Probing quantum interference in top production with the ATLAS detector

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on behalf of the ATLAS Collaboration

5th CMS Single Top Workshop
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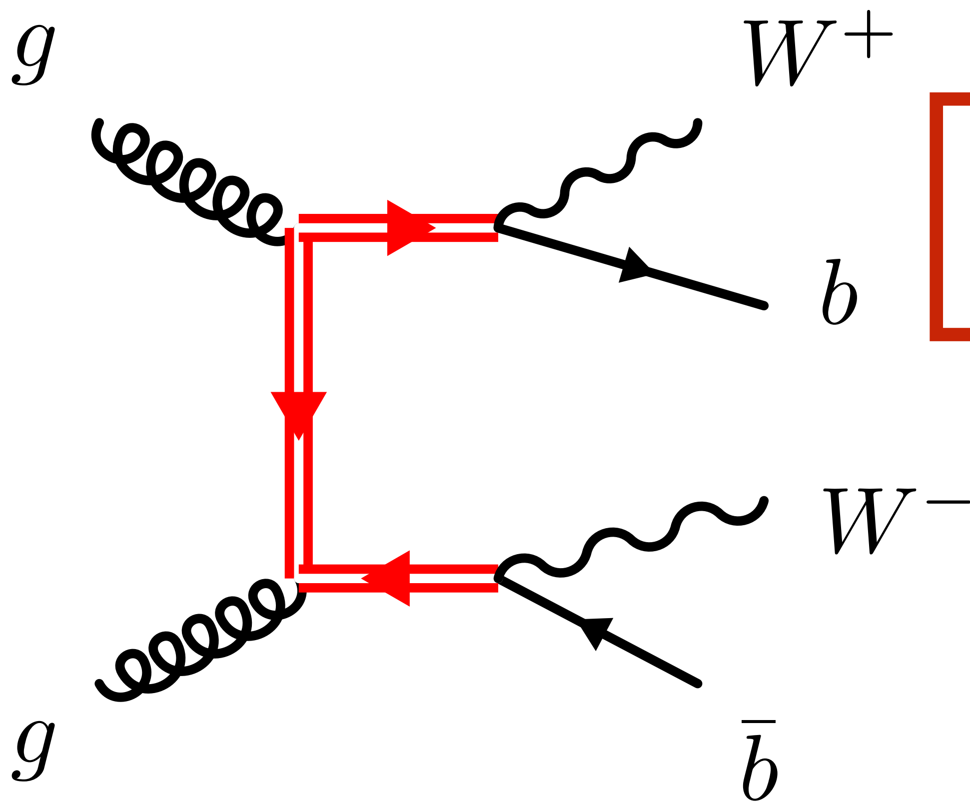
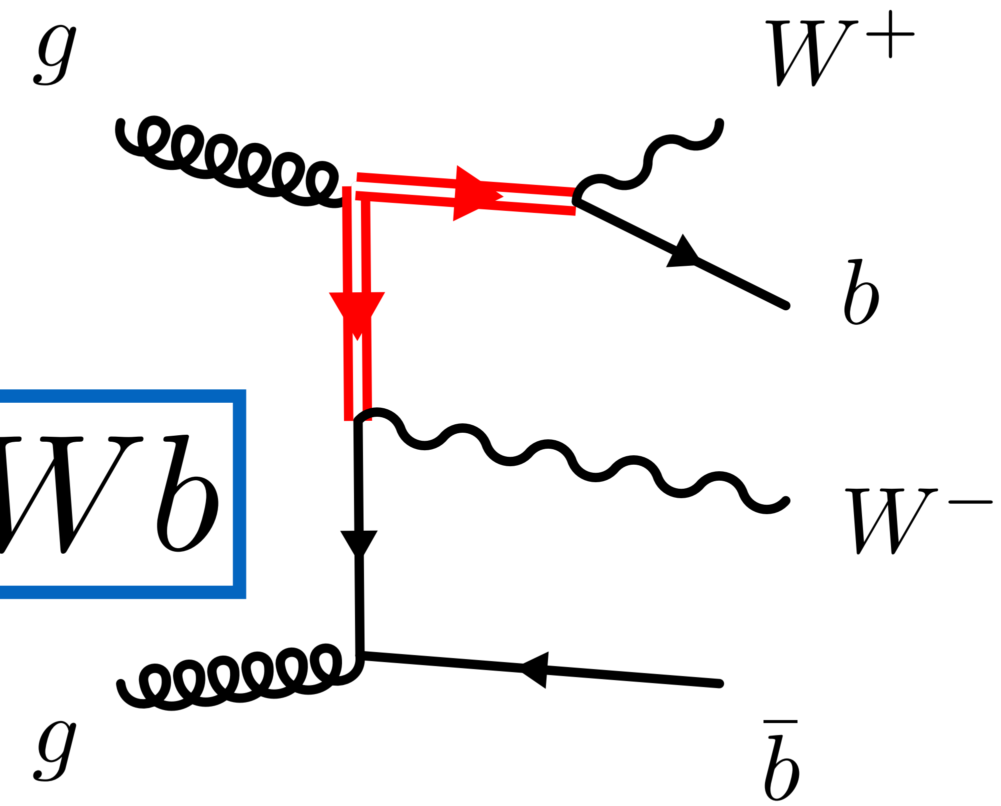
Introduction



$t\bar{t}$

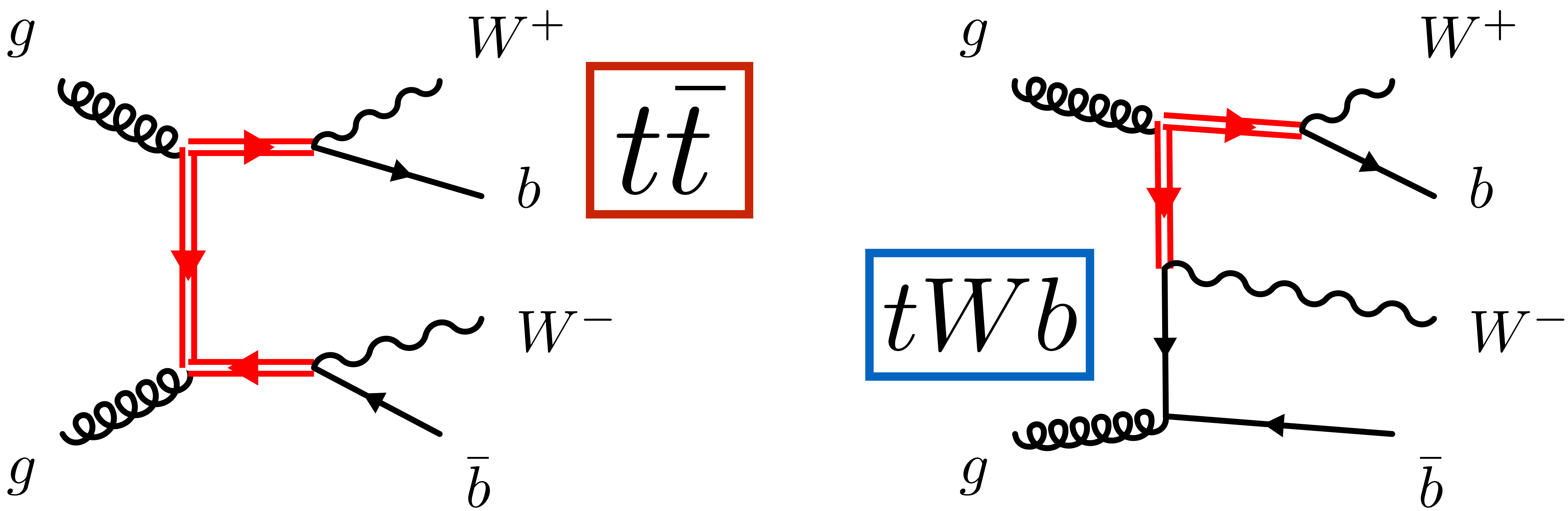
tWb



ttbar and single top processes with identical final states interfere!

$$\text{Total XS} \propto |\mathcal{A}|^2 = |\mathcal{A}_{t\bar{t}}|^2 + |\mathcal{A}_{tWb}|^2 + 2\mathrm{Re}\{\mathcal{A}^*_{t\bar{t}}\mathcal{A}_{tWb}\}$$

Introduction



- Standard calculations treat top decays in the narrow-width approximation, factorizing the two processes
- *ad-hoc* combination schemes exist to estimate size of this effect
  - Difference of predictions usually assessed as an uncertainty
- Measurement constructed to maximize the interference effect!
  - Will provide the first direct test of these schemes

Interference models (I)

0805.3067 [hep-ph]

- Two alternatives initially proposed to define tW process at NLO:
  - Diagram Removal (DR): remove all ttbar diagram contributions
    - 'Ignores' interference effects, but not gauge-invariant
    - tWb prediction ~ $|\mathcal{A}_{tWb}|^2$
  - Diagram Subtraction (DS): construct a term designed to cancel ttbar contribution when Wb pairs on-shell
    - Includes interference, subtraction only works 'on average'
    - tWb prediction ~ $|\mathcal{A}_{t\bar{t}}|^2 + |\mathcal{A}_{tWb}|^2 + 2\mathrm{Re}\{\mathcal{A}^*_{t\bar{t}}\mathcal{A}_{tWb}\} - \Phi$

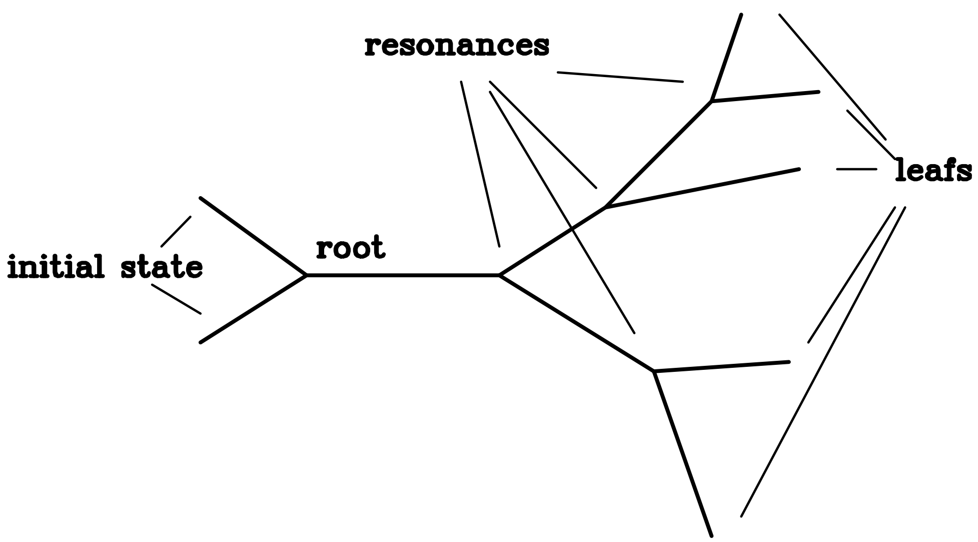
"tt subtraction term"

- More recent proposal of "DR2" ~ $|\mathcal{A}_{tWb}|^2 + 2\mathrm{Re}\{\mathcal{A}^*_{t\bar{t}}\mathcal{A}_{tWb}\}$

1207.1071 [hep-ph], 1607.05862 [hep-ph]

Interference models (II)

- Recently another solution became available 1607.04538 [hep-ph]
- lvlvbb process implemented in Powheg (NLO matched to PS)
  - Full NLO, with no narrow-width approximation
  - Includes cross-talk between top production and decay
  - Showering is "resonance-aware", preserving top mass



- Inclusive treatment→ interference is 'automatically' included
- Analysis plan:
  - Use DR, DS to design analysis and estimate uncertainties
  - Compare DR2, Powheg-Res lvlvbb to the unfolded data

Interference models (II)

- Recently another solution became available 1607.04538 [hep-ph]

This effect is measured in a new result from ATLAS:

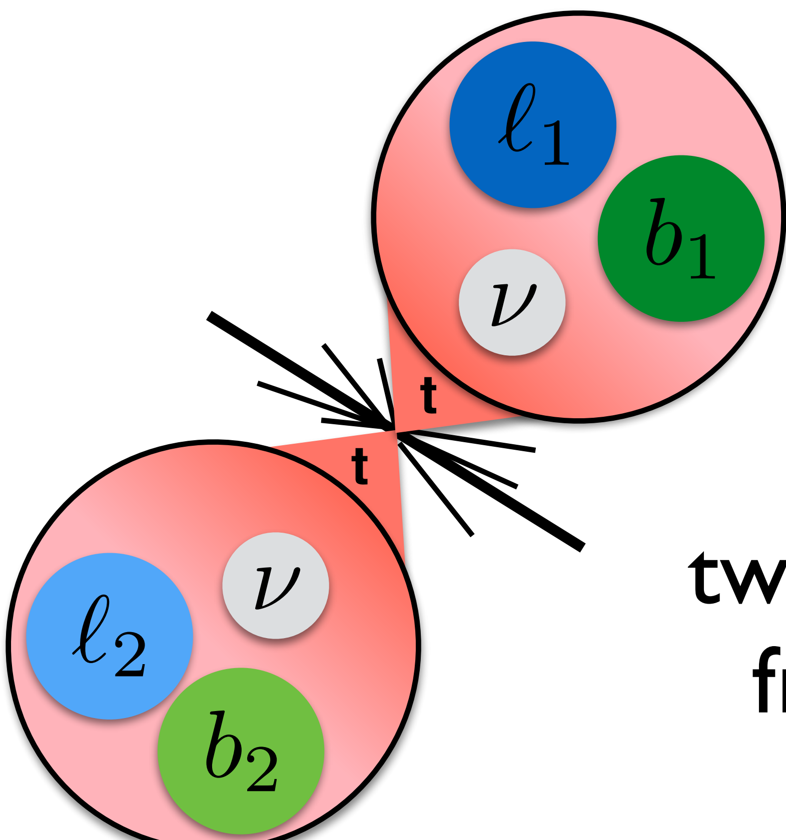
Probing the quantum interference between singly and doubly resonant top-quark production in pp collisions at $\sqrt{s}$ =13 TeV with the ATLAS detector

Phys. Rev. Lett. 121 (2018) 152002

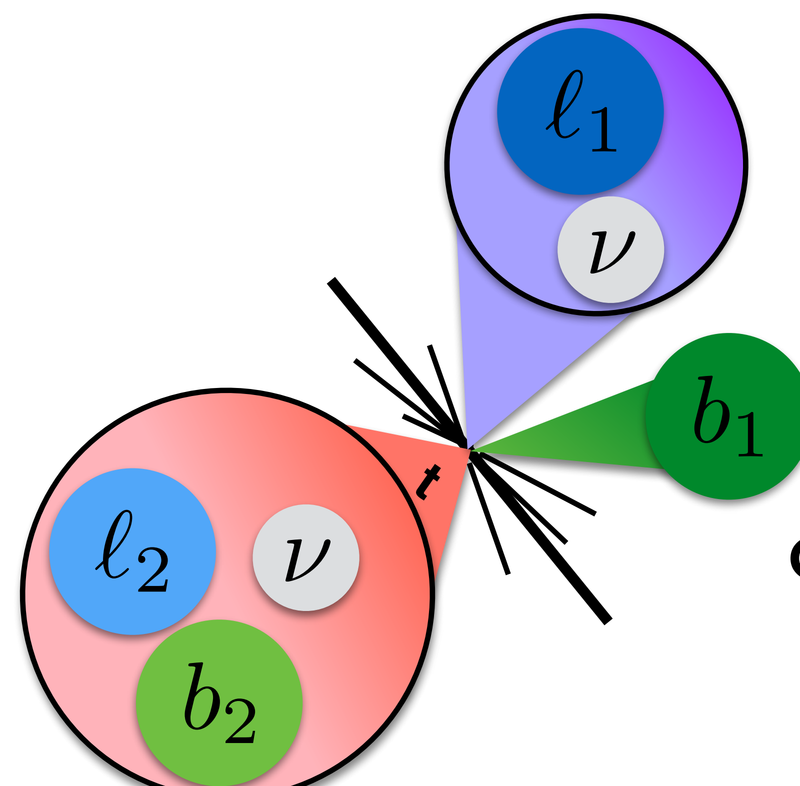
All plots can be found on the public webpage

Analysis strategy

- Define signal as the the **combined ttbar+tWb** process
- **Differential measurement** of an **interference-sensitive variable**
  - Scanning tWb/ttbar purity probes interference when both important
  - Interference depends on interplay between $\mathcal{A}_{t\bar{t}}$ and $\mathcal{A}_{tWb}$
- Idea: design observable differentiating the processes' resonant structure



ttbar:
two (b,l) pairs
from a top



tWb:
one (b,l) pair
from a top

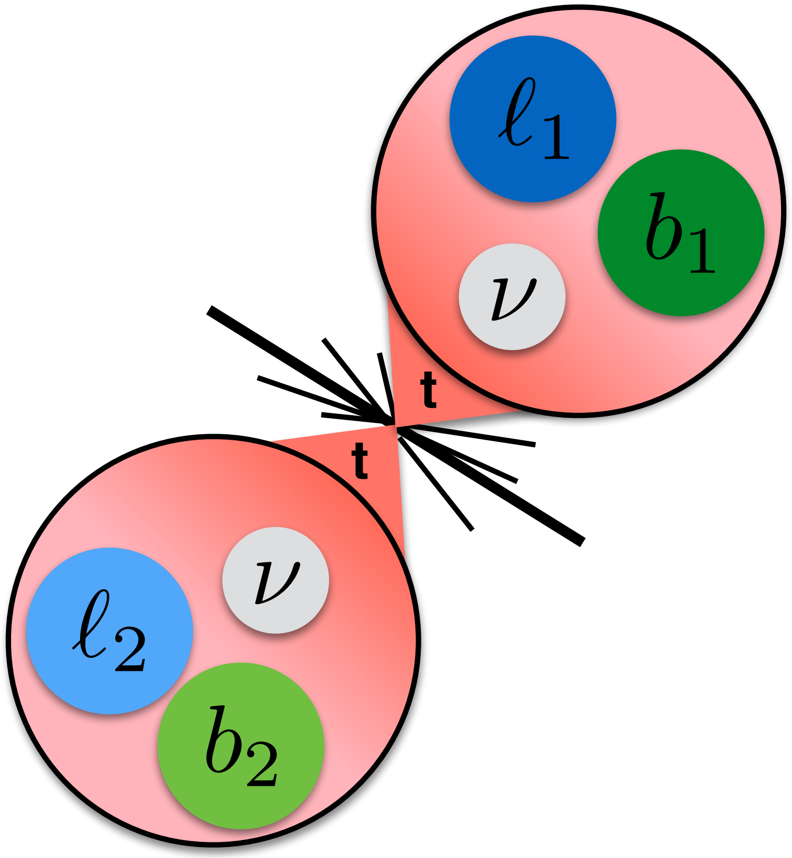
Analysis strategy

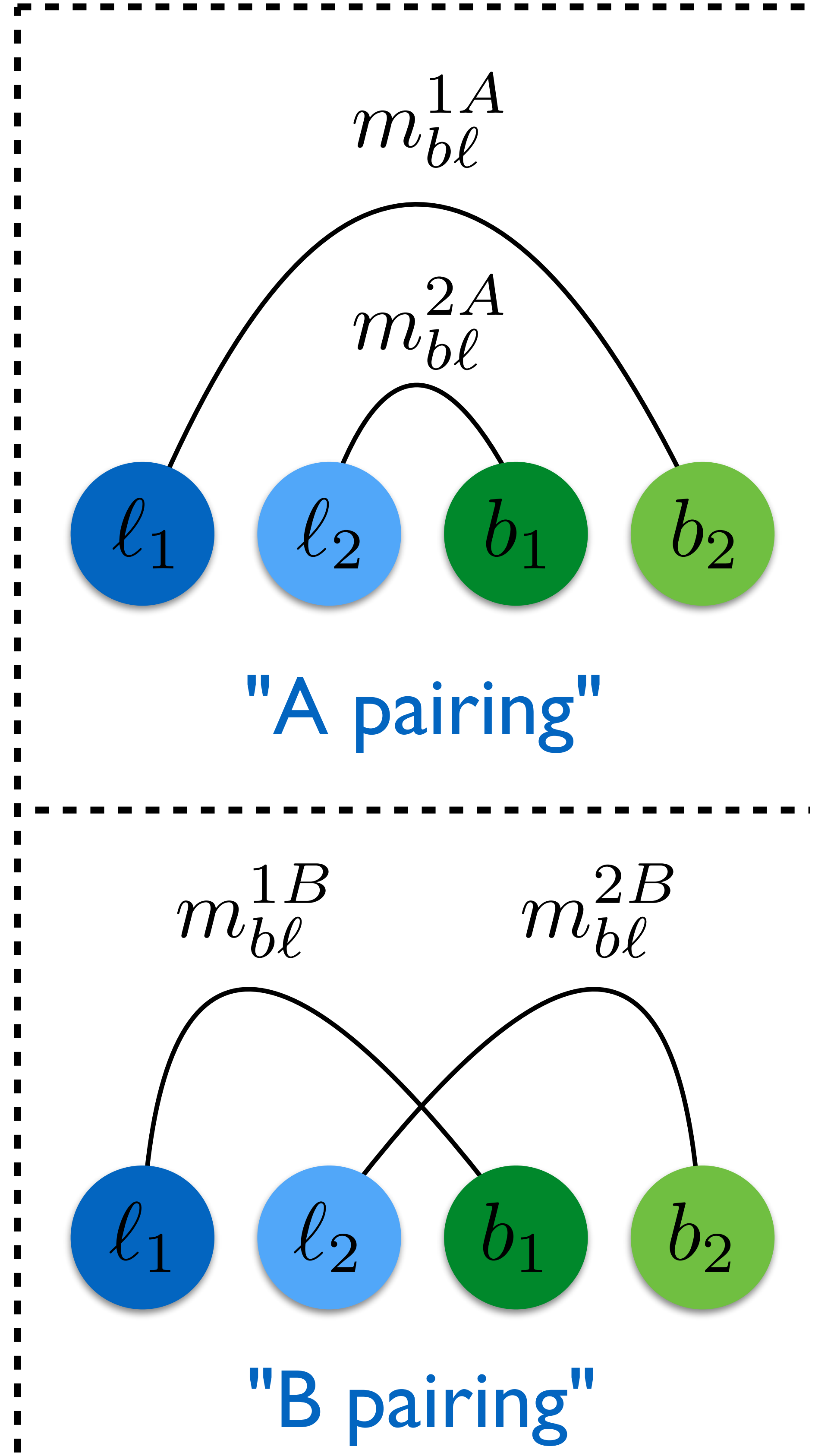
For ttbar events with correctly-identified b-jets and leptons

If the "A pairing" is correct:

Both $m_{b\ell}^{1A} < m_t$ and $m_{b\ell}^{2A} < m_t$

and thus $\max\{m_{b\ell}^{1A}, m_{b\ell}^{2A}\} < m_t$





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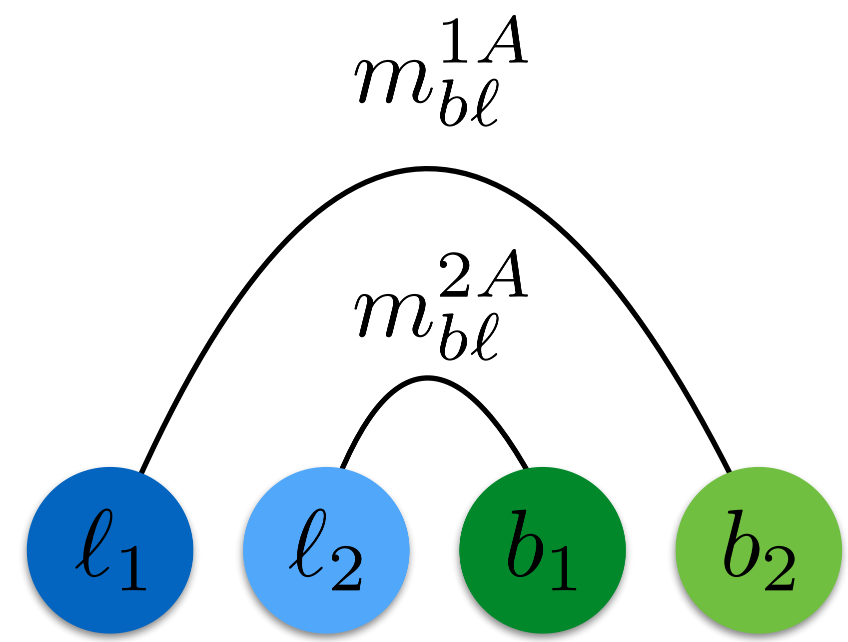
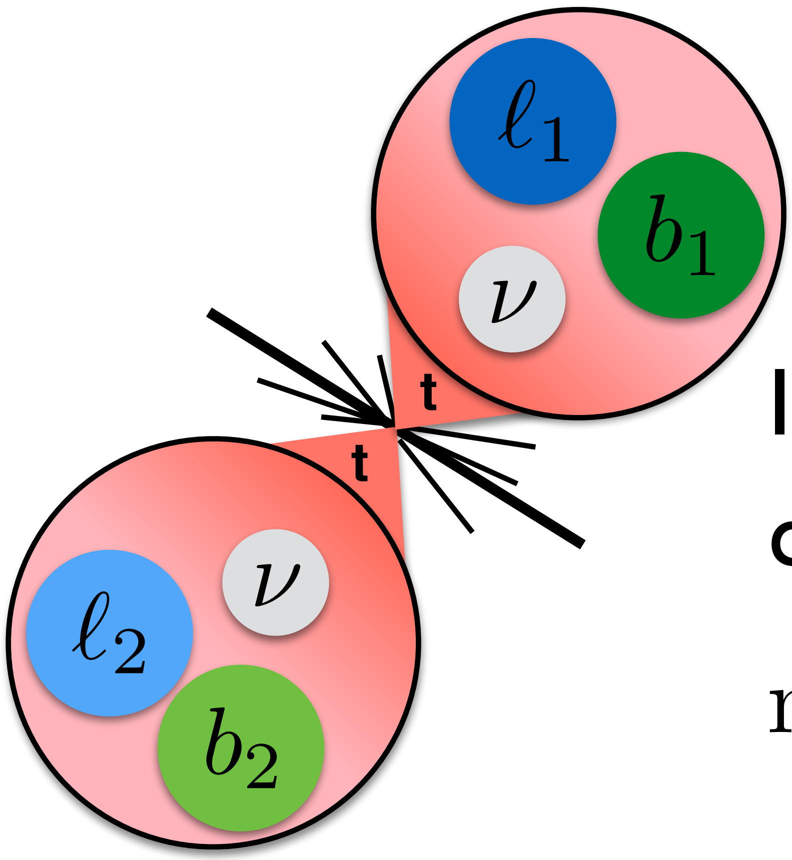
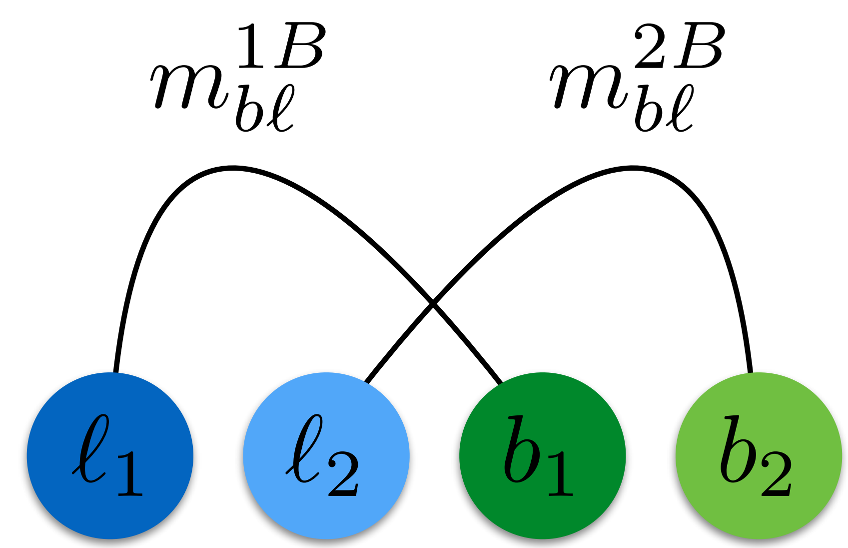


"A pairing"



If the "B pairing" is correct then must have:

$\max\{m_{b\ell}^{1B}, m_{b\ell}^{2B}\} < m_t$



"B pairing"

Analysis strategy

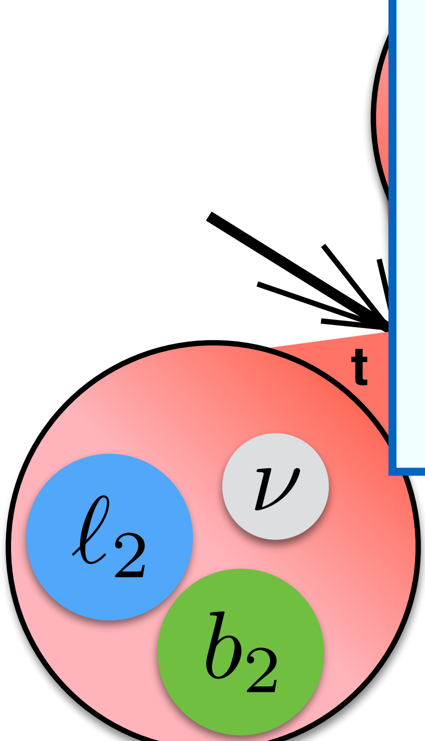
For ttbar events with correctly-
identified

Define $m_{b\ell}^{\mathrm{minimax}}$

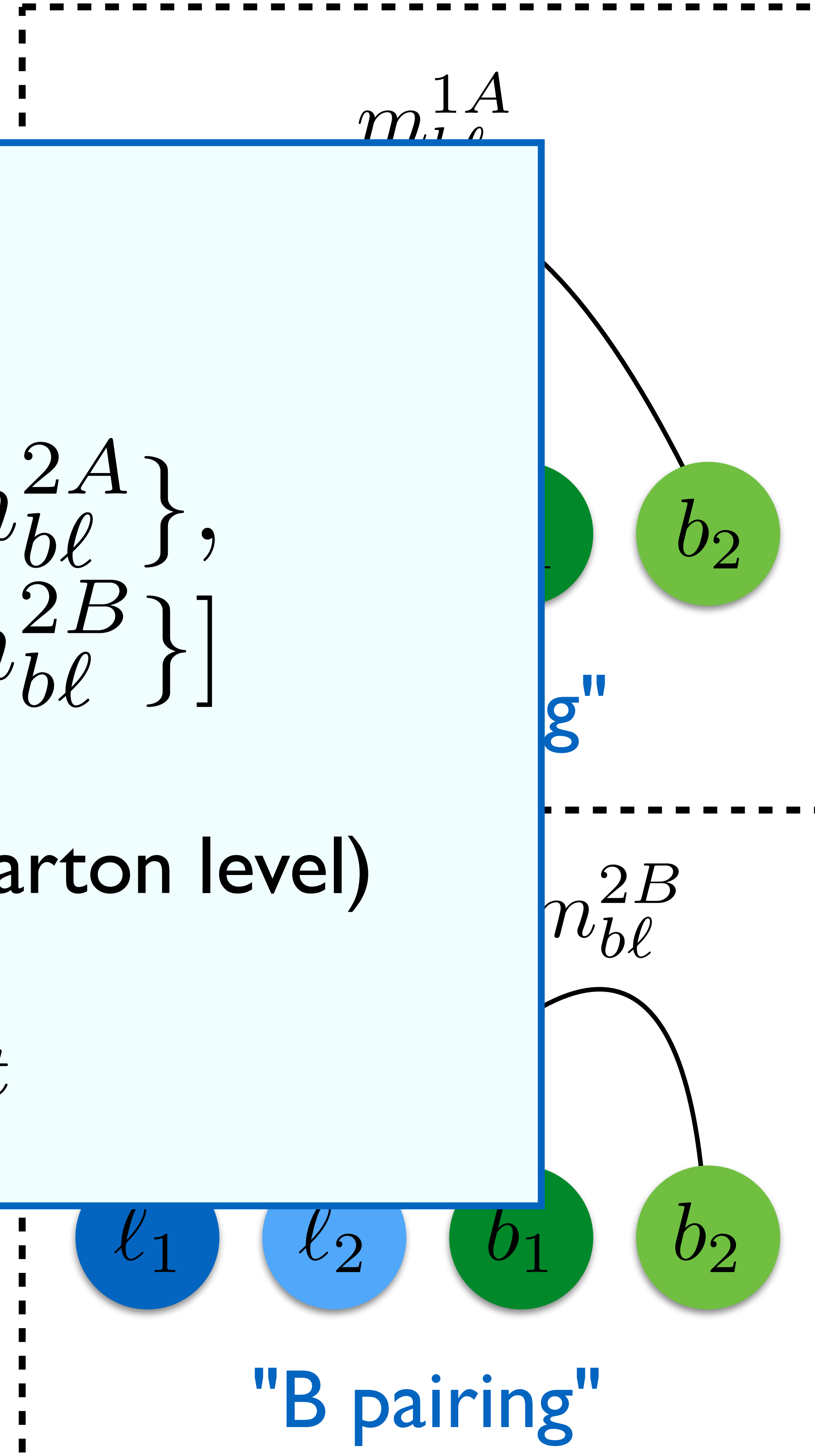
$$\min\left[\max\{m_{b\ell}^{1A}, m_{b\ell}^{2A}\}, \max\{m_{b\ell}^{1B}, m_{b\ell}^{2B}\}\right]$$

Then for ttbar events (at LO, parton level)

$$m_{b\ell}^{\mathrm{minimax}} < m_t$$



$$\max\{m_{b\ell}^{1B}, m_{b\ell}^{2B}\} < m_t$$



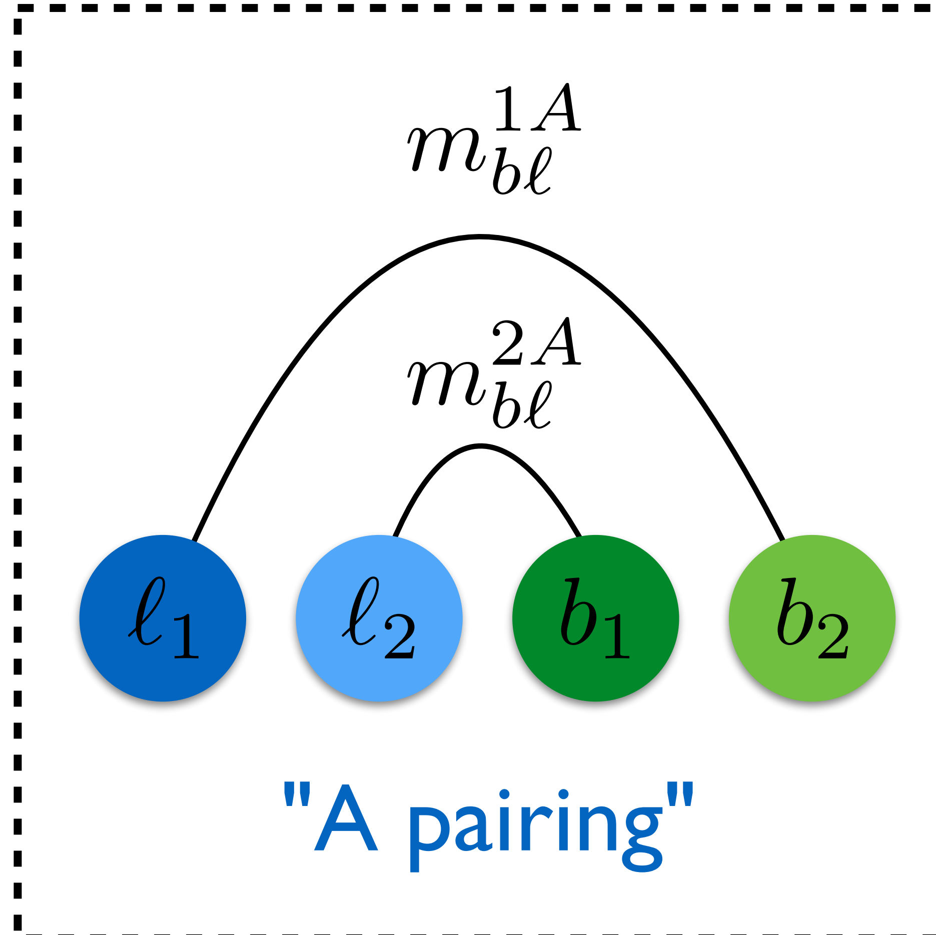
Analysis strategy

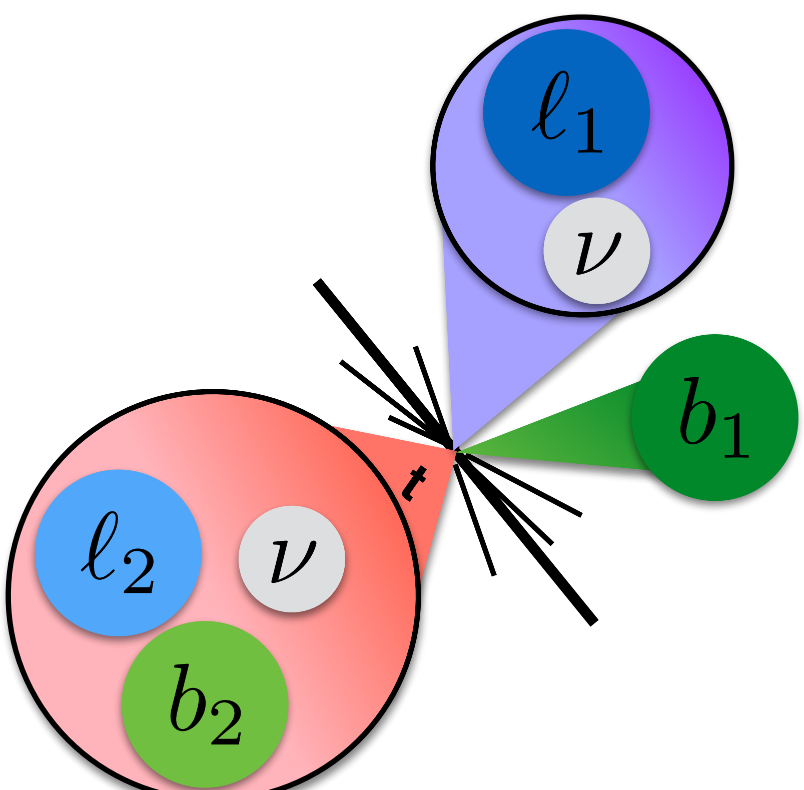
Consider now tWb events:

If the "A pairing" is correct:

One of $m_{b\ell}^{1A}$ or $m_{b\ell}^{2A}$ must be $< m_t$

But, can have $\max\{m_{b\ell}^{1A}, m_{b\ell}^{2A}\} > m_t$





Thus:

$$m_{b\ell}^{\text{minimax}} > m_t$$

Analysis strategy

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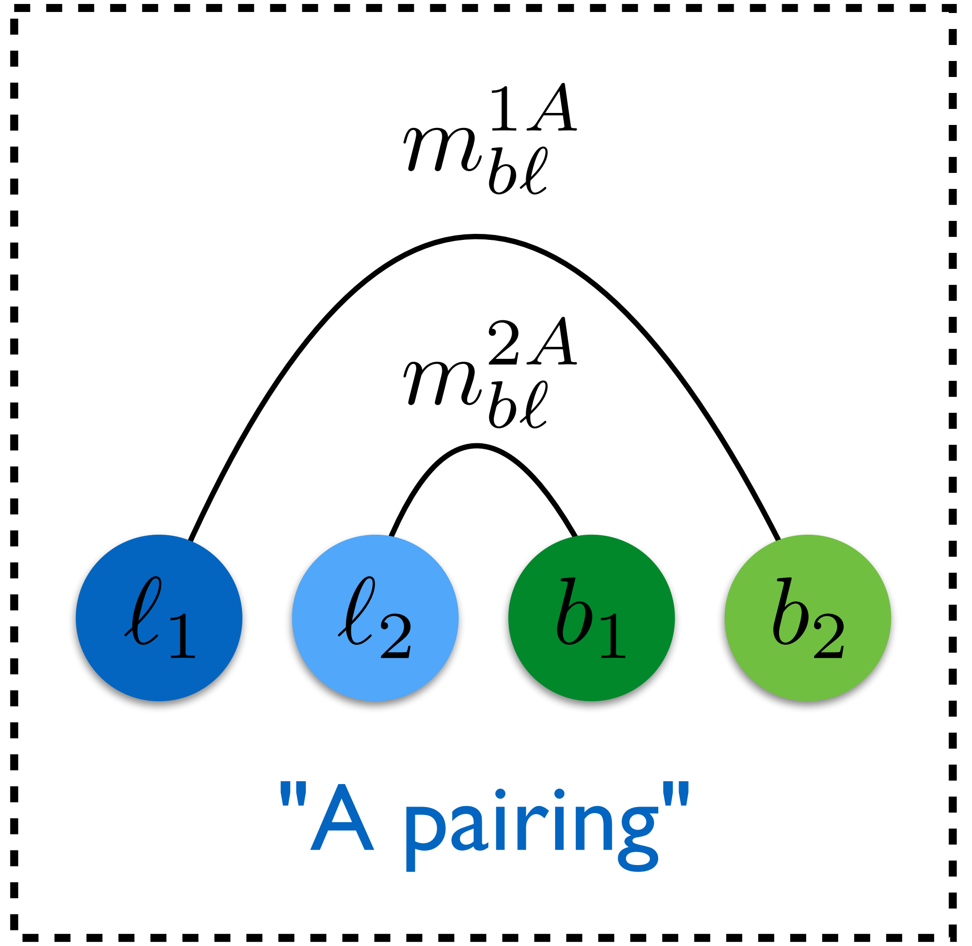
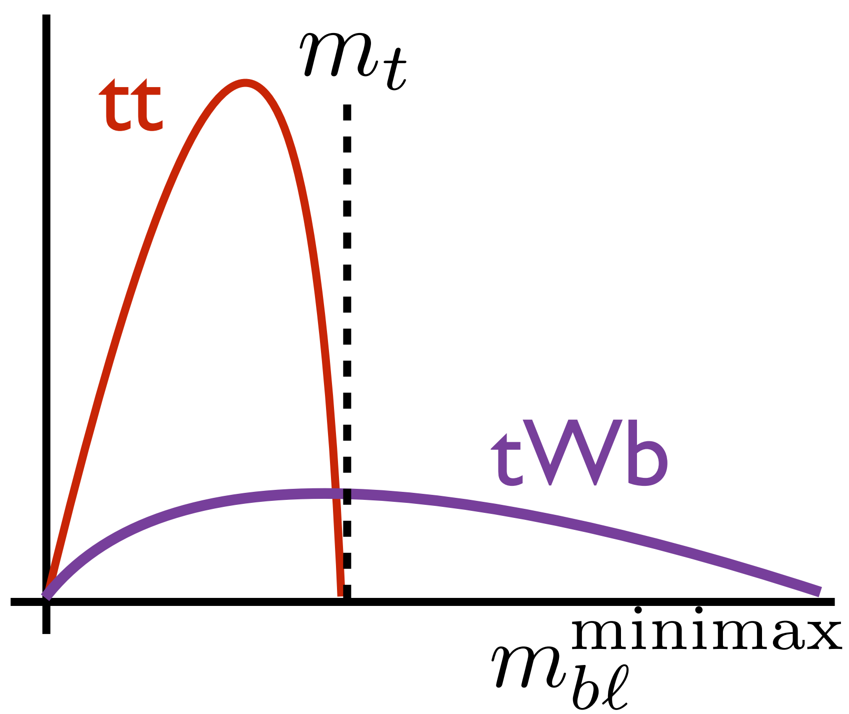


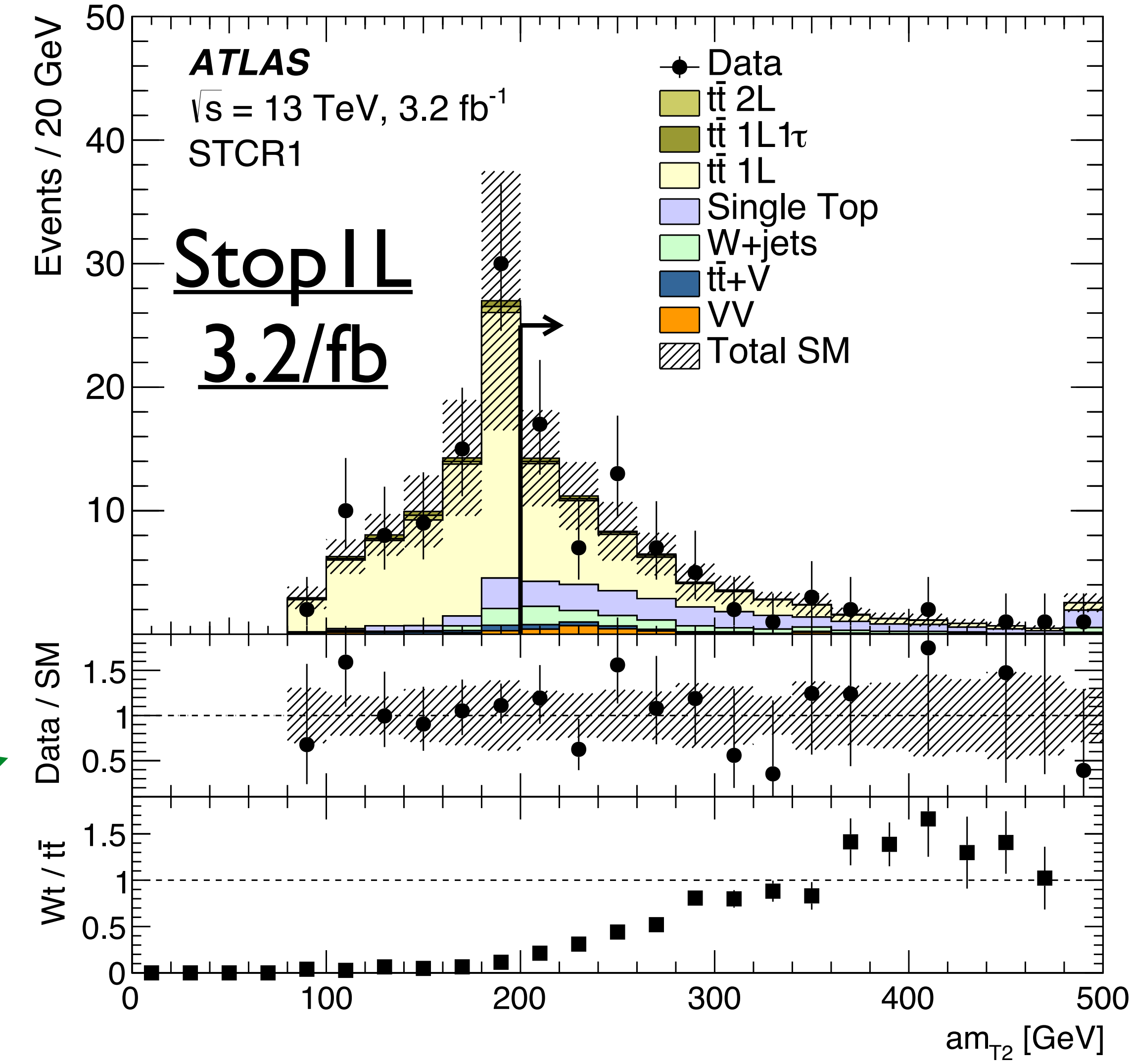


Thus:

$$m_{b\ell}^{\text{minimax}} > m_t$$

Inspiration from searches (aside)

- Stop searches suppress SM ttbar with similar tools
  - Inspiration for this measurement
- These "stransverse mass" variables (m_{T2}) are analogous to $m_{bl}^{minimax}$
  - Cut at top mass to remove ttbar, keeping SUSY signal



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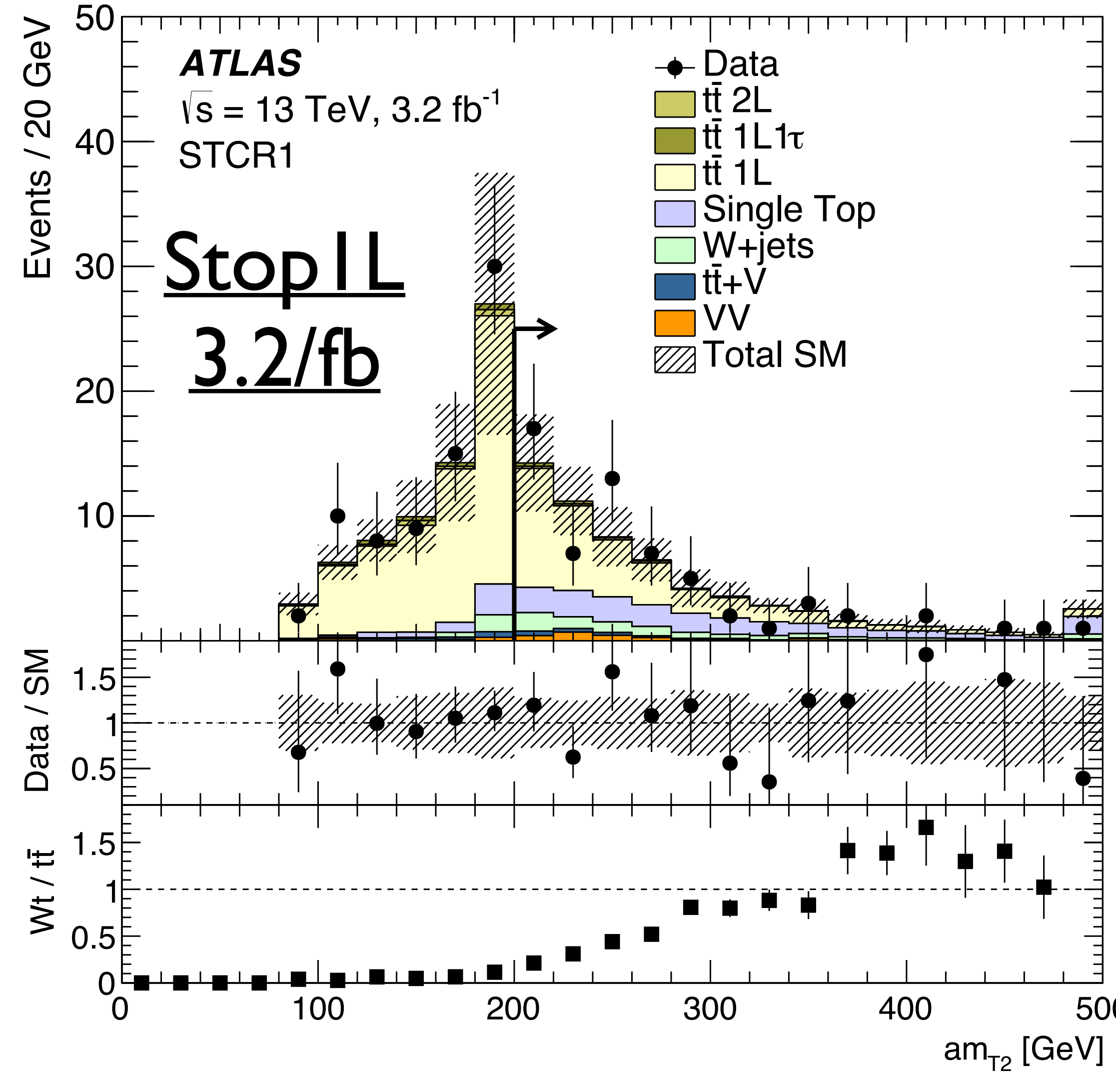
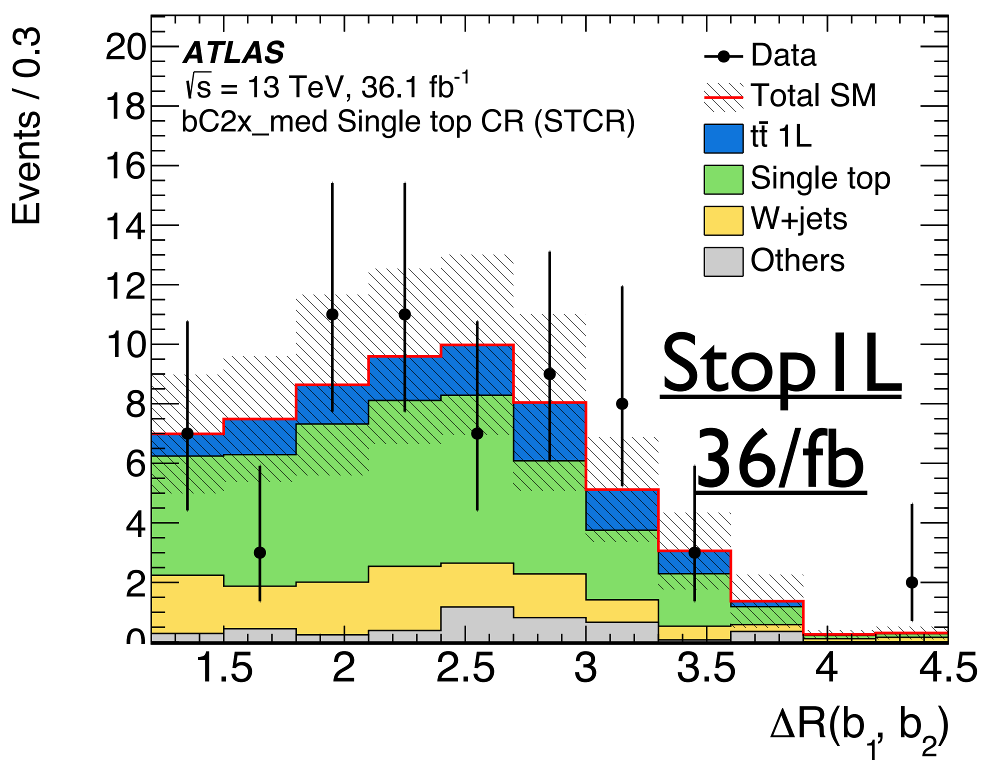
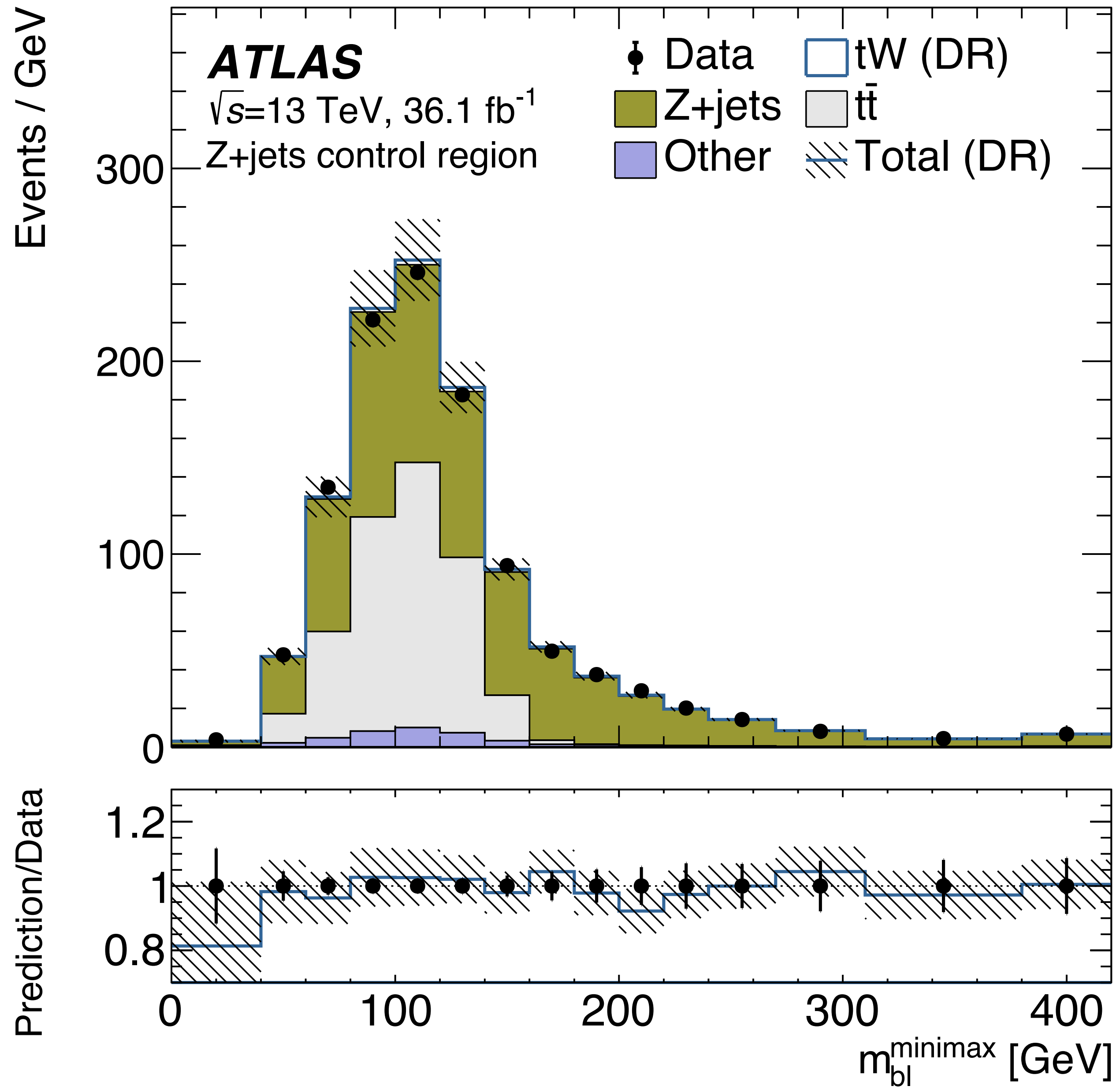




- Leads to regions highly enriched in tW
- Large DR / DS differences lead to a significant source of uncertainty!

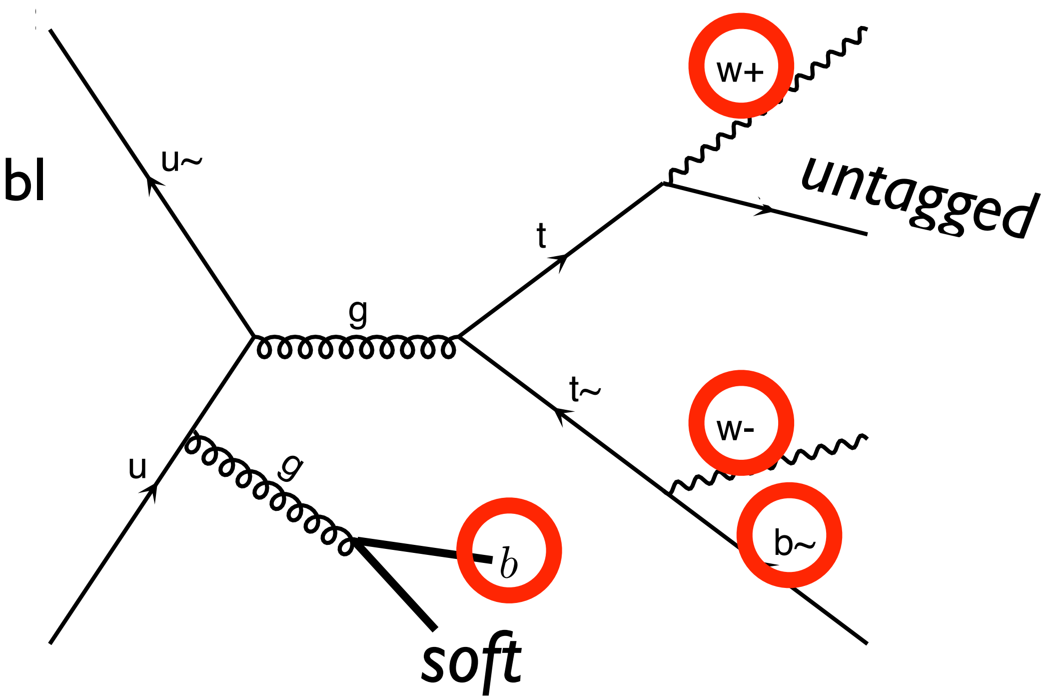
Selection, background estimation (I)

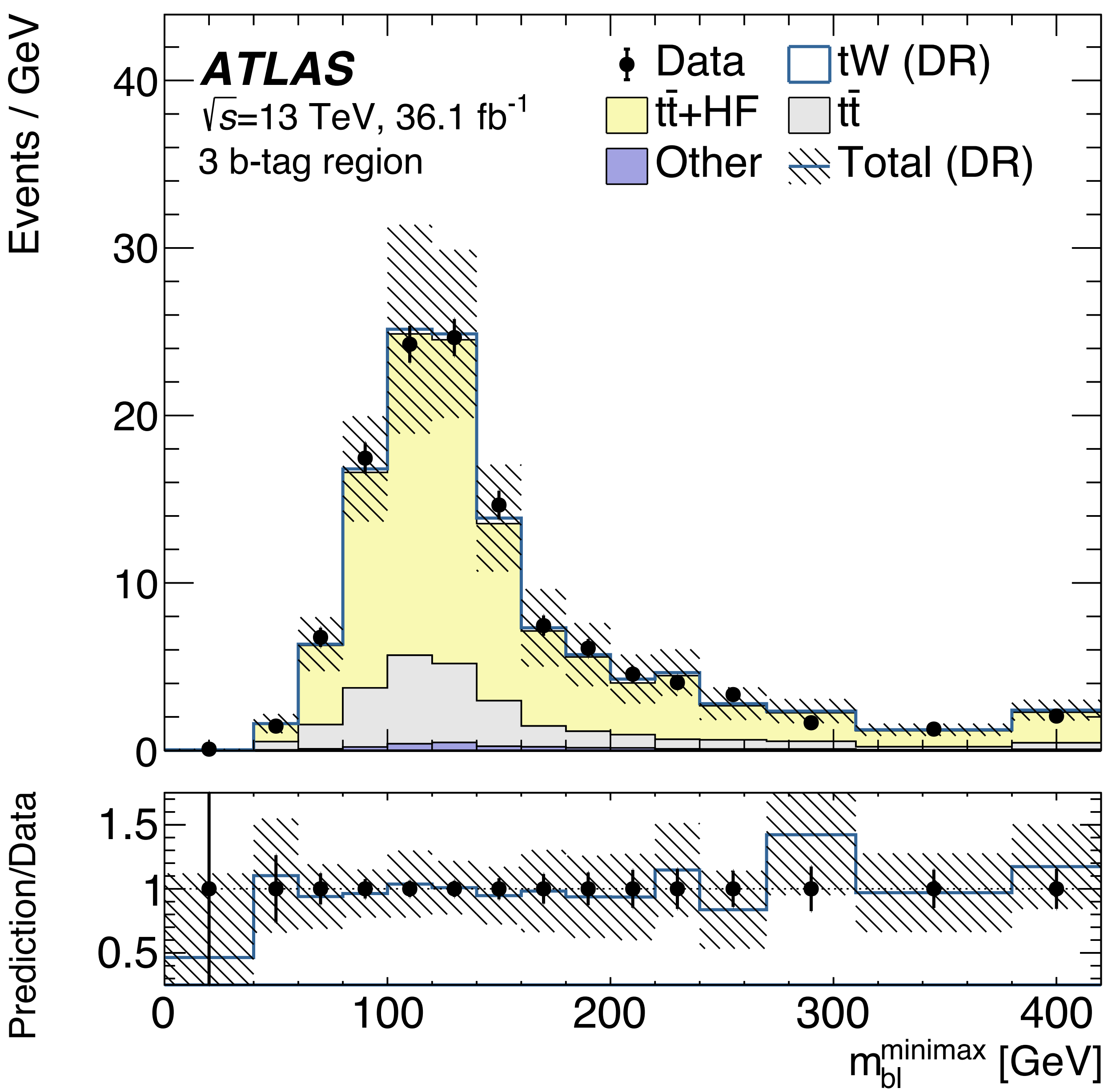
- Select events with two well-measured leptons and AntiKt4 jets
  - Require that 2 jets pass a tight b-tag requirement (60% eff)
    - Tight tag reduces ttbar with incorrectly tagged jets
- Z+b(b) background taken from data (define a m_{ll} CR)
  - For same-flavor events, require $|m_{ll}-m_Z| > 15$ GeV
- Select opposite-charge leptons
  - Fake lepton estimate from same-charge events
  - Negligible in signal region



Selection, background estimation (II)

- **ttbar + heavy flavor fakes the signal**
- 'wrong' jet tagged → ttbar with large m_{bl}
  - Veto events with third b-jet

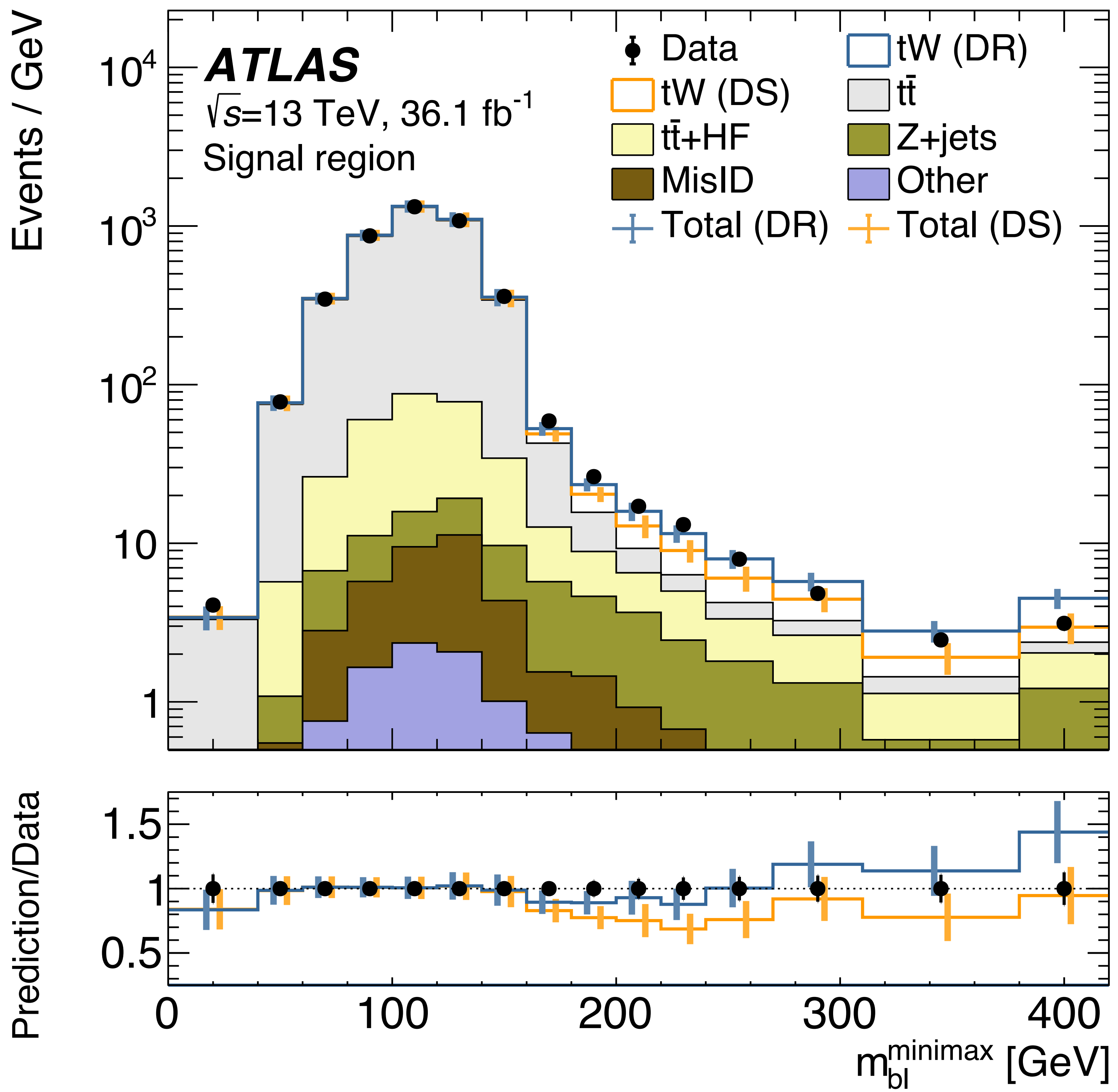




- tt+HF separated from the signal
  - Estimate using 3-tag events
- Modeling uncertainties enter only on (3b→2b) transfer factor
  - Check: $m_{bl}^{minimax}$ with leading b-jets is modeled well

Detector-level results

- Signal prediction from Powheg+Pythia6
  - ttbar is 'hvq'
- Predictions given for both the DR and DS schemes for tW
- High purity of tW events in the tail of the distribution



- To allow for additional comparisons, the data are unfolded to particle level…

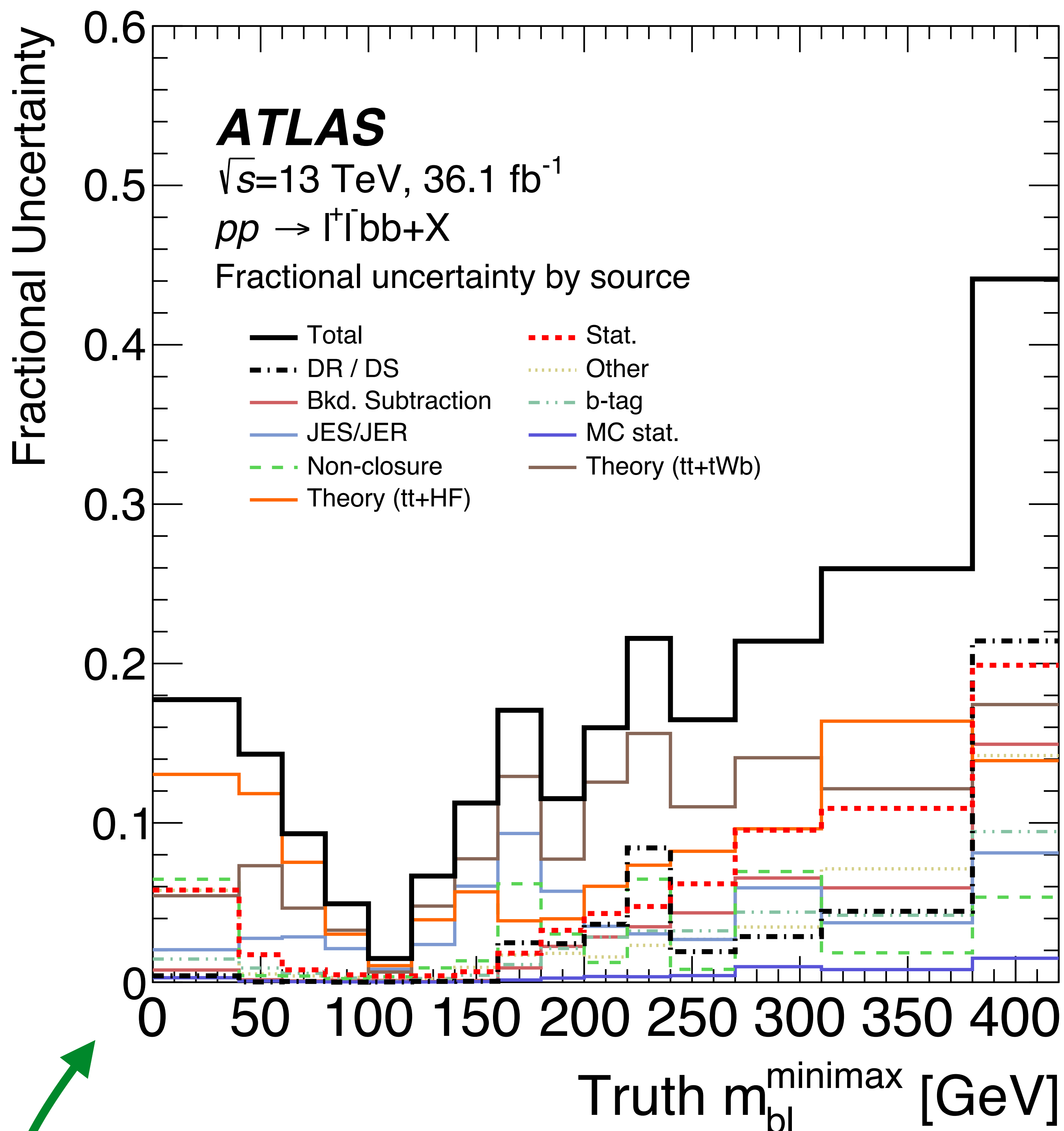
Particle-level selection

- Reminder:
  - **Signal process** to unfold is **tt+tWb combination**
  - all other processes are subtracted (including tt+HF)

- Particle-level selection is "the same" as at detector-level
  - Leptons "dressed" with FSR photons
  - Jets are built from stable truth particles (no muons or neutrinos)
    - b-tagged if a B-hadron is ghost-associated
  - Maintain all fiducial cuts as detector-level selection, including the m_{ll} window veto

- Unfold to particle level using the Bayesian iterative method

Uncertainties

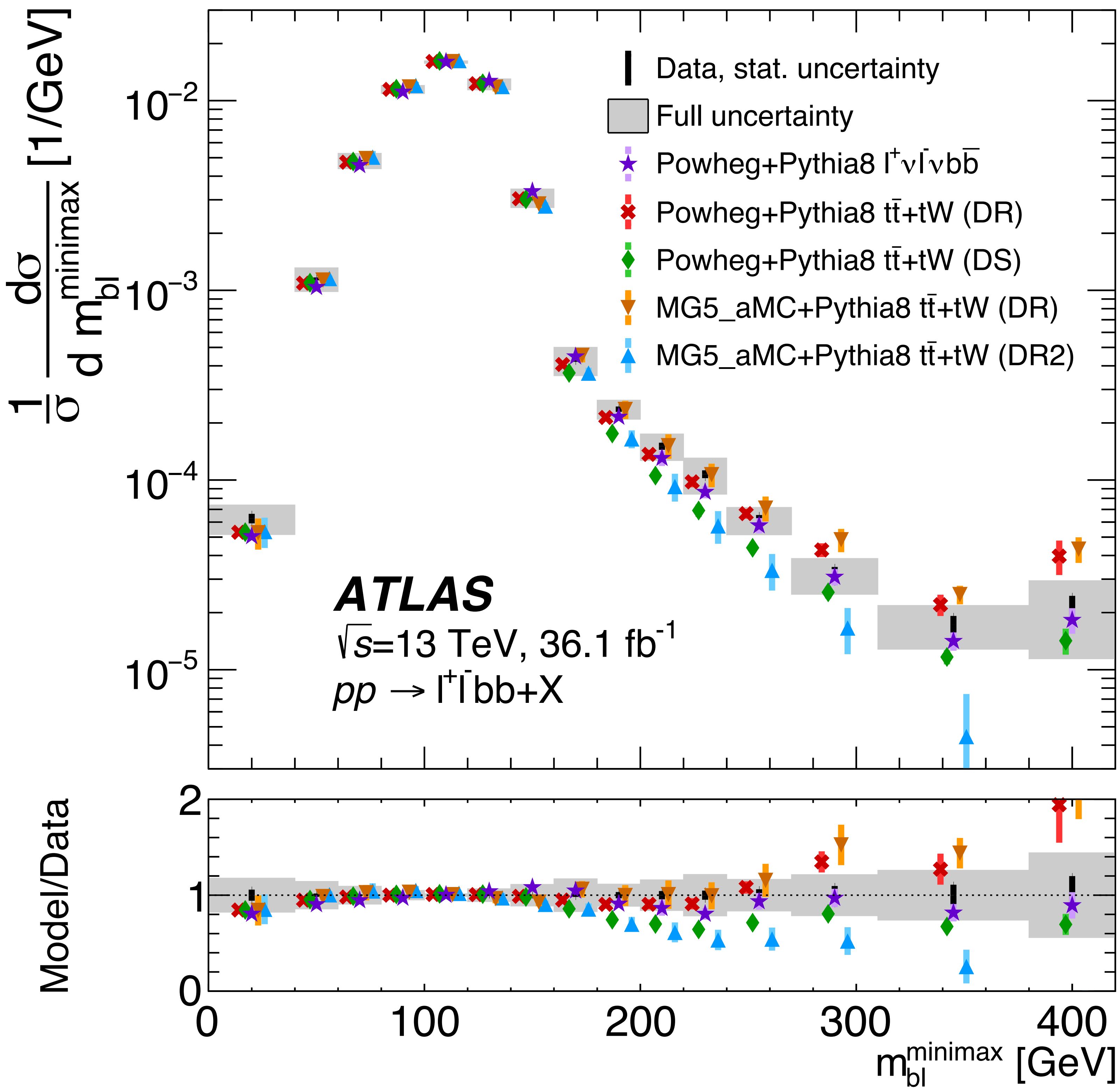


Uncertainty is on the unfolded, normalized distribution

- Uncertainties assessed by varying the model used to unfold the data
- Dominant contributions are due to top modeling
  - ttbar, tW, tt+HF
  - Difference due to unfolding with DR vs. DS is small!!
- Important experimental uncertainties: jet energy scale and b-tag efficiency
- Statistical uncertainties important in extreme bins

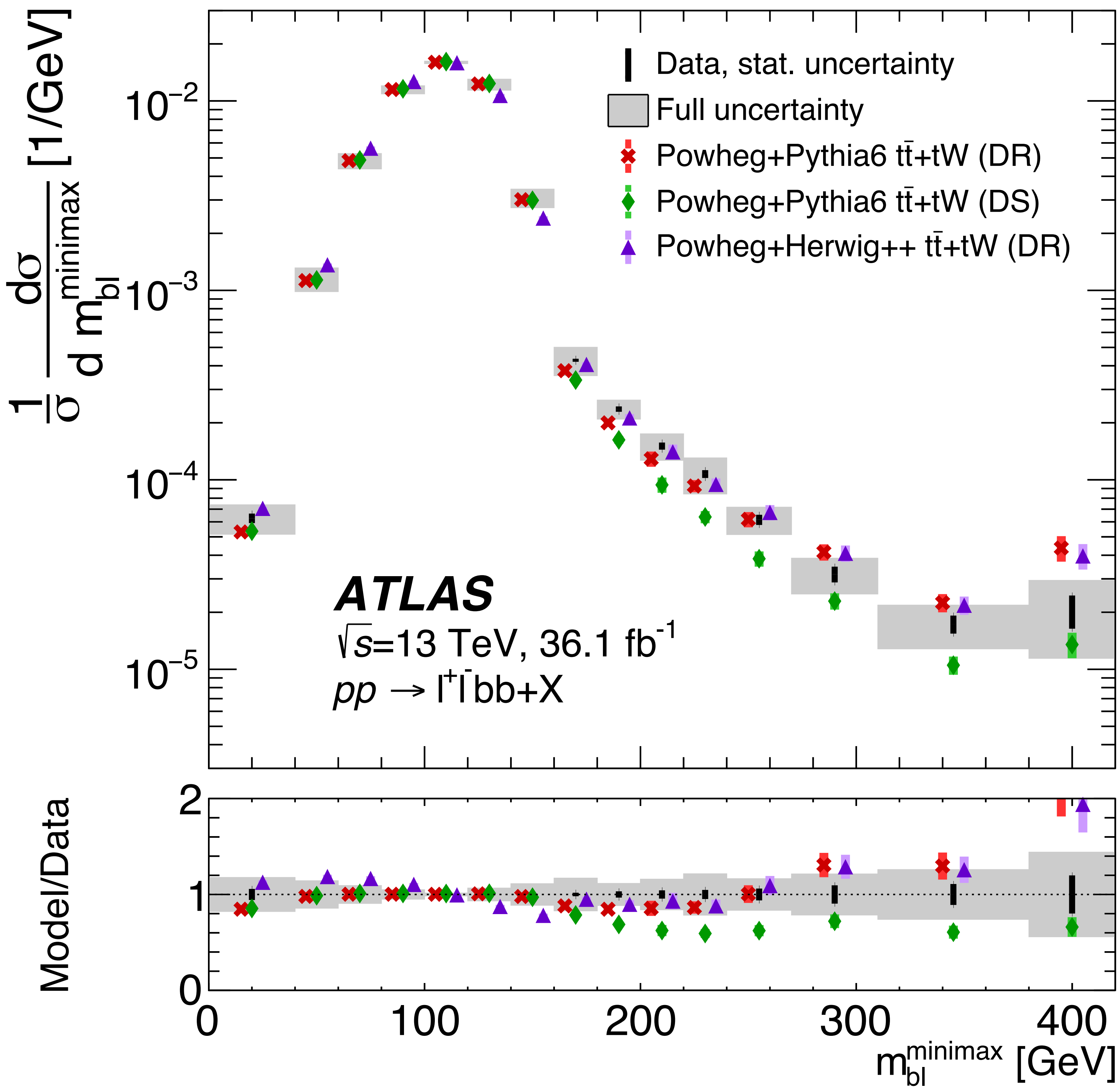
The unfolded results

- Powheg-Pythia8 lvlvbb describes the data well across the full spectrum
- Powheg+Pythia8 (hvq) models the ttbar core well, but…
  - In tail, the DR and DS predictions diverge
  - Consistent with data at ~2σ level
  - Difference brackets the data for most bins
- DR2 significantly under-predicts data in the tail



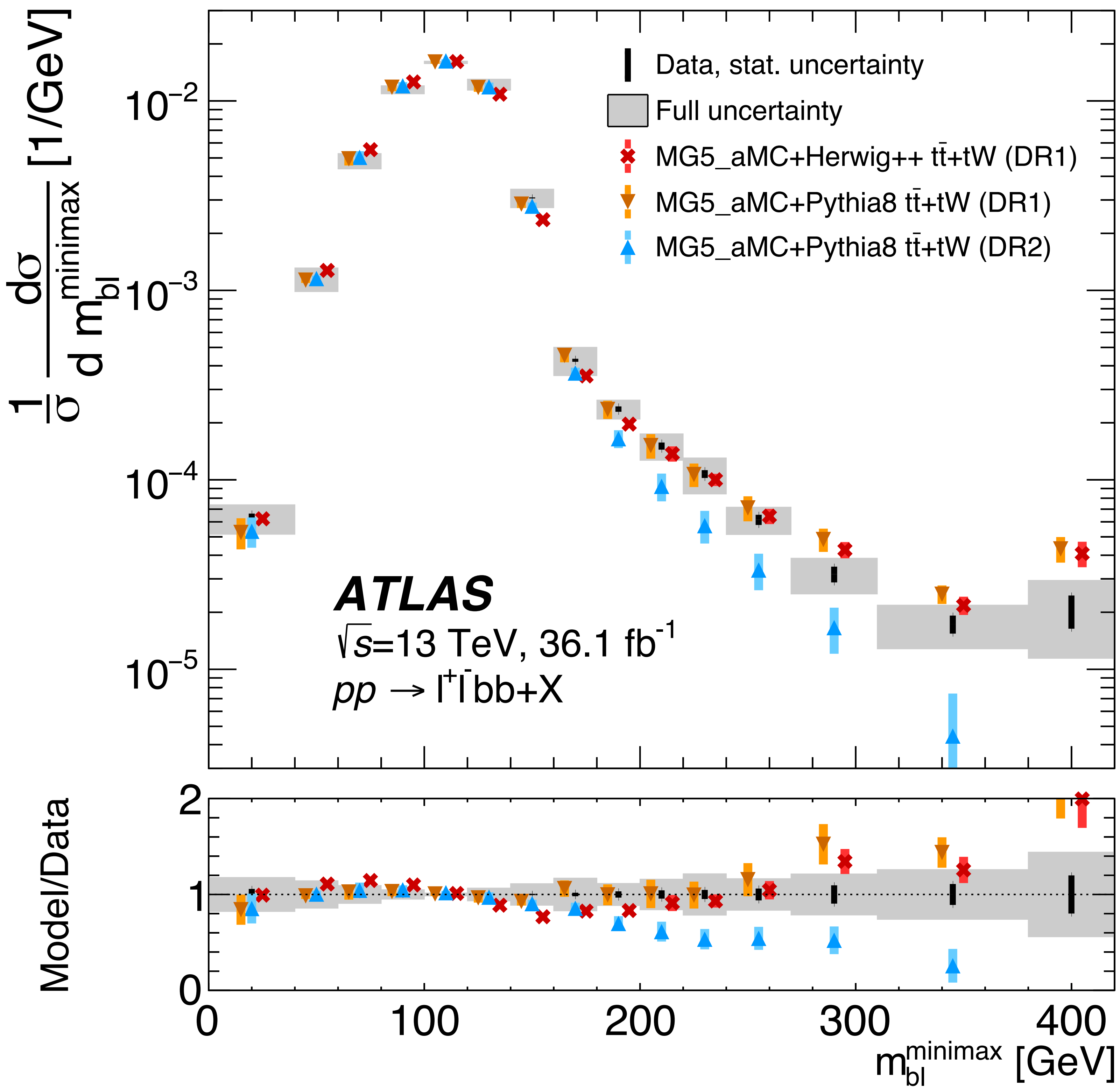
The unfolded results

- Additional comparisons:
- Powheg+Pythia6 DR and DS samples used for unfolding and all detector-level comparisons
  - Similar to the Pythia8 predictions
- Powheg+Herwig++ samples used to assess parton shower (PS) uncertainties
  - PS effects most significant below the top mass



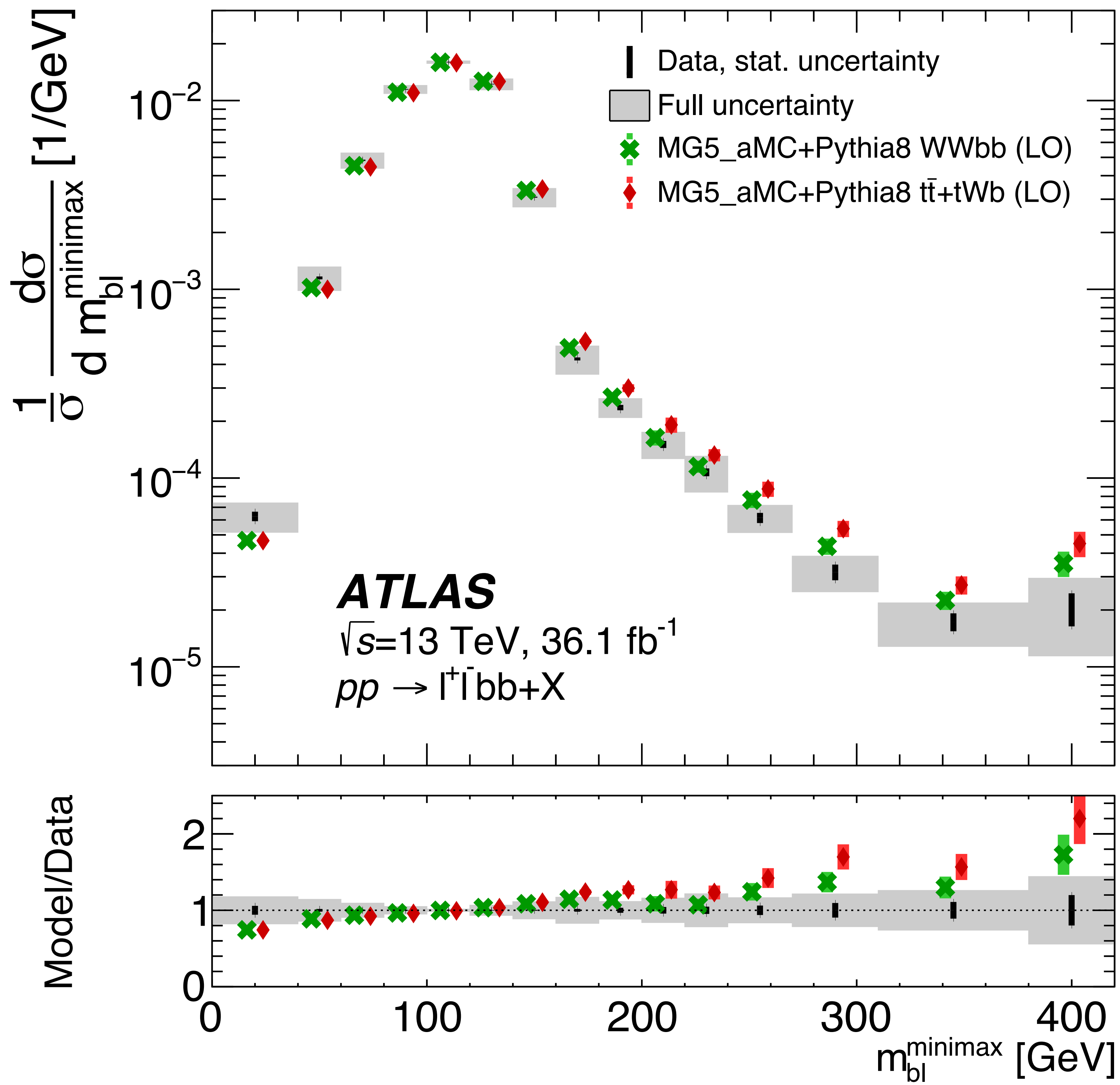
The unfolded results

- Additional comparisons:
- Madgraph samples allow for a direct comparison of DR1 versus DR2
- Poor modelling by DR2 due to interference scheme and not the choice of generator (MG vs. Powheg)
- Also shown:
  - Madgraph+H++ sample used for generator comparison



The unfolded results

- Additional comparisons:
- LO Madgraph samples generated with and without interference included
- Used by searches to estimate true effect size when DR/DS difference is large



Discussion and conclusions

- Present the **first measurement** of the combined **ttbar+tWb** process in a **region sensitive to their interference**
- While significantly different from each other, the DR and DS predictions are each within 2 sigma of the data
  - The DR/DS difference brackets the data in most bins
  - Assessing uncertainty from DR/DS is safe, if conservative
- The generator explicitly including interference (Powheg-Pythia8 lvlvbb) shows excellent agreement over the full spectrum
- This measurement provides a unique constraint on interference models and will guide future mode development and tuning

Backup

arXiv:0805.3067[hep-ph]