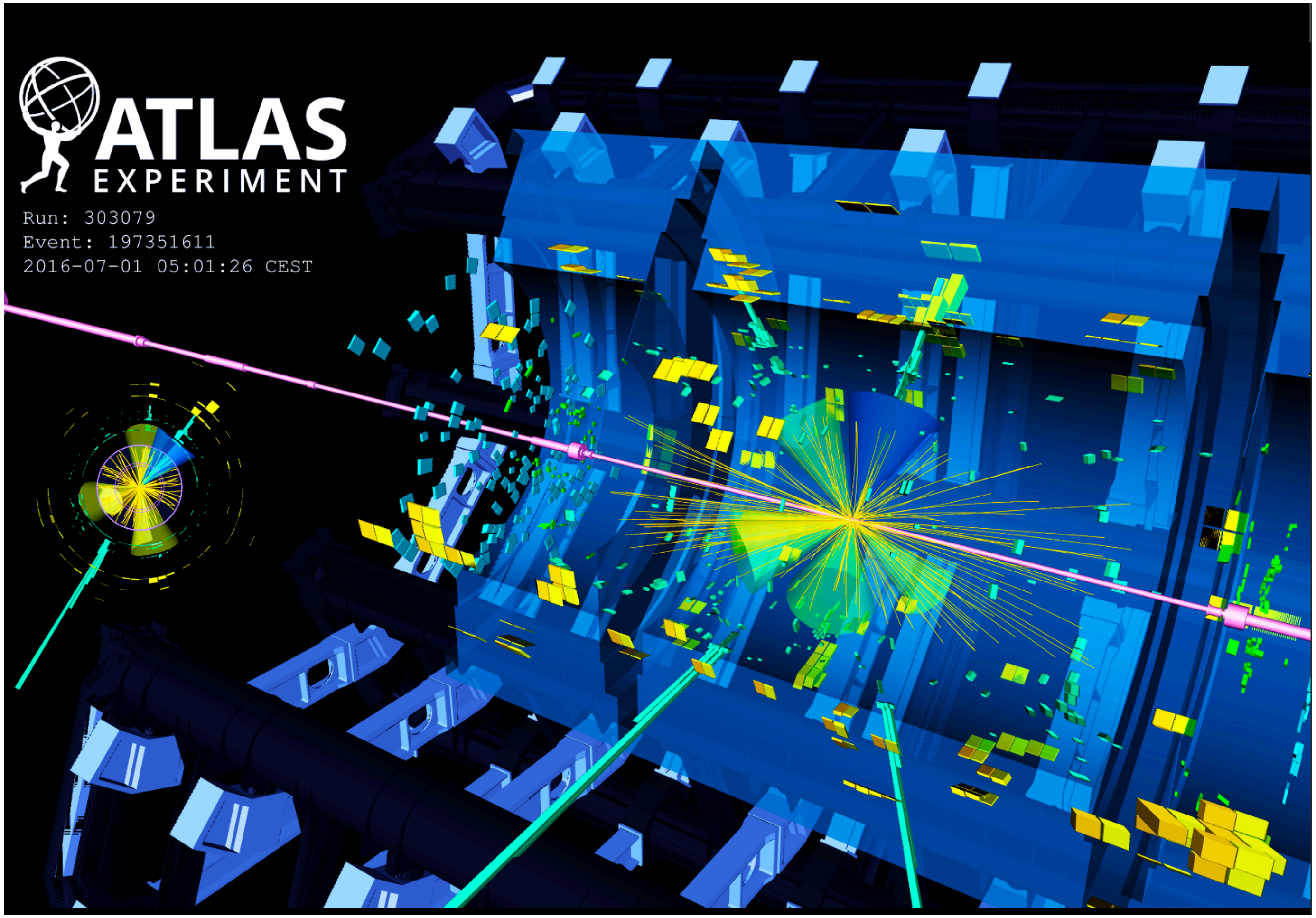
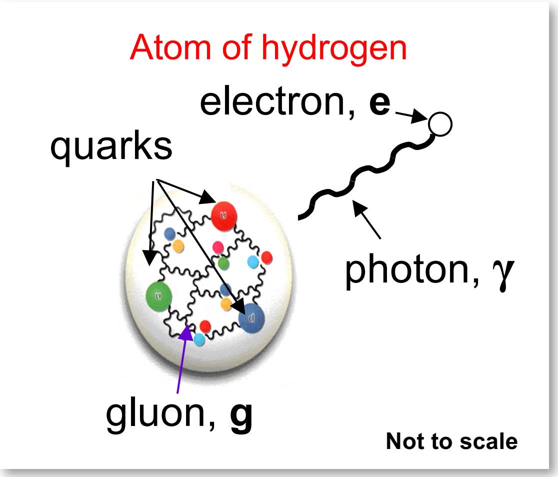
Measurement of top quark pair production in association with a Higgs ~~or Gauge~~ boson at the LHC with the ATLAS detector

Content

- The Standard Model of Particle Physics
- The Large Hadron Collider and the ATLAS detector
- Physics results: coupling of the top quark to Higgs boson
- Perspectives



The Standard Model of Particle Physics



Elementary particles cannot be broken down

Truly point like particles

* the basic constituents of **matter** (three families)

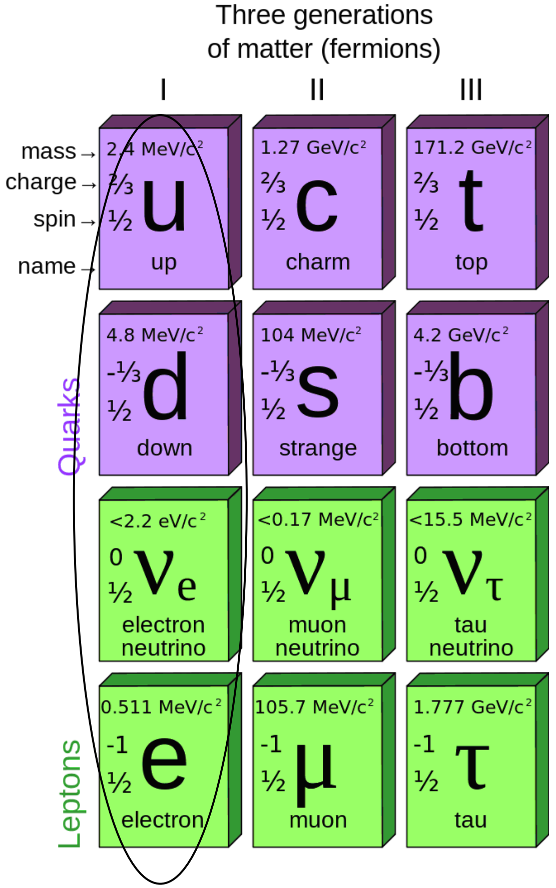
Fermions (spin 1/2 particles):

Quarks

- electric charge 2/3 or -1/3
- three colours
- cannot be found isolated in nature, must exist as **hadrons**

Leptons

- neutrinos, **electrically neutral**
- **charged leptons**, -1



Three generations of matter (fermions)

mass →
charge →
spin →
name →

	I	II	III
Quarks	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top
	4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom
Leptons	<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino
	0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau

Ordinary matter: what we are made of

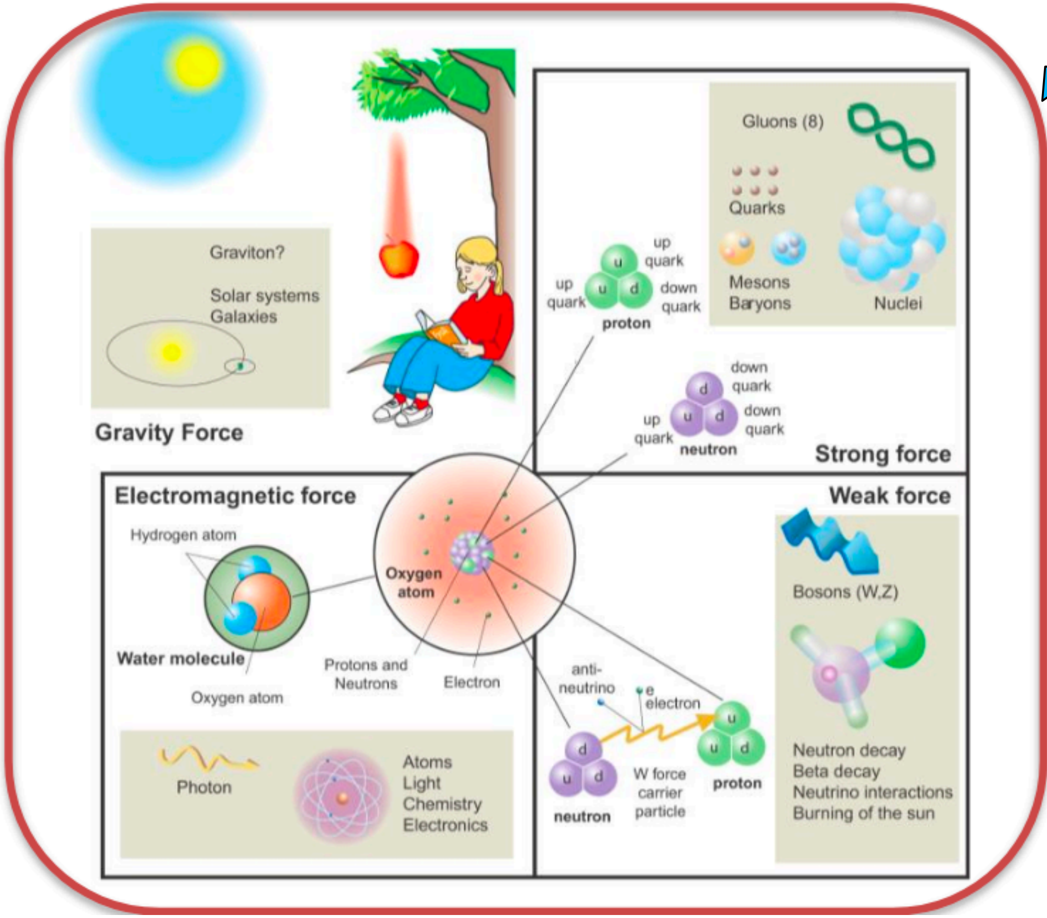
The Standard Model of Particle Physics

Elementary particles cannot be broken down

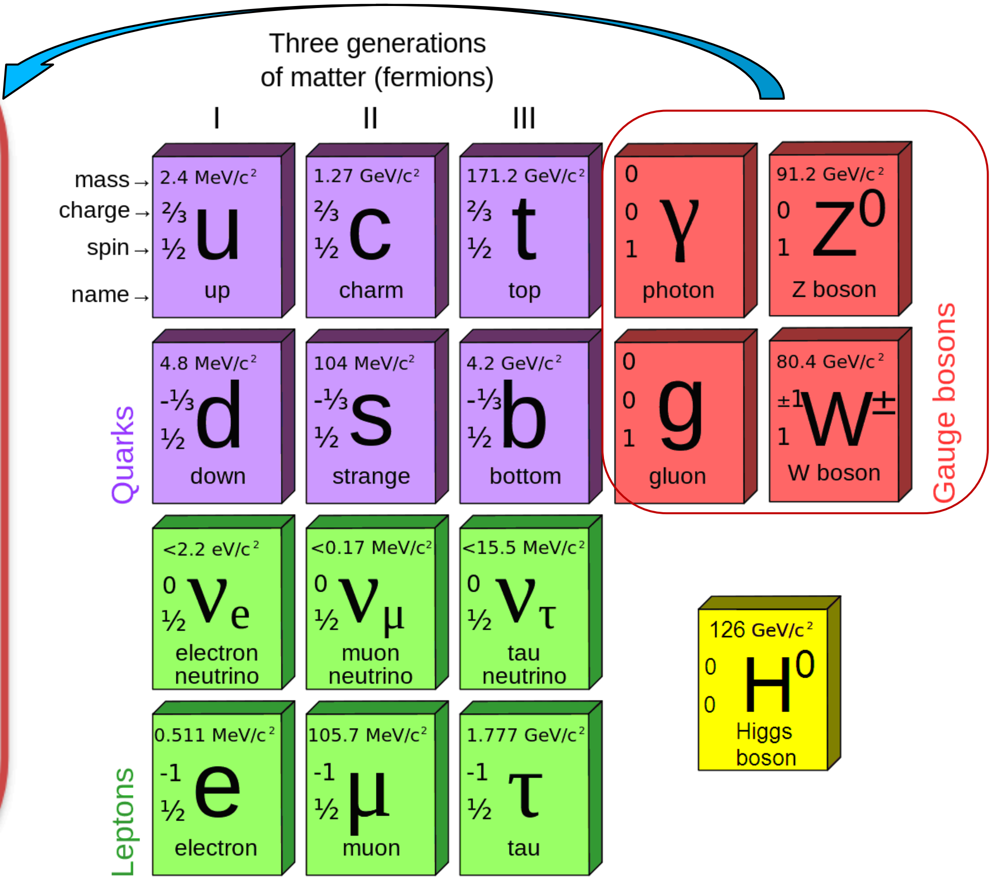
Truly point like particles

* the basic constituents of **matter** (three families)

* the **force carriers** of the fundamental interactions



Four forces govern our life



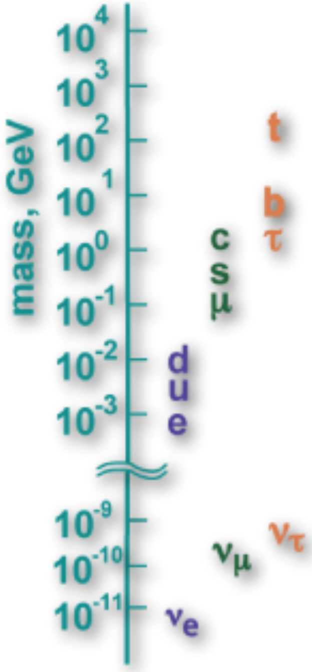
	I	II	III		
Quarks	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon	91.2 GeV/c^2 0 1 Z^0 Z boson
	4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon	80.4 GeV/c^2 ±1 1 $W^\pm$ W boson
Leptons	<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino		126 GeV/c^2 0 0 H^0 Higgs boson
	0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau		

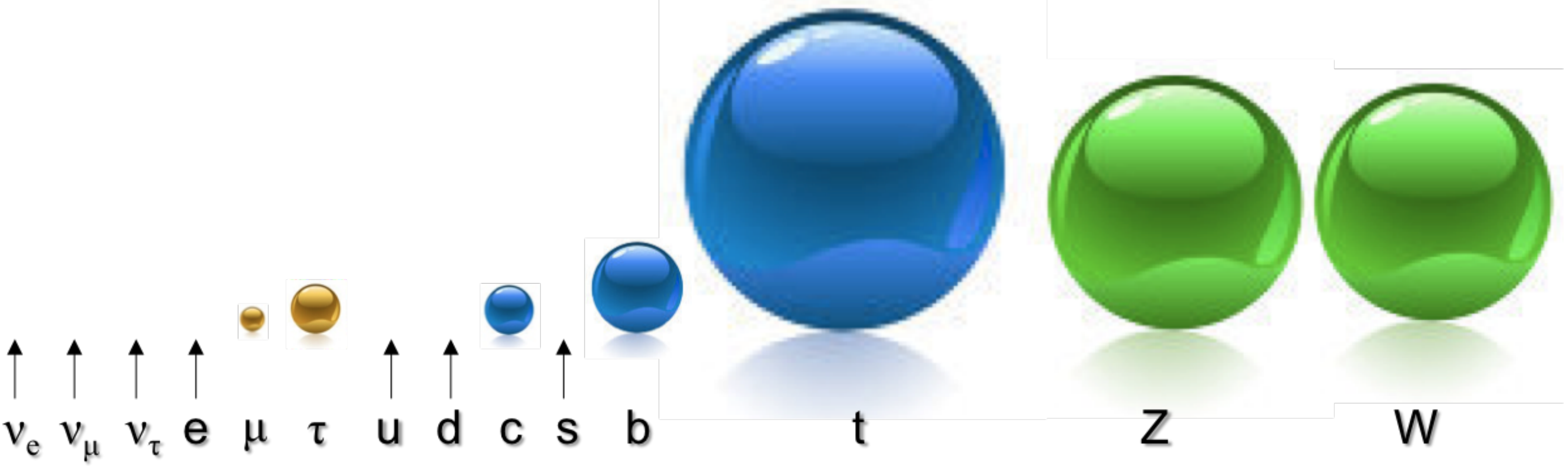
And the newly found Higgs to give us mass!

What is the origin of particle masses ?

In the Standard Model, elementary particles acquire mass via their interaction with the Higgs field.

Is there a specific particle that sticks out?





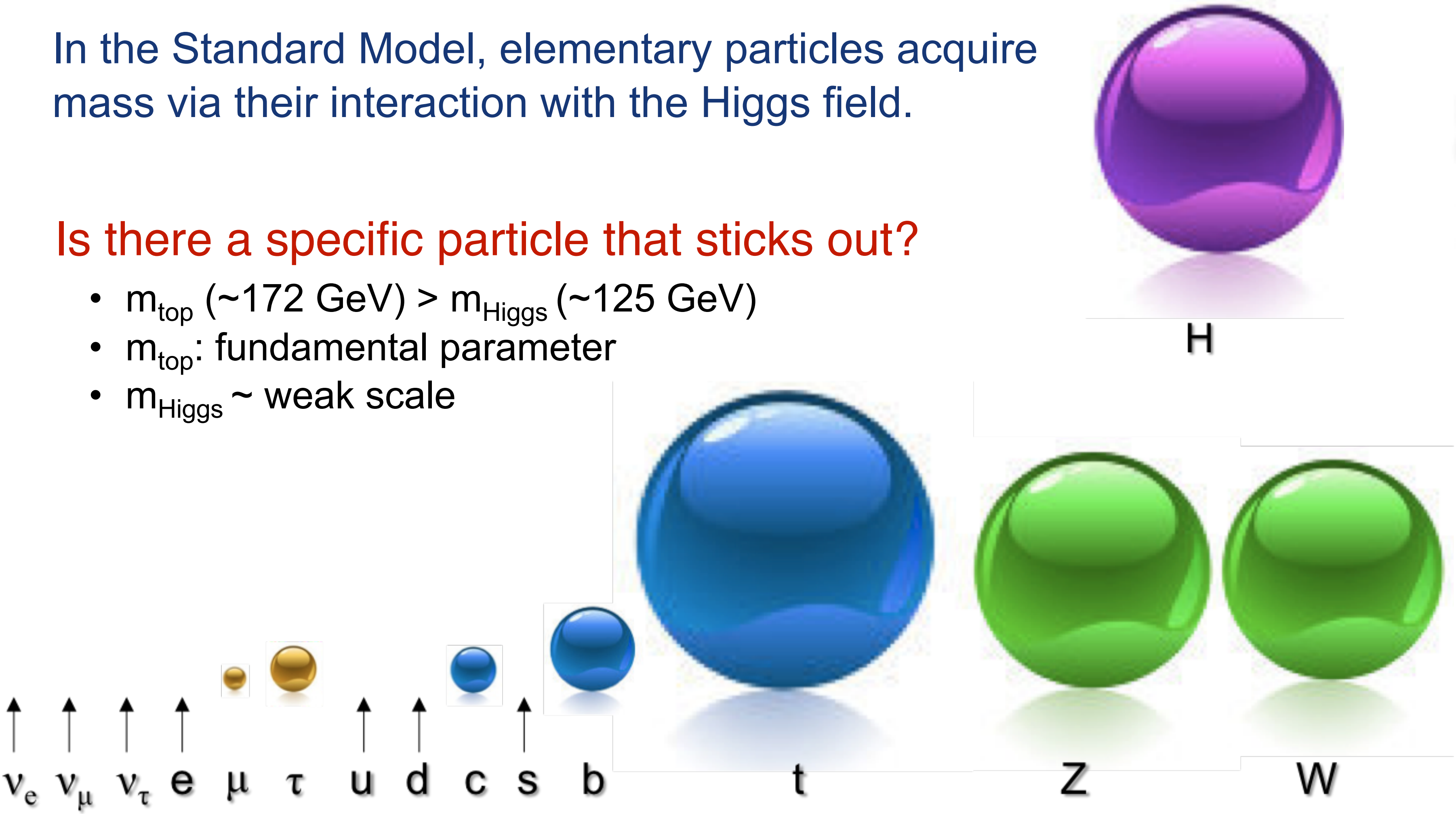
Volume of sphere proportional to particle mass

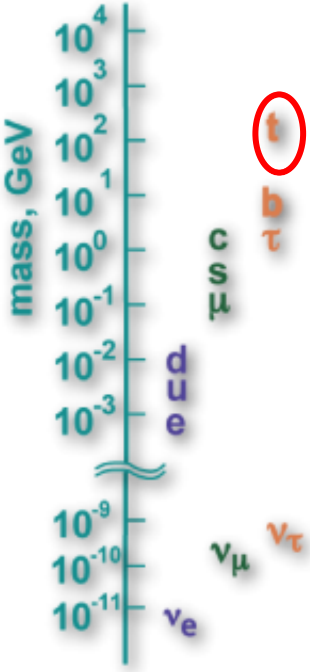
Top quark is special

In the Standard Model, elementary particles acquire mass via their interaction with the Higgs field.

Is there a specific particle that sticks out?

- m_{top} (~172 GeV) > m_{Higgs} (~125 GeV)
- m_{top}: fundamental parameter
- m_{Higgs} ~ weak scale





Volume of sphere proportional to particle mass

Top quarks

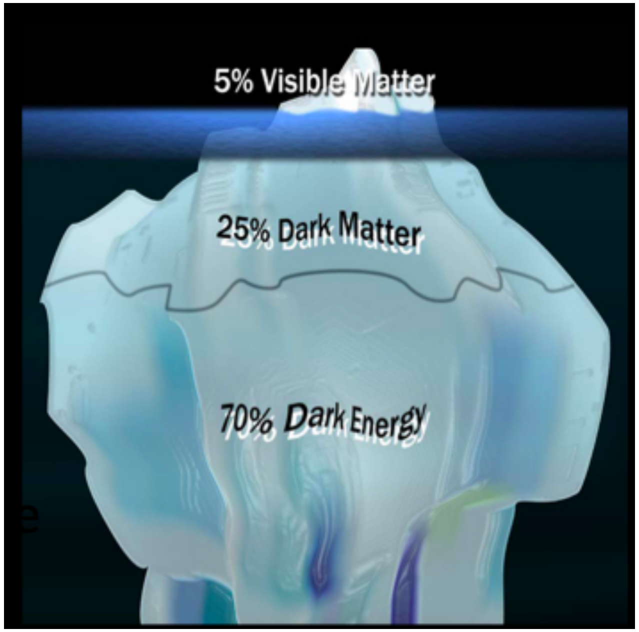
are crucial to pin down the Standard Model nature of the Higgs

can play an important role in the observations related to the electroweak symmetry breaking

The Standard Model does not explain the complete picture

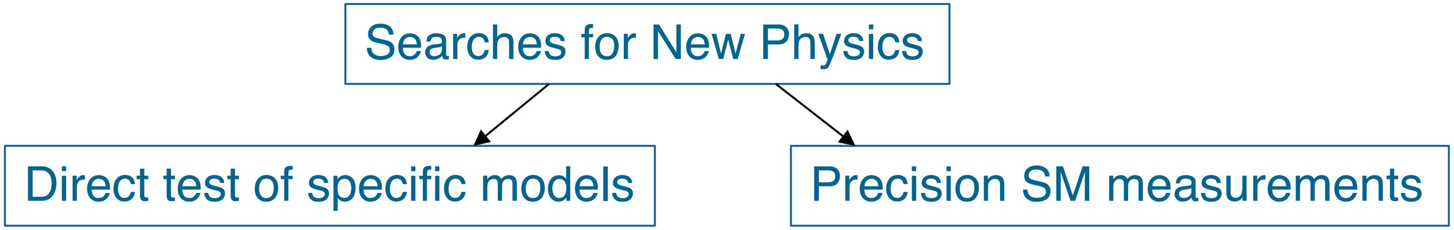
- Despite the SM success, several questions remain unanswered

✗ the nature of dark matter and dark energy
✗ the hierarchy problem: Higgs boson mass (~weak scale) much lighter than the Planck mass
✗ why only three families of elementary particles ?
✗ the non-zero neutrino masses
✗ the matter/antimatter imbalance in the Universe
✗ gravitation is missing in such theoretical scheme, …



… we just know the tip of the iceberg

- Extensive search for possible SM extensions, but not signs of New Physics yet



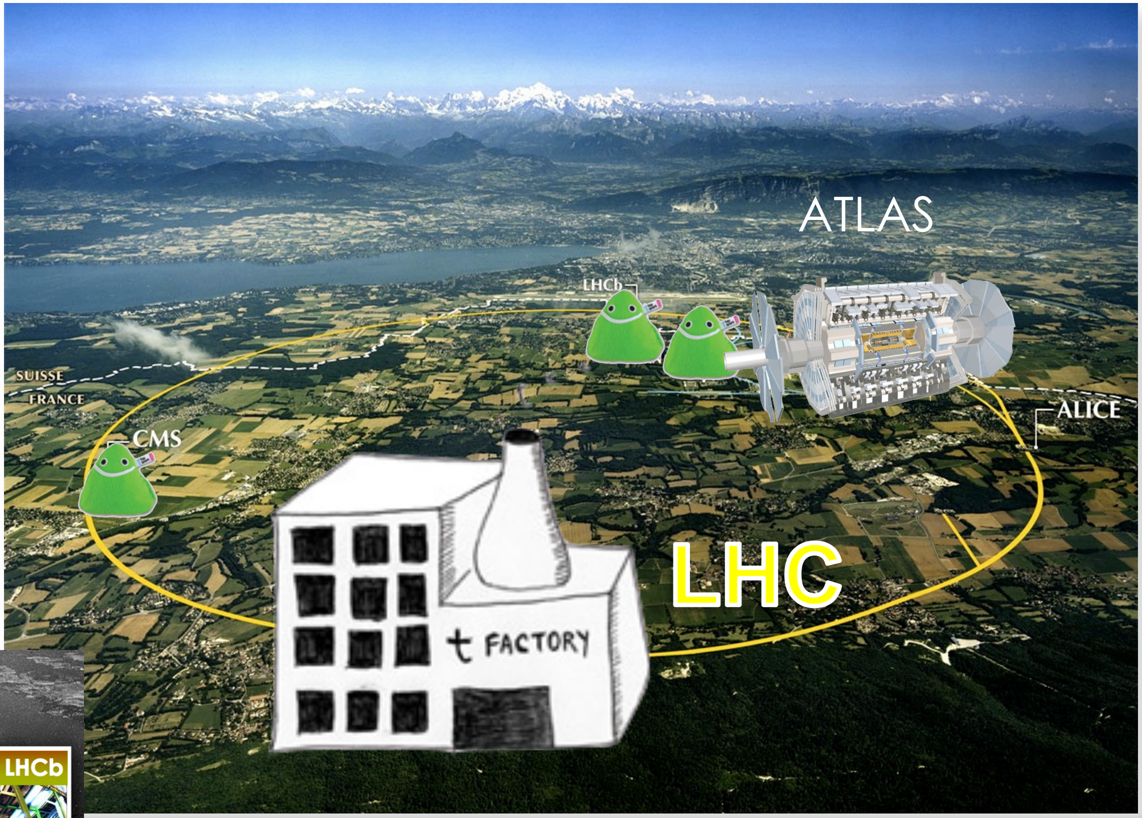
Searches for New Physics

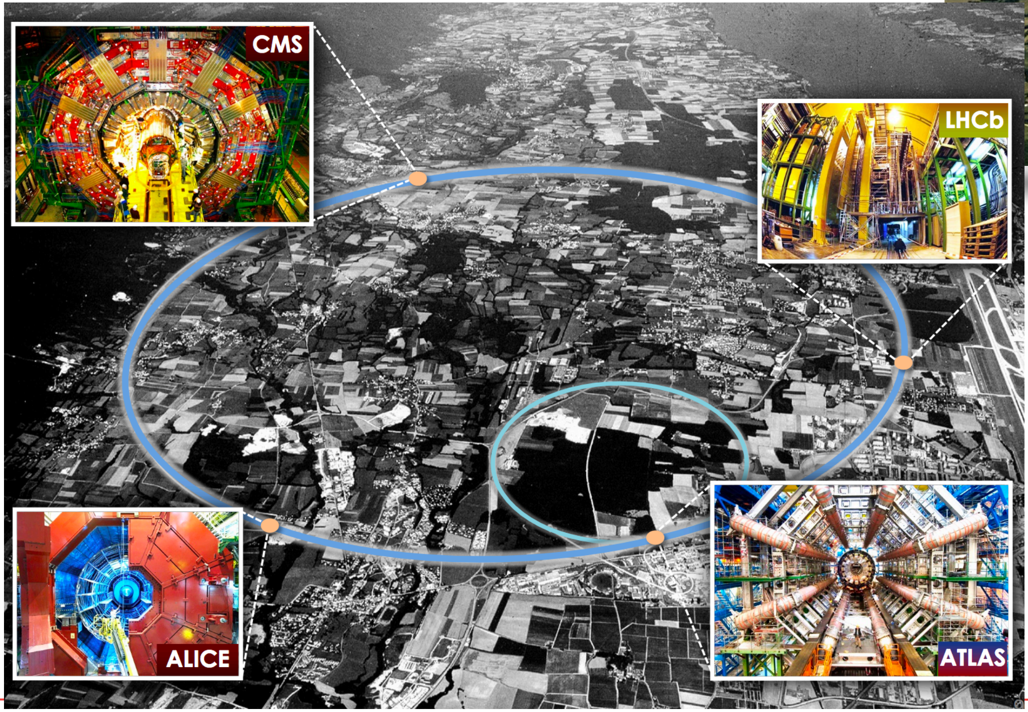
Direct test of specific models

Precision SM measurements

The Large Hadron Collider: factory of top quarks and more

Inelastic proton-proton reactions	10^9 / s
bb pairs	5 10^6 / s
tt pairs	8 / s
W $\rightarrow$ e ν	150 / s
Z $\rightarrow$ e e	15 / s
Higgs	0.5 / s
Gluino, Squarks (1 TeV)	0.03 / s





Run-I phase (2010-2012)

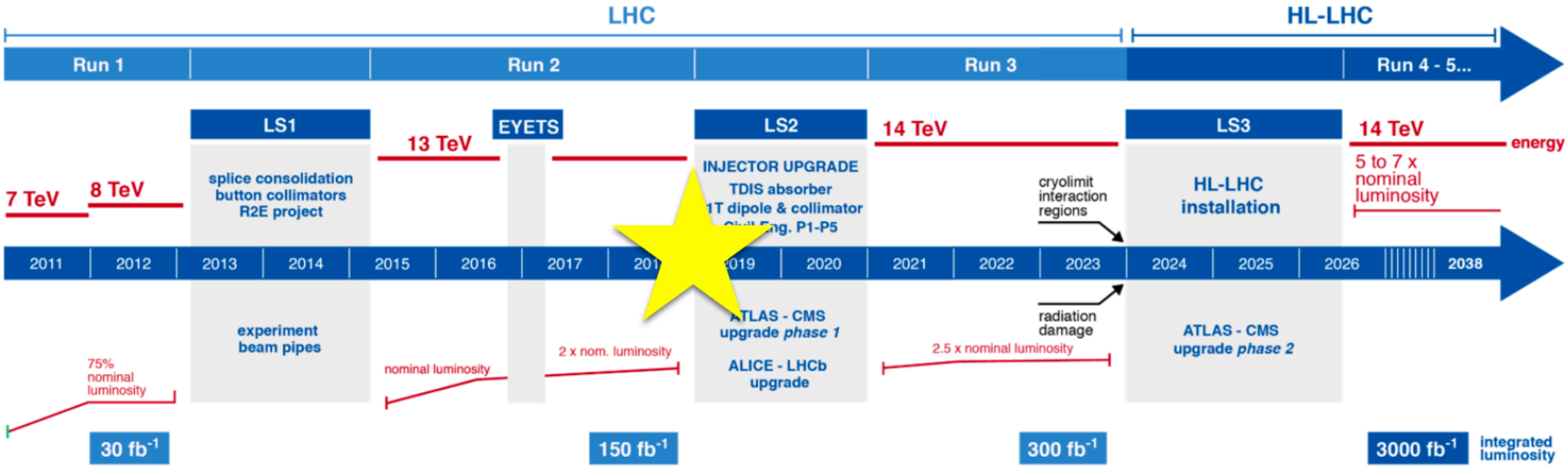
$\sqrt{s}$ = 7 TeV, L~5 fb^{-1}

$\sqrt{s}$ = 8 TeV, L~21 fb^{-1}

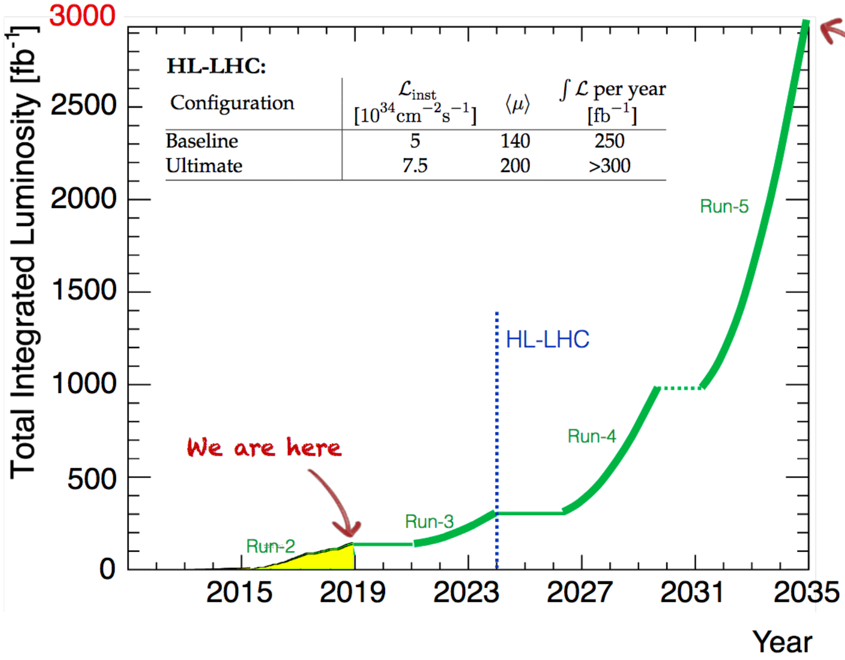
Run-II phase (2015-2018)

$\sqrt{s}$ = 13 TeV, L~140 fb^{-1} !!!!!

Only 4% of data collected so far at the LHC



past ⟵ **present** - - - - - - → **future**



HL-LHC:

Configuration	$\mathcal{L}_{\text{inst}}$ $[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	$\langle\mu\rangle$	$\int\mathcal{L}$ per year $[\text{fb}^{-1}]$
Baseline	5	140	250
Ultimate	7.5	200	>300

We will be going here

Possibly up to 4 ab^{-1}

$\sqrt{s}=14$ TeV

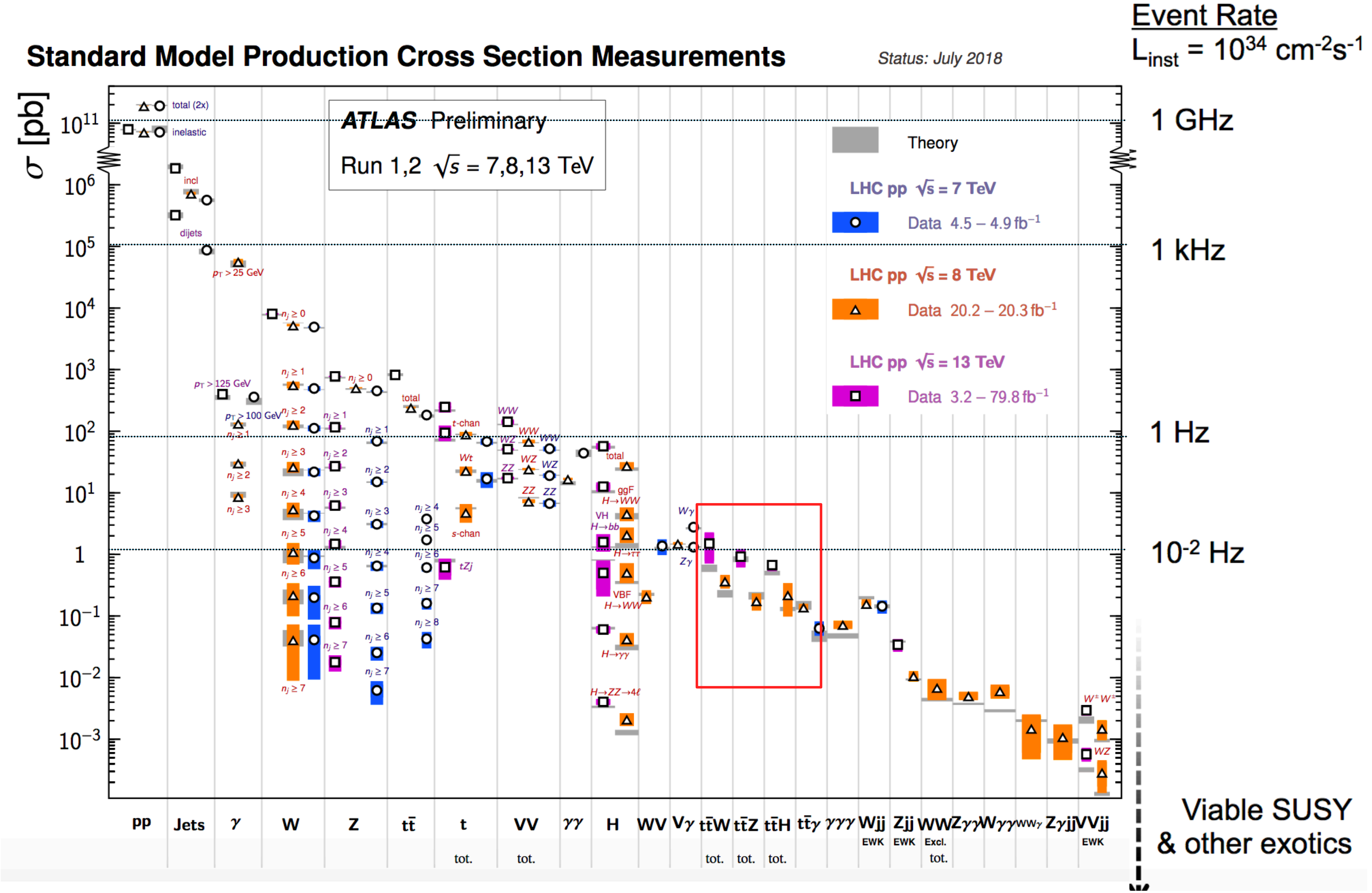
$3\ ab^{-1}$

$\sigma_{t\bar{t}}$	~ 1 nb	→	3B top pairs
$\sigma_{\text{t-channel}}$	~ 200 pb	→	600M tops
σ_{tW}	~ 75 pb	→	200M tops
$\sigma_{\text{s-channel}}$	~ 10 pb	→	30M tops
$\sigma_{tt\gamma/V/H}$	~ 1 pb	→	3M top pairs
σ_{tZ}	~ 100 fb	→	300k tops
σ_{tH}	~ 10 fb	→	30k tops

Reaching tt+X tiny signals

tt+X(W,Z,H) ~18-30 events/h

Very complex analysis with several final state objects.

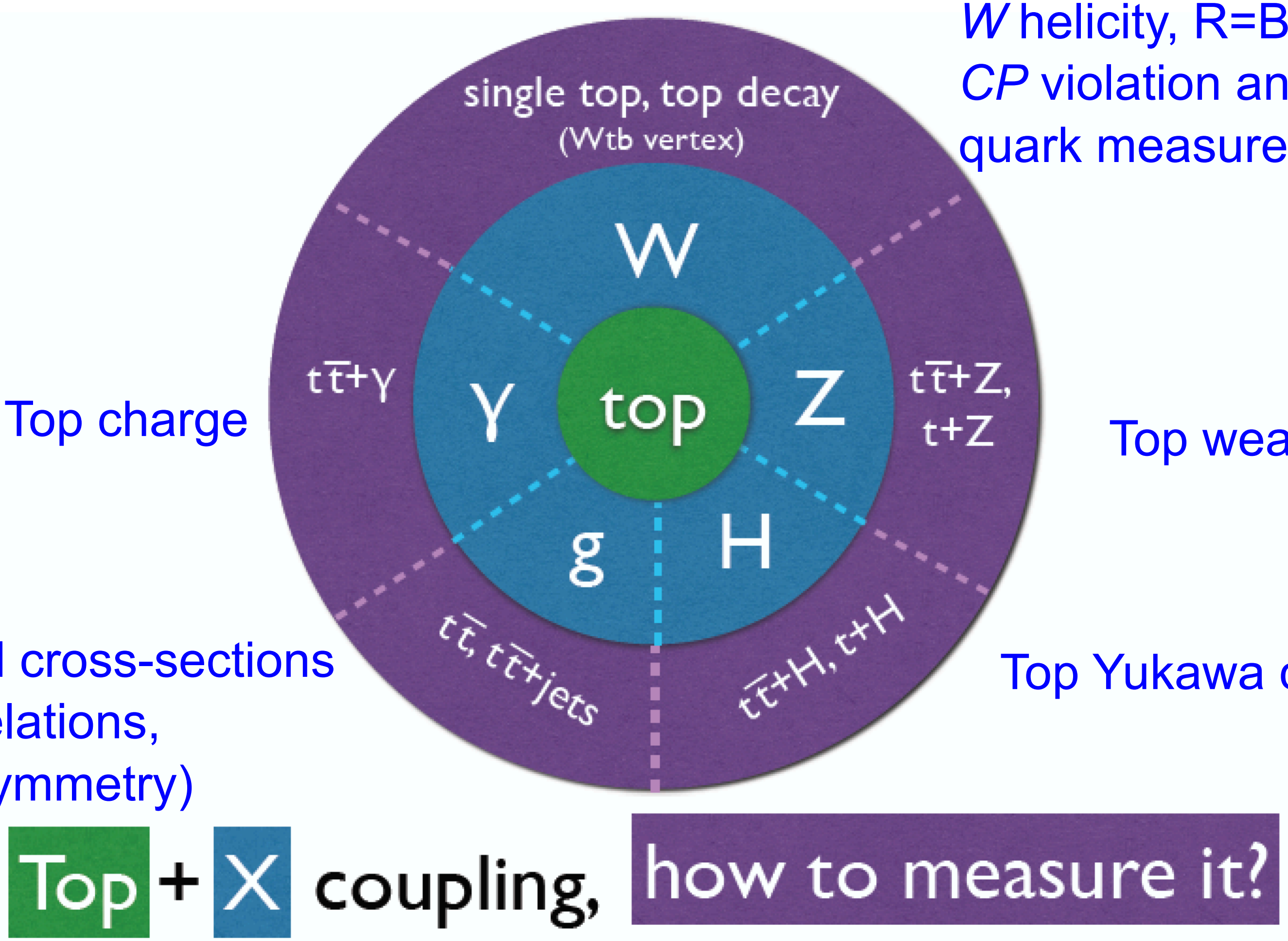


Standard Model Production Cross Section Measurements

Status: July 2018

Top quark couplings

Top quark couples to other SM fields through its **gauge and Yukawa interactions.**
t→*Wb* coupling measured already at the Tevatron.
High statistics at the LHC: *tt* + massive bosons (*Z*, *W* and *H*) becomes available
→ Observation of these processes reported at the LHC for the first time!!
Flagships measurements but very challenging, **both experimental & theoretical side**



W helicity, R=B(*t*→*Wb*)/B(*t*→*Wq*), *CP* violation and different single top quark measurements

Top charge

Top weak isospin

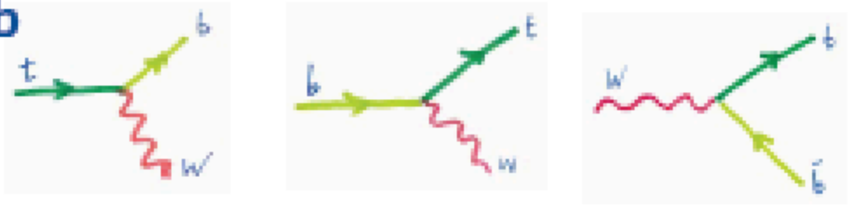
Top Yukawa coupling

Differential cross-sections (spin correlations, charge asymmetry)

Top quark couplings

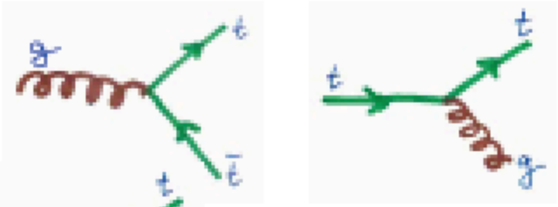
Flavour changing charged current

- **Wtb**



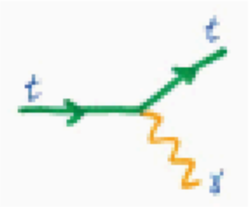
Flavour conserving neutral current

- **tgt**



- **tZt**

- **tγt**

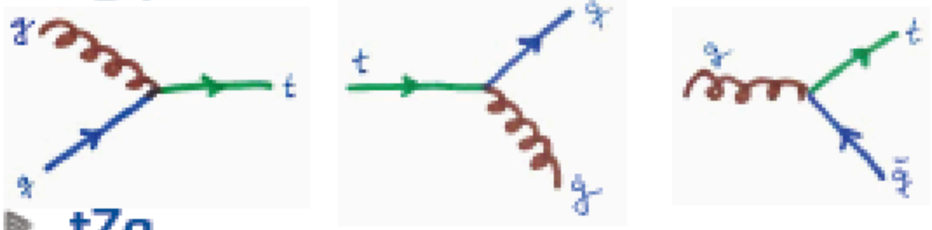


- **tHt**

One of the highlights of LHC Run-II

… and neutral current

- **tgq**



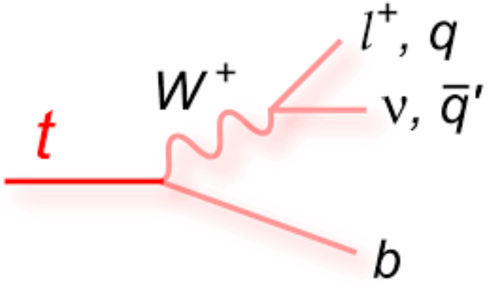
- **tZq**

- **tγq**

- **tHq**

Decay of the top quark and of the Higgs boson

t→Wb ~100%



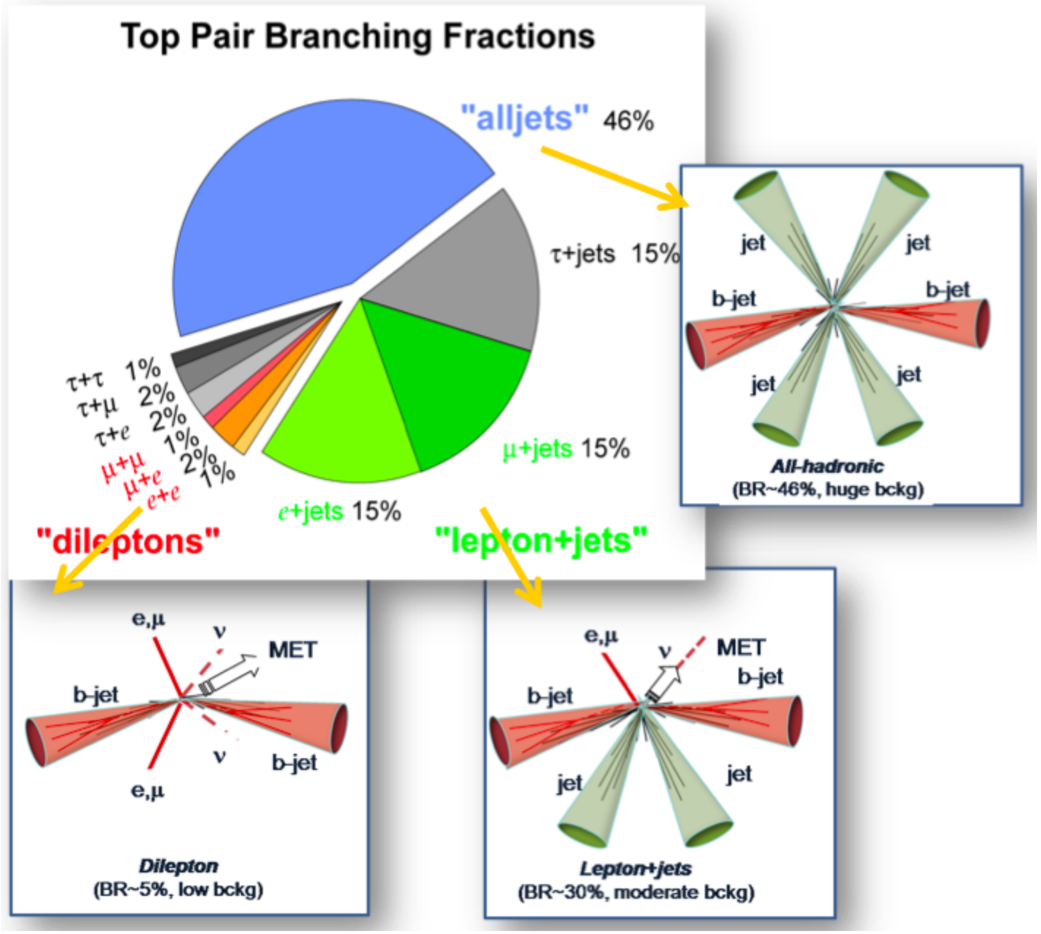
H→bb 58%

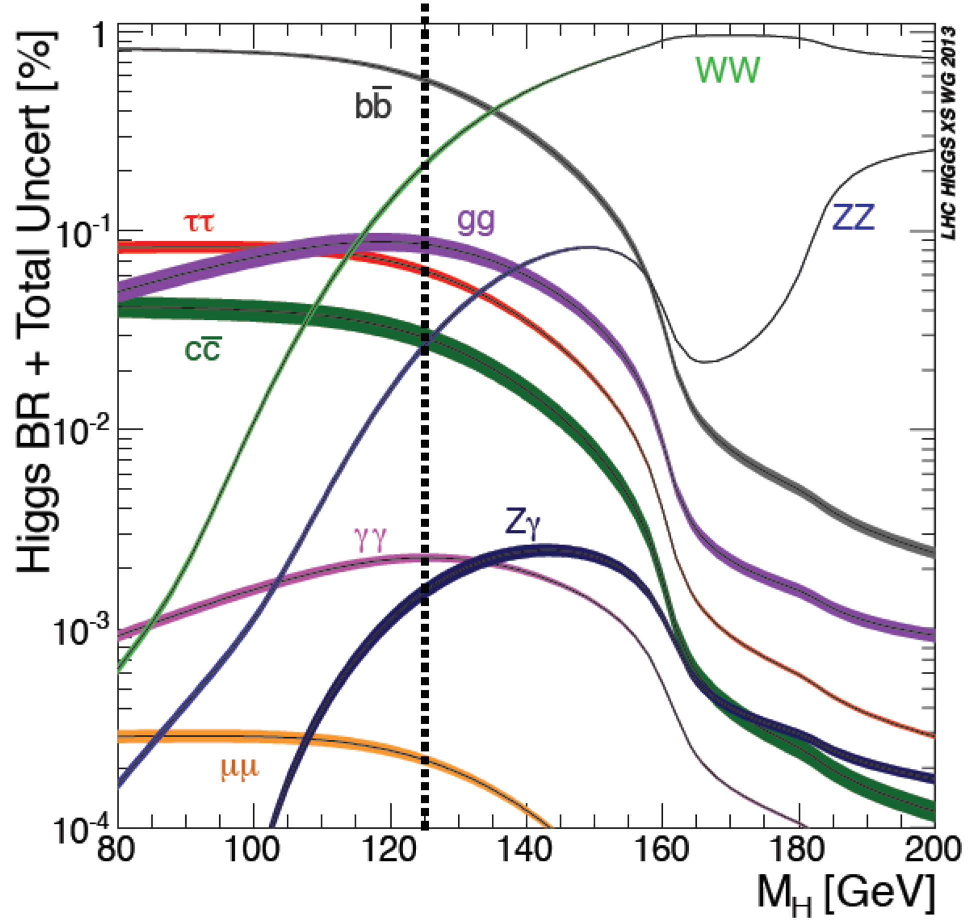
H→WW* 22%

H→ττ 6.3%

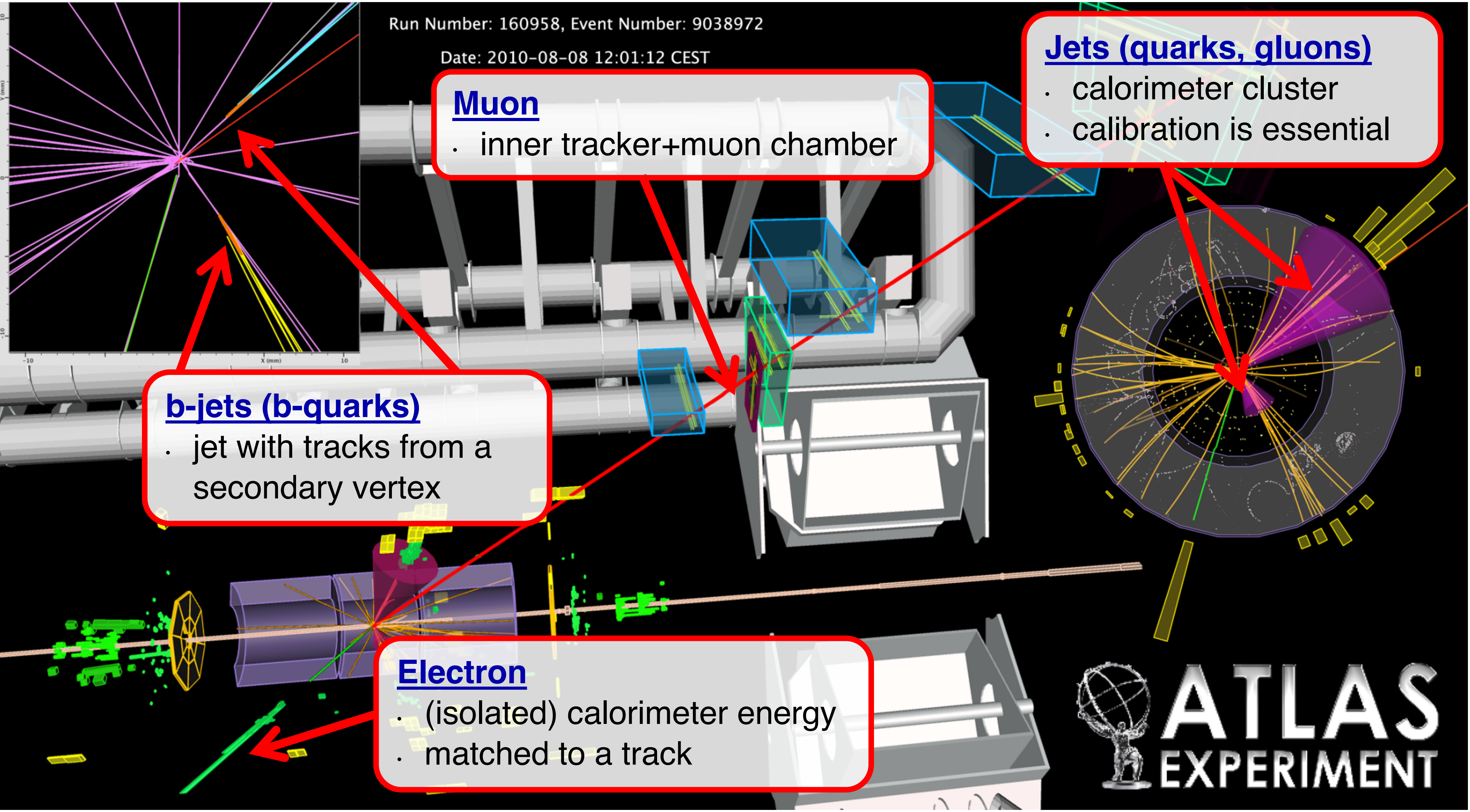
H→ZZ* 2.6%

H→γγ 0.23%





Full detector shining



Muon

- inner tracker+muon chamber

Jets (quarks, gluons)

- calorimeter cluster
- calibration is essential

b-jets (b-quarks)

- jet with tracks from a secondary vertex

Electron

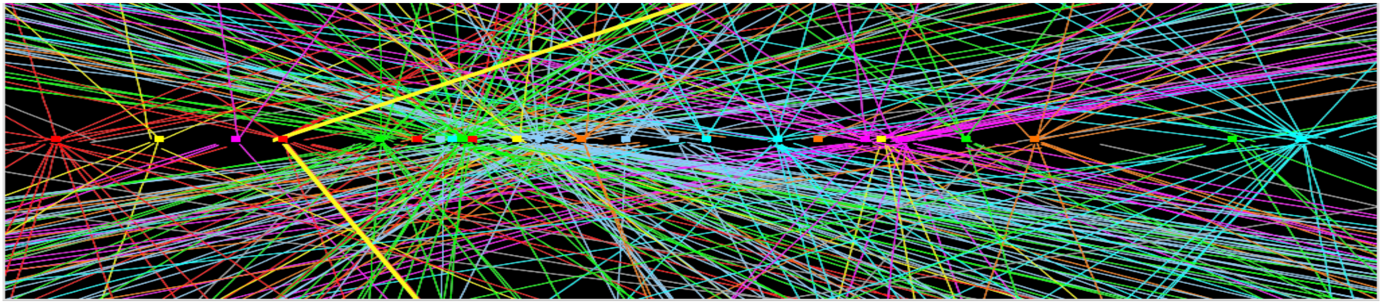
- (isolated) calorimeter energy
- matched to a track

Neutrinos

- from momentum conservation

Also hadronic taus

Several challenges…



Trigger challenge

How to select ~1500 out of 20M events per second while keeping the interesting (including unknown) physics

Computing challenge

How to reconstruct, store and distribute ~1500 increasingly complex events per second (~50 PB per experiment per year → now >300PB) [size: ~1MB/event]

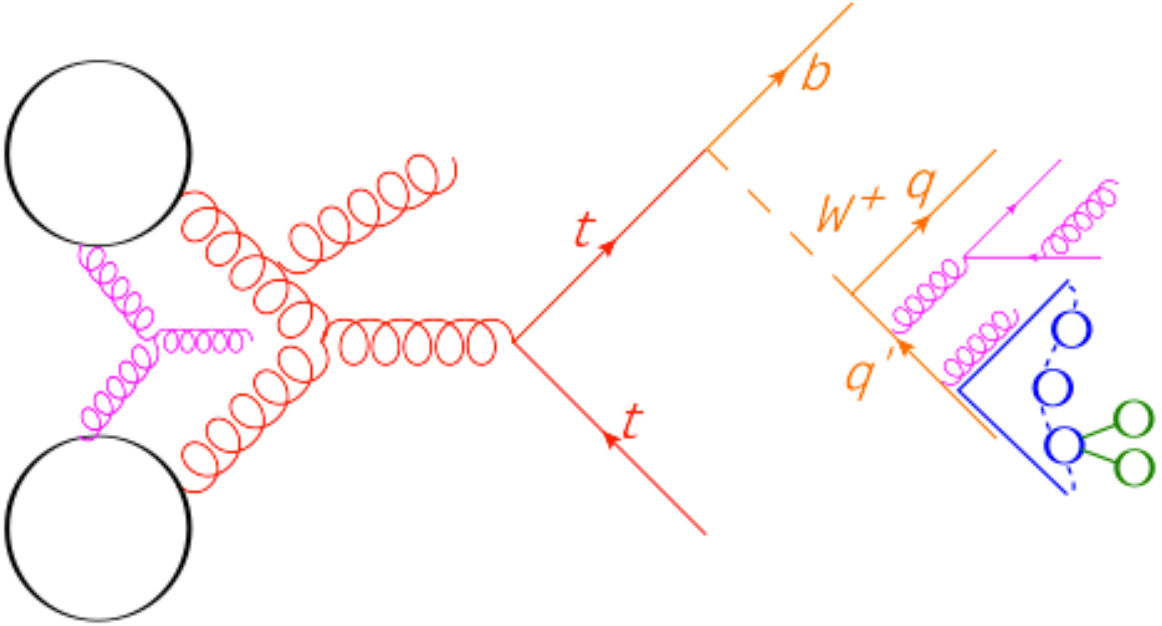
Analysis challenge

Maintain high (and as much as possible stable) reconstruction and identification efficiency for physics objects (e, μ, τ, jets, E_T^{miss}, b-jets) up to the highest pile-up

And also physics modelling uncertainties

Monte Carlo generators used at LHC include multi-leg or fixed NLO+PS predictions.

Theoretical modelling uncertainties are typically important/dominant.



- ■ Proton PDF
- ■ Hard process
- ■ Resonance decays
- ■ Parton shower, MPI
- ■ Hadronization
- ■ Hadron decays

Strategies to reach the ultimate precision:

→ Experimental side: measurements that allow constraining these uncertainties from data

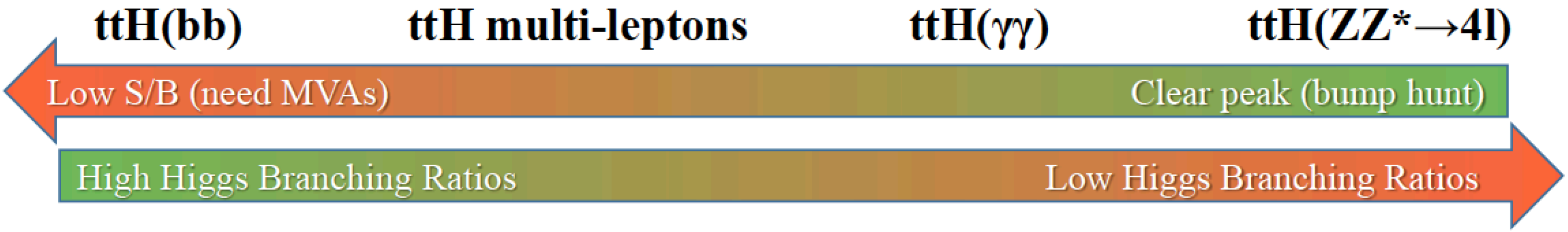
- differential measurements, ratios, etc.
- provide results at particle level in a fiducial region experimentally accessible

→ allow to improve MC tuning

→ Theoretical side: provide higher order calculations (NNLO corrections)

Challenging backgrounds

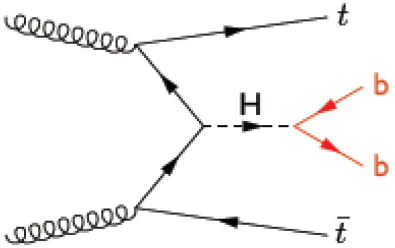
Categorization by Higgs boson decay:



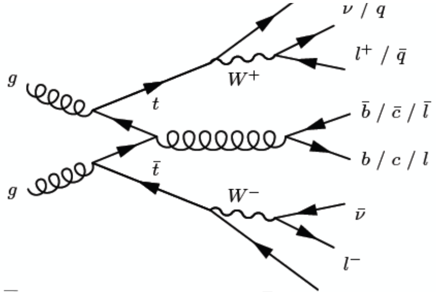
ttH(bb) **ttH multi-leptons** **ttH(γγ)** **ttH(ZZ*→4l)**

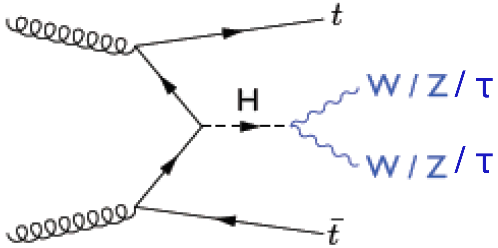
Low S/B (need MVAs) Clear peak (bump hunt)

High Higgs Branching Ratios Low Higgs Branching Ratios

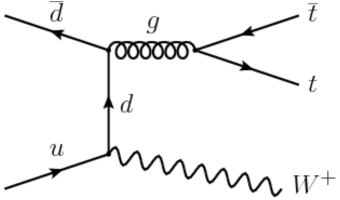


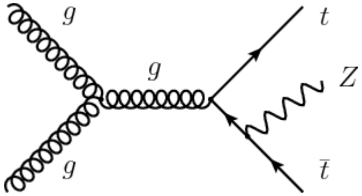
tt+H(H→bb) vs. *tt+jets(bb)*

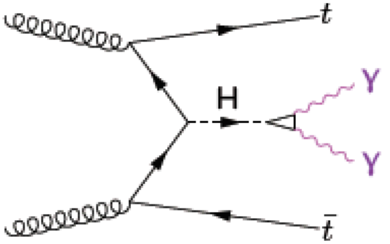




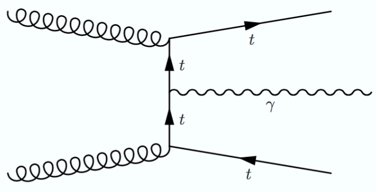
tt+H(H→WW,ττ,ZZ) vs. *tt+W/Z*





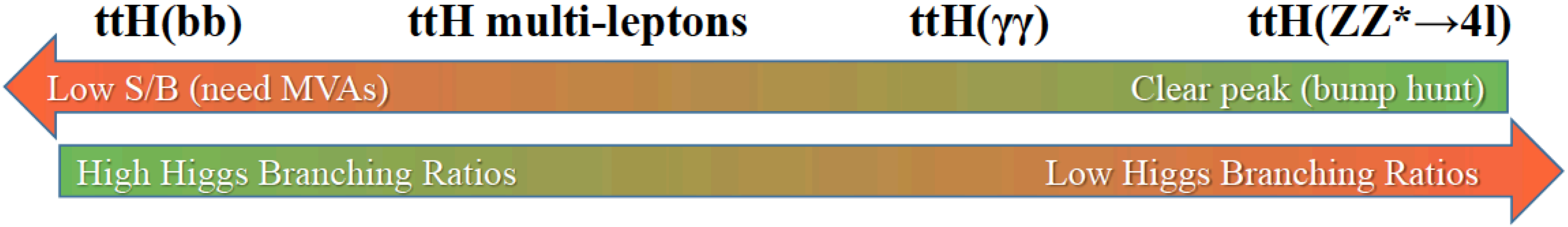


tt+H(H→γγ) vs. *tt+γ(γ)*



Evidence reported one year ago (2015+2016 dataset)

Categorization by Higgs boson decay:



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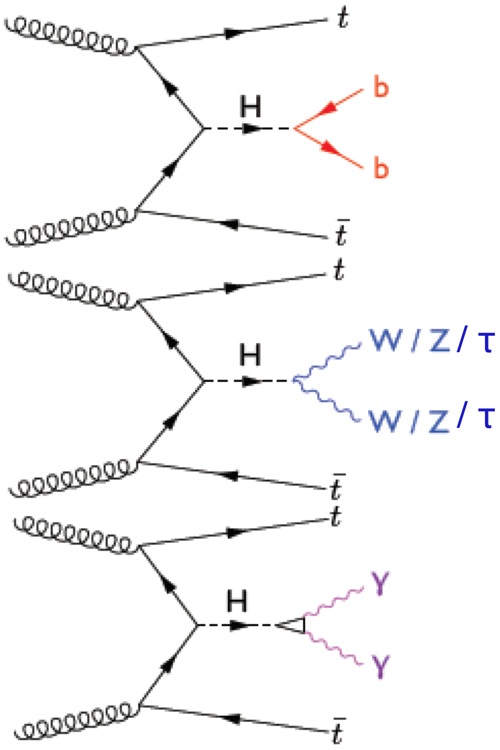


tt+H(H→bb) vs. *tt+jets(bb)*
Phys. Rev. D 97 (2018) 072016

tt+H(H→WW,ττ,ZZ) vs. *tt+W/Z*
Phys. Rev. D 97 (2018) 072003
ZZ→4l: JHEP 03 (2018) 095

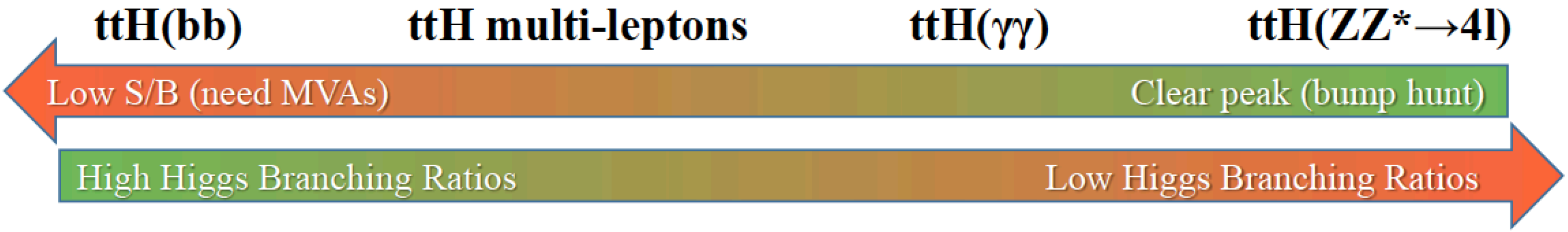
tt+H(H→γγ) vs. *tt+γ(γ)*
Phys. Rev. D 98 (2018) 052005

Evidence of *tt+H* process
4.2σ (3.8σ exp) [36 fb^{-1}@13 TeV]

Phys. Rev. D 97 (2018) 072003

And with more data... observation of *tt+H* process!

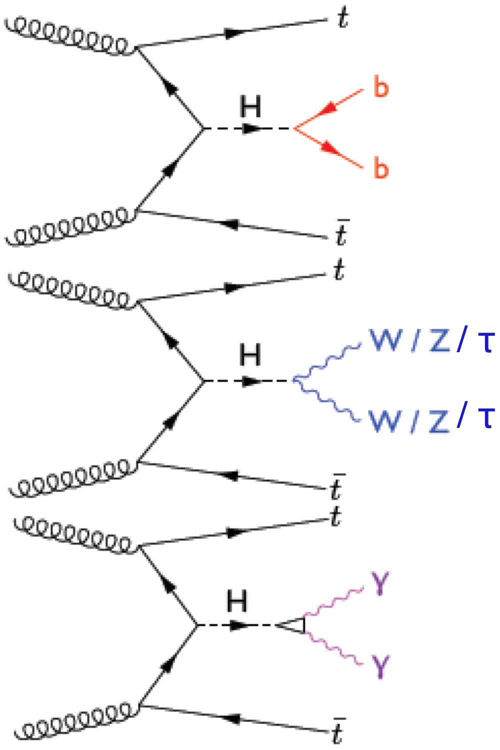
Categorization by Higgs boson decay:



ttH(bb) **ttH multi-leptons** **ttH(γγ)** **ttH(ZZ*→4l)**

Low S/B (need MVAs) — Clear peak (bump hunt)

High Higgs Branching Ratios — Low Higgs Branching Ratios



tt+H(H→bb) vs. *tt+jets(bb)*
Phys. Rev. D 97 (2018) 072016

tt+H(H→WW,ττ,ZZ) vs. *tt+W/Z*
Phys. Rev. D 97 (2018) 072003
ZZ→4l: Physics Letters B784 (2018)

New! @80fb^{-1}

tt+H(H→γγ) vs. *tt+γ(γ)*
Physics Letters B784 (

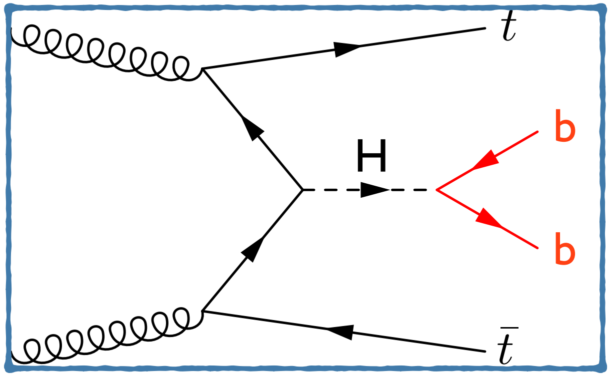
New! @80fb^{-1}

Evidence of *tt+H* process
4.2σ (3.8σ exp) [36 fb^{-1}@13 TeV]

↓

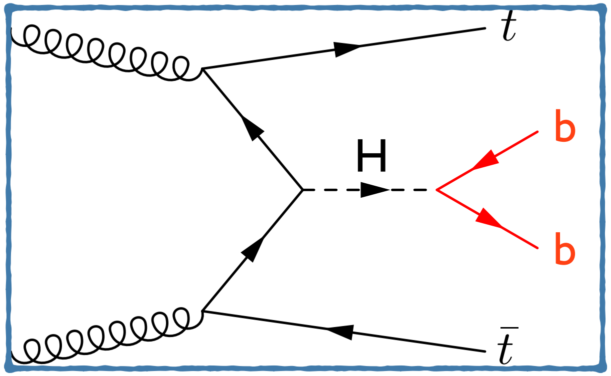
Observation of *tt+H* process

tt+H (bb)



- Fermion-only production and decay ☺
- Higgs boson reconstruction possible, but challenging due to multiple *b*-quarks and additional radiation in the final state ☺ ☹
- Irreducible *tt*+*bb* background: large theoretical uncertainty ☹

tt+H (bb): irreducible tt+bb background



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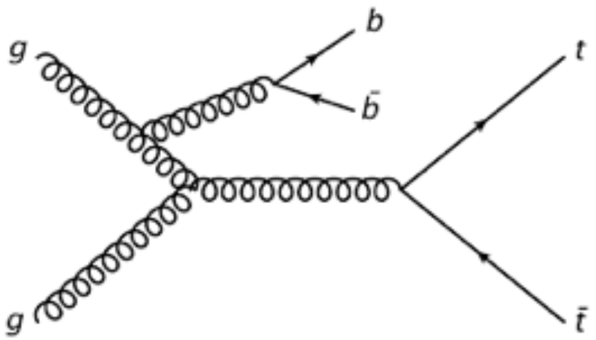
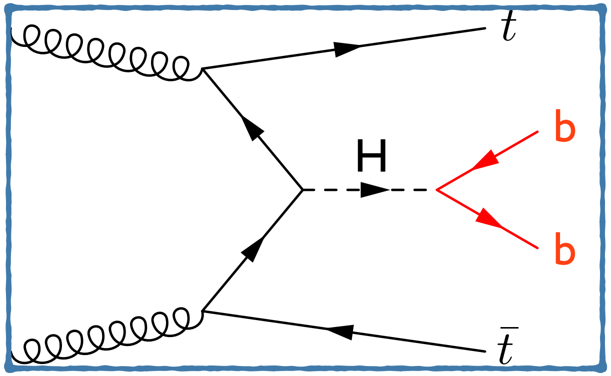
- Irreducible *tt+bb* background: large theoretical uncertainty ☹ ☹

Biggest challenge: good and precise modelling of the ***tt*+HF** (**≥1b**, **≥1c**) background



Nominal *tt*+jets sample (Powheg+Pythia8): 5-flavour scheme (m_b=0) Relative contribution of *tt*+≥1b subcomponents scaled to *tt+bb* NLO predictions by Sherpa+OpenLoops (4-flavour scheme, m_b!=0)

tt+H (bb): divide and conquer



- Fermion-only production and decay ☺
- Higgs boson reconstruction possible, but challenging due to multiple *b*-quarks and additional radiation in the final state ☺ ☹
- Irreducible *tt*+*bb* background has large theory uncertainty ☹

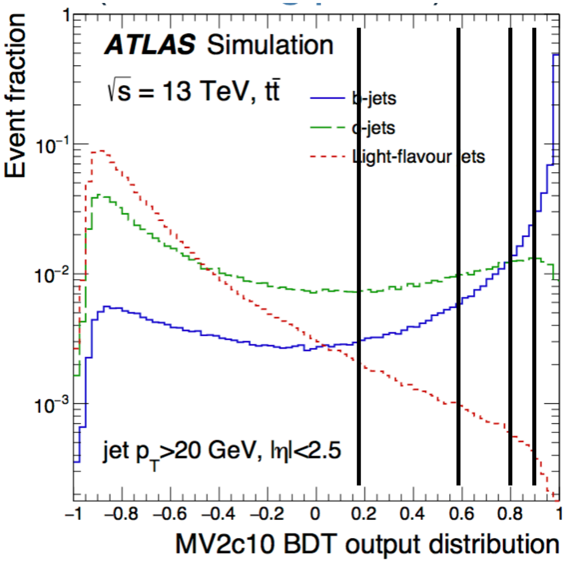
Analysis strategy

Categorization

1**ℓ** & 2**ℓ** (*e*,μ)

# of jets ➡

b-tag score of jets (4 working points)



10 CRs
9 SRs

Several categories with very different fractions of backgrounds *tt*+light, *tt*+≥1c, *tt*+≥1b and *tt*+*H* signal
+ Boosted category (1 top quark & *H*→*bb* in two large-cone jets)

tt+H (bb): divide and conquer

2 leptons

Resolved regime

≥3 jets, ≥2 medium b-jets

1 lepton

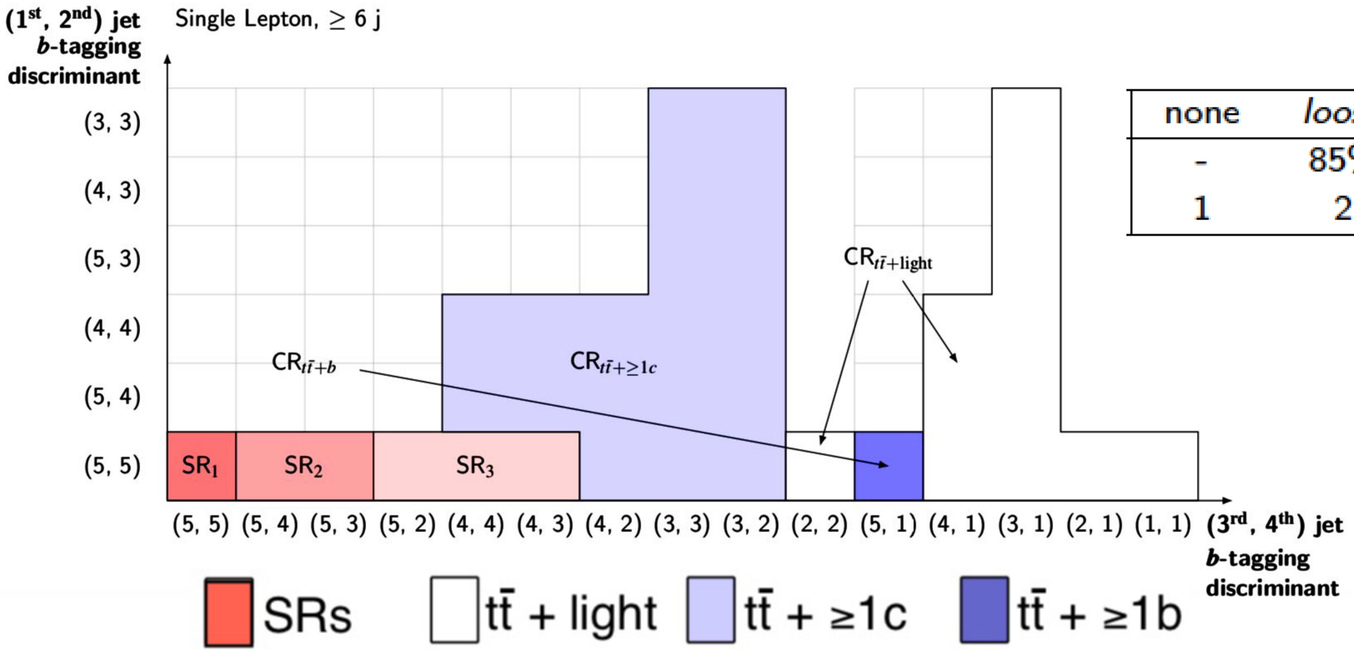
Resolved regime

≥5 jets, ≥2 very-tight or ≥3 medium b-jets

Boosted regime

boosted Higgs p_T>200 GeV *(2 loose b-jets)*,
boosted top p_T>250 GeV *(1 loose b-jet + ≥1 non-tagged jet)*
+ loose b-tagged jet

After this preselection, further categorize events
→ **control** (**background-enriched**) and **signal regions**



b-tagging discriminant

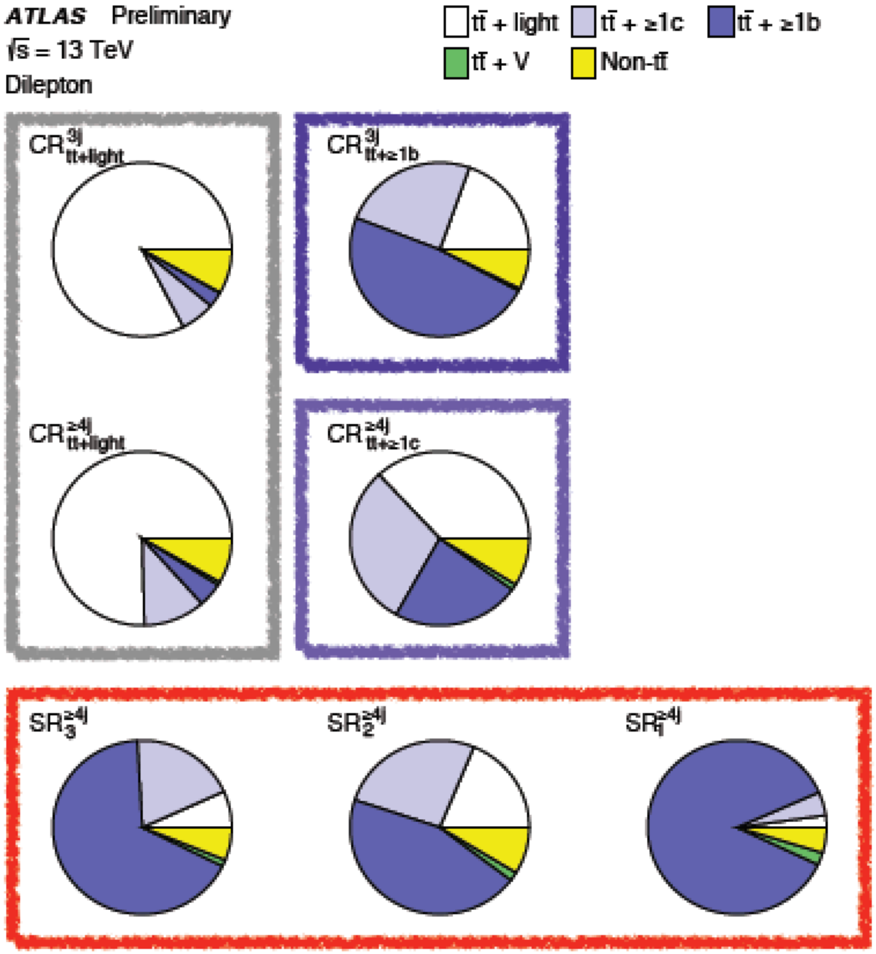
none	*loose*	*medium*	*tight*	*very-tight*
-	85%	77%	70%	60%
1	2	3	4	5

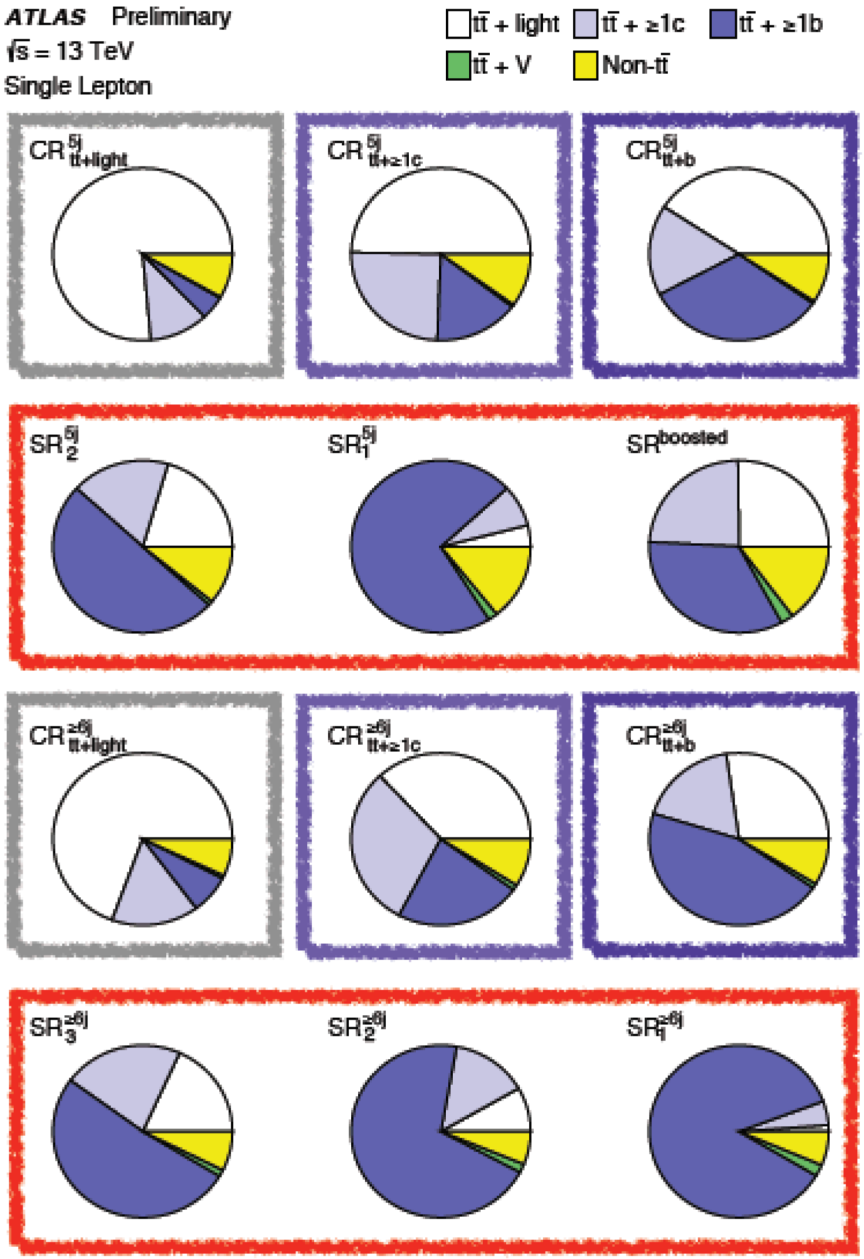
tt+H (bb): several control and signal regions

10 CRs with different compositions

9 SRs

- 3 dilepton (≥4 jets),
- 6 single lepton (=5 jets, ≥6 jets, boosted)





tt+H (*bb*): very sophisticated analysis

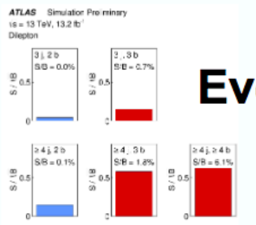
2 leptons

1 lepton

Resolved regime

Resolved regime

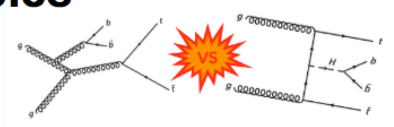
Boosted regime



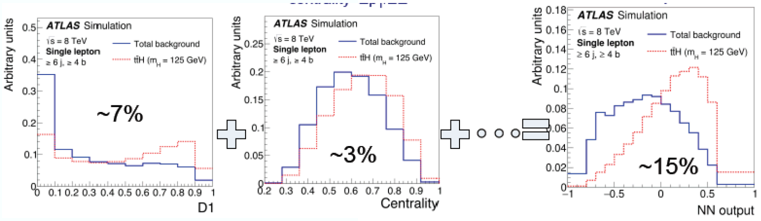
Events are categorised according to # of jets & # of b-tagged jets

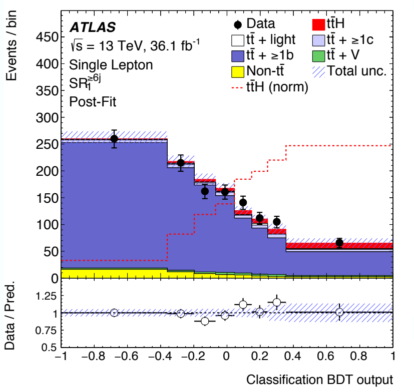
ttH reconstruction

Generic variables & ttH variables



MVA classifier & MEM classifier



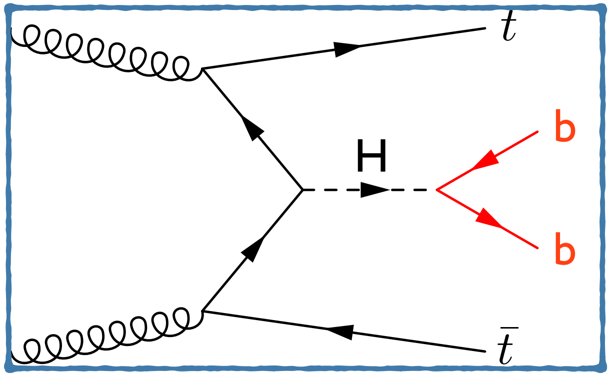


Perform a likelihood fit Data, bkg. MC, Signal MC

Extract a signal strength

μ_{ttH}

tt+H (bb): cascade of MVAs



- Fermion-only production and decay
- Higgs boson reconstruction possible, but challenging due to multiple *b*-quarks and additional radiation in the final state
- Irreducible *tt+bb* background has large theory uncertainty

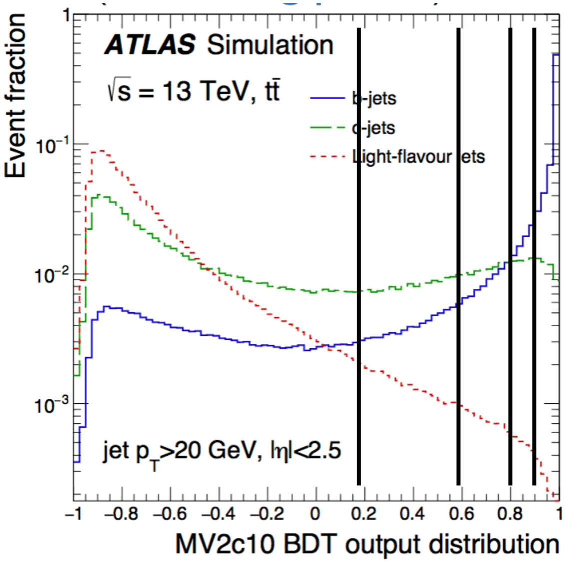
Analysis strategy - cascade of MVAs

Categorization

1*ℓ* & 2*ℓ* (e,μ)

# of jets

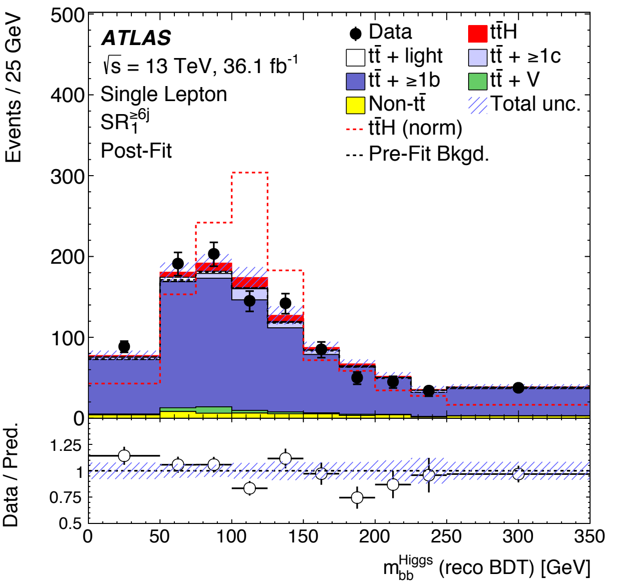
b-tag score of jets (4 working points)



10 CRs
9 SRs

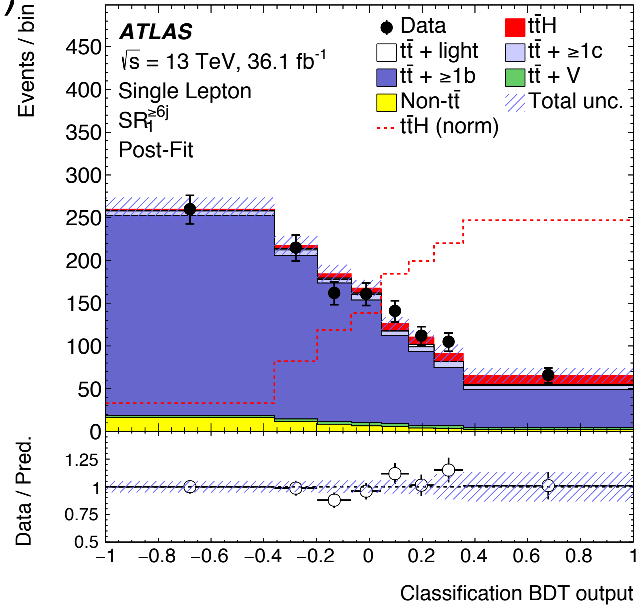
Intermediate BDT (in SRs)

Reco BDT, matrix element & likelihood discriminants (1*ℓ*)



Final BDT

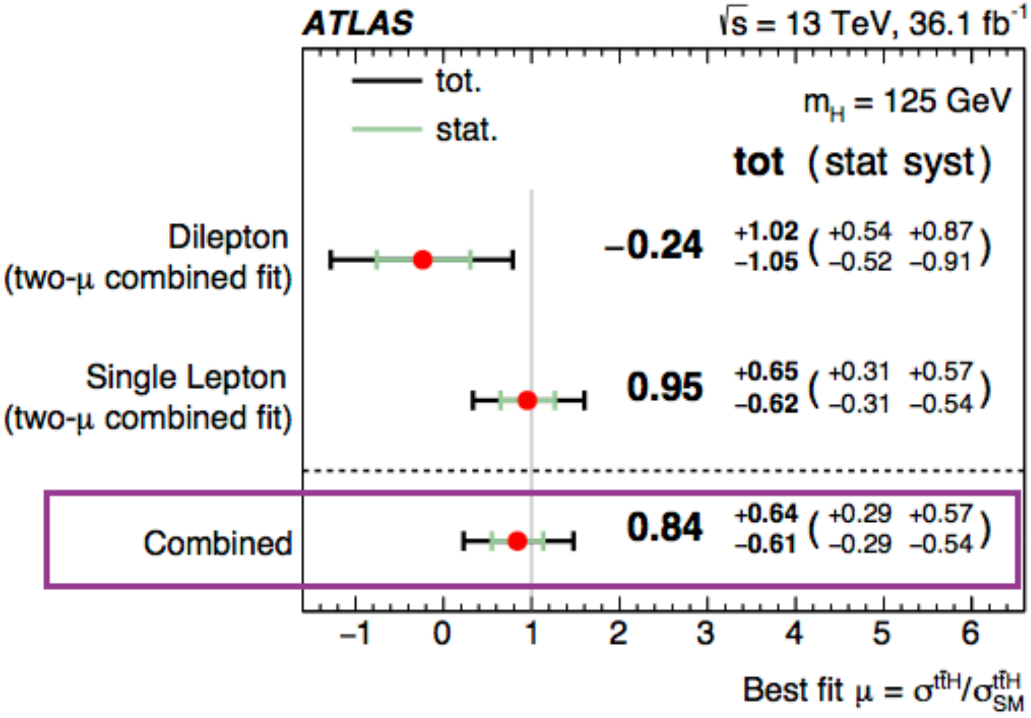
BDT: ttH vs. bkg



tt+H (bb): results

Signal extraction: Binned profile likelihood fit to all signal and control regions. Normalization of *tt*+≥1b and *tt*+≥1c left free-floating in the fit.

Signal strength: $\mu=\sigma/\sigma_{SM}$



$NF(t\bar{t}+\geq 1b) = 1.24 \pm 0.10$

$NF(t\bar{t}+\geq 1c) = 1.63 \pm 0.23$

Dominant systematics

- **Modelling of tt+≥1b (±0.46)**
- Limited MC statistics (±0.30)
- Jet flavour tagging (±0.16)
- Jet energy scale & resolution (±0.16)

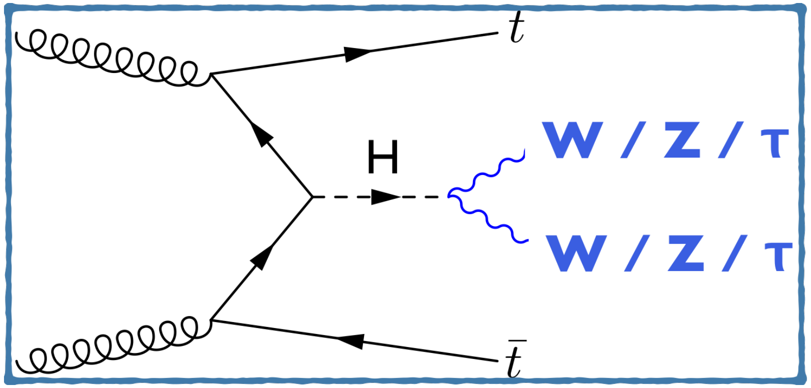
Significance:

1.4 σ (expected 1.6 σ)

Systematically limited:

Requires improvements from both theoretical and experimental communities!

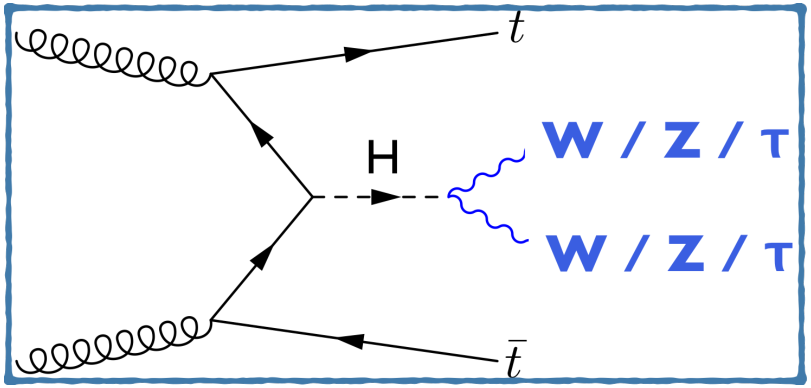
tt+H (multi-leptons)



- Targeting: **ZZ***, **WW*** and **ττ** decays combined with leptonic *tt* decays - distinct multi-lepton signatures* ☺
- Higgs reconstruction is difficult ☹

**ttH(ZZ→4ℓ) events within H→ZZ→4ℓ*

tt+H (multi-leptons): categorization & MVAs



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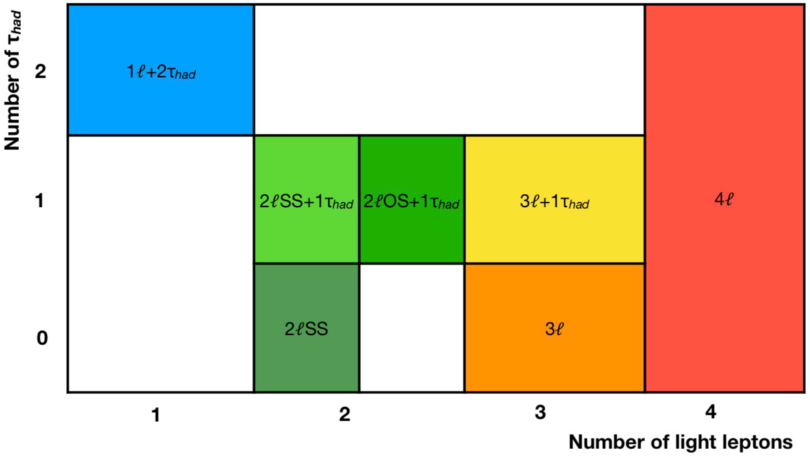
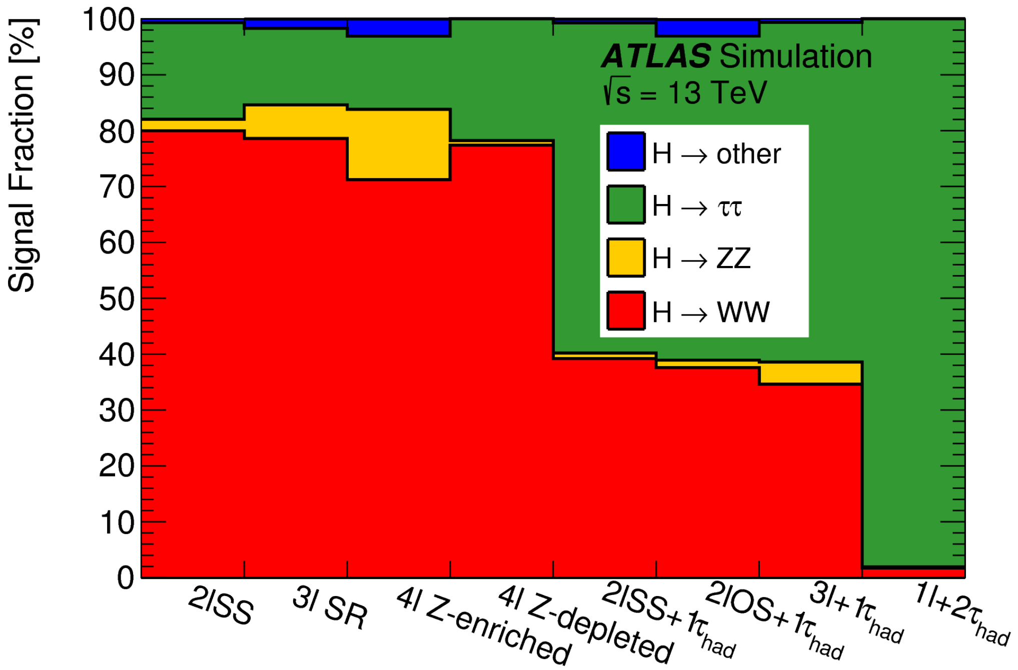
**ttH(ZZ→4ℓ) events within H→ZZ→4ℓ*

Categorization





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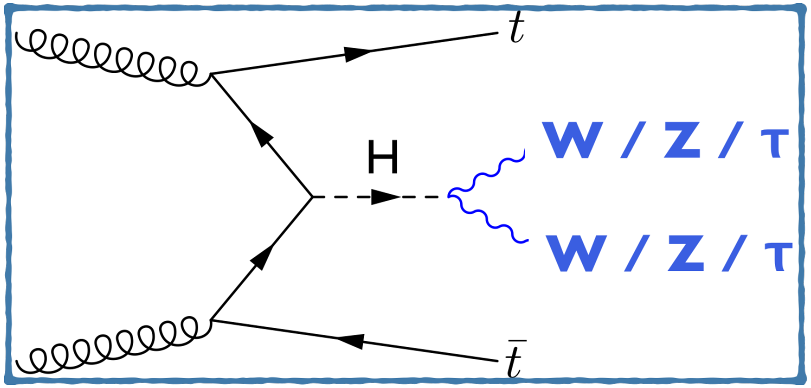

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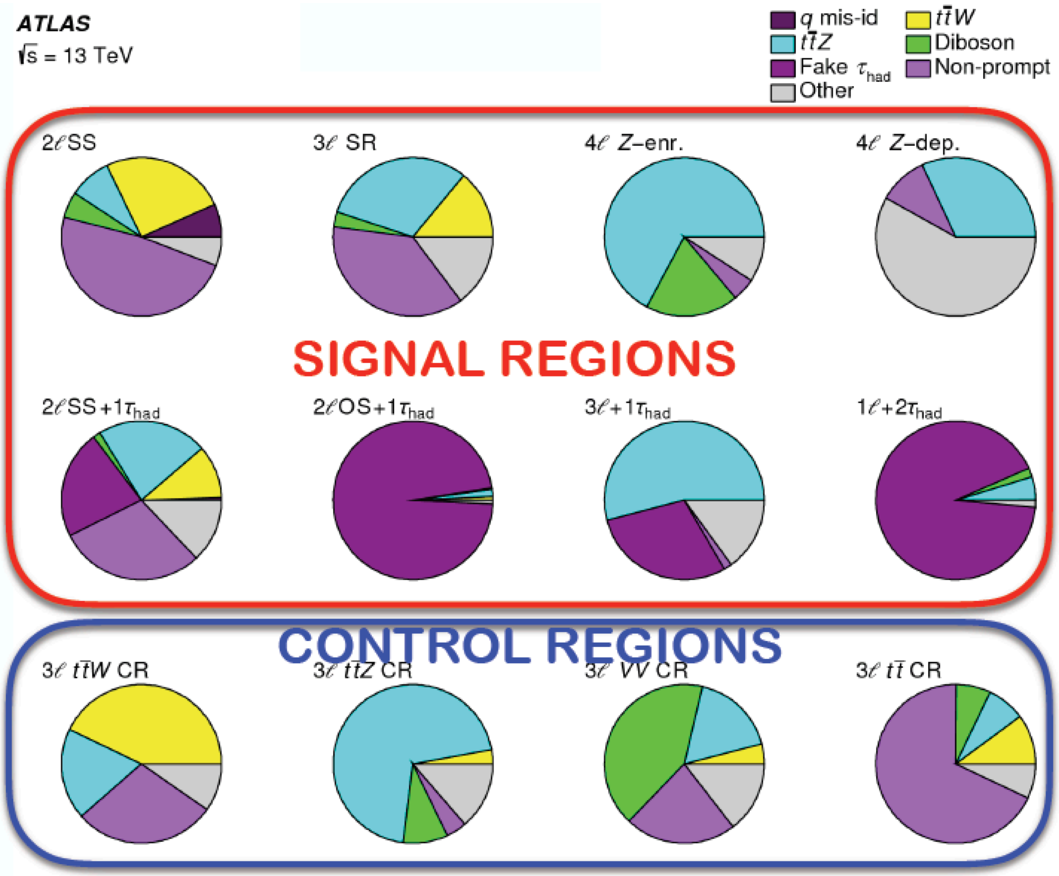


Main backgrounds

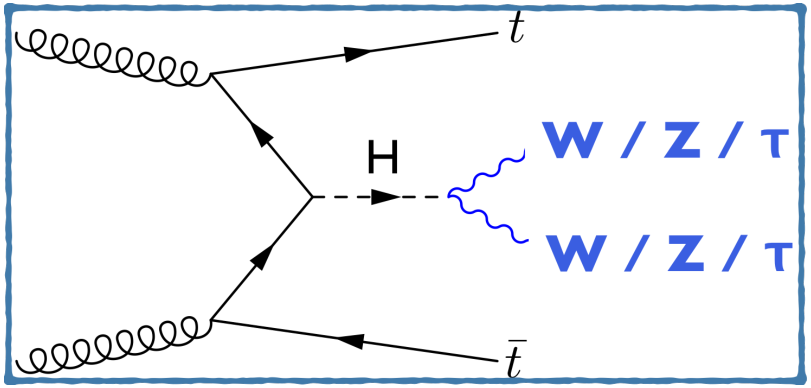
- Very different background composition

tt+W *tt+Z* *VV* *NonPrompt*

dedicated control regions for constraining irreducible backgrounds

mainly from tt (semileptonic b-decay, γ conversions), *estimated from data*

tt+H (multi-leptons): categorization & MVAs



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**ttH(ZZ→4ℓ) events within H→ZZ→4ℓ*

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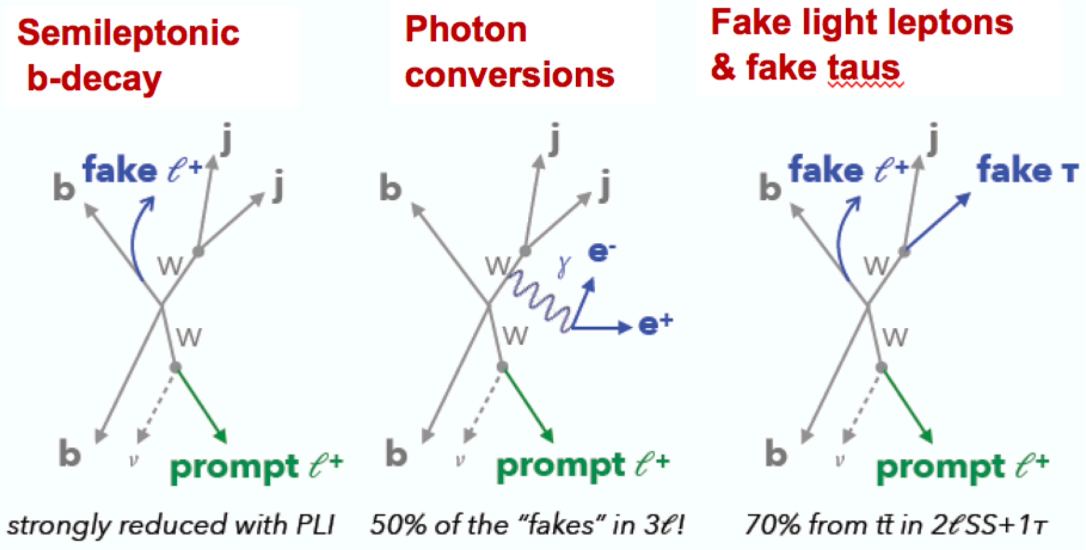
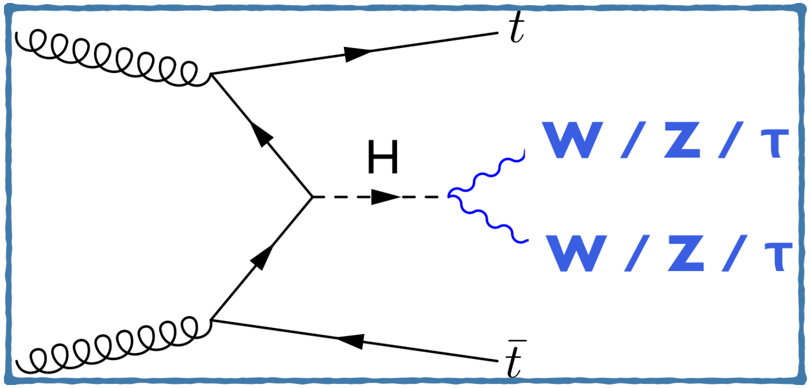


strongly reduced with PLI

50% of the "fakes" in 3ℓ!

70% from $t\bar{t}$ in 2ℓSS+1τ

tt+H (multi-leptons): categorization & MVAs



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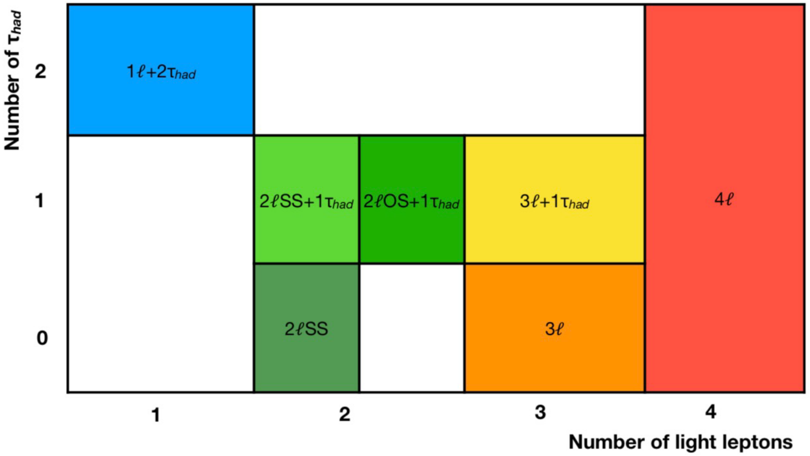
**ttH(ZZ→4ℓ) events within H→ZZ→4ℓ*

Categorization



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mainly from tt (semileptonic b-decay, γ conversions), *estimated from data*

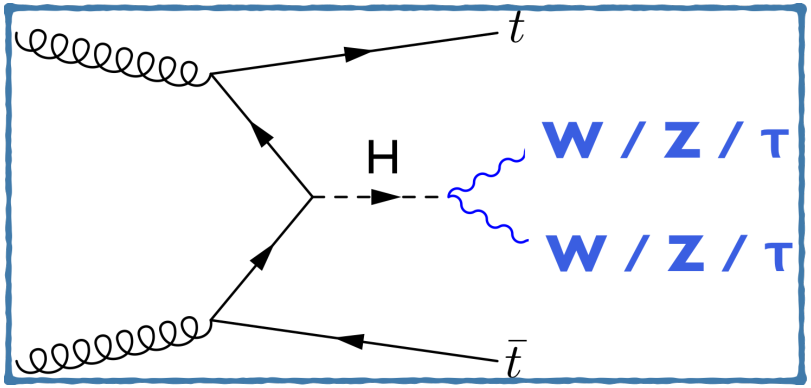
Object level discrimination:

Isolation BDT to reduce non-prompt background, Charge misID BDT

- lepton and overlapping track jets properties
- lepton track/calorimeter isolation variables

Factor $\mathcal{O}(20)$ rejection for leptons from b-hadrons

tt+H (multi-leptons): categorization & MVAs



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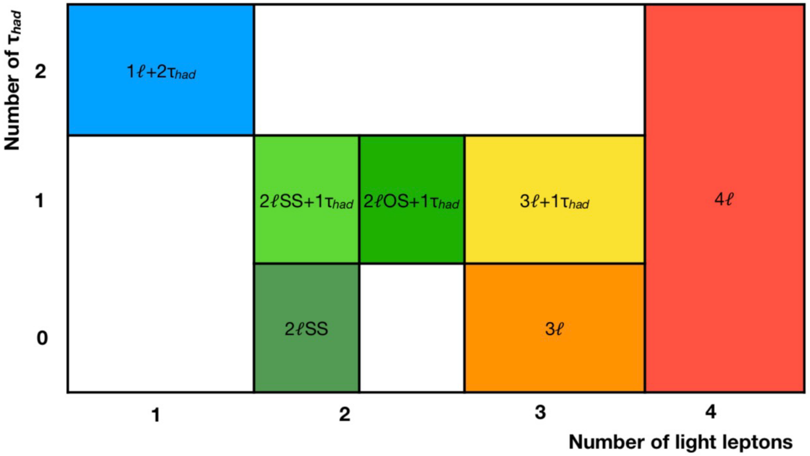
***ttH(ZZ→4ℓ) events within H→ZZ→4ℓ**

Categorization



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tt+W *tt+Z* *VV* *NonPrompt*

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mainly from tt (semileptonic b-decay, γ conversions), *estimated from data*

Object level discrimination:

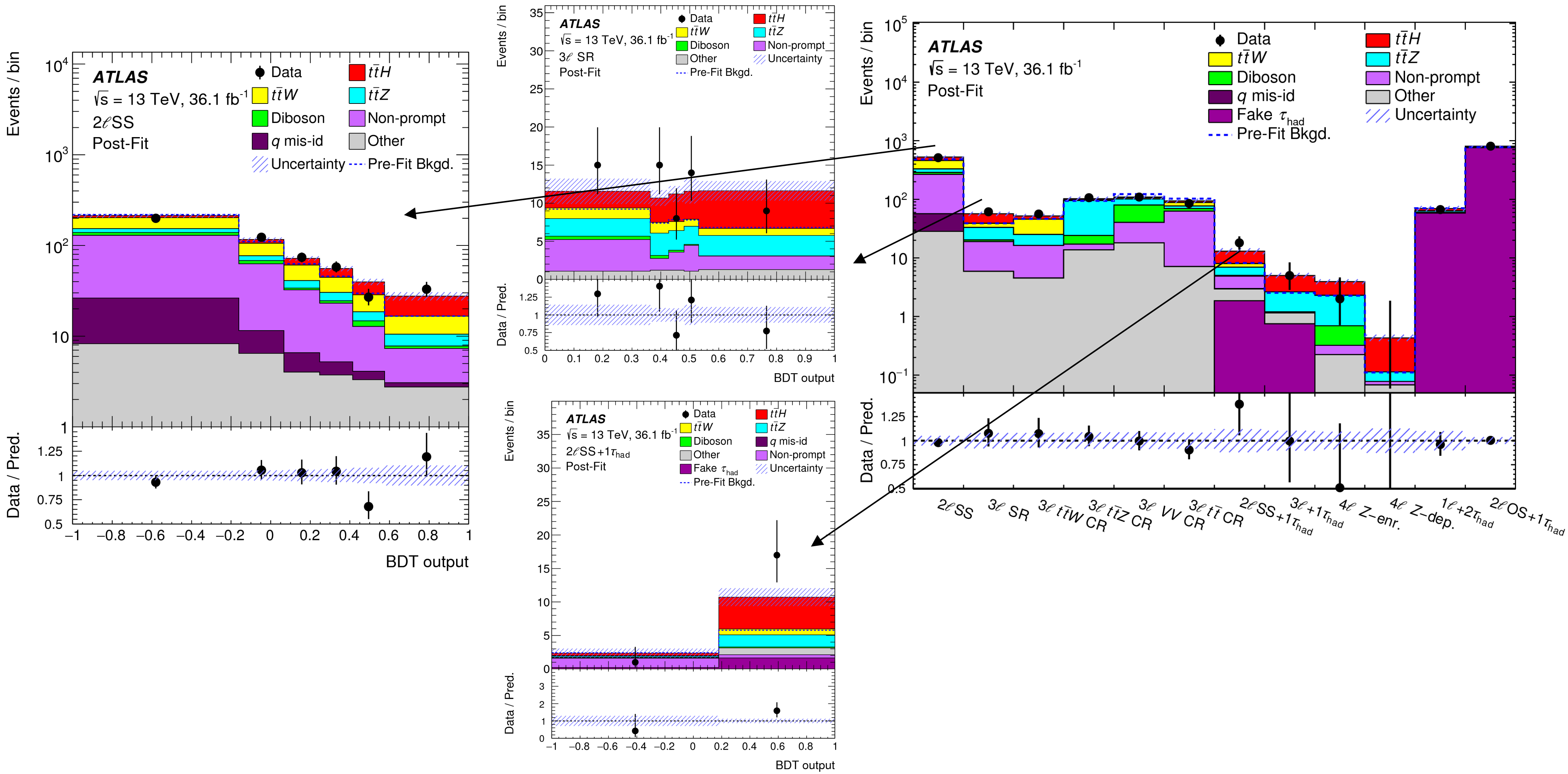
Isolation BDT to reduce non-prompt background, Charge misID BDT

- lepton and overlapping track jets properties
- lepton track/calorimeter isolation variables

Event level discrimination

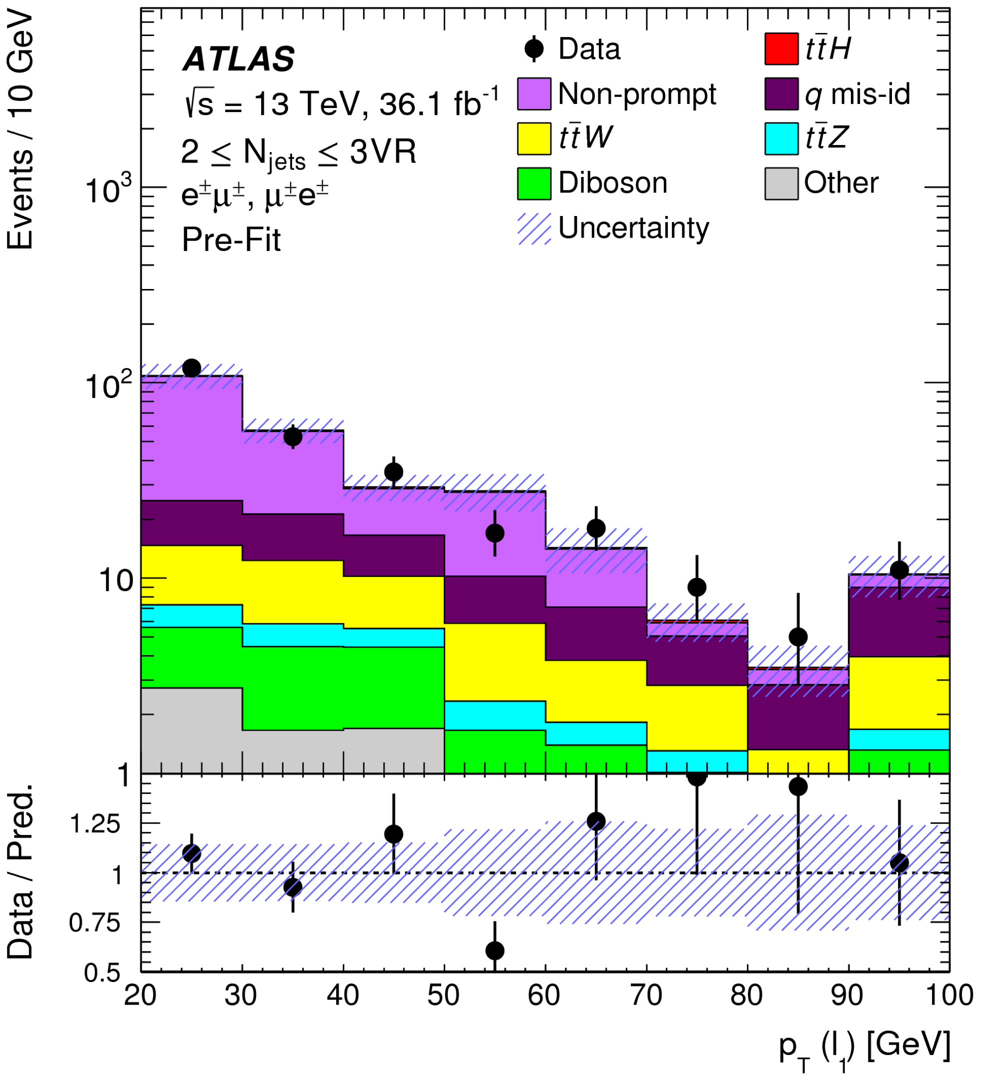
tt+H (multi-leptons): categorization & MVAs

	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{\rm had}$	2ℓSS$+1\tau_{\rm had}$	2ℓOS$+1\tau_{\rm had}$	$3\ell+1\tau_{\rm had}$
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	-	-	-	-	-

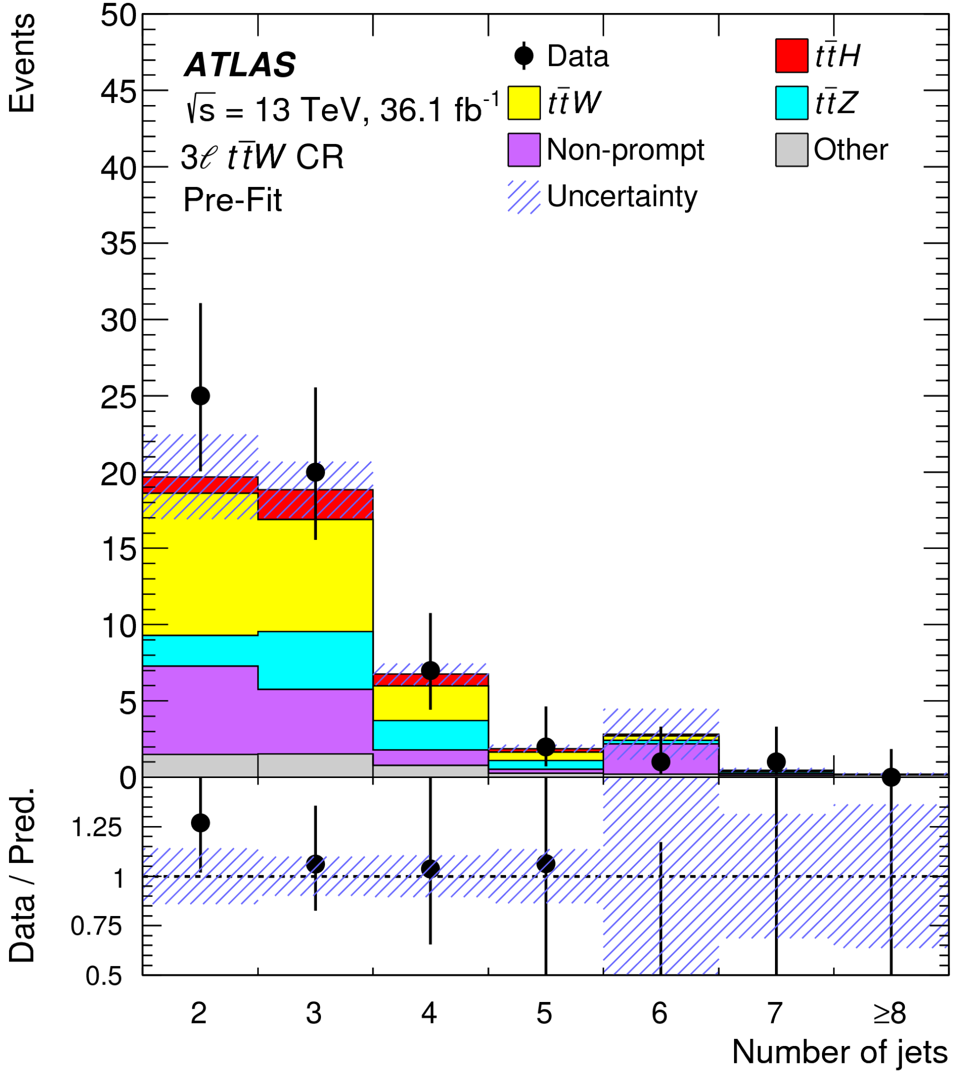


tt+H (multi-leptons): background validation

2ℓ SS "Low N_{jets}" region
$2 \leq N_{jets} \leq 3$,
$N_{b\text{-}jets} \geq 1$



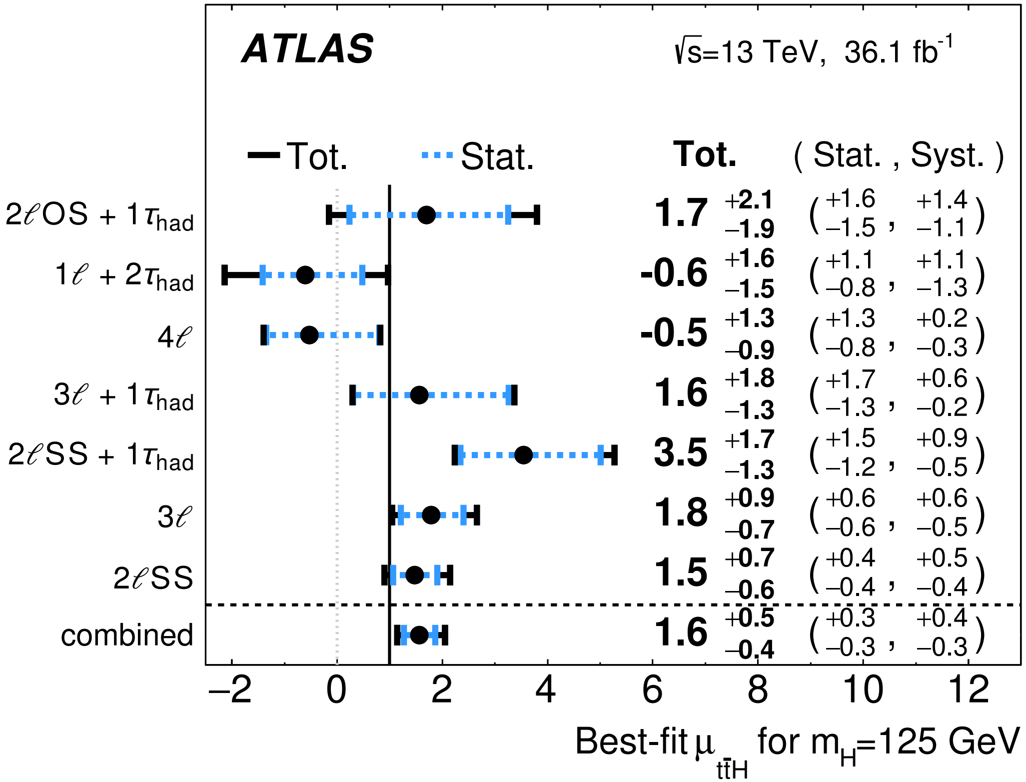
3ℓ+0τ
ttW CR



tt+H (multi-leptons): results

Signal extraction: Binned profile likelihood fit to all signal and control regions.

Signal strength: $\mu=\sigma/\sigma_{SM}$



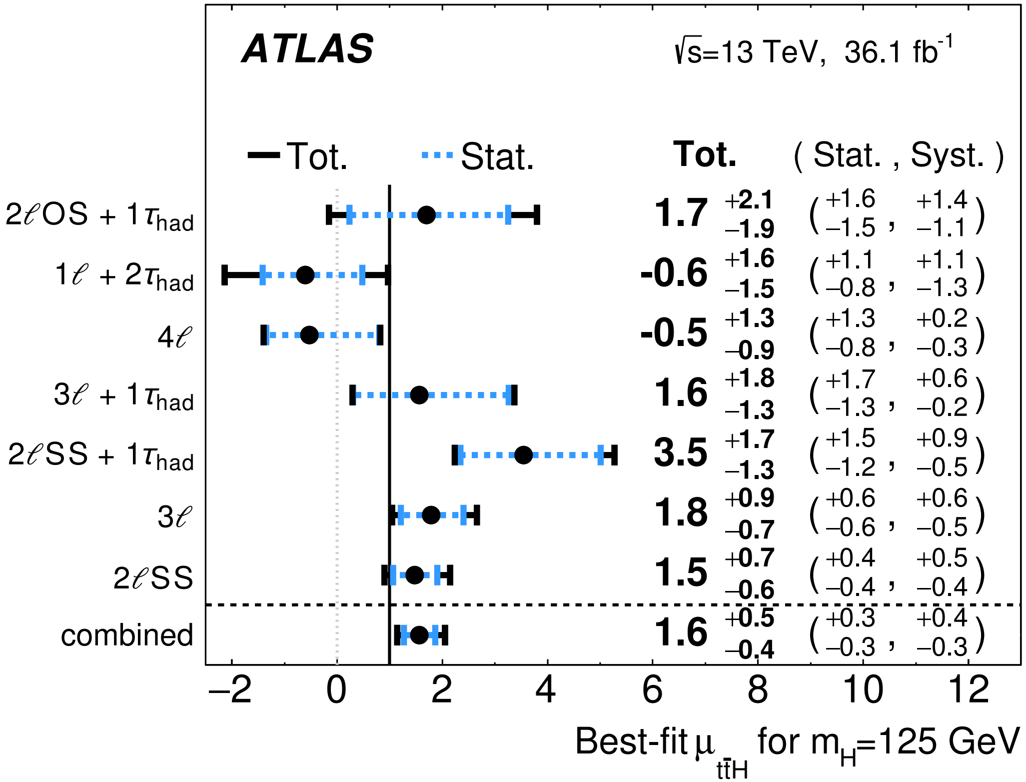
Channel	Significance	
	Observed	Expected
2ℓOS+$1\tau_{\text{had}}$	0.9σ	0.5σ
1ℓ+$2\tau_{\text{had}}$	-	0.6σ
4ℓ	-	0.8σ
3ℓ+$1\tau_{\text{had}}$	1.3σ	0.9σ
2ℓSS+$1\tau_{\text{had}}$	3.4σ	1.1σ
3ℓ	2.4σ	1.5σ
2ℓSS	2.7σ	1.9σ
Combined	4.1σ	2.8σ

Significance:
4.1 σ (expected 2.8 σ)

tt+H (multi-leptons): results

Signal extraction: Binned profile likelihood fit to all signal and control regions.

Signal strength: $\mu=\sigma/\sigma_{SM}$



Dominant systematics

tt+H theory cross-section unc. (+0.20,-0.10)

Jet energy scale/resolution (±0.17)

Non-prompt e/μ (±0.14)

large contribution from limited CR stat.

Significance:

4.1 σ (expected 2.8 σ)

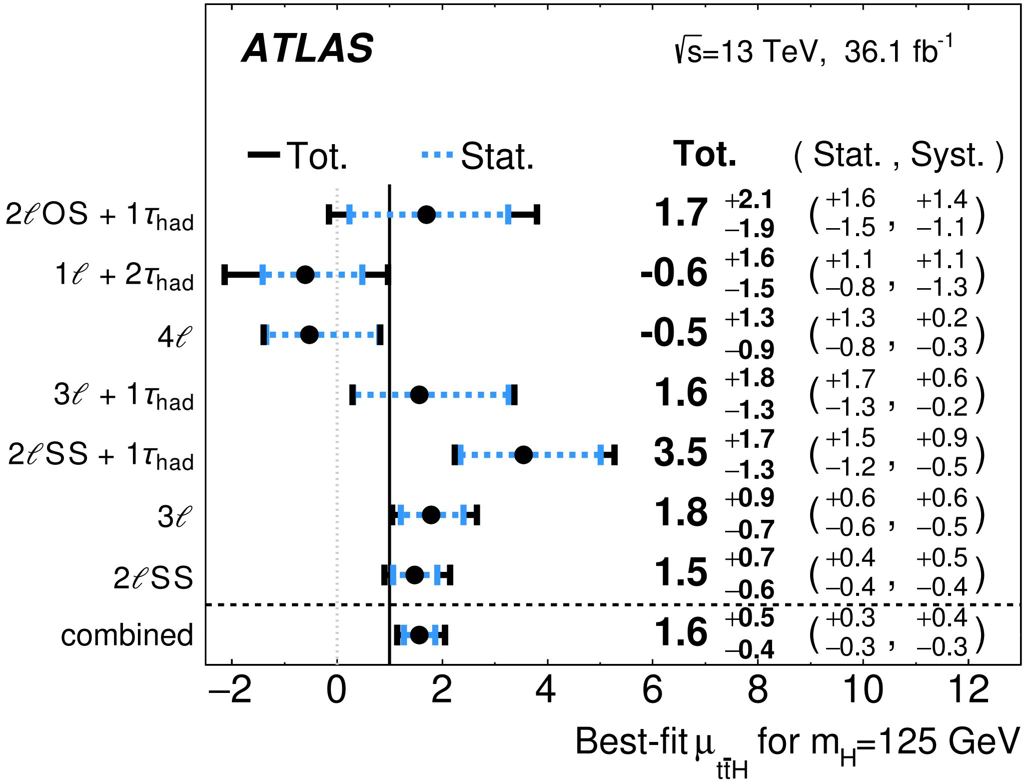
Systematic ~ statistical unc.

New data will improve the precision on channels that are still statistically limited and help constraining tt+Z & tt+W background

tt+H (multi-leptons): results

Signal extraction: Binned profile likelihood fit to all signal and control regions.

Signal strength: μ=σ/σ_{SM}

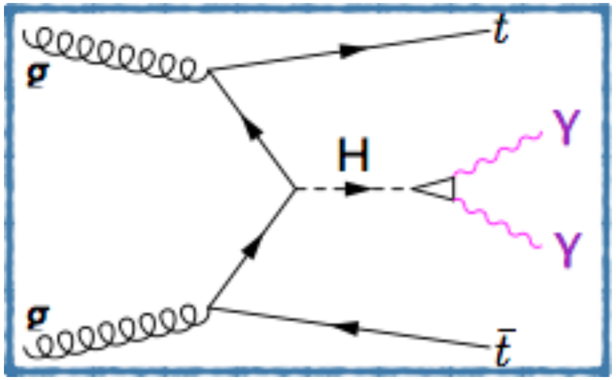


- Compatibility (7 chan.) = 34%
- Alternative fit:

tt̄Z and tt̄W normalisation free-floating very similar result, 15% loss in sensitivity

Significance:
4.1 σ (expected 2.8 σ)

tt+H (γγ)



- Small rate
- Higgs boson can be reconstructed as a “narrow” peak, side-bands can be used to estimate the background.

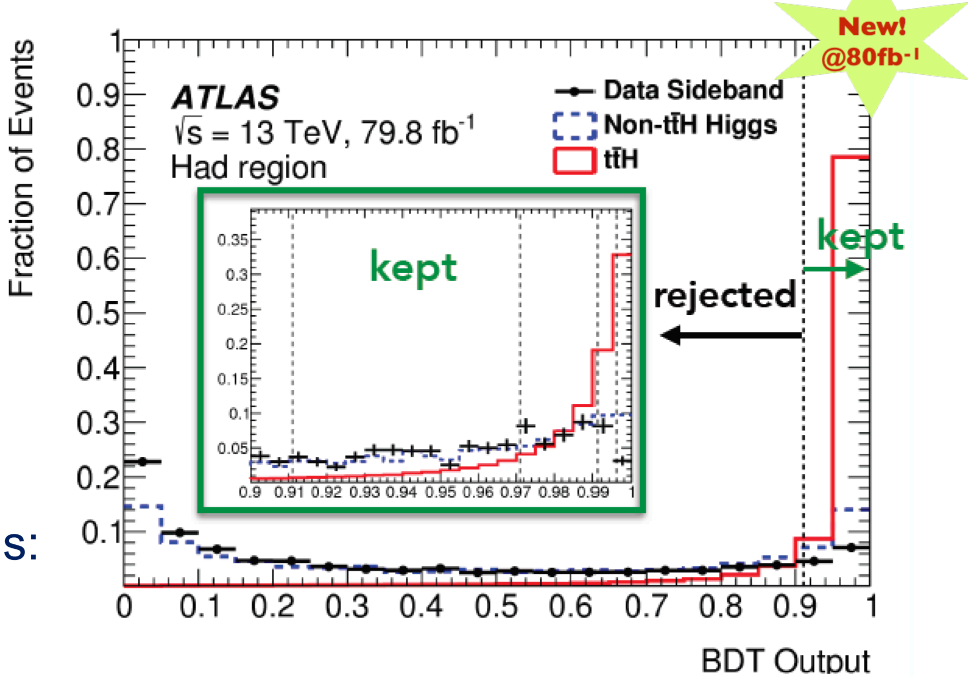
Analysis strategy (new!)

- Categorization based on *tt* decay: **leptonic** ($\geq 1\ell$) and **hadronic** (0ℓ)
- Further categorization based on **XGBoost BDT** discriminant value: **4 hadronic** and **3 leptonic** categories

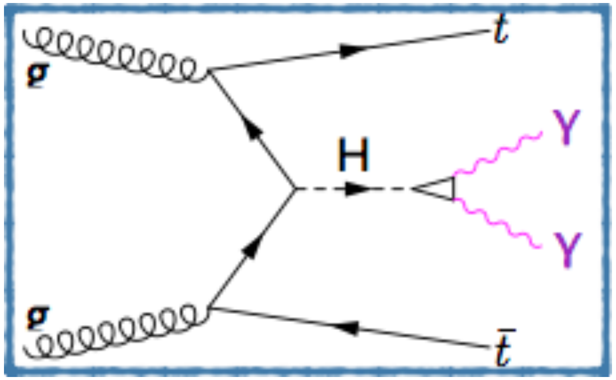
(events w/ low BDT scores rejected)

Input variables to XGBoost BDT:
photons 4-vectors (p_T/m_{yy}), jets,
E_T^{miss} (both cat),
lepton(s) (lep cat),
b-tag (had cat)

Training *tt+H* (from simulation) vs. main backgrounds:
γγ, tt+γγ (from data CRs), other *H* (from simulation)



tt+H (γγ)



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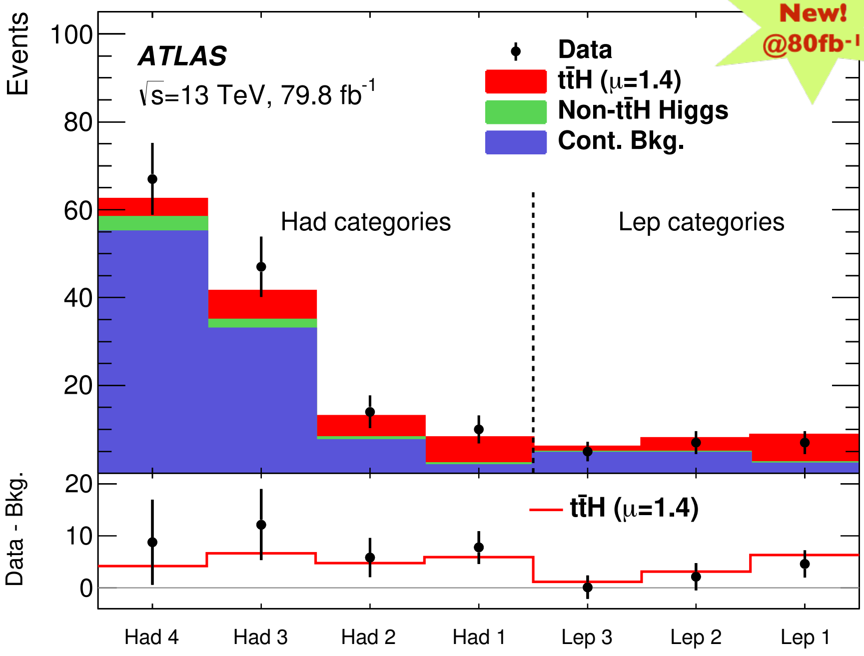
- Further categorization based on **XGBoost BDT** discriminant value: **4 hadronic** and **3 leptonic** categories

(events w/ low BDT scores rejected)

Input variables to XGBoost BDT:
photons 4-vectors ($p_T/m_{\gamma\gamma}$), jets,
E_T^{miss} (both cat),
lepton(s) (lep cat),
b-tag (had cat)

Training *tt+H* (from simulation) vs. main backgrounds:
γγ, *tt+γγ* (from data CRs), other *H* (from simulation)

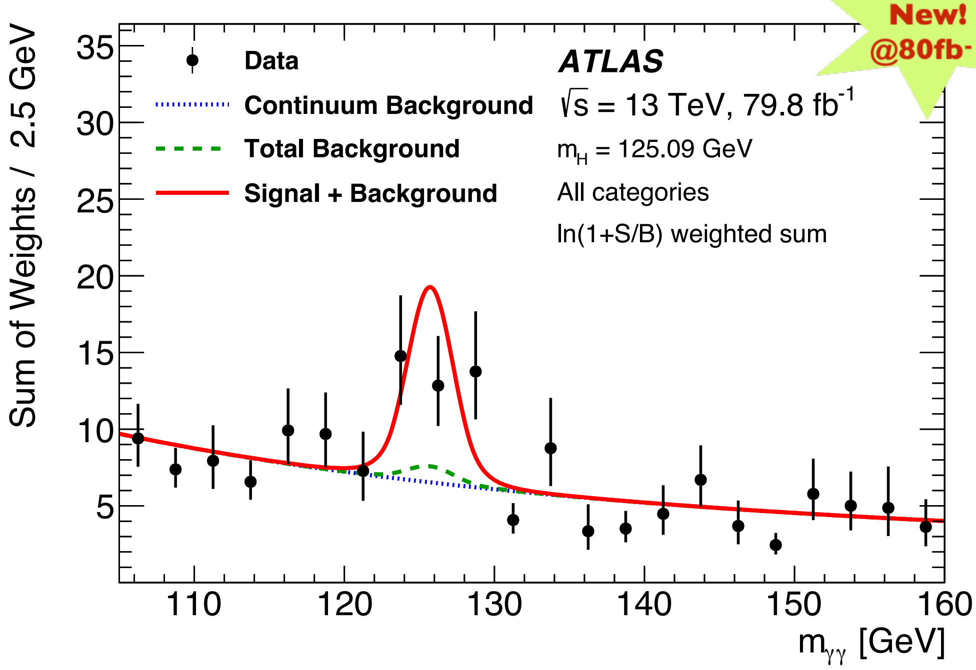


New!
@80fb^{-1}

tt+H ($\gamma\gamma$): results

Background estimation and **signal extraction**
performed by simultaneous **unbinned fit** of **$m_{\gamma\gamma}$** spectra (105-160 GeV) in all **7 categories**:

- Higgs signal parametrization: double-sided Crystal Ball function
- Continuous background parametrization: smooth function (power-law or exponential)

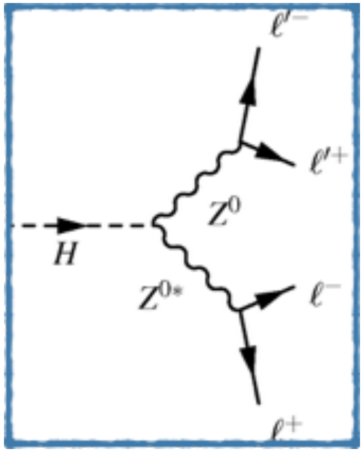


New!
@80fb^{-1}

Dominant uncertainties
statistical (~29%)
tt+H parton shower model (8%)
photon isolation, energy resolution & scale (8%)
jet energy scale & resolution (6%)

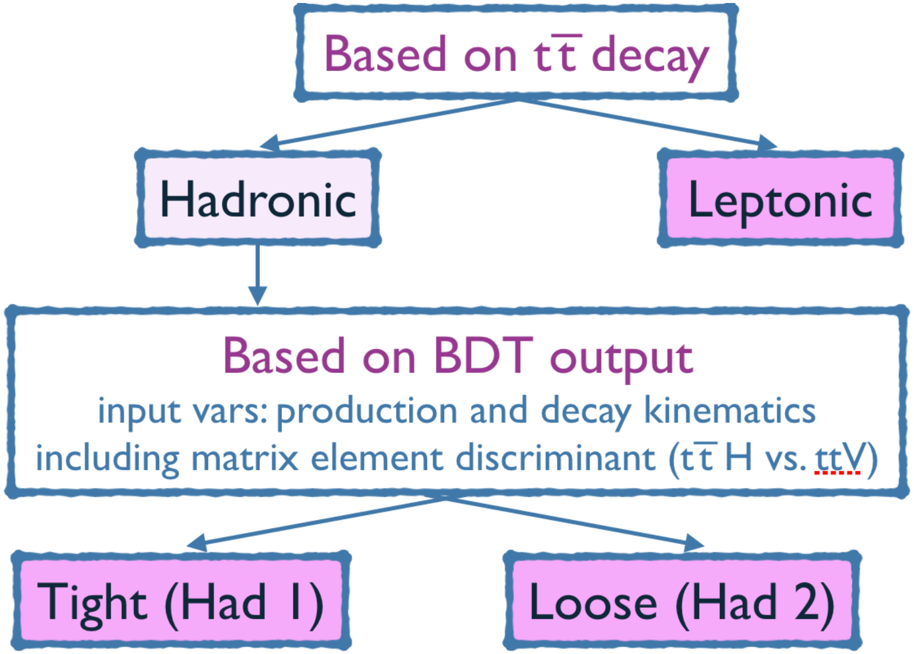
Significance:
4.1 σ (expected 3.7 σ)

tt+H (ZZ*→4l)



- Extremely low rate ☹
- Very clean final state with high S/B ☺

Analysis strategy (new!)



Based on $t\bar{t}$ decay

Hadronic

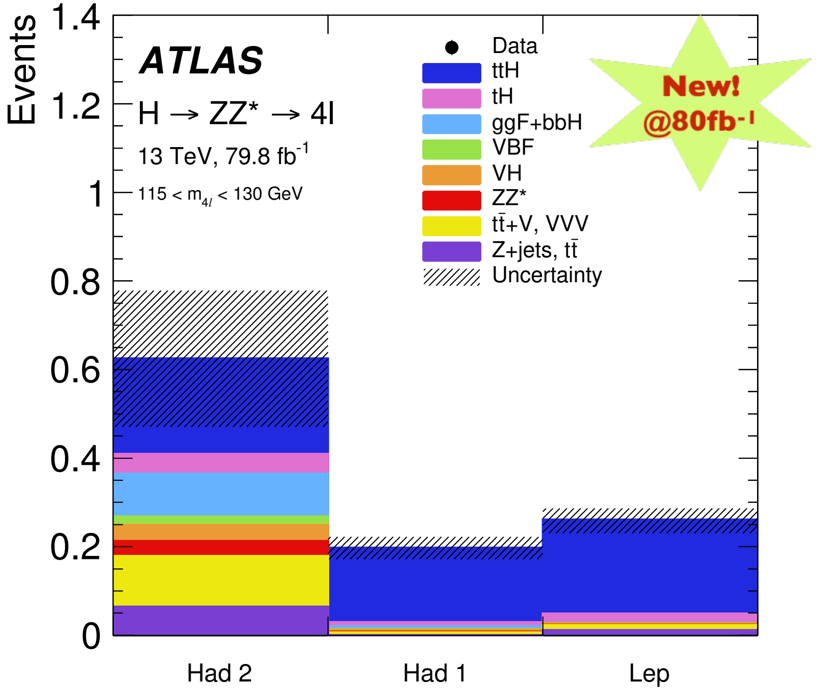
Leptonic

Based on BDT output

input vars: production and decay kinematics including matrix element discriminant ($t\bar{t}$H vs. ttV)

Tight (Had 1)

Loose (Had 2)



New! @80fb^{-1}

Simultaneous fit to all regions → no events observed

Exp. significance: expected 1.2 σ

Very statistically limited

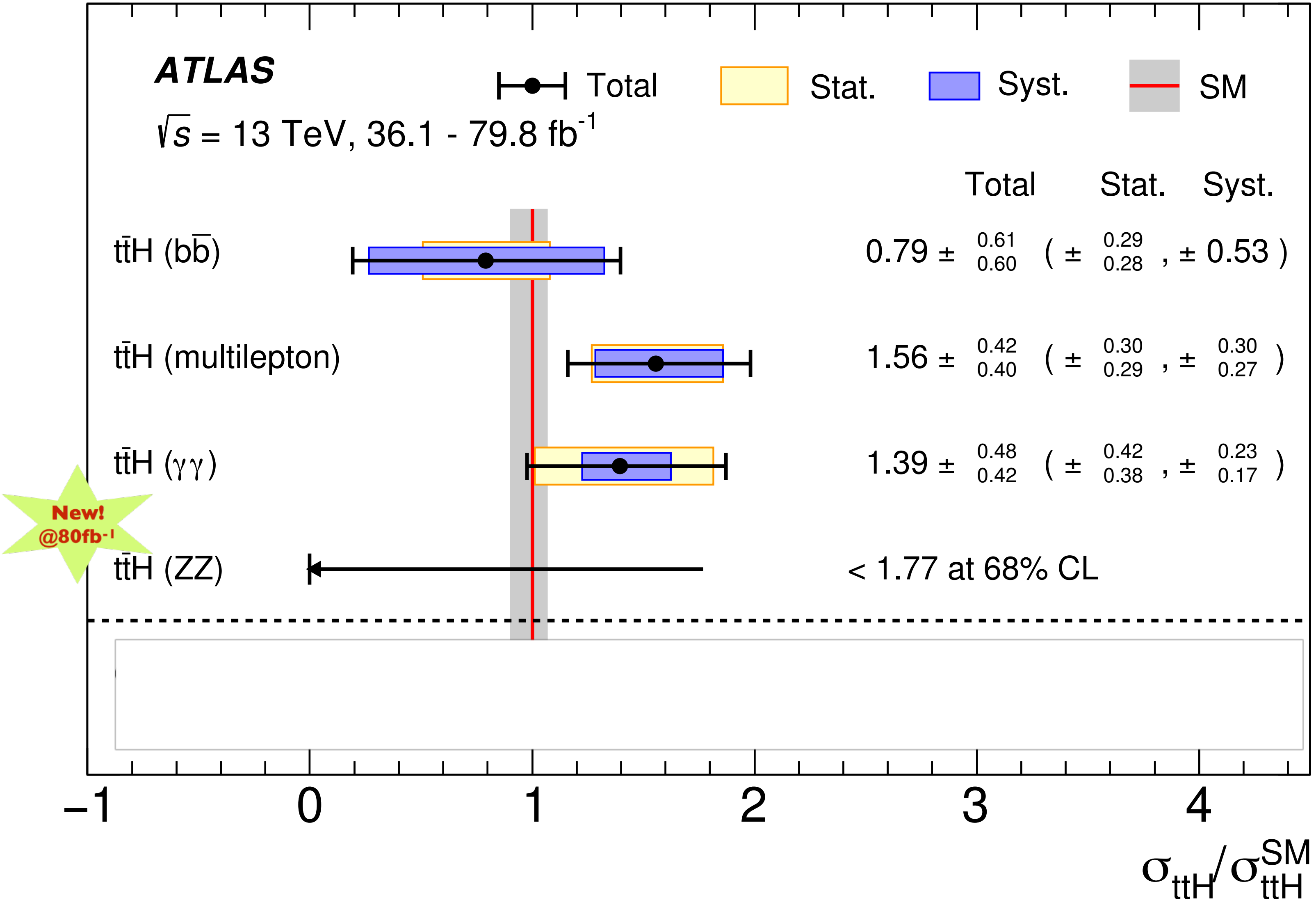
tt+H (γγ & ZZ*→4l)

- Extremely low rate ☹
- Very clean final state with high S/B ☺

New!
@80fb^{-1}

Bin	Expected				Observed
	$t\bar{t}H$ (signal)	Non-$t\bar{t}H$ Higgs	Non-Higgs	Total	Total
		$H \to \gamma\gamma$			
Had 1	4.2(11)	0.49(33)	1.76(55)	6.4(13)	10
Had 2	3.41(74)	0.69(56)	7.5(11)	11.6(15)	14
Had 3	4.70(88)	2.0(17)	32.9(22)	39.6(32)	47
Had 4	3.00(55)	3.2(31)	55.0(28)	61.3(47)	67
Lep 1	4.5(10)	0.25(9)	2.19(59)	6.9(12)	7
Lep 2	2.23(39)	0.27(10)	4.59(91)	7.1(10)	7
Lep 3	0.82(18)	0.30(13)	4.58(91)	5.70(88)	5
		$H \to ZZ^* \to 4\ell$			
Had 1	0.169(31)	0.021(7)	0.008(8)	0.198(33)	0
Had 2	0.216(32)	0.20(9)	0.22(12)	0.63(16)	0
Lep	0.212(31)	0.0256(23)	0.015(13)	0.253(34)	0

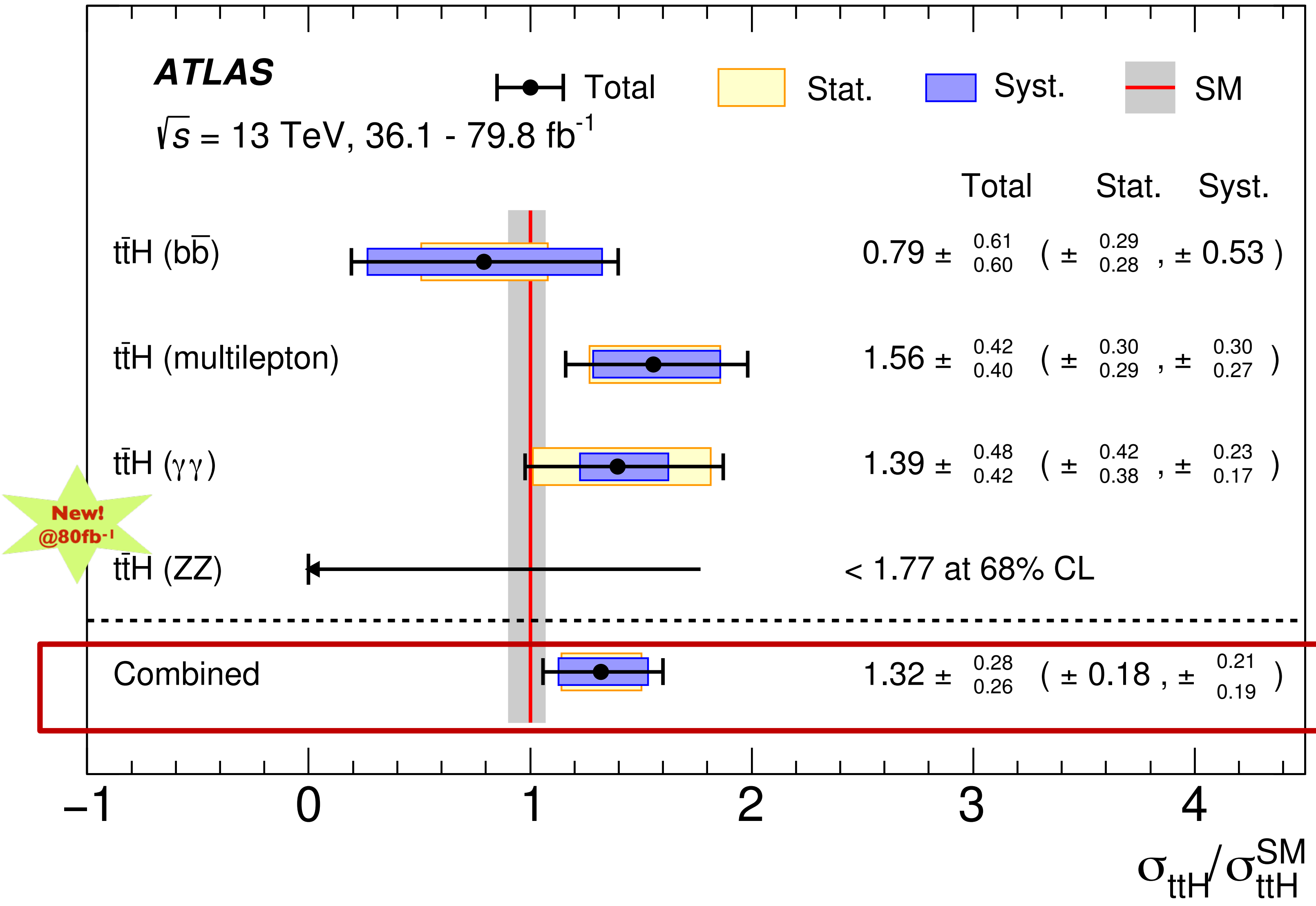
tt+H combination



Significance

Obs.	Exp.
1.6 σ	1.4 σ
4.1 σ	2.8 σ
4.1 σ	3.8 σ
0 σ	1.2 σ

tt+H combination



New!
@80fb-1

Significance

Obs.	Exp.
1.6 σ	1.4 σ
4.1 σ	2.8 σ
4.1 σ	3.8 σ
0 σ	1.2 σ
5.8 σ	**4.9 σ**

With Run 1:

6.3 σ **5.1 σ**

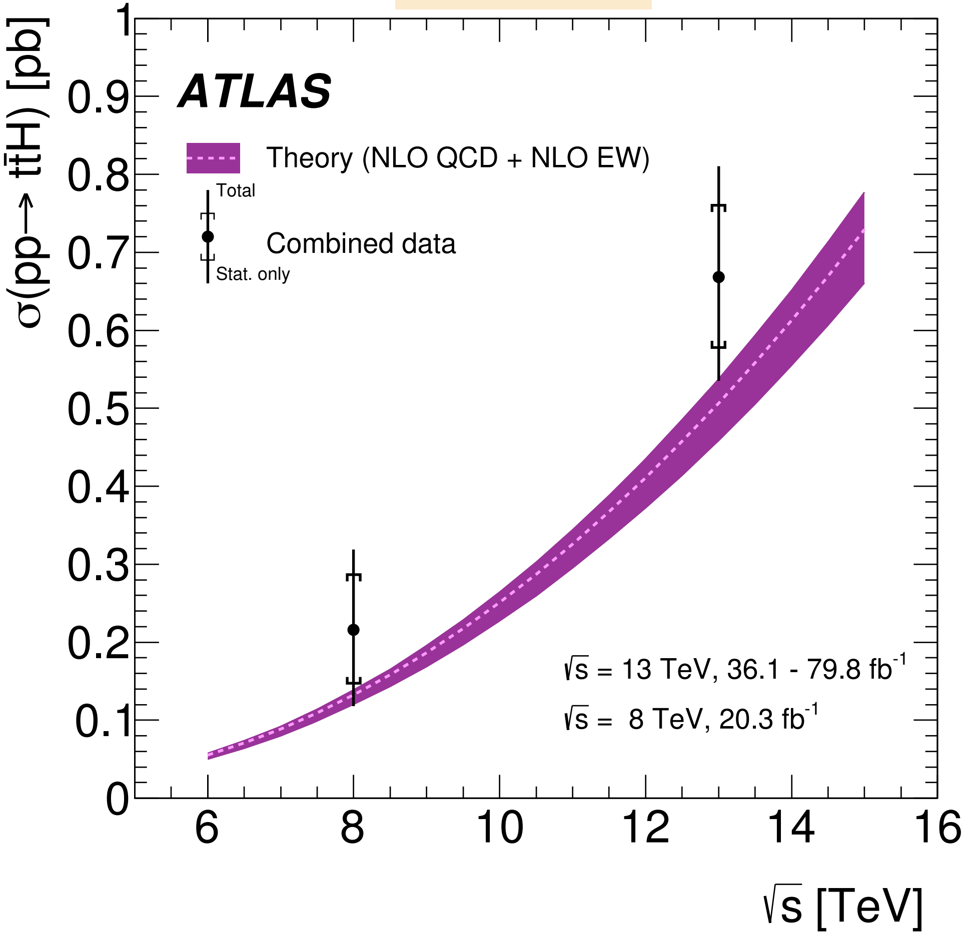
ttH cross-section measurement and top-Yukawa coupling

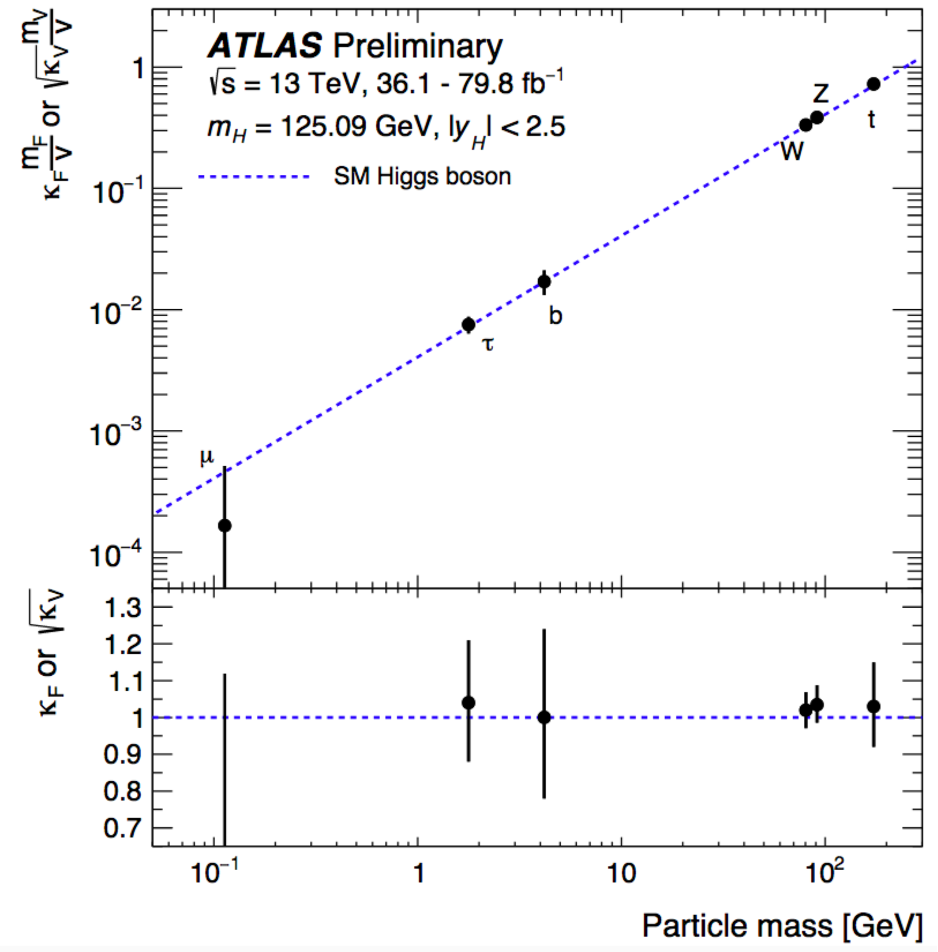
$$\sigma_{t\bar{t}H}(13TeV) = 670 \pm 90(stat)^{+110}_{-100}(sys)fb$$

$$\kappa_t = 1.03^{+0.12}_{-0.11}$$

σ_{ttH}~20%

κ_t~10%





ATLAS-CONF-2018-031

Dominant systematics

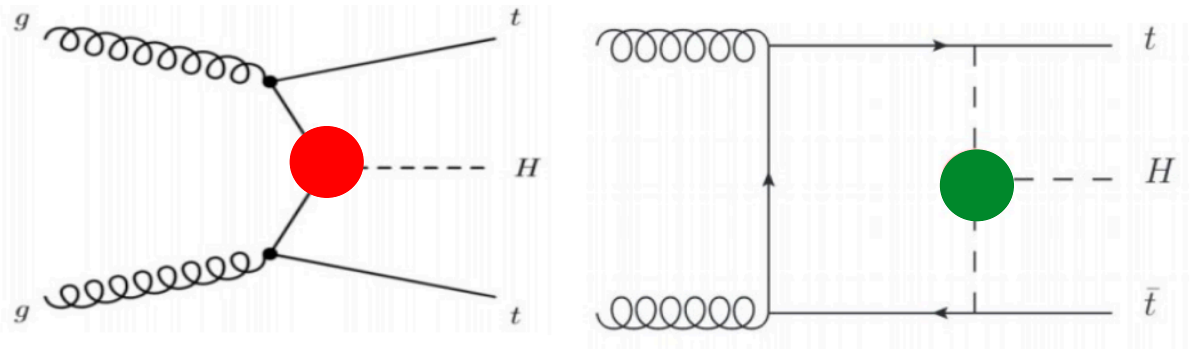
- tt+heavy flavour modelling (10%)
- tt+H modelling (6%)
- Non-prompt leptons (5%)

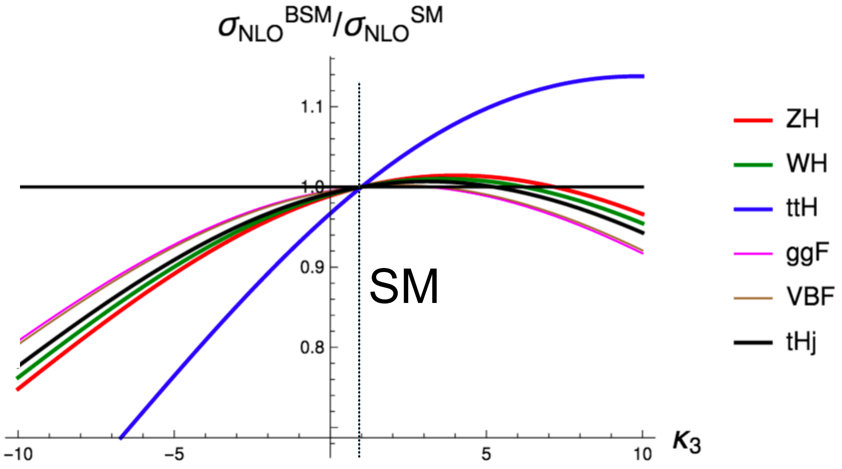
Very similar CMS results…

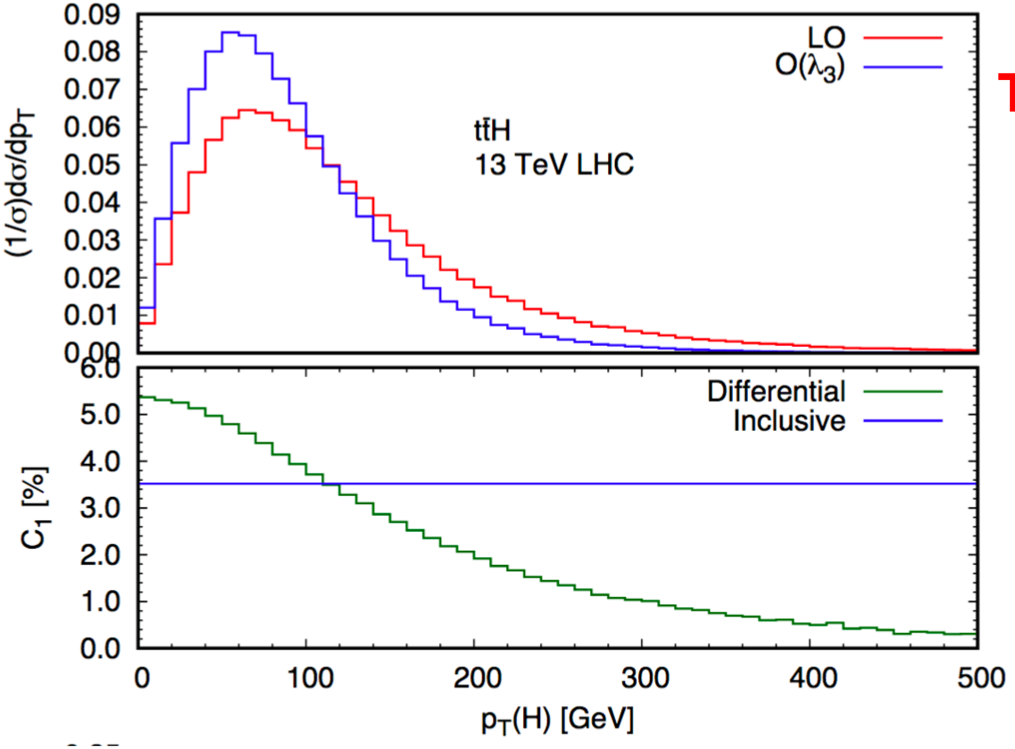
Imagine *ttH* is measured to be different from SM…

Who is the responsible ?

Eur. Phys. J. C (2017) 77: 887







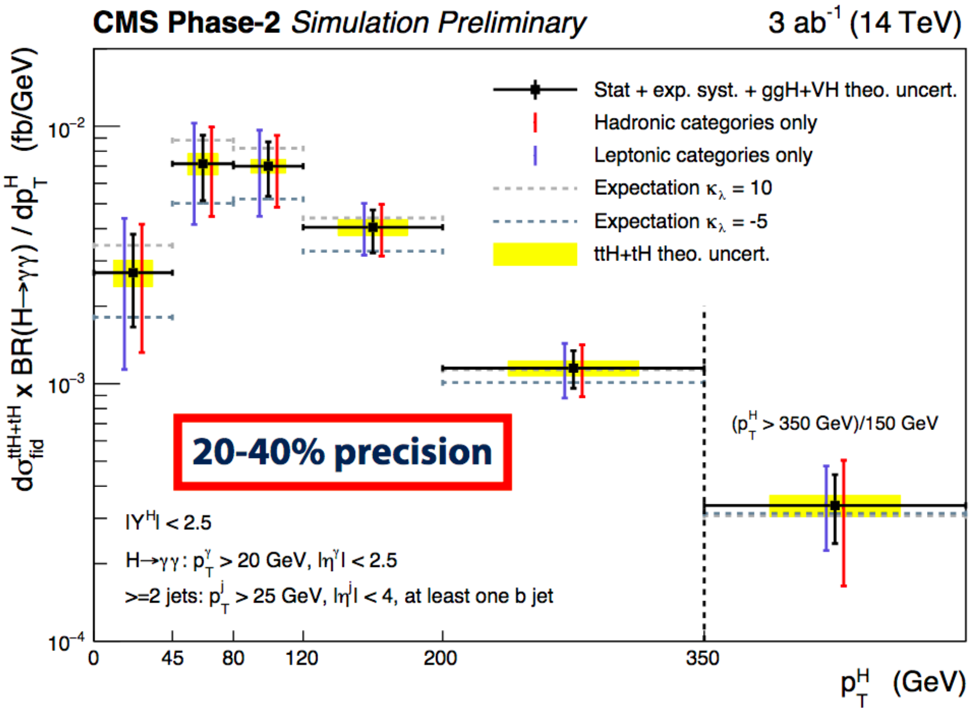
The power of differential measurements:

Variations in Higgs-self coupling (λ_3) will affect the shape of kinematic, e.g. low pt(H) region would be highly affected while it is not deformed in the tail…

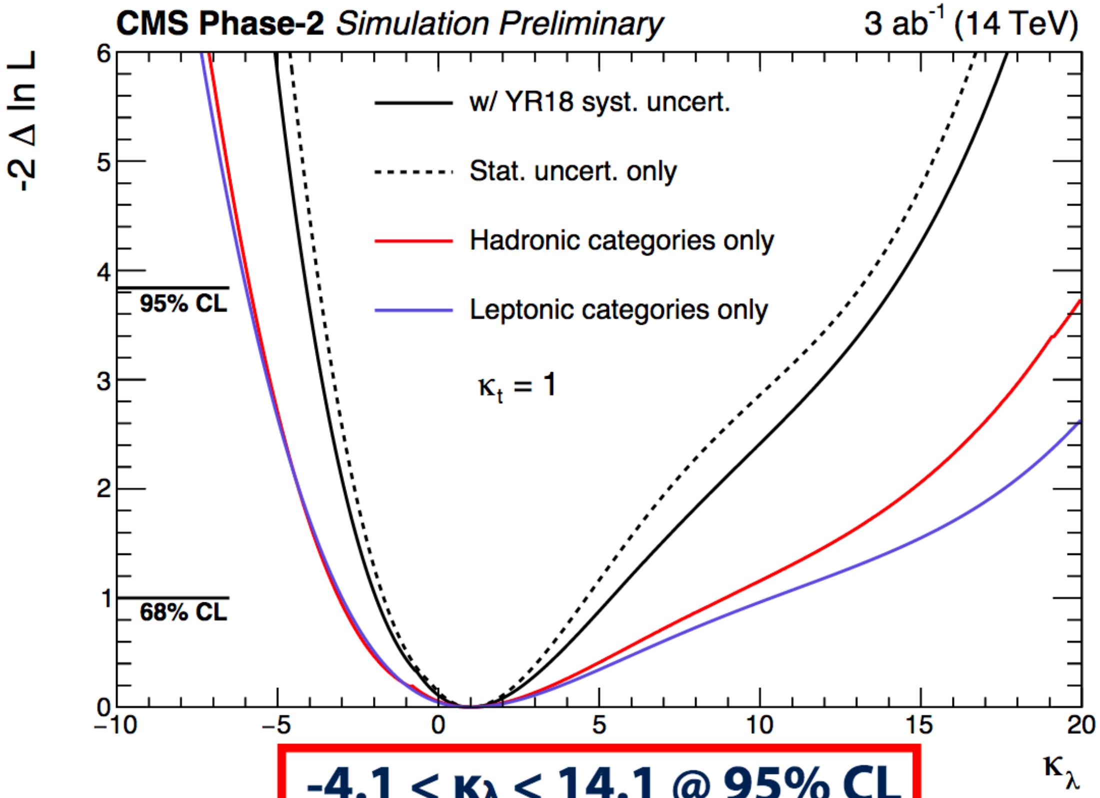
New Physics effects?

: differential measurements

… need to explore *ttH* differential regime …



20-40% precision

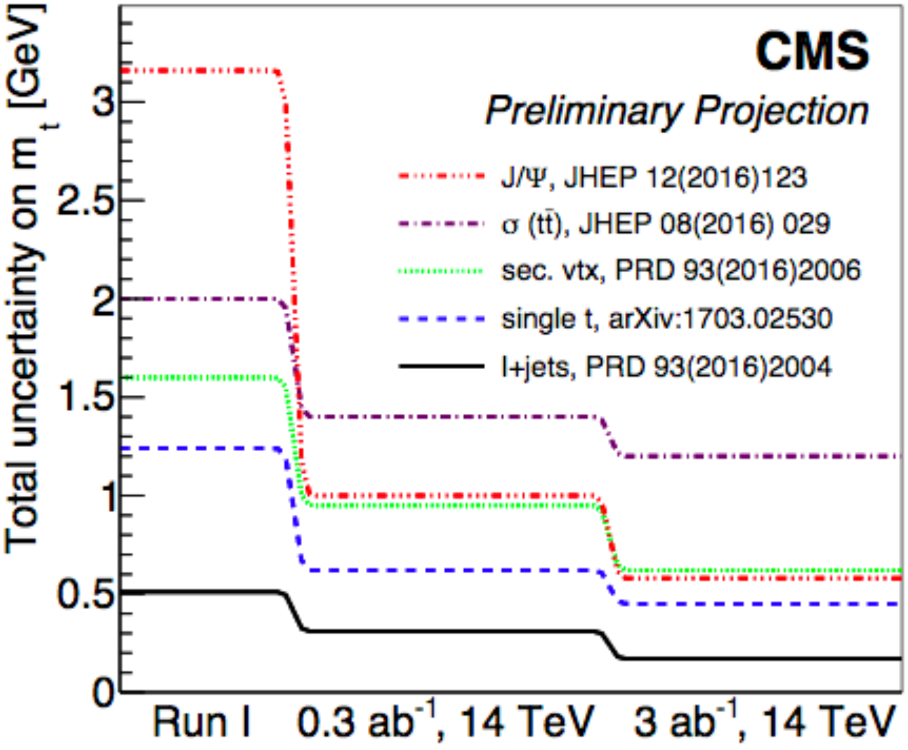


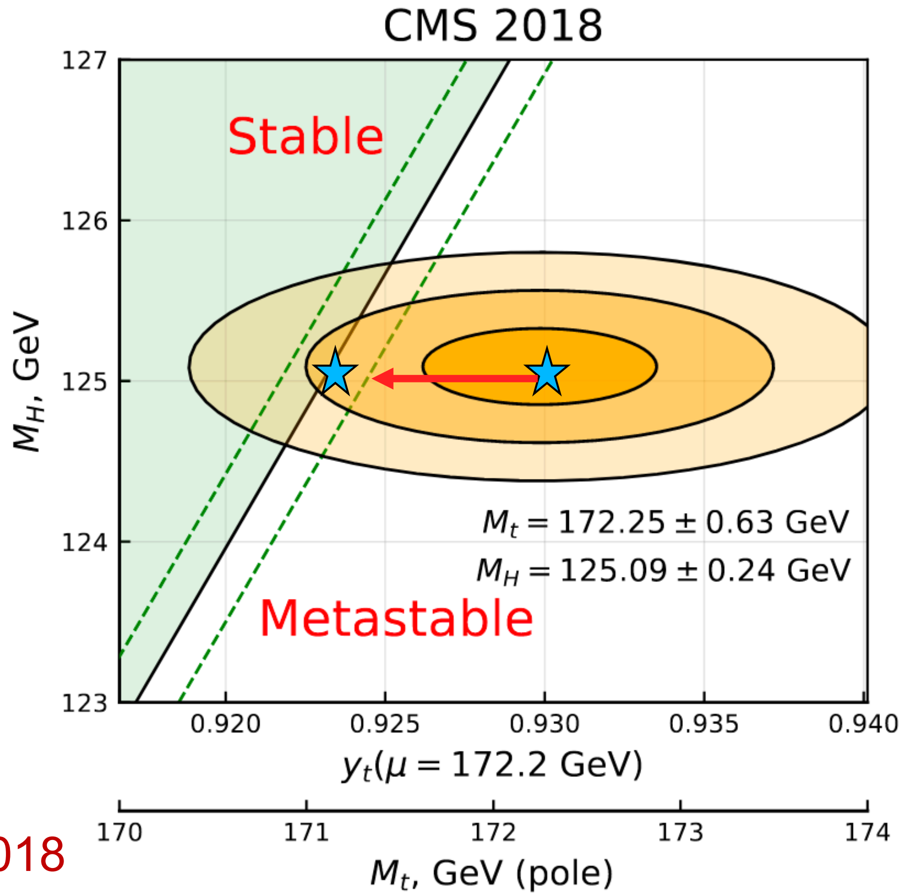
$-4.1 < \kappa_\lambda < 14.1$ @ 95% CL

and also further reduce uncertainties in top quark mass

Expectations for HL-LHC:
κ_t<4% and m_{top}~0.2 GeV (0.1%)

- Outstanding level of precision reached and continue pushing the limit.
- Common effort with the TH/MC community.
- Only 4% of the data have been collected so far,
  → a vast potential for discoveries!
- Exciting program ahead with great opportunities.





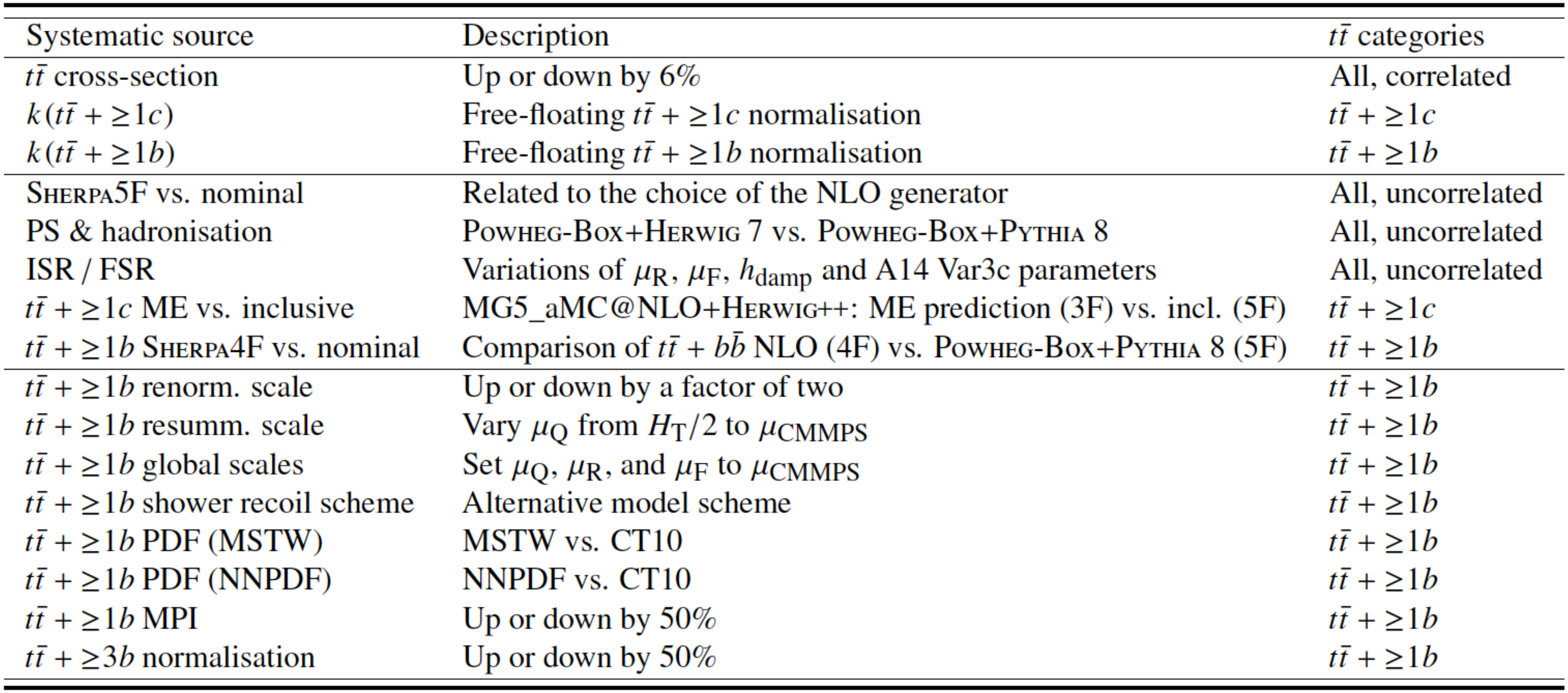
Fedor Bezrukov's talk
@ Higgs Couplings 2018

THANKS FOR YOUR ATTENTION

MERRY CHRISTMAS

BACK-UP

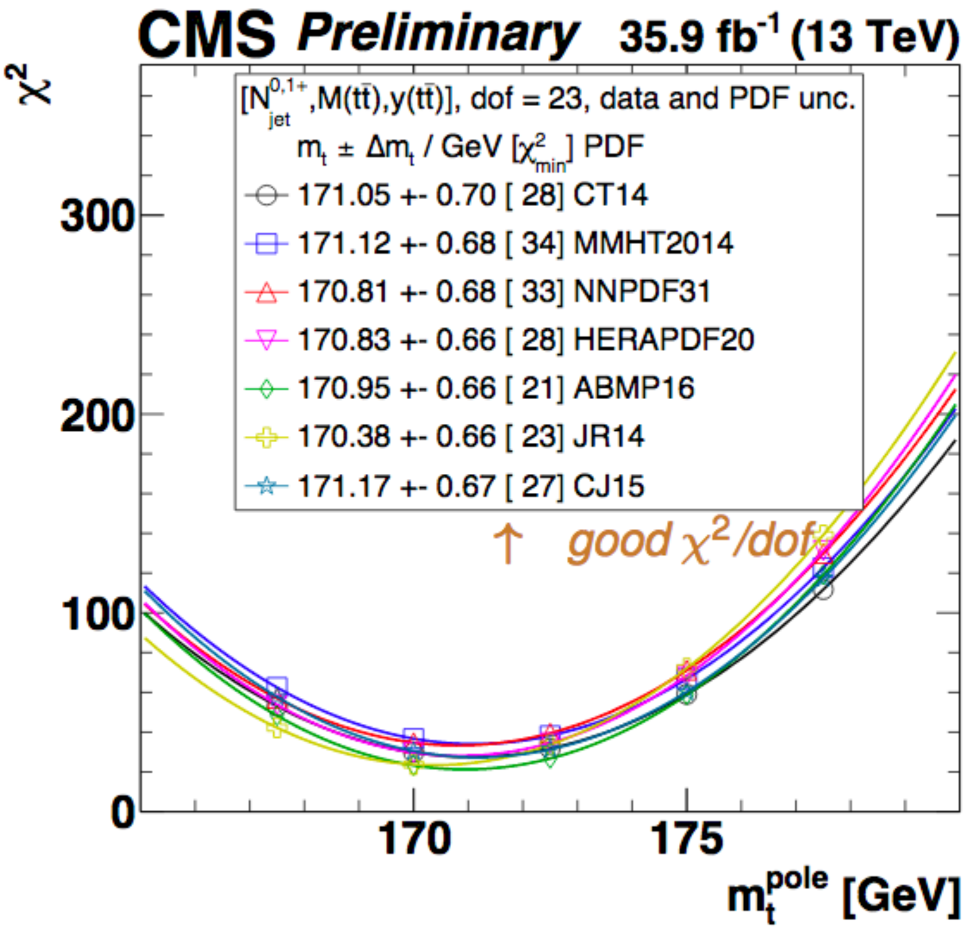
Process	Event generator	ME order	Parton Shower	PDF	Tune
$t\bar{t}H$	MG5_aMC	NLO	Pythia 8	NNPDF 3.0 NLO [71]	A14
	(MG5_aMC)	(NLO)	(Herwig++)	(CT10 [72])	(UE-EE-5)
$tHqb$	MG5_aMC	LO	Pythia 8	CT10	A14
tHW	MG5_aMC	NLO	Herwig++	CT10	UE-EE-5
$t\bar{t}W$	MG5_aMC	NLO	Pythia 8	NNPDF 3.0 NLO	A14
	(Sherpa 2.1.1)	(LO multileg)	(Sherpa)	(NNPDF 3.0 NLO)	(Sherpa default)
$t\bar{t}(Z/\gamma^* \to ll)$	MG5_aMC	NLO	Pythia 8	NNPDF 3.0 NLO	A14
	(Sherpa 2.1.1)	(LO multileg)	(Sherpa)	(NNPDF 3.0 NLO)	(Sherpa default)
tZ	MG5_aMC	LO	Pythia 6	CTEQ6L1	Perugia2012
tWZ	MG5_aMC	NLO	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}t$, $t\bar{t}t\bar{t}$	MG5_aMC	LO	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}W^+W^-$	MG5_aMC	LO	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}$	Powheg-BOX v2 [73]	NLO	Pythia 8	NNPDF 3.0 NLO	A14
$t\bar{t}\gamma$	MG5_aMC	LO	Pythia 8	NNPDF 2.3 LO	A14
s-, t-channel, Wt single top	Powheg-BOX v1 [74,75,76]	NLO	Pythia 6	CT10	Perugia2012
$VV(\to llXX)$, $qqVV$, VVV	Sherpa 2.1.1	MEPS NLO	Sherpa	CT10	Sherpa default
$Z \to l^+l^-$	Sherpa 2.2.1	MEPS NLO	Sherpa	NNPDF 3.0 NLO	Sherpa default

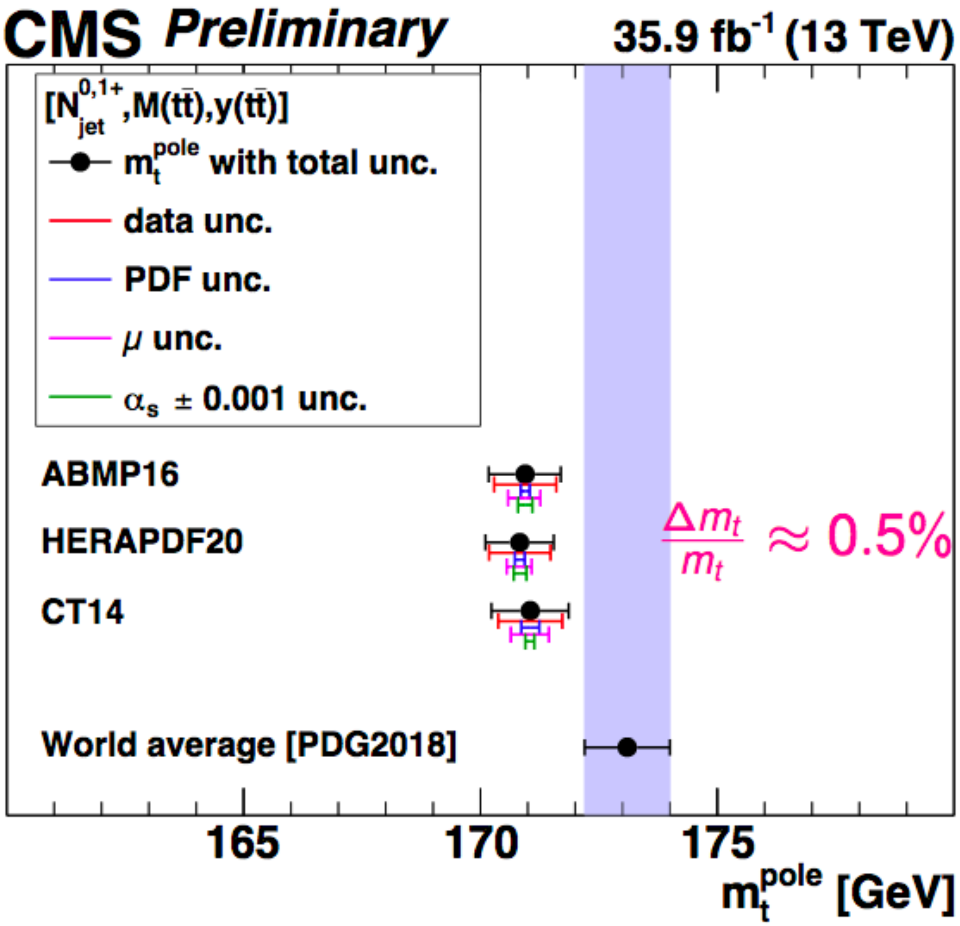


Systematic source	Description	$t\bar{t}$ categories
$t\bar{t}$ cross-section	Up or down by 6%	All, correlated
$k(t\bar{t}+\geq 1c)$	Free-floating $t\bar{t}+\geq 1c$ normalisation	$t\bar{t}+\geq 1c$
$k(t\bar{t}+\geq 1b)$	Free-floating $t\bar{t}+\geq 1b$ normalisation	$t\bar{t}+\geq 1b$
SHERPA5F vs. nominal	Related to the choice of the NLO generator	All, uncorrelated
PS & hadronisation	POWHEG-BOX+HERWIG 7 vs. POWHEG-BOX+PYTHIA 8	All, uncorrelated
ISR / FSR	Variations of μ_{R}, μ_{F}, h_{damp} and A14 Var3c parameters	All, uncorrelated
$t\bar{t}+\geq 1c$ ME vs. inclusive	MG5_aMC@NLO+HERWIG++: ME prediction (3F) vs. incl. (5F)	$t\bar{t}+\geq 1c$
$t\bar{t}+\geq 1b$ SHERPA4F vs. nominal	Comparison of $t\bar{t}+b\bar{b}$ NLO (4F) vs. POWHEG-BOX+PYTHIA 8 (5F)	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ renorm. scale	Up or down by a factor of two	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ resumm. scale	Vary μ_{Q} from $H_{\mathrm{T}}/2$ to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ global scales	Set μ_{Q}, μ_{R}, and μ_{F} to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ shower recoil scheme	Alternative model scheme	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ PDF (MSTW)	MSTW vs. CT10	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ PDF (NNPDF)	NNPDF vs. CT10	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 3b$ normalisation	Up or down by 50%	$t\bar{t}+\geq 1b$

- Many sources of modelling uncertainty considered:
  - Generator: Powheg+Pythia8 vs. Sherpa (5F)
  - Parton shower: Powheg+Pythia8 vs. Powheg+Herwig7
  - 5F vs. 4F in Sherpa+OpenLoops
  - Scale variations in Sherpa+OpenLoops
- All $t\bar{t}$+jets modelling uncertainties uncorrelated between $t\bar{t}+\geq 1b/\geq 1c/$light
- Scale variation uncertainties correlated across each $t\bar{t}+\geq 1b$ sub-component

Extraction of top quark pole mass from $N^{0,1+}_{jet}$,M(tt),y(tt)]



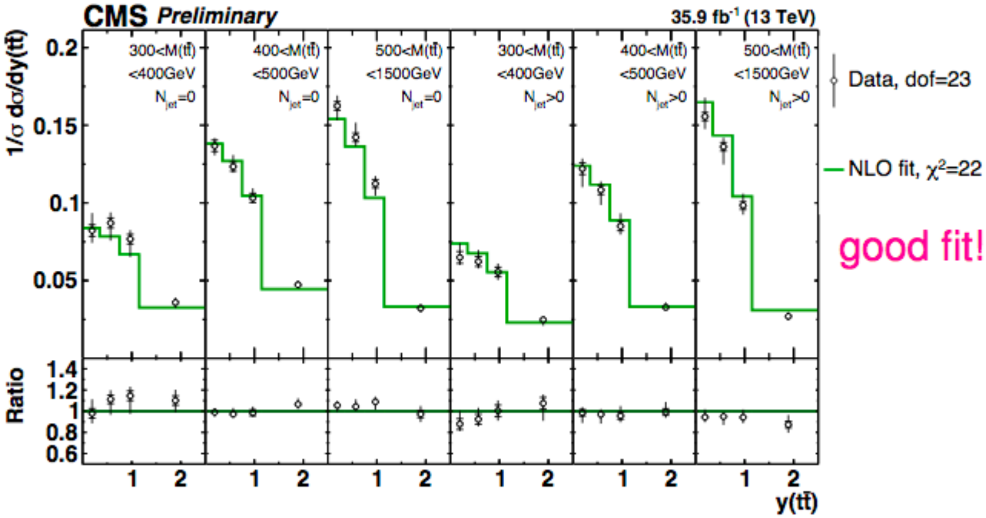


- used α_s from each PDF set ($\alpha_s = 0.118$ in CT and HERAPDF, $\alpha_s = 0.119$ in ABMP)
- precise determination of m_t^{pole} is possible using these data
- no significant dependence on PDF set

Simultaneous PDF+α_S+top quark pole mass fit

- followed standard approach: using HERA DIS data only, or HERA + $t\bar{t}$ data to demonstrate added value from $t\bar{t}$ on PDF and α_s determination
- settings follow HERAPDF2.0 fit (very similar to TOP-14-013), use xFitter-2.0.0
- input data: combined HERA DIS [1506.06042] + $t\bar{t}$ (further details in BACKUP)

Data sets	χ^2/dof	
	Nominal fit	$+[N_{\text{jet}}, y(\text{t}\bar{\text{t}}), \text{M}(\text{t}\bar{\text{t}})]$
CMS $\text{t}\bar{\text{t}}$		10/23
HERA CC e^-p, $E_p = 920$ GeV	55/42	55/42
HERA CC e^+p, $E_p = 920$ GeV	38/39	39/39
HERA NC e^-p, $E_p = 920$ GeV	218/159	217/159
HERA NC e^+p, $E_p = 920$ GeV	438/377	448/377
HERA NC e^+p, $E_p = 820$ GeV	70/70	71/70
HERA NC e^+p, $E_p = 575$ GeV	220/254	222/254
HERA NC e^+p, $E_p = 460$ GeV	219/204	220/204
Correlated χ^2	82	90
Log-penalty χ^2	+2	−7
Total χ^2/dof	1341/1130	1364/1151



good fit!

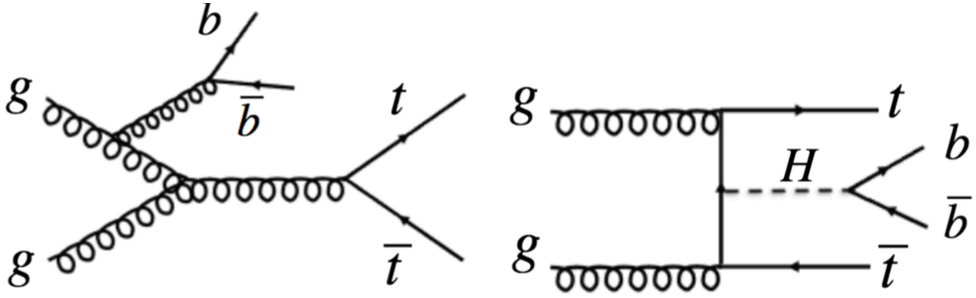
$$\alpha_s(M_Z) = 0.1135 \pm 0.0016(\text{fit})^{+0.0002}_{-0.0004}(\text{mod})^{+0.0008}_{-0.0001}(\text{par})^{+0.0011}_{-0.0005}(\text{scale}) = 0.1135^{+0.0021}_{-0.0017}(\text{total})$$

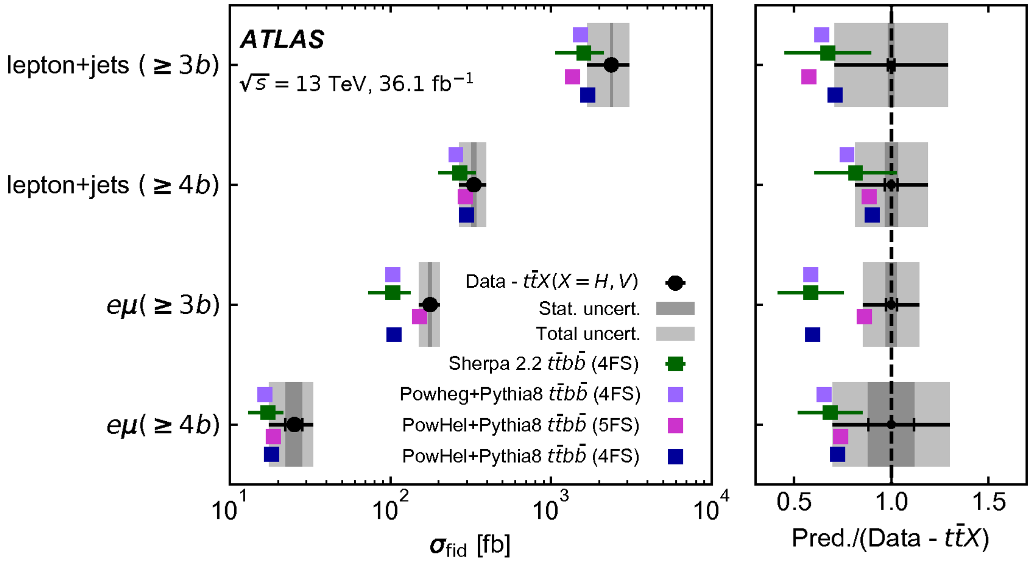
$$m_t^{\text{pole}} = 170.5 \pm 0.7(\text{fit})^{+0.1}_{-0.1}(\text{mod})^{+0.0}_{-0.1}(\text{par})^{+0.3}_{-0.3}(\text{scale})\ \text{GeV} = 170.5 \pm 0.8(\text{total})\ \text{GeV}$$

→ two SM parameters are simultaneously determined from these data to high precision with only weak correlation between them ($\rho = 0.3$) + constraints on PDFs (next slides)

https://indico.cern.ch/event/746611/contributions/3202851/attachments/1755641/

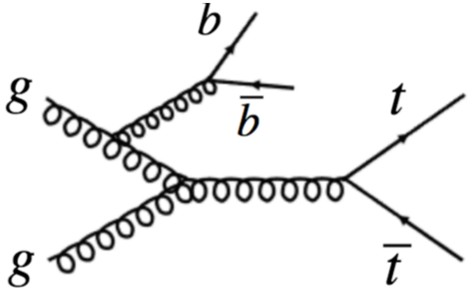
Top quark coupling to gluons and g→bb splitting: tt+bb

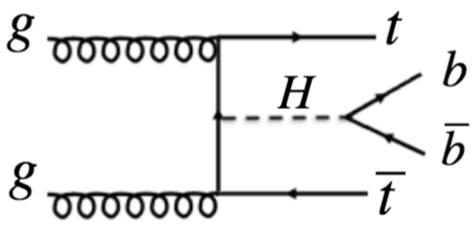


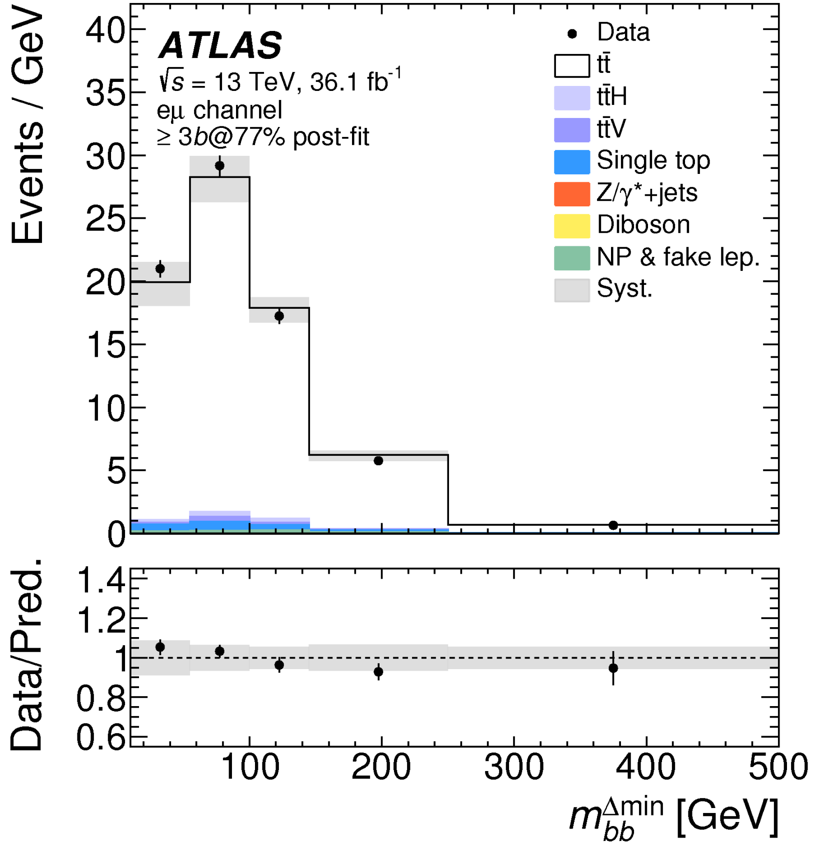


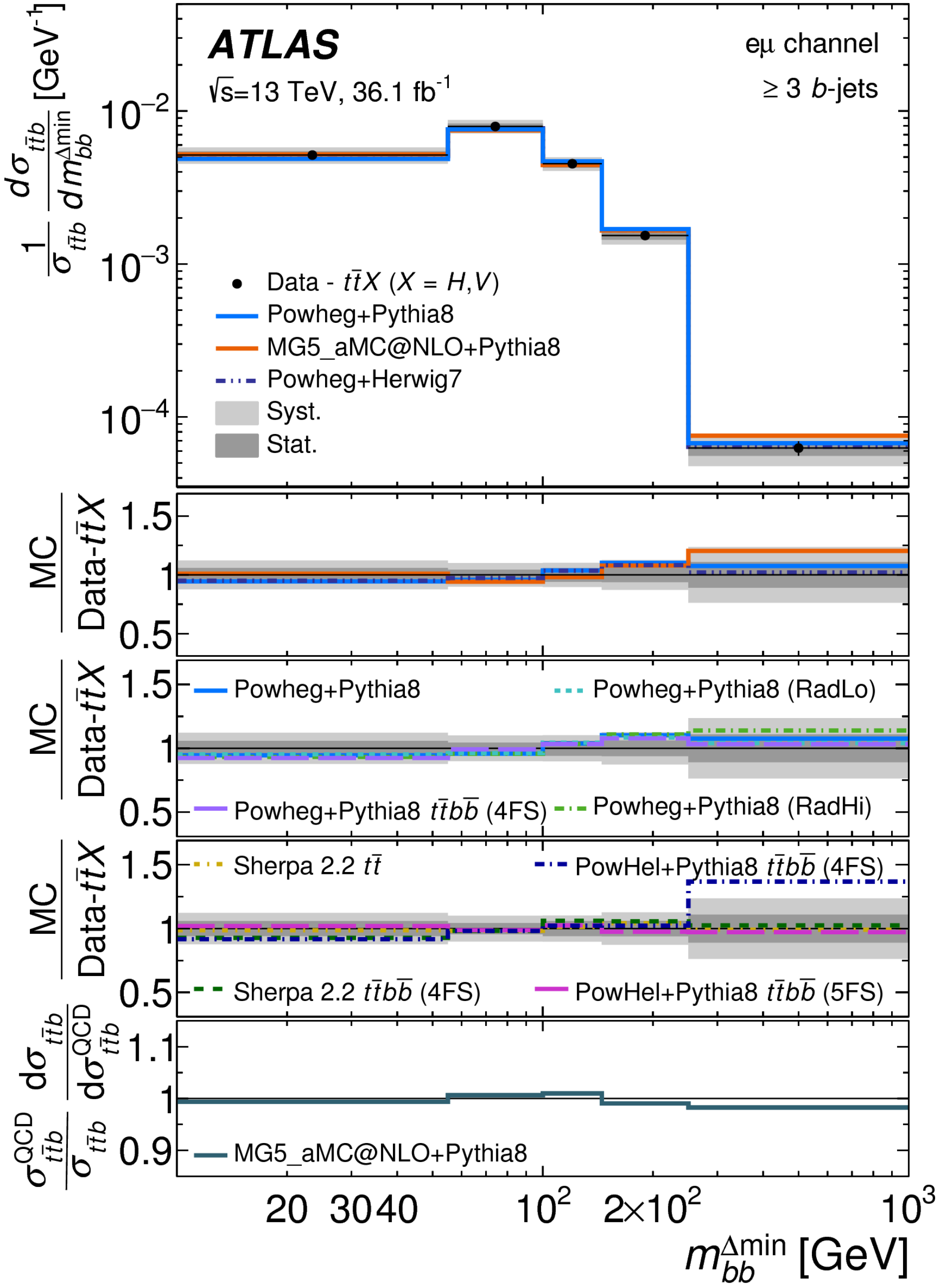
Generator sample	Process	Matching	Tune	Use
POWHEG-BOX v2 + PYTHIA 8.210	$t\bar{t}$ NLO	POWHEG $h_{\text{damp}} = 1.5m_t$	A14	nom.
MADGRAPH5_aMC@NLO + PYTHIA 8.210	$t\bar{t} + V/H$ NLO	MC@NLO	A14	nom.
POWHEG-BOX v2 + PYTHIA 8.210 RadLo	$t\bar{t}$ NLO	POWHEG $h_{\text{damp}} = 1.5m_t$	A14Var3cDown	syst.
POWHEG-BOX v2 + PYTHIA 8.210 RadHi	$t\bar{t}$ NLO	POWHEG $h_{\text{damp}} = 3.0m_t$	A14Var3cUp	syst.
POWHEG-BOX v2 + HERWIG 7.01	$t\bar{t}$ NLO	POWHEG $h_{\text{damp}} = 1.5m_t$	H7UE	syst.
SHERPA 2.2.1 $t\bar{t}$	$t\bar{t}$ +0,1 parton at NLO +2,3,4 partons at LO	MEPS@NLO	SHERPA	syst.
MADGRAPH5_aMC@NLO + PYTHIA 8.210	$t\bar{t}$ NLO	MC@NLO	A14	comp.
SHERPA 2.2.1 $t\bar{t}b\bar{b}$ (4FS)	$t\bar{t}b\bar{b}$ NLO	MC@NLO	SHERPA	comp.
POWHEG-BOX v2 + PYTHIA 8.210 $t\bar{t}b\bar{b}$ (4FS)	$t\bar{t}b\bar{b}$ NLO	POWHEG $h_{\text{damp}} = H_T/2$	A14	comp.
POWHEL + PYTHIA 8.210 (4FS)	$t\bar{t}b\bar{b}$ NLO	POWHEG $h_{\text{damp}} = H_T/2$	A14	comp.
POWHEL + PYTHIA 8.210 (5FS)	$t\bar{t}b\bar{b}$ NLO	POWHEG $h_{\text{damp}} = H_T/2$	A14	comp.

Top quark coupling to gluons and g→bb splitting: tt+bb



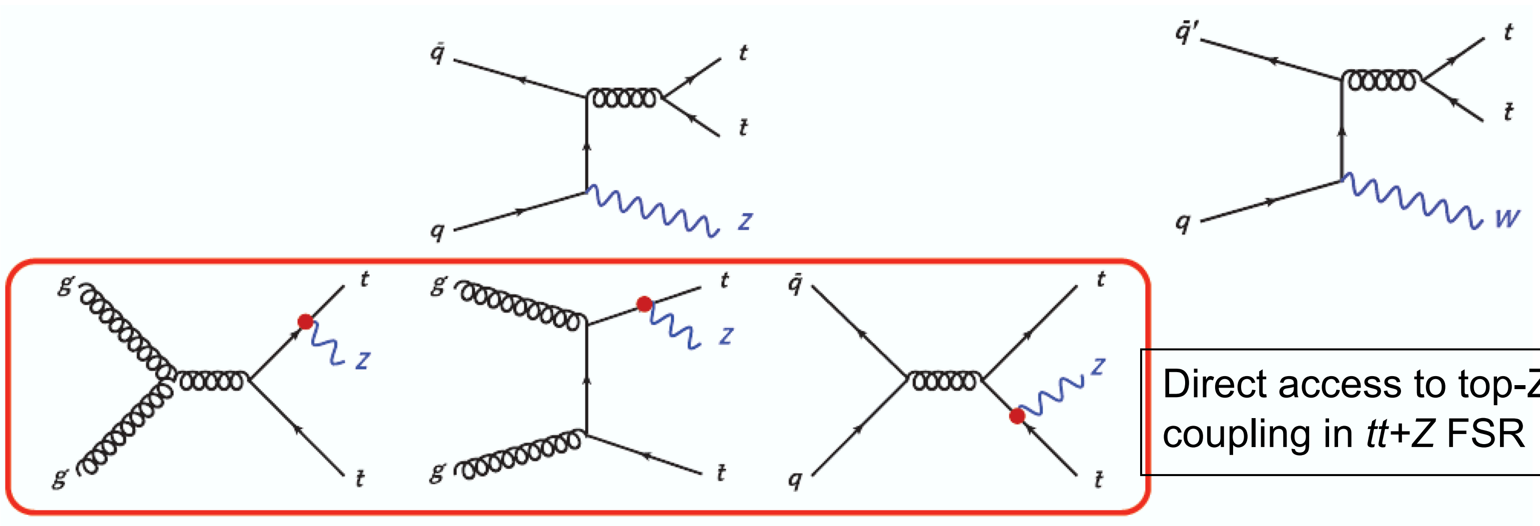






Top coupling to vector bosons: *tt+Z/W*

ttZ: directly sensitive to neutral current top coupling
ttW: charge asymmetric process, source of same-sign leptons,
→ Both are backgrounds for new physics searches and ttH(ML) process



Direct access to top-Z coupling in *tt*+*Z* FSR

observation with LHC Run-I 8 TeV data

New 13 TeV results ATLAS-CONF-2018-047

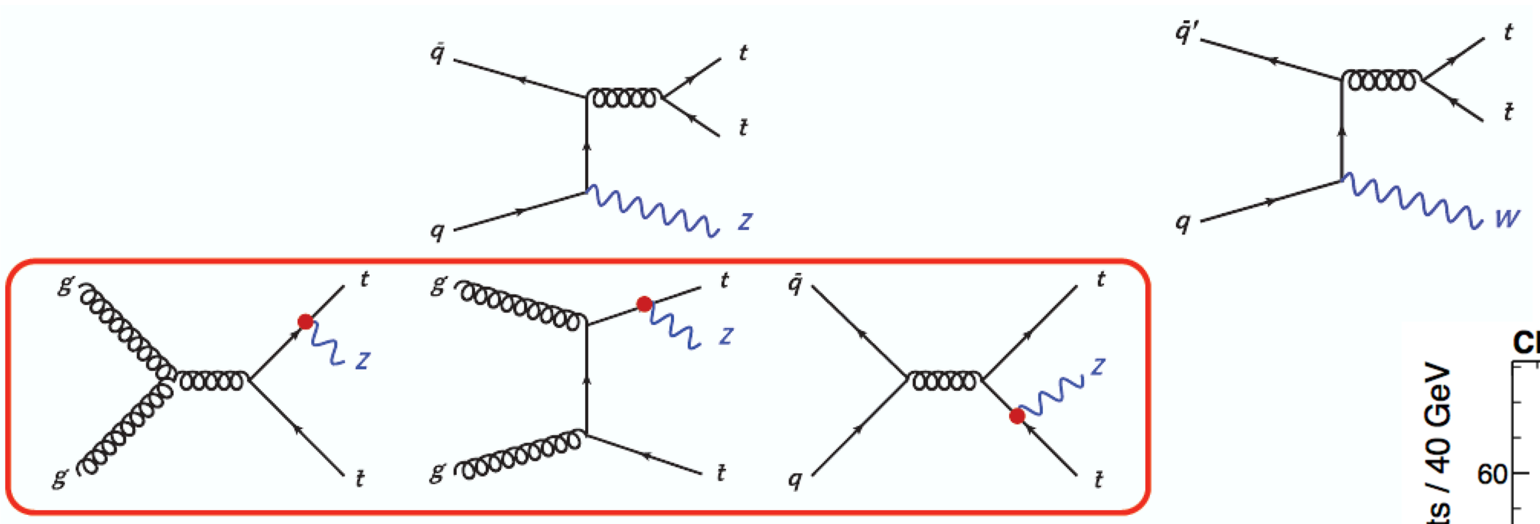
$$\gamma^{\mu}(C_V^{SM} - \gamma_5 C_A^{SM})$$

$$C_V^{SM} = T^3 - 2Q_t sin^2(\theta_W)$$

$$C_A^{SM} = T^3$$

Top coupling to vector bosons: *tt+Z/W*

ttZ: directly sensitive to neutral current top coupling
ttW: charge asymmetric process, source of same-sign leptons,
→ Both are backgrounds for new physics searches and ttH(ML) process

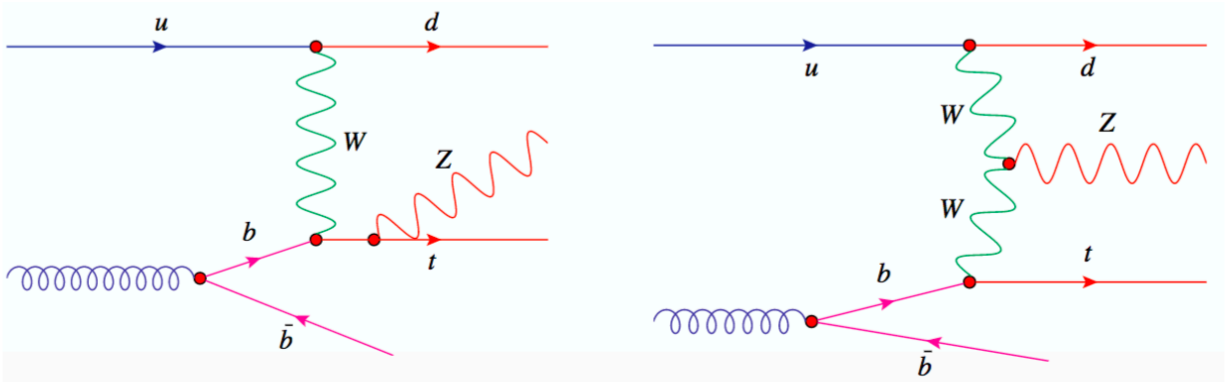


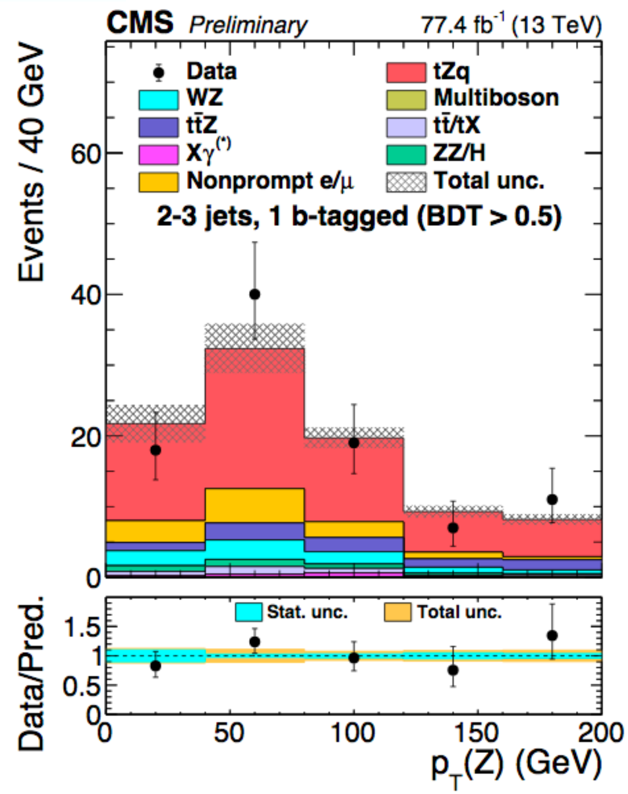
observation with LHC Run-I 8 TeV data

New 13 TeV results
ATLAS-CONF-2018-047

tZq: probes both *tZ* and *WWZ* coupling

observation reported by CMS two weeks ago





tt+Z/W: many experimental signatures

- Experimental analyses focus on 2l OS or SS, 3l and 4l channels with e and/or μ.

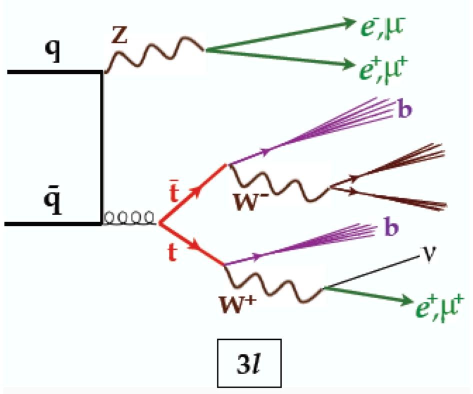
Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W$	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{\pm}\nu$	SS dilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{\pm}\nu$	Trilepton
$t\bar{t}Z$	$(q\bar{q}b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	OS dilepton
	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	Trilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{+}\ell^{-}$	Tetralepton

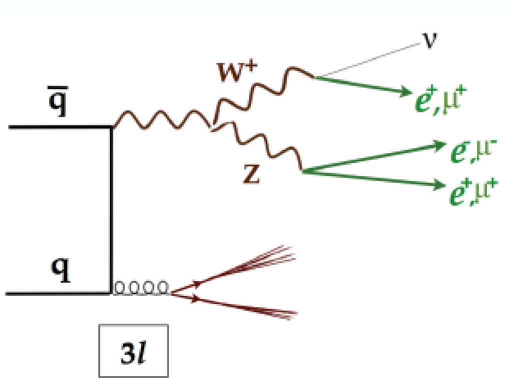
Z decay modes:
BR($Z \rightarrow ee/\mu\mu/\tau\tau$): 0.10
BR($Z \rightarrow \nu\nu$): 0.20
BR($Z \rightarrow jj$): 0.70

- Channels further split according to lepton flavour/charges, # jets, etc.
- Statistics, S/B ratio and main backgrounds vary across channels

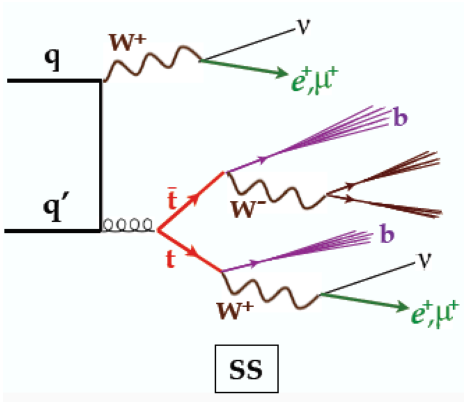
2lOSZ: Z+jets
3lZ: WZ+jets
4lZ: ZZ+jets

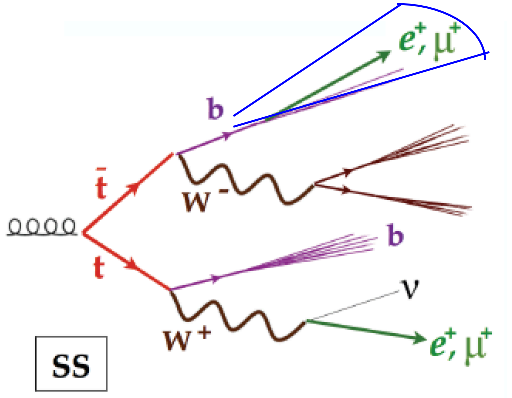
2lSS: non-prompt leptons





WZ(+HF)



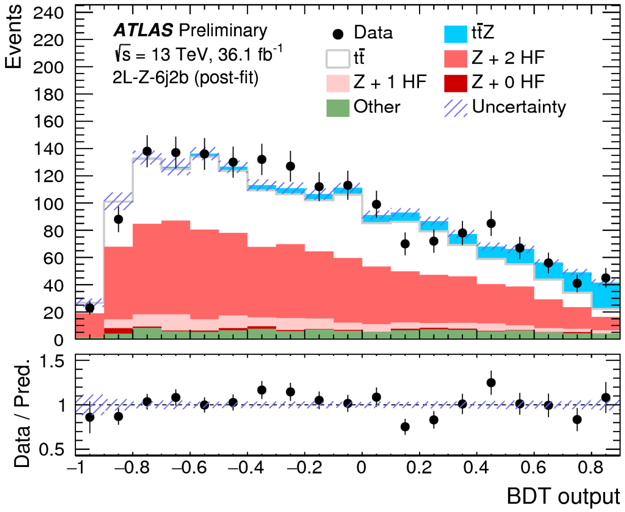


non-prompt ℓ (from tt̄)

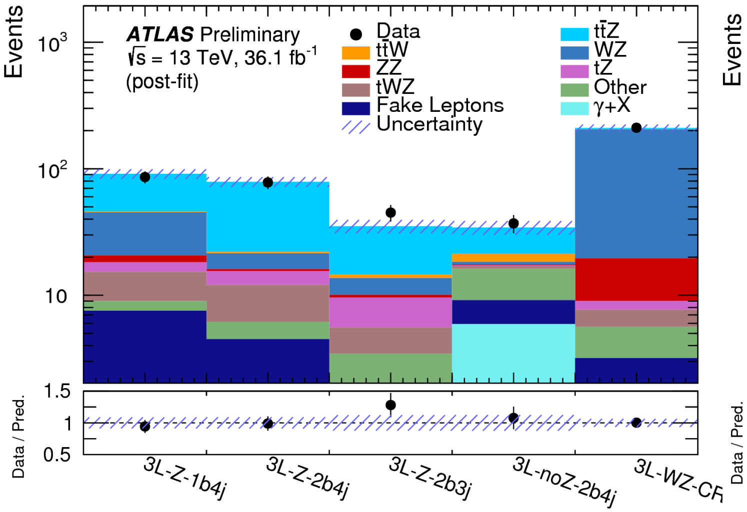
tt+Z/W: several analysis regions

tt+Z

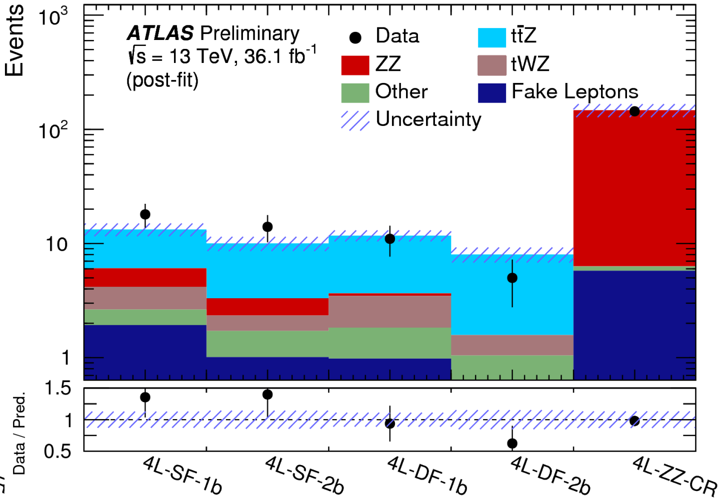
2lOS



3l

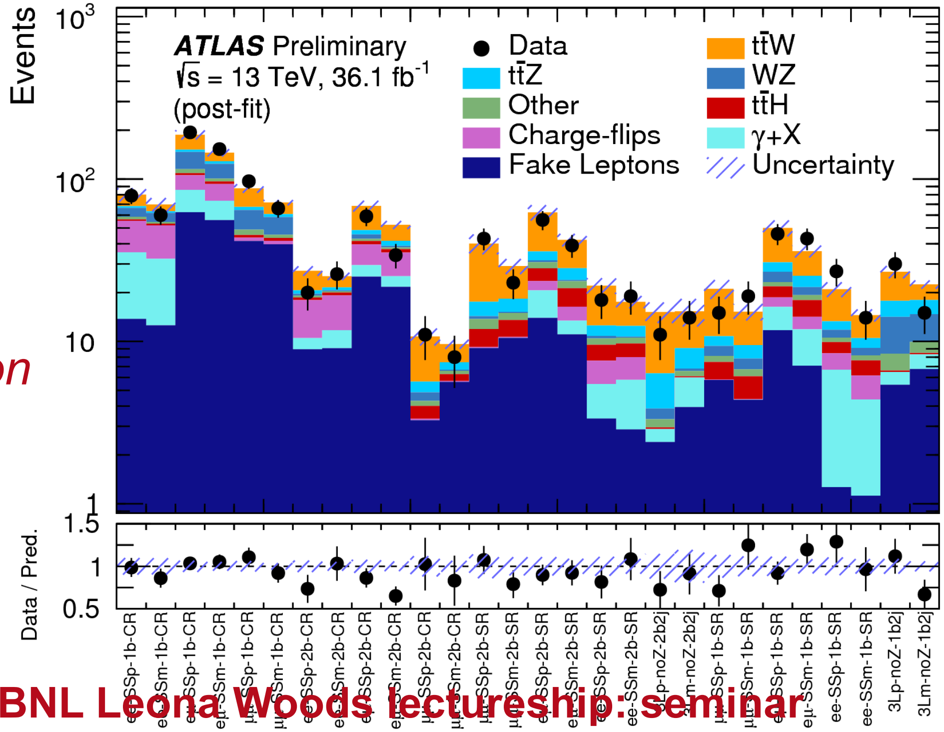


4l



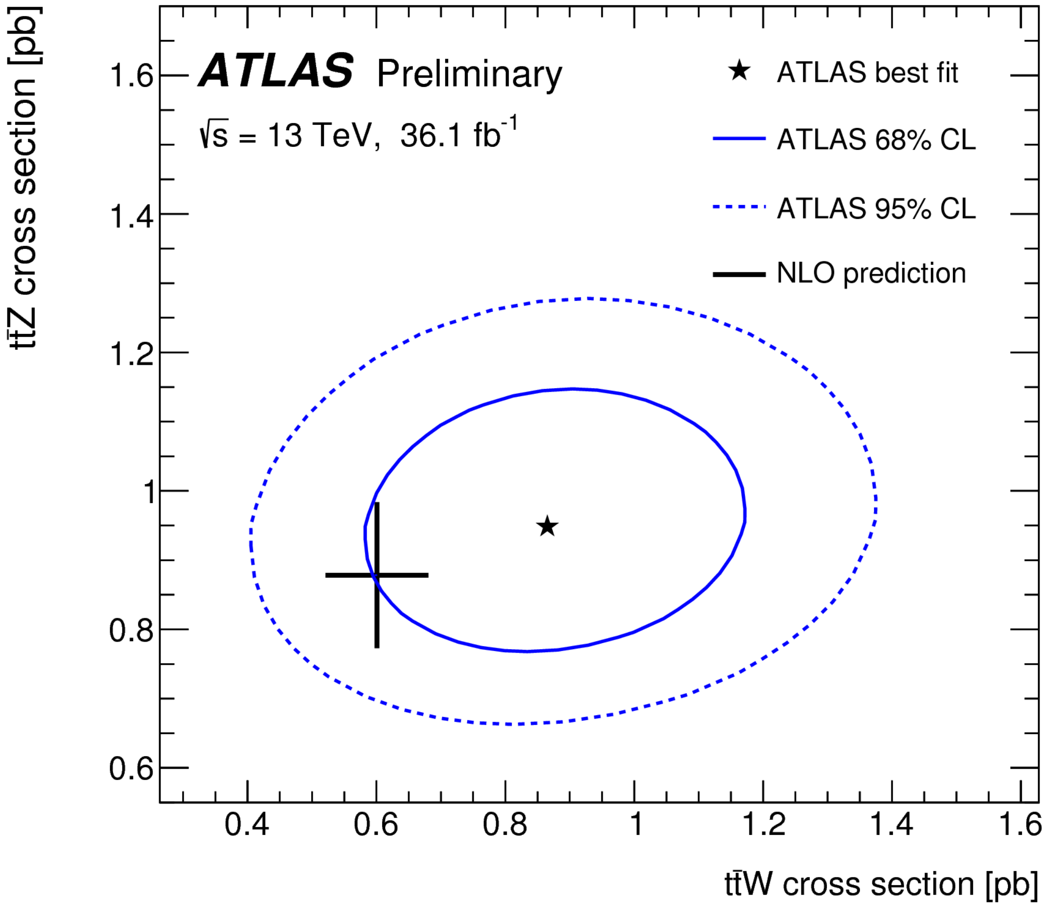
tt+W

Charge-asymmetric production

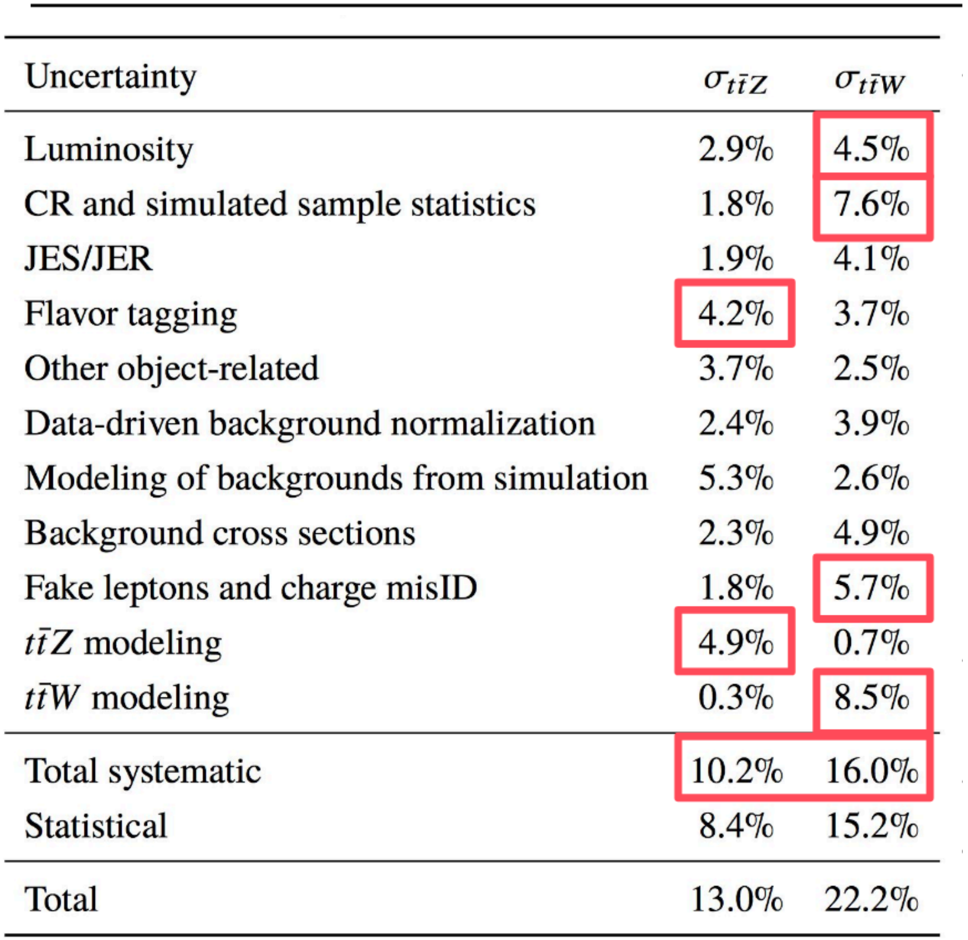


tt+Z/W: cross-section measurements

2D: tt+Z vs. tt+W



Inclusive cross-sections



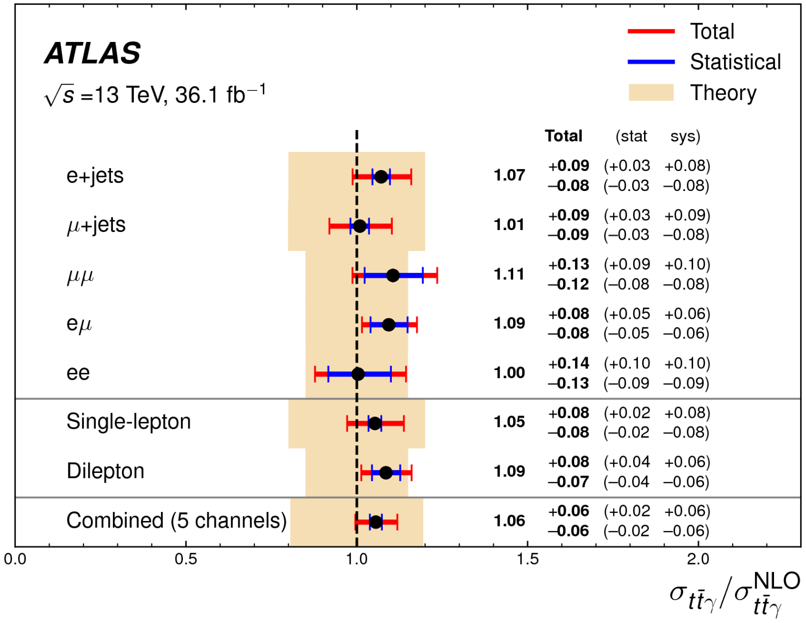
Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.9%	4.5%
CR and simulated sample statistics	1.8%	7.6%
JES/JER	1.9%	4.1%
Flavor tagging	4.2%	3.7%
Other object-related	3.7%	2.5%
Data-driven background normalization	2.4%	3.9%
Modeling of backgrounds from simulation	5.3%	2.6%
Background cross sections	2.3%	4.9%
Fake leptons and charge misID	1.8%	5.7%
$t\bar{t}Z$ modeling	4.9%	0.7%
$t\bar{t}W$ modeling	0.3%	8.5%
Total systematic	10.2%	16.0%
Statistical	8.4%	15.2%
Total	13.0%	22.2%

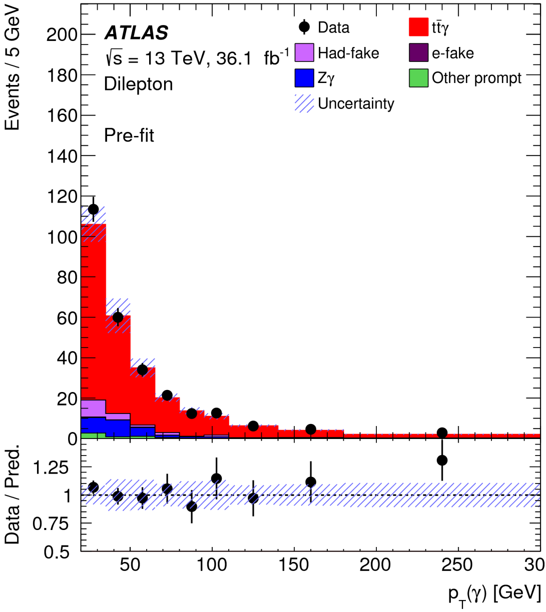
Top quark coupling to photons: *tt*+γ

- **7 TeV data: Observation of *tt*+γ (fiducial cross-section)**

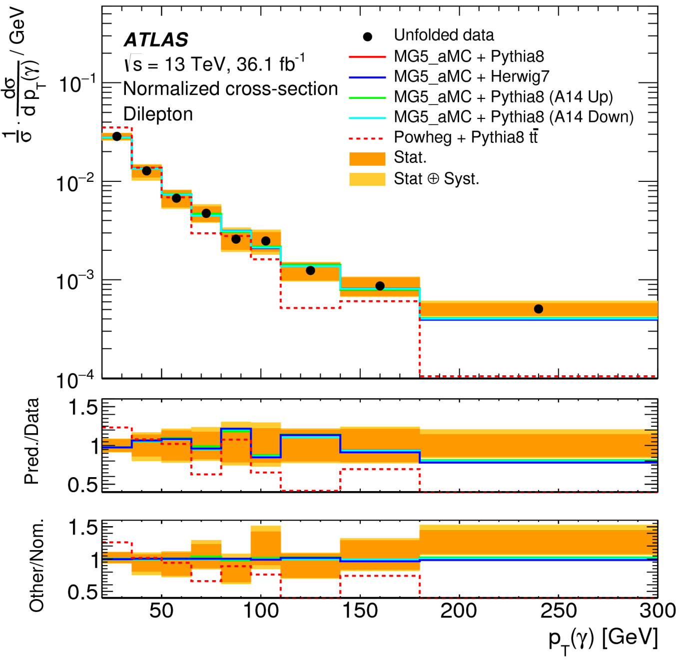
- **First differential measurements with 8 TeV data**
  in single lepton channel: photon p_T and $|\eta|$

- **At 13 TeV: single and dilepton channels explored** $p_T(\gamma)$, $|\eta(\gamma)|$, $\Delta R(\gamma,\ell)_{min}$, $[\Delta\eta(\ell,\ell)$, $\Delta\Phi(\ell,\ell)]$





2015+2016 data
36 fb^{-1}
arXiv: 1812.01697



In agreement with the NLO QCD+LO EW prediction

Main uncertainties

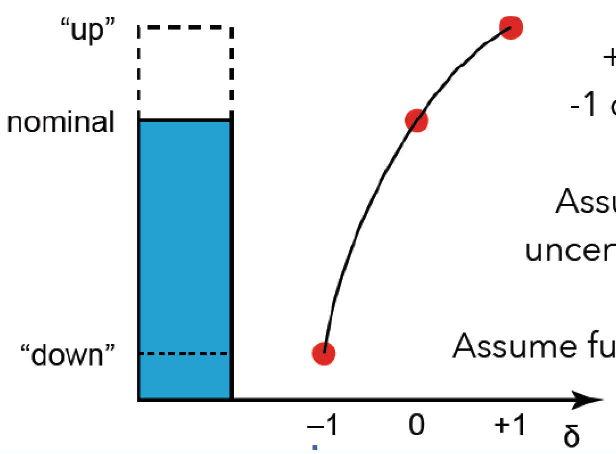
- Single-lepton: jet-related and background modelling
- Dilepton: data statistics, followed by signal and background modelling

tt+H (multi-leptons): systematic uncertainties

$$L(\mu,\theta) = L_{Pois}(\mu,\theta)\cdot\prod_{p}\frac{1}{\sqrt{2\pi}}\exp\left(-\frac{\theta_p^2}{2}\right)\cdot\prod_{i,j}\frac{1}{\sqrt{2\pi}\sigma_{\gamma,ij}}\exp\left(-\frac{(\gamma_{ij}-1)^2}{2\sigma^2_{\gamma,ij}}\right)$$

Systematic uncertainty	Type	Components
Luminosity	N	1
Pileup reweighting	SN	1
Physics Objects		
Electron	SN	6
Muon	SN	15
τ_{had}	SN	10
Jet energy scale and resolution	SN	28
Jet vertex fraction	SN	1
Jet flavor tagging	SN	126
$E_{\mathrm{T}}^{\mathrm{miss}}$	SN	3
Total (Experimental)	–	191
Data-driven non-prompt/fake leptons and charge misassignment		
Control region statistics	SN	38
Light-lepton efficiencies	SN	22
Non-prompt light-lepton estimates: non-closure	N	5
γ-conversion fraction	N	5
Fake τ_{had} estimates	N/SN	12
Electron charge misassignment	SN	1
Total (Data-driven reducible background)	–	83
$t\bar{t}H$ **modeling**		
Cross section	N	2
Renormalization and factorization scales	S	3
Parton shower and hadronization model	SN	1
Higgs boson branching fraction	N	4
Shower tune	SN	1
$t\bar{t}W$ **modeling**		
Cross section	N	2
Renormalization and factorization scales	S	3
Matrix-element MC event generator	SN	1
Shower tune	SN	1
$t\bar{t}Z$ **modeling**		
Cross section	N	2
Renormalization and factorization scales	S	3
Matrix-element MC event generator	SN	1
Shower tune	SN	1
Other background modeling		
Cross section	N	15
Shower tune	SN	1
Total (Signal and background modeling)	–	41
Total (Overall)	–	315

$$L_{Pois}(\mu) = \prod_{j}^{reg}\prod_{i}^{bins(j)}\frac{(\mu s_{ij}+b_{ij})^{n_{ij}}}{n_{ij}!}\exp\left(-(\mu s_{ij}+b_{ij})\right)$$



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

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

Assume full correlation between

One parameter of interest: μ(ttH)
315 nuisance parameters

tt+H (multi-leptons): object definition

	e					μ		
	L	L†	L*	T	T*	L	L†	L*/T/T*
Isolation	No	Yes				No	Yes	
Non-prompt lepton BDT	No		Yes			No		Yes
Identification	Loose			Tight		Loose		
Charge misassignment veto BDT	No				Yes	No		
Transverse impact parameter significance, $\lvert d_0 \rvert / \sigma_{d_0}$	< 5					< 3		
Longitudinal impact parameter, $\lvert z_0 \sin\theta \rvert$	< 0.5 mm							

L = Loose
L† = + Loose isolated
L* = + PLI isolated

T = Tight (PLI isolated)
T* = + QMisID MVA veto (el only)

Thad

Medium BDT ID to reject jets (1M, 1T in 1ℓ+2τ)

$p_T > 25$ GeV

BDT to reject el faking τ

τ-μ overlap removal

b-jet veto

Thad vertex is PV

Jets $p_T > 25$ GeV

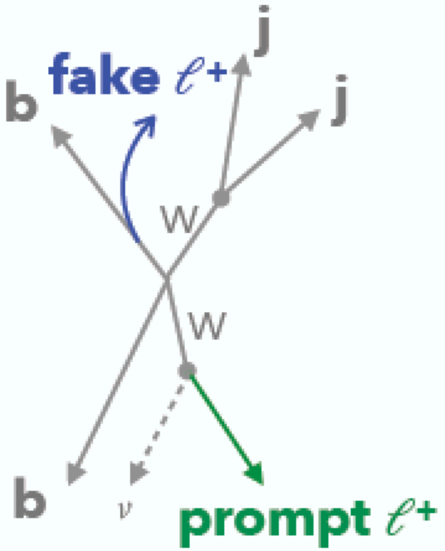
BJets MV2c10 70% WP

	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{\text{had}}$	$2\ell\text{SS}+1\tau_{\text{had}}$	$2\ell\text{OS}+1\tau_{\text{had}}$	$3\ell+1\tau_{\text{had}}$
Light lepton	2T*	1L*, 2T*	2L, 2T	1T	2T*	2L†	1L†, 2T
τ_{had}	0M	0M	–	1T, 1M	1M	1M	1M
$N_{\text{jets}}, N_{b-\text{jets}}$	$\geq 4, = 1, 2$	$\geq 2, \geq 1$	$\geq 2, \geq 1$	$\geq 3, \geq 1$	$\geq 4, \geq 1$	$\geq 3, \geq 1$	$\geq 2, \geq 1$

tt+H (multi-leptons): non-prompt and fake leptons

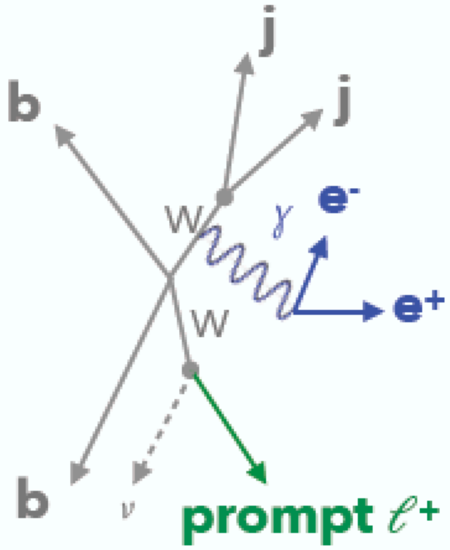
Method **[parametr.]**	2ℓSS+0τ			3ℓ+0τ	4ℓ	2ℓSS+1τ	Other τ channels
Non-prompt lepton	**DD (MM)** el: [p_T, NBjets] μ: [p_T, dR(μ,j)]				**pseudo-DD (Fake SF)**	**DD (FF)** el/μ: [p_T]	**MC** (very small)
DD/MC	ee: 2.0±0.5	eμ: 1.7±0.4	μμ: 1.5 ±0.5	SR: 1.8 ± 0.8			

Semileptonic b-decay



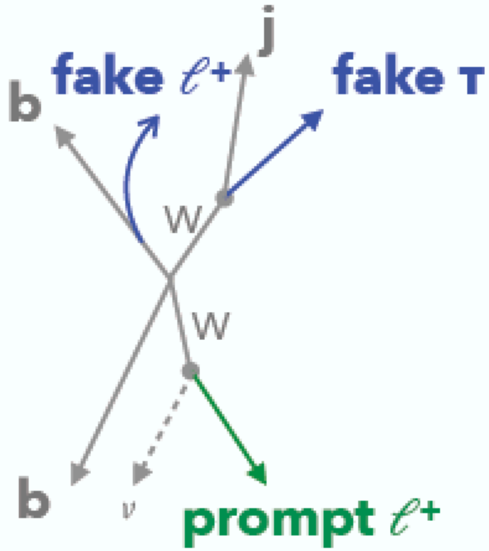
strongly reduced with PLI

Photon conversions



50% of the "fakes" in 3ℓ!

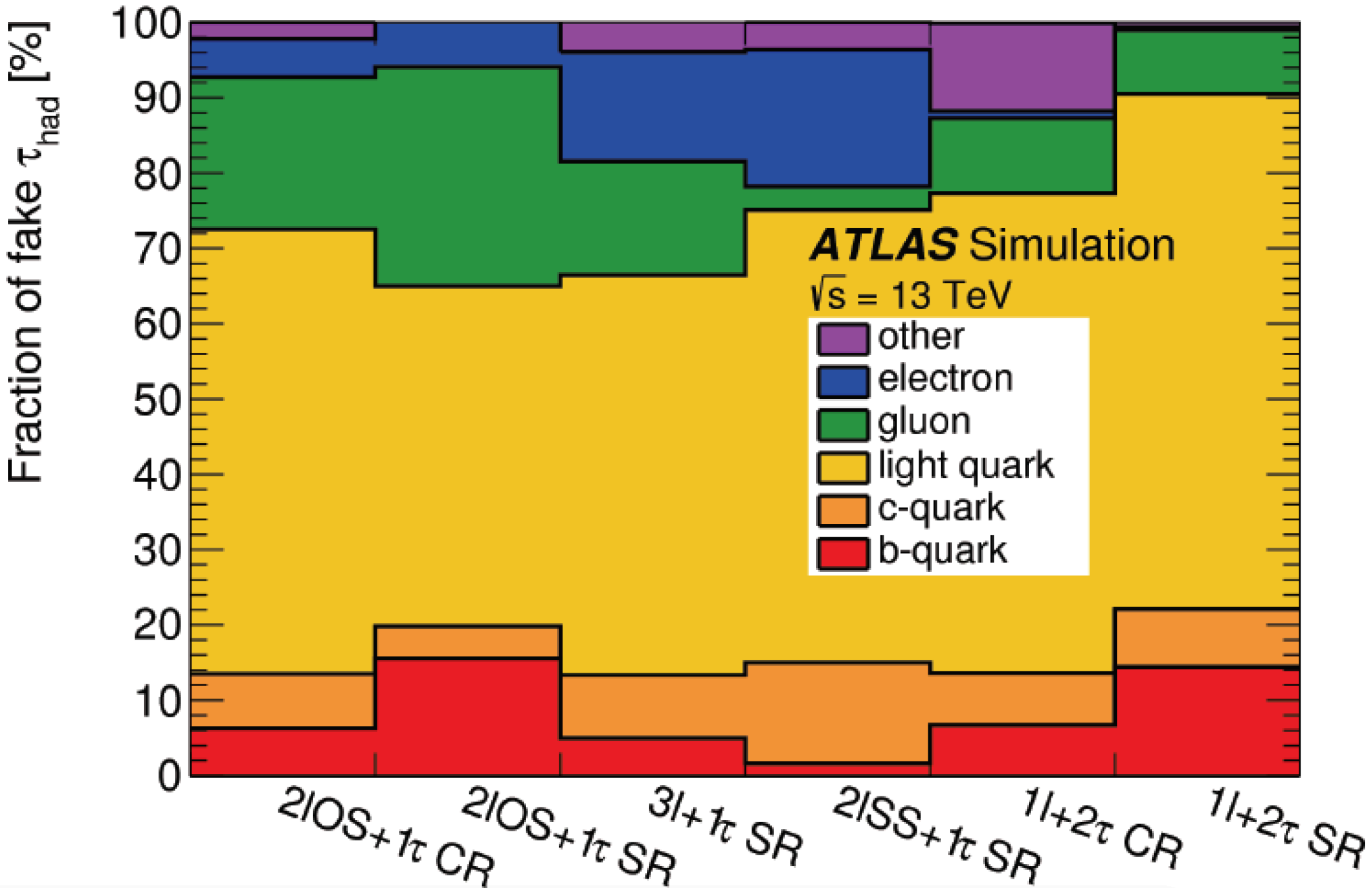
Fake light leptons & fake taus



70% from $t\bar{t}$ in 2ℓSS+1τ

tt+H (multi-leptons): fake taus

Estimate method **[parametrisation]**	**1ℓ+2τ**	**2ℓOS+1τ**	**2ℓSS+1τ**	**3ℓ+1τ**
Fake tau	**DD (SS data)**	**DD (FF)** [p_T]	**pseudo-DD (MC correction with 2ℓOS+1τ DD SF)**	



tt+H (multi-leptons): results

For most of the channels, MVAs are used to separate *tt+H* signal from *tt+V* and *tt*+jets (fakes). One of the most discriminant variables in nJets. Thus, *tt+W/Z*+jets estimation seems relevant…

tt+H → 4W+2b → 6j (inc. 2b)+2lSS +$E_{T,miss}$ or 4j (inc. 2b)+3l+$_{T,miss}$ or 4j (inc. 2b)+4l+$E_{T,miss}$

tt+V → 2W+V+2b → 4j (inc. 2b)+2lSS +$E_{T,miss}$ or 2-4j (inc. 2b)+3l+$E_{T,miss}$ or 2j (inc. 2b)+4l+$E_{T,miss}$

tt → 2W+2b → 4j (inc. 2b)+1l+$E_{T,miss}$ or 2j (inc. 2b)+2lOS +$E_{T,miss}$ [1 jet fakes a lepton]

Accuracy of *tt+Z/W* predictions of ~12-13% (NLO QCD+EW):

$$\sigma_{t\bar{t}Z} = 0.8393 \pm^{+9.6\%}_{-11.3\%} \text{(scale)} {}^{+2.8\%}_{-2.8\%}\text{(PDF)} {}^{+2.8\%}_{-2.8\%}(\alpha_S) \text{ pb}$$

$$\sigma_{t\bar{t}W} = 0.6008 \pm^{+12.9\%}_{-11.5\%} \text{(scale)} {}^{+2.0\%}_{-2.0\%}\text{(PDF)} {}^{+2.7\%}_{-2.7\%}(\alpha_S) \text{ pb}$$

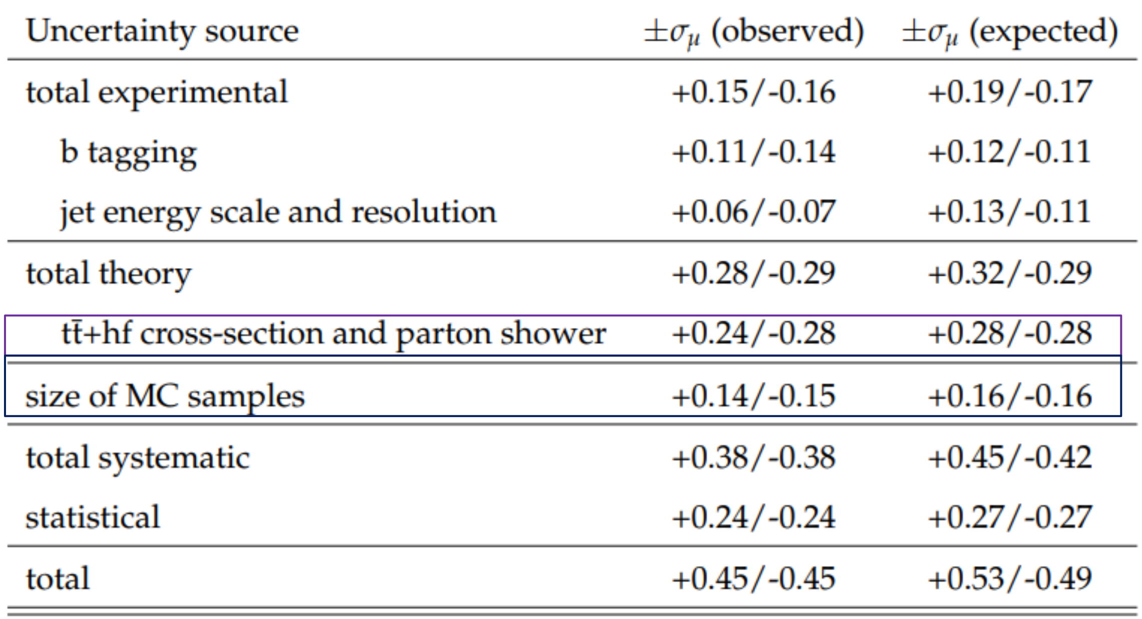
$$\mu = 1.6 \, {}^{+0.3}_{-0.3} \text{ (stat.) } {}^{+0.4}_{-0.3} \text{ (syst.)}$$

Uncertainty Source	$\Delta\mu$	
$t\bar{t}H$ modeling (cross section)	+0.20	−0.09
Jet energy scale and resolution	+0.18	−0.15
Non-prompt light-lepton estimates	+0.15	−0.13
Jet flavor tagging and τ_{had} identification	+0.11	−0.09
$t\bar{t}W$ modeling	+0.10	−0.09
$t\bar{t}Z$ modeling	+0.08	−0.07
Other background modeling	+0.08	−0.07
Luminosity	+0.08	−0.06
$t\bar{t}H$ modeling (acceptance)	+0.08	−0.04
Fake τ_{had} estimates	+0.07	−0.07
Other experimental uncertainties	+0.05	−0.04
Simulation sample size	+0.04	−0.04
Charge misassignment	+0.01	−0.01
Total systematic uncertainty	+0.39	−0.30

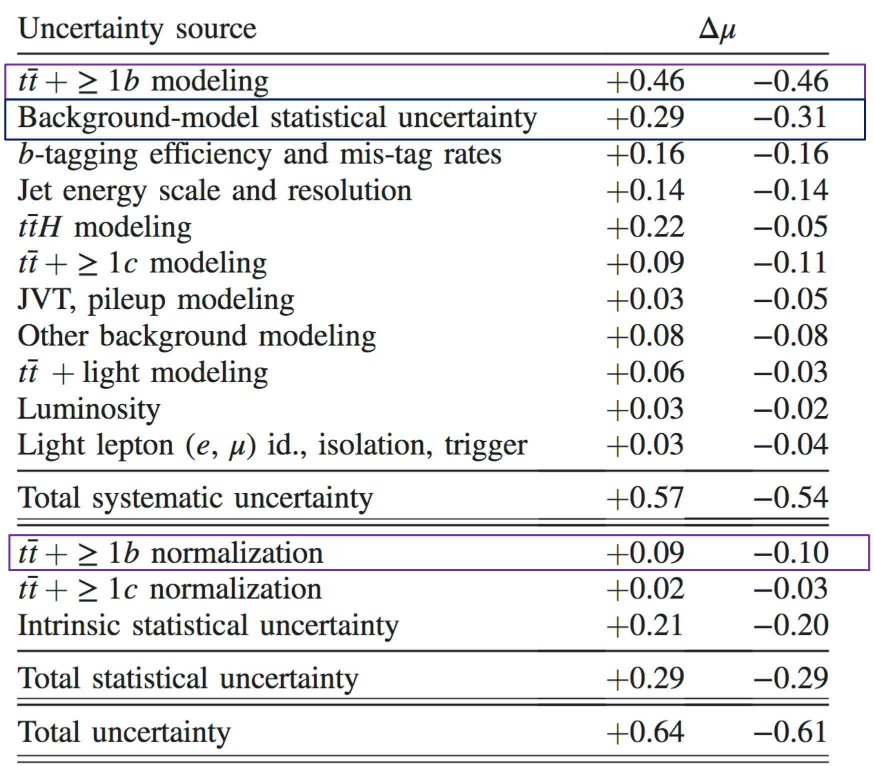
$$\mu = \mathbf{1.23} \, {}^{+0.45}_{-0.43} \quad {}^{+0.26}_{-0.25}\text{(stat.)} \, {}^{+0.37}_{-0.35}\text{(syst.)}$$

Source	Uncertainty [%]	$\Delta\mu/\mu$ [%]
e, μ selection efficiency	2–4	11
τ_h selection efficiency	5	4.5
b tagging efficiency	2–15 [57]	6
Reducible background estimate	10–40	11
Jet energy calibration	2–15 [65]	5
τ_h energy calibration	3	1
Theoretical sources	≈10	12
Integrated luminosity	2.5	5

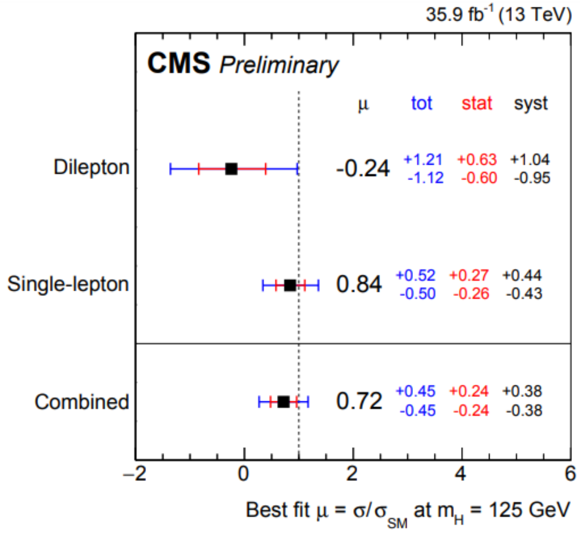
tt+H (bb): results

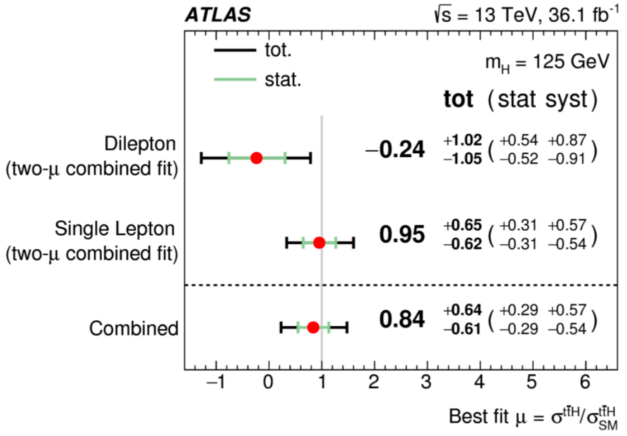


Uncertainty source	$\pm\sigma_\mu$ (observed)	$\pm\sigma_\mu$ (expected)
total experimental	+0.15/-0.16	+0.19/-0.17
b tagging	+0.11/-0.14	+0.12/-0.11
jet energy scale and resolution	+0.06/-0.07	+0.13/-0.11
total theory	+0.28/-0.29	+0.32/-0.29
$t\bar{t}$+hf cross-section and parton shower	+0.24/-0.28	+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



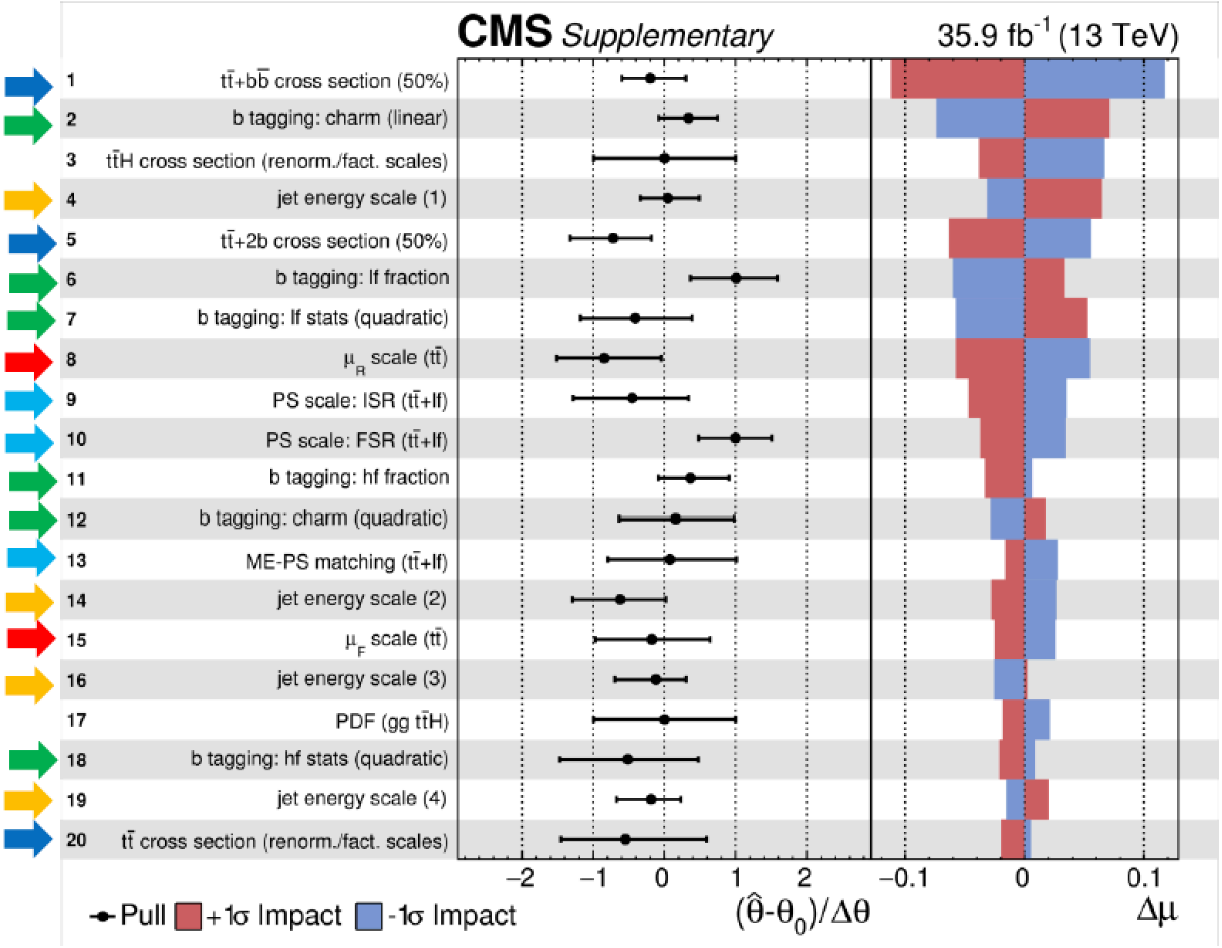
Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modeling	+0.46	−0.46
Background-model statistical uncertainty	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modeling	+0.22	−0.05
$t\bar{t} + \geq 1c$ modeling	+0.09	−0.11
JVT,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



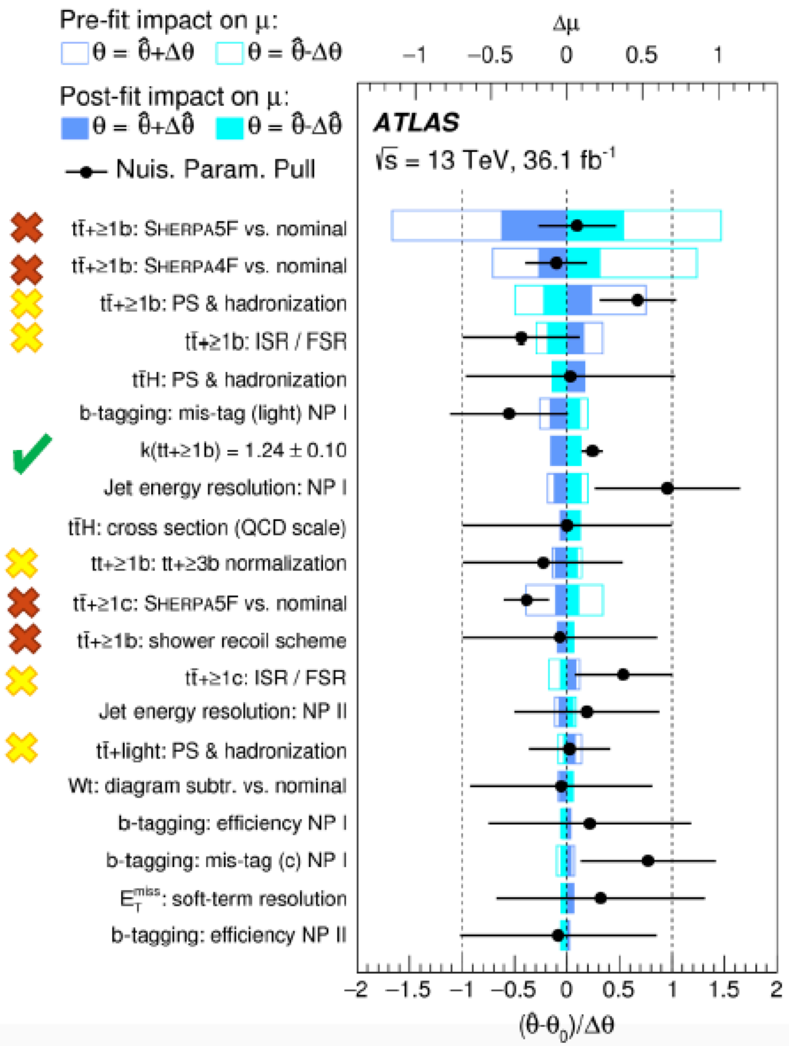


Latest *tt+H* (*H*→bb) results

➡ ttbar norm only
➡ ttbar norm but can affect njets shape
➡ ttbar norm+shape (can affect MVA shape)
➡ btagging
➡ JES/JER



ttbar syst legend
✓ CMS has it
✗ CMS partially has it
✗ CMS does not have it



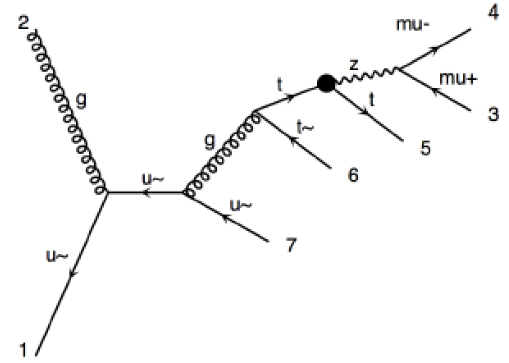
Towards a global fit at the LHC

Standard model deviations are described by higher dimensional operators.

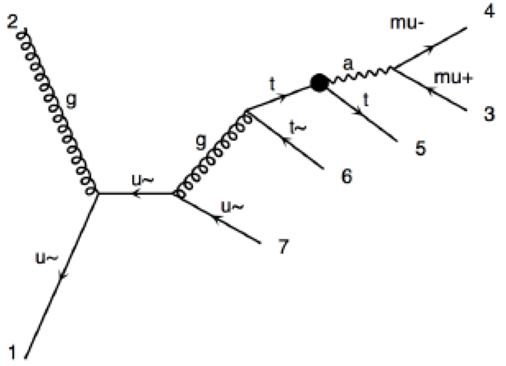
→ need to identify which operators contribute to each process

Process	O_{tG}	O_{tB}	O_{tW}	$O^{(3)}_{\varphi Q}$	$O^{(1)}_{\varphi Q}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	N		L	L				L		
$pp \to t\bar{q}$	N		L	L				L		
$pp \to tW$	L		L	L				N	N	N
$pp \to t\bar{t}$	L						N	L	L	L
$pp \to t\bar{t}\gamma$	L	L	L				N	L	L	L
$pp \to t\bar{t}Z$	L	L	L	L	L	L	N	L	L	L
$pp \to t\bar{t}h$	L						L	L	L	L
$gg \to H, H \to \gamma\gamma$	N						N			L

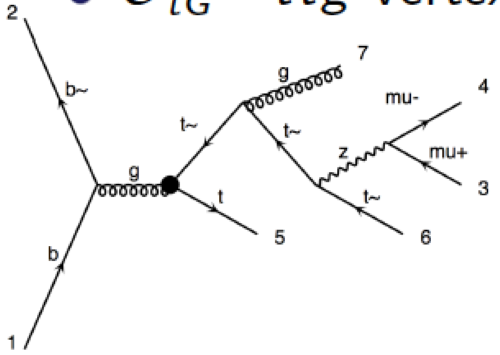
- $\mathcal{O}_{\phi t}, \mathcal{O}_{\phi Q^3}, \mathcal{O}_{\phi Q^1}$ - $t\bar{t}Z$ vertex
- $\mathcal{O}_{tW}, \mathcal{O}_{tB}$ - $t\bar{t}Z$ and $t\bar{t}\gamma$ vertices
- $\mathcal{O}_{tG}$ - $t\bar{t}g$ vertex



$\mathcal{O}_{\phi t}, \mathcal{O}_{\phi Q^3}, \mathcal{O}_{tW}, \mathcal{O}_{tB}$



$\mathcal{O}_{tW}, \mathcal{O}_{tB}$



$\mathcal{O}_{tG}$

EFT operators

Standard model deviations are described by higher dimensional operators:

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

Interference SM-BSM

Pure BSM term

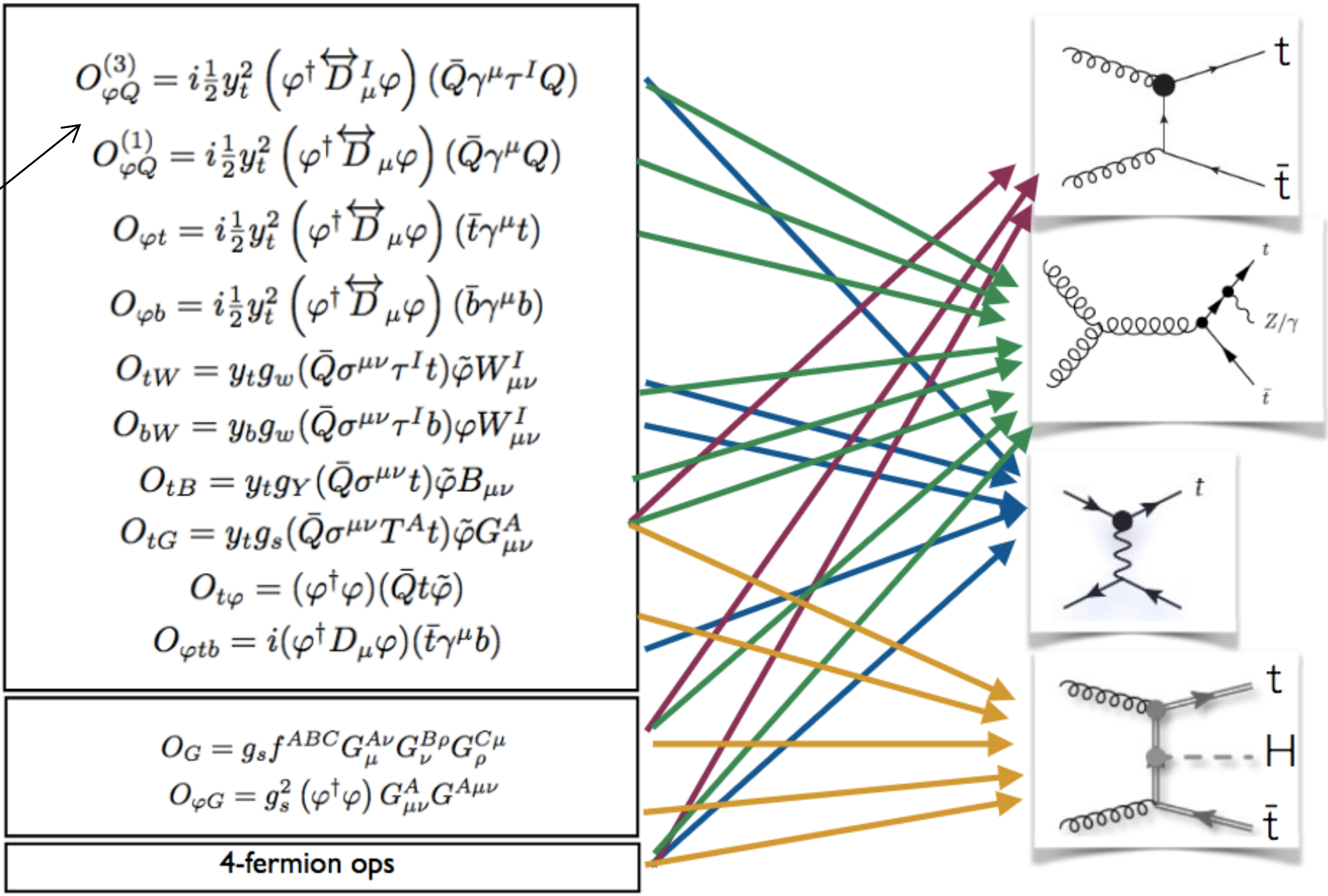
$$\sigma = \sigma_{SM} + \sum_i \frac{C_i}{(\Lambda/1\text{TeV})^2}\sigma_i^{(1)} + \sum_{i\leq j} \frac{C_i C_j}{(\Lambda/1\text{TeV})^4}\sigma_{ij}^{(2)}$$

Dimension 6 operators relevant for top quark physics.

modify vector and axial coupling of top to EW gauge bosons

O_{tB}, O_{tW}: EW dipole operator

O_{tG}: chromomagnetic dipole operator



$$O_{\varphi Q}^{(3)} = i\tfrac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu^I \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$

$$O_{\varphi Q}^{(1)} = i\tfrac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

$$O_{\varphi t} = i\tfrac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

$$O_{\varphi b} = i\tfrac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{b}\gamma^\mu b)$$

$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W_{\mu\nu}^I$$

$$O_{bW} = y_b g_w(\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W_{\mu\nu}^I$$

$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu}$$

$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G_{\mu\nu}^A$$

$$O_{t\varphi} = (\varphi^\dagger\varphi)(\bar{Q}t\tilde{\varphi})$$

$$O_{\varphi tb} = i(\varphi^\dagger D_\mu\varphi)(\bar{t}\gamma^\mu b)$$

$$O_G = g_s f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$$

$$O_{\varphi G} = g_s^2\left(\varphi^\dagger\varphi\right) G_{\mu\nu}^A G^{A\mu\nu}$$

4-fermion ops