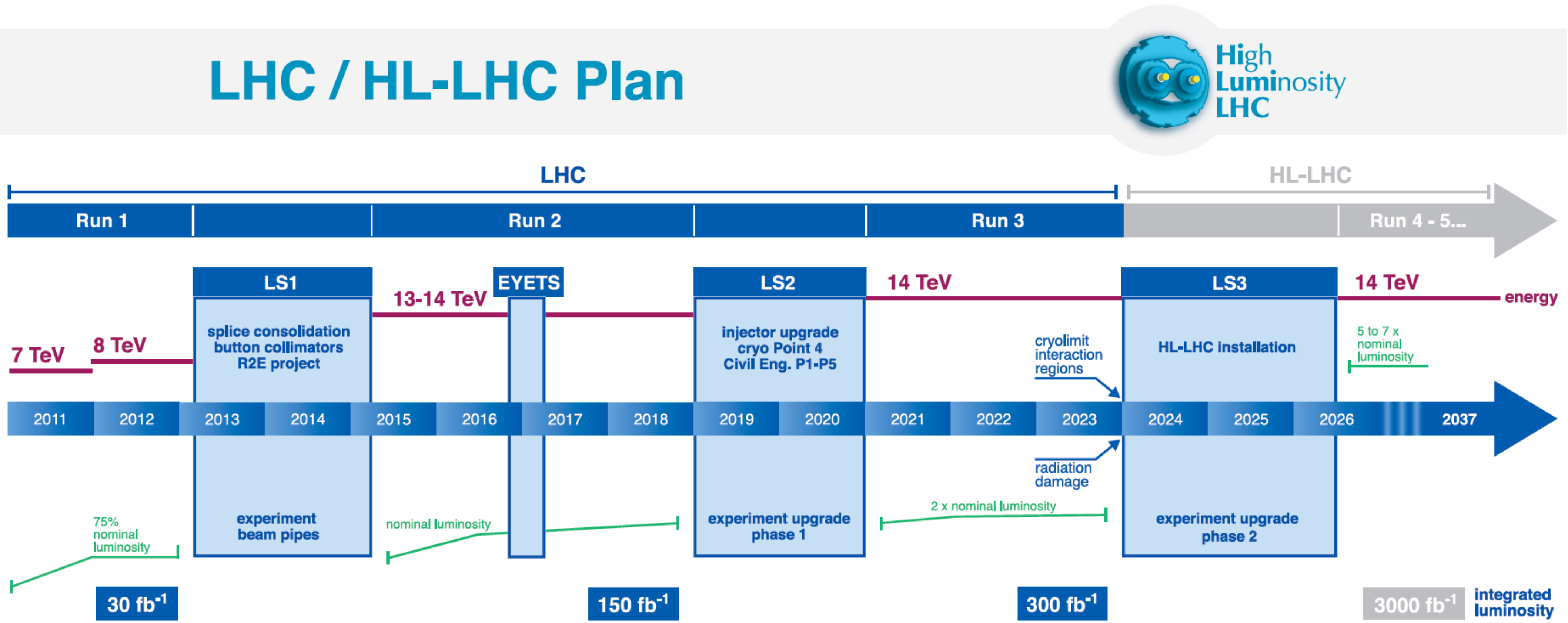
Physics Potential of The ATLAS Experiment at The High Luminosity LHC

Ben Smart,
on behalf of the ATLAS Collaboration,
at Deep Inelastic Scattering 2019, Tornio

Science & Technology Facilities Council
Rutherford Appleton Laboratory

ATLAS EXPERIMENT

- In the future, to improve our measurements and searches, the LHC and ATLAS will be upgraded:



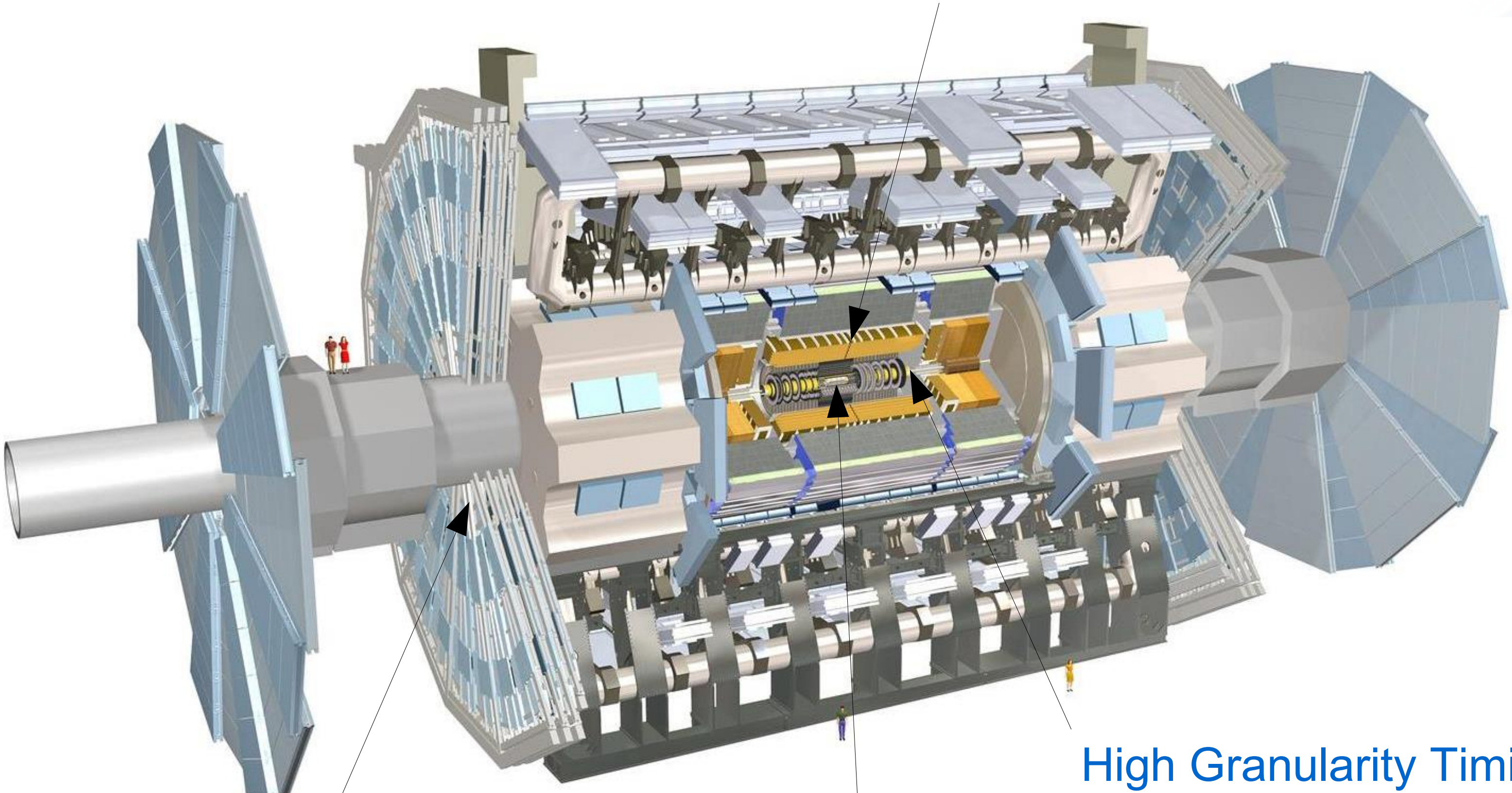
- The LHC will become the High-Luminosity-LHC, to produce 3000 fb^{-1} of integrated luminosity by 2037.
  Higher Energy → benefits searches for new particles.
  Higher integrated luminosity → benefits precision measurements and studies of rare processes.

- Instantaneous luminosity x5-7
  → Particle densities x5-7
- Integrated luminosity x10
  → Radiation damage x10

ATLAS Detector Upgrades For HL-LHC

Triggers
- L0 (Calo+Muon+ITk): 1 MHz
- L1: 400 kHz
- HLT: 10 kHz

Calorimeters
- New readout electronics allowing 1 MHz L0 trigger rate



High Granularity Timing Detector
- Silicon pixel sensors
- 2.7 < |η| < 4.2 acceptance
- 30 ps timing resolution

Muon systems
- New trigger and readout electronics
- Additional inner barrel layer for better acceptance

Inner Tracker (ITk)
- New all-Silicon tracker with |η| < 4.0 acceptance

- ATLAS prospect analyses for HL-LHC are performed in one of three ways, with scaled uncertainties, (and most theory uncertainties halved):

  Full-simulation
  - Full Geant4 detector simulation used.
  - Computationally expensive.
  - Used for detector performance studies (tracking, b-tagging, etc.)

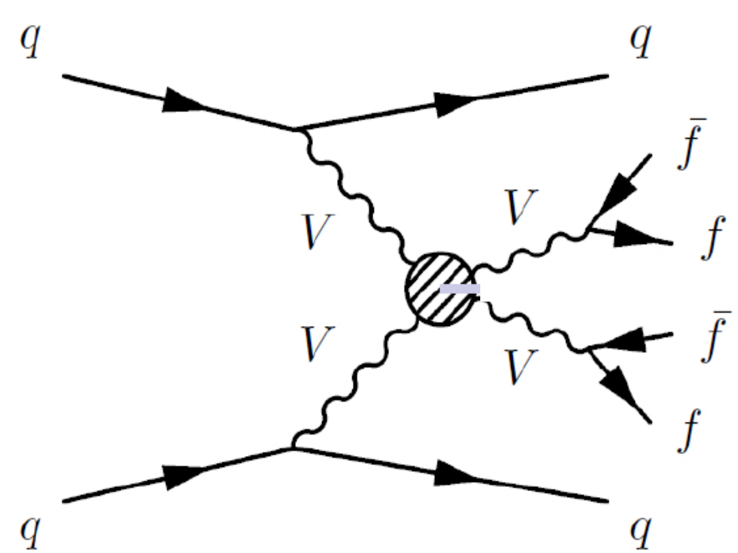
  Smeared truth-level analysis
  - Event generator output is smeared to emulate detector effects.
  - Smearing functions are derived from full simulation.
  - Less computationally expensive than full simulation.

  Scaled Run 2 results
  - Run 2 analyses scaled to 14 TeV.

- Latest HL-LHC results available in five HL-LHC 'Yellow Report' chapters: Standard Model, Higgs, SUSY+Exotics, Flavour Physics, Heavy Ions, and a Summary. Click on the orange text for web-links.

Standard Model Prospects

- Currently, ATLAS has observed WW and WZ VBS processes.
- It is still not known whether the Higgs boson completely preserves unitarity of the VV longitudinal scattering amplitude at all energies.
- VBS provides an excellent probe of EW symmetry breaking in the SM.
- Smeared truth-level analyses are used.
- At the HL-LHC, we expect 5σ observations of all VBS processes, with good precision.

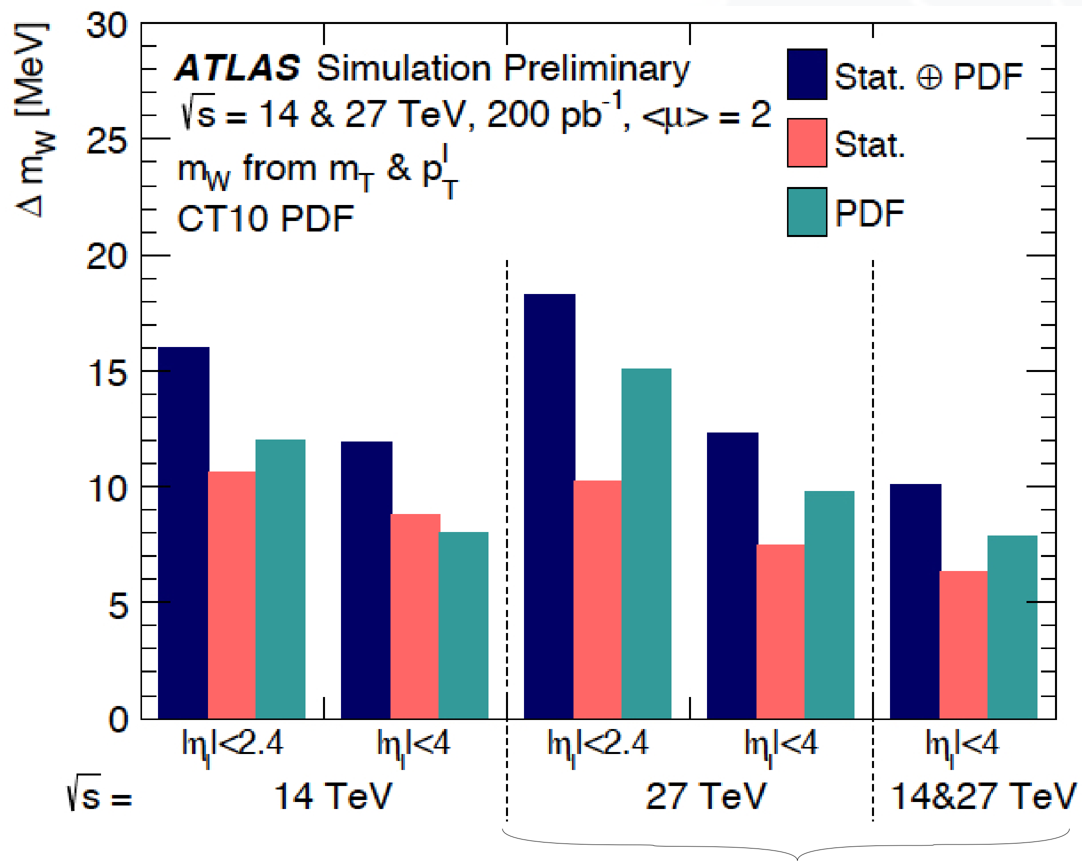


Process	$W^{\pm}W^{\pm}$	WZ	WV	ZZ
Final state	$\ell^{\pm}\ell^{\pm}$jj	3ℓjj	ℓjjjj	4ℓjj
Precision	6%	6%	6.5%	10–40%
Significance	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$

(Yellow Report HL-LHC Summary)
(CERN-LPCC-2018-03)

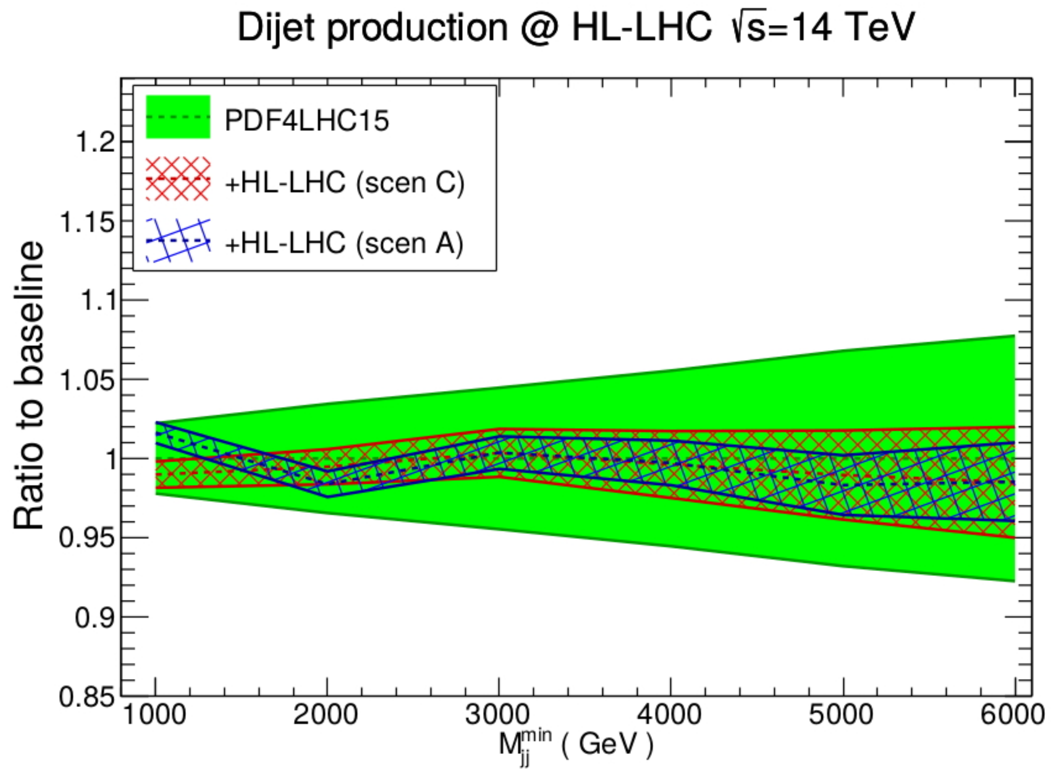
- Current ATLAS W mass accuracy is 19 MeV.
- With the HL-LHC, this is hoped to be reduced to 12 MeV.
- This is assuming current PDF uncertainties.
- Low pile up, <μ> = 2 runs, of interest for W mass measurement, would collect the data giving the HL-LHC results shown here in the plot in one week.
- The increased acceptance of the ATLAS tracker up to |η| < 4.0 benefits the study of W→lν decays, as shown in the plot.

(CERN-LPCC-2018-03)



HE-LHC results – outwith the scope of this talk

- With HL-LHC data, PDFs can be better constrained.
- Forward-W data available due to the increased acceptance of ATLAS will be particularly beneficial for this.



(CERN-LPCC-2018-03)

- Experimental systematic uncertainties will affect the constraining of PDFs.
  Scenario A = optimistic reduction of systematic uncertainties.
  Scenario C = conservative reduction of systematic uncertainties.

- Increased acceptance of ITk, Muon systems, plus HGTD, benefits pile-up rejection, and thus robustness against pile-up effects, for all analyses.

- Analyses with forward physics especially benefit from from increased angular acceptance:

Measurement precision

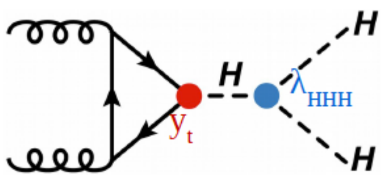
Physics channel	$\|\eta\|<2.7$	$\|\eta\|<4.0$	
Same-sign WW scattering	4.5%	4.0%	(ATL-PHYS-PUB-2017-023)
VBF $H\rightarrow WW^*$	22%	12%	(ATLAS-TDR-025)

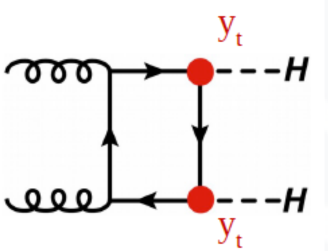
Higgs Prospects

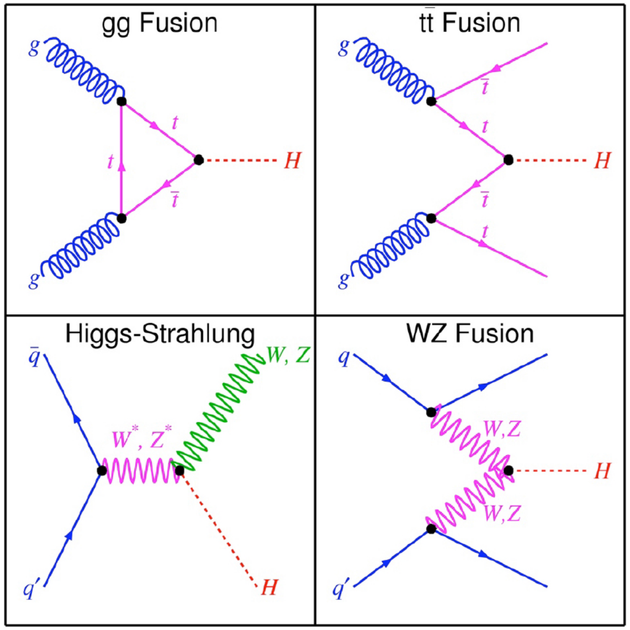
- The HL-LHC will be ideal for further study of the Higgs boson.

- HL-LHC will have more than 10 times the integrated luminosity of the LHC.
- Thus more than 10 times the number of Higgs bosons available to study at the HL-LHC compared to the LHC.

- ~100k Higgs to di-Higgs decays.





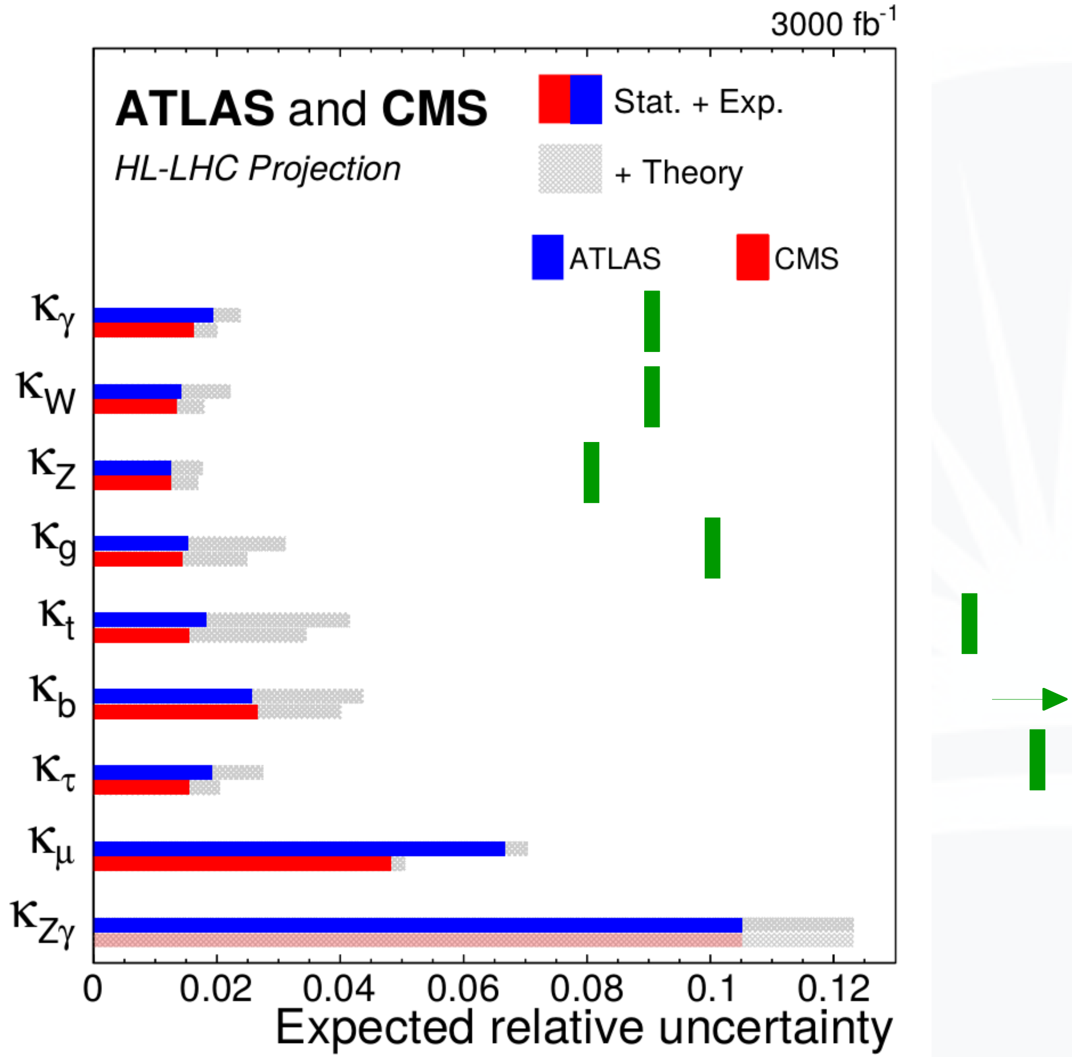


- Will allow precision Higgs measurements on the order of a few percent.

- Can further explore Higgs self-coupling through Higgs to di-Higgs decays.

- Increased sensitivity to rare decays and new physics.

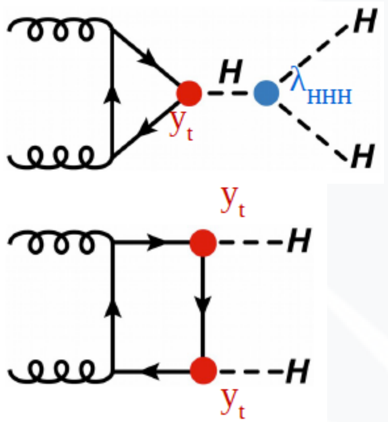
- Latest ATLAS+CMS results are given in the 'κ-framework'.
- This is a set of κ factors that linearly modify the coupling of the Higgs boson to SM elementary particles.
- $\kappa_i = 1$, for all i, is the SM.
- Thus if any κ is not equal to 1, we will have new physics.
- κ_λ corresponds to the Higgs self-coupling.

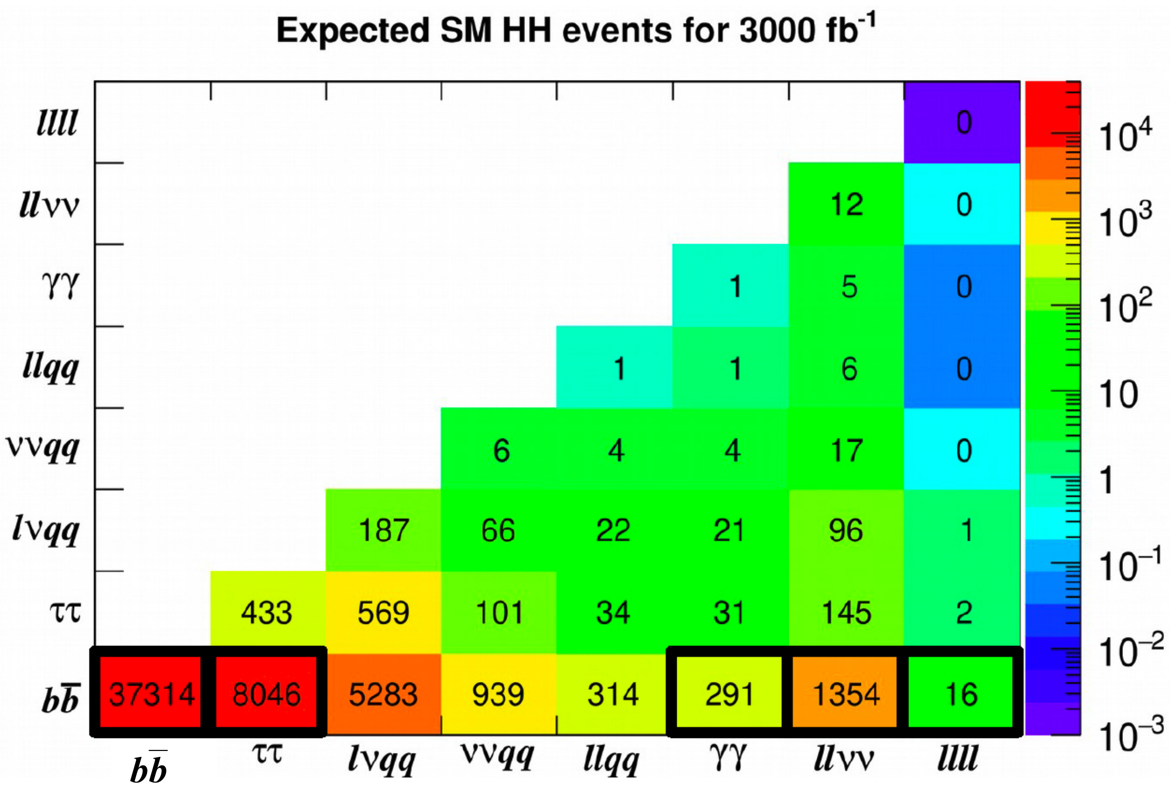


(CERN-LPCC-2018-04)

Latest ATLAS Run 2 results are shown in green (ATLAS-CONF-2019-005)

- The Higgs self-coupling is a crucial test of the Standard Model and electroweak symmetry breaking.
- It is accessible through Higgs to di-higgs decays.
- Different final states offer balance of cross-section v. clean identification.



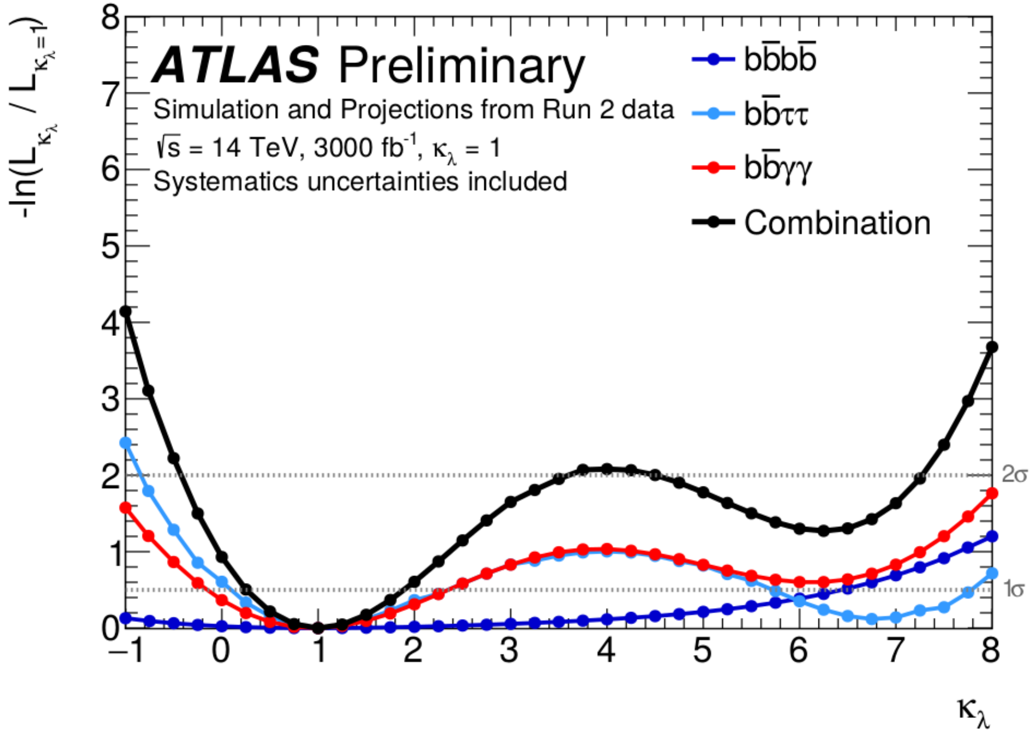


bbbb	Scaled Run 2 analysis	Largest BR, Large bkg, Challenging identification
bbττ	Scaled Run 2 analysis	Large BR, Small BG, Reasonable identification
bbγγ	Smeared truth-level analysis	Small BR, Clean identification + triggering

(ATL-PHYS-PUB-2018-053)

- Setting limits on the Higgs self-coupling modifying factor κ_λ allows to test the SM and for BSM physics, (κ_λ = 1 in the SM).

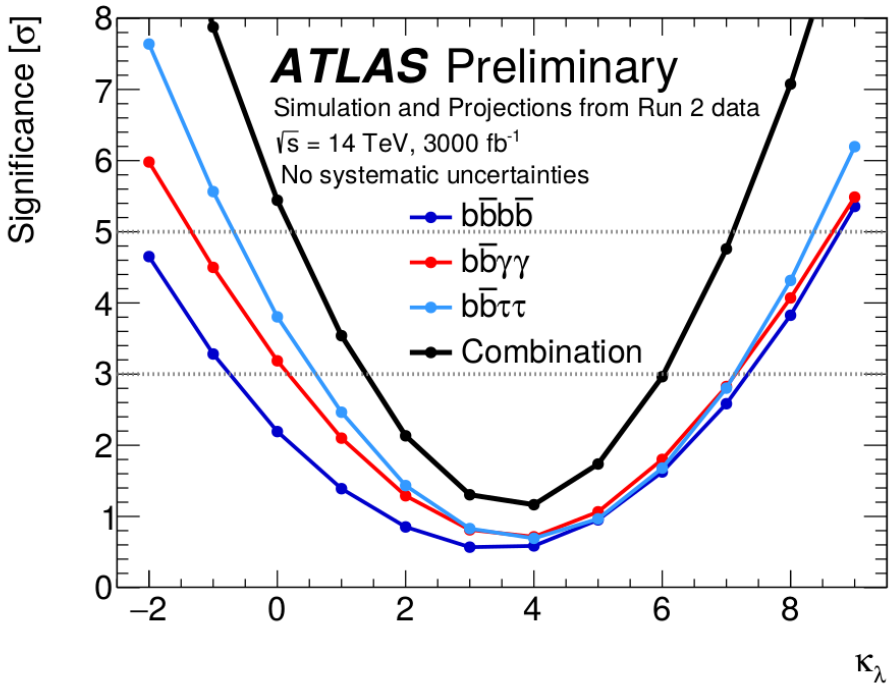
- Exclusion limits for different κ_λ values, assuming κ_λ = 1, are shown on the right.

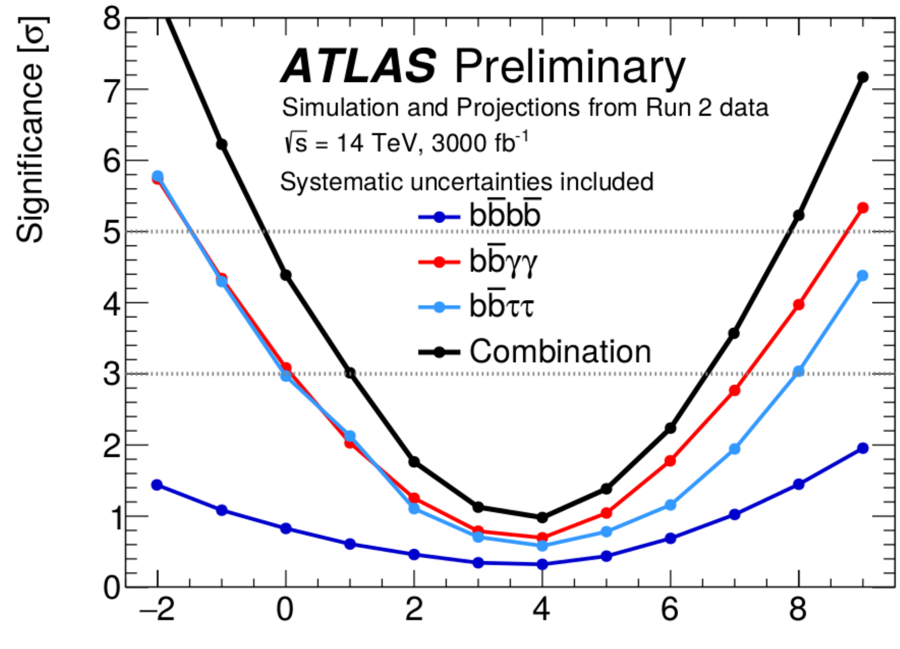


- As κ_λ increases, channel cross-sections increase, but acceptances decrease (analyses are optimised for κ_λ = 1), thus giving shape of curves above.

- Exclusion limits will improve with analyses optimised for different κ_λ values, but this is considerable work, hence is not prioritised at present.

- Evidence and observation of Higgs to di-Higgs decays depends on true value of κ_λ. ATLAS reaches 3.0 σ for $\kappa_\lambda = 1$.
- Combination of all channels required. Future improvements in analysis techniques and systematics will be of great benefit.
- Combined ATLAS+CMS Standard Model H→HH significance: 4.0 σ Full HL-HLC dataset required to measure Higgs self-coupling.

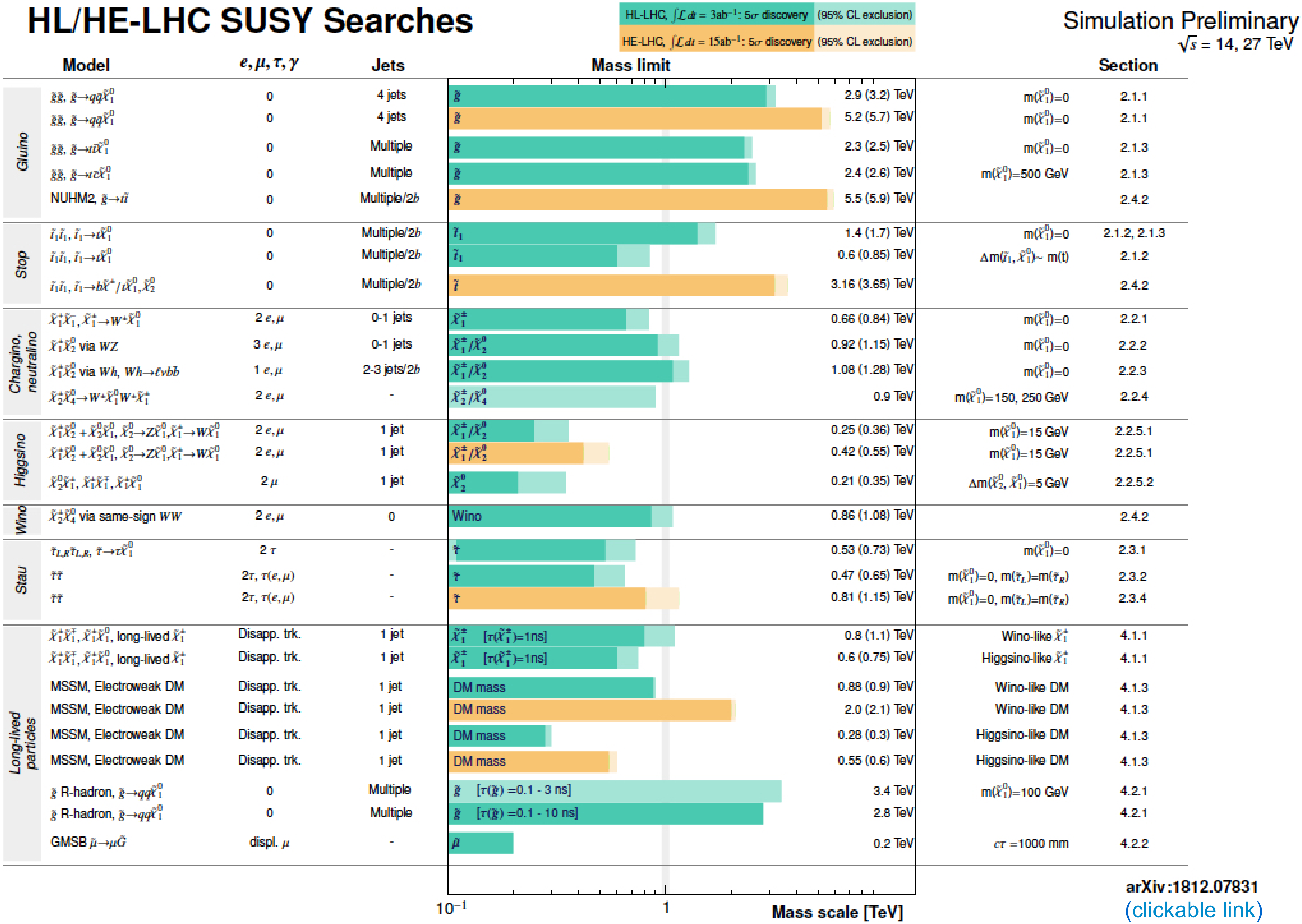




(ATL-PHYS-PUB-2018-053)

Beyond The Standard Model Prospects

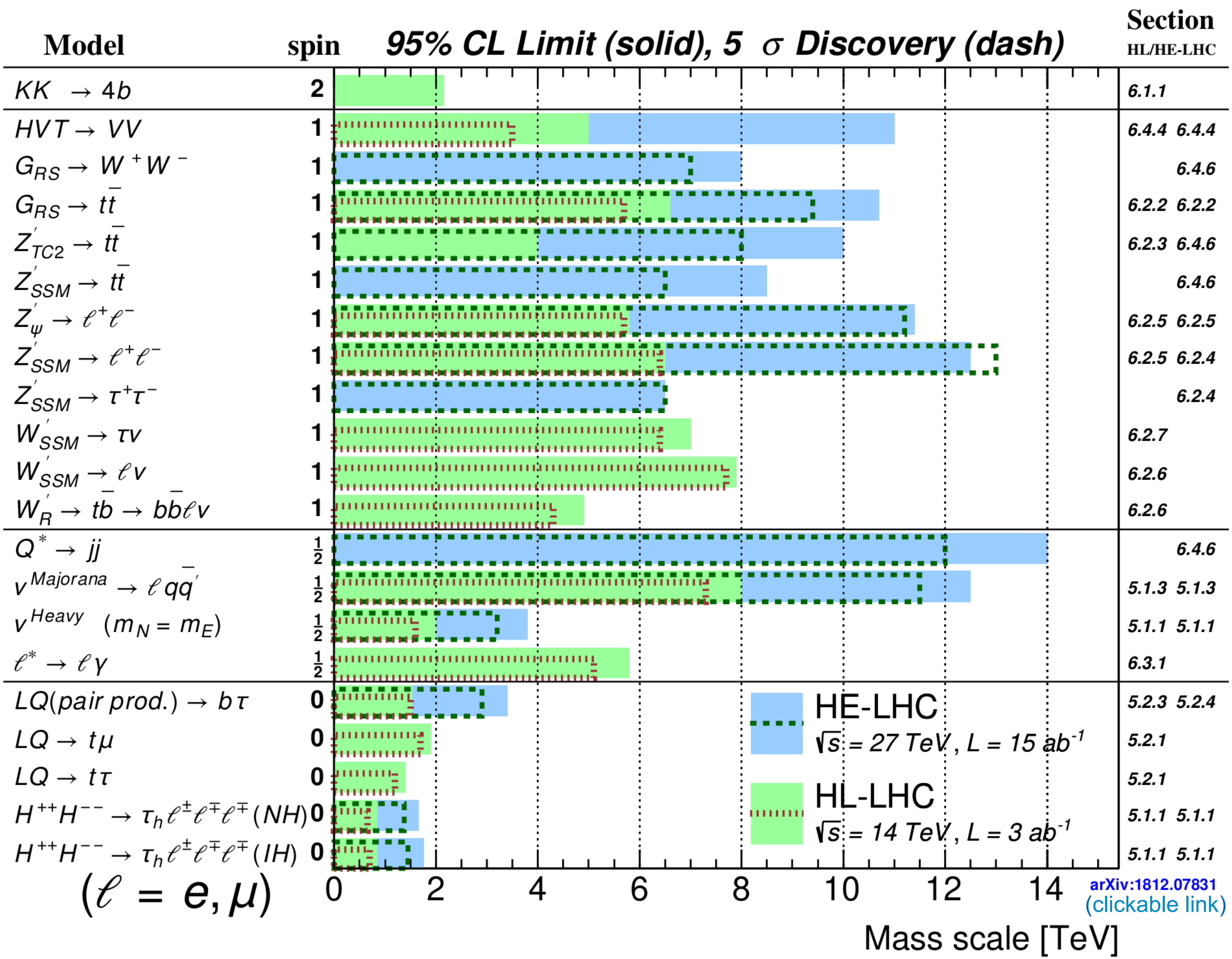
SUSY Mass-Scale Reach



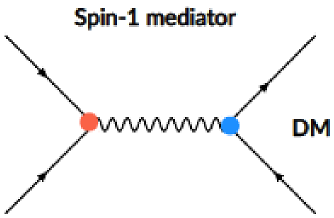
arXiv:1812.07831
(clickable link)

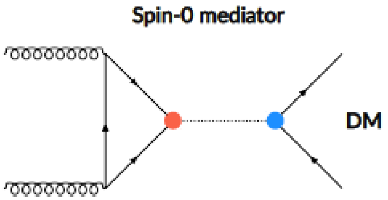
- 20-50% increase on current results in most cases.

Exotics Mass-Scale Reach

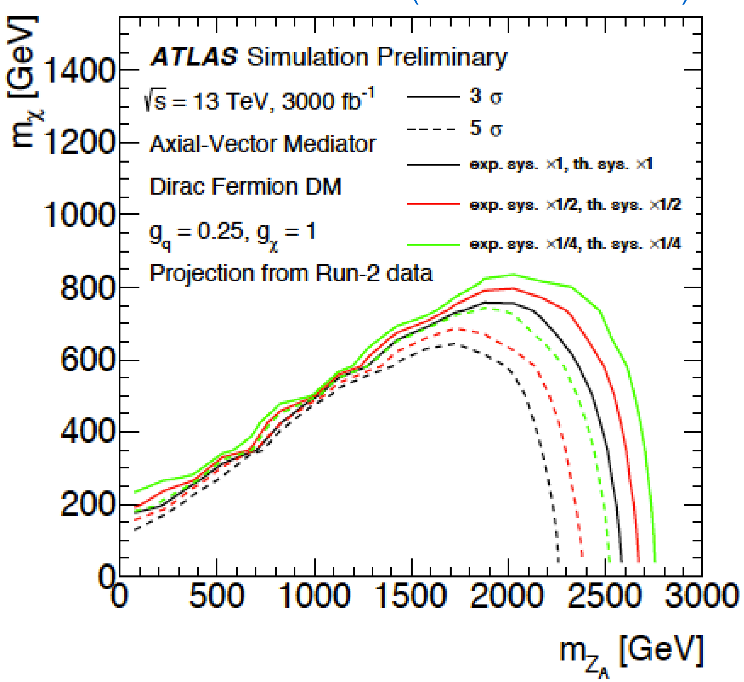


- Dark matter candidates postulated by, for example, SUSY.
- Also possible to produce 'simplified' DM models with fewer parameters.
    - Say, a mediator which decays to a DM particle and a SM particle, giving 4 parameters: m_{med}, m_{DM}, med-SM and med-DM couplings.





(CERN-LPCC-2018-05)



- 'Flagship' dark matter search: high-p_T jet + MET.
- With ATLAS at HL-LHC, discovery (exclusion) of m_{Z_A} up to 2.25 (2.65) TeV.
- Main uncertainties come from MC modelling, and jet/MET scale and resolution.

W' And Z' Searches

- W'→lν searches (l = e,μ)
  - Current Run 2 exclusion limit is 5.6 TeV.
  - With HL-LHC the limits become:

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

(CERN-LPCC-2018-05)

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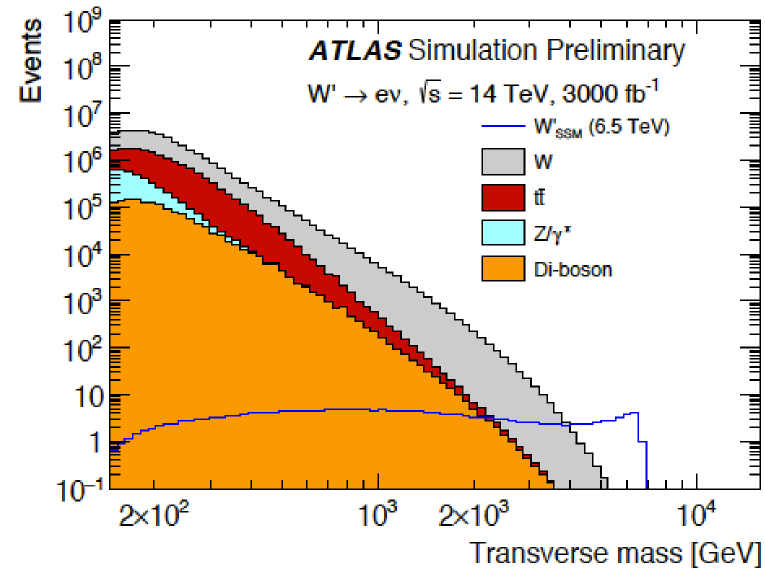


- Z'→ll searches (l = e,μ)
  - Current (139 fb^{-1}) limits shown below left.
  - HL-LHC limits shown below right.

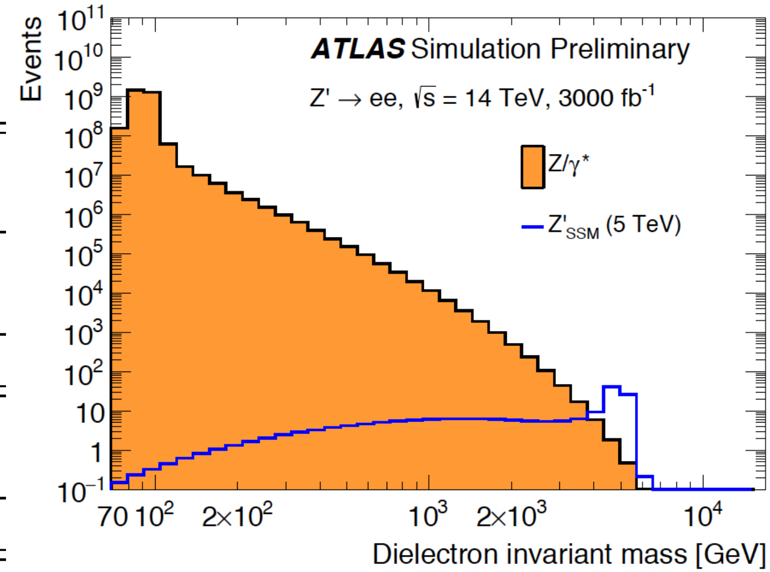
Model	Lower limits on $m_{Z'}$ [TeV]					
	ee		$\mu\mu$		$\ell\ell$	
	obs	exp	obs	exp	obs	exp
Z'_ψ	4.1	4.3	4.0	4.0	4.5	4.5
Z'_χ	4.6	4.6	4.2	4.2	4.8	4.8
Z'_{SSM}	4.9	4.9	4.5	4.5	5.1	5.1

(CERN-EP-2019-030)

Decay	$\sqrt{s} = 14$ TeV Exclusion	$\sqrt{s} = 14$ TeV Discovery
$Z'_{SSM} \to ee$	6.4 TeV	6.3 TeV
$Z'_{SSM} \to \mu\mu$	5.8 TeV	5.7 TeV
$Z'_{SSM} \to \ell\ell$	6.5 TeV	6.4 TeV
$Z'_\psi \to ee$	5.7 TeV	5.6 TeV
$Z'_\psi \to \mu\mu$	5.2 TeV	5.0 TeV
$Z'_\psi \to \ell\ell$	5.8 TeV	5.7 TeV

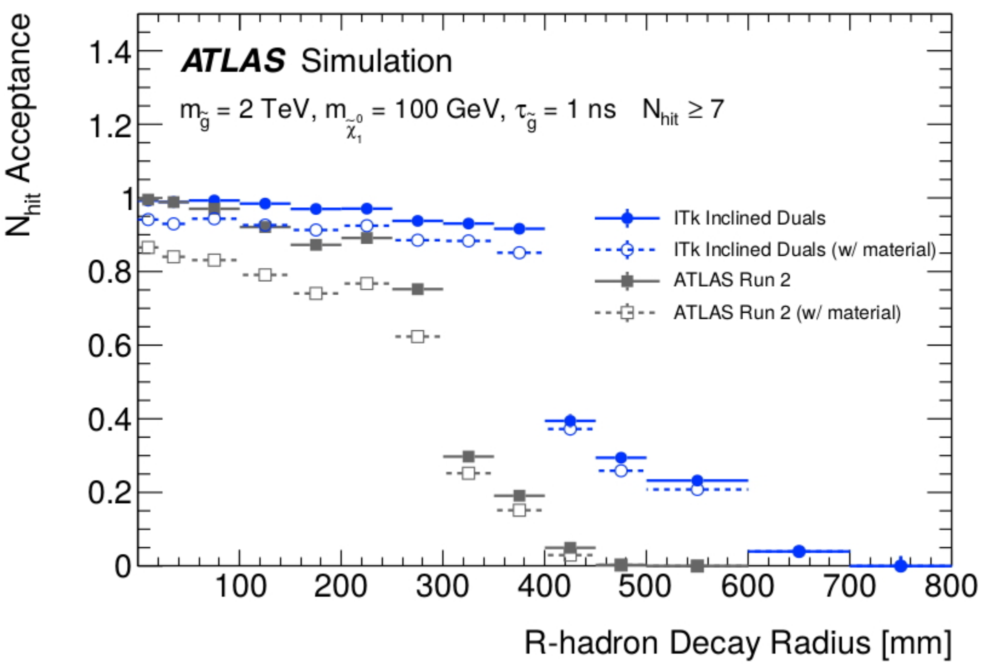
(CERN-LPCC-2018-05)

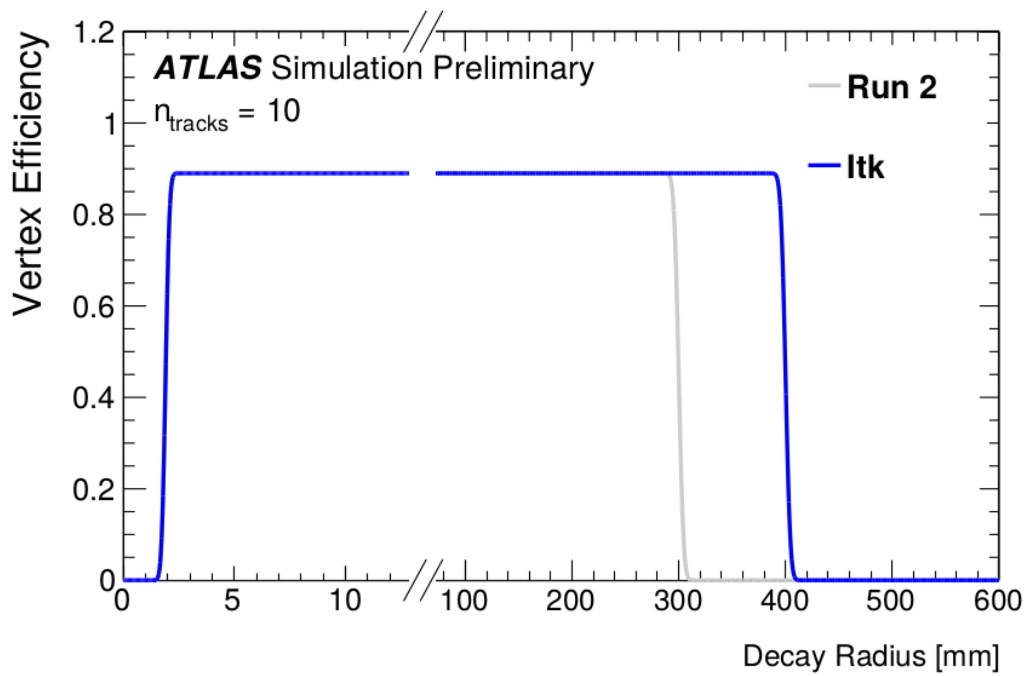
(CERN-LPCC-2018-05)



- ITk design allows for extended reach of long lived particle searches.

- More hits-on-track, with better hit-position resolution, of the ITk allows tracks originating from verticies at a larger radius to still be reconstructed, compared to the Run 2 Inner Detector.



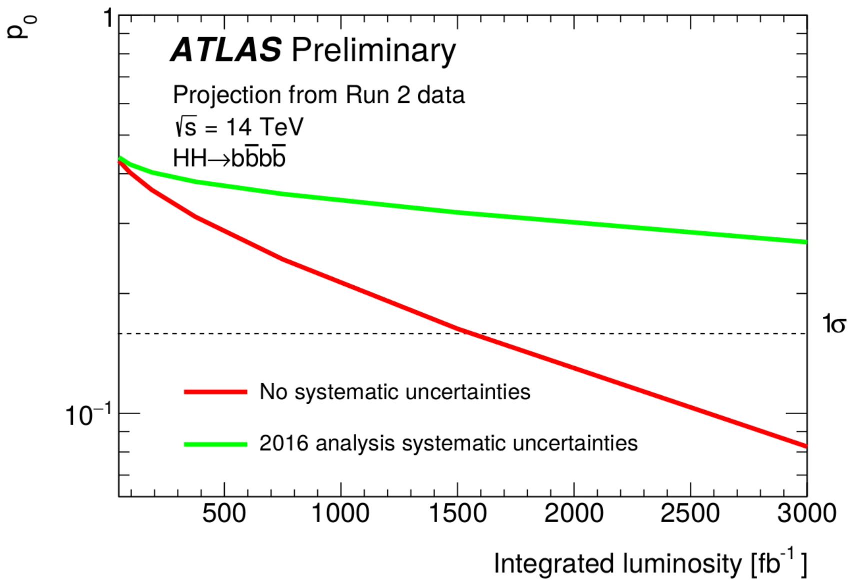


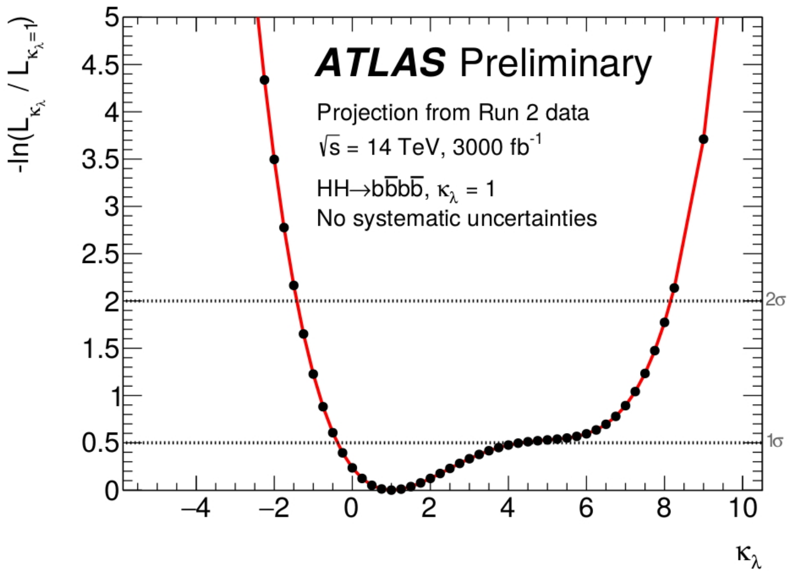
(CERN-LPCC-2018-05)

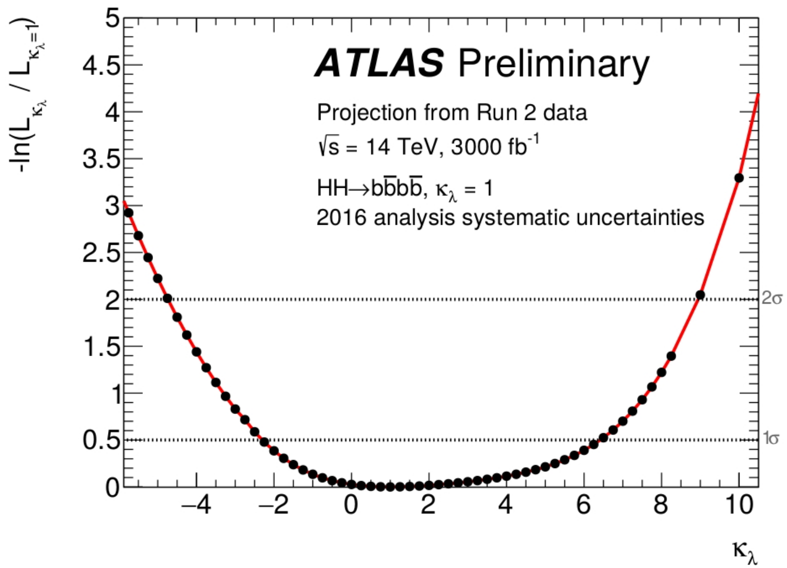
Summary

- In the future, the LHC and ATLAS will be upgraded:
  - The LHC will become the High Luminosity LHC, with <μ>=200 at $\sqrt{s}$ = 14 TeV, collecting 3000 fb^{-1} in 10 years.
  - ATLAS will receive upgrades to its trigger, muon, and calorimeter systems, as well as a new tracking detector.
- All these developments will benefit searches for new particles, precision measurements, and studies of rare processes, with the ATLAS Detector.
- The latest estimations of physics potential at the HL-LHC are given in the input to European Strategy CERN 'Yellow Report'.
  - Results are promising and very competitive.
  - But let's push to do even better!
    - 5 σ SM $H \rightarrow HH$ significance?

Backup



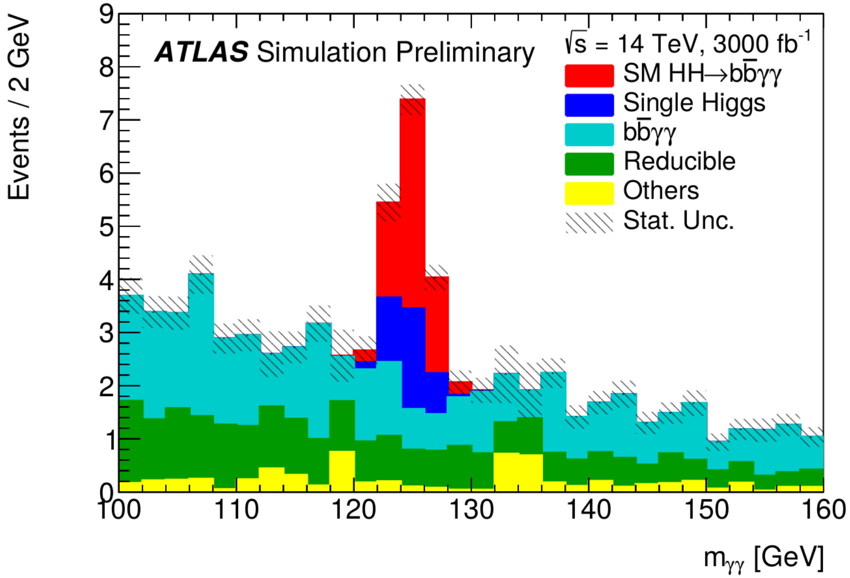


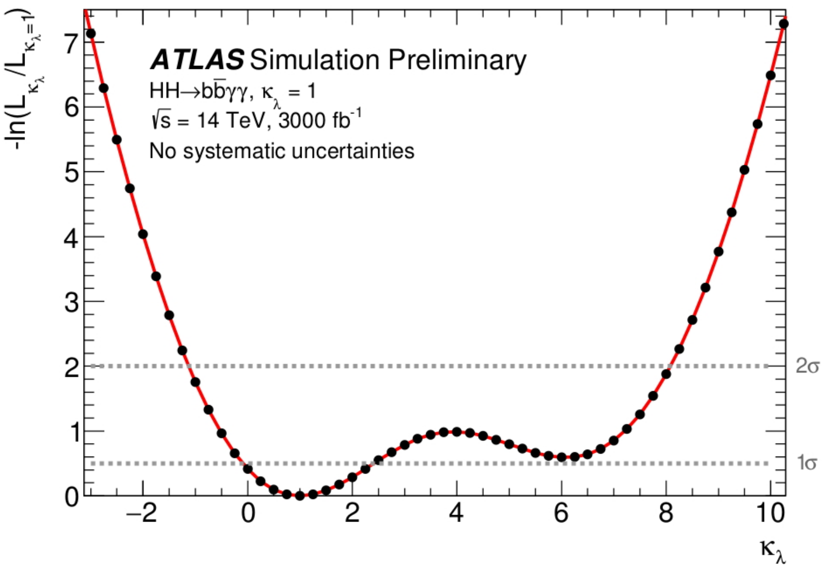


- As κ_λ increases, channel cross-section increases, but acceptance decreases (analysis is optimised for $\kappa_\lambda = 1$), thus giving shape of curves on the right.

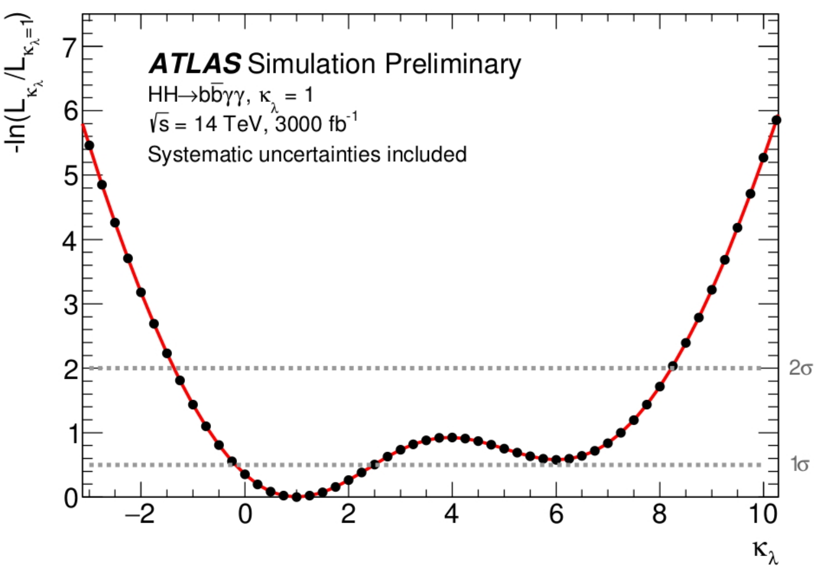
- With current systematic uncertainties, significance: 0.62 σ
- With zero systematic uncertainties, significance: 1.4 σ

(ATL-PHYS-PUB-2018-053)





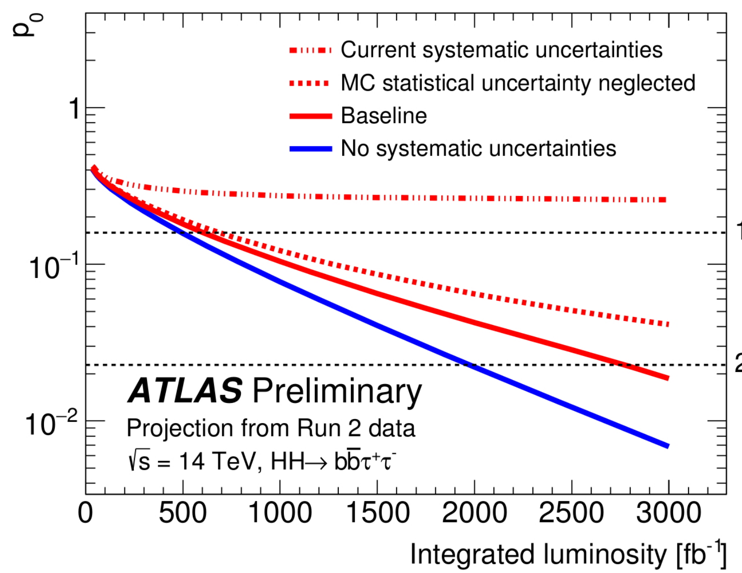
- Clean $\gamma\gamma$ peak.
- Small cross section.

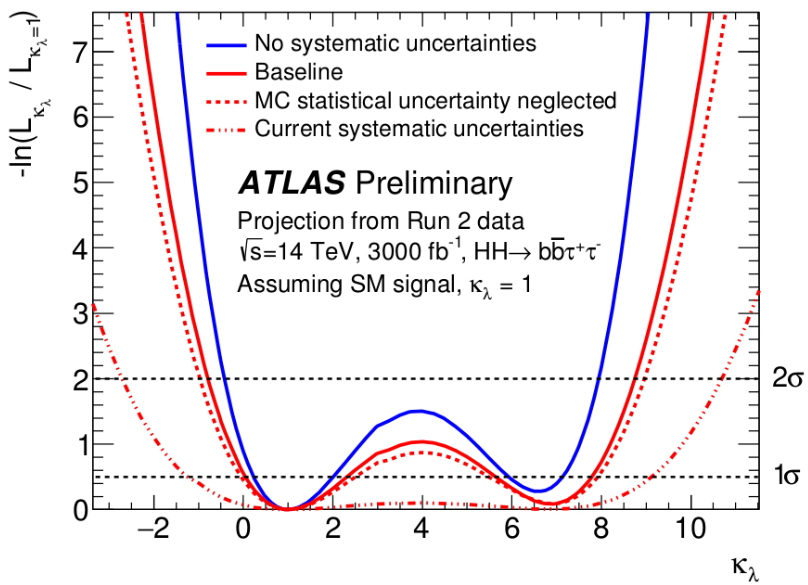


(ATL-PHYS-PUB-2018-053)

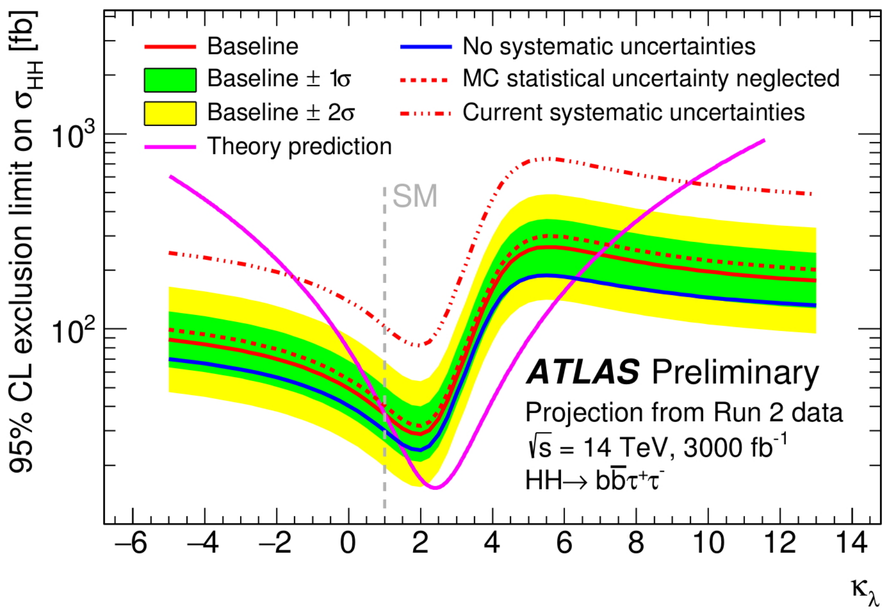
- Reducible background is $c\bar{c}\gamma\gamma$, $jj\gamma\gamma$, $b\bar{b}j\gamma$, $c\bar{c}j\gamma$, $b\bar{b}jj$.
  Other background is $Z(b\bar{b})\gamma\gamma$, $t\bar{t}$, $t\bar{t}\gamma$.

- Limits on κ_λ not dominated by systematic uncertainties.





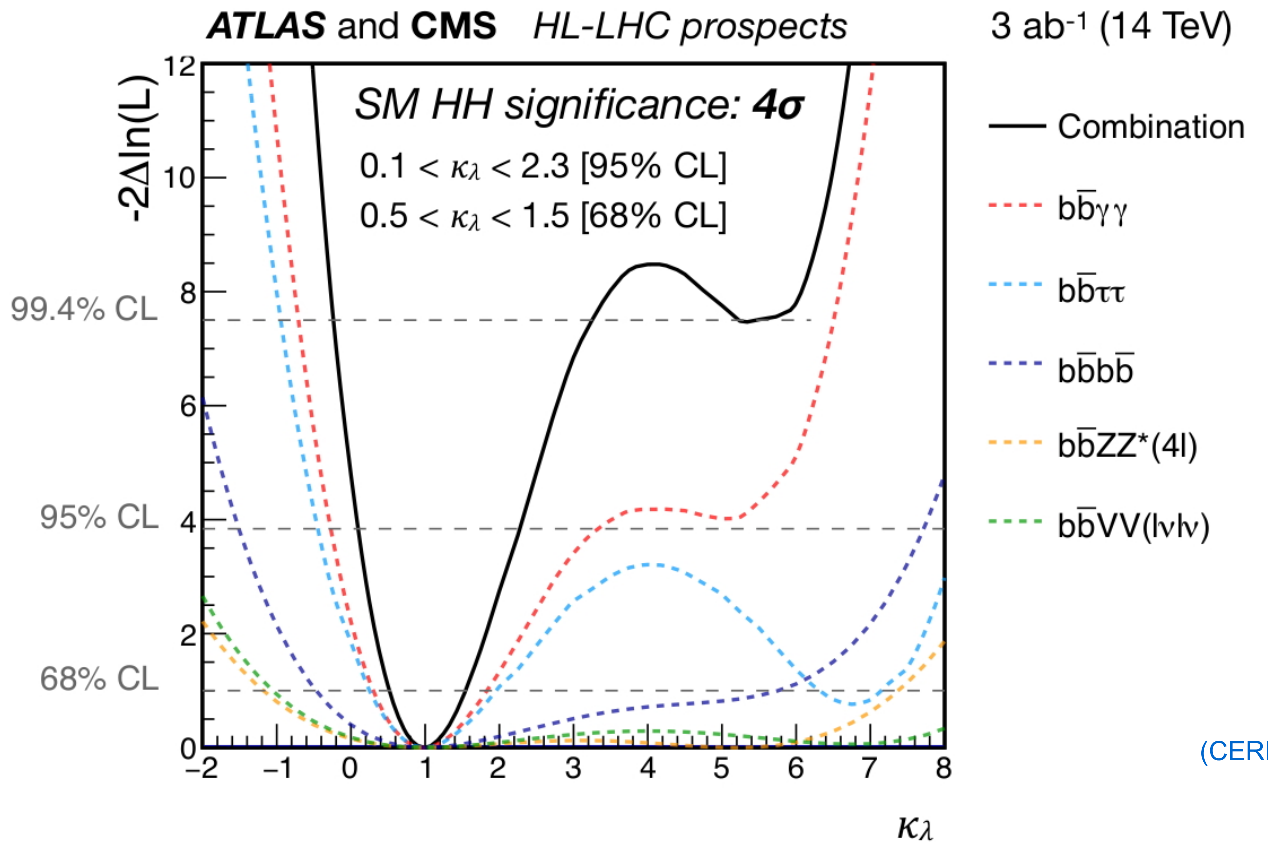
- Run 2 analysis is extrapolated to HL-LHC.
- $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ decay channels are considered.



- The κ_λ exclusion interval at 95% CL is, with current systematic uncertainties: $1.0 < \kappa_\lambda < 7.0$ with no systematic uncertainties: $1.4 < \kappa_\lambda < 6.3$

(ATL-PHYS-PUB-2018-053)

- Exclusion limits on Higgs self-coupling κ_λ when combining all HH channels and HL-LHC data from ATLAS and CMS.



(CERN-LPCC-2018-04)

- Combined Standard Model H→HH significance: 4 σ
  Full HL-HLC dataset required to measure Higgs self-coupling.
- The Higgs boson self-coupling can be constrained to
  $-0.1 \leq \lambda_{HHH}/\lambda SM_{HHH} \leq 2.7 \cup 5.5 \leq \lambda_{HHH}/\lambda SM_{HHH} \leq 6.9$, at 95% CL.