A primer to Long-Lived Particle phenomenology

Eric Conte (GRPHE-IPHC)

IRN Terascale
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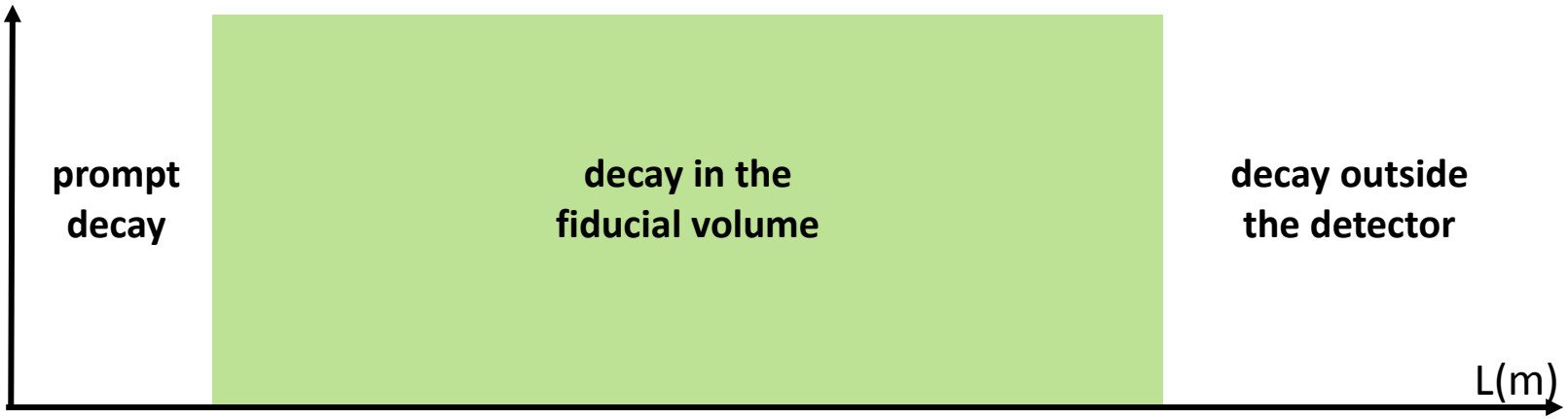
Introduction

What is a LLP (Long-Lived particle) for ATLAS and CMS?



Why LLP?

Currently no hint of New Physics at LHC!

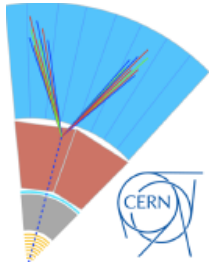
→ Explore ways that new physics could have escaped the attention of all these searches.

→ As most searches assume promptly decaying new particles, LLP can be a good way.

LLP Community Workshop

2 workshop in 2017 (CERN and Trieste) gathering CMS, ATLAS and LHCb

Goal: recommendations and guide lines for experiments (white paper)



Outlines

1. LLP in BSM models
2. Experimental signatures
3. Experimental selections
4. Reinterpretation issues

Outlines

1. **LLP in BSM models**
2. **Experimental signatures**
3. **Experimental selections**
4. **Reinterpretation issues**

(Displaced) supersymmetry

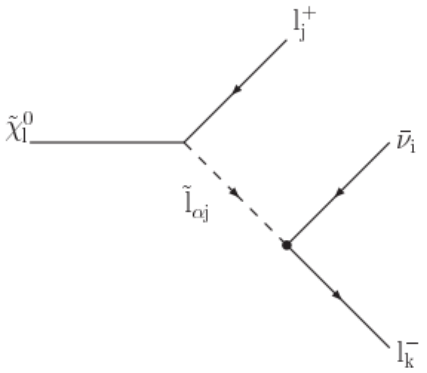
- **RPV-Supersymmetry:**

R-parity conservation is added for conserving L and B numbers.
→ R-parity violation : adding terms to superpotential

$$W_{\Delta B\neq 0} = \frac{1}{2}\lambda''_{\{ijk\}} U_i D_j D_k \text{ and } W_{\Delta L\neq 0} = \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk}\, L_i Q_j D_k + \epsilon_i L_i H_u$$

Phenomenological consequences: **the LSP is not stable**
Several possible kinds of LLP according to the the nature of LSP (neutralino, stop, …)

Ex:



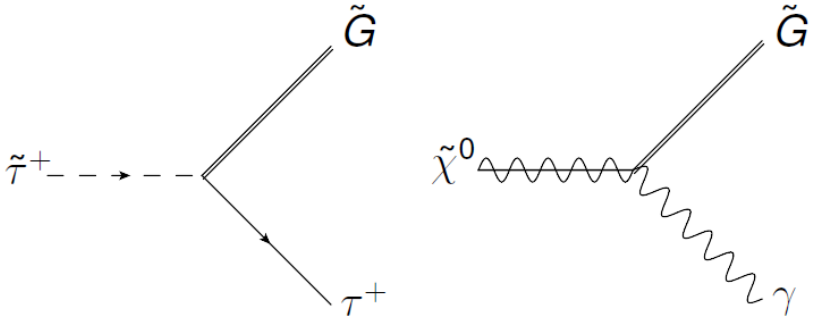
(Displaced) supersymmetry

- **AMSB (Anomaly Mediated Supersymmetry Breaking):**

  Some scenarios where the NSLP and LSP are very close in mass.
  Ex: LSP = $\widetilde{\chi_1^0}$ and NLSP = $\widetilde{\chi_1^+}$ and with ΔM ~ 160 MeV
  Only possible decay: $\widetilde{\chi_1^+} \rightarrow \widetilde{\chi_1^0} + \pi^+$
  → NLSP = LLP

- **GMSB (Gauge Mediated Supersymmetry Breaking):**

  - LSP = gravitino
  - Decays to gravitino suppressed by SUSY-breaking scale

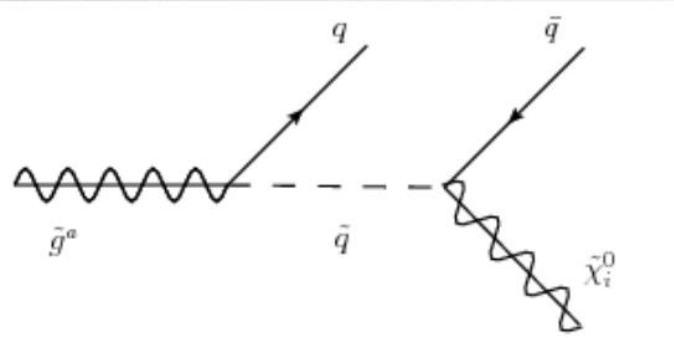


(Displaced) supersymmetry

- **Split Supersymmetry:**
  - All scalars but the SM higgs have a heavy mass.
  - Gluino, neutralinos and charginos have a low mass.

  Phenomenological consequences:
  - Gluinos are long-lived because they decay by heavy virtual squarks
  - Possible decays: $\tilde{g} \to \widetilde{\chi_1^0} q\bar{q}, \tilde{g} \to \widetilde{\chi_1^\pm} q\bar{q}', \tilde{g} \to \widetilde{\chi_1^0} g$

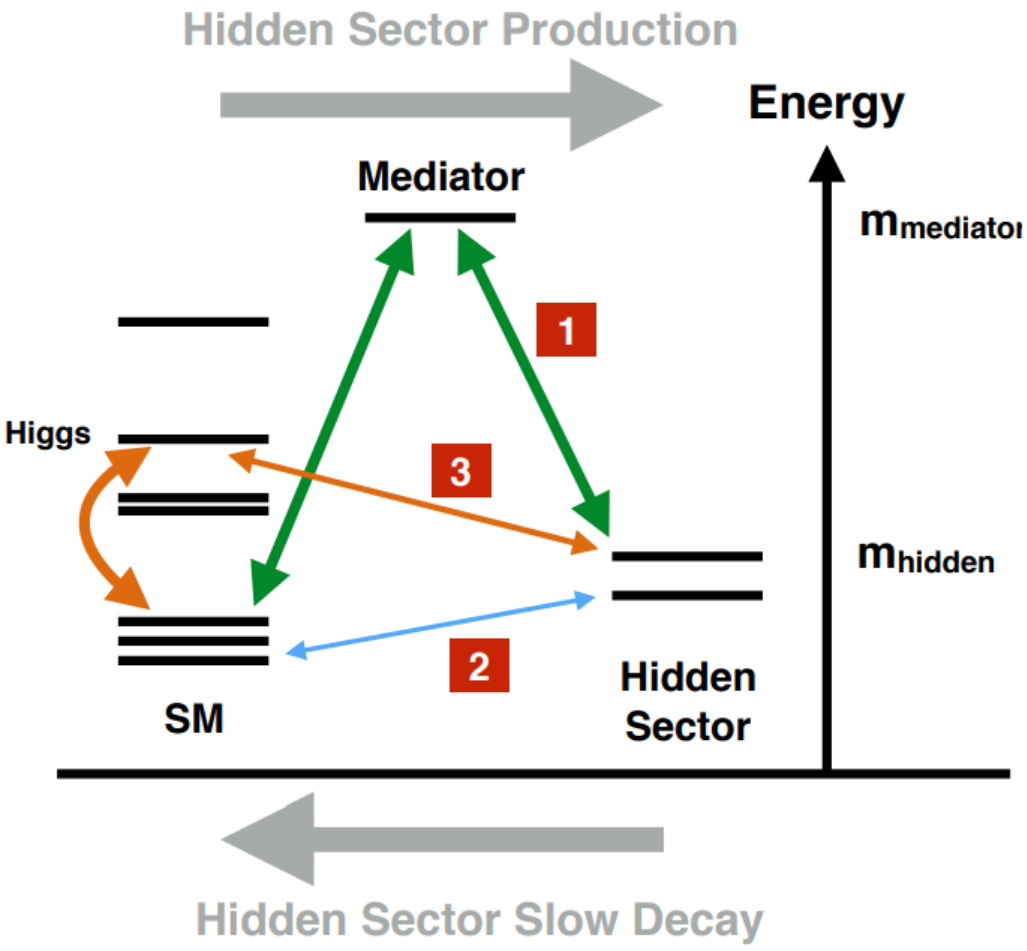
  → R-hadron



1.LLP in BSM models

Hidden sectors

arXiv:1702.02524 [hep-ph]s



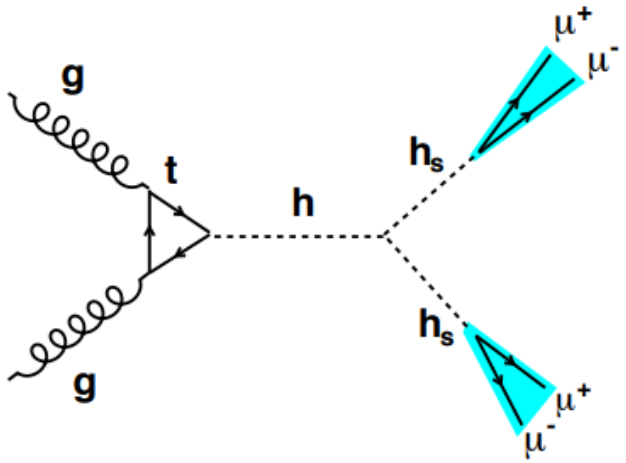
- New physics could lie at M_{hidden} < TeV hidden by small coupling to SM
  → **hidden sector**
- Hidden sectors can be connected to the SM via small effective couplings
  → **portals:**
  - By the production and decay of a heavy non-SM mediator
  - By small direct coupling
  - By exotic decay of the Higgs boson
- Portals = LLP

Hidden sectors

Several possible portal. Some examples:

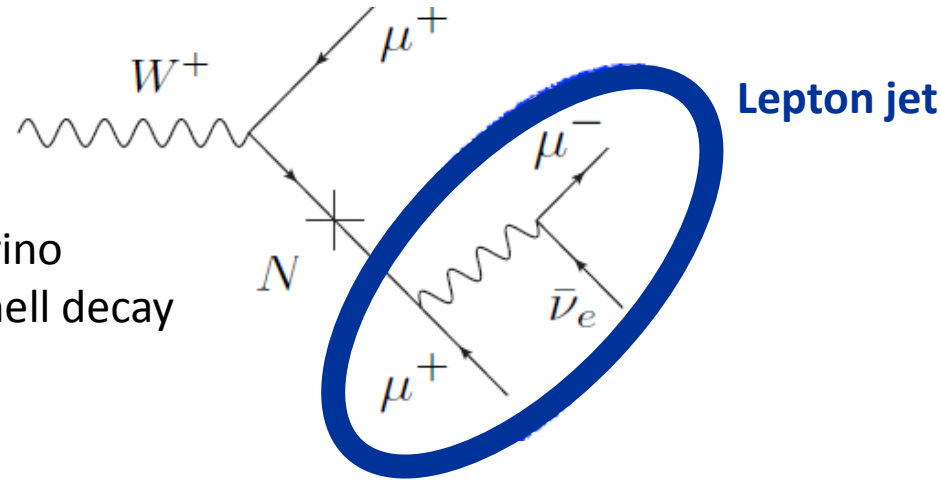
- **Higgs portal**

  the Higgs boson can decay into a pair of new scalar bosons



- **Neutrino portal**

  Heavy, right-handed neutrino
  Long lifetime due to off-shell decay



Lepton jet

Outlines

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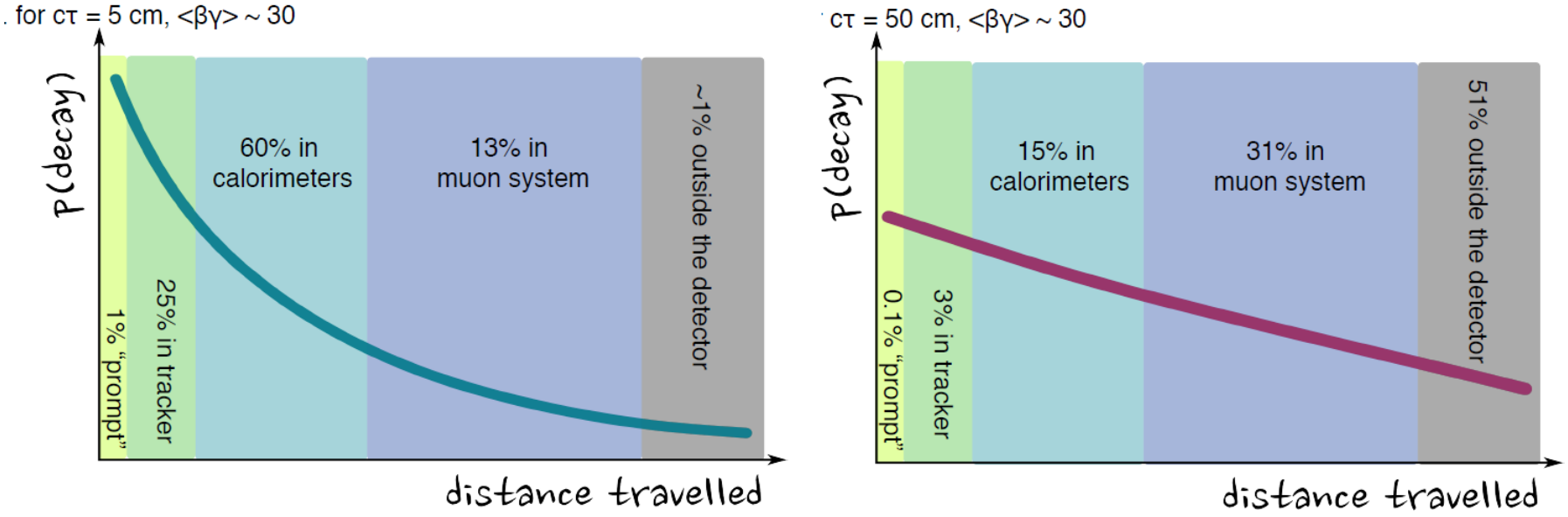
4. Reinterpretation issues

2.Experimental signatures

Search strategy is strongly-dependent on the proper lifetime and the boost of the LLP

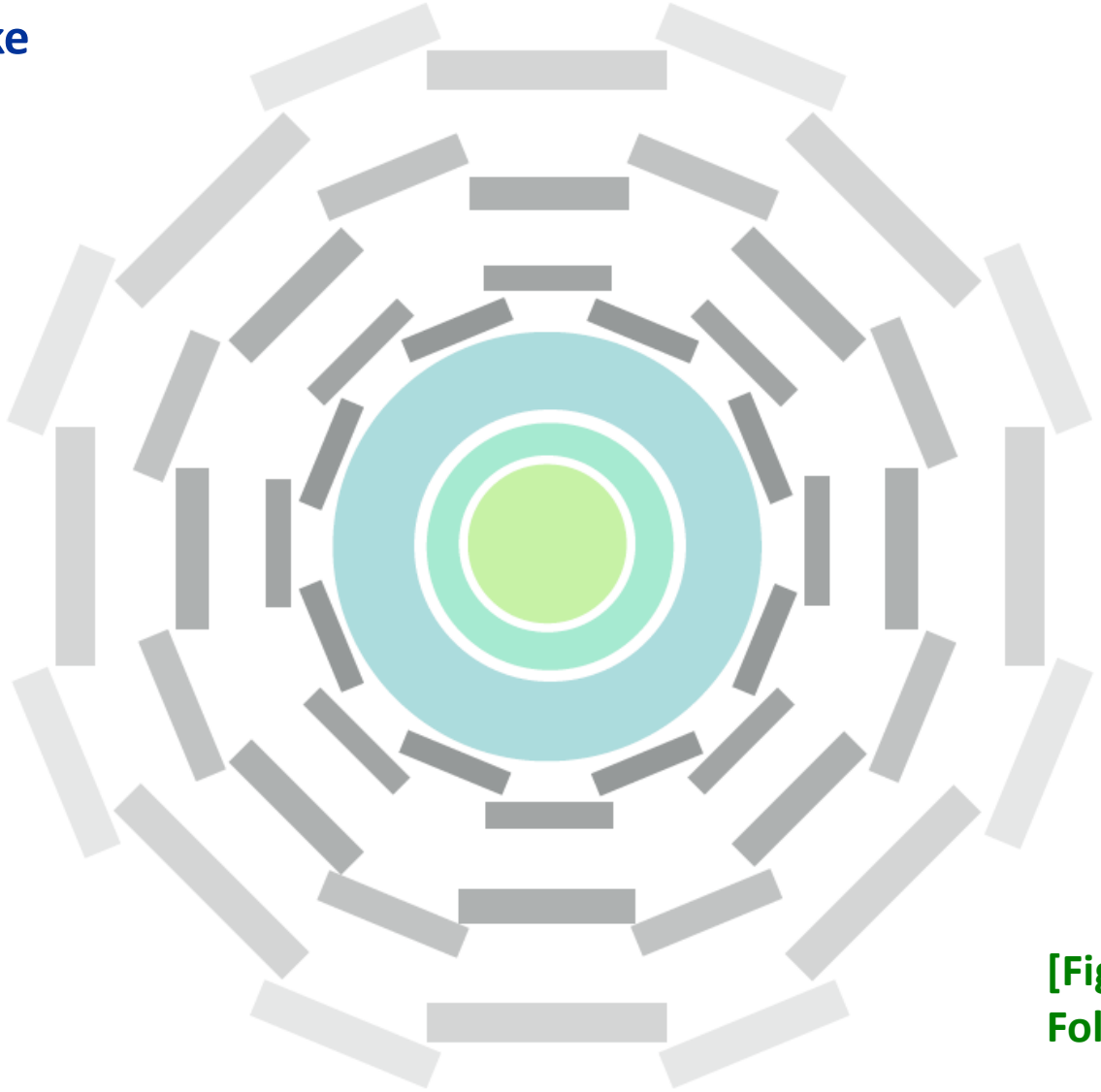


[Figures from Heather Russell]

Need to have probe LLP with different signatures and subdetectors

2.Experimental signatures

CMS/ATLAS-like detector



[Figure from Karri Folan DiPetrillo]

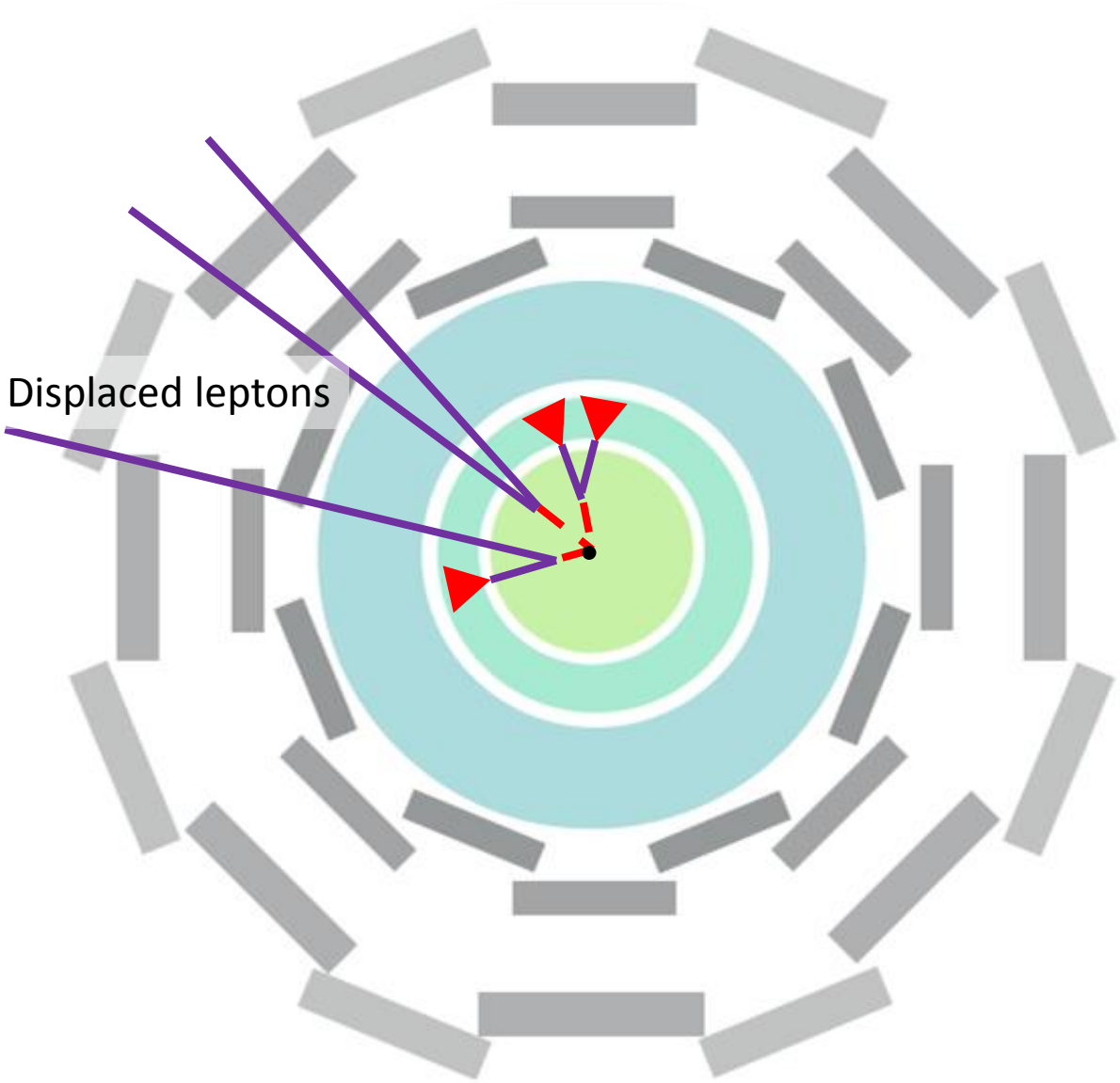
2.Experimental signatures

Displaced signatures

Displaced leptons

LLP decays into leptons
(Ex: $\widetilde{\chi_1^0}$ or $\tilde{t}$ in RPV-Susy)

Identification: large |d0|



[CMS: PRD91, 052012]
[CMS-PAS-EXO-16-022]
[CMS-PAS-HIG-16-035]

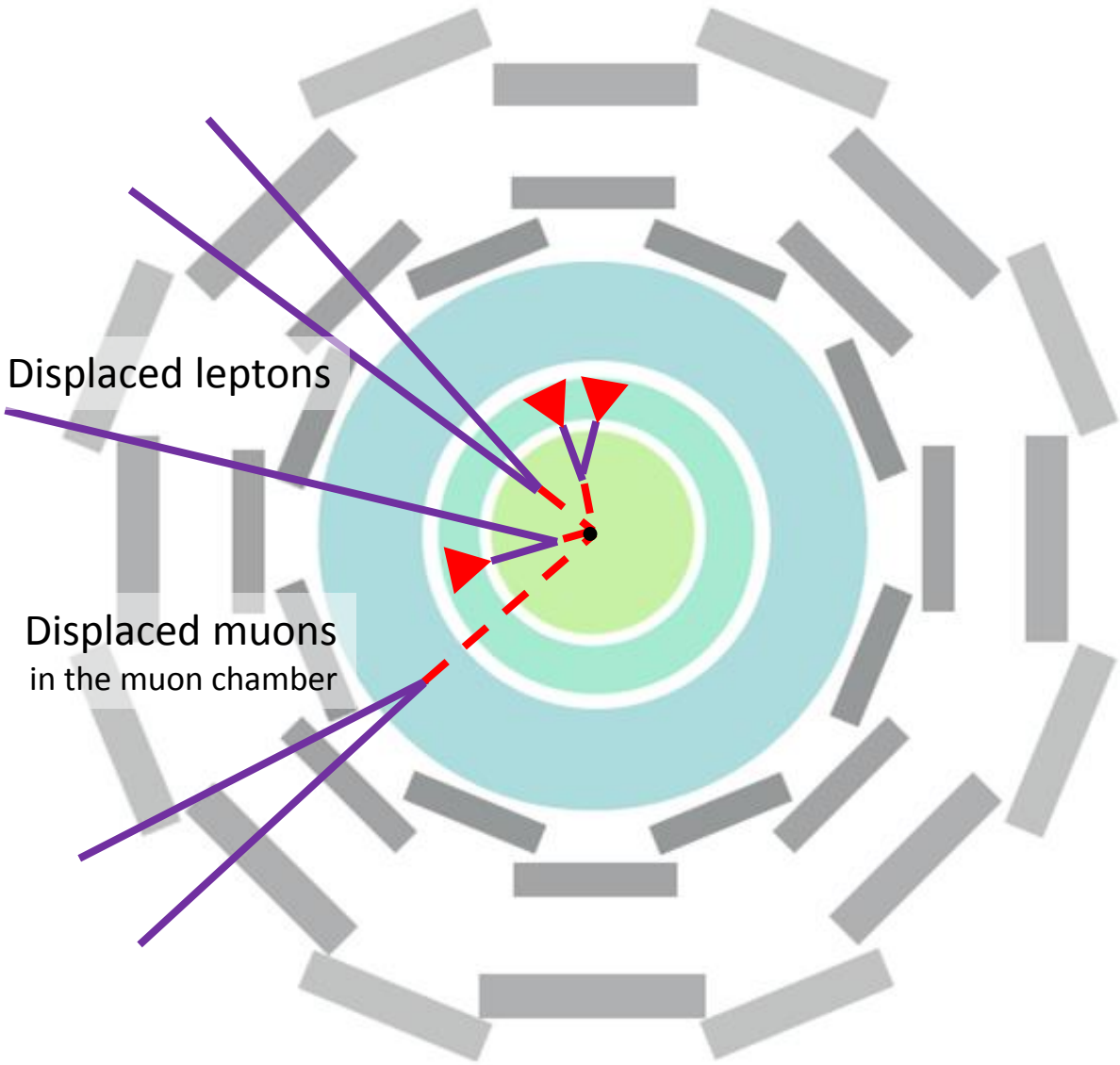
[ATLAS-CONF-2017-026]
[ATLAS-CONF-2016-042]

2.Experimental signatures

Displaced signatures

Displaced muons
with the muon chambers

Only the muon chambers are used

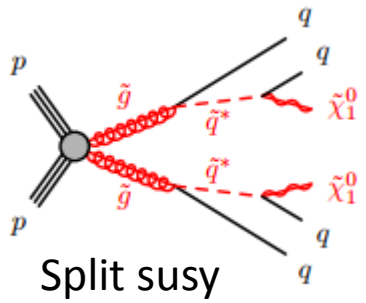


[CMS-PAS-EXO-14-012]
[ATLAS: PRD92(2015) 012010]

2.Experimental signatures

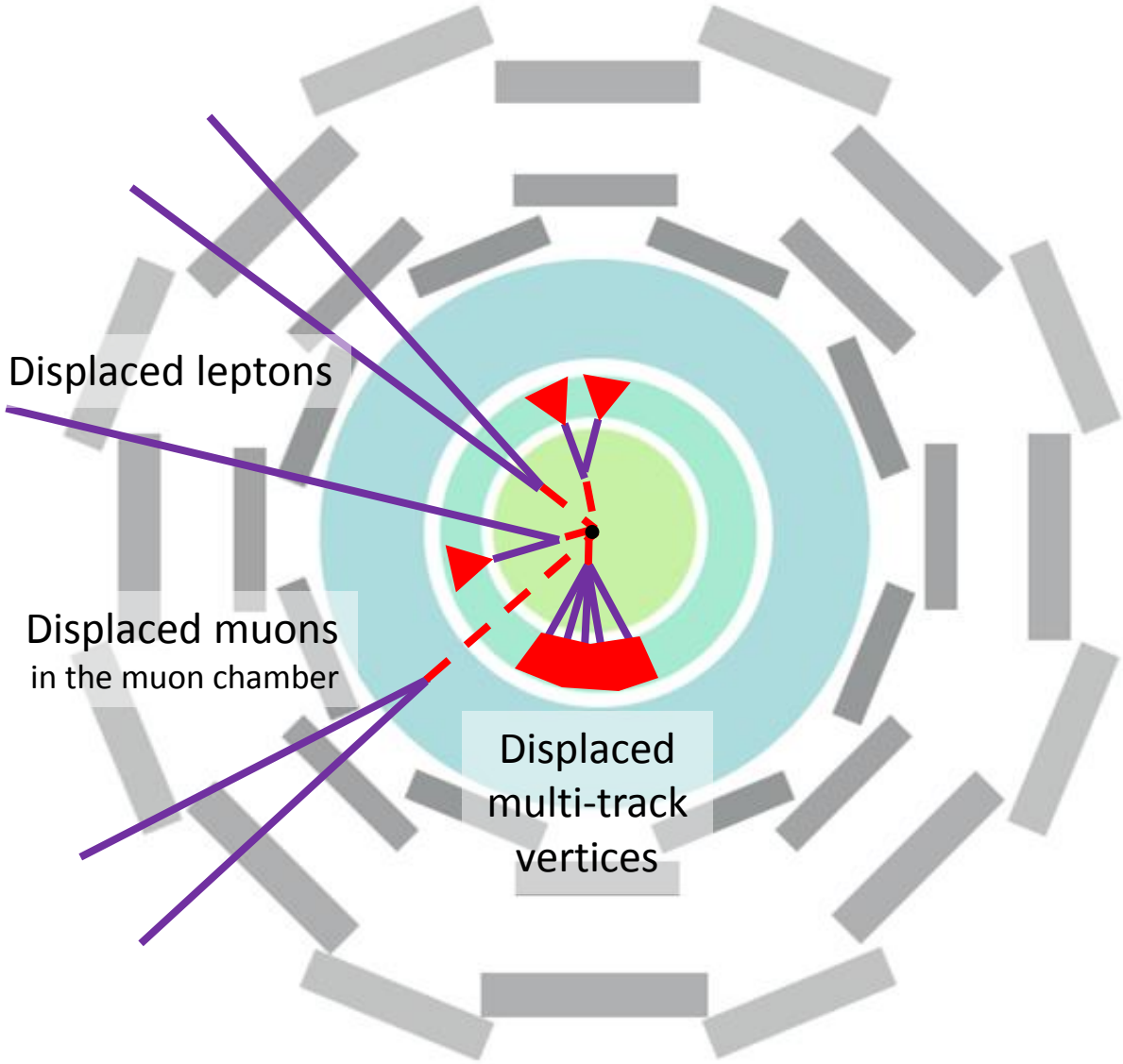
Displaced signatures

Displaced multi-track vertices



Split susy

Identification:
reconstructing vertex from the displaced tracks



[ATLAS: arXiv:1710.04901]
[ATLAS: PRD92(2015) 072004]

2.Experimental signatures

Displaced signatures

Displaced photons

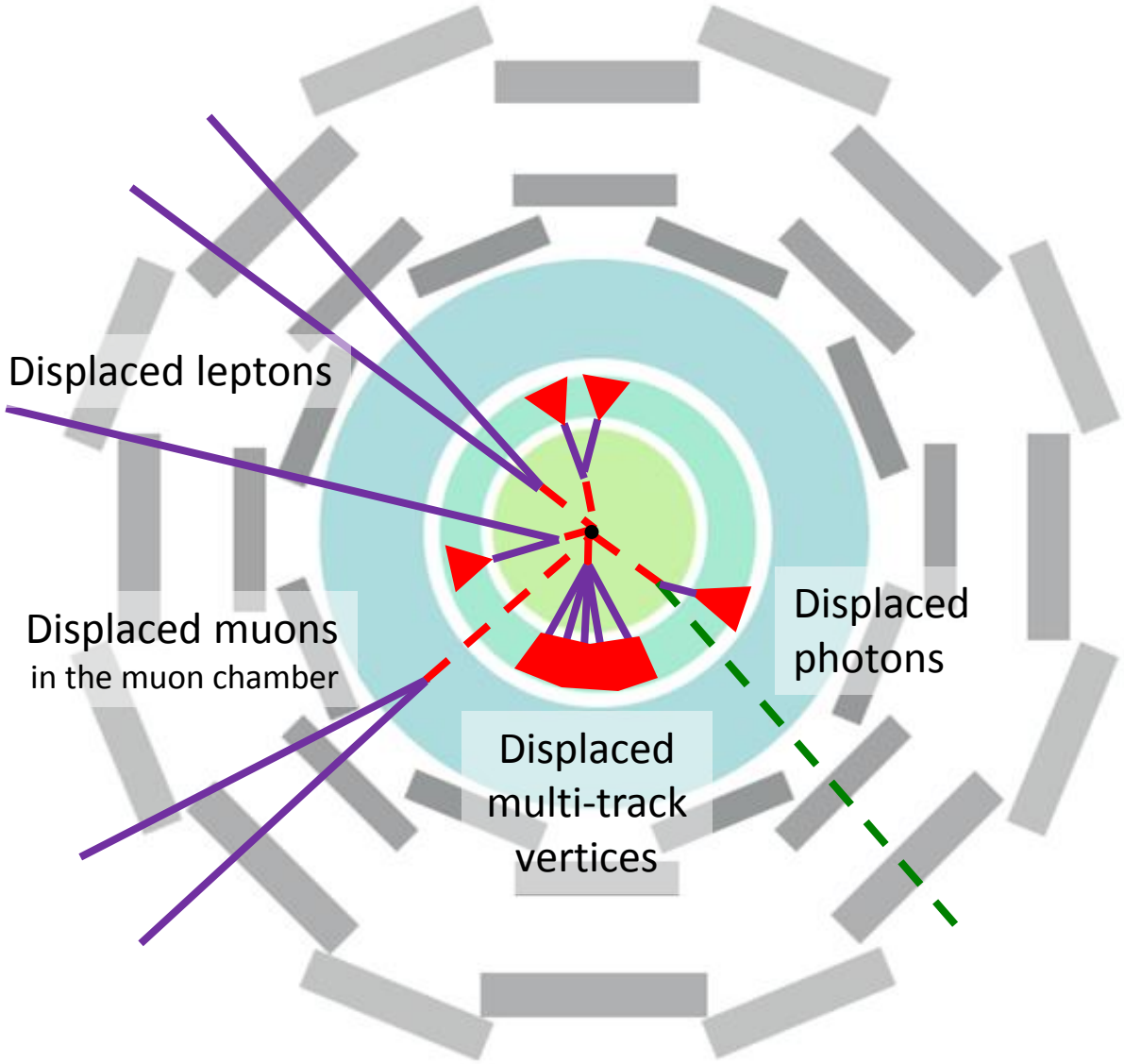
Ex: $\widetilde{\chi_1^0} \rightarrow \tilde{G} + \gamma$ (GMSB)

Identification:

- photon might not point back to the primary vertex
- photon might arrive late compared to a prompt photon

[CMS-PAS-EXO-16-003]
[CMS-PAS-EXO-12-035]

[ATLAS: PRD90(2014) 112005]



2.Experimental signatures

Displaced signatures

Displaced jets

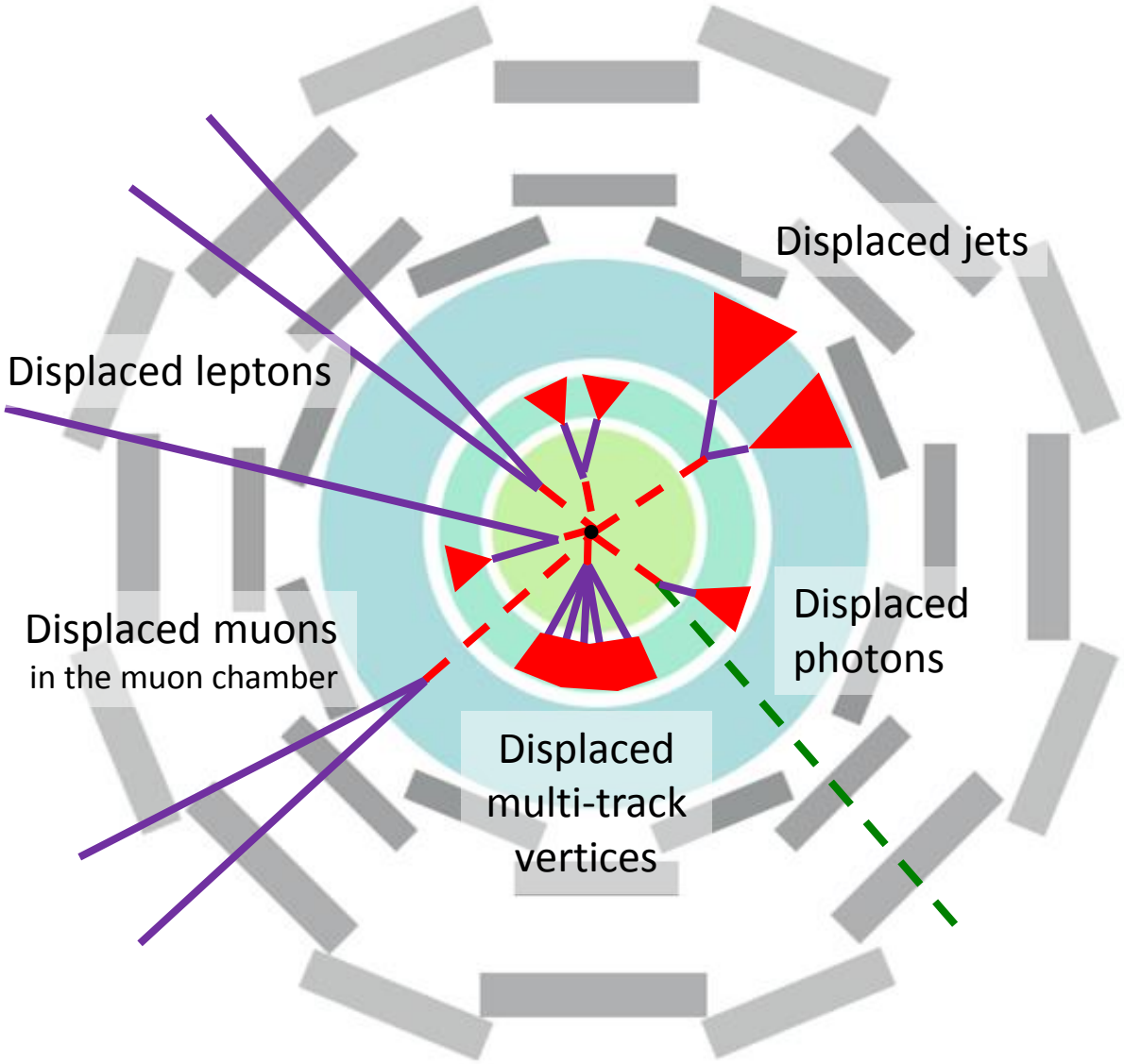
Ex: exotic decay of the Higgs boson H→2s→4f

Identification:

- Trackless jet
- Low ECAL/HCAL energy fraction

[CMS-EXO-16-003]

[ATLAS- CONF-2016-013]
[ATLAS: PRD92(2015) 012010]



2.Experimental signatures

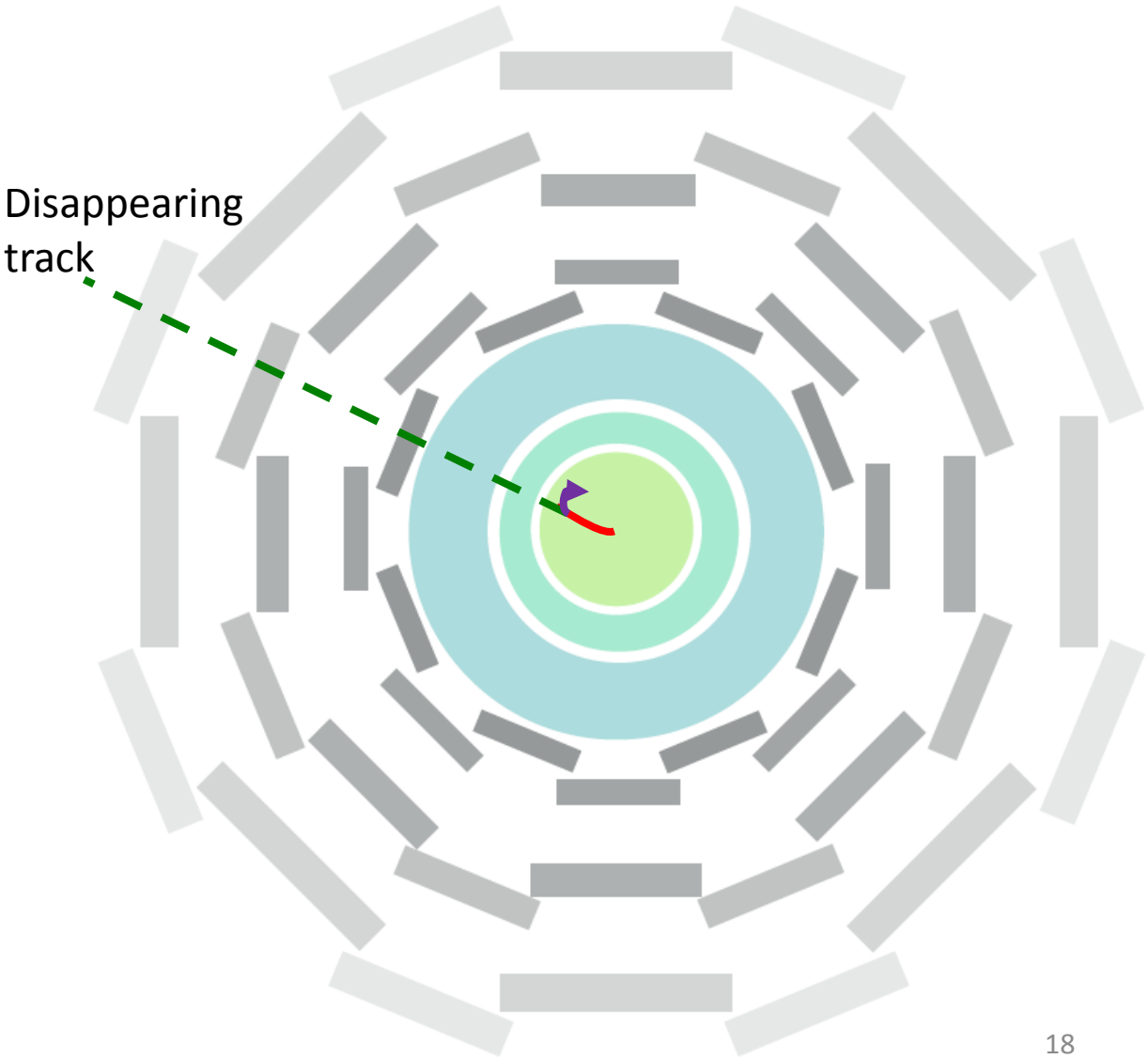
Other signatures

Disappearing track

LLP decays into undetectable particle (low momentum track)

Ex: $\chi_1^+ \rightarrow \chi_1^0 + \pi^+$ (AMSB)

Identification : missing outer hits in the track



[CMS-EXO-12-034]
[ATLAS-CONF-2017-017]

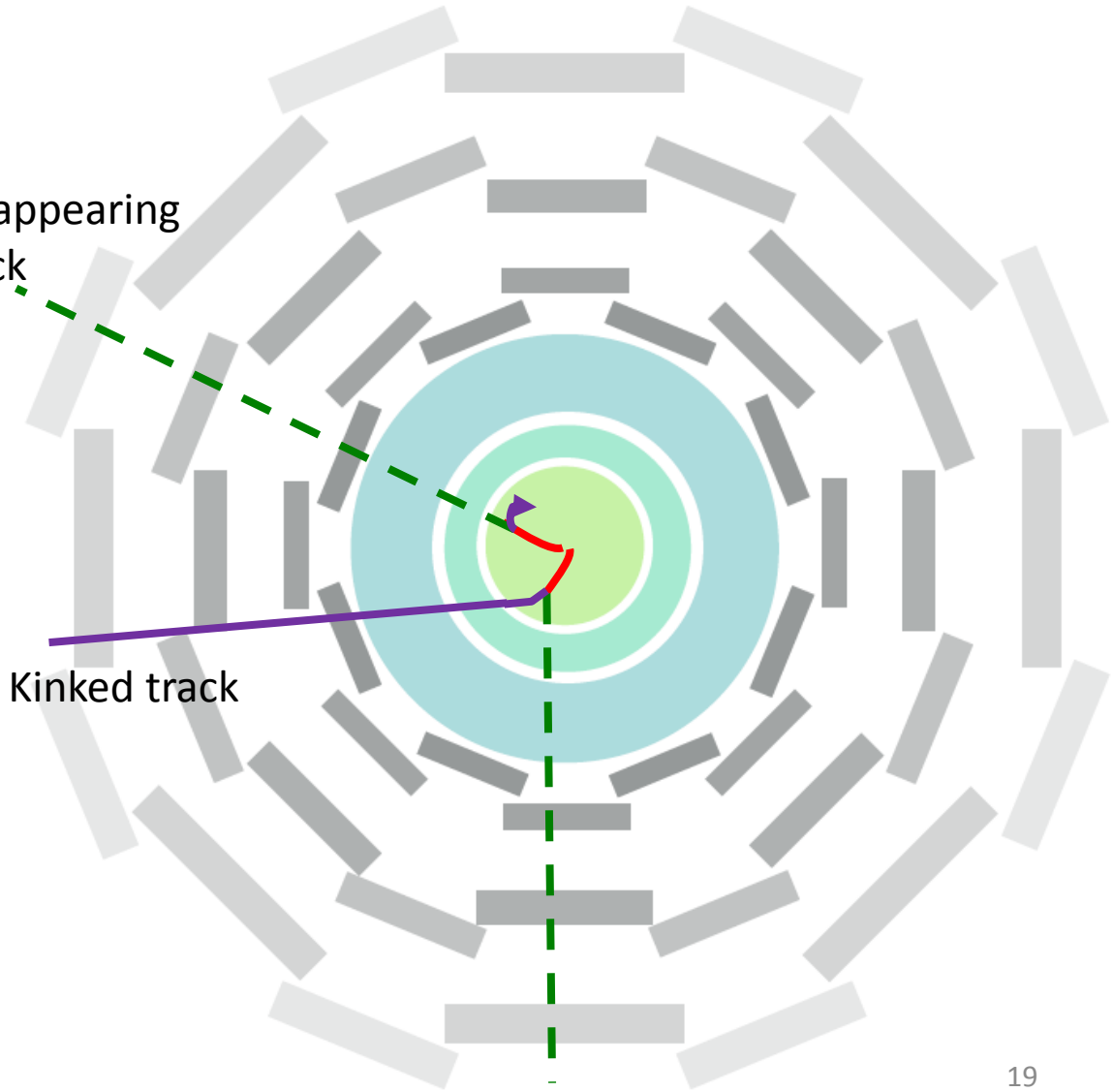
2.Experimental signatures

Other signatures

Kinked tracks

Similar to the disappearing tracks

Charged LLP + charged product ≡ track that abruptly changes direction



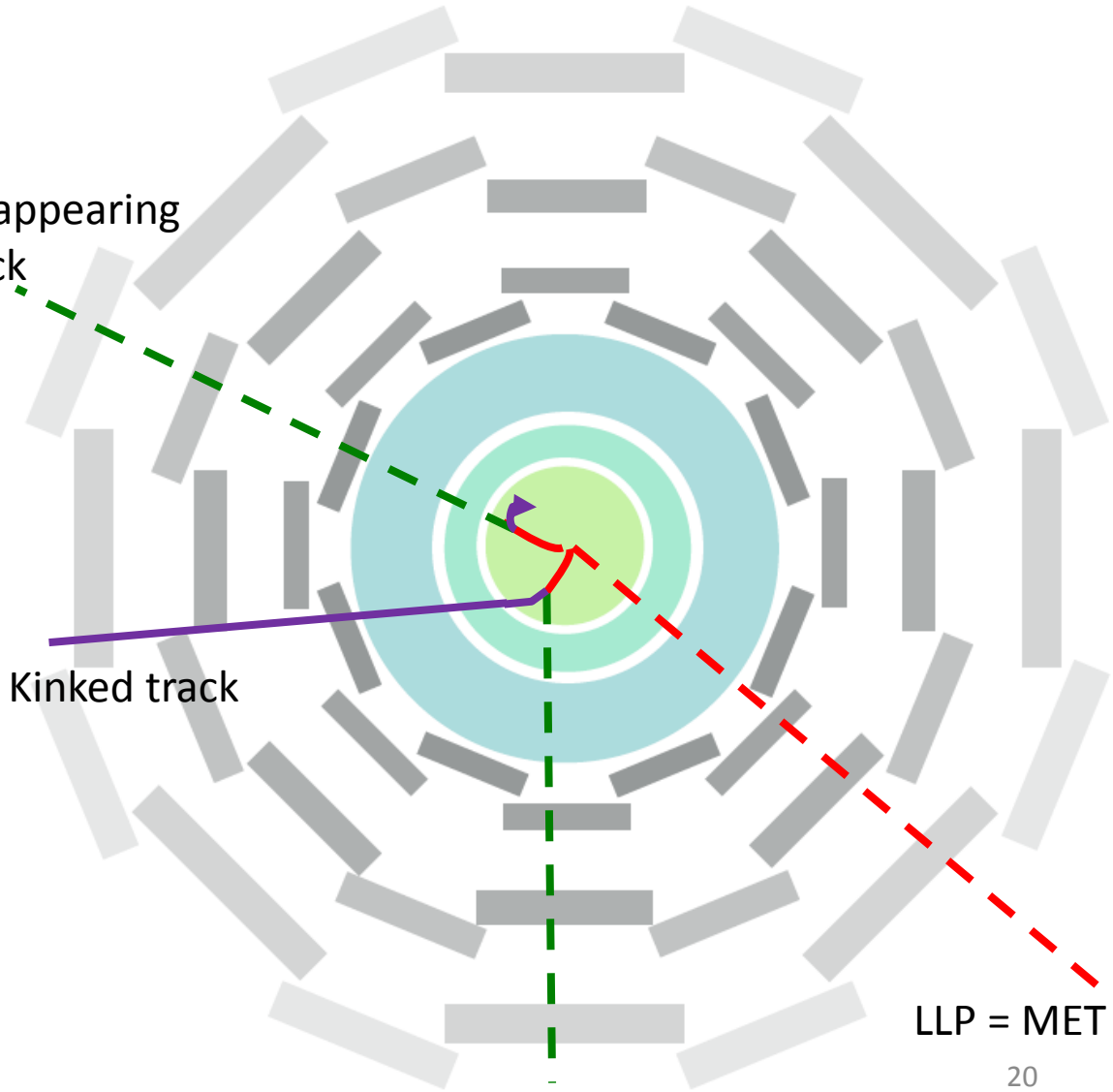
No public results

2.Experimental signatures

Other signatures

Heavy Stable Neutral Particle

Sensible to MET signature



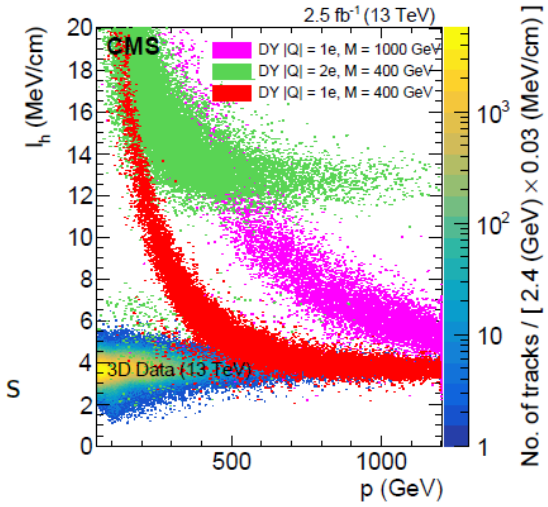
2.Experimental signatures

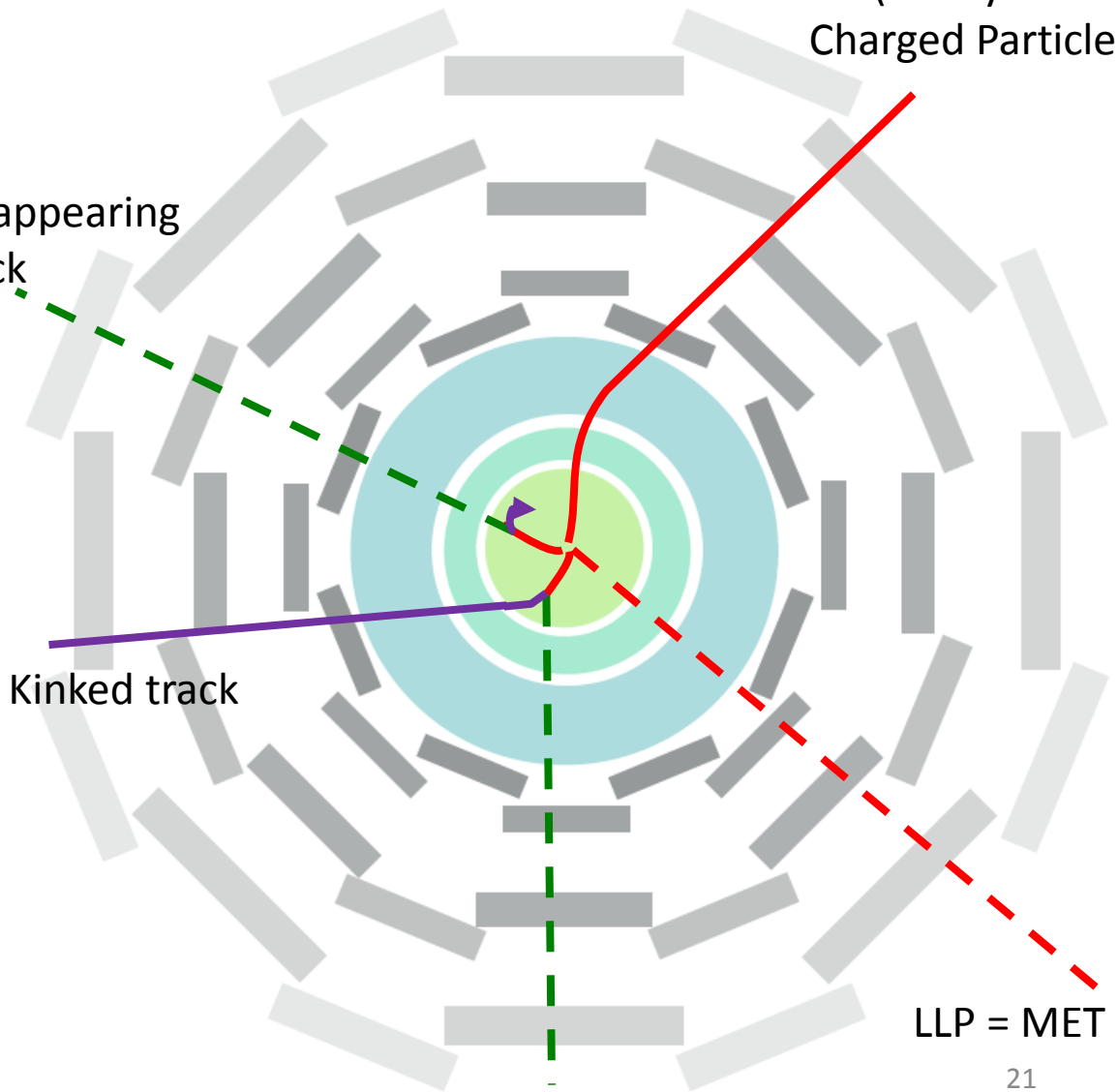
Other signatures

Heavy Stable Charged Particle

Identification:

- Higher rate of energy loss via ionization (dE/dx) in the tracker volume
- Longer time of flight (tracker + muon chamber)





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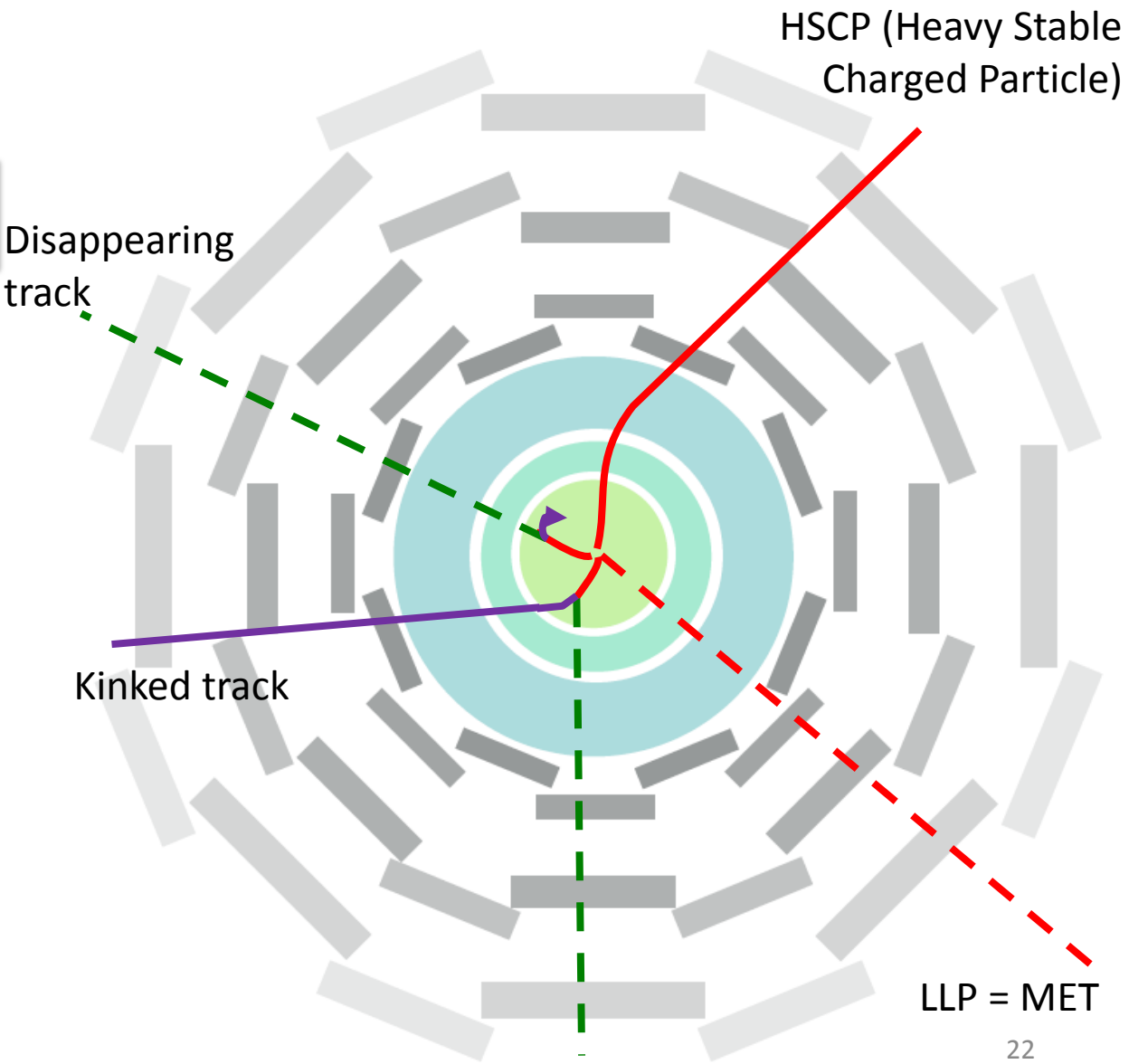
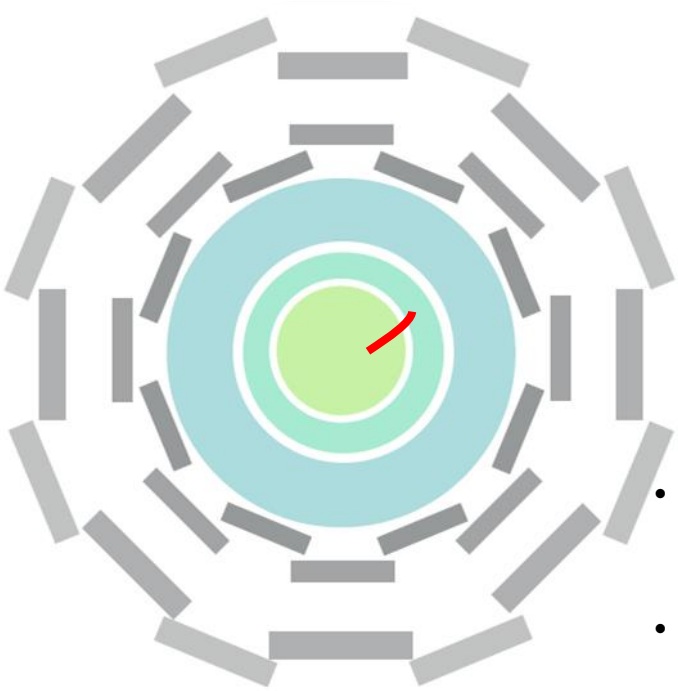


[CMS-EXO-15-010]
[CMS-EXO-16-036]

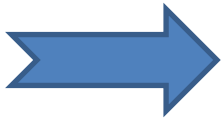
[ATLAS: PRD93 (2016) 112015]
[ATLAS: PRD760 (2016) 647-665]
[ATLAS: JHEP01 (2015) 068]

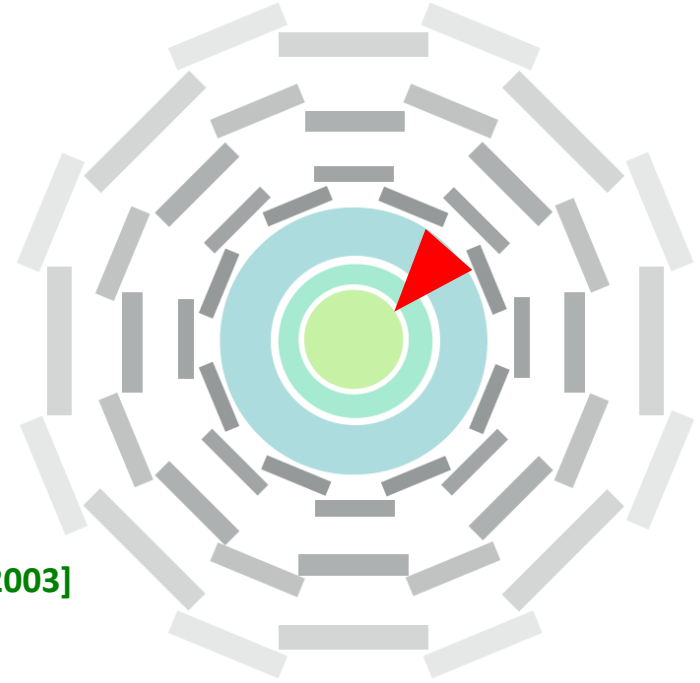
2.Experimental signatures

Stopped LLP



Several seconds, minutes, hours or months later





- Stopped LLP →jets
  [CMS-PAS-EXO-16-004]
  [ATLAS PRD88(2013) 112003]
- Stopped LLP → muons
  [CMS PAS-EXO-17-004]

Case of **LL gluino => R-hadrons** in split supersymmetry

- R-hadron interaction with calorimeter matter : gluino non-interating spectator, surrounding by a cloud of interacting quarks.
- Then gluino decays into $\tilde{\chi}^0$ + jets

Identification: a high-energy jet that is not coincident with the proton-proton collisions

Outlines

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3. Experimental side

Exotic signature → challenging analyses

Trigger challenge

- Possibility to use standard triggers but we need to be cunning: displaced e → γ trigger, displaced μ → muon-chamber-based trigger
- Some devoted trigger have been created: trackless jets, hip trigger, …
- But creativity in trigger strategy is constrained by rate budget and current trigger design.

Reconstruction challenge

- Standard algorithms are not designed for LLP
- Extending existing algorithms (ex: displaced tracks)
- Need manpower for development, validation, maintenance

Background challenge

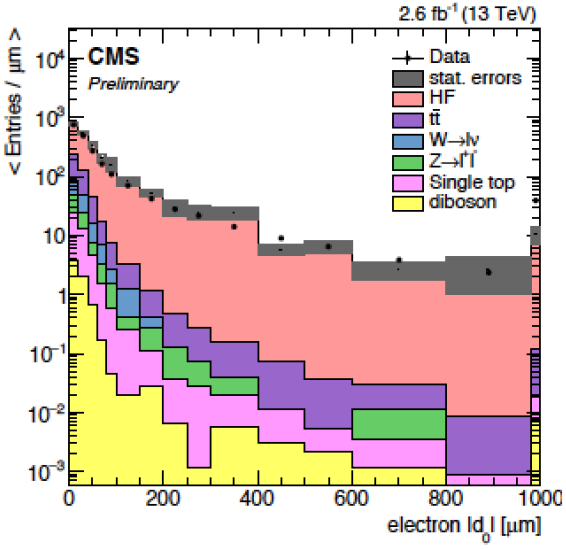
Several sources of background difficult to handle:

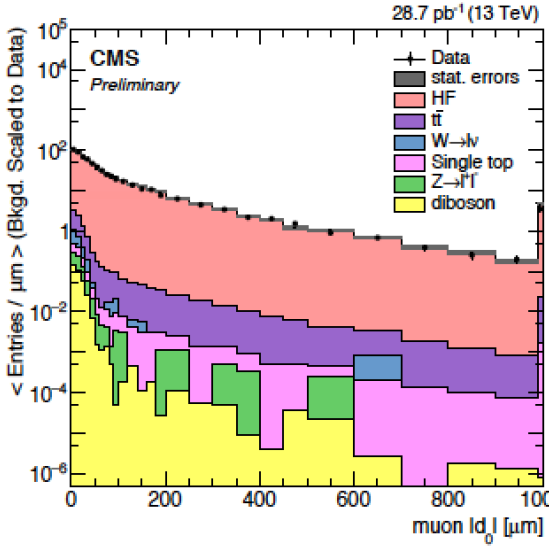
- SM long-lived particles
- Cosmics
- Beam-induced background
- Nuclear interaction, …

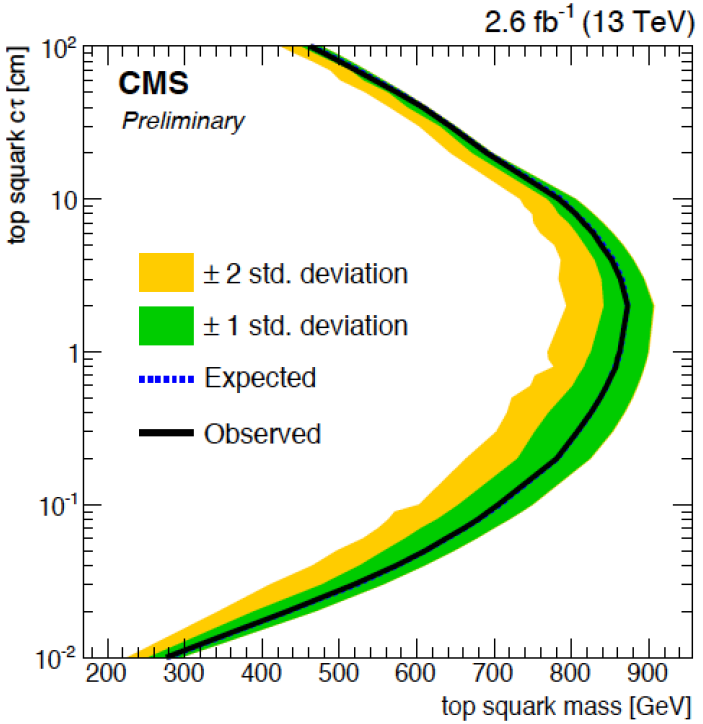
3. Experimental side

Example: CMS-EXO-16-022 – displaced eμ leptons

- **Models tested:** SUSY RPV with stop quarks decaying in e-mu
- **Trigger:** dedicated trigger to displaced e-μ (relaxing some constraints to PV, no track for e)
- **Reconstruction:** 8-TeV tracking performance (new algorithm available now for displaced)
- **Background:** non-QCD contribution, heavy-flavour QCD contribution

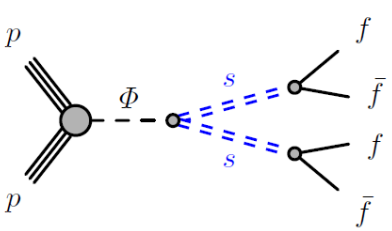




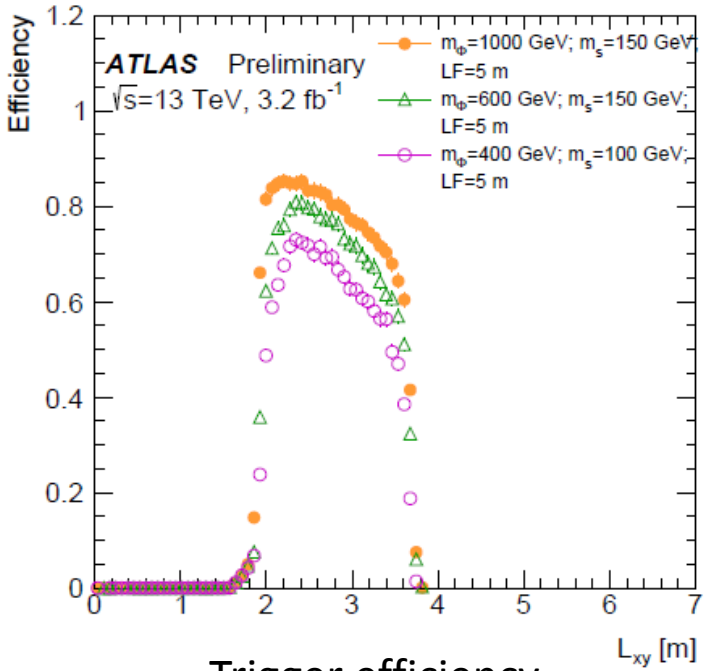


3. Experimental side

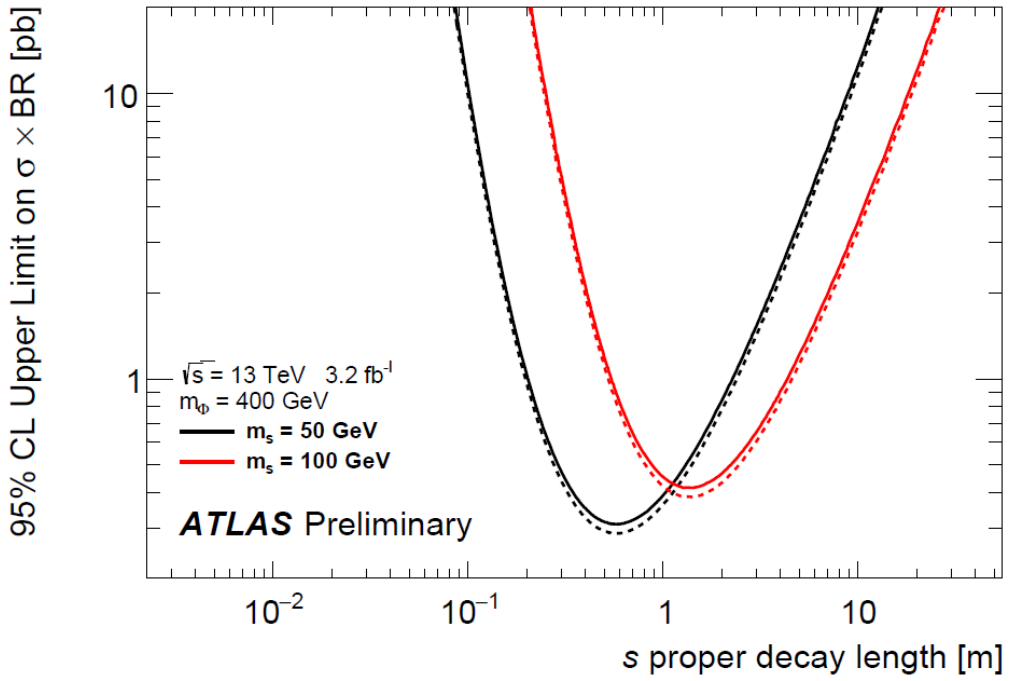
Example: ATLAS-CONF-2016-103 – displaced jets



- **Models tested:** hidden sector benchmark model
- **Trigger:** a dedicated trigger called *CalRatio-trigger :* trackless jet + properties of the jet
- **Reconstruction:** classical jet-clustering + BDT to select displaced jets
- **Background:** cosmics+beam induced backgrounds (a broad timing distribution), multijets processes (data-driven method estimation)



Trigger efficiency

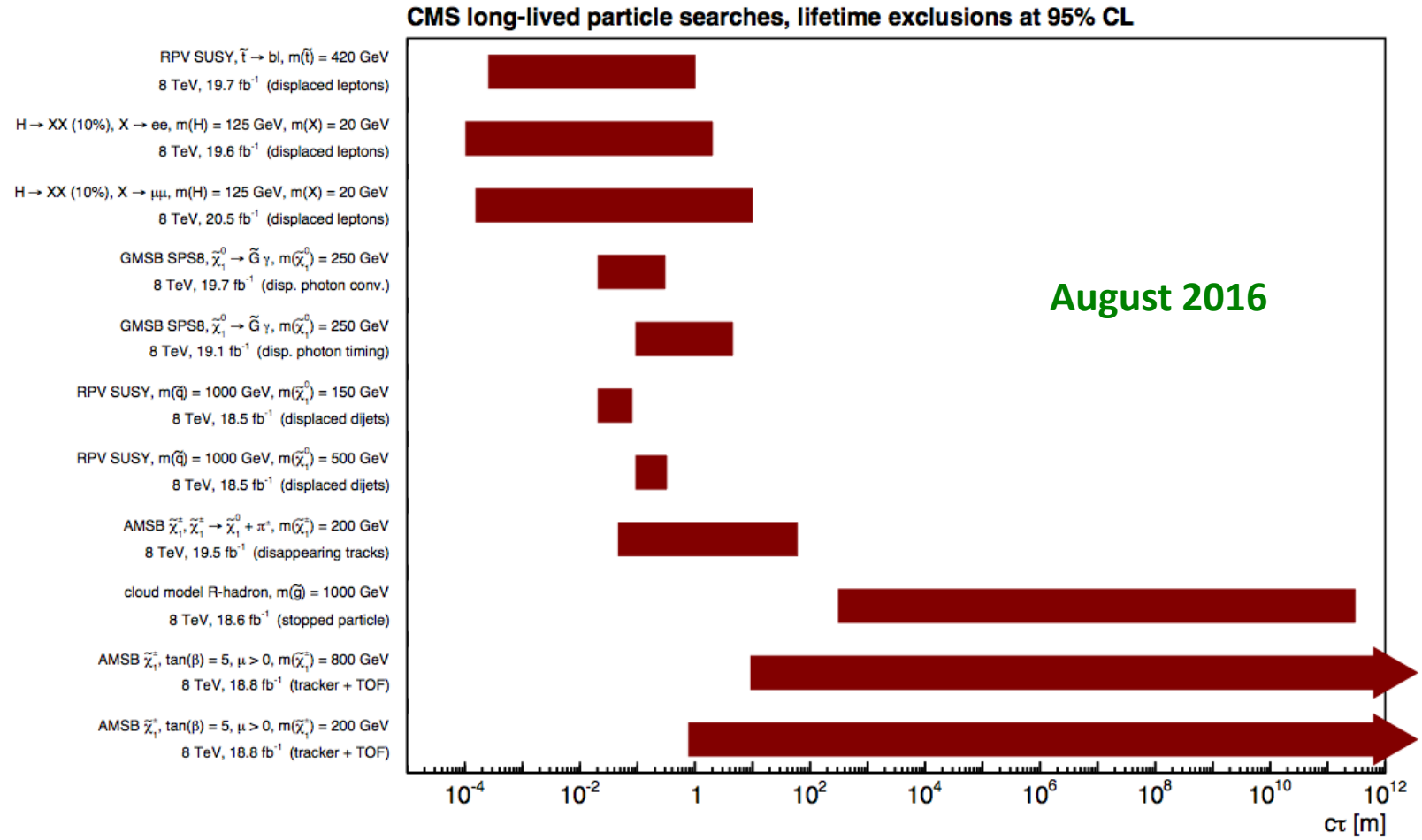


3. Experimental side

How to present all the LLP analysis results?

→ Difficult to have a clear overview

→ One attempt with some results



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4. Reinterpretation

Why reinterpretation?

Difficulty to be exhaustive in interpretation:

- covering all the parameter space of a given model
- testing all the existing models
- testing all the new models which could be conceived after the analysis

We must be able to launch an existing analysis, **tomorrow or in few years,** with a **different signal** benchmark and to compute a limit.

Solution 1

Use the **RECAST project** (***under development***) which :

- Captures the analysis code, the data, …
- Allows people to upload they own MC signal samples
- Launch automatically the codes and store results

→ Highly supported by the LLP community workshop

Solution 2

- Experimentalists provide all useful information to phenomenologists.
- Developing an external code which mimics the analysis results.

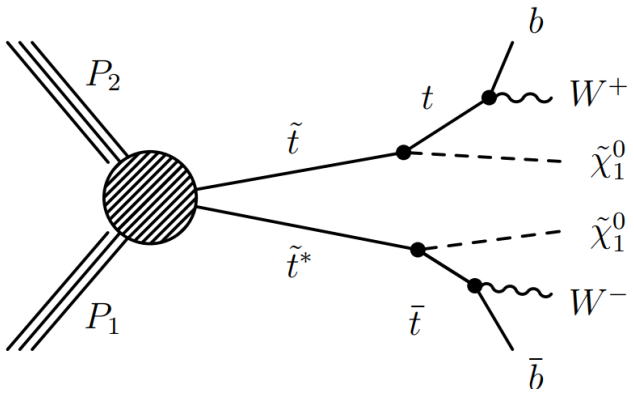
→ Approximations but much faster (useful for scan over parameter-space)
→ Identification of topologies or region not tested by experimentalists
→ Feedback to experimentalists

4. Reinterpretation

Solution 2

Based on Simplified Models

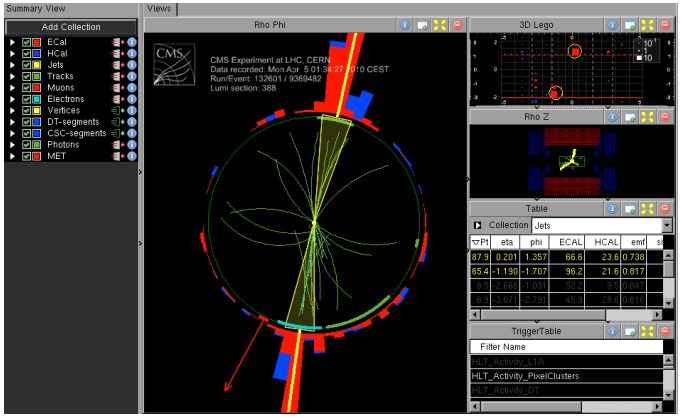
T2tt



- Work with event topology
- Properties are reduced to mass spectrum, xsection and BR

Extremely fast
Moderately accurate / general

Based on Detector simulation



- Mimicking simulation + reconstruction + selection acheived by CMS or ATLAS
- « Very-fast » simulation

Very-Fast
Accurate / general

4. Reinterpretation

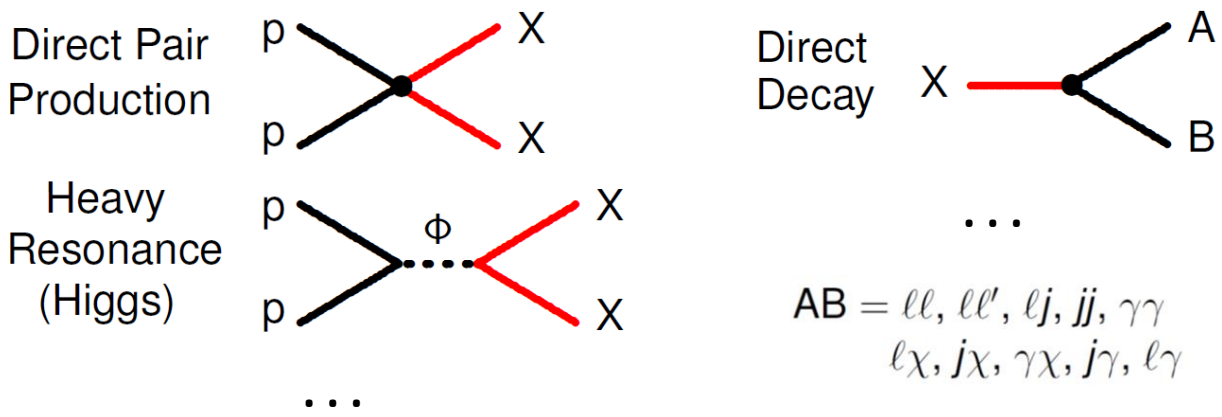
Simplified Models for Long-Lived Particles

Plethora of topologies and the number of simplified models must be reduced.

- **Choose a few simplified models** that highlight the limitations of the search and clearly illustrate where sensitivity is lost (low LLP mass, high LLP boost, …)
- **Factorization** the production mode and the decay mode

Simplified Models = Production modes ⊗ Decay modes

[Figures from Jared A. Evans]

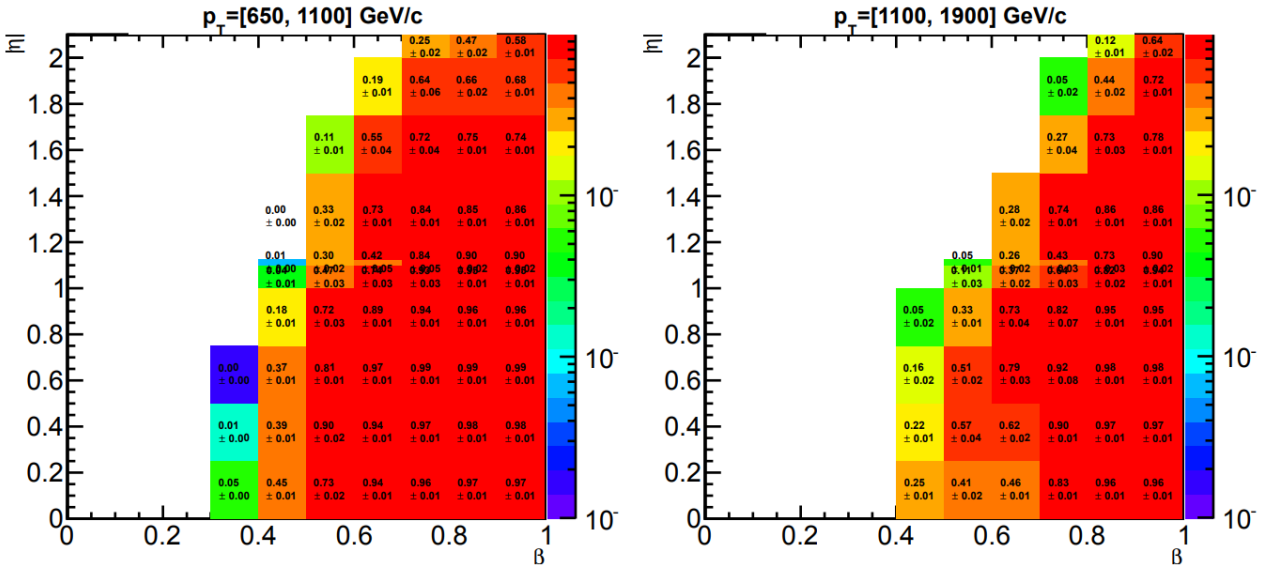


Need to create a common database (one goal of the LLP workshop)

4. Reinterpretation

Simplified Models for Long-Lived Particles

- **Efficiency maps** are required for recasting with Simplified Models.
  Which kind of information do we need? a compromise must be found to get a reasonnable number of parameters



A good example:
EXO-13-006 (HSCP analysis)
→ Numerous efficiency maps

Example: probability of a single long-lived particles passed the online selection as a function of true particle pT, β and |η|

- **Reinterpretation tools based on simplied models must be extended.**

4. Reinterpretation

Recasting based on detector simulation

detector simulation

Generic & global simulation

Full simulation of a detector with:
- Algorithms: calorimetry, energy-flow, …
- Parametrizations: smearing & efficiency
- Full pile-up simulation

Analysis-specific and light simulation

- Simulating only the main detector effects useful for the analysis
- Based essentially on smearing & efficiency ~ transfer functions

DELPHES fast simulation

- **CheckMate**
- **MadAnalysis 5**

- BuckFast from **Gambit**
- Detector effects in **Rivet** and **ATOM**

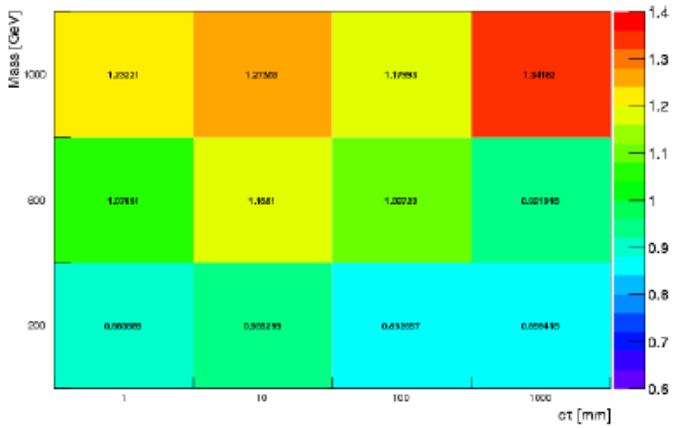
4. Reinterpretation

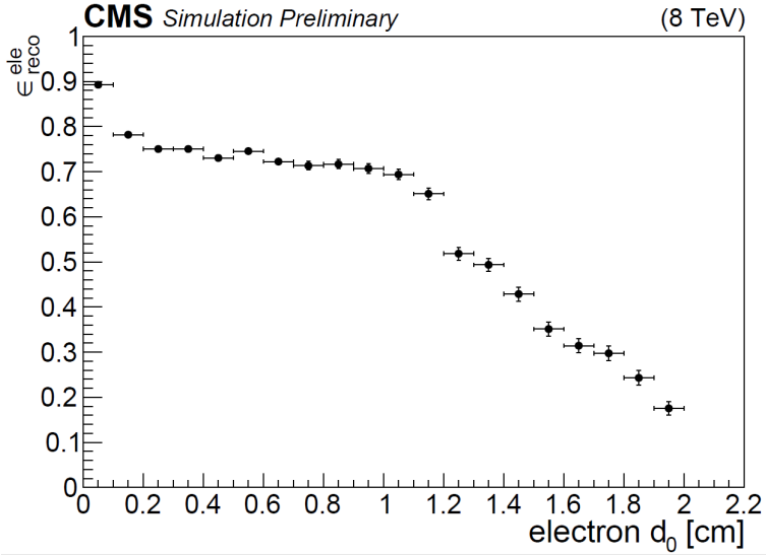
Recasting based on detector simulation: the pure parametric way

Example of CMS-EXO-16-022: displaced leptons e-μ

Efficiencies and resolution functions are available (plots & data table).

Cut Summary of CMS displaced $e\mu$
Preselection
1 OS $e^{\pm}\mu^{\mp}$ pair
$d_\ell > 100\,\mu$m
$p_{T,\ell} > 25$ GeV, $\lvert\eta_\ell\rvert < 2.5$
Reject $1.44 < \lvert\eta_e\rvert < 1.56$
$I^{calo,e}_{\Delta R<0.3} < 0.10$, $I^{calo,\mu}_{\Delta R<0.4} < 0.12$
$\Delta R_{\ell j} > 0.5$ $\forall$ jets with $p_T > 10$ GeV
$\Delta R_{e\mu} > 0.5$
$v_{T,\ell} < 4$ cm, $v_{Z,\ell} < 30$ cm
Veto additional leptons





Link: https://twiki.cern.ch/twiki/bin/view/CMSPublic/DisplacedSusyParametrisationStudyForUser

4. Reinterpretation

Recasting based on detector simulation : the Delphes way

The official Delphes package does not suit Long-lived particle analysis.
But by its modular architecture, people can develop new devoted modules.

Example:
MA5 tune of Delphes devoted to displaced leptons for recasting : CMS-EXO-16-022
→ Usual simulation + CMS efficiencies

See my talk of yesterday for more details about this implementation

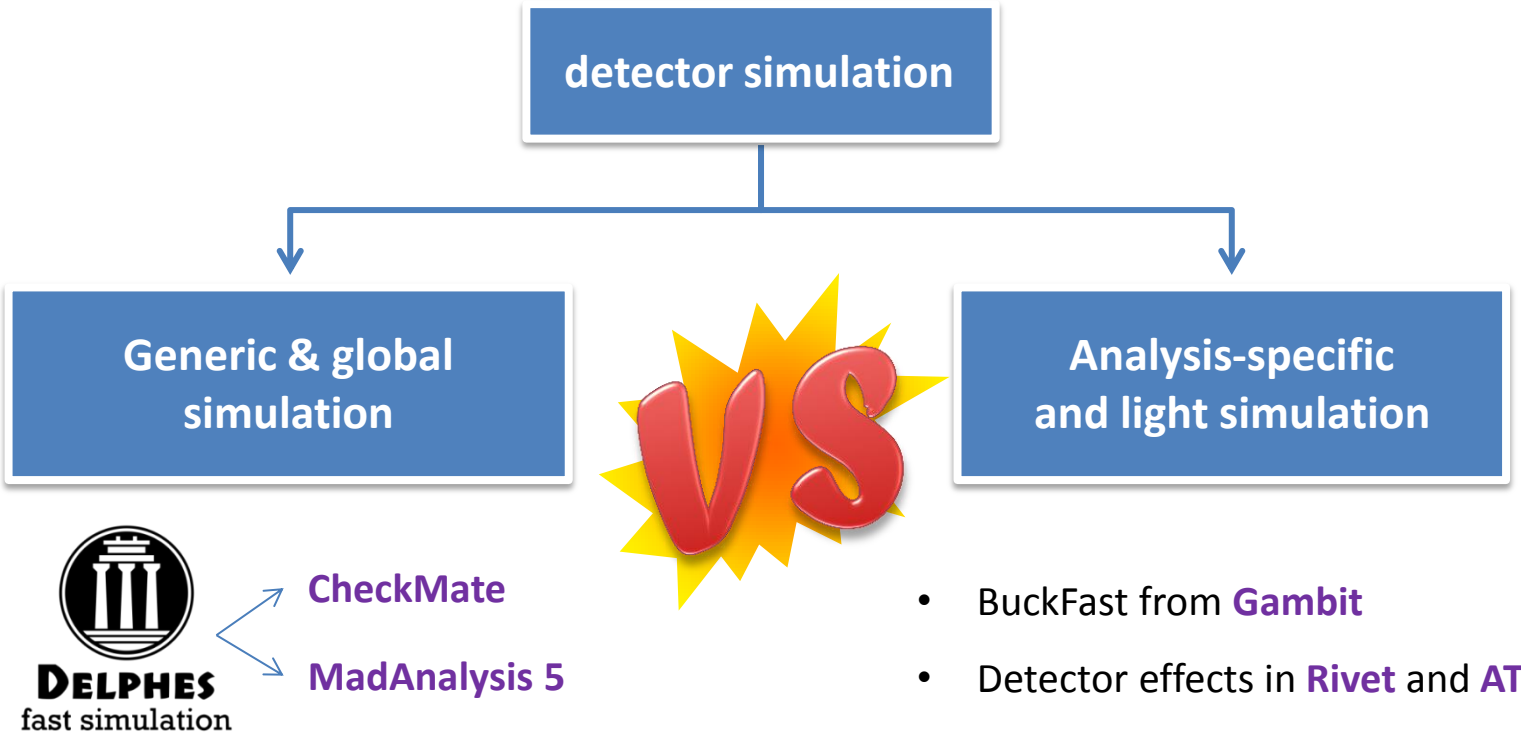
Besides, **some algorithms can be developed in the future**:

- Vertexing algorithms for secondary vertex
- Displaced jets based on realistic calorimetry

Limitation of these tools: no trigger, no fake and no instrumental background

4. Reinterpretation

Recasting based on detector simulation



Debate: Delphes vs specific parametrization?

- Analysis-signature dependent issue.
- Kinematical region dependent issue.

→ Performance of the two techniques should be compared on some analysis examples.

Summary

LLP in many BSM models:

- Supersymmetry: RPV, AMSB, GMSB, split susy, …
- Hidden sectors: Higgs portals, neutrino portals, …

Experimental signatures are numerous and exotic:

→ ATLAS and CMS program in LLP is rich and can be improved more

LLP analysis are challenging for :

- Trigger strategy?
- Non-standard reconstruction algorithm
- Background estimation

Reinterpretation: work in progress

- By simplified models: need to provide a collection of simplified models
- By detector simulation: parametric way or Delphes

Some recast attempts are available.

Interesting topics not covered:

- LHCb
- MATHUSLA
- HL-LHC