



# Prospects for Physics Beyond the Standard Model at the HL-LHC and HE-LHC

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International Linear Collider Workshop

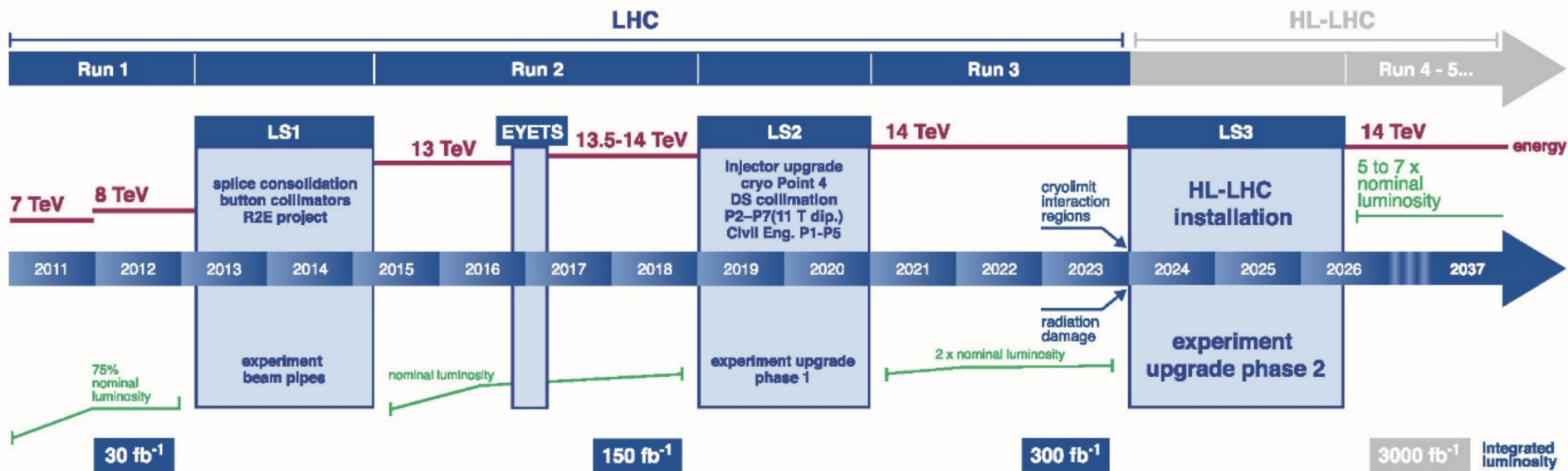
University of Texas Arlington

October 23, 2018



# HL-LHC and HE-LHC

## LHC / HL-LHC Plan



- ◆ HL-LHC = 3,000 fb<sup>-1</sup> at 14 TeV from 2026-2037
- ◆ HE-LHC = 15,000 fb<sup>-1</sup> at 27 TeV
  - ◆ Proposed for after HL-LHC
  - ◆ Based on 16T magnets in the current LHC tunnel (27km)

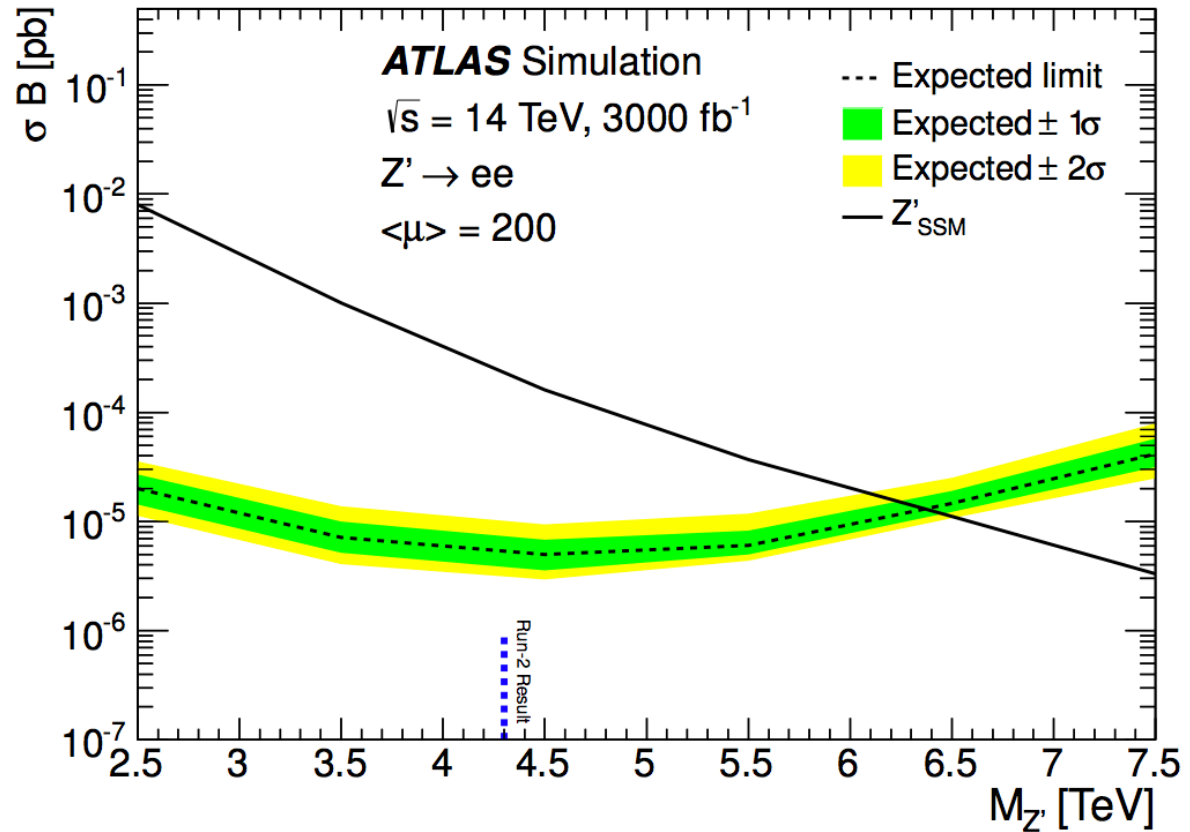
# Projecting Future Physics Reach

- ◆ Results shown here from a series of “Workshops on the Physics of HL-LHC, and perspectives on HE-LHE”
  - ◆ <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop>
  - ◆ Large effort across HEP to document projected performance at HL-LHE and HE-LHC
  - ◆ Working toward submission of a CERN Yellow Report to the “European Strategy on Particle Physics” update in 2019
- ◆ This talk gives a sampling of projections from ATLAS, CMS, and LHCb
  - ◆ Many more results available in recent workshops, including many nice studies from the theory community
    - ◆ <https://indico.cern.ch/event/686494/>
    - ◆ <https://indico.cern.ch/event/727604/>
    - ◆ <https://indico.cern.ch/event/760365/>

# High Mass Resonances

$$Z' \rightarrow e^+e^-$$

- ◆ High mass di-electron resonance search
- ◆ Interpretation in sequential SM  $Z'$  model
- ◆ Statistics limited
- ◆ Main experimental concern is electron momentum resolution

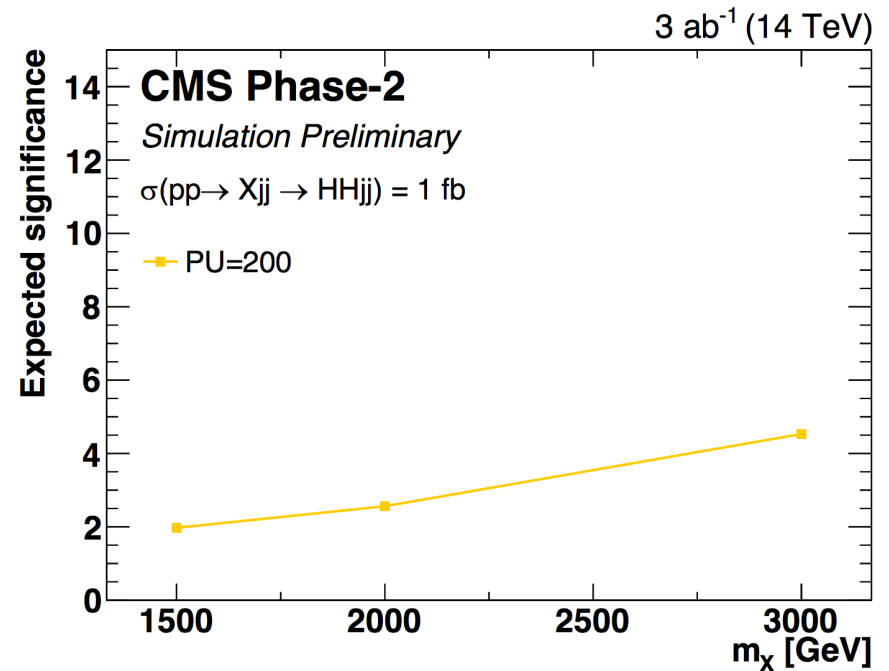
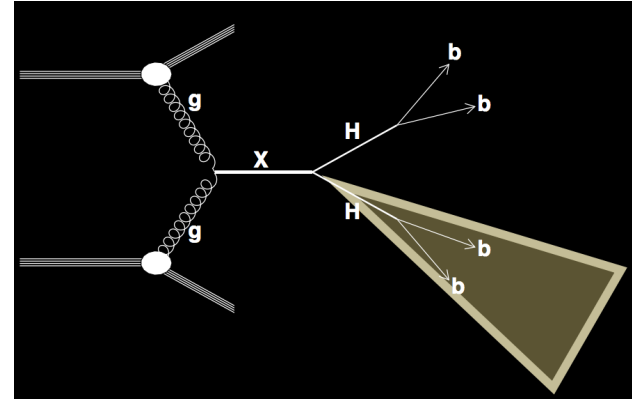


ATLAS-TDR-027

<http://cdsweb.cern.ch/record/2285582/files/ATLAS-TDR-027.pdf>

# $X \rightarrow HH \rightarrow 4b$

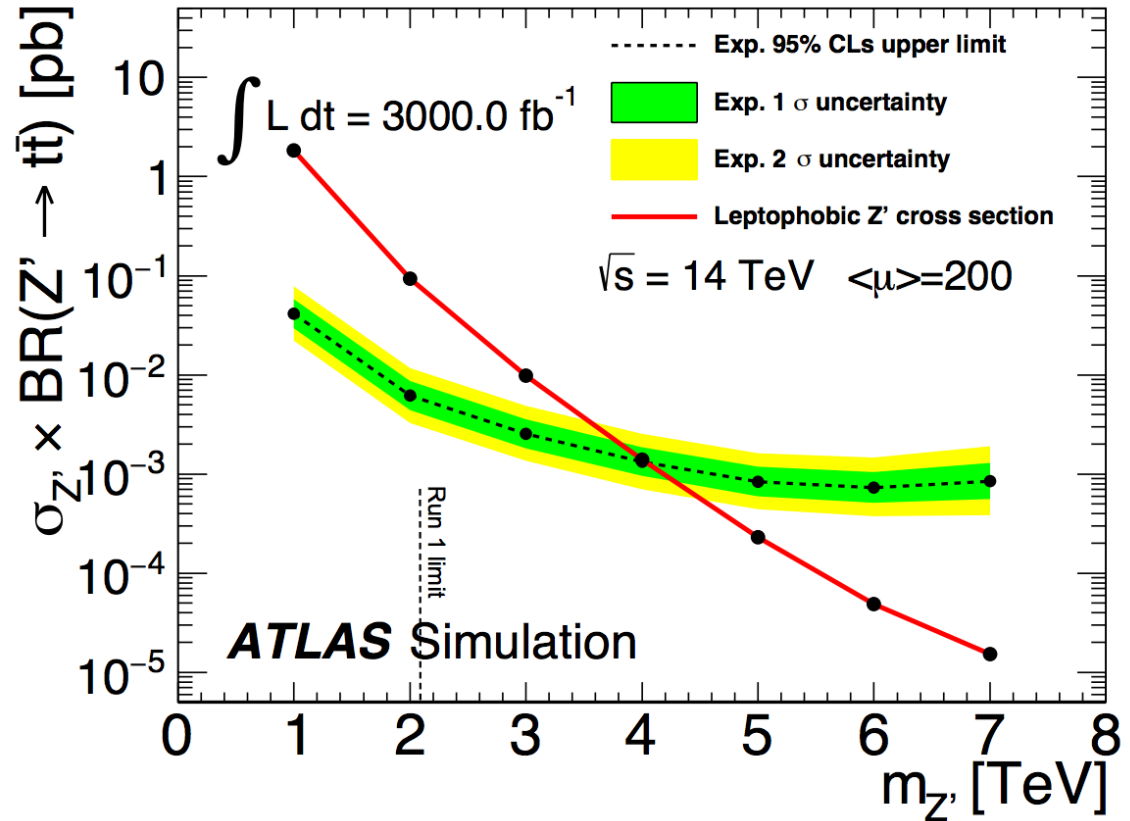
- ◆ Search for new particle decaying to HH
- ◆ New search in VBF channel
  - ◆ May be enhanced with new EW contributions
  - ◆ Accessible only at HL-LHC
- ◆ High mass  $X$  results in boosted  $H \rightarrow bb$  candidates
- ◆ Combine merged and resolved  $H \rightarrow bb$  reconstruction



CMS-FTR-18-003

# $t\bar{t}$ resonance

- ◆ Search for top/anti-top resonance at high mass
- ◆ Semi-leptonic channel:  $2b+l^-+2j$
- ◆  $Z'$  model interpretation
- ◆ Main background from SM  $t\bar{t}$
- ◆ Main sensitivity from boosted channel with hadronic top fully contained within one jet



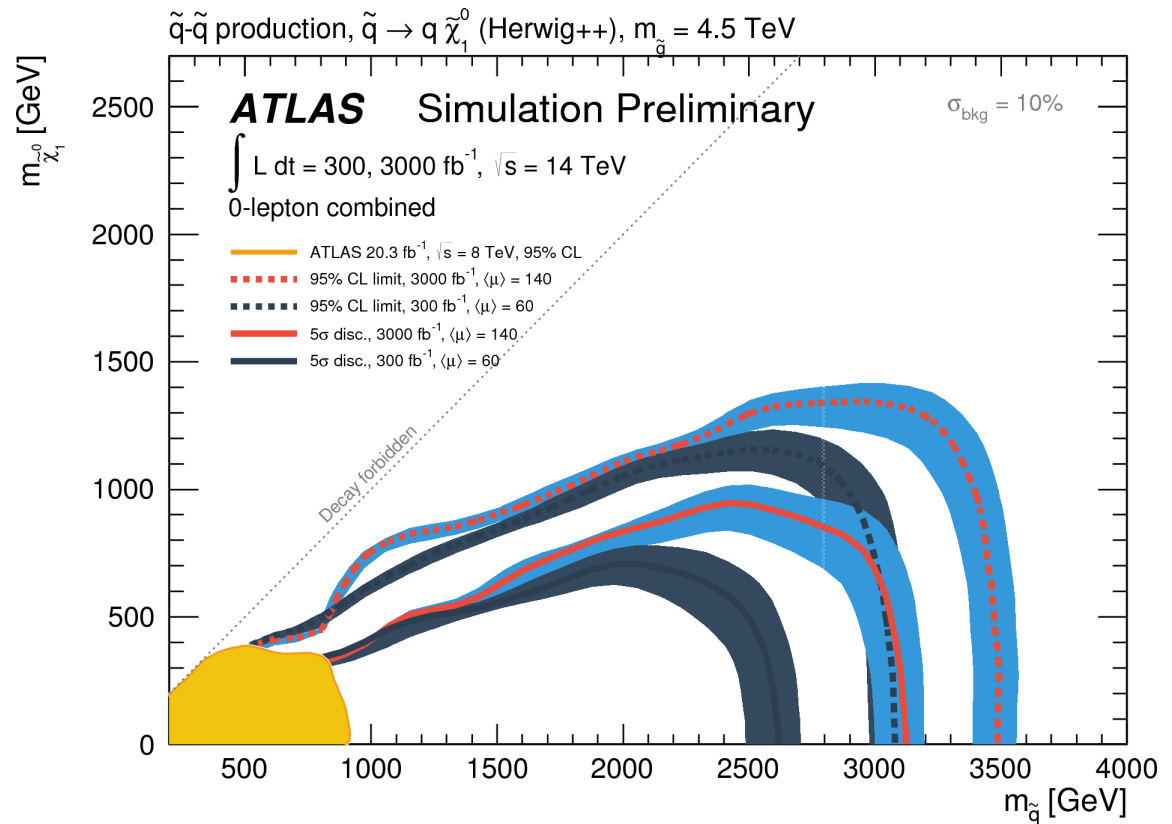
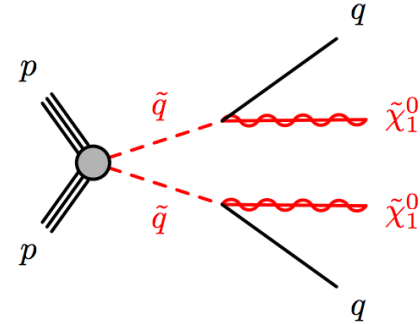
<http://cdsweb.cern.ch/record/2285582/files/ATLAS-TDR-027.pdf>

# Supersymmetry



# Strong SUSY production - squarks

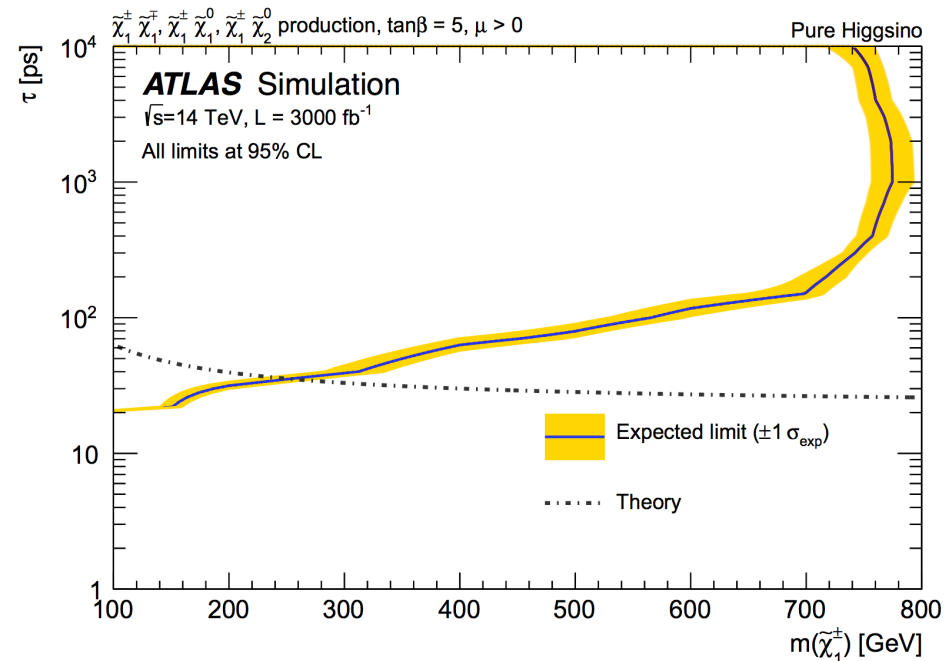
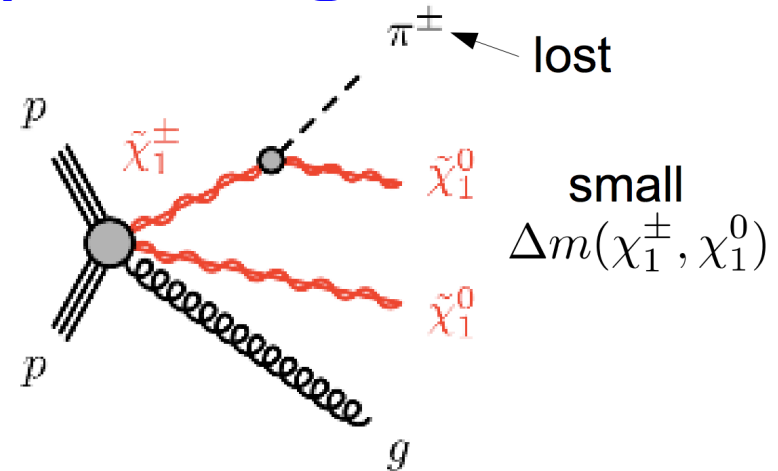
- ◆ Highest mass reach in strong SUSY production at pp machine
- ◆ Project sensitivity from 8 TeV hadronic search results
- ◆ Discovery reach out to 3 TeV



ATL-PHYS-PUB-2014-010

# Higgsinos with disappearing tracks

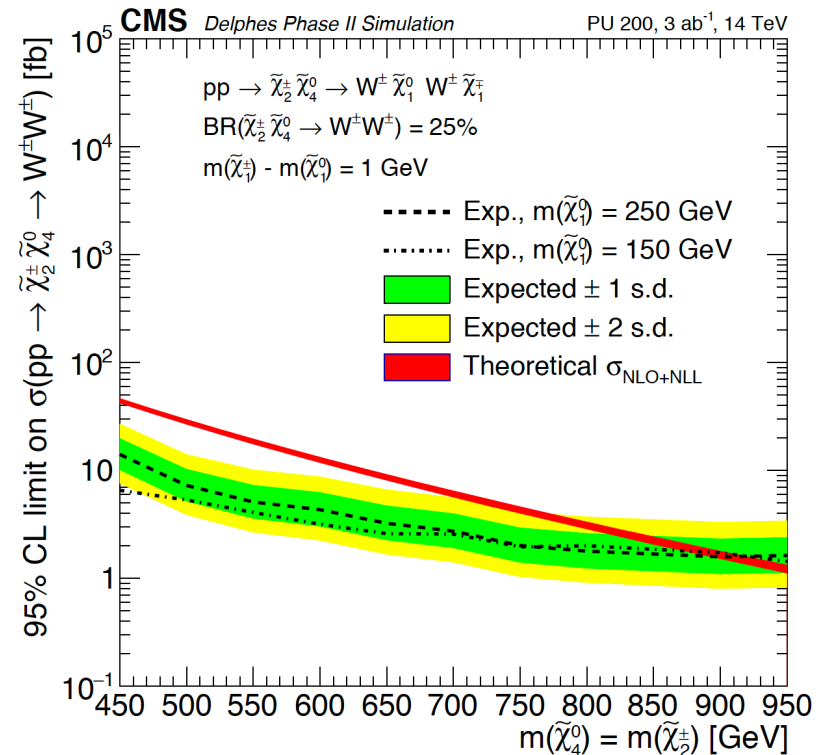
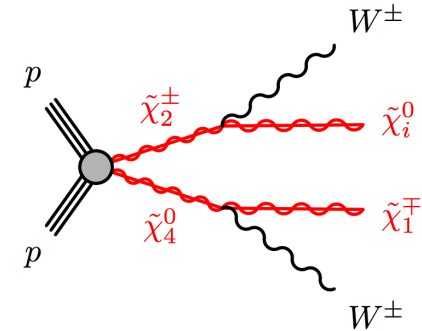
- ◆ Higgsino LSP  $\rightarrow$  nearly degenerate  $\chi^0$  and  $\chi^\pm$
- ◆ Results in track stub in detector
- ◆ Relies on accurate, multi-layer tracking to identify tracks that “disappear”
- ◆ Good reconstruction efficiency down to  $\sim 20$  cm
- ◆ Main challenge measuring detector-induced fake track stubs
  - ◆ Further study will improve limits



<https://cds.cern.ch/record/2285585/files/ATLAS-TDR-030.pdf>

# EW SUSY production

- ◆ Di-lepton events with the same charge sensitive to low mass EW SUSY states
- ◆ Reasonably high  $p_T$  leptons from larger  $\chi$  mass splittings
  - ◆ Alternative to direct Higgsino search, made possible by increased luminosity
- ◆ Reach to  $\sim 900$  GeV in  $\chi^0_4$  and  $\chi^{\pm}_2$  mass
  - ◆ Nearly independent of Higgsino ( $\chi^0_1$ ) mass



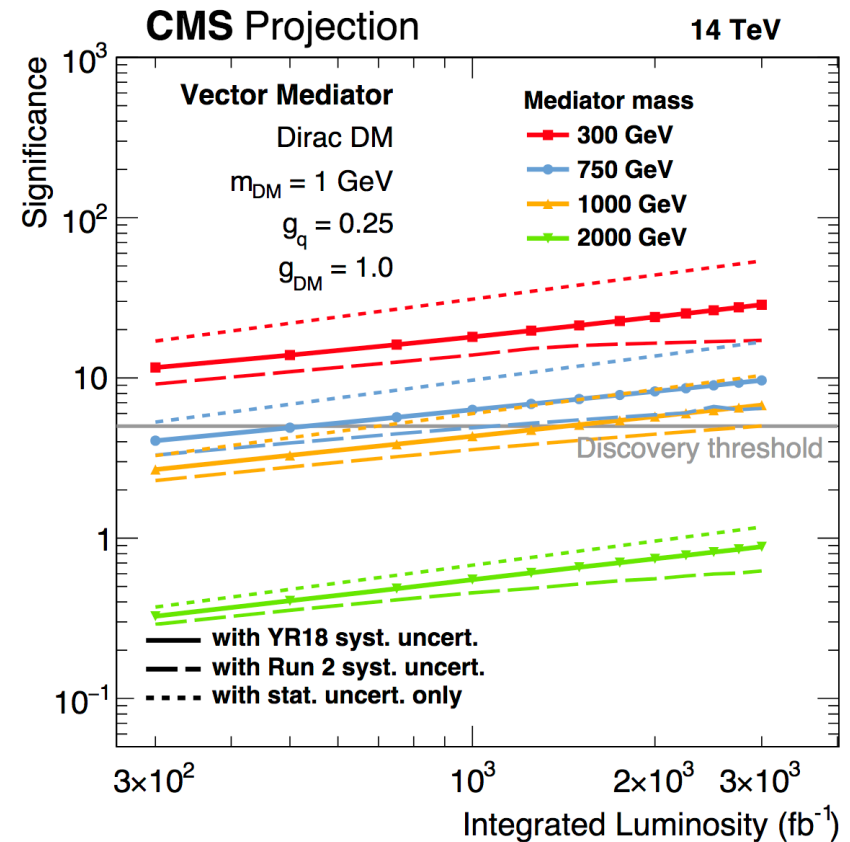
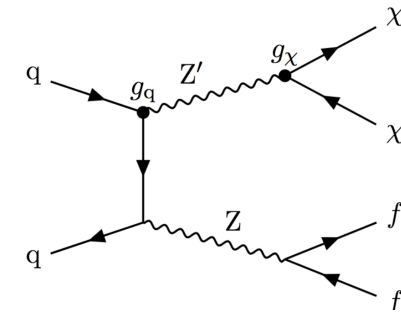
CMS-TDR-17-007

<https://cds.cern.ch/record/2293646>

# Direct Dark Matter

# dark matter + Z

- ◆ Search for Z plus missing energy as signature of DM produced in association with a Z (“mono-Z”)
- ◆ Reconstructed with  $Z \rightarrow$  dilepton events
- ◆ Interpretation in a simplified model framework with a  $Z'$  (vector) mediator
- ◆ Discovery reach for mediator masses up to 1 TeV

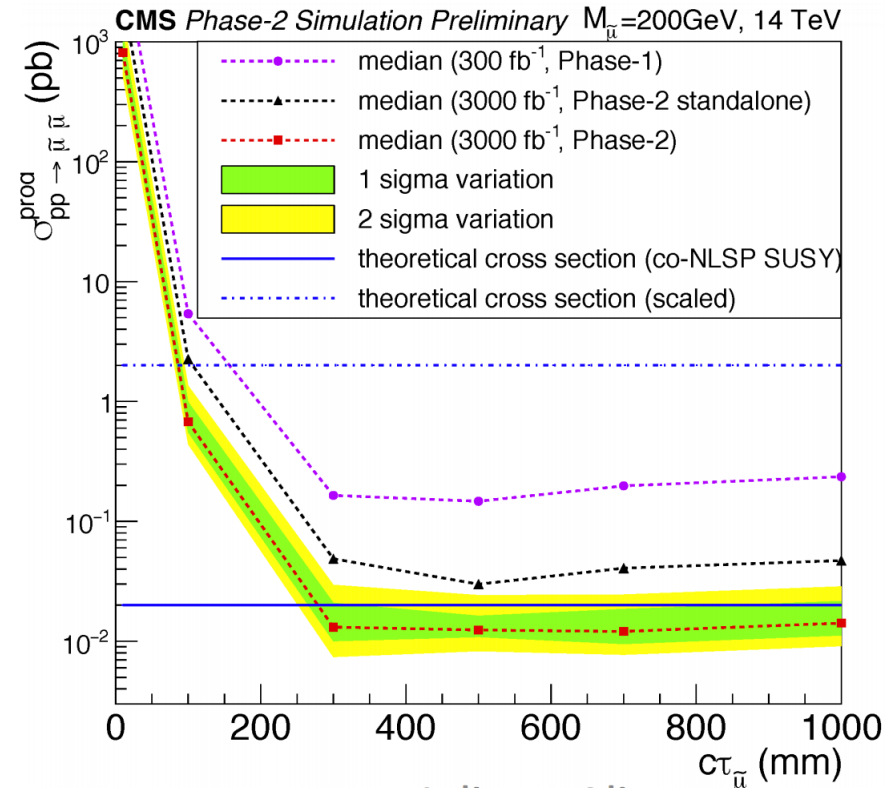
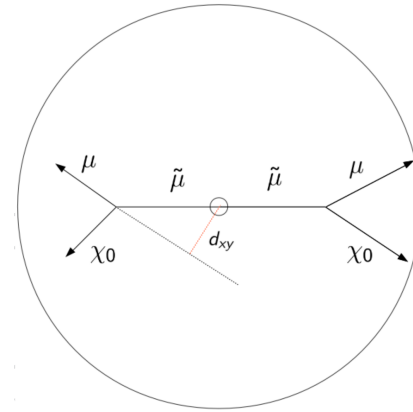


<https://cds.cern.ch/record/2644529>

# Long-lived Signatures

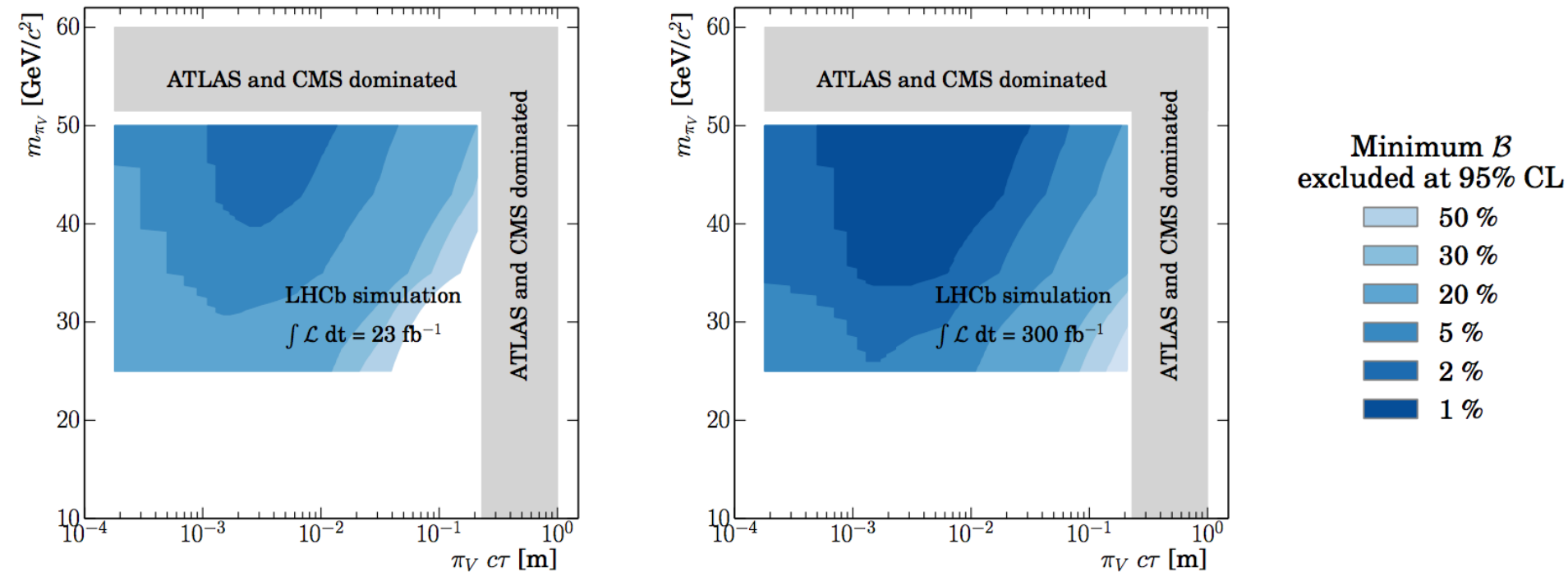
# Displaced muons

- ◆ Long-lived SUSY smuon pair search
- ◆ Results in 2 muons displaced from beamspot
- ◆ Upgraded muon system with additional hits allows track reconstruction without beamspot constraint
- ◆ Tracking sensitive to muons displaced by 0.01 – 1.0 meters
- ◆ Full HL-LHC luminosity needed to reach sensitivity



# Dark Photons

<https://arxiv.org/pdf/1808.08865.pdf>

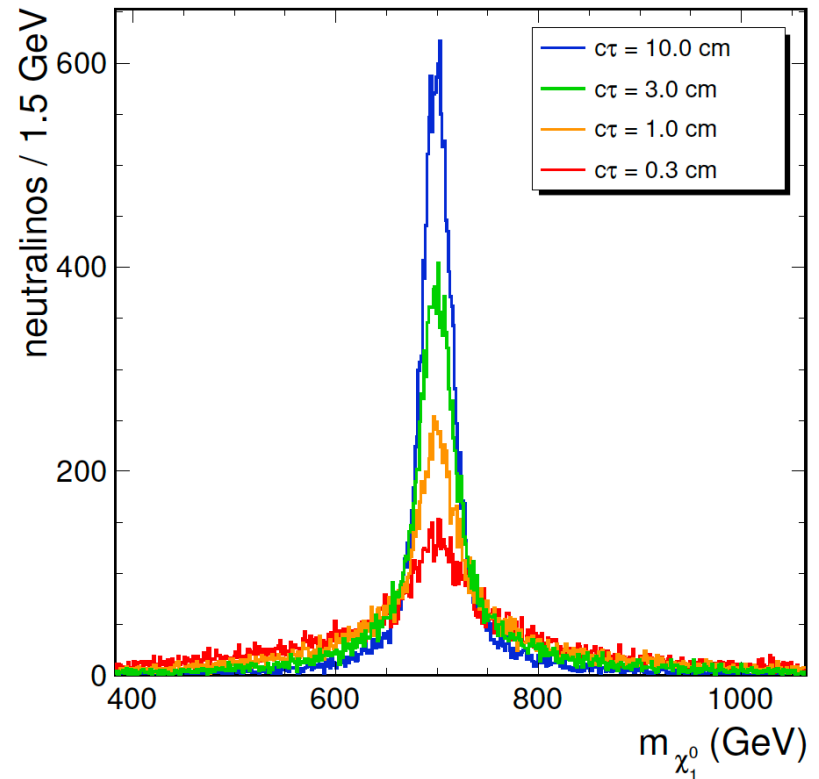
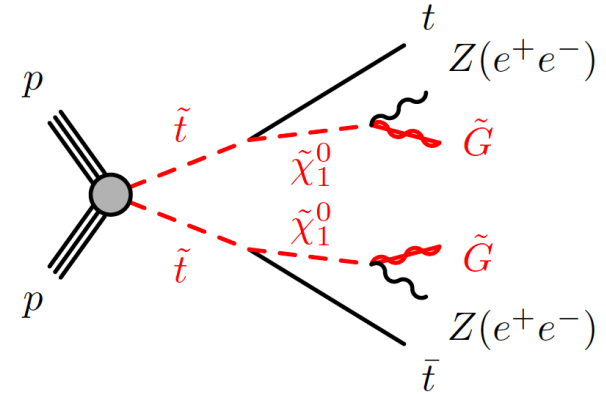


- ◆ Search for long-lived particle decaying to displaced dijet final state
  - ◆ Ex. Hidden valley pion in limit plots above
- ◆ Unique sensitivity from LHCb with forward detector and very precise track-based vertexing
- ◆ Results in unique sensitivity at low masses (25 - 50 GeV) and low lifetimes ( $< 20$  cm)



# Searching with fast timing

- ◆ Stop pair scenario with a long-lived  $\chi^0$  gives rise to a displaced  $Z \rightarrow e^+e^-$  vertex
- ◆ Can use 30 ps timing resolution to distinguish displaced vertex from primary vertex
- ◆ Together with track reconstruction allows for good  $\chi^0$  mass resolution, even with missing energy
- ◆ Full study of discovery reach under consideration



CMS-TDR-17-006

<https://cds.cern.ch/record/2296612>

# Conclusions

- ◆ Broad physics plan for HL-LHC
  - ◆ CERN Yellow Report aims to document reach across all areas
- ◆ High mass reach up to  $\sim 6$  TeV in most favorable channels
- ◆ Many detector upgrades planned to maintain and extend the physics reach in the HL-LHC era
- ◆ Some select HE-LHC results expected for CERN Yellow Report



# hadron collider parameters (pp)

parameter	FCC-hh		HE-LHC	(HL) LHC
collision energy cms [TeV]	100		<b>27</b>	14
dipole field [T]	16		<b>16</b>	8.3
circumference [km]	100		<b>27</b>	27
beam current [A]	0.5		<b>1.12</b>	(1.12) 0.58
bunch intensity [ $10^{11}$ ]	1 (0.5)		<b>2.2</b>	(2.2) 1.15
bunch spacing [ns]	25 (12.5)		<b>25 (12.5)</b>	25
norm. emittance $\gamma\epsilon_{x,y}$ [ $\mu\text{m}$ ]	2.2 (2.2)		<b>2.5 (1.25)</b>	(2.5) 3.75
IP $\beta^*_{x,y}$ [m]	1.1	0.3	<b>0.25</b>	(0.15) 0.55
luminosity/IP [ $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ]	5	30	<b>25</b>	(5) 1
peak #events / bunch Xing	170	1000 (500)	<b>800</b> (400)	(135) 27
stored energy / beam [GJ]	8.4		<b>1.4</b>	(0.7) 0.36
SR power / beam [kW]	2400		<b>100</b>	(7.3) 3.6
transv. emit. damping time [h]	1.1		<b>3.6</b>	25.8
initial proton burn off time [h]	17.0	3.4	<b>3.0</b>	(15) 40

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<https://indico.cern.ch/event/647676/contributions/2721141/attachments/1548876/2433767/HE-LHC-Machine-2017.pdf>