Top, bottom and charm Yukawa couplings

Alessandro Calandri
CPPM-Aix Marseille Université

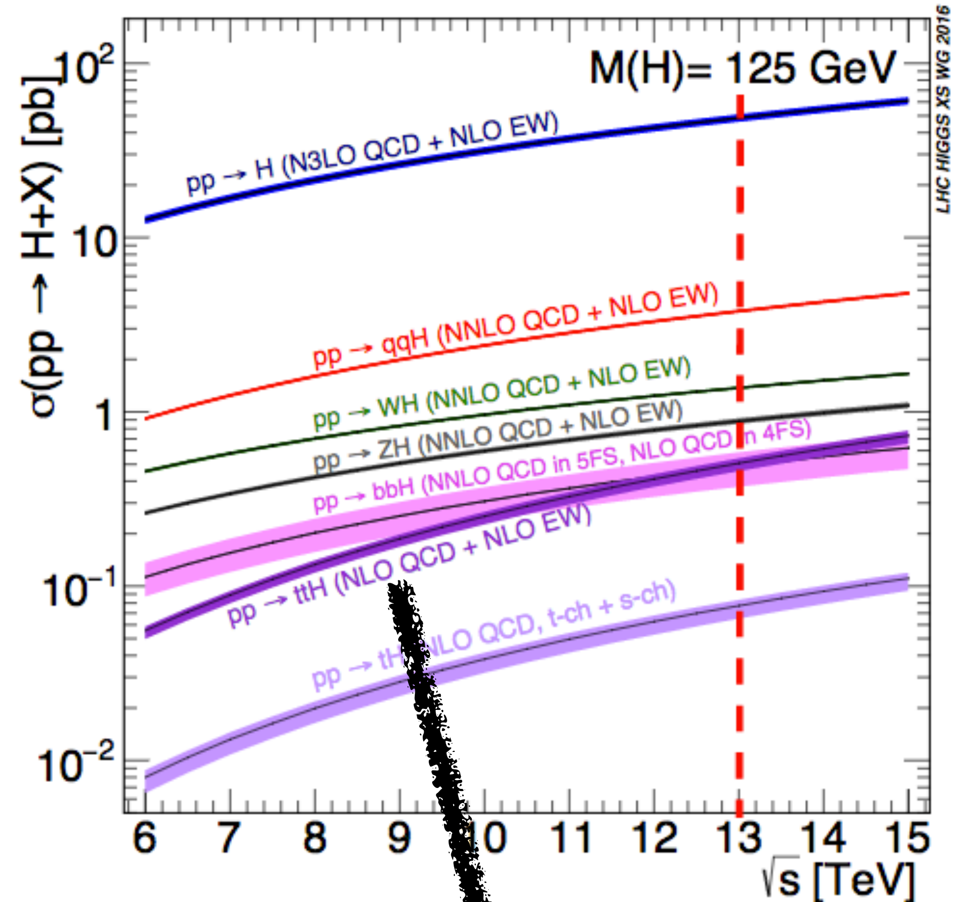
on behalf of the ATLAS, CMS and LHCb Collaborations

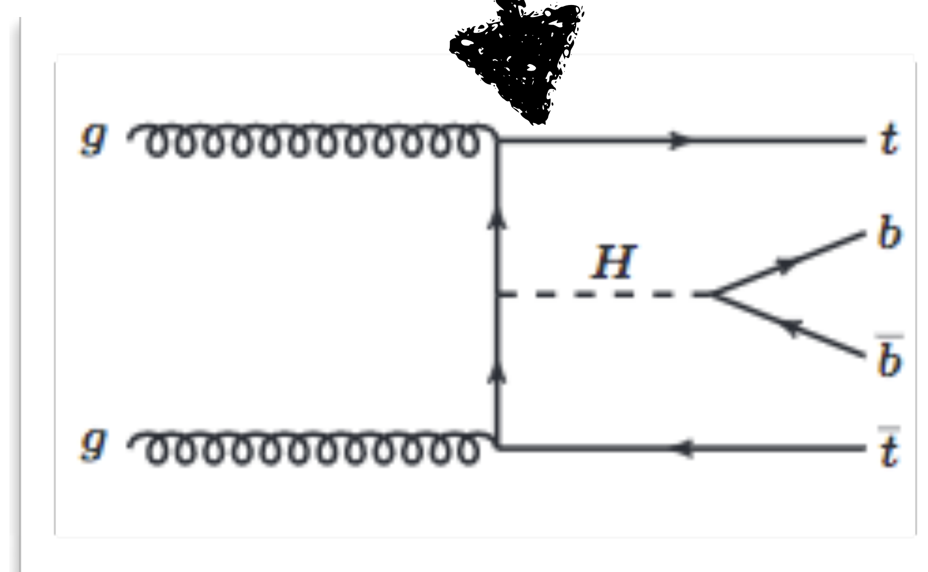
HL/HE LHC Workshop, April 4th-6th 2018 @ Fermilab

Charm/bottom and top-Higgs Yukawa couplings

➡ Constraints on charm, bottom and top Yukawa coupling are one of the benchmark results of the current LHC program

- deviations from SM expectations would reveal new physics
- charm and bottom couplings can be probed in VH→cc, H→J/ψγ, VH→bb, boosted H→bb
  - decay in bottom quarks characterized by highest BR in SM at 125 GeV
- top-Higgs Yukawa couplings can be probed in production (ttH)
  - very small production cross-section at √s=13 TeV (1% of the inclusive Higgs production at LHC)
  - challenging final state with large object multiplicity (jets, b-jets, leptons)
  - dominant backgrounds with large yields and theoretical uncertainties





➡ Prospect studies at HL-LHC also getting available

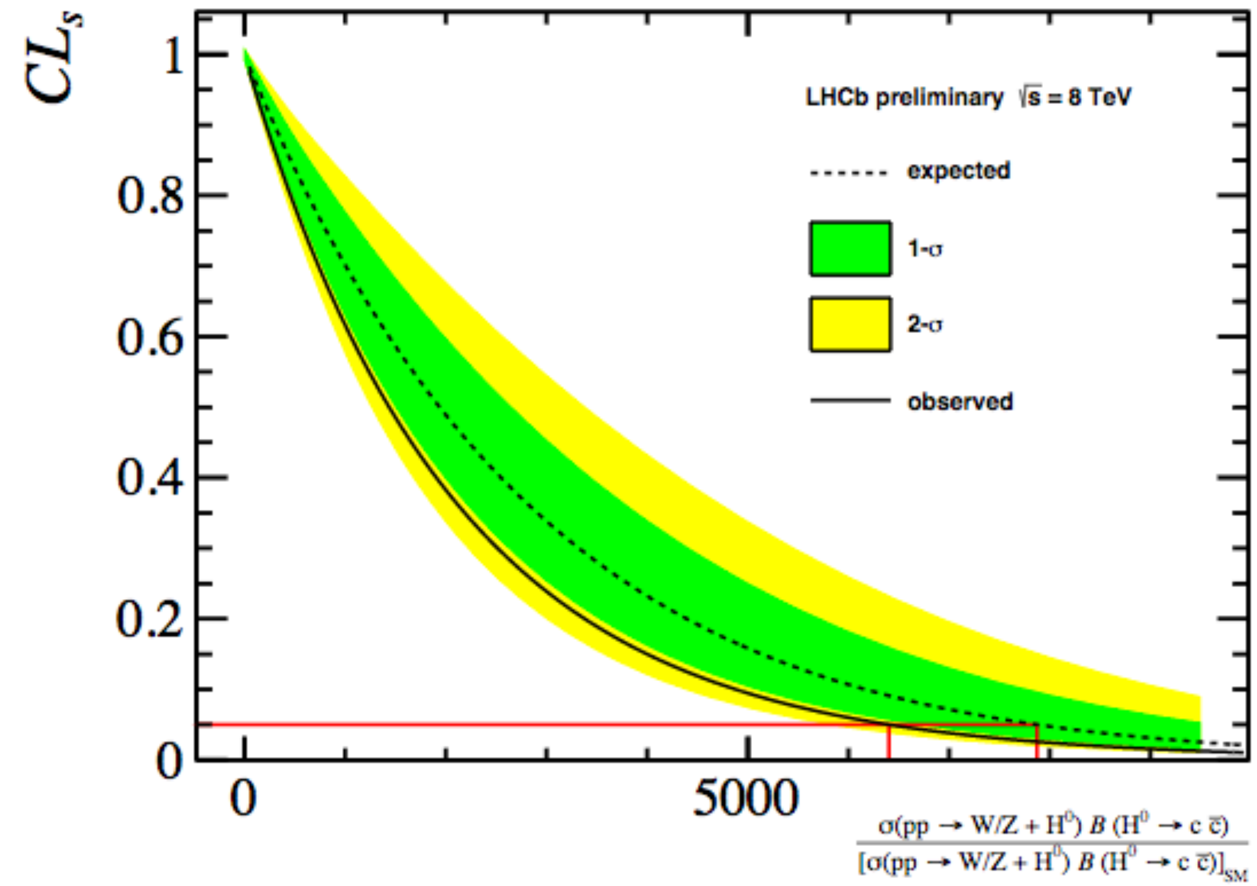
- projections on charm/bottom and top Yukawas at 3000 fb^{-1} extracted for √s=13 TeV

Search for VH→bb and VH→cc @ LHCb & ATLAS

➡ Search for VH→bb and VH→cc @ LHCb (2012 data, 1.92 fb^{-1})

LHCb-CONF-2016-006

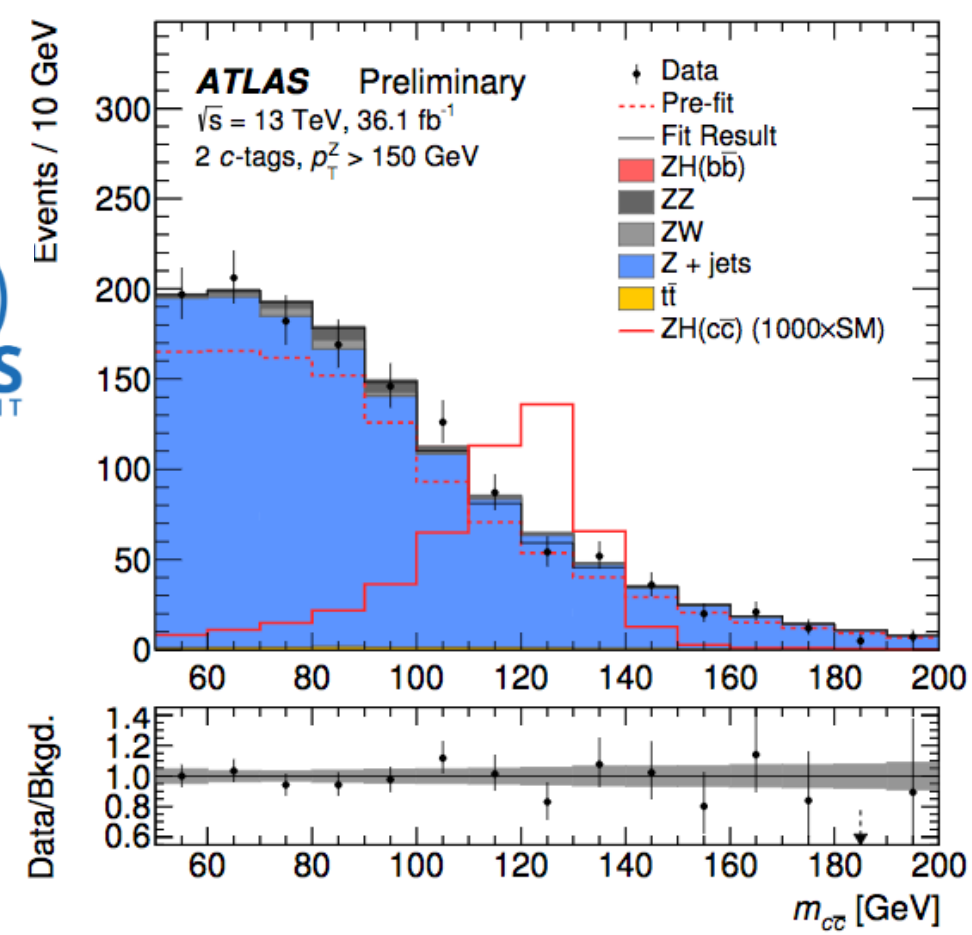
- analysis sensitivity is orders of magnitude above the SM - upper limits on SM processes
- multivariate discriminant to separate b-jets wrt light-flavour and c-jets
- limits - VH→bb @ 95% CL: 84 X SM (50XSM observed) - VH→cc @ 95% CL: 7900 X SM (6400XSM observed)



➡ Search for VH→cc @ ATLAS (2015+2106 data, 36.1 fb^{-1})

- focus on ZH production - H→cc invariant mass as discriminant (in 1/2 c-tag categories with additional requirements on pt^Z)
- new c-tagging algorithm developed by ATLAS for Run 2 analyses
- main background is Z+jets
- no significant evidence of ZH→cc production (limit at 110 SM predictions)

arXiv: 1802.04329 (submitted PRL)

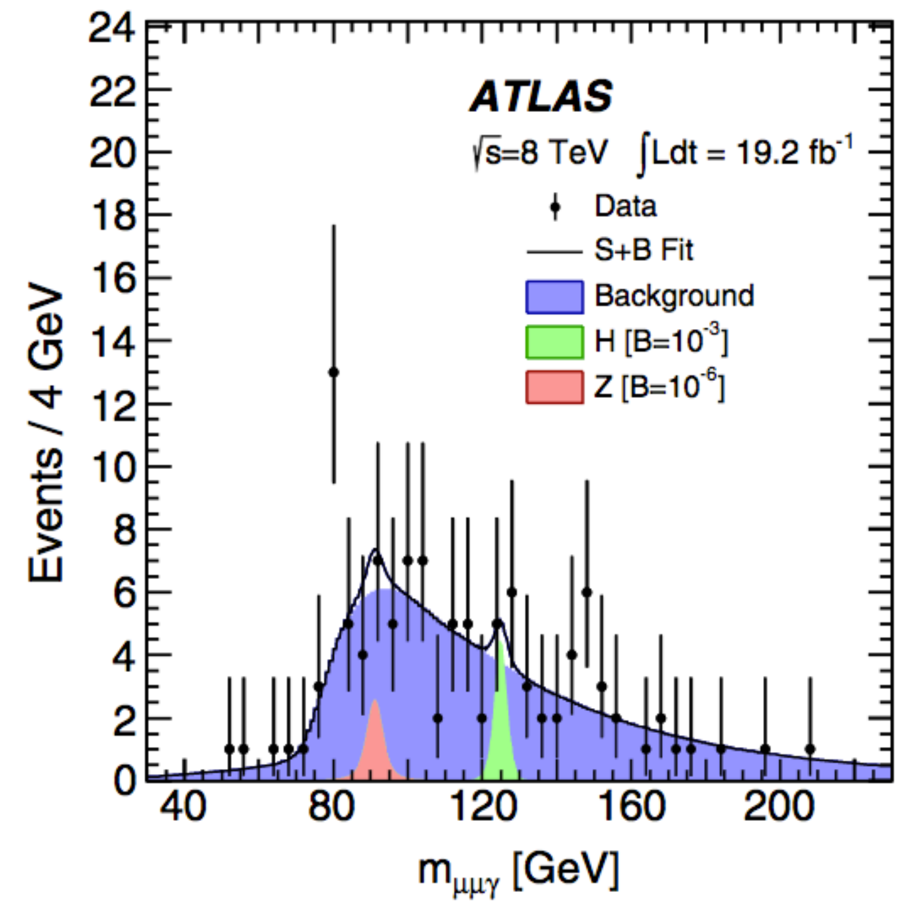


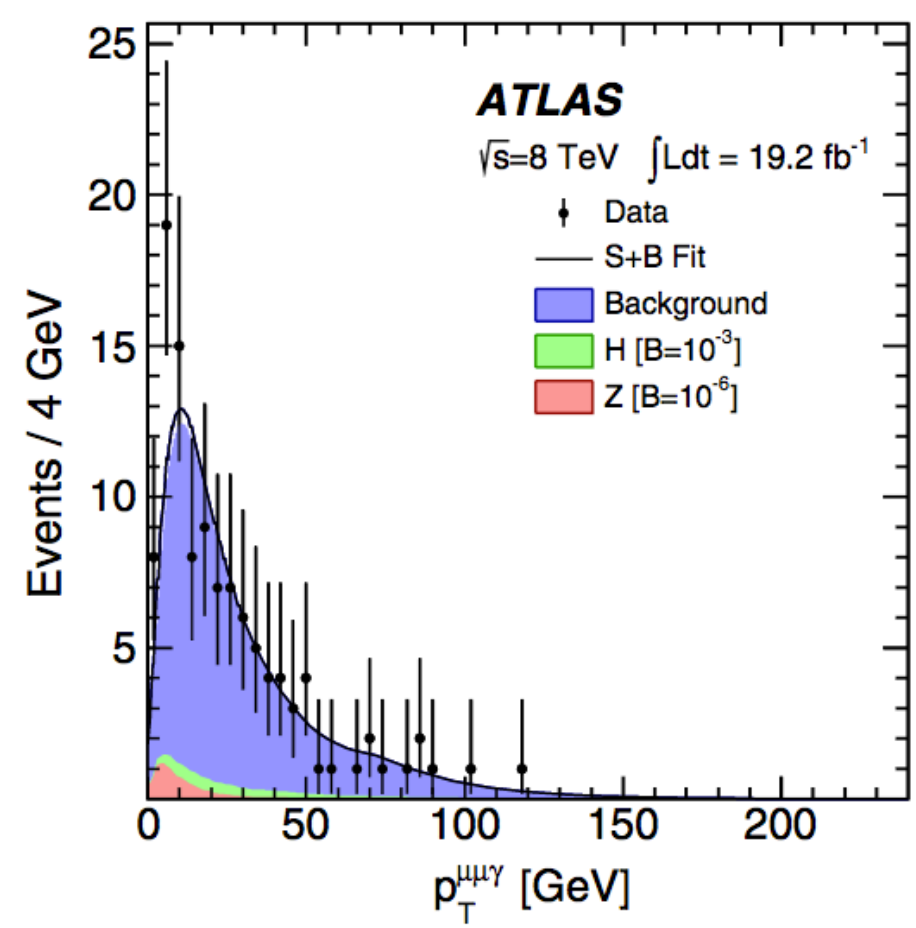
H/Z->J/ $\psi\gamma$ @ ATLAS

Phys.Rev.Lett. 114 (2015) no. 12, 121801

➡ Higgs couplings to charm quarks - sensitive to BSM physics

- analysis at 8 TeV with 20.3 fb^{-1}
- expected SM branching ratios
  - $BR(H \rightarrow J/\psi\gamma) = 2.8 \cdot 10^{-6}$
  - $BR(Z \rightarrow J/\psi\gamma) = 9.9 \cdot 10^{-8}$
- upper limit on BR $(H \rightarrow J/\psi\gamma)$ approximately 540 × SM predictions
- main background from inclusive QCD processes modelled with data driven templates to describe kinematic distributions
- Simultaneous unbinned maximum likelihood fit to $\mu\mu\gamma$ for the selected events
- No significant excess of events observed above the background

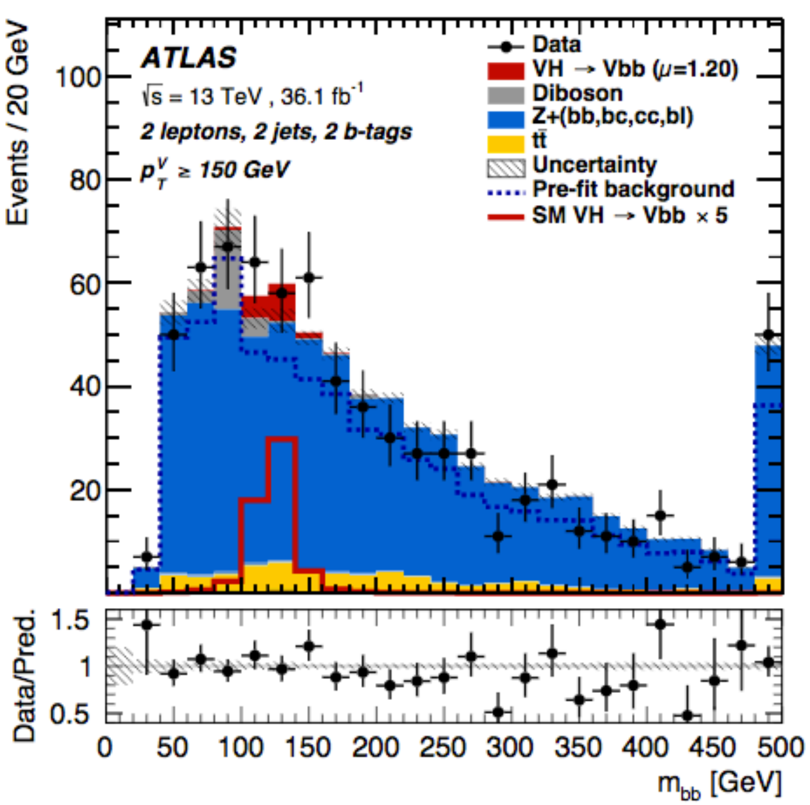


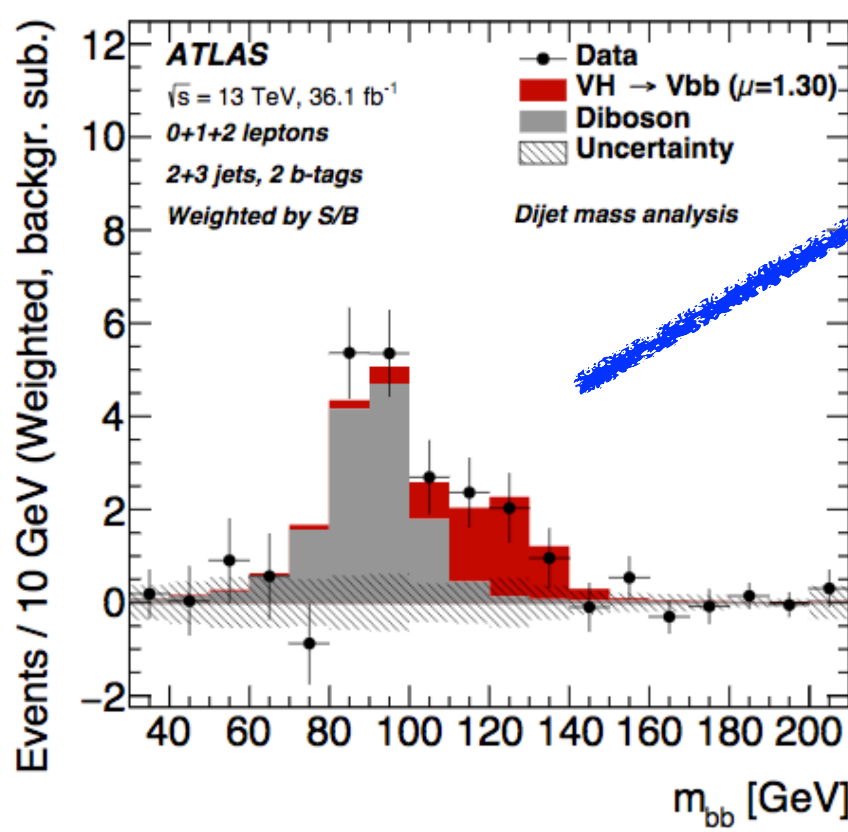


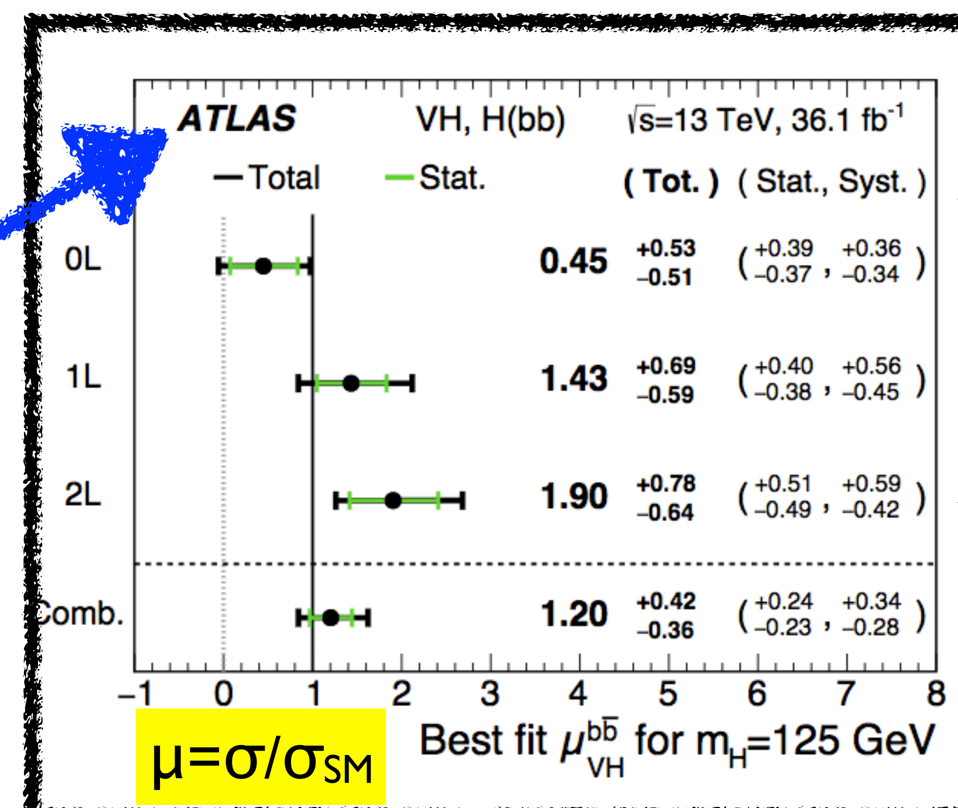
VHbb @ ATLAS

JHEP 12 (2017): 024

- Analysis with full 2015+2016 data (36.1 fb^{-1})
  - final state with 0, 1 and 2 leptons (e/μ) according to the decay of the vector boson
  - two or more b-jets tagged with MV2 b-tagging algorithm trained against light-flavour and c-jets
  - multivariate discriminant to discriminate VH→bb signal vs the sum of all background processes
  - VZ→bb channel used as analysis cross-check
  - systematic uncertainties for the modeling of the signal and background processes, for the limited size of the simulated samples and for the b-jet tagging play an important role
- Evidence of the VH→bb process (4.0σ expected, 3.6σ observed)
- Bottom Yukawa couplings consistent with Standard Model predictions







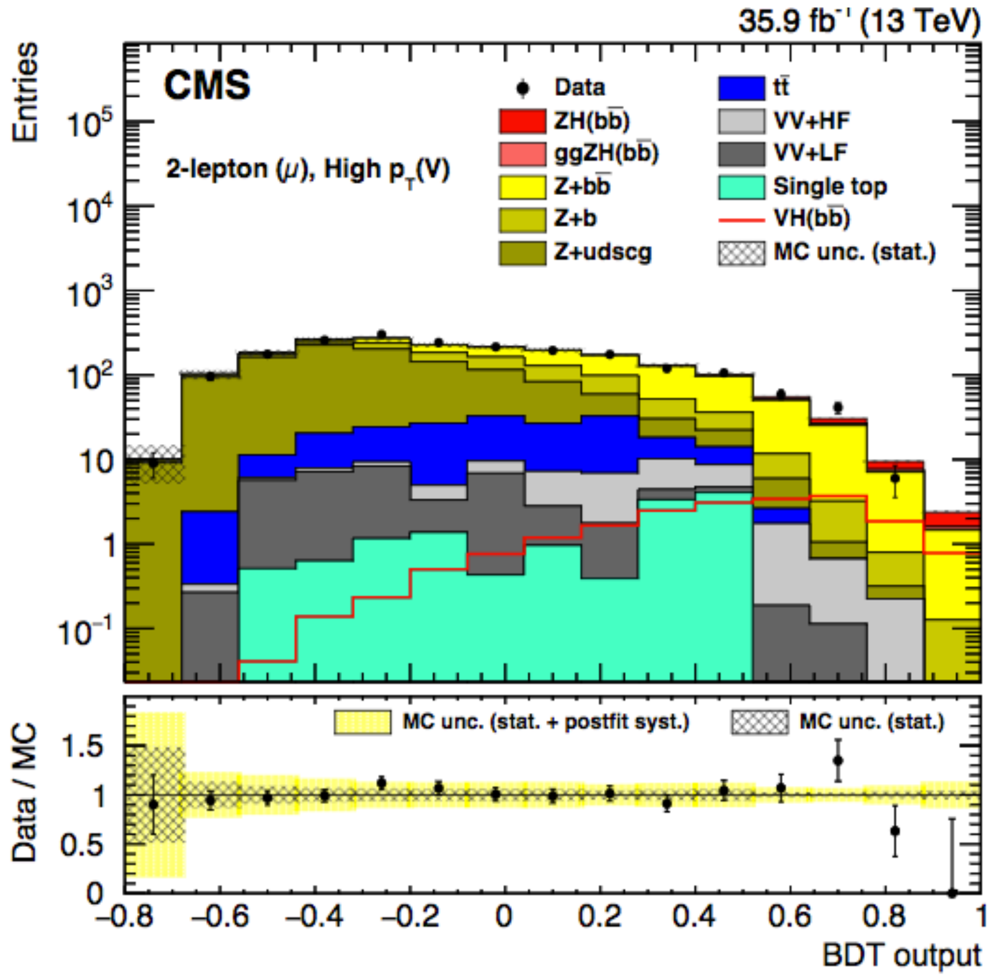
$\mu = \sigma/\sigma_{SM}$

VHbb in CMS

Phys. Lett. B 780 (2018) 501

➡ Analysis with full 2015+2016 data (35.8 fb^{-1})

- same final state as in ATLAS (0, 1 and 2-leptons)
- combined multivariate b-tagging algorithm with low-level (impact parameter, reconstruction of secondary vertex) inputs - significant b-jet efficiency and background (light-flavour and c-jets) rejection
- main backgrounds: V+jets, ttbar, single-top production and QCD multijet production
- multivariate regression (BDT) to improve invariant mass of di b-jet system and separate VH→bb
- main systematics uncertainty from background modeling



Source	Type	Individual contribution to the μ uncertainty (%)	Effect of removal to the μ uncertainty (%)
Scale factors ($t\bar{t}$, V+jets)	norm.	9.4	3.5
Size of simulated samples	shape	8.1	3.1
Simulated samples' modeling	shape	4.1	2.9
b tagging efficiency	shape	7.9	1.8
Jet energy scale	shape	4.2	1.8
Signal cross sections	norm.	5.3	1.1
Cross section uncertainties (single-top, VV)	norm.	4.7	1.1
Jet energy resolution	shape	5.6	0.9
b tagging mistag rate	shape	4.6	0.9
Integrated luminosity	norm.	2.2	0.9
Unclustered energy	shape	1.3	0.2
Lepton efficiency and trigger	norm.	1.9	0.1

➡ Evidence of the VH→bb process (2.8σ expected, 3.3σ observed)

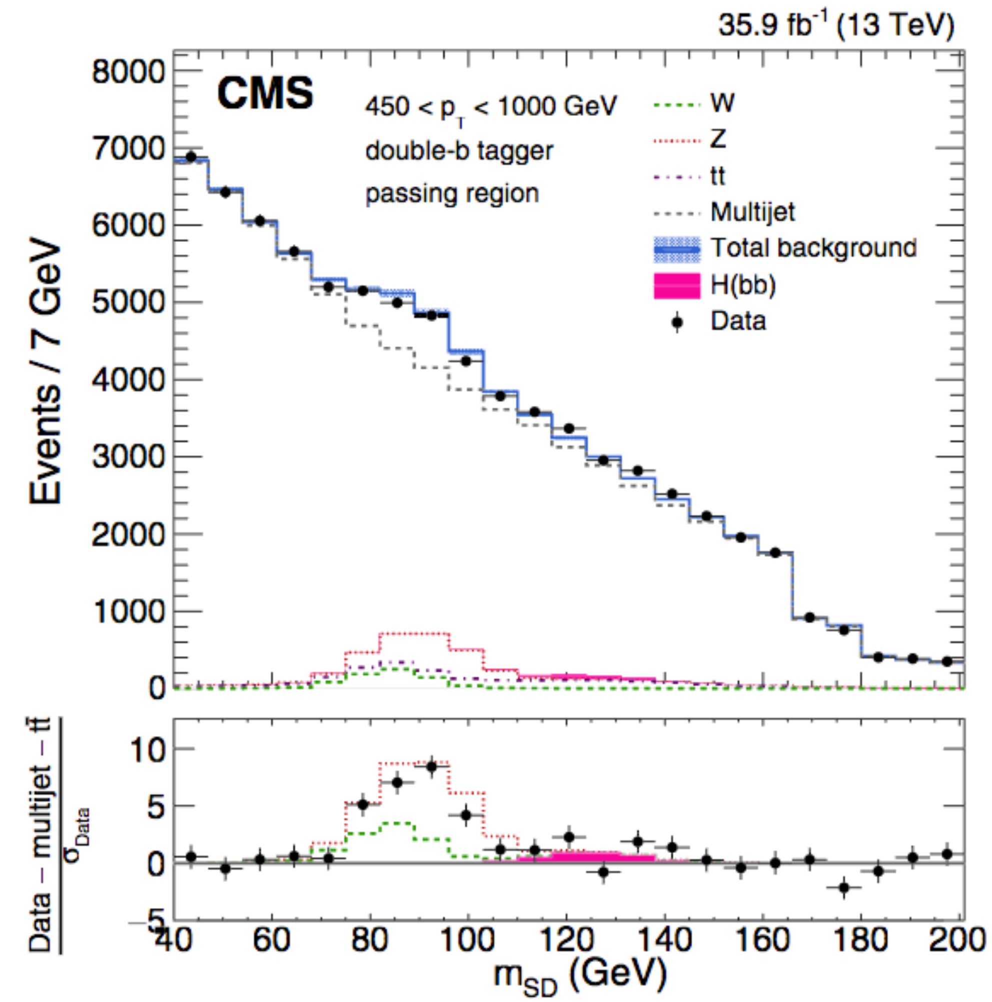
➡ Bottom Yukawa couplings consistent with Standard Model expectations

Boosted Hbb @ CMS

Phys. Rev. Lett. 120, 0718002

- Largest Higgs production and decay mode is gluon fusion in H→bb (58%)
  - very large QCD background (10^8 times larger)
  - accessible via boosted dijet topology → new physics probed in high Q^2 phase-space
  - using fat-jets (R=0.8) containing two b-quarks
  - double b-tagging algorithm combines vertexing and tracking information in a multivariate discriminant
  - QCD background estimated from data in sidebands
  - Higgs pt modelling - comparison of MC generators with different matrix-element and parton shower schemes (large modeling systematics)

- Observation of Z(bb) in single-jet topology
- Significance of Hbb is 1.5σ (0.7σ expected)



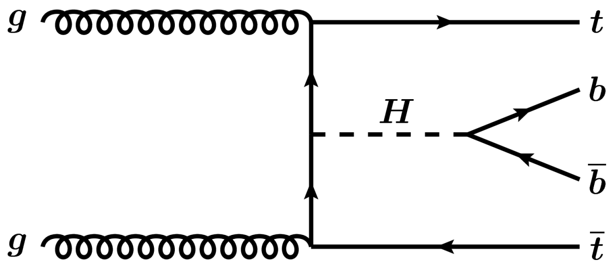
Systematic source	W/Z	H
Integrated luminosity	2.5%	2.5%
Trigger efficiency	4%	4%
Pileup	<1%	<1%
$N_2^{1,\mathrm{DDT}}$ selection efficiency	4.3%	4.3%
Double-b tag	4% (Z)	4%
Jet energy scale/ resolution	10/15%	10/15%
Jet mass scale (p_T)	0.4%/100 GeV (p_T)	0.4%/100 GeV (p_T)
Simulation sample size	2–25%	4–20% (GGF)
H p_T correction	…	30% (GGF)
NLO QCD corrections	10%	…
NLO EW corrections	15–35%	…
NLO EW W/Z decorrelation	5–15%	…

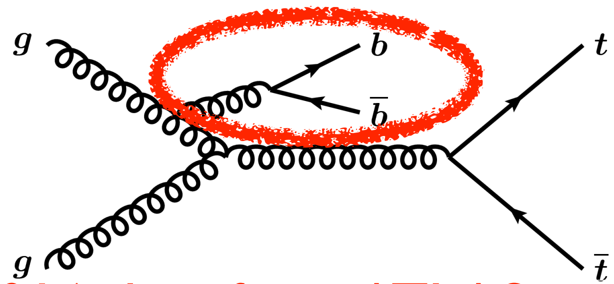
ttH->bb @ ATLAS/CMS

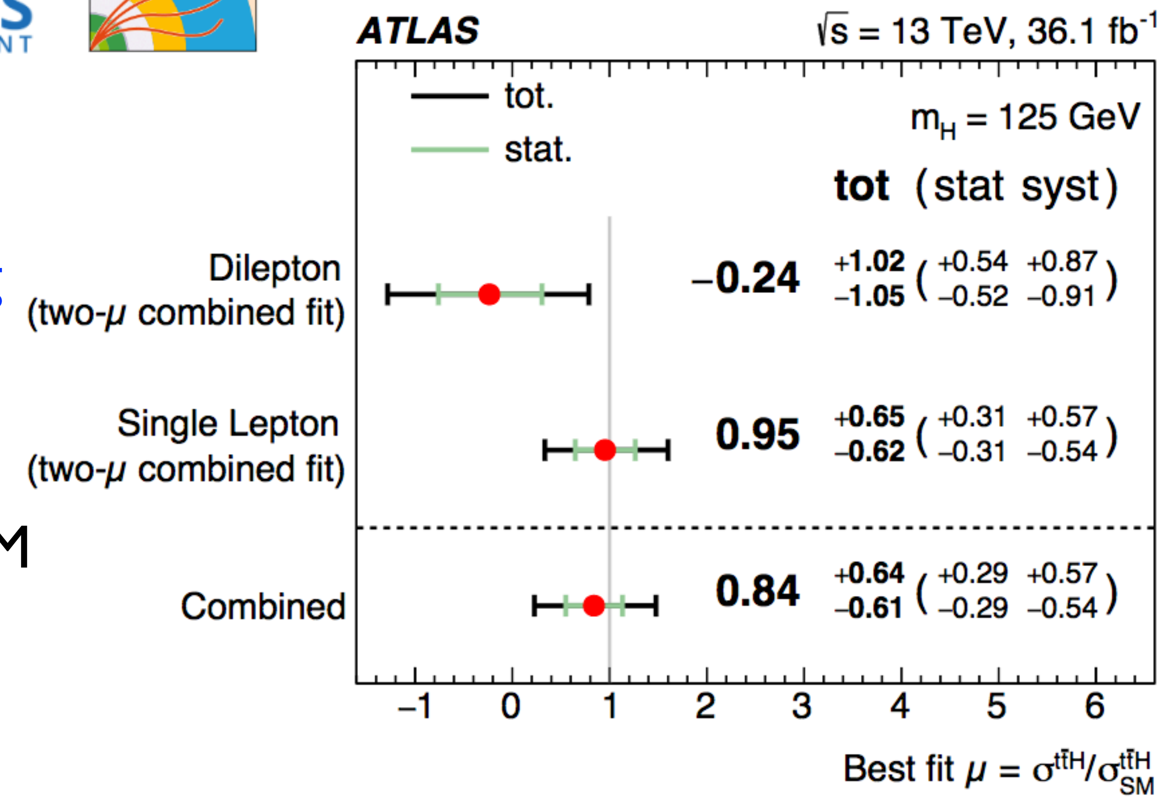
arXiv: 1712.08895 (accepted in PRD)

CMS-PAS-HIG-17-026

arXiv: 1803.06986 (CMS ttH full-had)

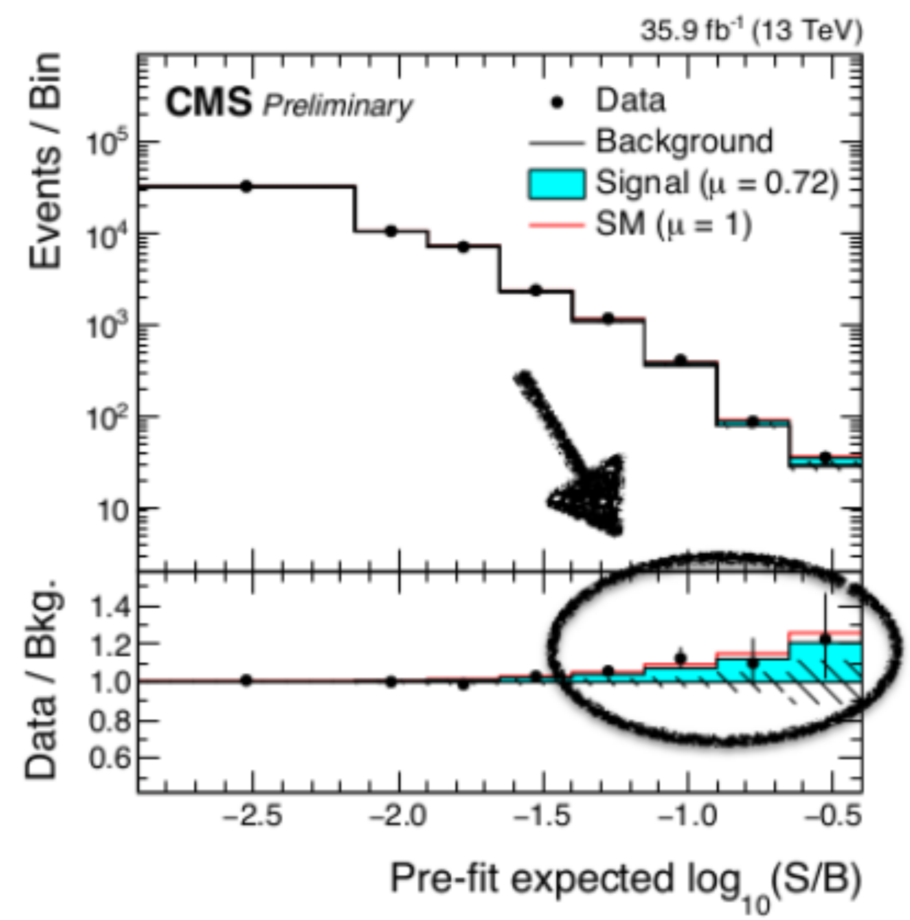






➡ Analyses with 2015+2016 data from ATLAS and CMS

- categories based on jet, b-jet multiplicity and b-tagging requirements (1-lepton and 2-lepton final states)
- analysis strategy based on multivariate classifiers (reconstruction, classification BDT, likelihood, and MEM in ATLAS, deep neural network CMS)
- main theoretical uncertainties on tt+HF (tt+≥1b) modeling
- CMS has also made public ttH(bb) full-hadronic final state



➡ Significances:

- 2.2σ expected significance (CMS), $\mu_{Combined}$=0.72±0.24(stat) ±0.38
- 1.6σ expected significance (ATLAS)
- main difference: no ttb generator comparison systematics in CMS

CMS-PAS-HIG-16-040

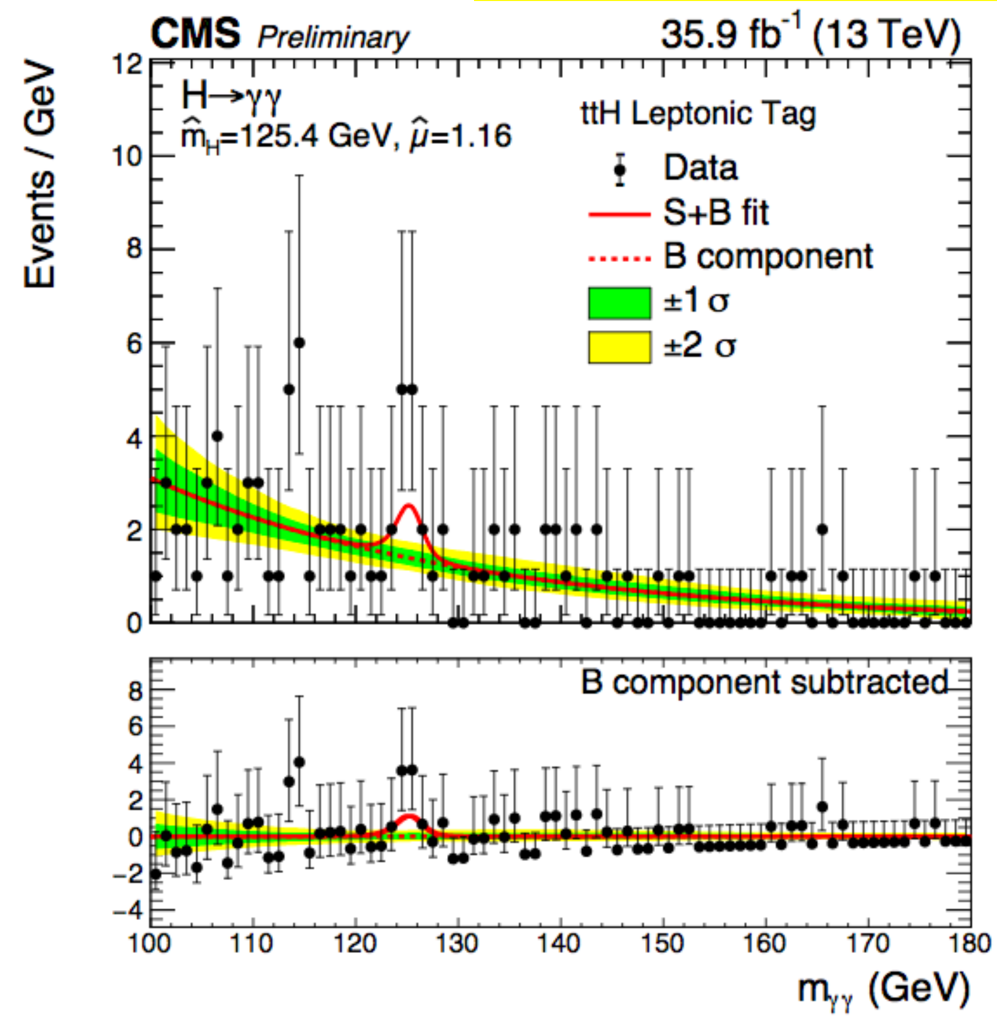
JHEP 11 (2017) 047

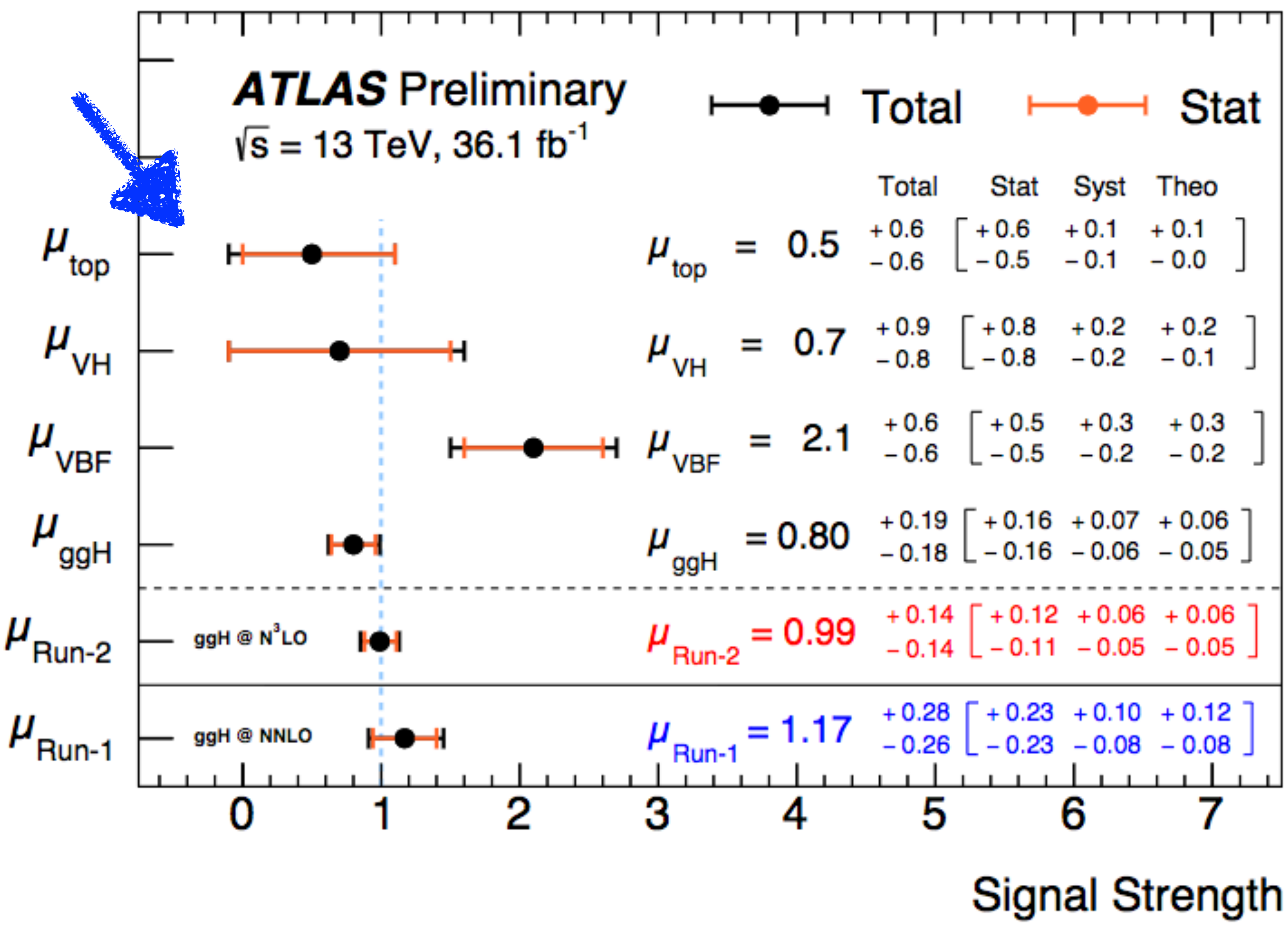
ttH→γγ, H→ZZ*→4l @ ATLAS/CMS

arXiv: 1802:04146 (submitted PRD)

High purity in H→γγ and H→ZZ*→4l

- very small signal yield
- various ttH-enriched categories
- background model extracted from sidebands
- observed signal strength in CMS ttH(H→γγ): $\mu_{Combined}=2.2\pm0.9$





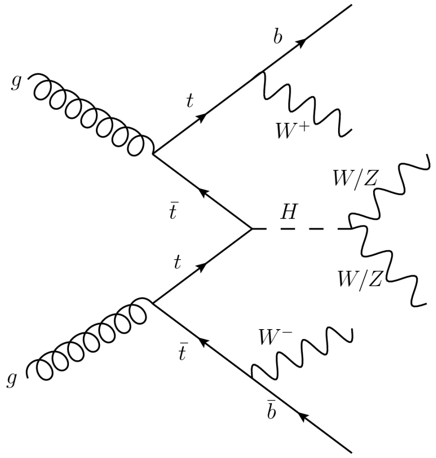
H→γγ

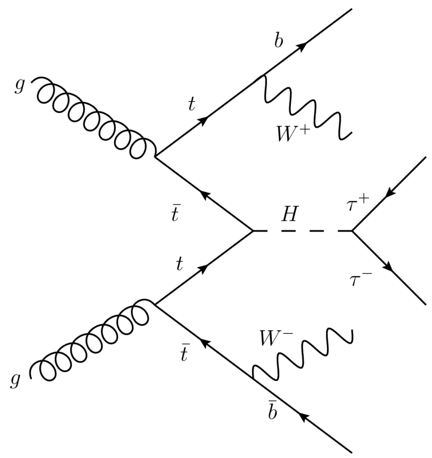
- results compatible with SM predictions
- dominated by data statistics

H→ZZ→4l

- upper limits (no event observed)

ttH->multileptons @ ATLAS/CMS

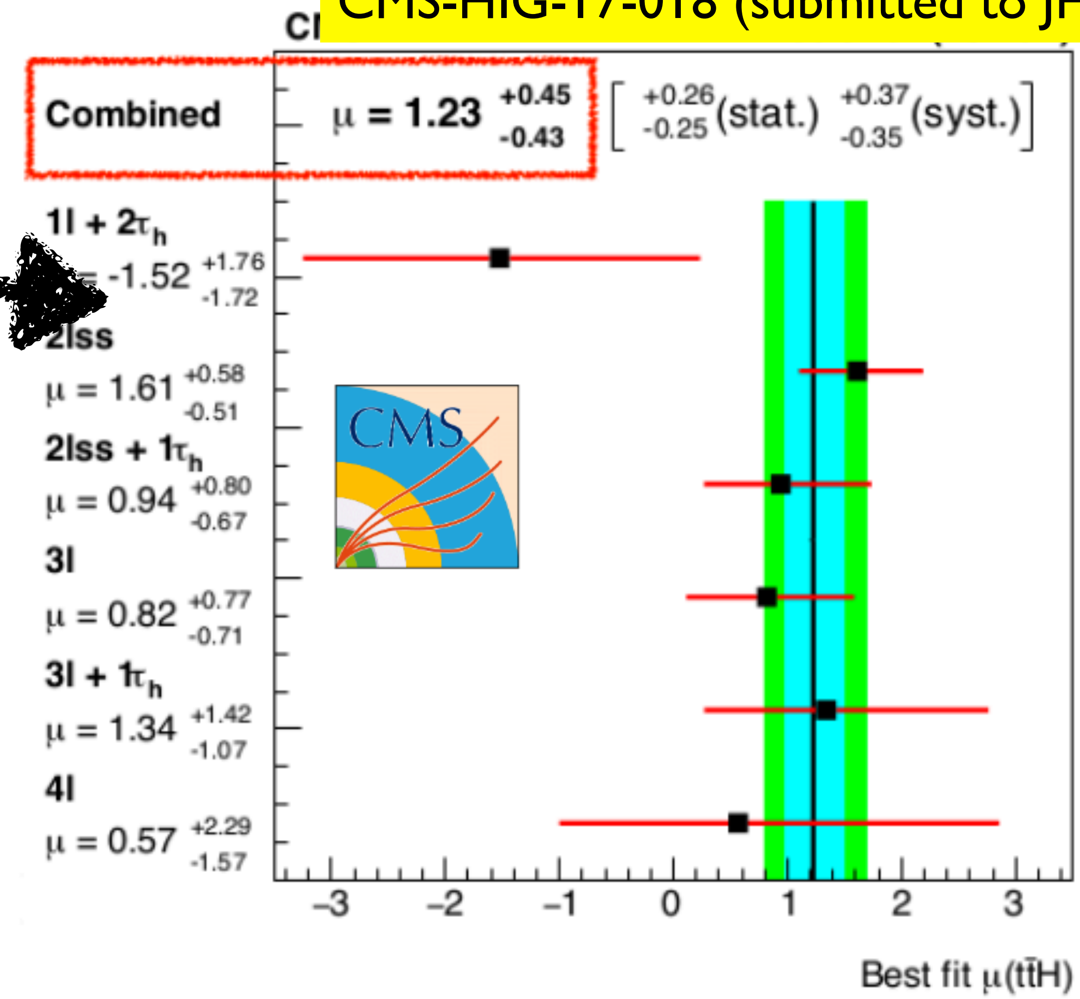


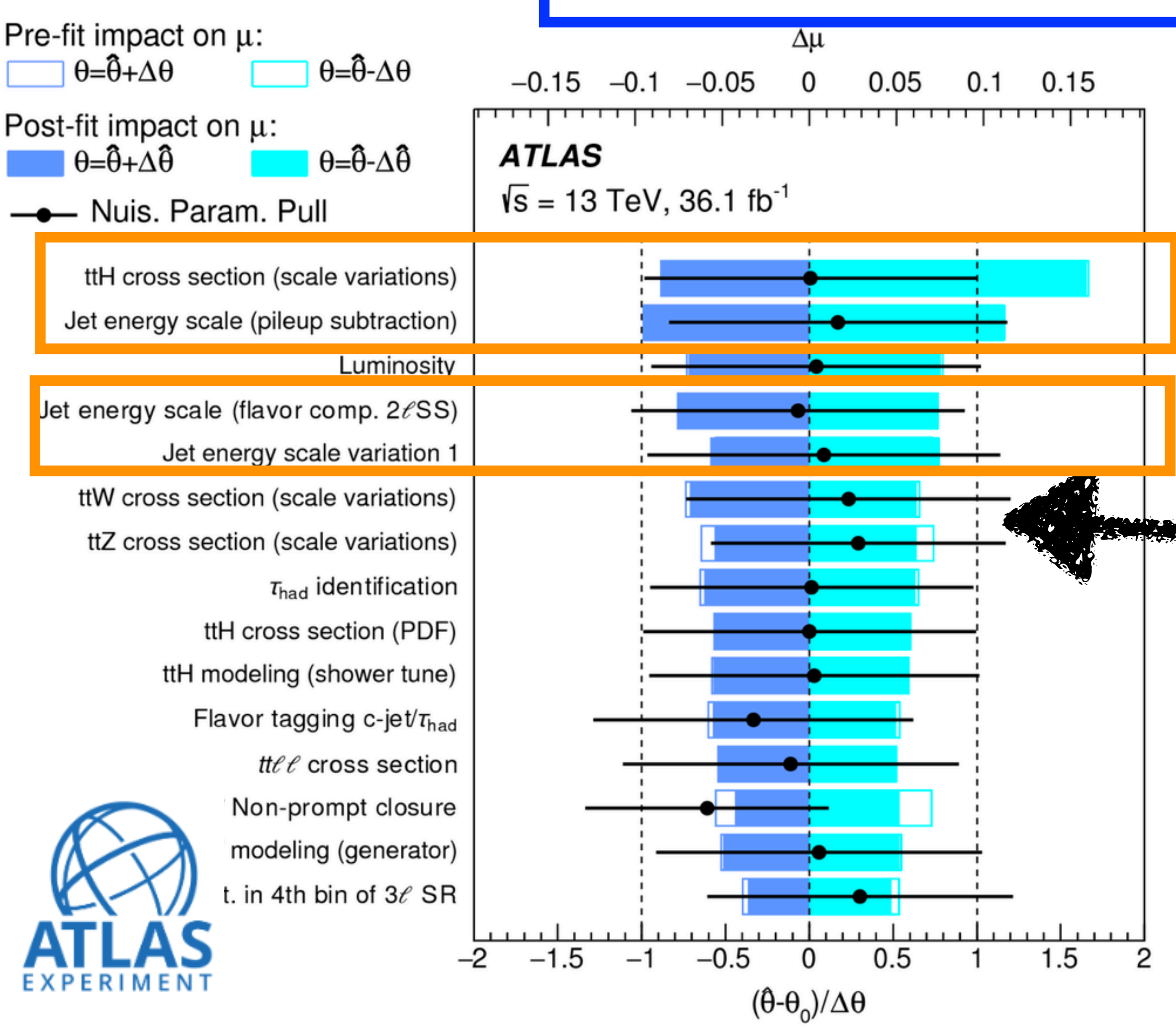


arXiv: 1712.08891 (accepted PRD)

- ✓ Signal strength μ_{ttH} =1.6±0.5/0.4 @ ATLAS, 1.2±0.4 @ CMS
- ✓ ttH signal significance: 4.1σ (expected 2.8σ) @ ATLAS, 3.1σ (expected 2.8σ) @ CMS
- ✓ Good compatibility among channels

CMS-HIG-17-018 (submitted to JHEP)

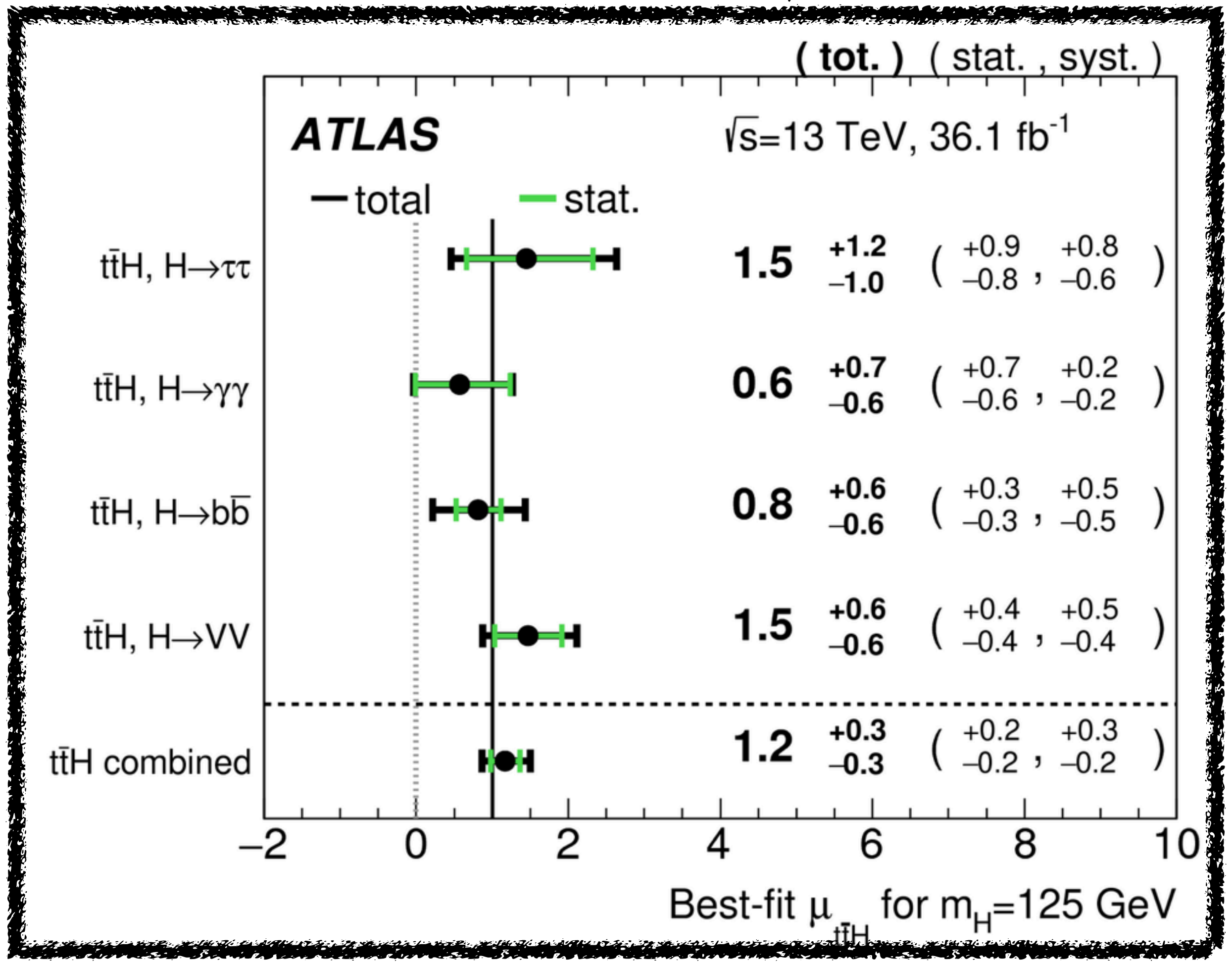




✓ Source of uncertainties

- ttH modeling (affecting SM ttH cross section in the denominator of μ)
- experimental uncertainties (jet energy scale, resolutions, b-tagging)
- non-prompt lepton estimate, lepton efficiency

Status of ttH results @ ATLAS and CMS



arXiv: 1712.08891 (accepted PRD)

CMS-PAS-HIG-17-026

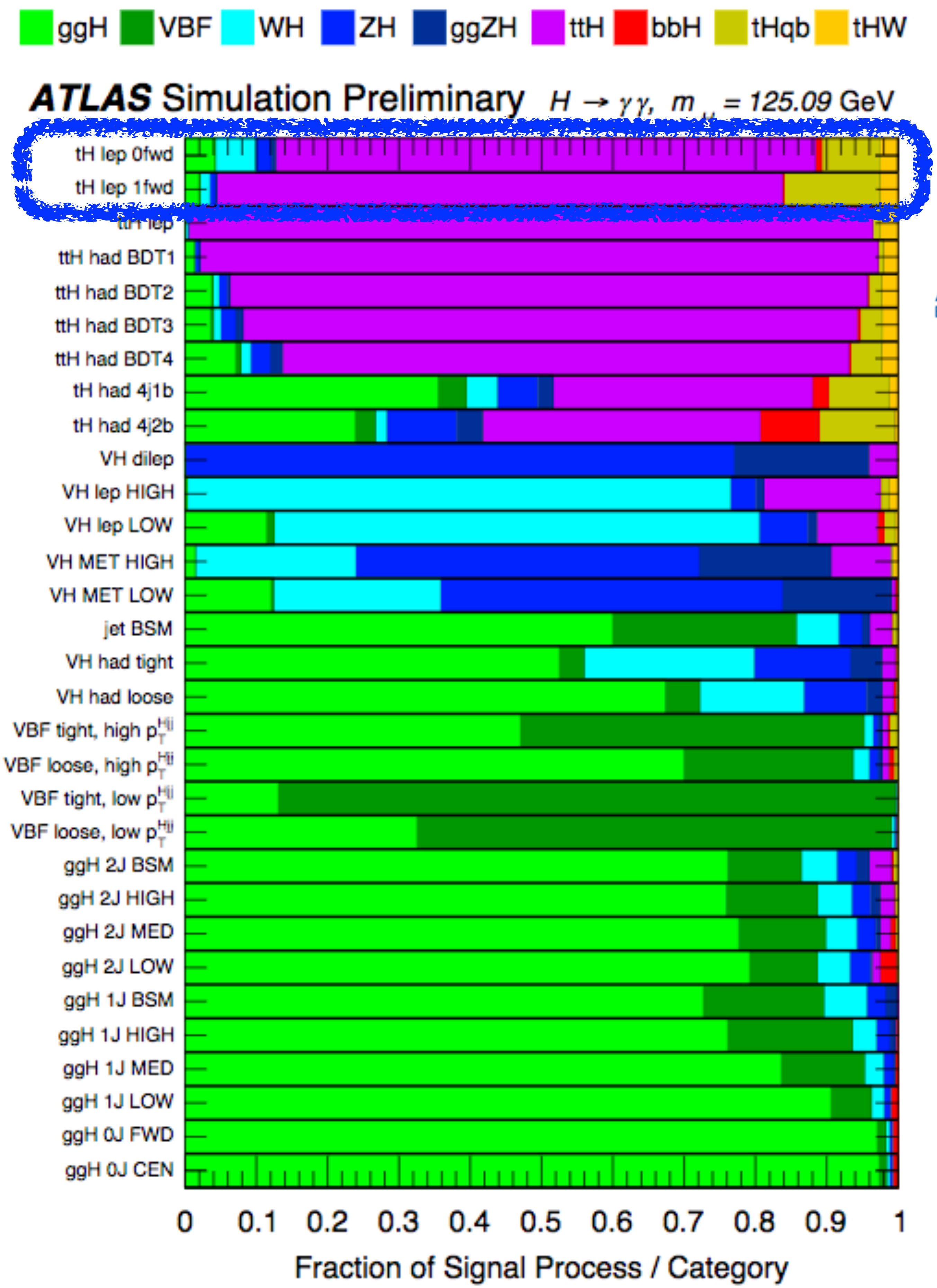
Uncertainty Source	$\Delta\mu$	
$t\bar{t}$ modeling in $H \to b\bar{b}$ analysis	+0.15	−0.14
$t\bar{t}H$ modeling (cross section)	+0.13	−0.06
Non-prompt light-lepton and fake τ_{had} estimates	+0.09	−0.09
Simulation statistics	+0.08	−0.08
Jet energy scale and resolution	+0.08	−0.07
$t\bar{t}V$ modeling	+0.07	−0.07
$t\bar{t}H$ modeling (acceptance)	+0.07	−0.04
Other non-Higgs boson backgrounds	+0.06	−0.05
Other experimental uncertainties	+0.05	−0.05
Luminosity	+0.05	−0.04
Jet flavor tagging	+0.03	−0.02
Modeling of other Higgs boson production modes	+0.01	−0.01
Total systematic uncertainty	+0.27	−0.23
Statistical uncertainty	+0.19	−0.19
Total uncertainty	+0.34	−0.30

➡ Combiation of ttH - evidence of ttH process in ATLAS and CMS

Uncertainty source	$\pm\sigma_\mu$ (observed)	$\pm\sigma_\mu$ (expected)
total experimental	+0.15/-0.16	+0.19/-0.17
b tagging	+0.11/-0.14	+0.12/-0.11
jet energy scale and resolution	+0.06/-0.07	+0.13/-0.11
total theory	+0.28/-0.29	+0.32/-0.29
tt̄+hf cross-section and parton shower	+0.24/-0.28	+0.28/-0.28
size of MC samples	+0.14/-0.15	+0.16/-0.16
total systematic	+0.38/-0.38	+0.45/-0.42
statistical	+0.24/-0.24	+0.27/-0.27
total	+0.45/-0.45	+0.53/-0.49

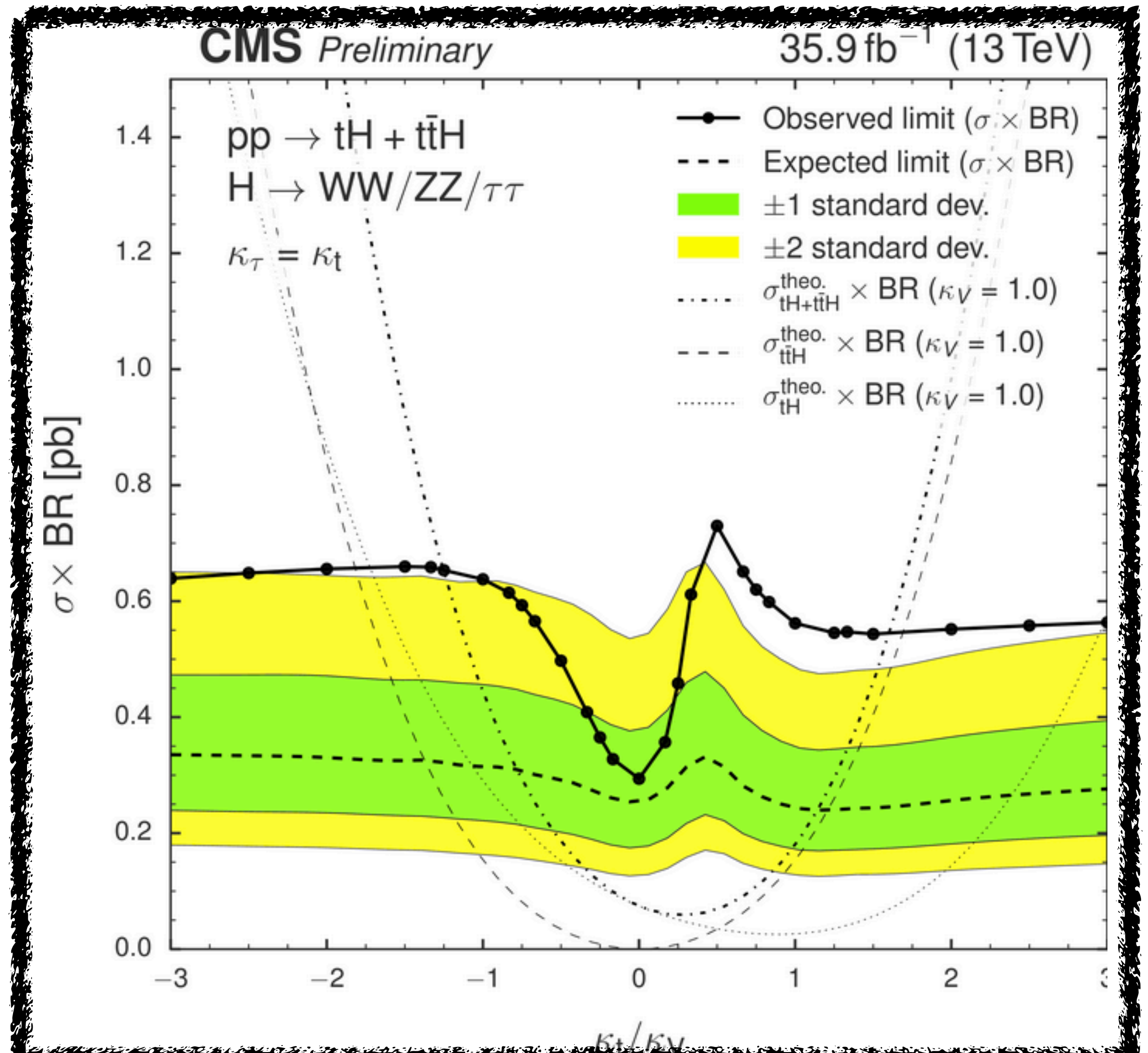
- tt+HF modeling in H→bb, ttH signal modeling for H→bb and H→Multilepton, theory systematics (tt+HF cross section and PS)
- simulation statistics is still an issue for both experiments
- experimental uncertainties are mostly dominated by lepton fakes (ML), jet energy scale and b-tagging

tH production



➡ Search for tH production in H→bb/ H→ML (CMS) and tH-enriched categories in H→γγ (ATLAS) final states to probe anomalous couplings

- upper limit on tH cross sections (far from SM expectation)
- measurement dominated by statistical uncertainties



Prospect studies for HL-LHC

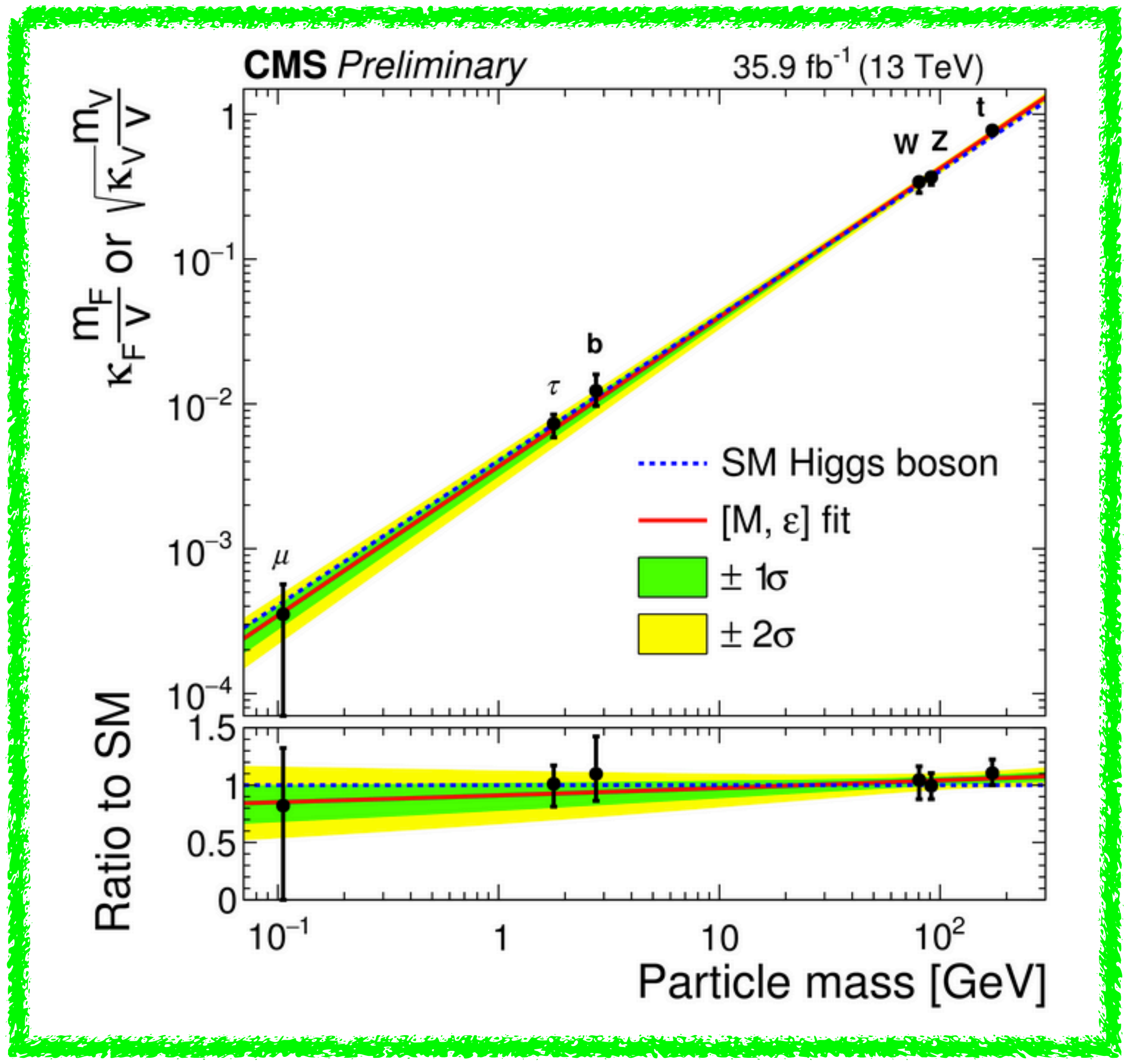
CMS-PAS-HIG-17-031

Prospects on couplings

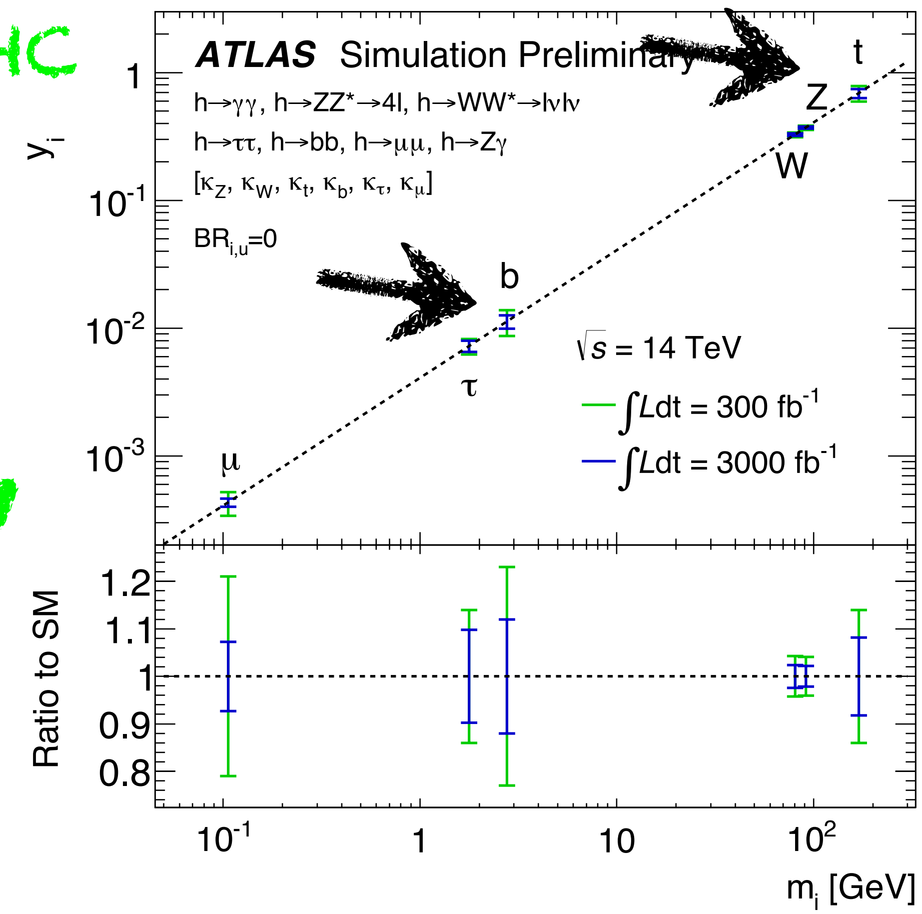
ATL-PHYS-PUB-2014-016

➡ Large improvement in top/bottom Yukawa coupling precision at High-Luminosity LHC (300 fb^{-1} and 3000 fb^{-1})

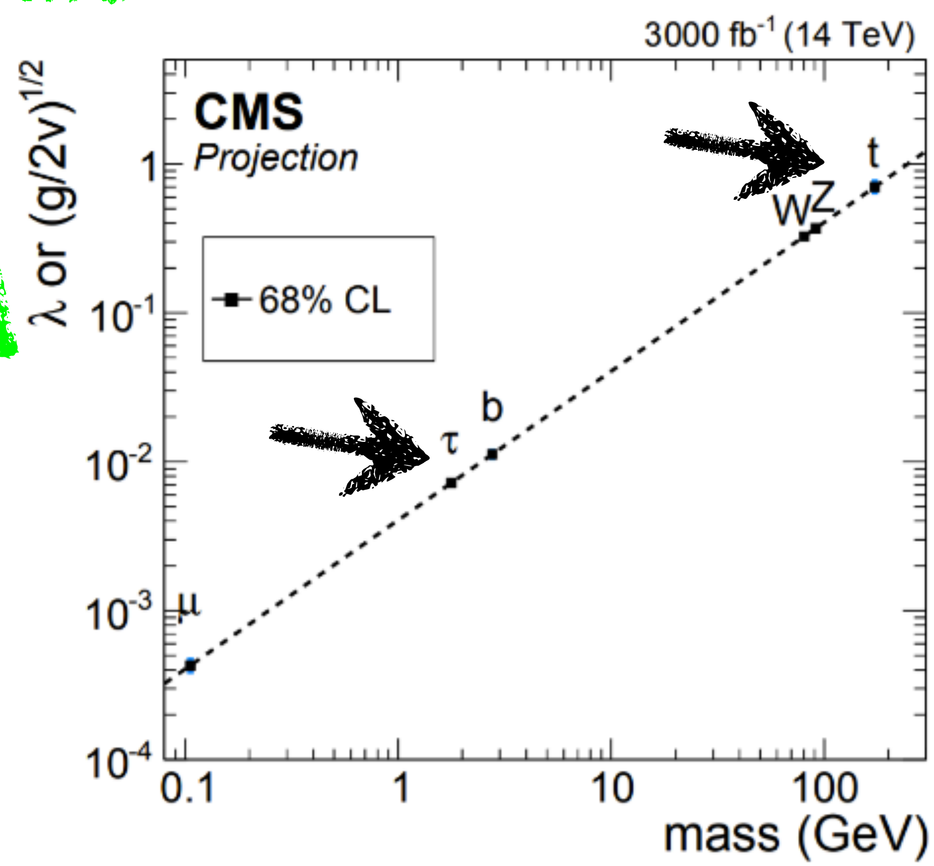
Run 2



HL-LHC

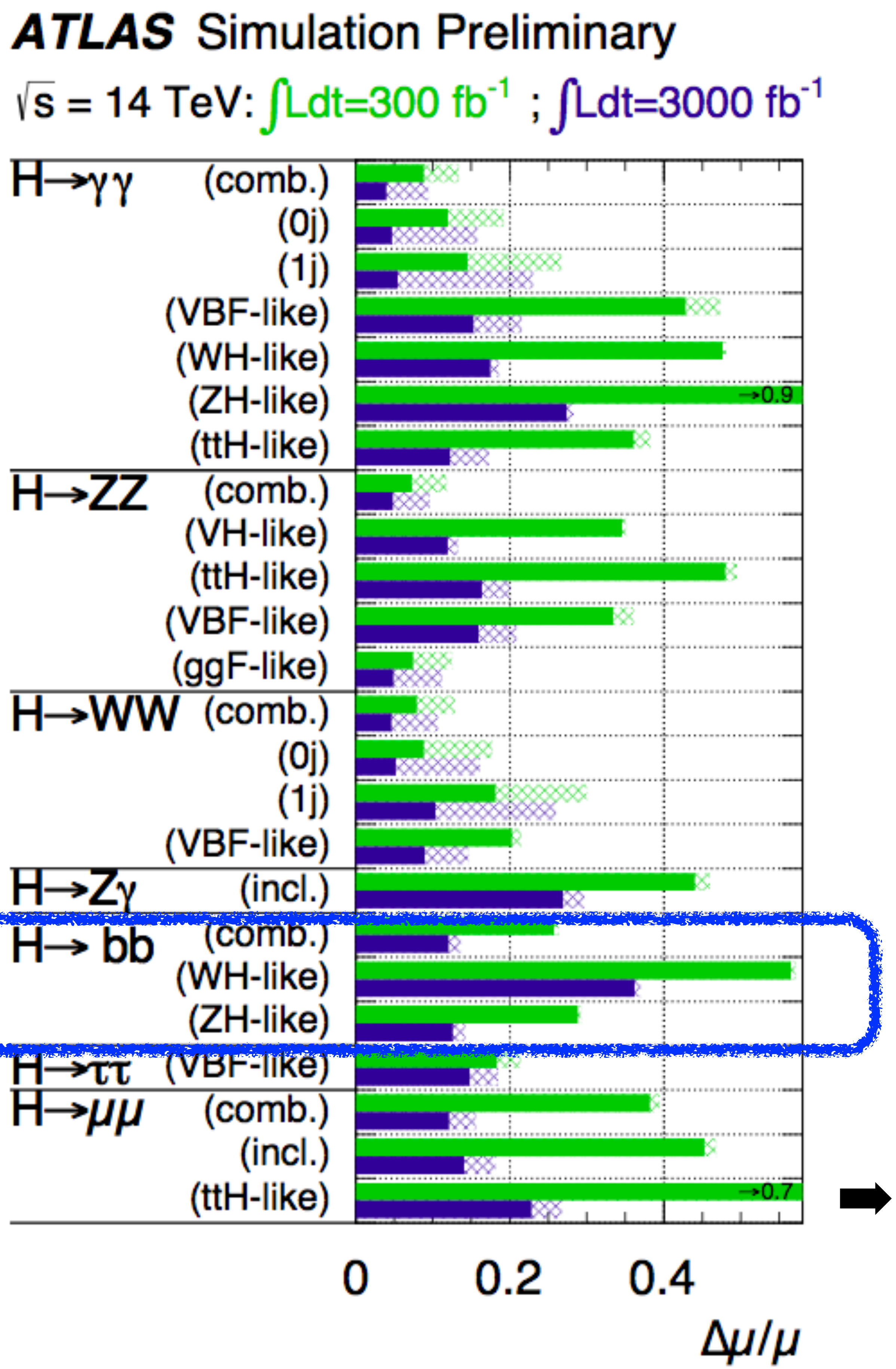


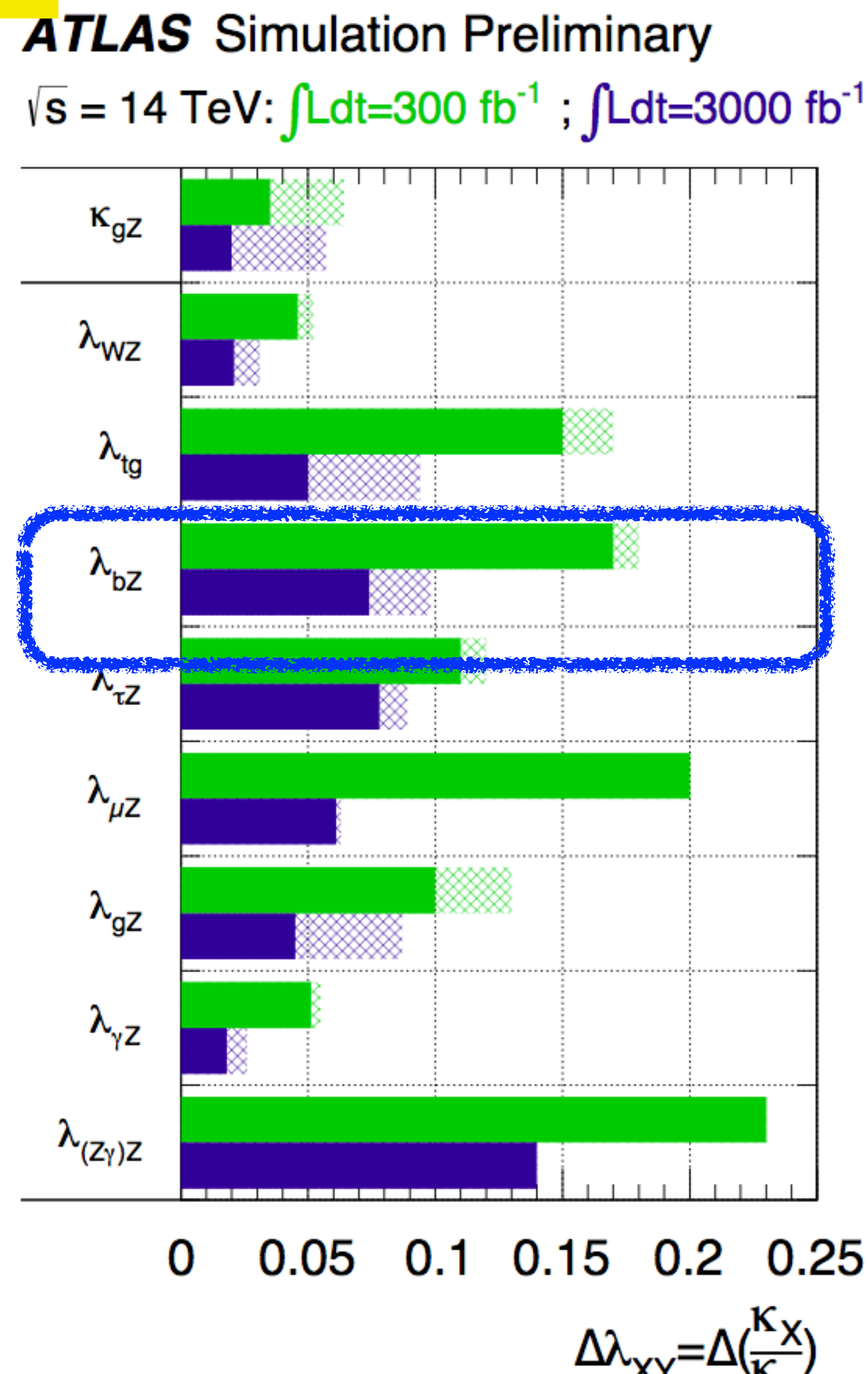
HL-LHC



Prospects on couplings (2) - Hbb

ATL-PHYS-PUB-2014-016





➡ Projection using Run 1 analysis strategy with expected performance at <μ>= 140 - all uncertainties (Run 1 experimental/theory systematics) and no theory uncertainties

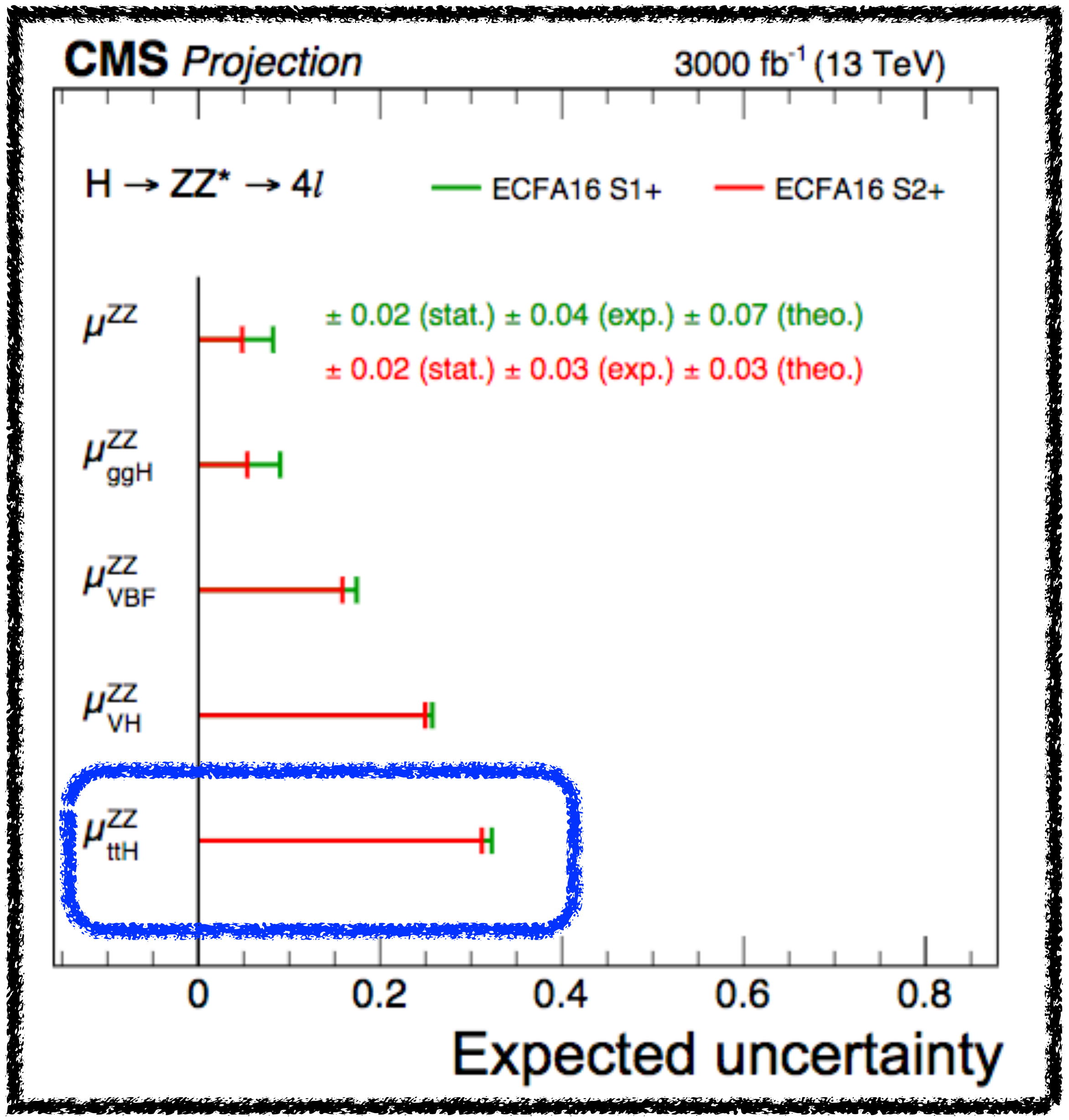
CMS-PAS-FTR-16-002

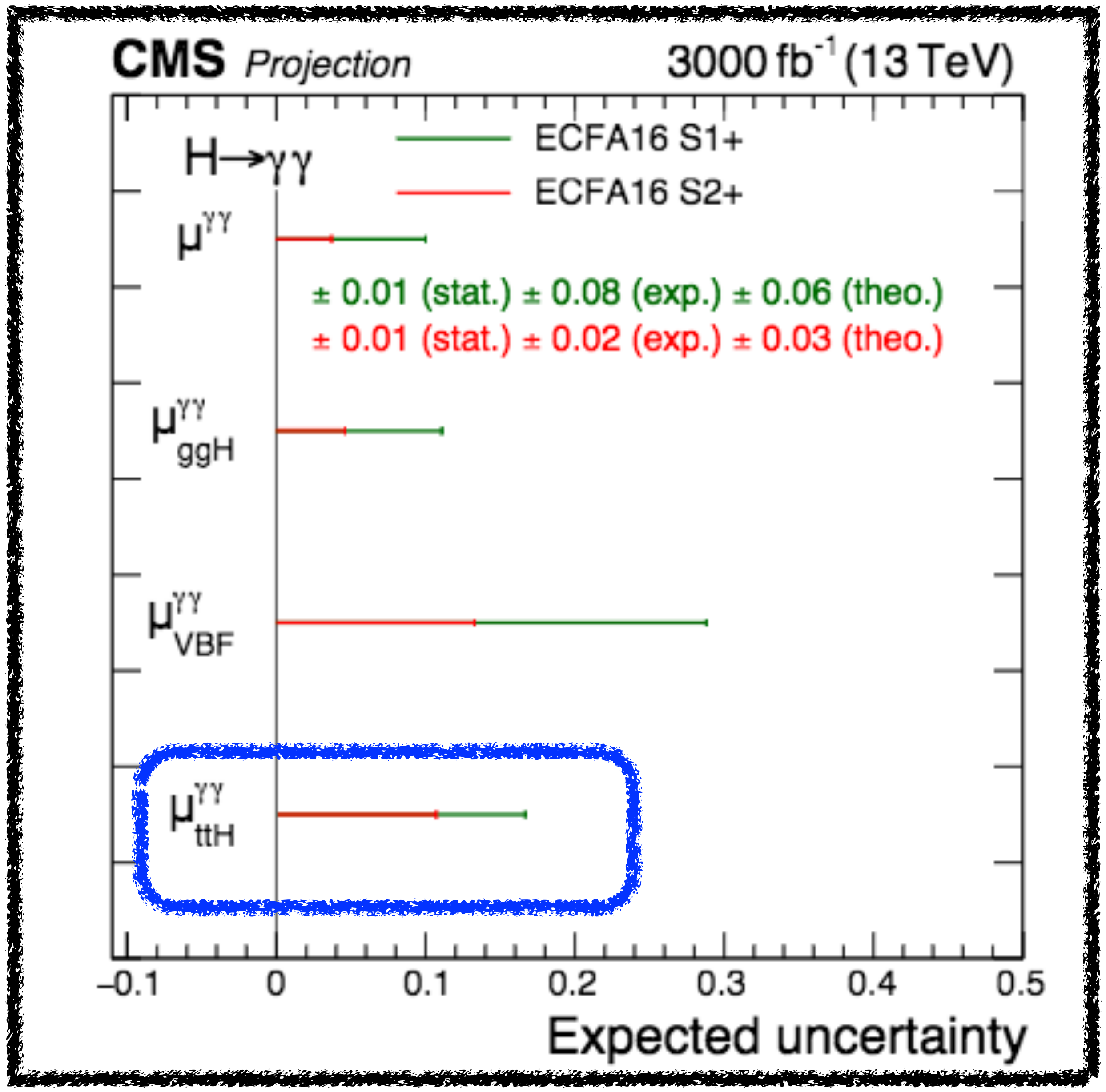
Prospects on couplings (3) - ttH

Projection on top-Yukawa couplings by extrapolation from Run 2 analysis

- S1+: systematics uncertainties kept same as Run 2 with presence of high pile-up and detector improvements, S2+: systematics scaled wrt Run 2 analysis (theory → 1/2, experimental → ∝ 1/L)

✓ H→γγ and H→ZZ*→4l are currently statistically-limited, multilepton will soon be systematically-limited and H→bb requires a lot more thoughts about ttb modeling already now in order to improve the current results



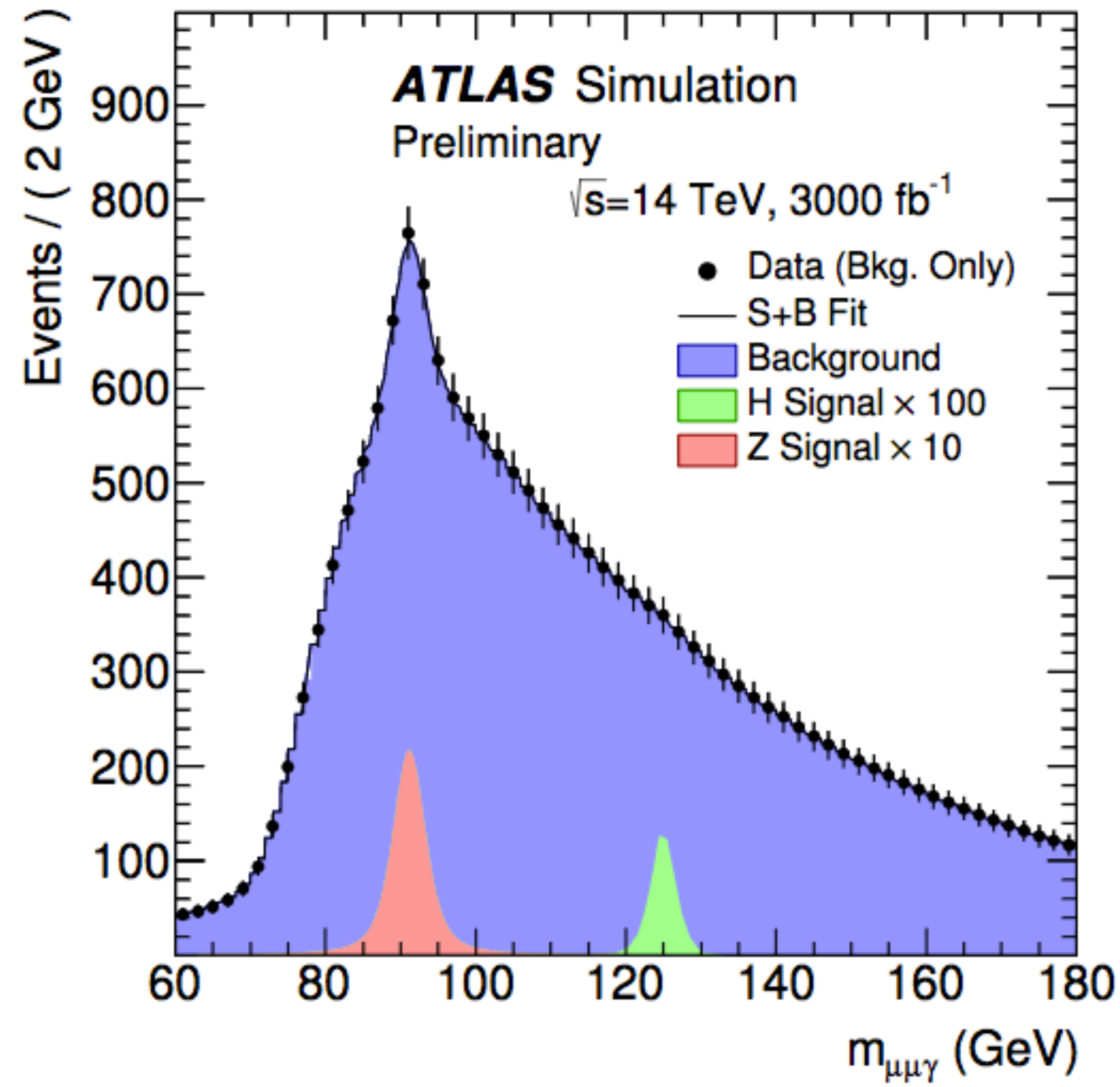


Prospects on $H \to J/\psi\gamma$ @ ATLAS

ATLAS-PHYS-PUB-2015-043

- Higgs couplings to charm quarks - sensitive to BSM physics

- extrapolation from Run 1 results to 300 fb^{-1} and 3000 fb^{-1} at 14 TeV
- same analysis selection to identify $J/\psi\gamma$ candidate as in Run 1
- using multivariate discriminant trained to enhance signal sensitivity
  - BDT with photon and di-muon pt + γ and μ isolation included as inputs
- main source of background is inclusive production of J/ψ and a reconstructed high energy photon
- simultaneous fit of $m(\mu\mu\gamma)$ vs $pt(\mu\mu\gamma)$
- for 3000 fb^{-1} → 95% CL limit on $\sigma(pp \to H) \times BR(H \to J/\psi\gamma)$ is ~ 15×SM



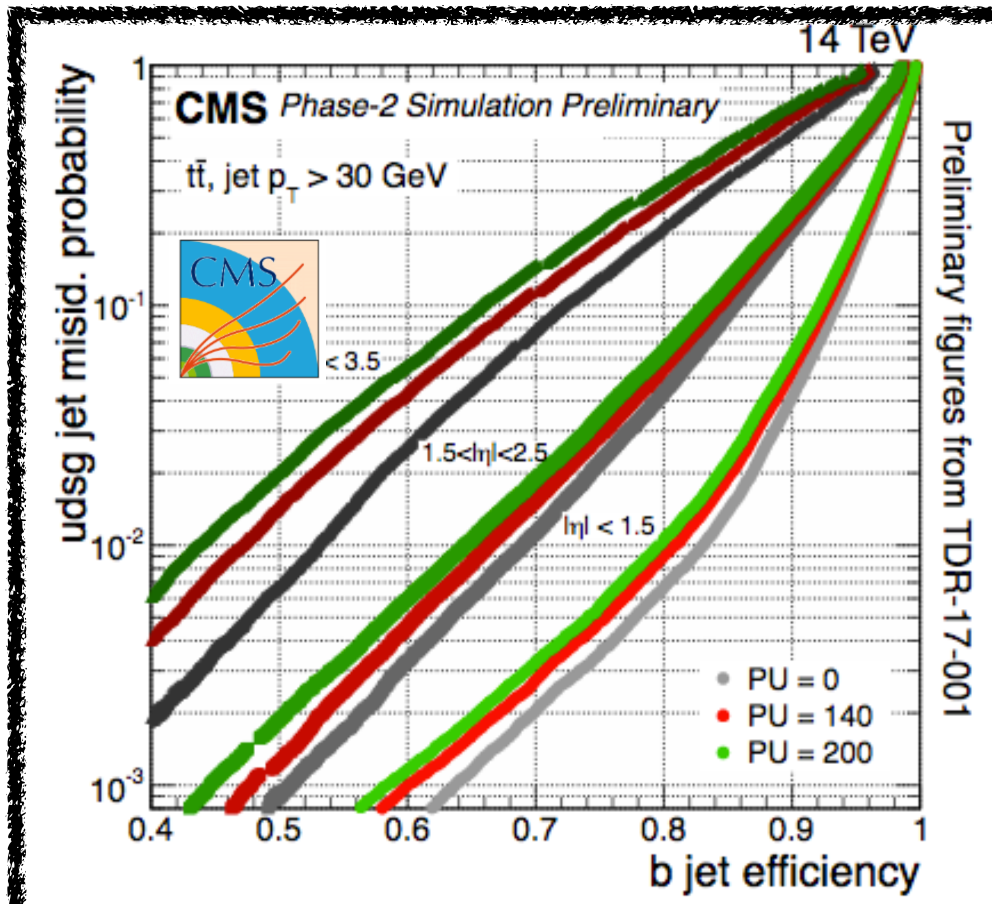
Integrated luminosity	Expected limit on $\sigma(pp \to H) \times BR(H \to J/\psi\gamma)$ [fb]
300 fb^{-1}	$8.6^{+2.4}_{-3.7}$
3000 fb^{-1}	$2.5^{+0.7}_{-1.0}$

Prospects on VHbb

TDR-17-001

ATLAS Pixel TDR

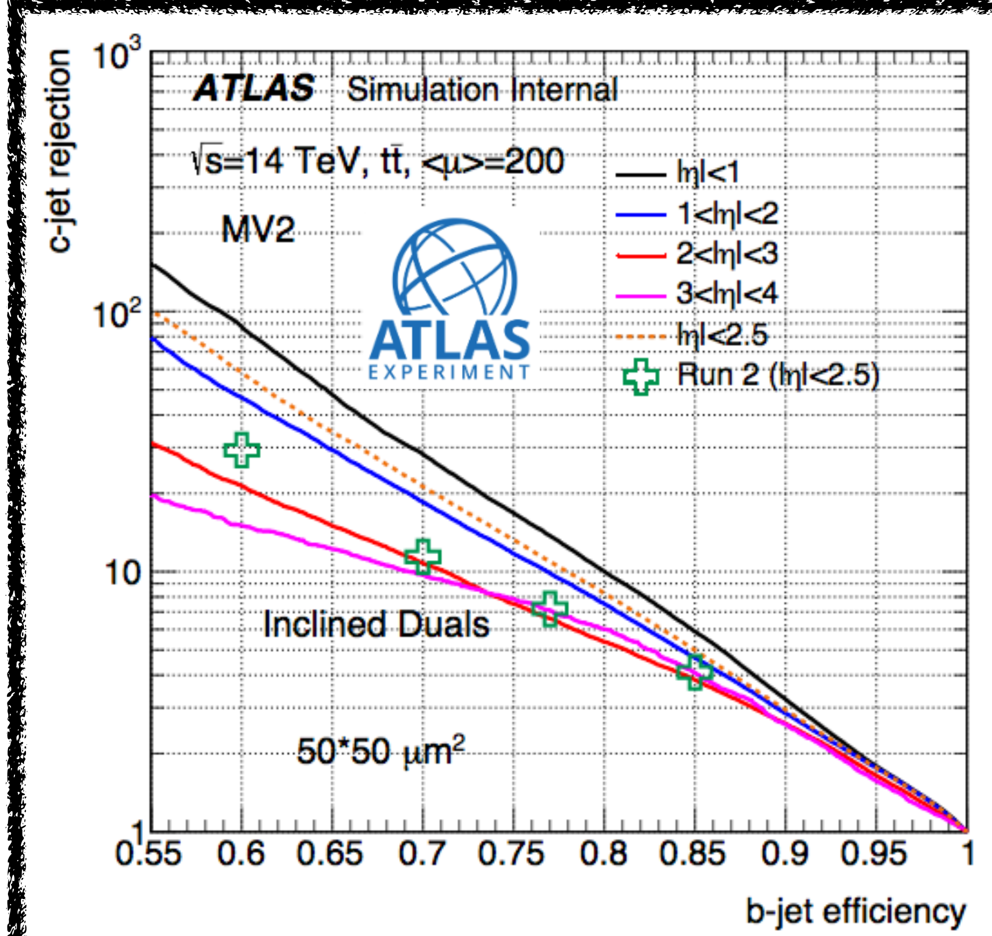
- ATLAS and CMS working on Run 2 extrapolation for HL-LHC (3000 fb^{-1} @ 14 TeV)
  - very significant improvement in b-tagging performance expected for HL-LHC (ATLAS and CMS Technical Design Reports)
- Implication of systematic uncertainties in extrapolation
  - signal and background modeling systematics currently dominant in Run 2 (e.g. V+jets and tt modeling)
  - experimental uncertainties (b-tagging, JES/JER)



- Prospect studies on Run 1 extrapolation at 3000 fb^{-1} by ATLAS (<μ>=140) → ~ 9.6σ significance (10% and 5% of the JES uncertainty for Scenario I and II)

ATLAS-PHYS-PUB-2014-011

		One-lepton	Two-lepton	One+Two-lepton
Stat-only	Significance	15.4	11.3	19.1
	$\hat{\mu}_{Stats}$ error	+0.07 − 0.06	+0.09 − 0.09	+0.05 − 0.05
Theory-only	$\hat{\mu}_{Theory}$ error	+0.09 − 0.07	+0.07 − 0.08	+0.07 − 007
Scenario I	Significance	2.7	8.4	8.8
	$\hat{\mu}_{w/Theory}$ error	+0.37 − 0.36	+0.15 − 0.15	+0.14 − 0.14
	$\hat{\mu}_{wo/Theory}$ error	+0.36 − 0.36	+0.14 − 0.12	+0.12 − 0.12
Scenario II	Significance	4.7	-	9.6
	$\hat{\mu}_{w/Theory}$ error	+0.23 − 0.22	-	+0.13 − 0.13
	$\hat{\mu}_{wo/Theory}$ error	+0.21 − 0.21	-	+0.11 − 0.11



Wrapping-up

➡ Very rich set of results on charm, bottom and top Yukawa couplings from ATLAS, CMS and LHCb with Run 2 data

- reached evidence (CMS and ATLAS) of $H\to bb$ and ttH top-Yukawa couplings ($H\to bb$, $H\to$multi-lepton, $H\to\gamma\gamma$ and $H\to ZZ^*\to 4l$), search for boosted $H\to bb$ (CMS)
- charm couplings currently extracted from $H\to J/\psi\gamma$ (Run 1 analysis) and $VH\to cc$ (LHCb and ATLAS)

➡ Results for top and bottom Yukawas for HL-LHC are getting available

- analyses mostly rely on Run 2 extrapolation with dedicated set of systematic uncertainties
- most of the couplings will reach very good precision at HL-LHC

➡ ATLAS, CMS and LHCb also working on prospect studies for $VH\to cc$

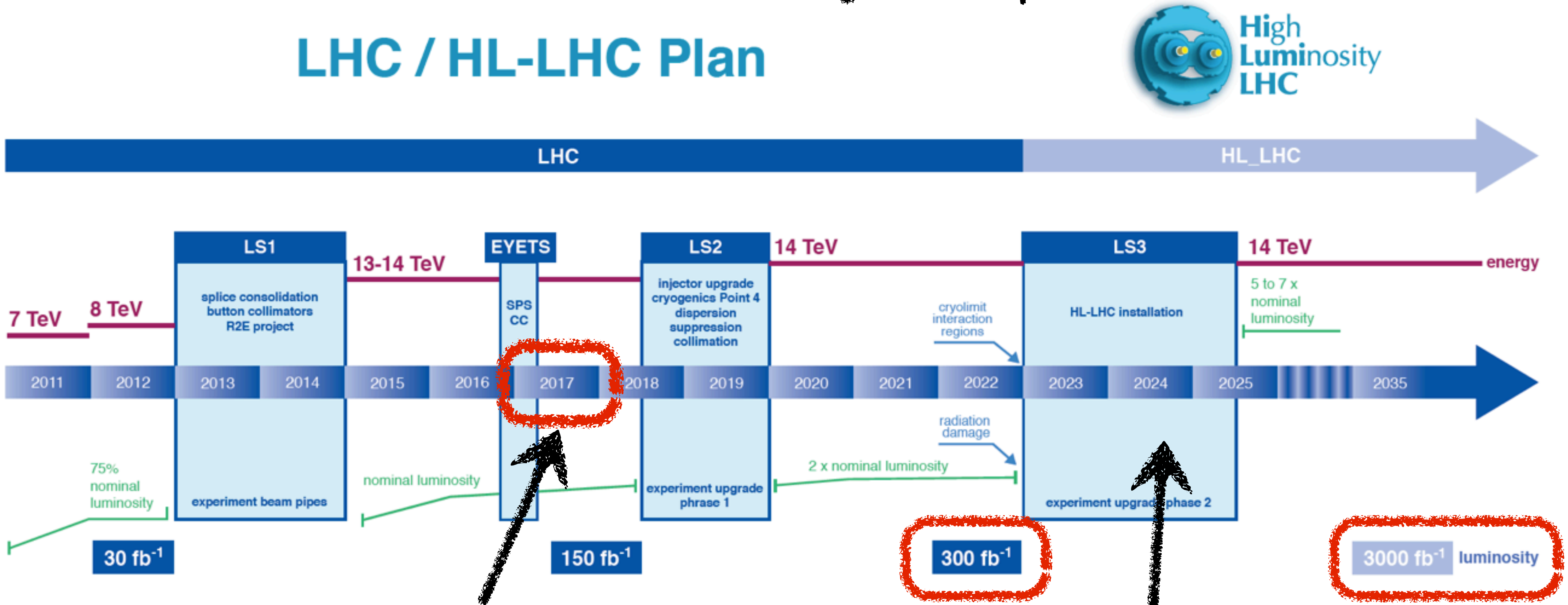
- ATLAS and CMS focus on extrapolation studies from Run 2 analysis at 3000 fb^{-1} @ 14 TeV
- additional studies on LHCb not based on Run 2-extrapolation

➡ Impact of systematics uncertainties need to be accounted for in these prospect studies

- implication of advanced experimental reconstruction techniques and corresponding uncertainties may change the picture quite a bit

Additional slides

The High-Luminosity LHC program



Now (√s=13 TeV), <μ>~38 (2017 data-taking)

Phase-II Atlas and CMS Upgrade

	Peak luminosity (cm^{-2} s^{-1})	μ (pile-up)
Current	$1.3 \cdot 10^{34}$	25
HL-LHC baseline	$5 \cdot 10^{34}$	140
HL-LHC ultimate	$7.5 \cdot 10^{34}$	200

- Increased instantaneous luminosity and mean number of interactions per bunch-crossing (pile-up)
- Integrated luminosity collected during HL-LHC ~ 3000 fb^{-1}
- Precision measurements on the Higgs sector (couplings, self-couplings, VBF production), rare-decays

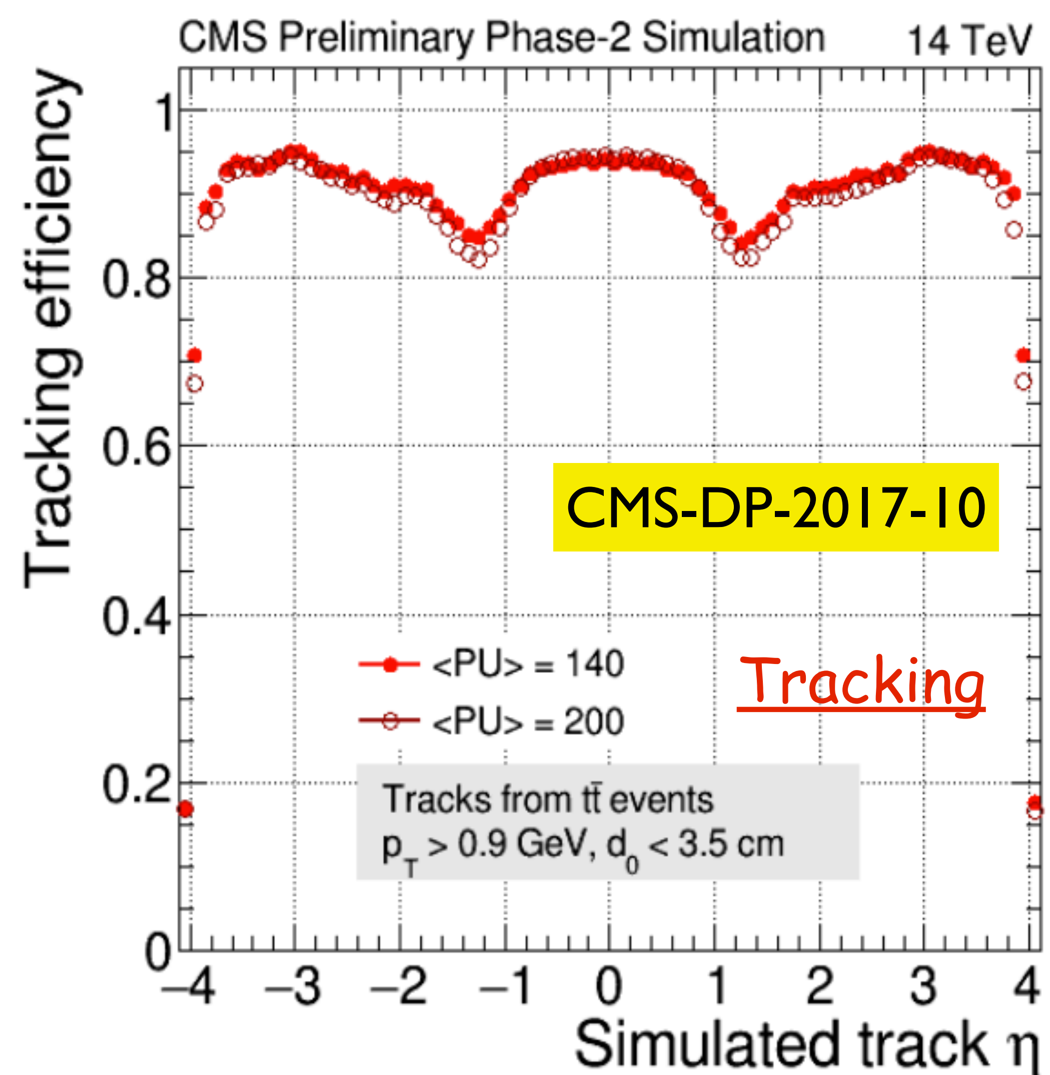
HL-LHC environment and object performance

✓ Very challenging environment at HL-LHC → detector requirements to maximize benefits from high luminosity

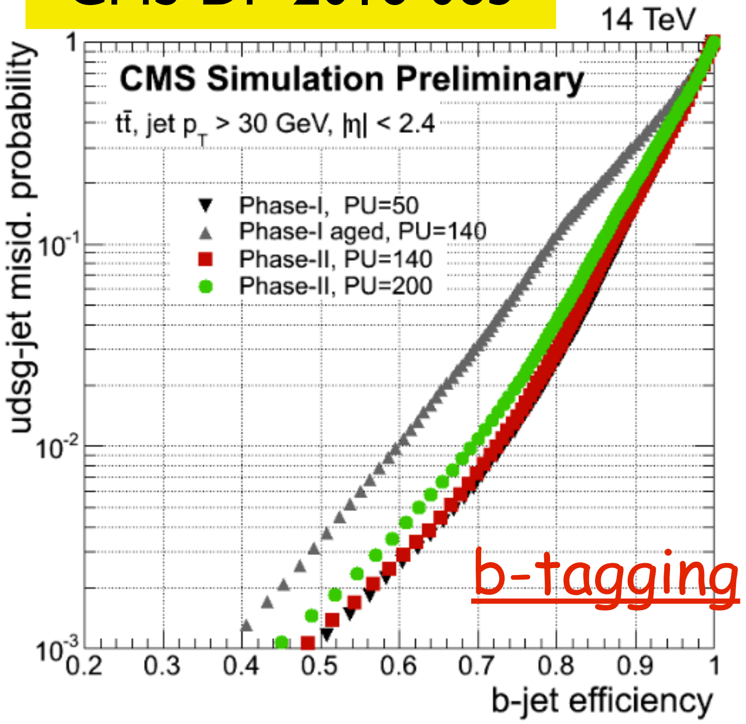
- large integrated radiation dose
- mitigation of pile-up effects
- sustain large event rate with more sophisticated trigger and data acquisition systems

✓ Important to keep good control over performance of physics objects (identification and reconstruction, background rejection)

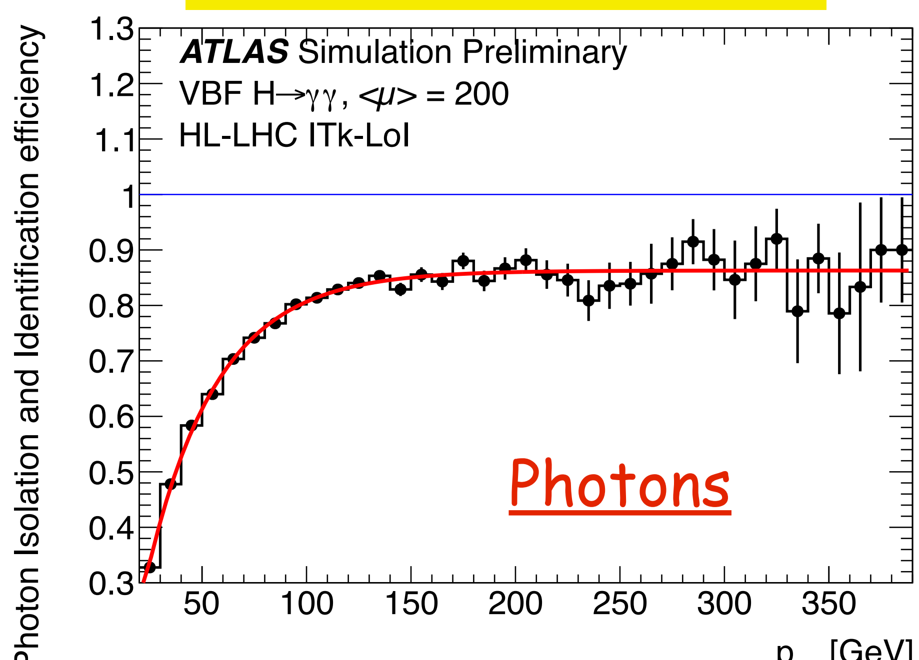
- track resolution, pile-up jet rejection, background rejection for b-tagging, identifications of electrons and photons



CMS-DP-2016-065



ATL-PHYS-PUB-2016-026



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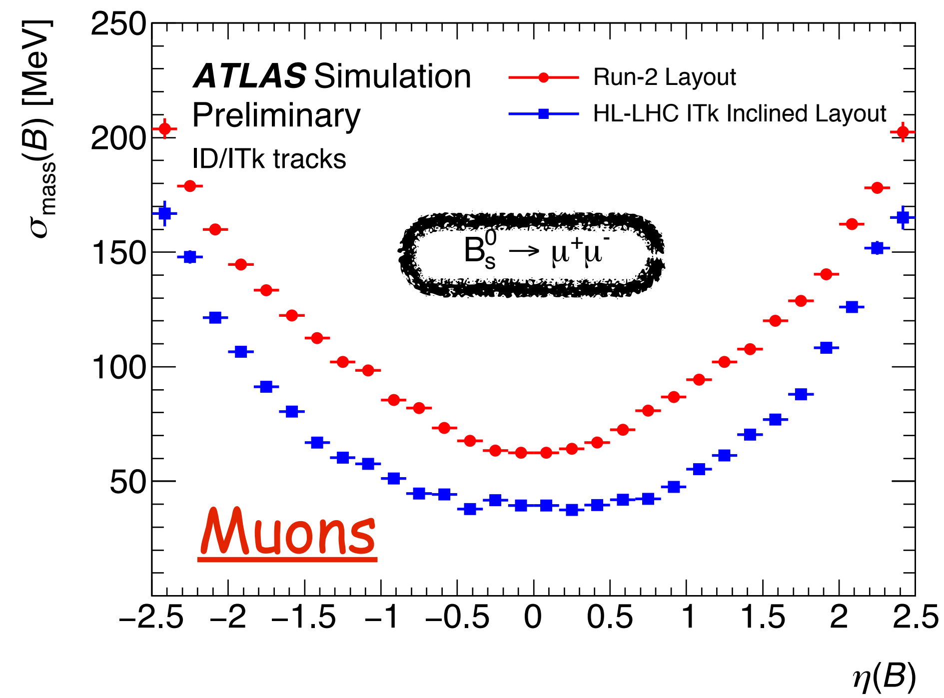


Systematic uncertainties

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modeling	+0.46	−0.46
Background-model stat. unc.	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modeling	+0.22	−0.05
$t\bar{t}+\geq 1c$ modeling	+0.09	−0.11
JVT, pileup modeling	+0.03	−0.05
Other background modeling	+0.08	−0.08
$t\bar{t}$ + light modeling	+0.06	−0.03
Luminosity	+0.03	−0.02
Light lepton (e,μ) id., isolation, trigger	+0.03	−0.04
Total systematic uncertainty	+0.57	−0.54
$t\bar{t}+\geq 1b$ normalization	+0.09	−0.10
$t\bar{t}+\geq 1c$ normalization	+0.02	−0.03
Intrinsic statistical uncertainty	+0.21	−0.20
Total statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61

✓ Analysis is largely systematics-limited (~62% total uncertainty on the ttH signal strength)

- main source is tt+≥1b modeling
- large contributions on available Monte Carlo statistics
  - mostly relevant for the largest systematics uncertainties (tt+≥1b)
- experimental uncertainties contributing less, b-tagging and jet energy scale/resolution

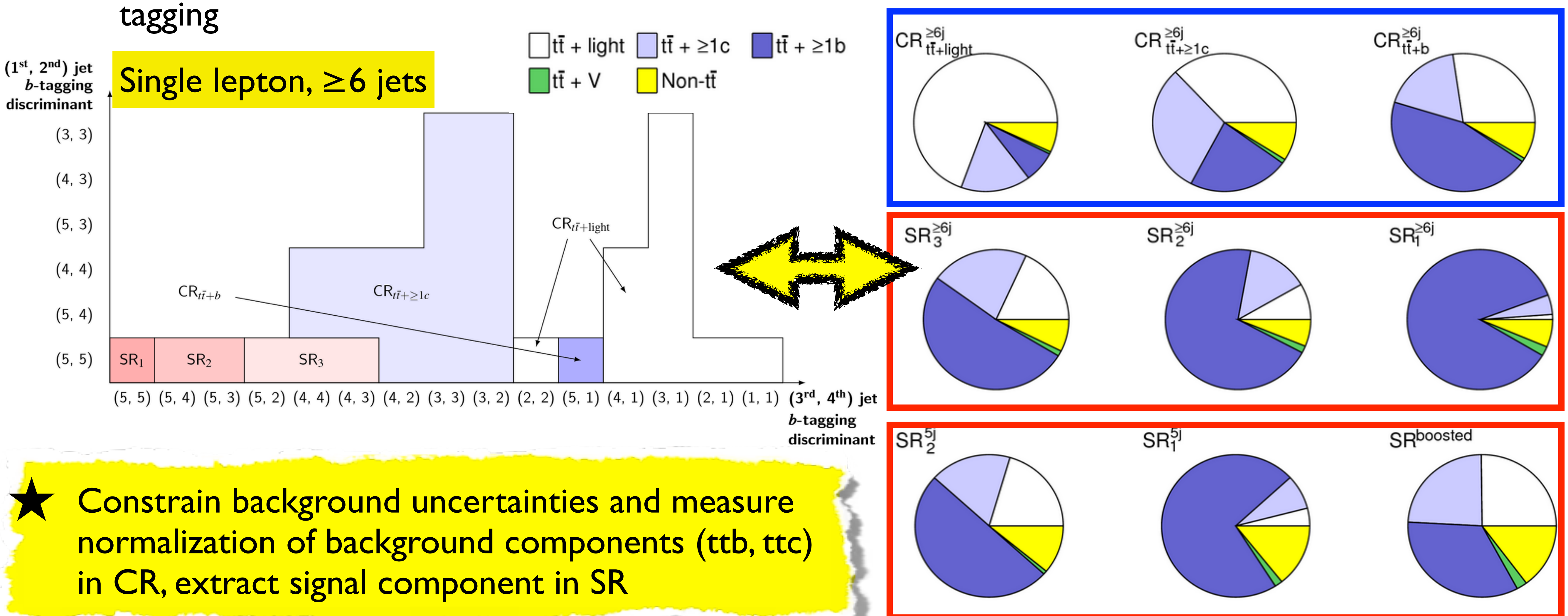
✓ Work ongoing to reduce the dominant tt+HF uncertainty

- data-driven approaches to estimate tt+HF component
- SM g→bb cross section measurement

Signal and control region - single lepton

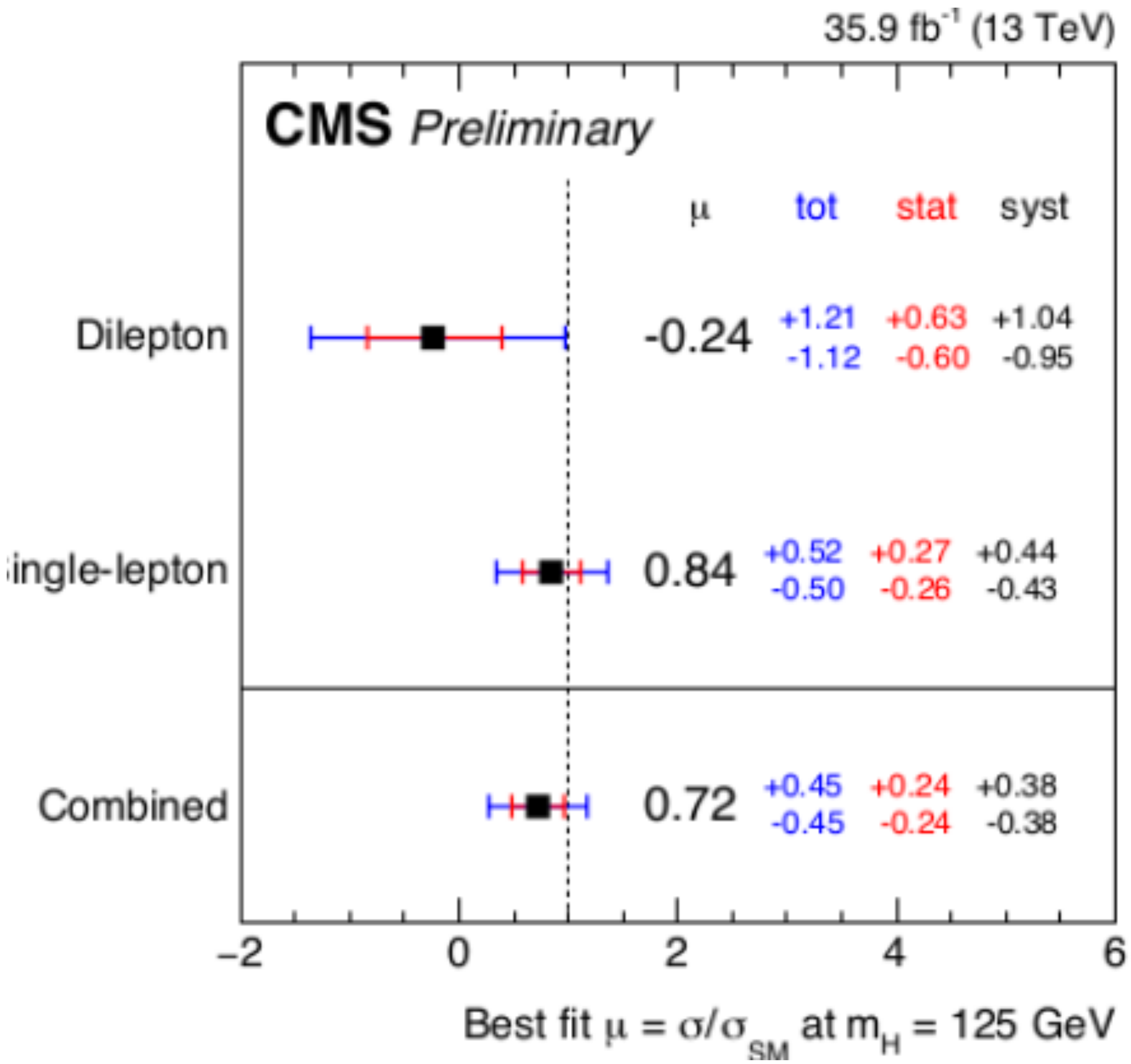
✓ Requirements on b-tagging discriminants for jets in the event defined to split phase-space and create signal and control region (≥5 jets and ≥6 jets)

- control regions (CR) enriched in reducible background
- signal region (SR) enriched in signal and reducible background (tt+≥1b)
- signal purity in ultra-pure signal region: 1.6-5.3%
- highest purity regions in single lepton ≥6j with 4b very tight b-tags
- control region dominated in tt+≥1c and tt+light and created by loosening requirements on b-tagging



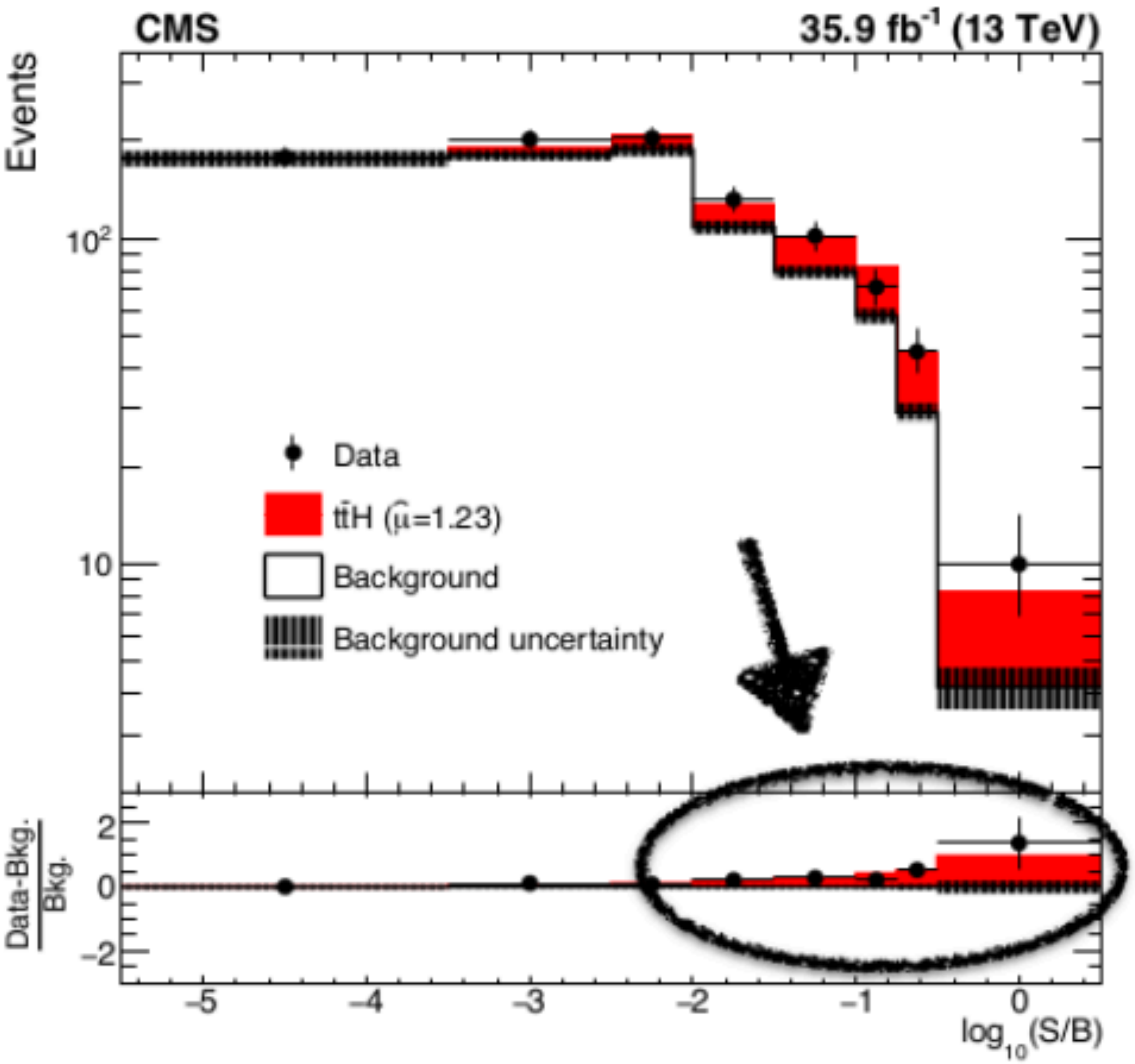
★ Constrain background uncertainties and measure normalization of background components (ttb, ttc) in CR, extract signal component in SR

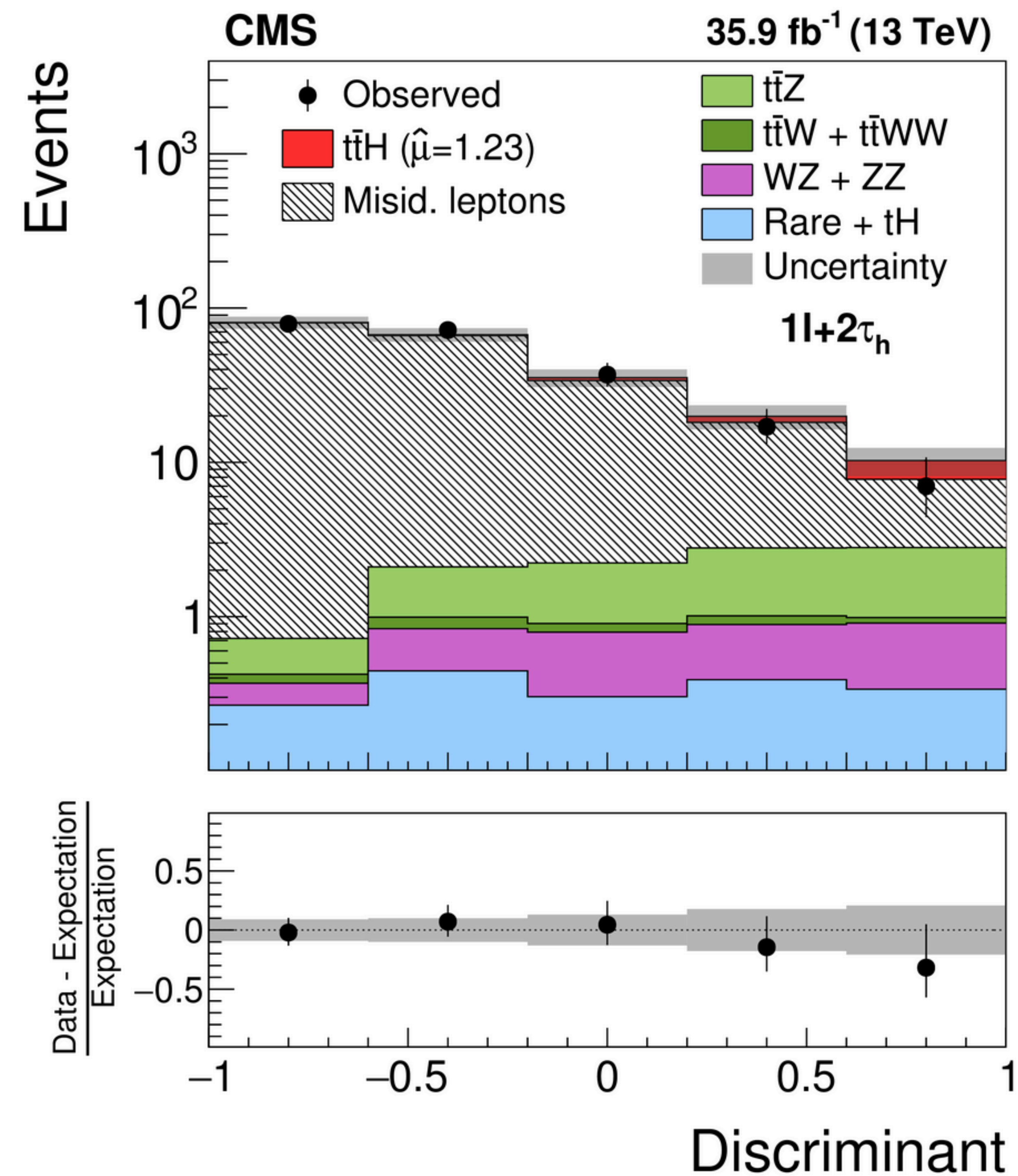
CMS results ttH(Hbb)



Uncertainty source	$\pm\sigma_{\mu}$ (observed)
total experimental	+0.15/-0.16
b tagging	+0.11/-0.14
jet energy scale and resolution	+0.06/-0.07
total theory	+0.28/-0.29
$t\bar{t}$+hf cross-section and parton shower	+0.24/-0.28
size of MC samples	+0.14/-0.15
total systematic	+0.38/-0.38
statistical	+0.24/-0.24
total	+0.45/-0.45

CMS results ttH(ML)

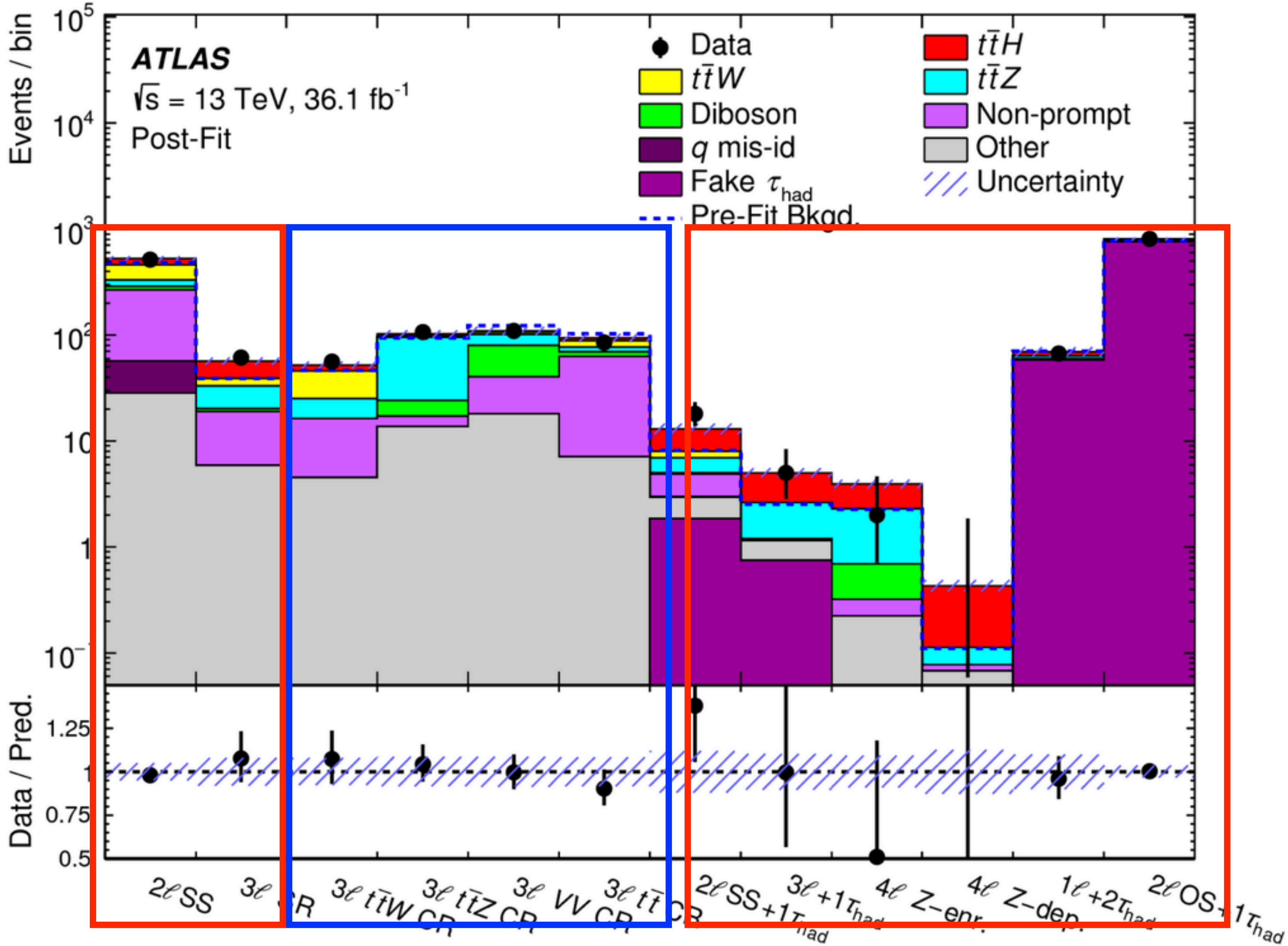




ttH(H->ZZ*, WW*, τ τ) - backgrounds (ATLAS)

- ✓ Prompt-leptons or T-jets estimated from MC
  - irreducible: ttW, ttZ and diboson
- ✓ Electron charge misidentification
  - data-driven estimate from misidentification rate in $Z \to e+e-$ vs $Z \to e+e+/Z \to e-e-$
- ✓ Fake or non-prompt light leptons
  - semileptonic b-hadron decays and photon conversions
  - data-driven estimation
- ✓ Fake hadronic taus
  - light-flavour jets and electron misidentified as taus
  - data-driven estimation in CR; extrapolation to SR
- ✓ New important reconstruction techniques
  - lepton reconstruction
  - BDT to mitigate charge misidentification
  - BDT to mitigate non-prompt e/μ

ttH(H->ZZ*, WW*, τ τ) - fits



✓ 8 signal regions and 4 control regions treated with BDT shape or 1-bin (BDT trained against dominant background of a given region)

VHbb - background modeling uncertainty @ ATLAS/CMS

- Monte Carlo for description of signals and background (multi-jet is data-driven)
  - uncertainties are extrapolated across regions and parametrized as uncertainties on ratio of yields
  - Shape uncertainties on BDT output are extracted for m(bb) and pt(V)
- Uncertainties derived on comparison of MC generators for background processes or data/MC checks in analysis control regions
  - no large overconstraints of background nuisance parameters

ATLAS EXPERIMENT

- Similar approach to evaluate uncertainties on background modeling in CMS
  - comparison of different MC generators - shape systematics extracted as difference of BDT shapes
  - for V+jets, the difference between shapes using MadGraph5_aMC@NLO at LO and NLO are considered
  - for ttbar, difference in shape between nominal Powheg vs MC@NLO
  - variations of internal scales (QCD/PDF scales)

CMS