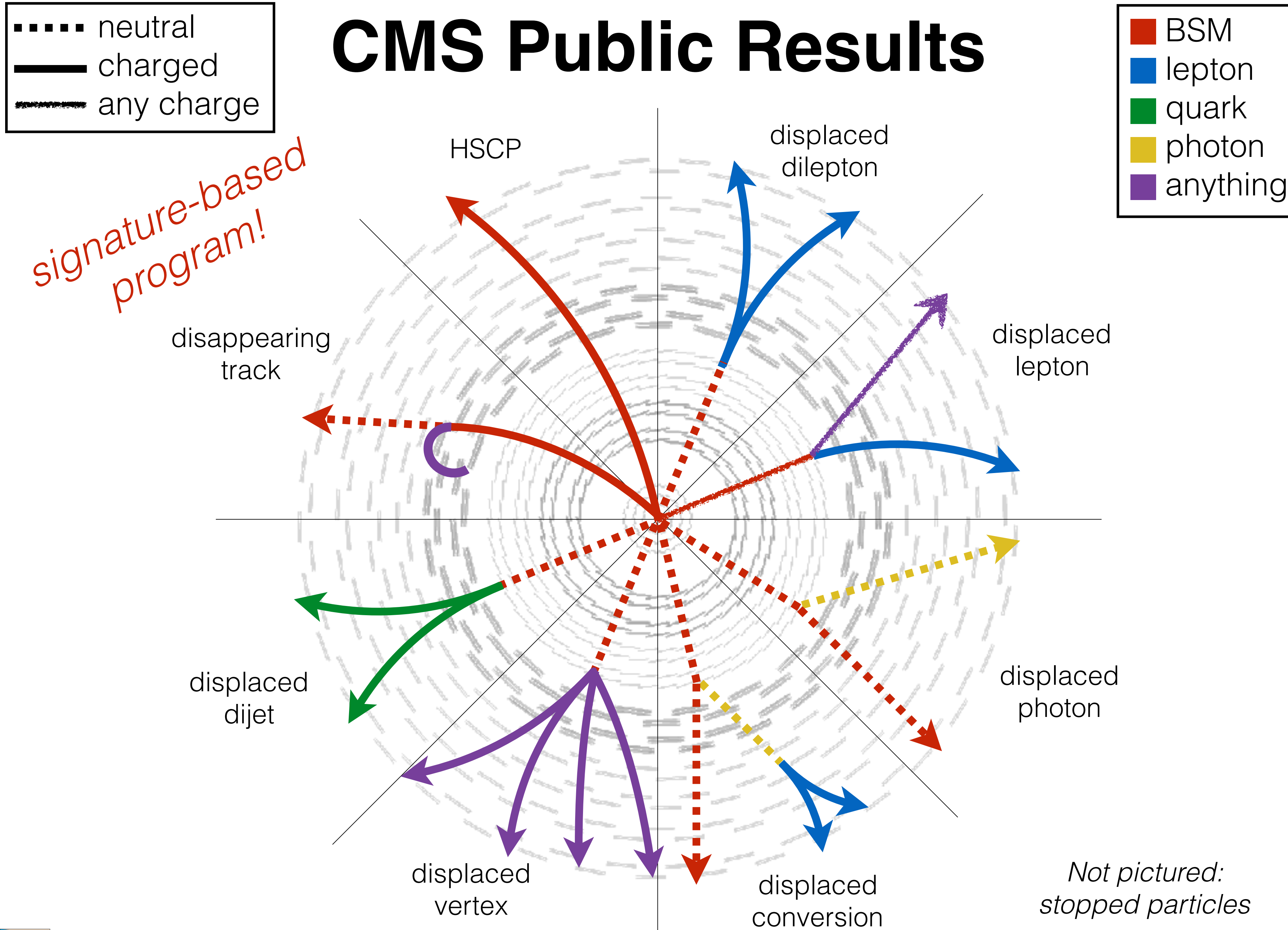
Long-Lived Particles at the LHC

Zhen Liu (Fermilab)

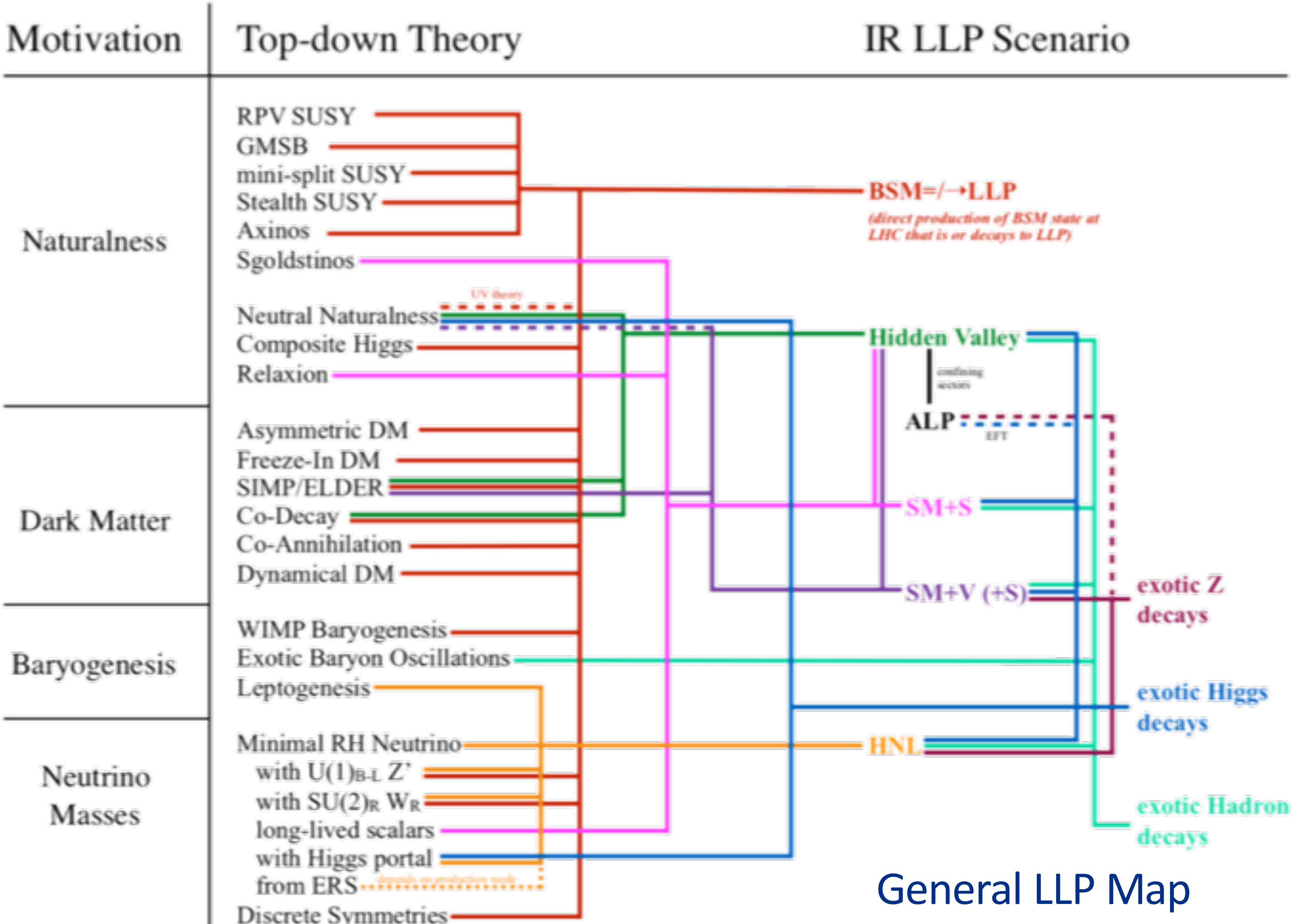
LPC Topic Of The Week (TOTW) seminar

Jun. 19th , 2018

CMS Public Results



Not pictured: stopped particles



General LLP Map

MATHUSLA physics case, D. Curtin et al, appearing tonight

Outline

- LLP Theory — ZL (chapter editor) et al, Simplified Models (chapter 2 of LLP community report: appearing soon)
- LLP Coverage — ZL, B. Tweedie, **1503.05923**
- Timing for LLP — Jia Liu, ZL, L.-T. Wang, **1805.05957**

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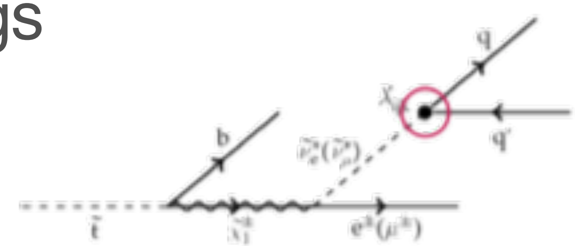
Easily long-lived: SUSY

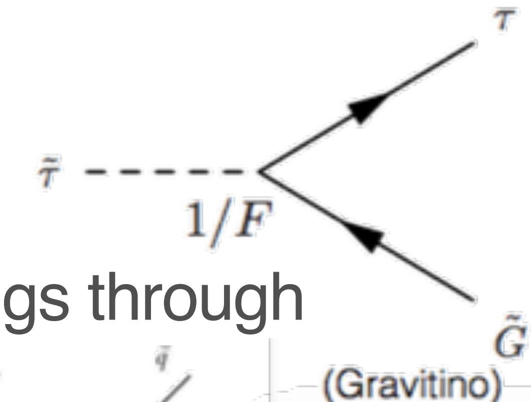
- RPV–small B/L-violating couplings

$$c\tau_{\rm RPV} \sim 0.1{\rm mm} \left(\frac{100\ {\rm GeV}}{\tilde{m}}\right)\left(\frac{10^{-6}}{\lambda}\right)^2$$



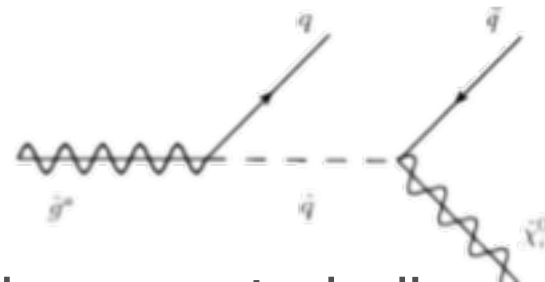
- Gauge mediation—suppressed couplings via SUSY breaking scale

$$c\tau_{\rm GMSB} \sim 0.1{\rm mm} \left(\frac{100\ {\rm GeV}}{\tilde{m}}\right)^5\left(\frac{\sqrt{F}}{100\ {\rm TeV}}\right)^4$$



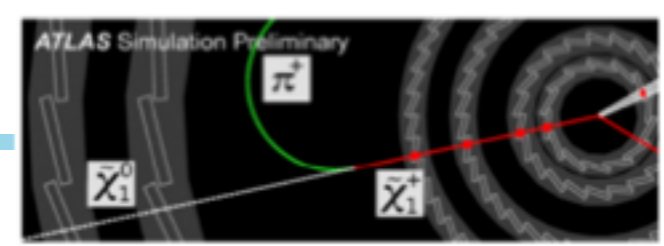
- Mini-split spectrum—suppressed couplings through ”decoupled” heavy particles

$$c\tau \approx 10^{-5}\ {\rm m} \left(\frac{m_{\tilde{q}}}{\rm PeV}\right)^4\left(\frac{\rm TeV}{m_{\tilde{g}}}\right)^5$$



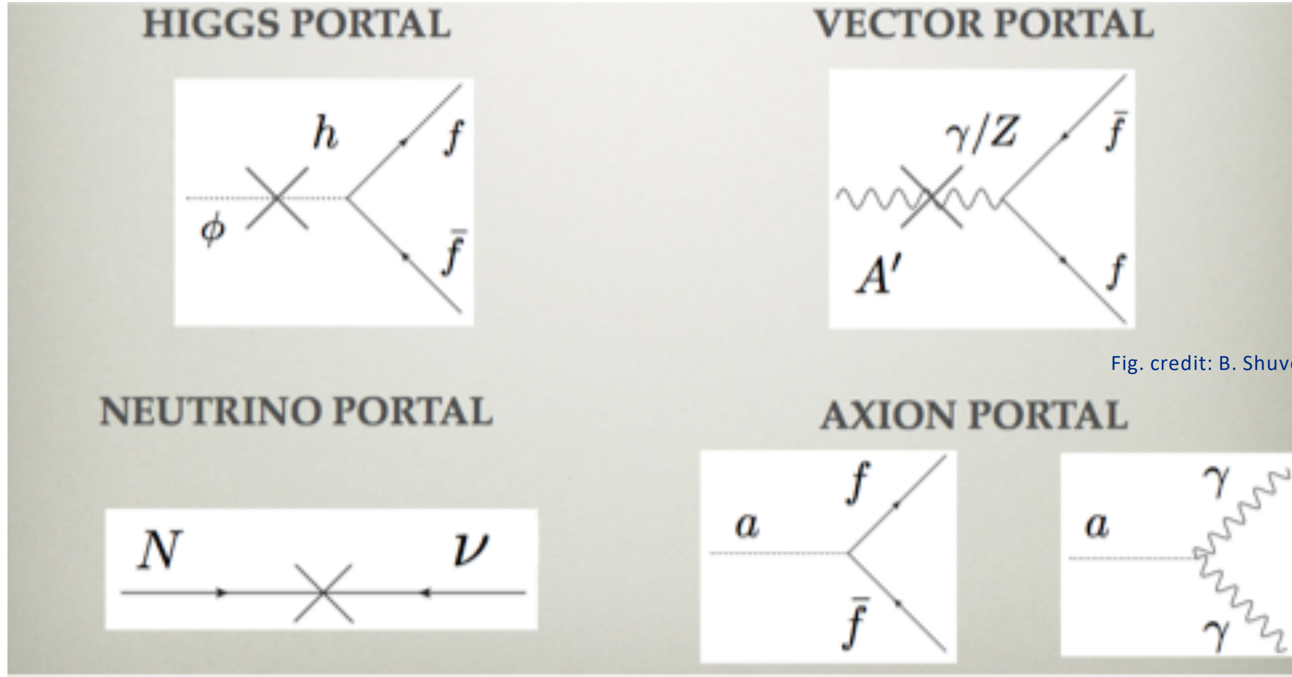
- Pure Wino/Higgsino–nearly degenerated, disappearing track

$$c\tau \approx 0.7\,{\rm cm} \times \left(\frac{\Delta m}{340\ {\rm MeV}}\right)^3$$



Easily long-lived: hidden sector

Hidden sector feeble couplings to SM via various portals, suppressed by the smallness of the couplings
(e.g., Strassler, Zurek, et al)

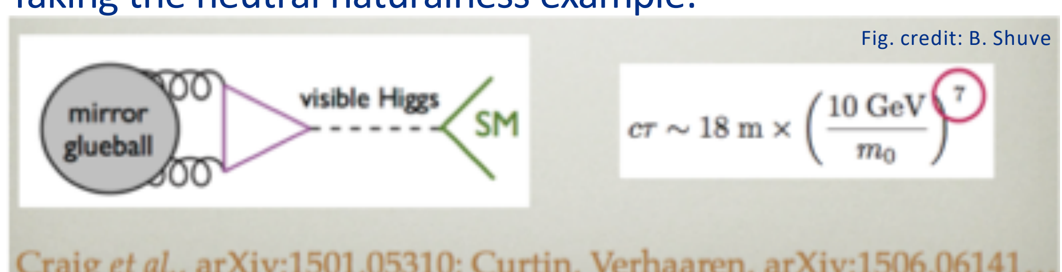


Can be related to big questions:

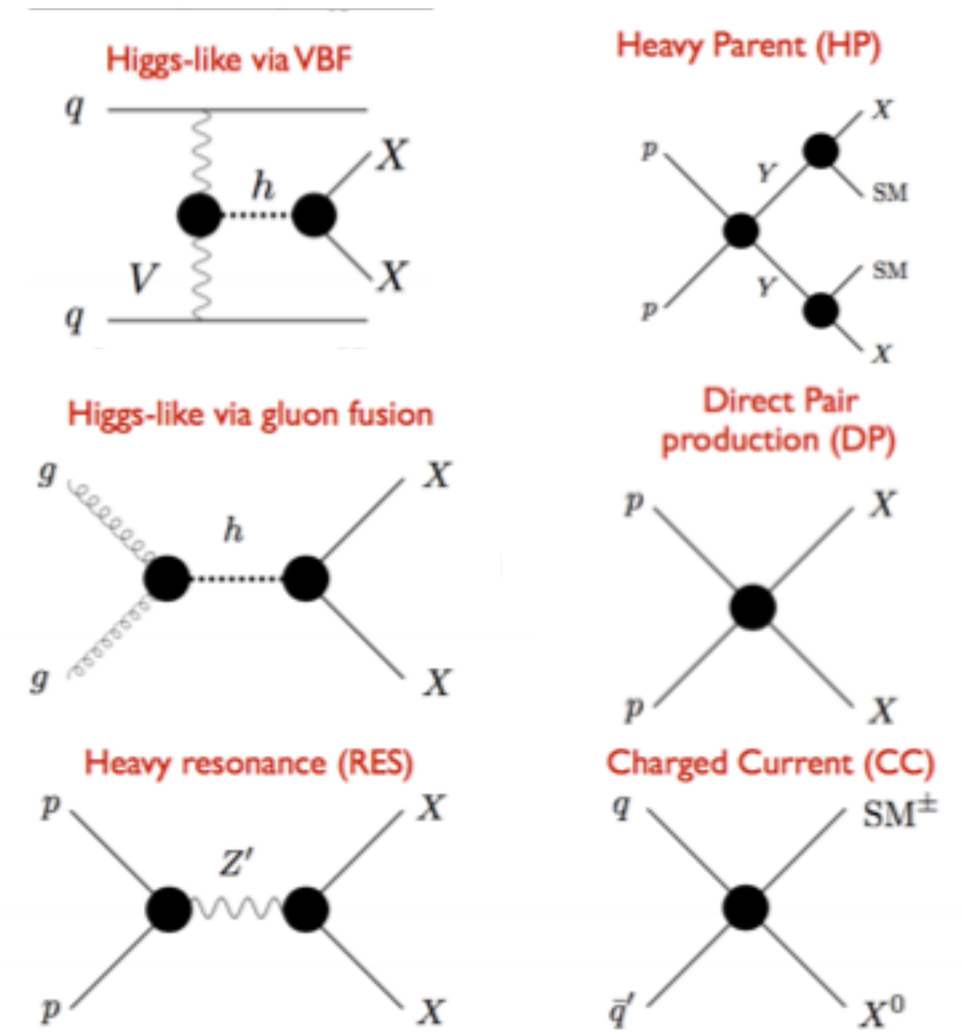
- Dark matter;
- Neutrino mass;
- Baryogenesis;

...etc.

Taking the neutral naturalness example:



Classification: Production



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Simplified Models (chapter 2 of LLP community report)

- Factorize production and decay;
- Production affects kinematics of LLP and trigger consideration (except for LLP triggers, which are rare currently);
- Decay affects search strategy in picking up the LLPs, convoluting with lab frame geometries;

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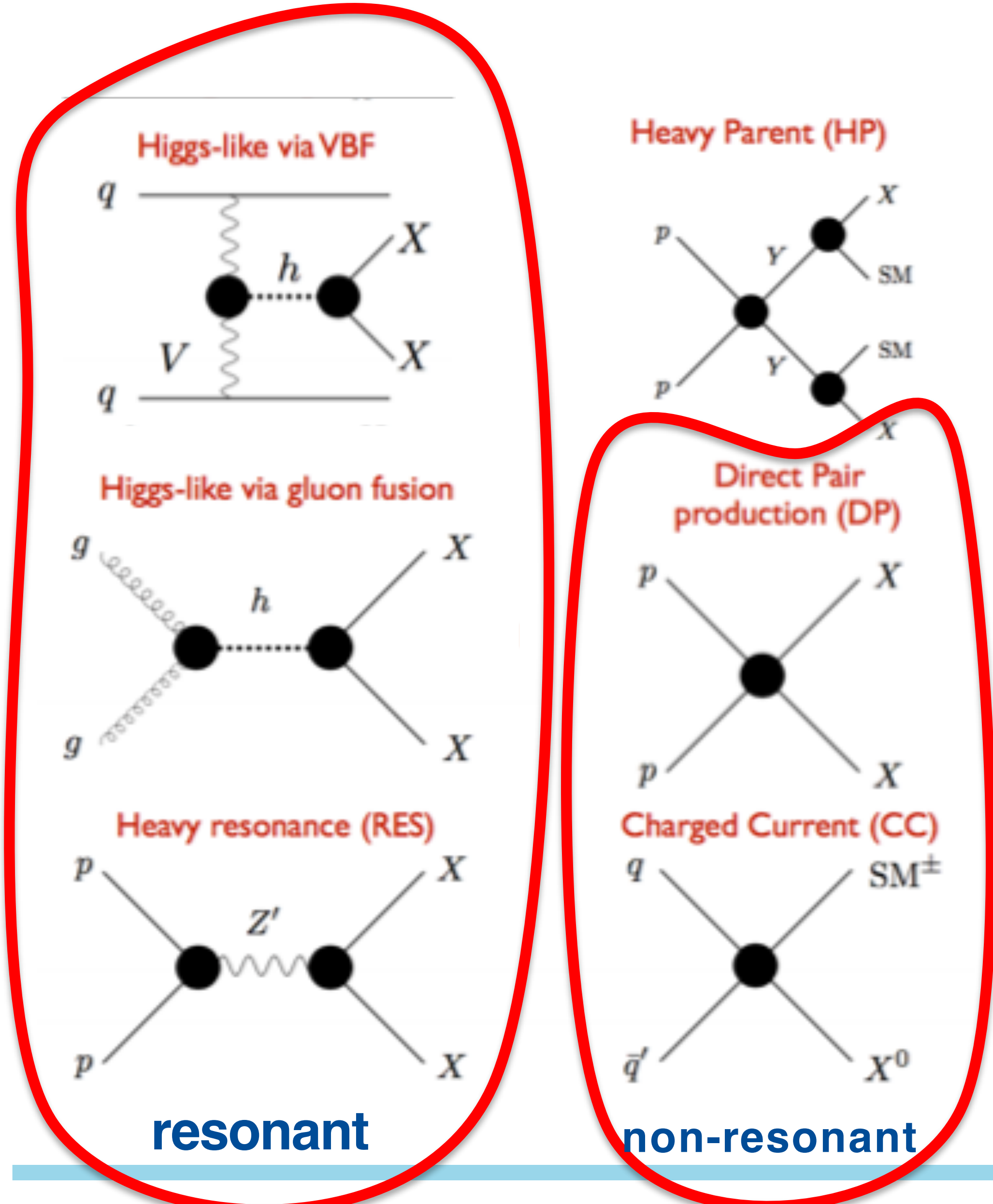

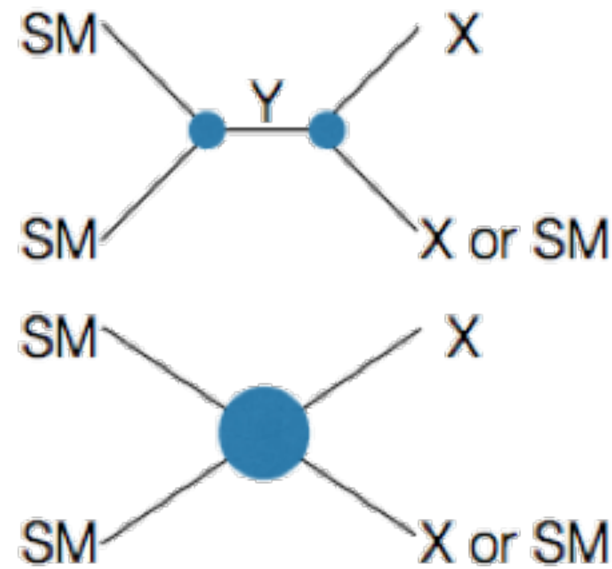

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- Production affects kinematics of LLP and trigger consideration (except for LLP triggers, which are rare currently);
- Decay affects search strategy in picking up the LLPs, convoluting with lab frame geometries;

Classification: Production, Decay and Models

Neutral Long-lived particles

LLP decay modes

Decay / Production	$\gamma\gamma(+\text{inv.})$	$\gamma+\text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell_\alpha^+\ell_{\beta\neq\alpha}^-(+\text{inv.})$
DPP: sneutrino pair	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q}\to jX$ or gluino pair $\tilde{g}\to jjX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell}\to\ell X$ or chargino pair, $\tilde{\chi}\to WX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h\to XX$ or $\to XX+\text{inv.}$	Higgs, DM*	†	Higgs, DM*	RHν	Higgs, DM* RHν*	RHν*
HIG: $h\to X+\text{inv.}$	DM*, RHν	†	DM*	RHν	DM*	†
RES: $Z(Z')\to XX$ or $\to XX+\text{inv.}$	Z', DM*	†	Z', DM*	RHν	Z', DM*	†
RES: $Z(Z')\to X+\text{inv.}$	DM	†	DM	RHν	DM	†
CC: $W(W')\to\ell X$	†	†	RHν*	RHν	RHν*	RHν*

Canonical production modes:
DPP, HP, HIG, RES, CC

Mapping to UV Models

X represents the LLP
*model definitely include missing energy;
+signature not appeared in the minimal/simplest model setup;

Classification: Production, Decay and Models

Charged Long-lived particles

LLP decay modes

Production \ Decay	$\ell + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell\gamma$
DPP: chargino pair or slepton pair	SUSY	SUSY	SUSY	
HP: $\tilde{q} \to jX$	SUSY	SUSY	SUSY	
ZP: $Z' \to XX$	Z', DM*	Z', DM*	Z'	
CC: $W' \to X + \text{inv.}$	DM*	DM*		

Canonical production modes

Mapping to UV Models

Colored Long-lived particles

LLP decay modes

Production \ Decay	$j + \text{inv.}$	$jj(+\text{inv.})$	$j\ell$	$j\gamma$
DPP: squark pair or gluino pair	SUSY	SUSY	SUSY	

Canonical production modes

Mapping to UV Models

and there are many more exotic signals:
Stopped particles, dashed tracks, coplanar tracks, fireballs, dark showers, etc;

A LLP model file library also under construction, many modes already tested

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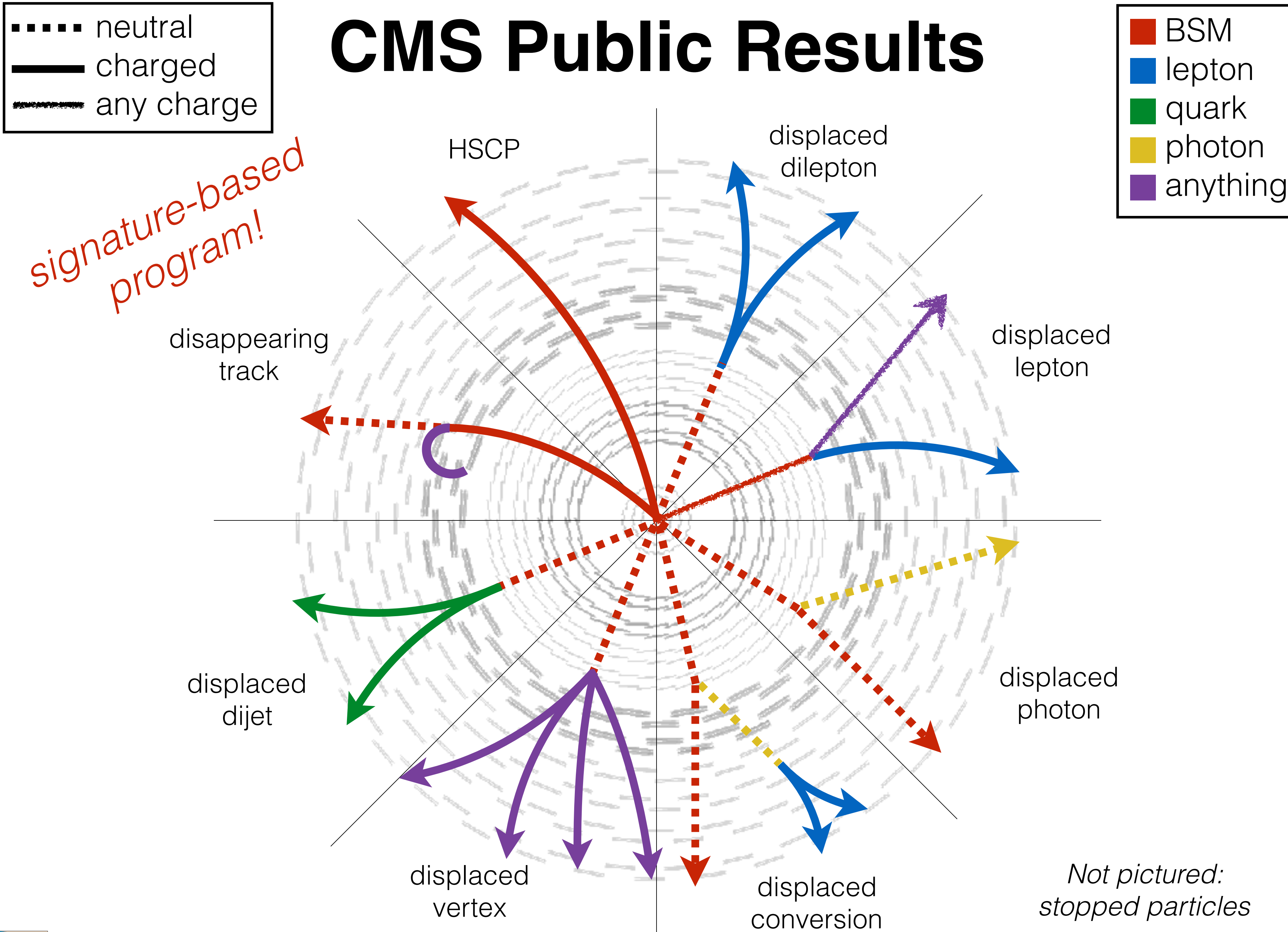
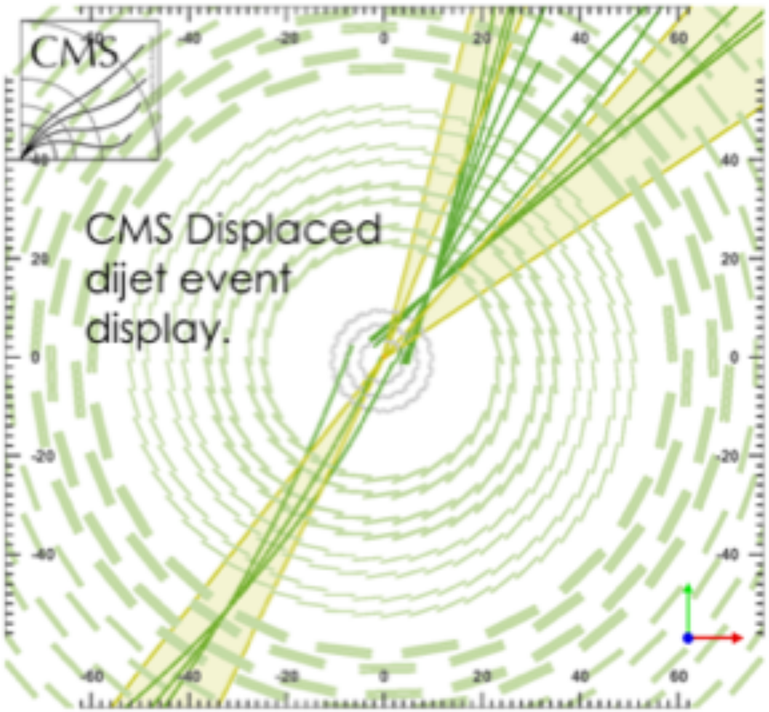


Not pictured: stopped particles

Enlarging the coverage: CMS Dijet



- 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
  - $N_{tracks} > 4, 5$
  - At most one prompt (IP <0.5 mm) track per jet
  - Dijet consistent with DV

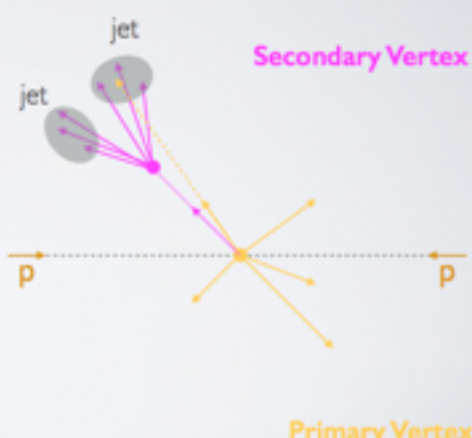


Fig. credit: E. Kuflik

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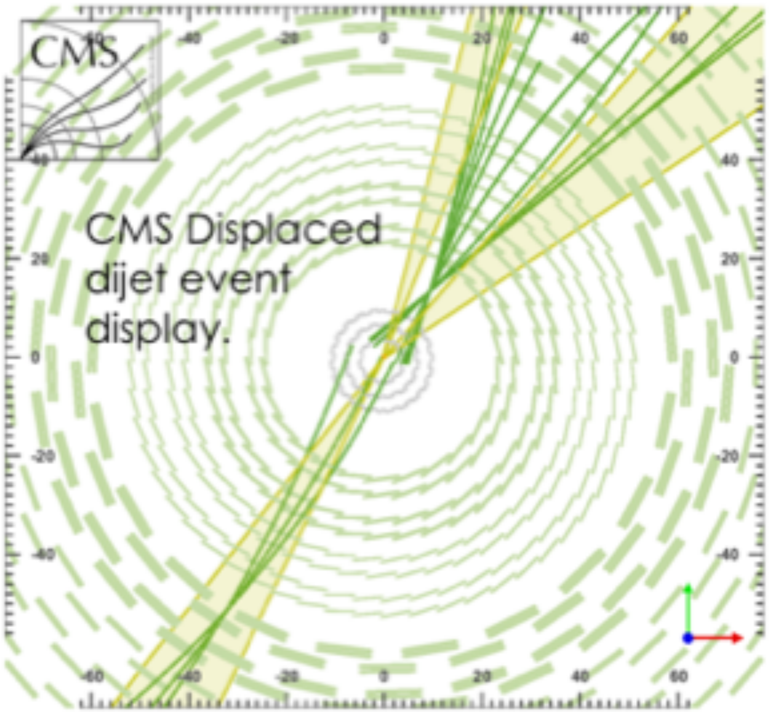

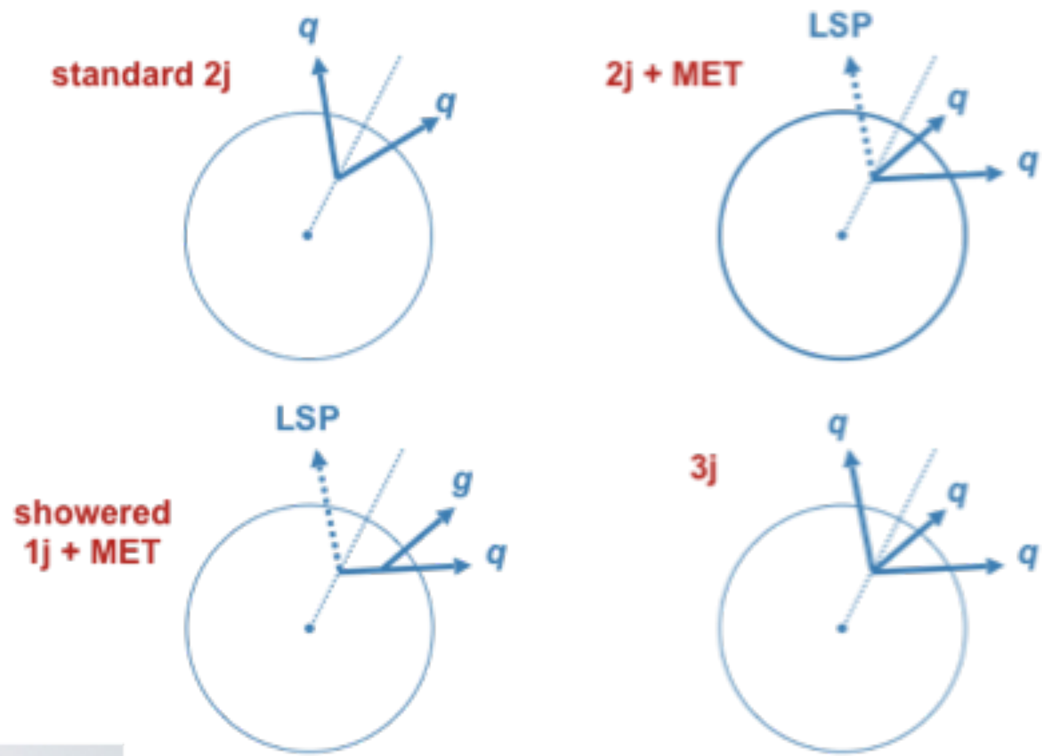

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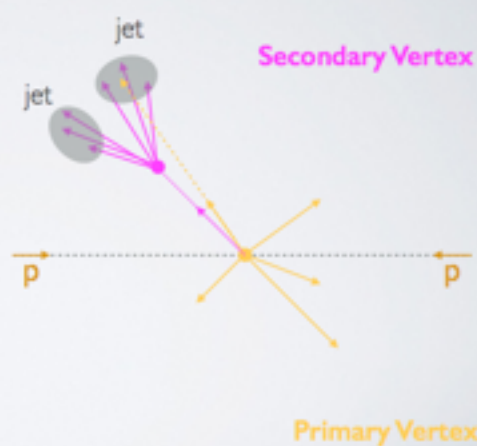

Fig. credit: E. Kuflik

- LLP searches usually are also sensitive to other decay topologies without/with little efficiency loss.
- We emphasis this point and show the power to all SUSY LLPs in our study.

Overview of our study

- $\tilde{t} \to \bar{d}_i \bar{d}_j$ via baryonic RPV including $\tilde{t} \to \bar{b}\bar{b}$
- $\tilde{g} \to u_i d_j d_k$ via baryonic RPV
- $\tilde{H} \to u_i d_j d_k$ (+soft) via baryonic RPV

Hadronic R-parity violation

- $\tilde{q} \to q\,\tilde{G}$ in GMSB
- $\tilde{g} \to g\,\tilde{G}$ in GMSB
- $\tilde{t} \to t^{(*)}\,\tilde{G}$ in GMSB
- $\tilde{H} \to h/Z\,\tilde{G}$ (+soft) in GMSB

gauge mediation

- $\tilde{g} \to q\bar{q}\tilde{B}$ in mini-split SUSY

mini-split

Our selection of signals (naïve naturalness driven, light Higgsino, stop and gluino) covers a large range of displace decay topologies, including 1j+MET, 2j+MET, 3j+MET, 2j, 3j, as well as heavy flavors, making it easy for theorists to estimate exclusions for their own models in concern.

Overview of our study

Applied to all models

- CMS displaced dijets (tracker)
- ATLAS low-EM jets (HCAL)
- ATLAS muon spectrometer vertices*
- CMS charged stable particles

Applied to models with leptonic decays

CMS displaced dileptons

CMS displaced electron & muon

ATLAS displaced muon + tracks

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* 7 TeV, 2 fb^{-1}
** All via direct pair-production

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Many results, great boost to LLP and SUSY LLP; to save time, I will only go through two results

- $\tilde{t} \to \bar{d}_i \bar{d}_j$ via baryonic RPV including $\tilde{t} \to \bar{b}\bar{b}$
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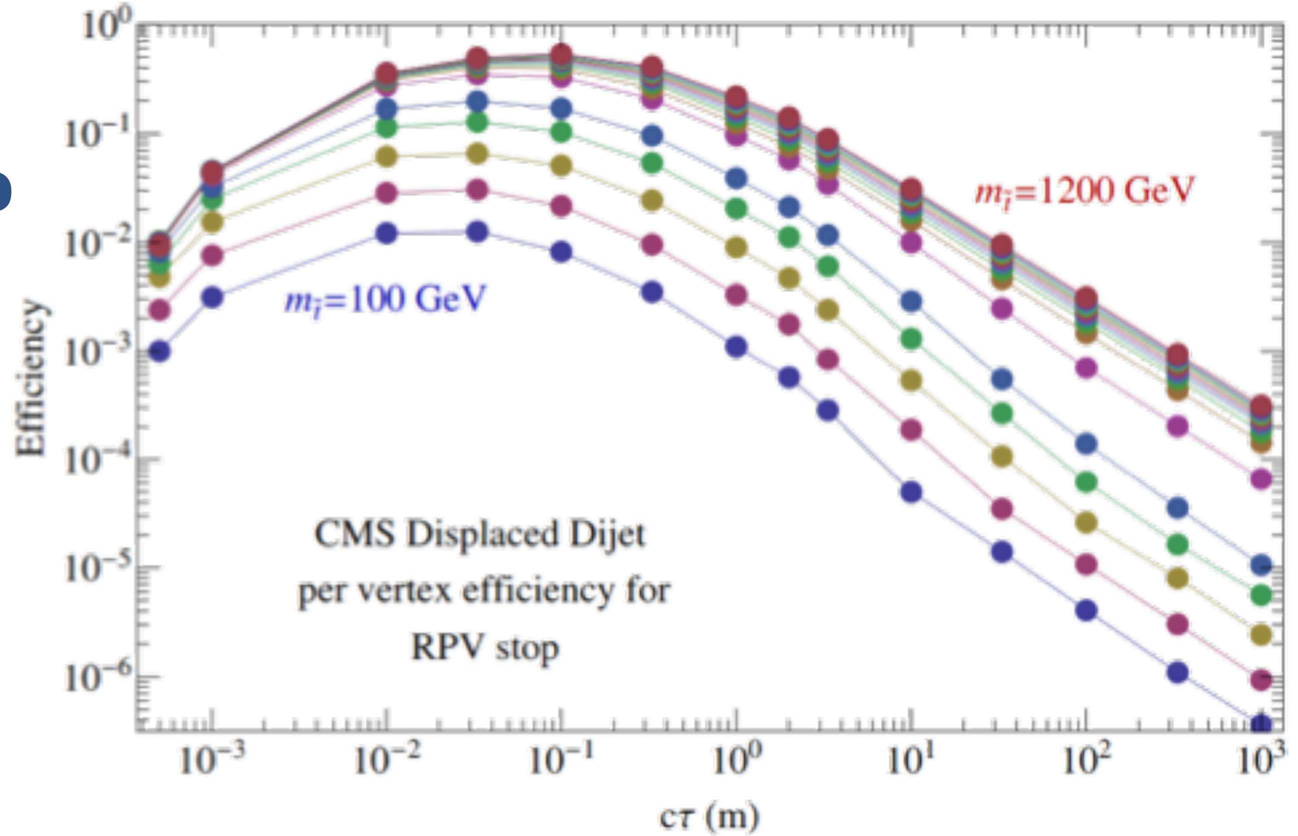
A Typical Efficiency MAP

With detailed simulation and our own modeling of the displacement, after carefully calibrating with existing searches, we can derive the limits from many search of our simplified models.



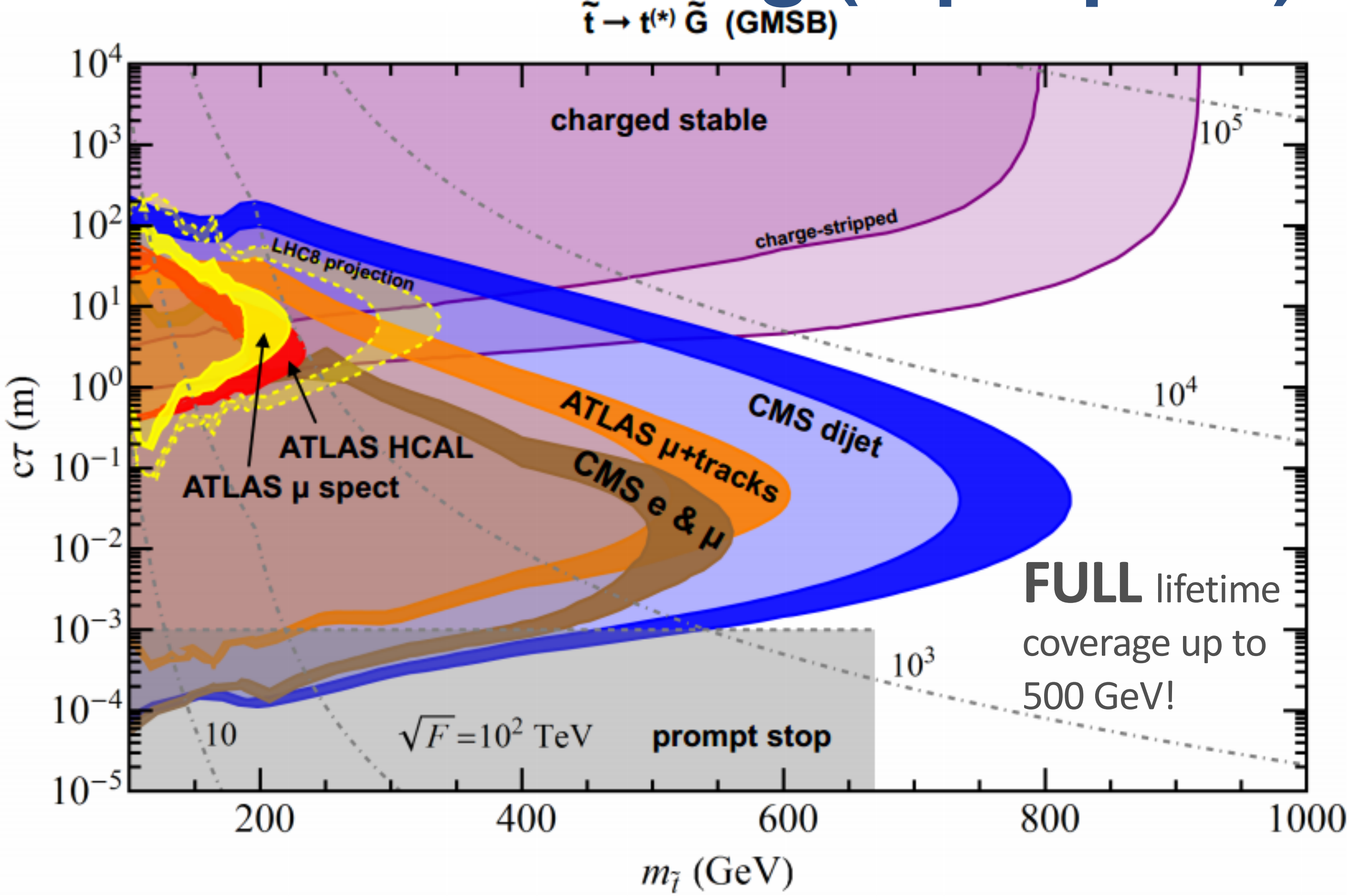
Efficiency map for RPV stop decays into light jet pairs in the CMS displaced dijet analysis.

- Lines at increase of 100 GeV
- Low mass suffers more for cuts on jet energy
- High mass approaches constant efficiency shape
- Low efficiency at low lifetime (cut to remove SM)
- (Shift in peak due to Lorentz Factor)

Gauge Mediation SUSY Breaking (top squark)

GMSB Stop ➞ Top$^{(*)}$ + Gravitino

- Displaced searches (dijet, μ+tracks, $e + \mu$, HCAL, μ spectrometer) covers mid-lifetime Heavy charges
- stable particle searches (pink; CHAMP/HSCP) covers long lifetime
- Prompt (gray) covers short lifetime



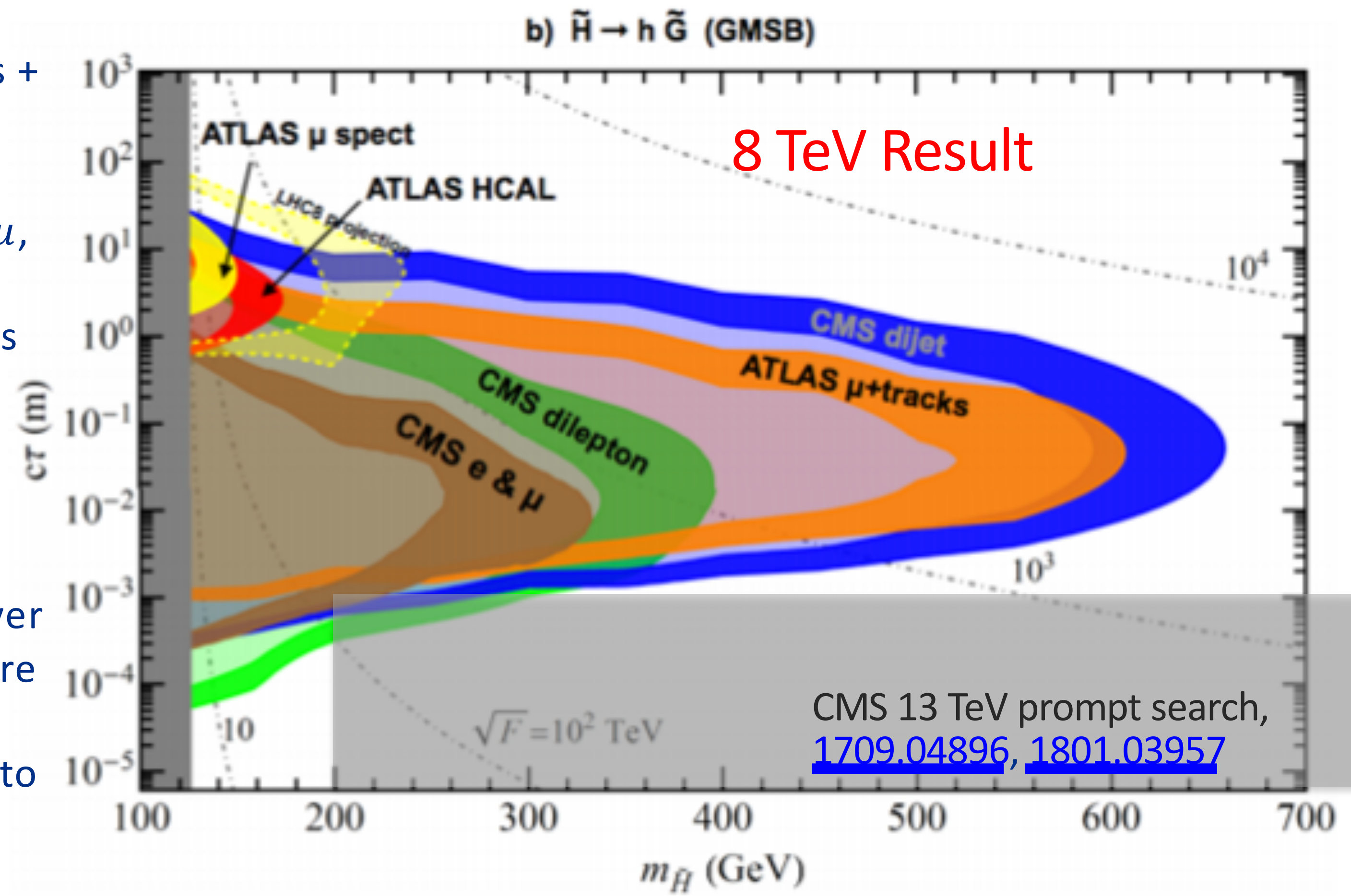
FULL lifetime coverage up to 500 GeV!

Dijet search has very good sensitivity reach, lepton plus tracks searches also sensitive to leptonic top- and b-decays. HCAL and muon spectrometer searches sensitive to higher lifetimes but so far suffers large efficiency cost. Optimization may provide additional information, e.g., heavy neutral displaced particles.

Gauge Mediation SUSY Breaking (Higgsino)

GMSB Higgsino ➞ Higgs + Gravitino

- Displaced searches (dijet, μ+tracks, $e+\mu$, HCAL, dilepton, μ spectrometer) covers mid-lifetime Heavy charges
- No stable particle searches (pink; CHAMP/HSCP) to cover long lifetime—as there is no charged LLP;
- No prompt searches to covers short lifetime due to large background;



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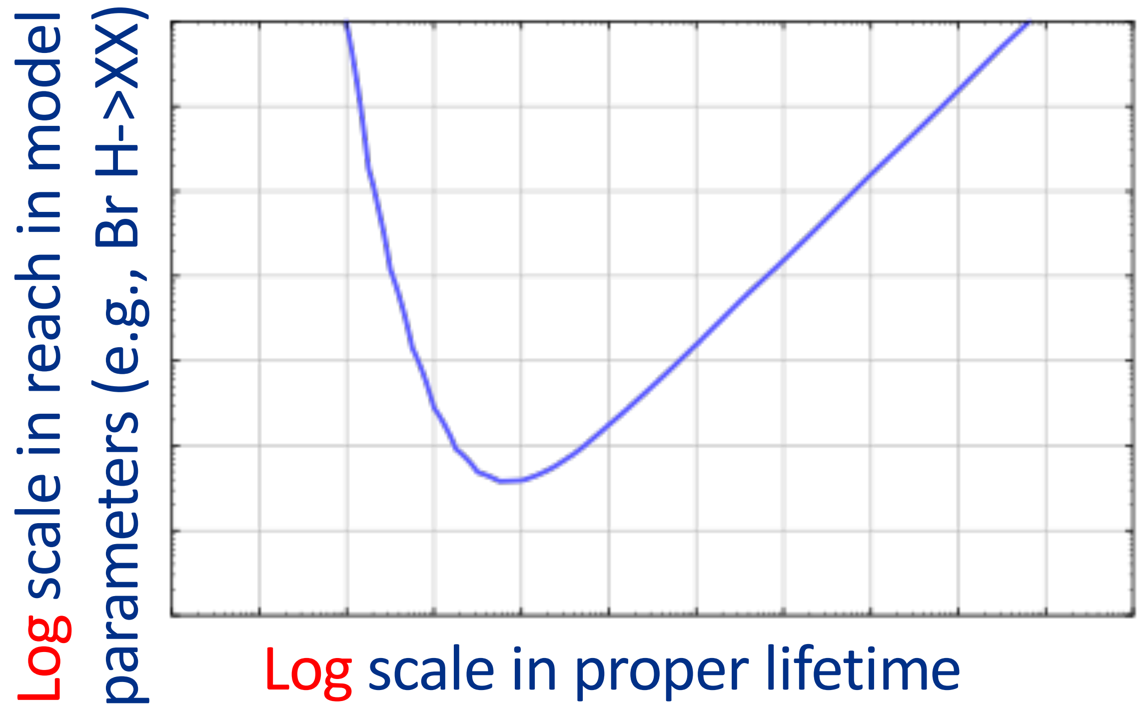
Realizing the great potential of the LHC

What's the best place to look for LLPs (short-lifetime-limit, and long lifetime-limit)?



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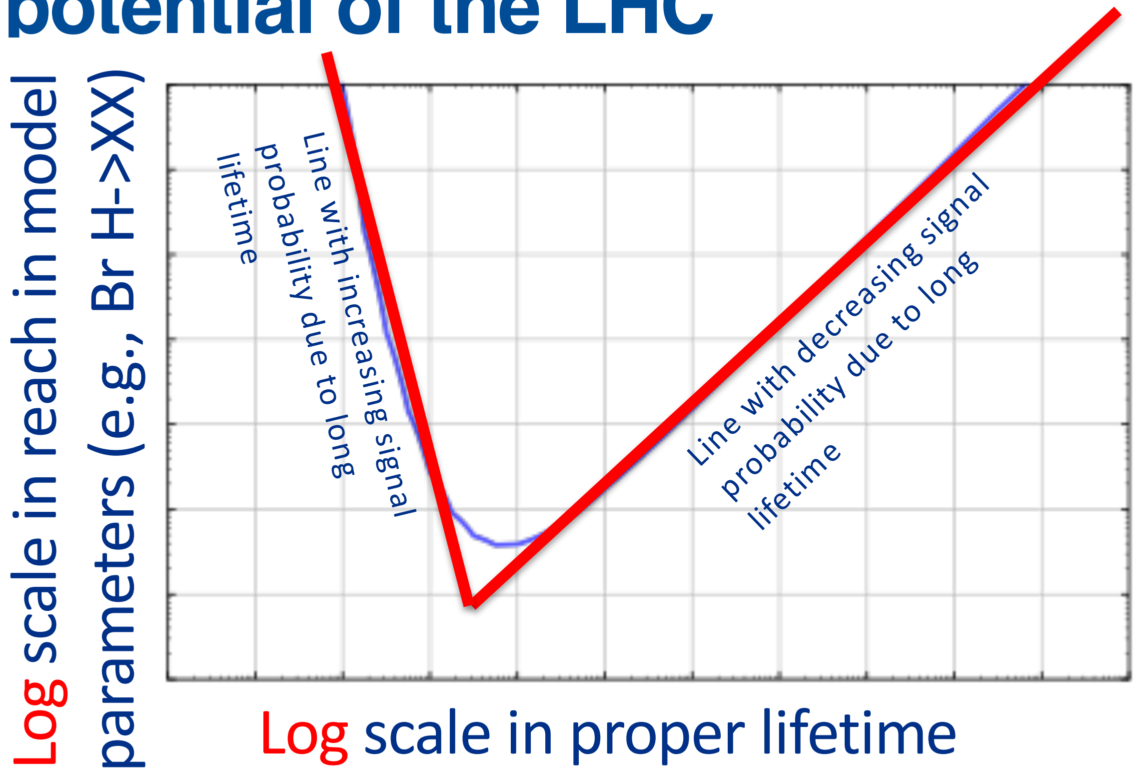

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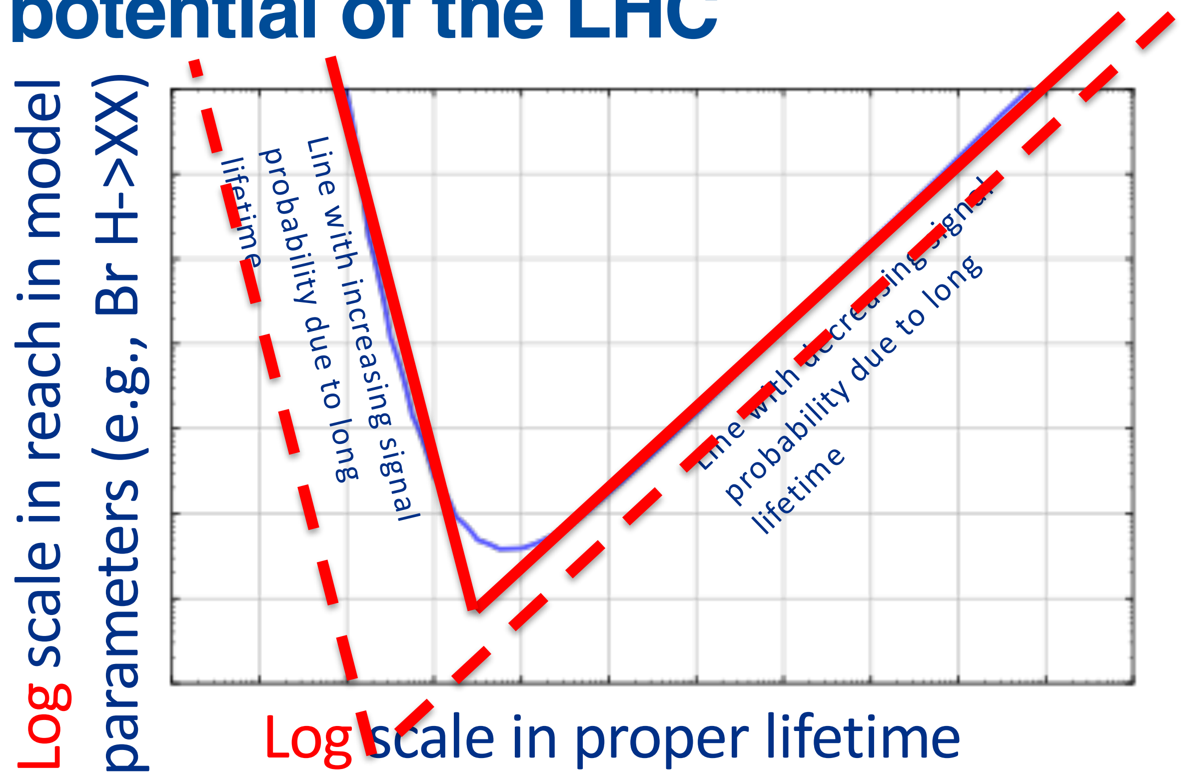


$$
\begin{aligned}
P_{\rm in} &= \frac{1}{4\pi}\int_{\Delta\Omega} d\Omega \int_{L_1}^{L_2} dL \frac{1}{d} e^{-L/d} \\
&\approx \frac{\Delta\Omega}{4\pi}\int_{L_1}^{L_2} dL \frac{1}{d} e^{-L/d} \\
&= \frac{\Delta\Omega}{4\pi}\left(e^{-L_1/d} - e^{-L_2/d}\right) \\
&\approx \boxed{\frac{\Delta\Omega}{4\pi}} \boxed{e^{-L_1/d}} \boxed{\frac{L_2 - L_1}{d}}
\end{aligned}
$$

LHC: ~1

~1

size/d

$$d = c\tau\gamma$$

$$n_{sig} = N_{prod} \times P_{in} \times \epsilon_{trig} \times \epsilon_{sig} \times \epsilon_{bkg}^{penalty}$$

Fermilab

*except for forward physics, e.g., LHCb, FASER

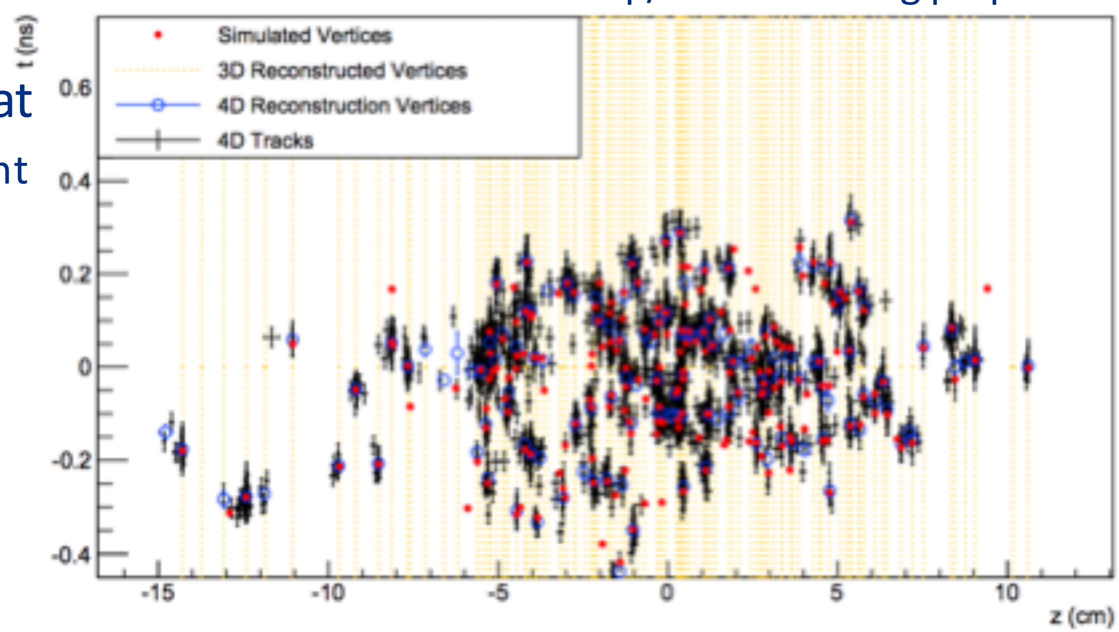
Precision timing--a new dimension

Precision timing information now compliments spatial information, and its bears great potential to fully realize LHC's physics reach in LLP.

For long-lived particles (whose lifetime is macroscopic >~ mm), they generically move slower and their long-lived nature substantiates their slowness in motion at colliders.

- 30 picosecond timing resolution at CMS after phase2 upgrade (in front of ECal, 1.2 m from beam);
- Proposed to enable 4d construction of vertices:
  - reducing the pile up level;
  - Reducing pile-up track mis-association in to the primary interaction;

ATLAS has similar endcap/forward timing proposal

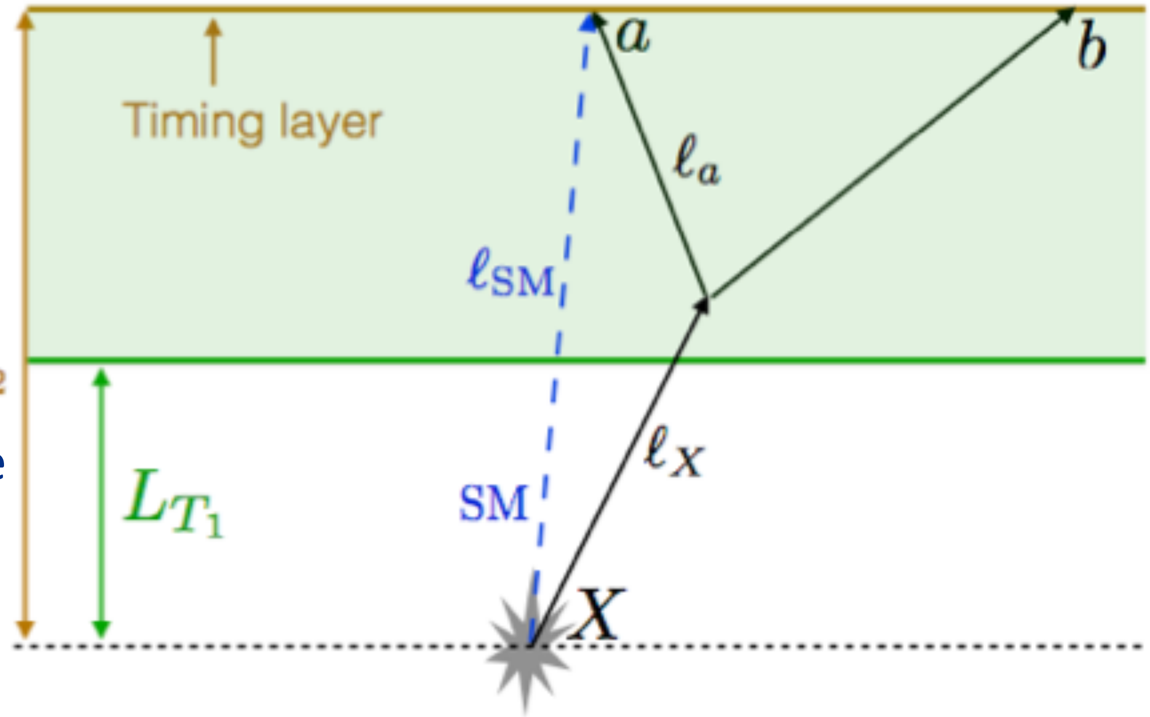


Timing BSM

$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}}$$

signal arrival time

SM reference particles arrival time



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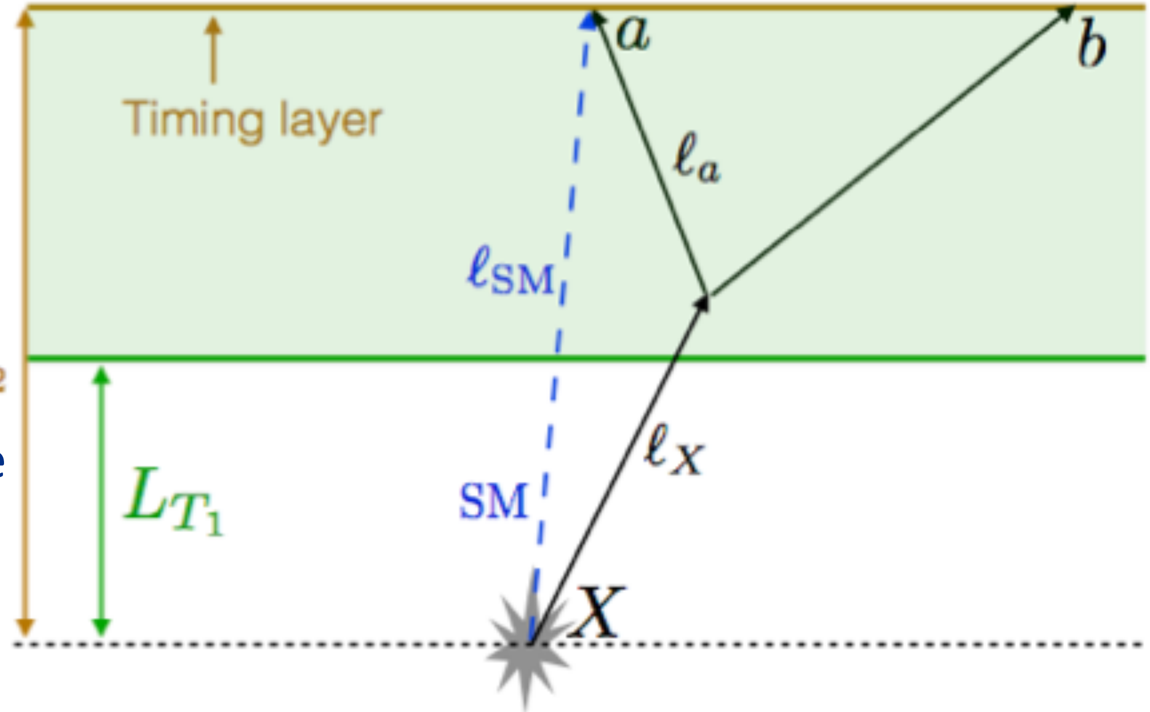


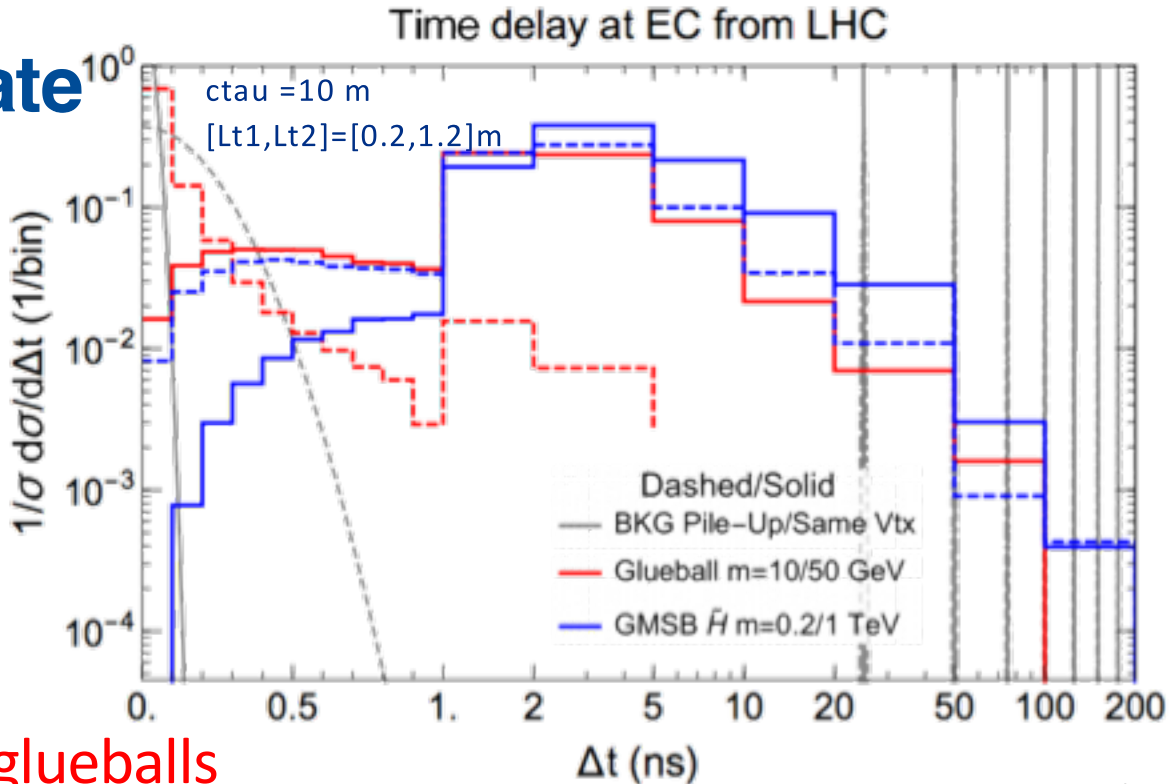
For CMS timing layer (1.2 m, t0=4 nanoseconds)*, 30 picosecond timing resolution indicates sensitivity to BSM signal having >1% velocity (boost factor $\gamma < 7$) /path difference w.r.t. SM particles!

LLP (with mass > 10s of GeV) typically all have much slower motion!

*for pseudorapidity 0; higher rapidity enlarges the timing difference;
*SM particles essentially all travel at speed of light;

LLPs arrive (very) late

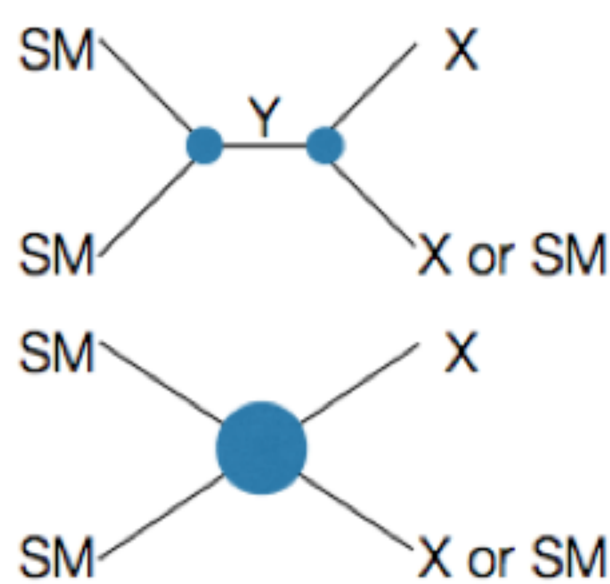
$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{SM}}{\beta_{SM}}$$



We also consider a possible timing layer outside Muon spectrometer, making use of the large LHC detector volume.

Signals:

- Red: Higgs decaying into glueballs (neutral naturalness)
- Blue: Higgsinos (GMSB SUSY)



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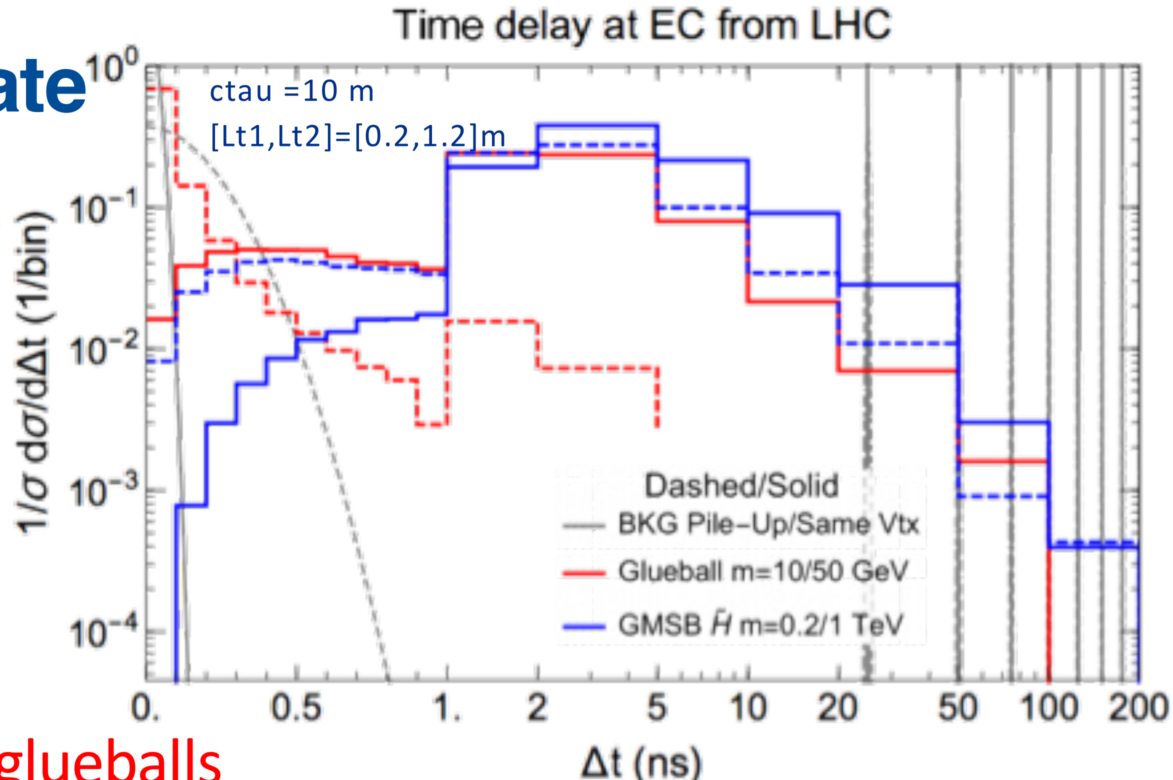

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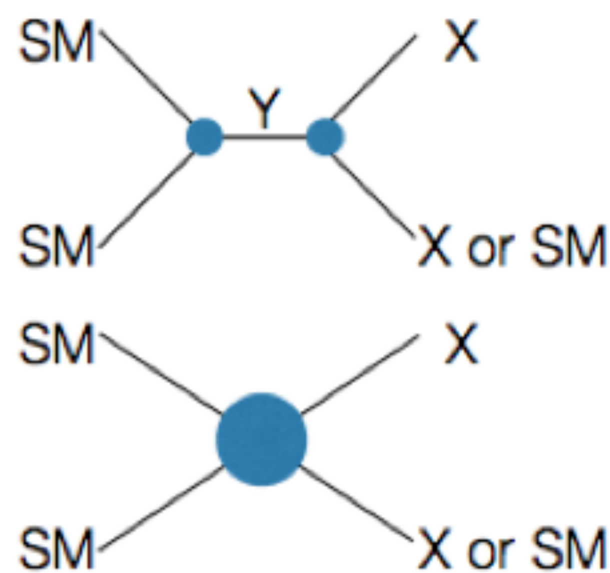
Backgrounds:

- Gray (Dashed): Pile-up with natural spread of 190 ps (beam property)
- Gray (Solid): Hard collision spread due to uncertainties in timing



Late comers will be spotted easily:

	L_{T_2}	L_{T_1}	Trigger	$\epsilon_{\rm trig}$	$\epsilon_{\rm sig}$	$\epsilon^j_{\rm fake}$	Ref.
EC	1.17 m	0.2 m	DelayJet	0.5	0.5	10^{-3}	[12]
MS	10.6 m	4.2 m	MS RoI	0.25, 0.5	0.25	5×10^{-9}	[24]

CMS timing module

ATLAS MS LLP search

(without timing)

Designed 2 generic search: no restriction on the signal, as long as they can deposit energy (30 GeV pT min)*

Multijet and pile-up background can be effectively rejected use timing*

Other backgrounds:

- Interaction with material
- Cosmic rays
- Beam halo

…

All have mature veto mechanism; need to revisit to see the impact of timing

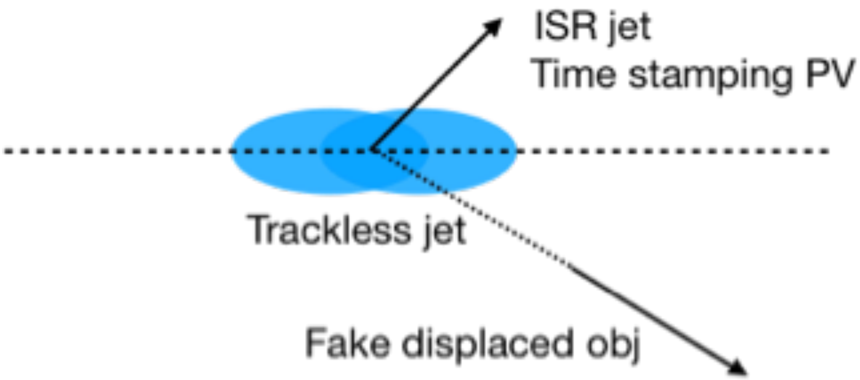
Late comers will be spotted easily:

	L_{T_2}	L_{T_1}	Trigger	$\epsilon_{\rm trig}$	$\epsilon_{\rm sig}$	$\epsilon^j_{\rm fake}$	Ref.
EC	1.17 m	0.2 m	DelayJet	0.5	0.5	10^{-3}	[12]
MS	10.6 m	4.2 m	MS RoI	0.25, 0.5	0.25	5×10^{-9}	[24]

CMS timing module

ATLAS MS LLP search

(without timing)



Same-vertex hard scattering background, time spread 30 ps (precision timing)

$$\text{EC}: \quad N^{\rm SV}_{\rm bkg} = \sigma_{\rm j} \mathcal{L}_{\rm int} \epsilon^{\rm EC}_{\rm trig} \epsilon^{j,{\rm EC}}_{\rm fake} \approx 1 \times 10^{11}$$

$$\text{MS}: \quad N^{\rm SV}_{\rm bkg} = \sigma_{\rm j} \mathcal{L}_{\rm int} \epsilon^{\rm MS}_{\rm trig} \epsilon^{j,{\rm MS}}_{\rm fake} \approx 4 \times 10^{5},$$

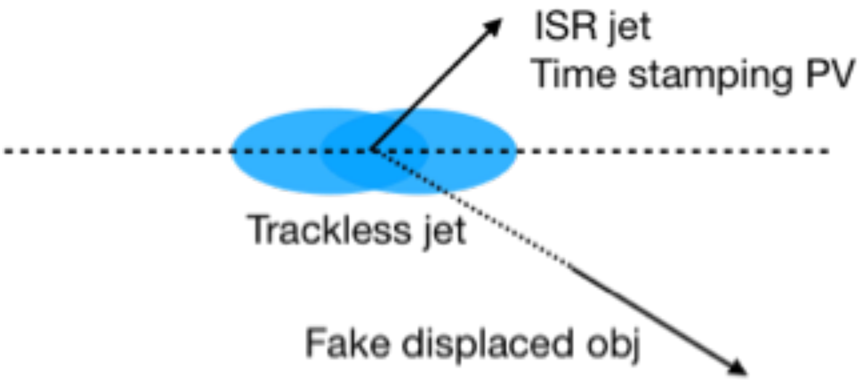
Late comers will be spotted easily:

	L_{T_2}	L_{T_1}	Trigger	$\epsilon_{\rm trig}$	$\epsilon_{\rm sig}$	$\epsilon^j_{\rm fake}$	Ref.
EC	1.17 m	0.2 m	DelayJet	0.5	0.5	10^{-3}	[12]
MS	10.6 m	4.2 m	MS RoI	0.25, 0.5	0.25	5×10^{-9}	[24]

CMS timing module

ATLAS MS LLP search

(without timing)



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$$\text{MS}: \quad N^{\rm SV}_{\rm bkg} = \sigma_{\rm j}\mathcal{L}_{\rm int}\epsilon^{\rm MS}_{\rm trig}\epsilon^{j,\rm MS}_{\rm fake} \approx 4 \times 10^{5},$$

Hard collision BKG: detector time resolution ~30 ps

EC (30ps) cut: Δt > 0.4 ns

MS (30ps) cut: Δt > 1ns

BKG(SV) << 1

The detector time resolution for MS can be downgraded to hundreds of ps

MS (200ps) cut:

Δt > 1ns

BKG(MS-SV) ~ 0.11

Late comers will be spotted easily:

	L_{T_2}	L_{T_1}	Trigger	$\epsilon_{\rm trig}$	$\epsilon_{\rm sig}$	$\epsilon^j_{\rm fake}$	Ref.
EC	1.17 m	0.2 m	DelayJet	0.5	0.5	10^{-3}	[12]
MS	10.6 m	4.2 m	MS RoI	0.25, 0.5	0.25	5×10^{-9}	[24]

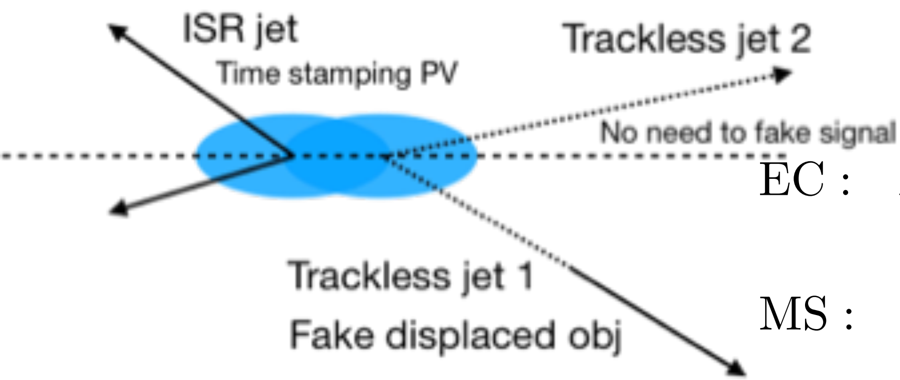
CMS timing module

ATLAS MS LLP search

(without timing)

Pile-Up background, time spread

190 ps (beam property)



$$\text{EC}: \quad N^{\rm PU}_{\rm bkg} = \sigma_{\rm j}\mathcal{L}_{\rm int}\epsilon^{\rm EC}_{\rm trig}\left(\bar{n}_{\rm PU}\frac{\sigma_{\rm j}}{\sigma_{\rm inc}}\epsilon^{j,{\rm EC}}_{\rm fake} f^j_{\rm nt}\right) \approx 2 \times 10^7,$$

$$\text{MS}: \quad N^{\rm PU}_{\rm bkg} = \sigma_{\rm j}\mathcal{L}_{\rm int}\epsilon^{\rm MS}_{\rm trig}\left(\bar{n}_{\rm PU}\frac{\sigma_{\rm j}}{\sigma_{\rm inc}}\epsilon^{j,{\rm MS}}_{\rm fake} f^j_{\rm nt}\right) \approx 50, \quad (5)$$

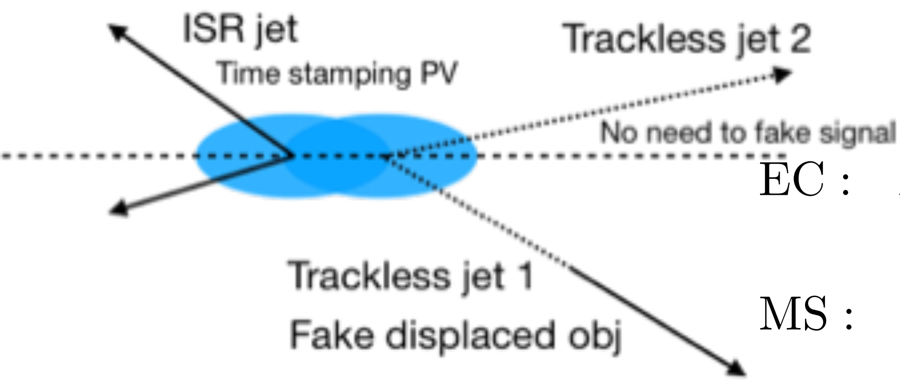
Late comers will be spotted easily:

	L_{T_2}	L_{T_1}	Trigger	$\epsilon_{\rm trig}$	$\epsilon_{\rm sig}$	$\epsilon^j_{\rm fake}$	Ref.
EC	1.17 m	0.2 m	DelayJet	0.5	0.5	10^{-3}	[12]
MS	10.6 m	4.2 m	MS RoI	0.25, 0.5	0.25	5×10^{-9}	[24]

CMS timing module

ATLAS MS LLP search

(without timing)



Pile-Up background, time spread

190 ps (beam property)

$$\text{EC}: \quad N^{\rm PU}_{\rm bkg} = \sigma_{\rm j}\mathcal{L}_{\rm int}\epsilon^{\rm EC}_{\rm trig}\left(\bar{n}_{\rm PU}\frac{\sigma_{\rm j}}{\sigma_{\rm inc}}\epsilon^{j,{\rm EC}}_{\rm fake} f^j_{\rm nt}\right) \approx 2\times10^7,$$

$$\text{MS}: \quad N^{\rm PU}_{\rm bkg} = \sigma_{\rm j}\mathcal{L}_{\rm int}\epsilon^{\rm MS}_{\rm trig}\left(\bar{n}_{\rm PU}\frac{\sigma_{\rm j}}{\sigma_{\rm inc}}\epsilon^{j,{\rm MS}}_{\rm fake} f^j_{\rm nt}\right) \approx 50, \quad (5)$$

Pile-up BKG: intrinsic resolution ~190 ps

EC (30ps) cut: Δt > 1 ns

BKG(EC-PU) ~ 1.3

MS (30ps) cut: Δt > 0.4 ns

BKG(MS-PU) ~ 0.86

The detector time resolution for MS can be downgraded to hundreds of ps

MS (200ps) cut: Δt > 1ns

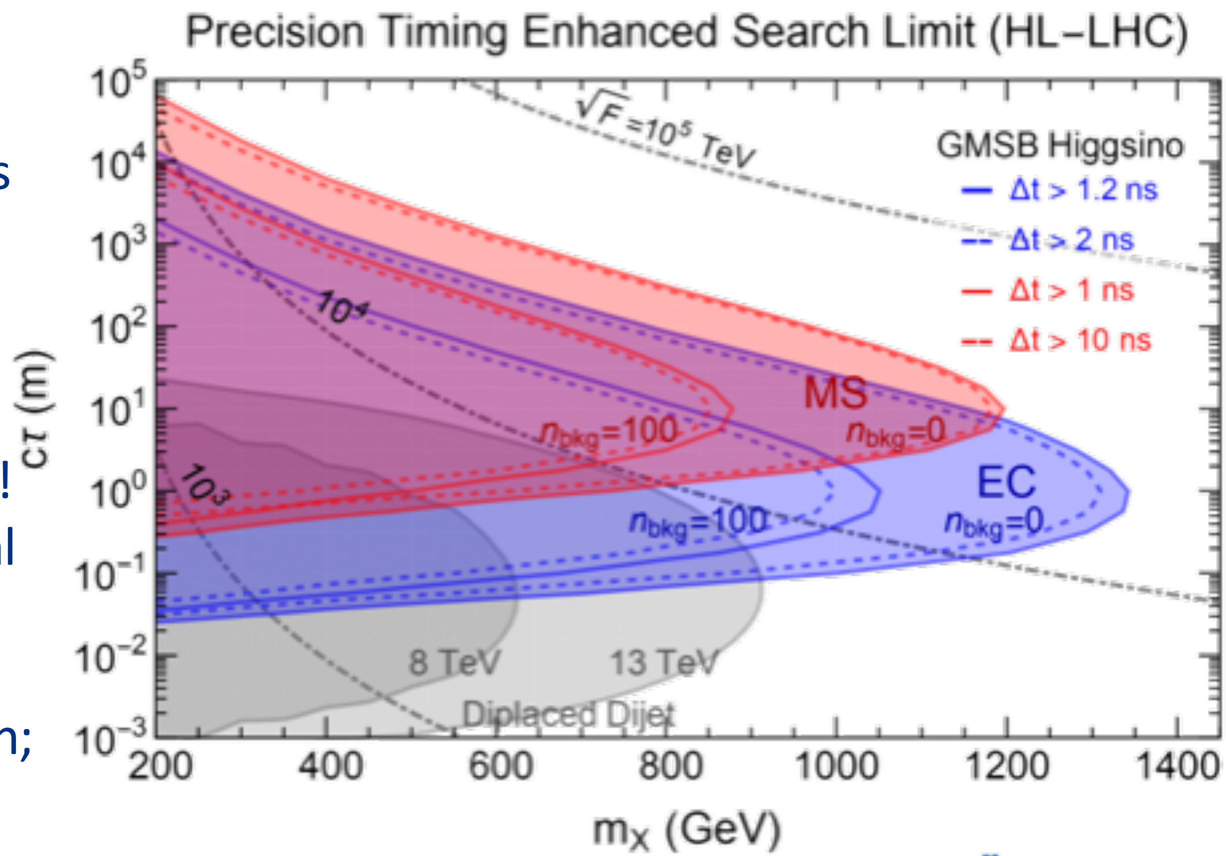
BKG(MS-PU) << 1

Late comers will be spotted easily:

	L_{T_2}	L_{T_1}	Trigger	ϵ_{trig}	ϵ_{sig}	ϵ^j_{fake}	Ref.
EC	1.17 m	0.2 m	DelayJet	0.5	0.5	10^{-3}	[12]
MS	10.6 m	4.2 m	MS RoI	0.25, 0.5	0.25	5×10^{-9}	[24]

CMS timing module
ATLAS MS LLP search
(without timing)

- EC: >0.8 ns or >1.2 ns timing cut (<25 ns always there)
- MS: 1 ns or 10 ns timing cut (0.2 ns or 2 ns resolution sufficient)
- Significant improvement!
- Little difference for signal as they are very slow
- large tolerance room if background non-gaussian;



Late comers will be spotted easily:

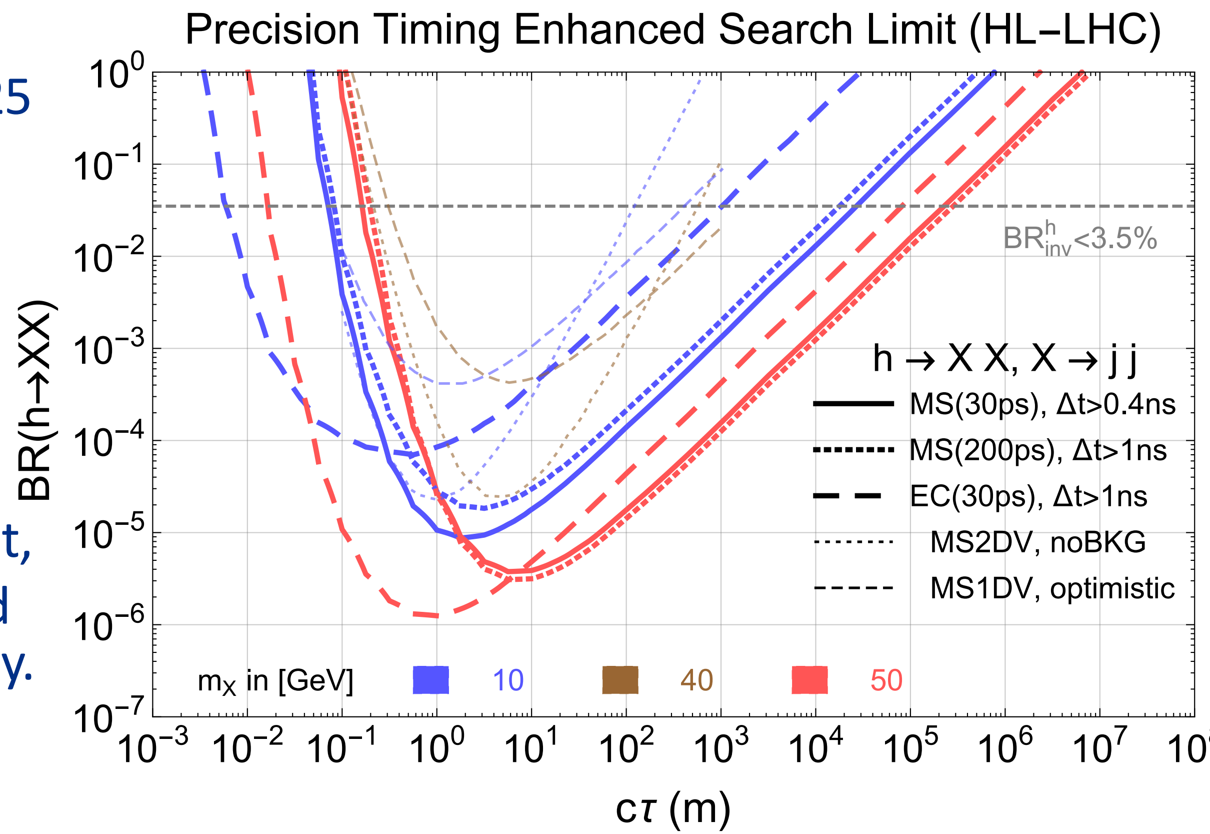
	L_{T_2}	L_{T_1}	Trigger	$\epsilon_{\rm trig}$	$\epsilon_{\rm sig}$	$\epsilon^j_{\rm fake}$	Ref.
EC	1.17 m	0.2 m	DelayJet	0.5	0.5	10^{-3}	[12]
MS	10.6 m	4.2 m	MS RoI	0.25, 0.5	0.25	5×10^{-9}	[24]

CMS timing module

ATLAS MS LLP search

(without timing)

- EC: >0.8 ns timing cut (<25 ns always there)
- MS: 0.2 ns or 1 ns timing cut (30 ps or 0.2 ns resolution sufficient)
- Significant improvement!
- 10 GeV benchmark point sensitive to the timing cut, as they are more boosted and having less time delay.



8 TeV results from C. Csaki, E. Kuflik, S. Lombardo, O. Slone, 1508.01522

13 TeV MS search projection (w.o. timing), C. Coccaro, D. Curtin, H. Lubatti, H. Russell, J. Shelton 1605.02742

Challenges (opportunities)

- Timing reducing background to 10^-10 level. Early measurement for HSCP (non-pointing photon) indicates the SM background behavior agree well with Gaussian up to 10^-6 (10^-4) level (experimental Monte Carlo went to 10^-9), where the plot ends (data insufficient); Would be an interesting SM property measurement;
- For EC search, timing layer will be there. Delayed jet (anything) trigger would require non-trivial effort to realize, low+high level with jet ROI; Once realized, could be universal boost to LLPs at the LHC!
- For MS search, a feasibility study on new timing layer options like this, balancing technology, design, cost, and physics goals would be a natural future step. As we have shown, except for the light LLP (~10 GeV), the large delay does not require 10s ps timing precision. Even (sub) nanosecond for the MS is sufficient;
- There are many more handles on the signal selection and background rejection can be used;

Summary and outlook

- LHC great detector for LLP searches, a rich program is still under development;
- Our recast study shows the broad coverage of LLP searches;
- All *traditional* LLP searches could be augmented by the timing information (re-optimization);
- New searches can capture general features of the LLP in a very robust way by exploiting their delayed feature;
- **Precision timing is a new dimension of particle physics information available for BSM searches**

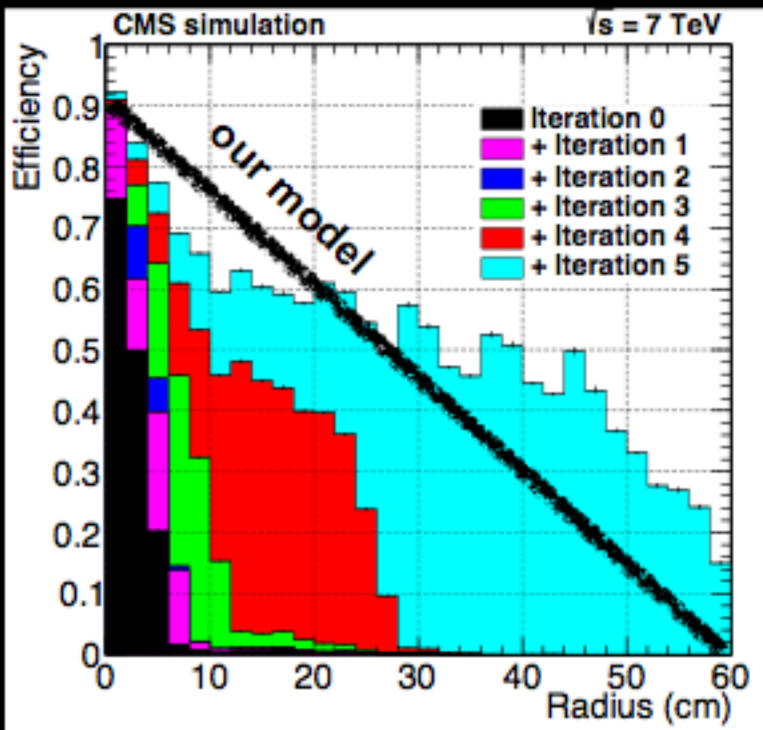
Thank you!

Backup

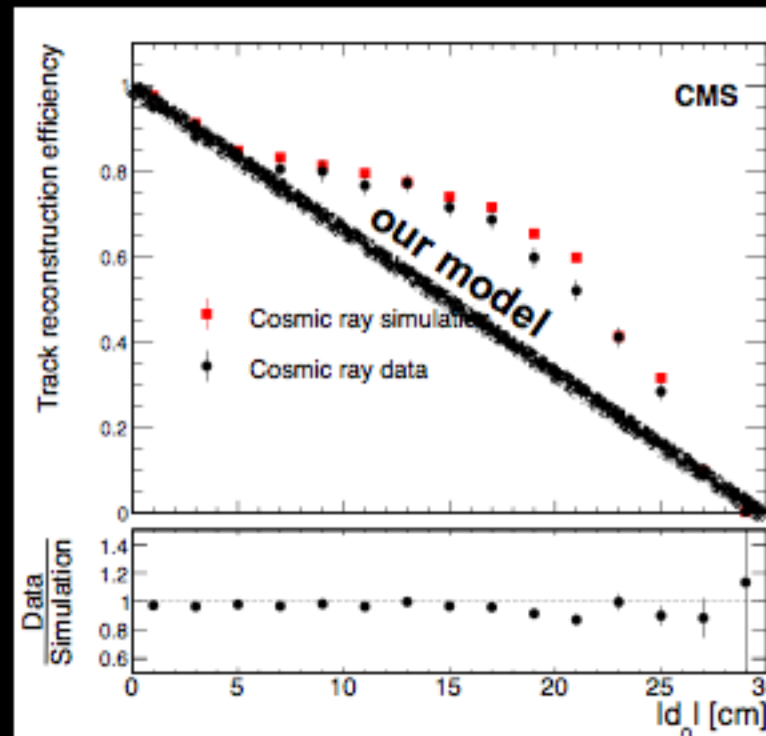
Detector Simulation Methodology

- Minimalistic
  - basic geometry, no detector granularity or energy smearing
  - perfect absorptive calorimeters
  - tracking/vertexing efficiencies with simple linear falloff models in radius, z, impact parameter
- Try to reproduce all explicitly studied models
  - employ constant fudge factors where necessary to mock up unreproducible reconstruction efficiencies
  - a (by now well-known) lesson for experimentalists: the broader the kinematic range of benchmarks tested, the better
- Even O(1) modeling errors can be acceptable
  - rapid evolution of rates near limit boundaries
  - but we try to do better where we can!

E.g., Tracking Efficiency at "CMS"



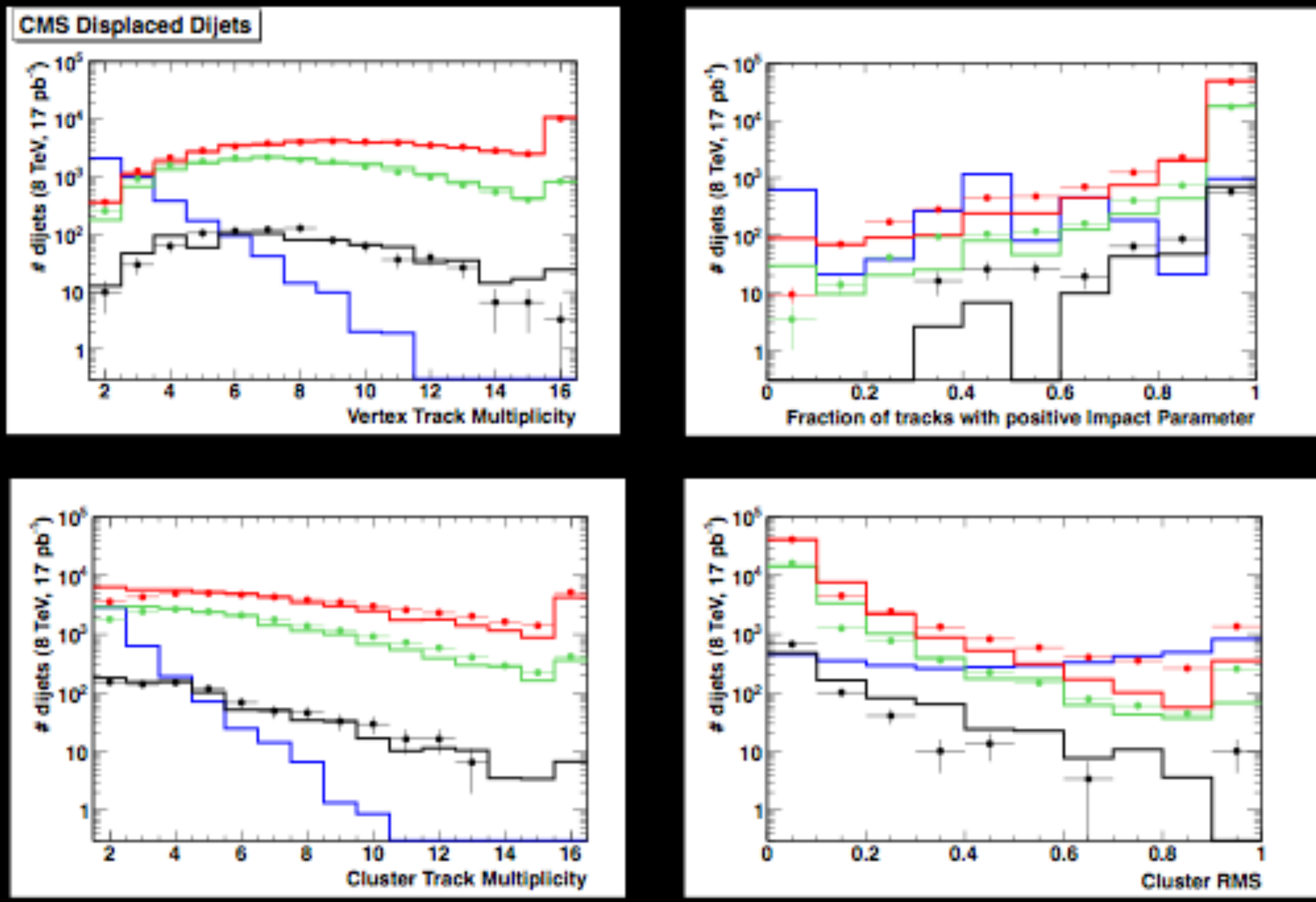
1405.6569



1411.6977

- linearly-falling inefficiency vs Lz (to 55 cm)

CMS Dijets Validation



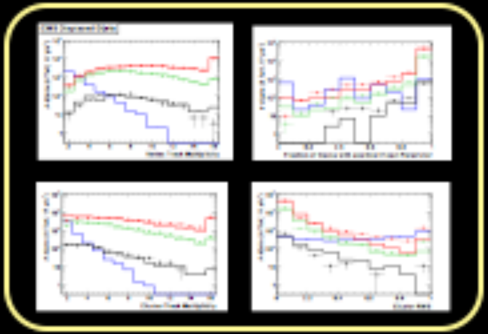
H(1000) → X(350) X(350), cτ = 35 cm

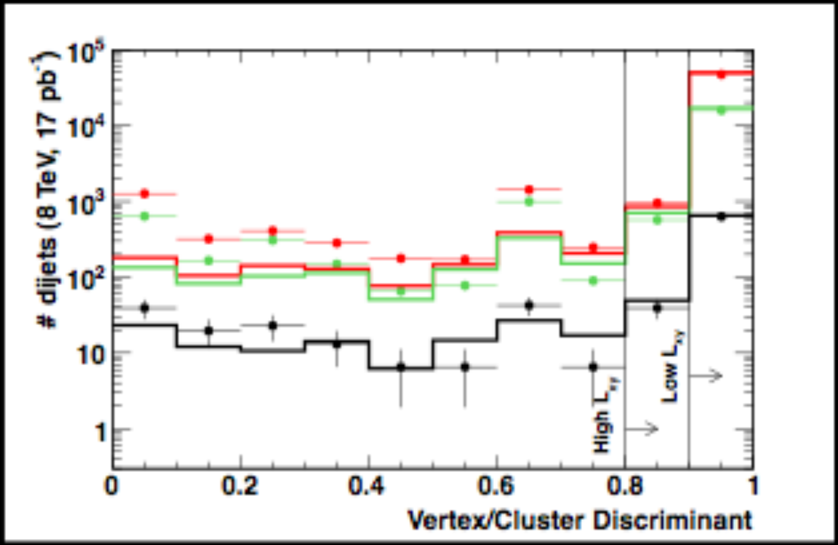
H(400) → X(150) X(150), cτ = 40 cm

H(200) → X(50) X(50), cτ = 20 cm

QCD background

CMS Dijets Validation





(Dominated by multiplicity variables)

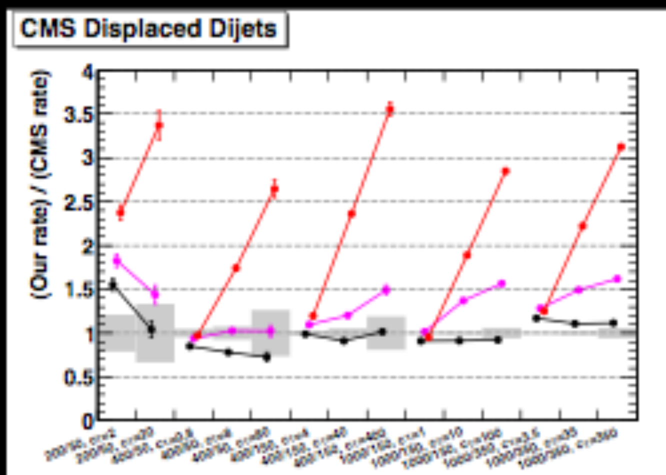
H(1000) → X(350) X(350), cτ = 35 cm

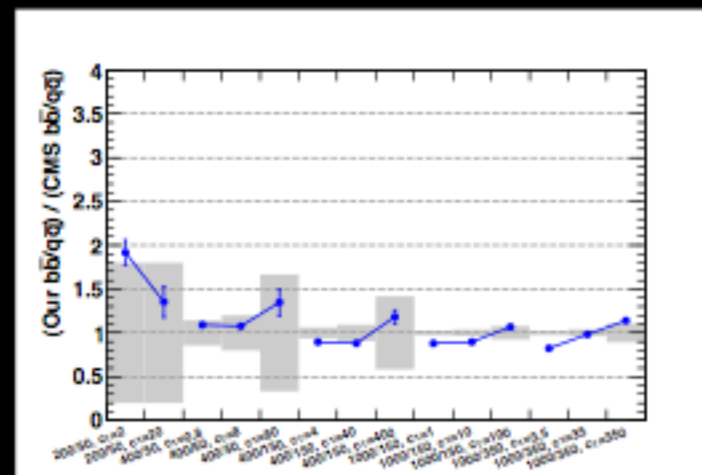
H(400) → X(150) X(150), cτ = 40 cm

H(200) → X(50) X(50), cτ = 20 cm

QCD background

Dijets Validation





Perfect tracking & vertexing

Imperfect tracking, perfect vertexing

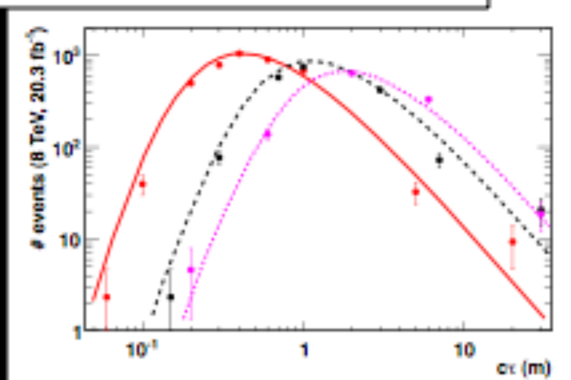
Imperfect tracking & vertexing

X → bb / X → qq

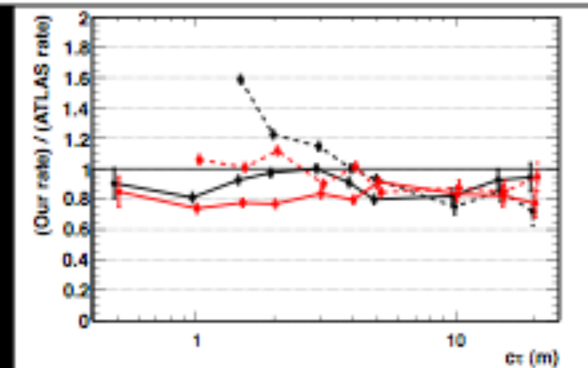
ATLAS HCAL & Muon Spectrometer Validations

* explicit max delay cut 5 ns

ATLAS low-EM jets



ATLAS muon spectrometer



* calibrated max delay 7 ns

H(126) → X(10) X(10)

H(126) → X(25) X(25)

H(140) → X(40) X(40)

H(120) → X(20) X(20) solid

H(120) → X(40) X(40) dashed

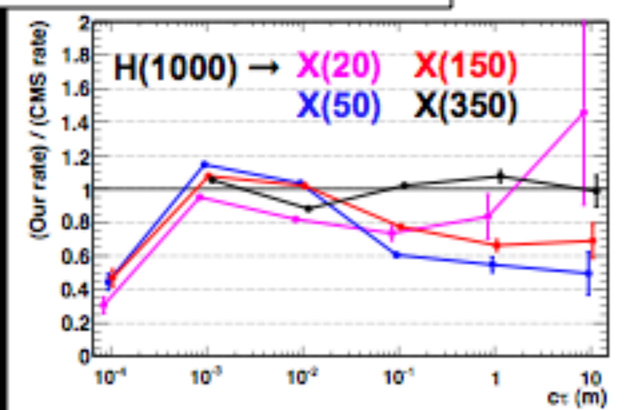
H(140) → X(20) X(20) solid

H(140) → X(40) X(40) dashed

Analyses specialized for low-mass scenarios
...We must blindly extrapolate to higher-mass SUSY models

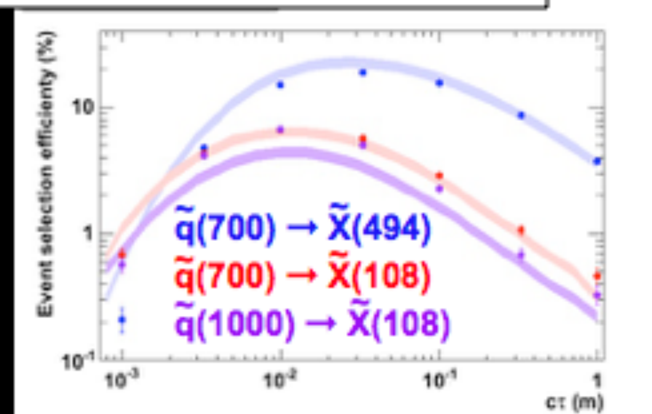
Lepton Validations

CMS dilepton



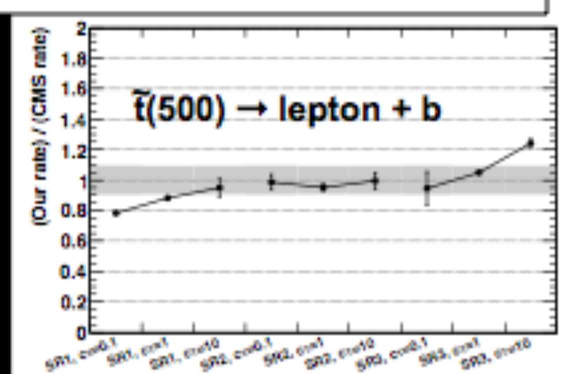
e⁺e⁻, one of several validations

ATLAS muon + tracks



LSP decay to *μqq*

CMS electron & muon



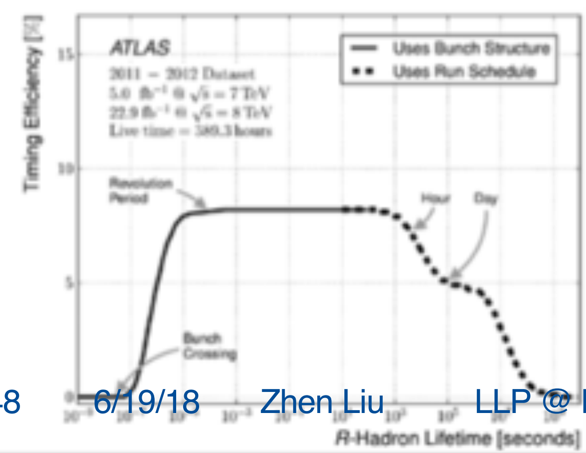
different impact pararameter regions

LLPs decaying to hadrons:

- signature could be displaced multi-track vertex
    + resolved jets (CMS, LHCb), or single boosted jet (ATLAS)
- a jet with no tracks & low EMF
    - ATLAS can trigger on this signature
- multi-track vertex in the muon system

Emerging jets

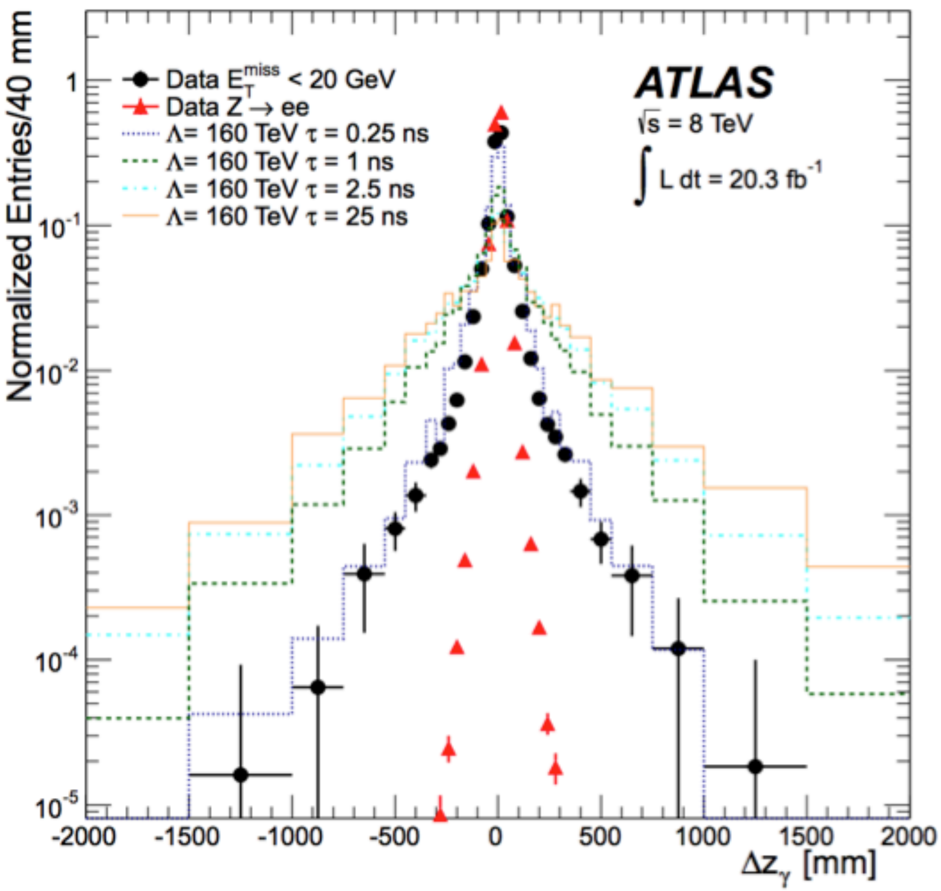
- multiple displaced vertices

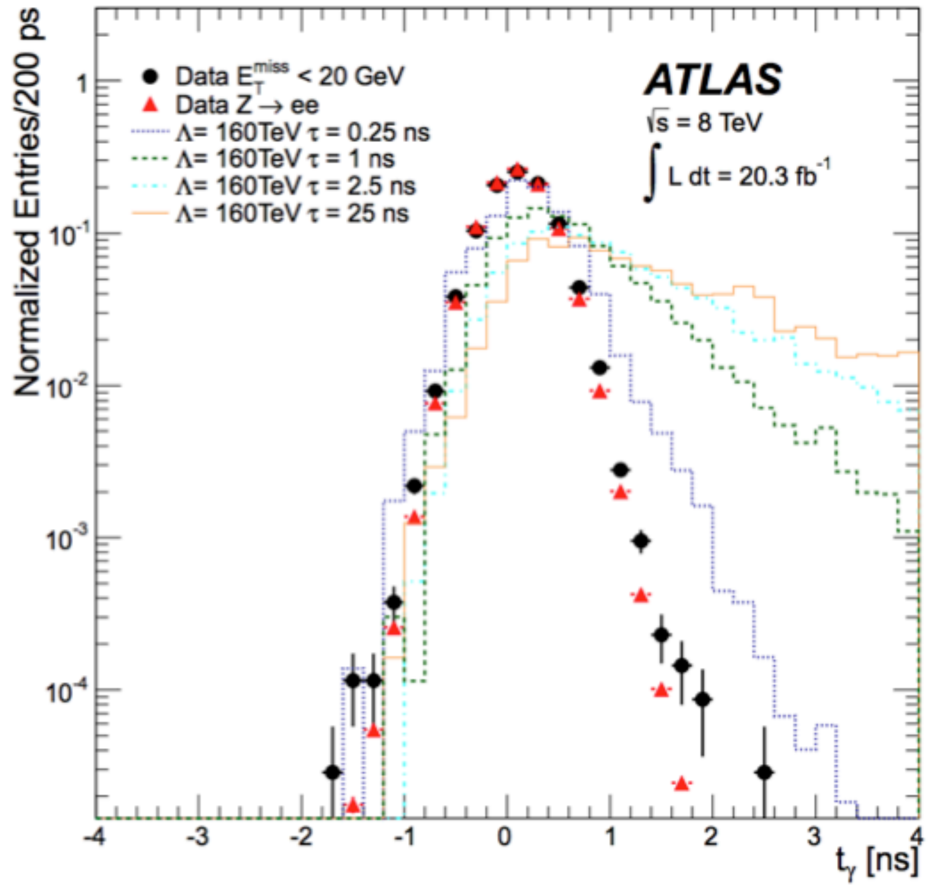


(very) late decays in the calorimeter

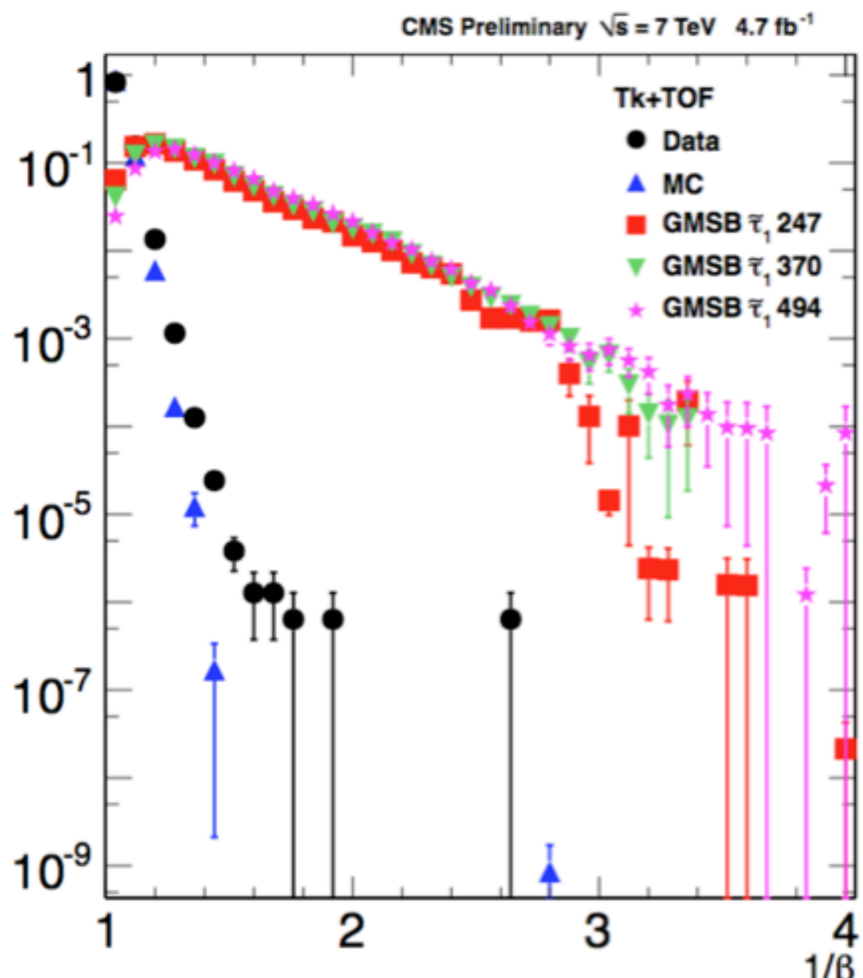
- ATLAS and CMS look for jets in empty bunch crossings (neither beam in the detector)

ATLAS non-pointing photon





CMS Heavy stable charged particle (HSCP) track+ToF



Fermilab

MS Volume

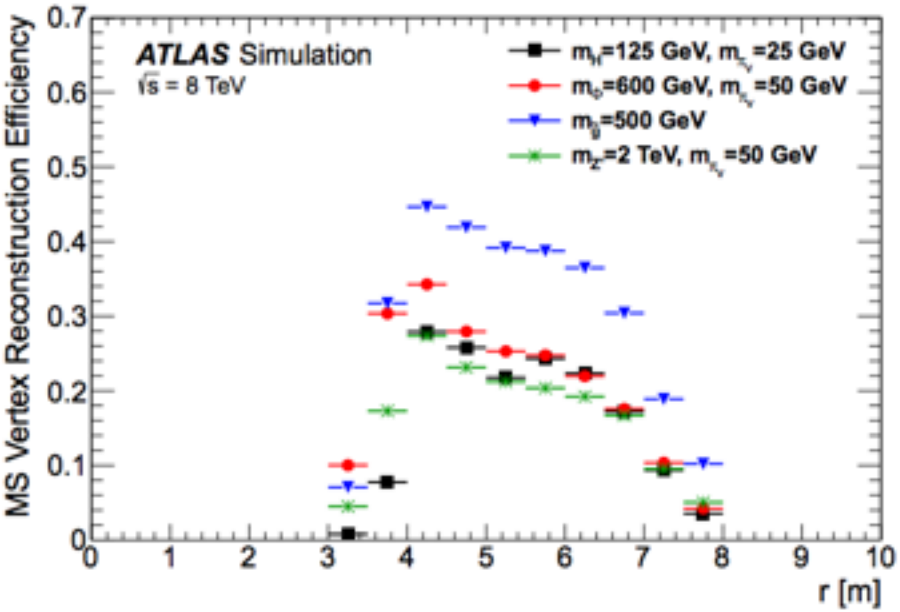


FIG. 7. Barrel MS vertex reconstruction efficiency as a function of the radial decay position of the long-lived particle for scalar boson, Stealth SUSY, and Z'benchmark samples.

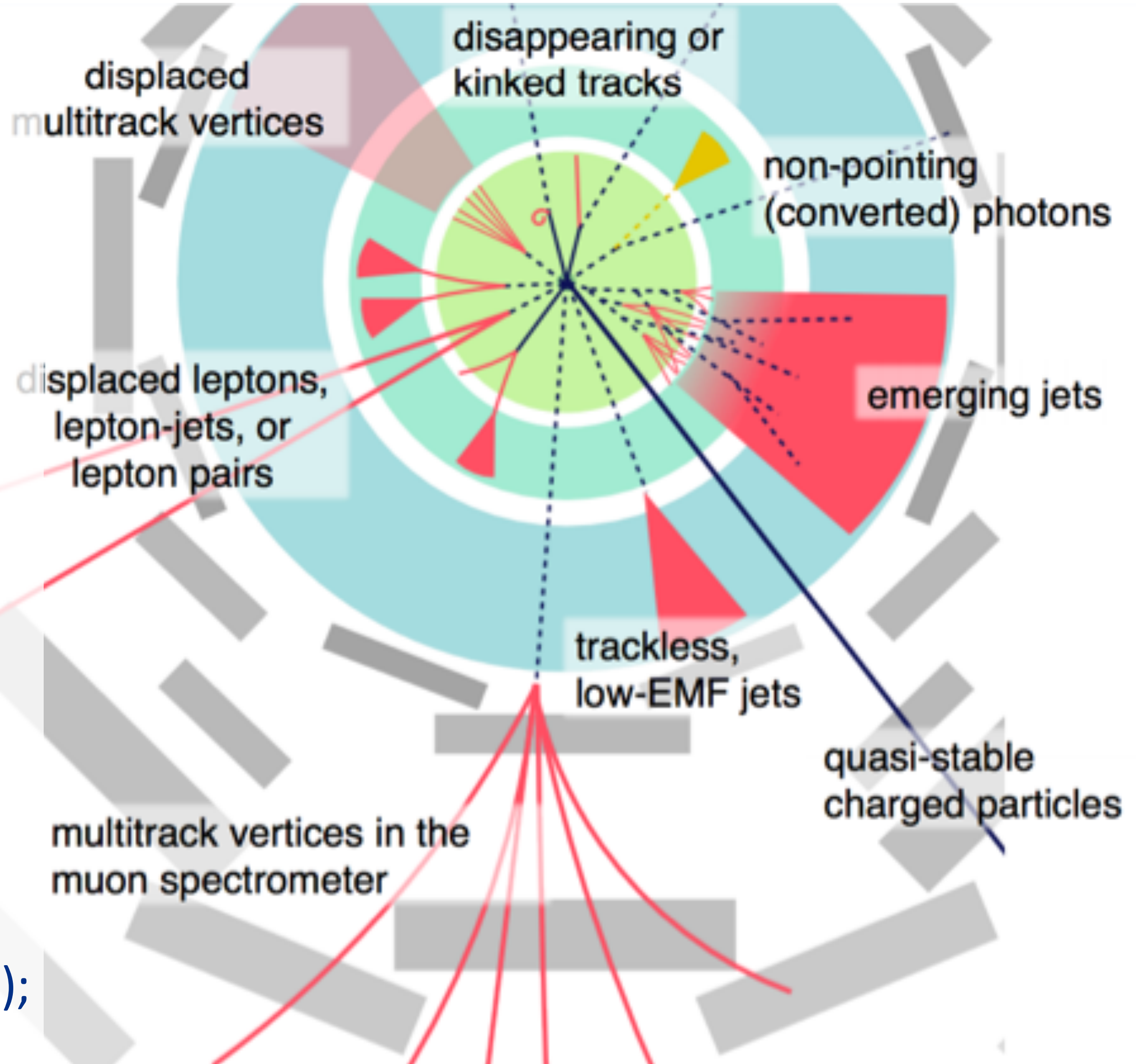
- Effective decay volume 4-7 m 4-10 m.
- New layer and upgrades might relax/extend the MS Vertexing length.
- We took the full volume in our study.
- If stick to 4-7 m, the efficiency will reduce by roughly a factor of 2.

Long-lived particles

current status and challenges also mentioned in many other talks in this workshop

These nonconventional and rich BSM signatures receives a lot of attention as:

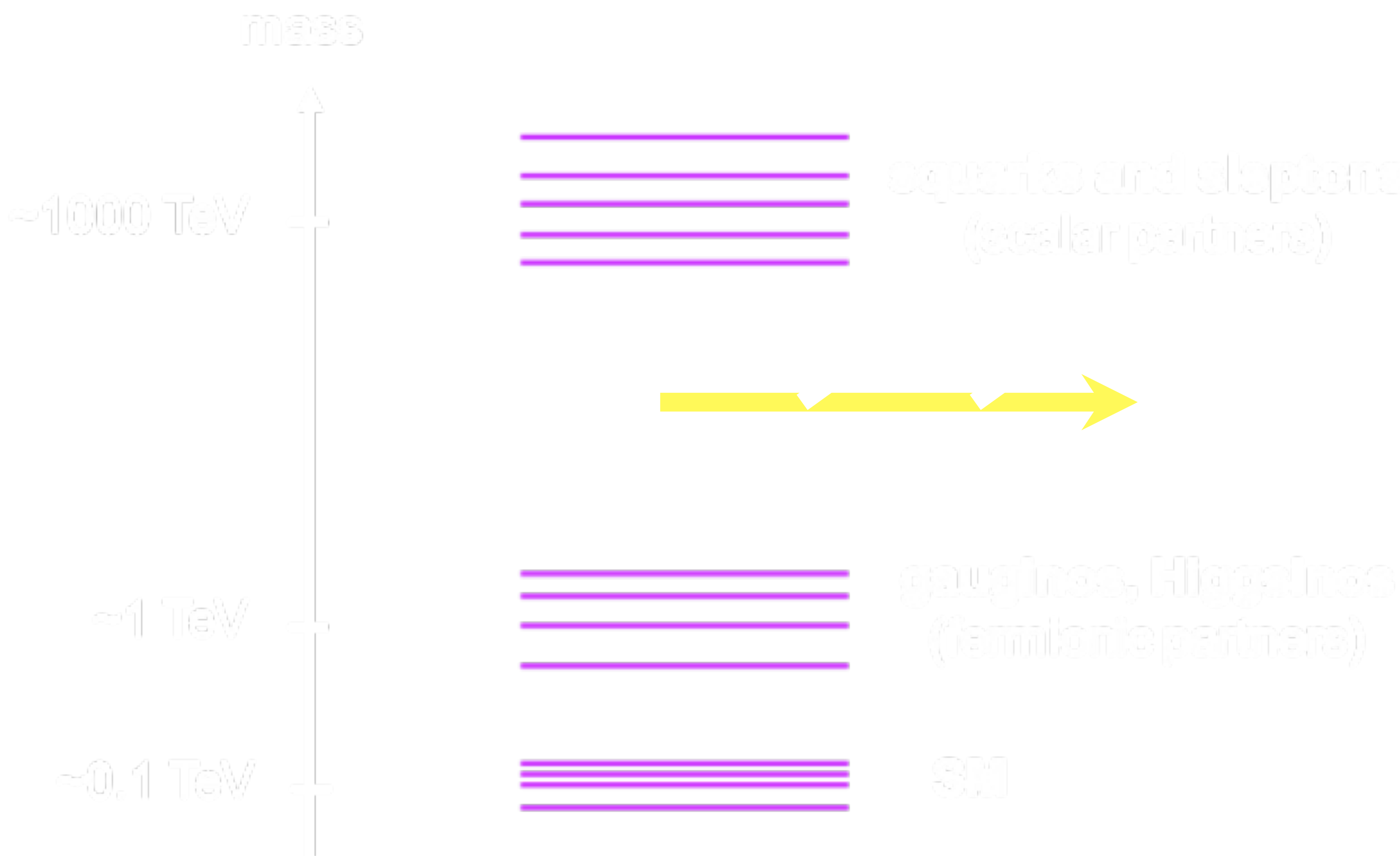
- Theoretically well motivated: SUSY (RPV, GMSB, Split, compressed, etc.), neutral naturalness, hidden valley, dark shower… etc;
- Experimentally challenging but bearing great potential for discovery:
  - New signatures could have been missed by conventional searches;
  - Low (zero) background analysis once carried out);



picture merit: Heather Russel

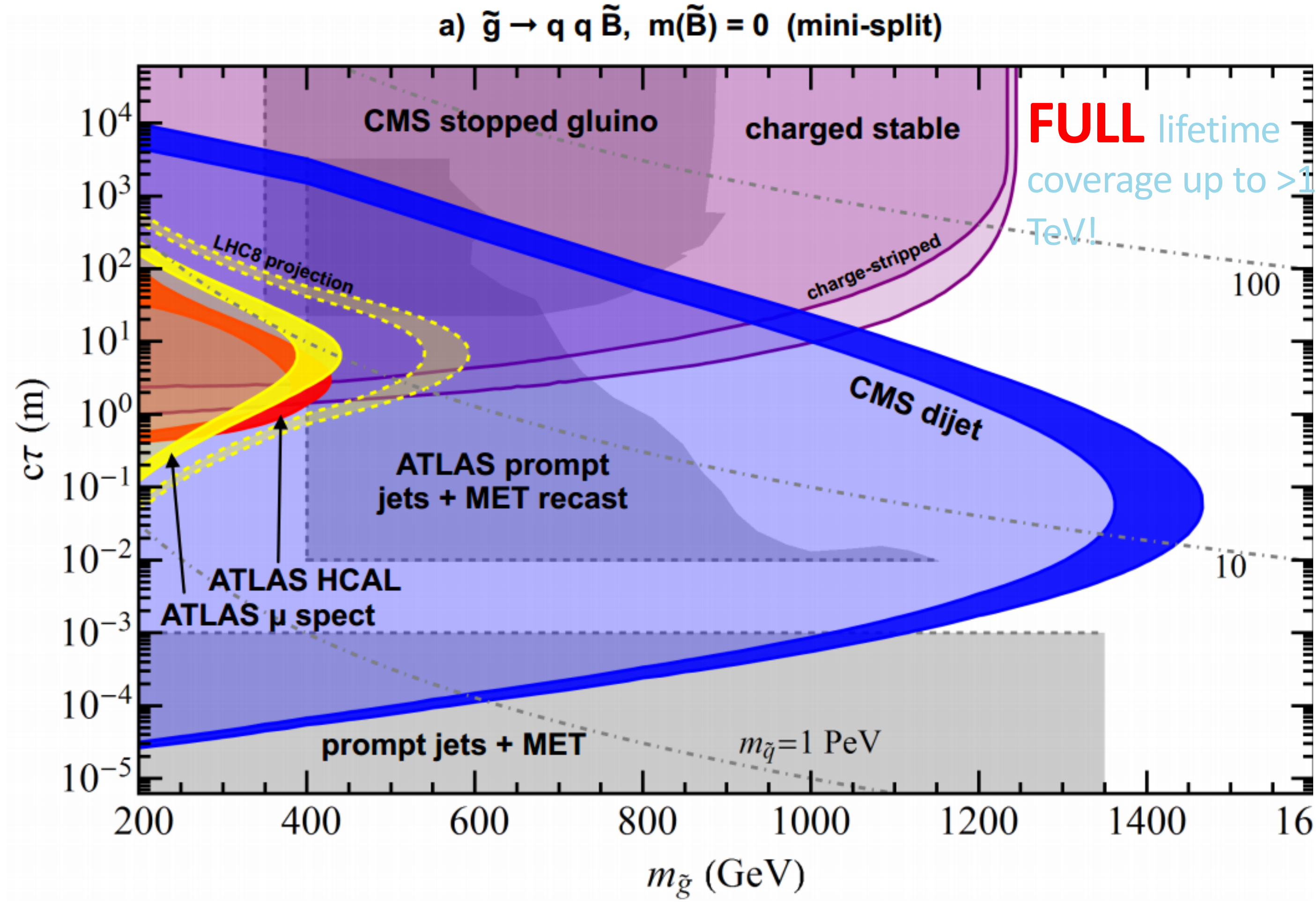
Results on Mini-split SUSY

Mini-Split Gluino → 2j + LSP



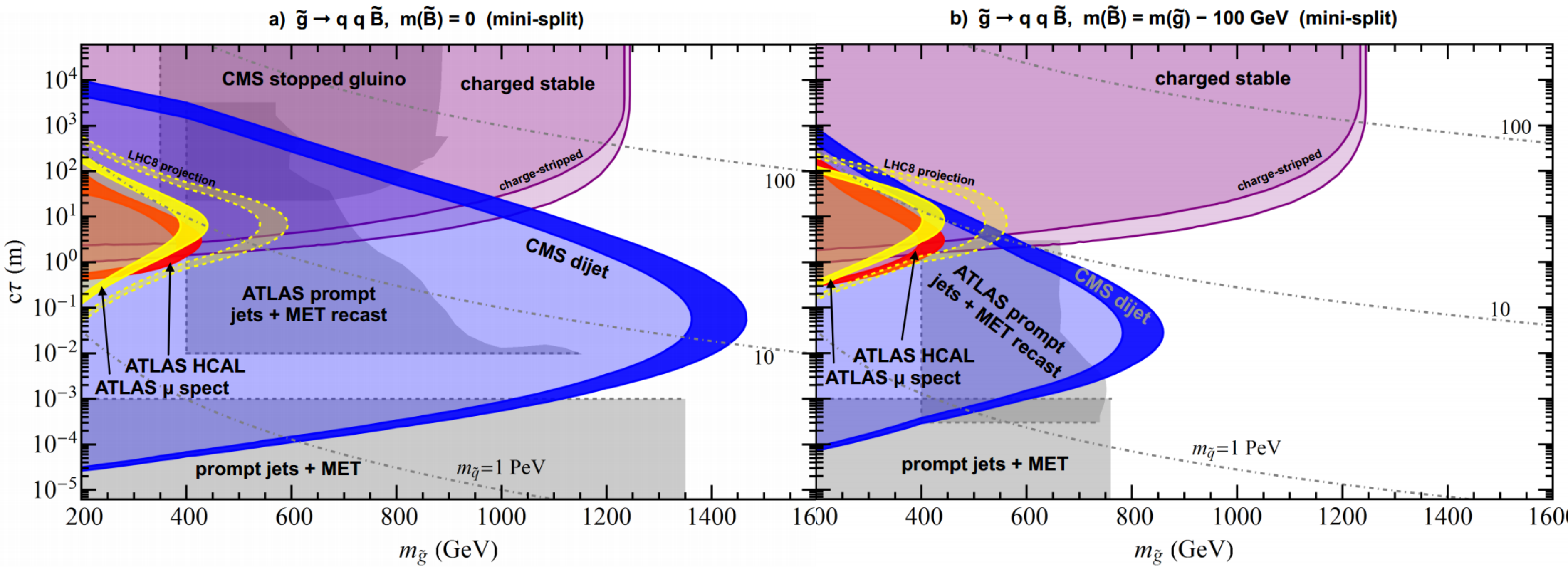
Arvanitaki, Craig, Dimopoulos, Villadoro (20

Mini-Split Gluino → 2j + LSP



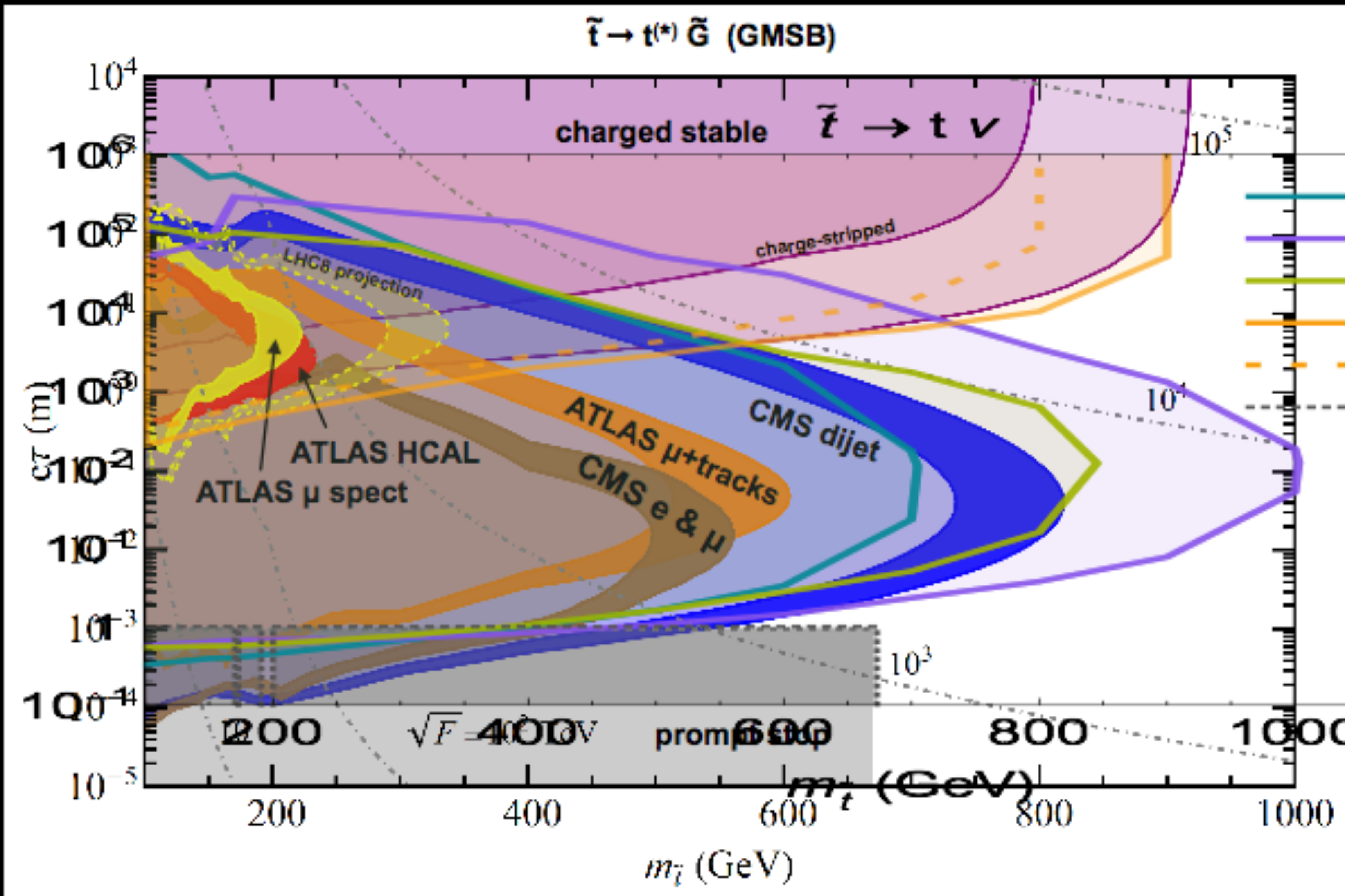
FULL lifetime coverage up to >1 TeV!

Mini-Split Gluino ➞ 2j + LSP

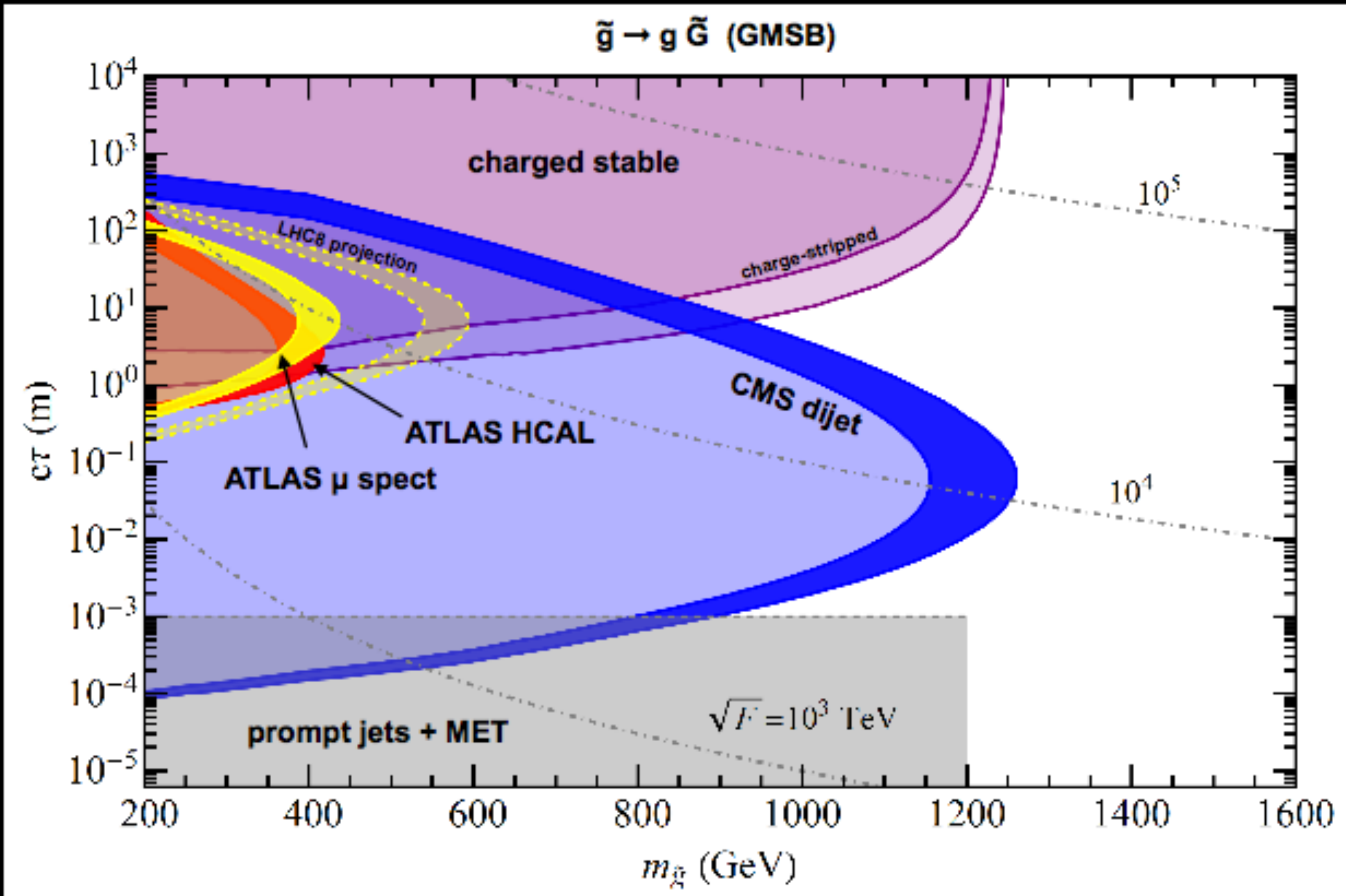


Csaki, et al (1505.00784) overlayed

GMSB Stop → Top$^{(*)}$ + Gravitino

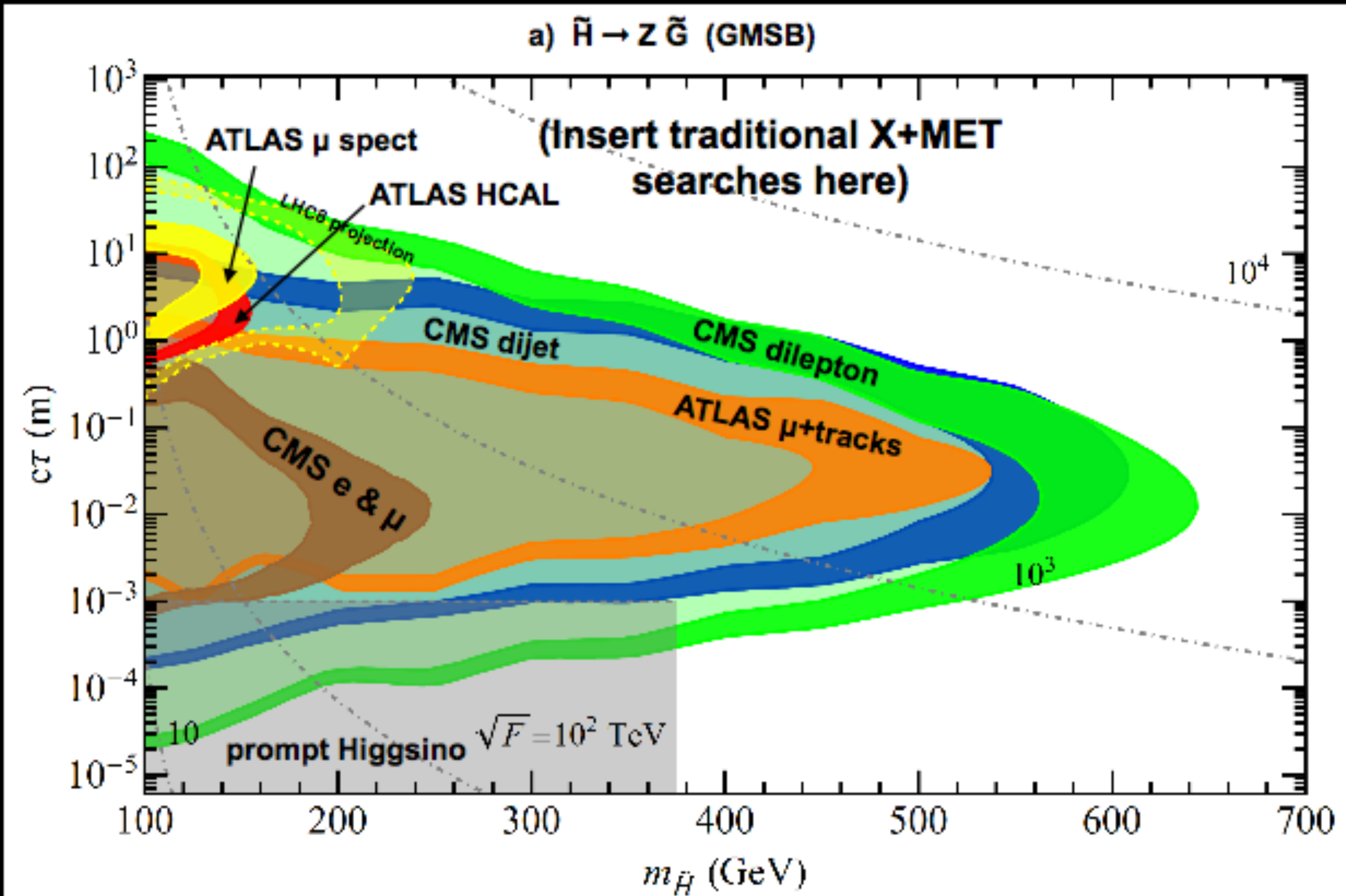


GMSB Gluino → g + Gravitino



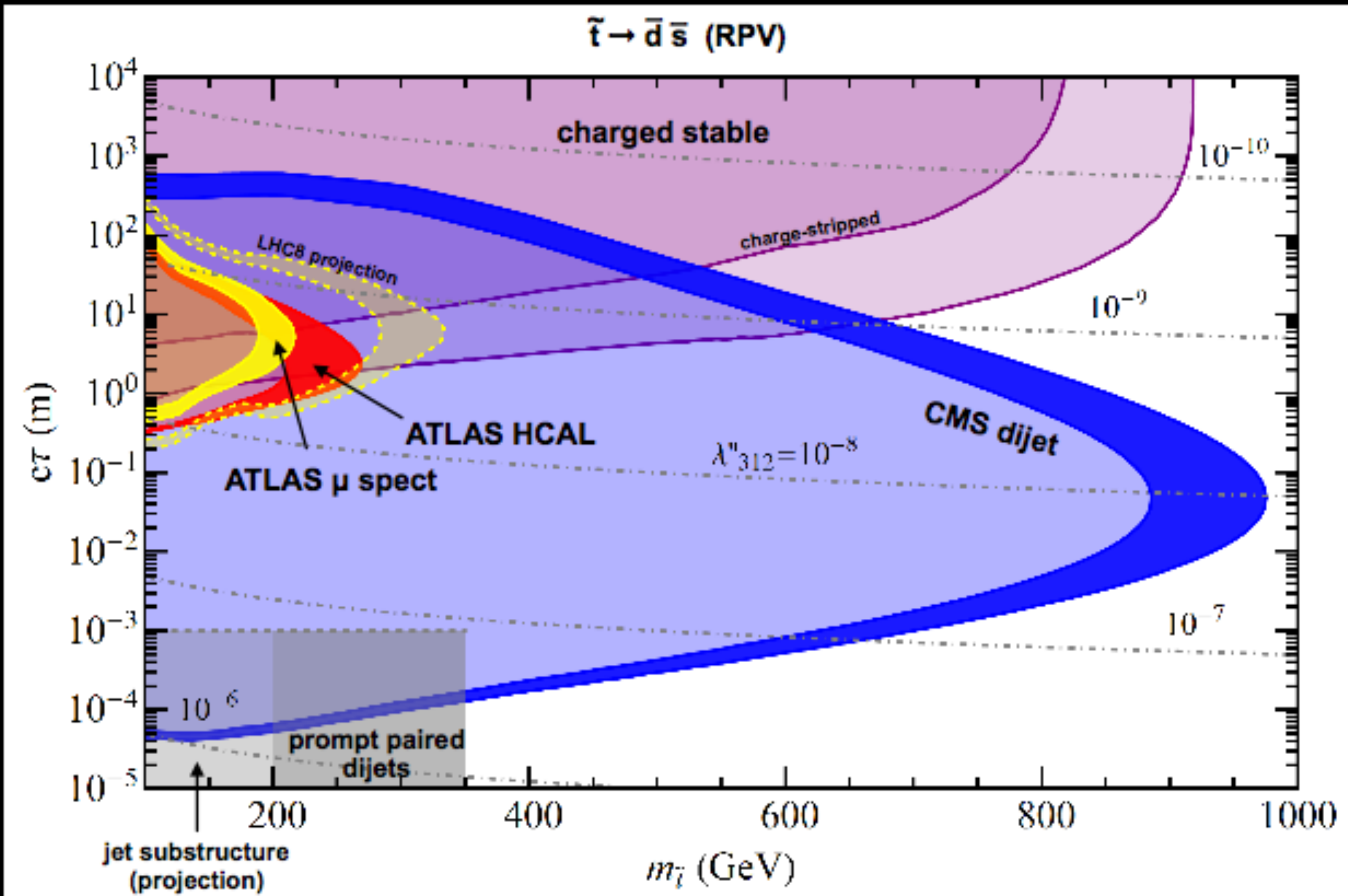
Needs to be re-evaluated with ATLAS DV+X!

GMSB Higgsino → Z + Gravitino



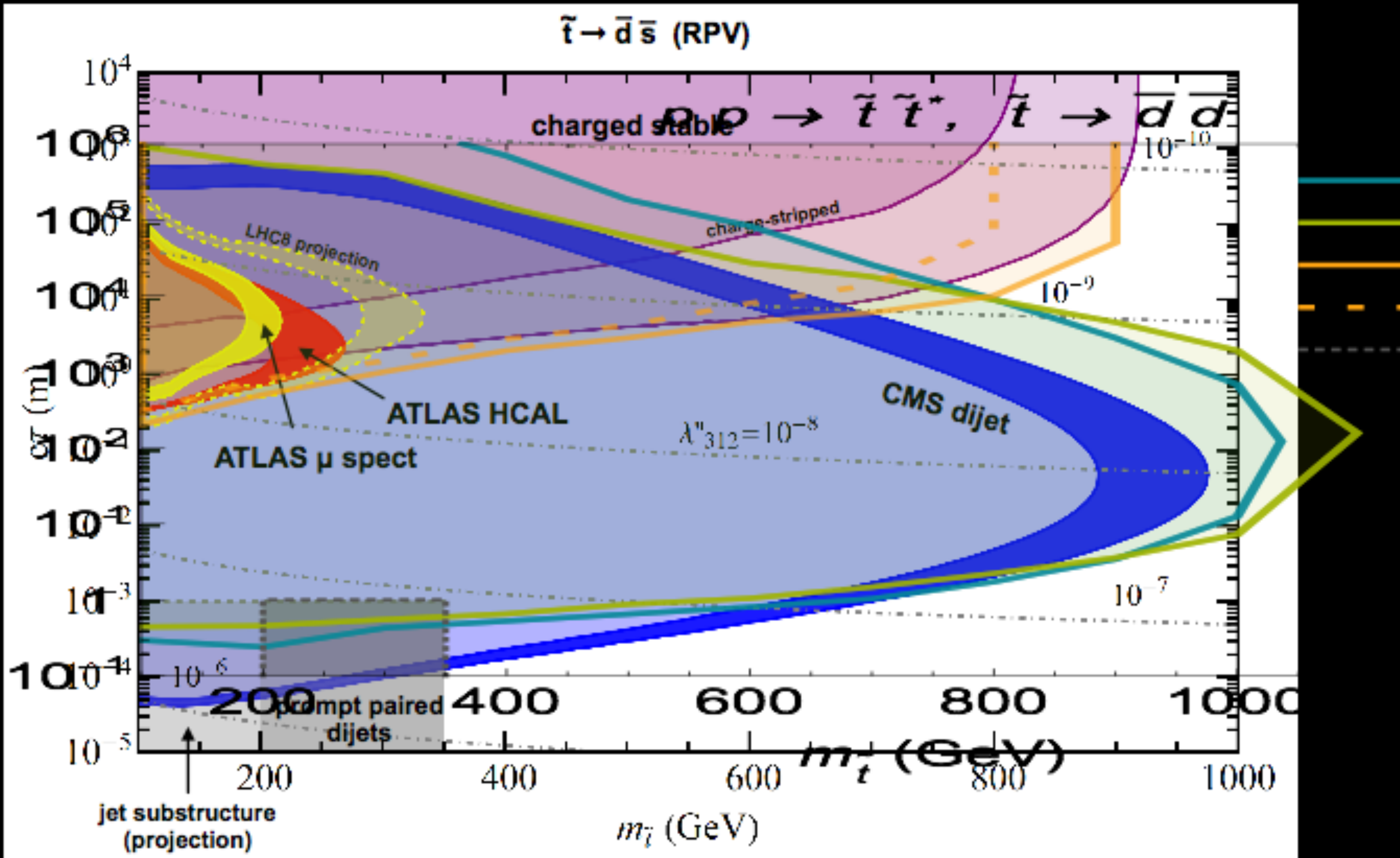
Results on RPV SUSY

RPV Stop → 2q (Light Flavors)

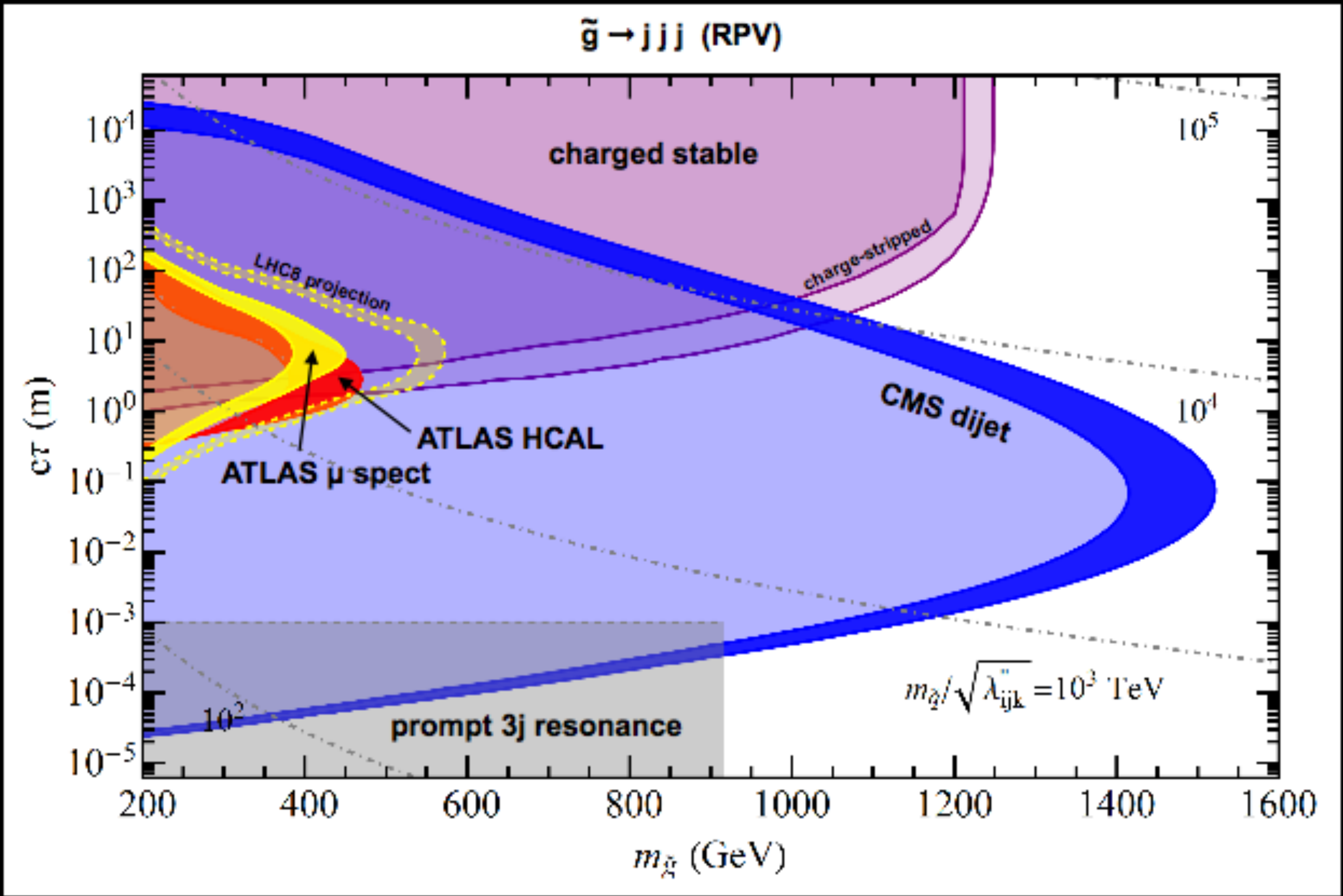


Csaki, et al (1505.00784) overlayed

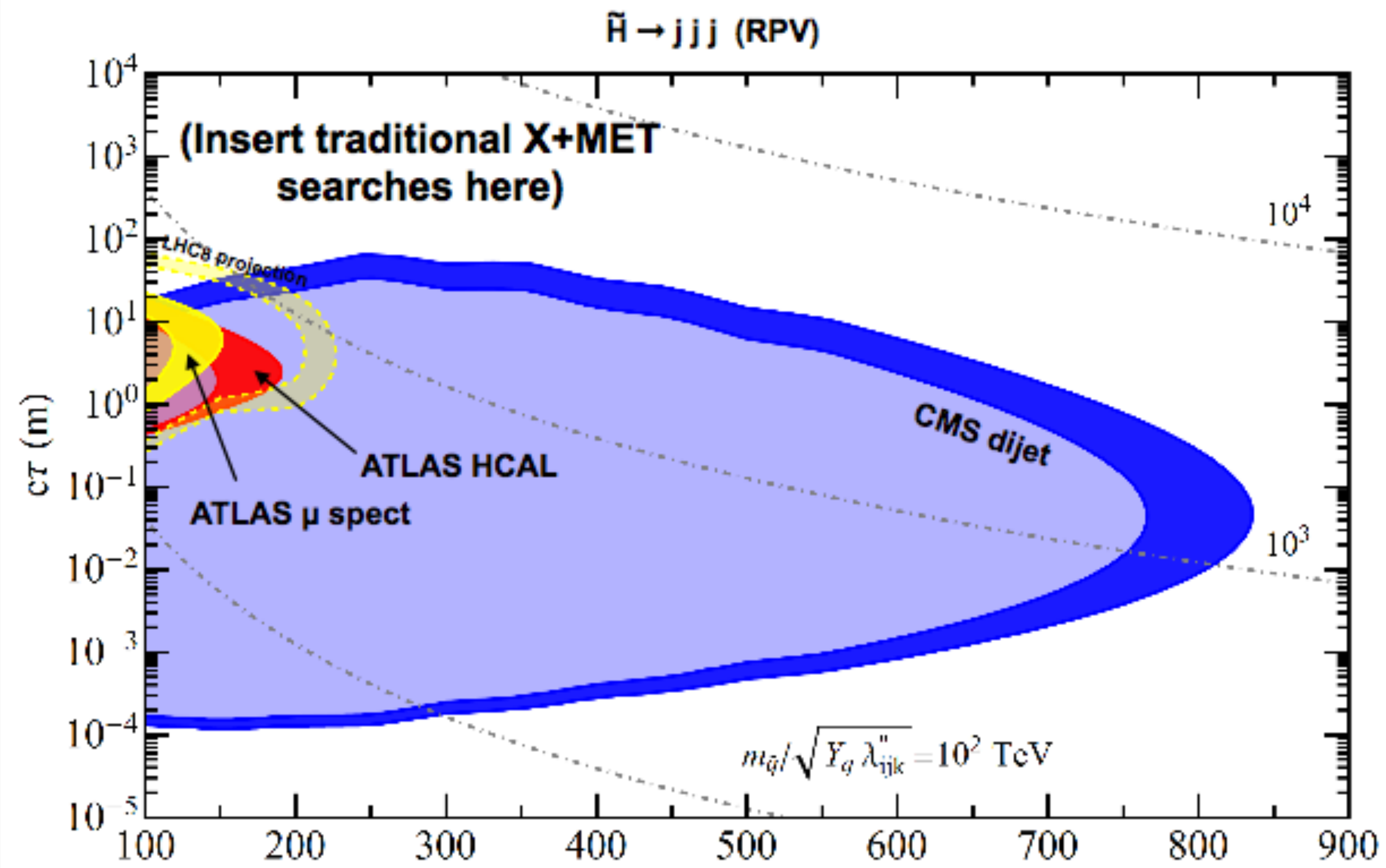
RPV Stop → 2q (Light Flavors)



RPV Gluino → 3q (Light Flavors)

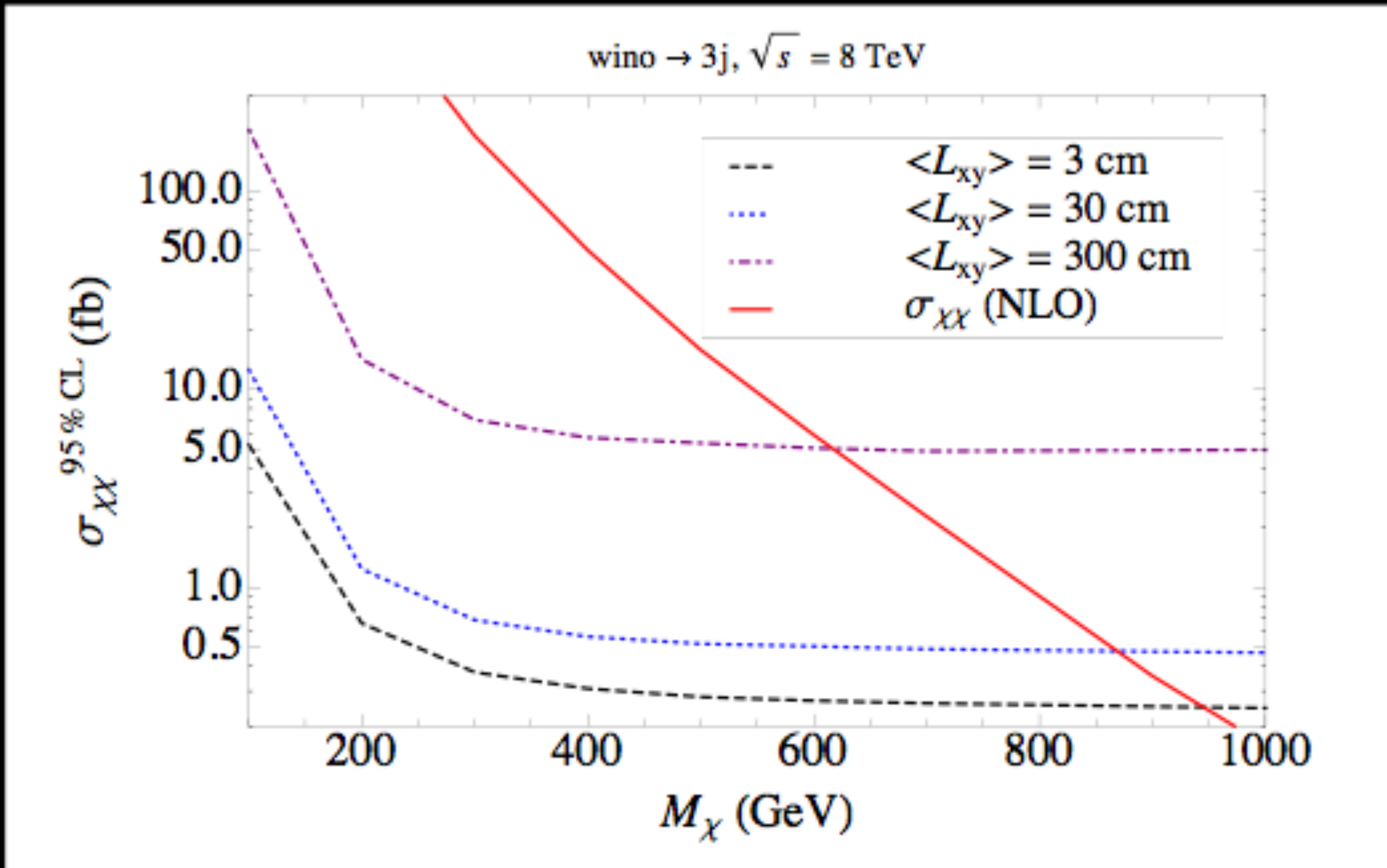


RPV Higgsino → 3q (Light Flavors)



* No prompt limits

RPV Wino → 3q (Light Flavors)



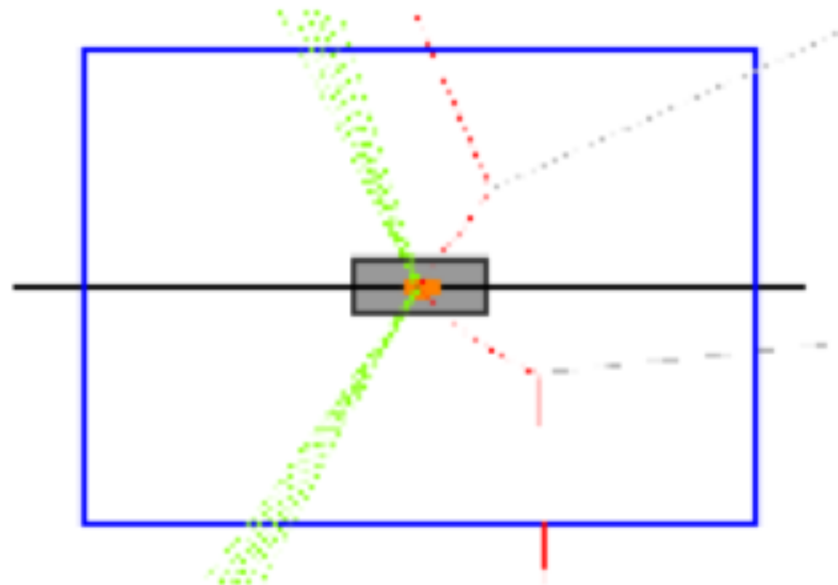
Cui & Shuve (1409.6729)

Leptonic decays

Displaced Leptons in Prompt Searches

Prompt lepton-based searches:

- Quality criteria drop displaced electrons
- Displaced muons veto events (cosmics)
- Vetoes range from 50 μm–1 mm



Prompt jets+$\not{E}_T$ searches:

- Veto events with leptons
- Definition not always transparent

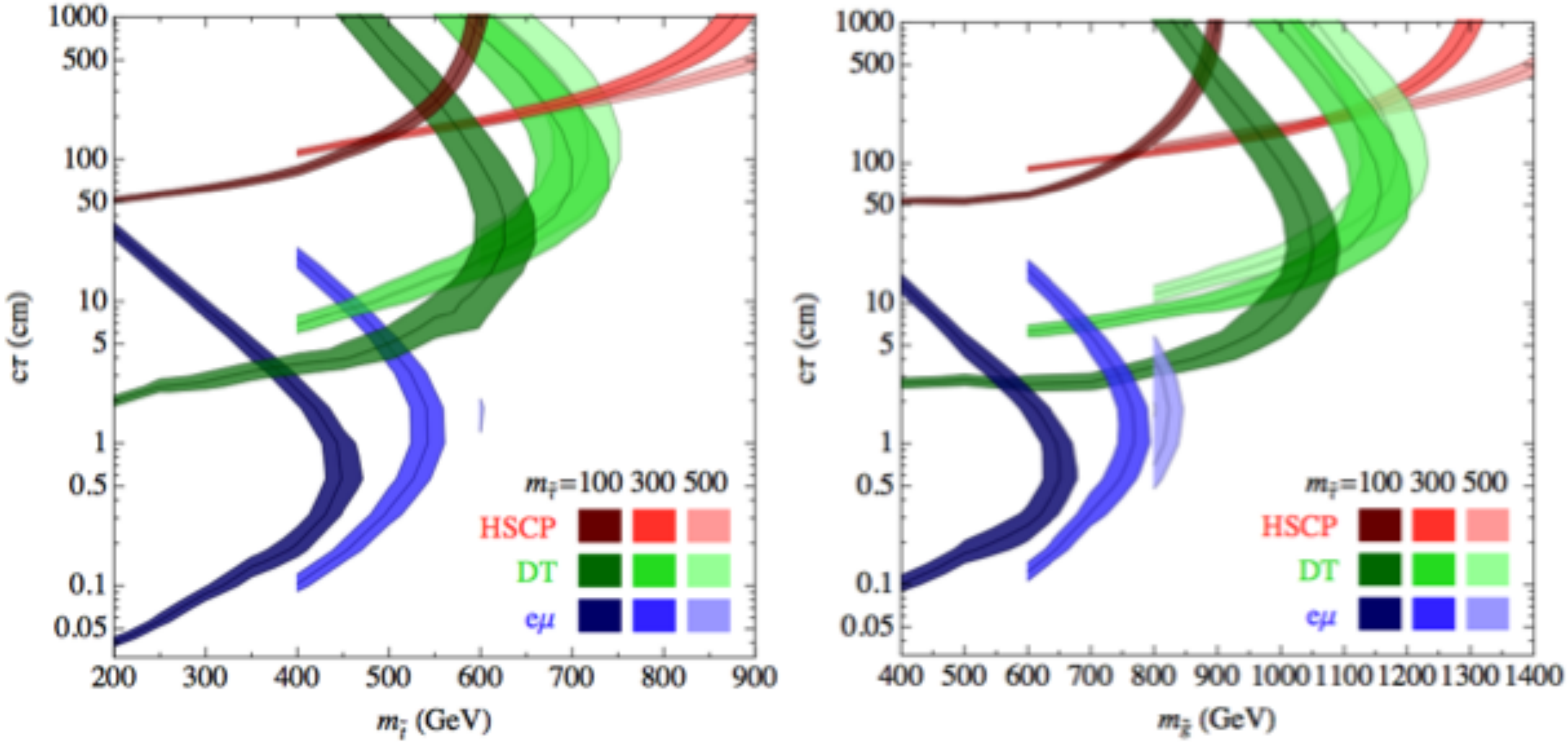
Very dangerous region!

$$pp \to \tilde{\ell}^+\tilde{\ell}^- + X \to \{\text{displaced muons}\} + X$$

lives in a prompt search blind spot!

Displaced electrons and taus $\Rightarrow$ reduced efficiency

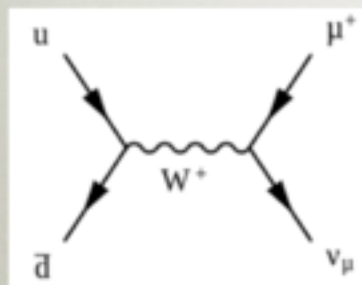
Displaced Leptons



arXiv:1601.01326

- Why are SM particle lifetimes long?
- *Example 1: charged pion*

$$\pi^+ \to \mu^+ \nu_\mu$$

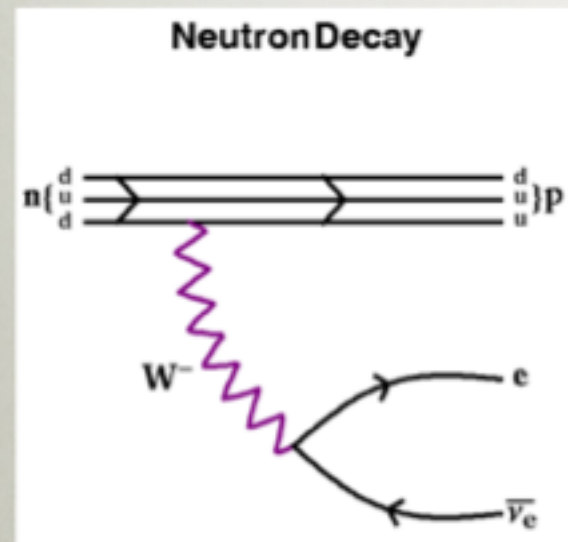


- Quark flavour conserved by all but weak interactions
- Decay highly off-shell:

$$\Gamma_{\pi^+} \sim g_W^2 \left(\frac{M_\pi}{M_W}\right)^4 M_\pi$$

See M. Strassler, various talks;
S. Knapen, LBL ATLAS trigger workshop

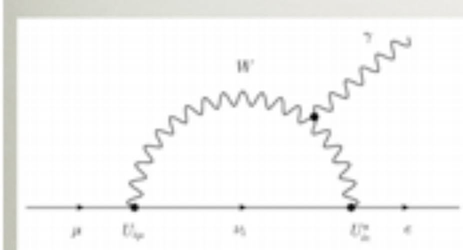
- Why are SM particle lifetimes long?
- *Example 2: neutron*



- Isospin ensures that proton and neutron are nearly degenerate
- Decay highly off-shell:

$$\Gamma_{\pi^+} \sim g_W^2 \left(\frac{M_n - M_p}{M_W}\right)^4 (M_n - M_p)$$

- *Example 3: flavour-changing neutral currents*



- Lepton flavour only violated by tiny neutrino Yukawa couplings/ neutrino masses

$$\mathrm{Br}(\mu \to e\gamma) \sim 10^{-54}$$

- SM particle lifetimes can be long if an **approximate symmetry** makes the particle stable
  - Typically has to do with "weakness" of weak interactions
  - This in turn arises from hierarchies of scale such as

$$\Lambda_{\mathrm{QCD}} \ll M_W$$

- Electroweak symmetry can lead to mass degeneracies, which suppress decay rates
- Small symmetry-breaking parameters can suppress decay rates

- **Direct Pair Production (DPP):** Here the LLP is dominantly pair-produced non-resonantly from SM initial states. This is most straightforwardly obtained when the LLP is charged under a SM gauge interaction. In this case, an irreducible production cross section is then specified by the LLP gauge charge and mass. DPP can also occur in the presence of a (heavy) t-channel mediator (e.g., an initial quark-antiquark pair may exchange a virtual squark to pair produce bino-like neutralinos); in this case the production cross section is a free parameter.

- **Heavy parent (HP):** In this case the LLP can be produced in the decay of a heavy parent particle that is itself pair produced from the pp initial state. The production cross section is essentially a free parameter, and is indirectly specified by the gauge charges and masses of the heavy parent particles. Heavy parent production gives very different kinematics for the LLP than direct pair production production, and will often produce additional prompt accompanying objects in the rapid cascade decays of the parents.

- **Higgs (HIG):** The LLP is produced through its couplings to the SM-like Higgs boson. This case has an interesting interplay of possible production modes. The dominant production is via gluon fusion, which features no associated objects beyond initial state radiation (ISR); owing to its role in electroweak symmetry breaking, however, the Higgs has associated production modes (VBF, VH), each with its own characteristic features. The best prospects are for LLP masses below $m_h/2$, in which case the LLPs can be produced on-shell in SM-like Higgs boson decays. LLPs with heavier masses can still be produced via an off-shell SM-like Higgs, albeit at lower rates. The LLP can be pair produced or singly produced through the Higgs portal depending on the model, and may also be produced in conjunction with missing energy. The cross section (or, alternatively, the Higgs branching fraction into the LLP) is a free parameter of the model.

- **Heavy resonance (ZP):** Here the LLP is produced in the decay of an on-shell resonance, such as a heavy Z' gauge boson initiated by $q\bar{q}$ initial state, or alternatively a heavy scalar[3], Φ. Note that production via an off-shell resonance is kinematically similar to the direct production (DPP) above. As with HIG, the LLP can be pair-produced or singly-produced (potentially in association with missing transverse momentum). Here, ISR is the dominant source of accompanying prompt objects.

- **Charged current (CC):** In models with weak-scale right-handed neutrinos, the LLP can be produced in the leptonic decays of W/W'. Single production is favored. Prompt charged leptons from the charged-current interaction are typical prompt objects accompanying the LLP.

Lessons from SUSY:

- Production typically through new particles charged under SM gauge interactions (gluinos, stops, Higgsinos, etc.)
    - Some new, **heavy** particles in spectrum
    - Can have prompt production of jets, leptons, MET, …
    - Often LLP pairs
- LLP decays give jets, leptons, MET, or could be **stable & charged**
- Sometimes spectra are compressed, so there is still benefit in looking at searches for softer objects

The Higgs Portal

- Can have variety of signatures based on whether pure-glue or quarks
- Different, long lifetimes for each type of hidden-sector particle
  - Scalar states can mix with SM Higgs, decay to bb, taus, etc
  - Vector mesons can mix with SM photon, decay to leptons
  - Some could be absolutely stable (giving rise to MET)
- Can also have mix of all of the above

*** see Matt's talk; also dark showers breakout session! ***

e.g., Strassler, Zurek 2006; Han *et al.*, 2007; Juknevich, Melnikov, Strassler, 2009; Schwaller, Stolarski, Weiler 2015; Cohen, Lisanti, Lou 2015; Pierce *et al.*, 2017; ….

Long-lived SM