ATLAS at the HL-LHC: The technological challenges for Higgs physics

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On behalf of ATLAS

CPAD Instrumentation Frontier Workshop

New Technologies for Discovery II

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Higgs Physics at LHC & HL-LHC

- What do we want to learn?
- Higgs boson (125 GeV) properties
  - Mass and spin-parity
  - Production mechanisms and couplings
- Electroweak symmetry breaking
  - Higgs field solely responsible?
  - Additional scalars or additional mechanism?
- Higgs as a portal for BSM
  - Dark matter, dark sector
  - New physics scenarios

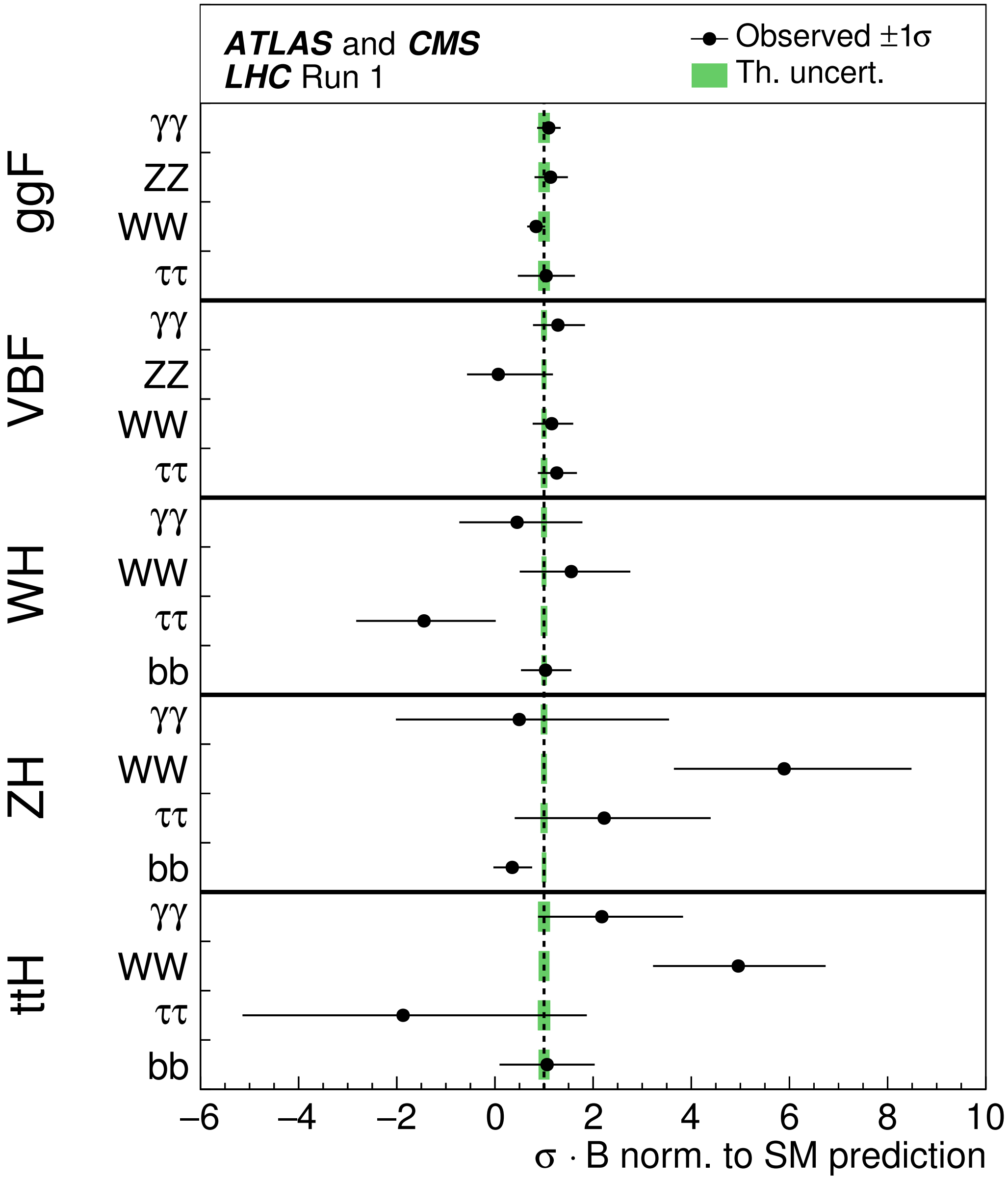
Higgs Properties

- **ATLAS+CMS Run 1 <u>mass</u>**
  125.09 ± 0.21 (stat) ± 0.11 (syst) GeV
  allows predictions of cross sections and BRs in SM

  arXiv: 1503.07589

- **<u>Production mechanisms</u> consistent with SM**
  ATLAS+CMS Run 1 combined signal strength 1.09 ± 0.11

arXiv: 1606.02266

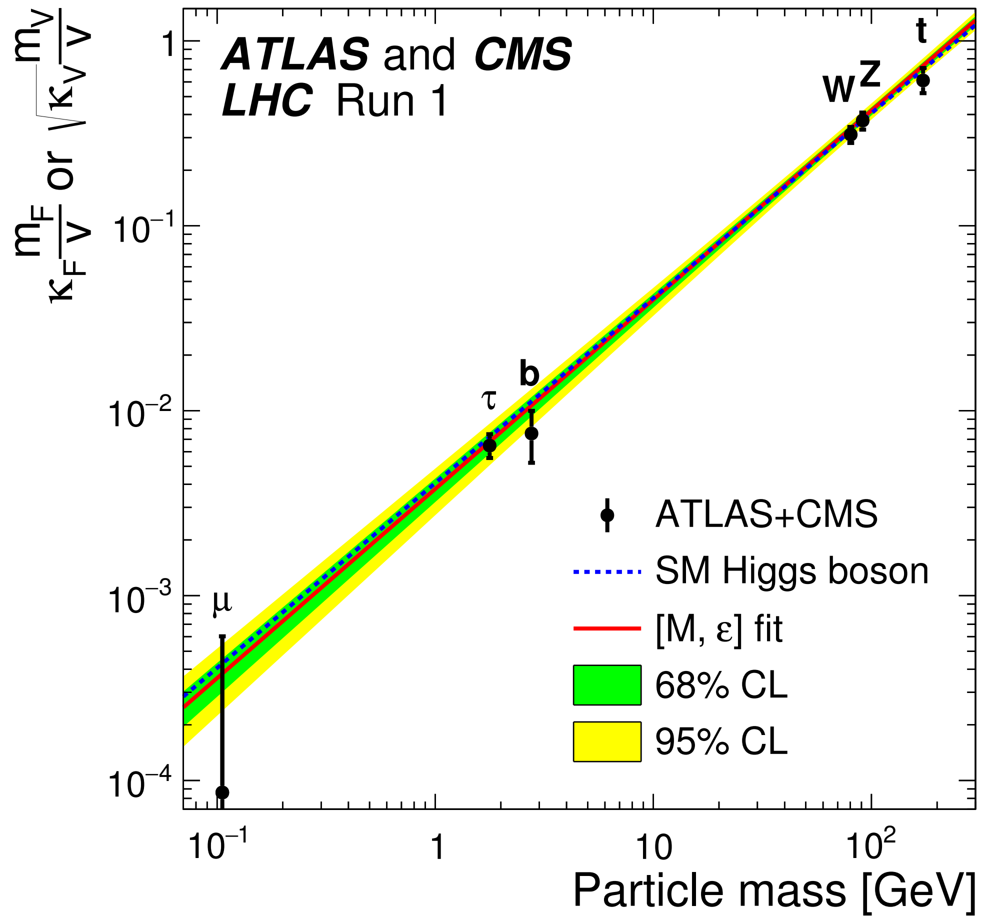


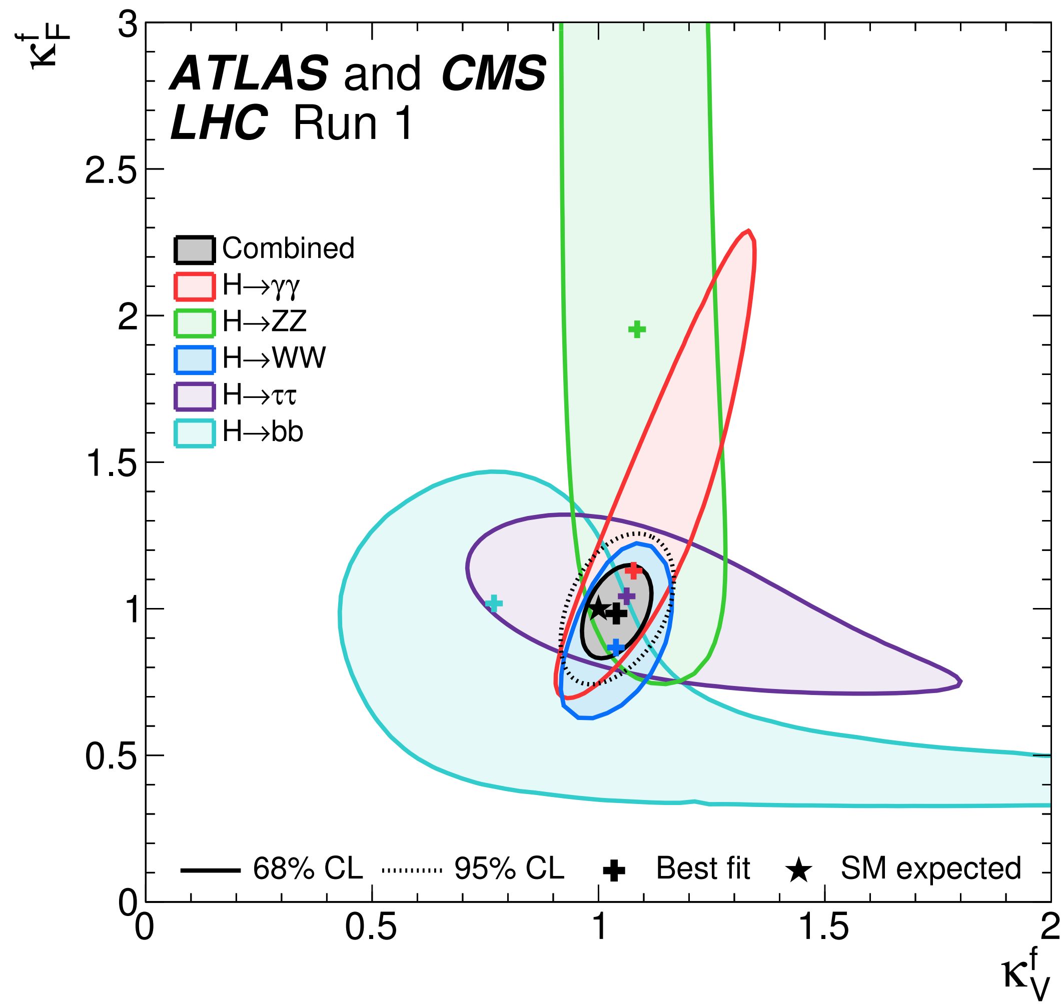
Higgs Properties

- **Couplings**

arXiv: 1606.02266

Consistent with SM
ATLAS+CMS Run 1

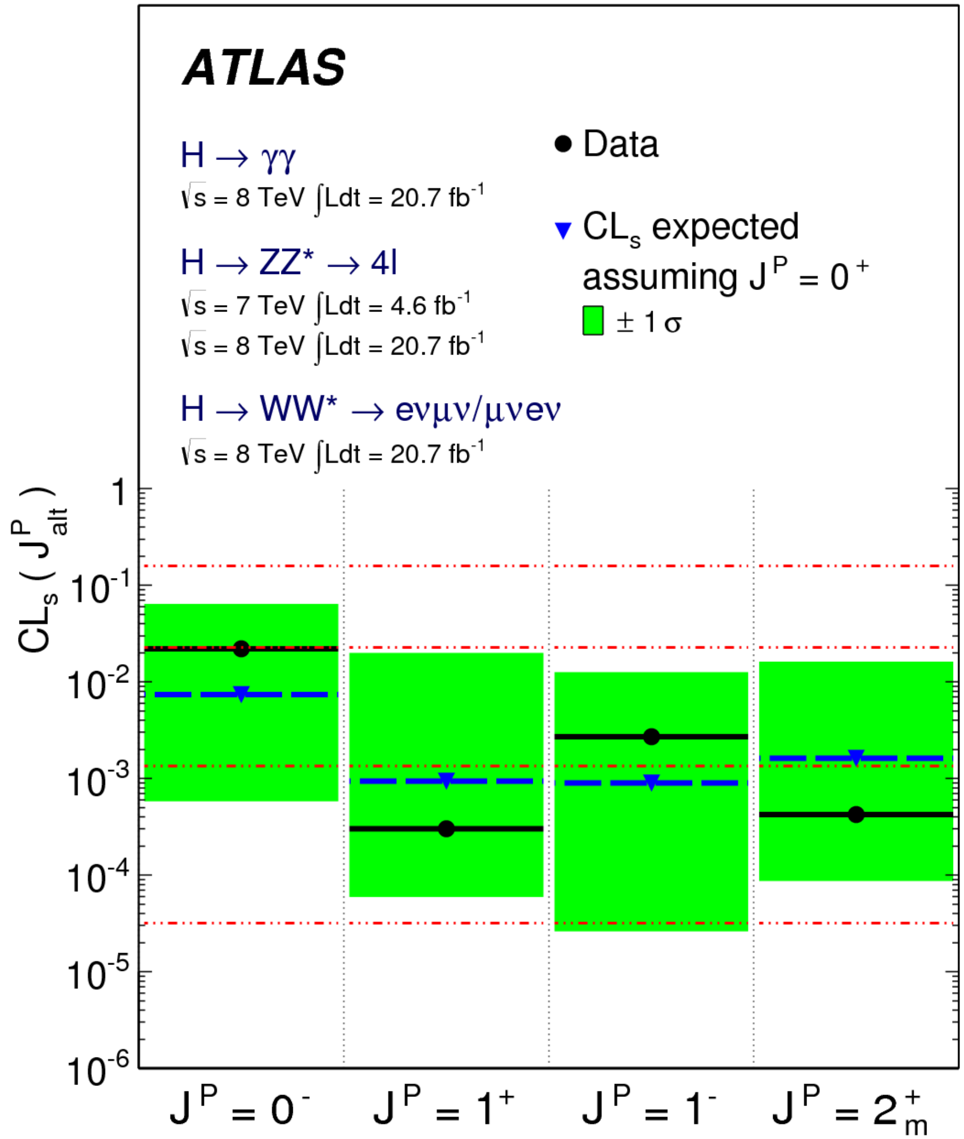




- **Spin & parity**

arXiv: 1307.1432

Run 1 data most consistent with SM scalar hypothesis



Higgs Properties

- **Couplings**
  What level of precision is required?

BSM theories predict deviations at ~1-10% level
Could be larger if new particles lighter than 1 TeV, deviation depends on 1 / (BSM scale)^2

➔ Need precision at or below 3% level on the couplings

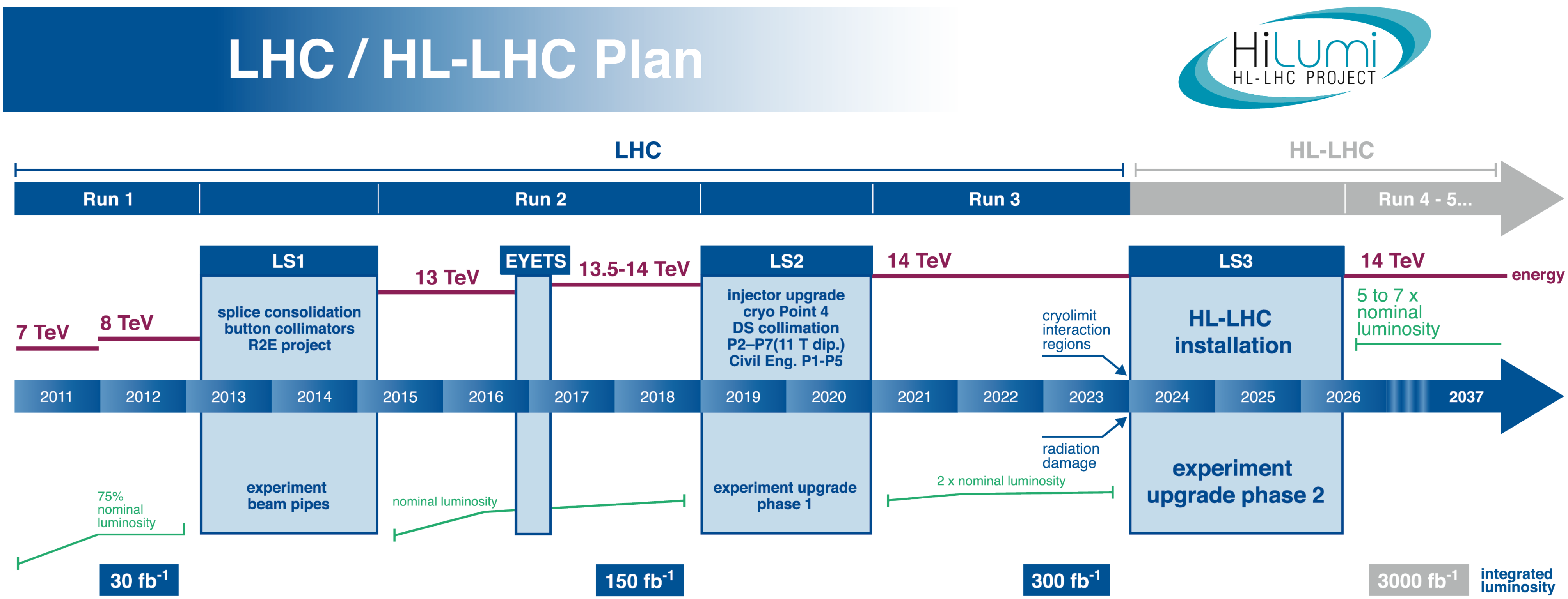
Snowmass Report: arXiv: 1310.8361

Table 1-8. *Generic size of Higgs coupling modifications from the Standard Model values when all new particles are $M \sim 1$ TeV and mixing angles satisfy precision electroweak fits. The Decoupling MSSM numbers assume $\tan\beta = 3.2$ and a stop mass of 1 TeV with $X_t = 0$ for the κ_γ prediction.*

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

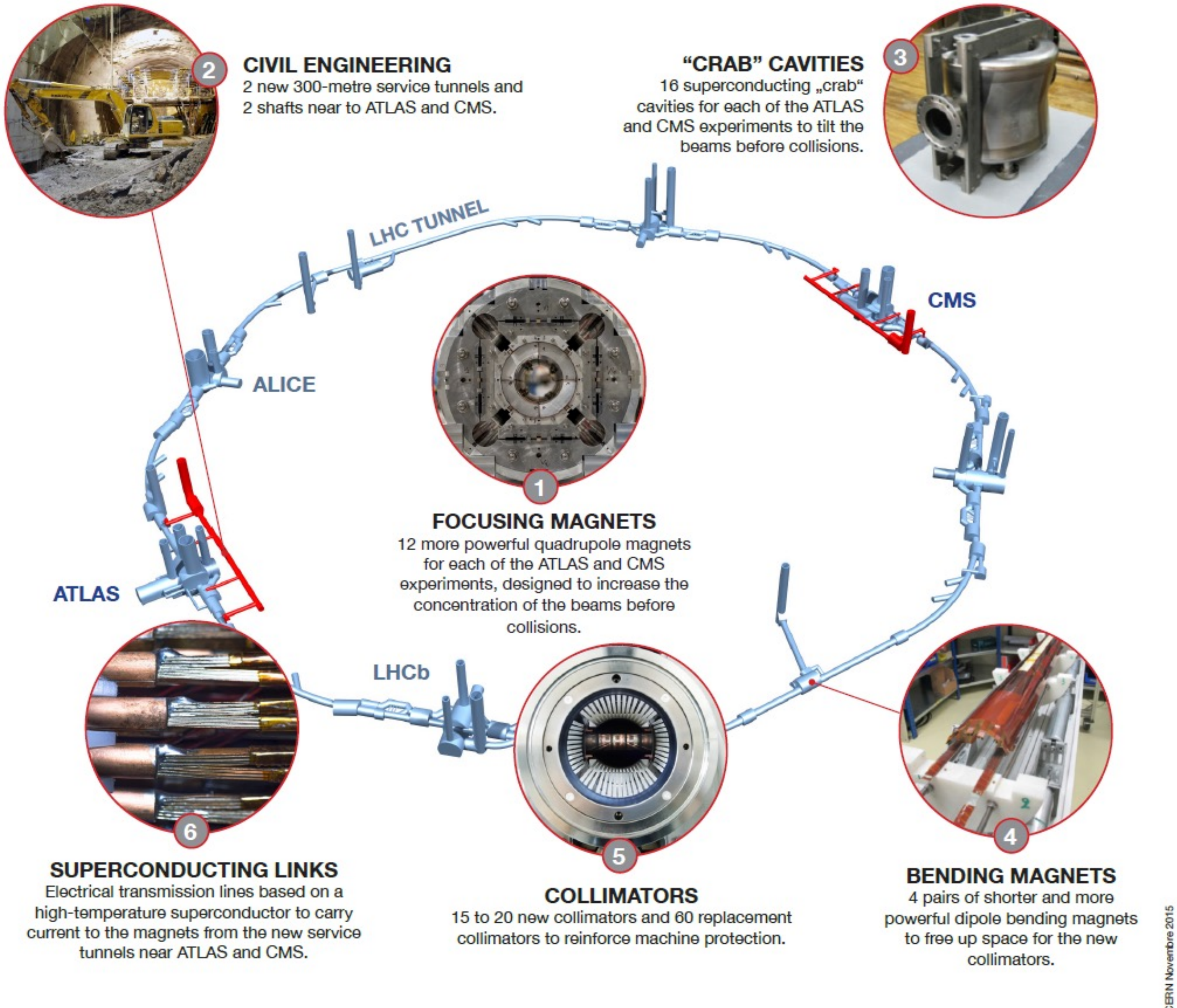
Planning for LHC & HL-LHC

- **LHC: deliver 300 fb^{-1} by the end of Run 3 (~2023)**
- **HL-LHC: increase integrated luminosity to 3000 fb^{-1} in ~10 years**
  - **Peak (leveled) luminosity of 5 – 7.5 x 10^{34} cm^{-2} s^{-1}**
  - **New injector complex, focusing quadrupole magnets, crab cavities, collimators, cryogenics upgrade**



http://hilumilhc.web.cern.ch/about/hl-lhc-project plot update 22.02.2016

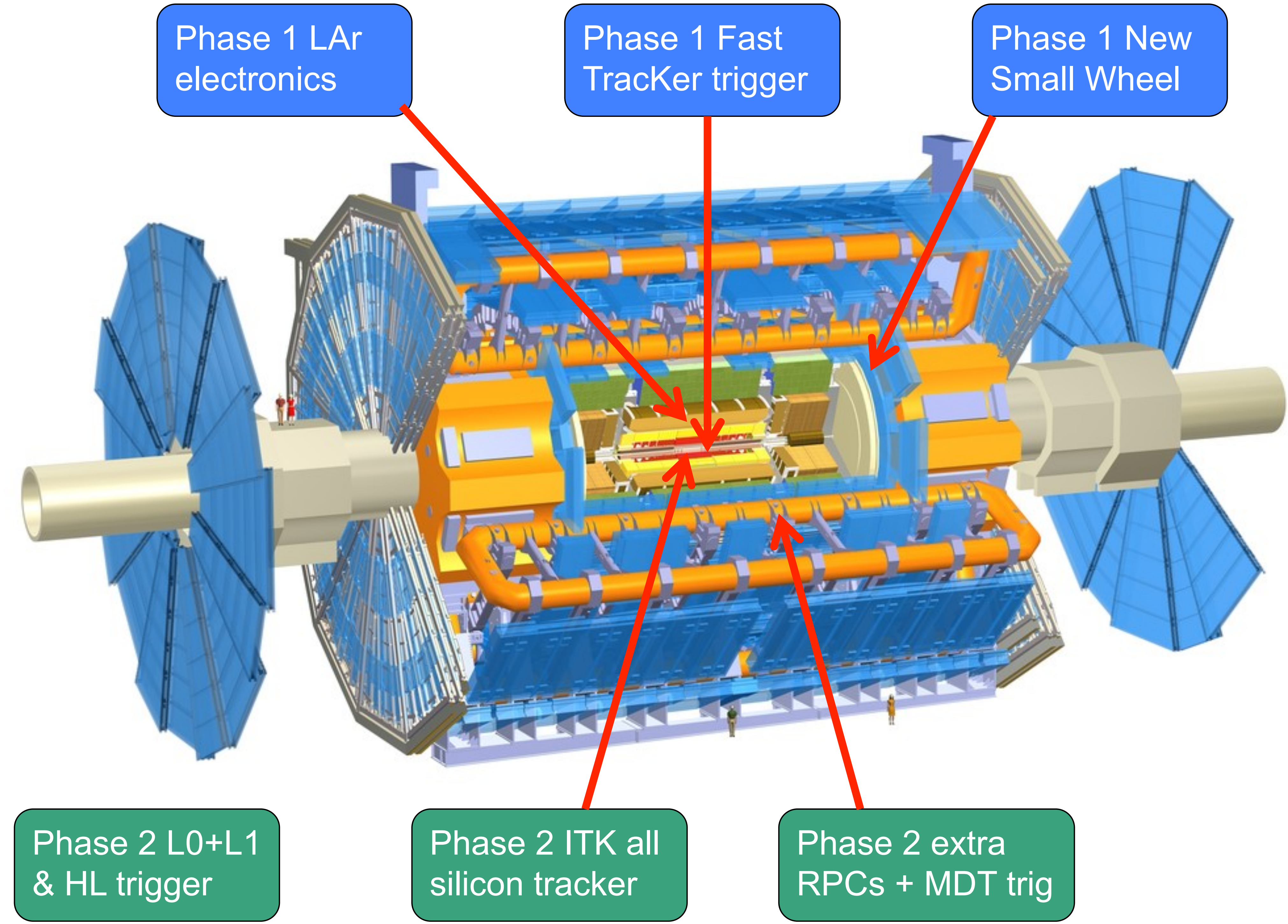
Planning for HL-LHC



Challenges at HL-LHC

- **Event rates**
  - **High luminosity and pileup normally would be handled via increased pT thresholds at the trigger level ➔ not acceptable for the physics program so require major upgrade of trigger system**
- **Pileup: expect average number of pp collisions up to <μ> = 200 (corresponding to 7.5 x 10^{34} cm^{-2} s^{-1})**
  - **Pileup mitigation heavily relies on tracking capabilities over large |eta| range**
- **Radiation damage**
  - **Radiation-hard detector technologies and electronics upgrade**

GOAL: Upgraded detector needs to maintain or exceed the performance of the current detector

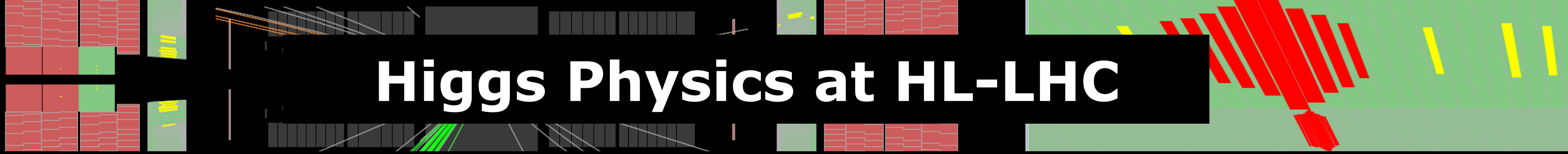

Phase 1 LAr electronics
Phase 1 Fast TracKer trigger
Phase 1 New Small Wheel
Phase 2 L0+L1 & HL trigger
Phase 2 ITK all silicon tracker
Phase 2 extra RPCs + MDT trig

ATLAS Detector Phase 1 Upgrade

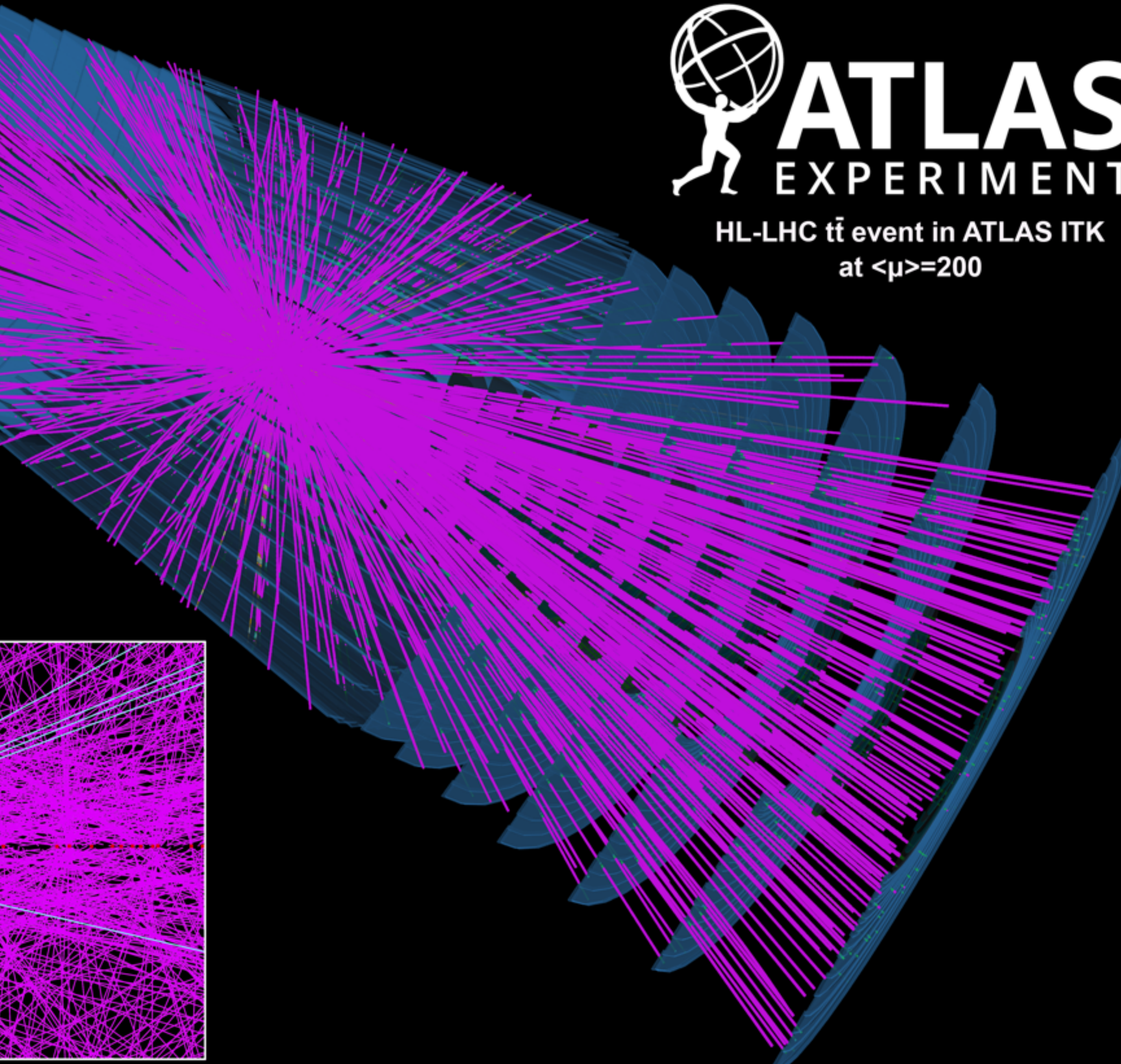
- **Fast TracKer (FTK) trigger system**
  - **New hardware track reco with associative memory for p_T > 1 GeV**
    ➔ High-quality tracking input to High Level Trigger (HLT)
- **Calorimeter trigger system and LAr trigger electronics**
  - **Improve granularity of Calo information for electron and jet reco by factor of 10**
    ➔ Improve background suppression in L1 trigger
- **Muon New Small Wheel**
  - **Improve granularity and robustness of endcap inner layer of the muon spectrometer**
    ➔ Lower background trigger rates at L1

ATLAS Detector Phase 2 Upgrade

- **Trigger / DAQ**
  - **Two-level custom hardware trigger (L0 up to 1 MHz and L1 up to 400 kHz)**
  - **FPGA technology for fast and powerful algorithms**
  - **New L1 track trigger for tracks within RoI and p_T > 4 GeV**
  - **New FTK++ trigger in HLT (rate up to 100 kHz, full tracking for p_T > 1 GeV)**
  - **HLT output rate up to 10 kHz**
- **Inner Tracker (ITK)**
  - **All-Silicon new tracker with coverage up to $|\eta| = 4.0$**
  - **5 layers Pixel + 4 double-sided layers Strips**
- **Calorimeters**
  - **New highly segmented precision timing detector $2.5 < |\eta| < 4.2$**
  - **Higher rate radiation hard readout electronics for LAr and Tile calos**
- **Muon Spectrometer**
  - **Finer granularity trigger with MDTs at L0/L1**
  - **New RPCs in barrel to increase coverage**

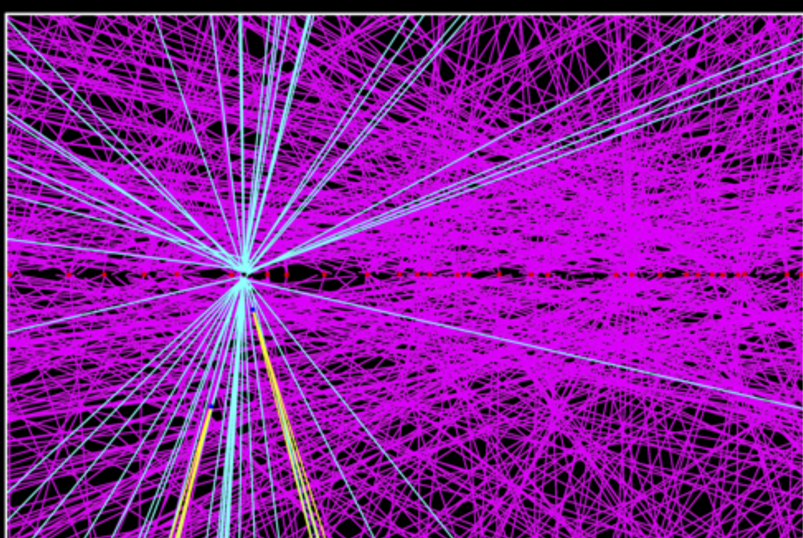


Higgs Physics at HL-LHC



HL-LHC $t\bar{t}$ event in ATLAS ITK
at <μ>=200

$t\,\bar{t}$ event
<μ> = 200

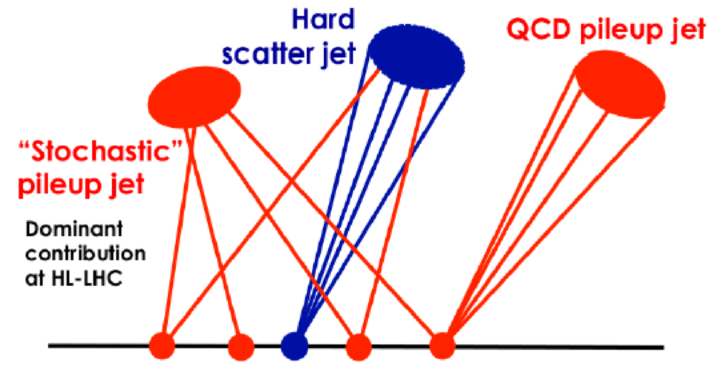


Physics Projections

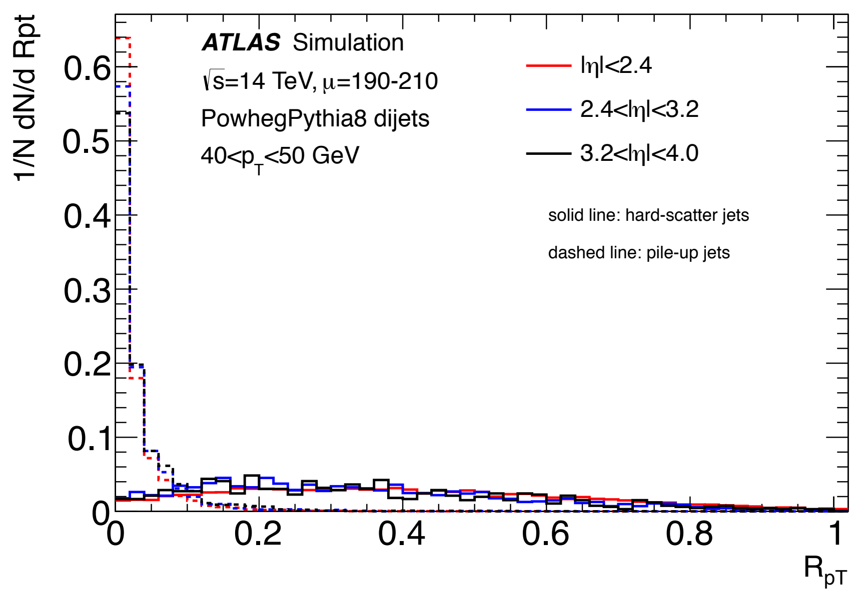
- **Scenarios**
  - **HL-LHC after Phase 2 upgrade: 3000 fb^{-1} at $\sqrt{s}$ = 14 TeV, μ = 140-200**
- **MC simulation**
  - **Event-generator level studies with parameterized detector/trig simulation**
  - **Effect of pile-up taken into account (overlay with pileup jets)**
  - **Parameterization of upgraded ATLAS detector response from *full* sim**
    - **Resolution and reconstruction efficiency for e, mu, tau, photon, (b-tag) jets**
    - **Rates for light- and c-jets to pass b-tag requirements**
    - **Parameterization depends on pileup**
- **Systematic uncertainties**
  - **Generally based on completed 8 TeV data analyses**
  - **Improvement from higher luminosity in case of statistical limitation (CR)**
- **Analysis techniques**
  - **Simple approaches used → sensitivity can be further improved**

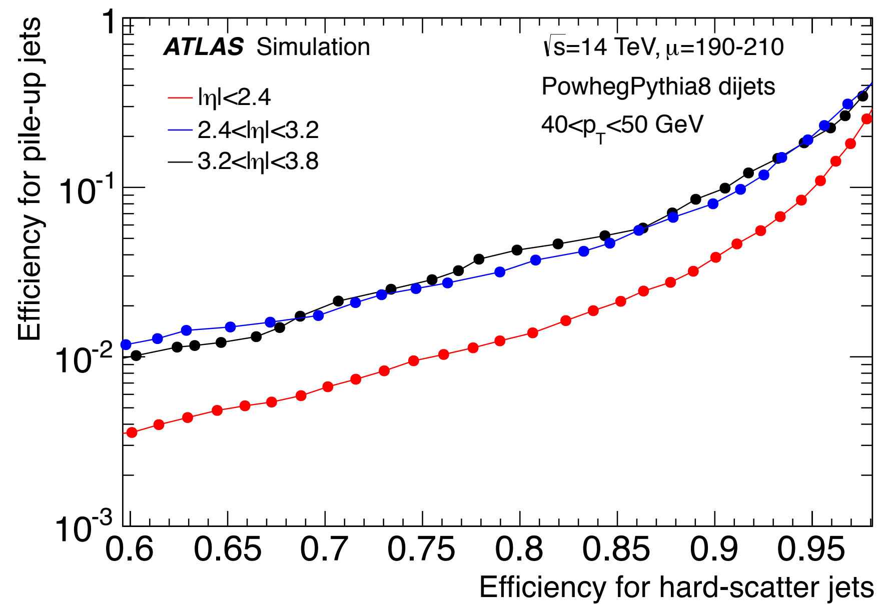
Pileup Jet Rejection

- **Expect 4.8 jets (p_T > 30 GeV and $|\eta|$ < 3.8) per event from pileup interactions**
- **Track confirmation**
  - **Identify hard scatter pp collision vertex: vertex with largest track $\Sigma\, p_T^2$**
  - **Discriminant: charged vertex fraction computed with tracks associated to the HS vertex**
  - **Reduce pileup jets by factor of 10 – 50**



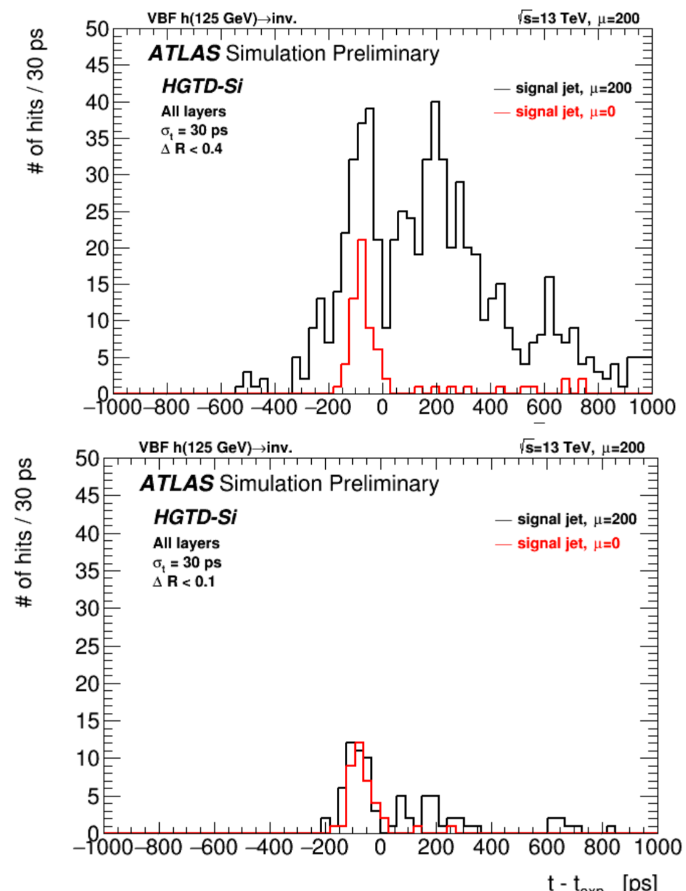
$$R_{pT} = \frac{\Sigma_i (p_T^{\mathrm{track},i})}{p_T^{\mathrm{jet}}}$$





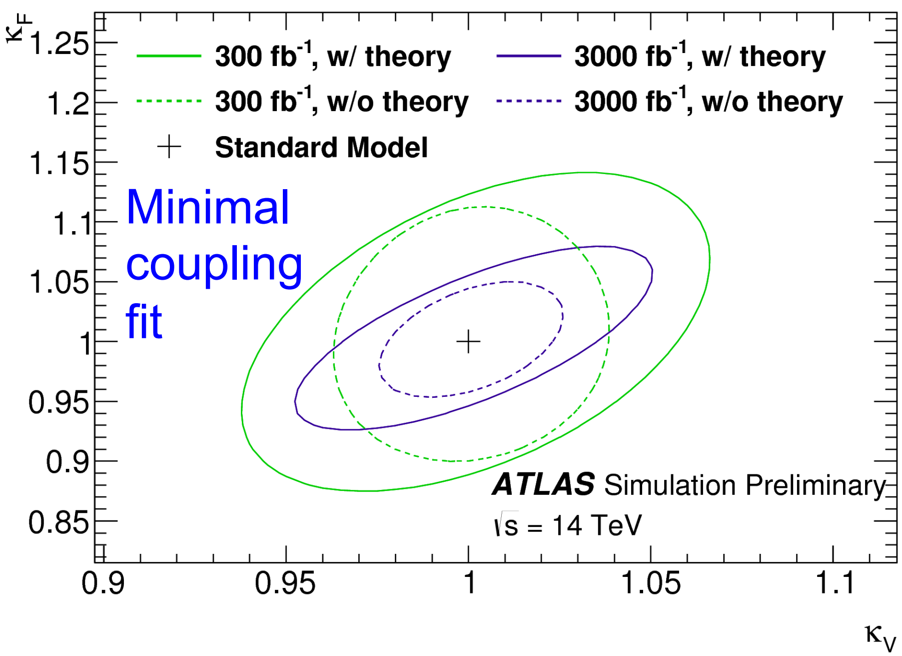
Pileup Jet Rejection

- **Pileup rejection with tracking relies on longitudinal extent of luminous region (spread ~50 mm)**
  - **Currently studying impact of different beam profiles to reduce collision vertex density along z**
- **Additional rejection can be achieved exploiting time profile (spread ~150 ps) with fast timing detector**
  - **Not included in physics projections in this talk**
  - **Plan to install high-granularity timing detector in front of endcap calorimeter for 2.5 < |η| < 4.2**
  - **Ultra fast silicon detector with time resolution of 30 – 50 ps**
  - **Potential for use in the trigger being explored**

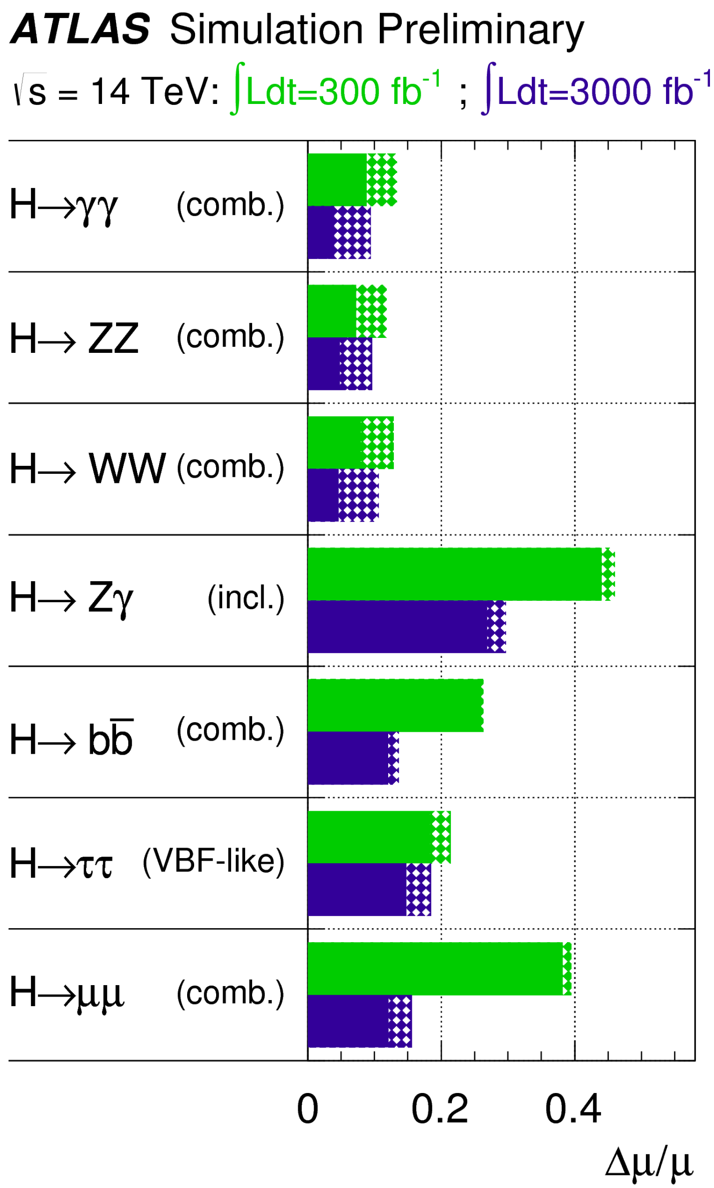


Higgs Couplings

- **Projections for ECFA 2014**
  - **Precision in signal strength $\mu = \sigma/\sigma_{SM}$ measurement (combination of different production mechanisms where available)**
  - **Precision in the Higgs couplings**
    1.7%(exp) to 3.3%(exp+th) for vector bosons
    3.2%(exp) to 5.1%(exp+th) for fermions



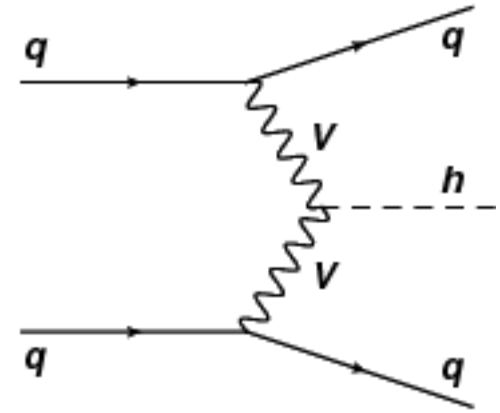
<μ> = 140



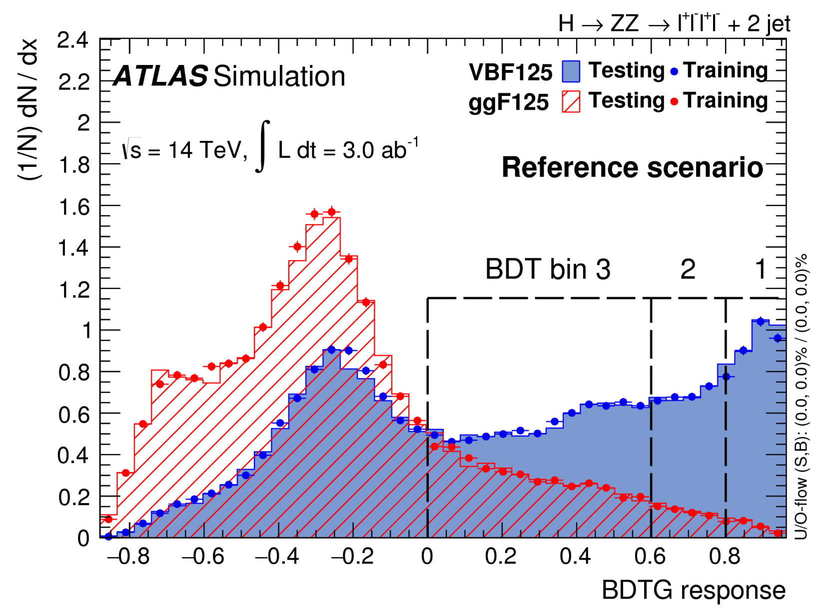
VBF H → ZZ* → ℓℓℓℓ

ATL-PHYS-PUB-2016-008

- **VBF 2nd largest Higgs production mechanism**
- **Trigger: single lepton or di-lepton (e or μ)**
- **Analysis**
  - **e or μ with p_T > 20, 15, 10, 7 GeV**
  - **2 forward jets with p_T > 30 GeV and |η| < 4.5**
  - **mjj > 130 GeV**
  - **BDT to discriminate VBF and ggF**
- **Pileup contamination in BDT bins**



	Pile-up impurity (%)		
Scoping scenario	Bin 1	Bin 2	Bin 3
VBF Sample			
Reference	2.0	4.6	13.1
Middle	3.0	6.4	23.6
Low	5.2	12.0	38.7
ggF Sample			
Reference	23.2	37.9	52.1
Middle	24.0	43.4	65.0
Low	41.2	59.4	76.2

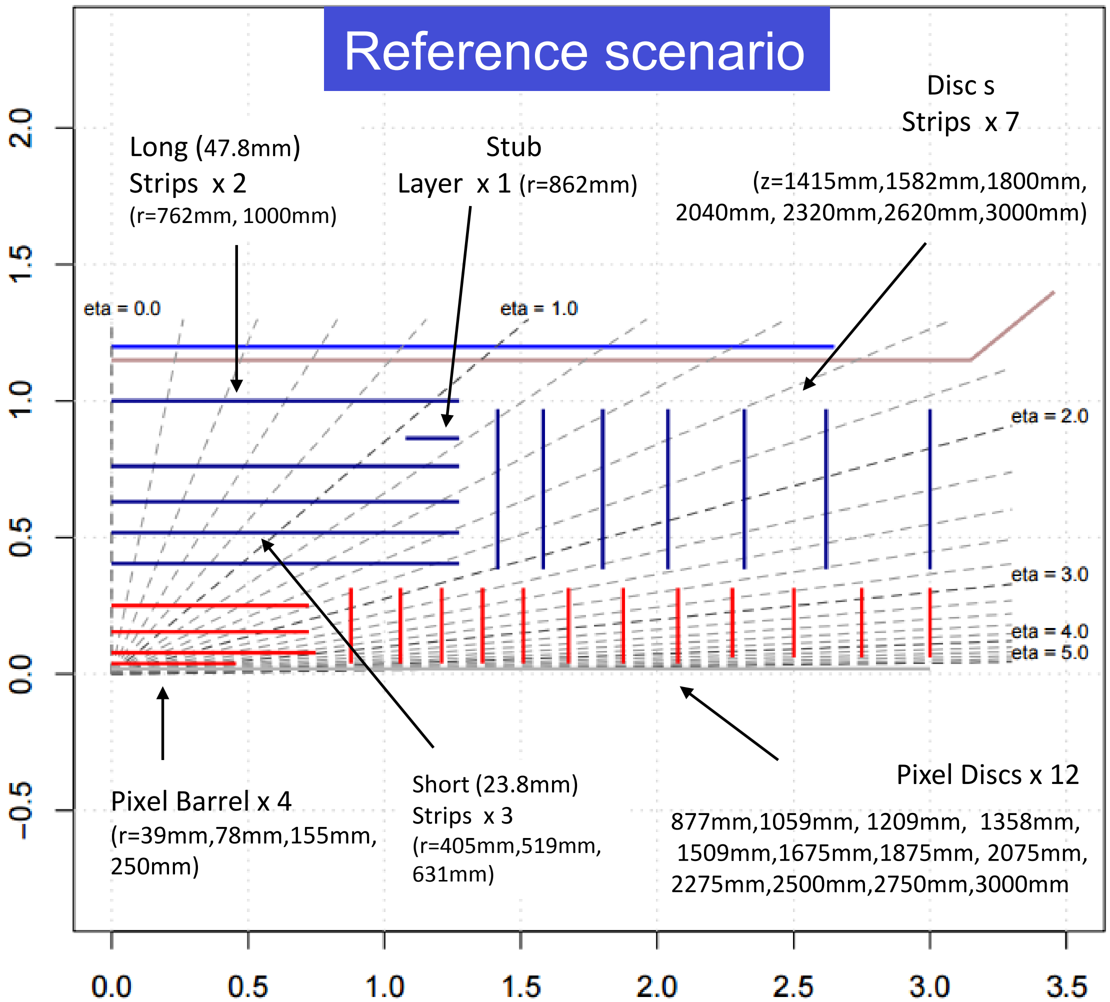


Middle & Low scenarios: reduced fwd trk coverage → higher pileup

Scoping scenarios

- **Middle & Low scenarios: reduced tracking coverage in η and in # detector layers**

	Reference	Middle	Low
ITk strips - changes w.r.t. LoI layout			
Remove Barrel layer 3			✗
Remove 1 Disc set		✗	✗
Remove 2 stereo layers			✗
Remove stub		✗	✗
ITk η-coverage	4.0	3.2	2.7



VBF H → ZZ* → ℓℓℓℓ

ATL-PHYS-PUB-2016-008

- **VBF signal significance 7.2 σ with theory uncertainties**

Scoping scenario	VBF + $2j$ events	ggF + $2j$ events	$qqZZ + 2j$ events	Z_0	$\Delta\mu/\mu$
Statistical uncertainty only					
Reference	192 (168)	287 (140)	39 (16)	10.2	0.152
Middle	218 (167)	454 (155)	69 (15)	9.5	0.157
Low	259 (159)	803 (182)	124 (21)	8.6	0.165
Statistical uncertainty + QCD scale var. uncertainty (S-T method)					
Scoping scenario	VBF + $2j$ events	ggF + $2j$ events	$qqZZ + 2j$ events	Z_0	$\Delta\mu/\mu$
Reference	192	287	39	7.2	0.182
Middle	218	454	69	6.9	0.192
Low	259	803	124	6.2	0.208

Key ingredients:

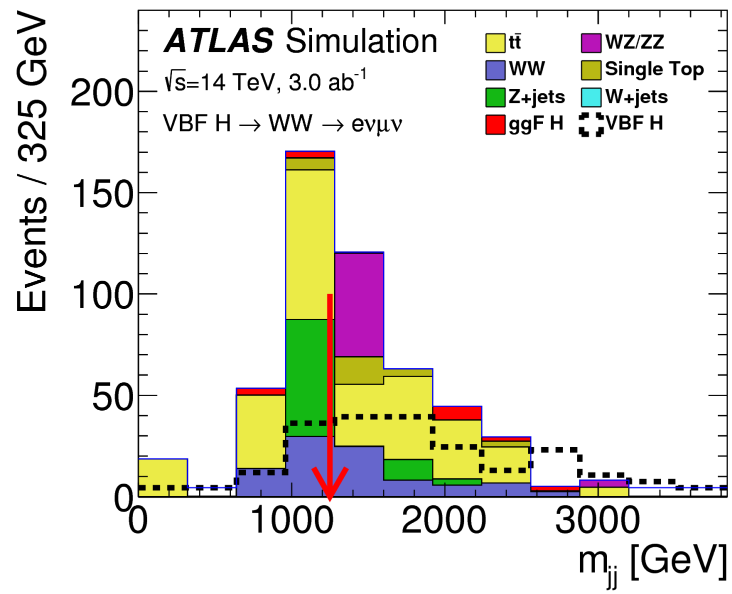
Pileup jet rejection, esp. in forward direction

Lepton trigger and low-p_T ID/reconstruction

VBF H → WW* → eνμν

ATL-PHYS-PUB-2016-018

- **Mixed lepton flavor final state to suppress Z background**
- **Trigger: single e/μ p_T > 25 GeV**
- **Analysis**
  - **Track confirmation to suppress pileup jets**
  - **2 forward jets with p_T > 70(60) GeV and 2.0 < |η| < 4.5 in opposite hemispheres**
  - **Forward jets fail b-tagging to suppress $t\bar{t}$**
  - **Central jet veto: No jet with p_T > 30 GeV between the two forward jets**
  - **Both e± and μ∓ between the two forward jets**
  - **E_T^{miss} > 20 GeV and mjj > 1250 GeV**



- **Event yields**
  - **Signal / Bkg = 0.49 (Reference)**
0.33 (Middle)
0.23 (Low)
  - **Increased number of pileup jets surviving track confirmation in scenarios with less tracking coverage ➔ efficiency of central jet veto decreases for signal**

- **Event yields**

Scoping scenario	N_{VBF}	N_{bkg}	N_{ggF}	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*+jets}	N_{W+jets}
Reference	200	410	57	48	55	146	20	27	0
Middle	153	457	46	91	36	164	27	23	3
Low	93	408	51	104	10	141	17	37	2

Increased non-resonant WW background for degraded scenarios due to pileup jets faking forward tagging jets
Other key ingredient: b-jet veto

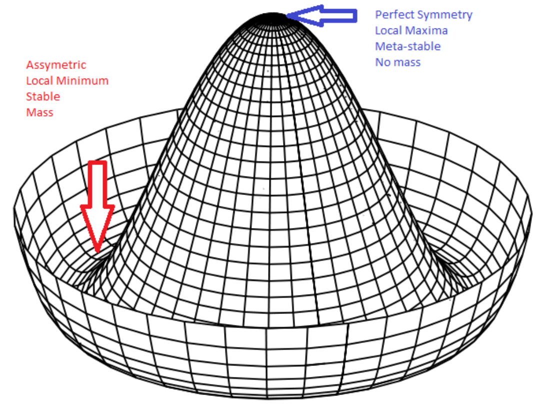
- **Signal strength precision and significance for different systematic uncertainties: Full 8 TeV analysis extrapolated, ½ uncertainty or none**

Scoping scenario	Δ_μ			Significance (σ)		
Signal unc.	Full	1/2	None	Full	1/2	None
Reference	0.20	0.16	0.14	5.7	7.1	8.0
Middle	0.25	0.21	0.20	4.4	5.2	5.4
Low	0.39	0.32	0.30	2.7	3.3	3.5

Higgs Self-coupling

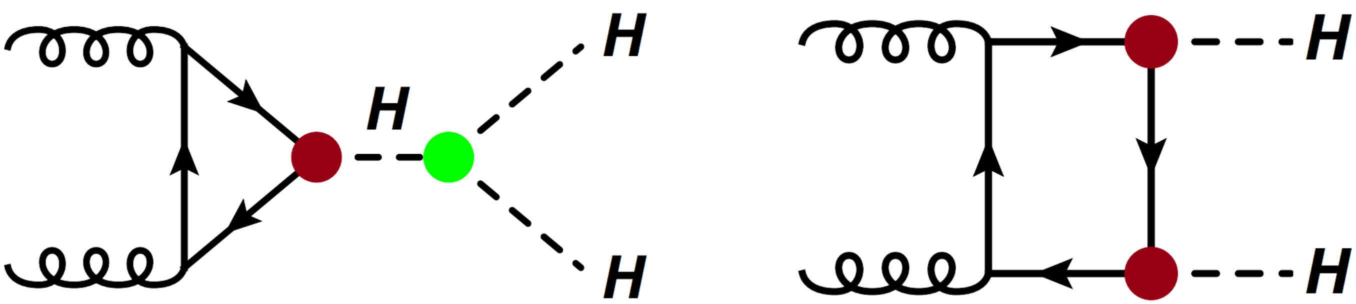
- **Test of Higgs potential and Electroweak symmetry breaking in the Standard Model**

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$$



  - **Given m_H = 125 GeV,**
    SM predicts $\lambda \approx 1/8$ and $|\mu^2| \approx m_W^2$

  - **Higgs pair production allows for a measurement of self-coupling λ**



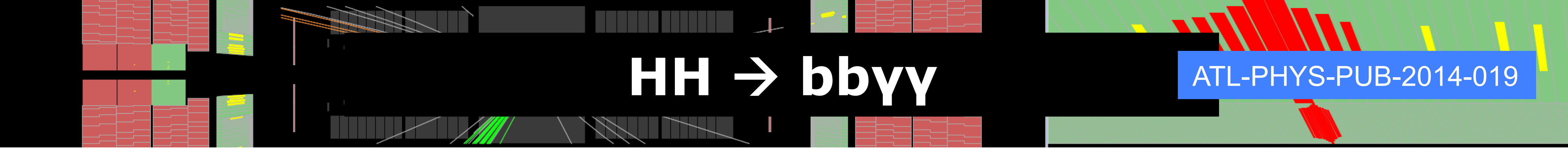
  - **Low cross section is a challenge: $\sigma \approx 40$ fb**

Higgs Self-coupling

- **Low cross section requires combination of different production mechanisms and decay modes**

Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	40,000
$b\bar{b} + W^+W^-$	25%	31,000
$b\bar{b} + \tau^+\tau^-$	7.3%	8,900
$ZZ + b\bar{b}$	3.1%	3,800
$W^+W^- + \tau^+\tau^-$	2.7%	3,300
$ZZ + W^+W^-$	1.1%	1,300
$\gamma\gamma + b\bar{b}$	0.26%	320
$\gamma\gamma + \gamma\gamma$	0.0010%	1.2

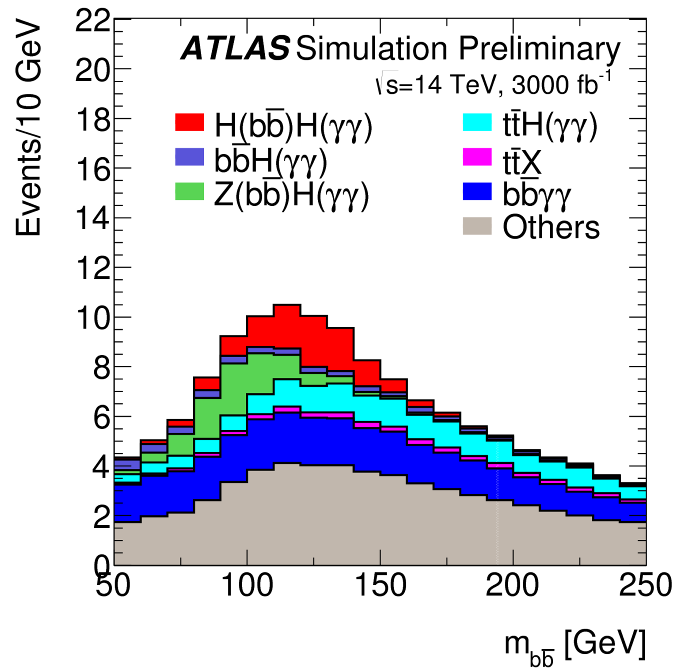
→ **ATLAS studied bb+bb, bb+ττ, bb+γγ modes**

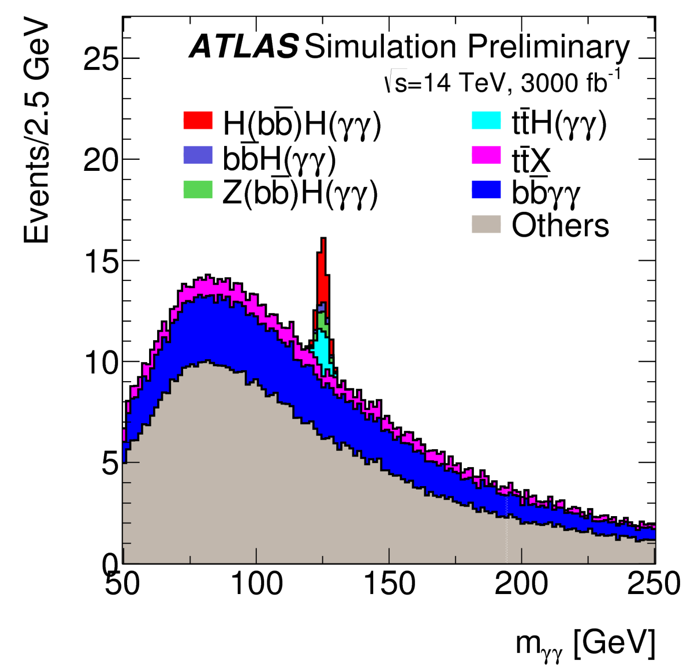


HH → bbγγ

ATL-PHYS-PUB-2014-019

- **Cleanest HH channel**
- **Analysis**
  - **2 b-tagged jets with p_T > 40, 25 GeV and $|\eta|$ < 2.5**
  - **2 isolated photons with p_T > 30 GeV and $|\eta|$ < 2.37 (transition region removed)**
  - **H candidate mass windows and p_T > 110 GeV, angular selection also applied**
  - **No pileup jets included in this analysis**
- **Event yields**
  - **Signal ≈ 8.4**
  - **Bkg ≈ 47**
  - **SM signal ~ 1.3 σ**
  - **$-1.3 < \lambda / \lambda_{SM} < 8.7$ at 95% CL**



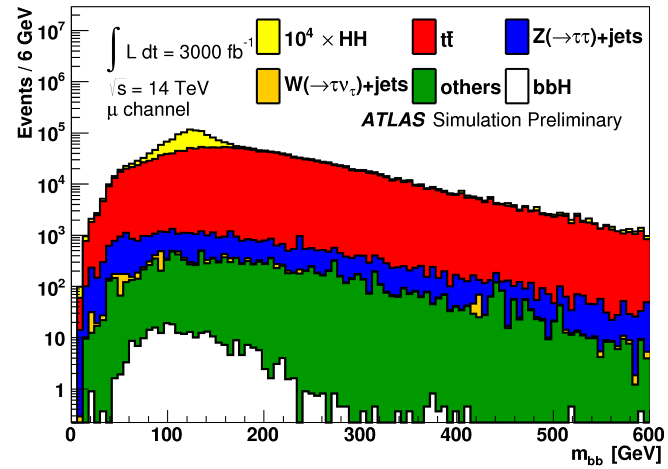


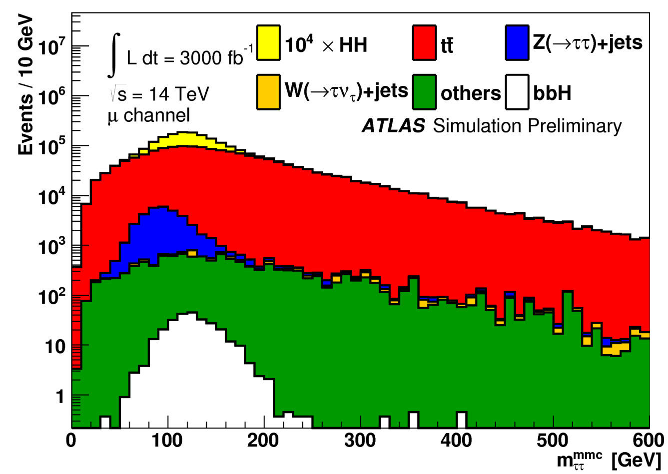
- **Concerns: trigger threshold, pileup impact, fake b-jets / photons**

HH → bbττ

ATL-PHYS-PUB-2015-046

- **Consider both leptonic and (semi-)hadronic tau decay channels**
- **Trigger: single e/μ p_T > 25 GeV, di-τ p_T(h vis) > 40 GeV**
- **Analysis**
  - **2 b-tagged jets with p_T > 30 GeV and |η| < 2.5**
  - **2 τ cands with p_T > 40(20) GeV hadr(lept), |η| < 2.5**
  - **Track confirmation to suppress pileup jets**
  - **H cand sel: mass window + min p_T, m_T**
- **Event yields**
  - **Signal ≈ 13 (hadhad), 14 (lephad)**
  - **Bkg ≈ 830 (hadhad), 880 (lephad)**
  - **SM signal ~ 0.6 σ (3% lumi, 3% bkg uncert.)**
  - **-4 < λ / λ_{SM} < 12 at 95% CL**
- **Concerns: trigger threshold, pileup impact, fake b-jets / taus**



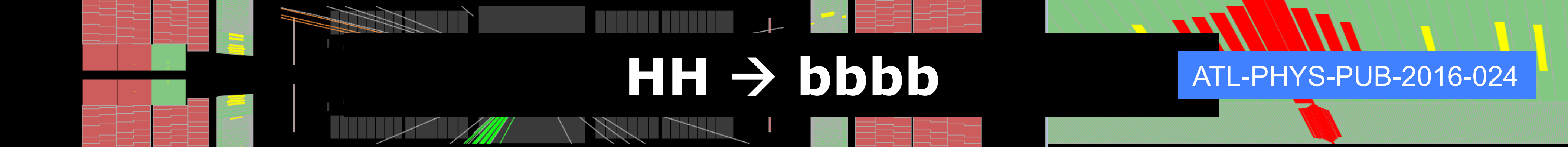


HH → bbbb

ATL-PHYS-PUB-2016-024

- HH → bb bb has largest rate (BR ~1/3) but huge multijet background
- Best upper limit from 13 TeV data: $\mu = \sigma/\sigma_{SM} < 29$ at 95% CL
- Projection based on 13 TeV data analysis
- Assume that adverse effects of pileup are compensated by improvements in detector and reconstruction algorithms

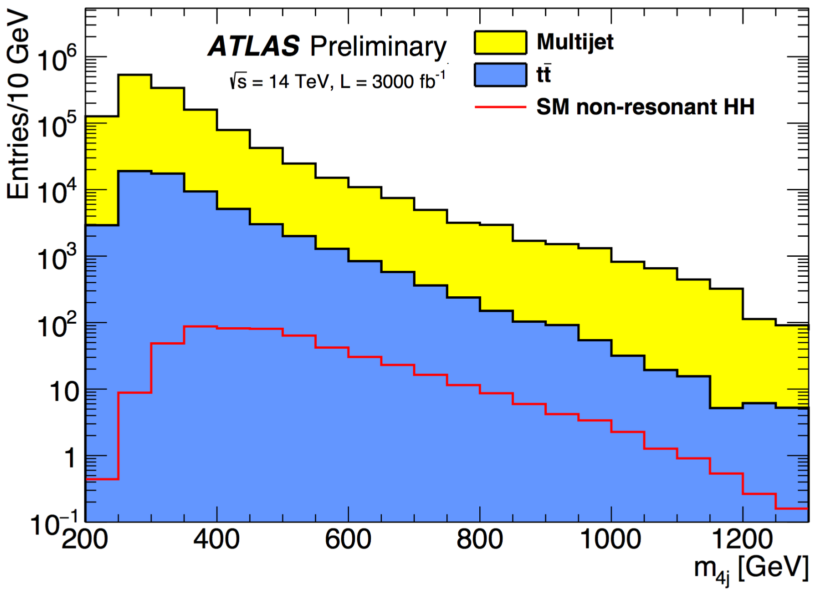
- Analysis
  - 4 b-tagged jets with $p_T > 30$ GeV and $|\eta| < 2.5$
  - 2 Higgs candidates satisfy mass, p_T, $\Delta\eta$ and ΔR requirements
  - Background 95% multijet + 5% top
  - 4-jet mass distribution shape and normalization from data control regions

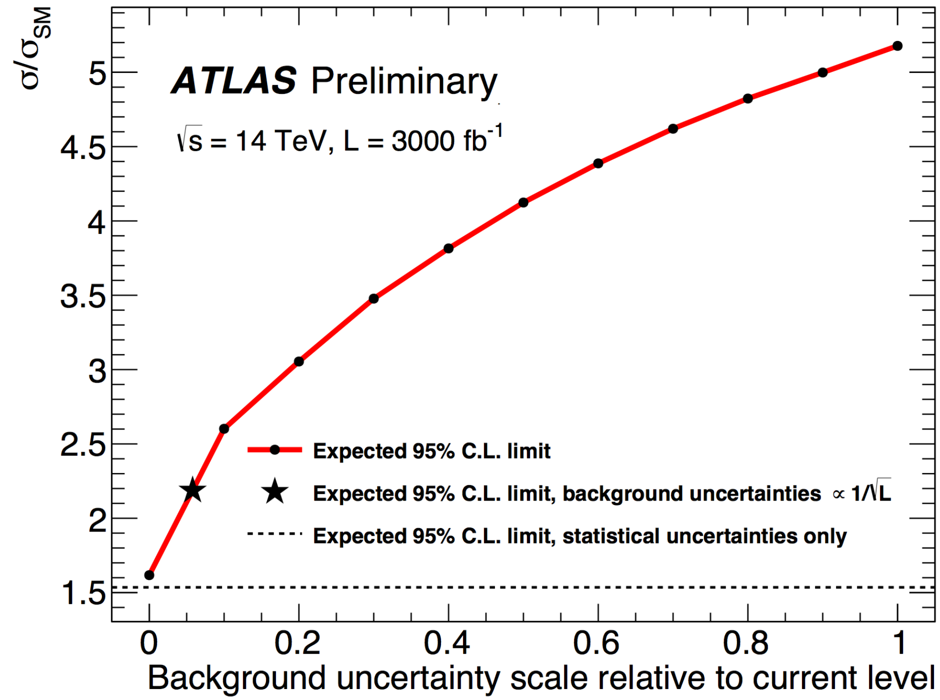


HH → bbbb

ATL-PHYS-PUB-2016-024

- **Extrapolated m4j spectrum from 13 TeV data analysis scaled by factor of 1.18 for CM energy of 14 TeV**



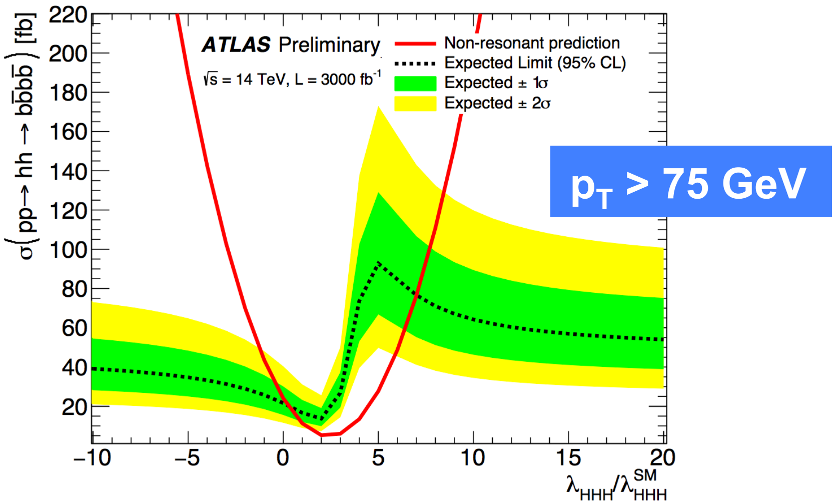


- **Acc x eff = 1.8% ➔ expect ~700 signal events**
- **0.2 < λ / λ_{SM} < 7.0 w/o syst uncertainties**
- **-3.5 < λ / λ_{SM} < 11 with current syst uncertainties**

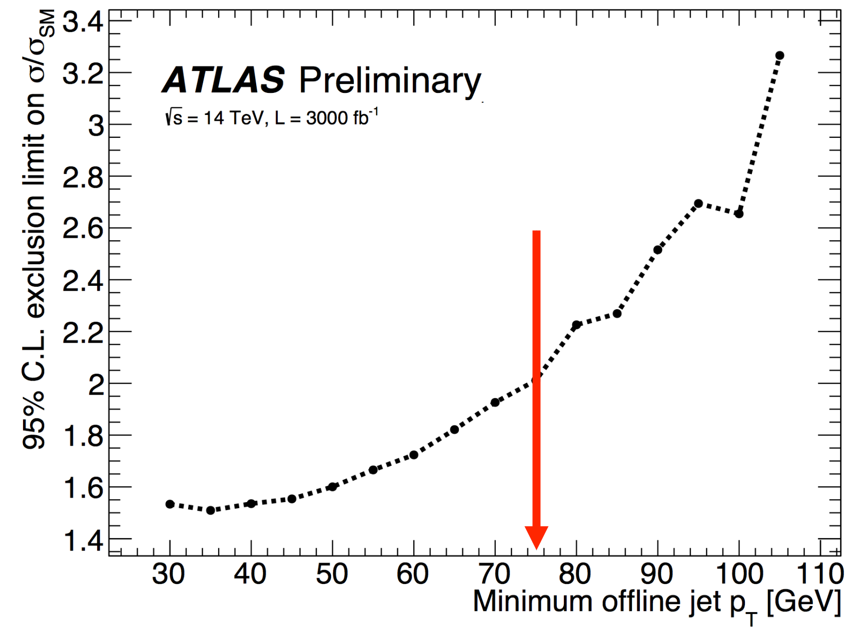
HH → bbbb

ATL-PHYS-PUB-2016-024

- **Impact of increasing multijet trigger p_T threshold**
  → estimate by increasing p_T threshold for jets in analysis
- **Increase of min p_T from 30 to 75 GeV (as in proposed trigger menu)**
  → 30% loss in sensitivity



(a) No systematics

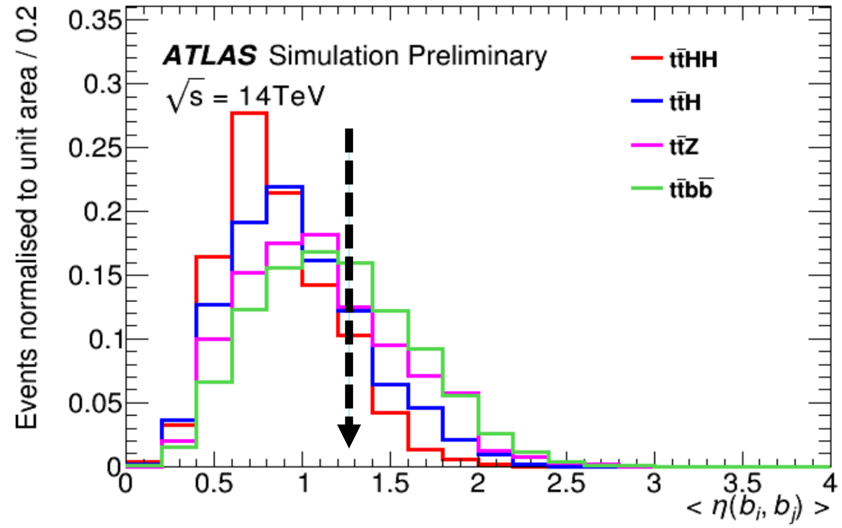


Jet Threshold [GeV]	Background Systematics	σ/σ_{SM} 95% Exclusion	$\lambda_{HHH}/\lambda_{HHH}^{SM}$ Lower Limit	$\lambda_{HHH}/\lambda_{HHH}^{SM}$ Upper Limit
30 GeV	Negligible	1.5	0.2	7
30 GeV	Current	5.2	-3.5	11
75 GeV	Negligible	2.0	-3.4	12
75 GeV	Current	11.5	-7.4	14

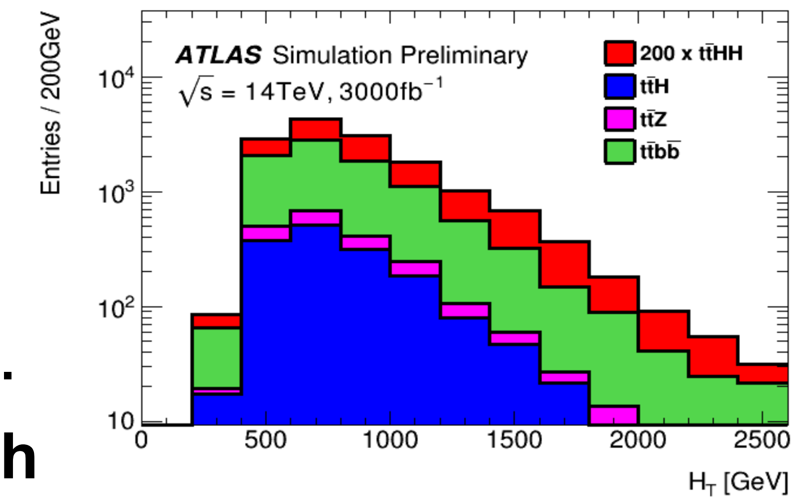
Key ingredients:
b-tagging efficiency
mistag rate +
jet trigger threshold
+ mass resolution

ttHH

- **Consider both H → bb and both t → b l v**
- **Trigger: single e/μ p_T > 25 GeV**
- **Analysis**
  - **≥7 jets with p_T > 30 GeV and $|\eta|$ < 4.0**
  - **≥5 jets b-tagged**
  - **Track confirmation to suppress pileup jets**
  - **Sel. on avg eta separation btw b-tagged jets t or H reco difficult due to combinatorics**



- **Event yields**
  - **Signal ≈ 19 (5 b-tags), 6 (≥6 b-tags)**
  - **Bkg ≈ 6600 (5 b-tags), 520 (≥6 b-tags)**
  - **SM signal ~ 0.35 σ**
  - **σ / σ_{SM} < 16 at 95% CL for 10% bkg uncert.**



- **Main background from ttbb events with W → cs and charm jet passing b-tagging requirements (only 3% of total bkg events has 6 true b-jets)**

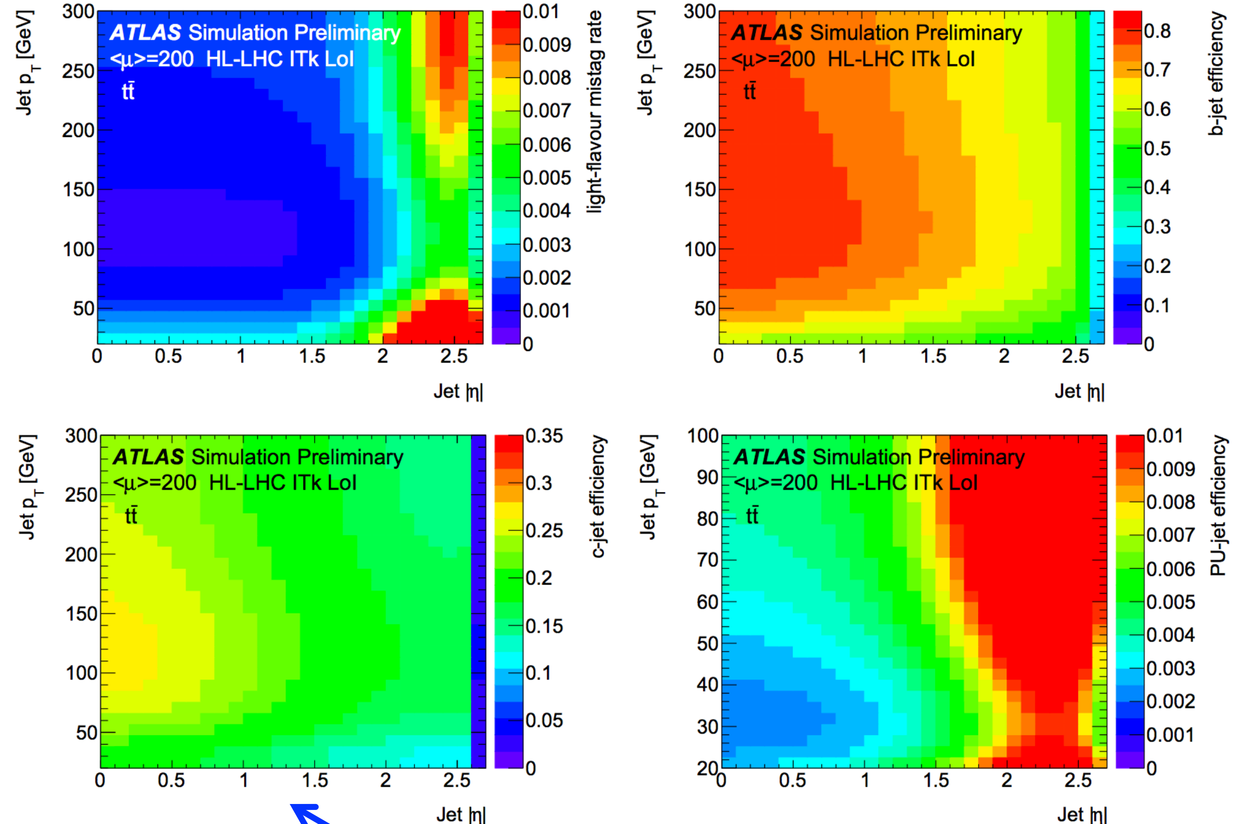
ttHH

ATL-PHYS-PUB-2016-023

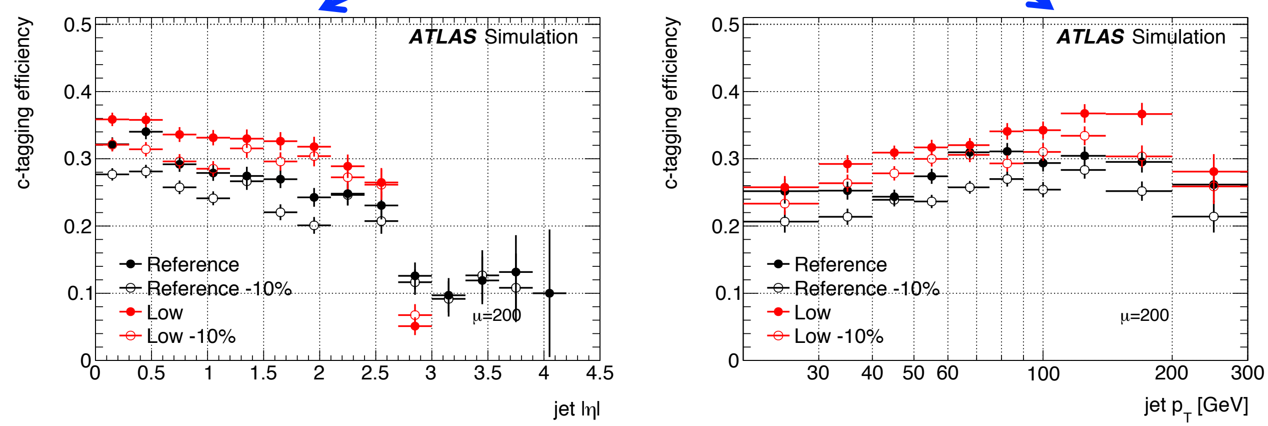
- **Efficiency to tag charm-jets ≈ 20% in $t\bar{t}$ MC sample for b-tagging 70% WP**

  Key ingredients:
  b-tagging efficiency
  & charm mistag rate

- **Scoping document: Impact of reduced trk coverage and reduced number of layers, as well as 10% dead modules**



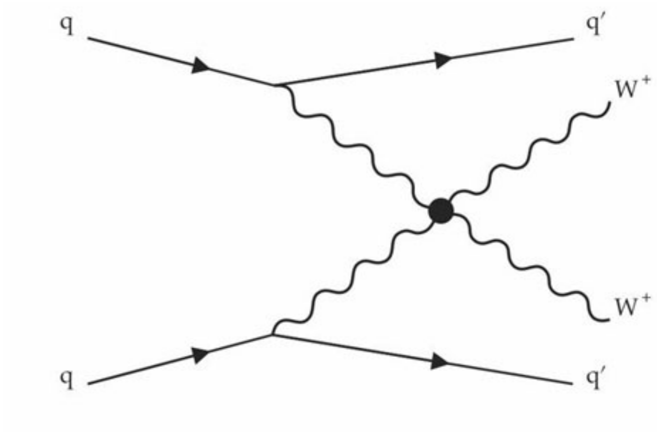
Charm-jet mistag rate

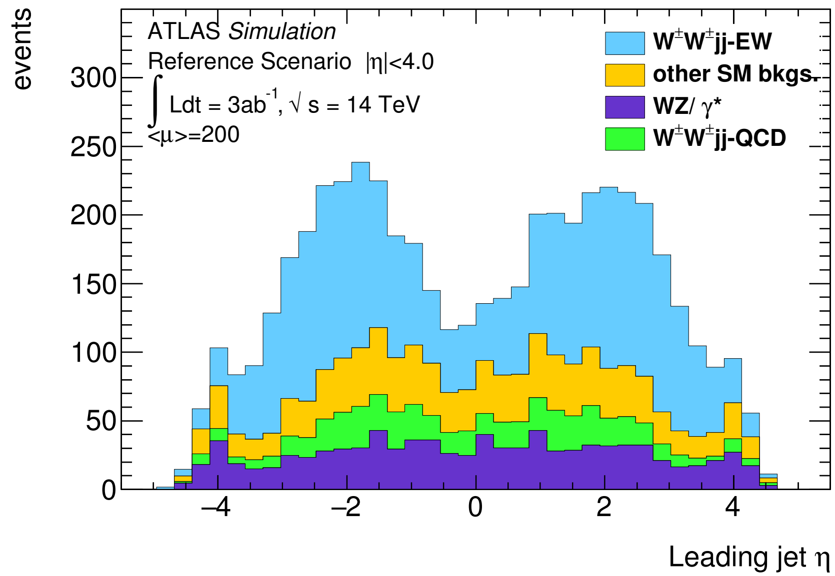


Vector Boson Scattering: W±W±

CERN-LHCC-2015-020

- **Test of Electroweak Symmetry Breaking**
- **Final state: 2 forward jets + 2 same-sign e/μ and E_T^{miss} (from W → lν decays)**
- **Trigger: single e/μ with p_T > 25 GeV**
- **Trk confirmation imposed on all jets**
- **Based on existing 8 TeV analysis**





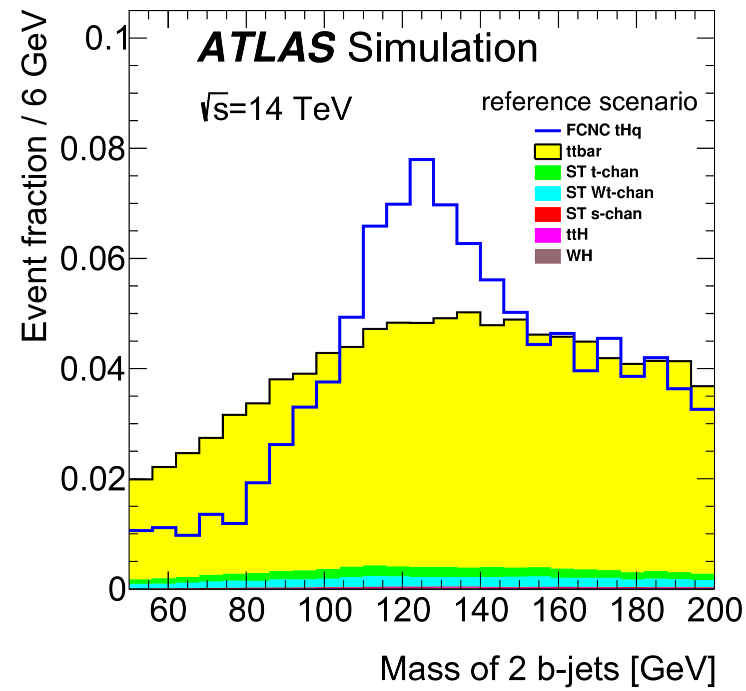
- **Strong degradation of signal significance for Middle & Low scenarios**
  - **Increased WZ+jj bkg due to 3rd e/μ out of acceptance**
  - **Higher pileup contamination for forward tagging jets**

Scenario	Z_{σ_B}	$\Delta\sigma/\sigma$
Reference scenario	11.3 ± 0.6	5.9%
Middle scenario	6.06 ± 0.3	11%
Low scenario	5.02 ± 0.2	13%

t → uH, cH FCNC

ATL-PHYS-PUB-2016-019

- **SM: BR(t → cH) ≈ 3 × 10^{-15}**
- **BSM: BR ≈ 10^{-5} – 10^{-3} in 2HDM, 10^{-9} – 10^{-5} in MSSM**
- **$t\bar{t}$ events with multi-channel selection: 2 or 3 b-jets + N jets + l ν**
- **Discriminant to identify H, W, t mass peaks: t → b W vs. t → c H**
- **Systematic uncertainty scenarios A: 2% lumi, 62% ttbar, 50% single top (set B has lower uncert.)**



Layout	Set	$t \to Hu$	$t \to Hc$	$t \to Hu + Hc$
Reference	A	$2.4 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$
	B	$2.4 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$
Middle	A	$2.9 \cdot 10^{-4}$	$2.4 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$
	B	$2.9 \cdot 10^{-4}$	$2.4 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$
Low	A	$3.5 \cdot 10^{-4}$	$3.0 \cdot 10^{-4}$	$1.7 \cdot 10^{-4}$
	B	$3.5 \cdot 10^{-4}$	$3.0 \cdot 10^{-4}$	$1.7 \cdot 10^{-4}$

Key ingredients:
b-tagging efficiency &
mistag rate
+ mass resolution

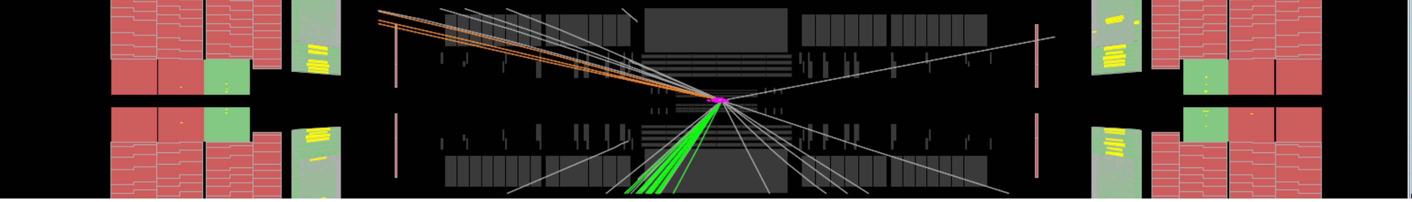
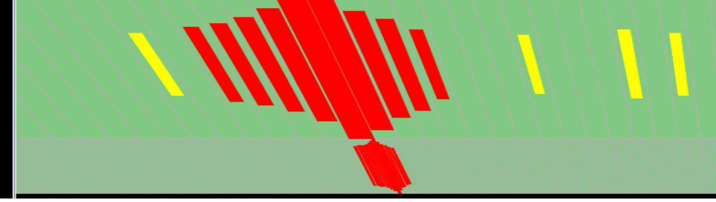
Summary

- Important Higgs physics program requires excellent performance of upgraded detector to cope with high event rates and pileup

- Large |eta| tracking coverage key to suppress pileup in some key measurement channels like VBF Higgs production

- Ability to measure Higgs self-coupling requires further improvements in analysis, reconstruction and low trigger thresholds + excellent b-tagging performance

- Rare Higgs decay modes (e.g. $H \rightarrow \mu\mu$ and $H \rightarrow Z\gamma$) are also an important part of the physics program

Additional material

References

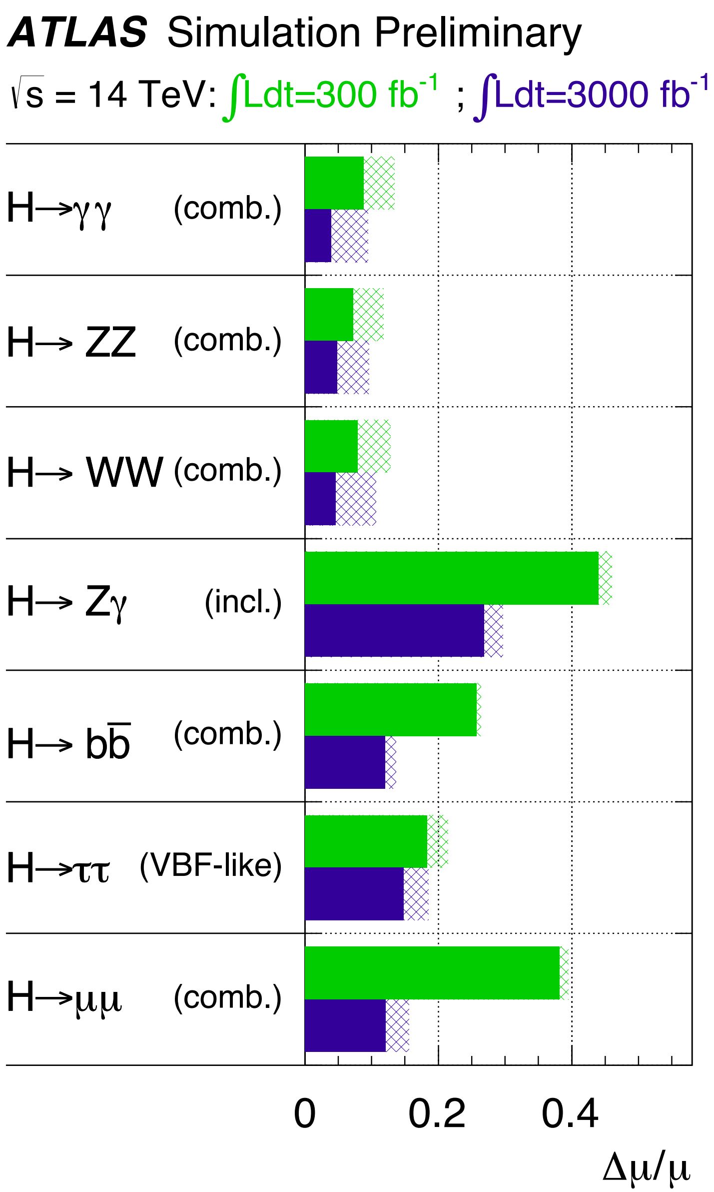
- **Public documents related to Upgrade Physics and Detectors**
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies
- **Detector**
  - **Scoping document**
    https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/UPGRADE/CERN-LHCC-2015-020
- **ECFA 2016**
  - https://indico.cern.ch/event/524795/

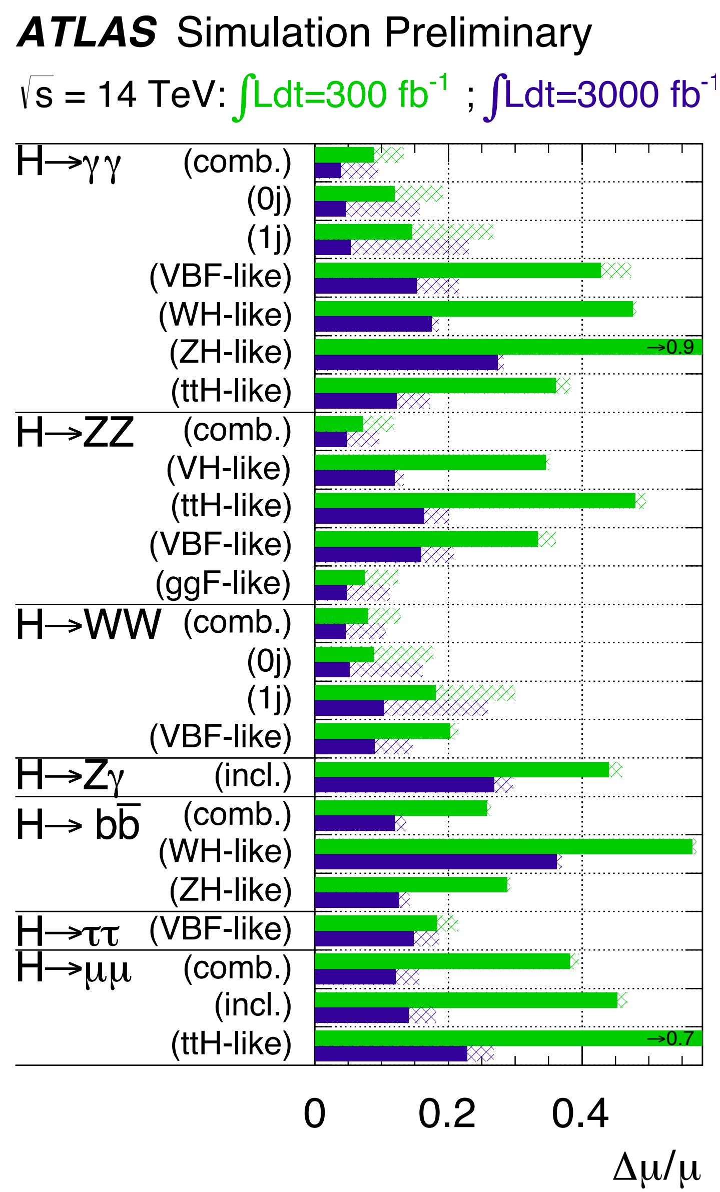
References

- **Higgs physics prospects**
  - **HH → bbbb (ATL-PHYS-PUB-2016-024)**
    http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2016-024/
  - **ttHH with HH → bbbb (ATL-PHYS-PUB-2016-023)**
    https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2016-023
  - **t → cH FCNC (ATL-PHYS-PUB-2016-019)**
    http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2016-019/
  - **VBF H → WW(*) → eν μν (ATL-PHYS-PUB-2016-018)**
    http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2016-018/
  - **VBF H → ZZ(*) → 4 l (ATL-PHYS-PUB-2016-008)**
    http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2016-008/
  - **HH → bbττ (ATL-PHYS-PUB-2015-046)**
    https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2015-046/
  - **HH → bbγγ (ATL-PHYS-PUB-2014-019)**
    http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2014-019/
  - **Projections for Higgs boson signal strengths and coupling parameters**
    http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2014-016/

Higgs coupling projections

ATL-PHYS-PUB-2014-016





VBF H → WW*

ATL-PHYS-PUB-2016-018

Category	$N_{\text{jet}} \geq 2$
Pre-selection	Two isolated leptons (one e and one μ) with opposite charge Leptons with $p_{\text{T}}^{\text{lead}} > 25$–$28$ GeV and $p_{\text{T}}^{\text{sublead}} > 15$ GeV $m_{\ell\ell} > 10$ GeV
Jet-corrected-track-$E_{\text{T}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}} > 20$ GeV
General selection	$p_T^{\text{jet}} > 70$ (60) GeV lead (sublead) $N_{\text{b-jet}} = 0$ (before pile-up jet removal) $p_{\text{T}}^{\text{tot}} < 20$ GeV veto (Collinear approx. $m_{\tau\tau} < 50$ GeV)
VBF topology	$m_{\text{jj}} > 1250$ GeV and $\lvert\eta_j\rvert > 2.0$, opposite hemisphere No jets ($p_{\text{T}} > 30$ GeV) in rapidity gap (CJV) Require both ℓ in rapidity gap
$H \to WW^* \to e\nu\mu\nu$ topology	$m_{\ell\ell} < 60$ GeV $\Delta\phi_{\ell\ell} < 1.8$ $m_{\text{T}} < 1.07 \times m_H$

	$N_{\text{jet}} \geq 2$	
Bkg. process	14 TeV (%)	Run-1 (%)
WW	10	30
VV	10	20
$t\bar{t}$	10	33
$tW/tb/tqb$	10	33
Z+jets	10	20
W+jets	20	30

Higgs Physics at HL-LHC