Measurement prospects for Higgs boson pair-production at the HL-LHC

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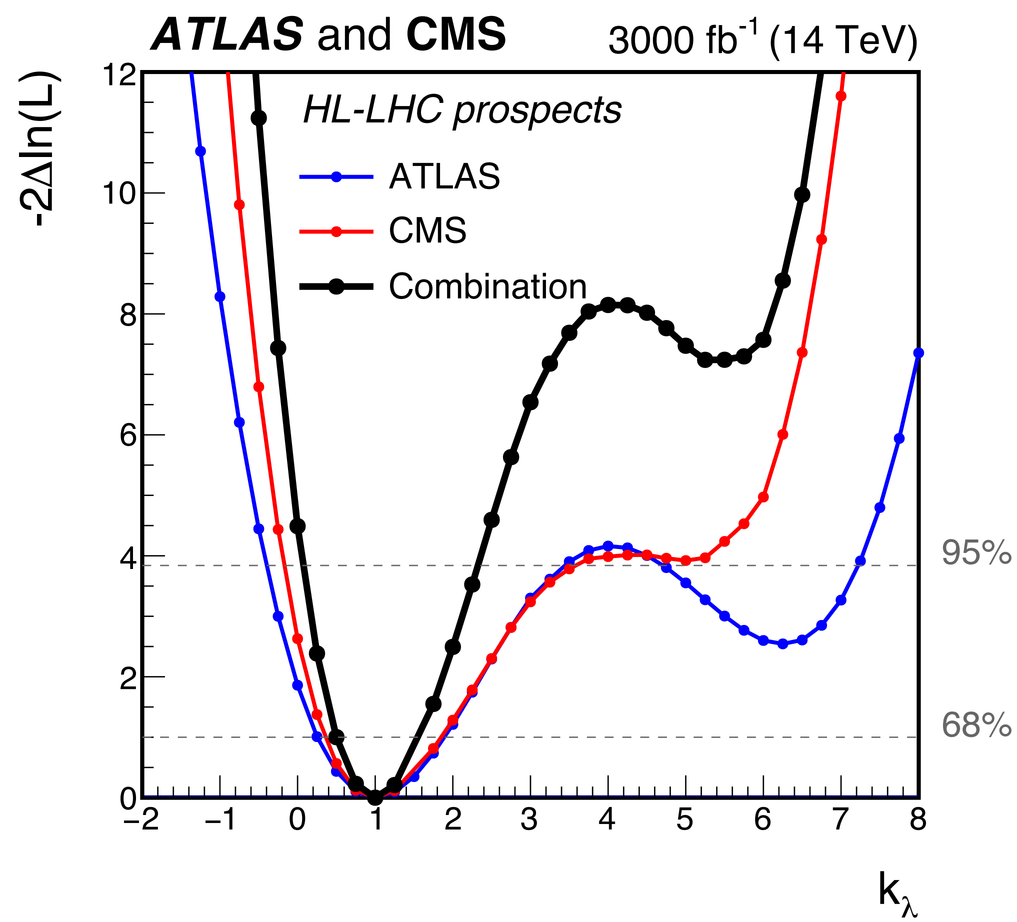
On behalf of the
ATLAS and CMS Collaborations



UNIVERSITY OF BIRMINGHAM

ATLAS EXPERIMENT

CMS

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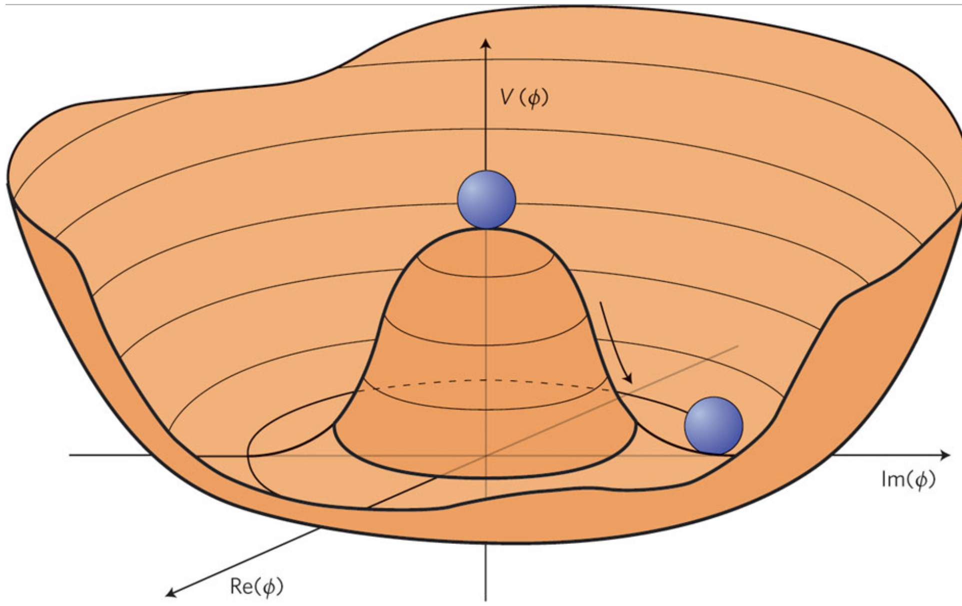
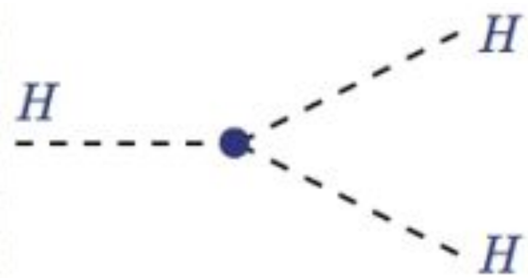
European Research Council
Established by the European Commission

Higgs boson self-coupling

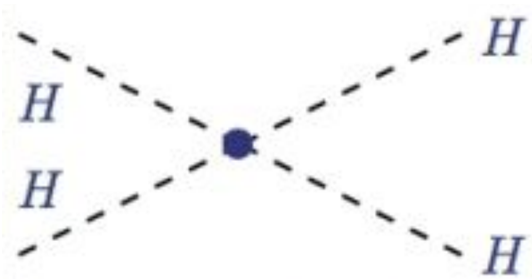
- **Electro-weak symmetry breaking foundation of SM**
  - Details have cosmological implications
  - What is the source of symmetry breaking?
  - Does the Higgs potential have the SM postulated shape?
  - Is there a Bardeen–Cooper–Schrieffer theory for our Landau-Ginzburg model?
- **Higgs self-coupling probes shape of potential**
  - Sensitive to new physics!
- **Trilinear and Quartic self-couplings in the SM**
  - Trilinear coupling probed through HH production
  - Quartic coupling further suppressed



$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



$$\lambda_{HHH} = 3m_H^2/v$$



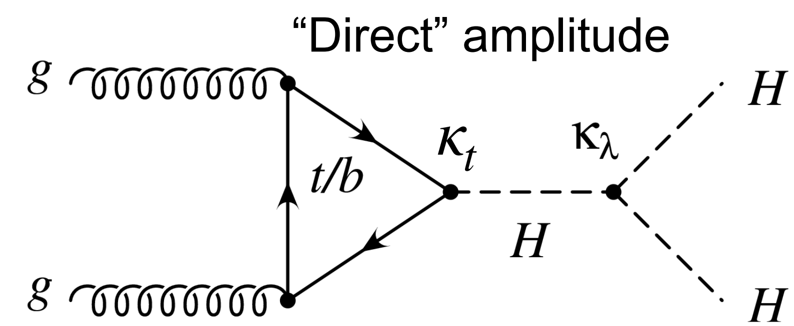
$$\lambda_{HHHH} = 3m_H^2/v^2$$

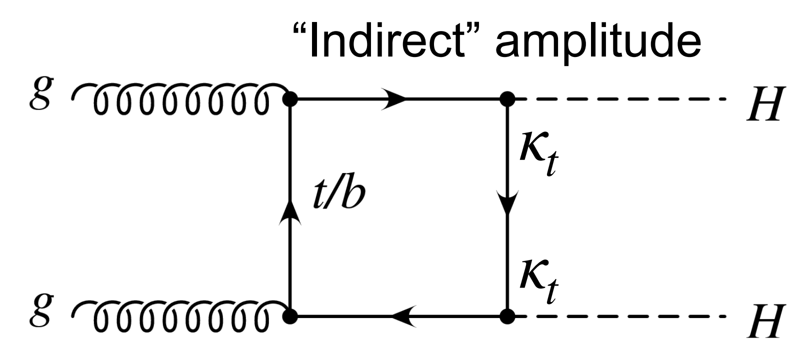
- **Indirect approaches to probe Higgs boson self-coupling**
  - Single Higgs boson production rate and differential distributions
  - Sensitive to trilinear H coupling through loops
  - See talk by S. P. Jones

HH production

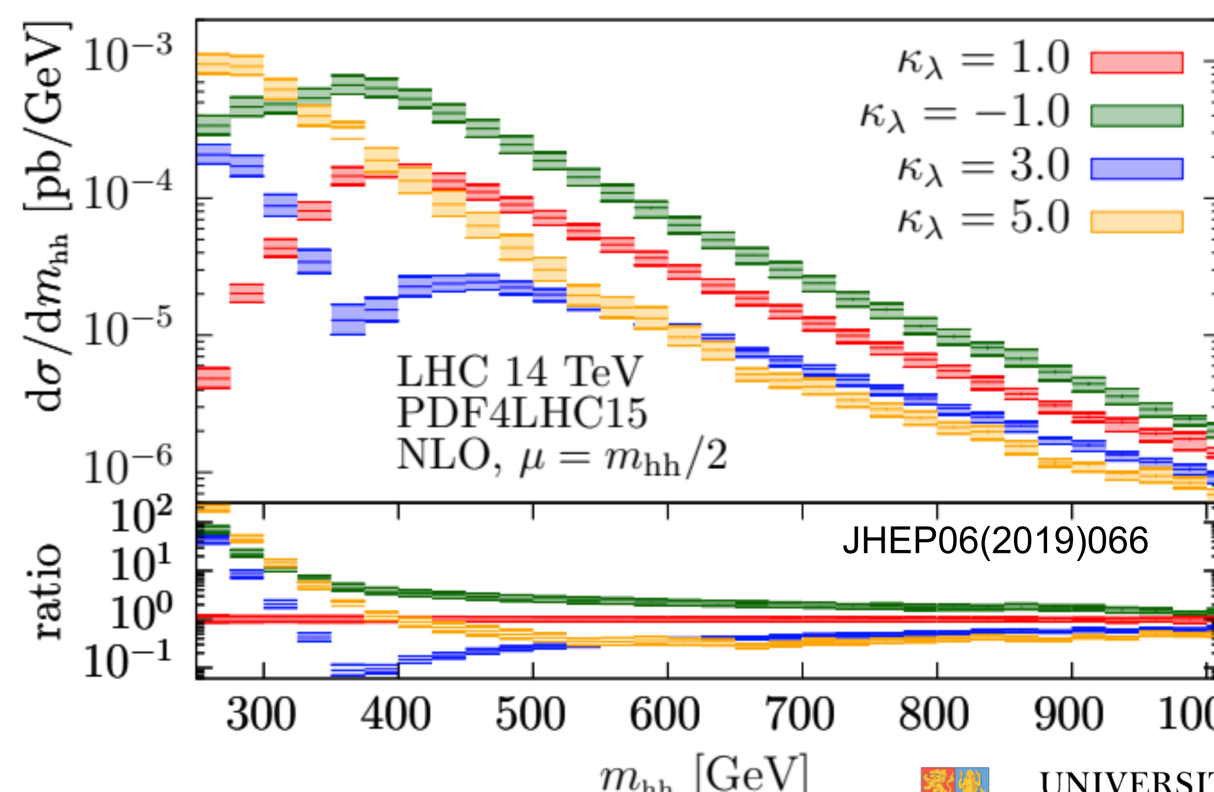
- **HH production is rare!**
  - $\sigma_{HH} \approx \sigma_H / 1500$
  - Gluon fusion dominates production
    - SM cross-section ~37fb @ 14TeV
    - ~90% of total
- **Gluon fusion** → Two contributions
  - **Direct amplitude:** $\sim \kappa_\lambda \kappa_t$
  - **Indirect amplitude:** $\sim \kappa_t^2$
  - **Destructive interference**
- **Kinematics** depend on Higgs self-coupling
  - Additional handle to κ_λ
- **HH: multiple final states**
  - H→bb is the protagonist

$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

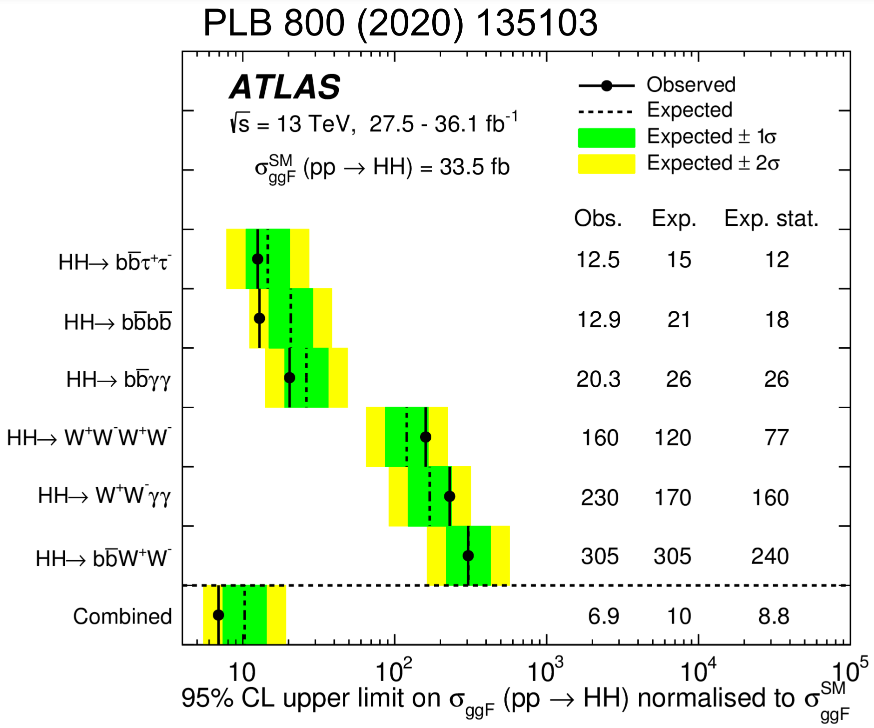


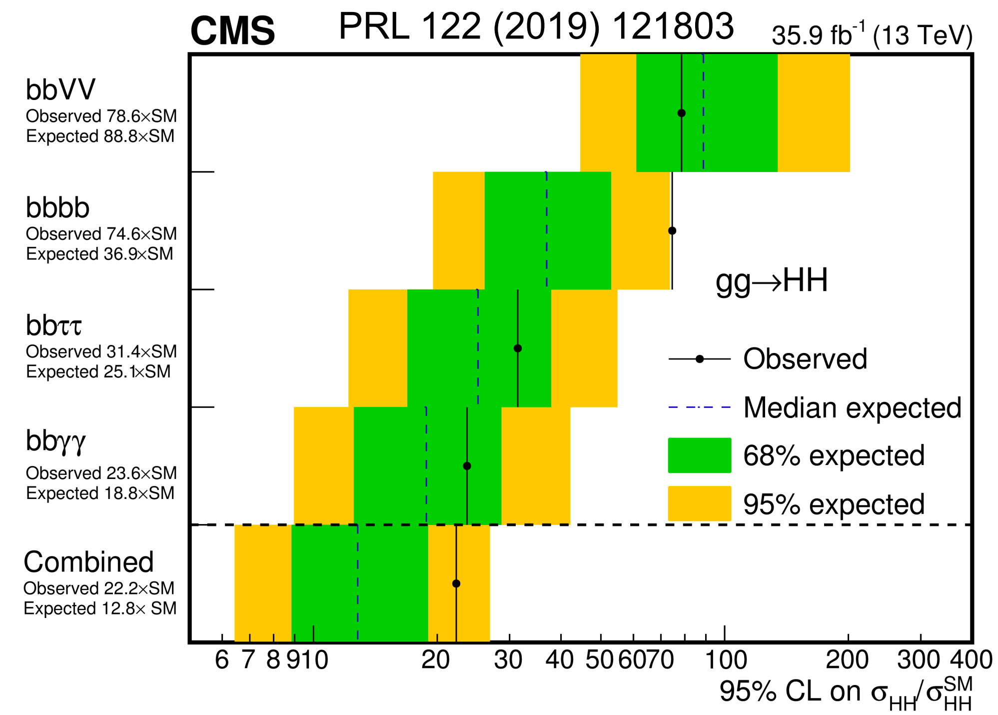


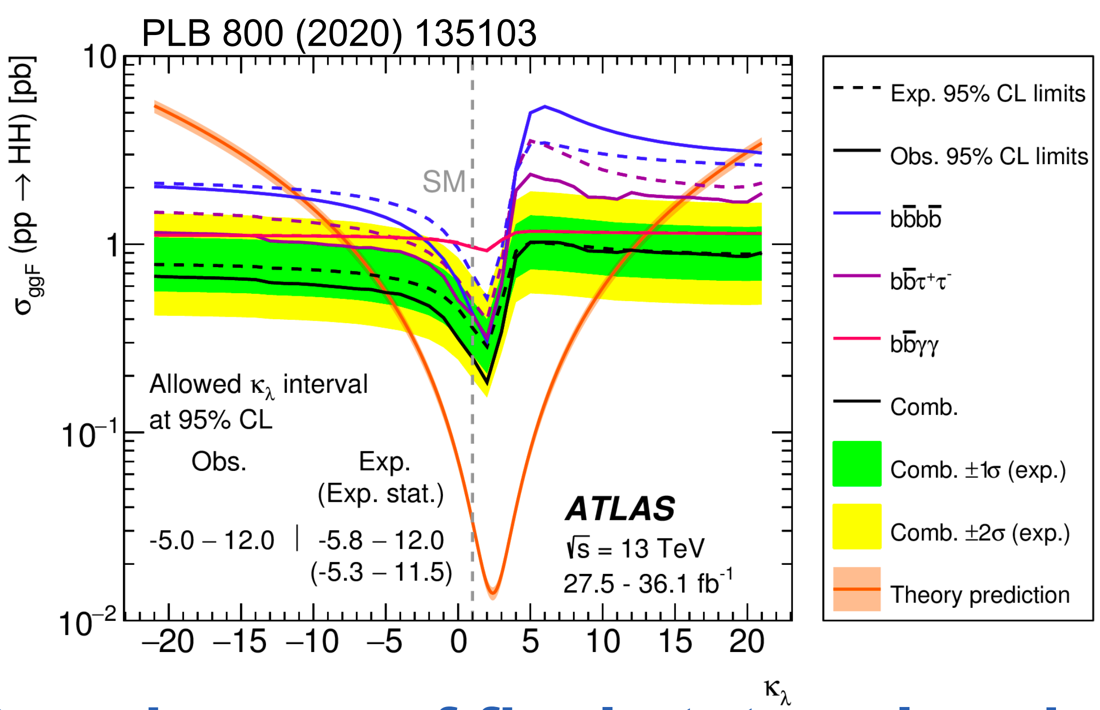
	bb	WW	ττ	ZZ	γγ
bb	33.9%				
WW	24.9%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.07%	
γγ	0.26%	0.10%	0.03%	0.01%	

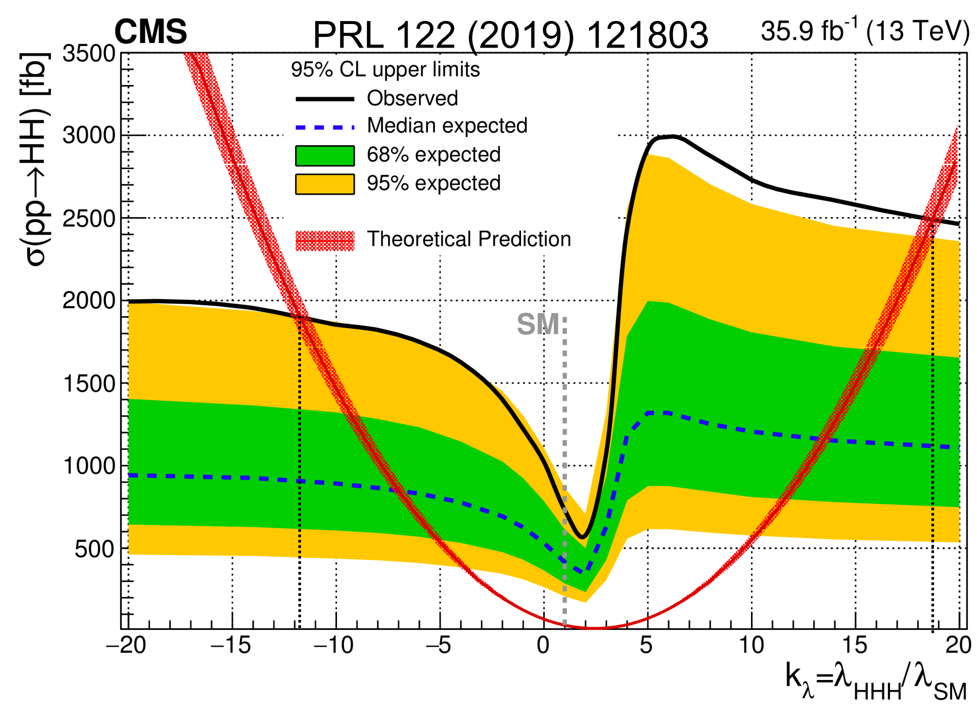


Experimental state-of-the-art



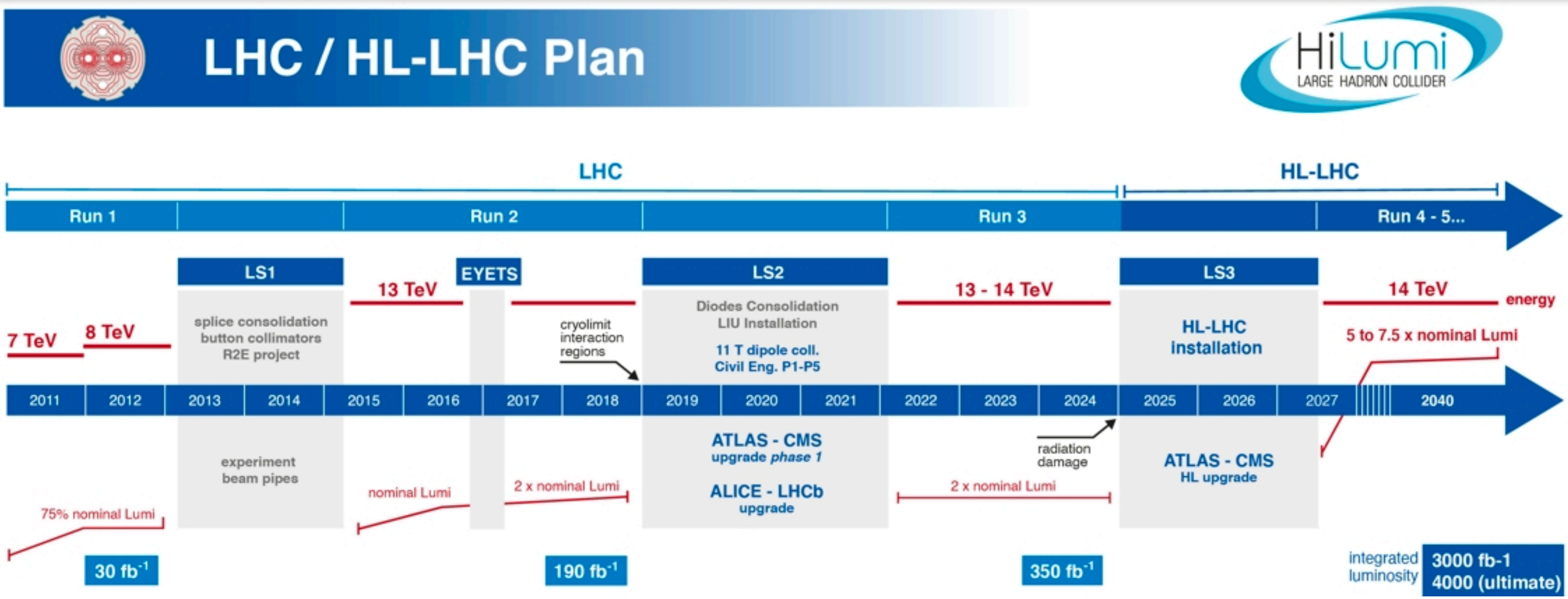






- **Broad range of final states already explored**
- Results with $\sim 35\ \mathrm{fb}^{-1}$ corresponding to 1/4 of the available Run 2 dataset
  - Further improvements expected, including Run 3 ($\sim 350\ \mathrm{fb}^{-1}$)
- **Details and latest results** in talks by E. Brost and A. Bethani

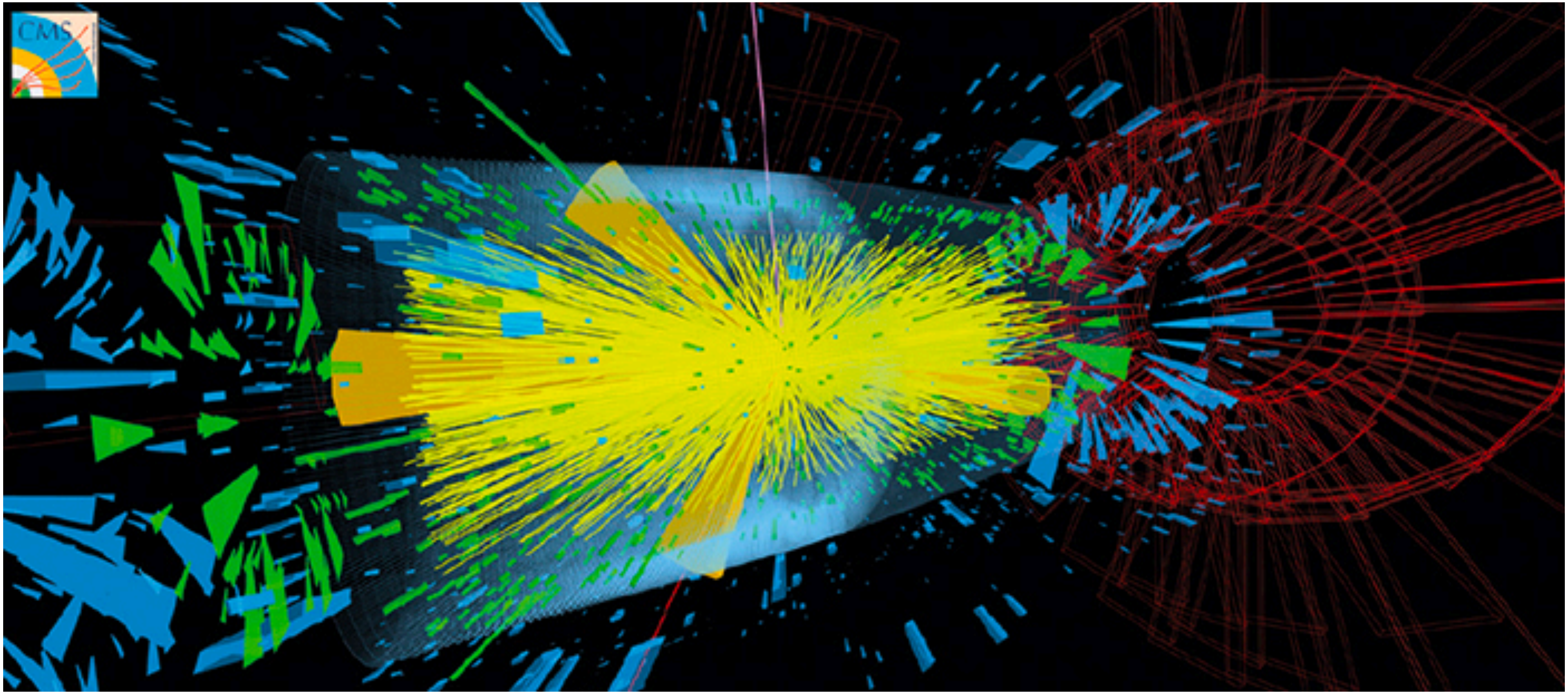
High Luminosity LHC



- **Extensive upgrades to accelerator complex** to maximise physics reach
  - 3000 fb^{-1} at 14 TeV (ultimately 4000 fb^{-1})
  - Instantaneous luminosity: $5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (ultimately $7.5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$)
  - Proton interactions per bunch crossing: $<\mu> \sim 140$ (ultimately $<\mu> \sim 200$)
- **Broad physics program:** SM, Higgs, top-quark, flavour, BSM searches
  - Study of Higgs boson self-coupling
  - Detailed measurements of Higgs boson properties
  - Searches for extended scalar sectors
- **Physics prospects updated** for European Strategy for Particle Physics
  - Assuming 3000 fb^{-1}

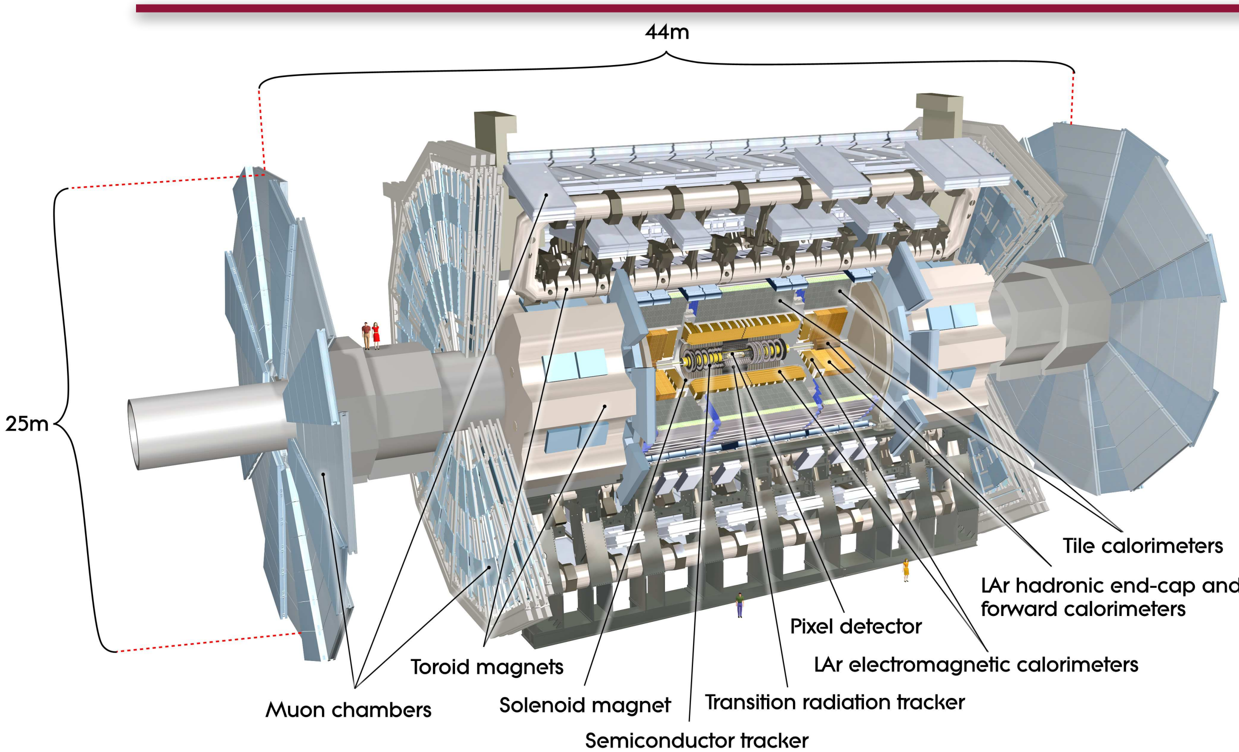
CERN-LPCC-2019-01

High Luminosity LHC



VBF H production at $< \mu > = 200$

ATLAS and CMS HL-LHC Upgrades



Muons: ATLAS-TDR-026
- Upgraded front-end & on-/off-detector readout/trigger electronics
- Additional RPC trigger chambers for |η|<1
- New trigger chambers RPC for |η|<1 and sMDTs
- Barrel recision measurements at trigger
- New Small Wheel
- High-η tagger (up to |η| < 4 still) considered

Trigger/DAQ: ATLAS-TDR-029
- Single L0 hardware trigger
- 1MHz output and 10μs latency
- 10kHz event data sent to storage with improved EF CPU-based farm

Inner Detector: ATLAS-TDR-025, ATLAS-TDR-030
- New all-silicon Inner TracKer (ITk)
- Improved |η| coverage 2.5 → 4

Calorimeters: ATLAS-TDR-027, ATLAS-TDR-028
- New read-out electronics
- Higher granularity at trigger

High Granularity Timing Detector: ATLAS-TDR-031
- 2.4<|η|<4.0
- 30ps timing resolution
- Pile-up suppression

MIP Timing Detector: CERN-LHCC-2017-027
- Positioned between tracker and ECAL
- 30 ps timing for |η|<3.0
- Pile-up suppression

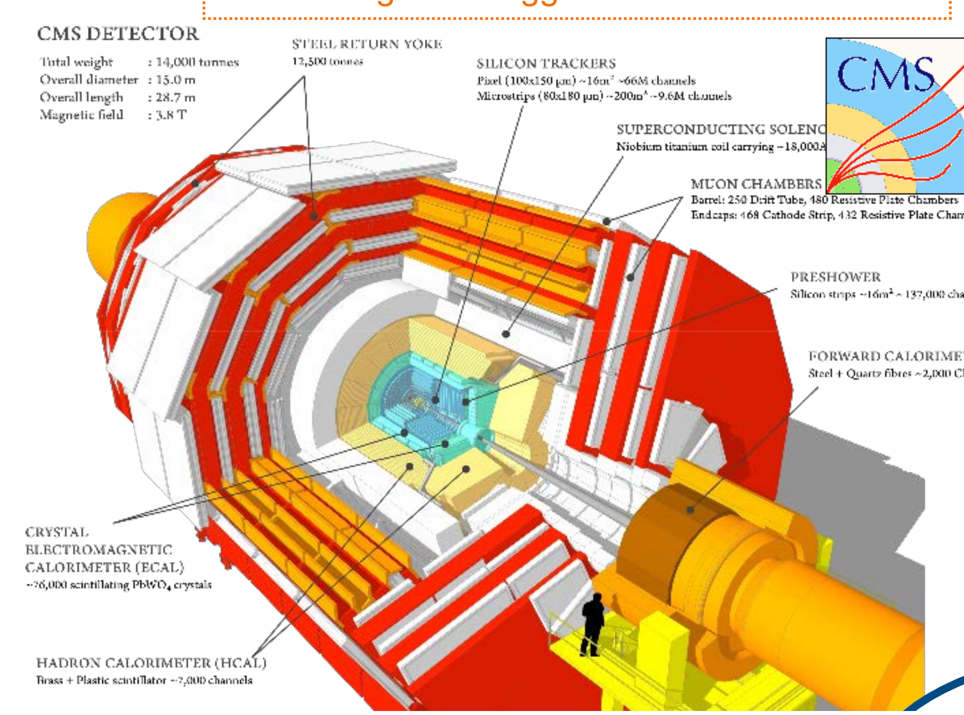
Trigger/DAQ: CMS-TDR-017, CMS-TDR-018)
- L1: 750 kHz output and 12.5μs latency; tracking/high granularity (Pflow-like) calorimeter information,
- HLT: 7.5 kHz output

Barrel Calorimeters: CMS-TDR-015
- ECAL/HCAL electronics upgrade
- ECAL crystal-level granularity at 40 MHz with precision timing
- Lower ECAL operating temperature

Endcap Calorimeters: CMS-TDR-019
- HGCal combined ECAL/HCAL
- 3D shower/precision timing ECAL/

Muons: CMS-TDR-016
- DT & CSC upgraded front-end electronics
- Endcap new RPCs and GEM
- Acceptance to |η| < 2.8

Tracker: CMS-TDR-014
- New silicon tracker (strips/pixels)
- Extended coverage to |η|<4.0
- Tracking at L1 trigger

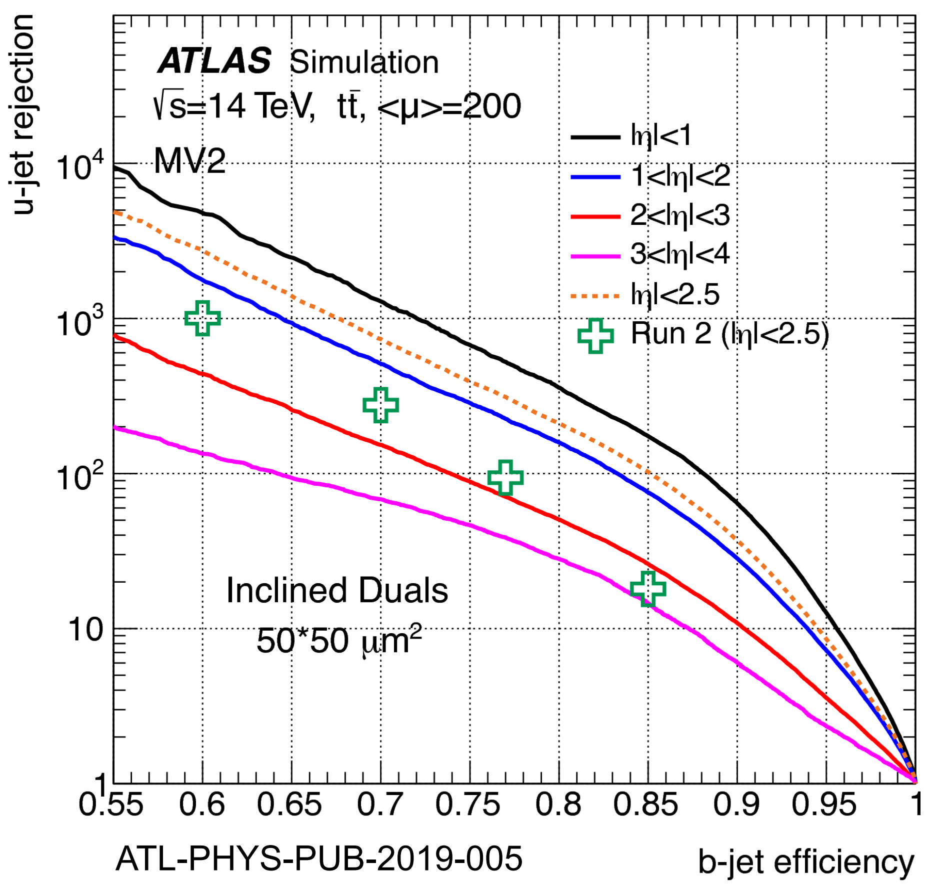


- **Maintain** detector performance
  - efficiency/rejection and resolution
- **Extend** η coverage
- **Upgrade trigger systems**
  - Bandwidth/latency & info granularity
  - Single e/μ p_T threshold: 27/27 (current) → 22/20 GeV
  - Maintain di-γ, di-tau and multi b-jet trigger thresholds
- Additional challenges: CPU, Sim, Disk space

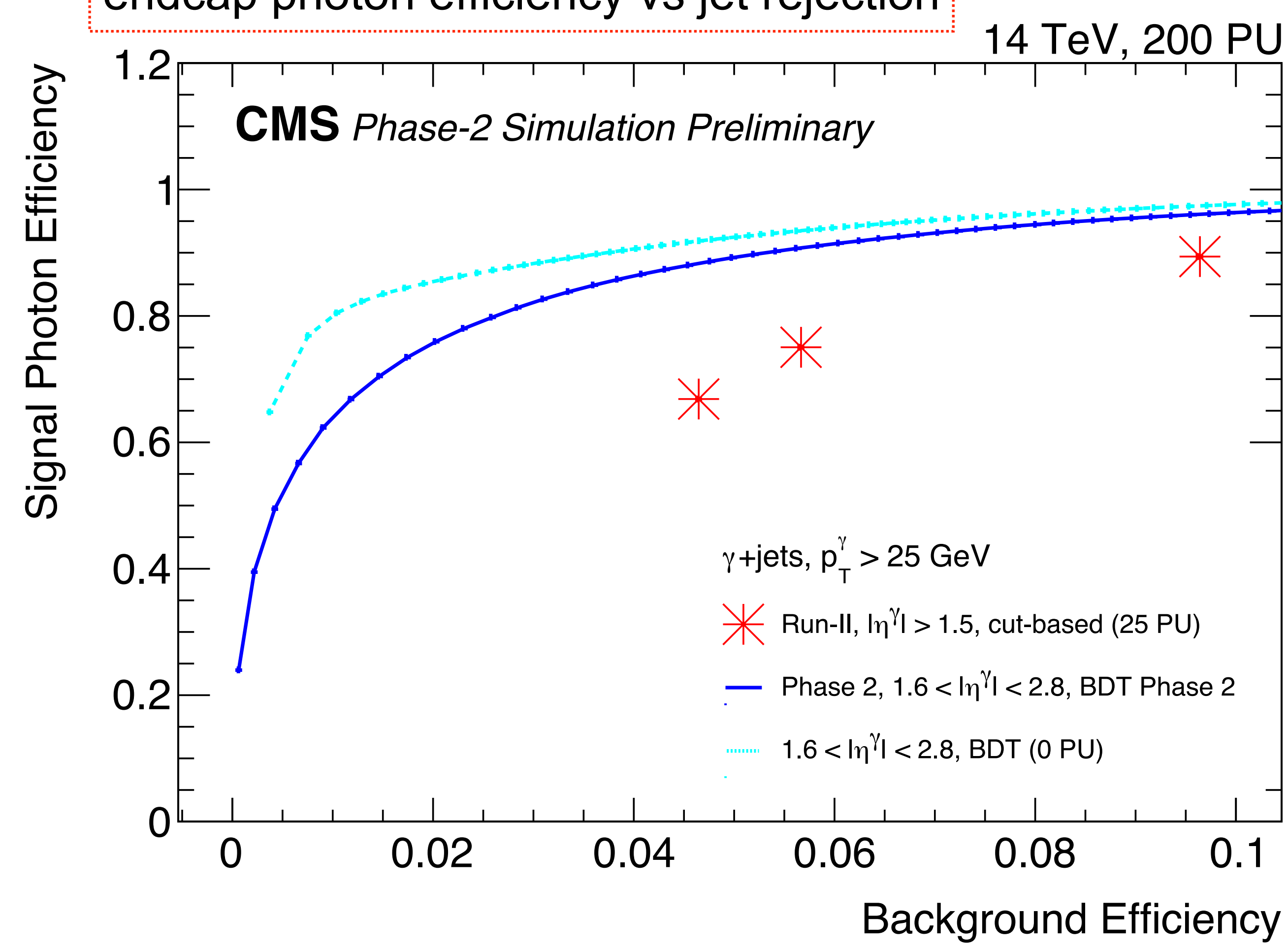
Expected Detector Performance

- Detector performance: **cornerstone for physics reach**
- **HH analyses span all physics objects**
- **Expected performance of upgraded detector**
  - Estimated with detailed full simulations
  - $<\mu> \sim 200$ considered to obtain conservative estimates

b-tagging efficiency vs light-jet rejection



endcap photon efficiency vs jet rejection



HH prospects at HL-LHC

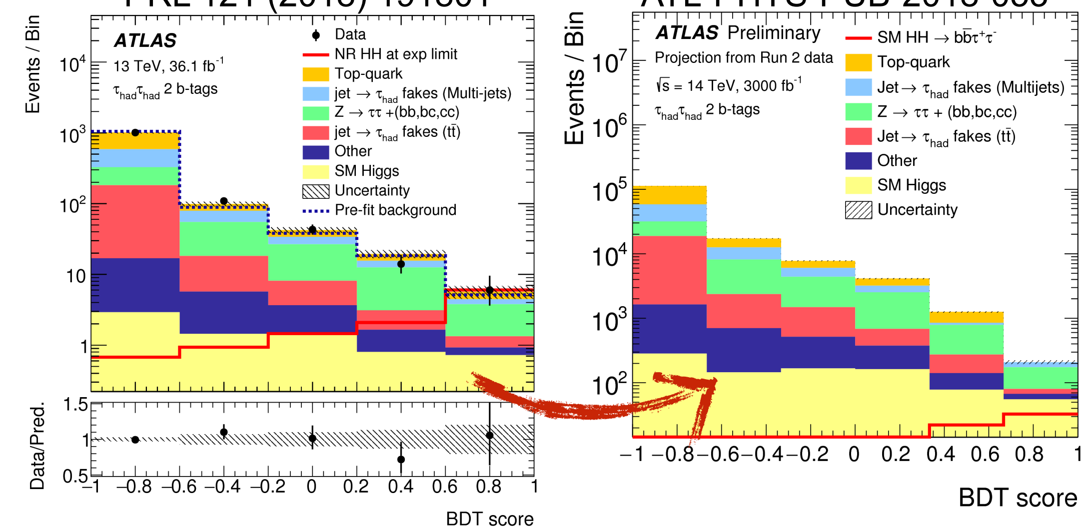
Final states explored:

- bbbb, bbττ, bbγγ, bbWW(→lνlν), bbZZ(→4l)

Channel	bbbb	$bb\tau\tau$	$bbWW(\ell\nu\ell\nu)$	$bb\gamma\gamma$	$bbZZ(\ell\ell\ell\ell)$
$\mathcal{B}$ [%]	33.9	7.3	1.7	0.26	0.015
Number of events	37000	8000	1830	290	17

Per experiment at 3000 fb^{-1}

PRL 121 (2018) 191801 ATL-PHYS-PUB-2018-053

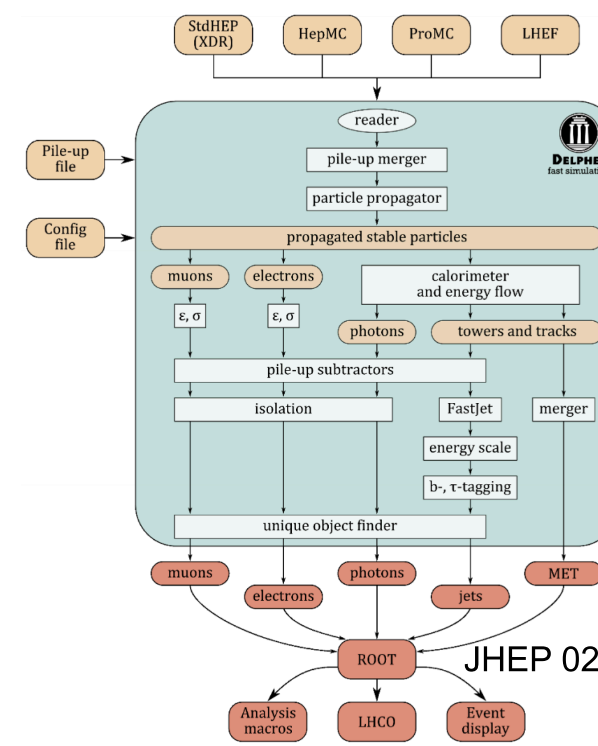


Strategy 1: Extrapolation of existing results

- Account for $\sqrt{s}$ and, partially, detector performance
- Full detail of published result
- ATLAS: bbbb, bbττ

Strategy 2: Parametric simulation

- Analysis design/optimisation
- Generator-level smearing/corrections; pile-up event overlay
- ATLAS bbγγ; CMS DELPHES parametric simulation



JHEP 02(2014)057

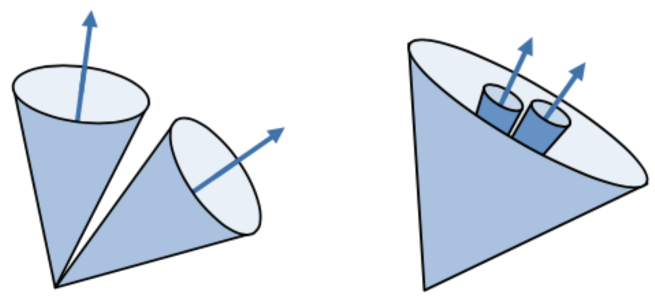
Systematic uncertainties crucial but difficult to predict

General guidelines; harmonised between ATLAS and CMS

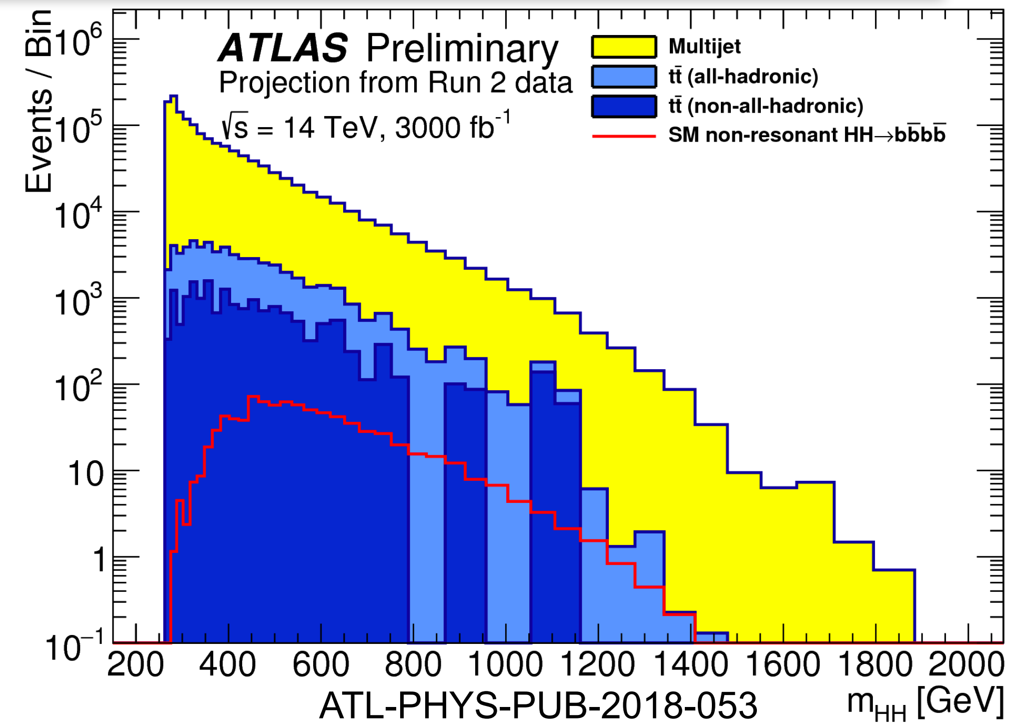
- Ignore MC statistical uncertainties
- Theory uncertainties reduced by 50%
- Detector-related uncertainties unchanged or revised from performance studies
- Uncertainties on methods unchanged

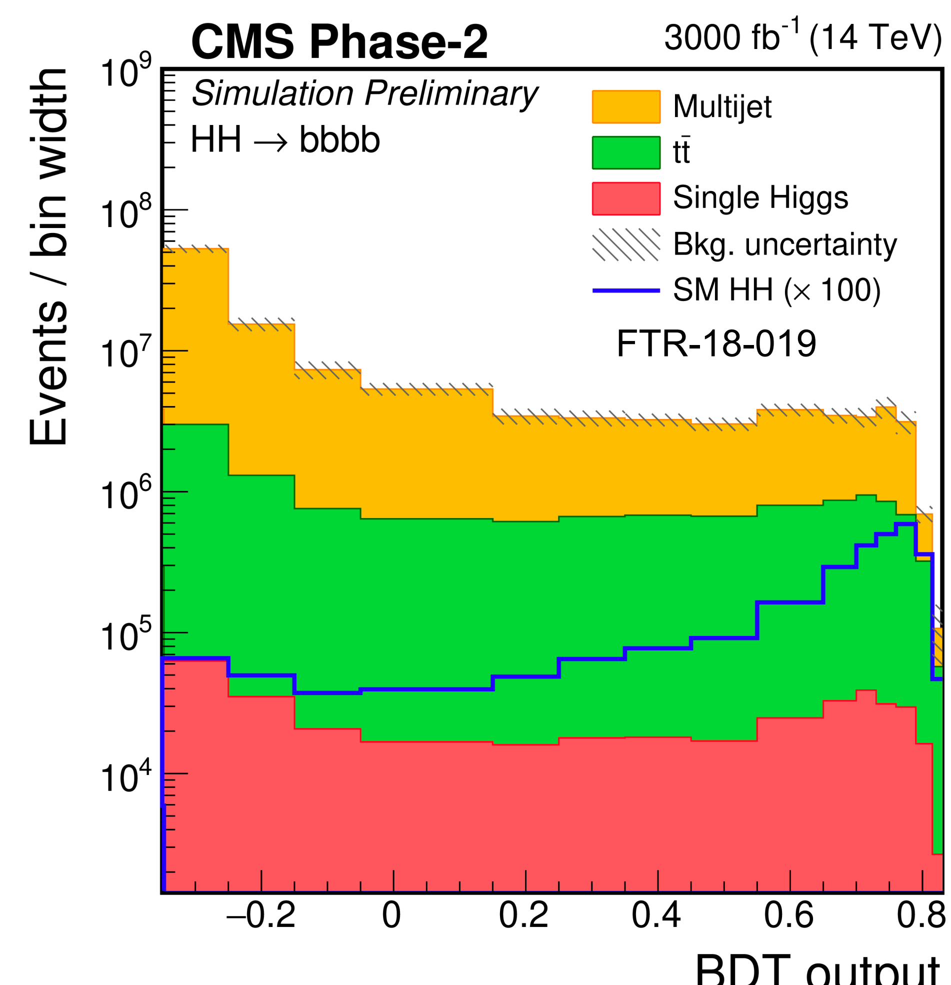
HH→bbbb

- **Two analysis regimes**
  - "Resolved"
  - "Boosted"($m_{HH} \gtrsim 1$ TeV) mostly sensitive to BSM



- **ATLAS**
  - Extrapolated "Resolved" 2016 data analysis
    - 4 jets pT>40 GeV and |η|< 2.5 (ε_b=70%)
    - σ_{HH}<13.0(20.7)xSM at 95% CL (27.5 fb^{-1})
    - Cut-based
  - Jet reco unchanged, ε_b+=8%
  - Main systematic: data-driven QCD background
    - Used Run 2 uncertainties (conservative)
- **CMS**
  - 4 jets pT>45 GeV and |η|< 3.5
  - b-tagging: ε=70%;1% light-flavour mis-tag rate
  - SM signal efficiency ~3.9%
  - S/B $\sim 1 \times 10^{-4}$
- **Final Discriminant**
  - ATLAS: m_{HH}
  - CMS: Boosted Decision Tree

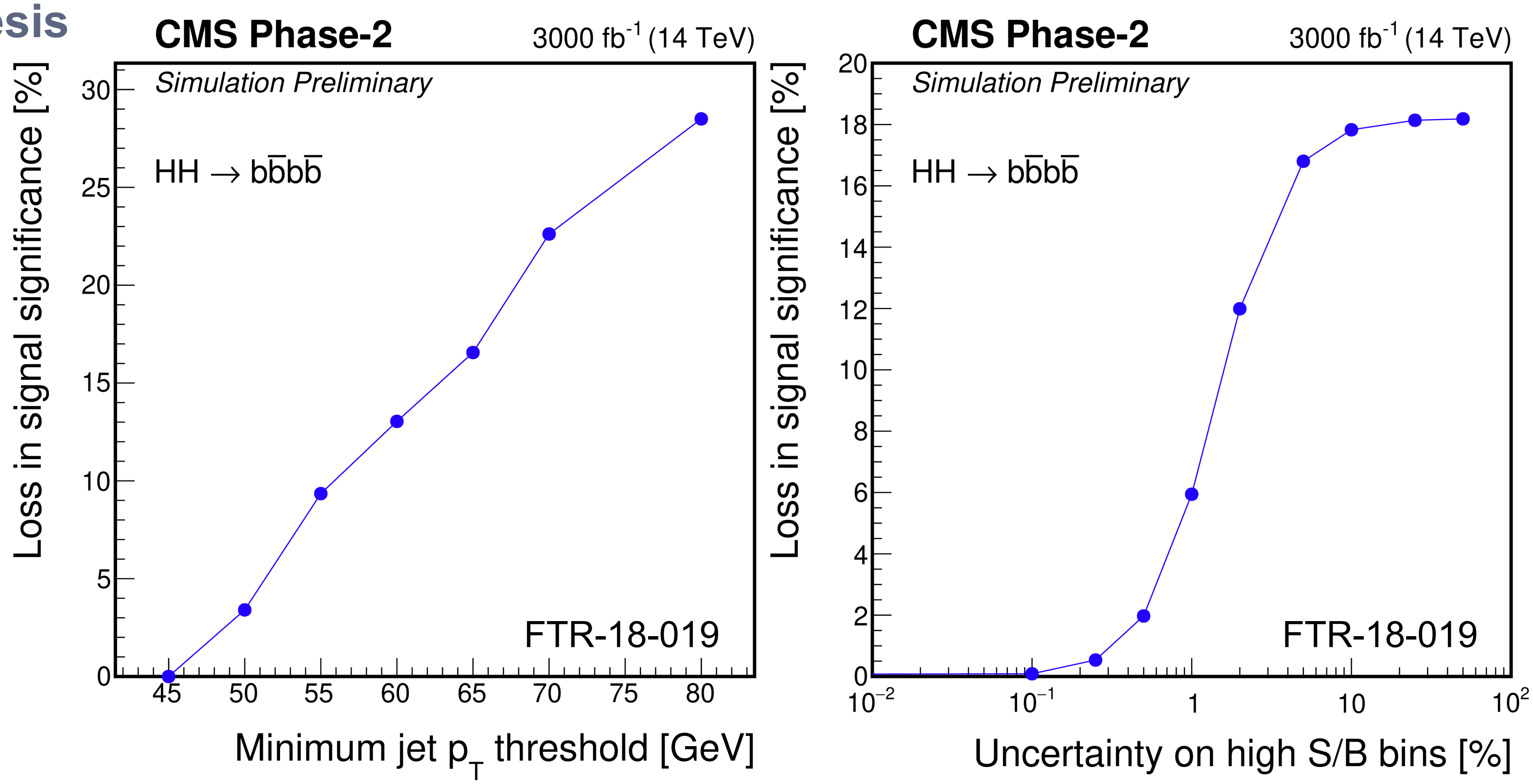


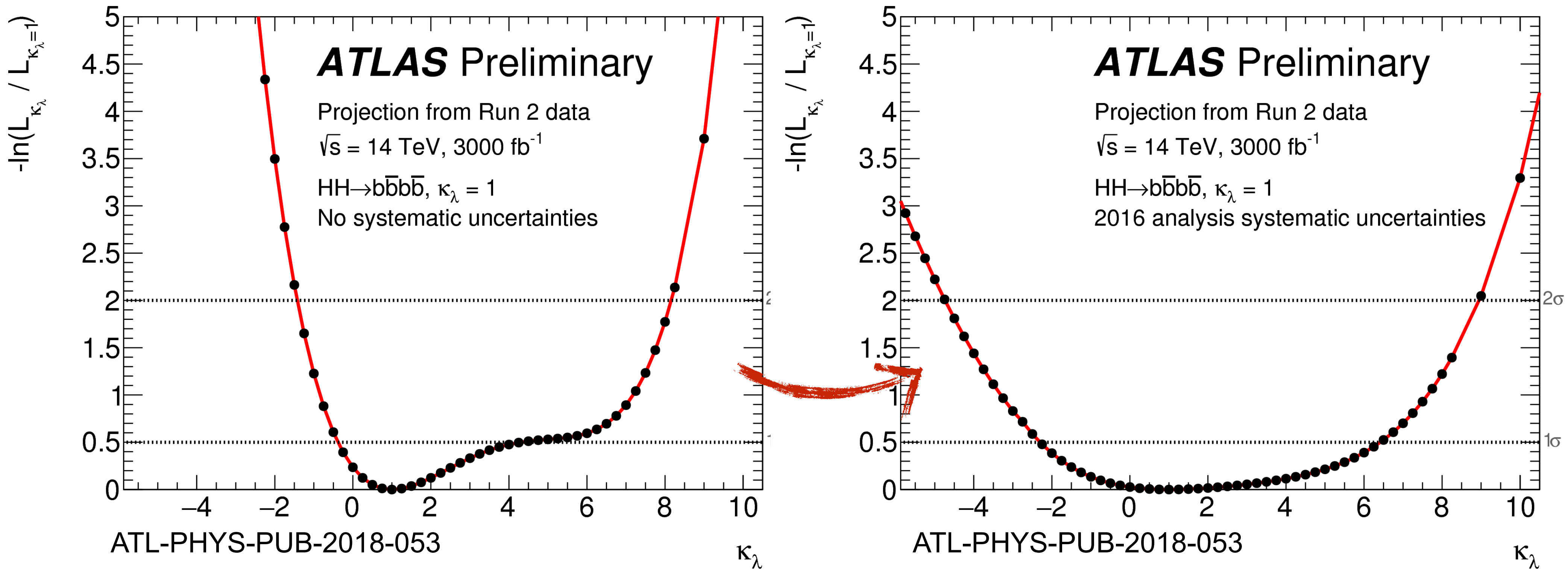


HH→bbbb

- Statistical Only in Parenthesis

- **ATLAS**
  - σ_{HH}< 3.3 (1.4)xSM 95% CL
  - significance 0.62 (1.4)σ
- **CMS**
  - σ_{HH}< 2.1 (1.6)xSM 95% CL
  - significance 0.95 (1.2)σ
- **Major Challenges**
  - Trigger thresholds
    - Run 2 trigger thresholds assumed
  - Background modelling





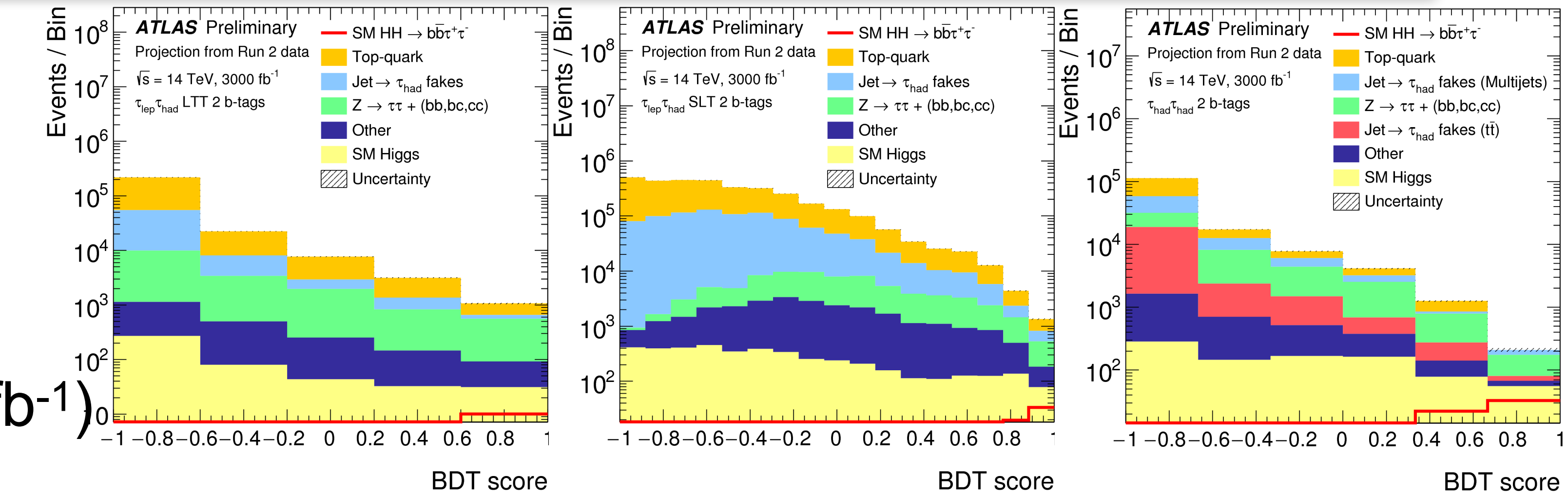
HH→bbττ

- $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$ considered
- **Triggers**
  - di-$\tau_{had\text{-}vis}$
  - single lepton & lepton-plus-$\tau_{had\text{-}vis}$
- **ATLAS**
  - Extrapolated Run 2 analysis (36.1 fb^{-1})
  - σ_{HH}<12.7 (14.8)xSM at 95% CL
- **CMS**

Lepton	Min. p_T [GeV]	Max. $\|\eta\|$	Max. iso [GeV]
Primary μ	23	2.1	0.15
Primary e	27	2.1	0.1
Veto e/μ	10	2.4	0.3
Hadronic tau	**Min. p_T [GeV]**	**Max. $\|\eta\|$**	
$\ell\tau_h$bb (ℓ = e, μ)	20	2.3	
$\tau_h\tau_h$bb	45	2.1	

ATLAS Run 2
p_T > 35/25 GeV

  - b-jets pT>30 GeV and |η|<2.4
  - S/B:
    - $\tau_{lep}\tau_{had}$: $\sim 2\times10^{-5}$
    - $\tau_{had}\tau_{had}$: ~ 0.05
- **Final Discriminant**
  - ATLAS: BDT (adaptive binning)
  - CMS: 10 fully-connected DNN (ensemble)
    - 3 hidden layers × 100 neurons
    - 52 variables



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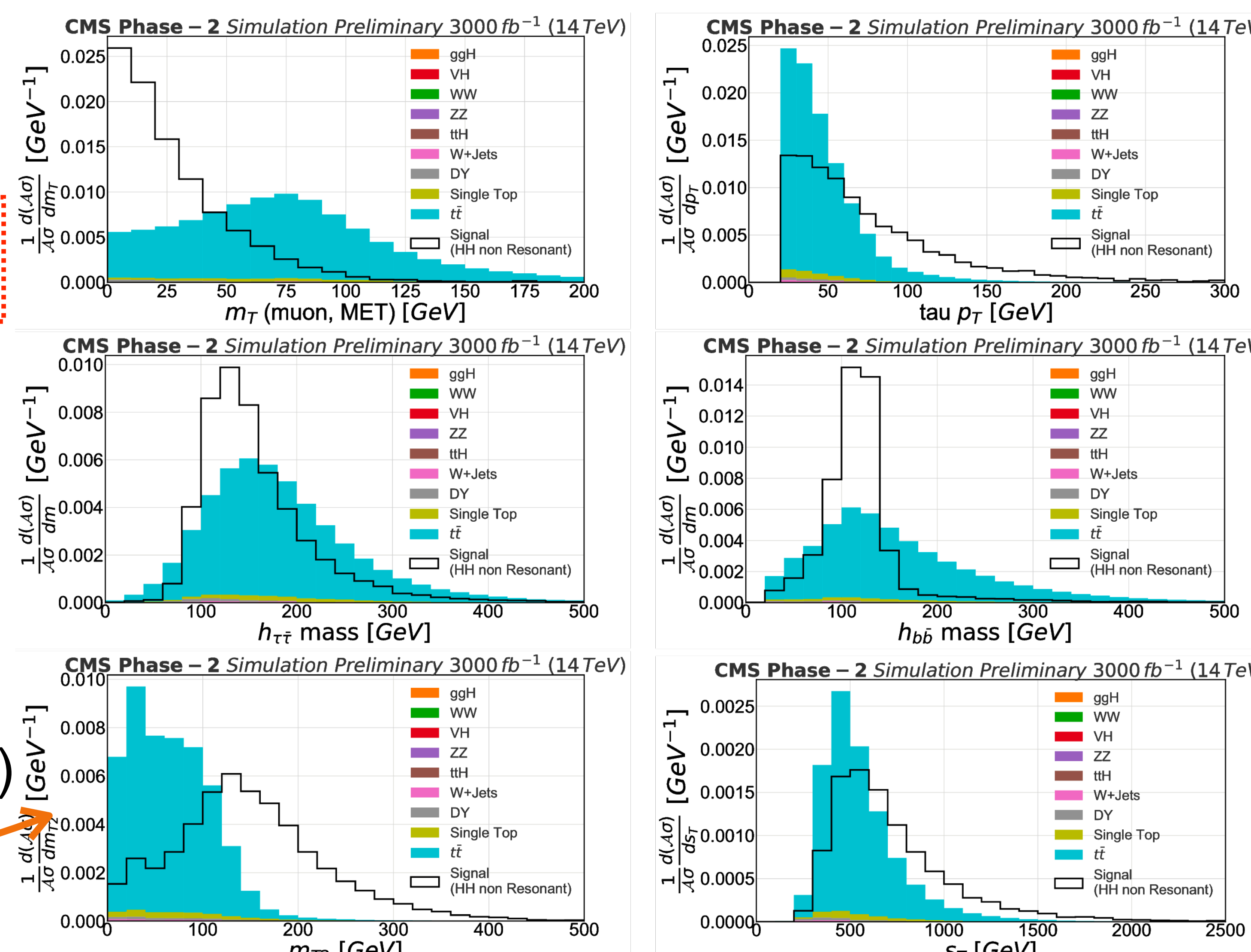
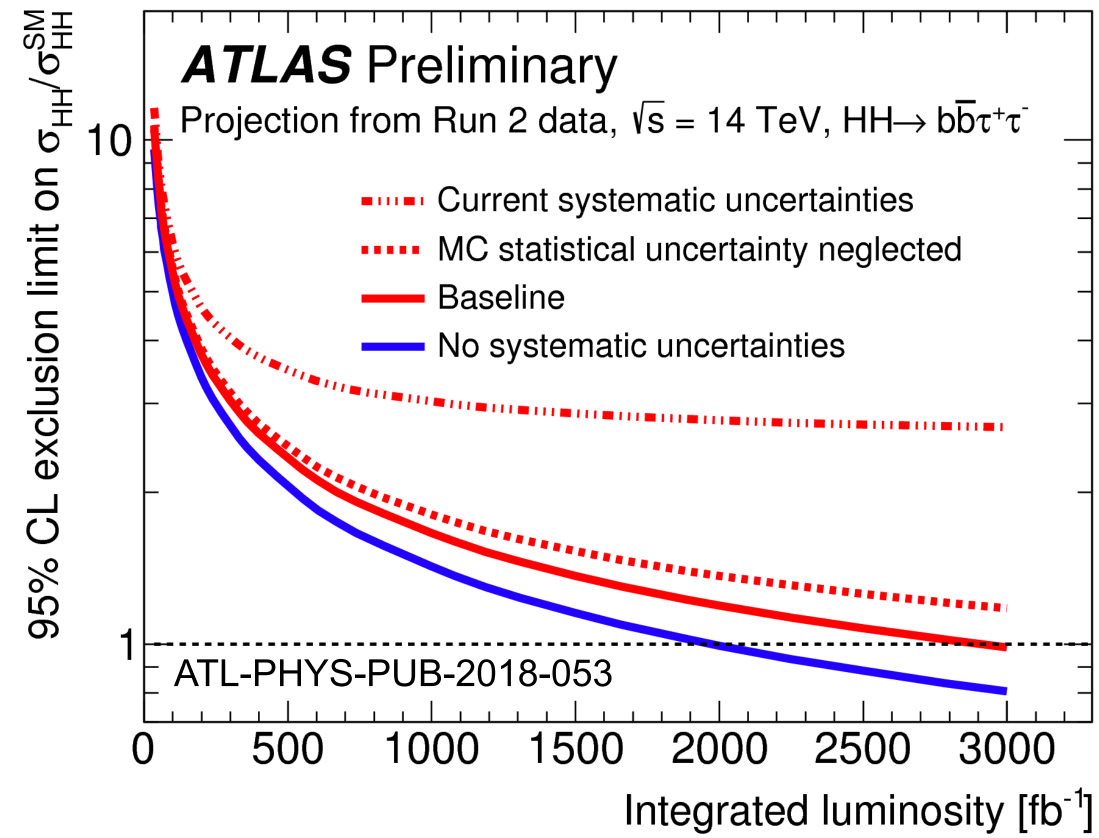


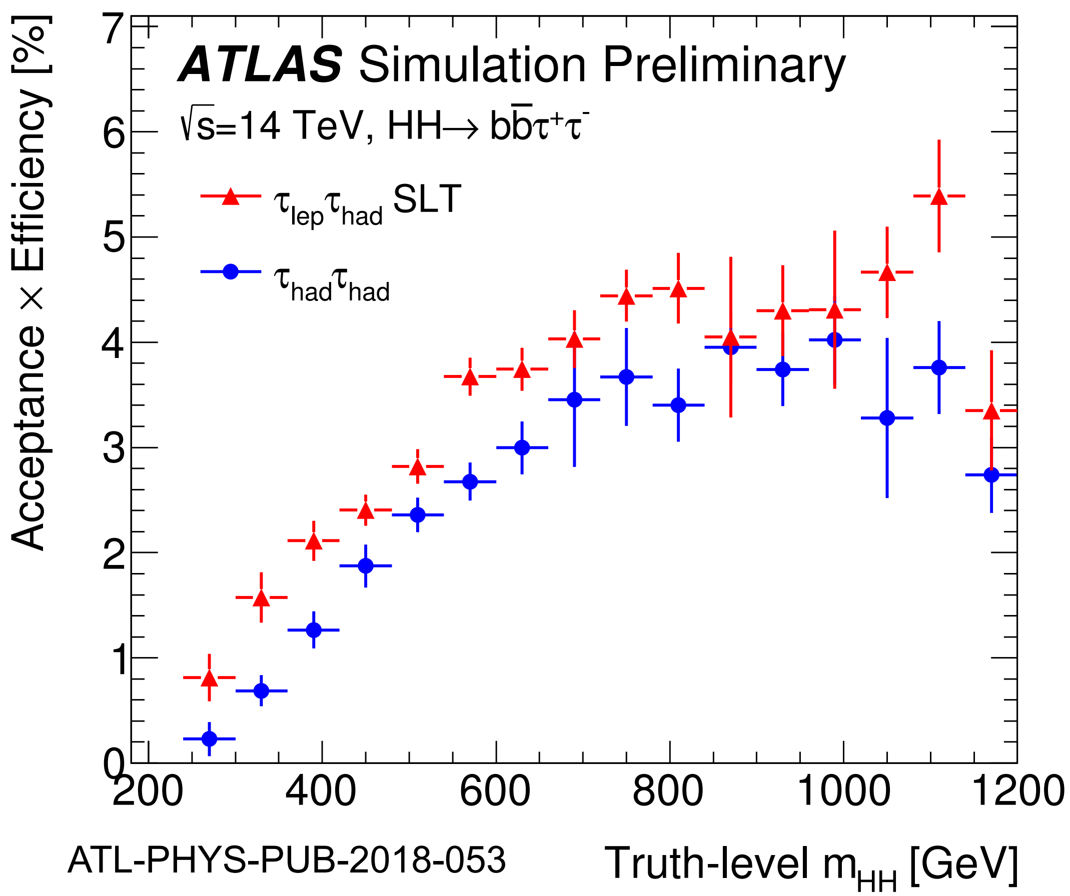
FTR-18-019

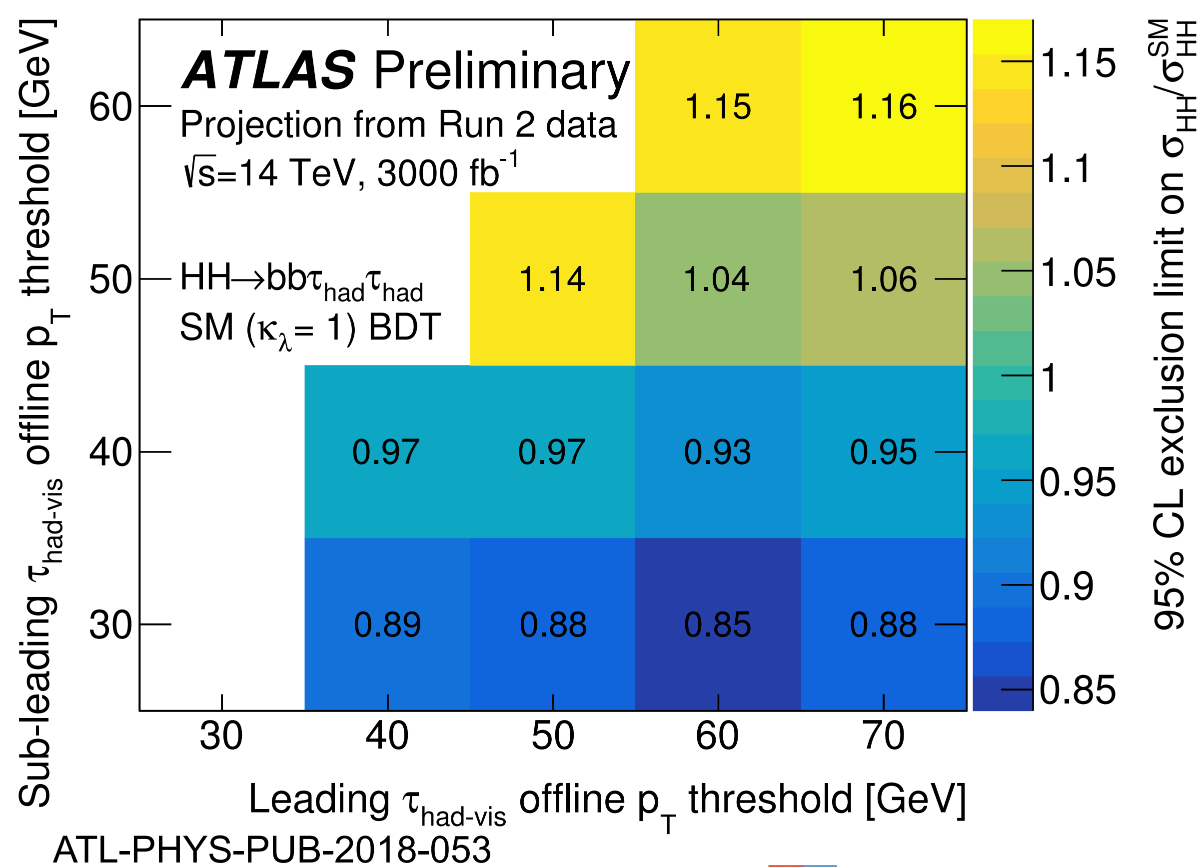
HH→bbττ

- Statistical Only in Parenthesis

- **ATLAS**
  - σ_{HH}< 0.99 (0.80)xSM 95% CL
  - significance 2.1 (2.5)σ
- **CMS**
  - σ_{HH}< 1.4 (1.3)xSM 95% CL
  - significance 1.4 (1.6)σ
- **Major Challenges**
  - Trigger thresholds
  - Systematic uncertainties







- **ATLAS and CMS parametric simulation**
- **Main backgrounds**: γγbb, γγjj, ttH

CMS bbγγ object preselection

Photon selections
$p_T/m_{\gamma\gamma} > 1/3$ (leading γ), $> 1/4$ (subleading γ) $\lvert\eta\rvert < 1.44$ or $1.57 < \lvert\eta\rvert < 2.5$ $100\,\text{GeV} < m_{\gamma\gamma} < 180\,\text{GeV}$
Jet selections
$p_T > 25\,\text{GeV}$ $\lvert\eta\rvert < 2.5$ $\Delta R_{\gamma j} > 0.4$ $80\,\text{GeV} < m_{jj} < 190\,\text{GeV}$ At least 2 b-tagged jet (loose WP)

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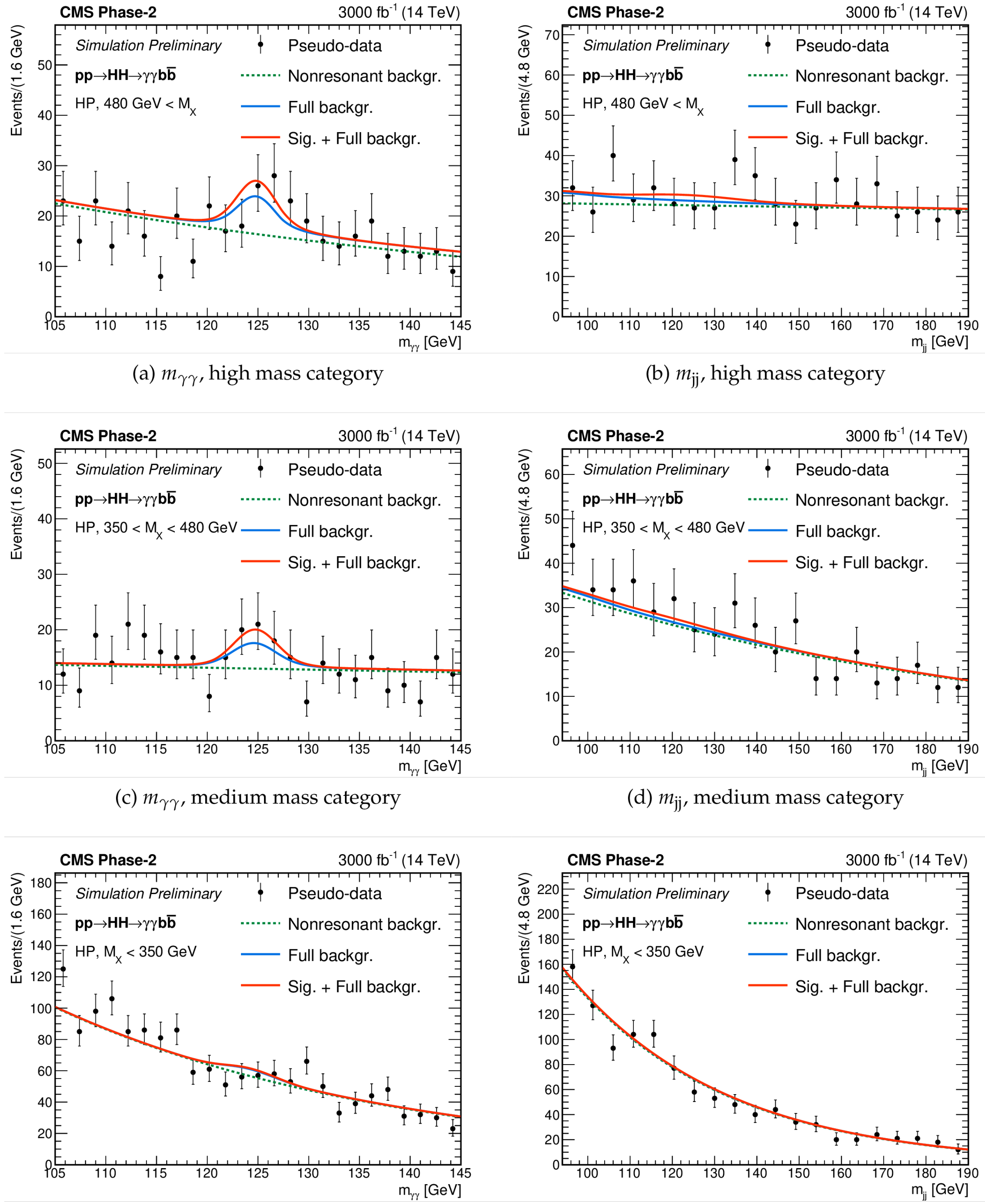
- **ATLAS MVA**
  - BDT (21 variables)
- **CMS MVA**
  - BDT against ttH (12 variables)
  - BDT against background (15 variables)
- **Final Discriminant**
  - ATLAS: $m_{bb\gamma\gamma}$
  - CMS: 2D-fit $m_{\gamma\gamma}$ and m_{bb}
    - 6 categories (m_{HH} and purity)



(a) $m_{\gamma\gamma}$, high mass category
(b) m_{jj}, high mass category
(c) $m_{\gamma\gamma}$, medium mass category
(d) m_{jj}, medium mass category
(e) $m_{\gamma\gamma}$, low mass category
(f) m_{jj}, low mass category

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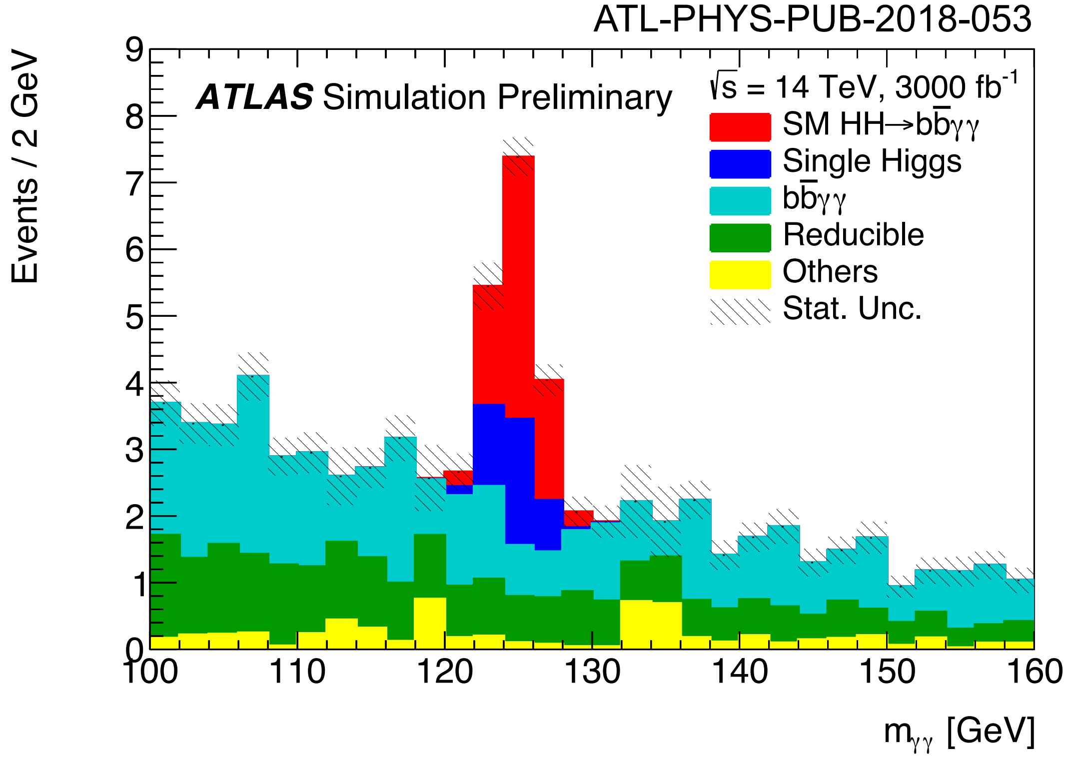
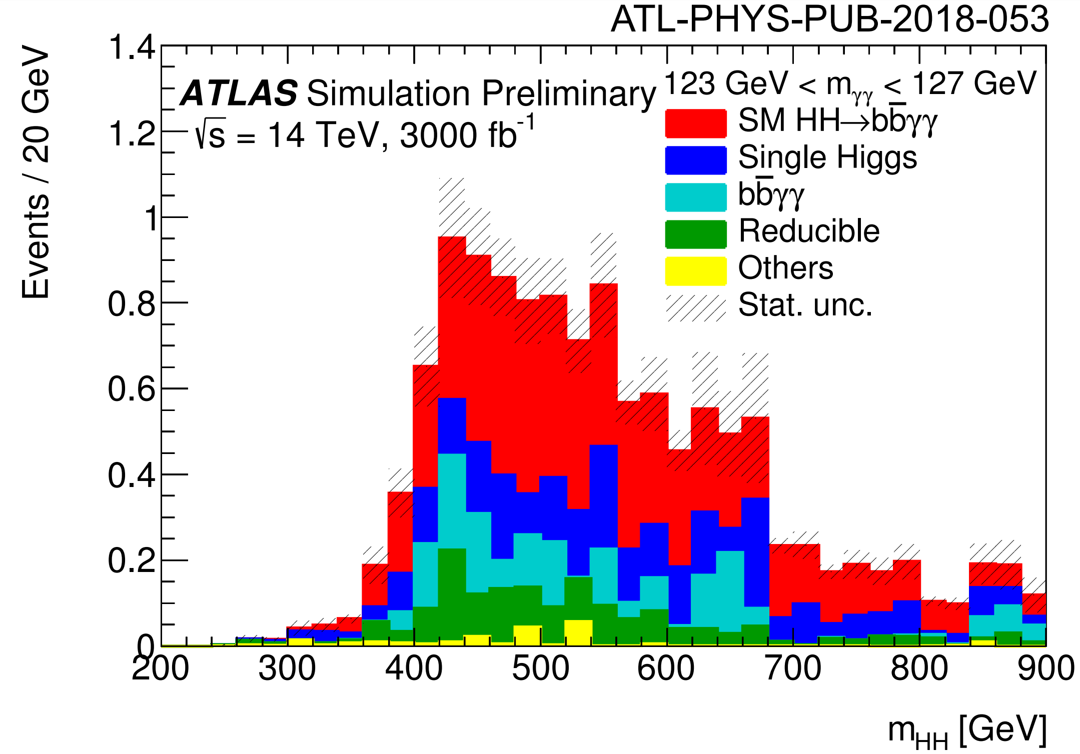
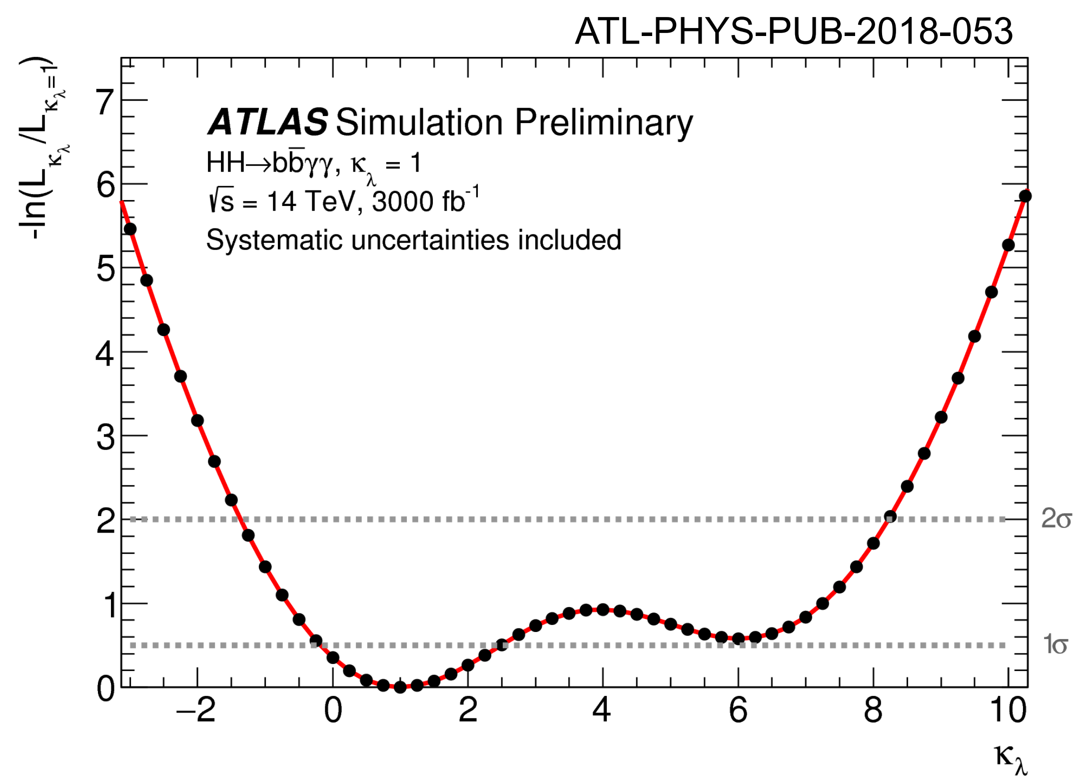
HH→bbγγ





- Statistical Only in Parenthesis

- **ATLAS**
  - σ_{HH}< 1.2 (1.1)xSM 95% CL
  - significance 2.0 (2.1)σ
- **CMS**
  - σ_{HH}< 1.1 (1.1)xSM 95% CL
  - significance 1.8 (1.89)σ



HH→bbWW(→lνlν) and HH→bbZZ(→4l)

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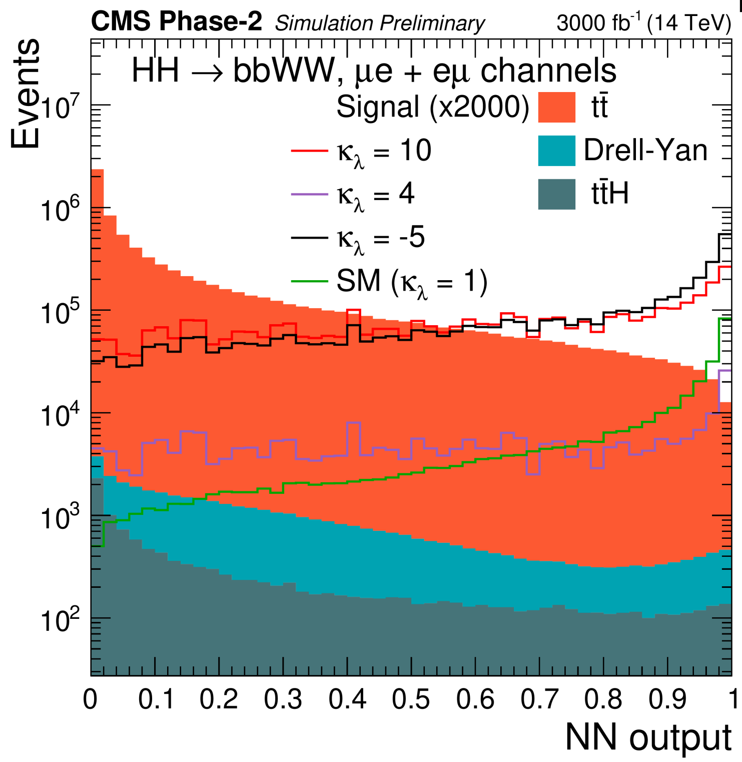
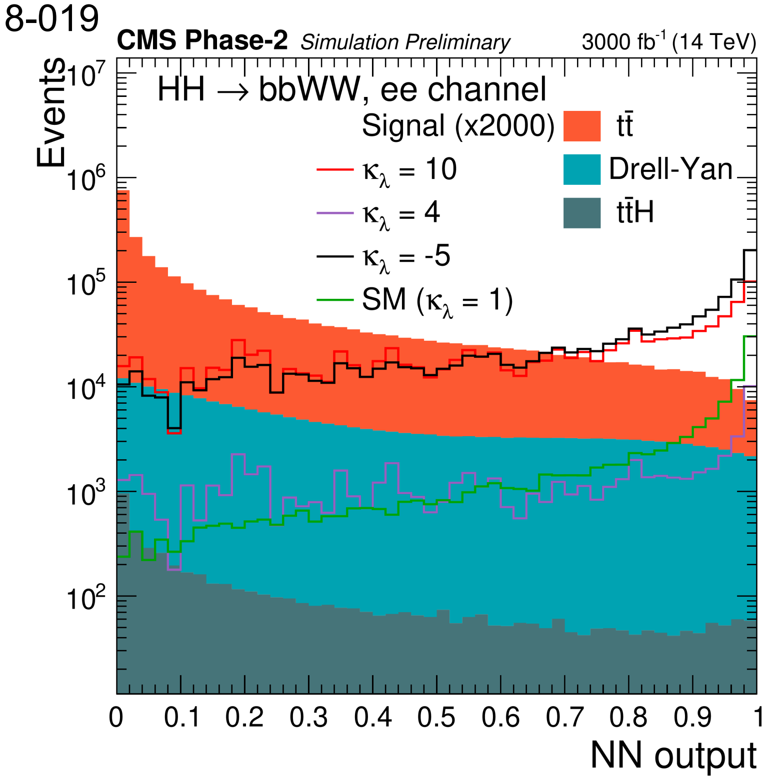
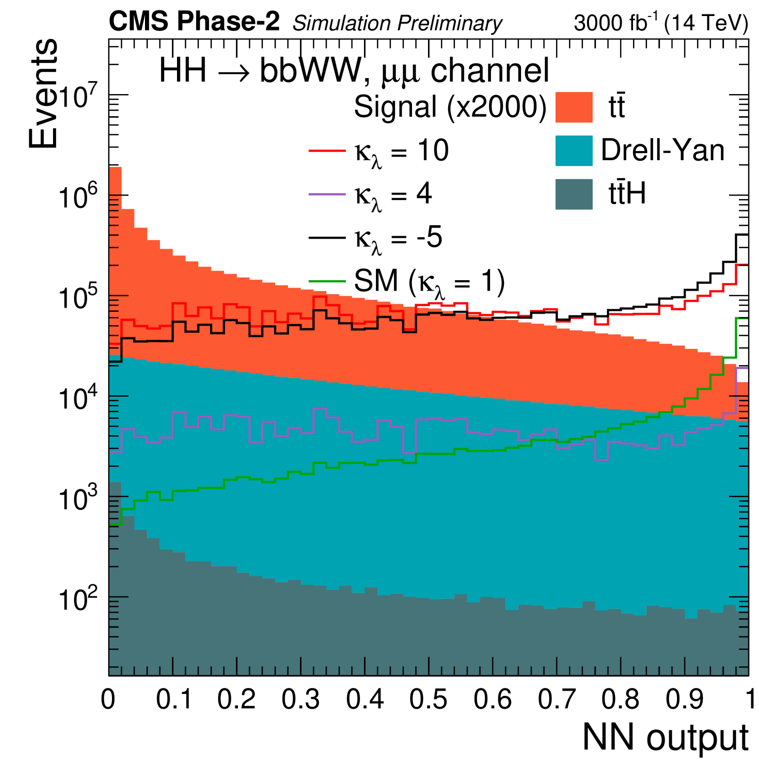


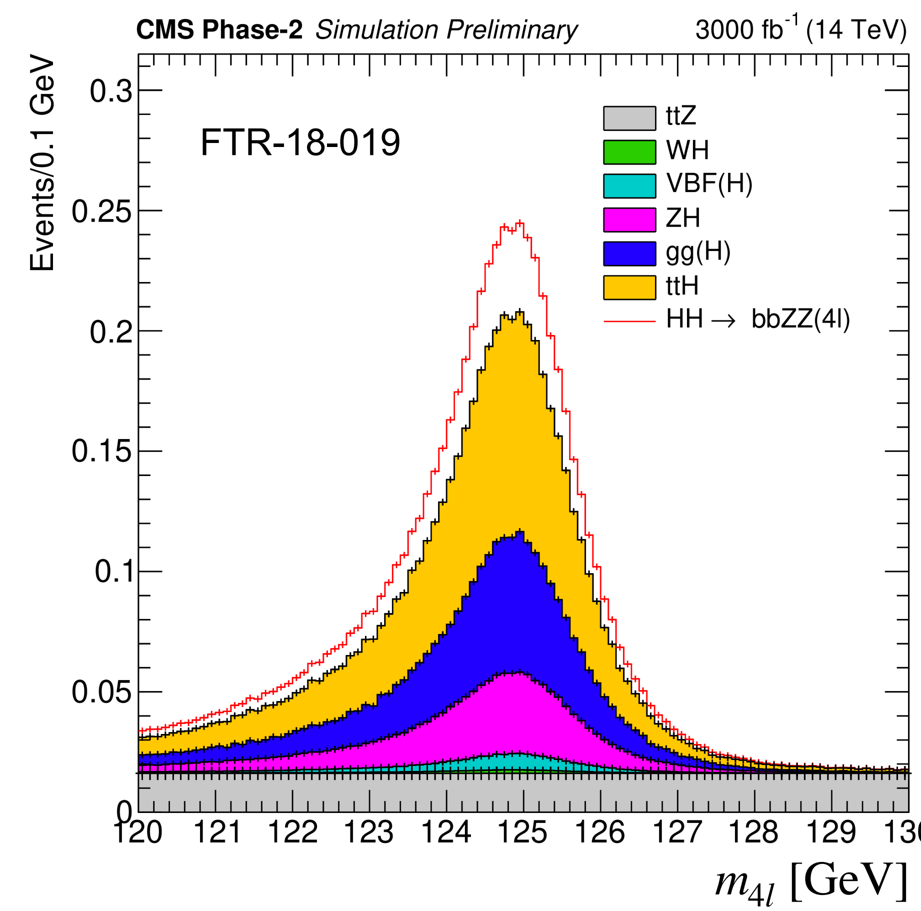




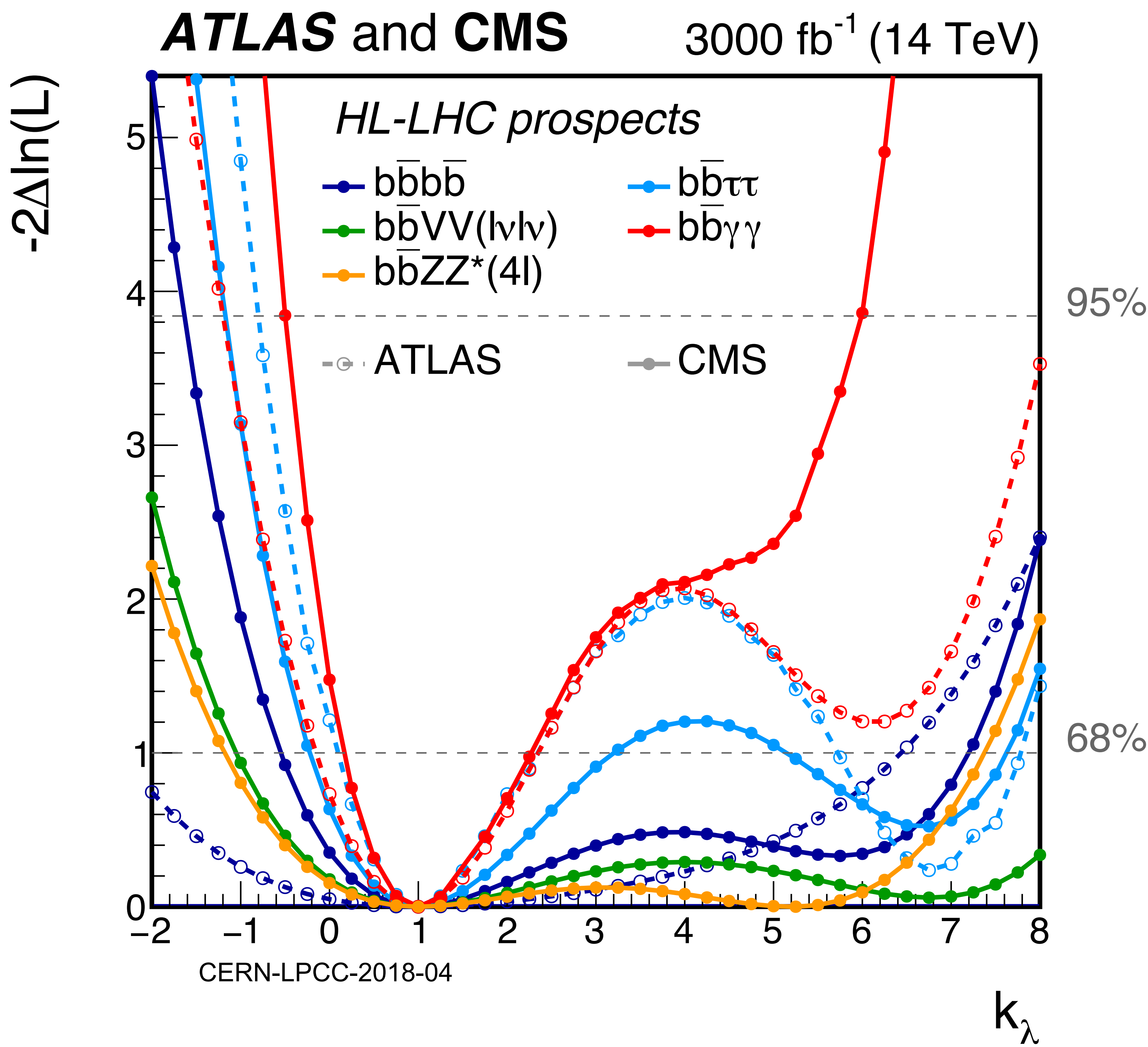
- Projections available only from CMS
- **HH→bbWW(→lνlν)**
  - Contributions: H→WW→lνlν and H→ZZ→llνν
  - Neural Network discriminant (9 variables)
  - σ_{HH}< 3.5 (3.3)xSM 95% CL
  - Significance 0.56 (0.59)σ
  - ATLAS 139 fb^{-1} σ_{HH}<40 SM (exp. 29^{+14}_{-9}xSM) at 95% CL

    [PLB 801 (2020) 135145]
- **HH→bbZZ(→4l)**
  - σ_{HH}< 6.6xSM 95% CL
  - Significance 0.37σ
  - Effect of systematics negligible

▷ **Statistical Only in Parenthesis**

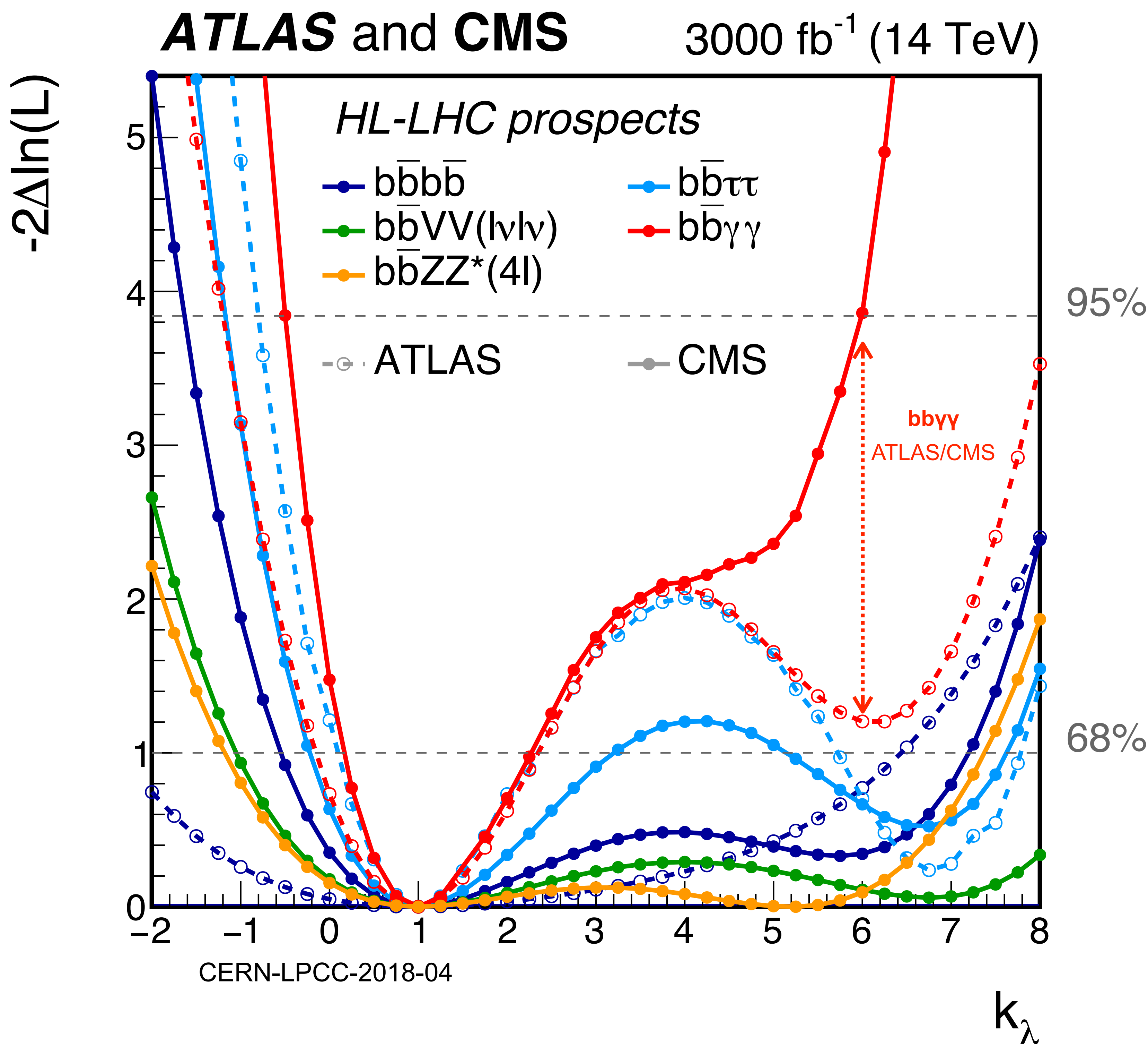


Overview of Individual Results



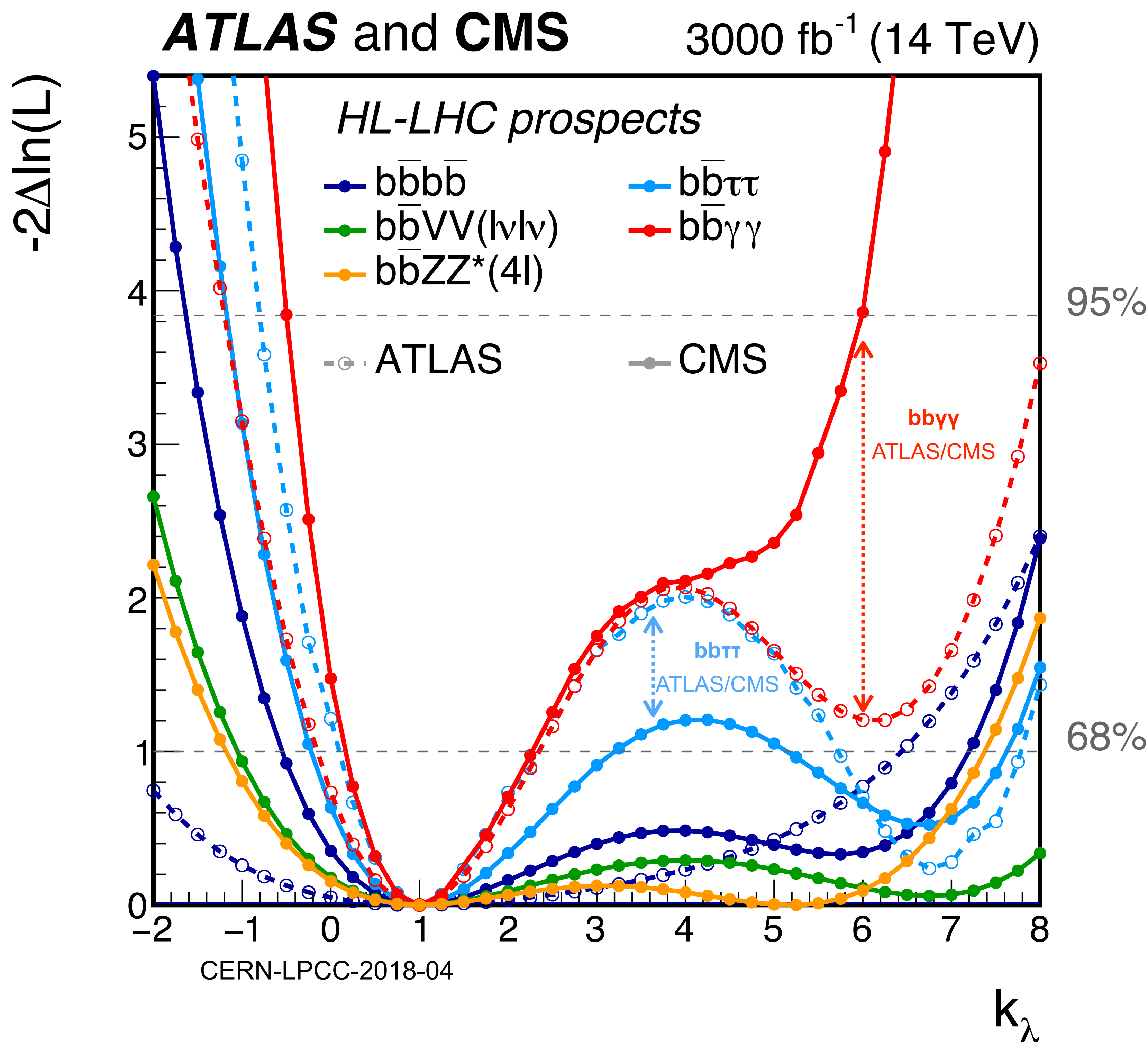
Overview of Individual Results

- **Differences in bbγγ**
  - CMS optimises BDT in m_{HH} bins
  - ATLAS optimised in SM HH



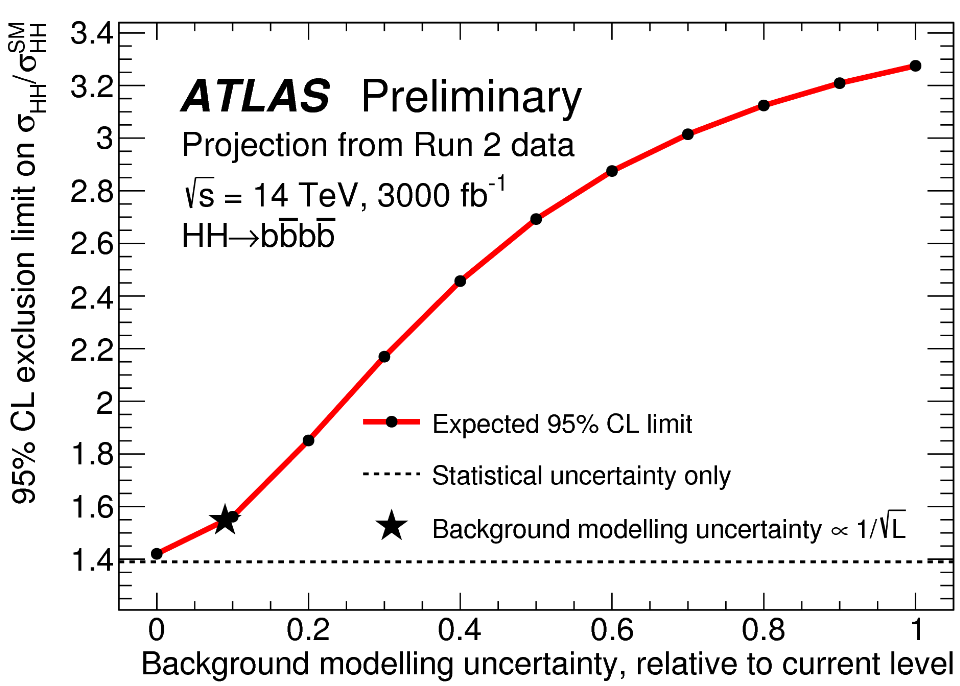
Overview of Individual Results

- **Differences in bbγγ**
  - CMS optimises BDT in m_{HH} bins
  - ATLAS optimised in SM HH
- **Differences in bbττ**
  - Different trigger assumptions

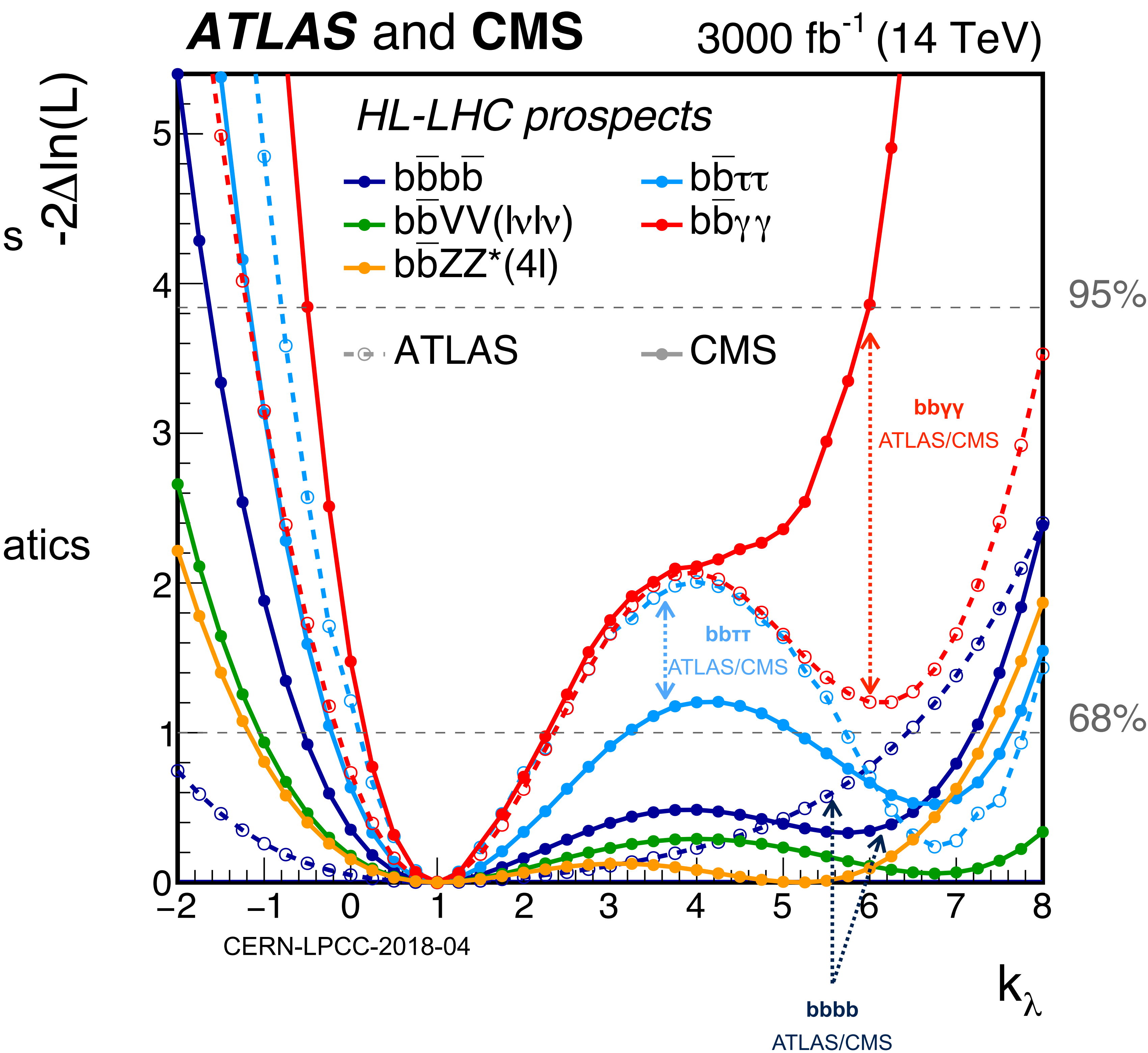


Overview of Individual Results

- **Differences in bbγγ**
  - CMS optimises BDT in m_{HH} bins
  - ATLAS optimised in SM HH
- **Differences in bbττ**
  - Different trigger assumptions
- **Differences in bbbb**
  - Systematics dominated
  - ATLAS proj. with Run 2 systematics
    - Very conservative



ATL-PHYS-PUB-2018-053



ATLAS and CMS Combination

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

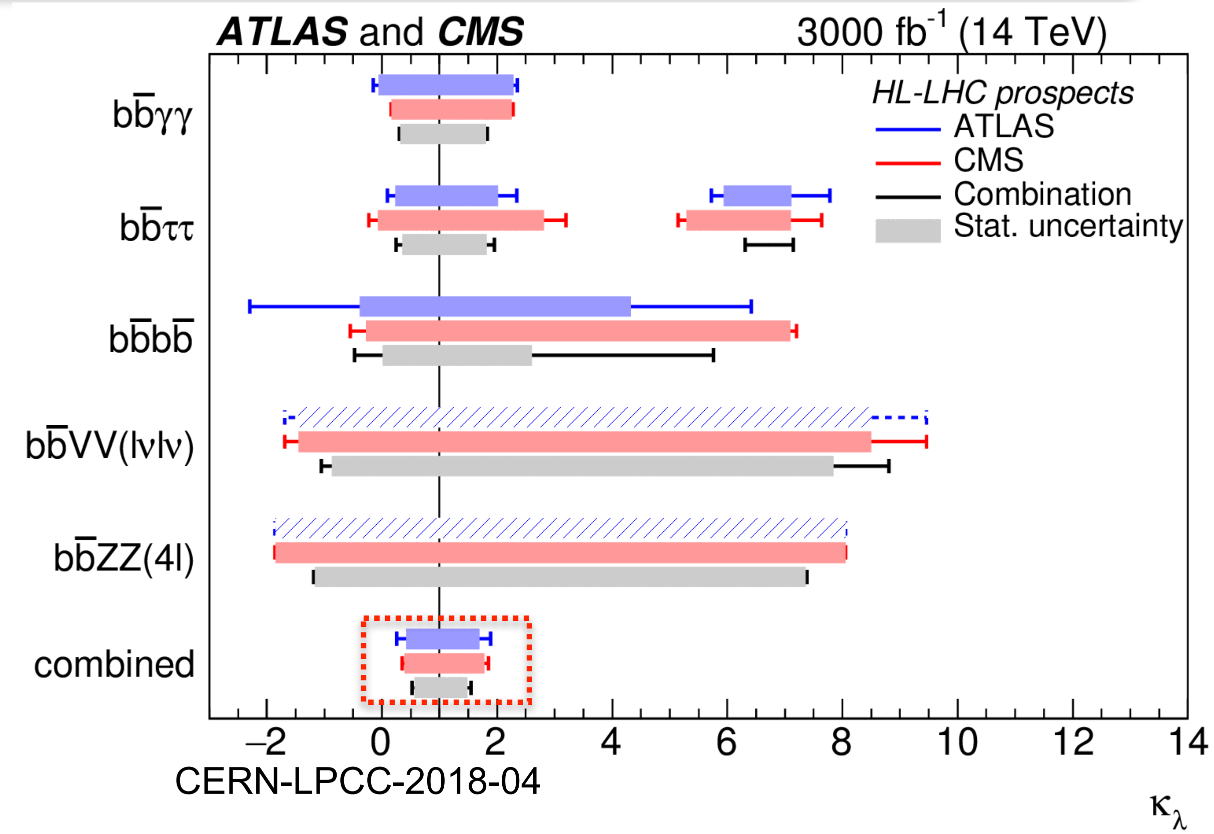
CERN-LPCC-2018-04

- **HH observation**
  - Expected combined significance 4σ

ATLAS and CMS Combination

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

CERN-LPCC-2018-04



- **HH observation**
  - Expected combined significance 4σ
- **Higgs boson self-coupling measurement**
  - $0.52 \leq \kappa_\lambda \leq 1.5$ ($0.57 \leq \kappa_\lambda \leq 1.5$) at 68% CL with (without) systematics

ATLAS and CMS Combination

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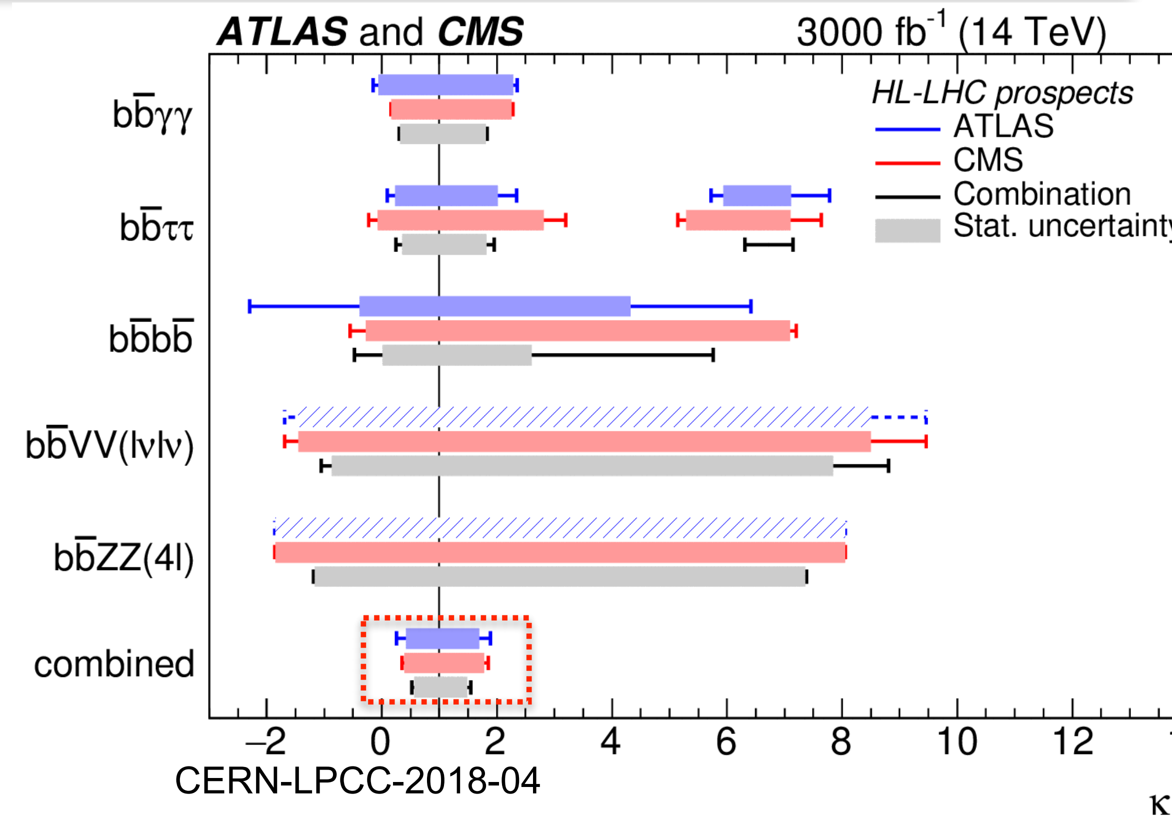
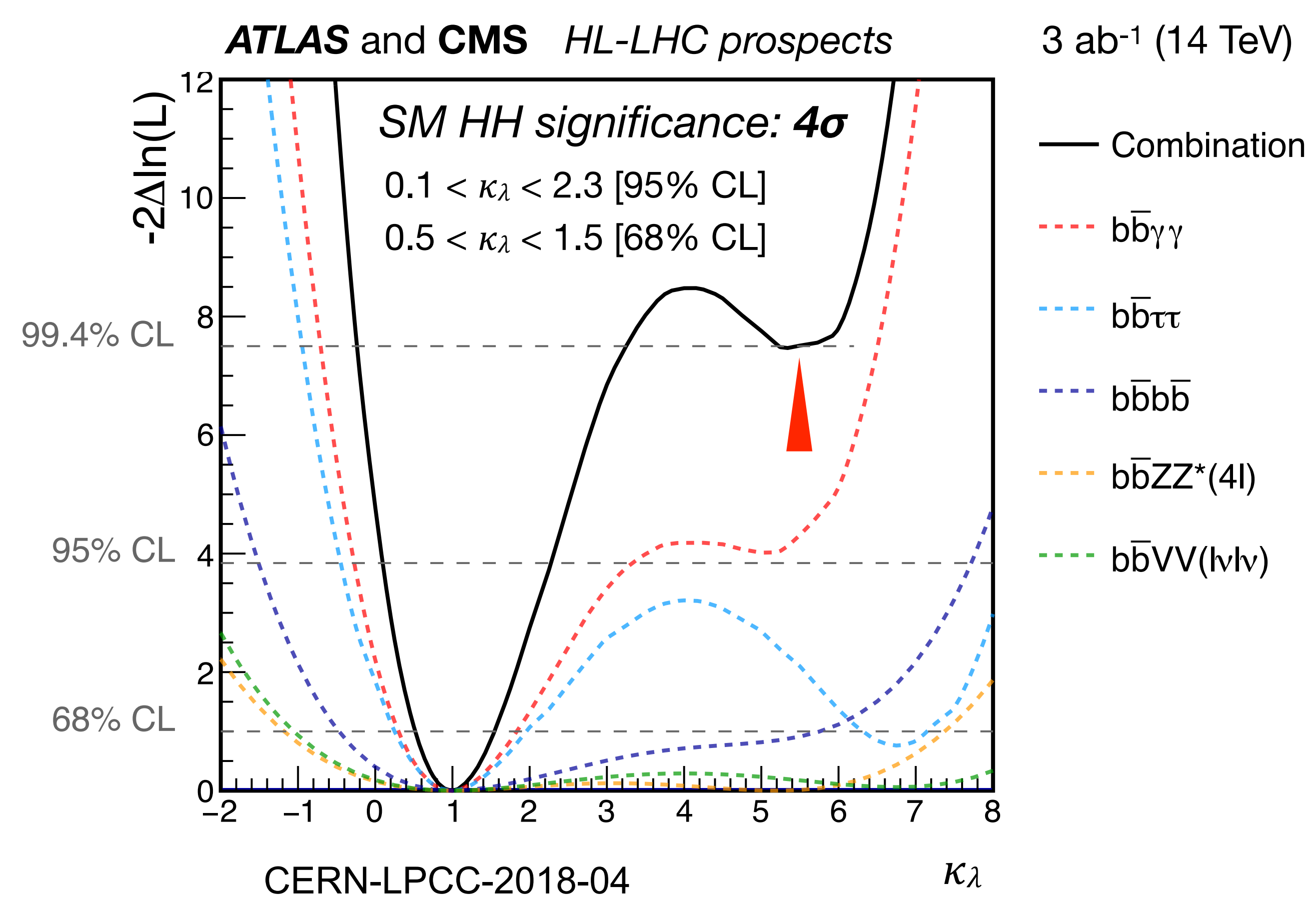
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

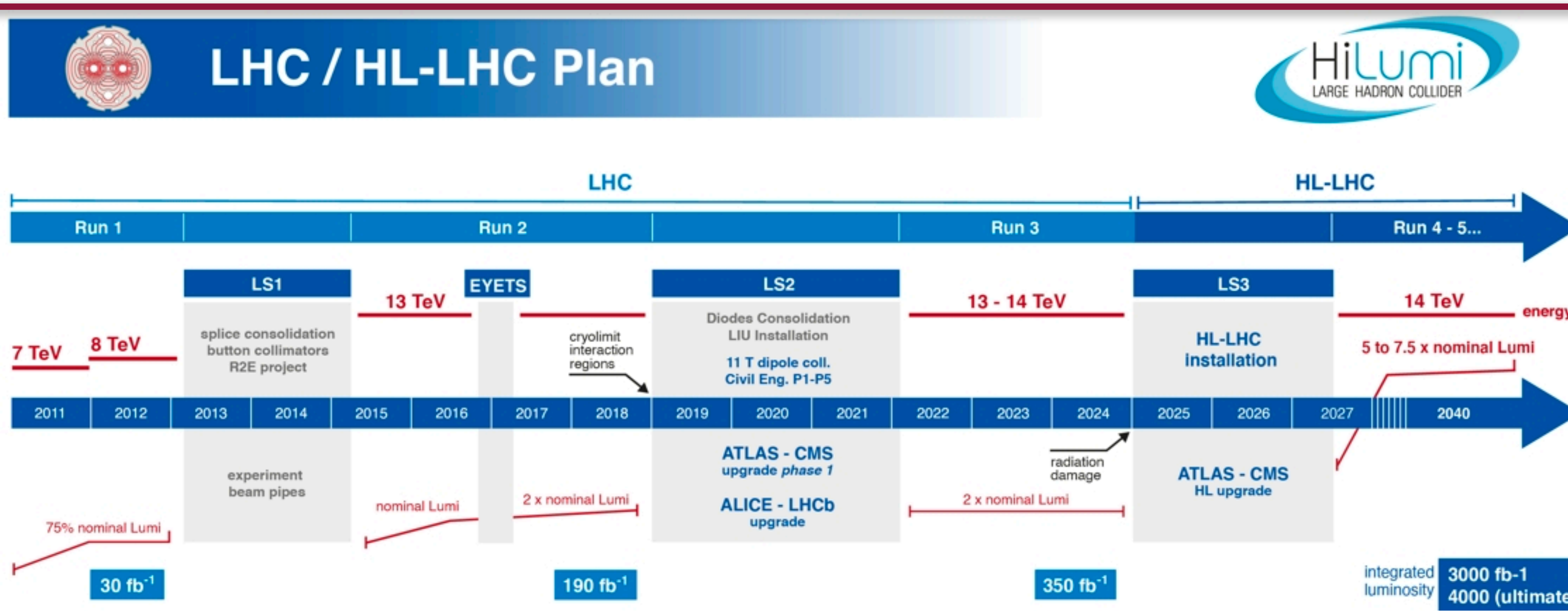
CERN-LPCC-2018-04



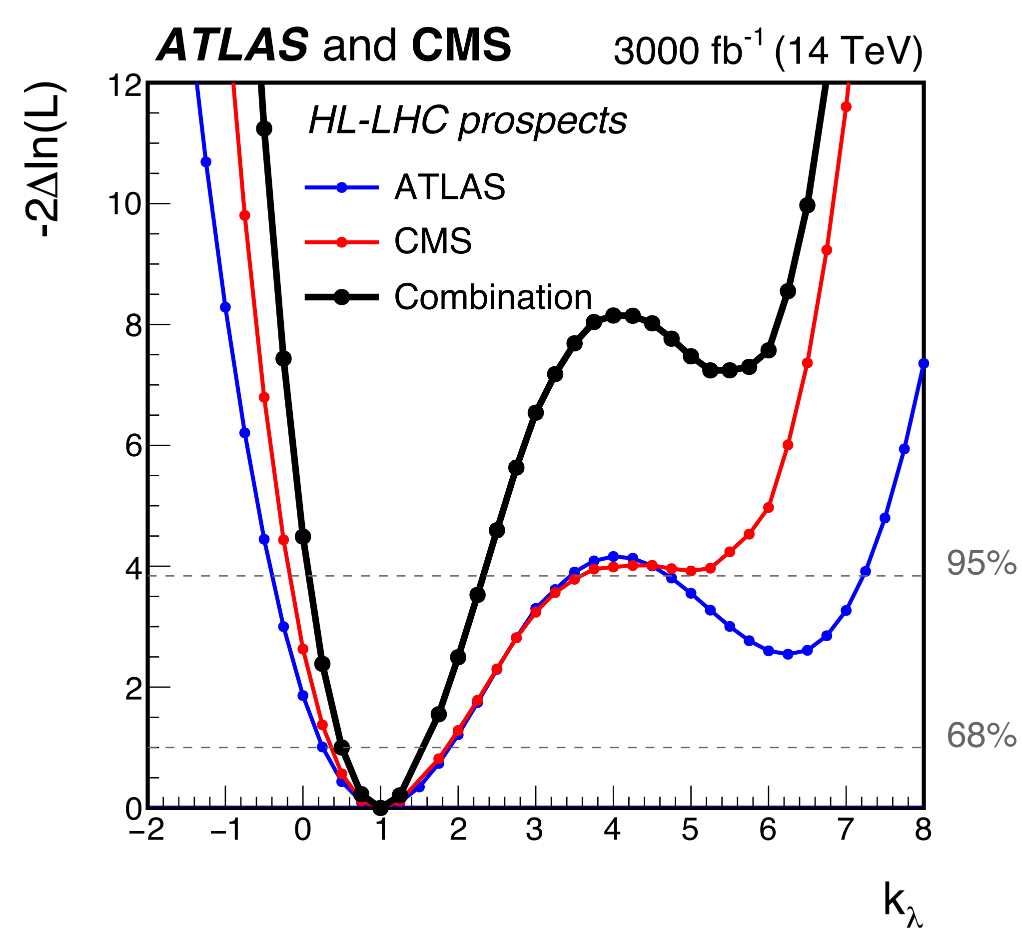


- **HH observation**
  - Expected combined significance 4σ
- **Higgs boson self-coupling measurement**
  - $0.52 \leq \kappa_\lambda \leq 1.5$ ($0.57 \leq \kappa_\lambda \leq 1.5$) at 68% CL with (without) systematics
  - 2nd minimum excluded at 99.4% CL

Summary



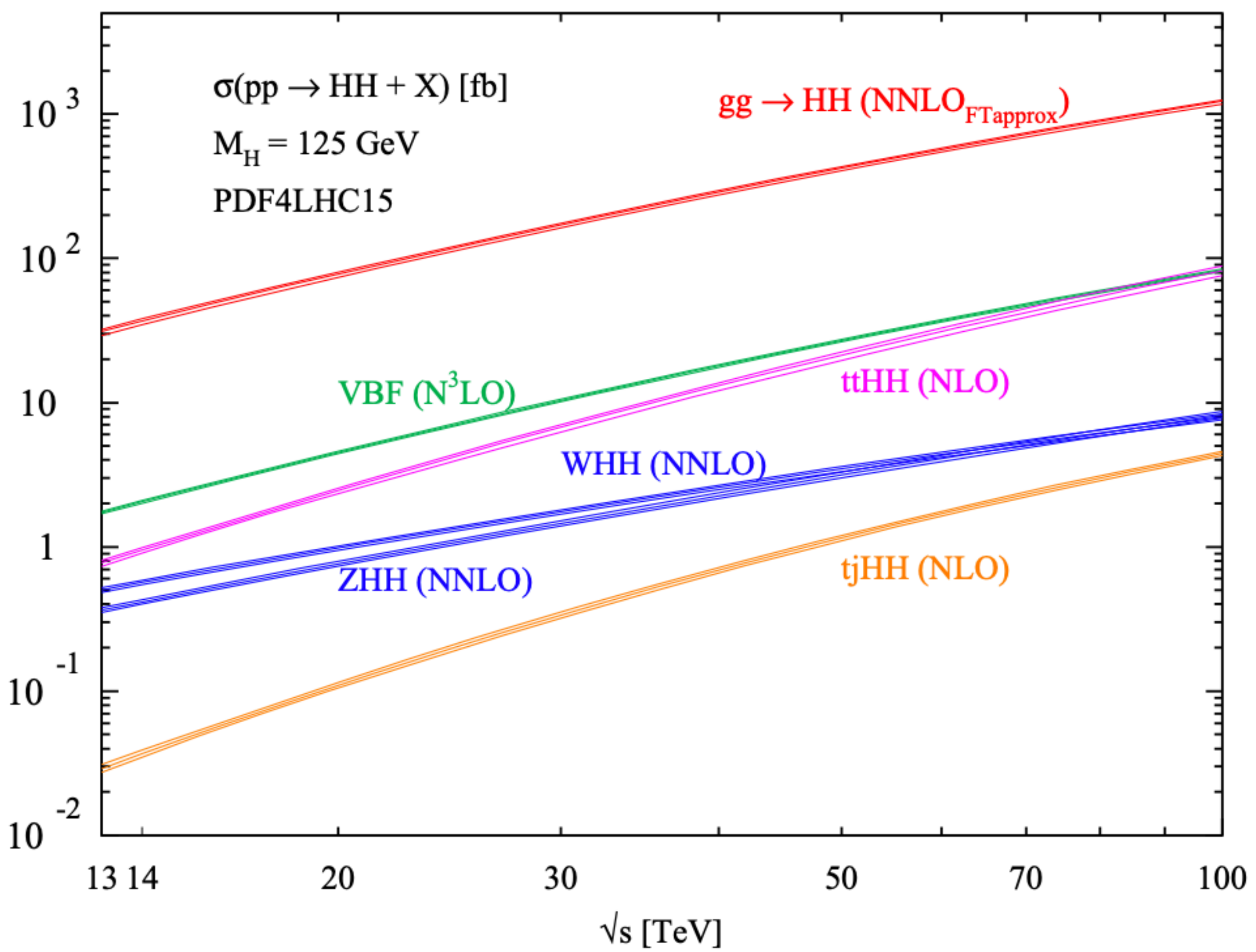
- Many open questions on details of EWSB
- **Higgs self-coupling within reach at HL-LHC**
  - ATLAS+CMS combined give 4σ for HH observation
  - $0.52 \leq \kappa_\lambda \leq 1.5$ at 68% CL
- **Many challenges ahead!**
  - Trigger thresholds
  - Control of systematics
- **Further room for improvement**
  - Focusing on most obvious channels
  - Time to improve and invent new methods!
- **Ground work (upgrades) happening now!**

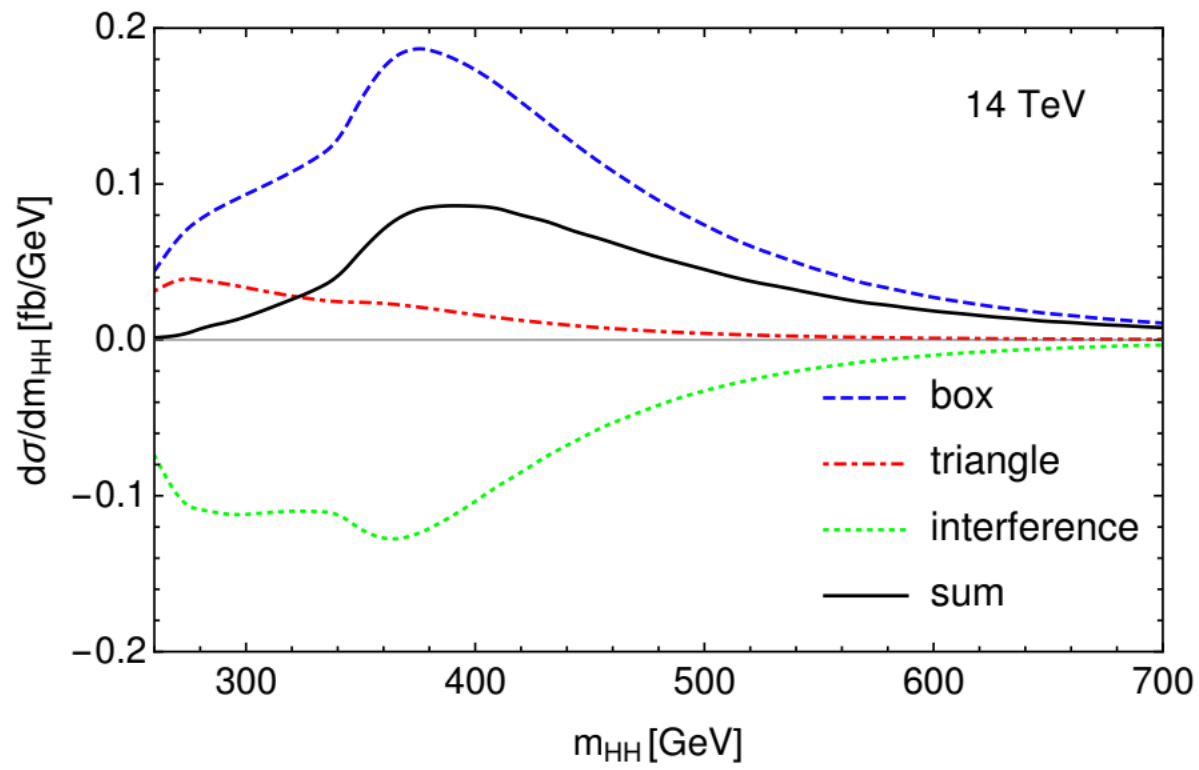


Additional Slides

HH production

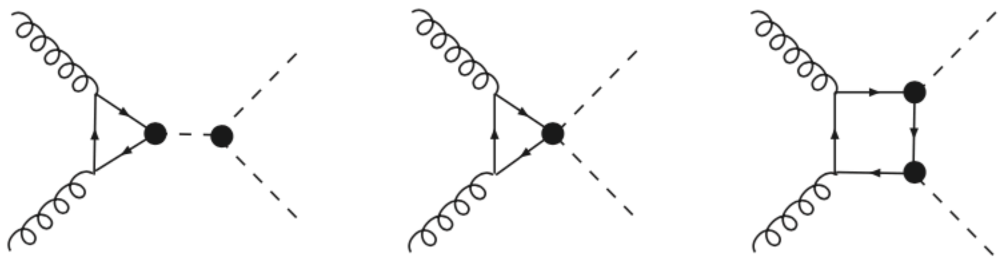
arXiv:1910.00012





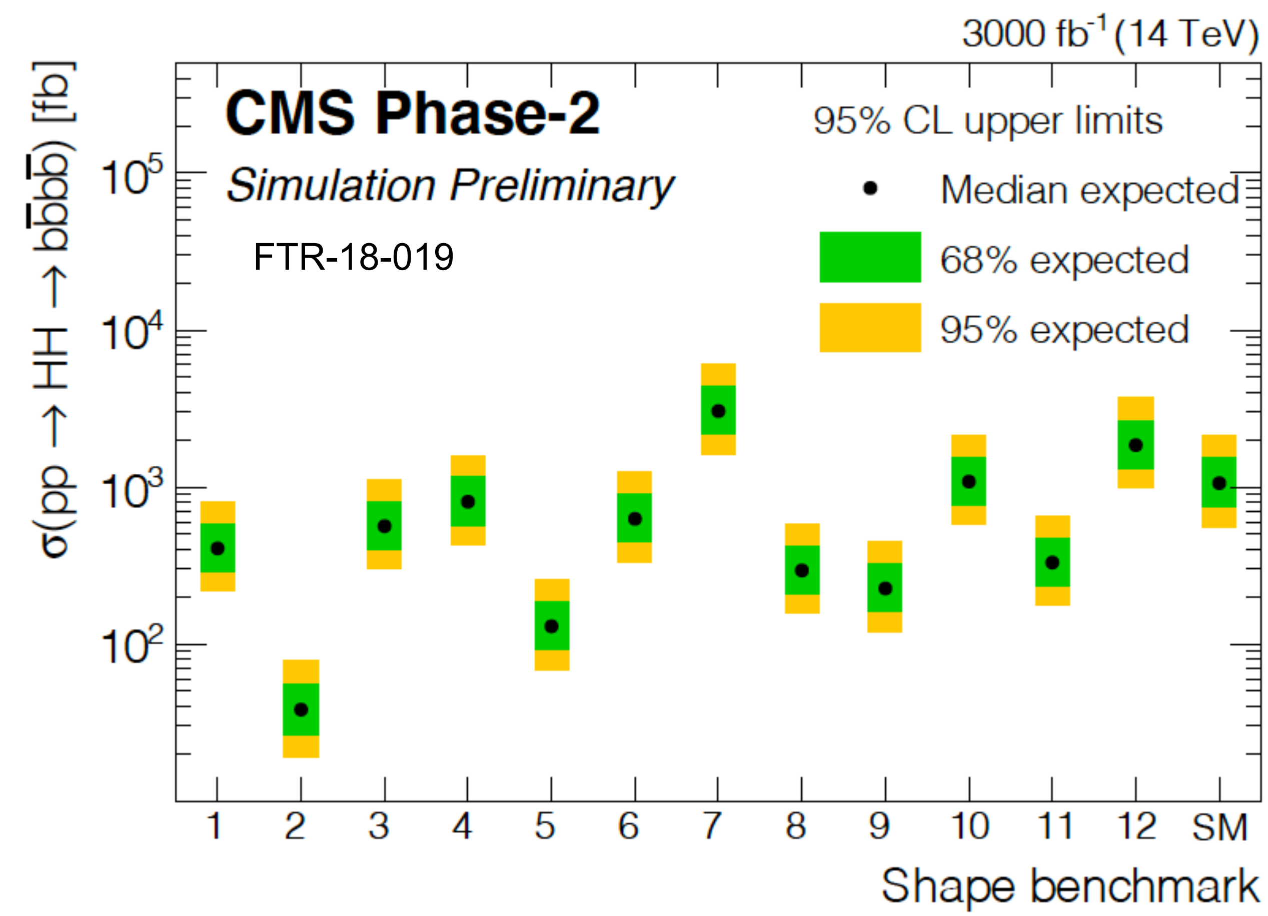
BSM searches

$$\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}m_h^2 h^2 - \kappa_\lambda \lambda_{SM} v h^3 - \frac{m_t}{v}(v + \kappa_t h + \frac{c_2}{v} h h)(\bar{t}_L t_R + h.c.) + \frac{1}{4}\frac{\alpha_s}{3\pi v}(c_g h - \frac{c_{2g}}{2v} h h) G^{\mu\nu} G_{\mu\nu} .$$



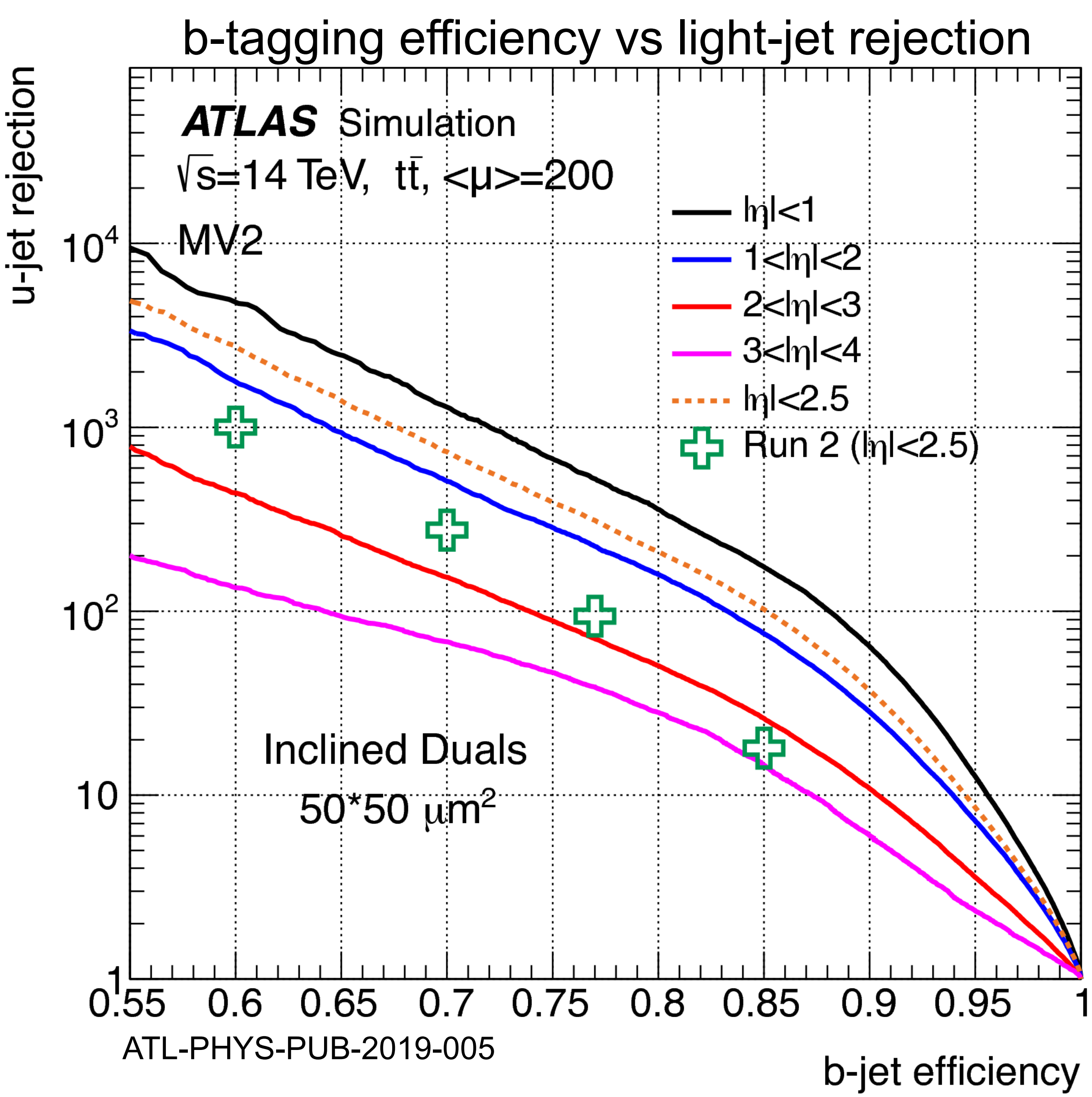
JHEP 04 (2016) 126

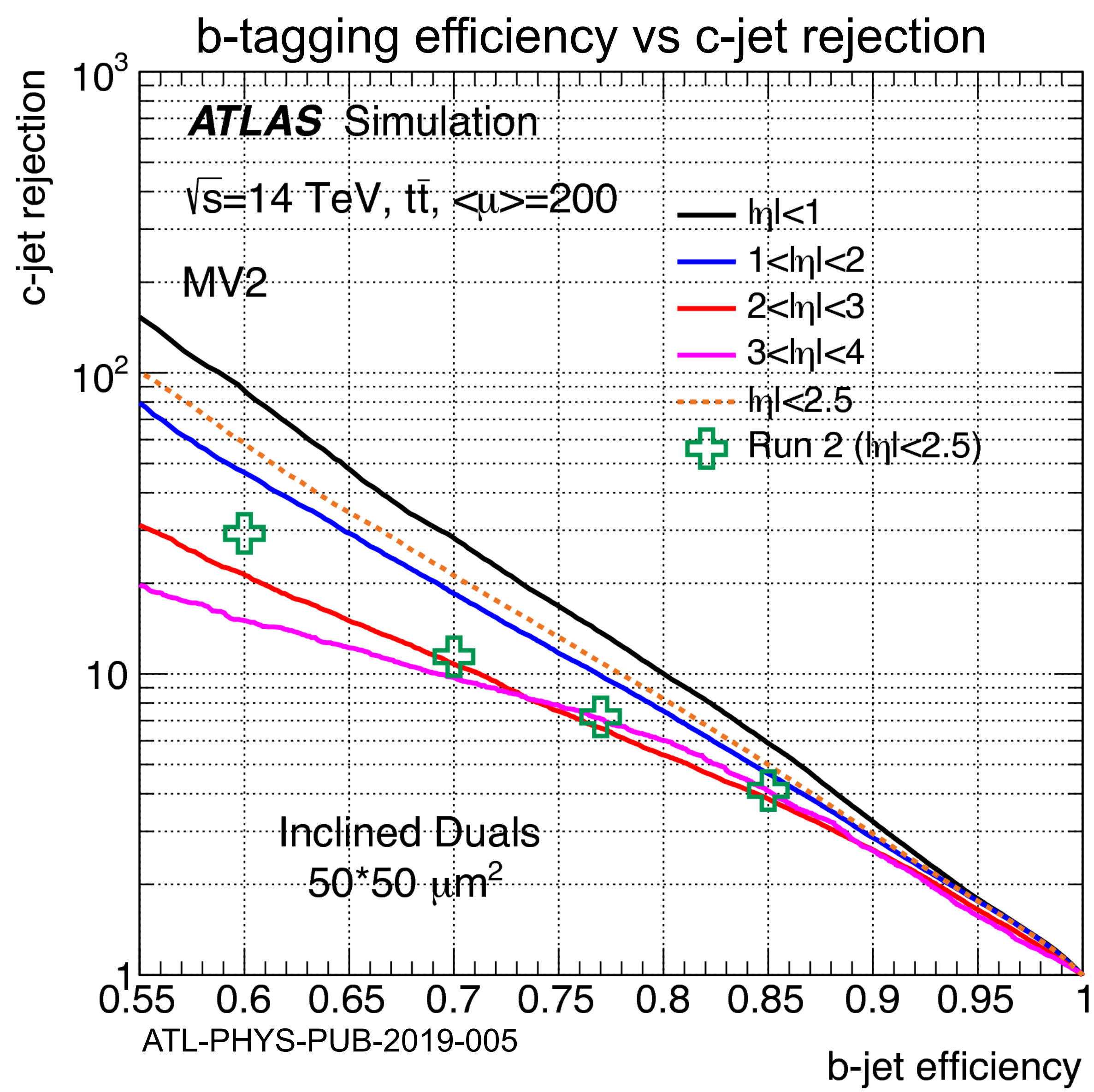
Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1	1
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1	-1
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0



Expected Detector Performance

- Detector performance: **cornerstone for physics reach**
- **HH analyses span all physics objects**
- **Expected performance of upgraded detector**
  - Estimated with CPU-intensive detailed simulations

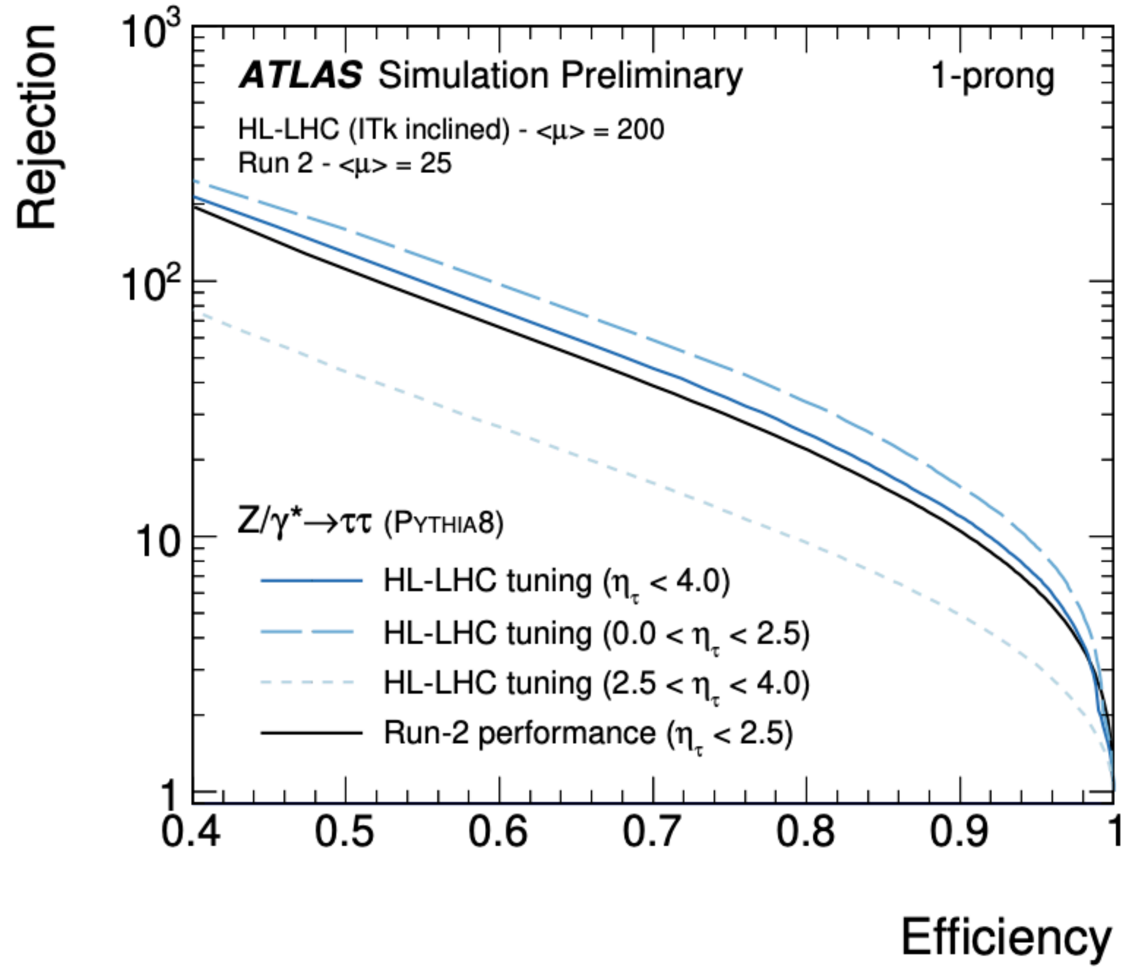


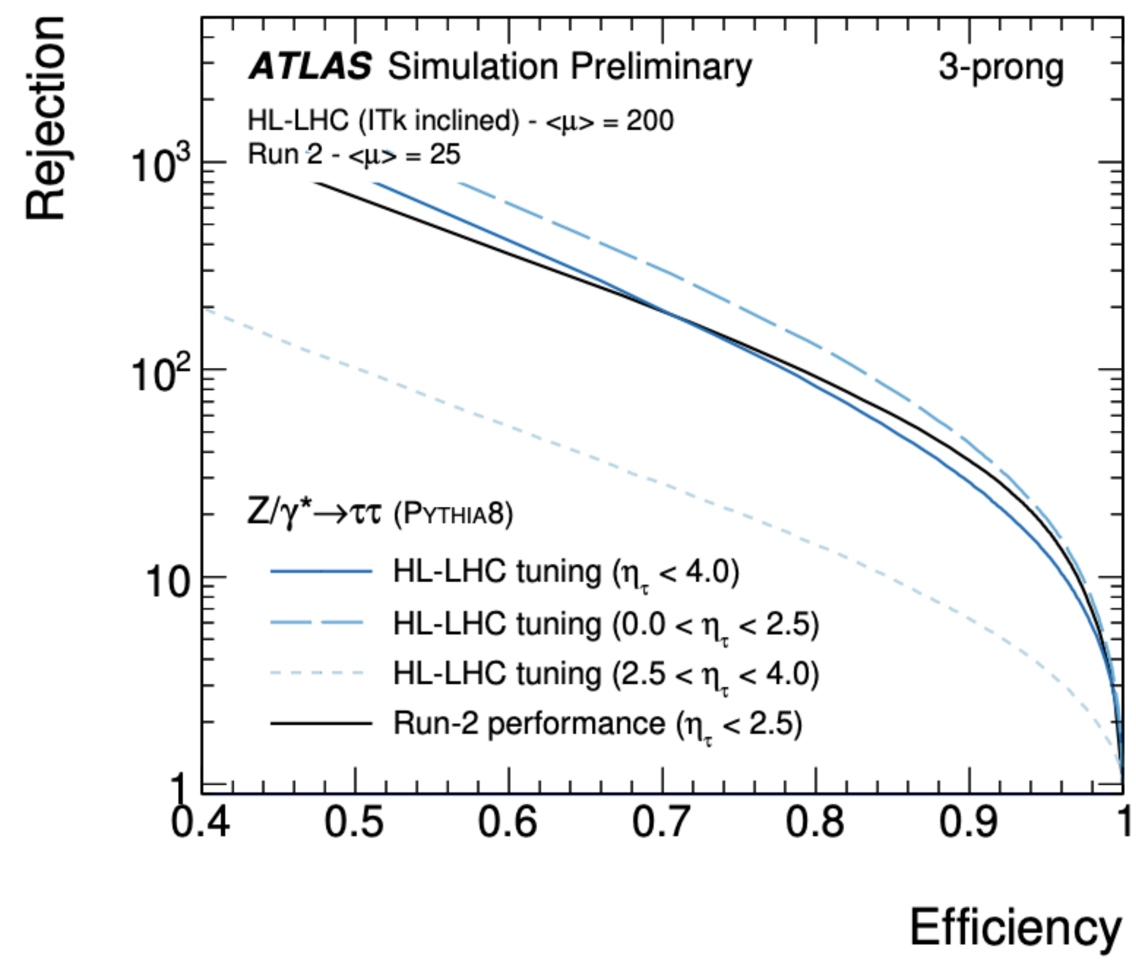


- b-tagging efficiency versus light- and c-jet rejection
  - Improved performance (x2.5 better light-jet rejection at ε=70%)
  - Extended coverage (up to |η|<4 with competitive performance)

τ-lepton reconstruction

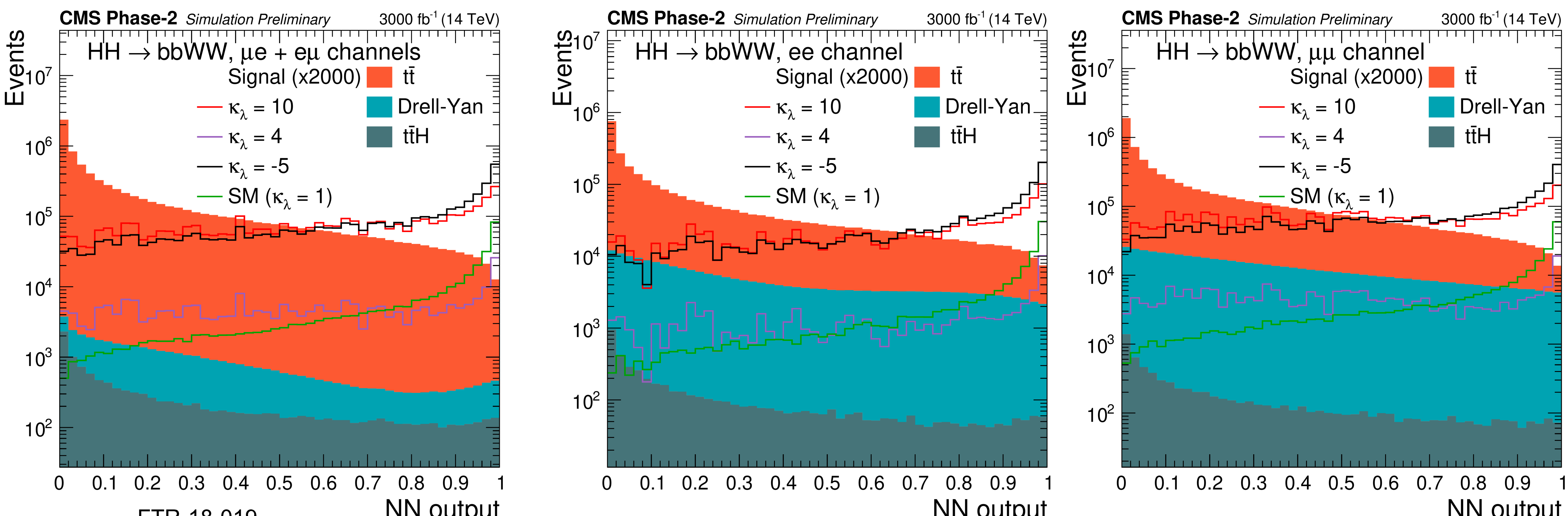
ATLAS-PHYS-PUB-2019-005





HH→bbWW(→lνlν)

- Final states currently considered only by CMS
- **HH→bbWW(→lνlν)**
  - Contributions: H→WW→lνlν and H→ZZ→llνν
  - Neural Network discriminant (9 variables)
  - σ_{HH}< 3.5 (3.3)xSM 95% CL
  - Significance 0.56 (0.59)σ
  - **Statistical Only in Parenthesis**



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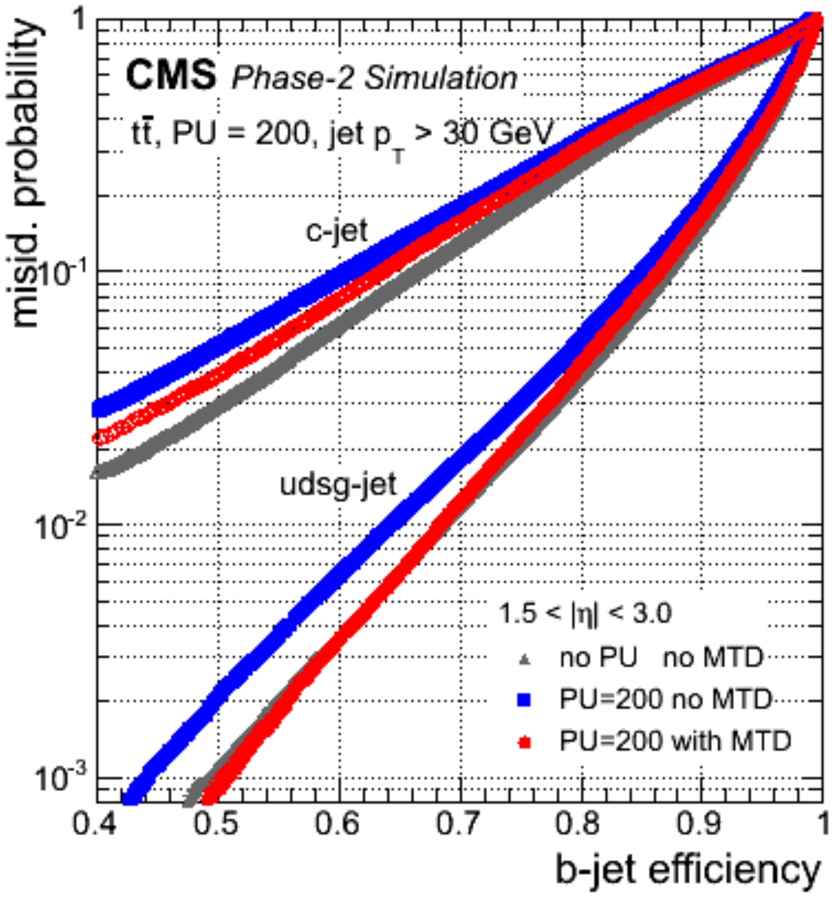
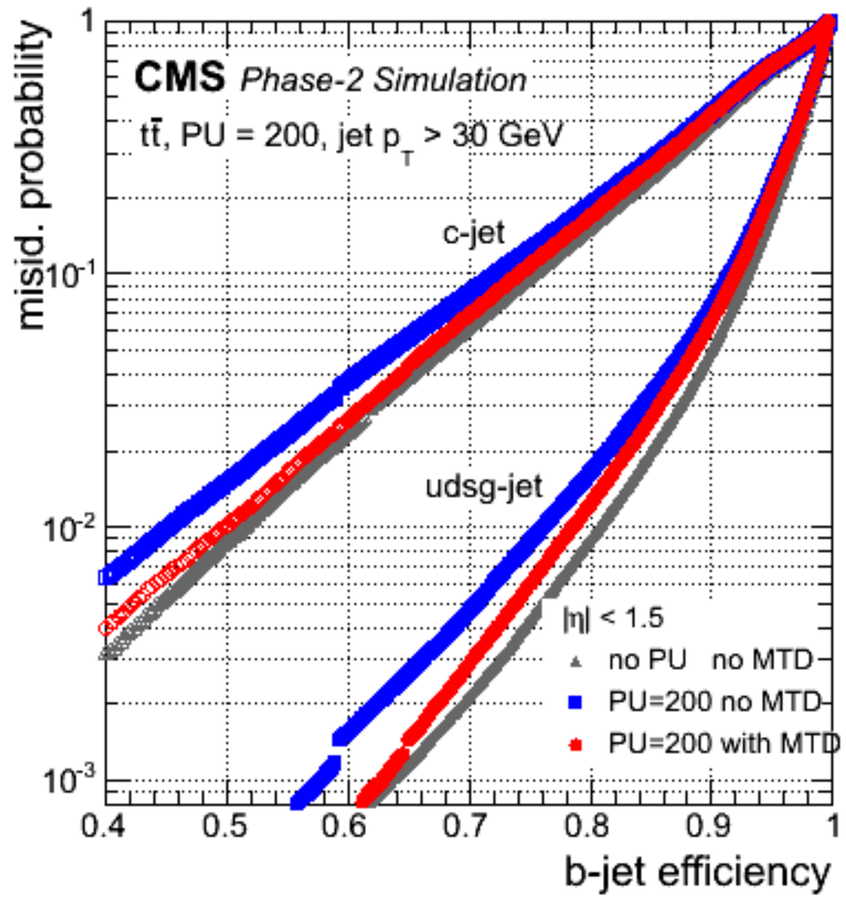
Effect of timing information

CMS-NOTE-2018-006





Systematic Uncertainties

CMS-NOTE-2018-006

Uncertainty	Working point/ component	Value
Electron ID	All WPs, $p_T > 20\,\text{GeV}$	0.5%
	All WPs, $10 < p_T < 20\,\text{GeV}$	2.5%
Photon ID		2%
Muon ID	All WPs	0.5%
Tau ID	All WPs	2.5%
Jet energy scale	Total	1–2.5%
	Absolute scale	0.1–0.2%
	Relative scale	0.1–0.5%
	PU	0–2%
	Jet flavor	0.75%
Jet energy resolution		3–5% as a function of η
b-tagging	b jets (all WPs)	1%
	c jets (all WPs)	2%
	Light jets, loose WP	5%
	Light jets, medium WP	10%
	Light jets, tight WP	15%
	Subjet b tagging	1%
	Double c tagging	
p_T^{miss}	Propagate jet energy corrections uncertainties (must)	
	Propagate jet energy resolution uncertainties (recommended)	
	Vary unclustered energy by 10% (recommended)	
Integrated luminosity		1%

ATL-PHYS-PUB-2018-053

Full signal region	$\tau_{lep}\tau_{had}$ channel (SLT)	$\tau_{lep}\tau_{had}$ channel (LTT)	$\tau_{had}\tau_{had}$ channel
$t\bar{t}$ fake-$\tau_{had\text{-}vis}$	-	-	20400 ± 2200
$t\bar{t}$	2218000 ± 13000	176000 ± 2300	57600 ± 2000
Single top	129200 ± 2800	8240 ± 230	4490 ± 150
Multijet fake-$\tau_{had\text{-}vis}$	-	-	33500 ± 2100
Fake-$\tau_{had\text{-}vis}$	867000 ± 13000	51100 ± 2300	-
$Z \to \tau\tau + (bb, bc, cc)$	51800 ± 2100	14600 ± 600	23800 ± 1100
Other	24300 ± 1000	1710 ± 160	2550 ± 350
SM Higgs boson	4280 ± 360	460 ± 40	900 ± 60
Total background	3295300 ± 1800	252050 ± 500	143200 ± 400
SM HH	107 ± 6	23.9 ± 1.3	81 ± 8
Last two bins	**$\tau_{lep}\tau_{had}$ channel (SLT)**	**$\tau_{lep}\tau_{had}$ channel (LTT)**	**$\tau_{had}\tau_{had}$ channel**
$t\bar{t}$ fake-$\tau_{had\text{-}vis}$	-	-	146 ± 19
$t\bar{t}$	1830 ± 40	1780 ± 30	370 ± 30
Single top	720 ± 20	420 ± 40	32.3 ± 2.8
Multijet fake-$\tau_{had\text{-}vis}$	-	-	100 ± 20
Fake-$\tau_{had\text{-}vis}$	640 ± 40	-	1210 ± 30
$Z \to \tau\tau + (bb, bc, cc)$	1290 ± 70	1150 ± 70	610 ± 60
Other	460 ± 20	180 ± 20	80 ± 10
SM Higgs boson	220 ± 10	64 ± 3	134 ± 8
Total background	5730 ± 90	4230 ± 90	1470 ± 90
SM HH	52 ± 3	16.2 ± 0.8	54 ± 5
Last bin	**$\tau_{lep}\tau_{had}$ channel (SLT)**	**$\tau_{lep}\tau_{had}$ channel (LTT)**	**$\tau_{had}\tau_{had}$ channel**
$t\bar{t}$ fake-$\tau_{had\text{-}vis}$	-	-	12.9 ± 2.0
$t\bar{t}$	235 ± 6	360 ± 30	0
Single top	283 ± 15	54 ± 3	0
Multijet fake-$\tau_{had\text{-}vis}$	-	-	33.7 ± 7.2
Fake-$\tau_{had\text{-}vis}$	300 ± 10	97 ± 9	-
$Z \to \tau\tau + (bb, bc, cc)$	340 ± 20	470 ± 40	95 ± 16
Other	105 ± 5	61 ± 7	12.2 ± 2.1
SM Higgs boson	78 ± 4	31 ± 2	55 ± 3
Total background	1343 ± 25	1069 ± 55	209 ± 17
SM HH	32.8 ± 1.6	9.8 ± 0.5	32 ± 3

ATL-PHYS-PUB-2018-053

Process	Events in sample	Events after pre-selection	Events passing BDT response	Events passing BDT response & 123 GeV $< m_{\gamma\gamma} <$ 127 GeV
$H(b\bar{b})H(\gamma\gamma)$, $\kappa_\lambda = 1$	3.0×10^2	20	8.0	6.46
$gg \to H(\to \gamma\gamma)$	3.0×10^5	28	0.85	0.68
$t\bar{t}H(\to \gamma\gamma)$	4.2×10^3	124	1.9	1.51
$ZH(\to \gamma\gamma)$	6.7×10^3	26	1.33	0.93
$b\bar{b}H(\to \gamma\gamma)$	3.8×10^3	3.7	0.028	0.025
Single-Higgs-boson background	3.2×10^5	182	4.1	3.2
$b\bar{b}\gamma\gamma$	4.3×10^5	10100	92	1.9
$c\bar{c}\gamma\gamma$	3.4×10^6	630	2.7	0.06
$jj\gamma\gamma$	4.8×10^7	690	4.6	0.12
$b\bar{b}j\gamma$	1.1×10^9	14000	130	1.16
$c\bar{c}j\gamma$	3.3×10^9	480	2.5	0.021
$b\bar{b}jj$	1.4×10^{12}	3600	26	0.16
$Z(\to b\bar{b})\gamma\gamma$	1.5×10^4	230	4.5	0.10
$t\bar{t}(\geq 1$ lepton)	1.6×10^9	3530	11.3	0.05
$t\bar{t}\gamma(\geq 1$ lepton)	1.5×10^7	5600	23	0.07
Continuum background	1.4×10^{12}	38900	297	3.7
Total background	1.4×10^{12}	39100	301	6.8

Table 11: Number of events passing the pre-selection criteria, the BDT response cut, and passing the additional requirement of 123 GeV $< m_{\gamma\gamma} <$ 127 GeV. The number of background events was obtained by counting final-state combinations passing the selection criteria in samples that were generated using a single random seed for the smearing functions. All numbers are normalised to 3000 fb^{-1}. The totals appear inconsistent due to rounding.