Phase-2 studies at CMS in the context of LLPs

Workshop: Searches for long-lived particles at the LHC in Trieste

Henning Keller, Kerstin Hoepfner
RWTH Aachen University, Physics Institute IIIa

on behalf of the CMS collaboration

Bundesministerium
für Bildung
und Forschung

III. Physikalisches
Institut A

RWTH AACHEN
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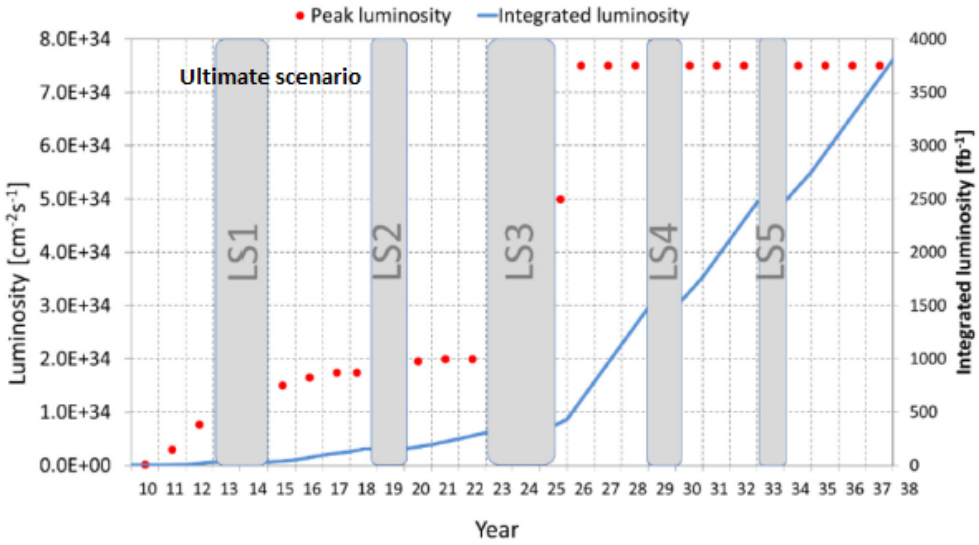
Upcoming High Luminosity Era at LHC

High-luminosity LHC:

- Parameter space tested is increasing in mass reach and in coupling strength
- Increasingly harsh environment, pileup, radiation



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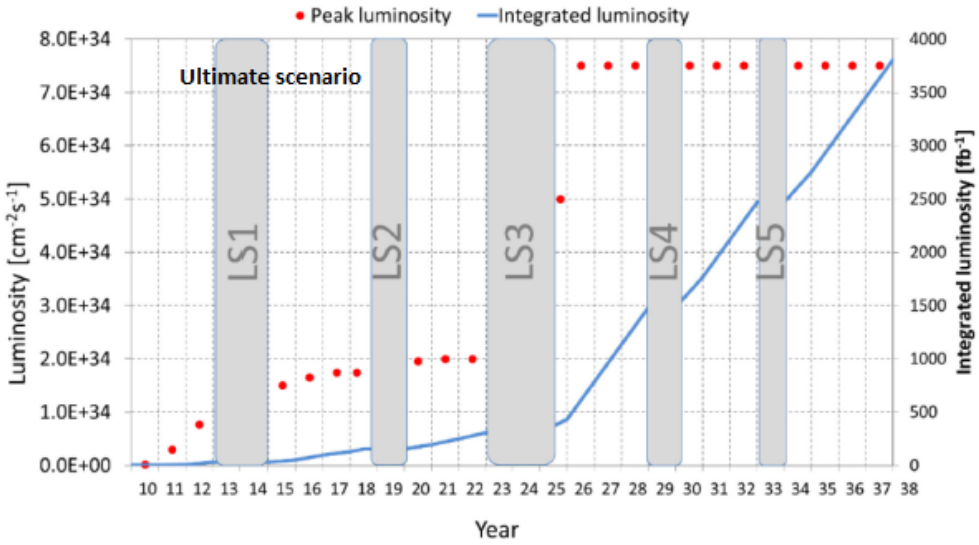
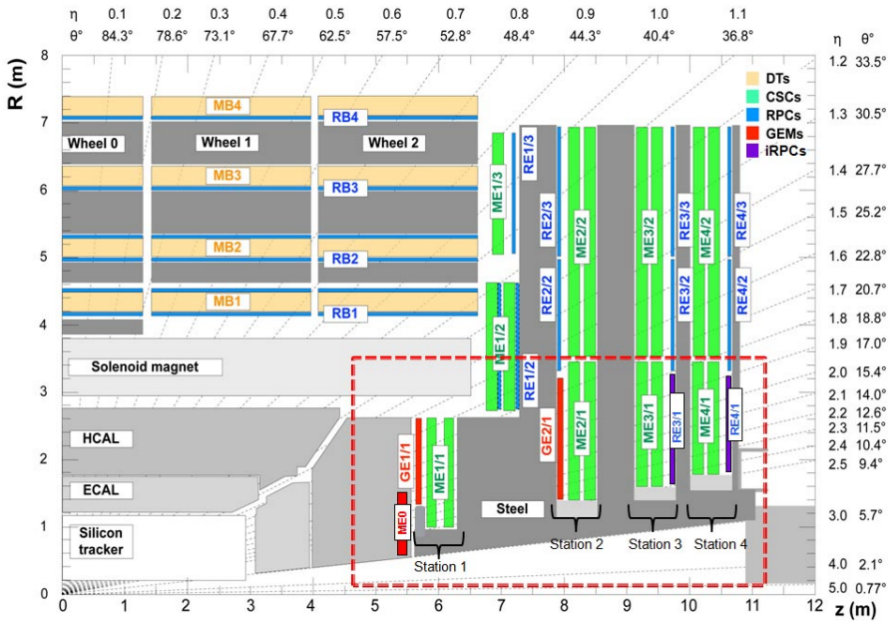
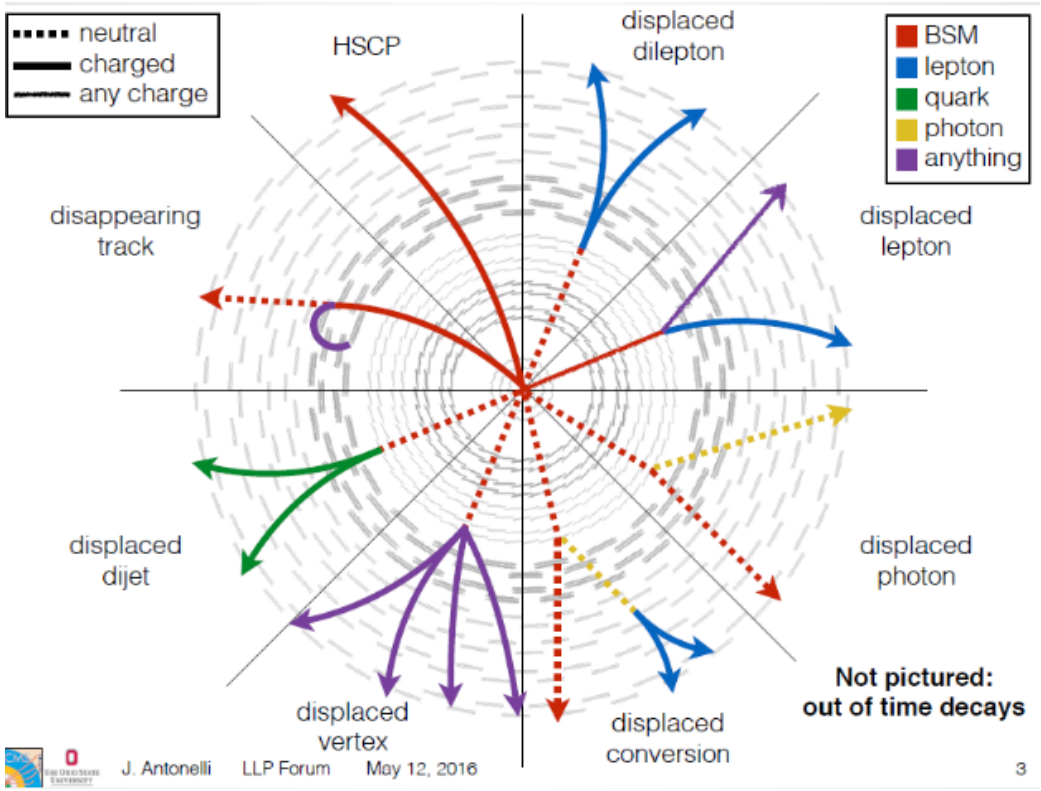




Muon Upgrade of CMS detector:

- New electronics for existing DT, CSC and RPC systems
- Addition of new GEM and iRPC detectors in endcap
- Goals are to maintain (or improve) triggering, reconstruction and identification capabilities

Overview of Long-Lived Signatures



- Large class of searches leading to displaced signatures (leptons, photons, jets)
- Another class: out-of-time signatures
- This talk focuses on displaced muons (in-time)

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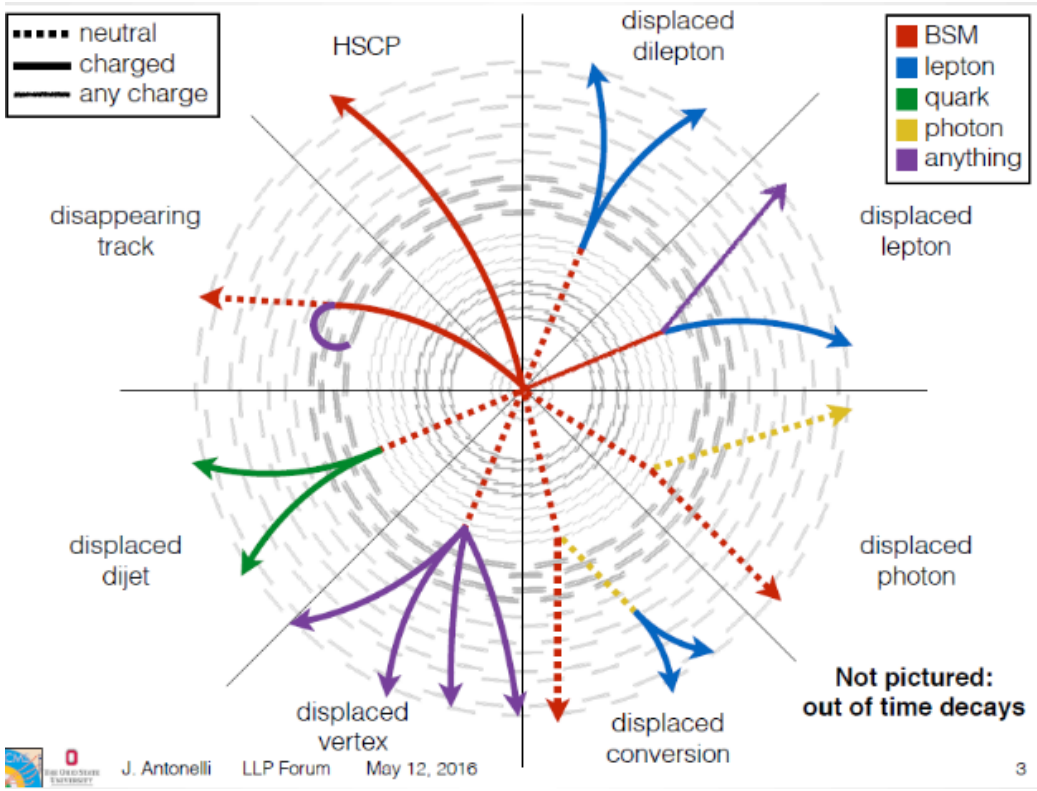

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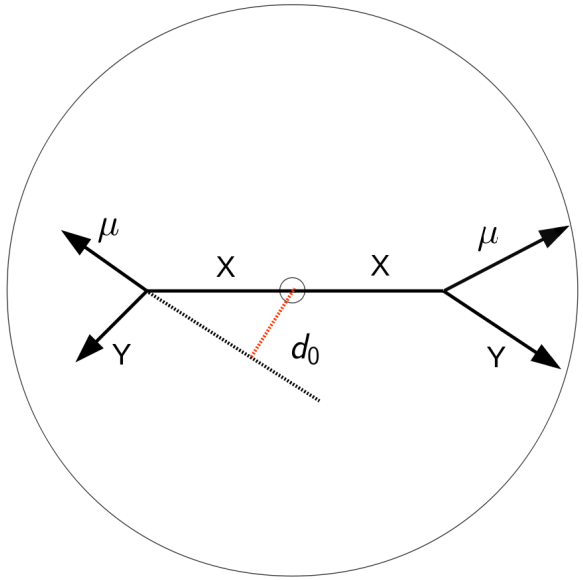
Challenging LLP signatures

- Non-standard objects, customize trigger/reconstruction/simulation
- Need to maintain dedicated detector capabilities, especially for HL-LHC
- Signature-driven searches, many BSM theories with possible LLP signature, select right one?

Displaced Muons from LLPs

Detector Signature:

- Assuming LLP decaying into muon
- Final state in detector consists of two displaced muons and missing transverse energy
- Transverse impact parameter d_0 important for reconstruction



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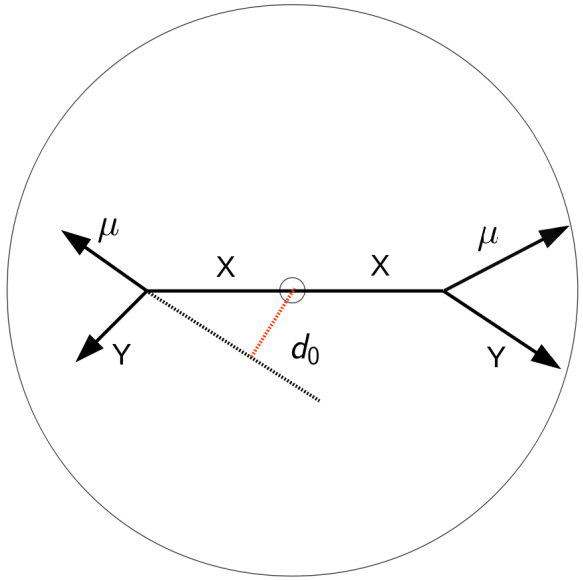

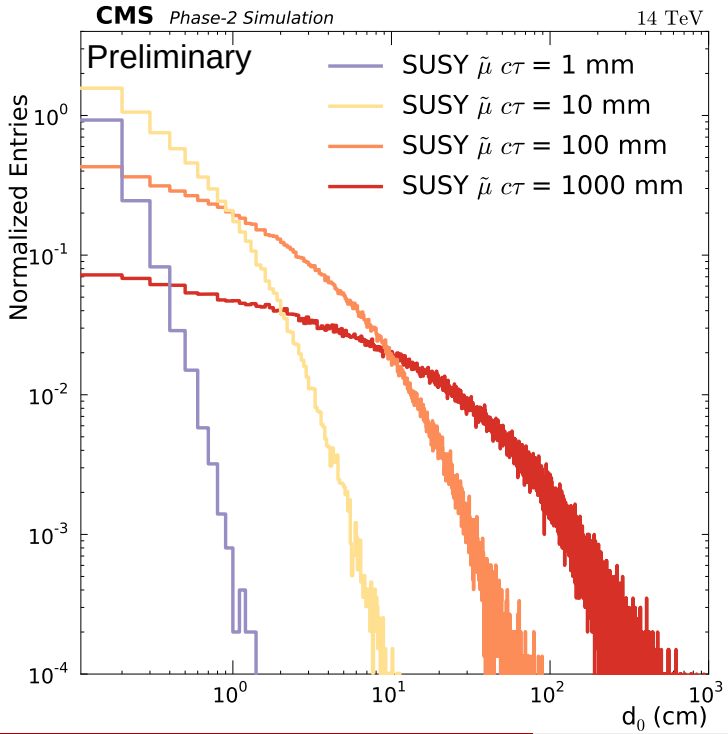

Features of parameter space:

- LLP masses up to 1 TeV
- Decay length of LLP quasi-prompt (10 mm) to long-lived (1 m)
- Low cross section $\sigma_{\text{prod}} < 10^{-2}$ fb, sensitive only with HL-LHC

Distant Relatives: Displaced Muons

On the one hand, muons are well-known and well-studied objects.
On the other hand, signature of displaced muons are VERY challenging and difficult to handle for Phase-2.

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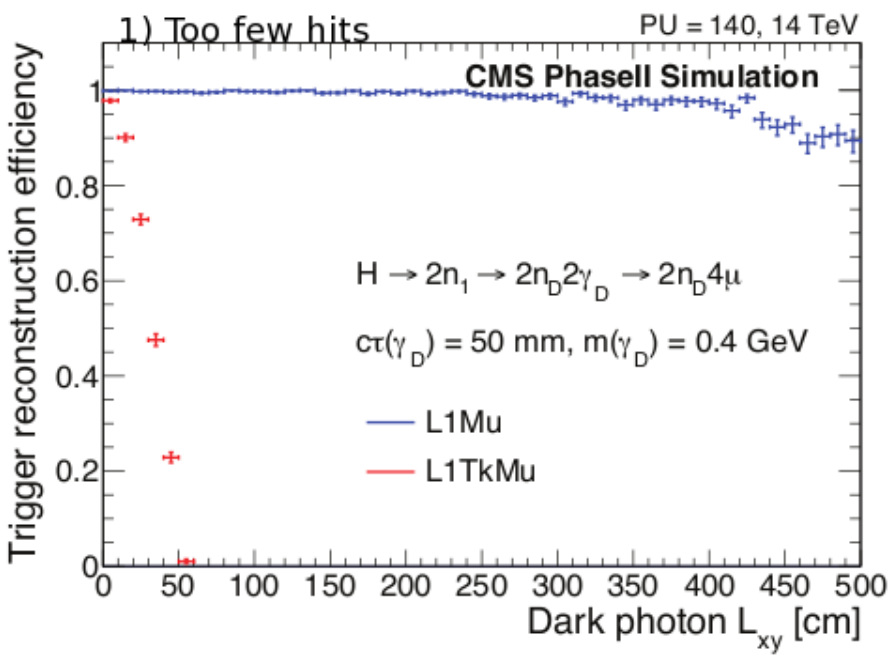
On the other hand, signature of displaced muons are VERY challenging and difficult to handle for Phase-2.

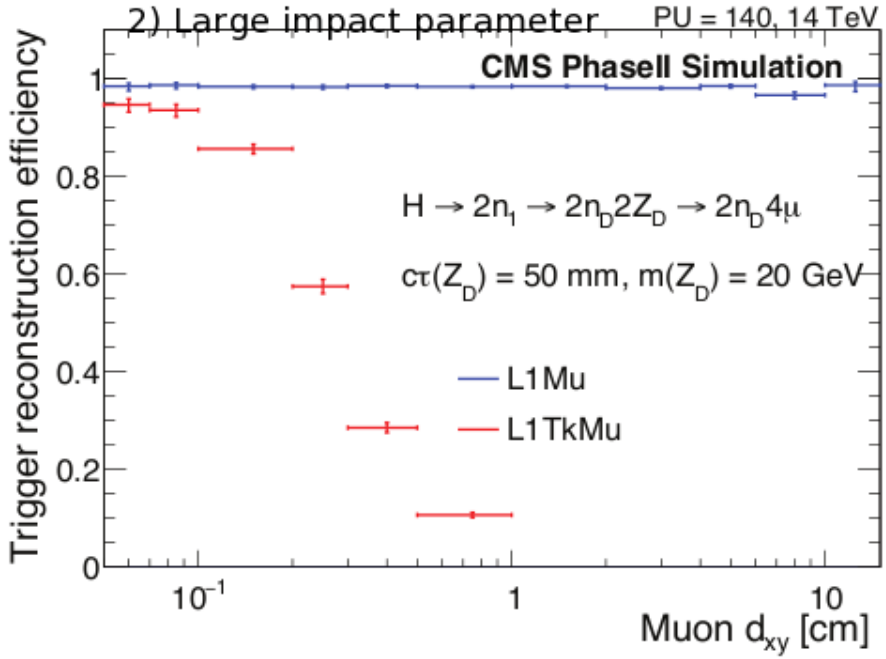
- Searches driven by detector signature
- Dedicated trigger streams for displaced muons (slide 6/7)
- Special reconstruction algorithms and their pecularities (slide 8)
- Unconventional analysis methods (slide 10)
- Background sources can be instrumental or cosmics, not only from SM (slide 9)

Triggering Displaced Muons in Phase-2

Challenge: Track trigger has implicit constraint on primary vertex

- Displaced signatures may yield either too few hits in tracker (1) or a large impact parameter (2)
  $\Rightarrow$ In these cases, track trigger fails
- Essential to maintain muon trigger capabilities , displaced triggering not possible w/o muon system in Phase-2

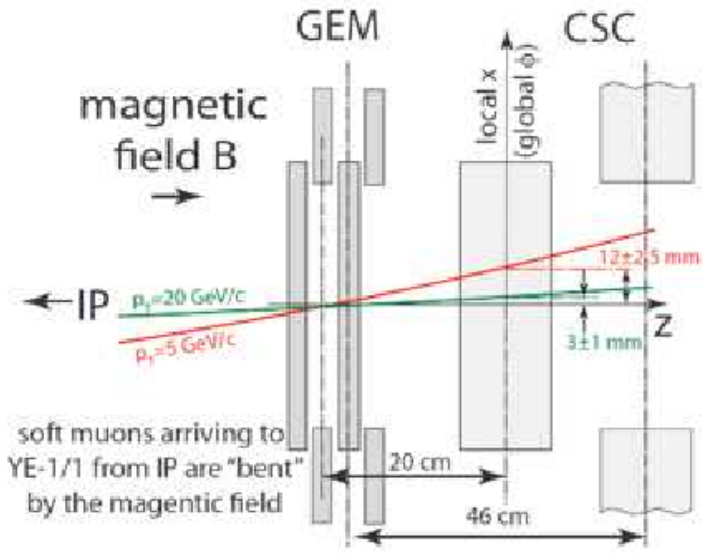


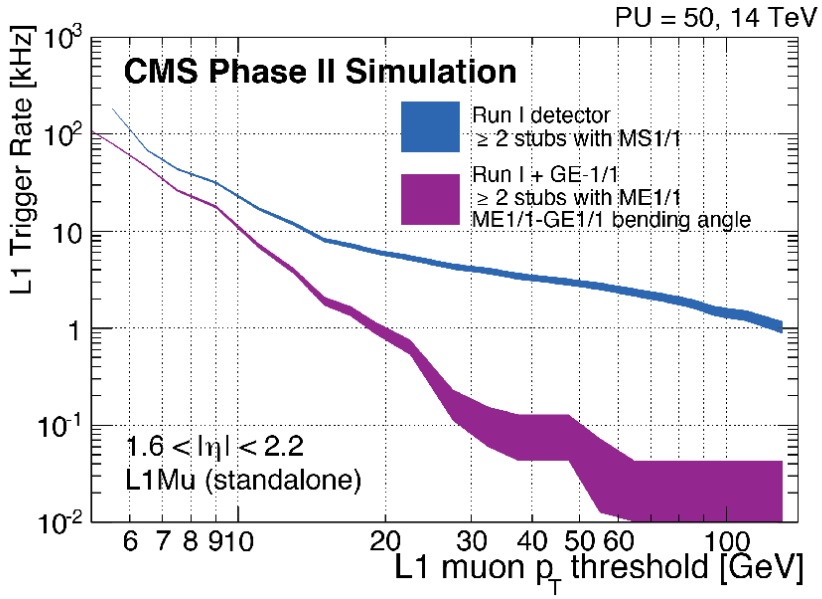


from CMS Muon Upgrade GE1/1 TDR (Sven Dildick)

More about Triggering

- Forward region: lower magnetic field, higher background
  $\Rightarrow$ Difficult to trigger muons
- Additional forward muon chambers help measuring bending angle
- Trigger rate can be reduced for Phase-2
- Trigger thresholds can be lowered



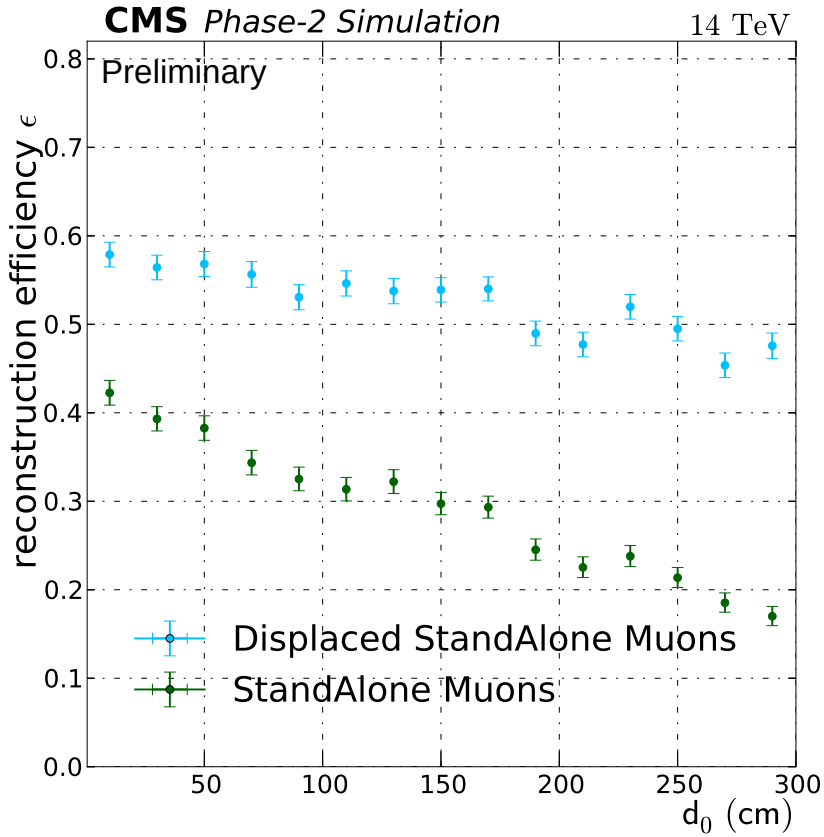


plots from CMS Muon Upgrade GE1/1 TDR and CMS-TDR-17-004

Reconstructing Displaced Muons in Phase-2

- Dedicated reconstruction algorithms in CMS software for displaced signature, without vertex constraint
- For large displacements (> 10 cm) muon systen information only for reconstruction

- Displaced track reconstruction in tracker becomes more difficult for Phase-2
- Essential to maintain muon system reconstruction and algorithms capabilities (for Phase-2)



Background

Standard Model Background

- QCD: Heavy quarks decaying non-prompt leading to displaced muons
- $t\bar{t}$: Leptonic decay of top quarks
- DY: Prompt muons badly reconstructed as displaced

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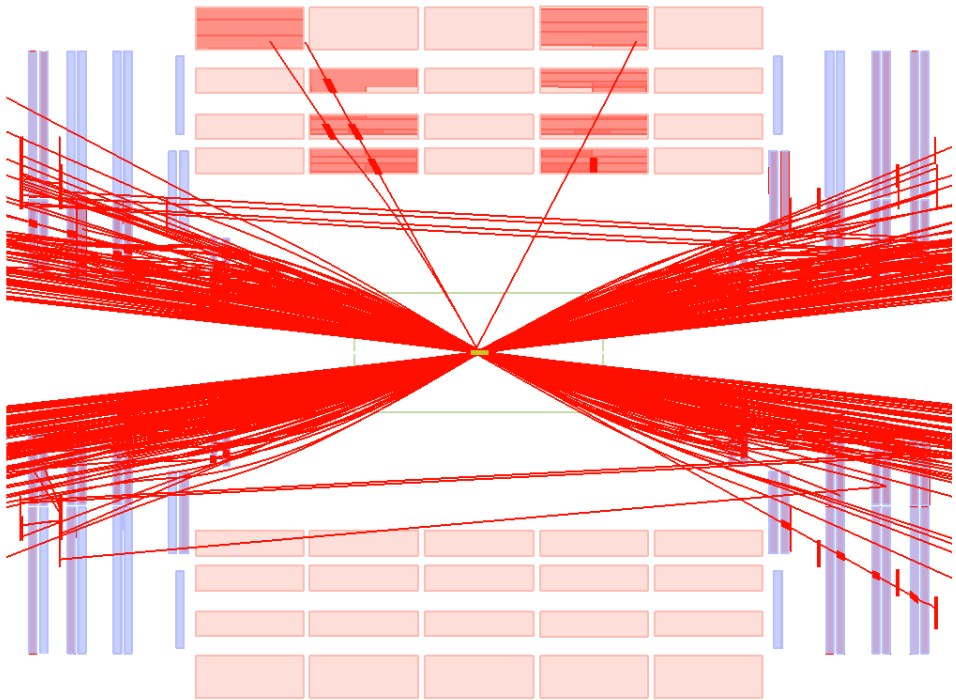
- What about cosmics?
  $\Rightarrow$ Reduced by selection cuts
- What about Beam Halo?
  $\Rightarrow$ Beam Halo included in simulation, but low-p_T (Liu, C. et al. https://doi.org/10.1140/epjc/s10052-008-0674-7)
- What about muons from pileup?
  $\Rightarrow$ Muons from pileup are low-p_T and cut away by selection



Selecting Displaced Muons in Phase-2

- Keep strategy as model-independent as possible $\rightarrow$ various models extending SM predict signature of displaced muons
- Using hits in muon system only w/o constraint to primary interaction vertex

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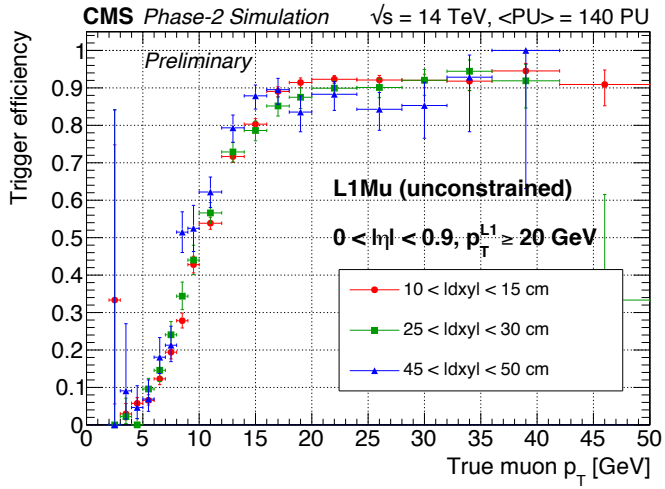
Pecularities of Object Selection

- Kinematic: $p_T > 30$ GeV, $|\eta| < 2.8$
  ⇒ Given by displaced trigger threshold, might be reduced to ≈ 20 GeV
- Significance of impact parameter: $\frac{d_0}{\sigma_{d_0}} \geq 5$
  ⇒ Reduces background statistics too much, cut applied in non-standard way (factorized)



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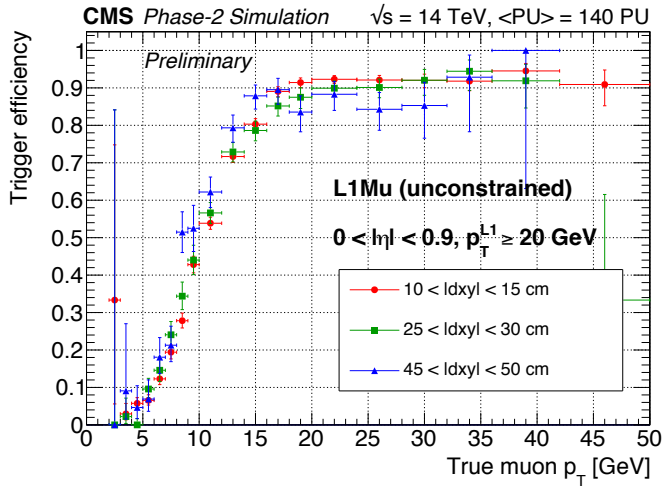

Event Selection

- Require ≥ 2 'good' displaced muons
- If there are more than 2 candidates, select the two with the highest significance on impact parameter

Signal Model: Slepton (co-)NLSP SUSY

- Gauge Mediated Supersymmetry Breaking (GMSB)
- Mass hierarchy: Light gravitino (LSP) in GeV range and heavy slepton(s) (NLSP) in TeV range
- Sleptons decays to Standard Model partner and gravitino
- Decay is heavily suppressed by SUSY breaking scale
  - $\Rightarrow$ Nature of NLSP important aspect
  - $\Rightarrow$ Lightest slepton which is the NSLP is long-lived

https://arxiv.org/pdf/1009.1665v2.pdf (Ruderman and Shih)
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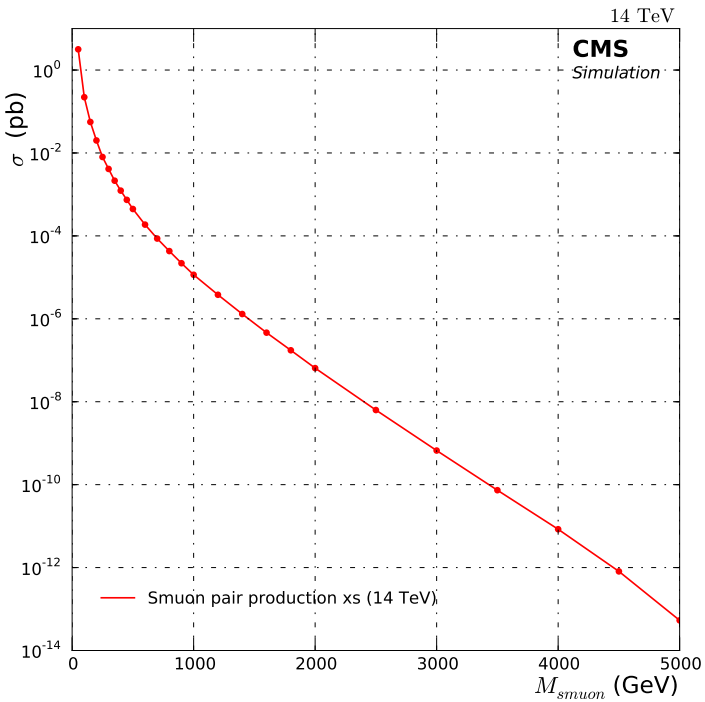
- Process: $q\bar{q} \rightarrow \tilde{\mu}\bar{\tilde{\mu}}$
- Smuon pair production via s-channel Z,γ exchange
- Decay: $\tilde{\mu} \rightarrow \mu + \tilde{G}$
- Final state: two muons and missing transverse energy



Event Yield and Discriminating Variable d_0

- Background typically low transverse impact parameter
- For high d_0, almost background-free
  $\Rightarrow$ Sensitivity scales with signal efficiency
- Need to define search region

  Every generated decay length $c\tau$ is associated with a search region:
  Example I: $c\tau = 500$ mm $\Rightarrow 50$ mm $\leq d_{0,\mu} < 500$ mm
  Example II: $c\tau = 1000$ mm $\Rightarrow 100$ mm $\leq d_{0,\mu} < 1000$ mm
- Event yield serves as input for statistical interpretation

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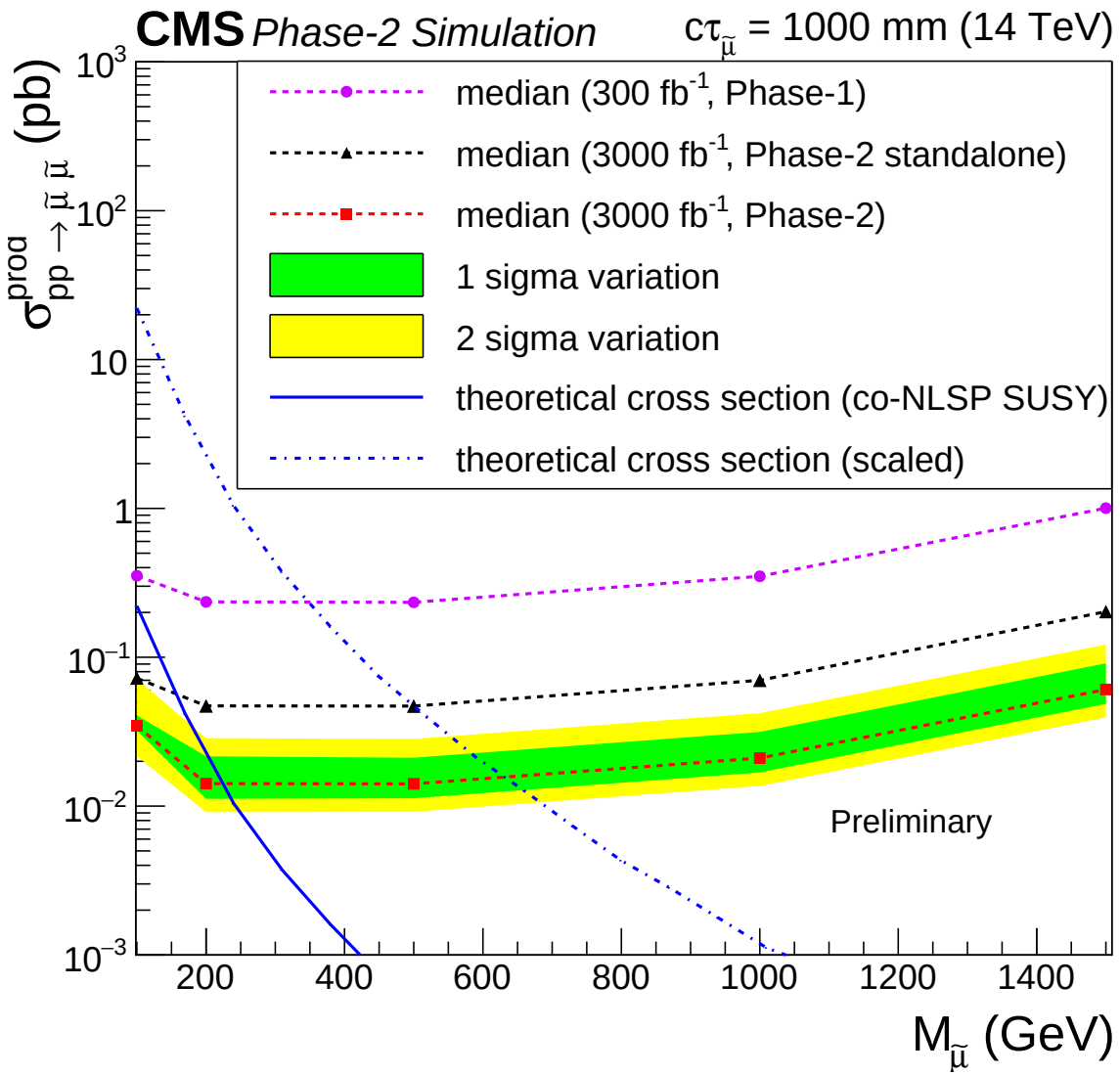
Luminosity	Event Yield 3000 fb^{-1}	
Search Region	50 mm $\leq d_{0,\mu} <$ 500 mm	100 mm $\leq d_{0,\mu} <$ 1000 mm
$Z/\gamma \rightarrow ll$+jets	-	-
$t\bar{t}$	0.0465	-
QCD	0.275	0.091
Displaced SUSY Mass=100 GeV	10.903	9.430
Displaced SUSY Mass=200 GeV	2.043	1.276
Displaced SUSY Mass=500 GeV	N/A	0.0284
Displaced SUSY Mass=1000 GeV	N/A	0.00049

CMS Upgrade Phase-2 versus Phase-1

At the end, another goal of this study is to see what the benefits of CMS Phase-2 upgrade are...

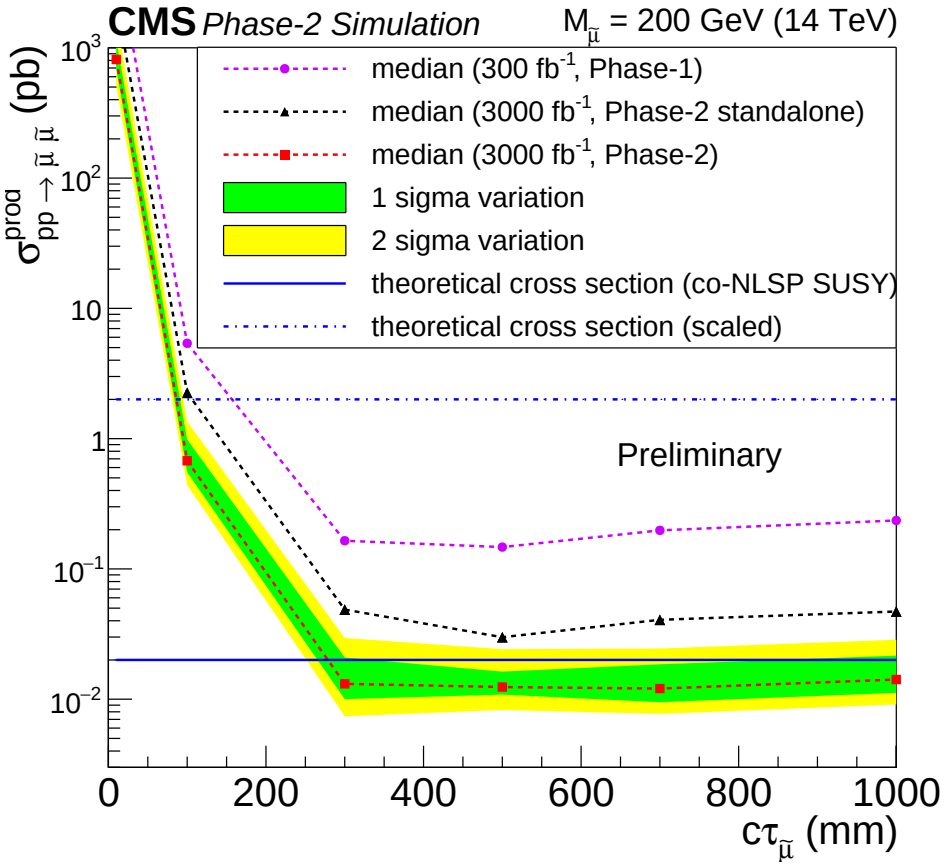
- Phase-2 scenario - Increased luminosity with Phase-2 CMS detector :
  - Integrated luminosity: 3000 fb^{-1}
  - Geometry: Phase-1 detector + additional forward muon detectors
  - Higher-efficiency trigger benchmark scenario with additional forward muon detector (90%)
  - PU 200
  - Reduced systematics
- Phase-1 scenario - Increased luminosity with Phase-1 CMS detector :
  - Integrated luminosity: 3000 fb^{-1}
  - Geometry: only Phase-1 detector
  - Lower-efficiency trigger benchmark w/o Phase-2 upgrade and aging (60%)
  - PU 200
  - Current systematics

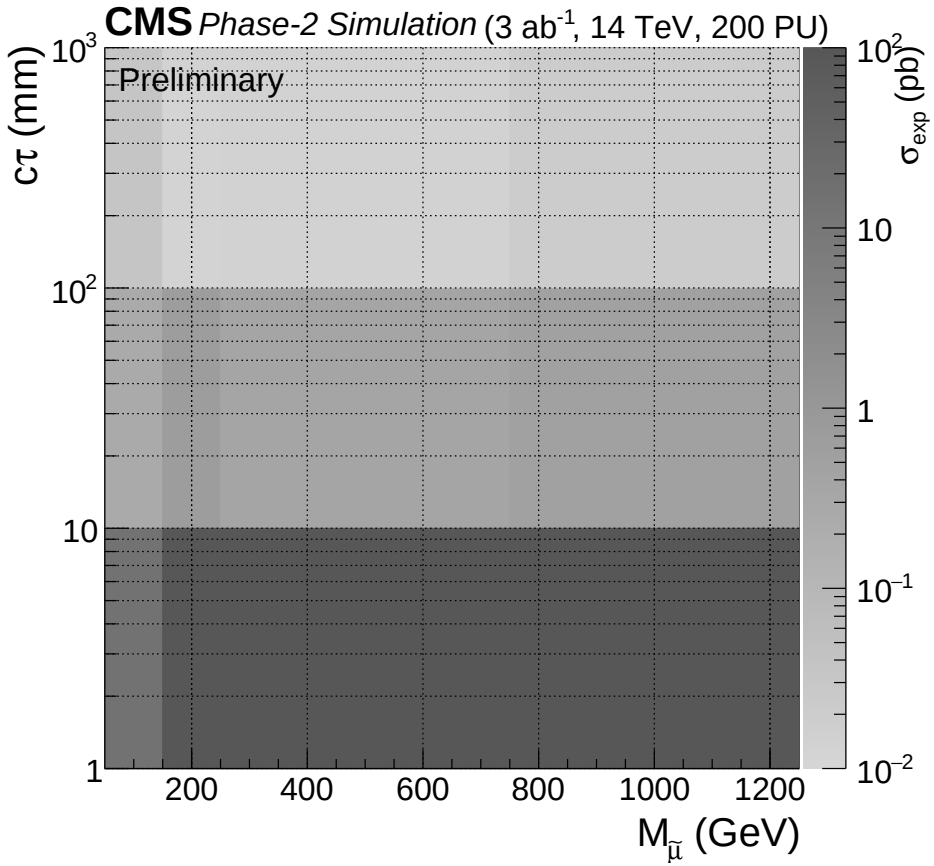
Exclusion Limits - Phase-1 vs Phase-2



- For 3000 fb^{-1} and Phase-2 scenario: mass limit at 220 GeV
- For 3000 fb^{-1} and Phase-2 scenario with standalone reconstruction efficiency: mass limit at $\approx$ 180 GeV
- For 300 fb^{-1} and Phase-1 scenario: no sensitivity
- Additional theo. cross section (co-NSLP $\cdot$ 100) for different models (change SUSY breaking scale)

Exploring Parameter Space





$\Rightarrow$ Reach of exclusion is significantly increasing from Phase-1 to Phase-2

$\Rightarrow$ Difference between Phase-2 with and without detector upgrade is not so big

One reason: Trigger Efficiency very conservative (maybe significantly less than 60 %)

Take Home Messages

- Trigger capabilities of muon system essential, Phase-2 CMS detector upgrade helps a lot (acceptance, rate/threshold)
- Challenging reconstruction algorithm for displaced muons, need to be maintained in future
- Instrumental background (pileup/beam halo) and cosmics reduced by analysis methods
- HL-LHC data needed we are sensitive to signal with very low cross section
- Statistical Interpretation (exclusion, sensitivity) calculated for different scenarios
- Sensitivity study for displaced muon signature, model-independent strategy
- Other upgrade studies can be found in Muon Phase-2 Upgrade TDR (CMS-TDR-17-003)

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Other Remarks

- Proposal for other models predicting displaced muons very welcome!

Thanks for opportunity to present in this workshop

Stay Tuned!!!

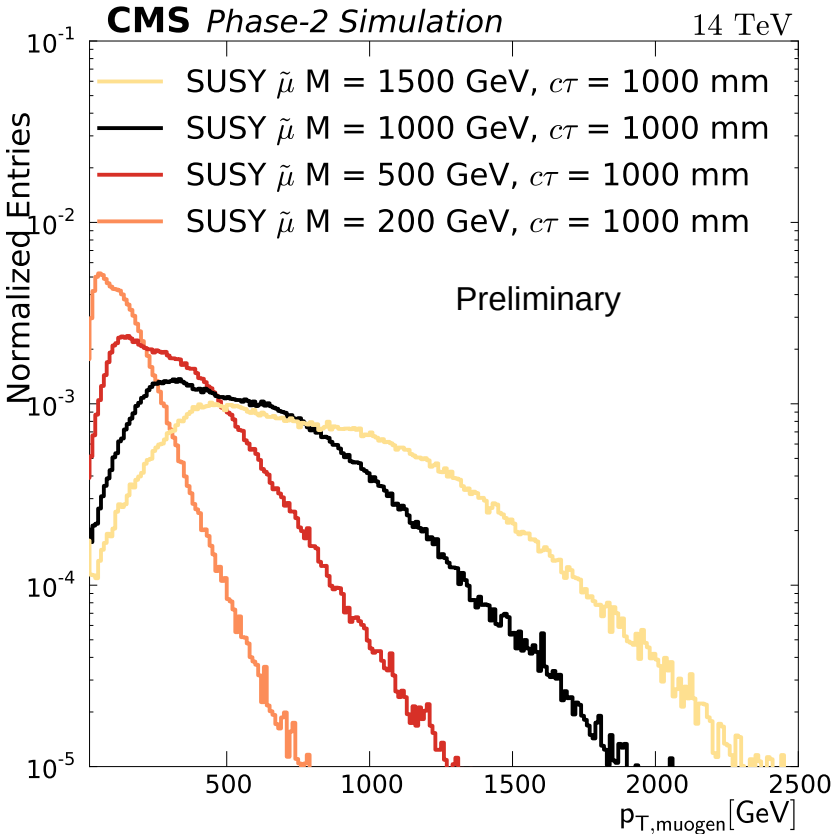
There is a lot of data ahead of us...
We will have a factor of ≈ 30 of the data at high energy what we have taken so far...

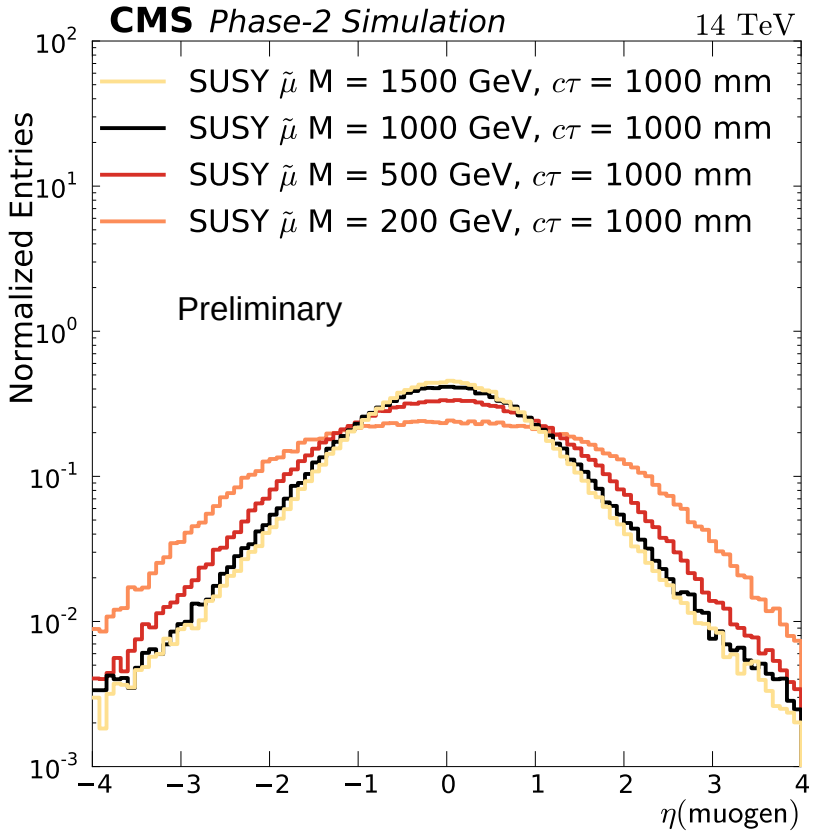
from https://de.wikipedia.org/wiki/Friaul-Julisch_Venetien

Additional slides...

Kinematic Variables on GEN Level

- Distributions of $p_T, \eta, \Delta R$ and missing transverse energy on GEN level





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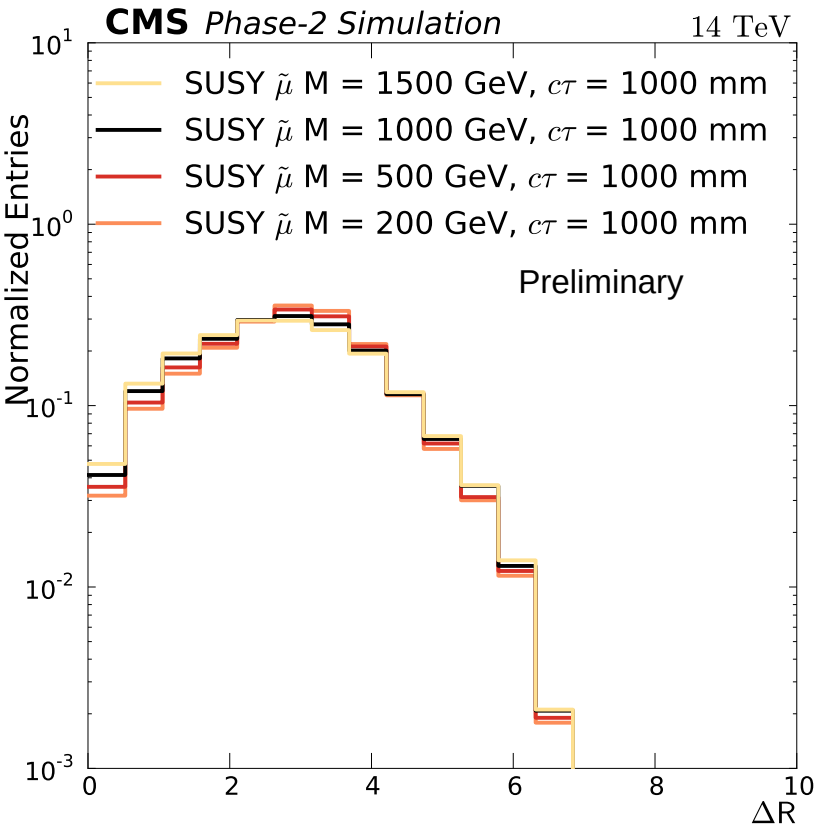
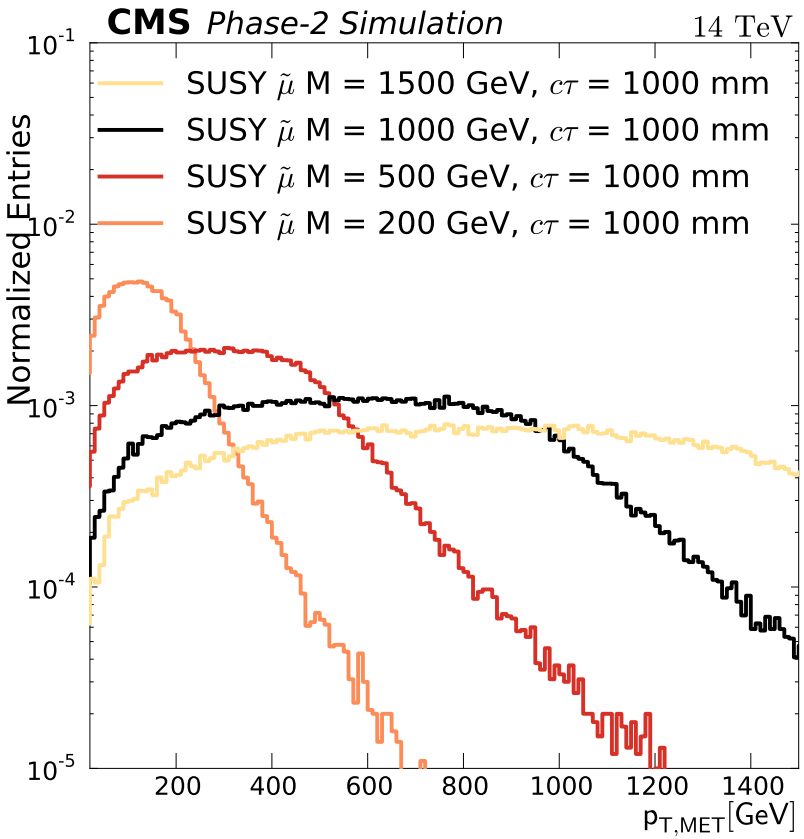
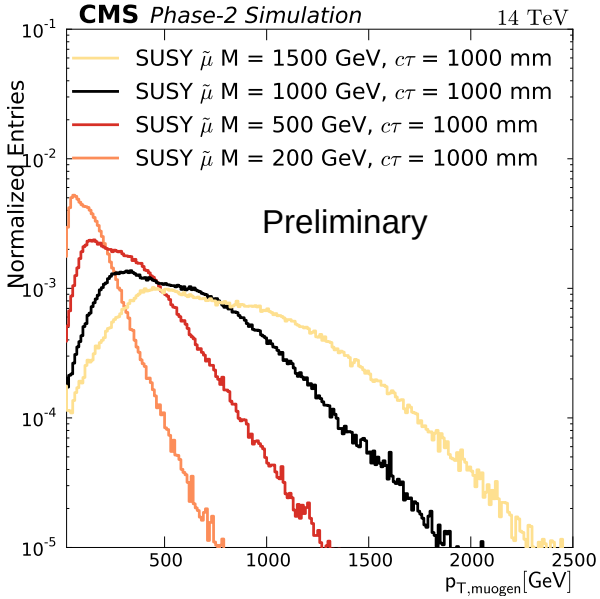
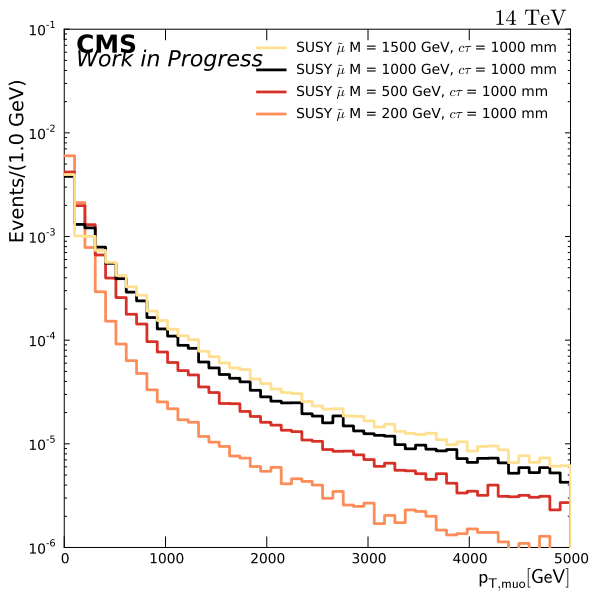


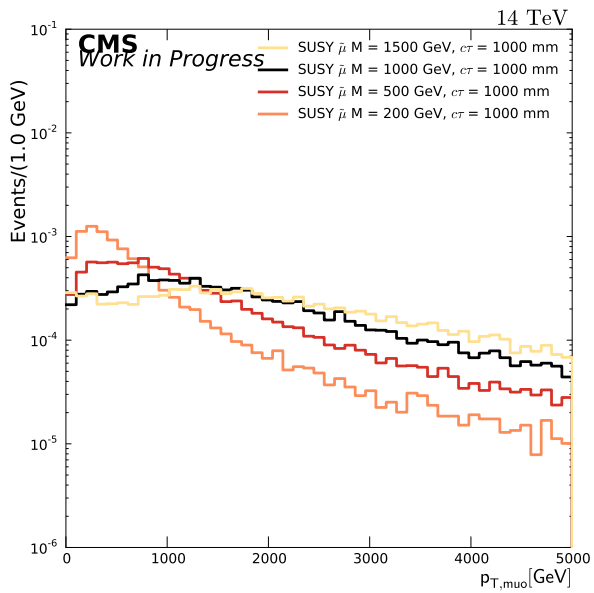


p_T Reconstruction in DSA Muons

- Here distribution on reconstruction level (without any selection and after full selection) are shown with no PU
- Only see effect of DSA muon reconstruction

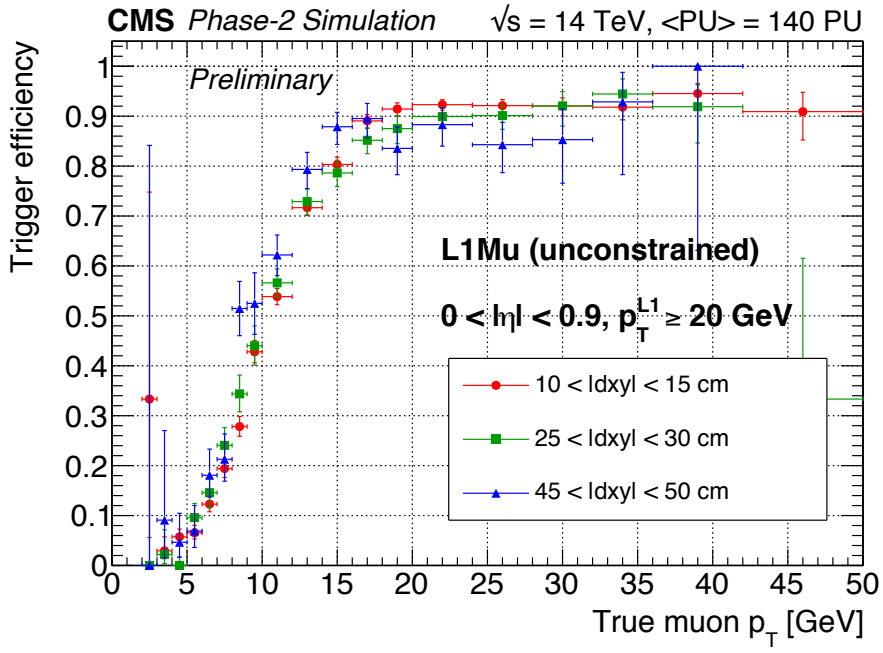






Trigger Scenarios

- Trigger efficiency for level-1 for displaced muons
- Threshold $\approx$ 15 GeV
- Analysis cut of 30 GeV very conservative (will be changed for future iterations)
- Severe degradation of trigger efficiency without CMS Phase-2 Muon Upgrade



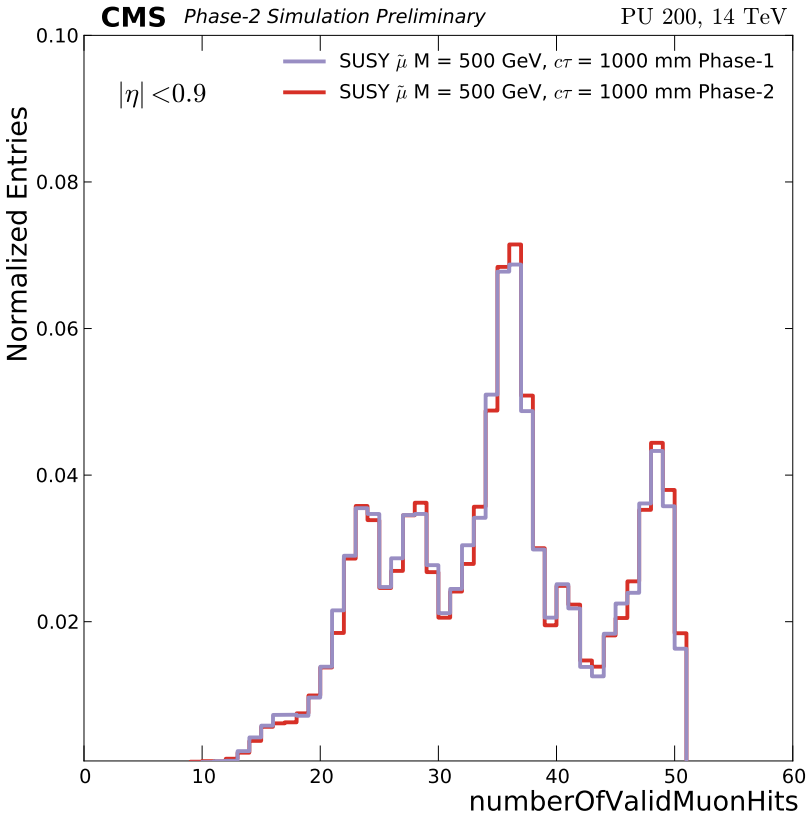
From CMS-TDR-17-004

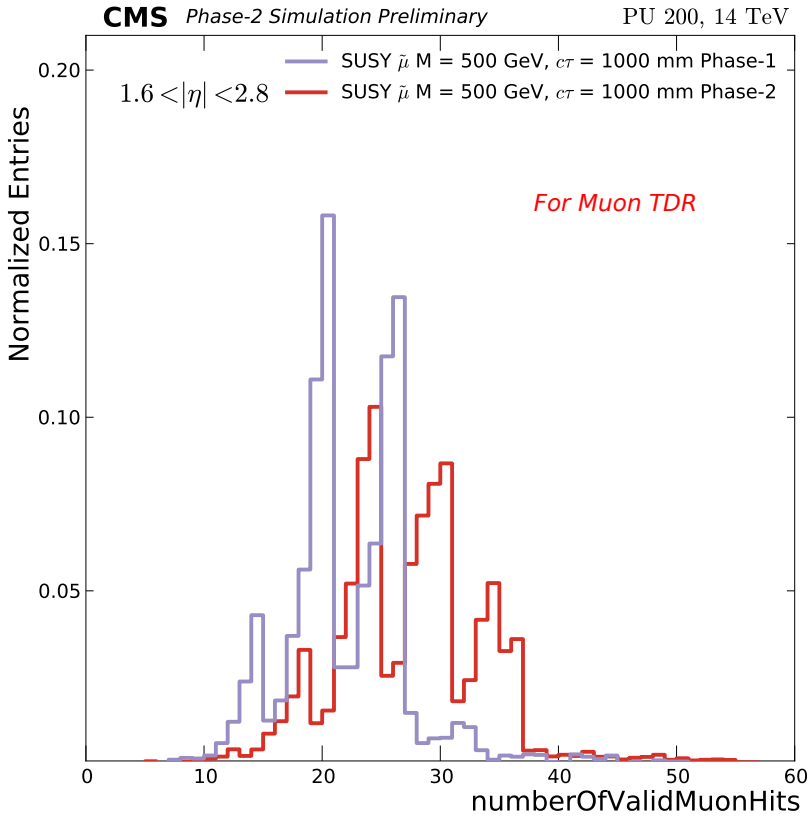
- Efficiencies of emulated displaced muon trigger assigned to the 3 detector regions for detector scenarios
- Benchmark scenarios, motivated by studies from CMS-TDR-17-004

η region	Barrel: $\lvert\eta\rvert < 0.9$	Overlap: $0.9 \leq \lvert\eta\rvert < 1.6$	Endcap: $1.6 \leq \lvert\eta\rvert < 2.8$
Phase-2 detector	90%	90%	90%
Phase-1 detector	60%	60%	60%

Phase-2 CMS Upgrade - Reconstruction

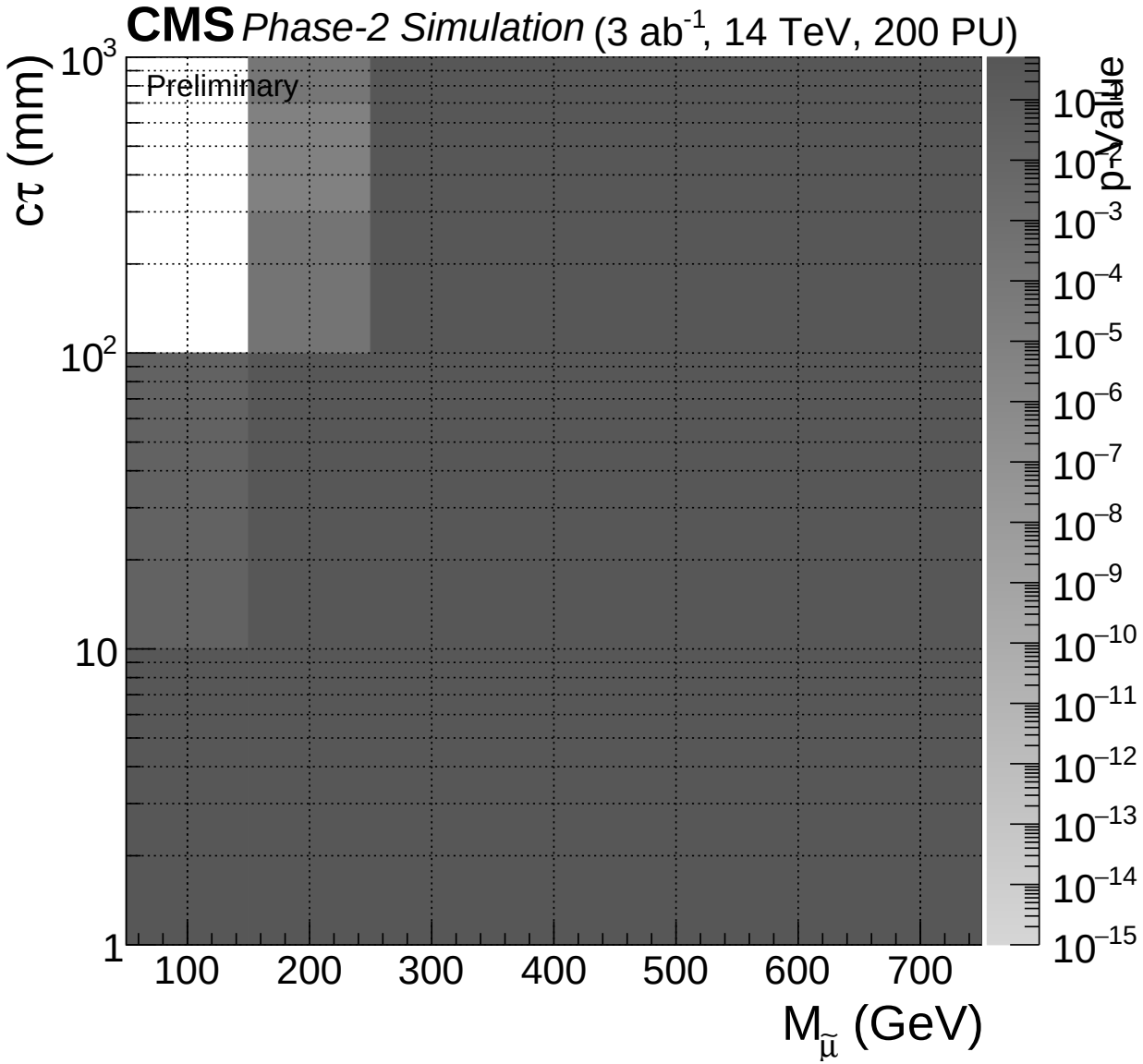
- Additional hits coming from new endcap muon stations allow to trigger efficiently displaced muons





$\Rightarrow$ Phase-2 upgrade provides additional hits in endcap region

Discovery Sensitivity - 2D plot



Selection

- Keep strategy as model-independent as possible → various models extending SM predict signature of displaced muons
- Displaced StandAlone (DSA) track reconstruction: similar to standard standalone muons - only using hits in muon system - but w/o constraint to primary interaction vertex

Muon Object Selection

- Kinematic: $p_T > 30$ GeV, $|\eta| < 2.8$
- Track Quality: $\chi^2/\text{ndof} \leq 2$
- Nb(ValidMuonHits) ≥ 17
- Isolation: sum of $|p_T|$ of PF candidates inside $\Delta R < 0.1$ smaller than $p_{T,\mu}$
- Impact Parameter: $\frac{d_0}{\sigma_{d_0}} \geq 5$ (factorized)

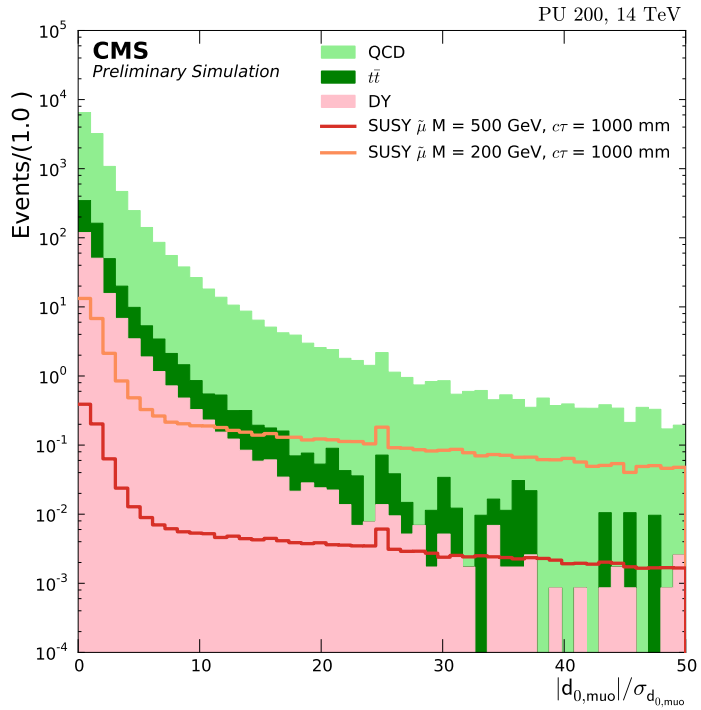
Event Selection

- Require ≥ 2 DSA muons fulfilling object selection
- $E_{T,miss} \geq 50$ GeV
- $\Delta R > 0.5$ (back-to-back)
- Opposite sign
- If there are more than 2 candidates, select the two with the highest significance on impact parameter

Factorized d_0 significance cut

- d_0 significance cut applied in standard way reduces statistics of background samples significantly
- Idea from Run-2 $e\mu$ analysis (CMS-PAS-EXO-16-022): Apply d_0 significance cut in factorized way

1. Determine fraction of muons passing the d_0 significance cut based on distribution shown right
2. Use factor as weight for each muon in further analysis



Sample	Displaced SUSY				QCD	$t\bar{t}$	DY
	M=200 GeV		M=500 GeV				
	$c\tau = 100$ mm	$c\tau = 1000$ mm	$c\tau = 100$ mm	$c\tau = 1000$ mm			
Weight	7.8 %	13.7%	8.5 %	14.0 %	2.7 %	0.47%	0.44%

Samples

QCD_Pt-20toInf_MuEnrichedPt15_TuneCUETP8M1_14TeV_pythia8
TTTo2L2Nu_TuneCUETP8M1_14TeV-powheg-pythia8
DYJetsToLL_M-50_TuneCUETP8M1_14TeV-madgraphMLM-pythia8_ext1

Systematic Uncertainties

- Systematic uncertainties taken from FTR-16-005:
  - Current Systematics: Using results from Run-2 analysis with 12.9 fb^{-1} and $\sqrt{s} = 13$ TeV
  - Reduced Systematics: Reduction of nominal values based on improvements in dataset size, detector performance, and theoretical accuracy among others

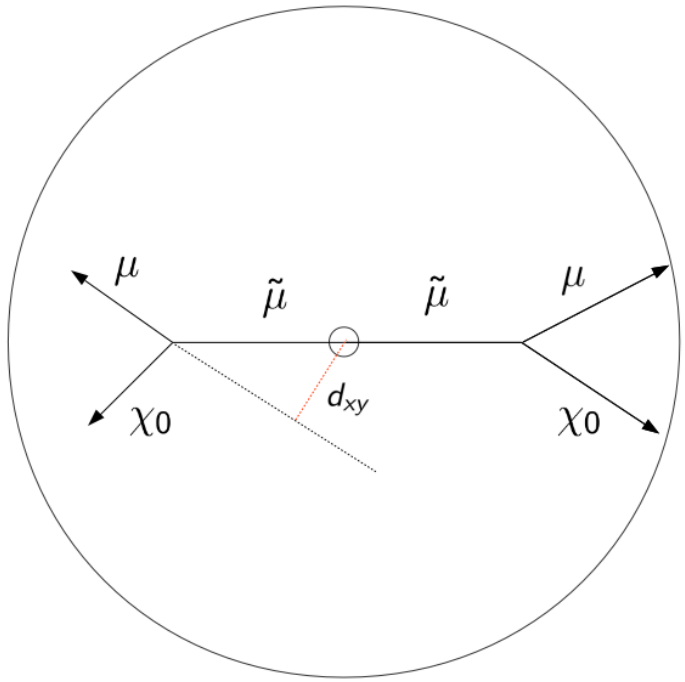
Source	Current Systematics	Reduced Systematics
Luminosity	6.2 %	1.5 %
Muon Trigger efficiency	5 %	1 %
Muon ID	2 %	1 %

- $t\bar{t}$ cross section: 15% (current) and 7.5% (reduced)
  $\Rightarrow$ Most probably dominating source of systematic uncertainty
- cross section on other processes: 5%

Statistical Interpretation

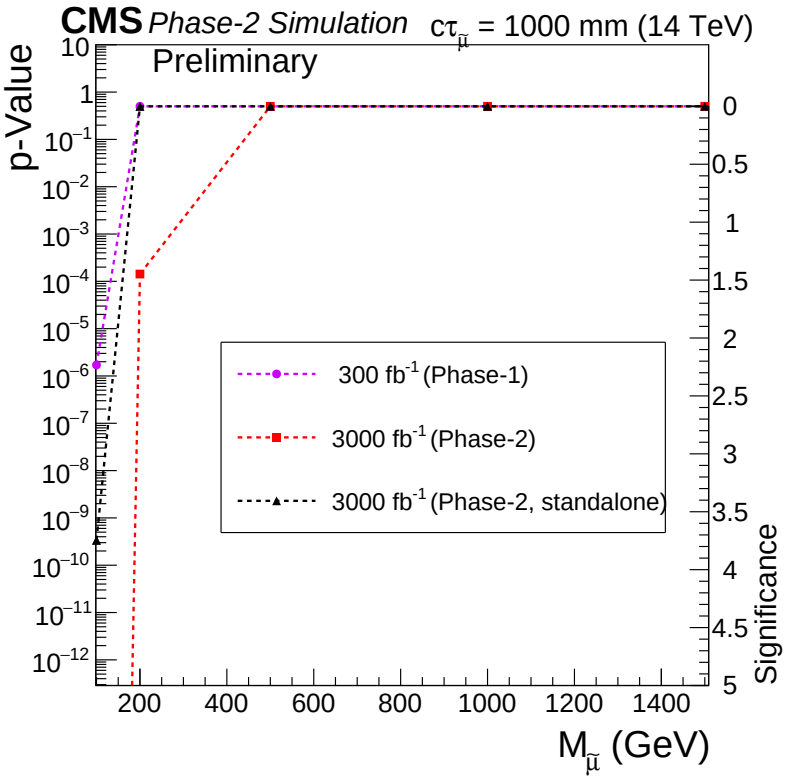
- 2 goals: Setting exclusion limits and determining discovery sensitivity
- Higgs combine tool
- Define search regions w.r.t. transverse impact parameter
- Procedure:
  - Bayesian approach
  - Single bin counting
  - Systematic uncertainties from FTR-16-005

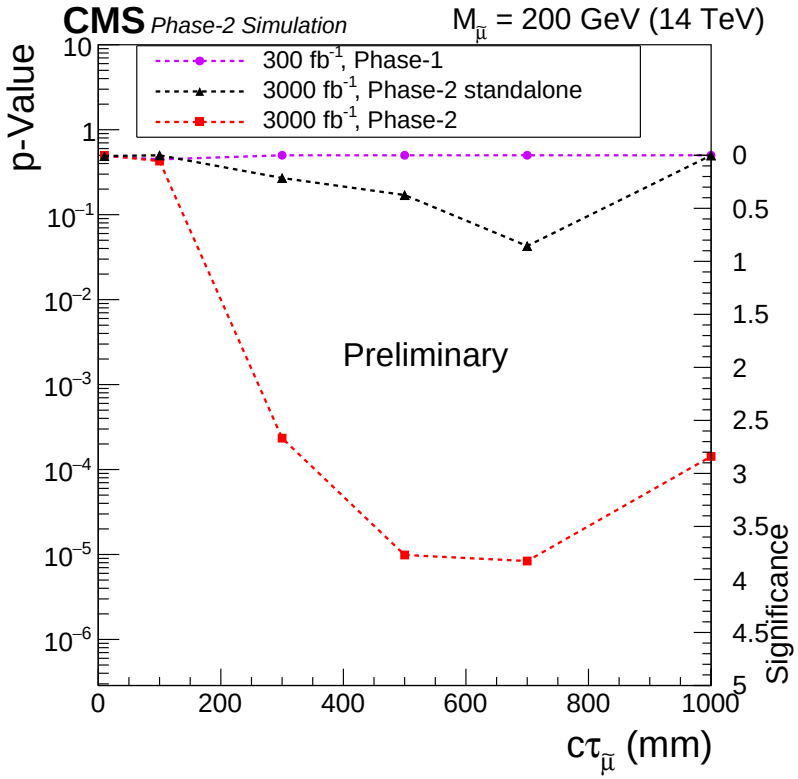
- Discriminating variable: d_0 of the 2 selected muons (2D)
- Transverse impact parameter gives measurement of displacement on reconstruction level



Discovery Sensitivity

- p-Value and significance as function of mass and decay length





$\Rightarrow$ Phase-2 scenario much more sensitive in terms of discovery

$\Rightarrow$ As a function of decay length differences are more visible

Parameters of Simulated Samples

- 10^5 events per sample
- Global tag: PhaseIITDRSpring17DR, CMSSW: 91X_upgrade2023_realistic_v3-v1
- Three PU scenarios: NoPU, PU140, PU200

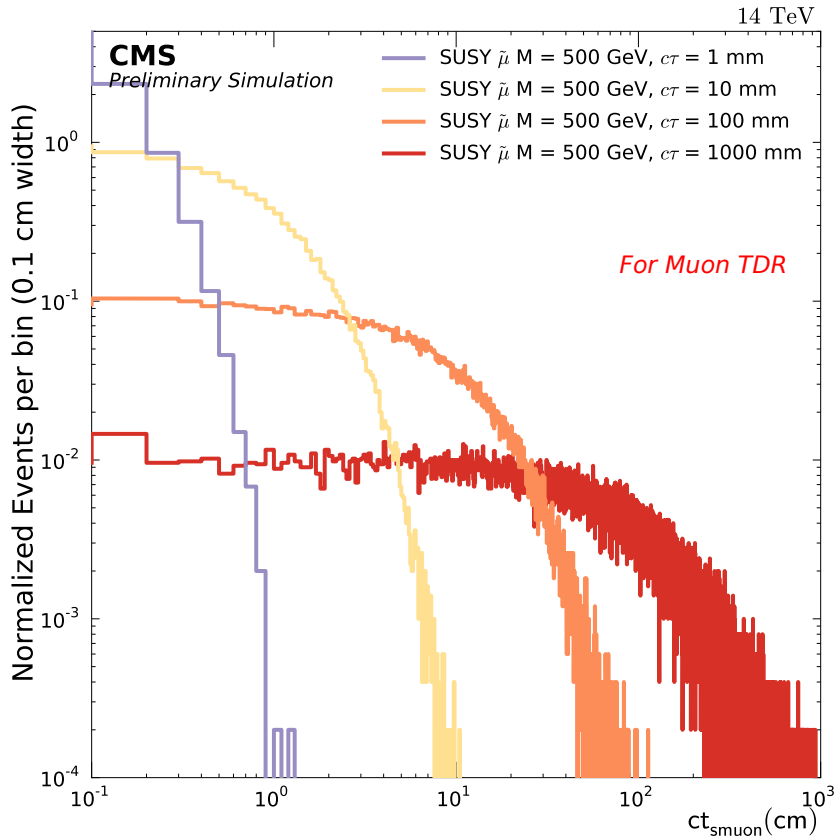
- Features of parameter space:

  O(TeV) masses

  $\frac{M_{\tilde{\mu}}}{\text{TeV}} \in \{0.1, 0.2, 0.5, 1.0, 1.5\}$

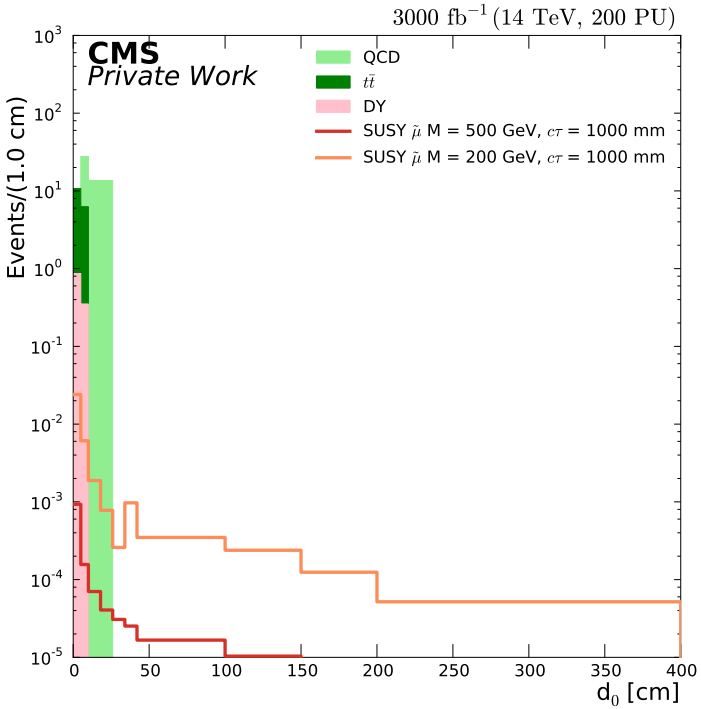
  From quasi-prompt to displaced

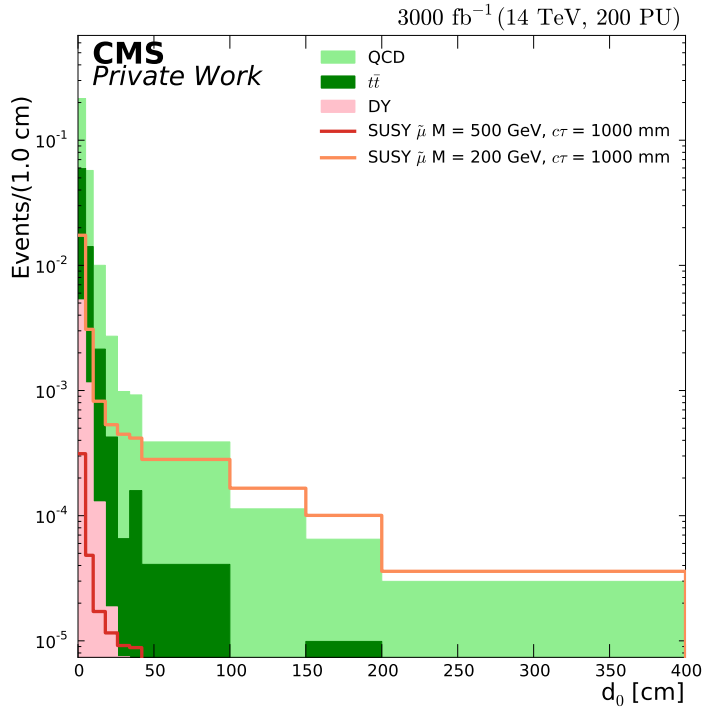
  $\frac{c\tau_{\tilde{\mu}}}{\text{mm}} \in \{10, 100, (300, 500, 700), 1000\}$



Factorized d_0 significance cut - Results

- Comparison of final d_0 distribution for first selected displaced muon
- Left: Applying standard d_0 significance cut
- Right: Factorized d_0 significance cut





$\Rightarrow$ Background with less spikes and higher stats

$\Rightarrow$ Background more reliable

Theory: Decay Length

- Decay length leads to distance L that the LLP travels inside the detector
- Phase-space factor
- $m_{\tilde{l}}$: mass of NSLP slepton
- F: SUSY breaking scale
- Kinematic factor

$$L = 9.9 \times 10^{-7} \left(\frac{m_{\tilde{\ell}}}{100\,\mathrm{GeV}} \right)^{-5} \left(\frac{\sqrt{F}}{10\,\mathrm{TeV}} \right)^{4} \left(E^2_{\tilde{\ell}} / m^2_{\tilde{\ell}} - 1 \right)^{1/2} \mathrm{cm}.$$