Overview of the Higgs and Standard Model physics at ATLAS

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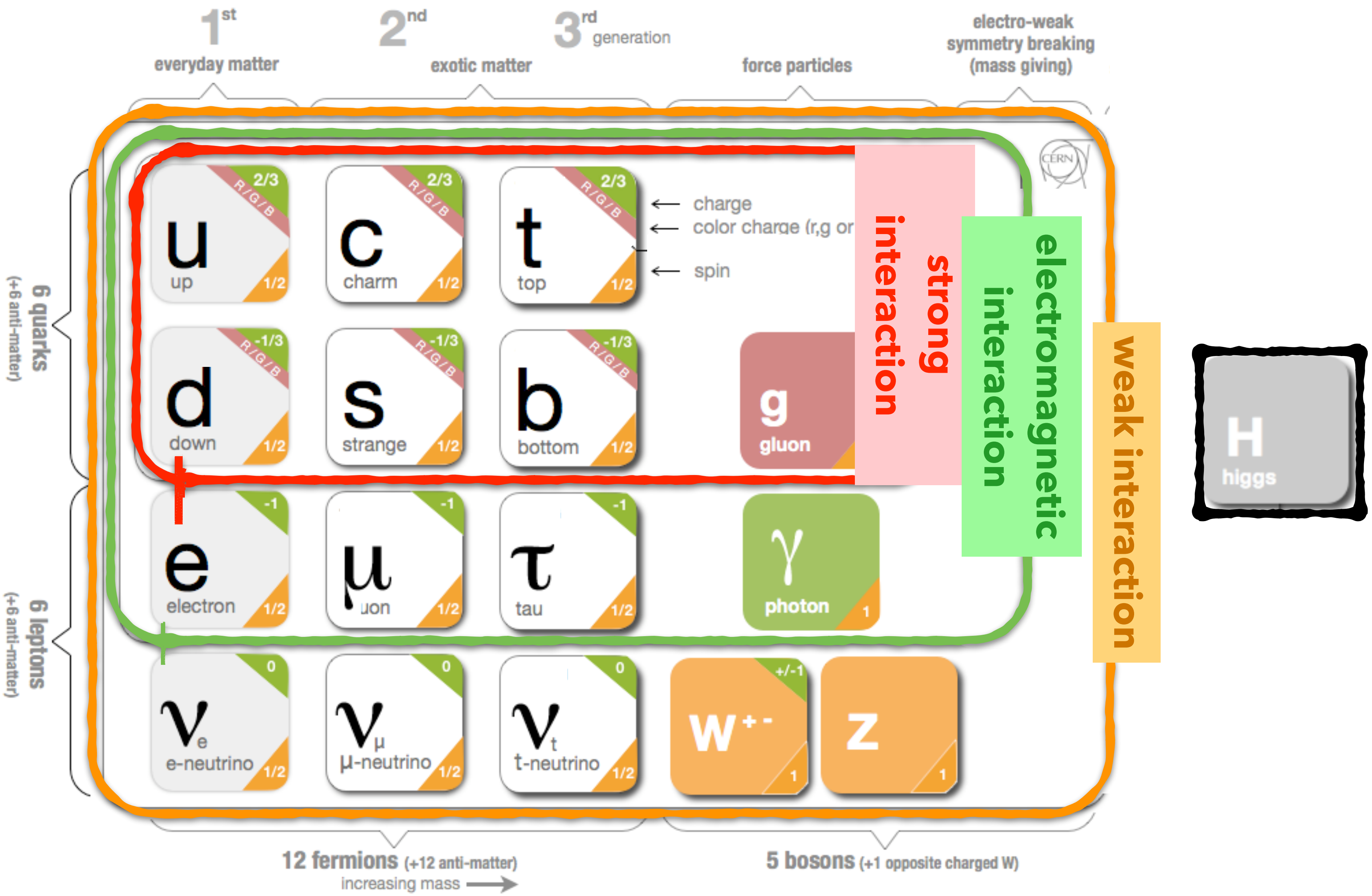
The Standard Model of Particle Physics

The SM provides unified picture of the electroweak (EW) and strong interactions

building blocks of matter: **fermions** (leptons and quarks)

force carriers: **bosons** (gluon, photon, W+-, Z)

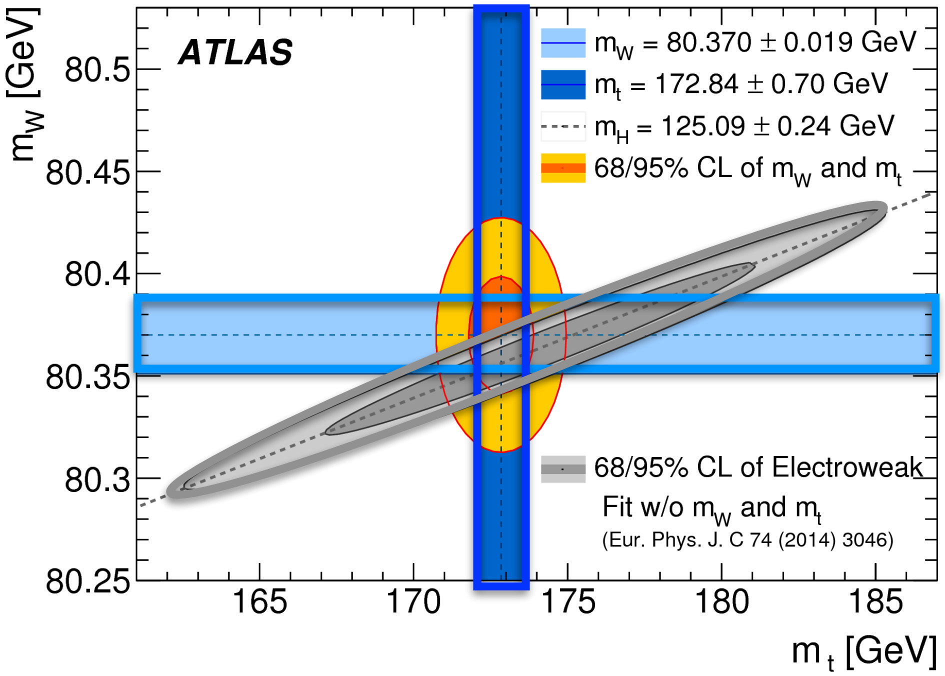
Higgs field: added to the SM to generate the mass of EW bosons and fermions



Outline

- **Detector performance**
- **Standard Model highlights**
  - W boson mass measurement
  - Top quark mass measurement
  - Single top and tZ production evidence
- **Higgs boson physics highlights**
  - Mass measurement
  - Differential cross section measurements
  - Higgs-fermion coupling measurements
  - Rare decays & HH: long term Higgs program
- **Conclusions**

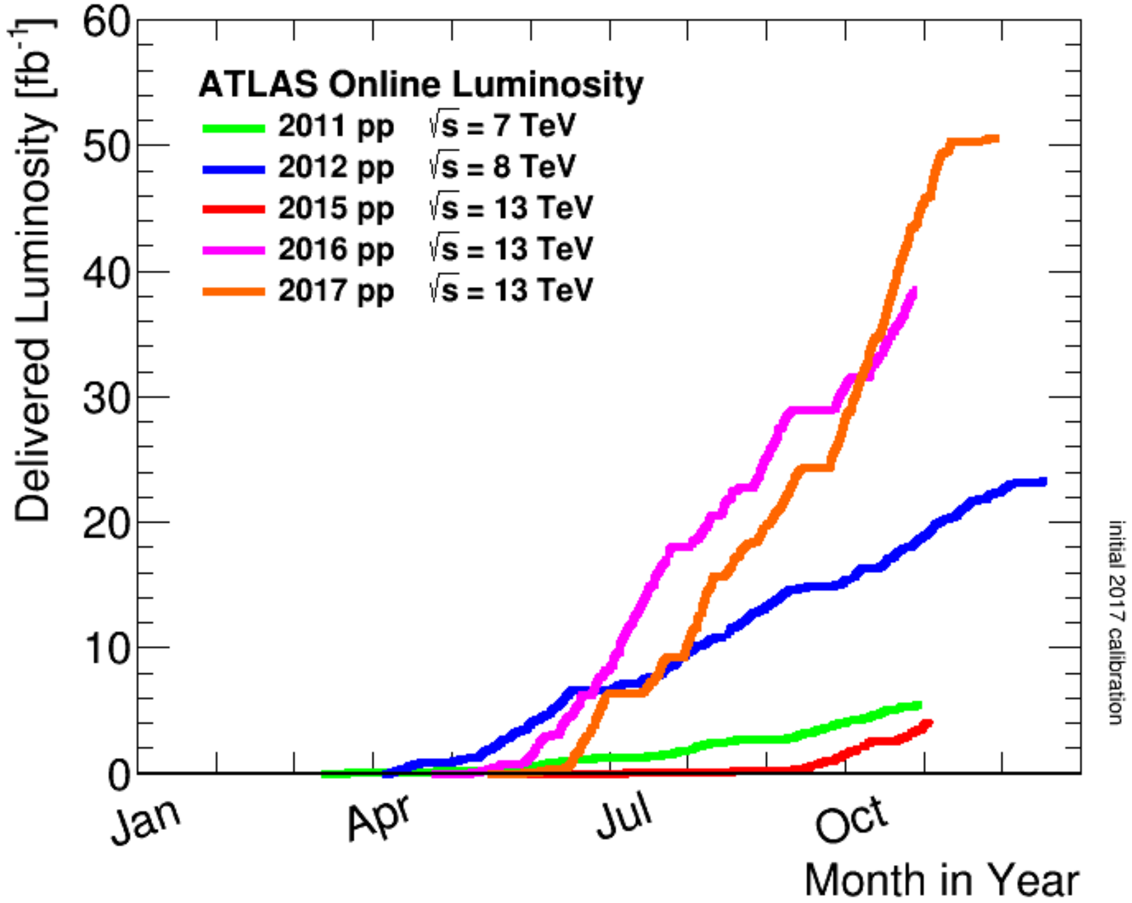
m(W), **m(top)**, **m(H)** are related to fundamental parameters of the Standard Model and provide key information to test its consistency

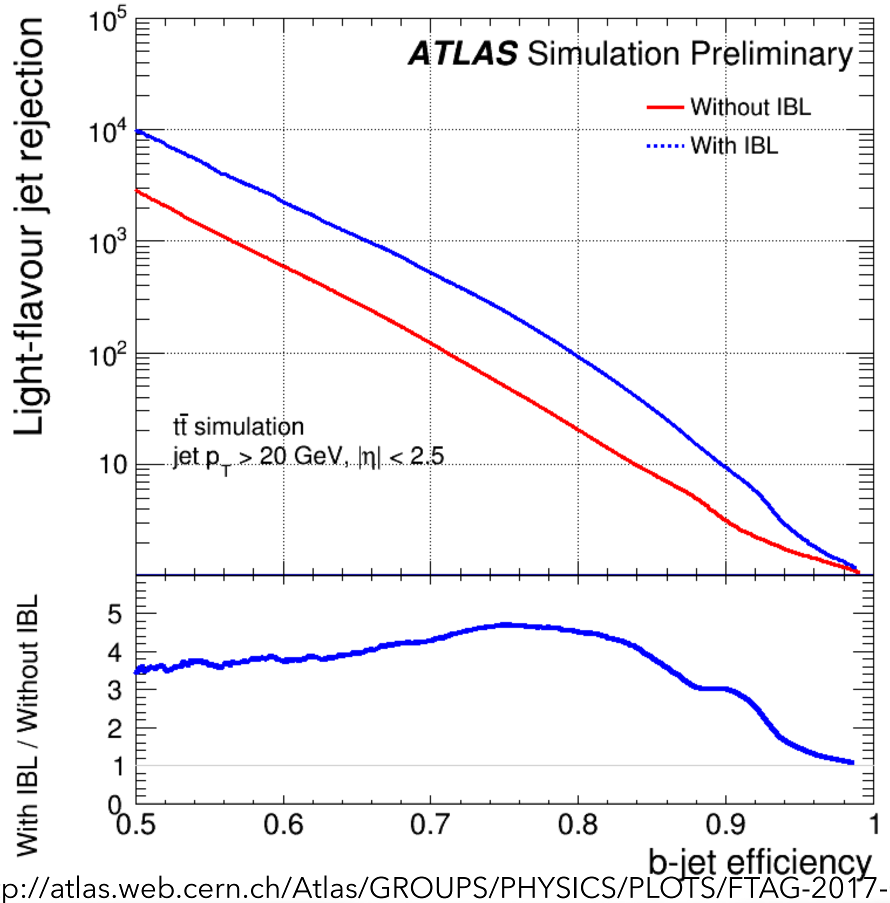


<u>**Disclaimer**</u>: as expected, the full ATLAS SM&Higgs program cannot be covered in 30′ - this is an overview of some of the most relevant recent results!

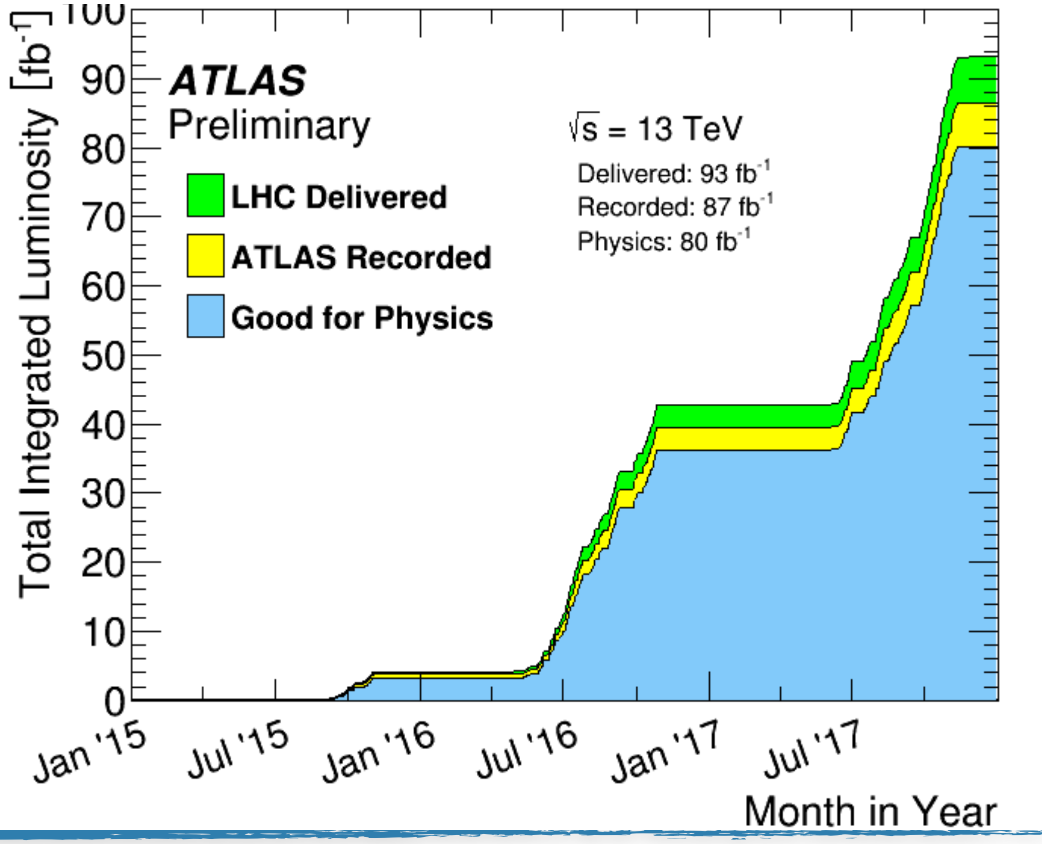
Detector performance (I)

- **Excellent performance of LHC and ATLAS in Run 2 so far**:
  - Record instantaneous luminosity for pp interactions in 2017: 2.06x10^{34} cm^{-2}s^{-1}
    - **double** the LHC design!
  - 80 fb^{-1} good for physics from 87 fb^{-1} recorded by ATLAS
- **Improved b-tagging** performance with the inclusion of **IBL (Insertable B-Layer)** for Run 2



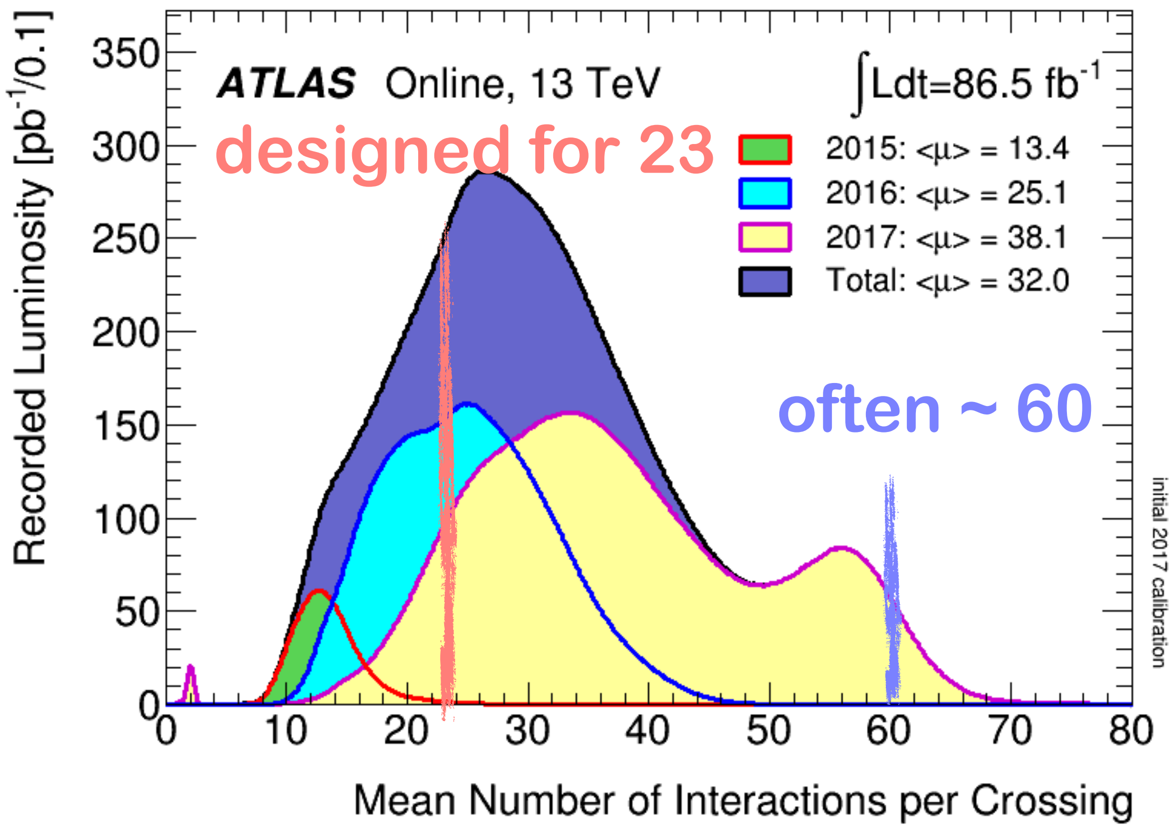


http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/FTAG-2017-005/



Detector performance (II)

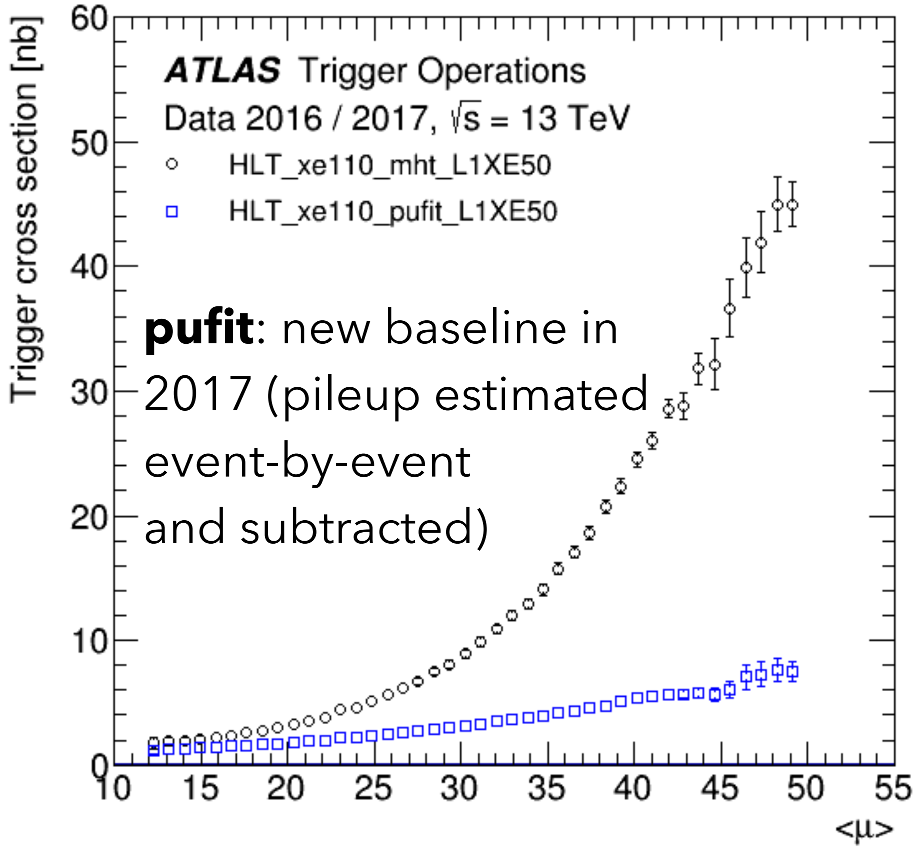
- **Biggest challenge**: robustness against pile-up
  - Controlling trigger rates at high interaction per bunch crossing
  - Online and offline reconstruction performance maintained even at the highest pile-up



designed for 23

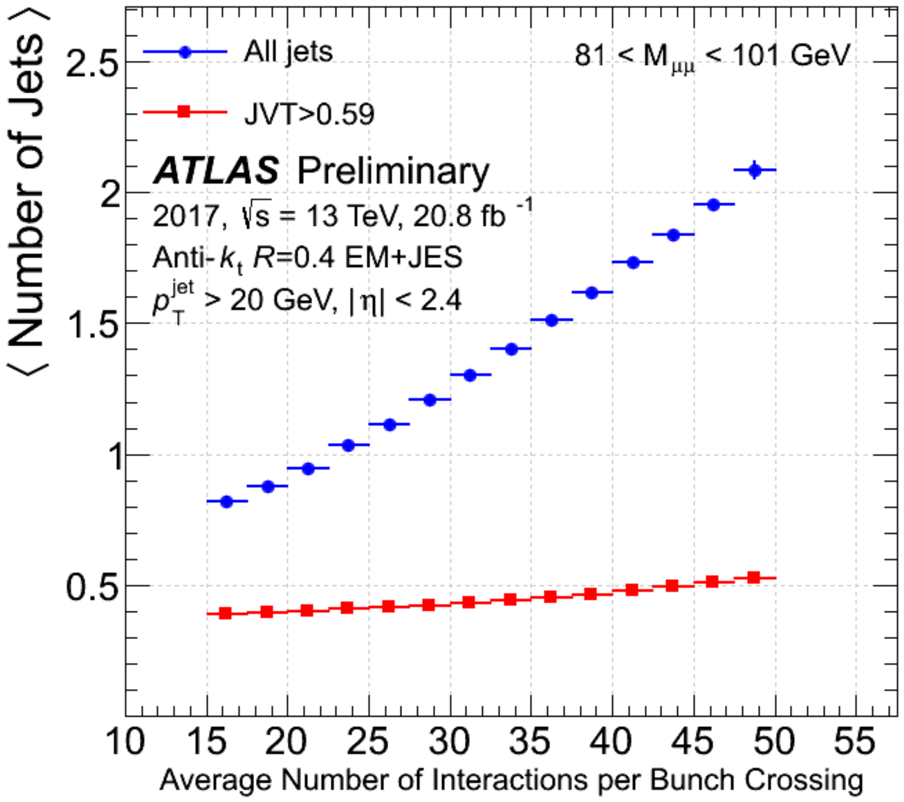
often ~ 60

improved HLT algorithms to suppress dependence of E_T^{miss} trigger rates on pile-up



pufit: new baseline in 2017 (pileup estimated event-by-event and subtracted)

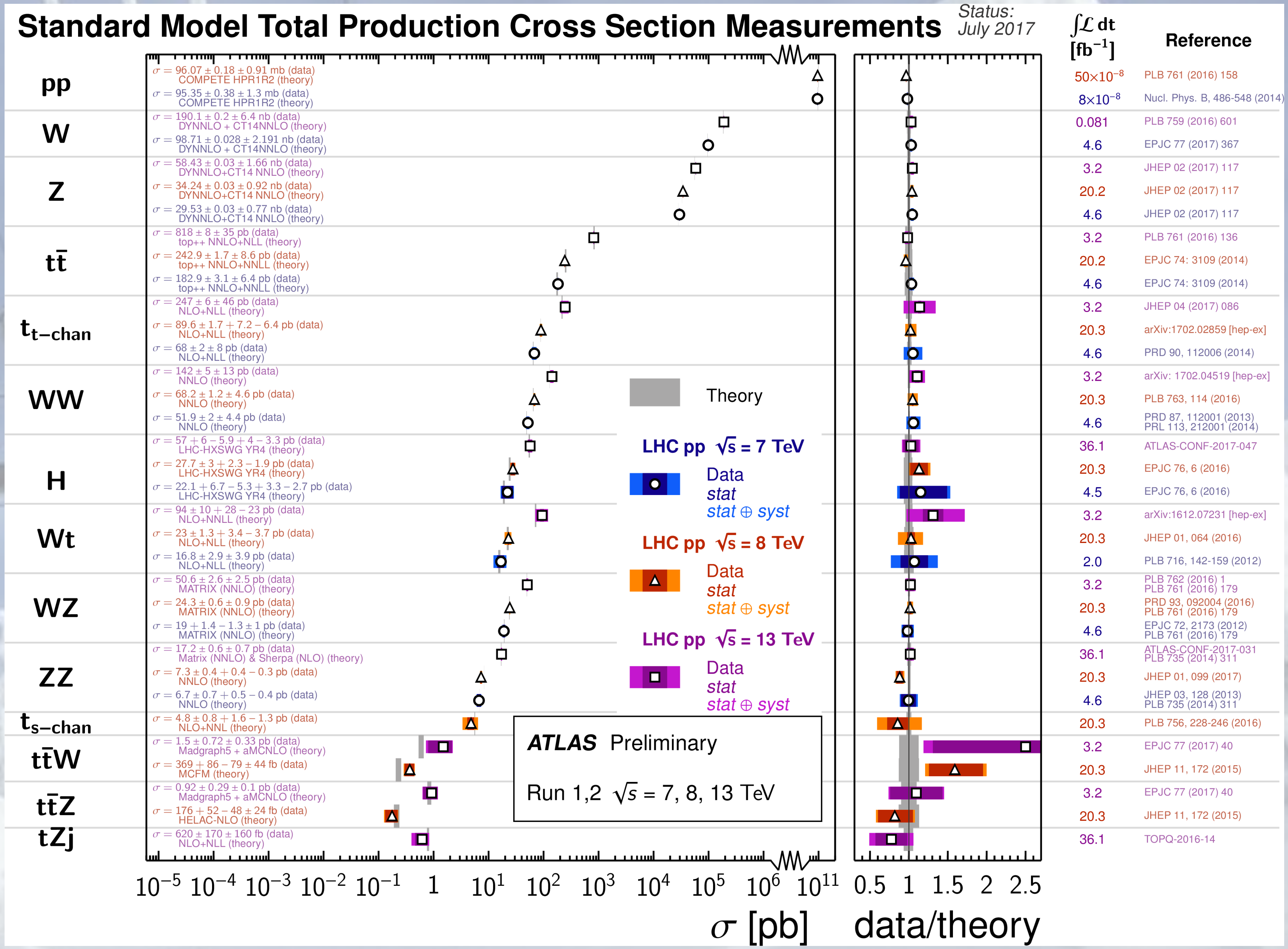
Jet Vertex Tagger (JVT) requirement applied to jets with $20 < p_T < 60$ GeV to reduce the fake jet rate

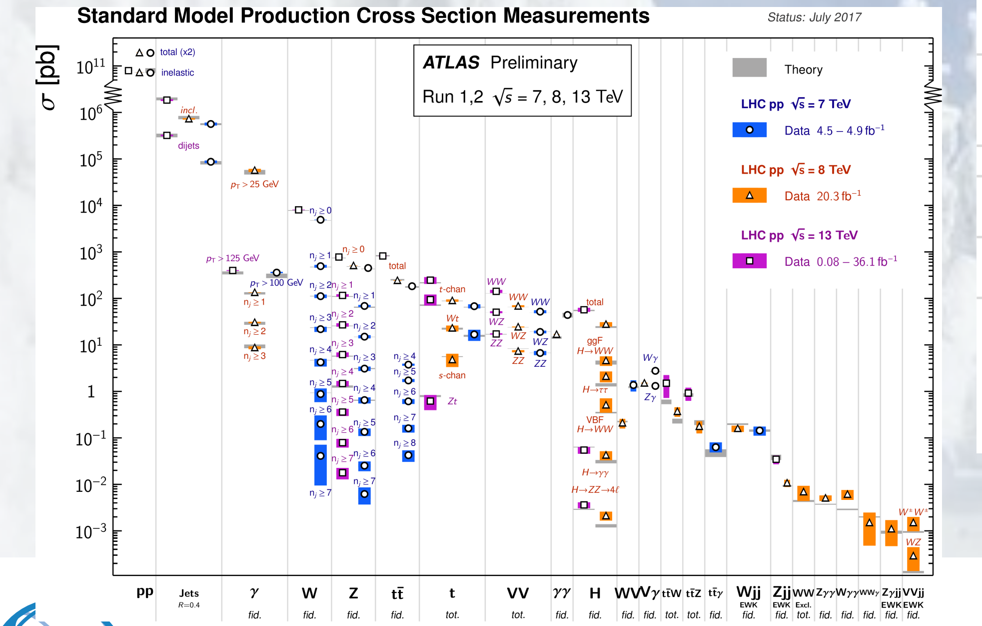


Standard Model (SM)

No measurements yet with 2017 data

- **SM cross section measurements in excellent agreement with theory so far**
  - Some deviations in tt̄W, updates with full 2015+2016 dataset to come…
- **Several new differential cross section measurements available**





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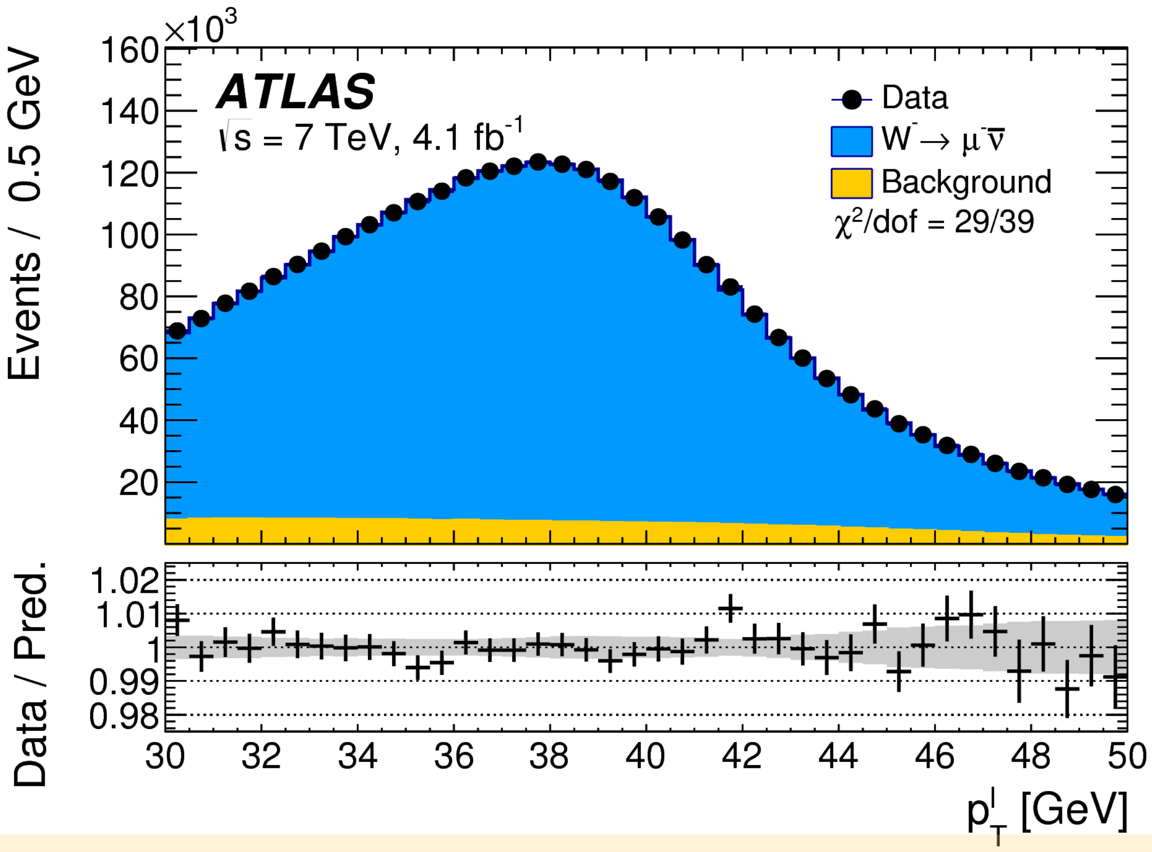
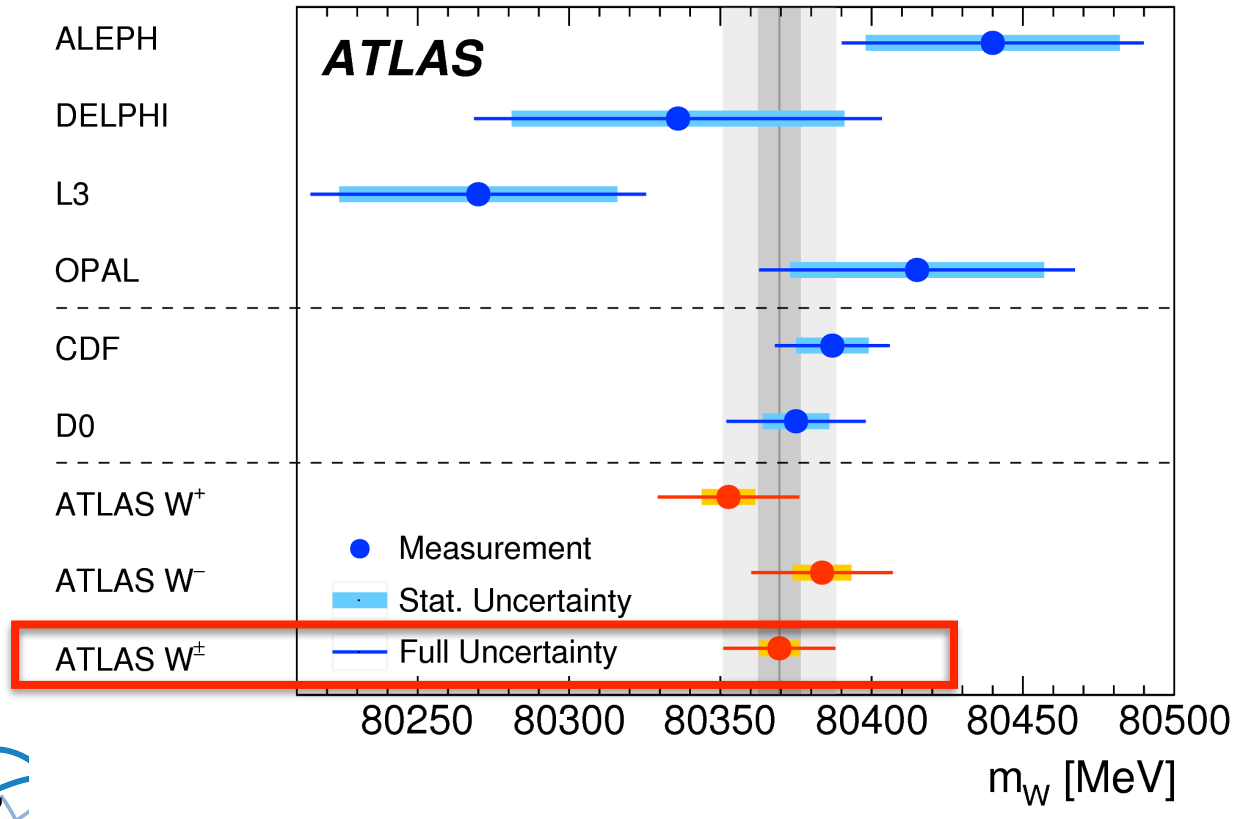
W boson mass

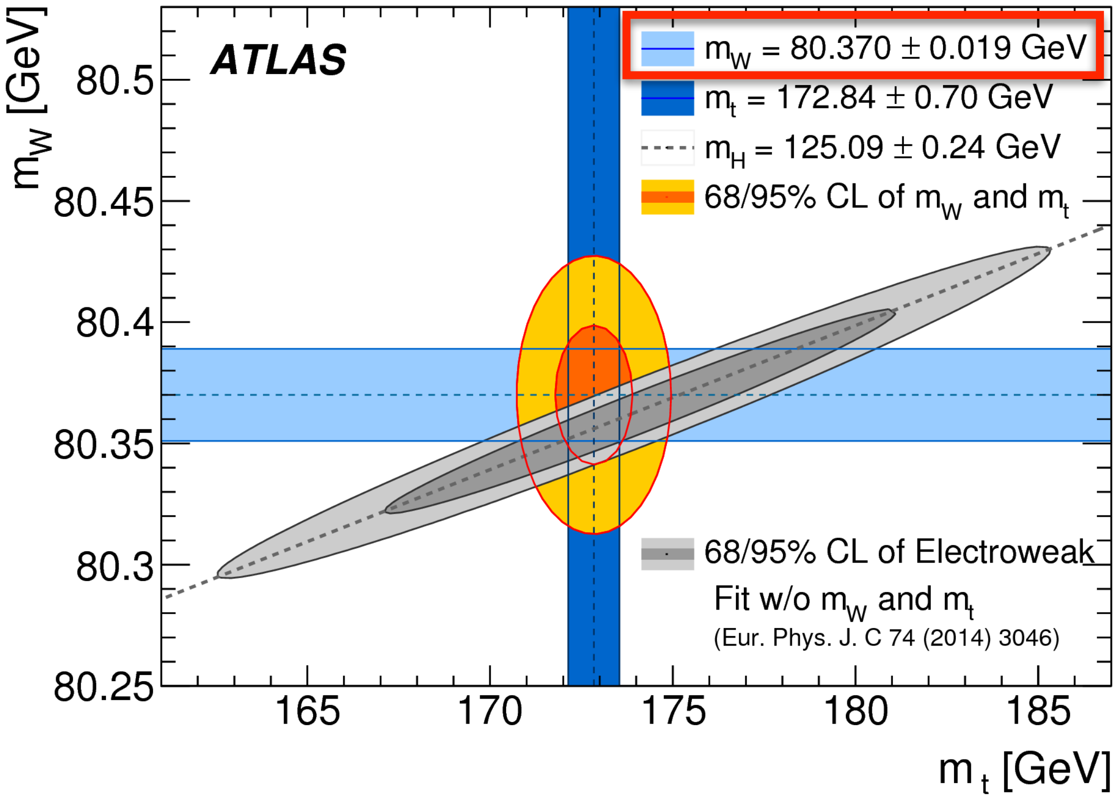
arXiv:1701.07240 - submitted to EPJC

- Uses 4.6 fb^{-1} of 7 TeV data (W→eν/μν)
- Impressive amount of work since 2011 to understand detector response and modelling of kinematic quantities
  - calibration of W recoil with Z →ℓℓ data
- First measurement at the LHC!
  - Similar precision to best previous single experiment measurement (from CDF)
- Result consistent with SM expectation
- Further progress requires improved **modelling**



m_W = 80.370 ± 0.019 GeV = ± 7 MeV (stat) ± 11 MeV (syst) ± 14 MeV (modelling)

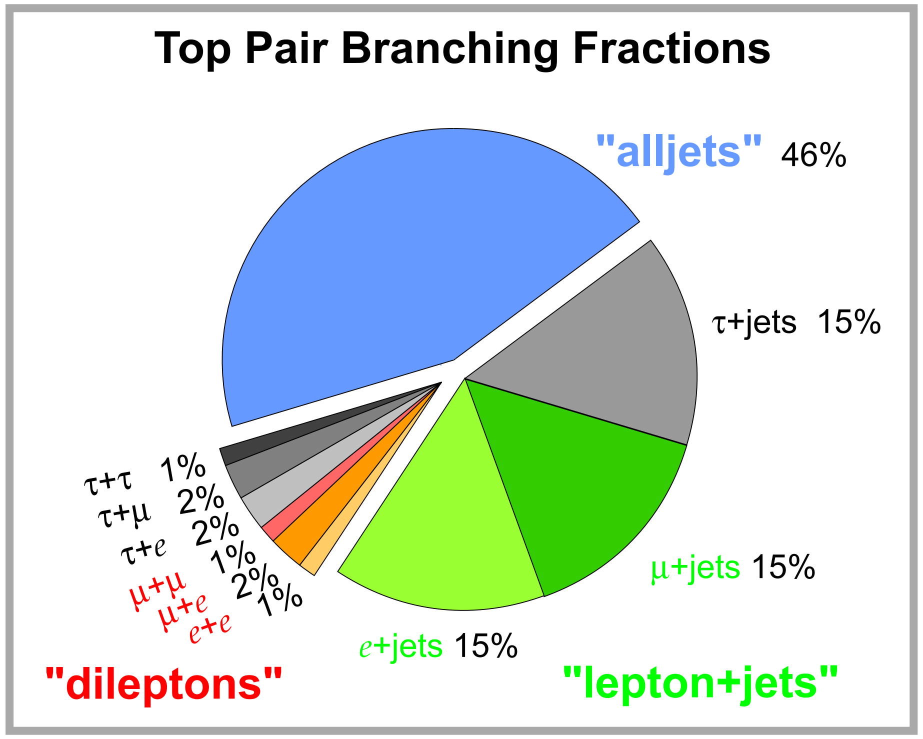




Top quark mass

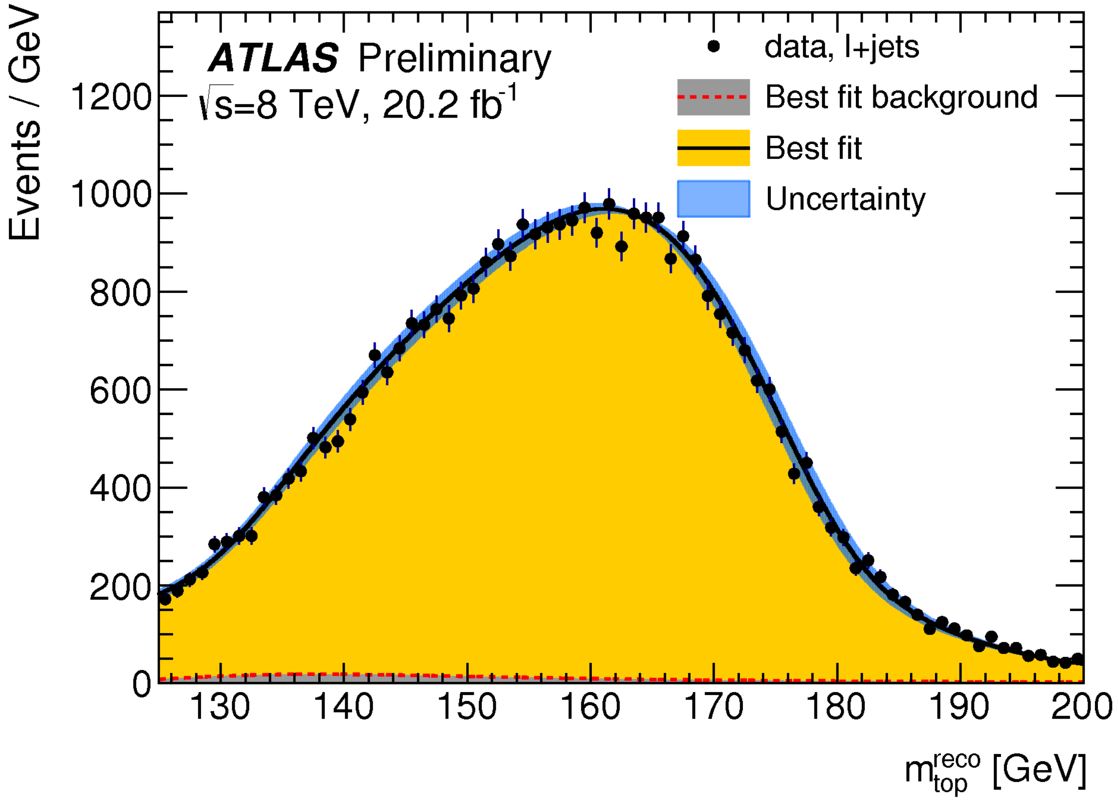
ATLAS-CONF-2017-071

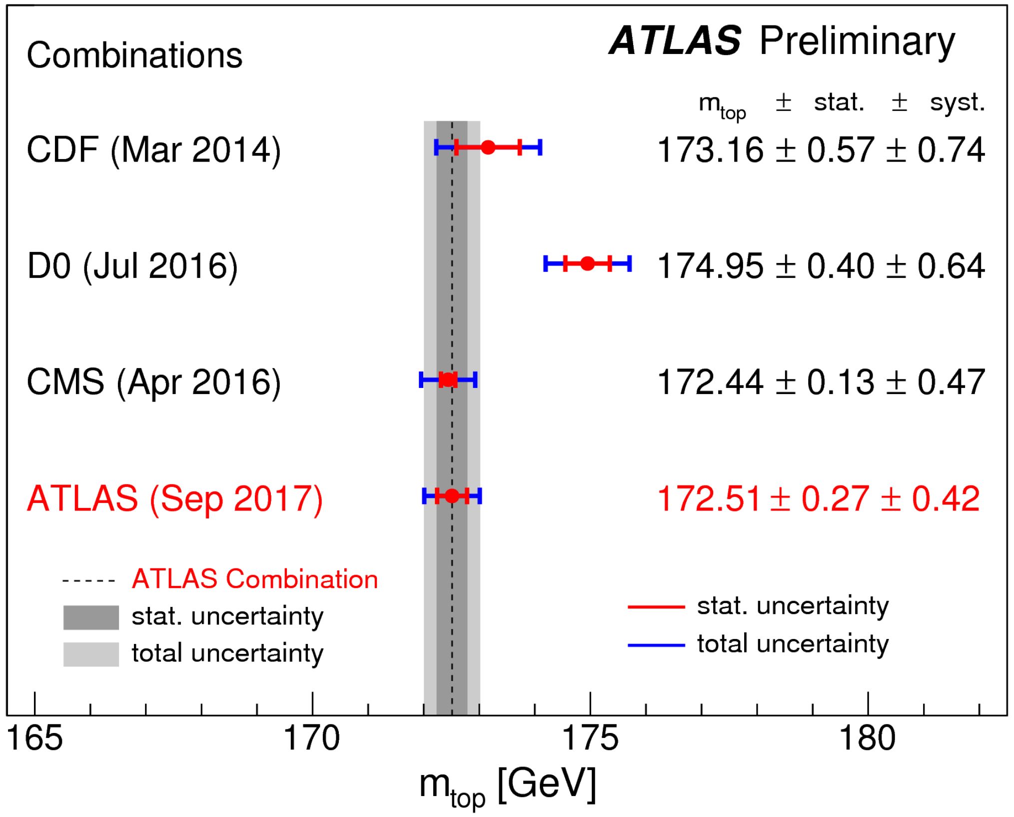
- Exploiting a 3D template technique: **top quark mass** determined together with a **global jet energy scale factor** and a **relative b-to-light-jet energy scale factor**
- Run 1 top quark mass combination at **0.3% precision level!**
  - Systematic uncertainties reduced in combination due to correlations between measurements



NEW

	top quark mass measurement [GeV]
ATLAS ℓ+jets 8 TeV	172.08 ± 0.39 (stat) ± 0.82 (syst)
ATLAS dilepton 8 TeV	172.99 ± 0.41 (stat) ± 0.74 (syst)
ATLAS Run 1 comb	**172.51 ± 0.27 (stat) ± 0.42 (syst)**



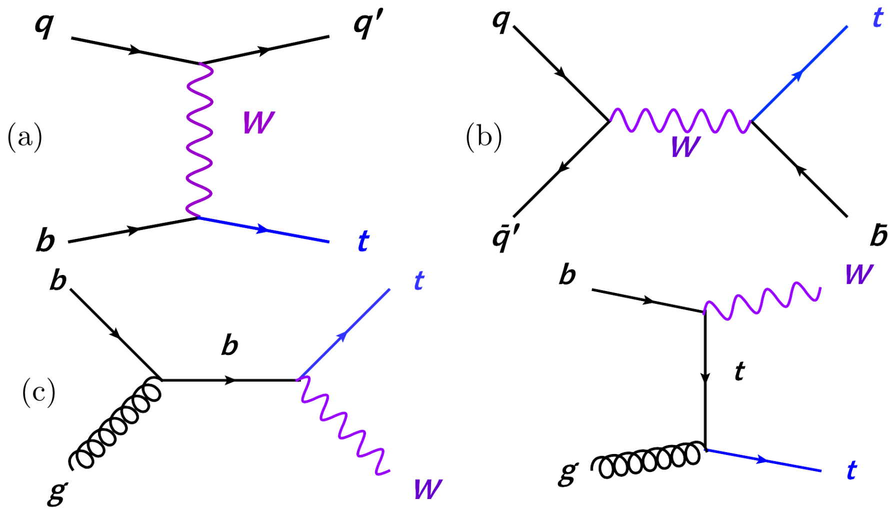


Single top (+Z) cross section

arXiv:1710.03659

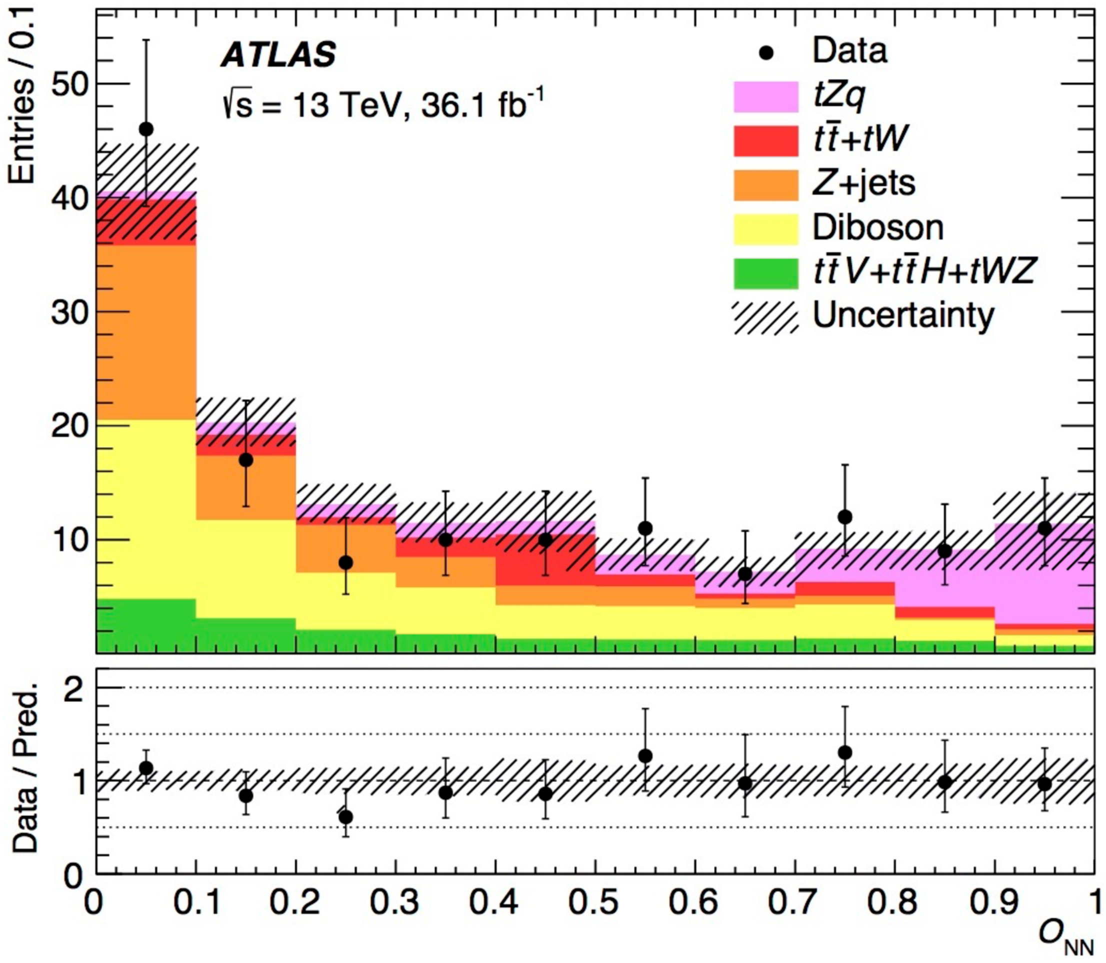
submitted to PLB

- **First**, evidence for single top quark production at LHC in t-channel (a), s-channel (b) and Wt-associated (c) production



tZ **= single top + Z radiated from W/fermion**

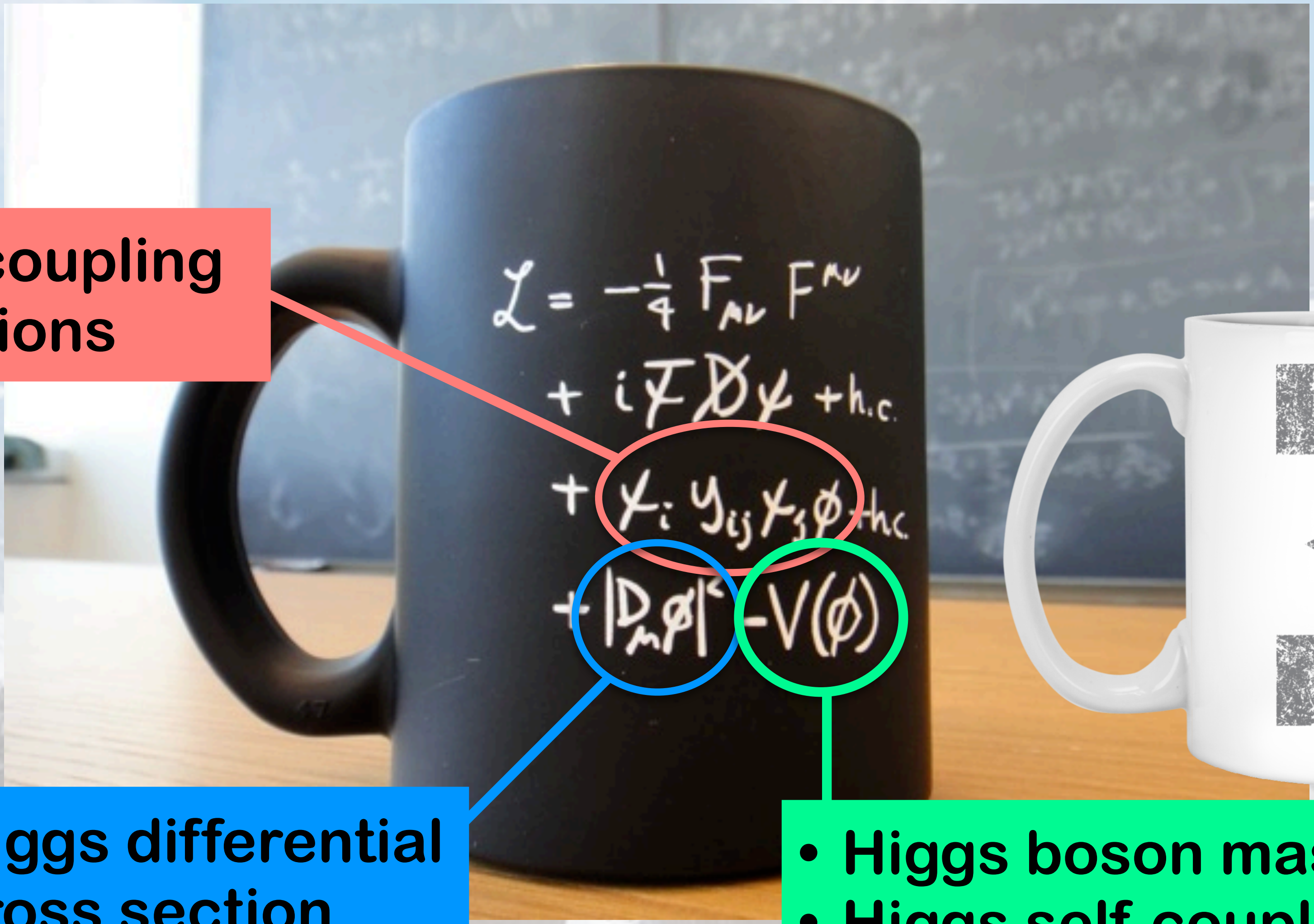
- Now, also evidence for **tZ production**
  - **Significance = 4.2σ** (5.4σ) observed (expected)
  - Cross-section = 620 ± 170 (stat) ± 140 (syst) fb
    - consistent with SM expectation



- Events containing **3 leptons** (e/μ, 2 originating from Z) and **two jets**, one of which is identified as a b-quark jet are selected
- The major backgrounds are diboson, $t\bar{t}$, and Z+jets
- Using **neural network** to improve the background rejection and extract the signal

Higgs boson physics

- Since its discovery in 2012, focus on **precision measurements of production and decay** of the Higgs boson, and the **search for additional BSM Higgs bosons**



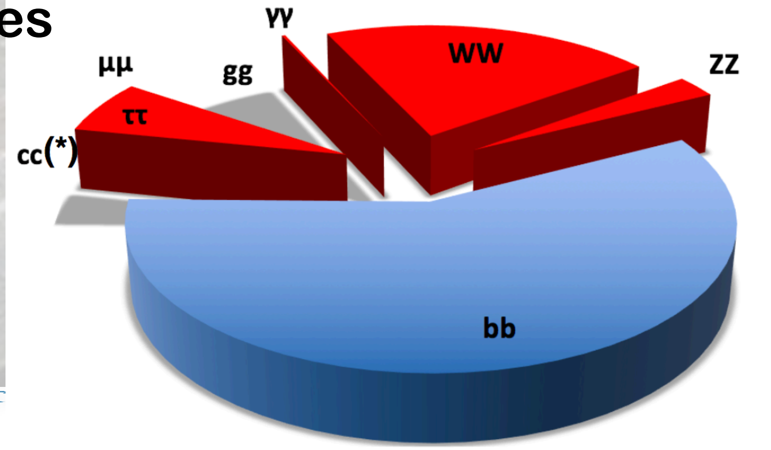
Higgs coupling to fermions

Higgs differential cross section

- **Higgs boson mass**
- **Higgs self-coupling**

$$V(h) = \frac{1}{2}m_h^2 h^2 + \lambda v h^3 + \frac{1}{4}\tilde{\lambda}$$

Higgs decay modes

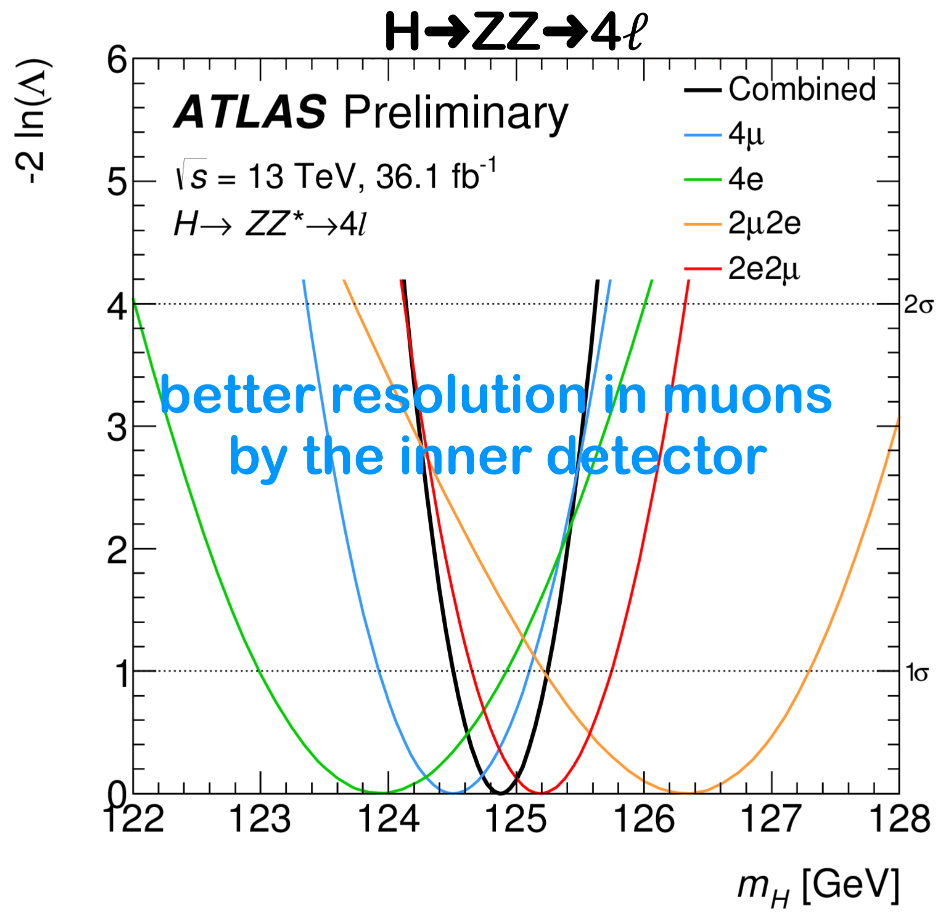


No measurements yet with 2017 data

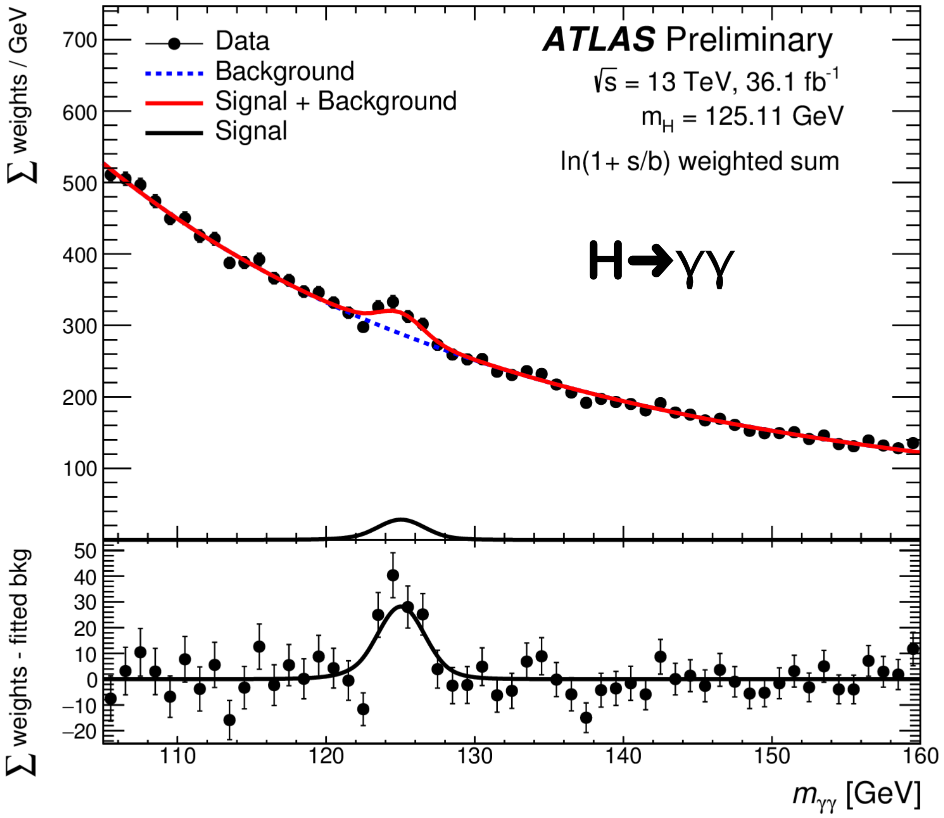
Higgs boson mass

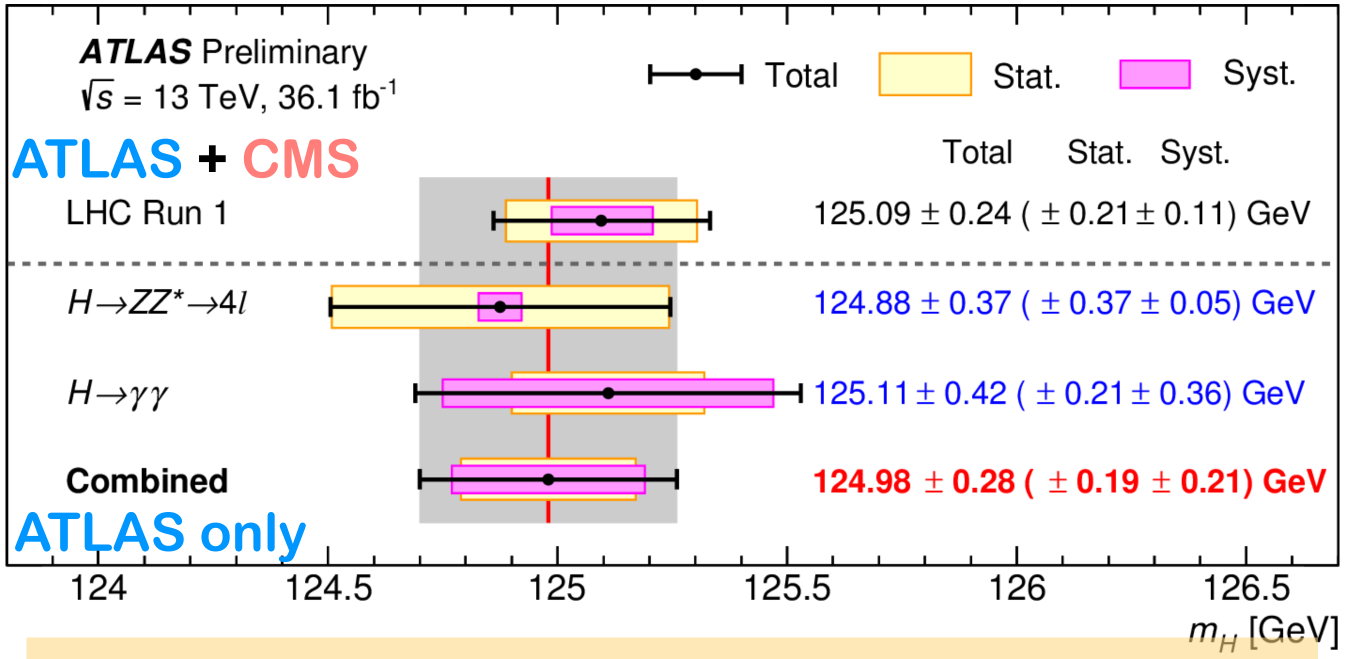
ATLAS-CONF-2017-046

- Higgs boson mass measured using kinematic categories from cross-section measurement in 4ℓ and γγ channels
- Complementary measurements:
  - **4ℓ** channel dominated by **stat** uncertainty
  - **γγ** channel dominated by **syst** uncertainty (γ energy scale calibration)
- In 4ℓ channel, measurements consistent between electron/muon sub-channels
- 4ℓ and γγ measurements consistent with each other
- Combined measurement consistent with Run-1



better resolution in muons by the inner detector





ATLAS + CMS

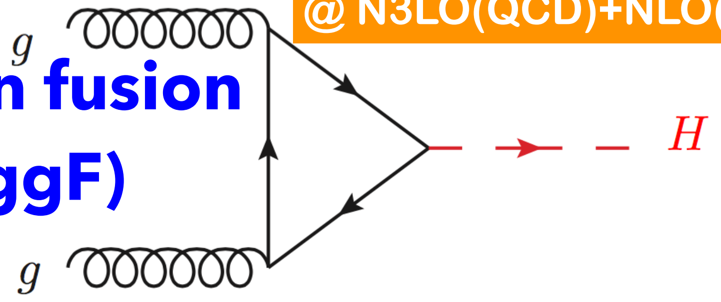
ATLAS only

2–per–mille precision from single experiment!
at the level of LHC Run 1 precision!

Higgs production modes: reminder

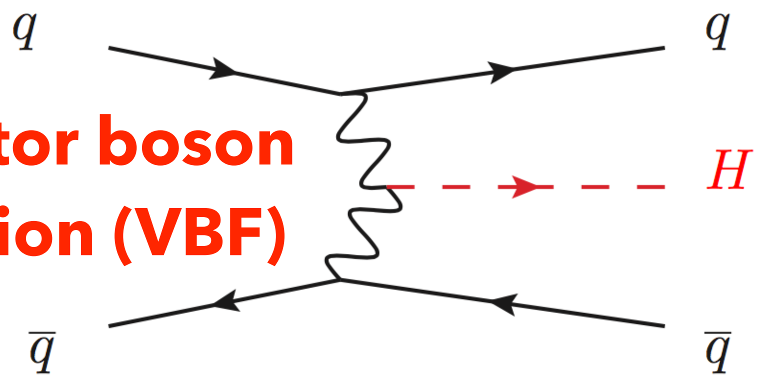
cross section calculation @ N3LO(QCD)+NLO(EW)

gluon fusion (ggF)

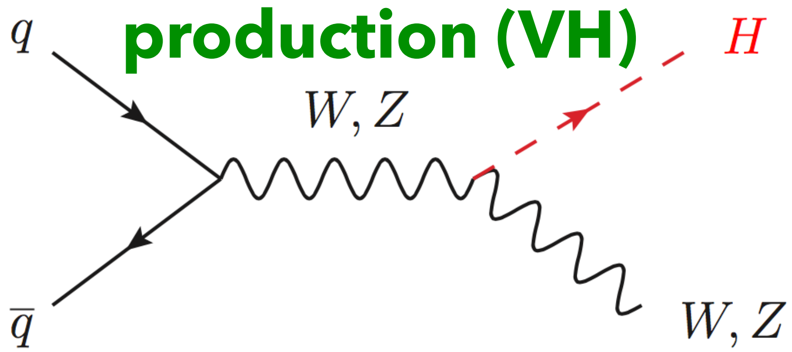


- Gluon fusion has the largest production rate, order of magnitude higher than VBF or VH
- Large cross section increase from 8 to 13 TeV, especially for $t\bar{t}H$ and tH

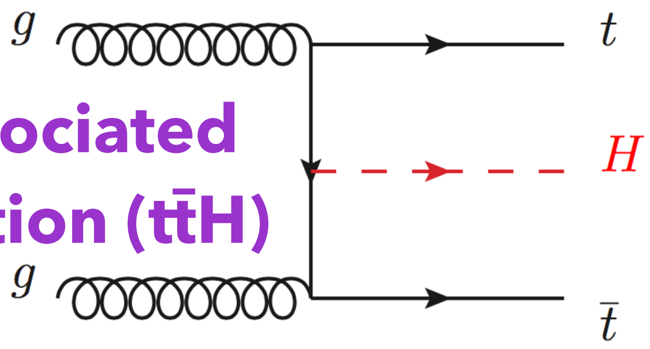
vector boson fusion (VBF)

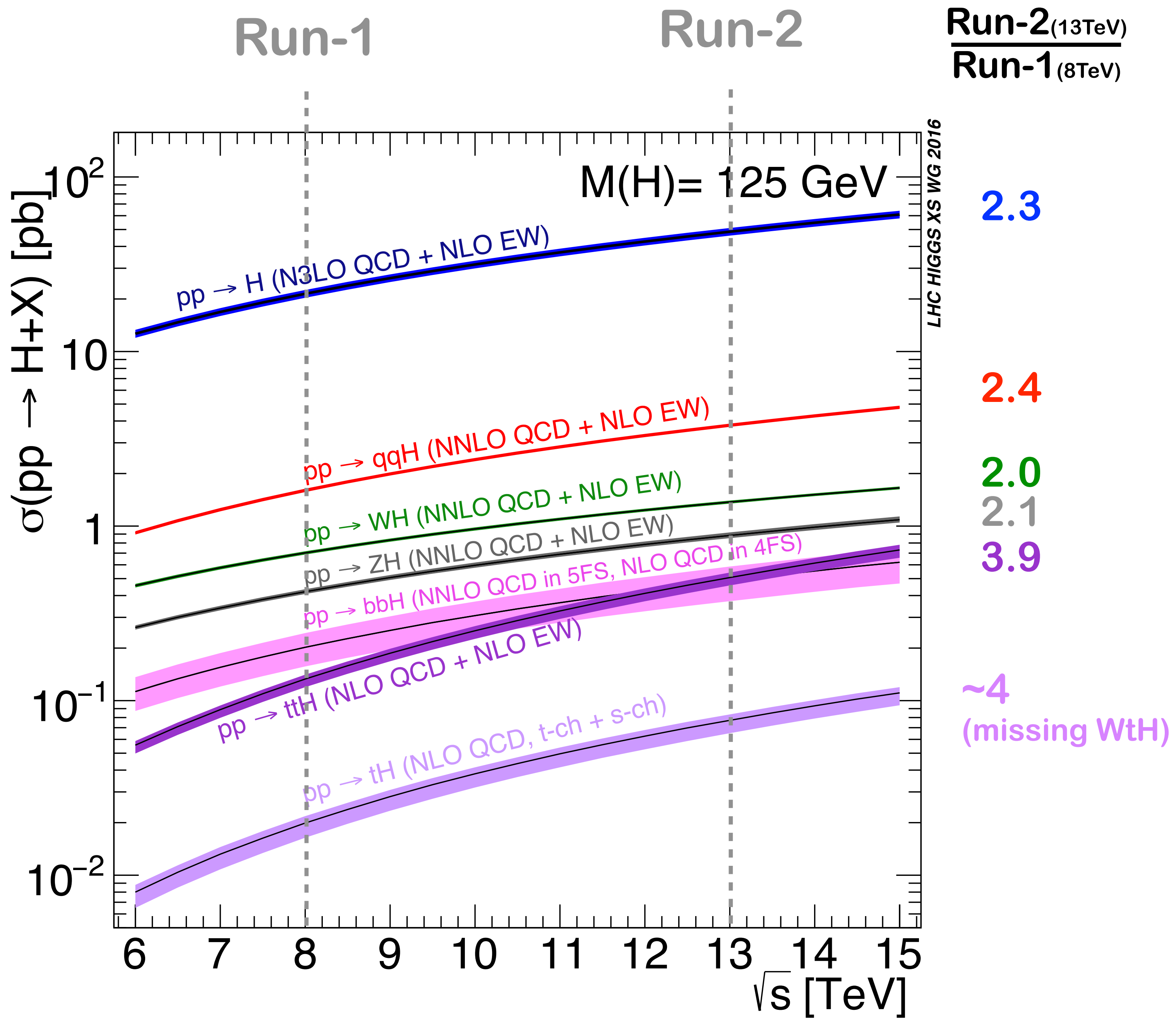


W, Z associated production (VH)



top associated production ($t\bar{t}H$)





Higgs differential cross section

JHEP 10 (2017) 132

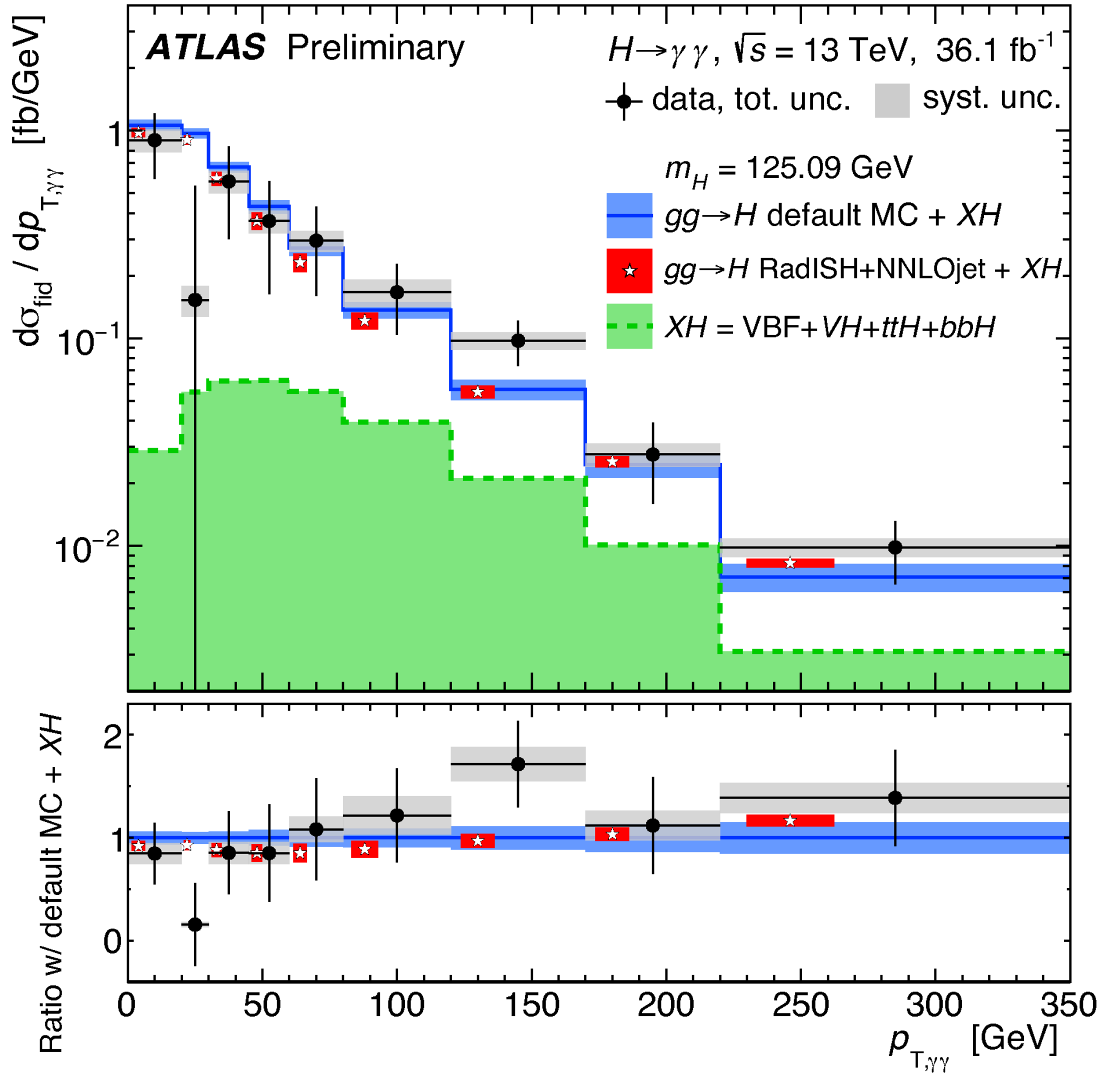
ATLAS-CONF-2017-045

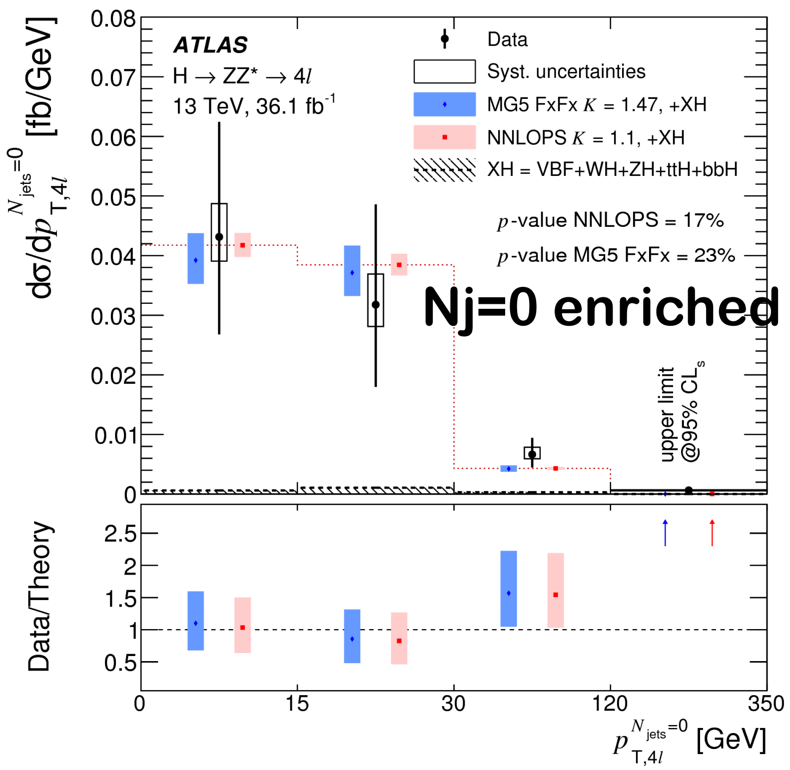
With increasing statistics

- Measure differential cross-sections as functions of **Higgs boson kinematics** and **kinematics of additional jets in H→γγ and H→ZZ*→4ℓ**

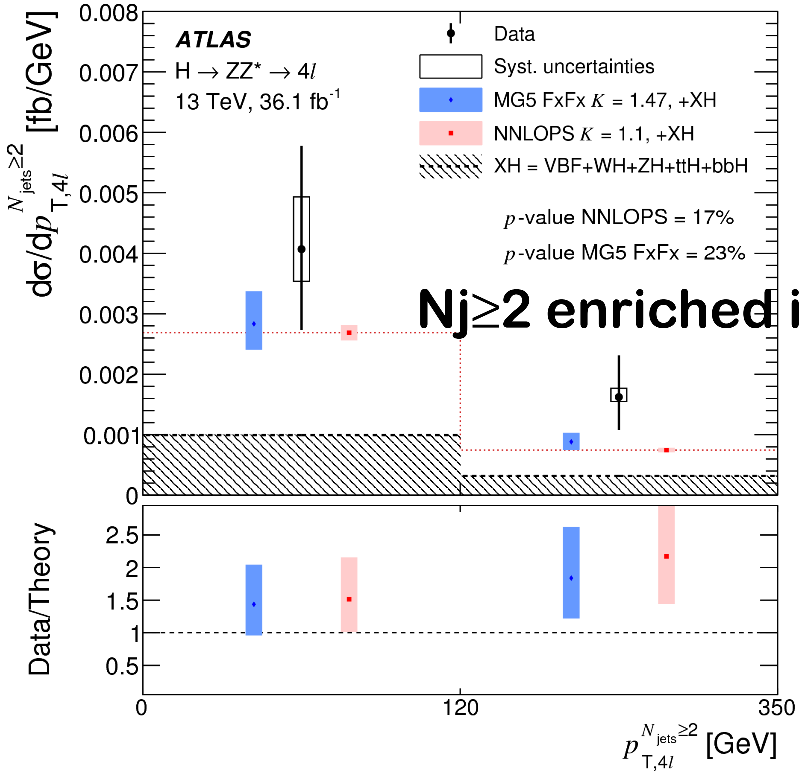
data/prediction agreement slightly worse towards higher jet multiplicity

pT (H) consistent with SM prediction in both channels





Nj=0 enriched in ggF

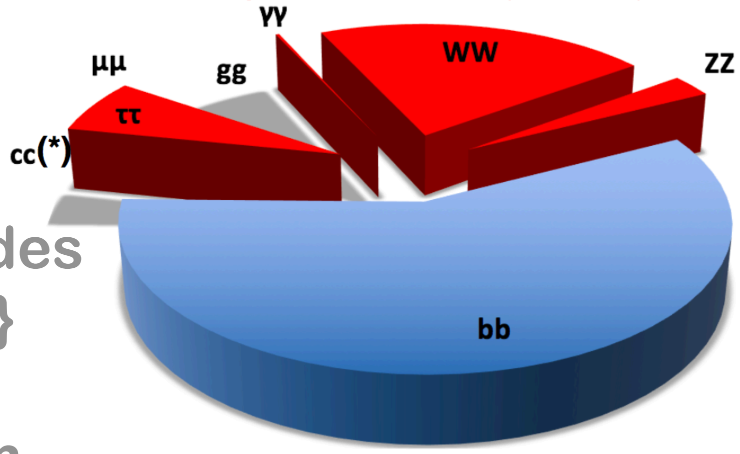


Nj≥2 enriched in VBF

Higgs coupling to fermions

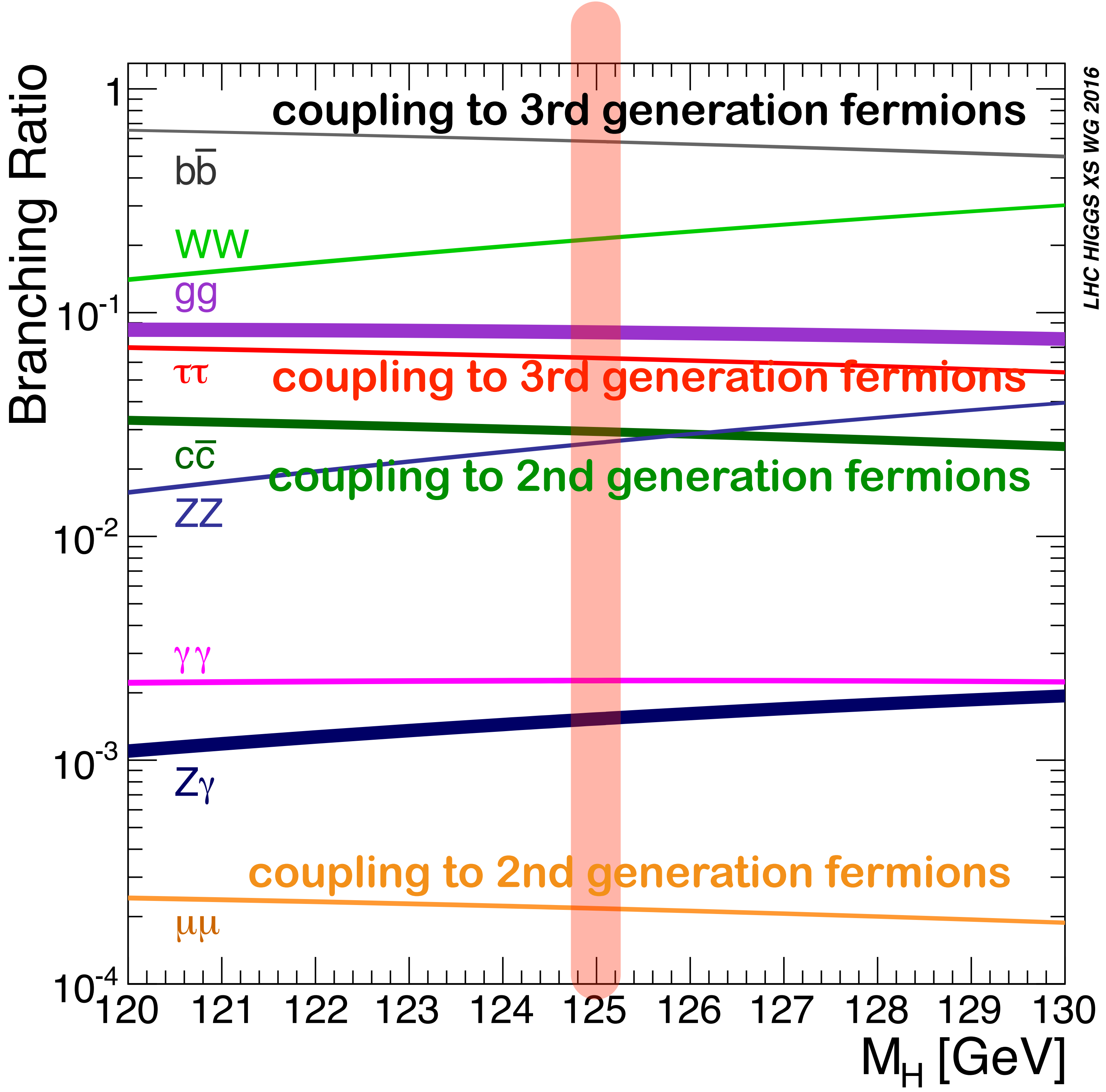
- **First evidence** of Higgs coupling to fermions from the **ττ channel** (ggF and VBF) in Run 1 JHEP 04 (2015) 117
- **New in Run 2:**
  - top Yukawa coupling: evidence for ttH production
  - b-quark Yukawa coupling: evidence in VH(H➜bb)
- **Longer term:**
  - Higgs coupling to 2nd generation fermions (cc, μμ)

observed decay modes (31%)

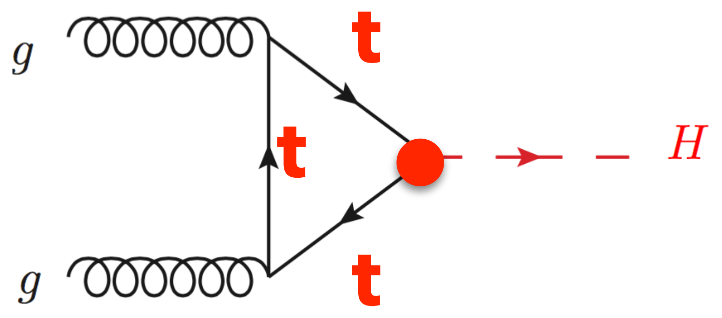


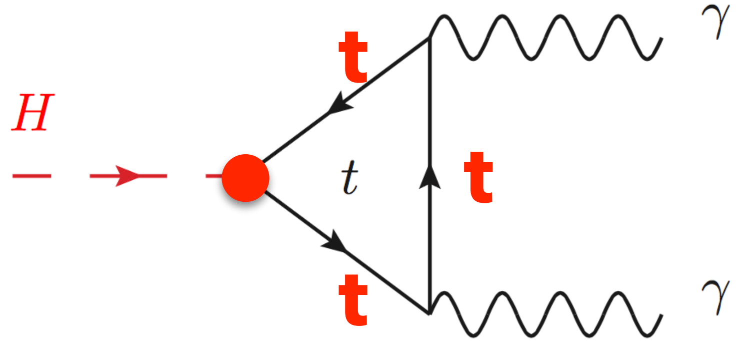
‘difficult’ modes {cc, gg, μμ} (11%)
➜ long term

evidence (58%)



Higgs coupling to fermions: top via $t\bar{t}H$

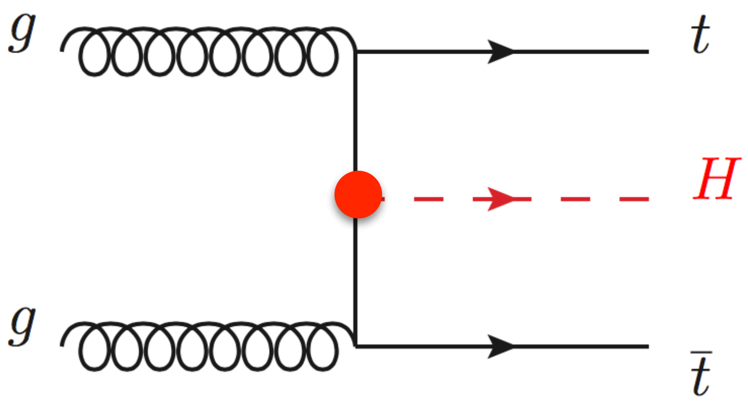


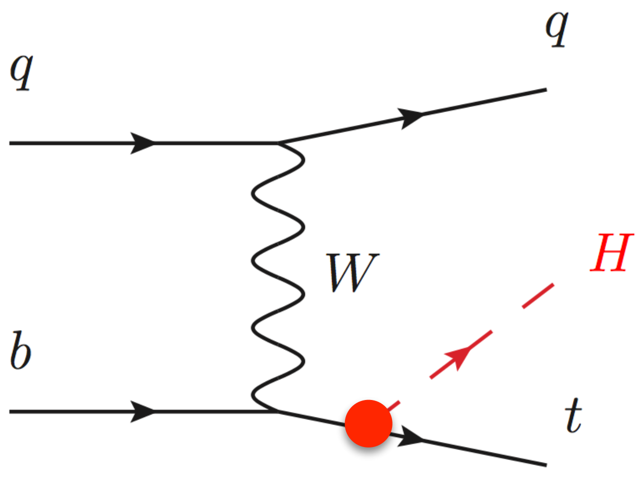


indirect top Yukawa coupling constraints from gluon fusion production and γγ decay…

… assuming no additional heavy particles which could couple to the Higgs boson!

direct top Yukawa coupling measurement only possible at the LHC via $t\bar{t}H$ and tH





Similar signature is visible in SUSY searches, VLQ, black holes or heavy charged Higgs

If such new physics scenarios exist, will see significant deviations from SM prediction

$t\bar{t}H$ analysis channels: summary

ttH
(H➔bb)

ttH
(H➔WW, ττ, ZZ)
‘multilepton’

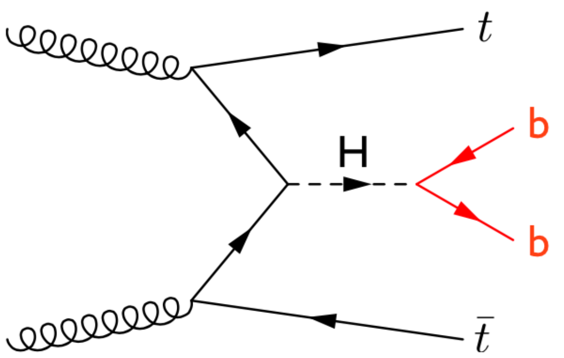
ttH
(H➔γγ, ZZ(➔4ℓ))

Low signal/background (need MVA) — **Clear peak (clean bump hunt)**

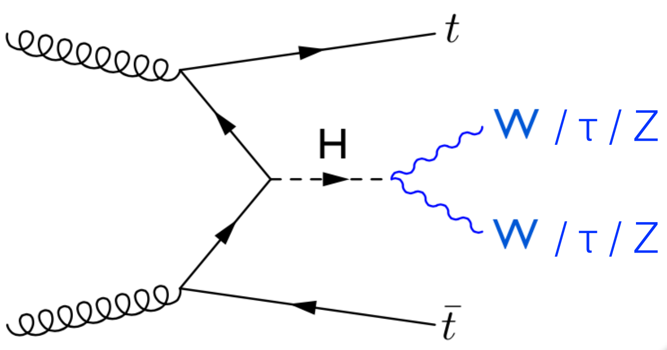
Large branching ratio (yields) — **Small branching ratio**

Difficult background modelling — **Simple background**

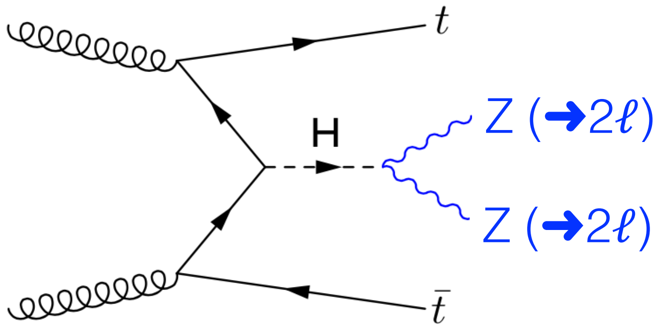
- large irreducible $t\bar{t}$+jets (HF) background
- final states with **multiple b-jets**

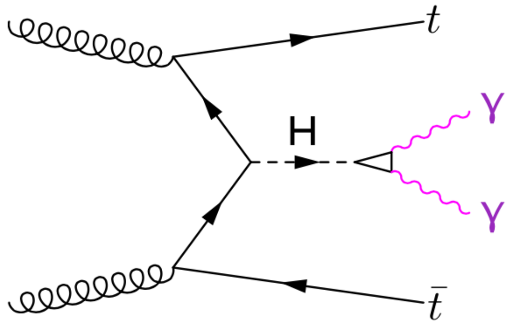


- leptonic decays of W / Z bosons and tau decays can give distinct **multilepton** signatures
- main background from $t\bar{t}$Z/W and non-prompt leptons



- **resonant** channels





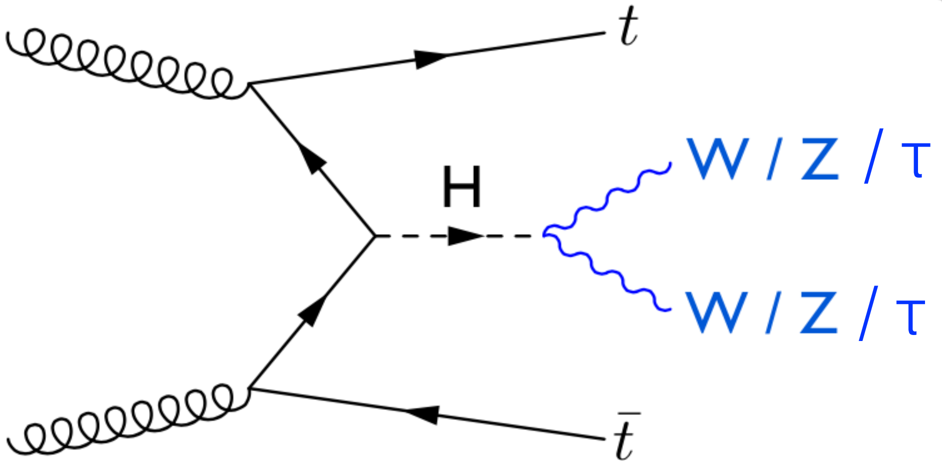
(ZZ➔4ℓ at m_H selection vetoed)

motivation ⟵ challenge

$t\bar{t}H$ (multileptons): analysis strategy

Target: $t\bar{t}H$ with

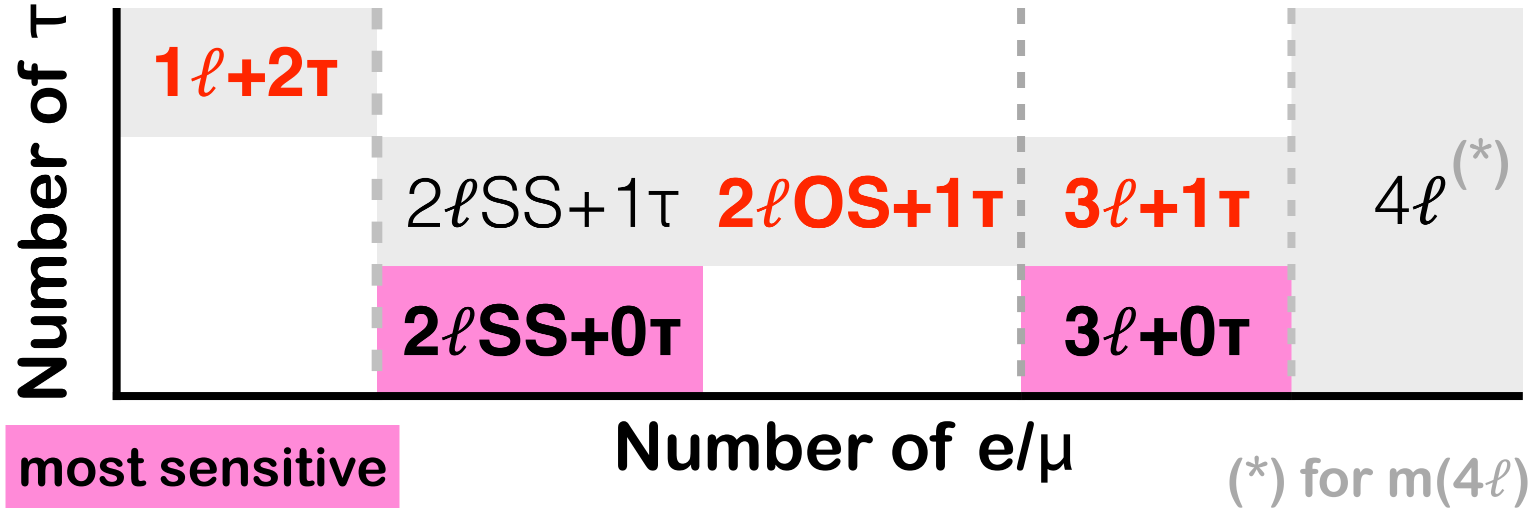
- $H \rightarrow WW/ZZ/\tau\tau \rightarrow \geq 1\ell$
- $t\bar{t} \rightarrow (\ell$+jets, dilepton)



High multiplicity final state

Rare in SM: same-sign 2ℓ, 3ℓ, 4ℓ

- Exploit presence of hadronically decaying τ



Number of τ

$1\ell+2\tau$

$2\ell SS+1\tau$ $2\ell OS+1\tau$ $3\ell+1\tau$ $4\ell^{(*)}$

$2\ell SS+0\tau$ $3\ell+0\tau$

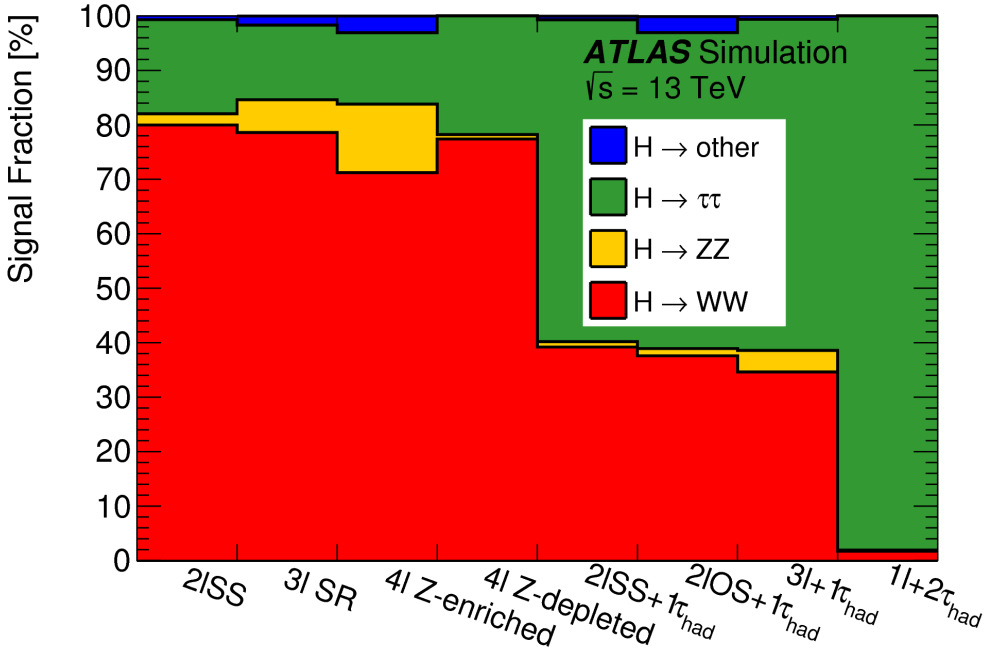
Number of e/μ

most sensitive

(*) for m(4ℓ) != Higgs mass window

Split in categories based on **number of e/μ** and **number of τ**

- **Loose** lepton definition (no isolation, loose ID)
- Dilepton and single lepton triggers



arXiv:1712.08891 submitted to PRD

$t\bar{t}H$ (multileptons): background

- **Signal extraction**: fit or cut on **BDTs (boosted decision tree)** to discriminate signal against the main background processes [except in 3ℓ+1τ]

	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{\text{had}}$	$2\ell\text{SS}+1\tau_{\text{had}}$	$2\ell\text{OS}+1\tau_{\text{had}}$	$3\ell+1\tau_{\text{had}}$
BDT trained against	Fakes and $t\bar{t}V$	$t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, VV	$t\bar{t}Z$ / -	$t\bar{t}$	all	$t\bar{t}$	-
Discriminant	2×1D BDT	5D BDT	Event count	BDT	BDT	BDT	Event count
Number of bins	6	5	1 / 1	2	2	10	1
Control regions	-	4	-	-	-	-	-

- **Non-prompt** lepton in $t\bar{t}$
  - semileptonic b-decay
  - γ conversions
- **Fake τ** from light/b-jets

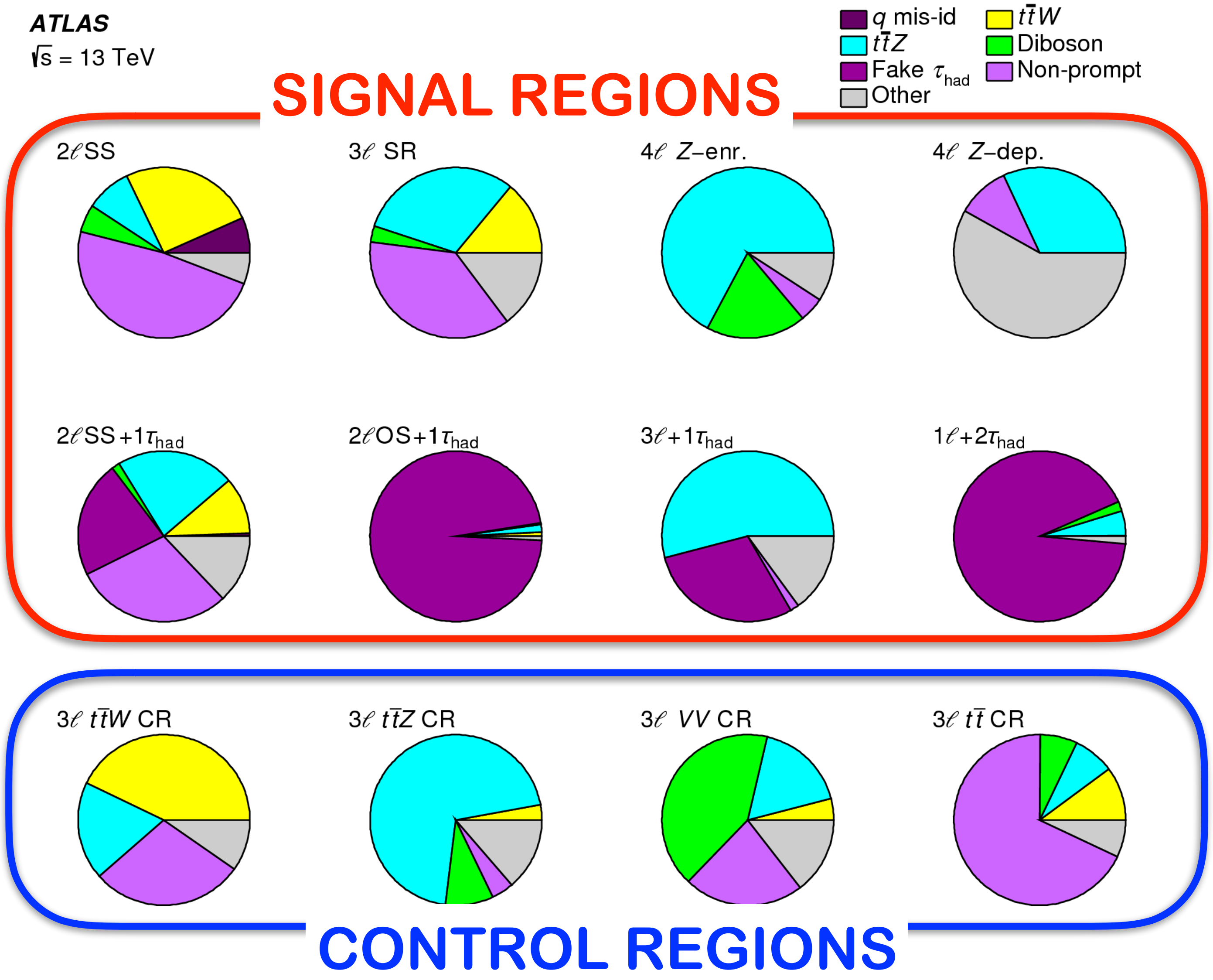
DATA-DRIVEN (DD): MATRIX METHOD (MM), FAKE FACTOR (FF)

- **Misidentified charge** lepton
  - e.g. trident electrons (Bremsstrahlung conversion)

DATA-DRIVEN (DD): LIKELIHOOD FIT

- **Irreducible backgrounds** with prompt-leptons ($t\bar{t}Z$, $t\bar{t}W$, VV)

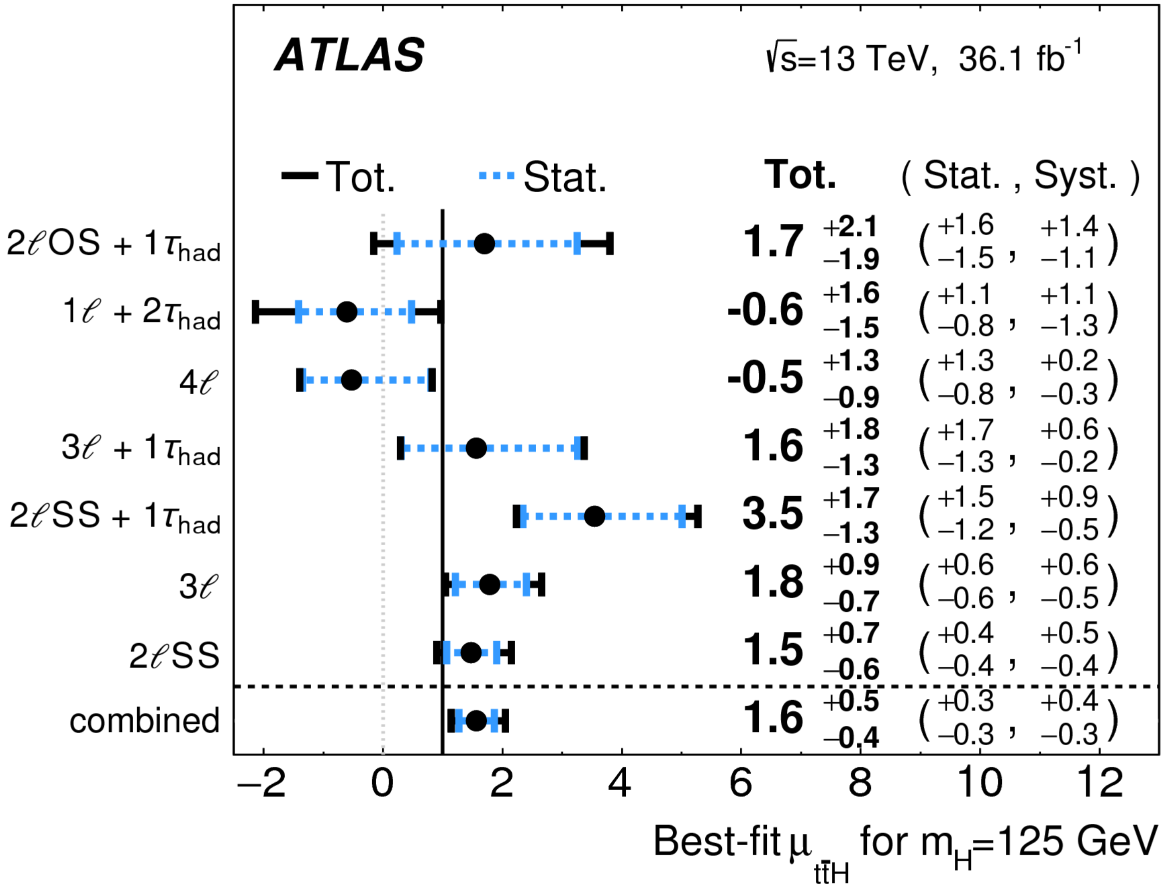
MC



"Other": 4tops, $t\bar{t}WW$, tH, tZ

arXiv:1712.08891 submitted to PRD

$t\bar{t}H$ (multileptons): results



Channel	Significance	
	Observed	Expected
$2\ell OS+1\tau_{had}$	0.9σ	0.5σ
$1\ell+2\tau_{had}$	-	0.6σ
4ℓ (*)	-	0.8σ
$3\ell+1\tau_{had}$	1.3σ	0.9σ
$2\ell SS+1\tau_{had}$	3.4σ	1.1σ
3ℓ	2.4σ	1.5σ
$2\ell SS$	2.7σ	1.9σ
Combined	4.1σ	2.8σ

- Statistical and systematic uncertainties are comparable
- **Largest systematic uncertainties**:
  - signal modelling, jet energy scale and resolution, and the non-prompt light ℓ estimates
- Significance with respect to background-only hypothesis = **4.1 σ (2.8 σ) obs (exp)**
- Compatible with SM (within 1.4σ)

(*) for m(4ℓ) != Higgs mass window

arXiv:1712.08891 submitted to PRD

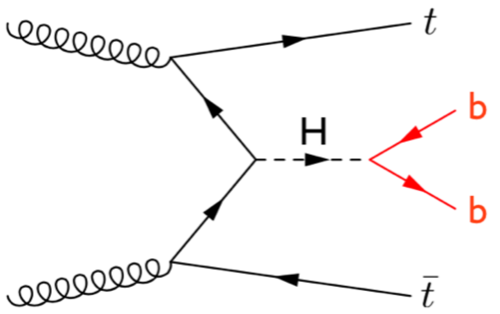
$t\bar{t}H$ ($H \to b\bar{b}$): analysis strategy

- **Biggest challenge**: good and precise modelling of the $t\bar{t}$+HF (≥1b, ≥1c) background
  - Nominal sample: 5-flavour scheme
  - Relative contribution of $t\bar{t}$+≥1b sub-components reweighted to $t\bar{t}+b\bar{b}$ predictions by Sherpa+OpenLoops (4-flavour scheme)

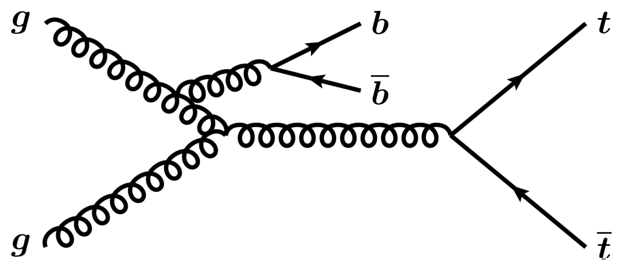
- **Channel categorisation** based on
  - Number of ℓ (1 or 2 opposite-sign)
  - Number of jets
  - Requirements on the b-tagging discriminant (4 calibrated working points)
  - Resolved or boosted, for single lepton channel

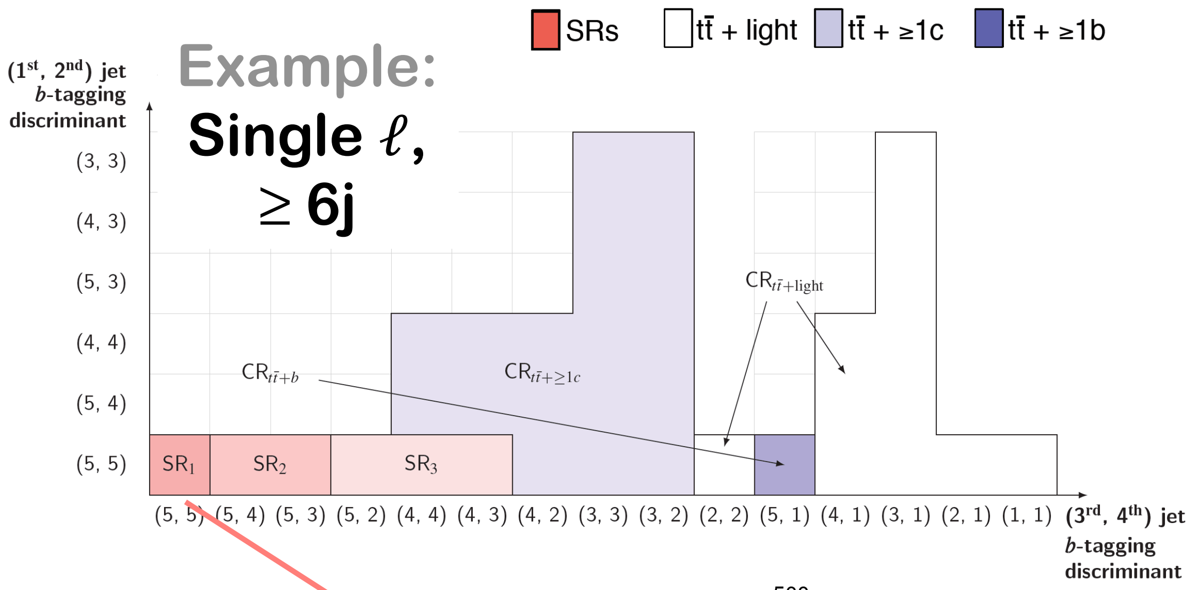
- **MVA analysis** needed to discriminate signal from the overwhelming background

signal (ttH)

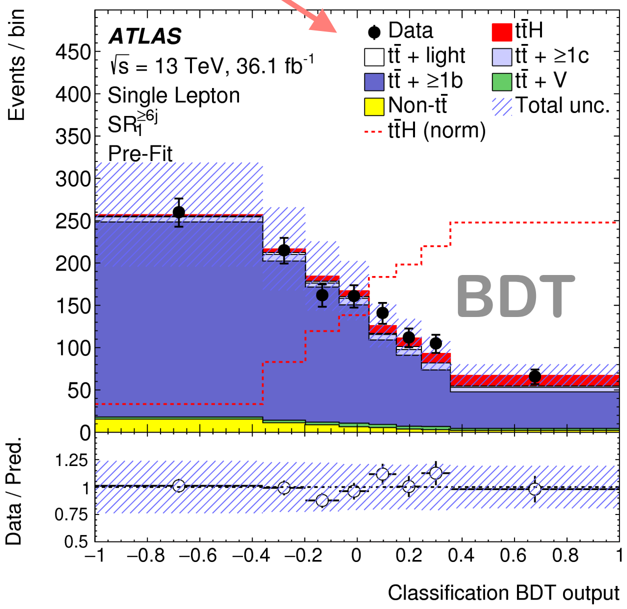


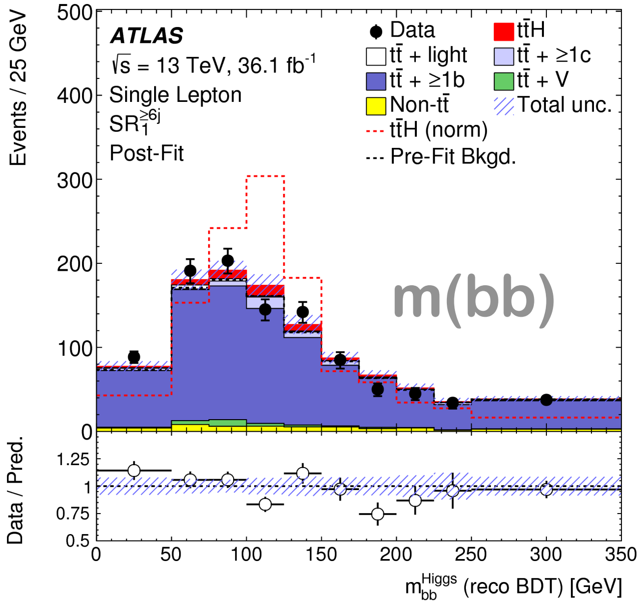
ttbb





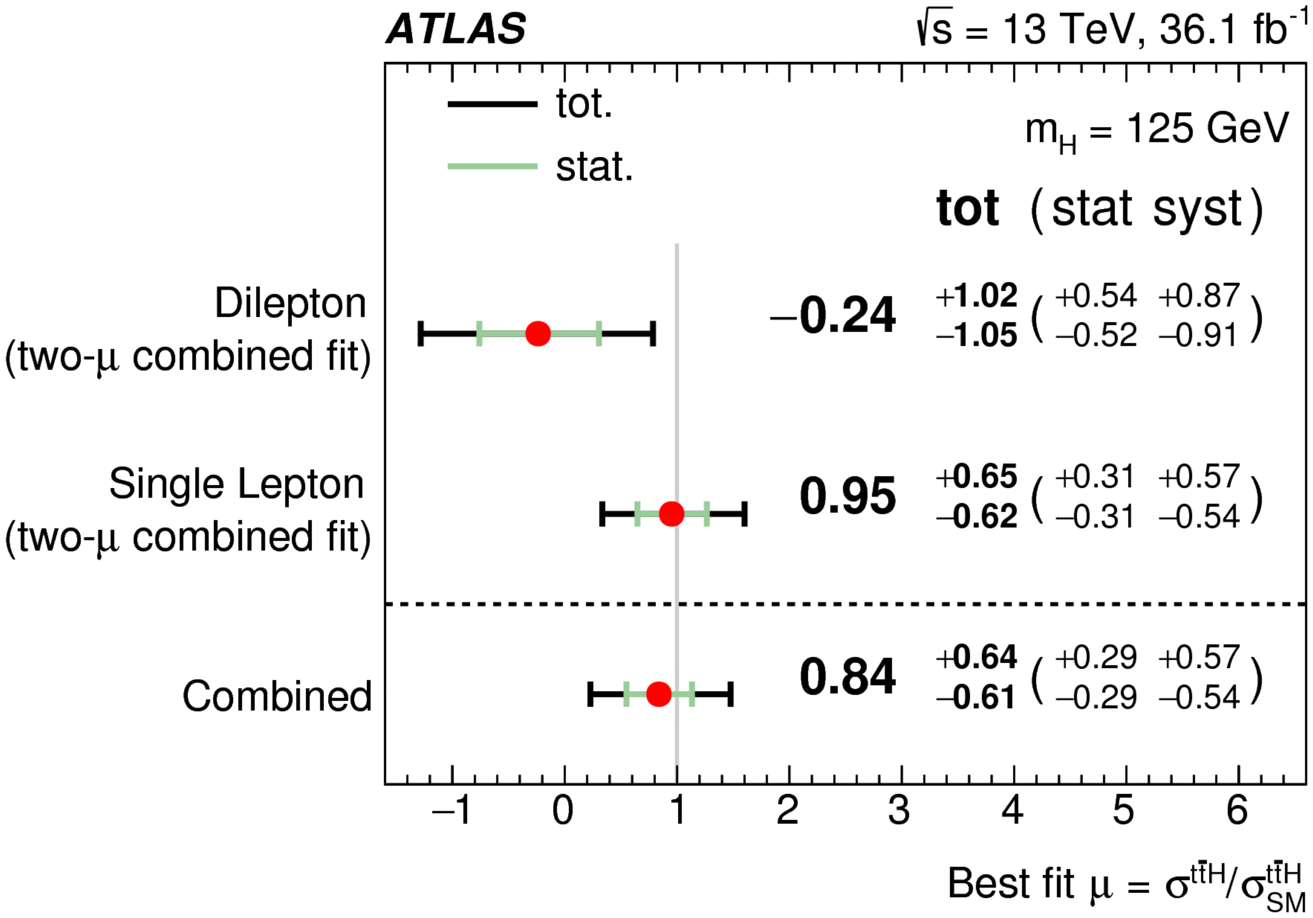
Example:
Single ℓ,
≥ 6j





arXiv:1712.08895 submitted to PRD

$t\bar{t}H$ ($H \rightarrow b\bar{b}$): results

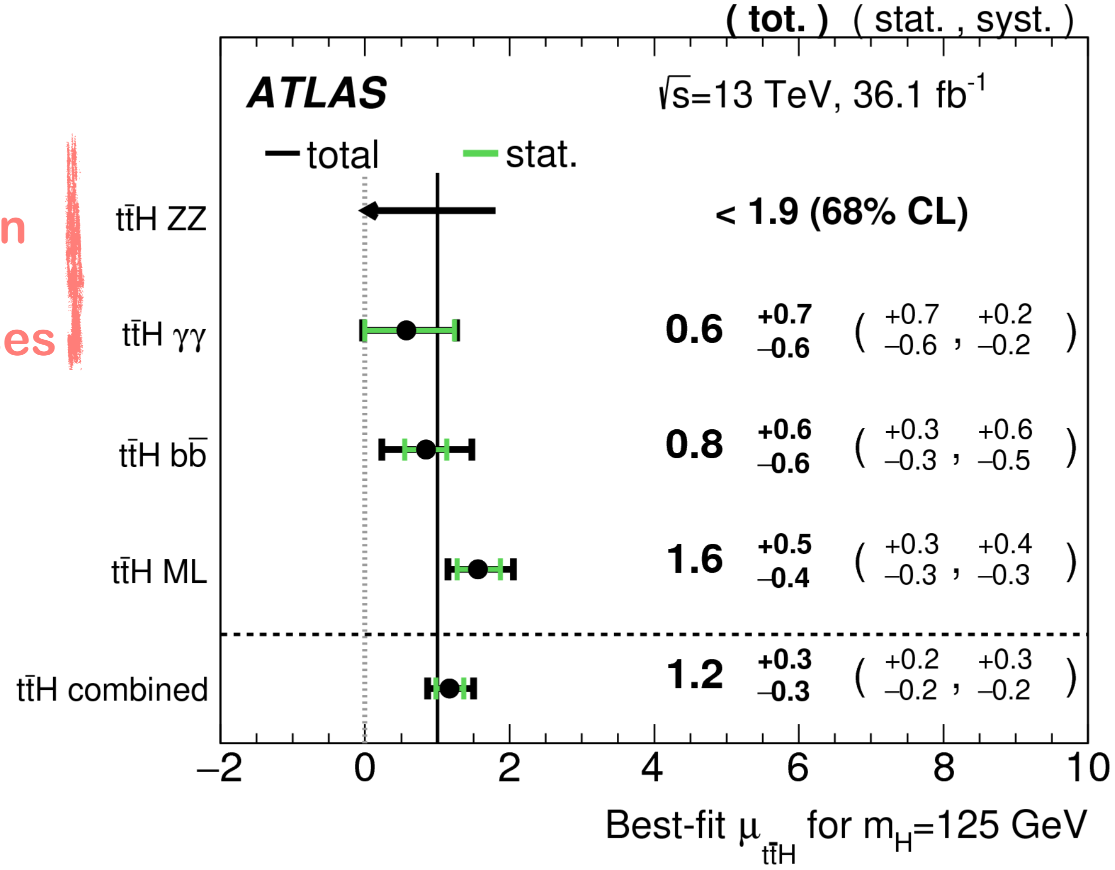


Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modeling	+0.46	−0.46
Background-model stat. unc.	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modeling	+0.22	−0.05
$t\bar{t} + \geq 1c$ modeling	+0.09	−0.11
JVT, pileup modeling	+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

- Normalisation factors for $t\bar{t}+\geq 1b$ and $t\bar{t}+\geq 1c$ left free-floating in the fit:
  - NF($t\bar{t}+\geq 1b$) = 1.24 ± 0.10
  - NF($t\bar{t}+\geq 1c$) = 1.63 ± 0.23
- Most relevant uncertainties related to $t\bar{t}+\geq 1b$ background modelling
- Analysis is **dominated by systematic** uncertainties
- Significance w.r.t background-only hypothesis: **1.4σ (1.6σ) obs (exp)**

arXiv:1712.08895 submitted to PRD

$t\bar{t}H$ combination

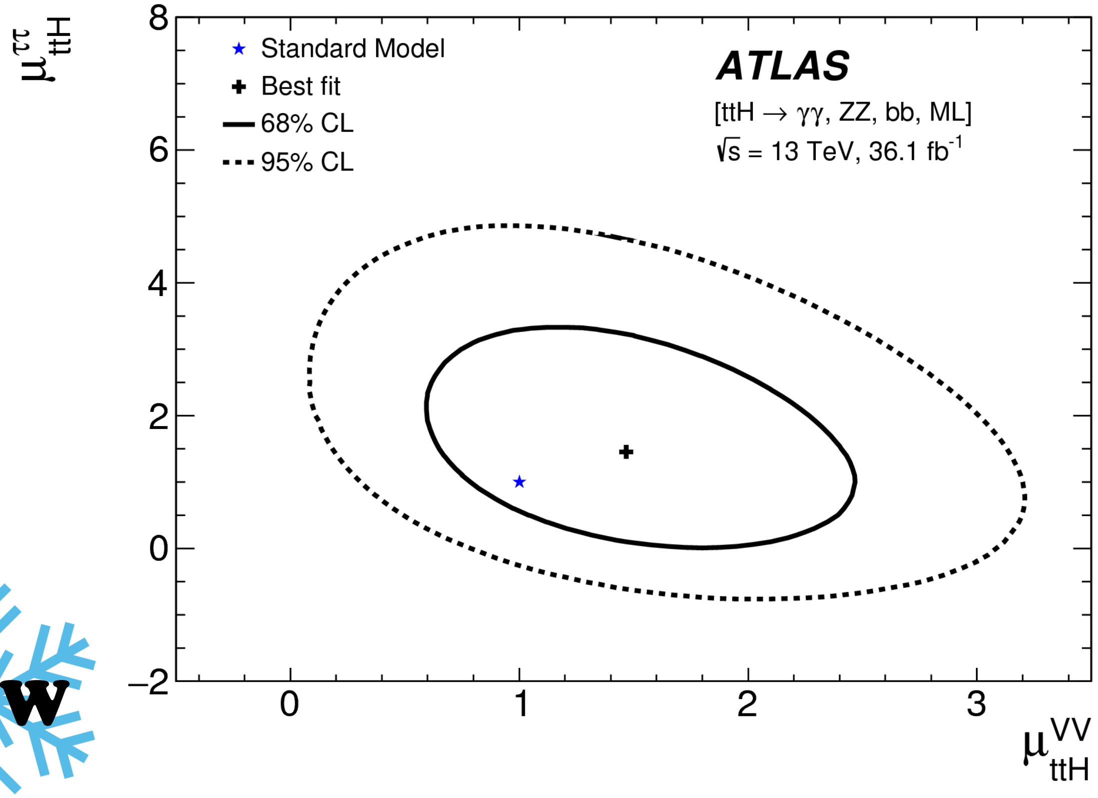


dedicated categories in H→γγ and H→ZZ analyses

Channel	Significance	
	Observed	Expected
Multilepton	4.1σ	2.8σ
$H \rightarrow b\bar{b}$	1.4σ	1.6σ
$H \rightarrow \gamma\gamma$	0.9σ	1.7σ
$H \rightarrow 4\ell$	—	0.6σ
Combined	4.2σ	3.8σ

- Combination of multilepton, $b\bar{b}$, γγ, and $ZZ \rightarrow 4\ell$ $t\bar{t}H$ analyses
- Results in agreement with the SM predictions
  - $\sigma(ttH) \quad = 590^{+160}_{-150}$ fb
  - $\sigma_{SM}(ttH) = 507^{+35}_{-50}$ fb
- Significance w.r.t background-only hypothesis: **4.2σ (3.8σ) obs (exp)**
  - **Evidence for $t\bar{t}H$ production!**

NEW

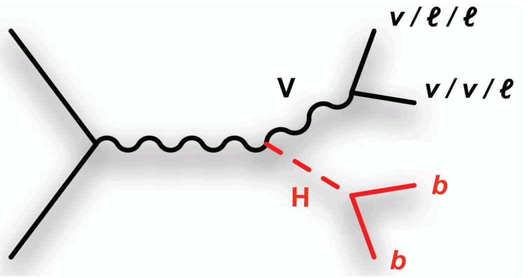


arXiv:1712.08891 submitted to PRD

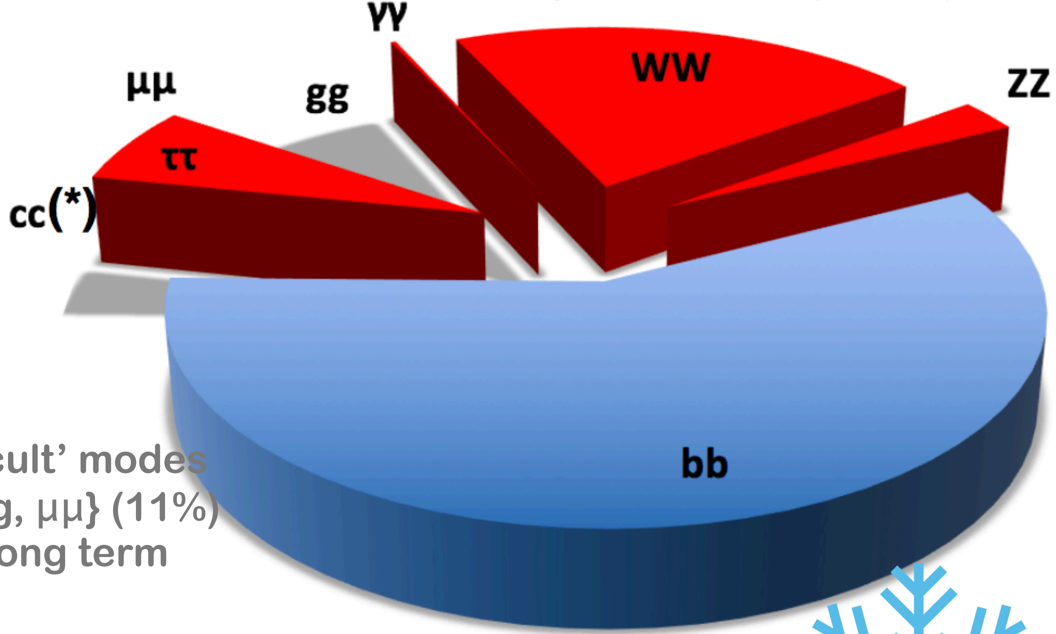
Higgs coupling to fermions: b-quark via VH(H➜$b\bar{b}$)

JHEP 12 (2017) 024

- **Leptons** from W/Z used for triggering/ background suppression
- **Three channels:**
  - 0-leptons (targeting ZH, Z➜νν)
  - 1-lepton (targeting WH, W➜ℓν)
  - 2-leptons (targeting ZH, Z➜ℓℓ)
- Main analysis based on multivariate analysis techniques
- **Run 2:** 3.5 (3.0) σ observed (expected)
- **Run 1+Run 2:** 3.6 (4.0) σ observed (expected)



observed decay modes (31%)

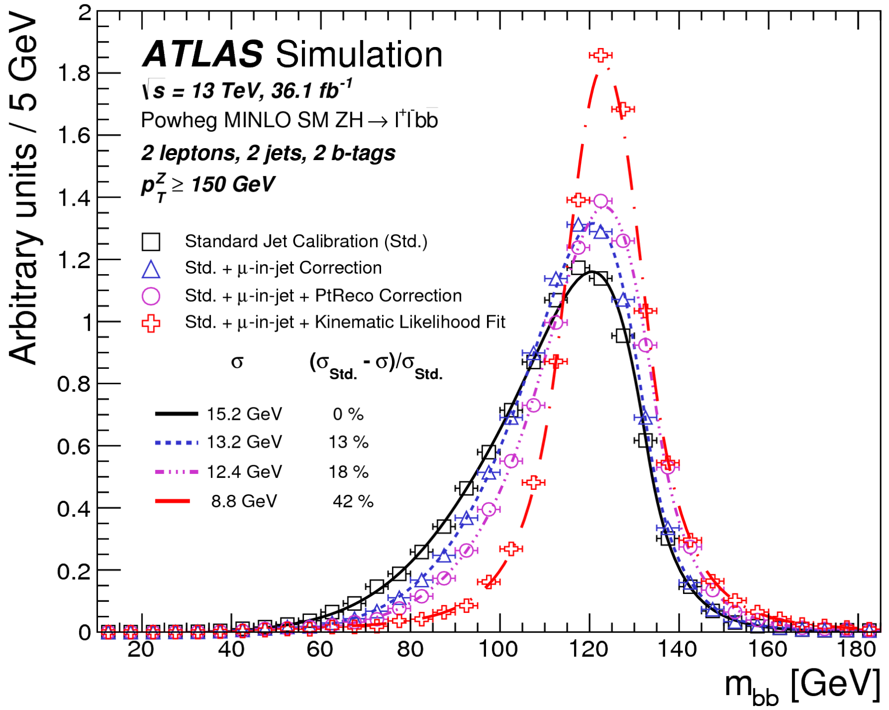


'difficult' modes {cc, gg, μμ} (11%) ➜ long term

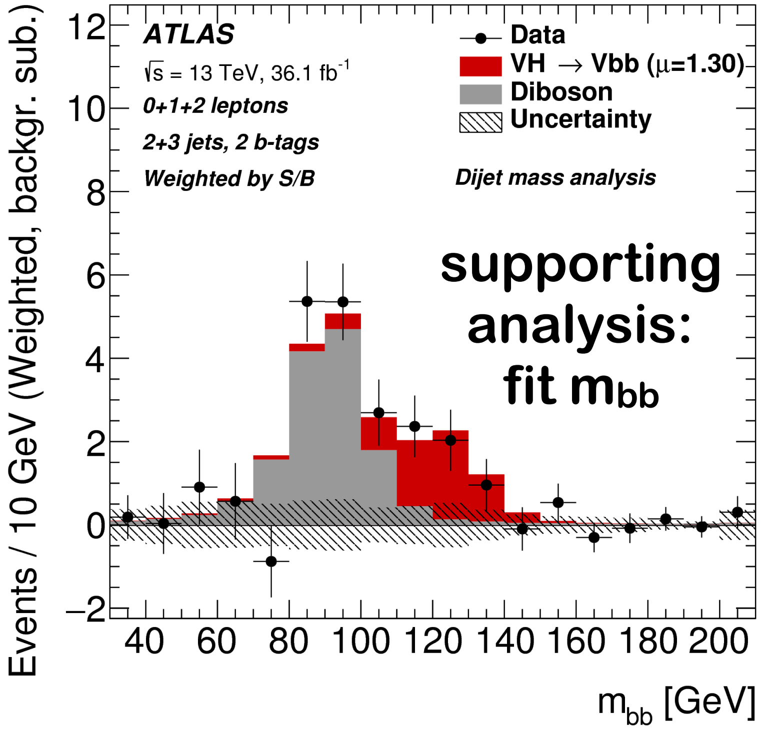
evidence (58%)

NEW

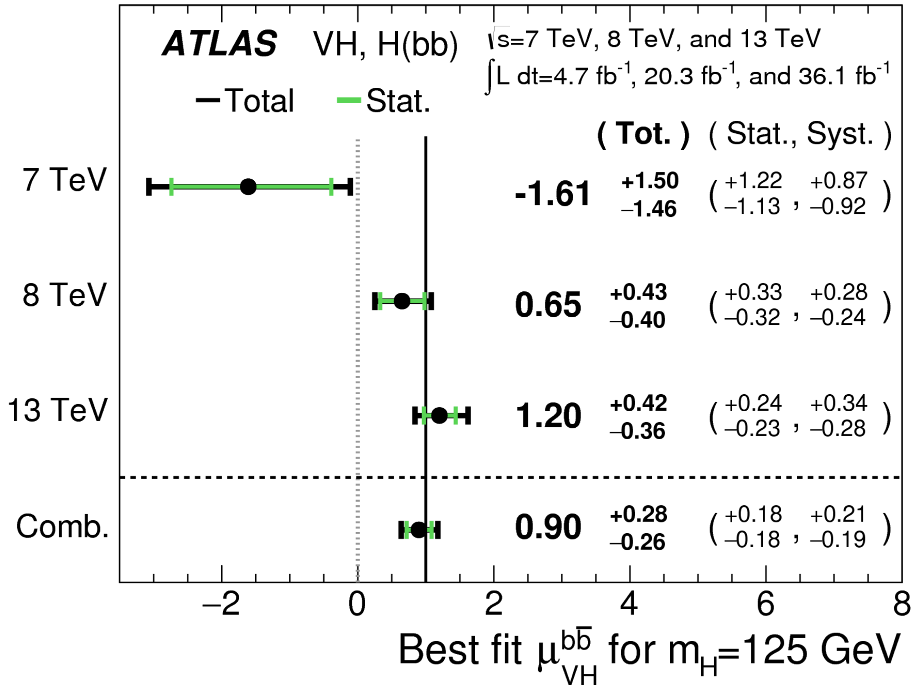
improved jet calibration + kinematic reconstruction



after subtracting all background except VV



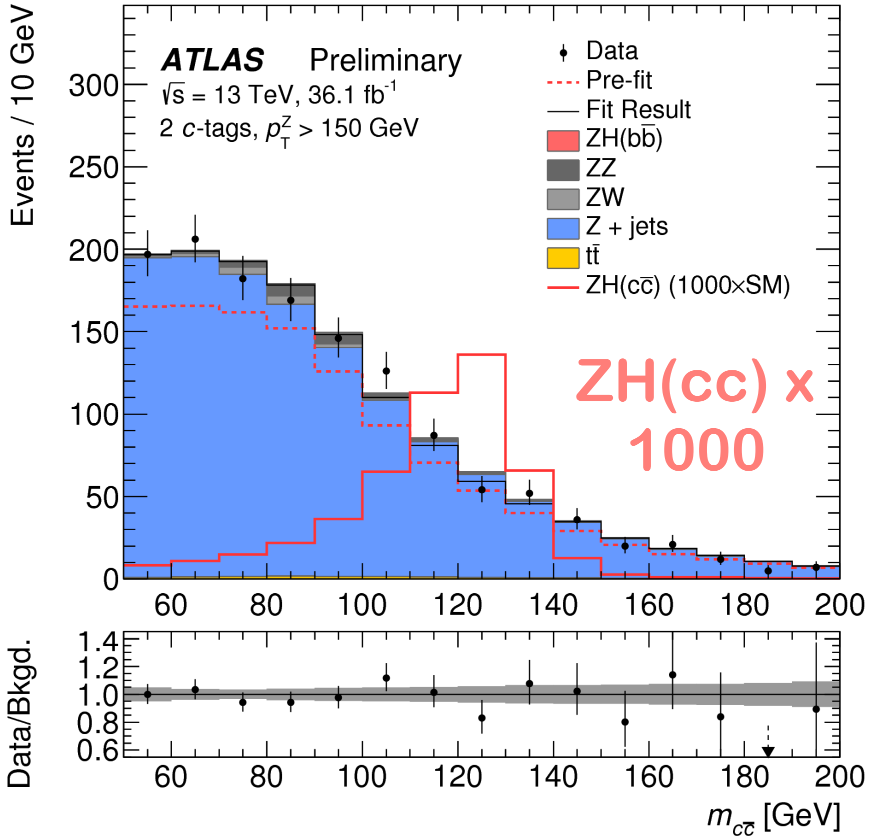
supporting analysis: fit m_{bb}



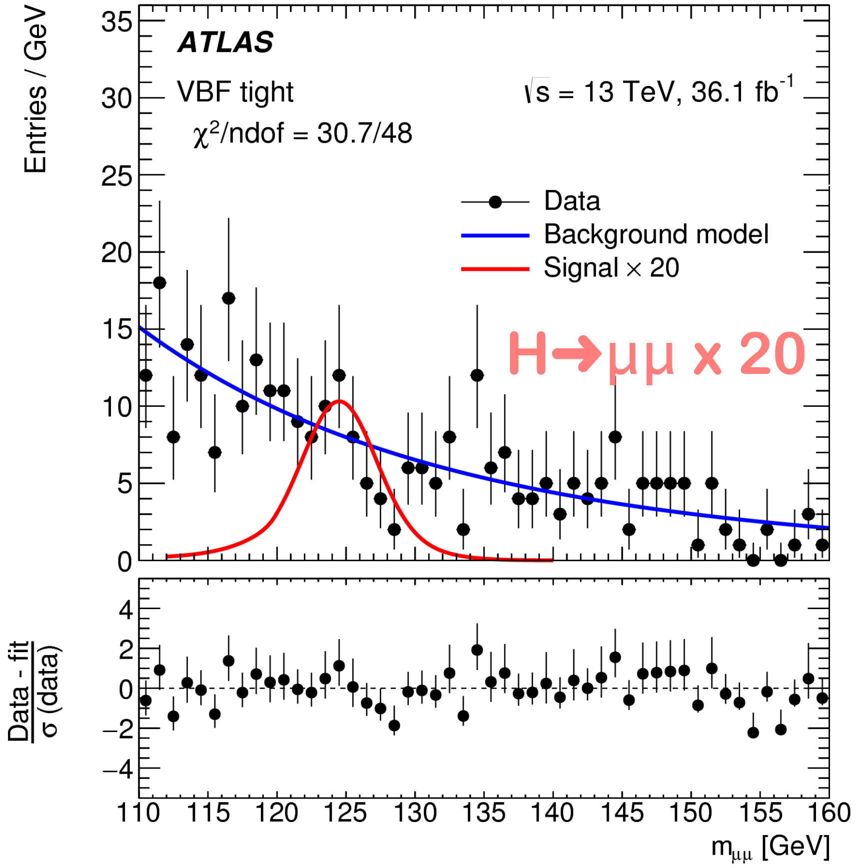
Rare(r) Higgs decays

Towards measurements of Yukawa coupling of 2nd generation fermions!

- Difficult decay modes
  - all using 36.1 fb^{-1} Run 2 data
  - ZH, H➔c$\bar{c}$ ATLAS-CONF-2017-078
    - Z decaying leptonically
    - Set upper limits for σ(pp➔ZH)x$\mathcal{B}$(H➔cc): < **2.7 pb observed** (3.9 pb expected)
    - SM value is 25.5 fb
    - Sensitivity to cc SM still quite far away!
  - H➔Zγ JHEP 10 (2017) 112
    - Z decaying leptonically
    - Set upper limits for σ(pp➔H)x$\mathcal{B}$(H➔Zγ): < **6.6 observed** (5.2 expected)**xSM**
    - SM value of $\mathcal{B}$(H➔Zγ) is 1.5x10^{-3}
  - H➔μμ PRL 119 (2017) 051802
    - Categories enriched in ggF and VBF Higgs production
    - Set upper limits for σ(pp➔H)x$\mathcal{B}$(H➔μμ): < **3.0 observed** (3.1 expected)**xSM**
    - SM value of $\mathcal{B}$(H➔μμ) is 2.2x10^{-4}



ZH(cc) x 1000



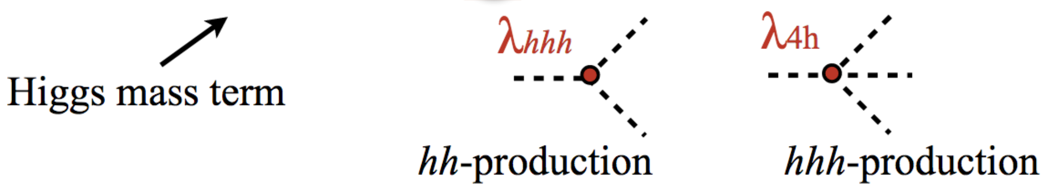
H➔μμ x 20

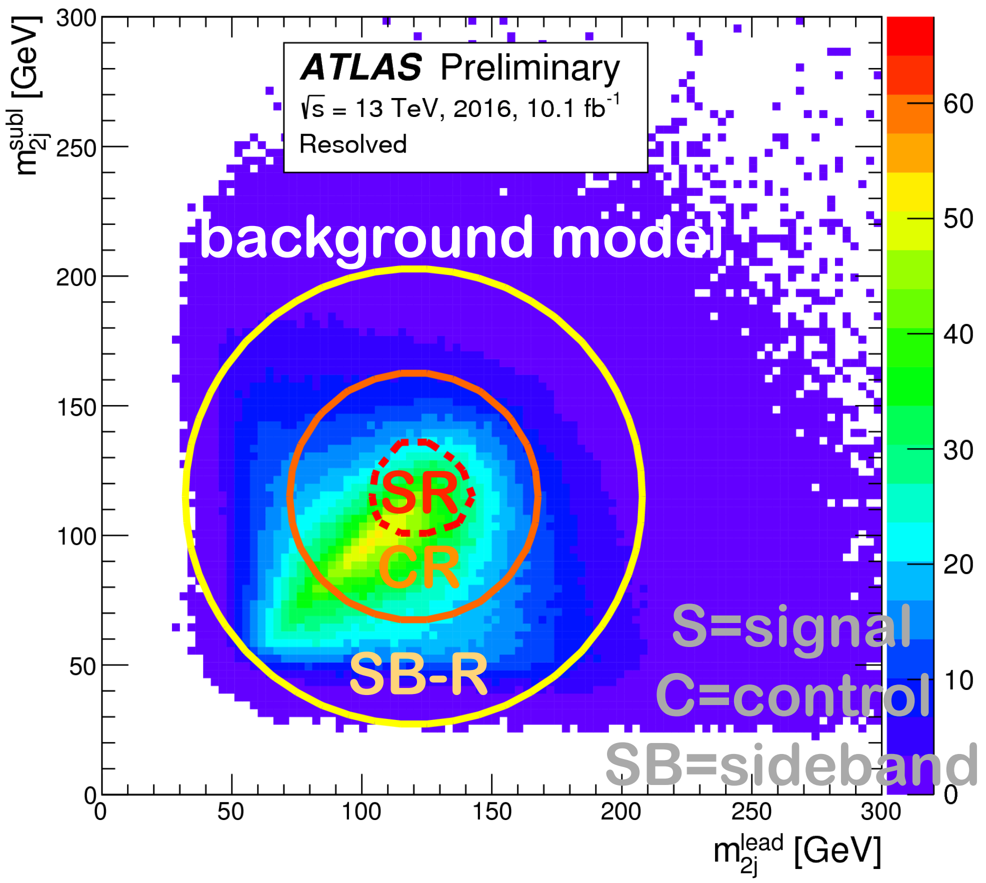
Higgs self-coupling

- Not only are we interested in studying the Higgs couplings to other particles…
  - We also want to understand its **self-coupling λ**!
  - λ is predicted once Higgs boson mass is known
    - Any deviation from the HH production measurement would imply new physics!

$$V = V_0 + \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

$$= V_0 + \frac{1}{2} m_h^2 h^2 + \underbrace{\boxed{\frac{m_h^2}{2v^2}}}_{\lambda_{hhh}} v h^3 + \frac{1}{4} \underbrace{\frac{m_h^2}{2v^2}}_{\lambda_{4h}} h^4$$

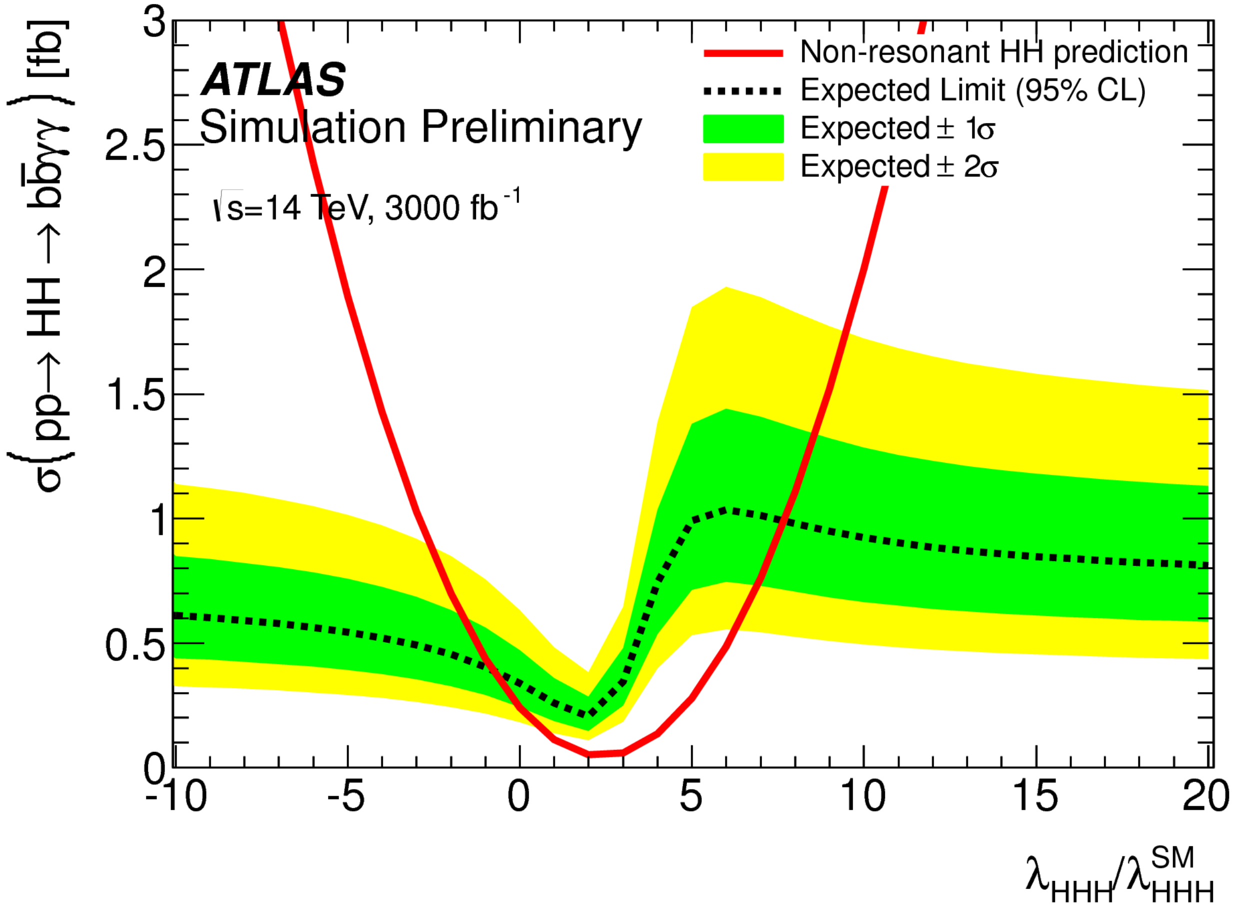




Search for HH with 13.1 fb^{-1} in bbbb final states

Upper limits σ(pp→HH)x$\mathcal{B}$(HH→bbbb) < 330 fb [**29 times the SM** = 11.3 fb !]

ATLAS-CONF-2016-049



Prospects at 3000 fb^{-1} (HL-LHC) in bbγγ final state

Single analysis: $-0.8 < \lambda/\lambda_{SM} < 7.7$

Expected significance = **1.05σ**

ATL-PHYS-PUB-2017-001

Conclusions

- Many ground-breaking ATLAS physics results with the 2015+2016 Run-2 dataset, including **evidence** for H➜$b\bar{b}$ and $t\bar{t}$H production
- Standard Model and Higgs measurements are reaching unprecedented precision
  - New analyses trying to target tough Higgs decays
  - Higgs self-coupling beyond current reach
- 2017 has been another record year - data on tape is larger than what we have analysed so far at 13 TeV!
- 2018 will bring even more data for pp and heavy ion collisions

Conclusions

Thanks to the LHC and injector complex team & my collaborators

The ATLAS Collaboration

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V.S. Bobrovnikov[111,c], S.S. Bocchetta[84], A. Bocci[48], C. Bock[102], D. Boerner[177], D. Bogavac[102], A.G. Bogdanchikov[111], C. Bohm[148a], V. Boisvert[80], P. Bokan[168,i], T. Bold[41a], A.S. Boldyrev[101], A.E. Bolz[60b], M. Bomben[83], M. Bona[79], J.S. Bonilla[118], M. Boonekamp[138], A. Borisov[132], G. Borissov[75], J. Bortfeldt[32], D. Bortoletto[122], V. Bortolotto[62a], D. Boscherini[22a], M. Bosman[13], J.D. Bossio Sola[29], J. Boudreau[127], E.V. Bouhova-Thacker[75], D. Boumediene[37], C. Bourdarios[119], S.K. Boutle[56], A. Boveia[113], J. Boyd[32], I.R. Boyko[68], A.J. Bozson[80], J. Bracinik[19], A. Brandt[8], G. Brandt[177], O. Brandt[60a], F. Braren[45], U. Bratzler[158], B. Brau[89], J.E. Brau[118], W.D. Breaden Madden[56], K. Brendlinger[45], A.J. Brennan[91], L. Brenner[45], R. Brenner[168], S. Bressler[175], D.L. Briglin[19], T.M. Bristow[49], D. Britton[56], D. Britzger[60b], I. Brock[23], R. Brock[93], G. Brooijmans[38], T. Brooks[80], W.K. Brooks[34b], E. 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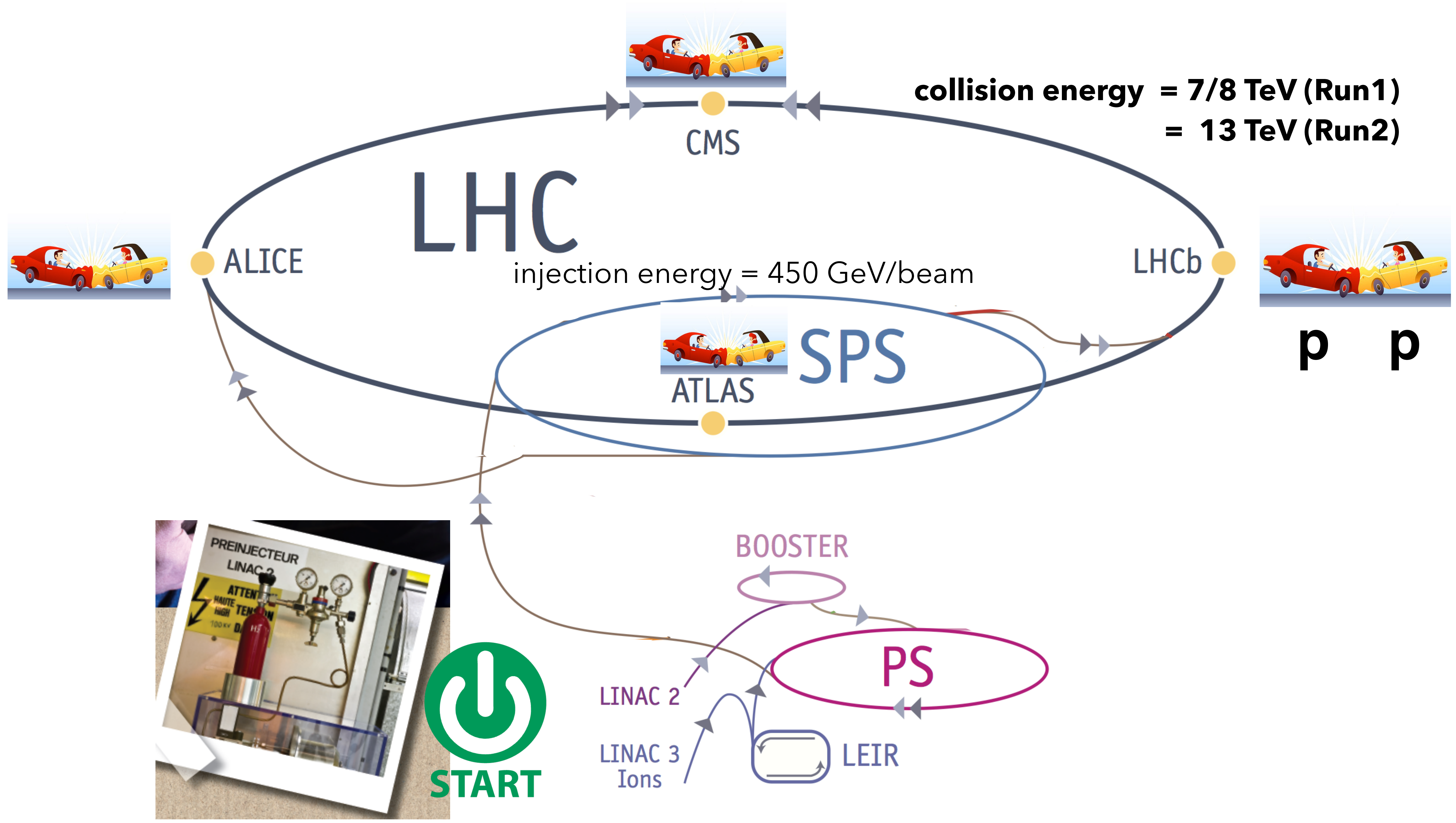
and thank you for your attention!

Supporting material

The Large Hadron Collider (LHC)



collision energy = 7/8 TeV (Run1)
= 13 TeV (Run2)

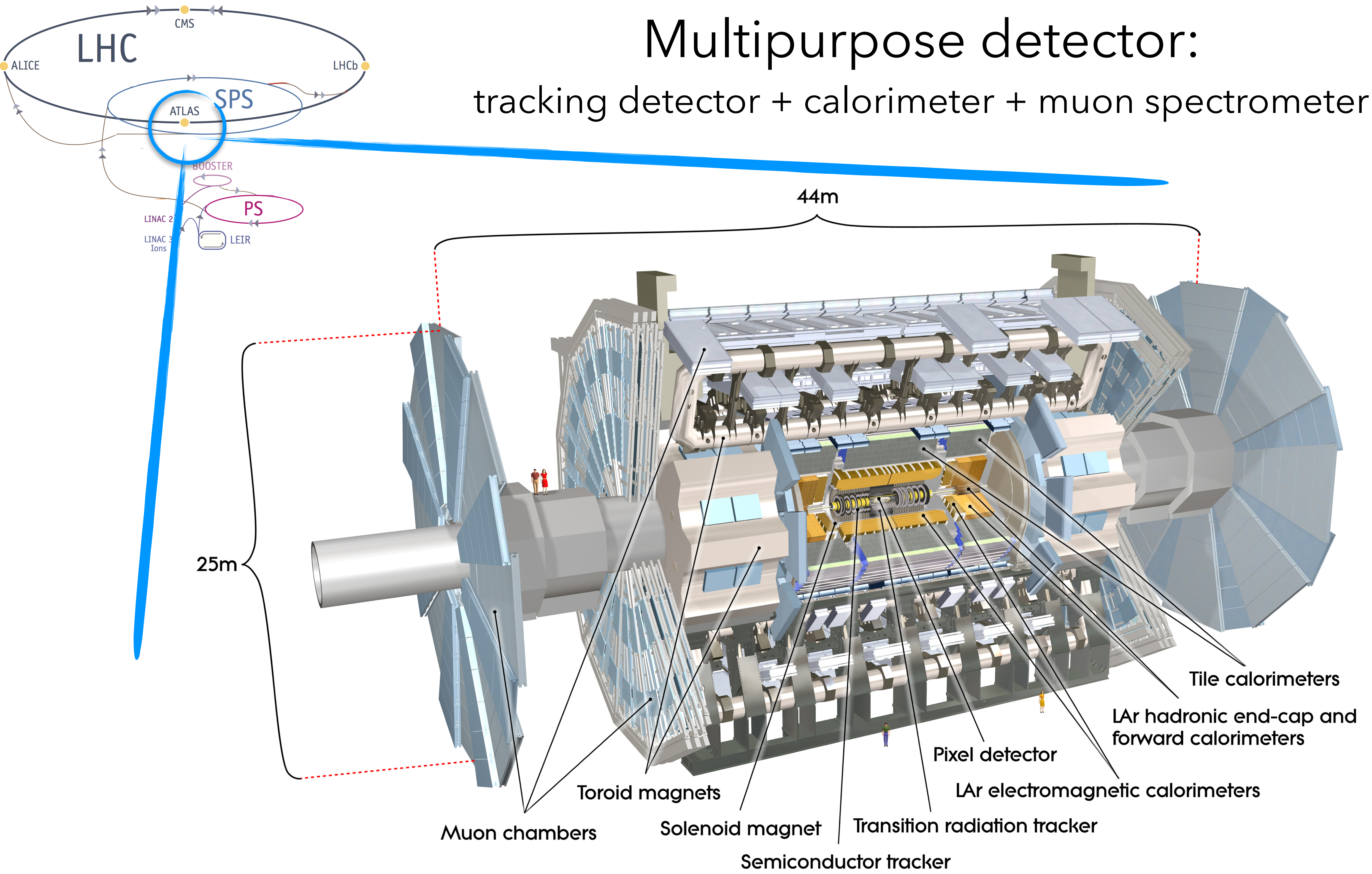
injection energy = 450 GeV/beam

The CERN accelerator complex & the collider

The ATLAS experiment

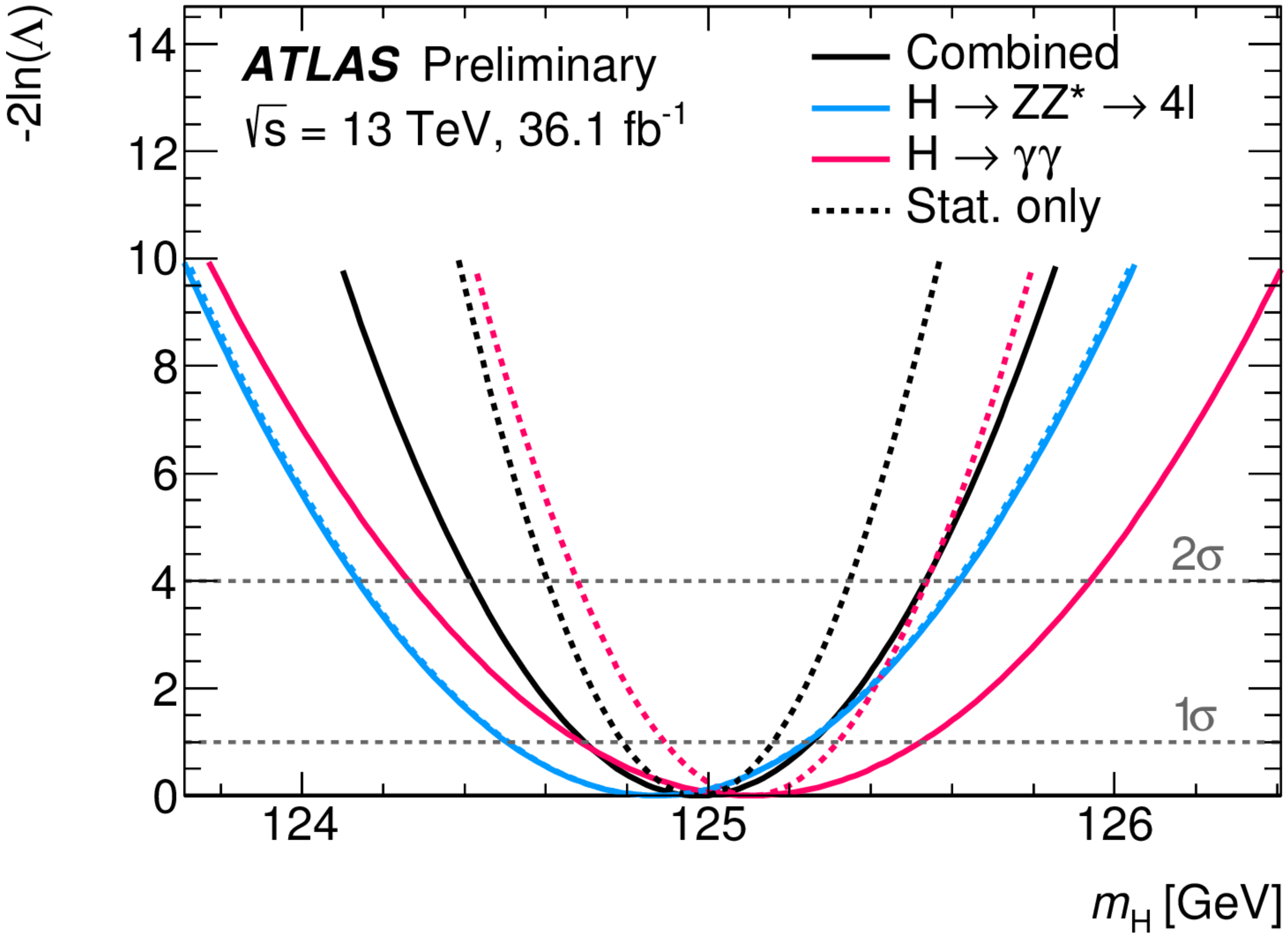
Multipurpose detector:

tracking detector + calorimeter + muon spectrometer

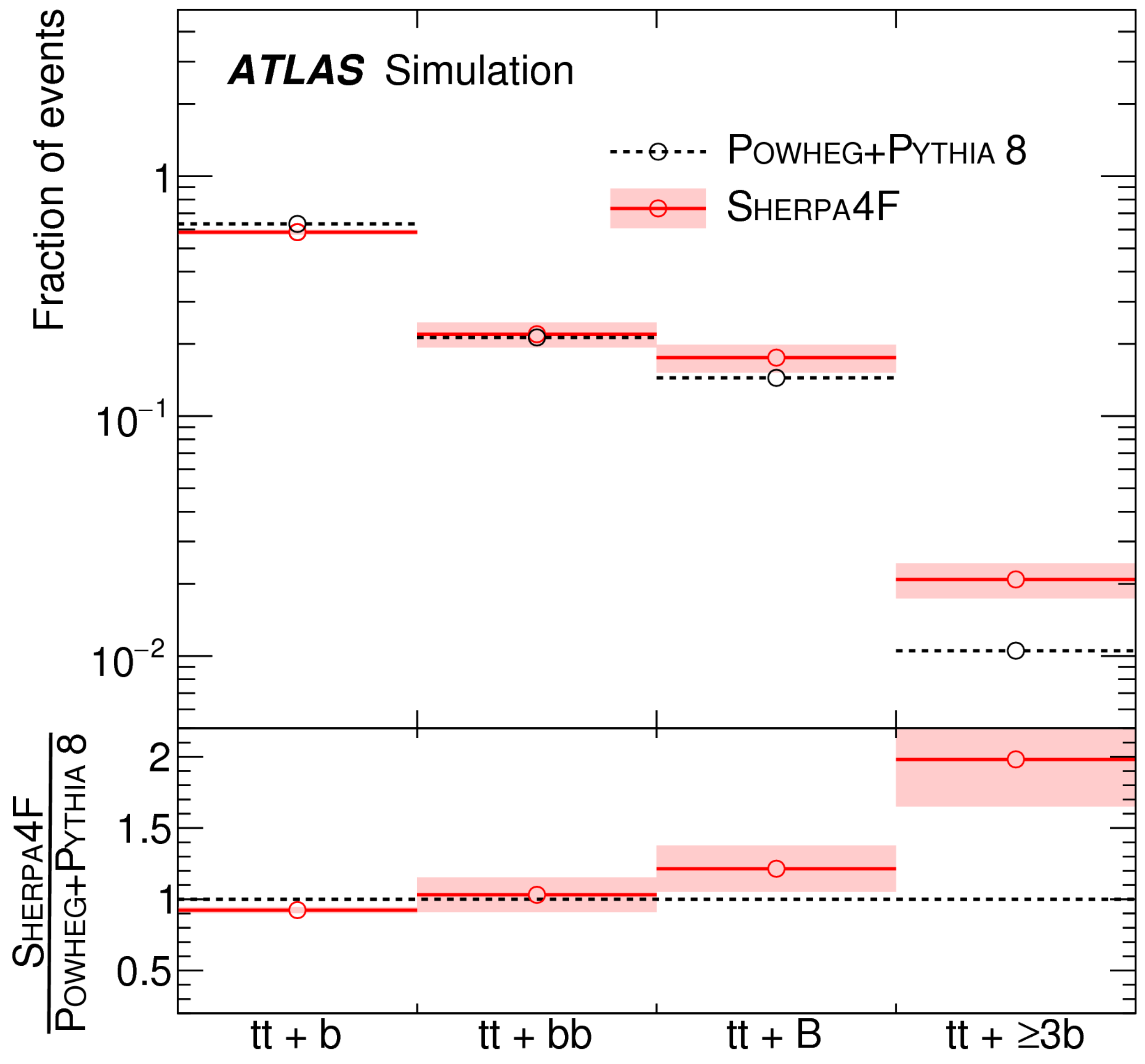


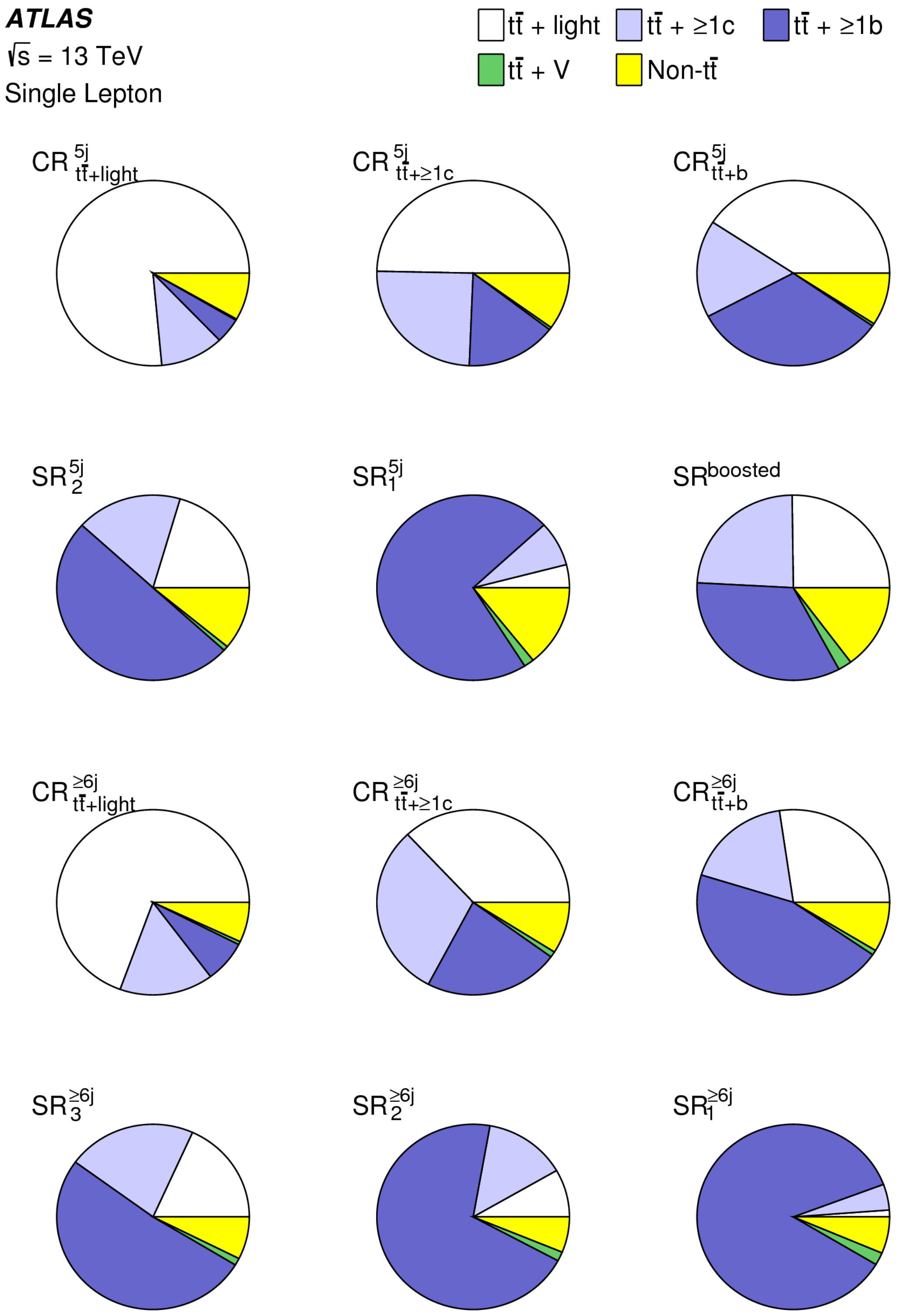
Higgs boson mass

ATLAS-CONF-2017-046



$t\bar{t}H$ ($H\to b\bar{b}$): $t\bar{t}$ modelling



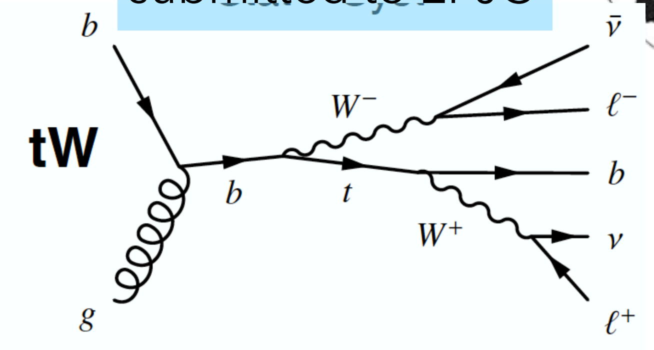


Wt differential cross section

arXiv:1712.01602

submitted to EPJC

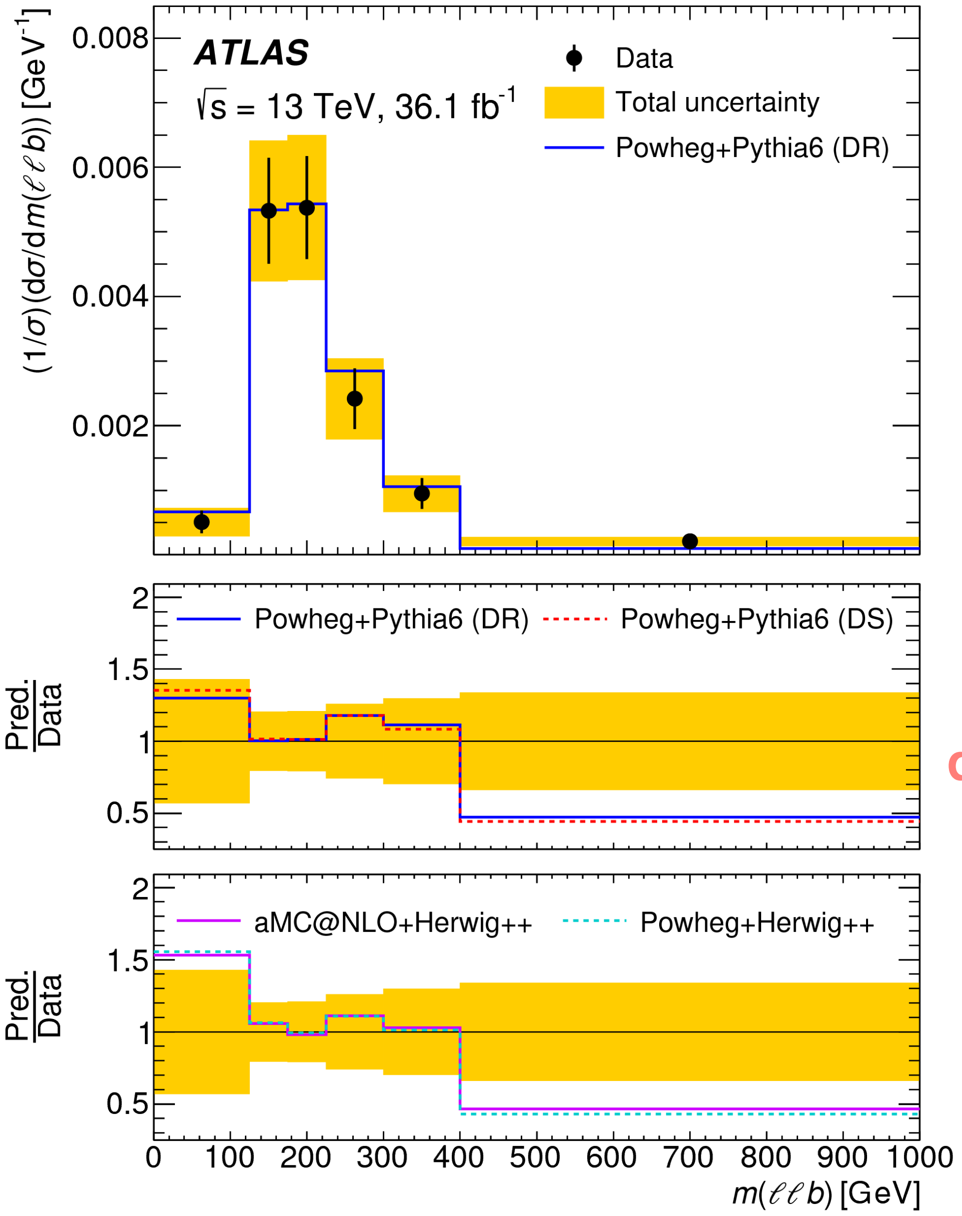
- **First**, evidence for single top quark production at LHC in t-channel (a), s-channel (b) and Wt-associated (c) production



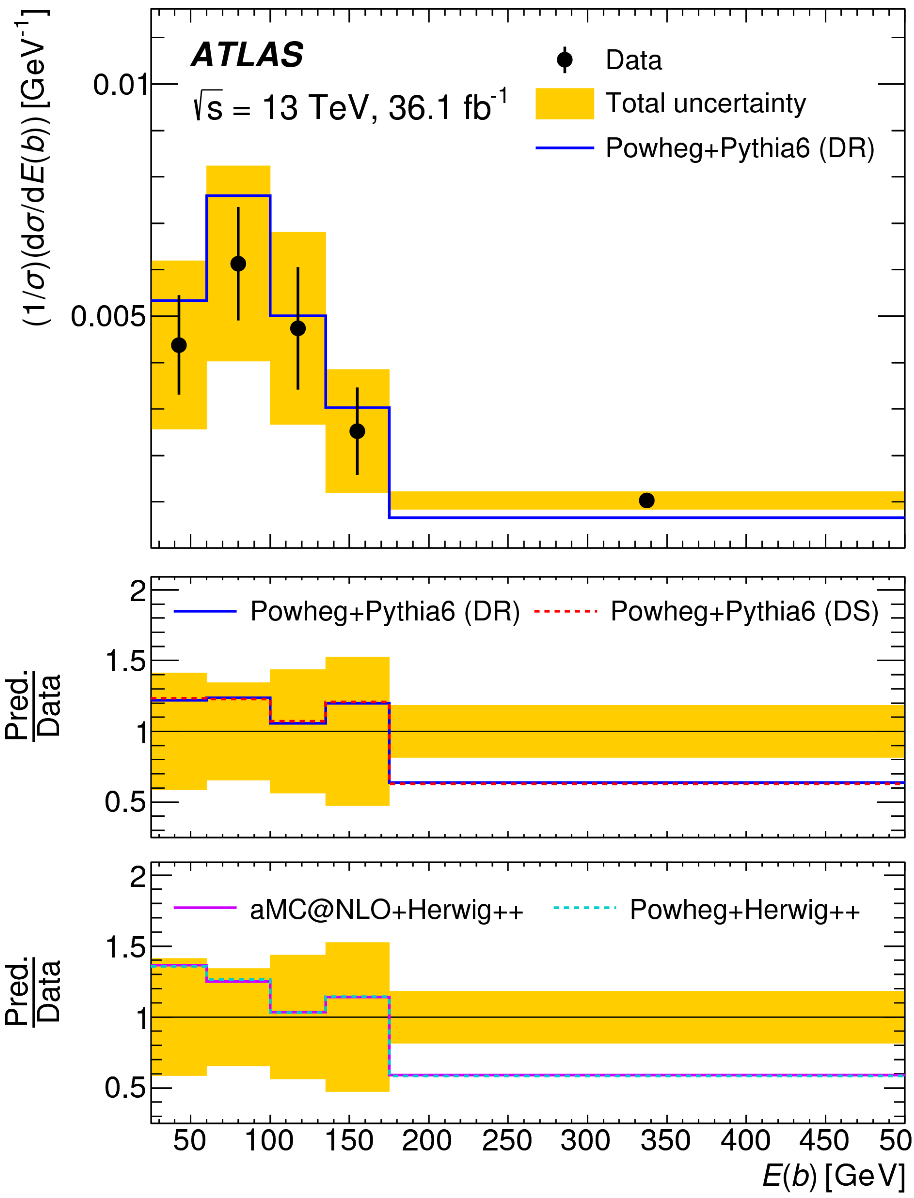
dilepton final state

- Now, also **differential cross section** of Wt for several particle-level observables

m(ℓℓb): probe Wt system



E(b): probe top production



Particle level vs NLO+PS

Measurement consistent with predictions

DR (Diagram Removal)
DS (Diagram Subtraction)
different treatment of Wt-$t\bar{t}$ interference

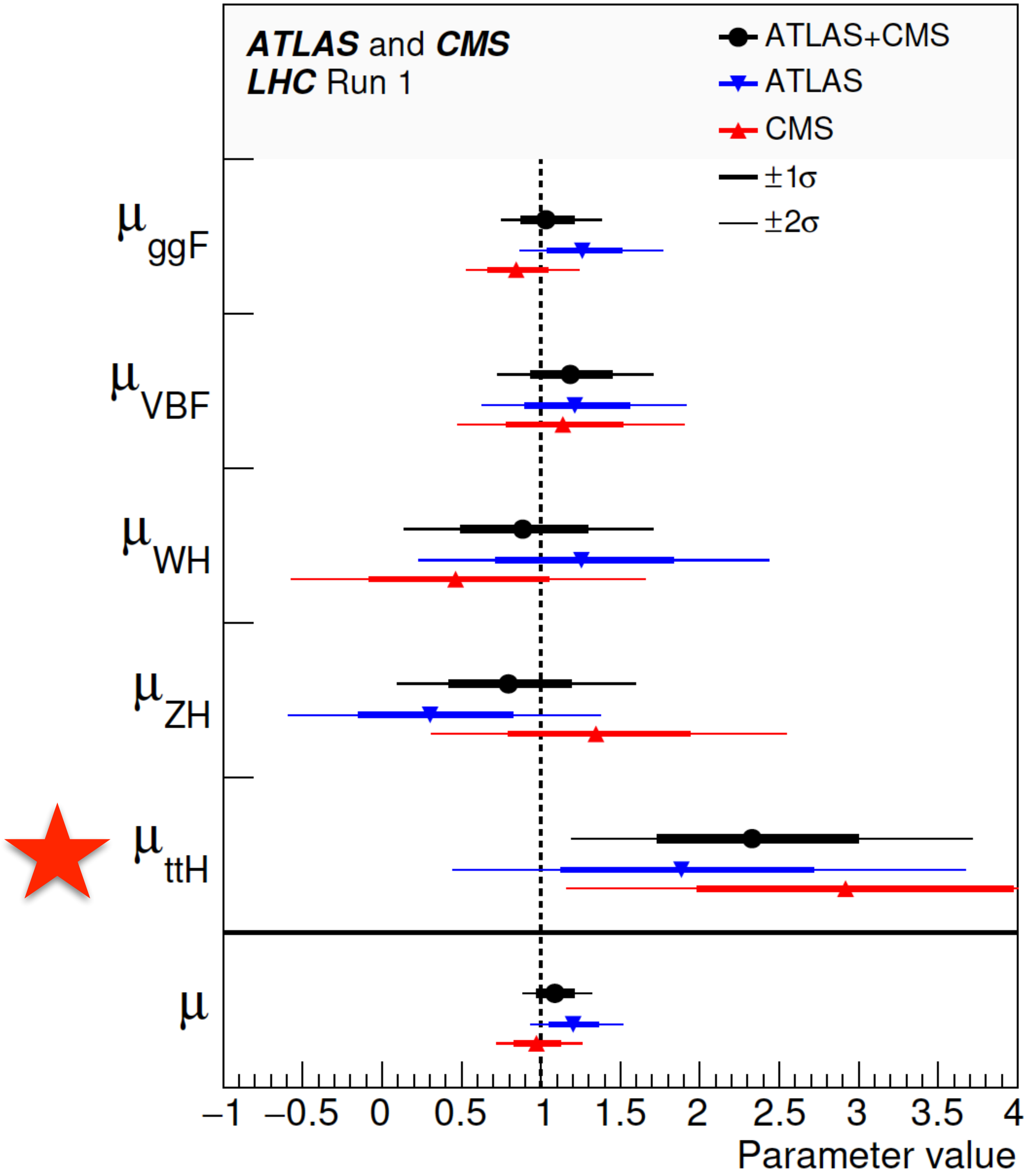
different matrix element generator

$t\bar{t}H$ interest: from Run-1 to Run-2

- Run-1 ATLAS+CMS Higgs combination:
  - $t\bar{t}H$ significance of 4.4 σ (2.0 σ expected)
- Excess in both ATLAS and CMS $\mu_{t\bar{t}H} = \sigma/\sigma_{SM}$
  - Originating from $t\bar{t}H$ multilepton analyses

- Big leap **(x4)** for $t\bar{t}H$ SM cross section from 8 to 13 TeV (*) and **high statistics** of top quark samples collected by the LHC make this SM search **extremely interesting** to be studied in Run-2!

JHEP08(2016)045



(*) Other background contributions cross section do not increase as much, but different kinematics at higher energies!

Most recent $t\bar{t}H$ results

🟩 2015+2016 data [~36 fb^{-1}]

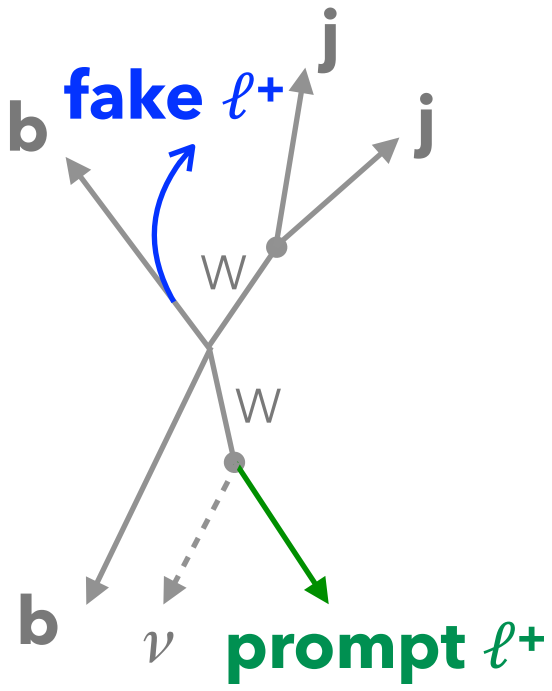
🟥 partial 2015+2016 data [~13 fb^{-1}]

	ATLAS EXPERIMENT	CMS
ttH multilepton ($H \rightarrow WW/\tau\tau/ZZ$)	🟩 ★ arXiv:1712.08891 submitted to PRD (including combination)	🟩 CMS-PAS-HIG-17-004 (ℓ only) 3.3σ (exp: 2.5σ) $\mu_{ttH} = 1.5 \pm 0.5$ CMS-PAS-HIG-17-003 (τ_{had}) 1.4σ (exp: 1.8σ) $\mu_{ttH} = 0.72\ ^{+0.62}_{-0.53}$
ttH(bb)	🟩 ★ arXiv:1712.08895 submitted to PRD	🟥 CMS-PAS-HIG-16-038 $\mu_{ttH} = -0.19 \pm 0.8$
ttH($ZZ \rightarrow 4\ell$)	🟩 arXiv:1712.02304 submitted to JHEP $\mu_{ttH} < 7.1$	🟩 arXiv:1706.09936 $\mu_{ttH} < 1.18$
ttH($\gamma\gamma$)	🟩 ATLAS-CONF-2017-045 1.0σ (exp: 1.8σ) $\mu_{ttH} = 0.5 \pm 0.6$	🟩 CMS-PAS-HIG-16-040 3.3σ (exp: 1.5σ) $\mu_{ttH} = 2.2\ ^{+0.9}_{-0.8}$
ATLAS+CMS Run1 combination	JHEP 1608 (2016) 045 4.4σ (exp: 2.0σ) $\mu_{ttH} = 2.3\ ^{+0.7}_{-0.6}$	

$t\bar{t}H$ (multileptons): non-prompt light ℓ (I)

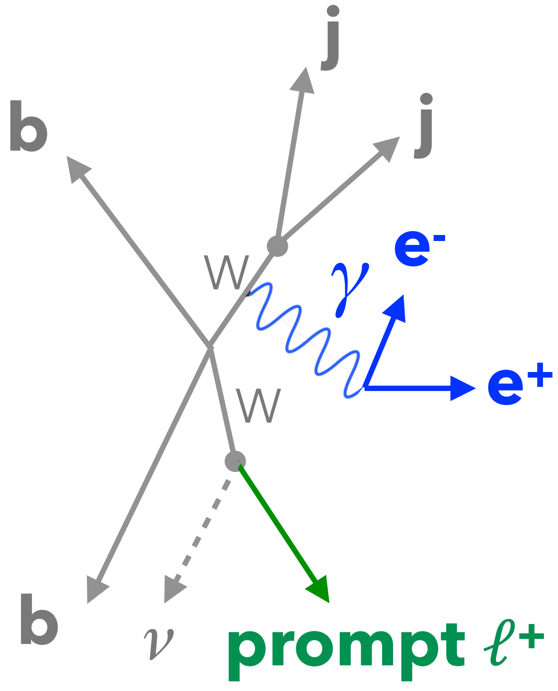
Method [parametr.]	$2\ell SS+0\tau$	$3\ell+0\tau$	4ℓ	$2\ell SS+1\tau$	Other τ channels
Non-prompt lepton	**DD (MM)** el: [p_T, NBjets] μ: [p_T, dR(μ,j)]		**pseudo-DD** **(Fake SF)**	**DD (FF)** el/μ: [p_T]	**MC** (very small)

Semileptonic b-decay



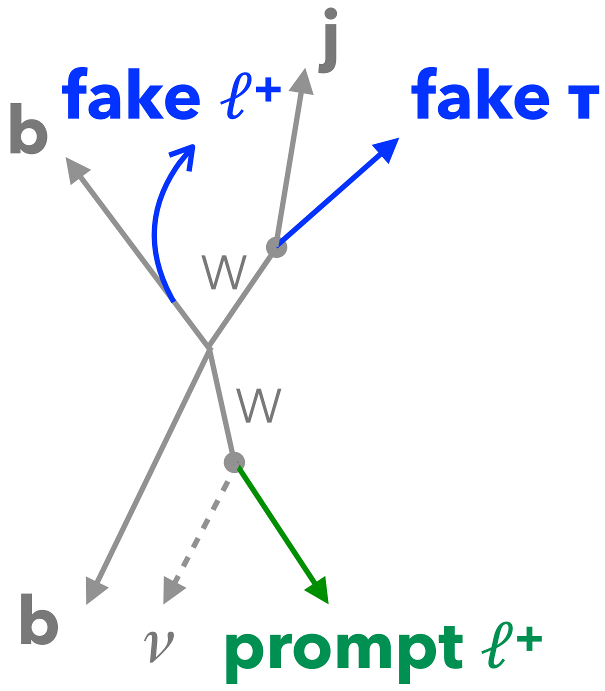
strongly reduced with PLI

Photon conversions



50% of the "fakes" in 3ℓ!

Non-prompt lepton & fake τ

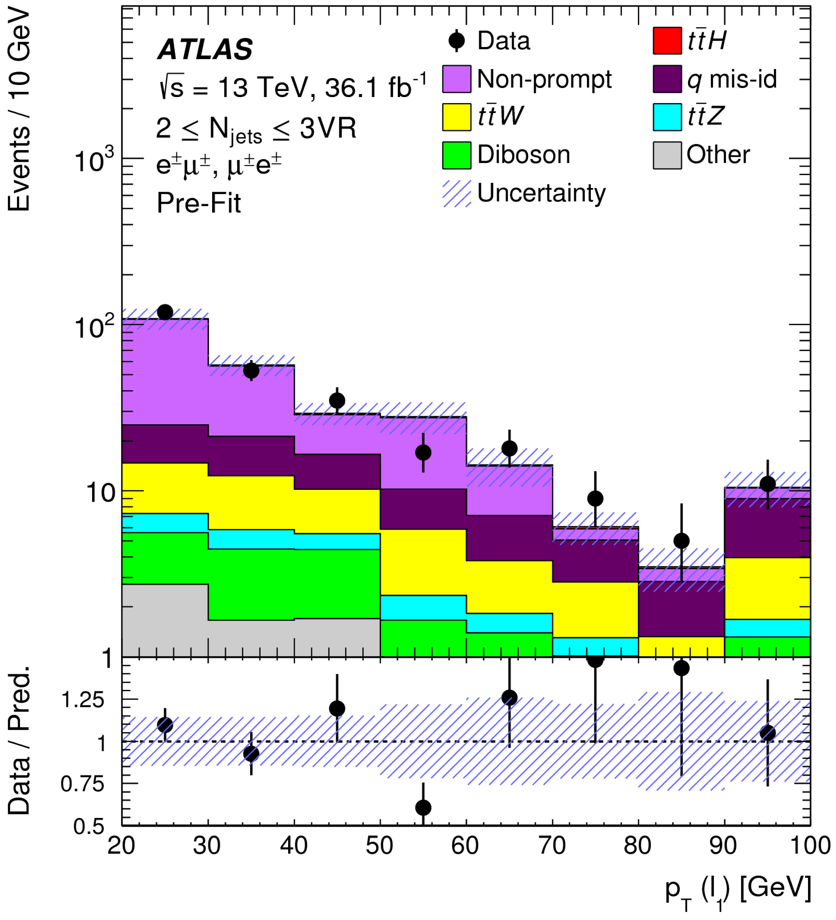


70% from $t\bar{t}$ in $2\ell SS+1\tau$

$t\bar{t}H$ (multileptons): fakes/non-prompt ℓ validation

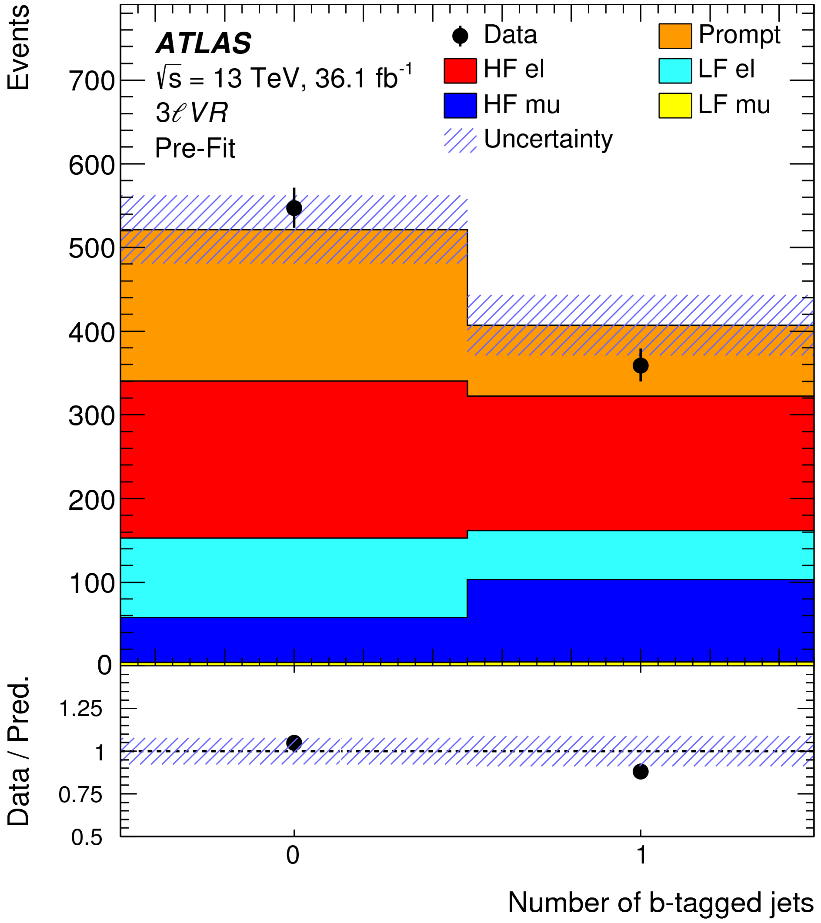
- Overall **reasonable data/prediction agreement** with estimates fakes in VRs

“Low N_{jets}”
$2 \leq N_{jets} \leq 3$, $N_{jets} \geq 1$



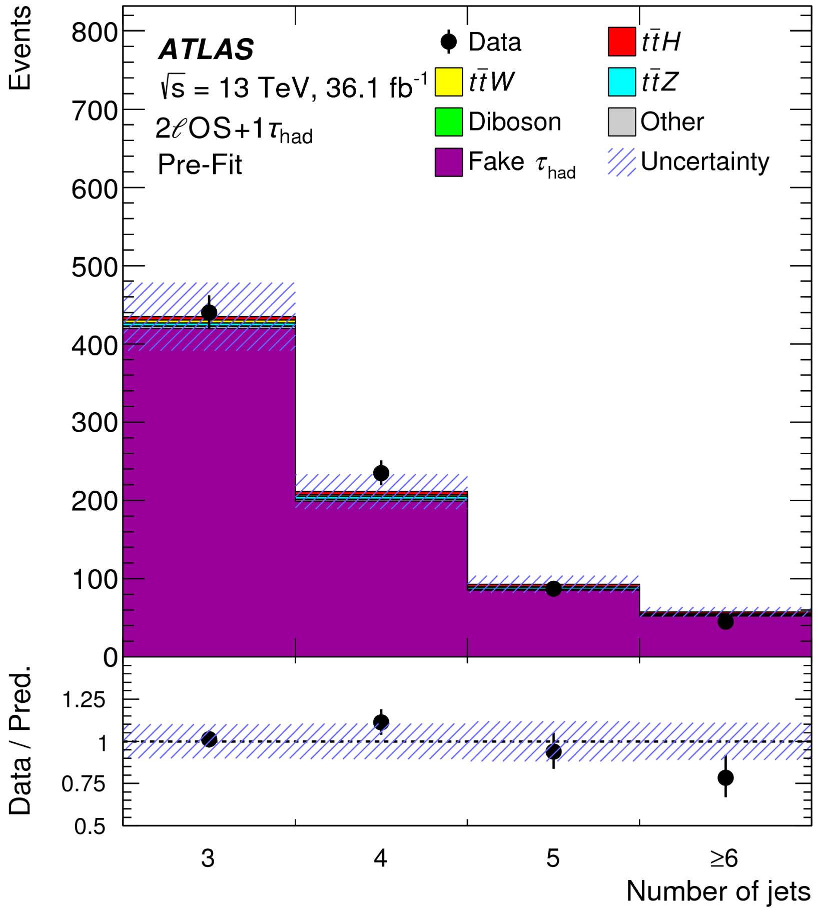
$2\ell SS+0\tau$
fake ℓ

“3 loose light ℓ”
$N_{jets} \geq 3$



4ℓ
fake ℓ

“Pre-selection”
$N_{jets} \geq 3$

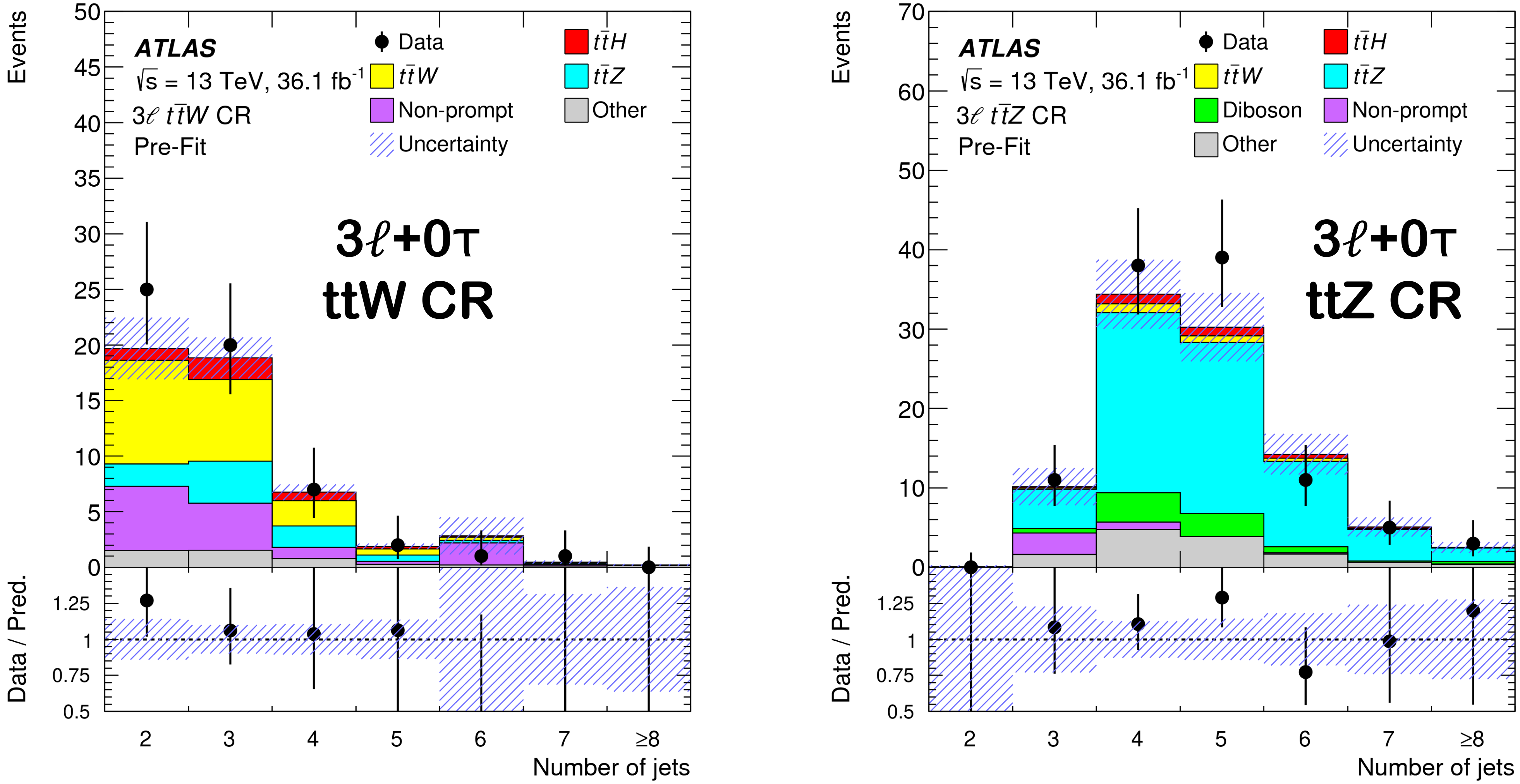


$2\ell OS+1\tau$
fake τ

arXiv:1712.08891 submitted to PRD

$t\bar{t}H$ (multileptons): prompt ℓ background validation

- Largest irreducible backgrounds: **$t\bar{t}W$, $t\bar{t}Z$, diboson**
- Estimated using **NLO MC samples**, with theory/modelling uncertainties:
  - Cross-section uncertainties
  - Scale variations
  - Generator comparisons
- Validated in several regions, eg: 3ℓ $t\bar{t}W/Z$ CRs built using the multinomial BDT
- Overall **good data/prediction agreement** in $t\bar{t}V$-enriched CRs using MC simulation
  - Also good agreement in cut-based VRs



$t\bar{t}H$ (multileptons): profile likelihood fit

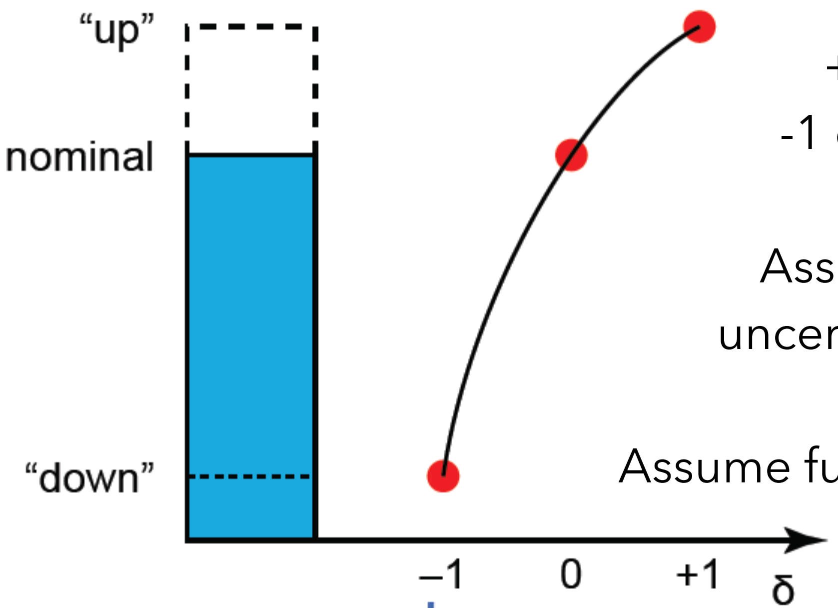
- Binned profile likelihood fit

$$L(\mu,\theta) = L_{Pois}(\mu,\theta)\cdot\prod_{p}\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{\theta_p^2}{2}\right)$$

- **Parameter of interest**: signal strength

$$\mu_{t\bar{t}H} = \frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}}$$

- **Systematic uncertainties** included in the fit as nuisance parameters θ
  - Need sufficiently flexible model of signal and background!



Given:
+1σ, nominal, and
-1 σ of each systematic

Assume interpolation of
uncertainty between [-1,1] σ

Assume full correlation between bins

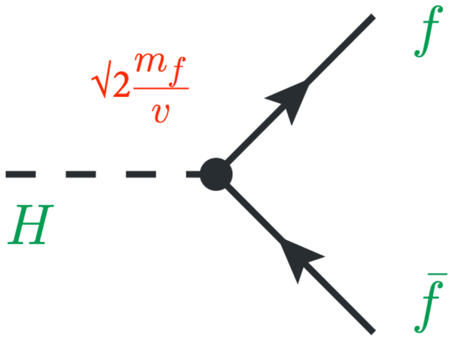
Constrain uncertainty in control region, propagate this knowledge to signal region

- Find best values for μ and θ from minimising the -log L
- Calculate experimental sensitivity in terms of the significance
  - Quantify level of disagreement between data and background-only hypothesis as Gaussian standard deviations (σ)

Top Yukawa coupling… why should we care?

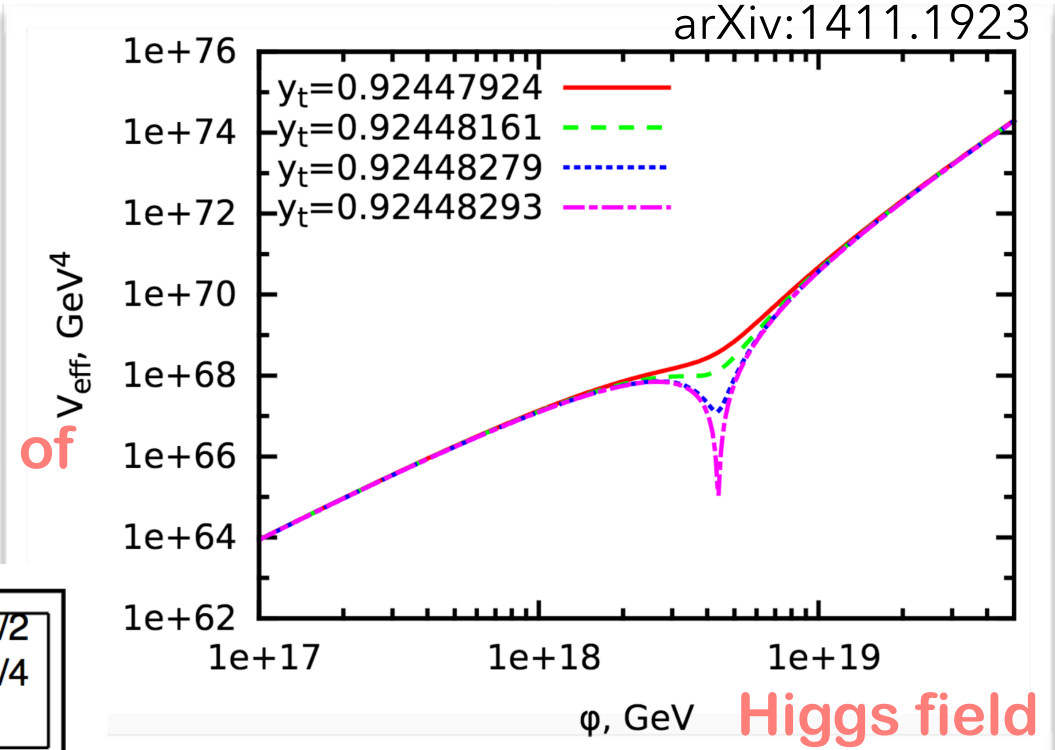
- The only fermion with such a natural coupling
- Does this point to a special role in electroweak symmetry breaking or beyond the SM physics?
- Top quark Yukawa coupling tells us about the stability of Universe and the required energy scale for new physics

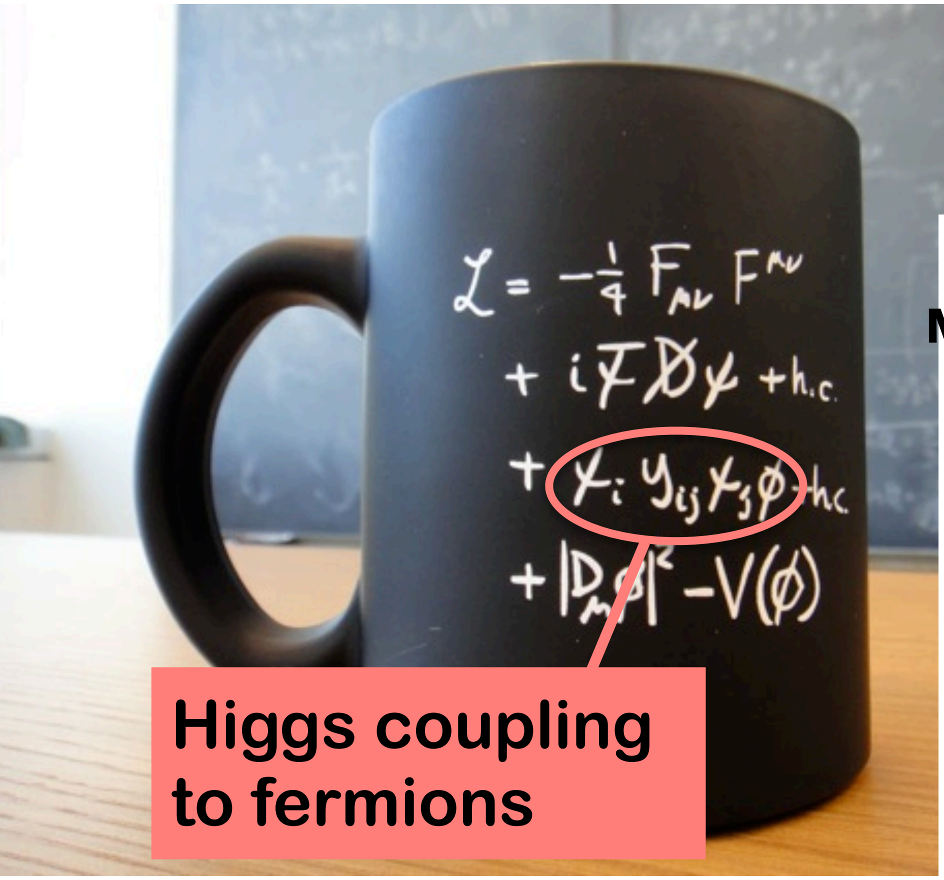
Top quark is the heaviest fermion in the SM ➜
Largest Yukawa coupling



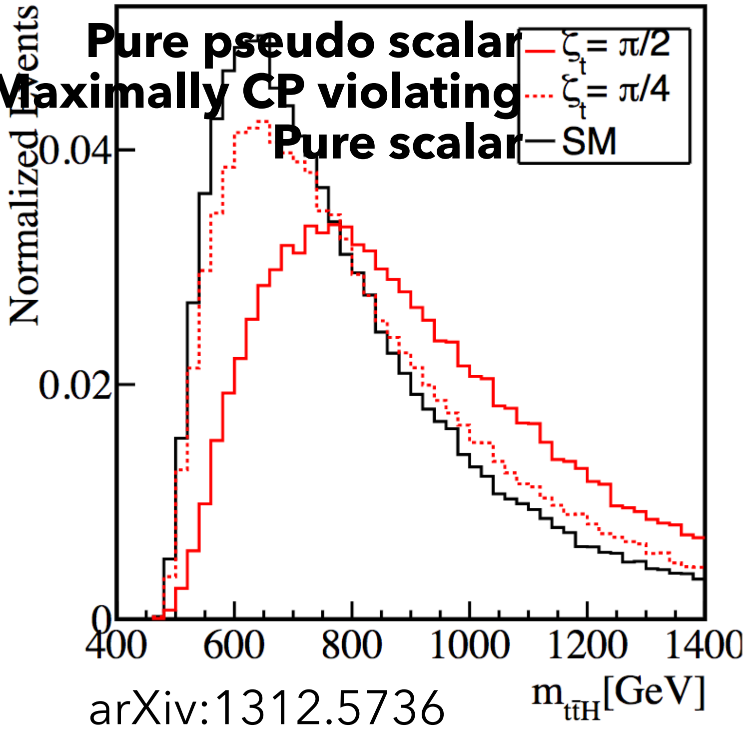
Is the Universe stable or only metastable?

effective potential of the Higgs field





Higgs coupling to fermions



arXiv:1312.5736

What is the CP nature of the Higgs boson?

- A CP admixture is still allowed
- Maybe tt̄H production can help us disentangle the BSM component