DISPLACED SEARCHES FOR HIGGS DECAYS AND BEYOND

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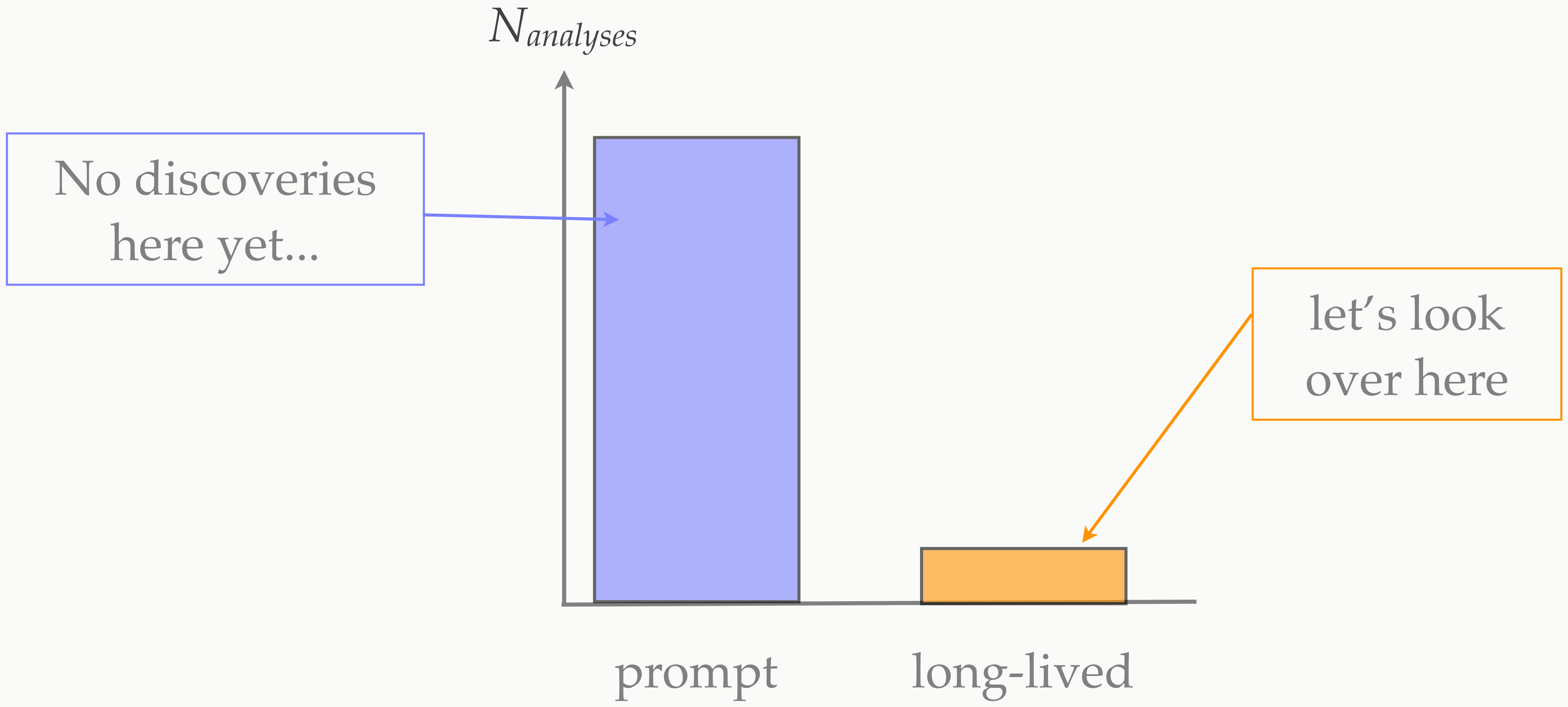
Long-lived particles at the LHC

- Why Long Lived Particles?

Long-lived particles at the LHC

- Why Long Lived Particles?
- Well, duh:

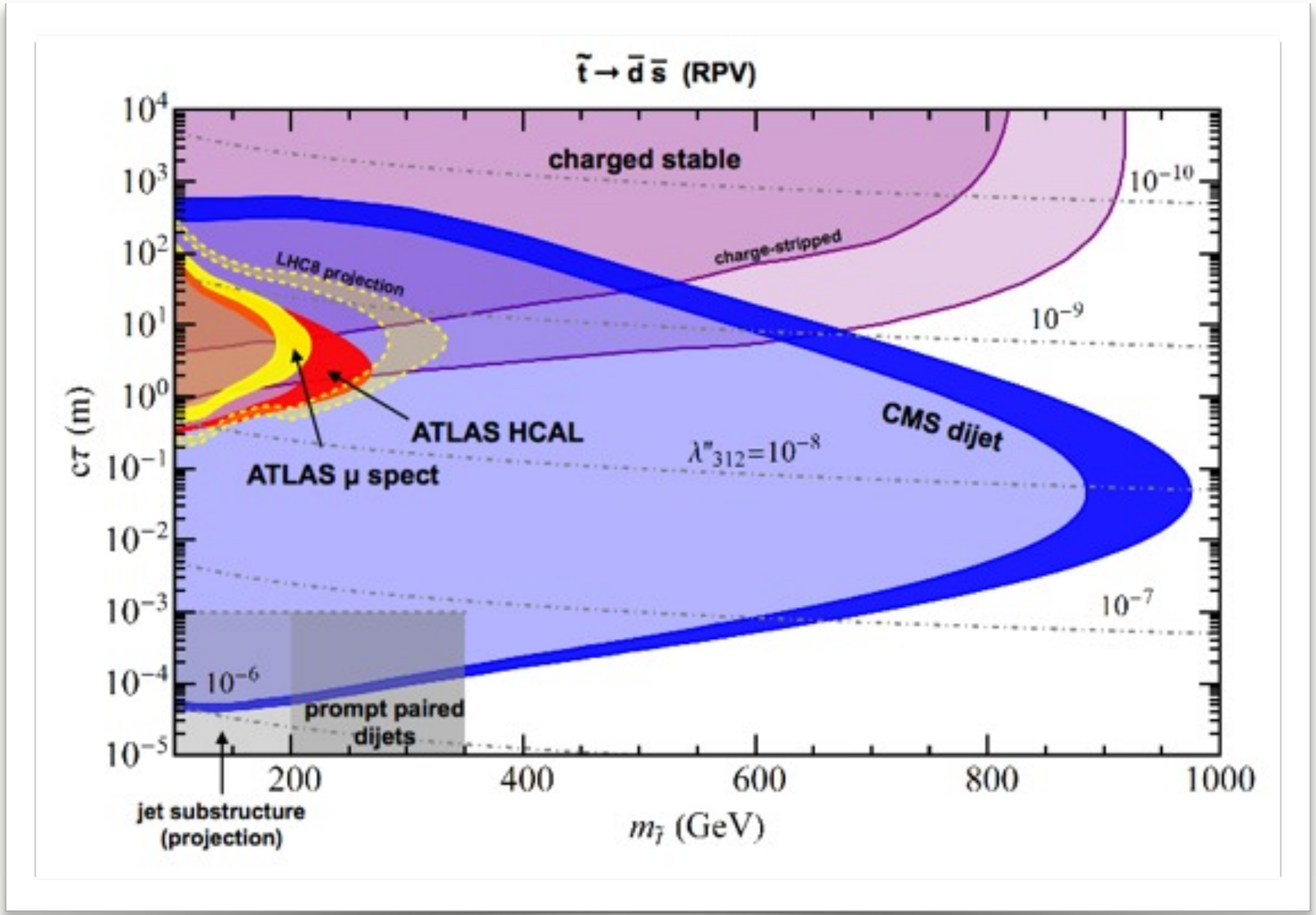


Why long-lived particles?

- but this is a major oversimplification!
- 1 prompt search $\neq$ 1 displaced search:
  - great power of LLP searches: intrinsically low SM background
    - SM: *b*-quark lifetime ~ 500 microns
  - displaced searches often relatively insensitive to details of decay
  - $\Rightarrow$ typically powerful, relatively inclusive searches

Why long-lived particles?

- Thus it is actually easier to make sweeping statements about displaced SUSY than prompt SUSY:



[Liu, Tweedie]

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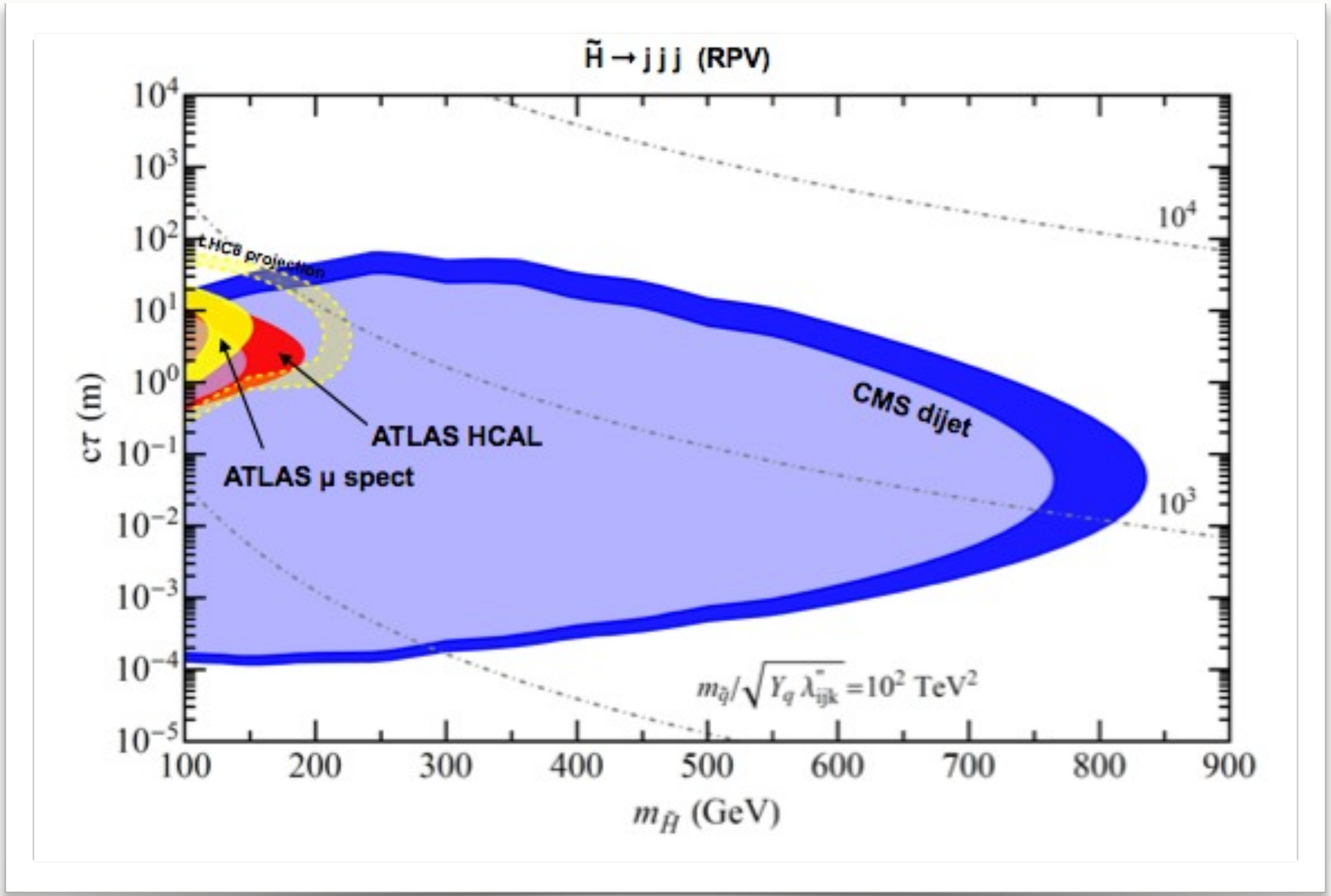
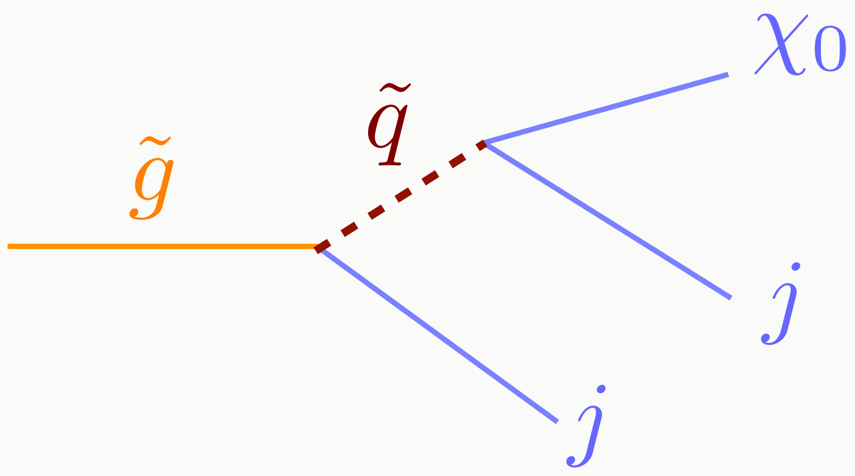


[Liu, Tweedie]

Why long-lived particles?

- Moreover, lack of prompt signals can predict displaced signals

- Perhaps SUSY is a little bit tuned:



- Mini-split: lifetime suppressed by high sfermion scale

$$c\tau \approx 100\mu m \times \left(\frac{m_{\tilde{q}}}{1000\,\mathrm{TeV}}\right)^4 \left(\frac{\mathrm{TeV}}{m_{\tilde{g}}}\right)^5$$

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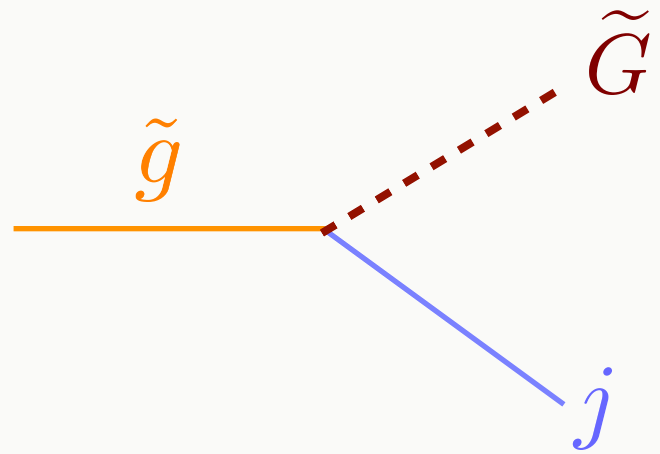


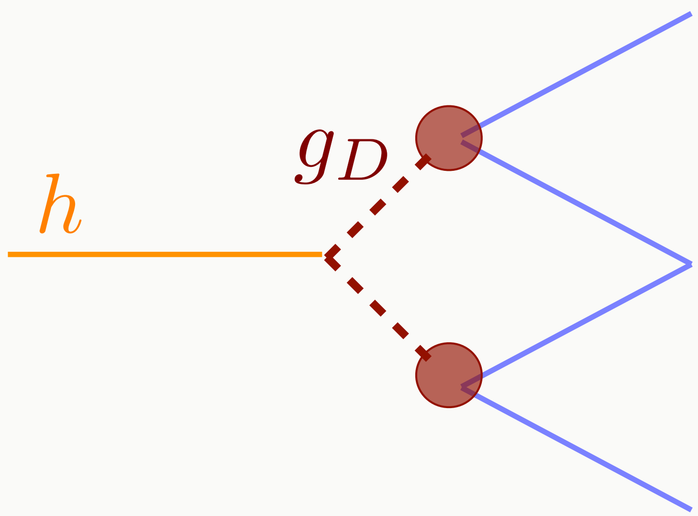
- GMSB: high SUSY-breaking scale suppresses gravitino couplings

$$c\tau \approx 100\mu m \times \left(\frac{\sqrt{F}}{100\text{ TeV}}\right)^4 \left(\frac{100\text{ GeV}}{m_{\tilde{g}}}\right)^5$$

Why long-lived particles?

- Moreover, lack of prompt signals can predict displaced signals

- SM partners that cure the hierarchy problem are neutral:



- Neutral naturalness: composite states decay via higher-dimension operators, small Higgs mixing

- cosmology offers separate motivations (RPV, DM, …)

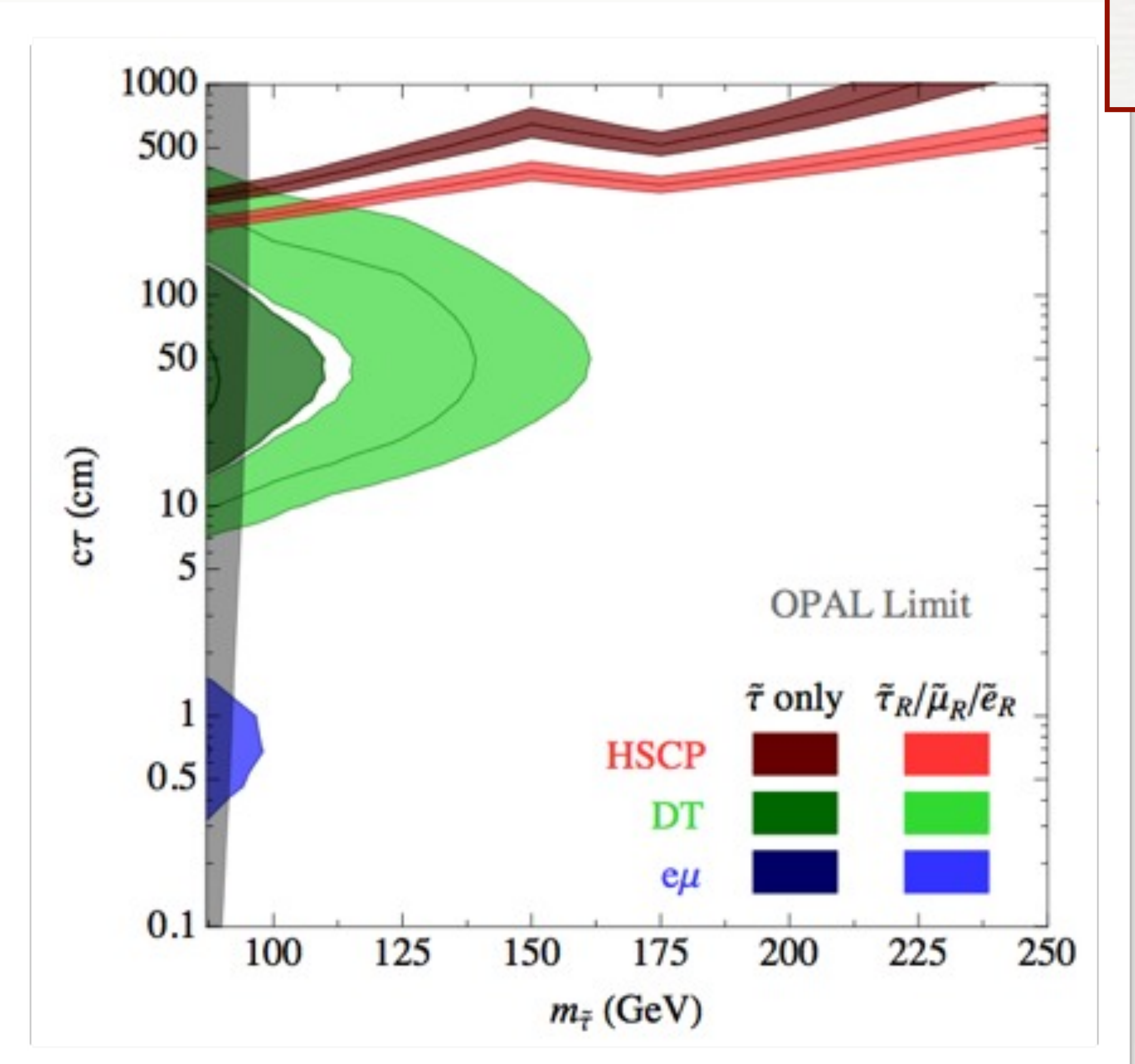
LLPs at the LHC

- LLP searches are not easy! Using detectors off-label
- nonstandard reconstruction poses challenges
    - for experimentalists: triggering, efficiencies, backgrounds
    - also for theorists: painstakingly built toolbox for understanding/reusing prompt searches does not apply
- $\Rightarrow$ Very important to assess coverage of current/planned program, aim to fill in gaps

LLPs at the LHC

- Gaps: which objects, what lifetimes

excellent sensitivity to detector-stable charged LLPs



[Evans, JS]

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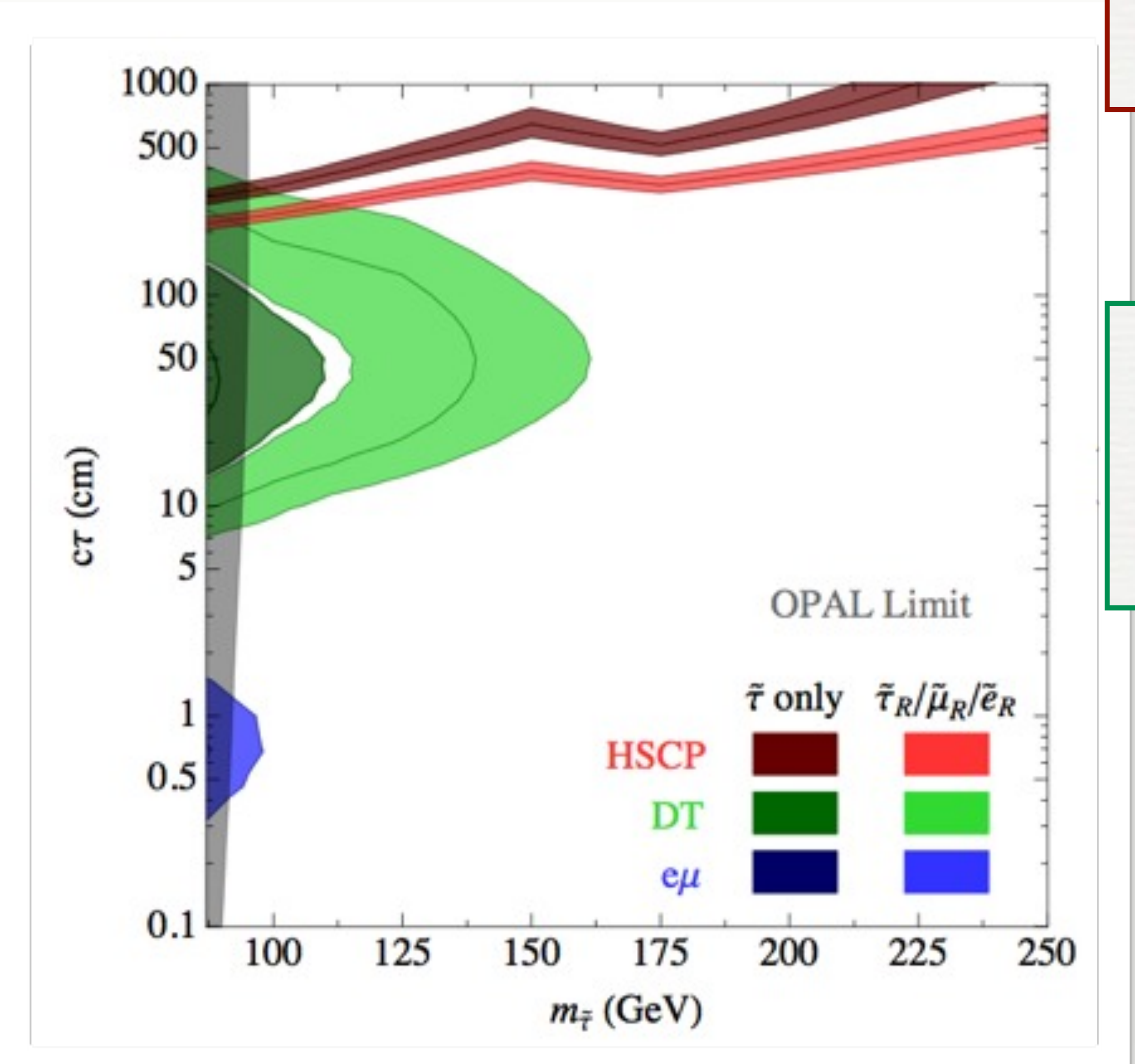

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large uncertainties: search very targeted to a different model

[Evans, JS]

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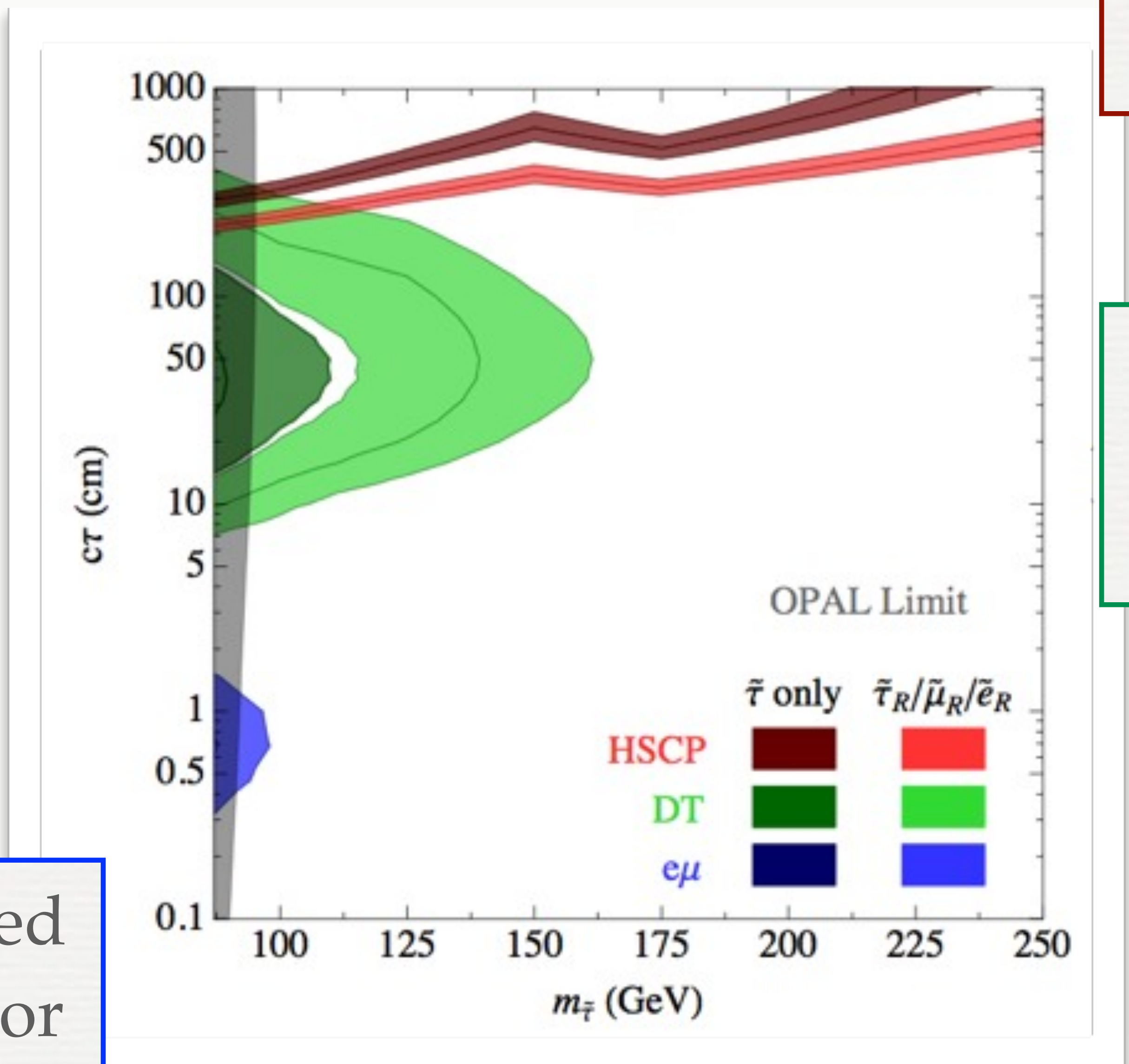

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newly instituted search, room for optimization

[Evans, JS]

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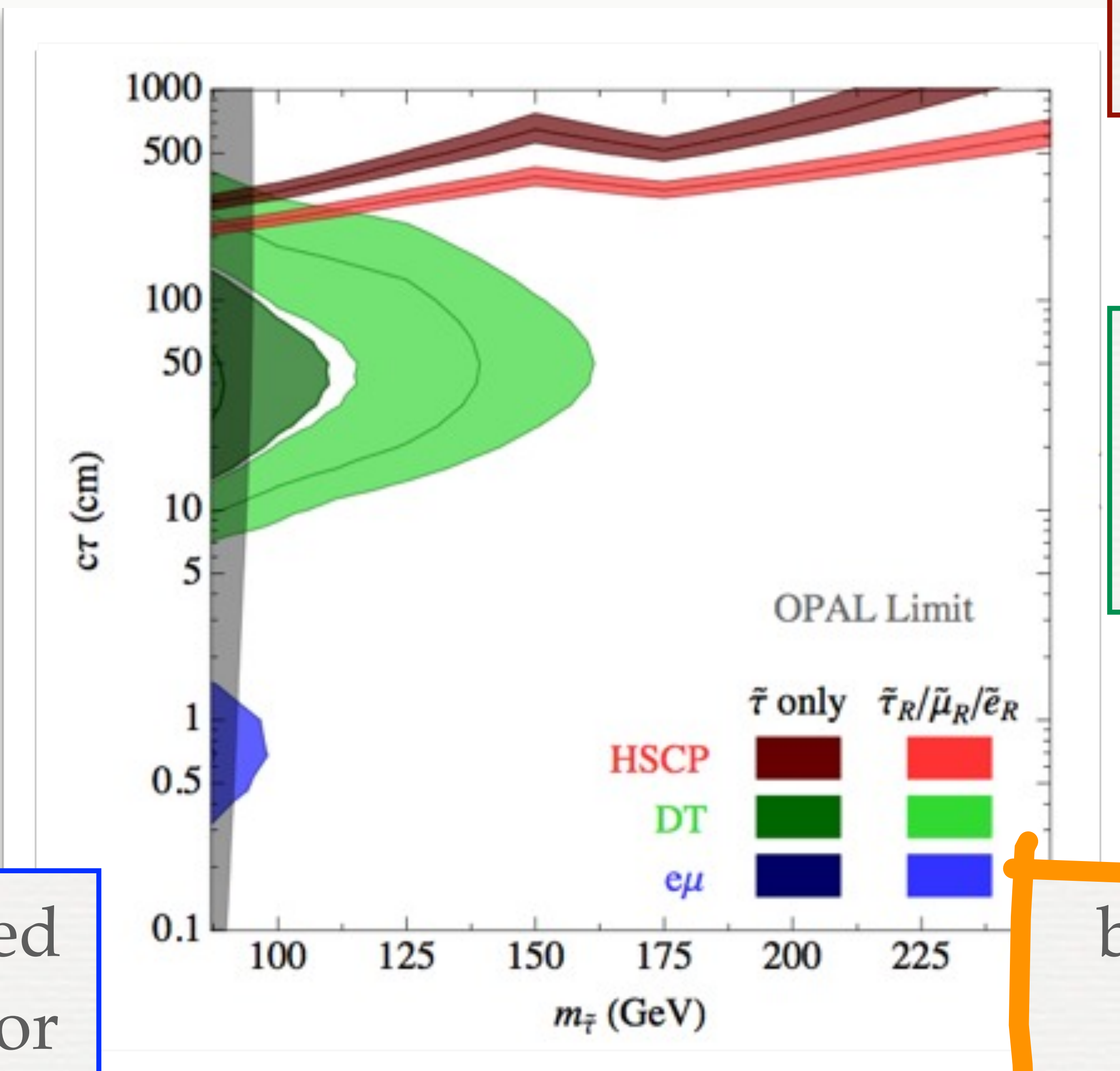

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border of prompt searches is too uncertain to show!

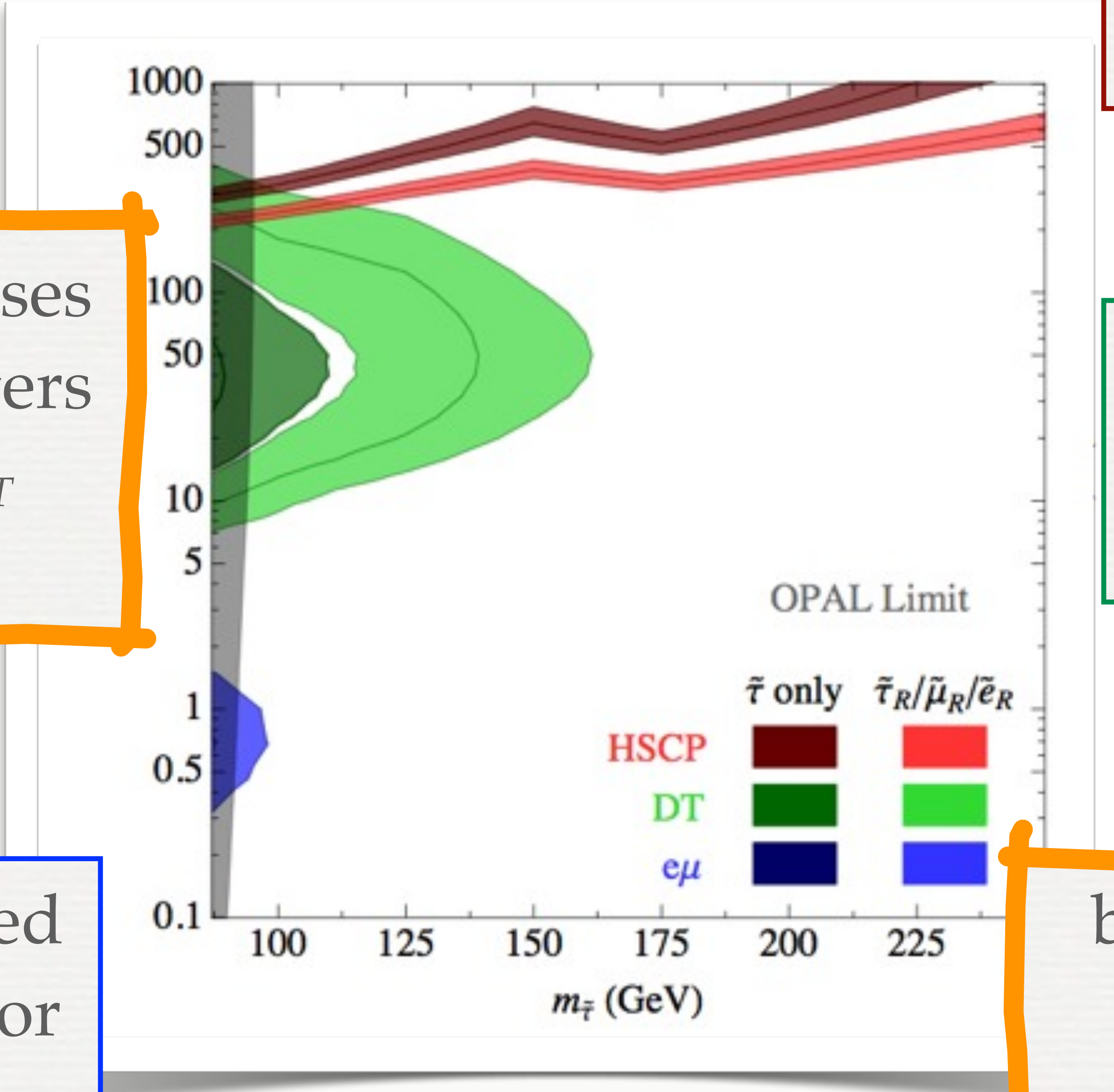
[Evans, JS]

LLPs at the LHC

- Gaps: which objects, what lifetimes

excellent sensitivity to detector-stable charged LLPs

all of these analyses use prompt triggers ⇒missing low p_T physics



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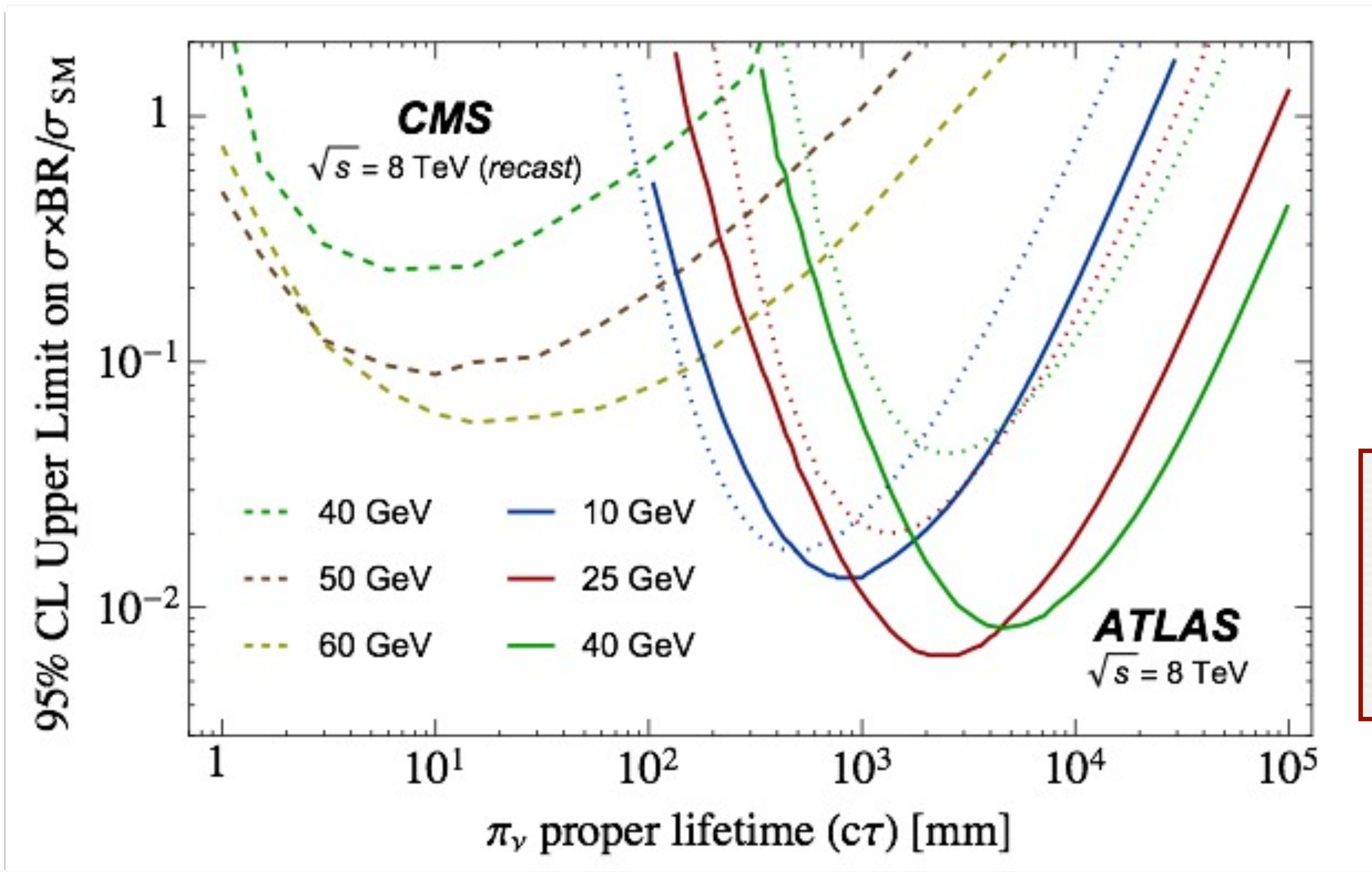
[Evans, JS]

LLPs at the LHC

- Exotic Higgs decays:

high HT requirement in trigger limits sensitivity at low mass, short lifetime



requirement of 2 DVs limits sensitivity at long lifetime

[Csaki, Kuflik, Lombardo, Slone]

LLPs at the LHC

- To extend coverage of proper lifetimes, design searches with a single displaced object
  - additionally, combined prompt + displaced triggers can significantly help improve acceptance for low-p_T signals like Higgs decays and direct stau production
- However: in this regime must contend with background
  - (weird SM physics) x (weird detector response), cannot model from first principles
  - background will increasingly be an issue even for searches with two displaced objects as luminosities increase

[Csaki, Kuflik, Lombardo, Slone; Coccaro, Curtin, Lubatti, Russell, JS]

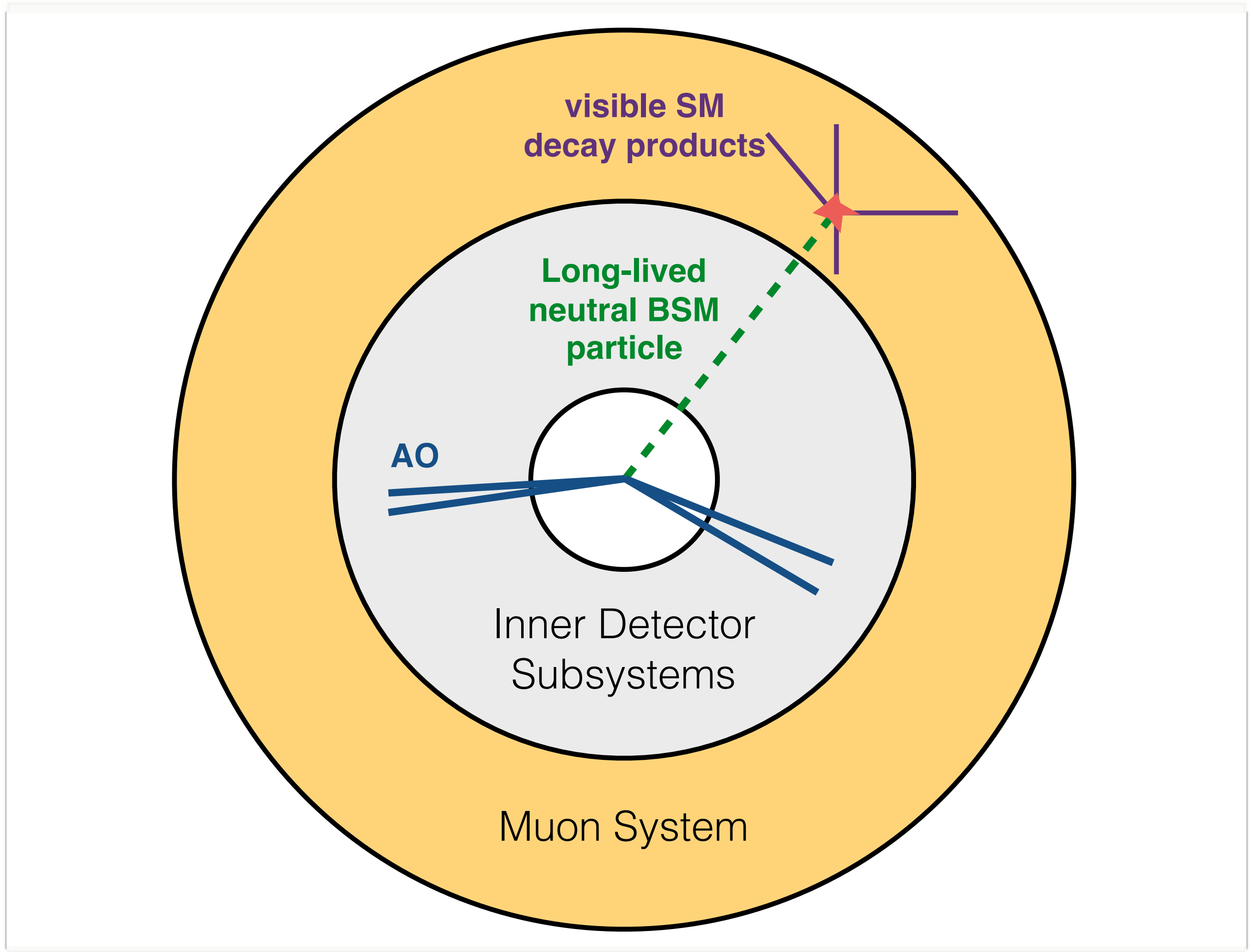
Background estimation

- A data-driven background estimation technique
  - relies on having a primary trigger accepting displaced objects
  - and a secondary trigger accepting kinematically similar but background-dominated events (via relaxed isolation criteria)
- Proof of concept: ATLAS triggers for displaced vertices (DV) in muon system
  - in principle strategy generalizes to other detector subsystems

[Coccaro, Curtin, Lubatti, Russell, JS]

Background estimation

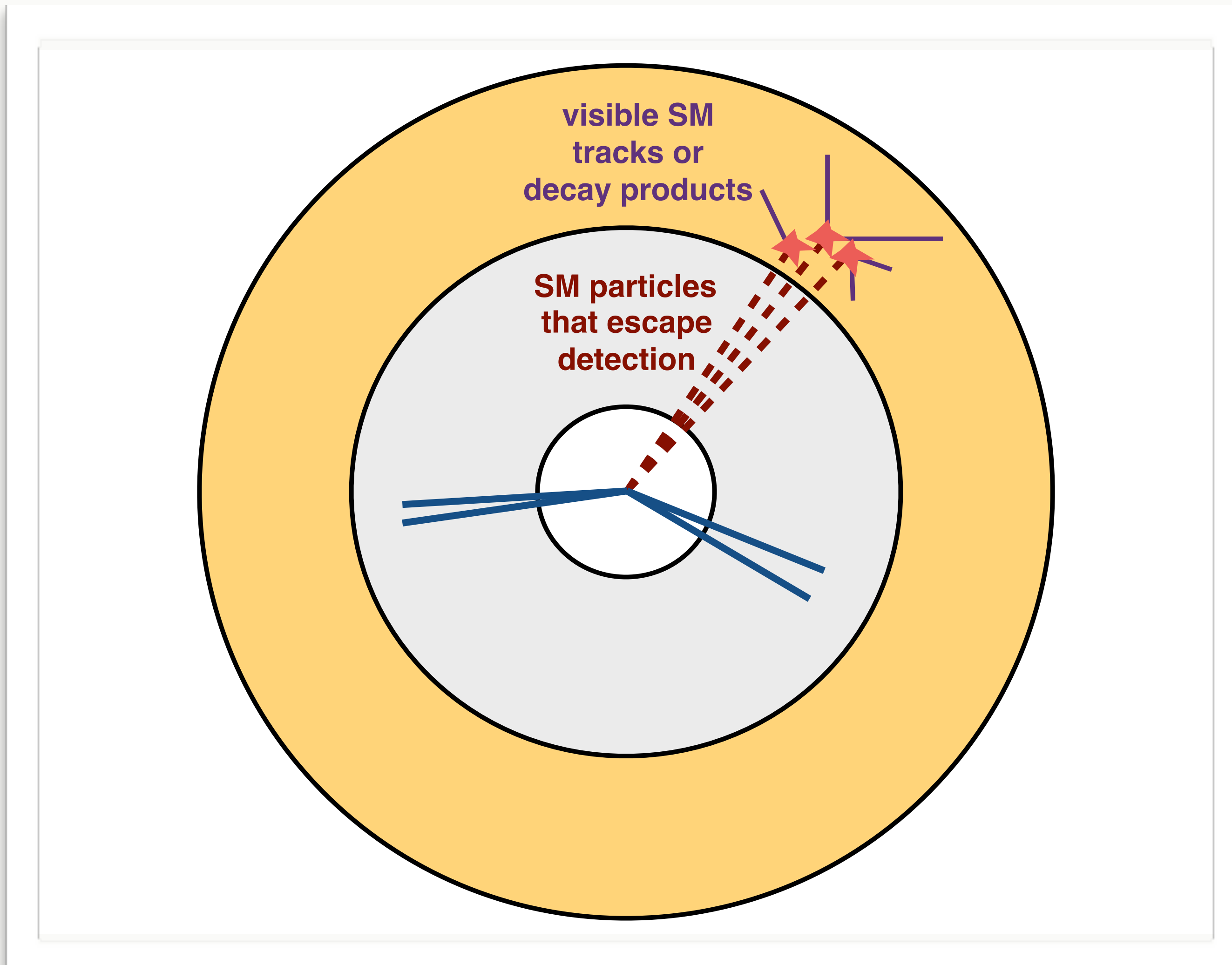
- Signal arrives on a dedicated 'iso' trigger, implemented in Run I



- Events with decays that occur in the muon system can reconstruct a DV and fire the trigger
- Reminder: can measure position of the DV, but not p_T, mass
- Trigger imposes isolation requirements on the DV

Background estimation

- This 'iso' event sample includes SM background:

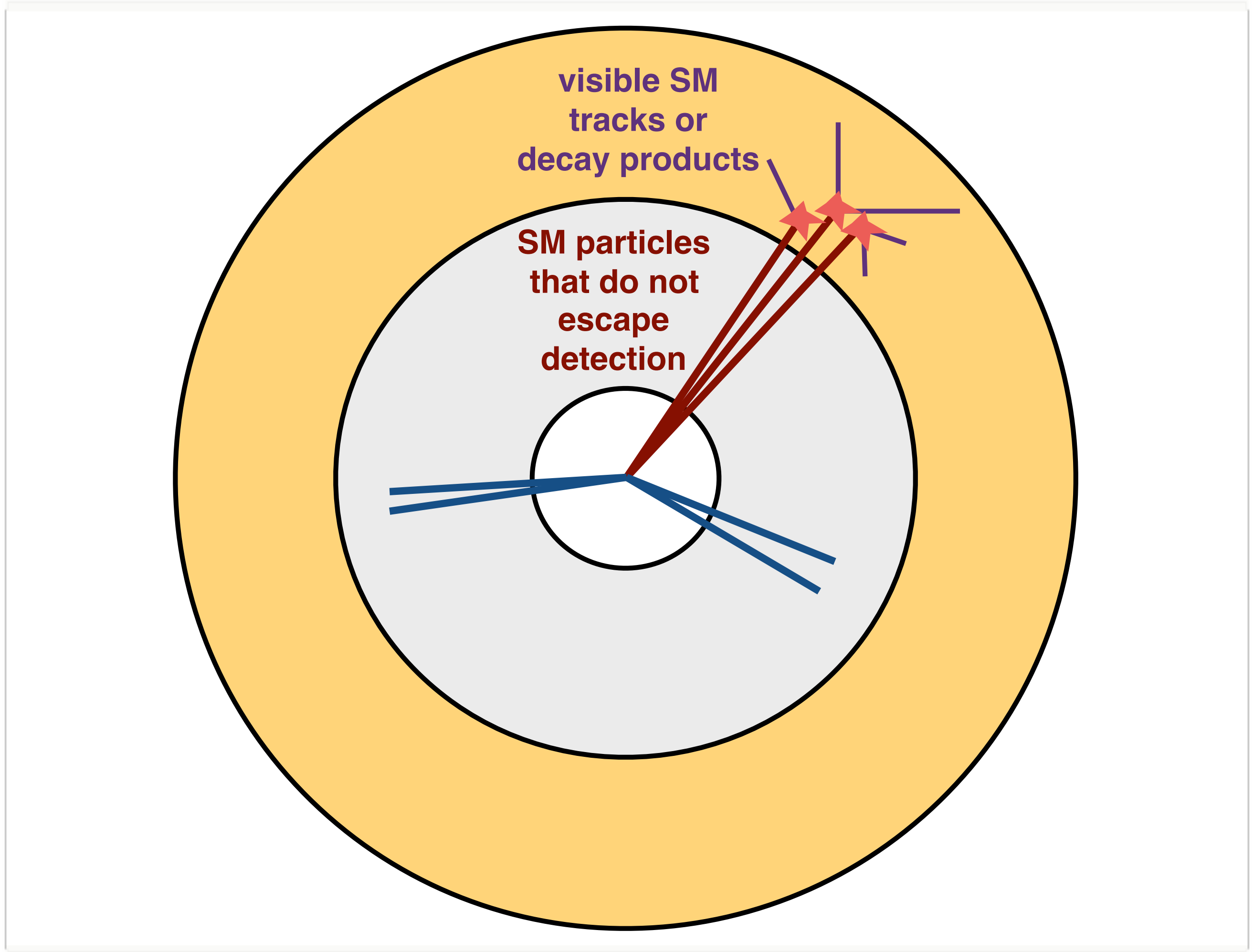


- Background dominated by QCD

- Again, cannot model this background reliably from first principles. Weird 'truth-level' physics and weird detector response

Background estimation

- A trigger that does not impose isolation requirements can record a useful sample of background events:



- Use control sample to estimate background from data.

- Simply obtaining related control sample is a major step: requires dedicated 'orthogonal' trigger (new in ATLAS Run 2)

Data-driving displaced backgrounds

- Rate of SM 'iso' events closely related to rate of SM 'non-iso' events:

$$\frac{\Delta\sigma^{\text{iso}}}{\Delta H'_T} = r(H'_T)\,\frac{\Delta\sigma^{\text{noniso}}}{\Delta H'_T}$$

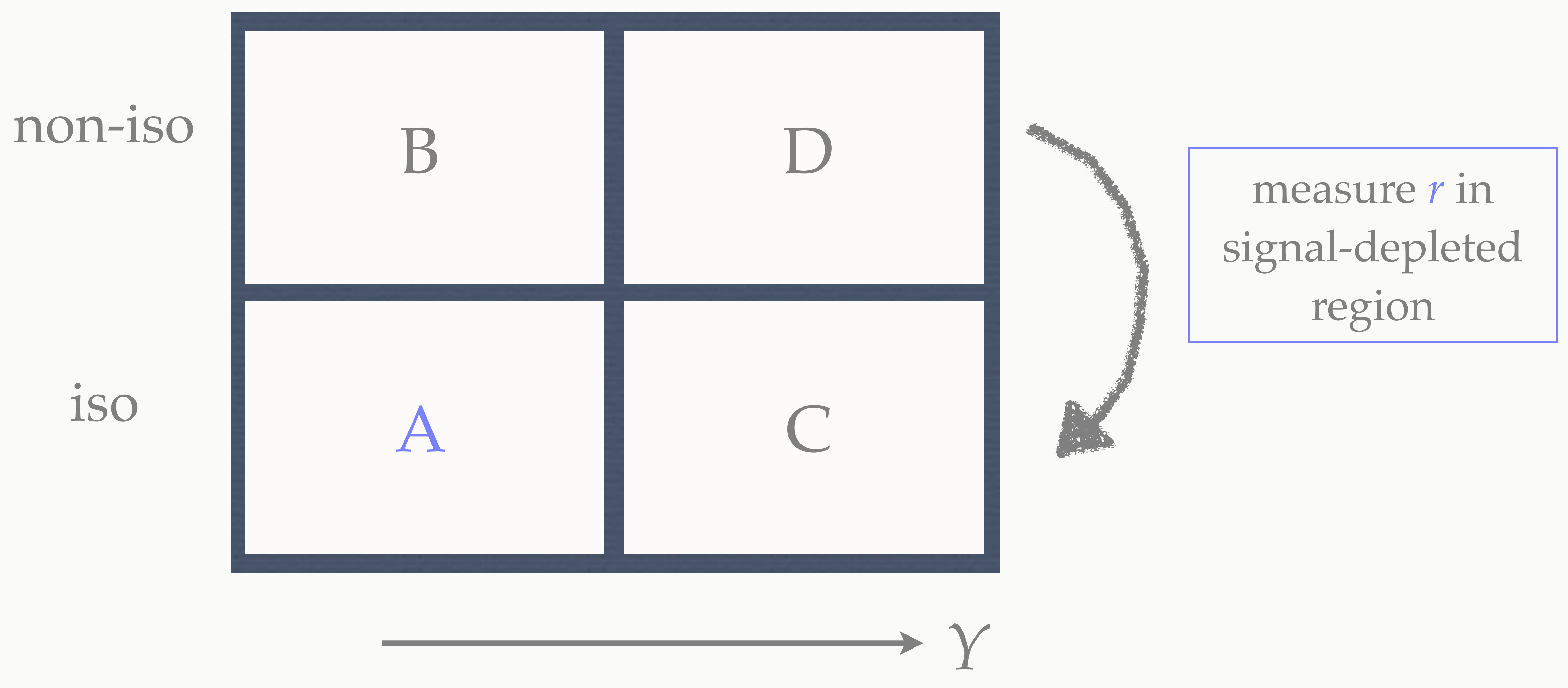
H_T': scalar sum of MET, jet p_T s, proxy for p_T of jet yielding DV. p_T spectrum of iso, non-iso jets similar but not identical.

non-isolated events occur at much larger rates: excellent control sample

rescaling function ~ $\epsilon^{\text{iso}}/\epsilon^{\text{noniso}}$,
to be measured in data.
Parameterization reflects assumption that efficiency depends largely on properties of a single jet

Data-driving displaced backgrounds

- To measure r, find a variable Y, depending on the signal model: then, bin-by-bin in H_T',



Data-driving displaced backgrounds

- If Υ is correlated with H_T', systematic bias in determining r:

$$\Delta H_T' \equiv \left| \frac{\langle H_T' \rangle_C - \langle H_T' \rangle_A}{H_{T1}' - H_{T2}'} \right| \neq 0$$

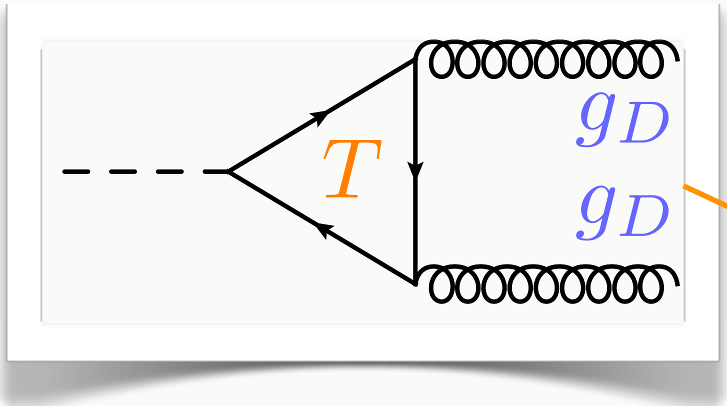
  - control by taking H_T' bins sufficiently small that r is slowly varying over the bin:

$$\frac{1}{\sqrt{N_c}\Delta H_T'} \gg \left| \frac{r(H_{T1}') - r(H_{T2}')}{\langle r(H_T') \rangle} \right|$$

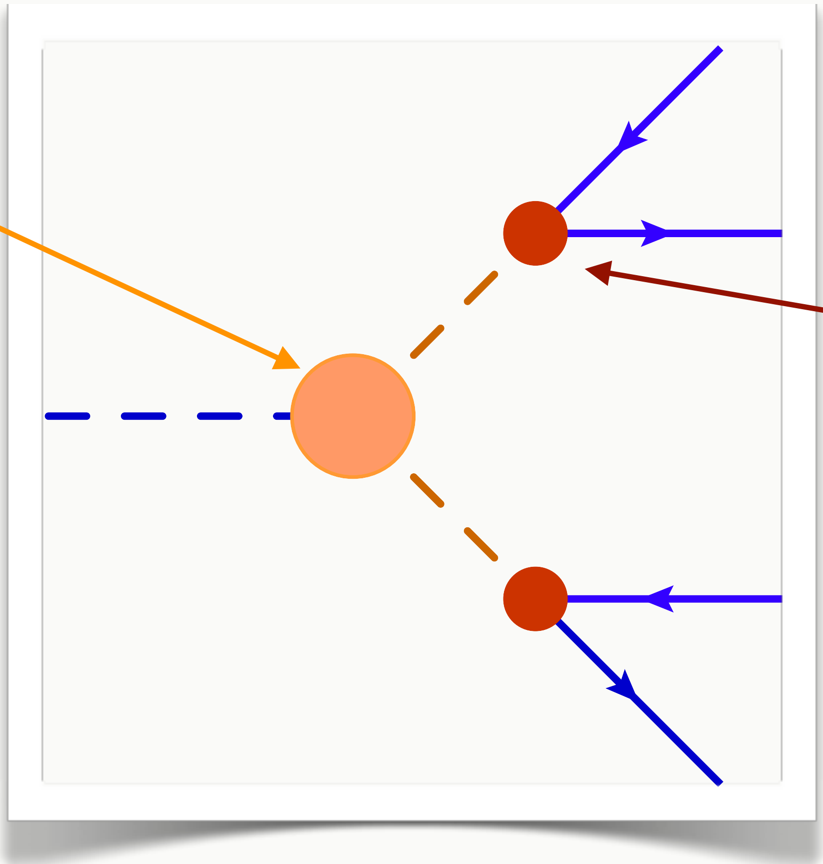
  - Trade-off to be optimized: statistical uncertainty for systematic uncertainty

Example: Higgs decay to X X

- Use as example signal model Higgs decays to LLPs
- Highly motivated: neutral naturalness



mirror top loop mediates decay to mirror gluons, which hadronize into (0++) glueballs

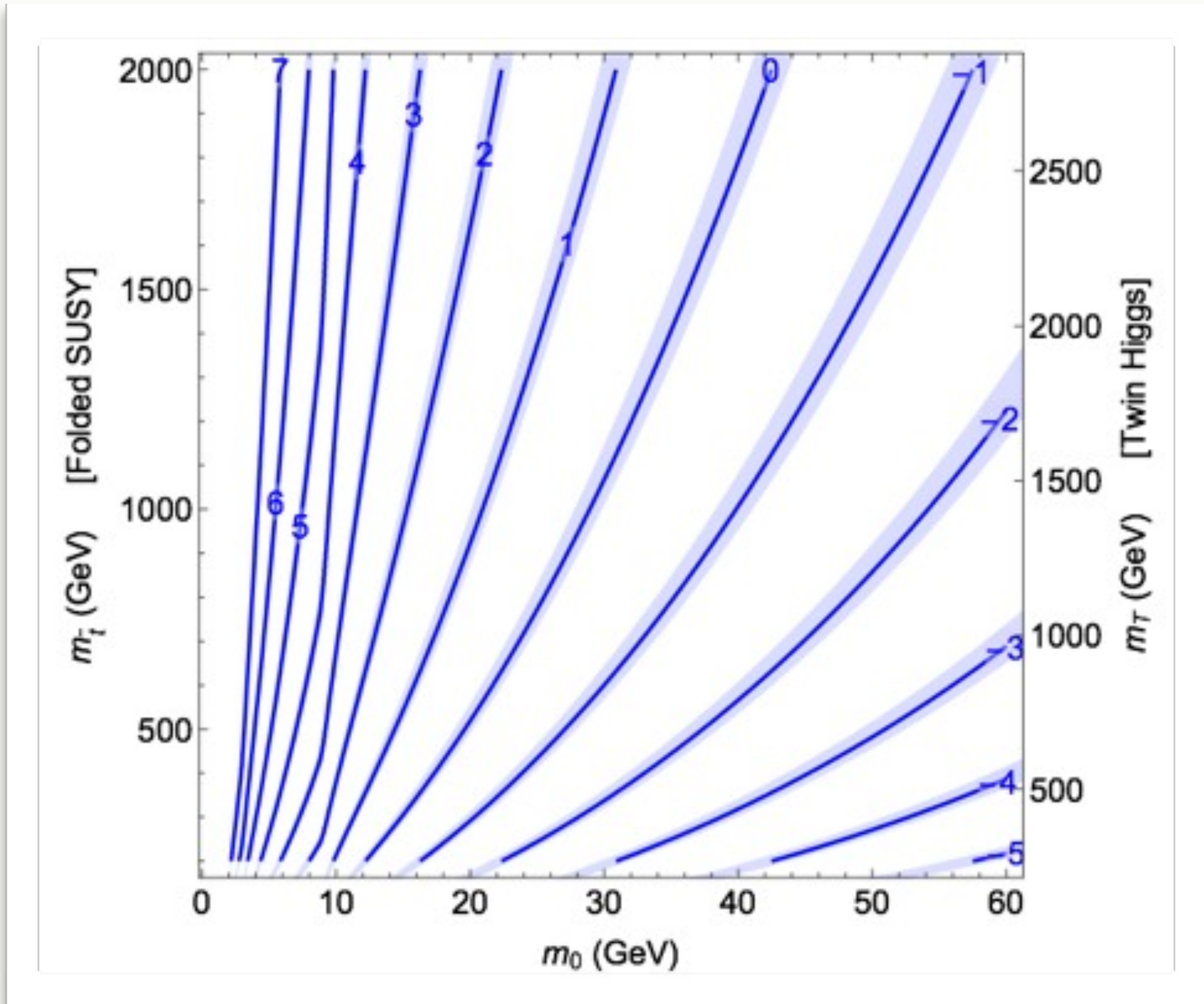


0++ glueballs decay via Higgs mixing: high-dimension operator, additionally suppressed by mixing, Yukawas

[Chacko, Goh, Harnik; Craig, Howe; Craig, Knapen, Longhi, Strassler; Curtin, Verhaaren; ...]

Example: Higgs decay to $X\, X$

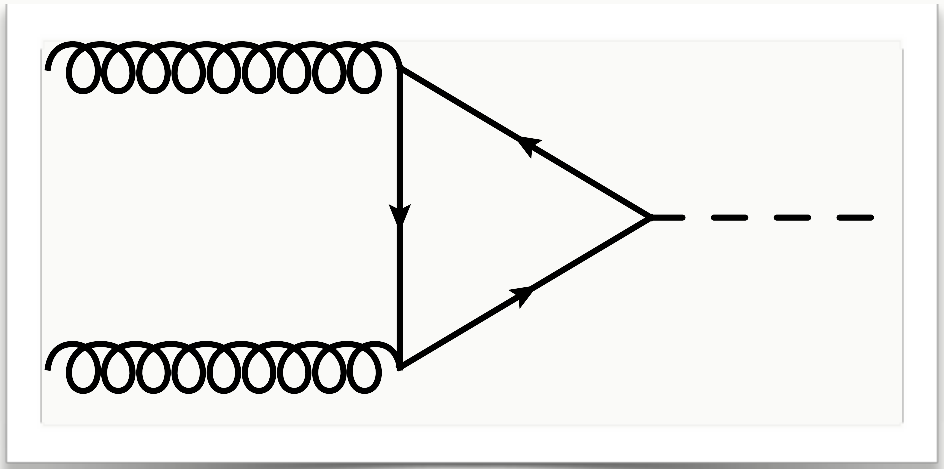
- Range of glueball lifetimes depends on mirror QCD scale, top partner mass:



[Curtin, Verhaaren]

Example: Higgs decay to $X X$

- Exotic Higgs decays are also one of the most challenging signals:
  - low-mass signal

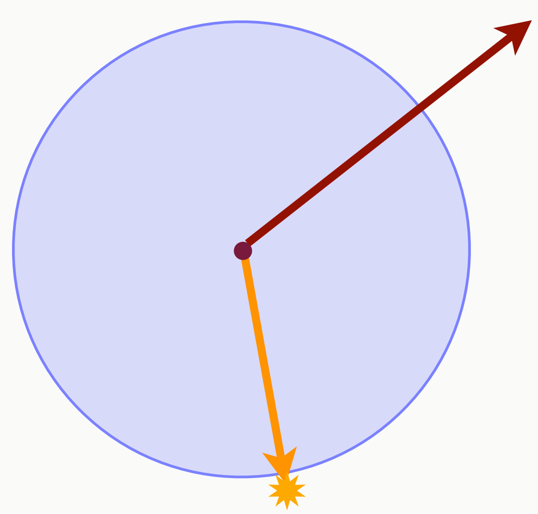


  - dominantly produced in gluon fusion, i.e., with no characteristic accompanying prompt objects
  - thus, simple choices of Y variable like N_b don't give adequate control region statistics

Example: Higgs decay to $X\,X$

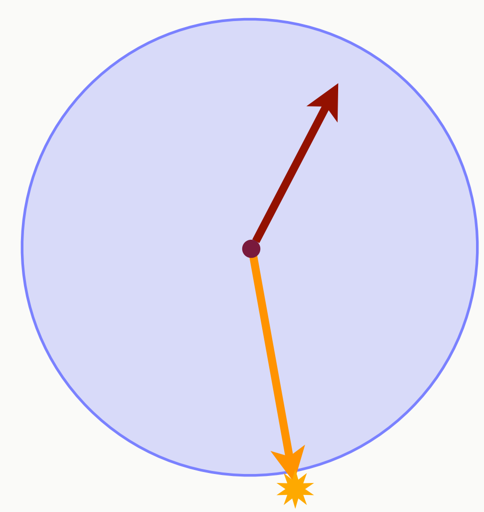
- Use existence of other LLP to determine Y:

long lifetime



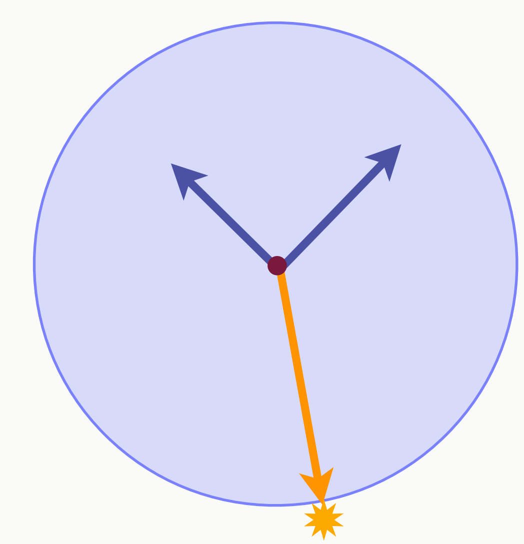
other X contributes MET

short lifetime



other X looks like a weird jet (trackless, low EM, …)

background

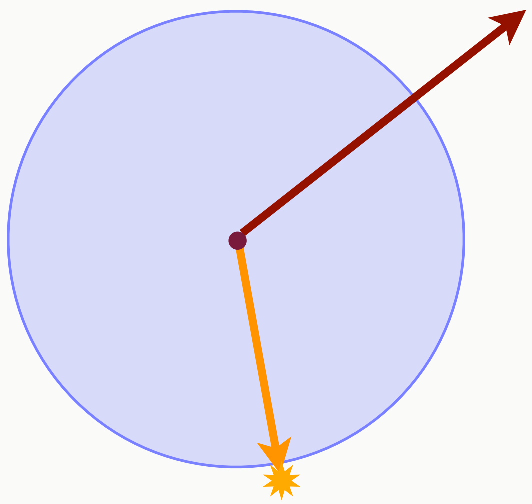


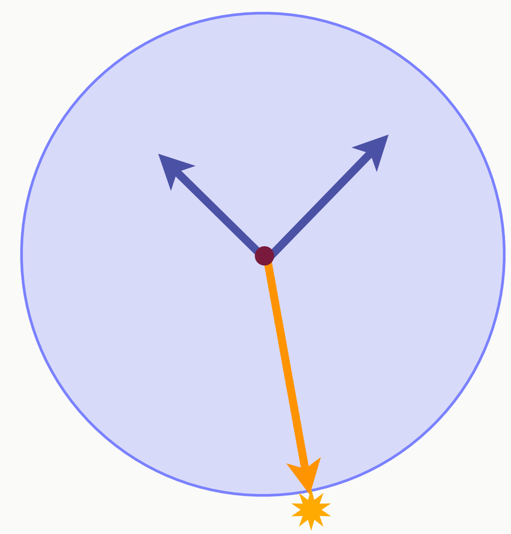
jets, MET aligned with DV

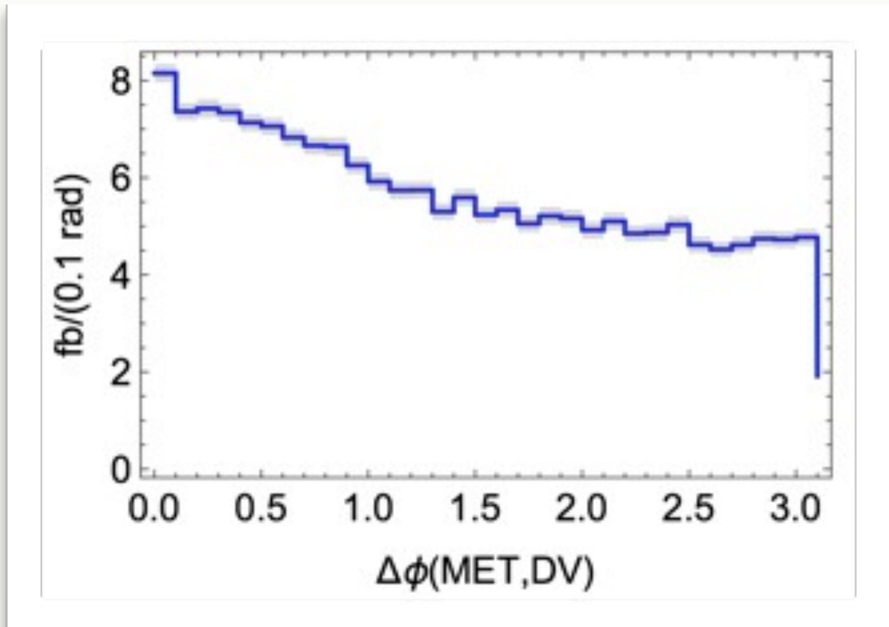
[Coccaro, Curtin, Lubatti, Russell, JS]

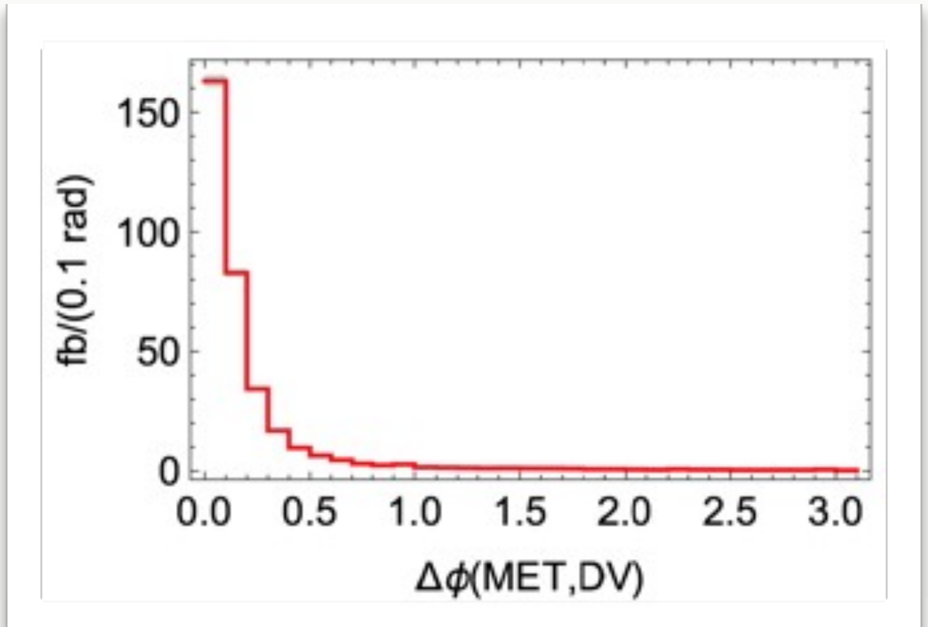
Example: Higgs decay to *X X*

- direction of MET distinguishes signal from background:









[Coccaro, Curtin, Lubatti, Russell, JS]

Modeling background

- Lack of public information makes modeling background rate, shape very challenging
  - do not have: separate H_T' spectra for iso, non-iso events
  - only total N_{bkd} reported, but efficiencies are different for barrel, endcap $\Longrightarrow$ iso DV efficiencies for QCD jets not publicly available
- Handled by making two very different background models

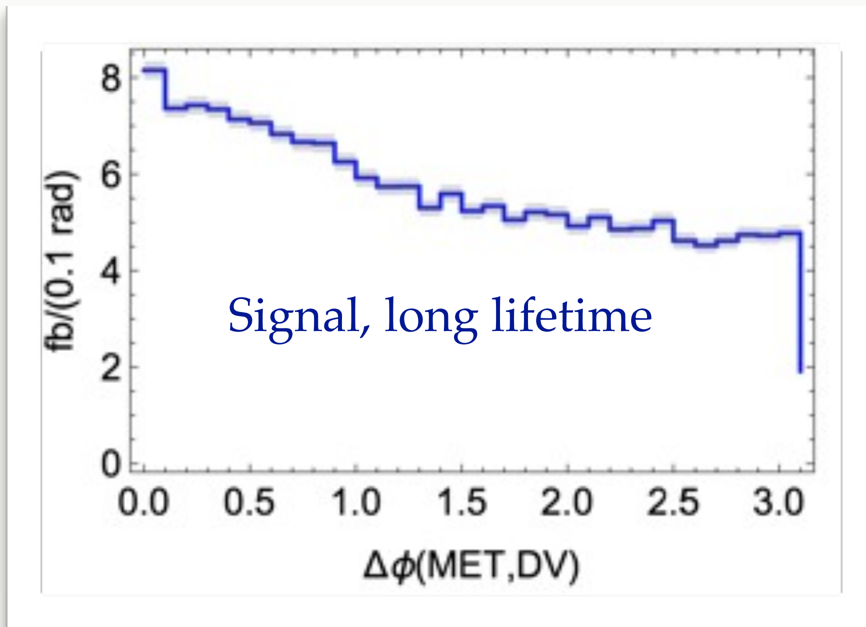
Theory wish list: efficiency maps, possibility of approving material post-publication

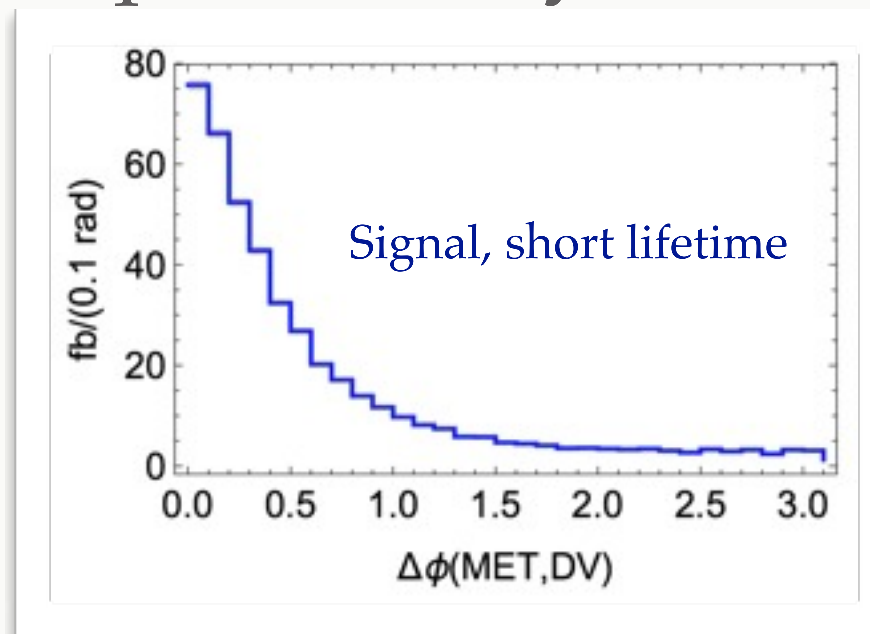
Modeling background

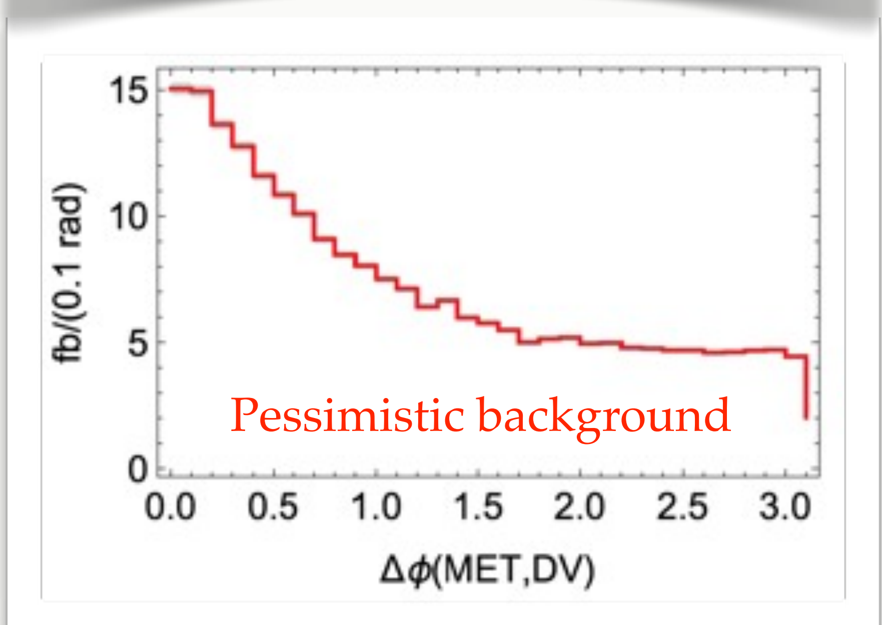
- Optimistic model:
  - assume probability of faking an isolated DV is linear in p_T above a threshhold (120 GeV), normalize to get number of 1, 2 DV events in Run I
- Pessimistic model:
  - assume all jets equally likely to fake an isolated DV, under-predicts Run I 2 DV rate given Run I 1 DV rate

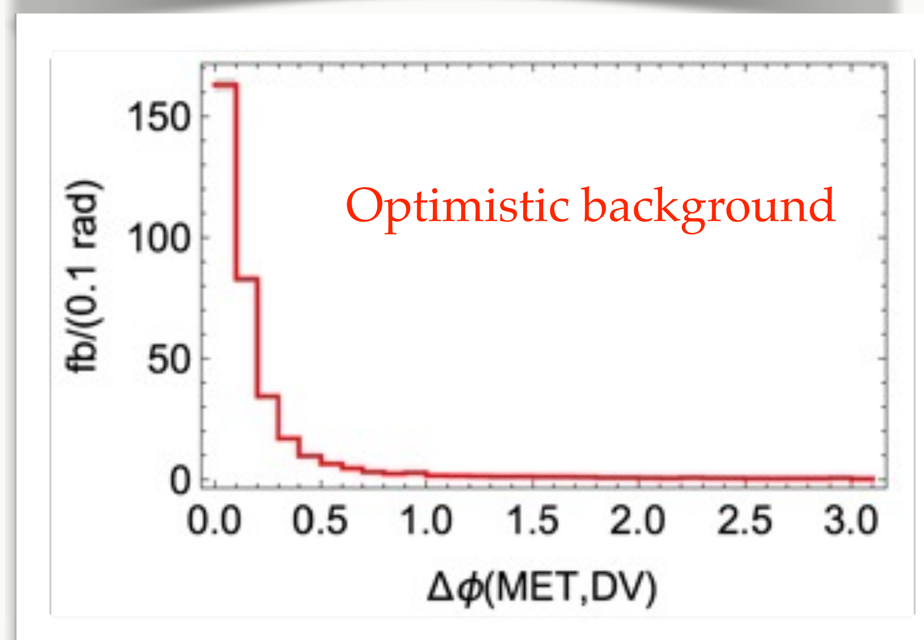
Distributions of Υ

- Resulting distributions for Υ are qualitatively distinct:





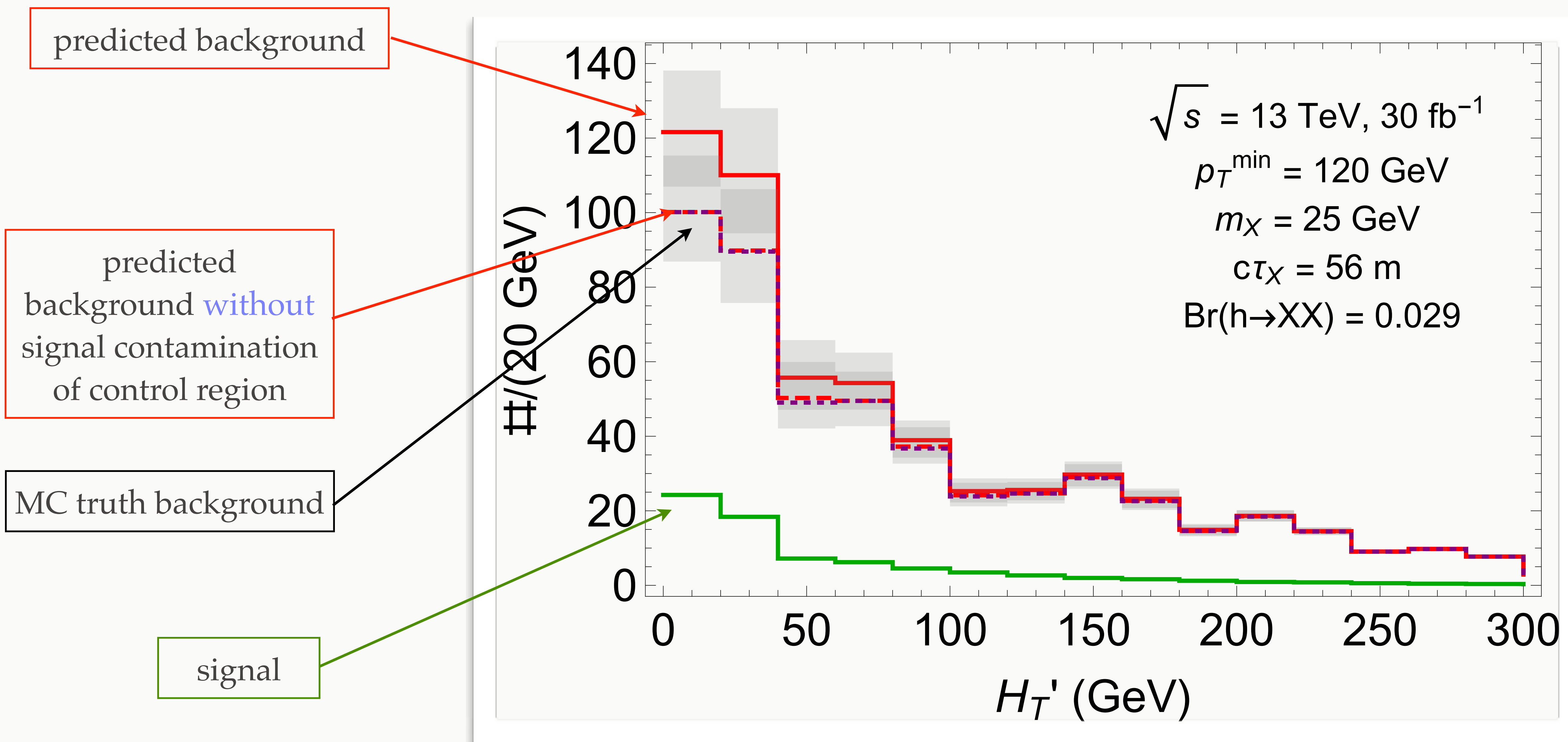




[Coccaro, Curtin, Lubatti, Russell, JS]

Example: Higgs decay to $X\,X$

- Self-consistent*

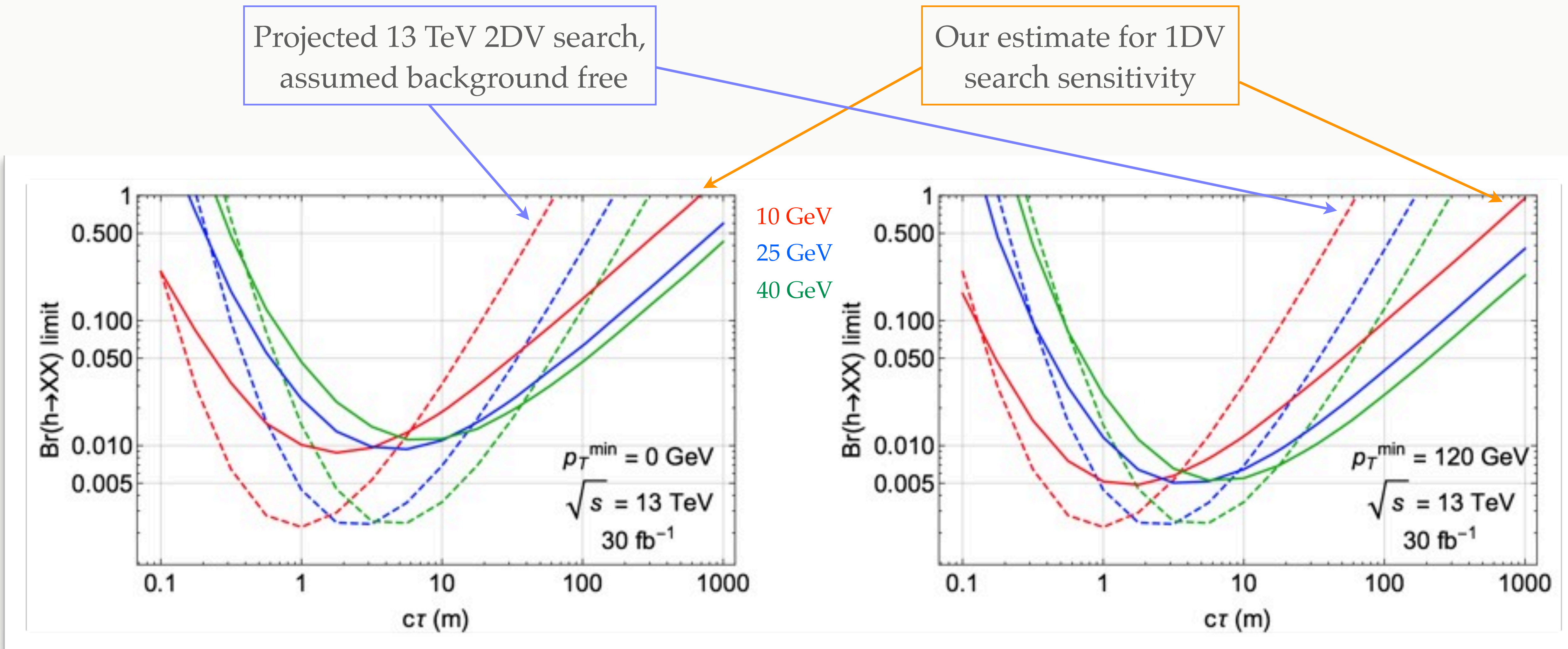


* Cannot explicitly evaluate systematic uncertainties in reweighting function

[Coccaro, Curtin, Lubatti, Russell, JS]

Example: Higgs decay to X X

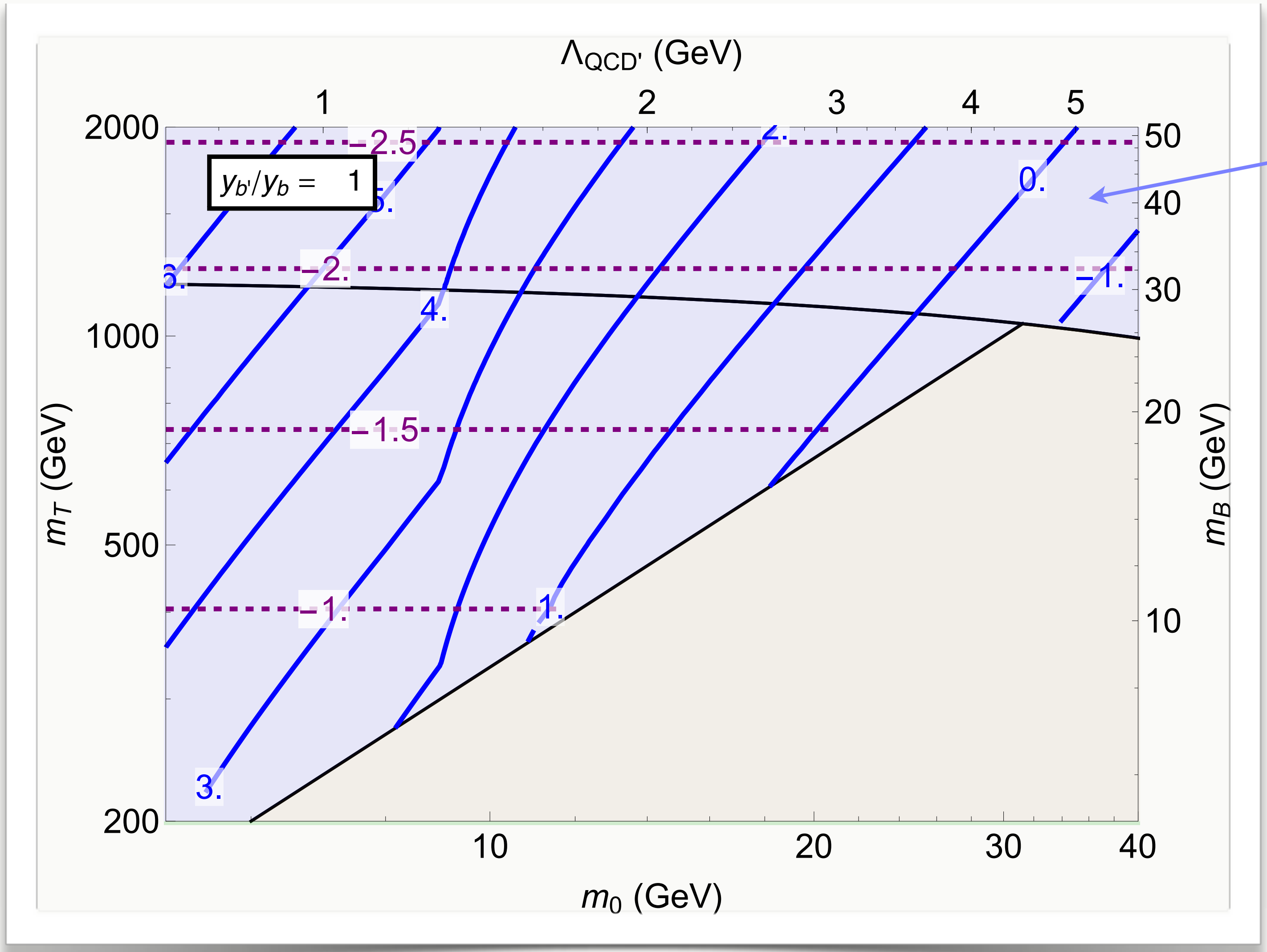
- Notable gains in sensitivity at long lifetime:



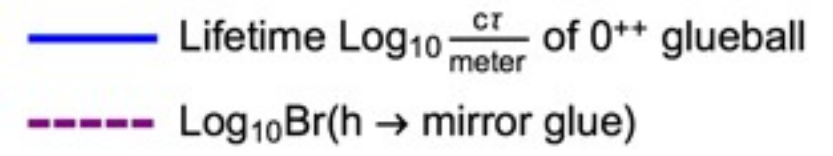
[Coccaro, Curtin, Lubatti, Russell, JS]

Example: Higgs decay to *X X*

- This accesses a very challenging chunk of parameter space in Twin Higgs models:



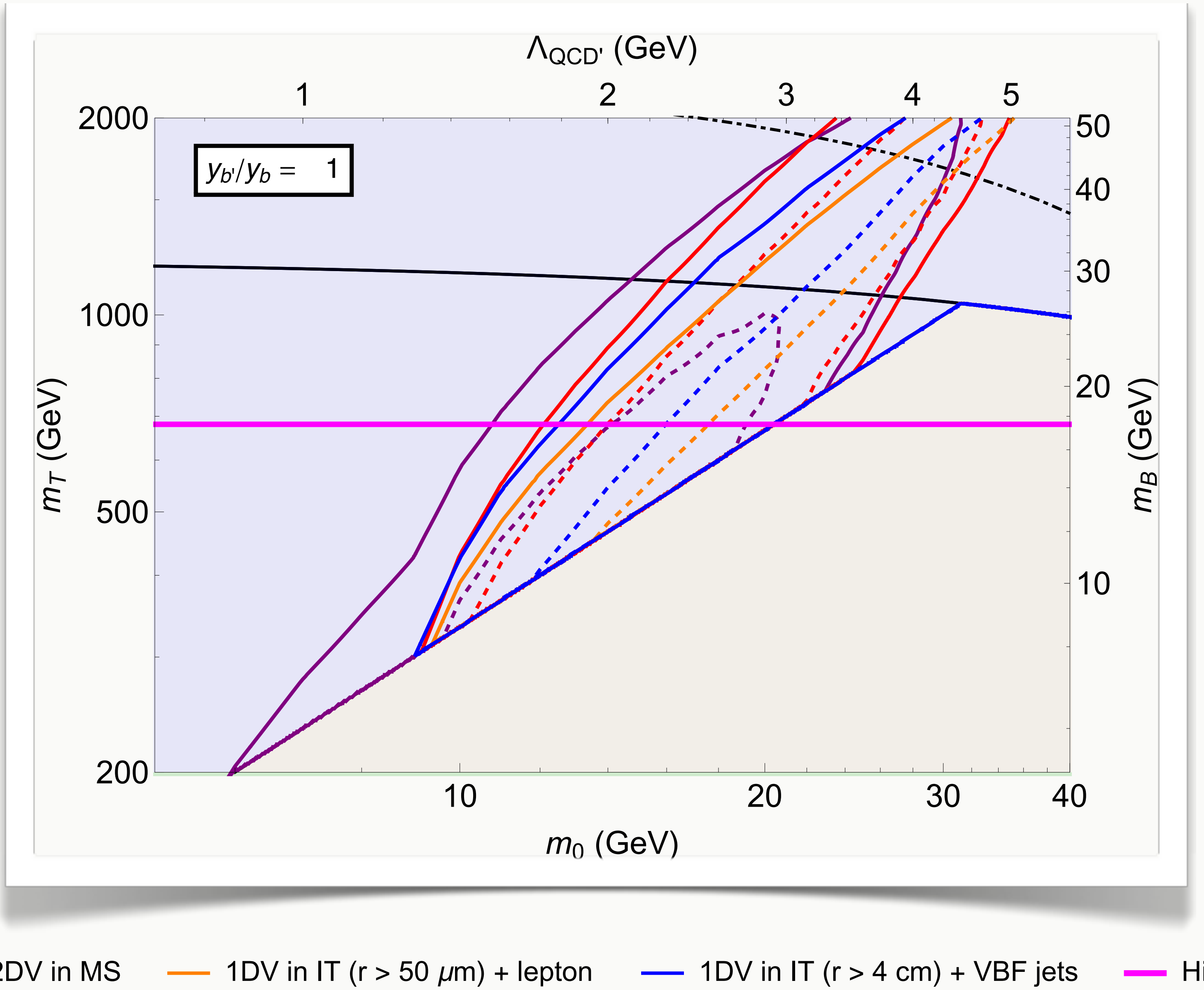
Higgs decays to mirror bottoms through mirror Yukawa, mirror bottomonia decay to long-lived glueballs: large production rates for very long lived states



[Coccaro, Curtin, Lubatti, Russell, JS]

Example: Higgs decay to *X X*

- Reach of 1DV search compared to other probes:



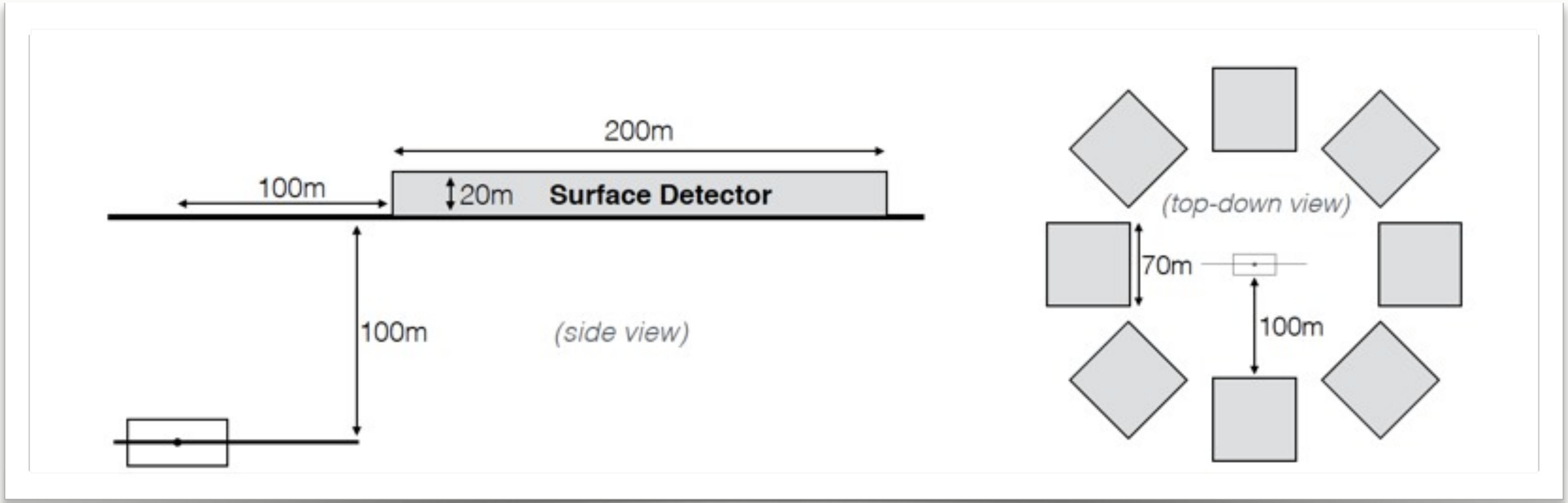
[Coccaro, Curtin, Lubatti, Russell, JS]

Beyond this simple example

- In MS, not sensitive to detailed properties of decay
- $\Rightarrow$ categorization of possible signals based on production mode: simplified model basis for displaced searches
  - each production mode naturally suggests choices of Y
  - e.g. weak production, as for sterile neutrinos: N_l
  - e.g. heavy flavor enriched, N_b
- More generally, looking for variations in r across a basis set of signal/control regions can reveal new physics

And even further beyond

- Proposed surface detector for very long-lived particles: MATHUSLA

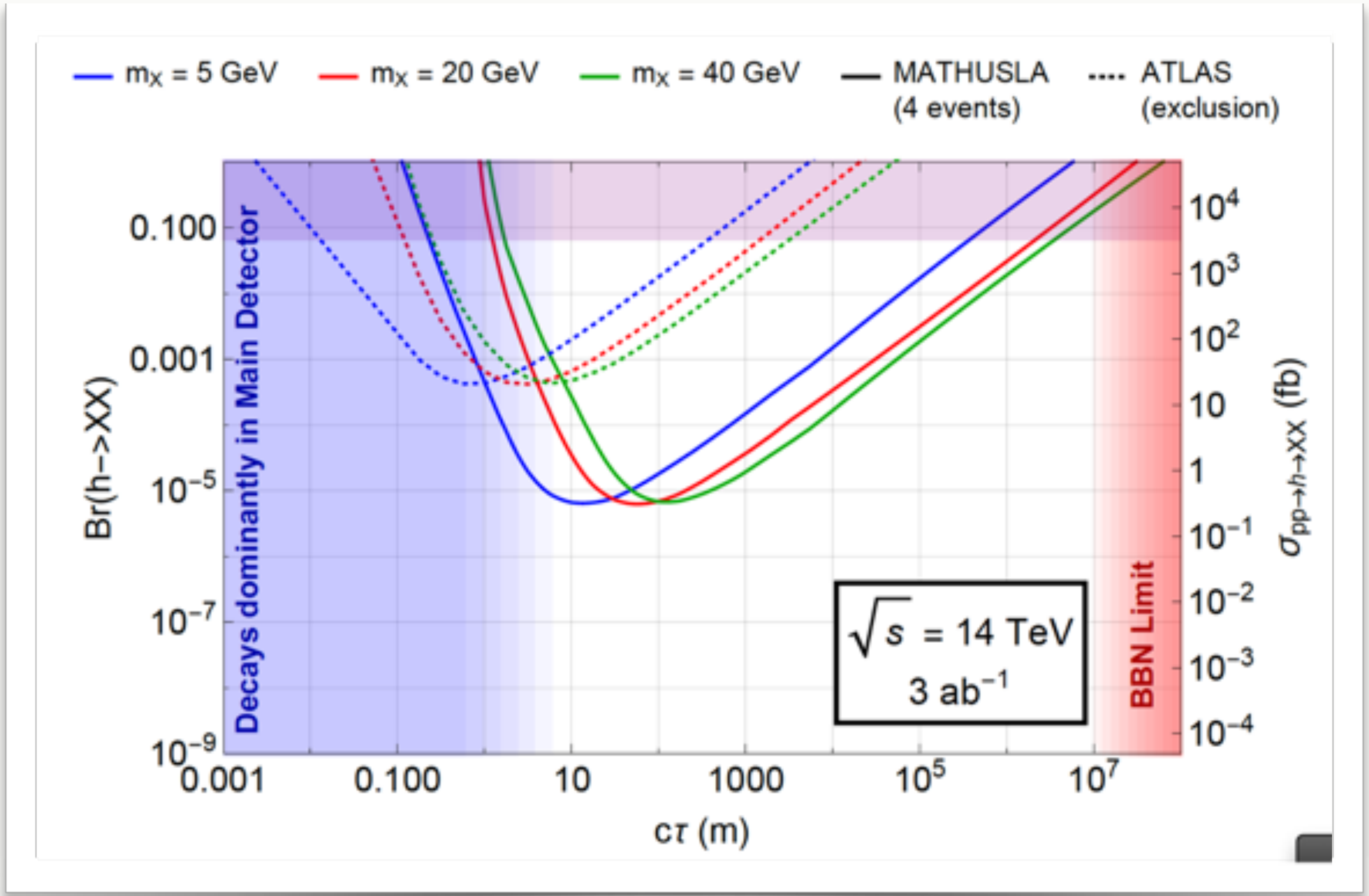


- Ask these people about pesky details like cost and feasibility

[Chou, Curtin, Lubatti]

And even further beyond

- Extends sensitivity out to cosmologically interesting lifetimes:



- Physics case in preparation (Curtin, McCullough, Meade, Papucci, JS)

[Chou, Curtin, Lubatti]

Conclusions

- Displaced decays of BSM states are a major discovery opportunity at LHC Run II and beyond
  - Technically challenging searches, areas of unexplored territory
- Single displaced vertex searches in the MS
  - Not background-free: develop techniques to data-drive background predictions
  - Proof of concept: $h \to XX$, major gains for long-lived X
- Need for concerted experimental/theory effort to evaluate gaps, usability
  - information! prompt/displaced boundary, efficiency maps