Recent $t\bar{t}H$ measurements with ATLAS

Merve Nazlim Agaras (LPC)

on behalf of the ATLAS Collaboration

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LHCP

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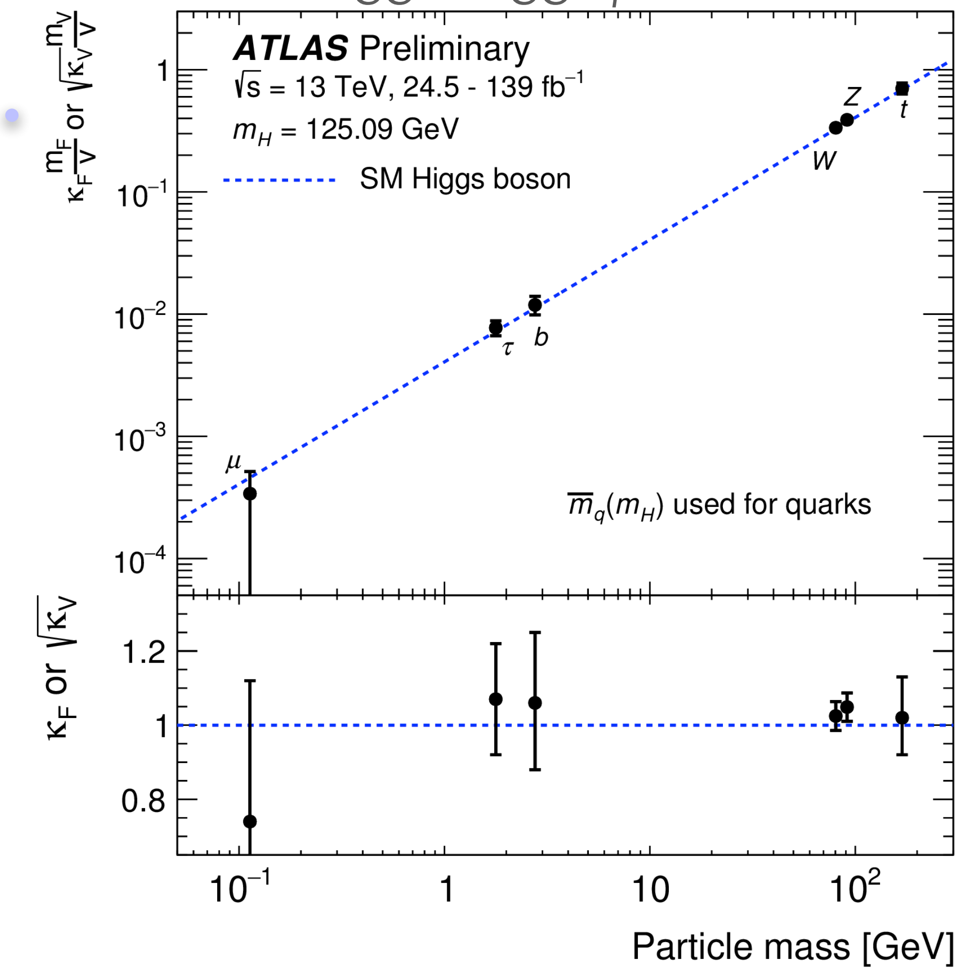
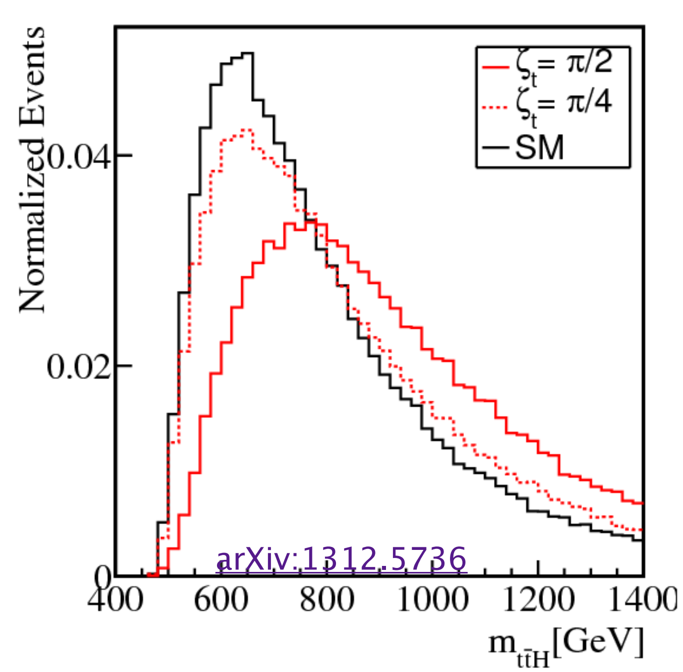
Top Yukawa Coupling

- Goal of the $t\bar{t}H$ measurement: Probing the **top-Yukawa coupling y_t (directly)**
  - Largest in the SM: $y_t = \sqrt{2}m_t/\nu \approx 1$
  - Relevant to: **Effective potential** of Higgs field, Higgs-self coupling, destabilises the vacuum, the required energy scale for new physics …
- What is the CP nature of the Higgs-top interaction?
  - Higgs-top coupling may have both scalar and pseudo-scalar components (CP-odd and CP-even)

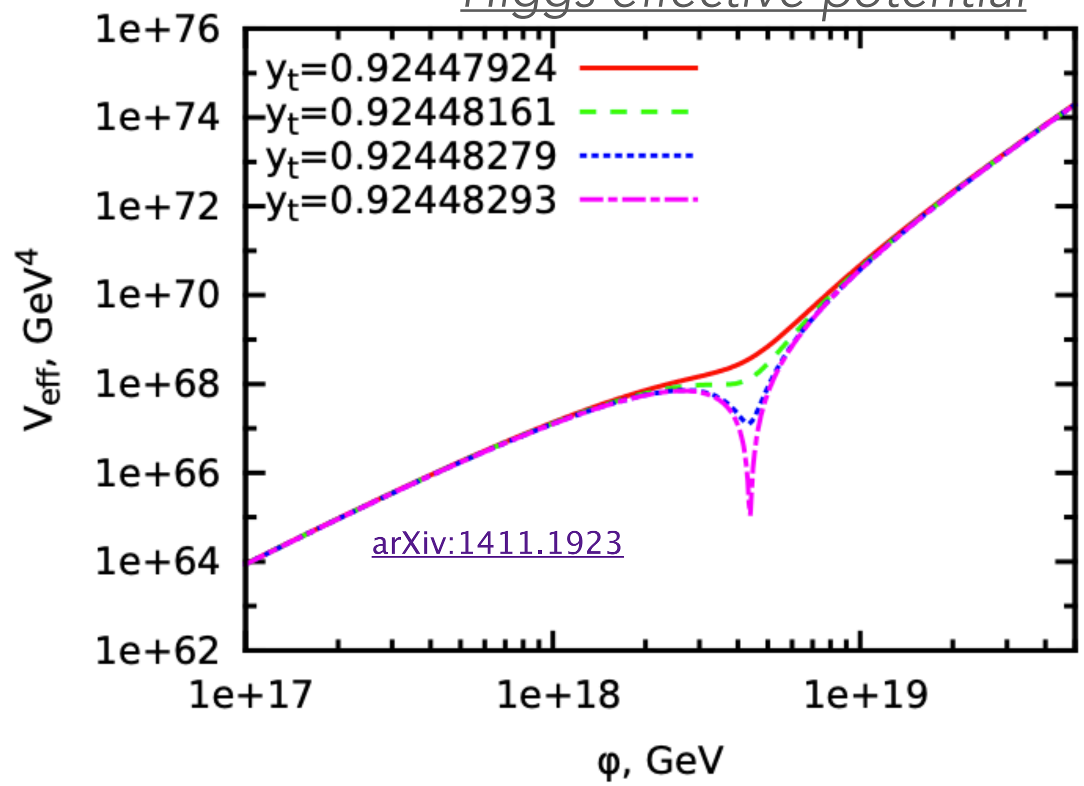
from ggF Higgs production



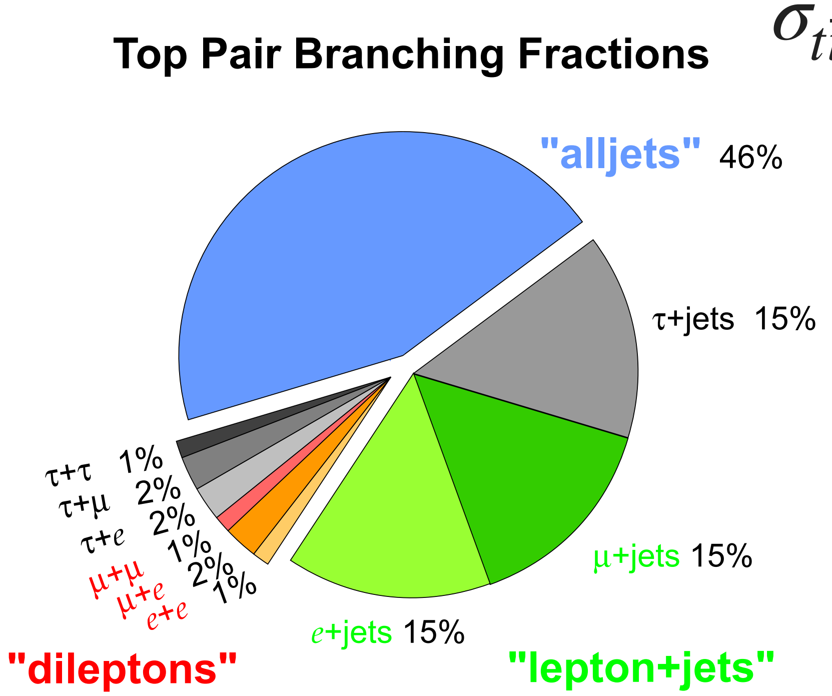
CP violation phase



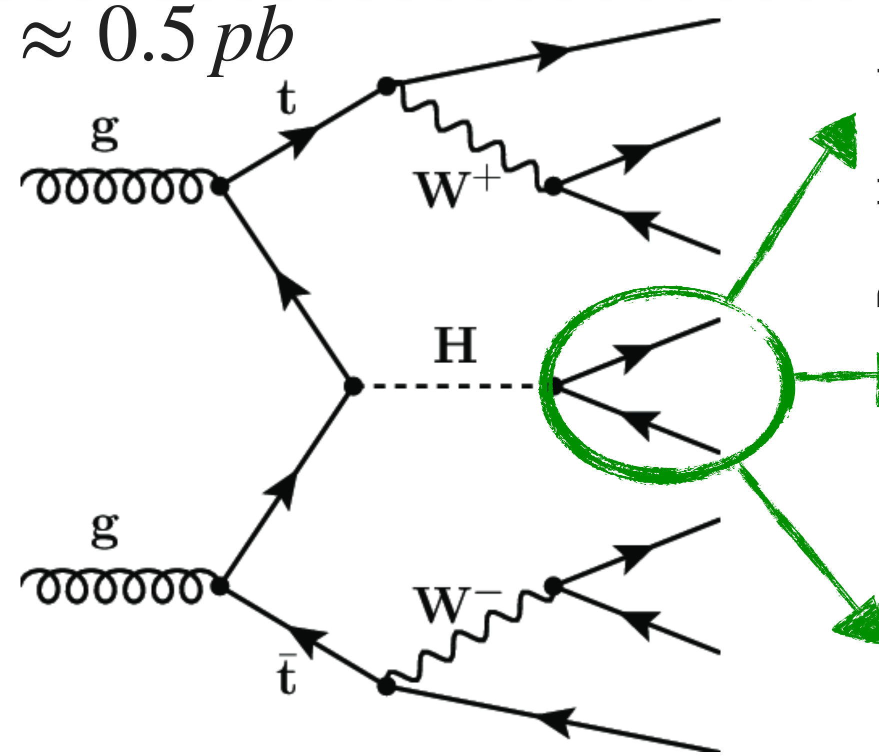
Higgs effective potential

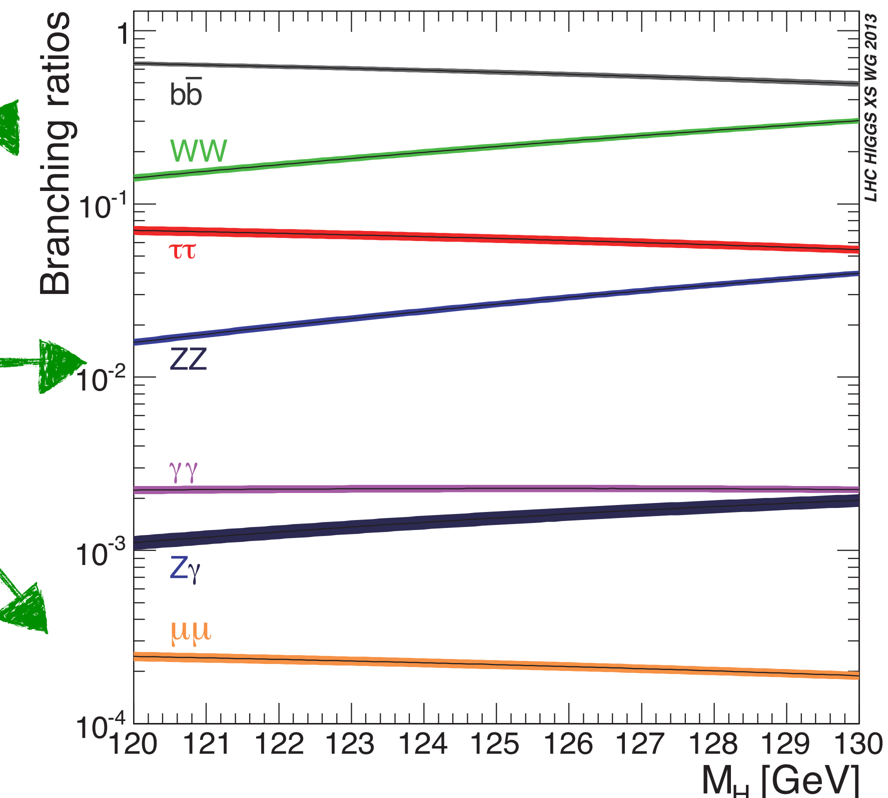


$t\bar{t}H$ Production at ATLAS



$\sigma_{t\bar{t}H} \approx 0.5\,pb$





Search channel (Higgs decay)	Benefits/challenges	Latest publications	Luminosity (fb^{-1})
$H \rightarrow b\bar{b}$	Wide Higgs peak, high rate/ difficult backgrounds	Phys. Rev. D 97 (2018) 072016	36
$H \rightarrow WW^*, ZZ^*, \tau\tau$ $(multilepton)$	Reasonable rate/no full reconstruction of Higgs/non-prompt backgrounds	ATLAS-CONF-2019-045	80
$H \rightarrow ZZ^* \rightarrow 4\ell$ $H \rightarrow \gamma\gamma$	Very clean/small rate	arXiv:2004.03447 ATLAS-CONF-2019-004	139
Combination	Phys. Lett. B 784 (2018) 173 (Observation)		80+36

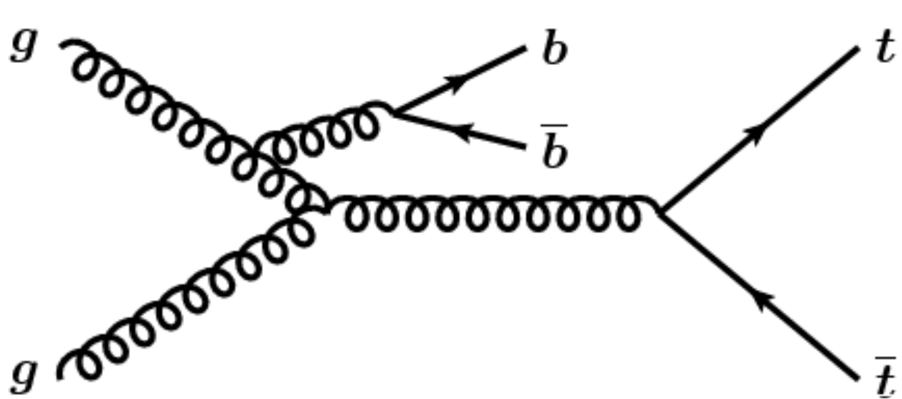
$t\bar{t}H\,(H \to b\bar{b})$

$36\,fb^{-1}$

- **Most common decay mode, but challenging final states**
  - Combinatorics from **many bjets**.
  - CRs to constrain various backgrounds and systematic uncertainties

- **Analysis regions**
  - lepton+jets, dileptonic channels
  - Resolved & boosted (for lepton+jets)
  - split **NJets**, **btagging** (order of tightness of the *b*-tagging WPs)

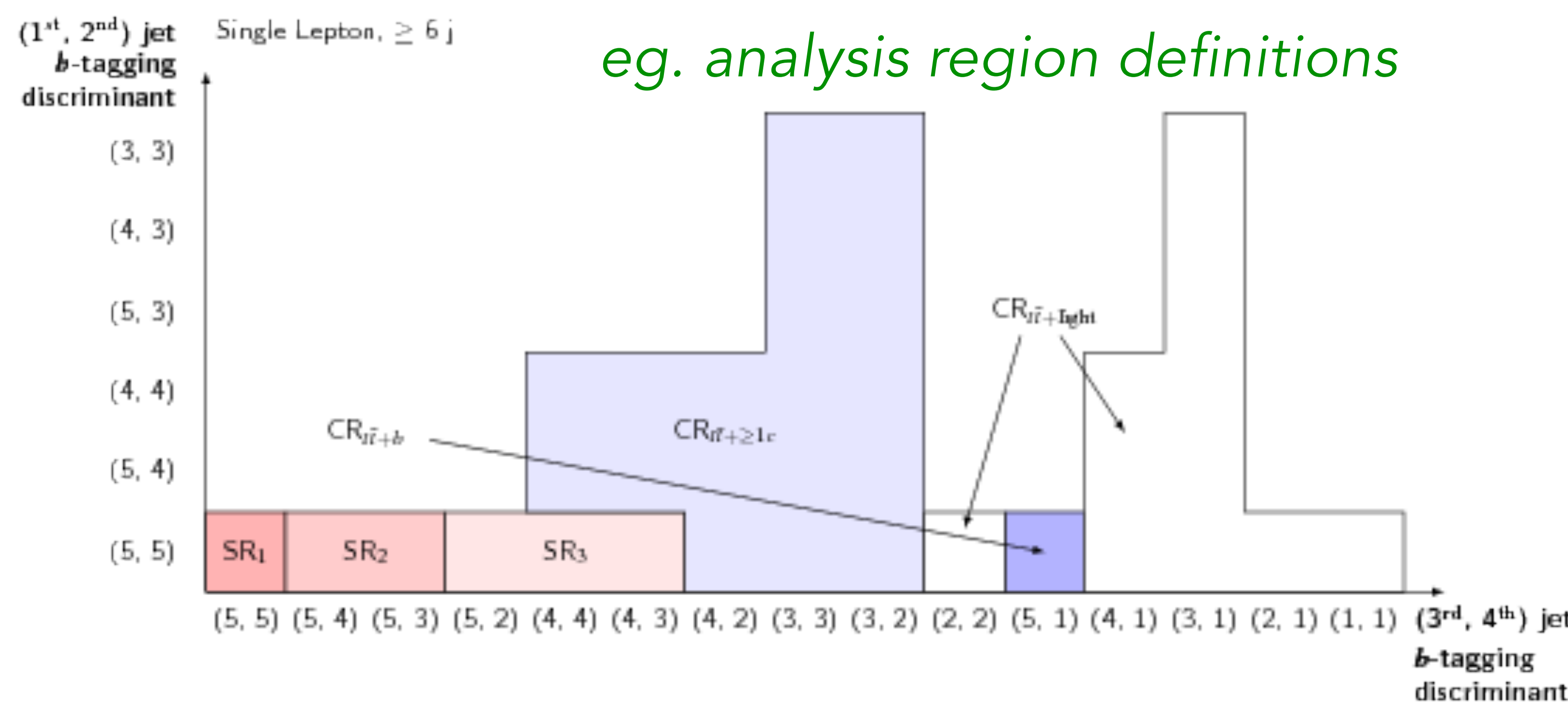
Main analysis challenge



- **Large background from $t\bar{t}$+jets (>=1b,>=1c, light-flavour)**
  - Nominal sample: @NLO 5-flavour scheme (with additional b-quark pair from PS)
  - Division of CRs depending on the $t\bar{t}$+**jet** flavour
  - Numerous uncertainties are implemented to cover the modelling differences.

→ Use of **reconstruction/MVA** techniques (details next slide)

eg. analysis region definitions



$t\bar{t}H\,(H \rightarrow b\bar{b})$

$36\,fb^{-1}$

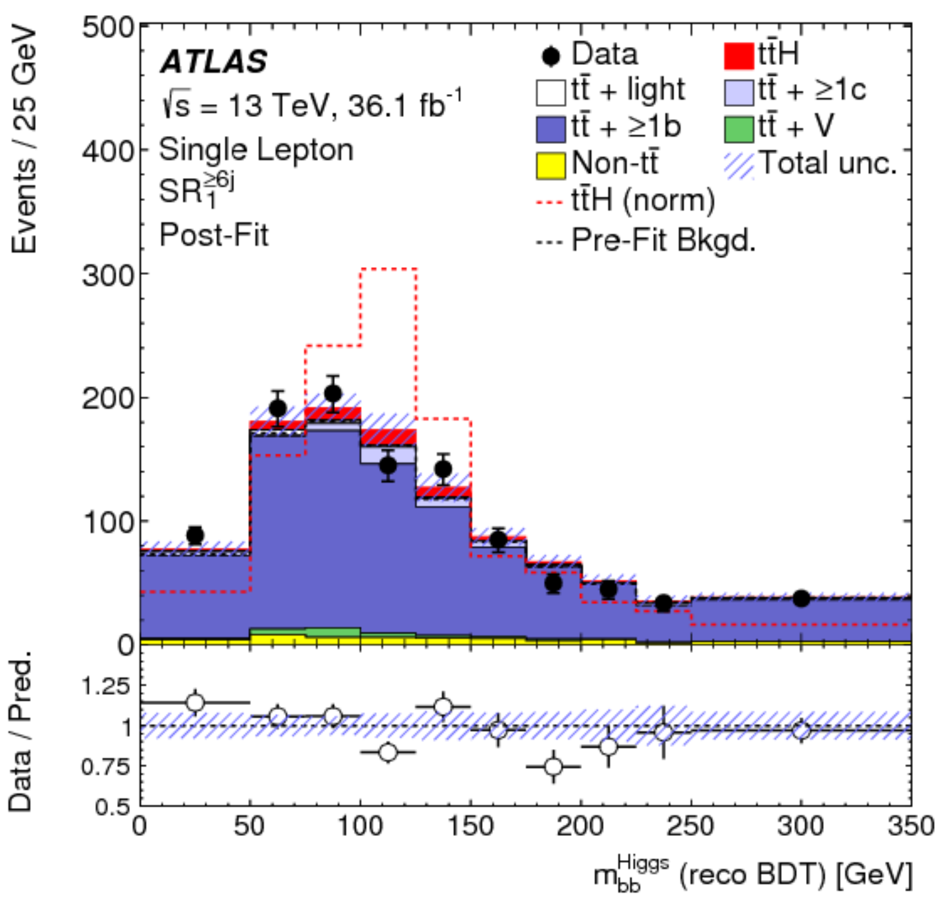
* **Signal extraction strategy (MVA methods)**
  - Intermediate —> to reconstruct the $t\bar{t}H$ system
  - Classification **BDT** —> to separate signal form background

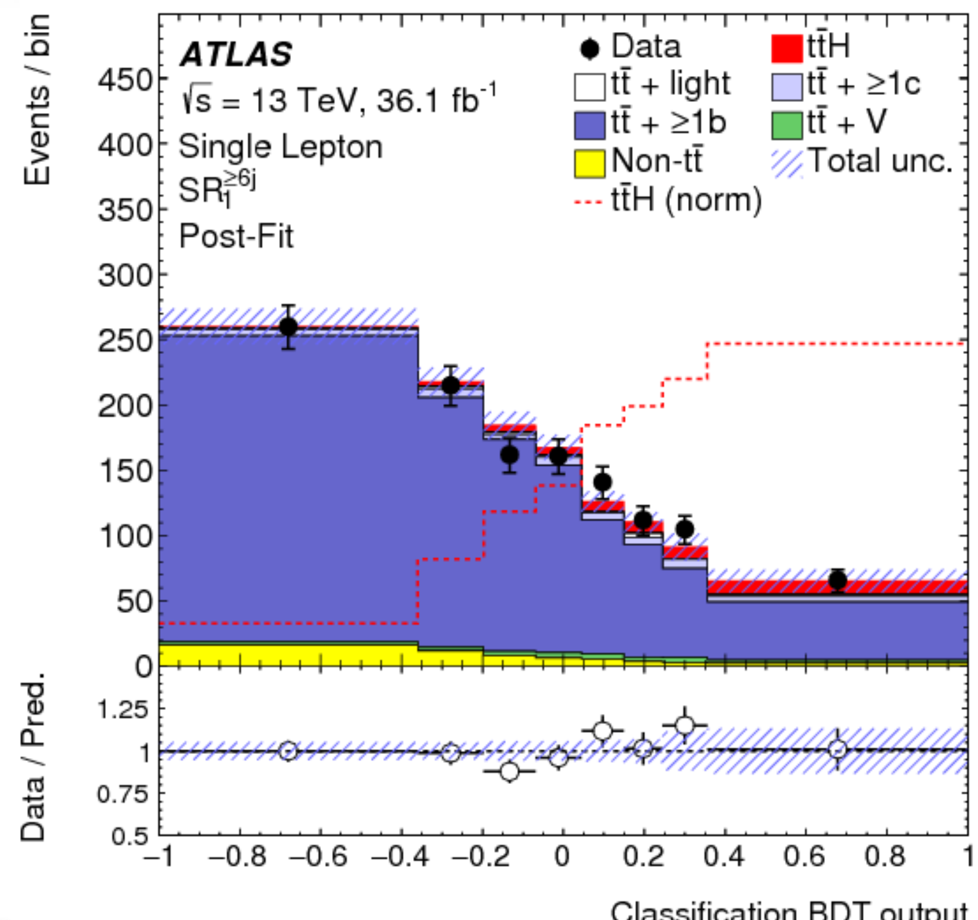
Intermediate MVAs

- Reconstruction BDT
- Likelihood discriminant
- Matrix Element Method

Classification BDT

- Highest BDT score for H and t + BDT output
- Kinematic variables $p^{sig}/p^{sig} + p^{t\bar{t}+jets}$ (av. over jet permutations)
- $MEM_d = log(L_S) - log(L_B)$
- b-tagging information



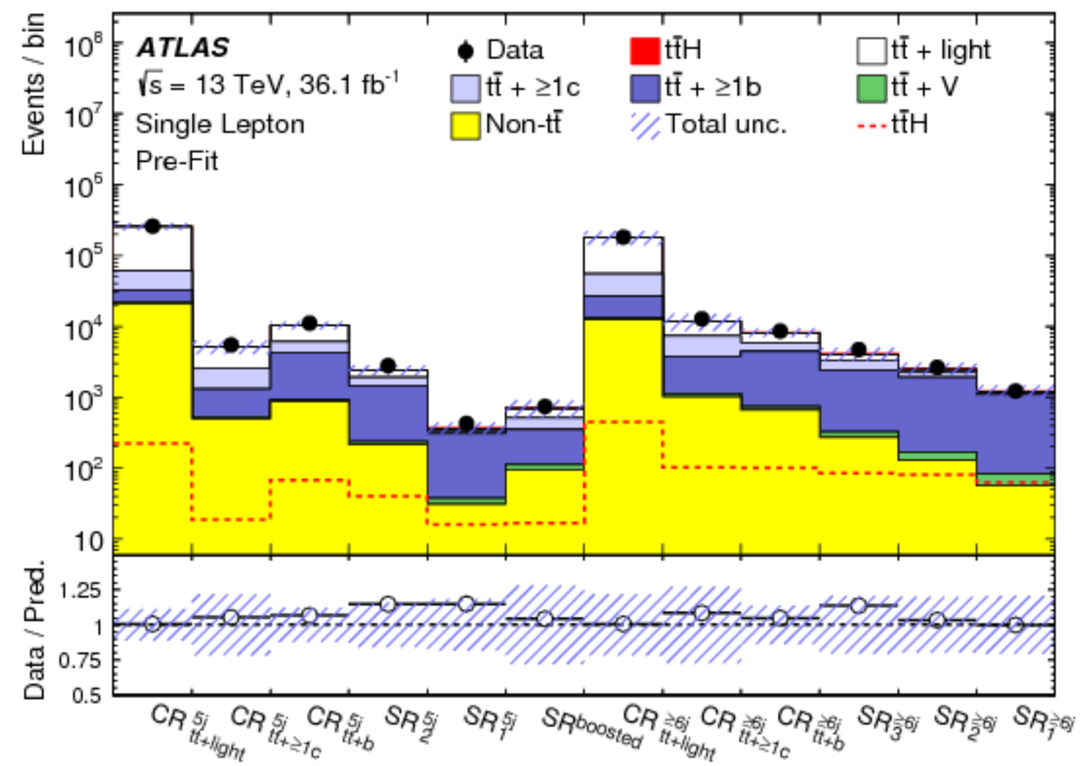


$t\bar{t}H\,(H \rightarrow b\bar{b})$

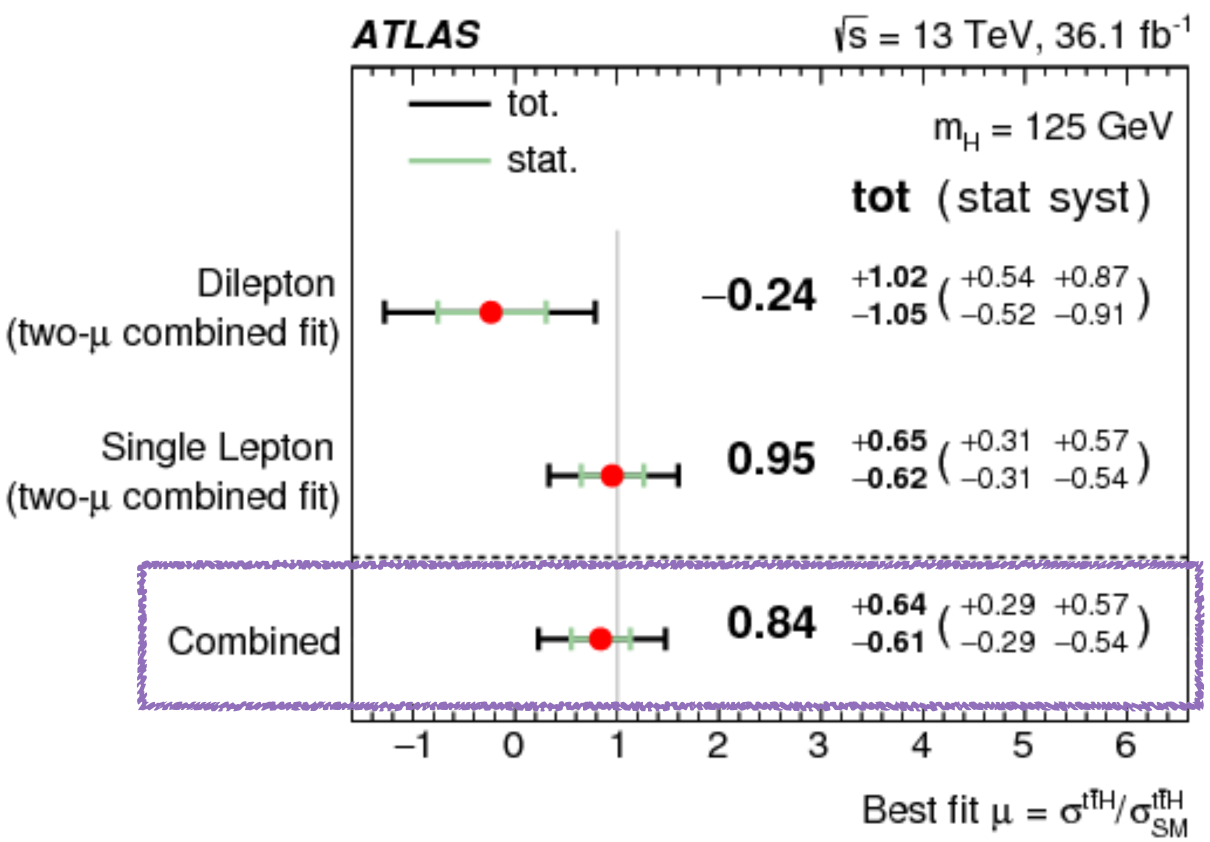
$36\,fb^{-1}$

* Fit model

- Profile likelihood fit ($\mu_{t\bar{t}H}$) of 10 CRs and 9 SRs
- BDT bins in SRs
- H_T bins or single bin CRs
- Free floating norm. of $t\bar{t} + \geq 1b$ and $t\bar{t} + \geq 1c$



eg. observed and expected yield comparison



Significance: 1.4σ (1.6σ exp.)

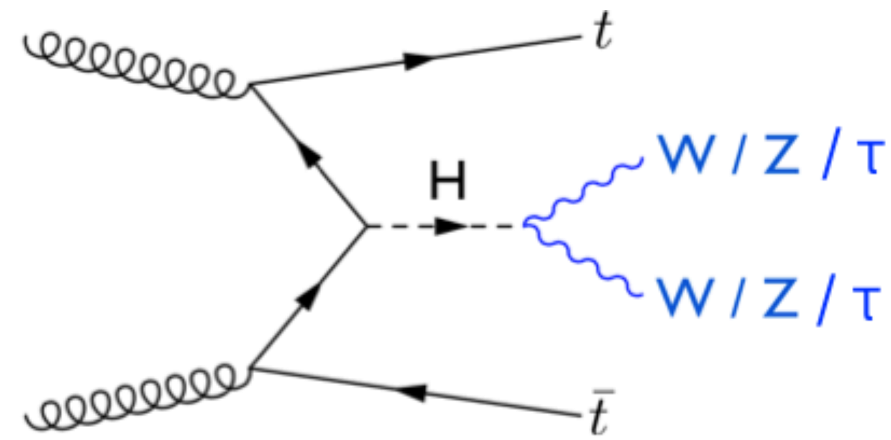
* Systematic uncertainties

- Modelling of $t\bar{t} + \geq 1b$ (± 0.46)
- MC statistical (± 0.30)
- Flavour tagging (± 0.16)
- Dominated by **systematic uncertainties**

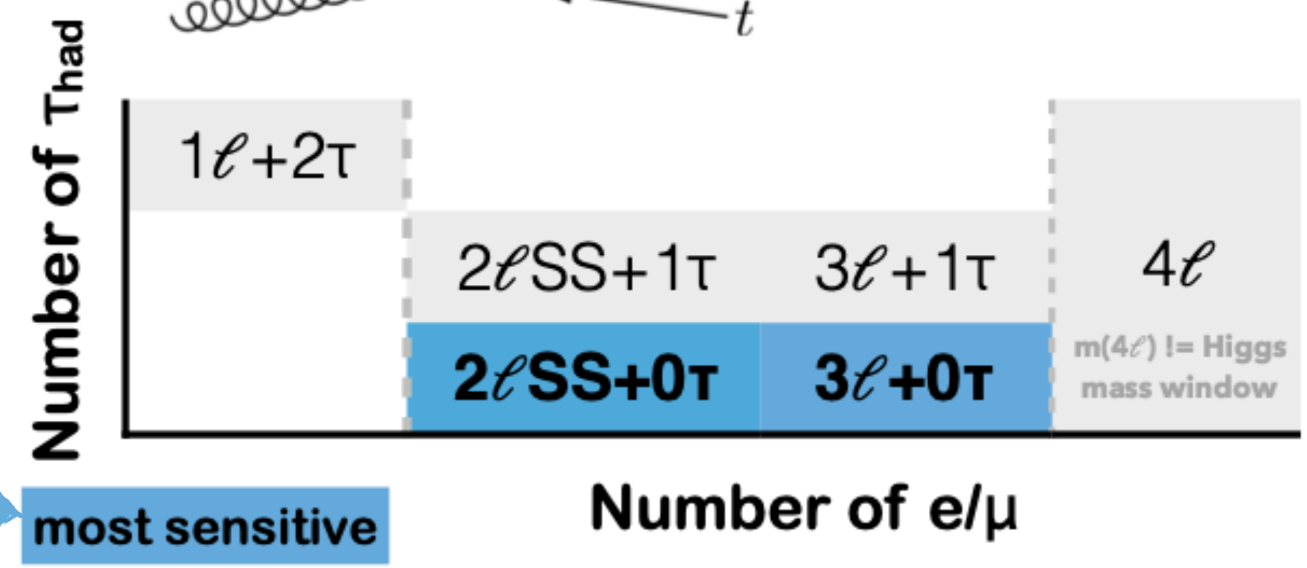
$t\bar{t}H\,(H \rightarrow multilepton)$

$80\,fb^{-1}$

* **Target**: $t\bar{t}H$ with
  - H—>WW/ZZ/$\tau\tau$—> $\geq 1\ell$
  - $t\bar{t}$—>(ℓ+jets, dilepton)



* **Analysis regions**
  - **charge** and **flavour** of leptons (ℓ≡e,μ,τ_{had})
  - number of **jets**
  - CRs to constrain backgrounds



* **Main backgrounds** : $t\bar{t}W, t\bar{t}Z, VV$ + non-prompt ℓ, charge mis-assigned ℓ, photon conversions ℓ (mainly $t\bar{t}$), fake τ_{had}

* To **reduce** the background contribution further lepton selections;
  - Sophisticated **BDT isolation** to suppress ℓ from semi-leptonic b-decays, **QMisID BDT**, material and γ^* **conversion** (CO) rejection ($m_{trk-trk}$)

$t\bar{t}H\,(H \rightarrow multilepton)$

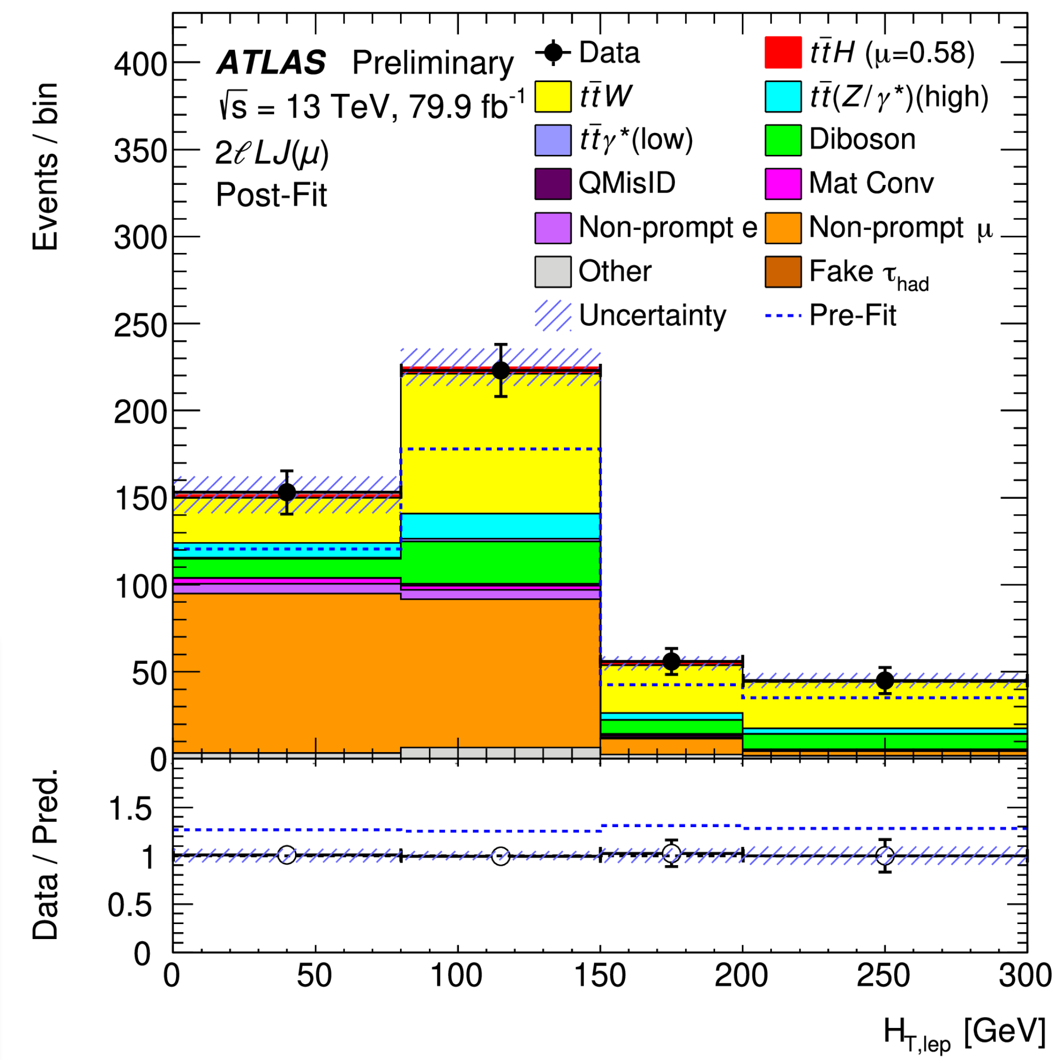
$80\,fb^{-1}$

Analysis regions

* “high NJets” ($\geq$ 4) —> Multi-dim. **BDT space, lepton charge**, and/or **lepton flavour**
  * Consist of SRs & CRs
  * BDT vs $\mathbf{t\bar{t}W}$/$\mathbf{t\bar{t}}$ in $2\ell SS$ - $\mathbf{t\bar{t}W}$,$\mathbf{t\bar{t}Z}$,**VV**,$\mathbf{t\bar{t}}$ in 3ℓ
* “low NJets” (2-3) —> $\Delta R(l_0, l_1), H_T$, **b-jet multiplicity,** lepton flavour, event yeild
  * discrimination power on $\mathbf{t\bar{t}W}$ and non-prompt backgrounds

Estimation of lepton backgrounds based on MC shapes; simultaneous fit to signal strength

* Normalisations of
  * Heavy flavour **non-prompt leptons** $b, c \rightarrow \ell X$ (electrons and muons)
  * electrons from **material CO** $\gamma \rightarrow \ell\ell_{\mathbf{soft}}$
  * electron from **internal CO** [low mass] $\gamma^* \rightarrow \ell\ell_{\mathbf{soft}}$
* Data-driven for the charge mis-assigned and fake τ_{had}



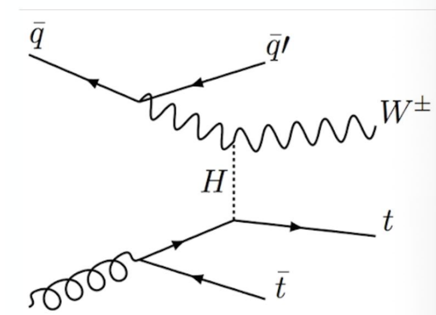
eg. example of LowNjet region in $2\ell SS$-$e\mu\mu\mu$ channel

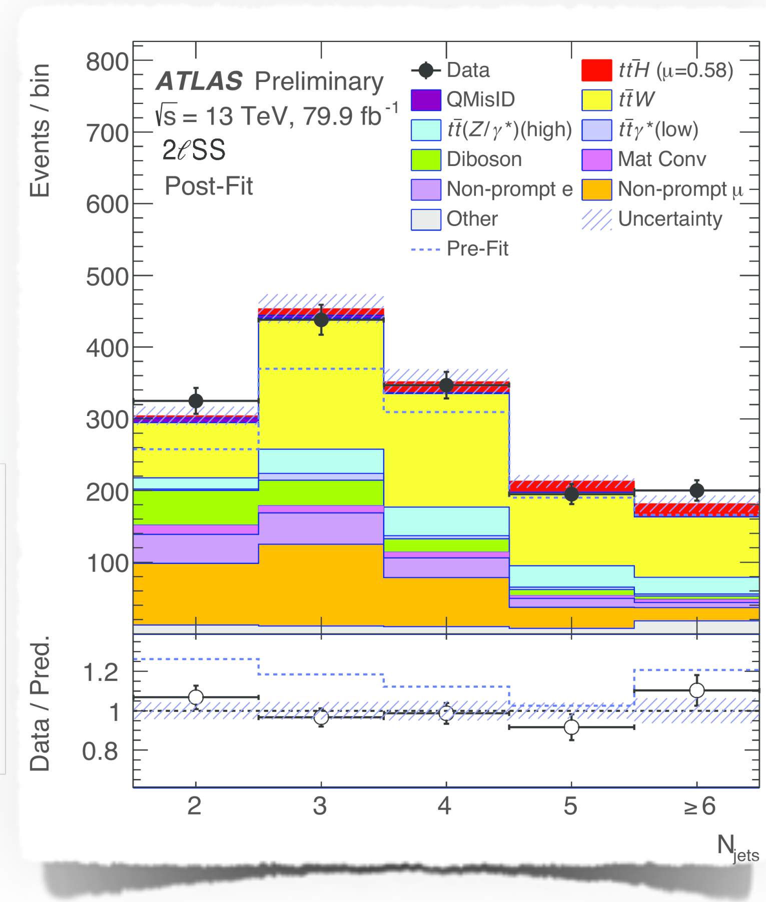
$t\bar{t}H\,(H \rightarrow multilepton)$

$80\,fb^{-1}$

* Normalisation of
  * **$t\bar{t}W$** (decorrelated between 2lSS0**τ** low NJets, 2lSS0**τ** high NJets, and 3l0**τ**)

* Observed more **$t\bar{t}W$** than expected
* Scale **Yellow Report 4** $t\bar{t}W$ cross section by **1.21**
  * to account for NLO **$t\bar{t}W$**+1 jet (qg initiated opened up)
  * **EWK effects** of order $\alpha_s\alpha^3$ (tW scattering NLO)
* Uncertainties to cover data/MC disagreements as a function of **NbJets** and **lepton total charge in $t\bar{t}W$ phase space**
  * Derived from the difference between data/MC
  * **Already** has stimulated some theory work!





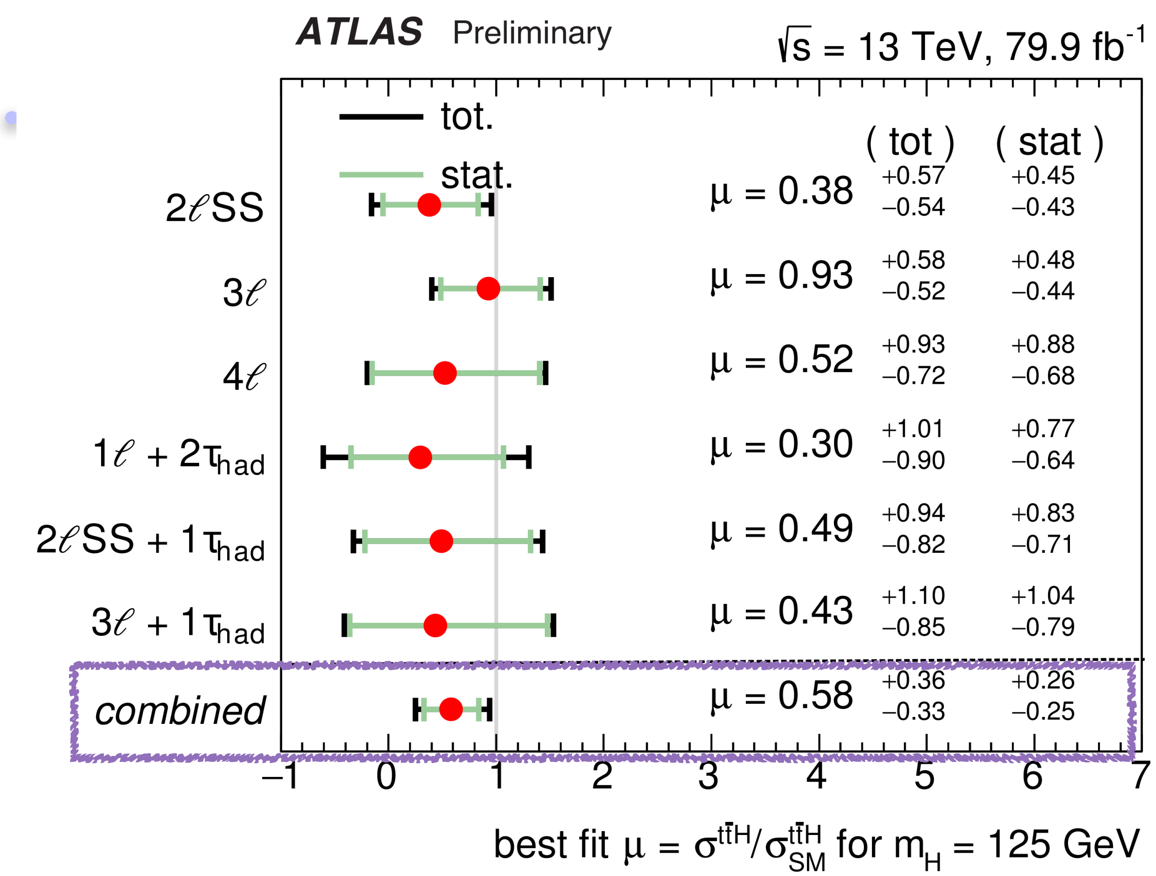
NF ($t\bar{t}W$) 2ℓ low NJet

NF ($t\bar{t}W$) 2ℓ high NJet

NF($t\bar{t}W$)	$1.56^{+0.30}_{-0.28}$ (2ℓLNJ)
	$1.26^{+0.19}_{-0.18}$ (2ℓHNJ)
	$1.68^{+0.30}_{-0.28}$ (3ℓ)

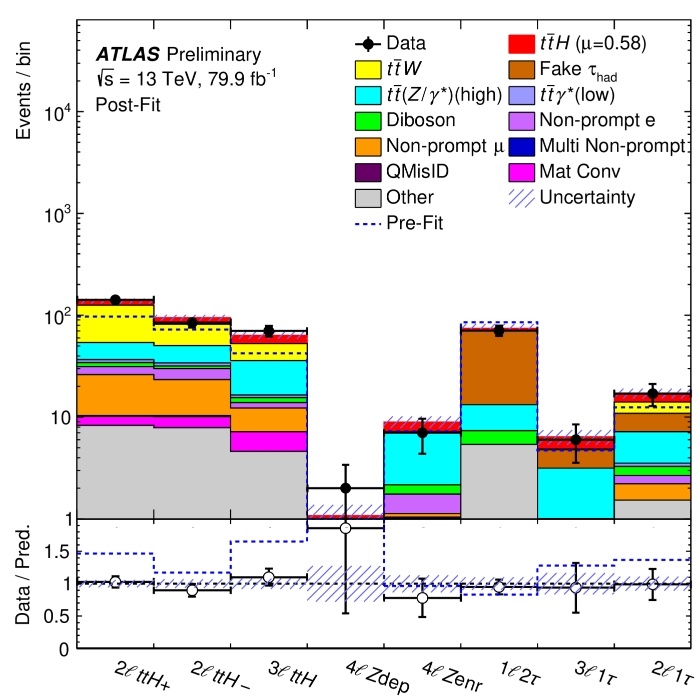
$t\bar{t}H$ ($H \rightarrow$ multilepton)

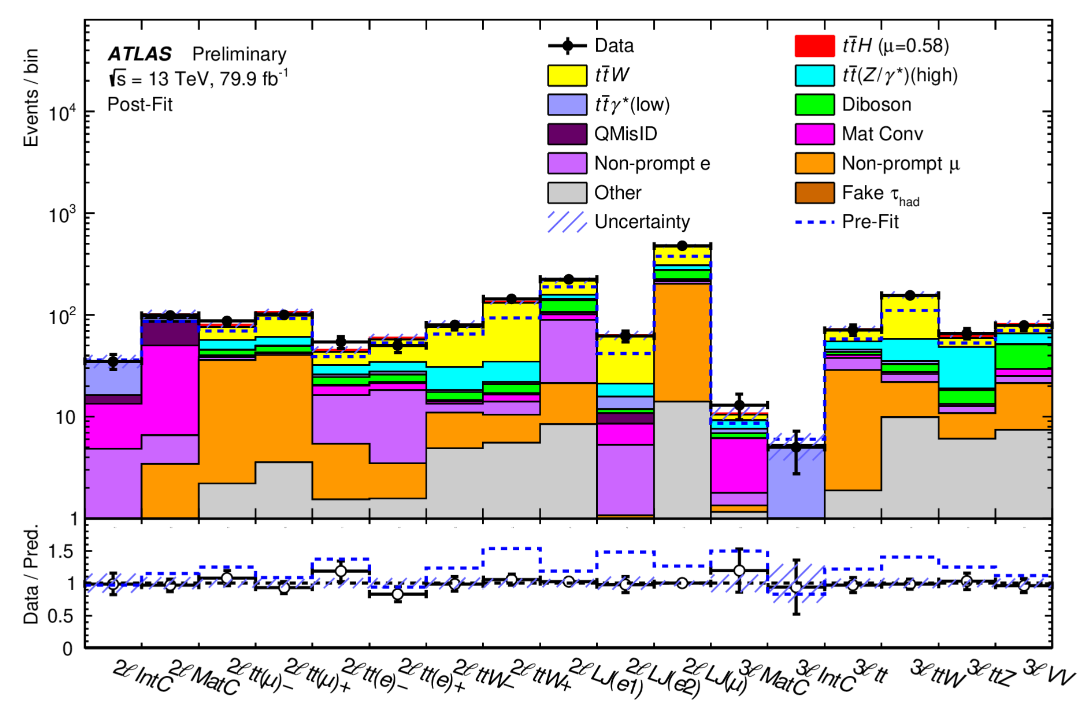
* **Fit model**
  * Profile likelihood fit ($\mu_{t\bar{t}H}$) of 17 CRs and 8 SRs
  * simultaneous fit to NFs & signal strength
* **Systematic uncertainties**
  * Jet energy scale and resolution (± 0.13)
  * $\mathbf{t\bar{t}\ell\ell}$ modelling (± 0.09)
  * $\mathbf{t\bar{t}W}$ modelling (± 0.08)



Significance: 1.8σ (3.1σ exp.)

SRs



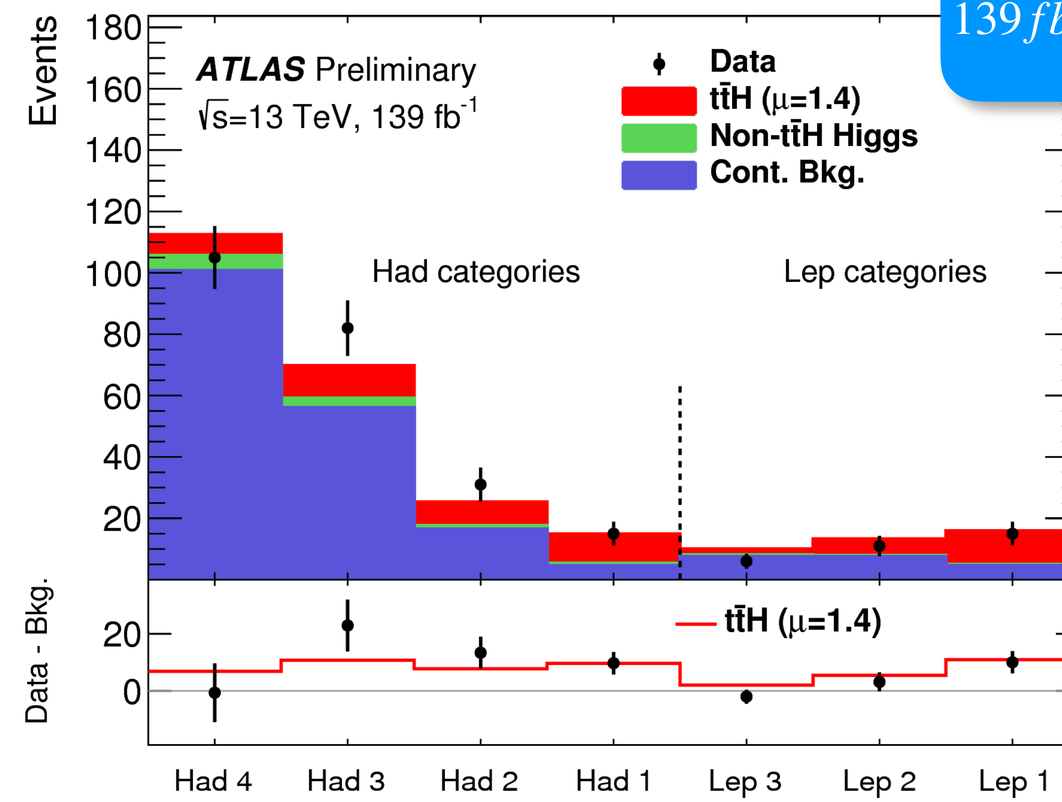


CRs

$t\bar{t}H\,(H \rightarrow \gamma\gamma)$

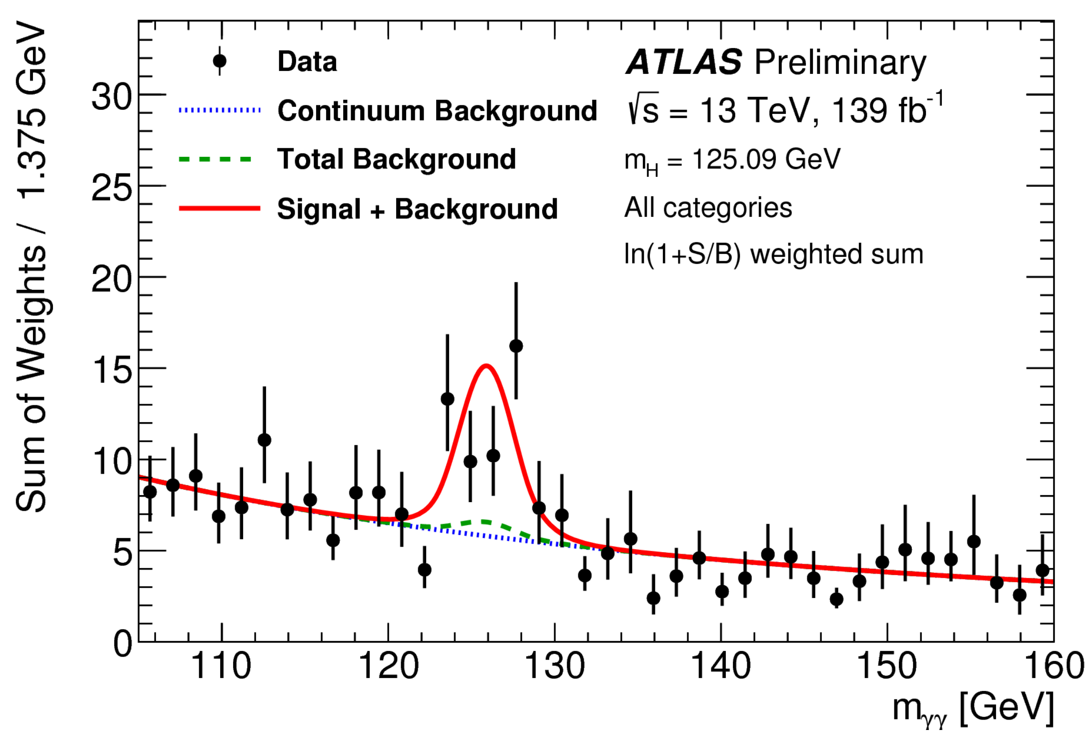
$139\,fb^{-1}$

* **Analysis regions**
  * Select two energetic and well isolated **photons**
  * Hadronic (0**ℓ,** 4 NJets, leptonic (≥1**ℓ,** 3 NJets) regions
  * all top decays are included
* Backgrounds
  * non-$t\bar{t}H$ production, $t\bar{t}\gamma\gamma\,, t\bar{t} + jets$
  * Determination of continuum background is ***data-driven***
  * Control samples to evaluate the function
* Defining **SRs**:
  * **BDTs** —> Inputs: photon, jet kinematics
  * Perform cut on BDT output to veto backgrounds and Categorise events passing



Significance: 4.9σ (4.2σ exp.)

$\mu_{t\bar{t}H} = 1.38^{+0.41}_{-0.36}$



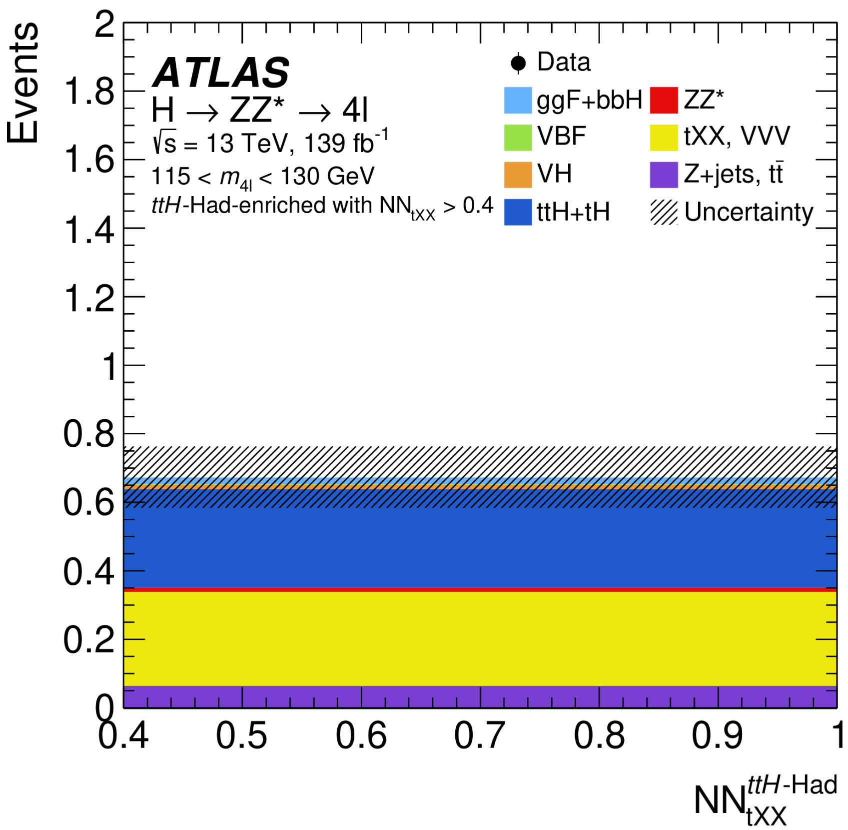
* **Fit setup & unc.**
  * Signal extracted from fit to $\mathbf{m_{\gamma\gamma}}$ distributions; *Double Sided Crystal Ball*
  * Results still statistically limited
  * Experimental (mainly on photons and jets) and theoretical unc. ($\mathbf{t\bar{t}H}$) included

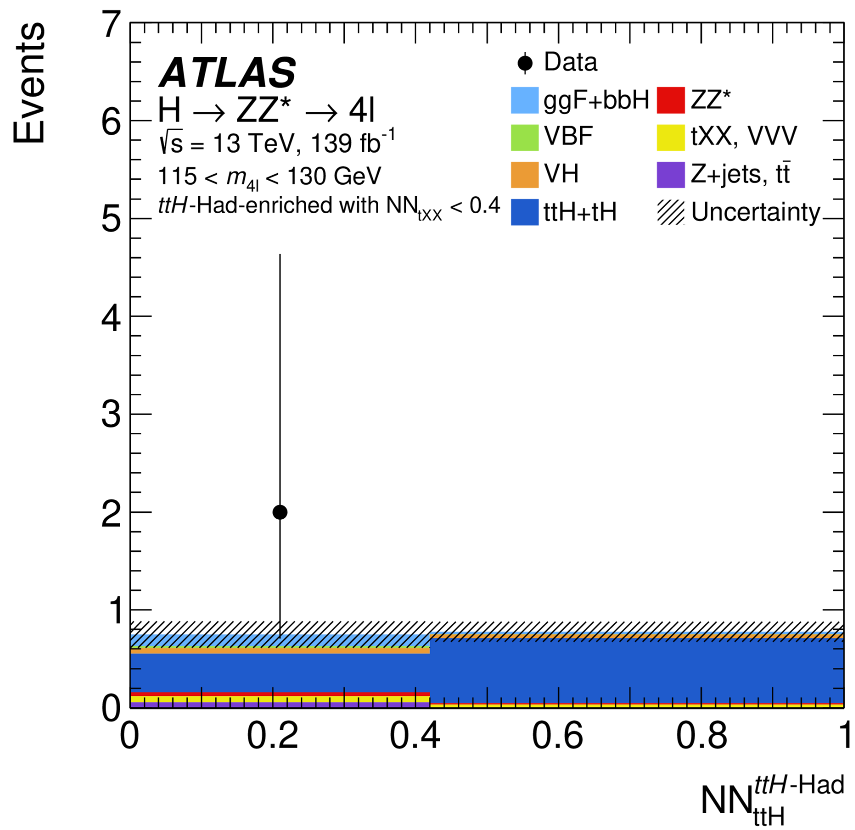
$t\bar{t}H\,(H \to ZZ^* \to 4l)$ Resonant

$139\,fb^{-1}$

* Searching Higgs Boson candidates $115 < m(4l) < 130\,GeV$
* Background in mass sidebands
* **Analysis regions**, based on $t\bar{t}$ decay
  * $t\bar{t}H$-Lep-enriched, event yield
  * $t\bar{t}H$-Had-enriched, exploit NN
    - $t\bar{t}H$ vs. tXX(ttZ) vs. ggF
    - resulting 2 independent outputs, $NN_{t\bar{t}H}$ & NN_{tXX} corresponding to the probability of the given process

$$\mu = 1.7^{+1.7}_{-1.2}\,(stat.) \pm 0.2\,(syst.) \pm 0.2\,(th.)$$

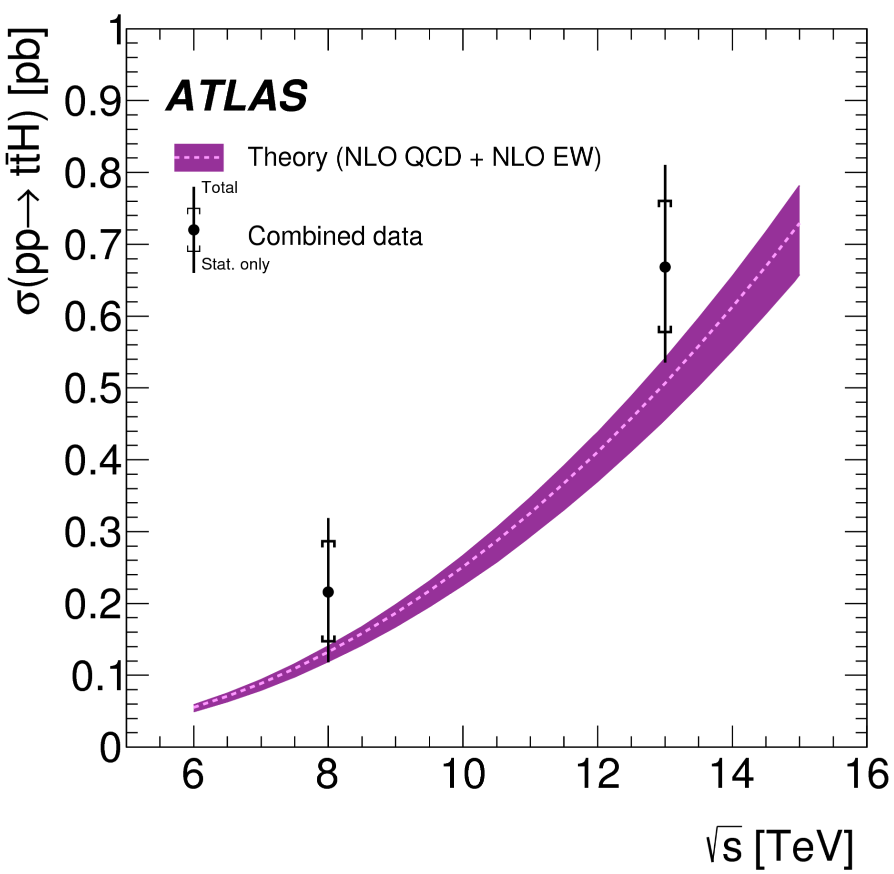




* Largely **statistically limited**
* **Three** candidates at ATLAS in full Run 2!

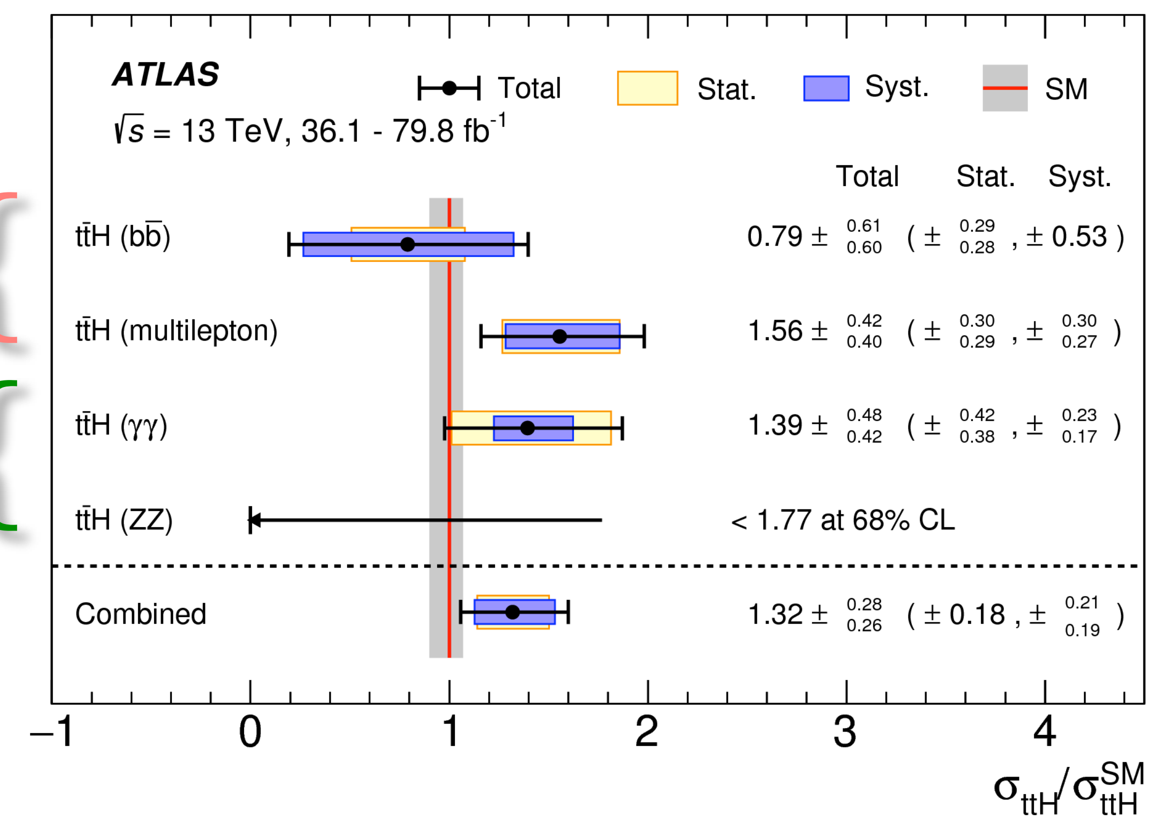
$t\bar{t}H$ Combination

* No combinations including all the latest results yet… but already 5σ observed!



$36\,fb^{-1}$

$80\,fb^{-1}$



Significance

Obs.	(Exp.)
1.4σ	(1.6σ)
4.1σ	(2.8σ)
4.1σ	(3.7σ)
0σ	(1.2σ)
5.8σ	**(4.9σ)**

Run1 + up to $80\,fb^{-1}$: **6.3σ** (5.1σ exp.)

Measurements **consistent with Standard Model.**

Conclusion

- The latest studies related to $t\bar{t}H$ measurements are presented

- ATLAS has established observation of $t\bar{t}H$ production by combining various Higgs decay channels
  - Results are compatible with SM

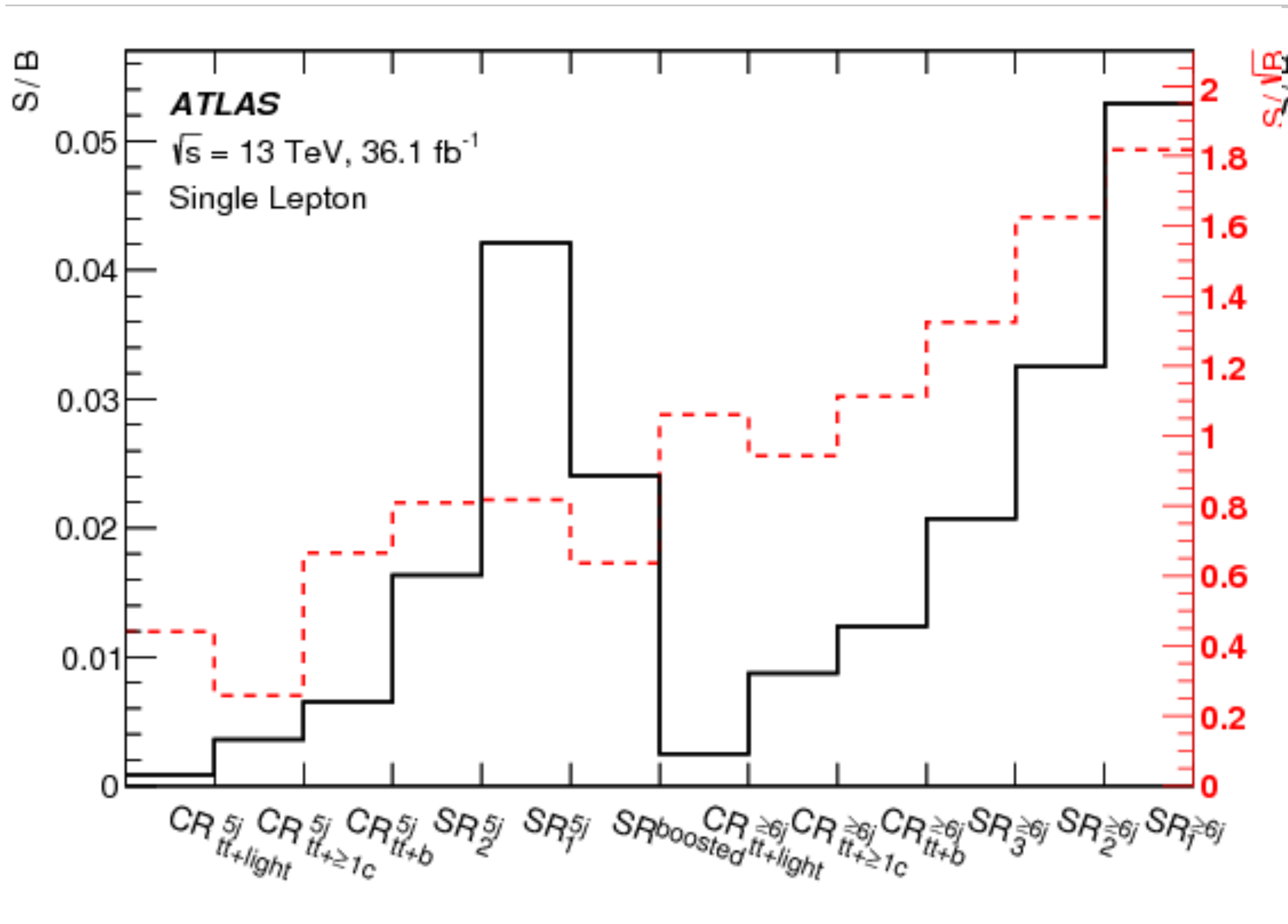
- Some individual channels updated their results with more data
  - Almost **observation** for $t\bar{t}H$ production in $H \rightarrow \gamma\gamma$ channel alone
  - 3 events are observed in $t\bar{t}H\,(H \rightarrow ZZ^{*} \rightarrow 4l)$

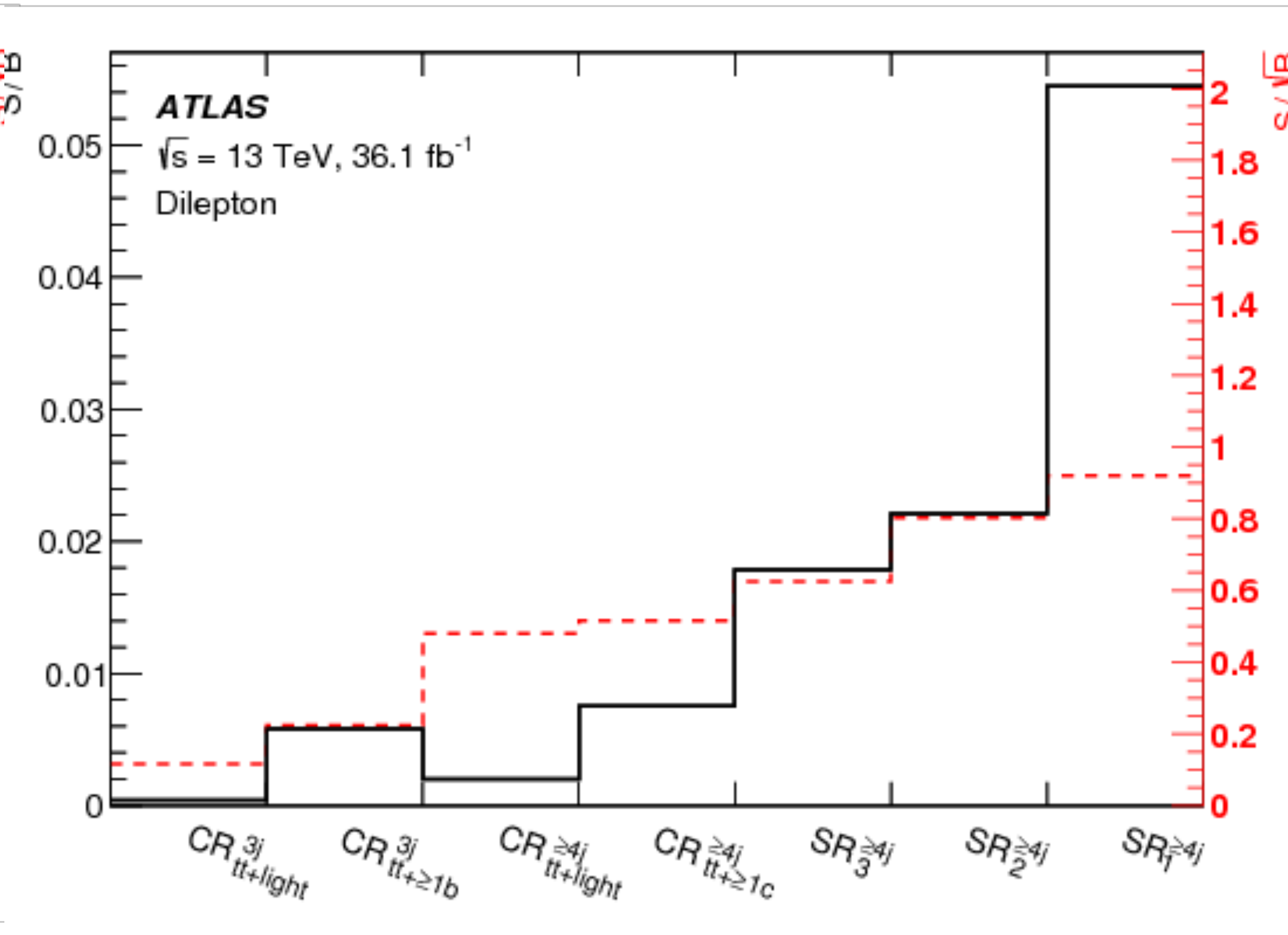
- Challenging backgrounds
  - Requires better understanding of background processes eg. $t\bar{t}W, t\bar{t}b\bar{b}$
  - Improvements are expected with Full Run2 data

- Full Run2 dataset will allow also new opportunities, including **differential** and **properties measurements**.

Backup

Backup





The ratios of S/B and $S/\sqrt{B}$ for each analysis categories in $t\bar{t}H(bb)$

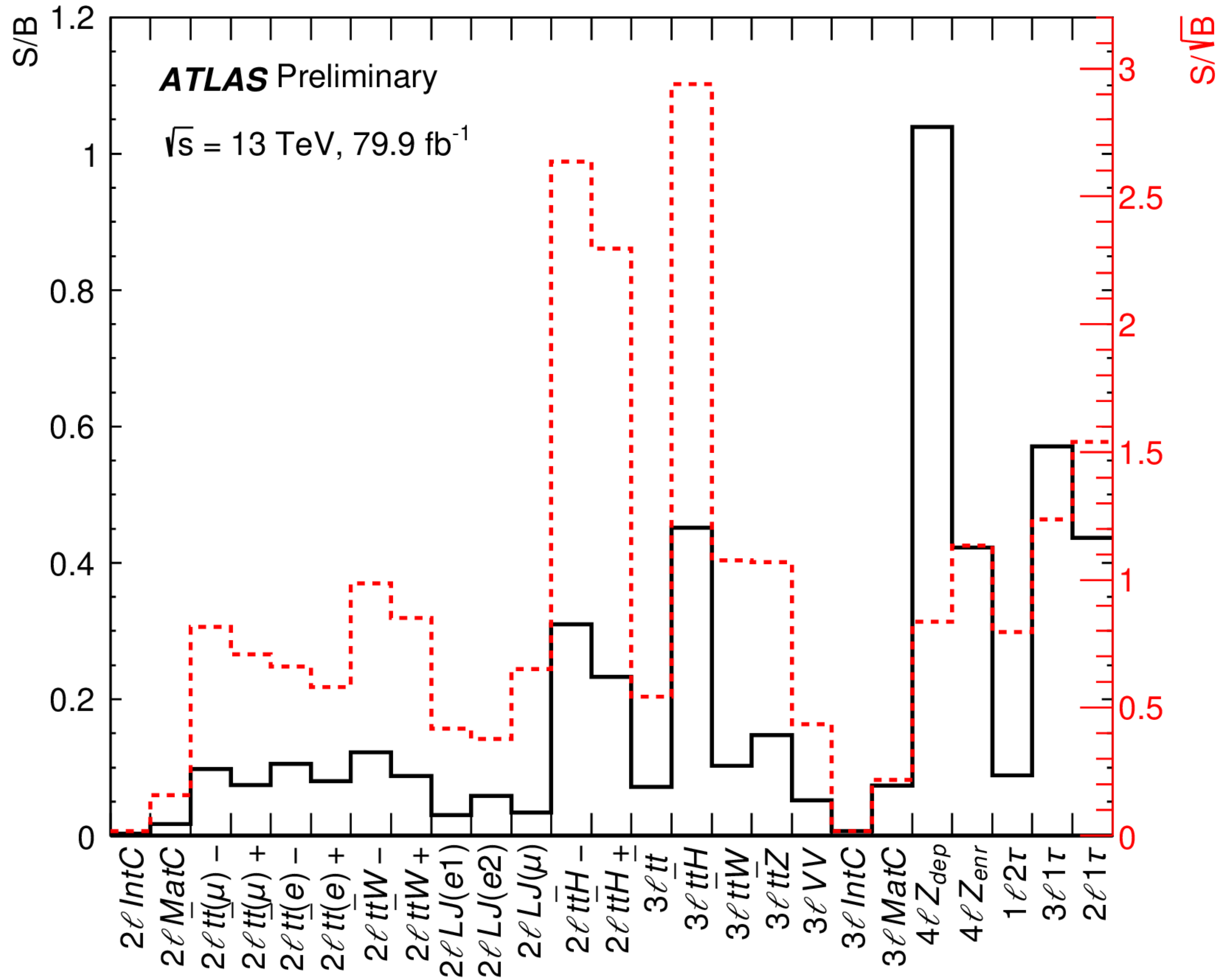
Single lepton + dilepton have similar purity; lower stats in dilepton

Boosted: two R=1.0 jets

→ H candidate p_T > 200 GeV, 2 b-tagged subjets

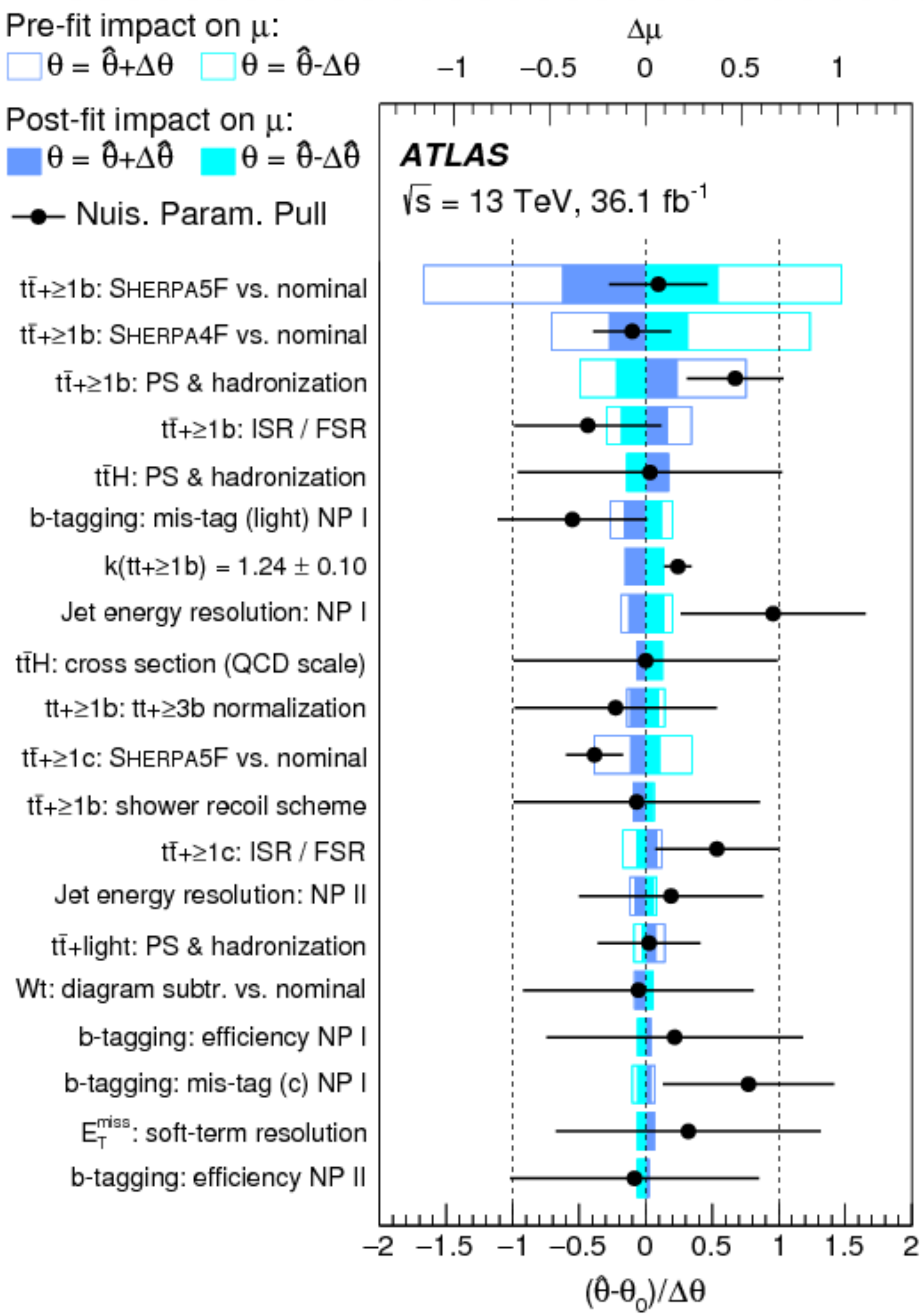
→ top candidate p_T > 250 GeV, one b-tagged subjet

Backup



* The ratios of S/B and $S/\sqrt{B}$ for each analysis categories in $t\bar{t}H$ - multi lepton

Backup



* Ranking of NPs in $t\bar{t}H(bb)$

Backup

Process	Generator	ME order	Parton shower	PDF	Tune
$t\bar{t}H$	POWHEG-BOX [23, 24]	NLO	PYTHIA 8	NNPDF3.0 NLO [25]/ NNPDF2.3 LO [48]	A14
	(POWHEG-BOX)	(NLO)	(HERWIG7)	(NNPDF3.0 NLO/ MMHT2014 LO [49])	(H7-UE-MMHT)
$tHqb$	MG5_aMC	LO	PYTHIA 8	CT10 [50]	A14
tHW	MG5_aMC	NLO	HERWIG++	CT10/ CTEQ6L1 [51, 52]	UE-EE-5
$t\bar{t}W$	SHERPA 2.2.1	MEPS@NLO	SHERPA	NNPDF3.0 NNLO	SHERPA default
	(MG5_aMC)	(NLO)	(PYTHIA 8)	(NNPDF3.0 NLO/ NNPDF2.3 LO)	(A14)
$t\bar{t}(Z/\gamma^*)$	MG5_aMC	NLO	PYTHIA 8	NNPDF3.0 NLO/ NNPDF2.3 LO	A14
	(SHERPA 2.2.0)	(LO multileg)	(SHERPA)	(NNPDF3.0 NLO)	(SHERPA default)
$t\bar{t} \to W^+bW^-\bar{b}l^+l^-$	MG5_aMC	LO	PYTHIA 8	NNPDF3.0 LO	A14
tZ	MG5_aMC	LO	PYTHIA 6	CTEQ6L1	Perugia2012
tWZ	MG5_aMC	NLO	PYTHIA 8	NNPDF2.3 LO	A14
$t\bar{t}t$, $t\bar{t}t\bar{t}$	MG5_aMC	LO	PYTHIA 8	NNPDF2.3 LO	A14
$t\bar{t}W^+W^-$	MG5_aMC	LO	PYTHIA 8	NNPDF2.3 LO	A14
$t\bar{t}$	POWHEG-BOX	NLO	PYTHIA 8	NNPDF3.0 NLO/ NNPDF2.3 LO	A14
Single top (t-, Wt-, s-channel)	POWHEG-BOX [53–55]	NLO	PYTHIA 8	NNPDF3.0 NLO/ NNPDF2.3 LO	A14
VV, $qqVV$, VVV	SHERPA 2.2.2	MEPS@NLO	SHERPA	NNPDF3.0 NNLO	SHERPA default
$Z \to l^+l^-$	SHERPA 2.2.1	MEPS@NLO	SHERPA	NNPDF3.0 NLO	SHERPA default

Backup

	e			μ		
	L	L*	T	L	L*	T
FixedCutLoose	No	Yes		No	Yes	
Non-prompt lepton BDT	No		Yes	No		Yes
Identification	Loose		Tight	Loose		
Charge mis-assignment veto	No		Yes	N/A		
ambiguity bit == 0	No		Yes	N/A		
Transverse impact parameter significance $\|d_0\|/\sigma_{d_0}$	< 5			< 3		
Longitudinal impact parameter $\|z_0 \sin\theta\|$	< 0.5 mm					

L = Loose

L* = Loose + FixedCutLoose

T = Tight

	electron	muon
ID	TightLH && ambiguityType == 0	Medium
Isolation	FixedCutLoose && PLV < -0.7	FixedCutLoose && PLV < -0.5
conv. suppression	$\Delta R_{ll} > 0.5$ && $\|\eta_e\| < 2.0$!ExtCo && !IntCo	
QmisID MVA	> 0.7	
impact parameter	$\|d0\|/\sigma(d0) < 5$ $z_0 \sin\theta < 0.5$ mm	$\|d0\|/\sigma(d0) < 3$ $z_0 \sin\theta < 0.5$ mm

- **Material conversion candidates** have a reconstructed displaced vertex with radius r > 20 mm that includes the track associated with the electron
  - The invariant mass of the associated track and the closest (in $\Delta\eta$) opposite-charge track reconstructed in the silicon detector, calculated at the conversion vertex, is required to be < 100 MeV.
- **Internal conversion candidates** are required to fail the requirements for material conversions, and the di-track invariant mass, this time calculated at the primary vertex, is also required to be < 100 MeV.
- **Very tight** electron candidates are tight electrons that fail the internal conversion and material conversion requirements, and have $|\eta| < 2$.
  - The latter requirement rejects a small fraction of electrons with a *large charge misidentification rate* because of the limited number of hits used in the track reconstruction.

Backup

Electrons

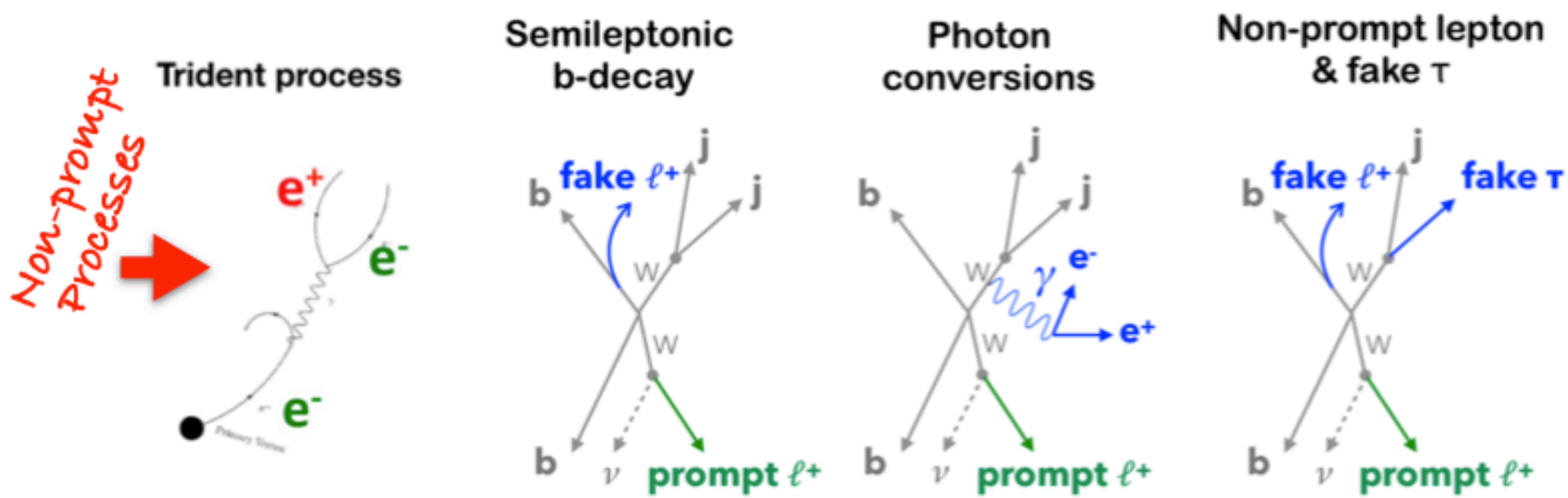
- Heavy flavour decays (b-decay)
- Conversions
- Charge misidentification

Muons

- Heavy flavour decays (b-decay)
- In-flight decays of π/K

Taus

- Light, heavy jets (quarks,gluons)
- Electrons



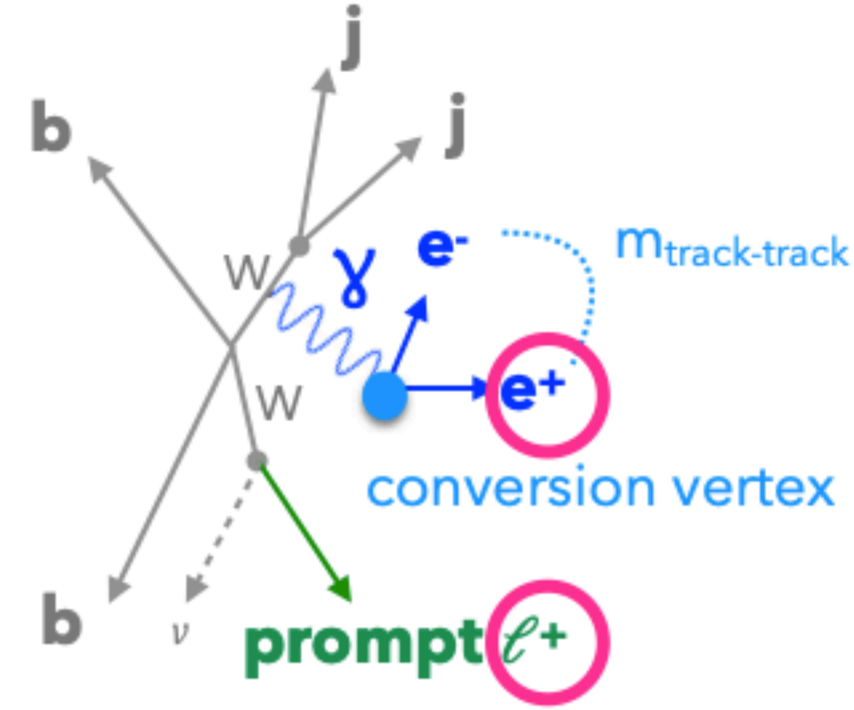
- Dedicated methods/control regions for each background source
  - Heavy Flavour, photon conversions (internal(γ^*)&material) —> Template Fit Method (semi data-driven)
  - Charge misidentification —> 3D Likelihood (data-driven)
  - τ Fakes —> Fake factor (data-driven)

Backup

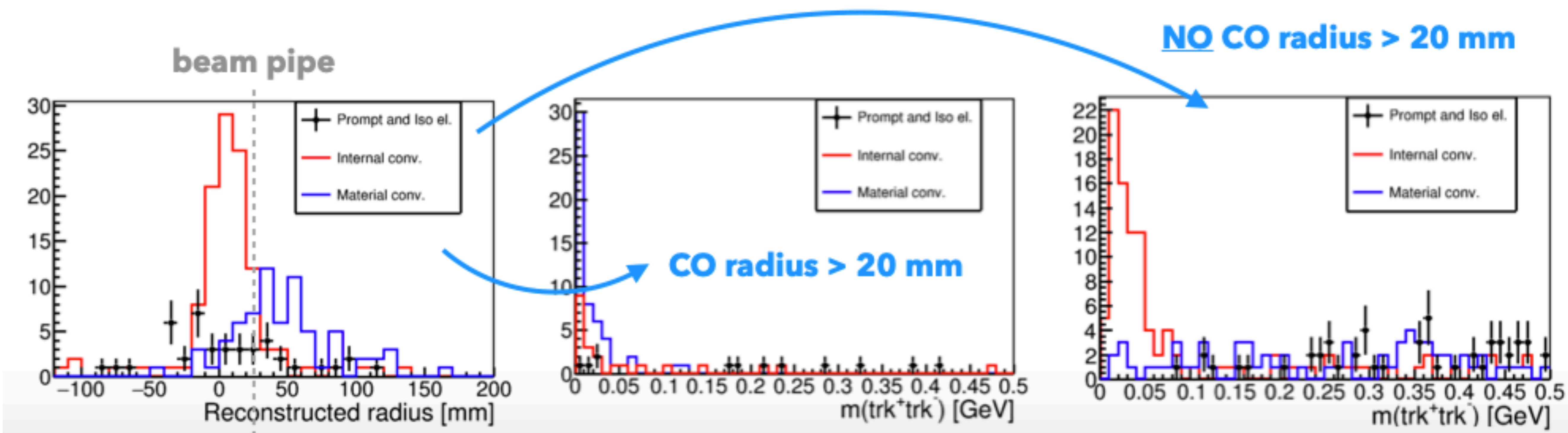
Tamara Vazquez Schröder

- internal ($\gamma^* \rightarrow e^+e^-$) and material electron **conversion** (CO) candidates further suppressed with **track invariant masses** and **conversion radius** in the transverse plane

electron CO selection	CO radius	$m_{track\text{-}track}$
(1) material CO	> 20 mm	< 100 MeV (wrt. CV)
(2) internal CO	**not (1)**	< 100 MeV (wrt. PV)
(3) very tight*	**not (1) and not (2)**	



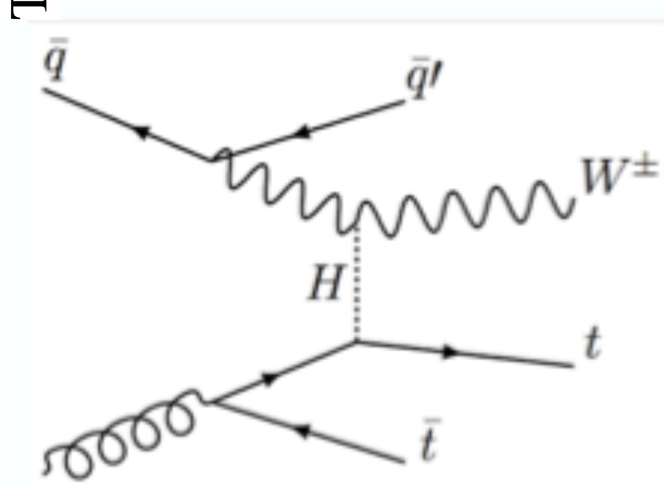
reduces conversions by ~50% at the cost of ~2% prompt electron efficiency



Backup

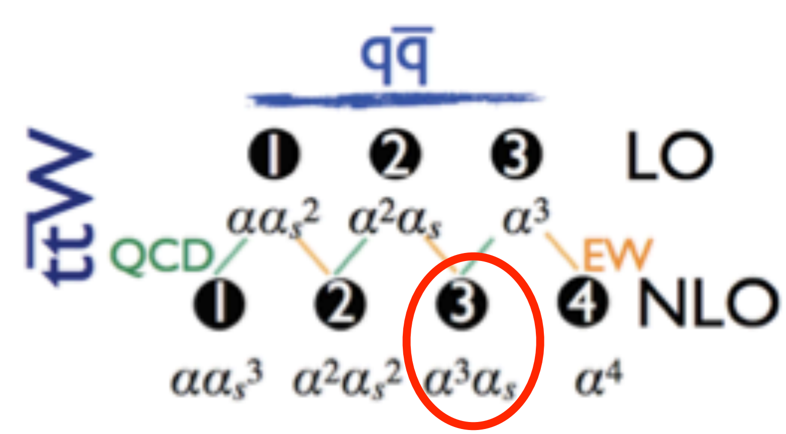
- A normalisation factor of **1.2** applied on top of the YR4 cross section for $t\bar{t}W$
- Origin of the correction factor:
  - Factor **1.11** to account for missing QCD corrections in higher order XS
    - ttW+0j@NLO ➜ $t\bar{t}$W+0,**1j**@NLO
    - estimated using dedicated samples generated with Sherpa 2.2.1 using the MEPS@NLO prescription, and cross-checked with the NLO generator MadGraph5_aMC@NLO 2.2.1 using the FxFx prescription
  - Factor **1.09** to account for missing EW corrections
    - [1711.02116] shows “subleading” NLO EWK corrections, not included in YR4 XS, can be large
    - primarily because of the large **NLO3 term** driven by the $t\bar{t}$W+1-jet diagrams with a Higgs boson exchanged in the t-channel

Tamara Vazquez Schröder



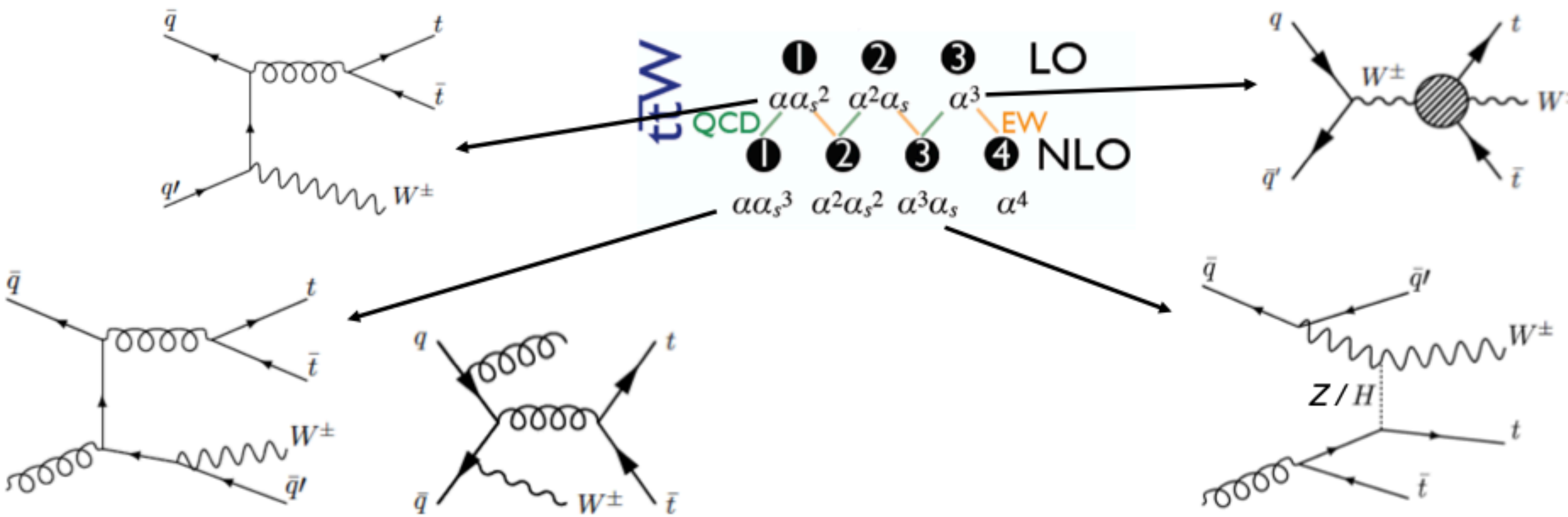
13 TeV

$\delta[\%]$	$\mu = H_T/2$
LO_2	-
LO_3	0.9
NLO_1	50.0 (25.7)
NLO_2	−4.2 (−4.6)
NLO_3	12.2 (9.1)
NLO_4	0.04 (−0.02)



Backup

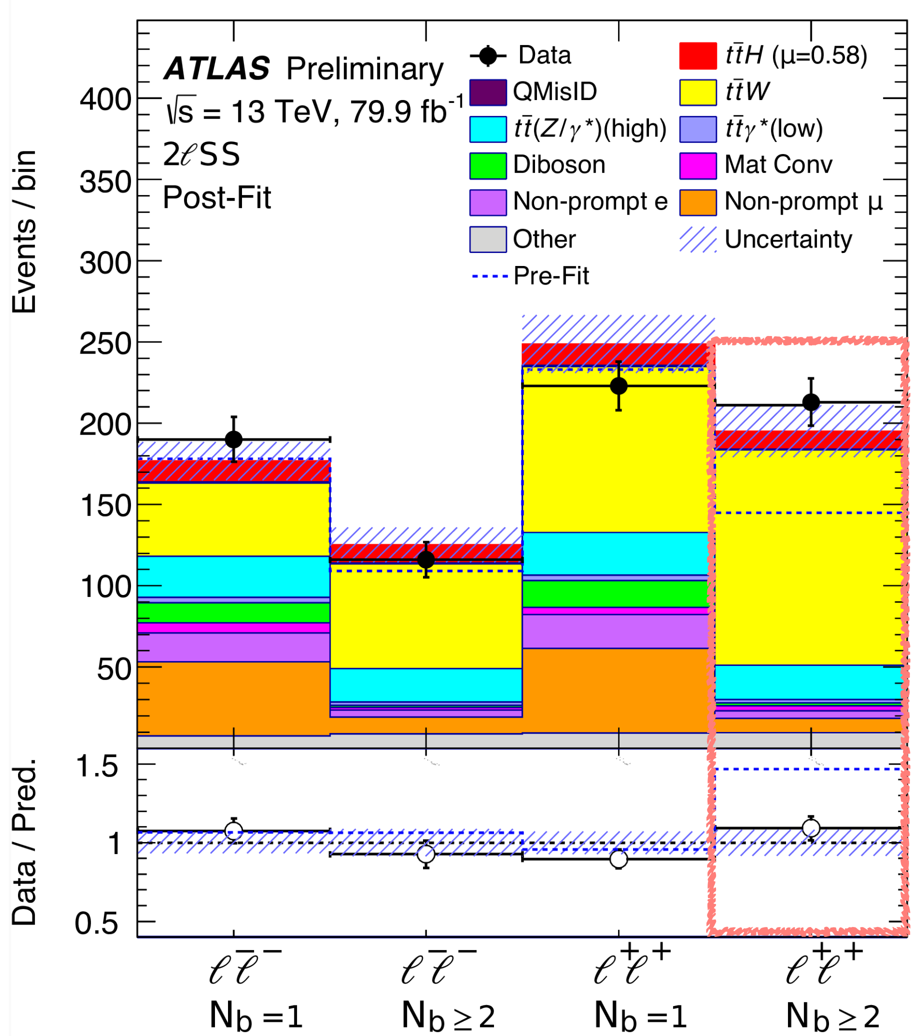
* Recent modelling studies for QCD and EWK corrections in ttH-ML phase space
  - arXiv: 2005.09427v1
  - arXiv: 2004.09552v1

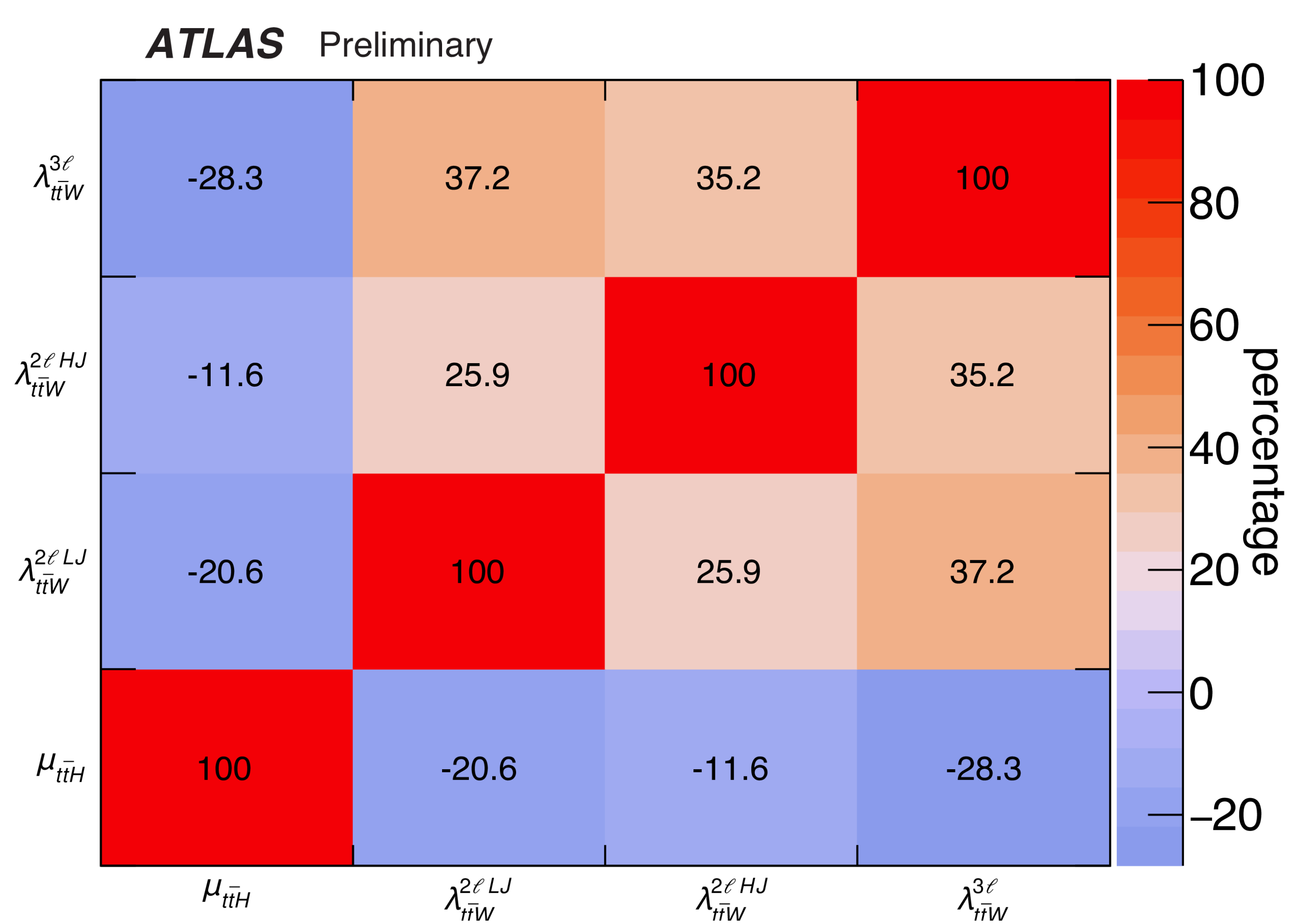


real extra emission attached to an EW vertex

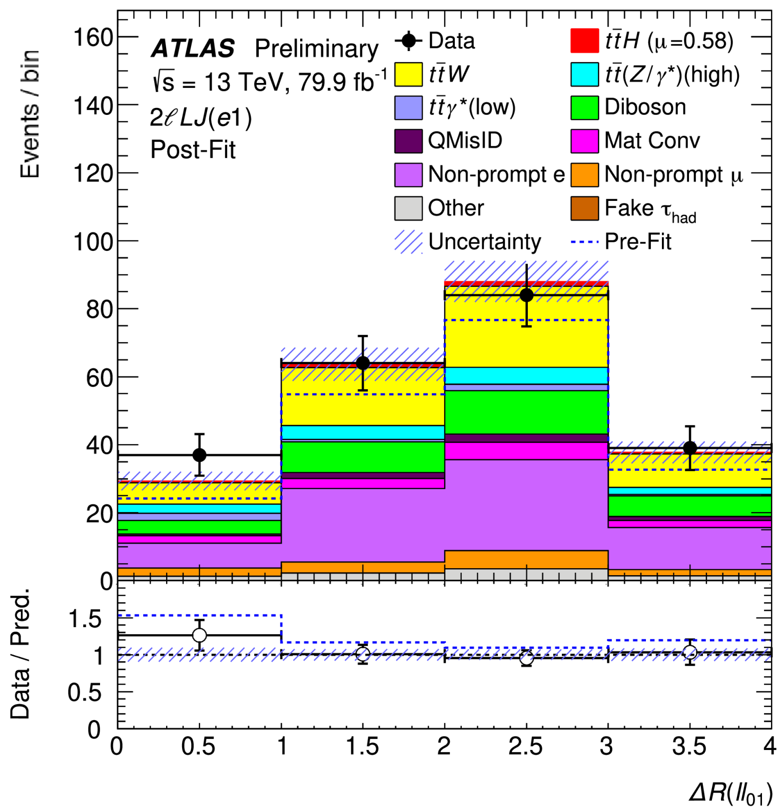
tW scattering (e.g. top-H and top-Z couplings)

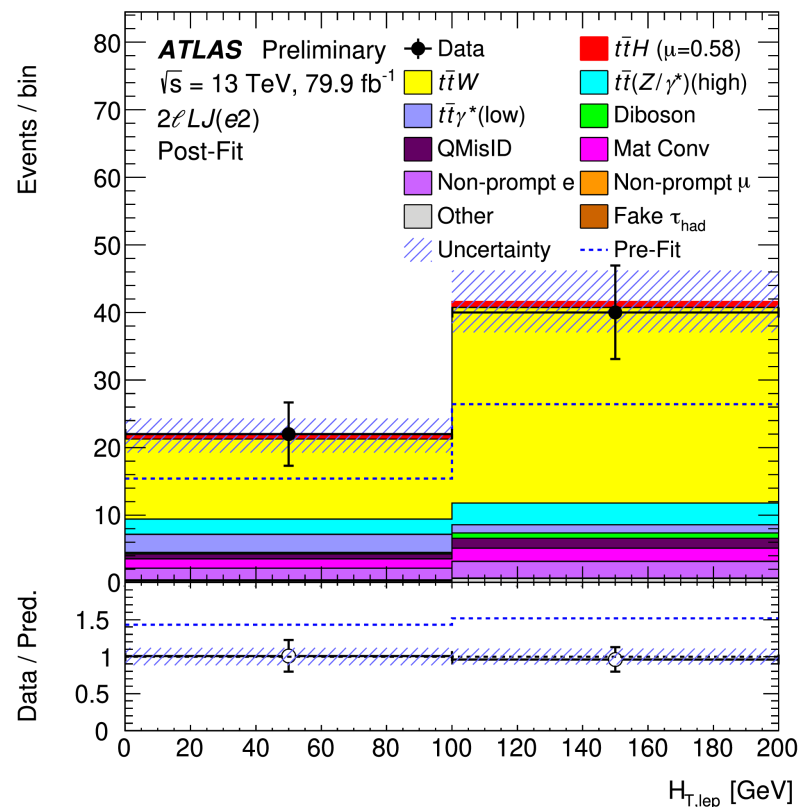
Backup

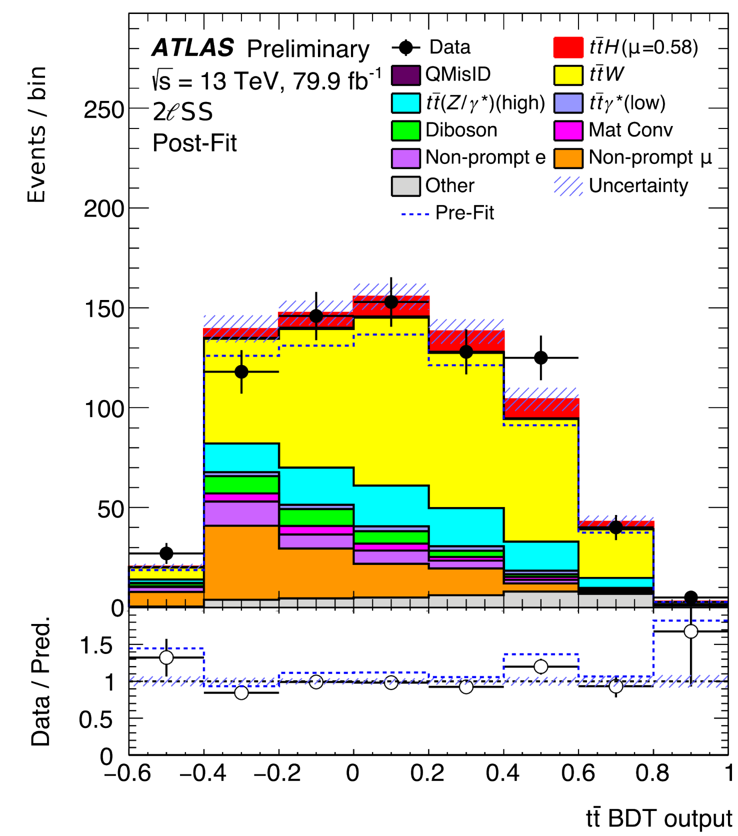

ATLAS Preliminary
√s = 13 TeV, 79.9 fb-1
2ℓSS
Post-Fit
Data
QMisID
tt̄(Z/γ*)(high)
Diboson
Non-prompt e
Other
Pre-Fit
tt̄H (μ=0.58)
tt̄W
tt̄γ*(low)
Mat Conv
Non-prompt μ
Uncertainty
Events / bin
Data / Pred.
ℓ⁻ℓ⁻ Nb =1
ℓ⁻ℓ⁻ Nb ≥ 2
ℓ⁺ℓ⁺ Nb =1
ℓ⁺ℓ⁺ Nb ≥ 2

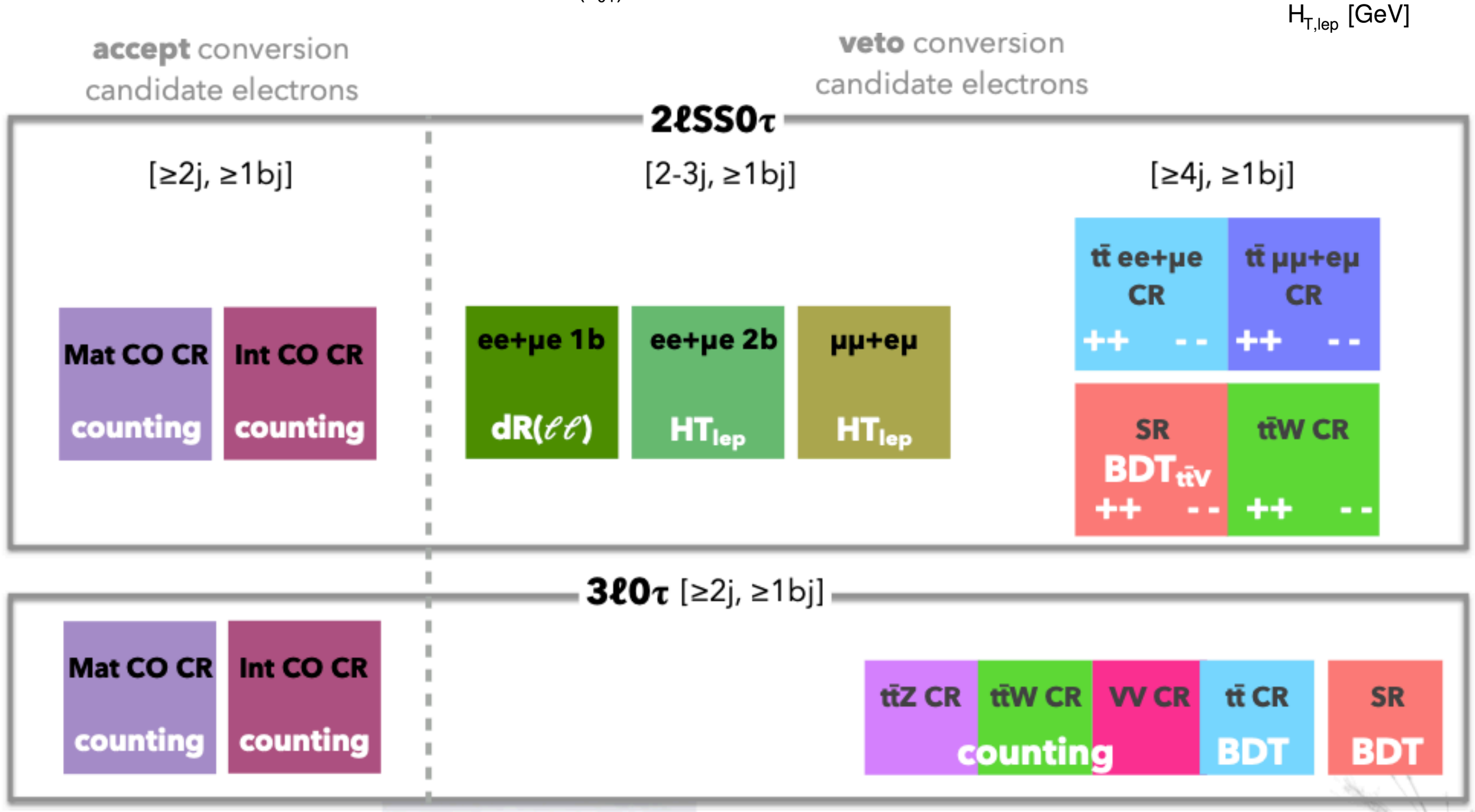

ATLAS Preliminary
percentage
λ^{3ℓ}_{tt̄W}: -28.3, 37.2, 35.2, 100
λ^{2ℓ HJ}_{tt̄W}: -11.6, 25.9, 100, 35.2
λ^{2ℓ LJ}_{tt̄W}: -20.6, 100, 25.9, 37.2
μ_{tt̄H}: 100, -20.6, -11.6, -28.3
μ_{tt̄H}
λ^{2ℓ LJ}_{tt̄W}
λ^{2ℓ HJ}_{tt̄W}
λ^{3ℓ}_{tt̄W}

Backup

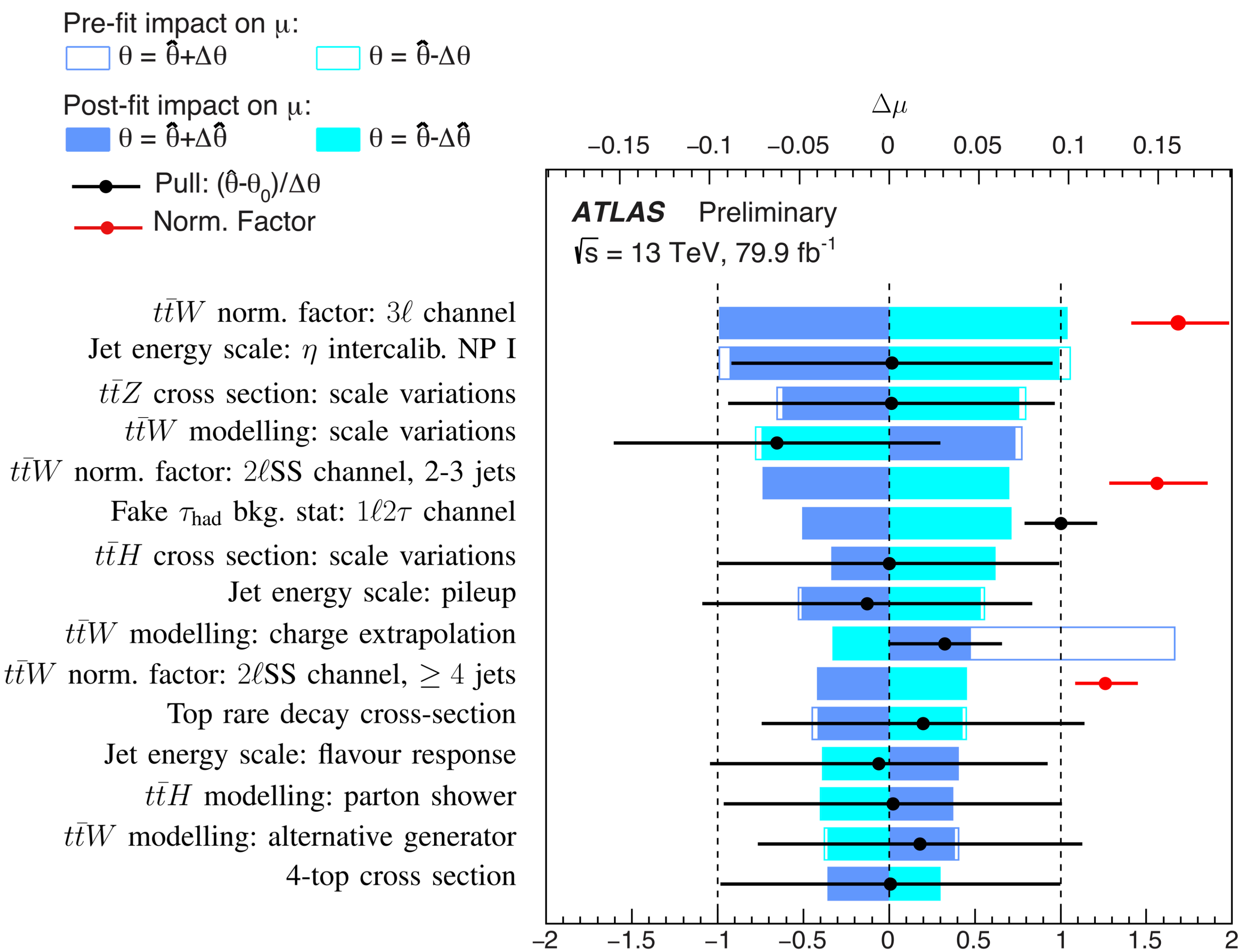

ATLAS Preliminary
√s = 13 TeV, 79.9 fb-1
2ℓLJ(e1)
Post-Fit
Data
tt̄H (μ=0.58)
tt̄W
tt̄(Z/γ*)(high)
tt̄γ*(low)
Diboson
QMisID
Mat Conv
Non-prompt e
Non-prompt μ
Other
Fake τhad
Uncertainty
Pre-Fit
Events / bin
Data / Pred.
ΔR(ll01)


ATLAS Preliminary
√s = 13 TeV, 79.9 fb-1
2ℓLJ(e2)
Post-Fit
Data
tt̄H (μ=0.58)
tt̄W
tt̄(Z/γ*)(high)
tt̄γ*(low)
Diboson
QMisID
Mat Conv
Non-prompt e
Non-prompt μ
Other
Fake τhad
Uncertainty
Pre-Fit
Events / bin
Data / Pred.
HT,lep [GeV]


ATLAS Preliminary
√s = 13 TeV, 79.9 fb-1
2ℓSS
Post-Fit
Data
tt̄H(μ=0.58)
QMisID
tt̄W
tt̄(Z/γ*)(high)
tt̄γ*(low)
Diboson
Mat Conv
Non-prompt e
Non-prompt μ
Other
Uncertainty
Pre-Fit
Events / bin
Data / Pred.
tt̄ BDT output

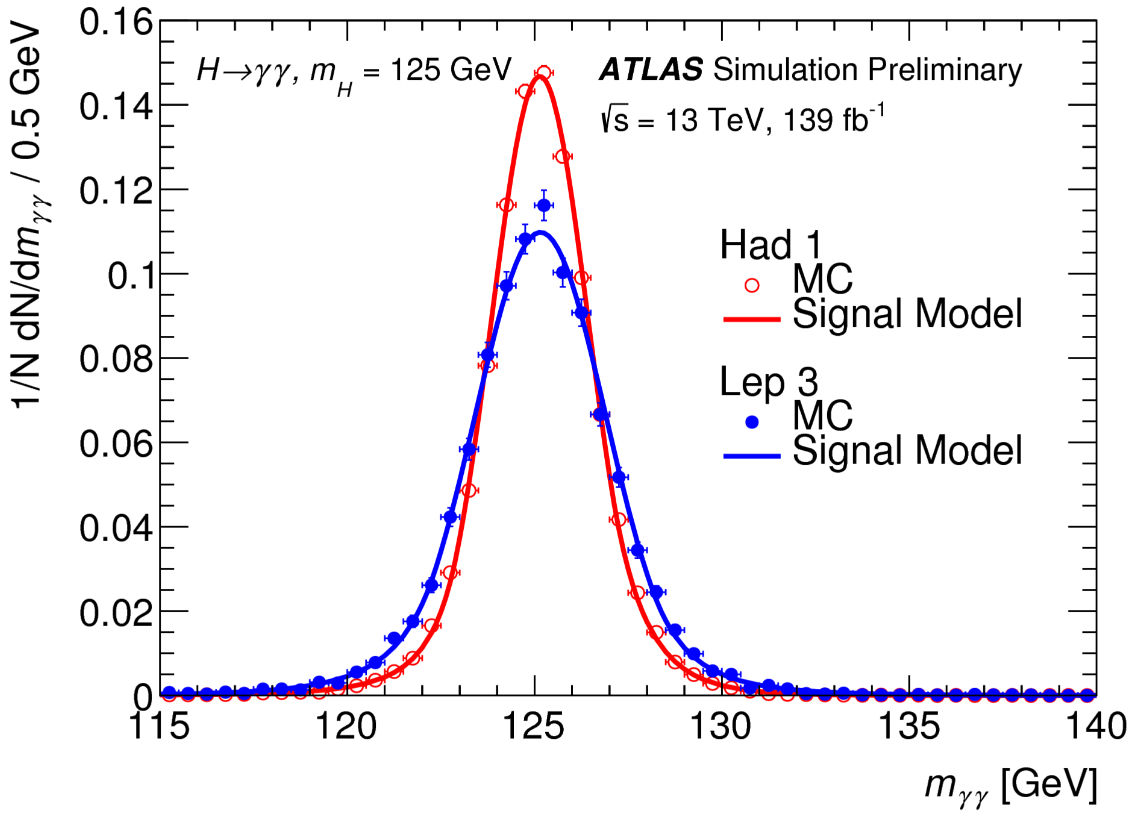

accept conversion candidate electrons
veto conversion candidate electrons
2ℓSS0τ
[≥2j, ≥1bj]
[2-3j, ≥1bj]
[≥4j, ≥1bj]
Mat CO CR counting
Int CO CR counting
ee+μe 1b dR(ℓℓ)
ee+μe 2b HTlep
μμ+eμ HTlep
tt̄ ee+μe CR ++ - -
tt̄ μμ+eμ CR ++ - -
SR BDTtt̄V ++ - -
tt̄W CR ++ - -
3ℓ0τ [≥2j, ≥1bj]
Mat CO CR counting
Int CO CR counting
tt̄Z CR
tt̄W CR
VV CR
counting
tt̄ CR BDT
SR BDT

Backup

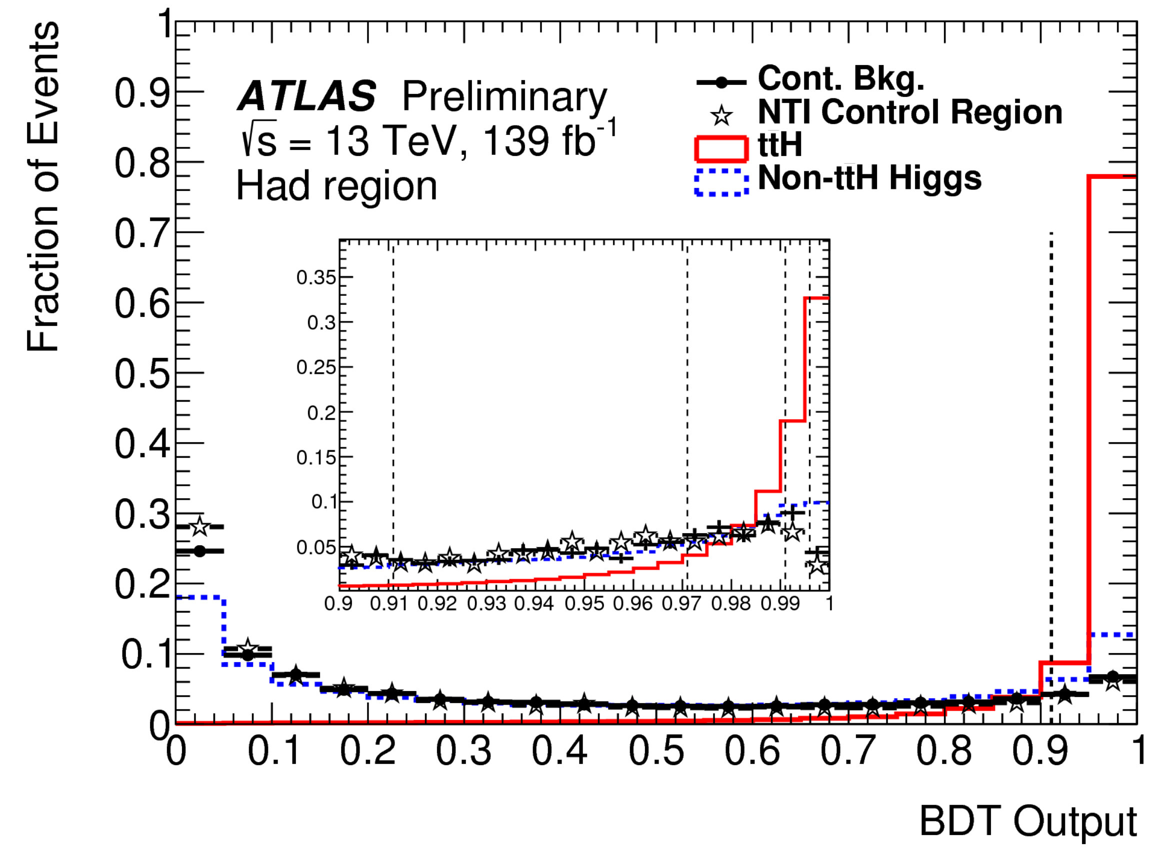


* Ranking of NPs in $t\bar{t}H$ - multi lepton

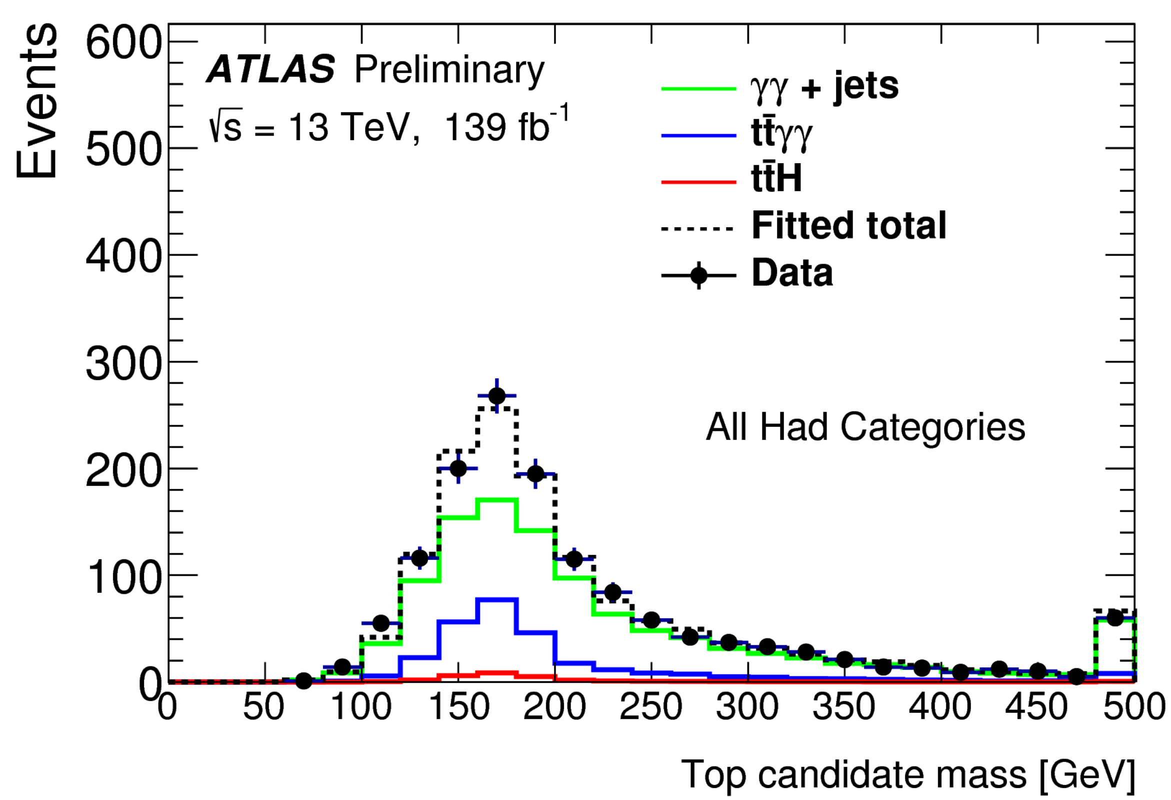
Backup



H→γγ, m_H = 125 GeV
ATLAS Simulation Preliminary
√s = 13 TeV, 139 fb-1
Had 1
MC
Signal Model
Lep 3
MC
Signal Model
1/N dN/dm_γγ / 0.5 GeV
m_γγ [GeV]

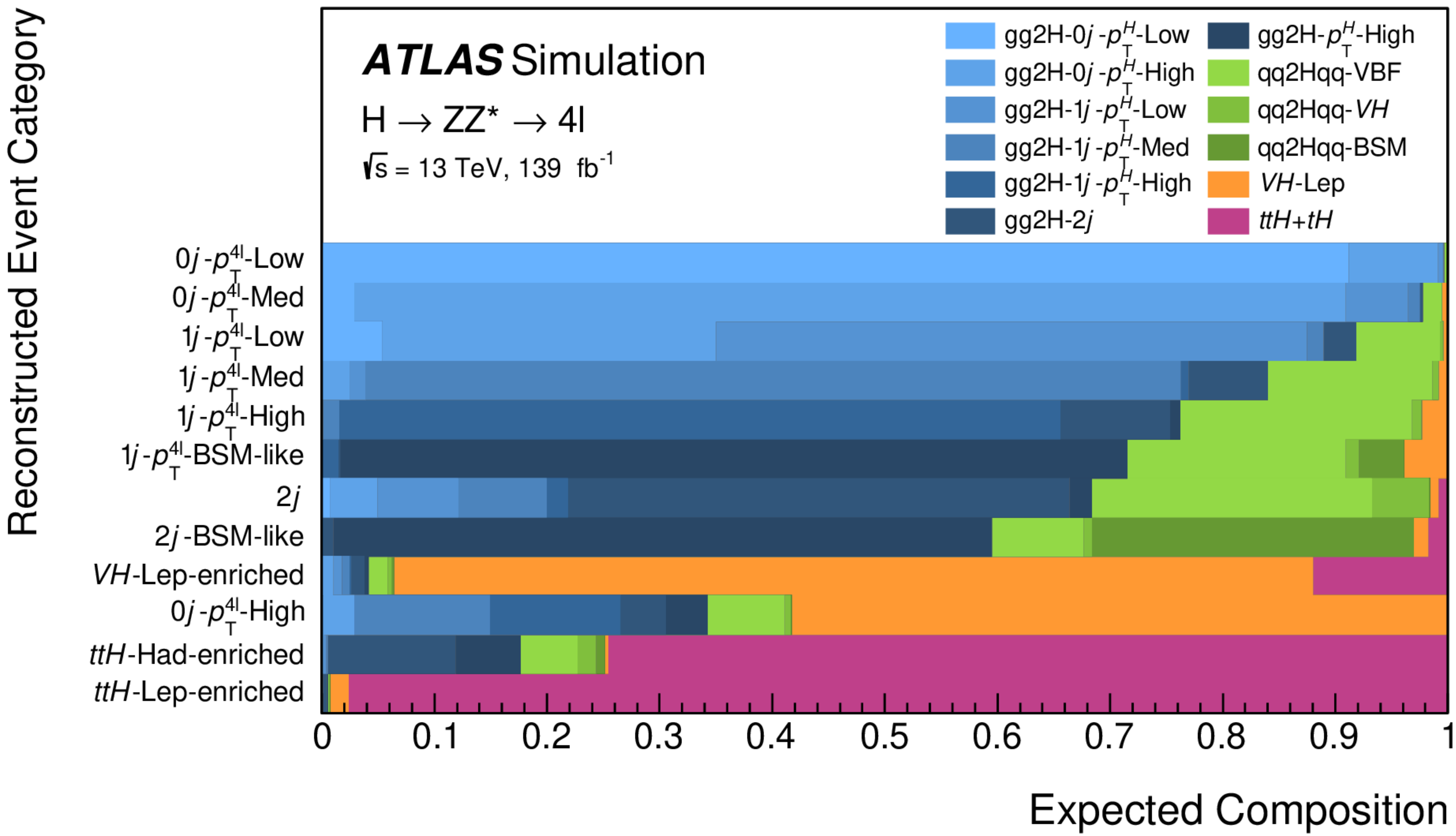


ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Had region
Cont. Bkg.
NTI Control Region
ttH
Non-ttH Higgs
Fraction of Events
BDT Output



ATLAS Preliminary
√s = 13 TeV, 139 fb-1
γγ + jets
tt̄γγ
tt̄H
Fitted total
Data
All Had Categories
Events
Top candidate mass [GeV]

Backup


ATLAS Simulation
H → ZZ* → 4l
√s = 13 TeV, 139 fb⁻¹
gg2H-0j-pTH-Low
gg2H-0j-pTH-High
gg2H-1j-pTH-Low
gg2H-1j-pTH-Med
gg2H-1j-pTH-High
gg2H-2j
gg2H-pTH-High
qq2Hqq-VBF
qq2Hqq-VH
qq2Hqq-BSM
VH-Lep
ttH+tH
Reconstructed Event Category
0j-pT4l-Low
0j-pT4l-Med
1j-pT4l-Low
1j-pT4l-Med
1j-pT4l-High
1j-pT4l-BSM-like
2j
2j-BSM-like
VH-Lep-enriched
0j-pT4l-High
ttH-Had-enriched
ttH-Lep-enriched
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Expected Composition