Searching for Displaced Higgs Decays

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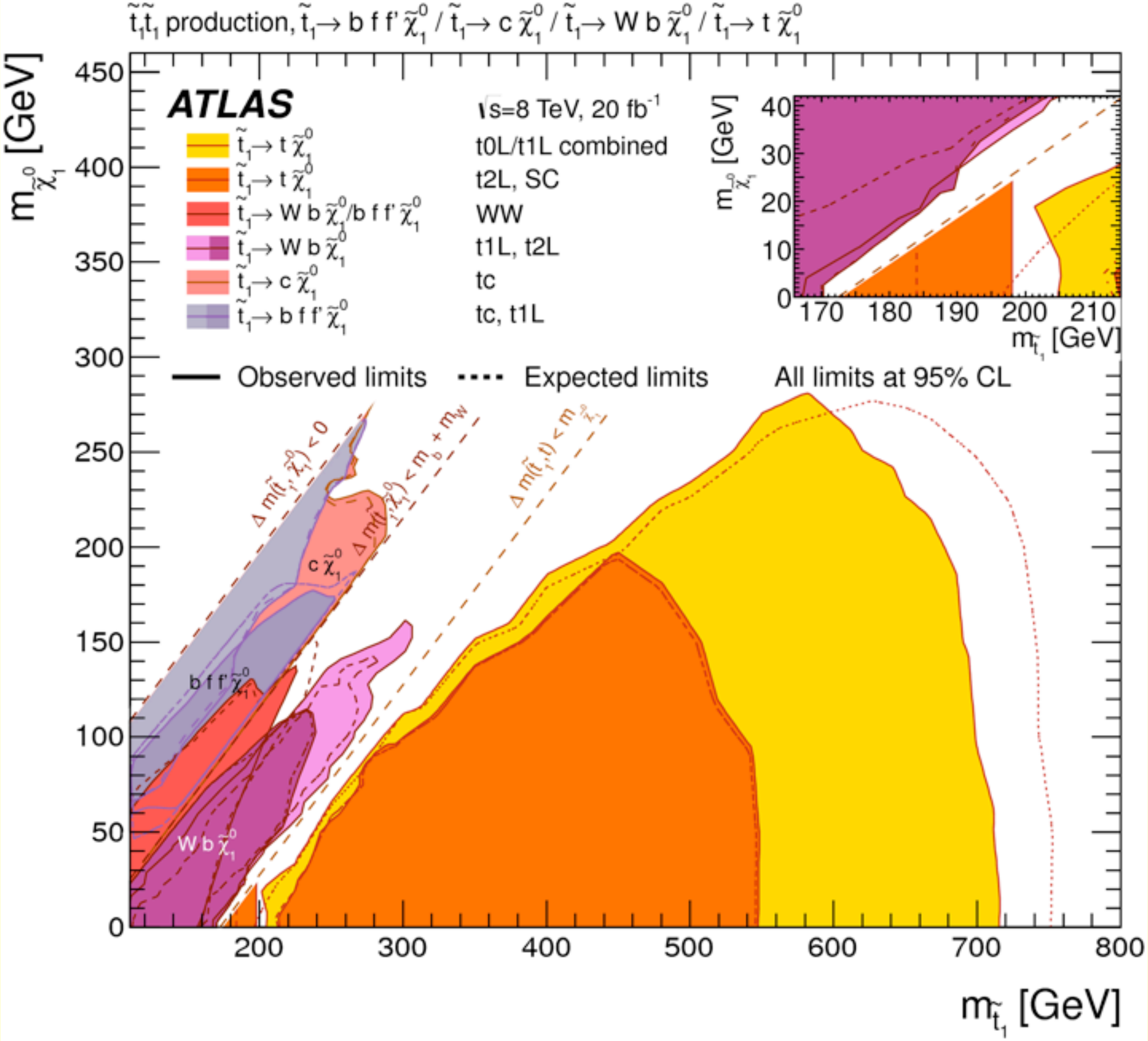
Hidden Naturalness Workshop
University of Maryland, April 29 2016

No sign of top partners as of today from LHC



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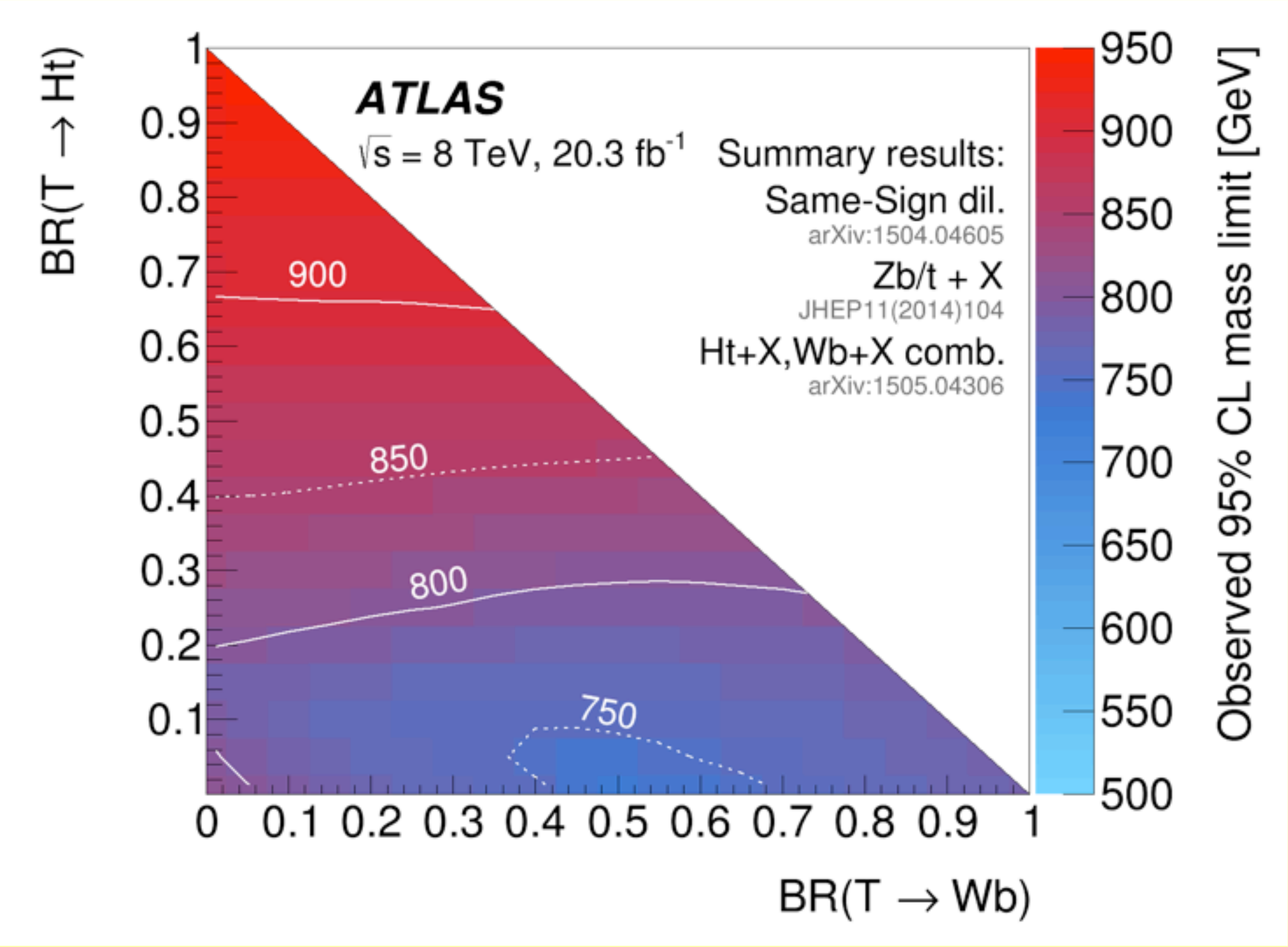


Displaced Higgs decays as signals of Neutral Naturalness

- A radical approach to hierarchy problem is top partners not colored (or maybe not charged under SM at all)

- Twin Higgs is most well-known example

(Chacko, Goh, Harnik)

- SM gauge group doubled, twin sector related by Z_2 symmetry to SM

- Other examples: Folded SUSY, quirky little Higgs, orbifold Higgs

Twin Higgs Redux (Chacko, Goh, Harnik)

- Consider H to be a fundamental under a global SU(4)

$$V = -m^2|H|^2 + \lambda|H|^4$$

- H develops a VEV and breaks SU(4)→SU(3): 7 GB's

- Gauge $SU(2)_A$ x $SU(2)_B$ subgroup of SU(4):
  explicitly breaks the global symmetry & gives mass to GB's:

$$H = \begin{pmatrix} H_A \\ H_B \end{pmatrix} \qquad \Delta V = \frac{9g_A^2}{64\pi^2}\Lambda^2|H_A|^2 + \frac{9g_B^2}{64\pi^2}\Lambda^2|H_B|^2$$

- If $\mathcal{Z}_2$ symmetry exchanging A and B, so $g_A = g_B \equiv g$ then quadratic potential does not break SU(4)

$$\Delta V = \frac{9g^2}{64\pi^2}\Lambda^2(|H_A|^2 + |H_B|^2) = \frac{9g^2}{64\pi^2}\Lambda^2(|H|^2)$$

Displaced Higgs decays as signals of Neutral Naturalness

•Phenomenology depends strongly on details of mirror sector.

•Interesting possibility: no light mirror quarks. In models with EW charged mirror this is a must.

•``Fraternal twin Higgs", only twin partner for 3rd generation (Craig, Katz, Strassler, Sundrum)

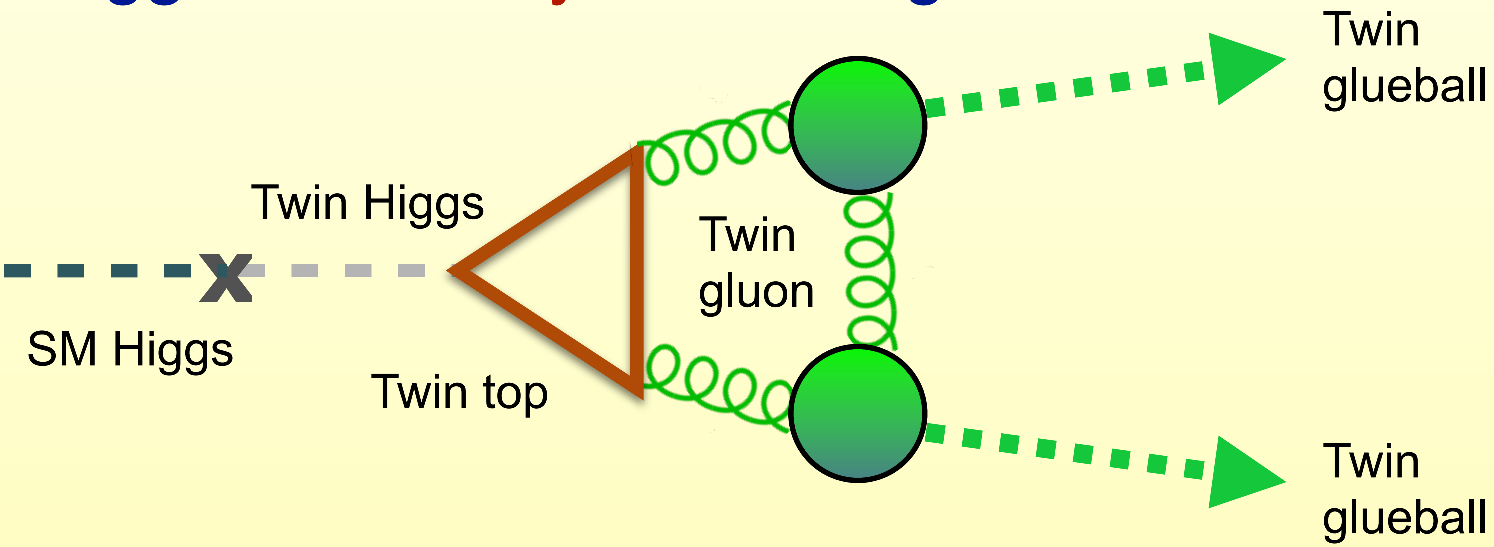
•Folded SUSY (Burdman, Chacko, Goh, Harnik)

•This case there will be light glueballs of QCD' which can mix with SM Higgs

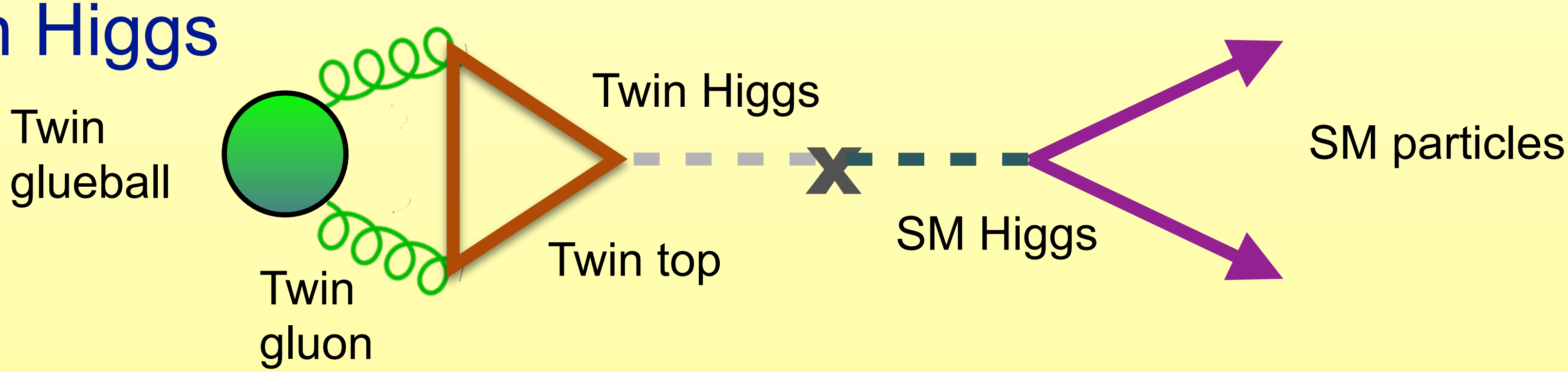
$$\mathcal{L}^{(6)} = \frac{\alpha_v\, y^2}{3\pi\, M^2} H^\dagger H \,\mathrm{tr}\, \mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}$$

Displaced Higgs decays as signals of Neutral Naturalness

- SM Higgs can decay to mirror glueballs

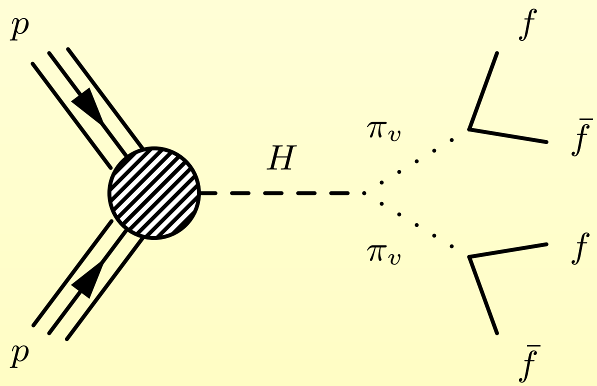


- Which can decay back to SM particles via mixing with Higgs



Displaced Higgs decays as signals of Neutral Naturalness

- Results in exotic Higgs decays which can be displaced depending on the lifetimes of the glueballs

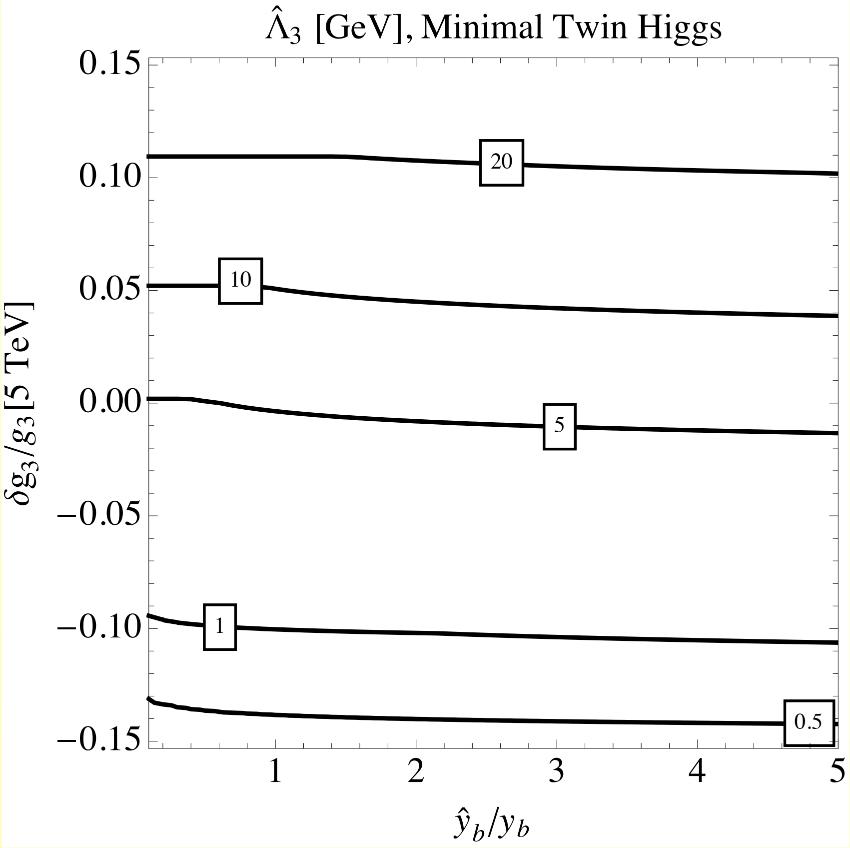


$$m_{\pi_\nu} = 10,\ 25,\ 40\ \text{GeV}$$

- We will be looking for this decay, without assuming anything else about the model, leave glueball mass, lifetime free parameter. Assume decay according to Higgs couplings.

Properties of twin glueball/QCD

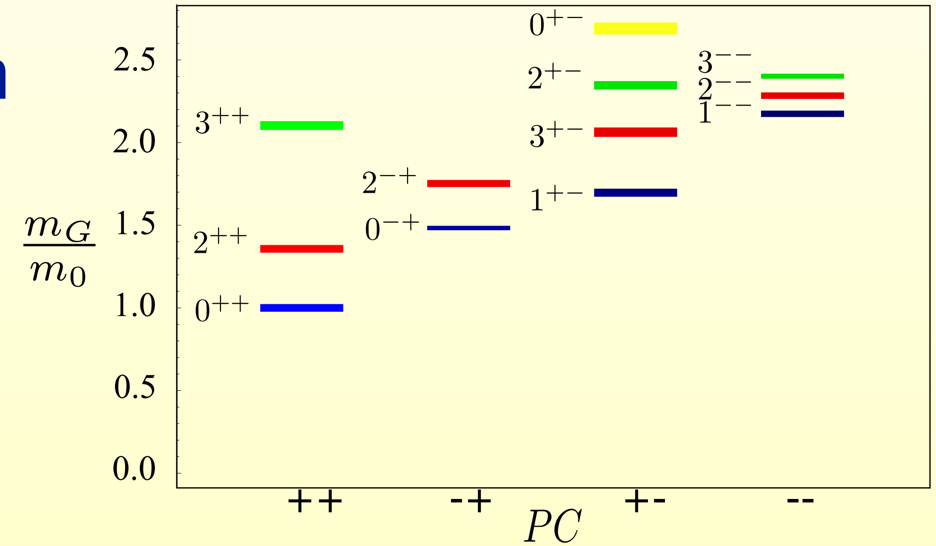
- Twin confinement scale



(Craig, Katz, Strassler, Sundrum)

Properties of twin glueball/QCD

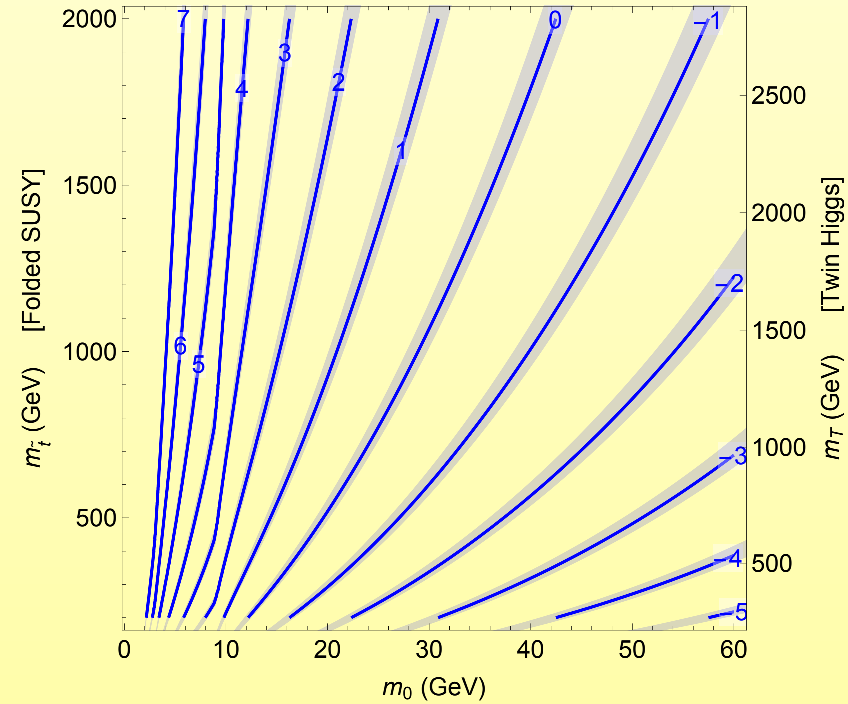
- Glueball spectrum



- Glueball lifetime

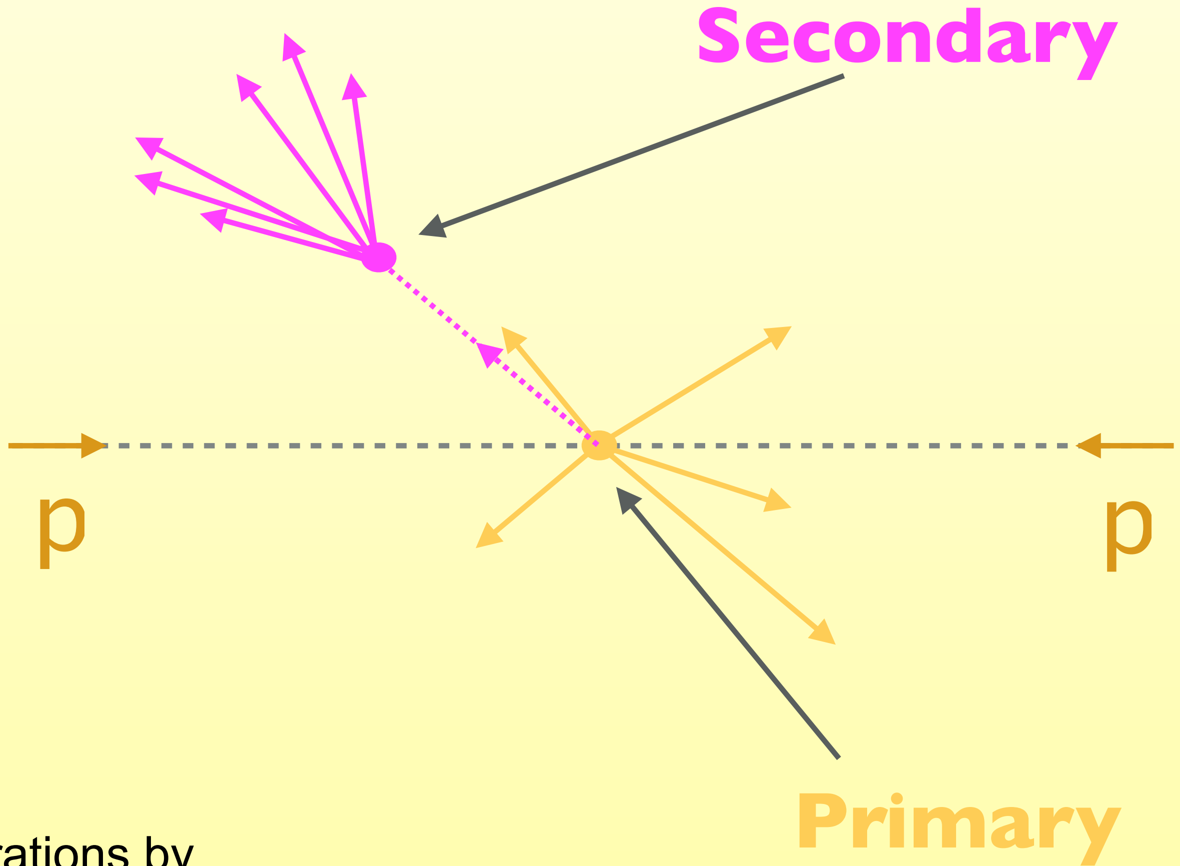
(Curtin, Verhaaren)

$$\log_{10} c\tau/m$$



A displaced vertex at the LHC

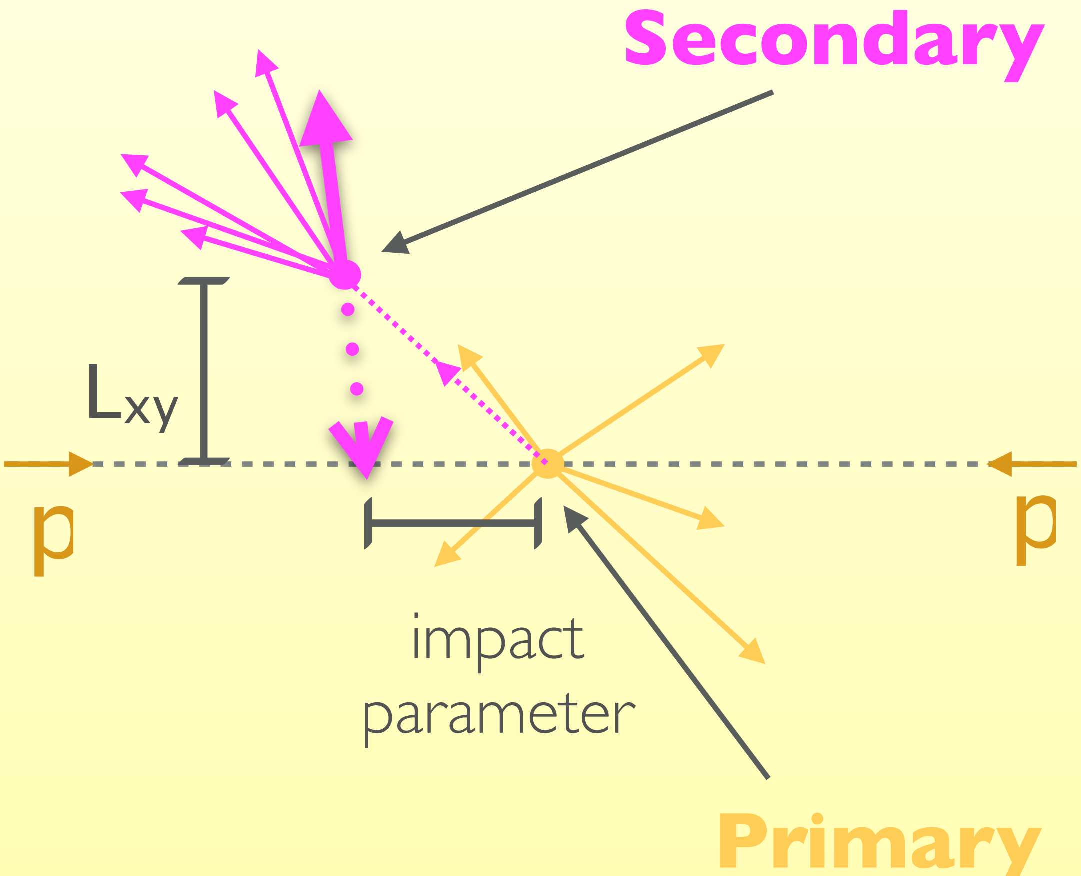
- A vertex in the tracker not aligned with beam axis (tracks not pointing back to primary vertex)



All illustrations by
Eric Kuflik

A displaced vertex at the LHC

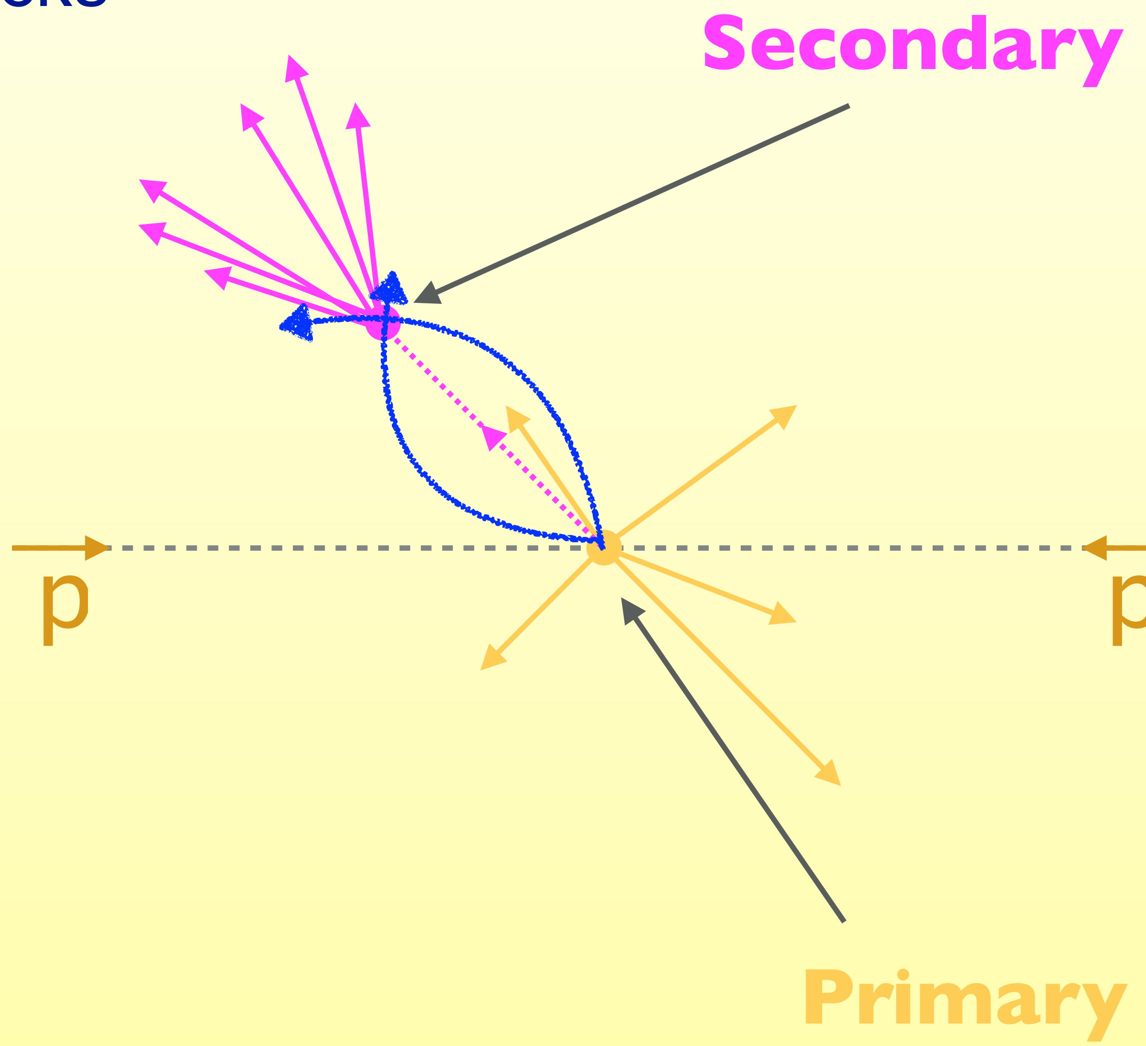
- Quantities characterizing displaced vertex



- Tracker sensitive to L_{xy} ~ 50 cm, IP ~ 0.5 mm to 30 cm acceptance

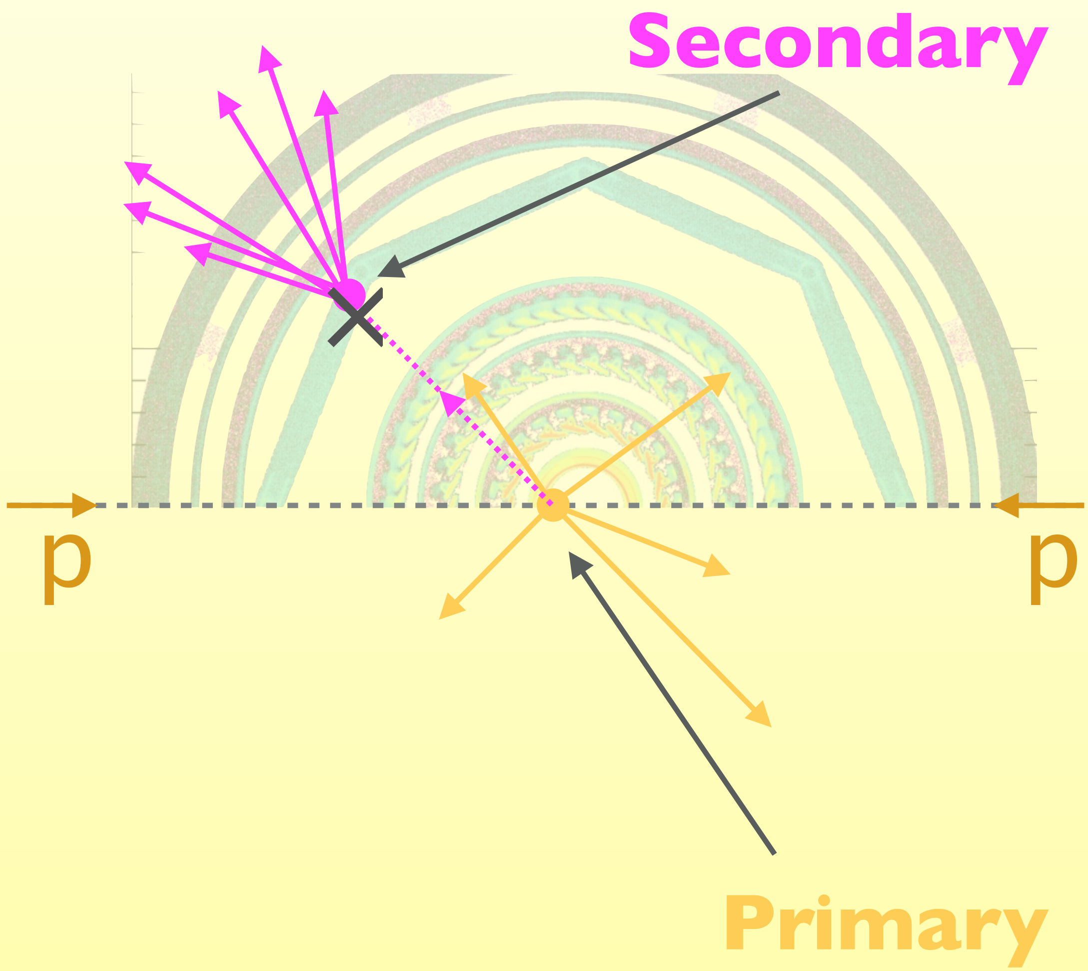
Backgrounds for displaced vertices

- Crossing tracks



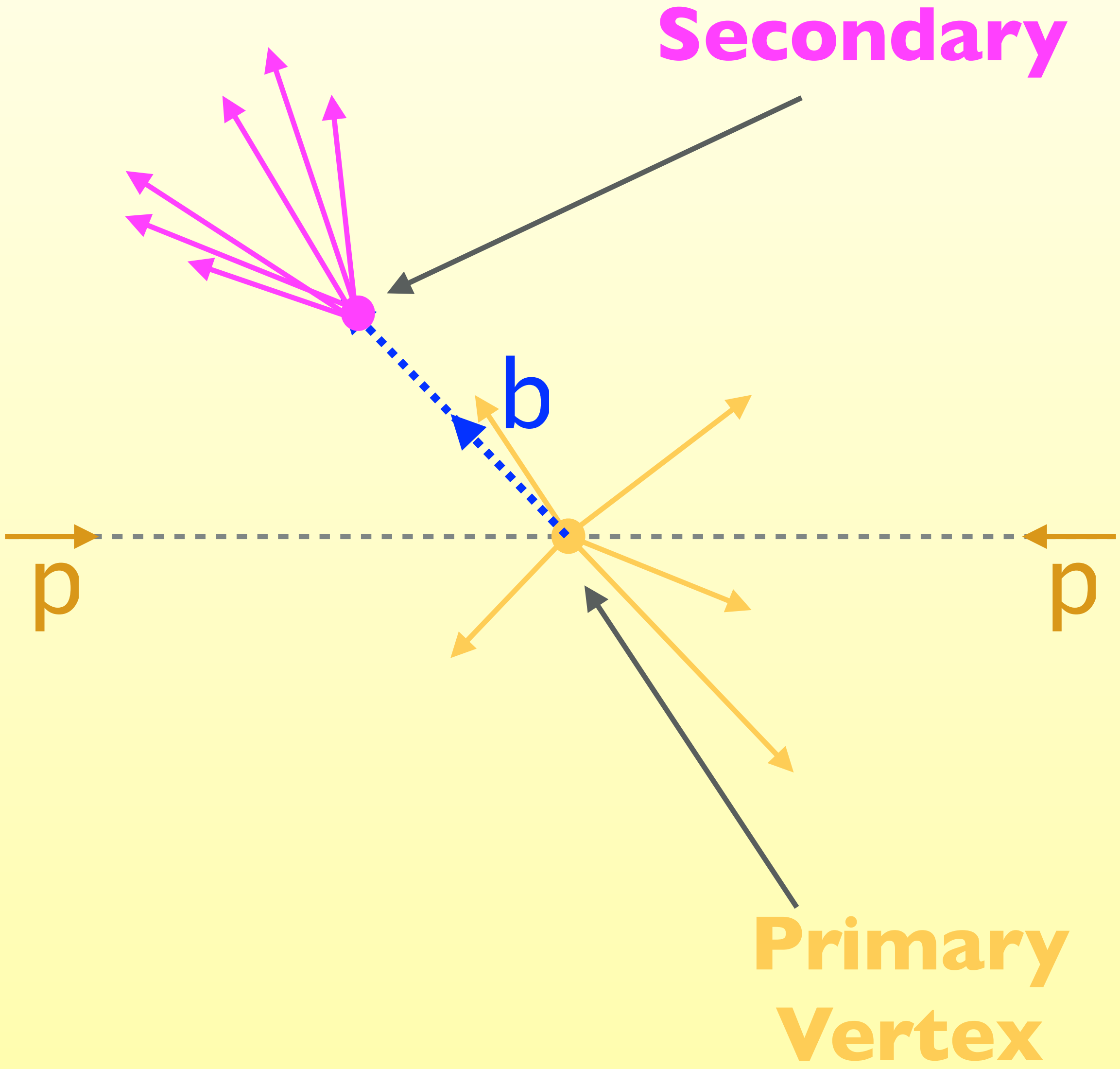
Backgrounds for displaced vertices

- Interaction with detector material



Backgrounds for displaced vertices

- b-jets
- cτ ~ 0.5 mm



Experimental searches

- Displaced vertex searches in tracker by ATLAS, CMS

$$\textbf{ATLAS DV} + \mu/e/\textbf{jets}/\textbf{MET}$$

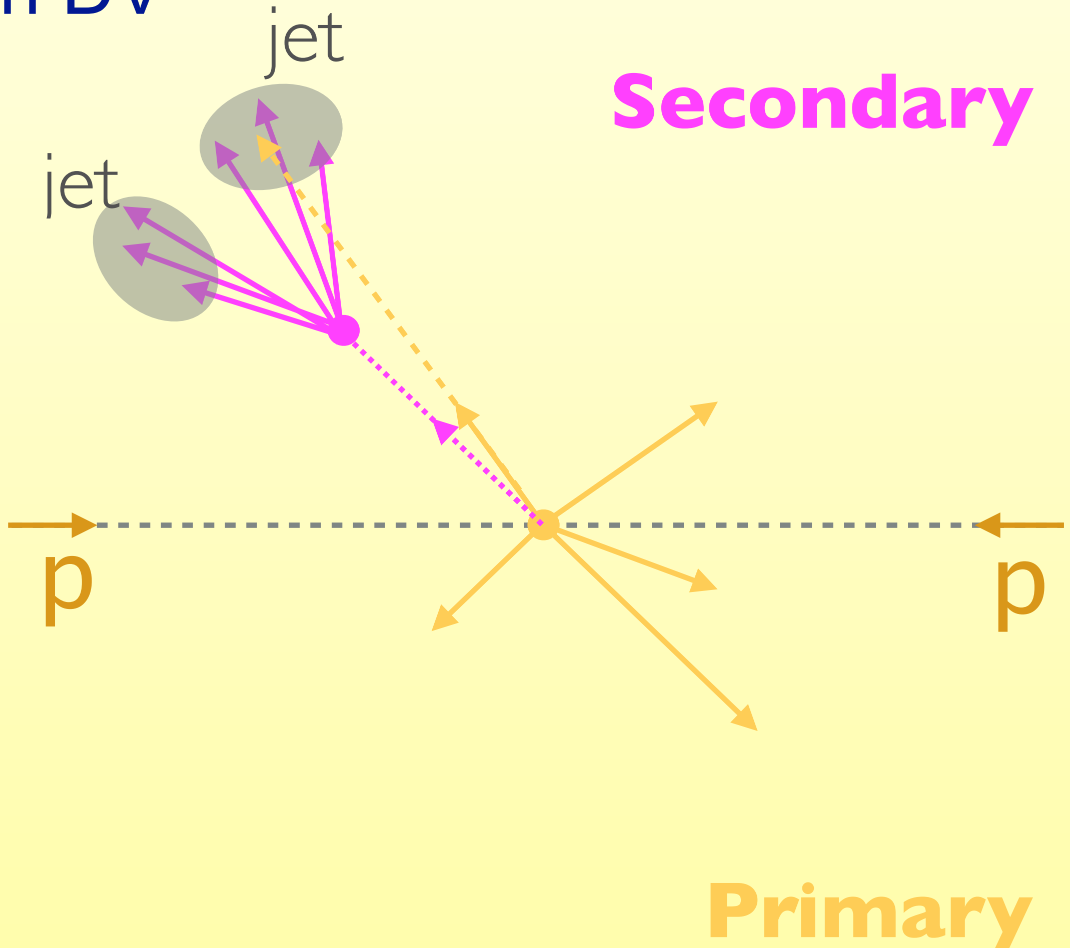
- 8 TeV, 20 fb^{-1}, DV in inner tracker + (1) muon (2) electron (3) jets (4) MET
- All background free

$$\textbf{CMS Displaced Dijet}$$

- 8 TeV, 18.6 fb^{-1}, dijets originating from DV. Not restrictive to just models with jets. Isolated leptons treated as jets, three jets also have large efficiency to be captured

CMS displaced dijet search

- Two displaced jets pT> 60 GeV
- HT>350 GeV, m_{DV}>4 GeV (no b's), N_{tracks}>4,5
- At most one prompt (IP<0.5mm) track per jet
- Dijet consistent with DV



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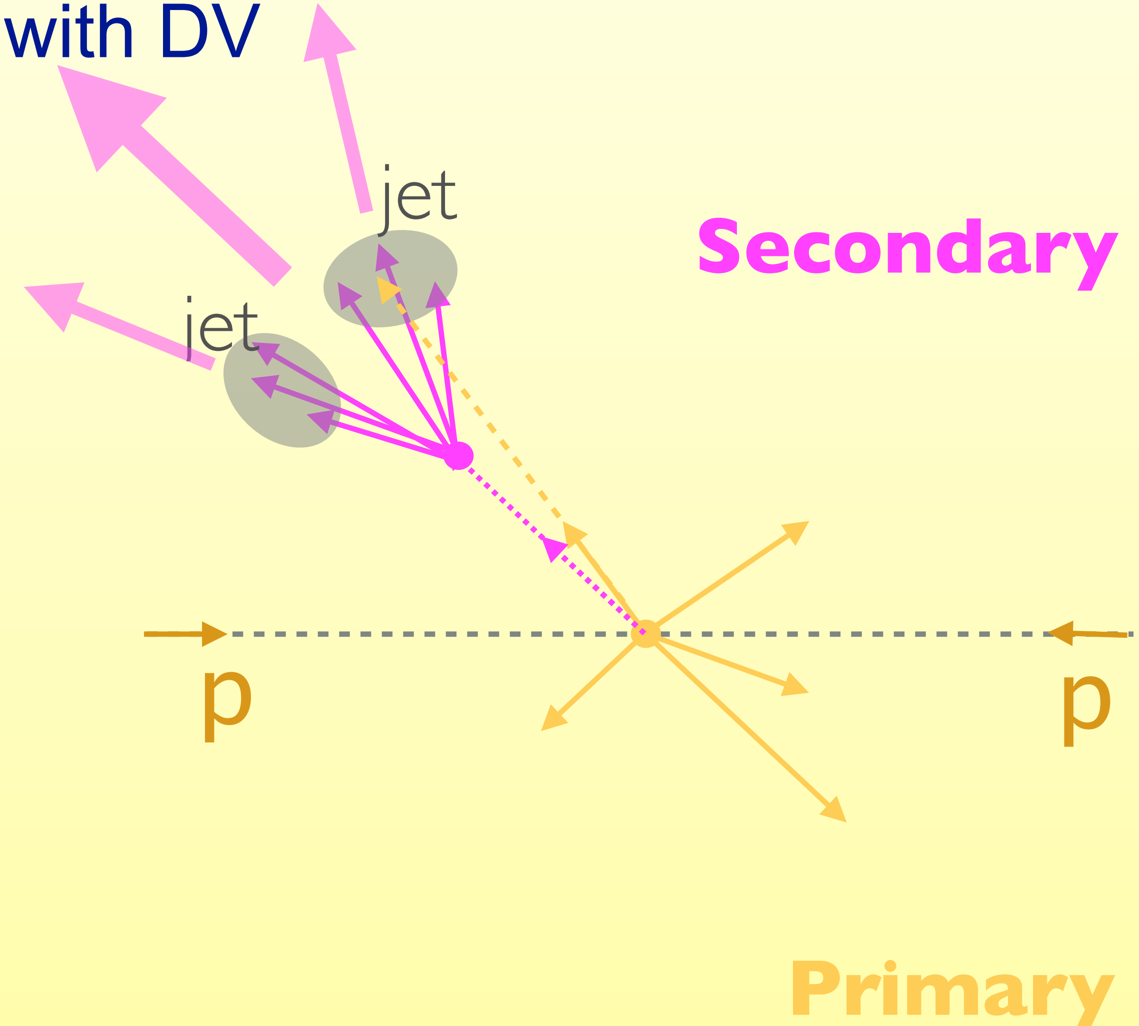

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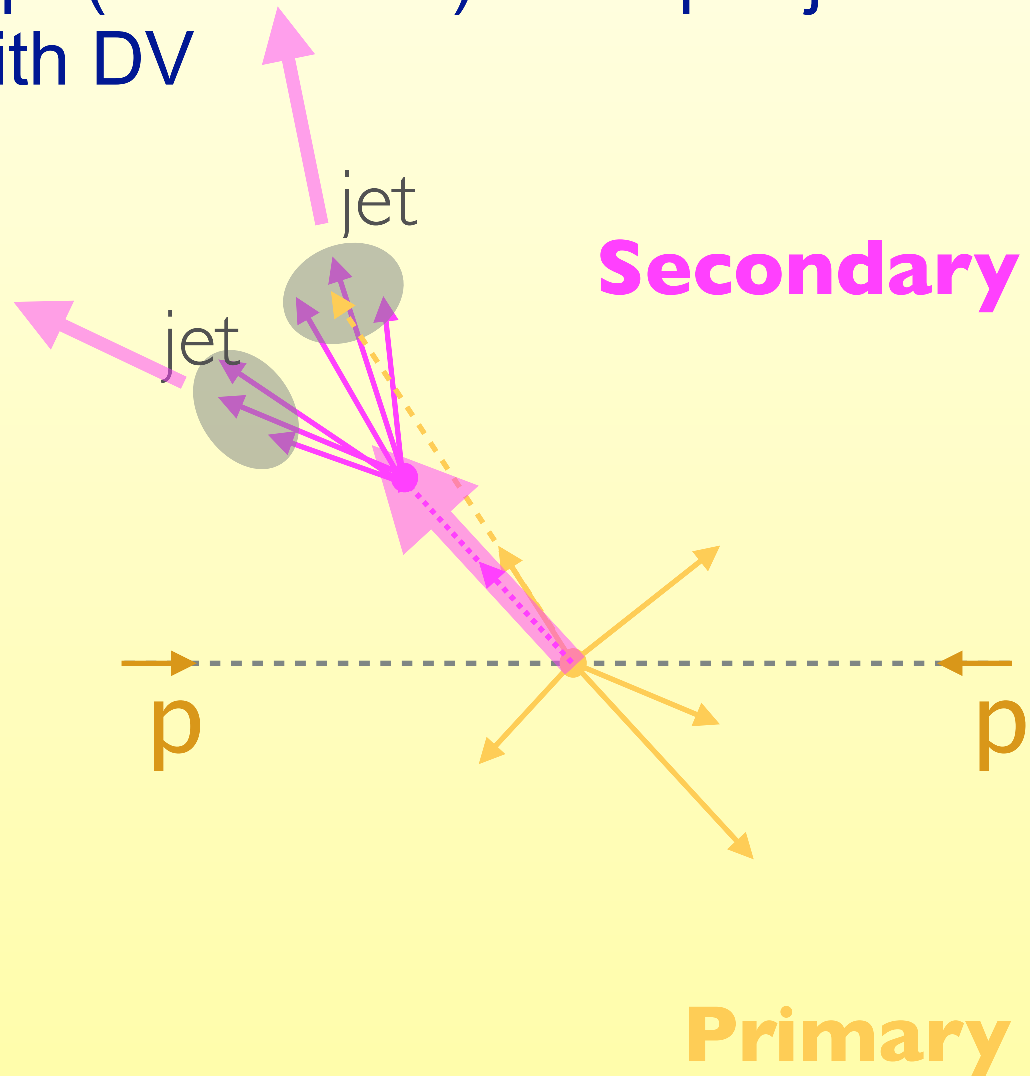
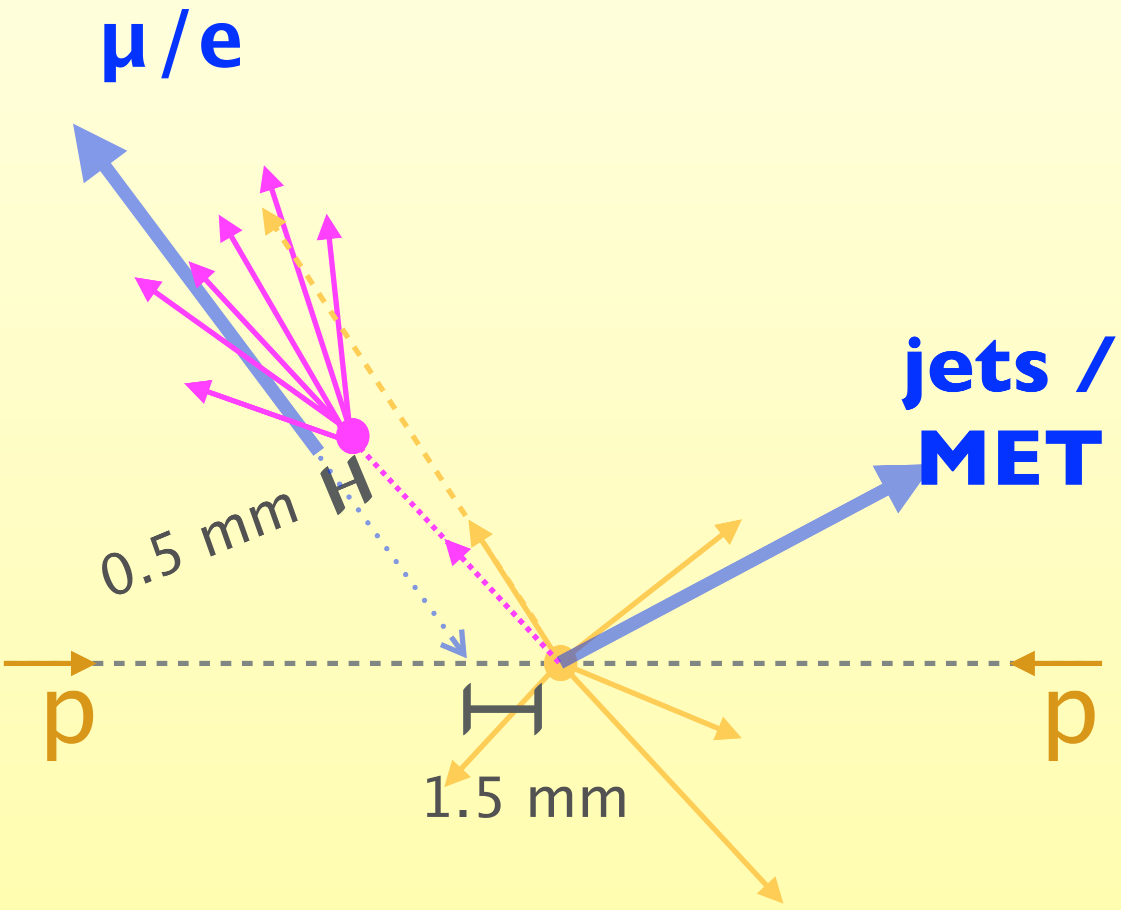
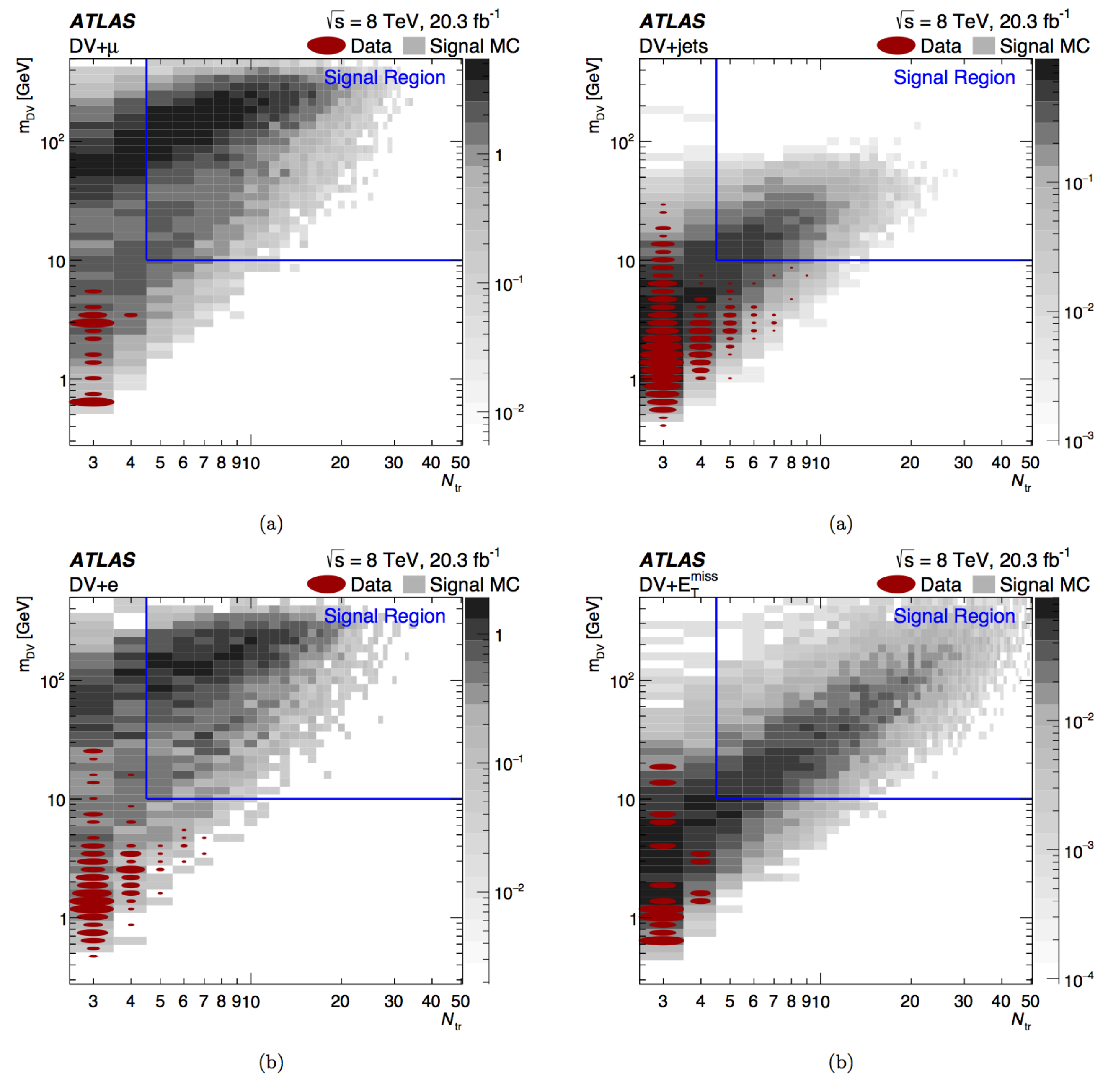


ATLAS DV+ muon/e/jets/MET

- DV with m_{DV}>10 GeV, N_{tracks}>5
- Trigger on associated object muon pT>55 GeV, e pT>125 GeV, MET>180 GeV, jets 4,5,6



ATLAS DV+ muon/e/jets/MET



Displaced Higgs decays

(Kuflik, Lombardo, Slone, C.C.)

- Run I analysis: assuming Higgs decays to 2 invisible particles, which in turn decay with couplings set by the SM Higgs couplings (but branching ratios differ due to phase space)

- Existing ATLAS analysis: require two displaced decays in same event. Two possible signals

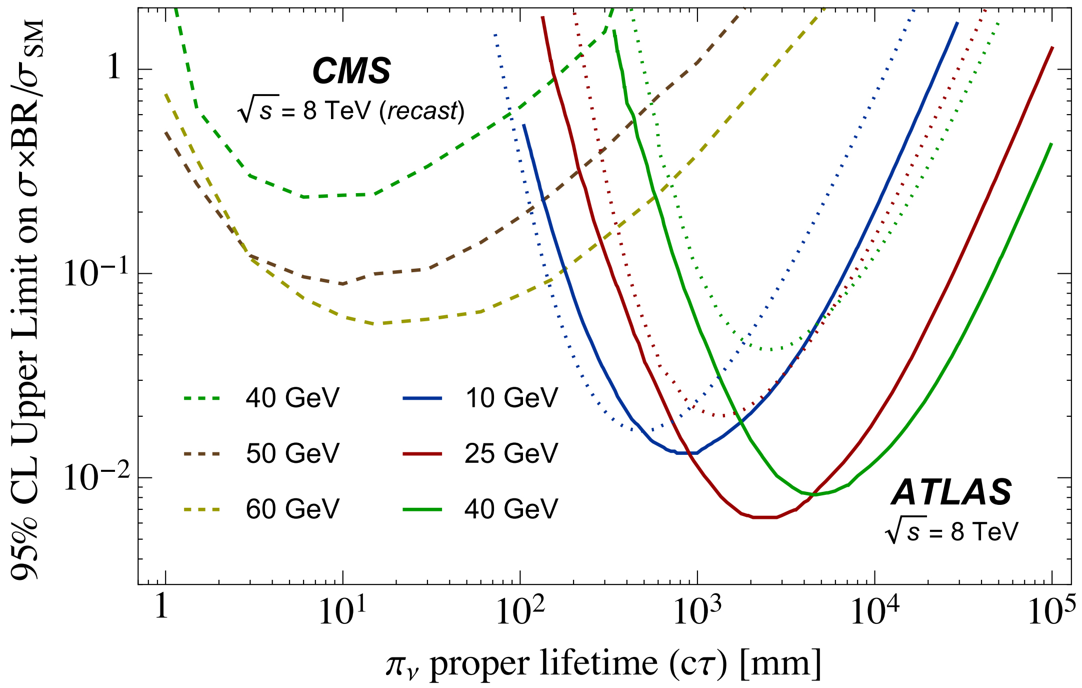
- Decays in muon chamber (solid line)

- Decays in hadronic calorimeter (dashed line)

- No sensitivity for smaller lifetimes - most unconstrained region for twin Higgs type models

Bounds from Run I

- First bounds on short lifetimes ≤10 cm from CMS displaced dijet search



Results

•Generated $10^4/\epsilon$ events for 10, 25 and 40 GeV m_π and liftetimes from 0.1 mm to 10m

•Feynrules→Madgraph→Pythia→Delphes3 pipeline

•Applied all cuts and reconstruction procedure of all displaced searches

Displaced Higgs decays

- Used existing tracker analysis to set bounds from existing Run I data on smaller lifetimes

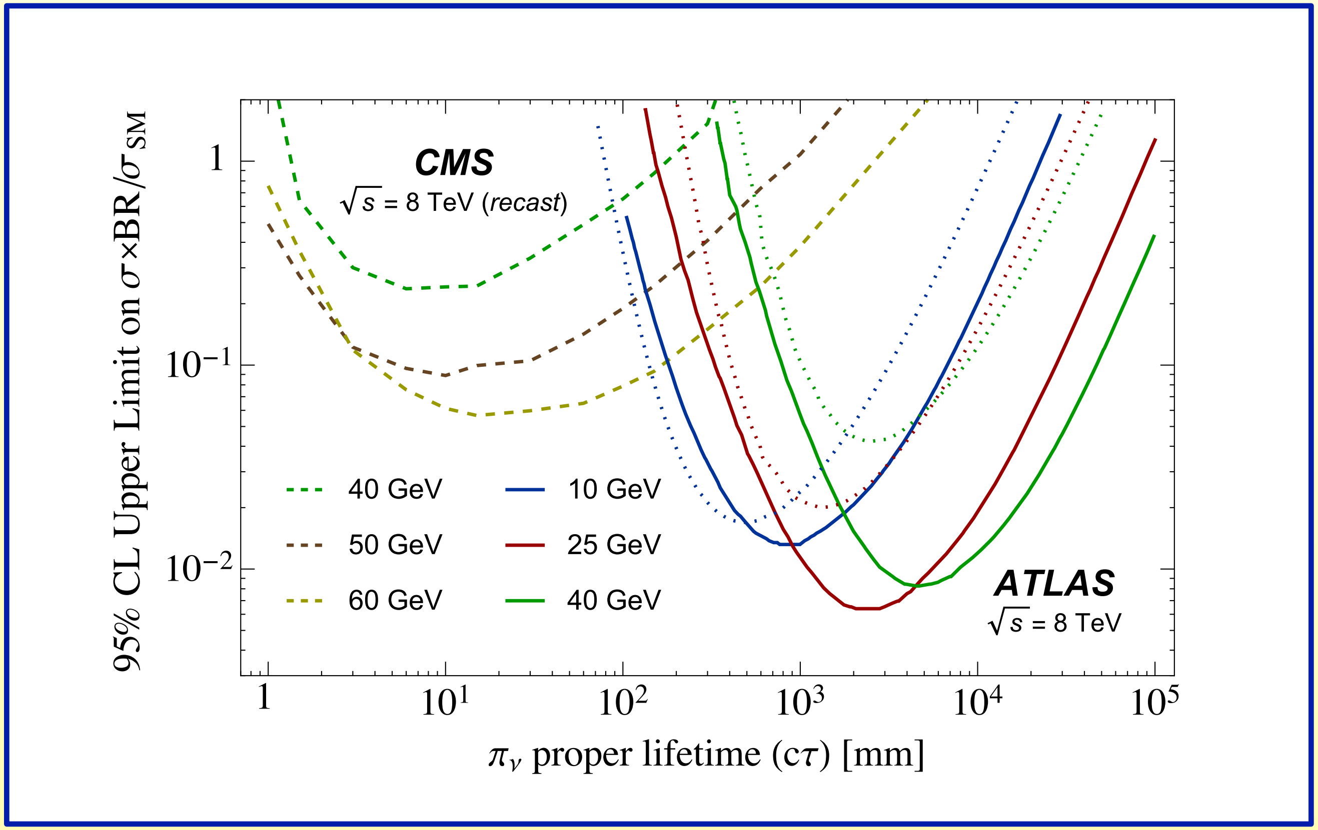
- Used CMS displaced dijet search based on displaced jet trigger (requiring two displaced jets)

- ATLAS displaced tracker searches give no constraint - usually require higher momentum triggers, but Higgs 125 GeV, intermediate particles 10-60 GeV mass, nothing really hard...

- Also light particles imply low track multiplicities, and typical DV searches require ≥ 5 tracks.

Bounds from Run I

- First bounds on short lifetimes ≤10 cm from CMS displaced dijet search



Displaced Higgs decays

- CMS displaced dijet trigger has track displacement requirement in the trigger

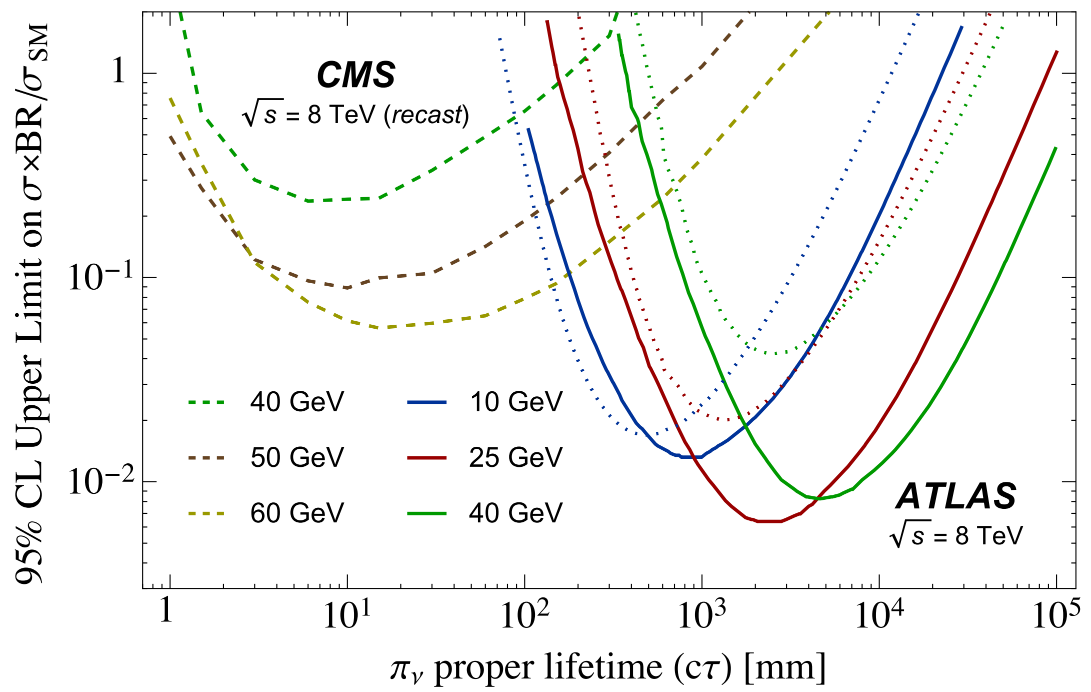
- ATLAS associated object trigger requirement is too high for a 125 GeV Higgs. None will pass.

- CMS trigger has lower momentum thresholds helping to pick up decay products from 125 GeV Higgs. Limiting factor still HT 350GeV trigger.

- This issue is also relevant for Run II

Bounds from Run I

- First bounds on short lifetimes ≤10 cm from CMS displaced dijet search



Triggers for Run II

Trigger	Trigger Requirement
Displaced jet [a]	$H_T > 175$ GeV or three jets with $p_T^{j1,2,3} >$ (92, 76, 64) GeV, $\lvert\eta_{j_{1,2,3}}\rvert < (5.2, 5.2, 2.6)$ with $\lvert\eta_{j_1}\rvert$ or $\lvert\eta_{j_2}\rvert < 2.6$, and two jets satisfying $m_{jj} > 500$ GeV and $\Delta\eta > 3.0$. A displaced jet satisfying $p_T > 40$ GeV, at most 1 prompt track (2D IP < 2.0 mm), and at least 2 displaced tracks.
Inclusive VBF	Two jets with $\lvert\eta_{j_1,j_2}\rvert > 2$, $\eta_{j_1} \cdot \eta_{j_2} < 0$, $\lvert\eta_{j_1} - \eta_{j_2}\rvert > 3.6$ and $m_{j_1,j_2} > 1000$ GeV.
VBF, h $\rightarrow b\bar{b}$	Three jets with $p_T^{j1,2,3} > (112, 80, 56)$ GeV and $\lvert\eta_{j_{1,2,3}}\rvert < (5.2, 5.2, 2.6)$ and at least one of the two first jets with $\lvert\eta_{j_1}\rvert$ or $\lvert\eta_{j_2}\rvert <$ 2.6.
Isolated Lepton	One lepton with $p_T > 25$ GeV, $\lvert\eta\rvert < 2.4$, and 3D IP < 1 mm. Isolation requires the summed p_T of all tracks with $p_T > 1$ and within $\Delta R < 0.2$ of the lepton is less than 10% of the lepton p_T.
Trackless jets	A jet with $p_T > 40$ GeV and $\lvert\eta\rvert < 2.5$ matched with a muon with $p_T > 10$ GeV within $\Delta R = 0.4$. No tracks with $p_T > 0.8$ GeV in the ID within a $\Delta\phi \times \Delta\eta$ region of 0.2×0.2.

Triggers for Run II

- CMS displaced jet trigger: weak VBF signature trigger plus one displaced jet (but 4 x larger Impact Parameter than Run I displaced dijet)

- VBF: usual VBF trigger - forward and backward jet, large invariant mass

- Isolated lepton: isolated from jets (to exclude decays from heavy quarks), for Vh production

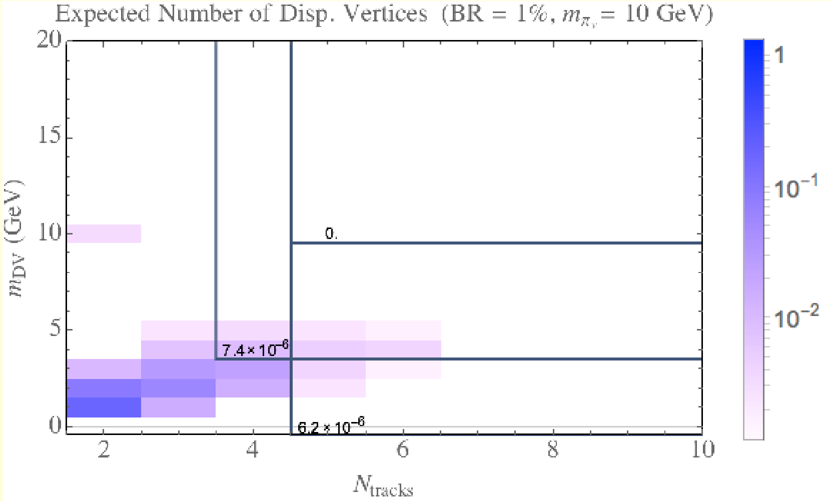
- Trackless jets (ATLAS only): jets w/o tracks in pixel detector, only good for longer lifetimes

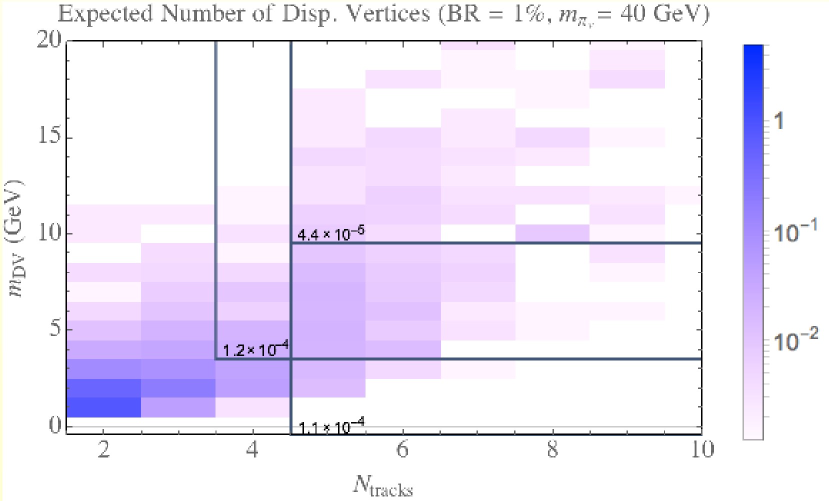
Acceptances

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	0.03%	1.3%	1.1%	**0.2%**	1.0 %	30.0%	25.1%	**3.9%**	1.0%	42.0%	34.7%	**5.1%**
	25	0.01%	0.8%	0.7%	**0.09%**	0.7%	20.4%	16.9%	**2.7%**	1.5%	45.3%	37.3%	**5.9%**
	40	0.02%	1.0 %	0.9%	**0.1%**	0.6%	19.7%	16.4%	**2.5%**	1.4%	44.6%	36.3%	**5.7%**
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%**

- VBF with additional bbbar is best
- Displaced jet competitive for larger lifetimes, likely has less background

Vertex requirements





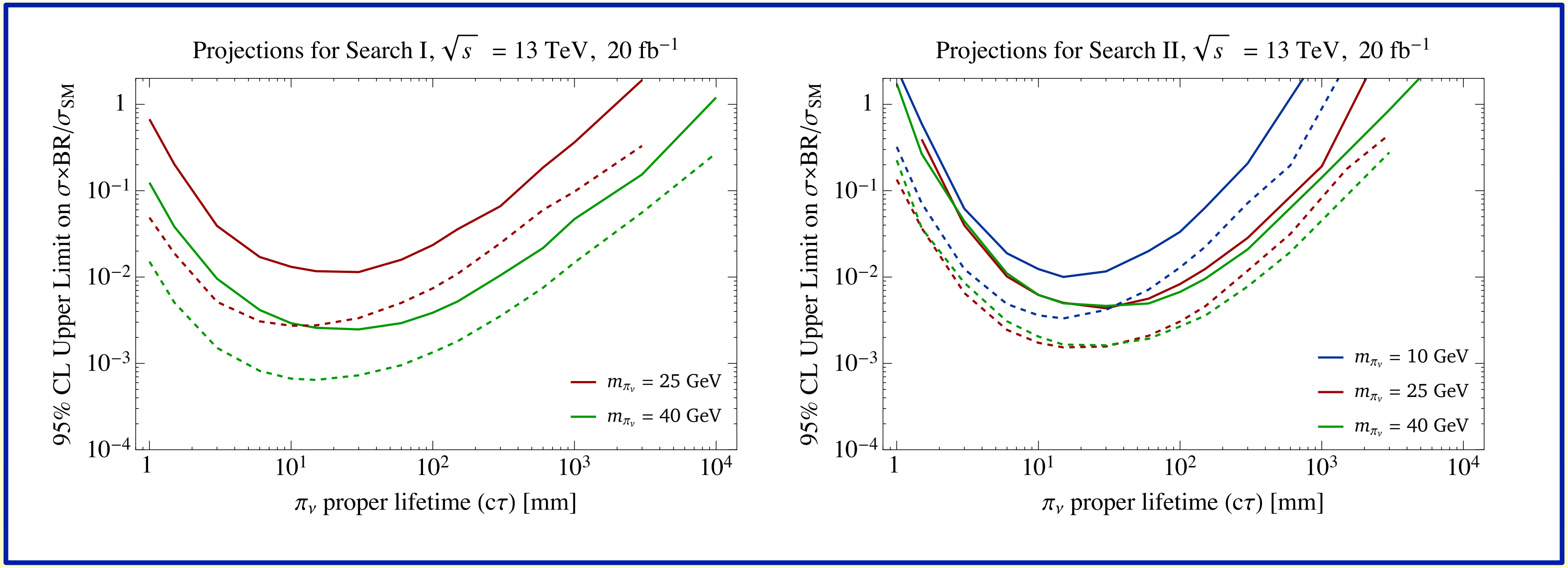
- Not only trigger issue - also difficult to reconstruct a high quality vertex from light long-lived particles

- Boxed regions: signal regions (# of tracks vs. mass of displaced vertex) - detector backgrounds outside

- Top right: existing single DV searches, bottom right existing two DV searches. Ideal: middle

- Low track multiplicity and mass! Need to modify tracker searches for light intermed. particles!

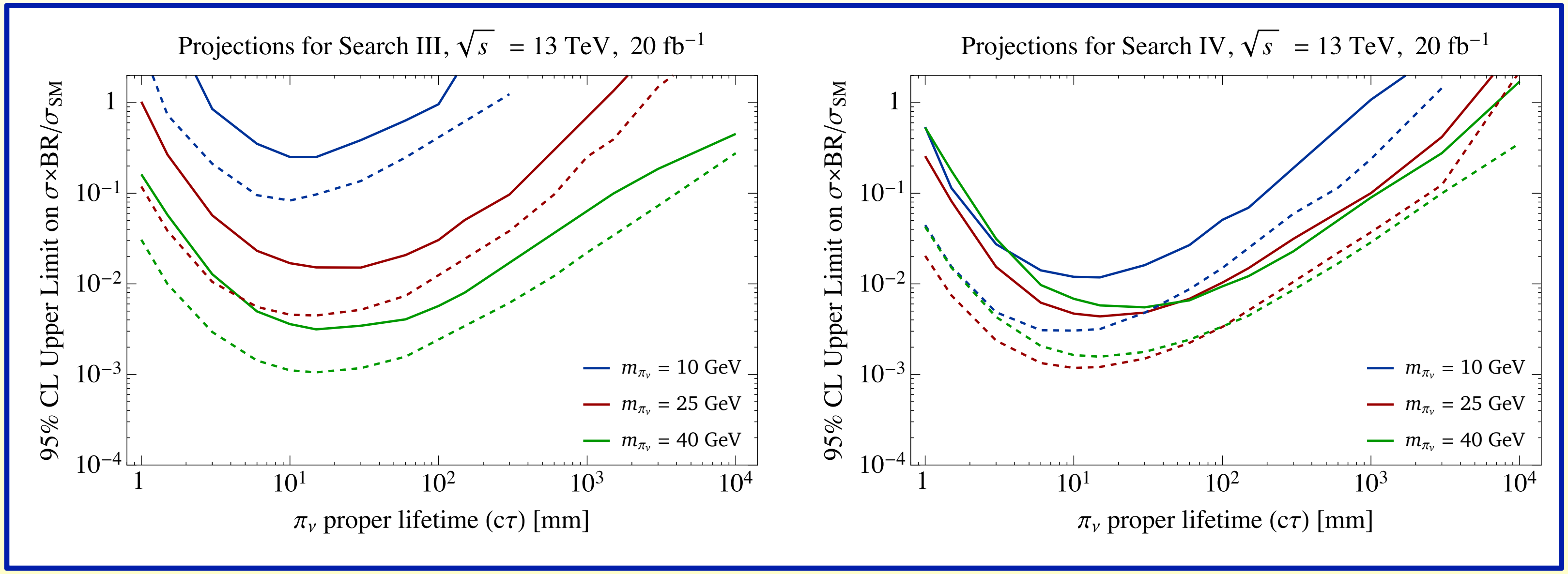
Projected Sensitivities Run II 20 1/fb



- Search I: one high mass (≥10 GeV) and ≥5 tracks single DV based on ATLAS search. Good for high mass ≥40 GeV (dashed: VBFbb, solid: displaced jet)

- Search II: One DV with high track multiplicity, no mass requirement to allow softer objects, but reproduce Higgs and intermed. particle masses

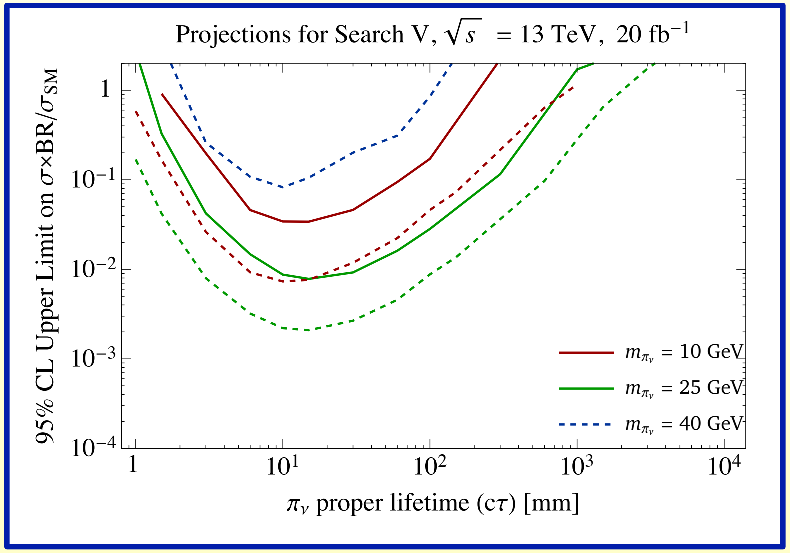
Projected Sensitivities Run II 20 1/fb



- Search III: one high mass (≥4 GeV), ≥4 tracks, pT≥ 8 GeV single DV with displaced dijet, similar to CMS dijet search

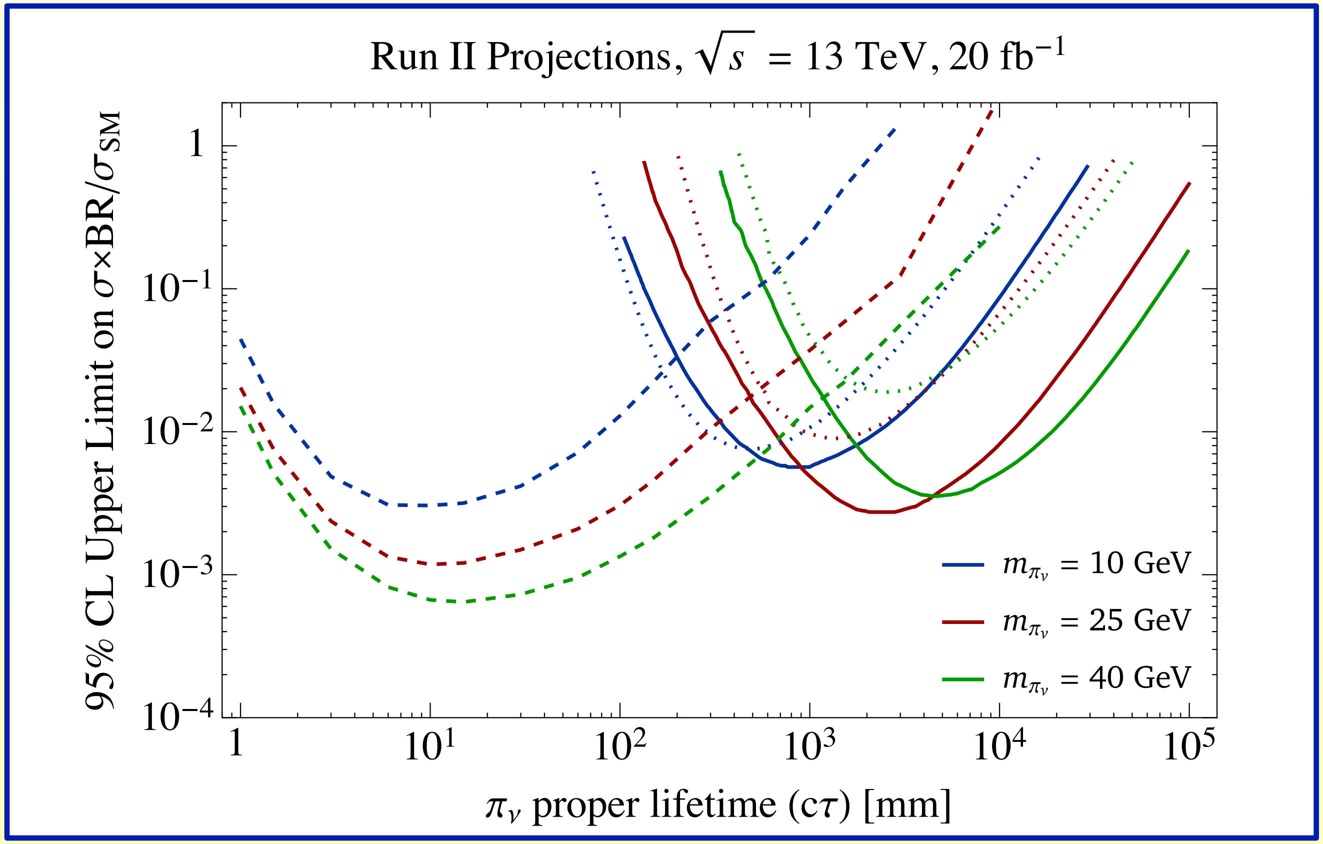
- Search IV: Same DV requirements as III but within a displaced jet with 2-prong substructure

Projected Sensitivities Run II 20 1/fb



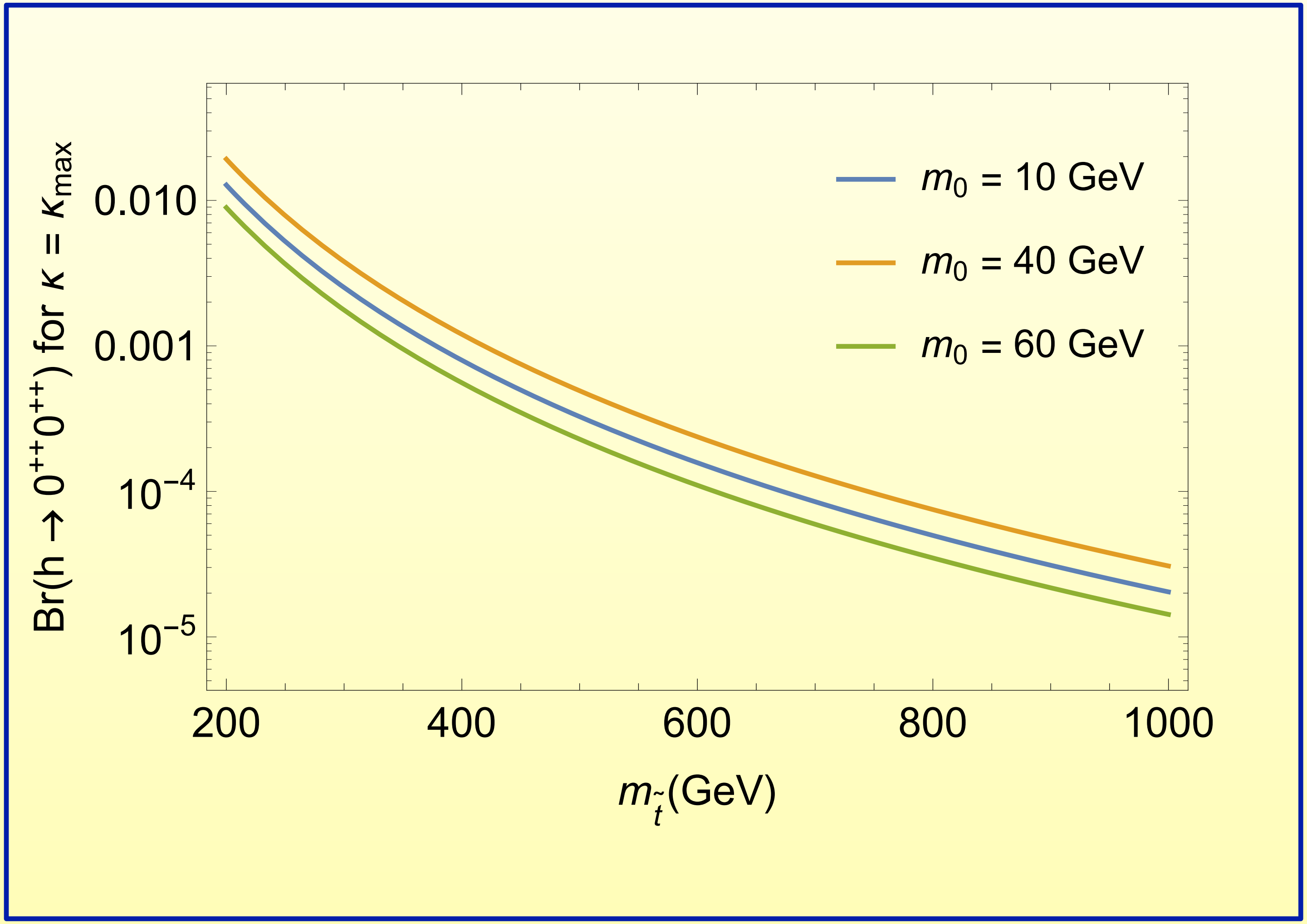
- Search V: two DV's with ≥5 tracks, as in ATLAS searches.

Projected Sensitivities Run II 20 1/fb



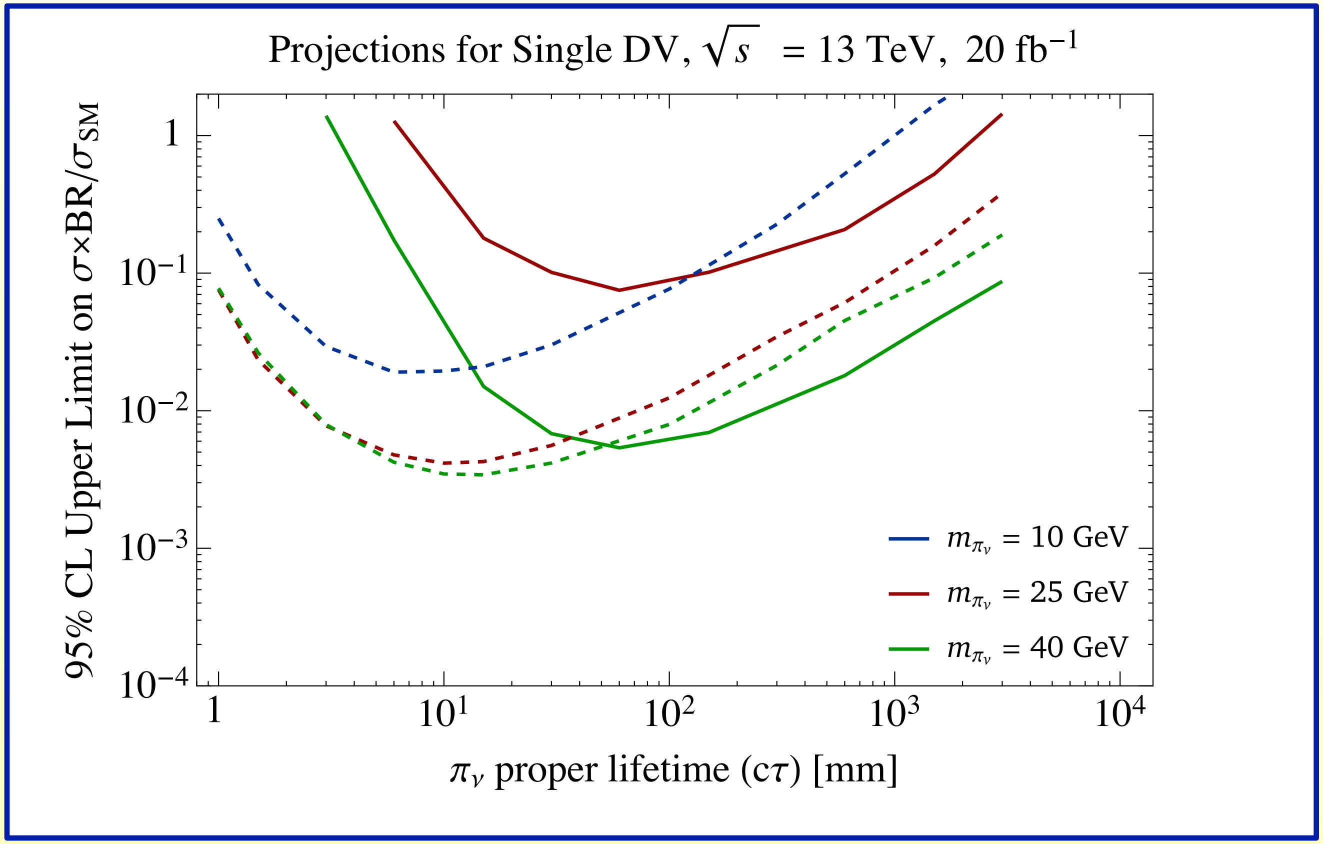
- Combined best sensitivities for five tracker searches and projected ATLAS result based on rescaling cross sections (10 GeV Search IV, 40 GeV: all reasonably effective)

Typical branching ratios



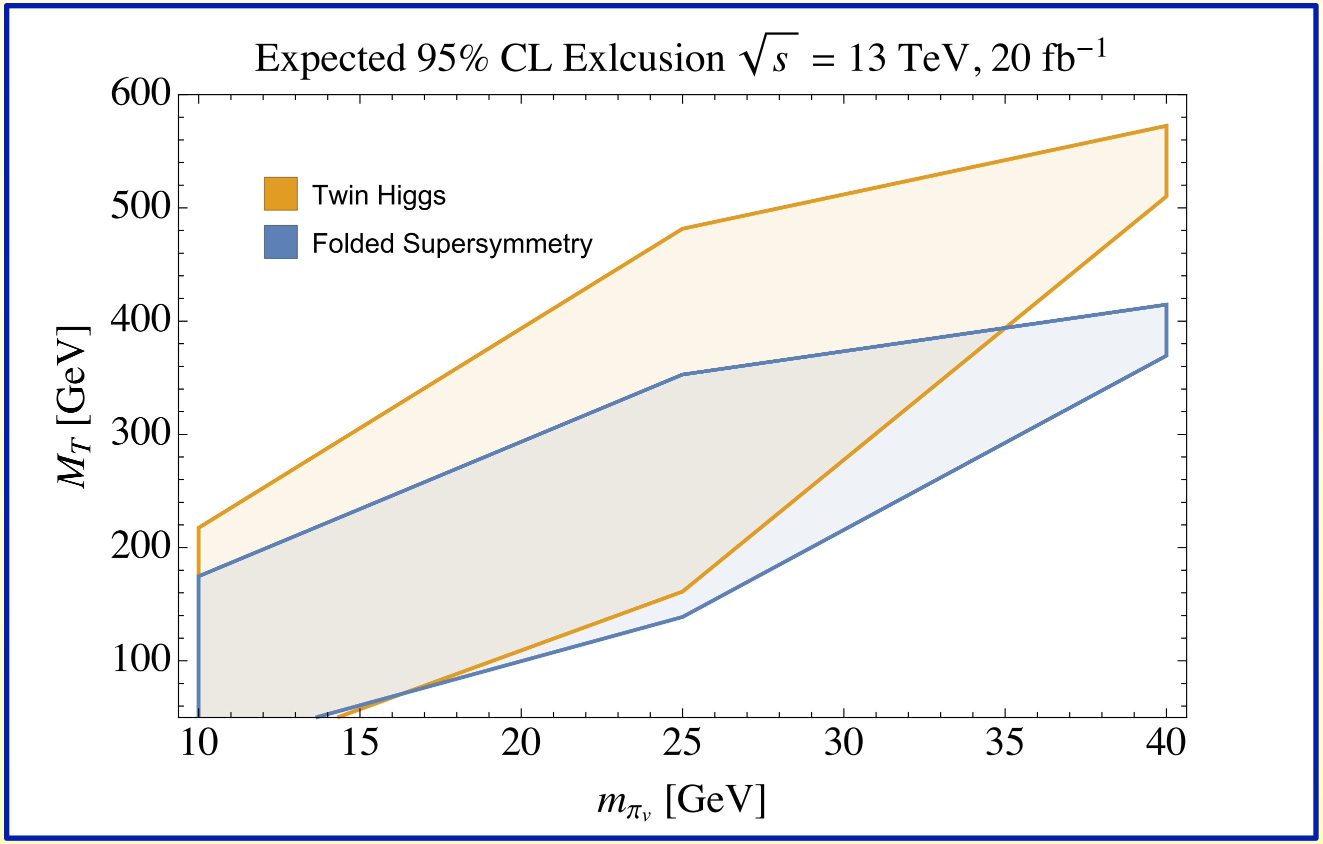
- Folded SUSY example (Curtin & Verhaaren)

Projected Sensitivities Run II 20 1/fb



- Combined sensitivity for case with just one displaced vertex, assuming the second particle just escapes the detector.

Projected Sensitivities Run II 20 1/fb



- Exclusion regions for top-partner mass vs. mirror glueball mass in Fraternal Twin Higgs (mirror top) and Folded SUSY (stop) models expected in Run II (thanks to David Curtin)

Summary

- Twin Higgs can avoid LHC bounds and have low tuning

- Models models often result in displaced Higgs decays

- Considered shorter lifetime tracker searches for displaced Higgs decays.

- Main issue is difficult to trigger on since everything soft

- First weak bounds from Run I for shorter lifetimes based on CMS displaced dijet search

- Run II at 20 1/fb can have sensitivities down to ~ 10^{-3} branching ratios. Main triggers VBF-like, searches similar to existing ATLAS and CMS searches with small additional modifications.