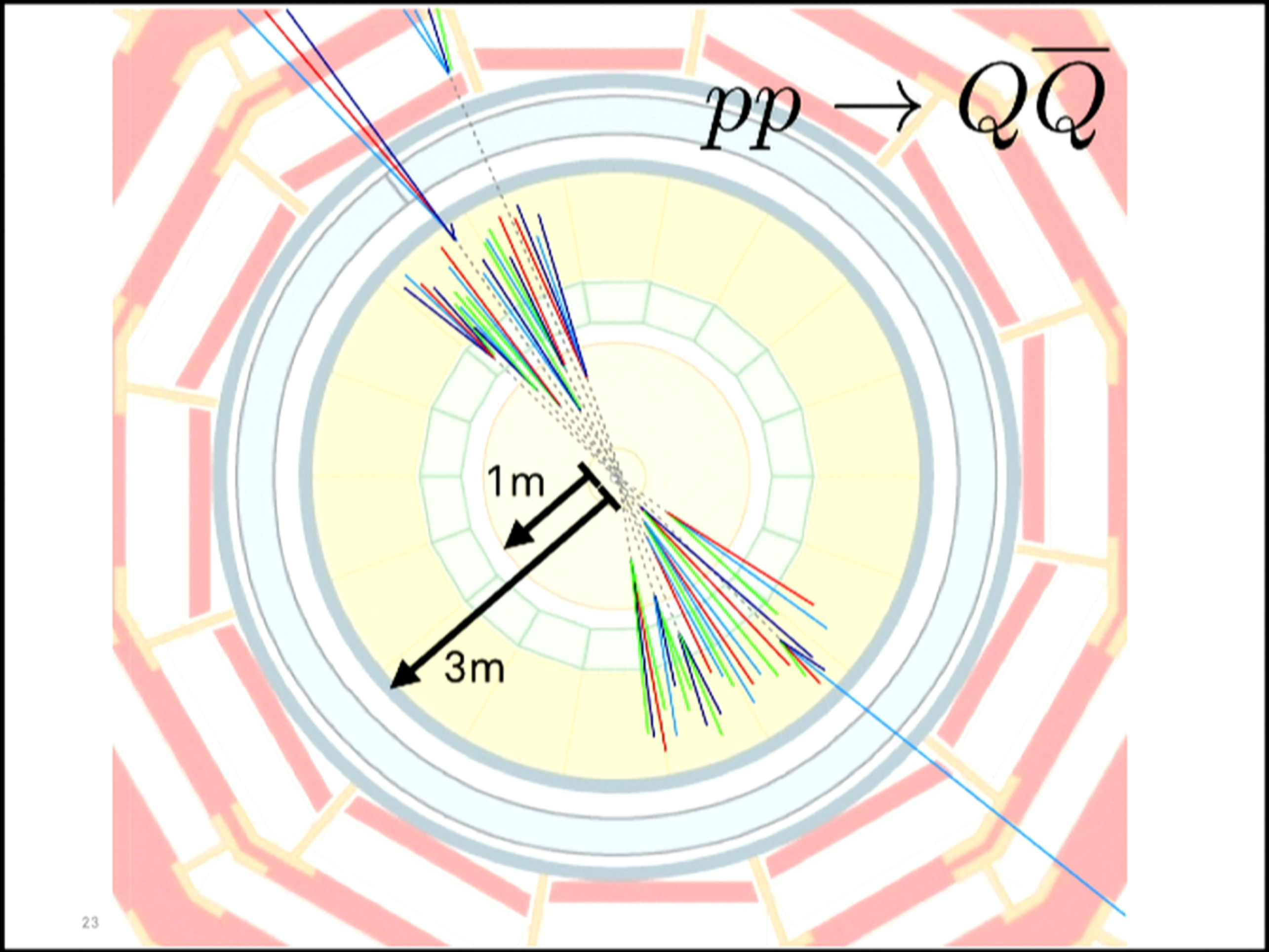
DECAY LENGTH



$$m_{\pi_d} = 5 \text{ GeV}$$

$$c\tau_0 = 15 \text{ cm}$$

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


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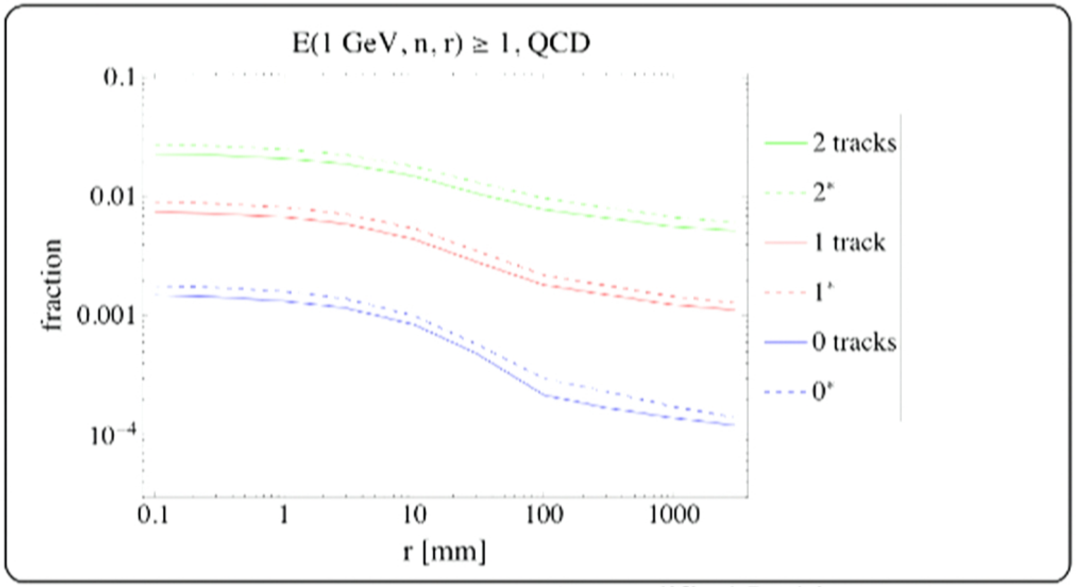
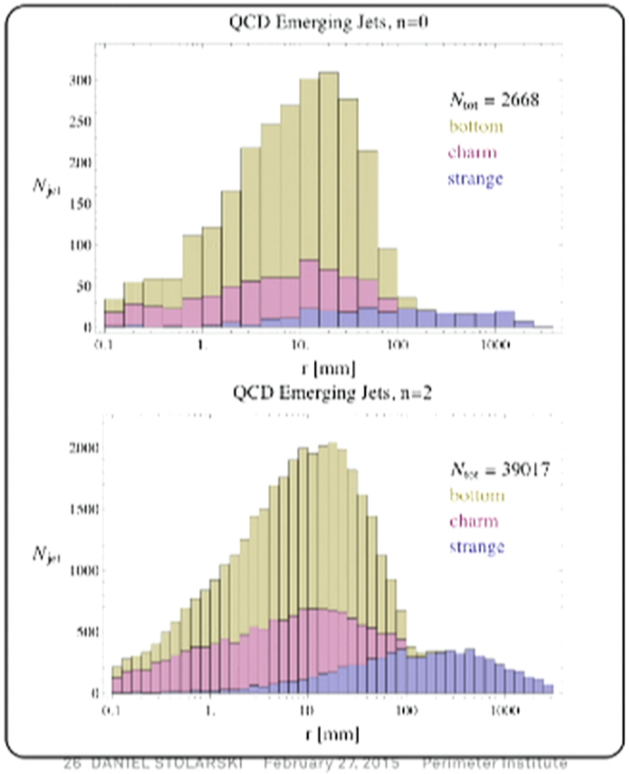
BACKGROUND?

QCD 4-jet production in PYTHIA 8 $p_T > 200$ 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

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

$N_c = 3$ and $n_f = 7$

Dark QCD already in PYTHIA!

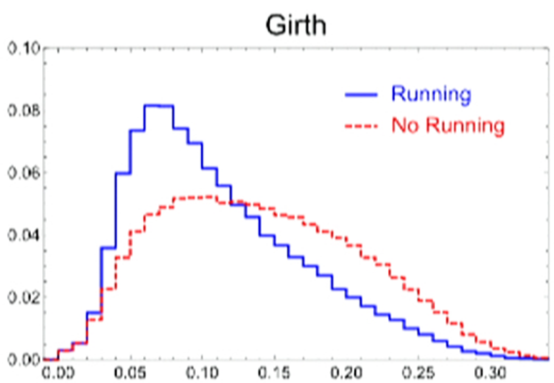
Carloni, Sjorstrand, 2010.

Carloni, Rathsman, Sjorstrand, 2011.

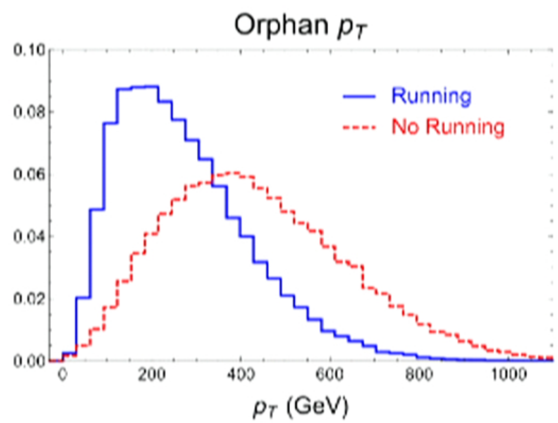
Run modified version with running.

COUPLING RUNNING

Modify PYTHIA to include gauge coupling running.



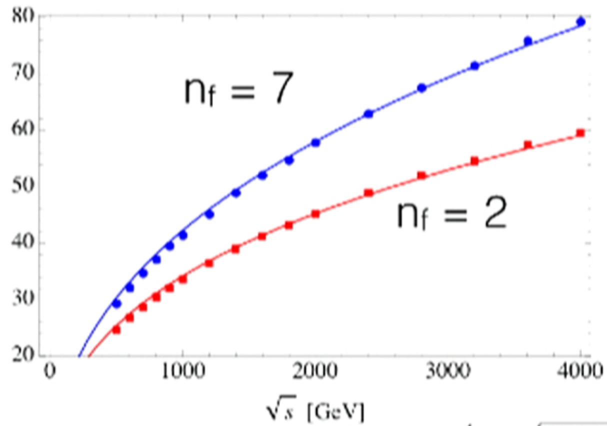
$$\text{girth} = \frac{1}{p_T^{\text{jet}}} \sum_i p_T^i \, \Delta R_i$$



p_T not in jets with $p_T > 200$ GeV

SIMULATION

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

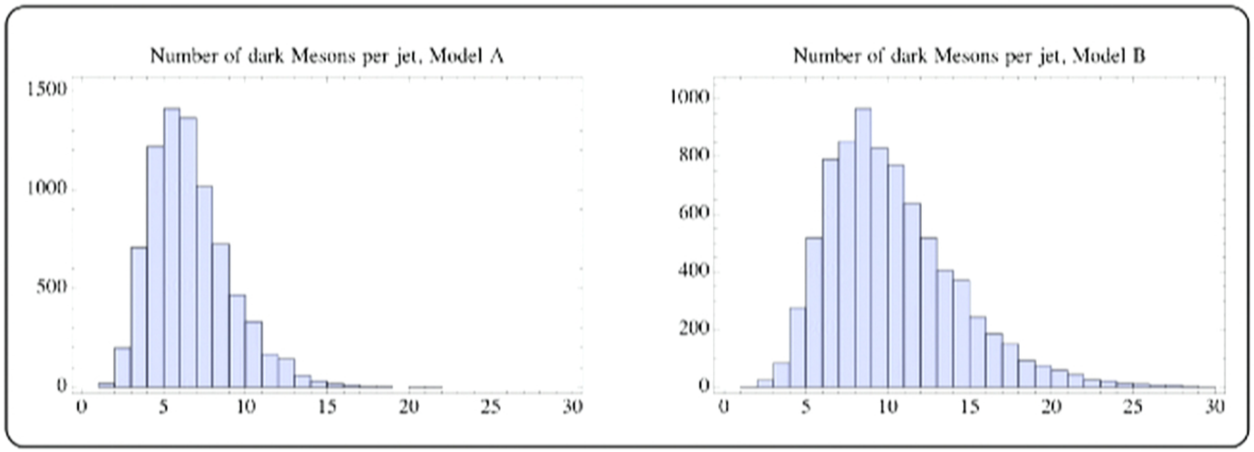


Ellis, Stirling, and Weber, 1996.

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

MESON MULTIPLICITY

Number of dark mesons in a jet.



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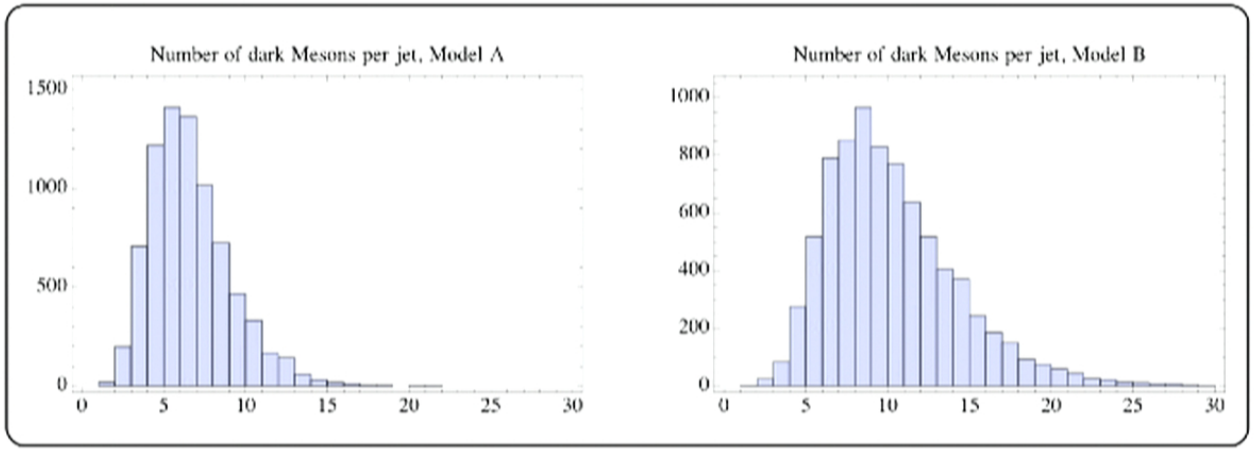


BENCHMARK MEDIATOR 2

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

Final state is

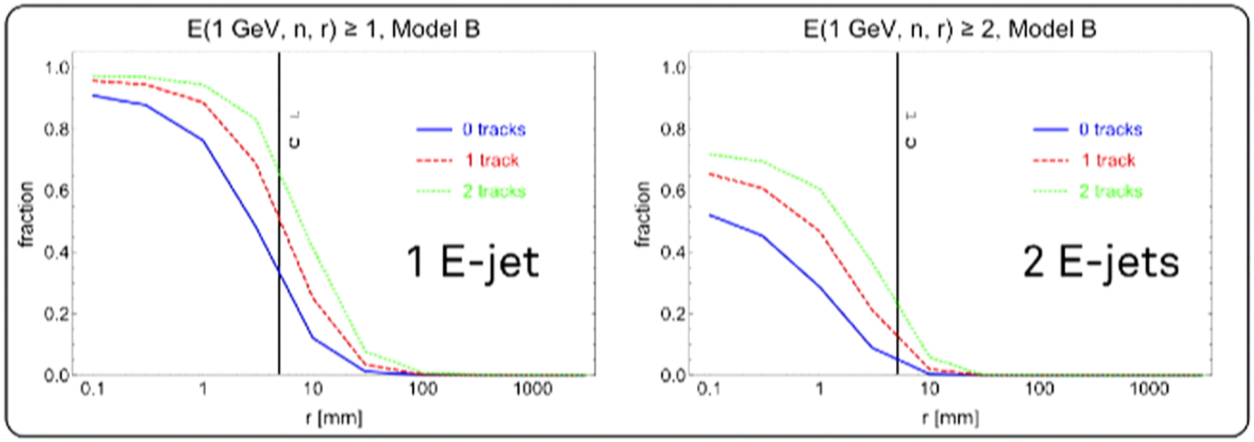
- 2 emerging jets

Cross section depends on couplings.

Work in progress.

SEARCH STRATEGY

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



$m_{\pi_d} = 2$ GeV $\qquad c\tau_{\pi_d} = 5$ 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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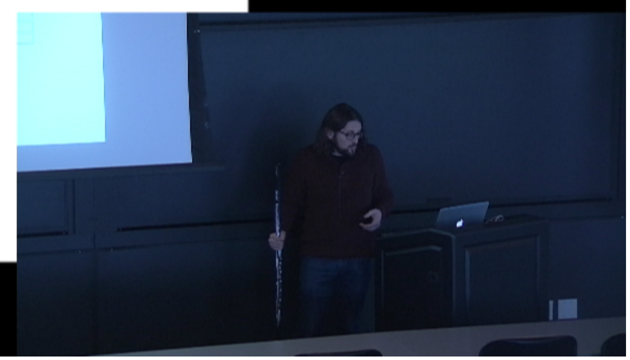
$E(1\,\text{GeV}, 0, 3\,\text{mm}) \geq 1$	4.1	4.1	54	67
$E(1\,\text{GeV}, 0, 3\,\text{mm}) \geq 2$	1.8	0.8	~ 0.08	~ 0.04
$E(1\,\text{GeV}, 0, 100\,\text{mm}) \geq 1$	1.7	$\lesssim 0.01$	11	15
$E(1\,\text{GeV}, 0, 100\,\text{mm}) \geq 2$	0.2	$\lesssim 0.01$	$\lesssim 0.02$	$\lesssim 0.02$

Requiring emerging jets changes the game.



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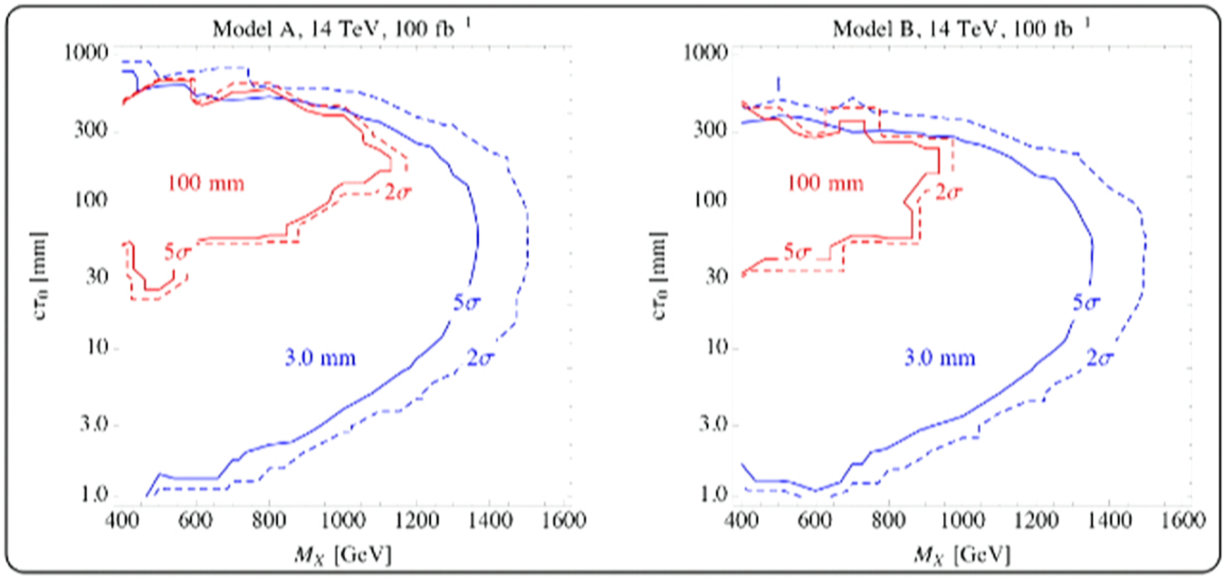
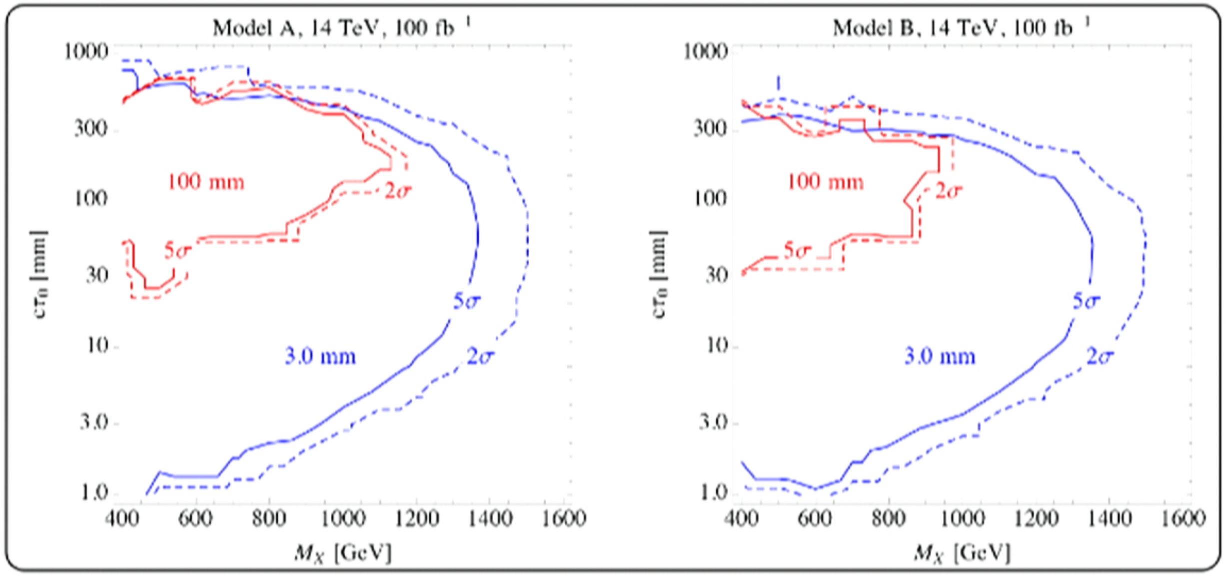
REACH



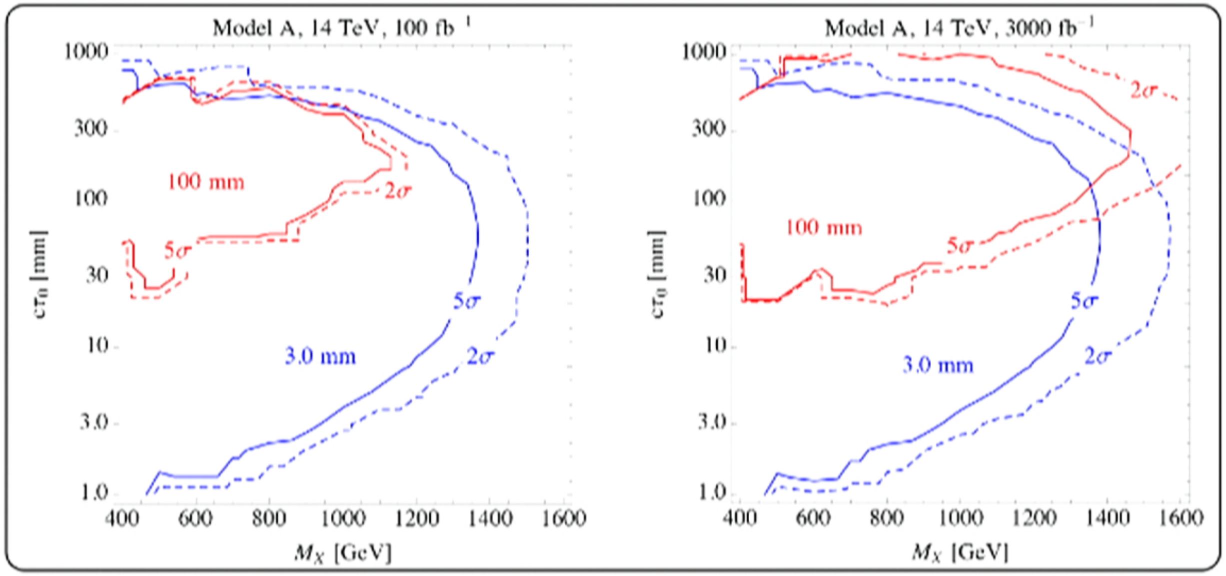
Assume 100% systematic error on background.

REACH



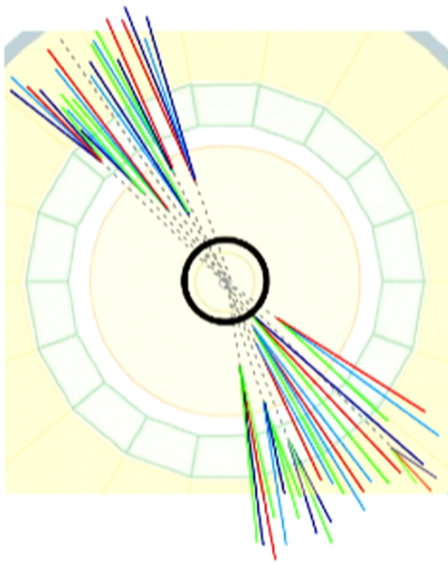
Assume 100% systematic error on background.

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.

ALTERNATIVE CUT FLOW

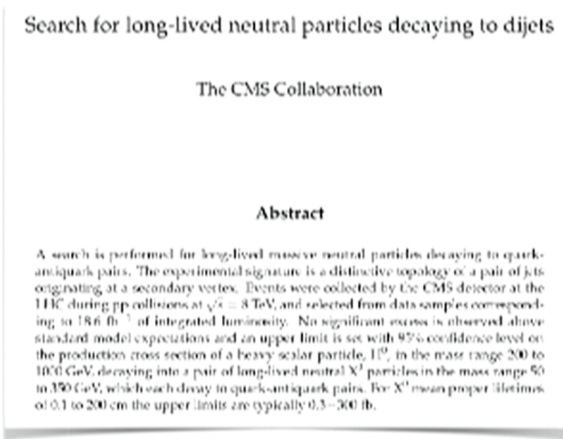
Cross sections in fb:

	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

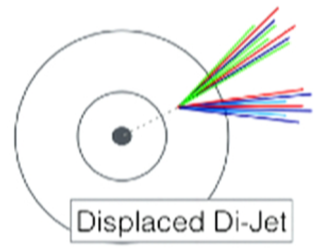


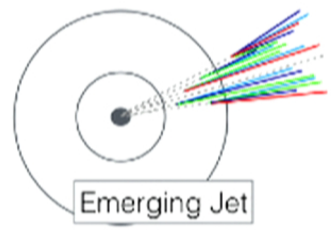
Search for long-lived neutral particles decaying to dijets

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.



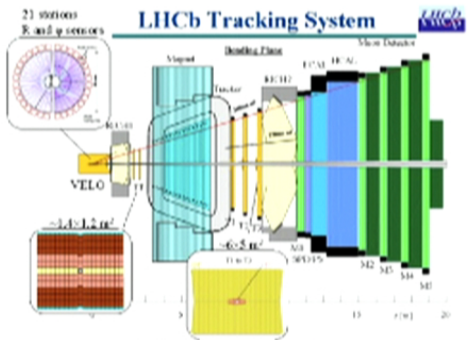


CMS Collaboration, Phys.Rev.D.91, 012017 (2015) [arXiv:1411.6530].

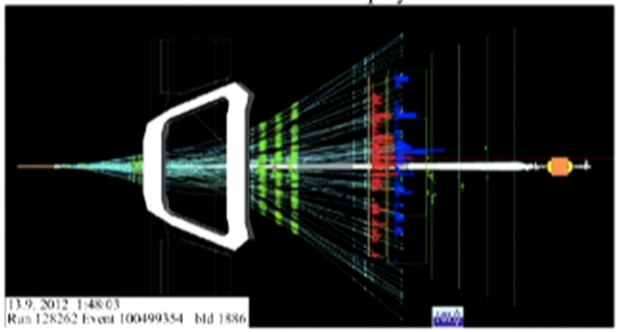
LHCb

LHCb has excellent tracking.

Limited coverage of event.



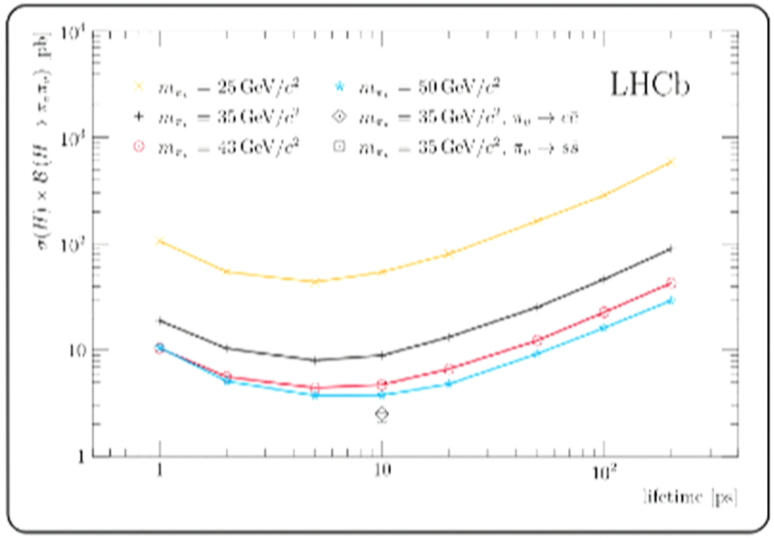
LHCb Event Display



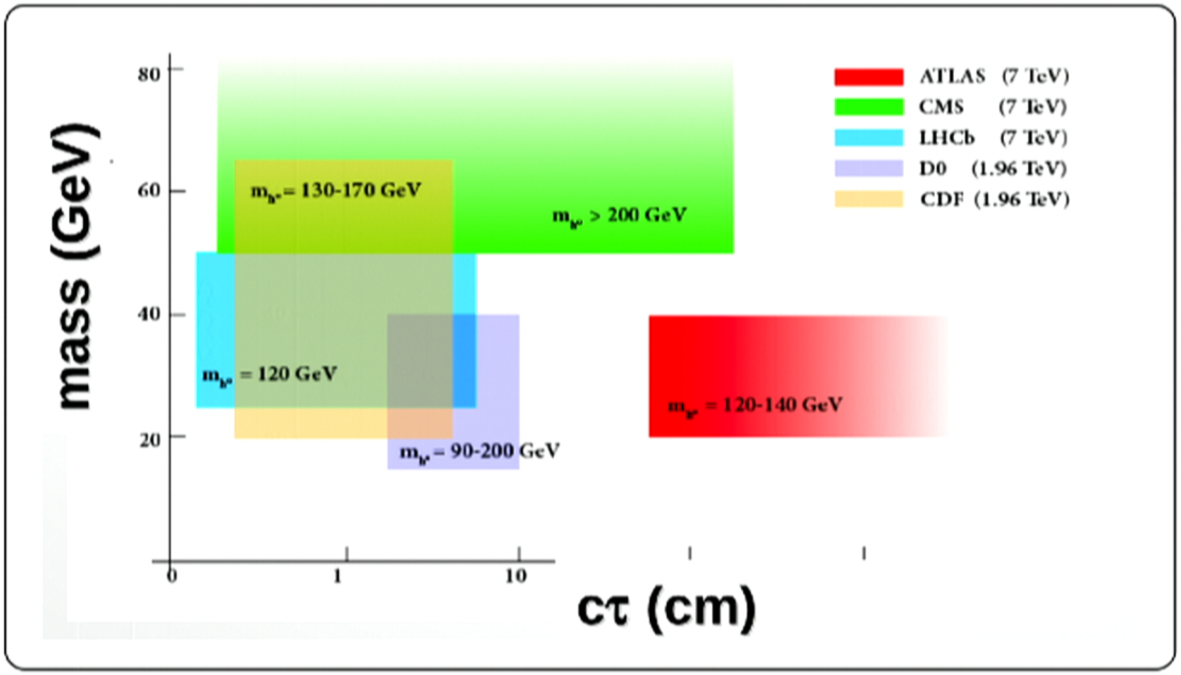
LHCb SEARCH

Again require to distinct jets with single vertex.

Insensitive to emerging pheno.



COMPLEMENTARITY



Talk by A. Hicheur, SILAFAE 2014

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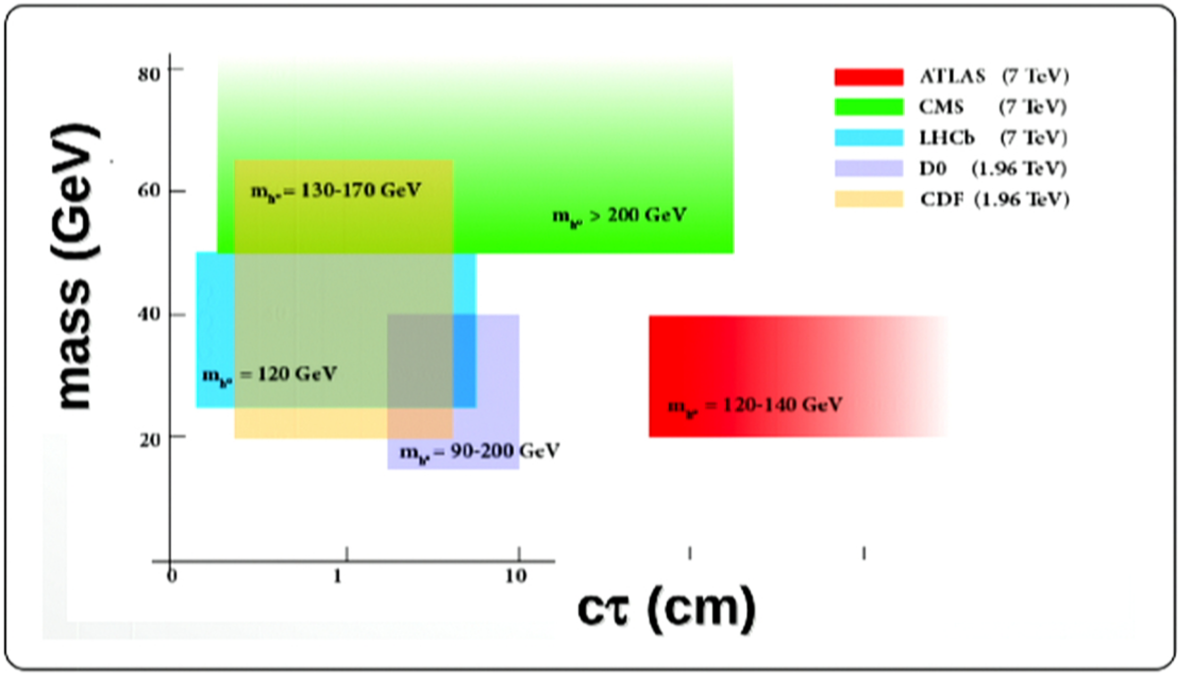
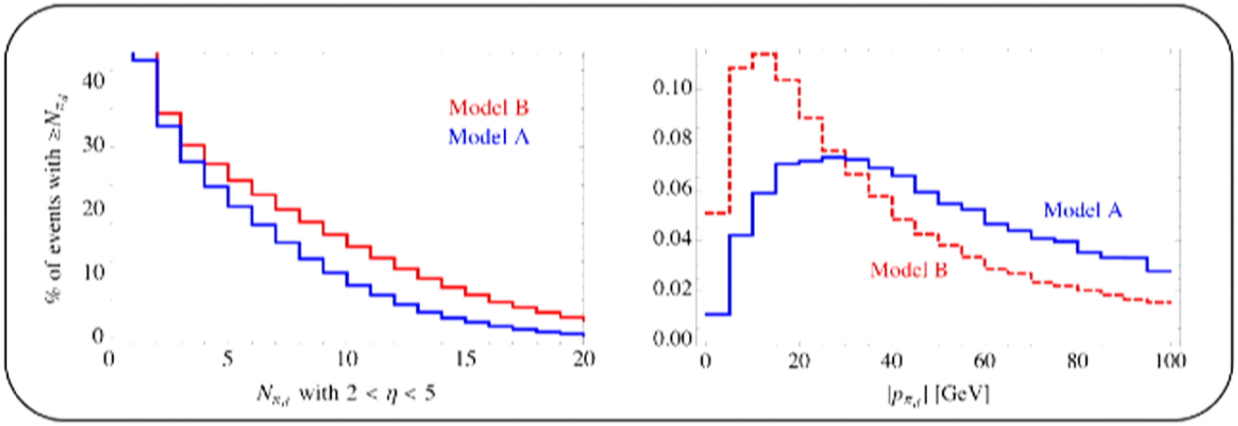
COMPLEMENTARITY



Talk by A. Hicheur, SILAFAE 2014

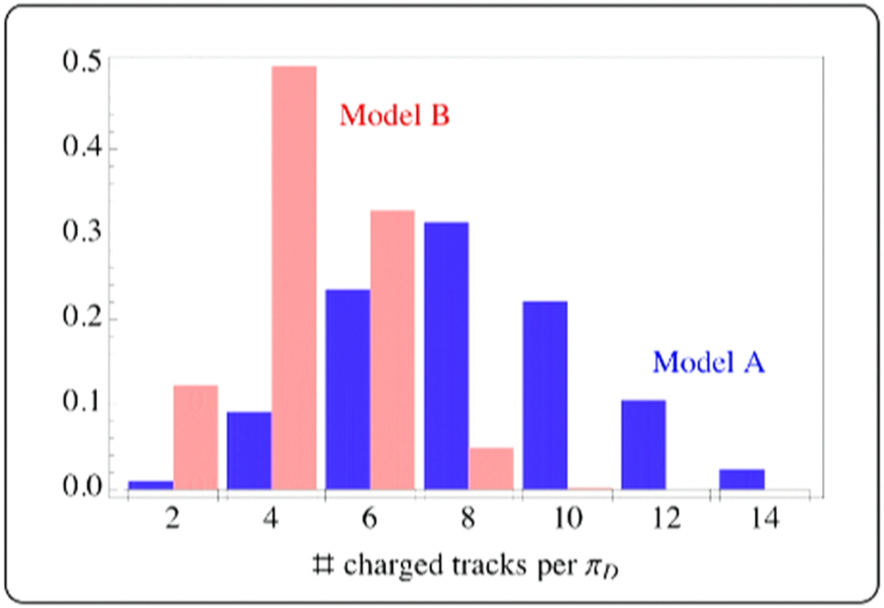
LHCb SENSITIVITY



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

~30% have > 2.

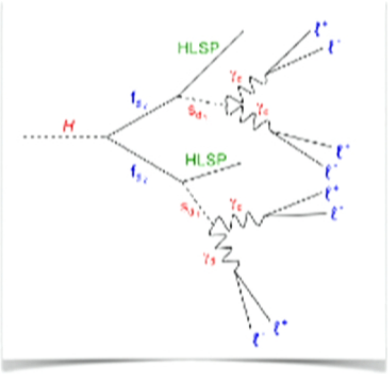
TRACK MULTIPLICTY



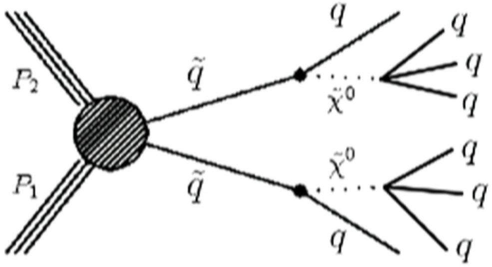
POWER OF EMERGING JET

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

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

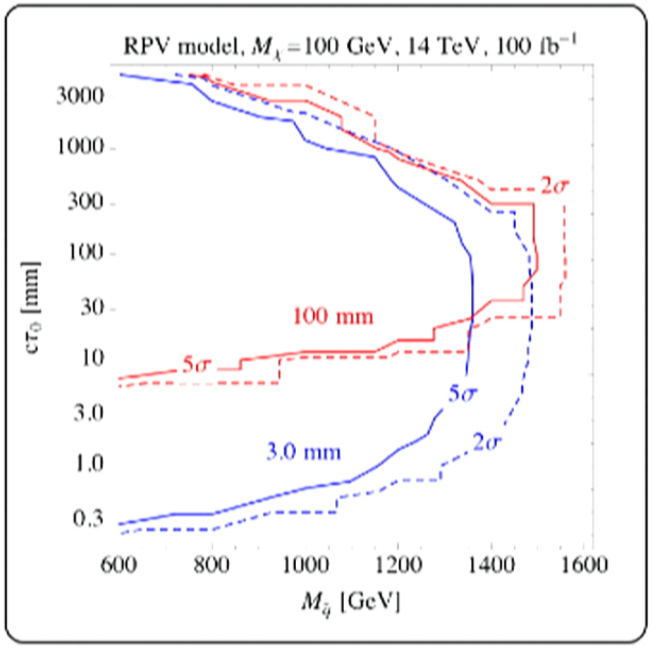


RPV NEUTRALINO



Squark pair production

Neutralino decay to 3 jets



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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.
- Opportunities for ATLAS, CMS, and LHCb. Exotics groups are investigating.

THANK YOU