



Prospects of HL-LHC

Hongbo Liao

Institute of High Energy Physics, Beijing, China

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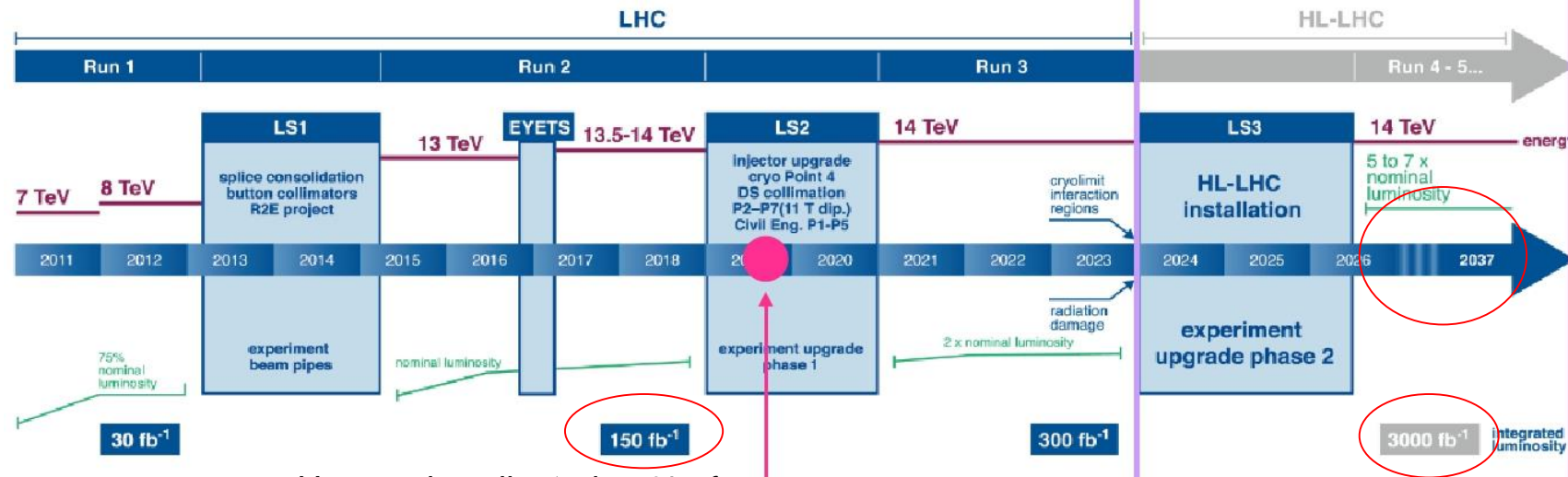
China LHC Physics Workshop (CLHCP2019)

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

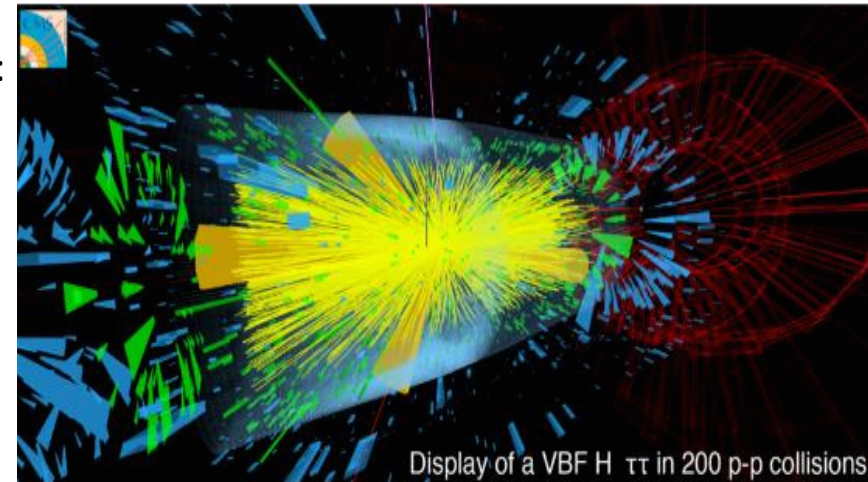
LHC / HL-LHC Plan



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

We are here

- ✓ Operation at up to $L=7.5 \cdot 10^{34} \text{ Hz/cm}^2$ (LHC Run-2: $2 \cdot 10^{34}$) to collect up to $L_{int} = 3000 \text{ fb}^{-1}$
- ✓ 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

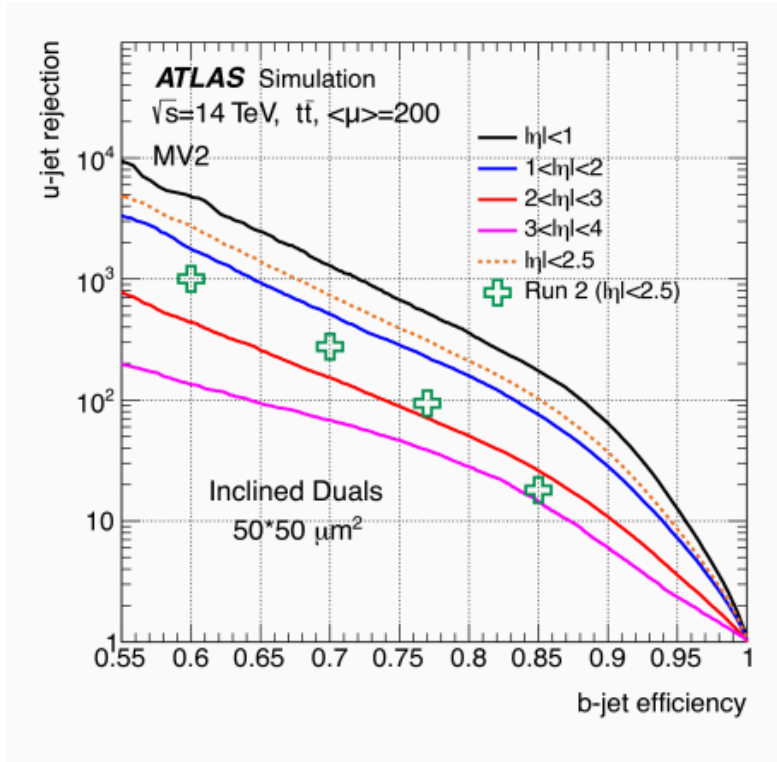


- ◉ Letter of Intent ([CERN-LHCC-2012-022](#))
- ◉ Phase-II Upgrade Scoping Document ([CERN-LHCC-2015-020](#))
- ◉ ITK Pixel TDR ([CERN-LHCC-2017-021](#))
- ◉ ITK Strip TDR ([CERN-LHCC-2017-005](#))
- ◉ LAr TDR ([CERN-LHCC-2017-018](#))
- ◉ Tile TDR ([CERN-LHCC-2017-019](#))
- ◉ Muon TDR ([CERN-LHCC-2017-017](#))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

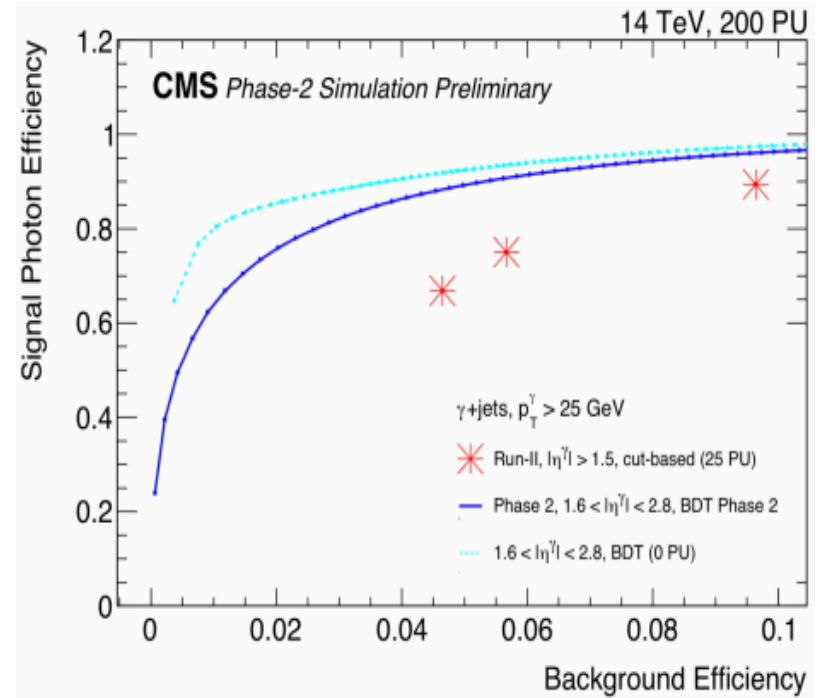
- ◉ CMS Phase-II TDR ([CERN-LHCC-2015-010](#))
- ◉ Phase-II Upgrade Scoping Document ([CERN-LHCC-2015-019](#))
- ◉ Tracker TDR ([CERN-LHCC-2017-009](#))
- ◉ Barrel Calo TDR ([CERN-LHCC-2017-011](#))
- ◉ Endcap Calo TDR ([CERN-LHCC-2017-023](#))
- ◉ Tile TDR ([CERN-LHCC-2017-019](#))
- ◉ Muon TDR ([CERN-LHCC-2017-012](#))
- ◉ 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

Projected Physics Results		
CMS-PAS-FYS-18-027	Constraining nuclear parton distributions with heavy ion collisions at the HL-LHC with the CMS experiment	December 2018
CMS-PAS-FYS-18-028	Anomalous couplings in the HZ final state at the HL-LHC	December 2018
CMS-PAS-FYS-18-029	Search for excited leptons in $(\ell\ell)$ final states in proton-proton collisions at the HL-LHC	December 2018
CMS-PAS-FYS-18-035	Performance of jet quenching measurements in pp and PbPb collisions with CMS at the HL-LHC	December 2018
CMS-PAS-FYS-18-032	High- p_T jet measurements at the HL-LHC	December 2018
CMS-PAS-FYS-18-029	Projection of differential σ production cross section measurements in the W or Z final states in pp collisions at the HL-LHC	December 2018
CMS-PAS-FYS-18-024	Vector Boson Scattering prospective studies in the ZZ fully leptonic decay channel for the High-Luminosity and High-Energy LHC upgrade	December 2018
CMS-PAS-FYS-18-022	Projection of the Run-2 BSM $(\ell\ell) \rightarrow \ell\ell$ limits for the High-Luminosity LHC	December 2018
CMS-PAS-FYS-18-028	Open heavy flavor and quarkonia in heavy ion collisions at HL-LHC	December 2018
CMS-PAS-FYS-18-028	Prospects for the measurement of observables and polarized $WZ \rightarrow 3\ell$ production cross sections at the High-Luminosity LHC	December 2018
CMS-PAS-FYS-18-029	Predictions on the precision achievable for small system flow observables in the context of the HL-LHC	December 2018
CMS-PAS-FYS-18-041	CP-violation studies at the HL-LHC with CMS using WZ decays to $3\ell\mu(3\ell\tau)$	December 2018
CMS-PAS-FYS-18-013	Measurement of rare $B \rightarrow \mu^+\mu^-$ decays with the Phase-2 upgraded CMS detector at the HL-LHC	December 2018
CMS-PAS-FYS-18-028	Search for heavy composite Higgs bosons at the High-Luminosity and the High-Energy LHC	December 2018
CMS-PAS-FYS-18-022	Expected sensitivities for WZ production at HL-LHC and HE-LHC	December 2018
CMS-PAS-FYS-18-029	Search for $\tilde{\chi}$ resonances at the HL-LHC and HE-LHC with the Phase-2 CMS detector	November 2018
CMS-PAS-FYS-18-040	Searches for light Higgs-like charged and neutral states at the HL-LHC with the Phase-2 CMS detector	November 2018
CMS-PAS-FYS-18-038	Final level track jet trigger for displaced jets at High Luminosity LHC	November 2018
CMS-PAS-FYS-18-039	Constraints on the Higgs boson self-coupling from $WWWW$ ($2 \rightarrow 2$) differential measurements at the HL-LHC	November 2018
CMS-PAS-FYS-18-029	Search for supersymmetry with direct stop production at the HL-LHC with the CMS Phase-2 detector	November 2018
CMS-PAS-FYS-18-038	Search for invisible decays of a Higgs boson produced through vector boson fusion at the High-Luminosity LHC	November 2018
CMS-PAS-FYS-18-027	Sensitivity projections for Higgs boson properties measurements at the HL-LHC	November 2018
CMS-PAS-FYS-18-036	Study of W^+W^- production via vector boson scattering at the HL-LHC with the upgraded CMS detector	November 2018
CMS-PAS-FYS-18-036	Projection of searches for pair production of scalar leptoquarks decaying to a top quark and a charged lepton at the HL-LHC	November 2018
CMS-PAS-FYS-18-032	Search sensitivity for dark photons decaying to displaced muons with CMS at the High-Luminosity LHC	October 2018
CMS-PAS-FYS-18-030	Projection of the Mono-Z search for dark matter to the HL-LHC	October 2018
CMS-PAS-FYS-18-039	Prospects for a search for gluon-mediated FCNC to top quark production using the CMS Phase 2 detector at the HL-LHC	November 2018
CMS-PAS-FYS-18-030	Search for vector boson fusion production of a massive resonance decaying to a pair of Higgs bosons in the four-lepton final state at the HL-LHC using the CMS Phase-2 detector	July 2018

ATLAS Physics Studies

Study Title	Document Number	Date	in (Days)
HL-LHC prospects for the measurement of Ω_{CDM}	ATL-PHYS-PUB-2018-049	17 DEC 18	14
Prospects for jet and photon physics at the HL-LHC	ATL-PHYS-PUB-2018-051	13 DEC 18	14
Prospect for deep cross section HL-LHC	ATL-PHYS-PUB-2018-047	13 DEC 18	14
Electroweak, leptonic, $130, 20, 20, 2$ kin. upgrade	ATL-PHYS-PUB-2018-048	10 DEC 18	14
Z to dipion or W, W^+W^- or $\gamma\gamma$ HV HL-LHC	ATL-PHYS-PUB-2018-044	09 DEC 18	14
HL-LHC prospect for top mass using ZW	ATL-PHYS-PUB-2018-042	04 DEC 18	14
Prospects for MET+jet	ATL-PHYS-PUB-2018-043	05 DEC 18	14
Differential cross section measurement prospects at HL-LHC	ATL-PHYS-PUB-2018-040	04 DEC 18	14
Prospects for $B_s \rightarrow J/\psi$ at HL-LHC	ATL-PHYS-PUB-2018-041	04 DEC 18	14
HL-LHC prospects of HL-LHC	ATL-PHYS-PUB-2018-030	19 DEC 18	14
Nuclear PDFs in Run 3 and 4	ATL-PHYS-PUB-2018-039	30 NOV 18	5/22/18
Prospect for a measurement of the Weak Mixing Angle in $p p \rightarrow Z\gamma\gamma$ final states with the ATLAS detector at the High-Luminosity Large Hadron Collider	ATL-PHYS-PUB-2018-037	29 NOV 18	14
Prospects for DM in VBF+MET and Photon+MET	ATL-PHYS-PUB-2018-038	30 NOV 18	14
WIMP DM pair + WZ quarks, $0, 2$ leptons	ATL-PHYS-PUB-2018-036	27 NOV 18	14
DM+MET prospects at HL-LHC	ATL-PHYS-PUB-2018-035	18 NOV 18	14
HL-LHC prospects for $\tau \rightarrow \mu\gamma$	ATL-PHYS-PUB-2018-032	20 NOV 18	14
Prospect studies for the production of three massive vector bosons with the ATLAS detector at the High-Luminosity LHC	ATL-PHYS-PUB-2018-030	14 NOV 18	14
Chargino-mediated pair disappearing track, soft leptons	ATL-PHYS-PUB-2018-027	15 NOV 18	14
Prospect study of electroweak production of a Z boson pair plus two jets at the HL-LHC	ATL-PHYS-PUB-2018-029	15 NOV 18	14
Prospects of H \rightarrow bb Resonance Search	ATL-PHYS-PUB-2018-028	13 NOV 18	14
Prospects for Higgs Signatures (2DM+4)	ATL-PHYS-PUB-2018-027	02 NOV 18	14
Prospects for the measurement of $\nu\tau\tau$ with the upgraded ATLAS detector	ATL-PHYS-PUB-2018-026	30 OCT 18	14
Prospects for Missing Dark Matter	ATL-PHYS-PUB-2018-024	30 OCT 18	14
Prospective study of vector boson scattering in HZ fully leptonic final state at HL-LHC	ATL-PHYS-PUB-2018-023	29 OCT 18	14
Prospects of VV Search and Measurement	ATL-PHYS-PUB-2018-022	30 OCT 18	14
3rd generation, 2 lepton, upgrade	ATL-PHYS-PUB-2018-021	30 OCT 18	14
Dark properties of heavy ion collisions in Run 3 and 4	ATL-PHYS-PUB-2018-020	23 OCT 18	5/22/18
Jet energy loss in heavy ion collisions in Run 3 and Run 4	ATL-PHYS-PUB-2018-019	23 OCT 18	5/22/18
LFC with photons in Run 3 and 4	ATL-PHYS-PUB-2018-018	04 OCT 18	5/22/18
HL-LHC/HE prospects at HL-LHC	ATL-PHYS-PUB-2018-016	07 AUG 18	14
Theory uncertainty impact projection studies	ATL-PHYS-PUB-2018-010	16 JUL 18	14
HL-LHC \rightarrow He-He prospects HL-LHC	ATL-PHYS-PUB-2018-008	24 MAR 18	14
Prospects for $B_s^0 \rightarrow \mu^+\mu^-$ in Run-2 and HL-LHC	ATL-PHYS-PUB-2018-005	10 MAR 18	13

Obviously cannot cover all

- 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**

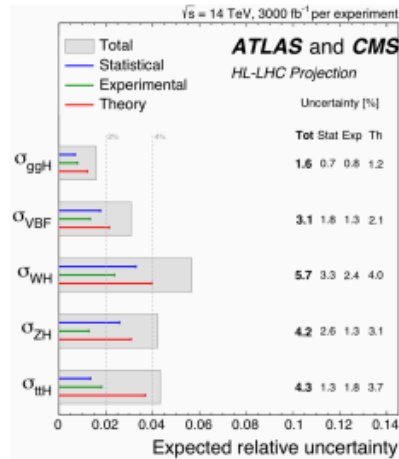
Projections for Higgs Signal Strength, Couplings, Mass, Width

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

Productions (ATLAS+CMS)

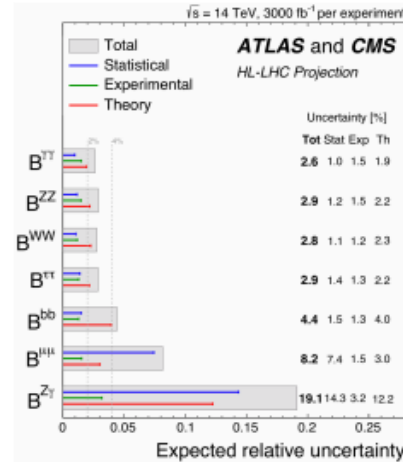
- ✓ ggF can be measured at ~2%
- ✓ WH can be measured at ~6%

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



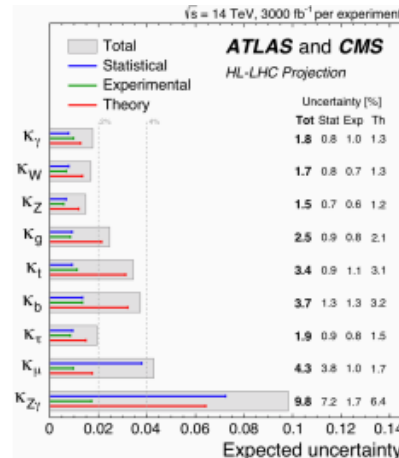
Decays (ATLAS+CMS)

- ✓ Gauge boson decays can reach ~3% precision
- ✓ Fermion decays (bb, $\tau\tau$) can reach ~3-4%
- ✓ $\mu\mu$ 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

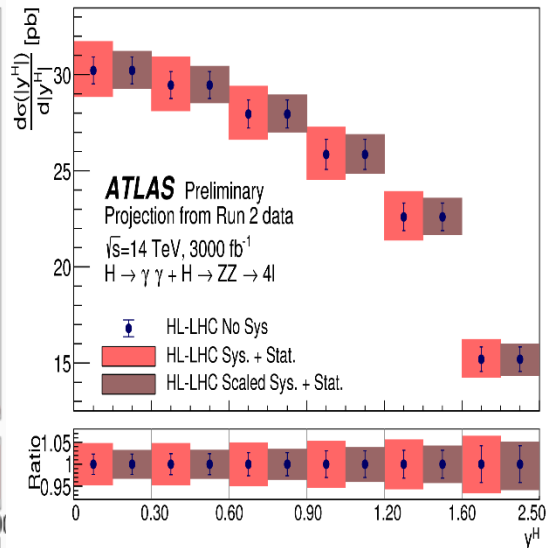
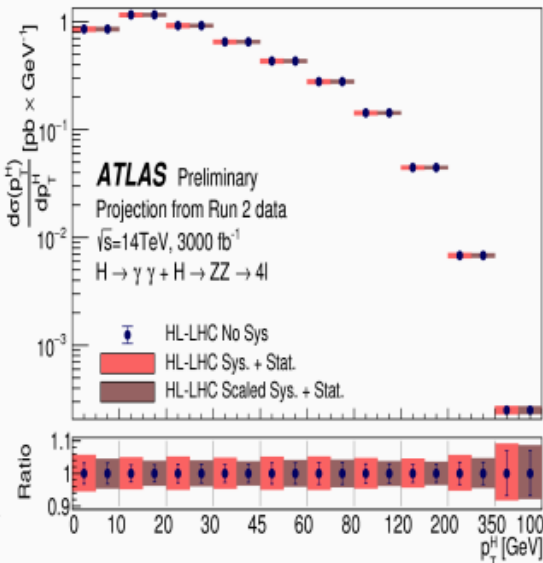
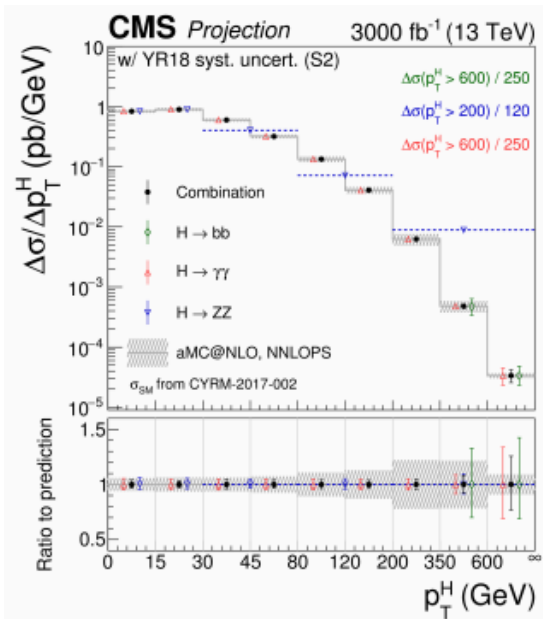
Width: 4.1 MeV (Run2: ATLAS < 14.4 MeV and CMS < 9.2 MeV)

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
- Most precisely measured by $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4l$ channels

ATL-PHYS-PUB-2018-040

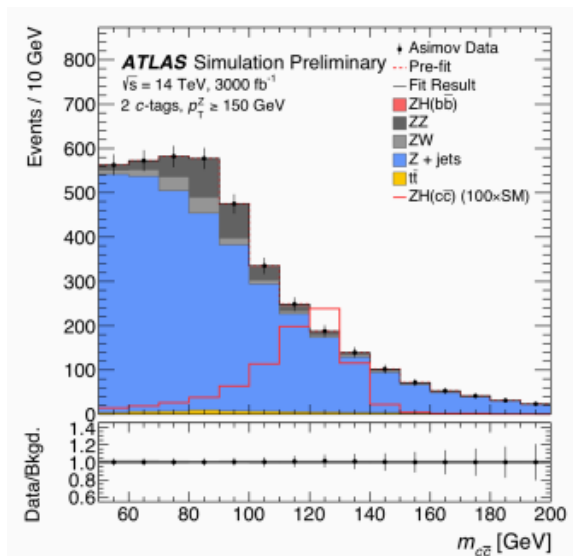
CMS-PAS-FTR-18-011



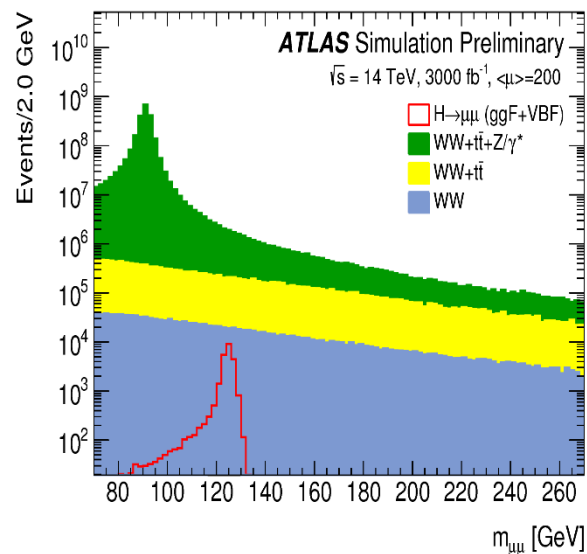
- Expect to probe with precision of ~10% at Higgs $p_T \sim 350\text{-}600$ GeV

Projections for Rare Higgs Decays

• $H \rightarrow c\bar{c}$



• $H \rightarrow \mu\mu$



- ✓ Extrapolate from Run2 search
 - ZH \rightarrow llcc
- ✓ Expect to set an upper limit on $\sigma \times \text{BR}$ at 95%CL of $6.3 \times \text{SM}$ (Run2: $110 \times \text{SM}$)
- ✓ May further improve sensitivity by including other channels :
 - WH \rightarrow lvcc
 - ZH \rightarrow vvcc

- ✓ Expect to observe via ggH and VBF productions
- ✓ significance $> 9\sigma$
- ✓ uncertainty on $\sigma \times \text{BR} < 13\%$
- ✓ Current limit : $\sigma \times \text{BR} < 2.1\text{-}2.9 \times \text{SM}$

ATL-PHYS-PUB-2018-016

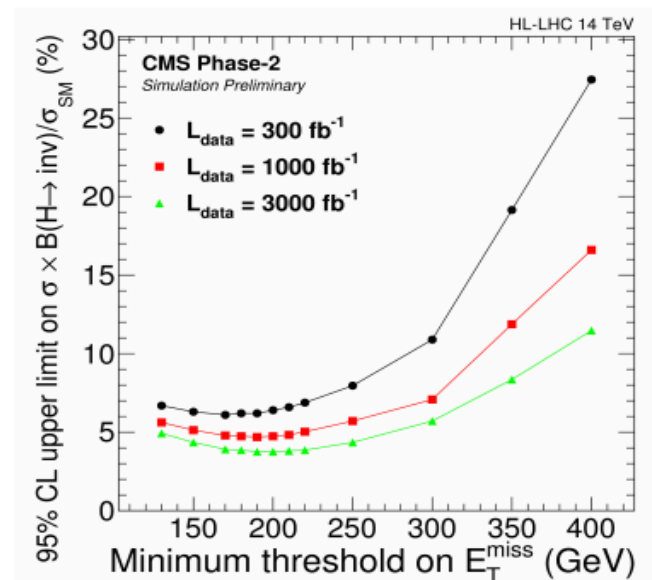
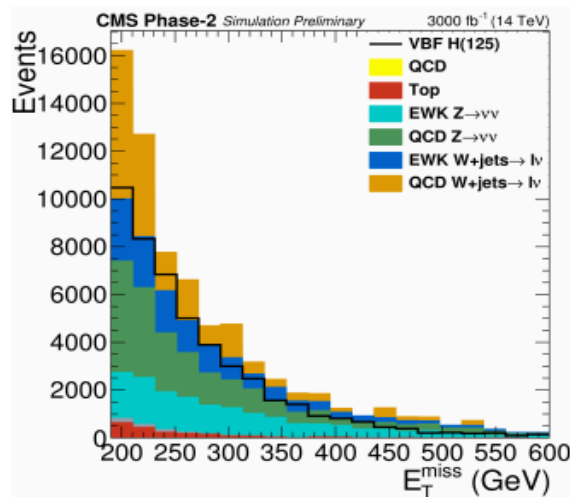
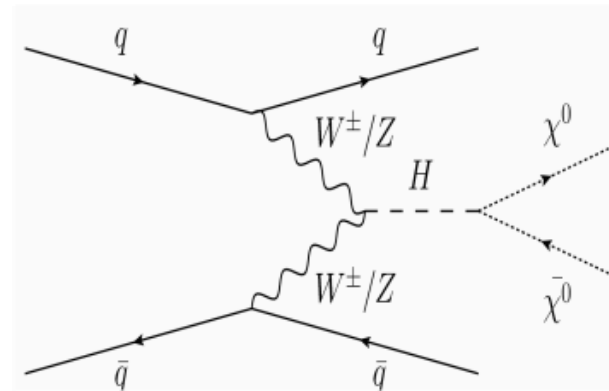
ATL-PHYS-PUB-2018-006

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)

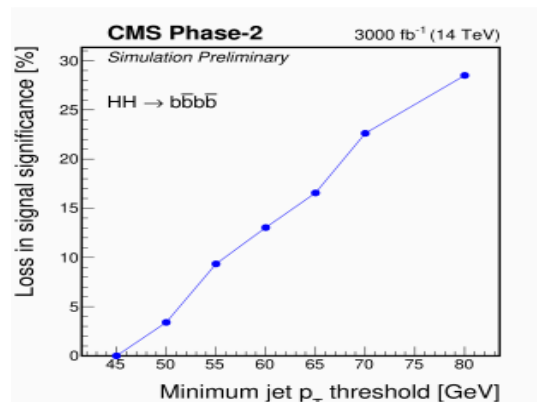
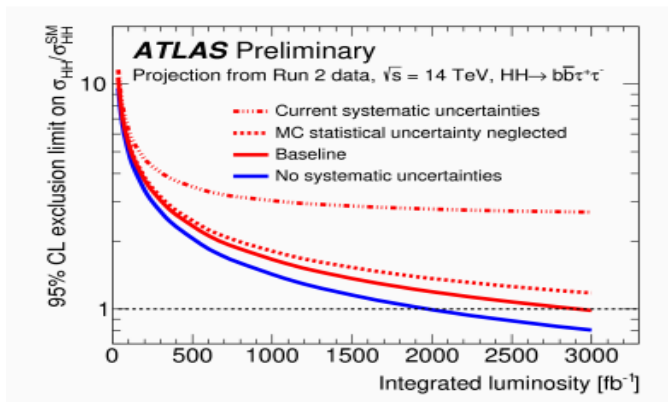
CMS-FTR-18-016

- 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 $BR(H \rightarrow inv) \sim 3.8\%$ at 95% CL (assume SM VBF production)
 - 5X smaller than current best limit
 - SM: $BR(H \rightarrow ZZ \rightarrow \nu\nu\nu\nu) \sim 0.1\%$



Di-Higgs : Projection for HL-LHC

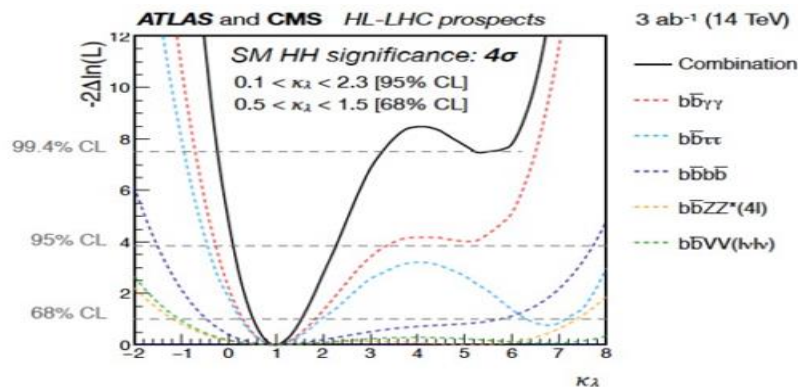
- Extrapolation based on current analyses and on the estimate of upgraded detector performance



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
$HH \rightarrow b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \rightarrow b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \rightarrow b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \rightarrow b\bar{b}VV(l\nu\nu)$	-	0.59	-	0.56
$HH \rightarrow b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined		Combined	
	4.5		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**

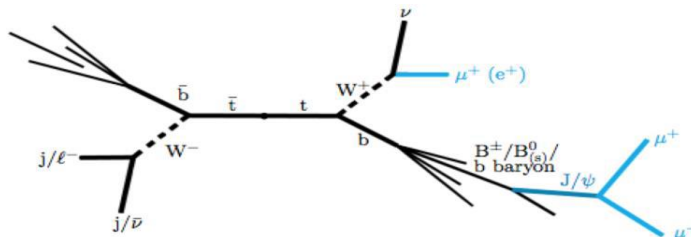
- kinematic reconstruction of $t\bar{t}$ or single top final state
 - jet systematics dominate
- usage of b-jet information via J/ψ final state
 - uncertainty on modelling of b-fragmentation or b-decay dominate
 - small BR, limited by statistics
- top quark mass from cross sections or distributions
 - theory and luminosity uncertainties dominate
- Usually ambiguity of top mass definition not considered

- **ATLAS projections using only J/ψ final states**

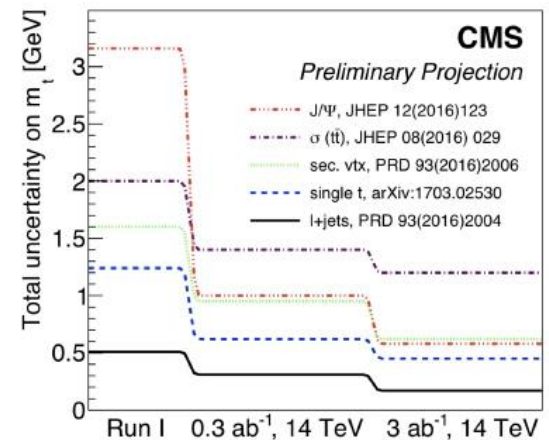
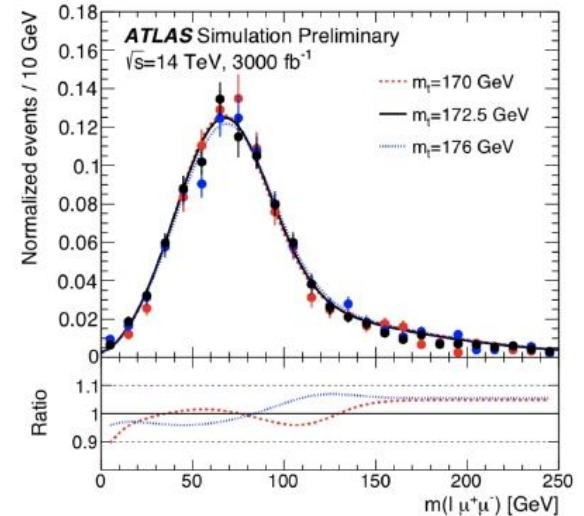
- Statistical uncertainty 0.14 GeV,
systematic uncertainty 0.48 GeV (0.28%)

- **CMS projections**

- Can reach between 0.1%-0.7% precision



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



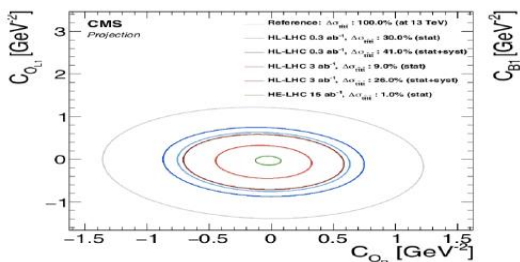
4-top production

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

- 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]

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



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

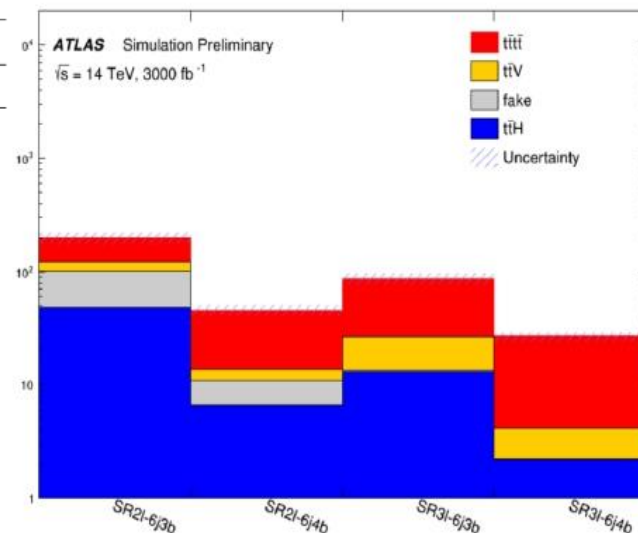
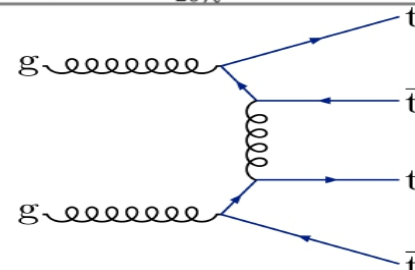
ATL-PHYS-PUB-2018-047

CMS-PAS-FTR-18-031

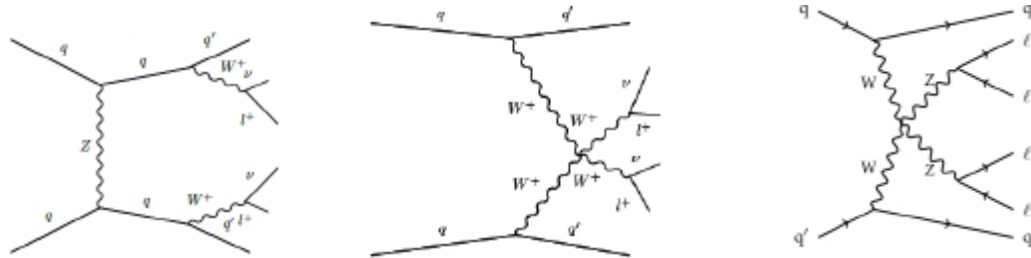
Chin. Phys. C42 (2018) 2, 023104

Phys. Rev. D 95, 053004 (2017)

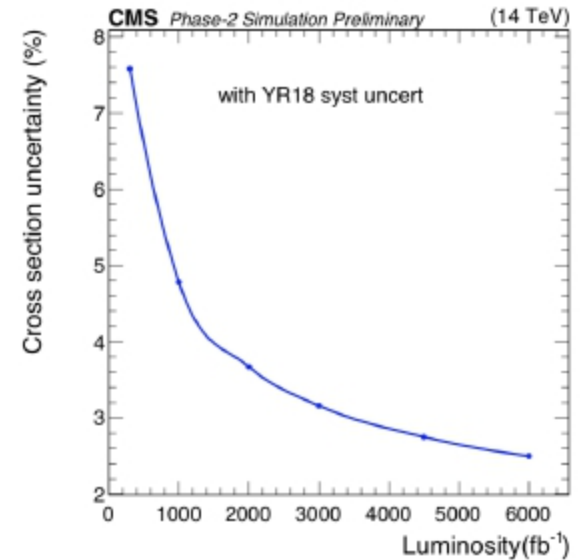
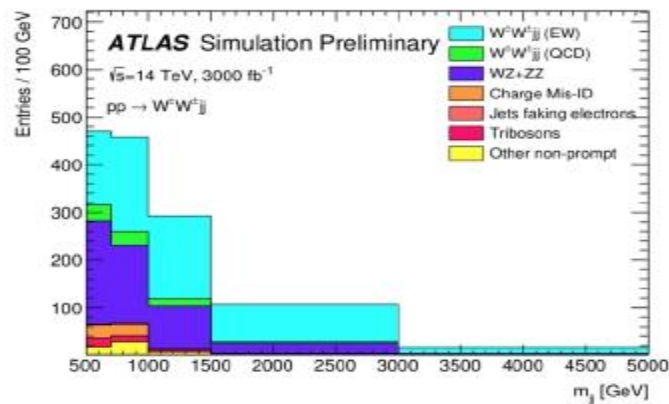
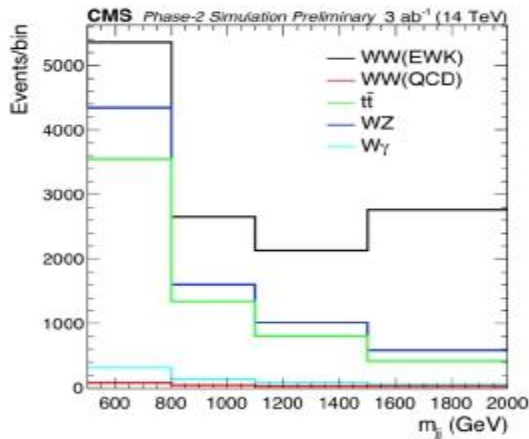
σ [fb]	LO + NLO	$\frac{\text{LO(+NLO)}}{\text{LO}_{\text{QCD}}(+\text{NLO}_{\text{QCD}})}$
14 TeV	15.83 ^{+18%} _{-21%}	1.11 (1.08)
27 TeV	143.93 ^{+17%} _{-20%}	1.11 (1.06)



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

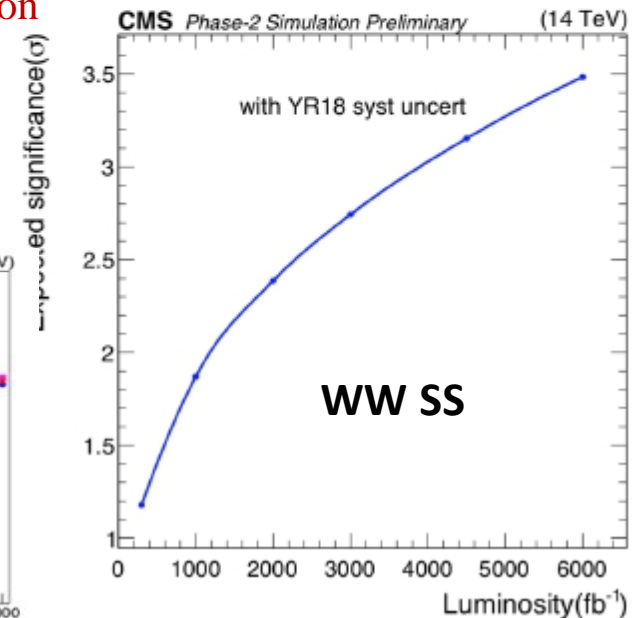
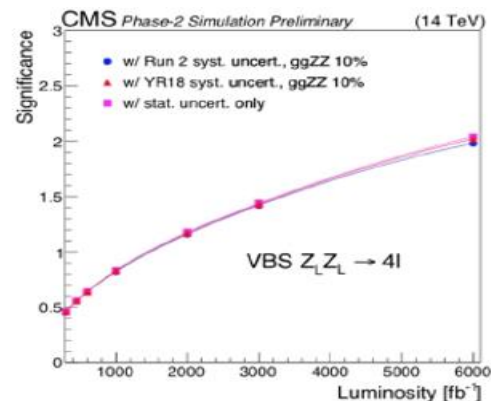
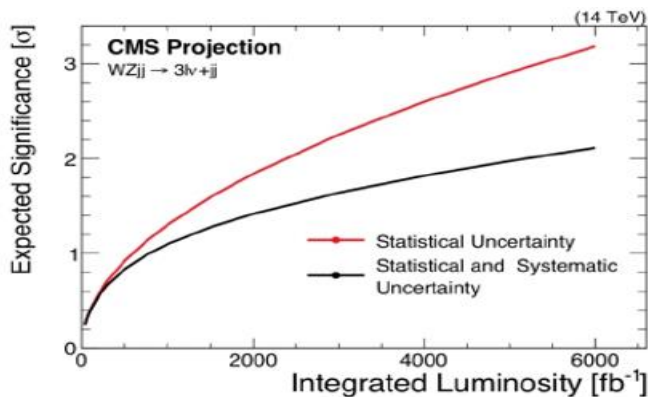
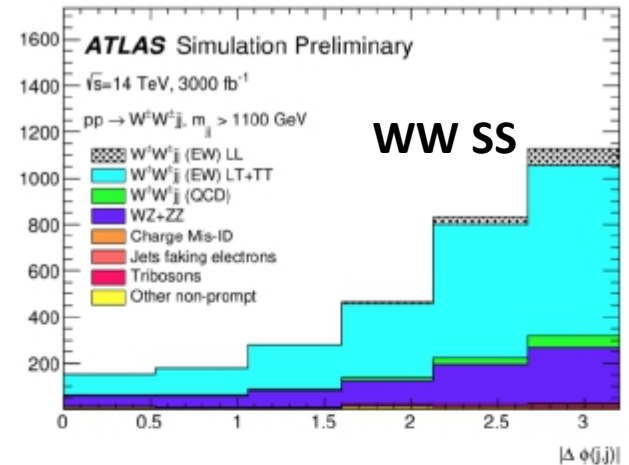
arXiv:1812.09740

arXiv:1901.04060

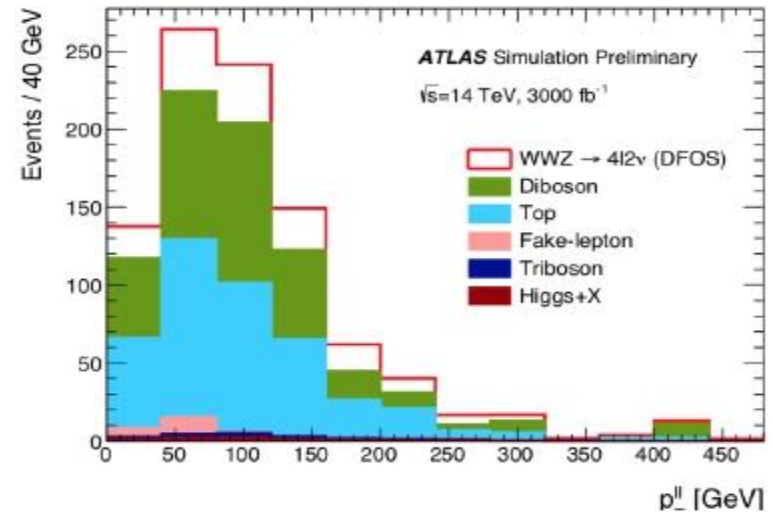
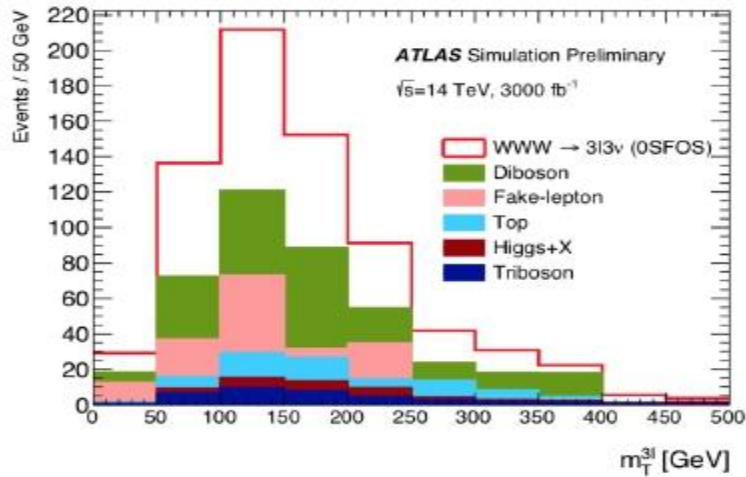
Process	W [±] W [±]	WZ	WV	ZZ
Final state	$\ell^\pm \ell^\pm jj$	$3\ell jj$	$\ell jjjj$	$4\ell jj$
Precision	6%	6%	6.5%	10–40%
Significance	> 5σ	> 5σ	> 5σ	> 5σ

VBS and LL Scattering Significance

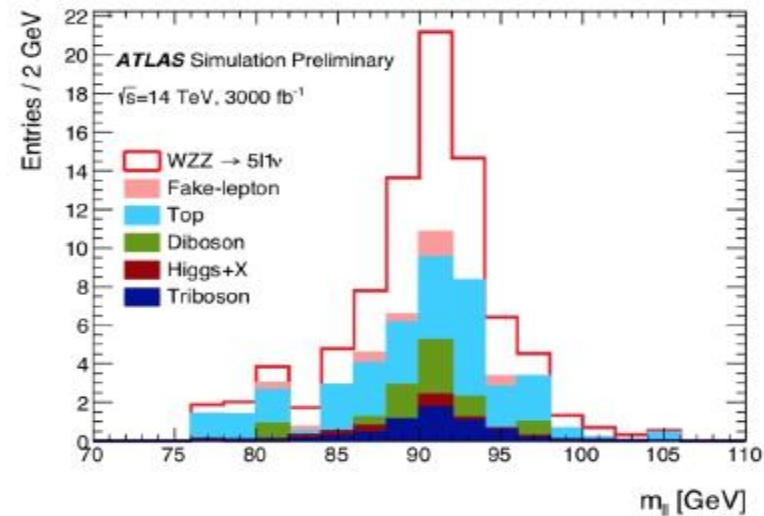
- The total vector boson scattering is composed of **three components**, depending on the polarization of the final-state vector bosons: both longitudinally polarized (LL), both transversely polarized (TT) and the mixed case (LT)
- ✓ The LL component is interesting as a direct probe of the unitarization 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



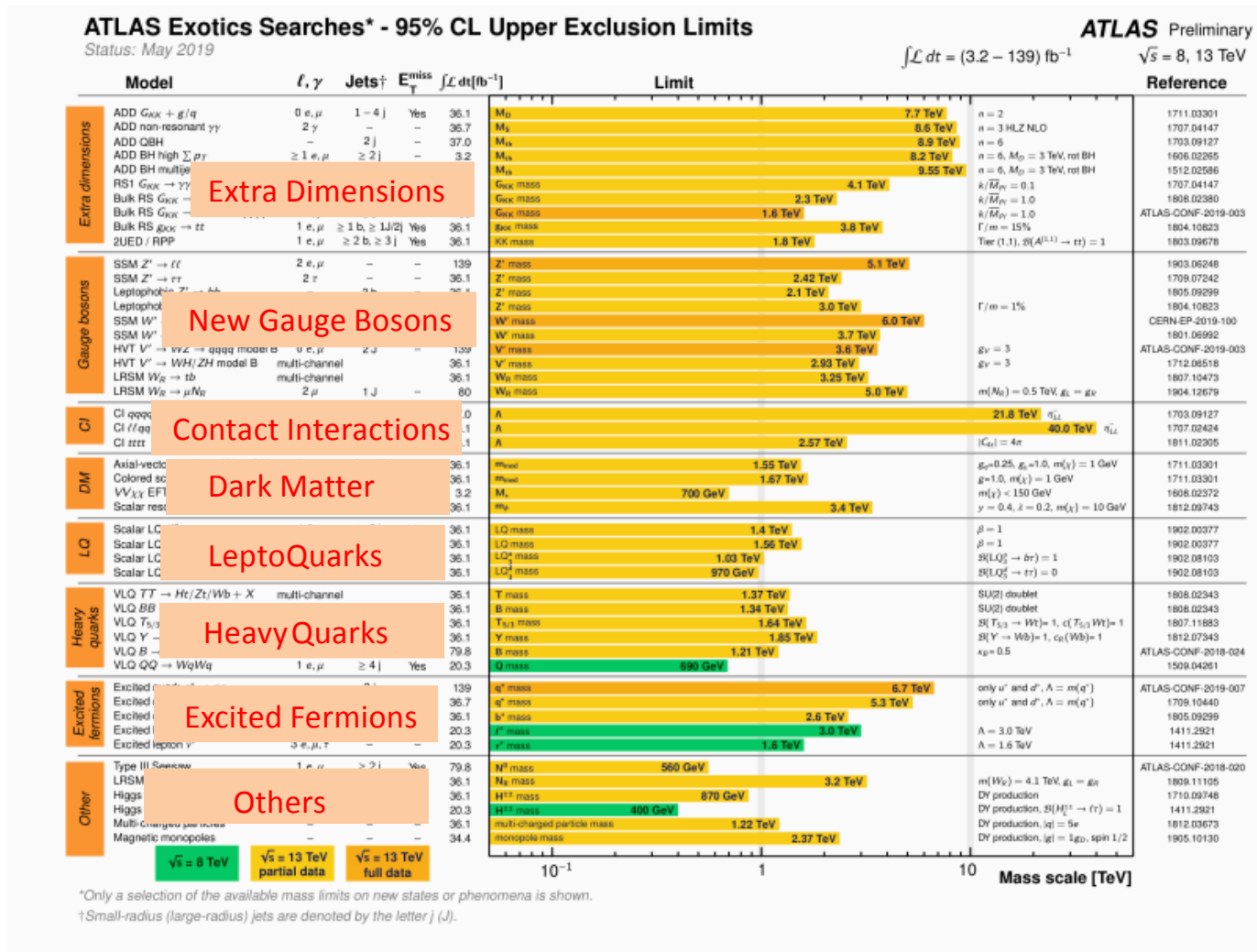
- VVV production has a low cross section but can be measured at the HL-LHC in different channels WWW, WWZ, WZZ



Process	WWW	WWZ	WZZ
Final state	3l3v	4l2v	5lv
Precision	11%	27%	36%
Significance	$> 5\sigma$	3.0σ	3.0σ

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

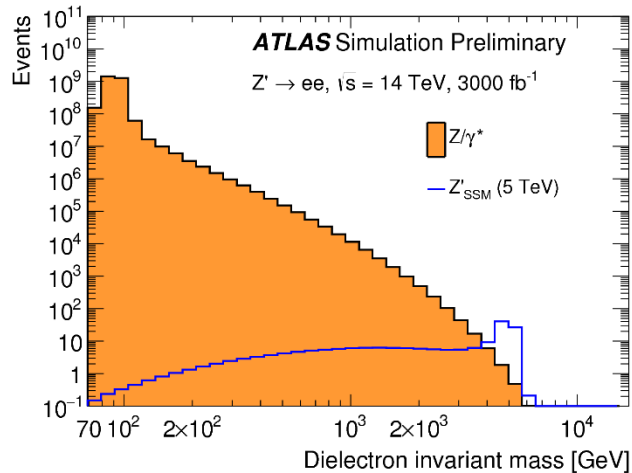
Search for New Physics : Exotics



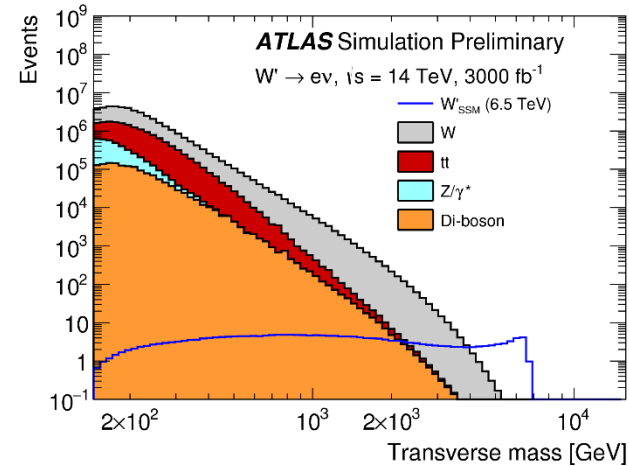
- ✓ Exotics searches at the LHC cover many different models
- ✓ Several searches have already been performed with full Run2 data
- ✓ Will only summarize a few topics and provide their potentials at HL-LHC

Resonance Search : di-lepton, lepton+MET

di-lepton



lepton+MET



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

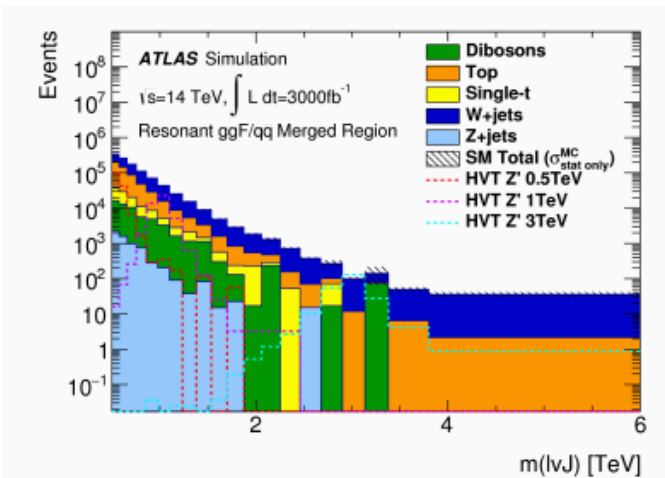
	HL-LHC		Run2
	Exclusion [TeV]	Discovery [TeV]	Exclusion [TeV]
W' _{SSM}			
ATLAS (ev, μν)	7.9	7.7	5.8 (139 fb ⁻¹)
CMS (τ _h ν)	7.0	6.4	4.0 (36 fb ⁻¹)
ATLAS (τ _h ν)			3.8 (36 fb ⁻¹)

- Extend Z'_{SSM} exclusion limit by ~ 1.4 TeV
- Overall uncertainty $\sim 6.5\% \times m_{ll}$ [TeV]
- Extend exclusion W'_{SSM} mass by ~ 2 TeV

Resonance Search : di-boson

ATL-PHYS-PUB-2018-022

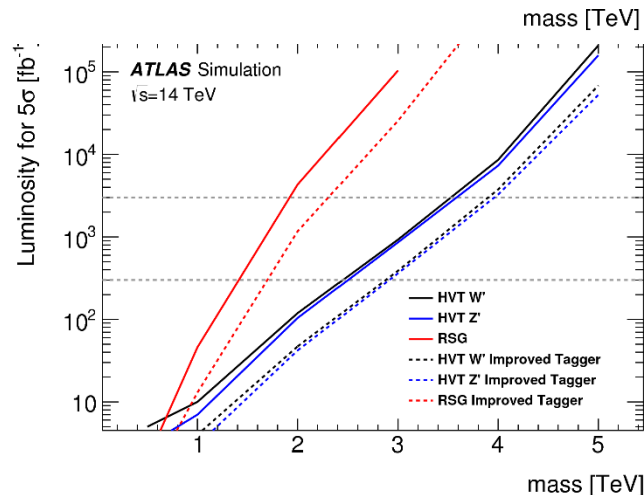
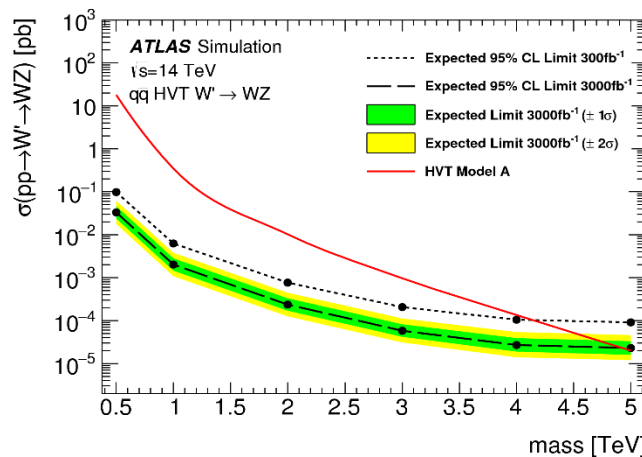
- Projection is studied for $X \rightarrow WV$, $W \rightarrow lv$ and $V(W,Z) \rightarrow qq$
 - ✓ Search for heavy resonance in ggF/qq and VBF production modes, and in resolved and boosted categories (for the decay of V)
 - ✓ Interpret search prospect in context of HVT, bulk RS model, narrow heavy scalar resonance



- Expected exclusion limits at 95% CL

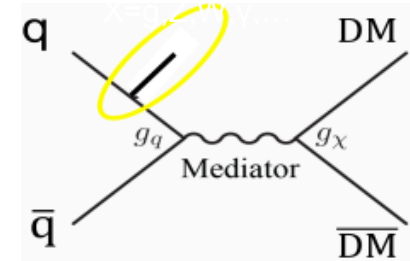
HVT, model A	HL-LHC	13 TeV, 36 fb ⁻¹ JHEP 03 (2018) 042
W'	4.9 TeV	2.9 TeV
Z'	4.9 TeV	2.85 TeV

- 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



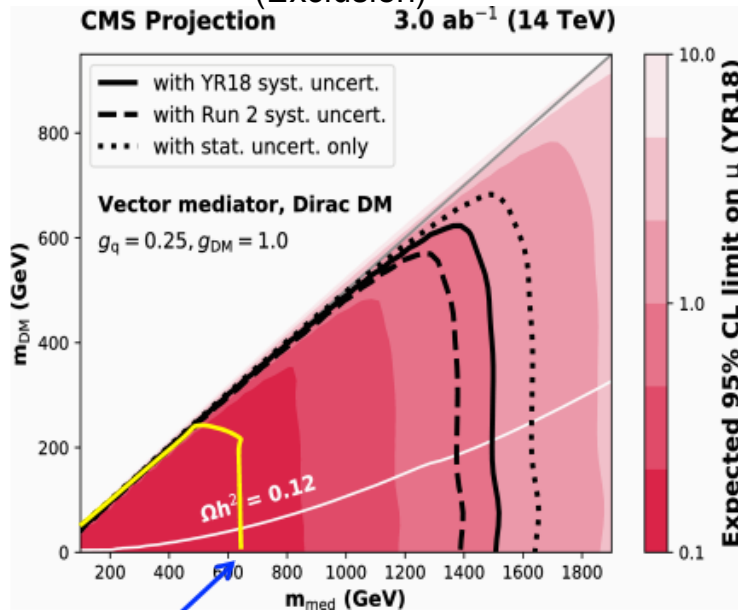
Dark Matter Searches

- 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 $E_T^{\text{miss}} + X$

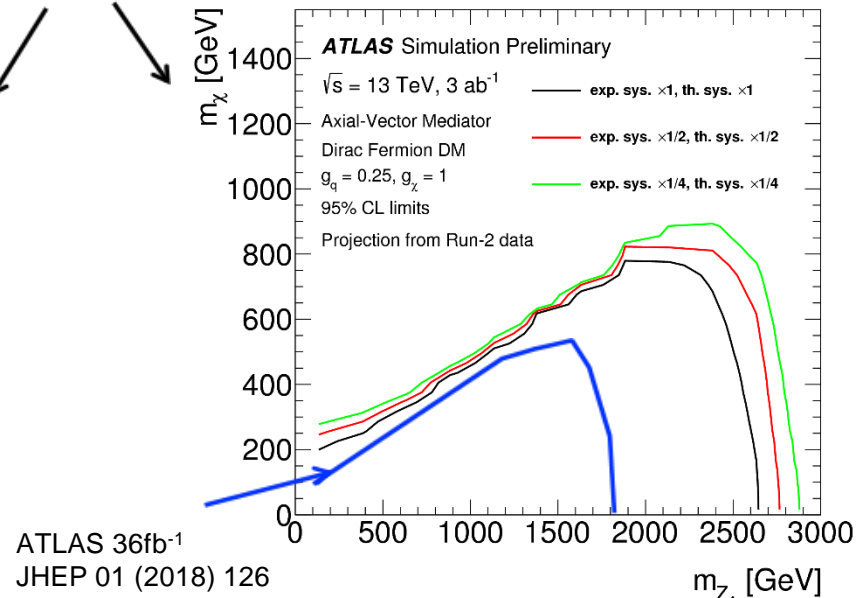
Mono-Z ($E_T^{\text{miss}} + 2\text{leptons}$) (Exclusion)



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

Searches are sensitive to systematic uncertainties

Mono-jet ($E_T^{\text{miss}} + \text{jet}$) (Exclusion)



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

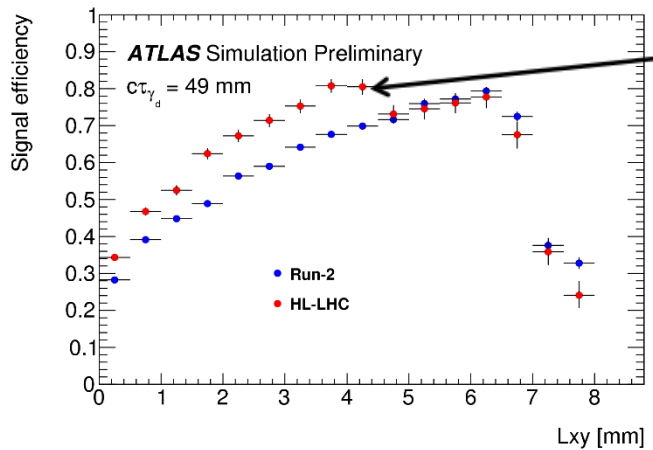
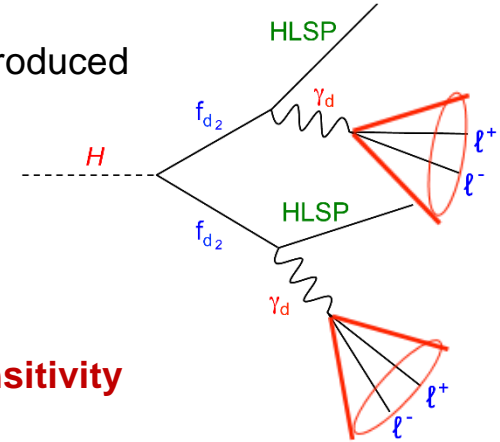
Large improvement compared to current LHC results

CMS-PAS-FTR-18-007

ATL-PHYS-PUB-2018-043

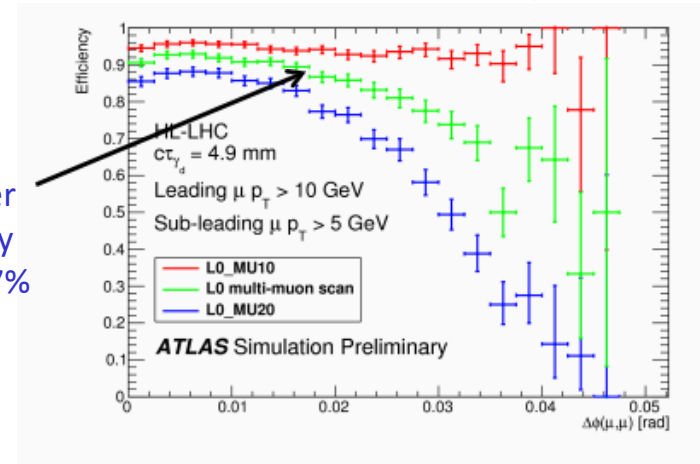
Long Lived Dark-Photons

- ✓ In some BSM a pair of long lived dark-photons (γ_d) can be produced from Higgs boson decay ($H \rightarrow 2\gamma_d + X$)
- ✓ 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 $\sim 7\%$



• Expected $c\tau$ ranged exclusion at 95% CL :

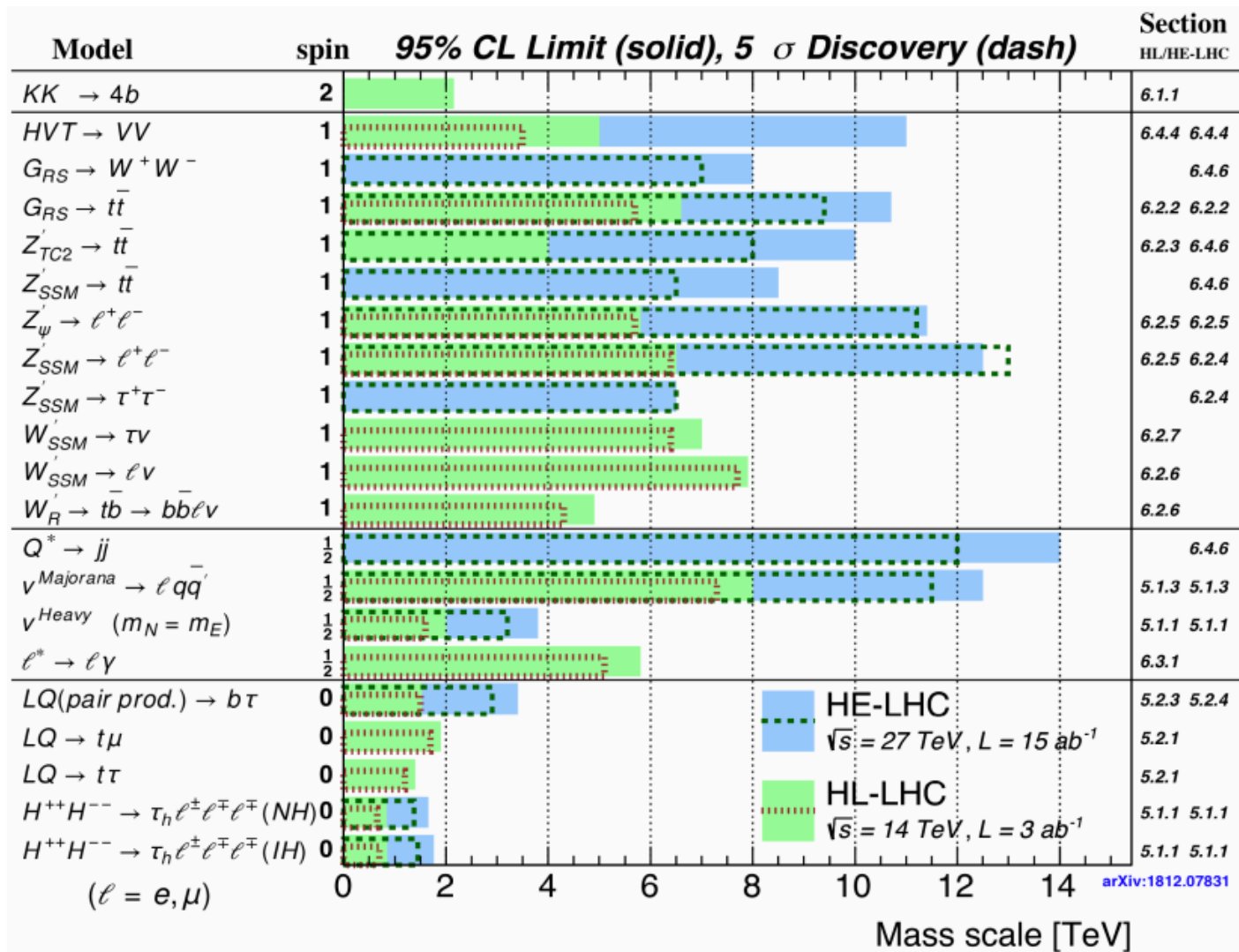
Excluded $c\tau$ [mm] muonic-muonic	Run-2	Run-3	HL-LHC	HL-LHC w/ L0 muon-scan
$BR(H \rightarrow 2\gamma_d + X) = 10\%$	$2.2 \leq c\tau \leq 111$	$1.15 \leq c\tau \leq 435$	$0.97 \leq c\tau \leq 553$	$0.97 \leq c\tau \leq 597$
$BR(H \rightarrow 2\gamma_d + X) = 1\%$	-	$2.76 \leq c\tau \leq 102$	$2.18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

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

ATL-PHYS-PUB-2019-002

30

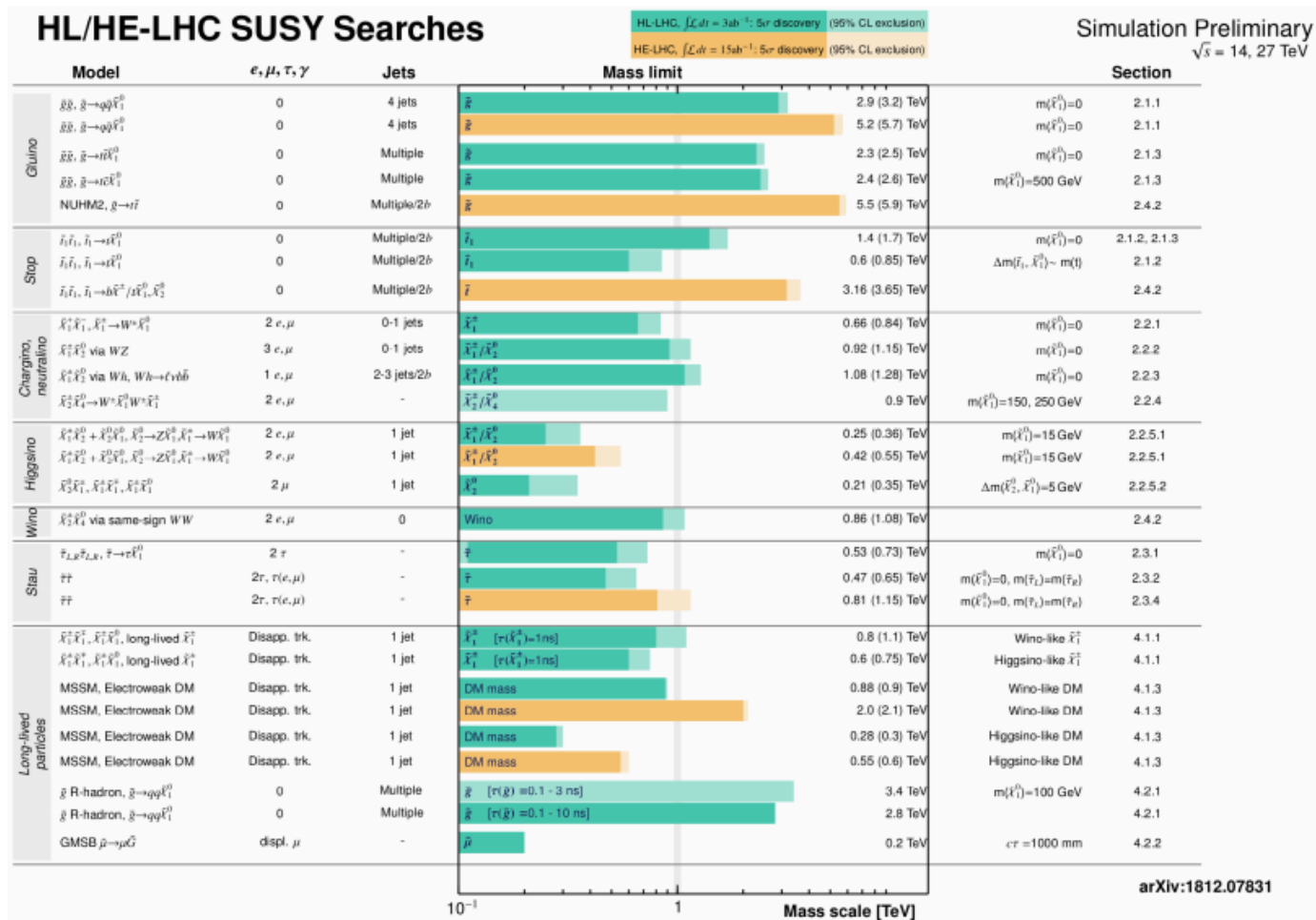
Exotics Search Reach at HL-LHC



✓ Many more projection studies on Exotic searches can be found at [arXiv:1812.07831](https://arxiv.org/abs/1812.07831)

SUSY Search Reach at HL-LHC

arXiv:1812.07831



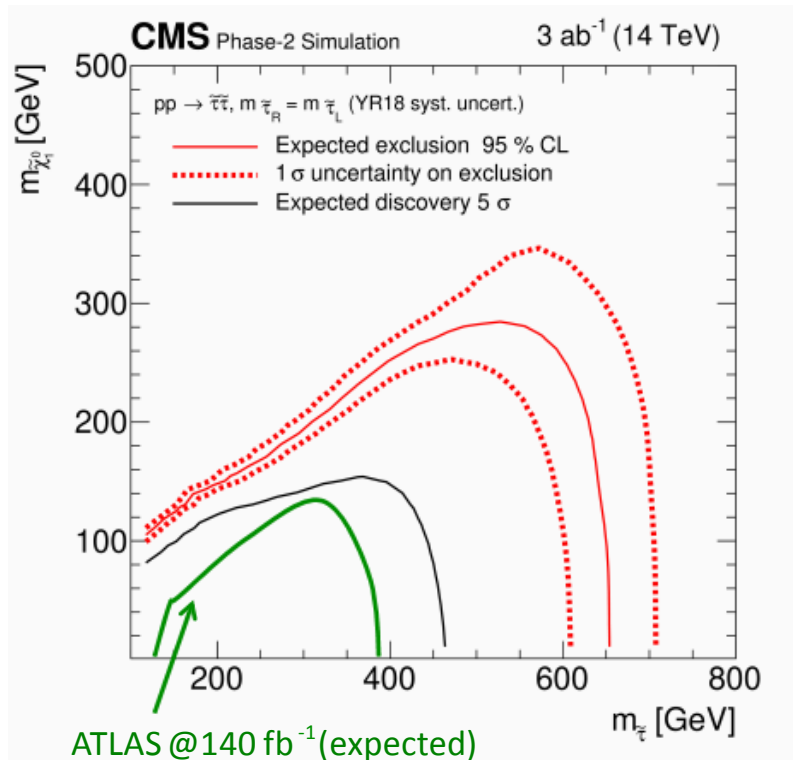
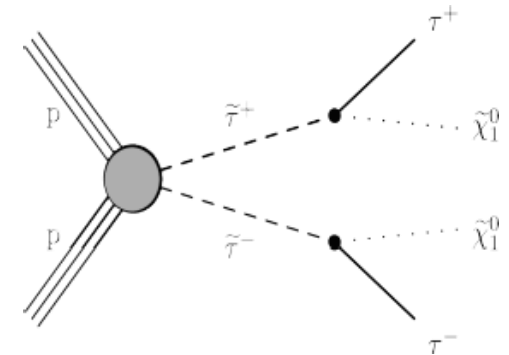
- Many studies of potential reach of SUSY searches at the HL-LHC have been performed
- Significant extension of reach from current Run2 results
- Present a couple of these studies

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

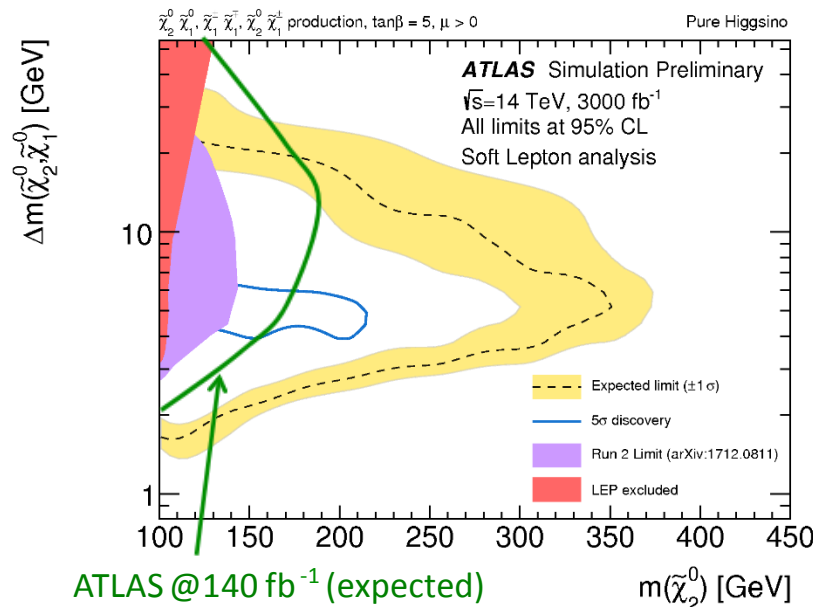
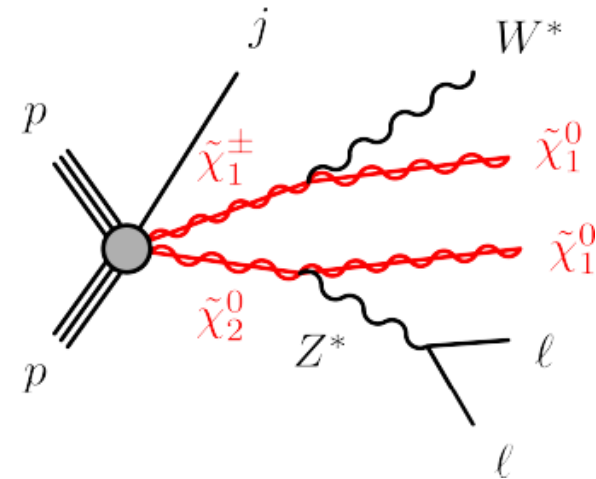
CMS-PAS-FTR-18-001

- 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

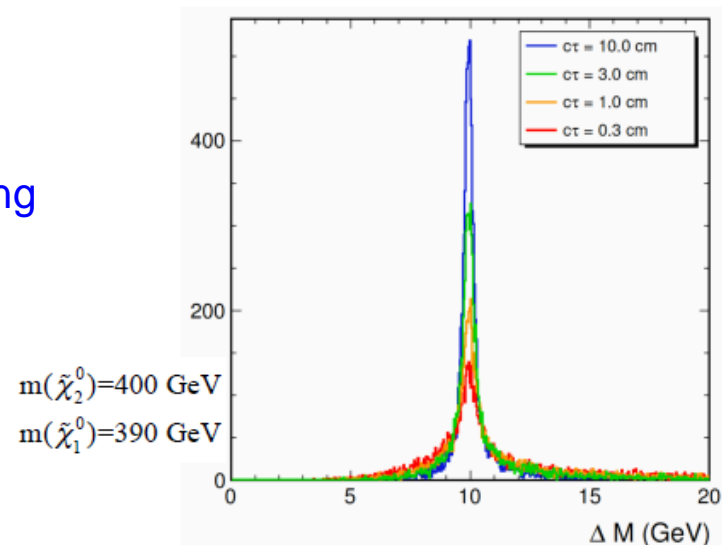
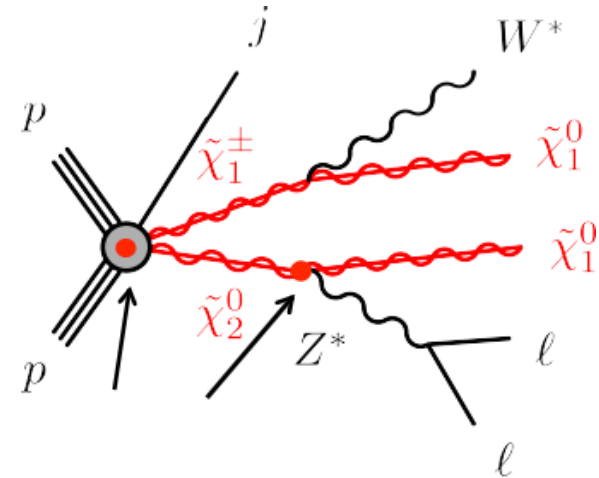
- Can assign timing for each vertex
 - Measure TOF of long lived particles

- Use the measured displacement between the vertices in space and time and the energy of the visible decay products ($Z \rightarrow ll$) to construct the $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$

*

- 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

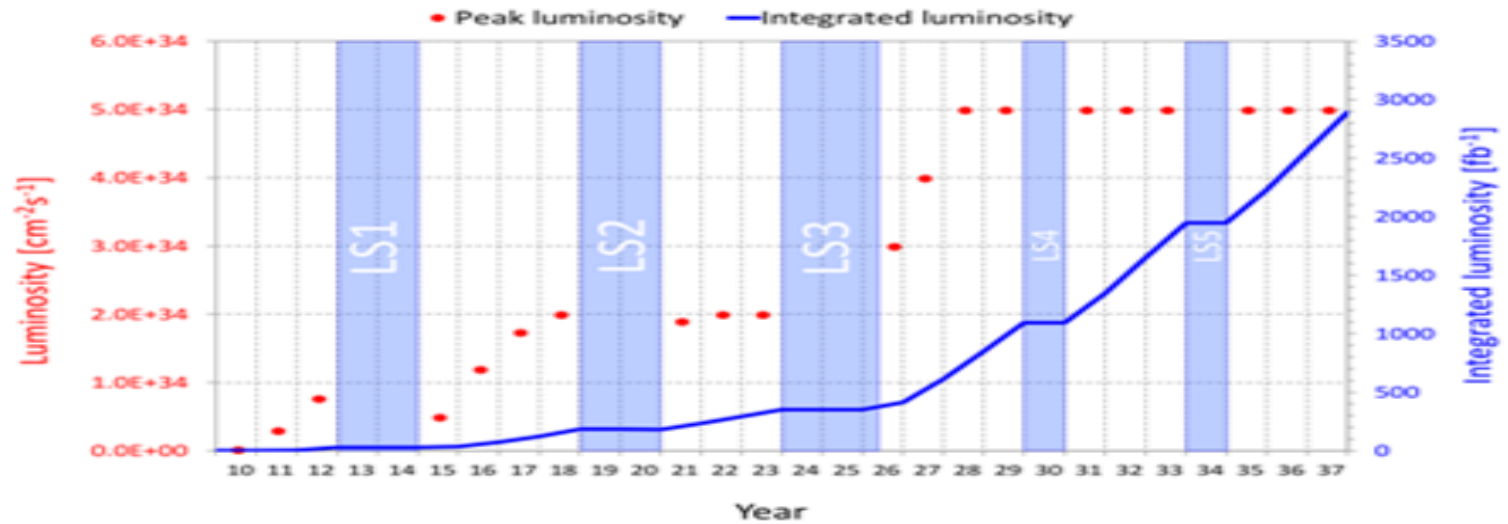
To reach the success of the HL-LHC program.

- ✓ 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 $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
integrated 3000 to 4000 fb^{-1}

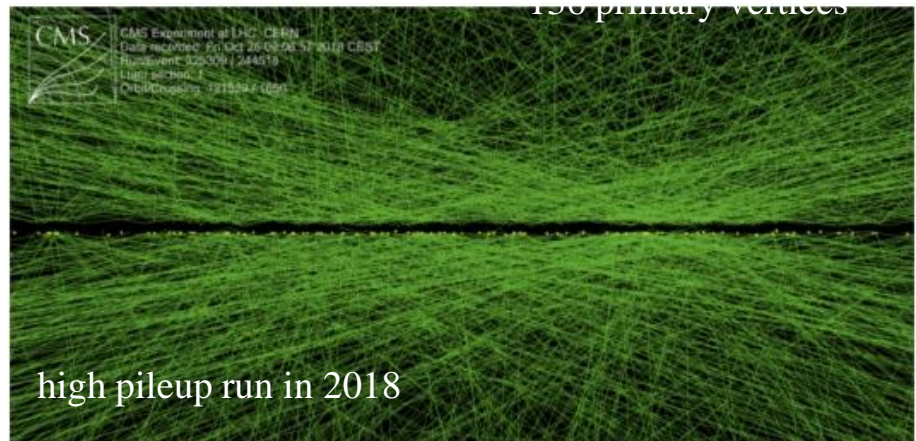
Challenges

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

