The Physics Potential of the HL-LHC Programme

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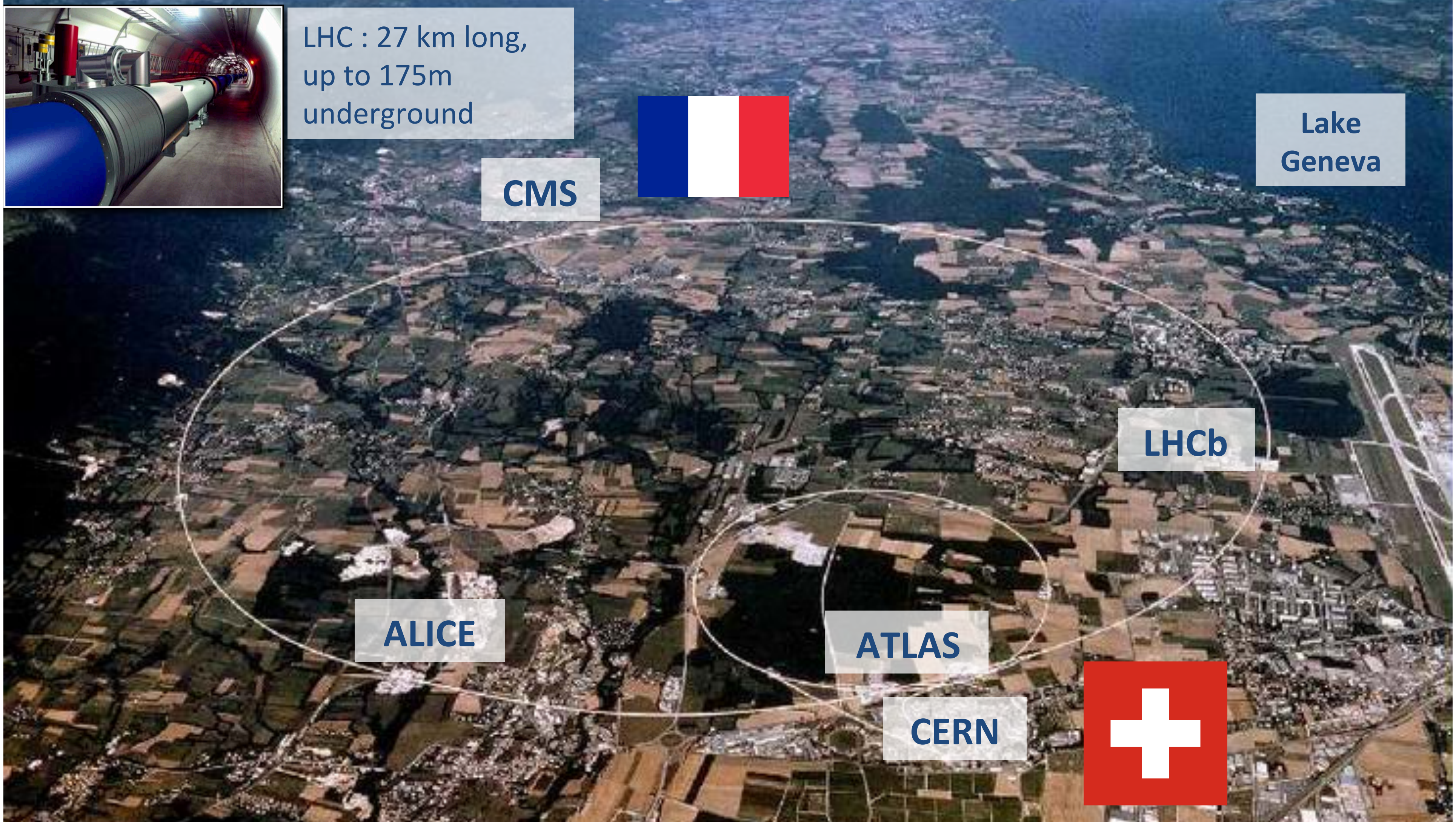
On behalf of the ATLAS and CMS Collaborations

Particle Physics
Gordon Research Conference

New Tools for the Next Generation of Particle Physics and Cosmology

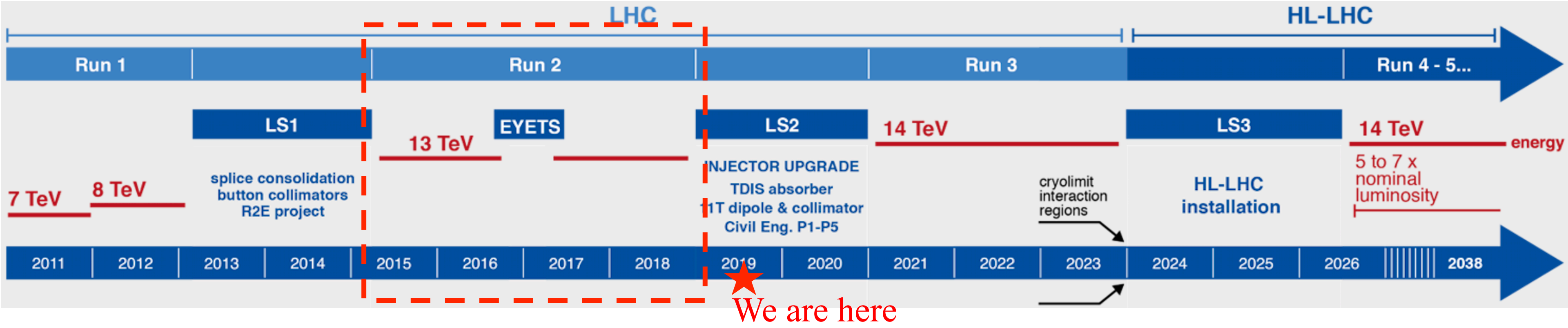
June 30 - July 5, 2019

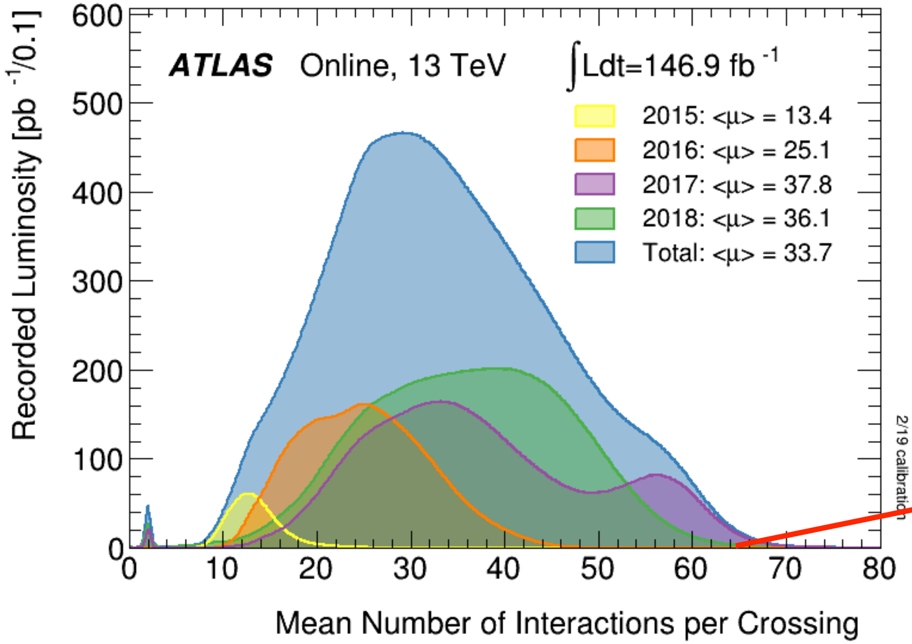
The LHC (Large Hadron Collider)

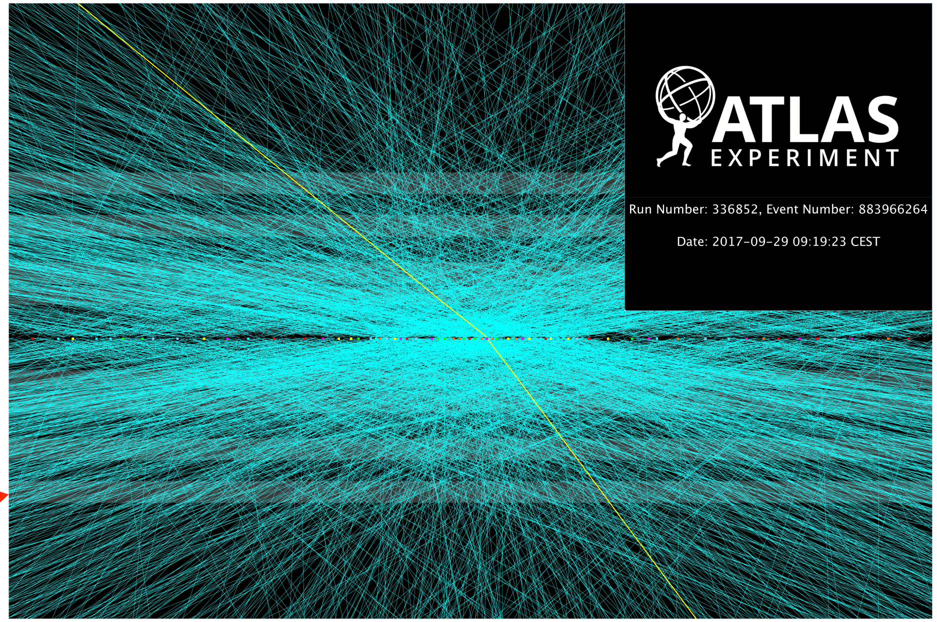


- p-p collider
- Design parameters:
  - $\sqrt{s}$ = 14 TeV, $L_{inst} = 10^{34}$ cm^{-2} s^{-1}
- Can also collide heavy ion particles
  - Pb, Xe

Run 2



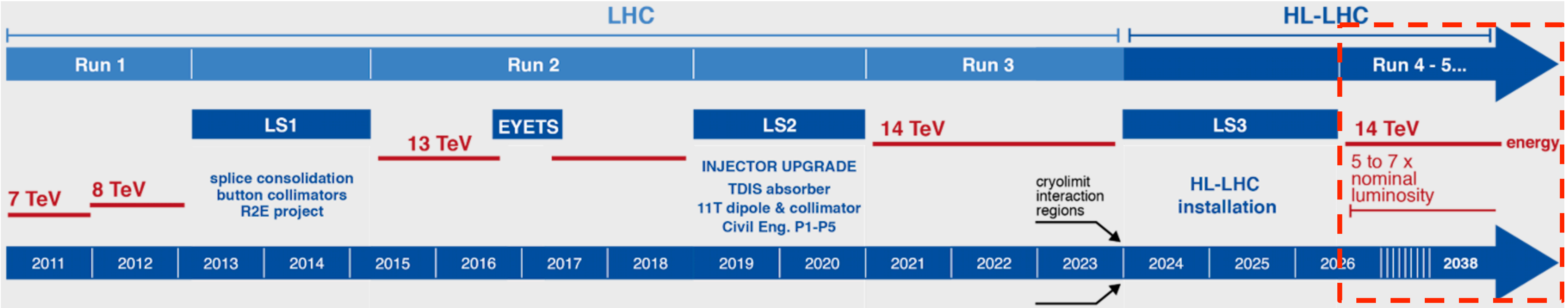


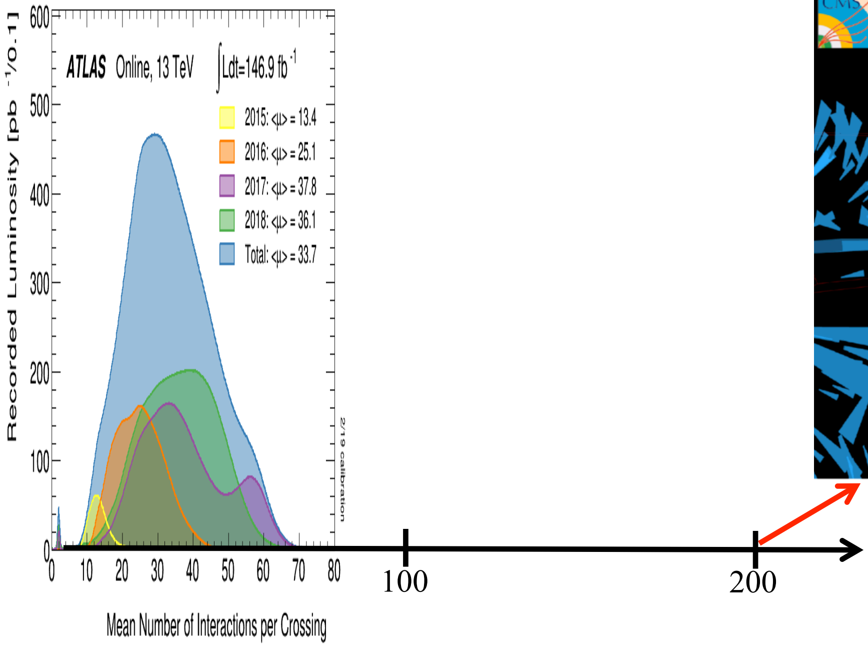


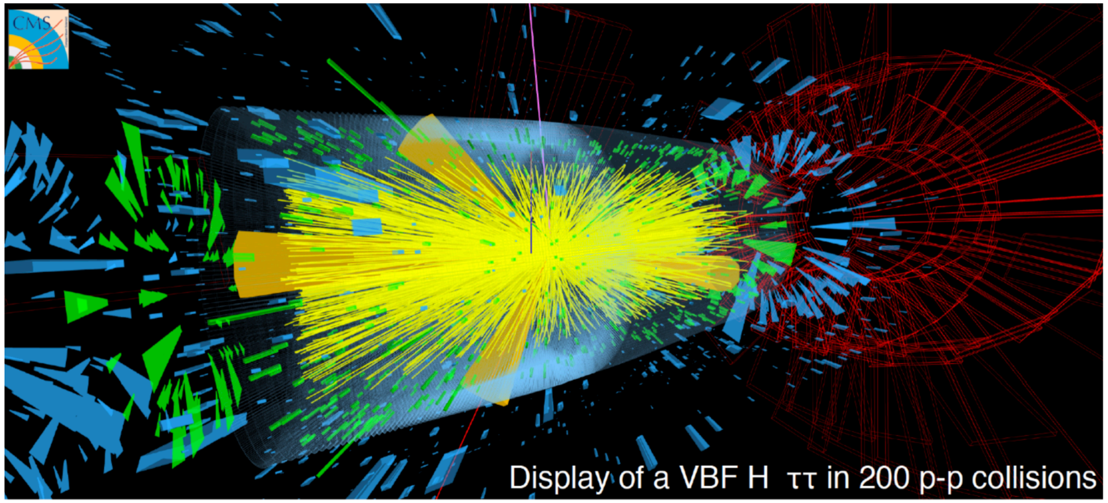
- $\sqrt{s}$=13 TeV
- $\int L$~140 fb^{-1} (good for physics)
- L_{max} ~ $2\times10^{34} cm^{-2}s^{-1}$
- Ave. #of interactions per crossing ~34

- $Z\rightarrow\mu\mu$ candidate event
- #of interacting per crossing = 65

HL-LHC





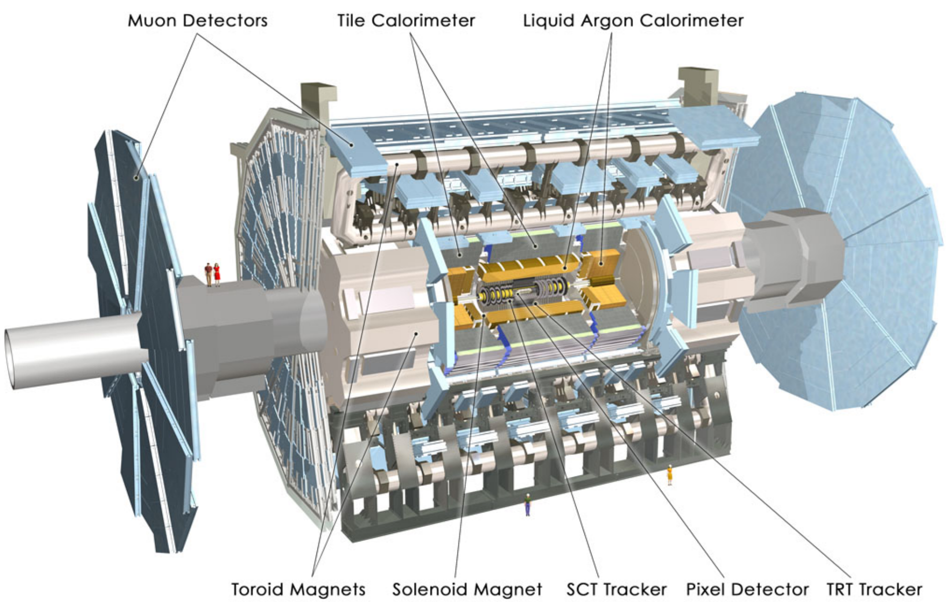


- $\sqrt{s}$=14 TeV
- $\int L \sim 3000\ \text{fb}^{-1}$
- $L \sim$ 5-7$\times 10^{34}\text{cm}^{-2}\text{s}^{-1}$
- Ave. #of interactions per crossing ~200

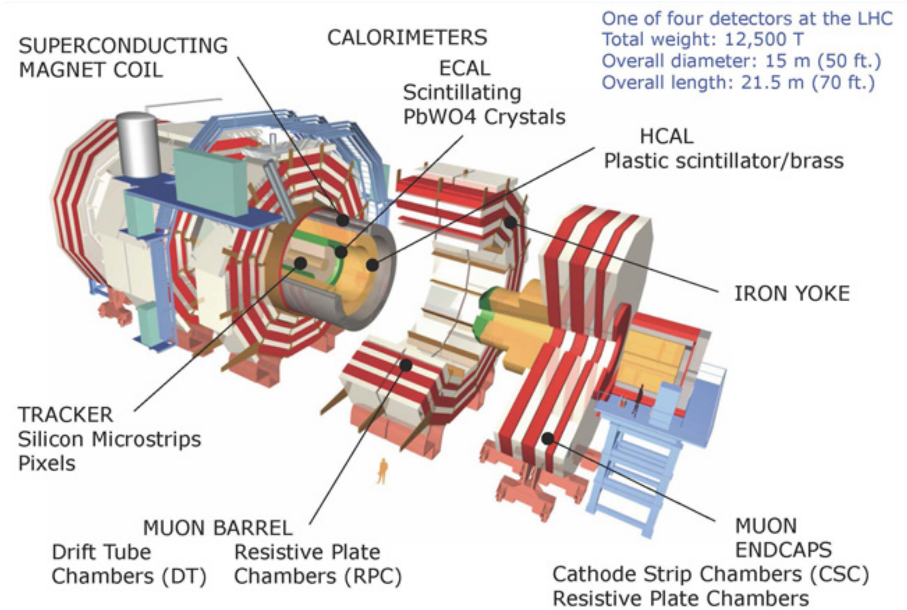
- A lot of data for
  - QCD and EWK precision measurements
  - Deep understanding of Higgs properties
  - Probe BSM in both direct searches and in precision measurements

Detectors

ATLAS



CMS



- Large sophisticated general purpose particle detectors.

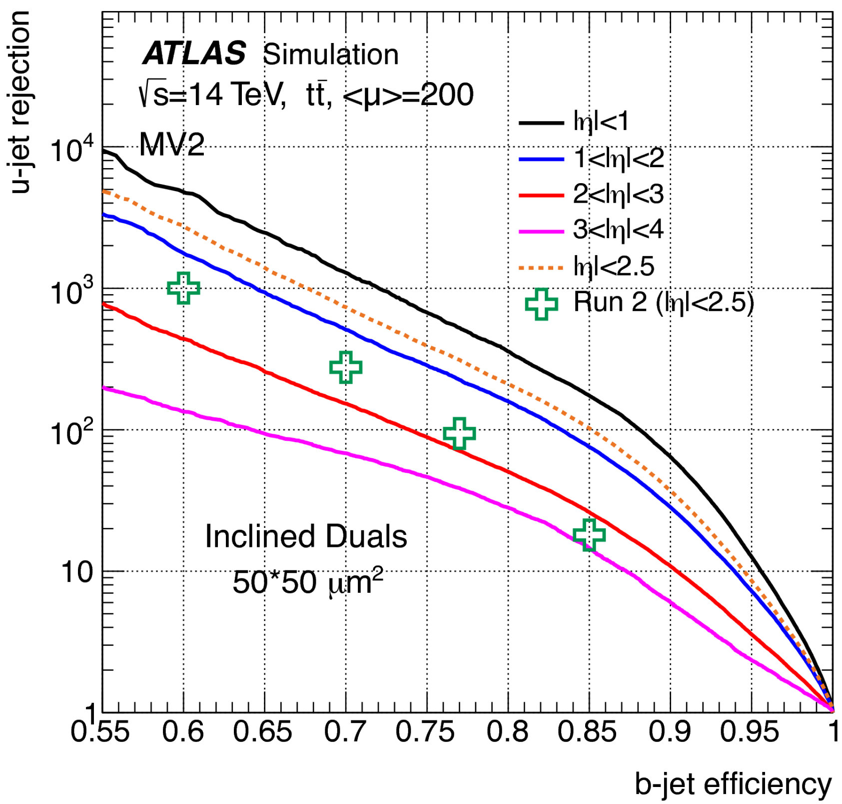
Upgrade for HL-LHC	ATLAS	CMS
DAQ & Trigger	L1, HLT~10 kHz	L1, HLT~7.5 kHz
Inner Tracker	New, up to |η|<4	
Calorimeter	Electronics upgrade for LAr & Tile	New high granularity endcap calorimeter
Muon	Electronics upgrade + new muon chamber	Improve muon system coverage
Timing detector	New High Granularity Timing Detector in endcap	Precise MIP timing layer in barrel & endcap

Detector Performance

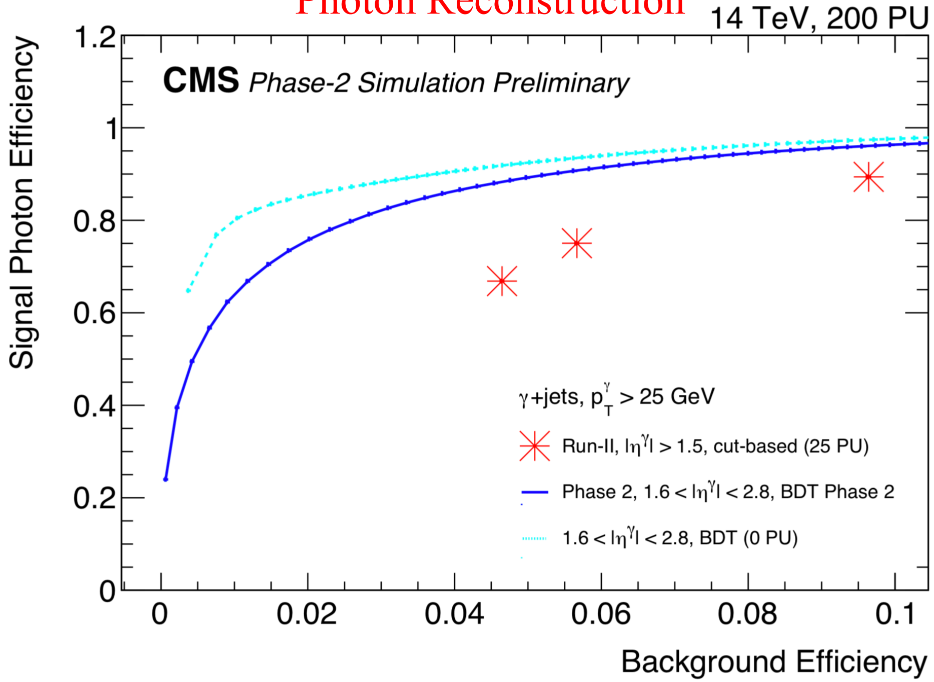
ATL-PHYS-PUB-2019-005

CMS-NOTE-2018-006

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 upgraded detector and HL-LHC condition
  - Existing results are **extrapolated** and take into account of increase in energy and performance of upgraded detector, or **parametric simulations** are used to allow full re-optimization of the analyses

- **Systematic uncertainties :**

- Baseline scenario ("YR18" or "S2") :
  - Theory uncertainties ½ of Run-2
  - No simulation statistical uncertainty
  - luminosity uncertainty ~1%
  - Statistical uncertainty reduced by $1/\sqrt{L}$
  - Uncertainties due to detector limitations remain unchanged or revised according to simulation studies of upgraded detector.

- Conservative scenario ("S1") :
  - Use uncertainties of Run-2 measurements, assuming the higher pile-up effects will be compensated by detector upgrades.

ATL-PHYS-PUB-2018-054
CMS-PAS-FTR-18-011

Broad Range of Physics Topics

Standard Model precision measurements

Higgs

Search for Beyond Standard Model

Heavy Flavor Physics

Heavy Ion Physics

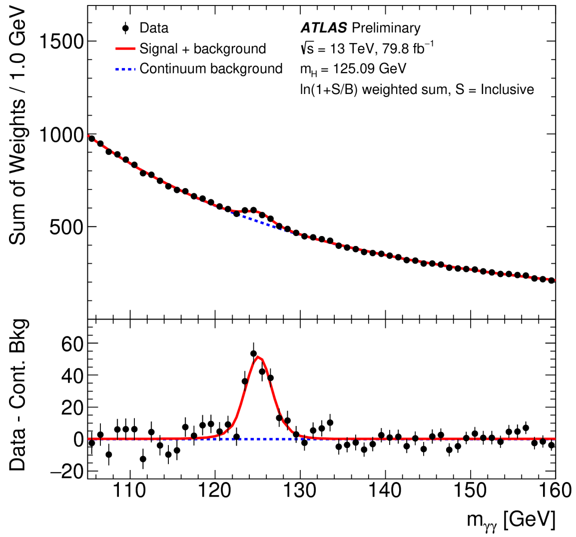
- Can only present short summary of recent results on a few topics and show their potentials at HL-LHC
  - Higgs
  - Exotics searches
  - Supersymmetry

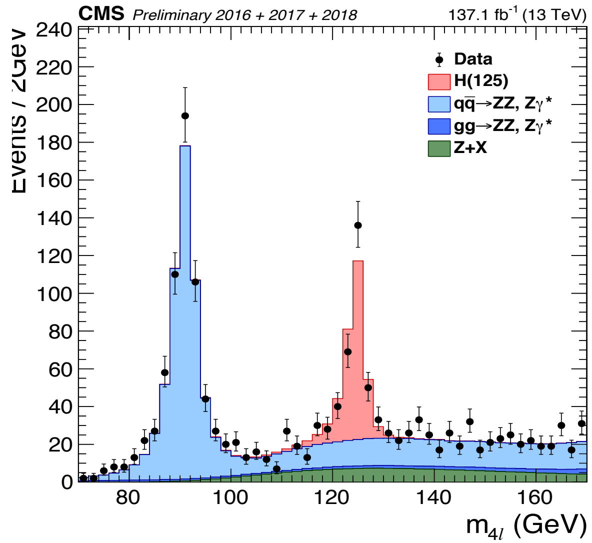
Projections for HL-LHC can be found in the Yellow Report :
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop
(arXiv:1902.00134 , arXiv:1812.07831)

Standard Model Higgs Boson

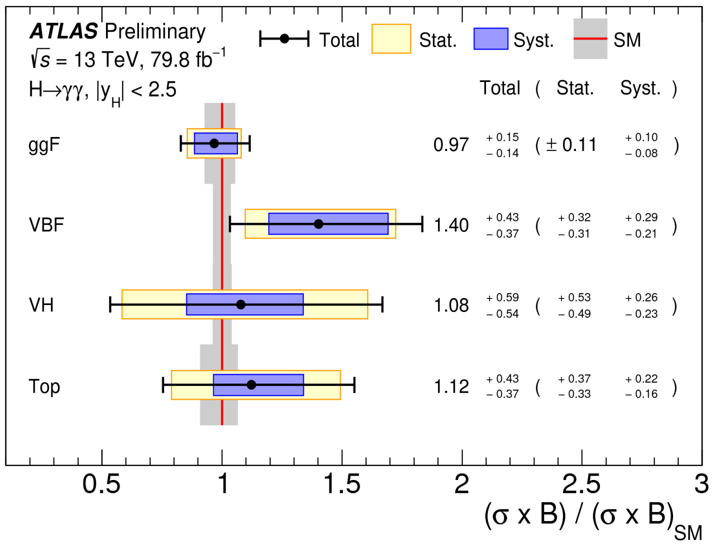
Updates on H→γγ , H→ZZ*→4l

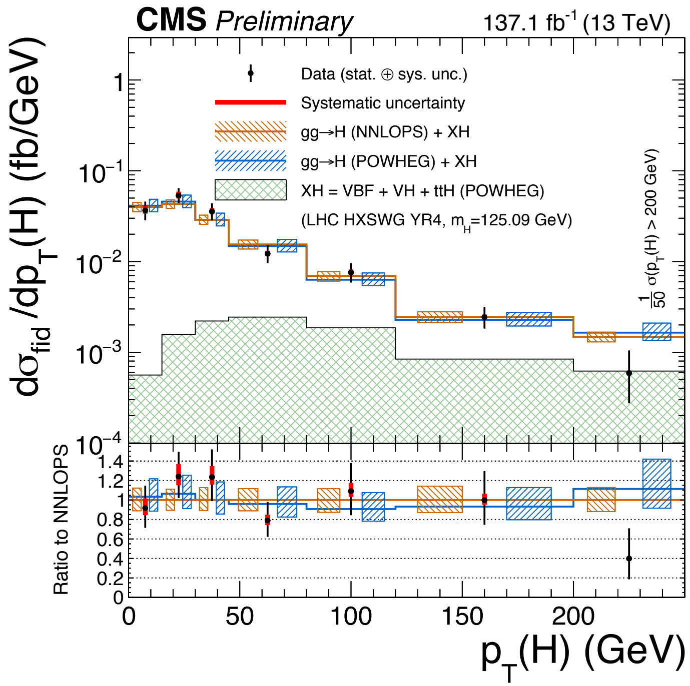
- Analyzed ~80 - 140 fb^{-1} Run-2 data
- Measure cross sections of individual production modes
- Study kinematic properties of Higgs production
  - Differential cross section
  - Production rates in excl. regions (simplified template cross section framework (STXS)).
    - Reduce model dependency
    - Maximize sensitivity to BSM





- Up to ~10-15% precision for best channel





ATLAS-CONF-2018-028

ATLAS-CONF-2018-018

CMS PAS HIG-18-029

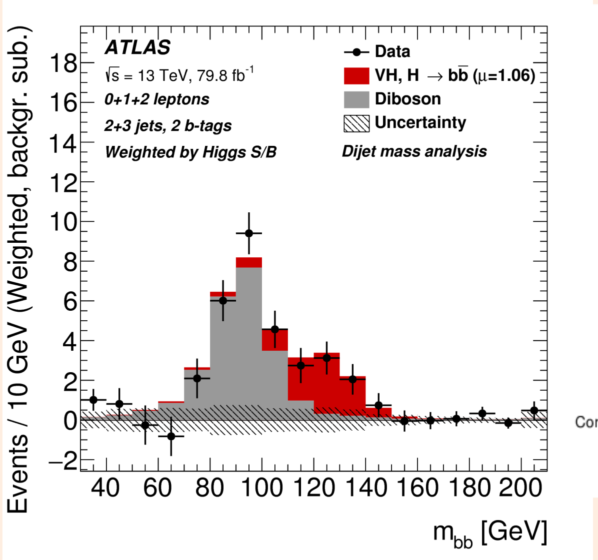
CMS PAS HIG-19-001

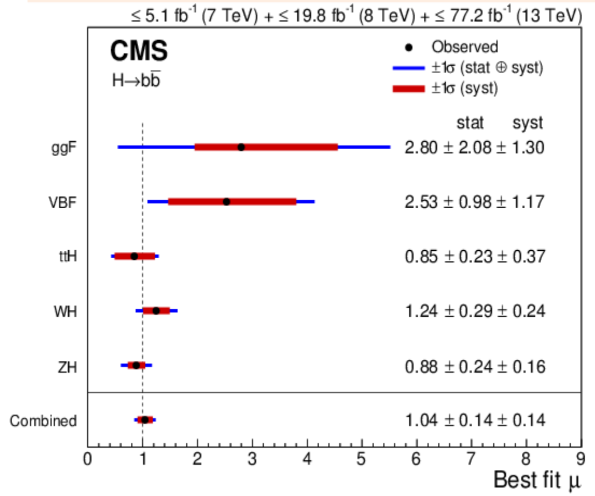
Observation of Higgs Couplings to 3rd Generation Quarks

- **H→bb** finally observed at LHC
- Most sensitive prod. channel : VH
- Include other prod. channel :
  - ggF, VBF, ttH
- Combined Run1 + Run2 (~80fb^{-1})
- Observed H→bb :
  - ATLAS : 5.4σ, CMS : 5.6σ

ATLAS PLB 786 (2018) 59

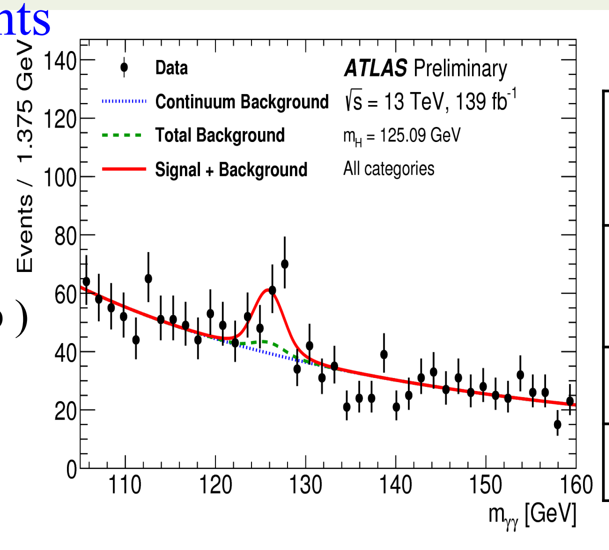
CMS PRL 121 (2018) 121801





Combined μ = 1.04±0.20
(Reach precision of ~20%)

- New updates from both experiments since observing **ttH** production
- ATLAS (full Run2) : in γγ
  - Obs.(exp.) sign=4.9 (4.2) σ
  - $\sigma_{ttH} \times B_{\gamma\gamma} = 1.59^{+0.43}_{-0.39}$ fb (SM: $1.15^{+0.09}_{-0.12}$ fb)
- CMS (2016+2017) :
  - update multi-lepton, γγ, bb
  - Extended categorization, dedicated BDT training, additional observables, new b-tagging



CMS

Decay ch	μ	Obs. sign.
Multi -lep	$0.96^{+0.34}_{-0.31}$	3.2σ
γγ	$1.7^{+0.6}_{-0.5}$	4.1σ
bb	$1.15^{+0.32}_{-0.29}$	3.9σ

ATLAS-CONF-2019-004

CM-PAS-HIG-18-018/019/030

Higgs Combination

- Combined all major production/decay mode measurements (13 TeV, L~36-80 fb^{-1})
- Global signal strength : $\mu_{global} = \frac{\sigma(\exp)}{\sigma(SM)}$

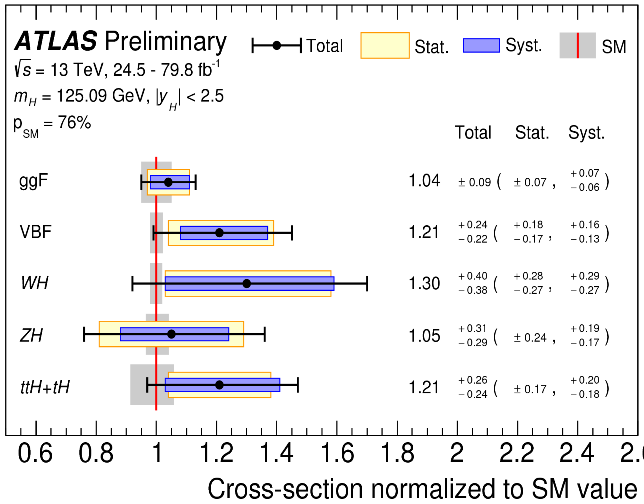
CMS arXiv:1809.10733

ATLAS-CONF-2019-005

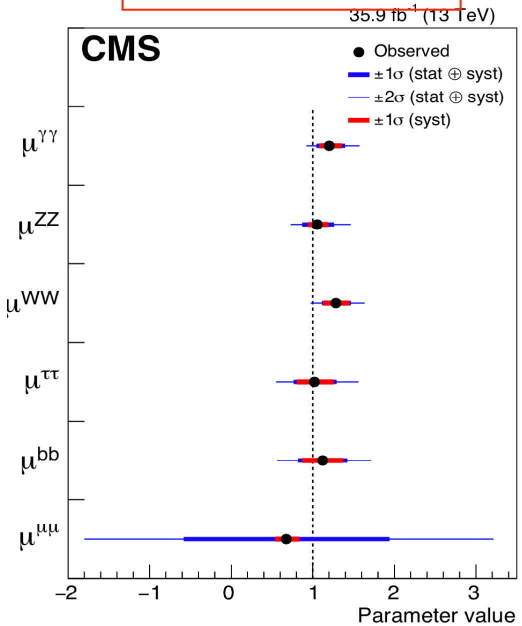
ATLAS : $\mu = 1.11^{+0.09}_{-0.08} = 1.11 \pm 0.05(\text{stat})^{+0.05}_{-0.04}(\exp)^{+0.05}_{-0.04}(\text{sign theo}) \pm 0.03(\text{bkg theo})$

CMS : $\mu = 1.17 \pm 0.10 = 1.17 \pm 0.06(\text{stat})^{+0.06}_{-0.05}(\text{sig theo}) \pm 0.06(\text{other syst})$

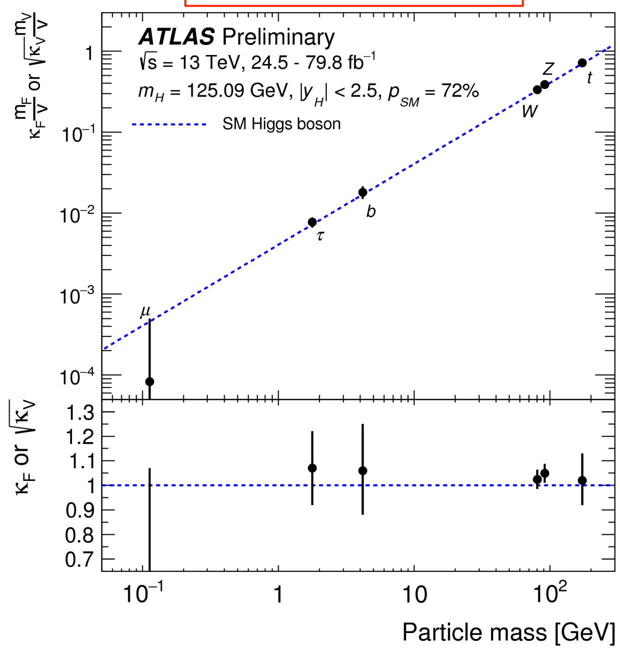
productions



decays



couplings



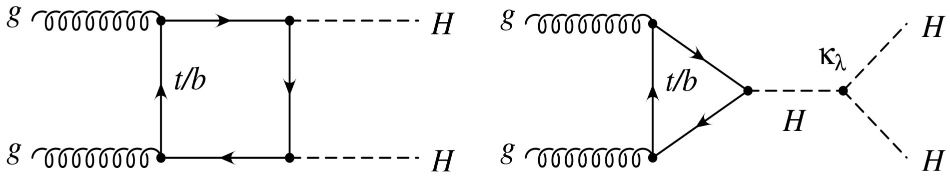
- Productions and decays are already probed with up to ~10-15% precision in best channels
- Extract coupling strength modifiers (in κ framework) as function of particle mass
- Assume no BSM contribution to Higgs decay
- Compatible to SM

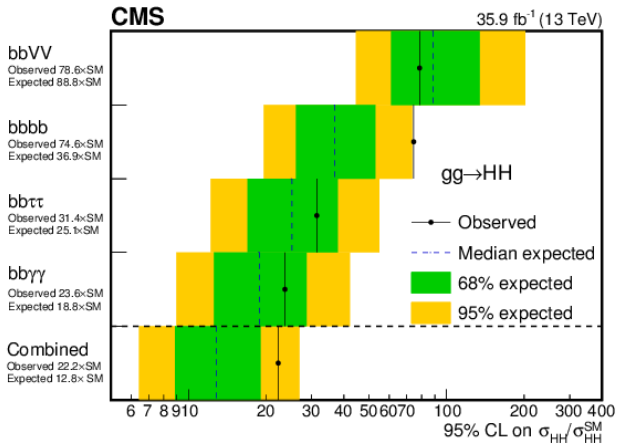
Di-Higgs Production

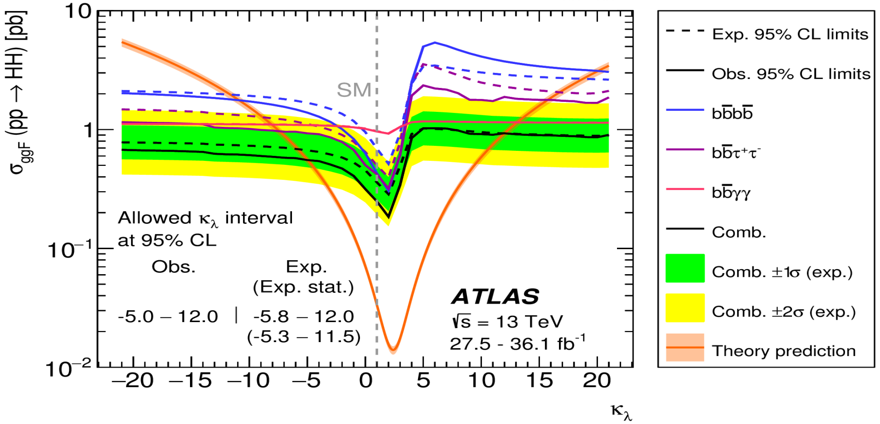
- Observation of di-Higgs production provides a direct measurement of the Higgs boson self-coupling λ_{HHH} and validate the BEH mechanism
- Performed search via ggF production in several di-Higgs decay channels

Most sensitive channels :

- $HH \to bbbb$: highest BR, large BG from multi-jets
- $HH \to bb\gamma\gamma$: clean, but small BR
- $HH \to bb\tau\tau$: moderate BG and BR
- $HH \to bbVV$: V(W,Z) decays leptonically







- Analyzed up to 36 fb^{-1} at 13 TeV
- Set limits on $\sigma(gg \to HH)$ at 95% CL
  - ATLAS : 6.9 (10) × SM
  - CMS : 22.2 (12.8) × SM

- Scanned $\kappa_\lambda = \dfrac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$ (Higgs self-coupling modifier)

- $\kappa_\lambda^{SM} = 1$
- Constraint κ_λ at 95% CL
  - ATLAS : $-5.0 < \kappa_\lambda < 12.0$ (exp. $-5.8 < \kappa_\lambda < 12.0$)
  - CMS : $-11.8 < \kappa_\lambda < 18.8$ (exp. $-7.1 < \kappa_\lambda < 13.6$)

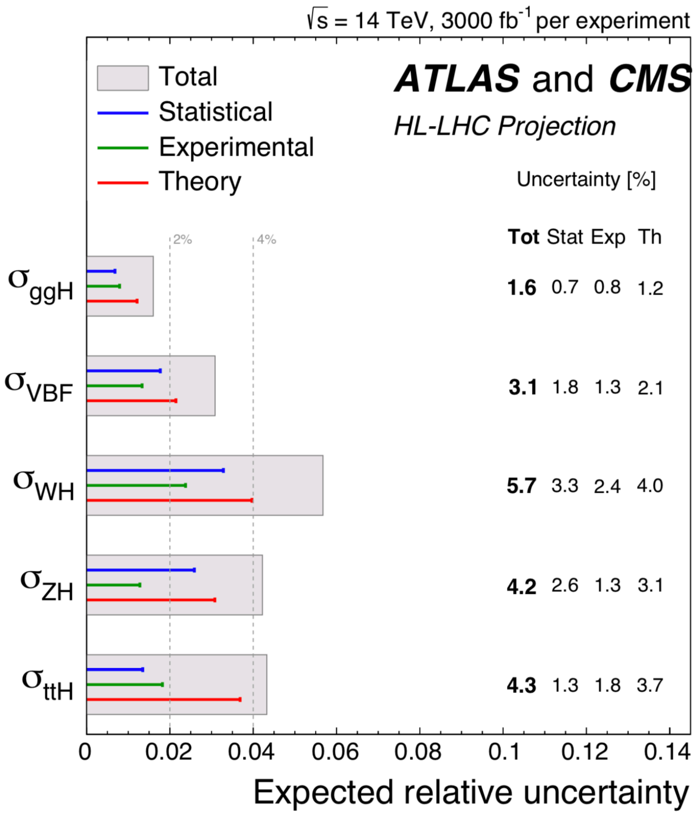
ATLAS arXiv:1906.02025 **CMS PRL 122 (2019) 121803**

Projection of Higgs Measurements at the HL-LHC

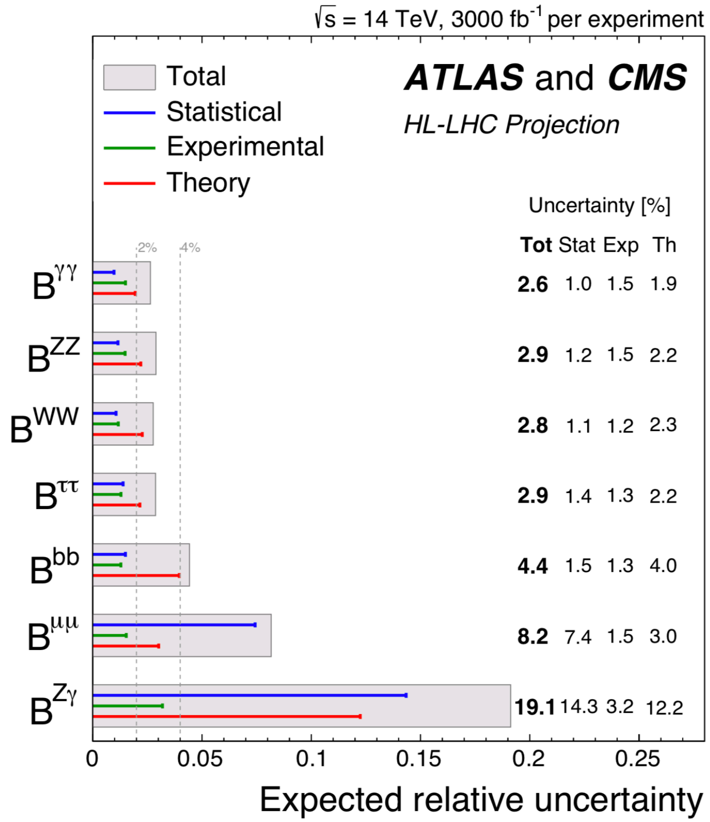
Projections for Production and Decay Measurements

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

productions (ATLAS+CMS)



decays (ATLAS+CMS)



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

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

arXiv:1902.00134

- In several cases the uncertainties will be dominated by theory

Projection for Higgs Mass Measurement

- Current PDG average (ATLAS+CMS) $m_H = 125.10 \pm 0.14$ GeV (from γγ, 4l(ZZ^*))
- γγ is now systematically limited
- 4l is statistically limited
  - Mass value will be driven by 4l (muon) channel

LHC Run1 : PRL 114 (2015) 191803
CMS (Run2, 36 fb^{-1}, 4l) : JHEP 11 (2017) 047
ATLAS (Run2, 36 fb^{-1}, γγ, 4l) : PLB 784 (2018) 345

- Extrapolate ATLAS Run2 4μ results to 3000 fb^{-1} in four scenarios
  - Total uncertainty vary between 33 to 52 MeV

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

- Expect better resolution from CMS due to stronger magnetic field
  - ➔ expect uncertainty < 20 MeV when combining CMS and ATLAS

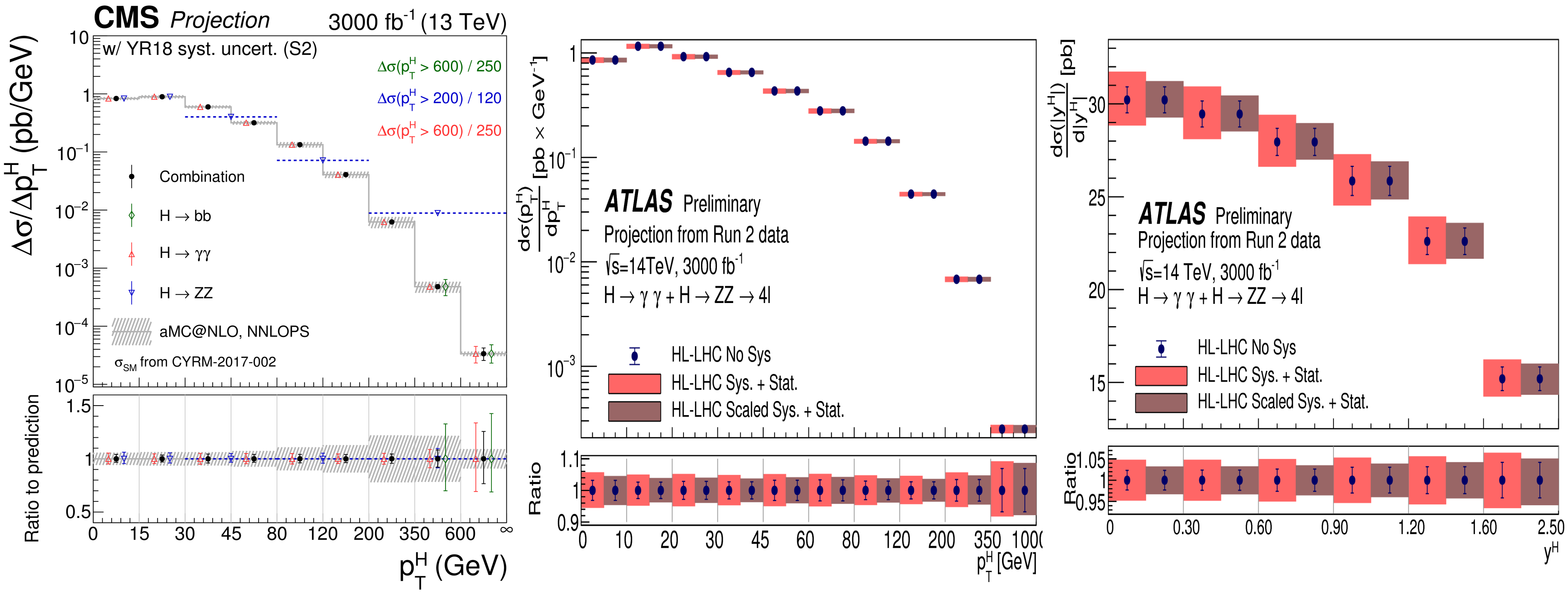
arXiv:1902.00134	ATL-PHYS-PUB-2018-054

Projections for Differential Distributions 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 $H \to \gamma\gamma$, $H \to ZZ^* \to 4l$ channels

ATL-PHYS-PUB-2018-040

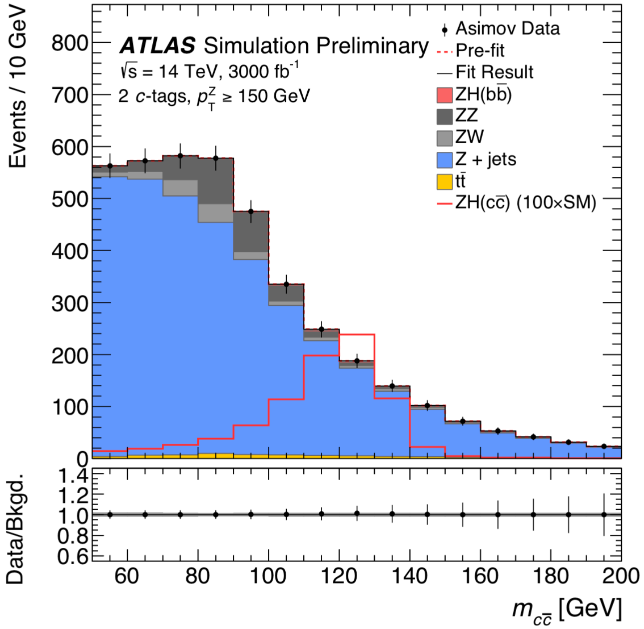
CMS-PAS-FTR-18-011



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

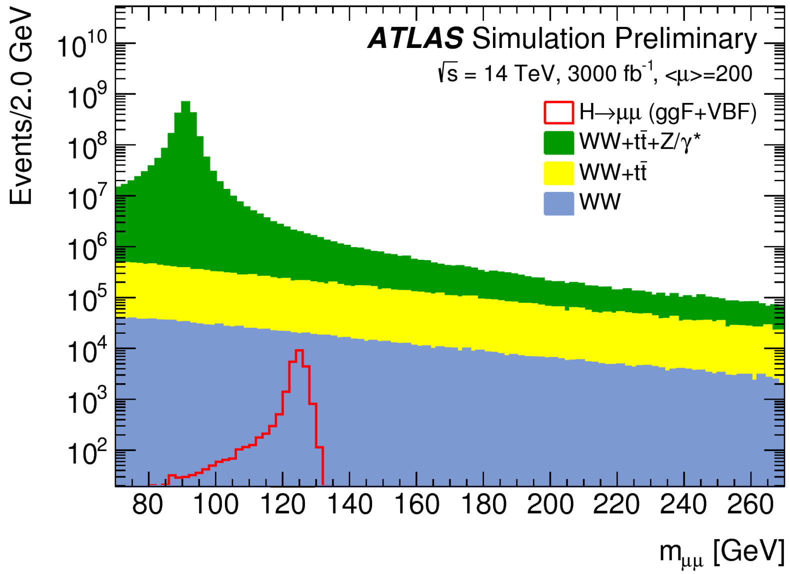
Projections for Rare Higgs Decays

- **H→cc**



- Extrapolate from Run2 36 fb^{-1} search in pp→ZH→llcc
- Expect to set an upper limit on σ×BR at 95% CL of 6.3×SM
    - Current limit : 110×SM
- Sensitivity can further improve by including other channels :
    - WH→lνcc
    - ZH→ννcc

- **H→μμ**



- Expect to observe such decay via ggH and VBF productions with significance >9σ and uncertainty on σ×BR < 13%
- Current limit : σ×BR <2.1-2.9×SM

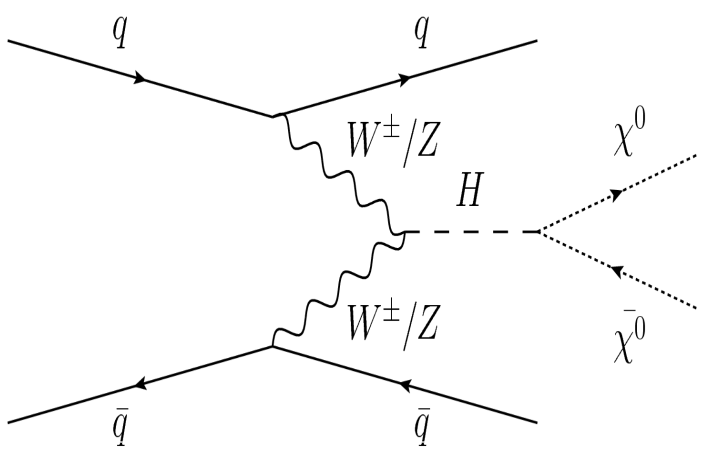
ATL-PHYS-PUB-2018-016

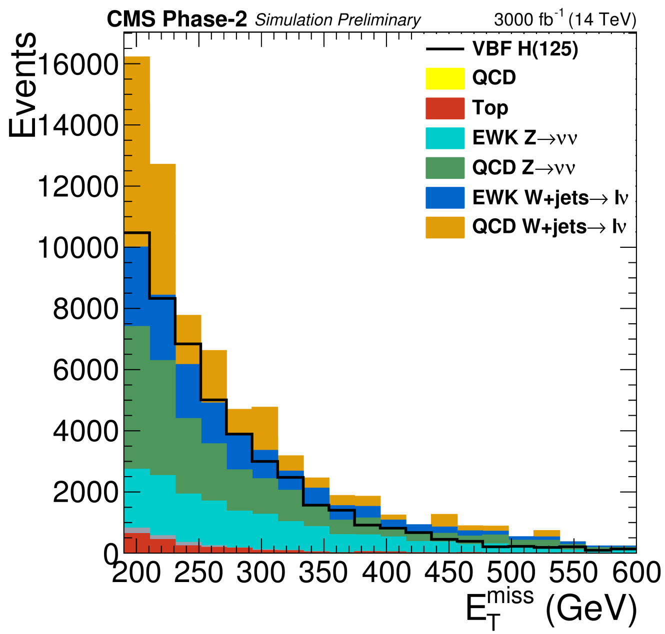
ATL-PHYS-PUB-2018-006

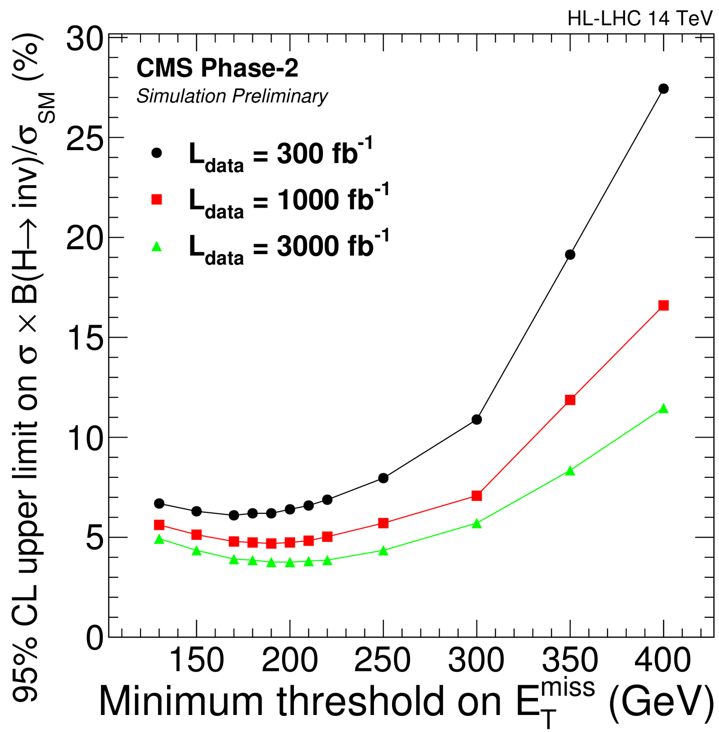
Projections for Higgs to Invisible Decays

CMS-FTR-18-016

- 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)
- Potential is studied with VBF channel
- Pileup suppression will be very important
  - Degrade MET resolution
  - False identification of pileup jets as VBF jets in forward region
- Expected reach of upper limit 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%

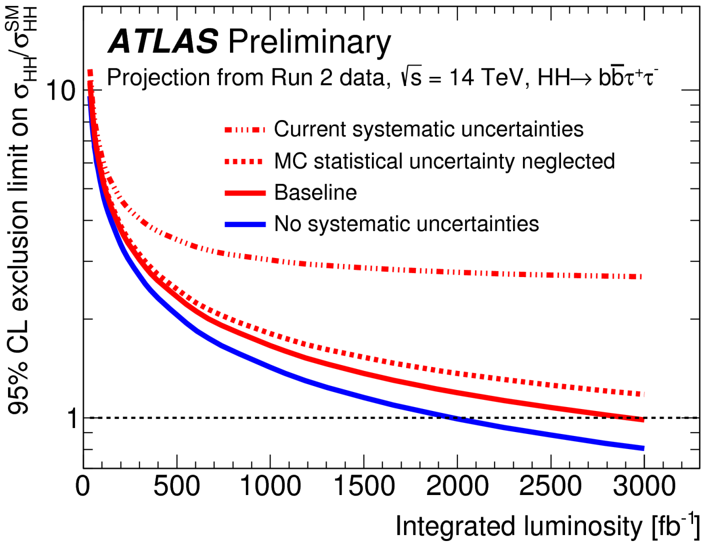


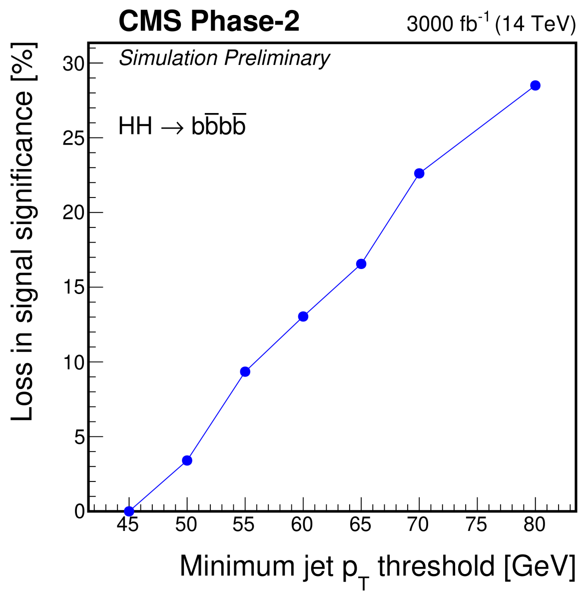




Di-Higgs : Projection for HL-LHC

- 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)

ATLAS

Channel	Significance: Statistical-only	Significance: Statistical + Systematic
$HH \to b\bar{b}b\bar{b}$	1.4	0.61
$HH \to b\bar{b}\tau^+\tau^-$	2.5	2.1
$HH \to b\bar{b}\gamma\gamma$	2.1	2.0
Combined	3.5	3.0

CMS

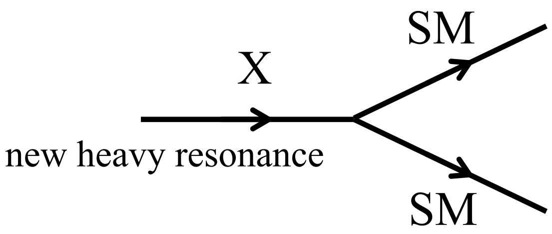
Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma^{SM}_{HH}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
$bb\tau\tau$	1.4	1.6	1.4	1.3
$bbWW(\ell\nu\ell\nu)$	0.56	0.59	3.5	3.3
$bb\gamma\gamma$	1.8	1.8	1.1	1.1
$bbZZ(\ell\ell\ell\ell)$	0.37	0.37	6.6	6.5
Combination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

- Combine ATLAS + CMS : 4.0 σ (stat.+syst.)   (4.5 σ (stat. only))
  - Precision of self-coupling modifier κ_λ can reach ~50%
- ***May even reach the discovery level of di-Higgs production at the end of HL-LHC !***

Search for New Physics : Exotics, SUSY

New Heavy Resonances

- Predicted by several beyond Standard Models theories



SM : lepton, quarks, boson

- Leads to final states signature : di-lepton, di-jet, di-boson

- Spin-0:
  - Higgs like particles in Minimal Supersymmetric SM (MSSM)

- Spin-1:
  - New gauge bosons (e.g. W', Z') in extended Gauge Symmetry or in Heavy Vector Triplet (HVT) model

- Spin-2:
  - Graviton as Kaluza-Klein excitation in models of Extra Dimensions

- Excited quarks : in compositeness model

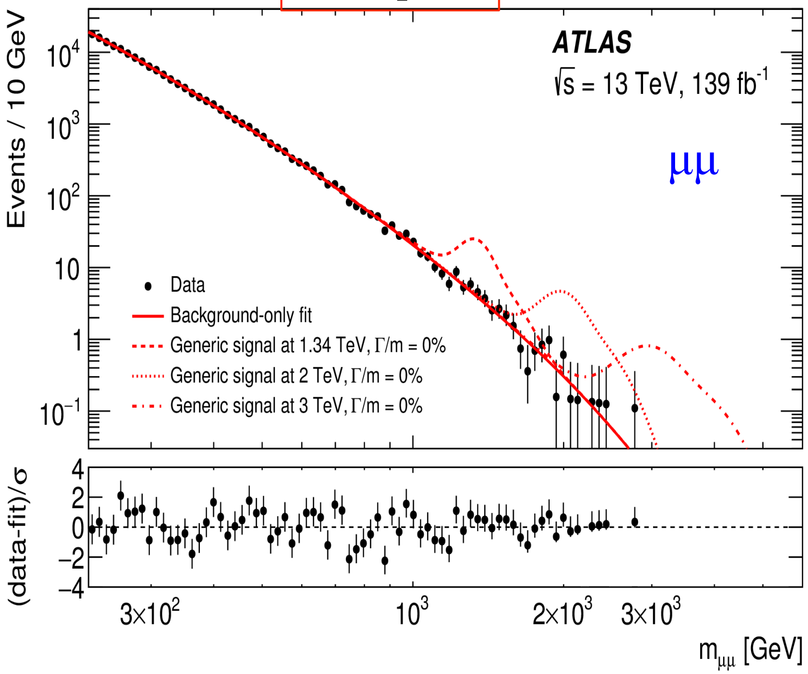
Resonance Search : di-lepton, lepton+E_T^{miss}

- Sensitive to heavy gauge boson from new symmetries
- Searched using full Run2 dataset in ee, μμ or e/μ+E_T^{miss} final states

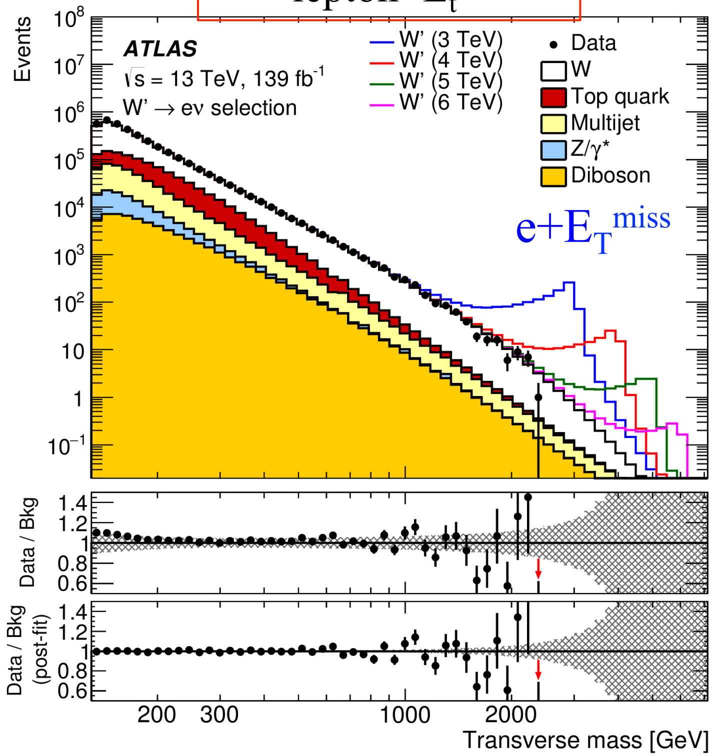
ATLAS arXiv:1903.06248

ATLAS arXiv:1906.05609

di-lepton



lepton+E_t^{miss}



- Search for bumps : no anomaly seen
- Set upper limits (at 95% CL) on heavy resonance mass for various models

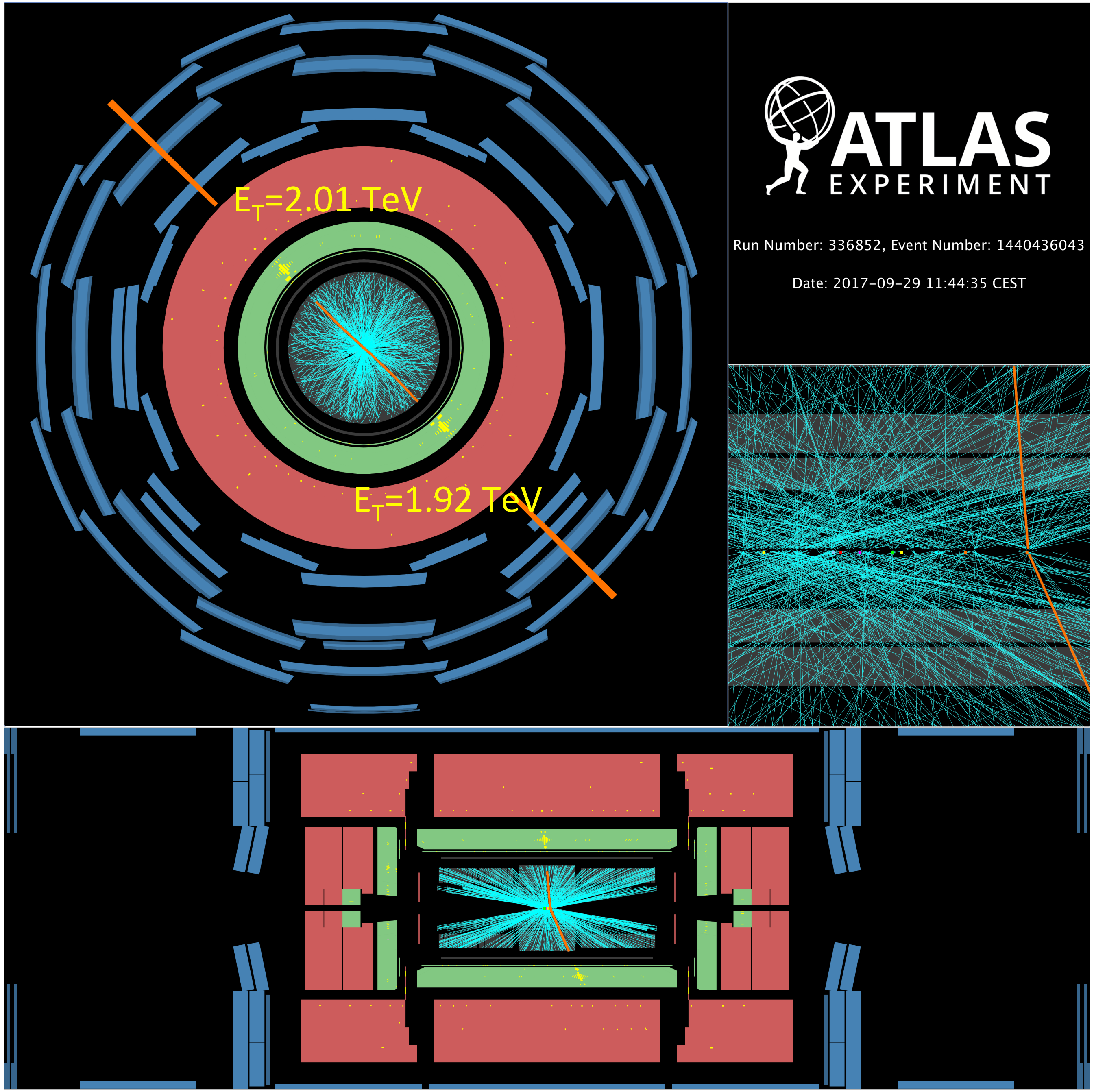
ATLAS (ee/μμ)

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

- Lower limits on SSM W' (→lν)
  - exclude mass below 6 TeV (5.8 TeV exp)

- SSM : Sequential SM , assume same fermion couplings as SM

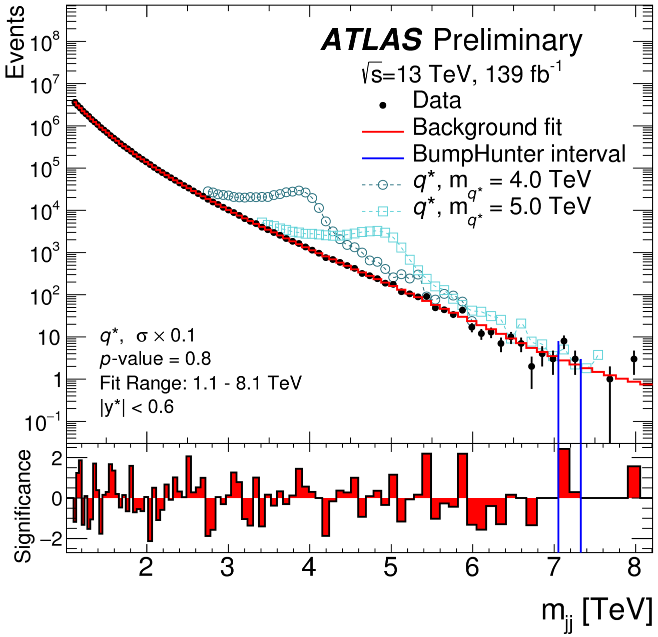
Highest di-electron Mass Event at ATLAS



- m_{ee} = 4.06 TeV

Resonance Search : di-jet, di-boson

di-jet

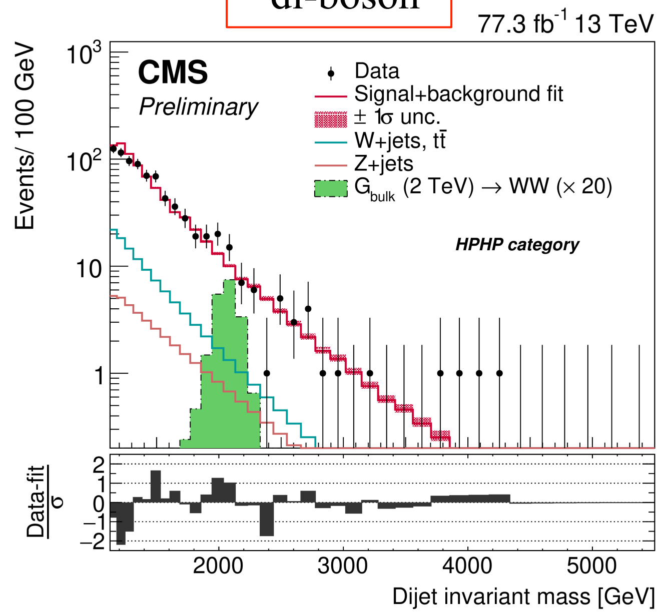


- Set limits on various models in narrow-width approximation

Excited Quark	Obs. (TeV)	Exp. (TeV)
ATLAS (139 fb^{-1})	<6.7	<6.4
CMS (77.8 fb^{-1})	<6.0	<6.0

- Also set upper limits on Gaussian-shaped signals of various widths in di-jet mass distribution

di-boson



- Search for $X \to VV \to qqqq$ (V=W or Z)

2 large-radius jets

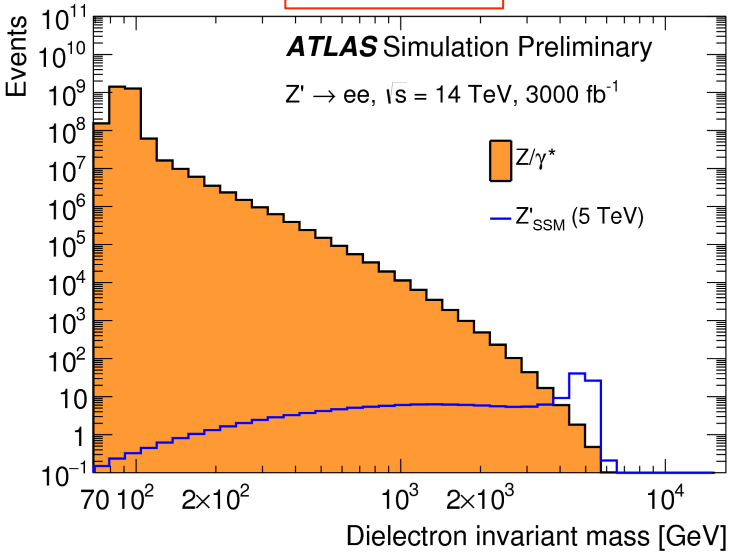
- Use large-radius jet substructure to identify W or Z decays to hadrons
- Constraint extra dimension and heavy bosons models
  - E.g. exclude Heavy Vector Triplet W'/Z' masses below ~3 – 3.8 TeV

ATLAS-CONF-2019-007 CMS PAS EXO-17-026 ATLAS-CONF-2019-003 CMS PAS B2G-18-002

Prospect of Heavy Resonance Search at HL-LHC

Resonance Search : di-lepton, lepton+E_T^{miss}

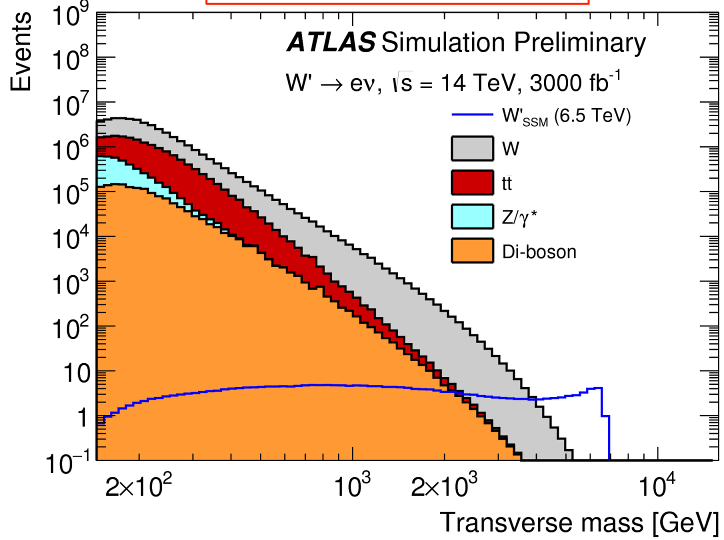
di-lepton



(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]
  - expt. (rec. Id, resolution) : ~2.9%×m_{ll} [TeV]
  - theory (dominated by PDF) : ~5.6%×m_{ll} [TeV]

lepton+E_t^{miss}



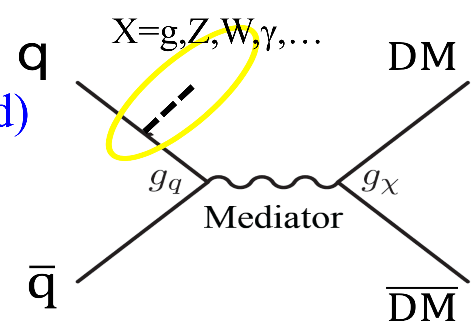
	HL-LHC		Run2
W'_{SSM}	Exclusion [TeV]	Discovery [TeV]	Exclusion [TeV]
ATLAS (eν, μν)	7.9	7.7	5.8 (139 fb^{-1})
CMS ($\tau_h\nu$)	7.0	6.4	4.0 (36 fb^{-1})
ATLAS ($\tau_h\nu$)			3.8 (36 fb^{-1})

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

ATL-PHYS-PUB-2018-044

CMS-FTR-18-030

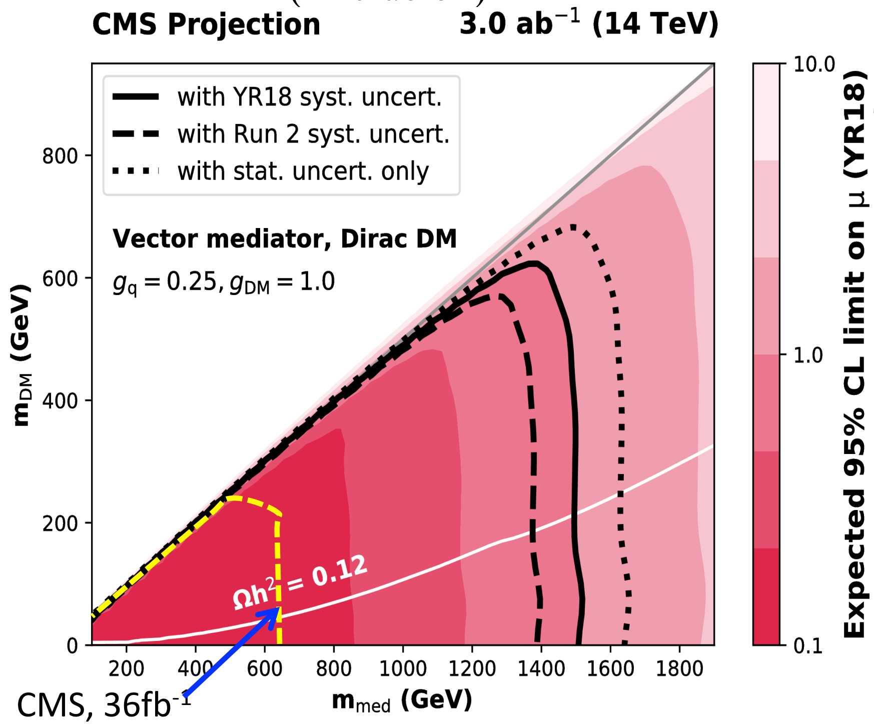
Dark Matter Searches



- 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 particles recoiling against it.
- Signature : Large E_T^{miss} + X

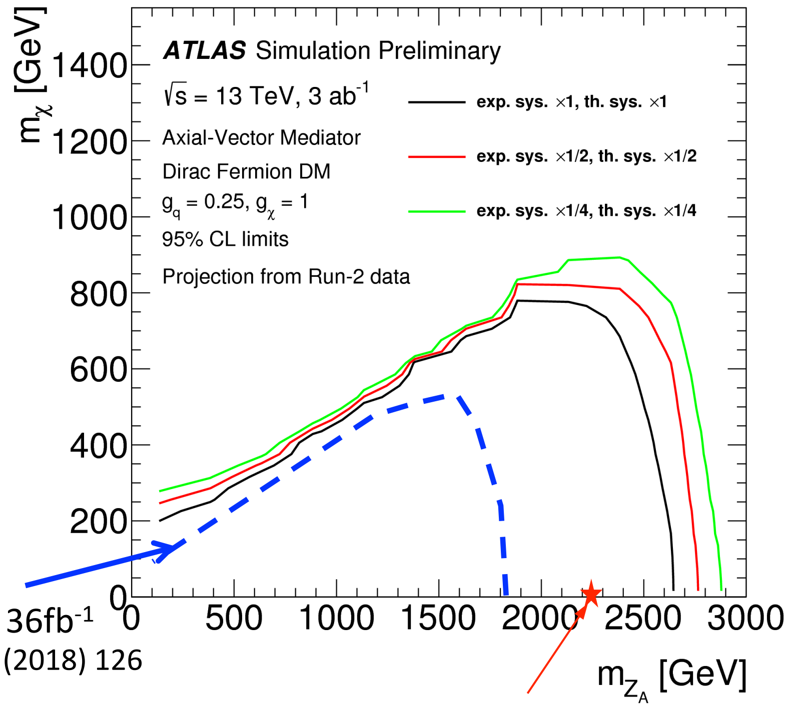
Searches are sensitive to systematic uncertainties

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



CMS, 36fb^{-1}
Eur. Phys. J. C 78 (2018) 291

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



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

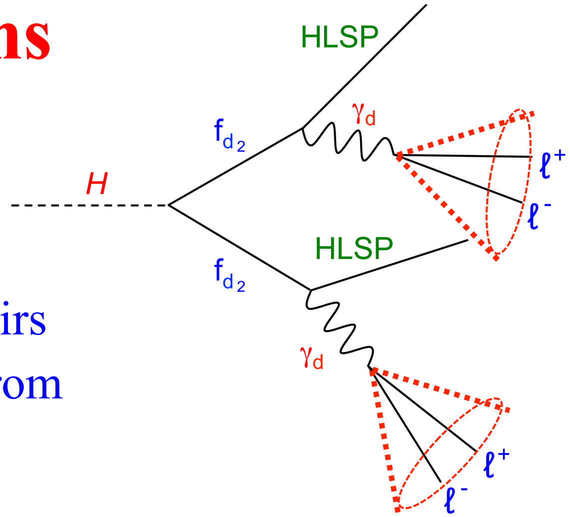
- Discovery could be reached for a signal with DM mass of 1 GeV and mediator mass of 2.25 TeV

Large improvement compared to current LHC results !

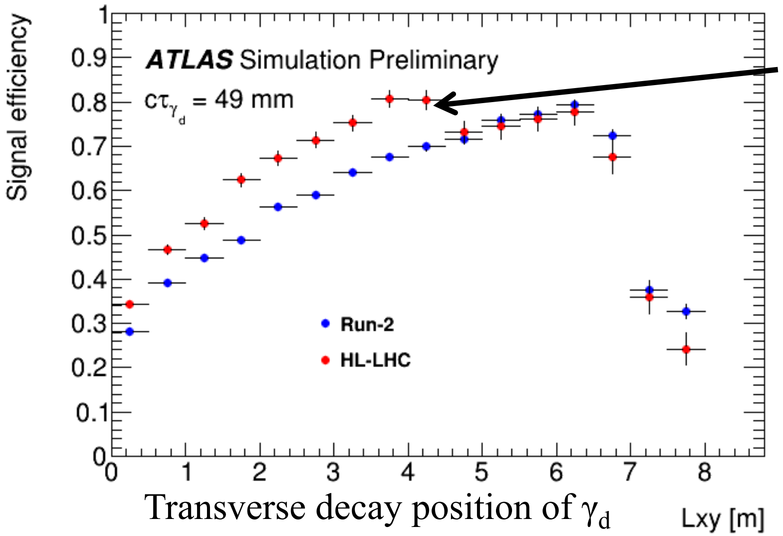
CMS PAS FTR-18-007

ATL-PHYS-PUB-2018-043

Long Lived Dark-Photons



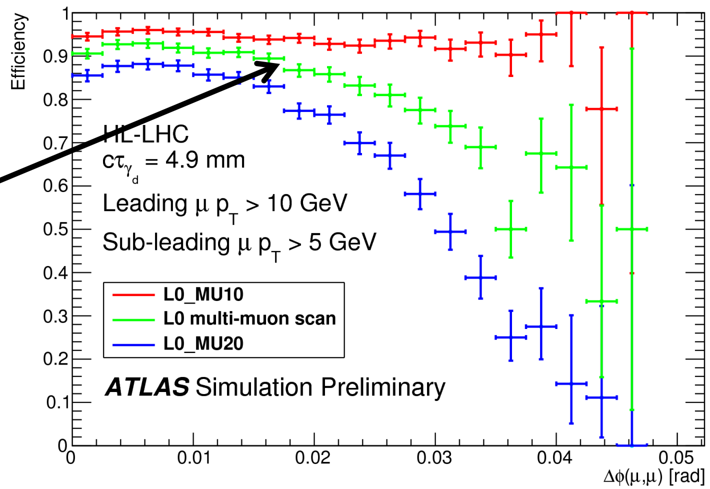
- In some BSM a pair of long lived dark-photons (γ_d) can be produced from Higgs boson decay ($H \rightarrow 2\gamma_d + X$)
- Each dark-photon can decay to a pair of displaced muons
- Dedicated triggers are required to select events with displaced μ pairs
- Specially designed low level triggers and muon detector upgrade from ATLAS at HL-LHC can improve search sensitivity



Additional inner muon RPC layer

Dedicated trigger algorithm to select multi-μ in a single "region of interest"

Overall efficiency improvement ~7%



- Expected cτ range exclusion at 95% CL :

Excluded $c\tau$ [mm] muonic-muonic	Run-2 (3.4 fb^{-1})	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%)

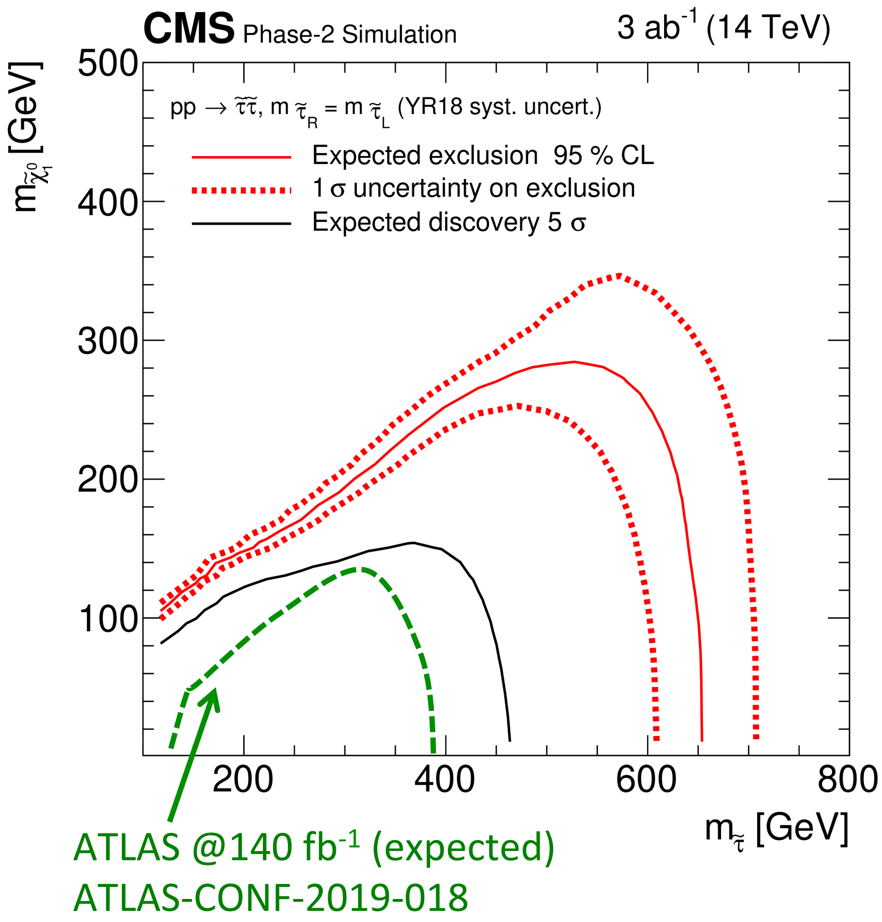
ATL-PHYS-PUB-2019-002

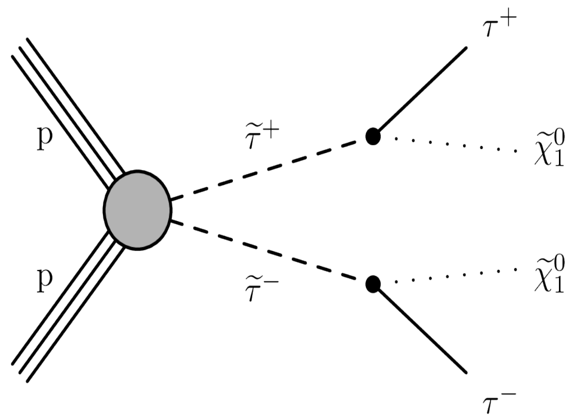
Projection for Stau Search

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
- Assume :
  - Degenerate scenario : $m(\tilde{\tau}_L) = m(\tilde{\tau}_R)$
  - $\tilde{\tau} \rightarrow \tau + \tilde{\chi}_1^0$





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

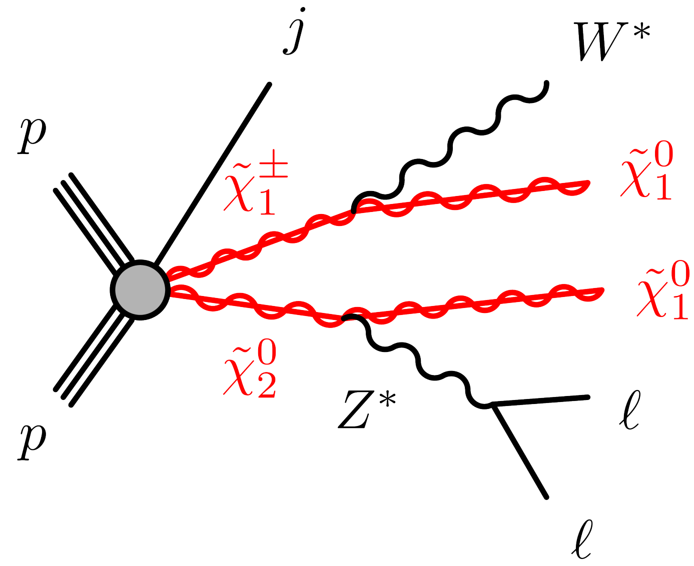
- Can exclude stau up to mass ~650 GeV and discovery reach up to ~450 GeV for massless neutralino.

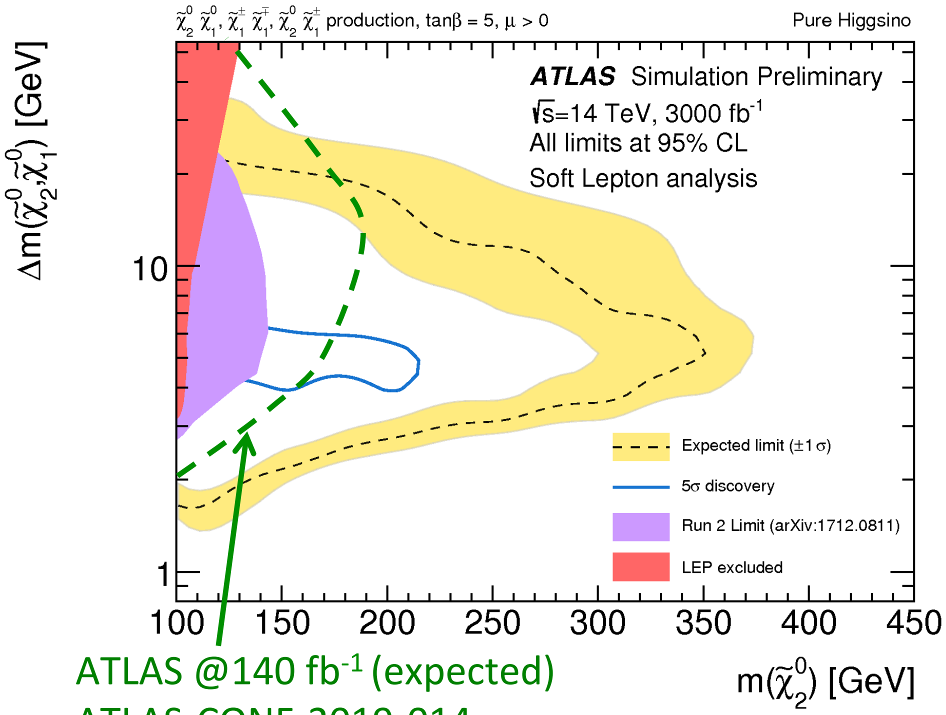
Projection for Higgsino-like Charginos and Neutralinos Search

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

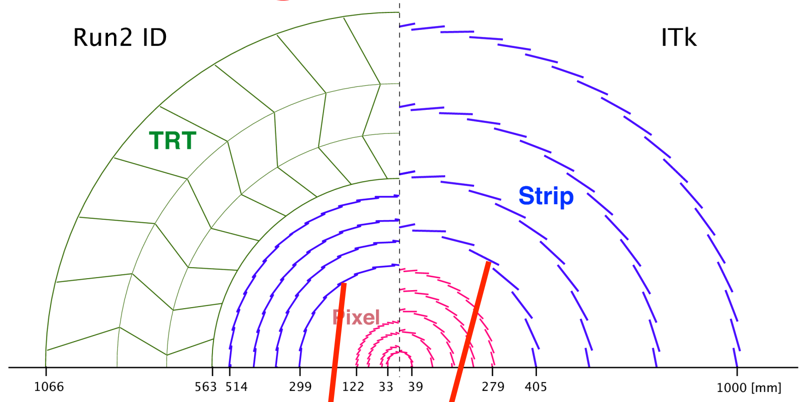
- Can exclude m($\tilde{\chi}_2^0$) up to ~350 GeV
- Large gain in expected sensitivity with respect to latest full Run2 results

Searches with Displaced Vertex Signature

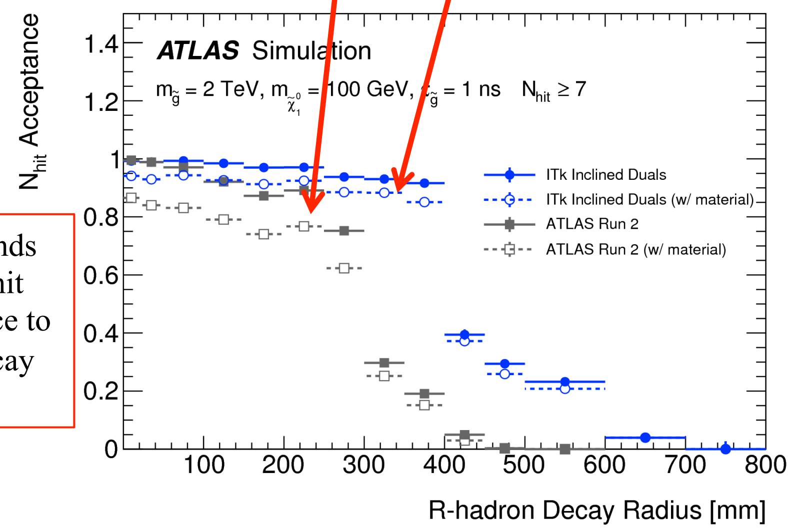
- A long lived particle may decay within the tracking detector and lead to a displaced vertex signature
- Larger silicon tracking volume could detect longer lived particles

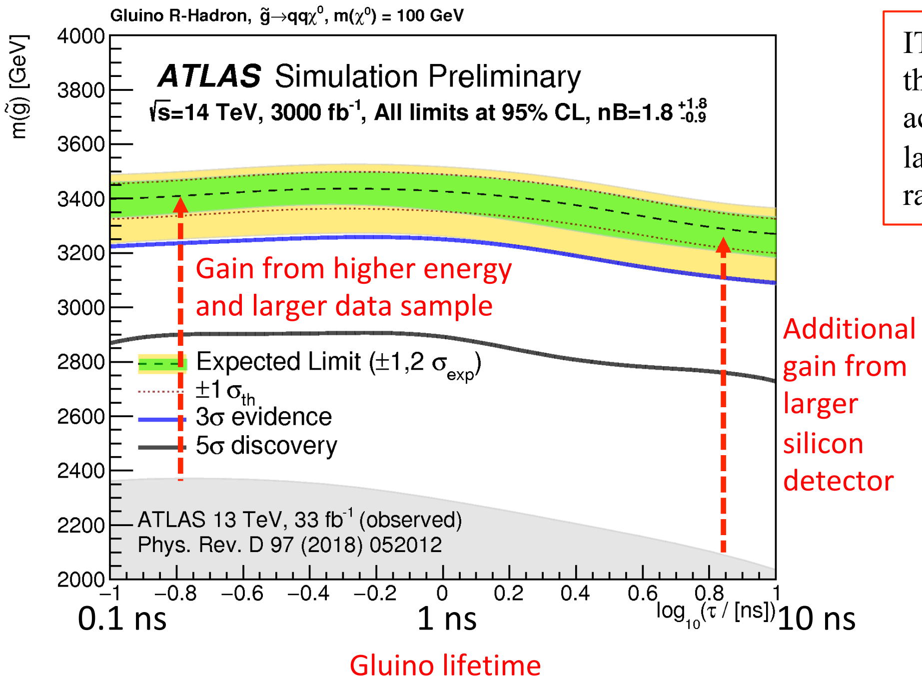
- ITK detector:
  - Larger eta coverage and larger silicon volume
  - Lower material budget

- Well reconstructed vertex require minimum number of silicon hits after decay



ITK extends the high hit acceptance to larger decay radius

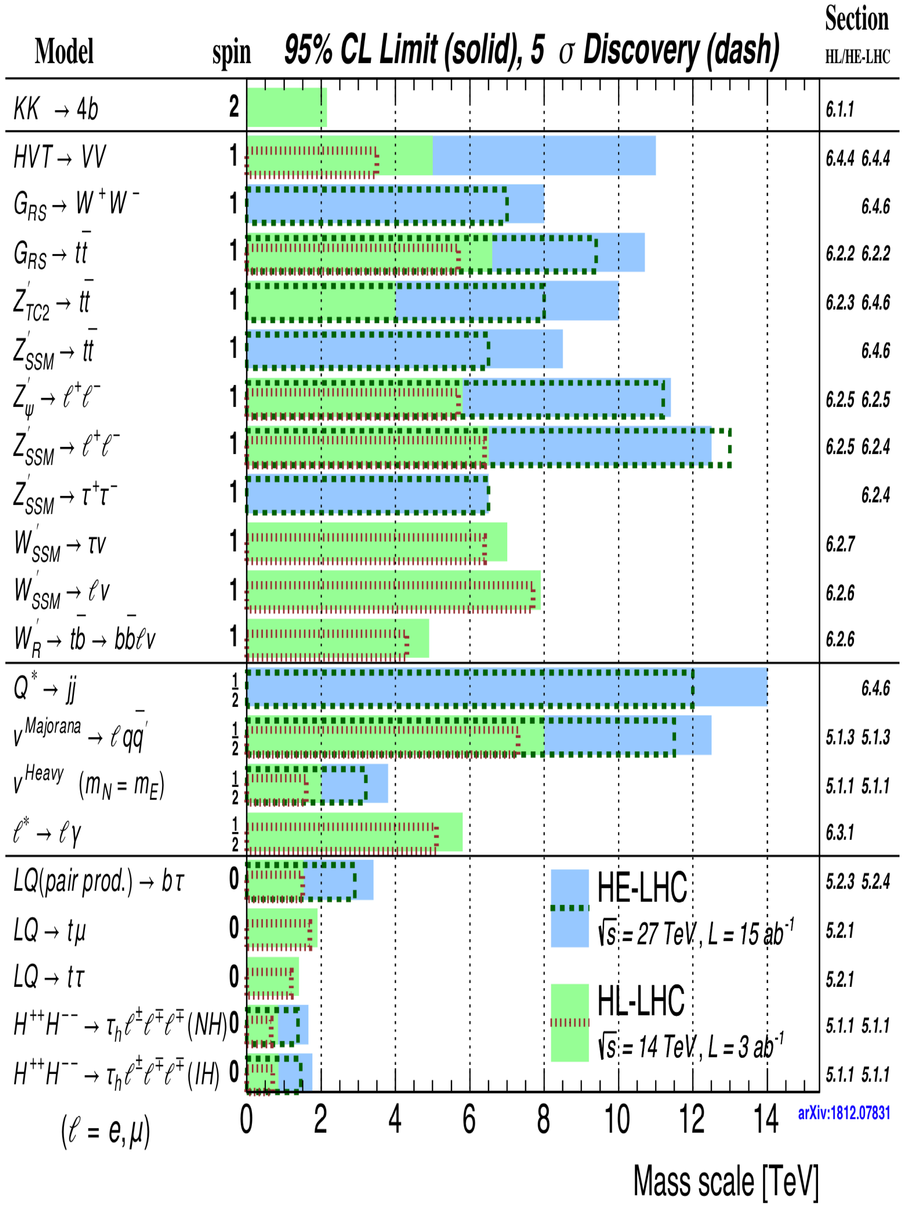


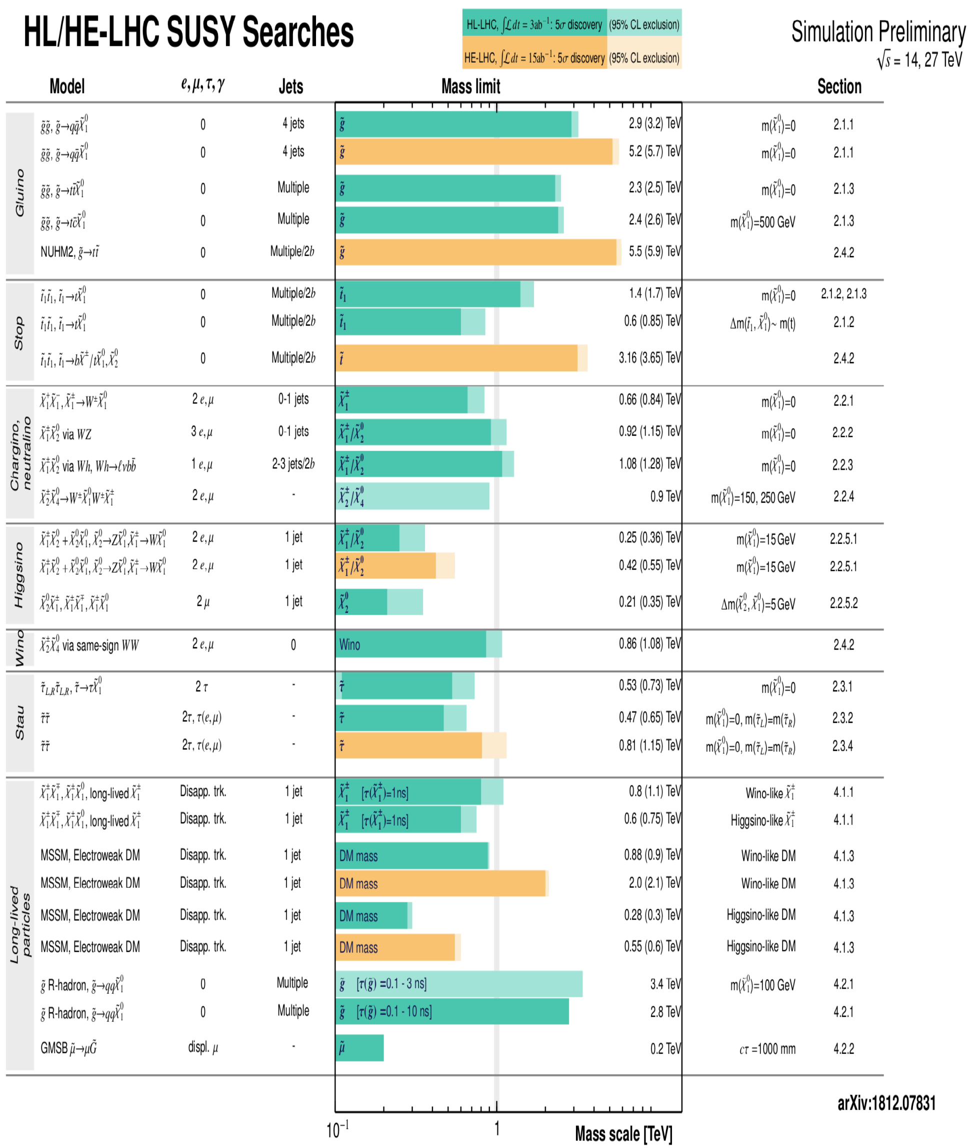


- Use the search for pair production of long lived gluino as an example to study the improvement gain with the new all-silicon tracking detector

ATL-PHYS-PUB-2018-033

Exotics/SUSY Search Reach at HL-LHC





•Many more projection studies on Exotic/SUSY searches can be found at :

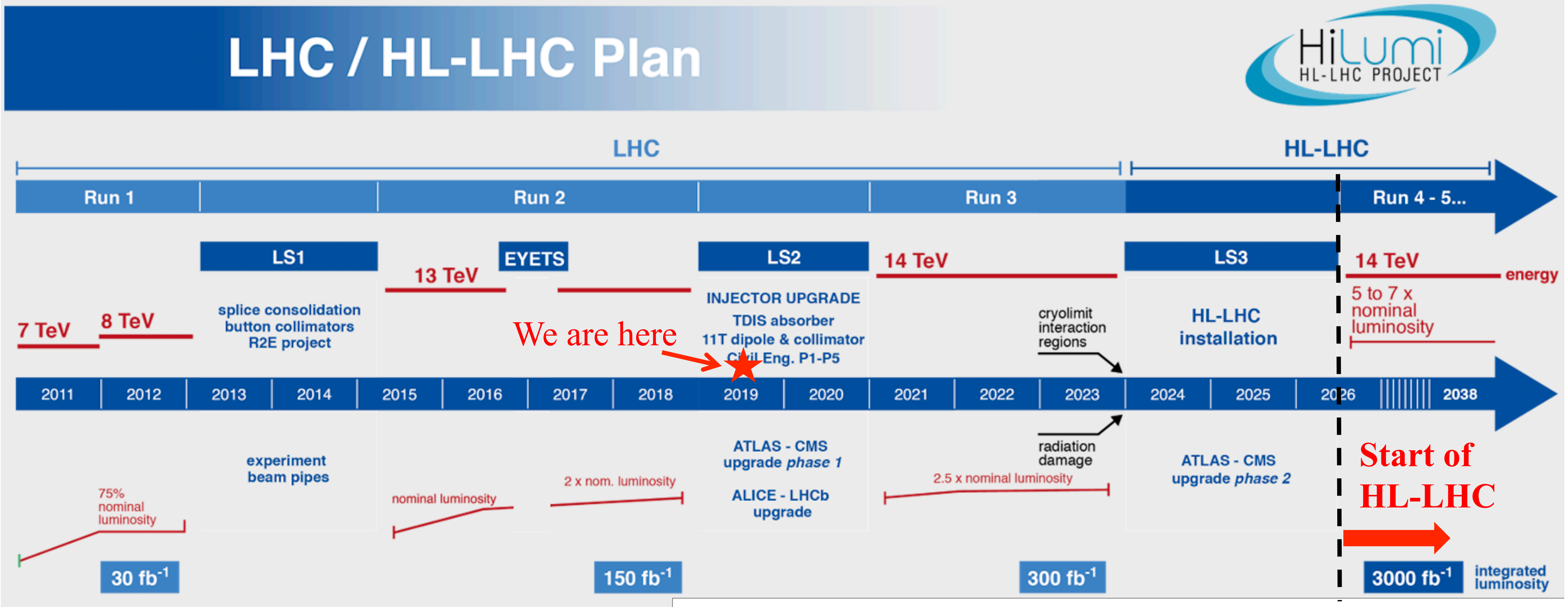
arXiv:1812.07831

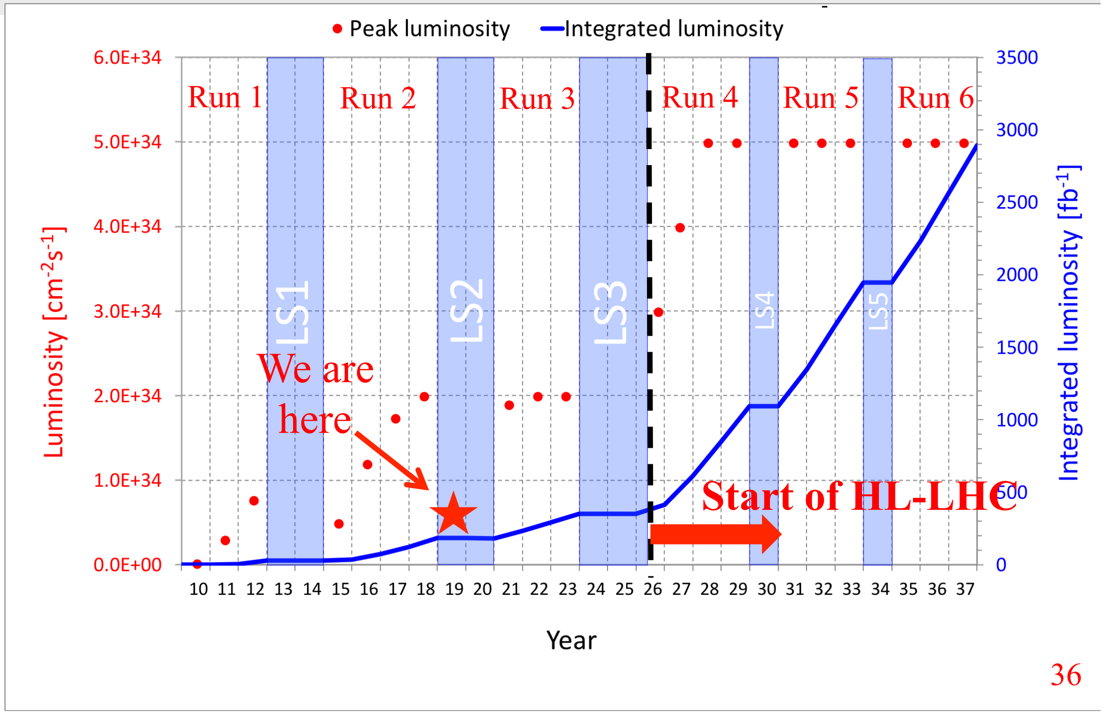
Summary

- 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
- Tremendous work has been performed by the community to determine the physics potential at the HL-LHC
  - Higgs productions and decays can be measured to a precision of a few percent and we may reach the discovery level of di-Higgs production at the end of HL-LHC
  - Large extensions can be made for Beyond SM searches with more data and improve detector performance
- However reduction of systematic uncertainties, improvement of theoretical understanding and innovation of advanced techniques will be important for the success of the HL-LHC program.

ATLAS and CMS public projection studies :
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/FTR/index.html

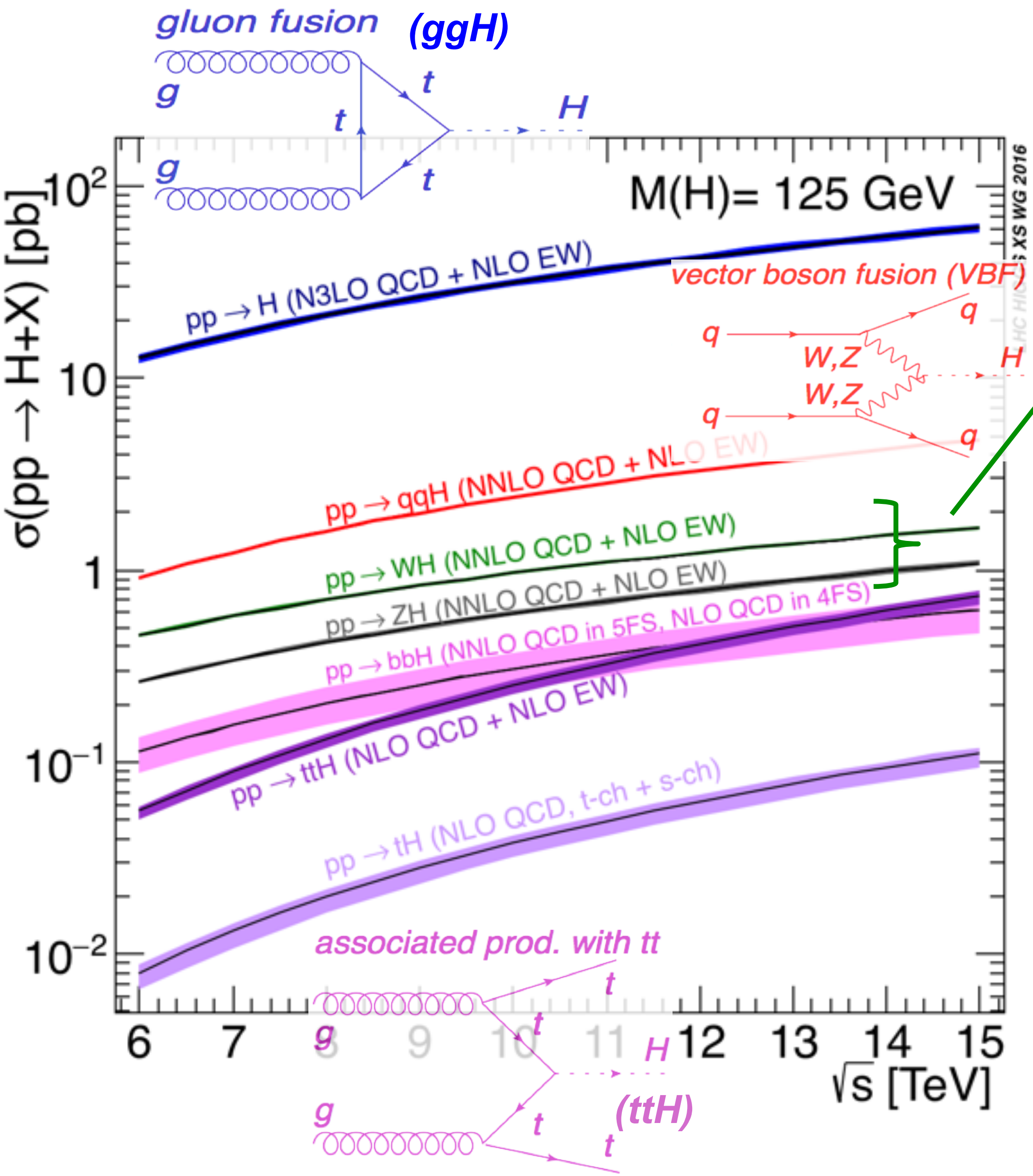
Backup

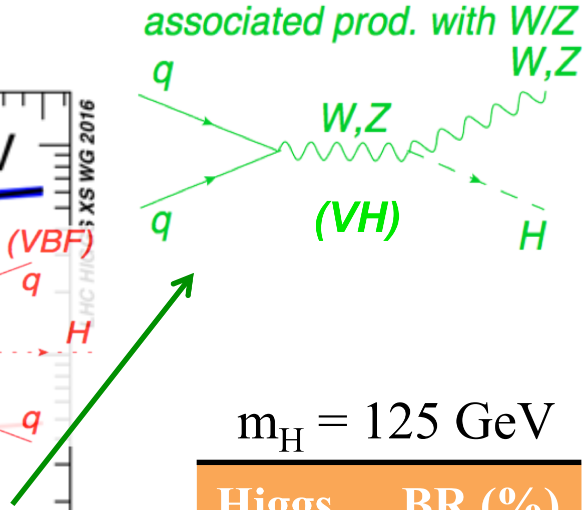




- Have only collected ~5% of the total dataset so far

Production and Decay





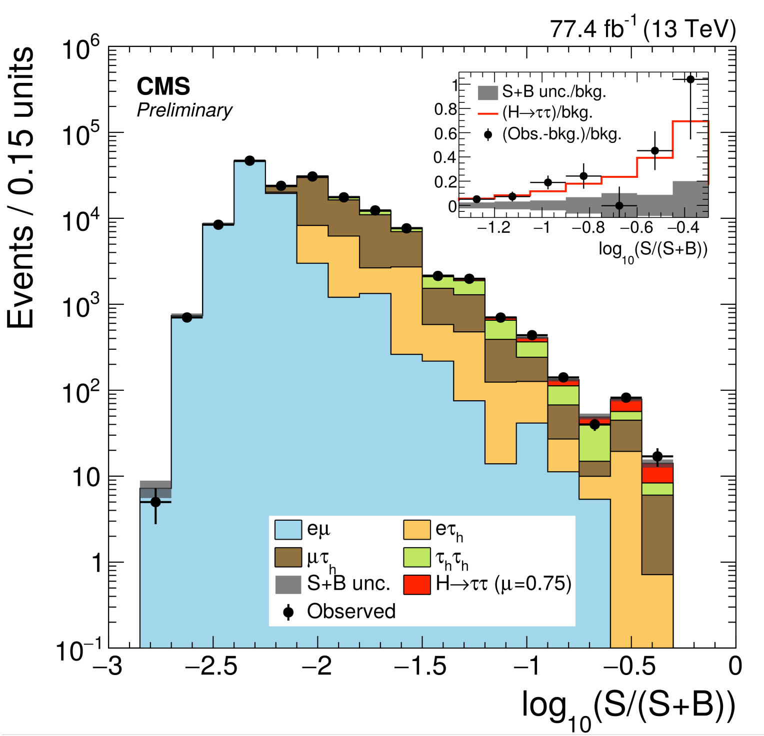
m_H = 125 GeV

Higgs decay	BR (%)	
bb	58	observed
WW	22	observed
ττ	6.3	observed
cc	2.9	limits
ZZ	2.8	observed
γγ	0.23	observed
Zγ	0.15	limits
μμ	0.022	limits

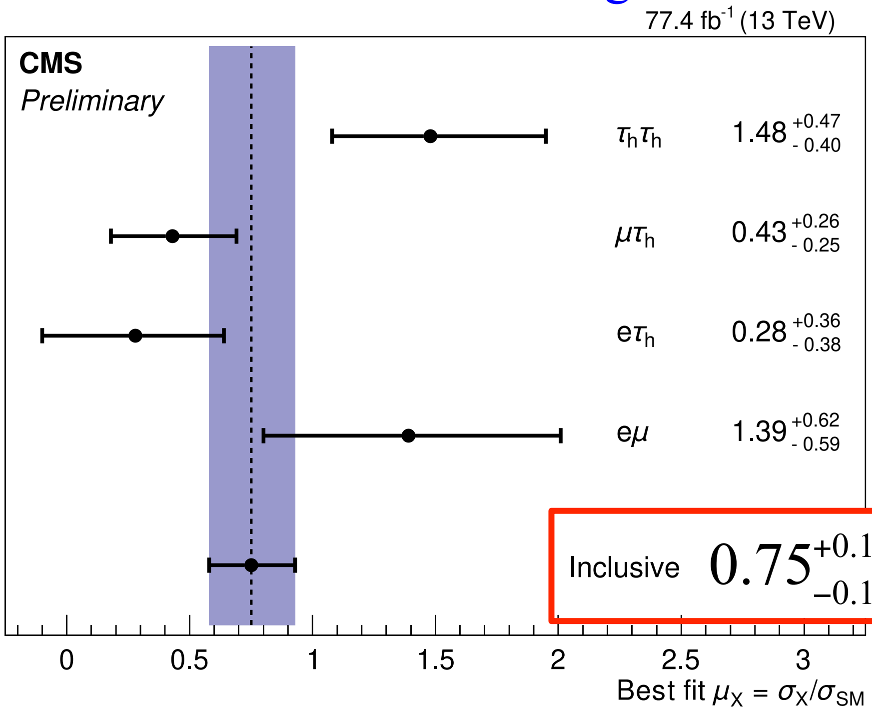
Fermions : H→ττ

CMS PAS HIG-18-032

- One of the decay channels to establish direct evidence for Yukawa couplings to fermions
- Observed in Run 1 by combining ATLAS and CMS. Obs. significance = 5.5 σ
- Later observed by individual experiment
- Recent update from CMS (77.4 fb^{-1})
  - Focus on ggH and VBF production
  - Employ NN classification to categorize signal and BG, improve sensitivity
- Measure cross sections of different production modes and kinematic regions



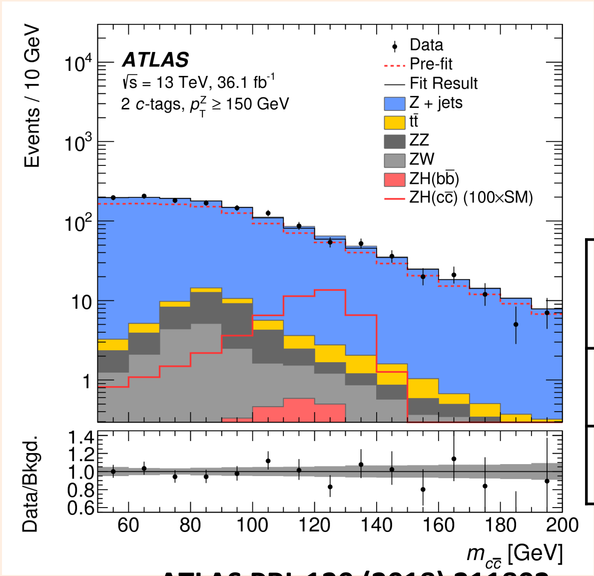
Signal at high S/(S+B) region



$\mu=1.09^{+0.27}_{-0.26}$ from analysis with 36 fb^{-1}

Rare and Invisible Decays

- Direct searches for H→cc, μμ to probe couplings to 2nd generation fermions
- H→cc (13 TeV, 36 fb^{-1})
- Difficult: large BG, challenging c-jet ID
  - c-jet tag eff. ~40%, b-/l-jet rejection ~4X/~20X
- Upper limit on σ(ZH→llcc)
  - Obs < 2.7 pb (110×SM)



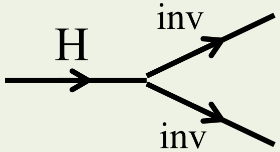
ATLAS PRL 120 (2018) 211802

- H→μμ: very small decay branching ratio
- Search signal mainly from ggH and VBF production

Expt.	Limit σ×BR Obs (Exp) ×SM	Data
ATLAS	2.1 (2.0)	Run2(80fb^{-1})
CMS	2.9 (2.2)	Run1+Run2(36fb^{-1})

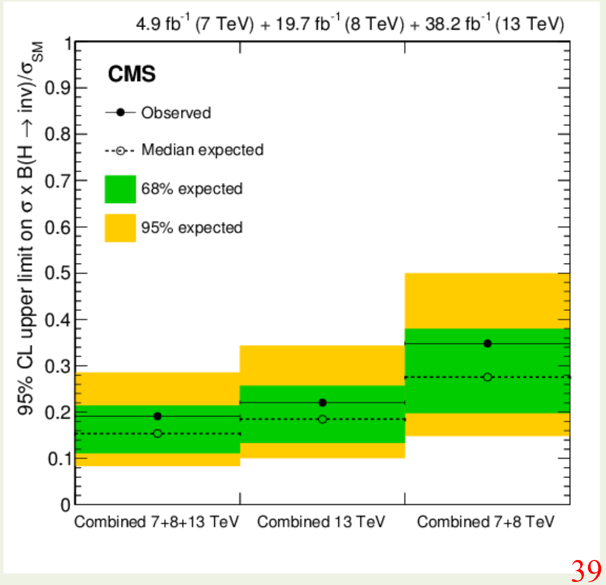
ATLAS-CONF-2018-026
CMS PRL 122 (2019) 021801

- 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)
- Perform direct searches in :
  - ggH : H→inv
  - VBF : qq→qqH→qq+inv (most sensitive)
  - VH : V→ll,qq, H→inv
  - ttH : H→inv (not in CMS combination)

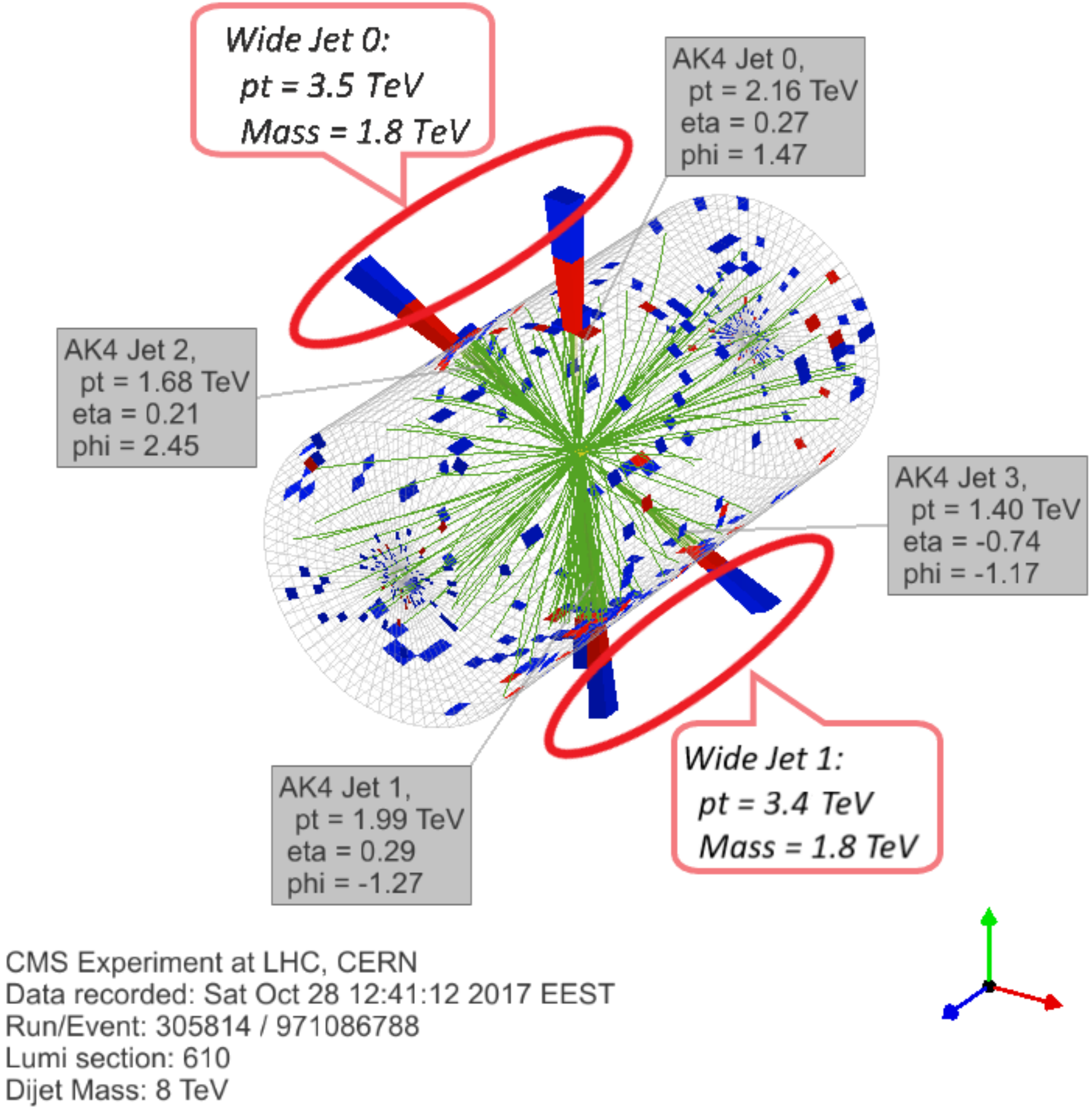


- Combined results from all channels, set limit on BR(H→inv) at 95%CL:
  - ATLAS : BR(H→inv)<0.26 ($0.17^{+0.07}_{-0.05}$)
  - CMS : BR(H→inv)<0.19 (0.15)

CMS arXiv:1809.05937
ATLAS arXiv:1904.05105



Highest di-jet Mass Event at CMS

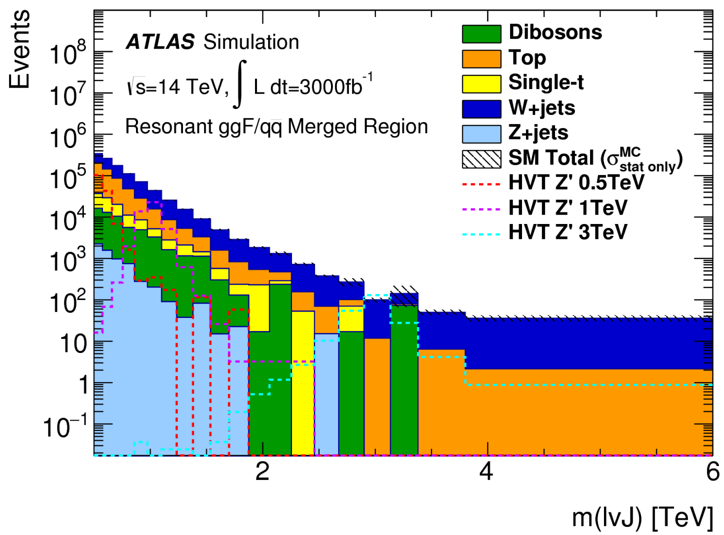


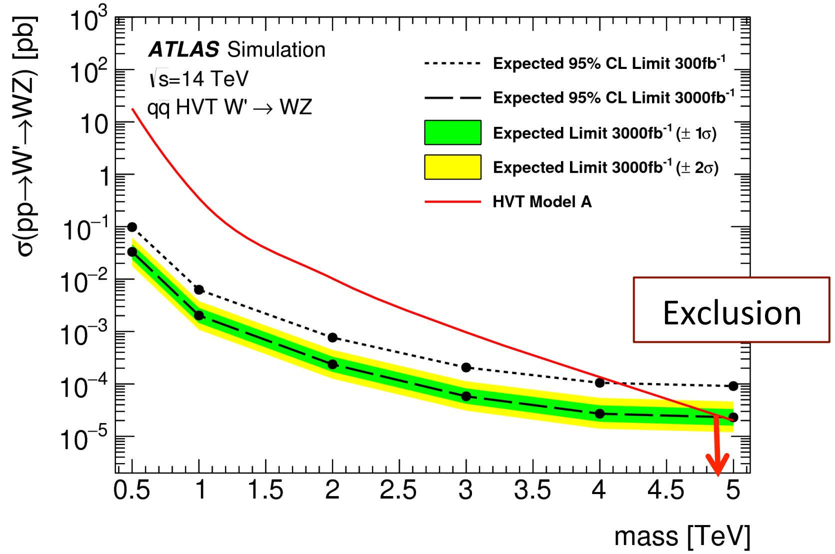
- Consists of 2 wide jets
- m_{JJ} = 8 TeV

Resonance Search : di-boson

ATL-PHYS-PUB-2018-022

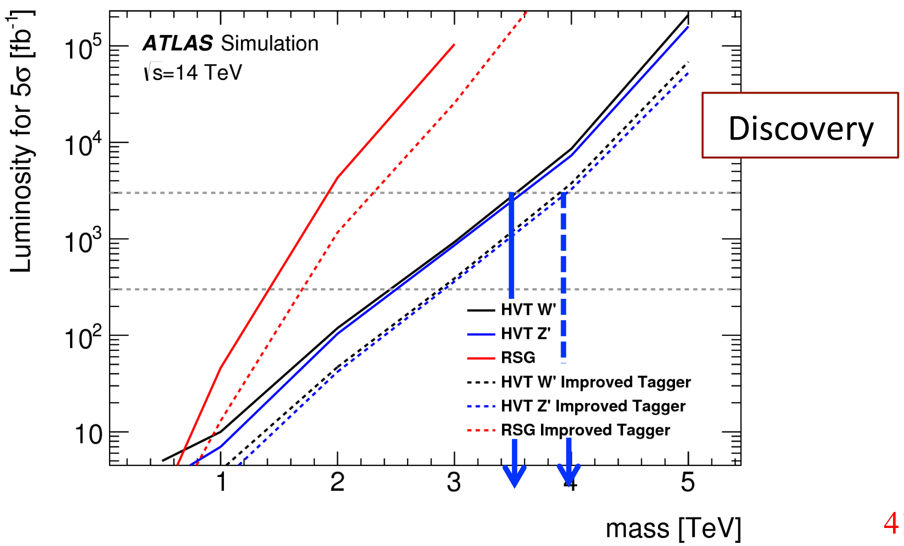
- Projection is studied for X→WV, W→lν and V(W,Z)→qq
- Search for heavy resonance in ggF/qq and VBF production modes, and in resolved and boosted categories (for the decay of V)
- Search prospect is interpreted in context of HVT, bulk RS model, narrow heavy scalar resonance





- Expected exclusion limits at 95% CL

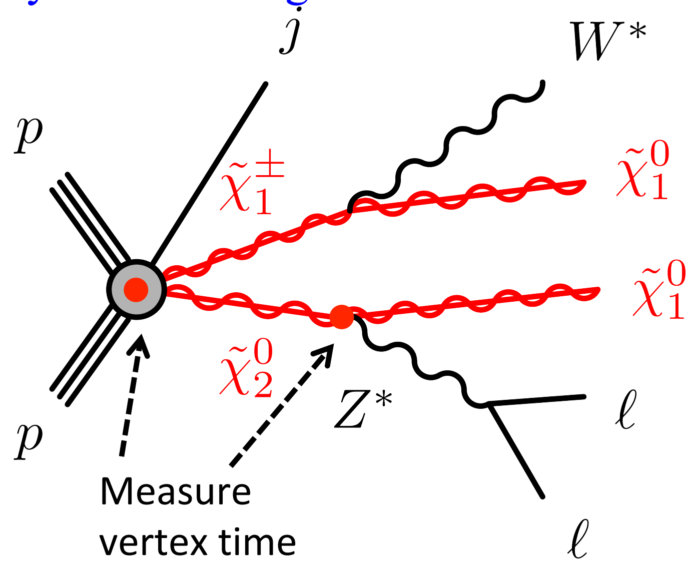
HVT, model A	HL-LHC	13 TeV, 36 fb-1 JHEP 03 (2018) 042
W’	4.9 TeV	2.9 TeV
Z’	4.9 TeV	2.85 TeV



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

Long Lived Charginos and Neutralinos

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

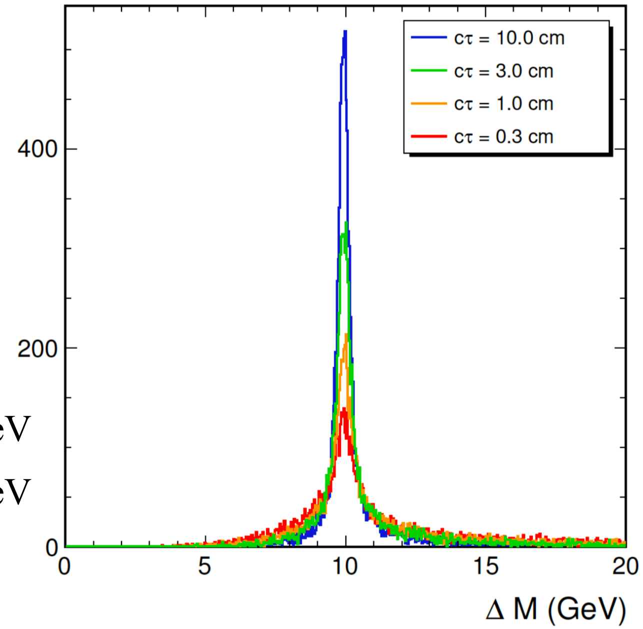


- Can use the MIP Timing Detector (MTD) of CMS HL-LHC to improve the search sensitivity
- MTD can measure minimum ionizing particles (MIPs) with time resolution of ~30ps
- Can assign timing for each vertex
  - Measure TOF of long lived particles
- Use the measured displacement between the vertices in space and time and the energy of the visible decay products ($Z^* \to ll$) 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

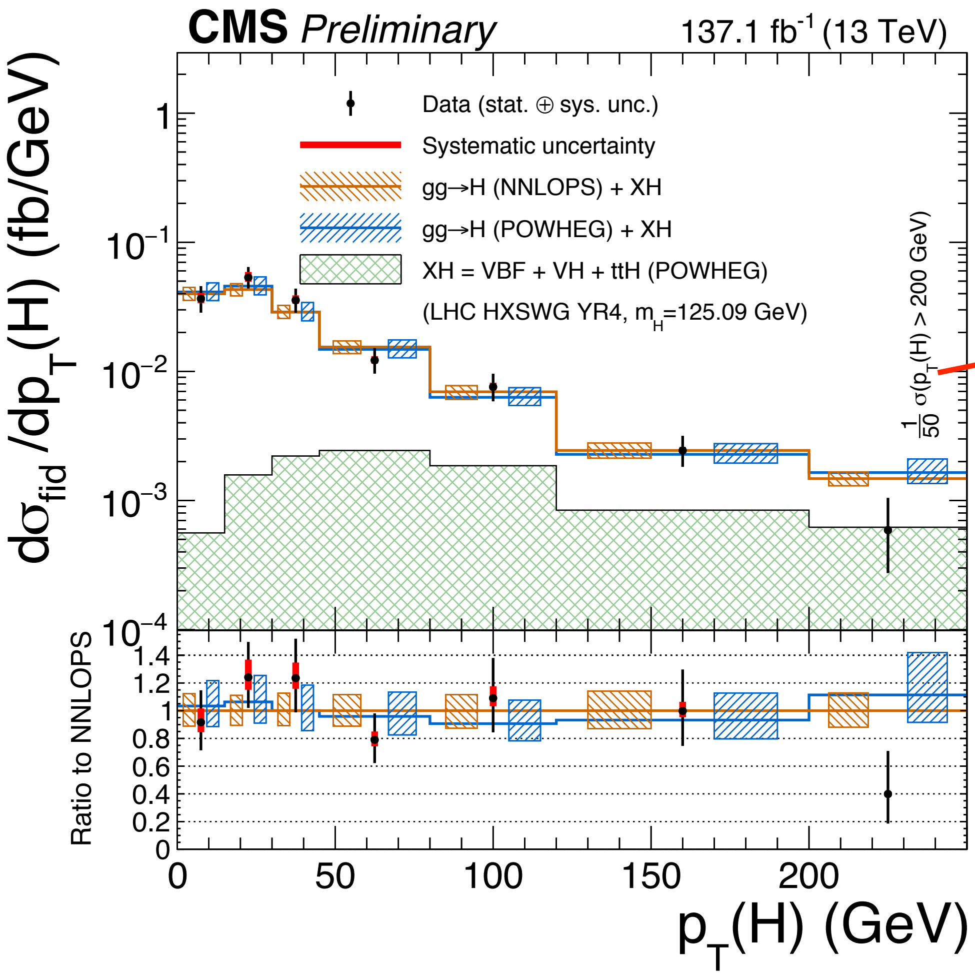
CMS CERN-LHCC-2017-027

$m(\tilde{\chi}_2^0)$=400 GeV

$m(\tilde{\chi}_1^0)$=390 GeV



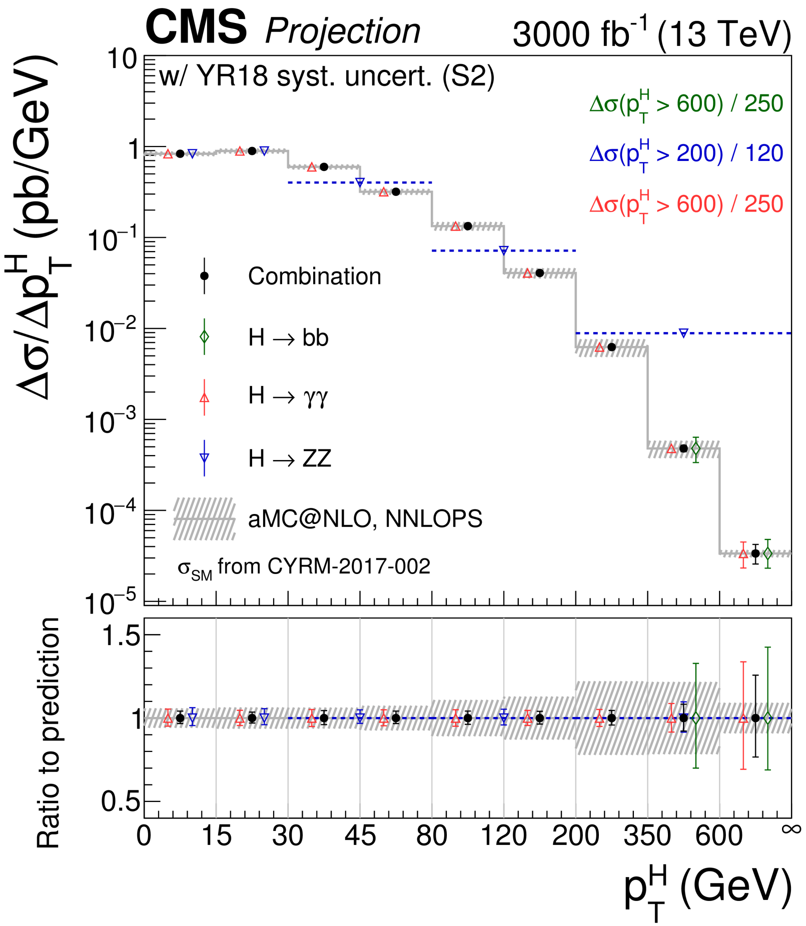
Updates on H→γγ , H→ZZ*→4l



For presentation purpose

CMS PAS HIG-19-001

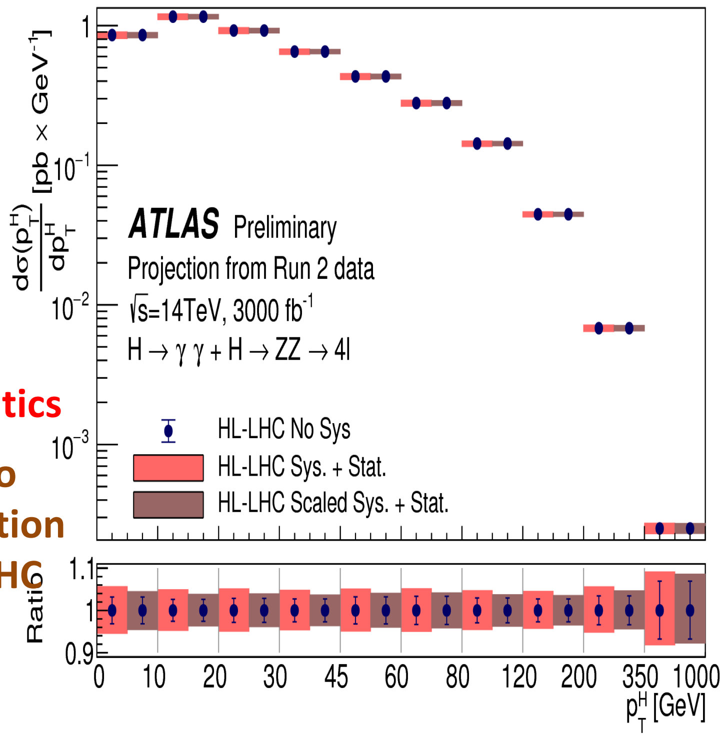
Projections for Differential Distributions Measurements



ATL-PHYS-PUB-2018-040	CMS-PAS-FTR-18-011

Run2 systematics

Scaled to expectation for HL-LHC



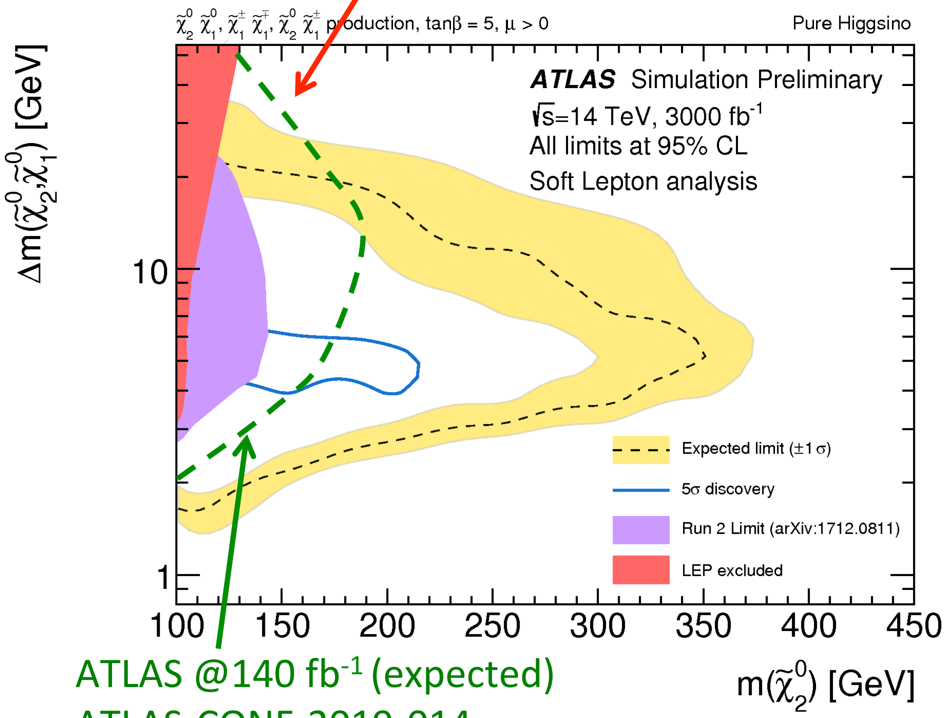
Systematic Uncertainties	Scale Factor
Jet energy scale, forward region	Set to 0
Jet energy scale, Jet punch-through	Set to 0
High-p_T jet energy scale	Set to 0
$H \to \gamma\gamma$ background modeling	Set to 0
4ℓ m_H	Scaled by 0.25
PDF	Scaled by 0.41
Jet flavor	Scaled by 0.5
Jet energy scale	Scaled by 0.5
Pileup modelling	Scaled by 0.5
QCD scale	Scaled by 0.5
Underlying event and parton shower modeling	Scaled by 0.5
Higgs branching ratios	Scaled by 0.5
Photon energy scale and resolution	Scaled by 0.8
Photon reconstruction, ID, and isolation	Scaled by 0.8
$qq \to ZZ$ irreducible background	Set to 2%
Luminosity	Set to 1% of expected integrated luminosity

Projection for Higgsino-like Charginos and Neutralinos Search

ATL-PHYS-PUB-2018-031

CMS-PAS-FTR-18-001

Softer MET cut compare to HL-LHC projection study



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

Possible HL-LHC Triggers

ATL-PHYS-PUB-2019-005

Table 2: Representative trigger menu for ATLAS operations at the HL-LHC. The offline p_T thresholds indicate the momentum above which a typical analysis would use the data. Where multiple object triggers are described only one threshold is given if both objects are required to be at the same p_T; otherwise, each threshold is given with the two values separated by a comma. In the case of the $e-\mu$ trigger in Run 2, two sets of thresholds were used depending on running period, and both are listed. This table is a subset of Table 6.4 from the TDAQ TDR [10].

Trigger Selection	Run 1 Offline p_T Threshold [GeV]	Run 2 (2017) Offline p_T Threshold [GeV]	Planned HL-LHC Offline p_T Threshold [GeV]
isolated single e	25	27	22
isolated single μ	25	27	20
single γ	120	145	120
forward e			35
di-γ	25	25	25
di-e	15	18	10
di-μ	15	15	10
$e-\mu$	17,6	8,25 / 18,15	10
single τ	100	170	150
di-τ	40,30	40,30	40,30
single b-jet	200	235	180
single jet	370	460	400
large-R jet	470	500	300
four-jet (w/ b-tags)		45(1-tag)	65(2-tags)
four-jet	85	125	100
H_T	700	700	375
E_T^{miss}	150	200	210
VBF inclusive (di-jets)			2x75 w/ ($\Delta\eta > 2.5$ & $\Delta\phi < 2.5$)

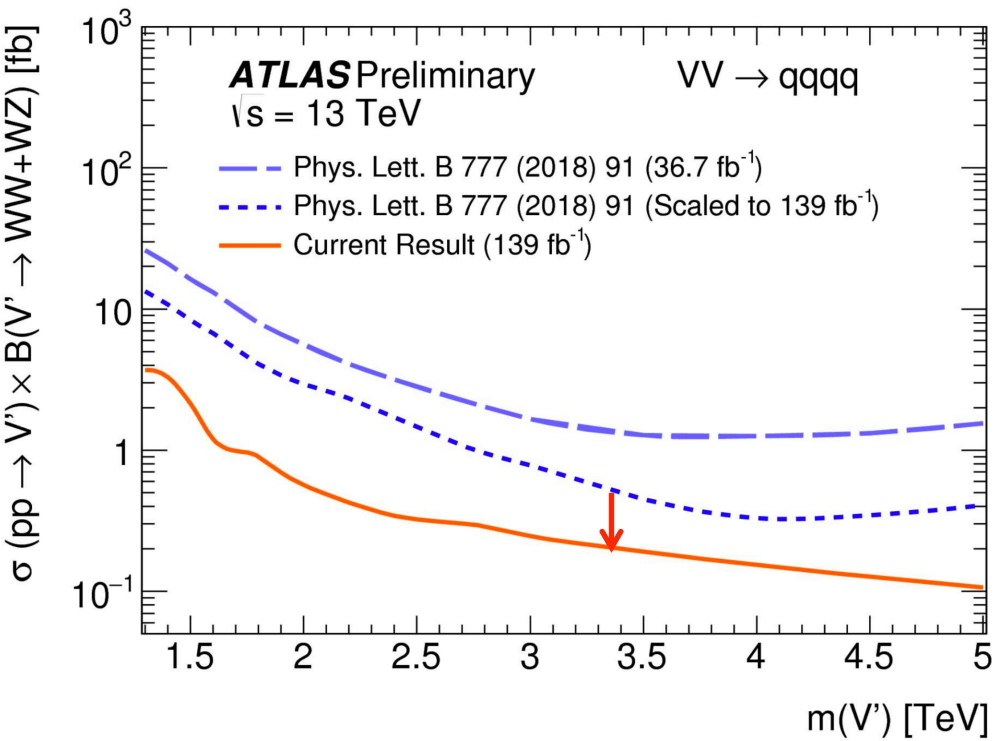
Example of S1 and S2 Uncertainty Scenarios

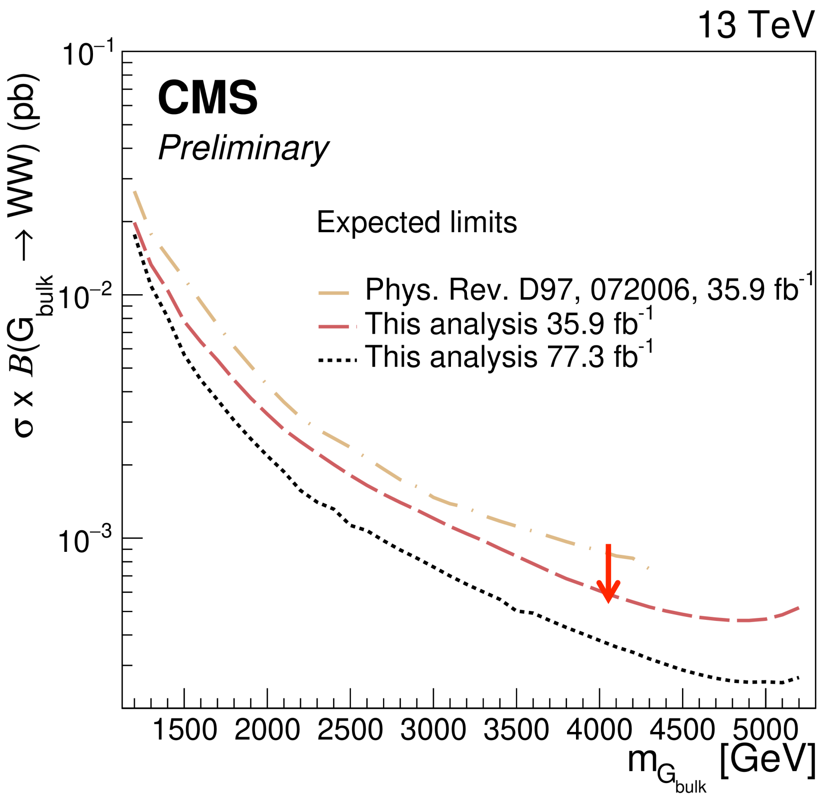
CMS-PAS-FTR-18-011

Table 1: The sources of systematic uncertainty for which minimum values are applied in S2.

Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy res.		Varies with p_T and η	Half of Run 2
MET scale		Varies with analysis selection	Half of Run 2
b-Tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Integrated lumi.		2.5%	1%

Resonance Search : di-boson





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