Recent progress on searching for LLPs using the CMS detector and preparation for Run3

Martin Kwok(Fermilab)

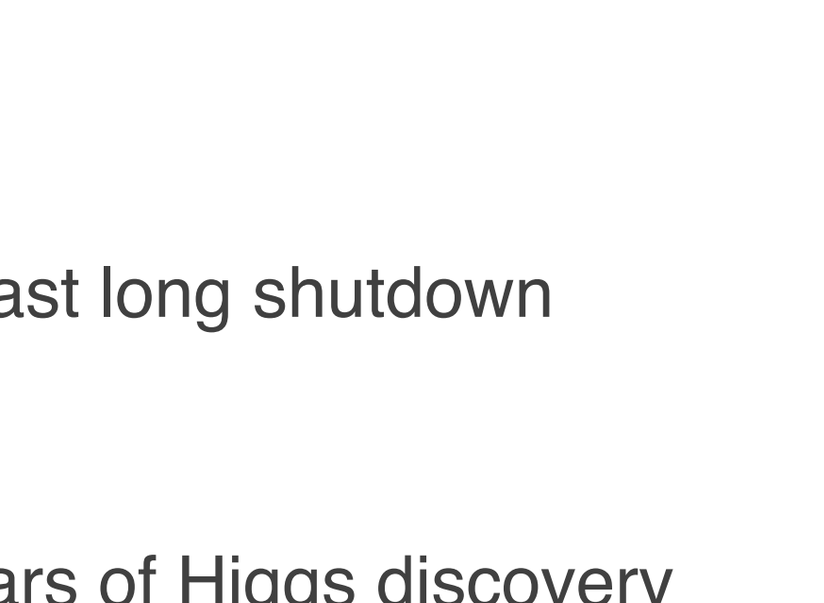
31 Oct, 2022

LLP12 workshop

Run 3 has started !

- CMS Run 3 so far:
  - Completed various phase-1 upgrade over the past long shutdown
    - HCAL phase-1 completed
    - GEM demonstrator installed
  - Long awaited 13.6 TeV collision just after 10 years of Higgs discovery

- Collected ~10% of Run 3 data
  - Run 3 data has ~10% luminosity of final HL-LHC
  - Had to extend TS1 due to a RF problem



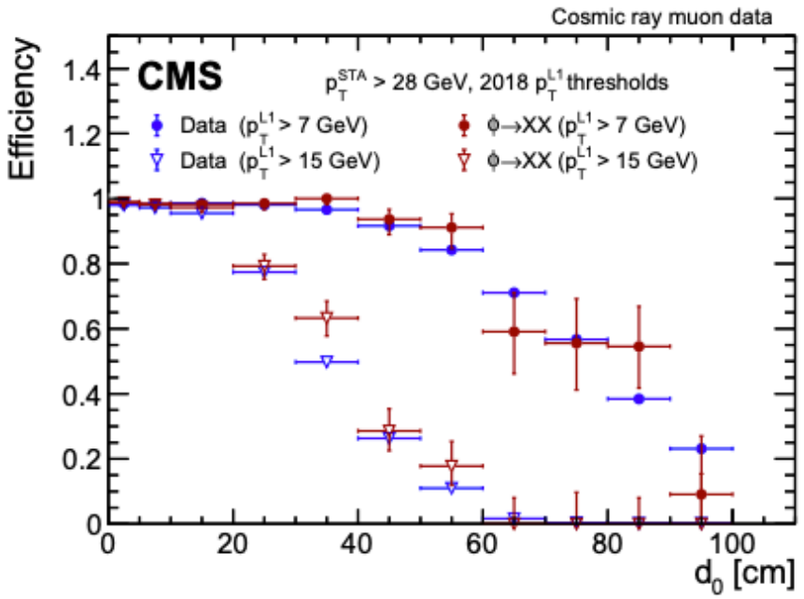
LLP in run 3

- CMS has gone through a "LLP upgrade” in run 3
  - >16 new LLP trigger paths, >100 Hz HLT bandwidth
  - New L1 + HLT capabilities
    - L1 Delayed Jets
    - L1 Muon Detector Shower (MDS)
  - LLP is one of the main focuses of CMS’s physics program

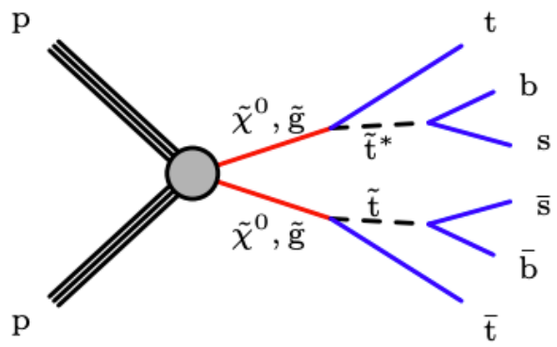
- Perspectives for LLP directions
  - MDS (different categories+ cross triggers for future)
  - B-parking for LLP
  - Re-interpretation

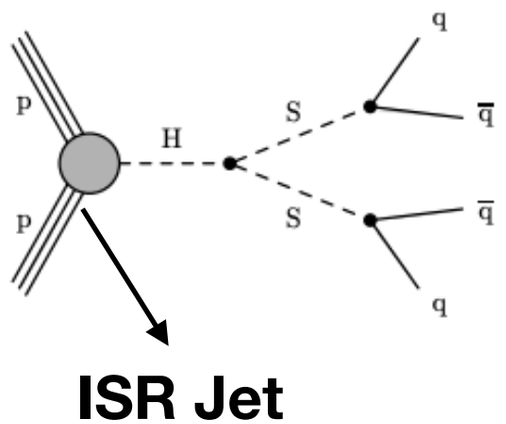
Trigger for LLP in Run 2

EXO-21-006



- CMS had a few dedicated LLP triggers in Run 2
  - Covering some important signatures
  - e.g. displaced muons/non-pointing photons
- Limitations of these dedicated triggers:
  - Lack of dedicated L1 seeds
    - e.g. incorrect pT assignment of displaced muon due to beam spot constrains
  - Mostly rely on pixel/tracker
    => Loses efficiency at larger displacement
- To extend beyond tracker, LLP searches rely on triggering with MET or associated prompt objects
  - Often pays the price of smaller cross sections/acceptance
    - e.g. Muon shower search (MET>200 GeV, signal acceptance ~O(1%))
  - Often limits sensitivity to low mass LLPs





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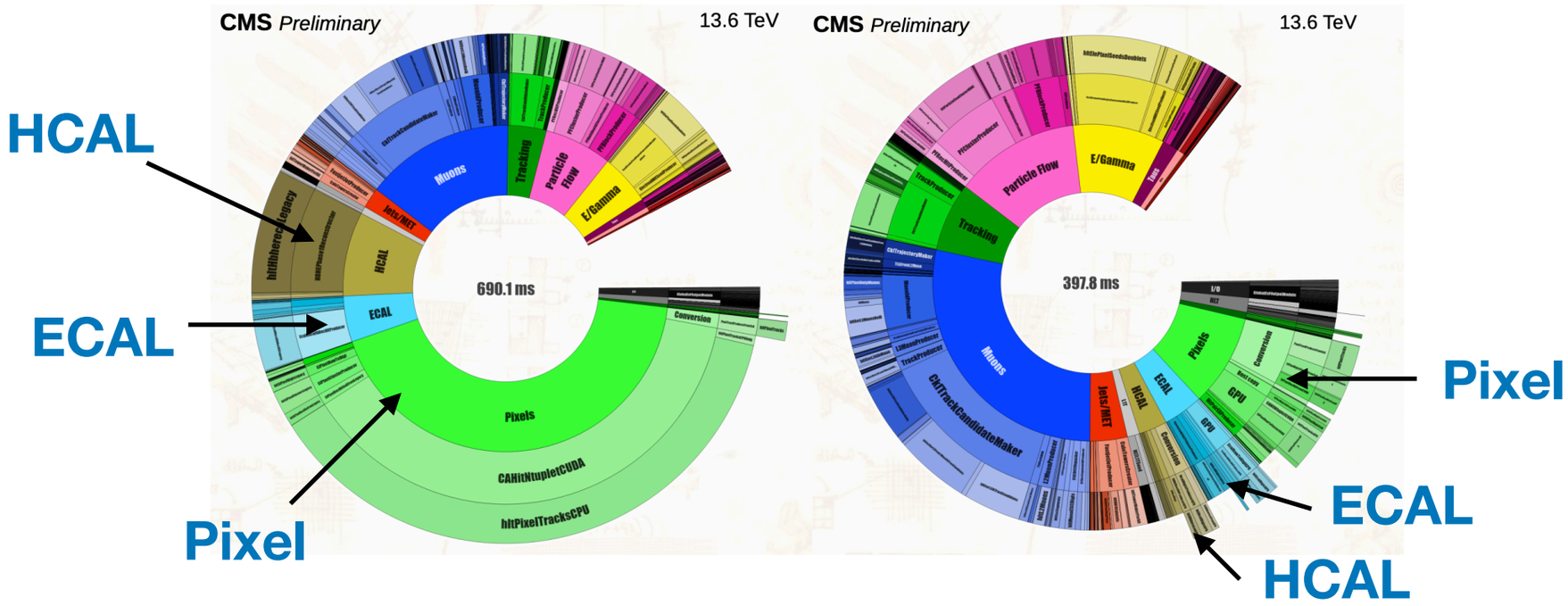
Trigger for LLP in Run 3

- CMS has gone through an “LLP upgrade” for run 3
  - More and Better
- A lot more dedicated LLP paths developed
  - Top-down: Physics coordination allocated trigger bandwidth and encouraged development very early on
  - Bottom-up: LLP is getting more attention in the community
- Better LLP triggers:
  - Developed dedicated L1 seeds (Hardware)
  - Adapt algorithms targeting LLPs (Software)
- Result: a comprehensive collection of displaced objects:
  - Displaced tracks
  - Displaced jets
  - Displaced electron/photon
  - Displaced tau
  - Displaced muon
  - New handle: Muon Detector Shower (MDS) + more…

Infrastructural improvement - GPU@HLT

- CMS deployed GPU@HLT for Run 3
  - Reduced ~80% of processing time/event!
  - Offloading ECAL/HCAL/Pixel local reconstruction to GPU
- More time for complicated HLT algorithms
  e.g. *displaced tracking*

CPU only **CPU+GPU**

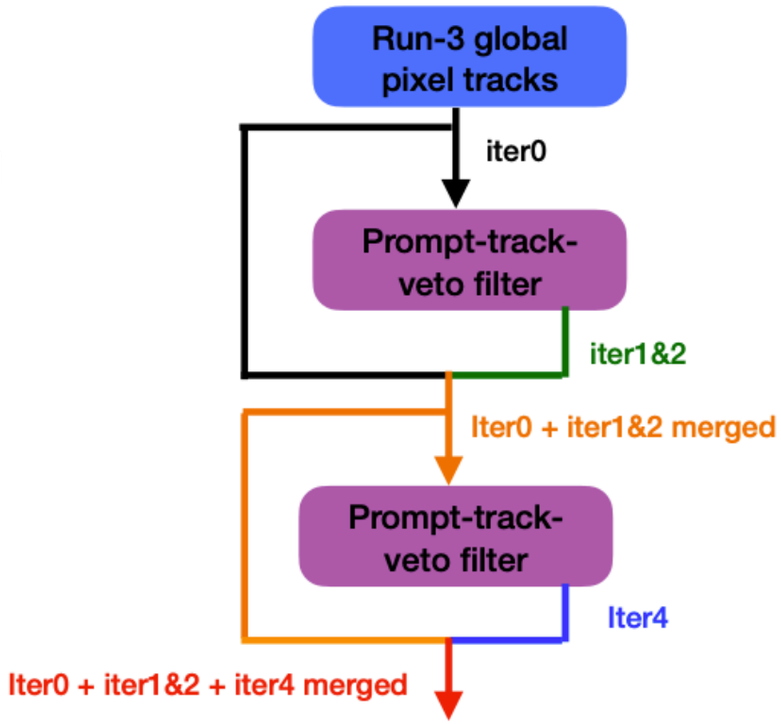


[Available on DPS soon]

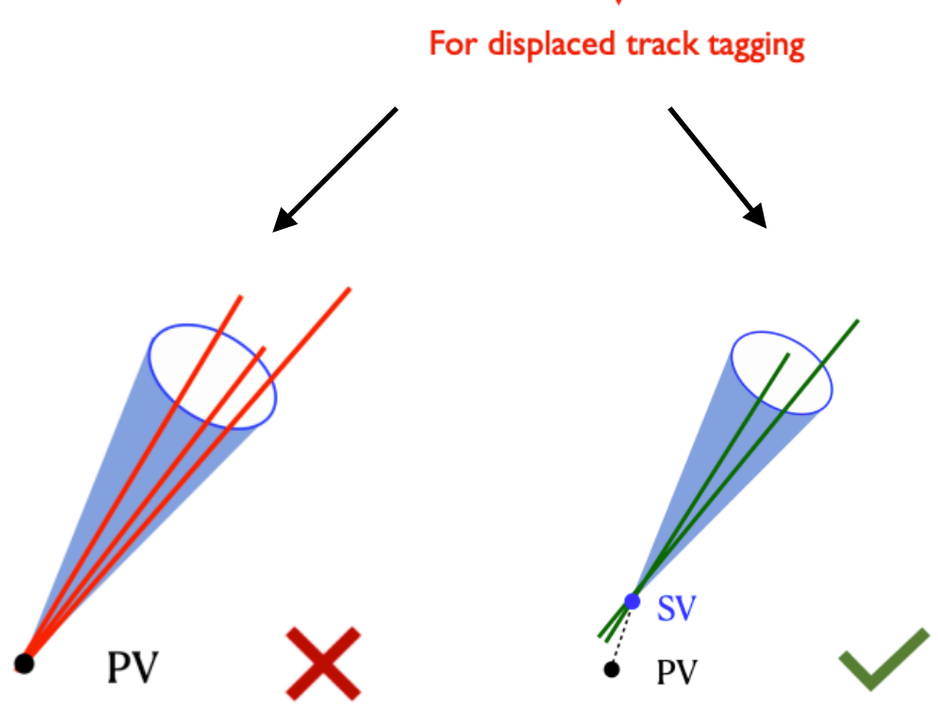
Displaced Tracking

From Jingyu Luo

- Commonly used in offline event selection in LLP, first used in EXO-19-021 for displaced jets search
- Displaced tracking @HLT:
  - Start with global tracks
  - Veto prompt tracks formed by different pixel seedings iteratively
  - Gives very ***pure*** displaced tracks



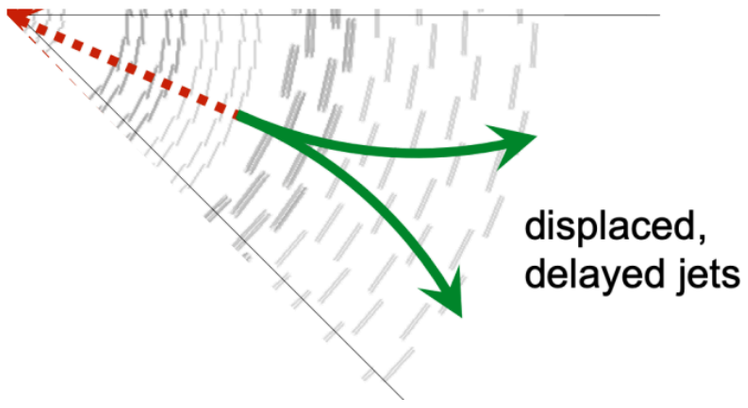
- Run 3: Tuned to be more inclusive for LLP signals
  - *Loosened* definition of prompt tracks and displaced tracks
  - Tighten *number* of prompt tracks



Displaced Jets

- Multiple efforts to cover different displacements
  - Go beyond tracker!

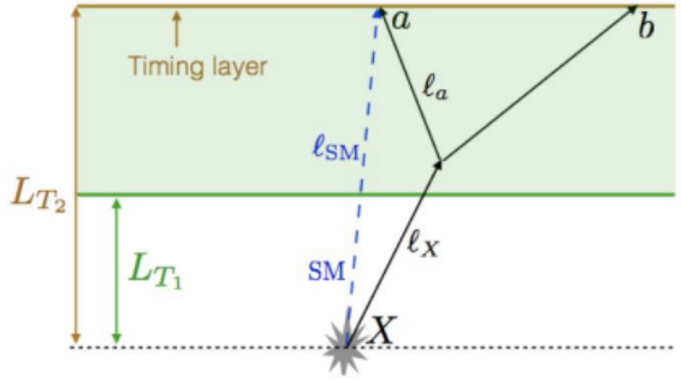
Tracker



Run 2: EXO-19-021

ECAL timing

PRL 122.131801 J. Liu, Z. Liu, L. T. Wang

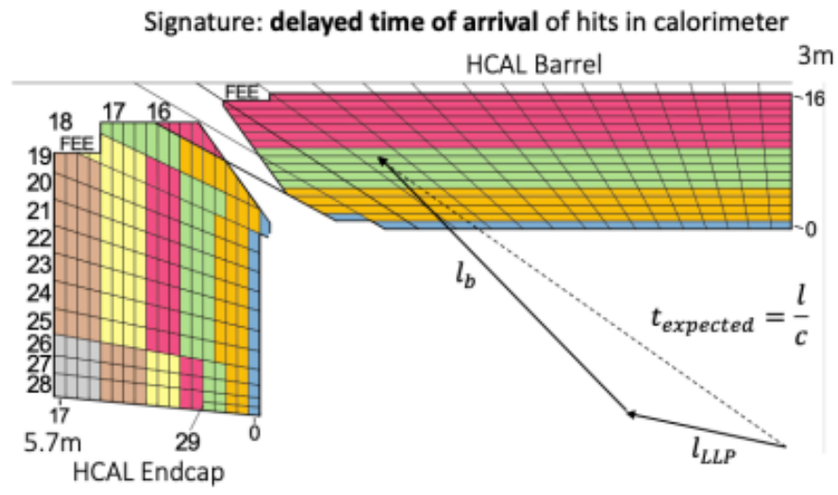


$$\Delta t = \frac{l_a}{\beta_a} + \frac{l_X}{\beta_X} - \frac{l_{SM}}{\beta_{SM}}$$

signal arrival time — background arrival time

Run 2: EXO-19-001
Run 2: PAS-EXO-21-014

HCAL timing

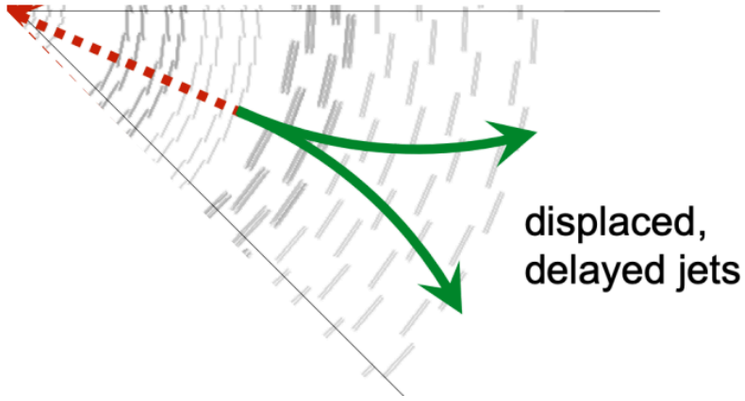


Run 3: NEW

Displaced Jets - ECAL Timing

- ECAL Lead-tungstate crystals have excellent time-resolution ~O(100ps)
  - New software module developed @HLT
  - Can be used to tag delayed jets
    - Stay tuned for a new run 2 result by Lisa

Tracker



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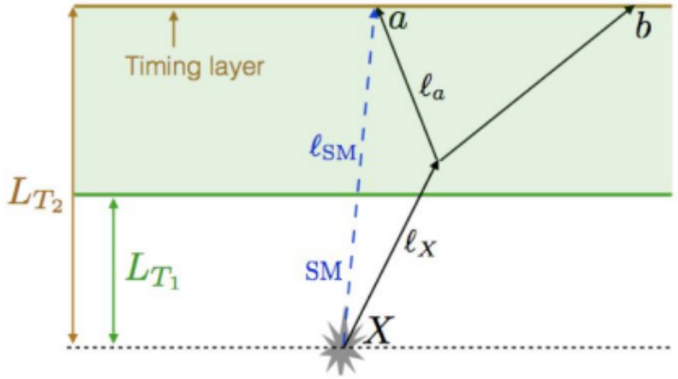

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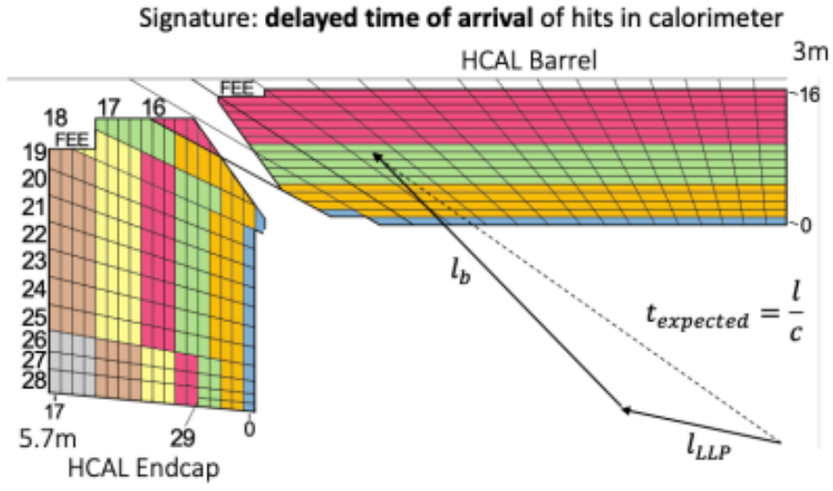
HCAL timing



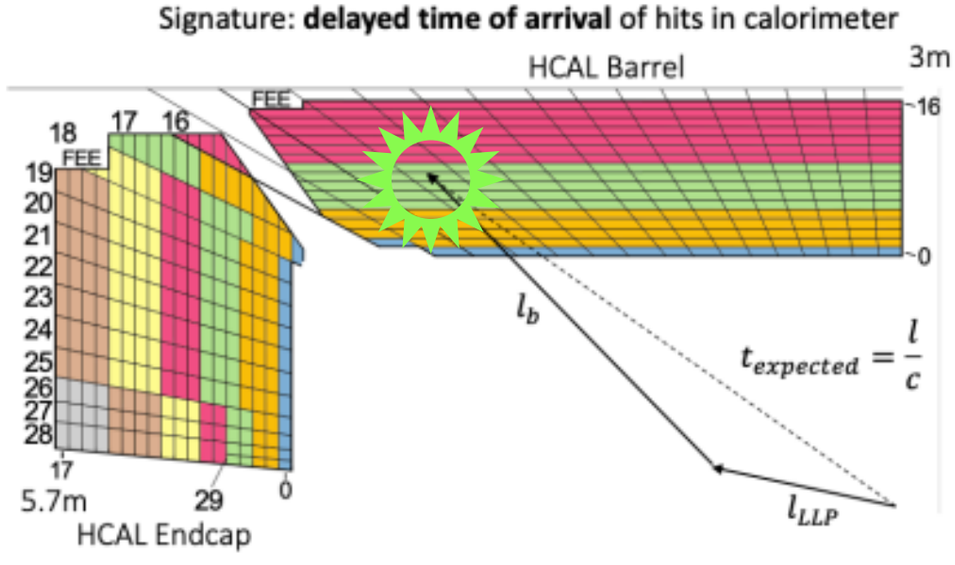
Run 3: NEW

Displaced Jets - HCAL Timing

- Utilize HCAL Phase-1 upgrade features:
  TDC info + *depth* segmentation
  - Frontend electronics gives digitized timing info in 0.5 ns steps(TDC)
- New L1 development!
  - HCAL backend electronics uses 4 *spare* bits to encode extra info per 4x4 HCAL cells
    - Energy in deeper HCAL layers
    - Veto prompt cells
    - Flag delayed cells
  - L1 delayed jets = at least 2 LLP towers in a jet
    - Rejects 99% QCD
- Hugh effort to develop multiple FWs and commission the L1 delay jets object!
- Fruitful reward at HLT:
  - Mix and match with delayed ECAL timing and/or displaced tracking

From Gillian Kopp

HCAL timing

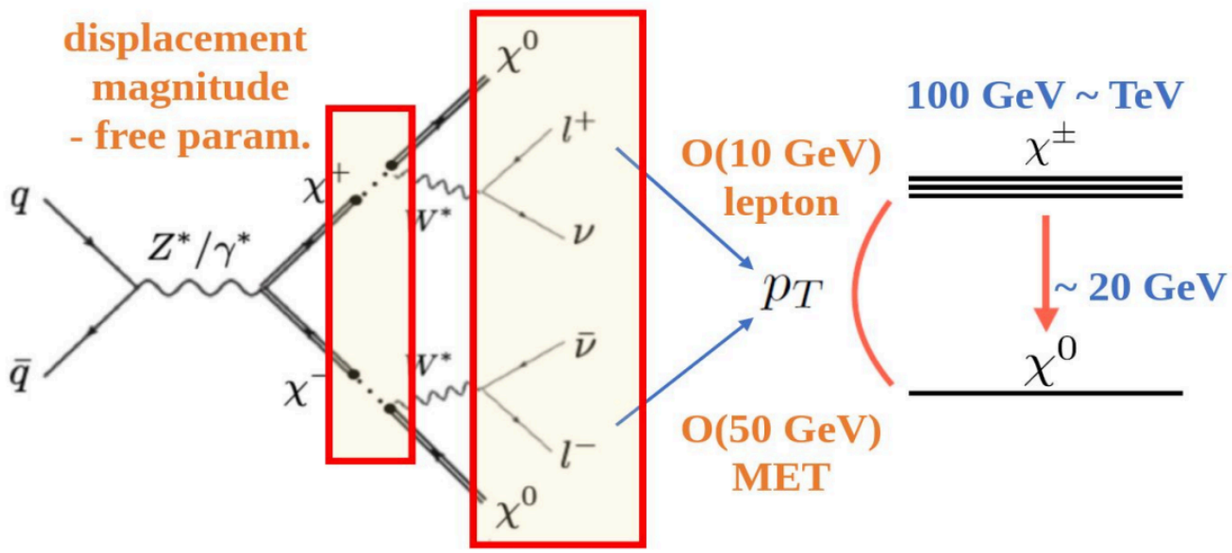


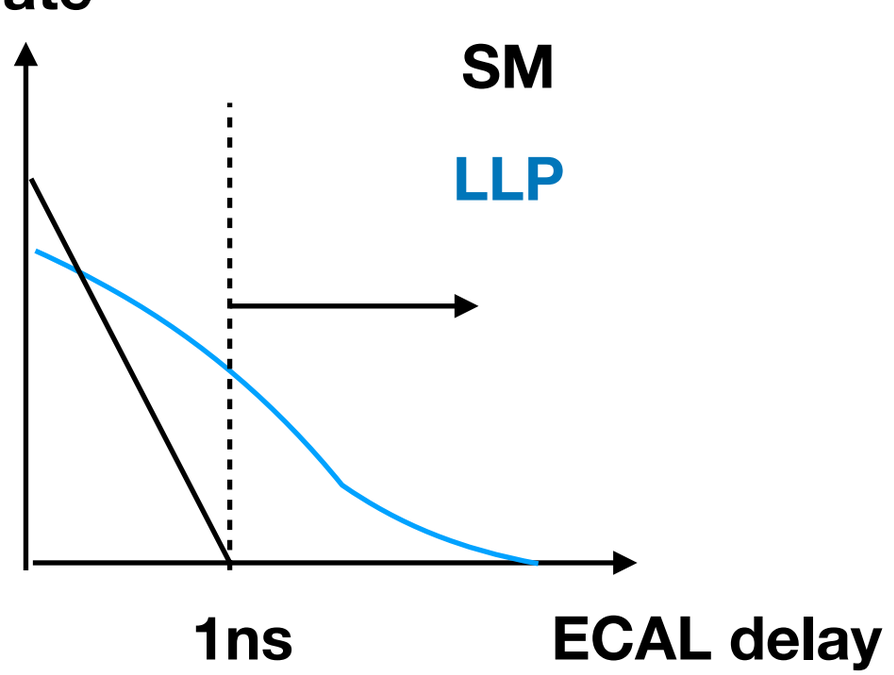
Soft displaced di-photon

- ECAL timing *alone* can be very powerful
  - SM background tend to fall sharply after ~1ns
  - Together with EM shower variables (e.g. shower shape, H/E etc) can bring pT thresholds as low as 10 GeV

- Covers LLP models with *soft* photons
  - Feature of compressed dark sector

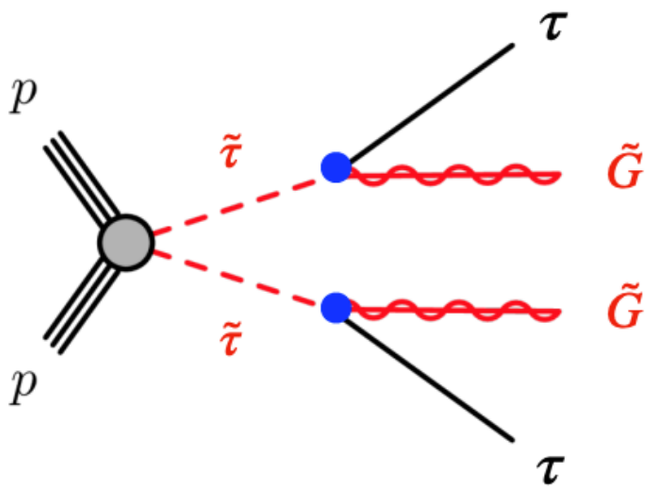
JHEP11(2020)

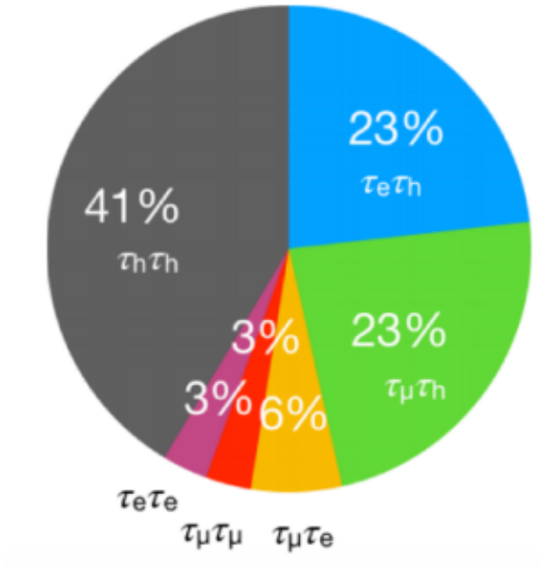




Displaced taus

- The “missing” displaced object
  - Challenging to build dedicated hadronic tau triggers
- Seeded by L1Taus
  - Based on calorimeters => No inefficiency of small tau displacement
- HLT: borrow *offline* algorithms to *online*
  - Run extra tracking iteration to build displaced tracks
  - Run HPS algorithm with *displaced* PF candidates
- Lowers tau pT thresholds





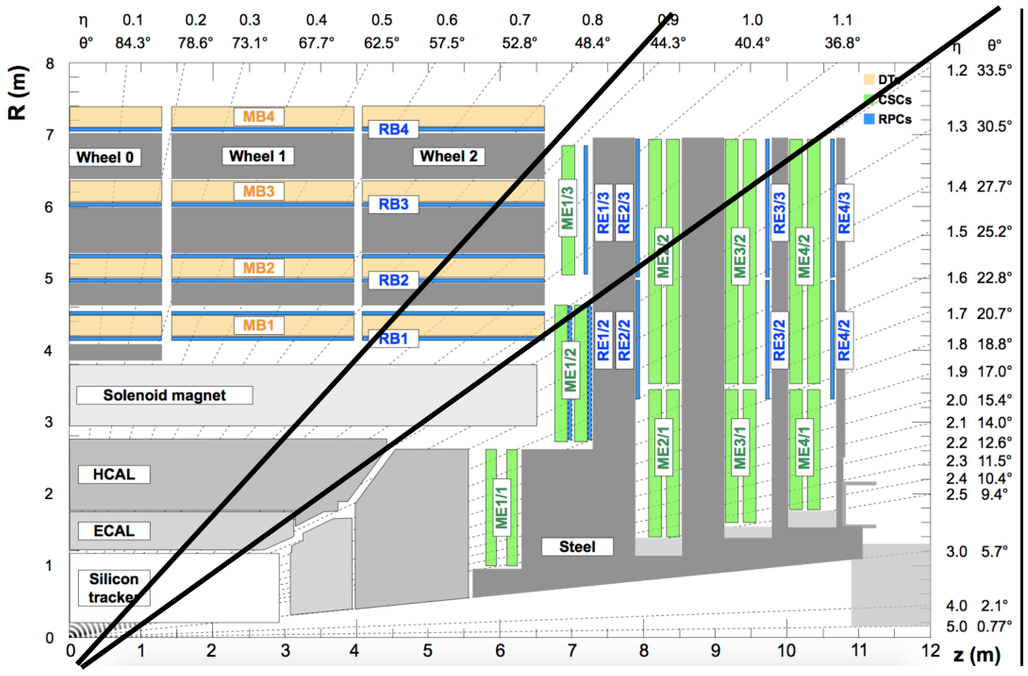
Displaced muon

- One of the first LLP triggers in CMS
- Main limitation comes from L1 beam spot constrains
  - Add *displaced* L1 muon to all regions
  - Barrel region deployed in Run 3!
    Overlapped/Endcap region is under-development
- Extend efficiency to O(m)

Barrel (DT)

- Kalman filter tracking without vertex constrain
- Homogeneous B-field + simple input make this possible

Overlapped (CSC+RPC+DT)

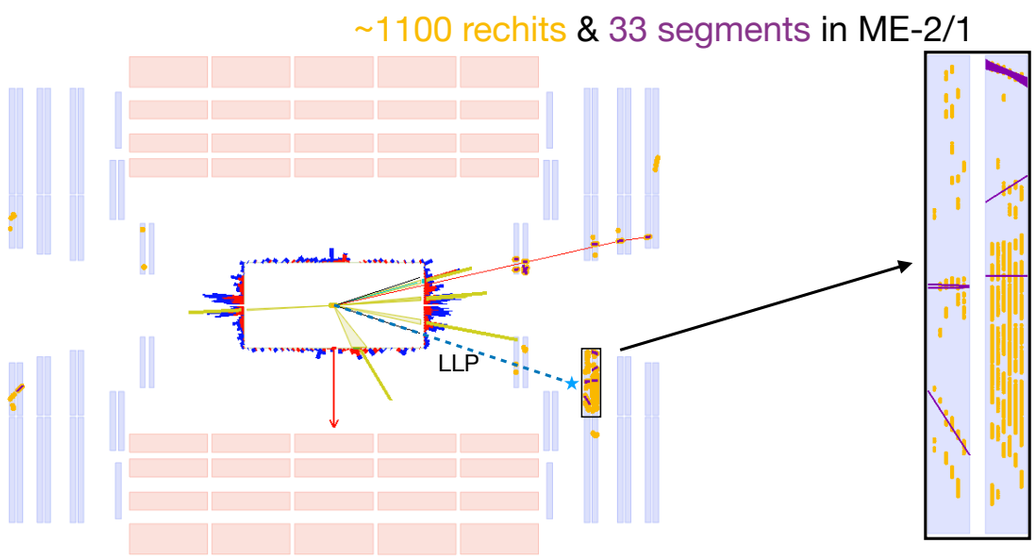


Endcap (CSC+RPC+DT+GEM)

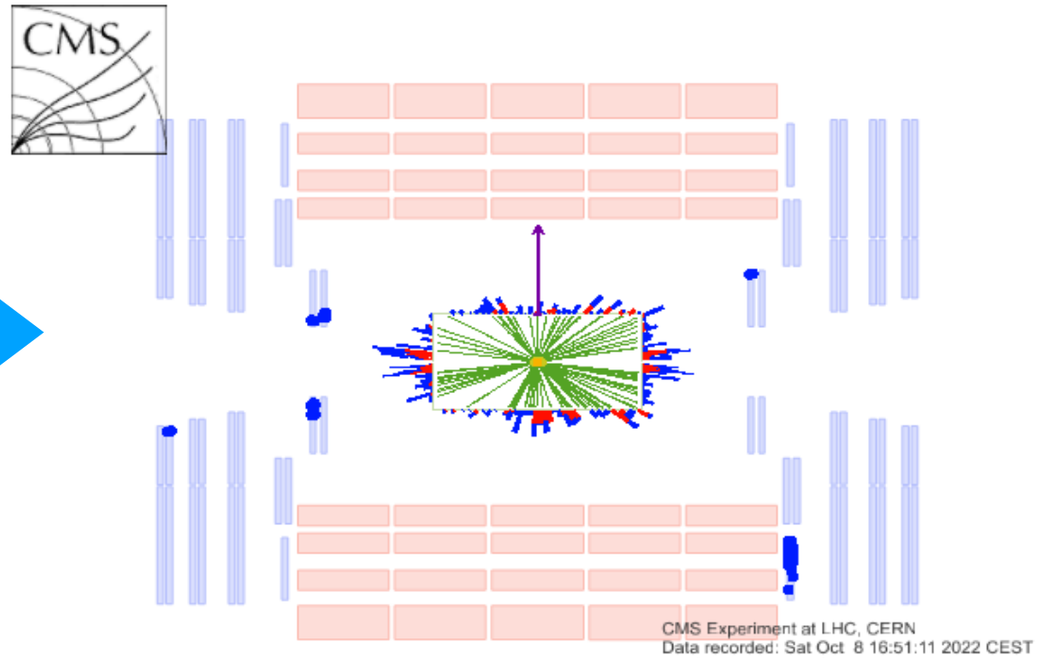
Muon Detector Shower (MDS)

- Neutral LLP decay in muon system and creates hadronic showers
- Powerful new signature for LLP search:
  - Outermost system -> longer lifetime
  - Good shielding (12-27 interaction length)
  - Unique to CMS muon system
- New L1 + HLT path implemented for the new signature
  - Almost unexplored dataset!

Simulation



Event recorded in October

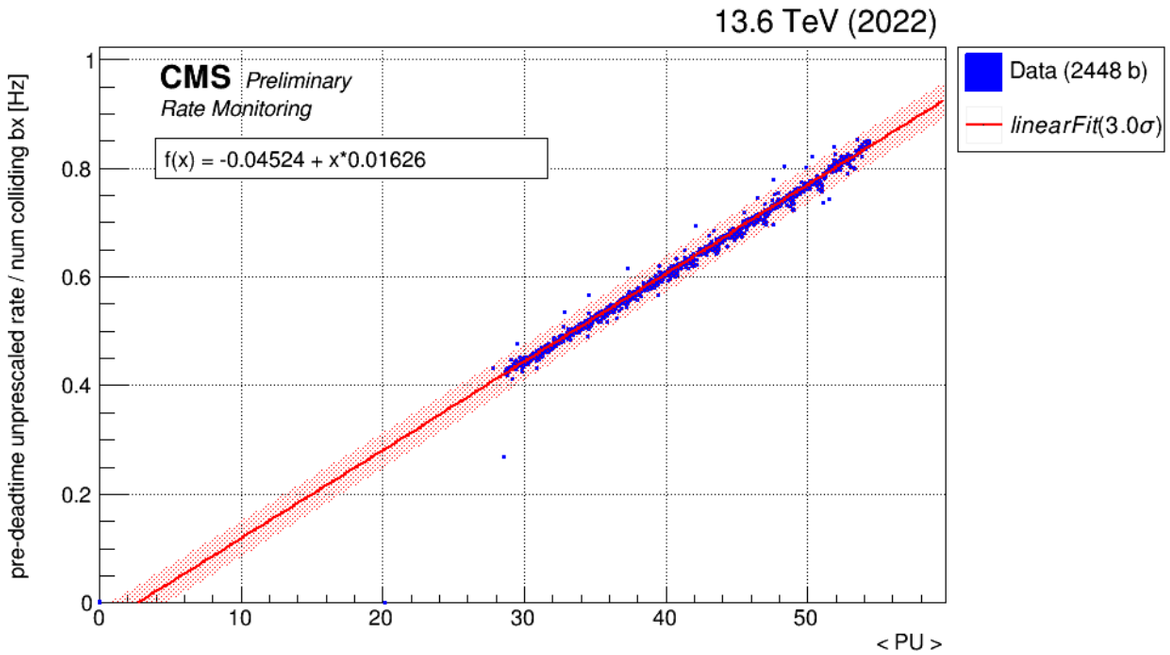


[Available on DPS soon]

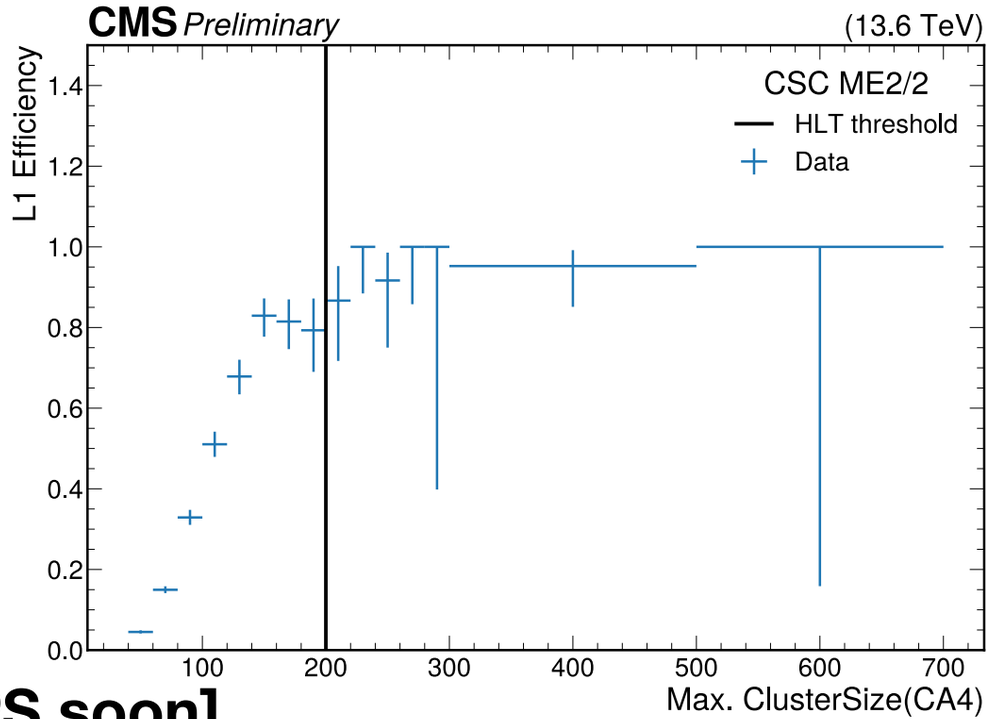
Muon Detector Shower (MDS) performance

- At L1, build shower candidates by hit-counting in CSC chambers
  - Only CSC has *spare bits* for LLP triggers (Up to 4 bits per chamber)
  - ~2% of L1 rate budget
  - Stable rates with good uniformity across CSC chambers
- At HLT, cluster offline shower object with CA algorithm
  - Cluster selections follow run 2 analysis as a baseline
  - Good efficiency w.r.t. offline cluster size

L1 rate v.s. PU



L1 efficiency v.s. HLT selection

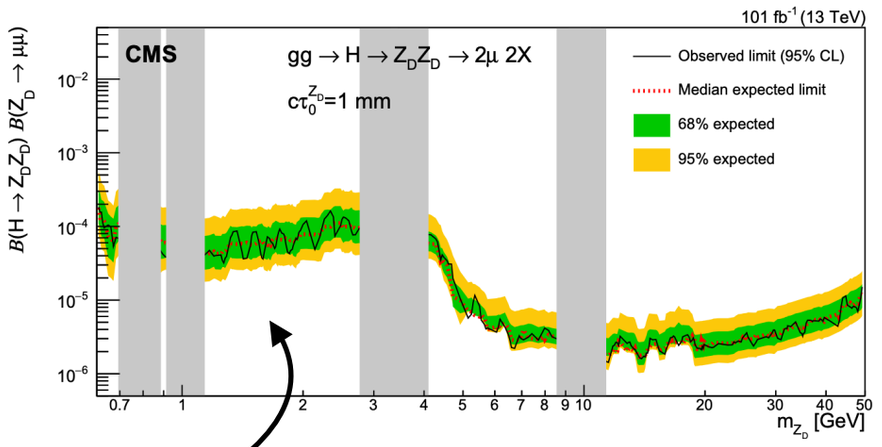


[Available on DPS soon]

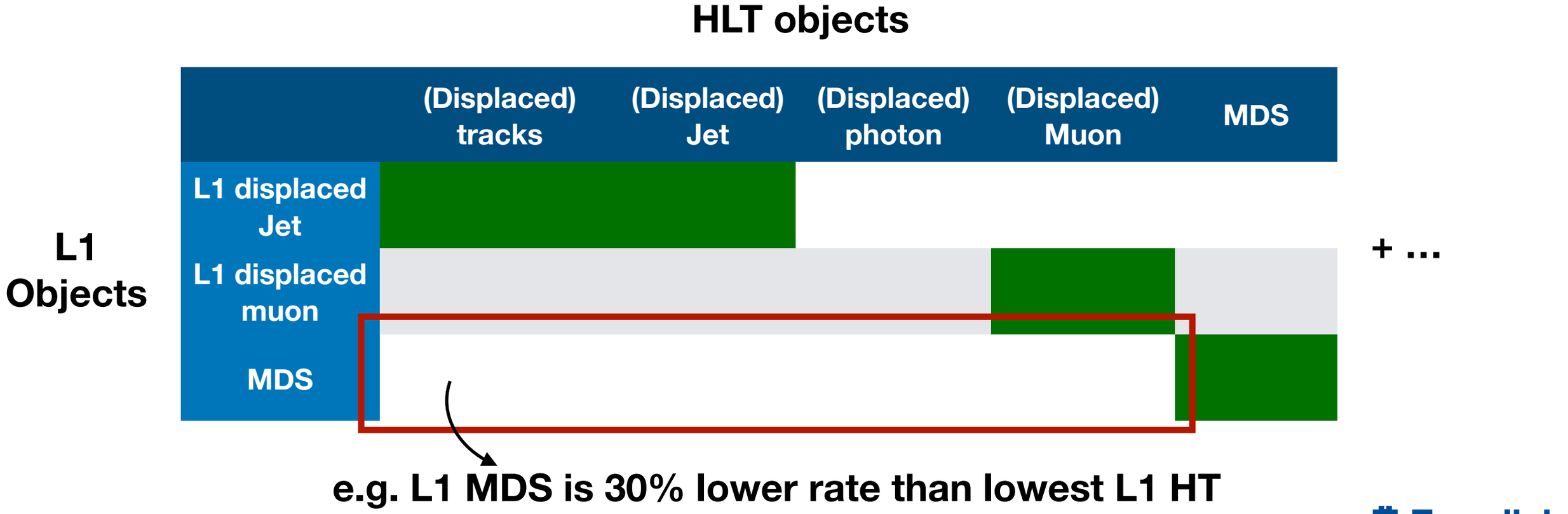
How do we make use of the “LLP” upgraded CMS?
A few personal thoughts

Even more trigger developments

- We've just collected 10% of 10% of data
  - 4 spare bits could make a difference!
- Make good use of LLP-L1 objects@ HLT
  - Many handles for rates (Tracking/Timing/MDS etc…)
- Scouting
  - Reduced amount of information, but lower thresholds
  - EXO-20-014 starts with pT>3 GeV OS di-muon in run 2



Low mass!



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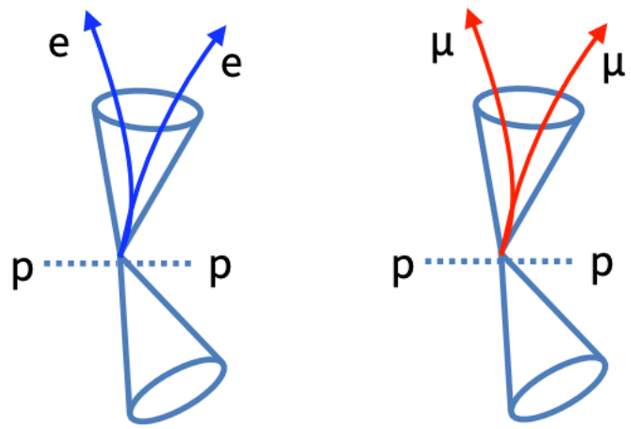
B-parking dataset

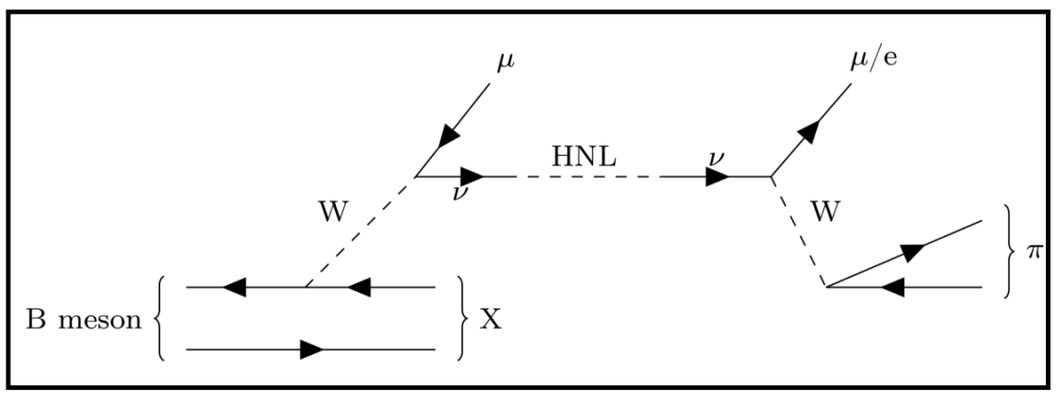
- CMS collected ~10 billion unbiased b-hadron decays

- Suitable for LLP produced in association with b-hadrons
  - Can have very large cross section!

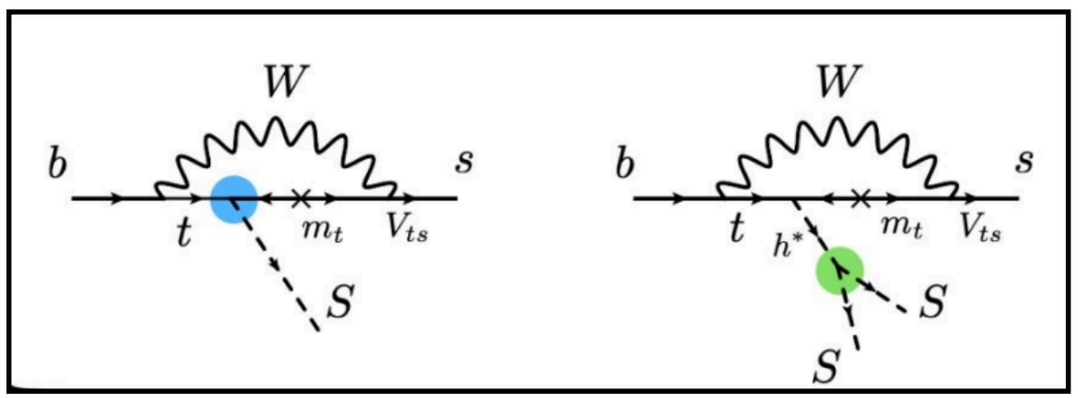
- B-parking @ Run 3
  - Adding di-muon/di-electron triggers with/without displaced vertex
    - As low as 4 GeV with mass restrictions



HNL from B meson Decay



H->SS produced in b-meson



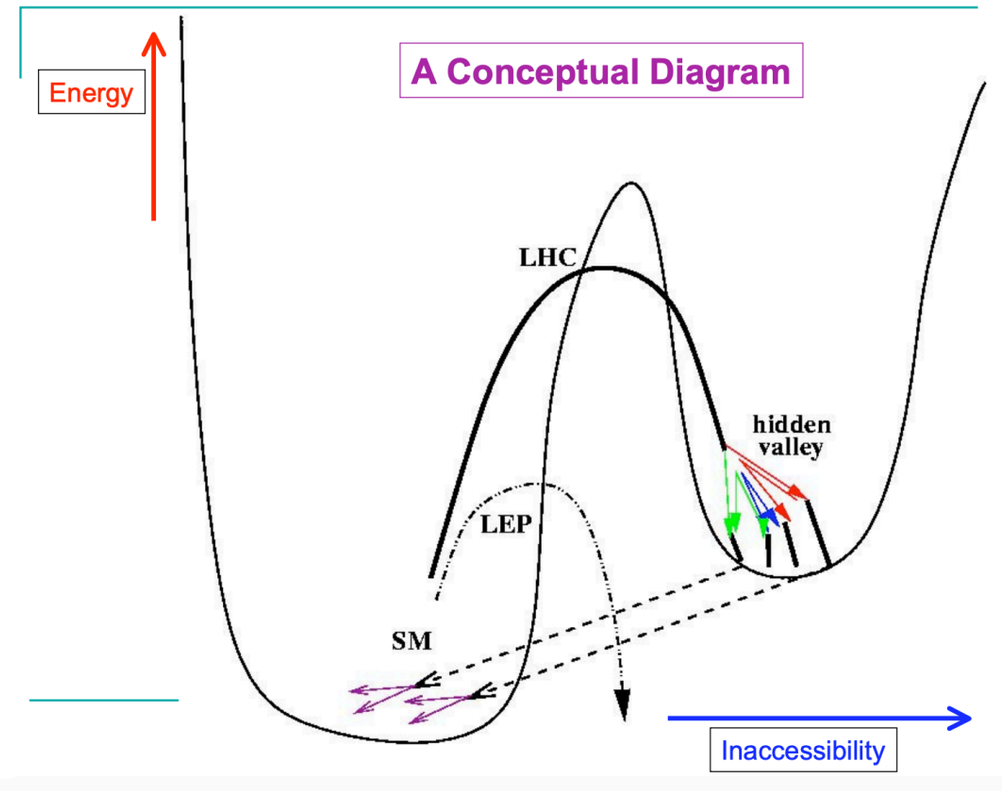
Re-interpretation

- LLP searches are signature-based search at heart
  - We designed our search to be as inclusive as possible
    => Make sure it can be used by others!
  - Hidden valley is a LARGE class of models
    with vastly different signatures

credit: Matt Strassler

- We provide re-interpretation materials
  - CMS guidelines: link
  - Cut flow/Correlation/event yields
    are very helpful

- See nice example by C. Wang later
  with MDS!



Conclusion

- Looking back at LLP11…
  - CMS made good progress to close down the major gaps

- CMS overcame many limitations of LLP analyses has faced in run 2
  - New dedicated LLP L1 seeds
    - Delayed Jet, MDS, displaced Muon
  - HLT software

- Exciting times ahead for LLP searches!

NOW: MAJOR GAPS

- Low-mass hadronic decays (especially at shorter lifetime)
- Singly produced LLPs, depending on search (lepton jets, ATLAS searches for decays in HCAL and MS)
- Low-mass (semi-)leptonic decays (especially < 20 GeV, in resonance regions)
- Slightly displaced leptons; displaced leptons not originating from vertex (depending on flavor structure)
- Displaced taus
- Non-pointing/delayed photons, especially low mass, singly produced, or without MET
- LLPs produced in high multiplicities, confining hidden sectors
- Quirky signatures

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Back up slides

Selected CMS LLP run 2 searches

	Signature	Triggers	Dedicated LLP trigger?
EXO-19-013	Jets with displaced vertices	HT>1050 GeV	No
EXO-19-021	Displaced Jets	HT+2 jets with displaced tracks	Yes (HLT)
EXO-18-003	Displaced leptons	Displaced-e: photon Displaced-mu: mu with no PV	Yes (HLT)
EXO-19-001	Delayed Jets +MET	MET >120 GeV	No
EXO-16-004	Stopped LLP	Empty bunch train triggers+Jet/Mu	No
EXO-19-010	Disappearing Tracks	MET>150GeV+isolated track>50GeV	Yes (L1+HLT)
EXO-19-005	Delayed photons	Non-pointing photons with elliptic EM shower	Yes (HLT)
EXO-21-006	Displaced di-muon	Displaced muons w/o vertex constrains	Yes (HLT)
EXO-20-003	Displaced Jet+Z	Trigger on Z->ll signatures	No
EXO-18-001	Emerging jet+jet	HT>900GeV	No
EXO-20-014	Displaced di-muon with scouting	Scouting OS di-muon pT>3 GeV	No