Aspen Center for Physics
29 March 2019

Expectations for sensitivity to BSM physics at the HL-LHC

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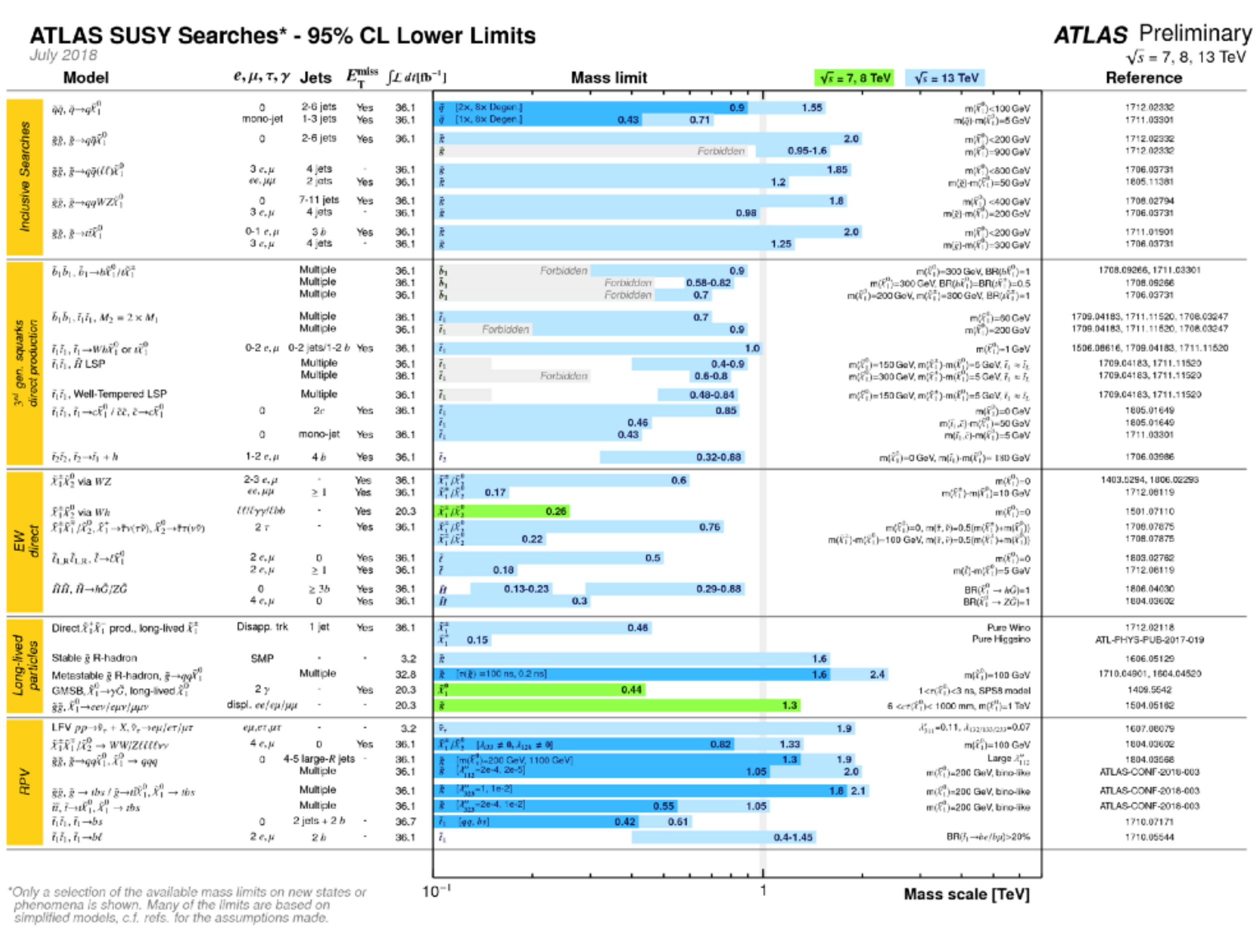
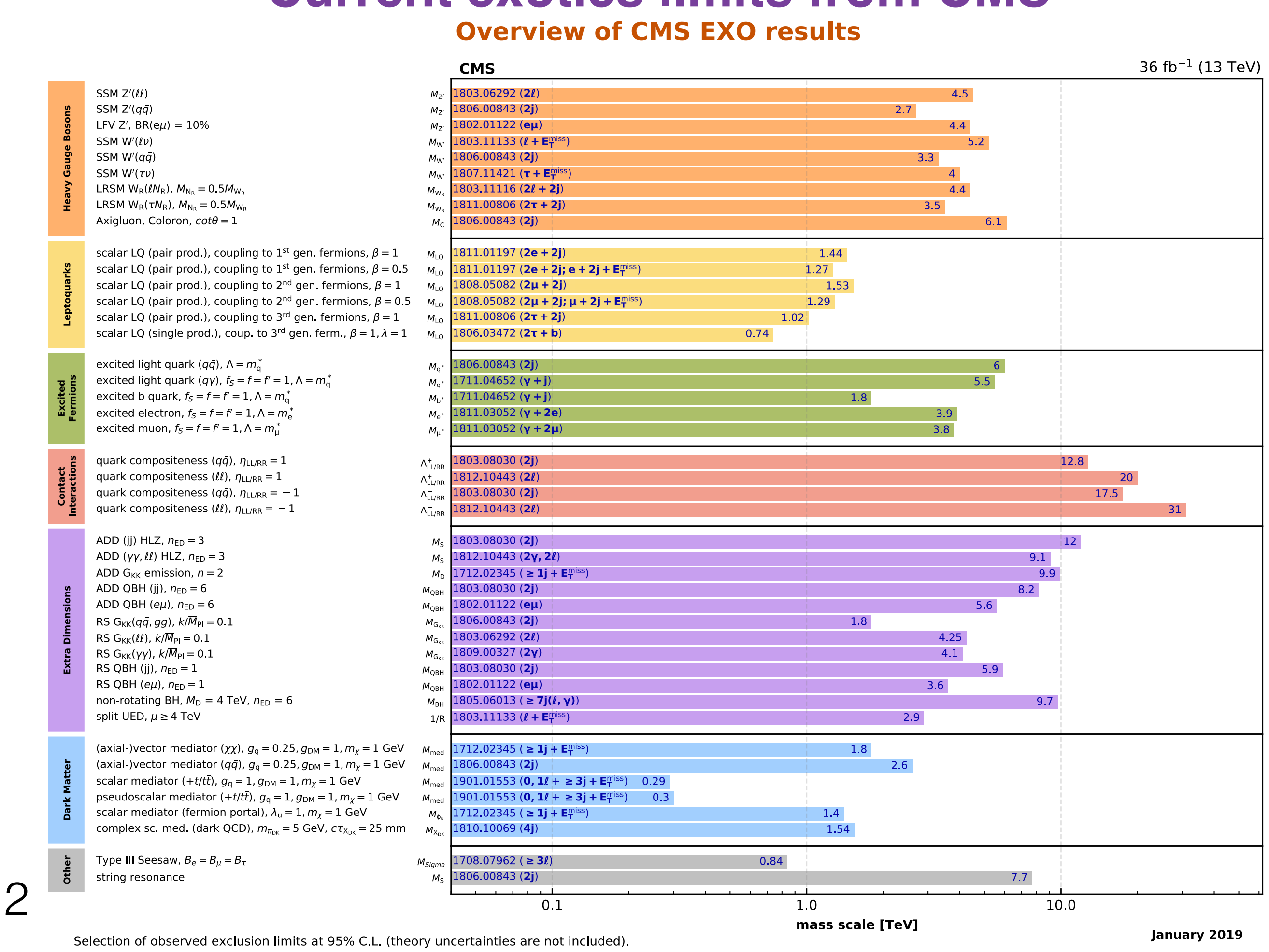
Overview

- Excellent performance of LHC and experiments in Run 1 and Run 2 lead to a plethora of SM measurements and searches for new physics
  - No signifiant deviation from SM expectation in measurements
  - No clear indication for new physics phenomena so far
- Upgrade of LHC and experiments to fully exploit potential and push discovery sensitivity significantly higher

Current supersymmetry limits from ATLAS



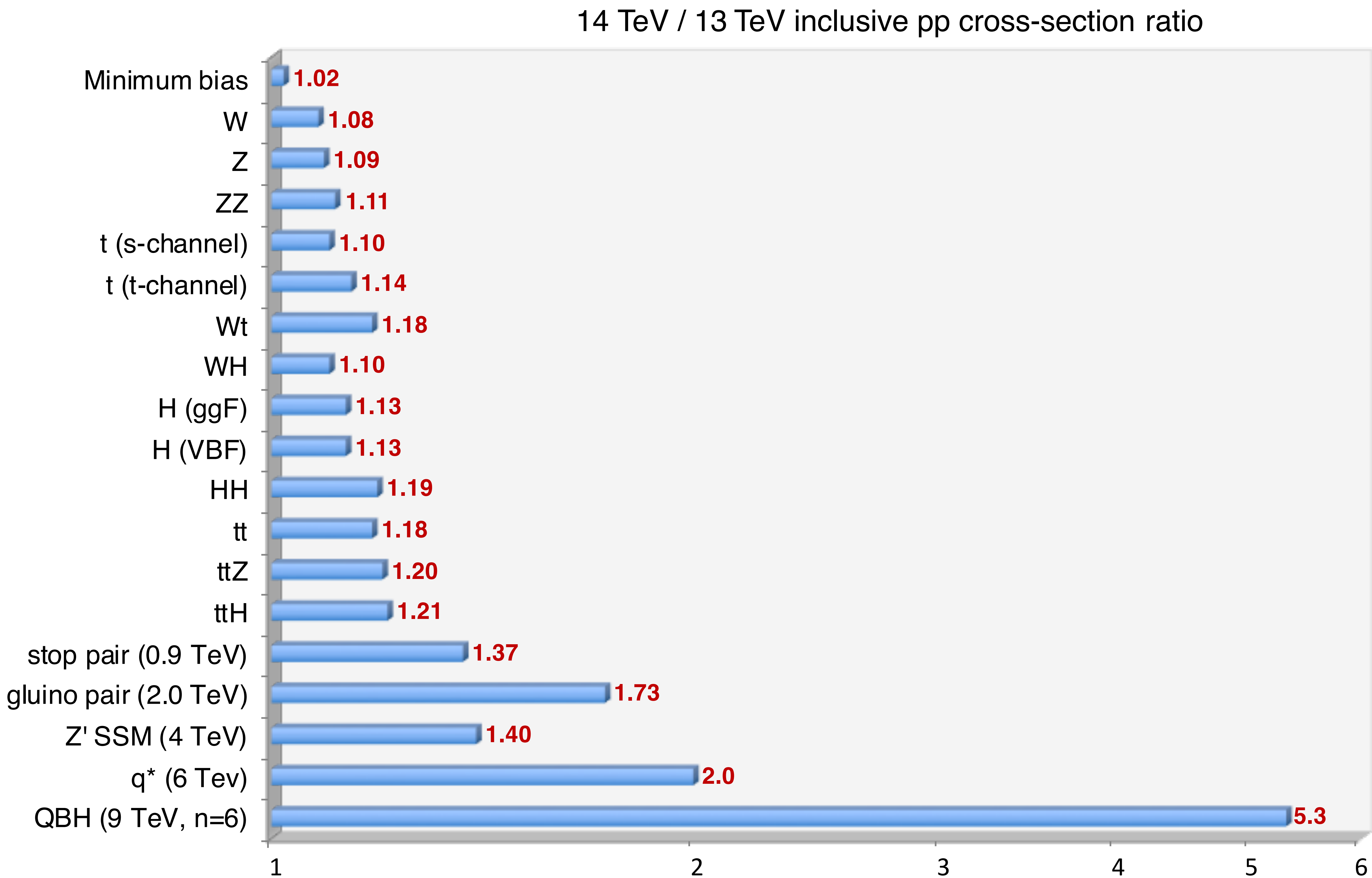
Current exotics limits from CMS



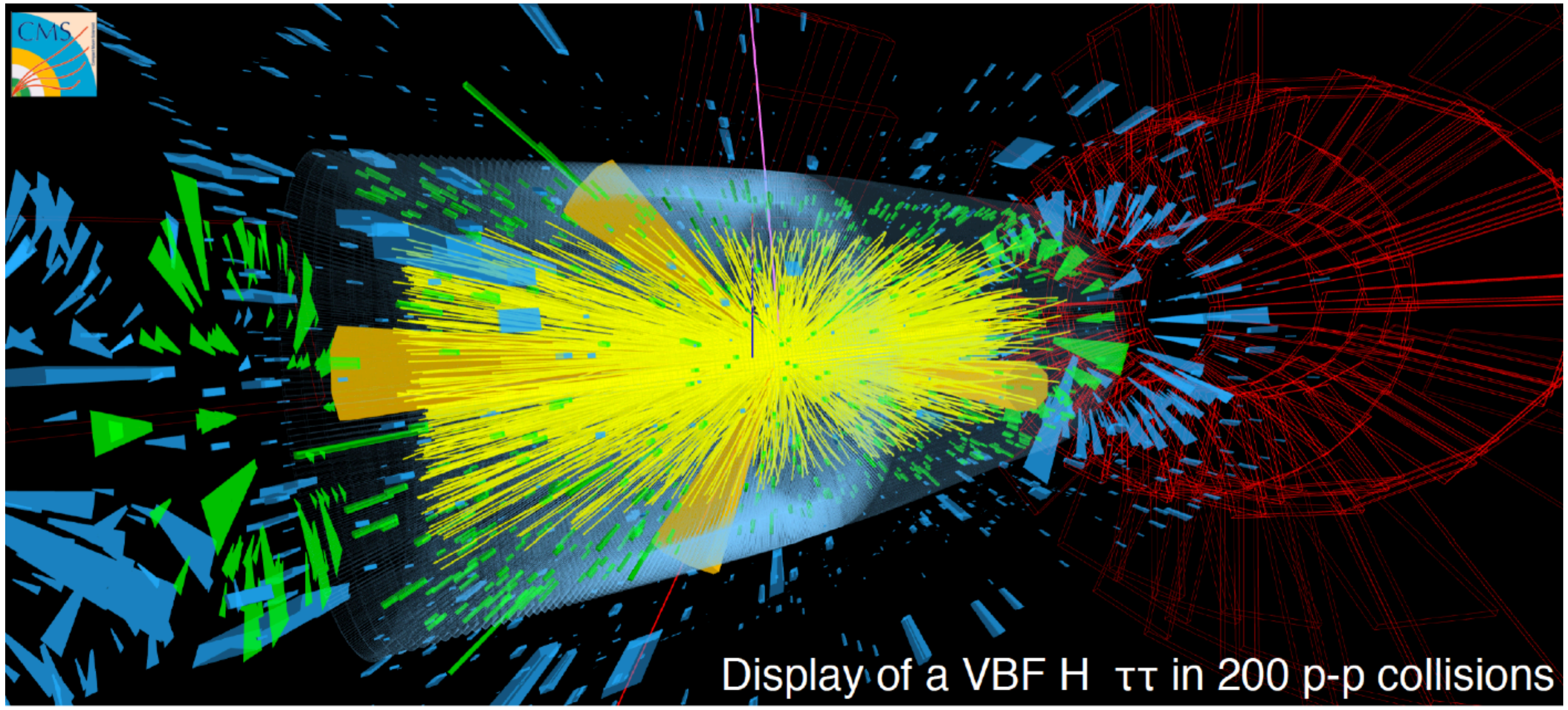
Setting the stage

- High Luminosity LHC (HL-LHC) outlook
  - 3000 fb^{-1} at center of mass energy of 14 TeV
  - Goals include deeper understanding of Higgs boson, precision measurements in QCD, EWK, Higgs, B physics, and probing physics beyond the standard model in both direct searches and precision measurements

Setting the stage

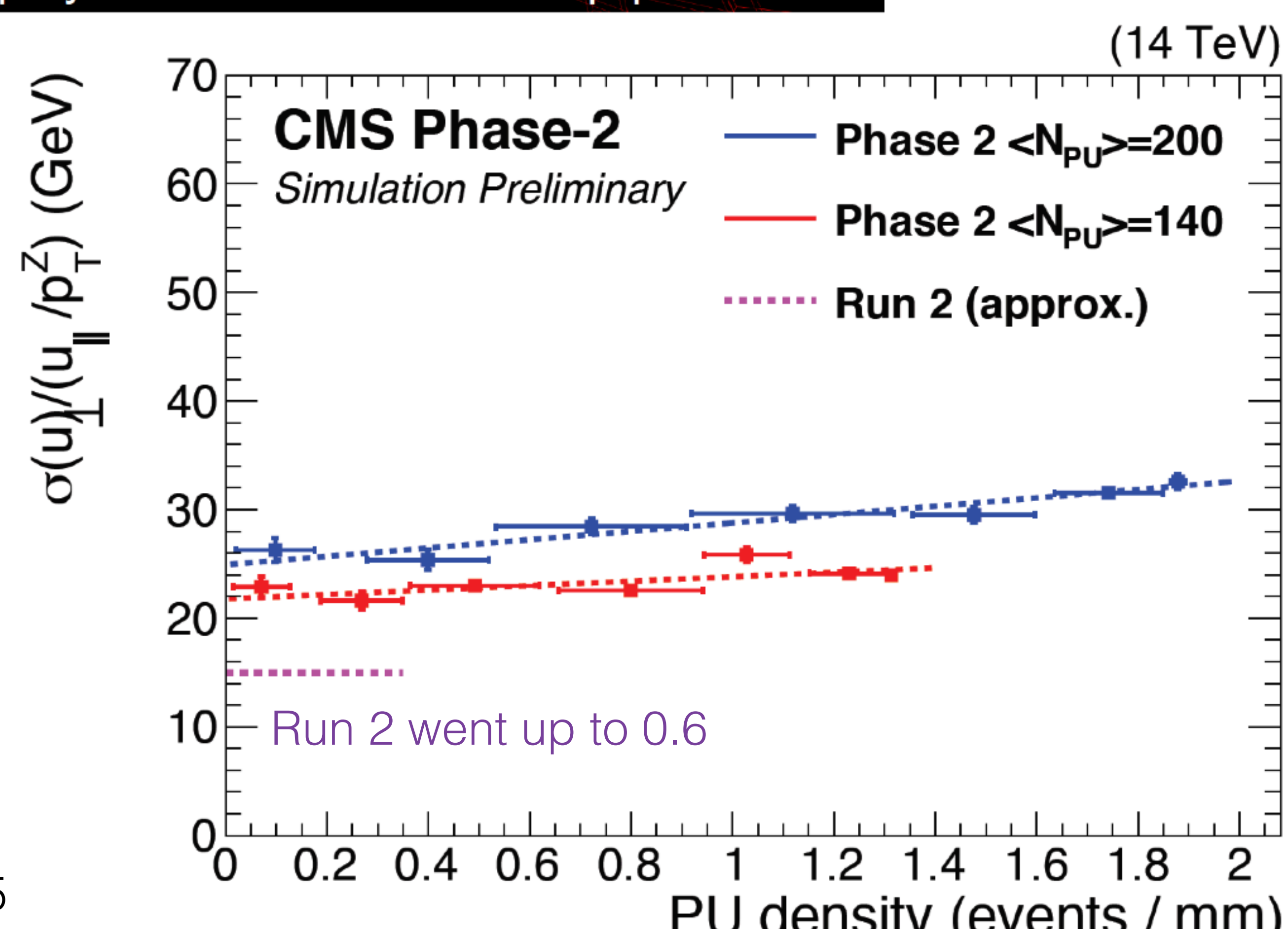


Challenges and opportunities: high (instantaneous) luminosity



- Average of 200 collisions per crossing
- Detector, trigger, reconstruction, performance, and analysis challenges

MET resolution

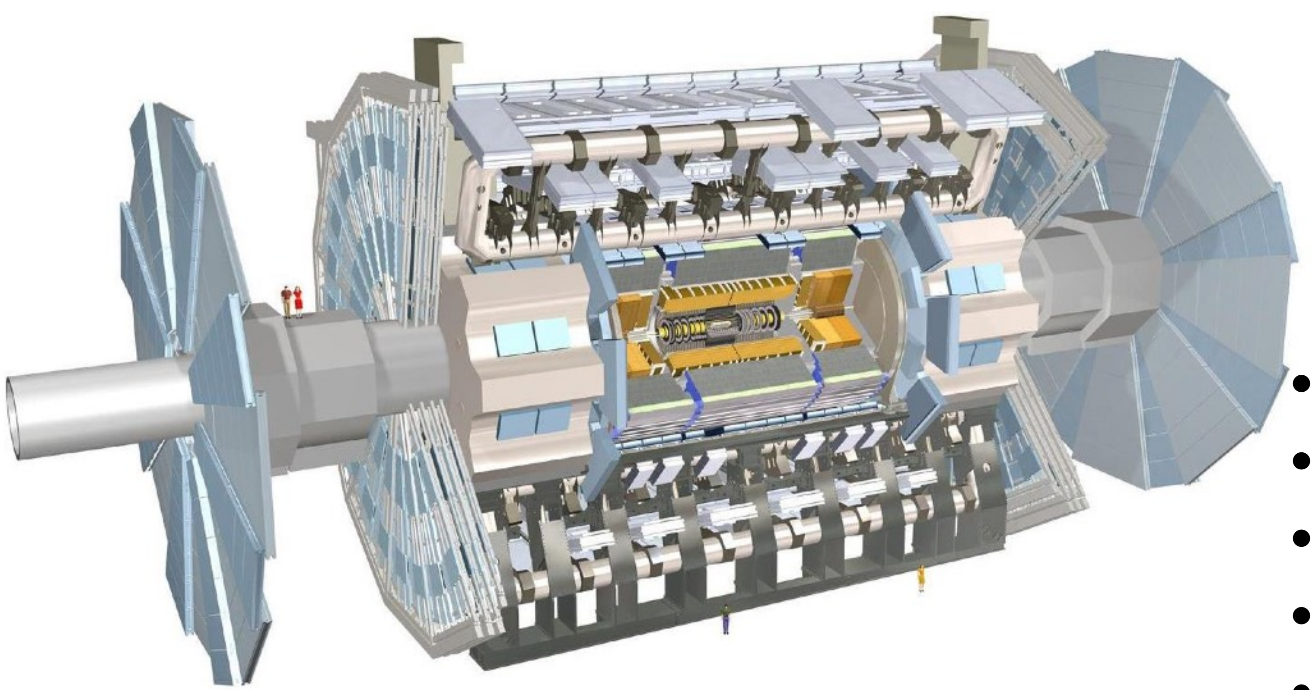


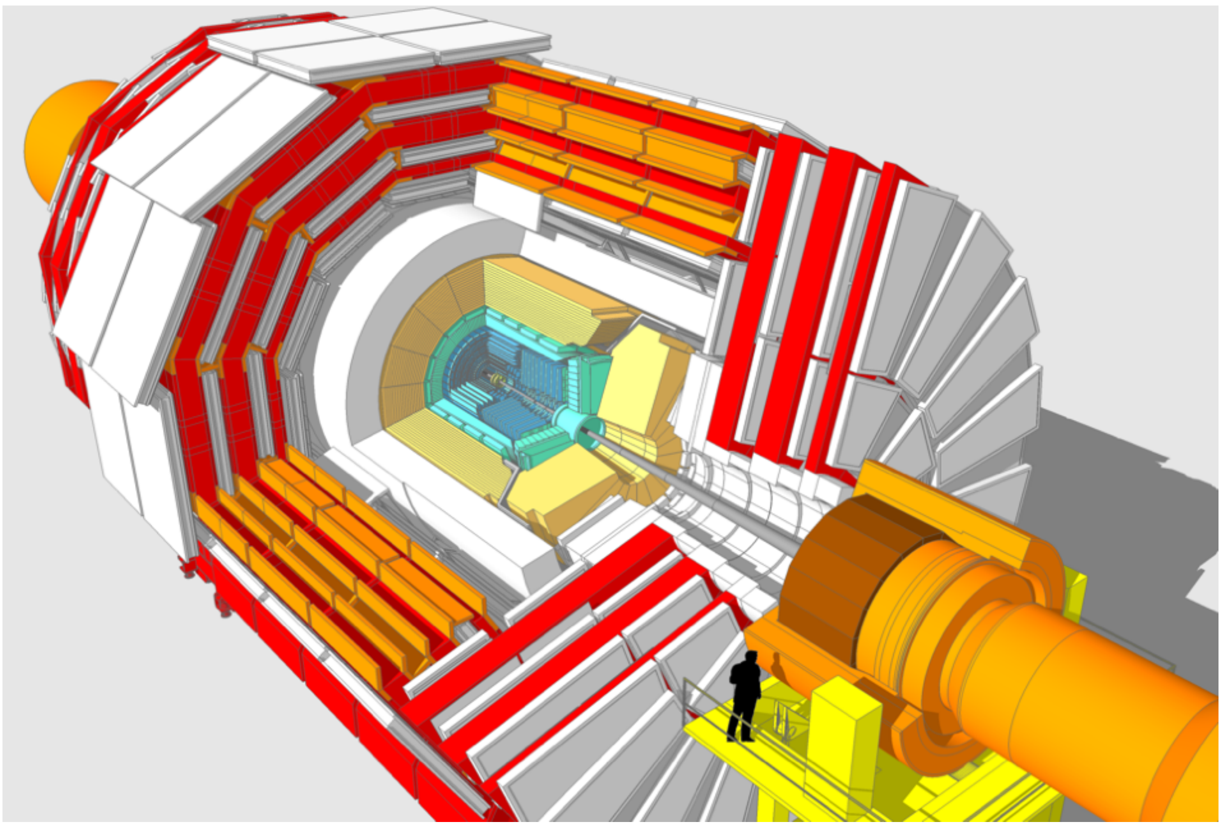
Upgraded detectors for HL-LHC

- Extensive detector upgrades to handle increased data rate, occupancy, pileup, and integrated luminosity

ATLAS upgrades include:

- Trigger and DAQ at L1 and HLT (10 kHz)
- Improved muon coverage and trigger
- Upgraded calorimeters and trigger
- New inner tracker, coverage to $|\eta| < 4$
- High-granularity timing detector in endcap





CMS upgrades include:

- Trigger and DAQ at L1 and HLT (7.5 kHz)
- Improved muon coverage and trigger
- Precise MIP timing layer in barrel and endcap
- New inner tracker, coverage to $|\eta| < 4$
- High-granularity endcap calorimeter

Overview of HL-LHC Working Group

- Collaboration of theorists and experimentalists to project physics reach of HL-LHC
- HL-LHC twiki here
  - WG1: SM final report
  - WG2: Higgs final report
  - WG3: BSM final report
  - WG4: Flavor physics final report
  - WG5: QCD and heavy-ions final report
- Final jamboree with many interesting talks

- **This talk will cover a small selection of highlights, mainly from ATLAS and CMS**

SUSY: breadth and reach

HL/HE-LHC SUSY Searches

HL-LHC, $\int\mathcal{L}dt = 3\text{ab}^{-1}$: 5σ discovery (95% CL exclusion)

HE-LHC, $\int\mathcal{L}dt = 15\text{ab}^{-1}$: 5σ discovery (95% CL exclusion)

Simulation Preliminary

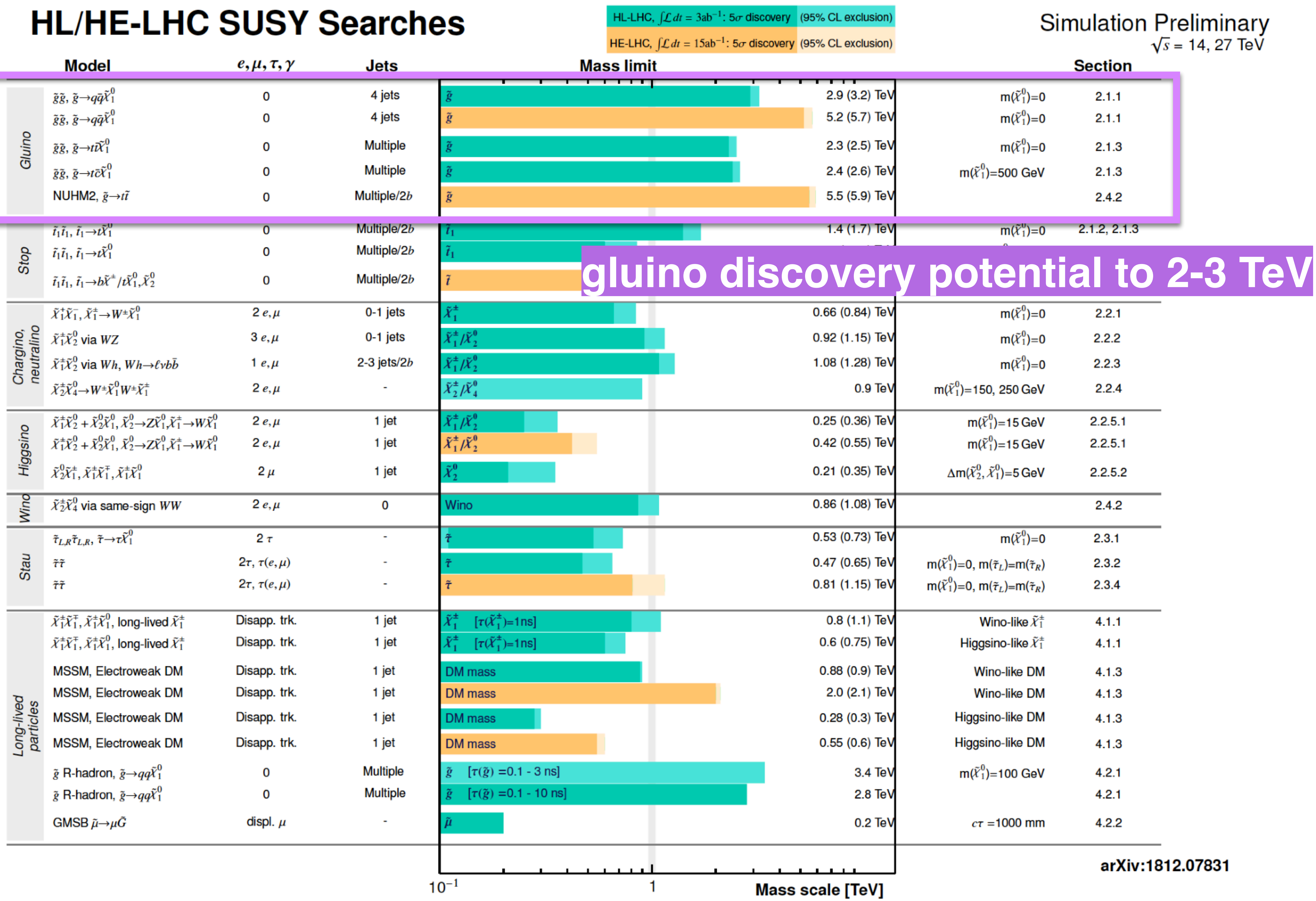
$\sqrt{s}$ = 14, 27 TeV

	Model	e,μ,τ,γ	Jets	Mass limit			Section
Gluino	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	4 jets	$\tilde{g}$	2.9 (3.2) TeV	$m(\tilde{\chi}^0_1)=0$	2.1.1
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	4 jets	$\tilde{g}$	5.2 (5.7) TeV	$m(\tilde{\chi}^0_1)=0$	2.1.1
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0	Multiple	$\tilde{g}$	2.3 (2.5) TeV	$m(\tilde{\chi}^0_1)=0$	2.1.3
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{c}\tilde{\chi}^0_1$	0	Multiple	$\tilde{g}$	2.4 (2.6) TeV	$m(\tilde{\chi}^0_1)$=500 GeV	2.1.3
	NUHM2, $\tilde{g}\to t\tilde{t}$	0	Multiple/$2b$	$\tilde{g}$	5.5 (5.9) TeV		2.4.2
Stop	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}^0_1$	0	Multiple/$2b$	$\tilde{t}_1$	1.4 (1.7) TeV	$m(\tilde{\chi}^0_1)=0$	2.1.2, 2.1.3
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}^0_1$	0	Multiple/$2b$	$\tilde{t}_1$	0.6 (0.85) TeV	$\Delta m(\tilde{t}_1,\tilde{\chi}^0_1)\sim m(t)$	2.1.2
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}^\pm/t\tilde{\chi}^0_1,\tilde{\chi}^0_2$	0	Multiple/$2b$	$\tilde{t}$	3.16 (3.65) TeV		2.4.2
Chargino, neutralino	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^\pm_1\to W^\pm\tilde{\chi}^0_1$	2 e,μ	0-1 jets	$\tilde{\chi}^\pm_1$	0.66 (0.84) TeV	$m(\tilde{\chi}^0_1)=0$	2.2.1
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	3 e,μ	0-1 jets	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.92 (1.15) TeV	$m(\tilde{\chi}^0_1)=0$	2.2.2
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh, $Wh\to\ell\nu b\bar{b}$	1 e,μ	2-3 jets/$2b$	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	1.08 (1.28) TeV	$m(\tilde{\chi}^0_1)=0$	2.2.3
	$\tilde{\chi}^\pm_2\tilde{\chi}^0_4\to W^\pm\tilde{\chi}^0_1 W^\pm\tilde{\chi}^\pm_1$	2 e,μ	-	$\tilde{\chi}^\pm_2/\tilde{\chi}^0_4$	0.9 TeV	$m(\tilde{\chi}^0_1)$=150, 250 GeV	2.2.4
Higgsino	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2+\tilde{\chi}^0_2\tilde{\chi}^0_1, \tilde{\chi}^0_2\to Z\tilde{\chi}^0_1, \tilde{\chi}^\pm_1\to W\tilde{\chi}^0_1$	2 e,μ	1 jet	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.25 (0.36) TeV	$m(\tilde{\chi}^0_1)$=15 GeV	2.2.5.1
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2+\tilde{\chi}^0_2\tilde{\chi}^0_1, \tilde{\chi}^0_2\to Z\tilde{\chi}^0_1, \tilde{\chi}^\pm_1\to W\tilde{\chi}^0_1$	2 e,μ	1 jet	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$	0.42 (0.55) TeV	$m(\tilde{\chi}^0_1)$=15 GeV	2.2.5.1
	$\tilde{\chi}^0_2\tilde{\chi}^\pm_1, \tilde{\chi}^\pm_1\tilde{\chi}^\mp_1, \tilde{\chi}^\pm_1\tilde{\chi}^0_1$	2 μ	1 jet	$\tilde{\chi}^0_2$	0.21 (0.35) TeV	$\Delta m(\tilde{\chi}^0_2,\tilde{\chi}^0_1)$=5 GeV	2.2.5.2
Wino	$\tilde{\chi}^\pm_2\tilde{\chi}^\pm_4$ via same-sign WW	2 e,μ	0	Wino	0.86 (1.08) TeV		2.4.2
Stau	$\tilde{\tau}_{L,R}\tilde{\tau}_{L,R}, \tilde{\tau}\to\tau\tilde{\chi}^0_1$	2 τ	-	$\tilde{\tau}$	0.53 (0.73) TeV	$m(\tilde{\chi}^0_1)=0$	2.3.1
	$\tilde{\tau}\tilde{\tau}$	2τ, $\tau(e,\mu)$	-	$\tilde{\tau}$	0.47 (0.65) TeV	$m(\tilde{\chi}^0_1)=0$, $m(\tilde{\tau}_L)=m(\tilde{\tau}_R)$	2.3.2
	$\tilde{\tau}\tilde{\tau}$	2τ, $\tau(e,\mu)$	-	$\tilde{\tau}$	0.81 (1.15) TeV	$m(\tilde{\chi}^0_1)=0$, $m(\tilde{\tau}_L)=m(\tilde{\tau}_R)$	2.3.4
Long-lived particles	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^\pm_1\tilde{\chi}^0_1$, long-lived $\tilde{\chi}^\pm_1$	Disapp. trk.	1 jet	$\tilde{\chi}^\pm_1$ [$\tau(\tilde{\chi}^\pm_1)$=1ns]	0.8 (1.1) TeV	Wino-like $\tilde{\chi}^\pm_1$	4.1.1
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^\pm_1\tilde{\chi}^0_1$, long-lived $\tilde{\chi}^\pm_1$	Disapp. trk.	1 jet	$\tilde{\chi}^\pm_1$ [$\tau(\tilde{\chi}^\pm_1)$=1ns]	0.6 (0.75) TeV	Higgsino-like $\tilde{\chi}^\pm_1$	4.1.1
	MSSM, Electroweak DM	Disapp. trk.	1 jet	DM mass	0.88 (0.9) TeV	Wino-like DM	4.1.3
	MSSM, Electroweak DM	Disapp. trk.	1 jet	DM mass	2.0 (2.1) TeV	Wino-like DM	4.1.3
	MSSM, Electroweak DM	Disapp. trk.	1 jet	DM mass	0.28 (0.3) TeV	Higgsino-like DM	4.1.3
	MSSM, Electroweak DM	Disapp. trk.	1 jet	DM mass	0.55 (0.6) TeV	Higgsino-like DM	4.1.3
	$\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$	0	Multiple	$\tilde{g}$ [$\tau(\tilde{g})$ =0.1 - 3 ns]	3.4 TeV	$m(\tilde{\chi}^0_1)$=100 GeV	4.2.1
	$\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$	0	Multiple	$\tilde{g}$ [$\tau(\tilde{g})$ =0.1 - 10 ns]	2.8 TeV		4.2.1
	GMSB $\tilde{\mu}\to\mu\tilde{G}$	displ. μ	-	$\tilde{\mu}$	0.2 TeV	$c\tau$ =1000 mm	4.2.2

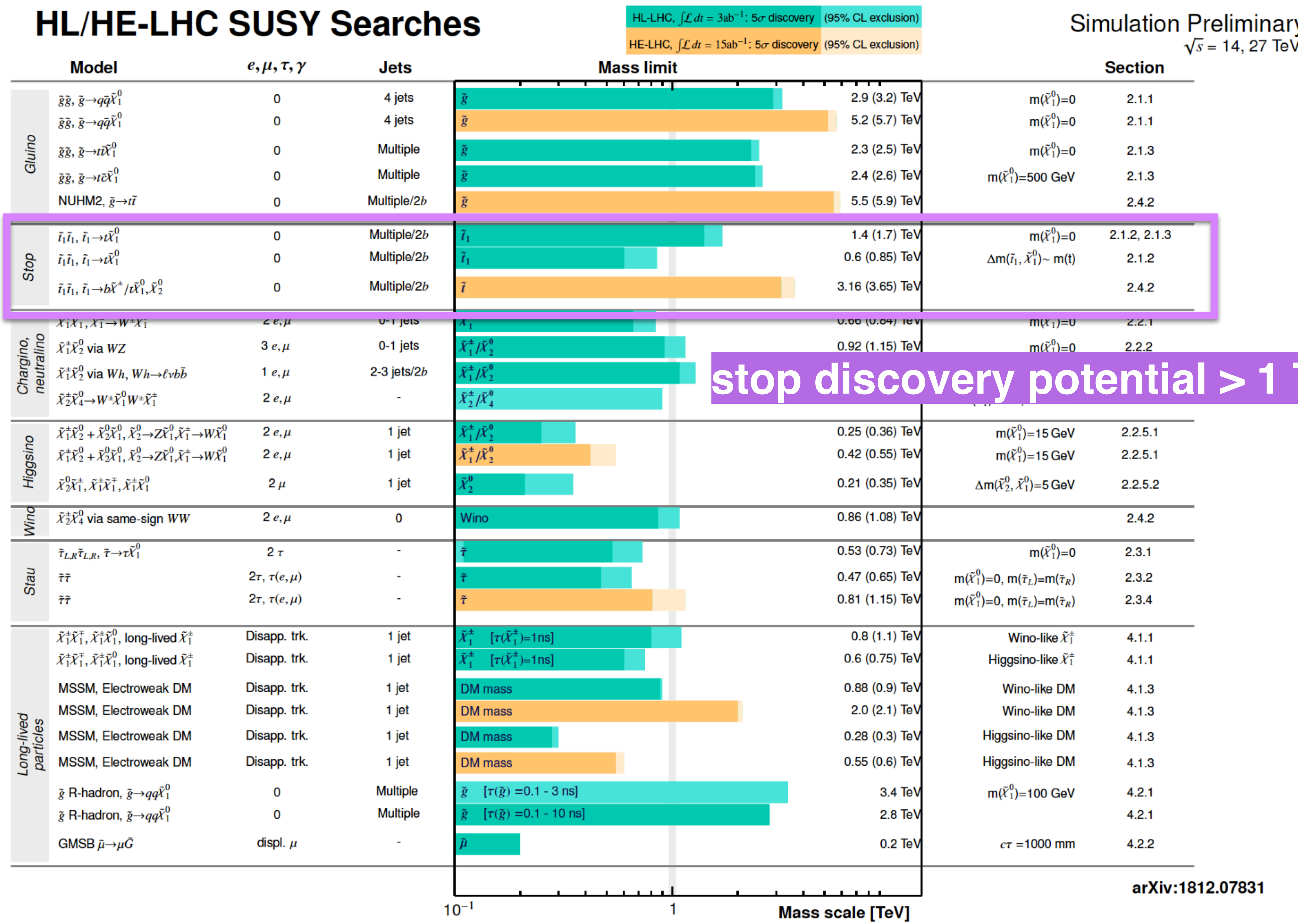
10^{-1} 1 Mass scale [TeV]

arXiv:1812.07831

SUSY: breadth and reach

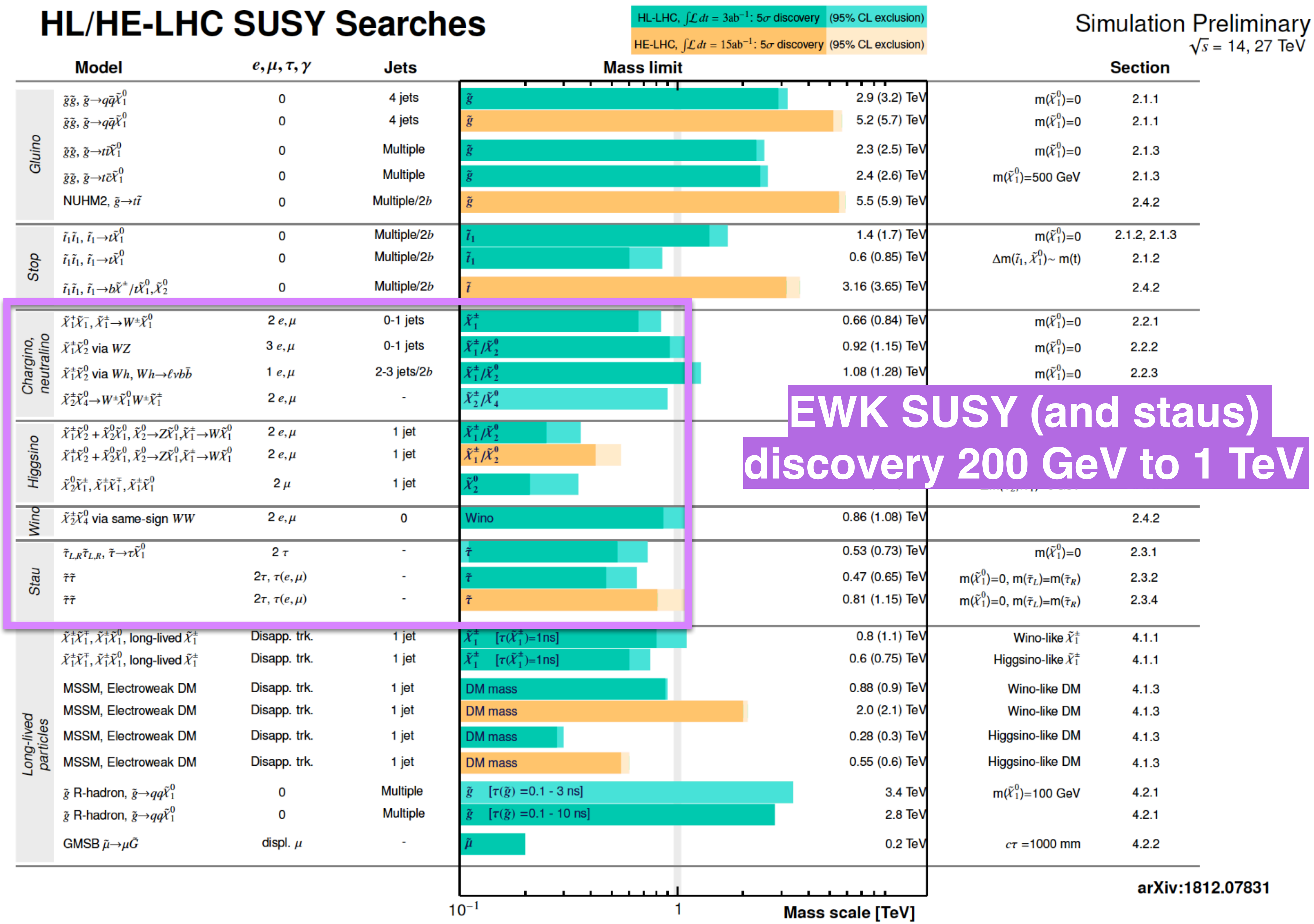


SUSY: breadth and reach



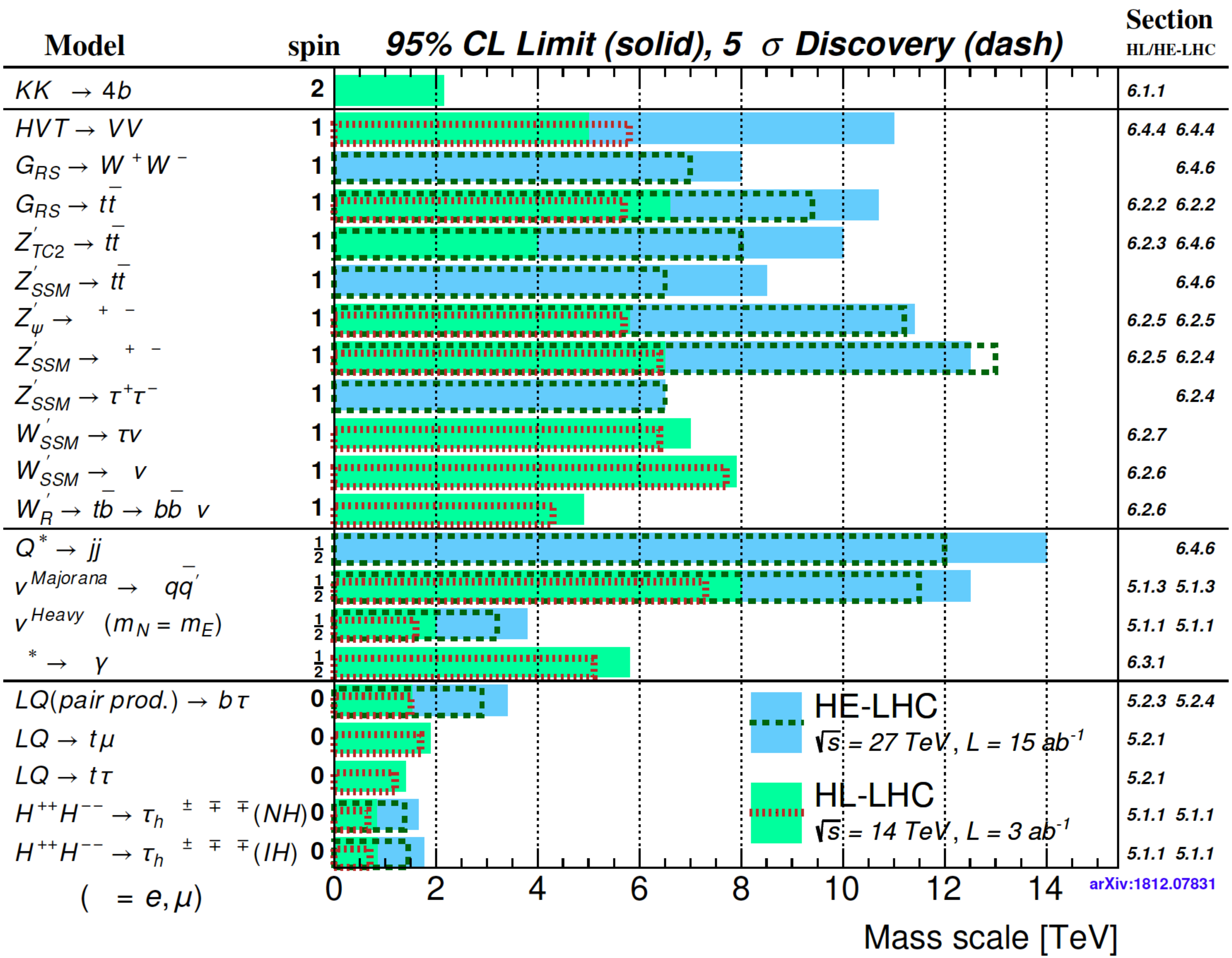
stop discovery potential > 1 TeV

SUSY: breadth and reach

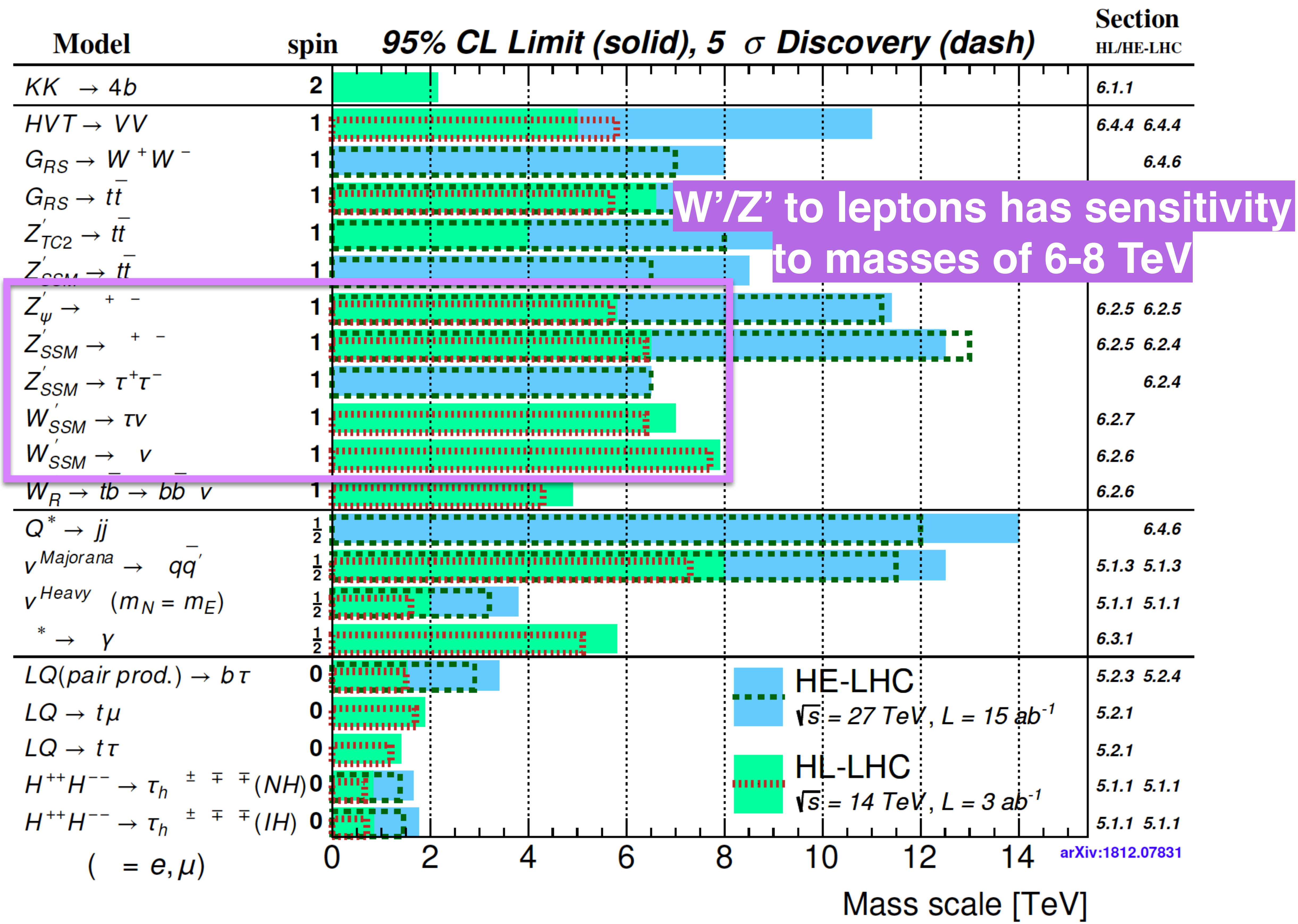


EWK SUSY (and staus) discovery 200 GeV to 1 TeV

Exotics: breadth and reach



Exotics: breadth and reach

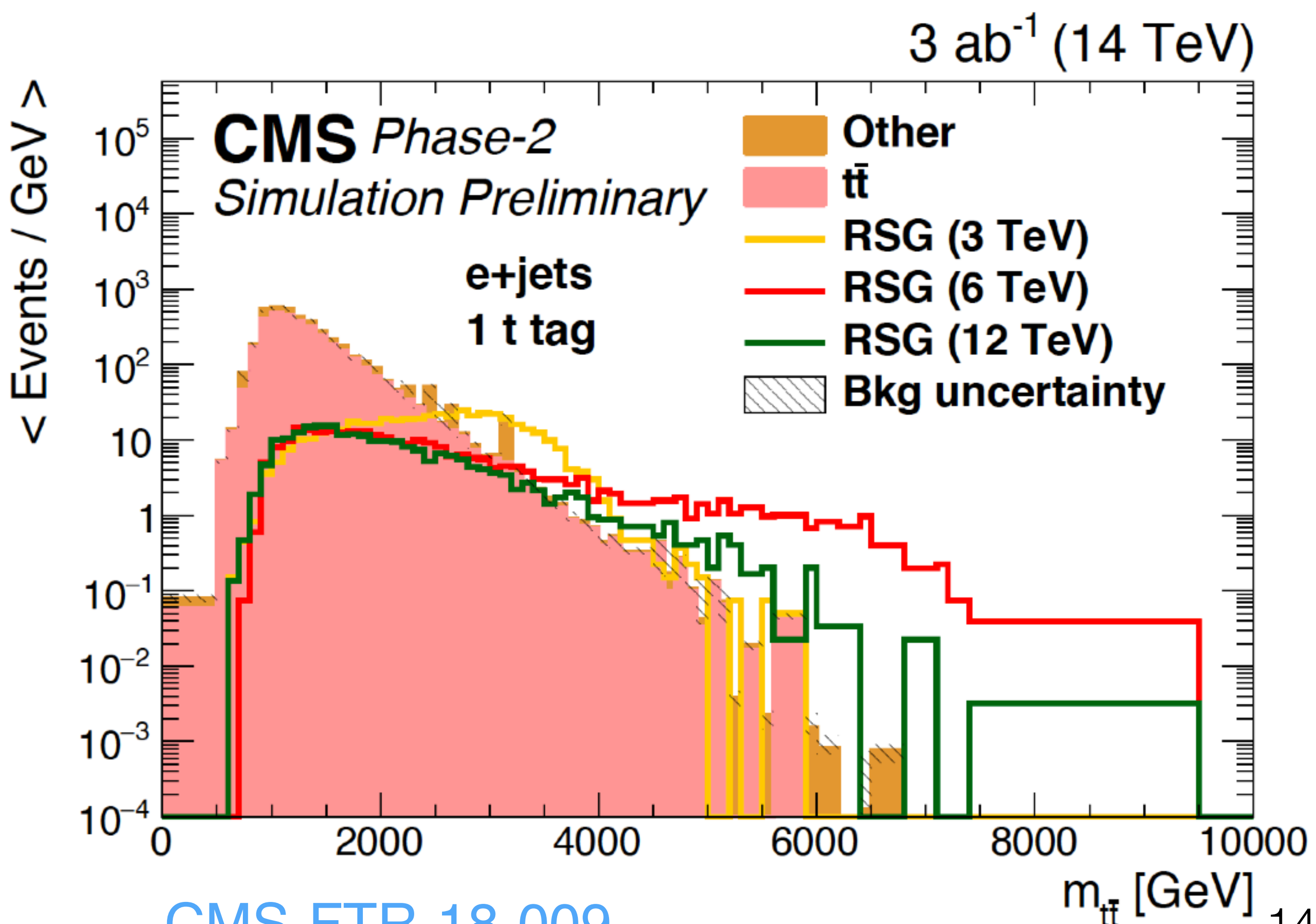


Resonance searches

clear gains from increased lumi and energy

- Continuation and expansion of the current resonance search program, across a vast variety of channels
  - requires continued excellent performance of object reconstruction and energy / mass resolution
  - high mass sensitivity is dominated by statistics
- W' discovery potential up to 7.7 TeV!
- RS Gluon discovery up to 5.7 TeV!

Decay	$\sqrt{s}=13$ TeV Exclusion	$\sqrt{s}=13$ TeV Discovery	$\sqrt{s}=14$ TeV Exclusion	$\sqrt{s}=14$ TeV Discovery
$Z'_{\mathrm{SSM}} \to ee$	6.0 TeV	5.9 TeV	6.4 TeV	6.3 TeV
$Z'_{\mathrm{SSM}} \to \mu\mu$	5.5 TeV	5.4 TeV	5.8 TeV	5.7 TeV
$Z'_{\mathrm{SSM}} \to \ell\ell$	6.1 TeV	6.1 TeV	6.5 TeV	6.4 TeV
$Z'_{\psi} \to ee$	5.3 TeV	5.3 TeV	5.7 TeV	5.6 TeV
$Z'_{\psi} \to \mu\mu$	4.9 TeV	4.6 TeV	5.2 TeV	5.0 TeV
$Z'_{\psi} \to \ell\ell$	5.4 TeV	5.4 TeV	5.8 TeV	5.7 TeV



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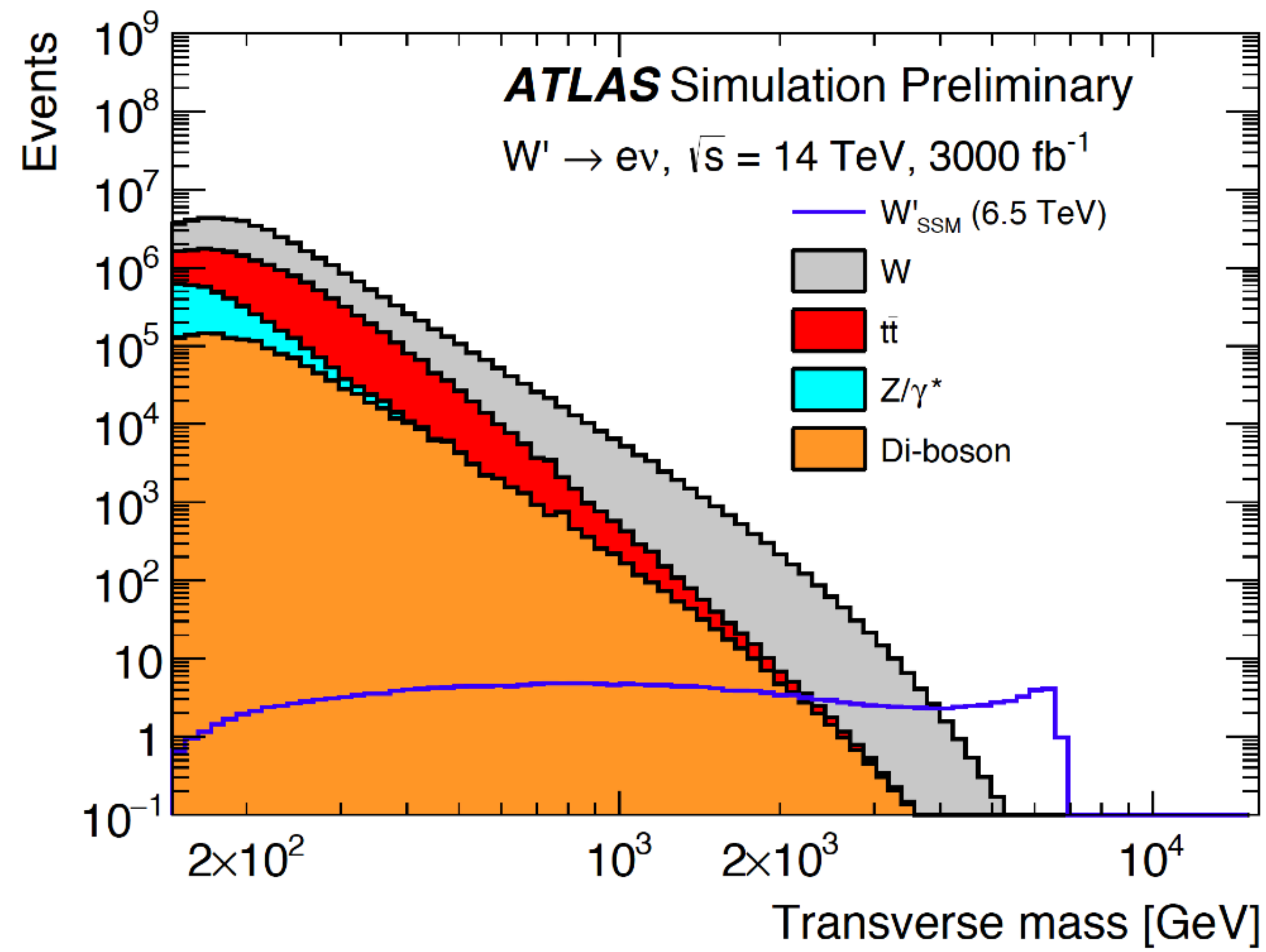
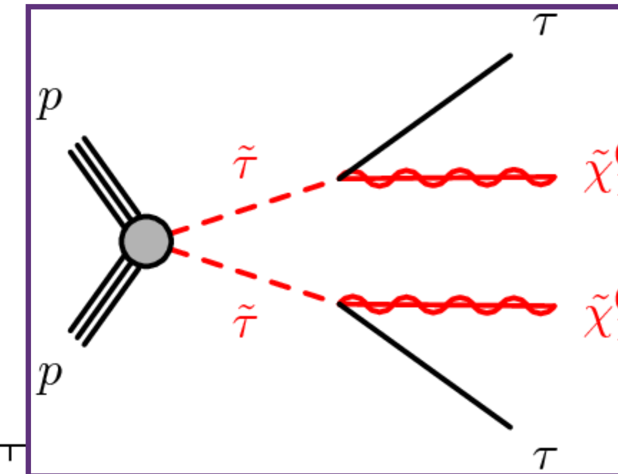
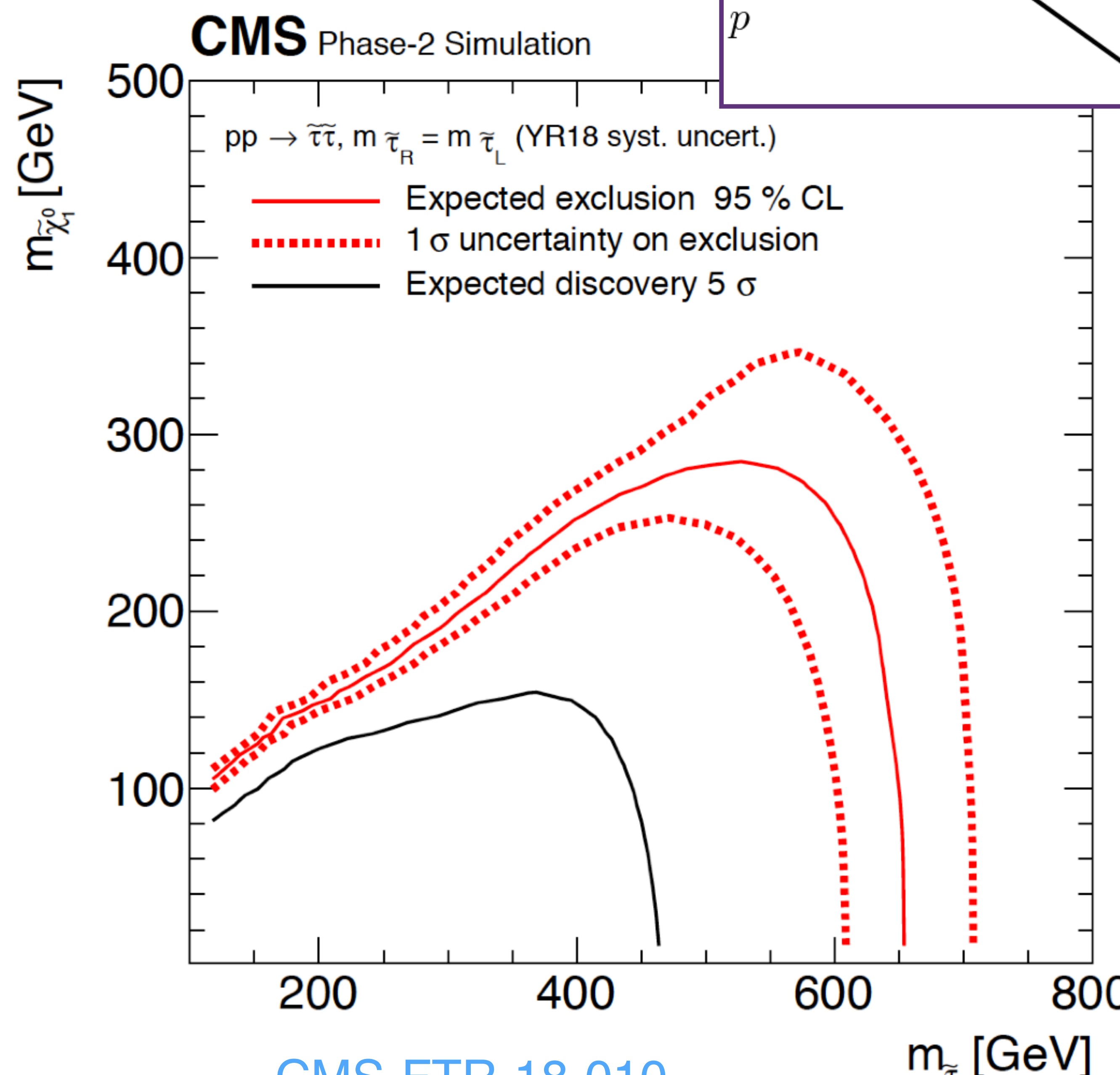


Supersymmetry: staus

new sensitivity relies on detector upgrades for taus

- Stau pair production, decaying to taus and neutralino, currently unconstrained by LHC
    - searched with signature of two hadronically decaying taus, and mixed hadronic / lepton signature
    - discovery sensitivity from each experiment up to 500 GeV
- Detector, trigger, and performance improvements are key
    - relies on ability to trigger taus efficiently at moderate energies
    - need to maintain low fake rake for taus at high pT



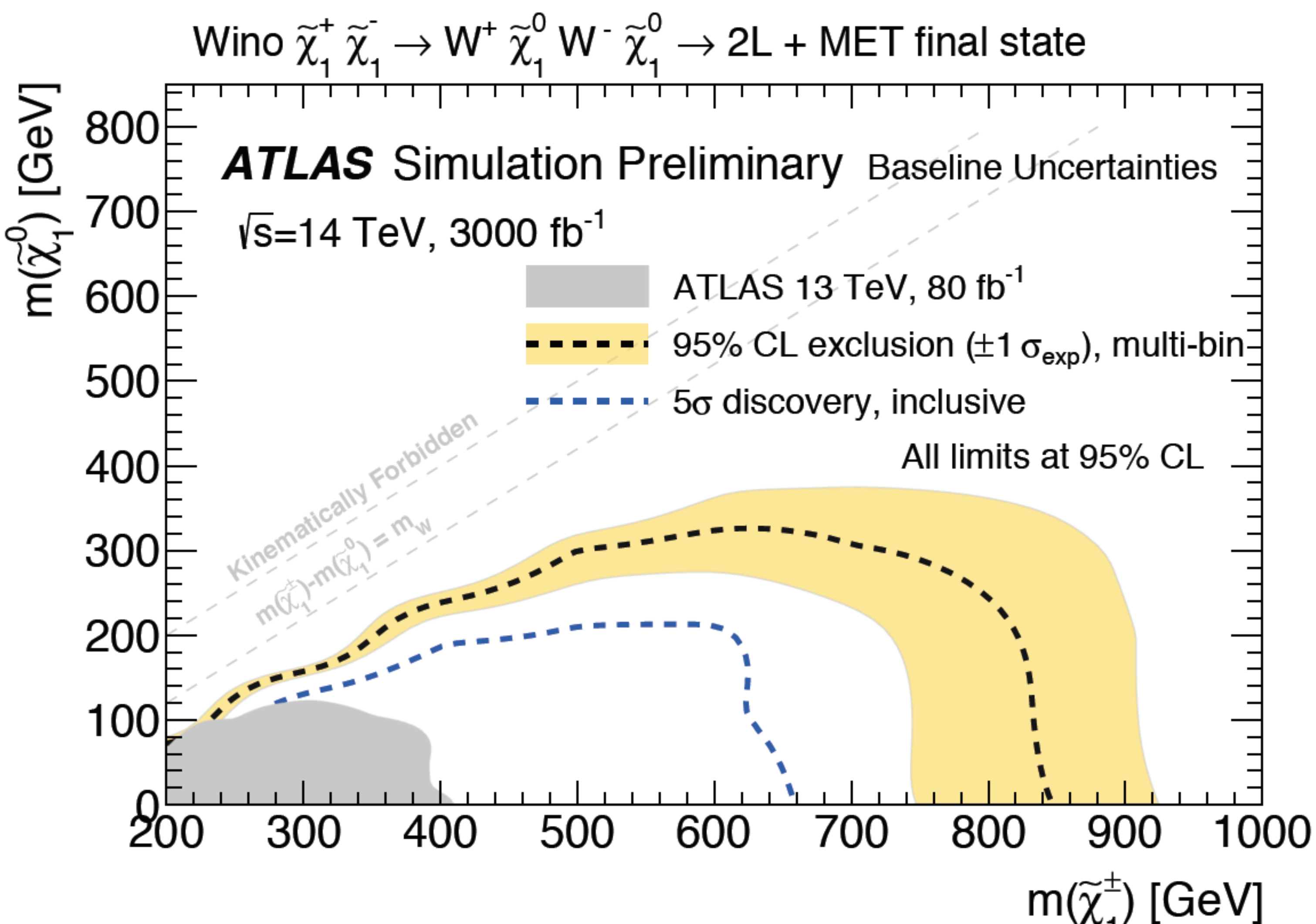


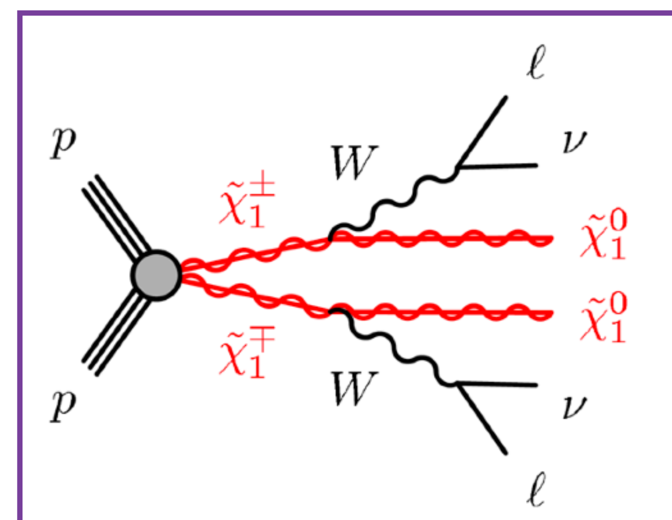
CMS-FTR-18-010

Supersymmetry: ewkinos

pushing down cross-section limits at lower masses

- Wino-like chargino states studied in multiple lepton final states
  - masses up to 650 (850) GeV can be discovered (excluded) from chargino decay to neutralino and W* or up to 900 GeV with degenerate $\tilde{\chi}_2^{\pm}\tilde{\chi}_4^0$
  - limits an order of magnitude beyond LEP and 500 GeV above current limits
  - HL-LHC will probe most of the natural EW SUSY parameter space for wino-like charginos
- Relies on vast upgrades to trigger at L1 and HLT to maintain lepton trigger thresholds!

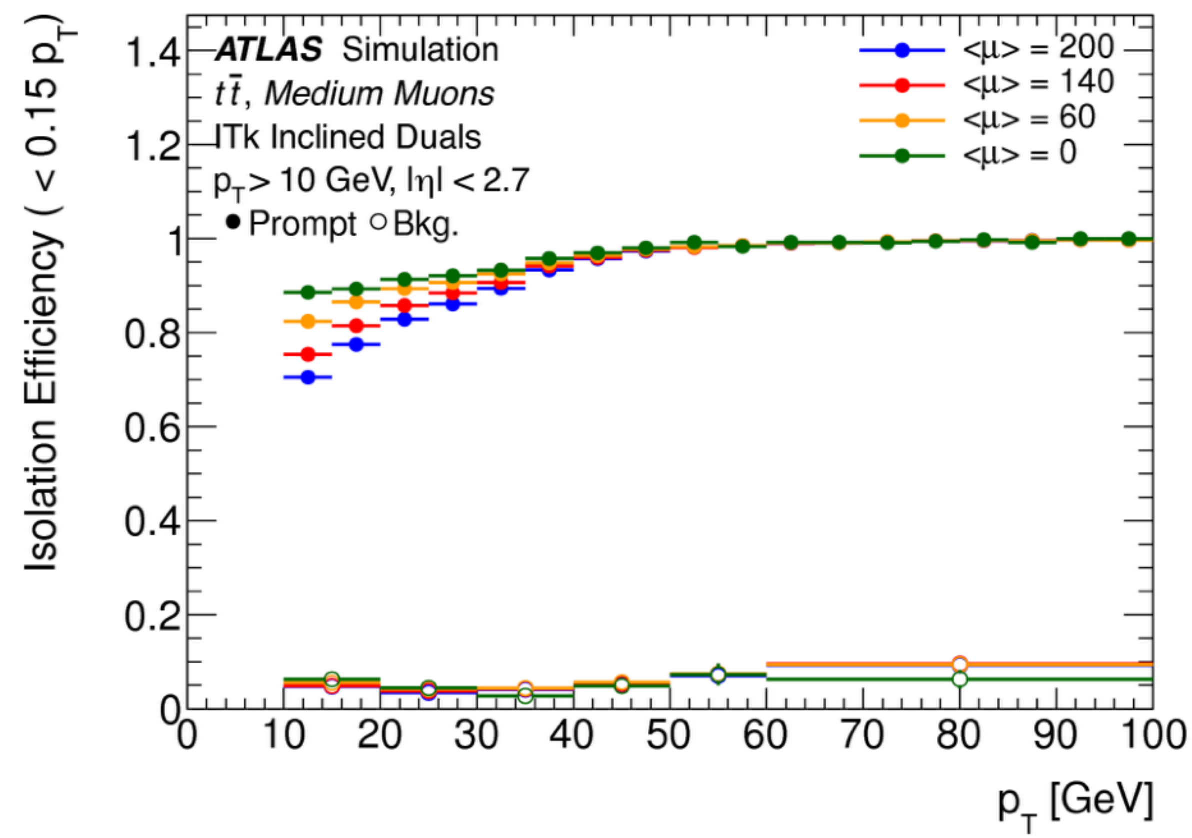


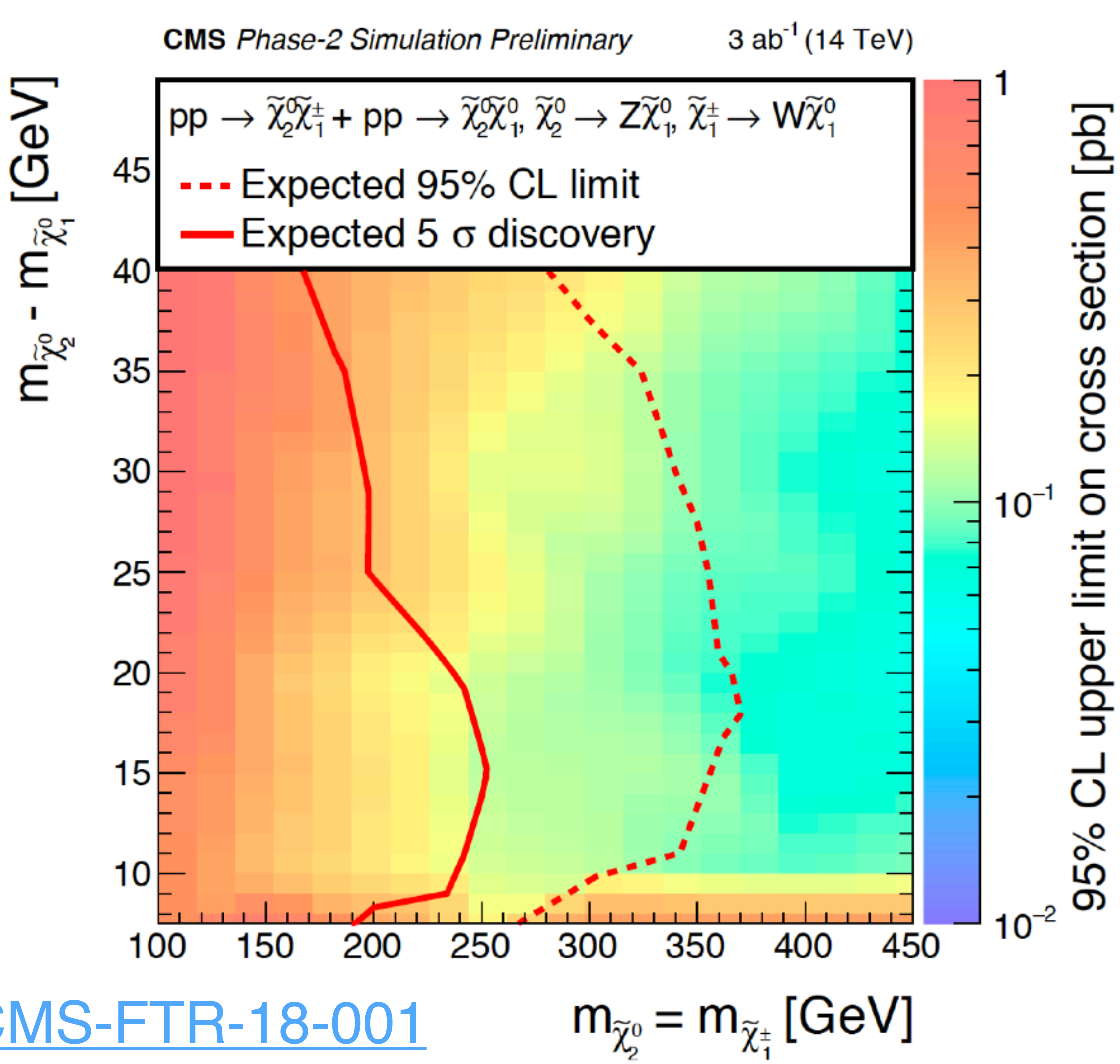


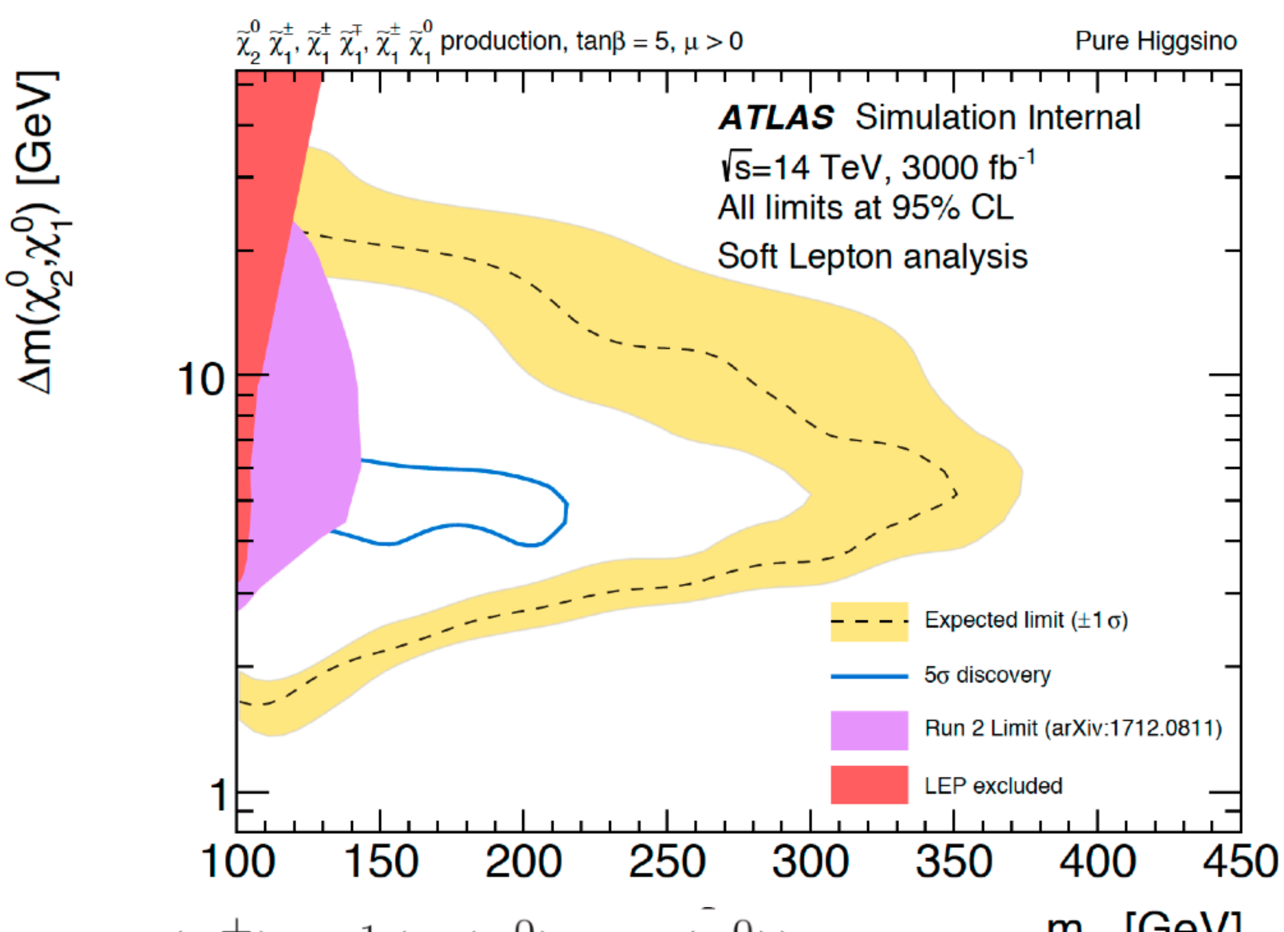
ATL-PUB-2018-048

Supersymmetry: ewkinos

- The last bastion of naturalness: higgsinos and compressed EW mass spectra
  - requires efficiently triggering and reconstructing leptons down to 3-5 GeV and difficult background rejection, including isolation
  - sensitive to higgsino masses up to 350 GeV for mass differences of > 5 GeV







$$m(\tilde{\chi}_1^{\pm}) = \frac{1}{2}(m(\tilde{\chi}_1^0) + m(\tilde{\chi}_2^0)).$$

CMS-FTR-18-001

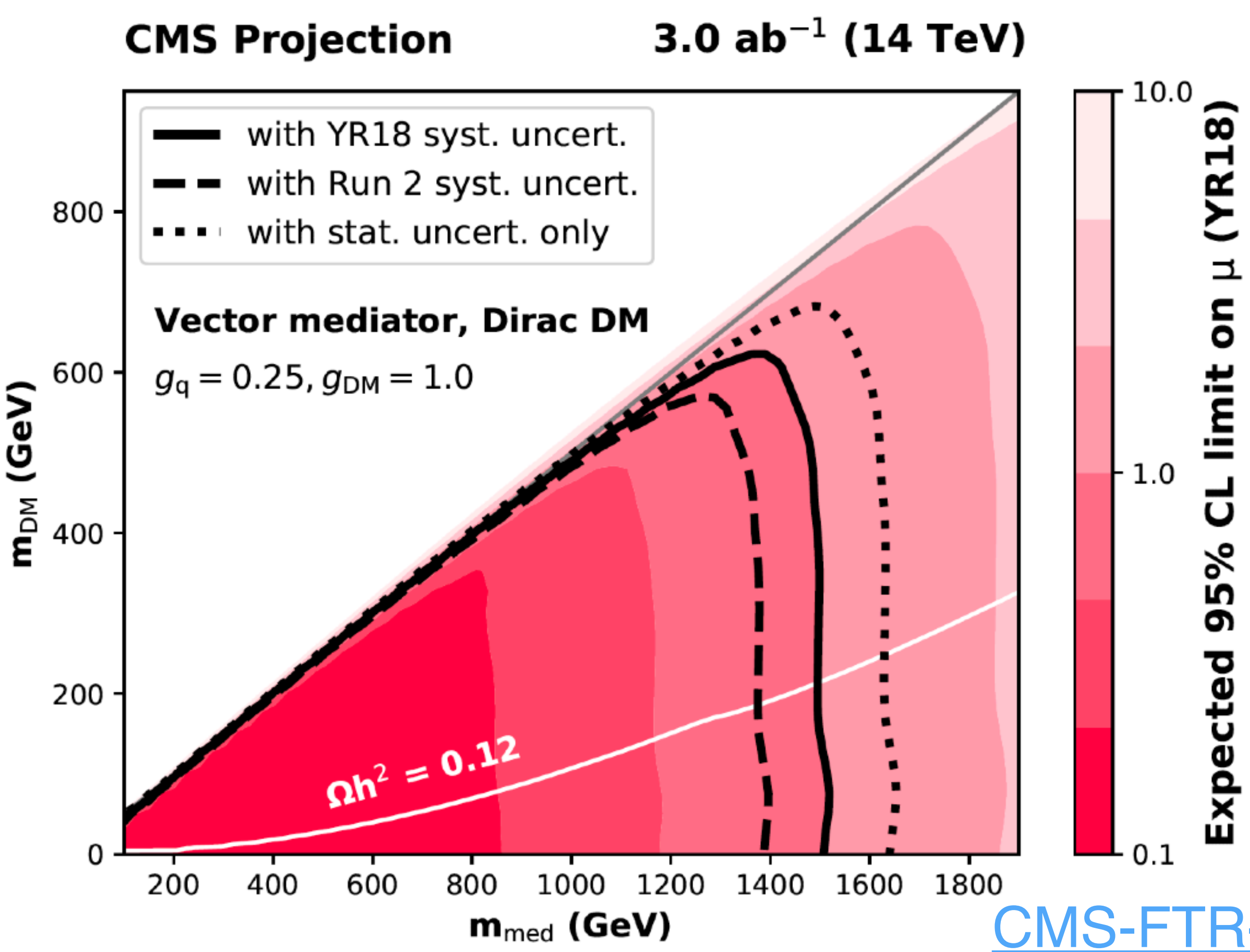
ATL-PUB-2018-048

Dark Matter searches

sensitive to systematic uncertainties

- Mono + X searches will continue to push sensitivity to DM produced in association with other objects
  - will be competitive in some regions with direct neutralino searches, sensitivity from 200 (300) GeV for higgsino (wino) neutralinos
  - quite sensitive to systematic uncertainties, largely on background (W/Z+jets, diboson) estimates

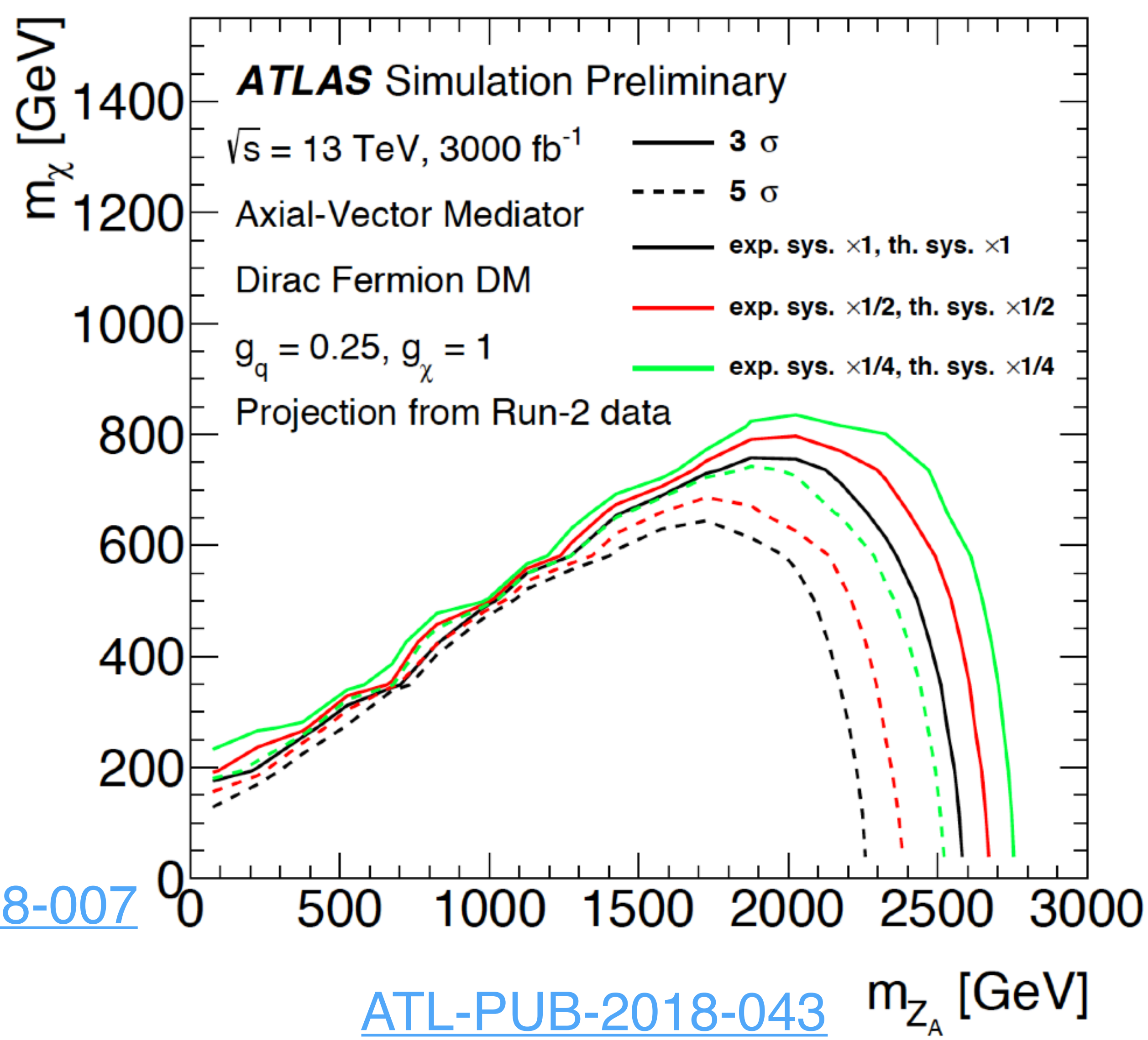
Exclusion sensitivity in mono-Z



CMS-FTR-18-007

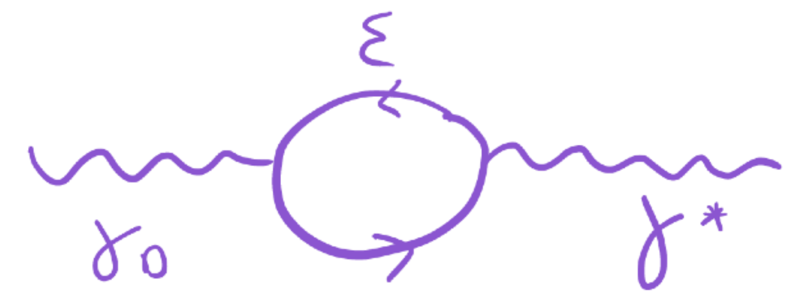
extends the sensitivity of mediator masses by up to a factor of 2 relative to current LHC results

Discovery reach for mono-jet

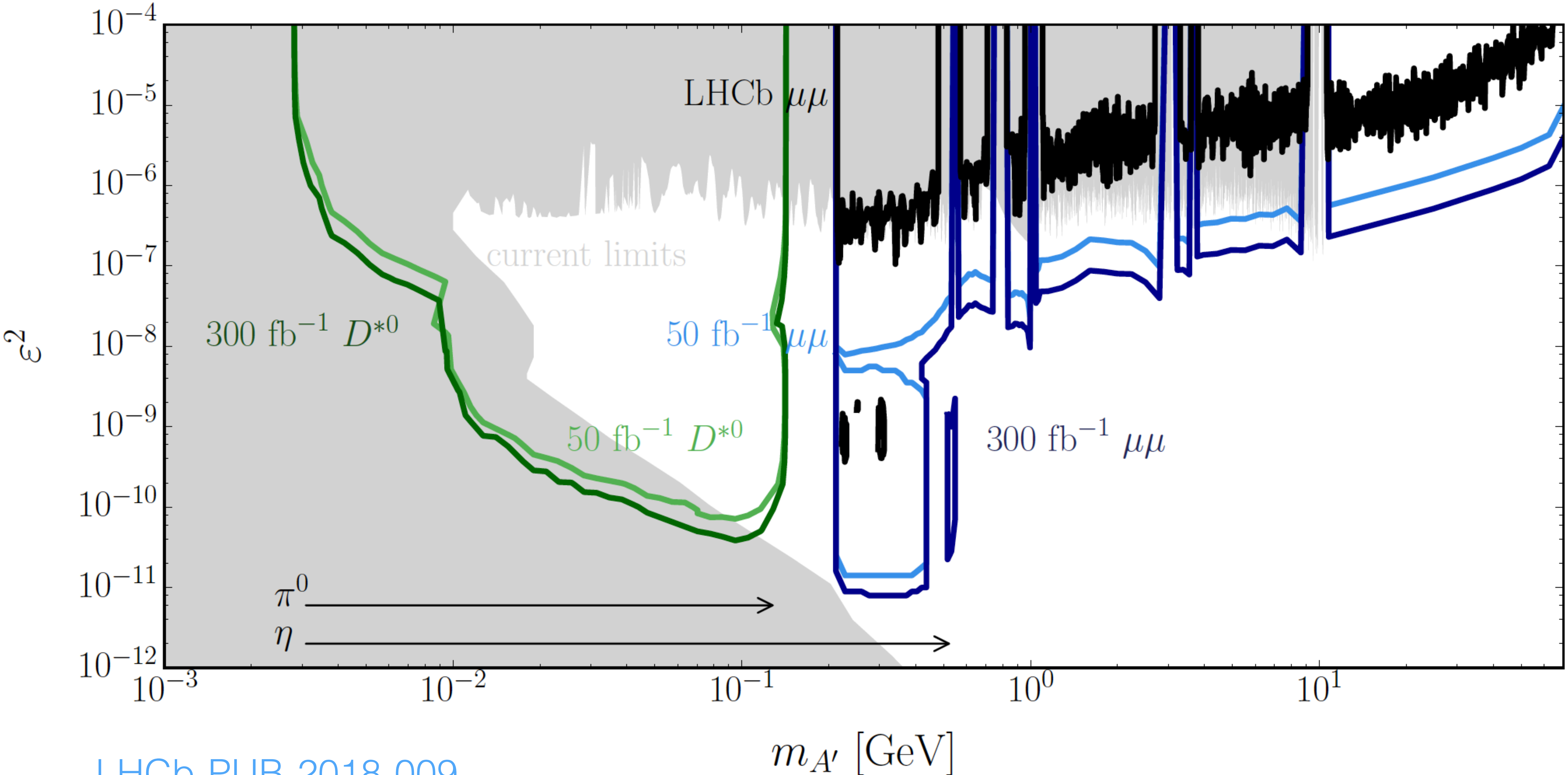


ATL-PUB-2018-043

Dark photons



- LHCb will use a combination of prompt, long-lived, and meson analyses to probe a large part of the mass and mixing plane for dark photons

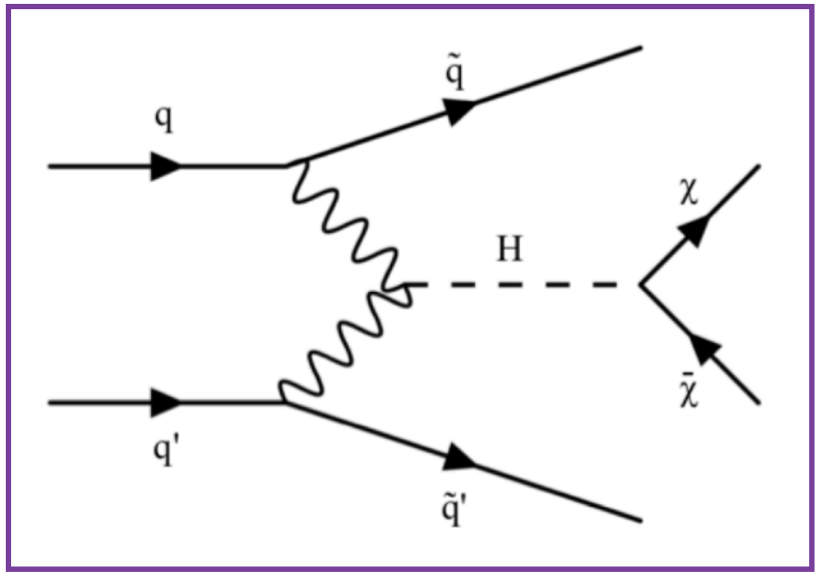


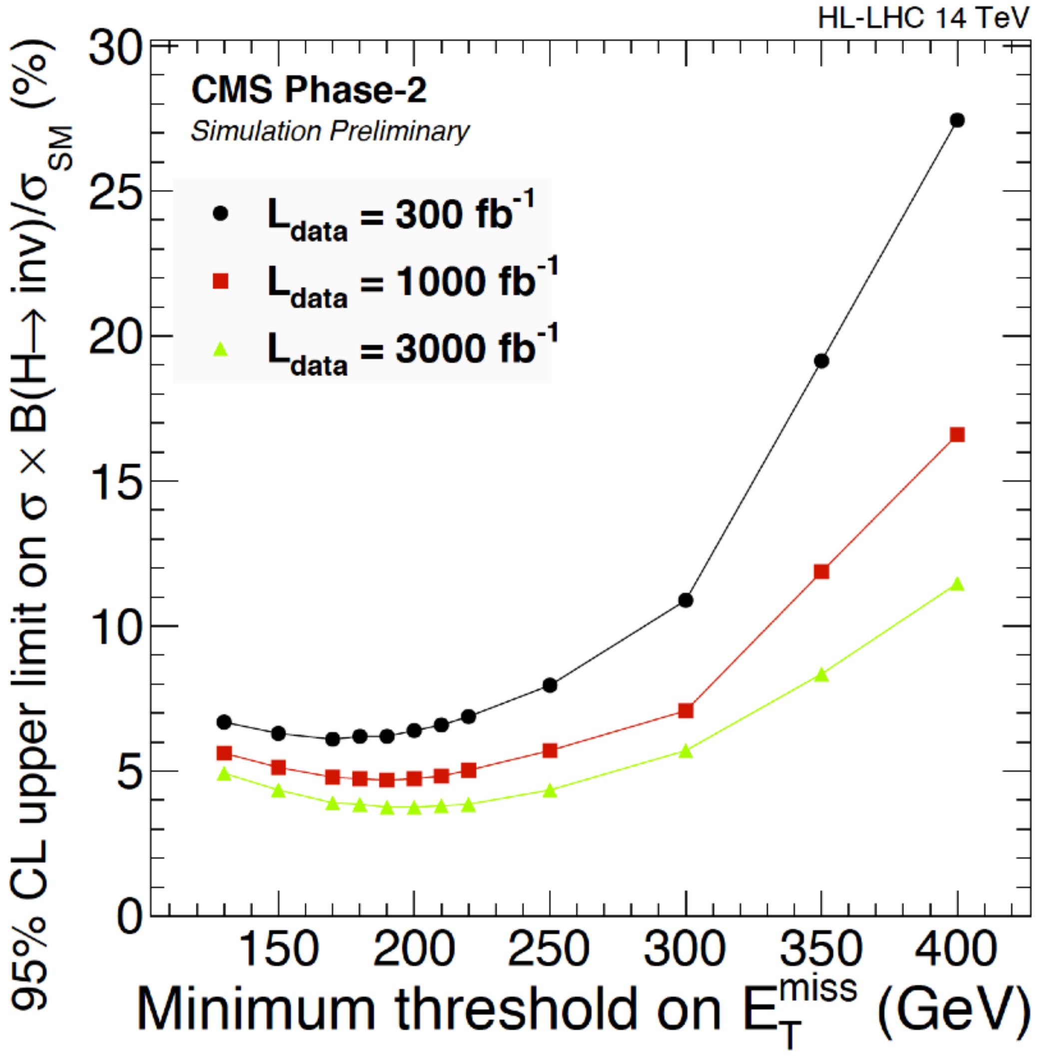
LHCb-PUB-2018-009

Higgs to invisible

Case study: pileup mitigation and importance of systematic uncertainties

- Higgs to invisible BR is powerful and model independent probe for light dark matter
  - current limit on BR (H—> inv.) is 0.19, mostly driven by vector boson fusion production
  - current limit has ~ equal syst. and stat. uncertainties
- Maintaining signal efficiency and background rejection is challenging at high pileup
  - main signal is 2 forward jets and MET
  - rejection of pileup jets is paramount
  - main backgrounds behave differently at HL-LHC relative to LHC
    - Z—> νν + jets
    - W—> νl + jets





CMS-FTR-18-016

Higgs to invisible

- Higgs to invisible BR is powerful and model independent probe for light dark matter
  - single channels from CMS/ATLAS expected to reach 4% on BR (H—> inv.)
  - combination of experiments and channels expected to give limit to **2.5%**
    - with significant work to mitigate pileup and reduce systematic and theoretical uncertainties

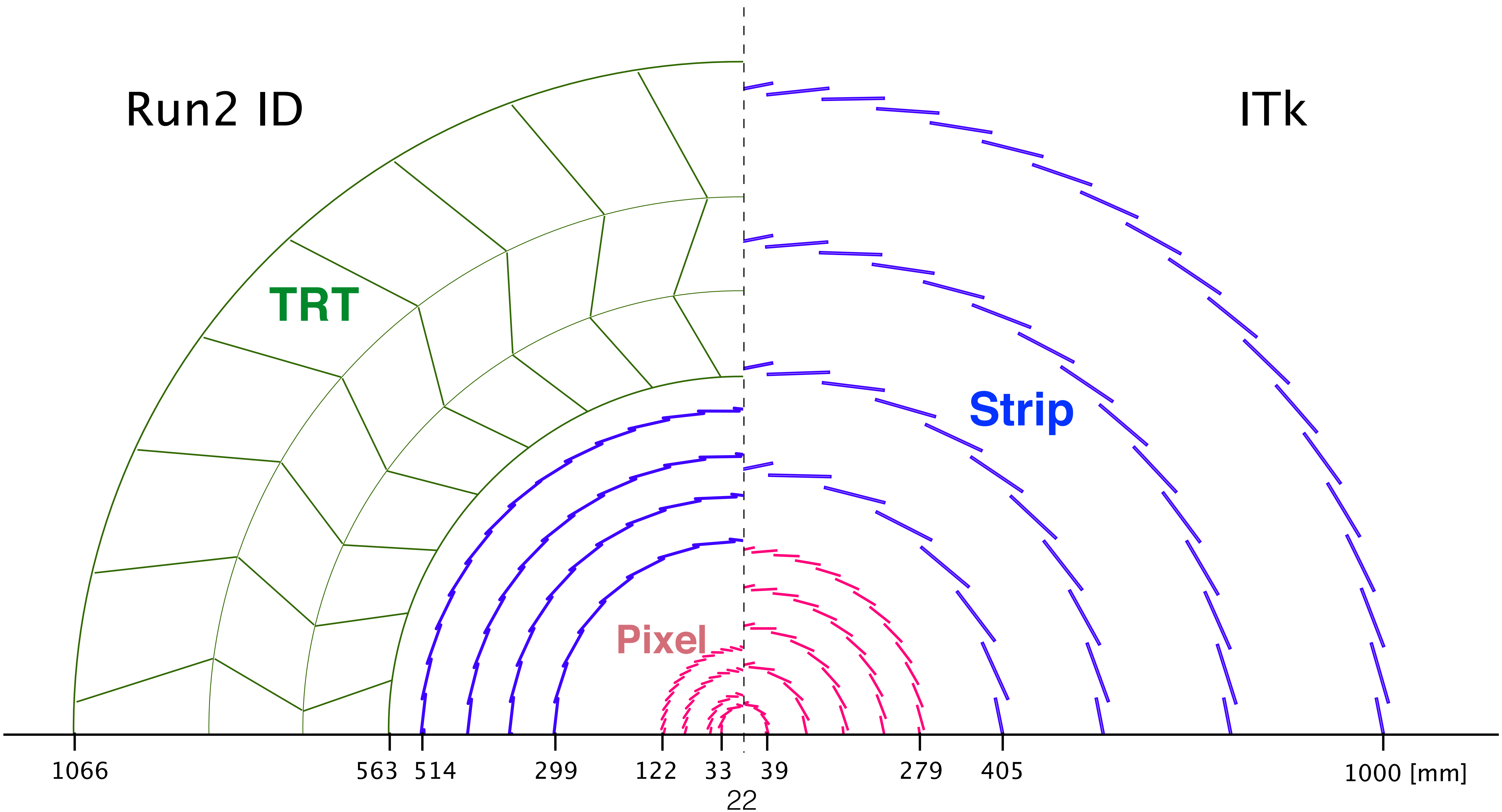
Run 2 syst ⟶ goal / assumptions for HL-LHC syst

Systematic	From Ref. [14]	This analysis
e-ID	1%(gsf)$\oplus$1%(idiso)	1%
μ-ID	1%(reco)$\oplus$1%(id)$\oplus$0.5%(iso)	0.5%
e-veto	0.6%(gsf)$\oplus$1.5%(idiso)	1%
μ-veto on QCD V+jets	5%(reco)$\oplus$5%(id)$\oplus$2%(iso)	2%
μ-veto on EWK V+2jets	10%(reco)$\oplus$10%(id)$\oplus$6%(iso)	6%
τ-veto	1–1.5% for QCD–EWK	0.5–0.75%
b-tag-veto	0.1% (sig) 2% (top)	0.05% (sig) 1% (top)
JES	14%(sig) 2%(W/W) 1%(Z/Z)	4.5%(sig) 0.5%(W/W) 0.2%(Z/Z)
Integrated luminosity	2.5%	1%
QCD multijet	1.5%	1.5%
Theory on W/Z ratio	12.5%	7%
ggH normalisation	24%	20%

different sources of systematic uncertainty considered in Ref. [14] and for the HL-LHC setup considered in this analysis.

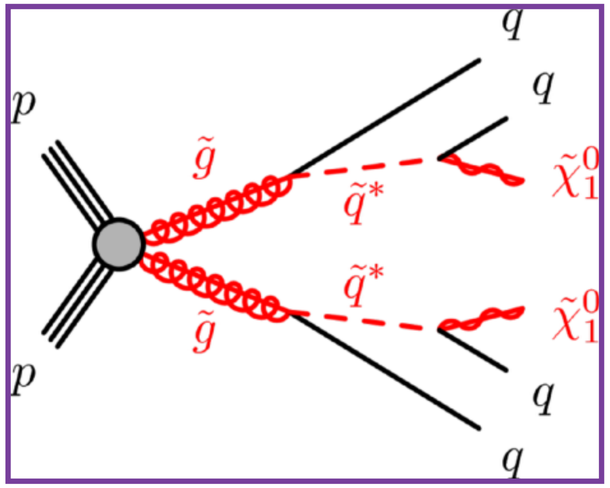
Challenges and opportunities: new detectors

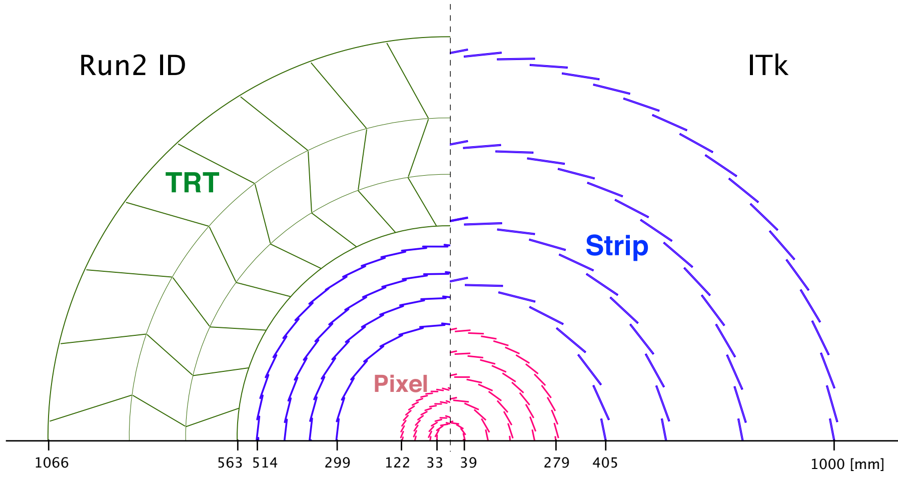
Case study: new inner detector in ATLAS and its impact on sensitivity of long-lived particle searches



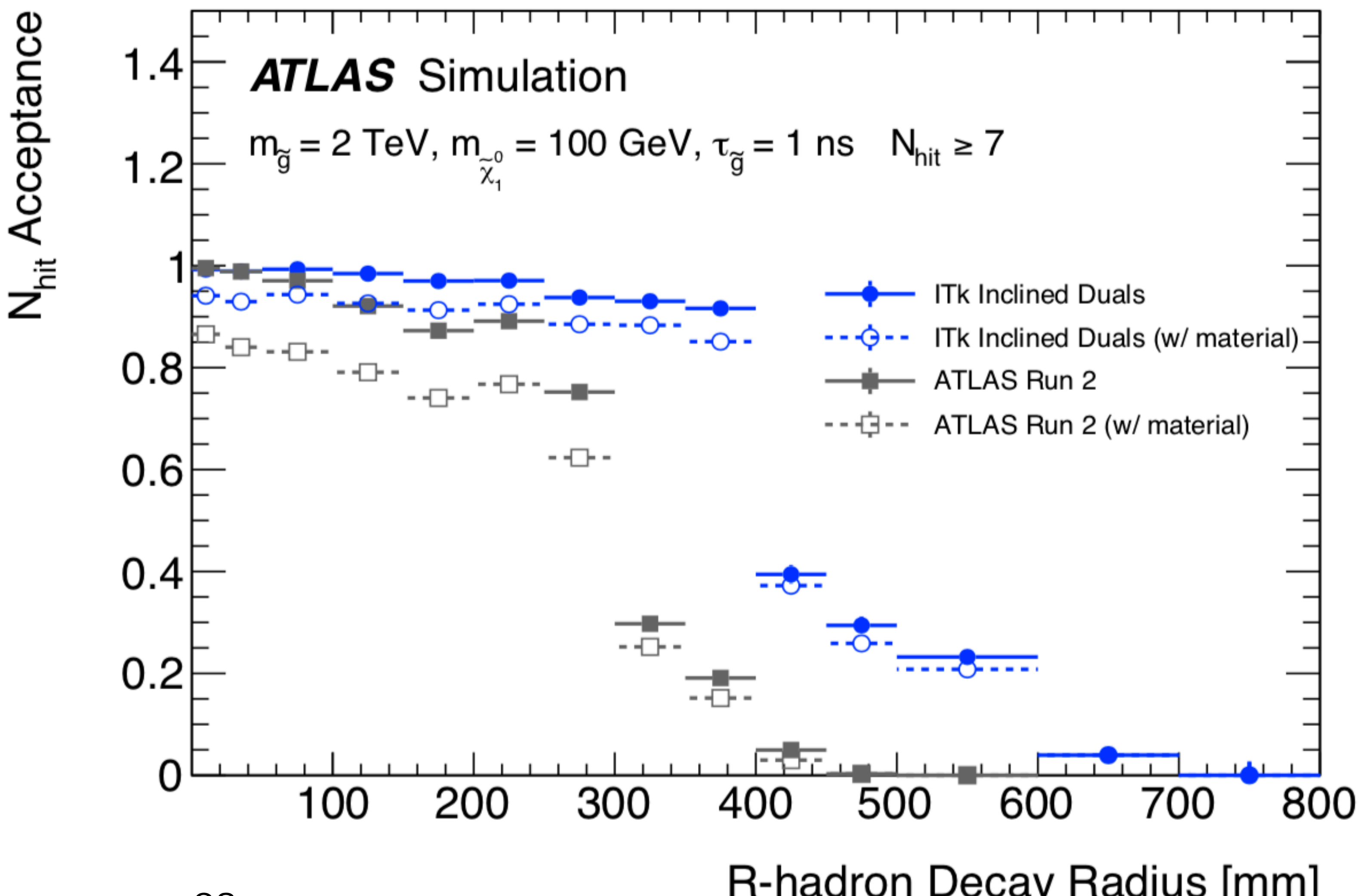
Displaced vertex signatures

- Displaced vertices in the inner detector are sensitive to long-lived particles with τ ~10 ps - 10 ns
    - decaying to multiple charged particles





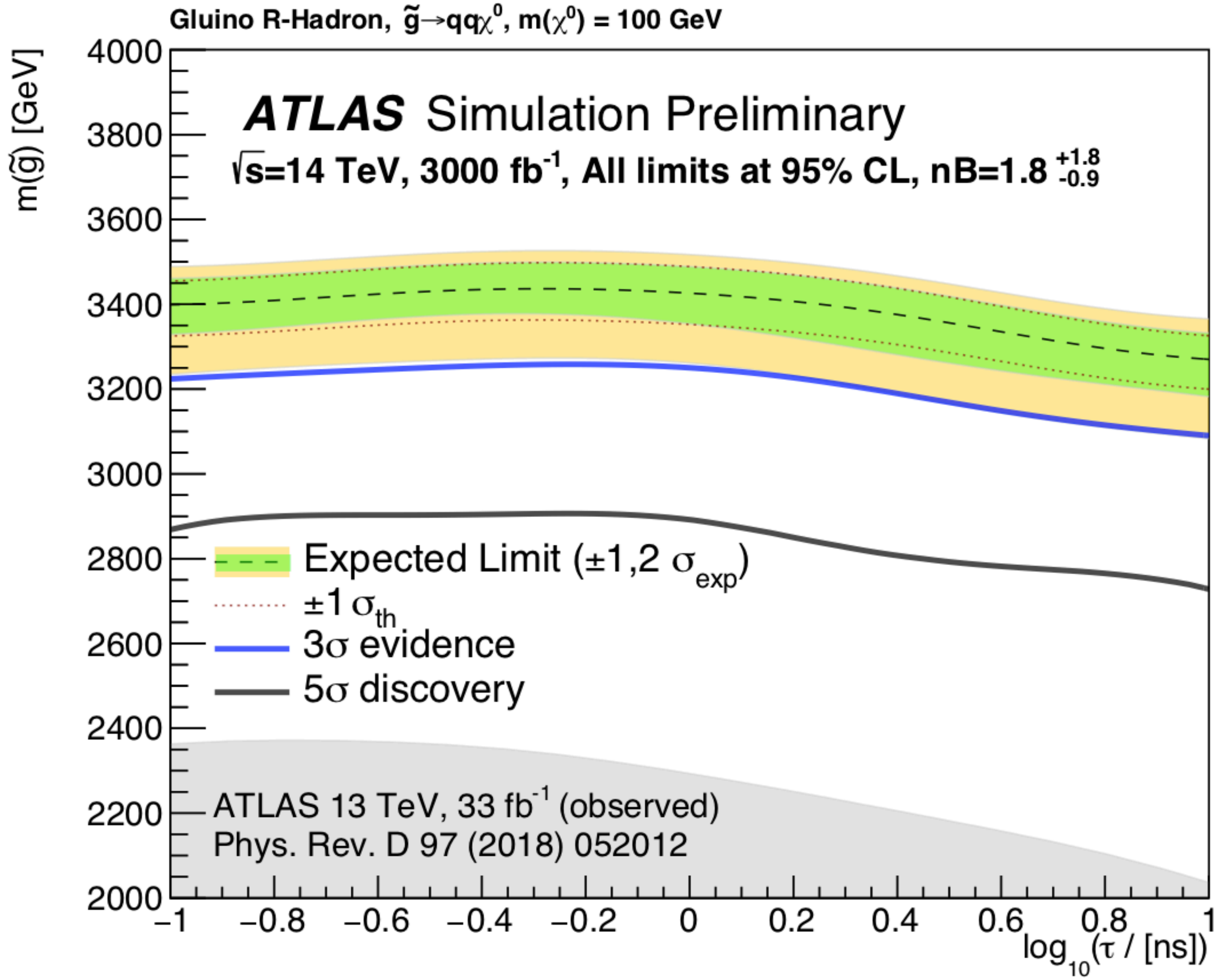
- Need a minimum number of silicon hits after decay to well-reconstruct vertex and reject background
    - reconstruction efficiency gains relative to current detector from larger silicon volume!



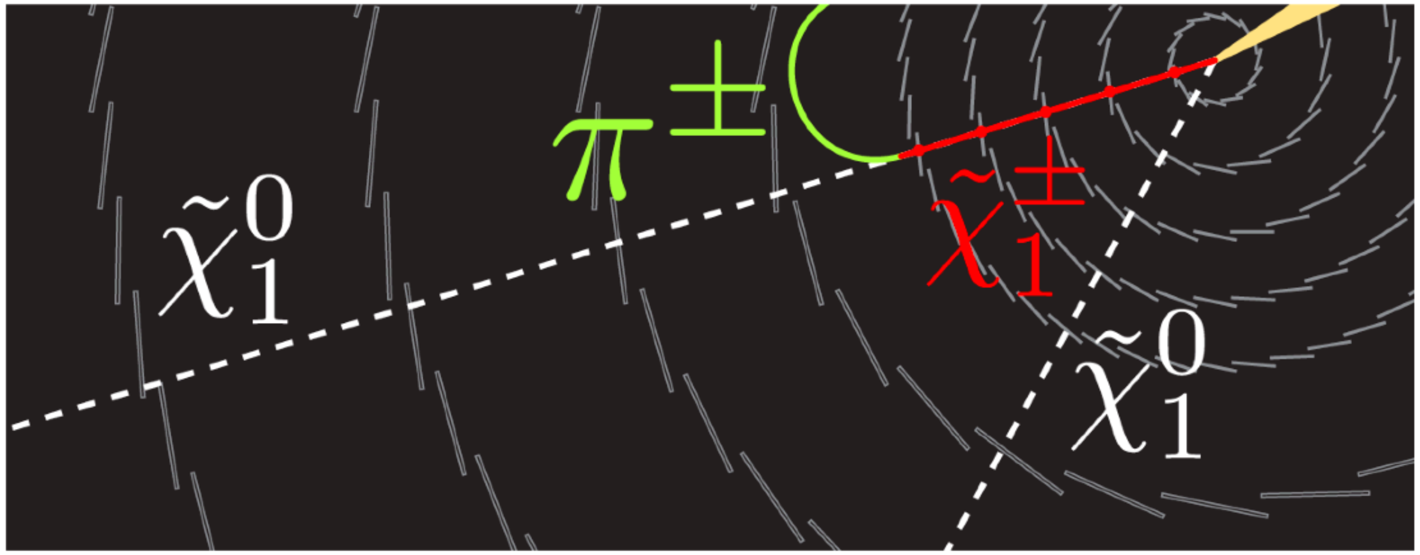
ATL-PUB-2018-033

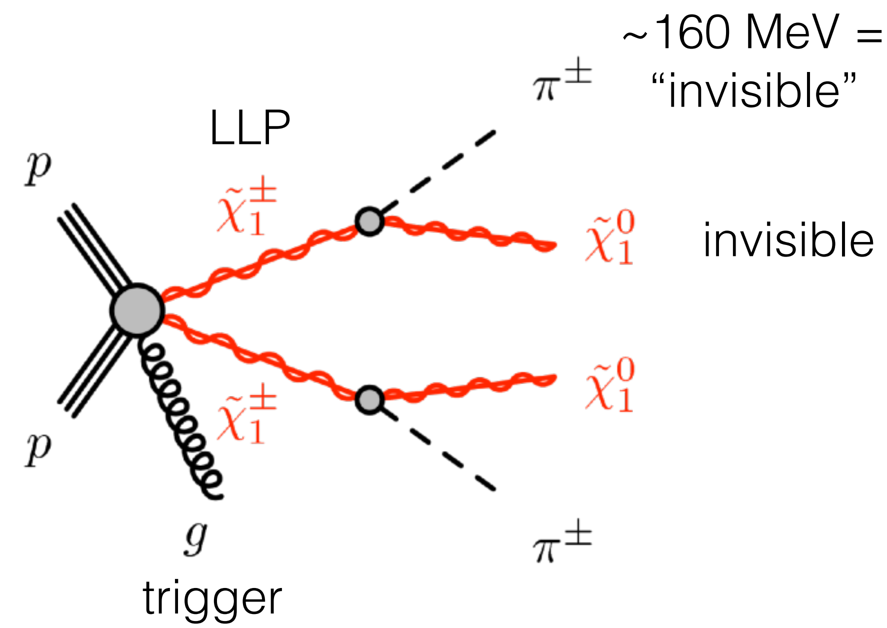
Displaced vertex signatures

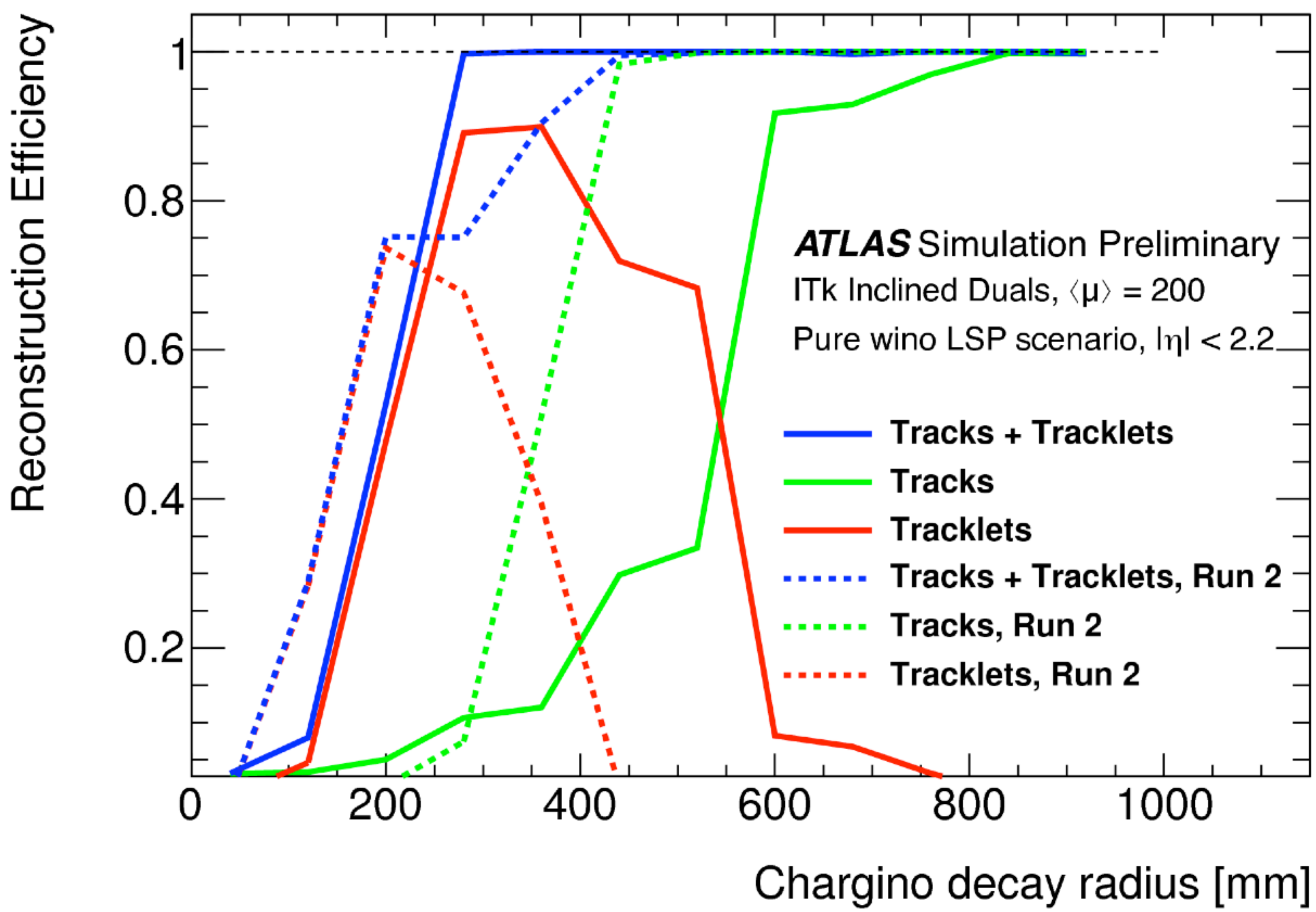
- Translates to increased relative sensitivity at larger lifetimes relative to current analysis, purely from new detector geometry



Disappearing tracks



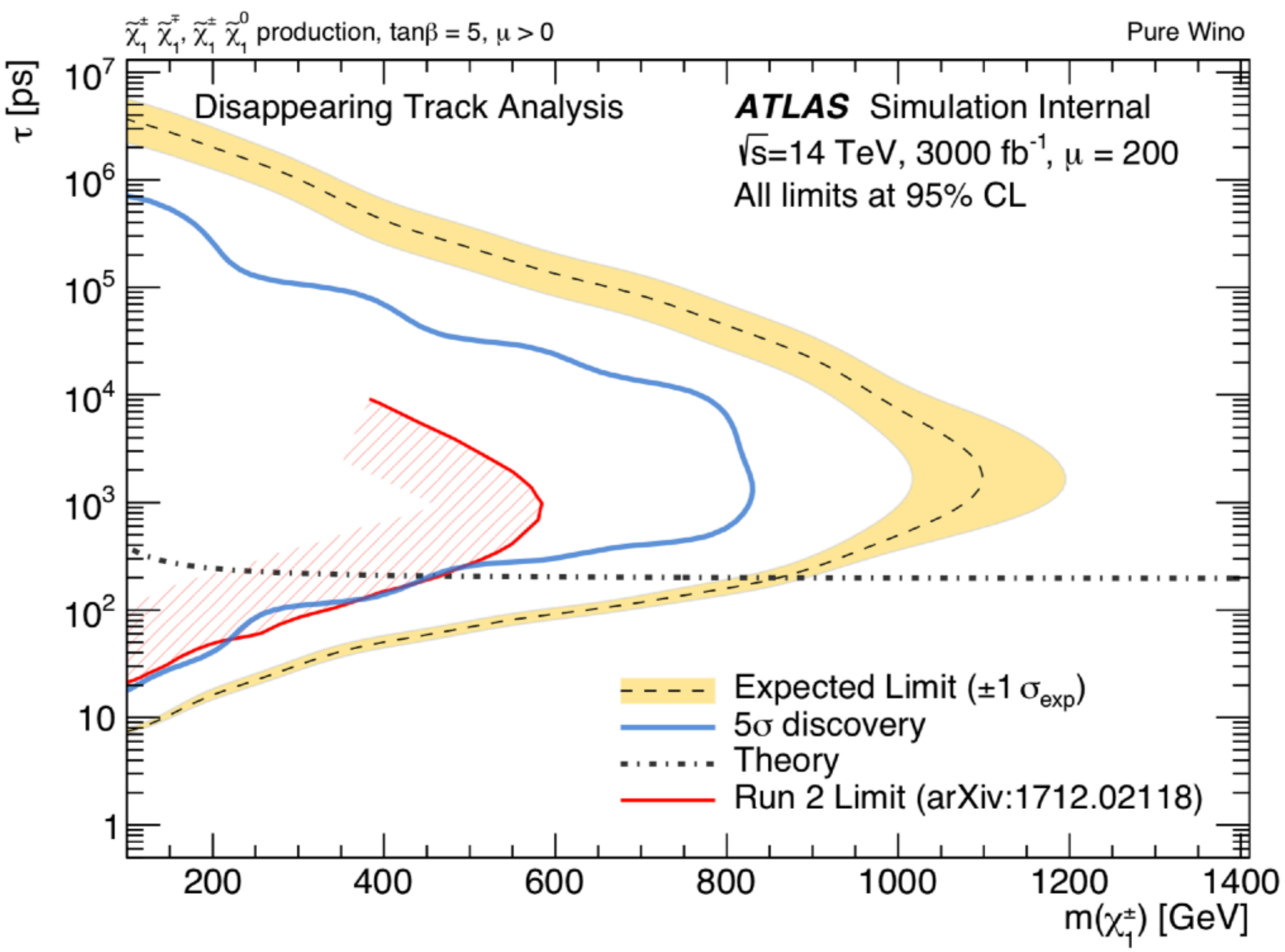


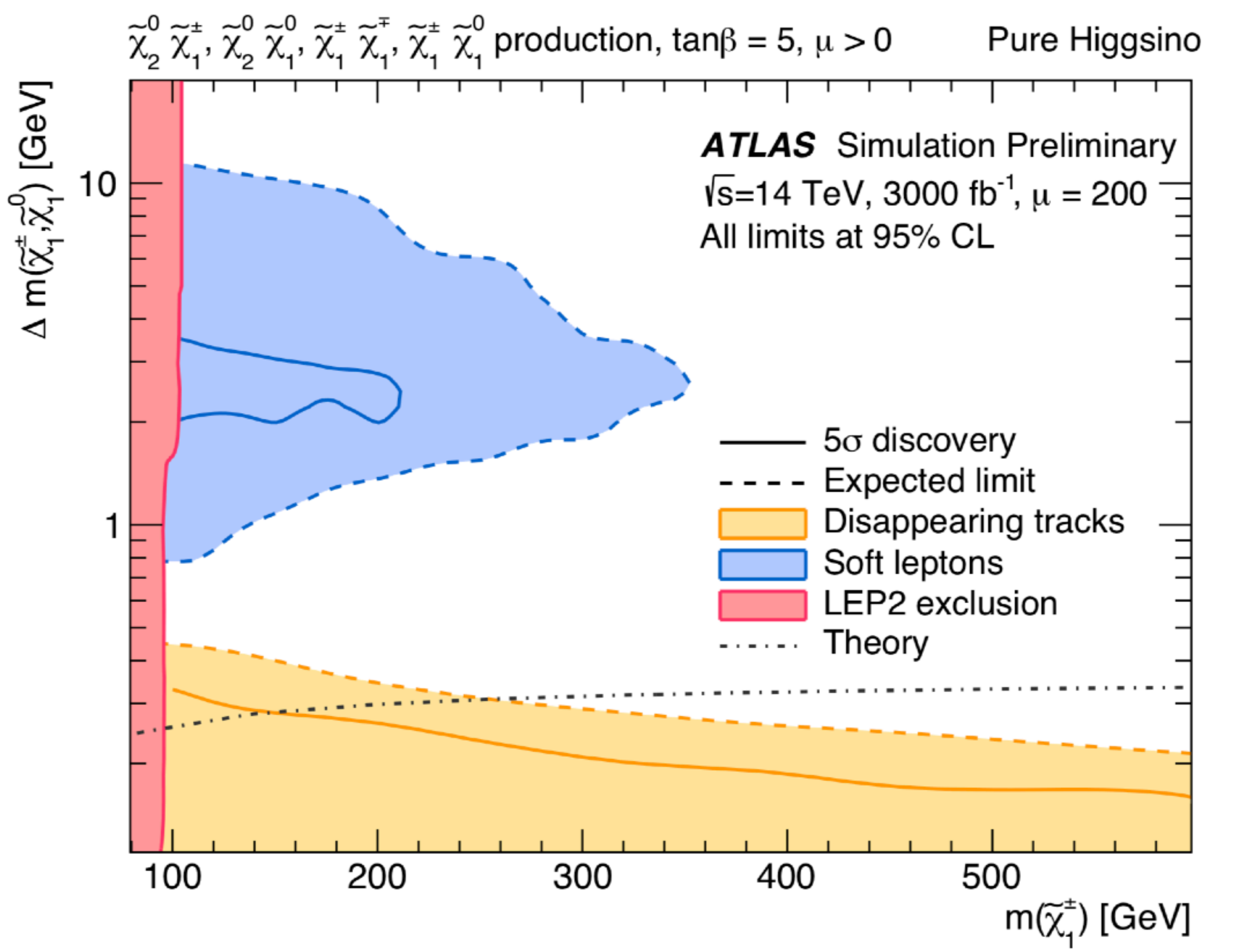


- Pure higgsino or wino LSP can give rise to long-lived chargino which decays to invisible
- Look for short track with 3 or 4 hits in pixel detector
- Efficiency of short tracks very sensitive to position of first few layers of pixel detector!

Disappearing tracks

- Sensitivity gains relative to Run 2 (3) more challenging at shorter lifetimes, solely from new detector geometry

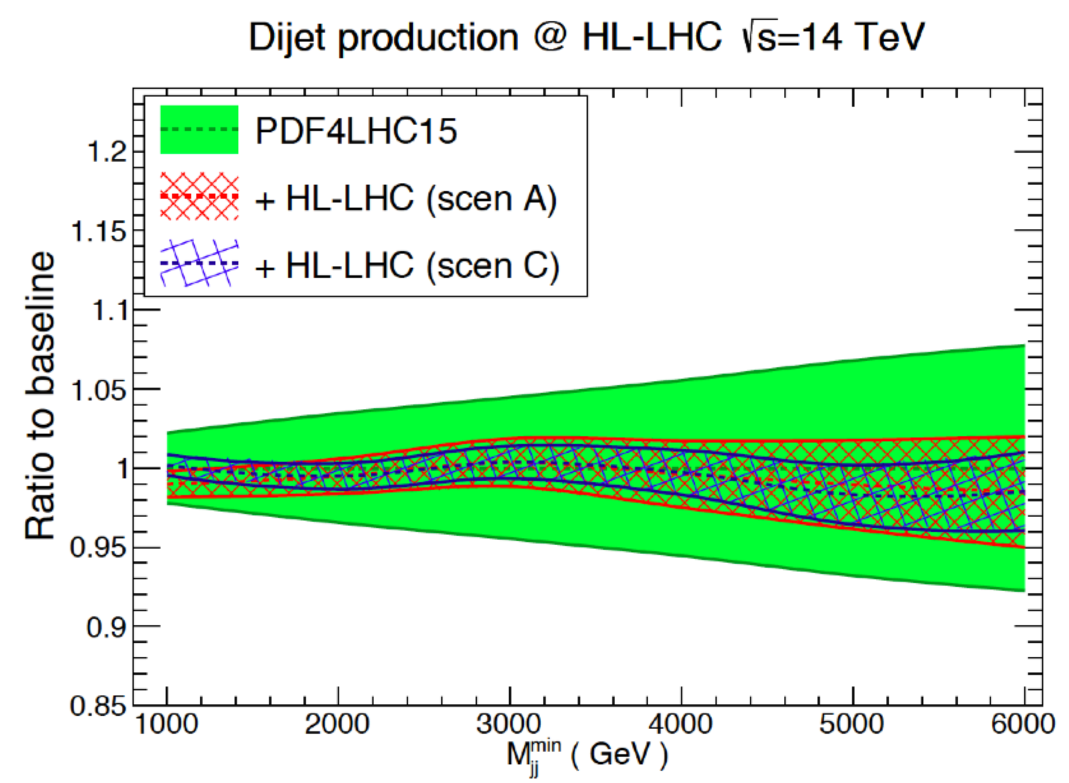




ATL-PUB-2018-048

Summary and outlook

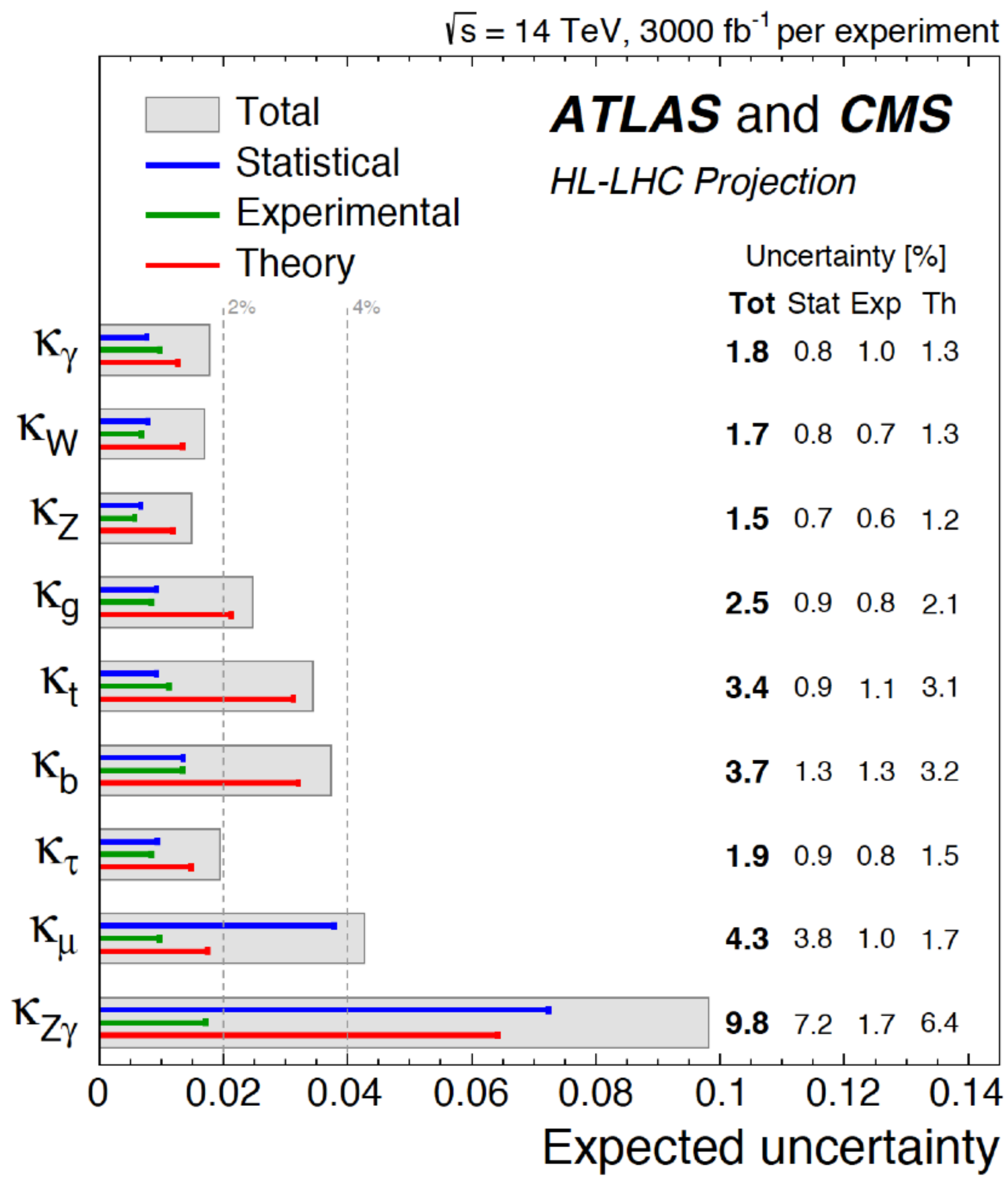
- Enormous work by community to study the potential physics reach of HL-LHC
- The work is just beginning
    - All projections rely on enormous work on many fronts — the accelerator upgrade, the detector upgrades, trigger, performance and reconstruction advancements, analysis improvements, theory improvements, PDF reduction, precise luminosity determination…
- Depending on the new physics, sensitivity (and the potential to discover!) new physics with masses from 200 GeV to 8 TeV
    - some channels have straightforward gains with higher energy, increased lumi, and upgraded detector
    - other channels will require more creative and sustained effort to improve over Run 3 sensitivity



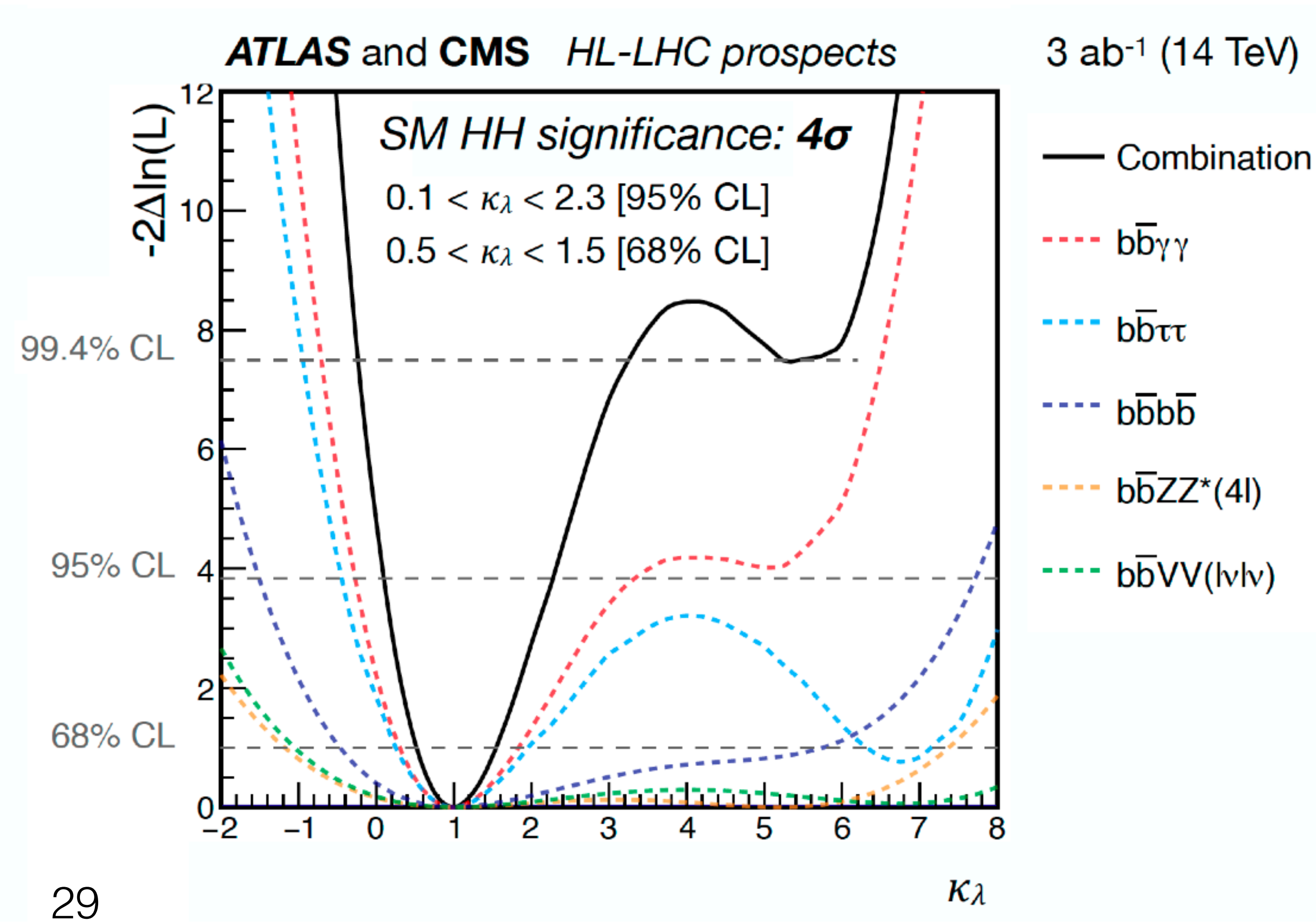
Backup

Higgs physics as a probe of BSM

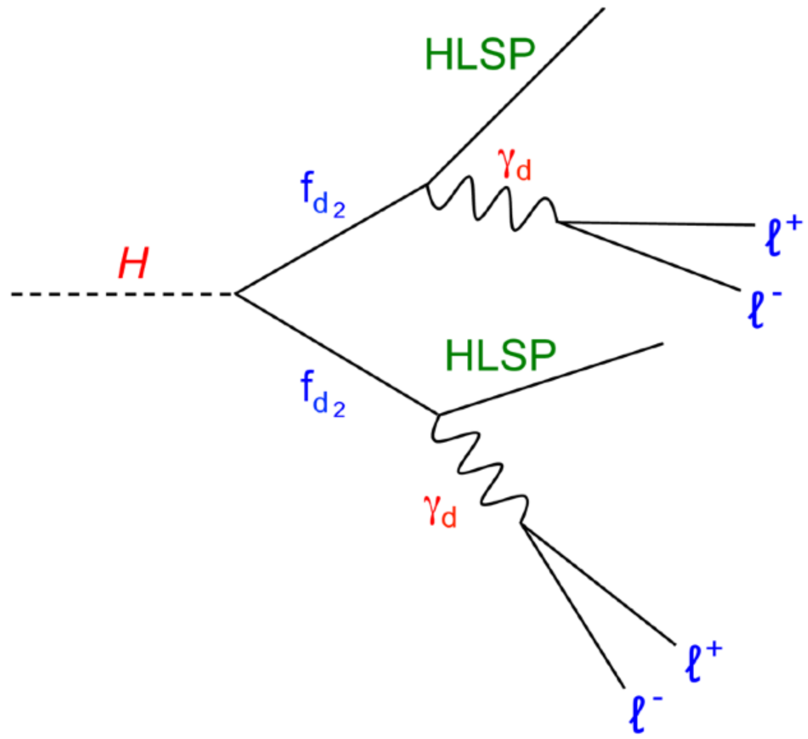
- Main Higgs couplings measured to % level precision
  - limited by theoretical systematic uncertainties
- First measurements of H—> μμ and H—>γZ
- Improved constraints on higgs self-coupling

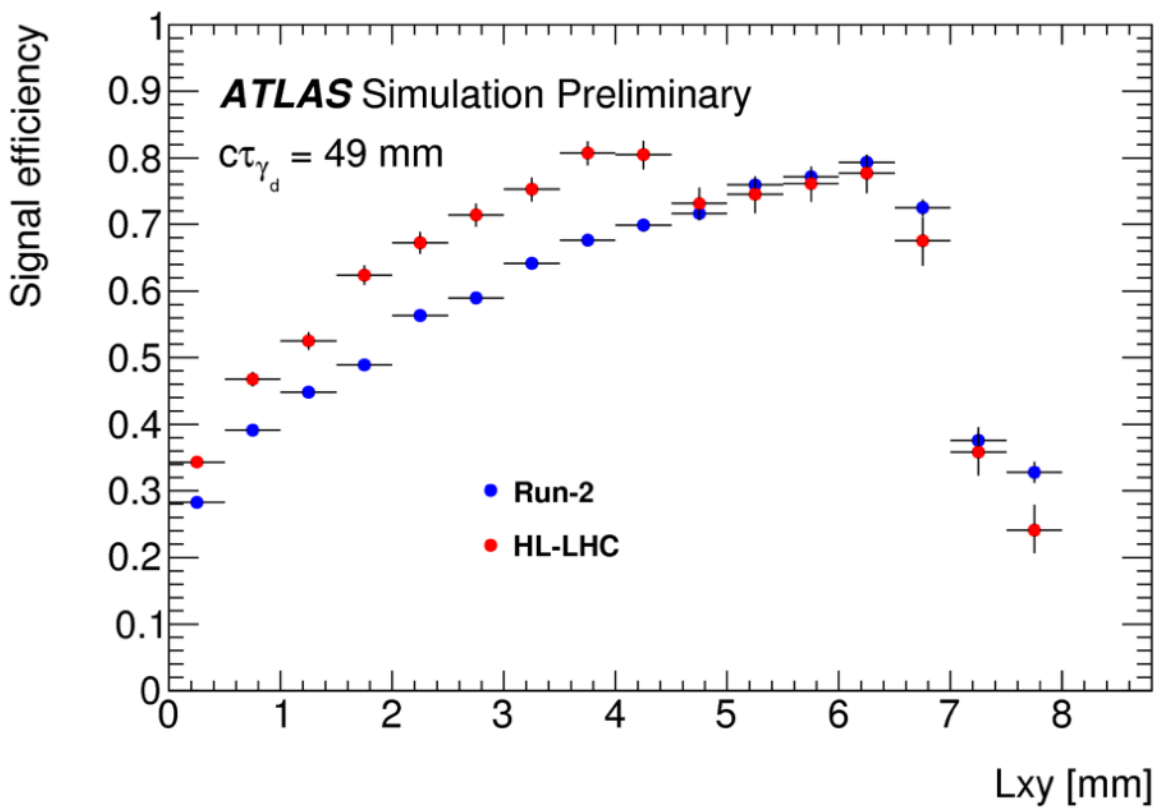


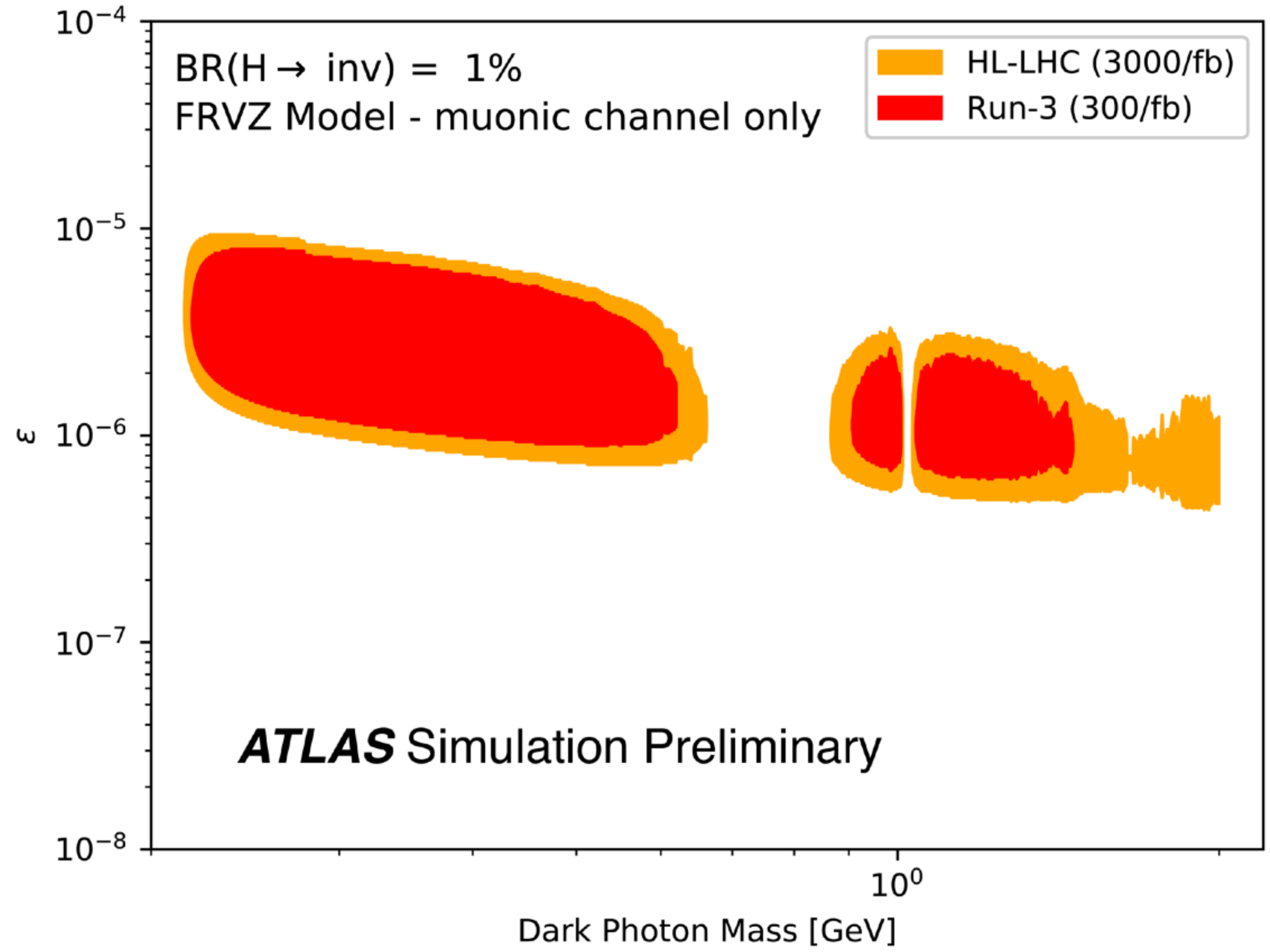
- Higgs self-coupling measured to $0.5 < \kappa_\lambda < 1.5$ at 68% CL



Higgs portal to dark photons

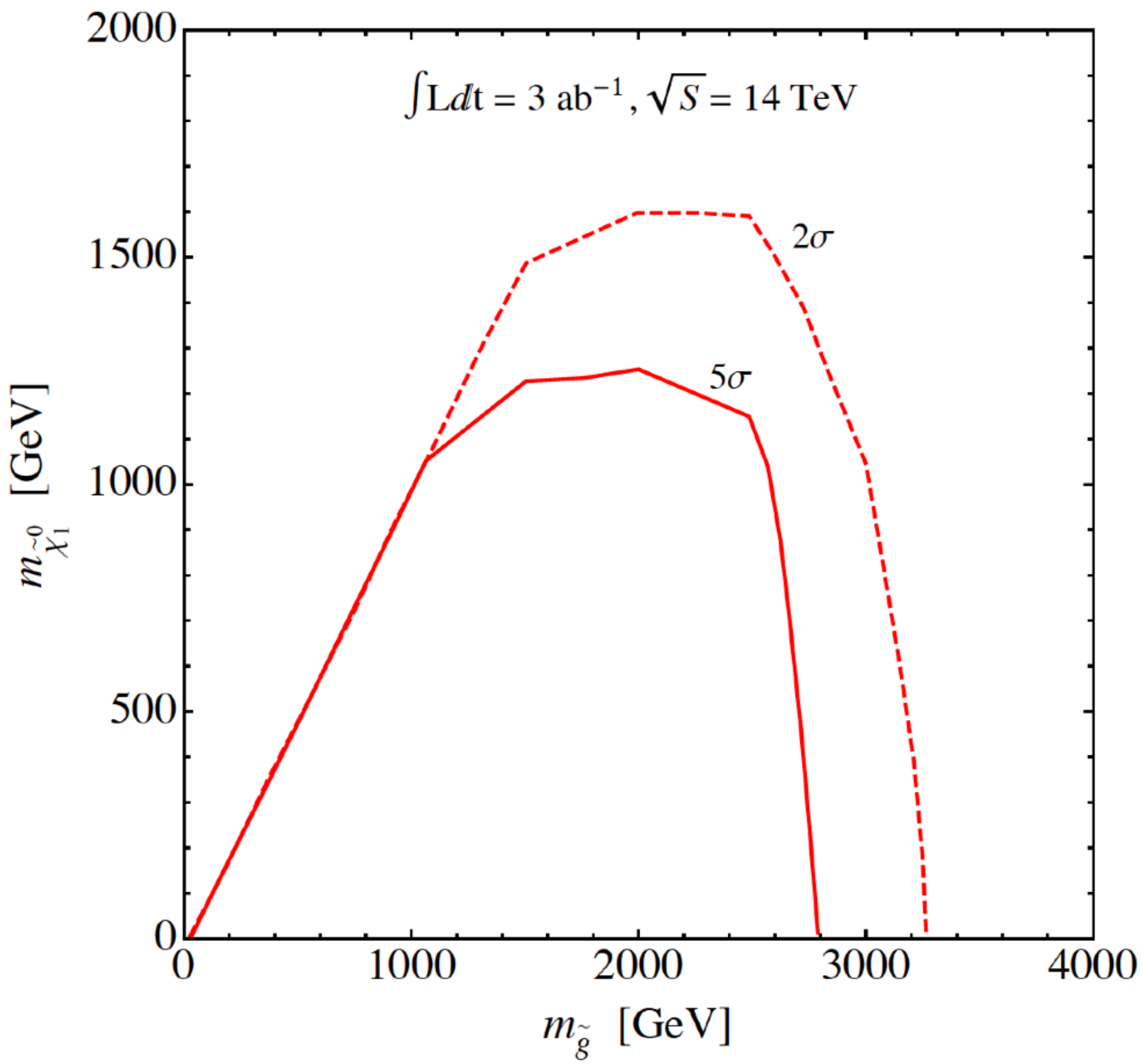






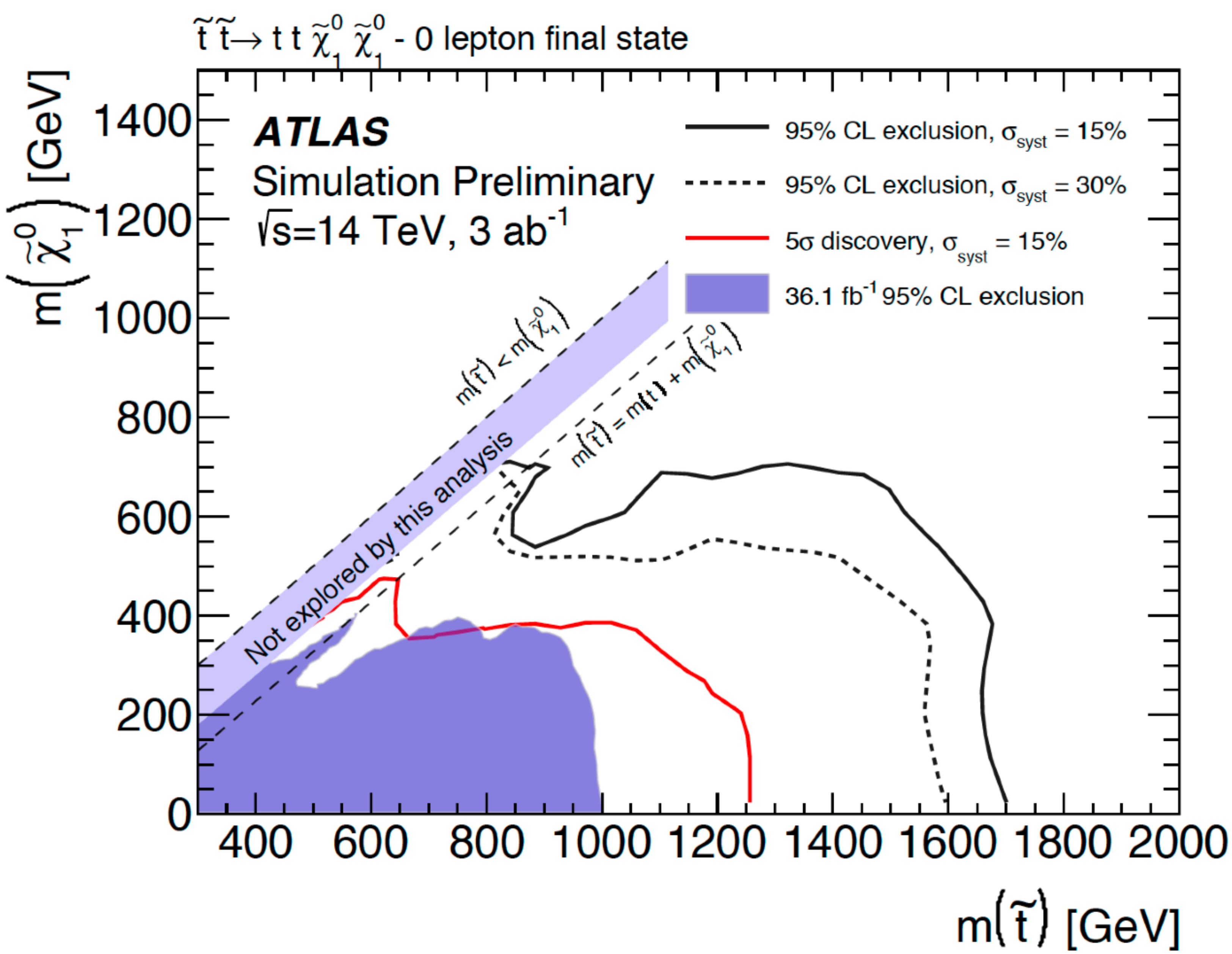
Supersymmetry: gluino and squarks

- Gluino pair production with prompt decay to quarks and neutralino
  - sensitivity to discover 2.8 TeV gluinos and exclude up to 3.2 TeV
  - nearly 1.0 TeV above current Run 2 limits



Supersymmetry: gluino and squarks

- Stop pair production, decaying to prompt top-pair and neutralinos
  - sensitivity to discover 1.25 TeV stops and exclude up to 1.7 TeV
  - nearly 700 GeV above current Run 2 limits



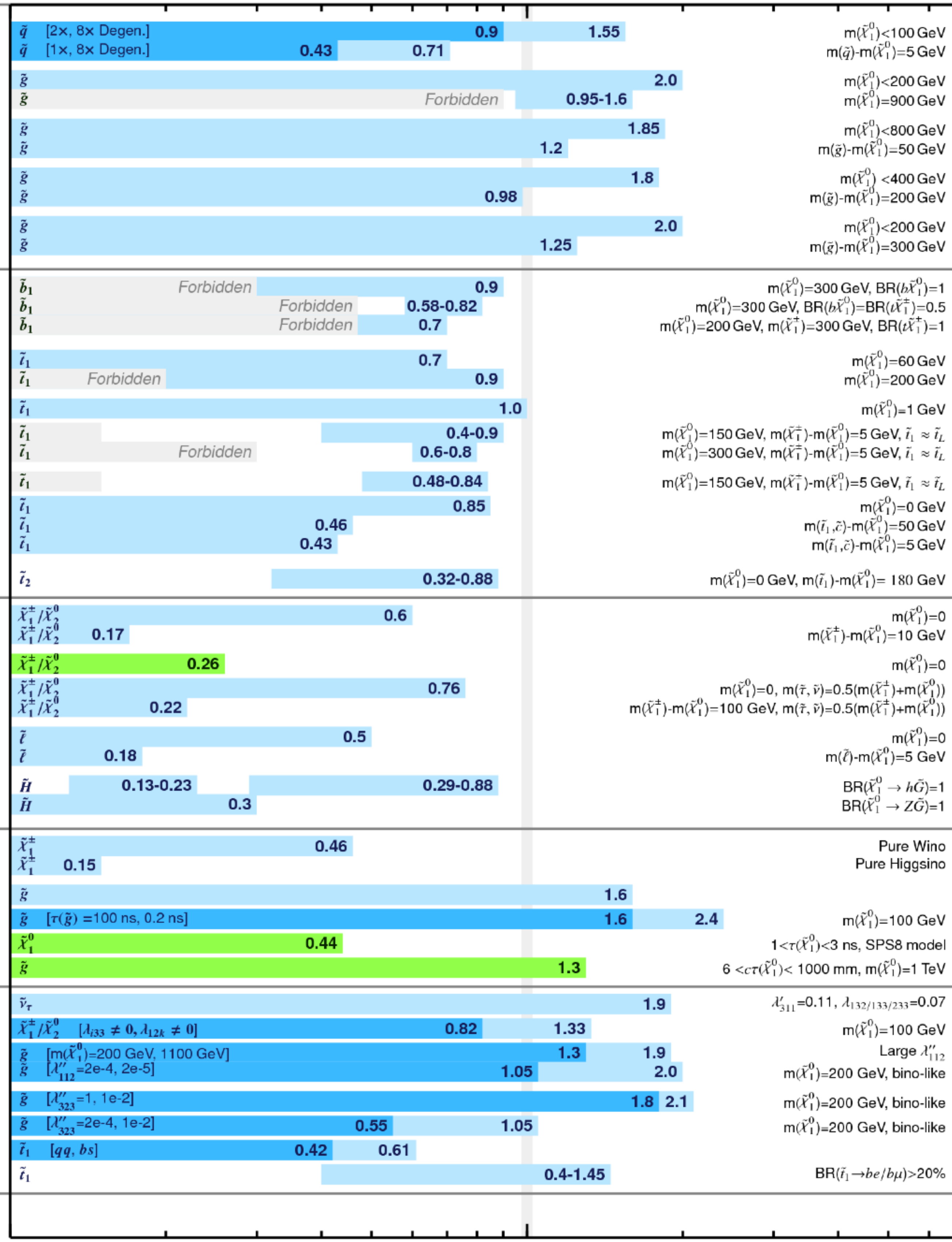
ATLAS SUSY Searches* - 95% CL Lower Limits

July 2018

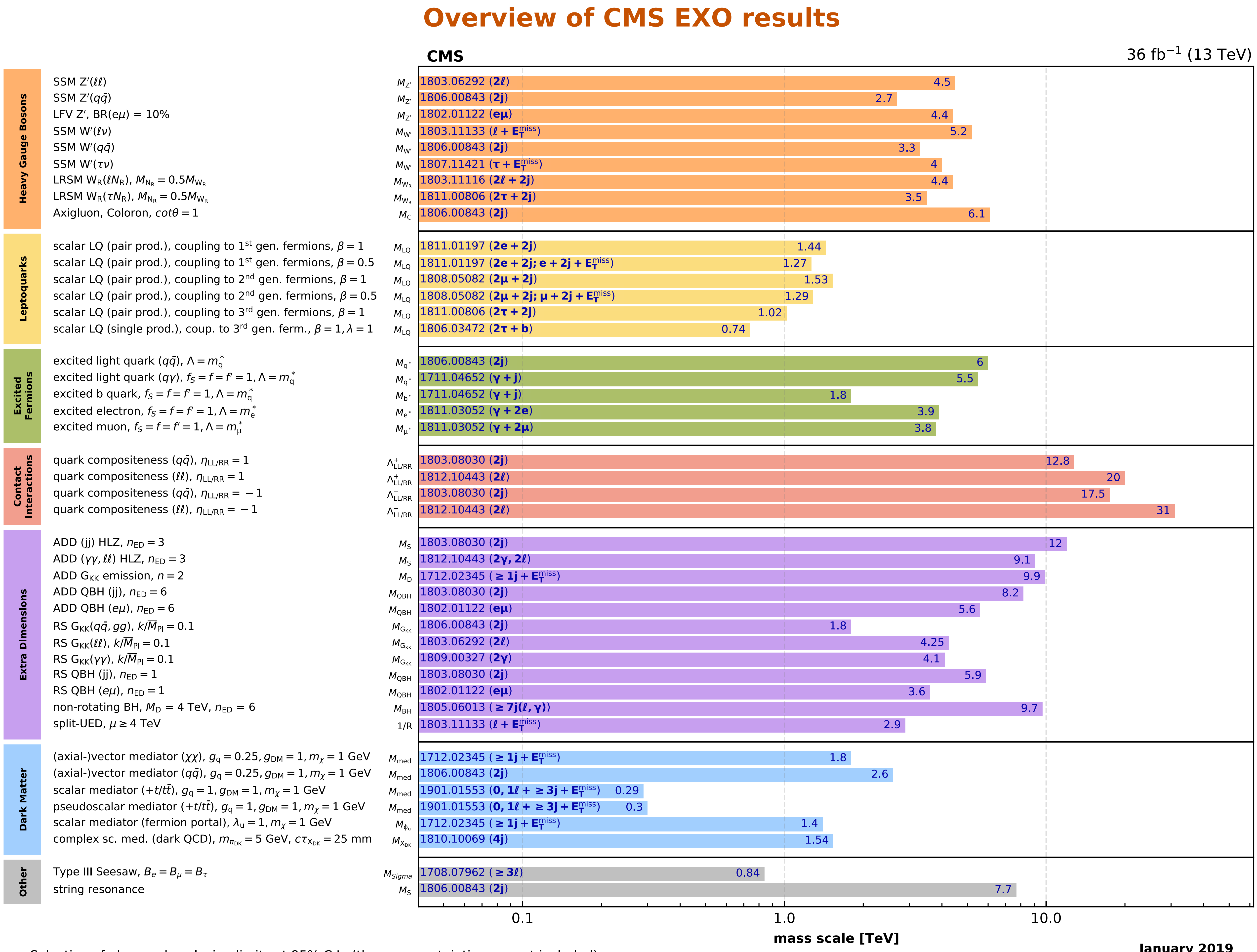
ATLAS Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ [2×, 8× Degen.] 0.9 1.55	$m(\tilde{\chi}_1^0)$<100 GeV	1712.02332
		mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 0.71	$m(\tilde{q})-m(\tilde{\chi}_1^0)$=5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.0	$m(\tilde{\chi}_1^0)$<200 GeV	1712.02332
						$\tilde{g}$ Forbidden 0.95-1.6	$m(\tilde{\chi}_1^0)$=900 GeV	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 e,μ	4 jets	-	36.1	$\tilde{g}$ 1.85	$m(\tilde{\chi}_1^0)$<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	Yes	36.1	$\tilde{g}$ 1.2	$m(\tilde{g})-m(\tilde{\chi}_1^0)$=50 GeV	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 1.8	$m(\tilde{\chi}_1^0)$ <400 GeV	1708.02794
		3 e,μ	4 jets	-	36.1	$\tilde{g}$ 0.98	$m(\tilde{g})-m(\tilde{\chi}_1^0)$=200 GeV	1706.03731
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	36.1	$\tilde{g}$ 2.0	$m(\tilde{\chi}_1^0)$<200 GeV	1711.01901
		3 e,μ	4 jets	-	36.1	$\tilde{g}$ 1.25	$m(\tilde{g})-m(\tilde{\chi}_1^0)$=300 GeV	1706.03731
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	$m(\tilde{\chi}_1^0)$=300 GeV, BR($b\tilde{\chi}_1^0$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.58-0.82	$m(\tilde{\chi}_1^0)$=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^\pm$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.7	$m(\tilde{\chi}_1^0)$=200 GeV, $m(\tilde{\chi}_1^\pm)$=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1, M_2 = 2\times M_1$		Multiple		36.1	$\tilde{t}_1$ 0.7	$m(\tilde{\chi}_1^0)$=60 GeV	1709.04183, 1711.11520, 1708.03247
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.9	$m(\tilde{\chi}_1^0)$=200 GeV	1709.04183, 1711.11520, 1708.03247
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	36.1	$\tilde{t}_1$ 1.0	$m(\tilde{\chi}_1^0)$=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{H}$ LSP		Multiple		36.1	$\tilde{t}_1$ 0.4-0.9	$m(\tilde{\chi}_1^0)$=150 GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
			Multiple		36.1	$\tilde{t}_1$ Forbidden 0.6-0.8	$m(\tilde{\chi}_1^0)$=300 GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$ 0.48-0.84	$m(\tilde{\chi}_1^0)$=150 GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}_1^0$	0	2c	Yes	36.1	$\tilde{t}_1$ 0.85	$m(\tilde{\chi}_1^0)$=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	$m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)$=50 GeV	1805.01649
		0	mono-jet	Yes	36.1	$\tilde{t}_1$ 0.43	$m(\tilde{t}_1,\tilde{c})-m(\tilde{\chi}_1^0)$=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$	1-2 e,μ	4 b	Yes	36.1	$\tilde{t}_2$ 0.32-0.88	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$= 180 GeV	1706.03986
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	2-3 e,μ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.6	$m(\tilde{\chi}_1^0)$=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.17	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=10 GeV	1712.08119
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	$\ell\ell/\ell\gamma\gamma/\ell bb$	-	Yes	20.3	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.26	$m(\tilde{\chi}_1^0)$=0	1501.07110
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.76	$m(\tilde{\chi}_1^0)$=0, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	1708.07875
						$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.22	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=100 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}_1^\pm)$+$m(\tilde{\chi}_1^0)$)	1708.07875
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	36.1	$\tilde{\ell}$ 0.5	$m(\tilde{\chi}_1^0)$=0	1803.02762
		2 e,μ	≥ 1	Yes	36.1	$\tilde{\ell}$ 0.18	$m(\tilde{\ell})-m(\tilde{\chi}_1^0)$=5 GeV	1712.08119
	$\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$	0	$\geq 3b$	Yes	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}_1^0 \to h\tilde{G}$)=1	1806.04030
		4 e,μ	0	Yes	36.1	$\tilde{H}$ 0.3	BR($\tilde{\chi}_1^0 \to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}_1^\pm$ 0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron	SMP	-	-	3.2	$\tilde{g}$ 1.6		1606.05129
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$		Multiple		32.8	$\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6 2.4	$m(\tilde{\chi}_1^0)$=100 GeV	1710.04901, 1604.04520
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 0.44	1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{g}$ 1.3	6 <$c\tau(\tilde{\chi}_1^0)$< 1000 mm, $m(\tilde{\chi}_1^0)$=1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0	Yes	36.1	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33} \neq 0, \lambda_{12k} \neq 0$] 0.82 1.33	$m(\tilde{\chi}_1^0)$=100 GeV	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ [$m(\tilde{\chi}_1^0)$=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	$m(\tilde{\chi}_1^0)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{g}\tilde{g}, \tilde{g} \to tbs$ / $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=1, 1e-2] 1.8 2.1	$m(\tilde{\chi}_1^0)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	$m(\tilde{\chi}_1^0)$=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e,μ	2 b	-	36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

Challenges and opportunities: uncertainties

- Many of the HL-LHC measurements and searches rely on reducing both theoretical and experimental systematic uncertainties
- Common assumptions include
  - Precision measurements assume a factor two reduction in theoretical uncertainties
  - Continued precise determination of luminosity in a harsher environment — to 2 or even 1% level requires new luminosity detectors and new analysis techniques
  - Continued SM measurements are essential to reduce PDF uncertainties by a factor of 2-4, which is already assumed in many of these results
    - New, more precise forward detectors in ATLAS and CMS, and LHCb measurements will help