High Luminosity yellow report: what does HL-LHC physics look like?

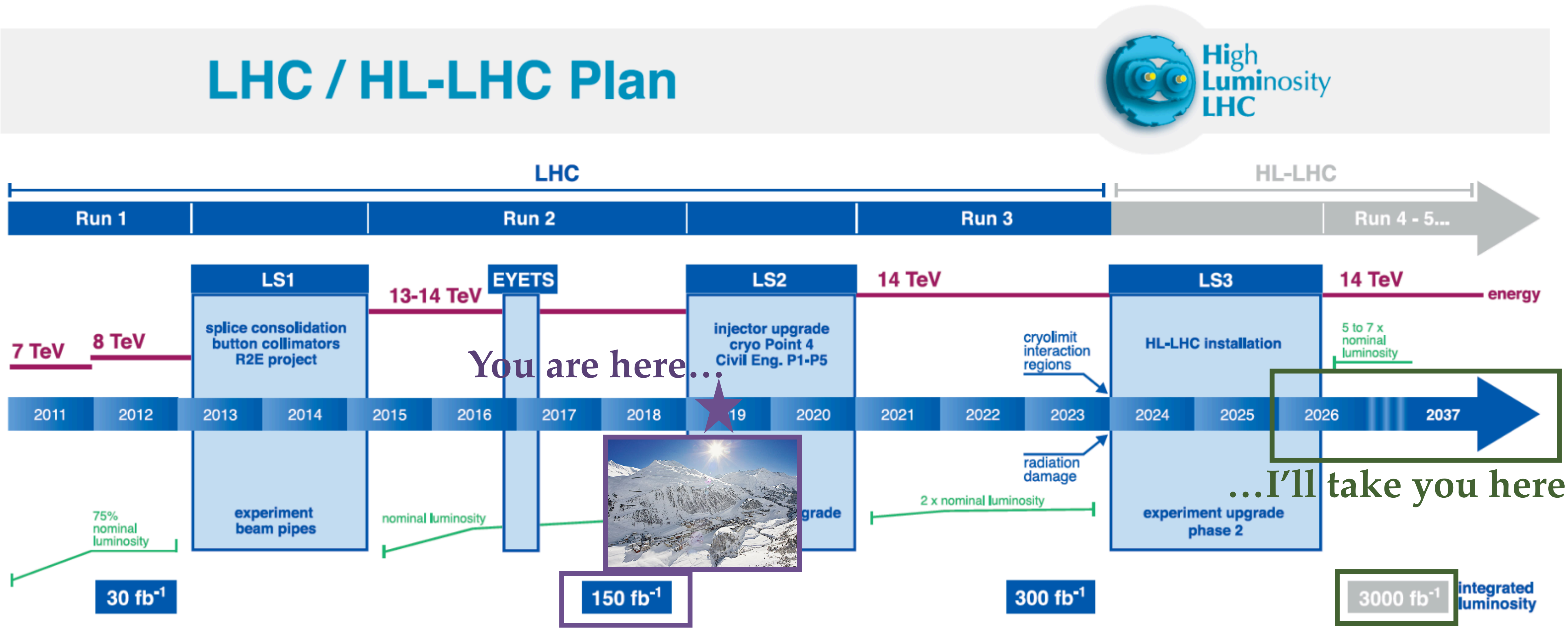
Dr. FRANCESCA C. UNGARO

The University of Melbourne

On behalf of the ATLAS
and CMS collaborations

ALPS 2019 (Fourth Alpine LHC Physics Summit) - 25th of April 2019 - Obergurgl, Austria

The High Luminosity LHC Upgrade

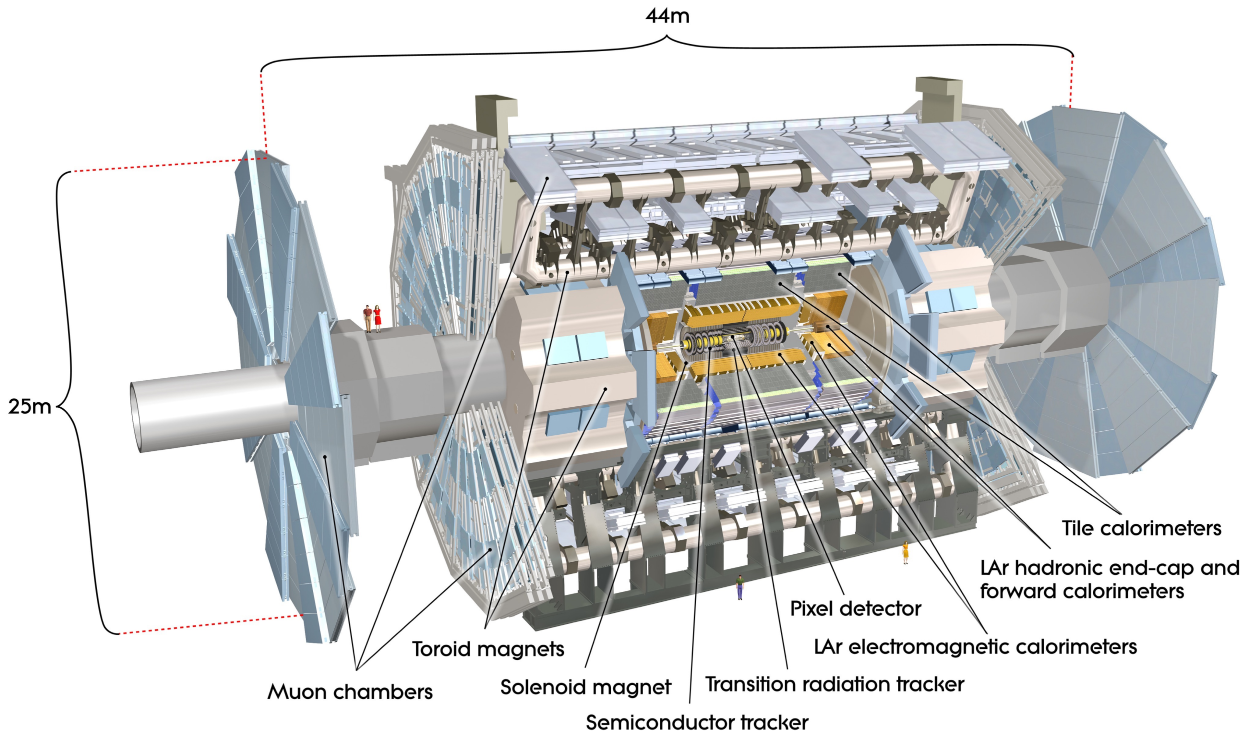


HL-LHC project approved

- **3000 fb^{-1}** of data at a centre of mass energy of **14 TeV**
- A lot of data for **EW** and **QCD** precision measurements, **Higgs boson** properties, **flavour physics**, **BSM** searches

Detectors Upgrade

ATLAS



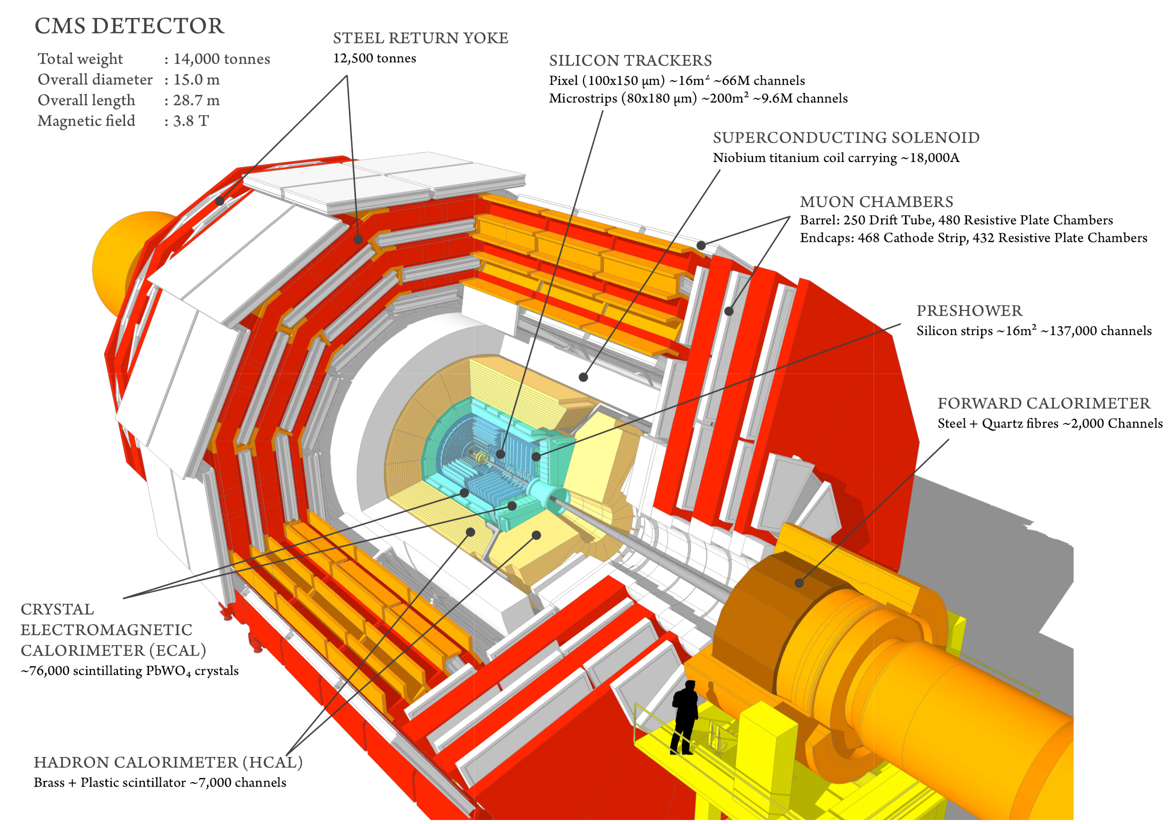
ATLAS upgrades include

- DAQ and trigger systems (L1 and HLT - 10 kHz)
- Extended **Inner Tracker** up to $|\eta|$<4
- **Electronics upgrade** for LAr and Tile calorimeters, muon system
- New **muon chamber** in the **inner endcap region**
- **High granularity timing detector** in endcap

CMS

CMS upgrades include

- DAQ and trigger systems (L1 and HLT - 7.5 kHz)
- Extended **Inner Tracker** up to $|\eta|$<4
- Improved **muon system coverage**
- Precise **MIP timing layer** in barrel and endcap
- **High granularity endcap** calorimeter



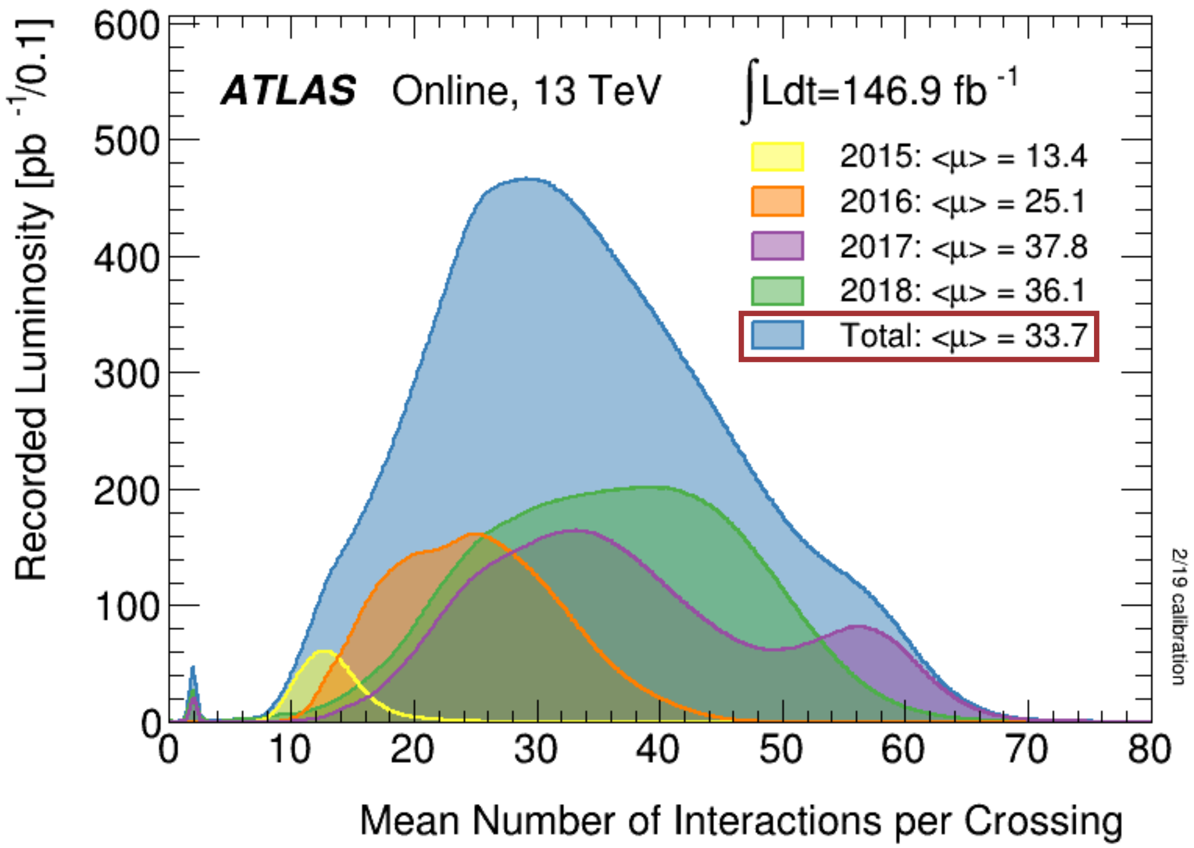
The High Luminosity LHC Challenges

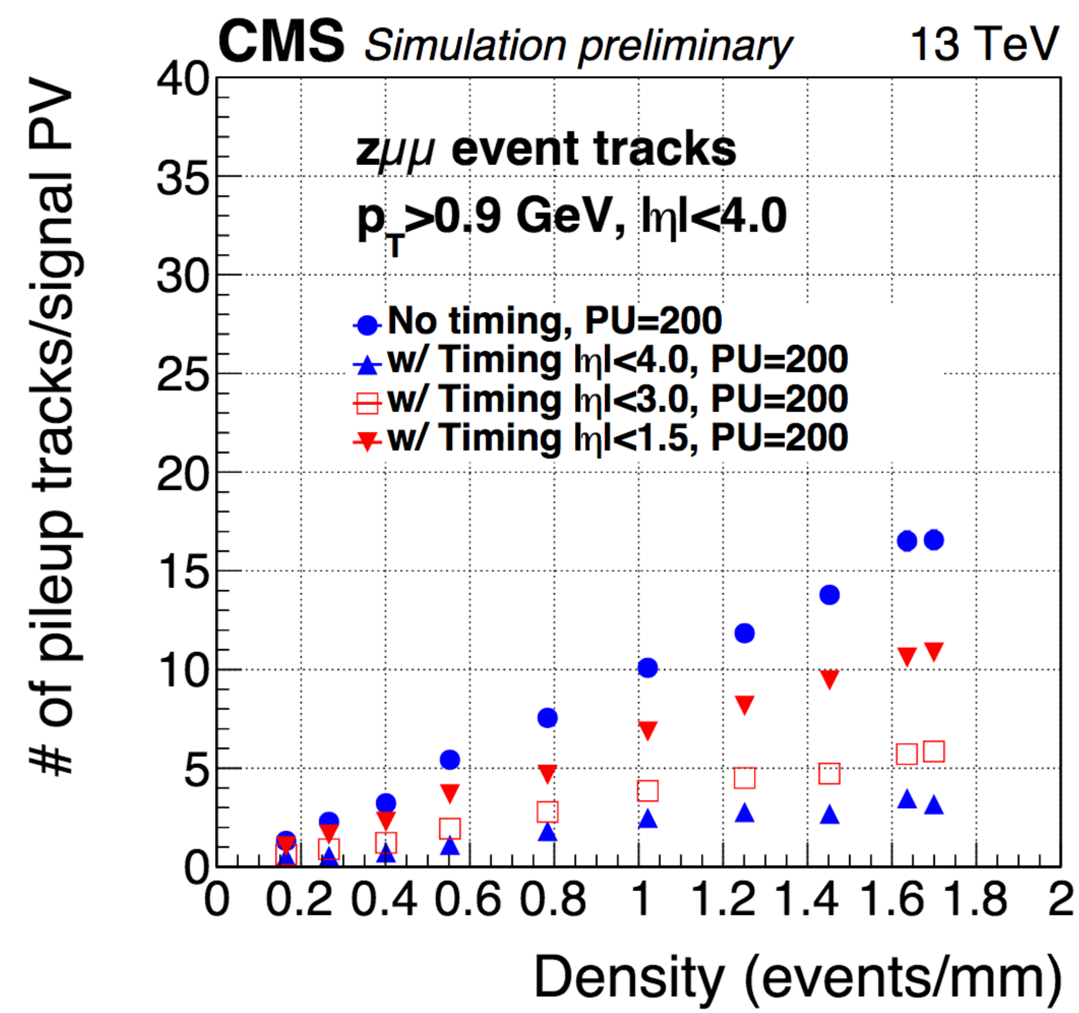
Great **opportunities** and great **challenges**

- Peak instantaneous luminosity for **HL-LHC** up to 7.5x10^{34} $cm^{-2}s^{-1}$
  Up to **200 p-p interactions** per bunch crossing!
- Difficult experimental conditions for trigger, particle reconstruction, performance, …

CMS-NOTE-2018-006

LHC p-p interactions





Physics Opportunities

Upgraded detectors open up new possibilities, e.g.

- exploit timing information for long lived particles searches
- sensitivity to forward events boosted by extended tracking

Large data sample benefits

- Lower statistical uncertainties
- Lower experimental systematic uncertainties (calibrations performed on larger dataset)
- Lower uncertainties on background prediction (high statistic control samples allows more precise constraints)

Exploit full **potential** of **upgraded detectors** and **large data sample**

- Collaboration of theorists and experimentalists (ALICE, ATLAS, CMS, LHCb) to **assess reach and precision**, identify new **opportunities**, explore **new directions**
- **Year-long workshop in 2017-2018**
- Input to European strategy link

Physics Program Overview

Five working groups focusing on different sectors of physics at hadron colliders

- WG1: **Standard Model** arXiv:1902.04070
  - Precision measurements (Weinberg angle, W and top masses, …)
  - Rare signatures (four tops, FCNC top decays, …)
- WG2: **Higgs** arXiv:1902.00134
  - Properties: couplings and self coupling, precision mass and width measurements, …
  - BSM Higgs searches, invisible decays
- WG3: **Beyond the Standard Model** arXiv:1812.07831
  - Prompt and long-lived particles signatures
  - Supersymmetry, dark matter, resonant searches, …

(highlights) covered today (ATLAS and CMS)

- WG4: **Flavour** arXiv:1812.07638
  - CKM observables
  - bottom, charm and strange probes for new Physics, LFV with taus
  - B anomalies studies
- WG5: **QCD matter at high density** arXiv:1812.06772
  - both heavy ions and proton beams

Not covered today

Higgs Boson Properties

arXiv:1902.00134

"The determination of Higgs boson properties […] is the primary target of the HL-LHC Physics program"

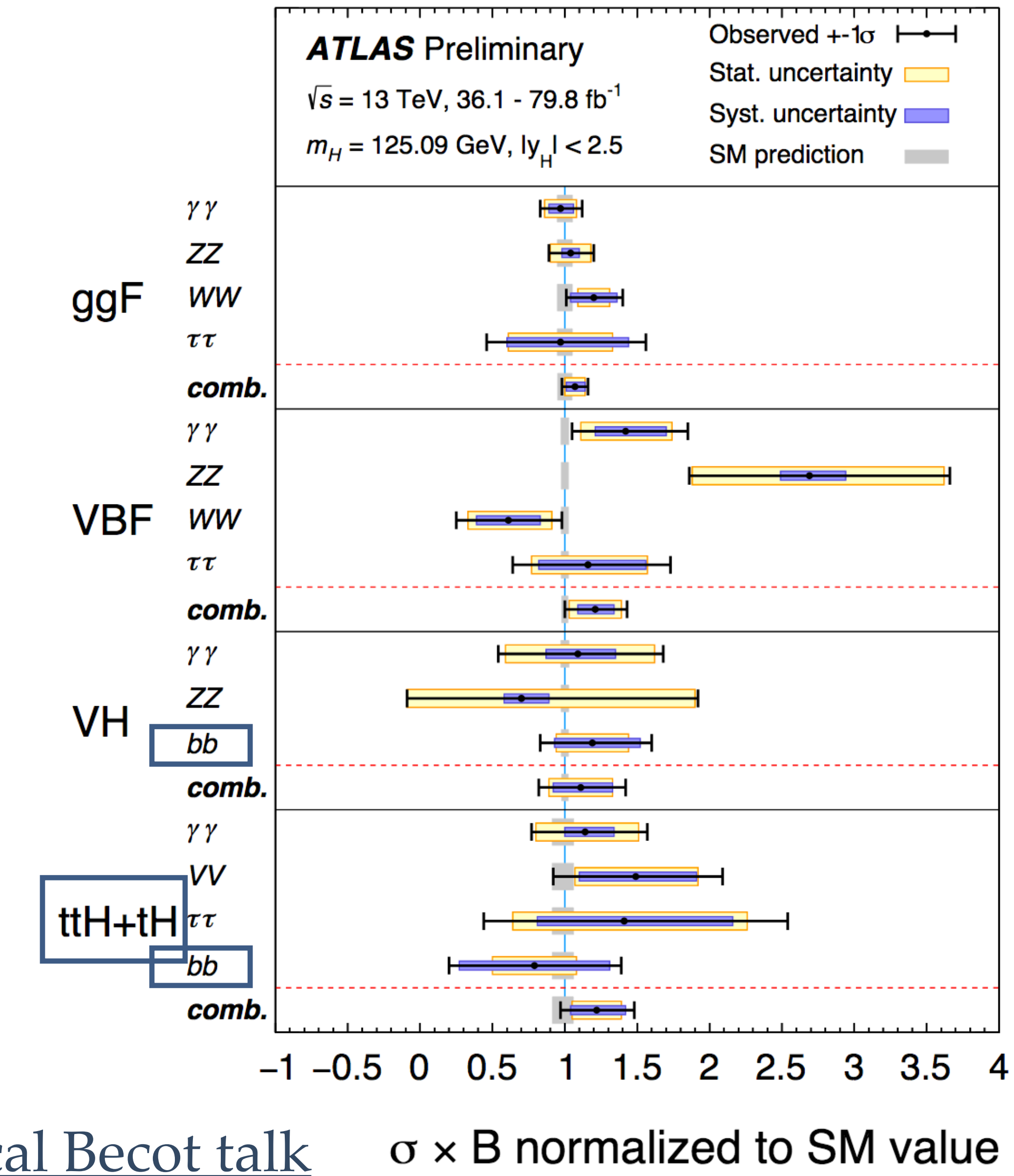
from the HL-LHC input to the European Strategy "The Physics potential of HL-LHC" (link to document)

Projections assumptions

- Theory uncertainties reduced by a factor two
  - Improved HL-LHC PDF set
- Current analysis techniques (space for improvement!)

Main goals

1. Access yet unobserved couplings
2. Precise measurement of couplings, width and mass
3. Higgs self couplings
4. Invisible decays
5. BSM Higgs

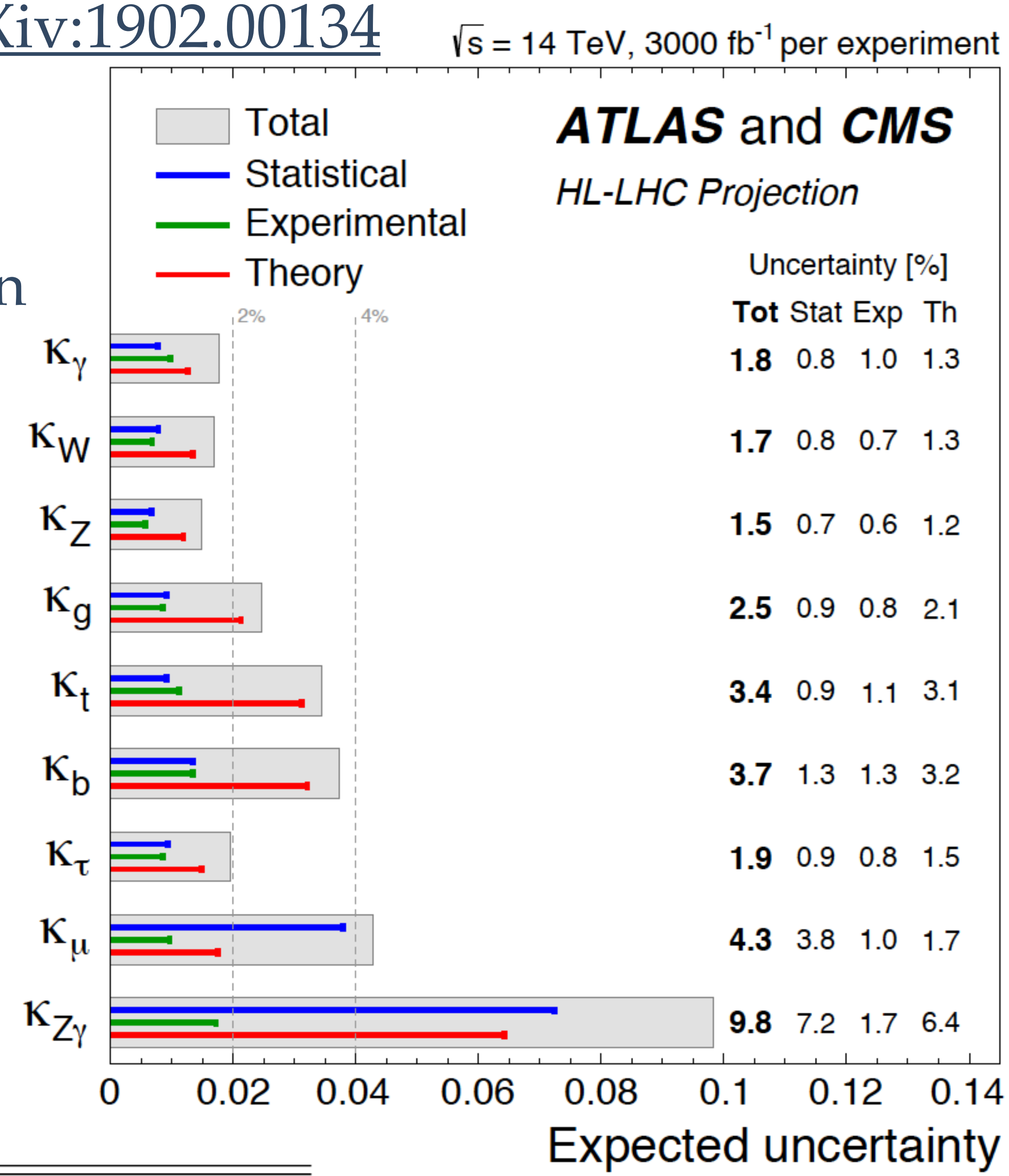


current status in Cyril Pascal Becot talk

Higgs Boson Couplings and Mass

arXiv:1902.00134

- precise measure of H→$\mu\mu$
- potential to observe H→$Z\gamma$
- Measurement of couplings k_i with 1-10% precision
  - dominated by theory uncertainties except for rare decays
- Percent-level constraints on k_i ratios
  - probes for new Physics in loops (e.g. k_γ/k_Z in gg→H loop)
- Current mass precision ~200 MeV
  - expected improvement up to a factor 7



ATL-PHYS-PUB-2018-054

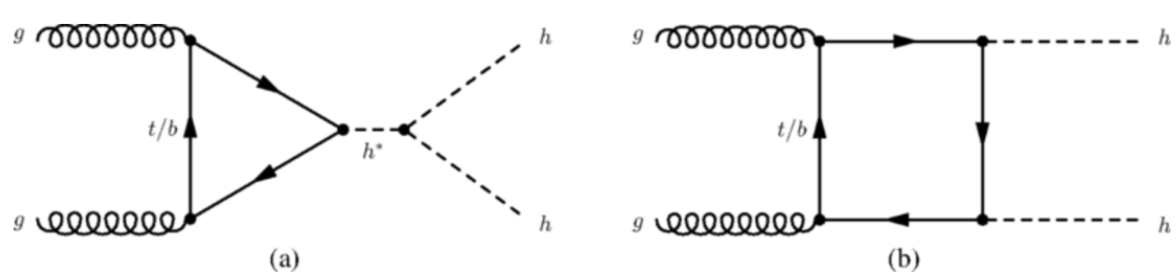
	Δ_{tot} (MeV)	Δ_{stat} (MeV)	Δ_{syst} (MeV)
Current Detector	52	39	35
μ momentum resolution improvement by 30% or similar	47	30	37
μ momentum resolution/scale improvement of 30% / 50%	38	30	24
μ momentum resolution/scale improvement 30% / 80%	33	30	14

Higgs Boson Self-Coupling

Self-coupling λ from analysis of HH mass spectrum shape and cross section measurement

- Channel combinations @ HL-LHC provides ~3σ per experiment
  - 4σ when combining ATLAS and CMS results assuming SM
  - remember: current analysis techniques!

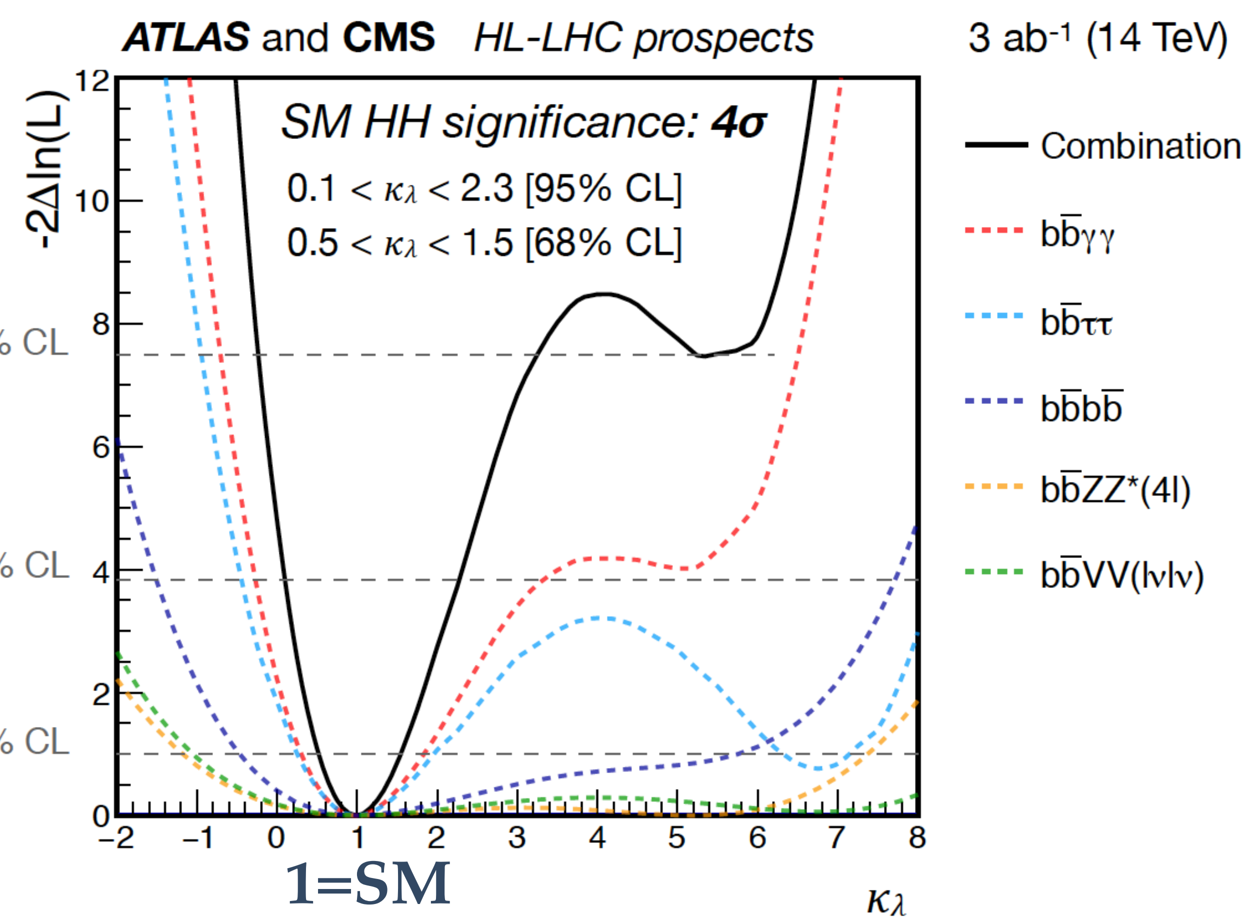
arXiv:1902.00134



Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
$bb\tau\tau$	1.4	1.6	1.4	1.3
$bbWW(\ell\nu\ell\nu)$	0.56	0.59	3.5	3.3
$bb\gamma\gamma$	1.8	1.8	1.1	1.1
$bbZZ(\ell\ell\ell\ell)$	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71

CMS-PAS-FTR-18-019

Exclusion limits



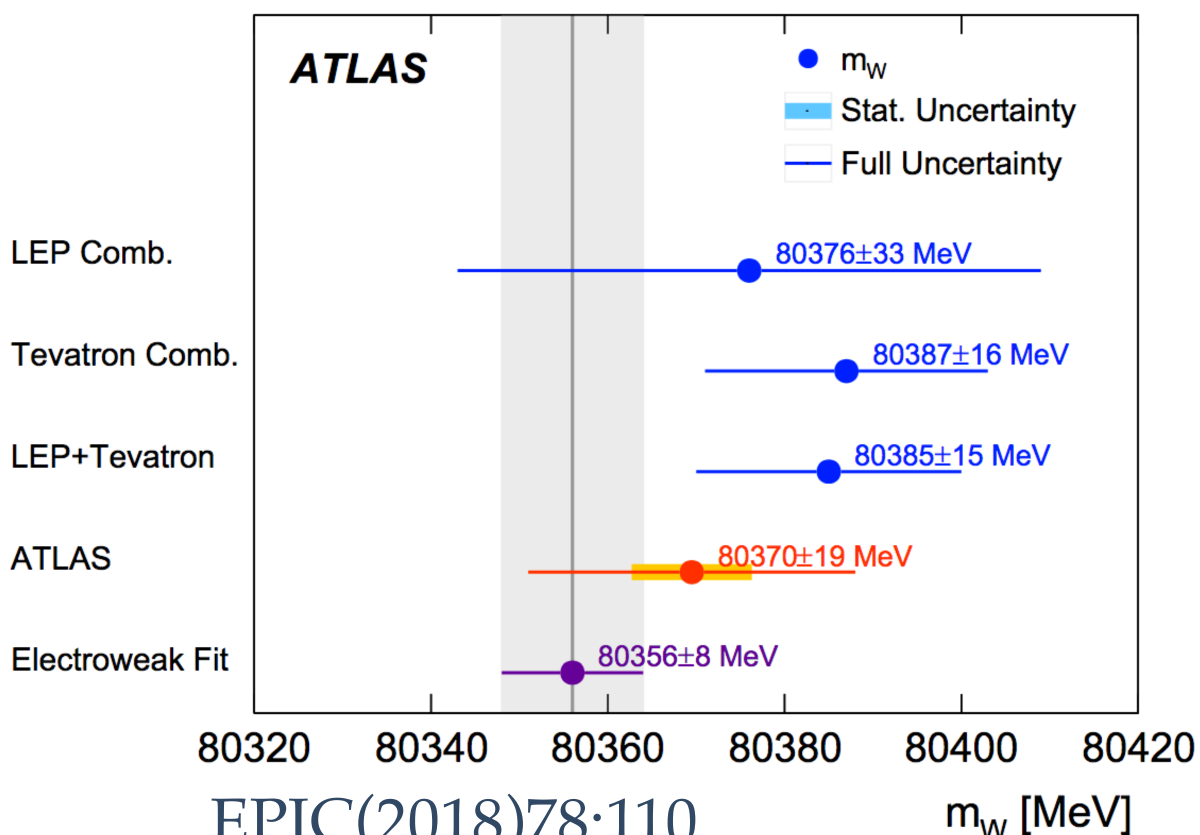
1=SM

Precision EW measurements: W mass

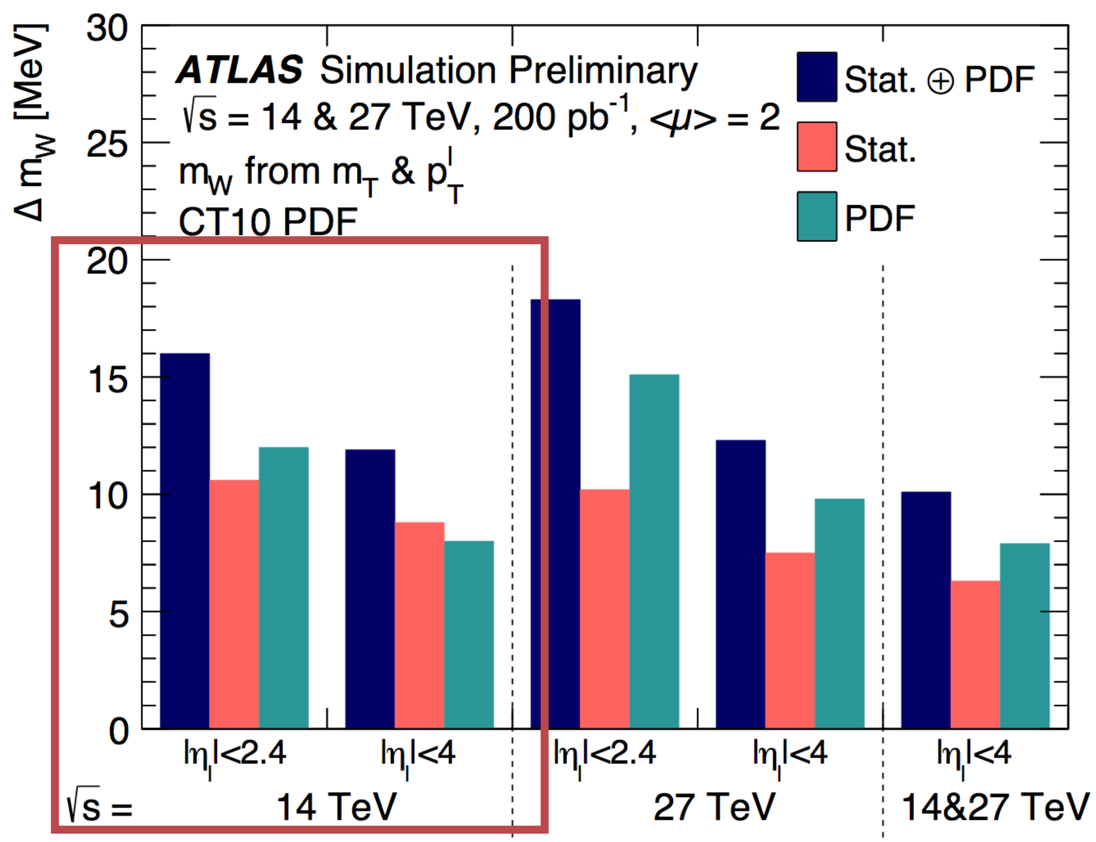
W mass measured from transverse mass in leptonic decays (electron or muon)

- Systematically limited
- Dedicated low pile-up runs ($5\text{x}10^{32}$ cm^{-2}s^{-1}, cfr $5\text{x}10^{34}$ cm^{-2}s^{-1}) to keep experimental systematic uncertainties to the level of statistical uncertainties
- Precise understanding of W boson recoil
- More efficient event selection thanks to forward tracking

arXiv:1902.04070



EPJC(2018)78:110

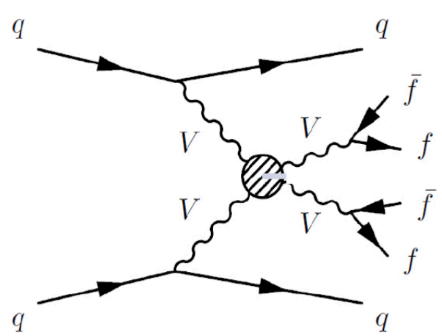


Use of HL-LHC PDF to further reduce uncertainty down to < 10 MeV

VBS Processes

VBS important test of EW symmetry breaking mechanism **current results in Dieter Zeppenfeld talk**

- Improved by higher statistics and instrumentation in forward region
    - e.g. WW VBS: forward tracking allows better WZ/ZZ/ttbar suppression (leptons identification) and pile-up suppression



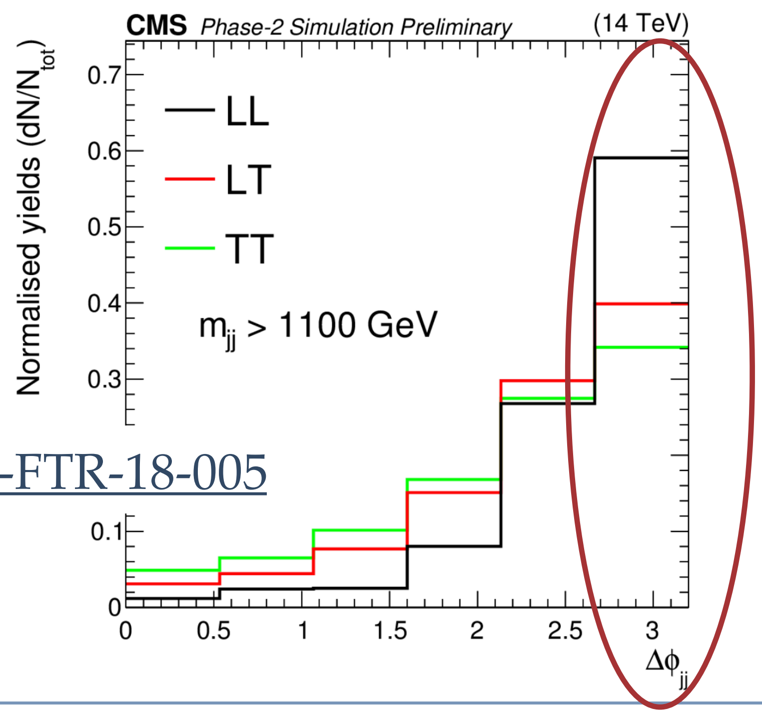
observed

Process	$W^{\pm}W^{\pm}$	WZ	WV	ZZ
Final state	$\ell^{\pm}\ell^{\pm}$jj	3ℓjj	ℓjjjj	4ℓjj
Precision	6%	6%	6.5%	10–40%
Significance	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$

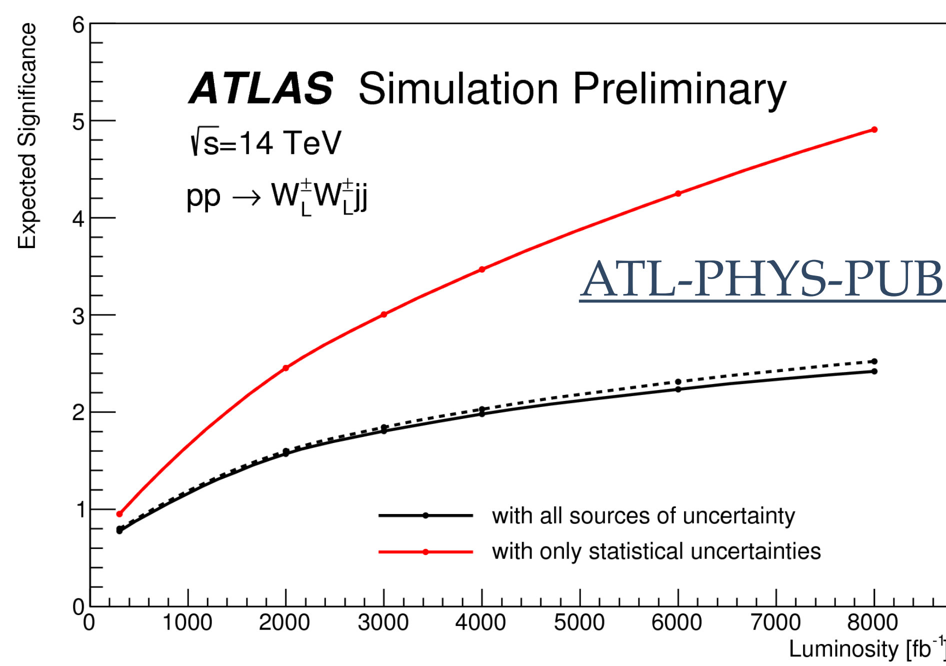
arXiv:1902.04070

Potential for measuring WW longitudinal polarization

- Still not known if Higgs boson preserves unitarity of longitudinal scattering amplitude for all energies



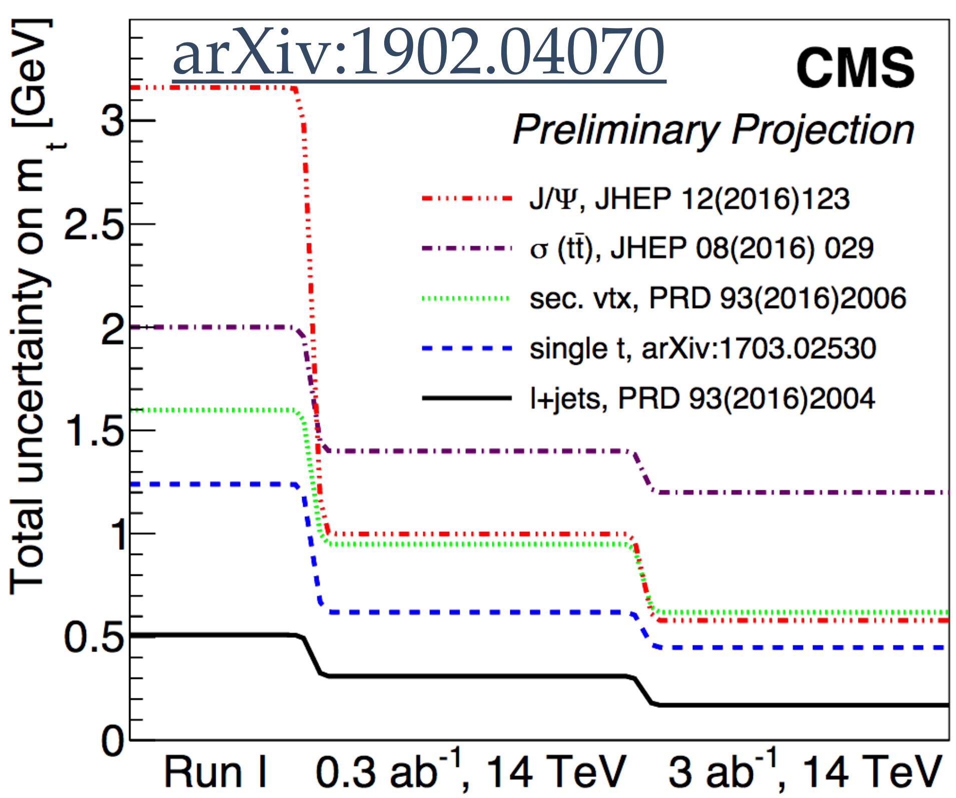
CMS-PAS-FTR-18-005

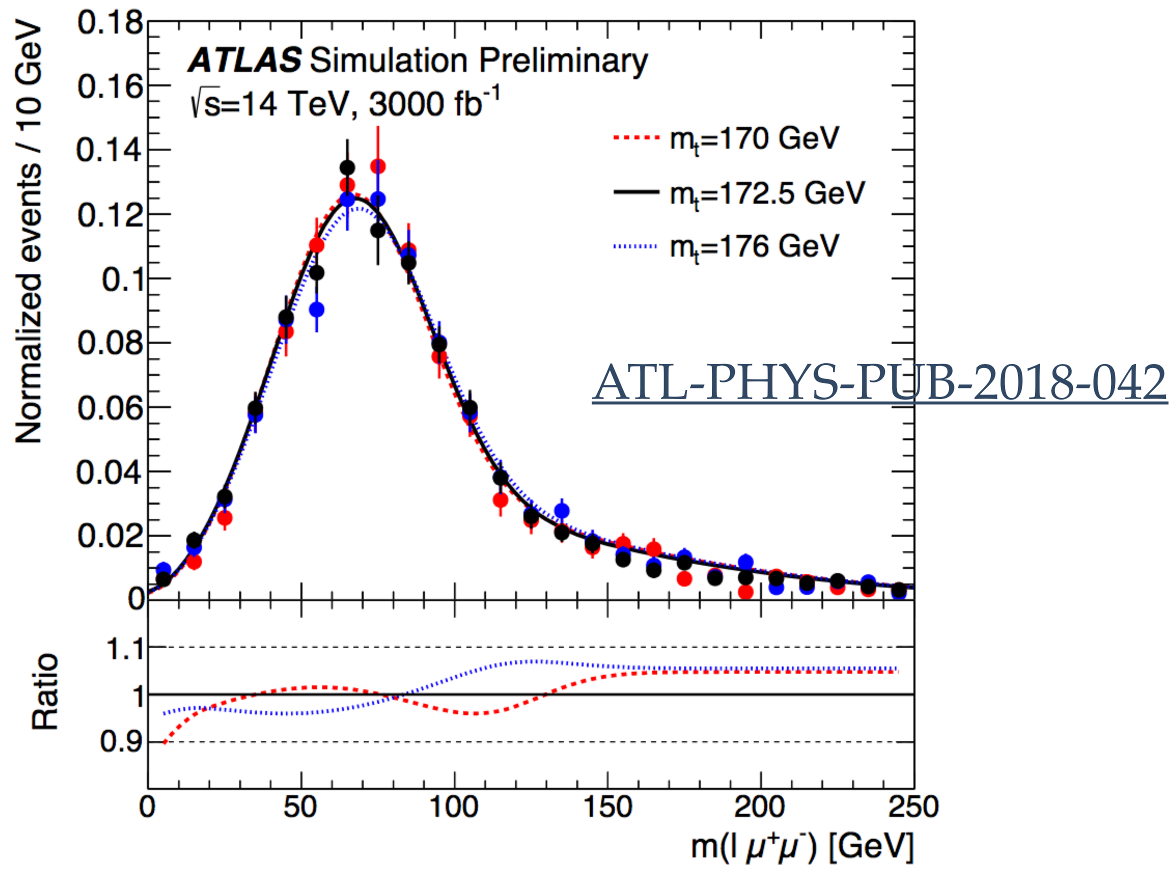


ATL-PHYS-PUB-2018-052

Top Quark Mass

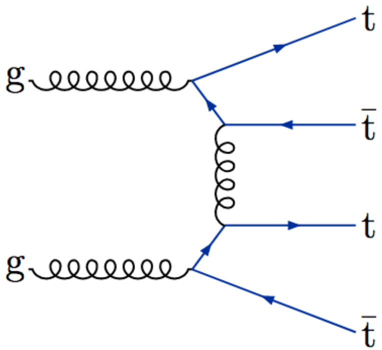
- Current most precise mass measurement **direct**
  - σ 500 MeV, to be reduced to 200 MeV @ HL-LHC
  - Measured top mass is value of top mass parameter in MC distribution best fitting
    - Sensitive to theoretical modelling uncertainties
- @HL-LHC more support measurements with competitive precision
  - e.g. B decaying into $J/\psi \rightarrow \mu\mu$ events
    - m($\ell\mu\mu$) sensitive to top mass (ℓ from W decay)
    - no reliance on jets

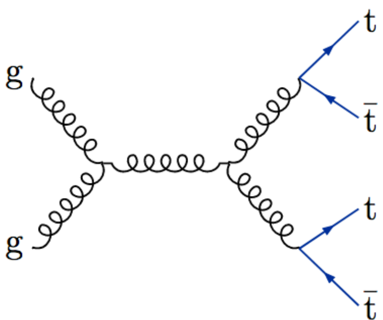


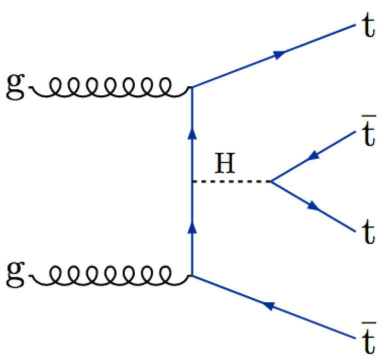


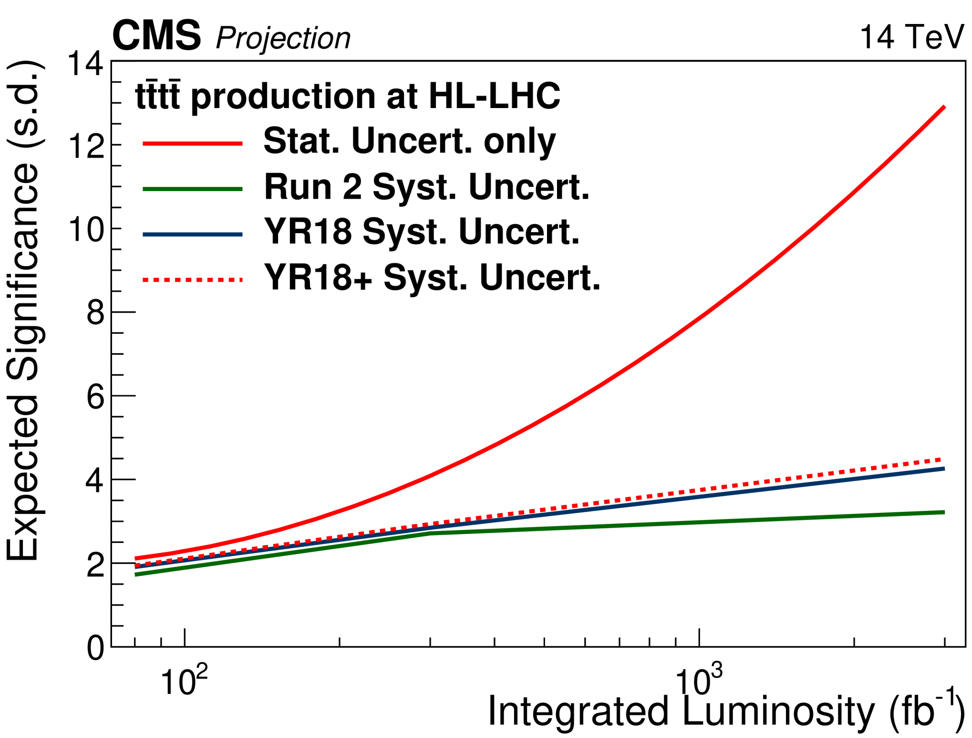
4-Tops Production

- Rare process sensitive to BSM Physics (e.g. dark matter mediator with Yukawa-like coupling)
- Background from other rare processes (VV, VVV, ttV, ttH) and events with mis-identified ("fake") leptons   arXiv:1811.02305   EPJC(2018)78:140
- Current sensitivity 1σ with events with two or three leptons
    - Upper limit on cross section 2 times SM value with 50% uncertainty
- Expected uncertainty @HL-LHC 20-30%







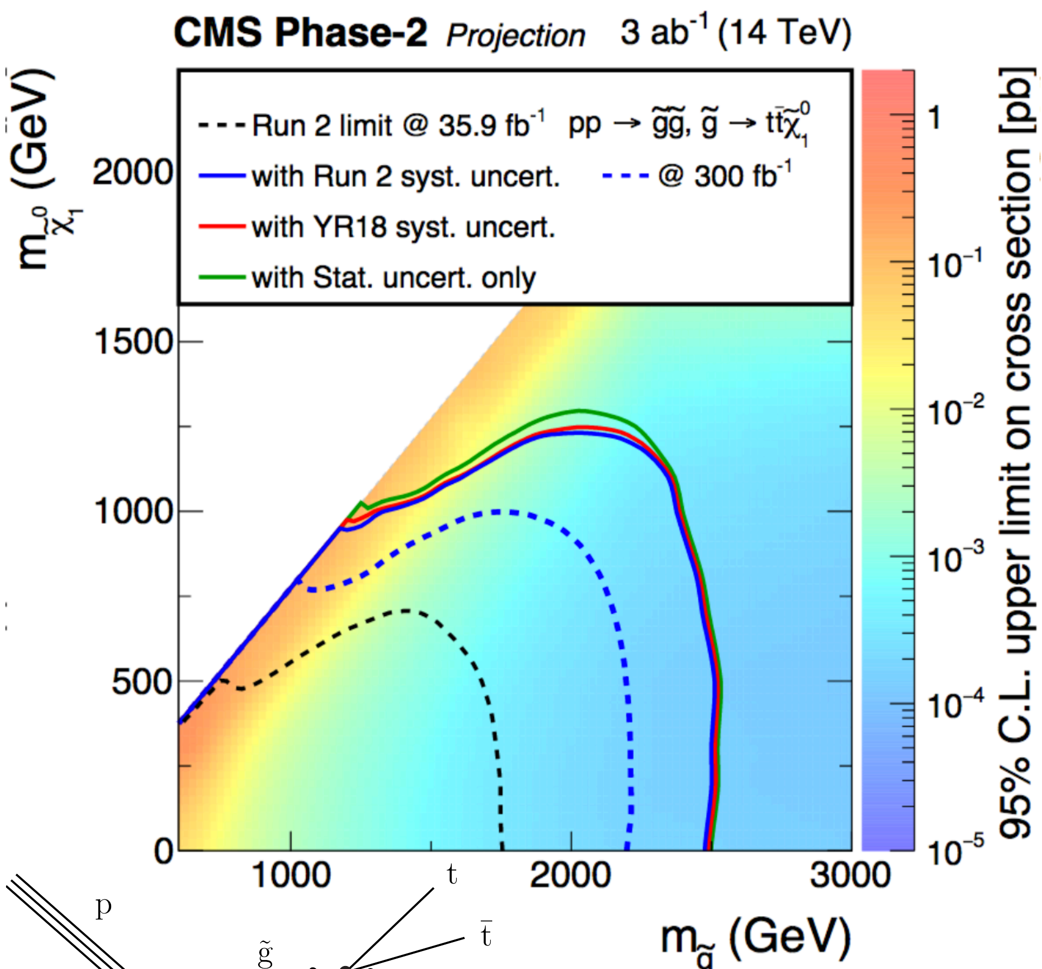


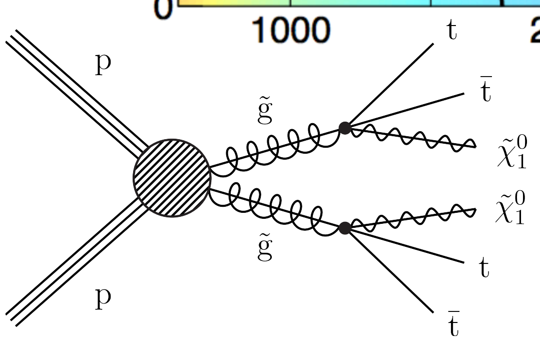
CMS-PAS-FTR-18-031

ATL-PHYS-PUB-2018-047

Int. Luminosity	$\sqrt{s}$	*Stat. only* (%)	*Run 2* (%)	*YR18* (%)	*YR18+* (%)
300 fb^{-1}	14 TeV	$^{+30}_{-28}$	$^{+43}_{-39}$	$^{+36}_{-34}$	$^{+36}_{-33}$
3 ab^{-1}	14 TeV	± 9	$^{+28}_{-24}$	$^{+20}_{-19}$	± 18
3 ab^{-1}	27 TeV	± 2	$^{+15}_{-12}$	$^{+9}_{-8}$	$^{+8}_{-7}$
15 ab^{-1}	27 TeV	± 1			

Strongly-produced SUSY





CMS-PAS-FTR-18-037

Results based on current analysis techniques

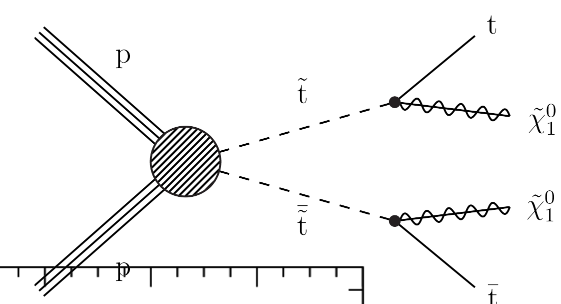
- S/B @ 14 TeV > S/B @ 13 TeV
- Bigger dataset allows for stricter selection criteria
- Generally reduced systematic uncertainties

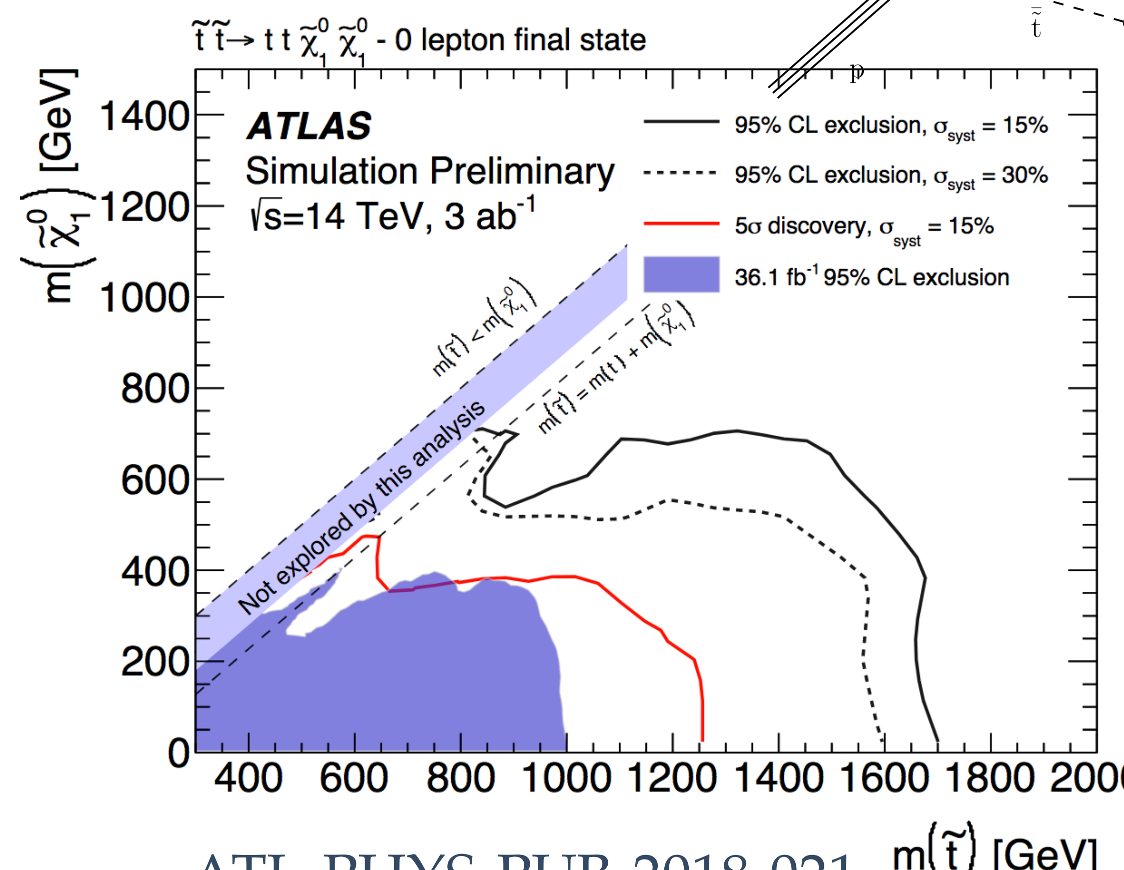
Gluino-Mediated stop production with *Razor variables*

- centre of mass of the sparticle-sparticle production

Direct stop pair production analysis

- re-clusetered (“fat”) jets for high mass splitting
- ISR-based selection for compressed scenario





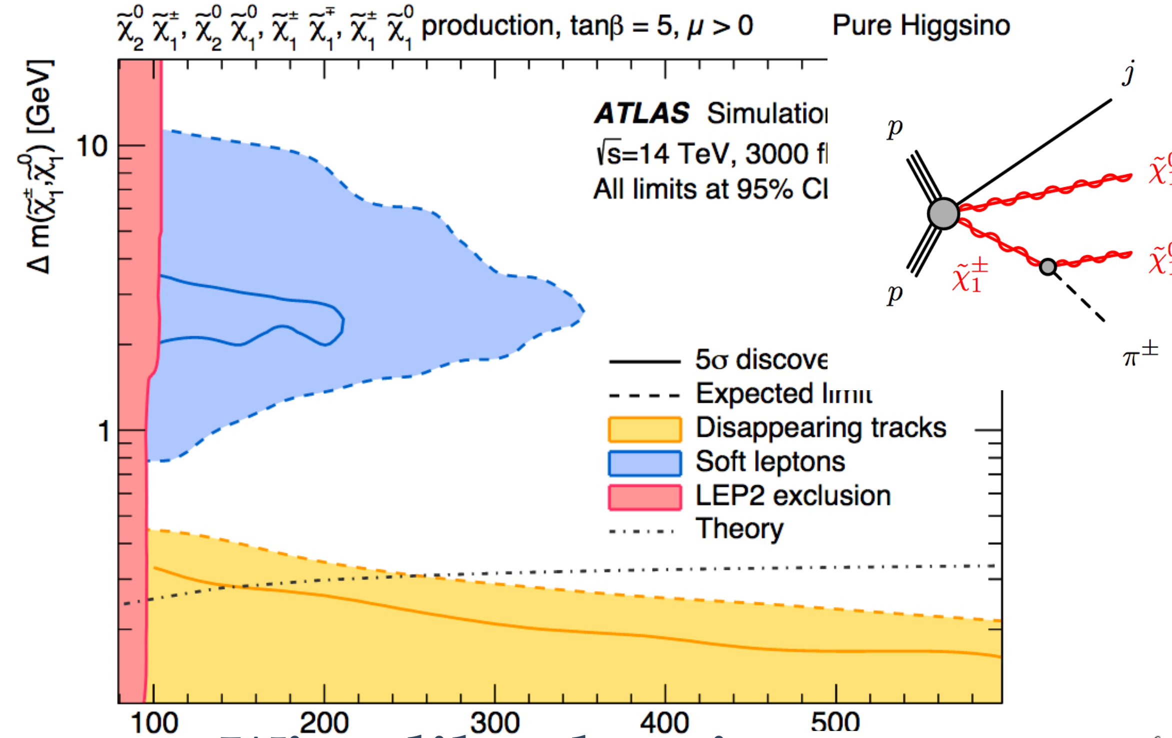
ATL-PHYS-PUB-2018-021

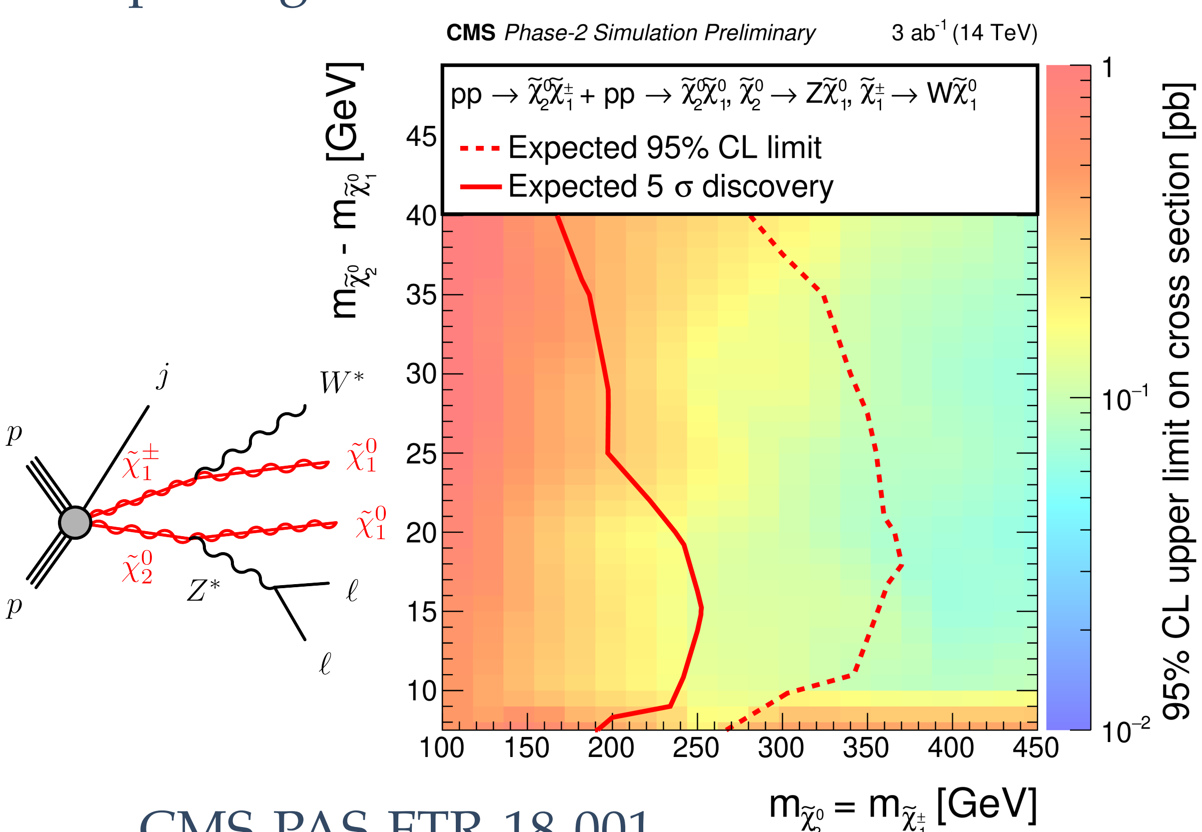
SUSY EW production

ATL-PHYS-PUB-2018-031

Higgsino-like LSP (naturalness motivated)

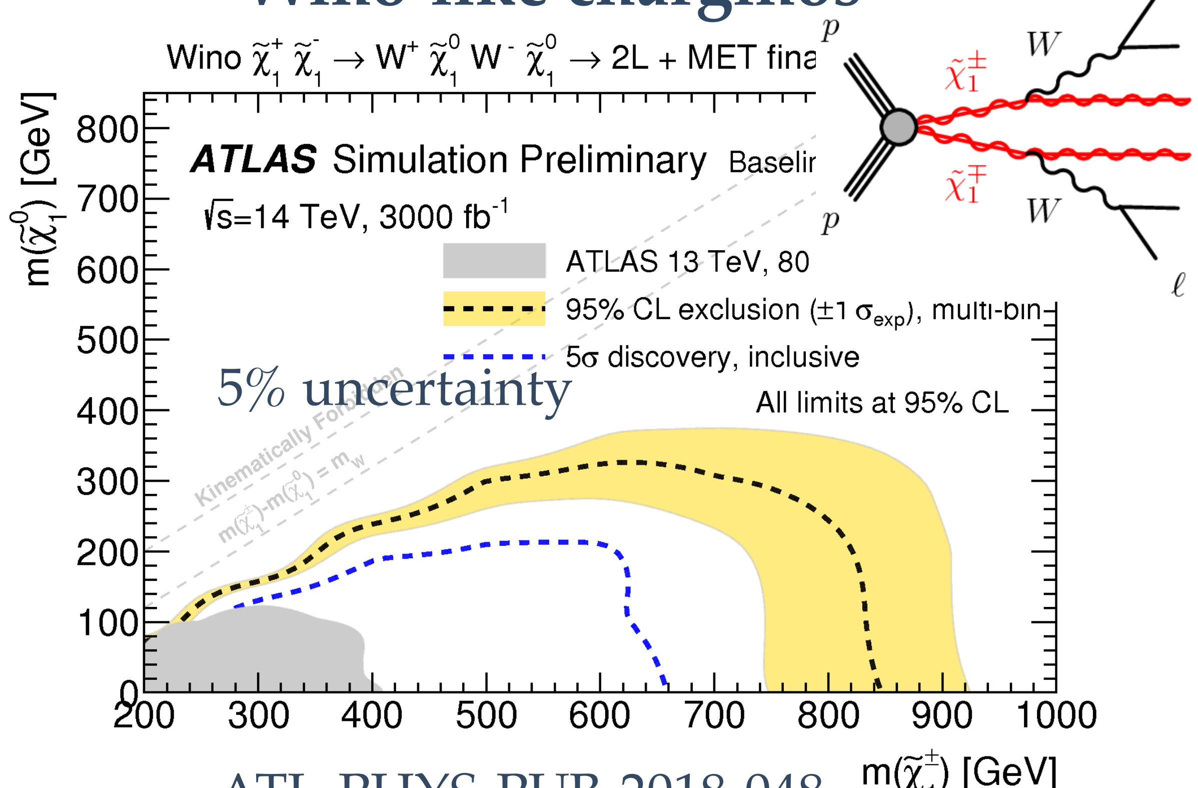
- Lightest chargino and second neutrino close in mass with LSP
    - soft objects in the final state
    - ISR-based selection
- Relies on upgrades to triggers at L1 and HLT to maintain low lepton thresholds (3-5 GeV)
- "Disappearing tracks" for even lower mass splitting





CMS-PAS-FTR-18-001

Wino-like charginos

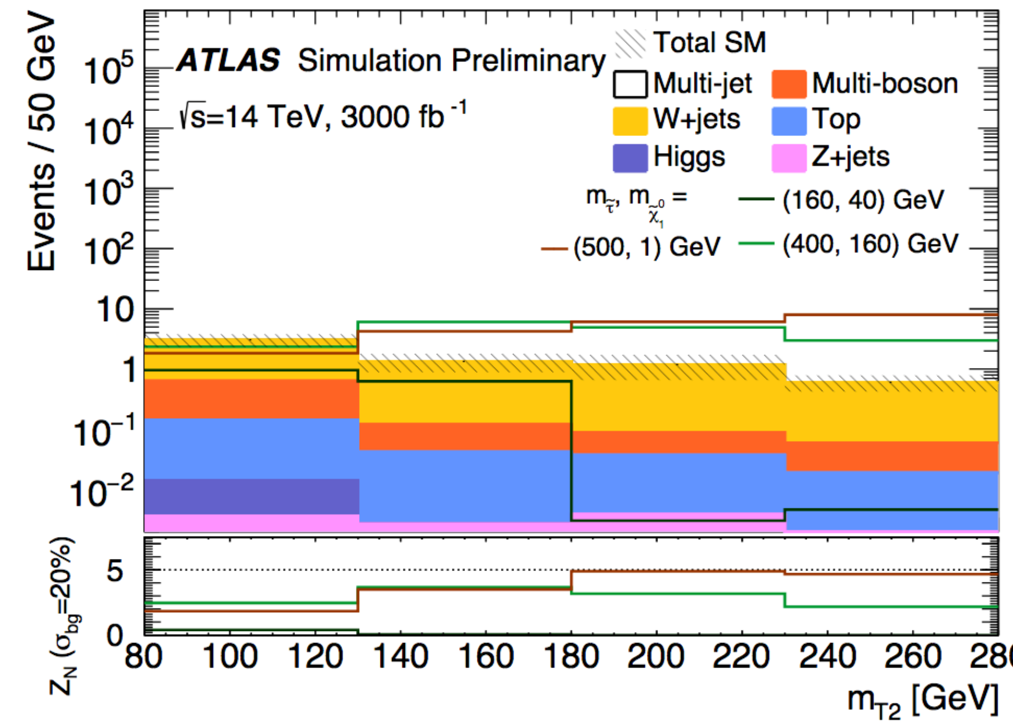


ATL-PHYS-PUB-2018-048

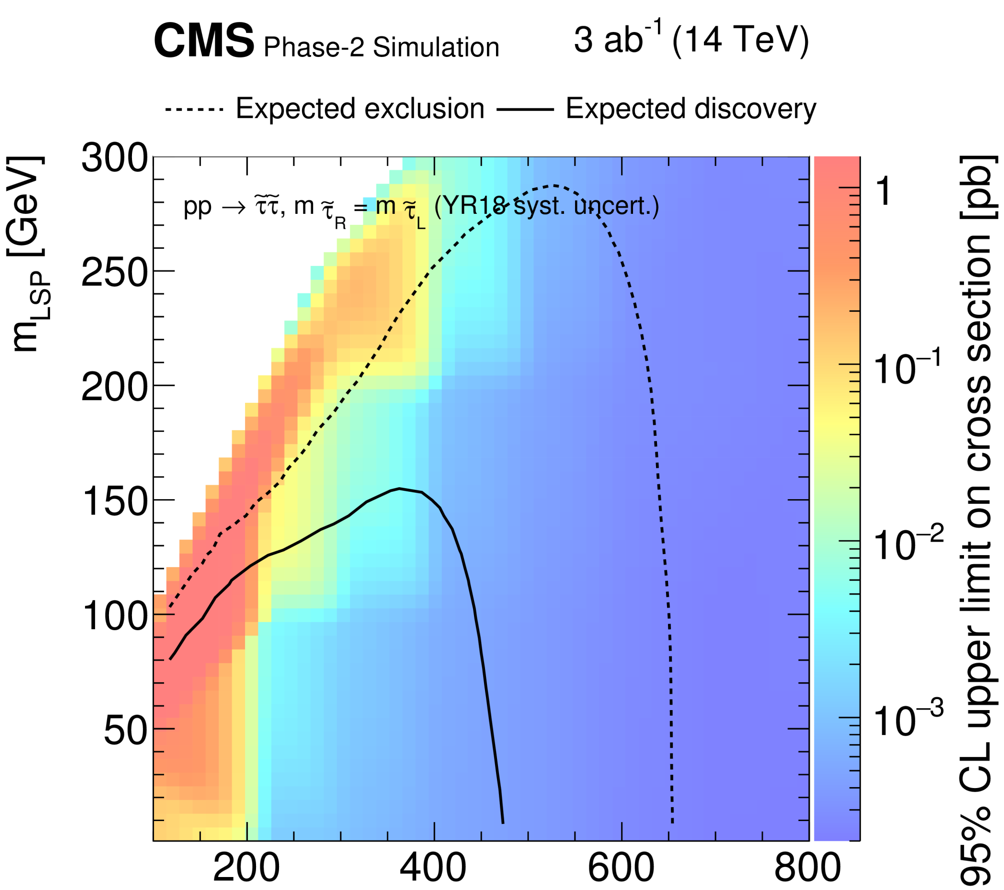
Stau Searches

Stau as **lightest slepton** (large tanβ)

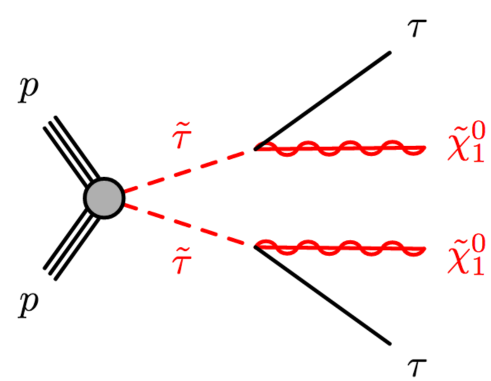
- signatures with at least one hadronically decaying tau
- Currently no sensitivity
- Small cross section (<1 fb^{-1} for m(stau) > 400 GeV @ 14 TeV)
  - Large size of sample @HL-LHC important
  - Sensitivity to right-handed tau limited by cross section

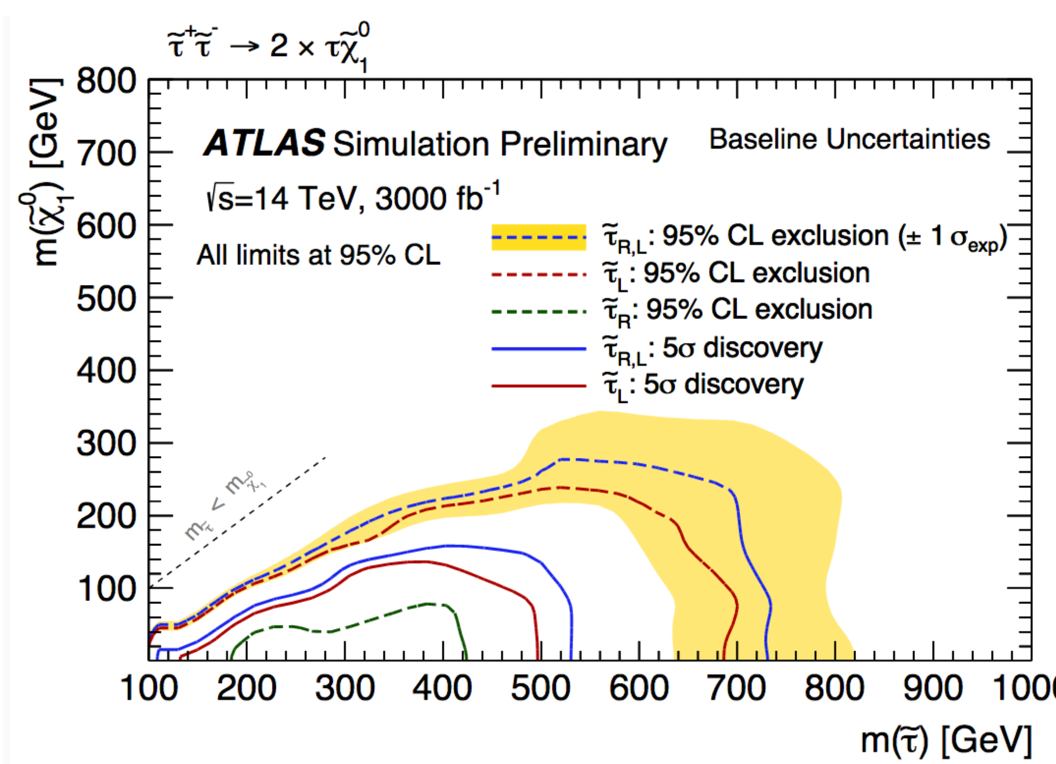


ATL-PHYS-PUB-2018-048



CMS-PAS-FTR-18-010



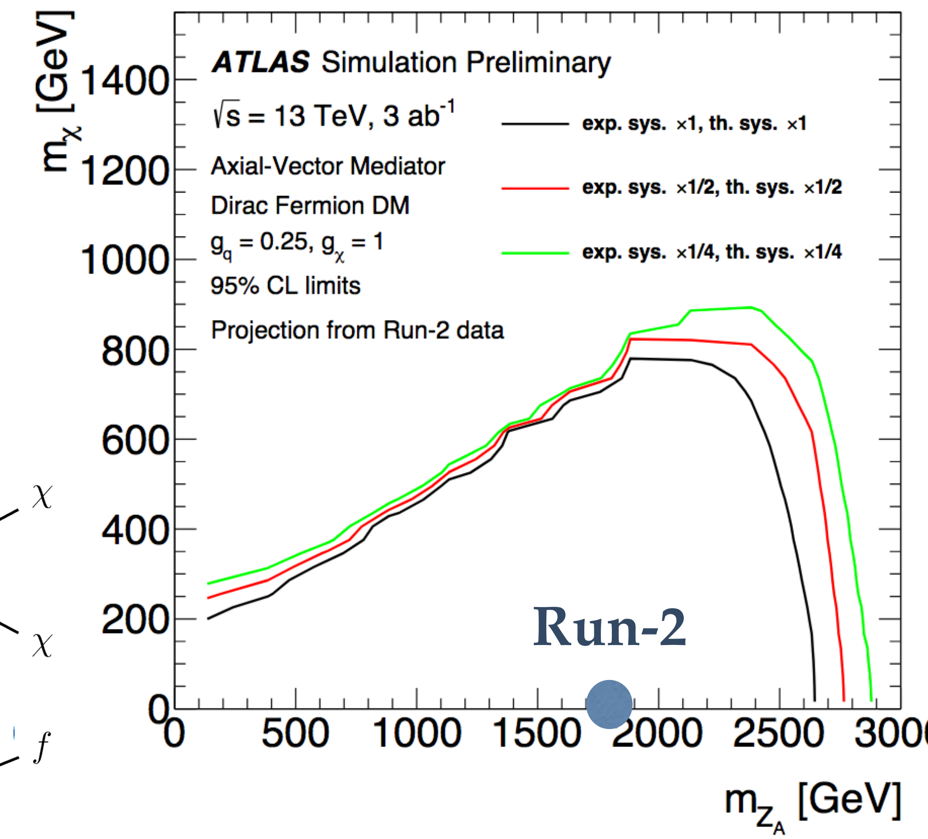


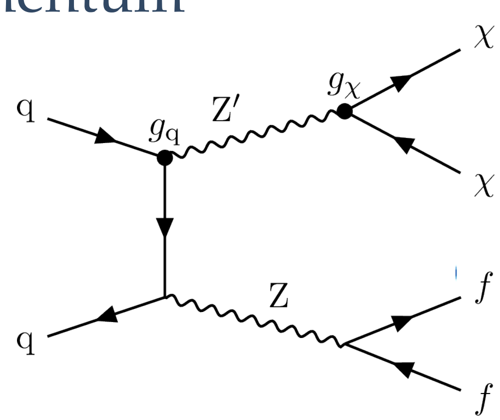
Dark Matter Searches

current status in Ren-jie Wang talk

Dark matter pair recoiling against **visible object -** *mono-X search*

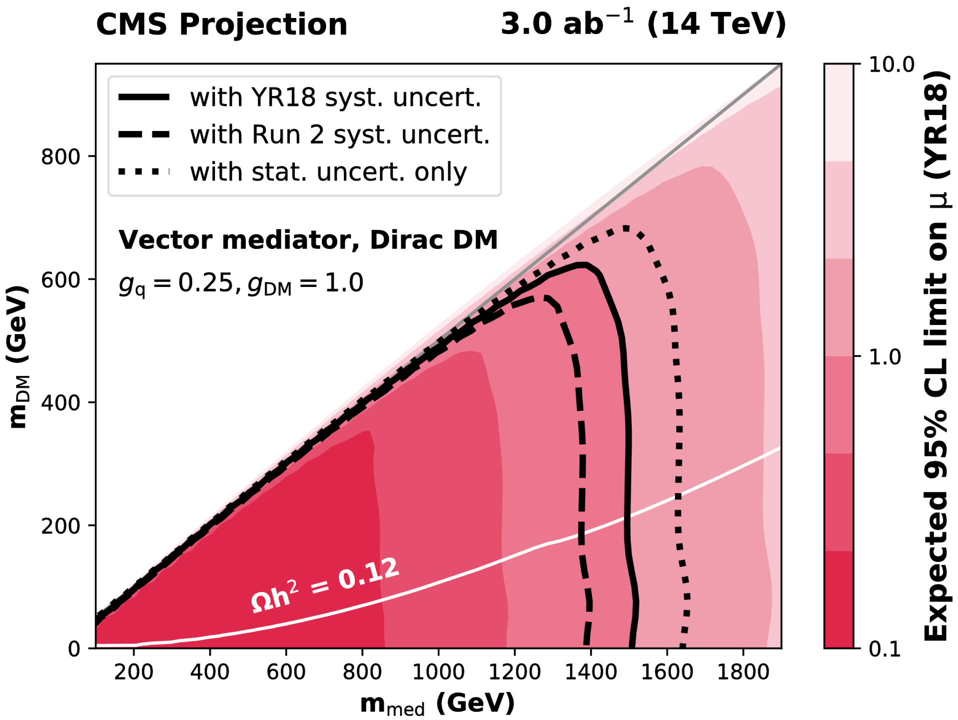
- Various models: EFT or simplified models, (axial-)vector or (pseudo-)scalar mediators, complete theories
- Flagship search: mono-jet
- One energetic jet and missing transverse momentum back-to-back
- Sensitive to systematic uncertainties on main background: Z and W bosons production





CMS-PAS-FTR-18-007

ATL-PHYS-PUB-2018-043



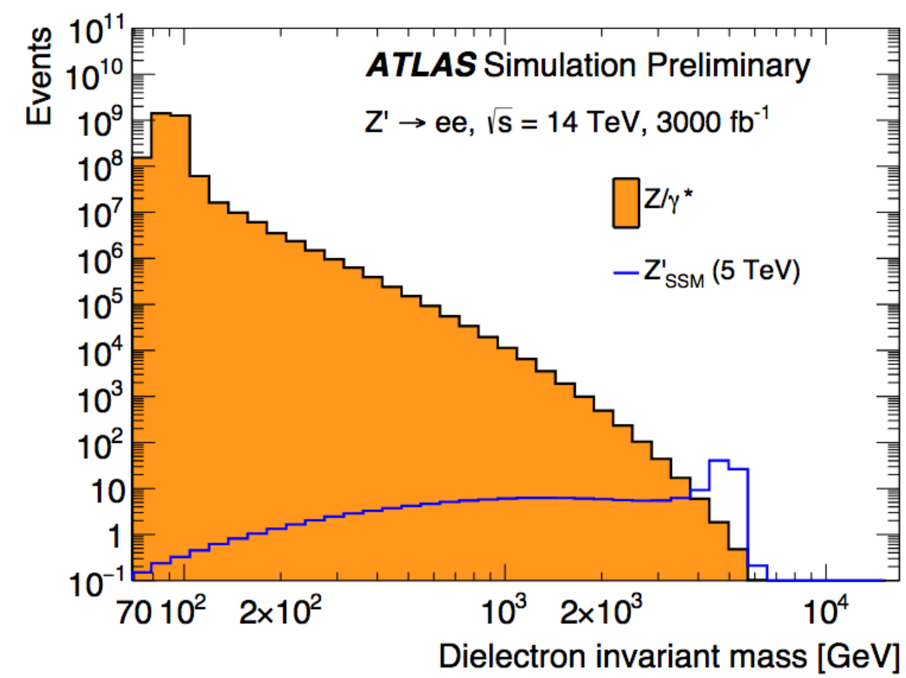
Source	Effect [%] $E_T^{miss} > 250$ GeV	$E_T^{miss} > 1000$ GeV
Experimental		
Jet and E_T^{miss} energy scales/resolutions	0.5	5.3
b-tagging efficiency	0.9	0.5
soft contributions to E_T^{miss}	0.4	1.7
lepton identification, reconstruction, E/p scale/resolution	0.2 – 1.7	0.3 – 2.3
Theoretical		
W/Z parton shower modelling, PDF	0.8	0.7
W/Z QCD and EW corrections	0.4	2
t-quark parton shower modelling, ISR/FSR, MC generator choice	0.3	~ 0
diboson MC generator choice, NLO cross-section	0.2	0.8

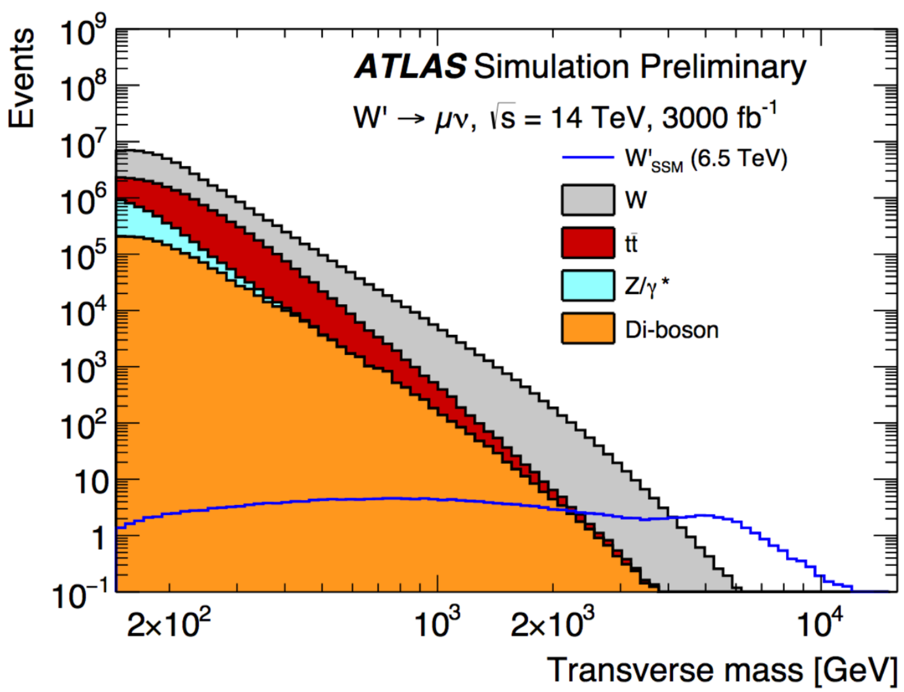
Resonance Searches

Huge expansion on the current resonant searches program

- Reach in the 6-8 TeV range for Z′-W′
  - 1 -2.5 TeV improvement!
- Requires good performance in energy and mass resolution

current status in Etienne Dreyer talk





ATL-PHYS-PUB-2018-044

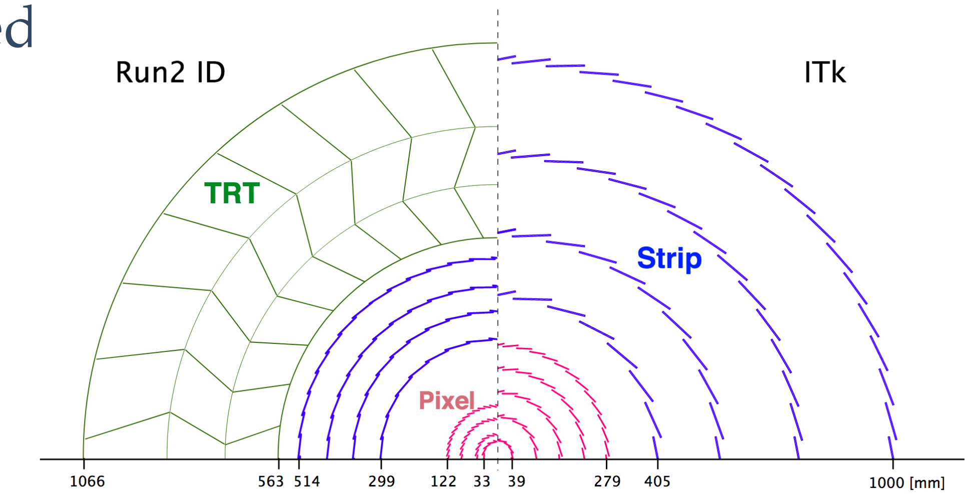
Decay	$\sqrt{s}$ = 13 TeV Exclusion	$\sqrt{s}$ = 13 TeV Discovery	$\sqrt{s}$ = 14 TeV Exclusion	$\sqrt{s}$ = 14 TeV Discovery
$Z'_{\mathrm{SSM}} \to ee$	6.0 TeV	5.9 TeV	6.4 TeV	6.3 TeV
$Z'_{\mathrm{SSM}} \to \mu\mu$	5.5 TeV	5.4 TeV	5.8 TeV	5.7 TeV
$Z'_{\mathrm{SSM}} \to \ell\ell$	6.1 TeV	6.1 TeV	6.5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

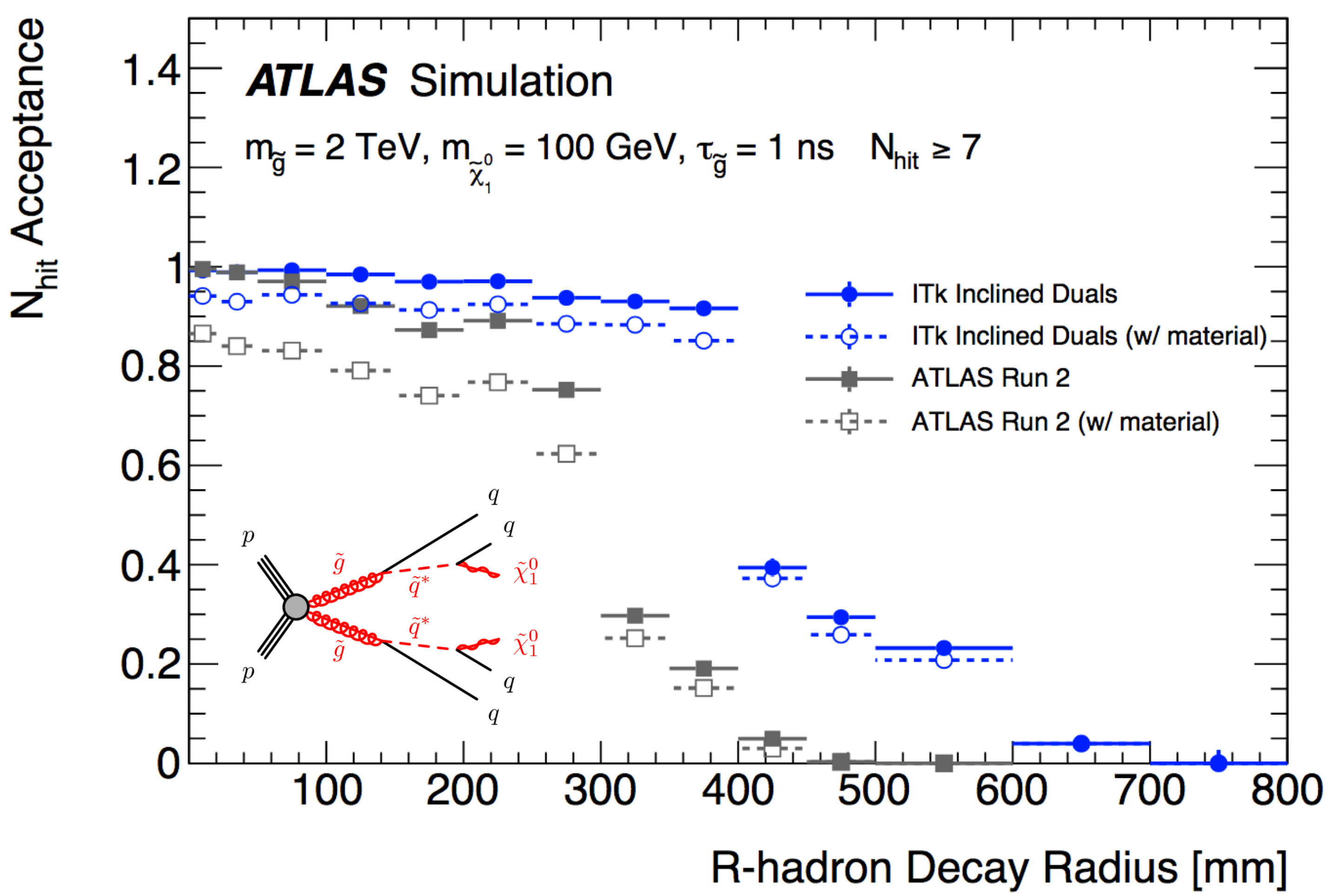
Decay	Exclusion [TeV]	Discovery [TeV]
$W'_{\mathrm{SSM}} \to e\nu$	7.6	7.5
$W'_{\mathrm{SSM}} \to \mu\nu$	7.3	7.1
$W'_{\mathrm{SSM}} \to \ell\nu$	7.9	7.7

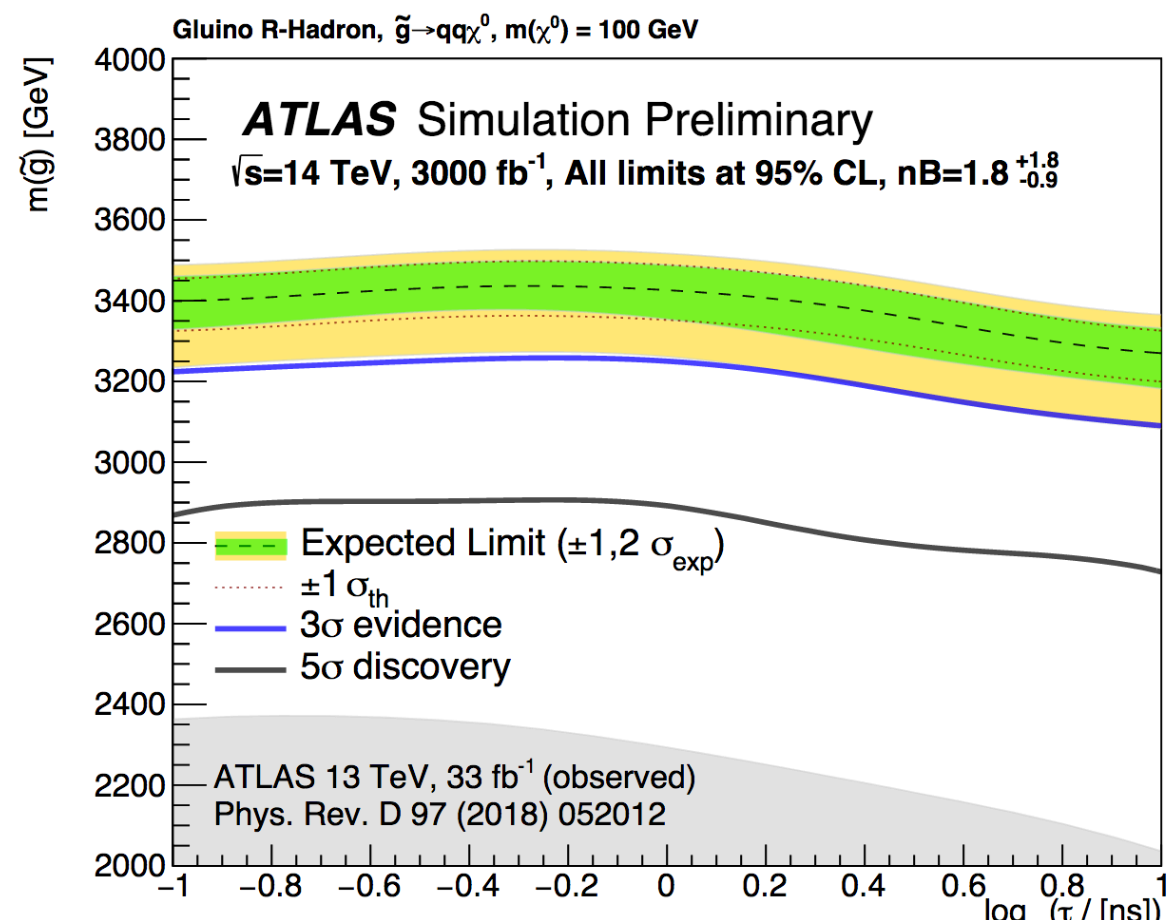
Long Lived Particles

Signatures with displaced vertices will benefit from upgraded tracker (more hits-on-track with better resolution)

- Case study R-hadrons: long-lived gluinos decaying in the tracker to multiple charged particles
- Minimum number of hits after decay to ensure efficient reconstruction and background rejection







ATL-PHYS-PUB-2018-033

Summary

HL-LHC opens up new possibilities in terms of

- Precision SM measurements
    - Higgs couplings and self couplings, more precise electro-weak measurements
- Detection and more precise measurement of rare processes
    - 4-tops production, multi-boson scattering and production
- Extension of the BSM search program
    - Pushing the boundaries of the current sensitivity and accessing untested processes (e.g. stau)

Ambitious program can be realised thanks to

- Upgraded detectors and data acquisition systems
- Bigger size of the dataset collected
- Reduced experimental uncertainties
- Reduced theoretical uncertainties
- Higher centre-of-mass energy of the collisions

Challenging experimental conditions means a fun time ahead!

Back-Up Slides

Physics Results Projections

- **Object reconstruction performance** assessed through **detailed simulation**
- **Extrapolation** of existing results through current statistical framework
- **Scale factors** to take into account performance of **upgraded detectors** and change in **cross section**
- Consider **current analyses techniques** (space for improvement)
- **Fast simulation** for the upgraded **CMS detector** performance (Delphes)
- **Particle-level** analysis with energy **smearing**, efficiencies and fake rates applied to generator level quantities to mimic upgraded **ATLAS detector**

"YR18" uncertainties

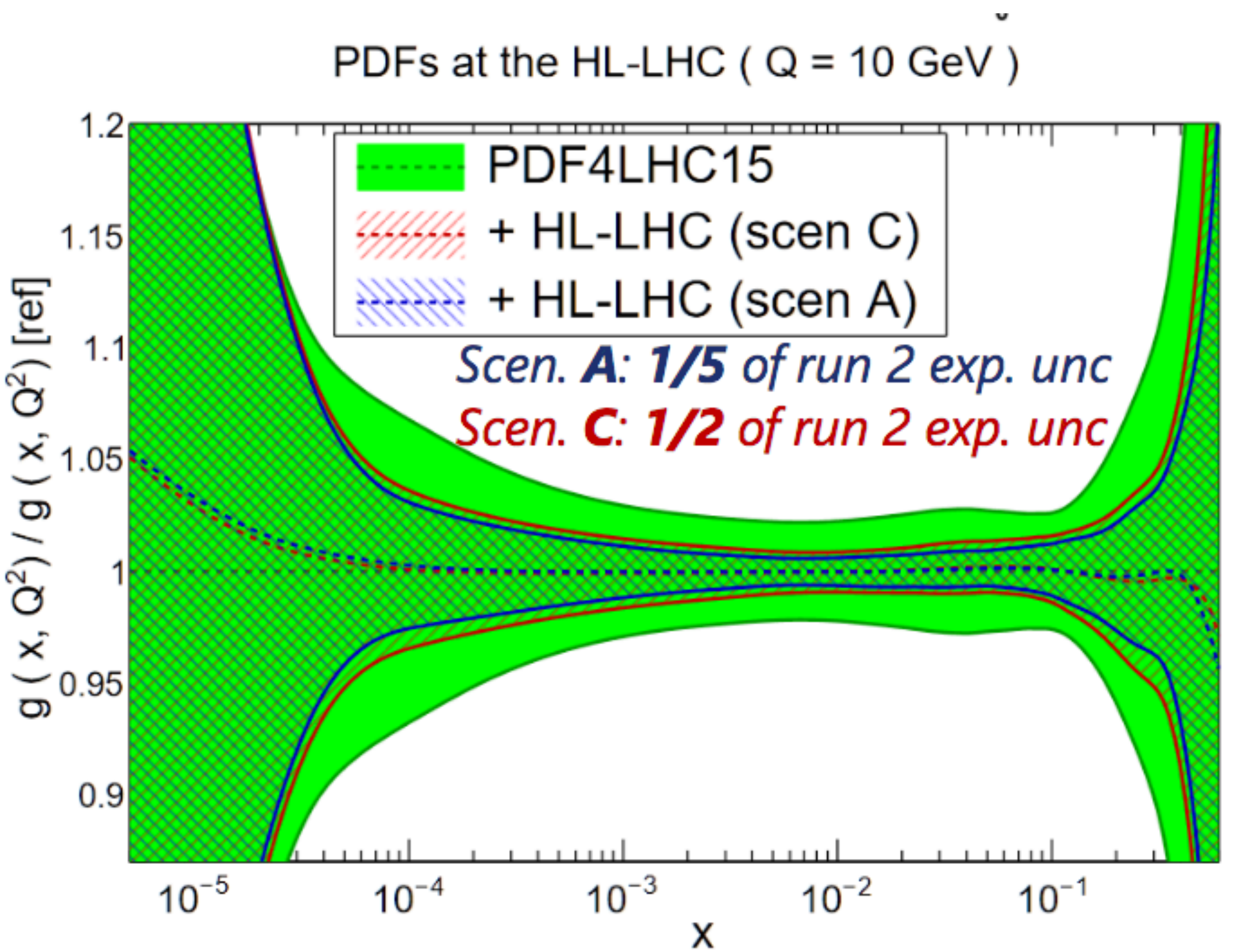
- Lower statistical uncertainties (scaled by $1/\sqrt{L}$)
- Detector related uncertainties unchanged or revised according to simulation
- Halved theoretical uncertainties (higher order calculations and reduced PDF uncertainties)
- Uncertainties on methods left unchanged
- Uncertainty on luminosity 1%

Compared with current level of uncertainty "Run-2 Uncertainty"

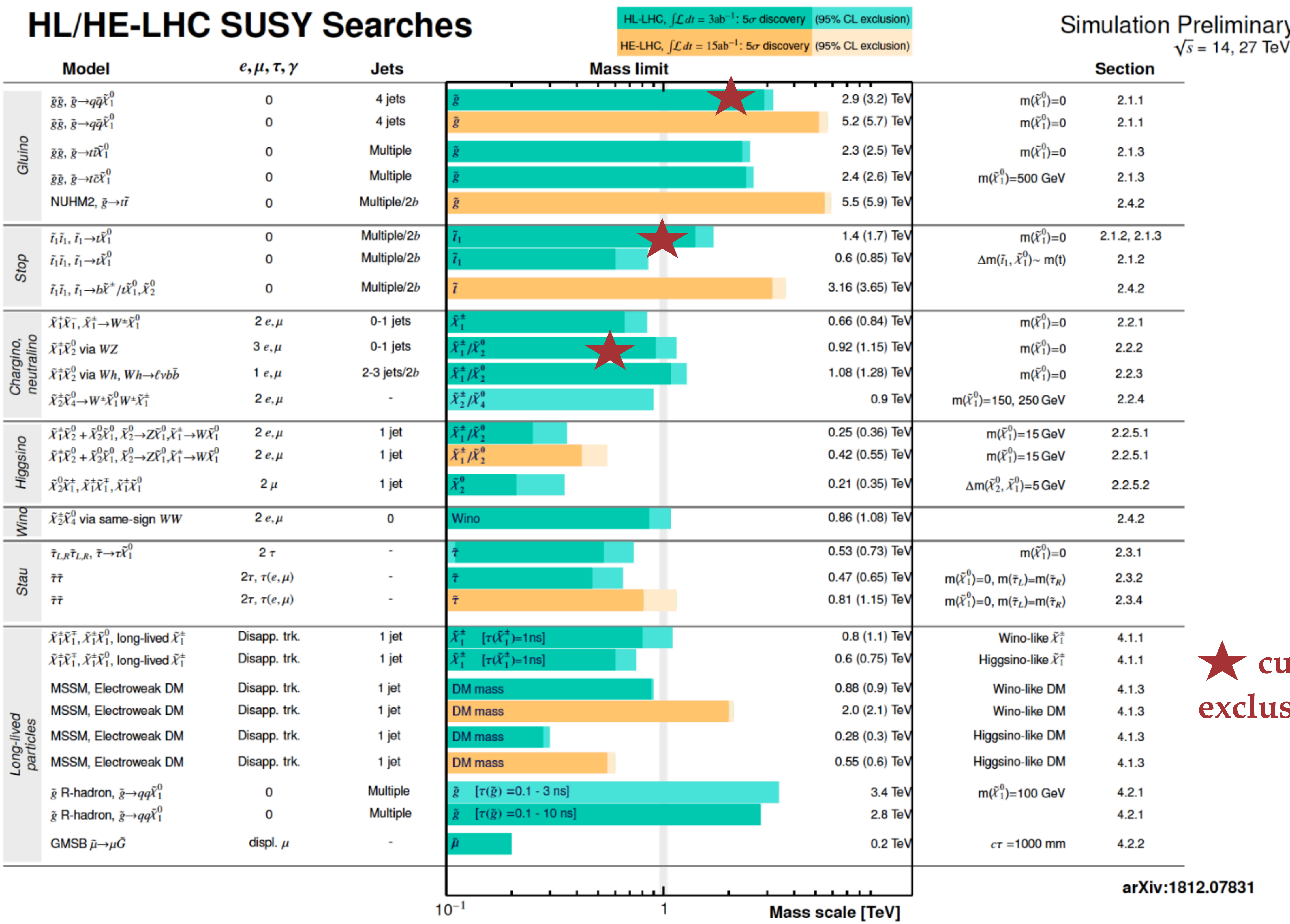
HL-LHC PDF Set

New generation of precision PDF sets including HL-LHC data

- Exploit improved experimental precision
- Profit from enhanced forward acceptance



SUSY Searches Reach



★ current exclusion limit

Exotics Searches Reach