Prospects of HL-LHC

Hongbo Liao

Institute of High Energy Physics, Beijing, China

2019.10.27

China LHC Physics Workshop (CLHCP2019)

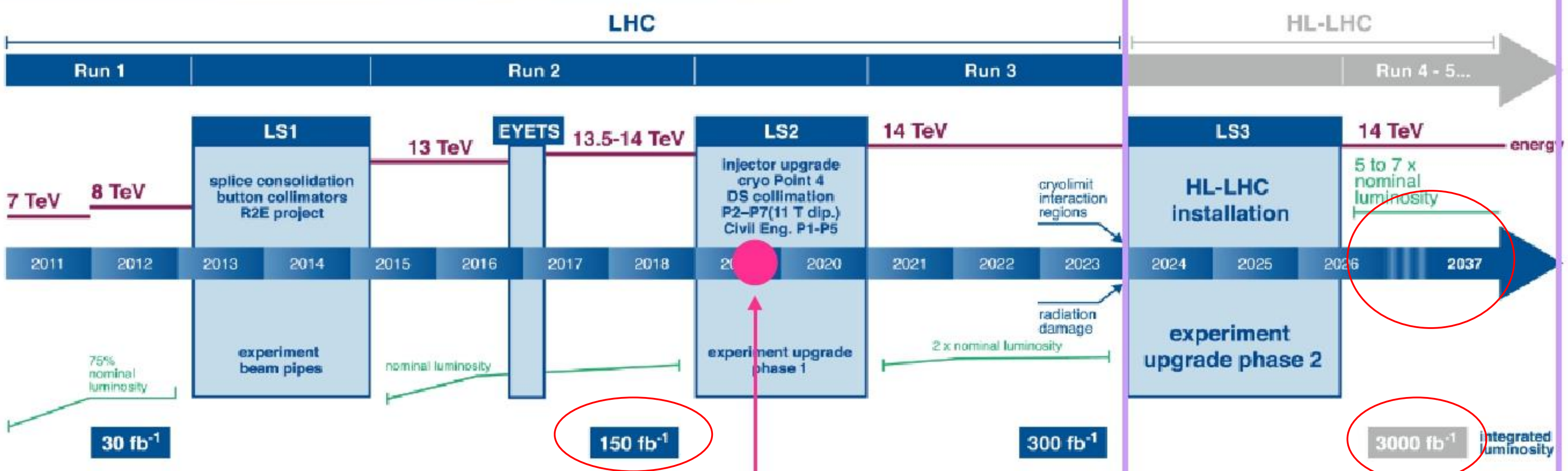
Why the HL-LHC ?

- strong case to go on exploring the TeV scale:
  - Standard Model works very well but does not explain everything
    - low mass of Higgs boson and naturalness hypothesis advocate for the existence of new particles at the TeV scale
    - SM does not provide Dark Matter particle candidate
  - currently no evidence for new physics

- HL-LHC will deliver 3000 - 4000 fb^{-1}, allowing
  - detailed studies of the Higgs boson : standard model or BSM ?
  - precise measurements of standard model, rare processes: indirect evidence for new physics ?
  - search for new particles and processes at the TeV scale (dark matter?)
  - investigate any anomaly / signal found at Run 3

❖ My apologies to LHCb, ALICE, heavy ion running

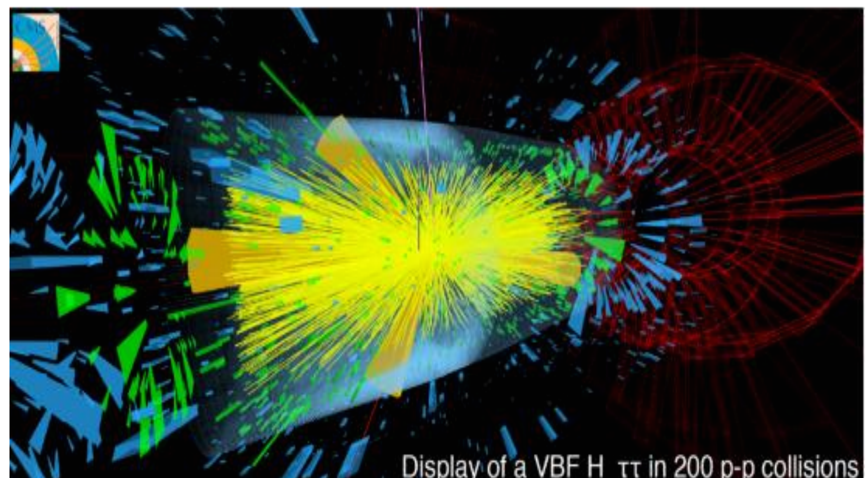
LHC / HL-LHC Plan



•Have only collected ~5% of the total dataset so far

We are here

- ✓ Operation at up to $L=7.5\cdot10^{34}Hz/cm^2$ (LHC Run-2: $2\cdot10^{34}$) to collect up to Lint = **$3000\ fb^{-1}$**
- ✓ Up to **200** (~ 37) **pp collisions** per bunch crossing at HL-LHC (LHC Run2)
  - Very challenging experimental conditions
  - Extensive detector upgrades to operate under HL-LHC conditions



Detector upgrades

ATLAS Detector

- Inner tracker
  - Completely replaced
  - Improved momentum resolution
  - Extend $|\eta|$ coverage from $|\eta|<2.5$ to $|\eta|<4$
- Calorimeters
  - LAr: entirely new frontend and readout electronics
  - Tile: new frontend and readout electronics, power supplies and optical link interface boards
- Muon spectrometer
  - Replace large fraction of frontend and on- and off-detector readout and trigger electronics
  - Additional muon chambers
- Trigger & data acquisition
  - Trigger and DAQ at L1 and HLT (10 kHz)
- High-granularity timing detector
  - Will be installed covering $2.4 < |\eta| < 4.0$ in front of the LAr calorimeter to reduce background from pileo jets

CMS Detector

- Silicon tracking system
  - Completely replaced
  - Improved momentum resolution
  - Extend $|\eta|$ coverage from $|\eta|<2.5$ to $|\eta|<4$
- Calorimeters
  - ECAL barrel: improved front-end electronics.
  - HCAL barrel: replaced read-out technology and scintillator tiles close to the beam line.
  - ECAL and HCAL end-caps replaced by a new combined electromagnetic and hadronic sampling calorimeter
- Muon spectrometer
  - Replace front-end electronics for drift tube and cathode strip chambers
  - Additional muon chambers in the forward region
- Trigger & data acquisition
  - Trigger and DAQ at L1 and HLT (7.5 kHz)
- Minimum ionizing particle timing detector
  - Will be installed between the tracker and the ECAL

Resist high radiation, better resolution, extend coverage, install timing layers, fast trigger, fast read-out and higher band-width

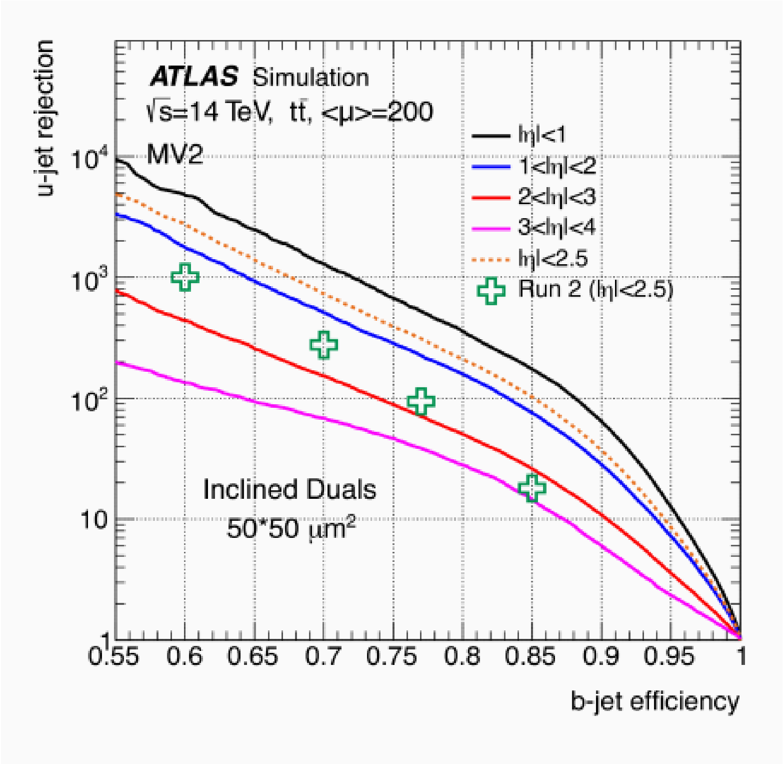
ATLAS & CMS upgrade documentations

- Letter of Intent (CERN-LHCC-2012-022)
- Phase-II Upgrade Scoping Document (CERN-LHCC-2015-020)
- ITK Pixel TDR (CERN-LHCC-2017-021)
- ITK Strip TDR (CERN-LHCC-2017-005)
- LAr TDR (CERN-LHCC-2017-018)
- Tile TDR (CERN-LHCC-2017-019)
- Muon TDR (CERN-LHCC-2017-017)
- TDAQ TDR (CERN-LHCC-2017-020)
- HGTD technical proposal (CERN-LHCC-2018-023)

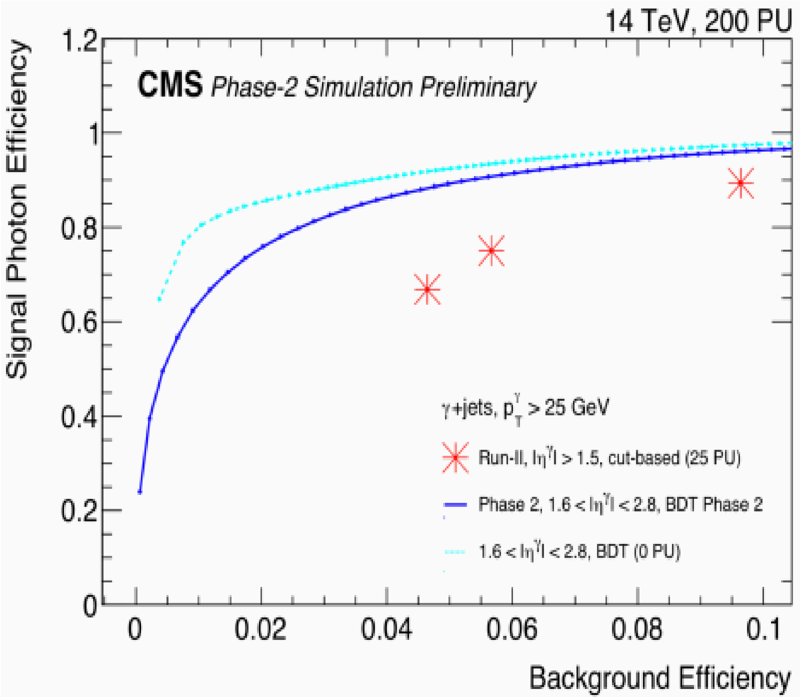
- CMS Phase-II TDR (CERN-LHCC-2015-010)
- Phase-II Upgrade Scoping Document (CERN-LHCC-2015-019)
- Tracker TDR (CERN-LHCC-2017-009)
- Barrel Calo TDR (CERN-LHCC-2017-011)
- Endcap Calo TDR (CERN-LHCC-2017-023)
- Tile TDR (CERN-LHCC-2017-019)
- Muon TDR (CERN-LHCC-2017-012)
- L1 Interim TDR (CERN-LHCC-2017-013)
- DAQ Interim TDR (CERN-LHCC-2017-014)
- Timing detector (CERN-LHCC-2017-027)

Detector Performance

Tag b-jets



Photon Reconstruction



✓ Expect similar or better reconstruction of physics objects at HL-LHC compared to Run-2

Physics Projection at HL-LHC

✓ Assume center of mass energy at 14 TeV and total integrated luminosity is 3000 fb^{-1}

✓ Methods for projection:

- **Detailed simulations** are used to access performance of reconstructed objects in upgraded detector and HL-LHC condition

- **Extrapolate** existing results and take into account of increase in energy and performance of upgraded detector, or use **parametric simulations** to allow full re-optimization of the analyses that profit from larger dataset without requiring all samples to be simulated in HL-LHC conditions.

Systematic uncertainties are taken into account based on studies performed for existing analyses and use common guidelines for projection.

✓ **Example in the case of Higgs projection studies:**

- Scenario-1 (S1) : Conservative, use uncertainties of current Run-2 measurements assuming the higher pile-up effects will be compensated by detector upgrades.
- Scenario-2 (S2) : Uncertainties approximately ½ of Run-2, assume improvements due to upgrade and reduced uncertainties on the methods reached at the end of HL-LHC. Uncertainty due to size of simulation is negligible. Luminosity uncertainty ~1%.

CERN yellow report

Many new projections on physics reach came available

CMS Physics Studies

Obviously cannot cover all

ATLAS Physics Studies

- Short summary of recent results on a few topics and show their potentials at HL-LHC

SM (Higgs, Top and EWK) and BSM (Exotics searches and SUSY)

Projection of SM (Higgs, Top and EWK) **at the HL-LHC**

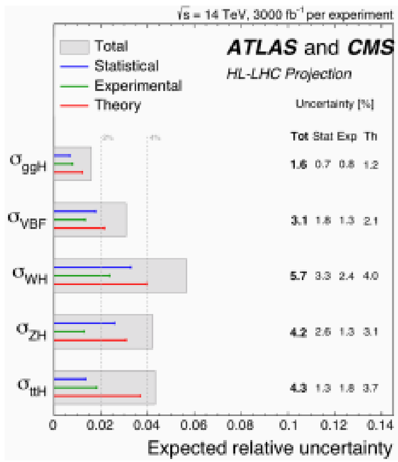
Projections for Higgs Signal Strength, Couplings, Mass, Width

- Combined all major production/decay mode measurements (assume S2 scenario)

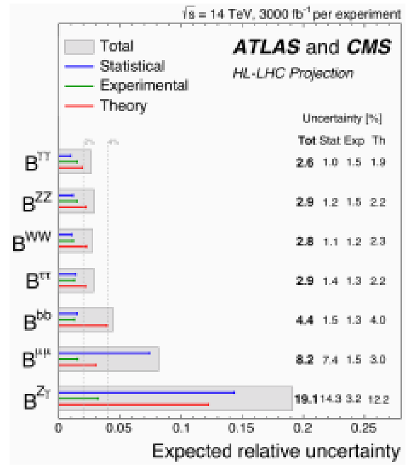
Productions (ATLAS+CMS

- ✓ ggF can be measured at ~2%
- ✓ WH can be measured at ~6%

ATL-PHYS-PUB-2018-054
CMS-PAS-FTR-18-011
arXiv:1902.00134



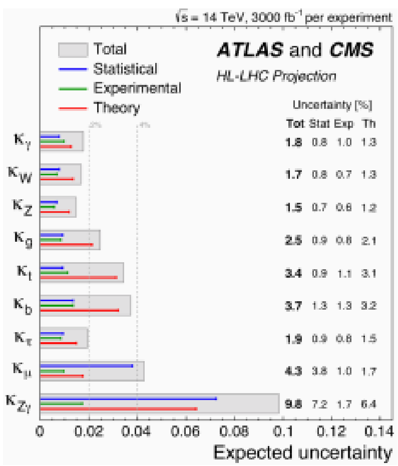
Decays (ATLAS+CMS



- ✓ Gauge boson decays can reach ~3% precision
- ✓ Fermion decays (bb,ττ) can reach ~3-4%
- ✓ μμ can be observed with ~8%

Couplings (ATLAS+CMS

Precision can improve by factors ~4-5 with respect to current measurements



Higgs mass, width

- ✓ 4 lepton (ZZ*) channel has the best precision
- ✓ Mass value will be driven by muon channel

Expected Higgs mass precision with 3 ab^{-1} (ATLAS)

	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

Width: 4.1 MeV (Run2: ATLAS < 14.4 MeV and CMS < 9.2 MeV)

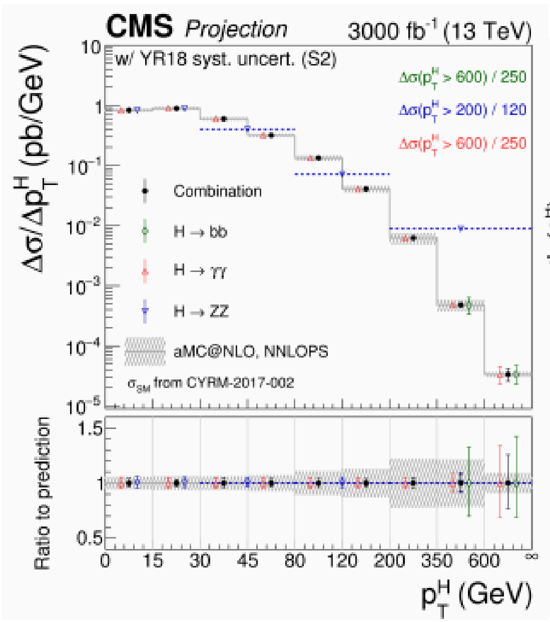
Projections Higgs Differential Measurements

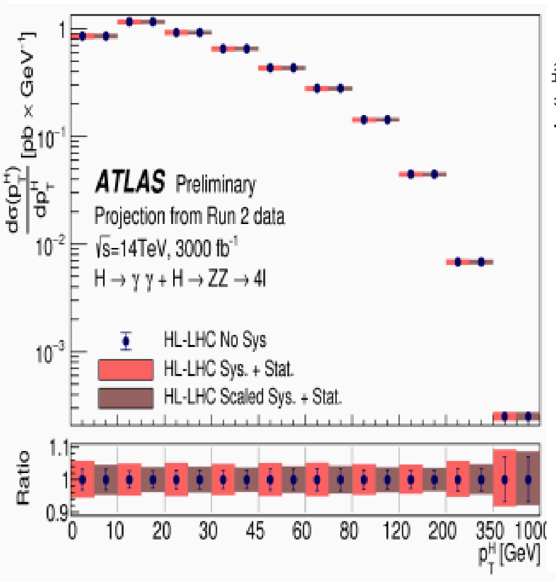
- Important to measure the differential distributions of Higgs production
  - Provide a probe of the SM
  - Constraint effects from beyond the SM
- Make projections based on Run 2 analyses

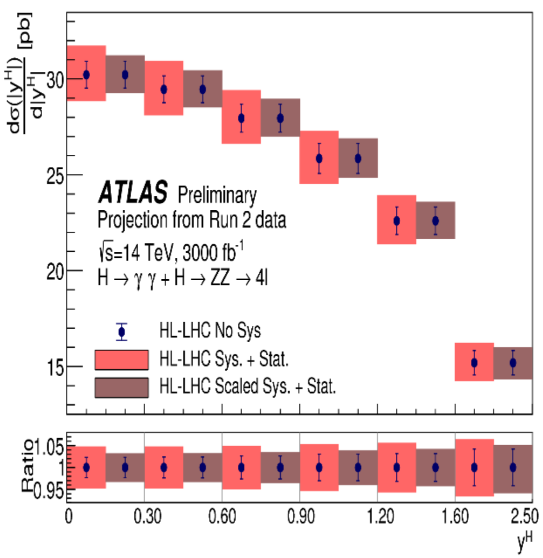
ATL-PHYS-PUB-2018-040

CMS-PAS-FTR-18-011

- Most precisely measured by H→γγ and H→ZZ*→4l channels



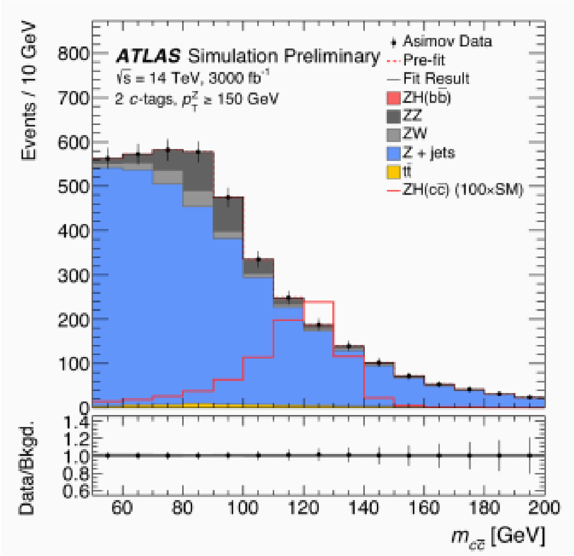




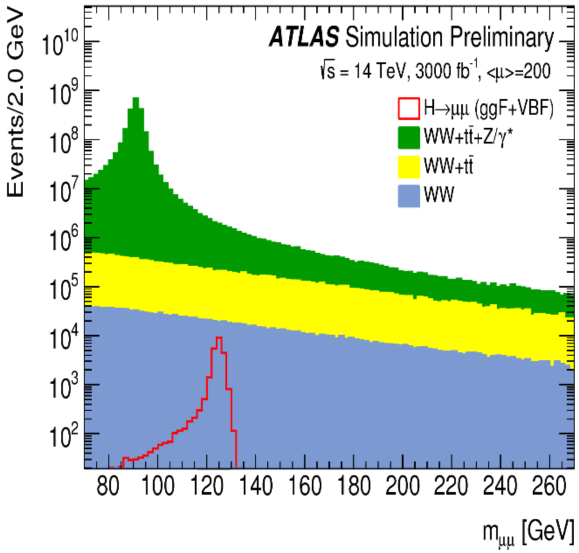
- Expect to probe with precision of ~10% at Higgs p_T ~350-600 GeV

Projections for Rare Higgs Decays

- $H \to cc$



- $H \to \mu\mu$



✓ Extrapolate from Run2 search
--- $ZH \to llcc$

✓ Expect to set an upper limit on σ×BR at 95%CL of 6.3×SM(Run2: 110×SM)

✓ May further improve sensitivity by including other channels :
--- $WH \to l\nu cc$
--- $ZH \to \nu\nu cc$

✓ Expect to observe via ggH and VBF productions

✓ significance >9σ

✓ uncertainty on σ×BR < 13%

✓ Current limit : σ×BR <2.1-2.9×SM

ATL-PHYS-PUB-2018-016

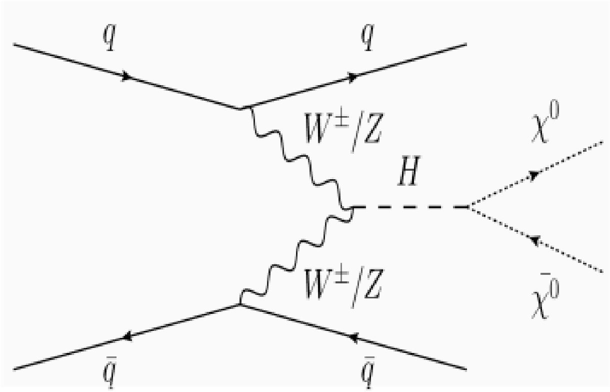
ATL-PHYS-PUB-2018-006

Projections for Higgs to Invisible Decays

- In some BSM Higgs boson may act as a portal between SM sector and dark sector
  - =>Higgs can decay into dark matter particles (invisible decay)

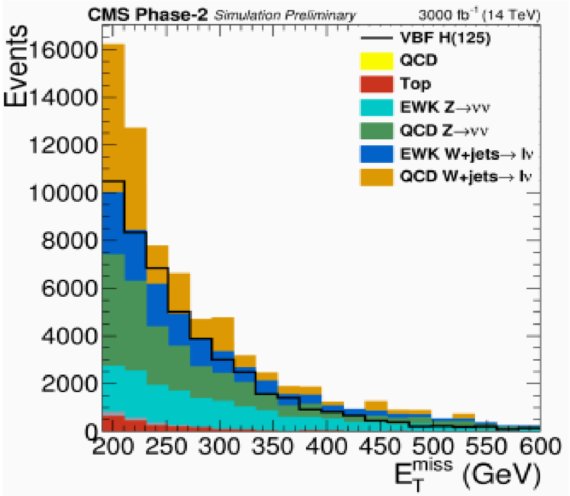
CMS-FTR-18-016

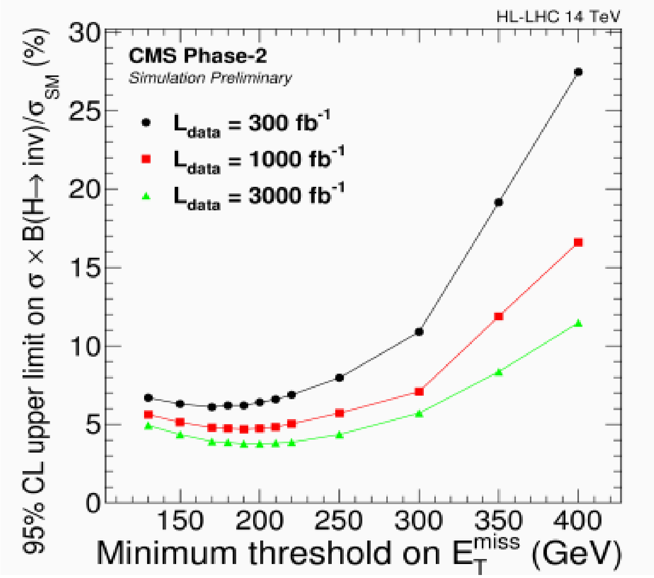
- Studied potential with VBF channel



- Pileup suppression will be very important
  - Degrade MET resolution
  - False identification of pileup jets as VBF jets in forward region

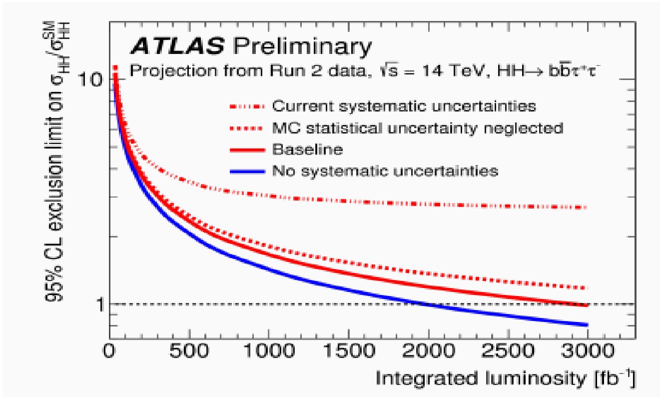
- Expect can reach upper limit of BR(H→inv)~3.8% at 95% CL (assume SM VBF production)
  - 5X smaller than current best limit
  - SM: BR(H→ZZ→νννν) ~ 0.1%

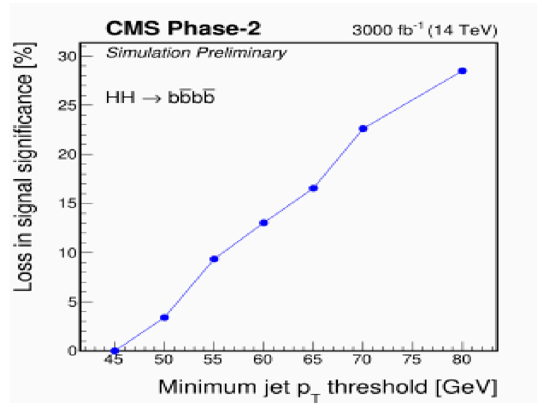




Di-Higgs : Projection for HL-LHC

- Extrapolation based on current analyses and on the estimate of upgraded detector performance





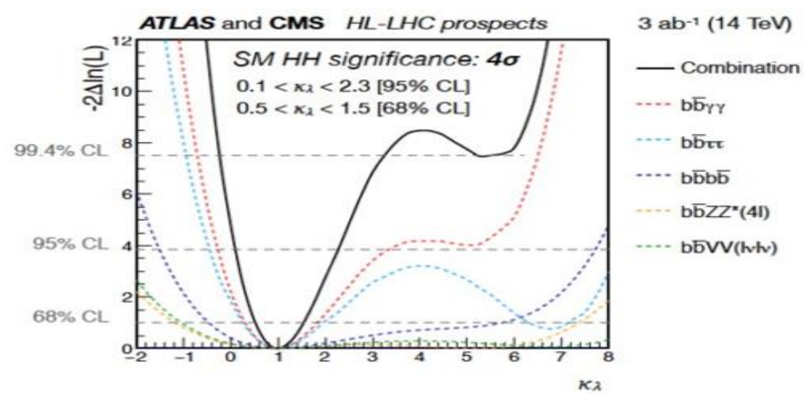
CMS-FTR-18-019

ATL-PHYS-PUB-2018-053

arXiv:1902.00134

- Vary the scenarios of systematic uncertainties
- High pileup at HL-LHC may require to raise trigger threshold (maybe a challenge for bbbb channel)

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	



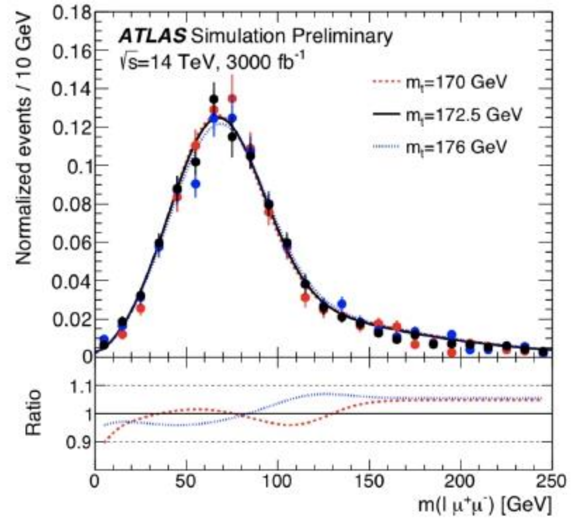
- ✓ Combine ATLAS + CMS : 4.0 σ (stat.+syst.)   (4.5 σ (stat. only))
- ✓ Precision of self-coupling modifier κ can reach ~50%

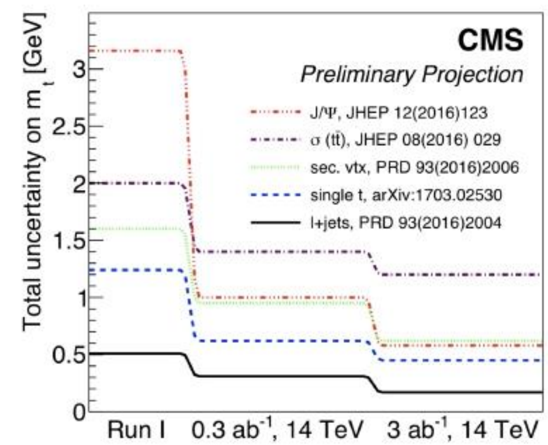
- ***May have a chance to reach the evidence level of di-Higgs production at the end of HL-LHC***

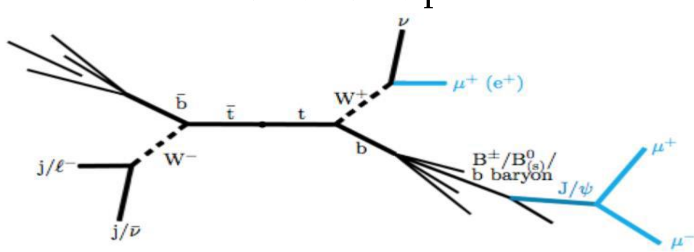
top mass

- **Projections using various techniques**
  - kinematic reconstruction of ttbar or single top final state
    - jet systematics dominate
  - usage of b-jet information via J/ψ final state
    - uncertainty on modelling of b-fragmentation or b-decay dominate
    - small BR, limited by statistics
  - top quark mass from cross sections or distributions
    - theory and luminosity uncertainties dominate
  - Usually ambiguity of top mass definition not considered
- **ATLAS projections using only J/ψ final states**
  - Statistical uncertainty 0.14 GeV, systematic uncertainty 0.48 GeV (0.28%)
- **CMS projections**
  - Can reach between 0.1%-0.7% precision

ATL-PHYS-PUB-2018-042 and CMS PAS-FTR-16-006







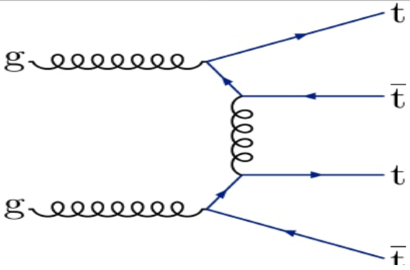
4-top production

- **Projections are focussed on SM measurement**
  - **Rare process** benefits from increased luminosity

ATL-PHYS-PUB-2018-047
CMS-PAS-FTR-18-031
Chin. Phys. C42 (2018) 2, 023104
Phys. Rev. D 95, 053004 (2017)

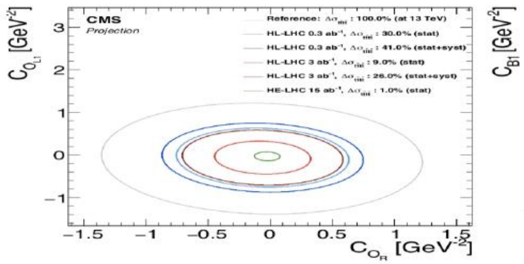
- ATLAS and CMS studies in 2 same charge leptons or 3 lepton channel, ≥ 6 jet, ≥ 3 b-tagged jets
- **Expect evidence for tttt with 300/fb at 14 TeV**
- Sensitivity to top Yukawa coupling modification is high
  - 14 TeV 3/ab $\sigma(t\bar{t}t\bar{t}) = 13.14 - 2.01\kappa_t^2 + 1.52\kappa_t^4$ [fb]
  - 27 TeV 15/ab $\sigma(t\bar{t}t\bar{t}) = 115.10 - 15.57\kappa_t^2 + 11.73\kappa_t^4$ [fb]

σ[fb]	LO + NLO	$\frac{\text{LO(+NLO)}}{\text{LO}_{\text{QCD}}(\text{+NLO}_{\text{QCD}})}$
14 TeV	$15.83^{+18\%}_{-21\%}$	1.11 (1.08)
27 TeV	$143.93^{+17\%}_{-20\%}$	1.11 (1.06)

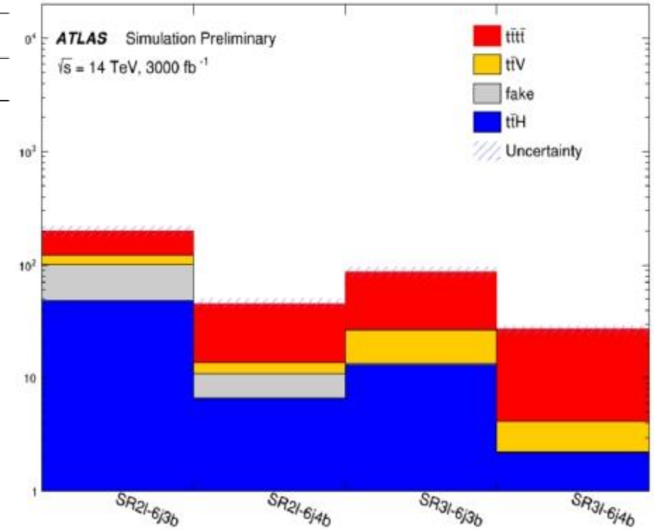


Int. Luminosity	$\sqrt{s}$	*Stat. only* (%)	*Run 2* (%)	*YR18* (%)	*YR18+* (%)
300 fb^{-1}	14 TeV	$^{+30}_{-28}$	$^{+43}_{-39}$	$^{+36}_{-34}$	$^{+36}_{-33}$
3 ab^{-1}	14 TeV	±9	$^{+28}_{-24}$	$^{+20}_{-19}$	±18

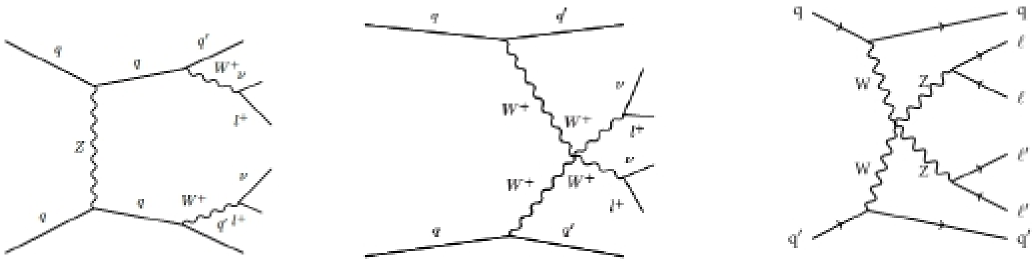
Also provided limits on EFT-couplings



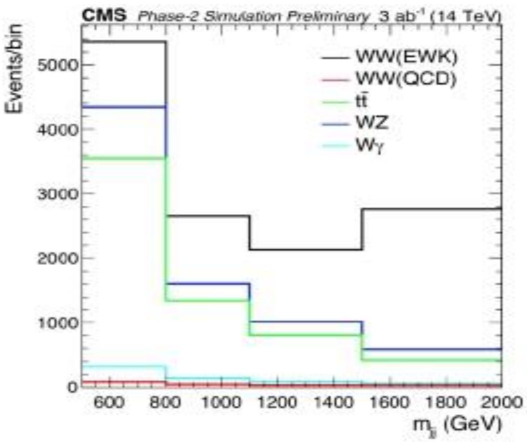
$$\mathcal{O}_R = (\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R)$$
$$\mathcal{O}_L^{(1)} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{Q}_L\gamma_\mu Q_L)$$
$$\mathcal{O}_B^{(1)} = (\bar{Q}_L\gamma_\mu Q_L)(\bar{t}_R\gamma_\mu t_R)$$
$$\mathcal{O}_B^{(8)} = \left(\bar{Q}_L\gamma_\mu T^A Q_L\right)\left(\bar{t}_R\gamma_\mu T^A t_R\right)$$

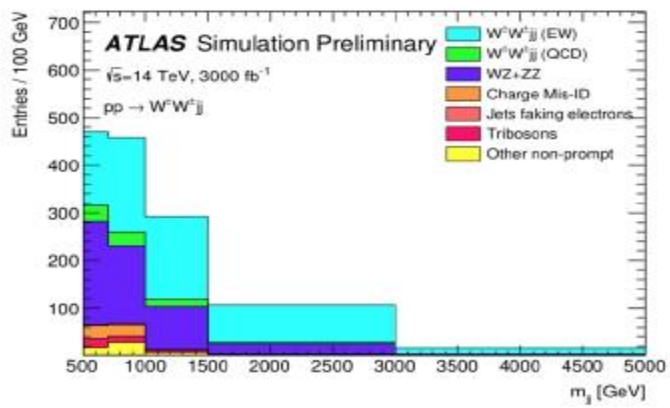


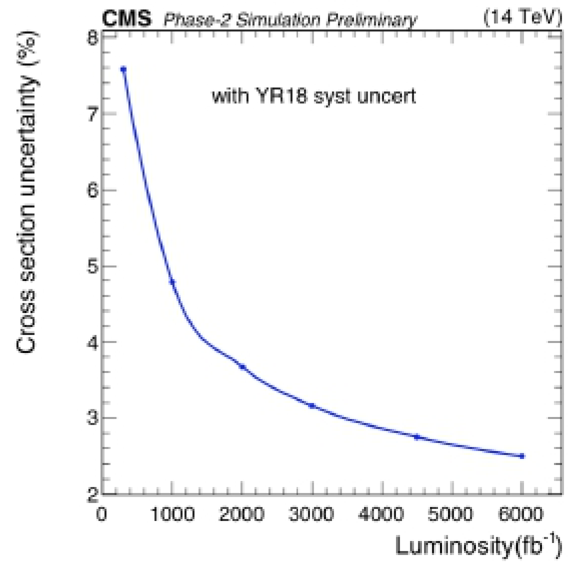
Vector Boson Scattering



…. etc producing WW,WZ and ZZ final states







- ✓ WW EWK is observed by both ATLAS and CMS with >5 sigma significance
- ✓ The WZ EWK is observed by ATLAS (CMS) 5.3 (2.2) sigma
- ✓ The ZZ EWK by CMS 2.7 obs
- ✓ 5sigma observation for all processes, with very good precision at HL-LHC

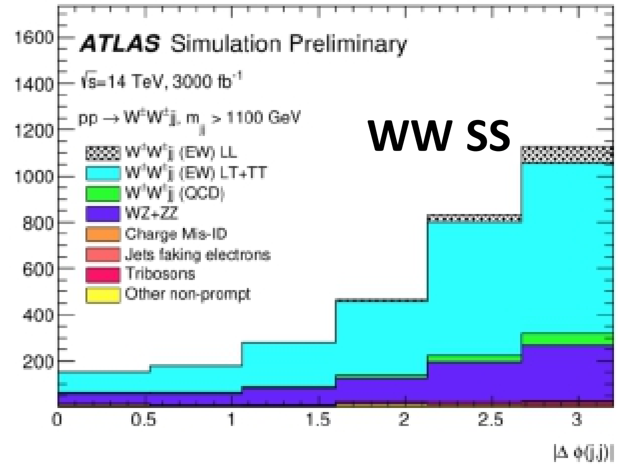
- ✓ Differential cross sections available even for ZZ

Phys. Lett. B 774 (2017) 682
arXiv:1812.09740
arXiv:1901.04060

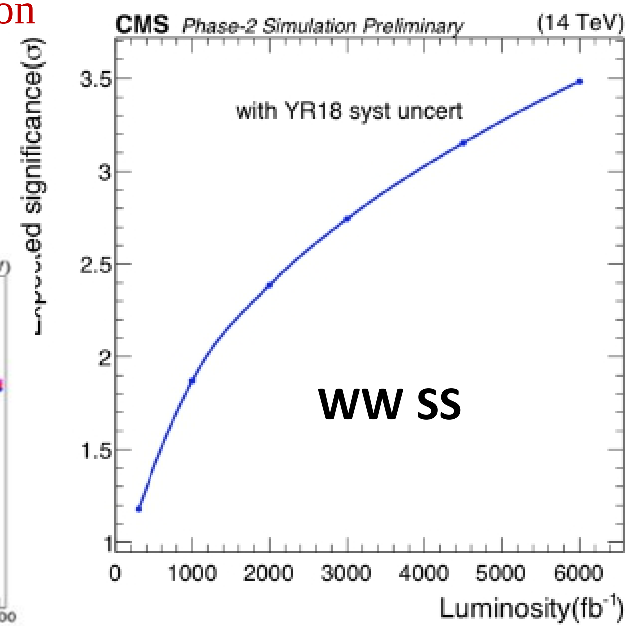
Process	$W^{\pm}W^{\pm}$	WZ	WV	ZZ
Final state	$\ell^{\pm}\ell^{\pm}$jj	3ℓjj	ℓjjjj	4ℓjj
Precision	6%	6%	6.5%	10–40%
Significance	$>5\sigma$	$>5\sigma$	$>5\sigma$	$>5\sigma$

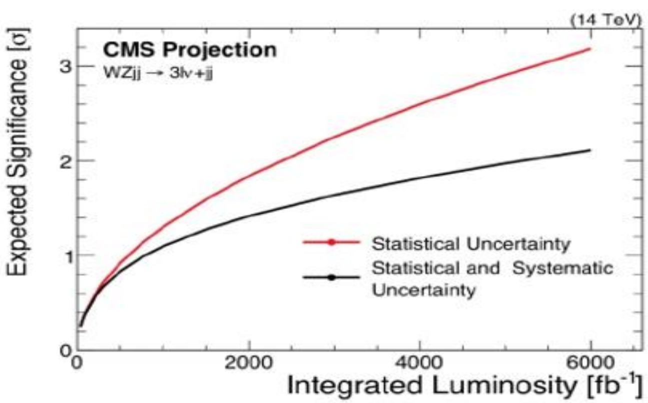
VBS and LL Scattering Significance

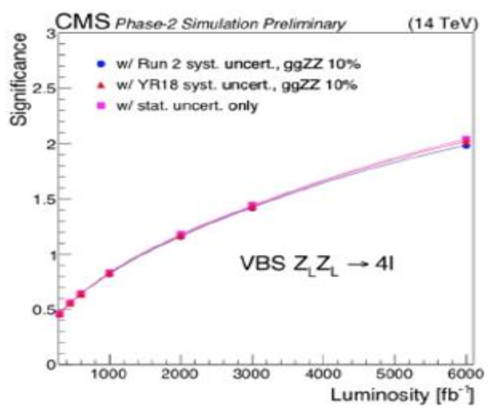
- The total vector boson scattering is composed of three components, depending on the polarization of the final-state vector bosons: both longitudinally polarized (LL), both transversely polarized (TT) and the mixed case (LT)



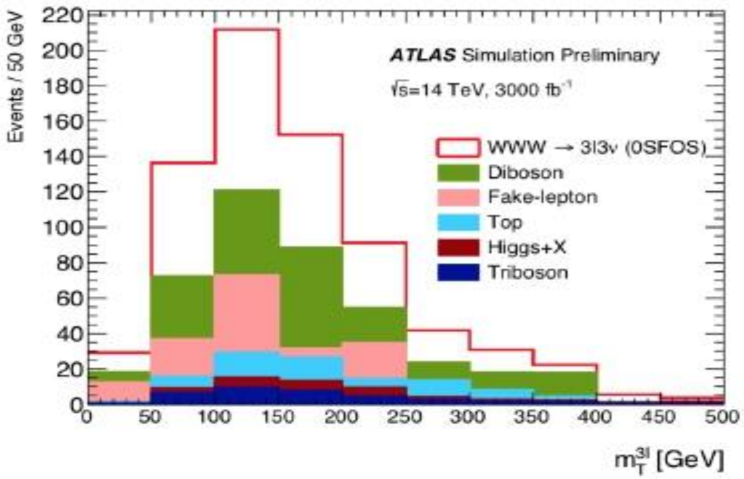
- ✓ The LL component is interesting as a direct probe of the unitarization mechanism of the VBS amplitude through Higgs and possible new physics.
- ✓ Use angular separation to measure LL signal
- ✓ Expected discovery significance for the longitudinal vector boson scattering increases as a function of the collected luminosity.
- ✓ **The polarized LL component is not expected to be observed in single channel and experiment –> combination**

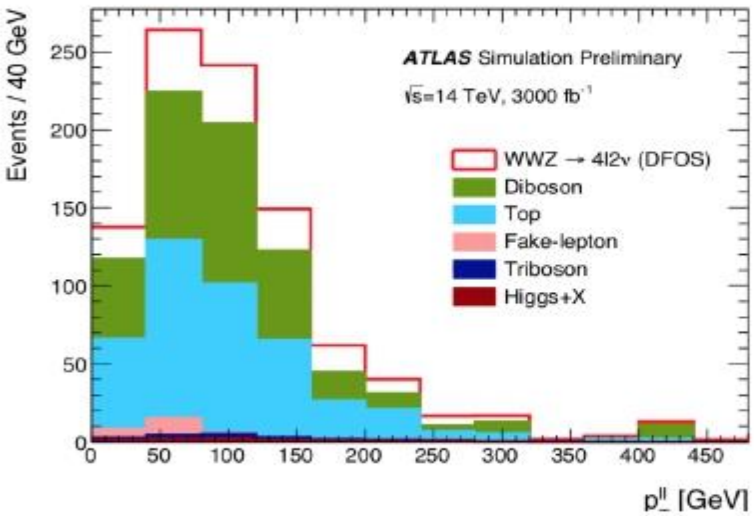




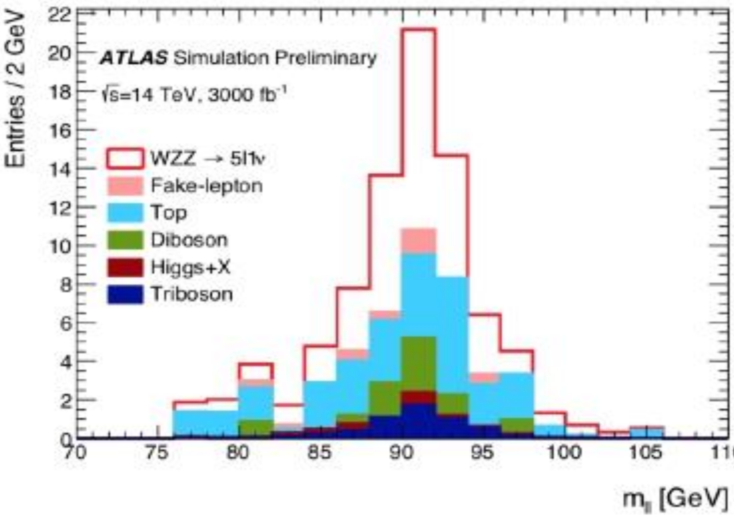


Tri-boson production





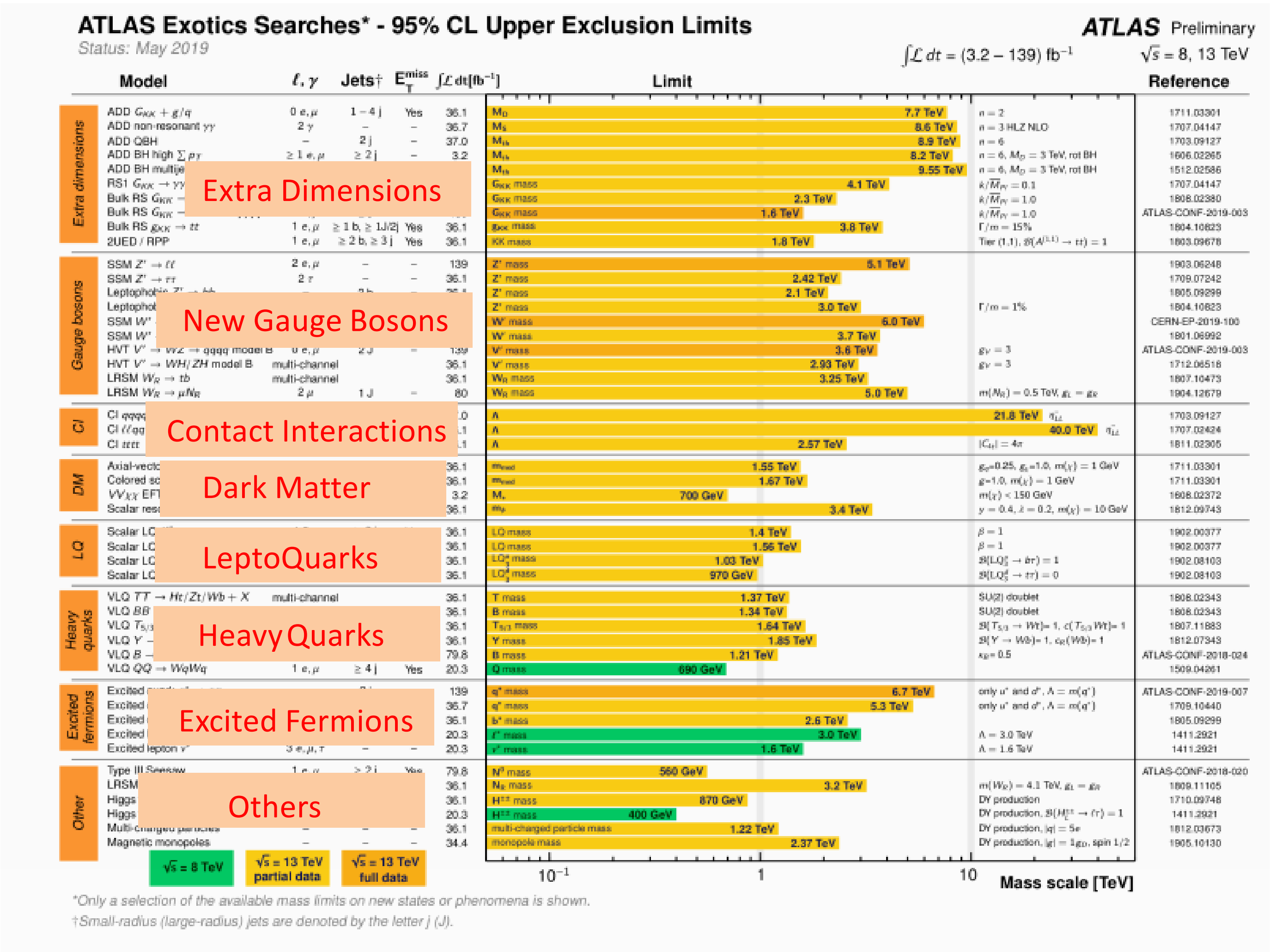
- VVV production has a low cross section but can be measured at the HL-LHC in different channels WWW, WWZ, WZZ



Process	WWW	WWZ	WZZ
Final state	$3\ell 3\nu$	$4\ell 2\nu$	$5\ell\nu$
Precision	11%	27%	36%
Significance	$> 5\sigma$	3.0σ	3.0σ

Projection of BSM (Exotics searches and SUSY) **at the HL-LHC**

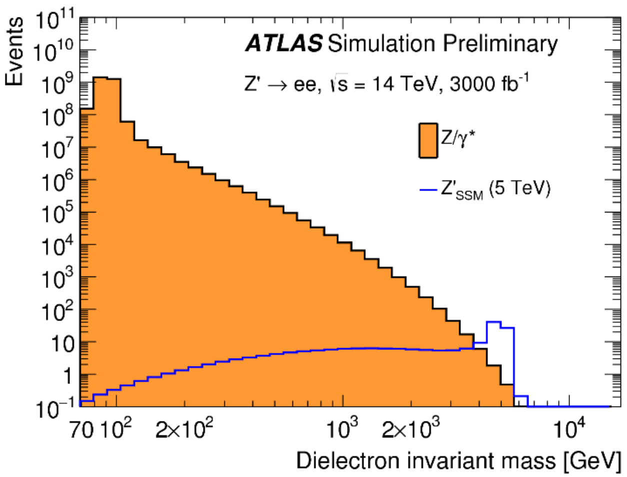
Search for New Physics : Exotics



- ✓ Exotics searches at the LHC cover many different models
- ✓ Several searches have already been performed with full Run2 data
- ✓ Will only summarize a few topics and provide their potentials at HL-LHC

Resonance Search : di-lepton, lepton+MET

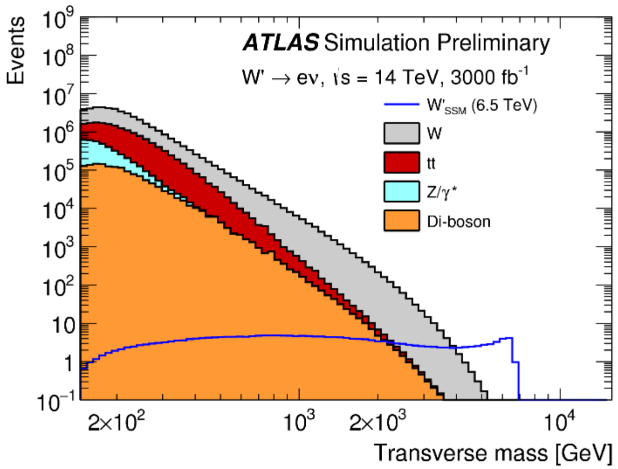
di-lepton



(ee+μμ)	HL-LHC		Run2 (139 fb^{-1})
Model	Exclusion [TeV]	Discovery [TeV]	Exclusion [TeV]
Z'(SSM)	6.5	6.4	5.1
Z'(ψ)	5.8	5.7	4.5

- Extend Z'_{SSM} exclusion limit by ~1.4 TeV
- Overall uncertainty ~6.5%×m_{ll} [TeV]

lepton+MET



	HL-LHC		Run2
W'_{SSM}	Exclusion [TeV]	Discovery [TeV]	Exclusion [TeV]
ATLAS (eν, μν)	7.9	7.7	5.8 (139 fb^{-1})
CMS ($\tau_h\nu$)	7.0	6.4	4.0 (36 fb^{-1})
ATLAS ($\tau_h\nu$)			3.8 (36 fb^{-1})

- Extend exclusion W'_{SSM} mass by ~2 TeV

ATL-PHYS-PUB-2018-044 **CMS-FTR-18-030**

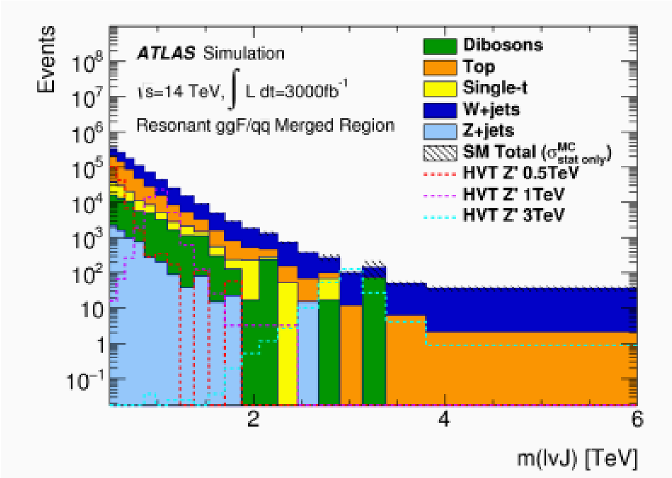
Resonance Search : di-boson

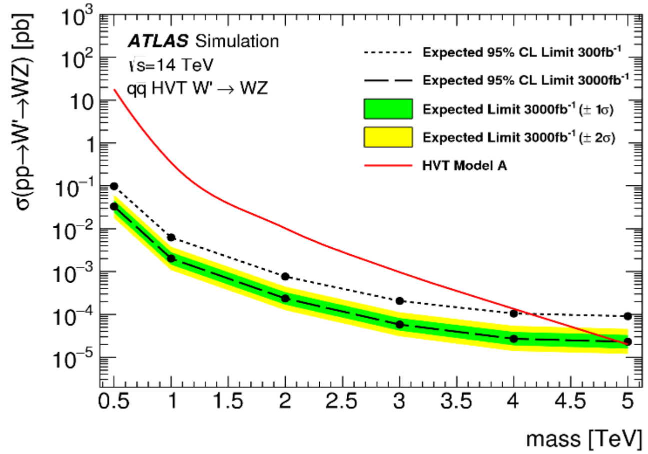
ATL-PHYS-PUB-2018-022

- Projection is studied for X→WV, W→lv and V(W,Z)→qq

✓ Search for heavy resonance in ggF/qq and VBF production modes, and in resolved and boosted categories (for the decay of V)

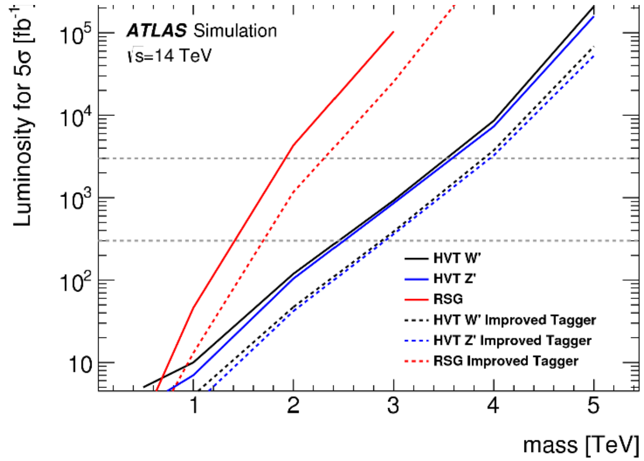
✓ Interpret search prospect in context of HVT, bulk RS model, narrow heavy scalar resonance





- Expected exclusion limits at 95% CL

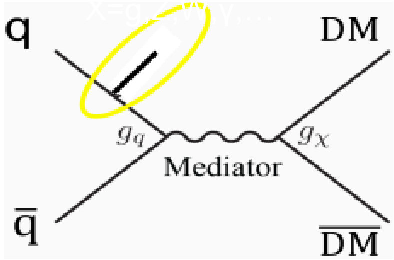
HVT, model A	HL-LHC	13 TeV, 36 fb-1 JHEP 03 (2018) 042
W'	4.9 TeV	2.9 TeV
Z'	4.9 TeV	2.85 TeV



- 5 σ discovery reach is up to ~3.5 Te V
  - Additional improvement in W/Z tagger can extend reach to ~3.9 Te V

Dark Matter Searches

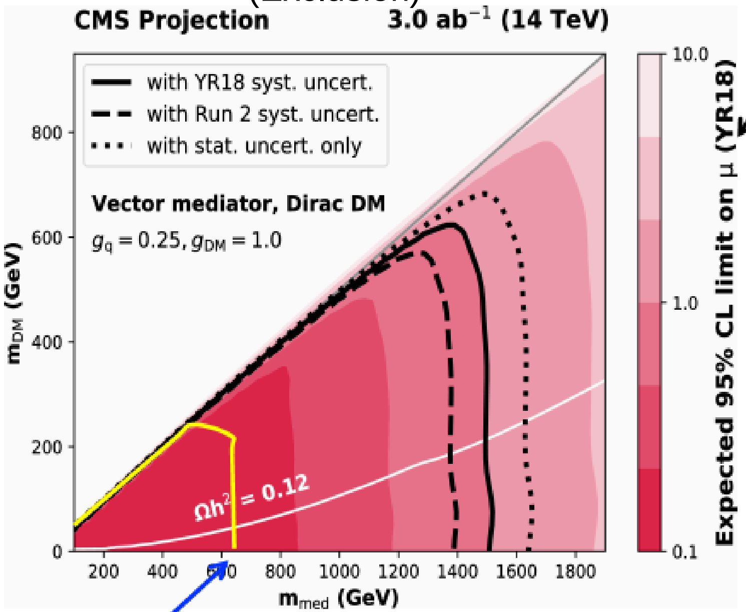
- At LHC dark matter (DM) can be produced via decay of a mediator (med) to the dark sector, and indirectly detected by measuring the SM particle recoiling against it.
  - Signature : Large E_T^{miss} + X



Mono-Z (E_T^{miss}+ 2leptons)

(Exclusion)

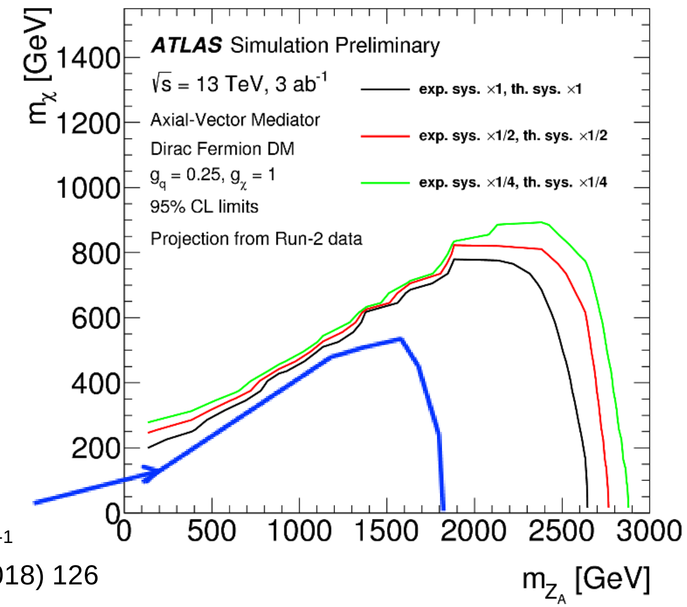
Searches are sensitive to systematic uncertainties



CMS 36fb^{-1}
EPJC 78 (2018) 291

Mono-jet (E_T^{miss} + jet)

(Exclusion)



ATLAS 36fb^{-1}
JHEP 01 (2018) 126

- Discovery could be reached for a signal with DM mass of 1 GeV and mediator mass of 2.25Te V

Large improvement compared to current LHC results

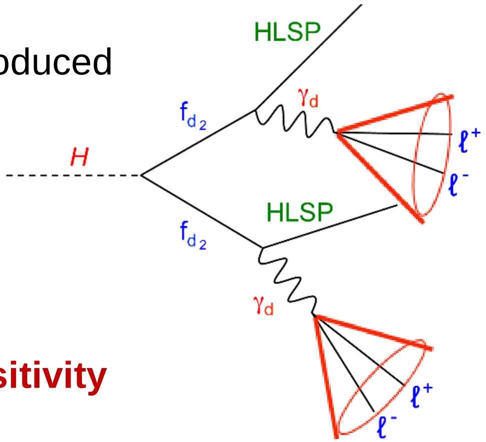
CMS-PAS-FTR-18-007

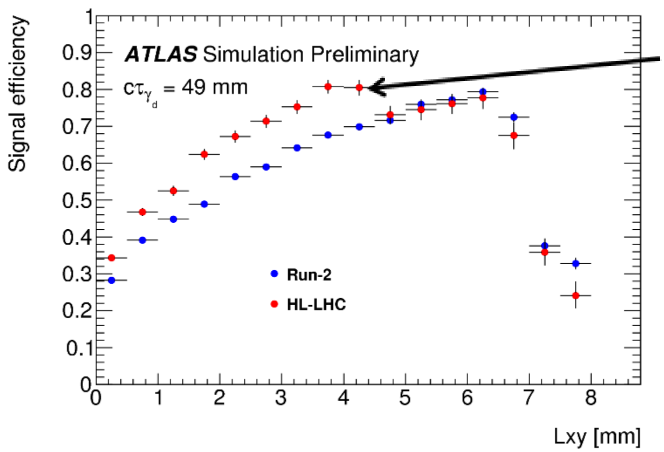
ATL-PHYS-PUB-2018-043

Long Lived Dark-Photons

- ✓ In some BSM a pair of long lived dark-photons (γ_d) can be produced from Higgs boson decay ($H \to 2\gamma_d + X$)
- ✓ Each dark-photons is light and boosted:
  - -- can decay to a displaced collimated jet of muons
- ✓ Dedicated triggers are required to select displaced μ pairs

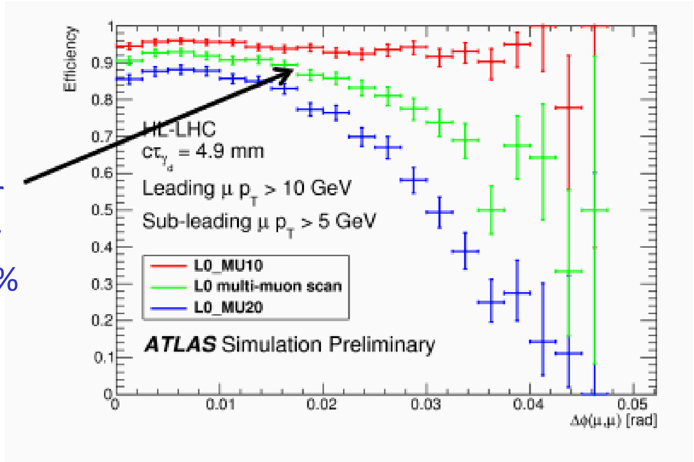
➢ **Specially designed low level triggers and muon detector upgrade from ATLAS at HL-LHC can improve search sensitivity**





Additional Inner RPC layer

Dedicated trigger Overall efficiency improvement ~7%



- Expected cτ ranged exclusion at 95% CL :

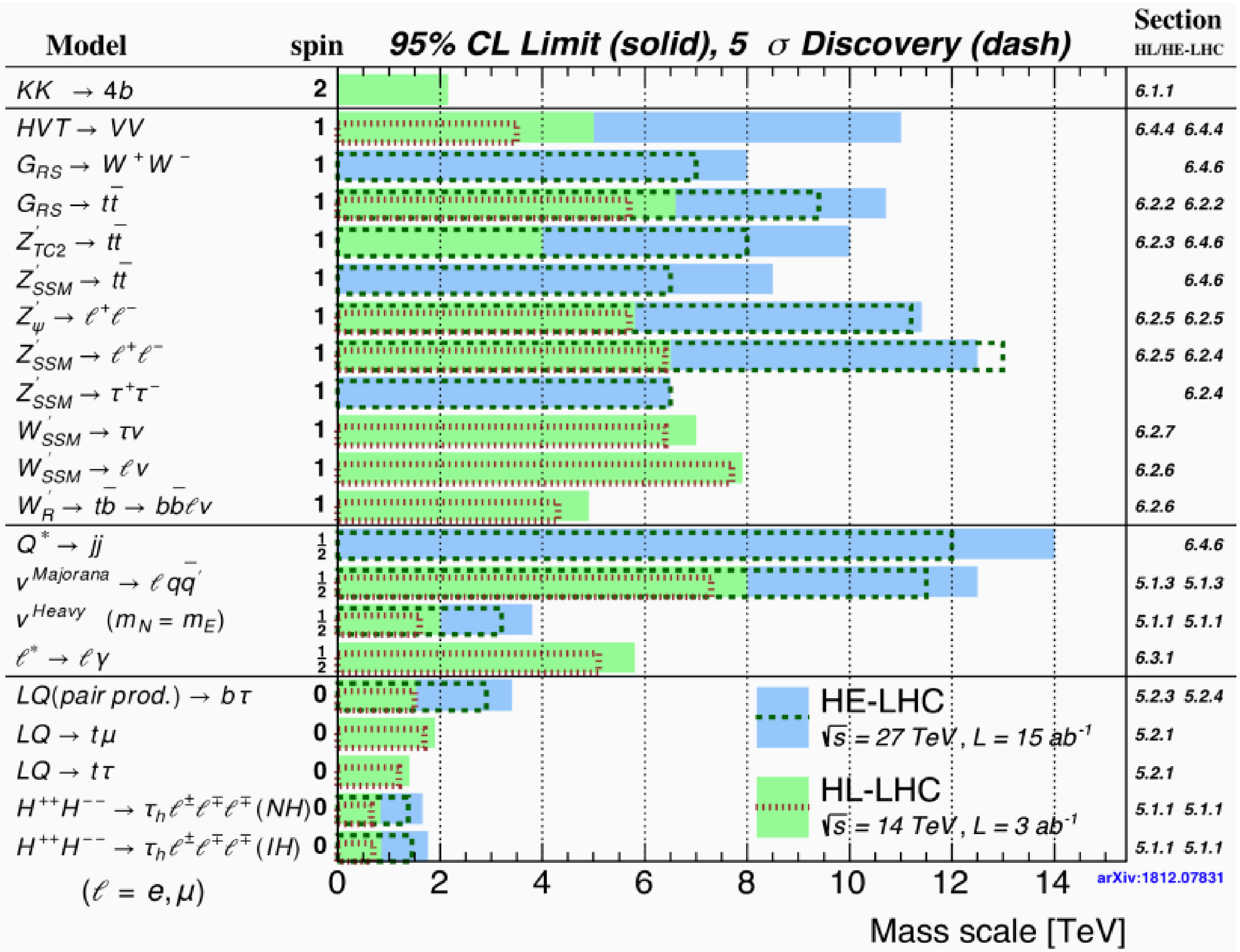
Excluded $c\tau$ [mm] muonic-muonic	Run-2	Run-3	HL-LHC	HL-LHC w/ L0 muon-scan
BR($H \to 2\gamma_d + X$)=10 %	$2.2 \leq c\tau \leq 111$	$1.15 \leq c\tau \leq 435$	$0.97 \leq c\tau \leq 553$	$0.97 \leq c\tau \leq 597$
BR($H \to 2\gamma_d + X$)=1 %	-	$2.76 \leq c\tau \leq 102$	$2.18 \leq c\tau \leq 142$	$2.13 \leq c\tau \leq 148$

assume BR($\gamma_d \to \mu\mu$)=45%)

ATL-PHYS-PUB-2019-002

30

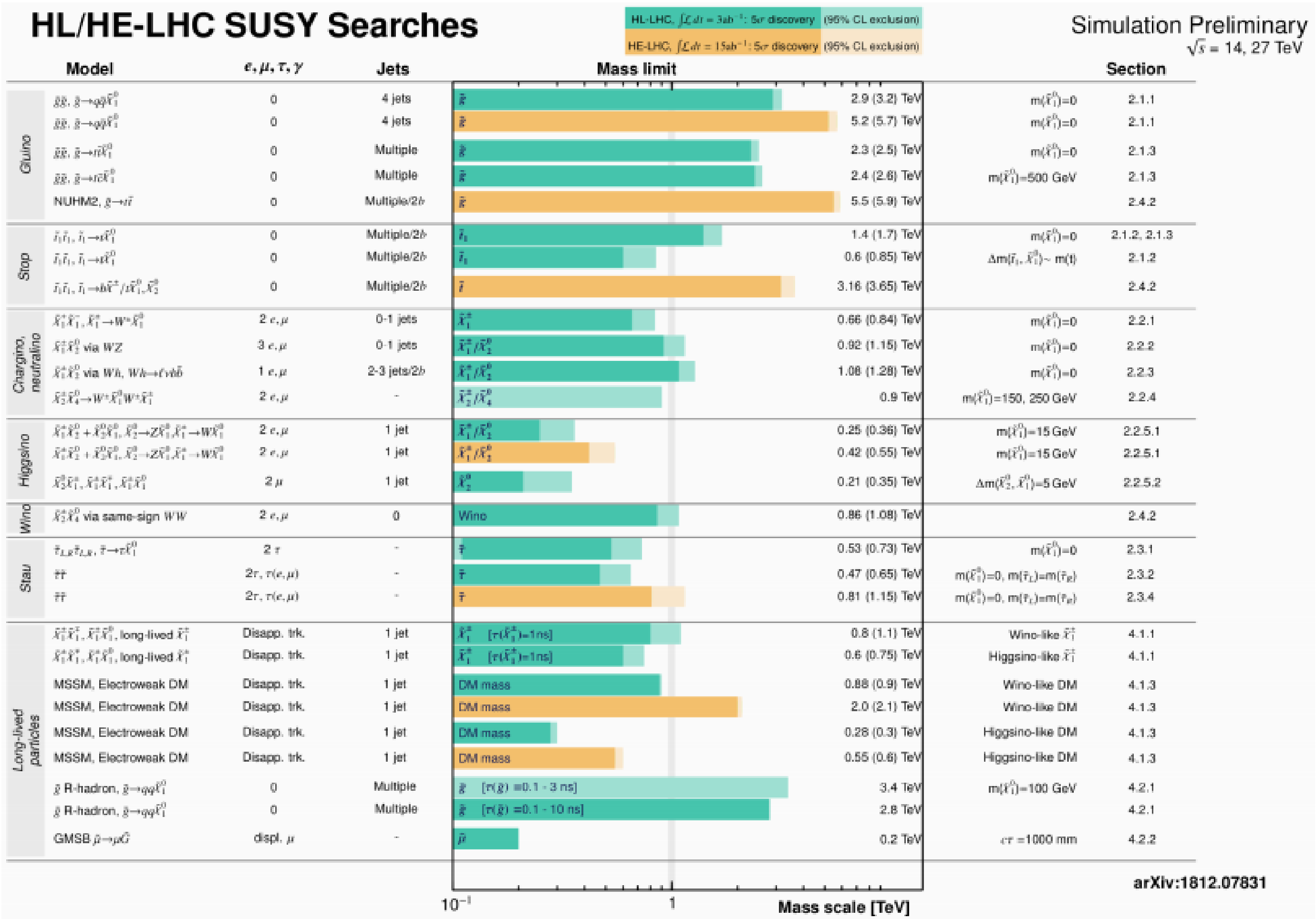
Exotics Search Reach at HL-LHC



✓ Many more projection studies on Exotic searches can be found at **arXiv:1812.07831**

SUSY Search Reach at HL-LHC

arXiv:1812.07831



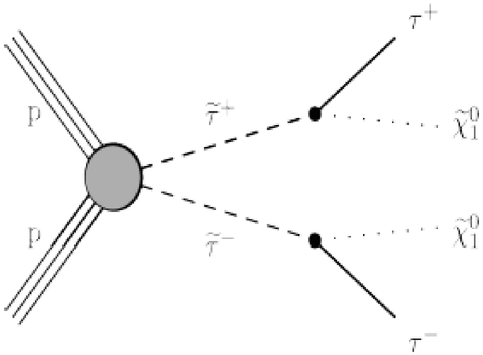
- Many studies of potential reach of SUSY searches at the HL-LHC have been performed
- Significant extension of reach from current Run2 results
- Present a couple of these studies

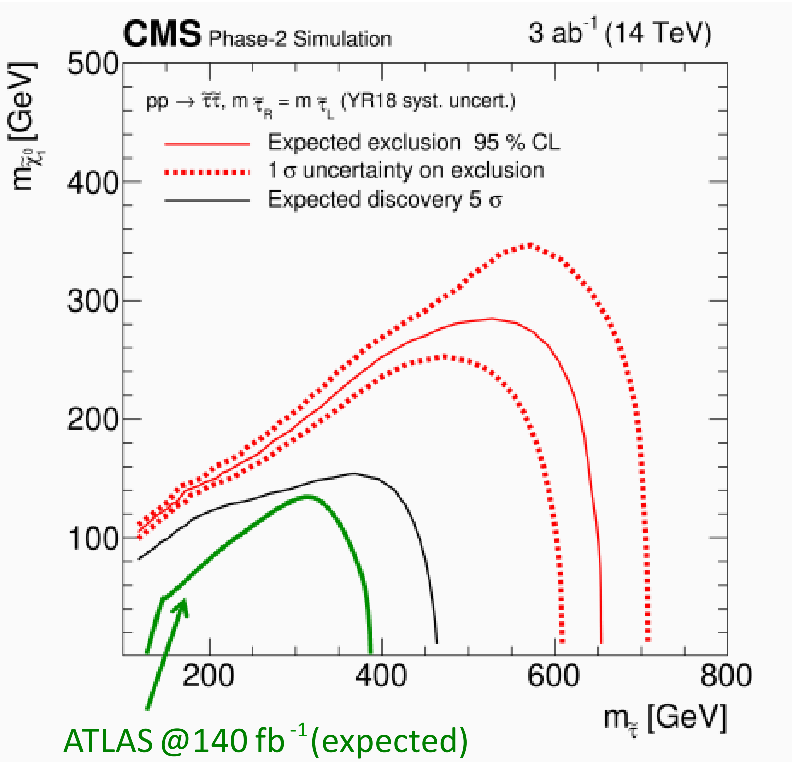
Projection for Stau Search

ATL-PHYS-PUB-2018-048

CMS-PAS-FTR-18-010

- ✓ Models with light staus can lead to a dark matter relic density consistent with cosmological observation
- ✓ Interesting to search for pair production of staus at the LHC





ATLAS @140 fb^{-1} (expected)
ATLAS-CONF-2019-018

Search in signatures of :
two hadronically decay taus
mixed hadronic / lepton

Exclusion (discovery) sensitivity from each experiment up to ~650 (~450) GeV

Only just getting sensitive at Run2 due to low production cross section

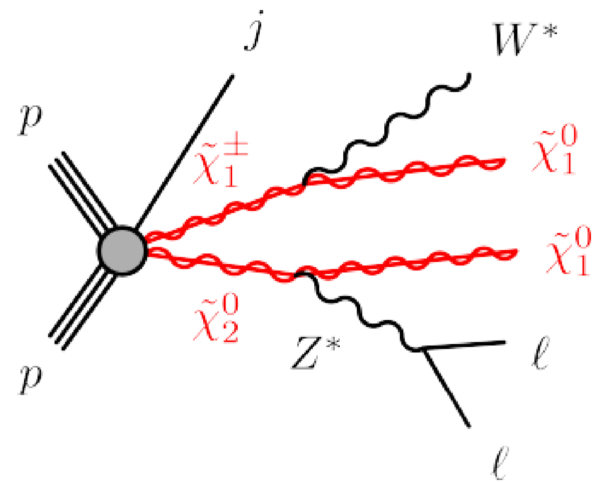
- (< 1 fb for m(stau)>400 GeV at √s=14 Te V)

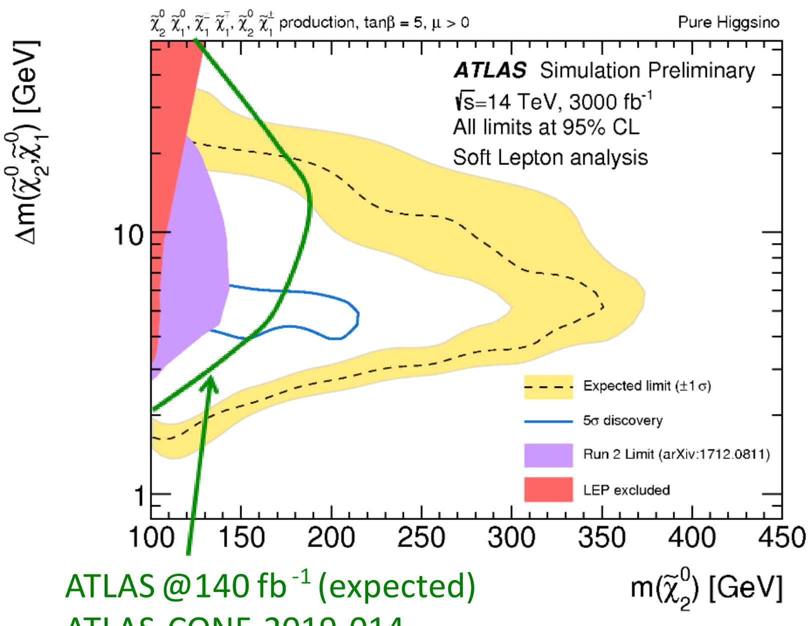
Projection for Higgsino-like Charginos and Neutralinos Search

ATL-PHYS-PUB-2018-031

CMS-PAS-FTR-18-001

- In natural supersymmetry scenario mass difference between the light Higgsino-like charginos and neutralinos $(\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0, \tilde{\chi}_1^0)$ can be small
  - This could lead to soft objects in final state
- Require a jet from initial state radiation (ISR) to boost the sparticle system in order to trigger on the signals
- Need efficient reconstruction of lepton down to a few GeV



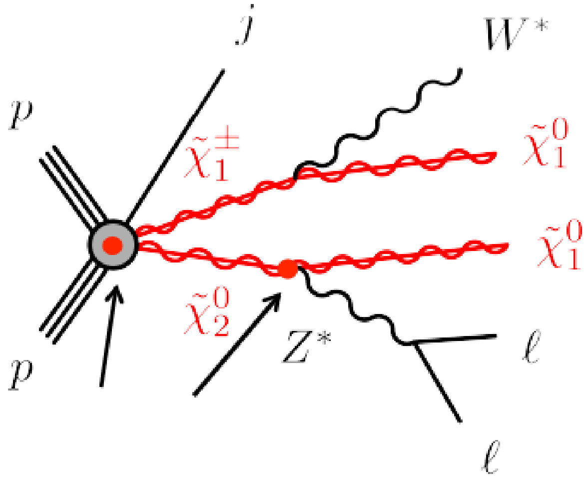


ATLAS @140 fb^{-1} (expected)
ATLAS-CONF-2019-014

- Can exclude m($\tilde{\chi}_2^0$) up to ~350 GeV
- Large gain in expected sensitivity with respect to latest full Run2 results

Long Lived Charginos and Neutralinos

- Near mass degenerate of light charginos and neutralinos may become long lived as a consequence of the heavy higgsinos

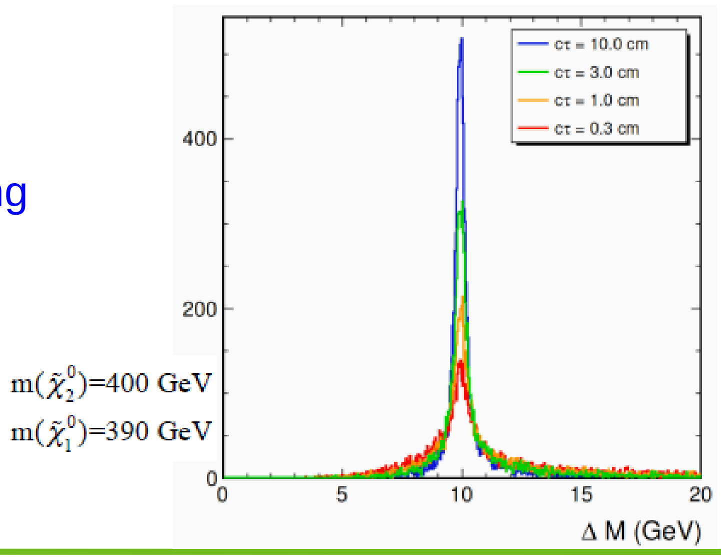


- Can use the MIP Timing Detector (MTD) of CMS HL-LHC to improve the search sensitivity
- Can assign timing for each vertex
  - Measure TOF of long lived particles
- Use the measured displacement between the vertices in space and time and the energy of the visible decay products (Z →*ll*) to construct the Δm $(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$

*

- Can use Δm as an additional discriminating variable to improve the search sensitivity

CMS CERN-LHCC-2017-027



Summary

✓ Many new results from ATLAS and CMS on the Run2 data have improved upon the measurements not just with more data but also with improvement in the analysis methods

✓ Huge work has been performed by the community to determine the physics potential at the HL-LHC

-- Higgs couplings can be measured to a precision of a few percent

-- We may have a hint of evidence of di-Higgs production at the end of HL-LHC

-- We may have discovery of some rare productions and decays:

4 top, tri-boson, $H \rightarrow \mu\mu$…..

-- Large extensions can be made for Beyond SM searches :

- High resonance masses can be excluded (discovered) up to ~8 (~7) TeV
- Dark matter searches reach can be extended by more than 50% compare to present results
- Significant extensions in SUSY searches are also expected

To reach the success of the HL-LHC program.

✓ Upgraded detectors

✓ Reduction of systematic uncertainties

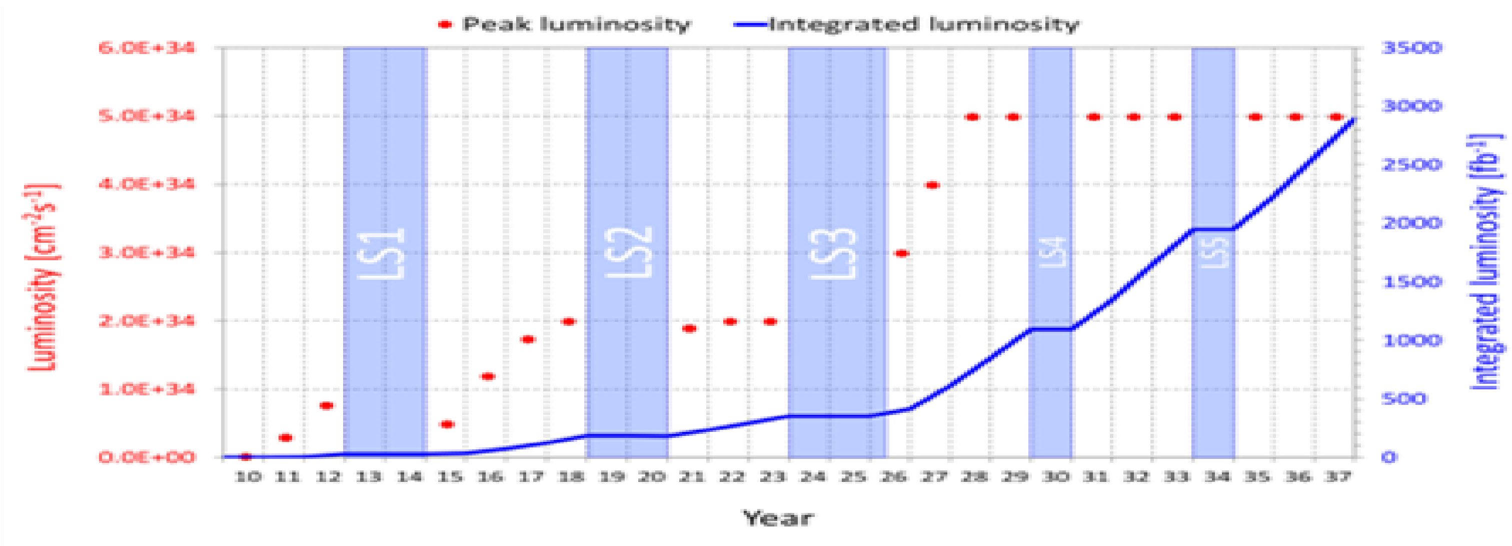
✓ Improvement of theoretical understanding

✓ Innovation of advanced techniques

→ ***Hard and exciting work for the next ~15 years !***

Backup

LHC / HL-LHC time-line



Phase-2 luminosity

instantaneous 5.0 to 7.5 x 10^{34} $cm^{-2}s^{-1}$

integrated 3000 to 4000 fb^{-1}

Challenges

high pileup from 140 to 200

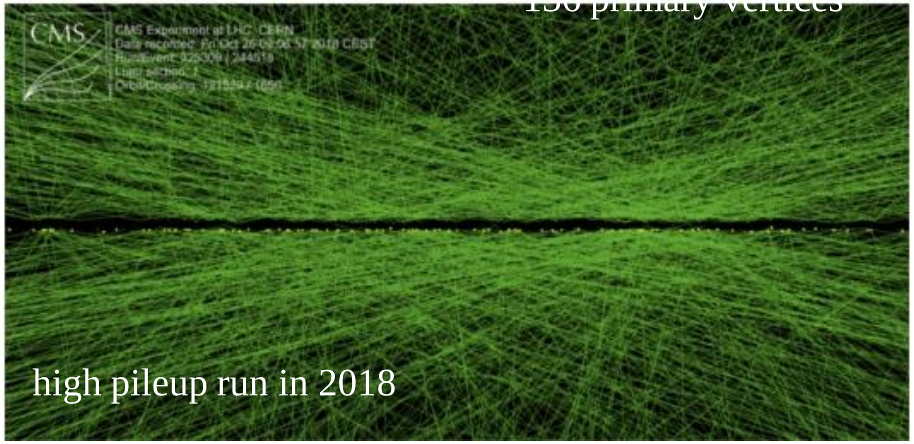
high irradiation

Phase-2 detectors requirements

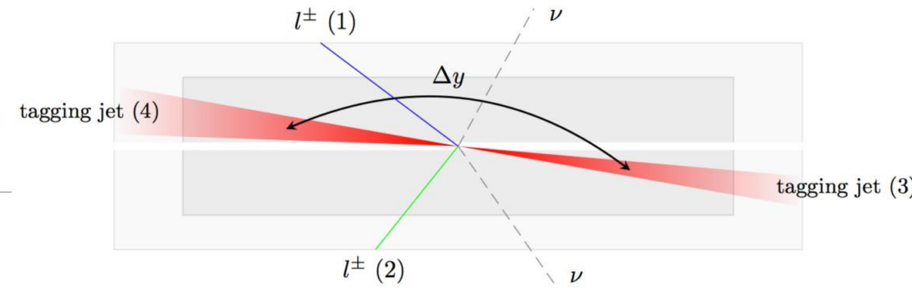
- maintain and improve the current physics performance during the entire HL-LHC
- detectors must resist to the high radiation levels : many have to be replaced in LS3 !
- improve the detector granularity (trackers, forward calorimeters)
- install timing layers
- fast trigger and fast read-out
- higher band-width
  - up to 10 / 7.5 kHz in ATLAS/CMS with 5 times more tracks and >5 times more channels)

-> computing challenge !

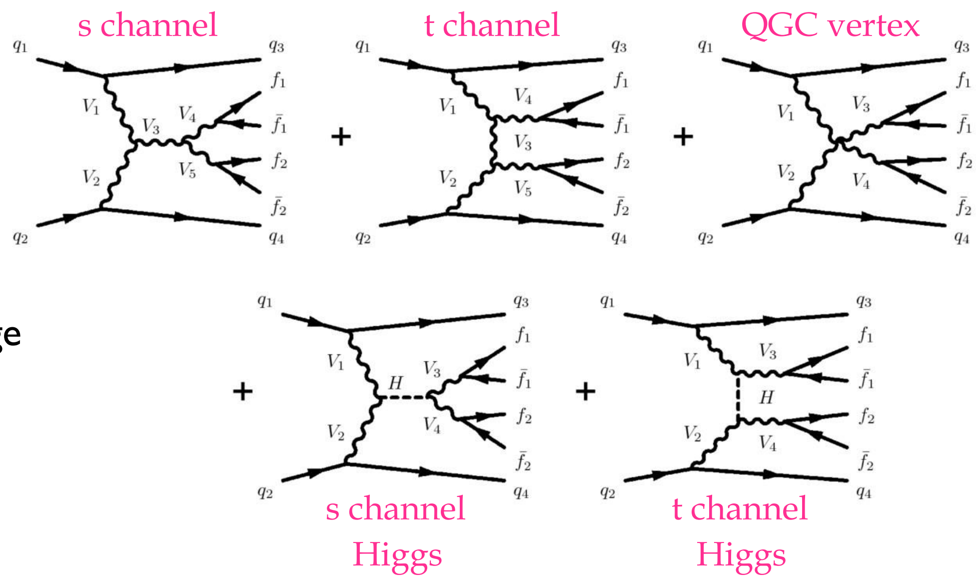
below the red line: beyond limit of currently used detector technologies in several systems



Vector Boson Scattering



- In the VBS topology, two incoming quarks radiate bosons which interact - final state of two jets and two massive bosons decaying to fermions
- This final state can be the result of EW production with and without a scattering topology, or of processes involving the strong interaction.
- Two "tag" jets with large rapidity separation and large invariant mass give a good experimental signature
- Backgrounds differ depending on final state



BROOKHAVEN NATIONAL LABORATORY