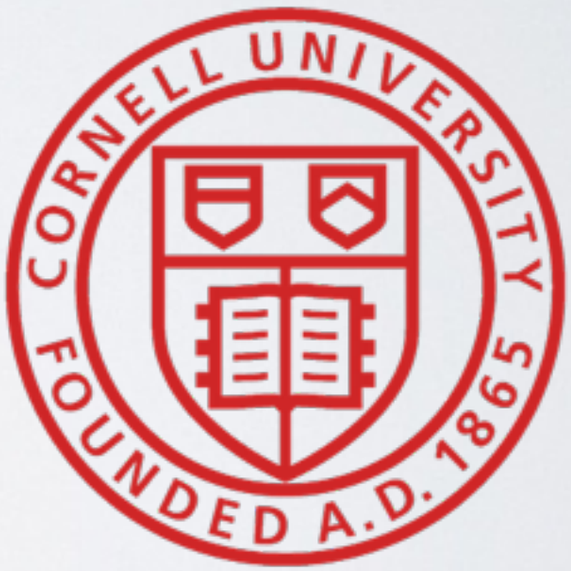
NEW IDEAS FOR DISPLACED HIGGS AT THE LHC

Eric Kuflik
Cornell University

C. Csaki, **EK**, S. Lombardo, O. Slone Phys.Rev. D92 (2015) 073008
& work in progress



האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

LONG LIVED PARTICLES

FROM

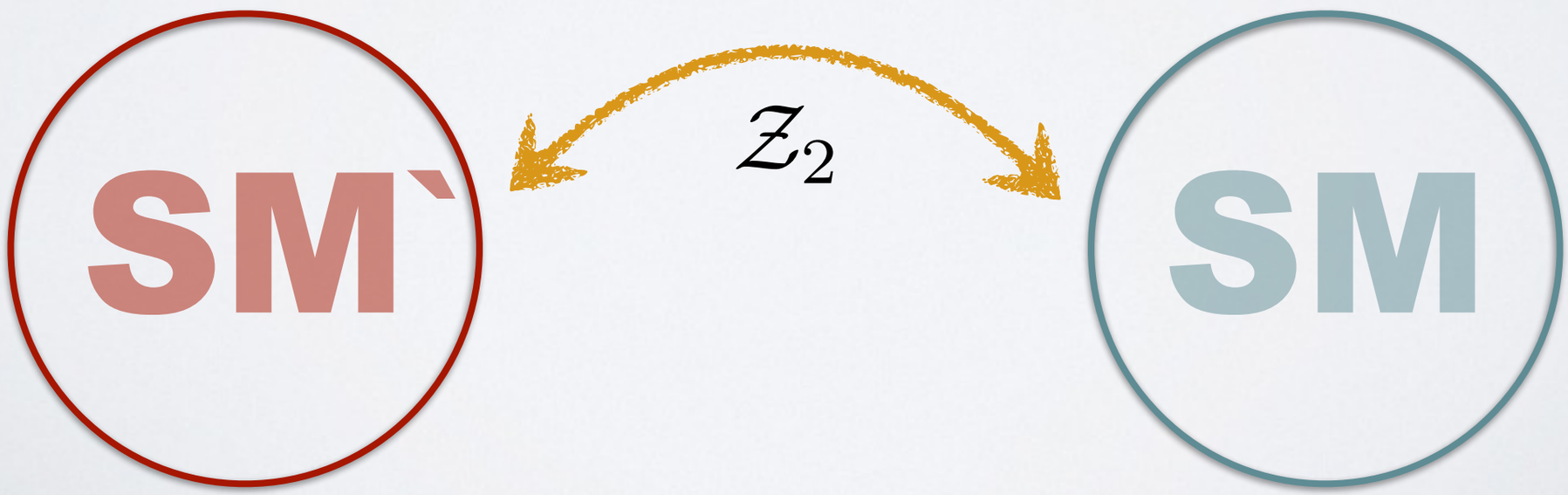
NEUTRAL NATURALNESS

THE TWIN HIGGS

Z. Chacko, H. Goh, R. Harnik, Phys.Rev.Lett. 96 (2006) 231802 [hep-ph/0506256]

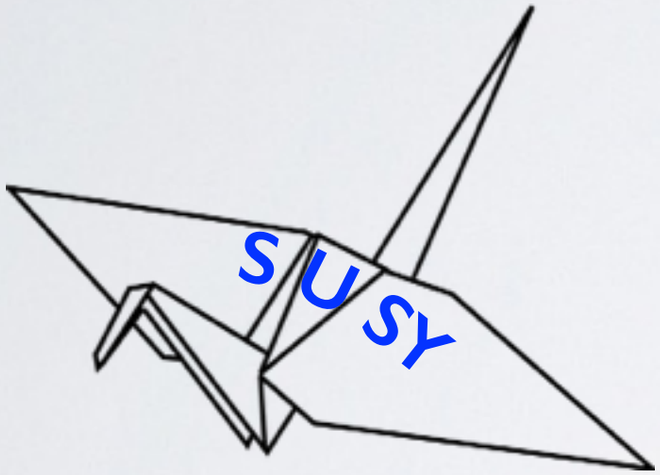
- Introduce a full copy of the SM, with same interaction strengths

- The "Twin" fields play the role of canceling the quadratic divergence



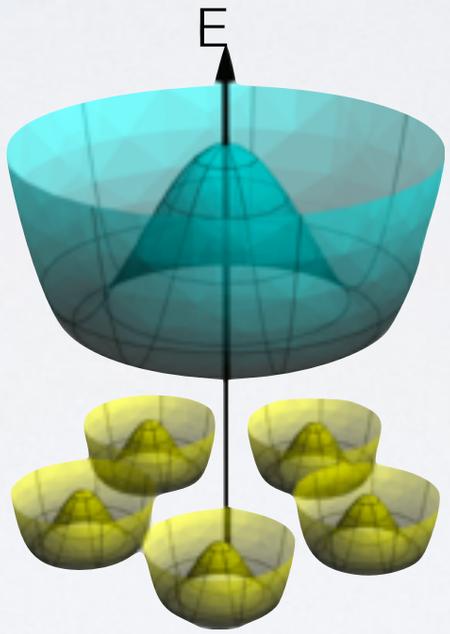
NEUTRAL NATURALNESS

Naturalness models of top partner
that are neutral under QCD



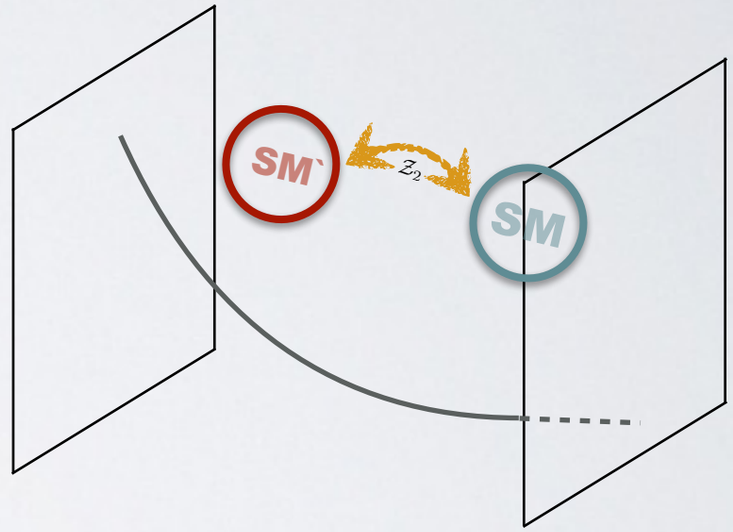
Folded Supersymmetry

G. Burdman, Z. Chacko,
H. Goh, R. Harnik



Orbifold Higgs

N. Craig, S. Knapen, P. Longhi



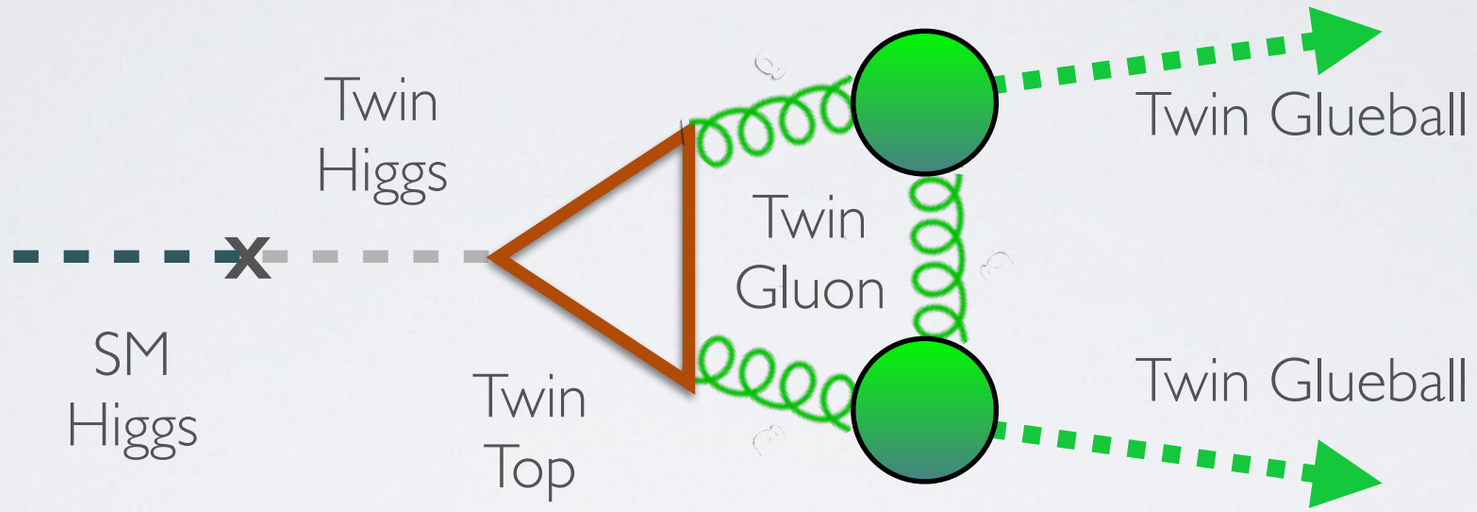
Holographic Twin Higgs

M. Geller, O. Telem

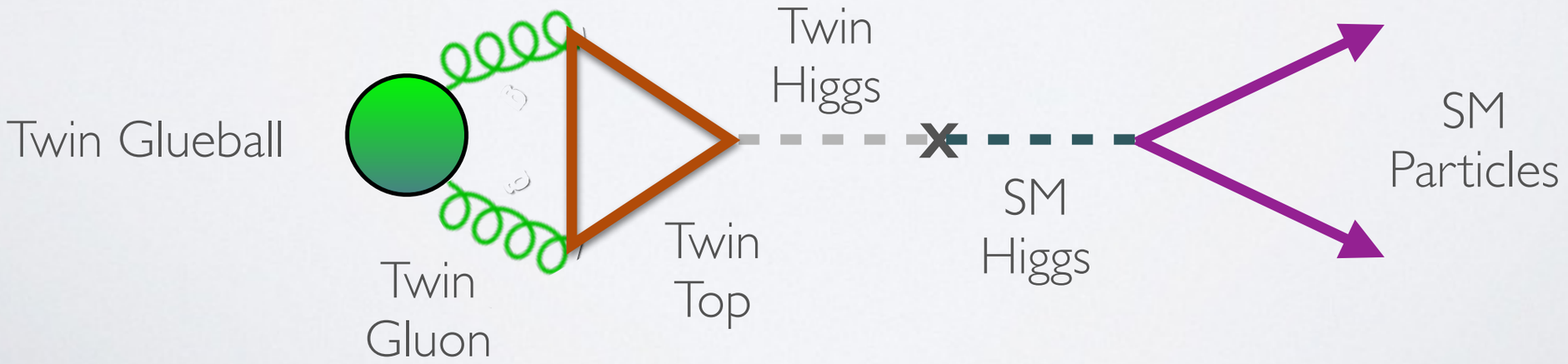
DISPLACED HIGGS

Strassler, Zurek (2008); Kang, Luty (2009); Juknevich, Melnikov, Strassler, (2009); Juknevich (2010); Curtin, Verhaaren, (2015); Craig, Katz, Strassler. Sundrum (2016); Coccaro, Curtin, Lubatti, Russell, Shelton (2016)

The SM Higgs can decay into Twin glueballs

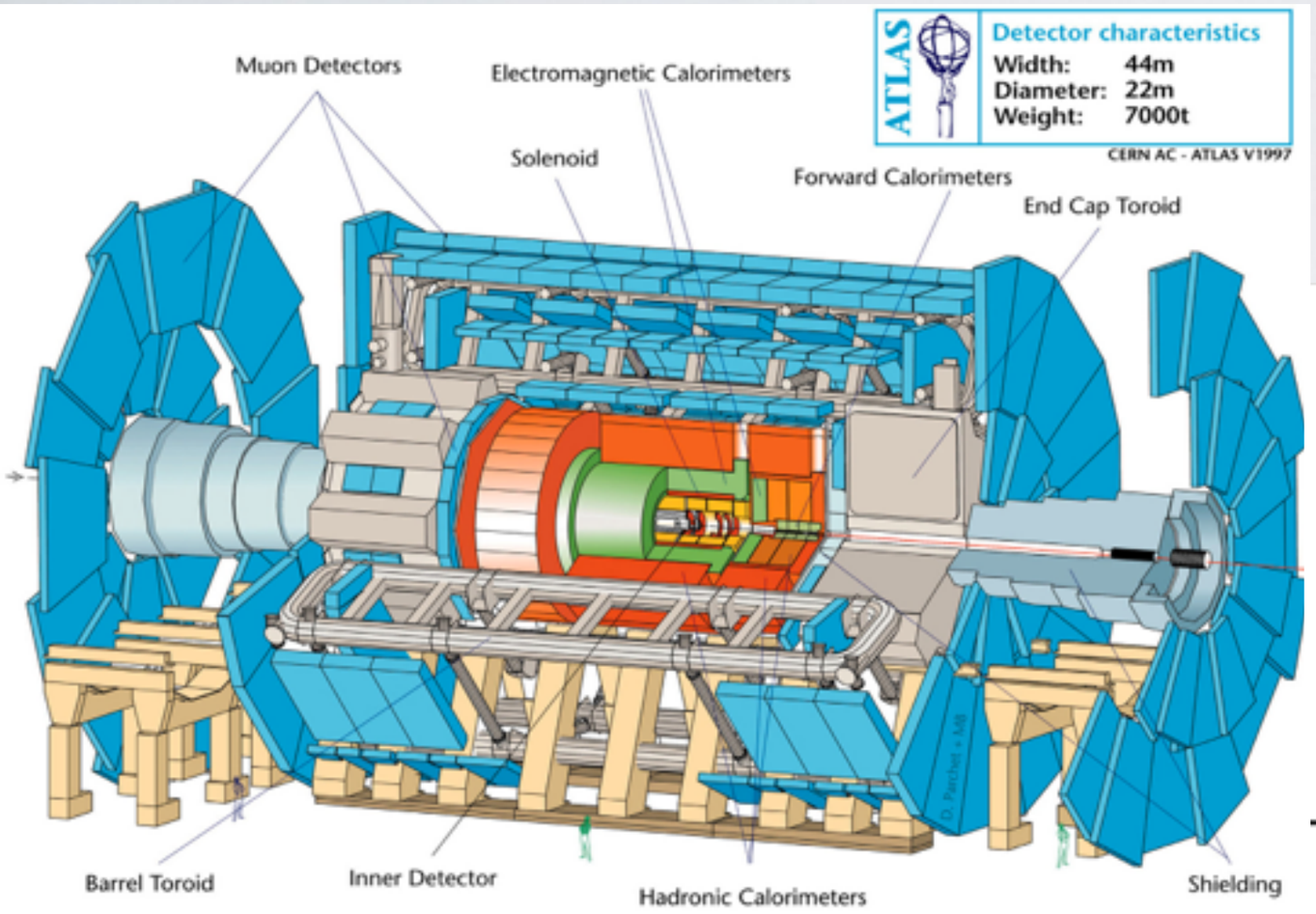


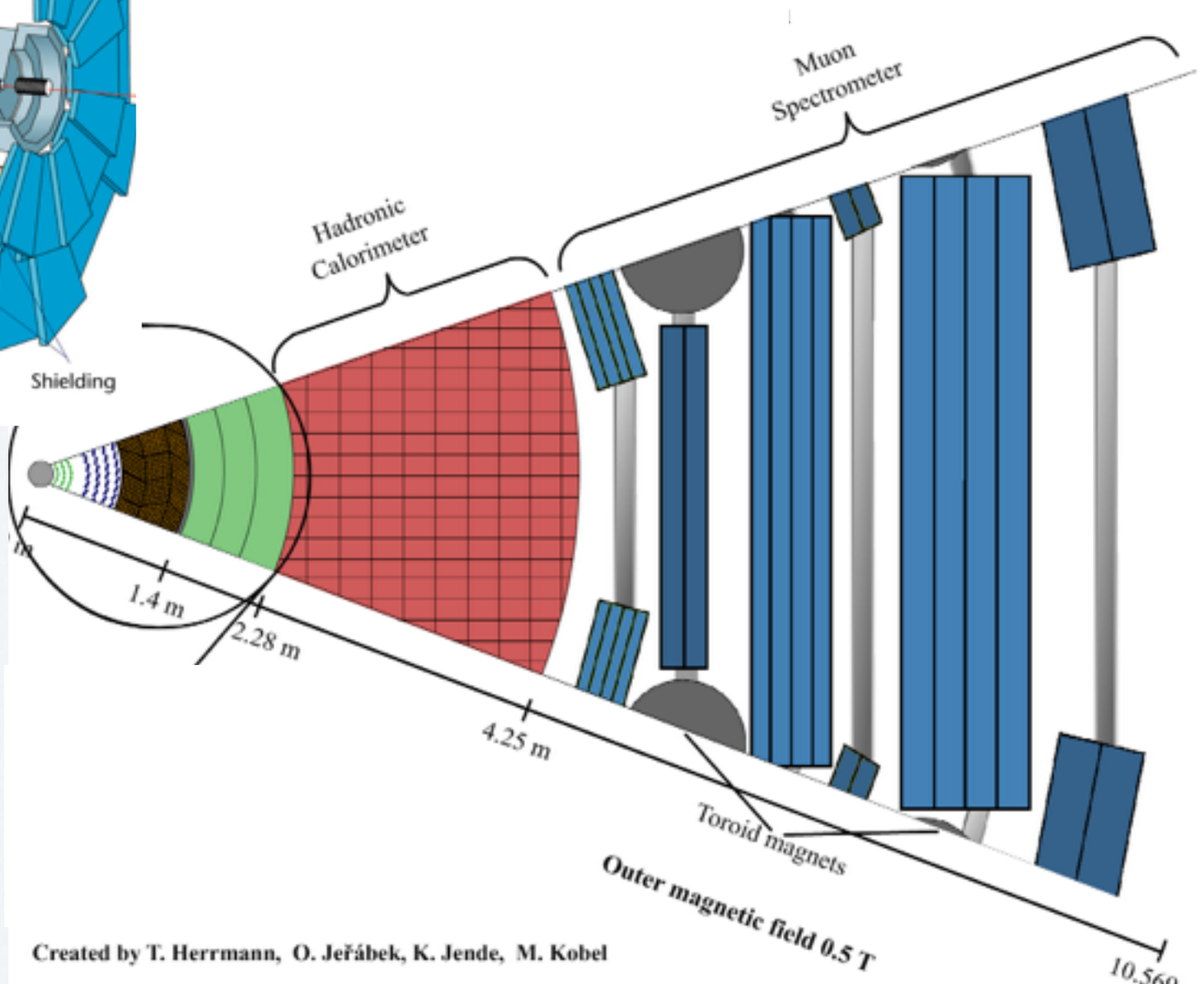
Which then decay back to the SM



DISPLACED SEARCHES AT THE LHC

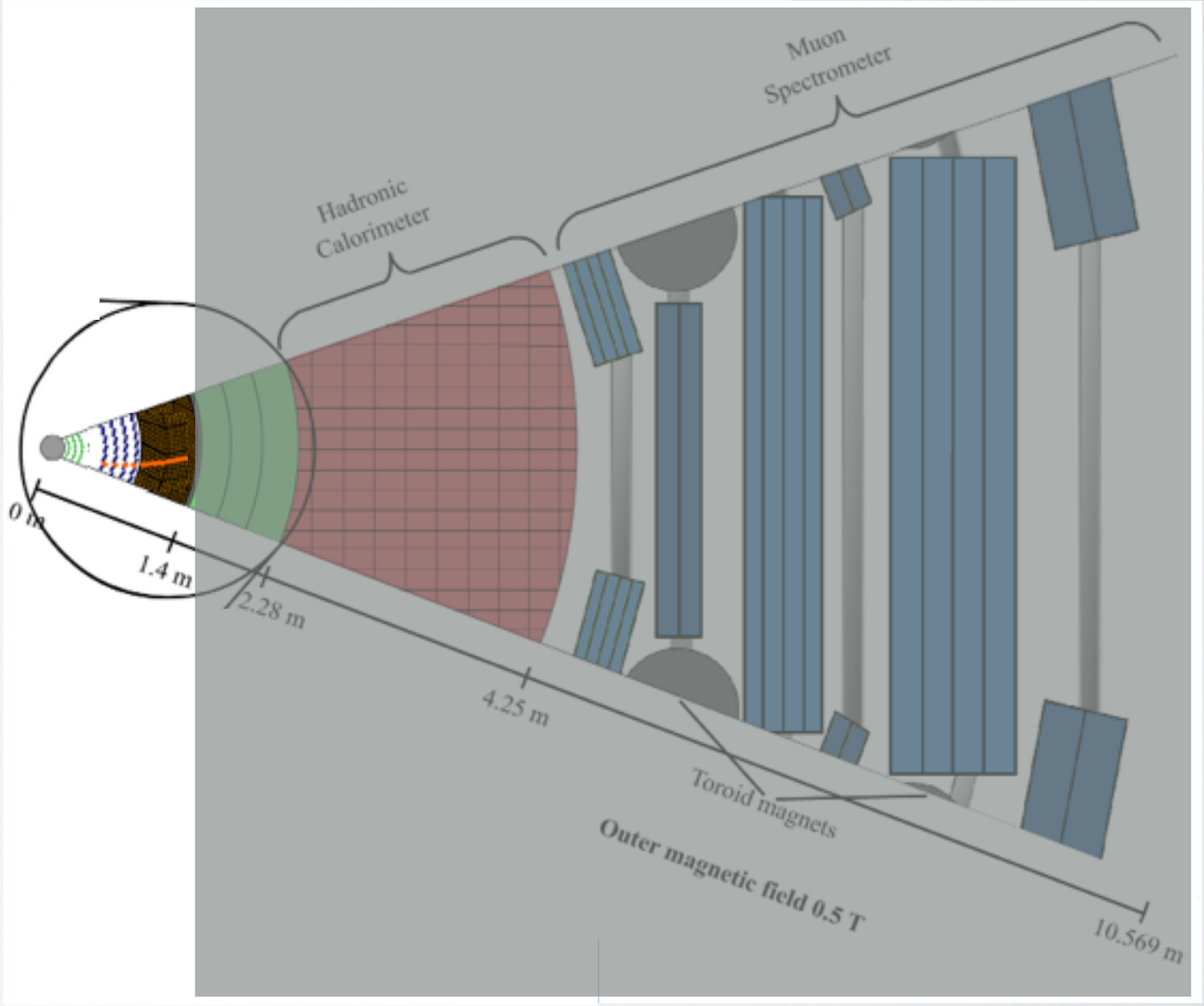
THE DETECTOR





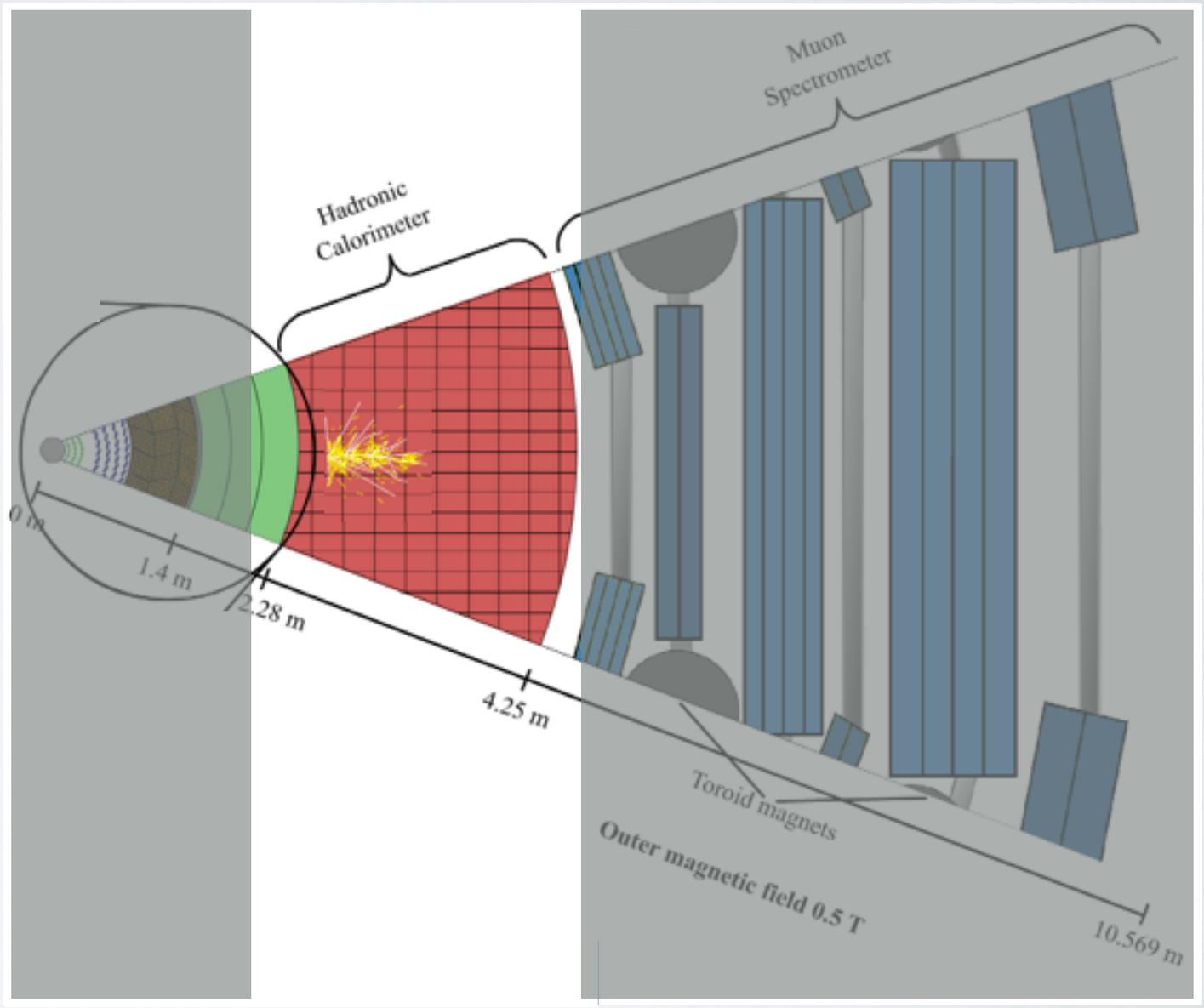
LONG LIVED SEARCHES

- Decays in the tracker:
  - Sensitive to decay lengths ~ 50 cm
  - ATLAS search for DV + muon/electron/jets/ MET (1504.05162)
  - CMS search for a displaced dijet (1411.6530)



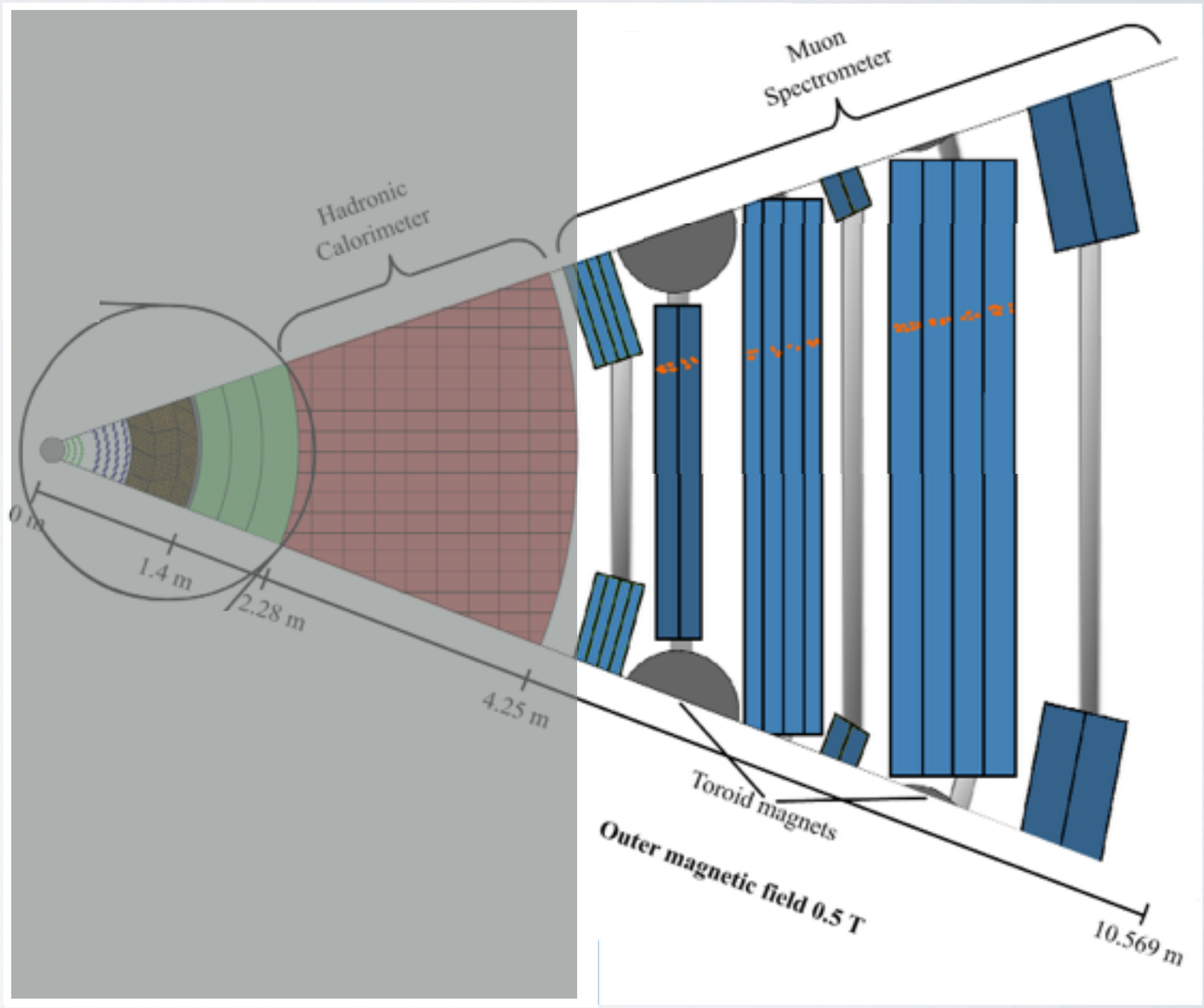
LONG LIVED SEARCHES

- Decays in the calorimeter:
  - Sensitive to decay lengths ~ few meters
  - ATLAS search for low electromagnetic fraction jets (1501.04020)



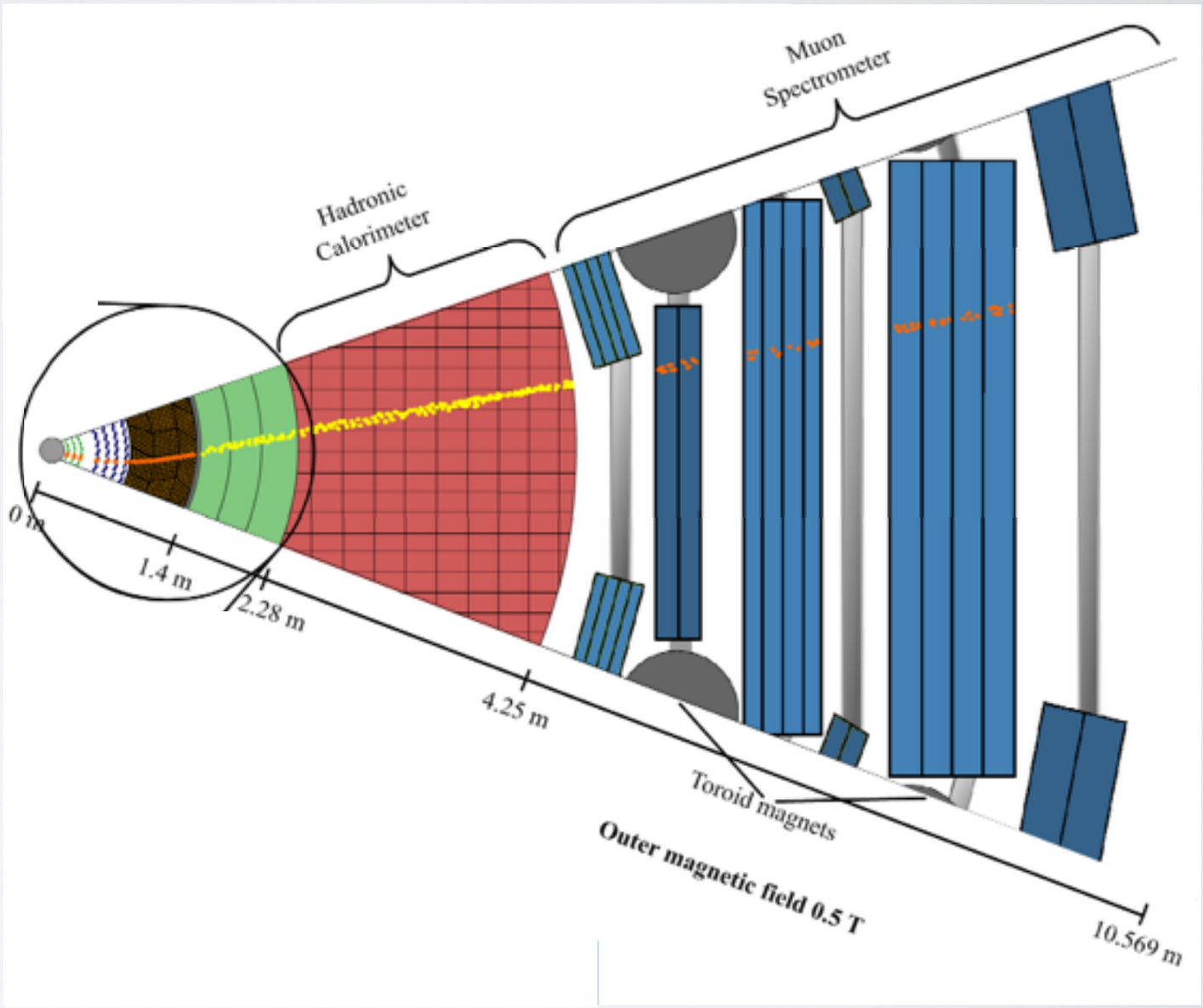
LONG LIVED SEARCHES

- Decays in the muon system:
  - Sensitive to decay lengths ~ several meters
  - ATLAS search for hadronic jets in the muon system (1504.03634)



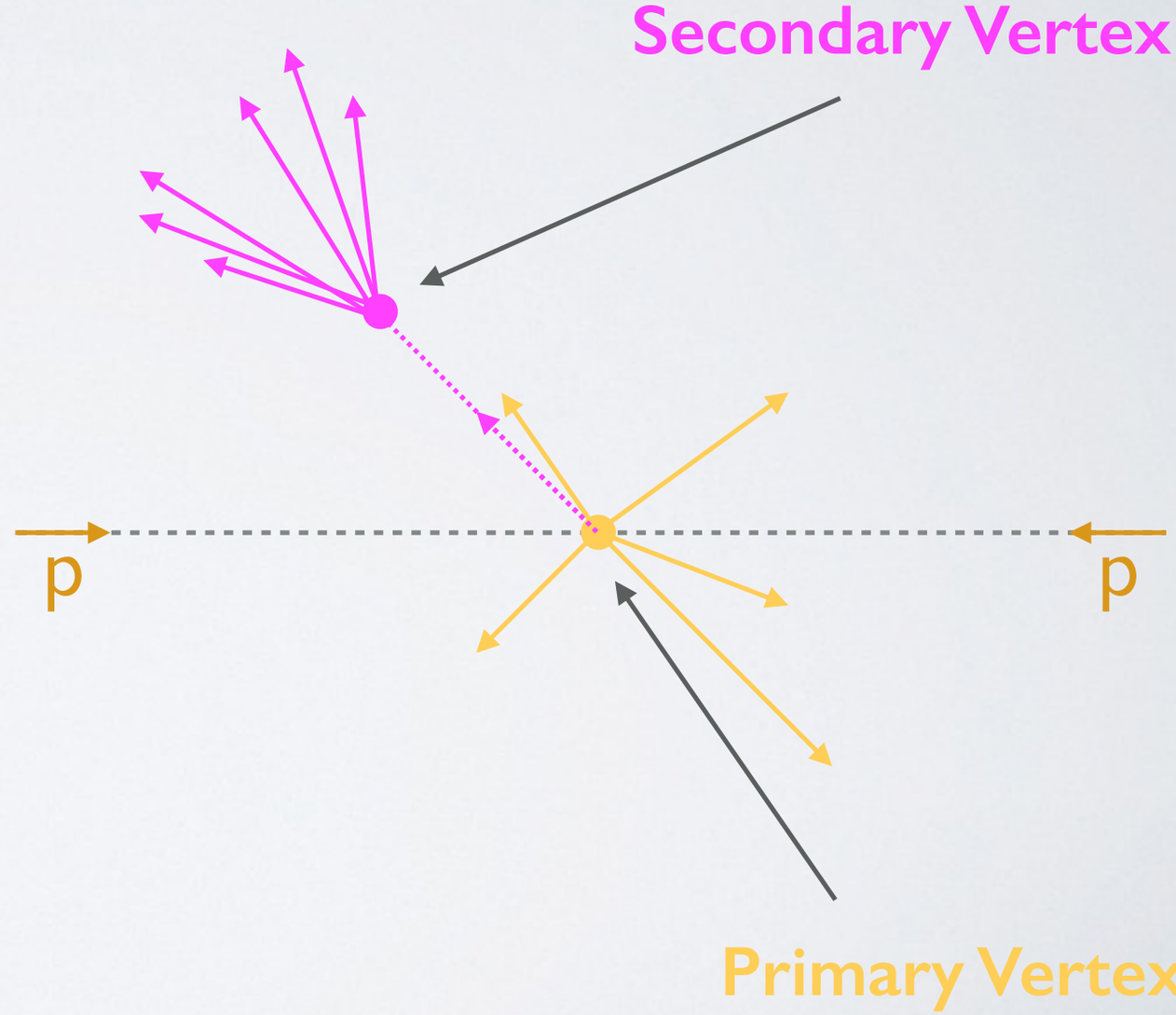
LONG LIVED SEARCHES

- Heavy stabled charged particles:
  - Sensitive to decay lengths > 10 meters
  - Search for muon-like objects, but slower and lose more energy
  - ATLAS (1411.6795)
    CMS (1305.04911)



DISPLACED VERTEX

- Search for a vertex in the tracker that is not aligned with beam axis



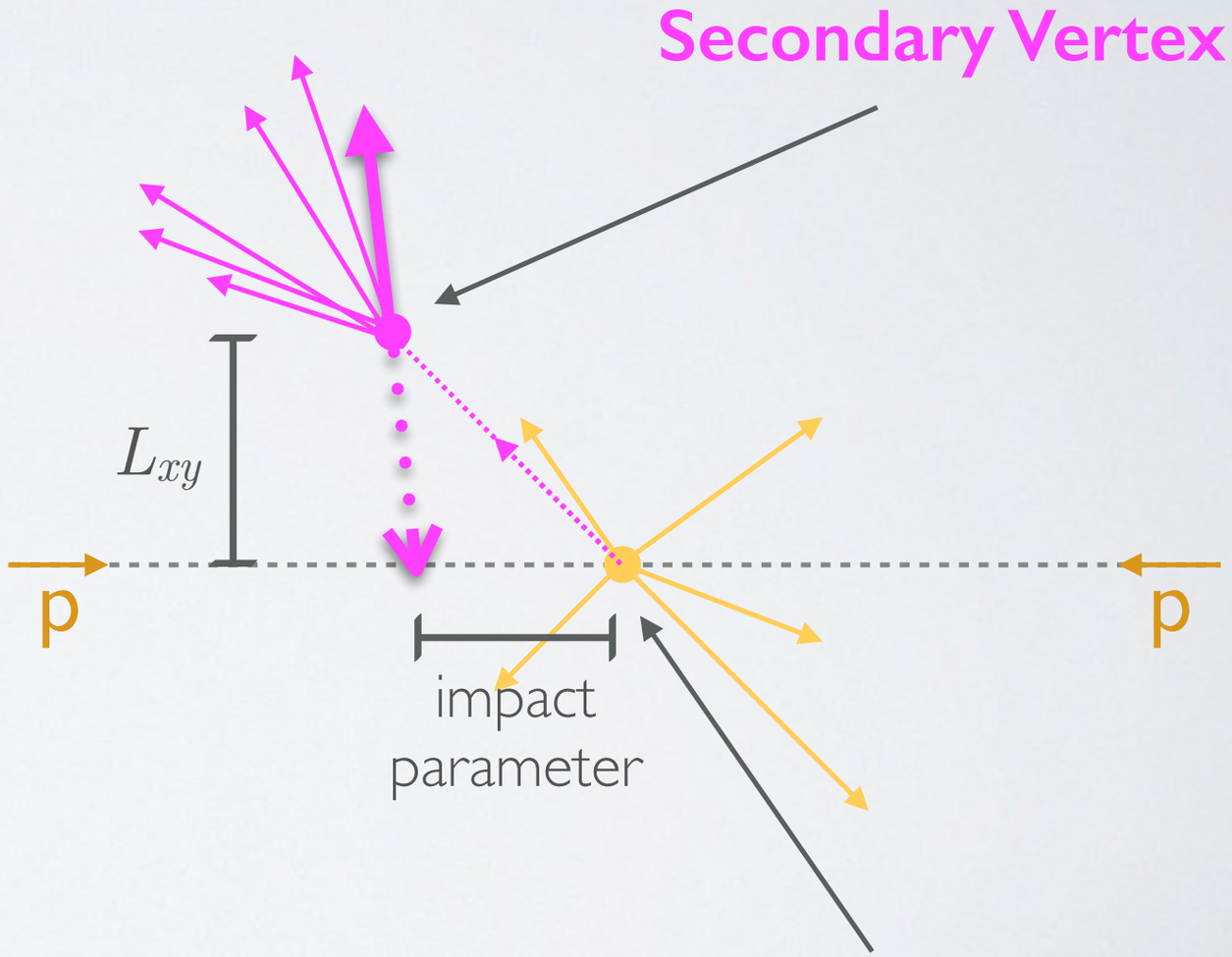
DISPLACED VERTEX

- Search for a vertex in the tracker that is not aligned with beam axis

- Sensitive to
  $L_{xy} \sim 50$ cm
  IP ~ 0.5 mm to 30 cm

- No Level 1 triggers

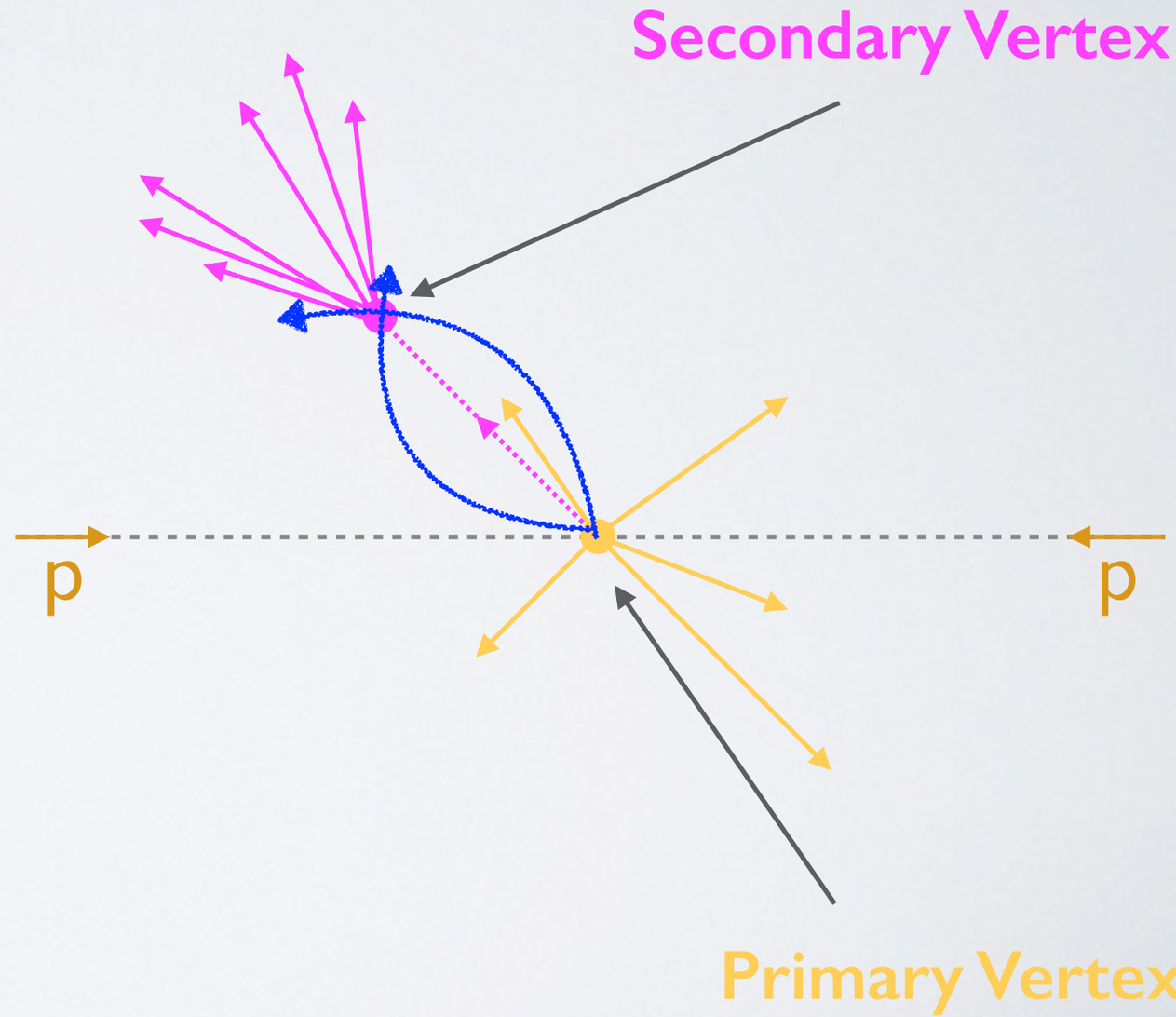
  Triggers require other hard objects



DISPLACED VERTEX

- Search for a vertex in the tracker that is not aligned with beam axis

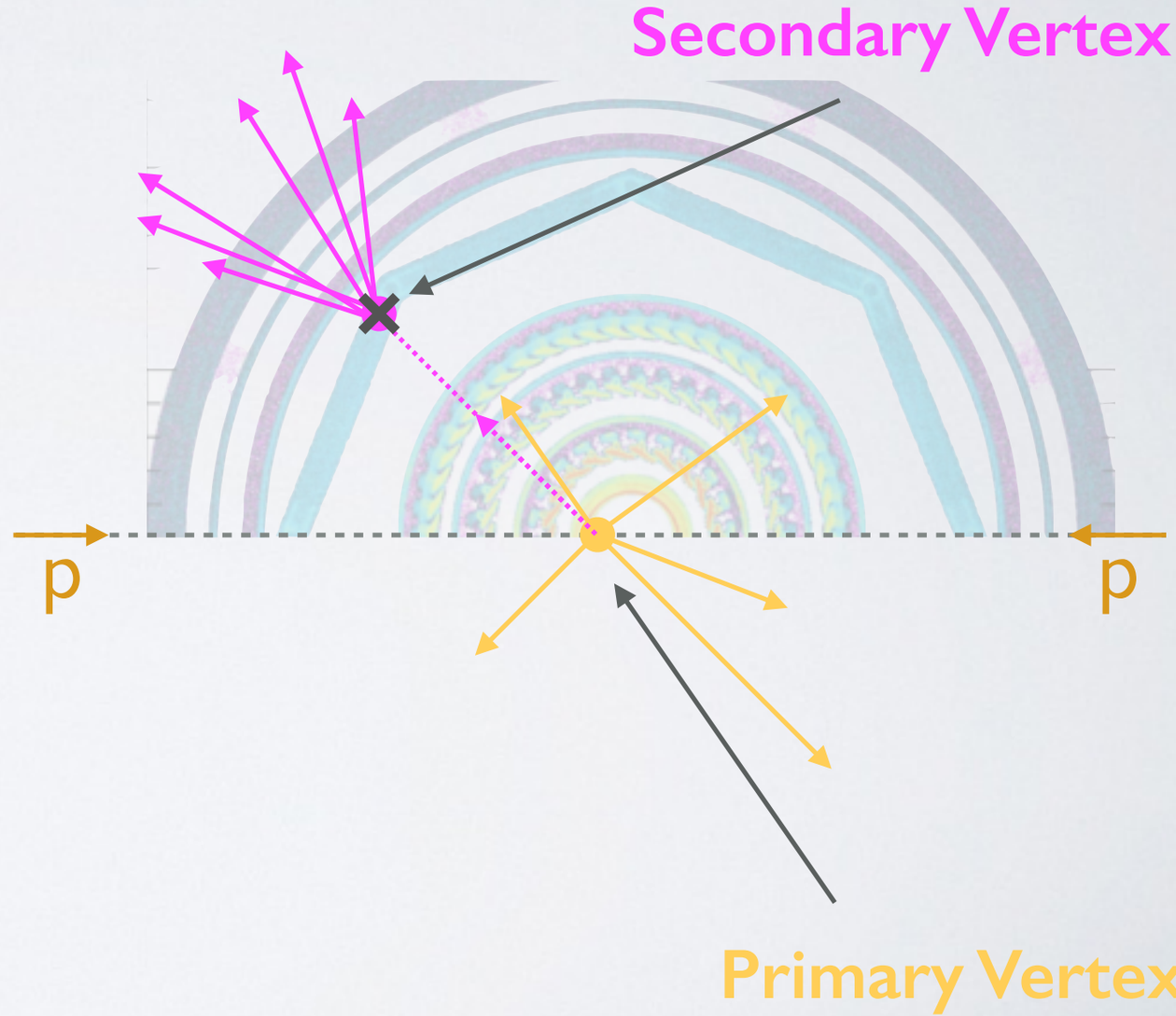
- Backgrounds:
  - Crossing tracks



DISPLACED VERTEX

- Search for a vertex in the tracker that is not aligned with beam axis

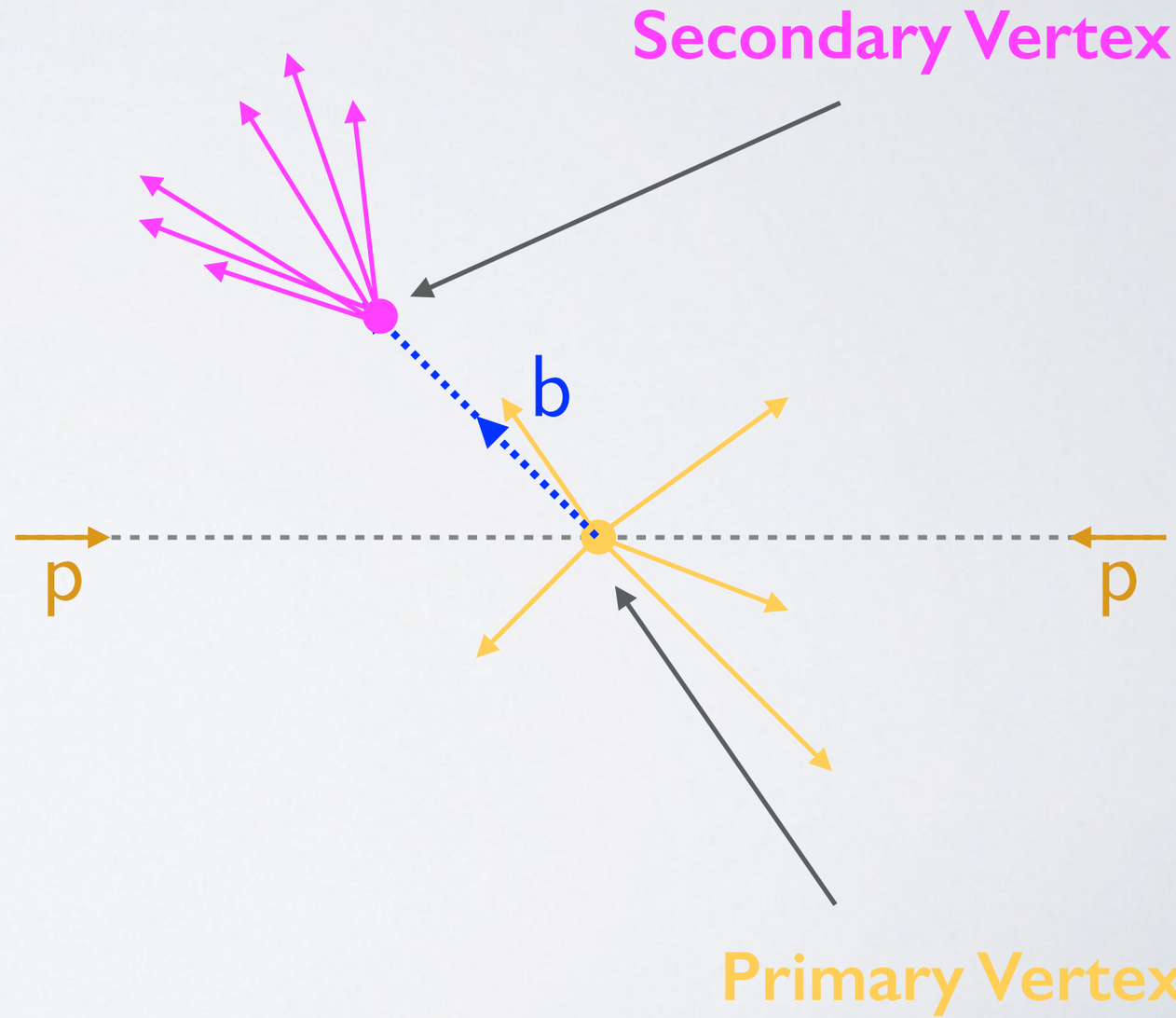
- Backgrounds:
  - Crossing tracks
  - Interactions with detector material



DISPLACED VERTEX

- Search for a vertex in the tracker that is not aligned with beam axis

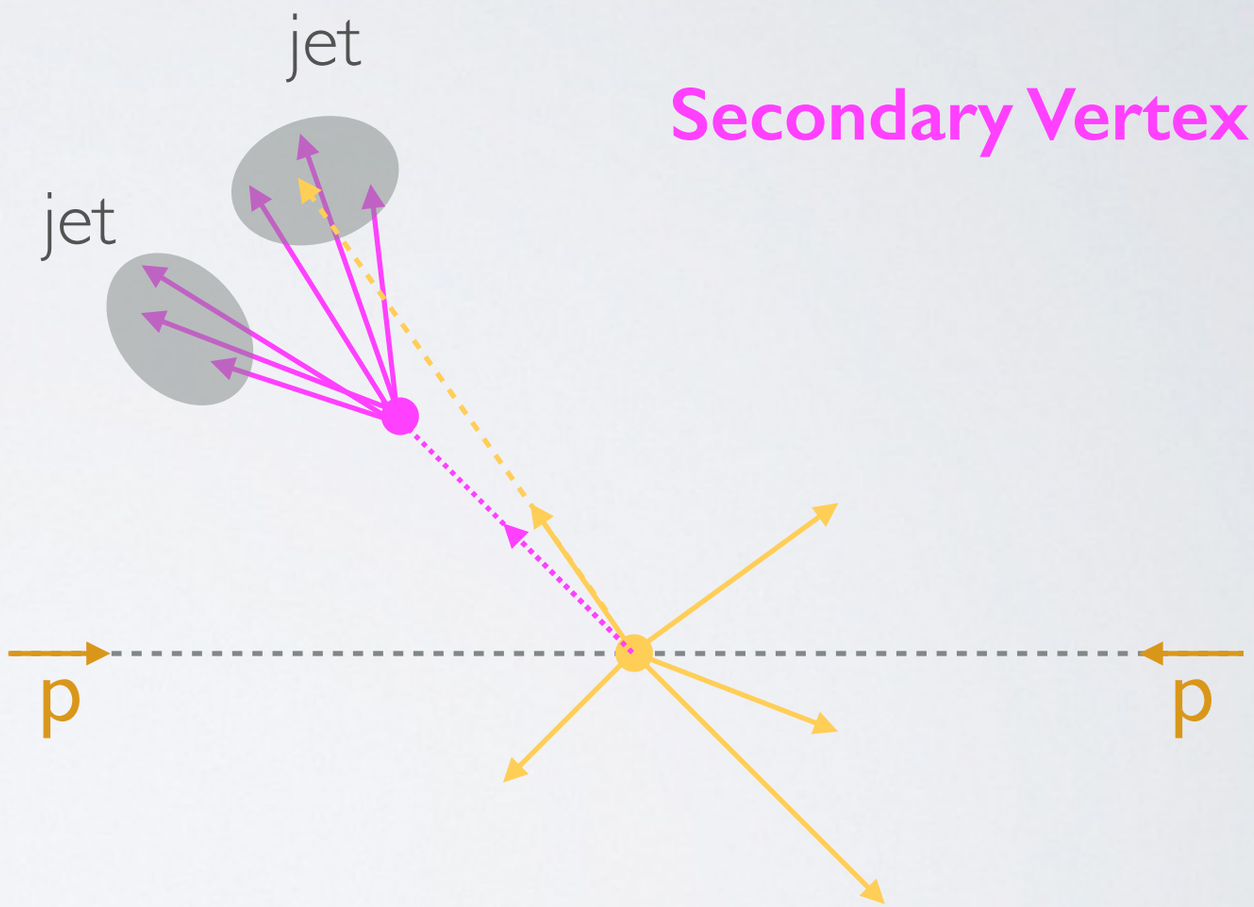
- Backgrounds:
  - Crossing tracks
  - Interactions with detector material
  - b-jets ($c\tau \sim 0.5$ mm)



CMS DISPLACED DIJET

Search for long-lived neutral particles decaying to quark-antiquark pairs in proton-proton collisions at sqrt(s) = 8 TeV

- Search for 2 displaced jets with p_T > 60 GeV (Leptons also counted as jets)
- Important cuts
  - H_T > 350 GeV (trigger)
  - m_{DV} > 4 GeV (no b's)
  - N_{tracks} > 4, 5
  - At most one prompt (IP <0.5 mm) track per jet
  - Dijet consistent with DV



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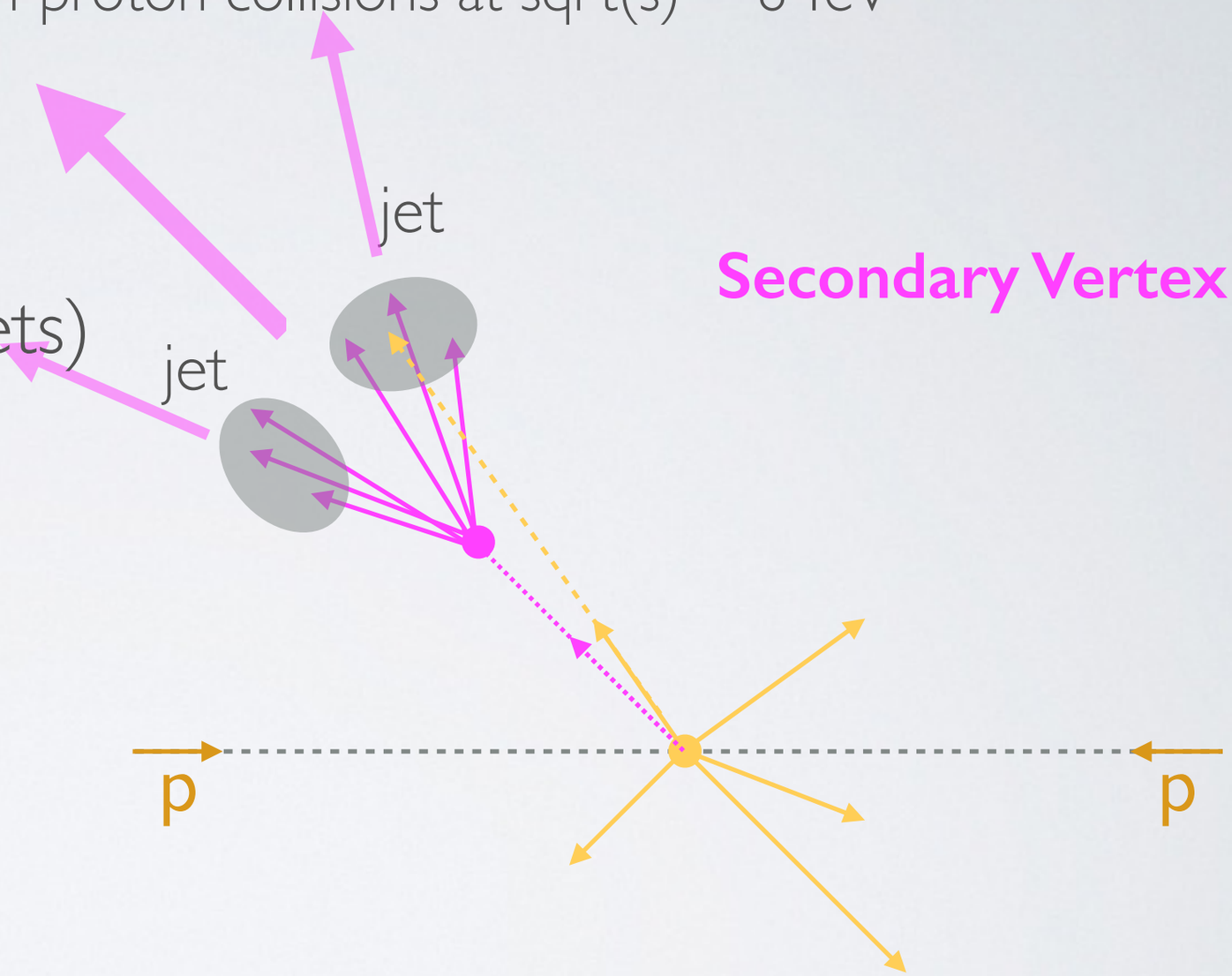

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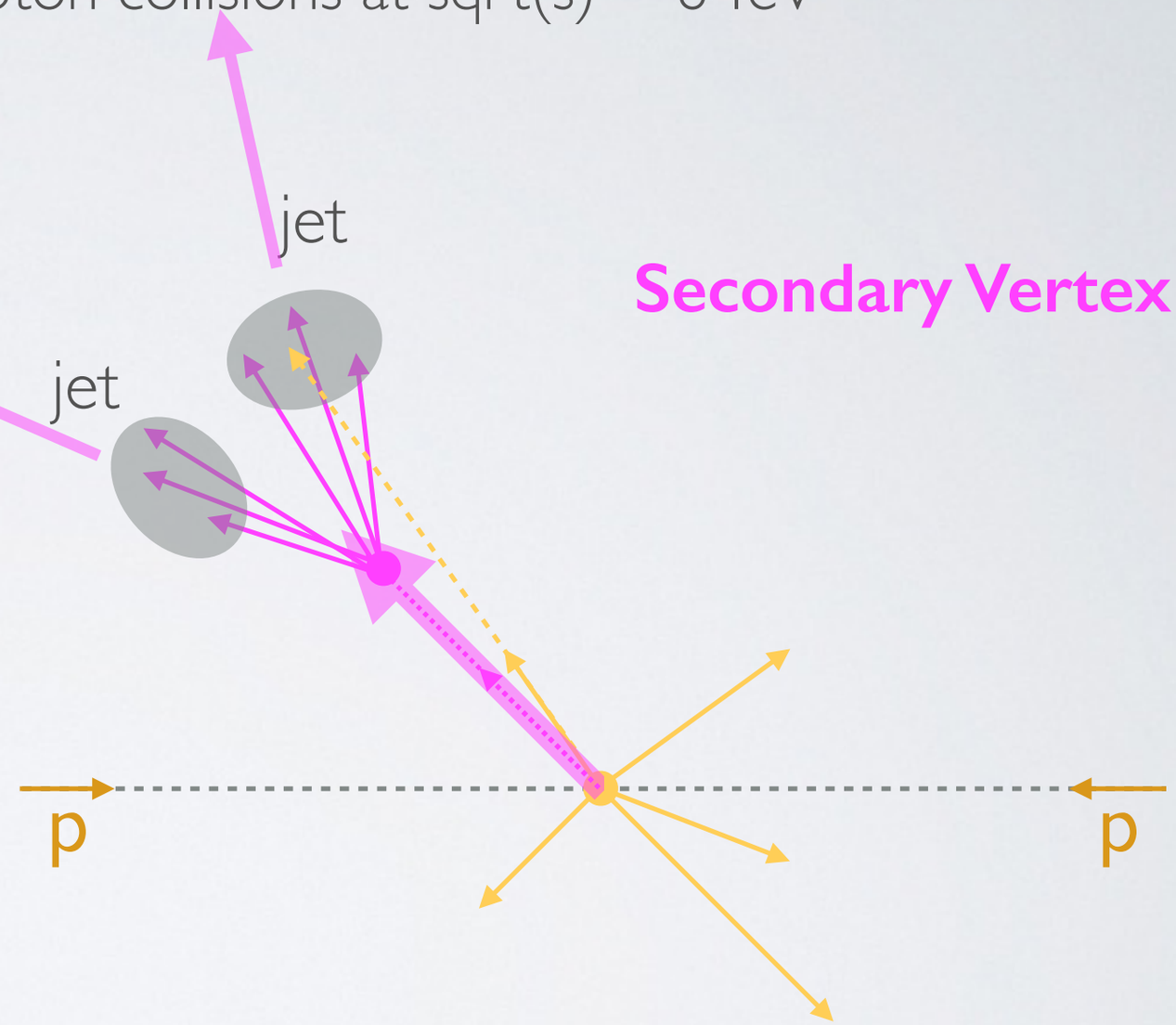
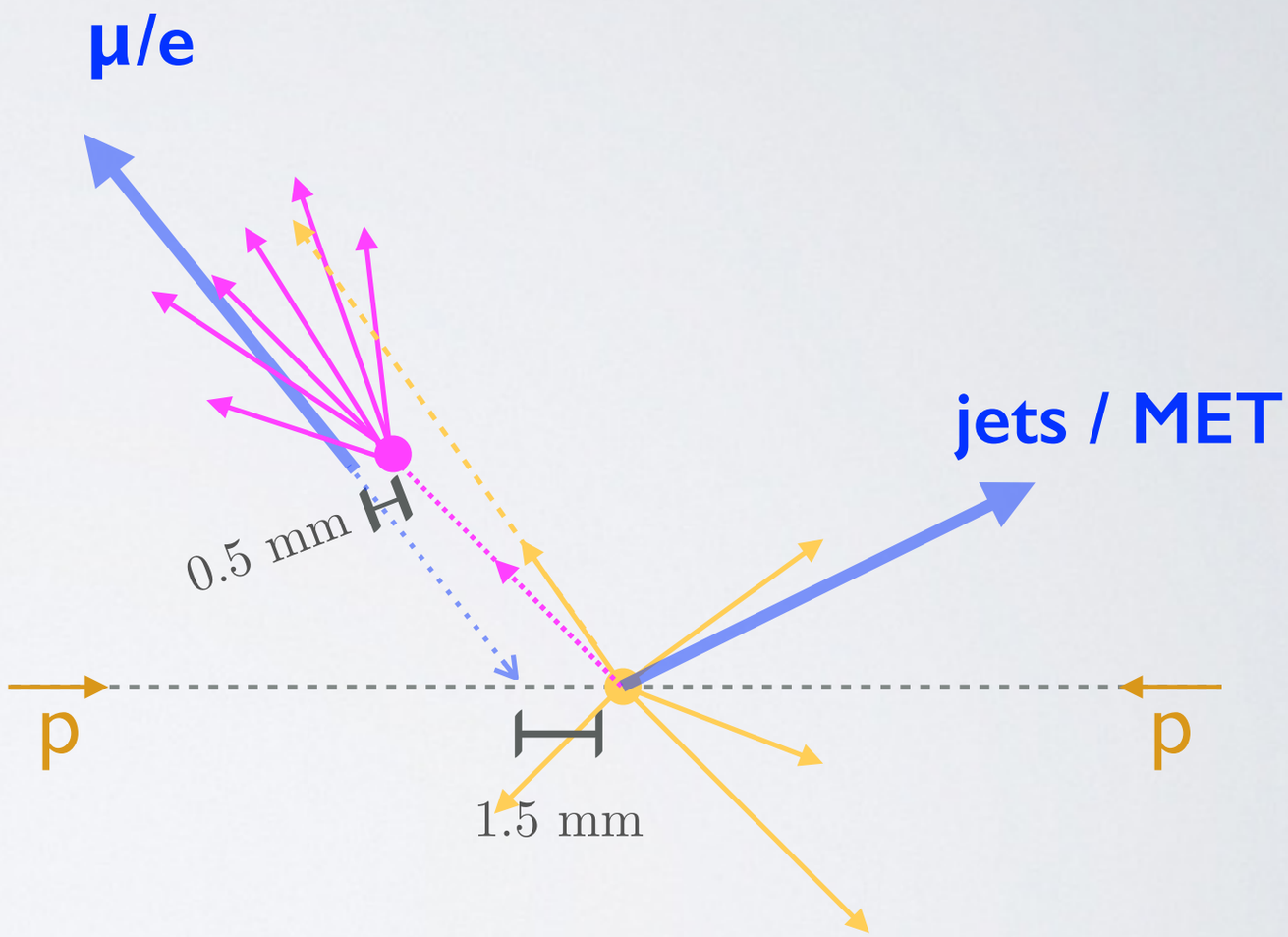


ATLAS DV + *muon/e/jets/MET*

Search for massive, long-lived particles using multitrack displaced vertices or displaced lepton pairs in pp collisions at sqrt(s) = 8 TeV with the ATLAS detector

- Search for displaced vertex with
  - $N_{tracks} > 5$
  - $m_{DV} > 10$ GeV
- Trigger/cut on associated object
  - muon, $p_T > 55$ GeV
  - electron, $p_T > 125$ GeV
  - MET > 180 GeV
  - Jets 4, 5 or 6, $p_T > 65, 60, 55$ GeV



PROBES OF DISPLACED HIGGS

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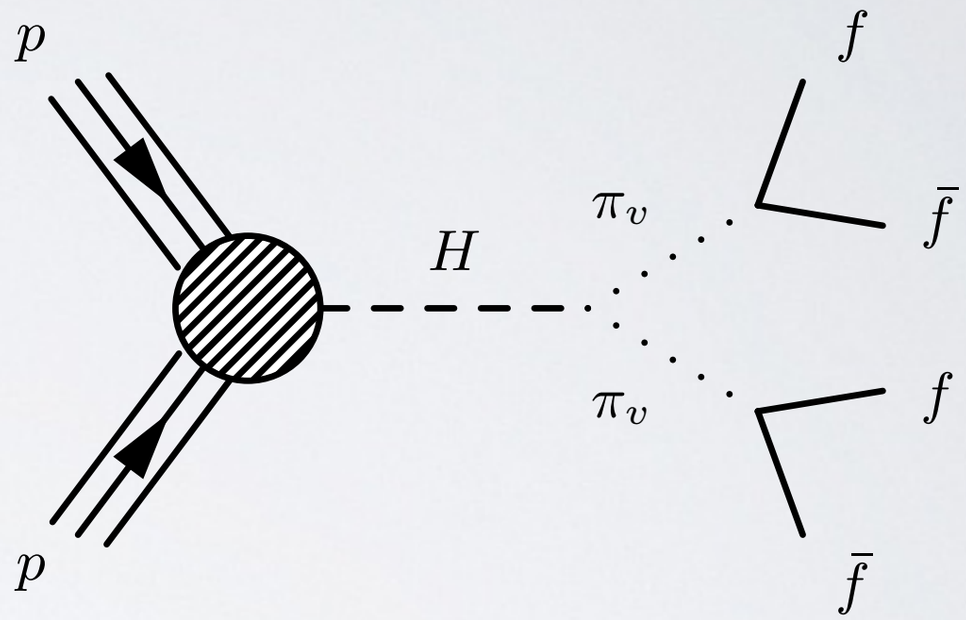
DISPLACED HIGGS

- Look for Higgs decay to two light particles
- Light particles decay to SM pairs
- Assume branching ratios proportional to Higgs couplings.



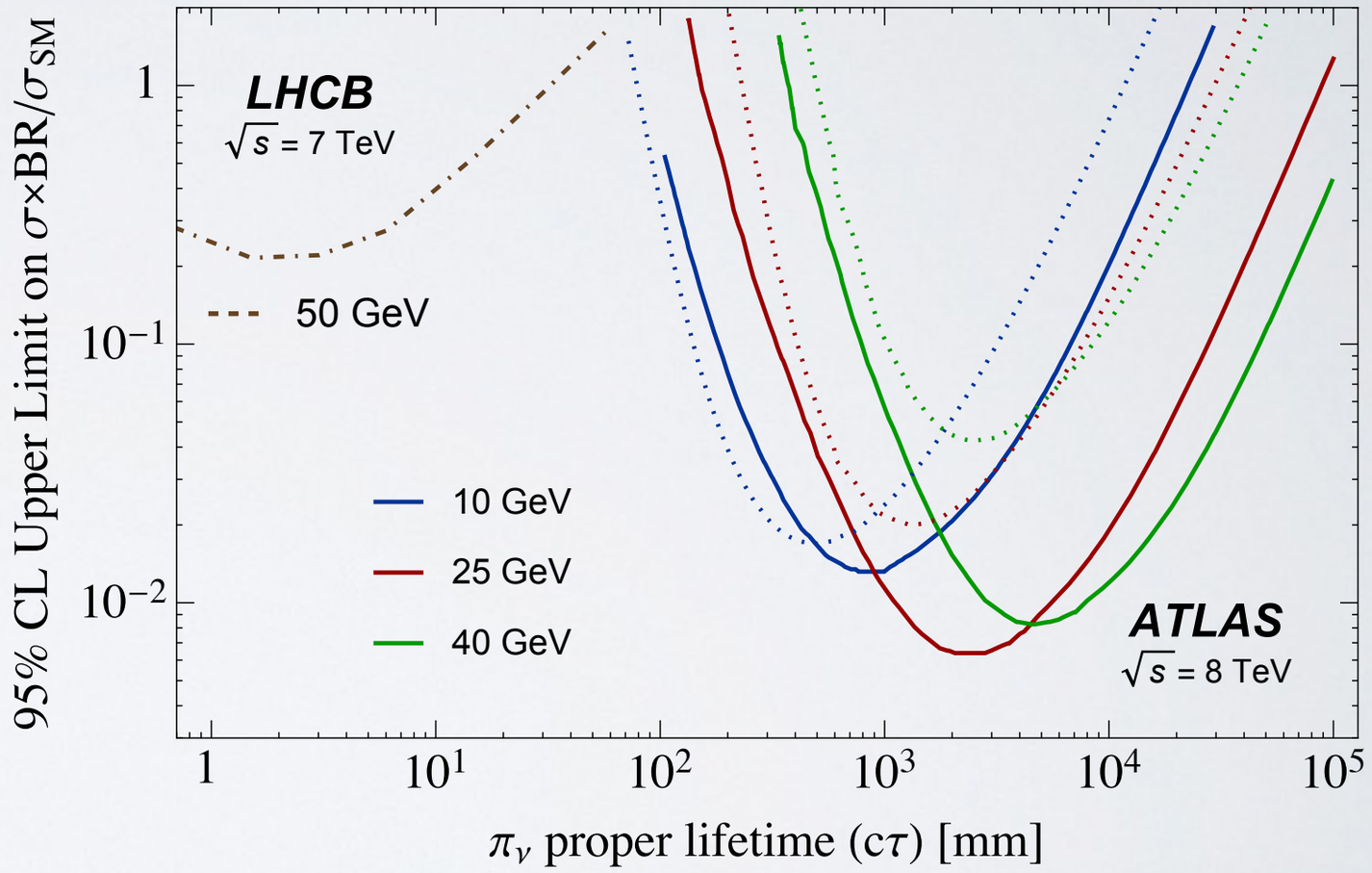
$$m_{\pi_\nu} = 10,\ 25,\ 40\ \mathrm{GeV}$$

EXISTING CONSTRAINTS

- ATLAS search for decays in the HCAL

- ATLAS search for decays in the muon system

- LHCB search for displaced vertices (0.26 fb^{-1})



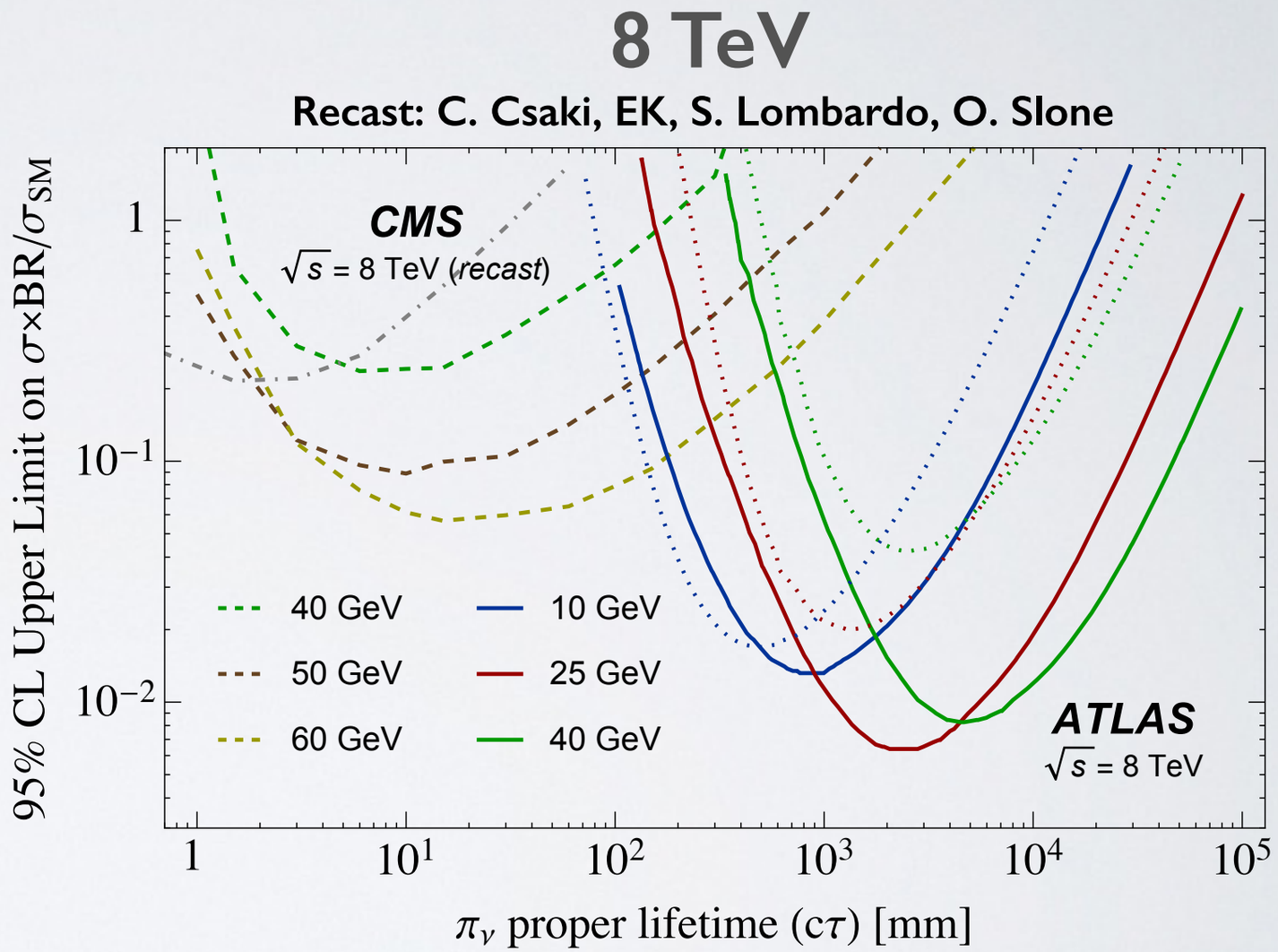
Twin Higgs: BR~10^{-4}

EXISTING CONSTRAINTS

- ATLAS DV search is not sensitive due to strong triggers for leptons, jets and MET

- Recast CMS dijet analysis - dedicated displaced trigger allows some coverage, but $H_T > 350$ GeV decreases efficiency.

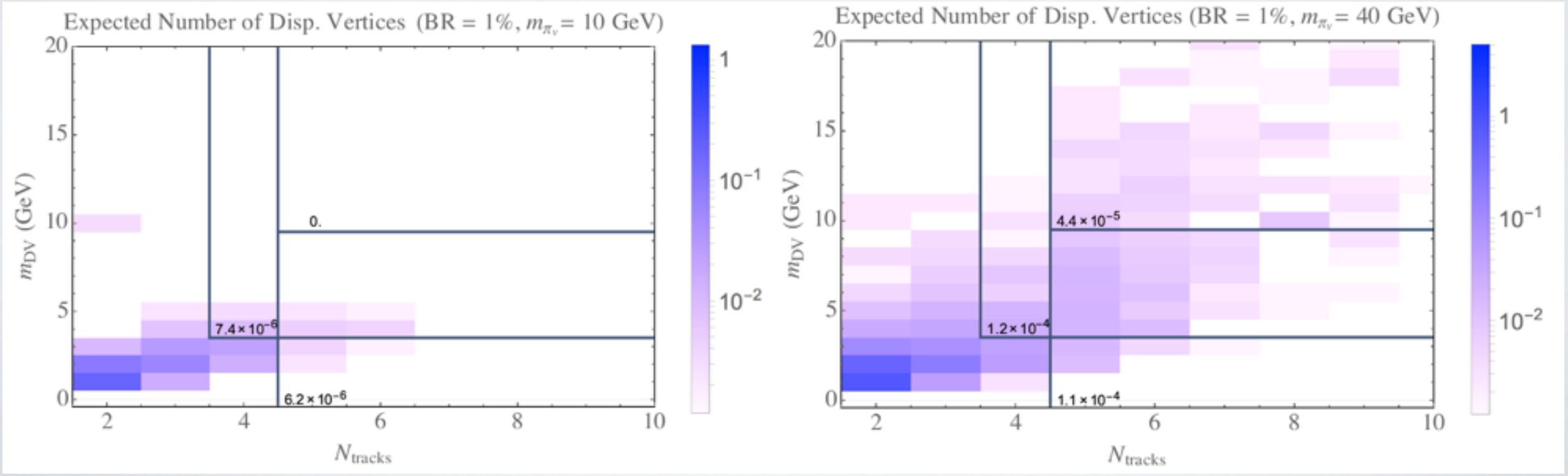
- Picks up boosted Higgs or w/ISR



Twin Higgs: BR~10^{-4}

RUN I SHORTCOMINGS

- Run I strategies not sufficient:
  - Triggers were too strong - required more energy than a typical Higgs event
  - Cuts on the displaced vertex too strong for light objects
- Need a more model-dependent search for lighter objects



Propose new search strategies.

RUN II - TRIGGERS

- New CMS dijet trigger. But new 4 x larger impact parameter than Run I
- For most lifetimes, use prompt triggers
- *Depends on backgrounds

Trigger	Trigger Requirement
Displaced jet	$H_T > 175$ GeV or three jets with $p_T^{j1,2,3} > (92, 76, 64)$ GeV, $\lvert\eta_{j1,2,3}\rvert < (5.2, 5.2, 2.6)$ with $\lvert\eta_{j1}\rvert$ or $\lvert\eta_{j2}\rvert < 2.6$, and two of the three 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) [a], and at least 2 displaced tracks.
Inclusive VBF	Two jets with $\lvert\eta_{j1,j2}\rvert > 2$, $\eta_{j1} \cdot \eta_{j2} < 0$, $\lvert\eta_{j1} - \eta_{j2}\rvert > 3.6$ and $m_{j1,j2} > 1000$ GeV.
VBF, h $\to b\bar{b}$	Three jets with $p_T^{j1,2,3} > (112, 80, 56)$ GeV and $\lvert\eta_{j1,2,3}\rvert < (5.2, 5.2, 2.6)$ and at least one of the two first jets with $\lvert\eta_{j1}\rvert$ or $\lvert\eta_{j2}\rvert < 2.6$.
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.

TRIGGER EFFICIENCIES

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%**

PROPOSED SEARCH STRATEGIES

- **Search I**: Single DV with $m_{DV} \geq 10$ GeV and $N_{tracks} \geq 5$ tracks based on ATLAS search. Good for high mass ≥ 40 GeV

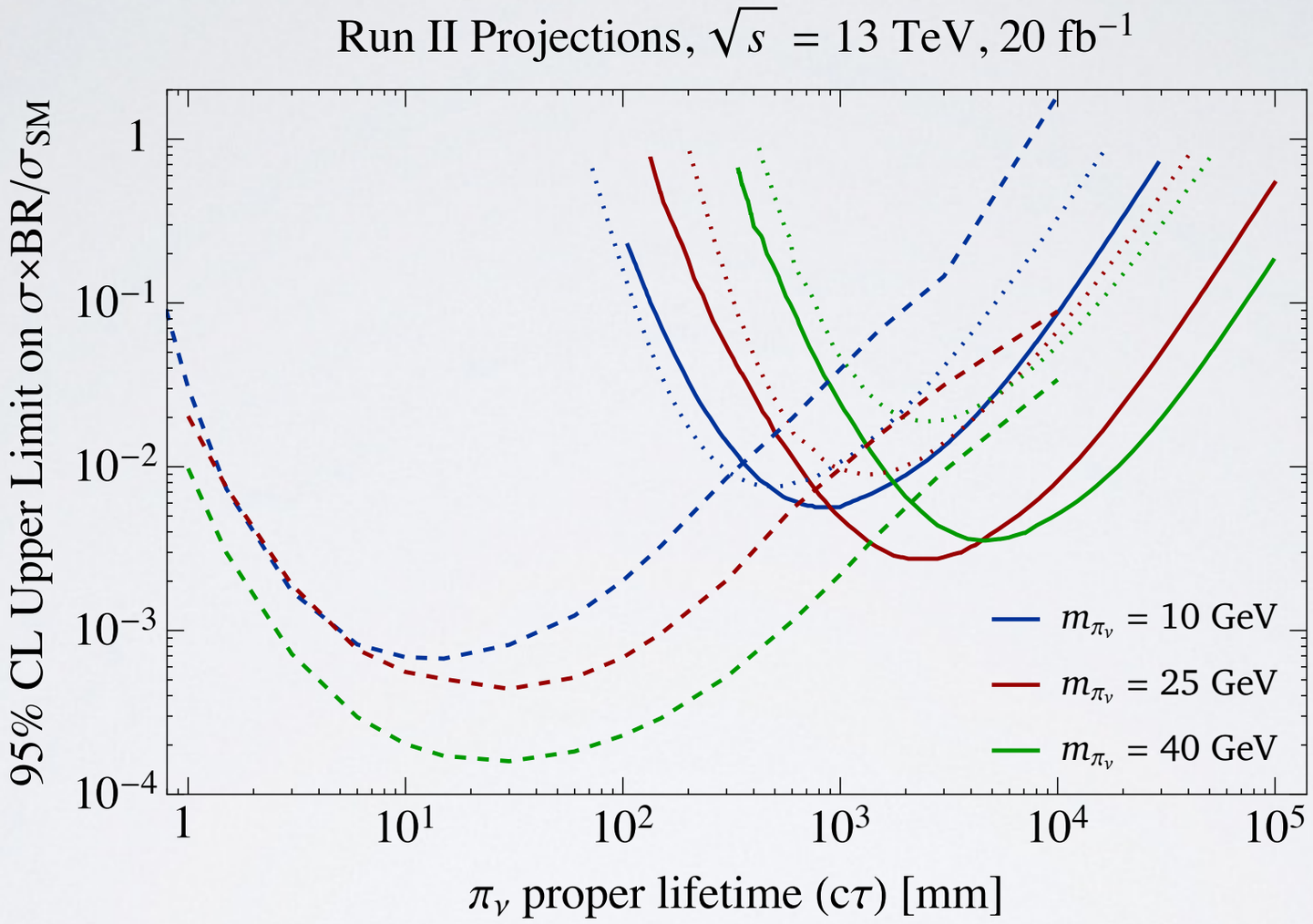
- **Search II**: One DV with $N_{tracks} \geq 5$, no mass requirement (allow softer objects), but reproduce Higgs and intermediate particle masses

- **Search III**: Single DV with $m_{DV} \geq 4$ GeV and $N_{tracks} \geq 4$ tracks based on CMS search.

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

- **Search V**: Search for 2 DVs ($N_{tracks} \geq 5$) in the same event, comparable to an ATLAS search.

COMBINED PROJECTIONS



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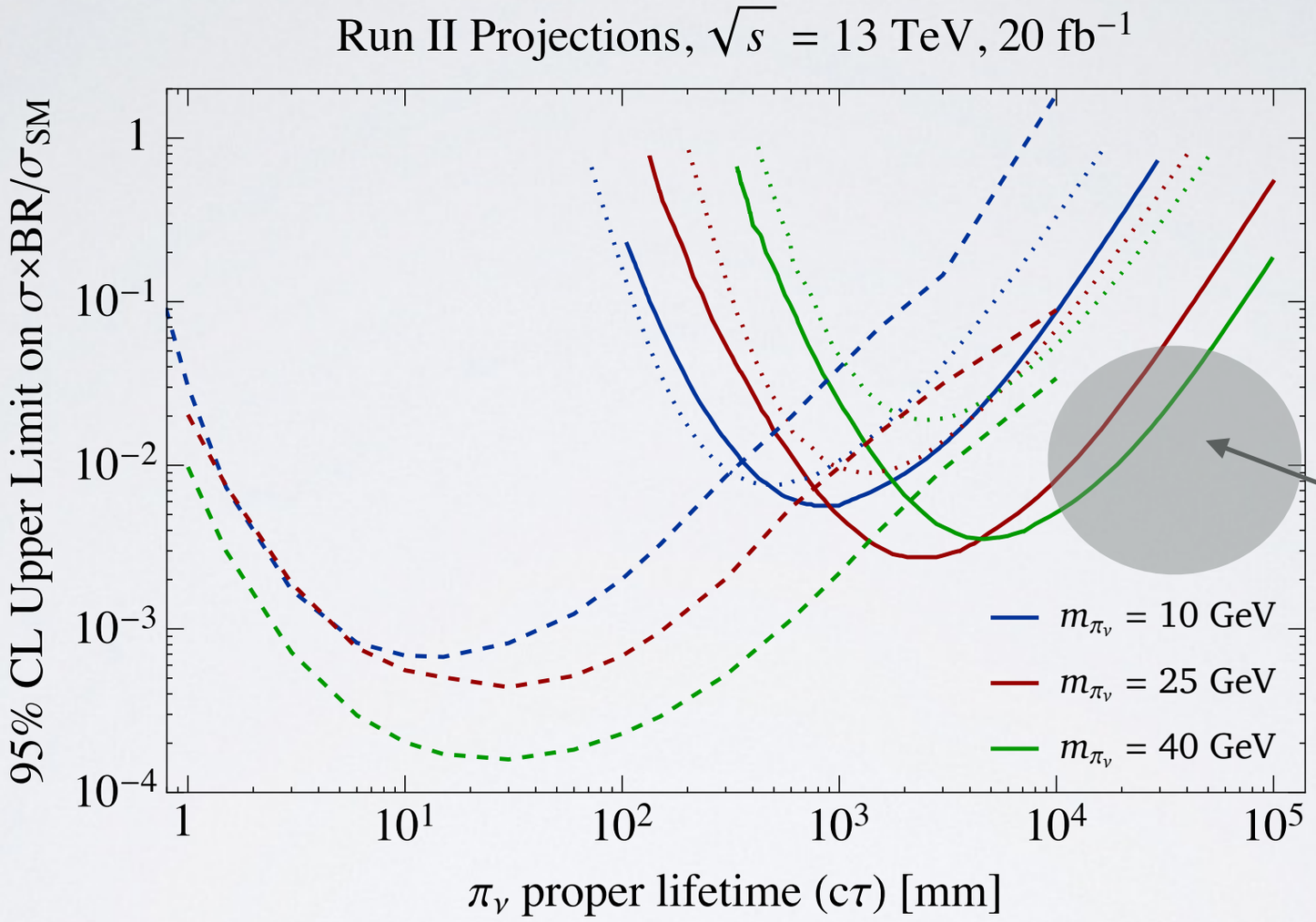
Can probe

COMBINED PROJECTIONS



Coccaro, Curtin, Lubatti, Russell, Shelton, (1605.02742)

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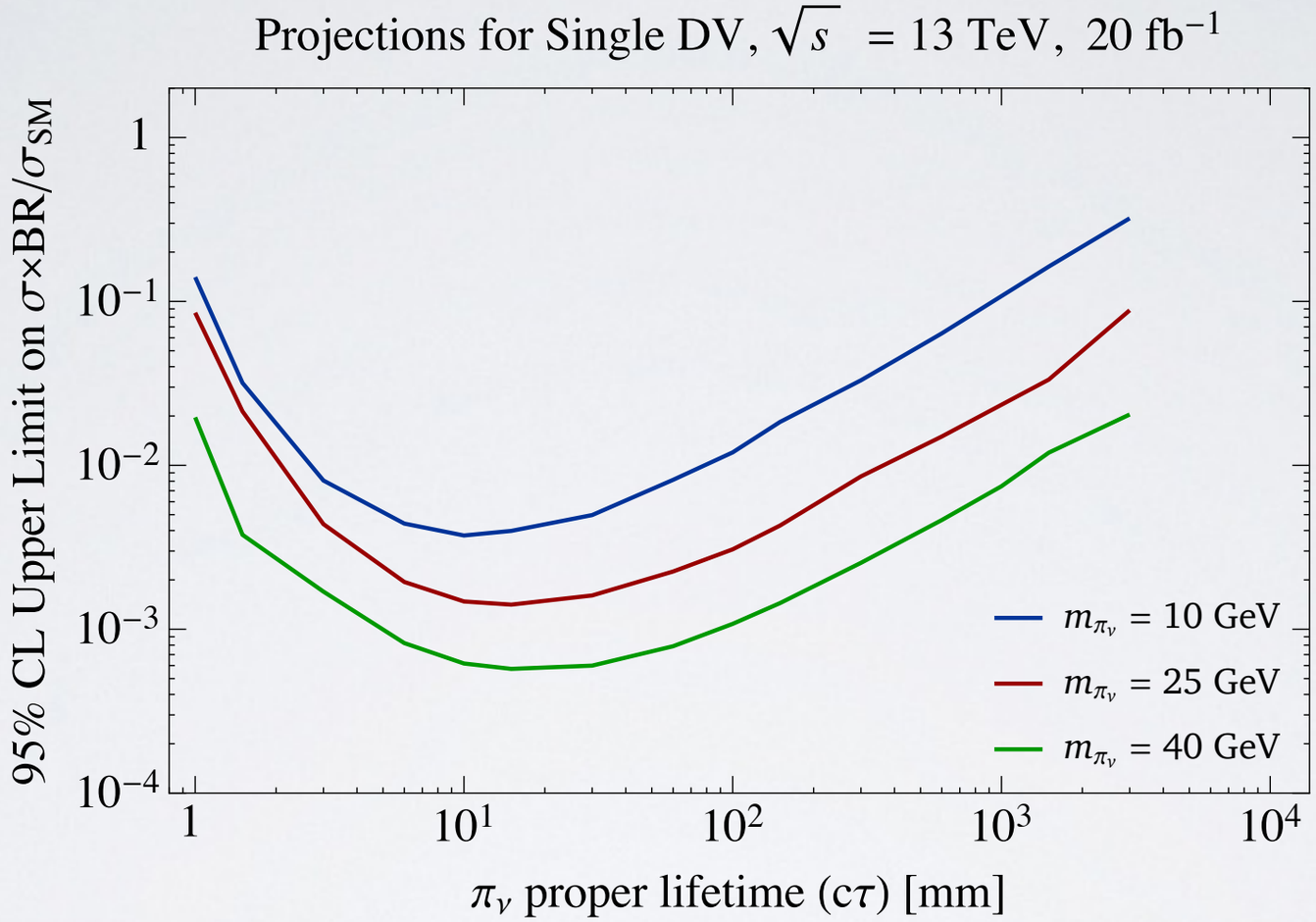
Can probe

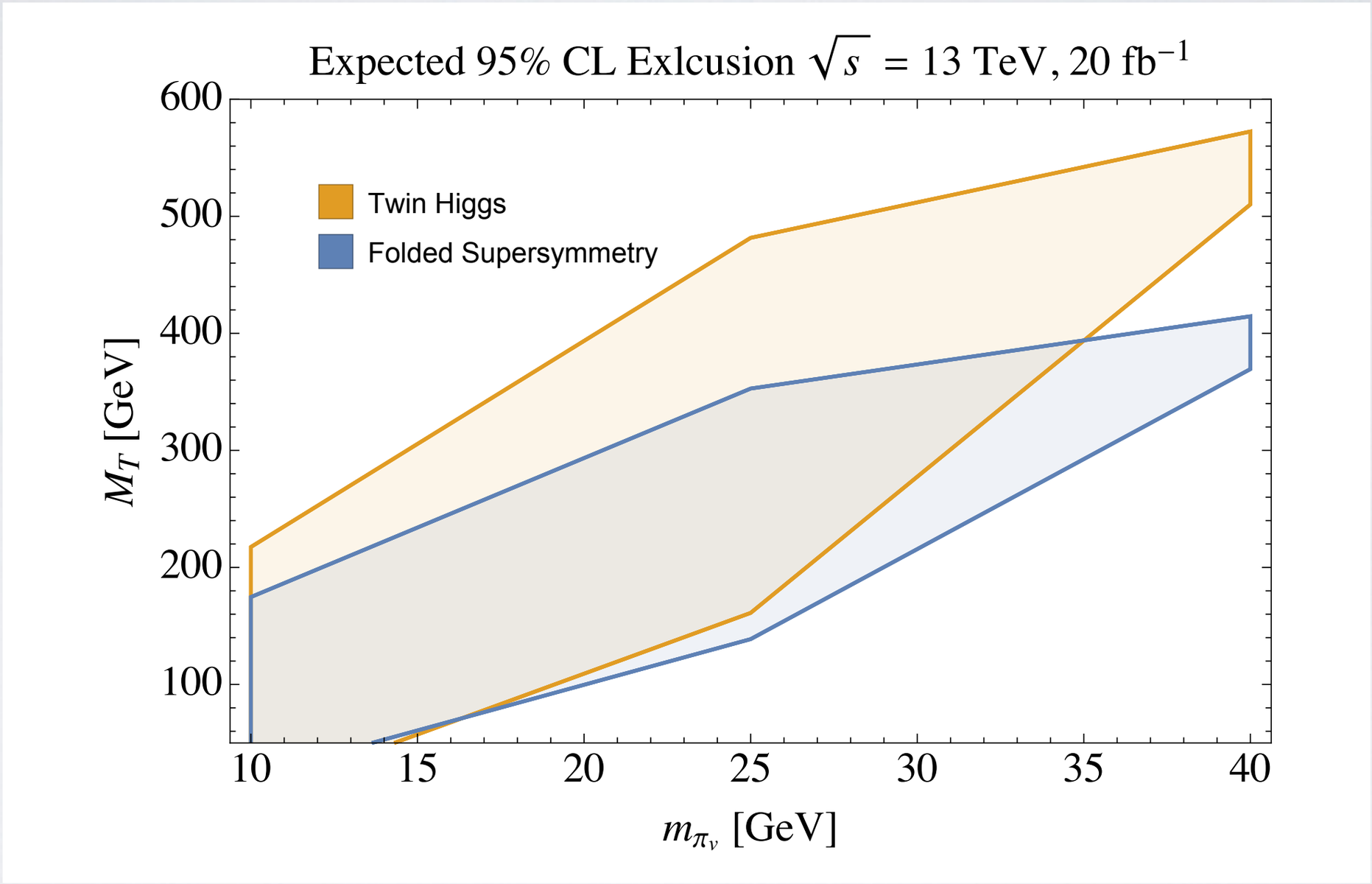
SINGLE DV



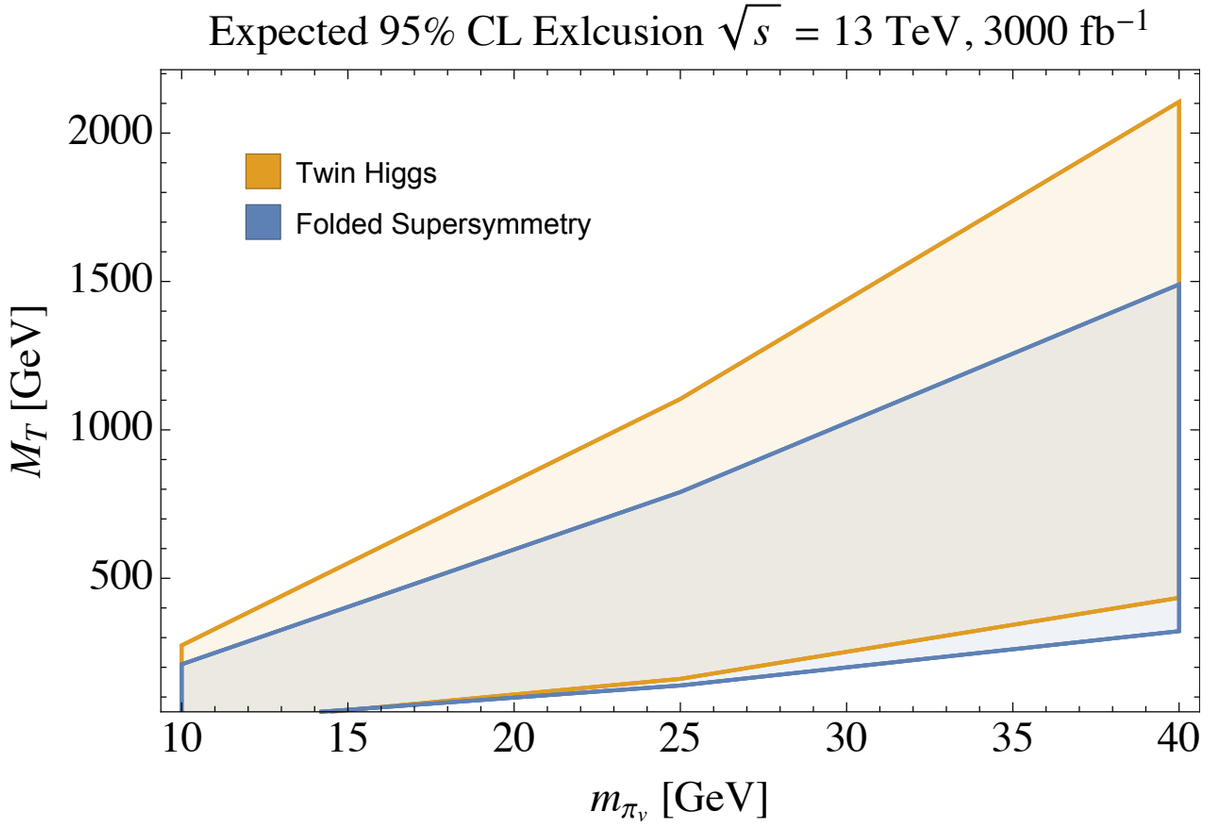
- **Combined Search III and IV**: sensitivity for case with just **one displaced vertex**, assuming the second particle just escapes the detector.

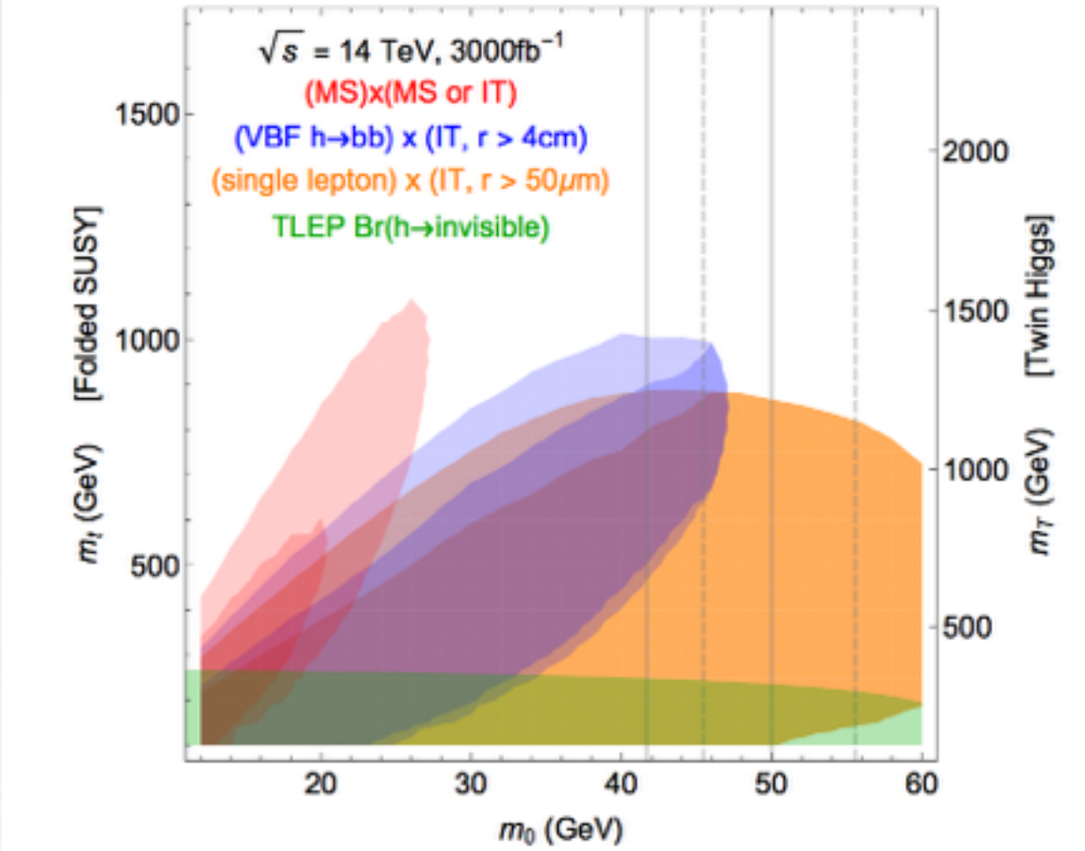
Unconstrained by existing DV searches

MODEL REACH


Expected 95% CL Exlcusion $\sqrt{s}$ = 13 TeV, 20 fb^{-1}
Twin Higgs
Folded Supersymmetry
M_T [GeV]
600
500
400
300
200
100
10
15
20
25
30
35
40
m_{π_v} [GeV]

NATURALNESS REACH

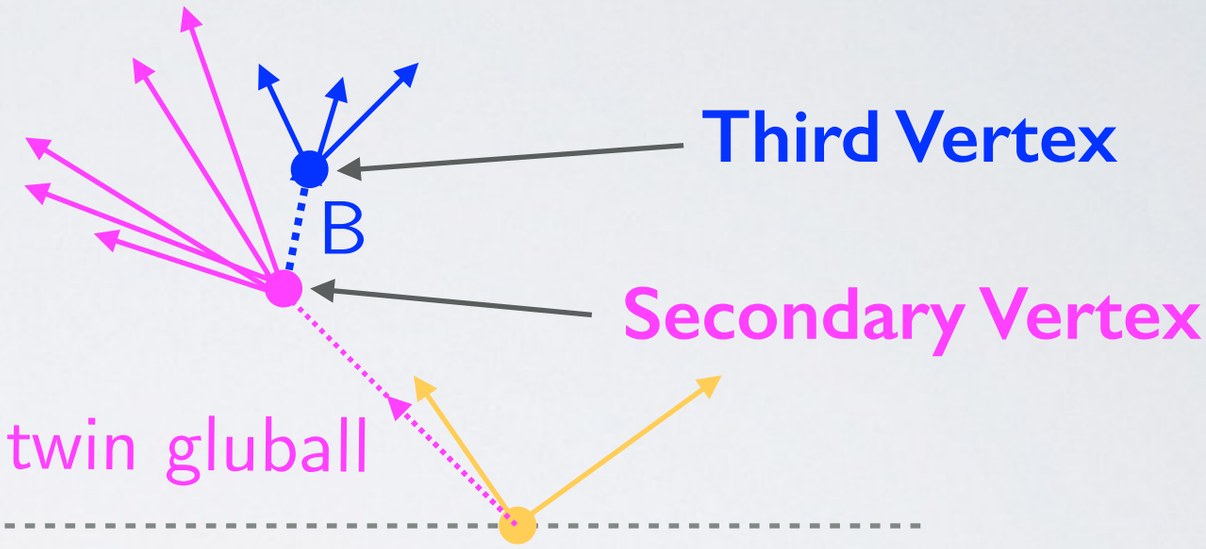




Curtin, Verhaaren (2015)
[arXiv:1506.061411]

WHAT CAN WE DO?

- Look for a third vertex from the B-decay.



- Improve triggers
- Robust model independent searches are excellent, but designed search could improve the reach.
- Understand backgrounds
- "LHCb has a unique coverage for long-lived particles with relatively small mass and lifetime, because its trigger makes only modest requirements on transverse momentum." - LHCb-PAPER-2014-062