Study of the quantum interference between singly and doubly resonant top-quark production in proton-proton collisions at the LHC with the ATLAS detector

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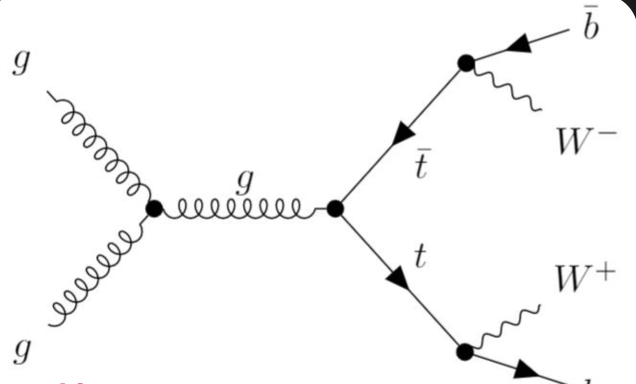
The $WbWb$ production cross-section at the NLO for Wt

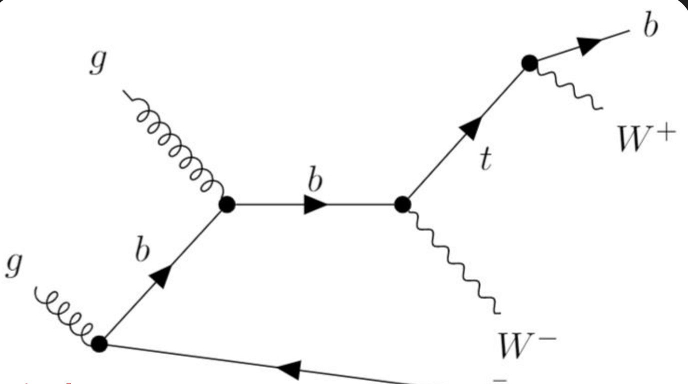
Top-quark production processes at the LHC:

LO:	Double t: $gg \to t\bar{t} \to WbWb$
LO:	Single t: $gb \to tW \to WbW$

LO:	Double t: $gg \to t\bar{t} \to WbWb$
NLO:	Single t: $gb \to tWb \to WbWb$



Doubly resonant (LO)



Singly resonant (NLO)

$$\alpha + \beta \to t + W + b \quad \Rightarrow \quad \mathcal{A}_{\alpha\beta} = \mathcal{A}_{\alpha\beta}^{(Wt)} + \mathcal{A}_{\alpha\beta}^{(t\bar{t})}$$

$$\sigma_{WbWb} \propto \left|\mathcal{A}_{\alpha\beta}\right|^2 = \left|\mathcal{A}_{\alpha\beta}^{(Wt)}\right|^2 + 2\mathcal{Re}\left\{\mathcal{A}_{\alpha\beta}^{(Wt)}\mathcal{A}_{\alpha\beta}^{(t\bar{t})}\right\} + \left|\mathcal{A}_{\alpha\beta}^{(t\bar{t})}\right|^2$$

Impacts on:

- SM physics and BSM physics
- Search for toponium resonance η_t formation in $WbWb$ phase-space

The DR and DS schemes in tW generators

- Diagram Removal (DR): all the doubly-resonant diagrams in the NLO Wt process amplitude are removed:

$$\left|\mathcal{A}_{\alpha\beta}\right|^2_{DR} = \left|\mathcal{A}^{Wt}_{\alpha\beta}\right|^2$$

- Diagram Subtraction (DS): NLO Wt cross-sections are modified by implementing a subtraction term, in order to locally cancel the $t\bar{t}$ contribution:

$$\left|\mathcal{A}_{\alpha\beta}\right|^2_{DS} = \left|\mathcal{A}^{Wt}_{\alpha\beta}\right|^2 - \left[\left|\mathcal{A}^{Wt}_{\alpha\beta} + \mathcal{A}^{t\bar{t}}_{\alpha\beta}\right|^2 - C^{SUB}\right]$$

Cross-section measurement: dataset and event selection

ATLAS Run-2 dataset (2015-2018): $\sqrt{s} = 13$ TeV corresponding to $\mathrm{L} = 139\ \mathrm{fb}^{-1}$

- Dilepton OS final state: $e\mu, ee, \mu\mu$ ⟶ selected by single μ/e triggers

- Interference term taken into account with DR and DS schemes

- Comparison with NLO + PS Powheg + Pythia8 predictions

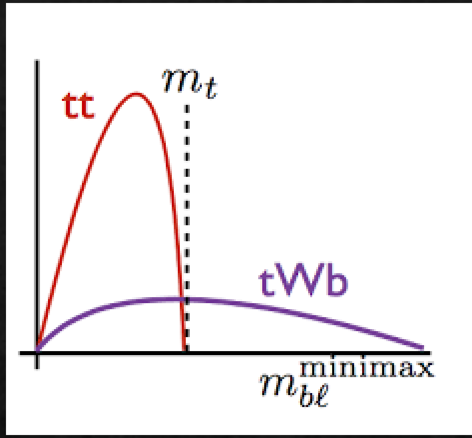
- Other requirements (kinematic cuts):
  1. $p_T^{\text{lepton}} > 28$ GeV, $p_T^{\text{jets}} > 25$ GeV and $|\eta| < 2.5$
  2. 2 b-tagged jets at 60% efficiency with veto on 3° b-tagged jet at 85% efficiency

Total events per sample

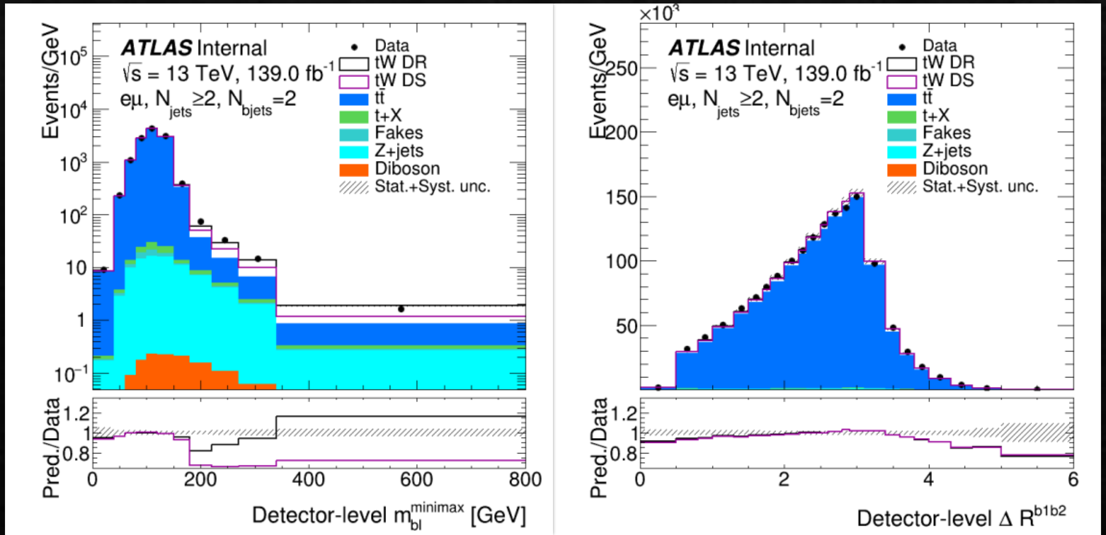
	Sample	Total events
signal	$t\bar{t}$	264000 ± 6000
signal	tW (DR)	8200 ± 180
bkg	$t\bar{t}V$	734 ± 3
bkg	Fakes	375 ± 7
bkg	Diboson	44.8 ± 0.9
bkg	Z+jets	2420 ± 33
	Expected	276000 ± 6000
	Observed	278333

Observables used in the analysis

- $WbWb$ final-state cross-section measured as a function of:
  1. $m_{bl}^{\mathrm{minimax}} \equiv \min\{\max(m_{b_1l_1}, m_{b_2l_2}), \max(m_{b_1l_2}, m_{b_2l_1})\}$
  2. $\Delta R(b_1, b_2)$ where $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$



Detector-level distributions for $m_{bl}^{\mathrm{minimax}}$ and $\Delta R(b_1, b_2)$



- Cross-section extraction as a function of:
  a) $m_{bl}^{\mathrm{minimax}}$ (1D)
  b) $\Delta R(b_1, b_2)$ (1D)
  c) $m_{bl}^{\mathrm{minimax}}$ in bins of $\Delta R(b_1, b_2)$ (2D)

Analysis strategy: the unfolding procedure

- *Unfolding* → data corrected for:
  1. Detector efficiency and finite resolution
  2. Limited geometrical acceptance
- TTbarUnfold (from RooUnfold) software
- *Iterative Bayesian* unfolding

Reconstructed spectrum → $\vec{R} = \boldsymbol{R} \cdot \vec{T}$ ← True spectrum

↑ Response matrix

$$\frac{d\sigma^{\text{fid}}}{dX^i} \equiv \frac{1}{\mathcal{L} \cdot \Delta X^i} \cdot \frac{1}{\epsilon^i} \cdot \sum_j M^{-1} \cdot f_{\text{acc}}^j \cdot \left(N_{\text{obs}}^j - N_{\text{bkg}}^j\right)$$

$$\frac{d\sigma^{\text{norm}}}{dX^i} = \frac{1}{\sigma^{\text{fid}}} \cdot \frac{d\sigma^{\text{fid}}}{dX^i}$$

Correction factors:

f_{acc}^j= acceptance factor

ϵ^i= inefficiency factor

Binning optimization

1. An *Iterative* procedure: $(T - R)$ vs T
2. Resolution in each bin of T: $2 \cdot \mathrm{RMS}\,(T - R)$
3. Starting from the first bin, merge bins until:
   - $\Delta_i > \delta \cdot 2 \cdot \mathrm{RMS}_i$
   - $\sigma_{\mathrm{stat}} \simeq \frac{\sqrt{N_i}}{N_i} < k\%$

   where δ = conservative factor, $k\%$ = upper limit for stat. uncertainty
4. Binning validation with "closure" tests

For 2D binning separate optimization of X and Y:

"X in bins Y" ⟹ X "*internal*" and Y "*external*"

Variable	Type	δ	k	Bin edges
$m_{bl}^{\mathrm{minimax}}$ [GeV]	1D	1	5%	0, 40, 60, 80, 100, 120, 150, 180, 220, 270, 340, 420, 580, 800
$\Delta R_{b_1 b_2}$	1D	1	5%	0, 0.5, 0.8, 1, 1.3, 1.5, 1.7, 1.8, 2, 2.2, 2.3, 2.5, 2.6, 2.8, 2.9, 3.1 3.4, 3.6, 3.8, 4, 4.3, 4.6, 5, 6
$m_{bl}^{\mathrm{minimax}}$ [GeV]	2D external	1	2%	0, 60, 90, 120, 160, 215, 800
$\Delta R_{b_1 b_2}$	2D external	1	0.5%	0, 1.5, 2, 2.4, 2.8, 3, 3.4, 6

1D and 2D external bin edges

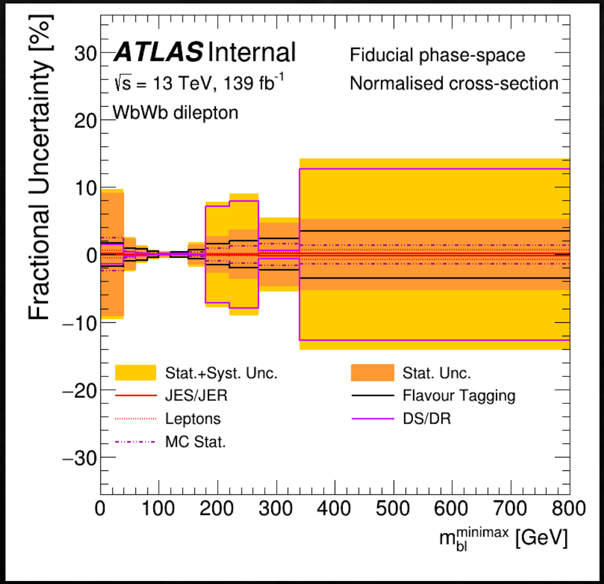
Variable	Type	δ	k	Bin edges
$m_{bl}^{\mathrm{minimax}}$ in $\Delta R_{b_1 b_2}$ (0, 1.5)	2D internal	2	5	0, 60, 110, 800
$m_{bl}^{\mathrm{minimax}}$ in $\Delta R_{b_1 b_2}$ (1.5, 2)	2D internal	2	5	0, 60, 100, 150, 220, 800
$m_{bl}^{\mathrm{minimax}}$ in $\Delta R_{b_1 b_2}$ (2, 2.4)	2D internal	2	5	0, 100, 140, 210, 800
$m_{bl}^{\mathrm{minimax}}$ in $\Delta R_{b_1 b_2}$ (2.4, 2.8)	2D internal	2	5	0, 90, 140, 200, 800
$m_{bl}^{\mathrm{minimax}}$ in $\Delta R_{b_1 b_2}$ (2.8, 3)	2D internal	2	5	0, 60, 100, 140, 200, 800
$m_{bl}^{\mathrm{minimax}}$ in $\Delta R_{b_1 b_2}$ (3, 3.4)	2D internal	2	5	0, 90, 140, 800
$m_{bl}^{\mathrm{minimax}}$ in $\Delta R_{b_1 b_2}$ (3.4 6)	2D internal	2	5	0, 70, 110, 160, 800

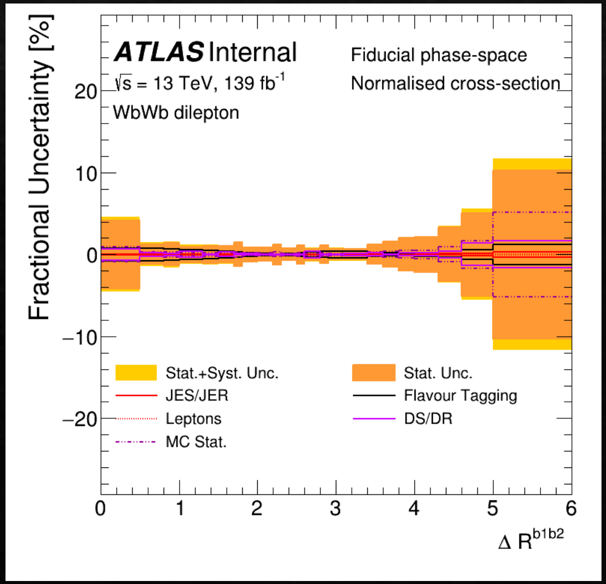
2D internal bin edges

Systematic uncertainties

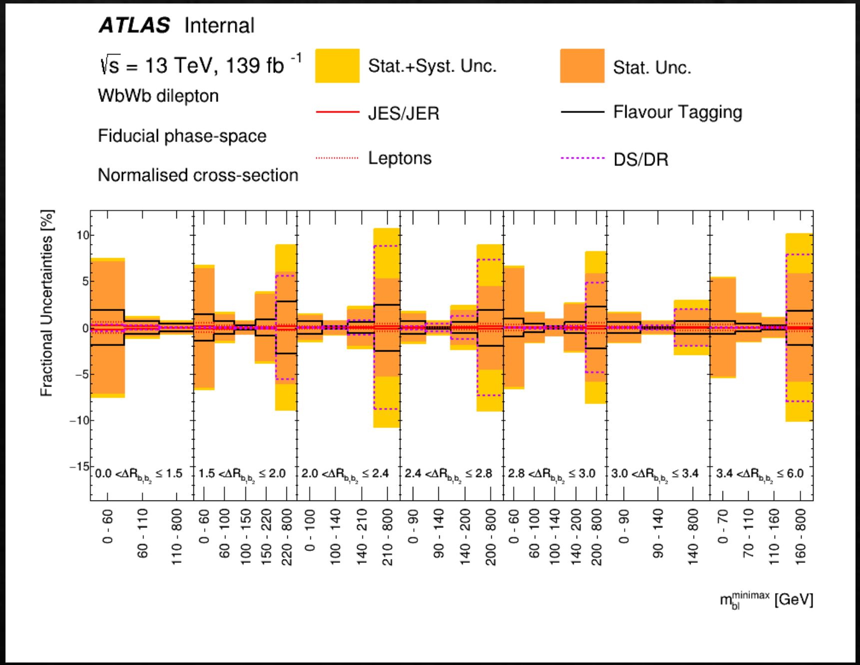
- Evaluated by:
  1. Unfolding the varied MC detector-level spectra with nominal corrections
  2. Compare the unfolded result with the particle-level distribution of the generator
- Detector-related systematics: lepton reconstruction efficiency, JVT, b-tagging, pileup reweighting and luminosity
- Signal modelling systematics: choice of removal scheme and finite sample statistics of MC generators

1D

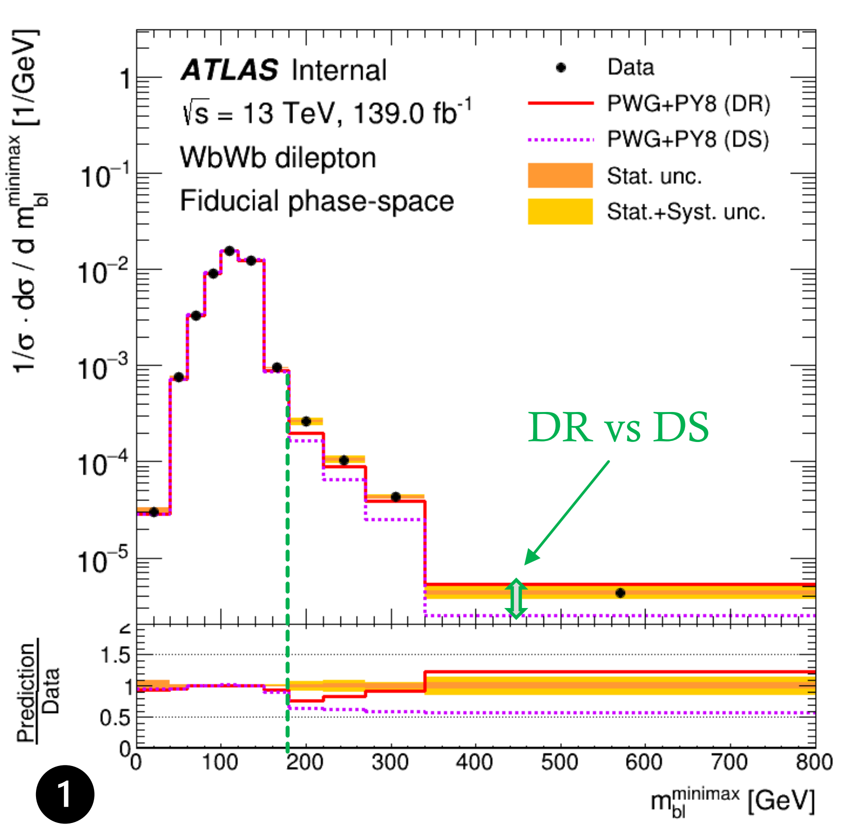


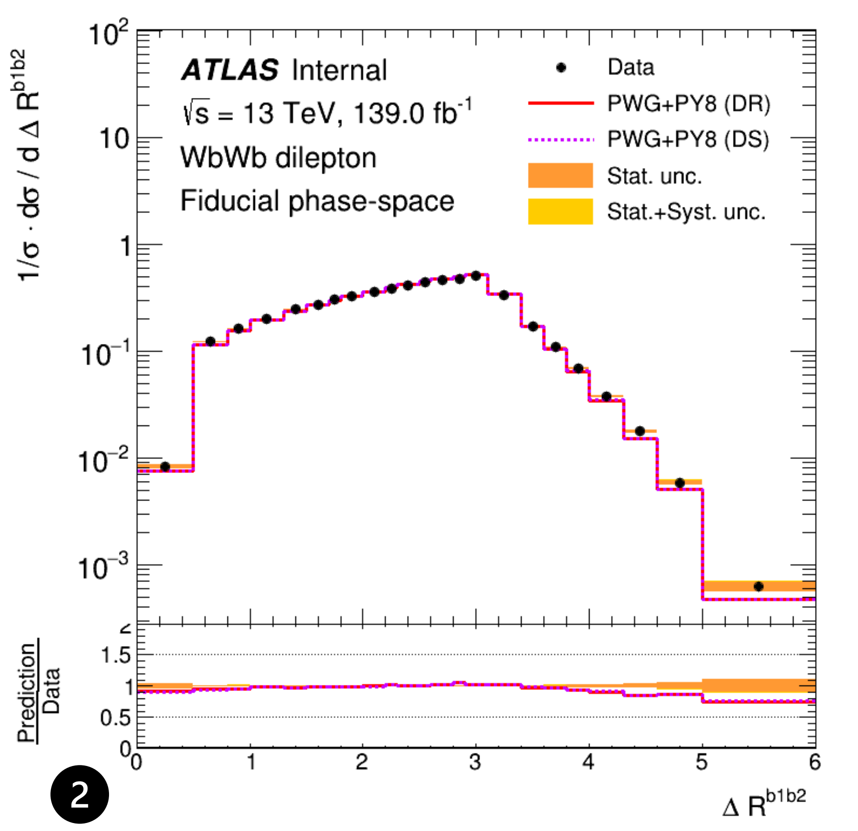


2D



Results (1): 1D cross-sections





1D cross-sections measurement as a function of:

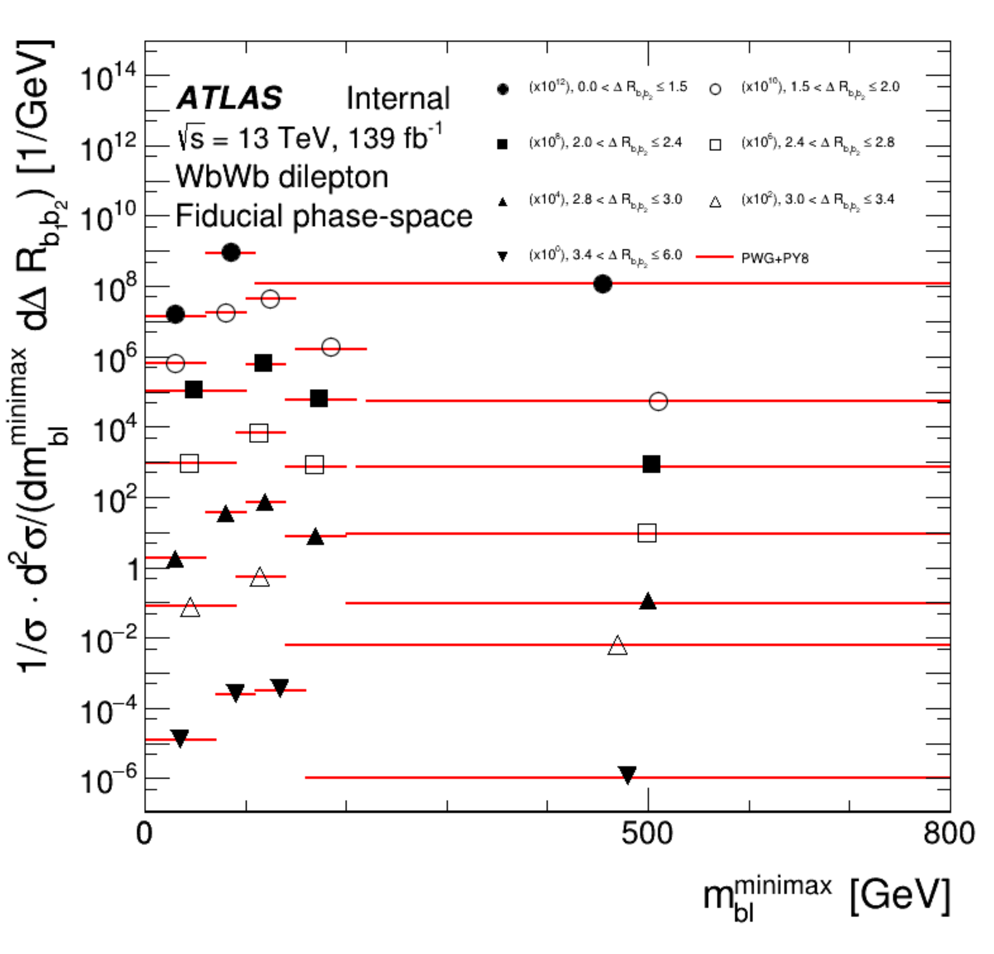
1. $m_{bl}^{minimax}$ (log)
2. $\Delta R(b_1, b_2)$ (log)

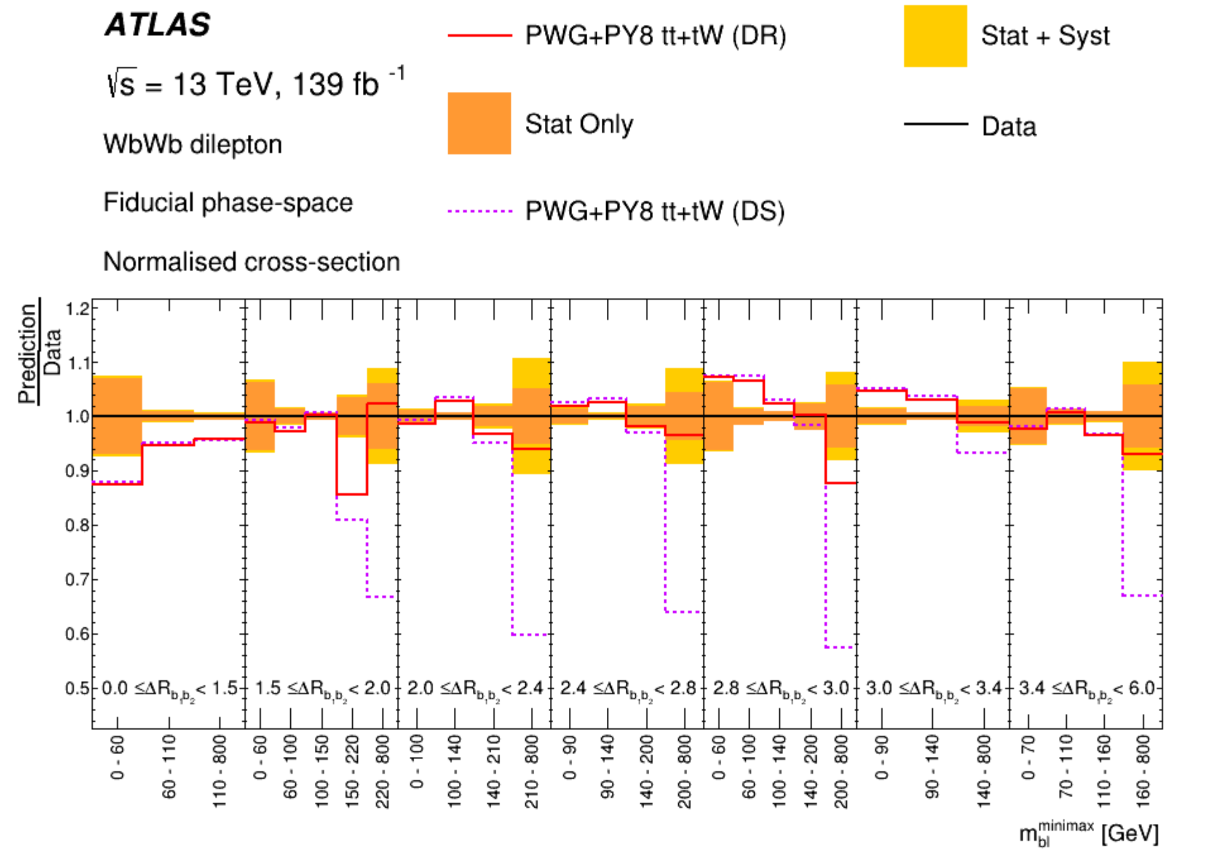
Sample	Fiducial cross-section [pb]
Data	7.49±0.22
$t\bar{t} + tWb$ (Powheg+Pythia8, DS)	7.4671±0.0017
$t\bar{t} + tWb$ (Powheg+Pythia8, DR)	7.4907±0.0015

Preliminary fiducial cross-section measurement (without proper evaluation of all the systematics)

Results (2): 2D cross-section

2D cross-section measurement as a function of m_{bl}^{minimax} in bins of $\Delta R(b_1, b_2)$





Conclusions and outlooks

- Results:
  - $WbWb$ cross-sections successfully measured and compared to DR and DS schemes
  - m_{bl}^{minimax} distributions and m_{bl}^{minimax} in bins of $\Delta R(b_1, b_2)$ seem to be better described by the DR scheme in the interference region
  - $\Delta R(b_1, b_2)$ distribution not enough sensitive to discriminate DR vs DS

- Analysis is going on with current improvements:
  1. Consider the other subdominant systematic uncertainties
  2. Perform the analysis in $e\mu$ channel only (suppress dominant $Z \rightarrow ll$ background)
  3. Measure the cross-section as a function of other interference-sensitive variables (ex: p_T^{lep} …)
  4. First public results are foreseen for Autumn 2022
  5. Search for possible signals of toponium-resonance formation in $WbWb$ phase-space

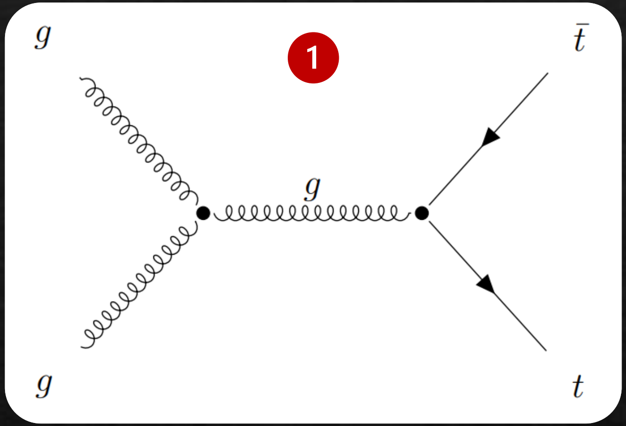
Thanks for your attention!

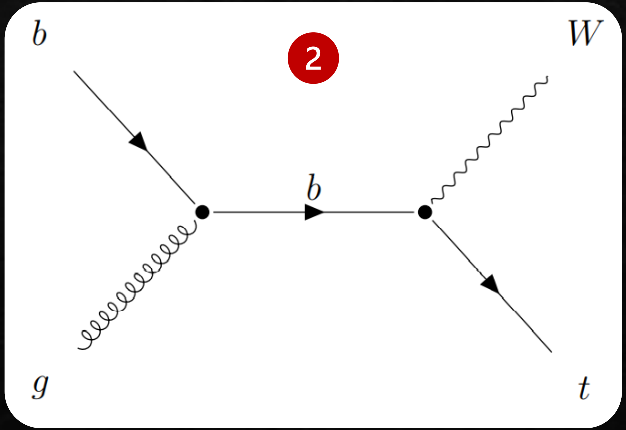

BACKUP

Top quark production processes at the LHC

- Top-quark production processes at leading-order (LO) at the LHC:
  - $t\bar{t}$ pair production (Fig. 1): $gg \rightarrow t\bar{t} \rightarrow WbWb$ (dominant)
  - Single-top production (Fig. 2): $gb \rightarrow tW \rightarrow WbW$ (subdominant)

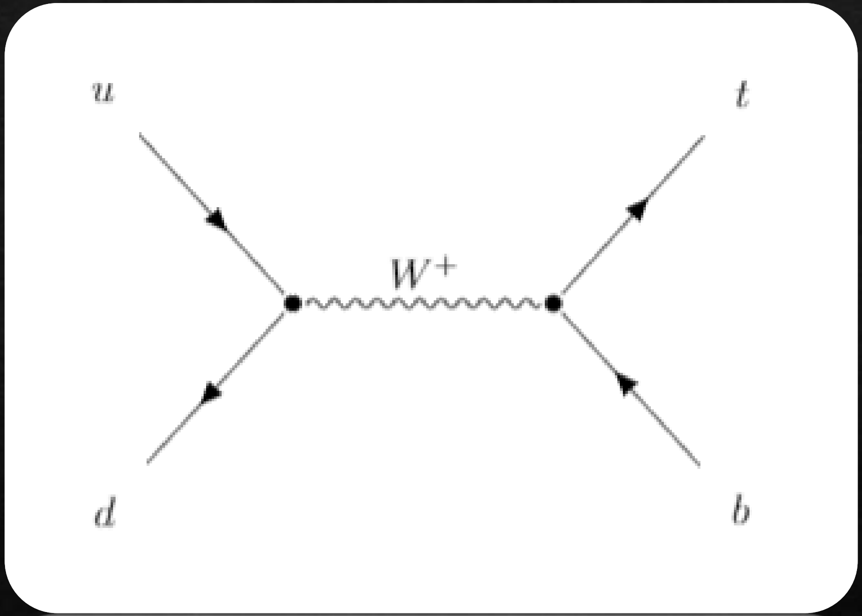
At LO $t\bar{t}$ and tW don't interfere (different final-states)



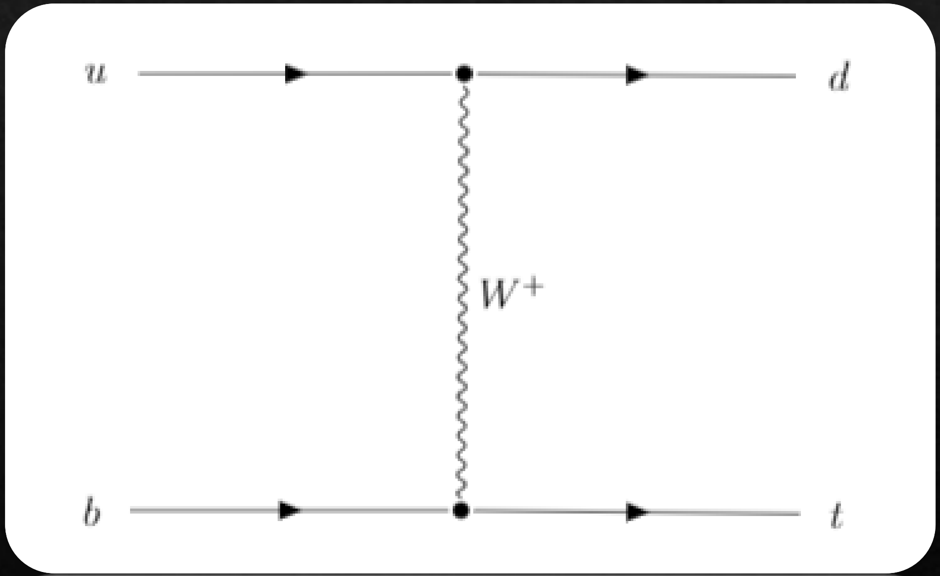


Other single-top production processes

s-channel



t-channel

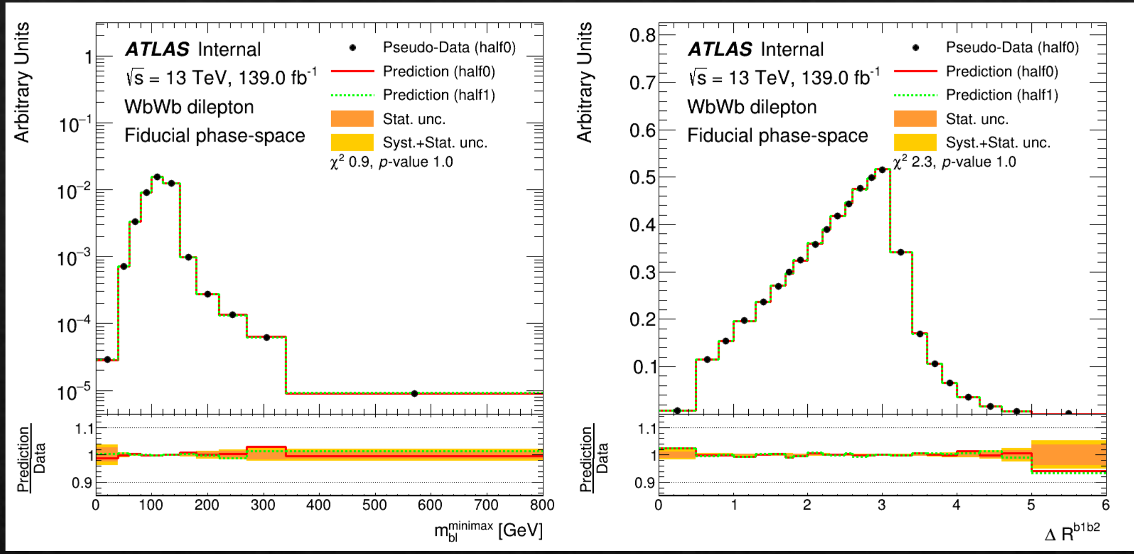


Closure tests

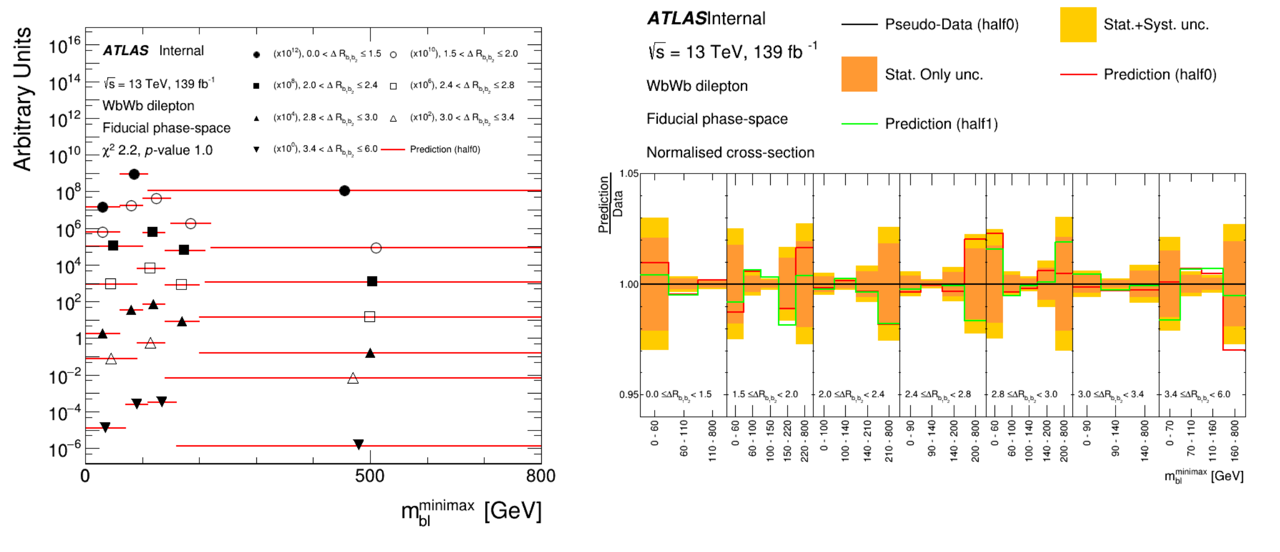
- Ensure the *stability* of the chosen bins

- Construction of two subsamples:
  a) half0: pseudo-data
  b) half1: MC signal

- Procedure:
  1. Unfolding half0 by applying corrections obtained with half1
  2. Compare unfolded half0 with particle-level spectra
  3. Evaluate with a χ^2

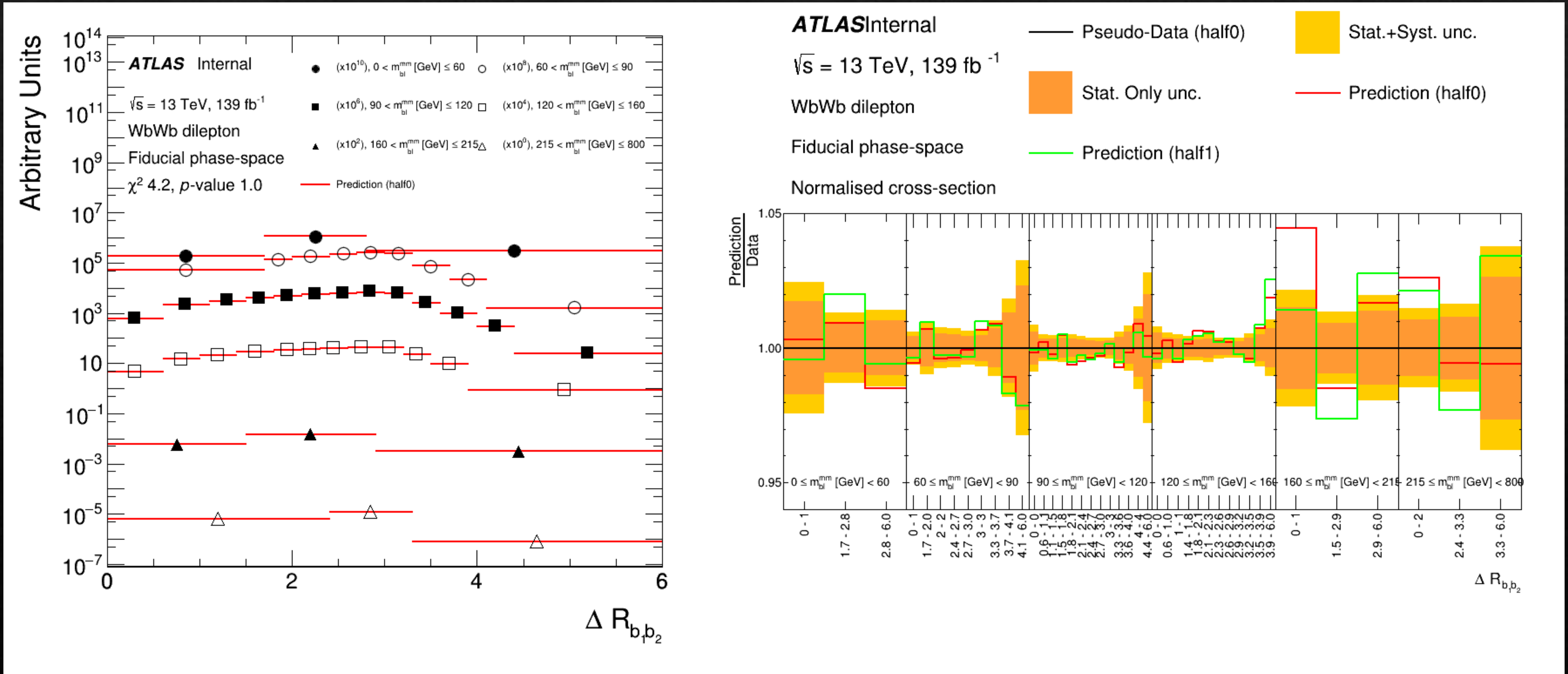


1D

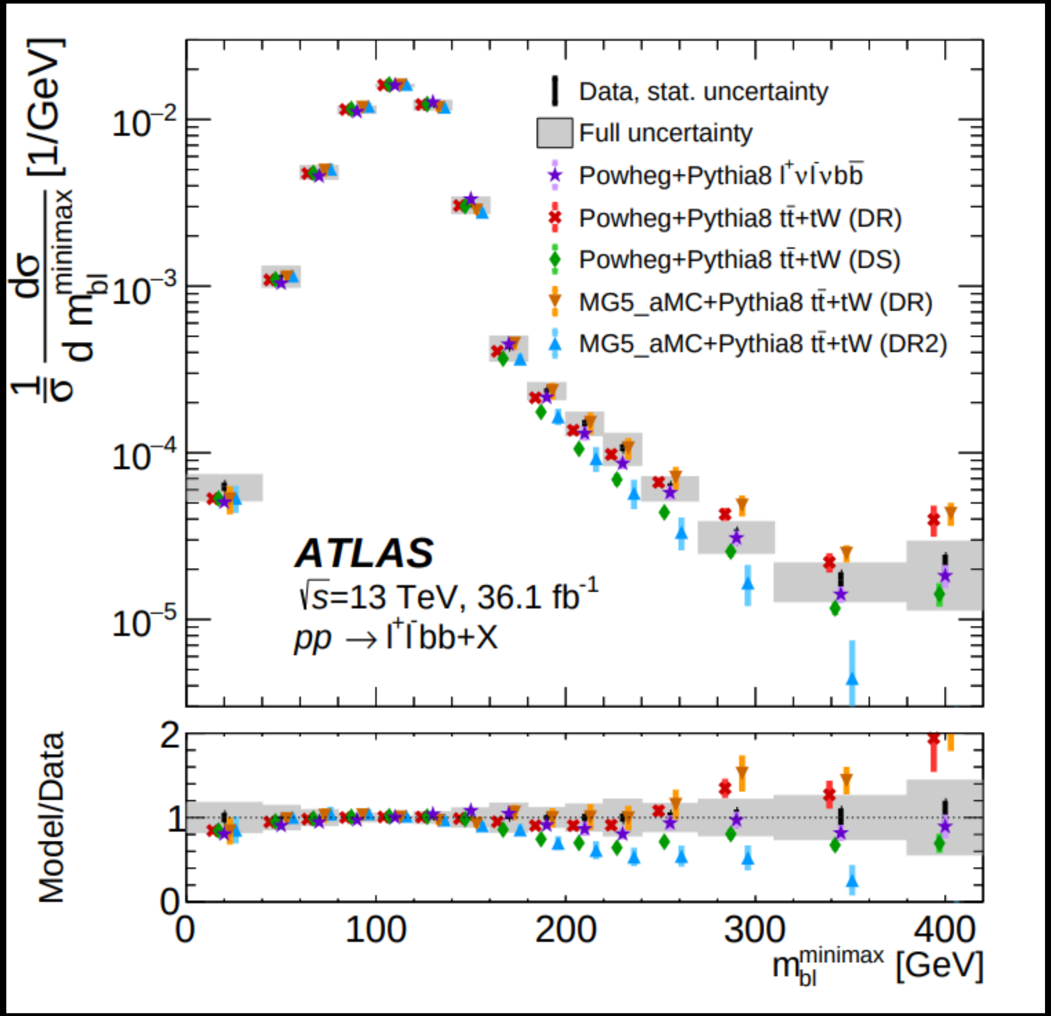


2D

Backup: closure tests for $\Delta R(b_1, b_2)$ in bins of $m_{bl}^{\mathrm{minimax}}$

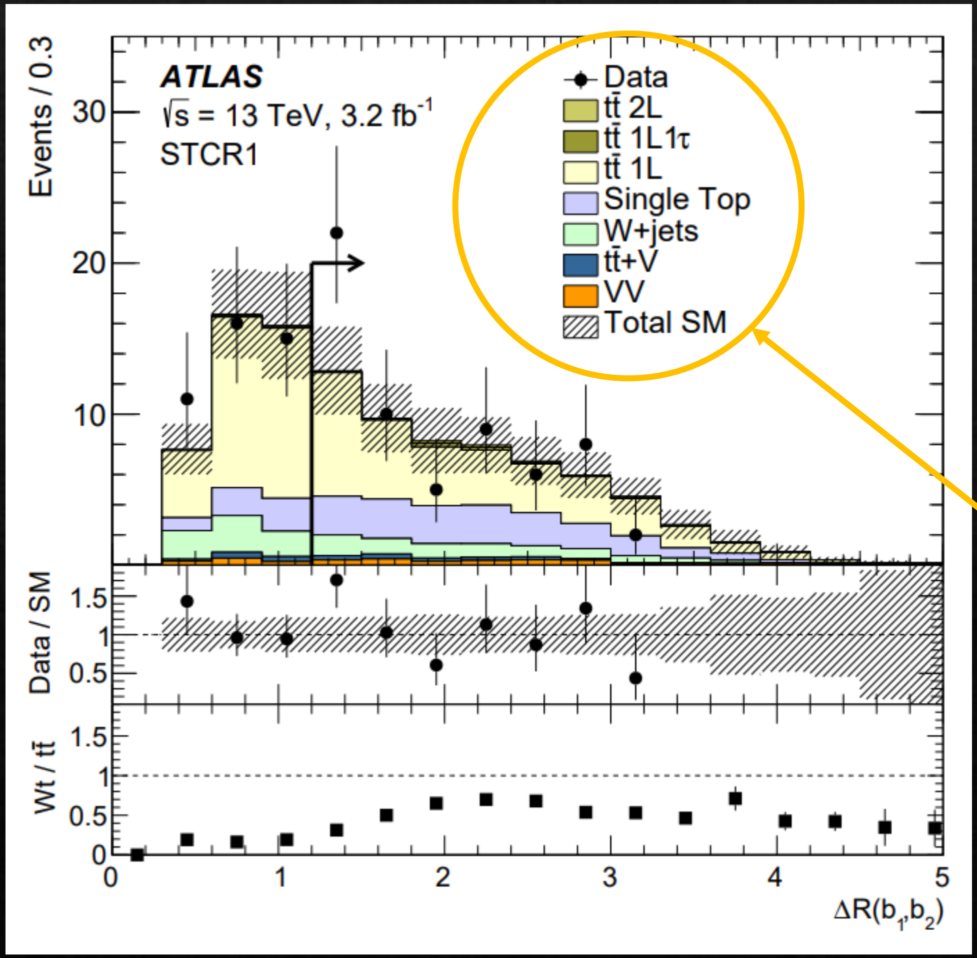


$WbWb$ cross-section previous measurement



- ❖ Measurement performed by ATLAS in 2018:
  - Partial Run-2 data ($\sqrt{s}$ = 13 TeV & L = 36.1 fb^{-1})
  - Dilepton OS final state: $ee, e\mu$ *and* $\mu\mu$

Impact of interference in BSM processes



CERN – *ATLAS*, 2016:

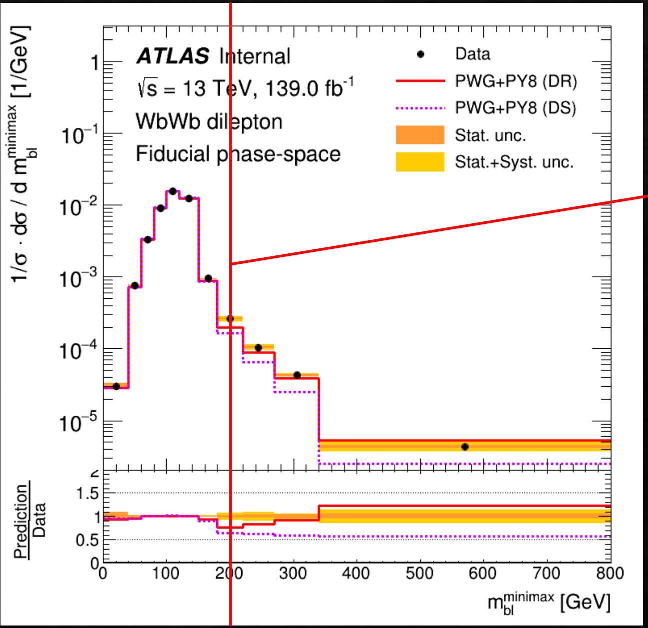
"Search for top squarks in final states with one isolated lepton, jets, and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector".

Background processes given by $t\bar{t}$ and Wt

The m_{bl}^{minimax} variable

$$m_{bl}^{\text{minimax}} \equiv \min\{\max(m_{b_1 l_1}, m_{b_2 l_2}), \max(m_{b_1 l_2}, m_{b_2 l_1})\}$$

- bl coming from t: on shell → two m_{bl} below the top mass bound
- bl coming from Wb: off shell → only a single m_{bl} below the top mass bound



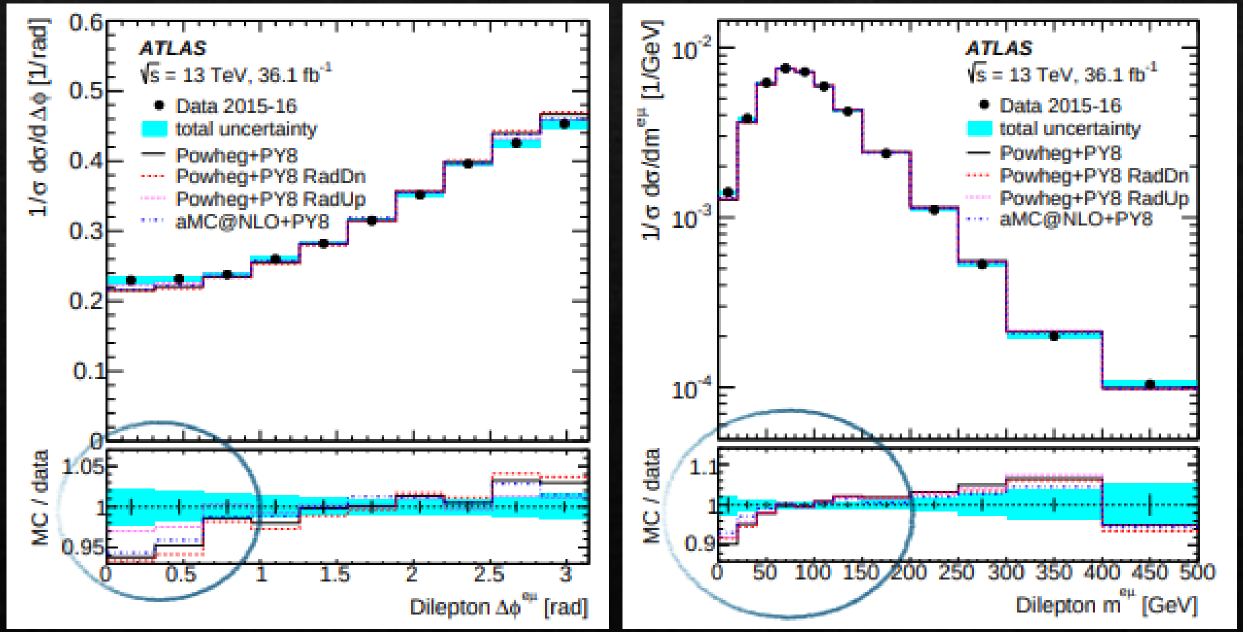
$m_{bl}^{\text{minimax}} > 200$ GeV, contribution of two on-shell top final-state is suppressed and interference become large

$WbWb$ sensitivity to toponium resonance formation

- Recent studies (ATLAS 2020): deviations between data and predictions in $t\bar{t} \rightarrow WbWb \rightarrow ll$ productions:
  - Possibility of a signal in toponium-resonance η_t formation at $\Delta\phi_{ll} < \frac{\pi}{5}$ and $m_{ll} < 50$ GeV

Excess of data could be explained by the existance of the η_t state

- $WbWb$ cross-section improvements would lead to a complete investigation of this process in $WbWb$ phase-space



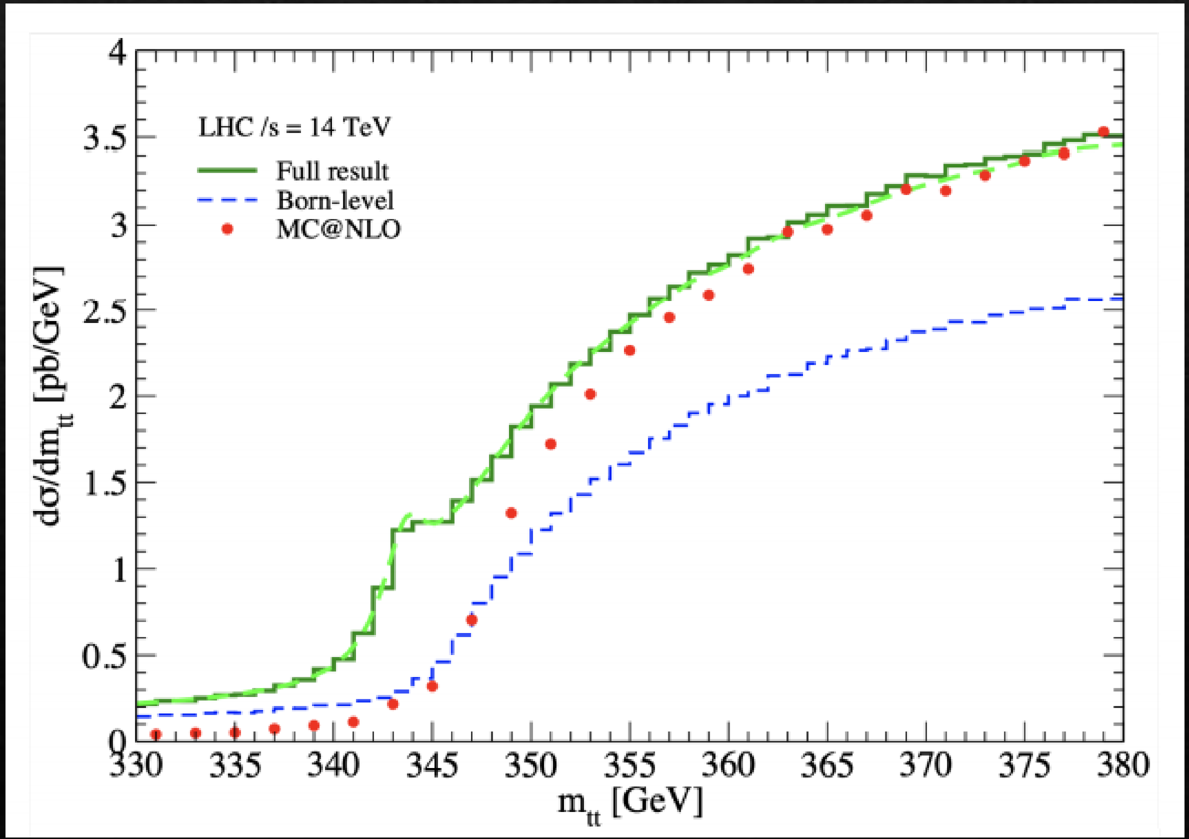
$WbWb$ cross-section for $t\bar{t}$ production, measured by ATLAS in 2020

Toponium resonance: main properties

$$pp \to \eta_t \to t^{(*)}\bar{t}^{(*)} \to W^+bW^-\bar{b}$$

- Main (expected) properties:
  - Spin state: $J^{PC} = 0^{-+}$ (dominant)
  - Mass: $m_{\eta_t} = 344$ GeV
  - Decay width: $\Gamma_{\eta_t} \approx 7$ GeV
  - Cross-section: $\sigma(13\text{ TeV}) \approx 6.5$ pb

- Threshold enhancement:
  - Full $WbWb$ differential distribution
  - NLO $WbWb$ differential distribution
  - Pure toponium contribution: green - red

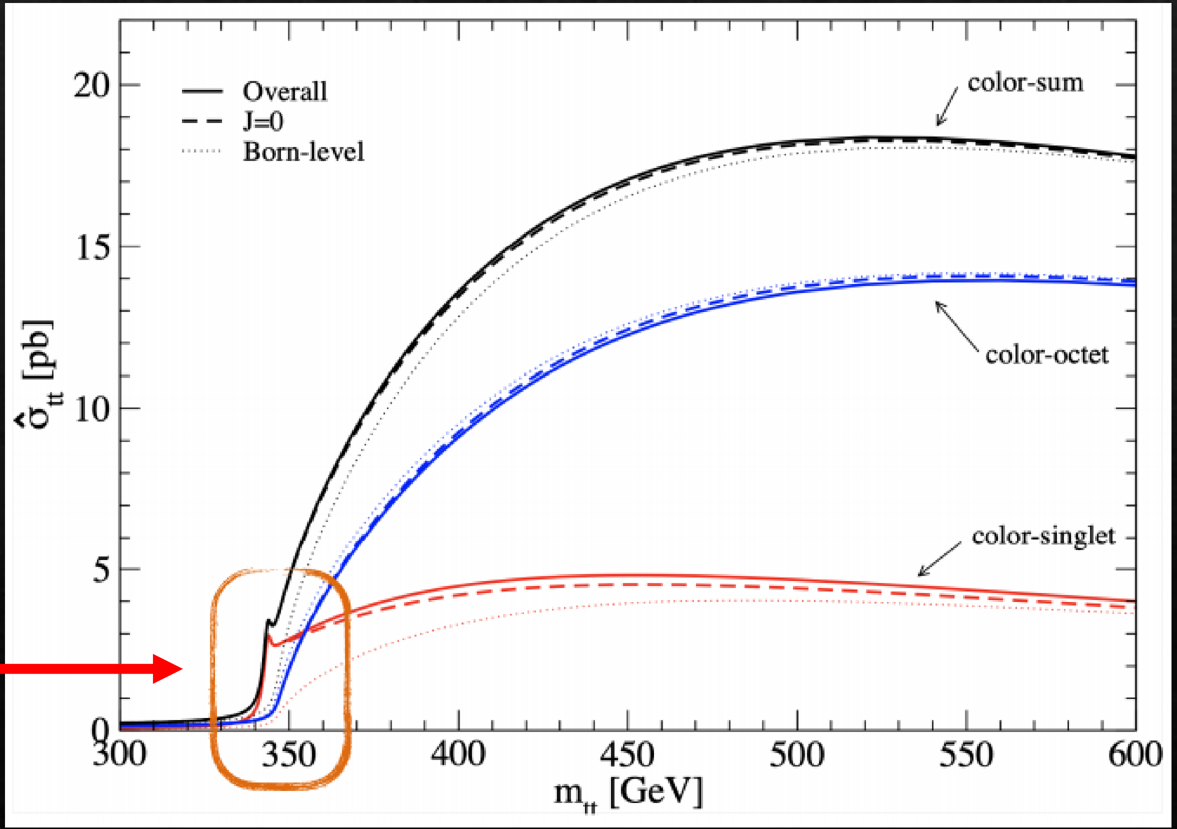


Toponium resonance: spin states

- Color singlet toponium ground states, two possible configurations:
  - $J = 1$ spin triplet state (ψ_t)
  - $J = 0$ spin singlet state (η_t)

- But toponium states decay instantly!

- Colour singlet dominate at threshold in *pp* colliders:
  - The gg-singlet channel dominates
  - The $J = 0$ state dominates ($L = S = 0$)



Toponium resonance: sensitive variables

- Angular separation between the two leptons in the rest frames:

$$(1+\cos\bar{\theta})(1+\cos\theta)+(1-\cos\bar{\theta})(1-\cos\theta)+2\sin\bar{\theta}\sin\theta\cos(\bar{\phi}-\phi)$$

- Dilepton invariant mass:

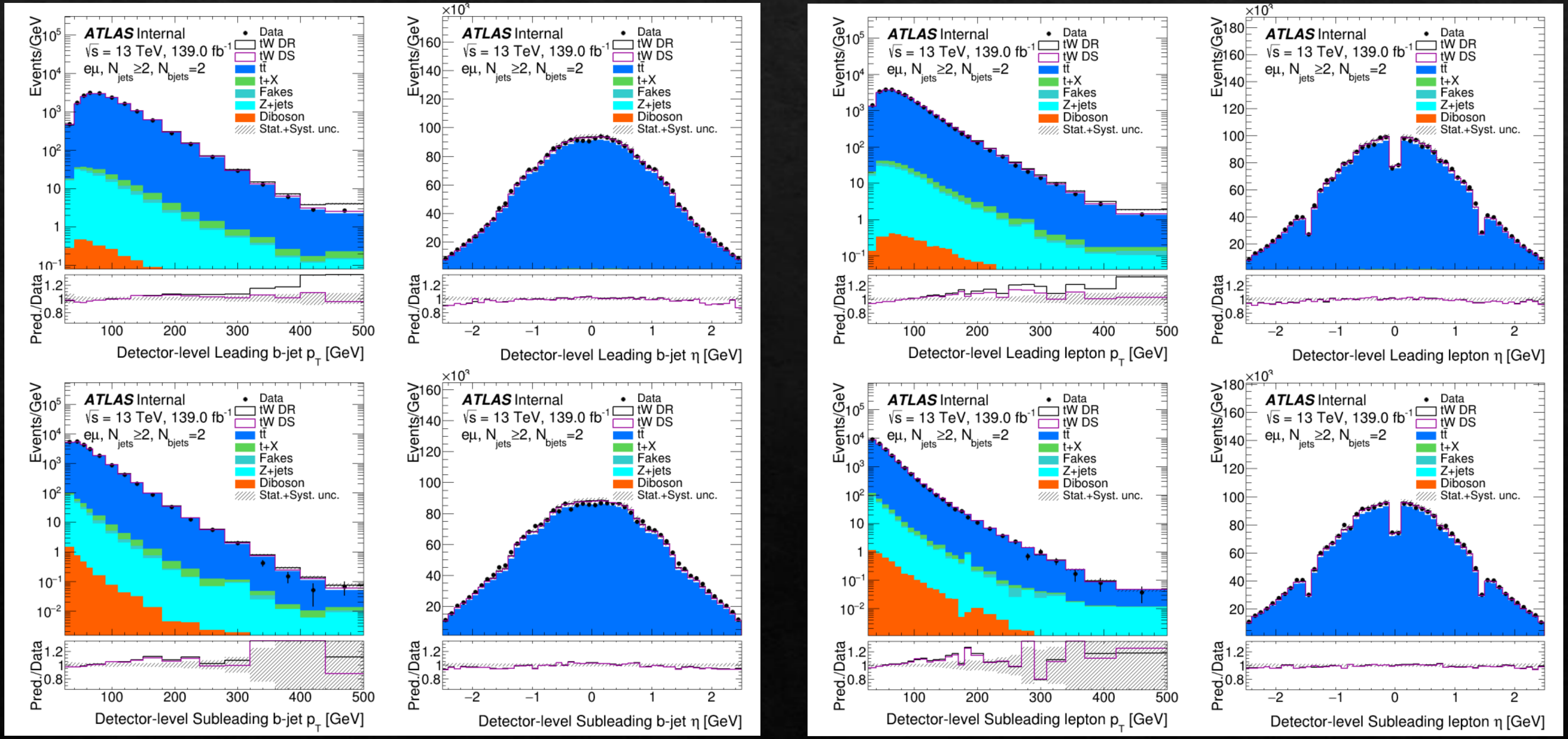
$$m^2_{\bar{l}l'}=2E_{\bar{l}}E_{l'}(1-\sin\bar{\theta}\sin\theta\cos(\bar{\phi}-\phi)-\cos\bar{\theta}\cos\theta)$$

- Azimuthal angle separation: $\Delta\phi_{ll}$

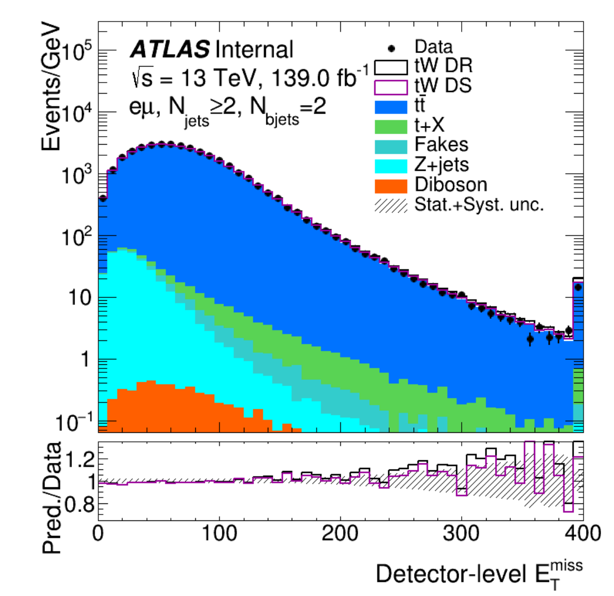
- Toponium characteristics: small m_{ll} and small $\Delta\phi_{ll}$

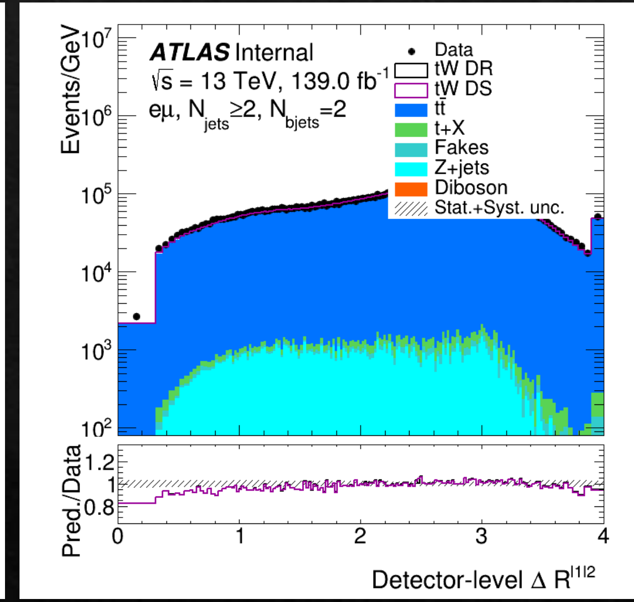
Backup: detector-level variables control plots (1)

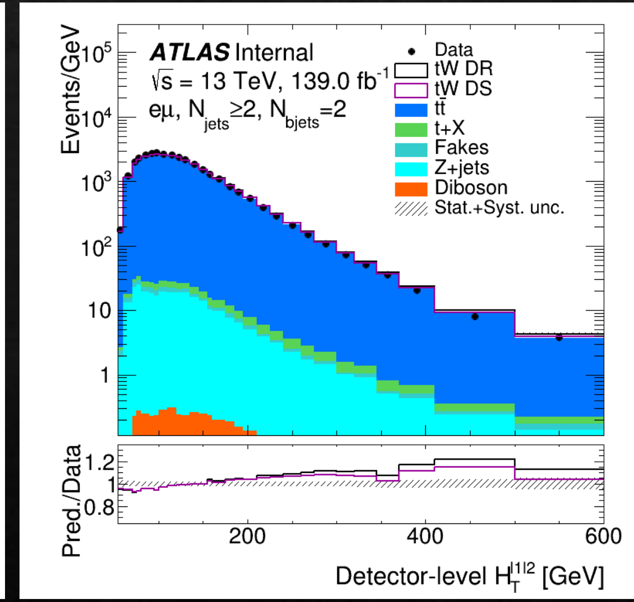
Detector-level distributions for leading and subleading leptons and *b*-jets p_T and η

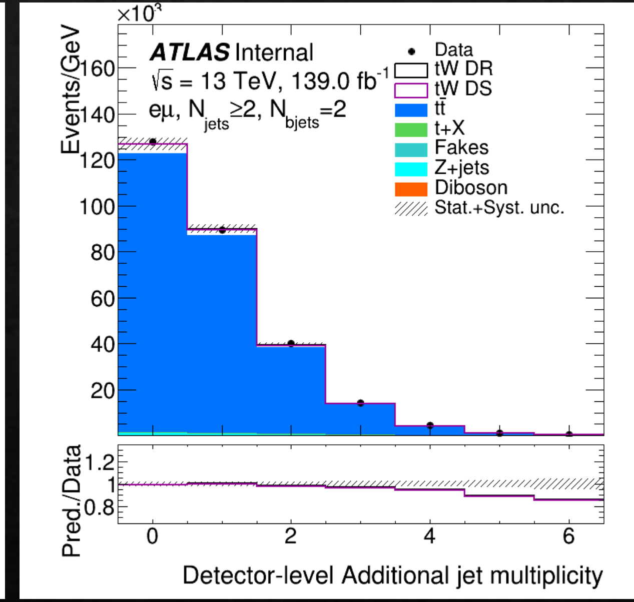


Backup: detector-level variables control plots (2)



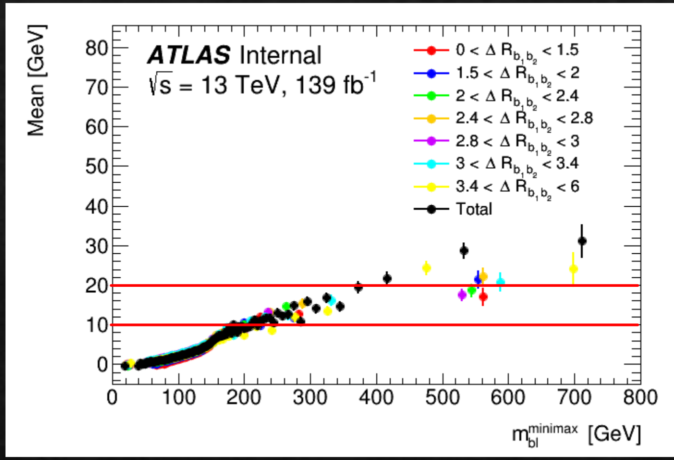


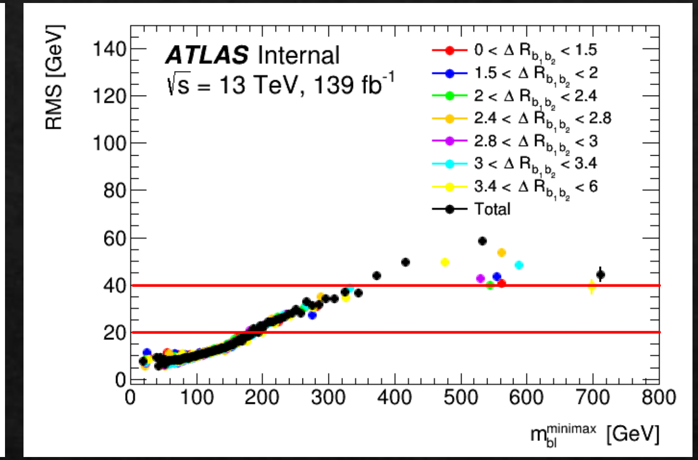




Backup: resolution plots

DS scheme





DR scheme