Search for heavy Higgs bosons from a g2HDM in multilepton plus b-jets final states in pp collisions at 13 TeV with the ATLAS detector

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Red LHC Workshop

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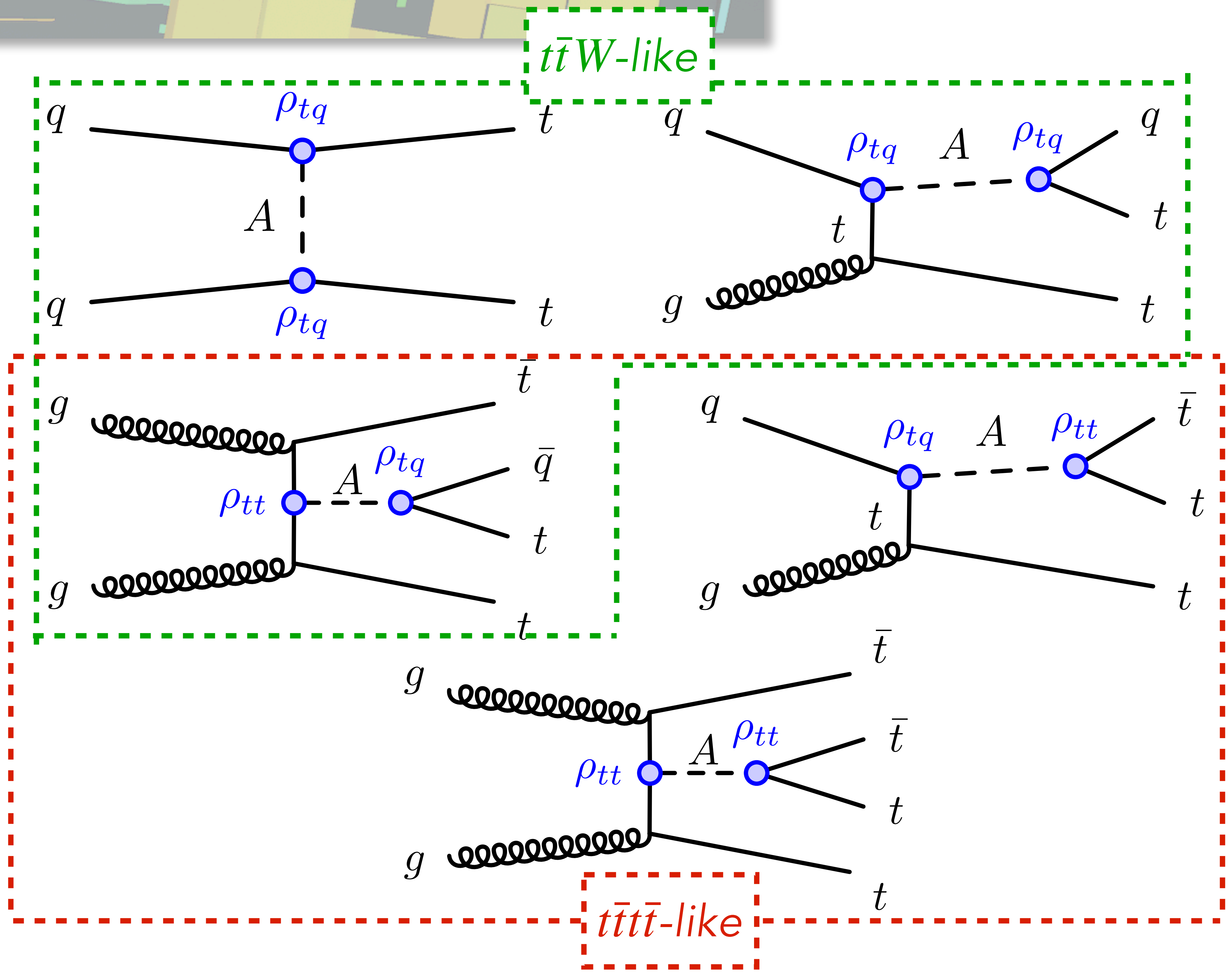
ATLAS EXPERIMENT

IFAE Institut de Física d'Altes Energies

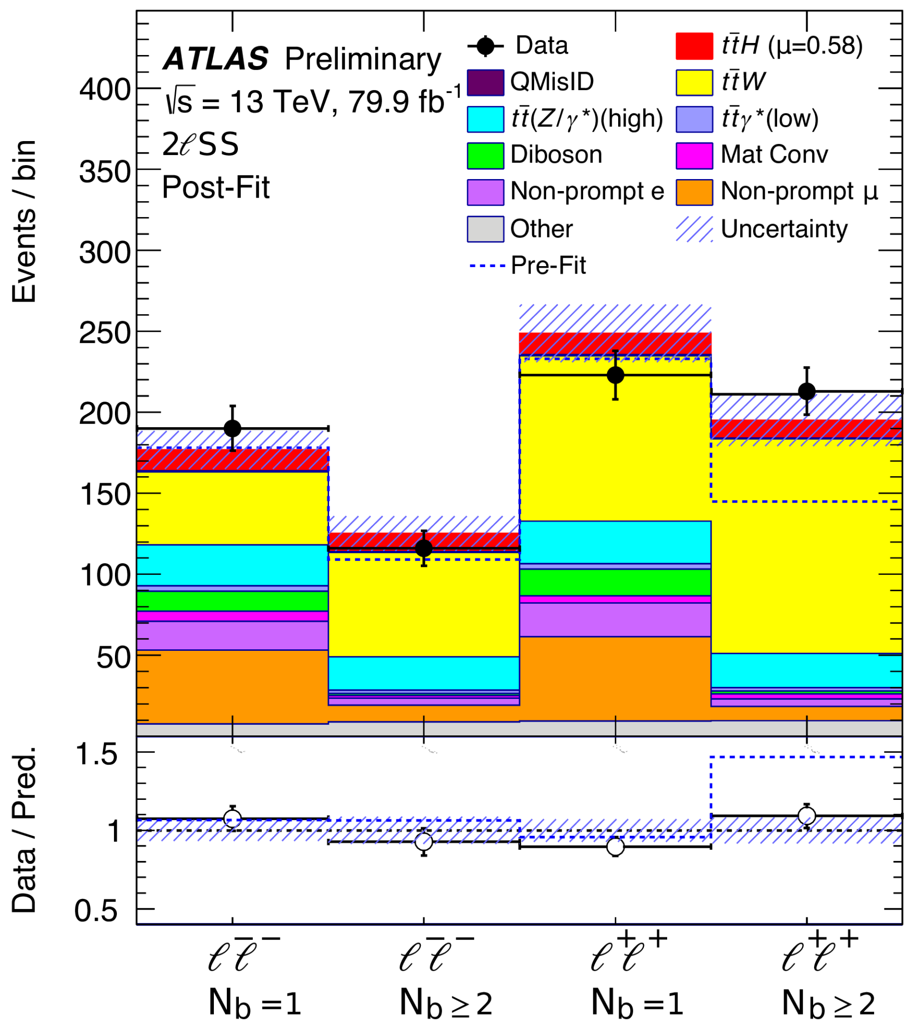
EXCELENCIA SEVERO OCHOA

Motivation

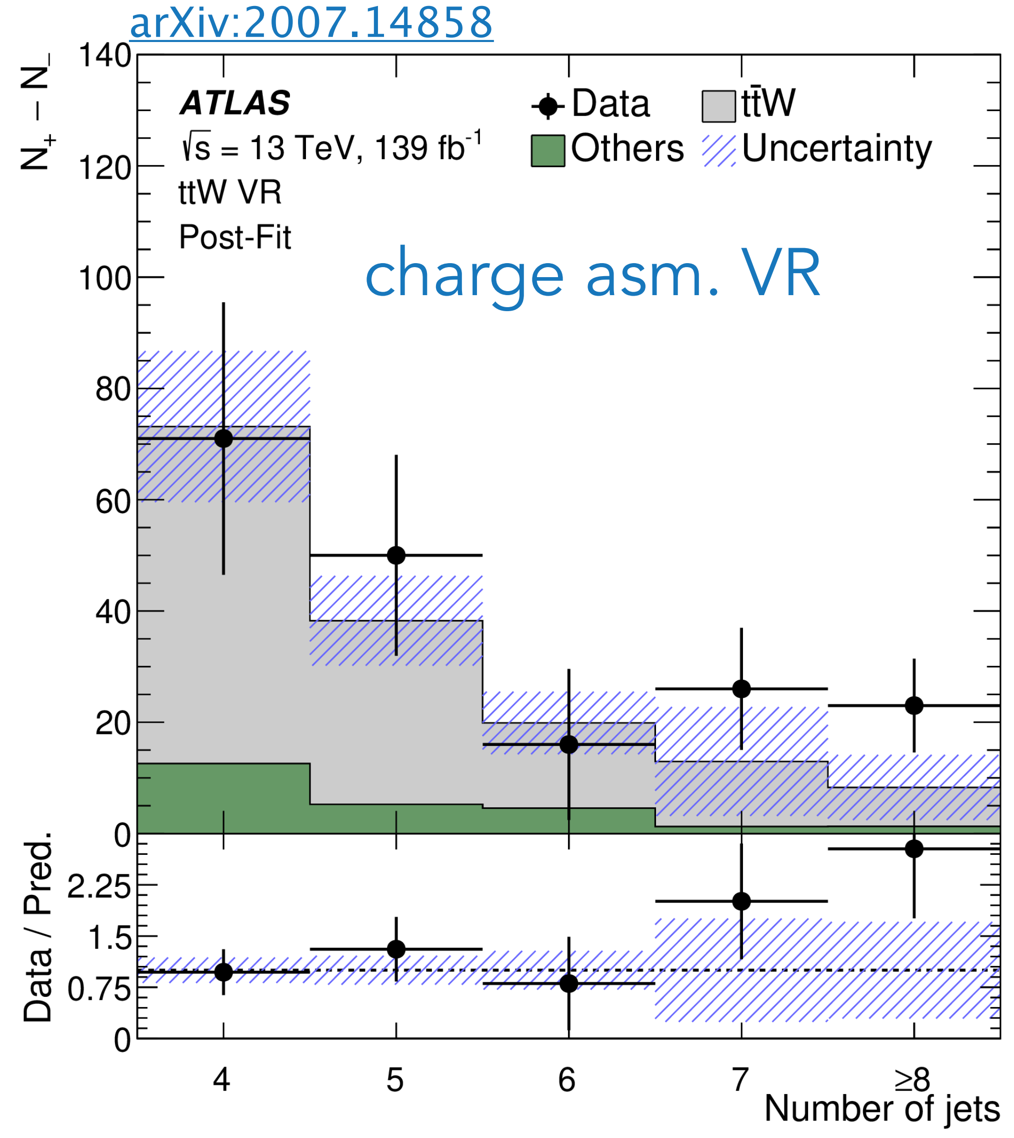
* General 2HDM: including off-diagonal Yukawa couplings for the second doublet in the alignment limit while dropping discrete symmetry (Z_2) which will allow for FCNH
  - Extra **sub-TeV** Higgs bosons (H^0, A^0) with extra Yukawa couplings: ρ_{tt}, ρ_{tu}, ρ_{tc}
  - Satisfy existing experimental constraints (Higgs coupling measurements, flavour physics, etc.), and can address several shortcomings of the SM: electroweak baryogenesis, strong CP problem, flavour problem, etc
  - Production modes with tH and ttH and resulting processes $sstt, ttq, ttt, tttq, tttt$ are studied
  - Final states with multiple leptons (2ℓSS, 3ℓ, 4ℓ) and b-jets studied (expect lepton charge asymmetry)
* Some analyses observed odd data features, that g2HDM model could explain
  - ttHML: tension in 2LSS (++) >=2bj region
  - SM 4top: also observed a lepton charge asymmetry at high Njets
  - Recent 4tops BSM search confirms this deviation and the asymmetric high nJets data/MC discrepancy



ATLAS-CONF-2019-045

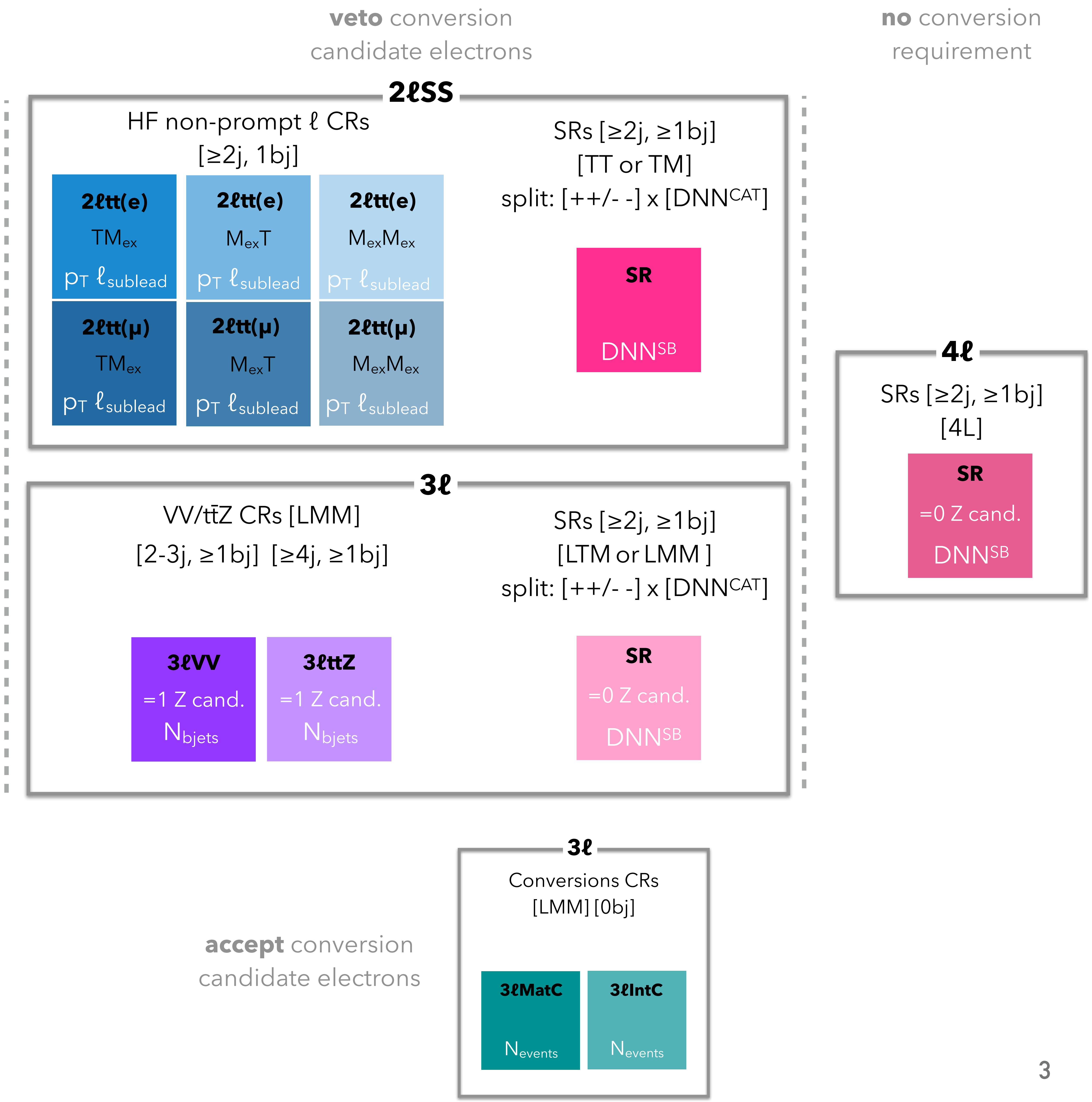


arXiv:2007.14858



Analysis strategy

* Use **tight lepton definition** to suppress reducible background
  - Non-prompt lepton veto BDTs
* **Estimate corrections** from data for various non-prompt ℓ (HF, conversions) and irreducible (VV+HF jets, $t\bar{t}Z$, $t\bar{t}W$) backgrounds in simultaneous fit CRs+SRs
  - Multiple **control regions** are defined in order to fit the normalisation of the leading backgrounds
* Signal regions
  - Split according to number of leptons, total lepton charge, and a **multi-output deep neural network classifier** (DNN^{CAT}) to categorise the different BSM signals
  - A second **DNN** is trained in a distance correlation (disCo) approach in each CAT to discriminate the signal from the backgrounds (DNN^{SB})
* Simultaneous profile likelihood fit of CRs+SRs



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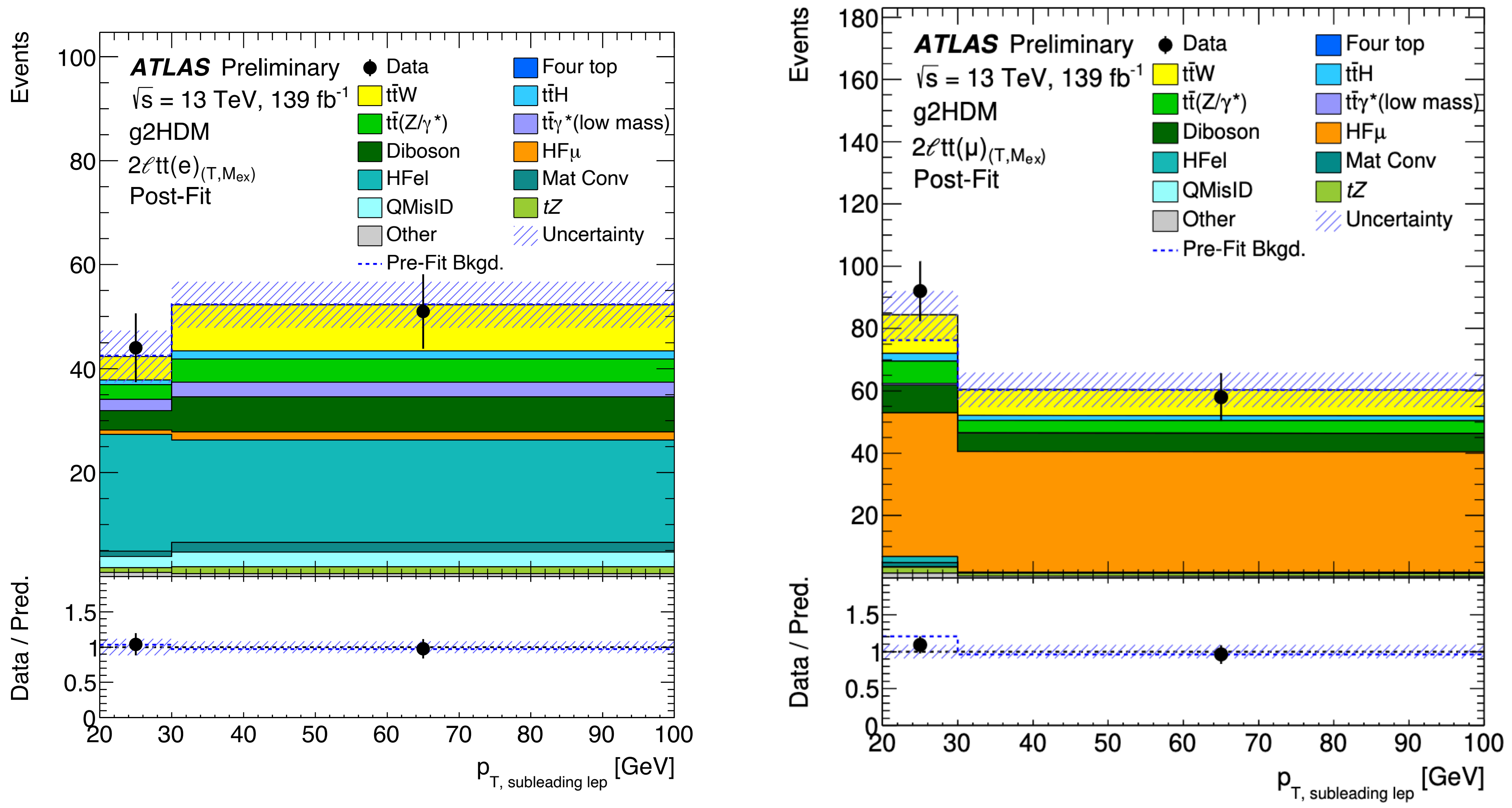
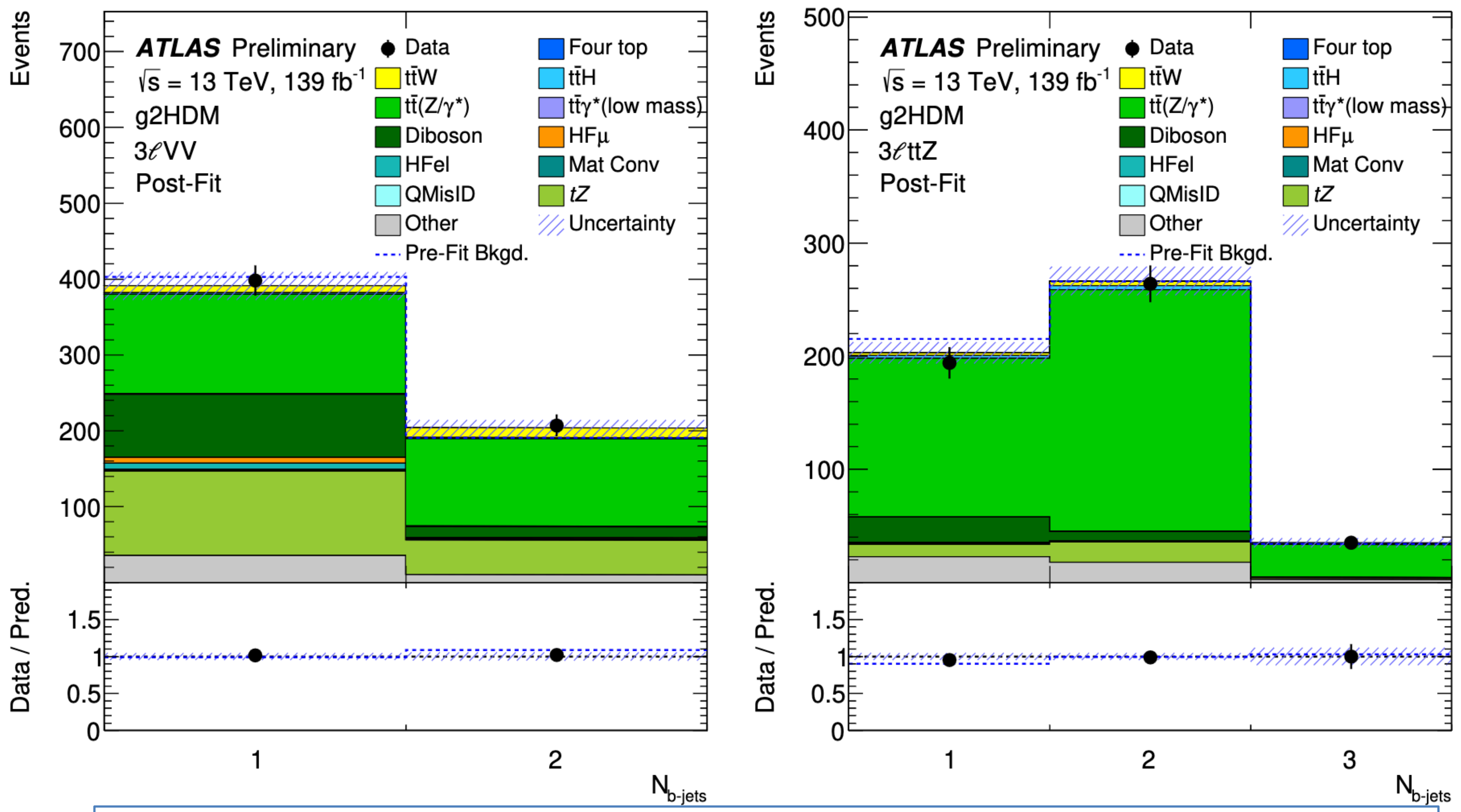


Data/MC comparison from CR dedicated for non-prompt electrons/muons from heavy-flavour decays



Good modeling of various Standard Model processes!

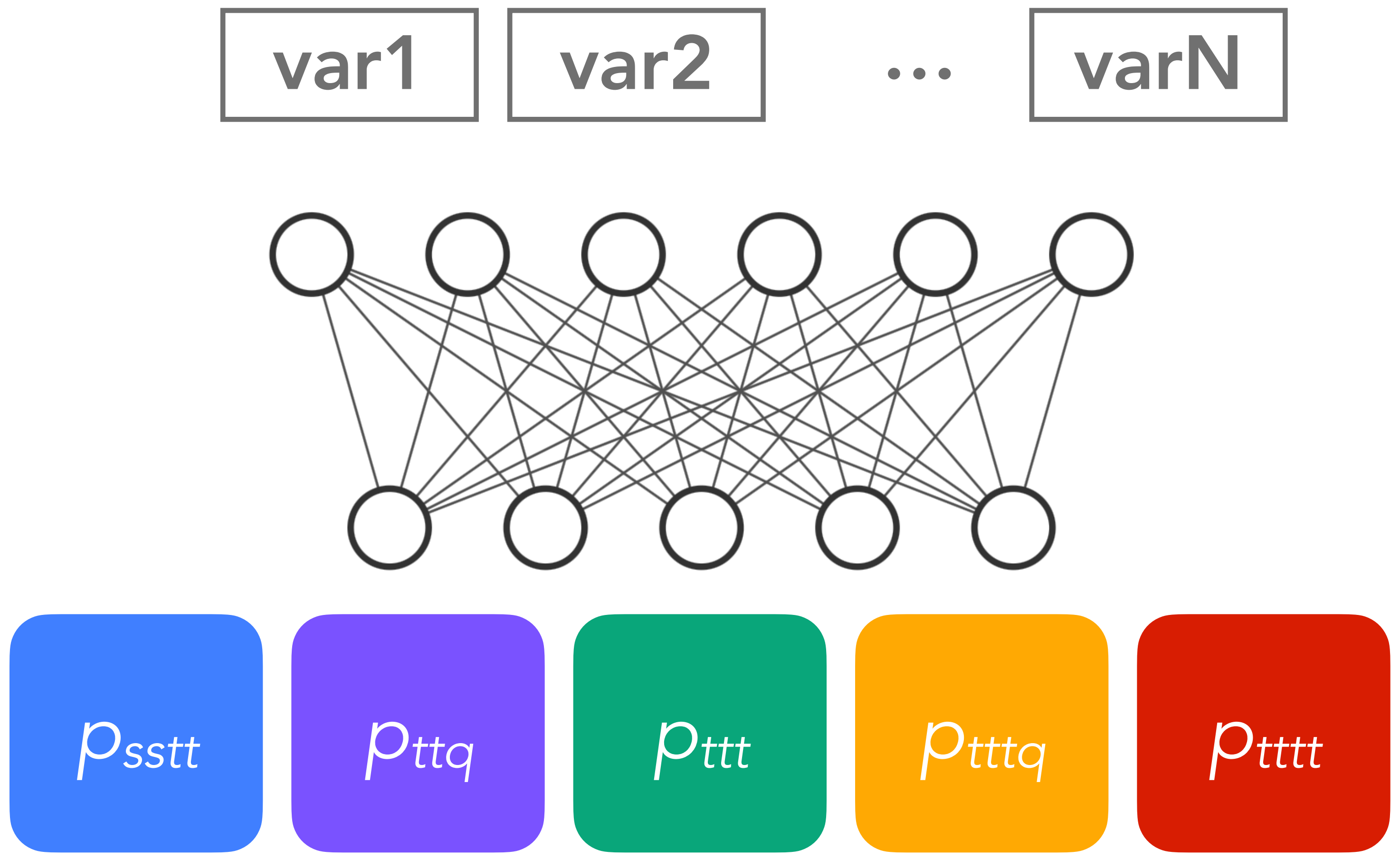
Data/MC comparison from CR dedicated for diboson and $t\bar{t}Z$ SM processes

Signal regions: Neural network(s)

1) (DNN^{CAT}) used to categorise the signal to various CATs has been trained separately for 2ℓSS & 3ℓ channels

- **2ℓSS**: 5 cat. (sstt, ttq, ttt, tttq, tttt)
- **3ℓ**: 3 cat. (ttt, tttq, tttt)

1st step



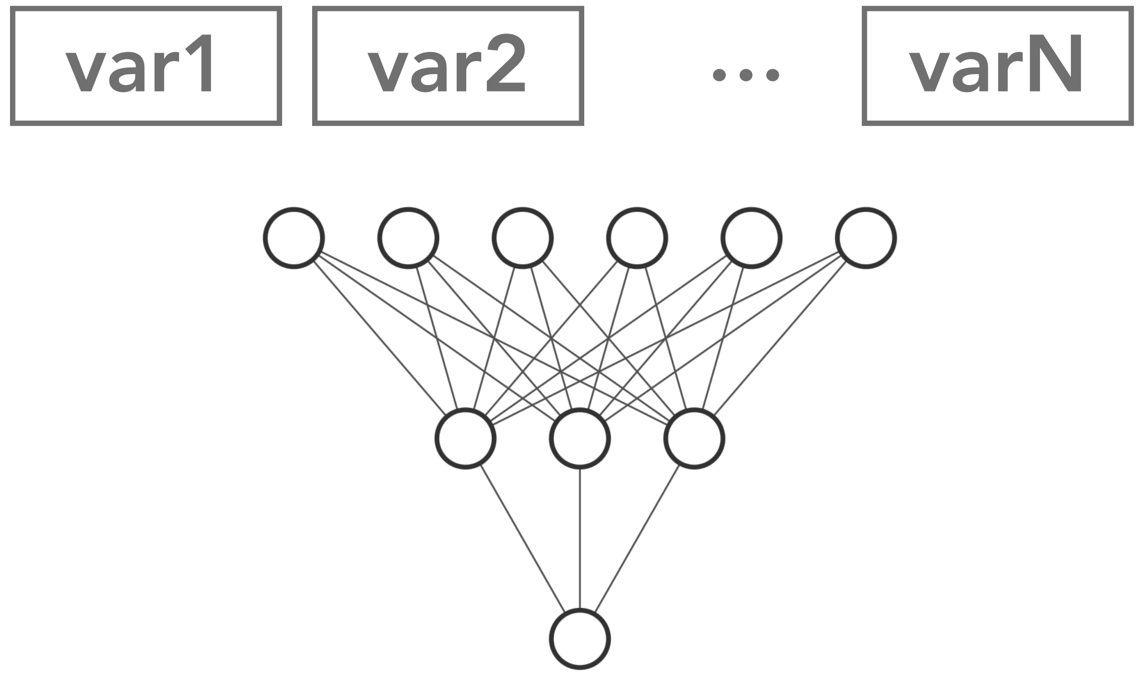
Class probabilities

2) (DNN^{SB}) used to discriminate the dedicated signal category from the background

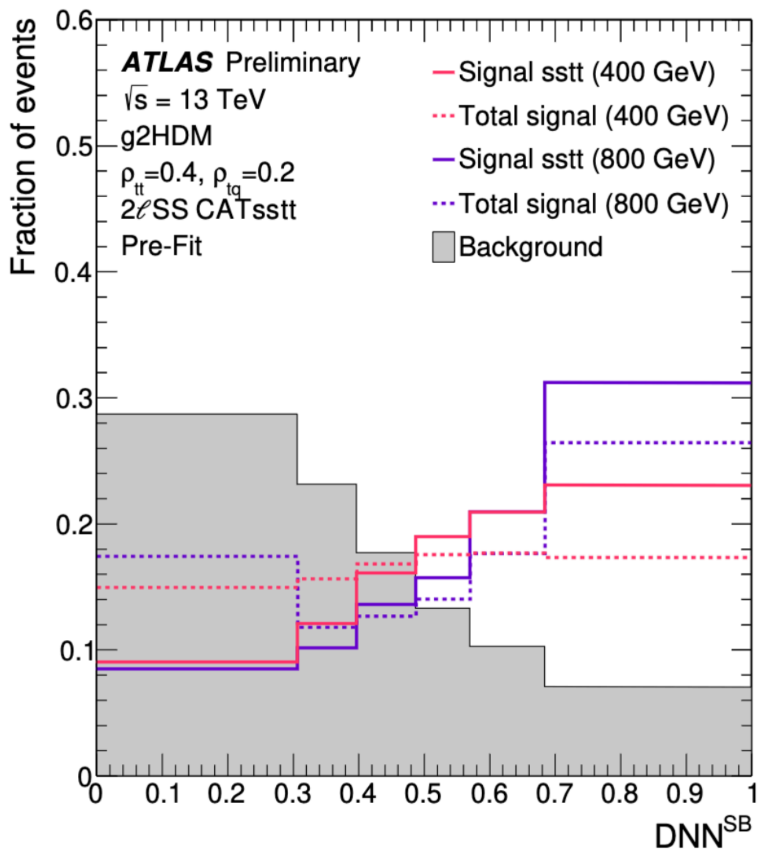
- **decorrelated** network from mass dependent variables (DisCo: Robust Networks Through Distance Correlation (arXiv))
- **2ℓSS**: 5 training, **3ℓ**: 3 training, **4ℓ**: 1 training

$$\ell = \ell_{\text{classifier}}(\vec{y}, \vec{y}_{true}) + \lambda \, \text{dCorr}^2(\vec{m}, \vec{y})$$

2nd step



CATs additionally split by charge to ++ and -- exploiting the additional separation between charge-symmetric and charge-asymmetric signal processes



Variable	DNN^{cat}	DNN^{SB}
Number of jets (N_{jets})	✓	✓
Sum of pseudo-continuous b-tagging scores of jets	✓	✓
Pseudo-continuous b-tagging score of 1st, 2nd, 3rd leading jet in p_T	✓	✓
Sum of p_T of the jets and leptons ($H_{T,jets}$, $H_{T,lep}$)	✓	✓
Angular distance of leptons (sum in the case of 3ℓ and 4ℓ)	✓	✓
Missing transverse energy	✓	✓
Leading transverse momentum of jet	-	✓
Invariant mass of leading lepton and missing transverse energy	-	✓
Di/tri/quad-lepton type variable (associated to the number of electrons/muons in event)	-	✓

Signal regions: Neural network(s)

1) (DNN^{CAT}) used to categorise the signal to various CATs has been trained separately for 2ℓSS & 3ℓ channels

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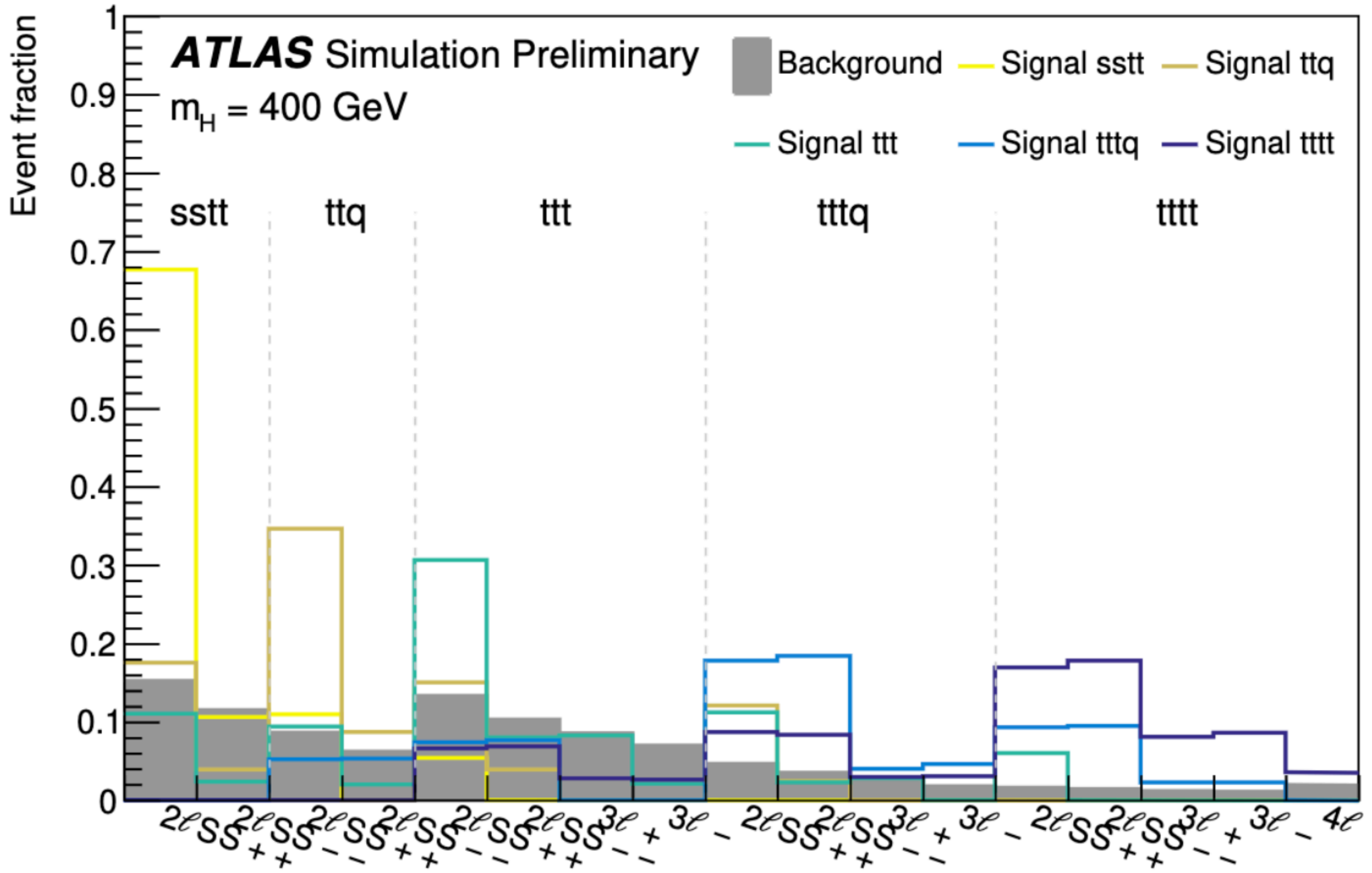

Normalized distributions of the categorization for each signal process, compared to the total expected background,

2) (DNN^{SB}) used to discriminate the dedicated signal category from the background

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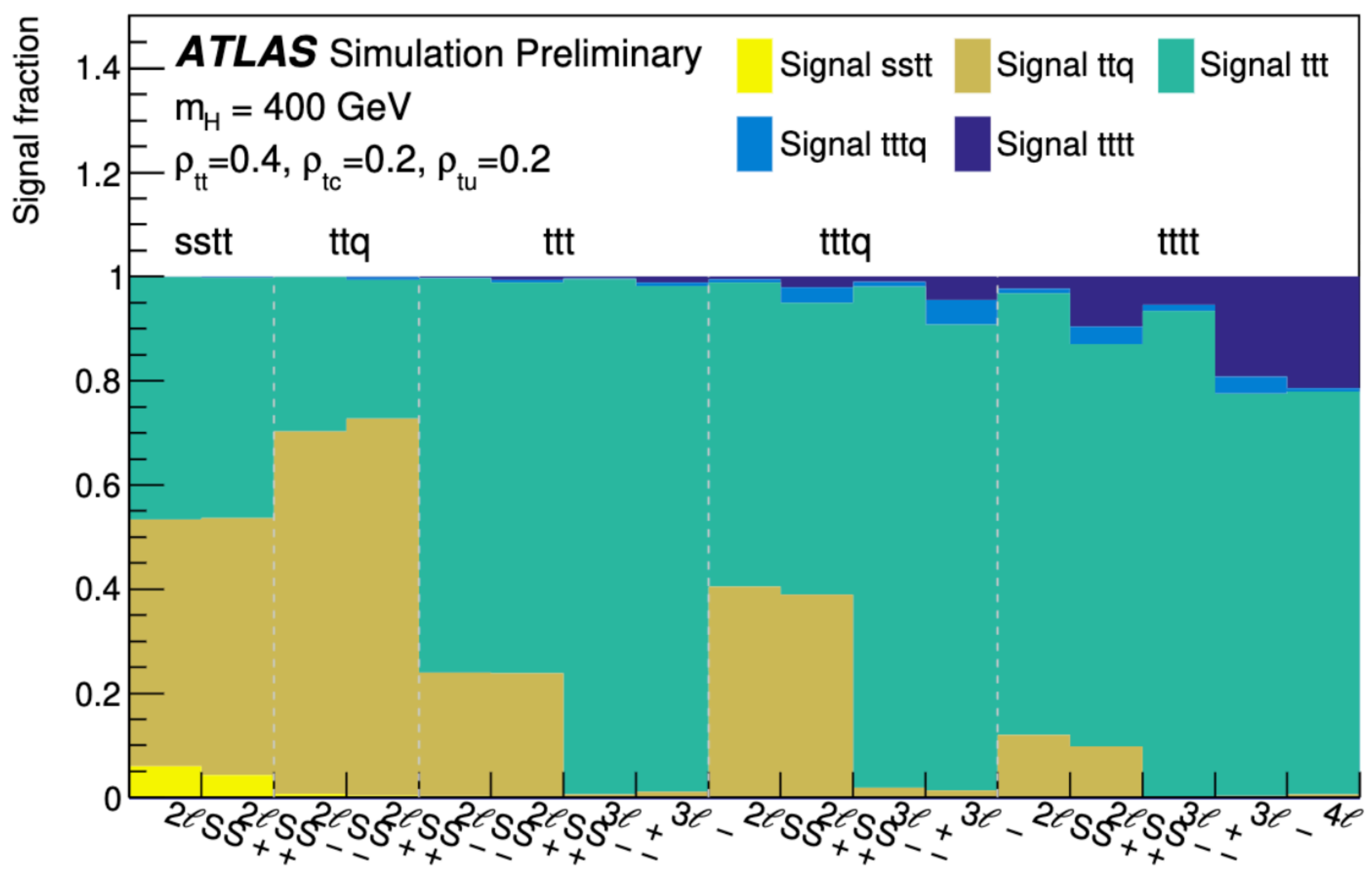
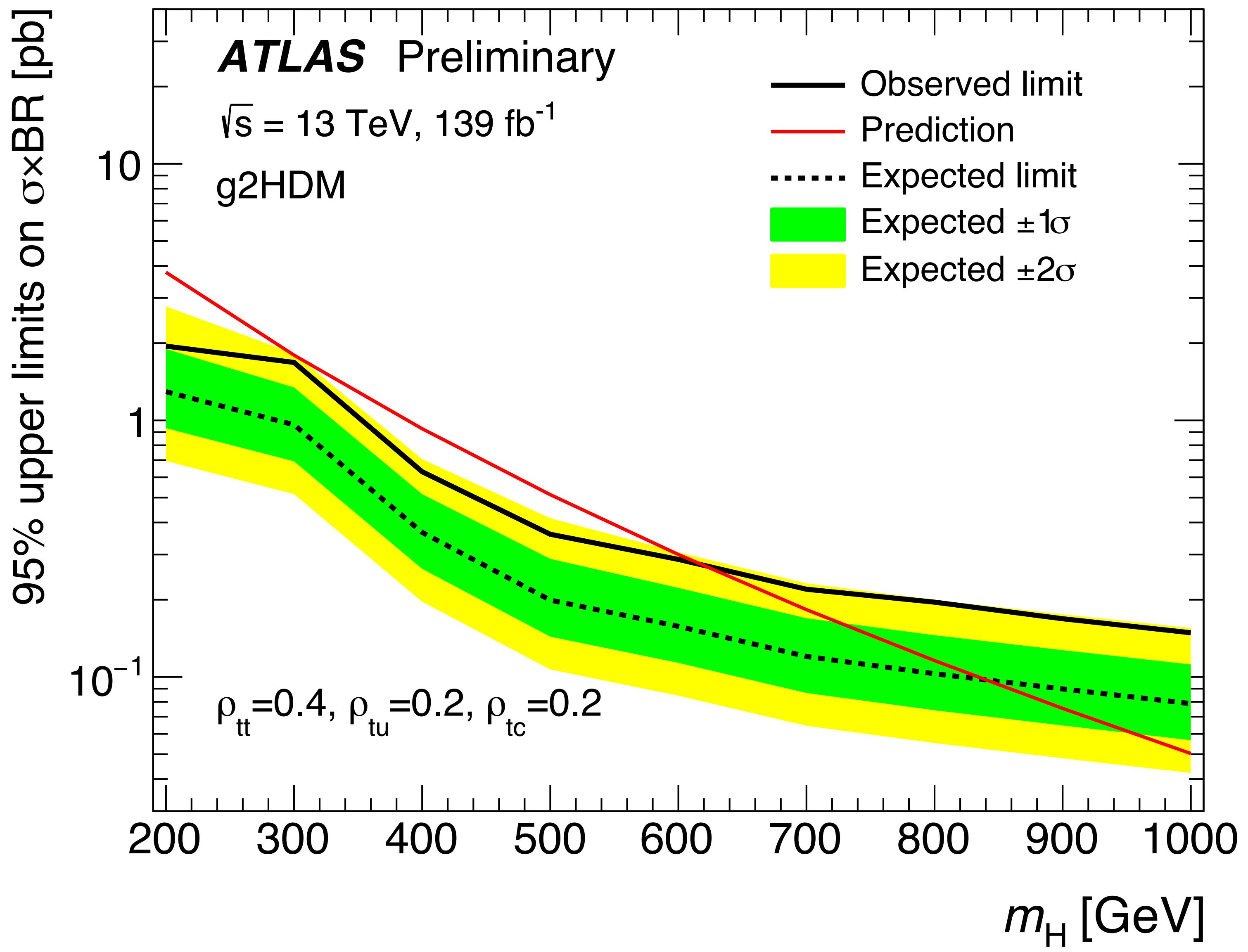


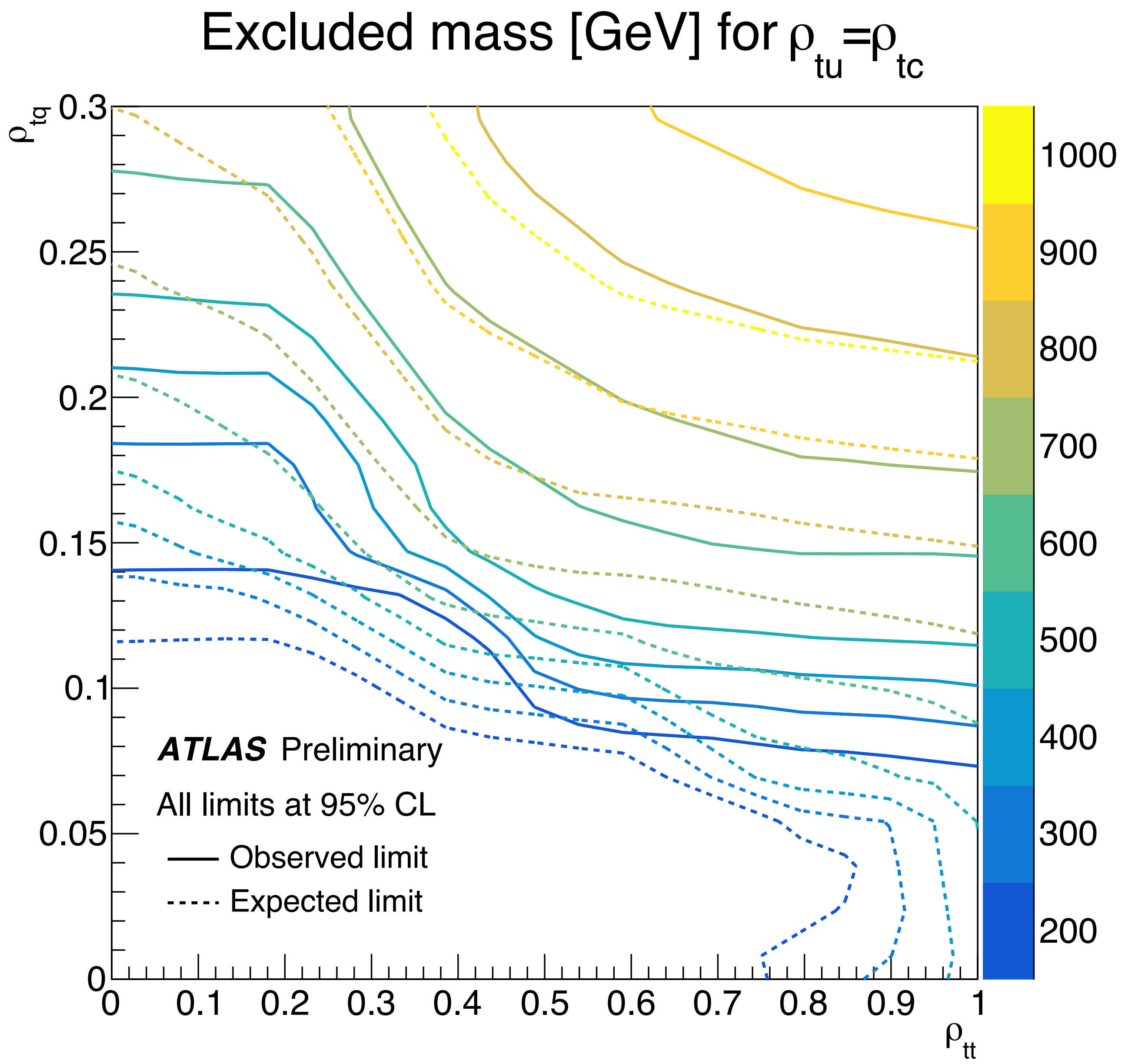
The expected fractional signal contribution in each category scalar masses for the coupling set ρ_{tt} = 0.4, ρ_{tc} = 0.2, ρ_{tu} = 0.2.

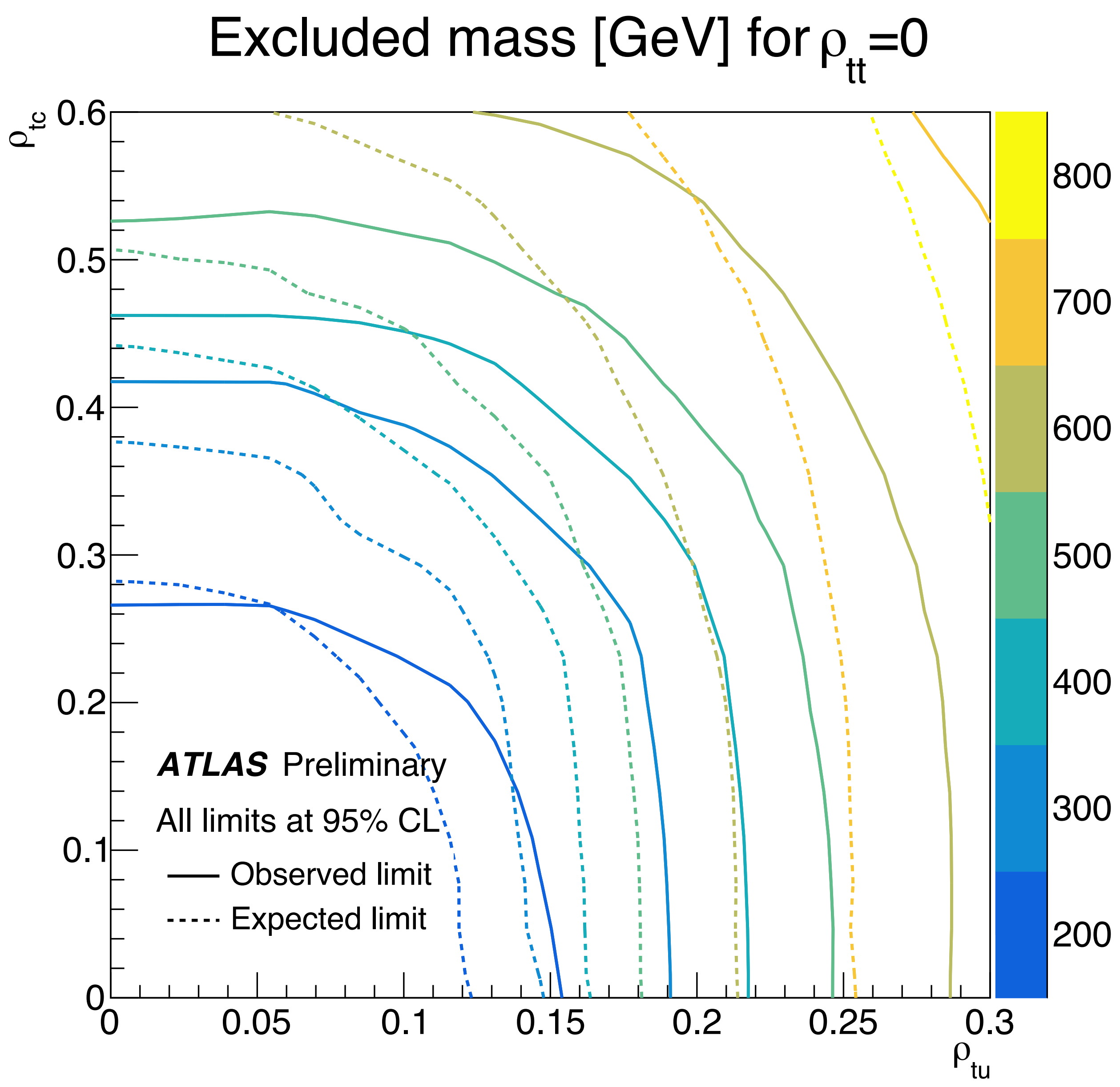
Results

* **95% CL upper limits** on the **σ x BR** for all the 2HDM signals together across different heavy Higgs masses (from 200 to 1000 GeV)
    - Assuming BSM signal corresponding to benchmark match $t\bar{t}W$ and 4-tops tensions: 400 GeV and $\rho_{tt} = 0.4,\ \rho_{tc} = 0.2,\ \rho_{tu} = 0.2$
    - Assuming $\rho_{tt} = 0$ **or** $\rho_{tq} = 0$



Observed exclusion limits on the σ x BR ratio for the benchmark coupling scenario $m_H < 630\ GeV$ excluded

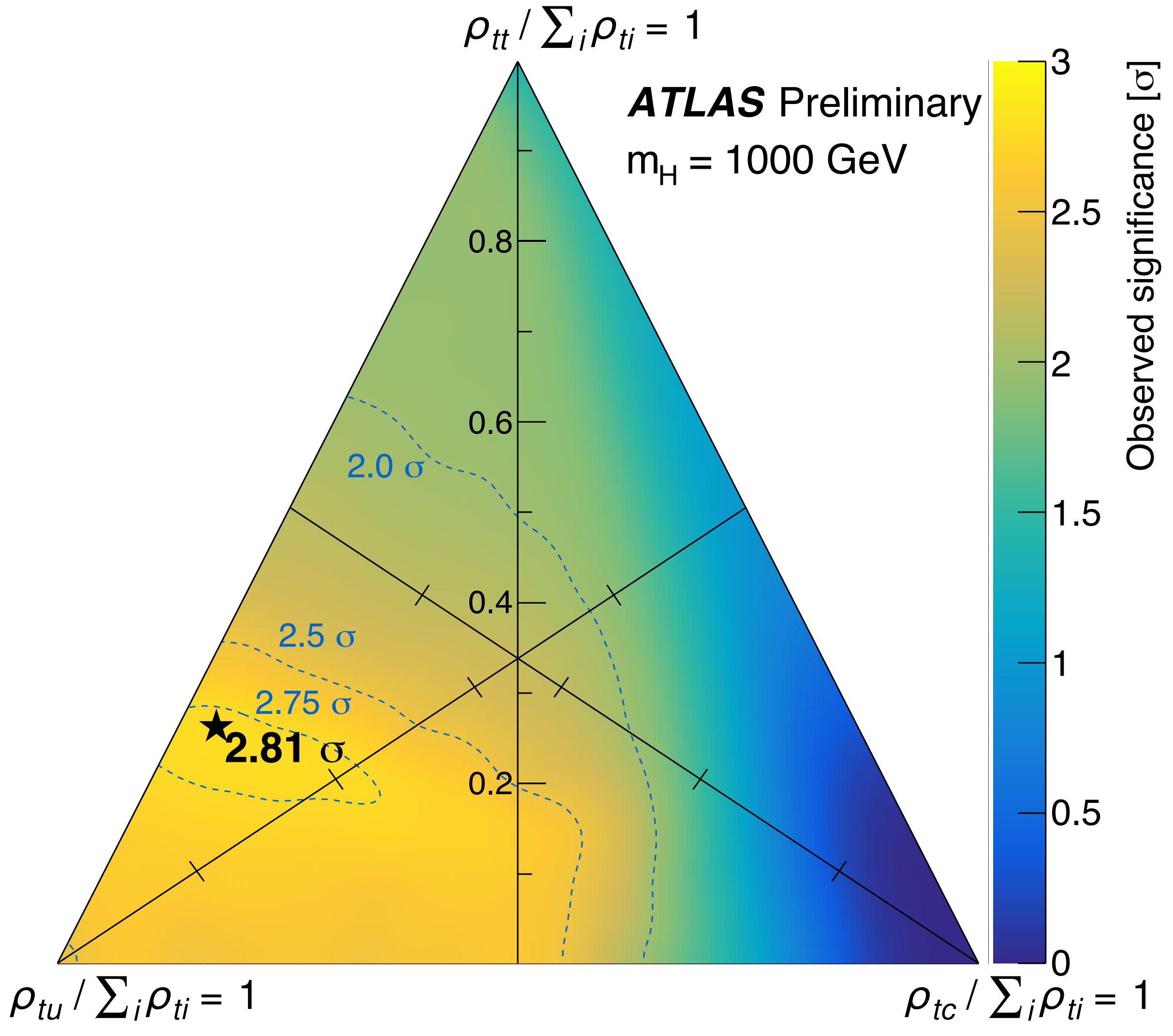




Observed (solid line) and expected (dashed line) exclusion limits on the scalar mass as a function of the coupling under $\rho_{tc} = \rho_{tu}$ (left) and $\rho_{tt} = 0$ (right) scenarios

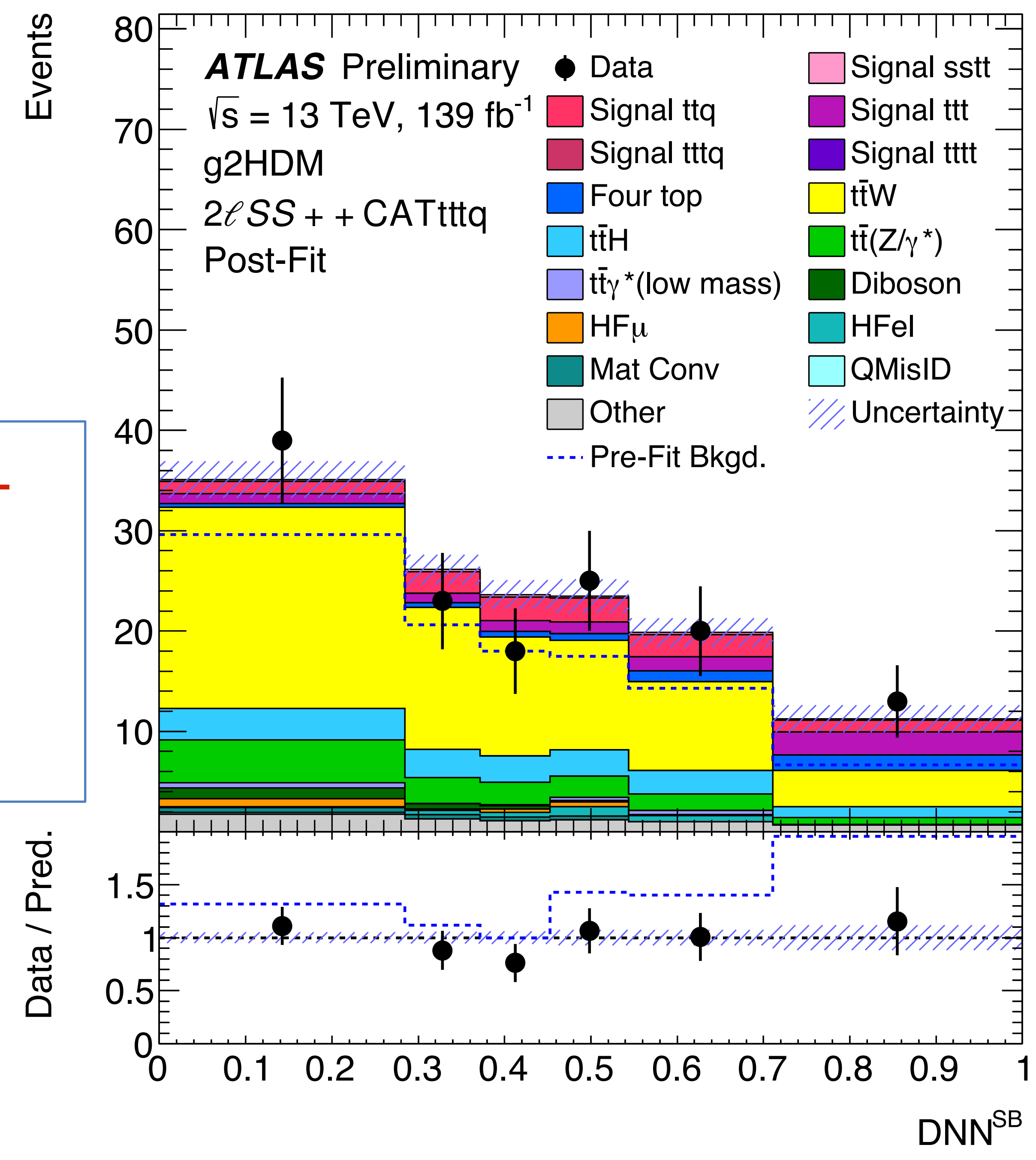
Results

- 95% CL upper limits on the σ x BR for all the 2HDM signals together across different heavy Higgs masses (from 200 to 1500 GeV)
  - Assuming BSM signal corresponding to benchmark match $t\bar{t}W$ and 4-tops tensions: 400 GeV and $\rho_{tt} = 0.4,\ \rho_{tc} = 0.2,\ \rho_{tu} = 0.2$
  - Assuming $\rho_{tt} = 0$ **or** $\rho_{tq} = 0$
- **Scan the full 4D planes of couplings** $(\rho_{tt},\ \rho_{tu}\ ,\rho_{tc})$ **vs mass**
  - **A mild excess is observed** over SM expectation to a local significance of **2.81**σ for a signal with $m_H = 1000\ GeV$ and $(\rho_{tt} = 0.32,\ \rho_{tc} = 0.05,\ \rho_{tu} = 0.85)$

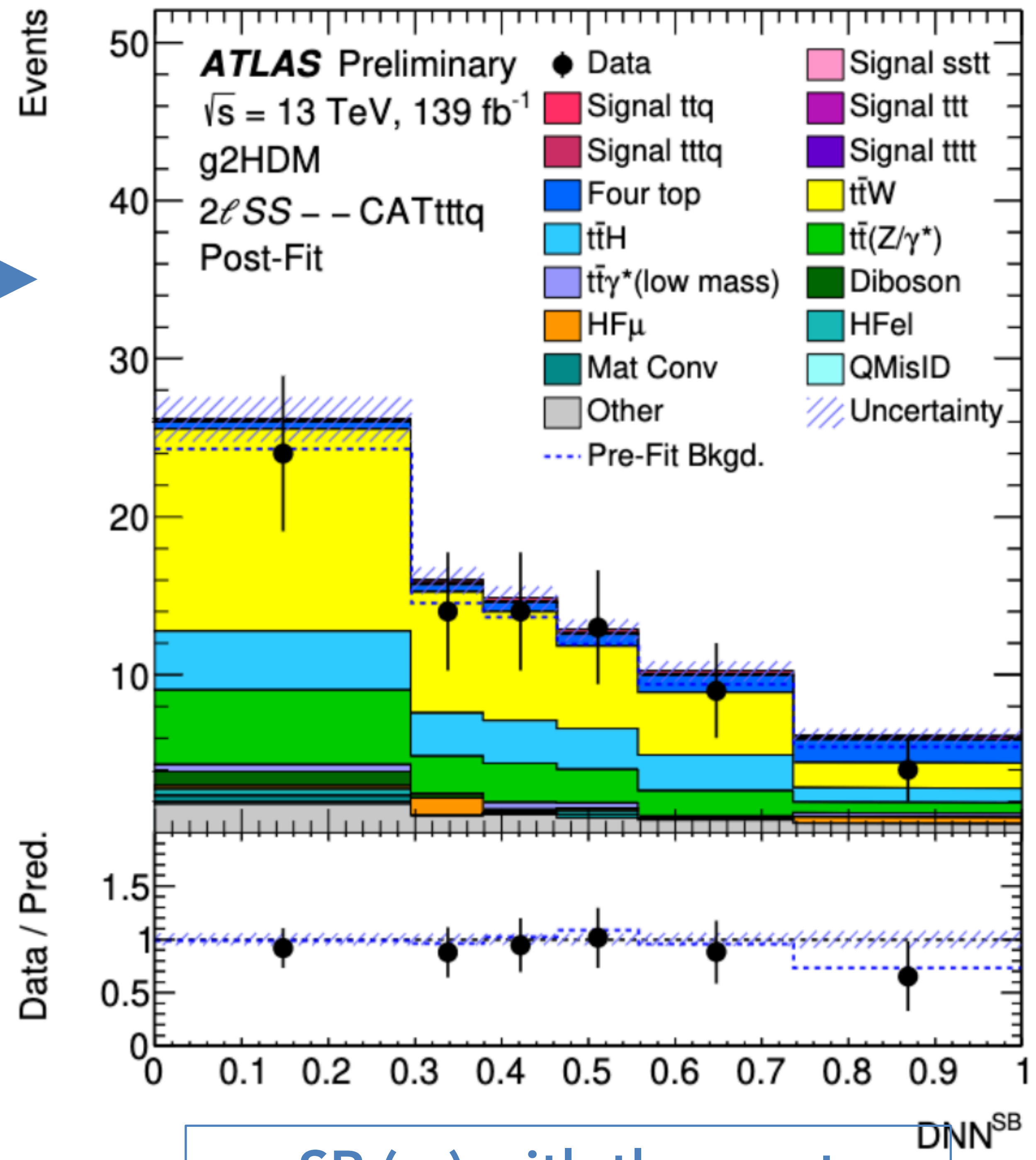


Scan of the couplings at $m_H = 1\ TeV$

Excess in ++ ttq/tttq categories



SR (++) with the most significant tension



SR (- -) with the most significant tension

Results

- 95% CL upper limits on the σ x BR for all the 2HDM signals together across different heavy Higgs masses (from 200 to 1500 GeV)
  - Assuming BSM signal corresponding to benchmark match $t\bar{t}W$ and 4-tops tensions: 400 GeV and $\rho_{tt} = 0.4,\ \rho_{tc} = 0.2,\ \rho_{tu} = 0.2$
  - Assuming $\rho_{tt} = 0$ **or** $\rho_{tq} = 0$
- **Scan the full 4D planes of couplings** $(\rho_{tt},\ \rho_{tu}\ ,\rho_{tc})$ **vs mass**
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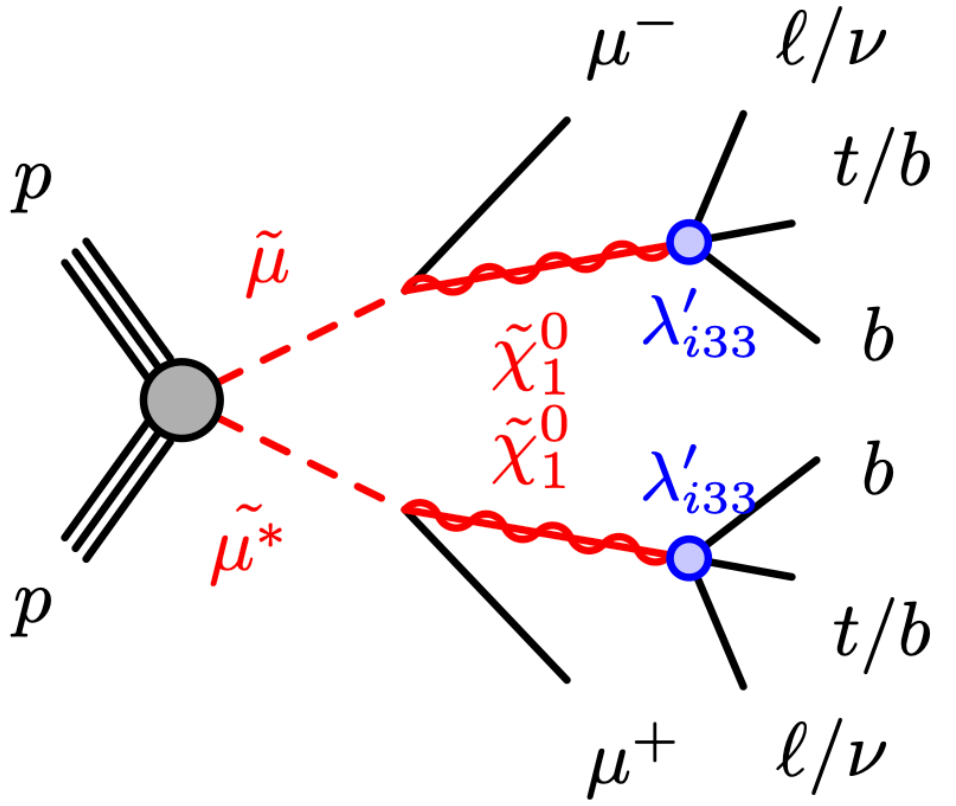
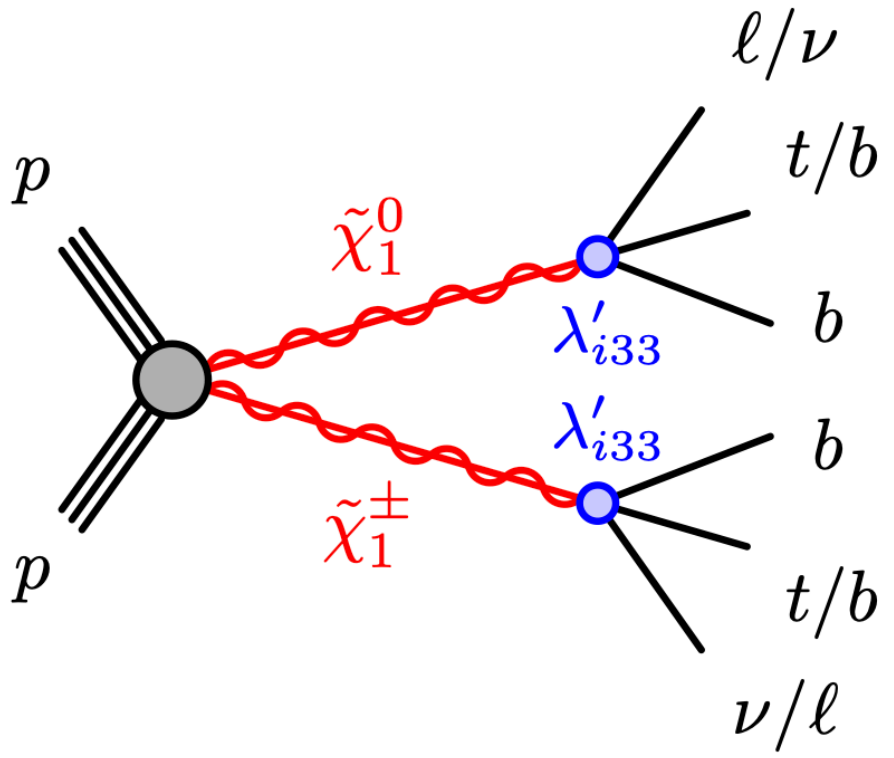
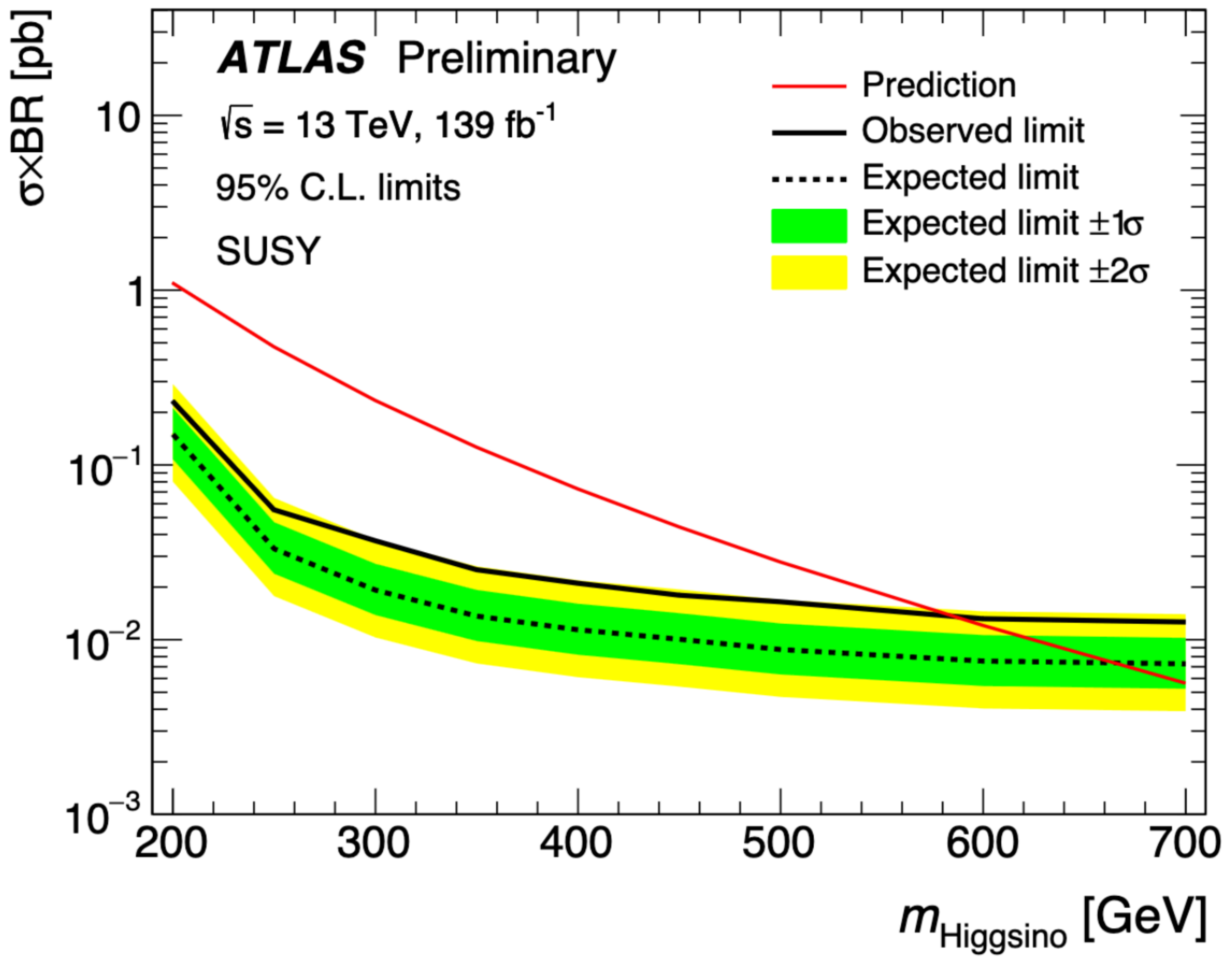
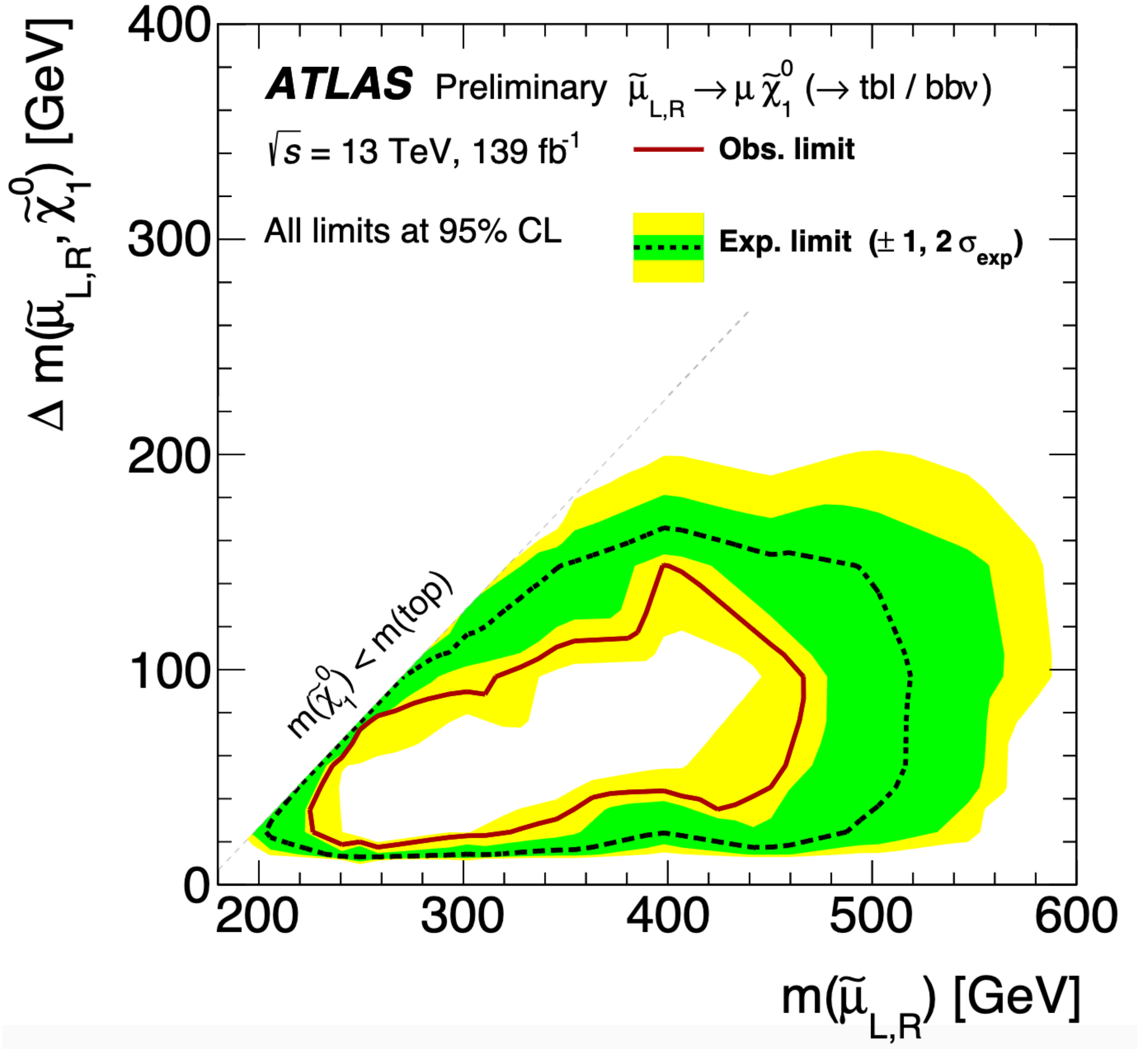
- **Bonus:** RPV SUSY interpretation (decay via a lepton-number- violating RPV coupling)
  - Set limits on wino, higgsino and smuon-bino models with RPV LQD coupling







Observed exclusion limits on the σ x BR ratio for Higgsino model $200 < m_H < 585\ GeV$ excluded



Observed exclusion limits on the σ x BR ratio for Smuon-bino model $225 < m_H < 600\ GeV$ excluded

Summary

* Analysis search for heavy Higgs bosons from a g2HDM in multilepton plus b-jets final states in pp collisions at 13 TeV with the ATLAS detector
  * Presented in conference note - Link
* Additional sensitivity to novel SUSY signals
* A mild excess is observed over the Standard Model expectation corresponding to a local significance of 2.81 standard deviations for a signal with $m_H = 1000\ GeV$ and $(\rho_{tt} = 0.32,\ \rho_{tc} = 0.05,\ \rho_{tu} = 0.85)$
* BSM signal profiting mostly from charge-asymmetric ++ ttq/tttq categories
* **New paper with updated mass points** is on the way, stay tuned!

Backup

Backup

Table 2: Description of the loose inclusive ("L"), medium inclusive ("M"), medium exclusive ("M_{ex}"), and tight ("T") lepton definitions. The electron e^* is required to fulfil, in addition to the corresponding lepton definition requirements, those corresponding to an internal or material conversion candidate.

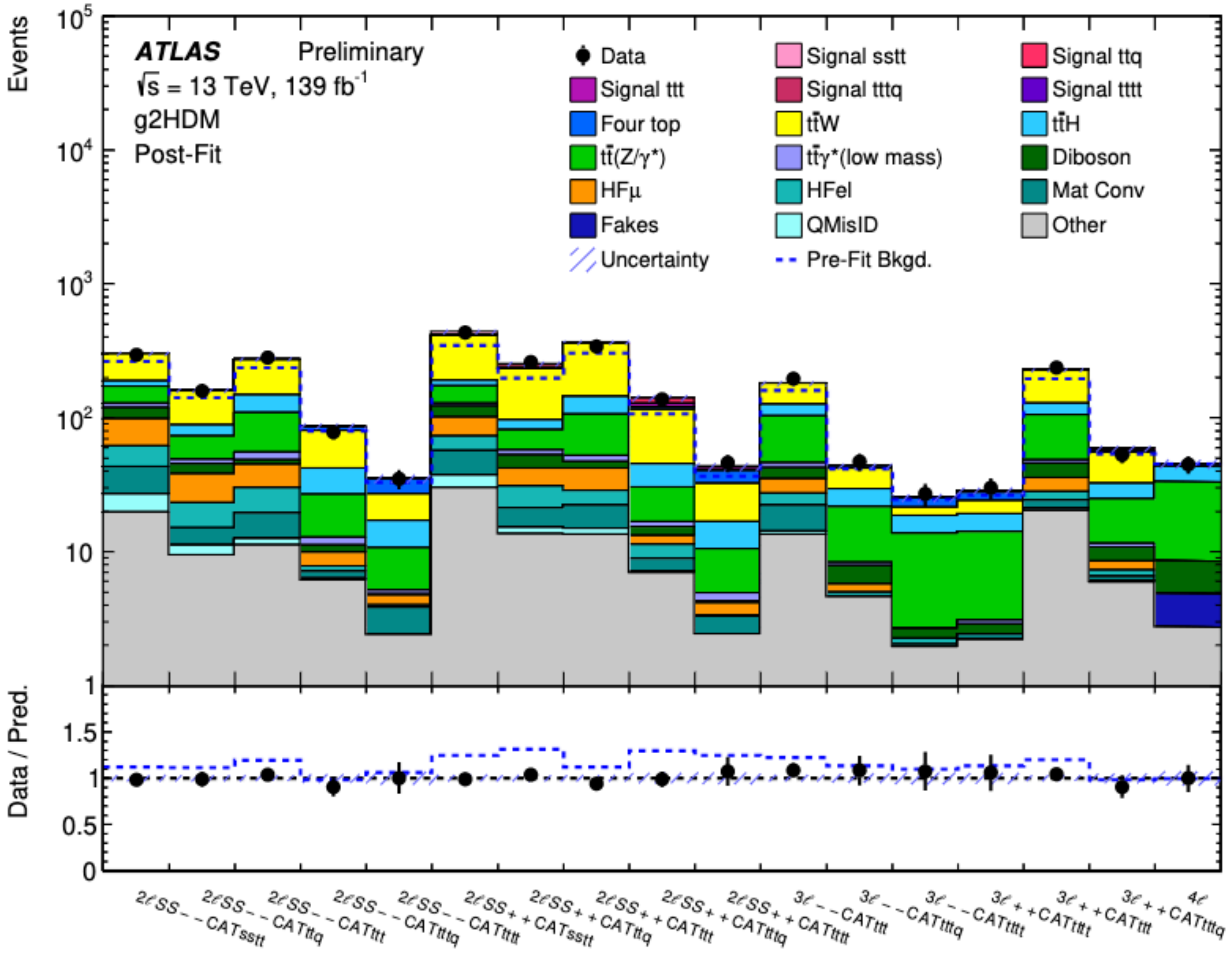
	e				μ			
	L	M	M_{ex}	T	L	M	M_{ex}	T
Isolation	Yes				Yes			
Non-prompt lepton BDT WP	No	*Tight*	*Tight-not-VeryTight*	*VeryTight*	No	*Tight*	*Tight-not-VeryTight*	*VeryTight*
Identification	Loose	Tight			Loose	Medium		
Electron charge-misassignment veto	No	Yes			N/A			
Electron conversion candidate veto	No	Yes (except e^*)			N/A			
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							

Backup

Table 4: Event selection summary in the control regions. The notation e^* is used to denote material conversion or internal conversion candidates, as described in Section 4. In the HF non-prompt lepton region naming, “2ℓSStt(e)” (“2ℓSStt(μ)”) refer to the control regions enriched in non-prompt electrons (muons) from semileptonic b-decays originating mostly from $t\bar{t}$ and with the lepton flavours for the leading and subleading leptons corresponding to “ee, μe” (“$\mu\mu$, $e\mu$”). The additional (T, M_{ex}), (M_{ex}, T), and $(M_{\text{ex}}, M_{\text{ex}})$ subscripts refer to the lepton definitions required for the leading and subleading leptons in each region.

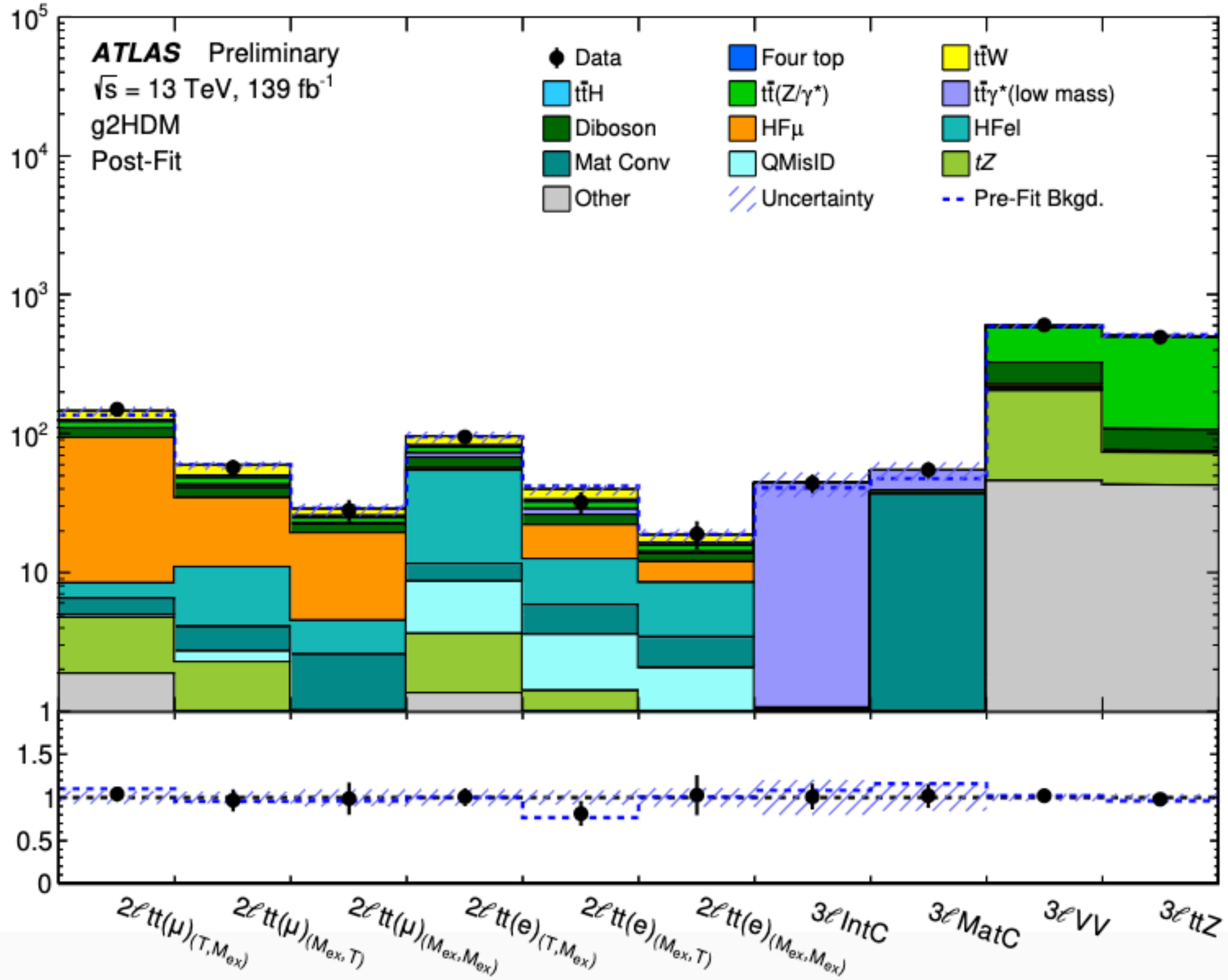
Control regions	WZ	$t\bar{t}Z$	Conversions	HF non-prompt
N_{jets}	2 or 3	≥ 4	≥ 0	≥ 2
$N_{b-\text{jets}}$	$\geq 1\ b^{60\%} \parallel \geq 2\ b^{77\%}$		$0\ b^{77\%}$	$1\ b^{77\%}$
Lepton requirement	3ℓ		$\mu\mu e^*$	2ℓSS
Lepton definition	(L, M, M)			$(T, M_{\text{ex}}) \parallel (M_{\text{ex}}, T) \parallel (M_{\text{ex}}, M_{\text{ex}})$
Lepton p_{T} [GeV]	(10, 20, 20)			(20, 20)
$m_{\ell^+\ell^-}^{OS-SF}$ [GeV]	>12		>12	–
$\lvert m_{\ell^+\ell^-}^{OS-SF} - m_Z \rvert$ [GeV]	<10		>10	–
$\lvert m_{\ell\ell\ell} - m_Z \rvert$ [GeV]	–		<10	–
$m_T(\ell_0, E_{\text{T}}^{\text{miss}})$ [GeV]	–			< 250
Region split	–	–	internal / material	subleading $e/\mu \times [(T, M_{\text{ex}}), (M_{\text{ex}}, T), (M_{\text{ex}}, M_{\text{ex}})]$
Region naming	3ℓVV	3ℓttZ	3ℓIntC	$2\ell\text{tt(e)}_{(T,M_{\text{ex}})}$, $2\ell\text{tt(e)}_{(M_{\text{ex}},T)}$, $2\ell\text{tt(e)}_{(M_{\text{ex}},M_{\text{ex}})}$
			3ℓMatC	$2\ell\text{tt}(\mu)_{(T,M_{\text{ex}})}$, $2\ell\text{tt}(\mu)_{(M_{\text{ex}},T)}$, $2\ell\text{tt}(\mu)_{(M_{\text{ex}},M_{\text{ex}})}$

Backup



ATLAS Preliminary
√s = 13 TeV, 139 fb-1
g2HDM
Post-Fit
Data
Signal sstt
Signal ttq
Signal ttt
Signal tttq
Signal tttt
Four top
ttW
ttH
tt(Z/γ*)
ttγ*(low mass)
Diboson
HFμ
HFel
Mat Conv
Fakes
QMisID
Other
Uncertainty
Pre-Fit Bkgd.
Events
Data / Pred.

(a)



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g2HDM
Post-Fit
Data
Four top
ttW
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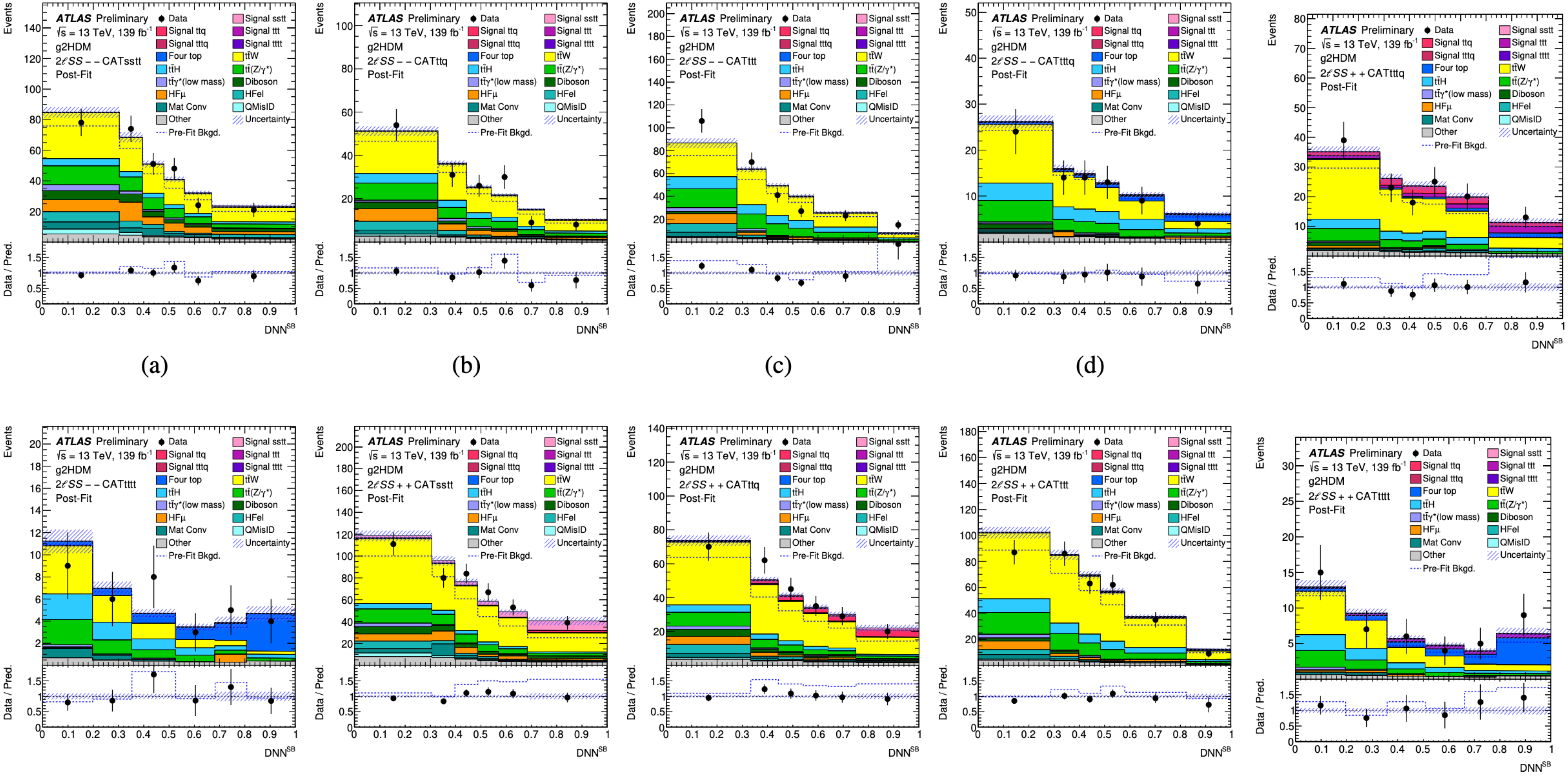
tt(Z/γ*)
ttγ*(low mass)
Diboson
HFμ
HFel
Mat Conv
QMisID
tZ
Other
Uncertainty
Pre-Fit Bkgd.
3ℓ IntC
3ℓ MatC
3ℓ VV
3ℓ ttZ

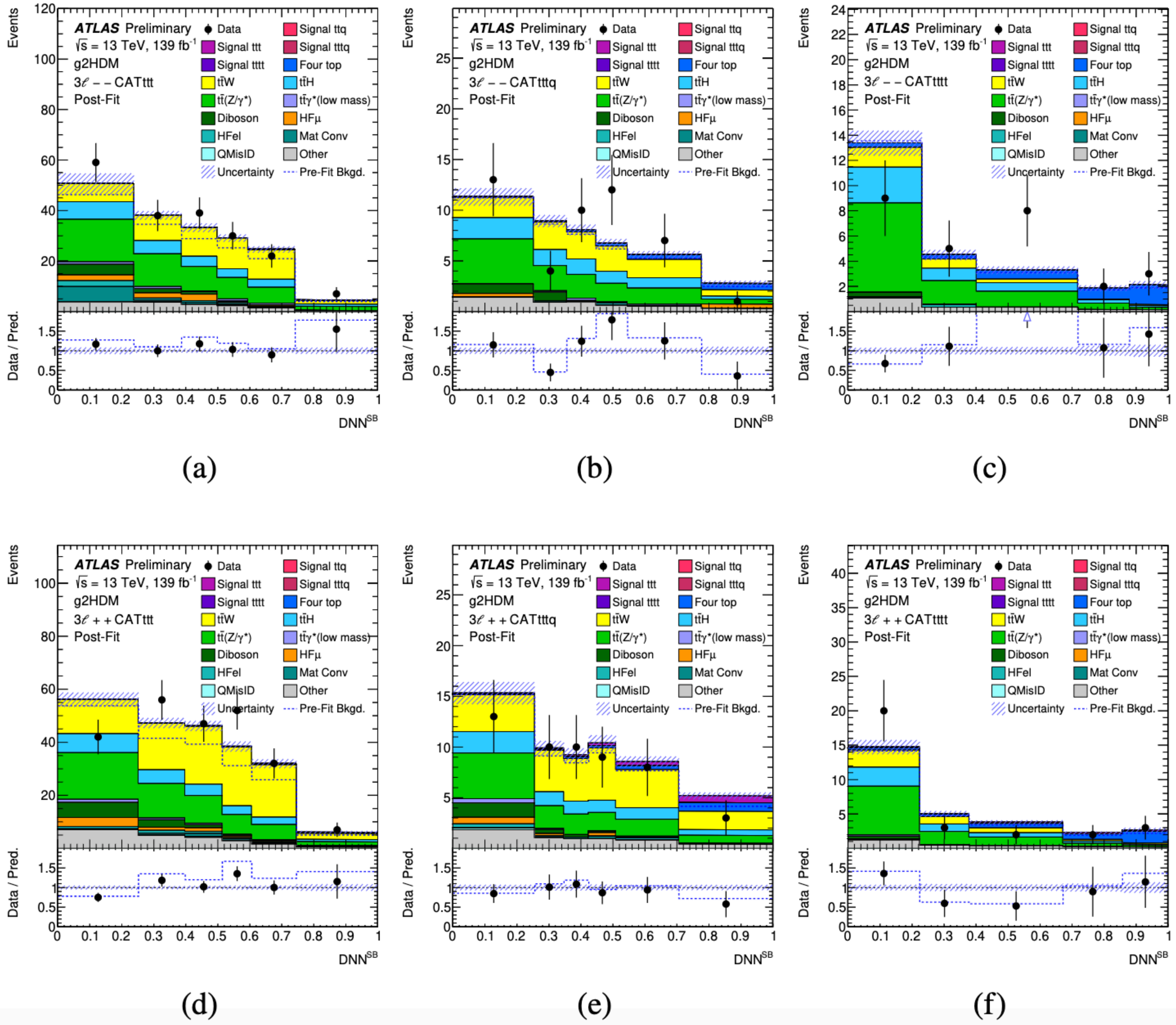
Backup



(a) (b) (c) (d)

(e) (f) (g) (h)

Backup


ATLAS Preliminary
√s = 13 TeV, 139 fb⁻¹
g2HDM
3ℓ − − CATttt
3ℓ − − CATtttq
3ℓ − − CATtttt
3ℓ + + CATttt
3ℓ + + CATtttq
3ℓ + + CATtttt
Post-Fit
Data
Signal ttq
Signal ttt
Signal tttq
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Four top
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Events
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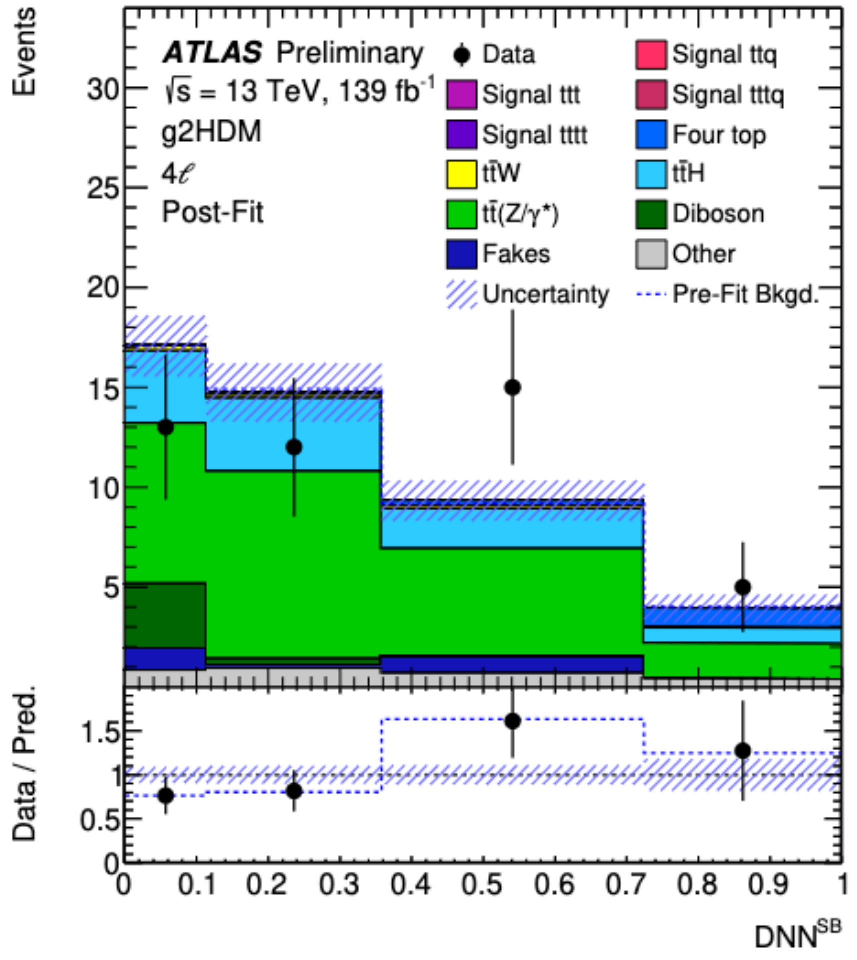
DNN^SB
(a)
(b)
(c)
(d)
(e)
(f)


ATLAS Preliminary
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DNN^SB

Backup

$\hat{\lambda}_e^{\text{Mat Conv}} = 1.16 \pm 0.29$

$\hat{\lambda}_\mu^{\text{had}} = 0.92 \pm 0.18$

$\hat{\lambda}_e^{\text{had}} = 1.05 \pm 0.31$

$\hat{\lambda}_{t\bar{t}W} = 1.50 \pm 0.14$

$\hat{\lambda}_{VV} = 0.85 \pm 0.30$

$\hat{\lambda}_{t\bar{t}Z} = 0.97 \pm 0.19$

$\hat{\lambda}_{t\bar{t}Z} = 0.97 \pm 0.19$

The sample used to model the $t\bar{t}W$ ($t\bar{t}Z/\gamma^*$) background was generated using SHERPA-2.2.10 [79] (SHERPA-2.2.11), where the matrix element (ME) was calculated for up to one (zero) additional parton at next-to-leading-order (NLO) in QCD and up to two partons at LO in QCD using COMIX [80] and OPENLOOPS [81] and merged with the SHERPA parton shower (PS) [82] using the MEPS@NLO prescription [83], with a CKKW merging scale of 30 GeV for the $t\bar{t}W$ sample. These samples are generated using the `NNPDF3.0nnlo` [84] PDF set. Both the factorisation and renormalisation scales are set to $\mu_r = \mu_f = m_T/2$ in the $t\bar{t}W$ sample, where m_T is defined as the scalar sum of the transverse masses $\sqrt{m^2 + p_T^2}$ of the particles generated from the ME calculation. The LO $t\bar{t}W$ electroweak (EW) contributions are obtained from a dedicated sample simulated with SHERPA-2.2.10. The invariant mass of the lepton pair ($m_{\ell^+\ell^-}$) in the $t\bar{t}Z/\gamma^*$ sample is set to be greater than 1 GeV. The complete $t\bar{t}W$ simulation is normalised to the total cross section of $\sigma(t\bar{t}W) = 614.7$ fb that comes from the SHERPA configuration outlined above considering NLO QCD and NLO EWK effects, based on a similar strategy as used in Ref. [85]. The $t\bar{t}Z/\gamma^*$ sample is normalised to the cross section $\sigma(t\bar{t}Z/\gamma^*) = 839$ fb, calculated at NLO QCD and NLO EW accuracy using MADGRAPH5_AMC@NLO [86] and scaled by an off-shell correction estimated at one-loop level in α_s.