Future directions of LHC analyses

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on behalf of the ATLAS and CMS collaborations

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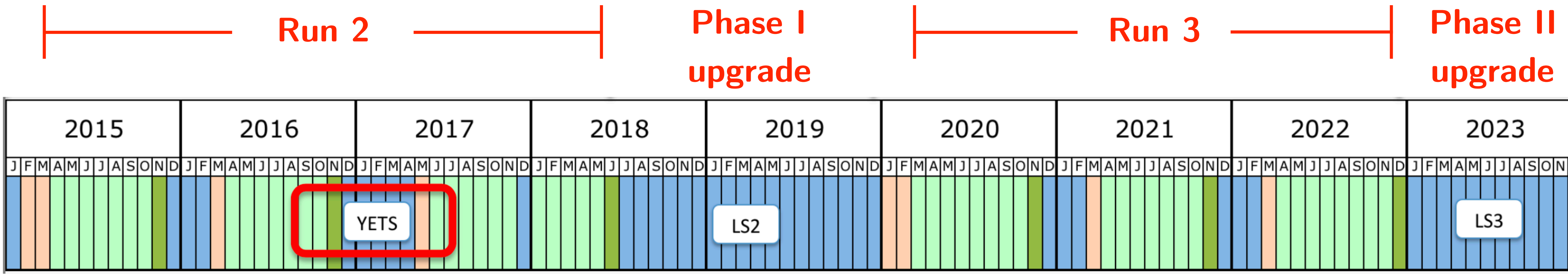
Overview

- **LHC schedule up to 2035** (Run 3 and High Luminosity LHC)

- Planned **upgrades**

- **Projections for Run 3 and HL-LHC**
  - Higgs
  - SUSY
  - Exotic final states

LHC schedule



Run 2

- $\sqrt{s} = 13$ TeV
- L=$1.7\cdot10^{34}$ cm^{-2}s^{-1}
- 25-50 interactions per crossing
- goal: $>$ 120 fb^{-1} till end of 2018

Run 3

- $\sqrt{s} = 13/14$ TeV
- L=$2\cdot10^{34}$ cm^{-2}s^{-1}
- 60 interactions per crossing
- goal: **300 fb^{-1}** till end of 2022

HL-LHC

- $\sqrt{s} = 14$ TeV
- L= $5\cdot10^{34}$ cm^{-2}s^{-1} ($7.5\cdot10^{34}$cm^{-2}s^{-1} ultimate achievable luminosity)
- 140 (200) interactions per crossing
- goal: **3000 fb^{-1}** till end of 2035

YETS: Year End Technical Stop
LS: Long Shutdown
- Proton Physics
- Heavy Ions
- Shutdown/Technical stop
- Commissioning

Detector upgrades

- **Phase I Upgrade**
  - ATLAS: track trigger (FTK), partial replacement of muon spectrometer, finer LAr trigger segmentation
  - CMS: changes in trigger hardware

- **Phase II Upgrade**
  - ATLAS: new inner tracker with extended η coverage, trigger and calorimeter upgrades, potentially new calorimeter/timing detector in forward region
  - CMS: new tracker with extended coverage, new end-cap calorimeters and extension of η coverage of muon spectrometer, replacement of ECal and Muon spectrometer electronics

Note:

✳ Studies here consider scenario with $<\mu>=60/140$ for Run-3/HL-LHC

✳ **projections** err on the **conservative** side - **better results to be expected with a more aggressive analysis strategy**

Higgs

Goals

- have enough statistics to **establish all production and decay modes**
  - 4% uncertainty on ggH attainable ⇒ stringent constraint on BSM processes
  - ttH measurable with 10% uncertainty ⇒ precise determination of top Yukawa coupling

- move from signal strength like measurements to more **model-independent cross-section measurements**: (i) fiducial, (ii) simplified template

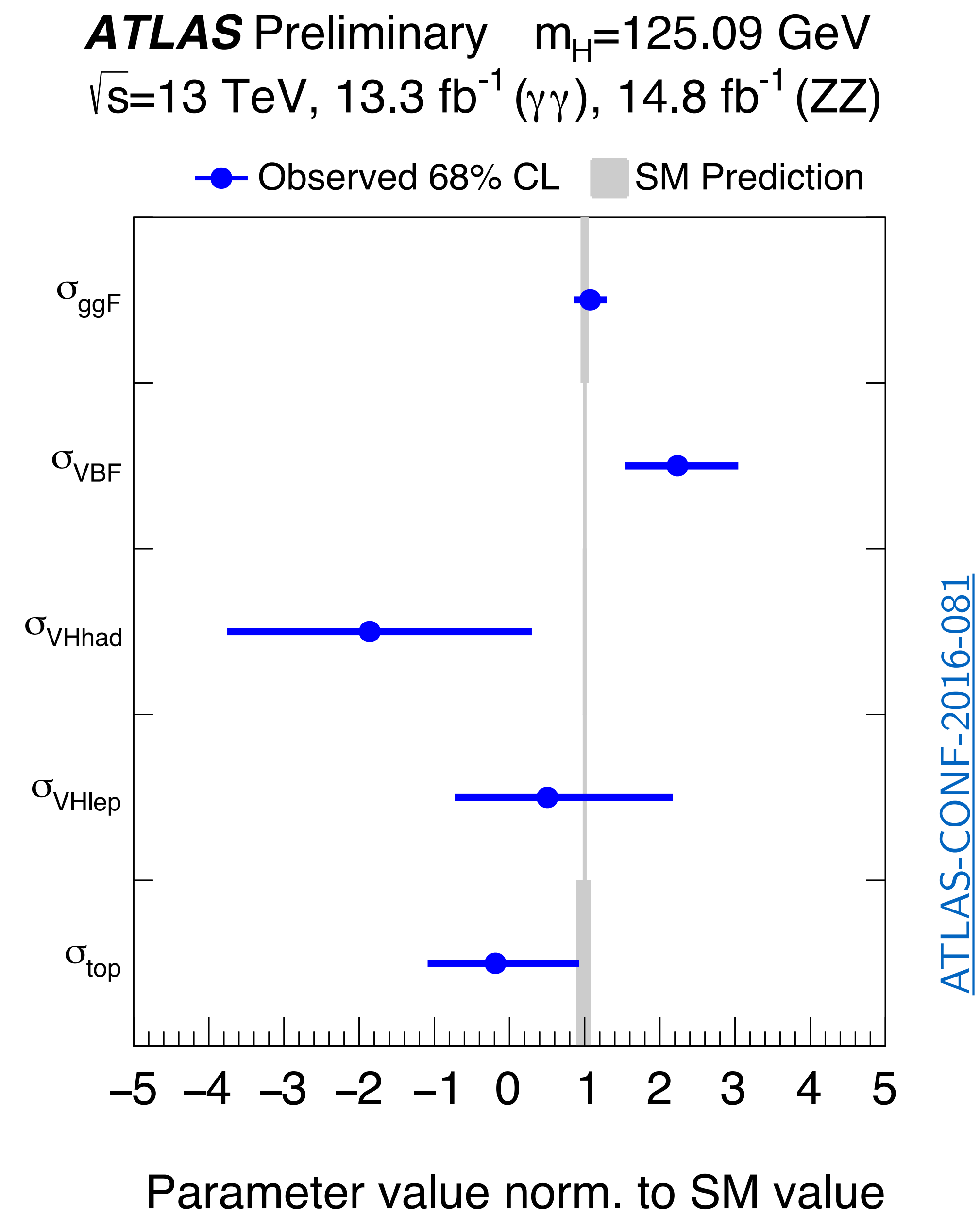
$\Delta\mu/\mu$	300 fb^{-1}	3000 fb^{-1}
$gg\rightarrow H$	6 - 12 %	4 - 11 %
VBF	15 - 18 %	9 - 15 %
WH	41%	18%
qqZH	80%	27 - 28 %
ggZH	4%	1.4 - 1.5 %
ttH	30%	10 - 16 %

ATL-PHYS-PUB-2014-016

- **midpoint between Run-1 style coupling measurements** (powerful but model dependent) **and differential measurements**

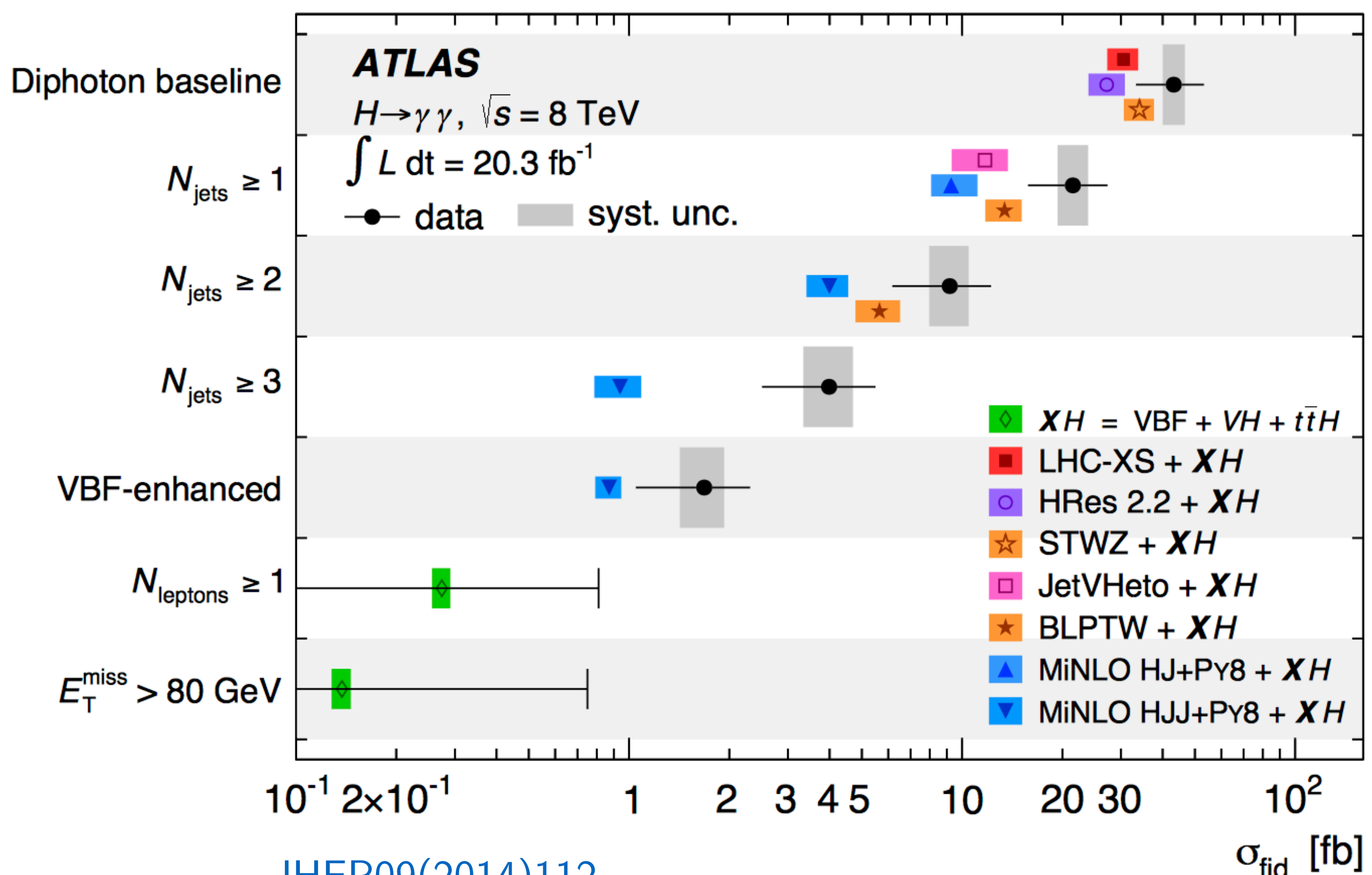
Guiding principles

- **minimize theory dependence**
  - measure σ instead of $\mu = \sigma/\sigma_{SM}$ (easier to compare with newer calculations etc)
  - do not assume SM properties for Higgs (use more general model, e.g. EFT)
  - measure in fiducial volume
  - separate bins which receive large BSM contributions
- **maximize sensitivity**
  - combine all decay channels



Differential cross-sections

- measurement in **fiducial volume** ⇒ minimize theory-dependent extrapolations
- **unfolding** of detector effects ⇒ long-term usability of results
- slicing of phase space to address different modelling issues
  - specific phase space slicing to enhance production modes and sensitivity to BSM models
  - Higgs kinematics: $p_T(h)$ ⇒ perturbative QCD, $|y(h)|$ ⇒ PDF
  - N_{jets} ⇒ sensitive to relative contributions of different production modes
  - angular variables: spin/CP properties



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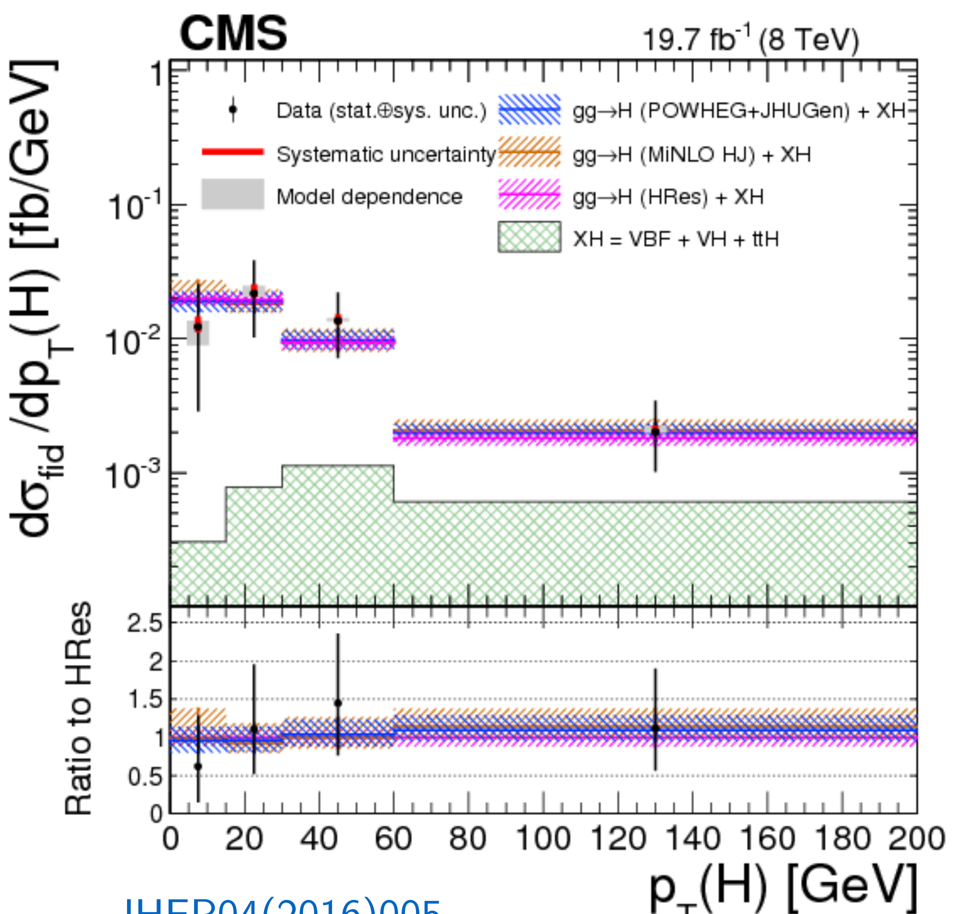

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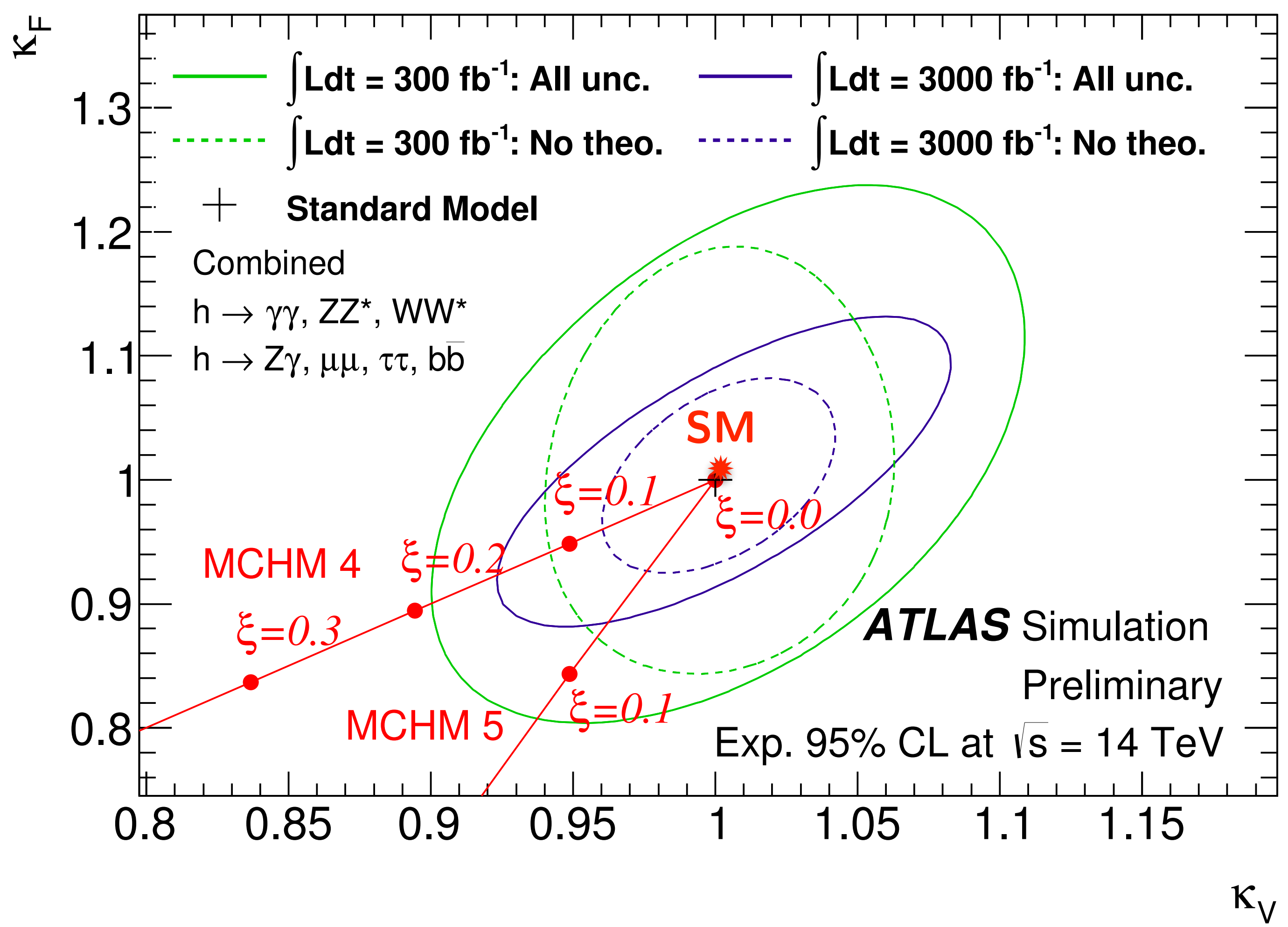
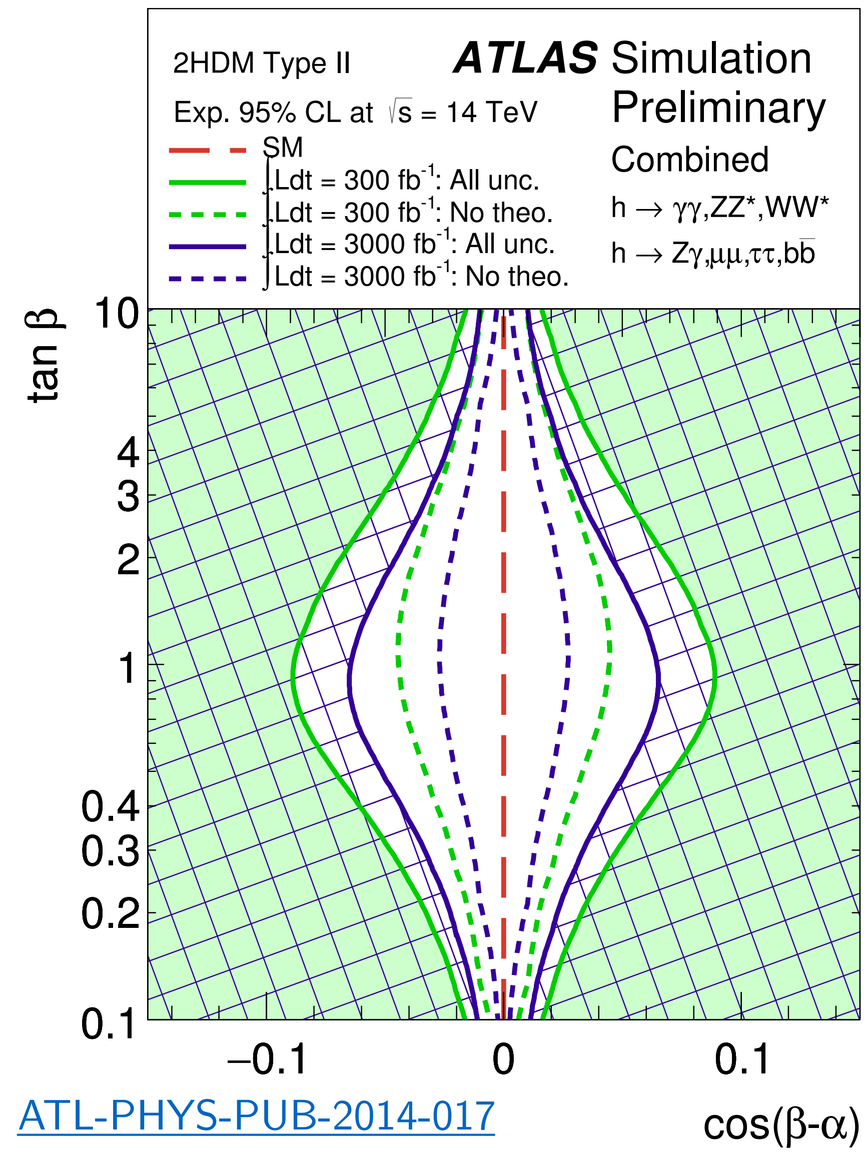
New physics through Higgs couplings

- **new physics** coupling to the Higgs sector ⇒ **modification of the Higgs couplings**
  - Higgs compositeness (e.g. $\kappa_V = (1-\xi)^{1/2}$)
  - 2 Higgs Doublet Models (e.g. $\kappa_V = \sin(\beta-\alpha)$)
  - Higgs-portal DM
- precision **coupling measurements** indirectly **probe and can constrain BSM models**

Minimal Composite Higgs Models



2 Higgs Doublet Models



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Higgs pair production

- hh production one of the main goals of HL-LHC
- gives access to **trilinear Higgs coupling λ_{hhh}** ; needed for fully reconstructing the **shape of the Higgs potential**
- Very low cross-section **only possible in HL-LHC**
- 3 channels
  - bbbb : BR = 33% (41k expected events)
  - $bb\tau\tau$: BR = 7.4% (9k expected events)
  - $bb\gamma\gamma$: BR = 0.3% (330 expected events)
- CMS expected combined significance: 1.9 σ

CMS-PAS-FTR-15-002

- ATLAS: limits on trilinear coupling with different scenarios for systematic uncertainties

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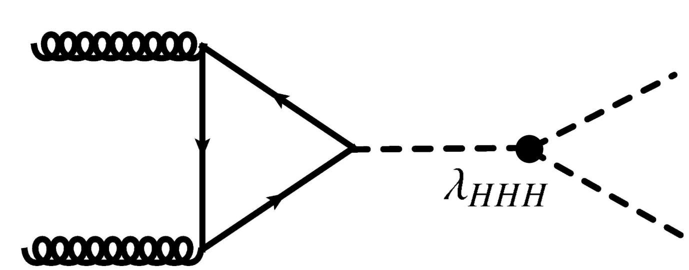
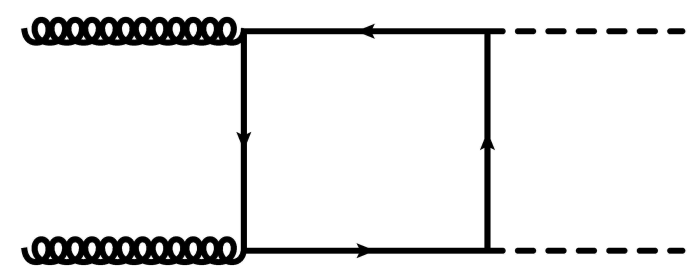
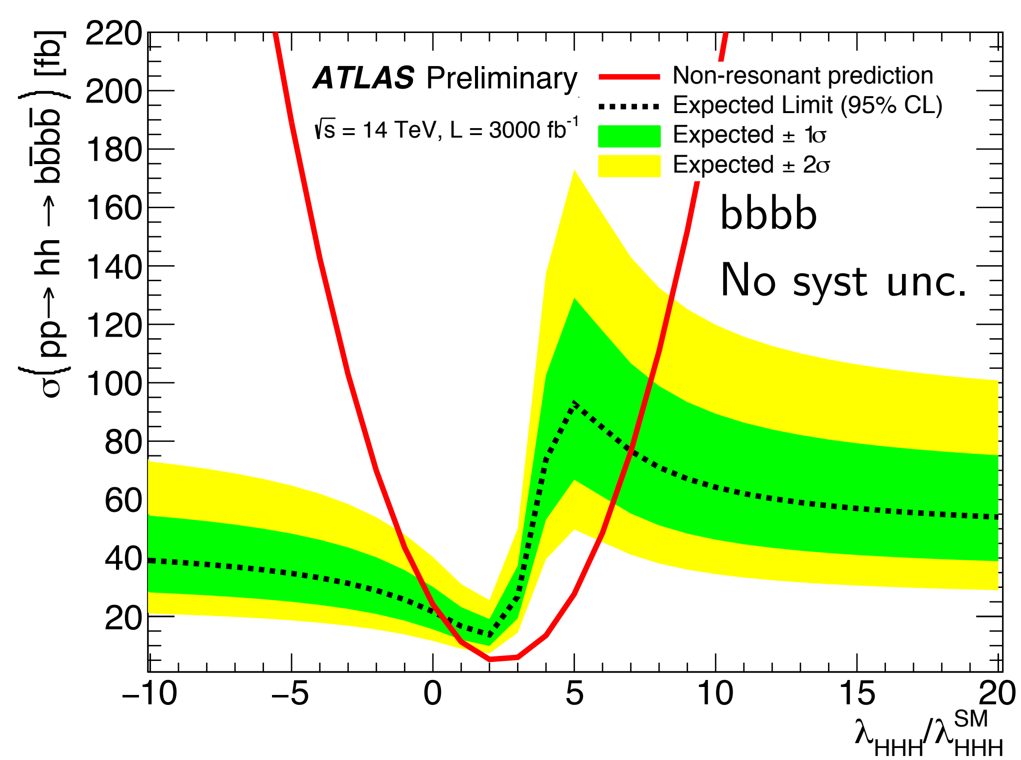






SUSY

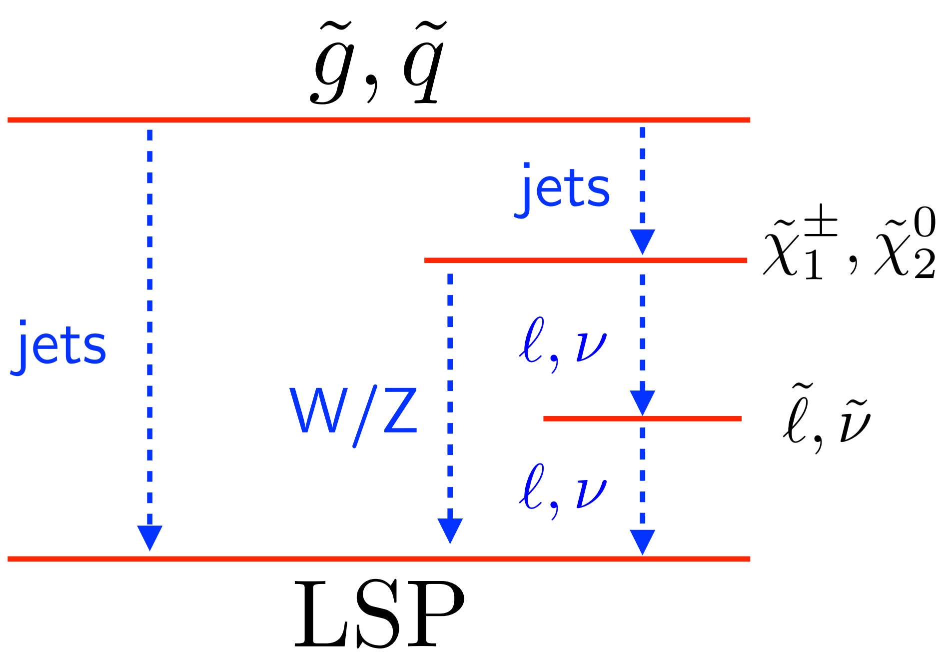
Supersymmetry

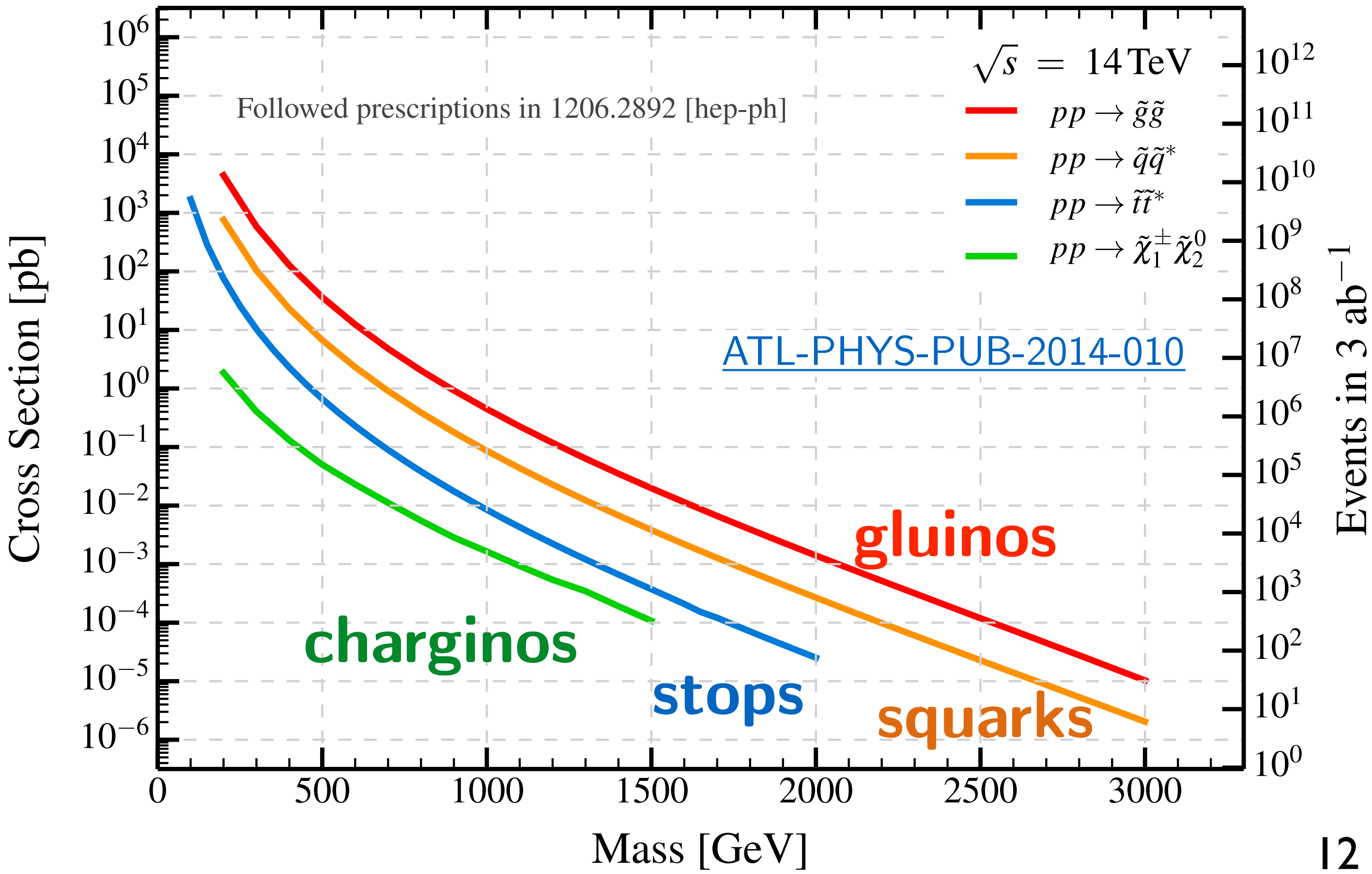
Advocated as candidate theory to resolve

- gravity/QFT unification
- gauge coupling unification
- naturalness in the scalar sector of SM ⇒ gluinos/squarks with m ≲ 1 TeV

- **Very complicated parameter space**
  - use **signature-based simplified models**

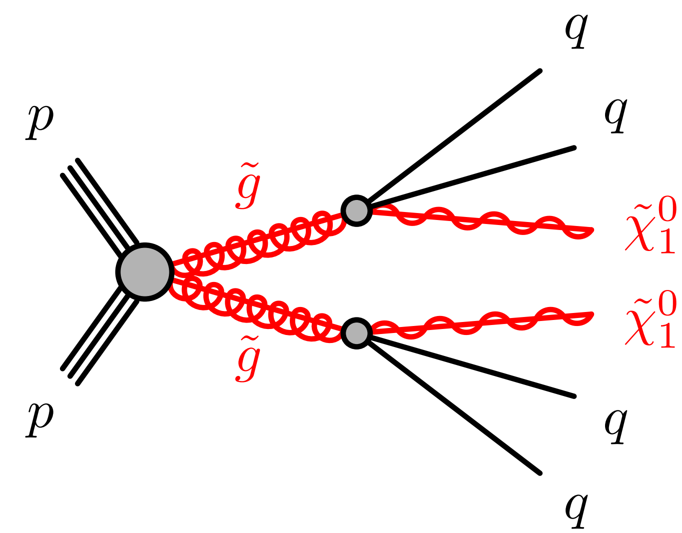
- First line of attack
  - strongly produced sparticles (large cross-section)

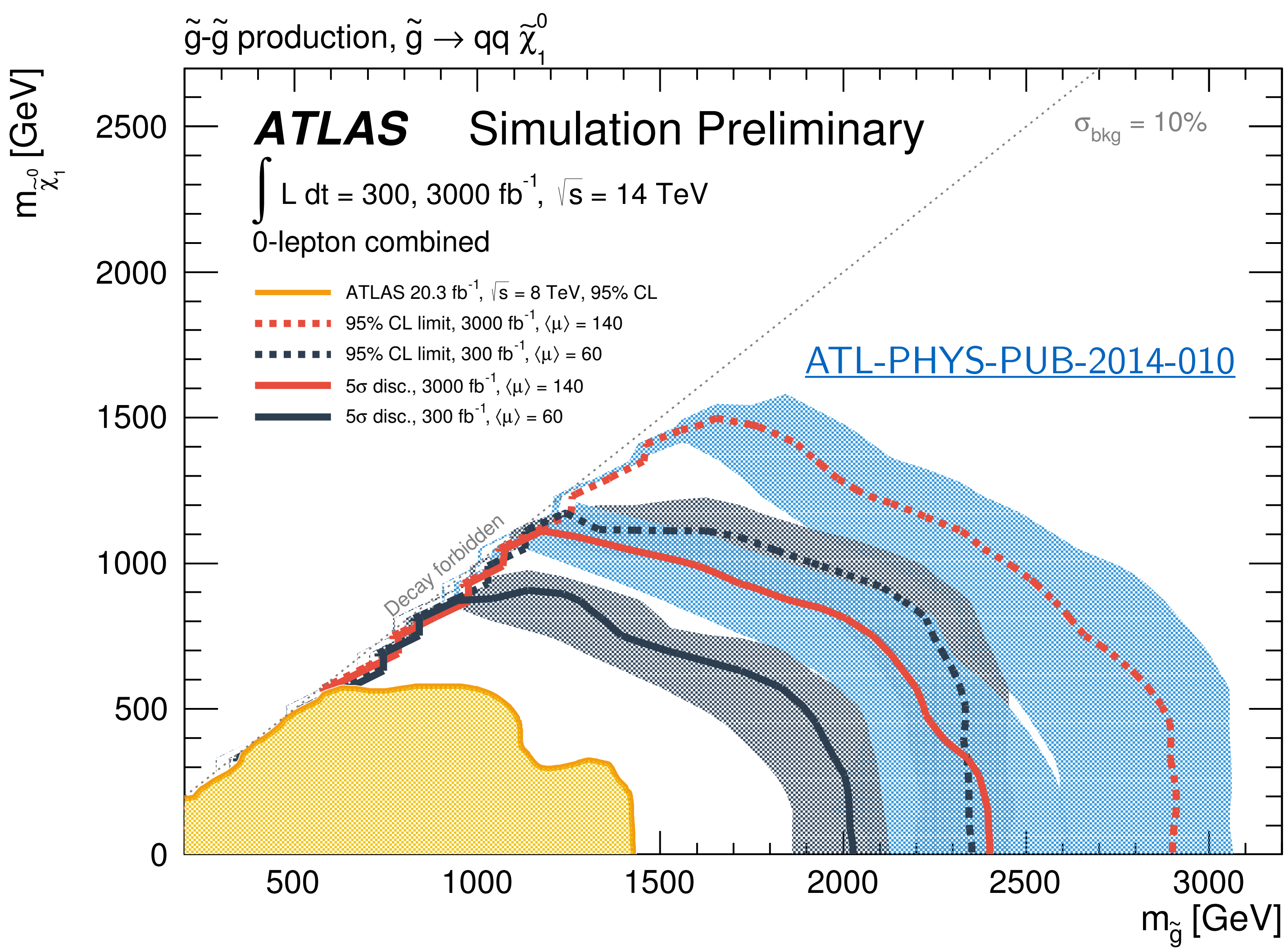


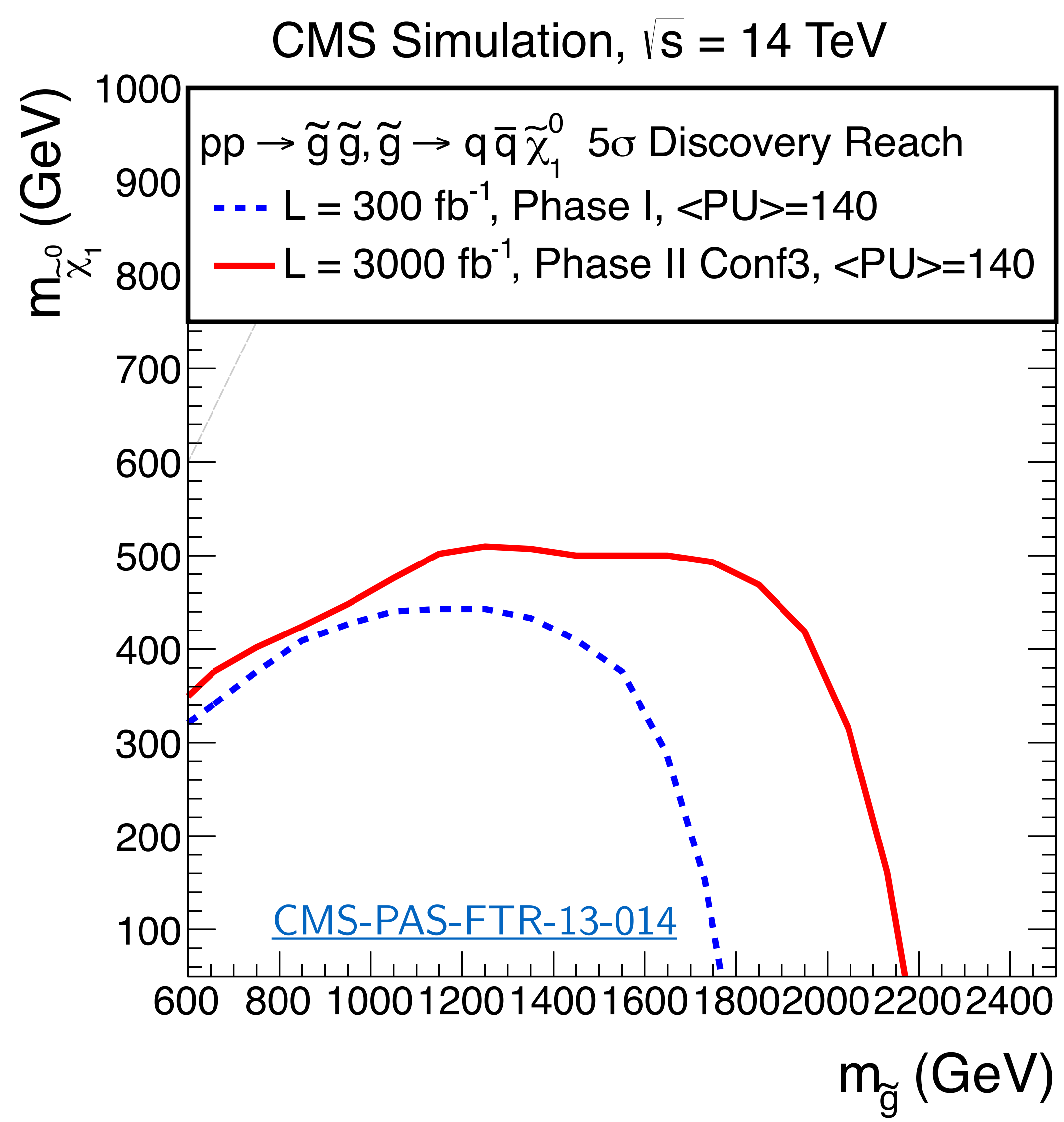


Pair-produced gluinos

- focus on R-parity conserving models
- long decay chains leading to **multiple jets**, **E_T^{miss} and no leptons**
- expected **5σ discovery** for **gluino masses up to 2 (2.35) TeV** for 300 (3000) fb^{-1}
- can exclude gluino masses up to 2.9 TeV with 3000 fb^{-1}

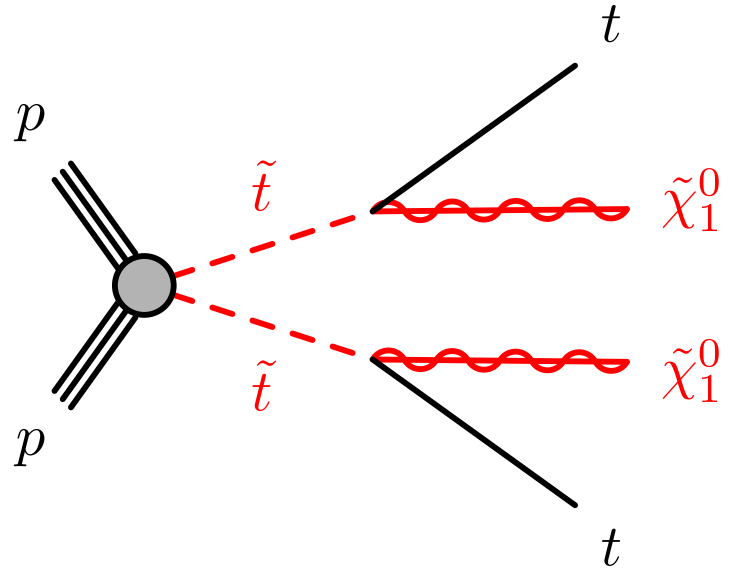






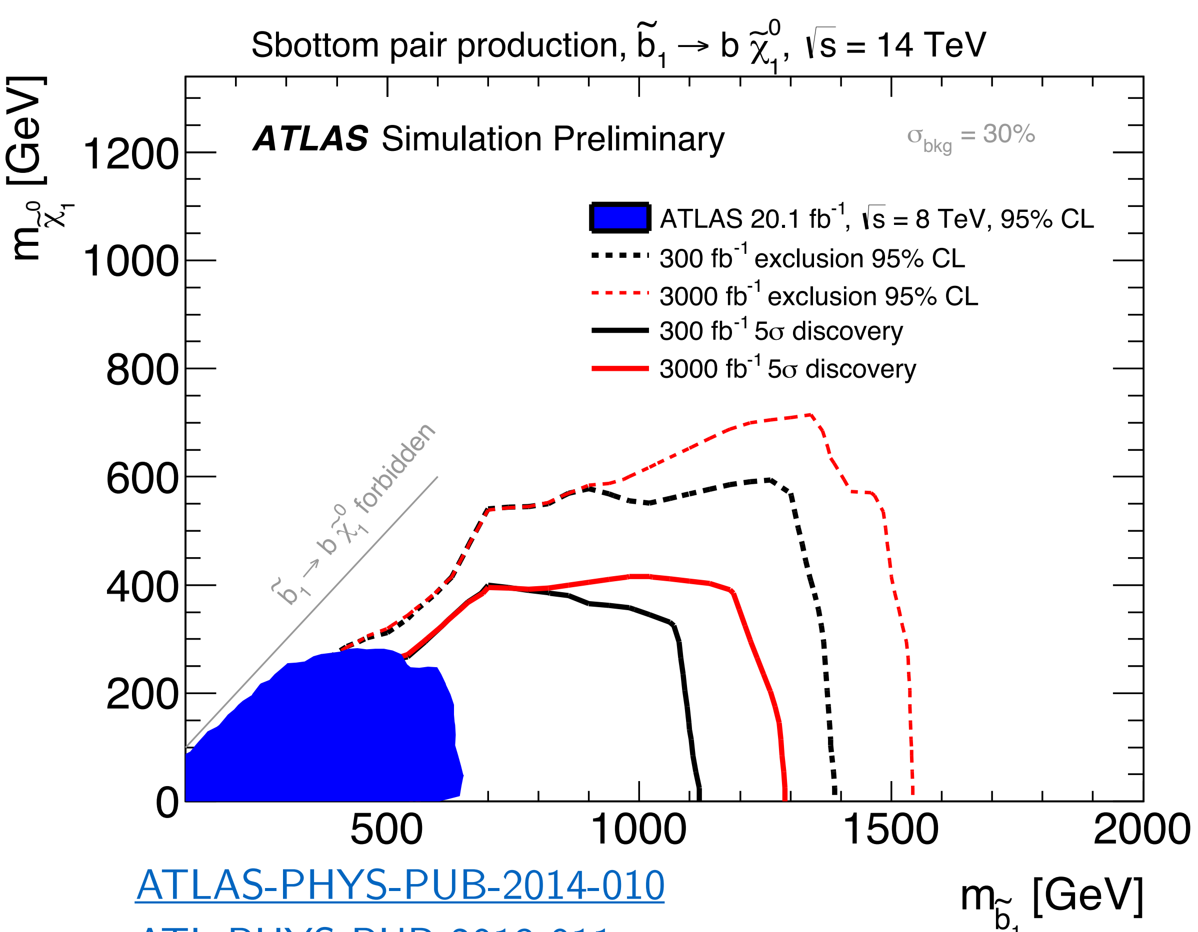
3rd generation squarks

- Need stops with m $\lesssim$ 1 TeV to cancel large radiative corrections to Higgs mass (naturalness)
- Expect **5σ discovery** up to **1.1 (1.3) TeV for sbottom** quarks and **0.9 (1.1) TeV for stops** at 300 (3000) fb^{-1}
- Also studied sensitivity to **compressed mass spectra** - exclusion limits for **stop mass up to 500 (700) GeV**



ATLAS-PHYS-PUB-2016-022

- Exclusion limits expected to surpass 1 TeV for 3000 fb^{-1}



ATLAS-PHYS-PUB-2014-010

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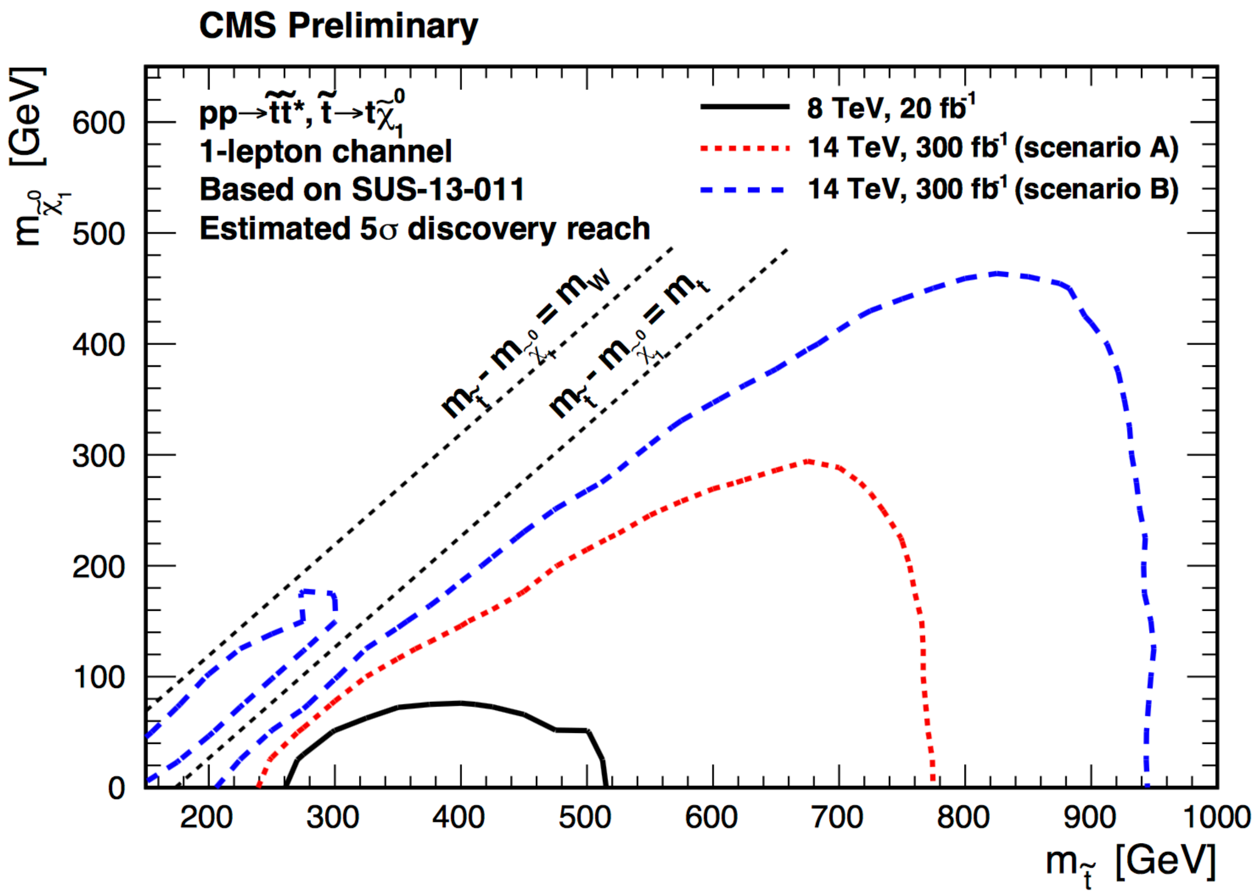
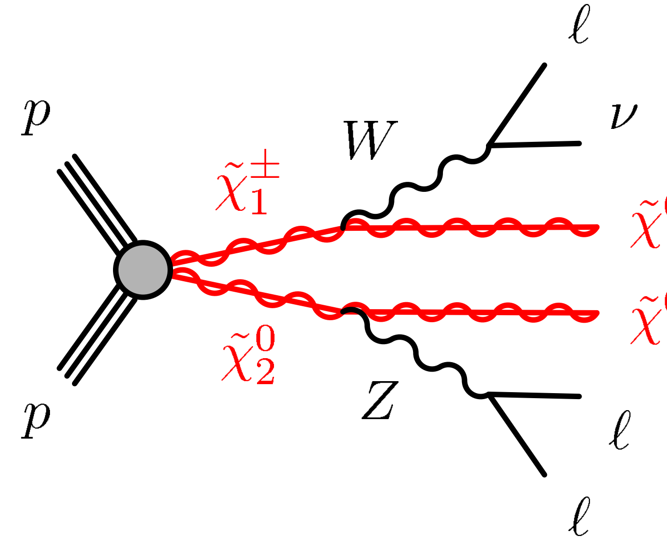
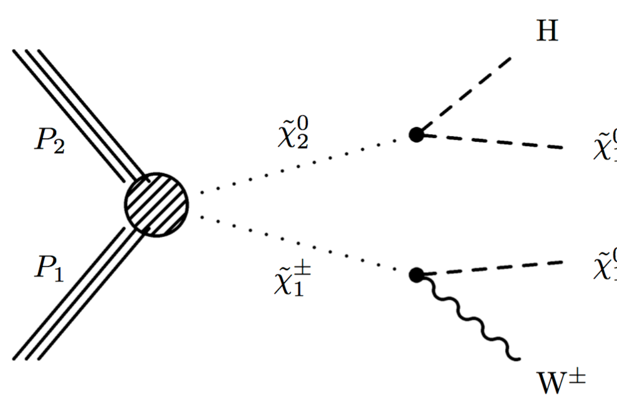


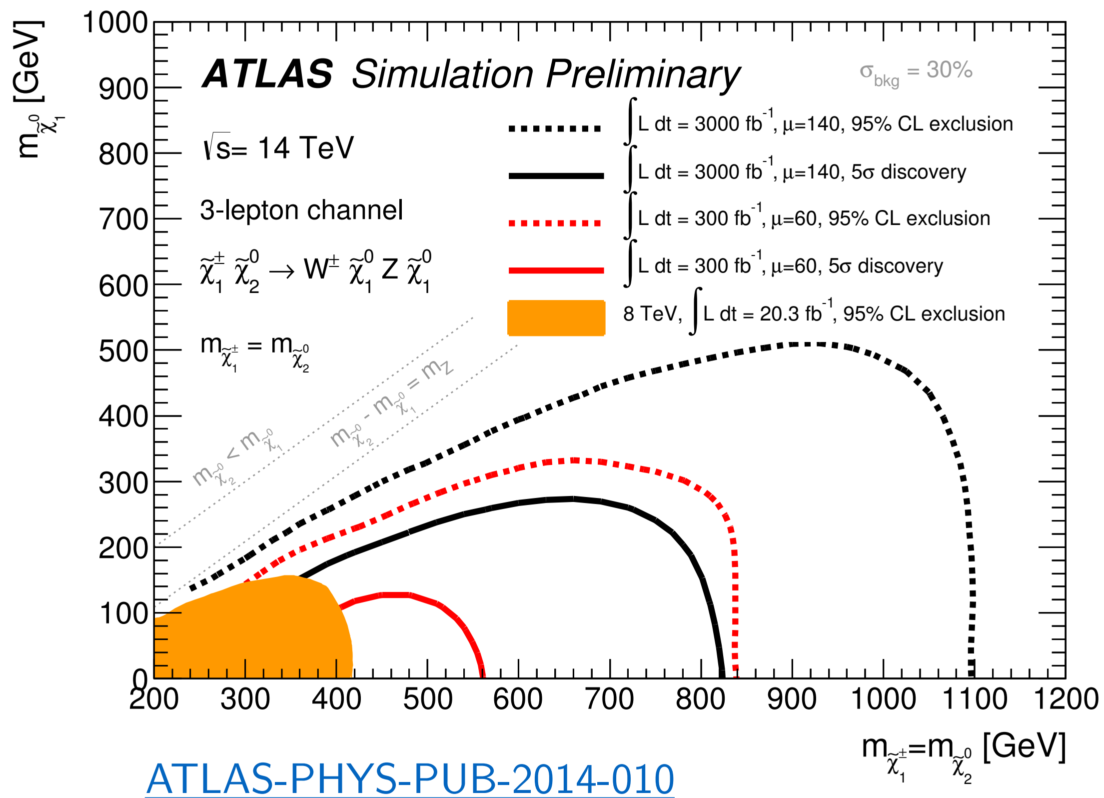
CMS-NOTE-13-002

Neutralinos/Charginos

- **EW production** of SUSY particles has low cross-section but **becomes important at high luminosities**
- Signatures:
  - WZ-mediated: **3 leptons**
  - Wh-mediated: **1 lepton + 2 taus/2 b-jets**
- **5σ discovery**: chargino masses up to **550 (800) GeV** at at 300 (3000) fb^{-1}
- Exclusion: chargino masses up to 800 (1100) GeV at 300 (3000) fb^{-1}







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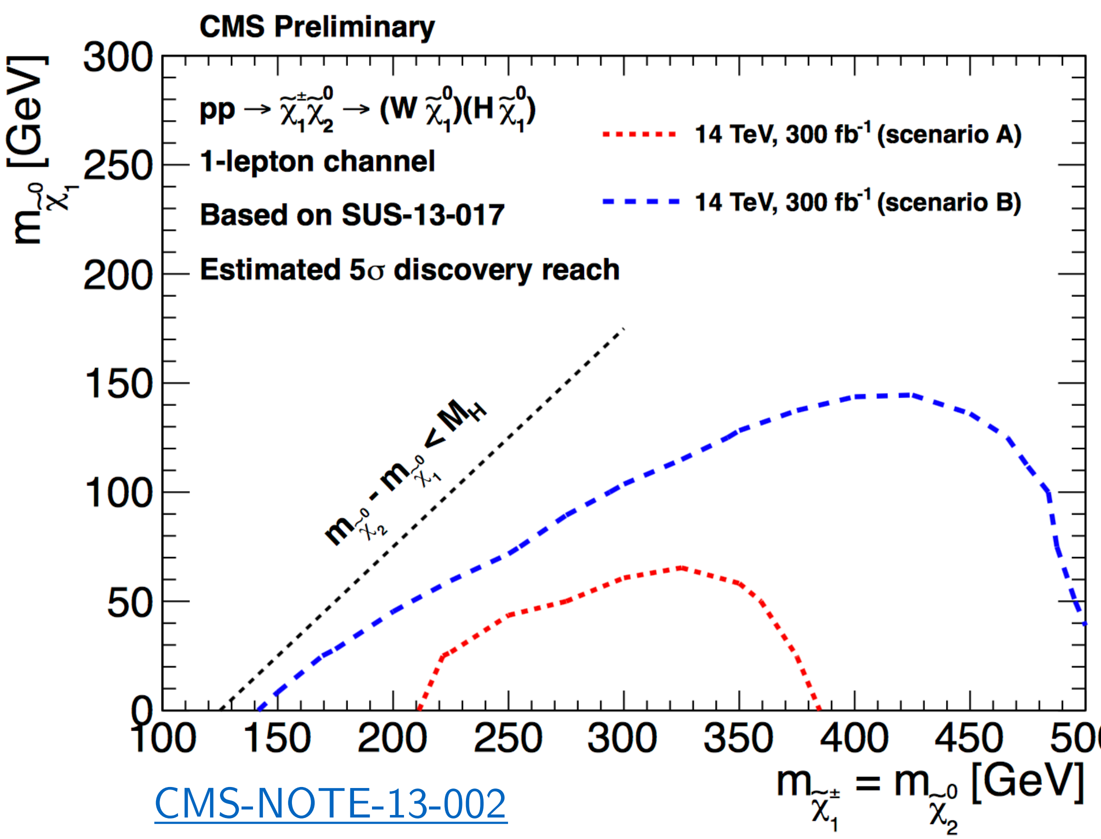


CMS-NOTE-13-002

Summary for SUSY prospects

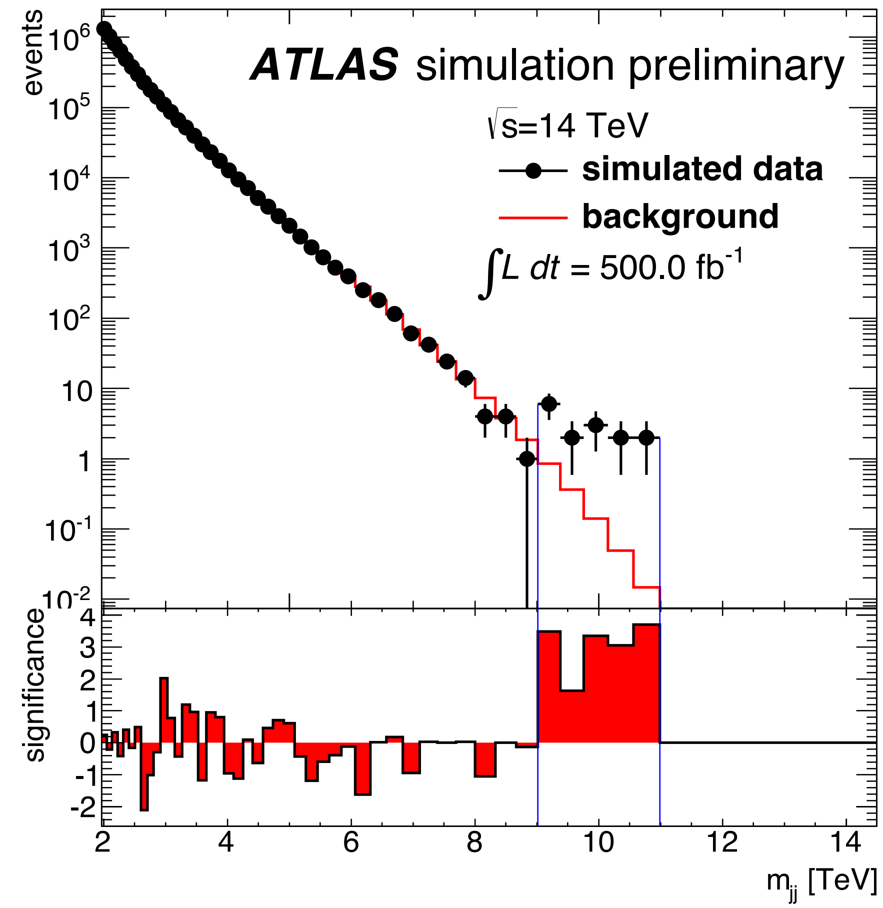
- High luminosity will allow to probe rare processes and higher masses
- EW production of SUSY particles will become important in HL-LHC
- Small gain from increase of c.o.m. energy will enhance SUSY production rates
- HL-LHC to put tight constraints on natural SUSY

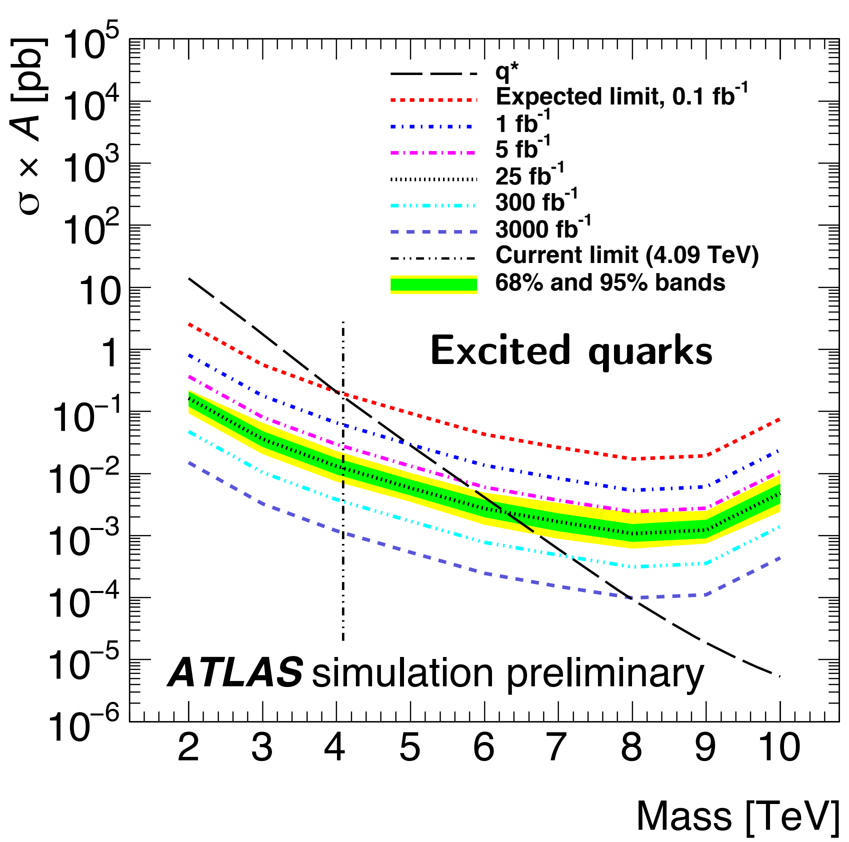
Approximate 95% CLs exclusion limits			
Luminosity	Gluino	Stop	Light squarks
Current	2 TeV	1 TeV	2 TeV
300/fb	2.4 TeV	1.4 TeV	2.4 TeV
3000/fb	2.9 TeV	1.8 TeV	2.9 TeV

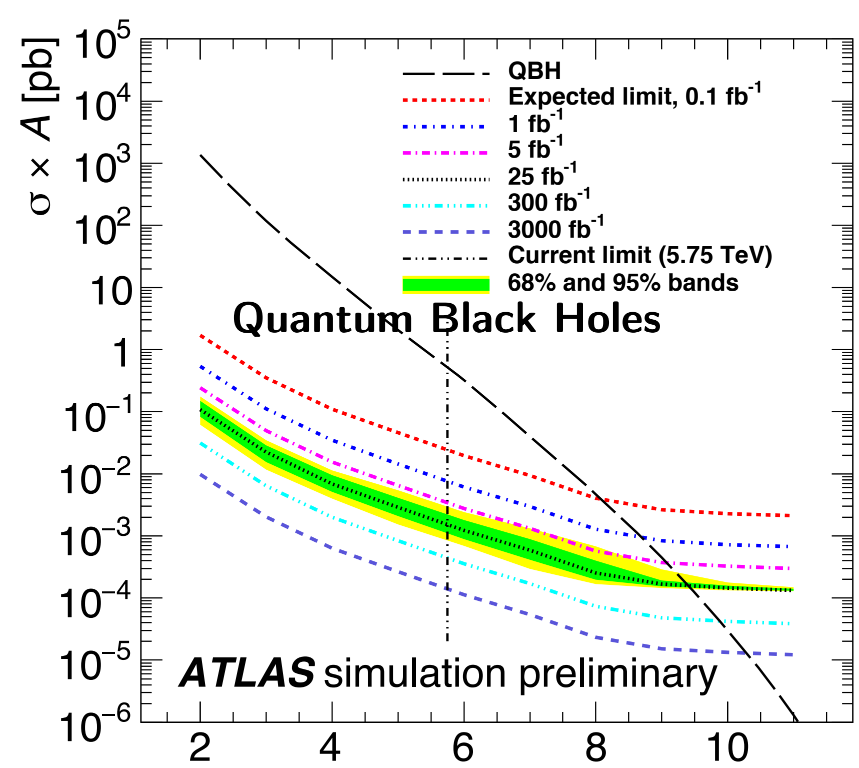
Exotics

Di-jet resonances

- Plethora of new physics models predicting resonances decaying to 2 jets: quantum black holes, excited quarks, Z'/W' bosons, W* bosons
- Greatly profit from increase in c.o.m energy
- Look for:
  - **bumps in m_{jj}**
  - **deviations from flat distribution in $\chi = \exp|y_1 - y_2|$**
- Here: sensitivity projections using m_{jj} spectrum
  - m(q*) > 6 TeV (current) → 7-8 TeV (Run 3 - HL-LHC)
  - m(QBH) > 9 TeV → 10-10.5 TeV







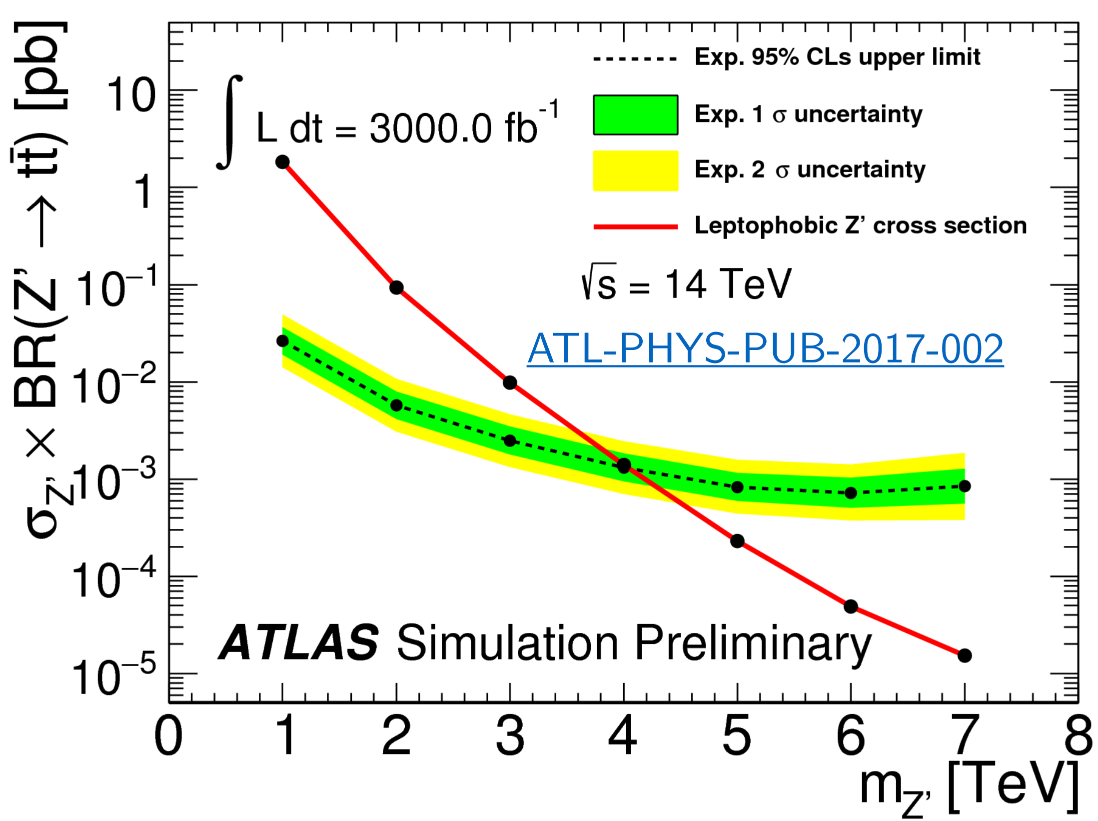
ATL-PHYS-PUB-2015-004

Di-lepton and di-top resonances

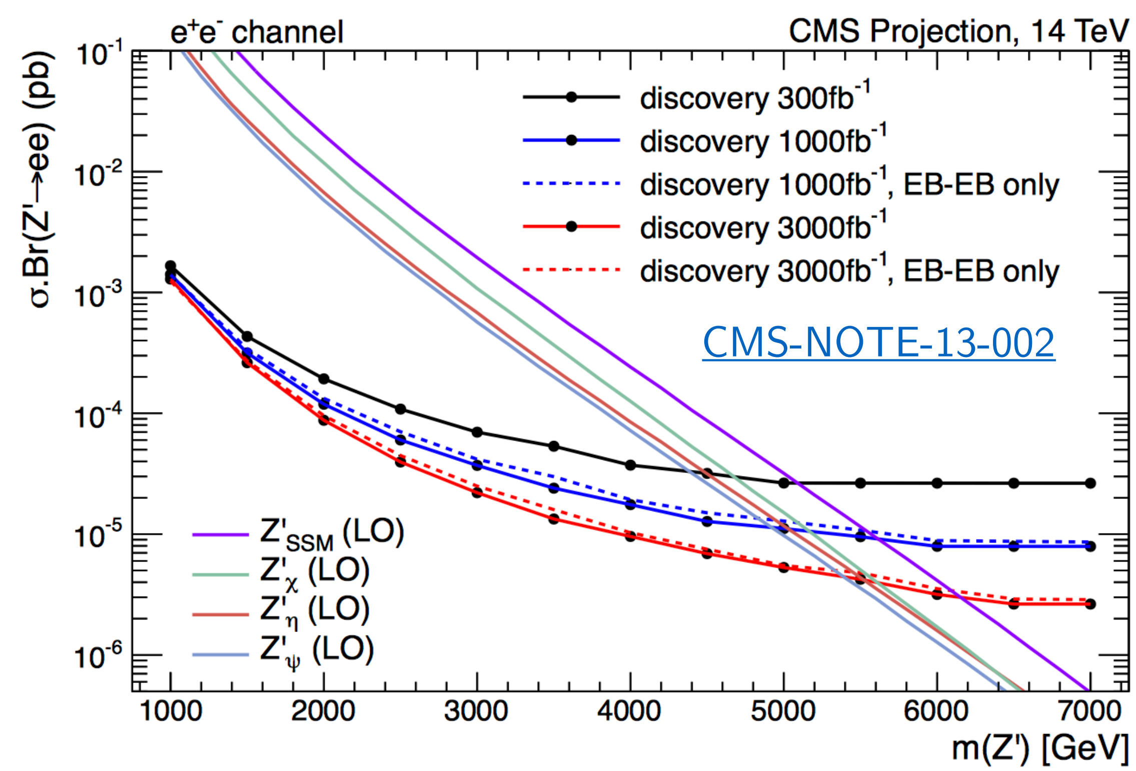
- Resonances decaying to top quarks arise in several BSM extensions: **topcolor, Kaluza-Klein gluons**
  - Lepton+jets channel used: 1lep + 1 small-R jet + 1 large-R jet (top-candidate)
  - $p(t\bar{t}) = p^{\text{lep}} + p^{\nu} + p^{\text{jet}}_{\text{small}-R} + p^{\text{jet}}_{\text{large}-R}$
- Di-lepton decays of new resonances (e.g. Z') also easy to reconstruct

- Expected discovery of Z' up to 5-6 TeV
- **Exclusion limit** for Z' **increased by 1 TeV with 10x more luminosity**

Z' decaying to top pair

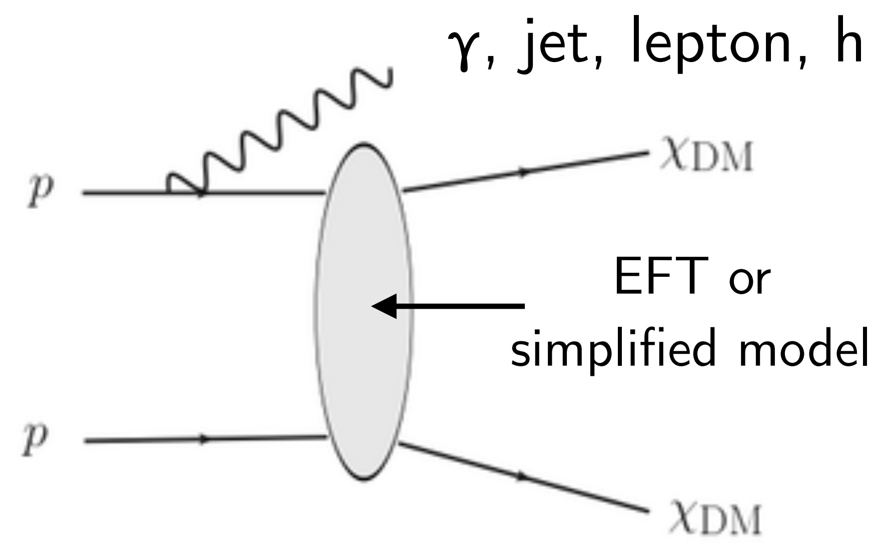


Expected discovery for Z' → e⁺e⁻

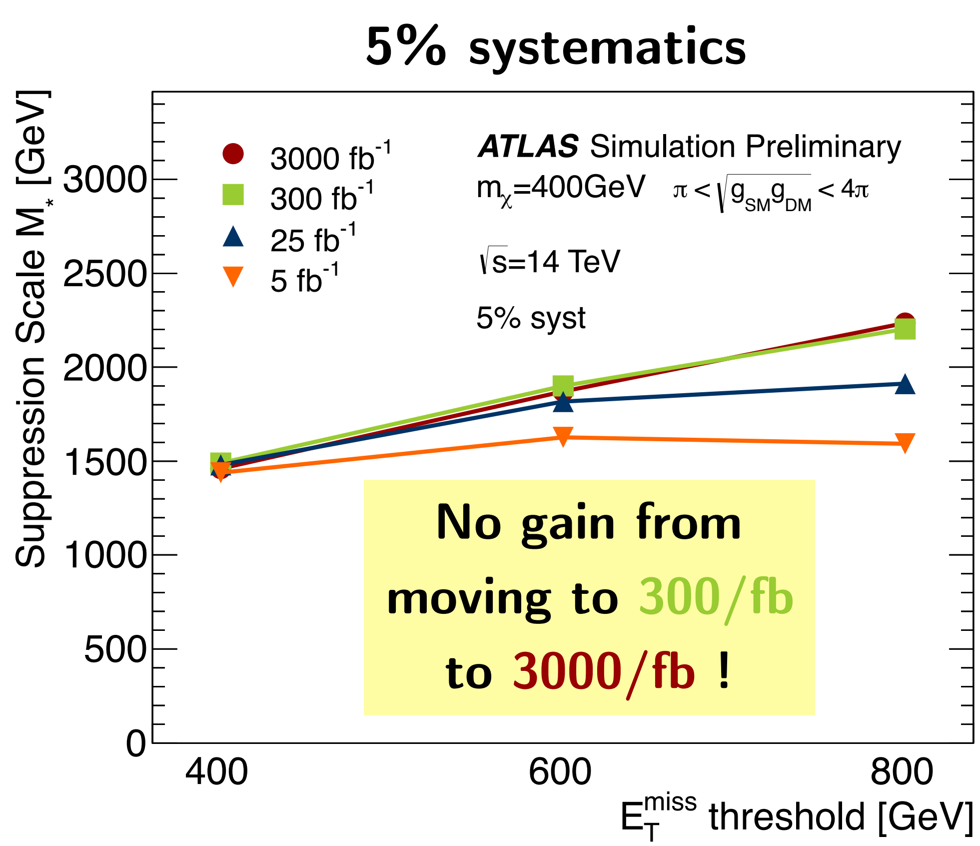


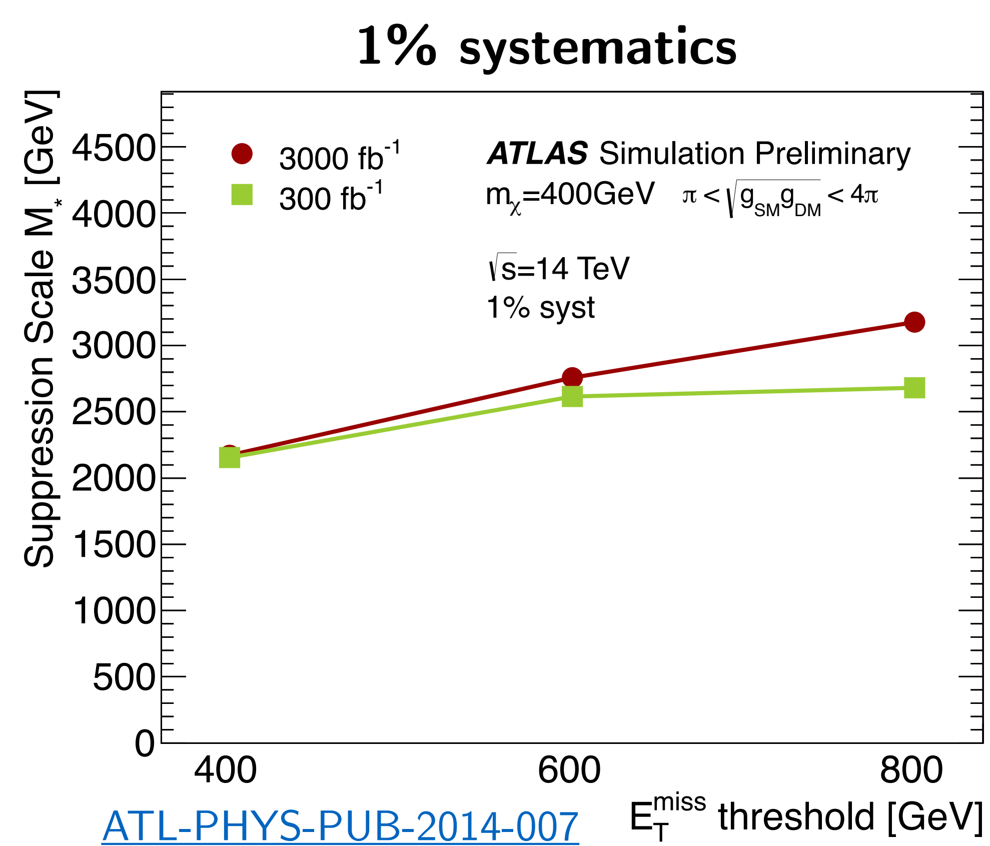
WIMP Dark Matter

- Principle of detection: reconstruction of object (γ, jet, lepton, Higgs) recoiling against MET from WIMPs
- **2 approaches**:
  - **EFT**: low-energy non-renormalizable theory only valid for $Q < \sqrt{g_{\rm SM} g_{\rm DM}} M_* < 4\pi M_*$ (taken into account when comparing with other experiments)
  - **Simplified models**: mediator not integrated out, defined in terms of masses, couplings and spin of mediator/DM particles



Expected limit on M∗ for different E_T^{miss} thresholds



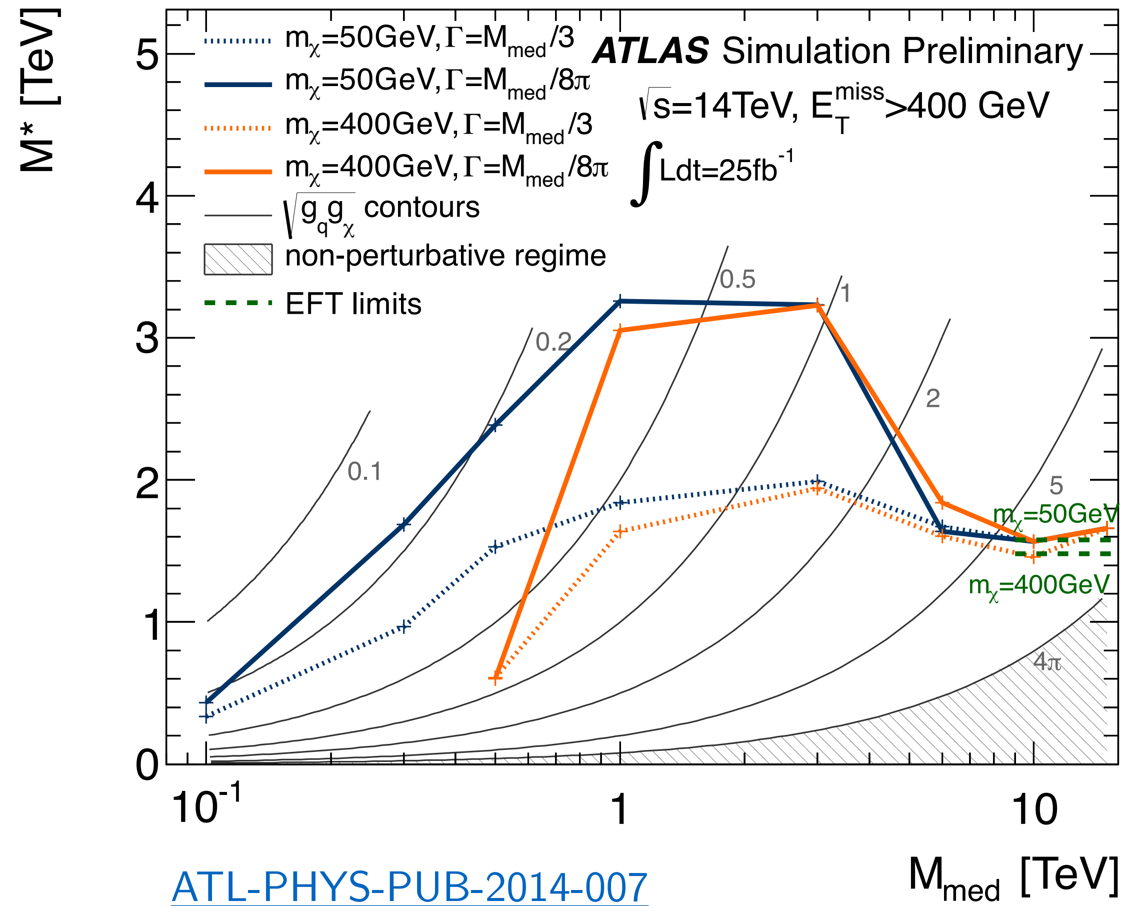


ATL-PHYS-PUB-2014-007

➡ We don't only need to collect more data; we need to reduce the systematics too!

Mono-jet and mono-lepton exclusion limits

- Simplified models allow to cover more of the parameter space when compared to EFT
- Limits **competitive at low m_χ compared to non-collider experiments**



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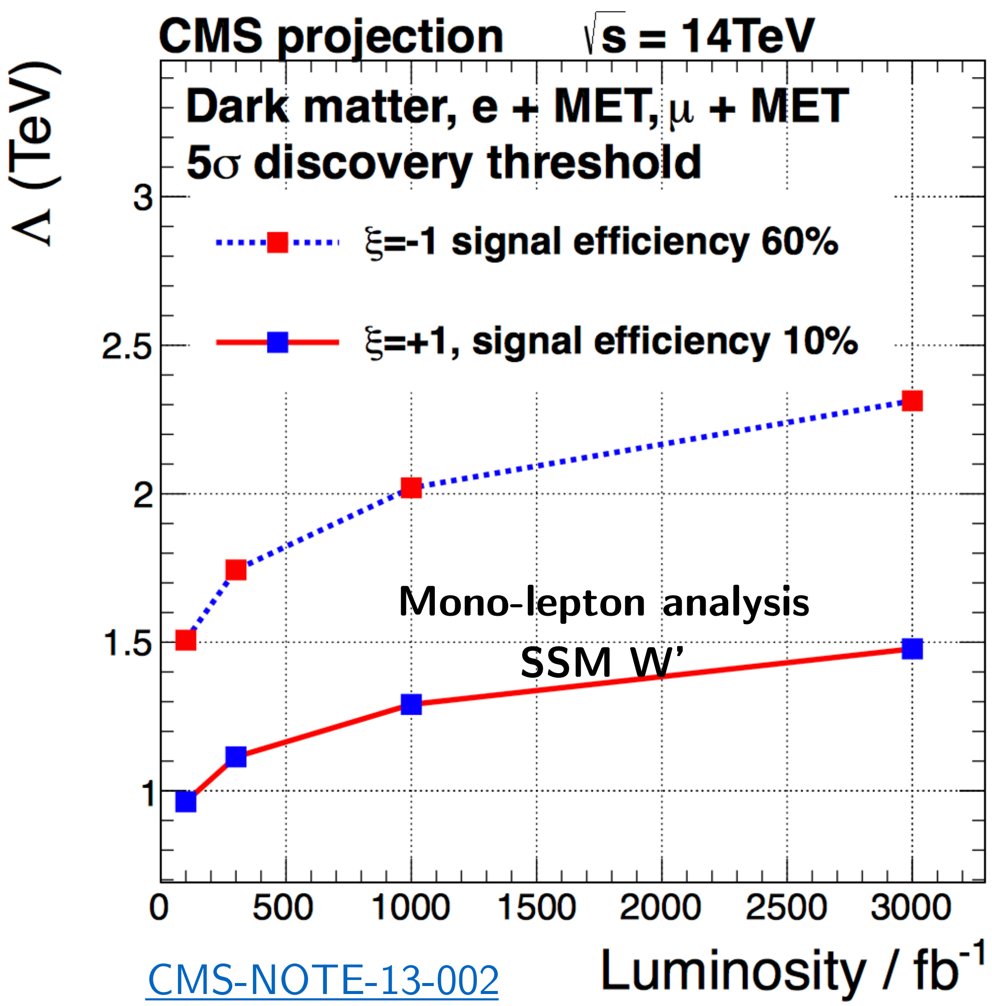

CMS-NOTE-13-002

- **50% improvement in limits expected with 3000 fb^{-1}**

Summary

- **Increase in luminosity** will allow to
  - probe channels with low cross-section
  - significantly increase discovery potential/expected exclusion limits
- **Higgs**: what was once a search becomes a measurement
  - shift towards **precision and model-independence**
- Hopefully we'll be soon be able to say the same for **SUSY** and **Exotics**
  - till then expect **significant improvement on discovery potential/ exclusion limits**
- **Improving detector performance/modelling quintessential** for ensuring a broadened physics reach in the HL-LHC - requires input from both the **experiment & theory** community