# Displaced Muons at HL-LHC with CMS

HE/HL-LHC workshop at CERN

BSM WG3

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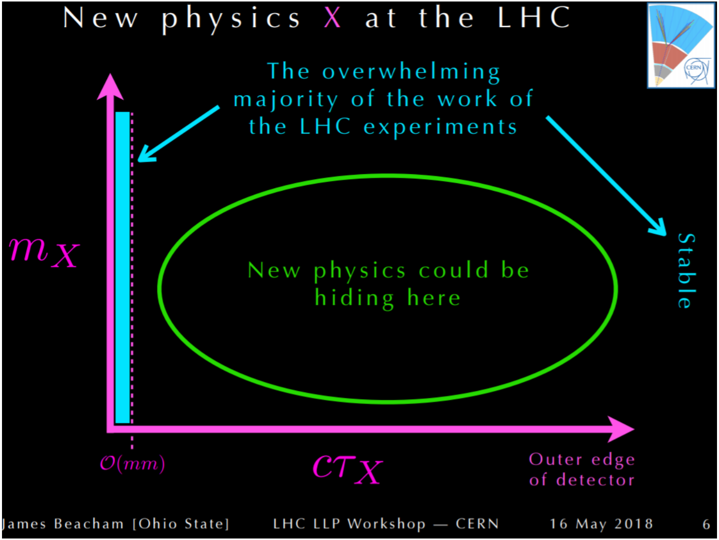
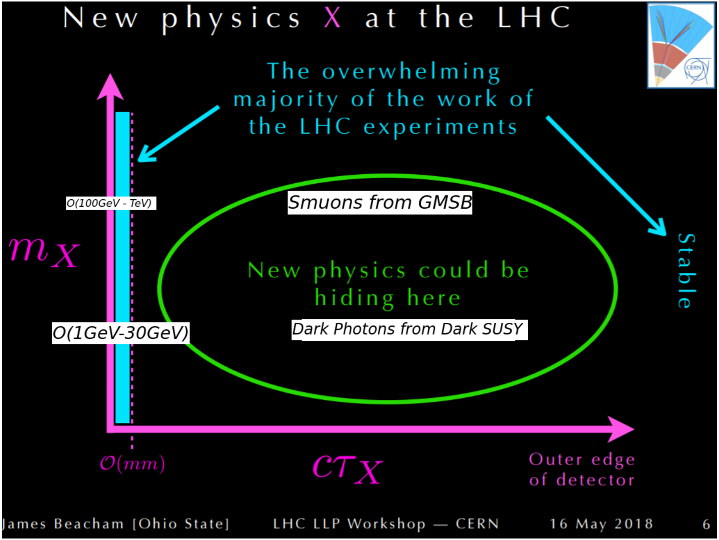
# Where to look for new physics at LHC?

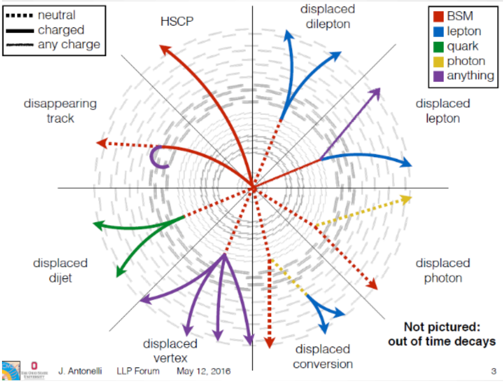



▸ Intro Talk for LLP workshop in May 2018 given by James Beacham

# Where to look for new physics at LHC?



# Overview of Long-Lived Signatures



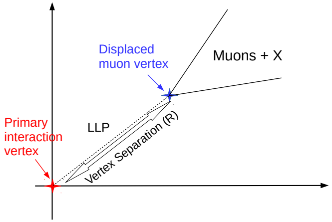

- Large class of searches leading to displaced signatures (leptons, photons, jets)
- Another class: out-of-time signatures
- This talk focuses on displaced muons (in-time)

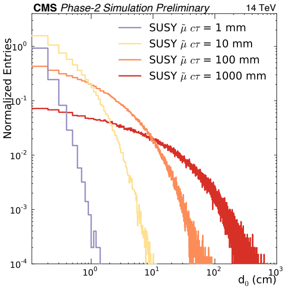
## Challenging LLP signatures

- 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

## Detector Signature:

- Assuming long-lived particle decaying into muon(s)
- Final state consists of two or more displaced muons and missing transverse energy
- Transverse impact parameter $d_O$, Vertex separation $R$




## Features of parameter space:

- LLP masses of up to TeV
- Decay length of LLP quasi-prompt ($c\tau = 10$ mm) to long-lived ($c\tau = 1$ m)
- Focusing on large $c\tau$ to probe new phase-space

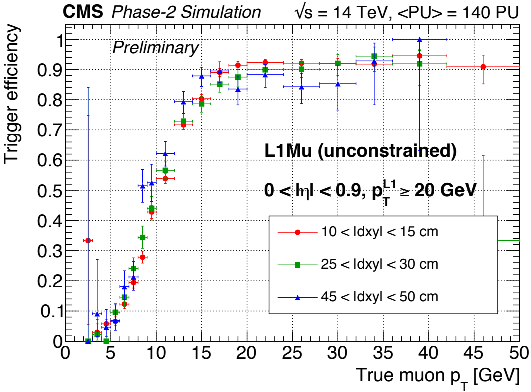
# A Distant Relative: Displaced Muons

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.

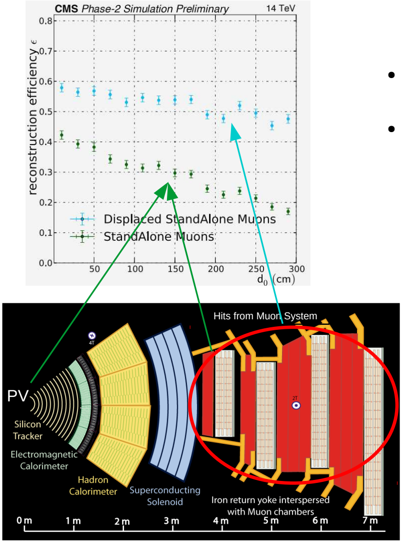
- Searches driven by detector signature
- Dedicated trigger streams for displaced muons (slide 7)
- Special reconstruction algorithms and their pecularities (slide 8)
- Non-standard analysis methods (slide 9)
- Background sources can be instrumental or cosmics, not only from SM (slide 11)

# Displaced Muon Trigger in Phase-2

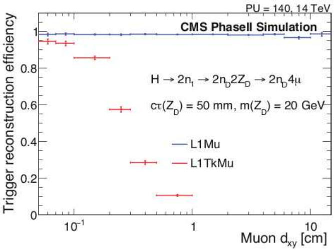
- Trigger efficiency of 90% at L1 for displaced muons
- Use offline cut of 20 GeV to reach plateau of trigger efficiency
- Fluctuation of plateau are taken into account by applying 10% systematic uncertainty




- Benchmark scenario, motivated by studies from ▸ CMS-TDR-17-004




- In this study, muon system information only for reconstruction
- Higher reconstruction efficiency for displaced algorithm (no vertex constraint)



# Selecting Displaced Muons in Phase-2

- Keep strategy as model-independent as possible $\rightarrow$ 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: $p_T > 20$ GeV, $|\eta| < 2.8$
- Track Quality: $\chi^2/\text{ndof} \leq 2$
- Nb(ValidMuonHits) $\geq 17$
- 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 $\geq 2$ DSA muons fulfilling object selection
- $E_{T,miss} \geq 50$ GeV
- $\Delta R(\text{muo1,muo2}) > 0.05$
- $\cos(\theta_{\text{muo1,muo2}}) < -0.99$: Reject cosmics with back-to-back kinematics
- If there are more than 2 candidates, select the two with the highest significance on impact parameter

## Standard Model Background

- QCD (PYTHIA8)
  - Heavy quarks decaying non-prompt leading to displaced muons
- $t\bar{t}$ (POWHEG)
  - Muons from b-decays as well as leptonic decay of top quark
- DY (MADGRAPH@NLO)
  - Prompt muons badly reconstructed as displaced

## Samples

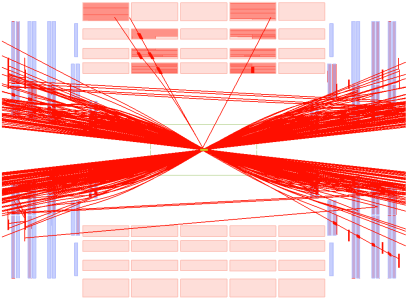
- Full Simulation with CMSSW
- Hadronization with PYTHIA8

# Other Backgrounds

- Cosmic ray muons:
  - Independent of CMS Phase-2 and luminosity
  - Reduced by implementation of back-to-back cut
  - Tested rejection of displaced muons with test sample using data sample while pp collisions absent and LHC clock on:

    Rejection power of cosmic ray muons after full selection $< 10^{-9}$

- Beam halo muons:
  - Increased in Phase-2 with higher instantaneous luminosity
  - Included in simulation
  - Signature not favoured by reconstruction algorithms
  - Removed by selection due to low-$p_T$ ▸ Liu, C. et al.

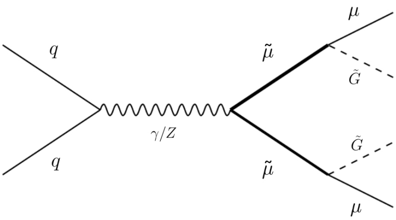


# Smuons as LLPs

- SUSY with Gauge Mediated Supersymmetry Breaking (GMSB)
- Mass hierarchy: Light gravitino (LSP) in GeV range and heavy slepton(s) (NLSP) in TeV range
- Massive smuons of several 100 GeV up to 1.5 TeV

## Production/Signature of Smuons at LHC

- Pair-produced long-lived smuons
- Production via s-channel Z,$\gamma$ exchange
- Decay of long-lived smuon: $\tilde{\mu} \rightarrow \mu + \tilde{G}$
- Final state: two high-$p_T$ muons and missing transverse energy




▸ Ruderman and Shih

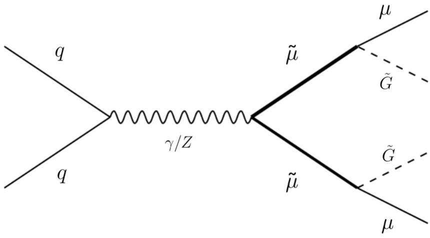
▸ Theory paper

# Decay of Smuons

- Sleptons decays to Standard Model partner and gravitino
- Decay is heavily suppressed by SUSY breaking scale $\sqrt{F}$

$$c\tau_{\tilde{\mu}} = c \cdot \frac{\hbar}{\Gamma_{tot}} = 9.87 \cdot 10^{-6} \left(\frac{m_{\tilde{\mu}}}{100\ \text{GeV}}\right)^{-5} \left(\frac{\sqrt{F}}{10\ \text{TeV}}\right)^{4}\ \text{mm}$$

- SUSY breaking scale can be of the order of O(1000 TeV) $\Rightarrow c\tau_{\tilde{\mu}} \approx 1$ m.
- Nature of NLSP important aspect
- Smuon which is the NLSP is long-lived



# Systematic Uncertainties

- Systematic uncertainties taken from former studies on BSM physics for Phase-2 PAS-FTR-16-005:
  - Current Systematics: Using results from Run-2 analysis with 12.9 fb$^{-1}$ and $\sqrt{s} = 13$ TeV
  - Reduced Systematics: What systematic uncertainty are we expecting today for analysis in O(10y)
  - Reduction based on improvements in dataset size, detector performance, and theoretical accuracy among others

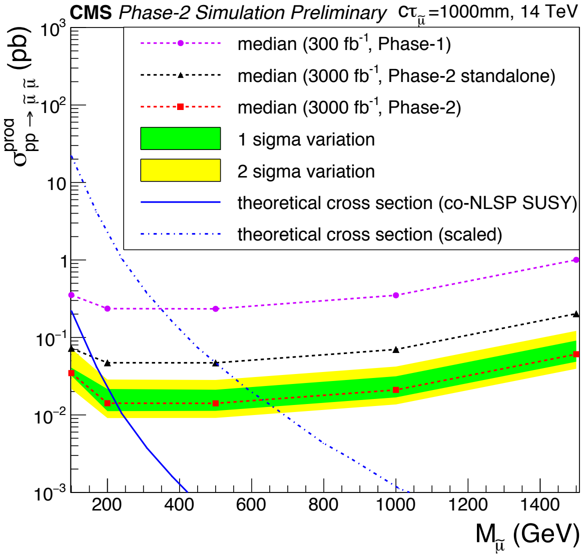
| Source | Current Systematics | Reduced Systematics |
|---|---|---|
| Luminosity | 6 % | 1.5 % |
| Trigger Efficiency | 7.5 % | 10 % |
| Identification | 2 % | 1 % |
| Cross Section (QCD, Drell-Yan) | 5 % | 2.5 % |
| Cross Section ($t\bar{t}$) | 15 % | 7 % |

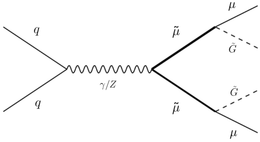
# Event Yield

- For large vertex separation ($R$), almost background-free
  $\Rightarrow$ Sensitivity scales with signal efficiency
- Need to define search region
  e.g. 1 cm $< R$ (for $c\tau = 10$ mm), 10 cm $< R$ (for $c\tau = 100$ mm),
  80 cm $< R$ (for $c\tau = 10^3$mm)
- Event yield serves as input for statistical interpretation

| $m_{\tilde{\mu}}[GeV]$ | $c\tau[mm]$ | Event Yield Signal | $t\bar{t}$ | Drell-Yan | QCD |
|---|---|---|---|---|---|
| 200 | 1000 | 5.37 | 0.36 | 0.033 | 0.028 |
| 200 | 700 | 3.97 | 0.36 | 0.033 | 0.028 |
| 200 | 500 | 5.50 | 0.36 | 0.033 | 0.028 |
| 200 | 300 | 4.80 | 0.36 | 0.033 | 0.028 |
| 200 | 100 | 1.42 | 7.7 | 4.6 | 11.1 |
| 200 | 10 | 0.14 | 32 | 390 | 1500 |
| 100 | 1000 | 29.89 | 0.36 | 0.033 | 0.028 |
| 100 | 700 | 29.08 | 0.36 | 0.033 | 0.028 |
| 100 | 500 | 32.51 | 0.36 | 0.033 | 0.028 |
| 100 | 300 | 26.63 | 0.36 | 0.033 | 0.028 |
| 100 | 100 | 9.52 | 7.7 | 4.6 | 11.1 |
| 100 | 10 | 1.48 | 32 | 390 | 1500 |

# Exclusion region for Smuons

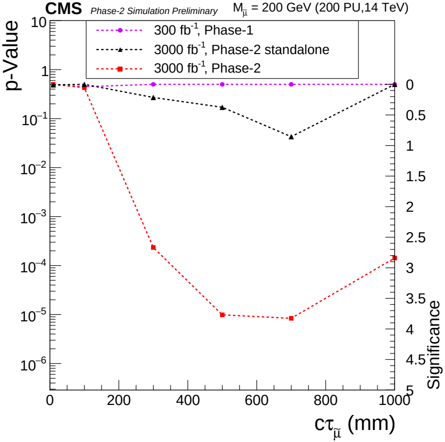


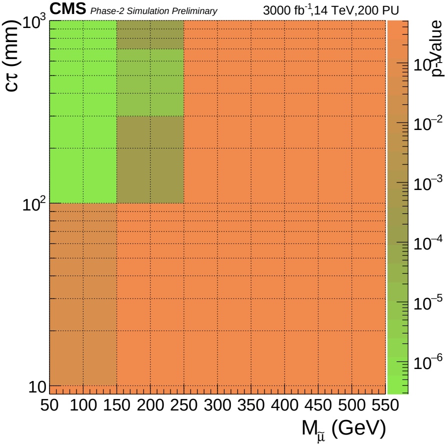




- Limits set on smuons from GMSB SUSY
- For 3000 fb$^{-1}$ and Phase-2 scenario: mass limit at 220 GeV

# Search Sensitivity for Smuons at HL-LHC

- Discovery sensitivity using same input as for limit setting




- Sensitive to discovery ($5\sigma$) for $M_{\tilde{\mu}} \approx 100$ $GeV$
- Sensitive to evidence ($3\sigma$) for $M_{\tilde{\mu}} \approx 200$ $GeV$

# Conclusion

- Sensitivity study for displaced muon signature
- Model-independent strategy
- Searching for smuons from GMSB SUSY
- Investigating parameter space for exclusion/discovery
- Discovery sensitivity for smuons lighter than 200 GeV ($3\sigma$)

## Outlook

- Re-interpretation using dark photons in the pipeline
- Contribute to Yellow Report with both interpretation (hopefully...)

Thank you for your attention!

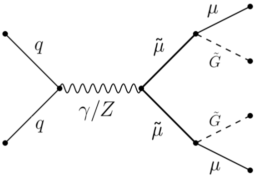
# Additional slides...

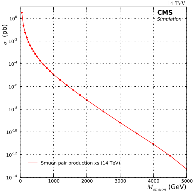
# Long-lived smuons in NLSP SUSY

- 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

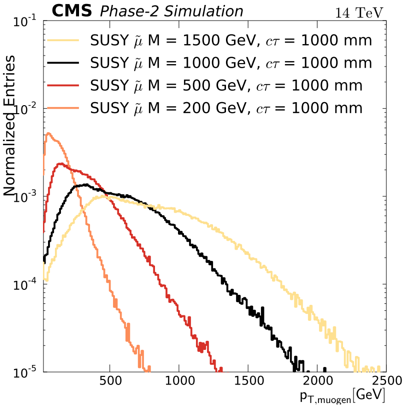
Ruderman and Shih
Theory paper

- Process: $q\bar{q} \rightarrow \tilde{\mu}\bar{\tilde{\mu}}$
- Smuon pair production via s-channel Z,$\gamma$ exchange
- Decay: $\tilde{\mu} \rightarrow \mu + \tilde{G}$
- Final state: two muons and missing transverse energy



- Distributions of $p_T, \eta$ on GEN level



# Details of Simulated Smuon Samples

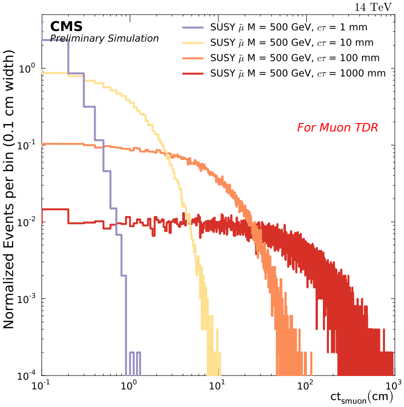
- $10^5$ events per sample
- Full simulation of detector (CMSSW)
- Two pileup scenarios available: NoPU, PU200

- Features of parameter space:

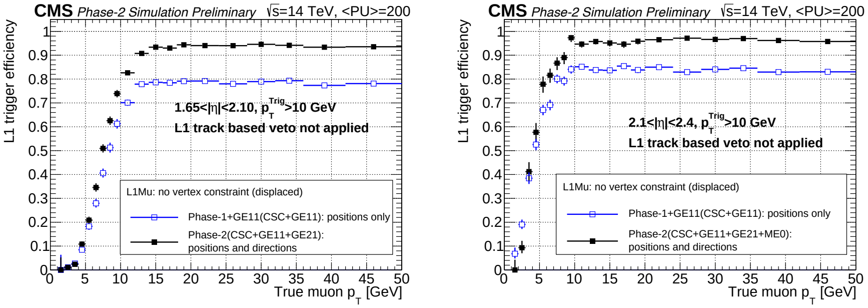
  O(TeV) masses
  $\frac{M_{\tilde{\mu}}}{\text{TeV}} \in \{0.1, 0.2, 0.5, 1.0, 1.5\}$

  From quasi-prompt to displaced

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



L1 trigger in forward region, plateau at around $\approx 10$ GeV
Threshold for endcap displaced muon algorithm
Efficiency well above 90% for displacements of up to $d_{xy} = 50$ cm



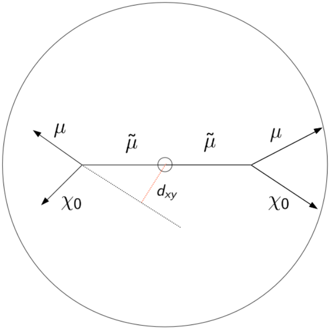
# Scenarios

- Phase-2 scenario:
  - Integrated luminosity: 3000 $\text{fb}^{-1}$
  - Geometry: Phase-2 detector
  - Higher-efficiency trigger benchmark scenario (90%)
  - Pileup scenario: PU 200
  - Expected systematics [**?**]
- Phase-1 scenario:
  - Integrated luminosity: 300 $\text{fb}^{-1}$
  - Geometry: Phase-1 detector
  - Lower-efficiency trigger benchmark (60%)
  - Pileup scenario: PU 200
  - Current systematics [**?**]
- Scenario assuming SA reconstruction efficiency = 1/3 DSA reconstruction efficiency
  - Integrated luminosity: 3000 $\text{fb}^{-1}$
  - Geometry: Phase-2 detector
  - Higher-efficiency trigger benchmark scenario (90%)
  - Pileup scenario: PU 200
  - Expected Systematics

# Statistical Interpretation

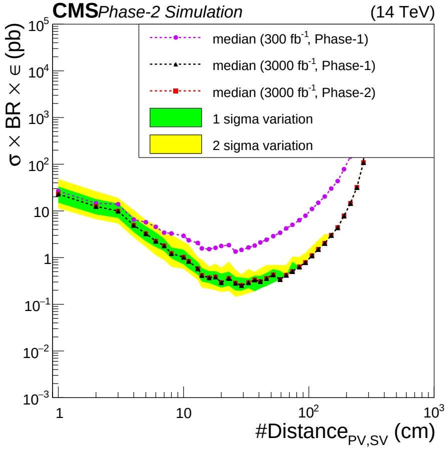
- 2 goals: Setting exclusion limits and determining discovery sensitivity
- Higgs combine tool
- Define search regions w.r.t. transverse impact parameter
- Procedure:
  - Bayesian approach
  - Single bin counting
  - Systematic uncertainties from FTR-16-005

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



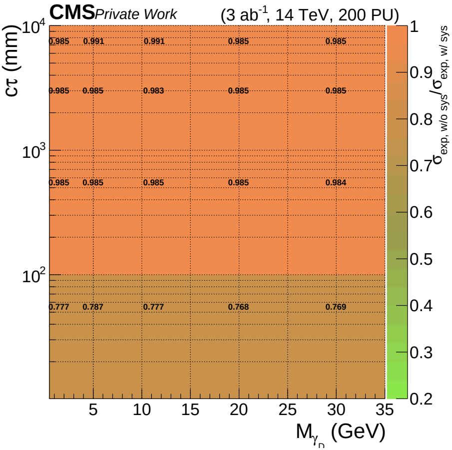
# Scanning boundary of signal regions

- Scanning lower bound of signal region
- Lower bound checked by eye



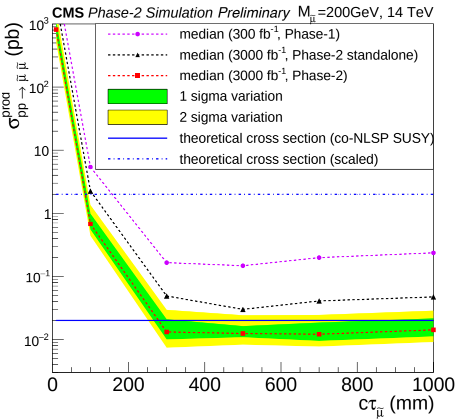
# Influence of systematics on limit setting

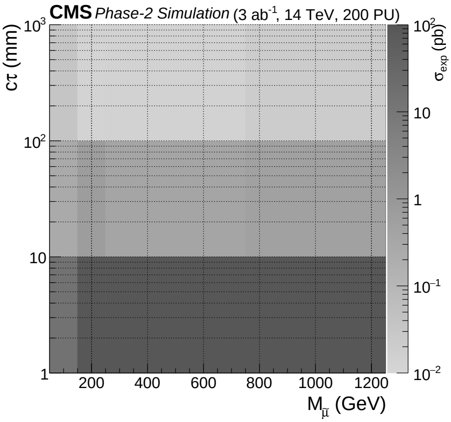
- Showing ratio of expected limit w/ and w/o including systematic uncertainties




⇒ In the sensitive region this analysis is driven by statistical uncertainties

# Exploring Parameter Space




⇒ Reach of exclusion is significantly increasing from Phase-1 to Phase-2