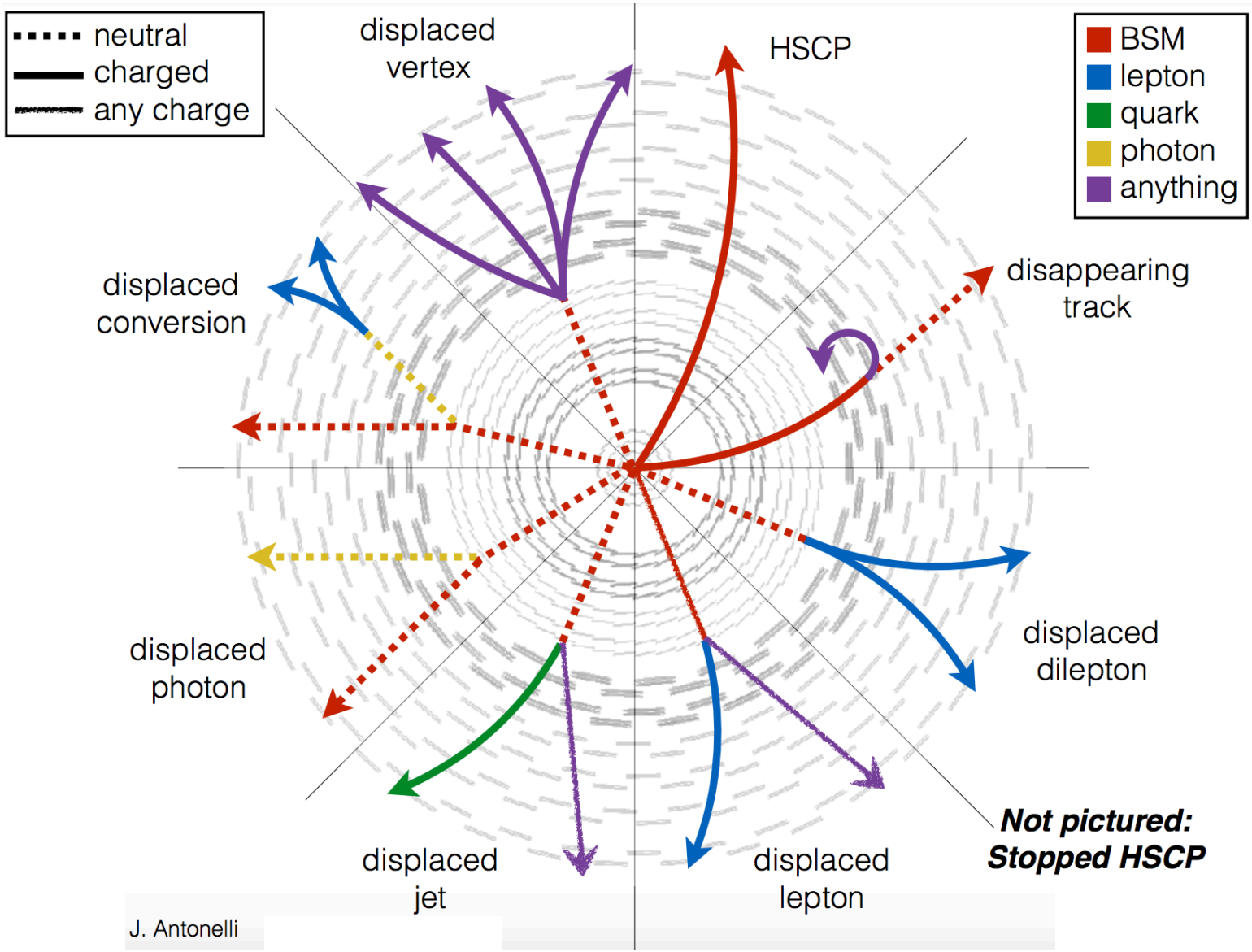
CMS Long-Lived Particle Searches at the HL-LHC

Juliette Alimena, on behalf of the CMS Collaboration

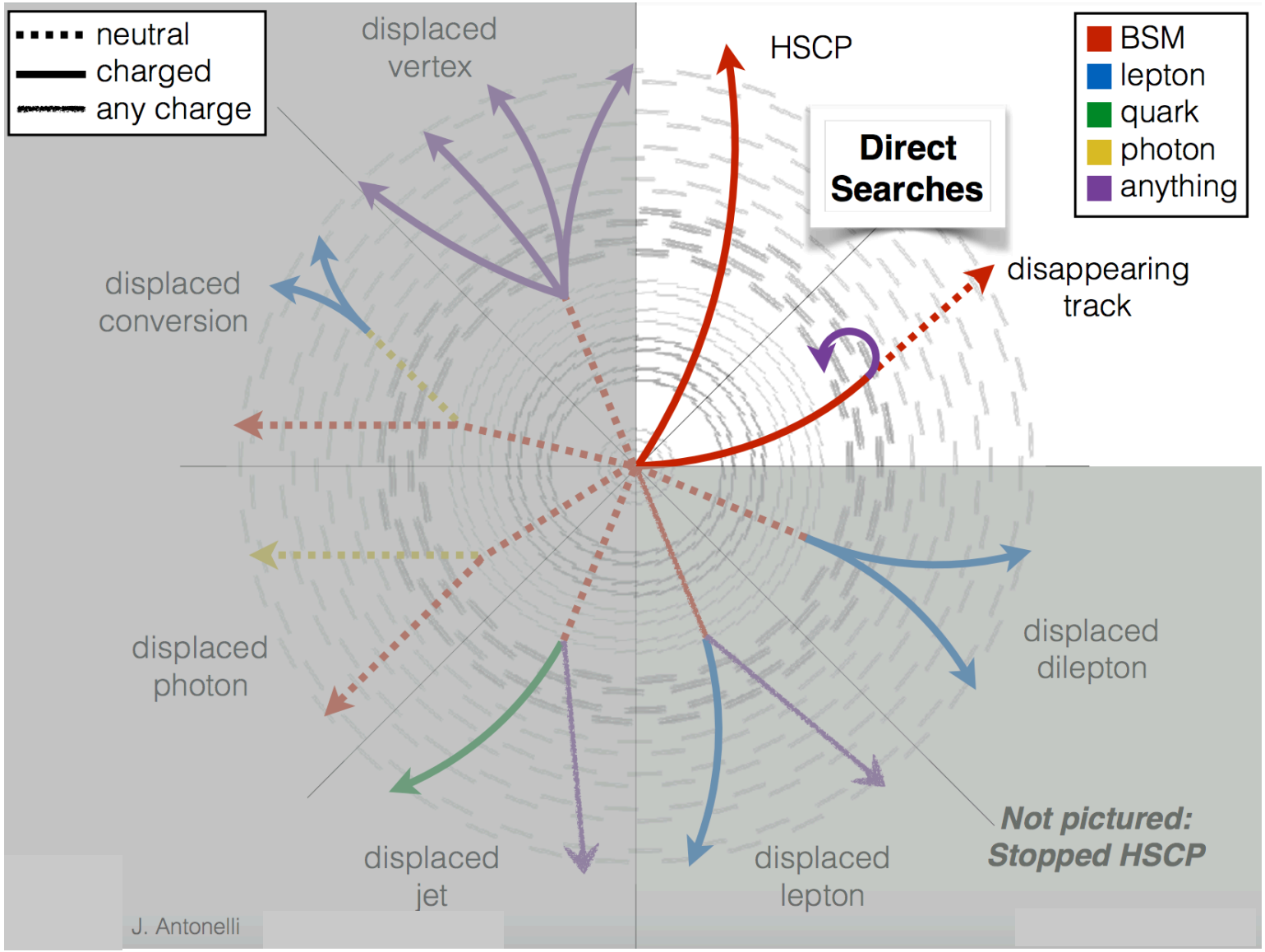
HLHE-LHC2017: Workshop on the physics of HL-LHC, and perspectives at HE-LHC, 30 Oct – 1 Nov 2017, CERN, Geneva (Switzerland)

October 31, 2017

Long-Lived Particle Searches



Direct Searches



Heavy Stable Charged Particles: **Tracker Upgrade (I)**

CMS-TDR-17-001

- **HSCPs: New, heavy particles could propagate through the detector before decaying**
  - Could look like heavy, **highly-ionizing**, slow-moving muons

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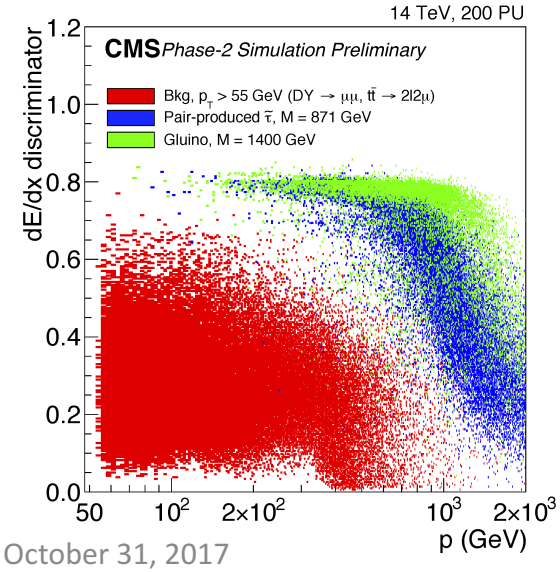
Phase-2 Inner Tracker (Pixels):

- dE/dx measurement from analogue Time over Threshold readout
- Similar to dE/dx measurements from current pixels and strips



dE/dx discriminator shows large separation between signal and background

Heavy Stable Charged Particles: Tracker Upgrade (I)

CMS-TDR-17-001,
CMS-PAS-EXO-14-007

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Phase-2 Inner Tracker (Pixels):

- dE/dx measurement from analogue Time over Threshold readout
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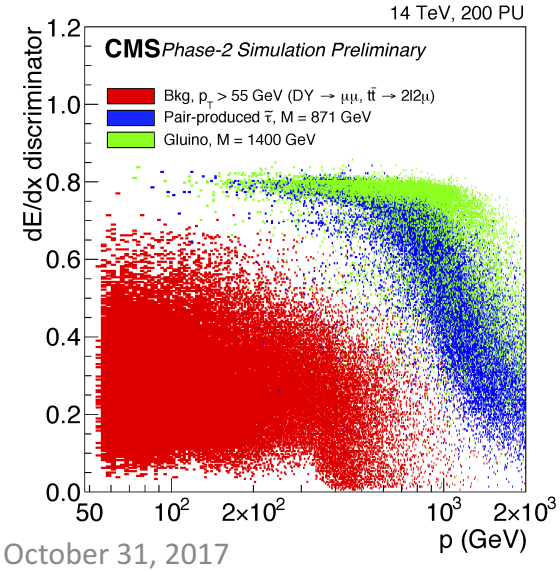
Phase-2 Outer Tracker (Strips):

- Readout is binary, cannot provide full dE/dx discriminator
- Original Phase-2 strips planned with no dE/dx at all



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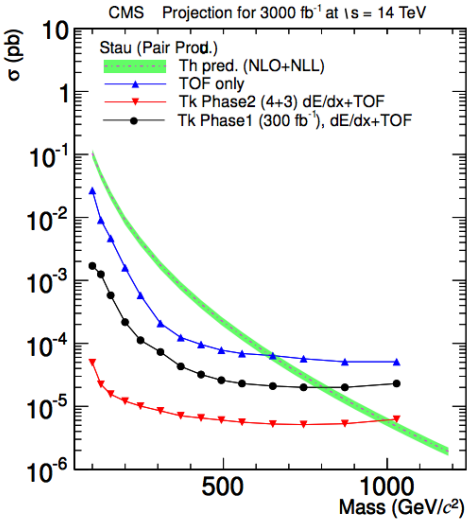


With no dE/dx information at all, HSCP stau Phase-2 limit projection is worse than with the Phase 1 detector!

Heavy Stable Charged Particles: Tracker Upgrade (I)

CMS-TDR-17-001

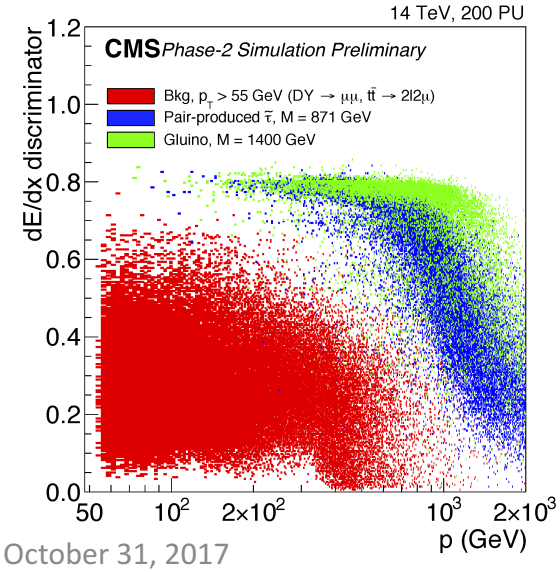
- **HSCPs: New, heavy particles could propagate through the detector before decaying**
  - Could look like heavy, **highly-ionizing**, slow-moving muons

Phase-2 Inner Tracker (Pixels):

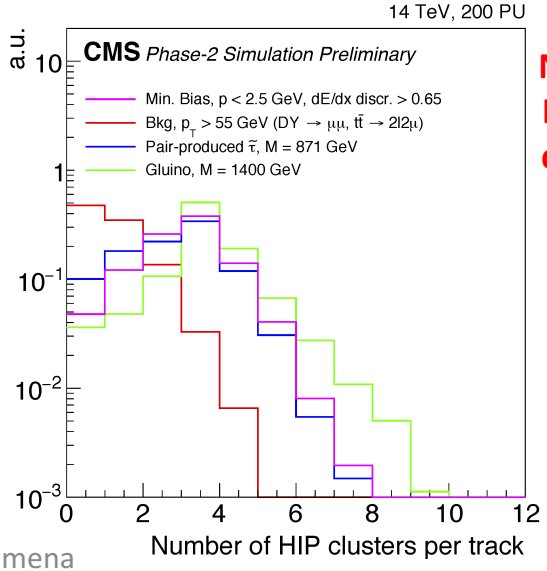
- dE/dx measurement from analogue Time over Threshold readout (currently set to 4 bits resolution)
- Similar to dE/dx measurements from current pixels and strips

Phase-2 Outer Tracker (Strips):

- Readout is binary, cannot provide full dE/dx discriminator
- **However**, implemented dedicated hit-over-threshold bit ("HIP flag"), currently set to 1.4*MIP charge



dE/dx discriminator shows large separation between signal and background



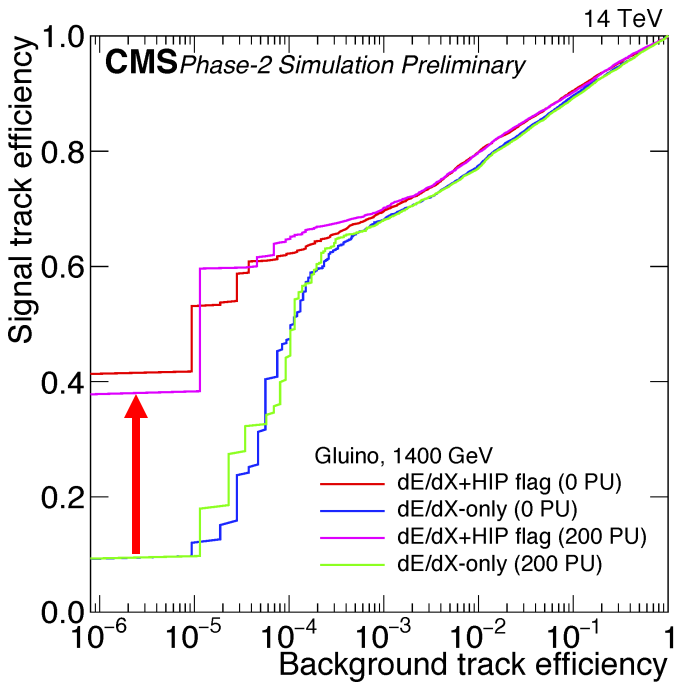
Number of clusters with HIP flag set shows good discrimination between signal and background

Heavy Stable Charged Particles: **Tracker Upgrade (II)**

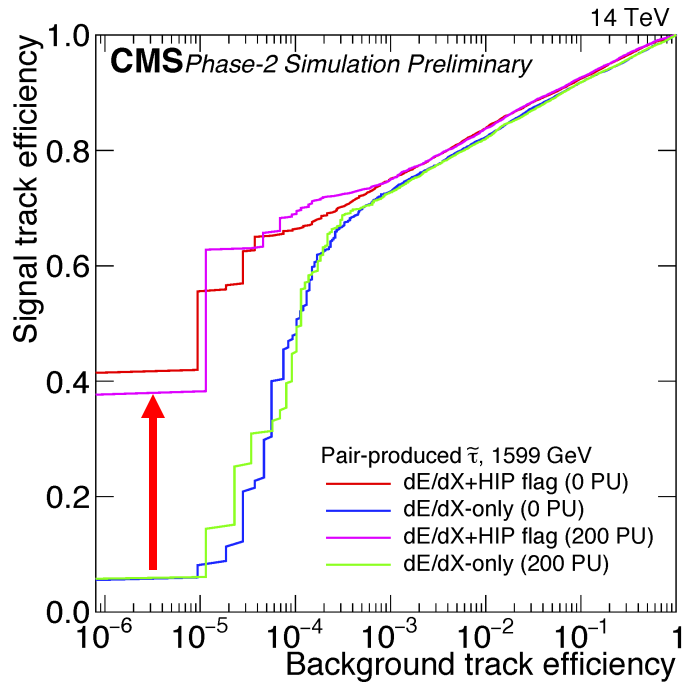
CMS-TDR-17-001

Impact on the HSCP analysis of the Phase-2 inner tracker dE/dx discriminator and outer tracker HIP flag:

Gluino, 1400 GeV



Stau, 1599 GeV



HIP flag is critical to restore tracker sensitivity to HSCPs in Phase 2

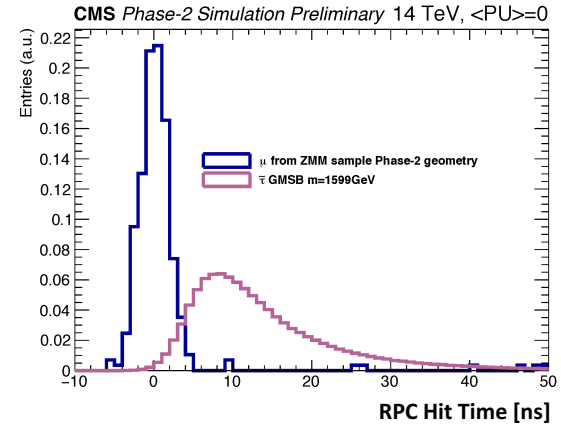
Heavy Stable Charged Particles:

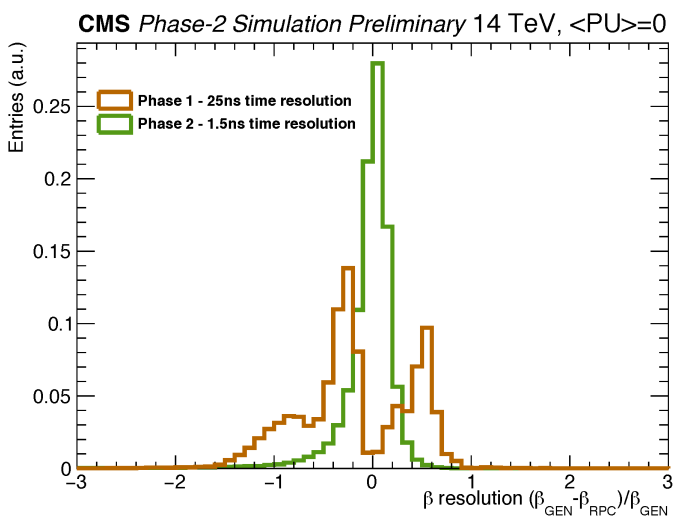
CMS-TDR-17-003

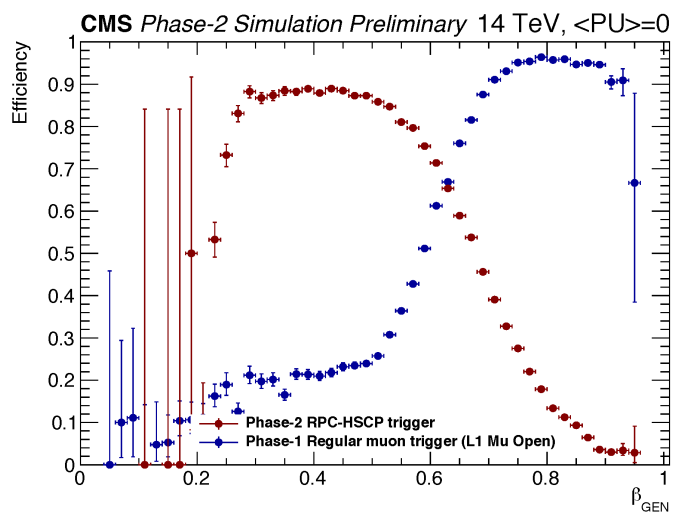
RPC Trigger Upgrade (I)

See poster by G. Sanchez for more details

- HSCPs could look like heavy, highly-ionizing, **slow-moving** muons
- **RPC upgrade (RPC Link Board System) will provide ~1.5 ns time of flight resolution to each RPC station**
- RPC-HSCP trigger algorithm: linear fit to time at each RPC hit as a function of its distance from the IP







Upgraded RPC Link Board System will allow us to trigger, at the correct BX, HSCPs with velocities as low as β ~ 0.25

Heavy Stable Charged Particles:

RPC Trigger Upgrade (II)

CMS-TDR-17-003,
Eur. Phys. J. C (2015) 75:325

Impact on the HSCP analysis of the Phase-2 RPC trigger:

HSCP Mass Resolution:

Resolution from Phase-2 RPC trigger

Is comparable to

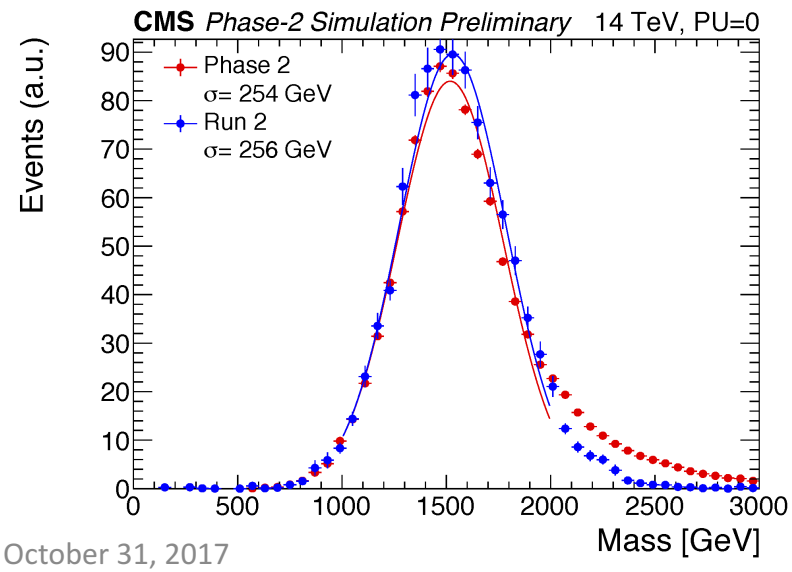
Resolution from Run 2 offline TOF measurement (from DTs and CSCs)

HSCP Reconstruction Efficiency:

As a function of |η| and β

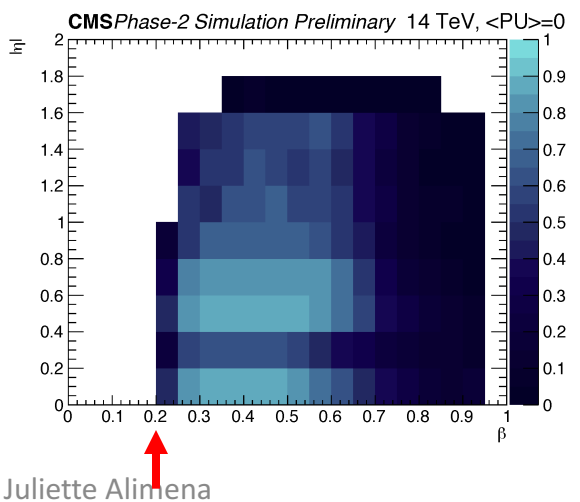
With the Phase-2 RPC trigger, we can increase the reconstruction efficiency for low β, as compared to Run 2

Stau, 1599 GeV



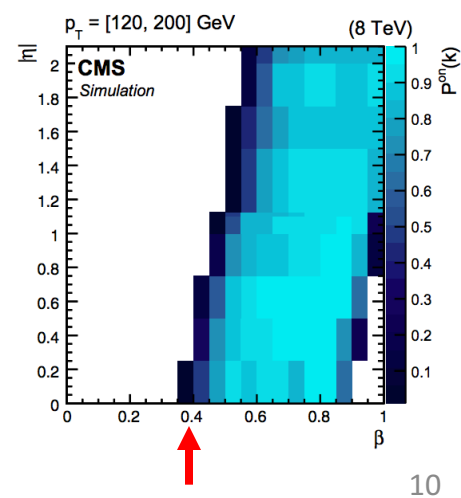
Phase-2 with RPC Trigger

Full p_T range

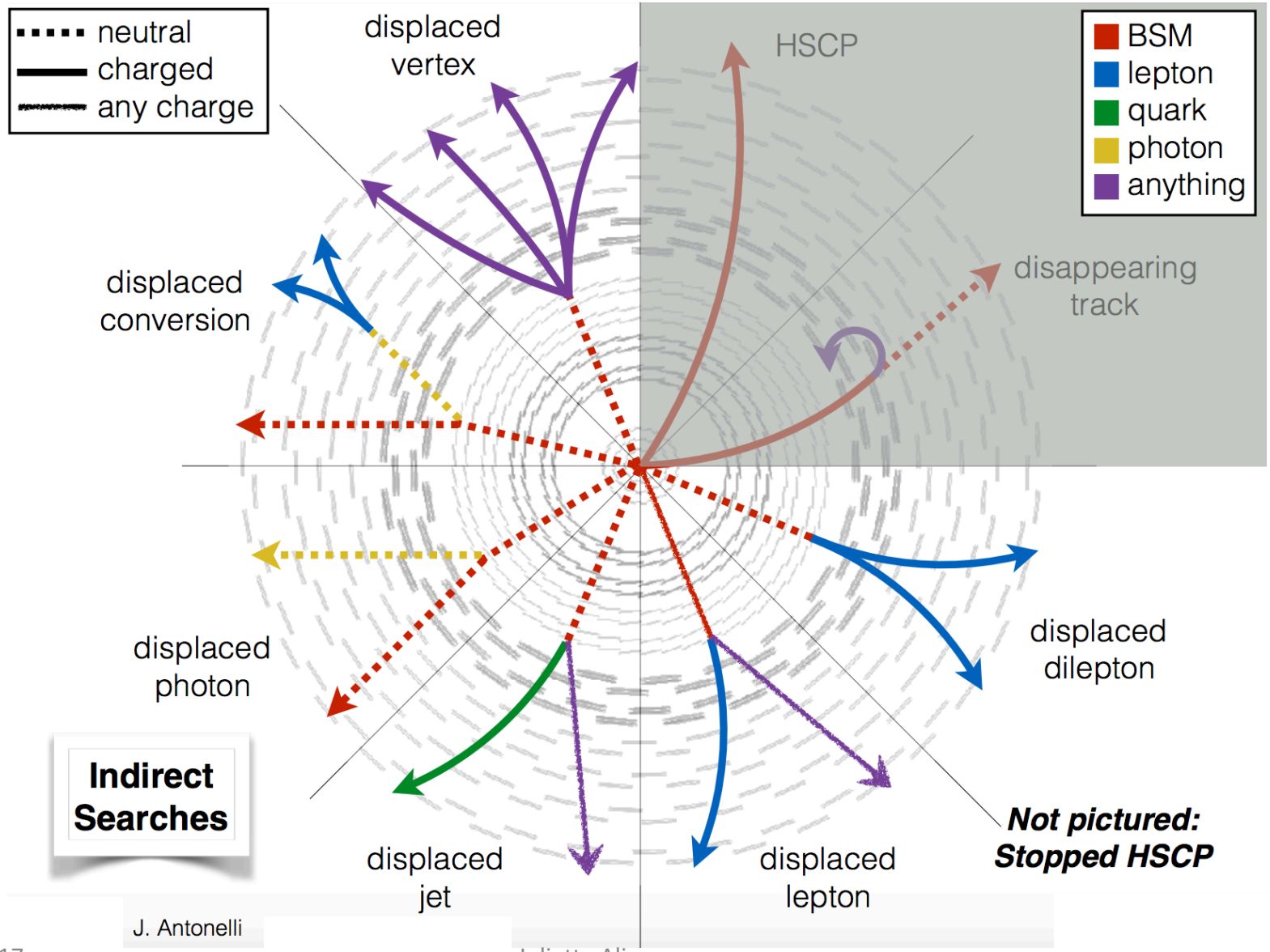


Run 2 with Online Selection

120 < p_T < 200 GeV



Indirect Searches



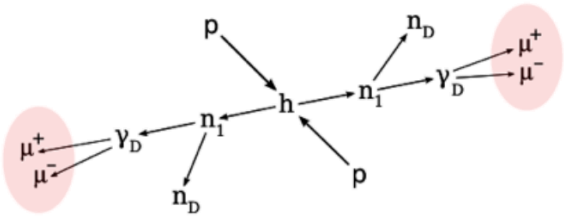
Long-Lived Dark Z Bosons (I): **Muon Trigger Upgrade**

CMS-TDR-17-003

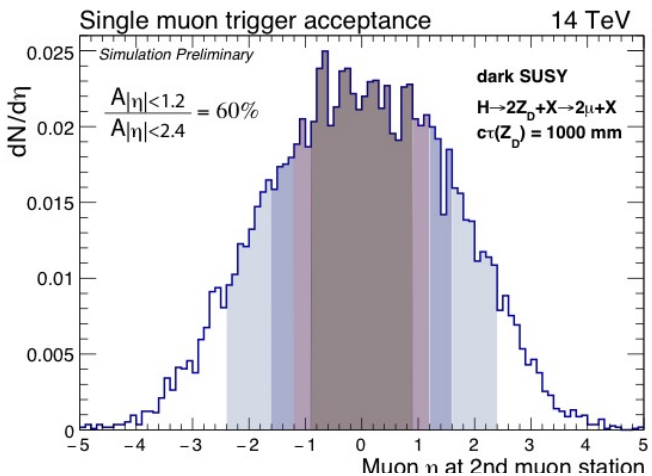
- Long-lived dark Z boson in dark SUSY:

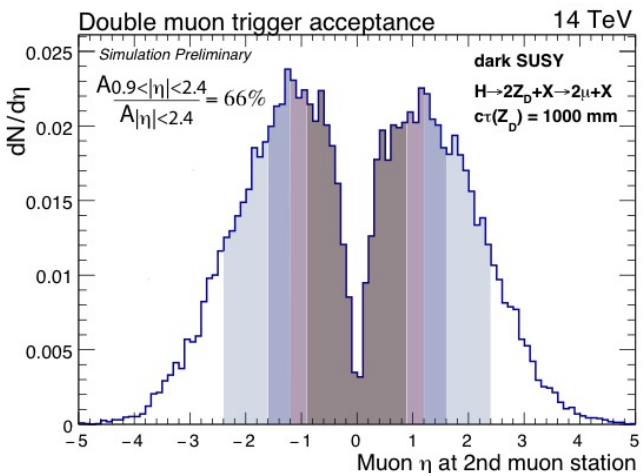
$$H \rightarrow Z_d Z_d + X$$

- Decay signature: four displaced muons



Need a suite of displaced muon triggers to cover the range of possible signatures:





High momentum muon signatures:

- Decays of heavy particles
- Can use single muon trigger
  - Significant fraction of acceptance in the barrel region

Low momentum muon signatures:

- Decays of relatively light particle
- Will require a dimuon trigger with low enough thresholds
  - Endcap region becomes very important

Long-Lived Dark Z Bosons (II): **Muon Trigger Upgrade**

CMS-TDR-17-003

- As part of the Phase-2 muon system upgrade, new **Gas Electron Multiplication** (GEM) detectors will be installed:
  - **GE1/1, GE2/1: Improve muon triggering in 1.6 |η| < 2.4 (2.15 for GE1/1)**
  - ME0: Improve muon ID and triggering up to |η| ~ 2.8
  - GEMs can handle high Phase-2 rate in forward region better than current CMS CSCs and RPCs

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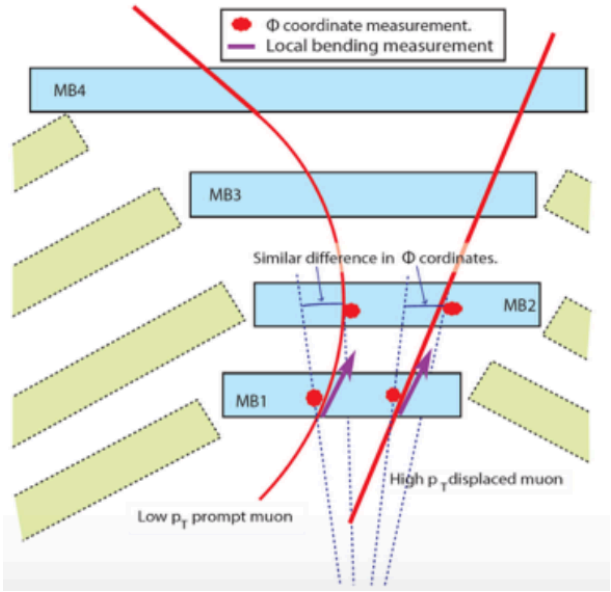
- **Can use the measurement of the muon direction within a single station to discriminate high p_T displaced muons from low p_T prompt muons**



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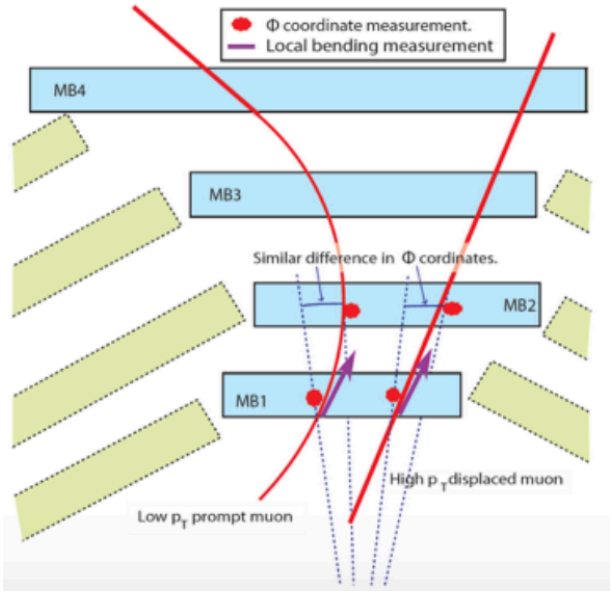
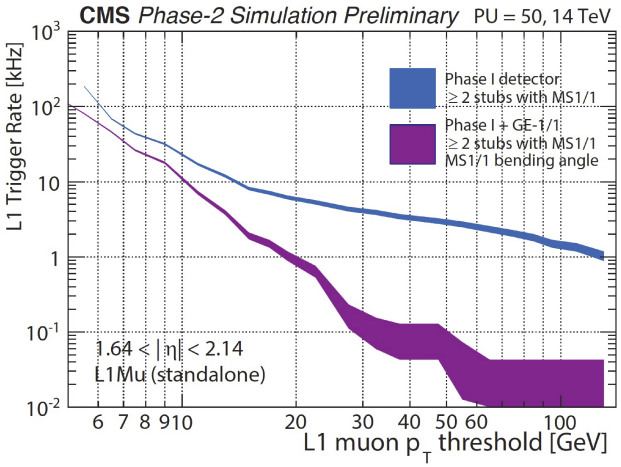
- **Can use the measurement of the muon direction within a single station to discriminate high p_T displaced muons from low p_T prompt muons**
- Measurement of muon direction in new GE1/1 and existing CSC ME1/1 chambers → **efficient rejection of mismeasured muons that dominate the L1 rate**



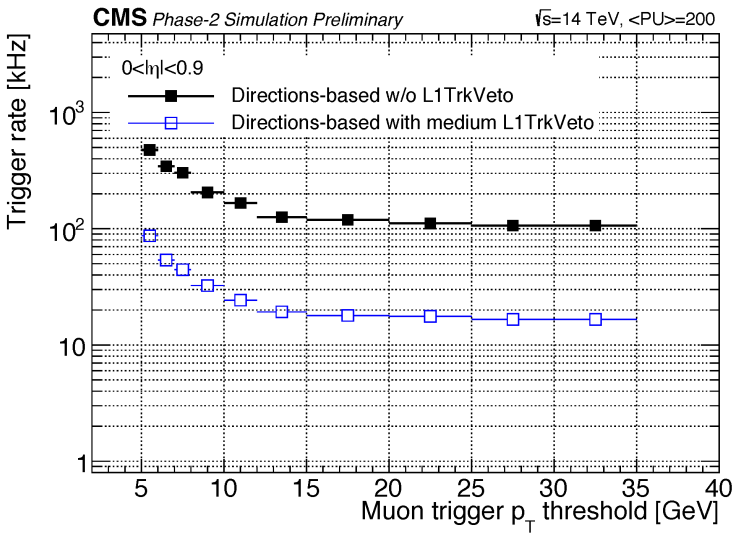


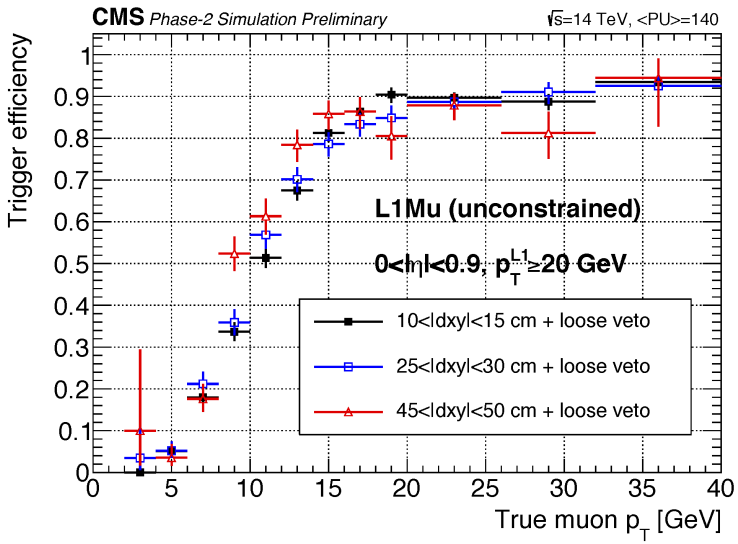
Long-Lived Dark Z Bosons (III): Muon Trigger Upgrade

CMS-TDR-17-003

- L1 muon candidates will be loosely matched to L1 Track trigger candidates
- L1 Track trigger will not be able to reconstruct displaced tracks
- **However**, besides muon direction measurement within a station (previous slide), have another handle for displaced muons:
- Can veto event if L1Mu matched to L1 track, since tracker tracks would not be reconstructed for displaced muons

Barrel Displaced Muon Trigger





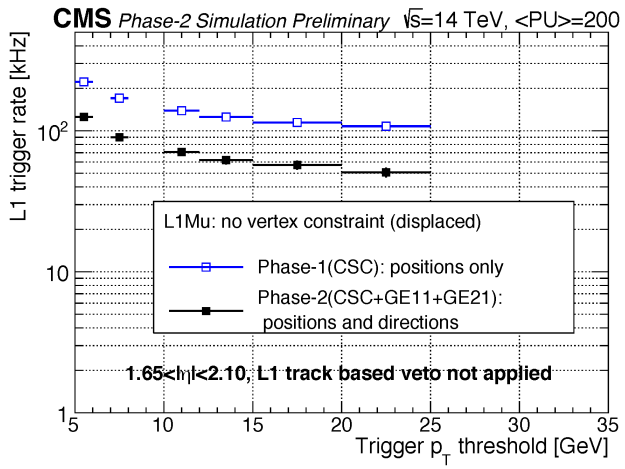
Rate under control, trigger efficiency high even for displaced muons

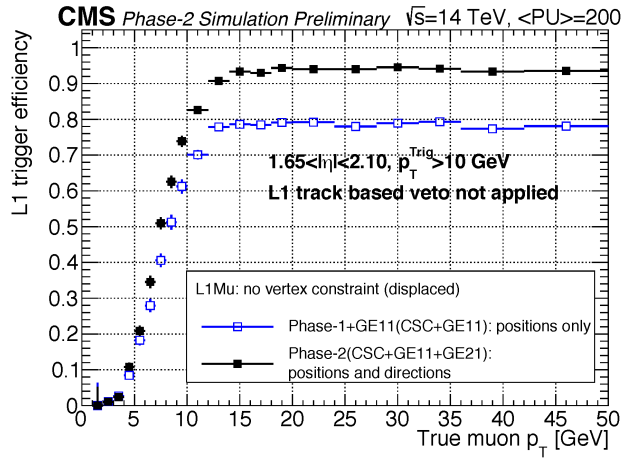
Long-Lived Dark Z Bosons (IV):

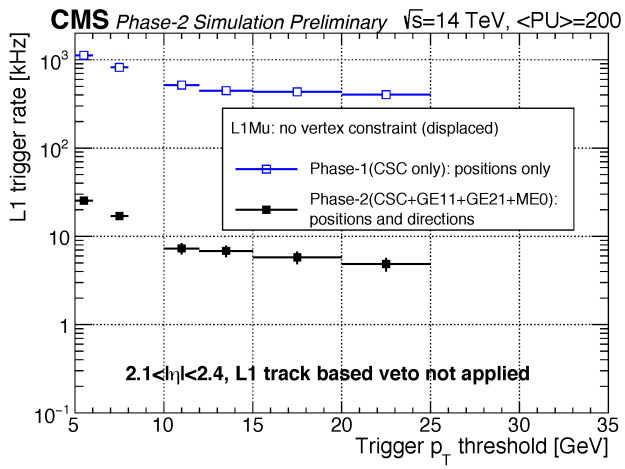
CMS-TDR-17-003

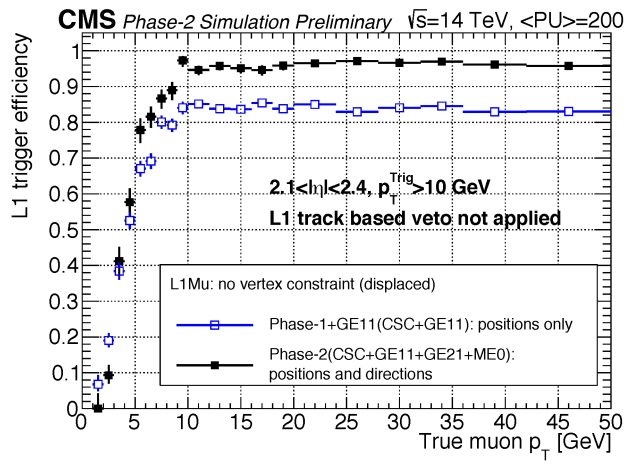
Muon Trigger Upgrade

Endcap Displaced Muon Trigger





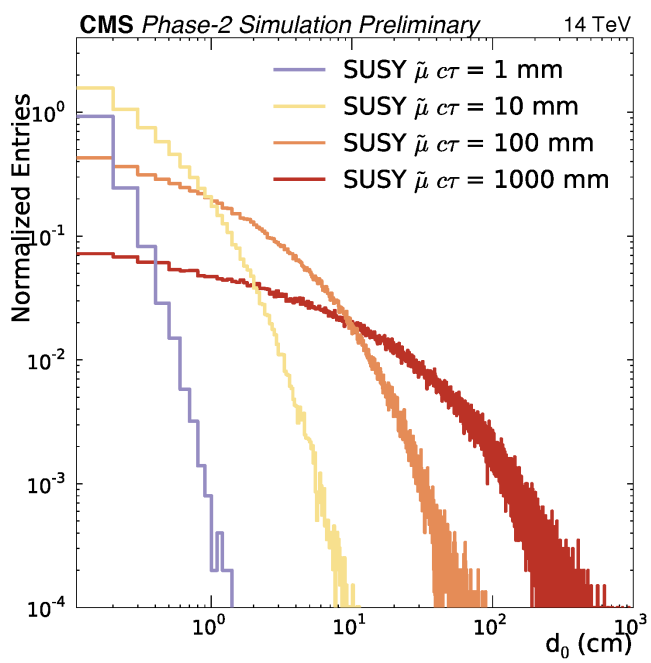


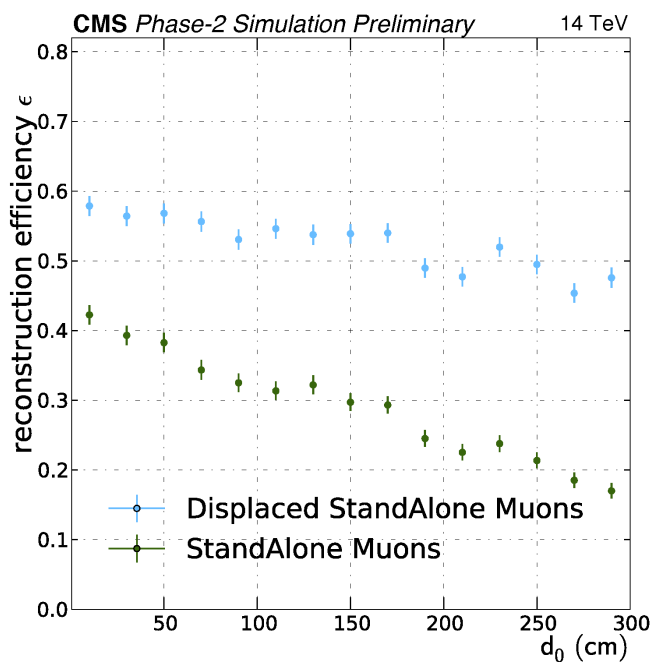


GEM detectors key to keep rate under control, trigger efficiency high even for displaced muons

Long-Lived Smuons (I): **Muon System Upgrades**

- Long-lived smuon in GMSB: $q\bar{q} \to \tilde{\mu}\bar{\tilde{\mu}}, \tilde{\mu} \to \mu\tilde{G}$
- Decay signature: two displaced muons + MET
- Decay length: 10 mm to 1 m
- Low production cross section (~10^{-2} fb for 1 TeV smuon)





Displaced StandAlone Muons: Dedicated muon reconstruction algorithm using only hits in the muon system and no constraints to the IP

Improved muon reconstruction efficiency using Displaced StandAlone Muons, compared to standard muon-only reconstruction (StandAlone Muons)

Long-Lived Smuons (II): **Muon System Upgrades**

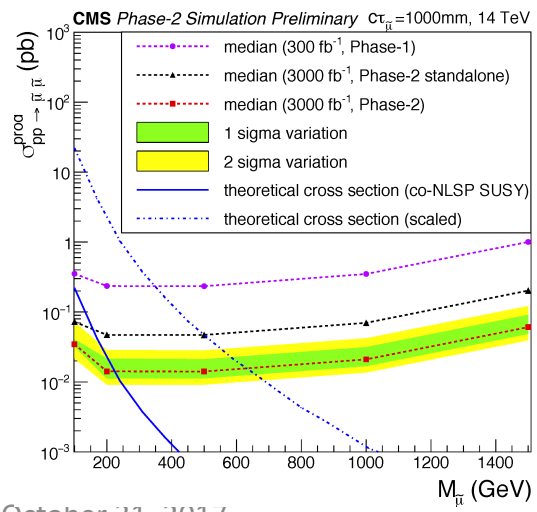
CMS-TDR-17-003, CMS-FTR-16-005

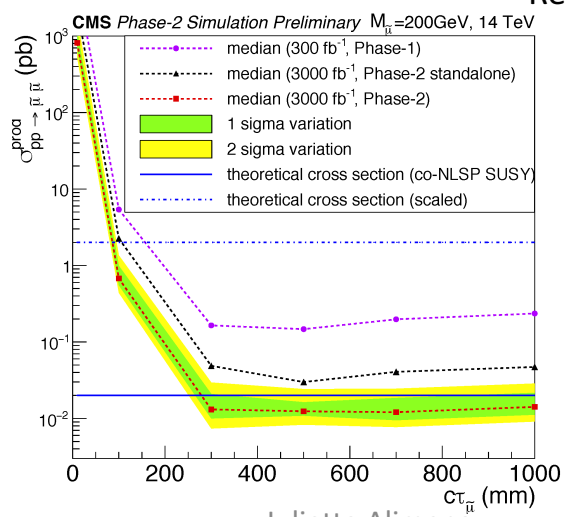
Backgrounds:

- QCD: Heavy quarks with non-prompt decays produce displaced muons
- $t\bar{t}$: Leptonic decay of top quarks
- DY: Prompt muons that are poorly reconstructed as displaced
- Cosmic muons, beam halo, pileup are removed by selection criteria (p_T> 30 GeV)

Scenario Assumptions:

- Phase-1 Scenario:
  - Phase-1 CMS detector
  - PU200, 300 fb^{-1}
  - 60% trigger efficiency benchmark
  - Phase-1 analysis systematic uncertainties
- Phase-2 Scenario:
  - Phase-1 CMS detector + forward muon detectors
  - PU200, 3000 fb^{-1}
  - 90% trigger efficiency benchmark
  - Reduced systematic uncertainties

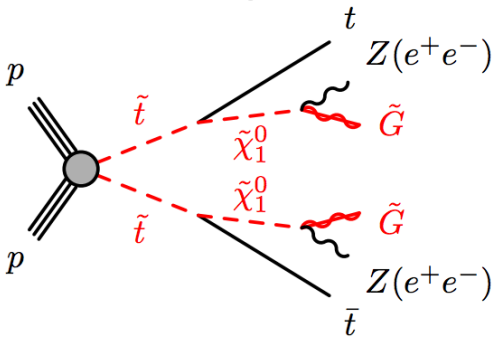




Analysis is sensitive only with the HL-LHC

Long-Lived Neutralinos: **MIP Timing Detector (MTD)**

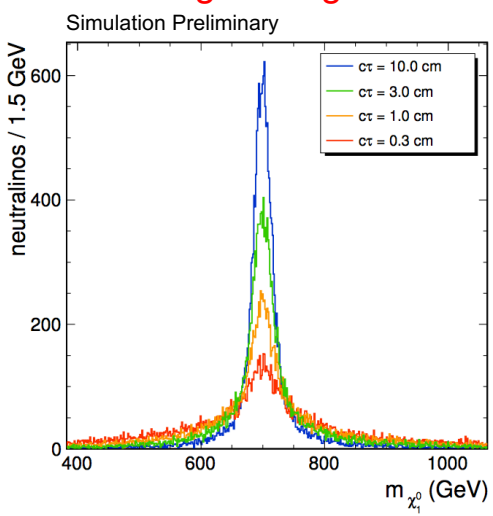
- Long-lived neutralinos in GMSB
- Generator-level study with PYTHIA8
  - Smear tracks, vertices, electron momentum (see backup for resolution assumptions)
- Plots shown for $M(\tilde{t})$ = 1 TeV, $M(\tilde{\chi}_1^0)$ = 700 GeV



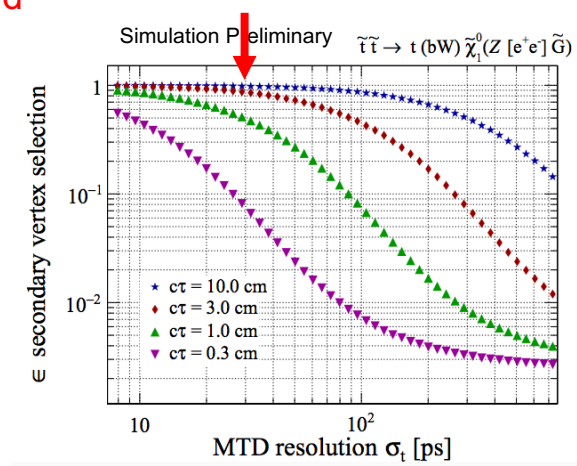
Reconstructed Mass of Neutralino:

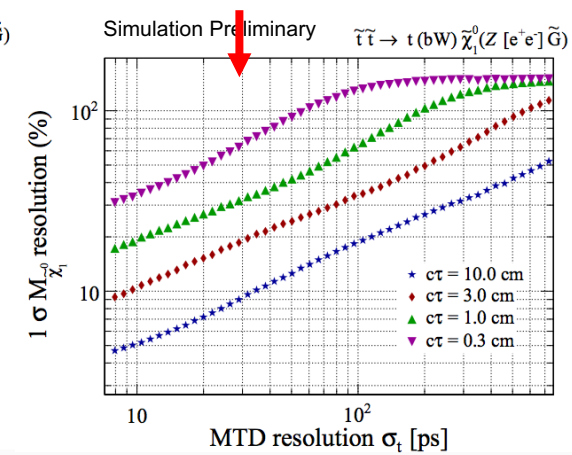
Assume 30 ps timing resolution of MTD

Can use to distinguish signal from background



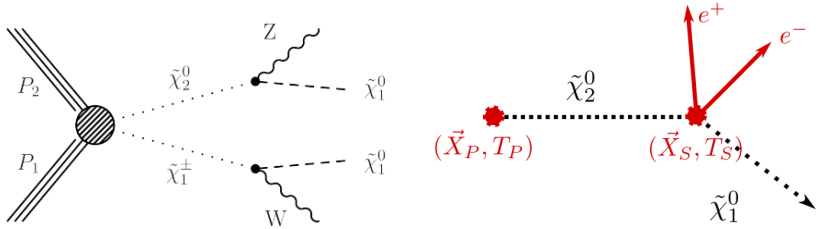
Events are required to have a displaced secondary vertex with 3σ significance in both space and time:





Long-Lived Neutralinos with Mass Difference: MTD

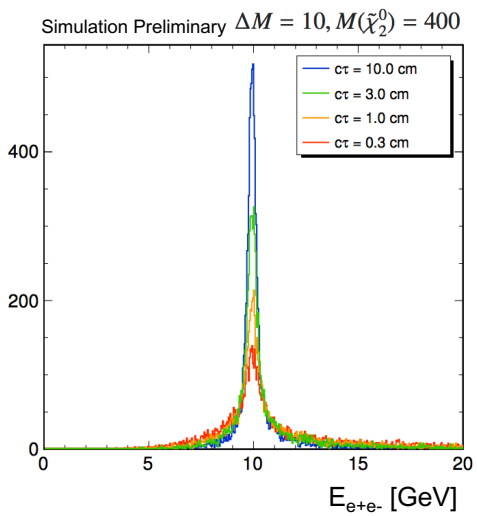
- Long-lived neutralinos with small mass difference
- Similar generator-level study as previous slide
- Plots shown for $M(\tilde{\chi}^{\pm}) = M(\tilde{\chi}_2^0)$ = 400 GeV, $M(\tilde{\chi}_1^0)$ = 390 GeV



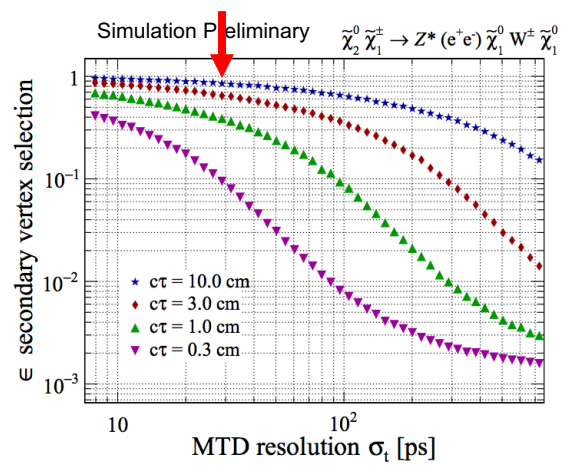
Reconstructed E_{e+e-}

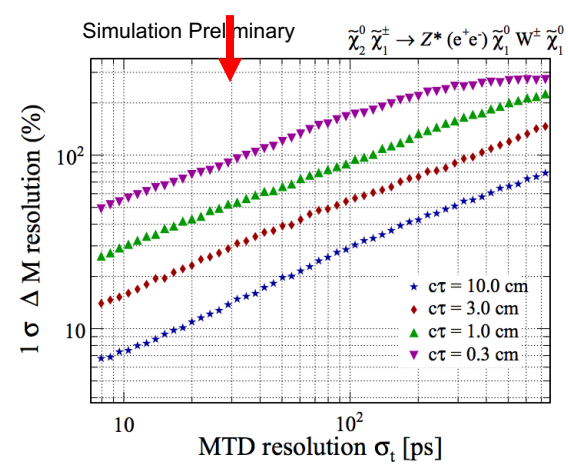
$$E = \Delta M = M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0)$$

Assume 30 ps timing resolution of MTD



Events are required to have a displaced secondary vertex with 3σ significance in both space and time:





- **Phase-2 hermetic timing layer is crucial to assign times to vertices**
- **With this timing information, can reconstruct LLP time-of-flight and mass**

Summary

- The High-Luminosity LHC will be a time of exciting physics potential and many experimental challenges
- The CMS Phase-2 upgrades will address these challenges and increase the physics potential
- CMS exotic long-lived particles searches will benefit from the upgraded detectors mentioned here, as well as the other upgrades → stay tuned!

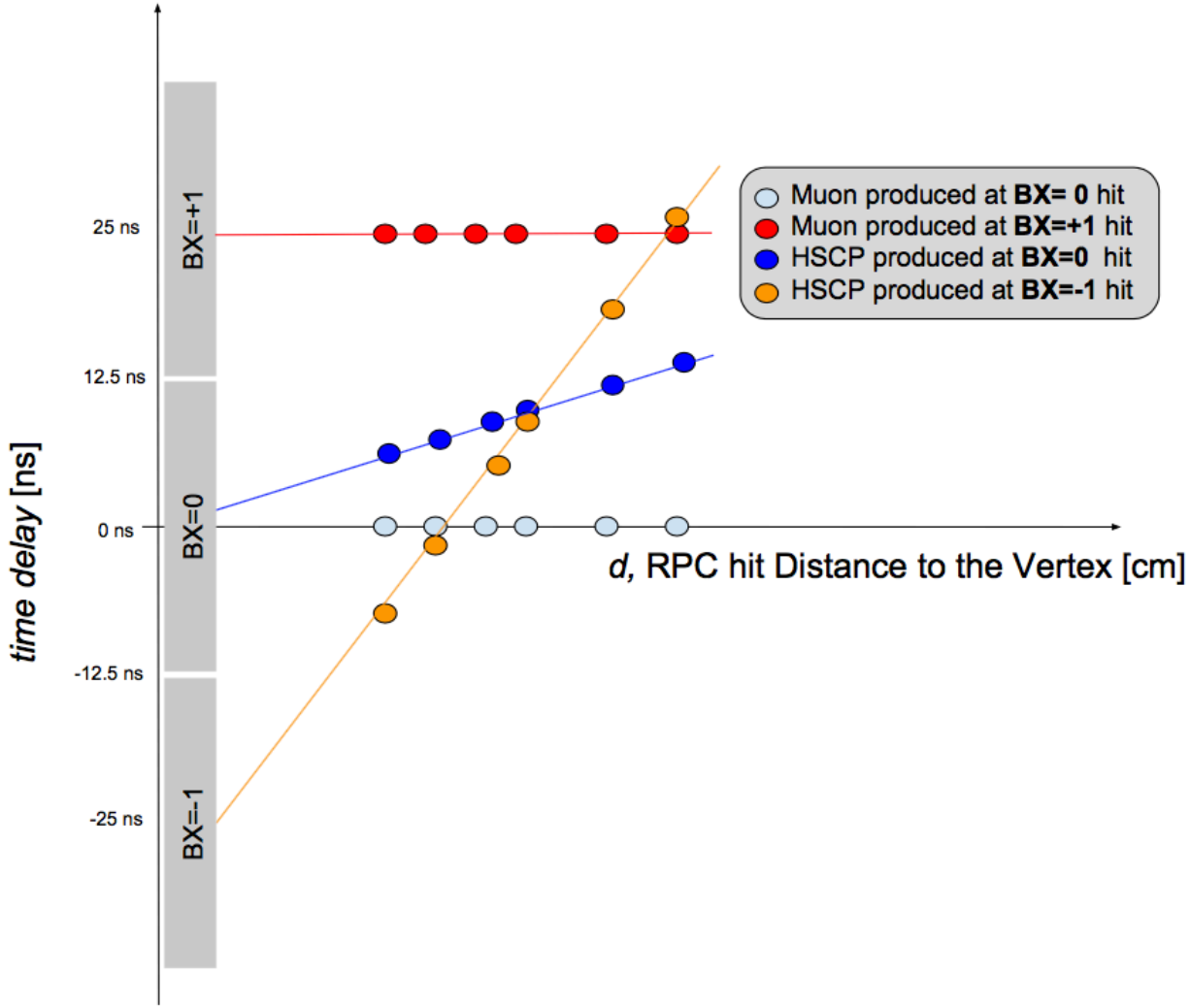

Happy Halloween
wallpapersbuzz

Backup

Sources

- The Phase-2 Upgrade of the CMS Tracker, CMS-TDR-17-001-001, https://cds.cern.ch/record/2267042
- The phase-2 upgrade of the CMS muon detector, CMS-TDR-17-003-002, https://cds.cern.ch/record/2279132
- Estimated Sensitivity for New Particle Searches at the HL-LHC, CMS-PAS-FTR-16-005, https://cds.cern.ch/record/2274436
- Enhanced scope of a Phase 2 CMS detector for the study of exotic physics signatures at the HL-LHC, CMS-PAS-EXO-14-007, https://cds.cern.ch/record/2206863
- Khachatryan, V., Sirunyan, A.M., Tumasyan, A. et al. Eur. Phys. J. C (2015) 75: 325. DOI:10.1140/epjc/s10052-015-3533-3

Phase-2 RPC HSCP Trigger Algorithm



Long-Lived Neutralinos

- Generator-level study with PYTHIA8

Smearing

- Track resolution: 10μm and 30μm in transverse and longitudinal impact parameter (JINST 9 P10009, 2014) $\rightarrow$ use 30μm for simplicity
- PV resolution: 10-12um in each of three dimensions (JINST 9 P10009, 2014)
- Electron momentum resolution is 2%
- Timing resolution for tracks is 30 ps