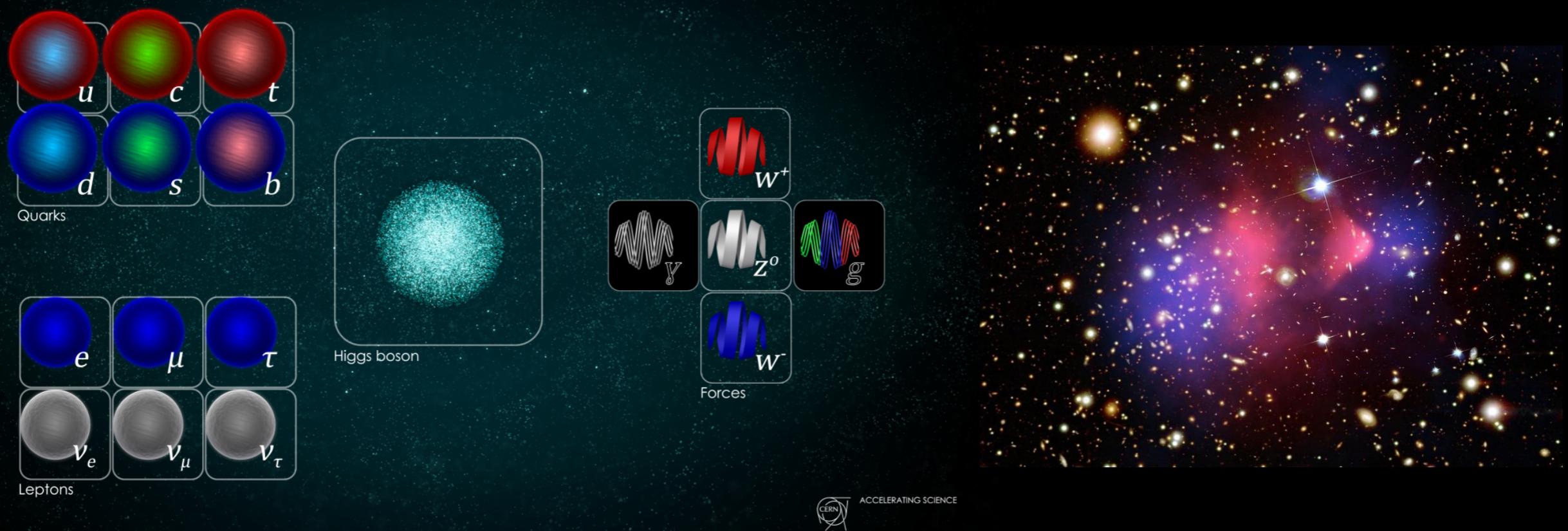
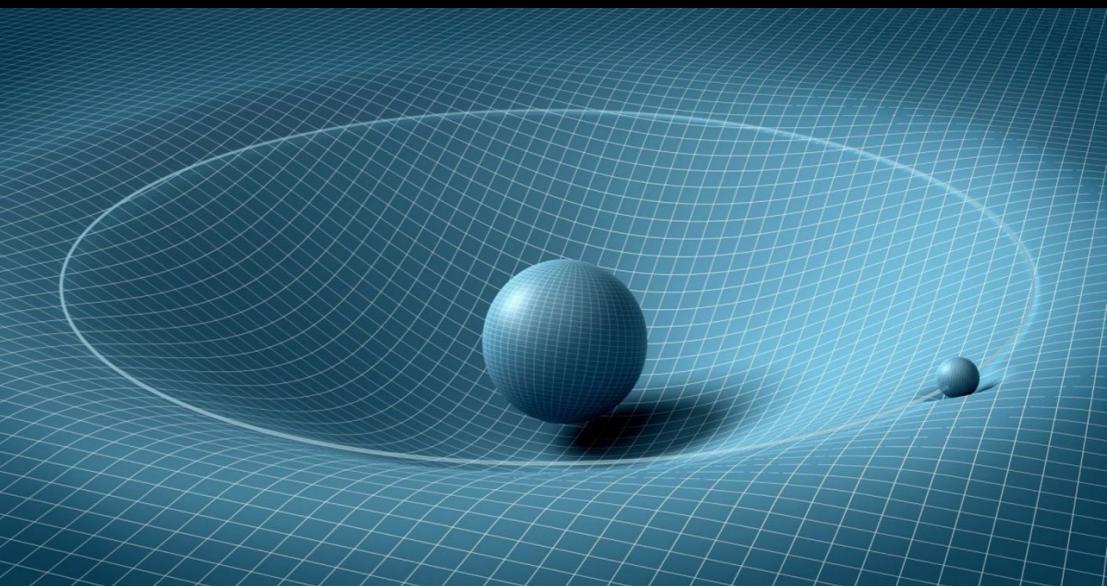


An Overview of Long-Lived Particle Searches at the LHC

Zach Flowers
KU PALOOZA
February 25th, 2021

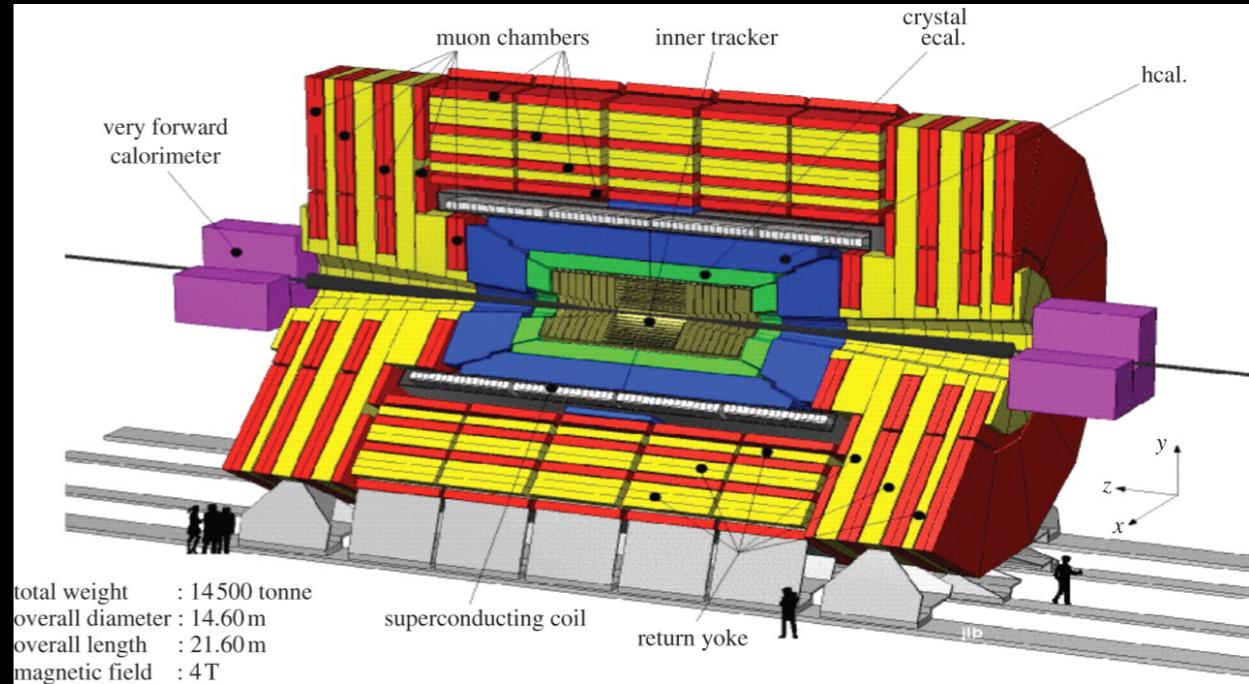
Standard Model

- Standard model has been rigorously tested and works extremely well for describing interactions at small scales
- However the SM is not a “theory of everything”
 - Issues with things such as gravity & Dark Matter

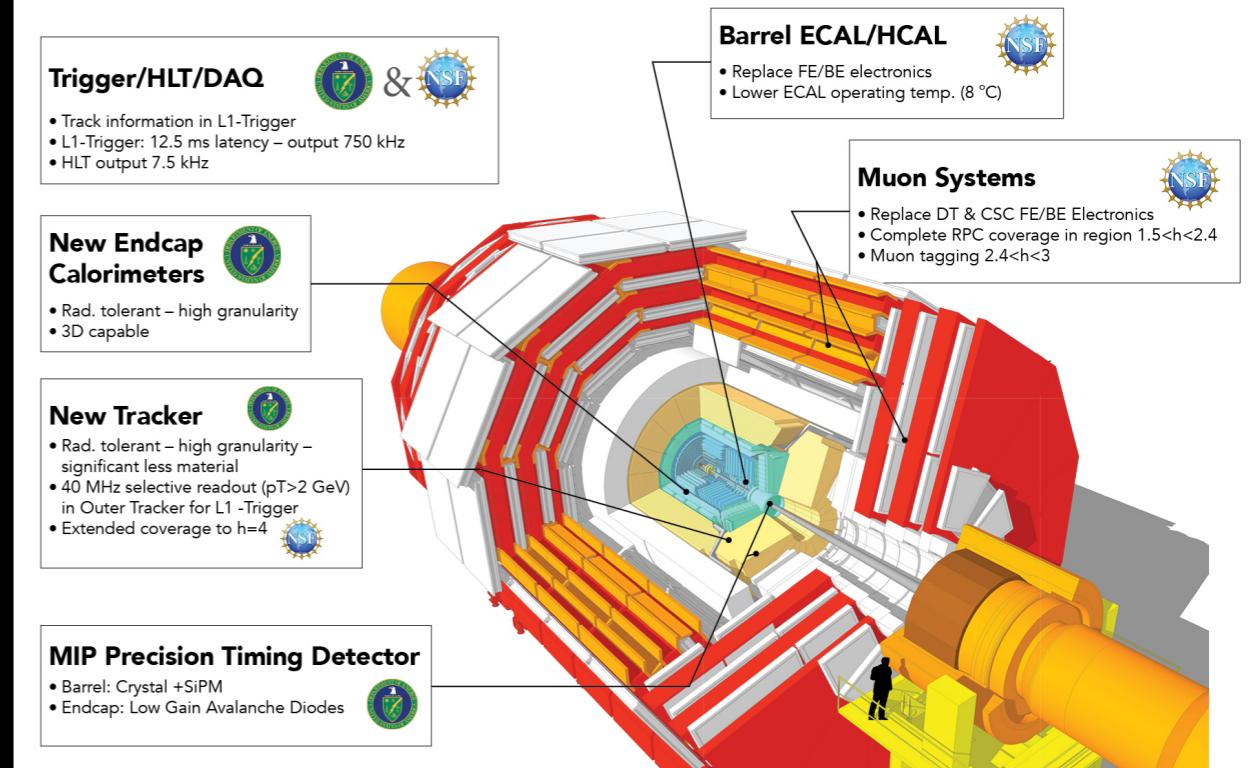


Compact Muon Solenoid

- LHC is the best tool for studying interactions at small scales
- CMS is a general purpose detector
 - Discovered the Higgs boson back in 2012
 - Receiving a plethora of upgrades in the next half decade that could open many doors to new physics (HL-LHC)

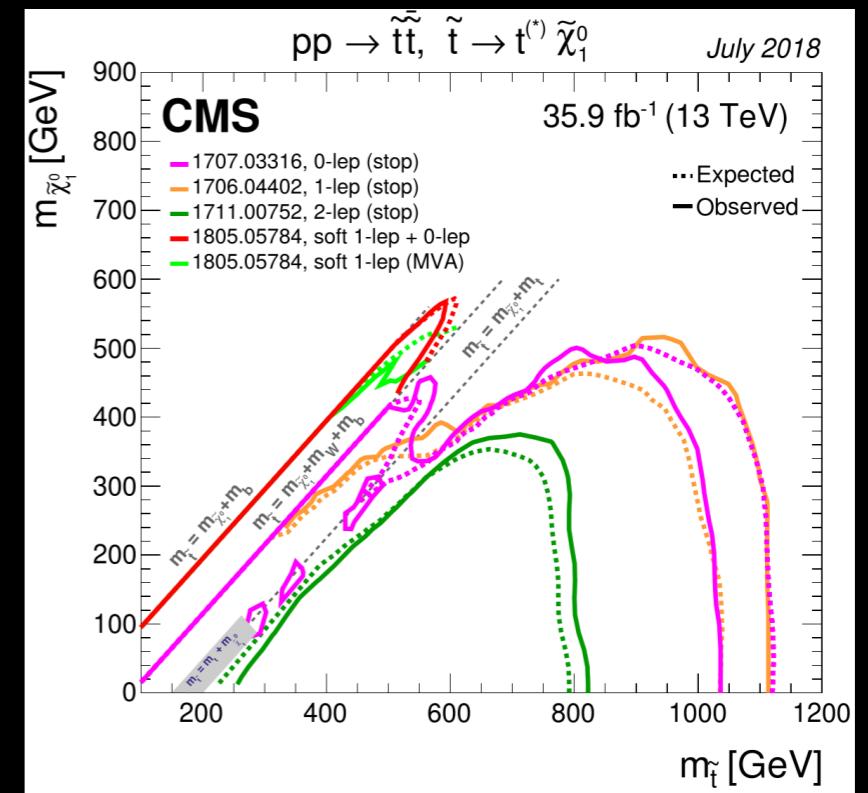
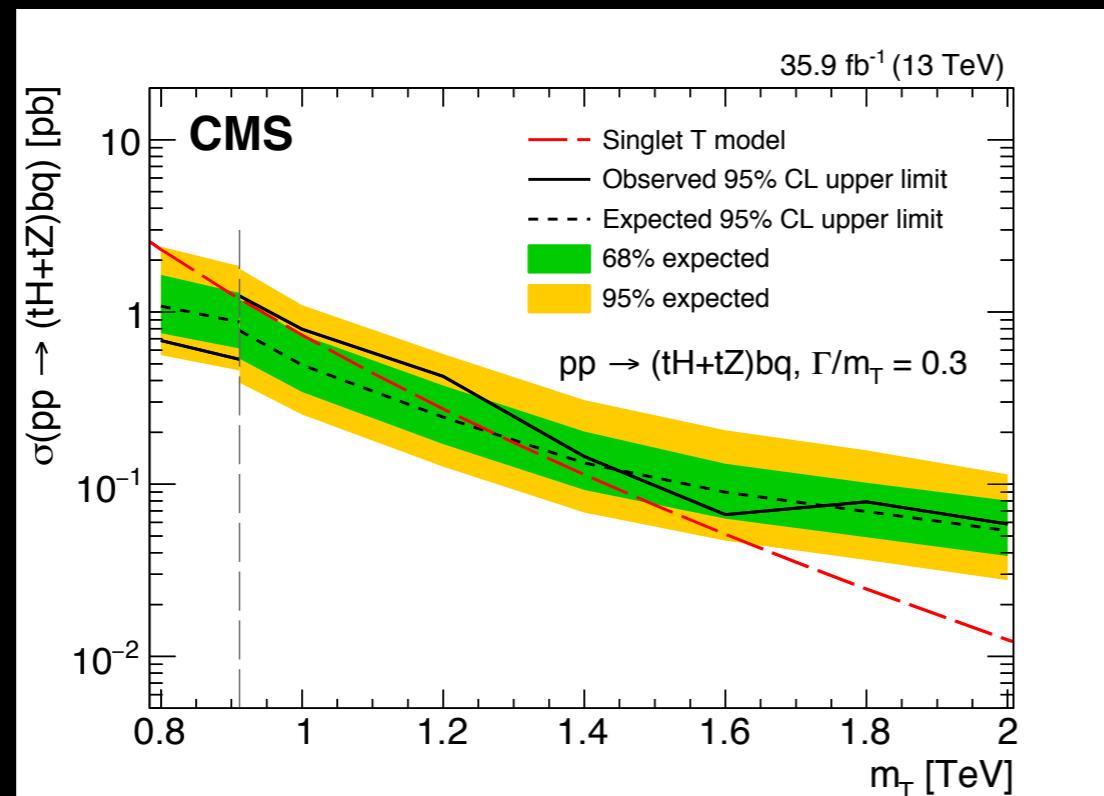
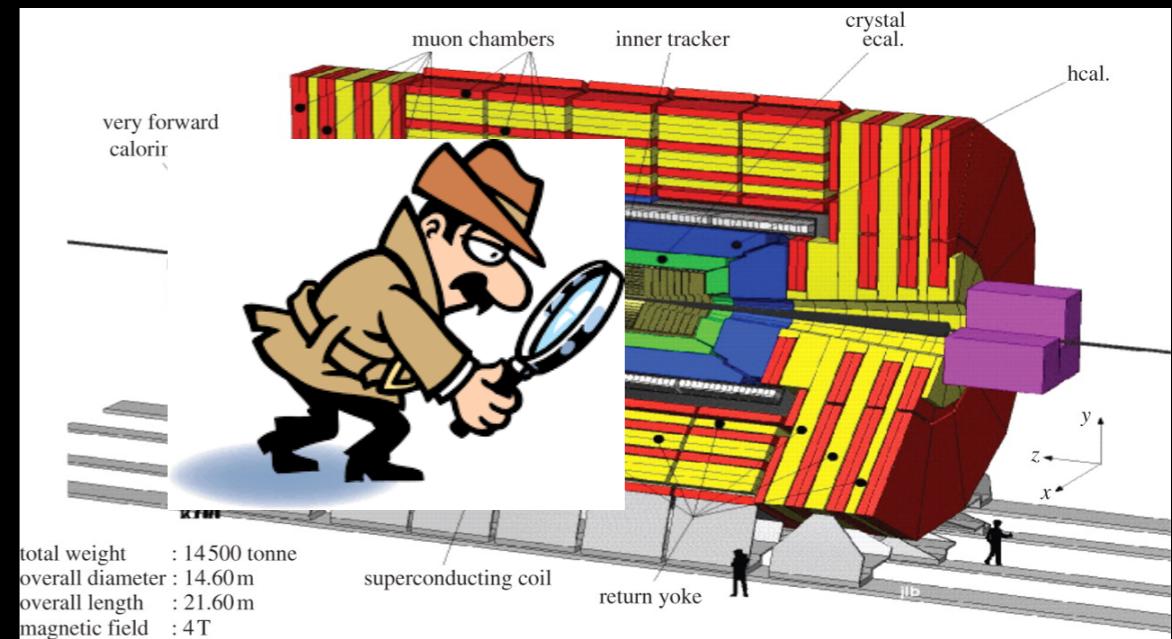


Summary of CMS HL-LHC Upgrades



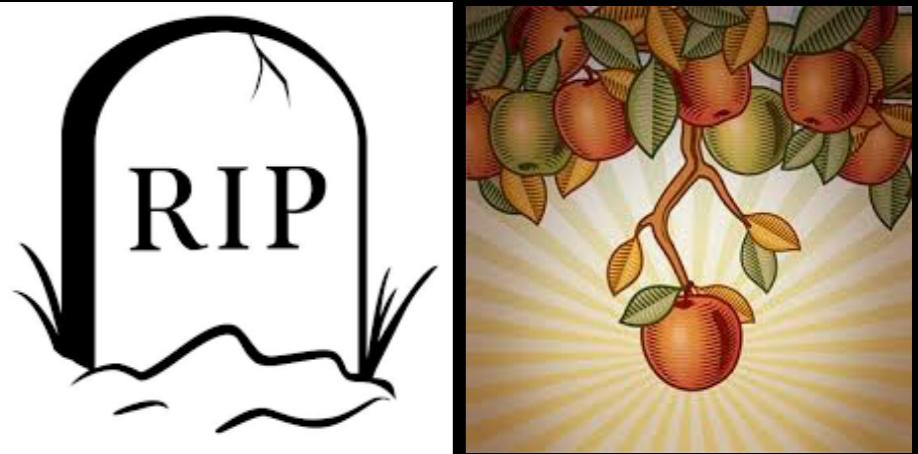
We Search

- Now we search for new physics at the LHC
- If we do not find anything we set a limit on the rate at which that thing is produced
- Have done a lot more searching than discovering



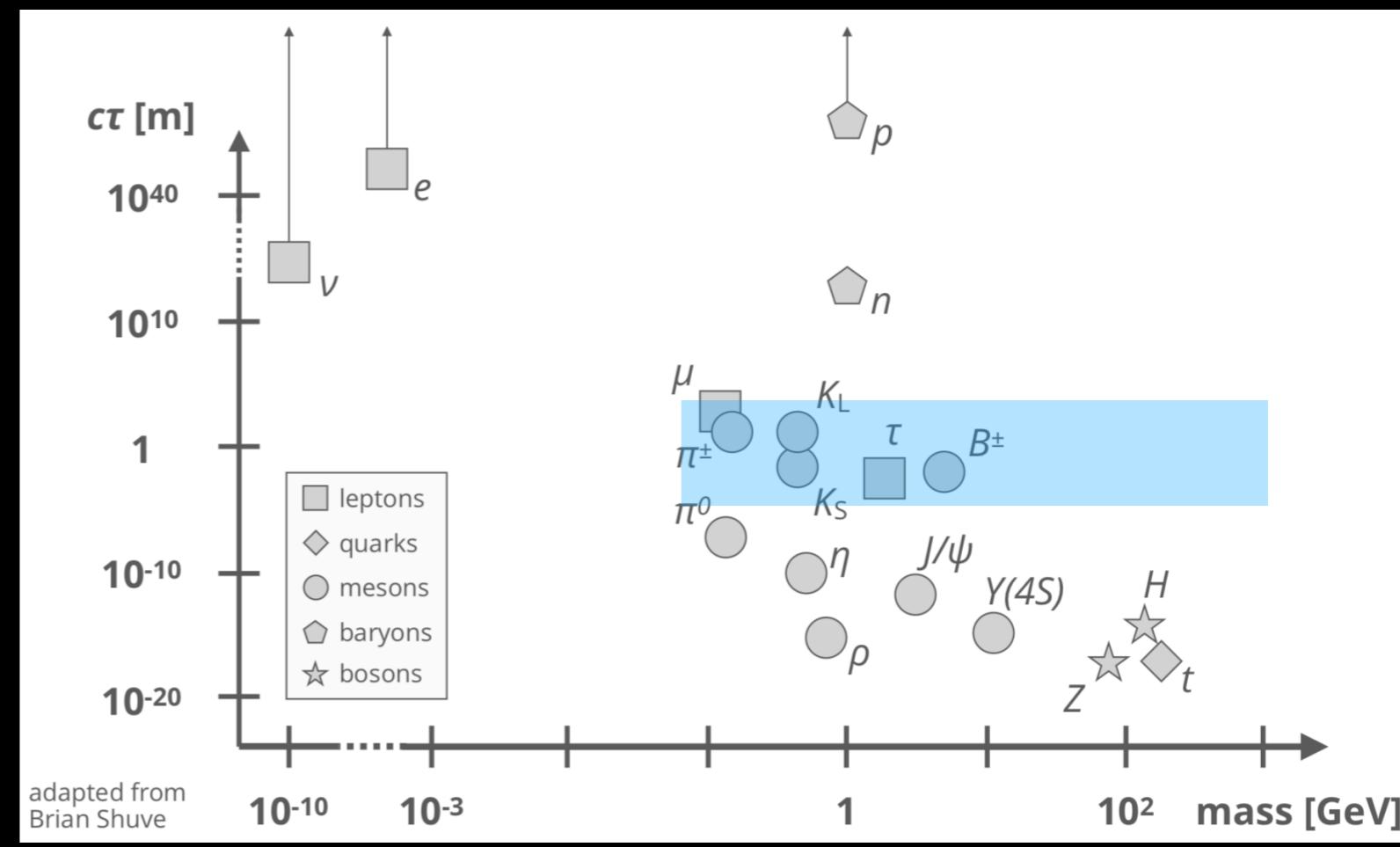
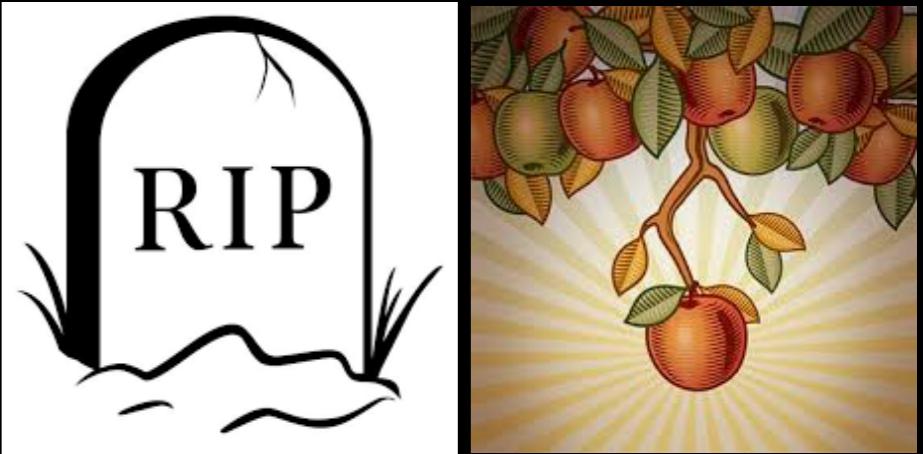
It's Not Over Yet

- All of the low hanging fruit has withered away
- Long-lived particles (LLPs) are one way that we can start being more creative



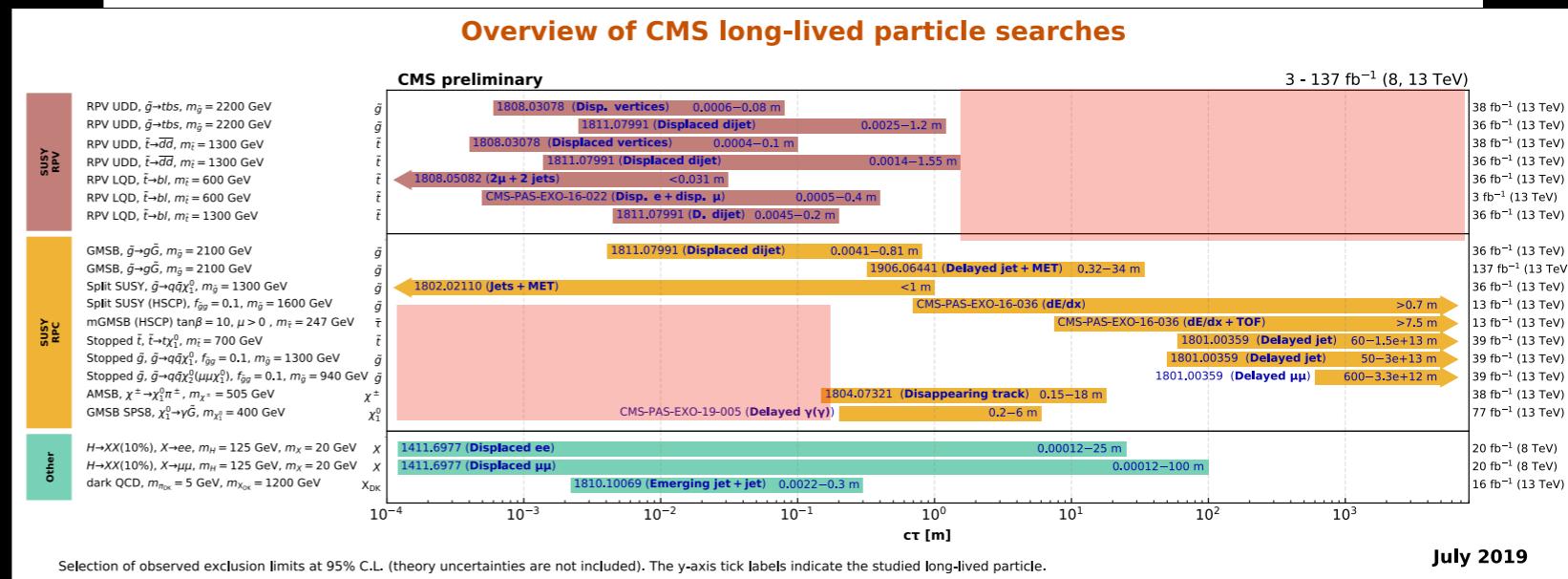
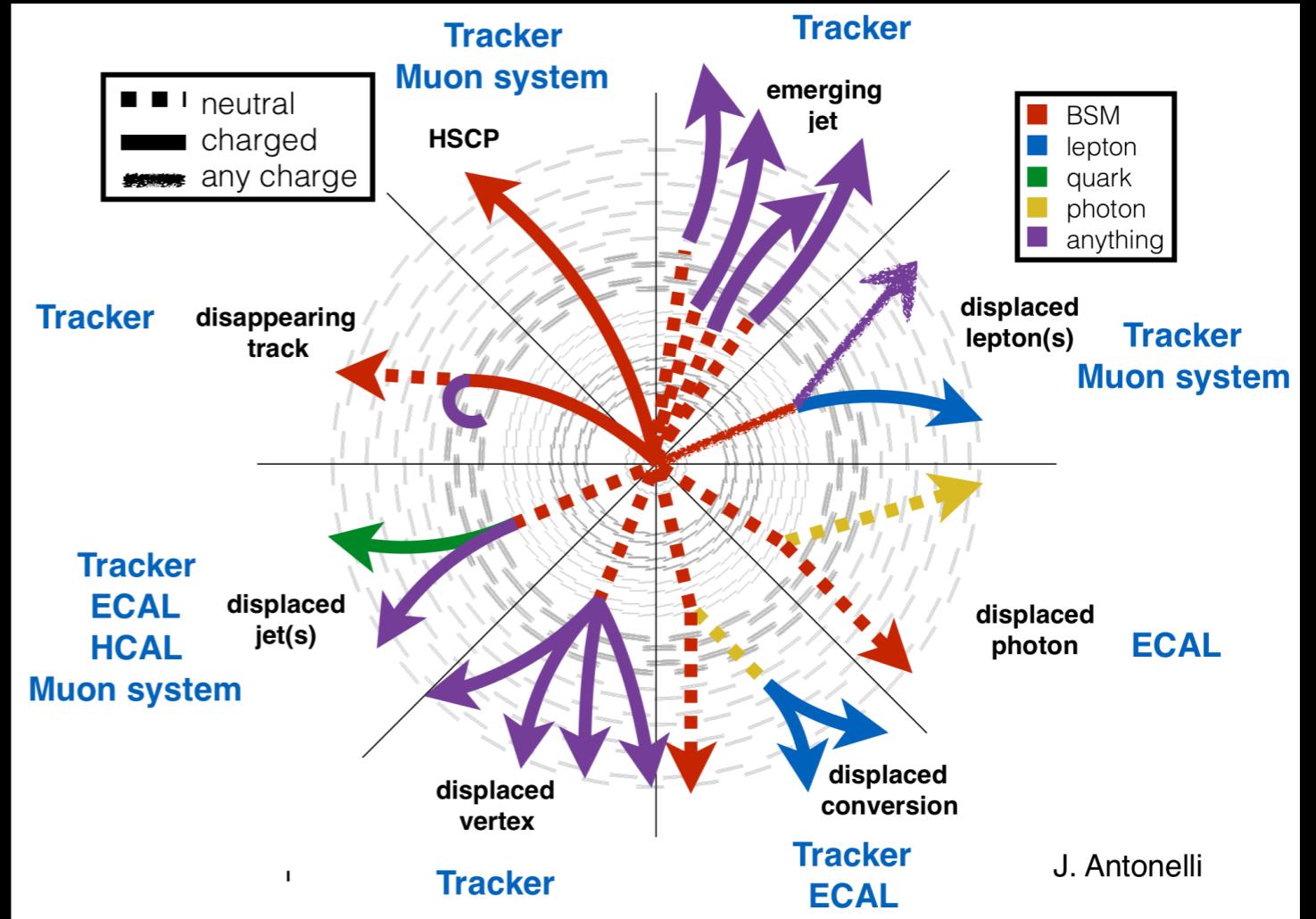
LLPs

- All of the low hanging fruit has withered away
- Long-lived particles (LLPs) are one way that we can start being more creative
- LLPs are particles that fly for some significant amount of time before either decaying or being detected
- Lots of examples in the standard model
- Why not in new physics?



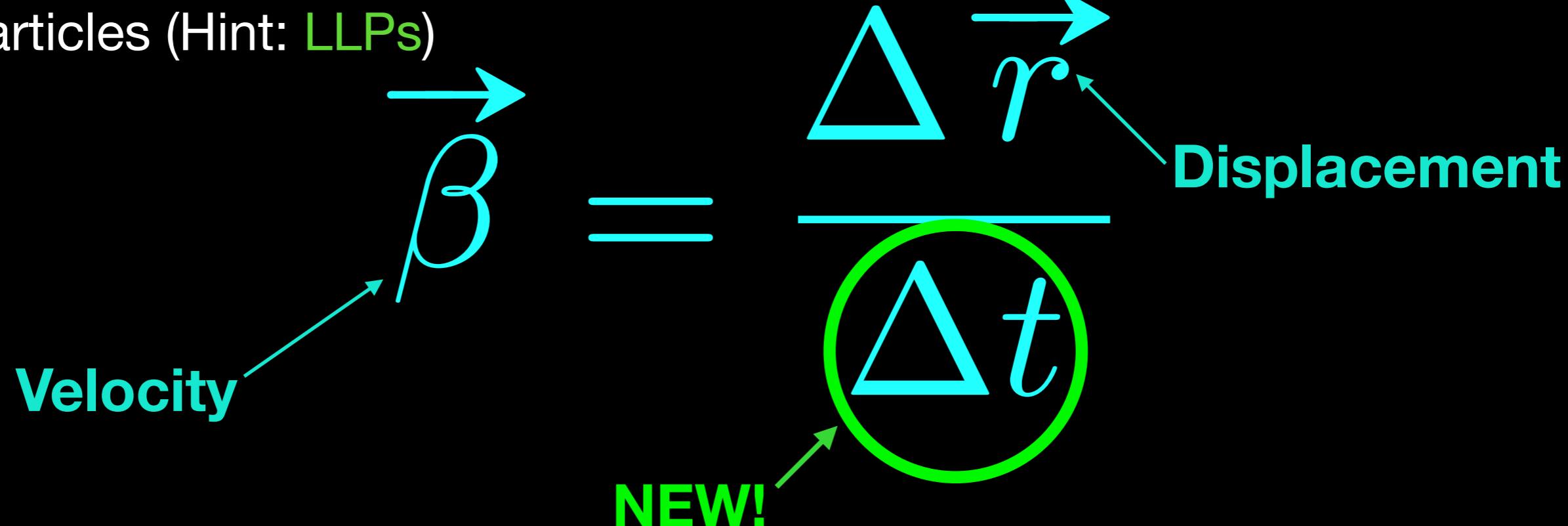
LLP Searches At The LHC

- Multi-Front Attack by CMS
 - Many creative searches but still have a lot of ground to cover
- HL-LHC presents new opportunities to push the boundaries even further

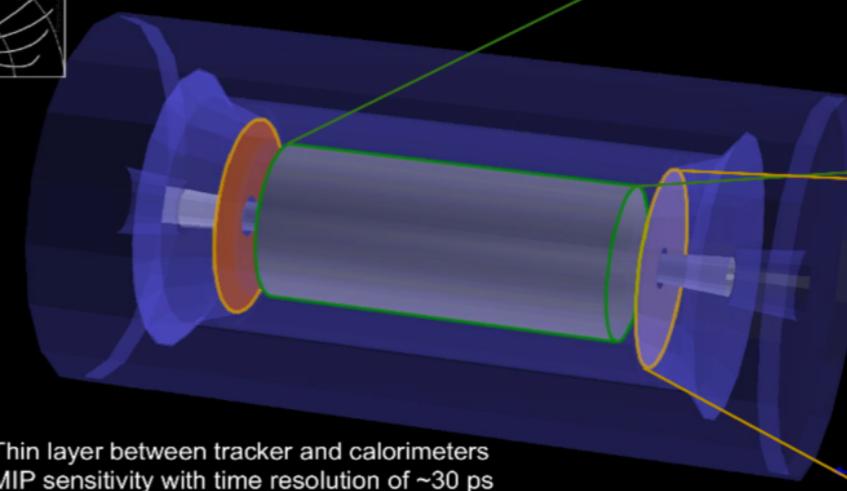


Timing Detectors at the HL-LHC

- CMS has been developing new timing detectors for the HL-LHC
 - Pileup Mitigation
 - Higgs Measurements
 - B-tagging Improvements
 - Determine the **velocities** of particles (Hint: LLPs)

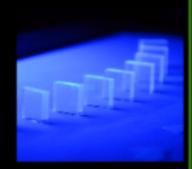
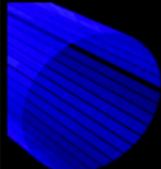


MTD design overview



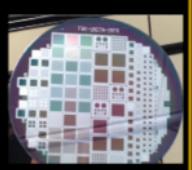
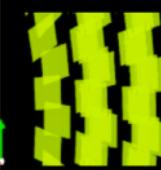
BARREL

TK/ECAL interface ~ 25 mm thick
Surface ~ 40 m²
Radiation level ~ 2×10^{14} n_{eq}/cm²
Sensors: LYSO crystals + SiPMs



ENDCAPS

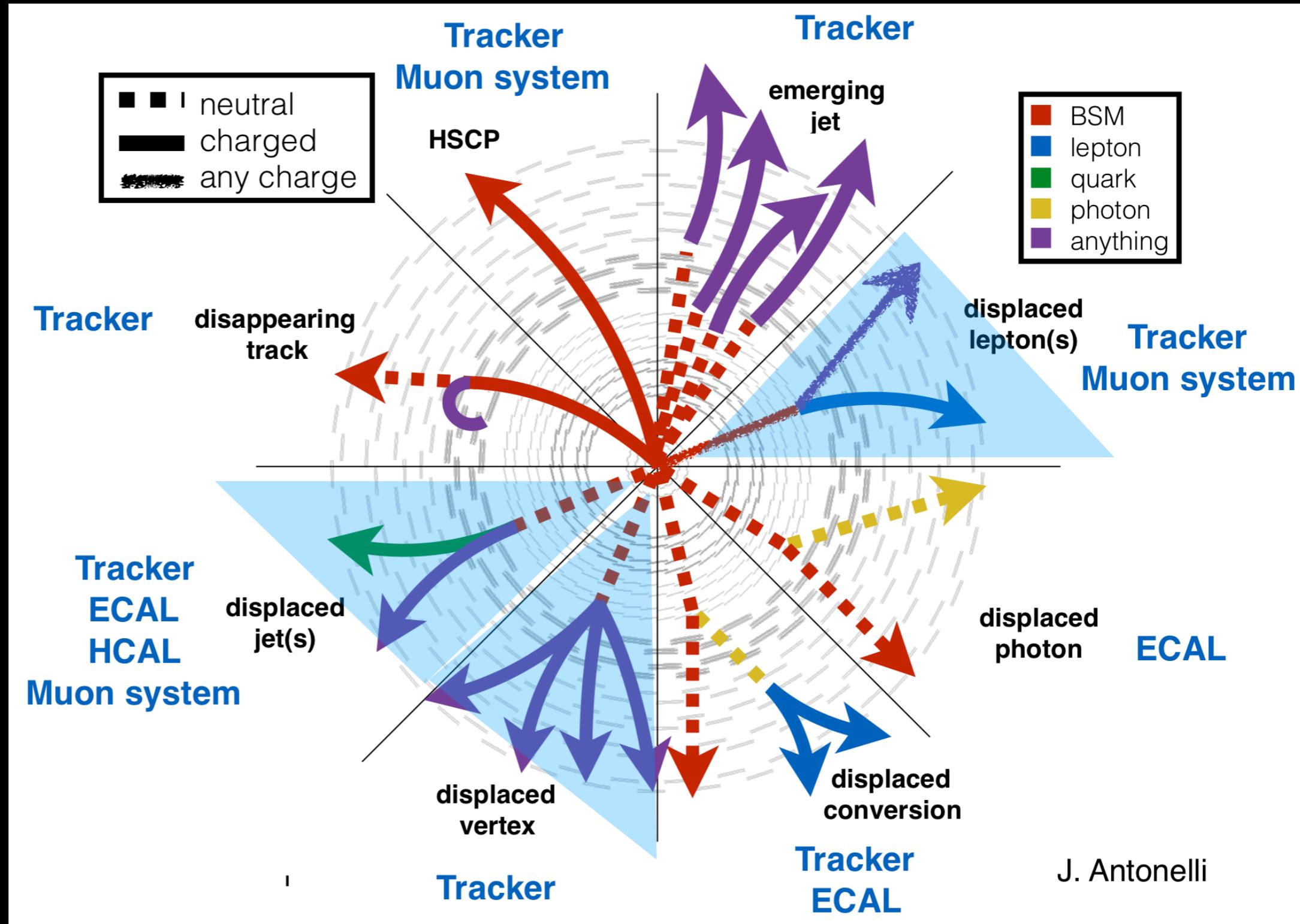
On the CE nose ~ 42 mm thick
Surface ~ 12 m²
Radiation level ~ 2×10^{15} n_{eq}/cm²
Sensors: Si with internal gain (LGAD)



- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of ~30 ps
- Hermetic coverage for $|\eta| < 3$

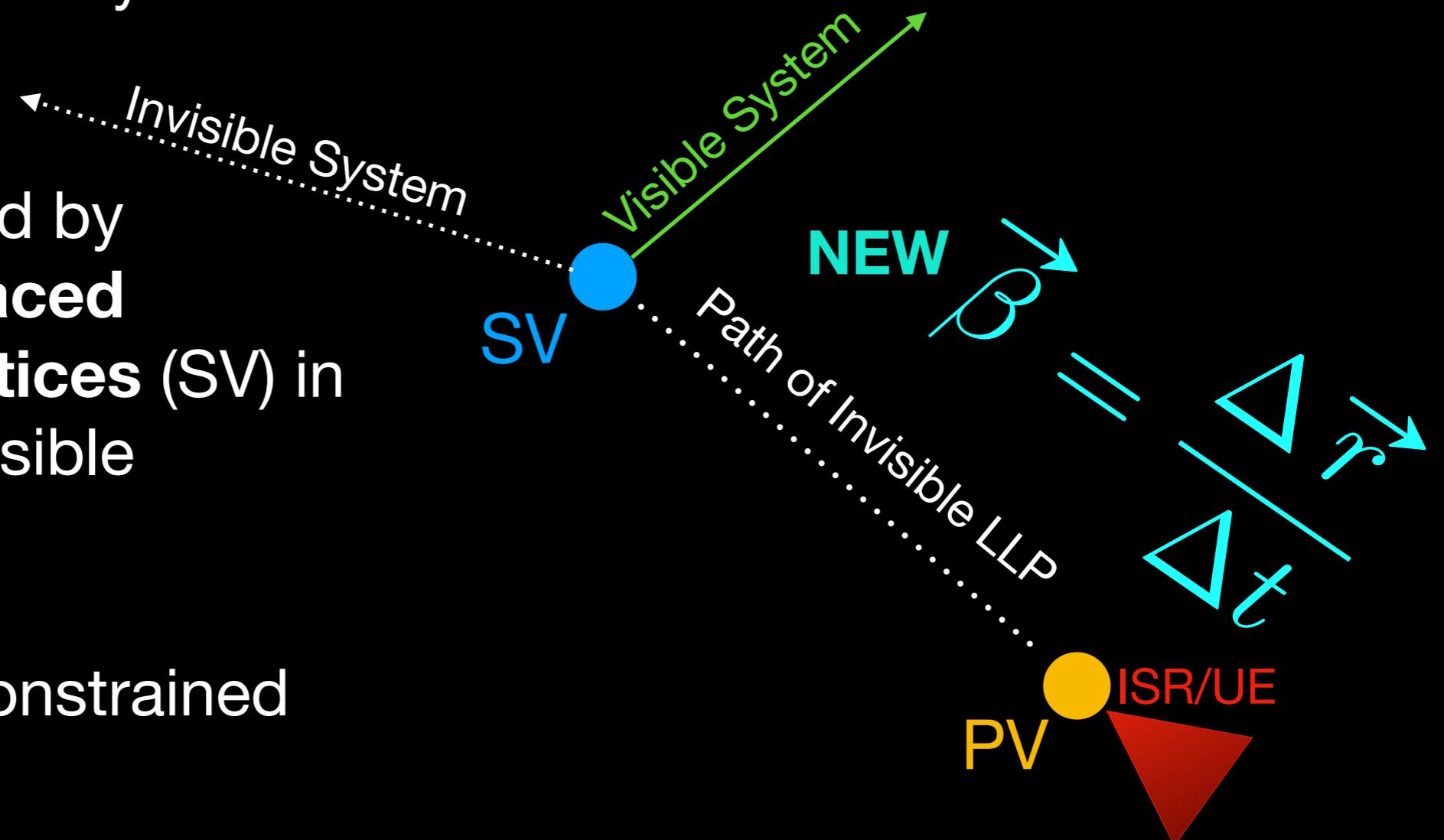
LLP searches at the LHC

- Going to focus on one specific type of LLP case



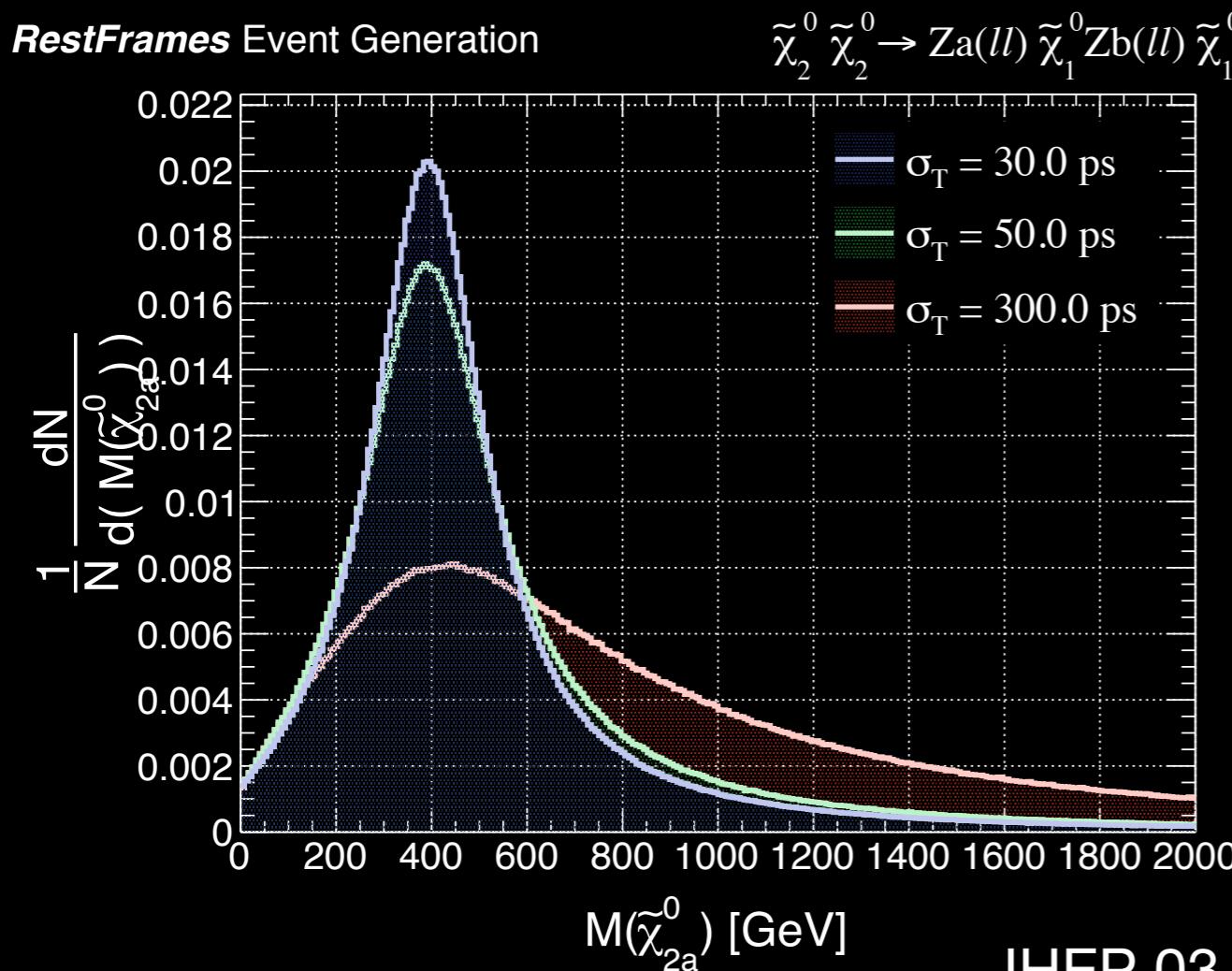
Neutral LLP Topology

- Possibly most **difficult** to study something neutral (invisible) that decays semi-invisibly
- Typically studied by counting **displaced secondary vertices** (SV) in events with invisible systems
- This is under-constrained without timing

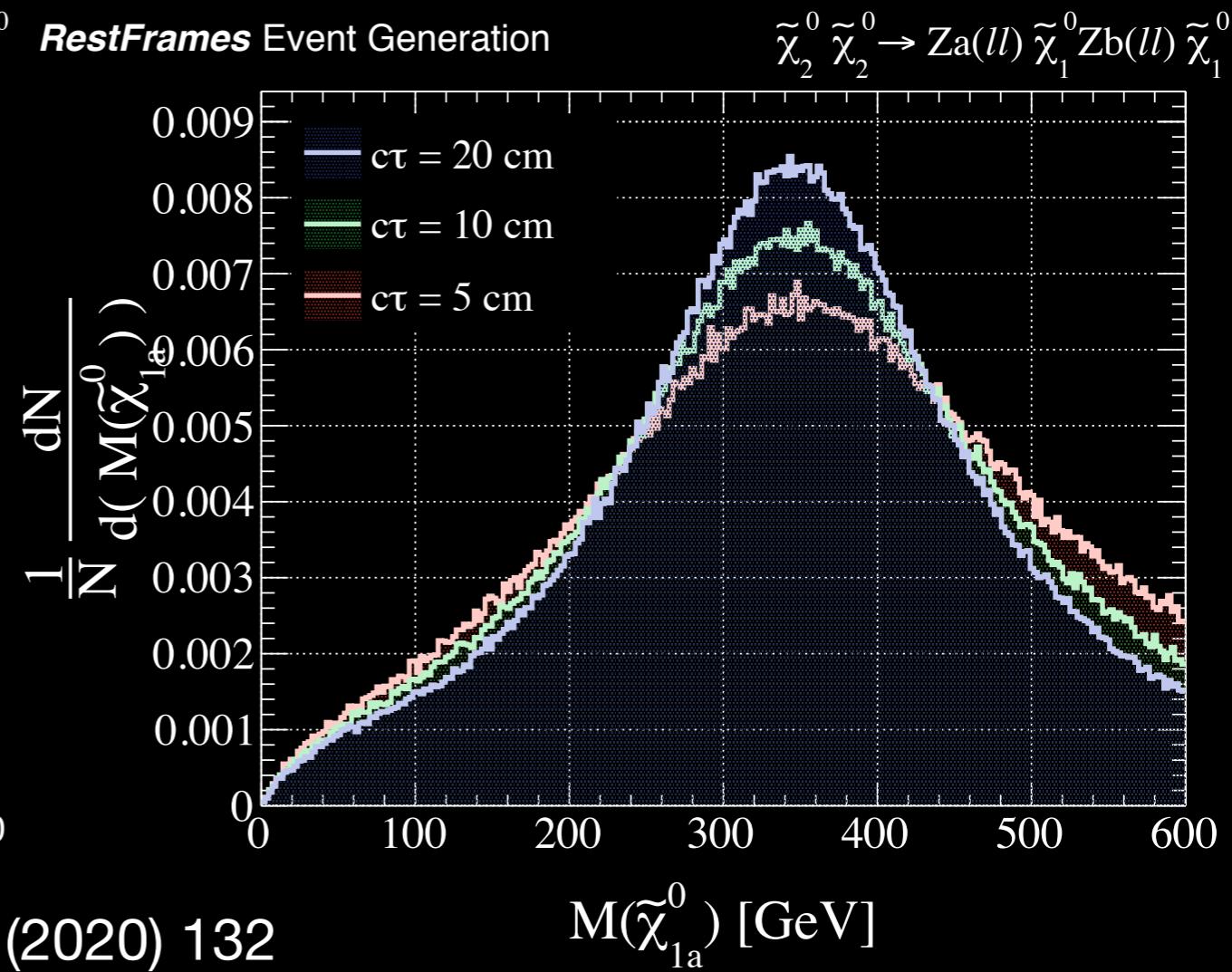


Math Happens

- With this new timing information we will be able to measure LLP masses and fully reconstruct events containing them
- Now, counting experiments can become bump hunts!



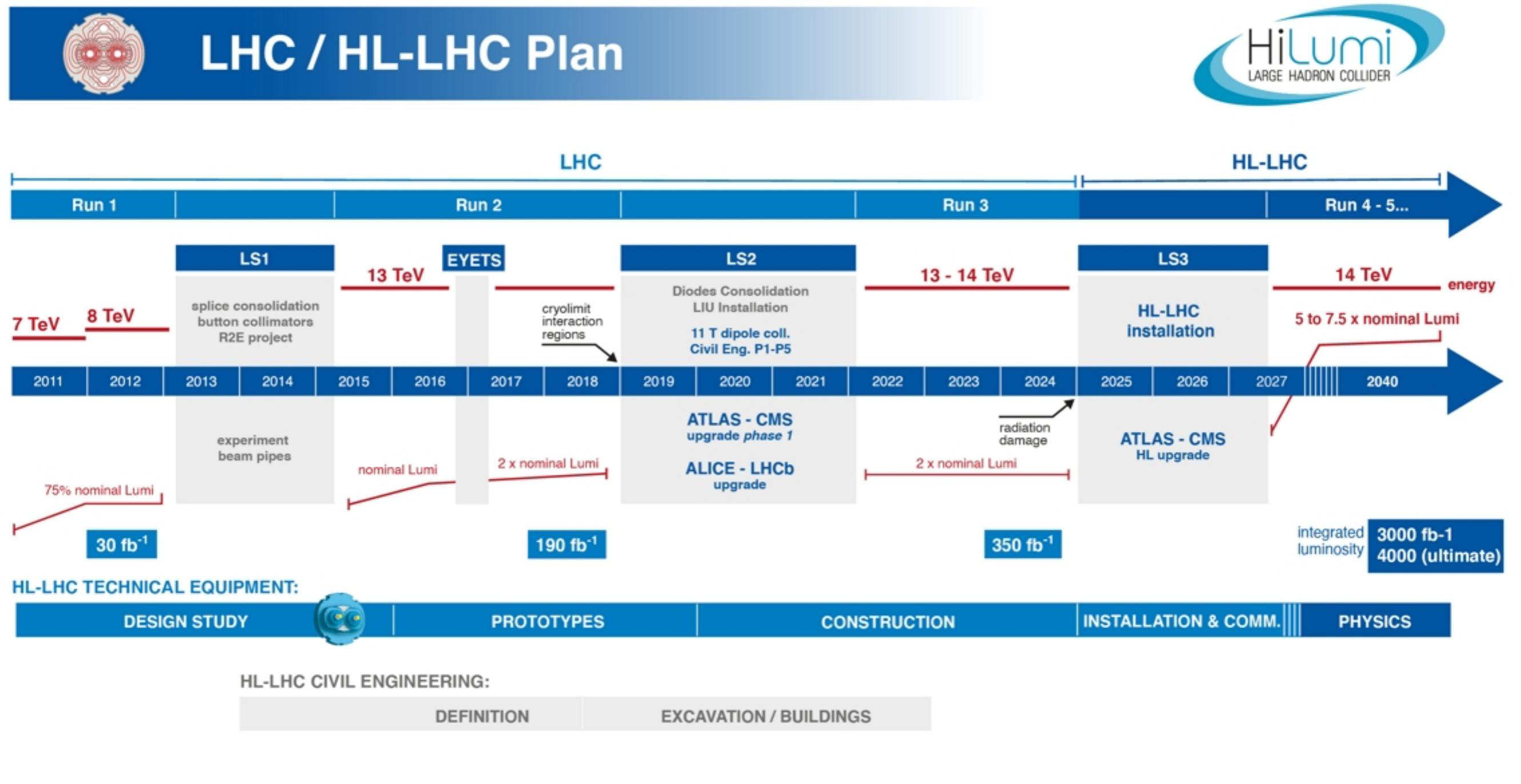
JHEP 03 (2020) 132



Summary

- CMS has come a long way with respect to understanding the really tiny stuff
 - Need to be more creative to see cool, new, and more relevant stuff
- The HL-LHC era presents new opportunities to rethink searches with new tools
 - With **new** information we can **reconstruct** events with LLPs that were previously **under-constrained**

Backup



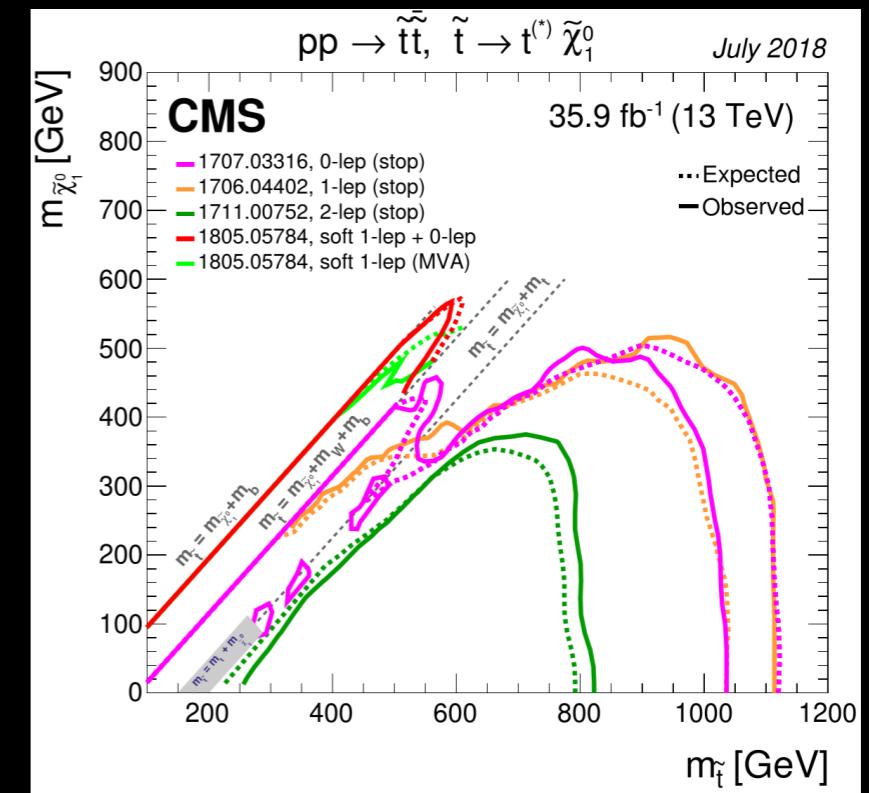
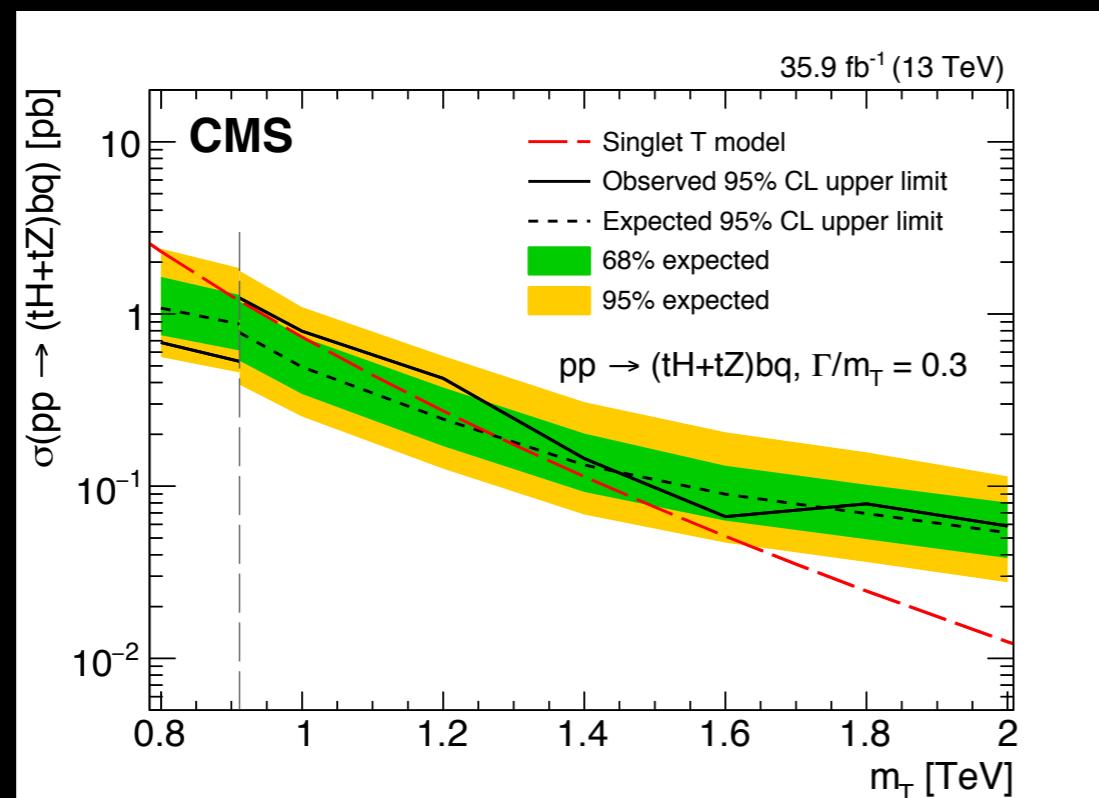
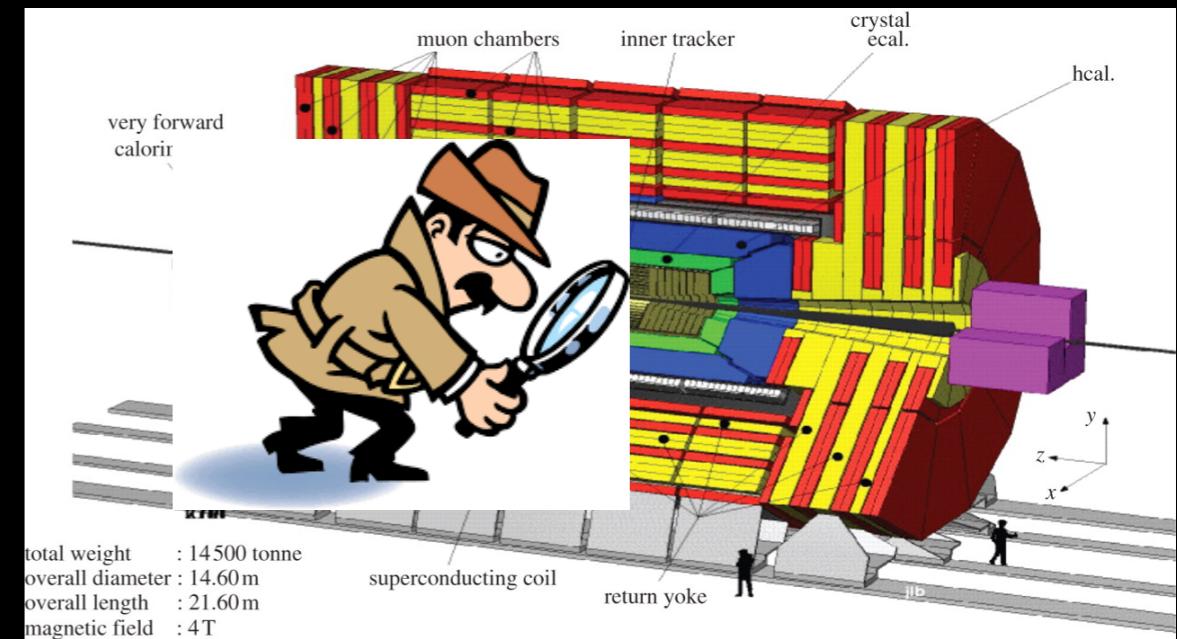
Large Hadron Collider



- Large ring that accelerates protons to nearly the speed of light
- Hosts many different experiments

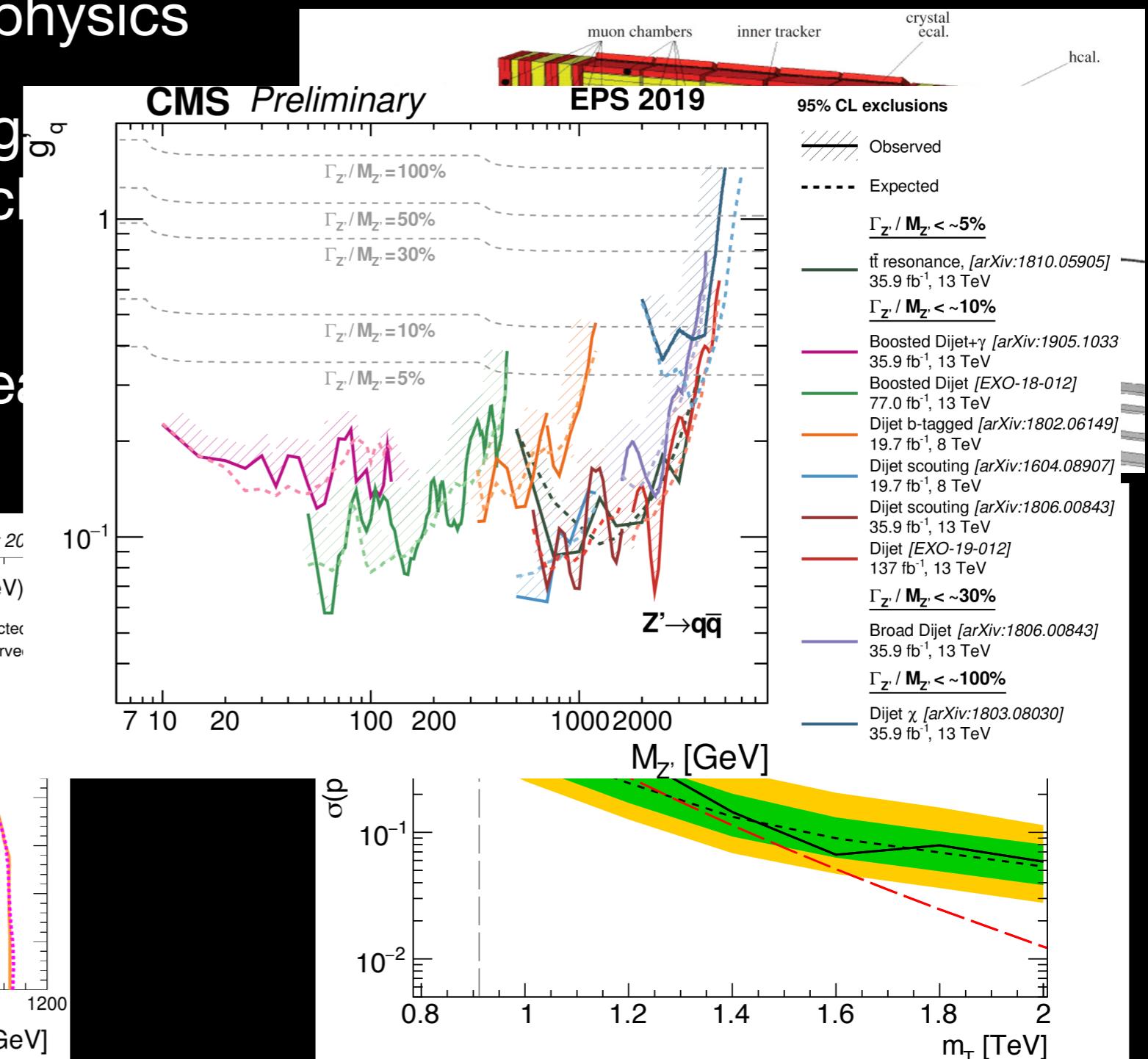
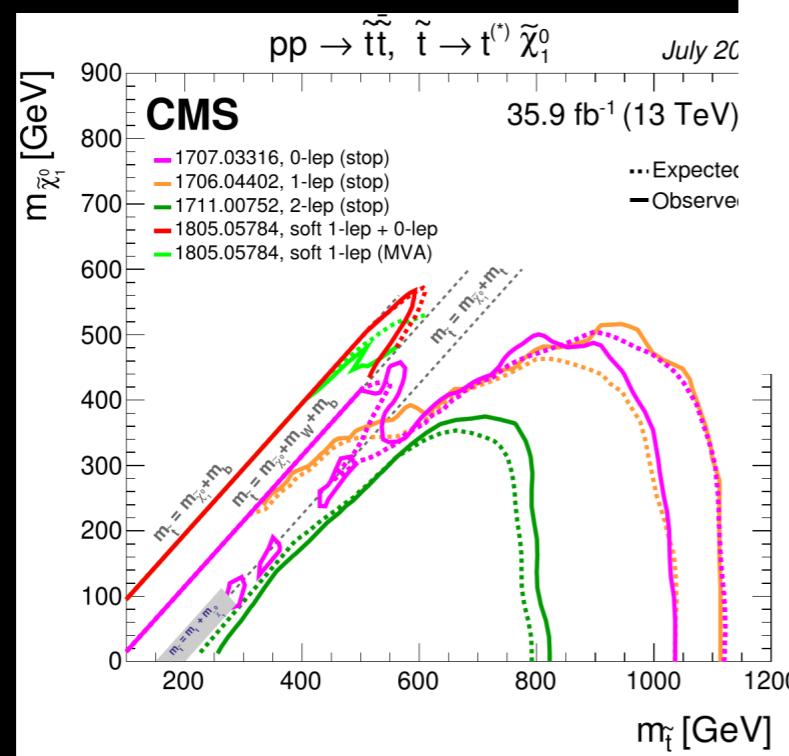
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- Now we search for new physics
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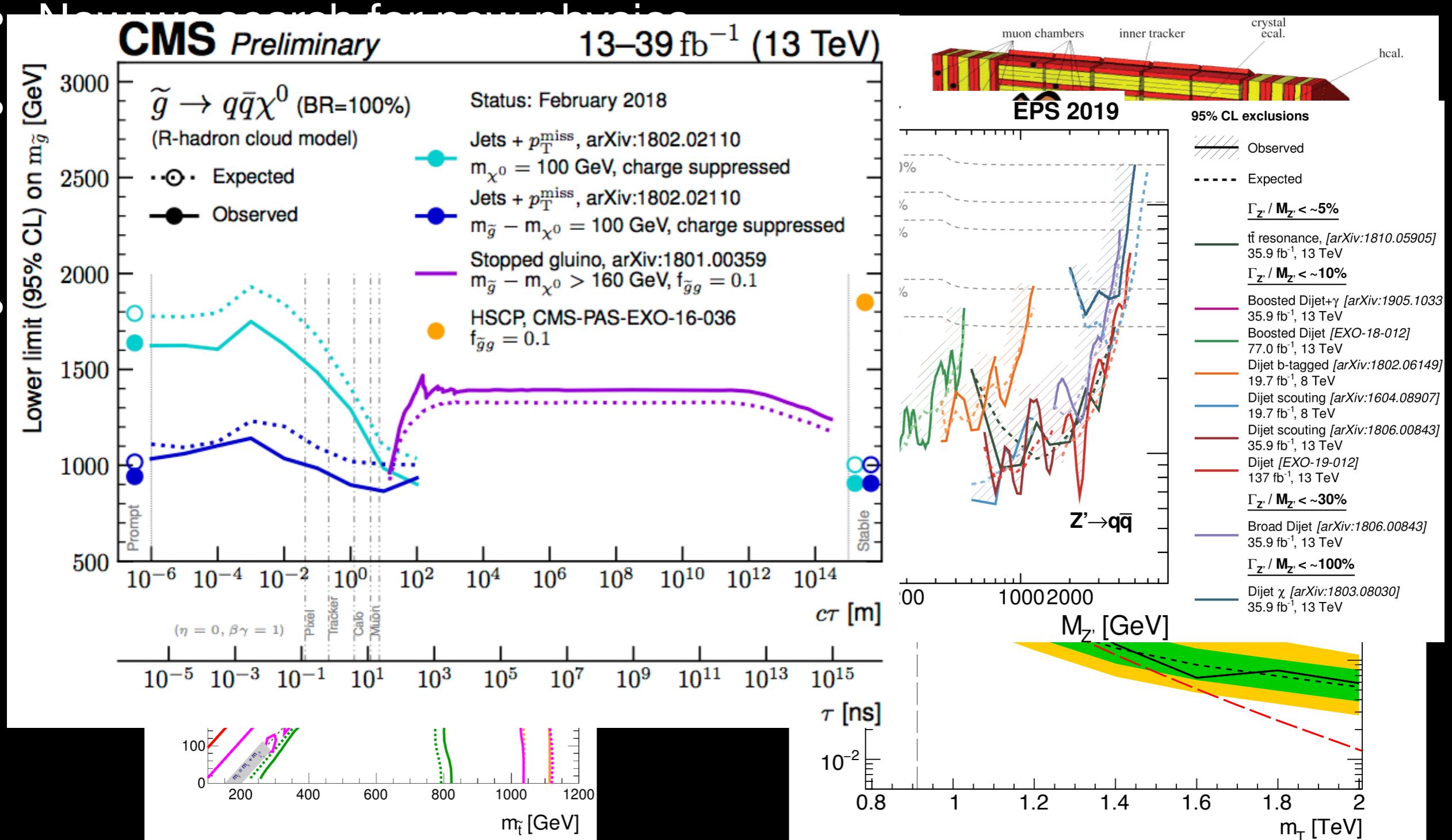


We Search And Search

- Now we search for new physics
- If we do not find anything, a limit on the rate at which thing is produced
- Have done a lot more searching than discovering

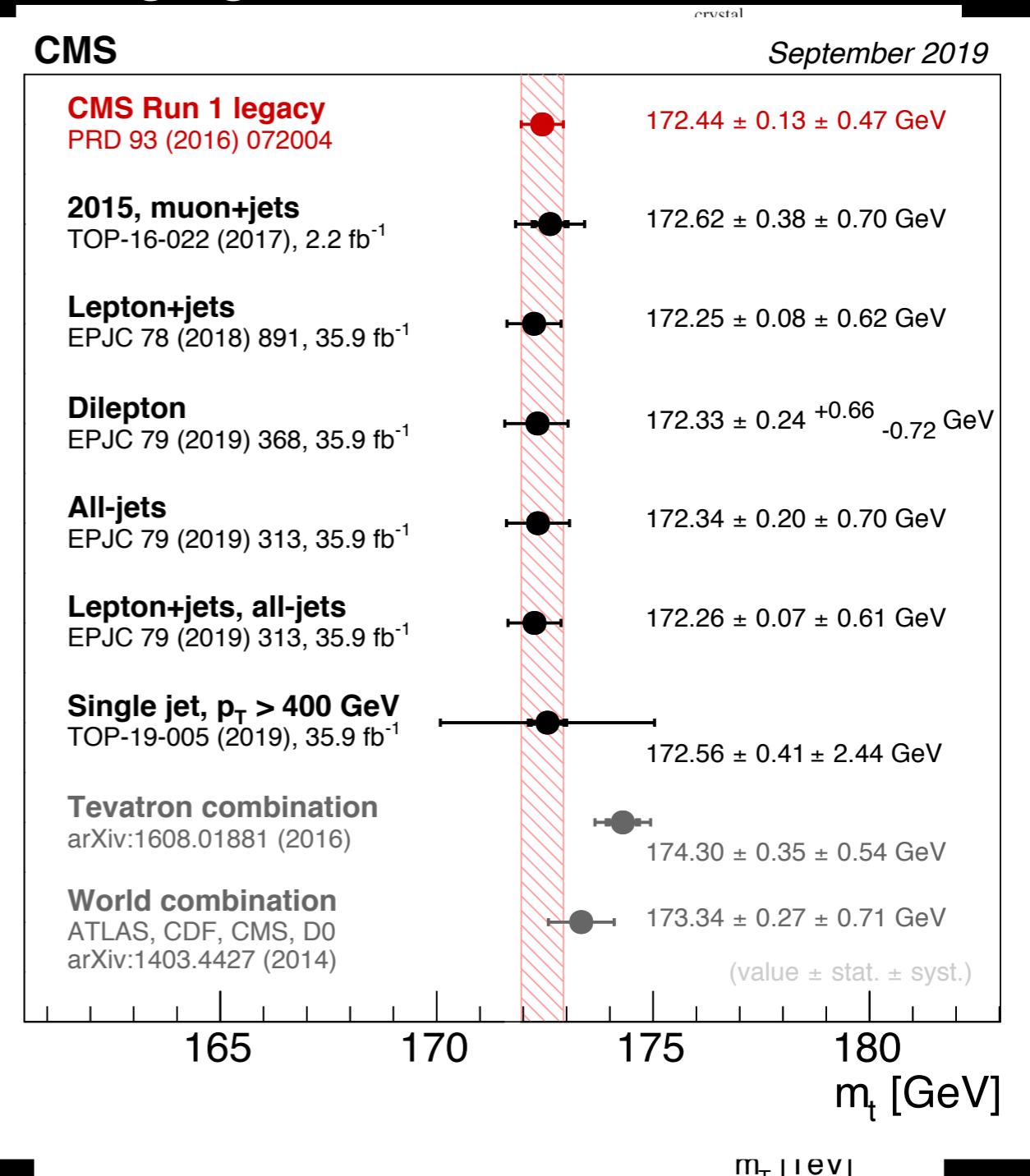
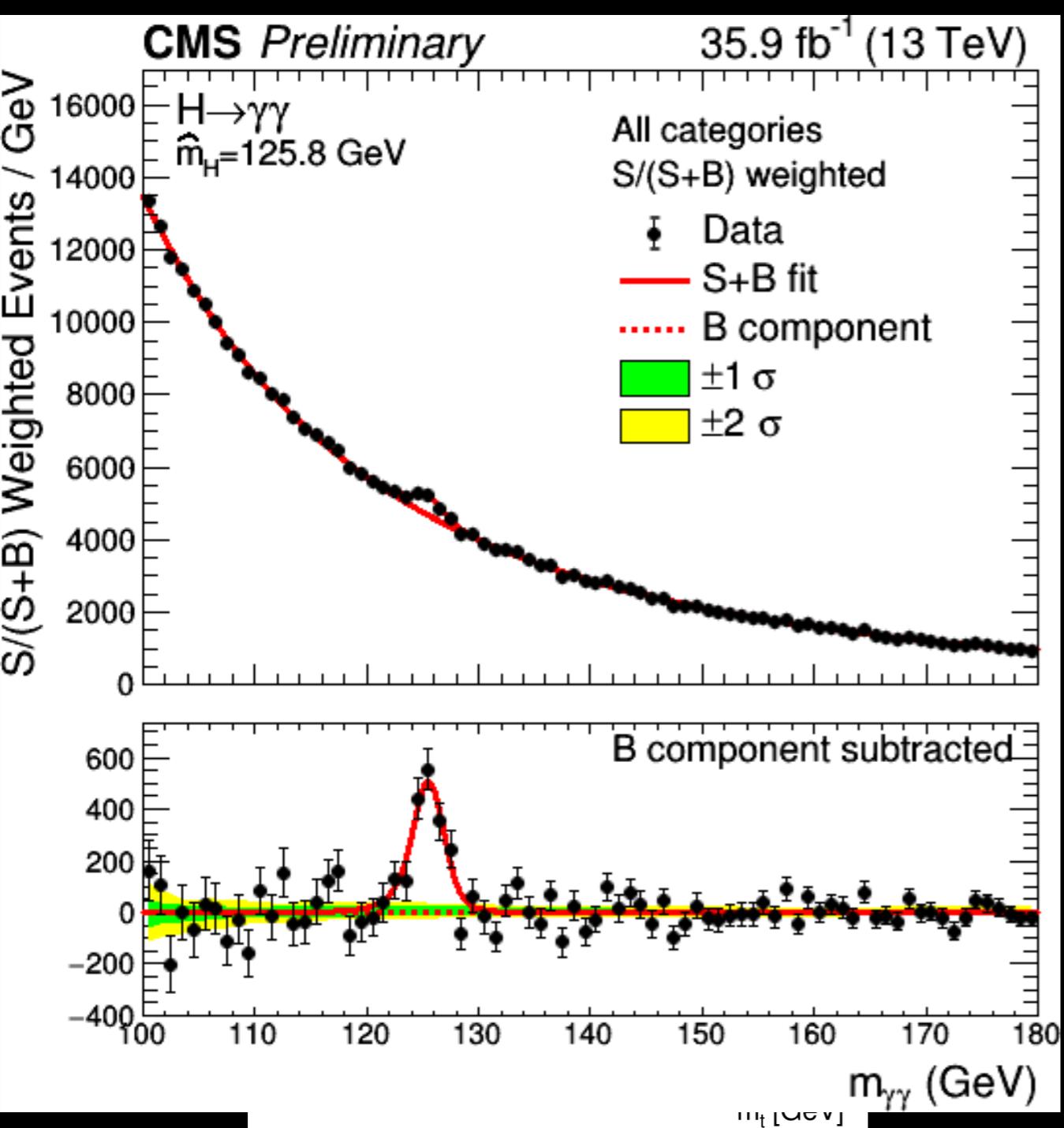


We Search And Search And Search Some More



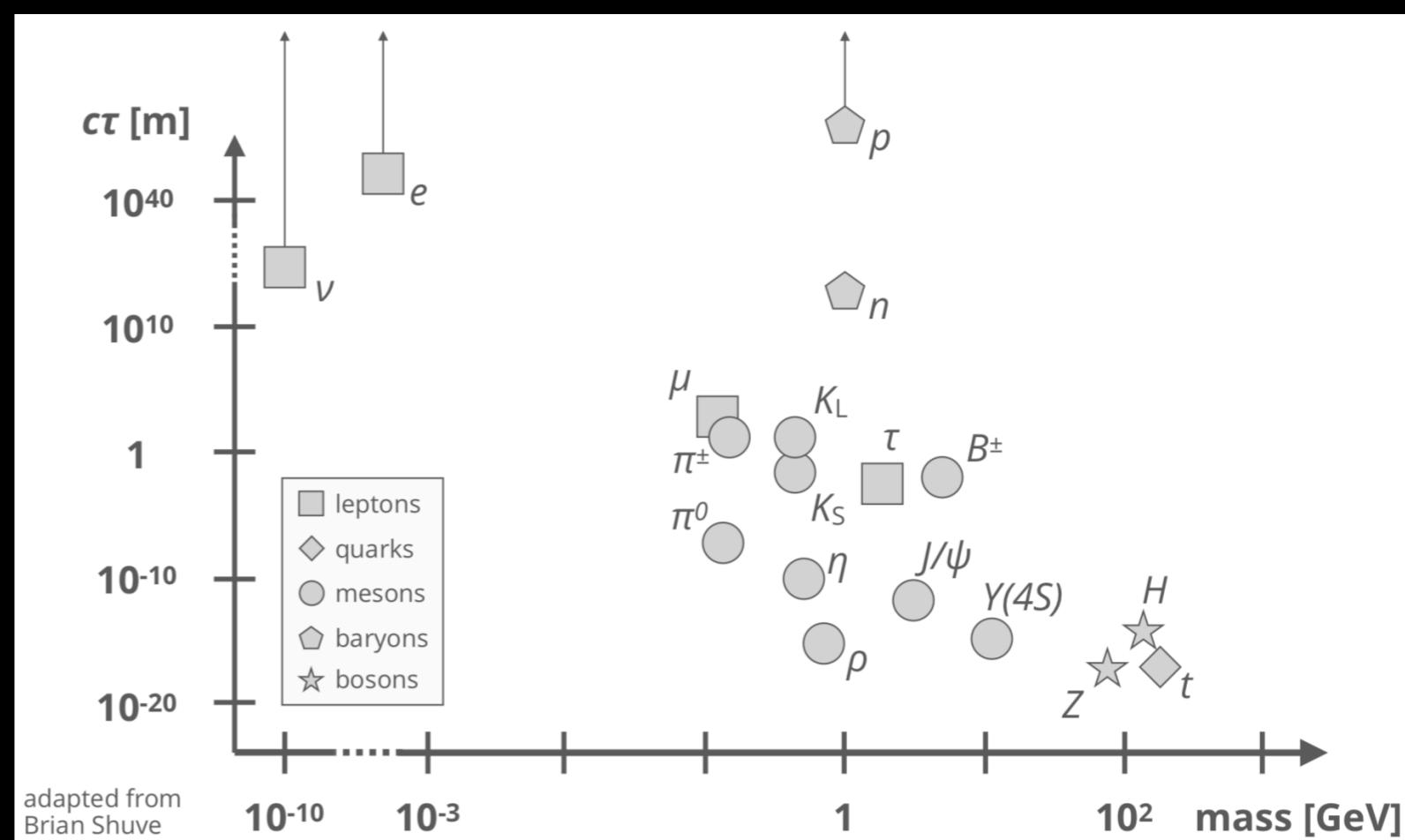
We Search And Search And Search Some More

Sometimes we measure something again...



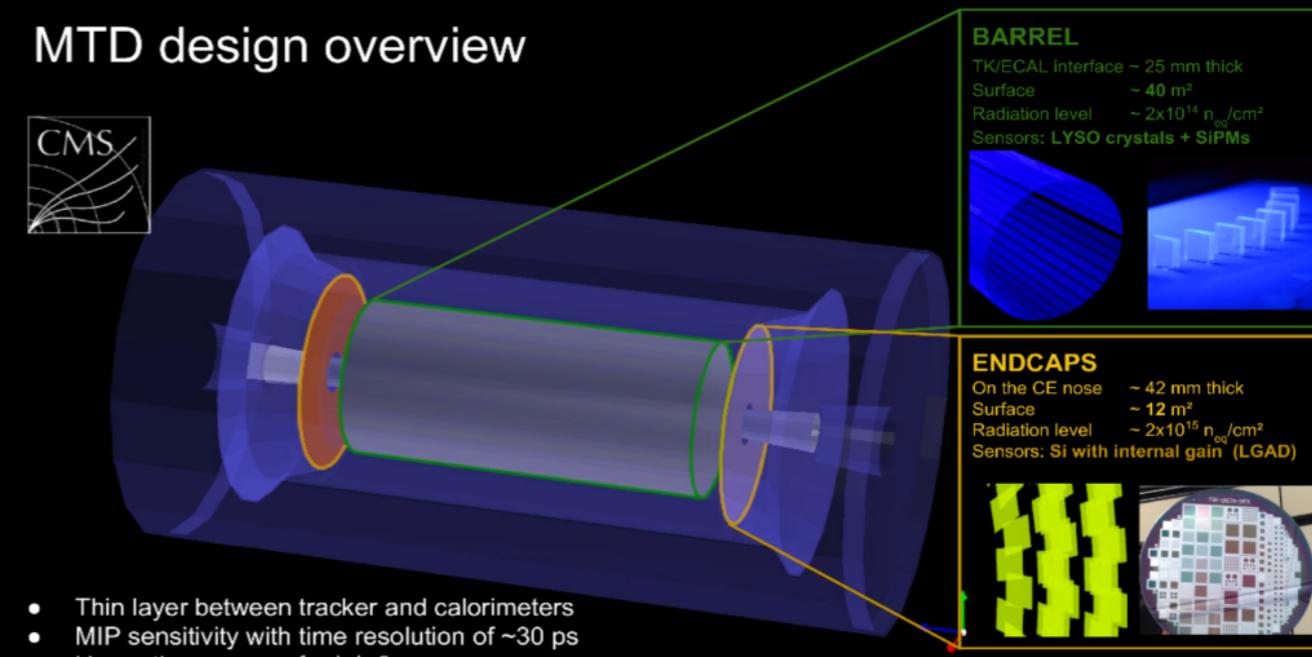
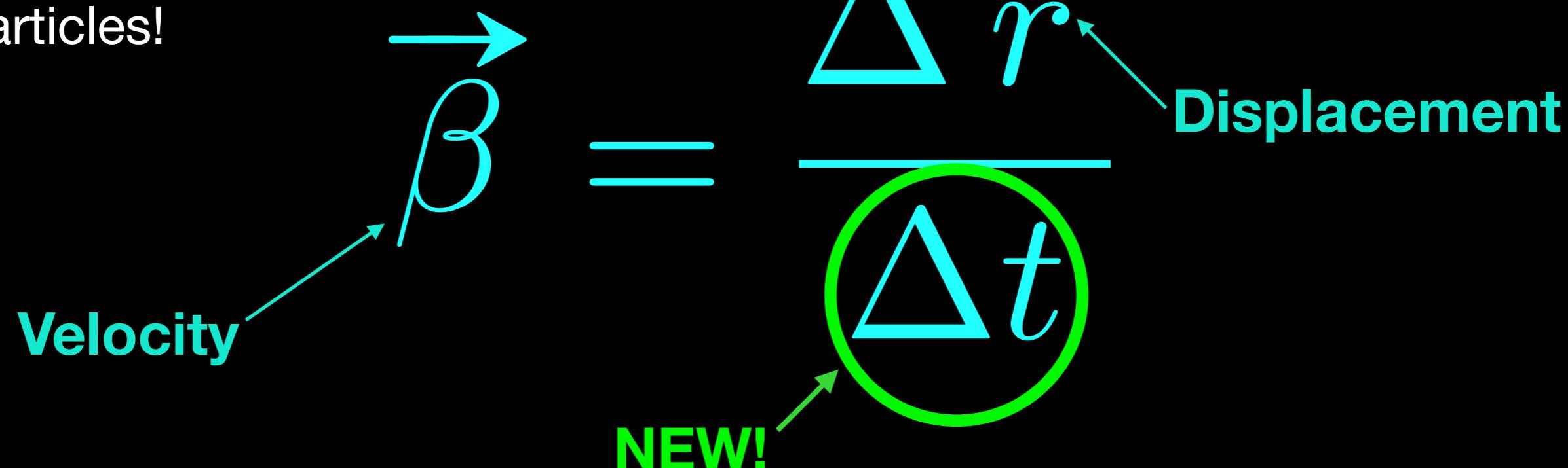
LLPs in General

- Particle that flies for some significant amount of time before either decaying or being detected
- Lots of examples in the standard model
- Why not in new physics?



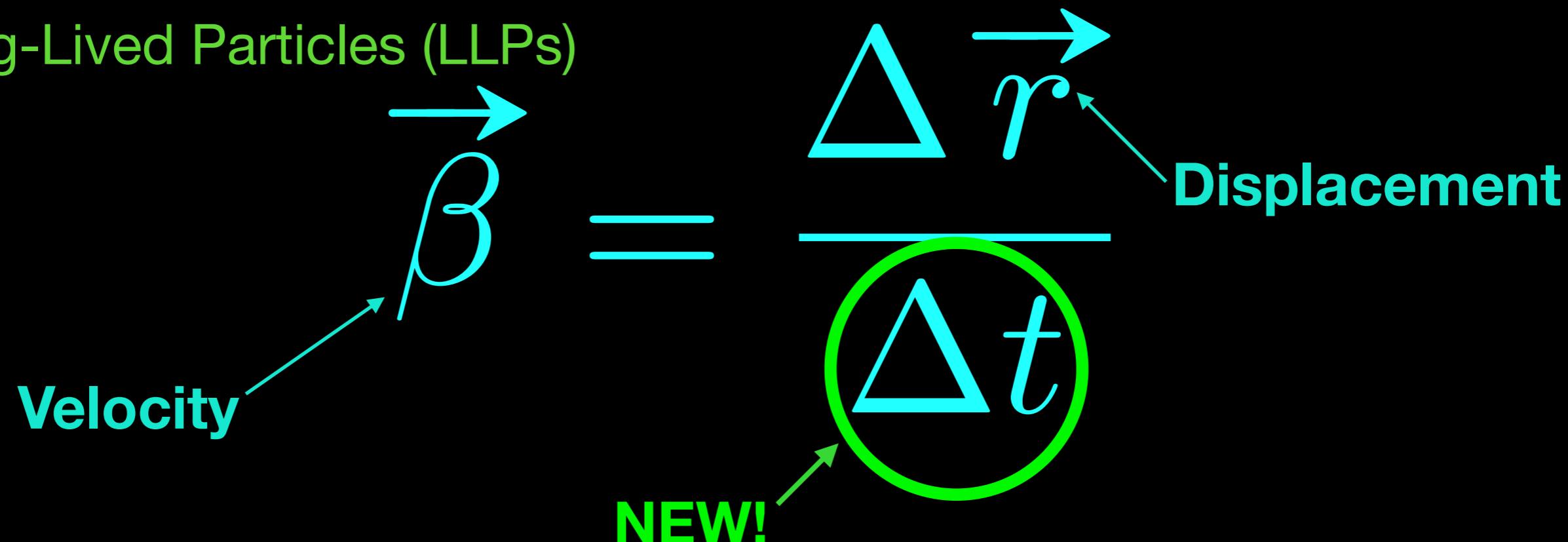
Timing Detectors at the HL-LHC

- There will be challenges during the High-Luminosity run of the LHC (inc. pileup)
- CMS and ATLAS have been developing new timing detectors to combat these issues
- These detectors can also be used to determine the velocities of particles!

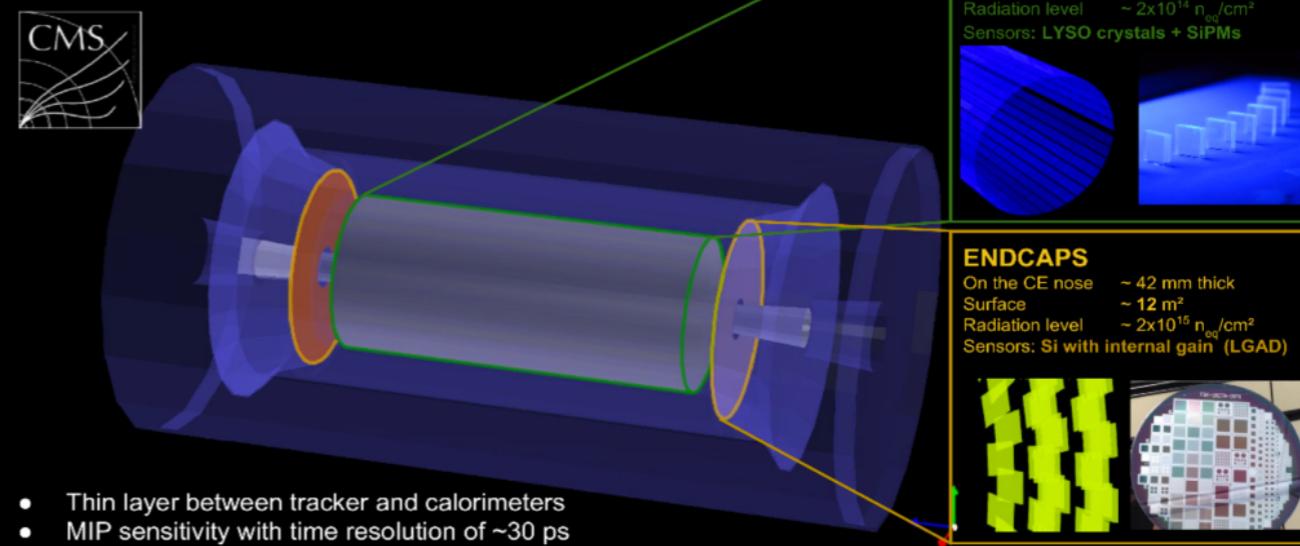


What Can We Do Now?

- Higgs Physics
 - Self-coupling
 - Precise mass measurements
- B-tagging Performance
 - Rare B-meson decays
- Long-Lived Particles (LLPs)



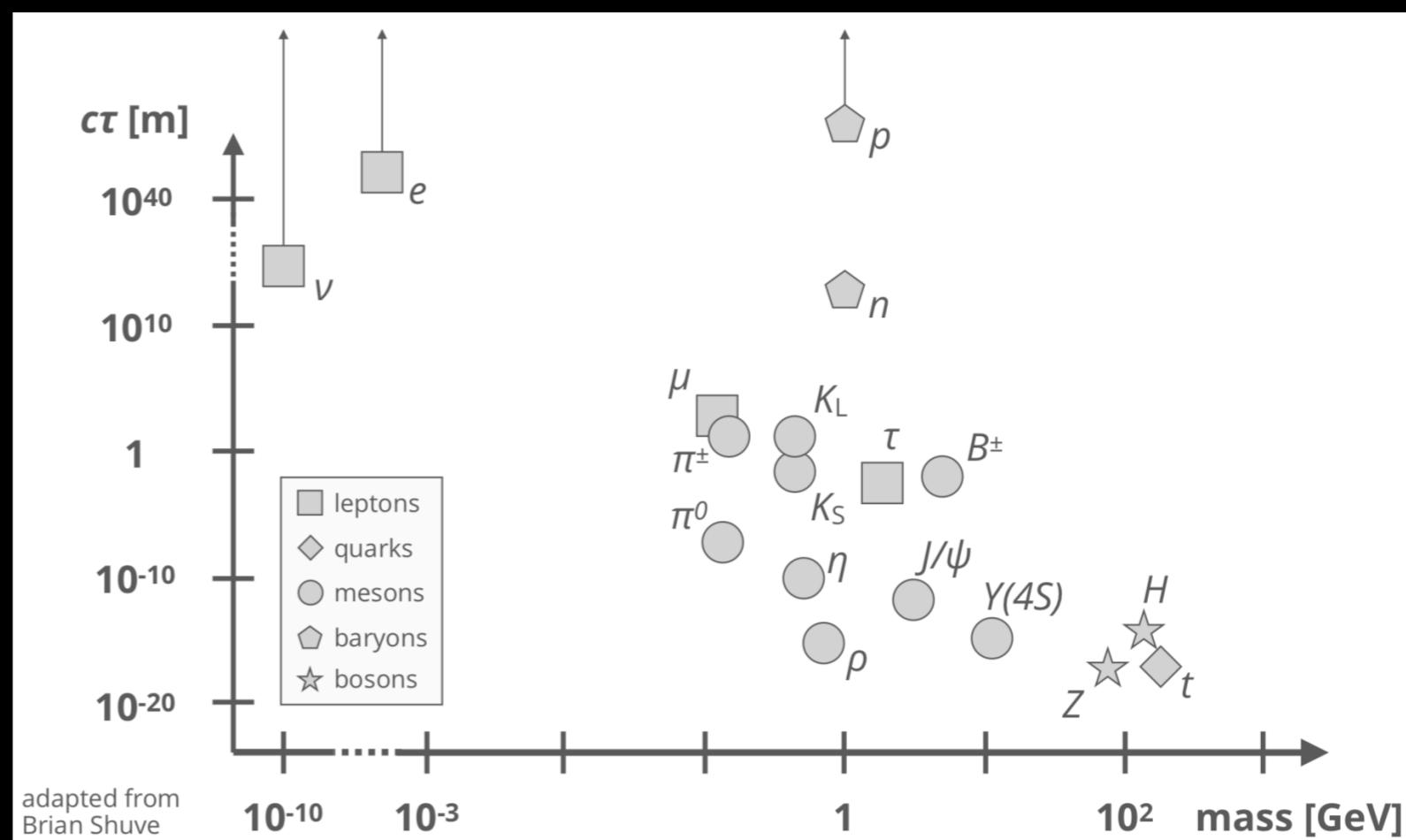
MTD design overview



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- MIP sensitivity with time resolution of ~30 ps
- Hermetic coverage for $|\eta| < 3$

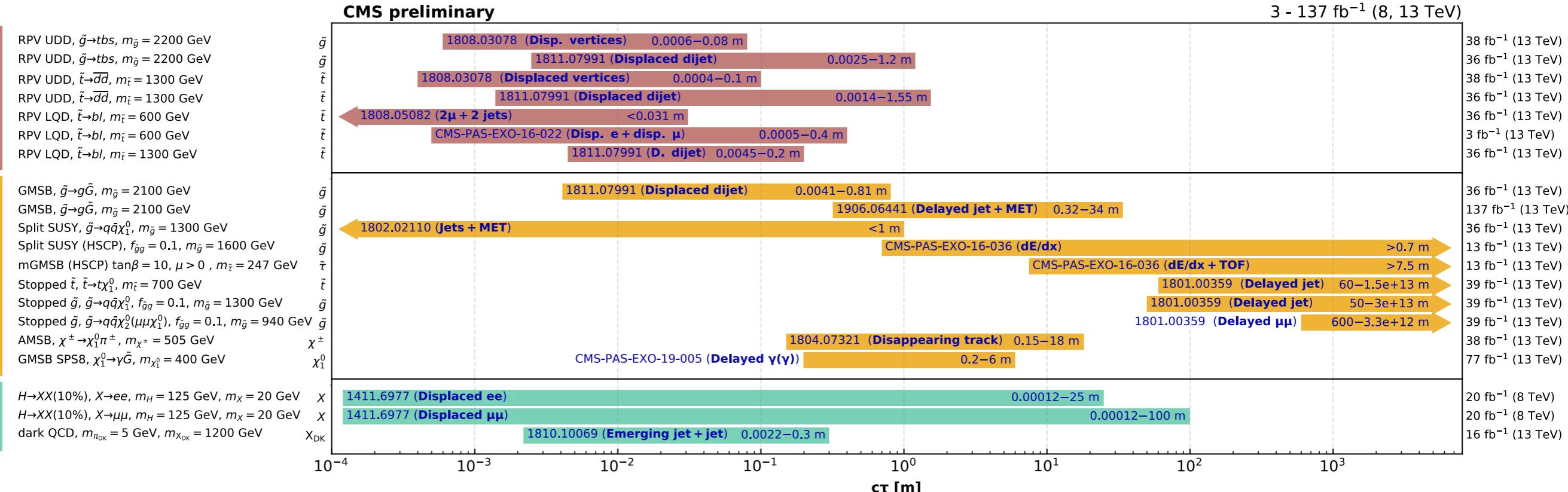
LLPs in General

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The Story So Far

Overview of CMS long-lived particle searches

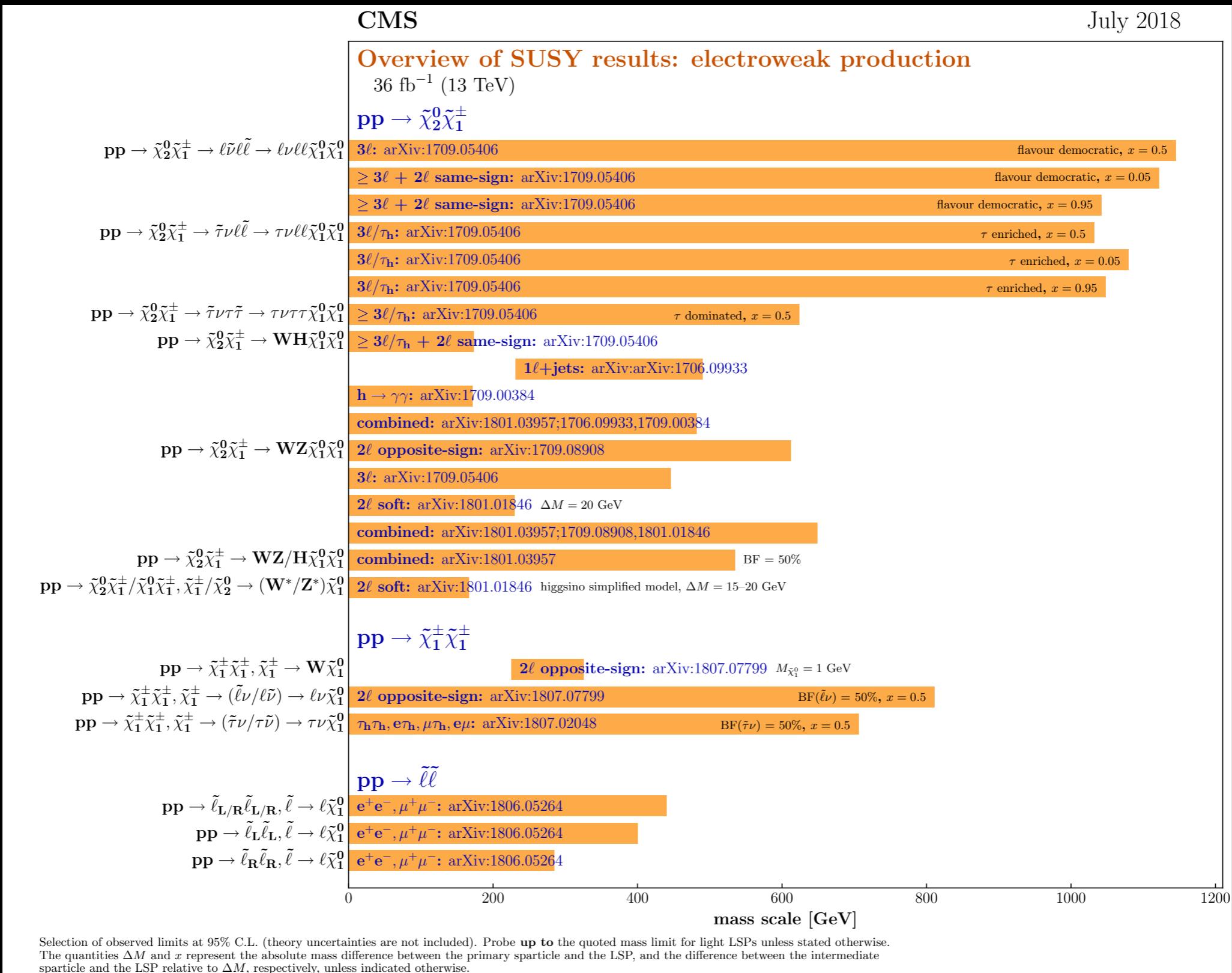


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

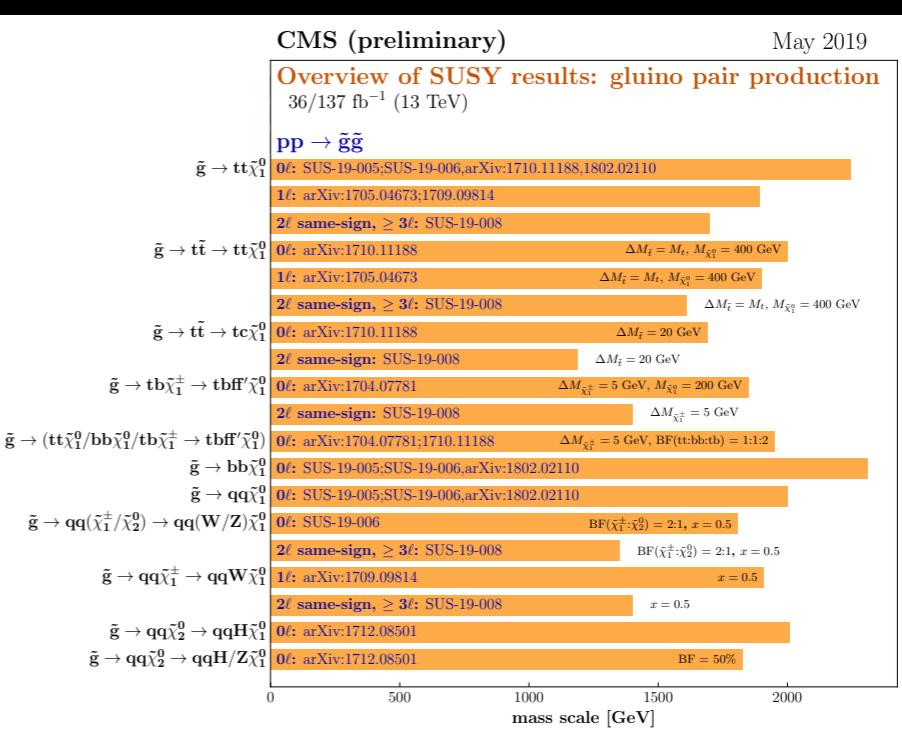
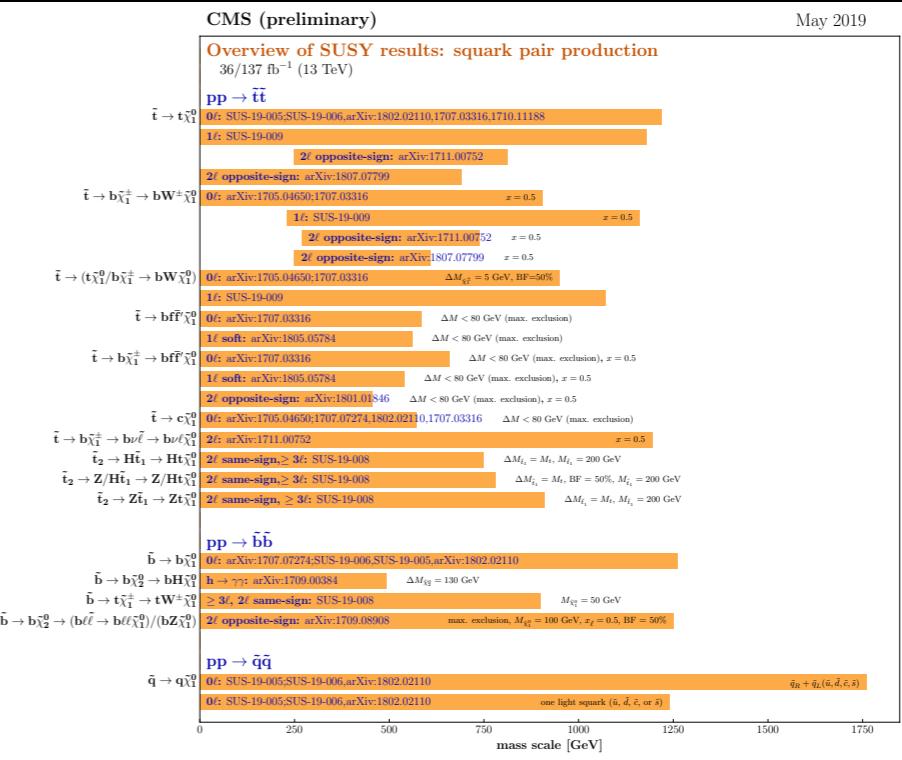
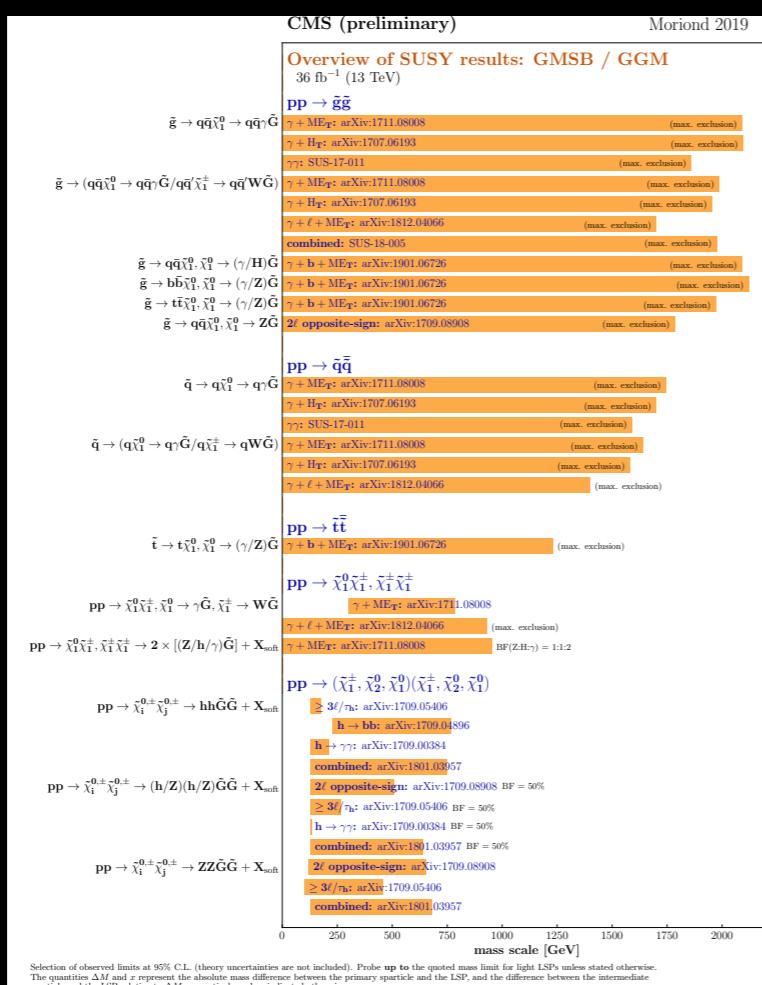
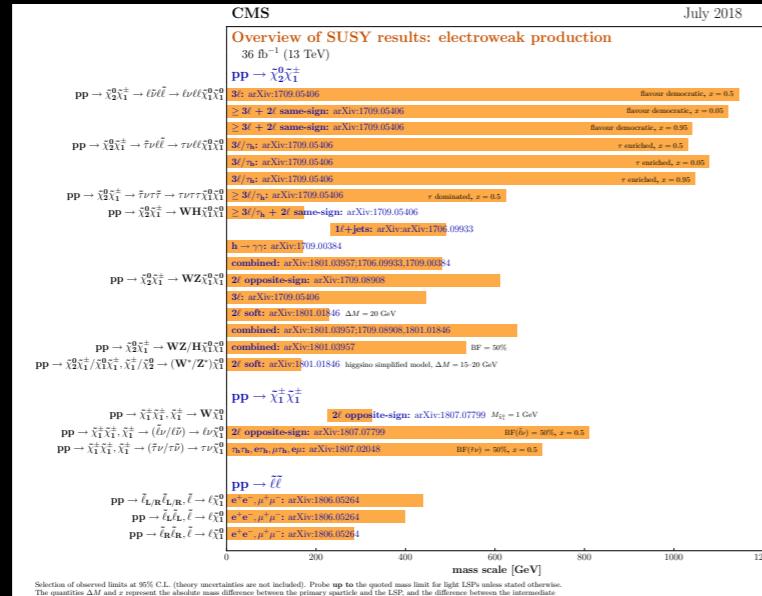
The Story So Far

CMS

July 2018

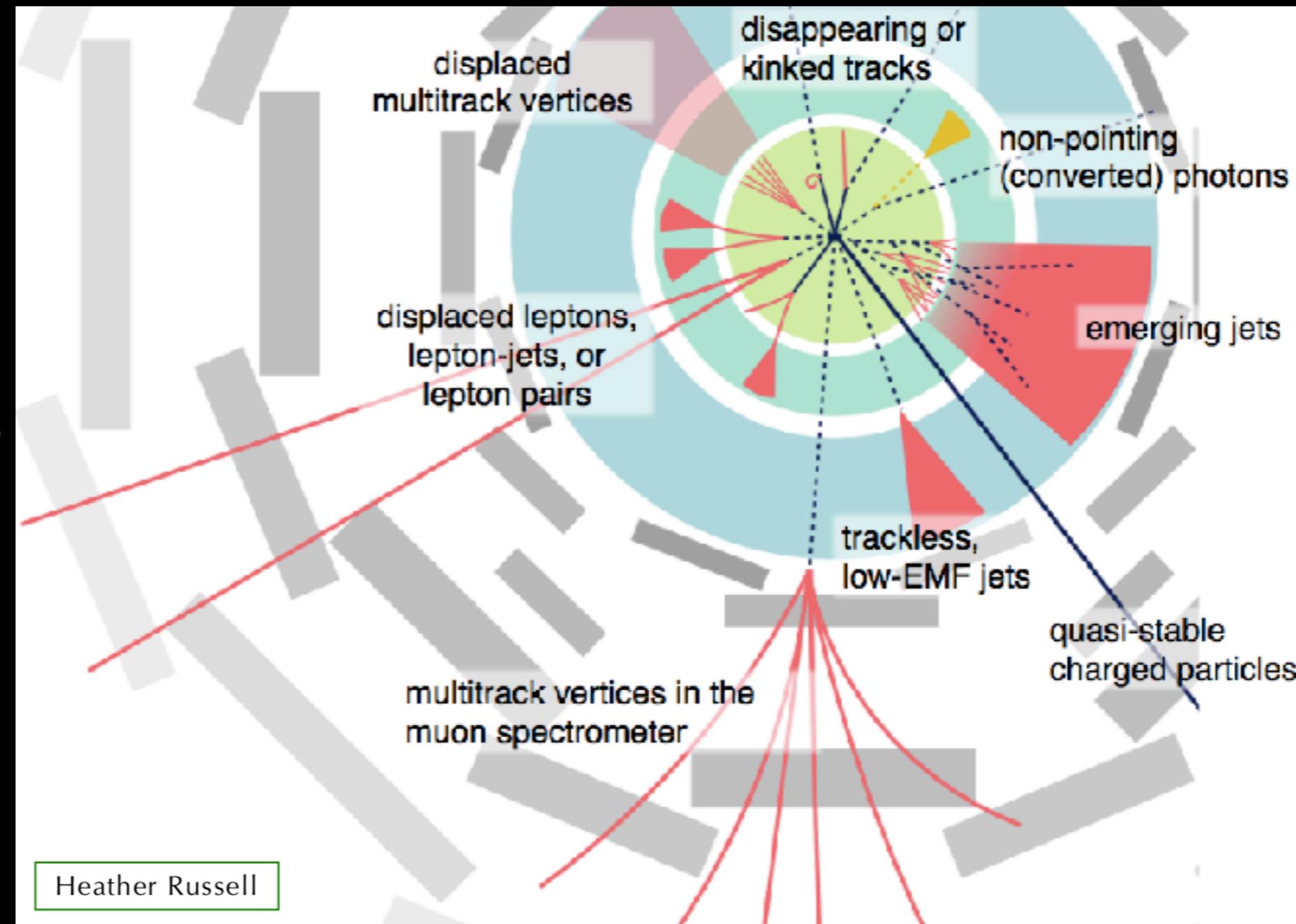


The Story So Far



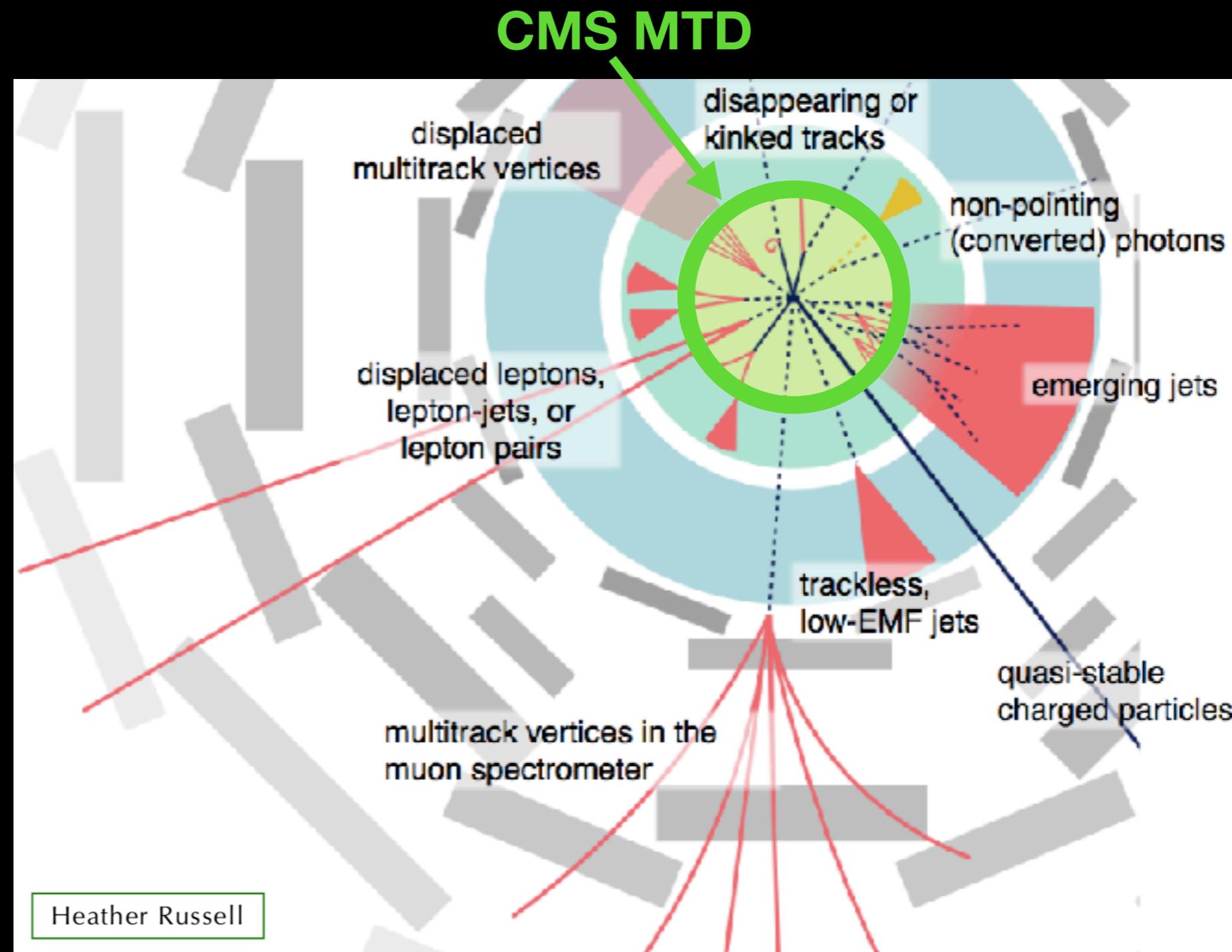
LLP searches at the LHC

- Multi-front Attack by CMS and ATLAS



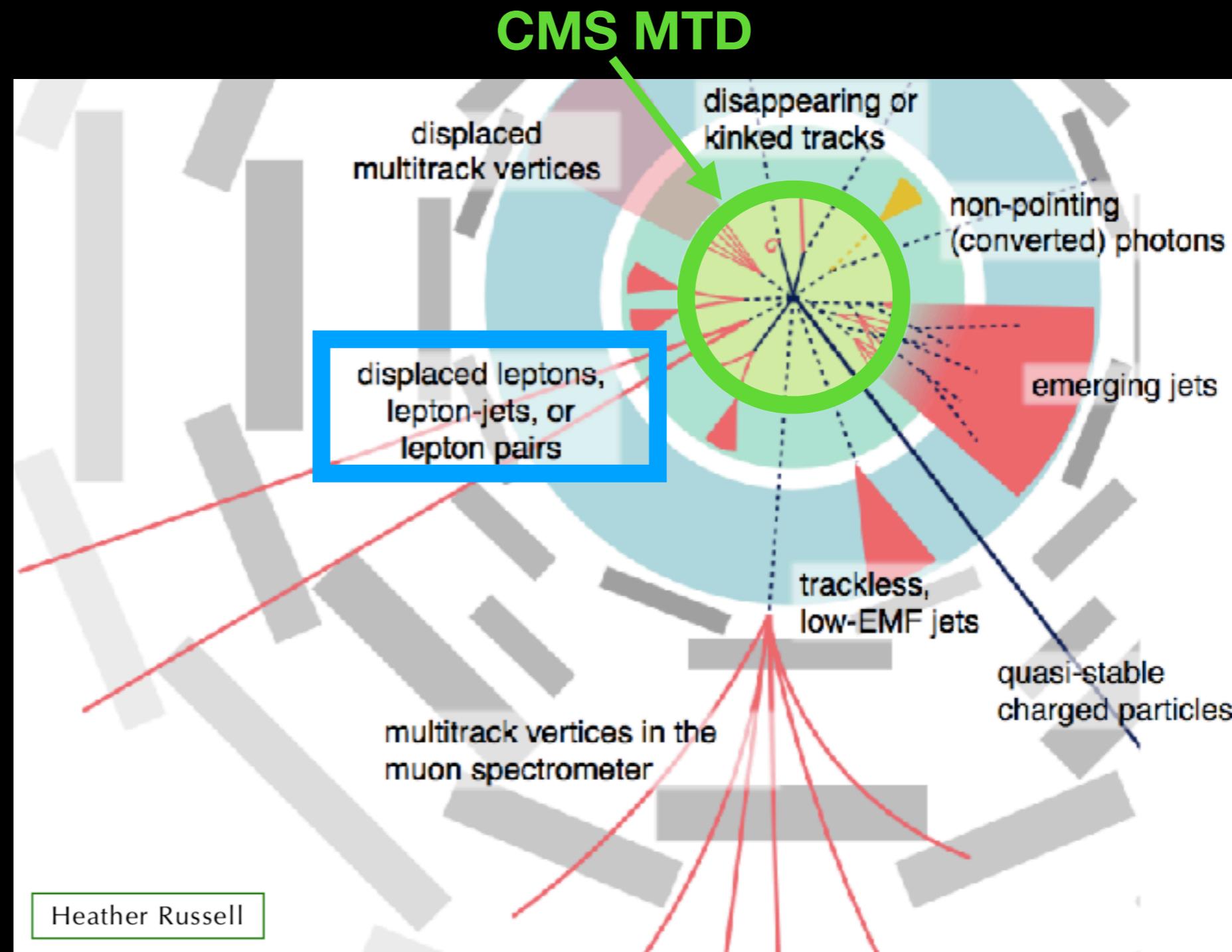
LLP searches at the LHC

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- Timing information can assist in these searches!



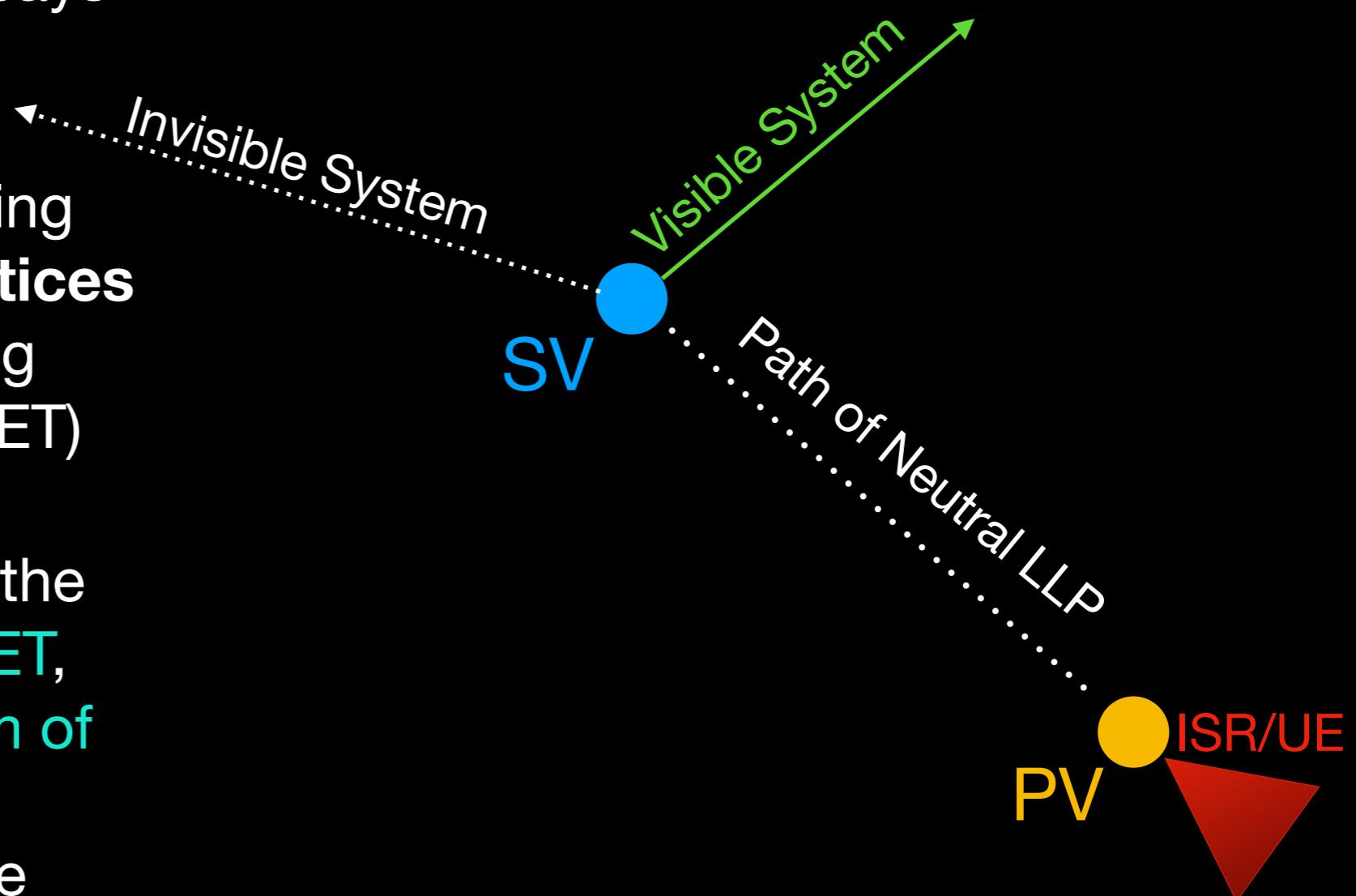
LLP searches at the LHC

- Multi-front Attack by CMS and ATLAS
- Timing information can assist in these searches!
- Focus on a particular case



Neutral LLP Topology

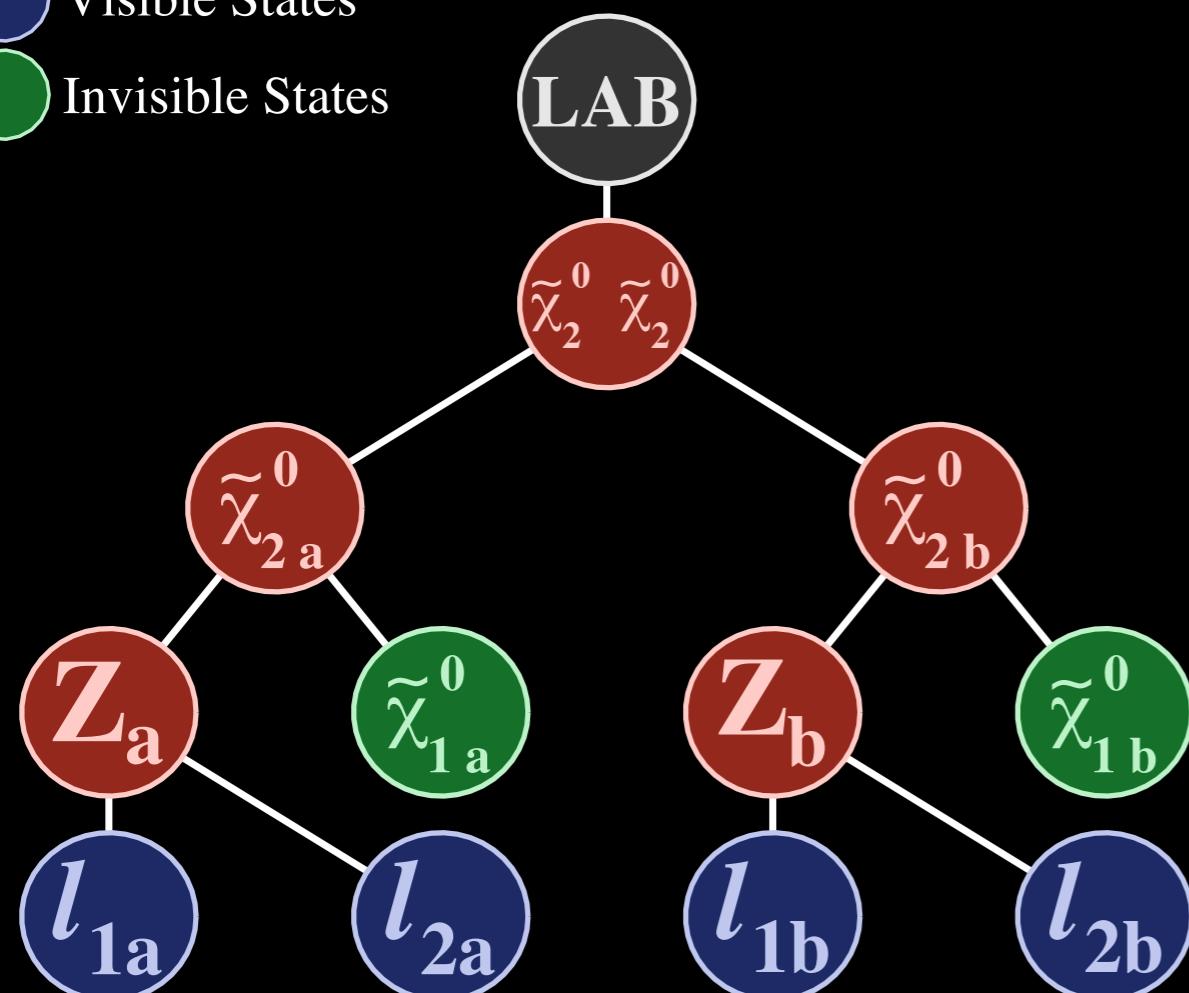
- Possibly most **difficult** to study something neutral that decays semi-invisibly
- Typically studied by counting **displaced secondary vertices** in events with large Missing Transverse Momentum (MET)
- However, just by knowing the **velocity** of the LLP, the **MET**, and the **energy/momentum** of the **visible system** we can **RECONSTRUCT** the entire event!



Details of this Study

- SUSY Electroweakinos
 - Masses of order **100s** of GeV and sometimes **compressed**
 - Detector smearing is modeled from a combination of MadGraph, Pythia and Delphes
 - Analysis is performed with RestFrames
 - Resolutions motivated by a public CMS HL-LHC run card from Delphes
 - Primary vertex resolution $\sim 20 \mu\text{m}$
 - Secondary vertex resolution $\sim 65 \mu\text{m}$
 - Timing resolution $\sim 30 \text{ ps}$ unless otherwise noted
 - Timing layer in CMS is **hermetic**

 Lab State
 Decay States
 Visible States
 Invisible States

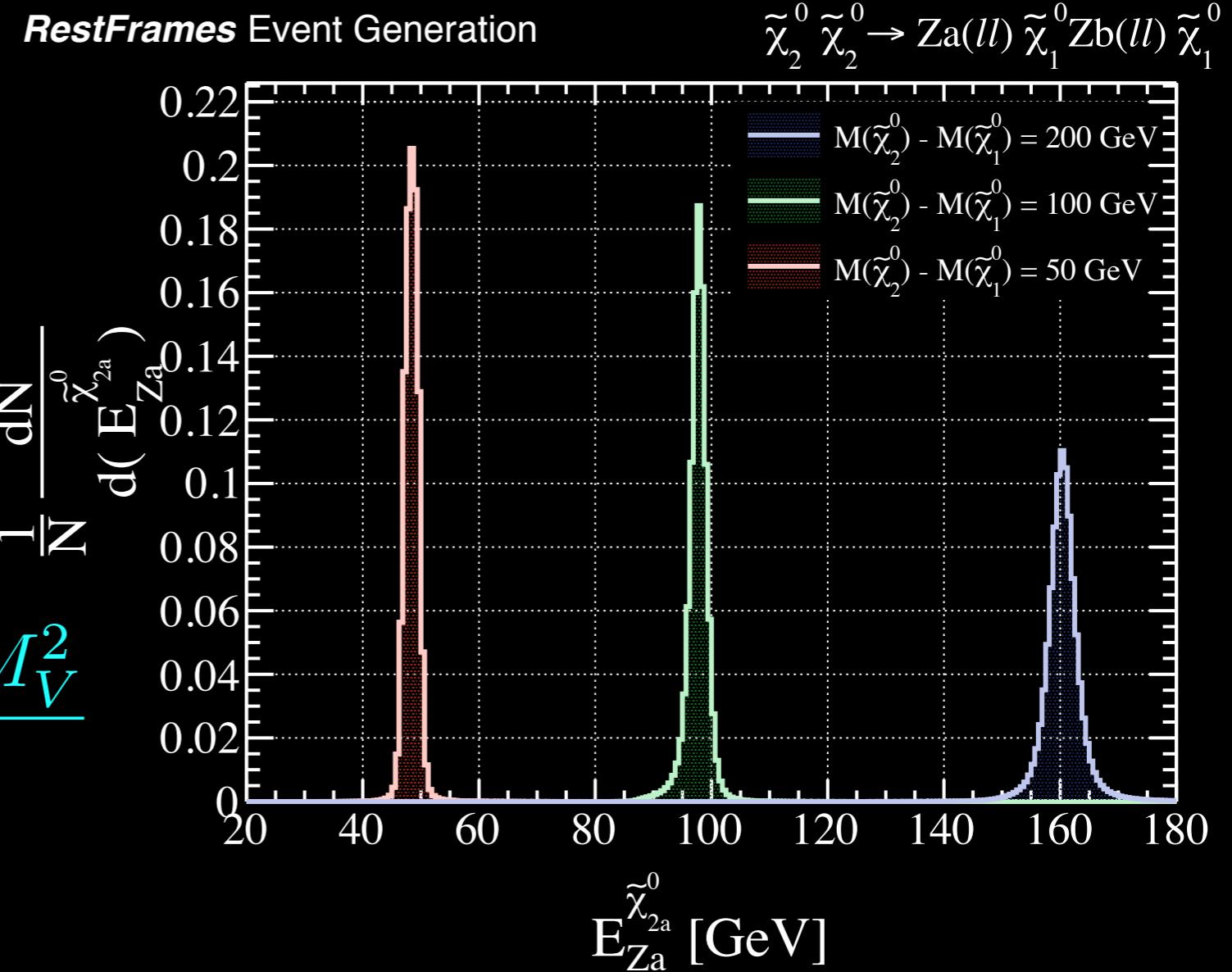


Mass Sensitive Variables

- With the **velocity** of the LLP particle we can evaluate things (like **energy**) in its rest frame

$$E_V^{LLP} \sim \frac{M_{LLP}^2 - M_{LSP}^2 + M_V^2}{2M_{LLP}}$$

Energy of the visible decay product evaluated in the LLP rest frame

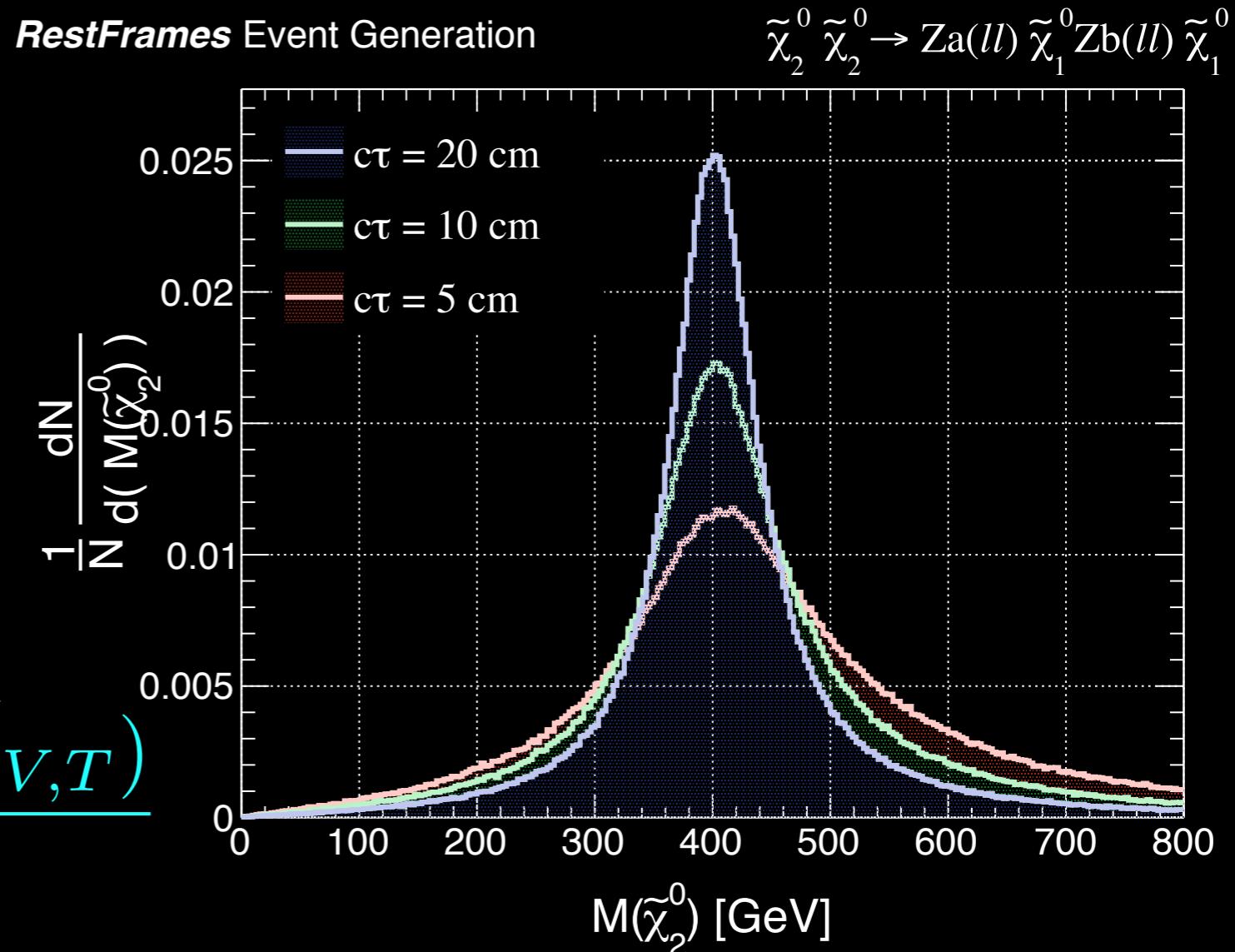


No assumption on the LSP or the other half of the event

Measuring Absolute Masses

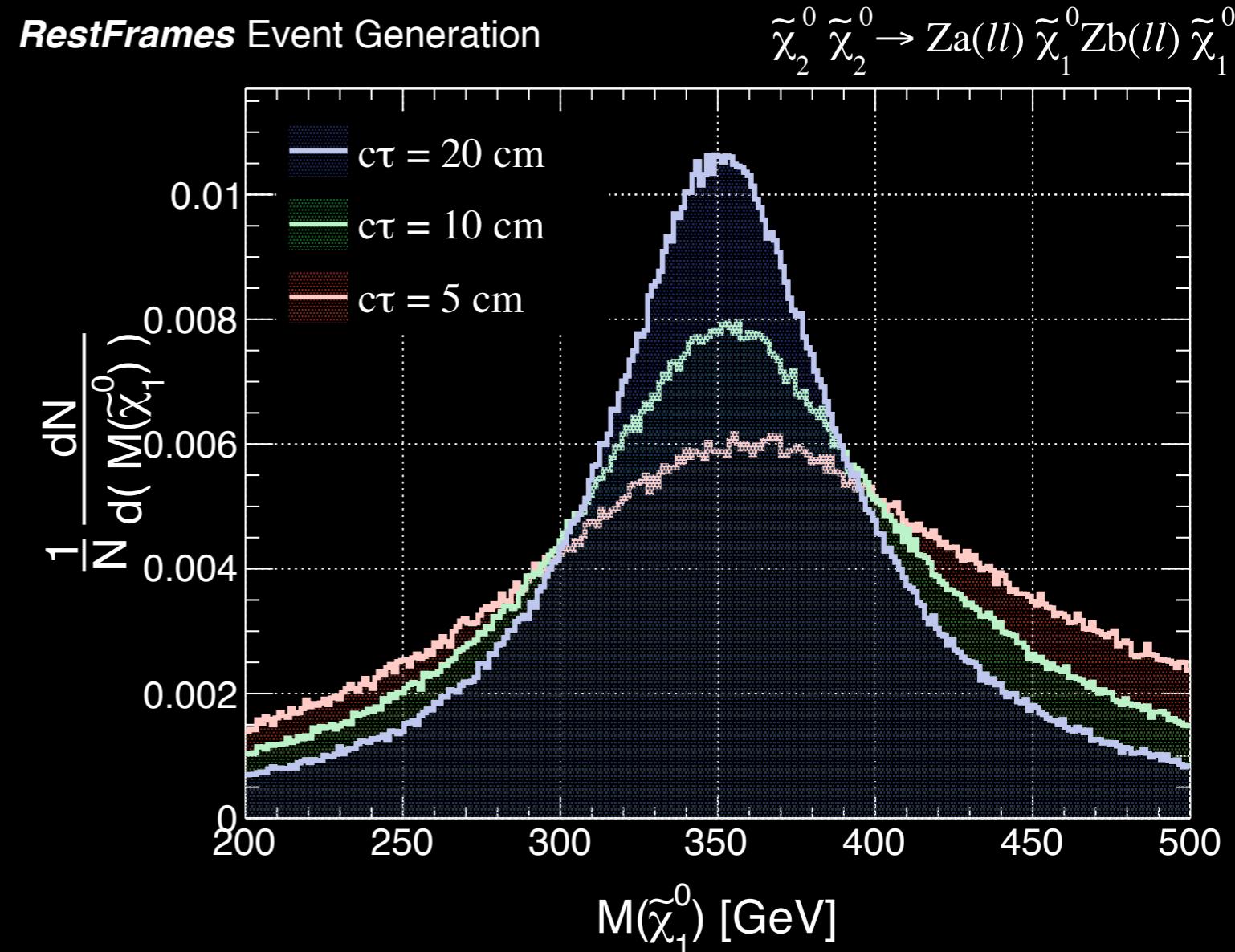
- By incorporating the measured **MET** we can now calculate an **absolute mass sensitive quantity**

$$M_{LLP} = \frac{\hat{\beta}_{LLP,T} \cdot (\vec{E}_T + \vec{P}_{V,T})}{\gamma_{LLP} |\vec{\beta}_{LLP,T}|}$$



Measuring Absolute Masses

- We can also **calculate** the **LSP** mass from the **previous** two quantities

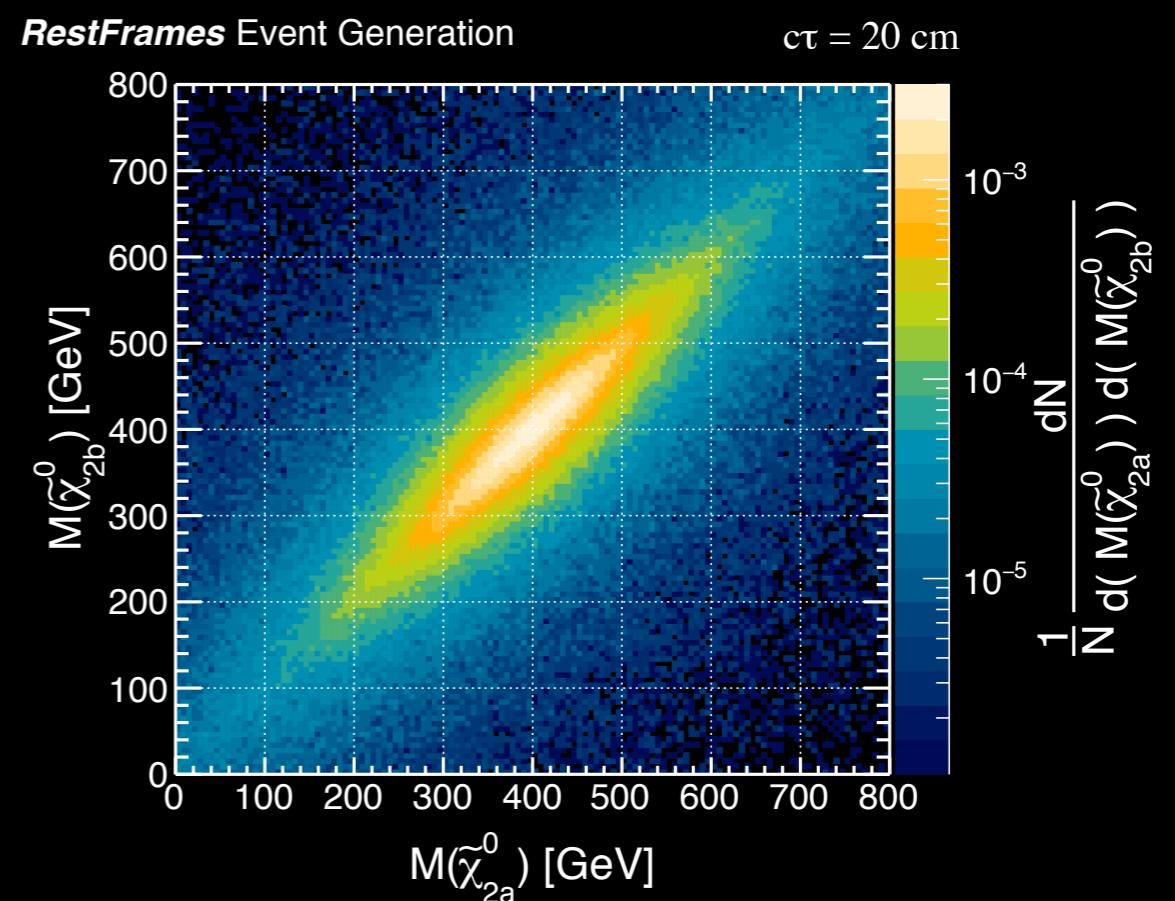
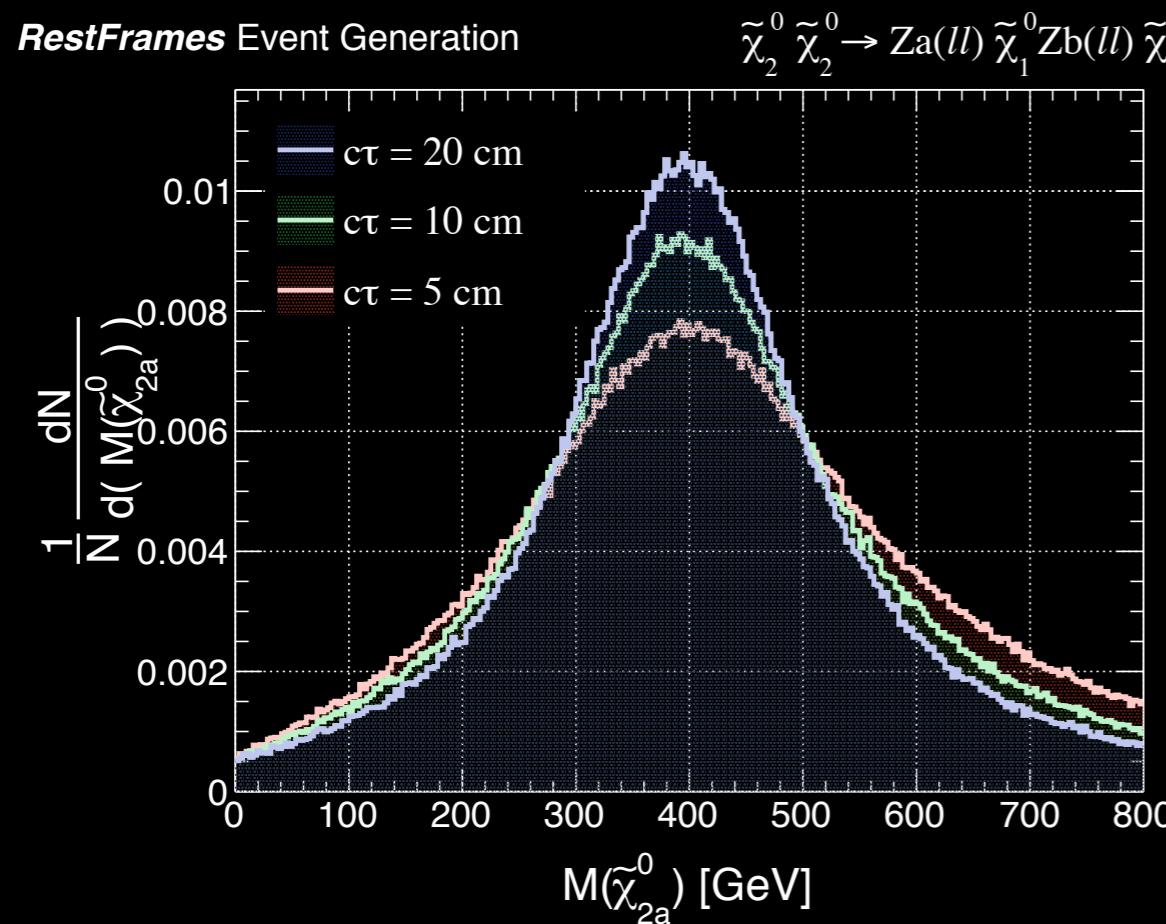


$$M_{LSP} = \sqrt{M_{LLP}^2 - 2M_{LLP}E_V^{LLP} + M_V^2}$$

Masses with two LLPs

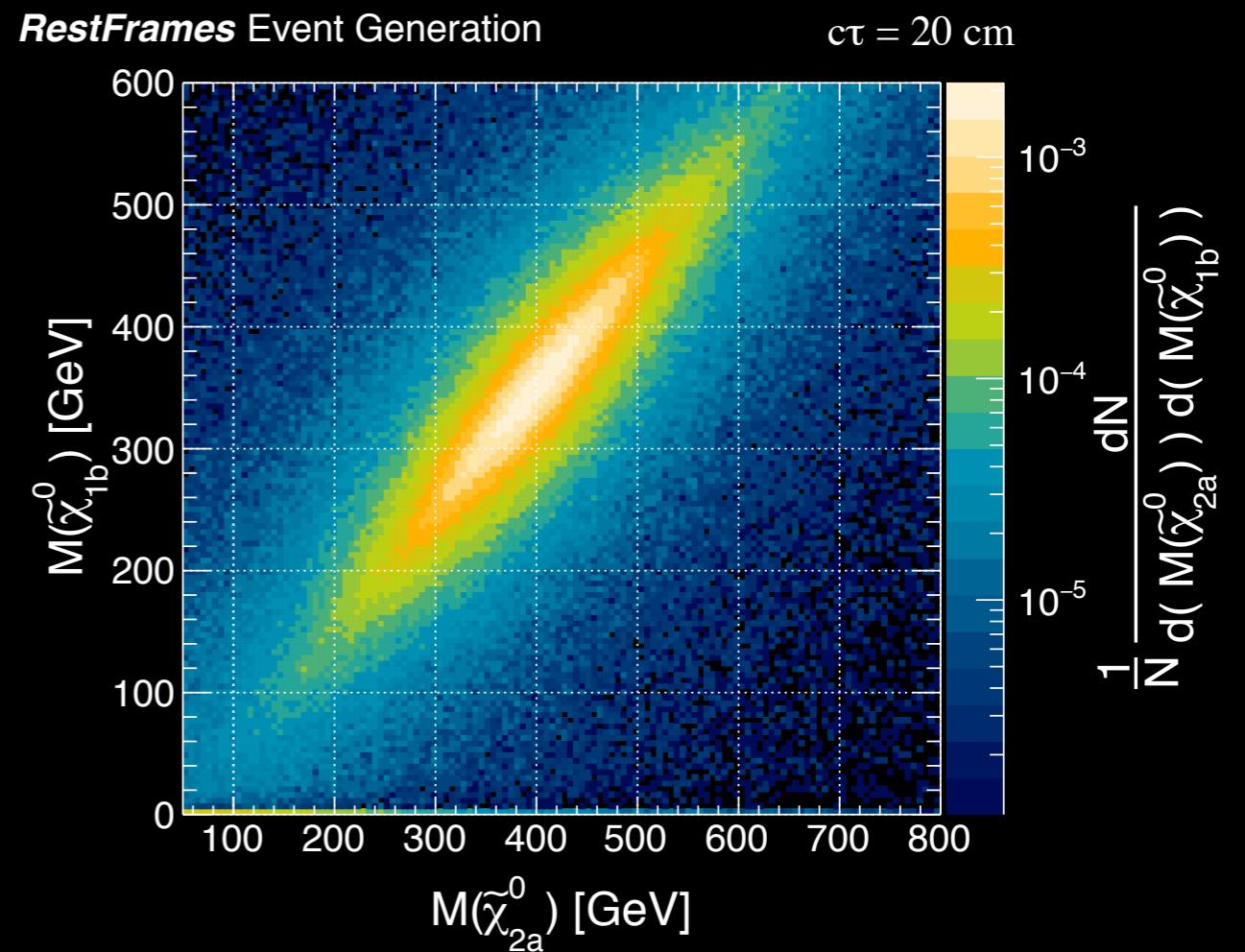
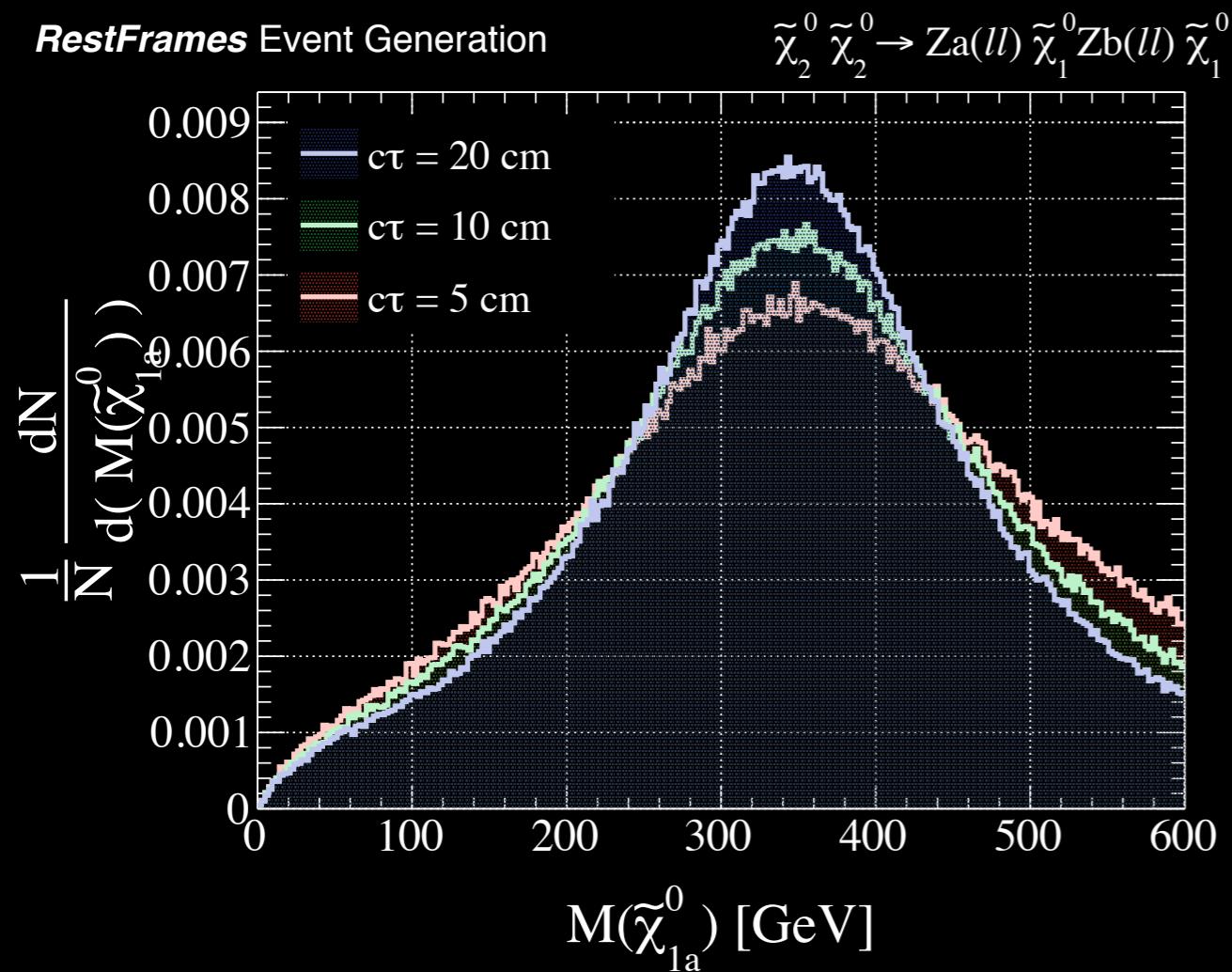
- Even with two LLPs we can still determine each LLP mass almost independently

$$M_{LLP_a} = \frac{(\overrightarrow{E}_T + \vec{P}_{V,T}) \times \hat{\beta}_{LLP_b,T} \cdot \hat{z}}{\gamma_{LLP} |\beta_{LLP_a,T}| (\hat{\beta}_{LLP_a,T} \times \hat{\beta}_{LLP_b,T}) \cdot \hat{z}}$$



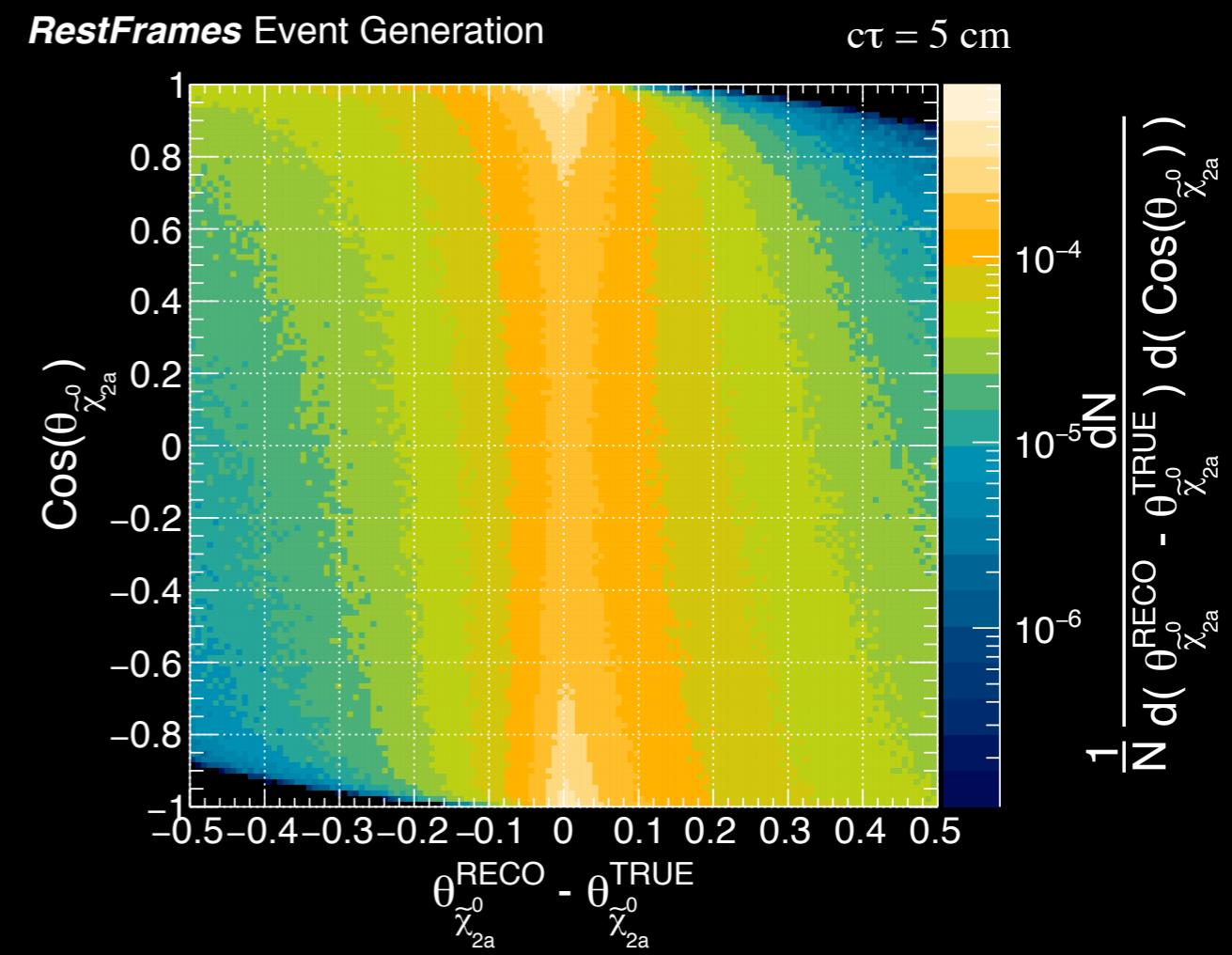
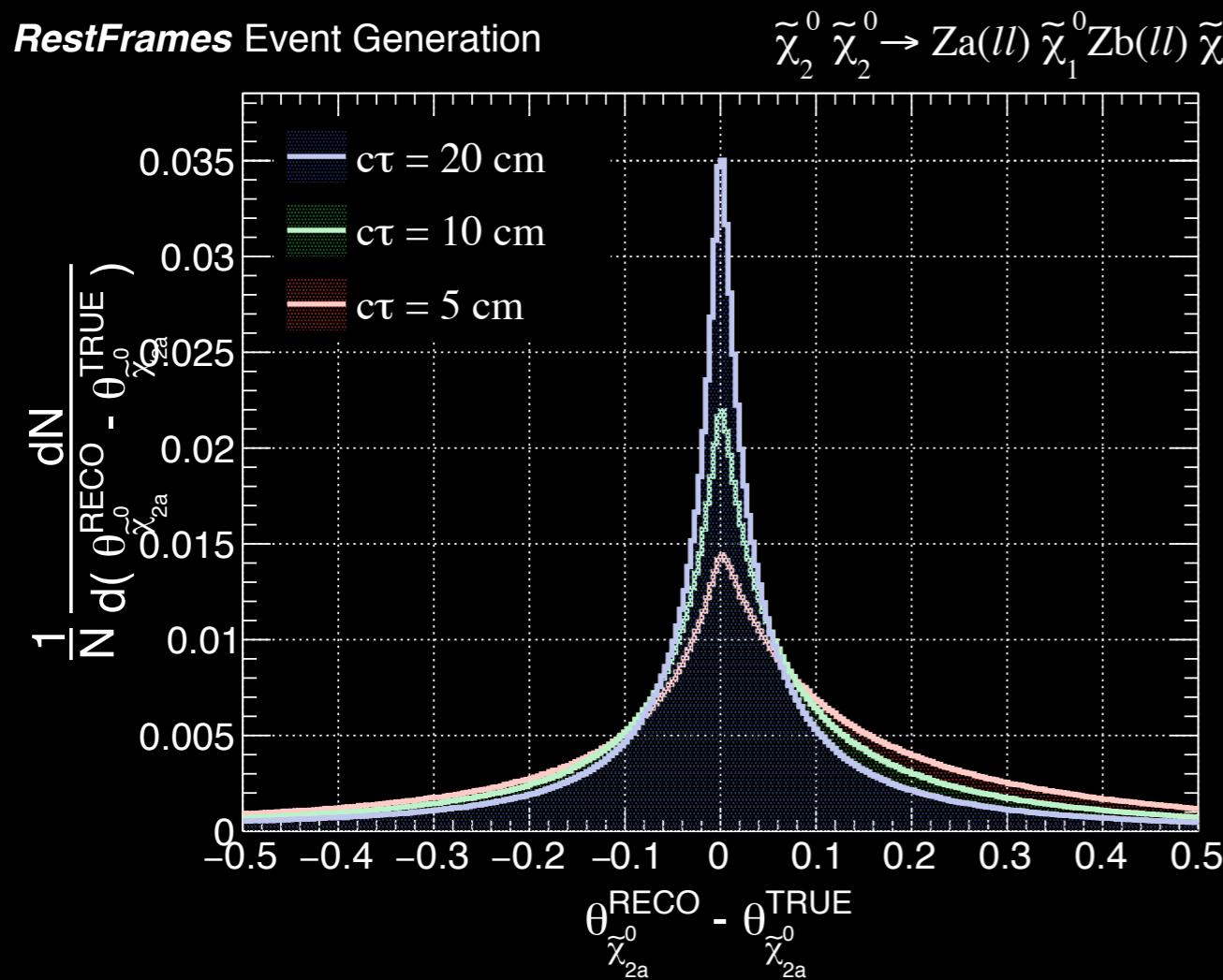
Masses with two LLPs

- Even with two LLPs we can still determine each LSP mass almost independently



Full Event Reconstruction

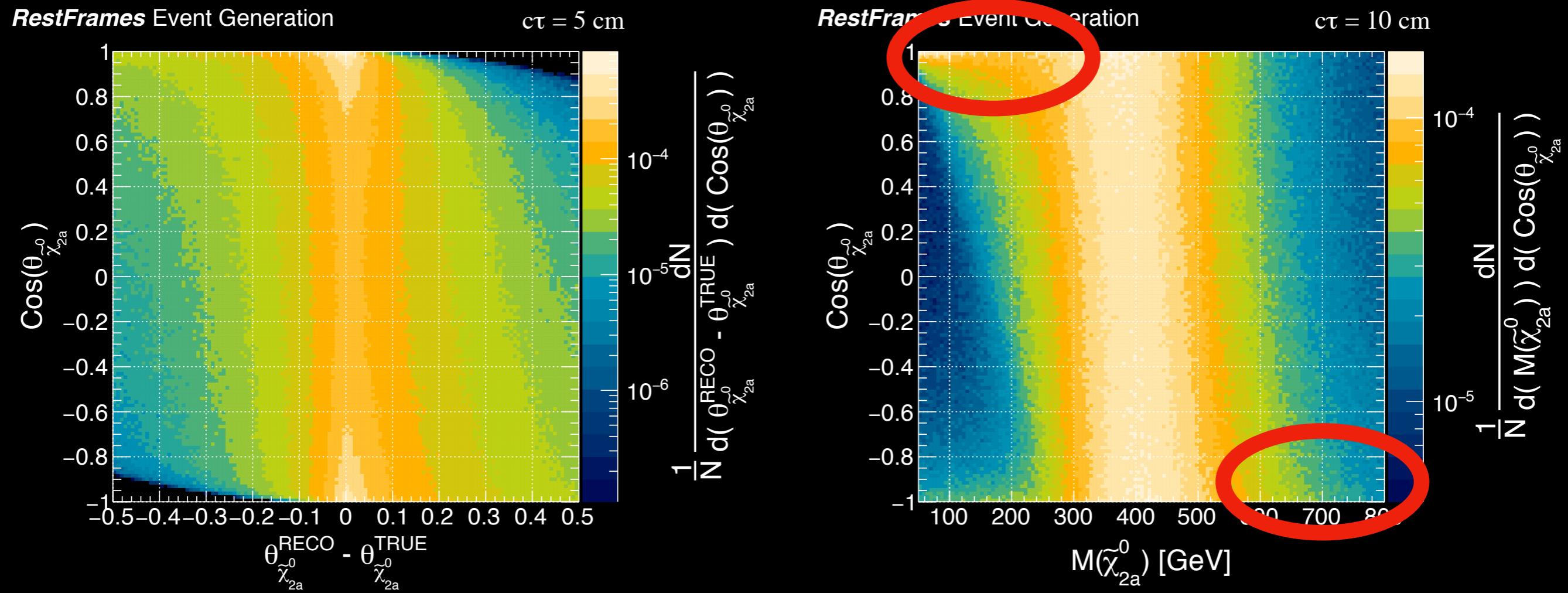
- Masses are the most interesting quantity but we can also measure the decay angles



- LLP Mass = 400 GeV, LSP Mass = 350 GeV

Full Event Reconstruction

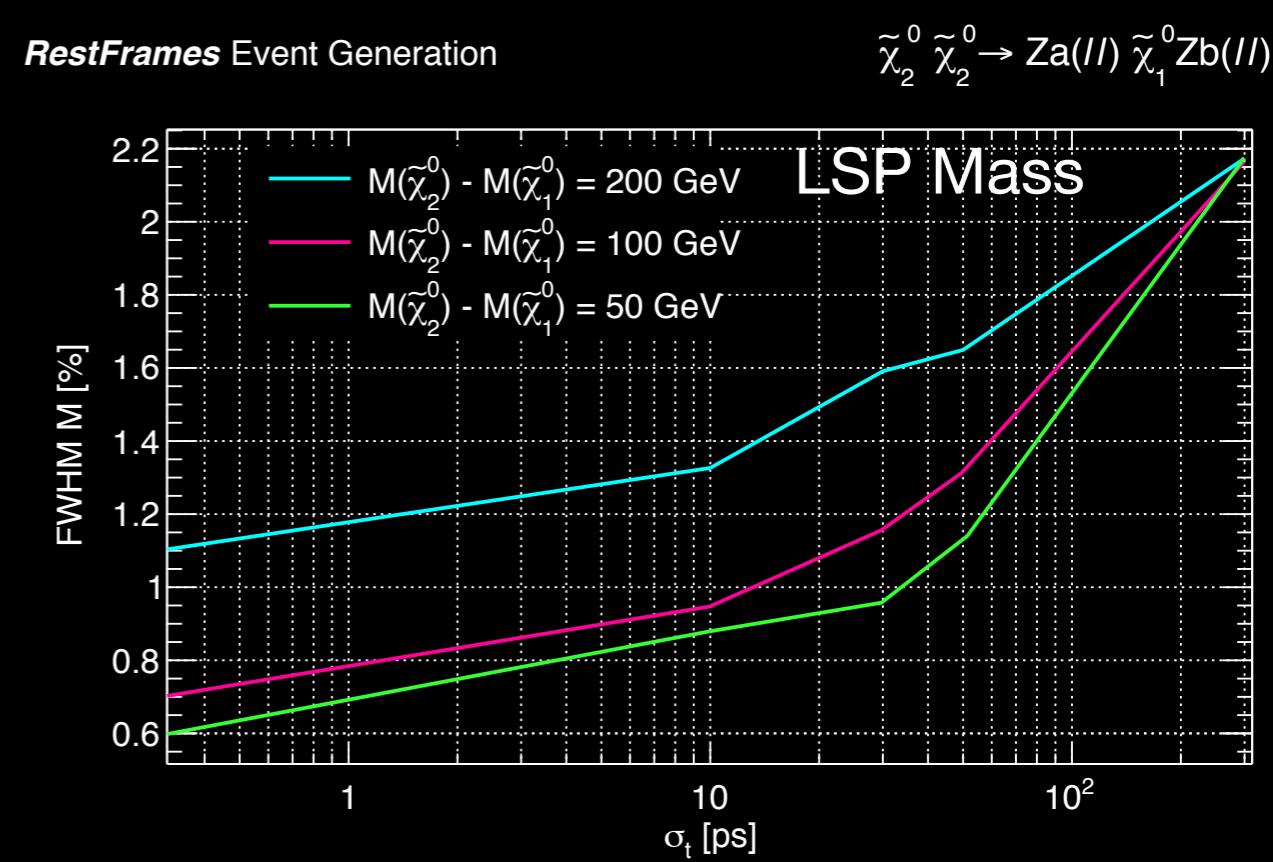
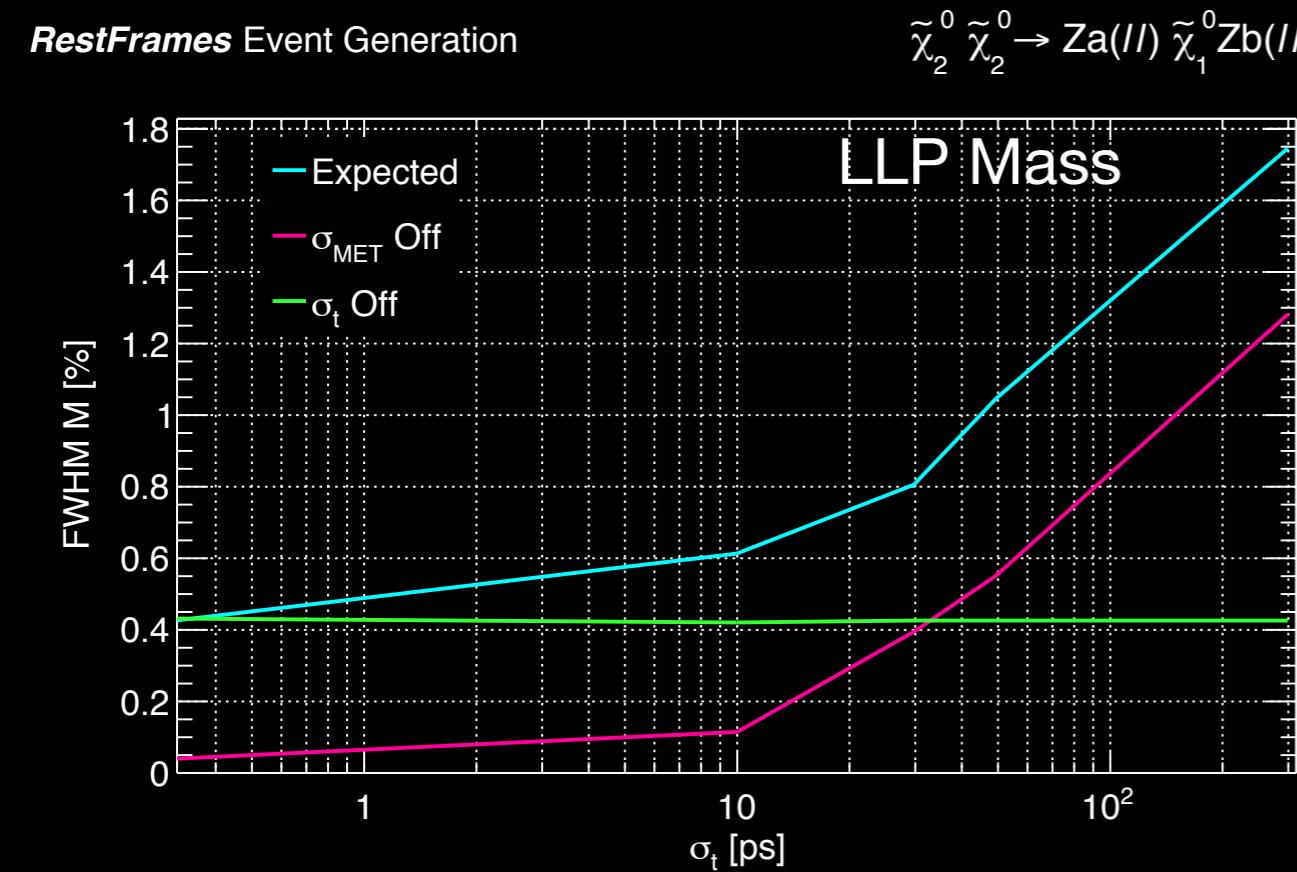
- Masses are the most interesting quantity but we can also measure the decay angles
- The cosine of one of these angles is correlated with mis-measured events



- LLP Mass = 400 GeV, LSP Mass = 350 GeV

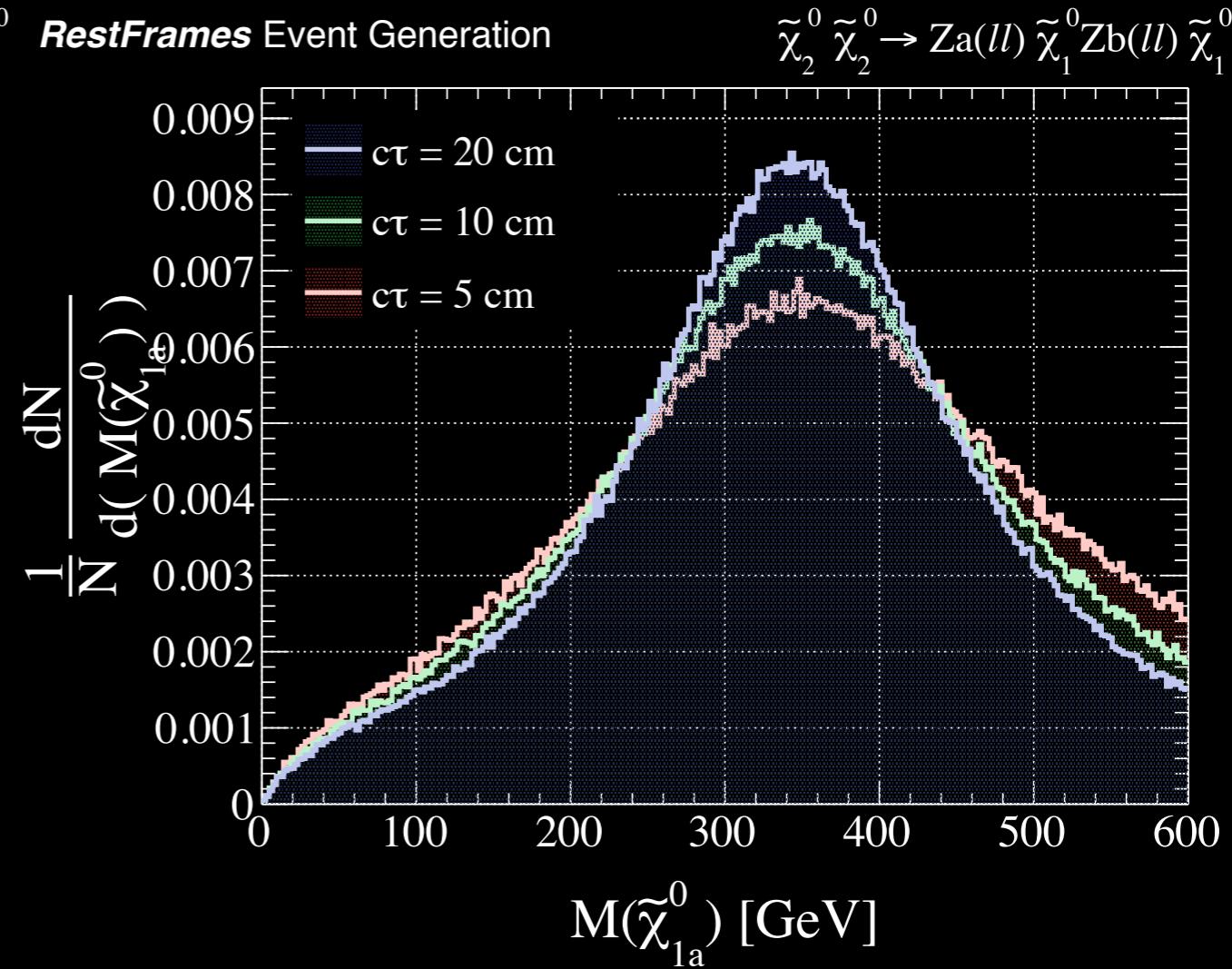
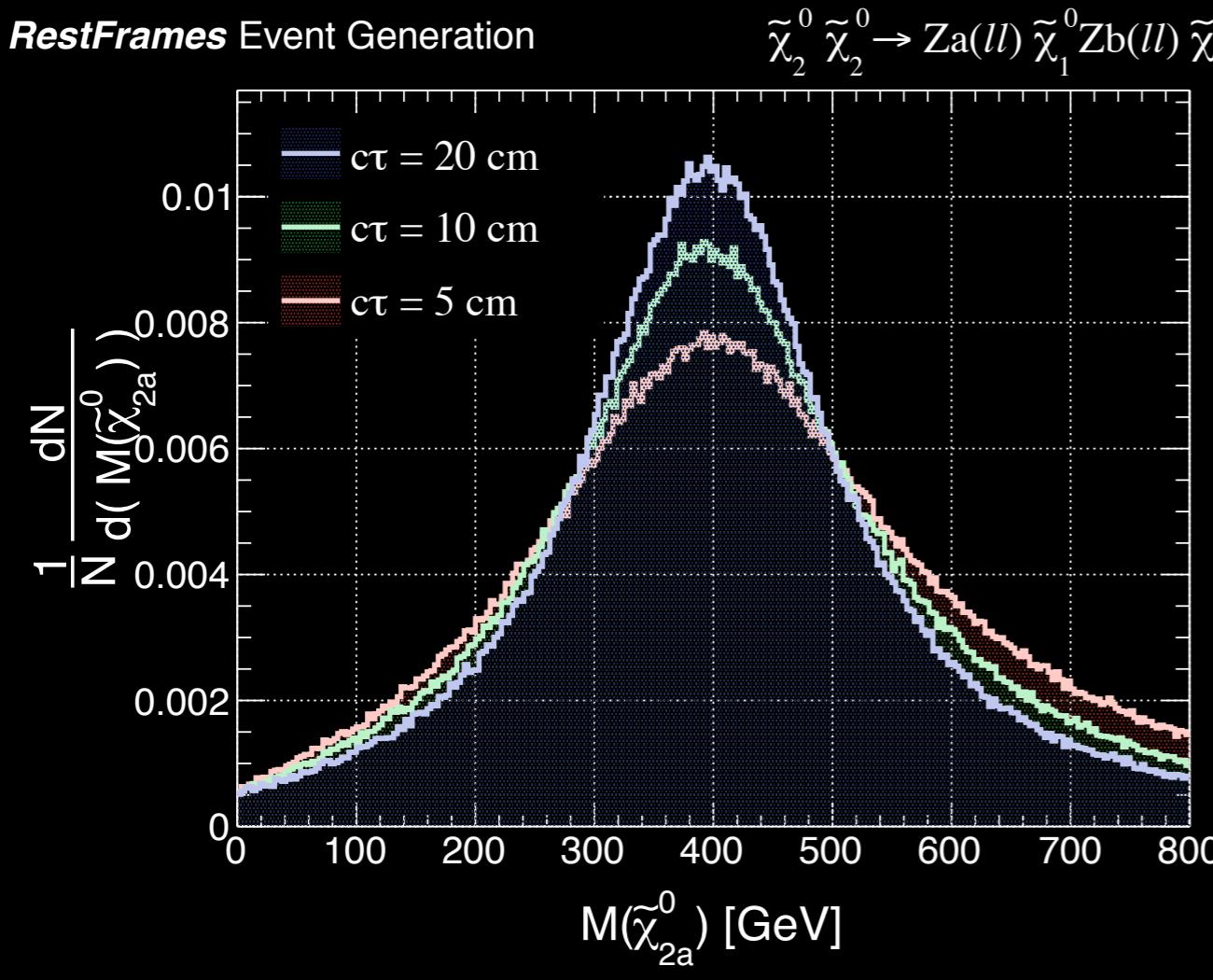
Relative Mass Resolution

- Evaluated the mass resolution as a function of timing resolution and other uncertainties
 - 30 ps** time resolution is well motivated by these results!
 - LSP mass resolution **improves** for larger LSP masses



Outlook

- Hermetic precision timing detectors during the HL-LHC will provide new information
- With timing information we are able to measure and see LLP masses in previously under-constrained final states
 - Now, counting experiments can become bump hunts!



Summary

- With **new** information we can **reconstruct** events that were previously **under-constrained**
- In addition to **determining masses** in events with neutral LLPs, this study has quantified how the performance of the mass reconstruction depends on **timing resolution**
- Future work will consider how to best confront **backgrounds** and incorporate full detector effects

Reconstruction Efficiency

