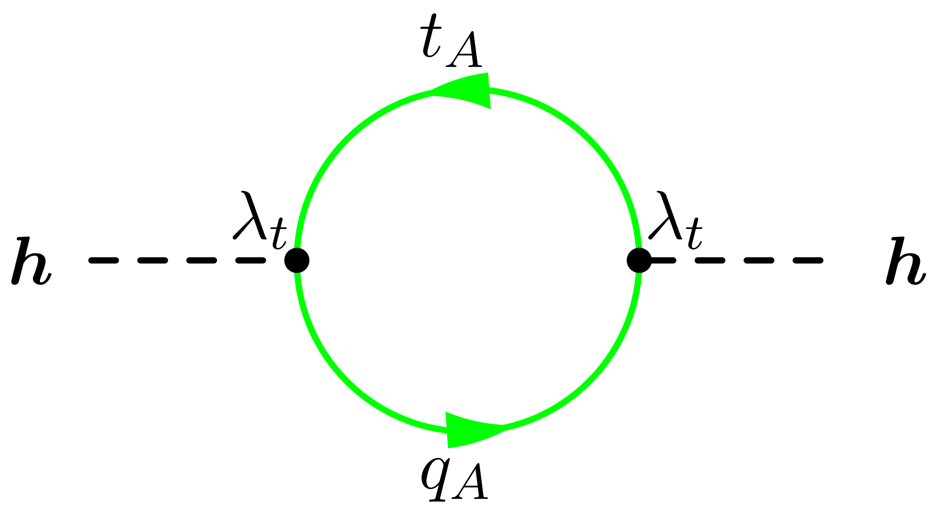
CONFINING HIDDEN SECTORS AT THE LHC AND BEYOND

In collaboration with Pedro Schwaller, Andreas Weiler, Dylan Linthorne, Wafia Bensalem, and Paul Archer-Smith.

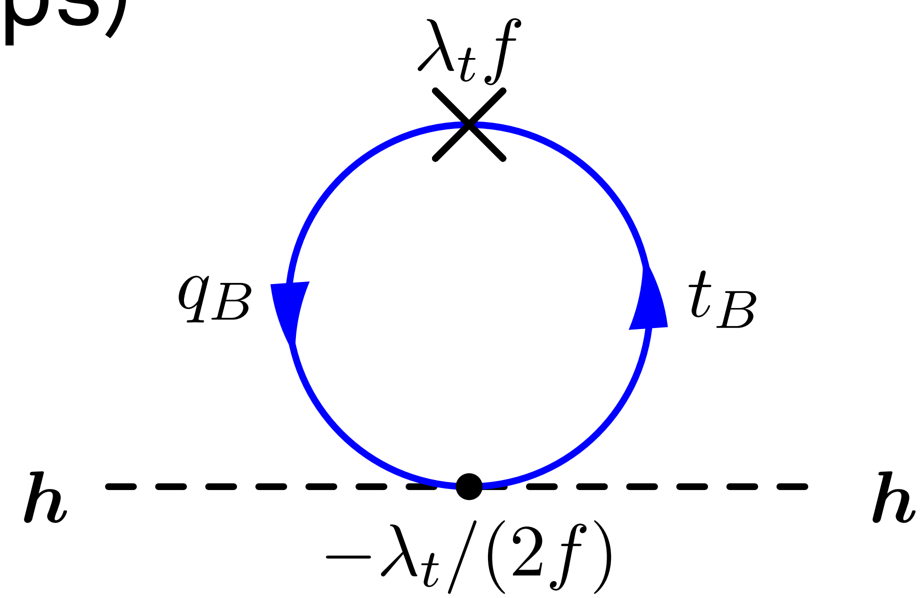
DANIEL STOLARSKI

MOTIVATION 1

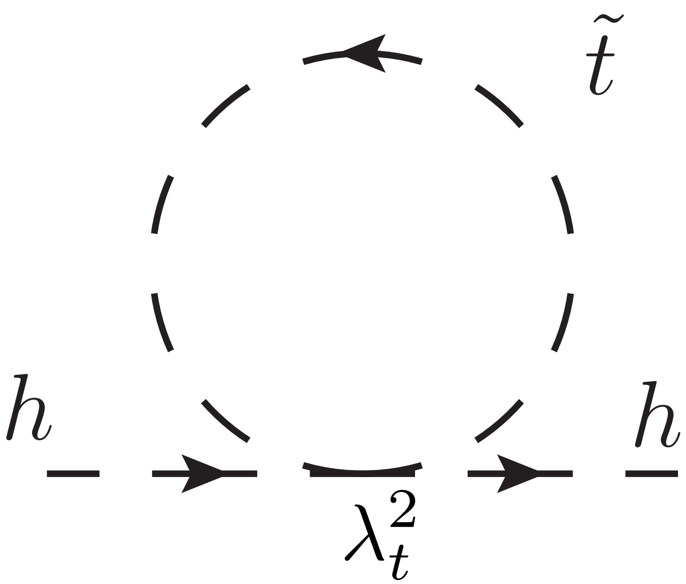
Gauge hierarchy problem:



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

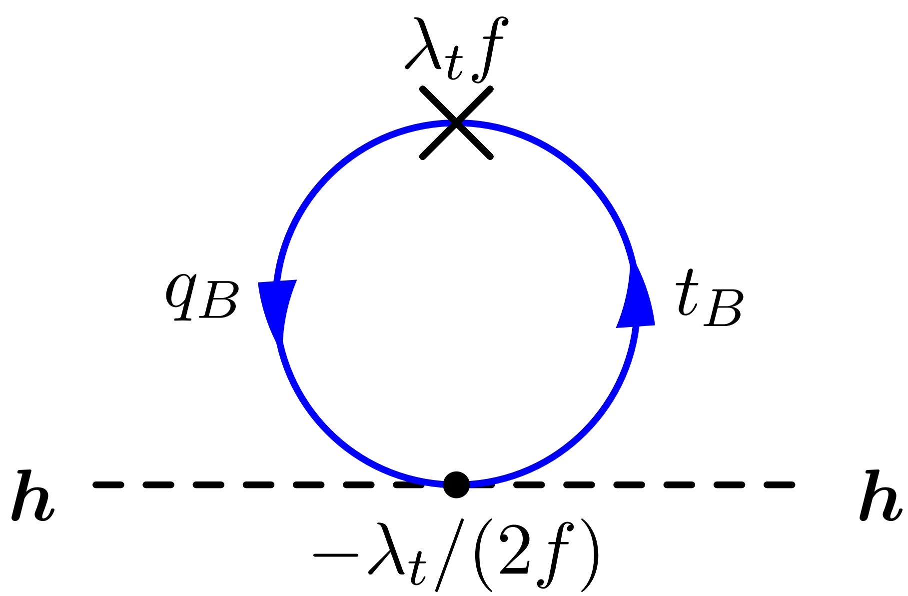


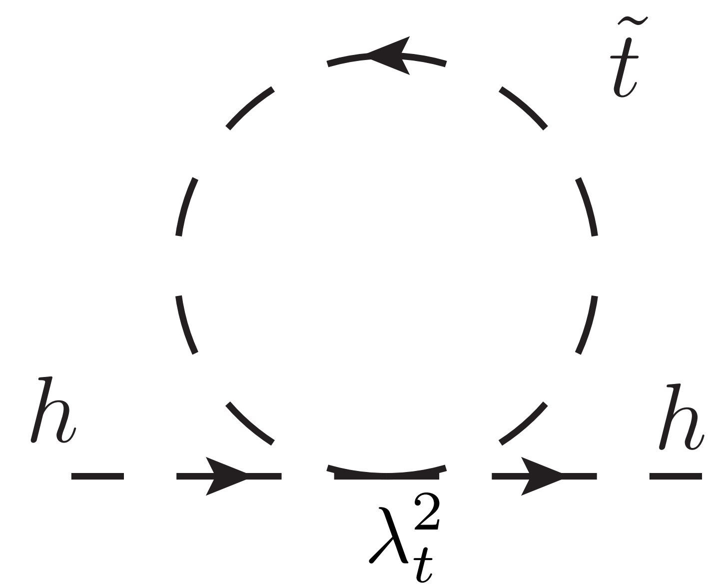
or



TWIN HIGGS/FOLDED SUSY

No! But still need factor of 3.



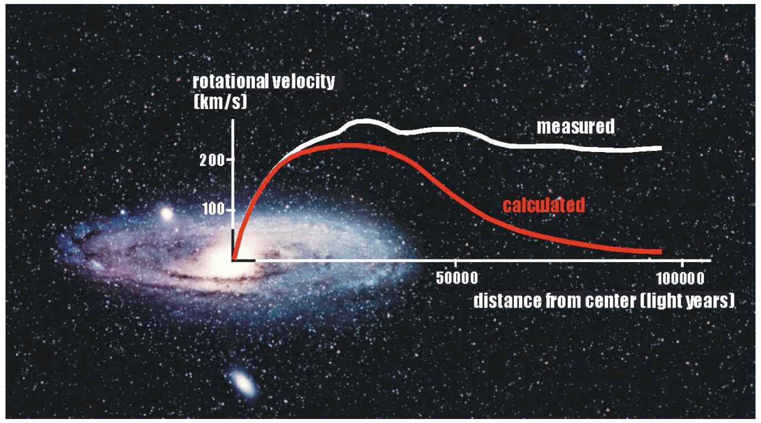


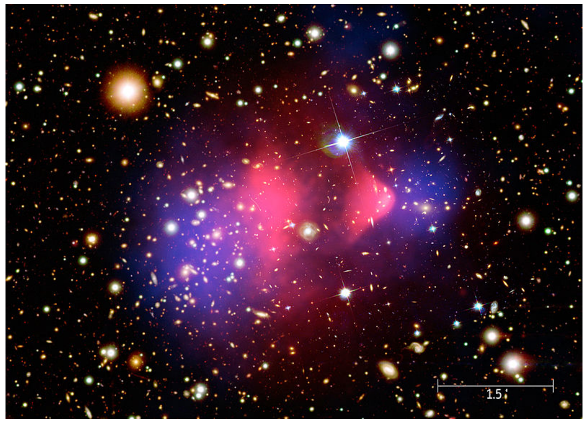
Chacko, Goh, Harnik, hep-ph/0506256.
Burdman, Chacko, Goh, Harnik, hep-ph/0609152.

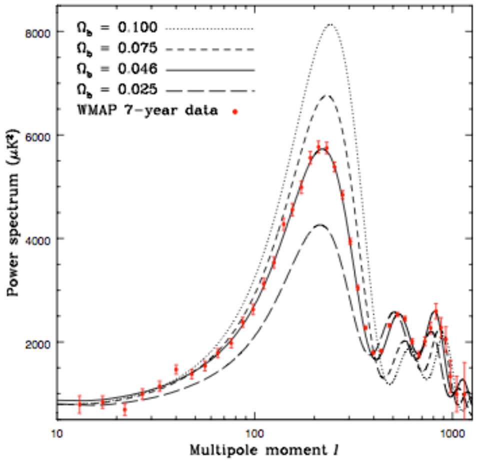
Most models have twin colour which confines around GeV scale (or slightly higher).

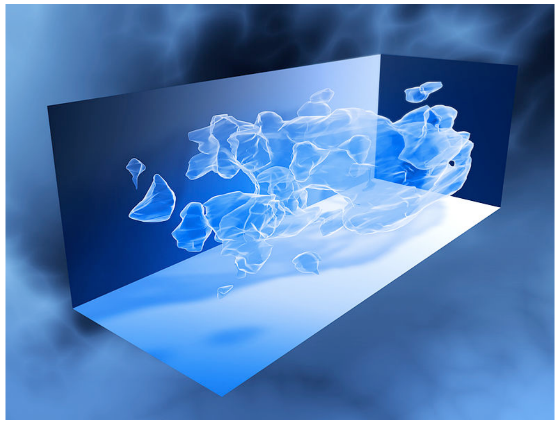
MOTIVATION 2

We have seen dark matter in the sky.

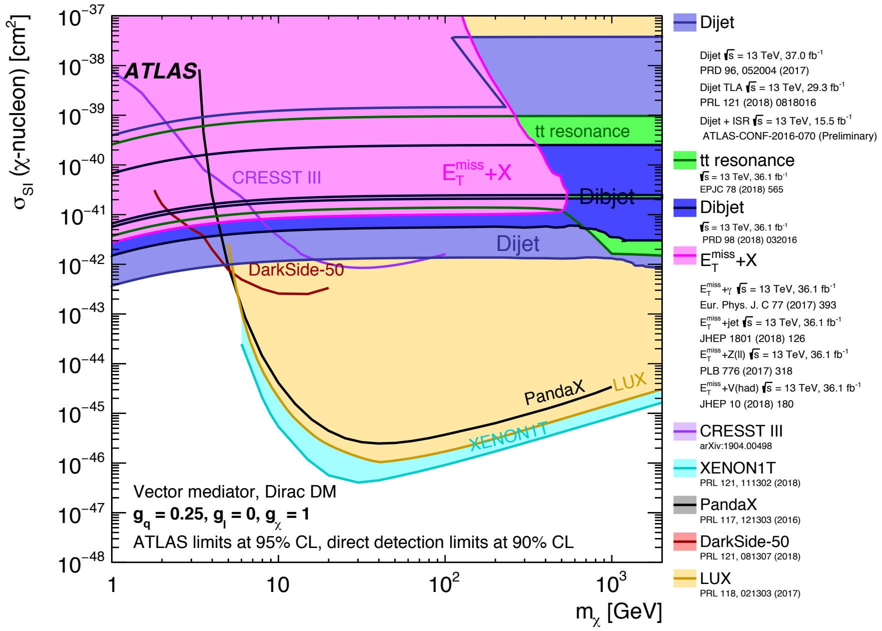


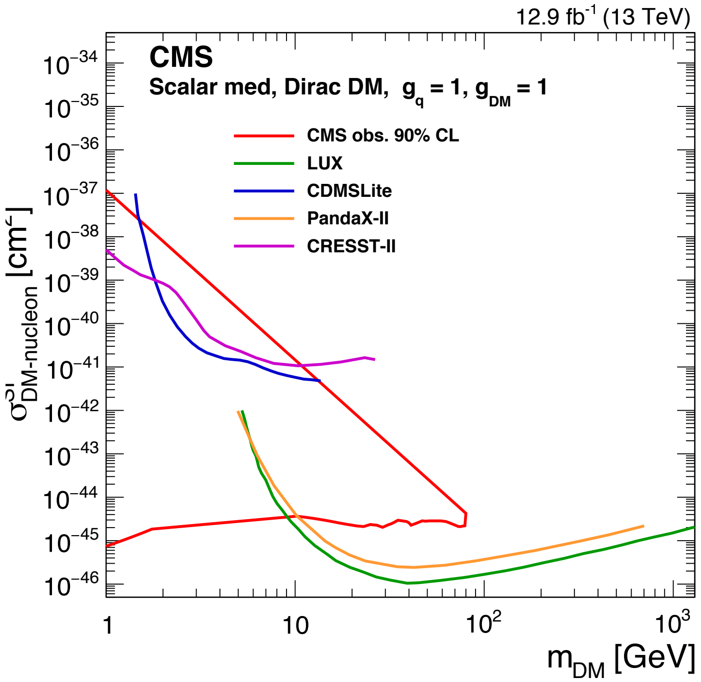


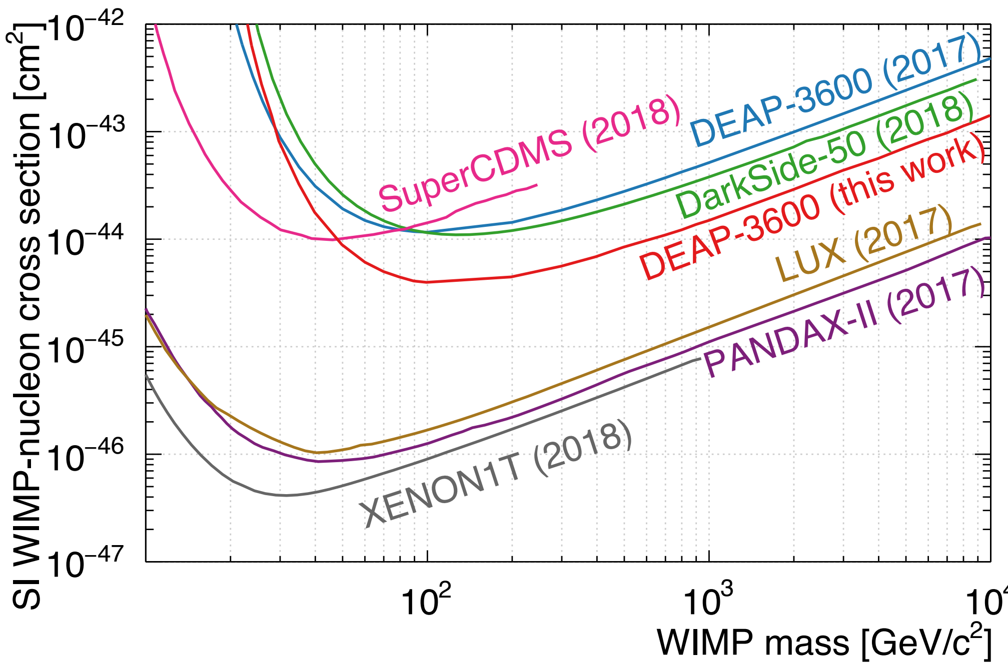




But not in the lab.







ASYMMETRIC DARK MATTER

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

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

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Controlled by complicated (known) QCD dynamics

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Unknown dynamics of baryogenesis

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?

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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]].

Agrawal, Kilic, Swaminathan, Trendafilova, Phys. Rev. D. 95 1 015031, (2017) [arXiv:1608.04745 [hep-ph]].

For a review see K. Petraki and R. R. Volkas, Int.J.Mod.Phys.A 28,

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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 we get both?

GETTING THE MASS

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

Controlled by complicated (known) QCD dynamics

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

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GETTING THE MASS

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QCD like

?

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?

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DARK QCD

Bai, Schwaller, PRD 13.

Λ_{dQCD}

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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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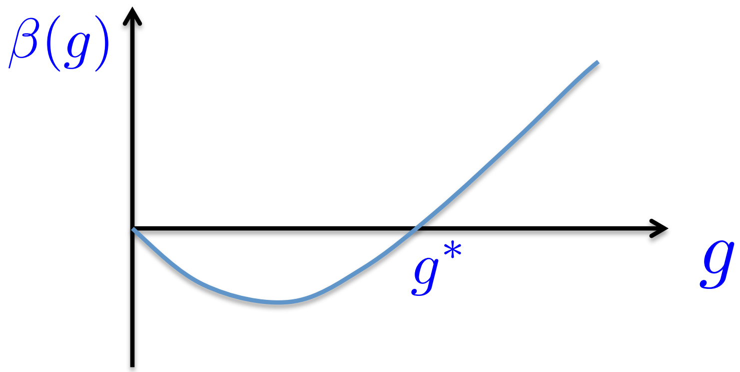
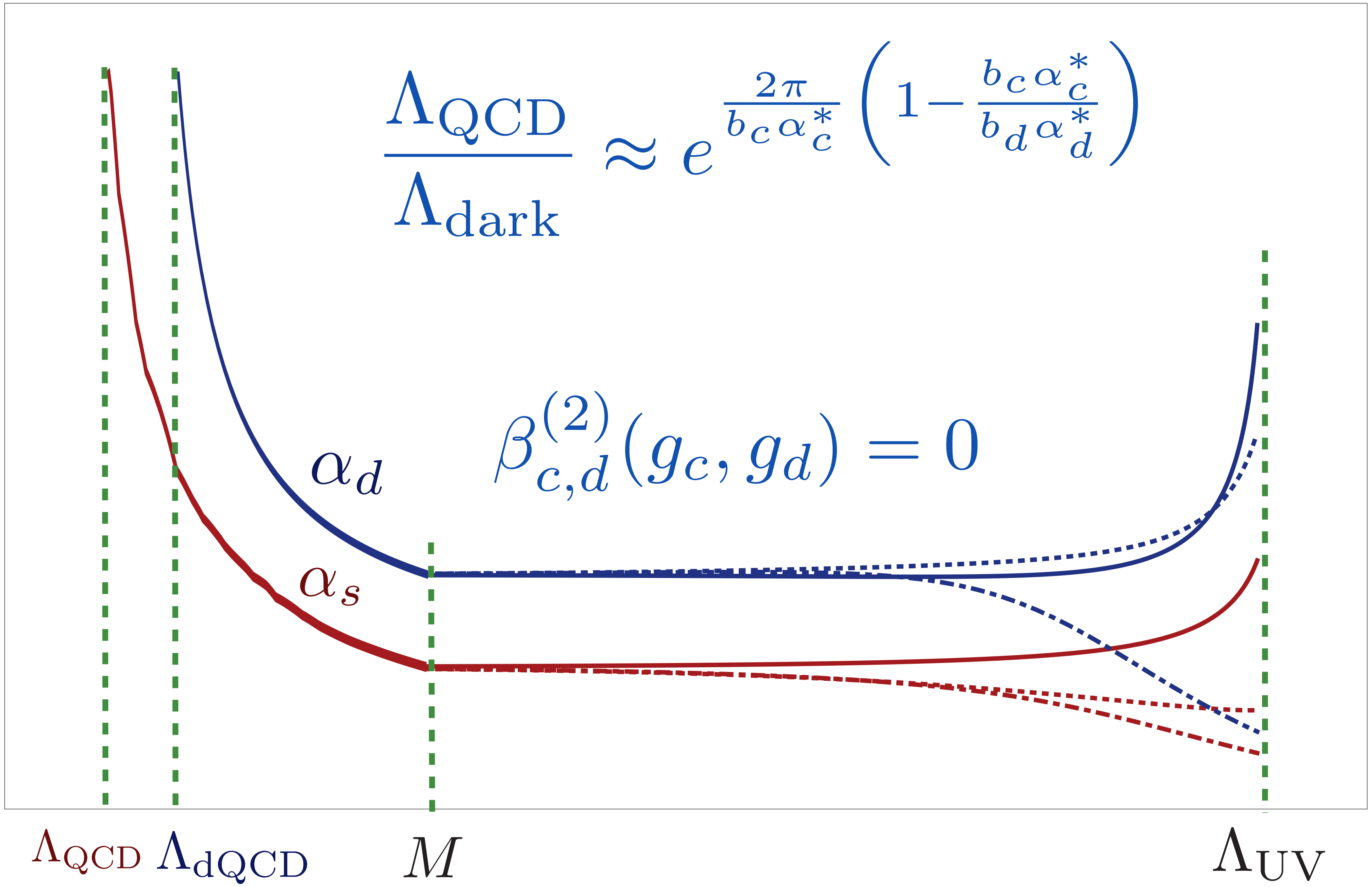
Search for model with perturbative fixed point.

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



SCALES ARE RELATED



Bai, Schwaller, PRD 13.

SCALES ARE RELATED

Example

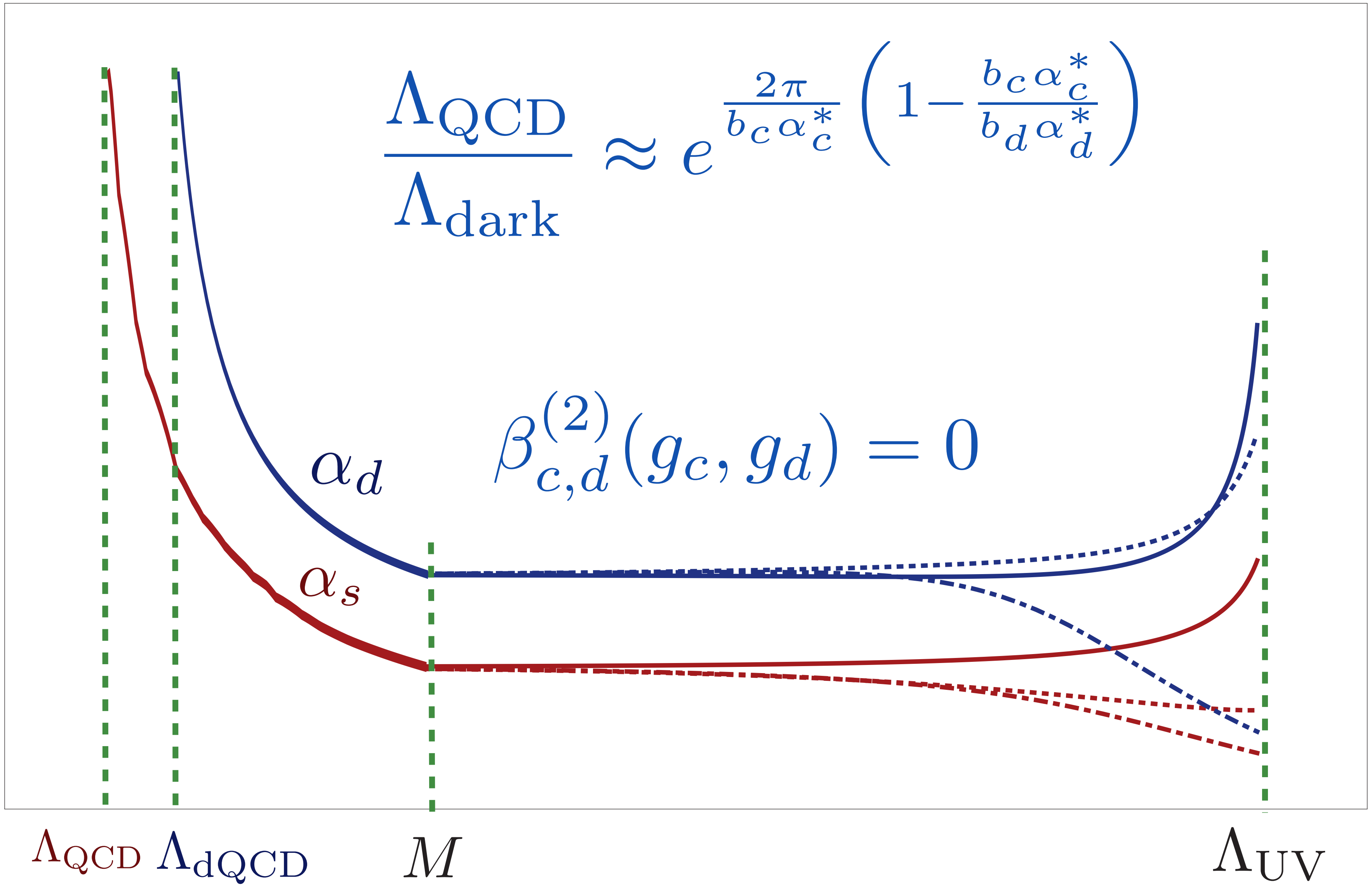
Fixed points:

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

$M = 870\ GeV$

DM mass:

$M_{DM} \approx 3.5\ GeV$



Bai, Schwaller, PRD 13.

DARK MATTER

Can co-generate DM and baryon asymmetry.

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

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$d_i \rightarrow$ SM quark

$\Phi \rightarrow$ bifundamental scalar

$\overline{Q} \rightarrow$ dark quark

DARK MATTER

Can co-generate DM and baryon asymmetry.

$$\underbrace{\overline{Q}}_{\text{dark quark}}\ \underbrace{\Phi}_{\text{bifundamental scalar}}\ \underbrace{d_i}_{\text{SM quark}}$$

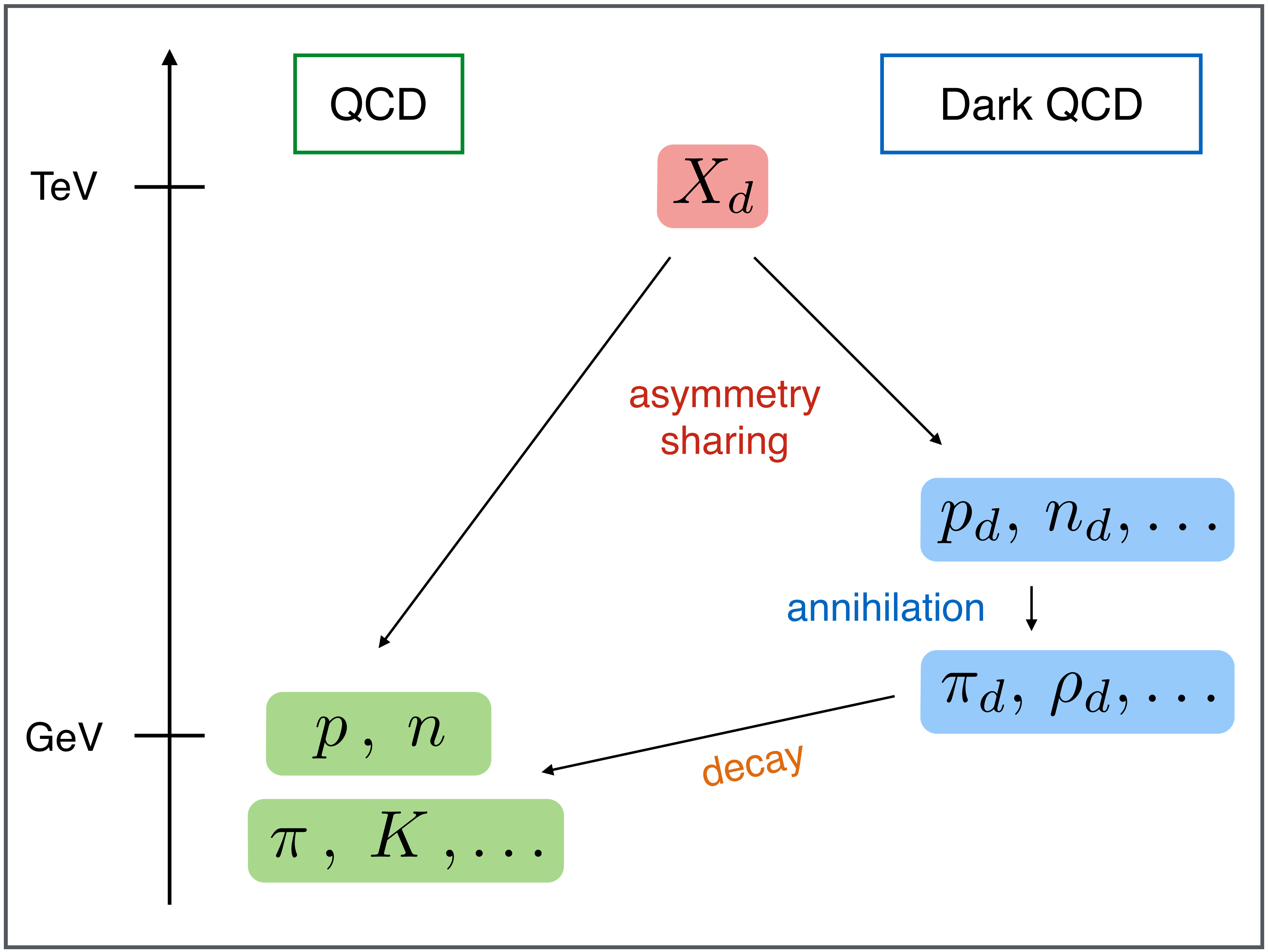
Dark matter is strongly self interacting — potentially solves various problems of cold dark matter.

- 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 flavours.

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

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

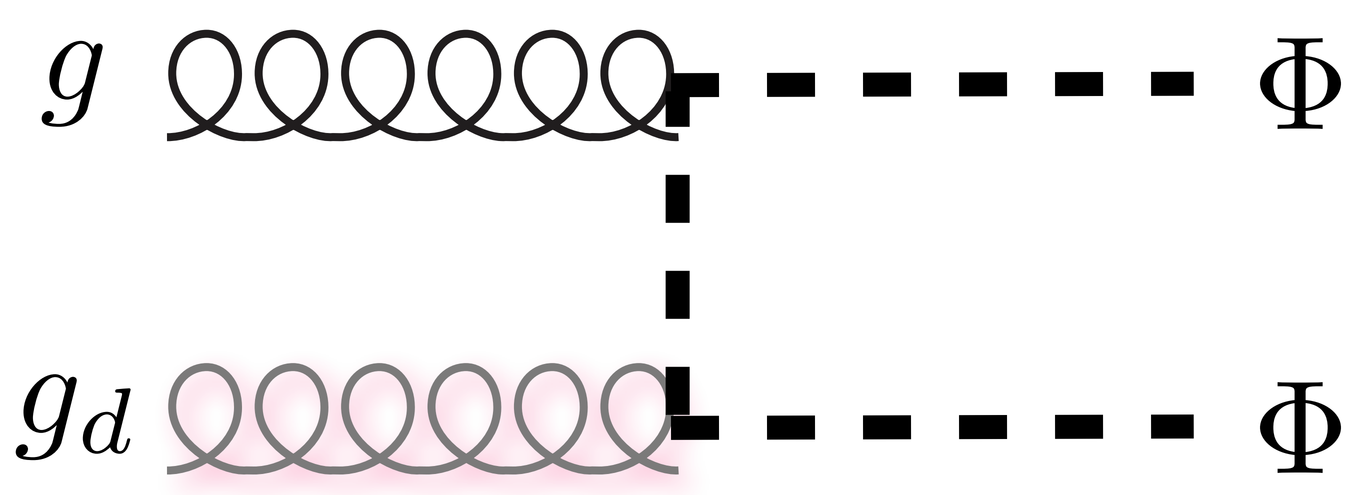
Decays on collider times

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 colour and dark colour.

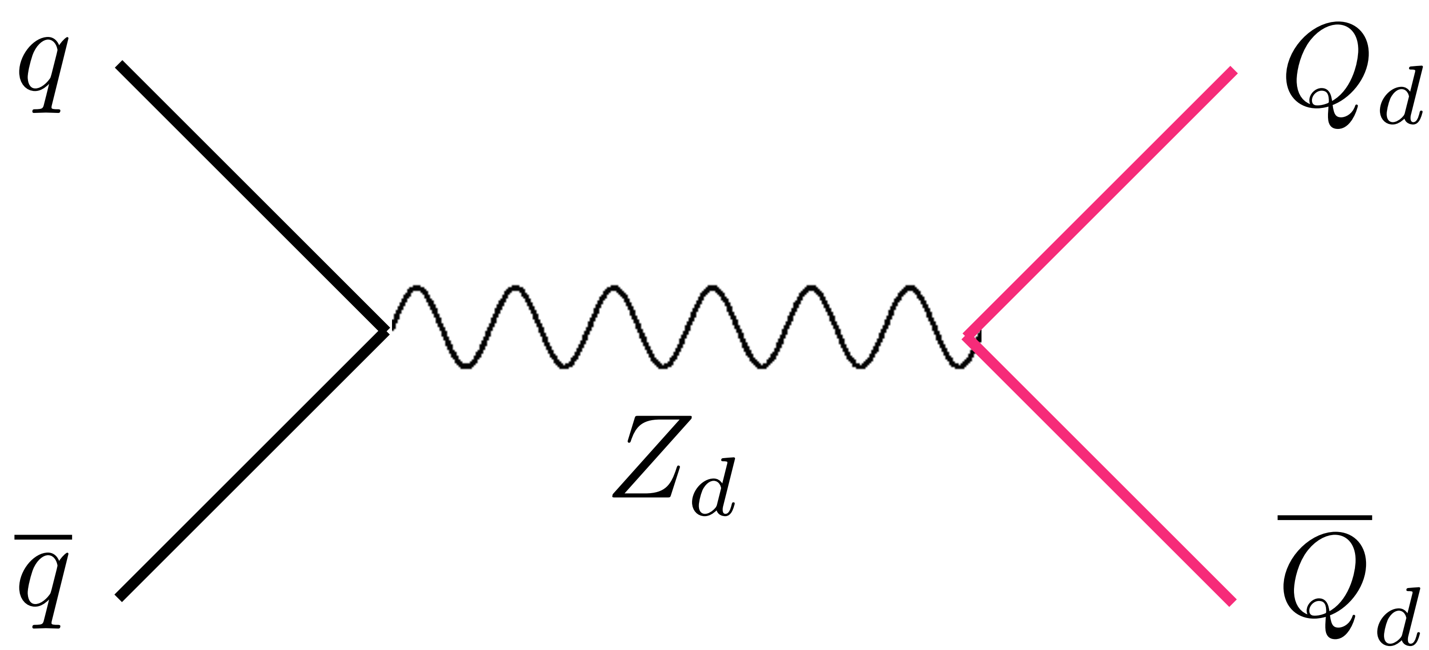


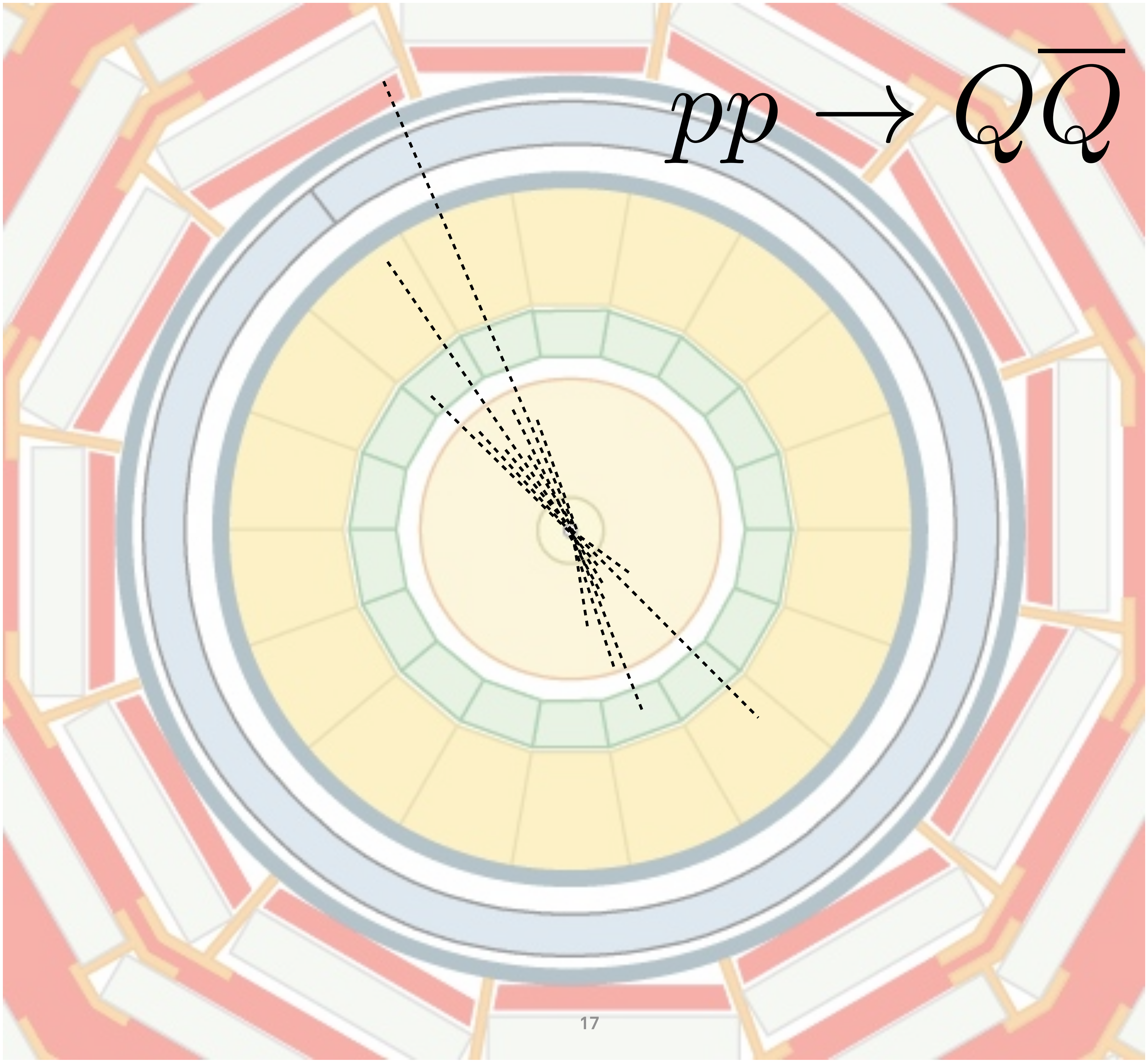
MEDIATORS

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.



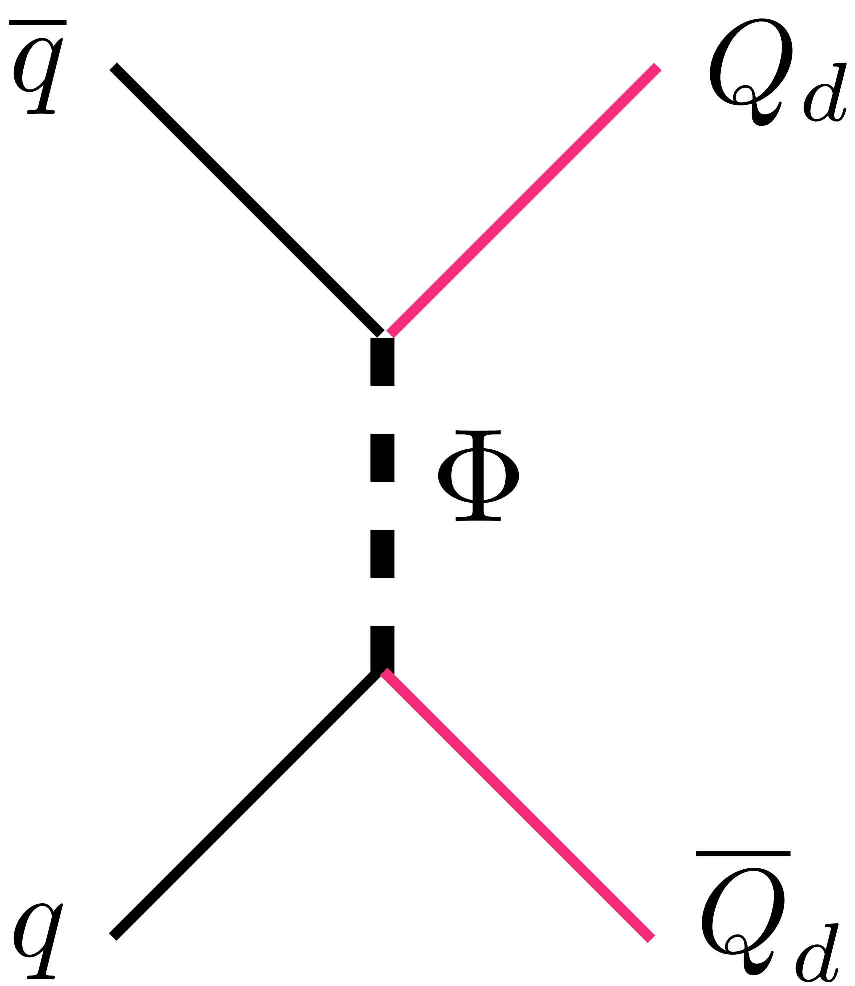


$$pp \to Q\overline{Q}$$

PION DECAY

Operator used to generate asymmetry mediates decay:

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



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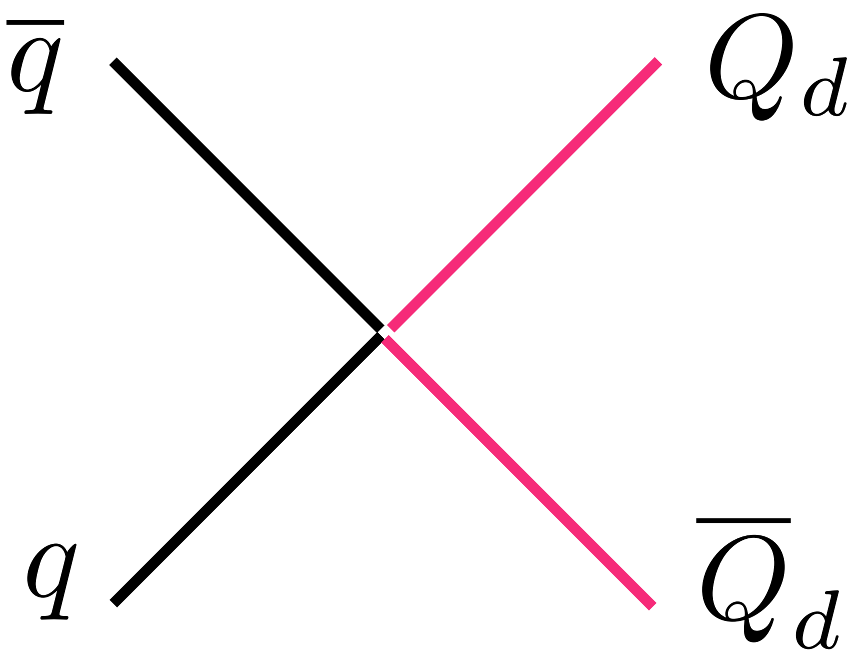
Integrate out Φ



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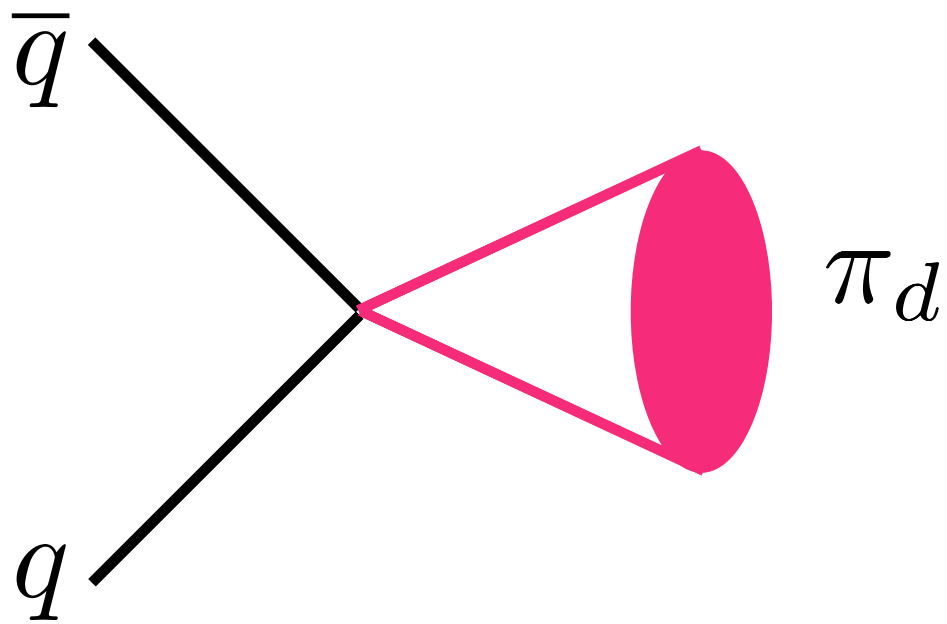
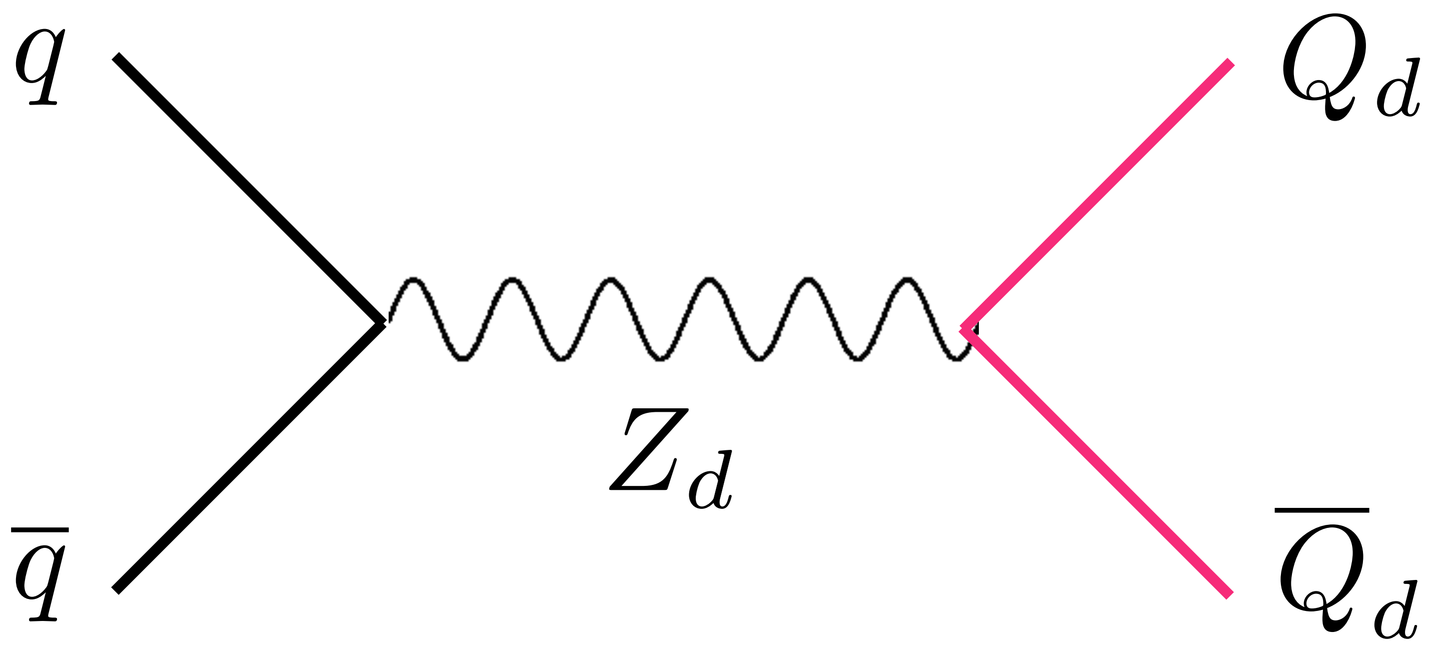


Dark pion decays to quarks

PION DECAY

Same story for Z_d model:



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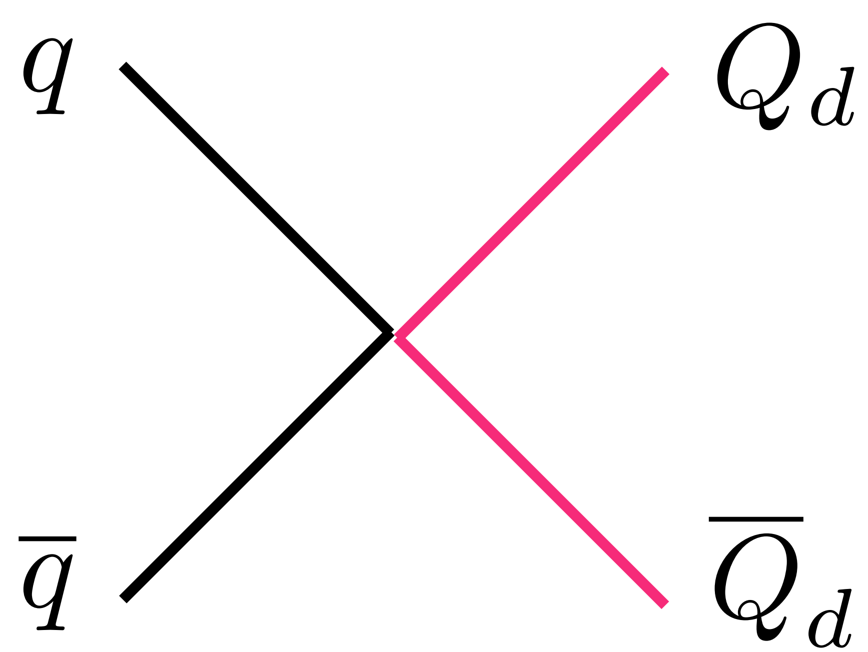

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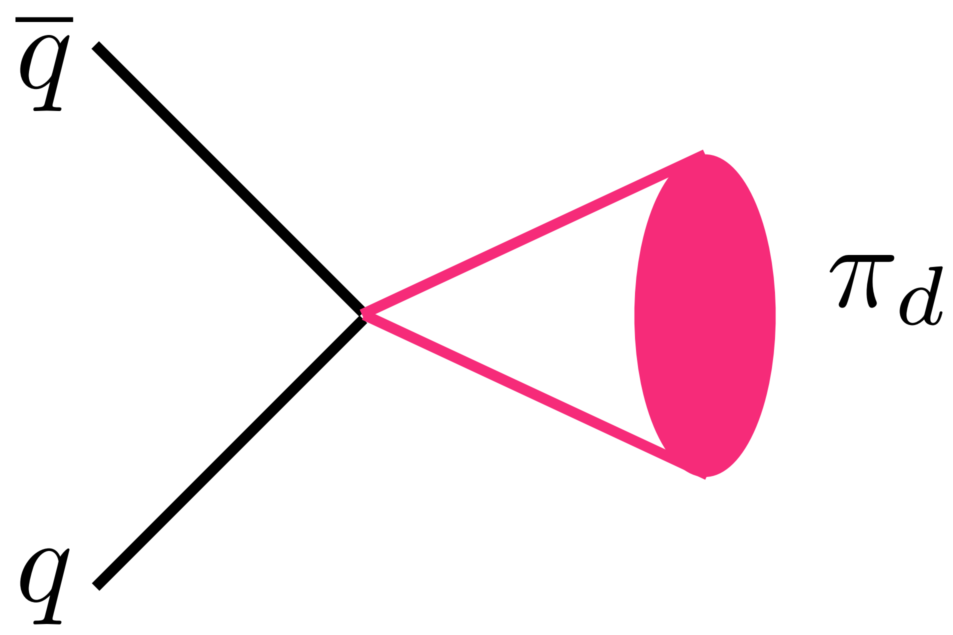
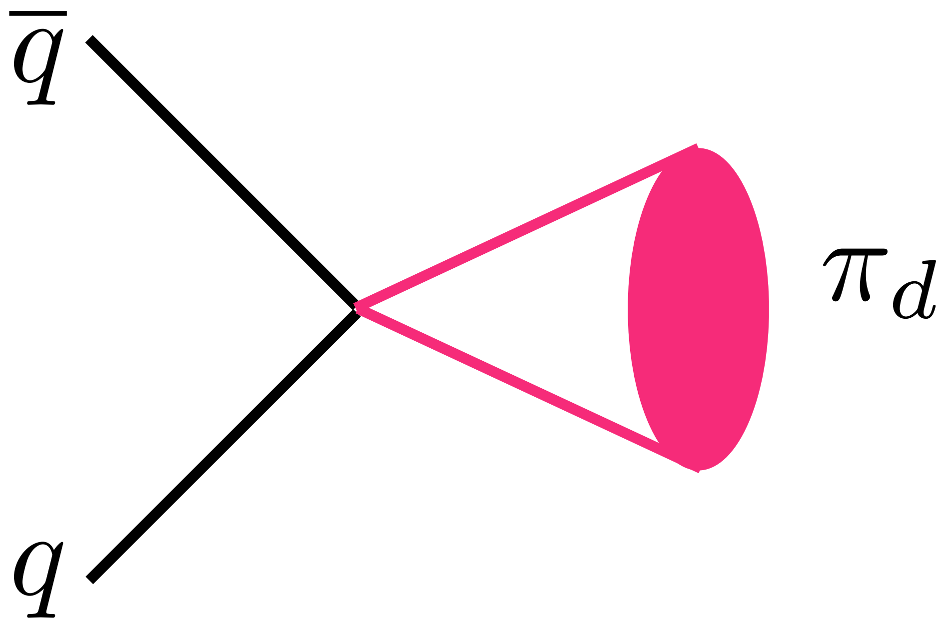


DECAY LENGTH

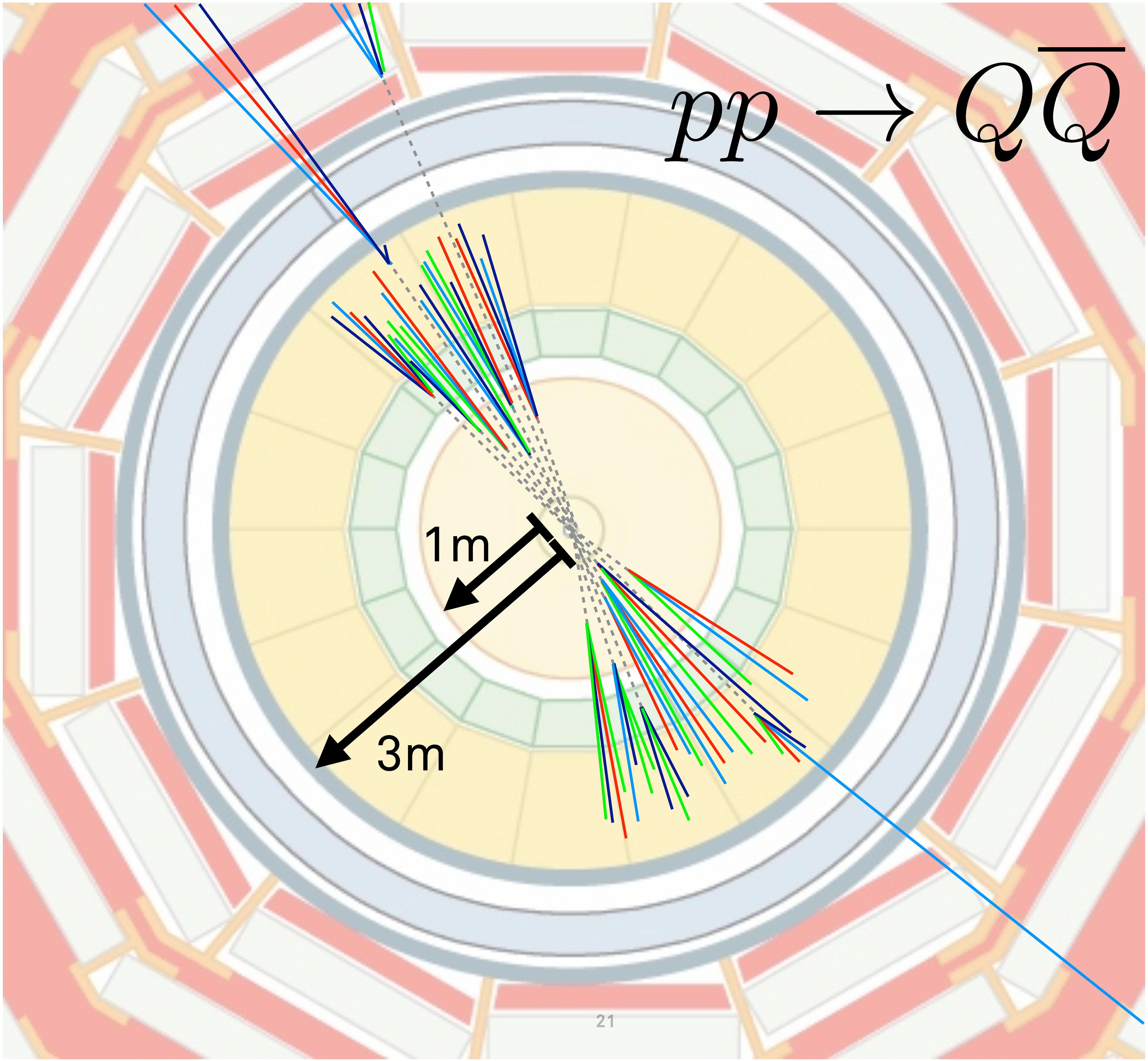


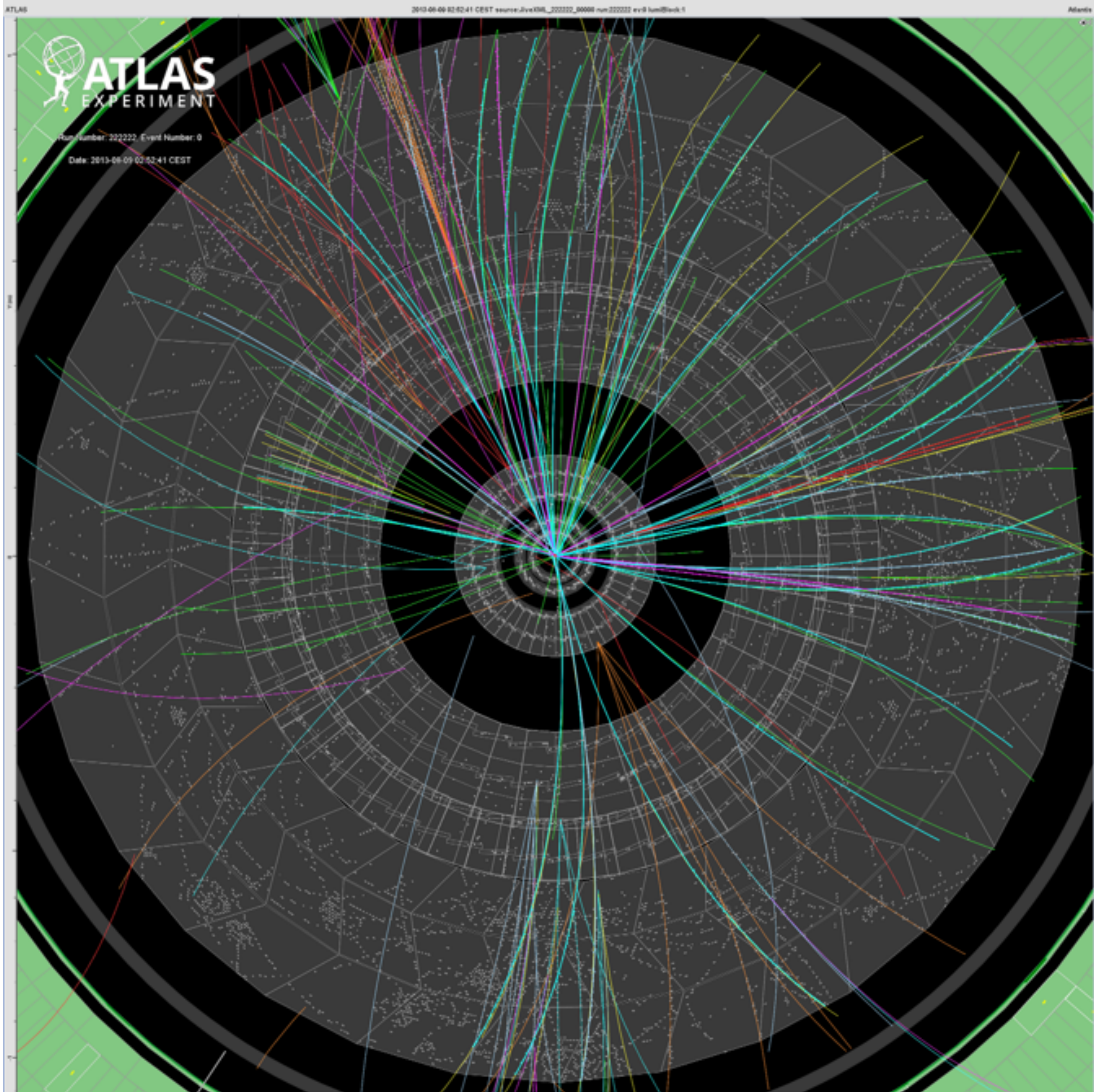
$$\frac{1}{M_X^2}\overline{Q}\gamma_\mu Q\,\bar{d}_R\gamma^\mu d_R$$

Can use (dark) chiral Lagrangian to estimate:

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

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


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



James Beacham, ATLAS Dark Sector Workshop, Cosenza, Italy, Feb 10, 2016.

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!

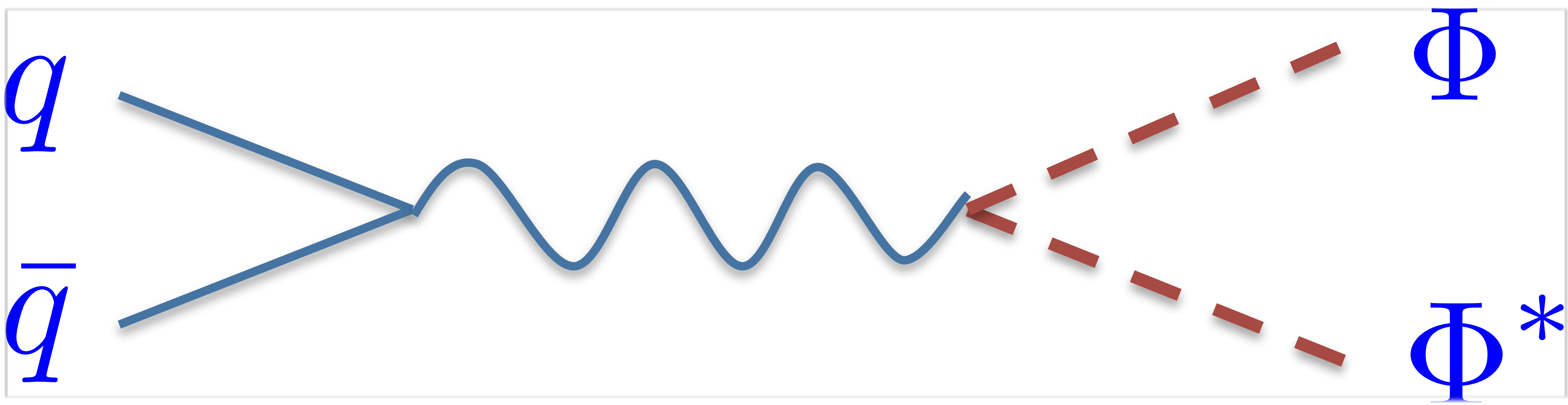
Carloni, Sjorstrand, 2010.

Carloni, Rathsman, Sjorstrand, 2011.

We had to modify Pythia to make hidden sector more realistic, our code is now implemented (v > 8.226).

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

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

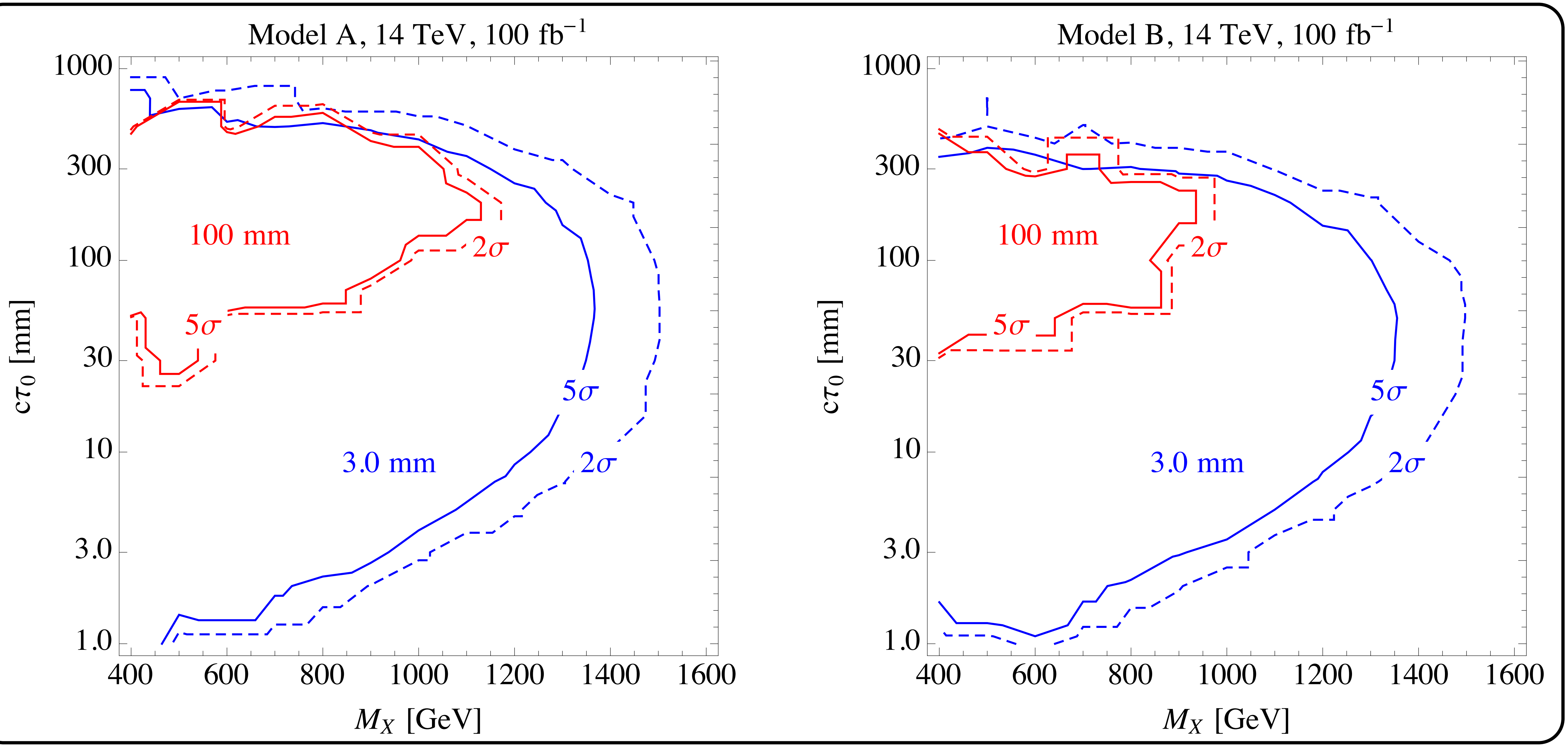
Final state is

- 2 emerging jets

Cross section depends on couplings.

I will come back to this scenario.

PROJECTED REACH



Schwaller, DS, Weiler, arXiv:1502.0409.

DEDICATED CMS SEARCH

Journal of High Energy Physics

February 2019, 2019:179 | Cite as

Search for new particles decaying to a jet and an emerging jet

Authors | Authors and affiliations

The CMS collaboration, A. M. Sirunyan, A. Tumasyan, W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth, V. M. Ghete, J. Hrubec, show 2286 more

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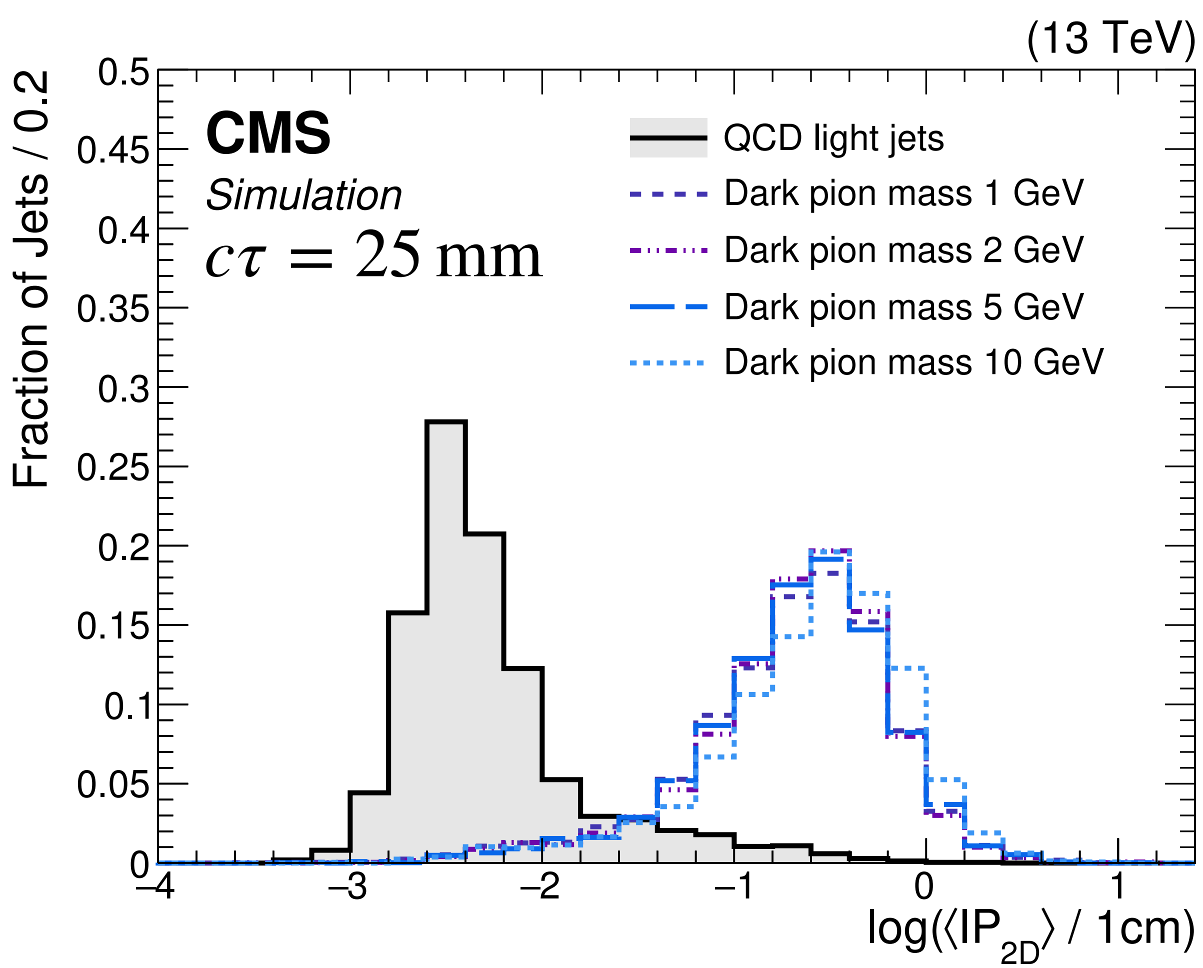
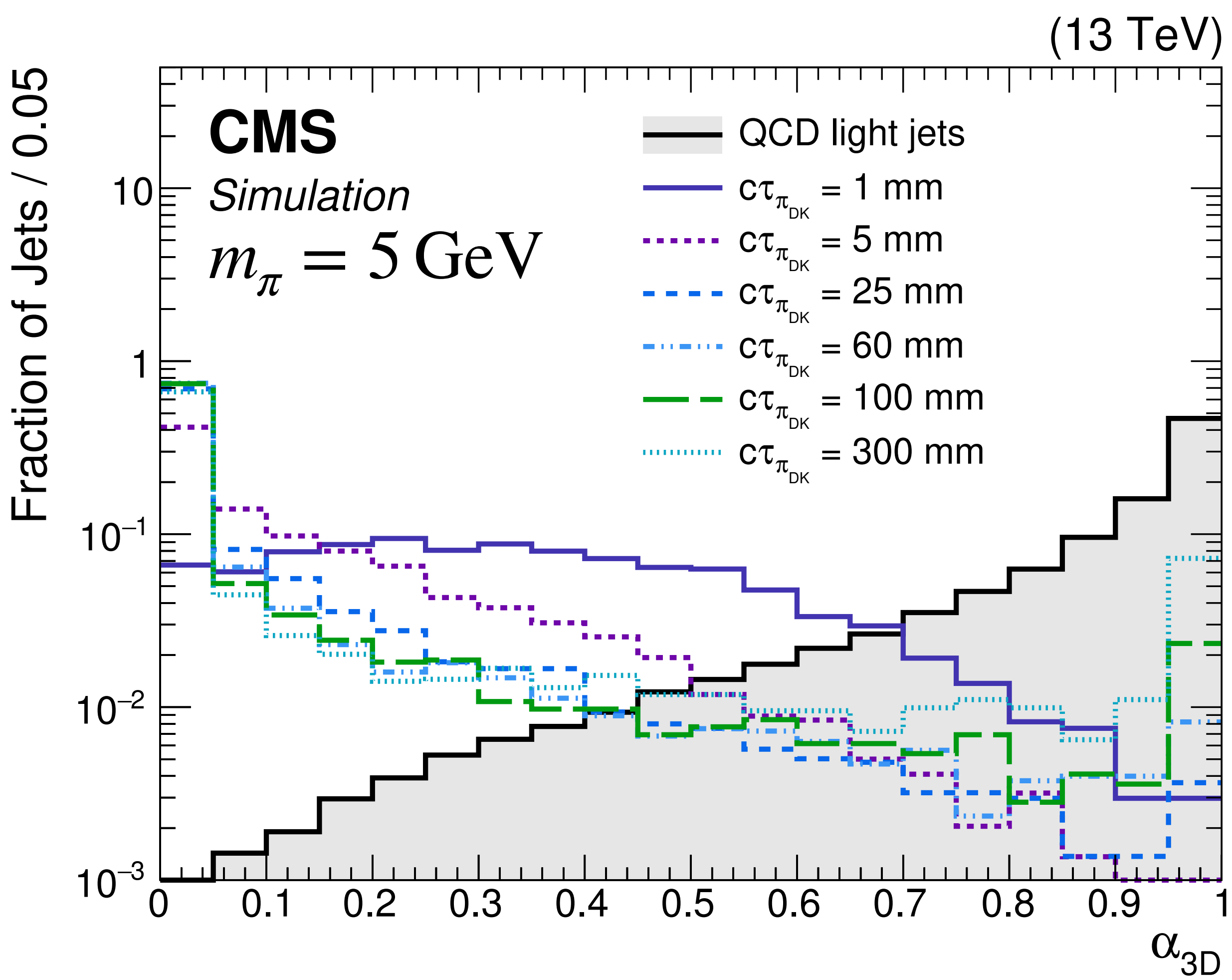
DISCRIMINATING VARIABLES

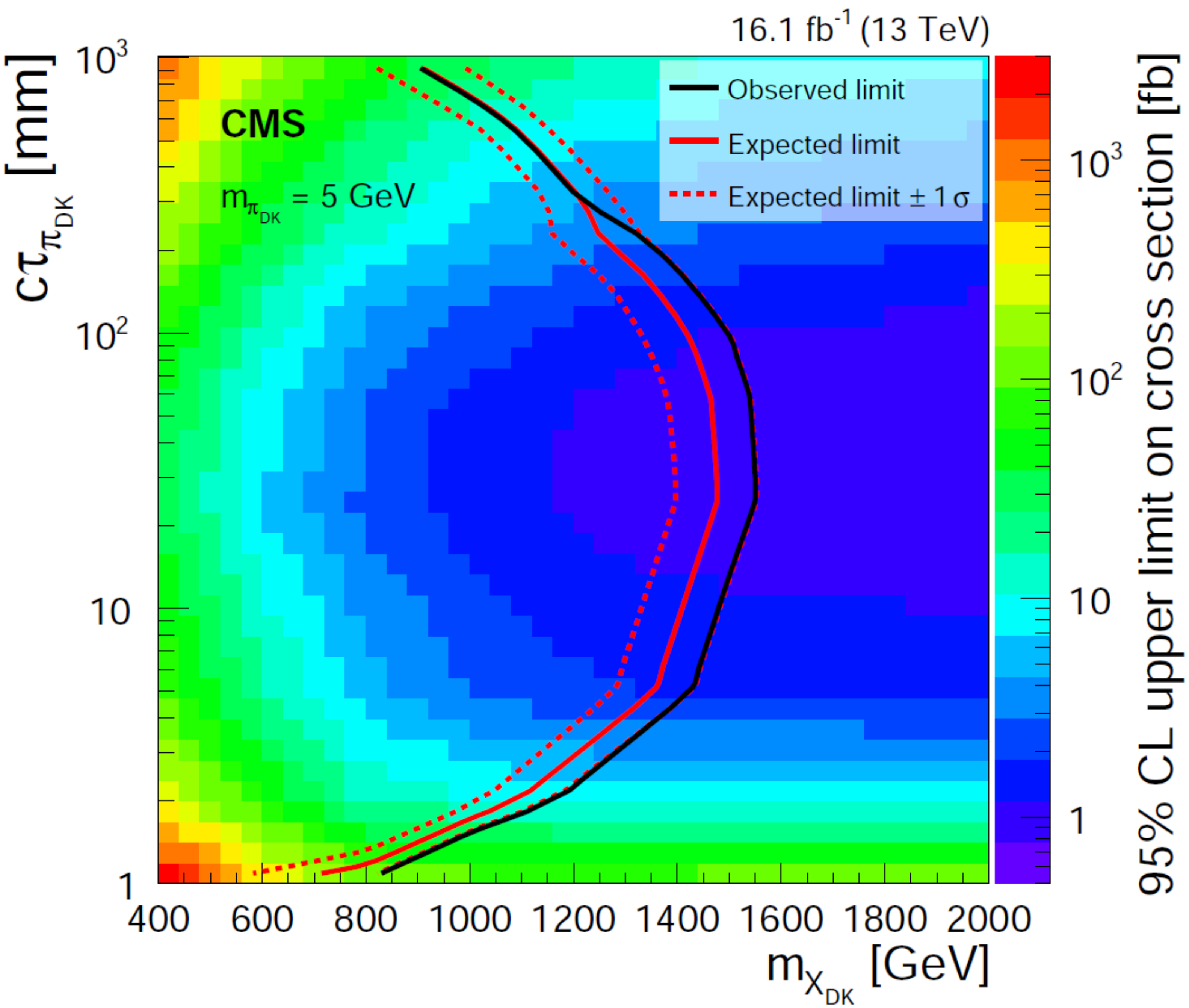




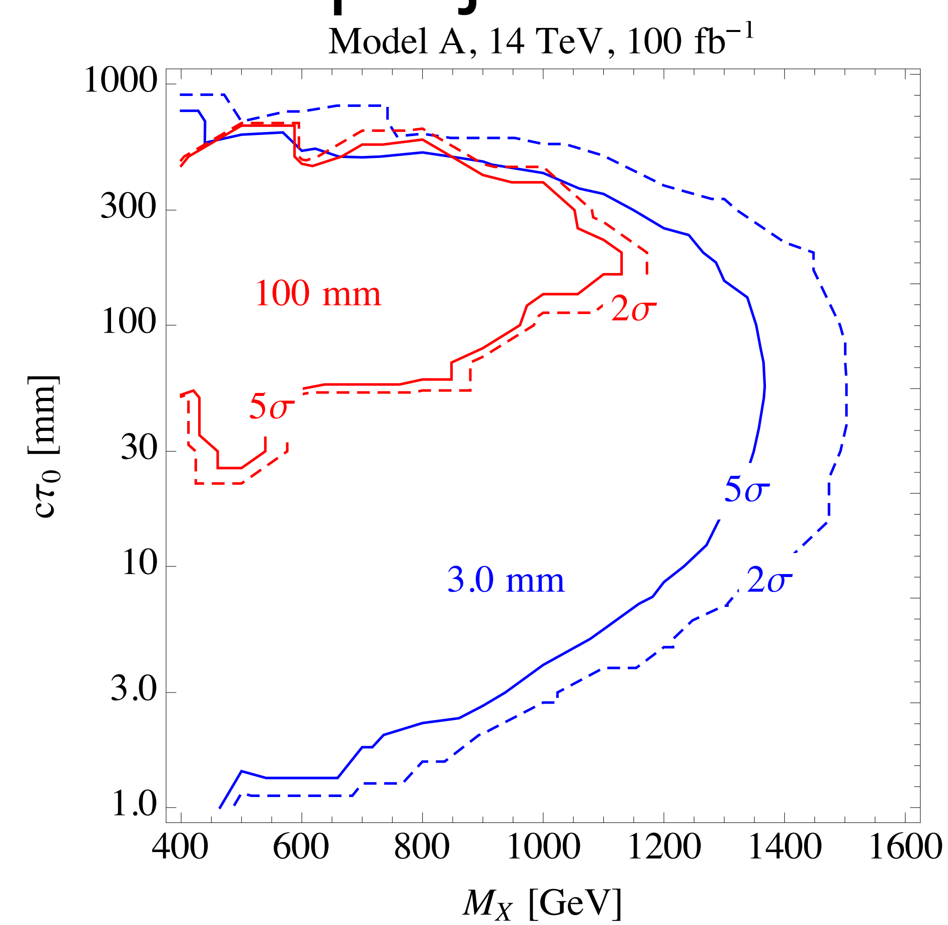
Average transverse impact parameter.

Momentum fraction below a given displacement.

LIMIT



Our projection:



SIGNAL REGIONS

Search used several signal regions.

Set number	Expected	Observed	Signal	Model parameters		
				$m_{\mathrm{X_{DK}}}$ [GeV]	$m_{\pi_{\mathrm{DK}}}$ [GeV]	$c\tau_{\pi_{\mathrm{DK}}}$ [mm]
1	$168 \pm 15 \pm 5$	131	36.7 ± 4.0	600	5	1
2	$31.8 \pm 5.0 \pm 1.4$	47	$(14.6 \pm 2.6) \times 10^2$	400	1	60
3	$19.4 \pm 7.0 \pm 5.5$	20	15.6 ± 1.6	1250	1	150
4	$22.5 \pm 2.5 \pm 1.5$	16	15.1 ± 2.0	1000	1	2
5	$13.9 \pm 1.9 \pm 0.6$	14	35.3 ± 4.0	1000	2	150
6	$9.4 \pm 2.0 \pm 0.3$	11	20.7 ± 2.5	1000	10	300
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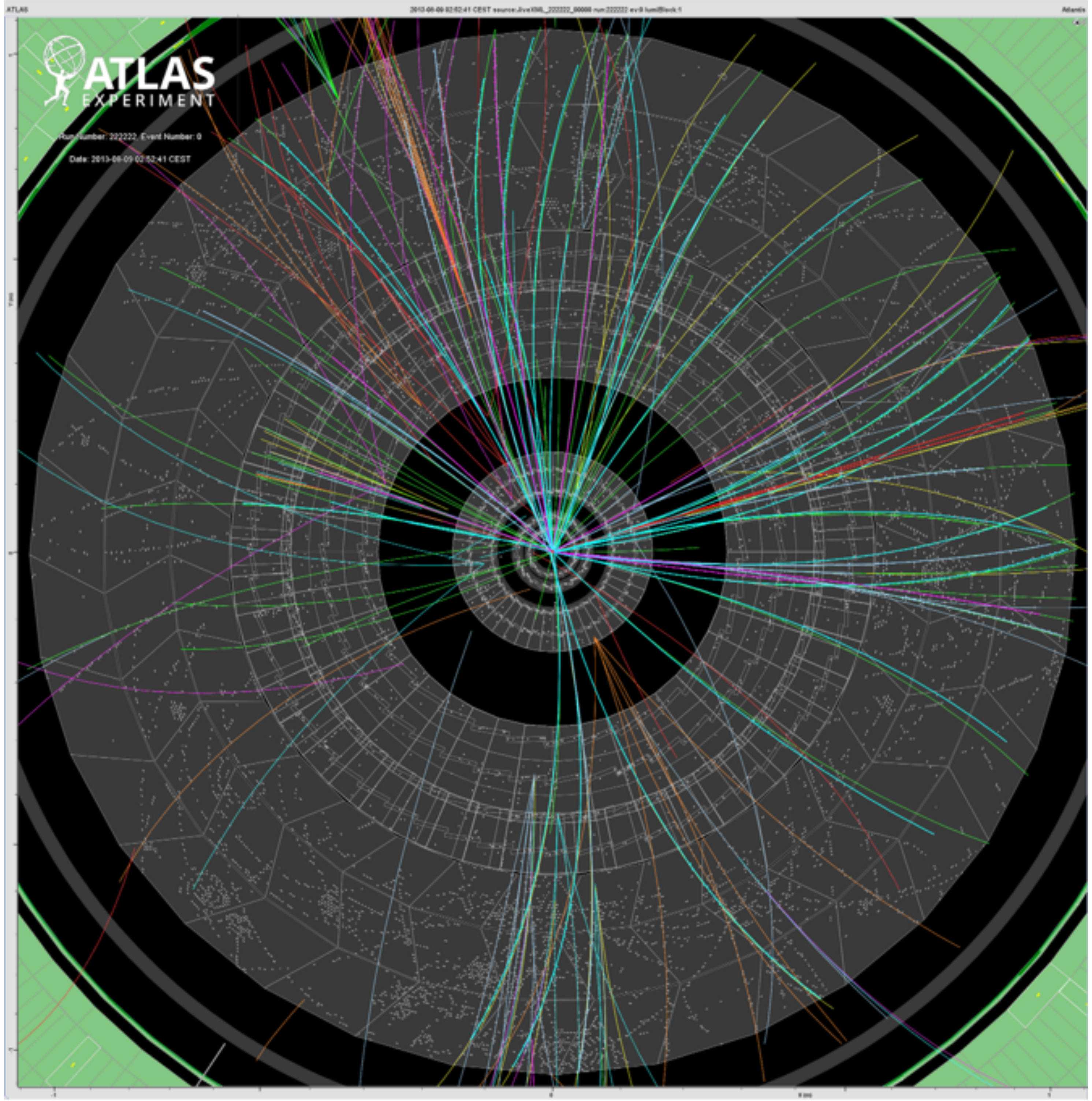
Me (dumb): Should I be excited about a ~3**σ** excess in set 2?

Ted (smart): Good question! I would say, it will be interesting to repeat the analysis next year with close to 10x more data!

ATLAS DEDICATED SEARCH

ATLAS has a dedicated search in progress.

Carleton ATLAS group is involved.



James Beacham,
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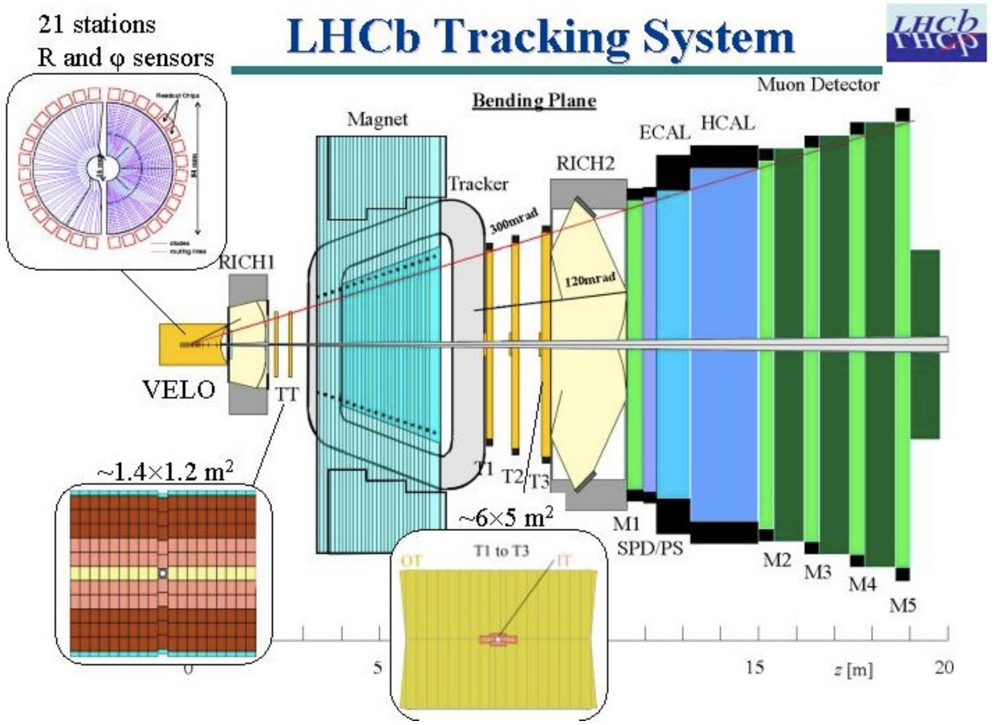
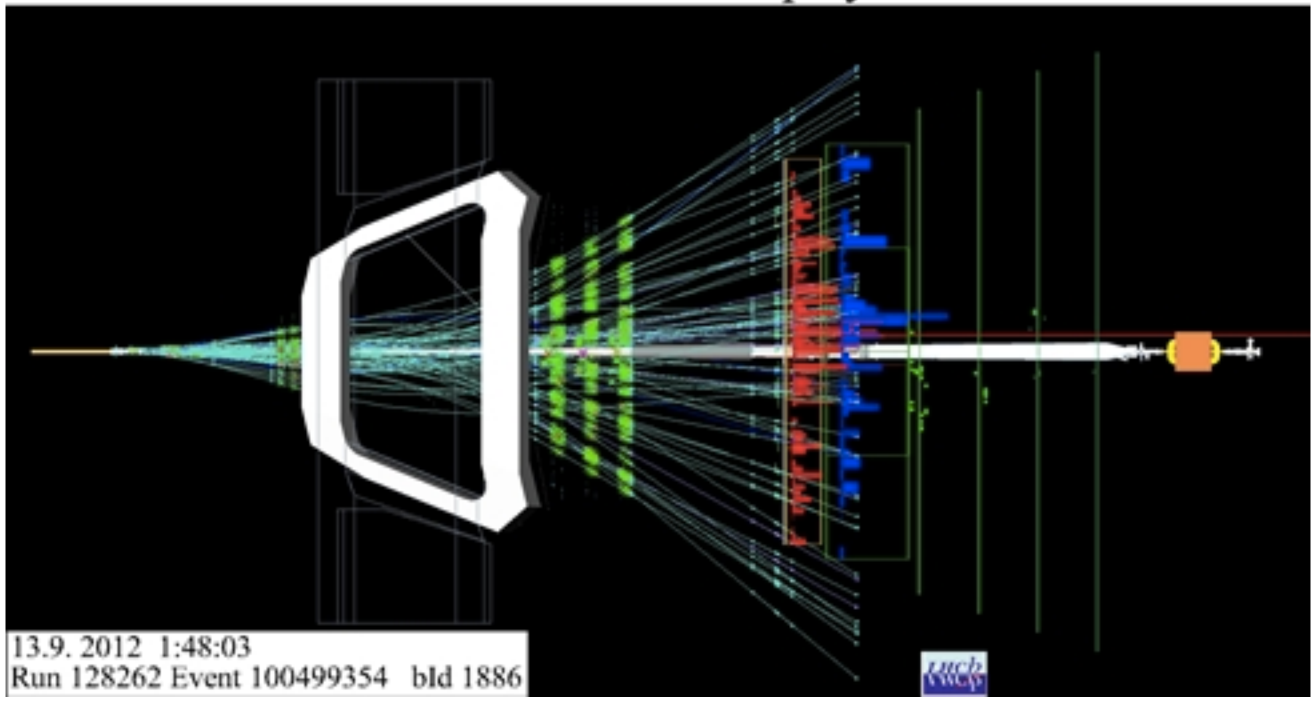
LHCb

LHCb has excellent tracking.

Limited coverage of event.

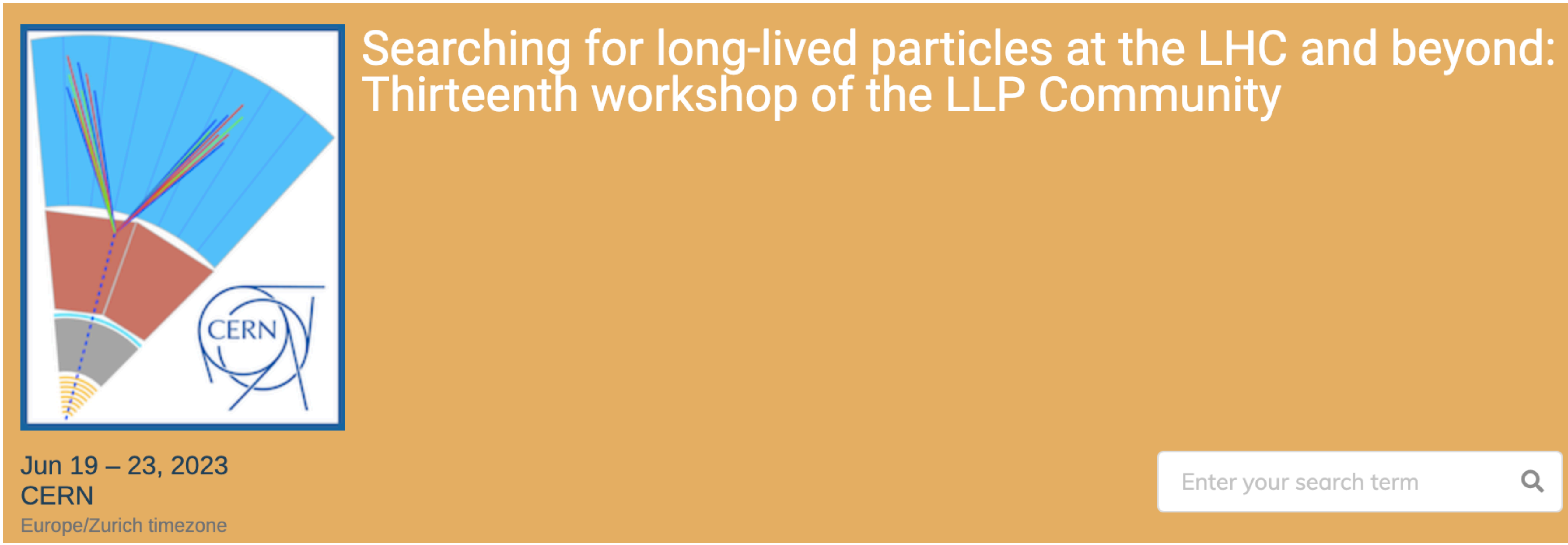


LHCb Event Display



POTPOURRI

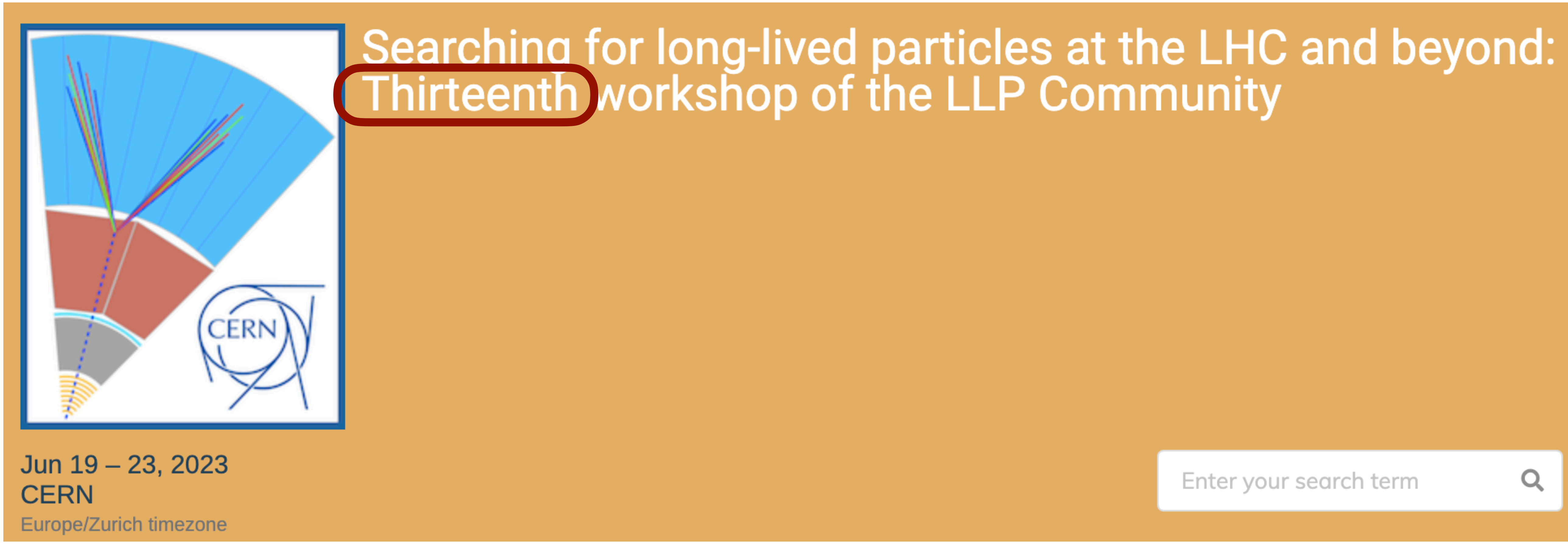
LLP COMMUNITY



Joint effort between experimentalists and theorists.

Lots to do if people are interested.

LLP COMMUNITY



Joint effort between experimentalists and theorists.

Lots to do if people are interested.

LLP COMMUNITY

Searching for long-lived particles beyond the Standard Model
at the Large Hadron Collider

March 6, 2019

Editors:
Juliette Alimena[(1)] (Experimental Coverage, Backgrounds, Upgrades), James Beacham[(2)] (Document Editor, Simplified Models), Martino Borsato[(3)] (Backgrounds, Upgrades), Yangyang Cheng[(4)] (Upgrades), Xabier Cid Vidal[(5)] (Experimental Coverage), Giovanna Cottin[(6)] (Simplified Models, Reinterpretations), Albert De Roeck[(7)] (Experimental Coverage), Nishita Desai[(8)] (Reinterpretations), David Curtin[(9)] (Simplified Models), Jared A. Evans[(10)] (Simplified Models, Experimental Coverage), Simon Knapen[(11)] (Dark Showers), Sabine Kraml[(12)] (Reinterpretations), Andre Lessa[(13)] (Reinterpretations), Zhen Liu[(14)] (Simplified Models, Backgrounds, Reinterpretations), Sascha Mehlhase[(15)] (Backgrounds), Michael J. Ramsey-Musolf[(16,126)] (Simplified Models), Heather Russell[(17)] (Experimental Coverage), Jessie Shelton[(18)] (Simplified Models, Dark Showers), Brian Shuve[(19,20)] (Document Editor, Simplified Models, Simplified Models Library), Monica Verducci[(21)] (Upgrades), Jose Zurita[(22,23)] (Experimental Coverage)

arXiv:1903.04497 (301 pages)

DARK SHOWERS

P. Schwaller

DARK SHOWERS

Lots more interesting theory and experimental work.

Working towards a thorough experimental program.

Many interested experimentalists.

New Frontiers: Dark Showers

Contents

Chapter editors: Simon Knapen, Jessie Shelton

Contributors: Michael Adersberger, James Beacham, Malte Buschmann, Cari Cesarotti, Marat Freytsis, Gregor Kasieczka, Dylan Linthorne, Sascha Mehlhase, Matt Reece, Sophie Renner, Jakub Scholtz, Pedro Schwaller, Daniel Stolarski, Yuhsin Tsai

SNOWMASS ACTIVITY

arXiv > hep-ph > arXiv:2203.09503

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High Energy Physics – Phenomenology

[Submitted on 17 Mar 2022 (v1), last revised 27 Jun 2022 (this version, v2)]

Theory, phenomenology, and experimental avenues for dark showers: a Snowmass 2021 report

Guillaume Albouy, Jared Barron, Hugues Beauchesne, Elias Bernreuther, Marcella Bona, Cesare Cazzaniga, Cari Cesarotti, Timothy Cohen, Annapaola de Cosa, David Curtin, Zeynep Demiragli, Caterina Doglioni, Alison Elliot, Karri Folan DiPetrillo, Florian Eble, Carlos Erice, Chad Freer, Aran Garcia-Bellido, Caleb Gemmell, Marie-Hélène Genest, Giovanni Grilli di Cortona, Giuliano Gustavino, Nicoline Hemme, Tova Holmes, Deepak Kar, Simon Knapen, Suchita Kulkarni, Luca Lavezzo, Steven Lowette, Benedikt Maier, Seán Mee, Stephen Mrenna, Harikrishnan Nair, Jeremi Niedziela, Christos Papageorgakis, Nukulsinh Parmar, Christoph Paus, Kevin Pedro, Ana Peixoto, Alexx Perloff, Tilman Plehn, Christiane Scherb, Pedro Schwaller, Jessie Shelton, Akanksha Singh, Sukanya Sinha, Torbjörn Sjöstrand, Aris G.B. Spourdalakis, Daniel Stolarski, Matthew J. Strassler, Andrii Usachov, Carlos Vázquez Sierra, Christopher B. Verhaaren, Long Wang

112 pages.

FUTURE DETECTORS

Many concepts for additional detectors to detect LLPs produced in LHC collisions.

- milliQan
- SHiP
- MATHUSLA
- MoEDAL-MAPP taking data
- FORMOSA
- FASER under construction
- CODEX-b
- AL3X
- ANUBIS
- SND

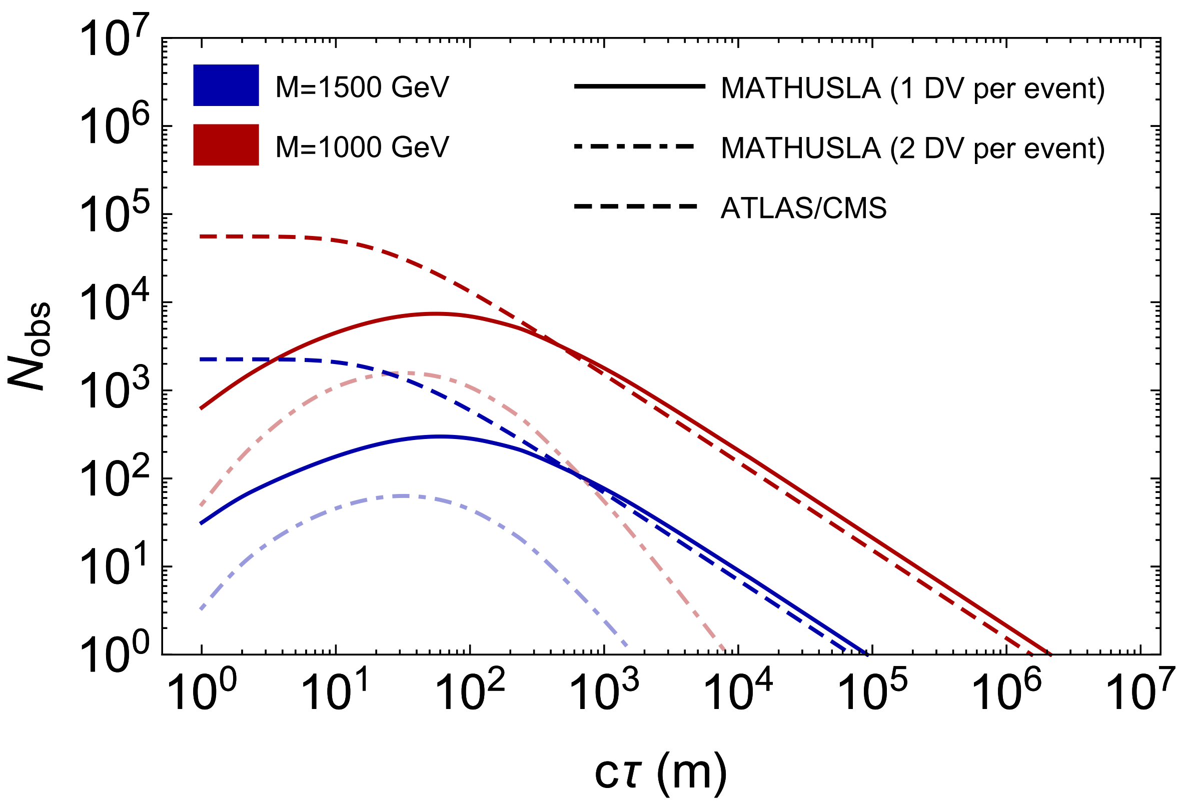
FUTURE DETECTORS

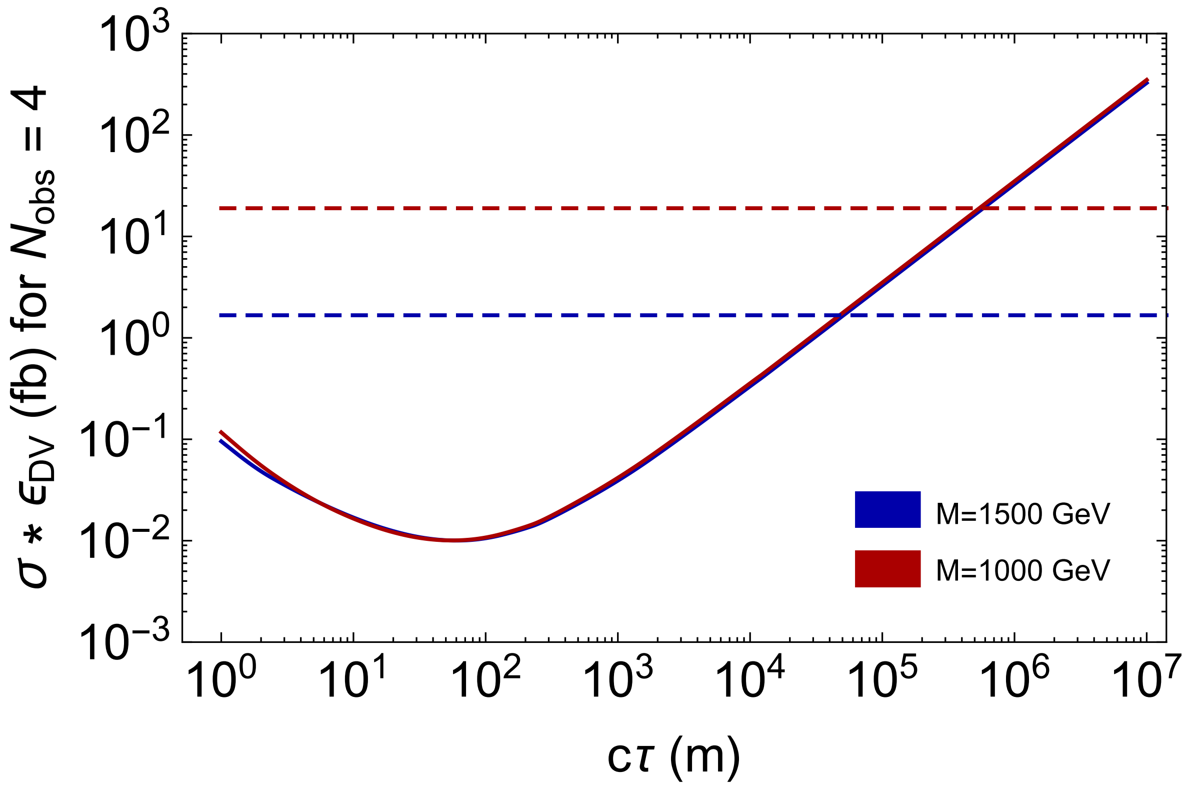
A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case

1504.04855

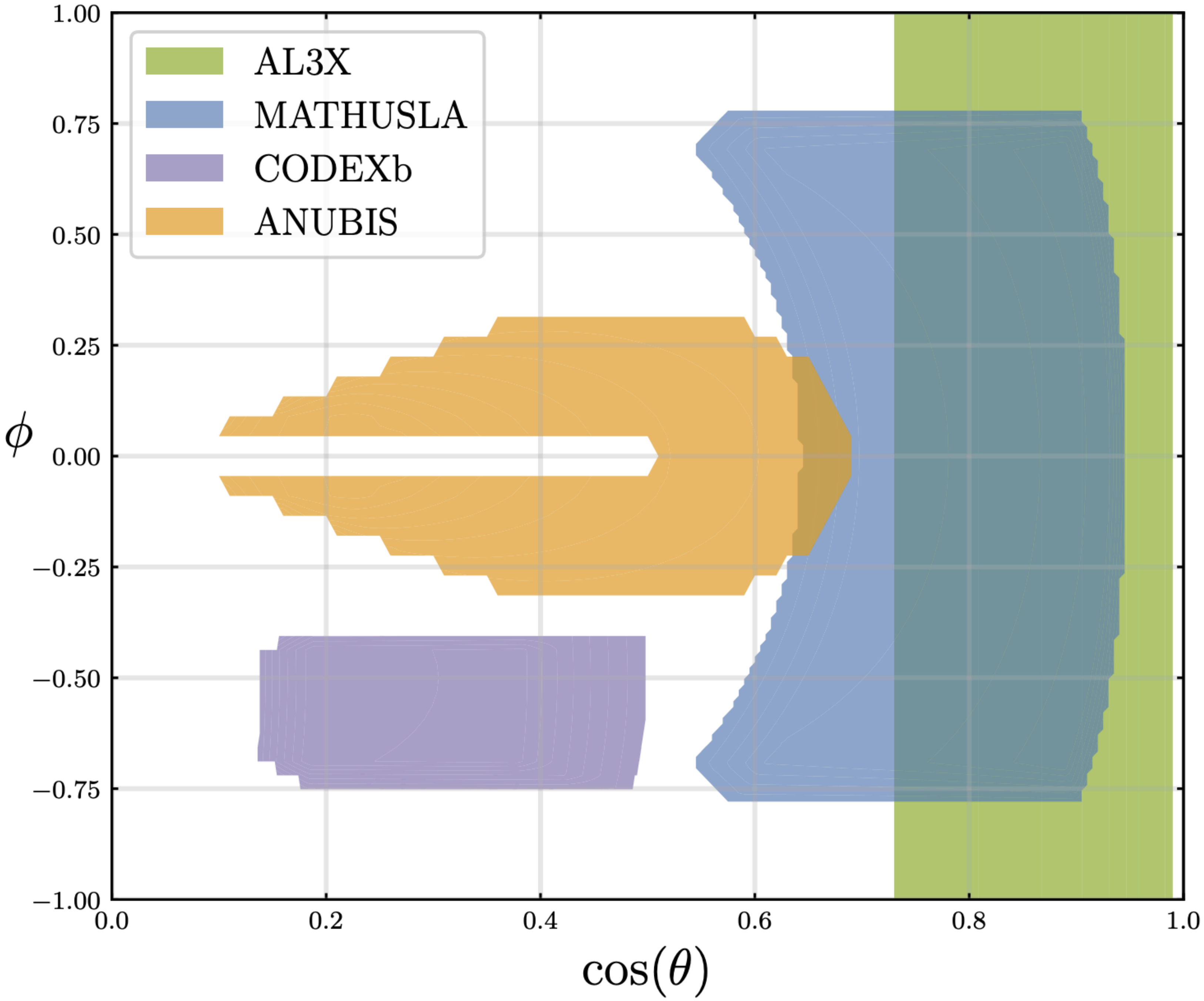
Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case

1806.07396





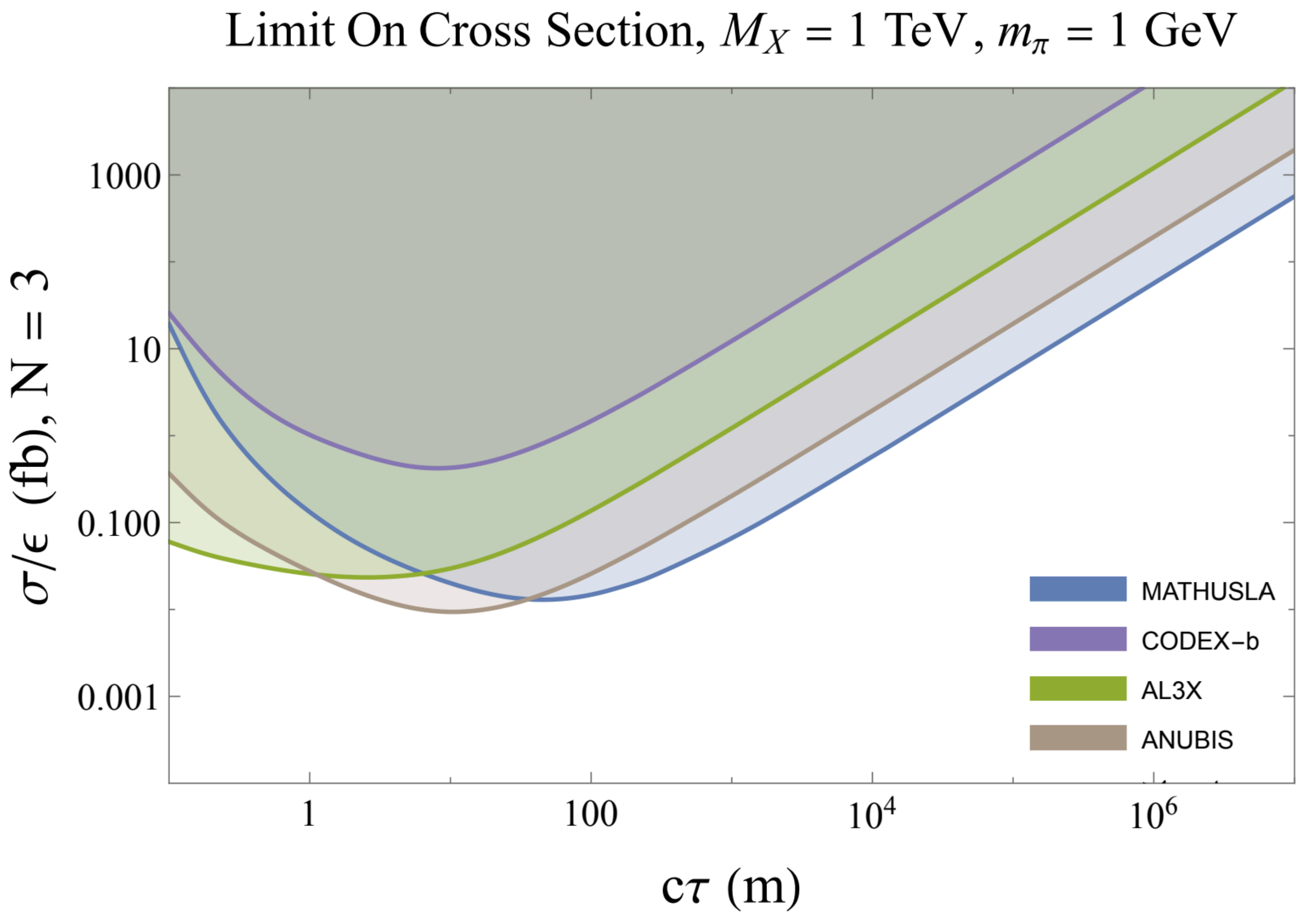
GEOMETRY

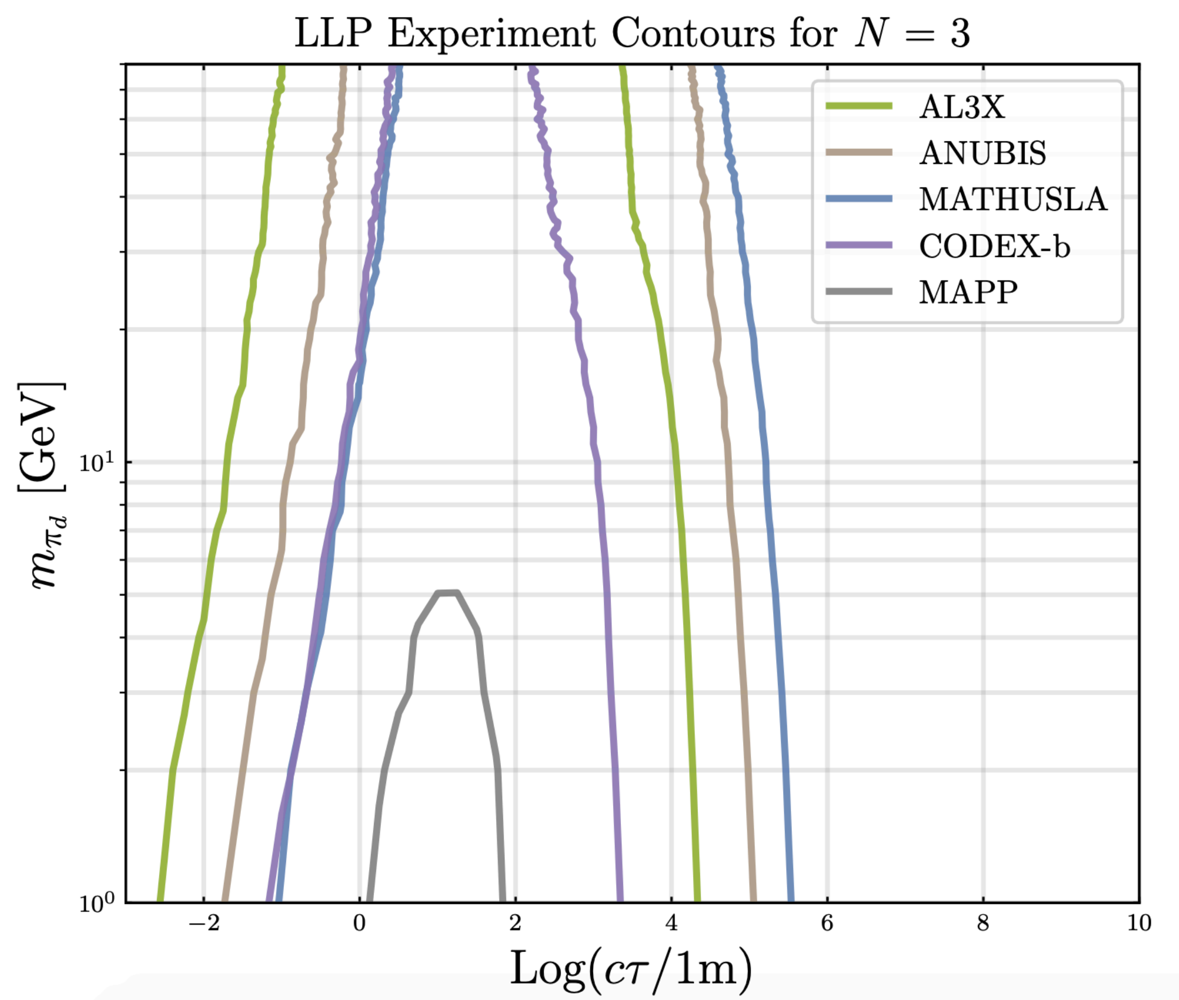


Other detectors are forward, have much smaller efficiency for heavy mediators.

Archer-Smith, Linthorne, DS, arXiv:2112.05690.

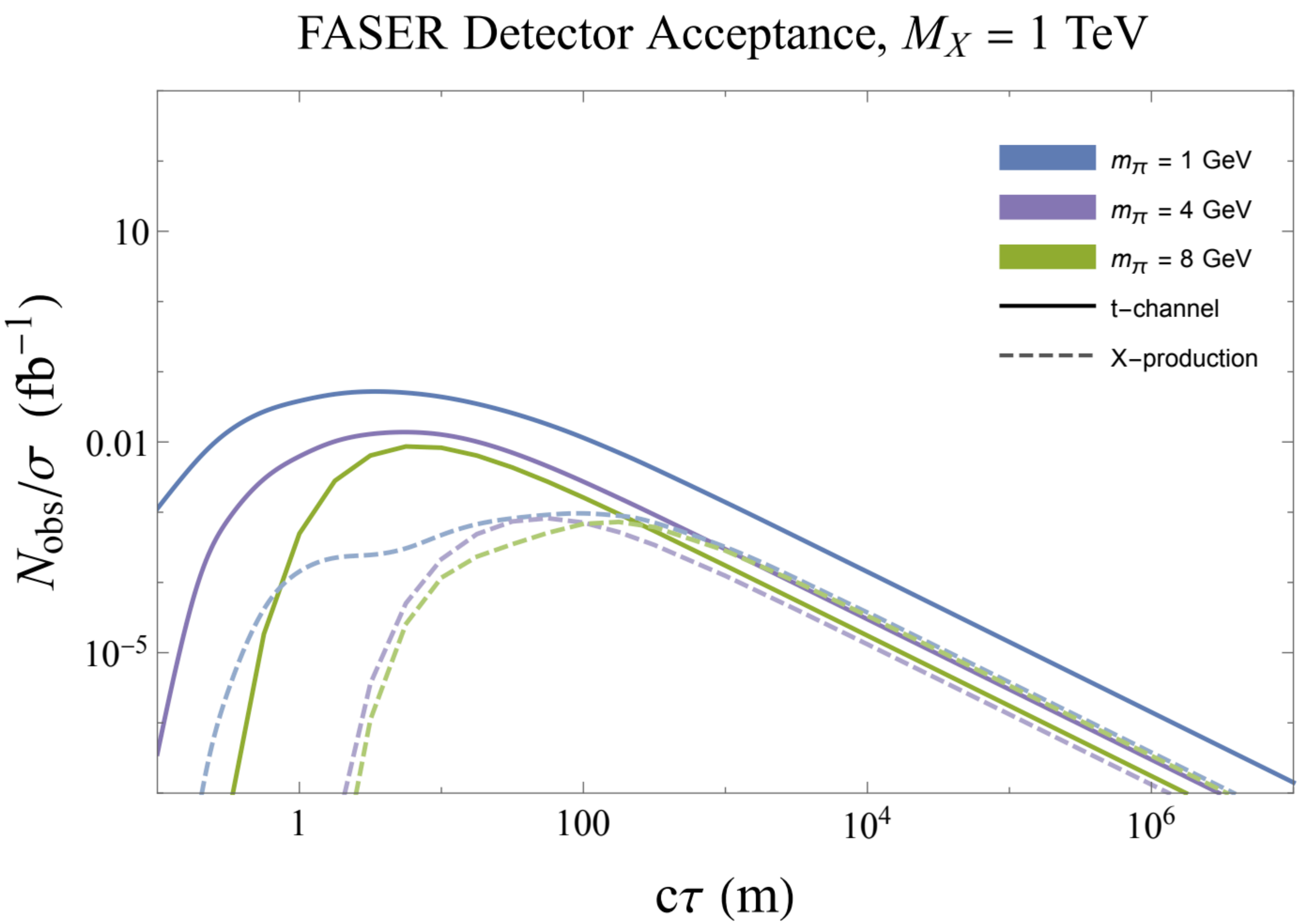
COMPARISON

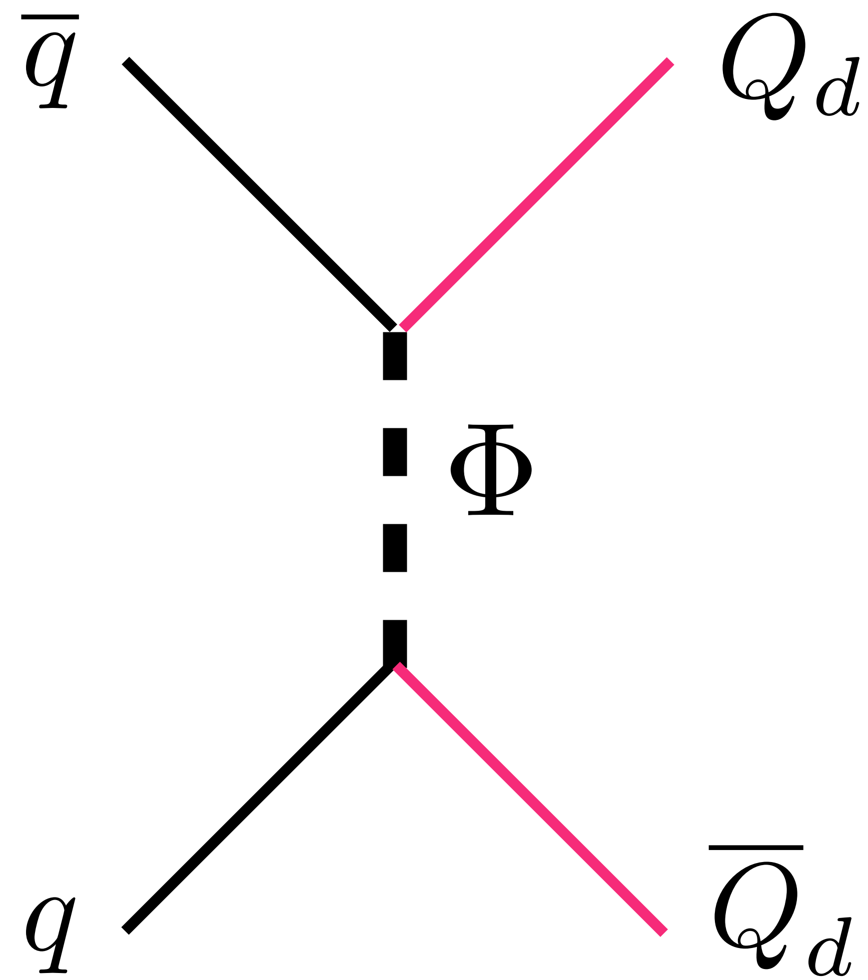




Archer-Smith, Linthorne, DS, arXiv:2112.05690.

T-CHANNEL





Archer-Smith, Linthorne, DS, arXiv:2112.05690.

TRIGGERING?

LHC experiments need to reduce data rate from ~10 MHz to ~ 1 kHz.

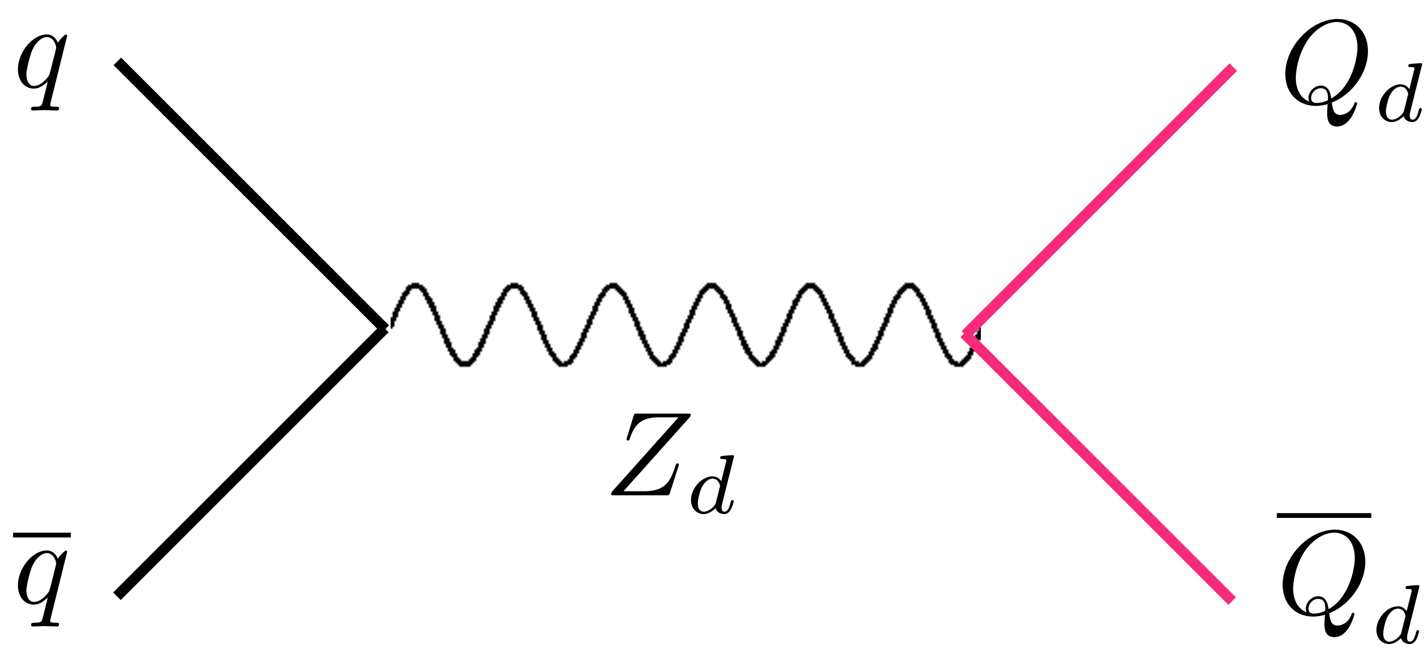
Current triggers look for total energy, jets, leptons, etc.

Not designed for exotic scenarios like emerging jets.

TRIGGER STRATEGIES

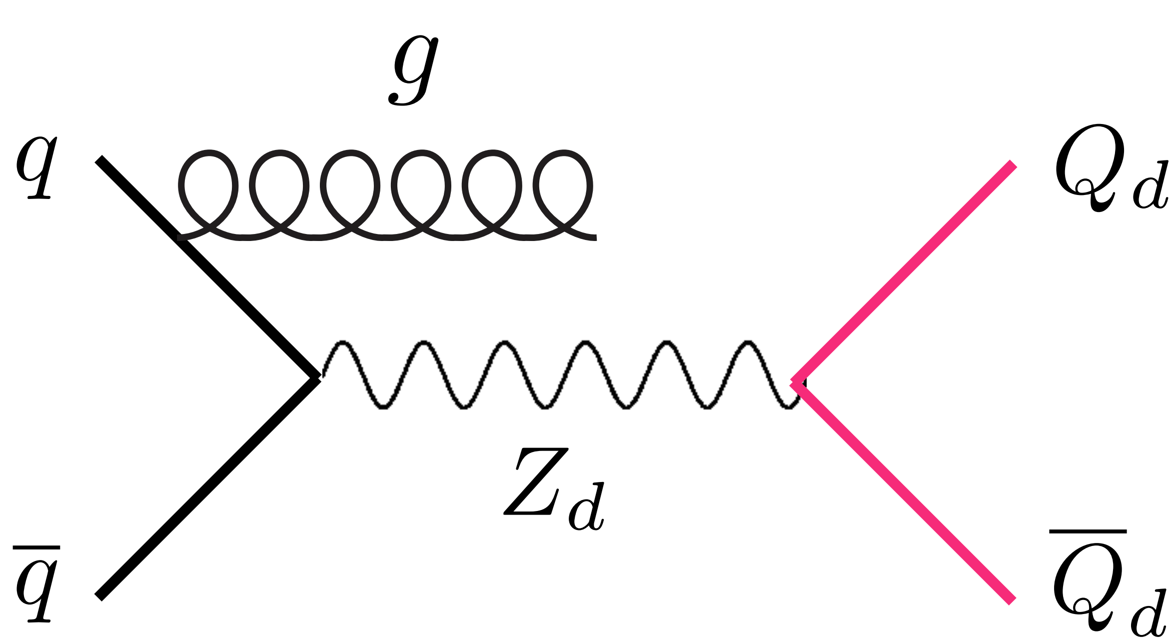
Original study used high mass mediators that produce extra jets: this makes triggering easy.

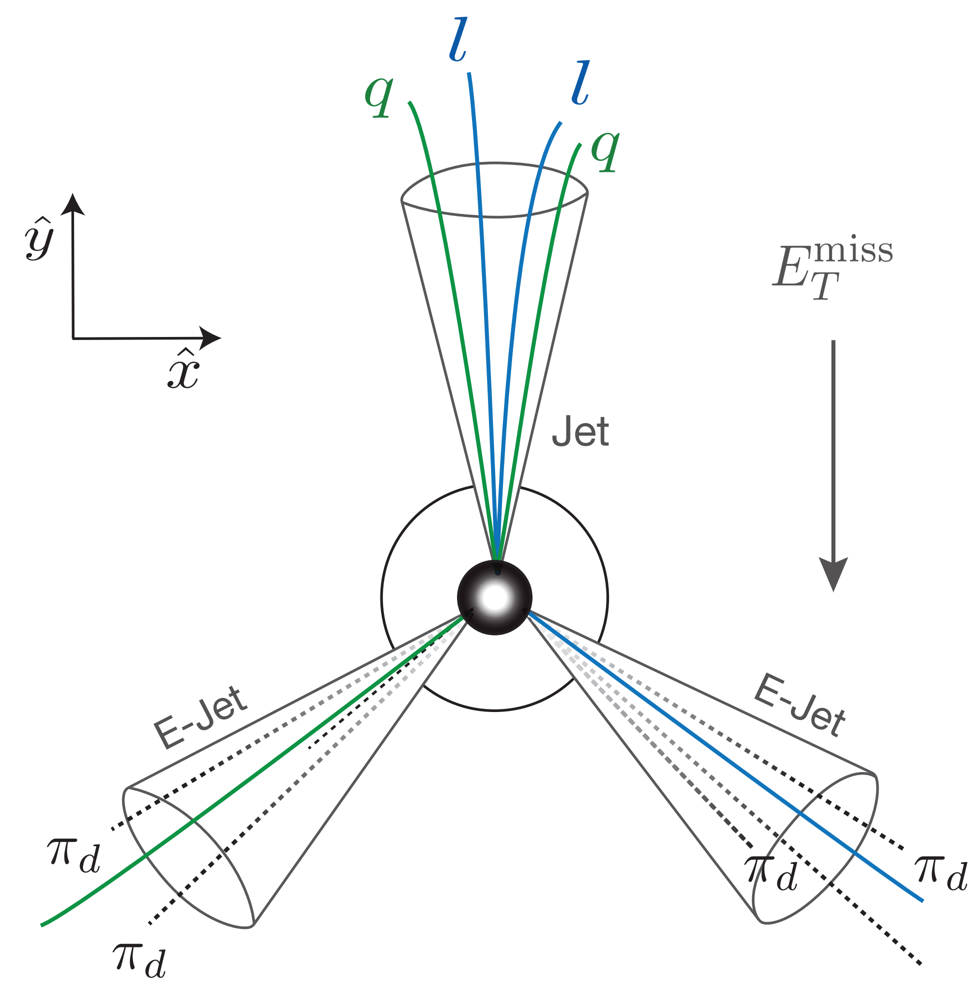
Can consider more difficult case with vector mediator (with potentially lower mass):



ISR TRIGGERS

Strategy: Radiate a gluon (or a photon, W/Z, etc).

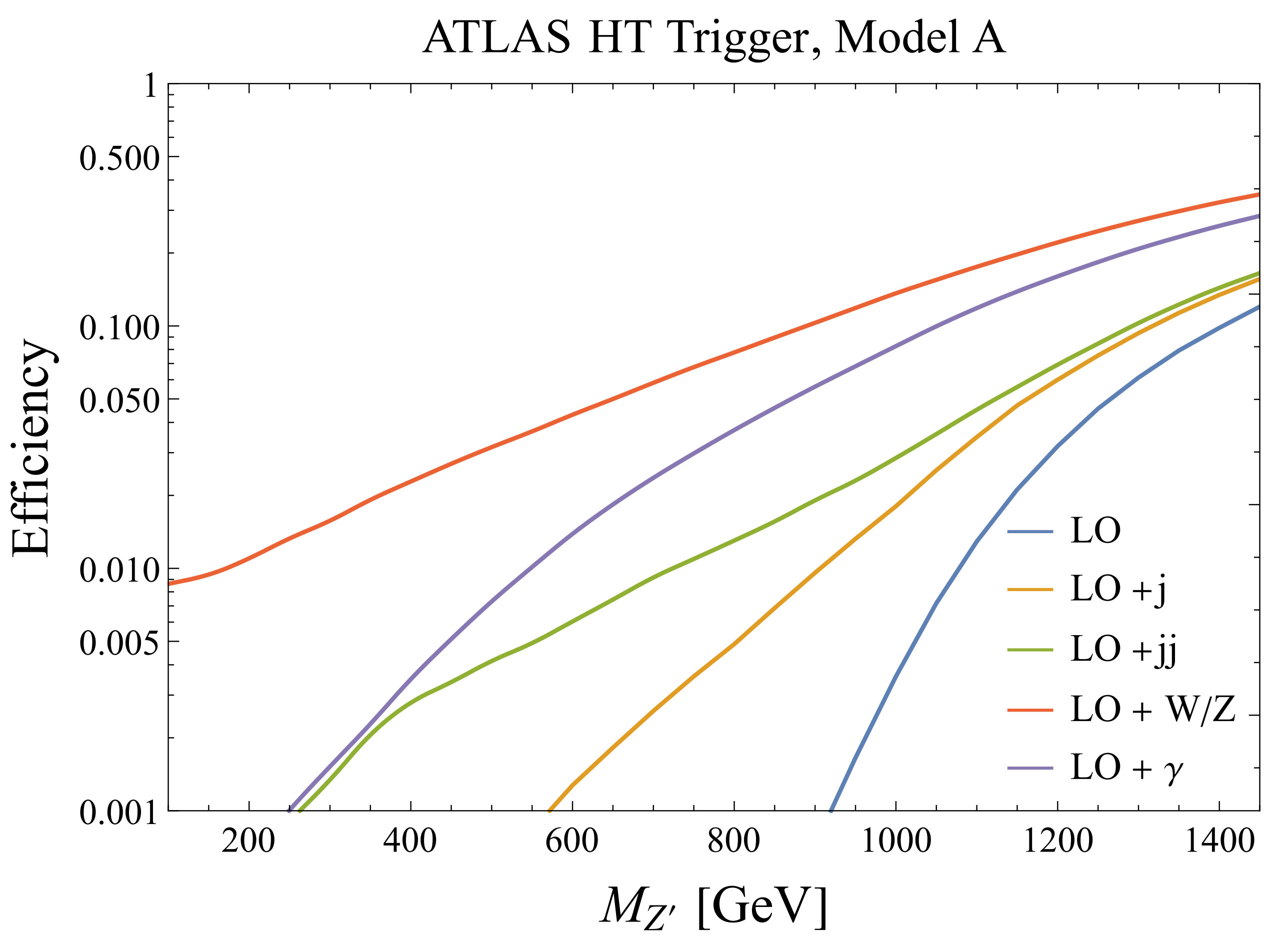


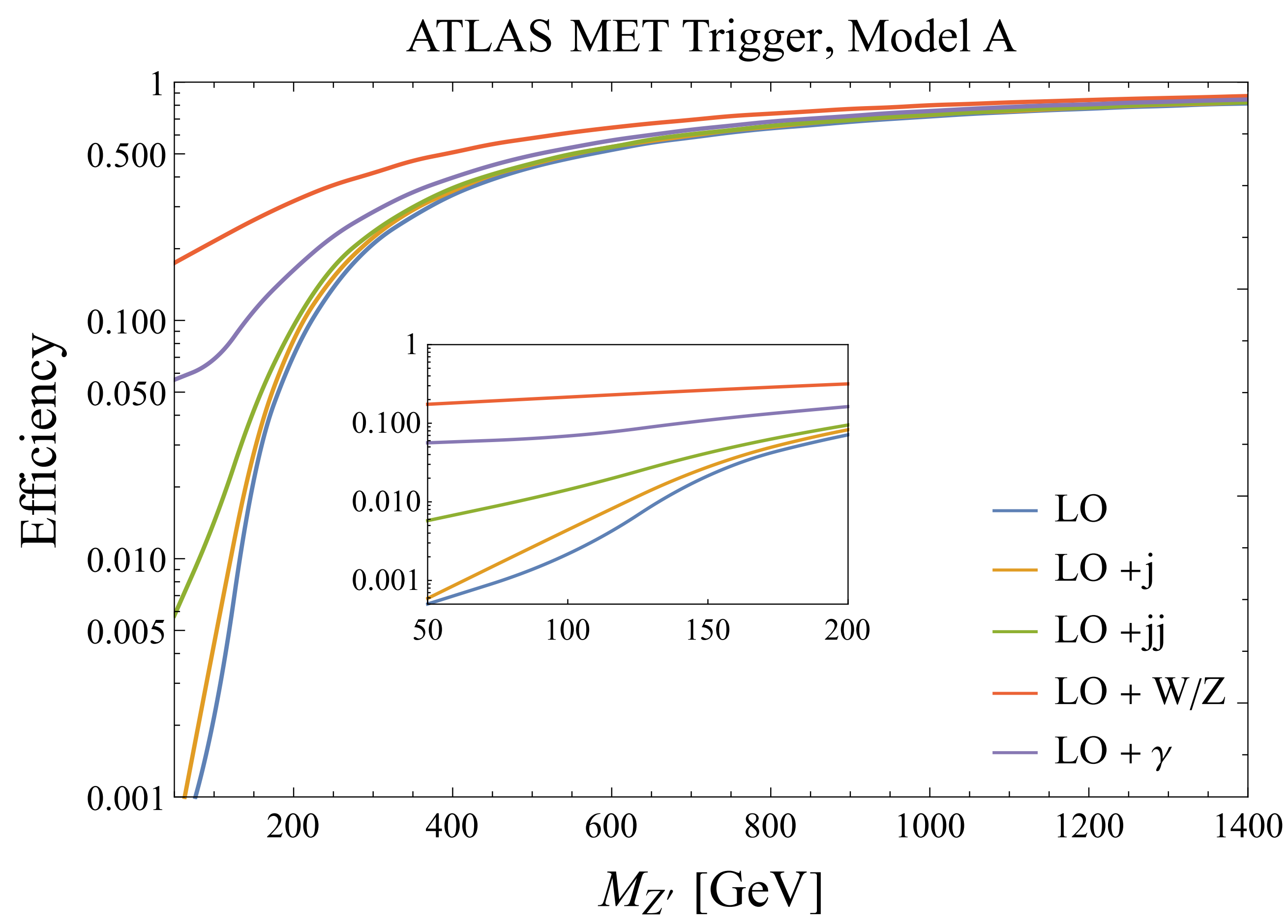


Goodman et.al. 1008.1783.

Fox et. al., 1109.4398.

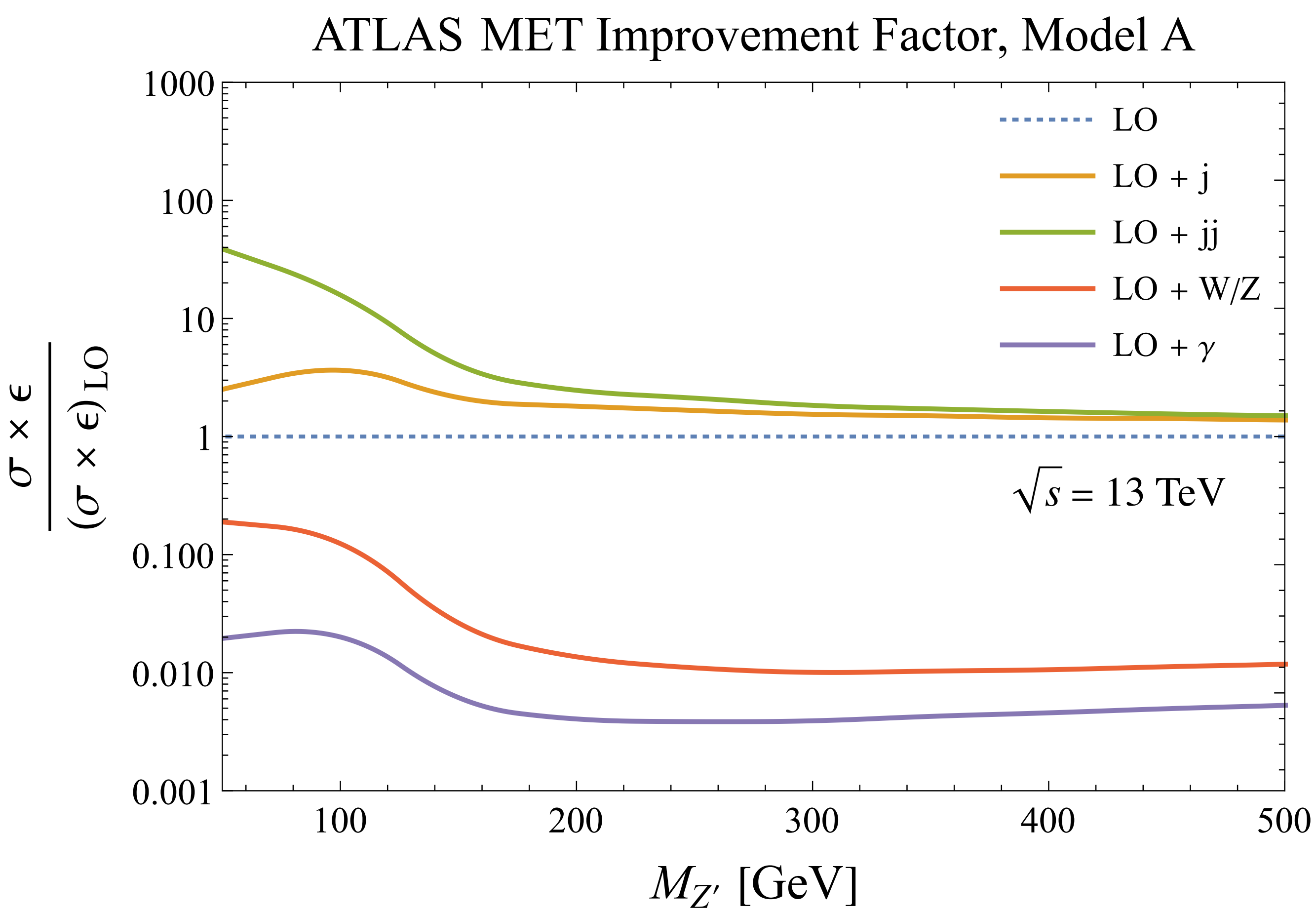
EFFICIENCY IMPROVEMENT

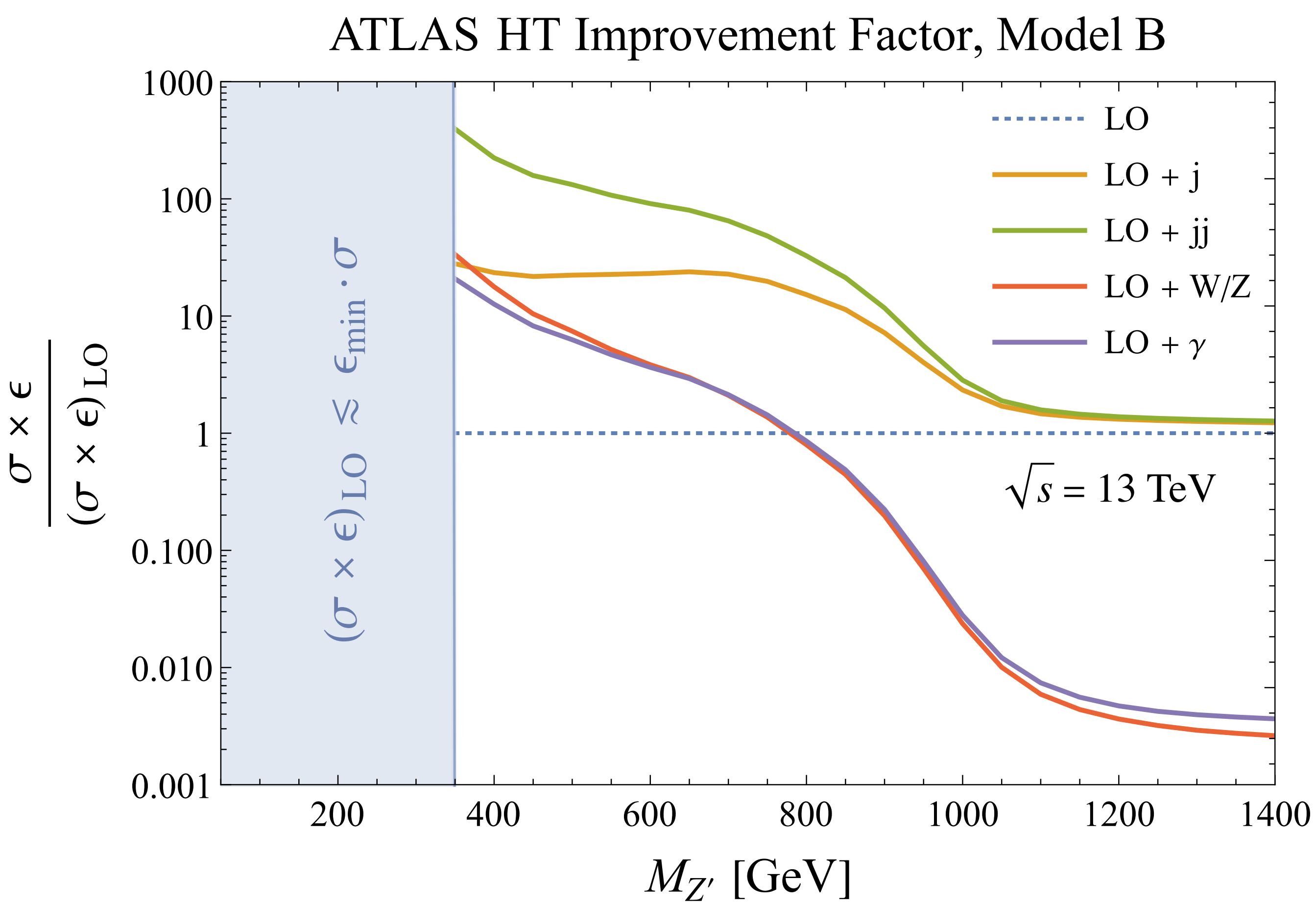




Linthorne, DS, arXiv:2103.08620.

RATE IMPROVEMENT





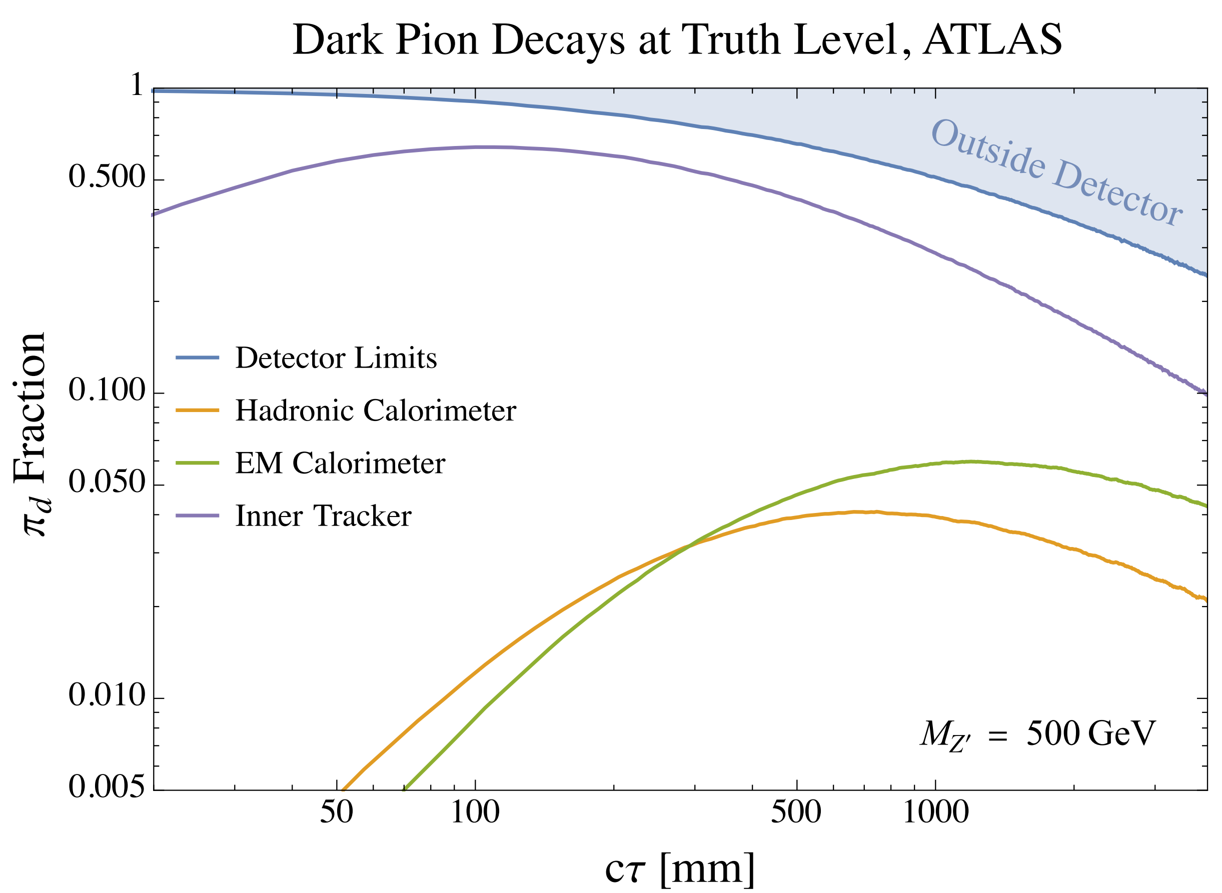
Linthorne, DS, arXiv:2103.08620.

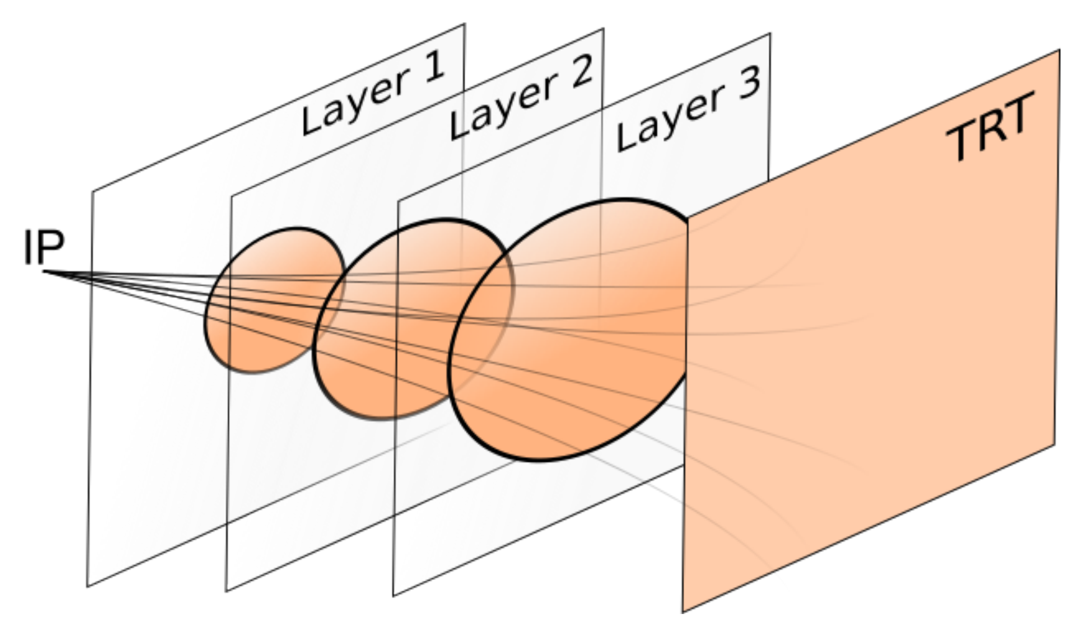
NEW TRIGGERS?

The tracker has the largest number of decays.

Can we just count hits in different layers of the tracker?

Fast: do not have to reconstruct tracks.

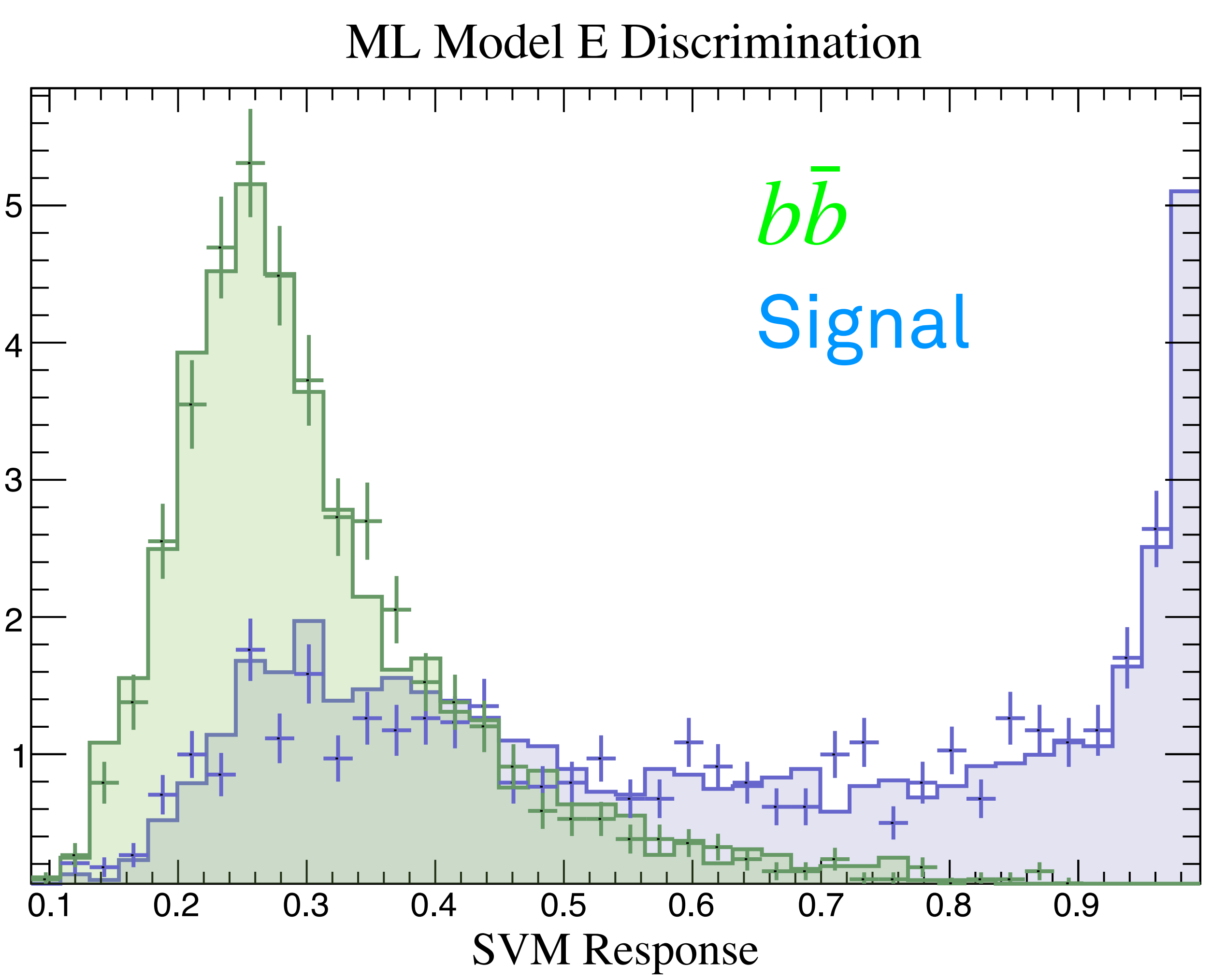




THE MACHINE LEARNS

Use machine learning to enhance discriminating power.

Downside of ML:
no physical understanding. Not a problem for triggers.

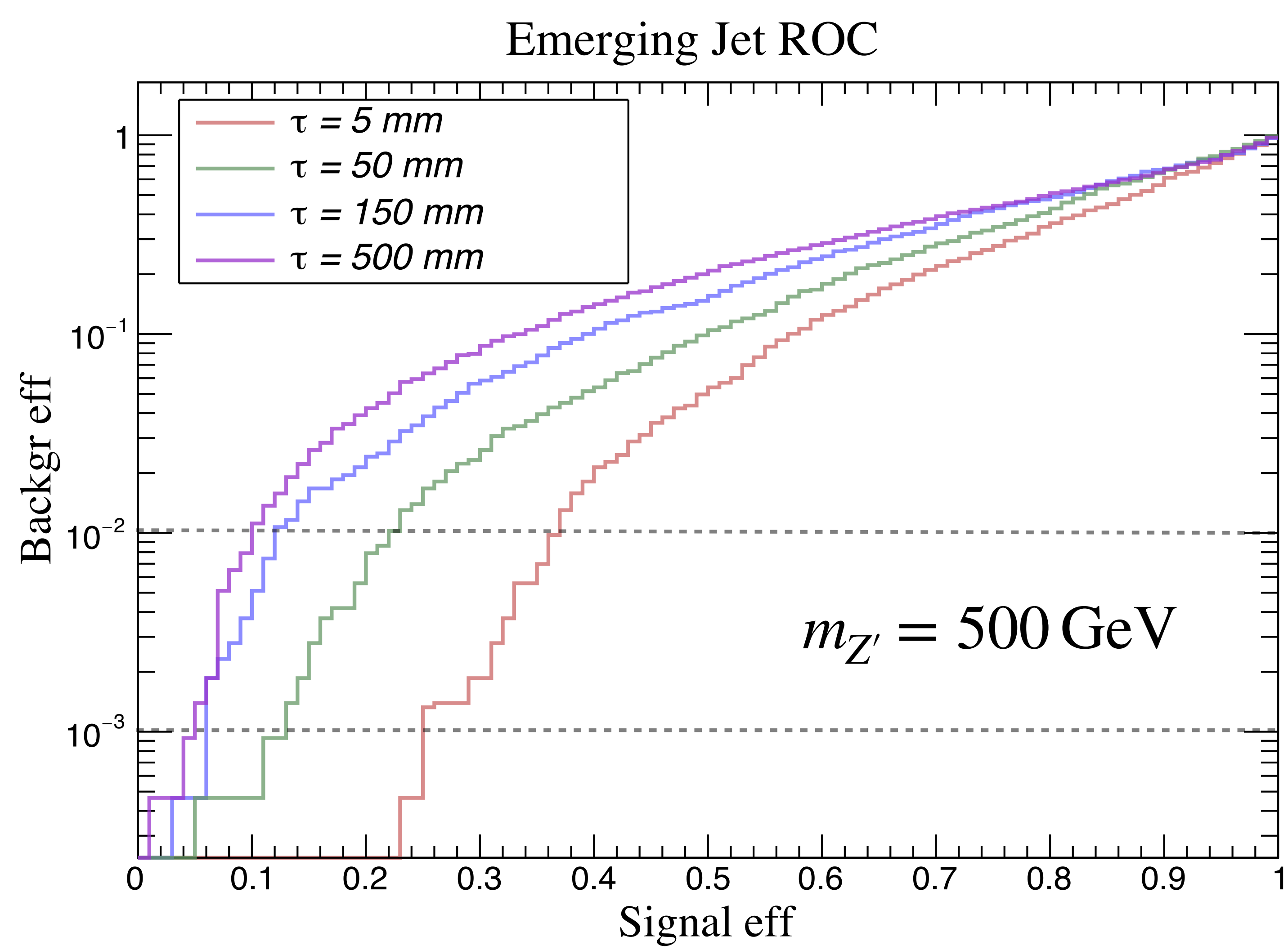


Linthorne, DS, arXiv:2103.08620.

EFFICIENCY

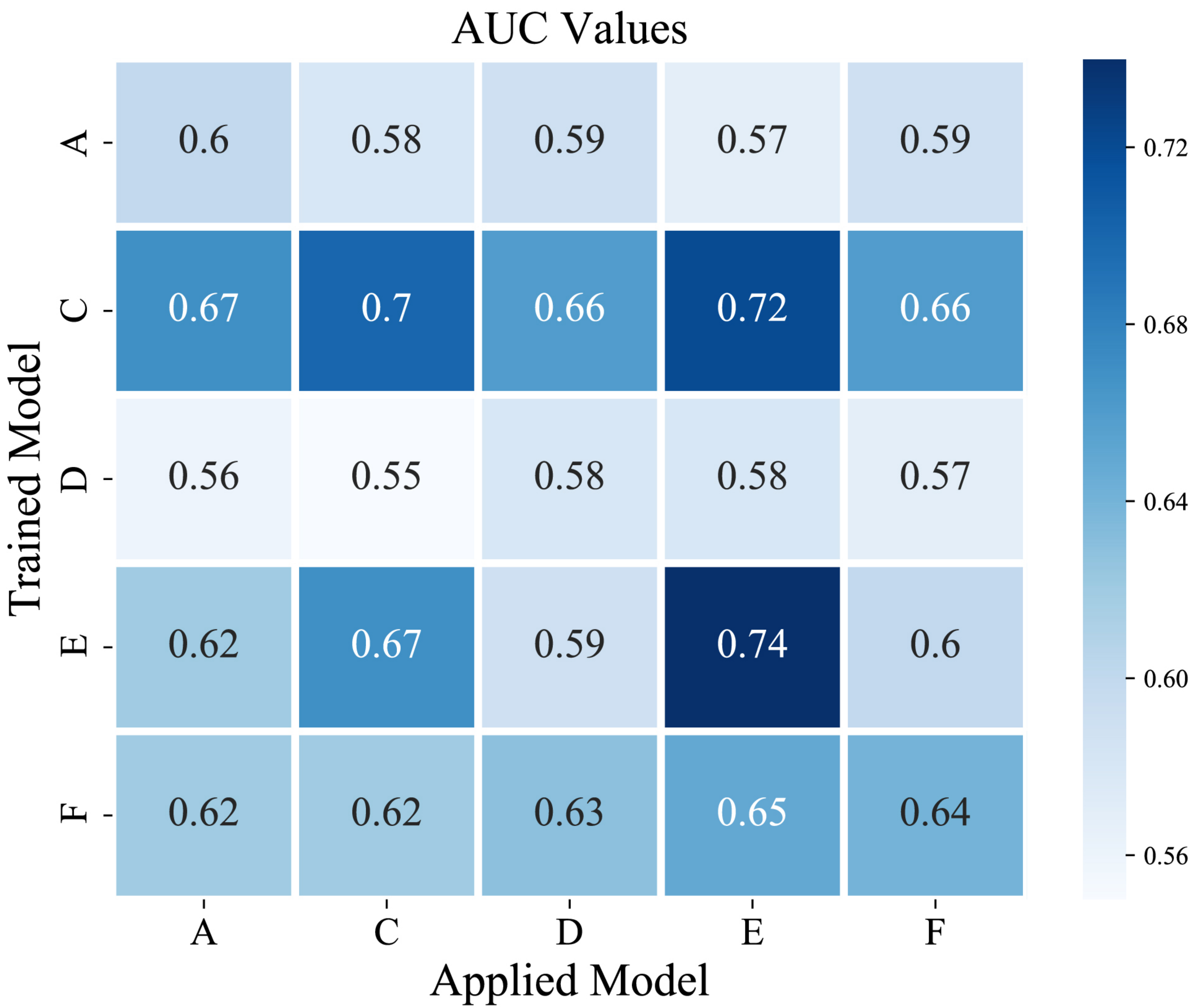
Need to reject hard QCD at ~1/1000.

Can get efficiencies of ~10%.



See also:
Alimena, Iiyama, Kieseler, 2004.10744 and Bernreuther et. al. 2011.06604.

UNIVERSALITY



FLAVOUR CONSTRAINTS

Yukawa couplings to mediator has flavour and dark flavour indices.

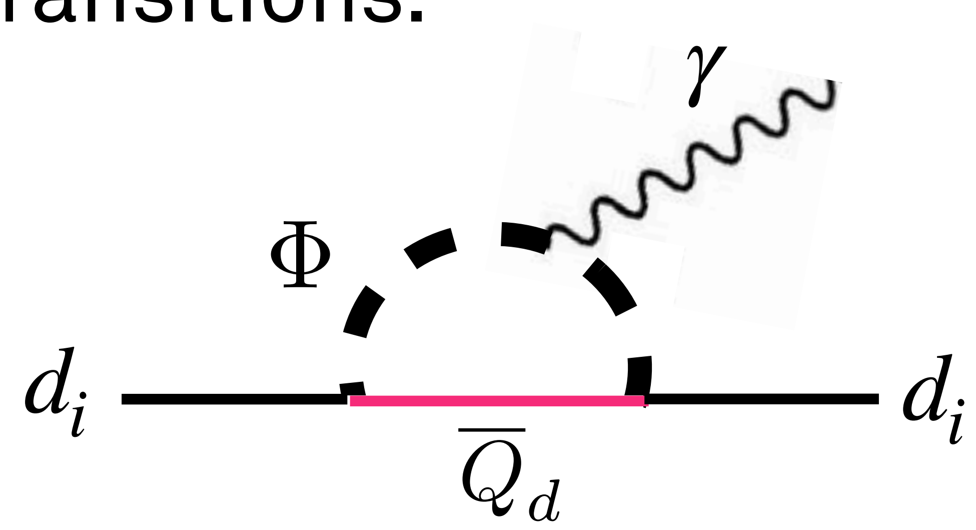
$$\lambda_{ij}\,\bar{Q}_j\,\Phi\,d_i$$

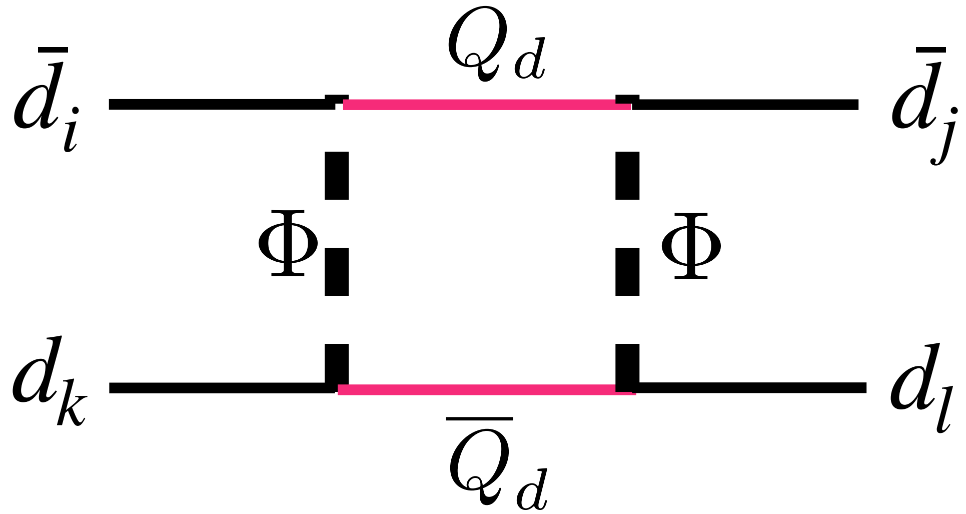
$d_i \rightarrow$ SM quark (d, s, b)

$\Phi \rightarrow$ bifundamental scalar

$\bar{Q}_j \rightarrow$ dark quark

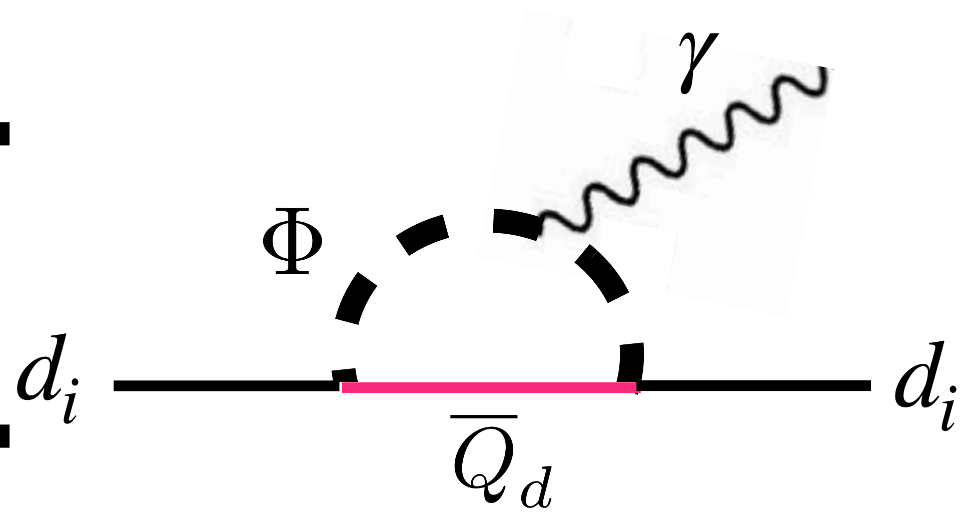
One loop processes can lead to flavour and CP violating transitions.





ELECTRIC DIPOLE MOMENTS

TeV scale CP violating new physics typically strongly constrained by (C)EDM bounds.

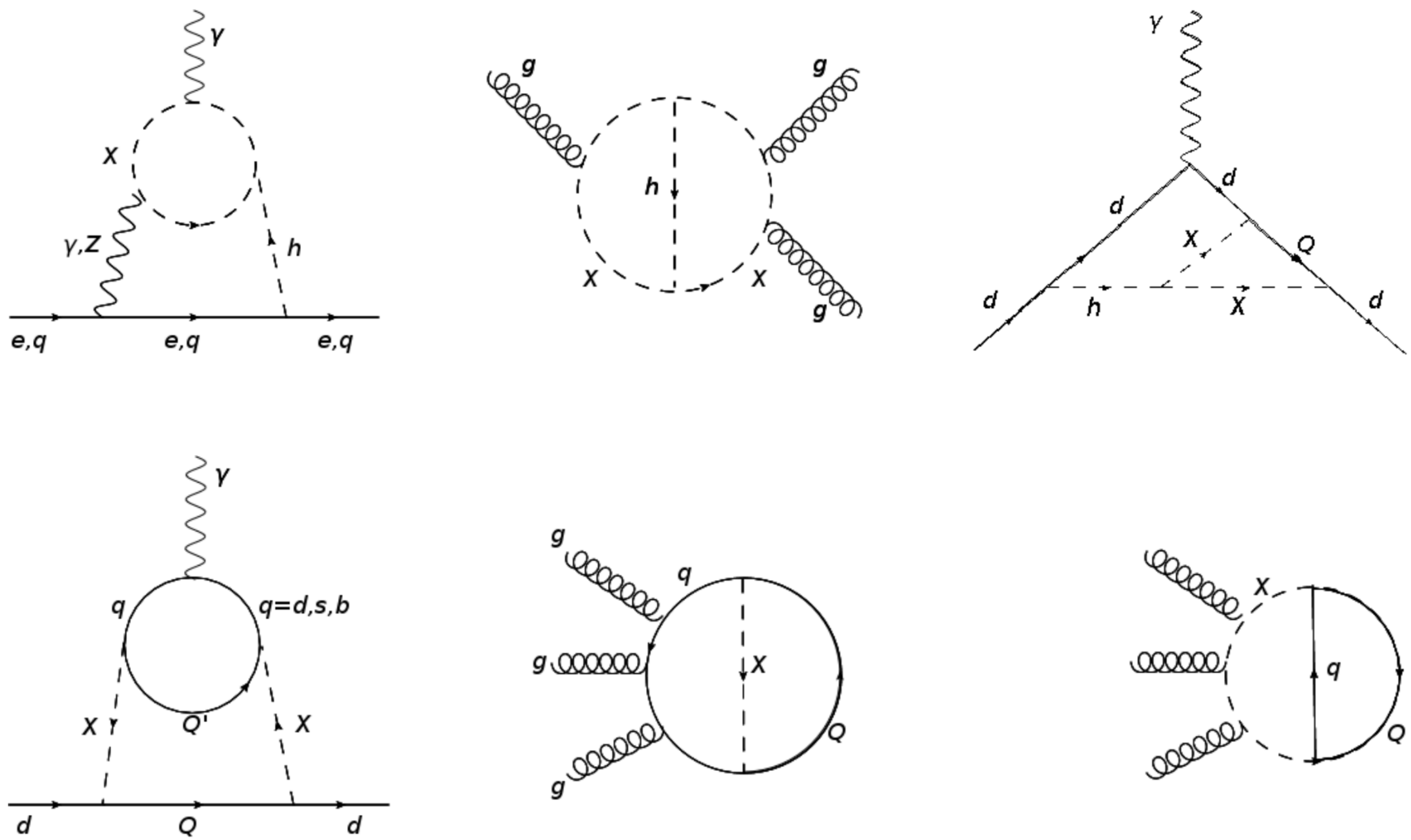
Im[]

$$\propto \mathrm{Im}\left[\lambda_{dQ}\lambda^*_{dQ}\right] = 0$$

Bensalem, DS, arXiv:2111.05515.

ELECTRIC DIPOLE MOMENTS

Two loop diagrams are all real by similar arguments.



Bensalem, DS, arXiv:2111.05515.

ELECTRIC DIPOLE MOMENTS

Leading contribution to nEDM is at 3 loop!

$$\sim e\,\lambda_{ij}^4 \left(\frac{1}{16\pi^2}\right)^3 \left(\frac{m_d}{M_X^2}\right) \sim 10^{-29}\ e\cdot\mathrm{cm}\left(\frac{\mathrm{TeV}}{M_x}\right)^2 < 10^{-26} e\cdot\mathrm{cm}$$

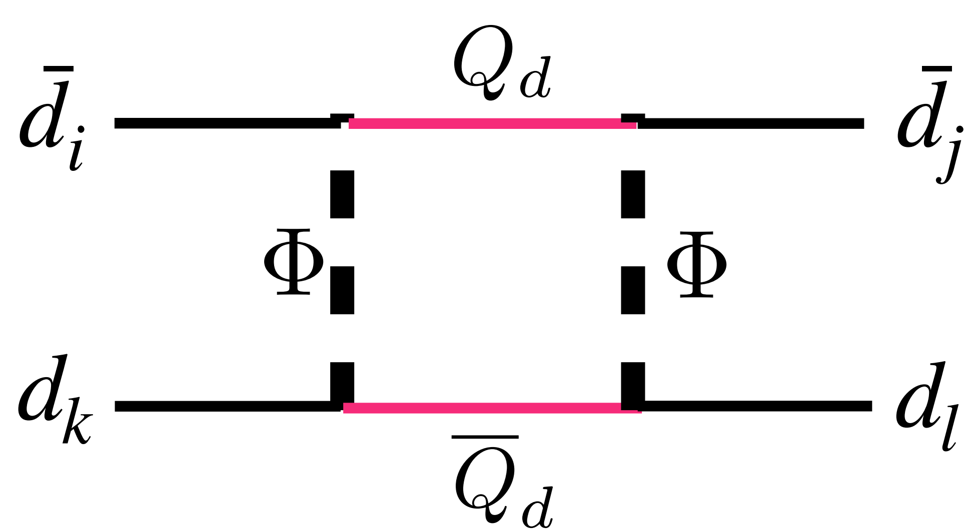
EDMs do not constrain this model (yet).

Bensalem, DS, arXiv:2111.05515.

FLAVOUR CONSTRAINTS

Low energy flavour experiments place constraints on the real and imaginary parts of expressions like:

$$\frac{1}{M_\Phi^2}\sum_{QQ'}\lambda_{qQ}\lambda^*_{q'Q}\lambda_{qQ'}\lambda^*_{q'Q'}$$



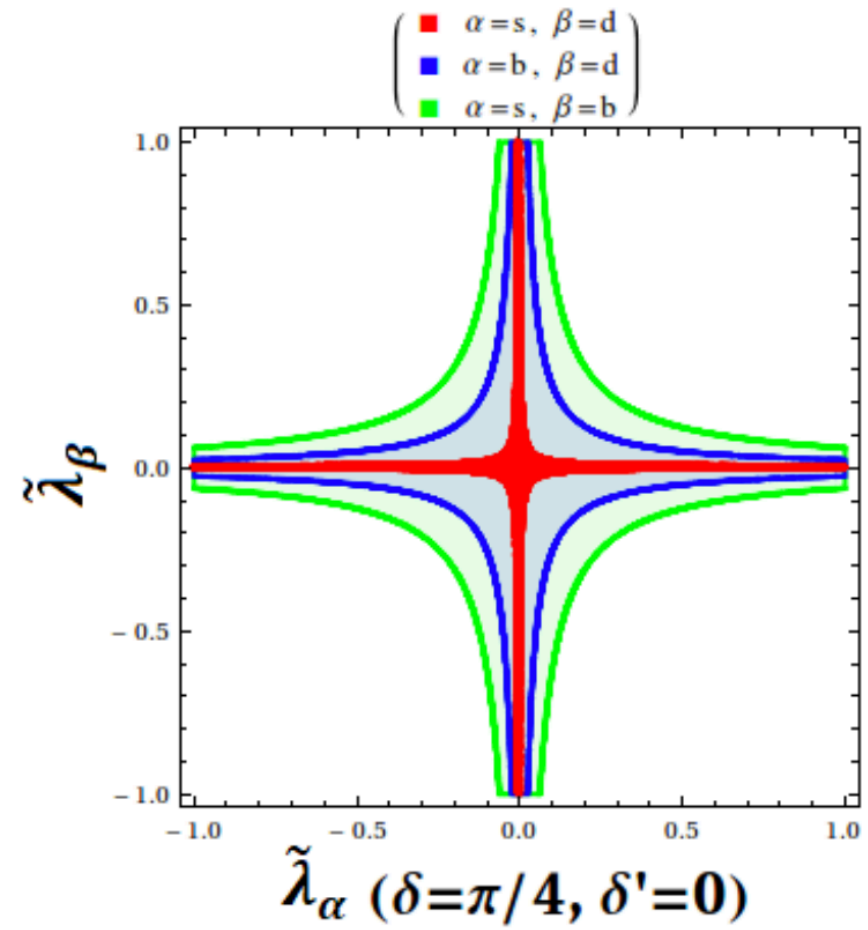
q=s, q'=d: Kaons

q=b, q'=d,s: B mesons.

See also: Renner, Schwaller, 1803.08080.

FLAVOUR CONSTRAINTS

Can parameterize λ matrix various different ways to explore allowed space.



Observables	Constraints
ΔM_K	$-6.93 \times 10^{-4} \leq N_c \mathrm{Re}\left[(\xi_K^*)^2\right]\left(\frac{1\ \mathrm{TeV}}{M_X}\right)^2 \leq 3.77 \times 10^{-4}$
ΔM_d	$N_c \mid \xi_{B_d}^2 \mid \left(\frac{1\ \mathrm{TeV}}{M_X}\right)^2 \leq 6.55 \times 10^{-4}$
ΔM_s	$N_c \mid \xi_{B_s}^2 \mid \left(\frac{1\ \mathrm{TeV}}{M_X}\right)^2 \leq 13.15 \times 10^{-3}$
$\lvert\epsilon_K\rvert$	$N_c \mid \mathrm{Im}\left[(\xi_K^*)^2\right] \mid \left(\frac{1\ \mathrm{TeV}}{M_X}\right)^2 \leq 1.64 \times 10^{-6}$
$S_{\psi K_S}$	$-0.86 \times 10^{-4} \leq N_c \mathrm{Im}\left[(\xi_{B_d}^*)^2\right]\left(\frac{1\ \mathrm{TeV}}{M_X}\right)^2 \leq 3.12 \times 10^{-4}$
$S_{\psi\phi}$	$-3.54 \times 10^{-3} \leq N_c \mathrm{Im}\left[(\xi_{B_s}^*)^2\right]\left(\frac{1\ \mathrm{TeV}}{M_X}\right)^2 \leq 3.88 \times 10^{-3}$

Bensalem, DS, arXiv:2111.05515.

MESON DECAY

SM mode	BR(SM)	BR(Exp)	BR(Projected Exp)	NP modes
$B_d \to \nu\bar{\nu}$ $B_d \to \nu\bar{\nu}\nu\bar{\nu}$	1.24×10^{-25} [76] $(1.51 \pm 0.28) \times 10^{-16}$ [77]	$< 2.4 \times 10^{-5}$ BaBar [74]	$< 1.5 \times 10^{-6}$ Belle II [75]	$B_d \to Q\bar{Q}$ $B_d \to \pi_D\pi_D$
$B_s \to \nu\bar{\nu}$ $B_s \to \nu\bar{\nu}\nu\bar{\nu}$	3.07×10^{-24} [76] $(5.48 \pm 0.89) \times 10^{-15}$ [77]	—	$< 1.1 \times 10^{-5}$ Belle II [75]	$B_s \to Q\bar{Q}$ $B_s \to \pi_D\pi_D$
$B_d \to \pi^0\nu\bar{\nu}$	$(1.2 \pm 0.15) \times 10^{-7}$ [86]	$< 0.9 \times 10^{-5}$ Belle [85]	$\mathcal{O}(10^{-7})$ Belle II	$B_d \to \pi^0 Q\bar{Q}$ $B_d \to \pi^0\pi_{\rm D}$
$B_d \to K_{\rm S}\nu\bar{\nu}$	$(2.00 \pm 0.25) \times 10^{-6}$ [87]	$< 1.3 \times 10^{-5}$ Belle [85]	$\mathcal{O}(30\%)$ Belle II	$B_d \to K_{\rm S} Q\bar{Q}$ $B_d \to K_{\rm S}\pi_{\rm D}$
$B^+ \to \pi^+\nu\bar{\nu}$	$(2.39 \pm 0.30) \times 10^{-7}$ [86]	$< 1.4 \times 10^{-5}$ Belle [85]	$\mathcal{O}(10^{-7})$ Belle II	$B^+ \to \pi^+ Q\bar{Q}$ $B^+ \to \pi^+\pi_{\rm D}$
$B^+ \to K^+\nu\bar{\nu}$	$(4.00 \pm 0.50) \times 10^{-6}$ [87]	$< 1.9 \times 10^{-5}$ Belle [85]	$\mathcal{O}(20\%)$ Belle II	$B^+ \to K^+ Q\bar{Q}$ $B^+ \to K^+\pi_{\rm D}$
$K_{\rm L} \to \pi^0\nu\bar{\nu}$	$(3.00 \pm 0.31) \times 10^{-11}$ [91]	$< 4.9 \times 10^{-9}$ KOTO [92]	$\mathcal{O}(20\%)$ KOTO Step2 [96]	$K_{\rm L} \to \pi^0\pi_{\rm D}$
$K^+ \to \pi^+\nu\bar{\nu}$	$(9.11 \pm 0.72) \times 10^{-11}$ [91]	$< 1.78 \times 10^{-10}$ NA62 [93]	—	$K^+ \to \pi^+\pi_{\rm D}$

Bensalem, DS, arXiv:2111.05515.

CP ASYMMETRIES

NP mode	Asym Type	SM	# DF	Asym(NP)
$B_d \to Q\bar{Q}$	Mixing	$\simeq 0$	1	$-\sin\left[2(\beta+\delta_{dbQ})\right]\sin(\Delta M_d t)$
$B_s \to Q\bar{Q}$	Mixing	$\simeq 0$	1	$-\sin\left[2(\beta_s+\delta_{sbQ})\right]\sin(\Delta M_s t)$
$B_d \to \pi^0\pi_{\mathrm{D}}$	Mixing	$+\sin(4\beta)\sin(\Delta M_d t)$	≥ 2	$+\sin\left[2(\beta+\delta_{dbQ})\right]\sin(\Delta M_d t)$
$B_d \to K_{\mathrm{S}}\pi_{\mathrm{D}}$	Mixing	$-\sin\left[2(\beta+\beta_s)\right]\sin(\Delta M_d t)$	≥ 2	$-\sin\left[2(\beta+\delta_{sbQ'})\right]\sin(\Delta M_d t)$
$B^+ \to \pi^+\pi_{\mathrm{D}}$	Direct	$\simeq 0$	≥ 2	$\propto \sin(\delta_{dbQ_1}-\delta_{dbQ_2})$
$B^+ \to K^+\pi_{\mathrm{D}}$	Direct	$\simeq 0$	≥ 2	$\propto \sin(\delta_{sbQ_1}-\delta_{sbQ_2})$
$K_{\mathrm{L}} \to \pi^0\pi_{\mathrm{D}}$	Grossman-Nir	$(4.3)\sin^2(\beta_s-\beta)$	≥ 2	$(4.3)\sin^2(\delta_{dsQQ'})$

CONCLUSIONS

- Confining dark sectors are well motivated extensions of the SM.
- Emerging jets are novel and interesting, LHC experiments are starting a dedicated search program. Future detectors may also have sensitivity to discovery.
- Strategies presented here can reach very low cross sections, sensitive to broad class of displaced models.
- Trigger efficiencies at low mass can be improved by adding radiation effects and possibly with new triggers.
- Lots more to do from both bottom up perspective (other kinds of dark sectors) and top down (flavour structure, unification).

THANK YOU