Precision measurement of the Z-boson transverse momentum with the ATLAS detector

Ben Davis-Purcell

Supervised by Dr. Manuella Vincter

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The ATLAS Experiment with the Large Hadron Collider (LHC) at CERN

- CERN: Huge particle physics laboratory best known for housing the LHC, the most powerful particle accelerator ever built
- ATLAS: General-purpose detector that measures the properties of particles created from LHC proton-proton collisions
- Collisions involve “bunches” of protons: ~100 billion protons/bunch, 1 bunch/25 ns, ~0-100 pp collisions/bunch (*pileup*)

Performance

- Does this algorithm work well?
- Example: new machine learning technique accurately reproduces a previous result

Searches

- Does this new process/particle exist?
- Example: looking for dark matter particles within the ATLAS dataset

ATLAS EXPERIMENT

Analyses

Measurements

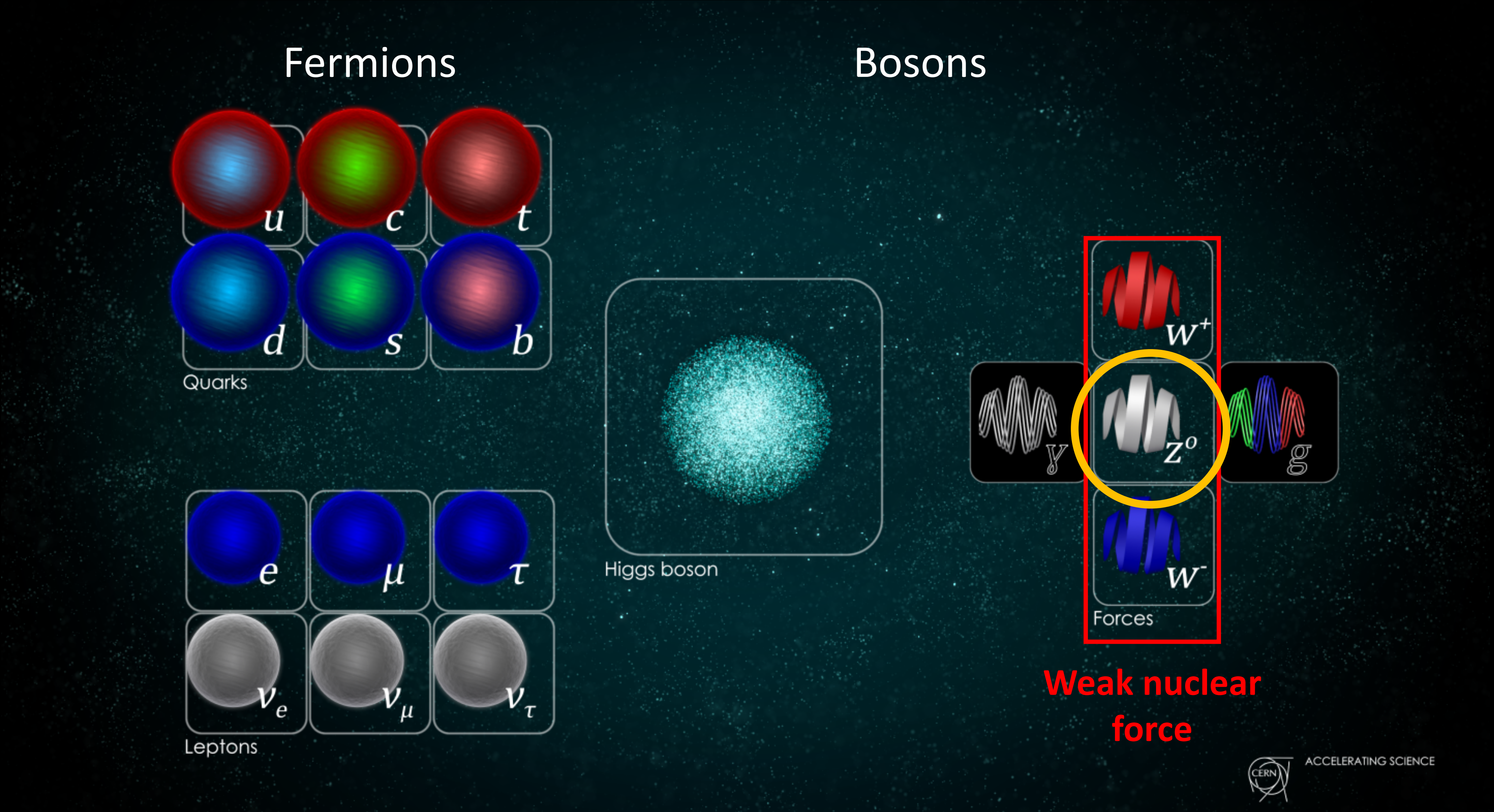
"Known" Processes

- Can we measure this for the first time?
- Example: first measurement of light-by-light scattering

Precision Measurements

- Can we reduce the error bars for this well-known property/process?
- Example: more data improves the precision of the *W*-boson mass by reducing the stat. uncertainty, constraining the Standard Model

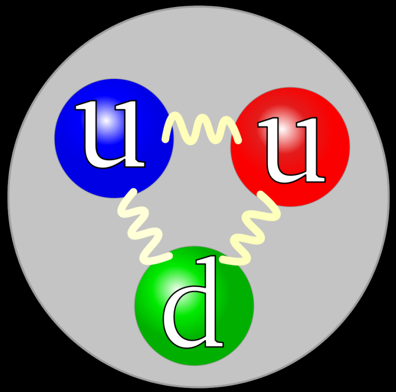
Standard Model of Particle Physics



Weak nuclear force

Measurement of the Z-boson Transverse Momentum (p_T^Z)

$$pp \to Z \to l^+ l^-$$



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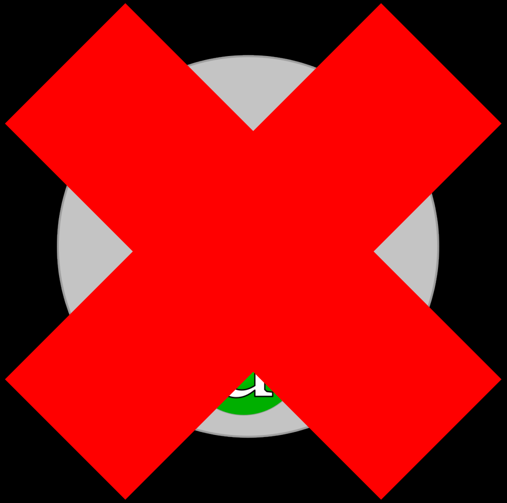

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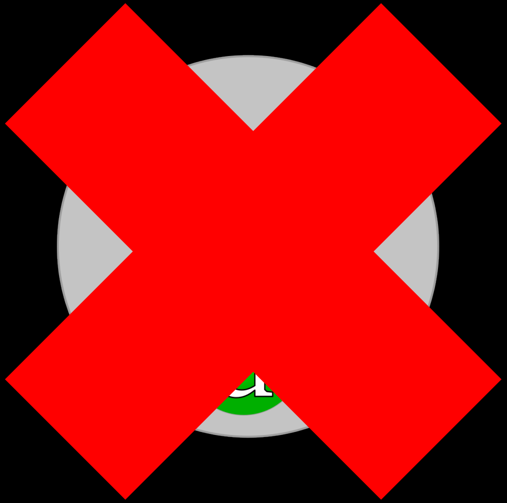

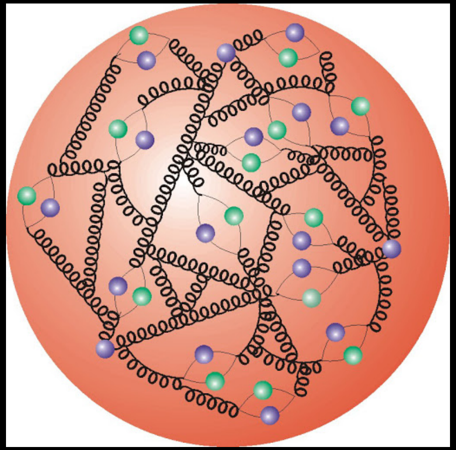

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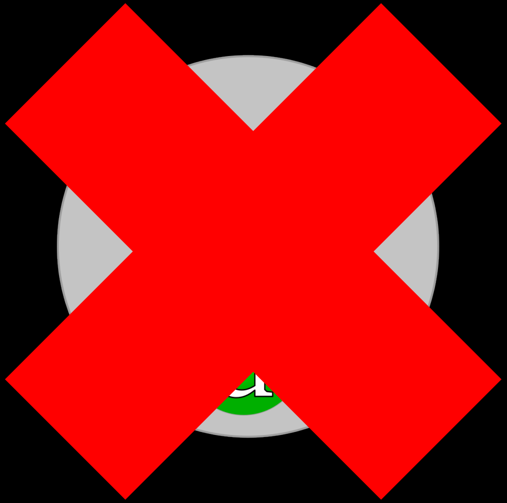
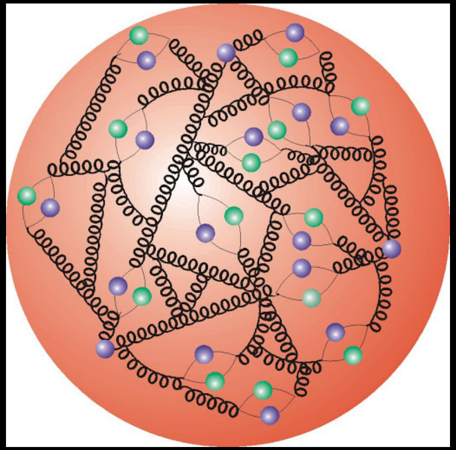
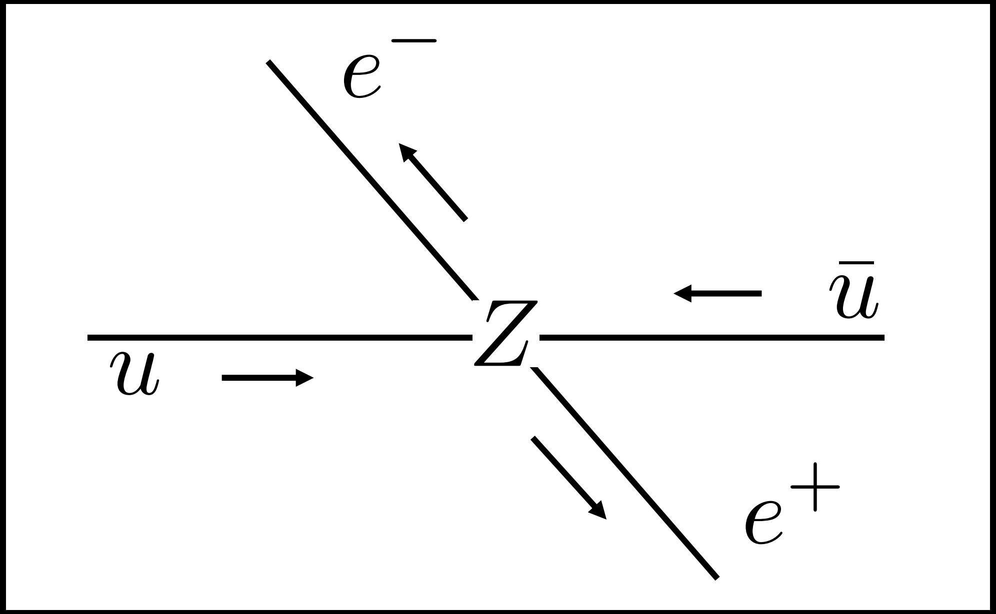
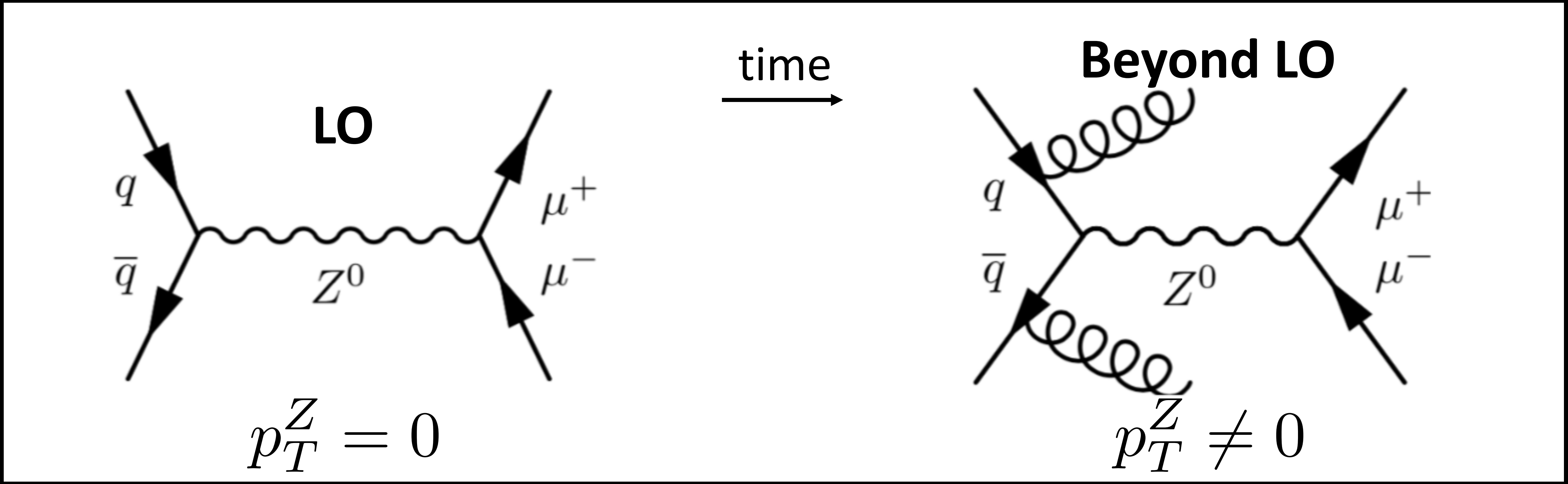






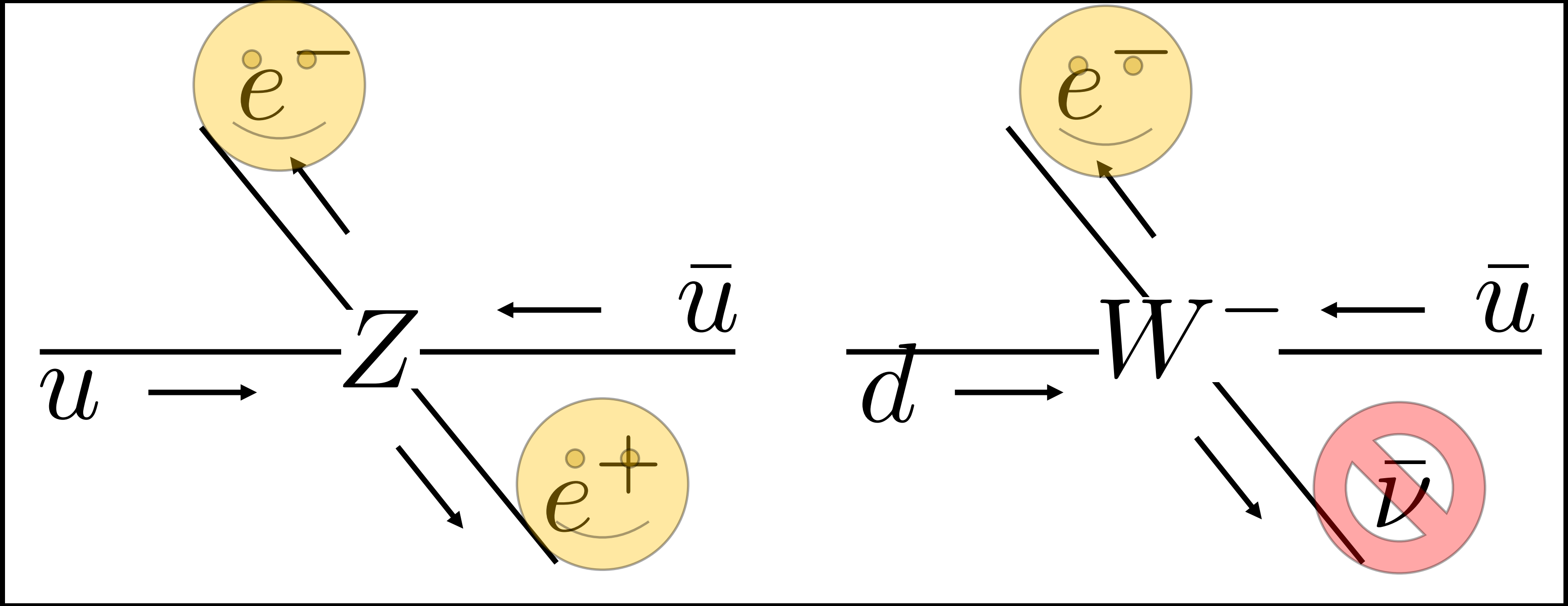
At first glance, by momentum conservation we would expect $p_T^Z = 0$!

Motivation for p_T^Z



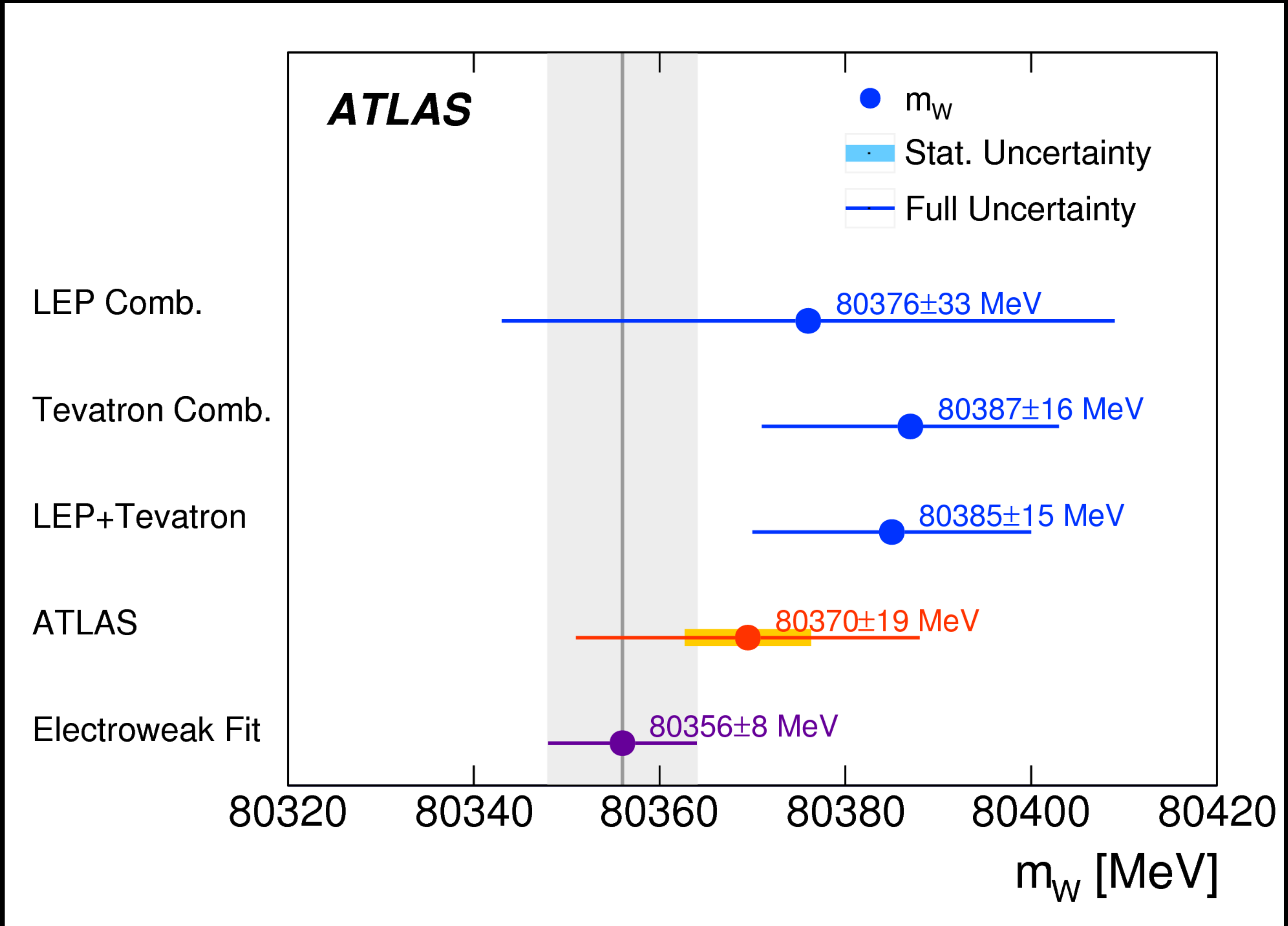
- p_T^Z is an excellent probe of Quantum Chromodynamics (QCD) beyond Leading Order (LO)
- Use this info. to better understand interactions within the proton

Motivation for p_T^Z



- Z and W have a similar decay schematically; however, we can measure $e^{\pm}$ or $\mu^{\pm}$ but not ν
- Important for reducing uncertainties on the W-boson mass; p_T^W is required for measuring m_W, use Z-boson as a proxy to calibrate p_T^W

W-boson Mass Measurement (m_W)



Measurements

Prediction

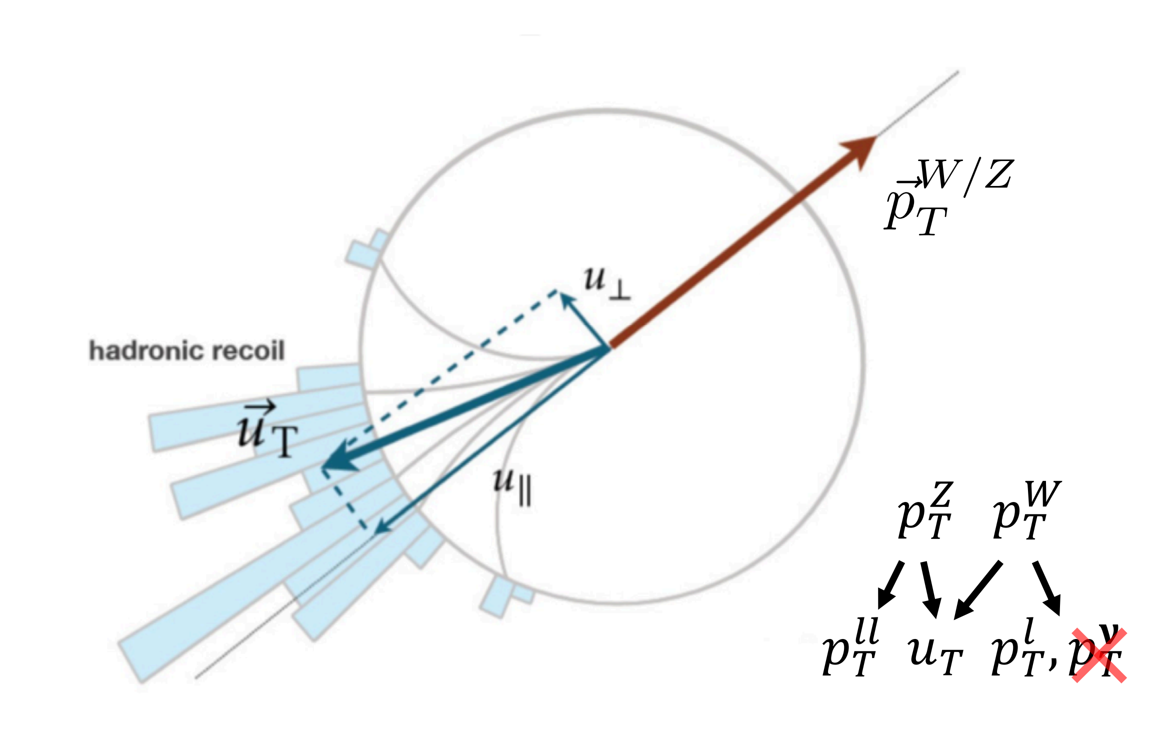
Experiment uncertainty > theory uncertainty!

https://arxiv.org/abs/1701.07240

How *Z* Supports *W*

Z decay: $Z \rightarrow l^+ l^-$ *W* decay: $W^\pm \rightarrow l^\pm \nu$

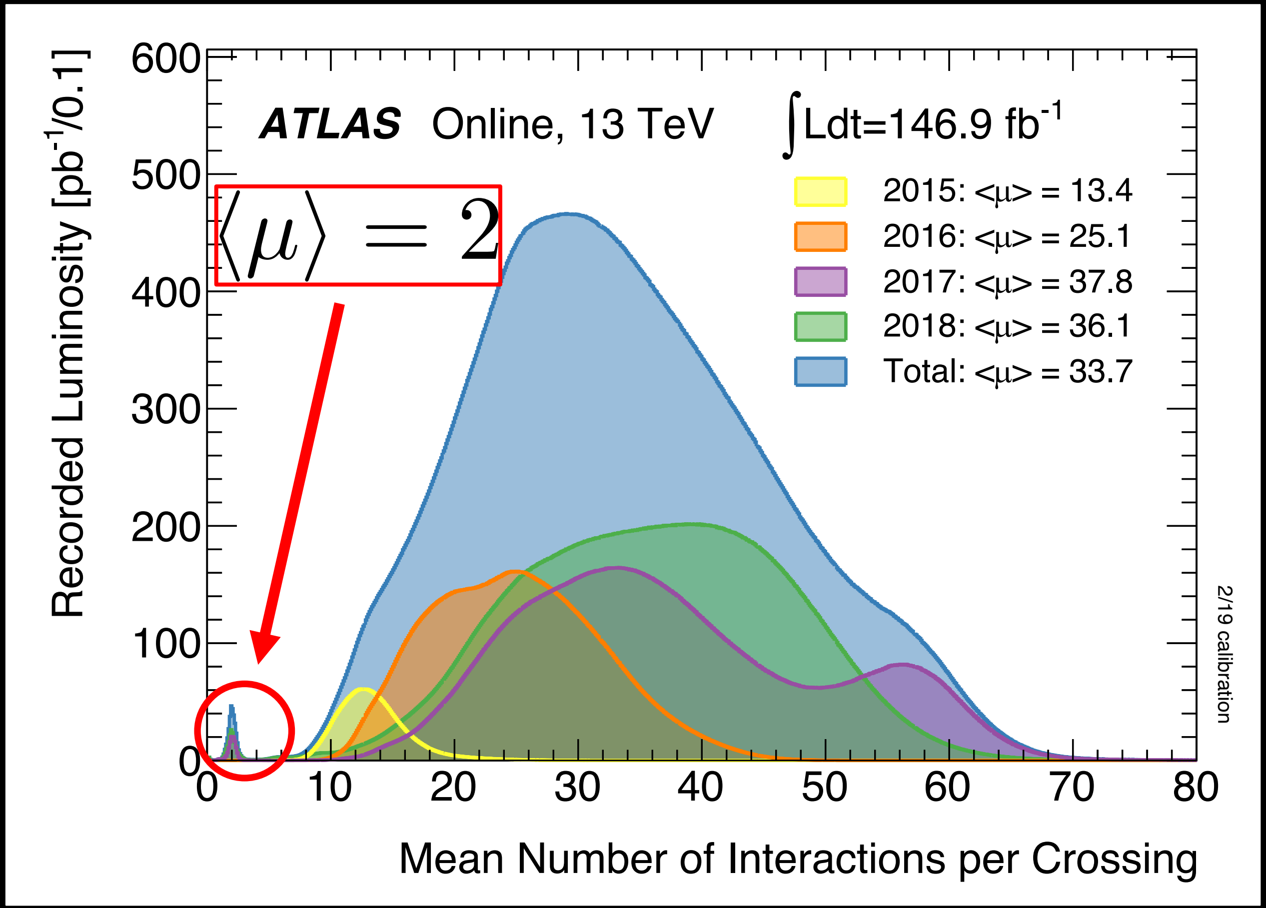
- Neutrino from *W* escapes as missing energy; must use only *hadronic recoil* (u_T) to measure p_T^W but can measure p_T^Z with both p_T^{ll} and u_T

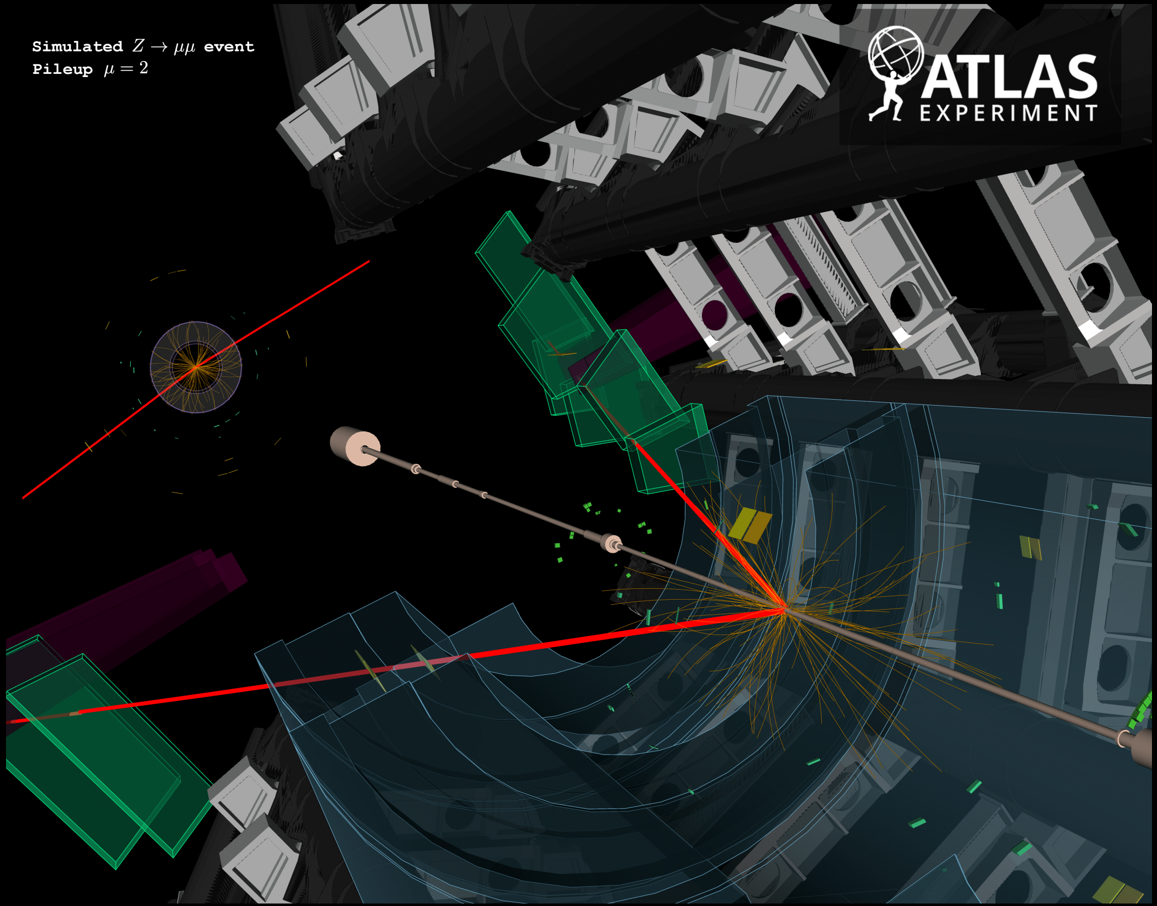


$$\vec{p}_T(W/Z) = \vec{p}_T^{lepton1} + \vec{p}_T^{lepton2} = -\vec{u}_T$$

- p_T^{ll} and u_T are theoretically equal but hadronic recoil is inherently more difficult to measure
- Low pileup (μ) environment improves u_T resolution

Low Pileup Environment

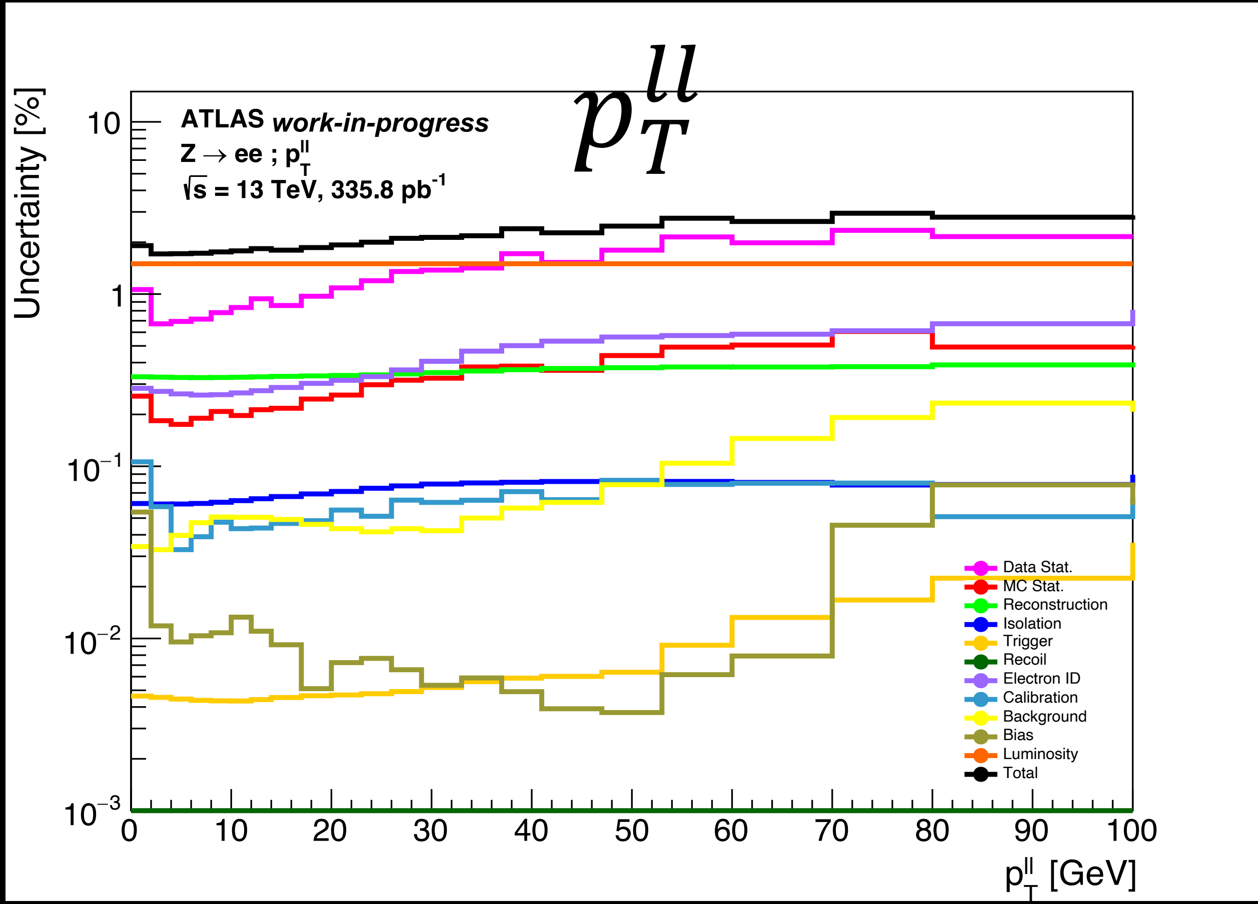


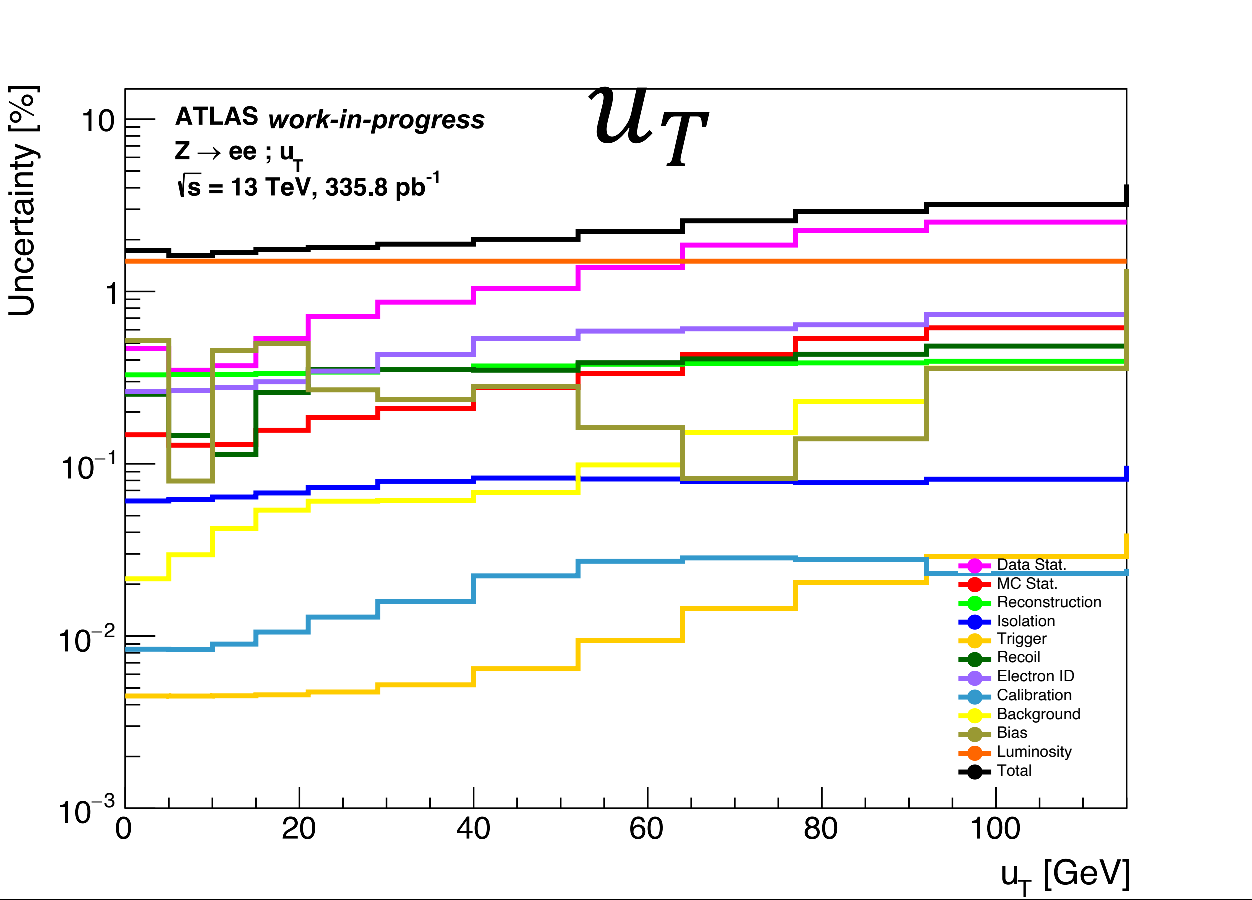


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2

Fewer proton-proton collisions = cleaner environment = improved u_T measurement!
Downside: reduced statistics

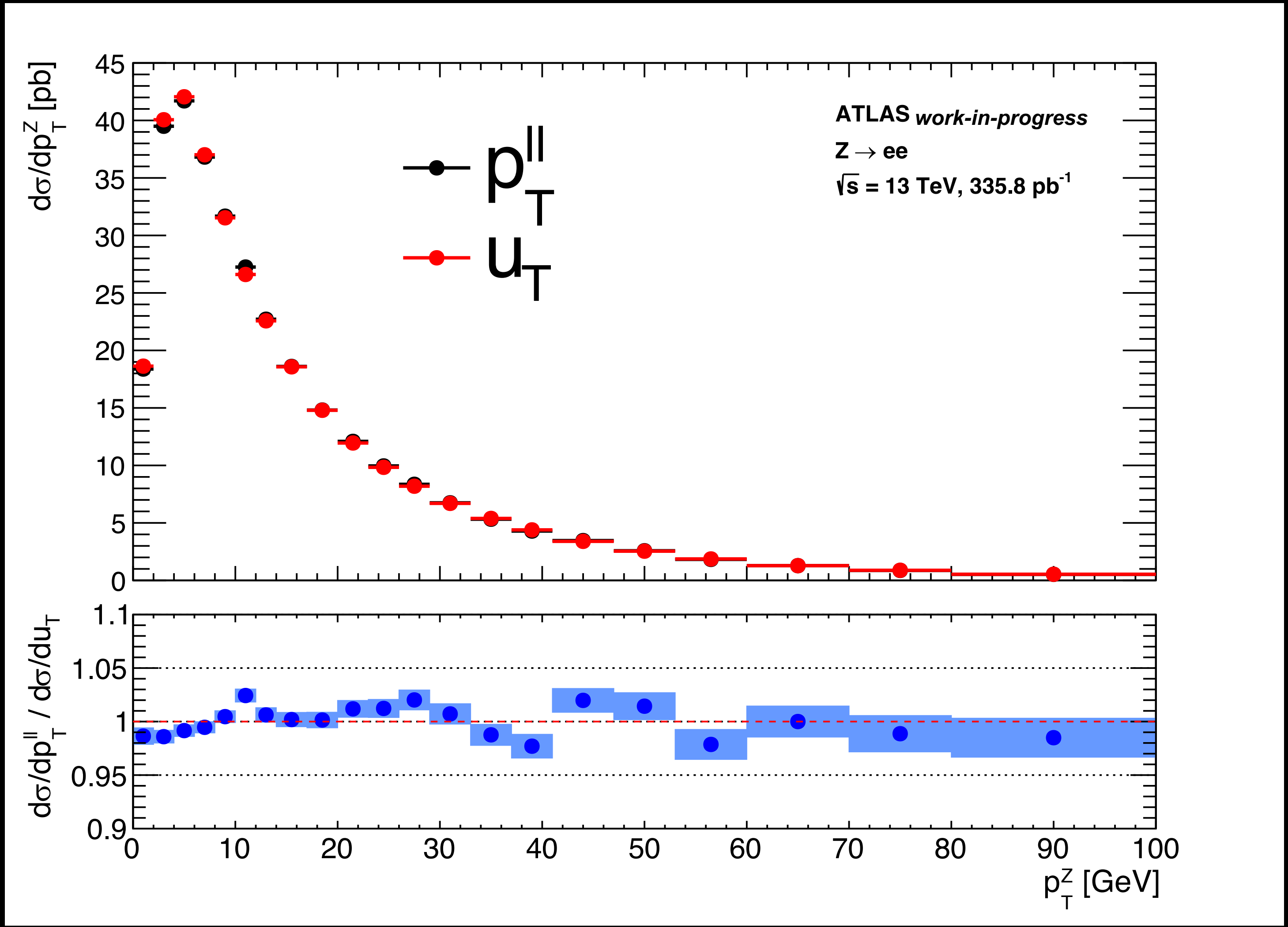
Measurement Uncertainties





- Only limited by statistics (pink) and luminosity (orange)! Systematic errors total < 1%

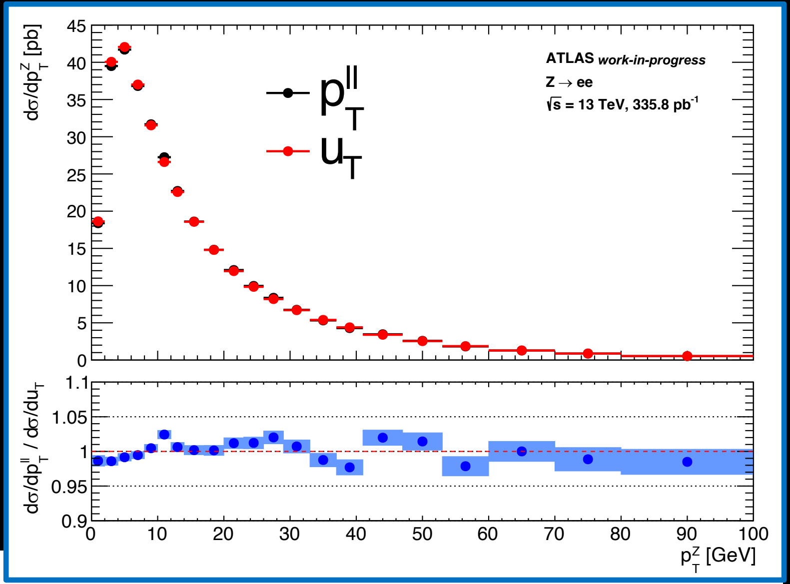
Observable Cross-Section Comparison

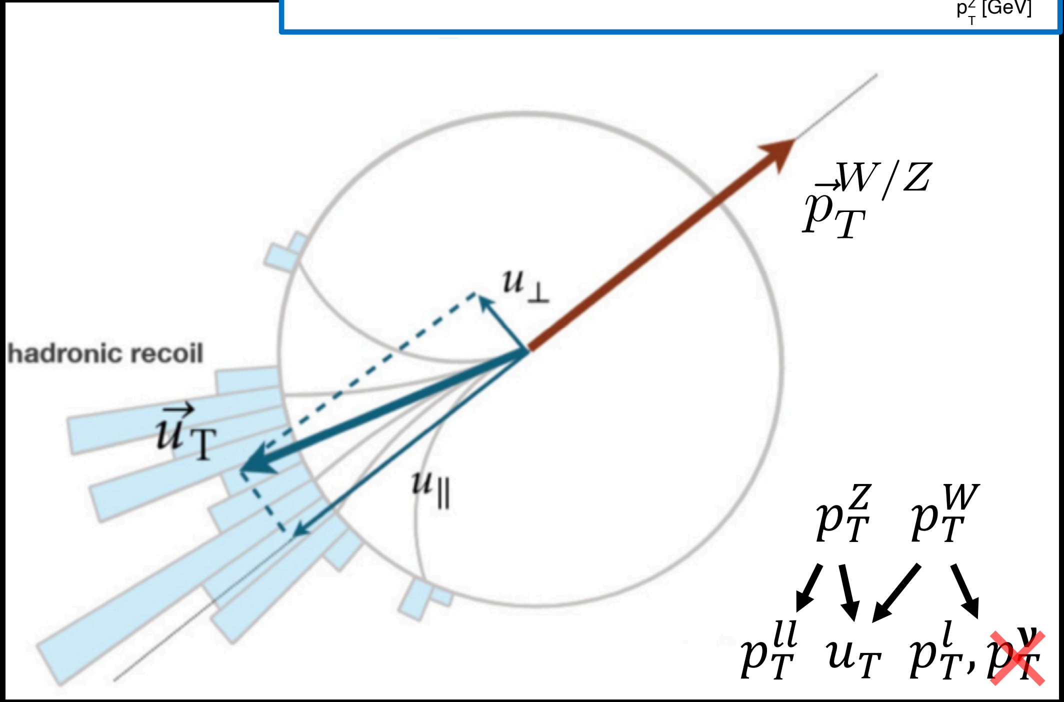


- Cross-section should be independent of observable: both p_T^{ll} and u_T are measures of p_T^Z
- Excellent agreement seen, confirming the efficacy of the u_T measurement

Summary

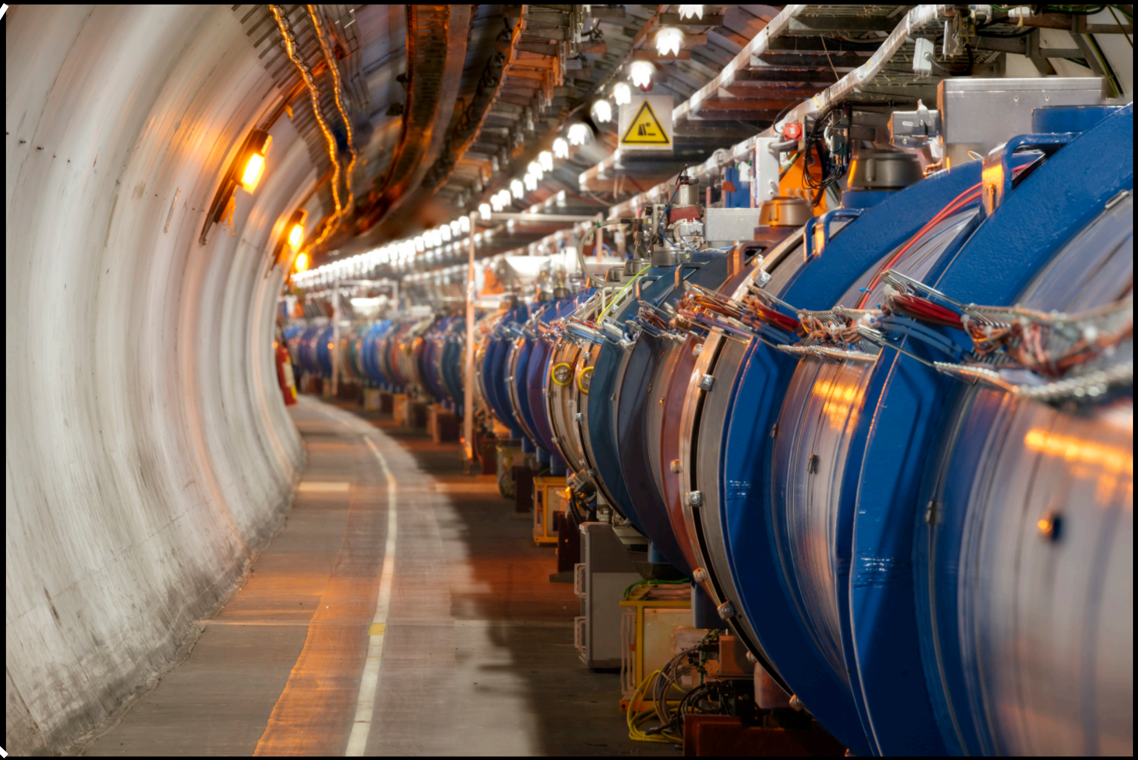
- p_T^Z differential cross-section measurement made at E_{CM} = 5, 13 TeV
- Clean low pileup environment allows for precise measurement of hadronic recoil (u_T)
- both p_T^{ll} and u_T have systematic error below 1%
- Finalizing precision p_T^Z and p_T^W measurements with low pileup data





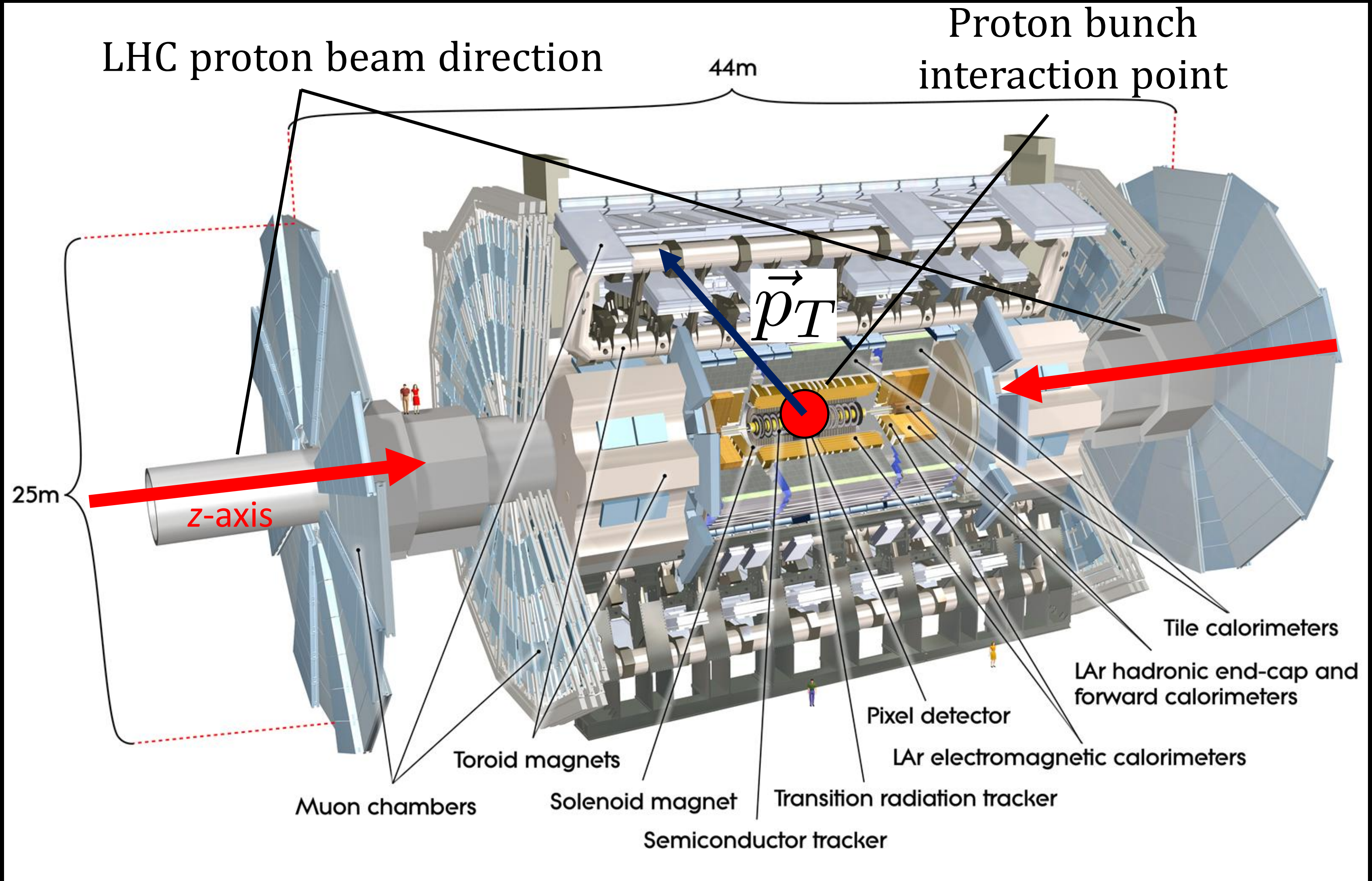
Large Hadron Collider (LHC) at CERN

- CERN: Huge particle physics laboratory near Geneva, Switzerland
- Best known for housing the LHC, the most powerful particle accelerator ever built
- LHC: 27 km circumference ring that accelerates and collides protons to 0.99999999 x (the speed of light), recreating the energy density of less than one billionth of a second after the Big Bang!

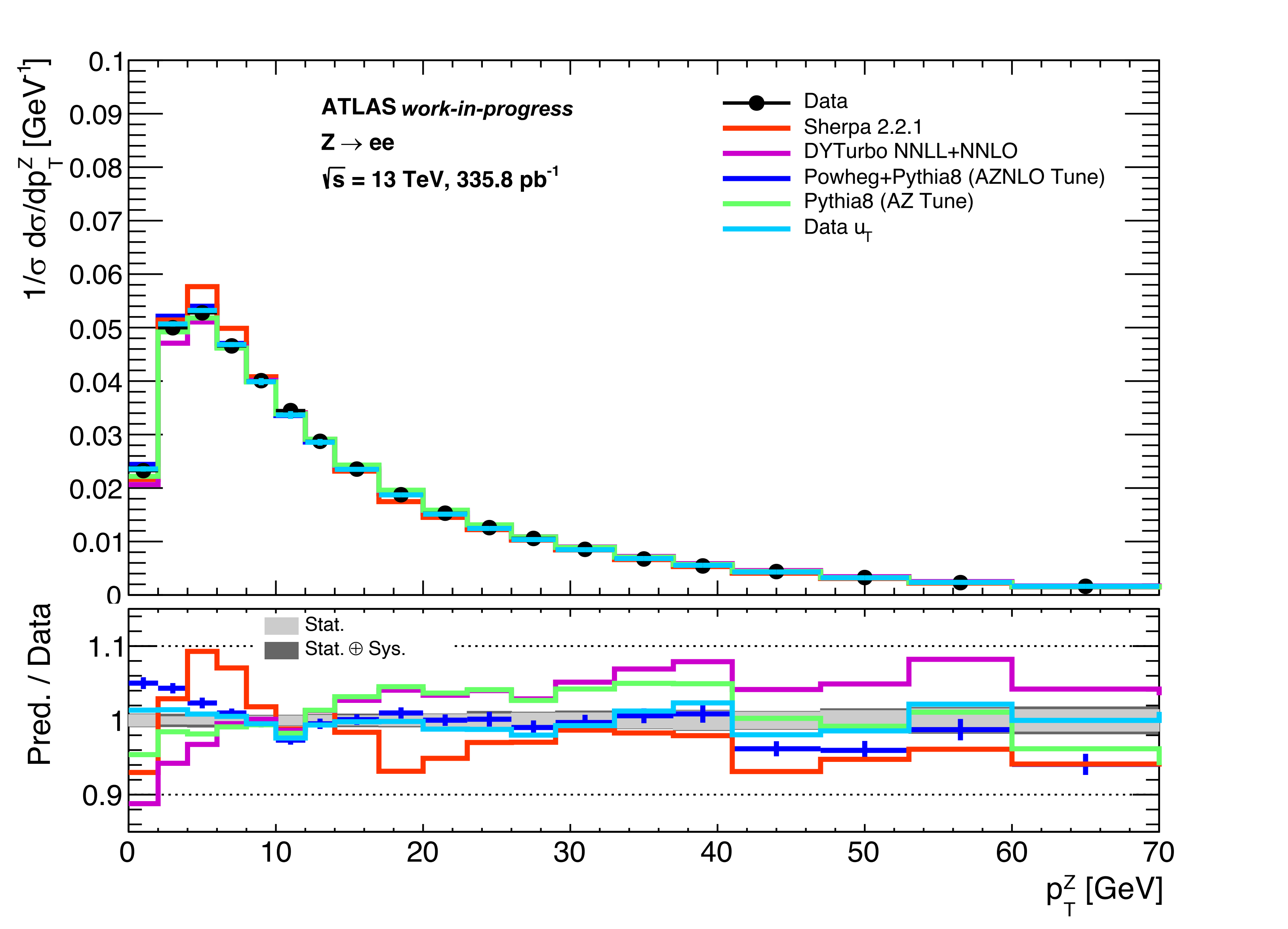


The ATLAS Experiment

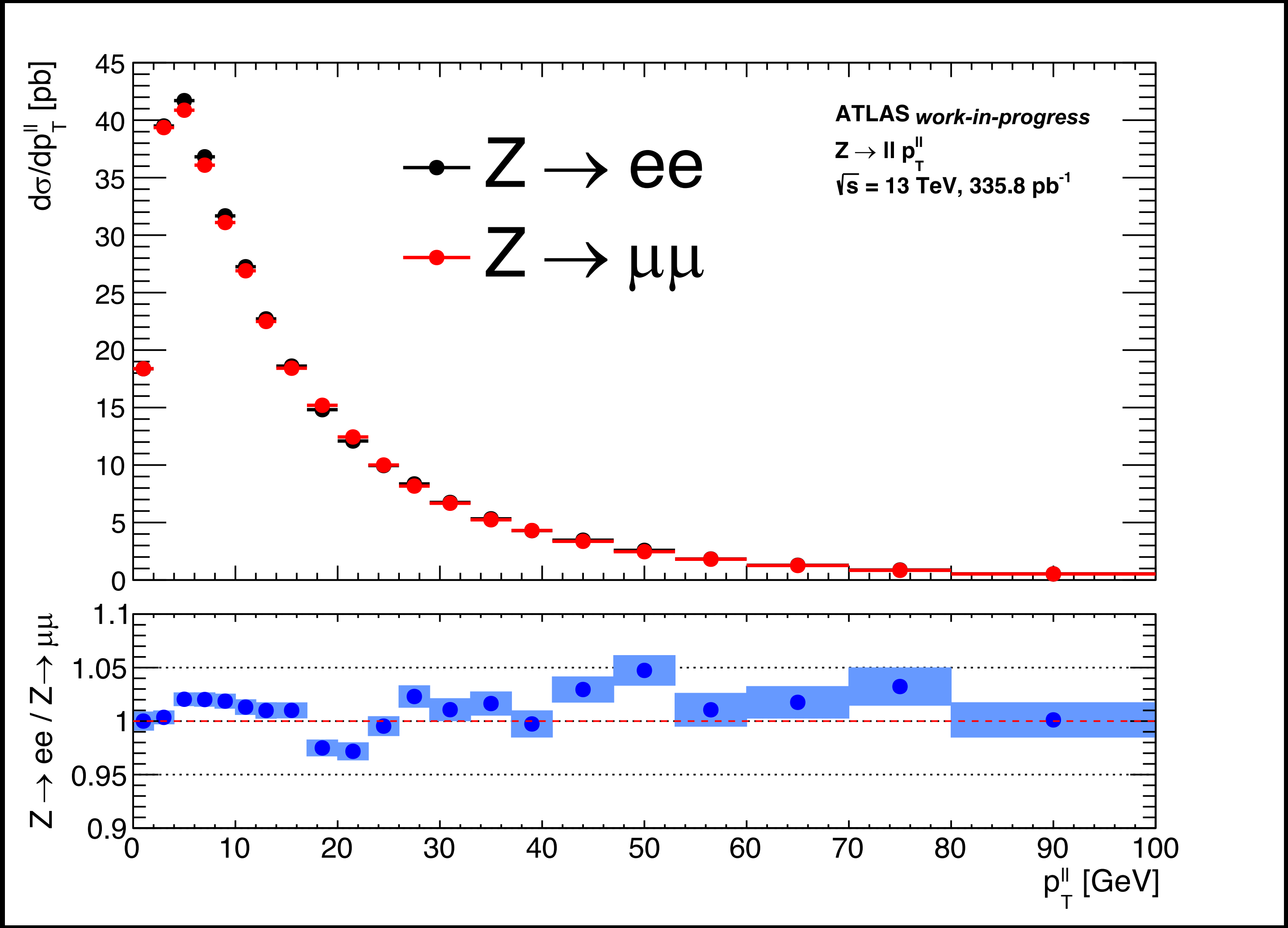
- General-purpose detector designed to measure the properties of the particles created from the LHC proton-proton collisions
- LHC collides “bunches” of protons: about 100 billion protons per bunch; 1 bunch every 25 ns; multiple collisions per bunch: *****pileup*****
- More than 1 billion particle interactions in the detector every second!



Normalized Differential Cross-Section

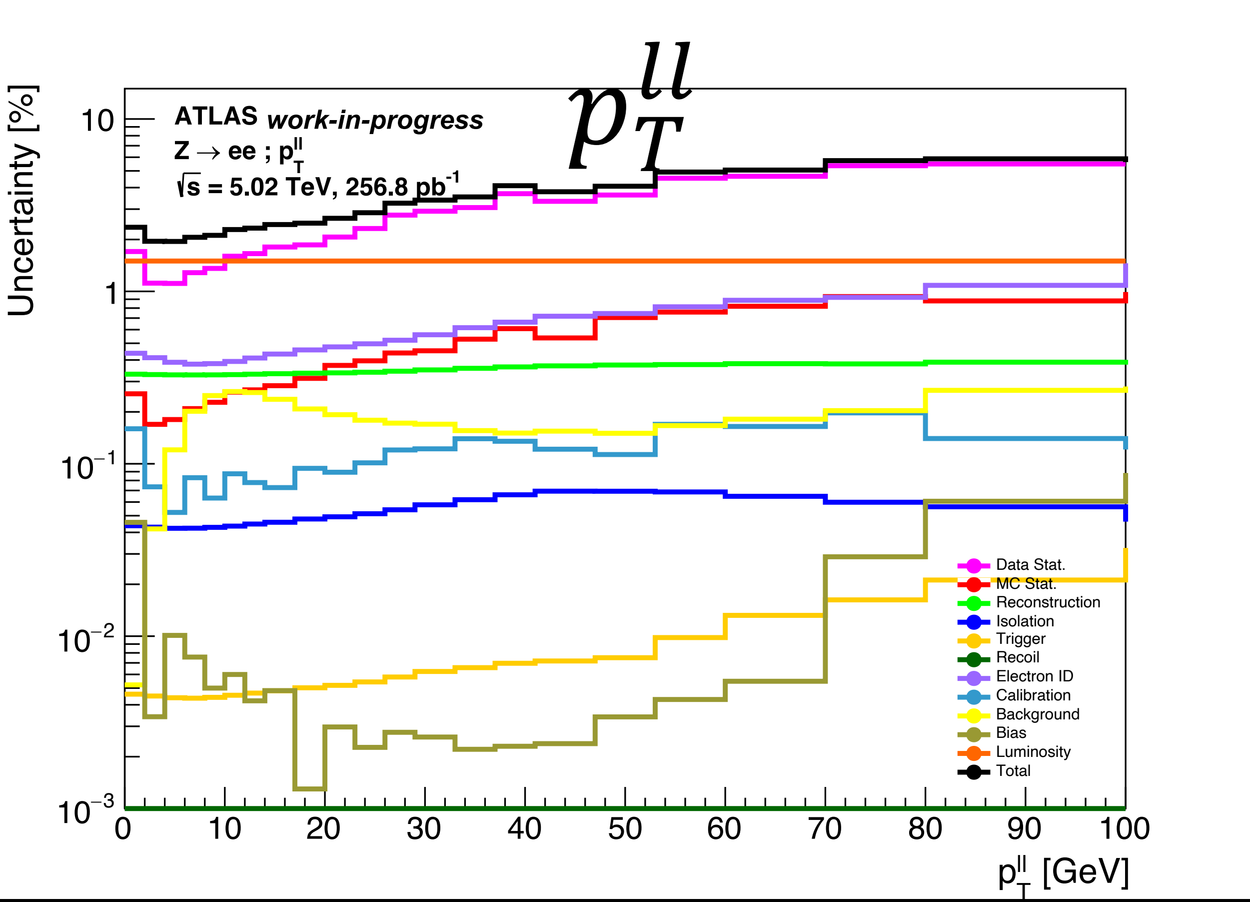


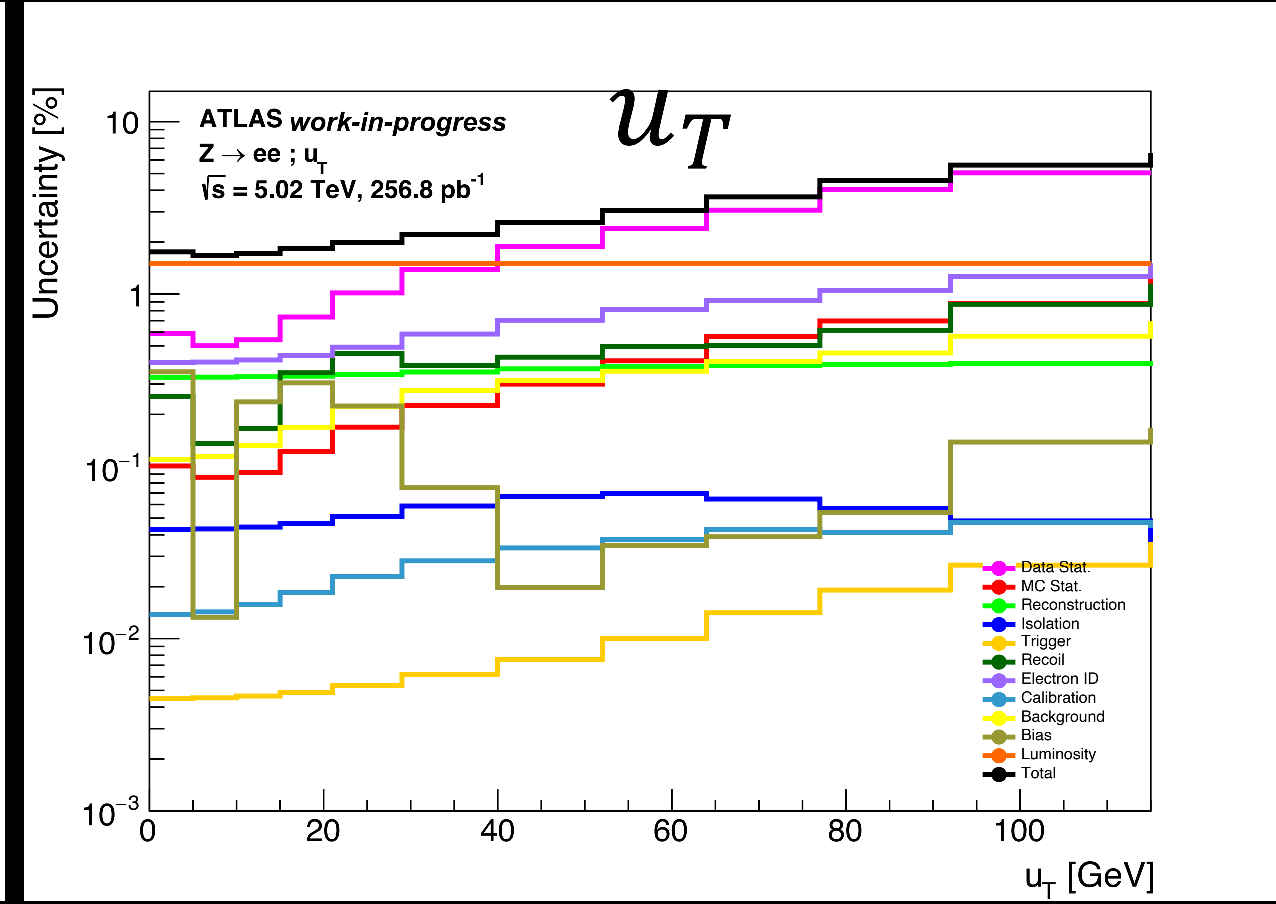
Lepton channel cross-section comparison



- Cross-section should be independent of lepton channel due to lepton universality
- Good agreement seen between channels

Measurement Uncertainties @ 5 TeV





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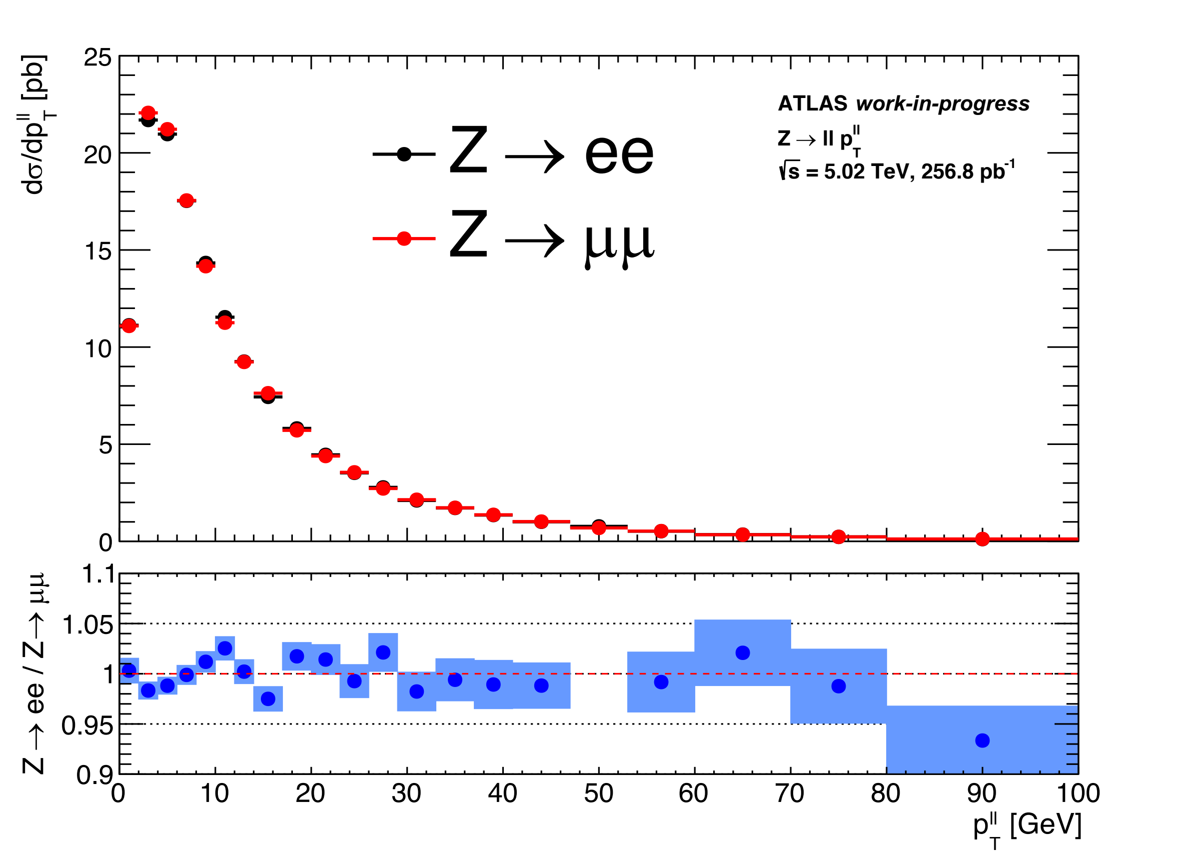
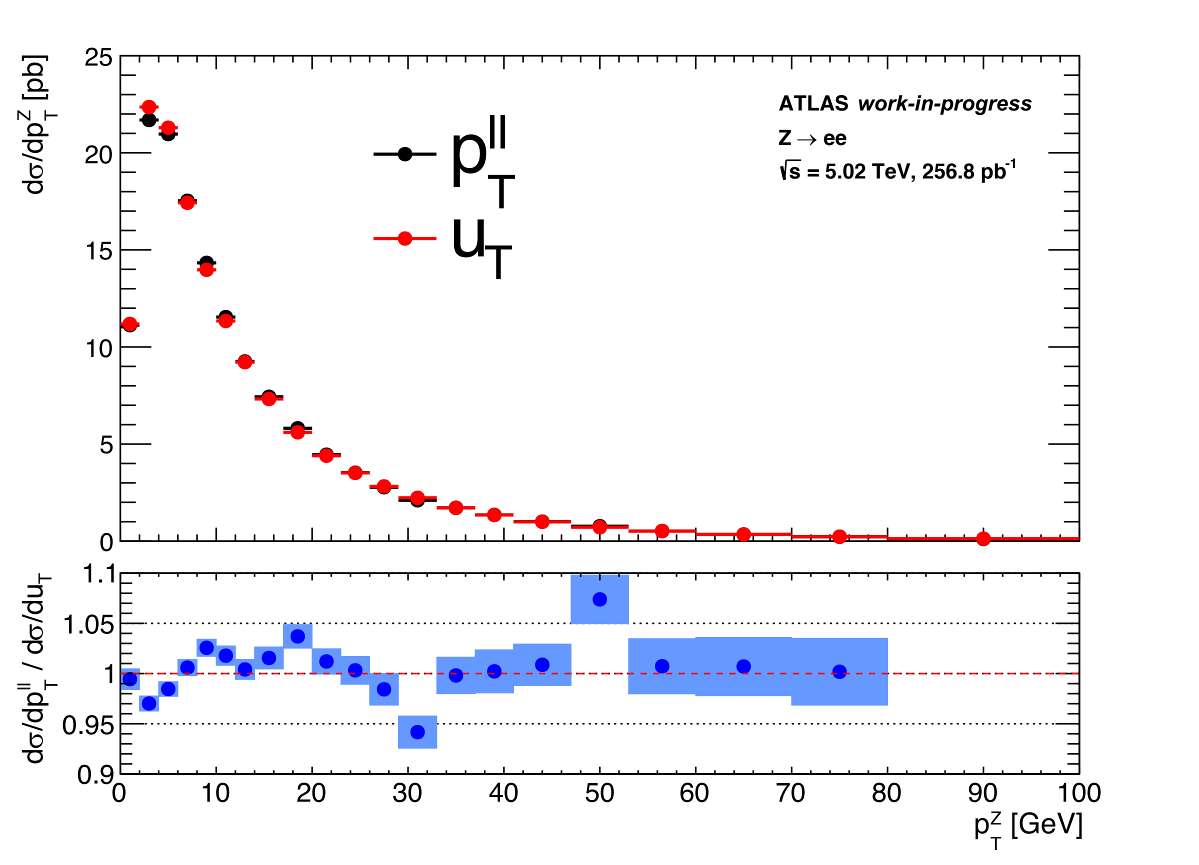


Observable cross-section comparison



E_{CM} = 5 TeV

Normalized Differential Cross-Section