Cross section measurement in the process pp$\rightarrow$ WWbb with the ATLAS experiment

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IMPRS Young Scientist Workshop
24.11.2023

ATLAS EXPERIMENT

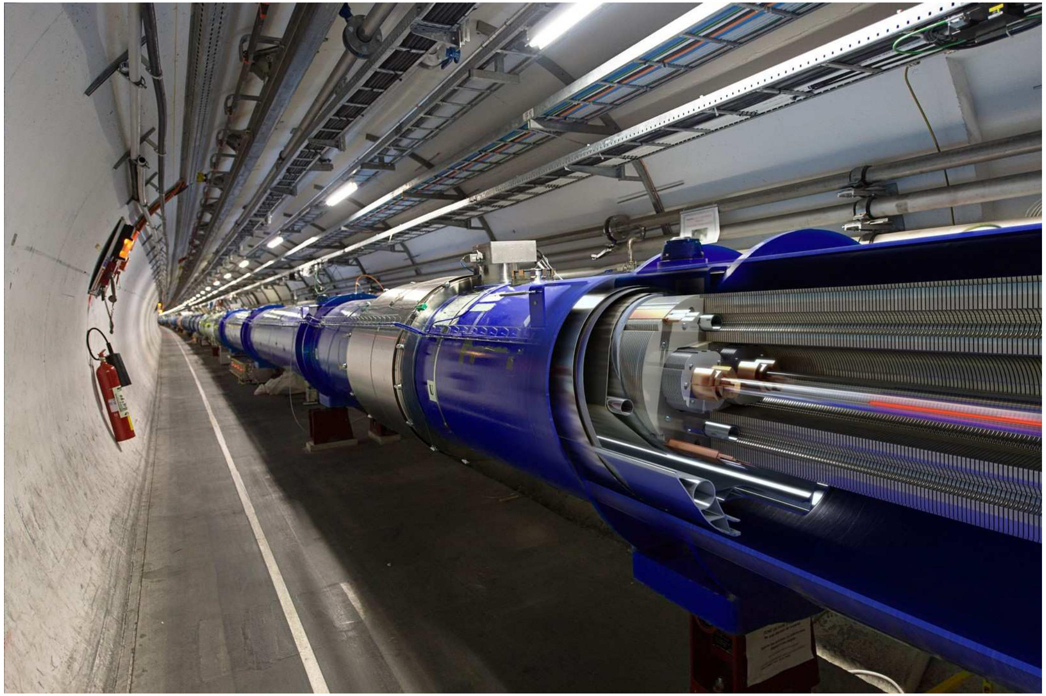
MAX-PLANCK-INSTITUT FÜR PHYSIK

Large Hadron Collider

Large: Circumference 27 km, up to 100 m below surface

Hadron: Accelerates protons (and lead ions) to up to 7 TeV

Collider: 4 interaction points



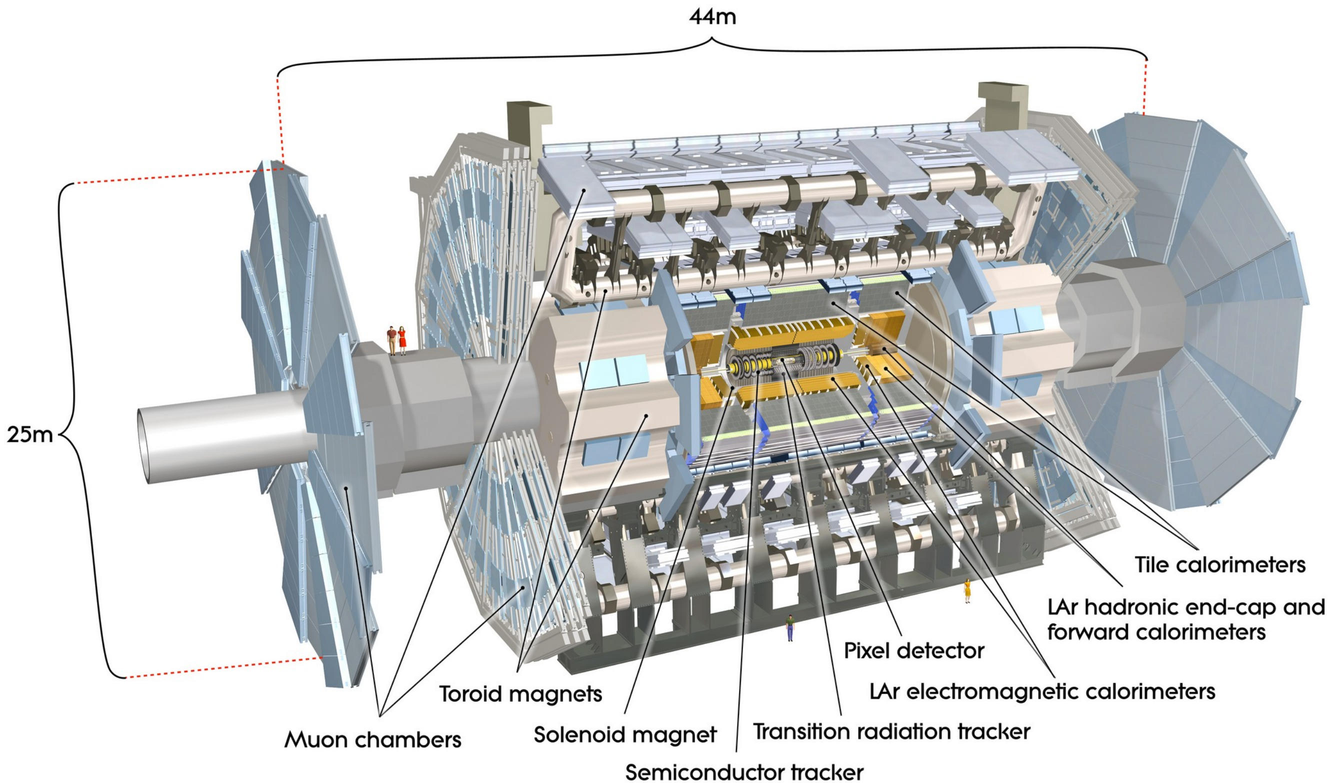
ATLAS Experiment

Collider experiment @ LHC

- Collisions of proton bunches
  - $\sqrt{s}$ = 13 TeV
  - Every 25 ns
  - Up to 50 pp collisions at a time (pile up)

- **Layered detector design with**
  - Tracking detectors
  - Calorimeters (electro-magnetic and hadronic)
  - Muon chambers
  - Solenoid magnet

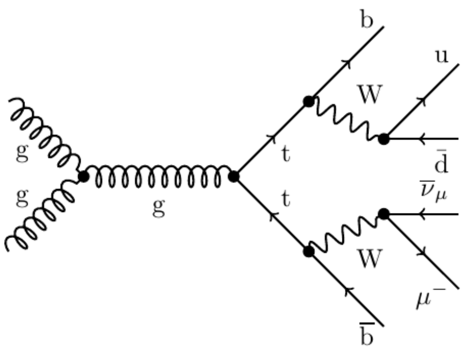
- **We collide partons from the proton**
  - Initial momentum along beam axis not known
  - Measure transverse momentum



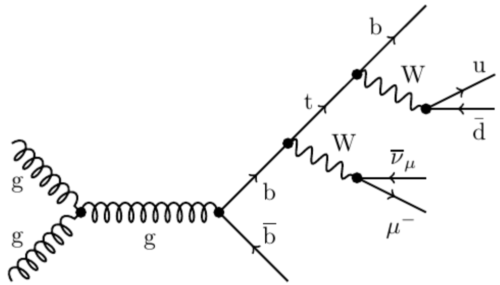
What contributes to *pp* → *WWbb*?

WWbb **is not just top quark pair production ...**

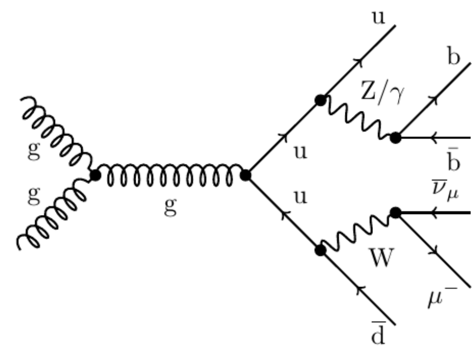
tt-production



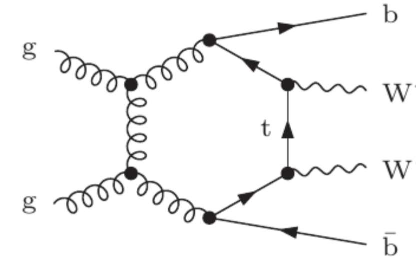
tW process @NLO



EW processes (no top)



Hexagon diagrams



→ **All of these diagrams interfere!**

Motivation of the analysis

- Details of *WWbb* modeling (interference) are relevant for *tt* & top-quark mass analyses, *SUSY* searches, etc..
- *WWbb* is also an interesting process on its own
  - Comparison of the data to fixed-order-predictions
  - Sensitivity to top mass m_t and width Γ_t, α_s, PDFs, ...

Reconstruction of one event

Matrix element picture modified by parton shower and hadronisation

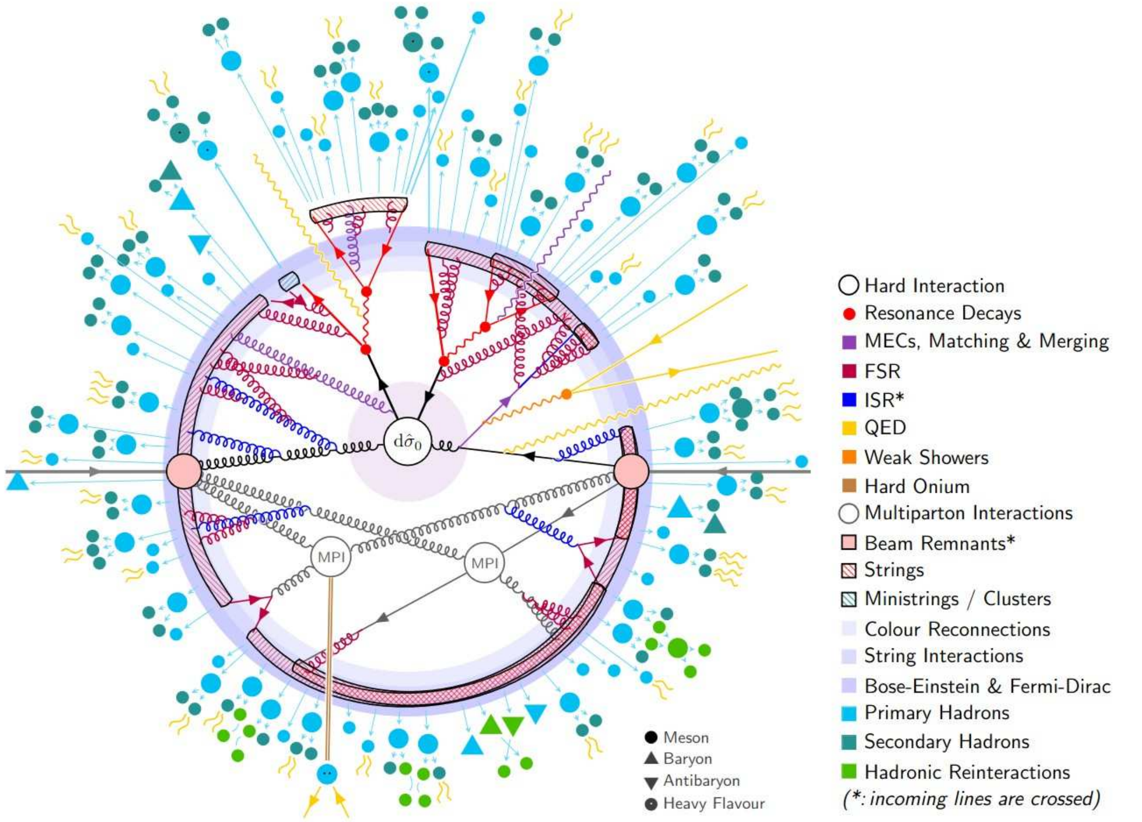


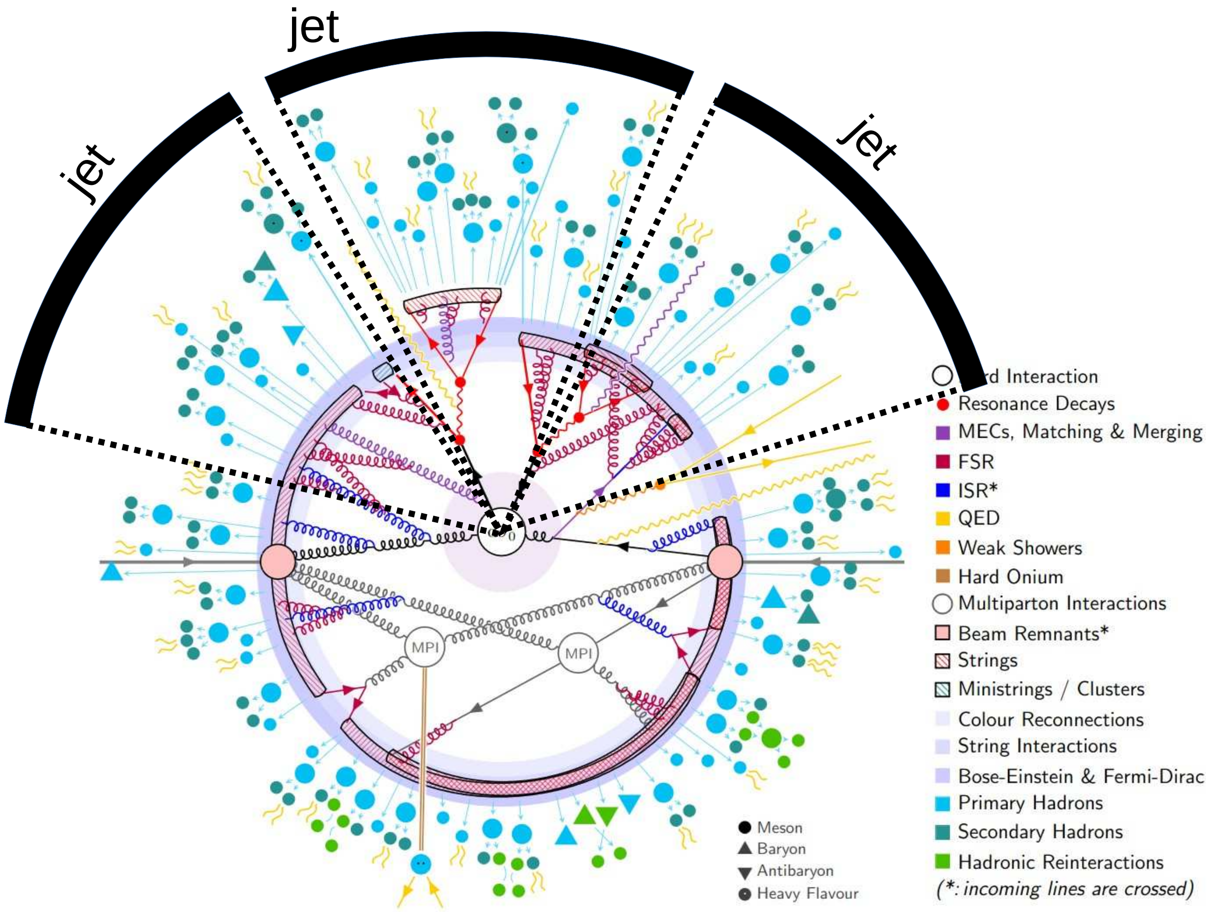
Figure taken from Bierlich et al. arXiv:2203.11601v1

Reconstruction of one event

Matrix element picture modified by parton shower and hadronisation

- Reconstruct jets as approximation of ME
- Which objects are of interest?
  - → Focus on hard (high p_T) objects
- ATLAS: anti-k_t jets with $R=0.4$

→ Instead of quarks we measure jets



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WWbb decay channels

There are three possible *WWbb* final states

- The two b quarks will form jets in the detector

- Both W bosons decay hadronically
  + High statistics
  - Large background contribution
  - Difficult jet assignment

- Both W bosons decay leptonically
  + Clean sample (small background contribution)
  - Lower statistics
  o Covered by another analysis team

- One W boson decays leptonically, the other one hadronically
  + Good tradeoff between statistics and background
  → This is what we are interested in!

W^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	(MeV/c)
$\ell^+\nu$	[b]	(10.86 ± 0.09) %		–
$e^+\nu$		(10.71 ± 0.16) %		40189
$\mu^+\nu$		(10.63 ± 0.15) %		40189
$\tau^+\nu$		(11.38 ± 0.21) %		40170
hadrons		(67.41 ± 0.27) %		–

Figure taken from M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018) and 2019 update

WWbb in the single lepton channel

Event selection

- Exactly one lepton (*e* or *μ*)
- „Missing transverse energy“ (due to the Neutrino)
- Identify two jets originating from *b* quarks (so-called *b*-tagging)

  → Large cross section and high statistics
- Plot shows data-MC comparison

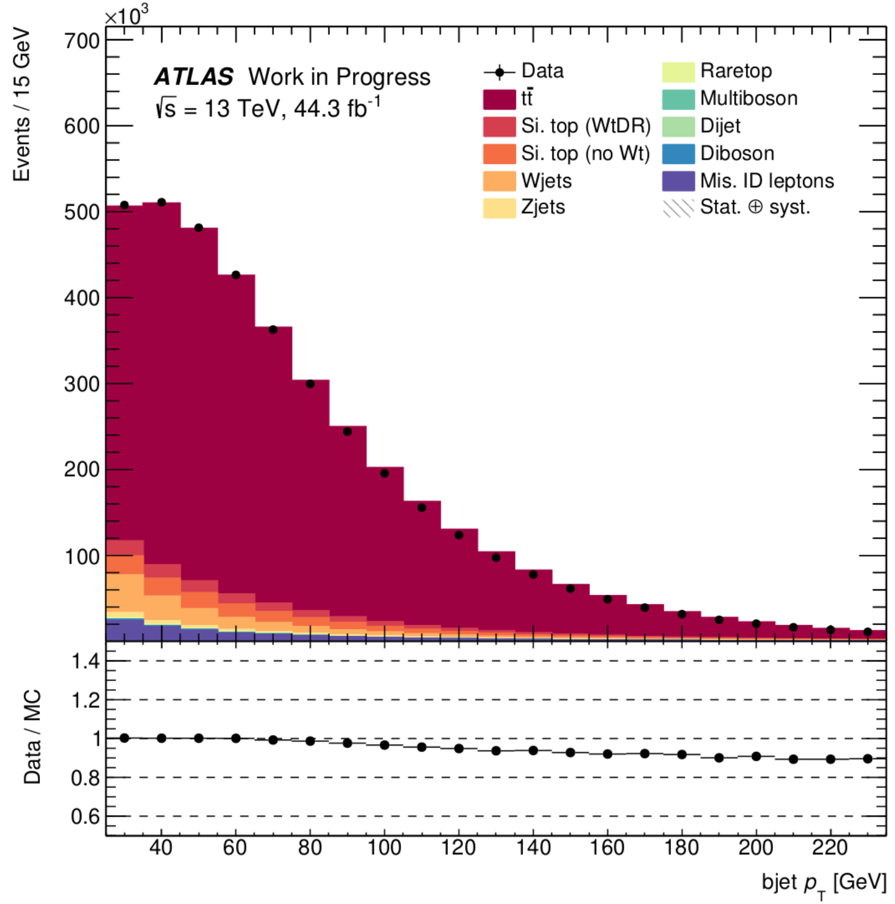
  → MC simulation includes signal and background processes

  → Background contribution is small

What about the second W-boson?

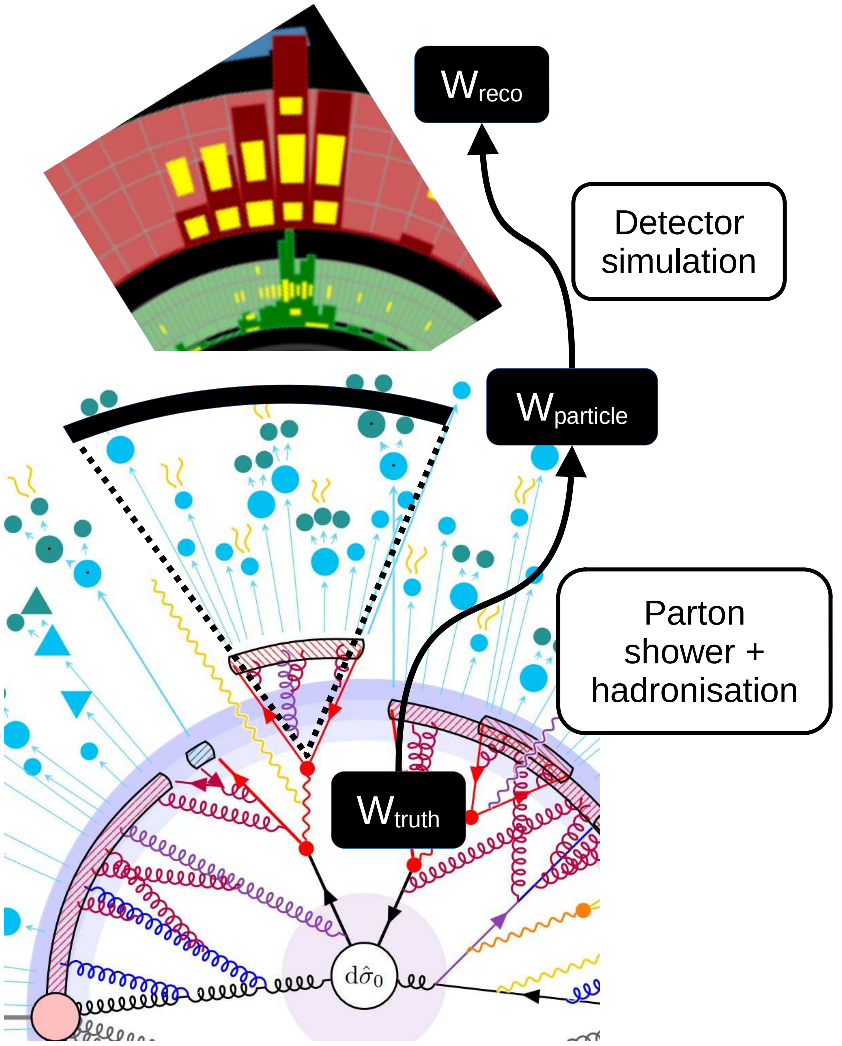
→ Decays into quarks that turn into jets

→ Reconstruct W_{had} from light (non-*b*) jets



Hadronic *W boson*

- For this study: *tt* events only
- *W* boson decays into exactly two quarks
  → Reconstruct *W* from two jets?
- Compare the true *W* (before the decay) to the particle level *W* (after hadronisation and clustering) and the detector level *W* (after detector simulation)



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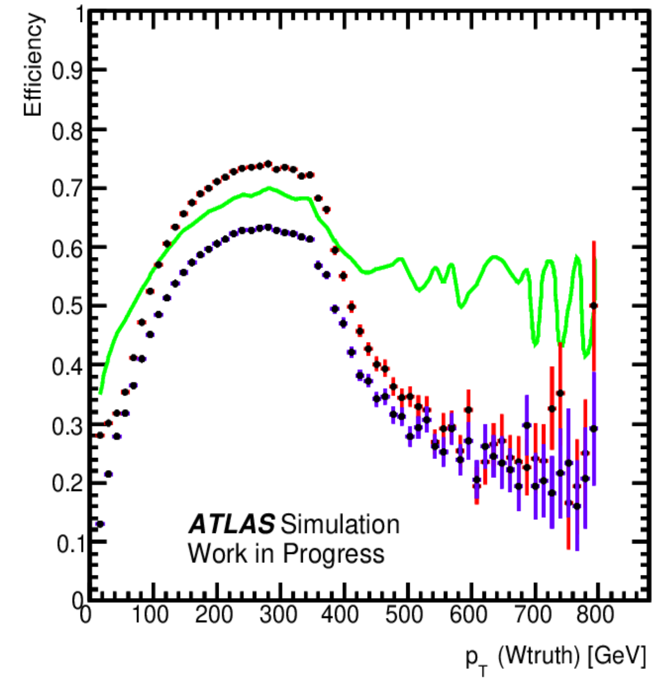
  → Reconstruct *W* from two jets?
- Compare the true *W* (before the decay) to the particle level *W* (after hadronisation and clustering) and the detector level *W* (after detector simulation)
- Calculate invariant mass of all 2-jet combinations
  → Select the pair closest to the *W* mass (80.4 GeV)
- Apply same reconstruction on particle and detector level
- Consider them matched when

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.5$$

- Efficiency = $\frac{\#\text{Matched}}{\#\text{All}}$

Select 2-jet candidate closest to *m(W)*



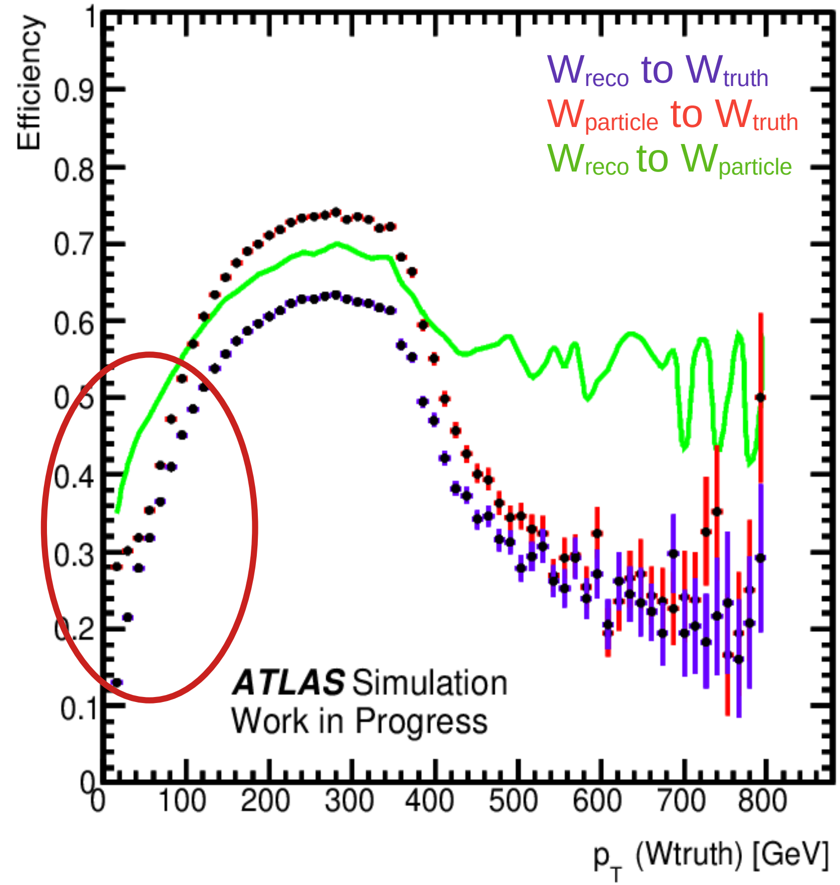
Compare the various levels

- W_{reco} to W_{truth}
- $W_{particle}$ to W_{truth}
- W_{reco} to $W_{particle}$

Why is the performance so poor?

Low p_t range

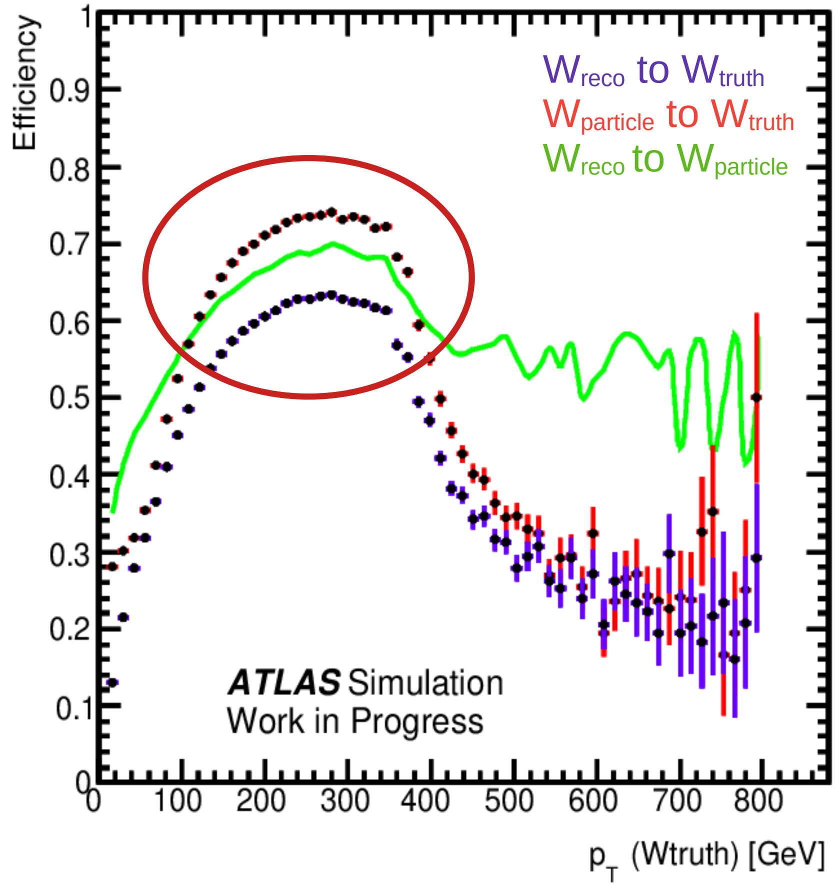
- Cut applied in pre-selection:
  $p_t(jets)$ > 20 GeV
- Low $p_t(W)$ → low $p_t(jets)$ → Jets from the W may not pass the p_t cut



Why is the performance so poor?

Medium p_t range

- Efficiency limited by badly reconstructed events
  → Better selection criterion?
  → Apply cuts on the reconstructed *W*?



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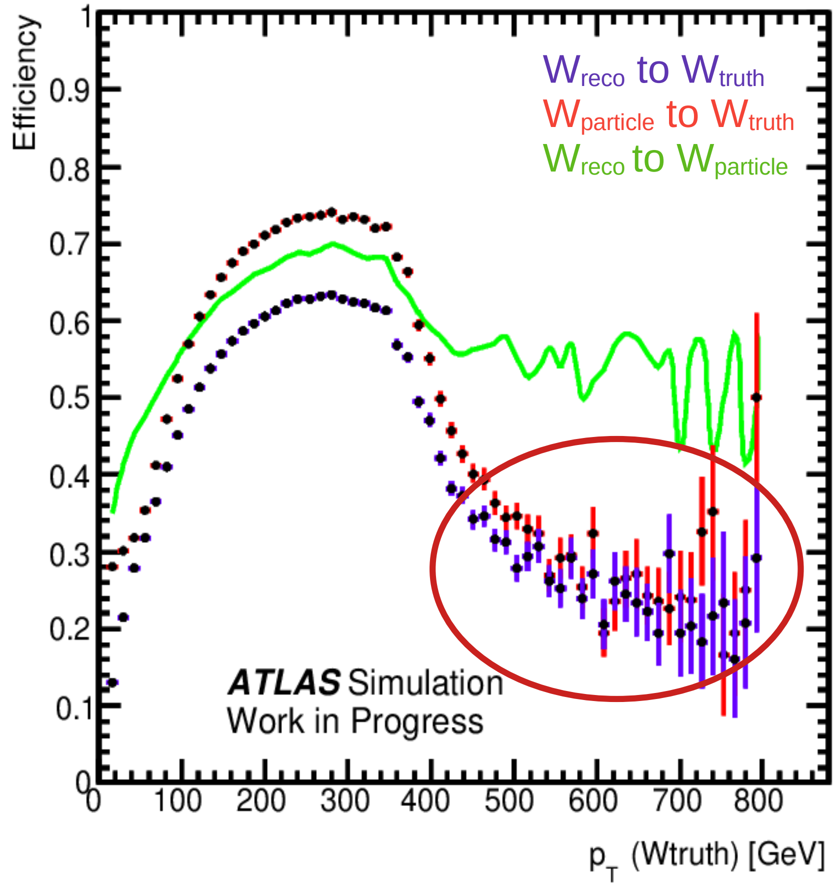
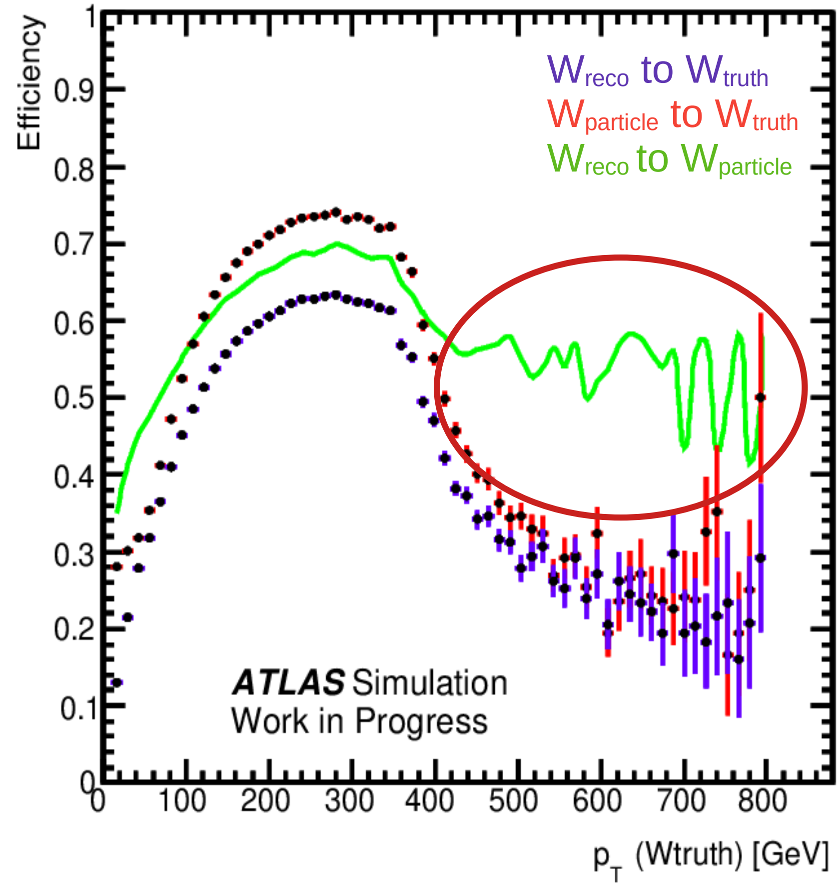


High p_t range (boosted)

- At high $p_t(W)$ the angle between the decay products is small
  → They may be clustered into one jet
- Allow also reconstruction from a single jet?

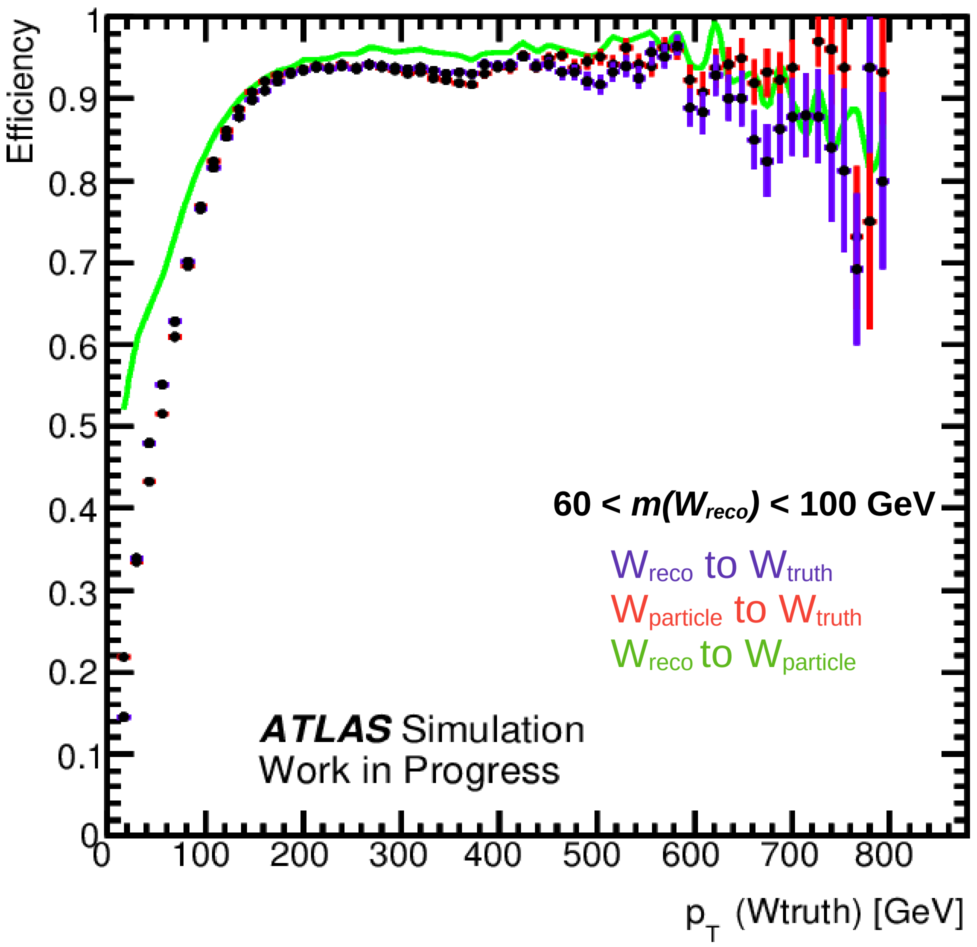
Why is the performance so poor?



Why is the green line so different?

- Compares reco to particle level
  → No indication if the reconstructed object is indeed a *W*
  → Ignore this line for now
  → Focus on blue curve instead

W_{had} - optimised reconstruction



Preselect three objects

- Leading jet (highest p_T)
- Subleading jet
- Sum of leading and subleading jet 4-vectors

↓

Calculate the invariant mass of all three objects

↓

Select object. with mass closest to m(*W*)

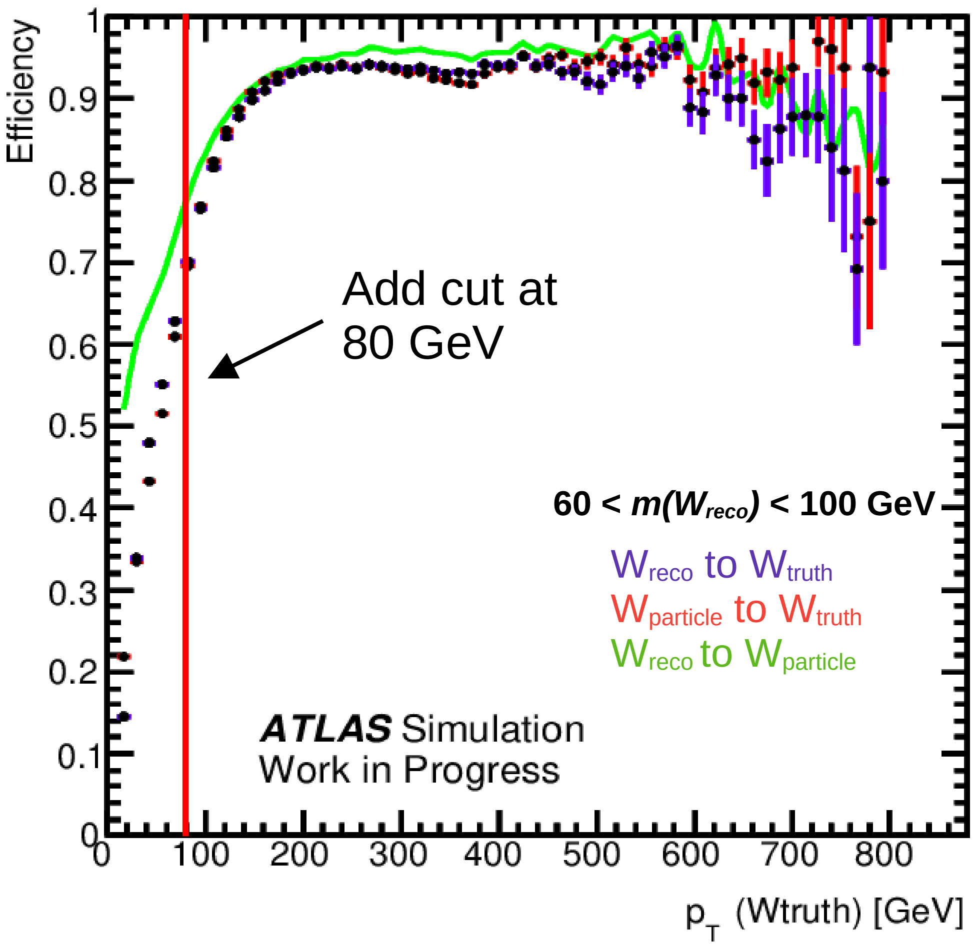
↓

Check if 60 < $m(W_{reco})$ < 100 GeV is fulfilled

↓

This is the reconstructed *W*!

W_{had} - optimised reconstruction



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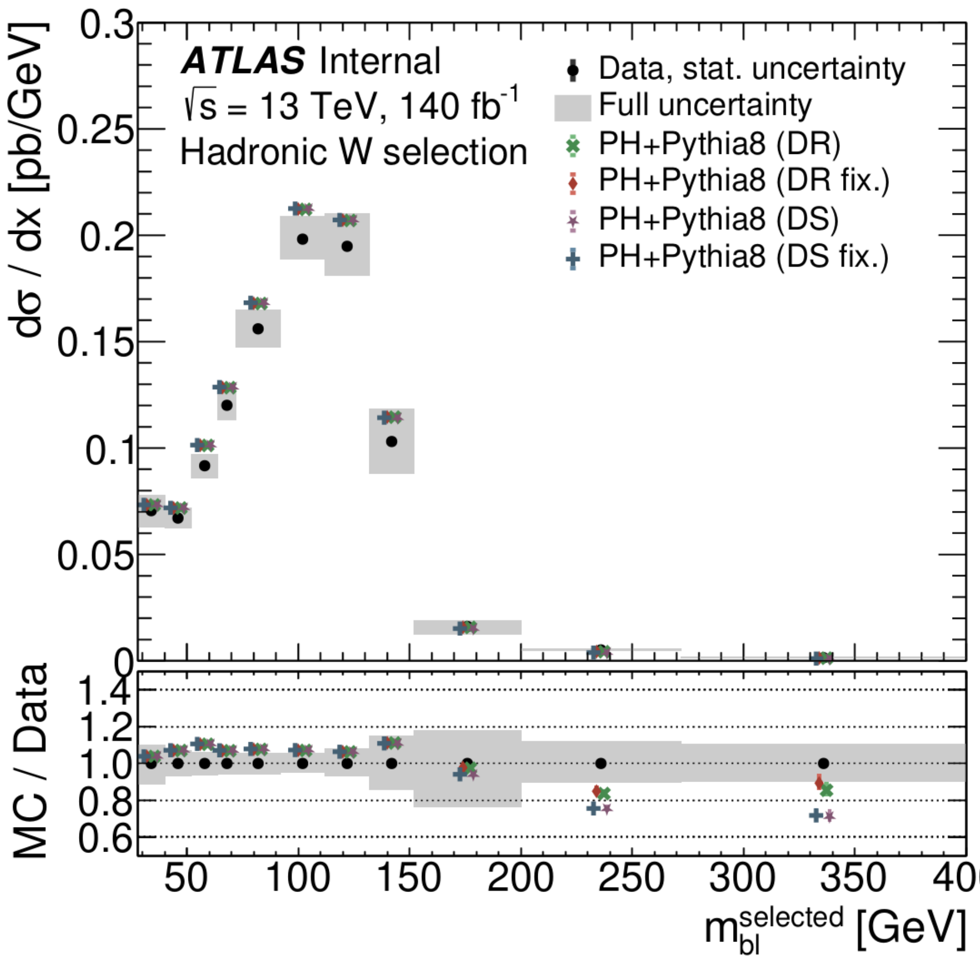
Cross section results

Data needs to be *unfolded*

- Correct for detector effects
- Data are presented on particle level
  → Allows comparison of data to MC predictions

Calculate invariant mass of lepton and assigned b-jet

- Observable is constrained by top mass
- Distribution exhibits sensitivity to top mass

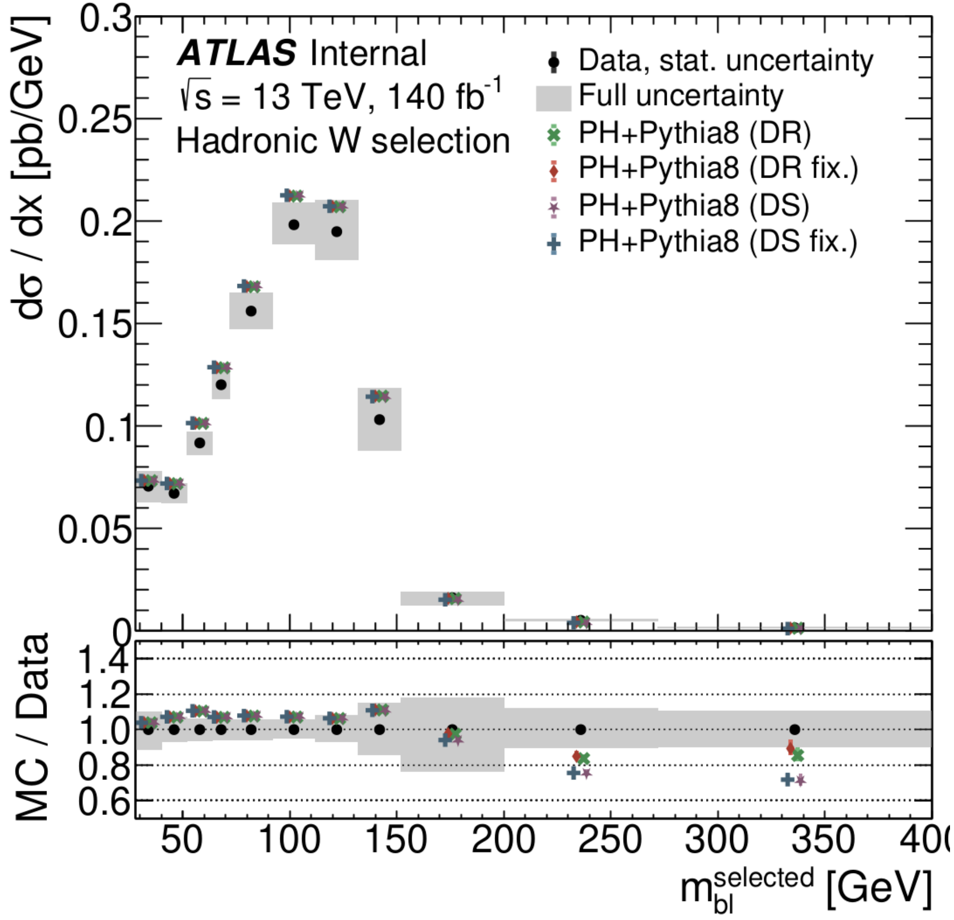


Summary

- **ATLAS measurement with WWbb**
- **final state in single lepton channel**
  - Understand modeling effects
  - Probe sensitivity to SM parameters
  - Compare to fixed order calculations

- **Reconstruct W boson explicitly**
  - Use 1 or 2 jets for the reconstruction
  - Apply *m* and p_T cuts on reconstructed *W* to improve reconstruction and reduce background

- **Cross section results**
  - Presented one preliminary cross section plot as a function of *m(bl)*
  - Currently preparing publication of results

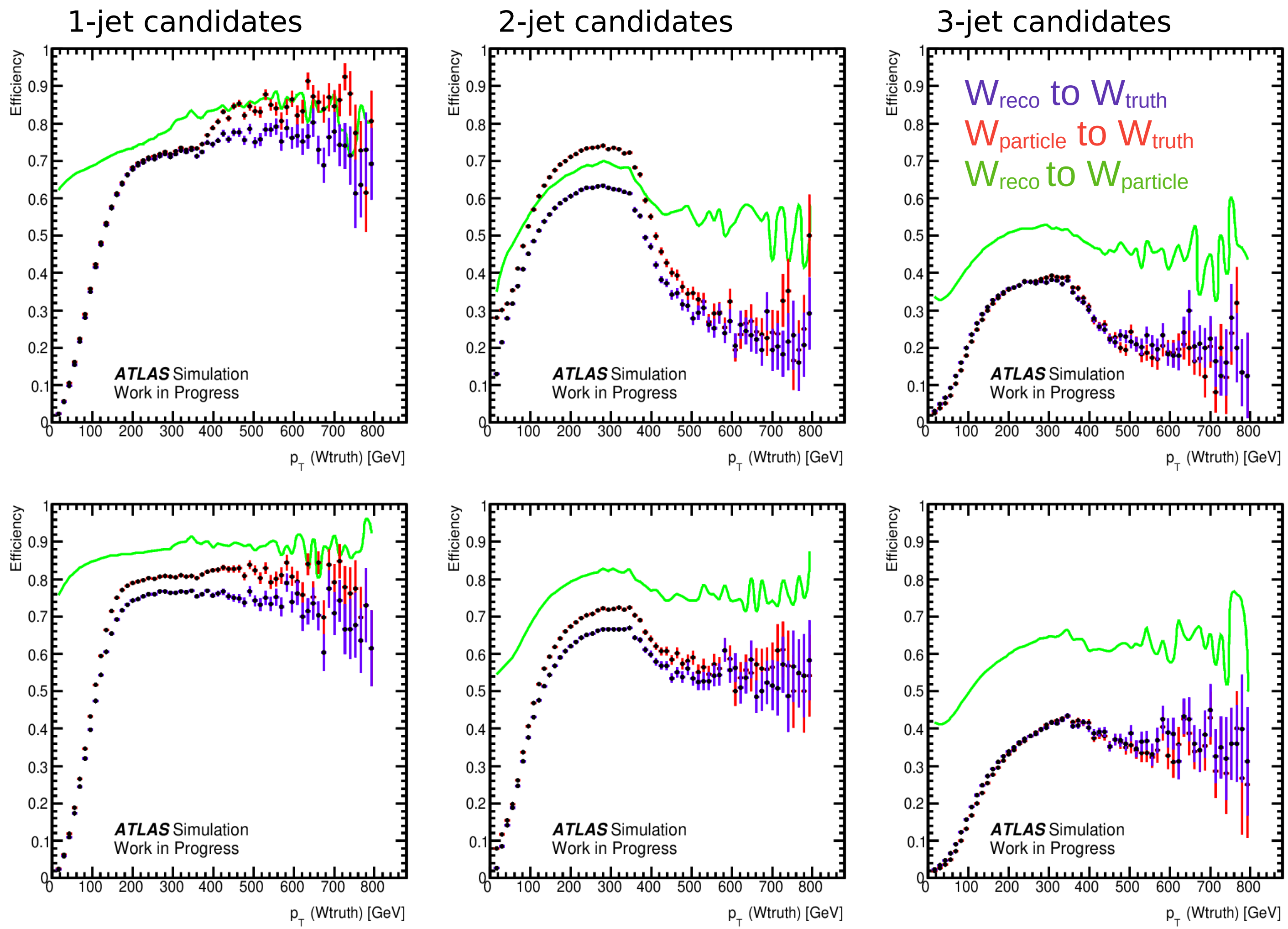


Backup

W_{had} – Naive reconstruction

- Find all 1-, 2- and 3-et combinations (sum of the the 4-vectors)
- Select combination with smallest mass difference to m_W

- Find all 1-, 2- and 3-et combinations (sum of the the 4-vectors)
- Select combination with highest p_T



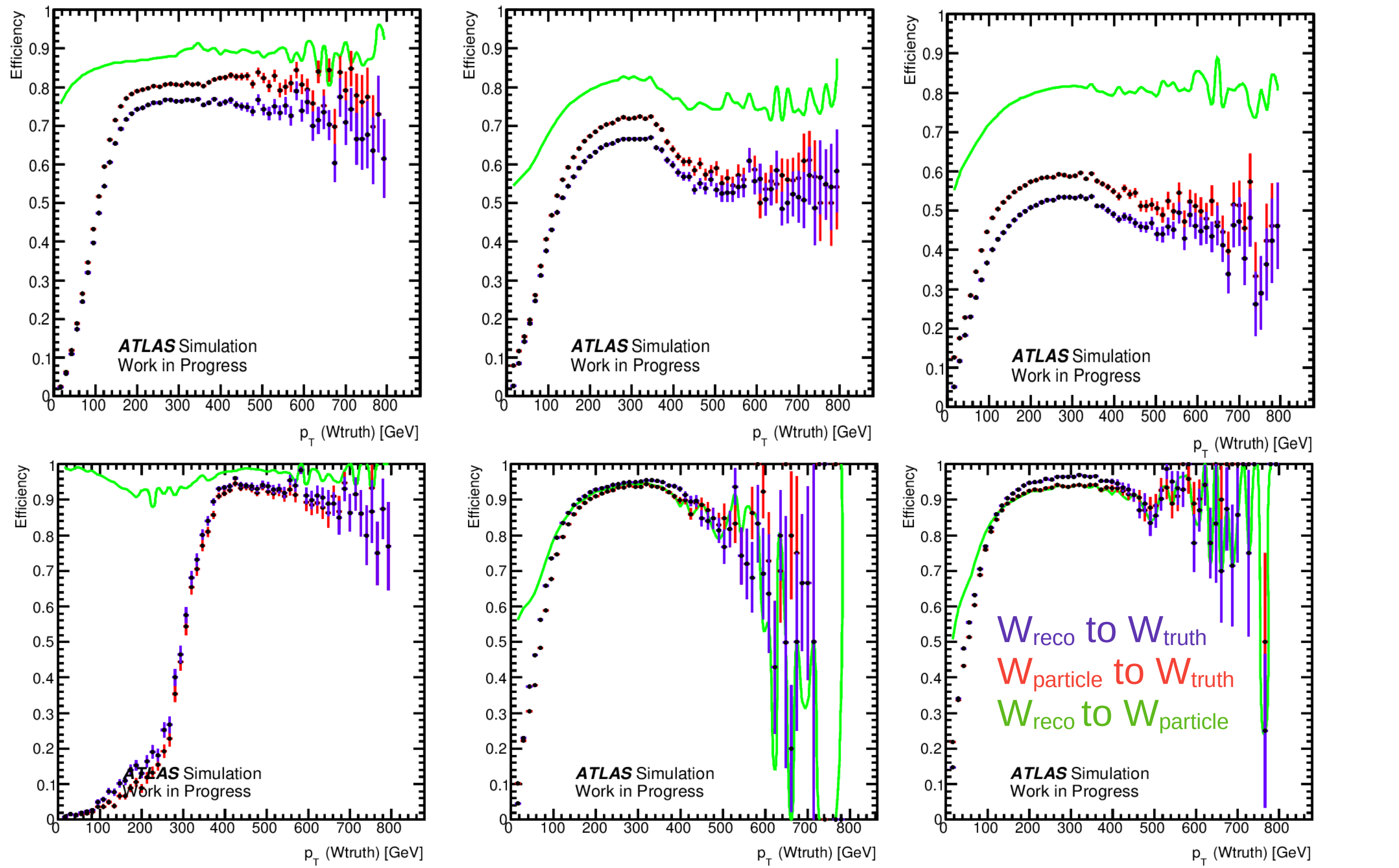
→ p_T Sortierung erzielt höhere Effizienzen als die Massen Sortierung
→ Kombiniere 1-, 2- und 3-Jet Kandidaten

W_{had} – Verbesserte Rekonstruktion

- „Harte“ Objekte liefern höhere Effizienzen
- Betrachte nur
  - härtesten Jet,
  - härteste 2-Jet Kombination
  - Kobination aus den härtesten 2 Jets

- Betrachte nur die Events mit $M(W_{reco}) > 65$ GeV

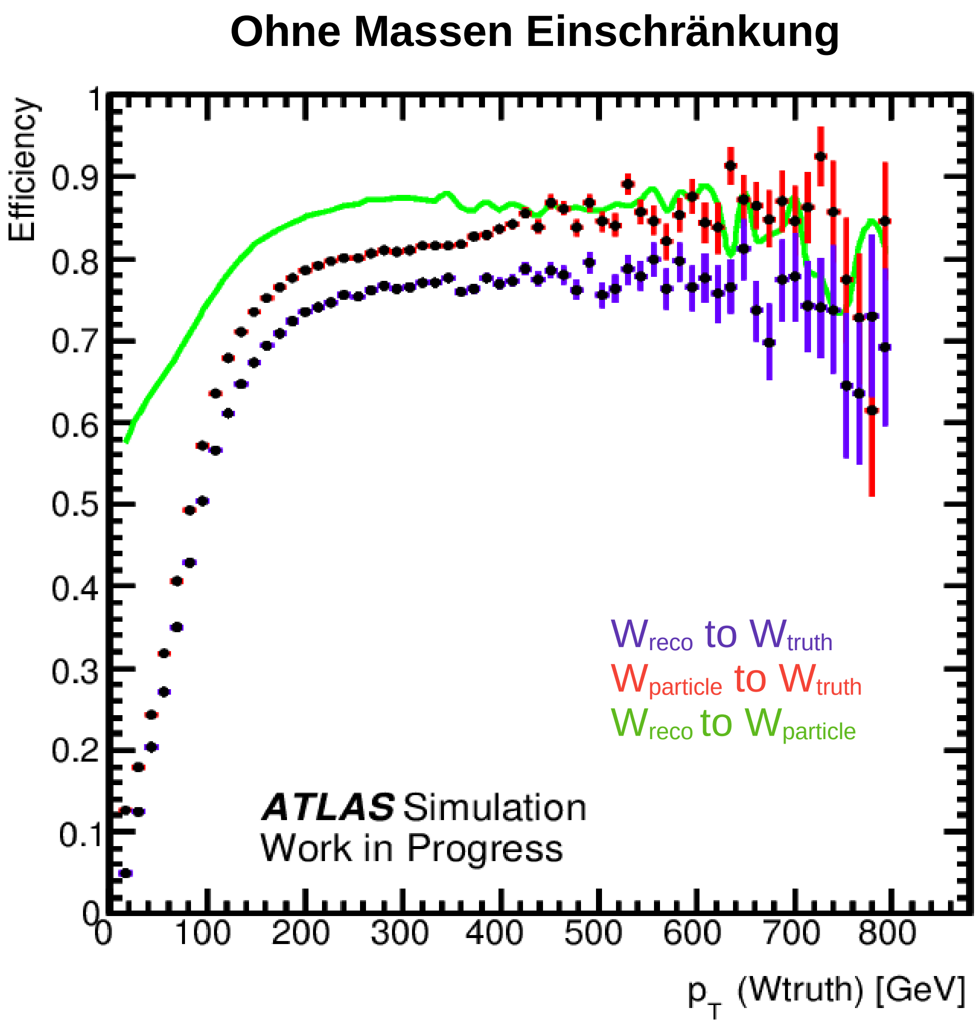
Härtester Jet | Härteste 2-Jet Kombination | Härtester + zweit-härtester Jet



→ **Ein Massencut erhöht die Effizienz**

→ **Kombiniere 1- und 2-jet Kandidaten**

W_{had} - Kombinierte Rekonstruktion



Vorauswahl mit 5 Objekten

- Härtester Jet,
- Zweit-härtester Jet
- Kombination aus den 2 härtesten Jets
- Härteste 2-Jet Kombination
- Härteste 3-Jet Kombination

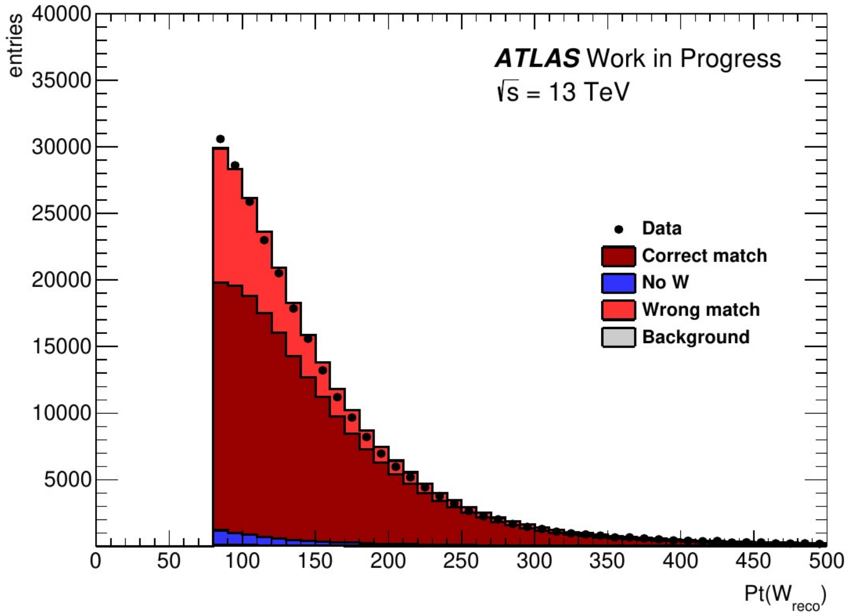
↓

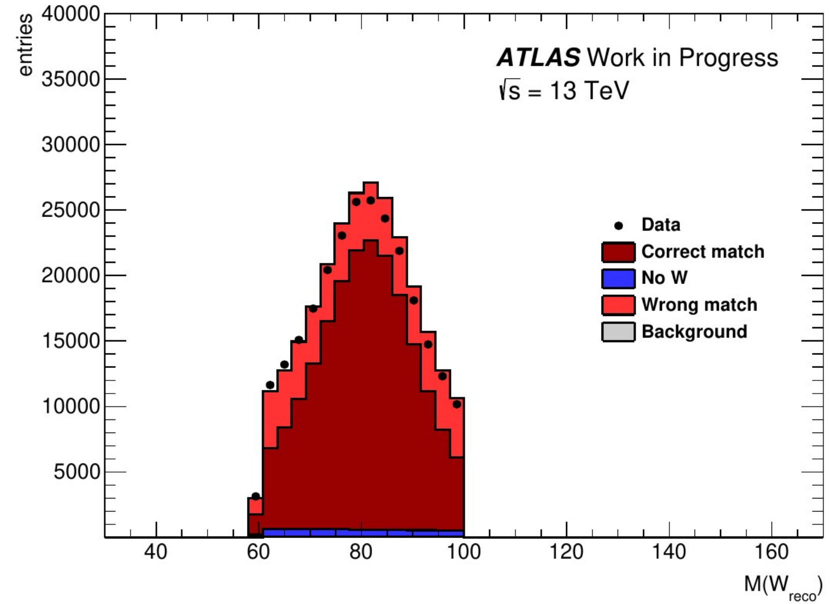
Rechne die invariante Masse der 5 Objekte aus

↓

Wähle das Objekt dessen Masse am nächsten an m_W ist → Rekonstruktion auf Teilchen- und Detektor-Level

Reconstructed W_{had}





p_T and mass distribution of the reconstructed *W* on detector level

- Correct match: $\Delta R(W_{reco},W_{truth}) < 0.4$
- Wrong match: $\Delta R(W_{reco},W_{truth}) > 0.4$
- No W: There is no W_{truth}

→ **Consider all signal and backgorund processes**

→ **Good performance of the reconstruction algorithm**

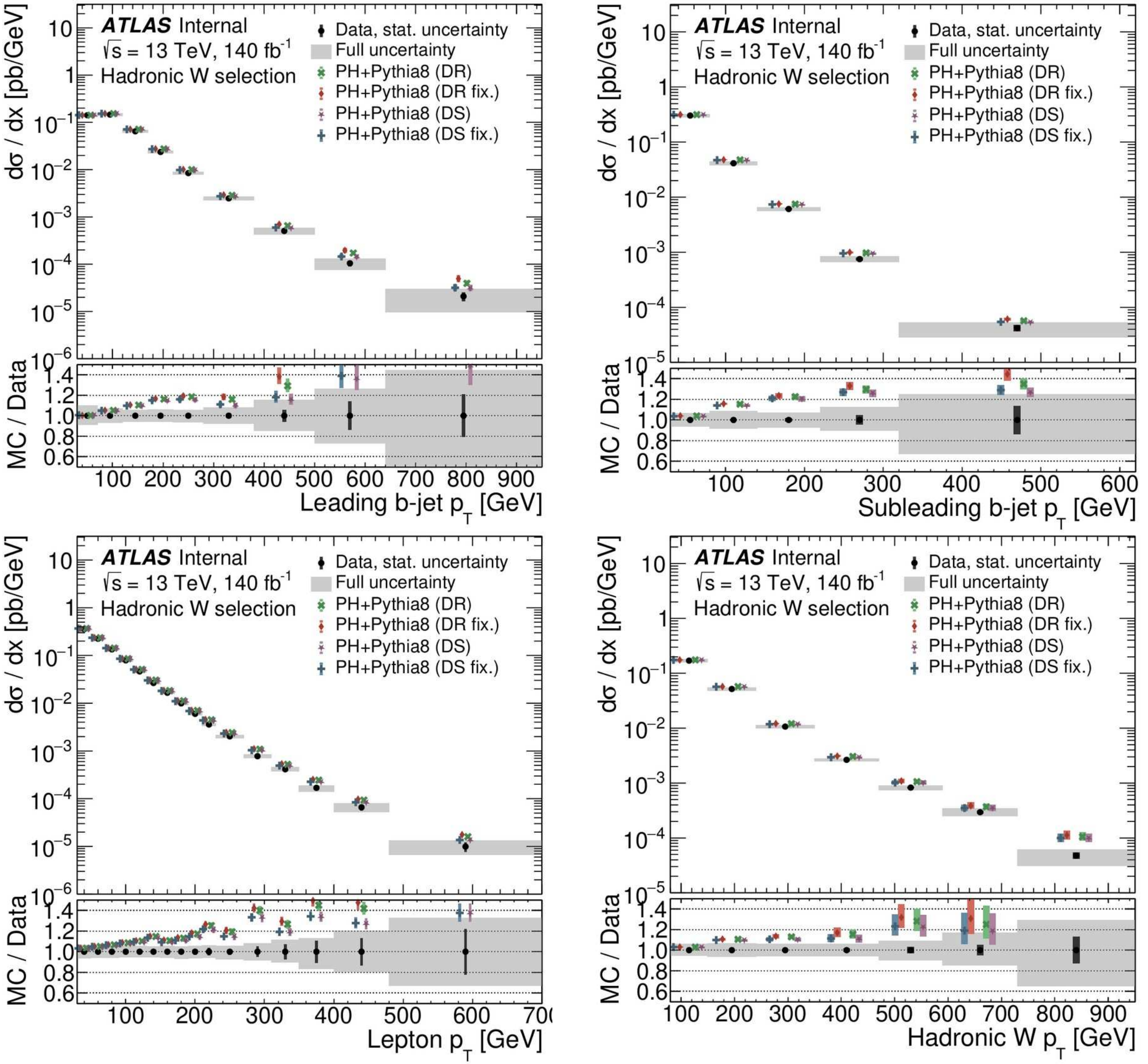
Cross section results

Data needs to be *unfolded*

- Correct for detector effects
- Data are presented on particle level
- Allows comparison of data to MC predictions

Plots show the p_T distribution of *W*, leading *b*-jet, subleading *b*-jet and *l*

- Large p_T range can be measured
- Good agreement between data and MC



Cross section results

Add 4-vectors and calculate invariant mass (bl, Wbbl)
→ Slope of the distribution exhibits sensitivity to top mass