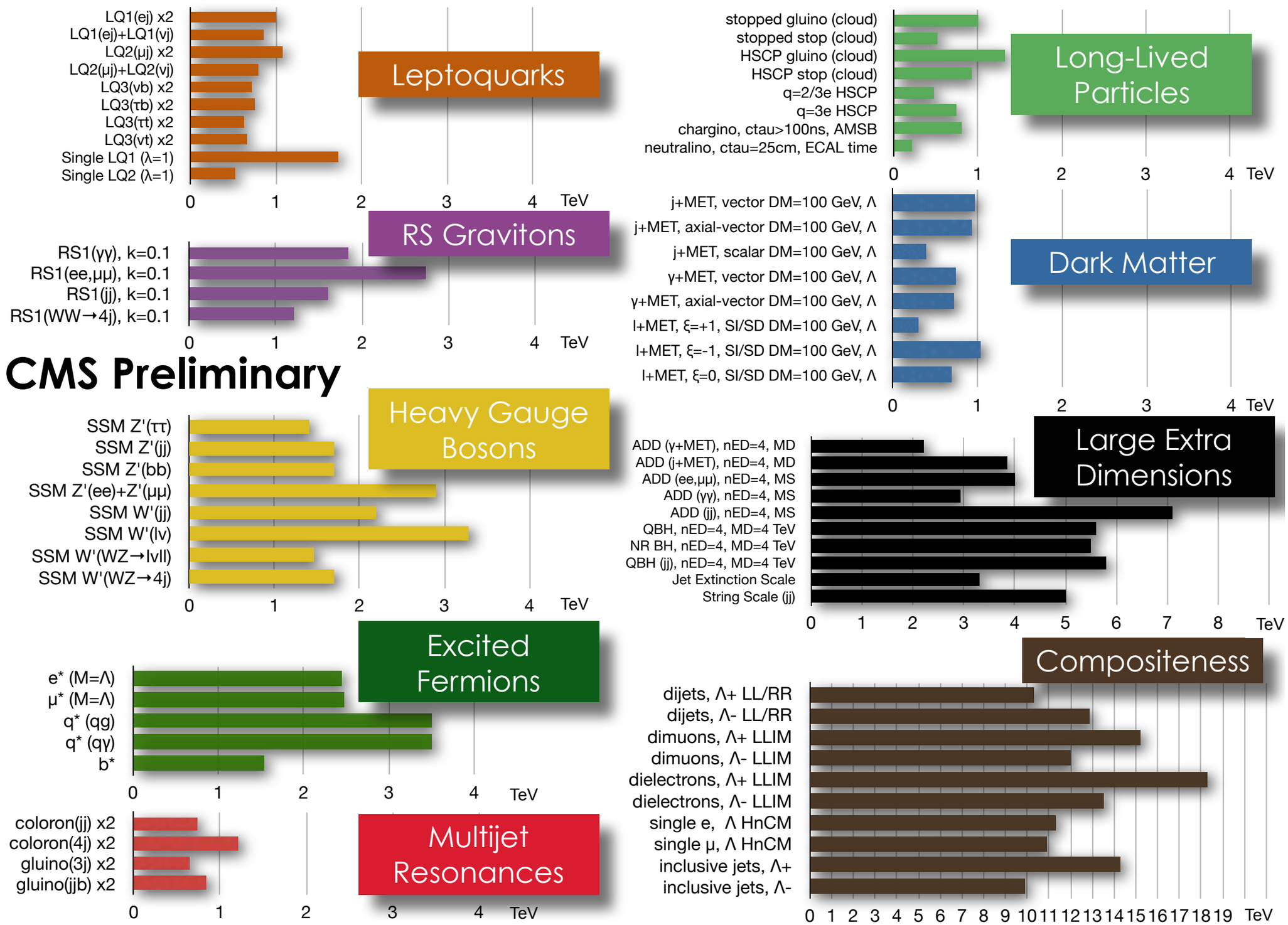
THEORY MOTIVATION FOR EXOTIC SIGNATURES: PROSPECTS AND WISHLIST FOR RUN II

DANIEL STOLARSKI

LHCP August 31, 2015

WHAT IS EXOTICS?



CMS Exotica Physics Group Summary – Moriond, 2015

WHAT IS EXOTICS?

ATLAS Exotics Searches* - 95% CL Exclusion

Status: July 2015

ATLAS Preliminary

$\int \mathcal{L}\,dt = (4.7 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	20.3	M_D 5.25 TeV	$n = 2$	1502.01518
	ADD non-resonant $\ell\ell$	$2e,\mu$	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\to \ell q$	$1\,e,\mu$	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	1407.1376
	ADD BH high N_{trk}	$2\,\mu$ (SS)	–	–	20.3	M_{th} 4.7 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\,e,\mu$	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1405.4254
	ADD BH high multijet	–	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1503.08988
	RS1 $G_{KK} \to \ell\ell$	$2\,e,\mu$	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	$2\,\gamma$	–	–	20.3	G_{KK} mass 2.65 TeV	$k/\overline{M}_{Pl} = 0.1$	1504.05511
	Bulk RS $G_{KK} \to ZZ \to qq\ell\ell$	$2\,e,\mu$	2 j / 1 J	–	20.3	G_{KK} mass 740 GeV	$k/\overline{M}_{Pl} = 1.0$	1409.6190
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	$1\,e,\mu$	2 j / 1 J	Yes	20.3	W' mass 760 GeV	$k/\overline{M}_{Pl} = 1.0$	1503.04677
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 500-720 GeV	$k/\overline{M}_{Pl} = 1.0$	1506.00285
	Bulk RS $g_{KK} \to t\bar{t}$	$1\,e,\mu$	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	$2\,e,\mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	KK mass 960 GeV		1504.04605
Gauge bosons	SSM $Z' \to \ell\ell$	$2\,e,\mu$	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	$2\,\tau$	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	SSM $W' \to \ell\nu$	$1\,e,\mu$	–	Yes	20.3	W' mass 3.24 TeV		1407.7494
	EGM $W' \to WZ \to \ell\nu\ell'\ell'$	$3\,e,\mu$	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	$2\,e,\mu$	2 j / 1 J	–	20.3	W' mass 1.59 TeV		1409.6190
	EGM $W' \to WZ \to qqqq$	–	2 J	–	20.3	W' mass 1.3-1.5 TeV		1506.00962
	HVT $W' \to WH \to \ell\nu bb$	$1\,e,\mu$	2 b	Yes	20.3	W' mass 1.47 TeV	$g_V = 1$	1503.08089
	LRSM $W'_R \to t\bar{b}$	$1\,e,\mu$	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to t\bar{b}$	$0\,e,\mu$	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	17.3	Λ 12.0 TeV	$\eta_{LL} = -1$	1504.00357
	CI $qq\ell\ell$	$2\,e,\mu$	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	1407.2410
	CI $uutt$	$2\,e,\mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	Λ 4.3 TeV	$\lvert C_{LL}\rvert = 1$	1504.04605
DM	EFT D5 operator (Dirac)	$0\,e,\mu$	≥ 1 j	Yes	20.3	M_* 974 GeV	at 90% CL for $m(\chi) < 100$ GeV	1502.01518
	EFT D9 operator (Dirac)	$0\,e,\mu$	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	$2\,e$	≥ 2 j	–	20.3	LQ mass 1.05 TeV	$\beta = 1$	Preliminary
	Scalar LQ 2nd gen	$2\,\mu$	≥ 2 j	–	20.3	LQ mass 1.0 TeV	$\beta = 1$	Preliminary
	Scalar LQ 3rd gen	$1\,e,\mu$	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	Preliminary
Heavy quarks	VLQ $TT \to Ht + X$	$1\,e,\mu$	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	$1\,e,\mu$	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	$1\,e,\mu$	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	$2/\geq 3\,e,\mu$	≥2/≥1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	$T_{5/3} \to Wt$	$1\,e,\mu$	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV		1503.05425
Excited fermions	Excited quark $q^* \to q\gamma$	$1\,\gamma$	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q^* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1407.1376
	Excited quark $b^* \to Wt$	1 or 2 e,μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	$2\,e,\mu$, $1\,\gamma$	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
	Excited lepton $\nu^* \to \ell W, \nu Z$	$3\,e,\mu,\tau$	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \to W\gamma$	$1\,e,\mu$, $1\,\gamma$	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	$2\,e,\mu$	2 j	–	20.3	N^R mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2\,e,\mu$ (SS)	–	–	20.3	$H^{\pm\pm}$ mass 551 GeV	DY production, $BR(H_L^{\pm\pm} \to \ell\ell)=1$	1412.0237
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	$3\,e,\mu,\tau$	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $BR(H_L^{\pm\pm} \to \ell\tau)=1$	1411.2921
	Monotop (non-res prod)	$1\,e,\mu$	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	Preliminary

10^{-1} 1 10 **Mass scale [TeV]**

$\sqrt{s} = 7$ TeV $\sqrt{s} = 8$ TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

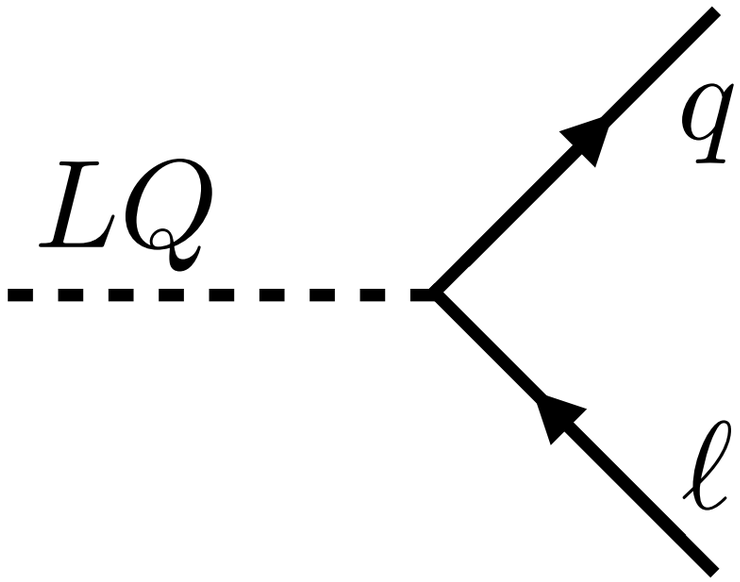
NON-SUSY?

Appears to be non-SUSY signatures.

Nearly everything on previous pages can be SUSY.

Example: Leptoquark

$$\mathcal{L} = LQ\ q\ \ell$$



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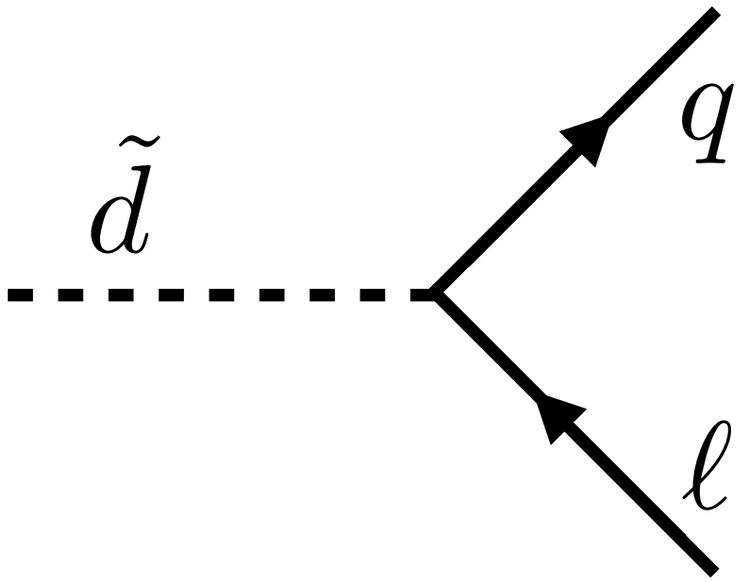
$$\mathcal{L} = \tilde{d}\, q\, \ell$$



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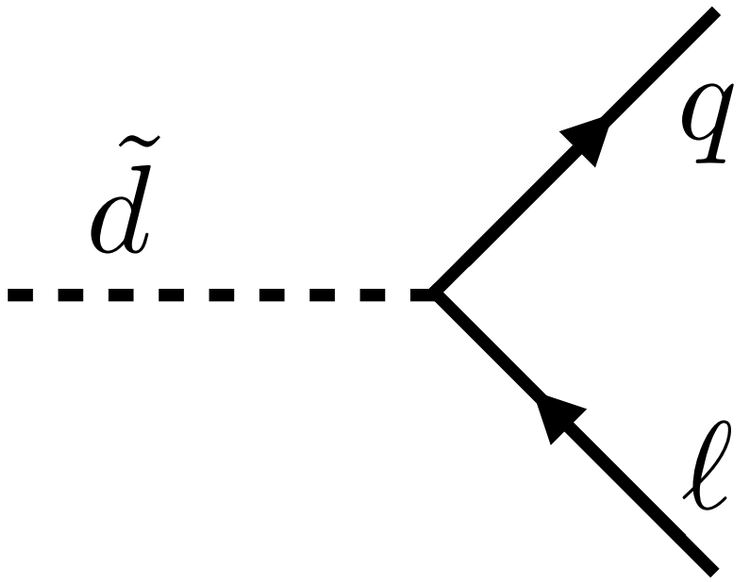
Example: Leptoquark

$$\mathcal{L} = \tilde{d}\, q\, \ell$$

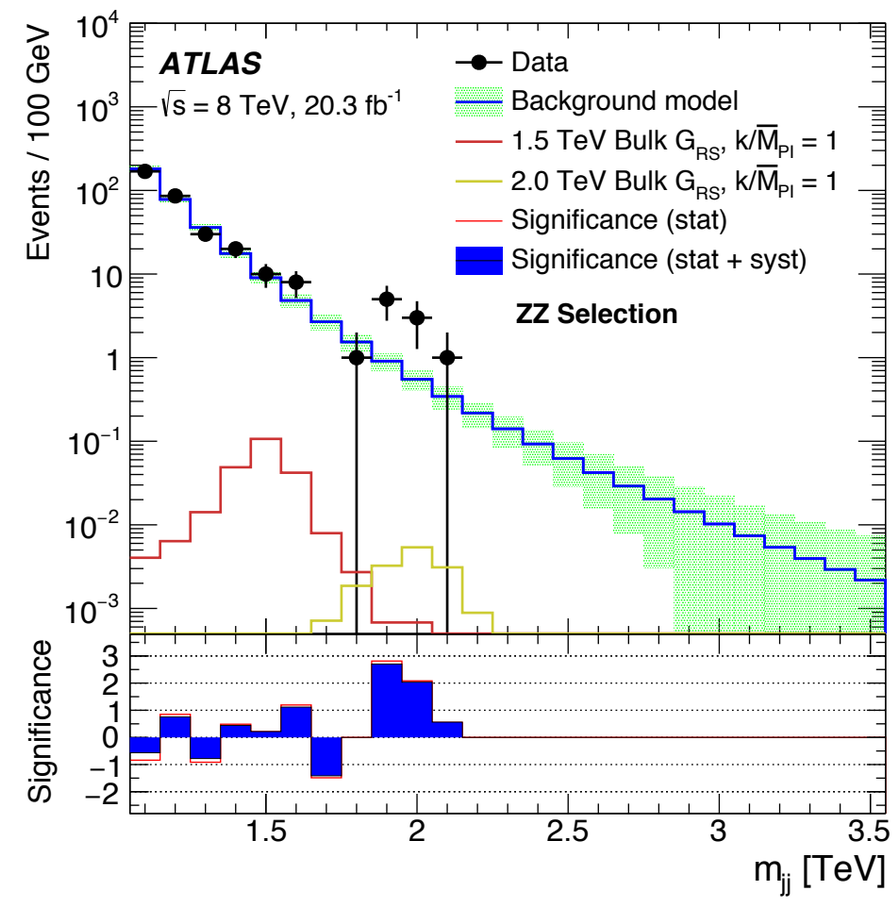
$$W = \lambda'\, L\, Q\, D$$



Leptoquark = down squark

ONE MORE EXAMPLE

Diboson resonance (W' or Z'):



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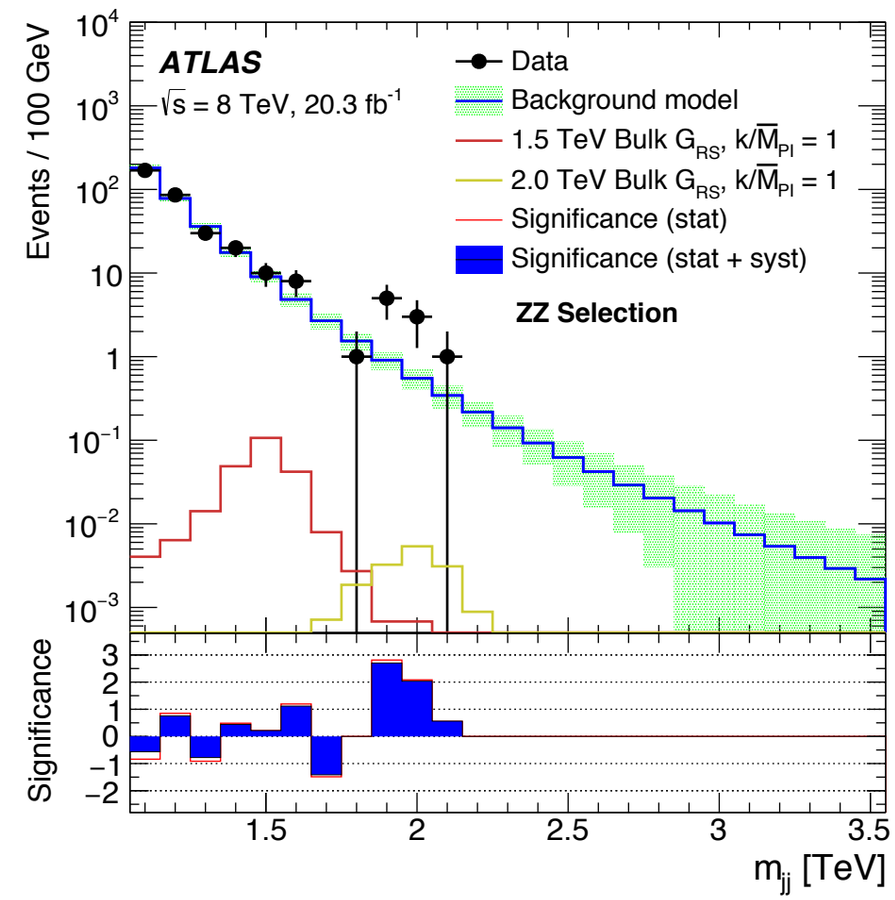
Diboson resonance (W' or Z'):

In SUSY Higgs quartic and physical mass are determined by gauge structure: $m_h \leq m_Z$

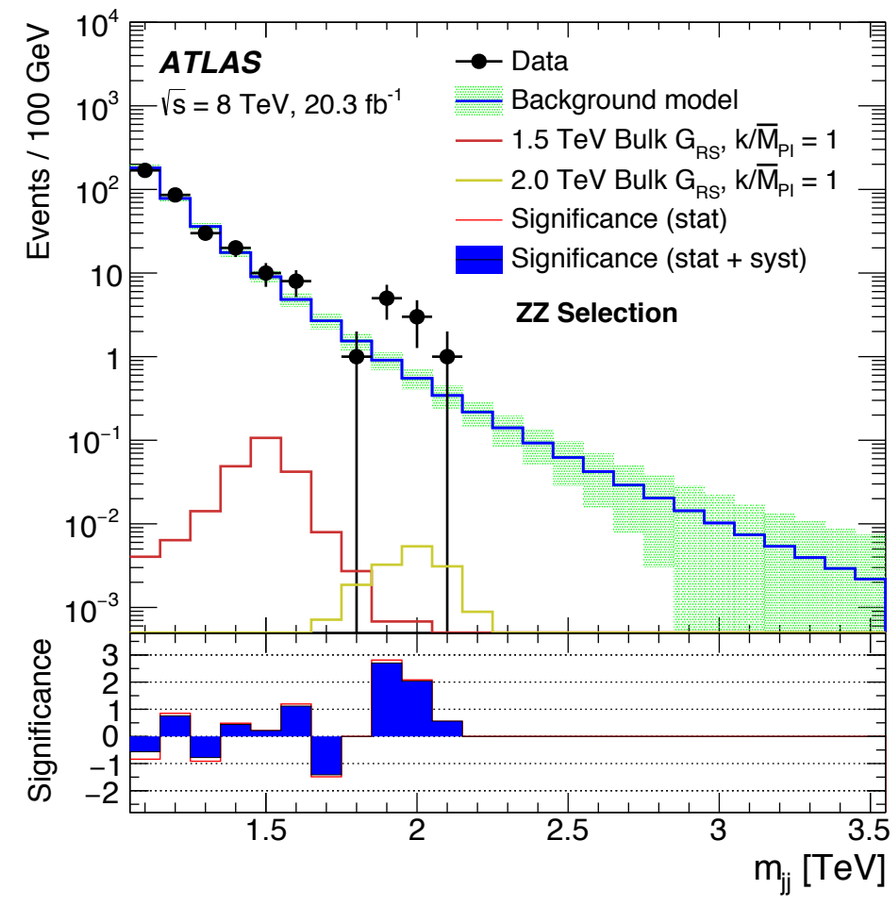


ONE MORE EXAMPLE

Diboson resonance (W' or Z'):

In SUSY Higgs quartic and physical mass are determined by gauge structure: $m_h \leq m_Z$

Elegant solution to Higgs mass problem is new gauge force: "non-decoupling *D*-terms."



Batra, Delgado, Kaplan, Tait, hep-ph/0309149.
Maloney, Pierce, Wacker, hep-ph/0409127.

See also Petersson and Torre, arXiv:1508.05632.

EXOTICS ARE

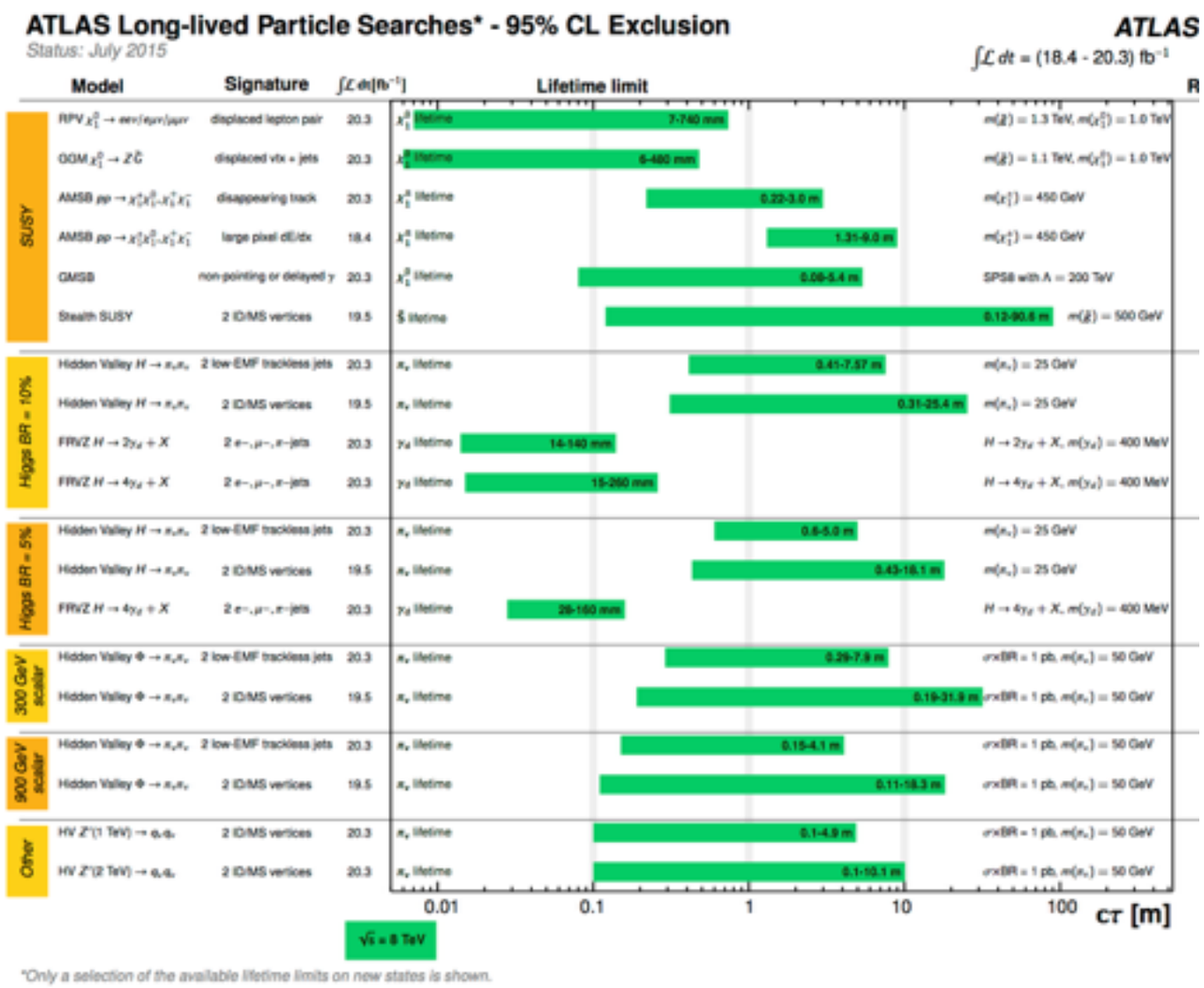
Use more experimental definition of exotics:

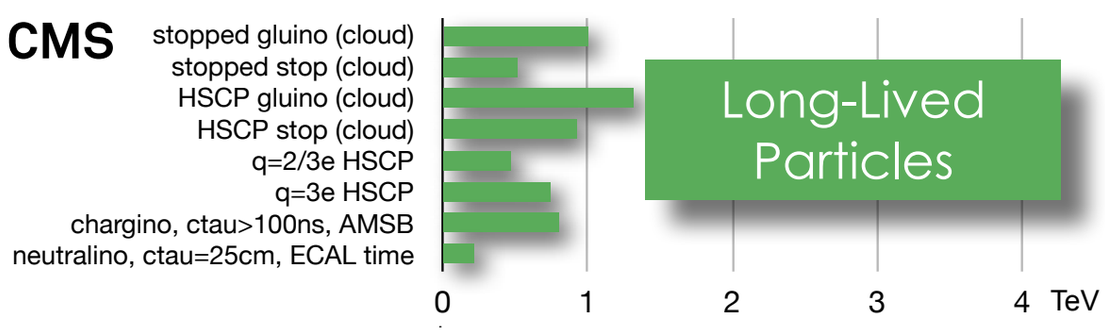
New objects that are not produced in the SM.

Focus this talk on long-lived objects.

Disclaimer: Even with this narrow definition, I will not cover all possible scenarios, I will just give a taste of some of them.

CURRENT SEARCHES



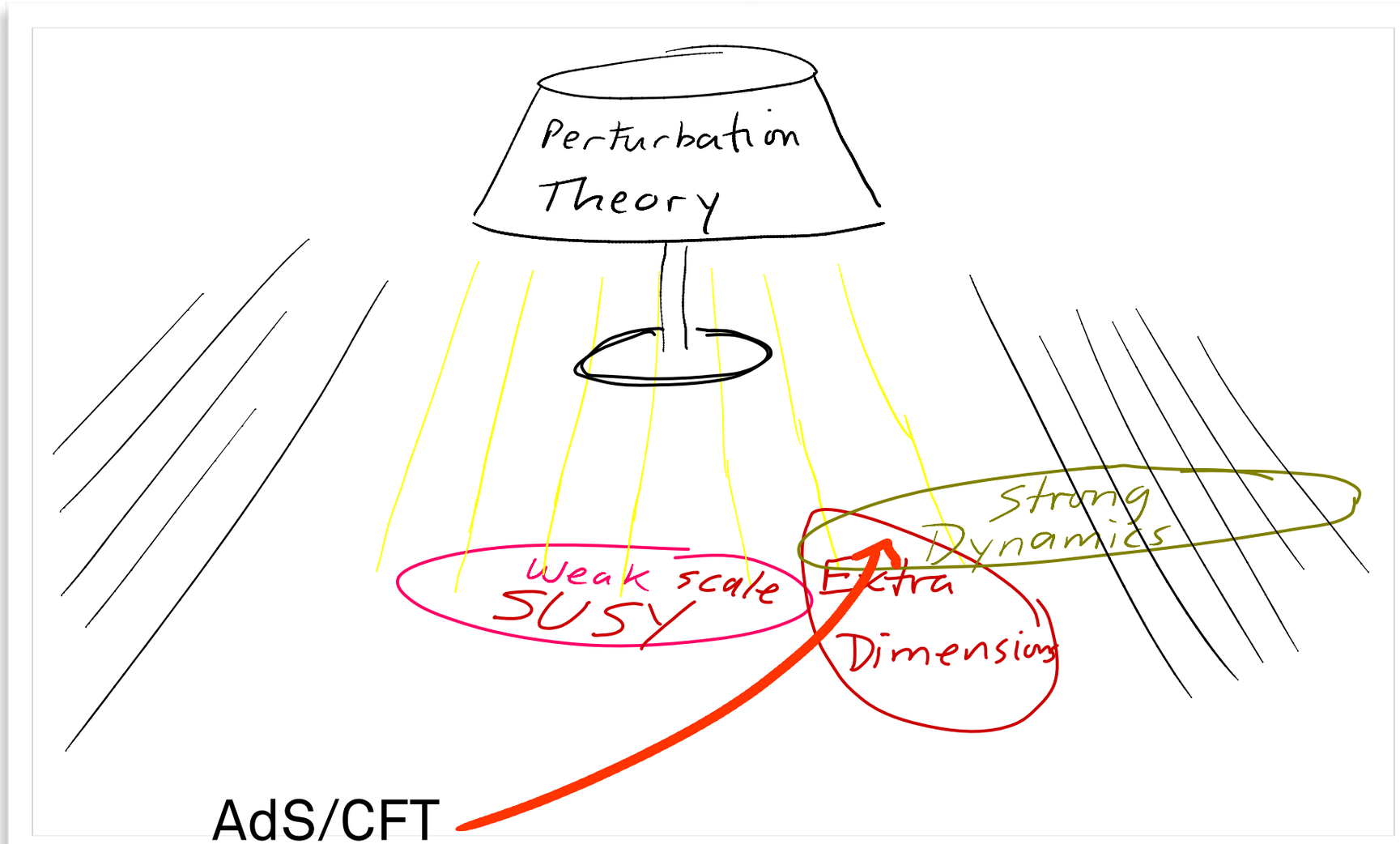


See talks by Daniela Salvatore and Malgorzata Kazana in this session.

Maybe also Zhu and De Cosa in this afternoon's plenary.

GENERAL MOTIVATION

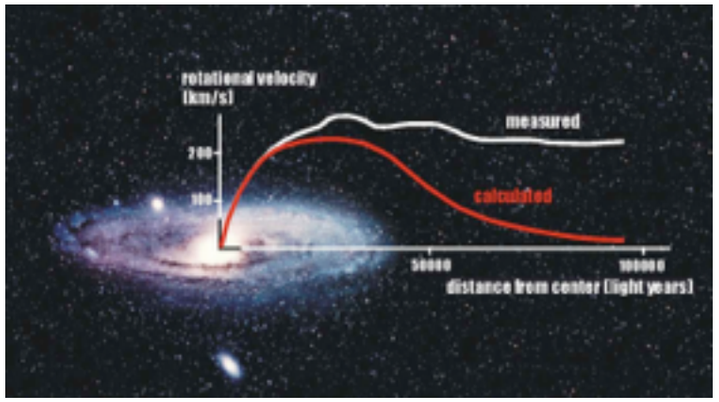
Getting away from the lamp post

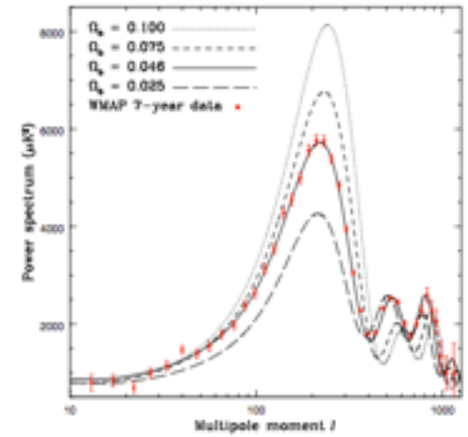


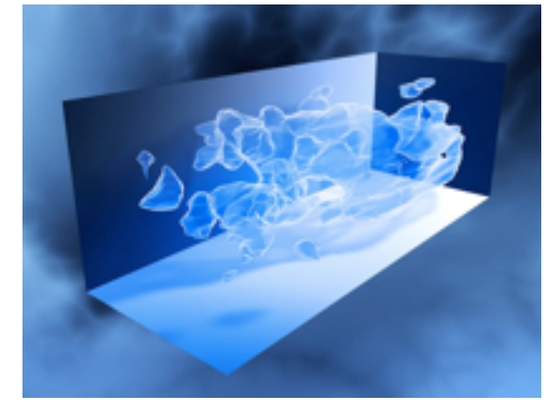
R. Sundrum

DARK MATTER

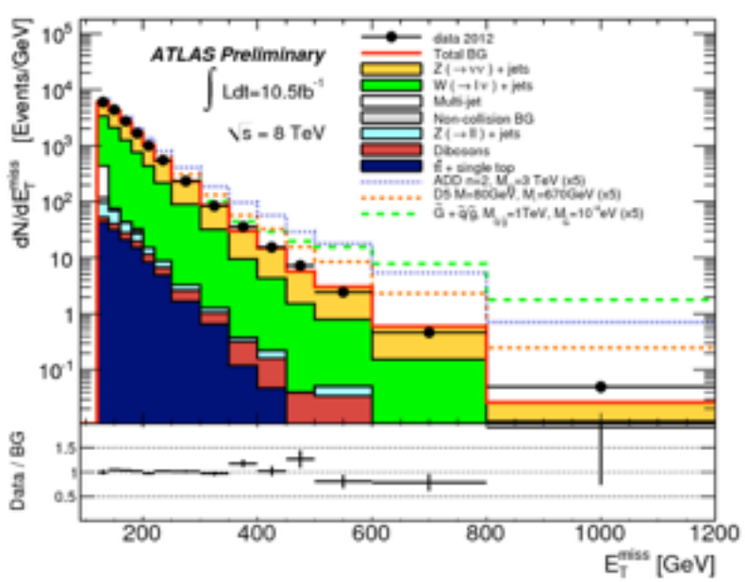
We have seen dark matter in the sky.

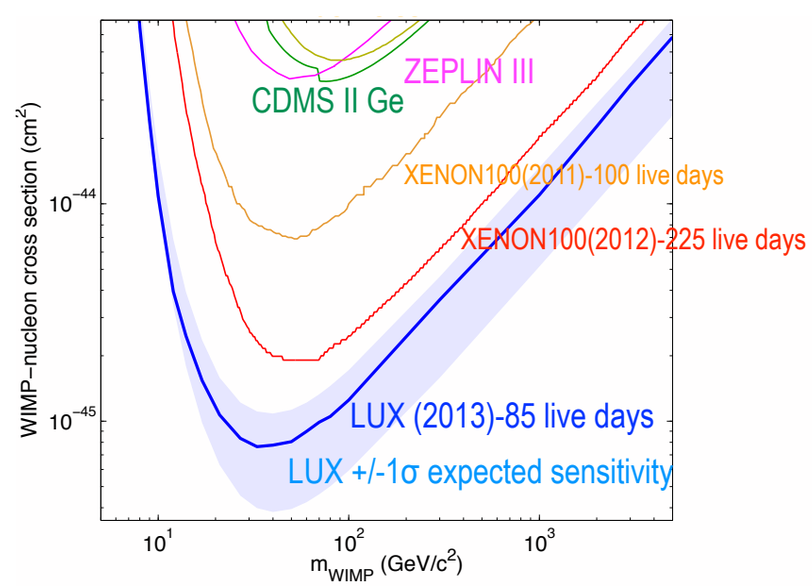






But not in the lab.



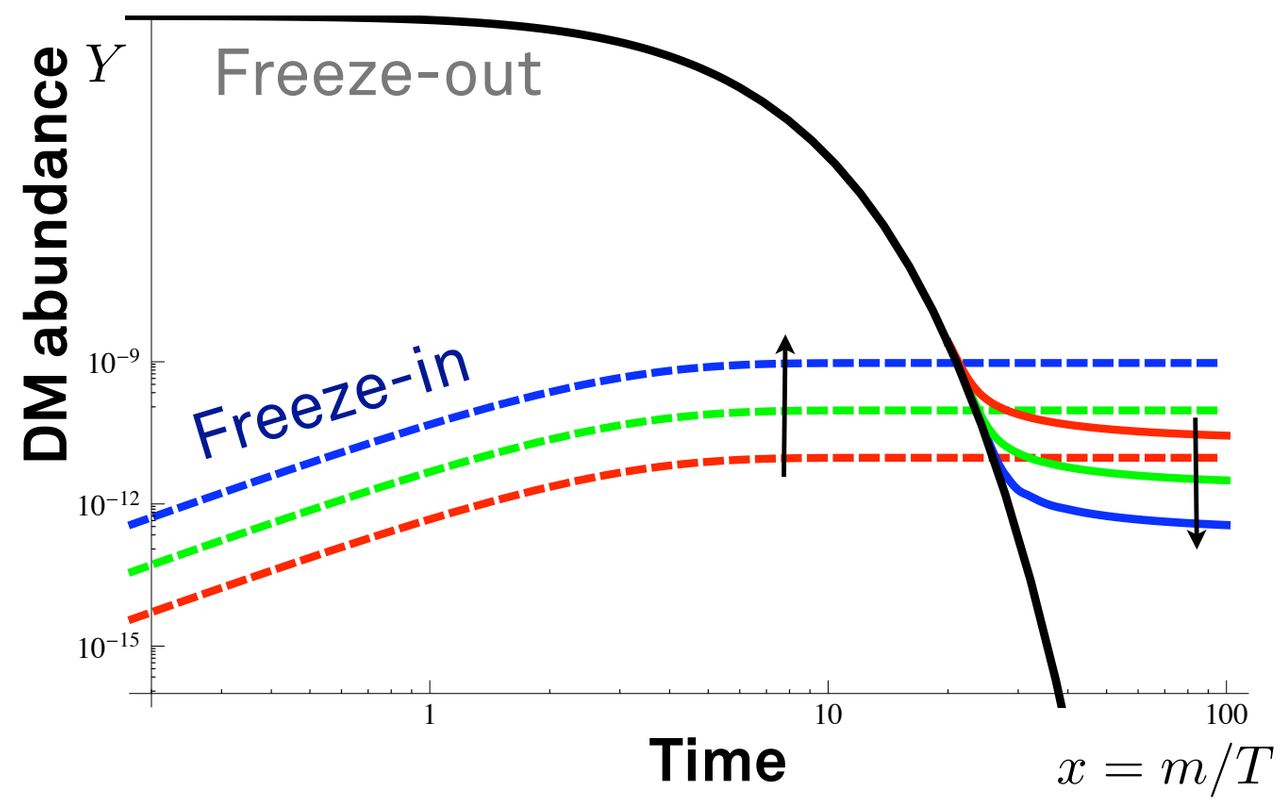


FREEZE-IN

Weak coupling of DM to thermal bath.

DM never in equilibrium, bath slowly leaks energy into DM sector.

Thermal abundance set by small coupling.



Hall, Jadamzik, March-Russel, West, arXiv:0911.1120.

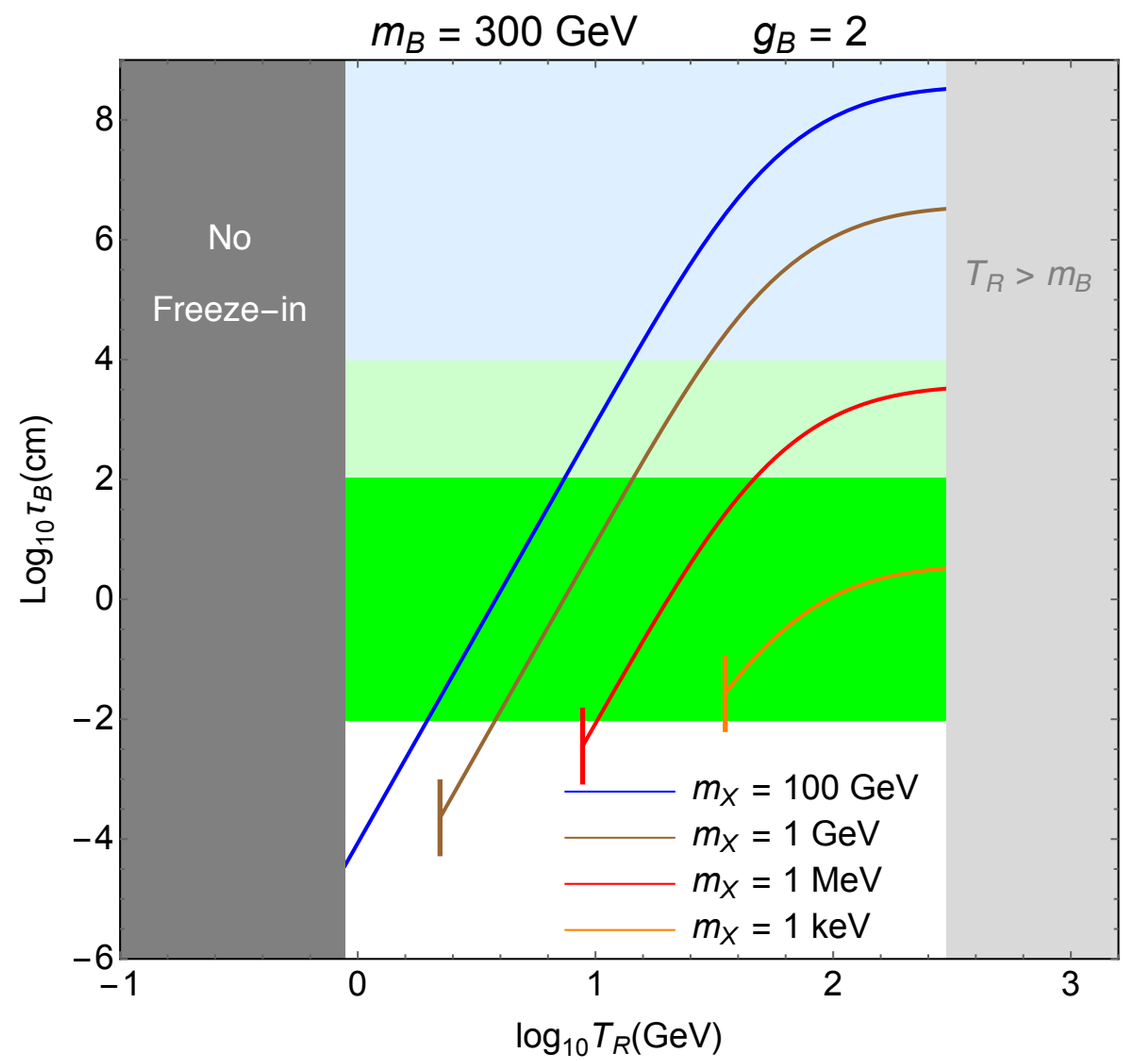
FREEZE-IN

$$B \to A_{\rm SM} X$$

DM

Big coupling to SM, small coupling to DM.

Co, D'Eramo, Hall, Pappadopulo, arXiv: 1506.07532.



Shaded region	Decay length	Signature from LOSP	Neutral	Charged
Dark green	$10^{-2}\mathrm{cm} < \tau_B < 10^{2}\mathrm{cm}$	Displaced vertices	✓	✓
Light green	$10^{2}\mathrm{cm} < \tau_B < 10^{4}\mathrm{cm}$	Displaced jets/leptons	✓	✓
Light blue	$10^{4}\mathrm{cm} < \tau_B$	Stopped particle decays	X	✓

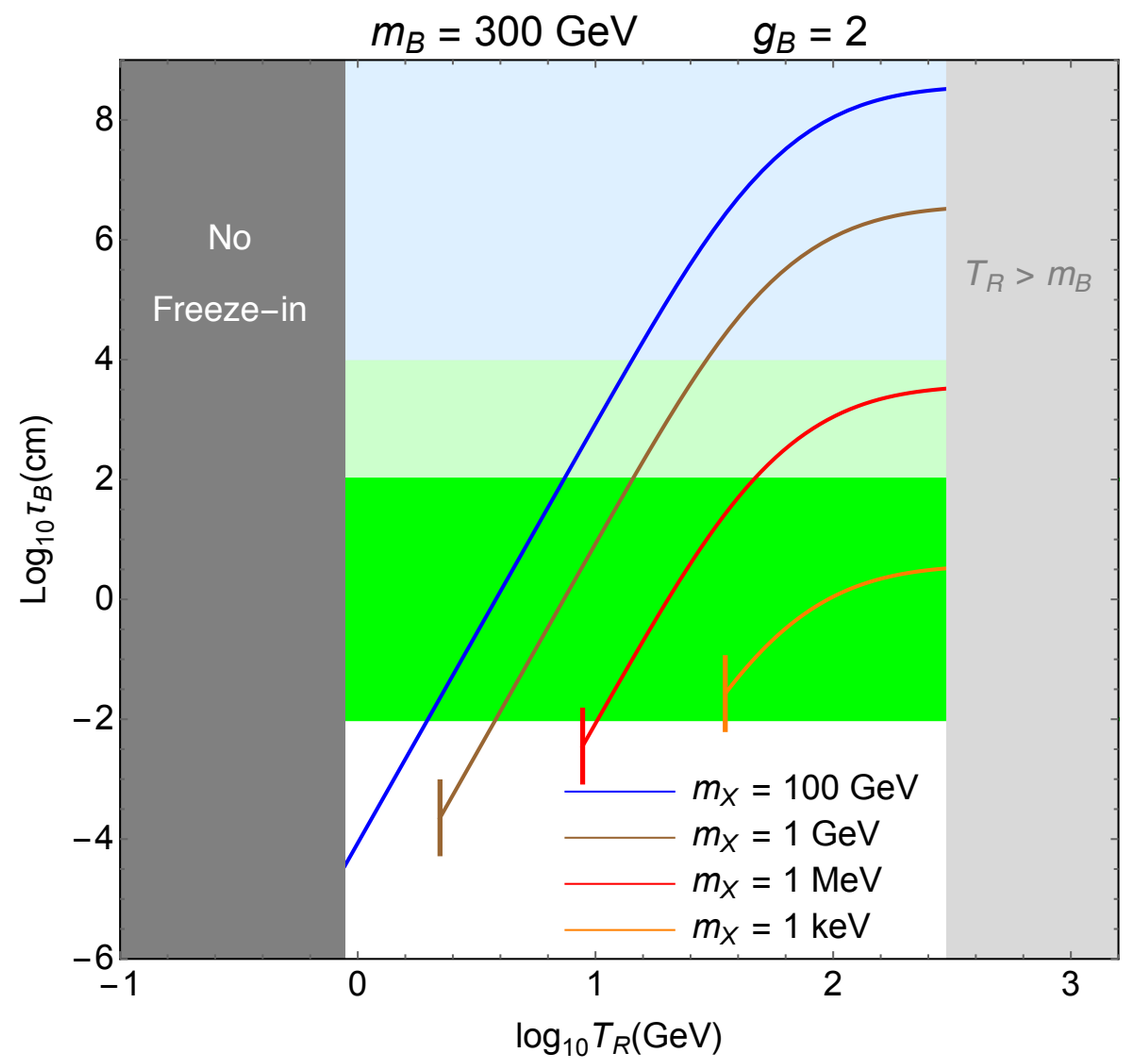
FREEZE-IN

$$B \to A_{\rm SM} X$$

$$\downarrow$$

Any SM state:

$h,\ Z,\ \ell^+\ell^-,\ q\bar{q},\ \gamma\ , \ldots$



Co, D'Eramo, Hall, Pappadopulo, arXiv: 1506.07532.

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ASYMMETRIC DARK MATTER

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

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

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ASYMMETRIC DARK MATTER

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Controlled by complicated (known) QCD dynamics

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Controlled by complicated (known) QCD dynamics

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Unknown dynamics of baryogenesis

ASYMMETRIC DARK MATTER

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Controlled by complicated (known) QCD dynamics

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?

Unknown dynamics of baryogenesis

ASYMMETRIC DARK MATTER

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

QCD like

?

Controlled by complicated (known) QCD dynamics

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

$$\Omega_B = m_p n_B$$

?

Unknown dynamics of baryogenesis

MANY PAPERS

S. Nussinov, Phys.Lett.B.165 (1985) 55.

D. B. Kaplan, Phys.Rev.Lett.B.68 (1992) 741-3.

...

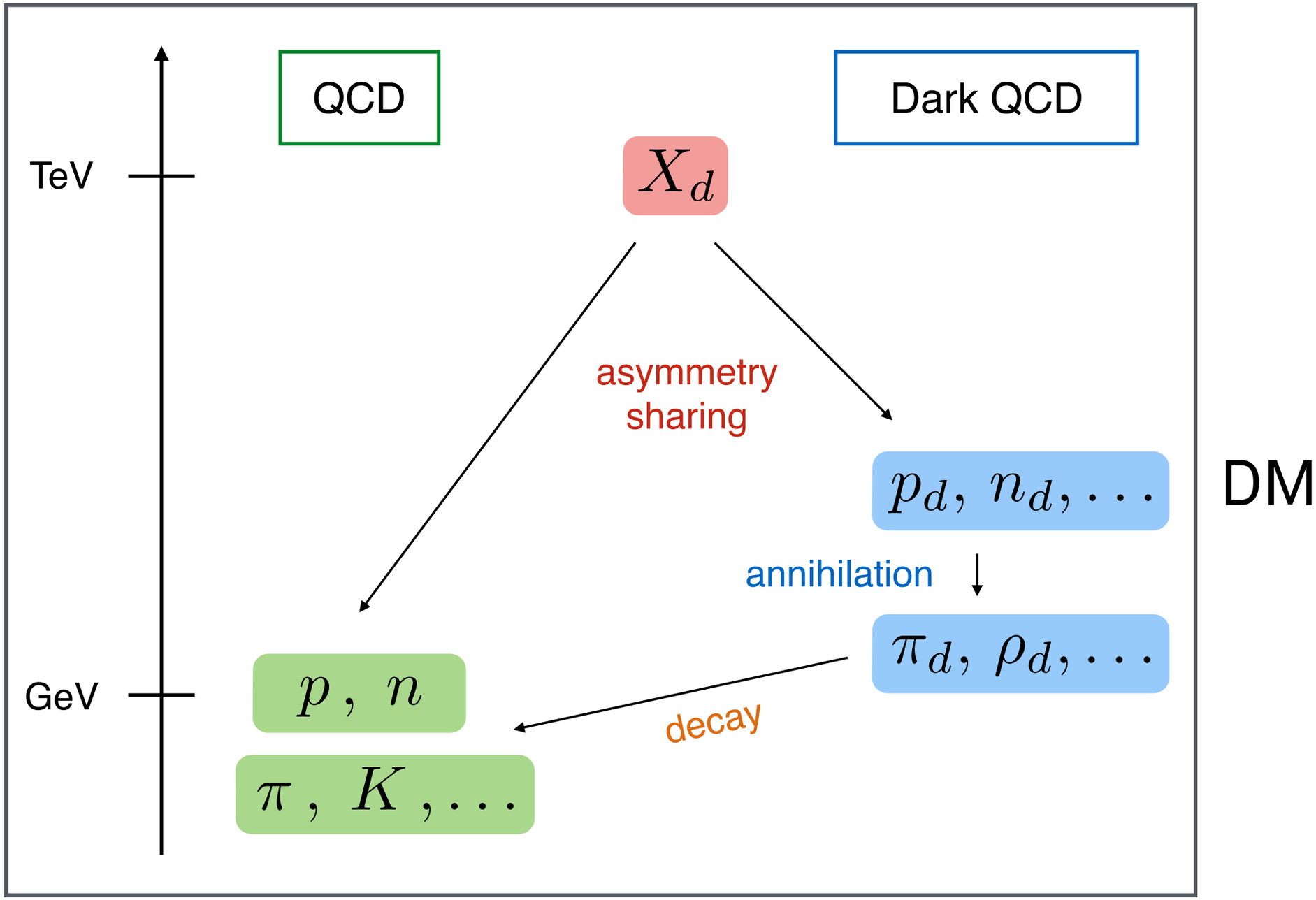
D. E. Kaplan, M. A. Luty, K. M. Zurek, arXiv:0901.4117.

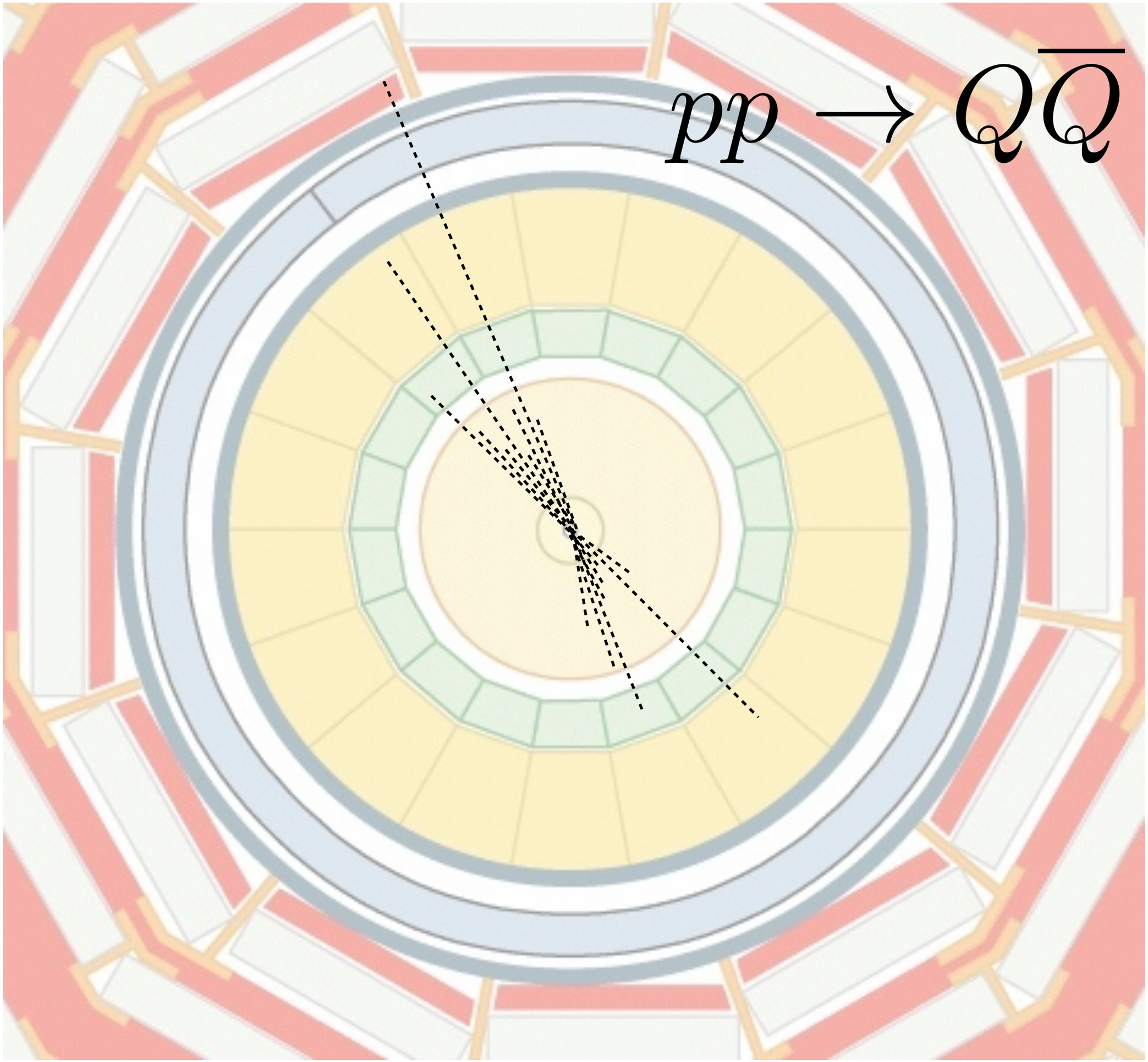
Bai and Schwaller, arXiv:1306.4676.

K. K. Boddy, et.al. arXiv:1402.362.

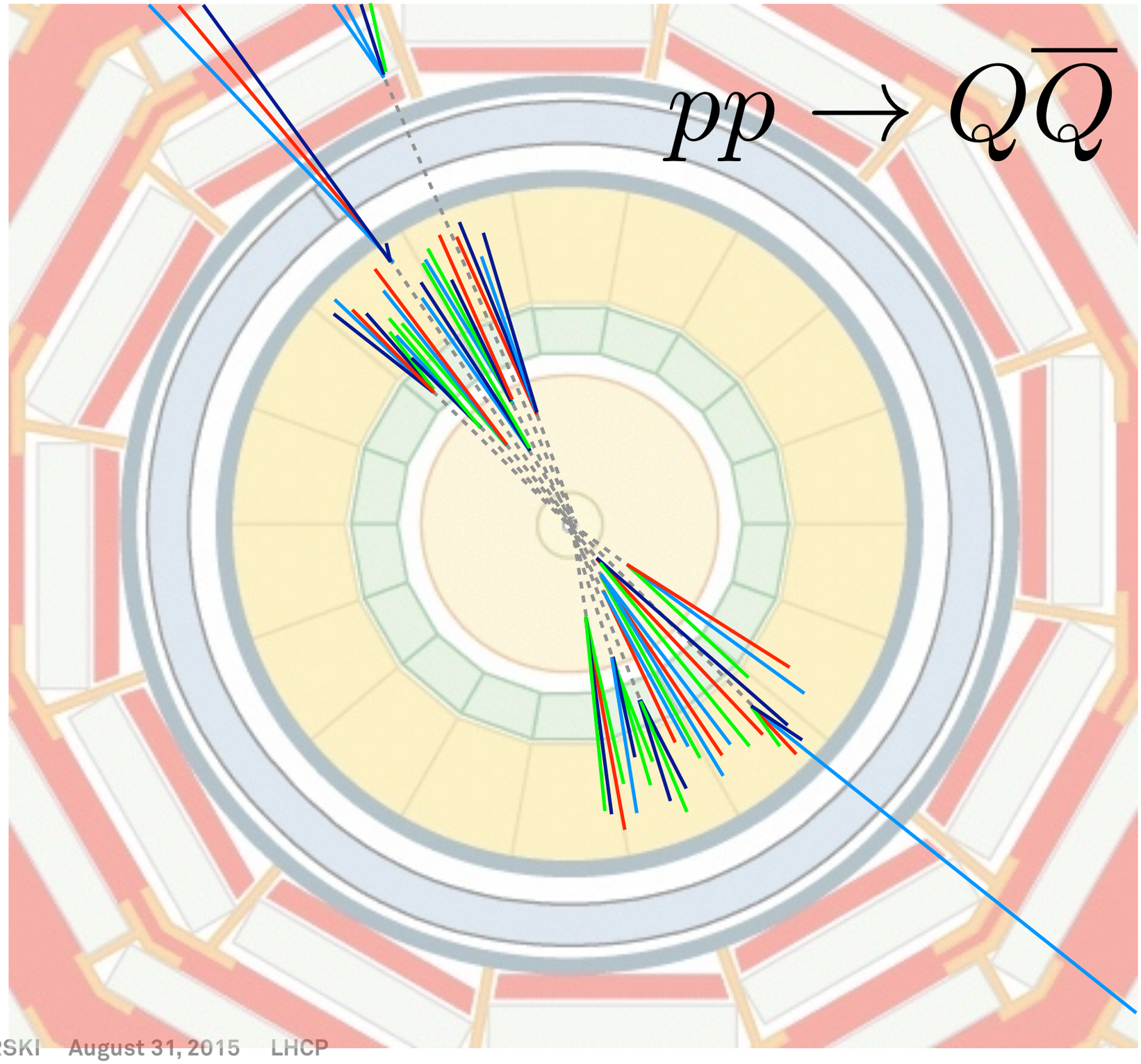
For a review see K. Petraki and R. R. Volkas, Int.J.Mod.Phys.A 28, 1330028 (2013) [arXiv:1305.4939 [hep-ph]].

GENERAL PICTURE




$pp \to Q\overline{Q}$

EMERGING JETS



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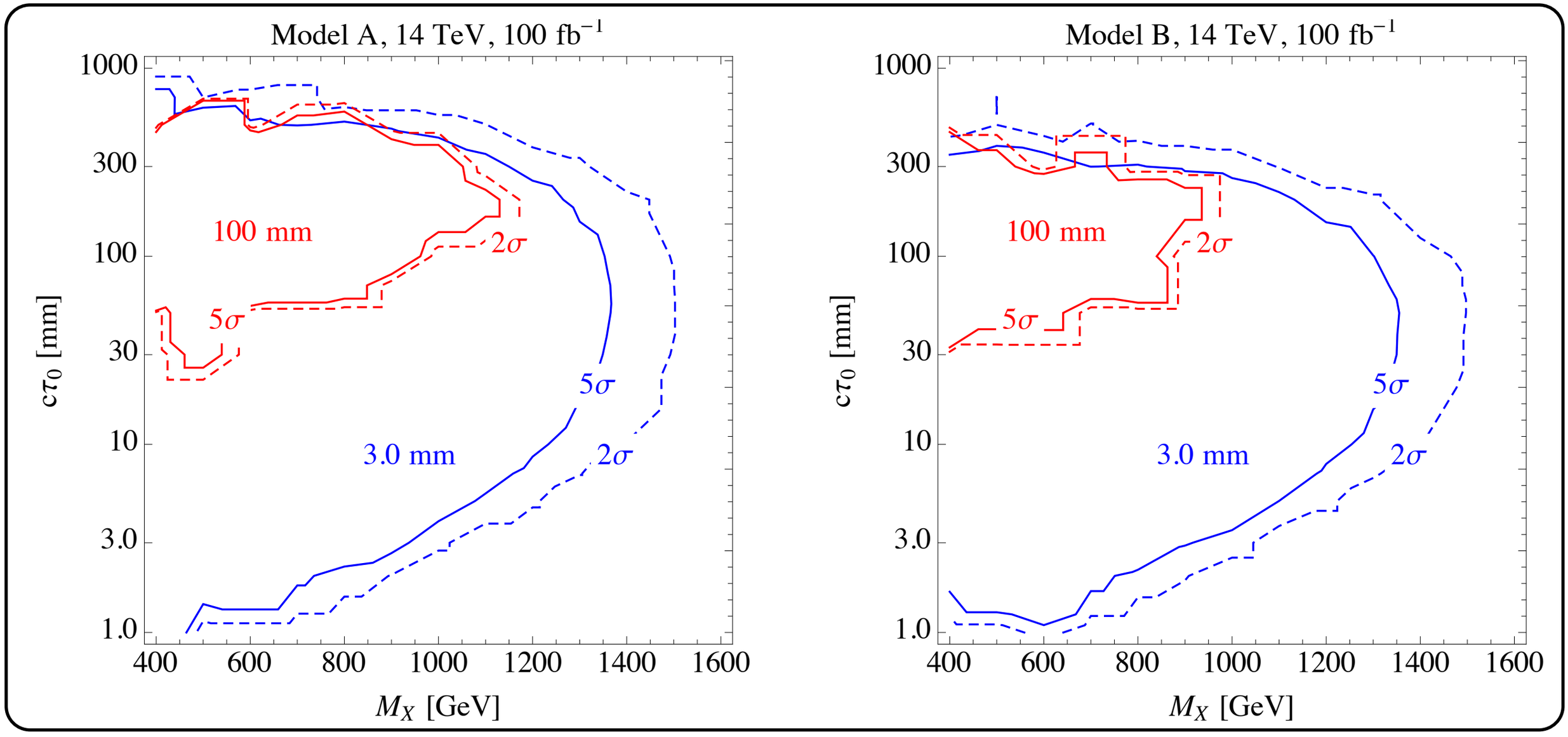
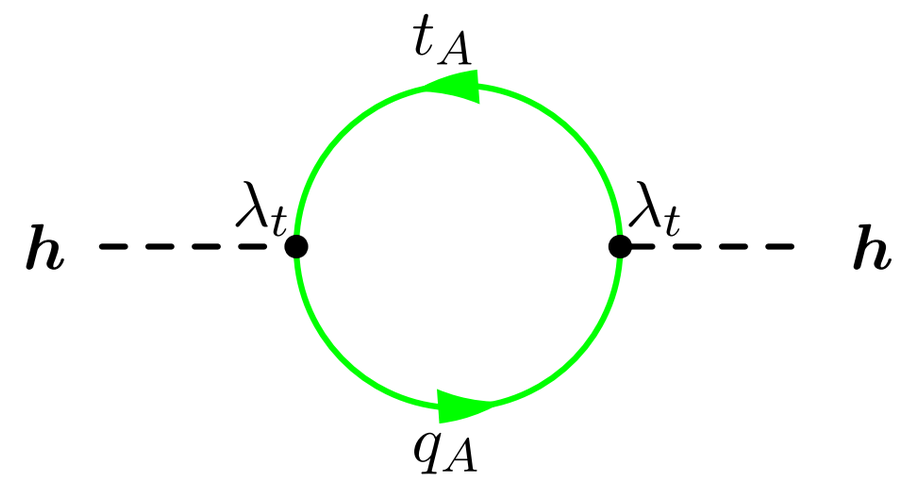


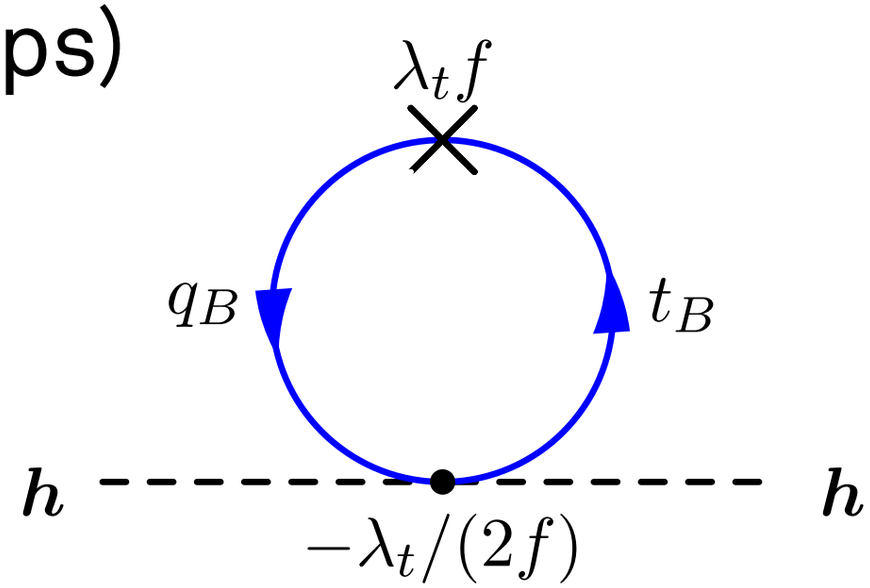
Schwaller, DS, Weiler, arXiv:1502.05409.

TWIN HIGGS/FOLDED SUSY

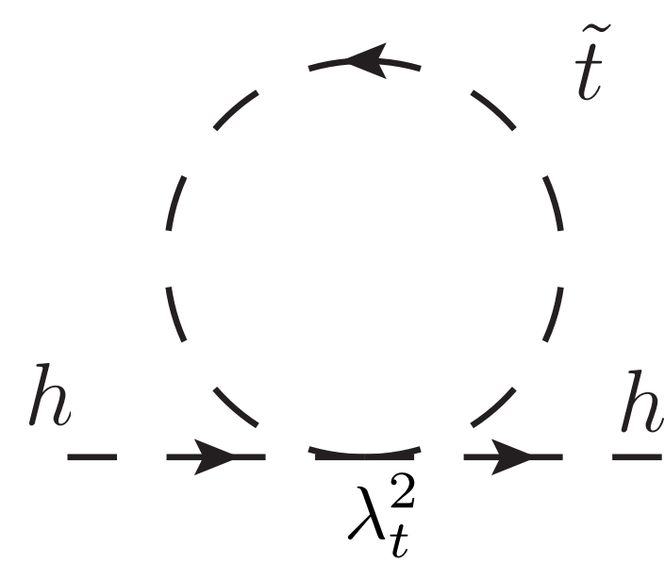
Gauge hierarchy problem:



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



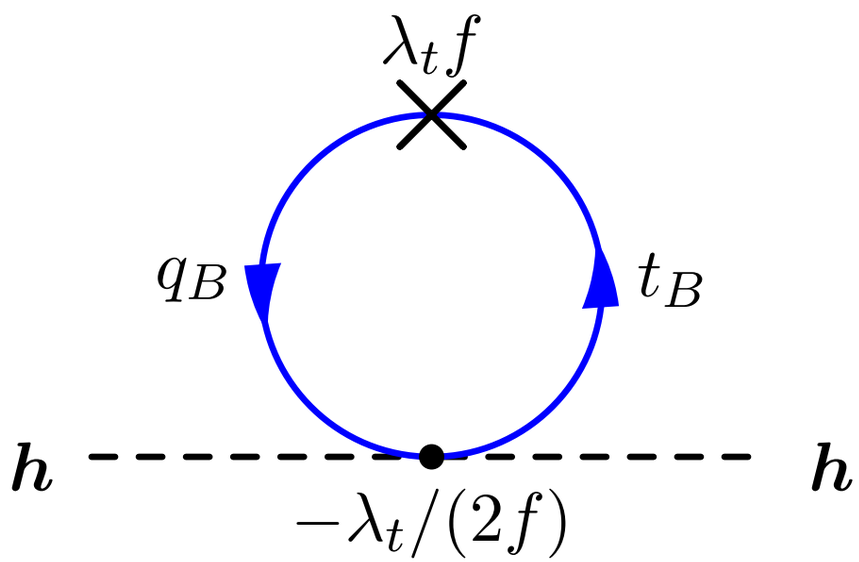
or

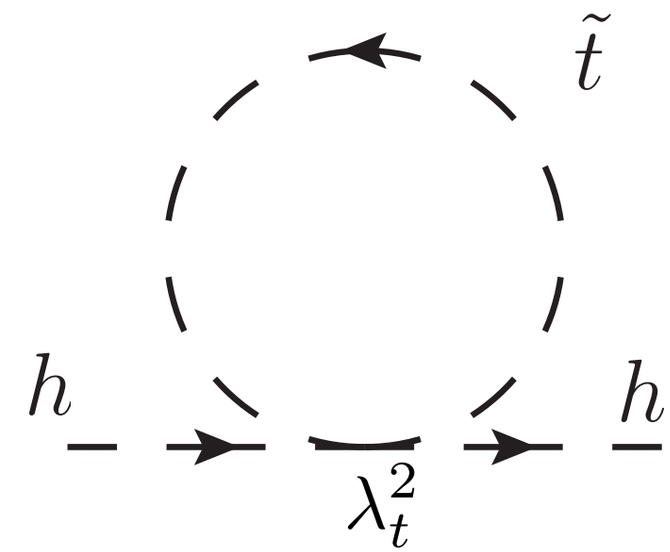


Do these partners need to be colored?

TWIN HIGGS/FOLDED SUSY

No! But still need factor of 3.

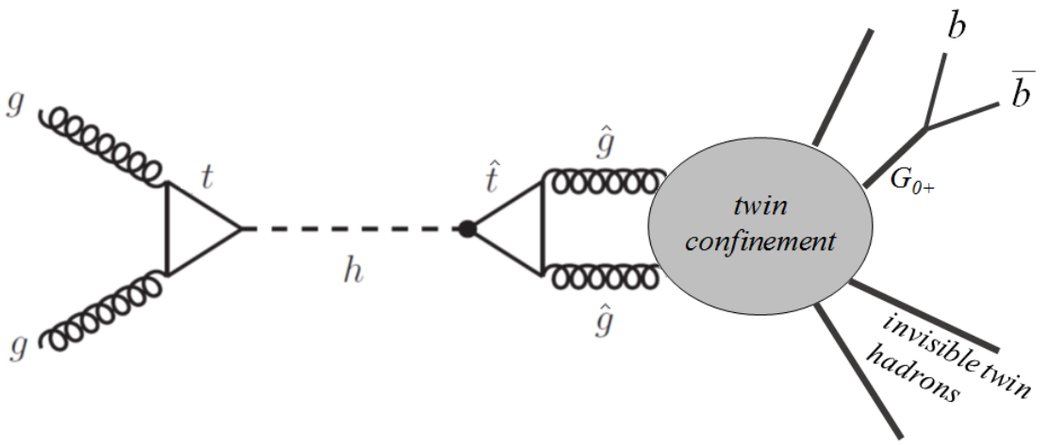




Chacko, Goh, Harnik, hep-ph/0506256.
Burdman, Chacko, Goh, Harnik, hep-ph/0609152.

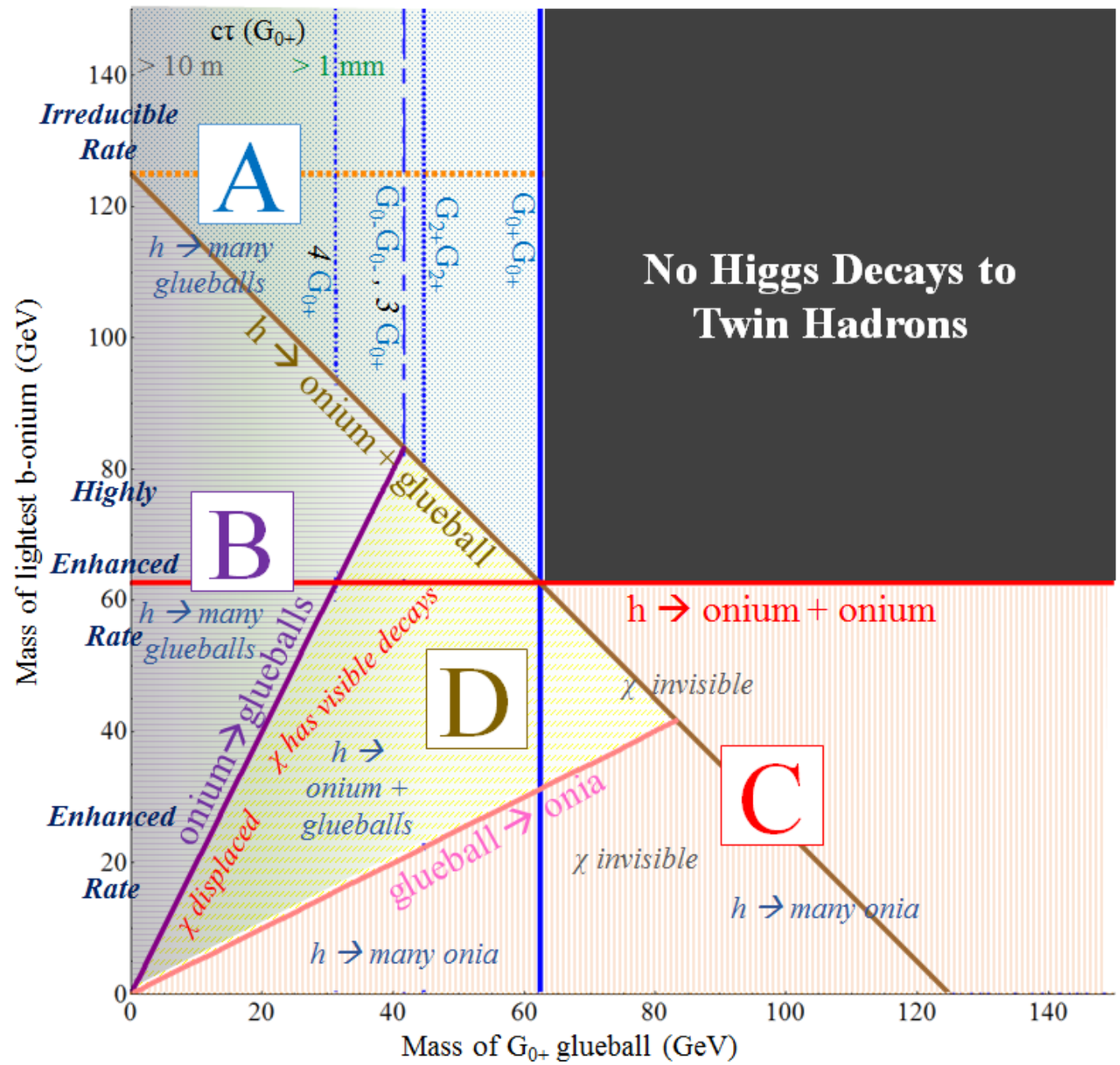
Most models have twin color which confines around GeV scale (or slightly higher).

HIGGS DECAYS



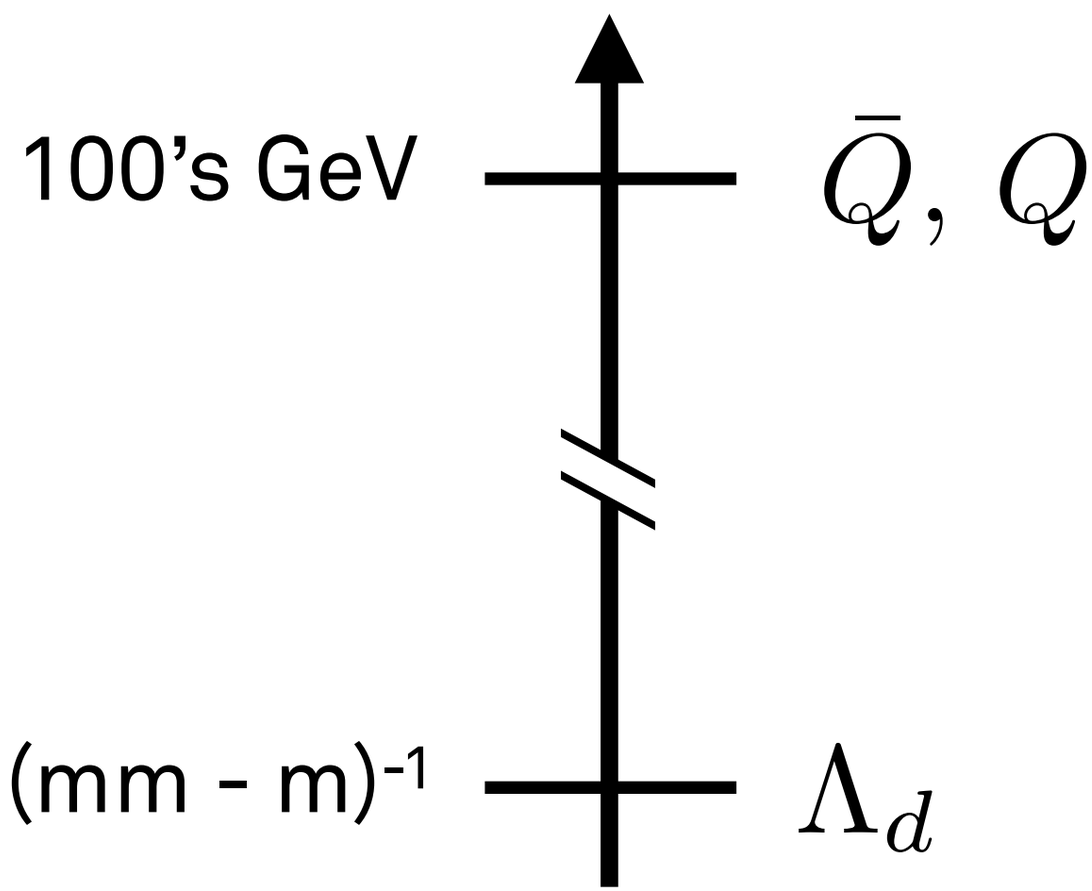
Craig, Katz, Strassler, Sundrum, arXiv:1501.05310.

See also Curtin, Verhaaren, arXiv:1506.06141
for more detailed pheno and Csaki, Kuflik, Lombardo, Slone, arXiv:1508.01522
for other displaced Higgs scenarios.



QUIRKS!

Can imagine taking confinement scale of twin/dark QCD to be much lower.

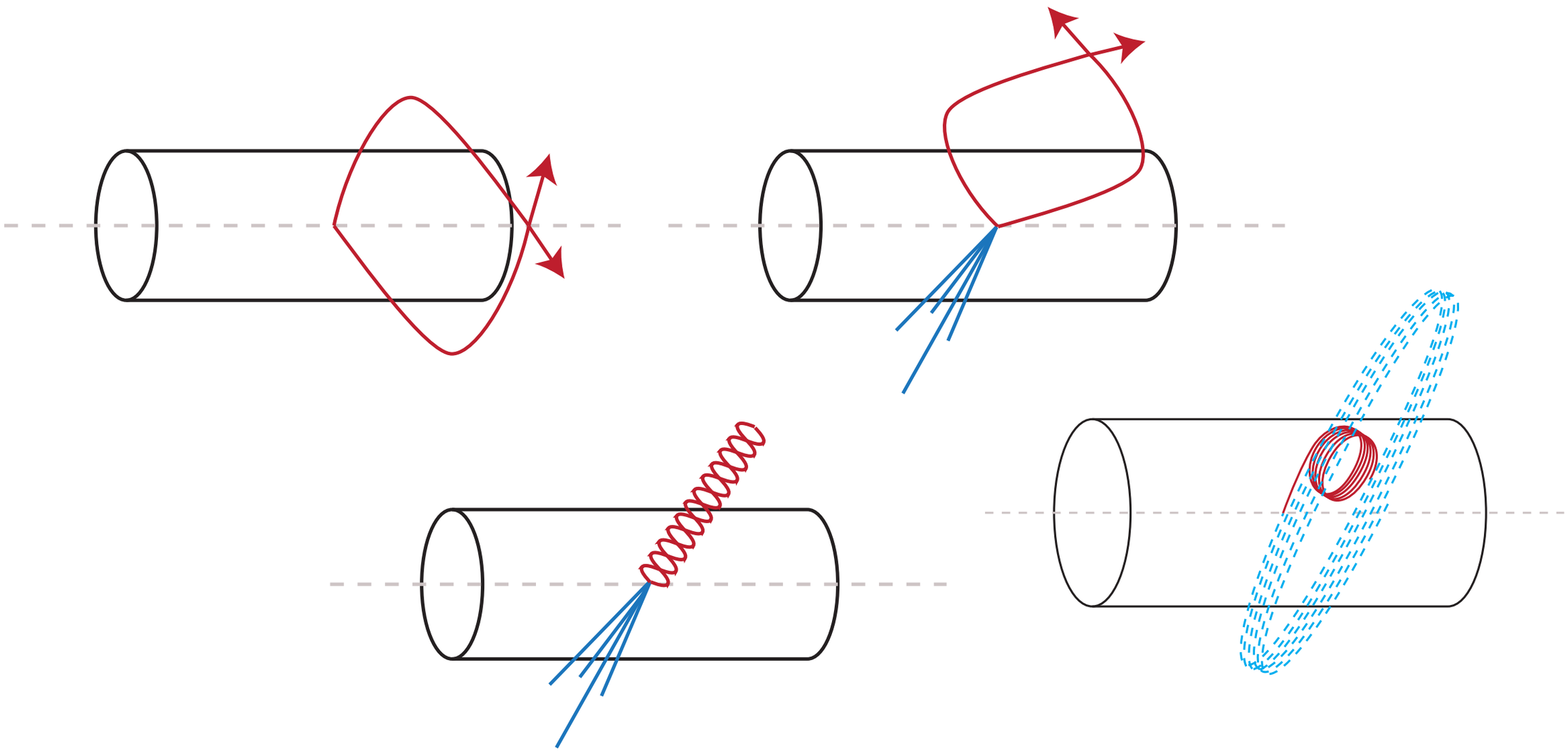


Quirks charged under SM and dark color.

Dark color confinement scale.

QUIRKS!

Confinement string can have macroscopic length.



Luty, Kang, arXiv:0805.4642.

NOTE ON TRIGGERS

Exotic

Standard

Trigger	m_{π_v} (GeV)	$c\tau = 1$ mm				$c\tau = 10$ mm				$c\tau = 100$ mm			
		ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}	ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}	ϵ_{ggF}	ϵ_{VBF}	ϵ_{VH}	ϵ_{Total}
Displaced jet	10	0.01%	0.03%	0.03%	**0.01%**	0.3%	0.7%	0.6%	**0.3%**	5.5%	13.1%	10.8%	**6.3%**
	25	0%	0.02%	0.02%	**0.002%**	0.1%	0.3%	0.3%	**0.1%**	6.3%	16.5%	13.4%	**7.4%**
	40	0%	0.03%	0.03%	**0.004%**	0.2%	0.5%	0.5%	**0.2%**	6.6%	17.8%	14.2%	**7.8%**
Inclusive VBF	10	1.9%	15.5%	0.8%	**2.8%**	1.8%	15.5%	0.7%	**2.8%**	1.6%	15.1%	0.6%	**2.6%**
	25	1.7%	15.3%	0.7%	**2.7%**	1.7%	15.3%	0.7%	**2.7%**	1.6%	15.2%	0.6%	**2.6%**
	40	1.6%	15.2%	0.7%	**2.6%**	1.6%	15.2%	0.7%	**2.6%**	1.6%	15.2%	0.6%	**2.6%**
VBF, $h \to b\bar{b}$	10	5.8%	20.3%	13.1%	**7.2%**	5.8%	20.2%	13.0%	**7.2%**	3.5%	13.3%	8.1%	**4.4%**
	25	4.6%	16.6%	10.9%	**5.8%**	4.7%	16.7%	10.9%	**5.9%**	4.2%	15.2%	9.7%	**5.3%**
	40	4.0%	14.2%	9.2%	**5.0%**	4.0%	14.2%	9.2%	**5.0%**	3.8%	13.9%	8.9%	**4.8%**
Isolated Lepton	10	3.6%	3.7%	14.7%	**4.1%**	1.0%	1.0%	12.5%	**1.5%**	0.1%	0.2%	11.8%	**0.6%**
	25	1.0%	1.5%	13.0%	**1.6%**	0.3%	0.4%	11.9%	**0.8%**	0.05%	0.07%	11.7%	**0.6%**
	40	1.0%	1.4%	12.6%	**1.6%**	0.3%	0.4%	11.9%	**0.8%**	0.05%	0.07%	11.6%	**0.6%**
Trackless jet	10	0.02%	0.04%	0.04%	**0.02%**	0.8%	1.5%	1.3%	**0.9%**	2.0%	2.4%	2.2%	**2.0%**
	25	0.02%	0.04%	0.06%	**0.02%**	0.5%	1.0%	0.8%	**0.6%**	3.6%	5.9%	5.0%	**3.8%**
	40	0.01%	0.02%	0.03%	**0.01%**	0.1%	0.2%	0.2%	**0.1%**	2.1%	4.1%	3.3%	**2.3%**

Standard triggers can be very effective for exotic searches.

Csaki, Kuflik, Lombardo, Slone, arXiv:1508.01522.

WISHLIST

- More searches for distinct collider objects.
- Searches for different SM states originating in all different places in the detector.
- More general use of triggers, including multi-jet and VBF.
- Keep searches as model-independent as possible.

THANK YOU