Prospects for BSM Searches at the HL-LHC with CMS

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(University of Illinois at Chicago)

-- On behalf of the CMS Collaboration

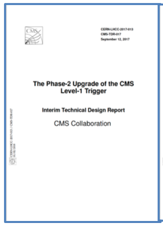
High-Luminosity LHC

- Currently SM works beautifully, no direct evidence of new physics yet
- Naturalness argument and low mass of Higgs boson provide strong motivation for new particles and/or interactions at the TeV scale
- HL-LHC will deliver 3/ab data, provide unprecedented window for searching new particles/phenomena at the TeV scale

Summary of CMS HL-LHC Upgrades

Trigger/HLT/DAQ

- Track information at L1-Trigger
- L1-Trigger: 12.5 µs latency - output 750 kHz
- HLT output ≃7.5 kHz



CERN-LHCC-2017-013
CMS-TDR-017
September 12, 2017

The Phase-2 Upgrade of the CMS Level-1 Trigger

Interim Technical Design Report

CMS Collaboration

CERN-LHCC-2017-014
CMS-TDR-018
12 September 2017

The Phase-2 Upgrade of the CMS DAQ

Interim Technical Design Report

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Barrel EM calorimeter

- Replace FE/BE electronics
- Lower operating temperature (8◦)

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12 Sep 2017

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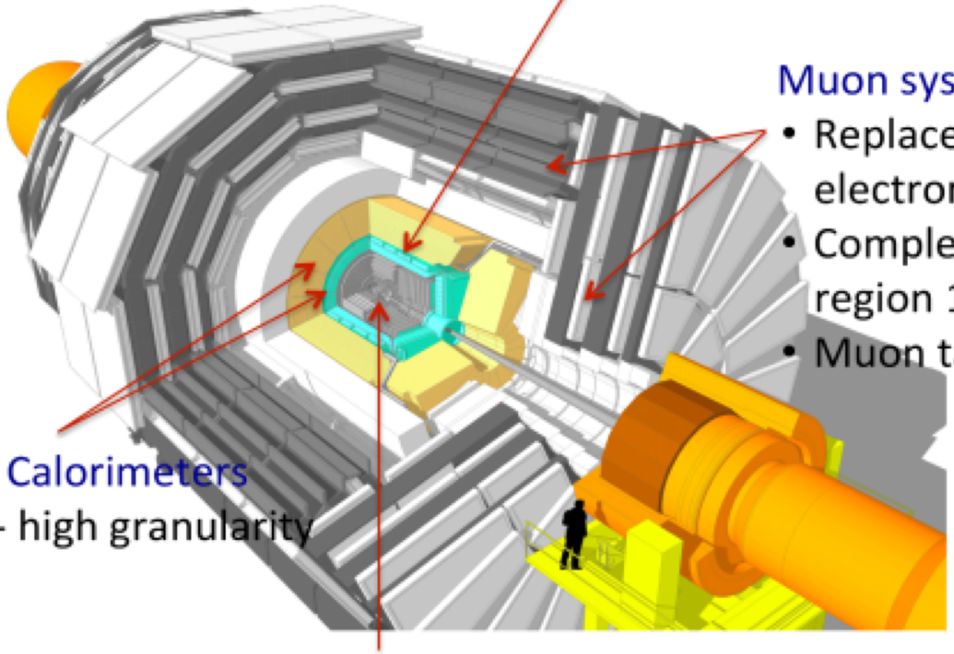
The Phase-2 Upgrade of the CMS Barrel Calorimeters

TECHNICAL DESIGN REPORT



Muon systems

- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

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12 September 2017

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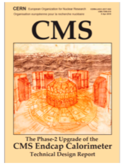
The Phase-2 Upgrade of the CMS Muon Detectors

TECHNICAL DESIGN REPORT



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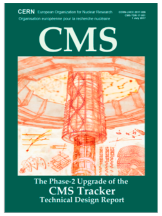
The Phase-2 Upgrade of the CMS Endcap Calorimeter Technical Design Report

Replace Endcap Calorimeters

- Rad. tolerant - high granularity
- 3D capability

Replace Tracker



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CMS

The Phase-2 Upgrade of the CMS Tracker Technical Design Report

- Rad. tolerant - high granularity - significantly less material
- 40 MHz selective readout (Pt≥2 GeV) in Outer Tracker for L1-Trigger
- Extend coverage to $\eta = 3.8$

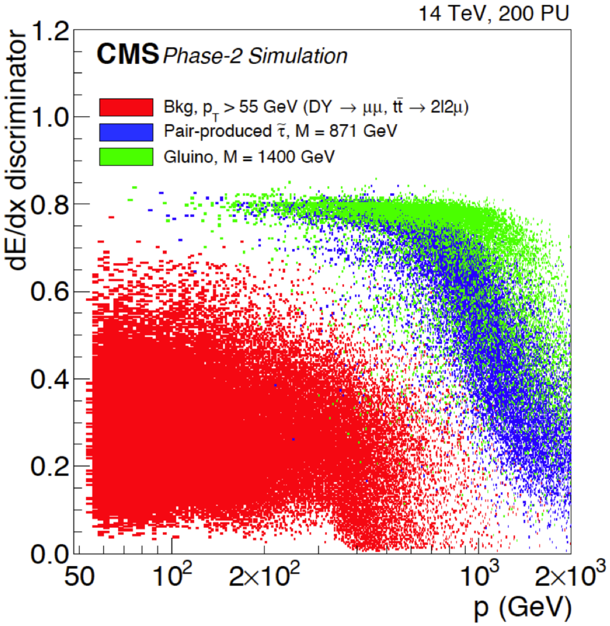
Analysis Strategies

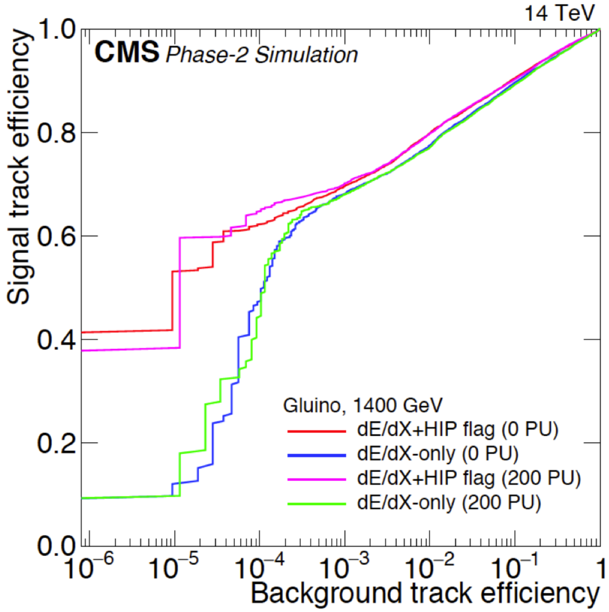
- **Two methods – either projection from present analysis or parametrized simulation**
- **Projections from a present analysis**
  - Existing signal and background samples (simulated at 13 TeV) scaled to higher luminosity and √s=14 TeV.
  - Apply analysis steps (cuts) from present analyses.
  - Three scenarios for systematics:
    1. keep present systematics
    2. improved by a fixed factor
    3. no systematics, only statistics

- **Full analysis with parametrized detector performance**
  - Delphes with up-to-date phase-2 detector performance (tracking, vertexing, timing, pileup mitigation algorithms, increased acceptance, performance of new detectors)
  - Consider <PU> = 140/200
  - Dedicated simulation of signal and background samples
  - Analysis steps (cuts) guided by present analysis. Limited optimization for HL conditions. Cross checks with present analysis.

Heavy Stable Charged Particle

- Heavy stable charged particles with long lifetime, moving slowly and heavily ionizing the sensor material as they pass through the detector
  - Stau and gluino in Split SUSY scenarios, with small cross section
- Look for anomalously high energy loss through ionization (dE/dX) in the tracker
  - Maintain Phase-1 dE/dx measurement in the Phase2 Inner Tracker,
  - Extend discrimination with HIP flag by adjustable threshold in the Outer Tracker modules

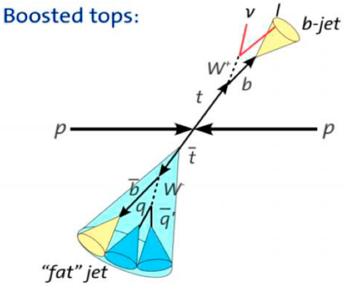




CMS-TDR-014

Z’→ttbar Resonance Search

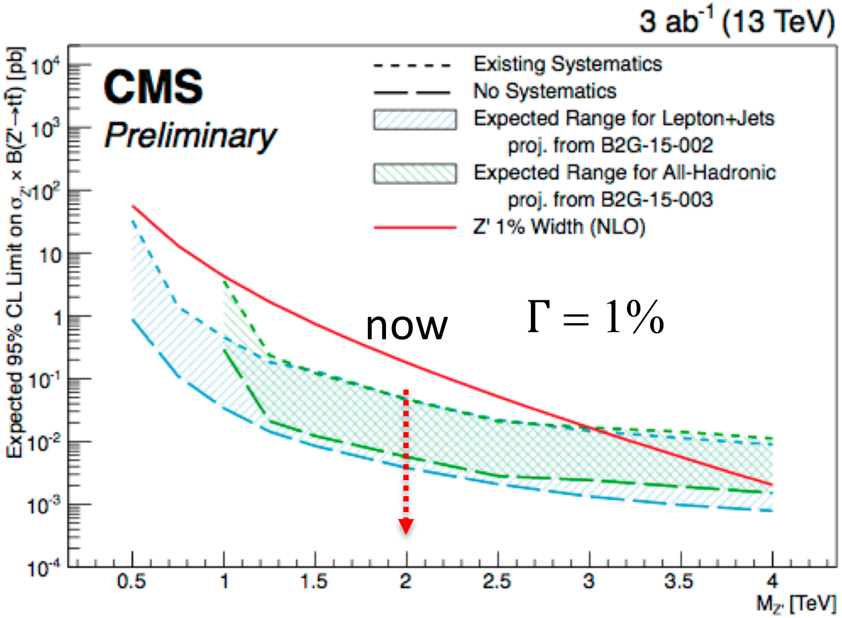
- Z′→ttbar studied in two distinct channels
  - Semileptonic (l + b-jet + jet + MET) [B2G-15-002]
  - All-hadronic channel (jets) [B2G-15-003]
- Both rely on high p_T top reconstruction

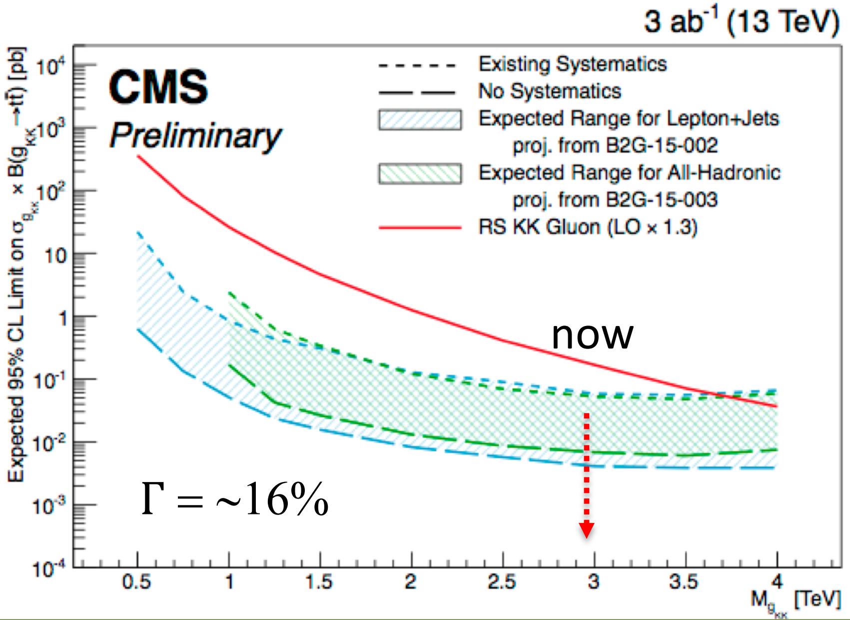


Project to 3/ab , with different scenarios for systematic uncertainties:

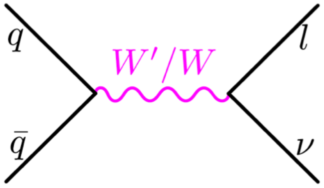
1. Leave systematics unchanged
2. No systematic uncertainties applied – best scenarios

CMS-DP-2016-064

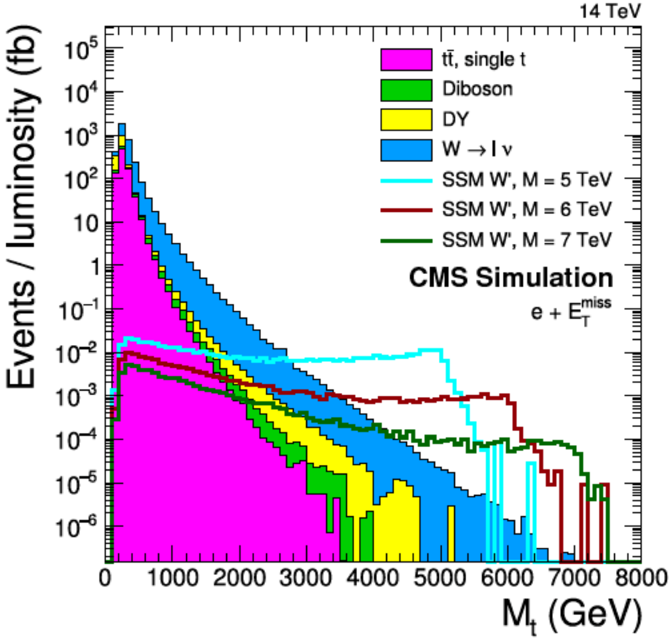




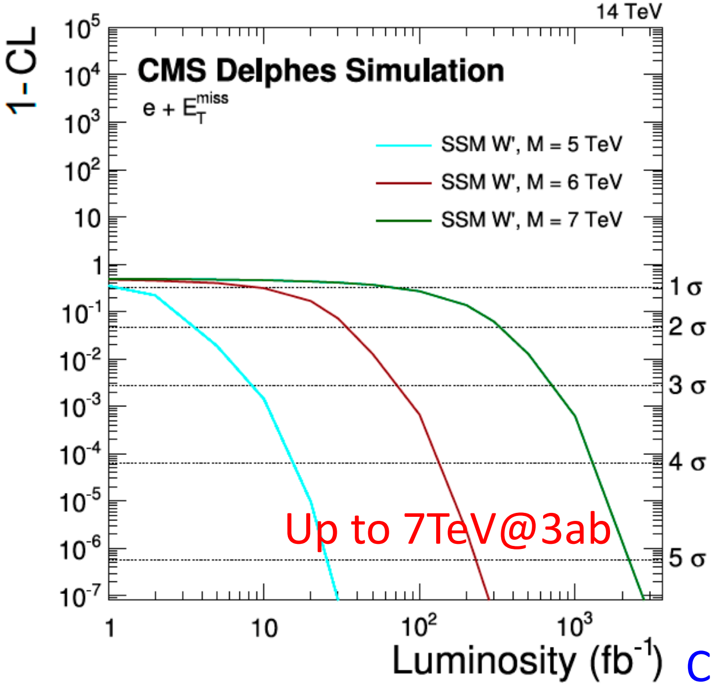
Search for W'→lν



- Tail search for W'→lν with full Delphes analysis
- Discriminating variable M_T from (e, MET)
    - Electron channel with good resolution at very high mass and rather flat resolution.
- Assume systematics from run-2.
- To understand the M_T tail and performance of high p_T leptons.



$$M_T = \sqrt{2p_T^l E_T^{\text{miss}}(1 - \cos[\Delta\phi(\vec{p}_T^{\,l}, \vec{p}_T^{\,\text{miss}})]}$$



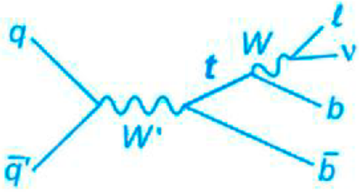
Up to 7TeV@3ab

CMS-EXO-14-007

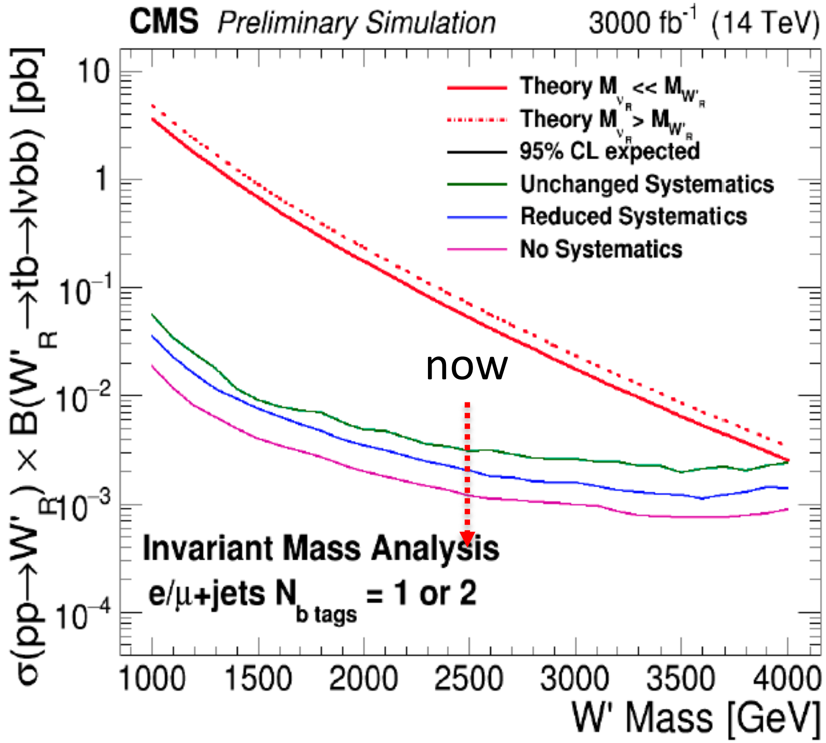
Search for W'→tb

- Projection from B2G-16-017 to HL-LHC
- Two scenarios to extrapolate systematics from 12.9/fb to 3/ab

1. Leave systematics unchanged, simply scale templates with lumi
2. Reduce most experimental to percent level, theory uncertainties by factor 2
   →Impact on projected exclusion limit: 4(4.2) TeV for case 1(2)
3. No systematics

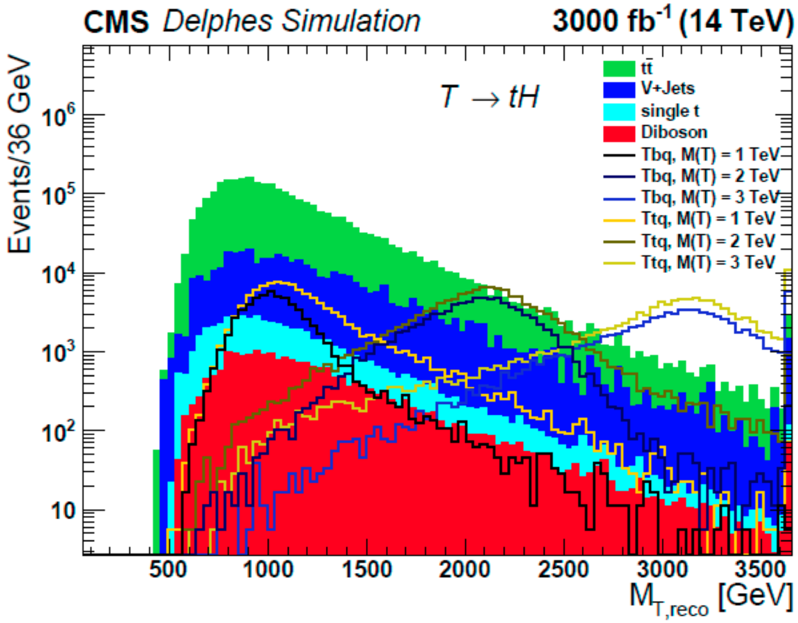


CMS-DP-2016-064



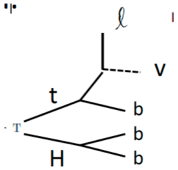
Vector-like Quark

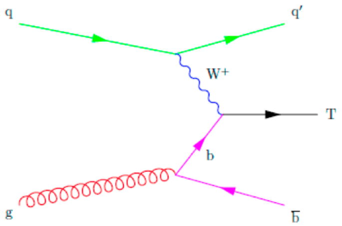
- Search for electroweak production of single T (T→tH) with Delphes analysis
- Benchmark BR(T→tH) =0.25 for LH Tbq, BR(T→tH)= 0.5 for RH Ttq
- Event signature has a very forward jet that can benefit from forward upgrade.
- Higgs tagging in AK8 jets, will benefit from b-tagging improves with phase-II detector.

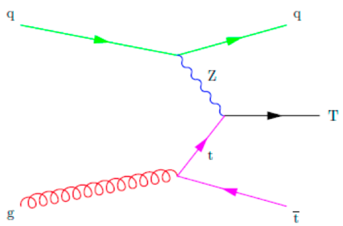


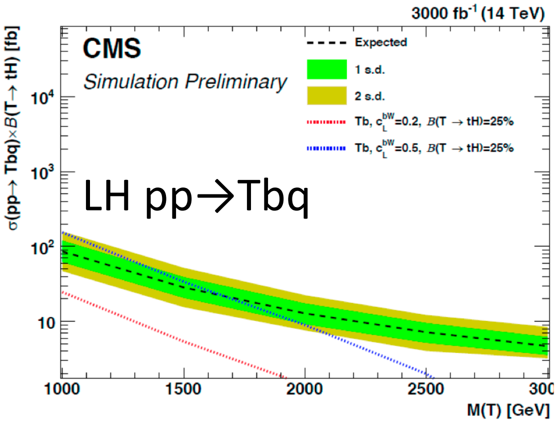
CMS-B2G-15-008

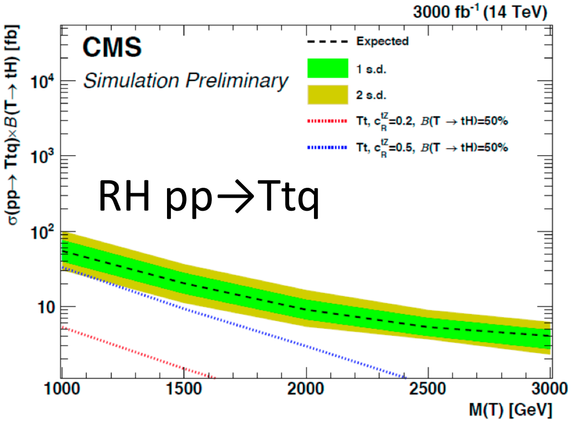
CMS-DP-2016-064











Dark Matter

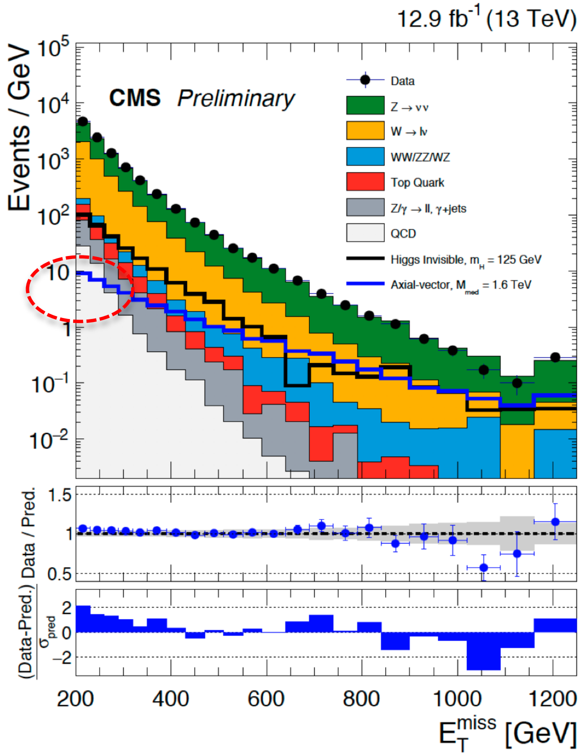
- LHC provides complementary sensitivity for direct detection experiments, allows the study of different types of interaction
- Interpretation in simplified models following LHC DM forum (arXiv:1507.00967) with 4 parameters (M_{med}, M_{DM}, g_{SM}, g_{DM})
- Full monojet analysis carried out on

Delphes samples

  - Follow CMS-EXO-16-037 procedure

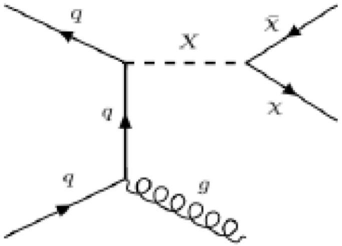
- Final state: large MET (>200 GeV) + jet
- Dominant: 70% Z(vv)+jets; 30% W(lv)+jets
  - Estimated with data-driven method

  using muons control region Z(mm), W(mv)



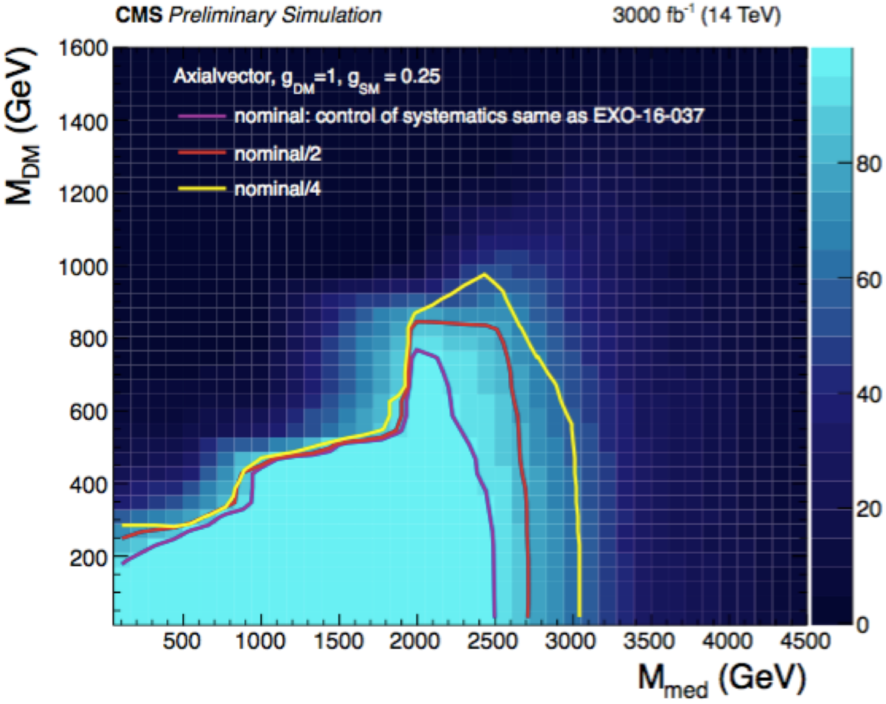
Dark Matter: Axialvector

- Bin MET distribution in 22 exclusive bins.
- Extend to MET > 2.4 TeV (now 1.2 TeV).



Spin-1 mediator, axial vector
g_{SM} = 0.25,
g_{DM} = 1

CMS-DP-2016-064

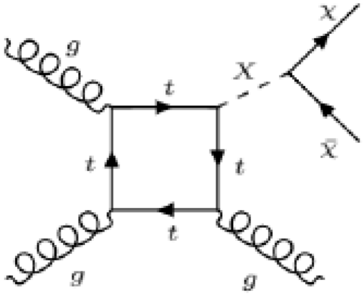


- Systematics scenarios:
  1. Nominal = assume the systematic control of the MET distribution same as the current CMS-EXO-16-037 analysis
  2. Nominal divided by 2
  3. Nominal divided by 4

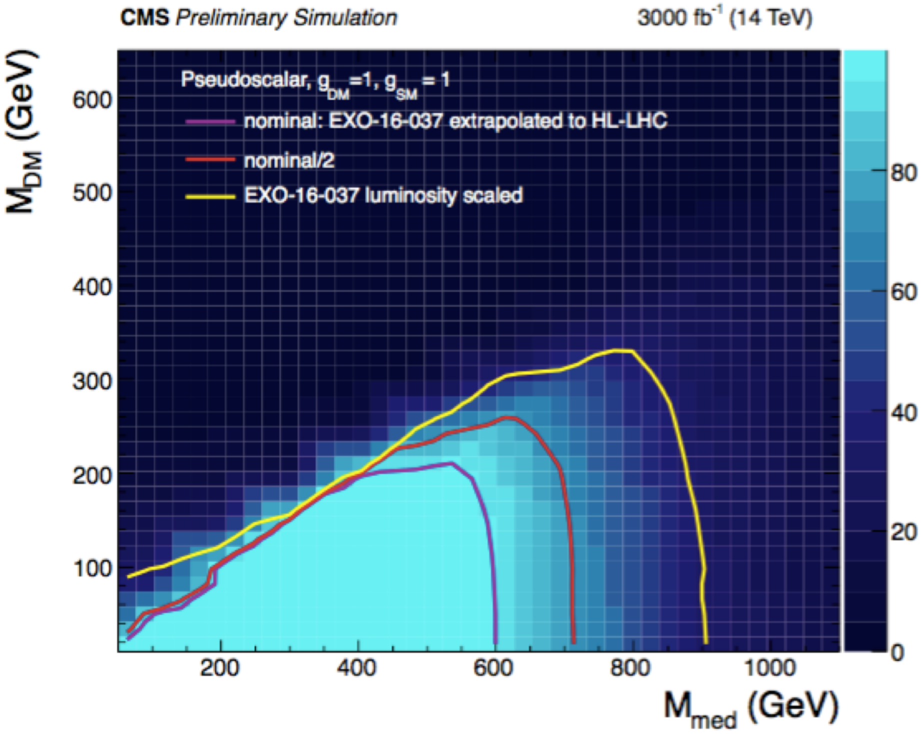
Current reach for M_{med}~ 2 TeV

Dark Matter: Pseudoscalar

- Same MET binning as EXO-16-037
- Low MET systematics are dominated by the uncertainty on lepton identification/isolation efficiency for the control sample
- High MET systematics are dominated by statistics
- Systematics scenarios:
  1. Nominal = scale run-2 systematics at low MET to HL-LHC recommendation, scale high MET systematics by luminosity
  2. Nominal divided by 2
  3. Scale run-2 systematics in the full MET range by luminosity



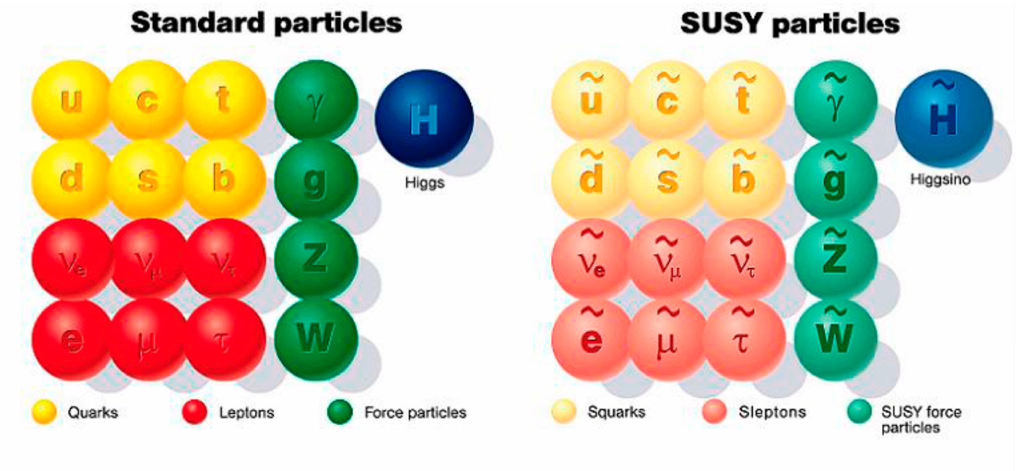
Spin-0 mediator, pseudoscarlar g_{SM} = 0.25, g_{DM} = 1



Current reach for M_{med} ~ 400GeV

Search for Supersymmetry

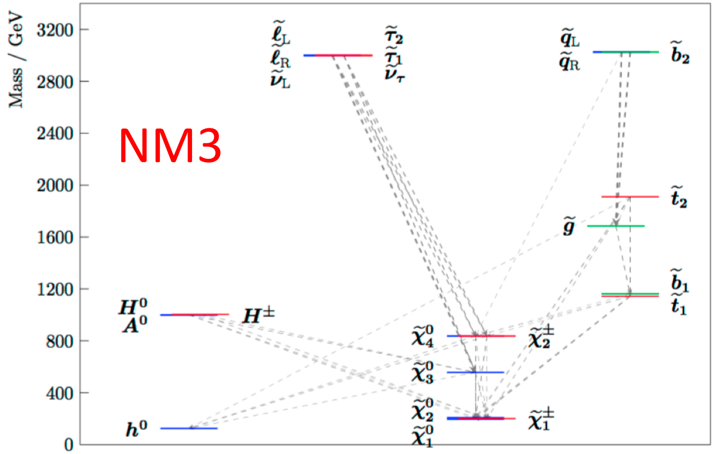
Supersymmetry is one of the best motivated theories for physics beyond the SM

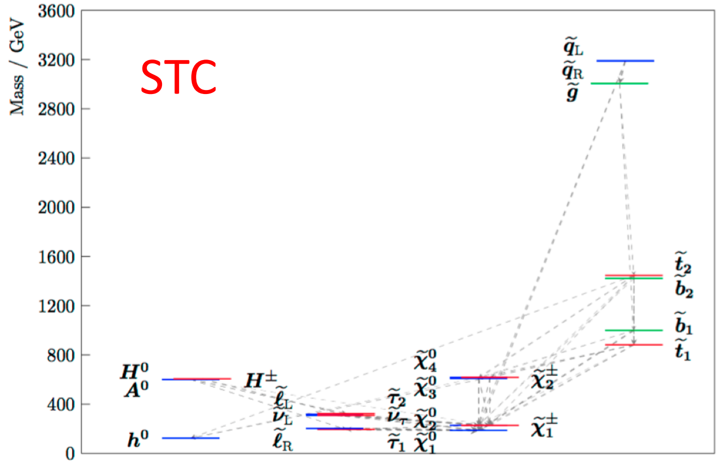


- Search for SUSY is one of the major goals of LHC
  - Currently working toward the full Run2 results
- For HL-LHC, other SUSY models move into focus.
  - Explore higher mass, low cross section & compressed mass spectra.
  - Study properties if new particle(s) discovered
  - Special signatures such as heavily ionizing and long-lived particles

SUSY Models

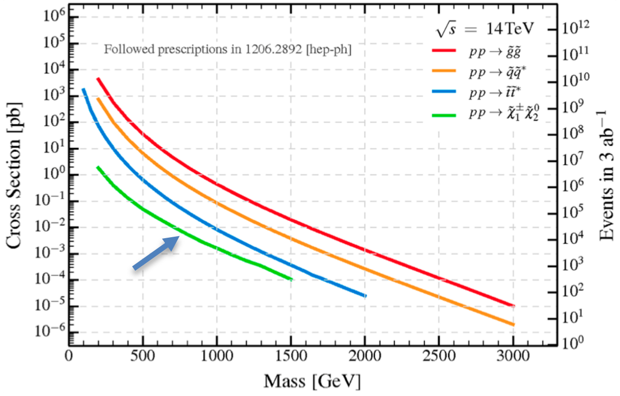
- Natural scenarios (NM1, NM2, NM3)
  - strong interaction sector and decay BR of the gluinos similar in the three models
    - NM1 (Bino like LSP)
    - NM2 (Wino like LSP)
    - NM3 (Higgsino like LSP)
- Stau co-annihilation model (STC)
  - light stau1 almost mass degenerate with bino-like neutralino1
- Stop co-annihilation model (STOC)
  - light stop1 almost mass degenerate with bino-like neutralino1
  - stop decays into charm-neutralino1
  - gluino-gluino & gluino-squarks cross-sections are smaller but not negligible





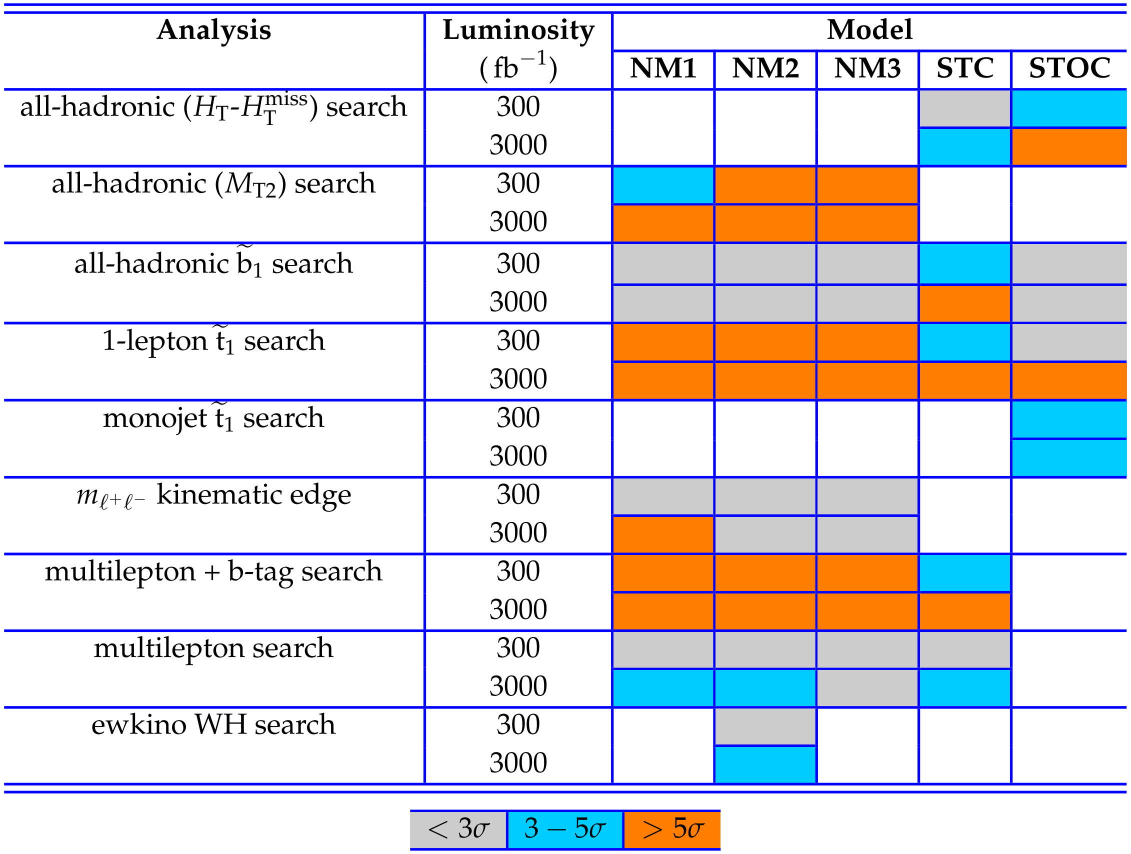
Full Search Spectrum

- 9 searches carried out with Delphes simulation with 140PU assumption
- Different types of SUSY models lead to different patterns of discoveries in different final states after different amounts of data.
- Electroweakinos searches expected to benefit from high-lumi, due to its small XS



Exploring SUSY model space

Exploring experimental signature space



Analysis	Luminosity (fb^{-1})	Model				
		NM1	NM2	NM3	STC	STOC
all-hadronic (H_T-H_T^{miss}) search	300				▨	🟦
	3000				🟦	🟧
all-hadronic (M_{T2}) search	300	🟦	🟧	🟧		
	3000	🟧	🟧	🟧		
all-hadronic $\tilde{b}_1$ search	300	▨	▨	▨	🟦	▨
	3000	▨	▨	▨	🟧	▨
1-lepton $\tilde{t}_1$ search	300	🟧	🟧	🟧	🟦	▨
	3000	🟧	🟧	🟧	🟧	🟧
monojet $\tilde{t}_1$ search	300					🟦
	3000					🟦
$m_{\ell^+\ell^-}$ kinematic edge	300	▨	▨	▨		
	3000	🟧	▨	▨		
multilepton + b-tag search	300	🟧	🟧	🟧	🟦	
	3000	🟧	🟧	🟧	🟧	
multilepton search	300	▨	▨	▨	▨	
	3000	🟦	🟦	▨	🟦	
ewkino WH search	300		▨			
	3000		🟦			

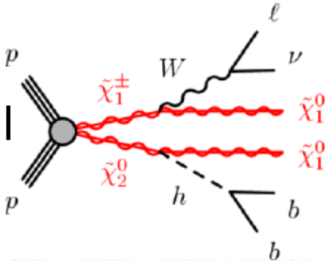
▨	🟦	🟧
$< 3\sigma$	$3-5\sigma$	$> 5\sigma$

CMS-SUS-14-012

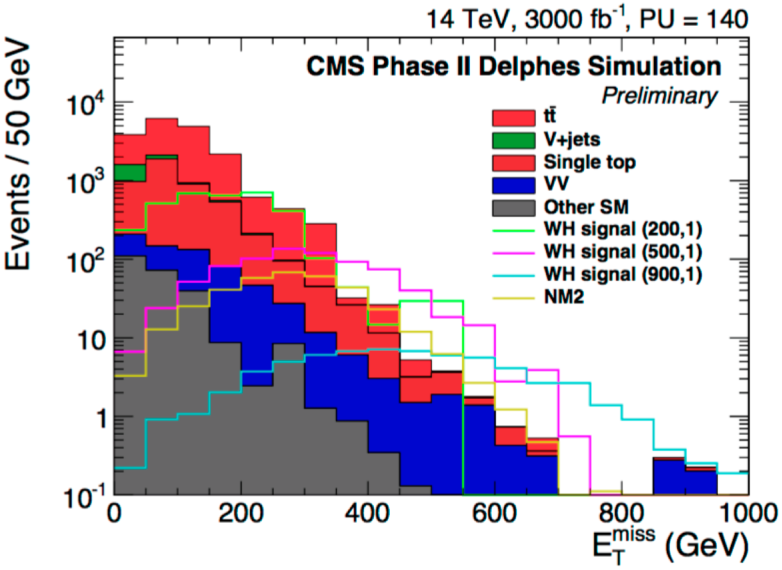
Search for C1N2 decaying into Wh

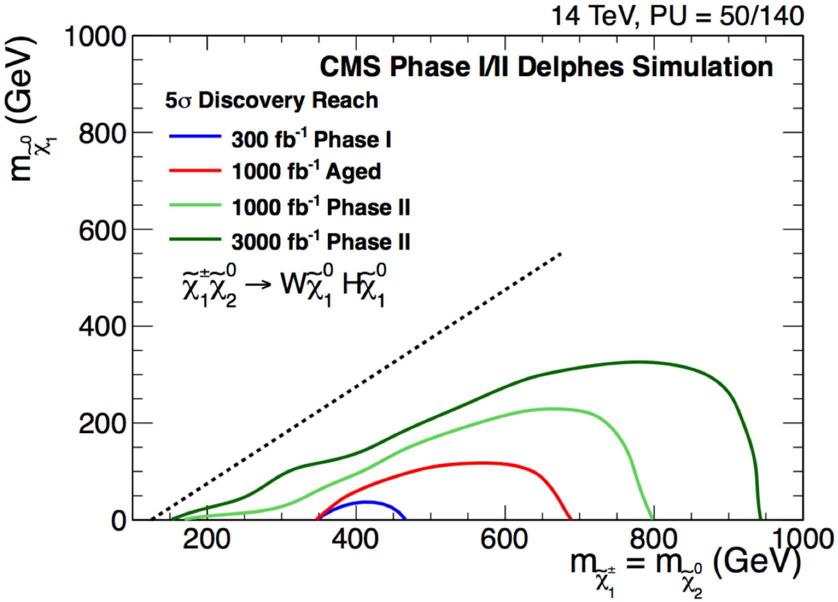
CMS-SUS-14-012

- Search for $\chi_1^{\pm}\chi_2^0$ production with Delphes
  - Signal region defined by M(bb), MT, MET etc
  - MET and M_{CT} are the essential observables to discriminate signal from background
  - systematic uncertainties assumed to be 1/2 w.r.t to that measured in 8 TeV analyses
- Large gain in discovery potential
- Detector upgrade is crucial for b-tagging and MET performance



$$\begin{aligned} M_{\mathrm{CT}}^2(j_1,j_2) &= [E_{\mathrm{T}}(j_1)+E_{\mathrm{T}}(j_2)]^2 - [\vec{p}_{\mathrm{T}}(j_1)-\vec{p}_{\mathrm{T}}(j_2)]^2 \\ &= 2p_{\mathrm{T}}(j_1)p_{\mathrm{T}}(j_2)(1+\cos\Delta\phi(j_1,j_2)) \end{aligned}$$



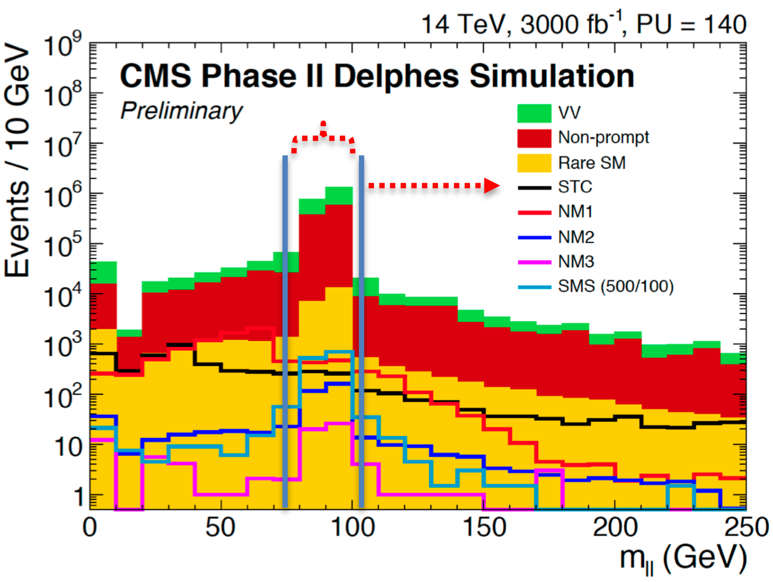


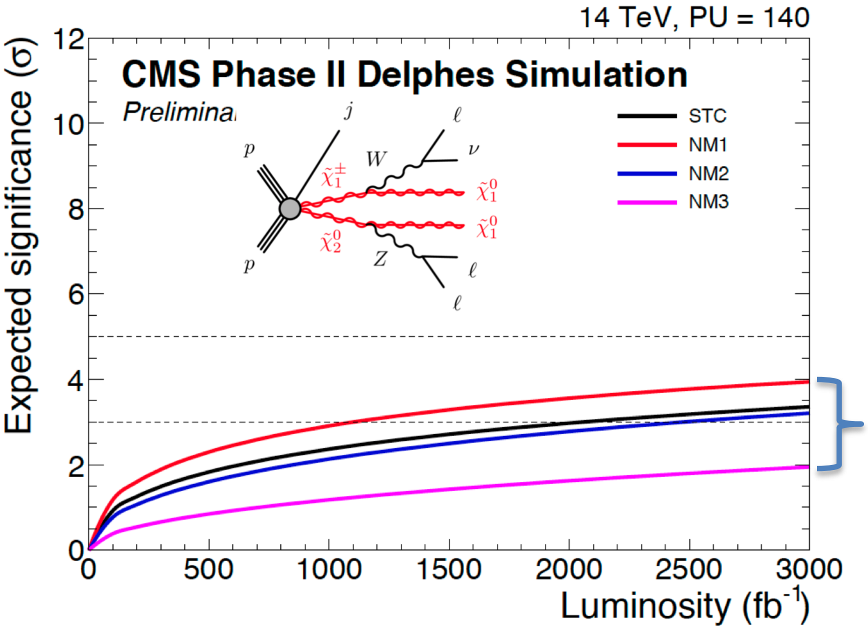
Search for C1N2 decaying into WZ

[CMS-SUS-14-012](CMS-SUS-14-012)

- Search for $\chi_1^{\pm}\chi_2^0$ production where $\chi_1^{\pm} \rightarrow W^{\pm}\chi_1^0$, $\chi_2^0 \rightarrow Z\chi_1^0$ through opposite-sign same-flavor leptons pair (OSSF)
  - Separate invariant mass of OSSF for “on-Z” and “high-Z”
  - Search binned by MET, MT, and invariant mass of OSSF
- Sensitivity strongly depends on EWK-inos composition, affects cross-sections

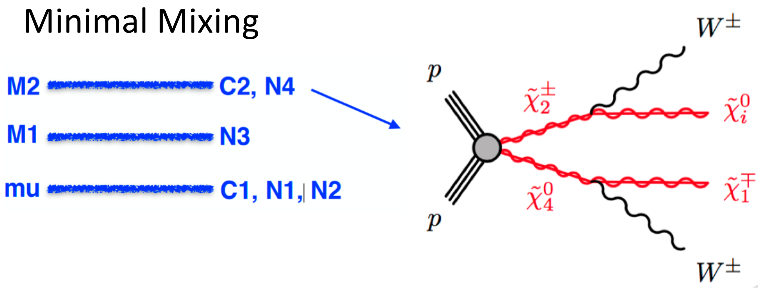
C1, N2 mass (GeV)	Wino C1N2 σ (fb)	Higgsino C1N2 σ (fb)
100	22670	3277
200	1807	244
300	387	51
400	121	16
500	46	6
600	20	3

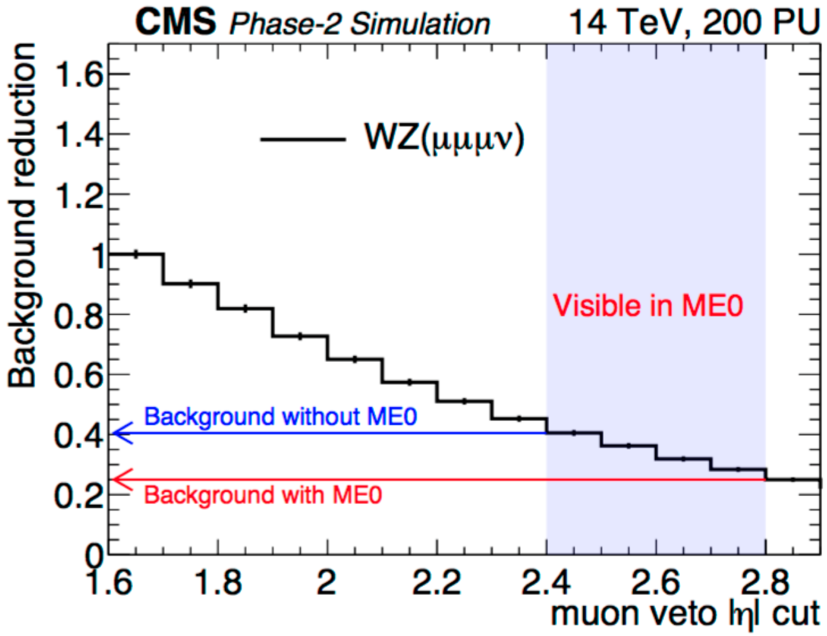




Search for C2N4 decaying into WW

- In radiatively-driven natural SUSY C2N4 has largest visible cross-section
  - 25% BR into same sign Ws
- Search for final state with two same charge leptons and large MET
  - Veto third lepton, b-tagged jet and high p_T jets
- Dominant background from SM WZ production, in which the third lepton is lost
  - Extended coverage of muon system can reduce the WZ background by a factor of 2





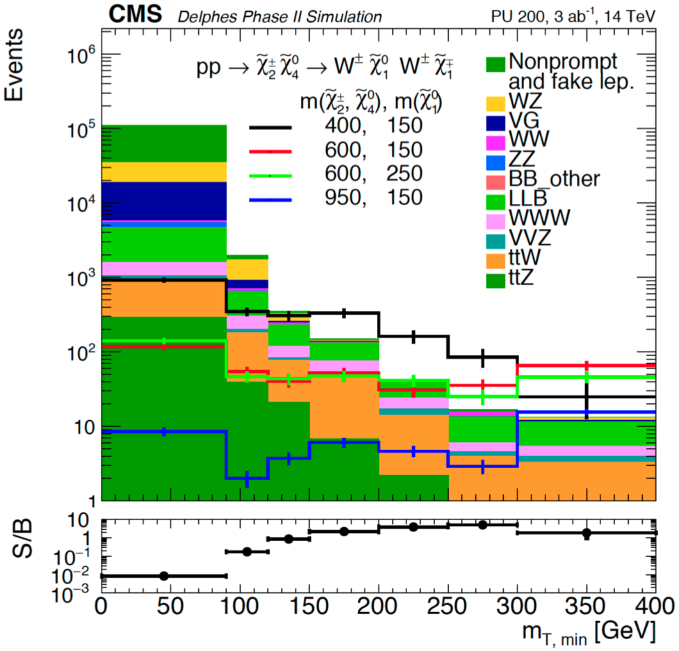
CMS-TDR-016

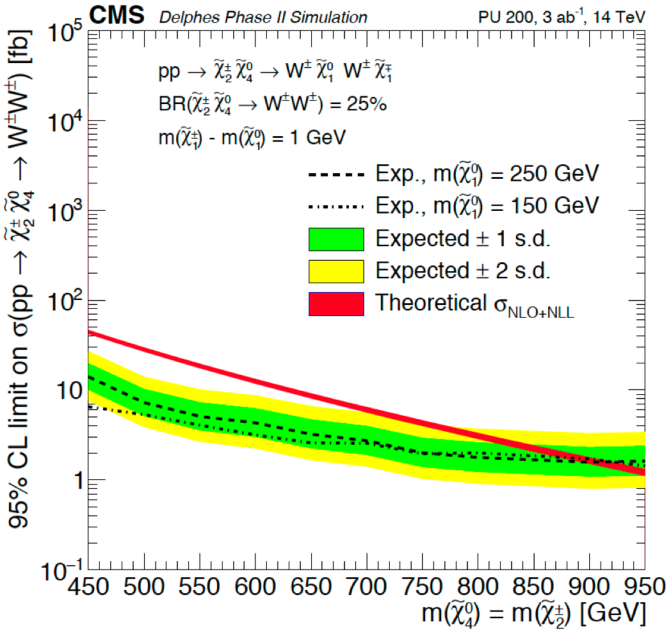
Search for C2N4 decaying into WW

- Dominant backgrounds are dibosons, suppressed by $m_{T,\min}$ variables
    - Search regions binned by 7 $m_{T,\min}$ range
- Search sensitive up to ~900 GeV scale for both assumptions on N1 (150, 250 GeV)
- Sensitivity depends on the value of N1 mildly at large C2/N4 mass, while more significant when C2, N4 mass approach N1

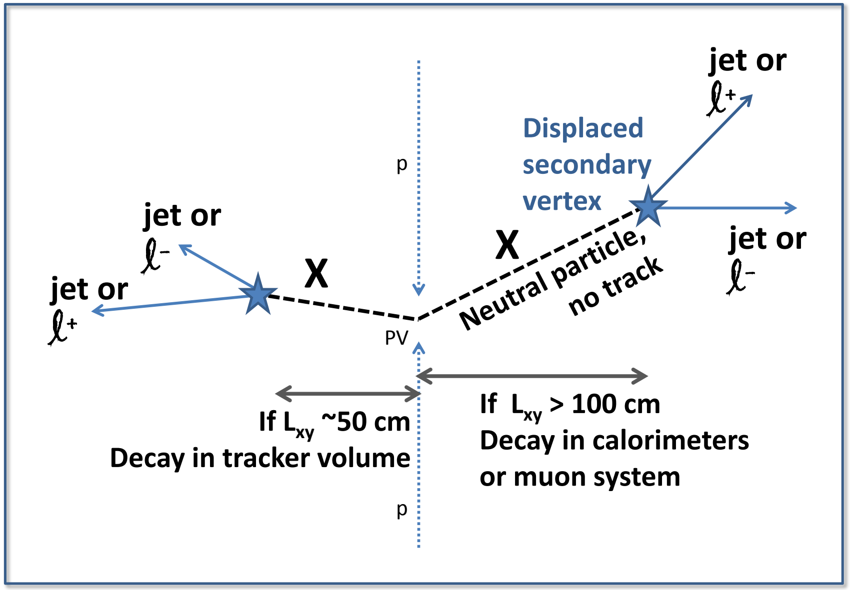
CMS-TDR-019

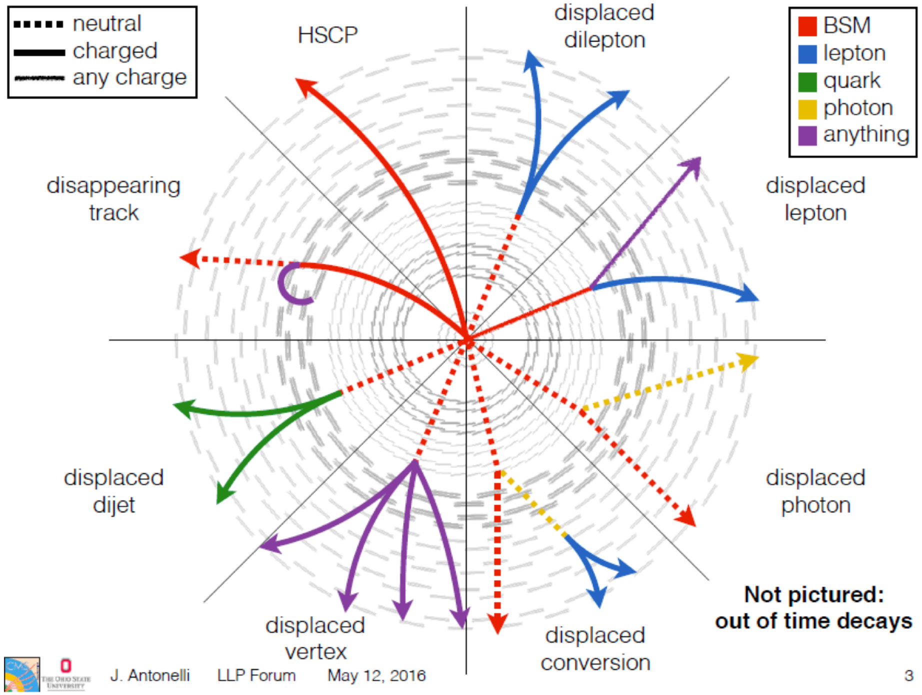
$$m_{T,\min} = \min[m_{T(\mathrm{lep}_1,p_T^{\mathrm{miss}})}, m_{T(\mathrm{lep}_2,p_T^{\mathrm{miss}})}].$$





Long Live Particle



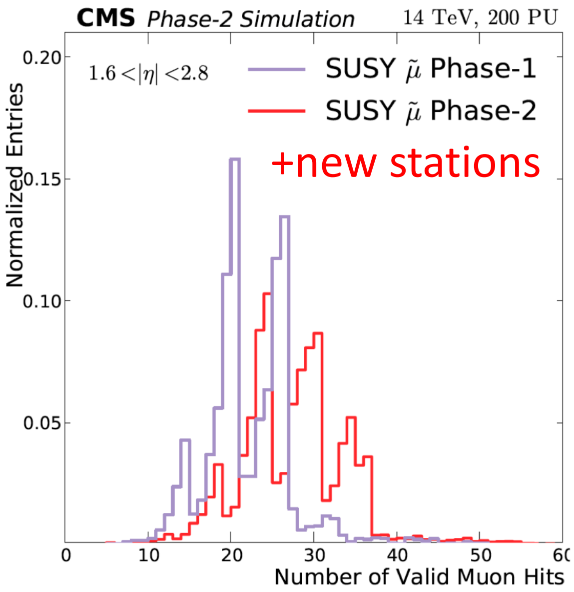


- Signature driven searches; a new focus at the LHC, for present and future.
- **Non-standard** objects, need to maintain **dedicated** detector capabilities

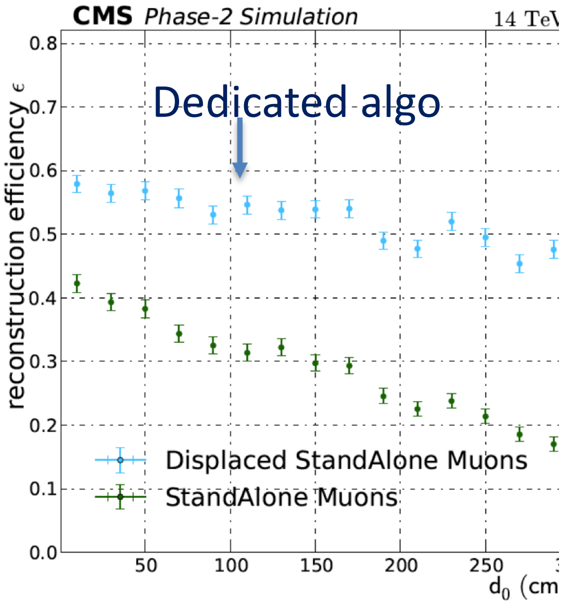
Displaced Muons

- sMuons in gauge-mediated SUSY breaking models could have a significant lifetime
  - Clean final state: two smuons decay far from primary vertex + MET
  - Cross section varies by breaking scale, tan β or modified parameters
- Phase 2 upgrade moun system and algorithm improved displaced muon efficiency
- Impact parameter significance $d_0/\sigma(d_0)$ to suppress QCD, ttbar, Z/DY backgrounds
- Challenge: keeping trigger thresholds at ~10GeV in 200PU environment

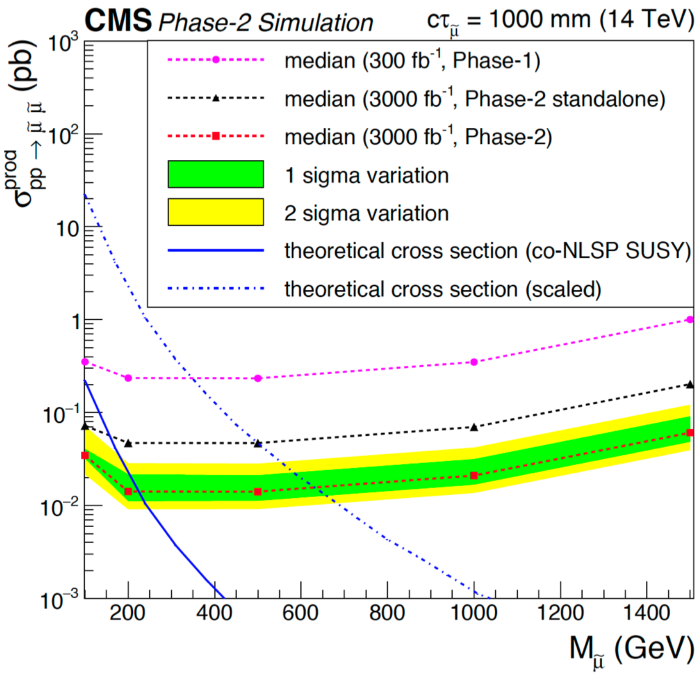
CMS-TDR-016



+new stations



Dedicated algo



Outlook

- We have gotten a variety of interesting physics results from LHC already, and we expect a lot more during the future LHC running
- Run 2, Run 3, and HL-LHC will provide a comprehensive physics program for BSM searches
- Detector upgrades (phase1 & phase2) are underway to enable this interesting physics program
- In preparation for a CERN Yellow Report as input to the European Strategy group by the end of 2018.
  - to review, extend and further refine our understanding of the physics potential of the High Luminosity LHC

Stay tuned!