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

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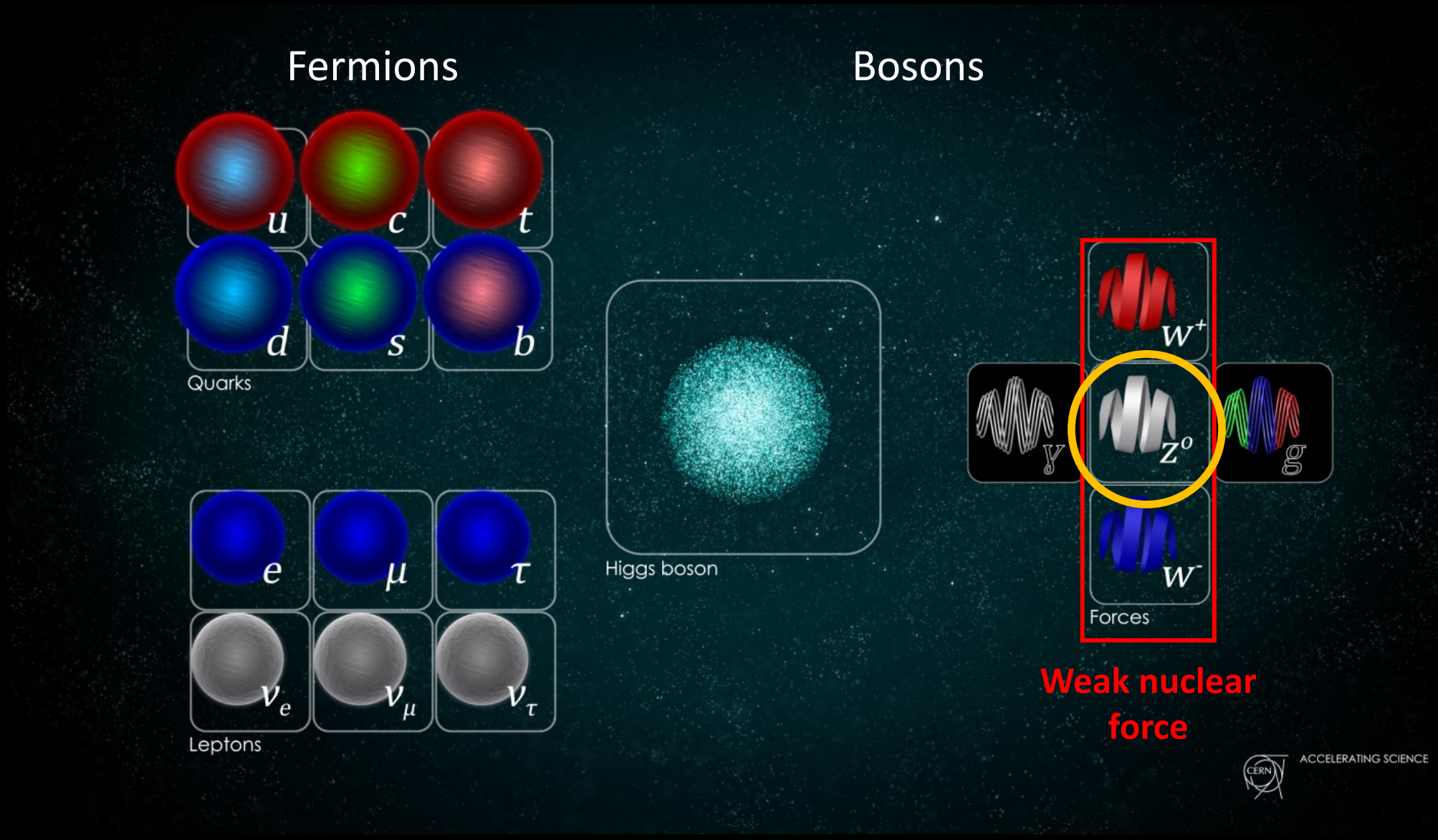
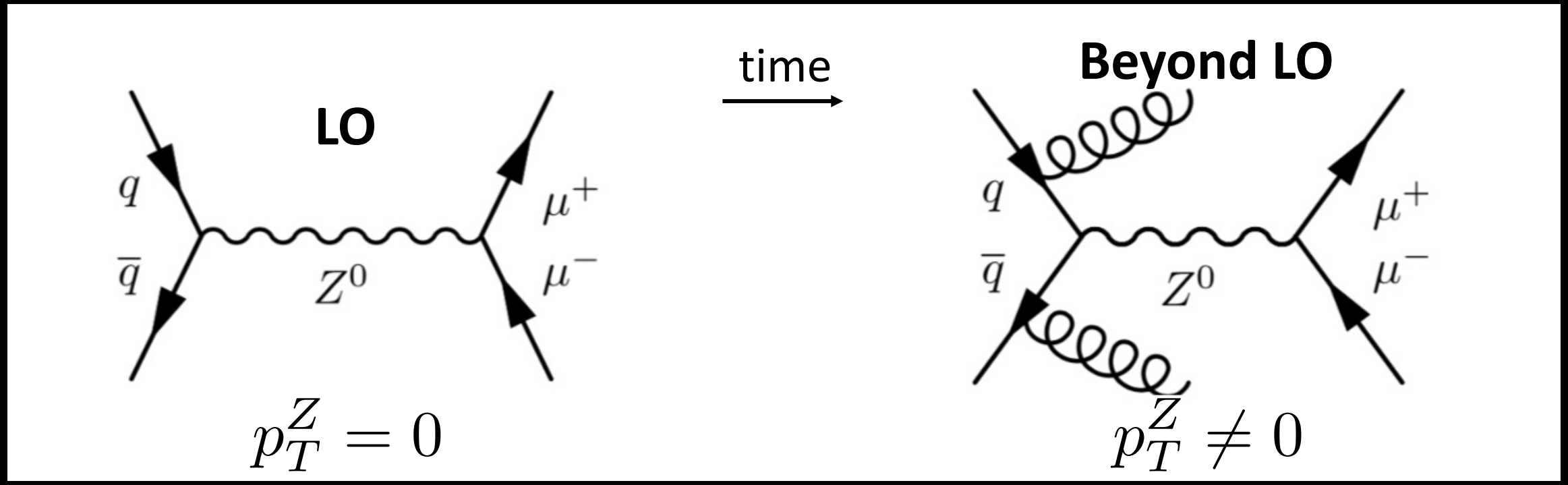
The ATLAS Experiment with the Large Hadron Collider (LHC) at CERN

- 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*)

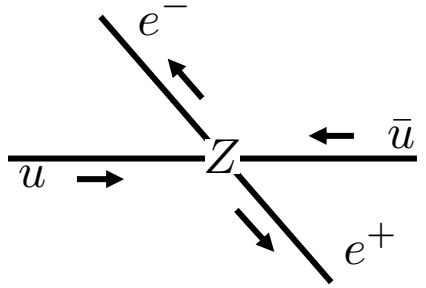
Standard Model of Particle Physics



Z-boson Transverse Momentum (p_T^Z)

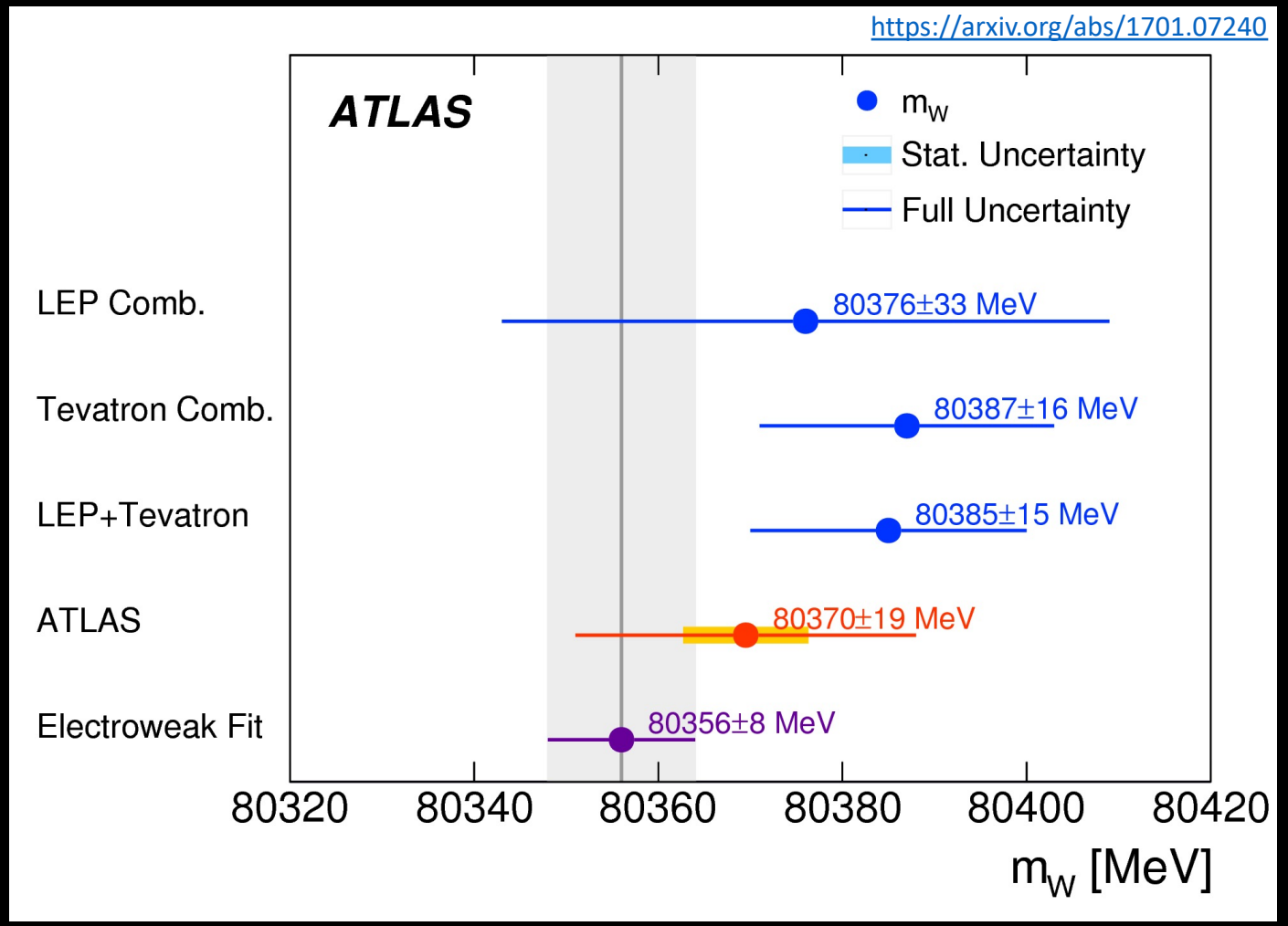


(**LO** schematic)



- 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

W-boson Mass Measurement (m_W)



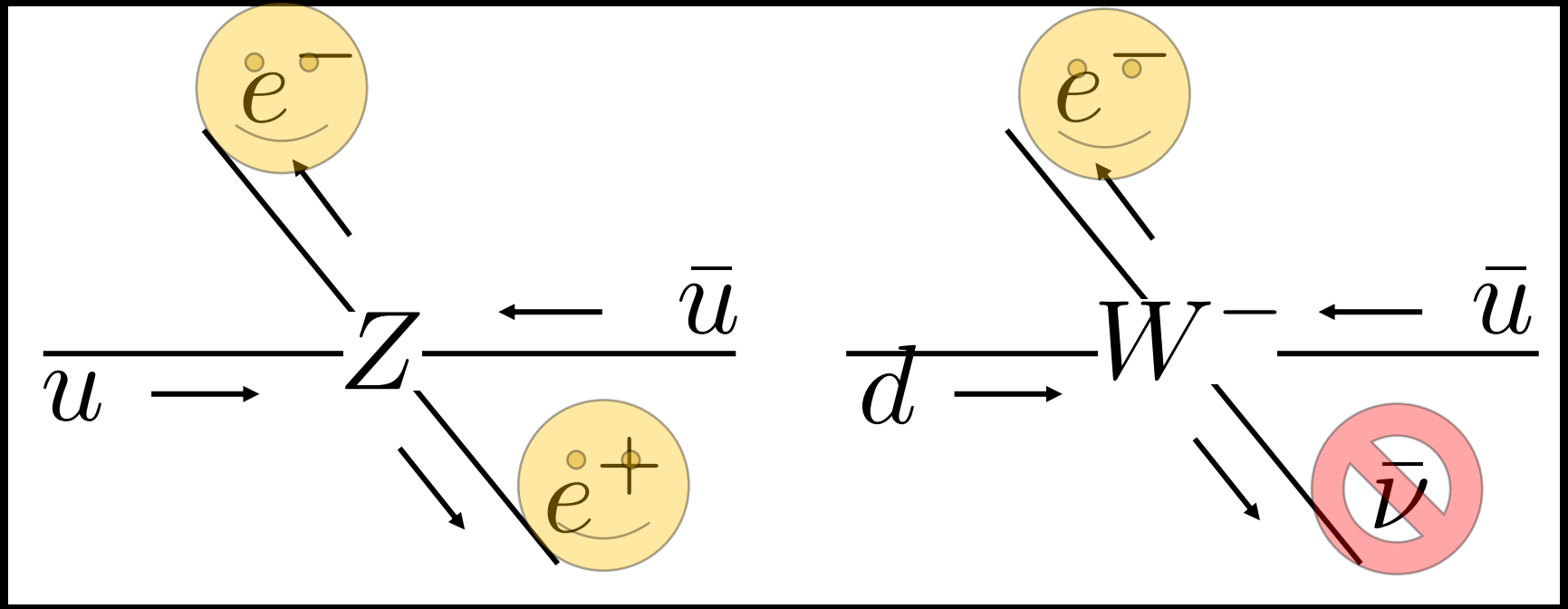
- m_W measured by fitting templates to p_T^l and m_T

$$m_T = \sqrt{2p_T^l \left(p_T^l + p_T^W\right)\left(1 + \cos\Delta\phi\right)}$$

- Systematic uncertainties on p_T^l and m_T account for ~50% of the measurement error on m_W

- **Experiment uncertainty > theory uncertainty!**
- **To improve m_W measurement, need p_T^Z (and p_T^W) systematic uncertainties to be < 1%**

Motivation for p_T^Z



- *Z* and *W* have a similar decay schematically; however, we can measure electrons and muons ($e^{\pm}/\mu^{\pm}$) but not neutrinos (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

How *Z* Supports *W*

Z decay: $Z \rightarrow l^+ l^-$

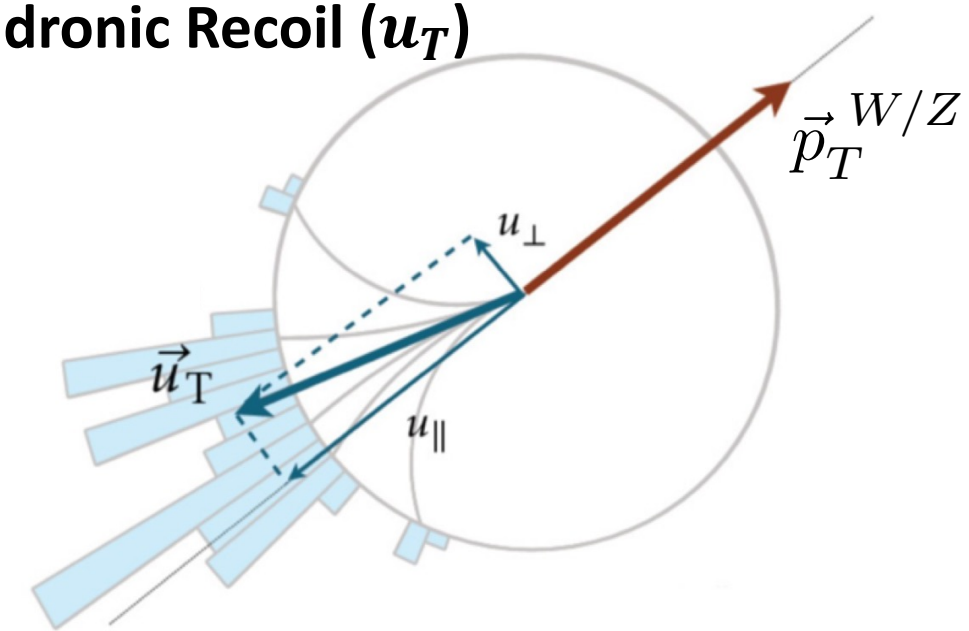
W decay: $W^{\pm} \rightarrow l^{\pm} \nu$

$$\vec{p}_T^{\,W/Z} = \vec{p}_T^{\,lepton_1} + \vec{p}_T^{\,lepton_2} = -\vec{u}_T$$

→ Only *Z* (p_T^{ll})

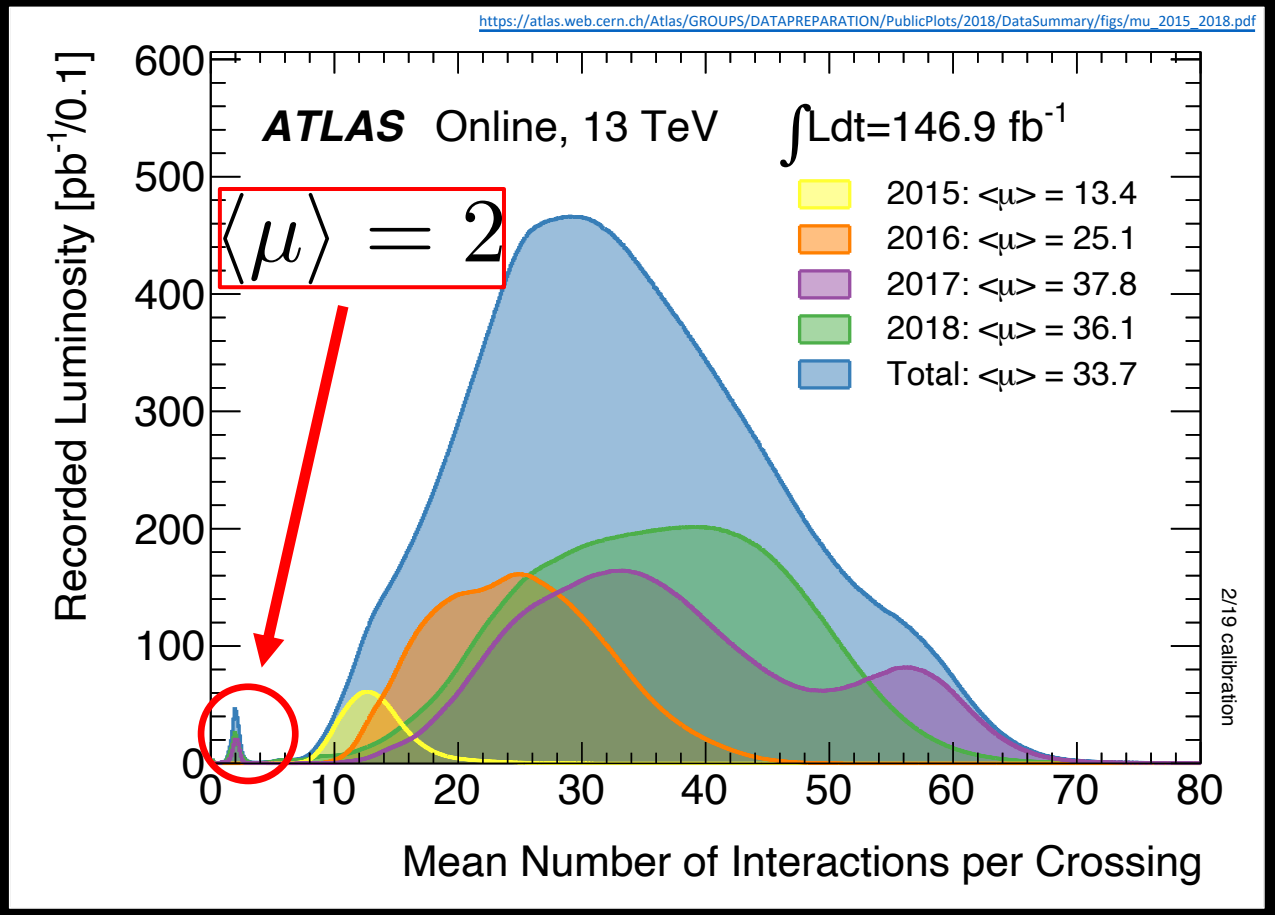
→ *W* & *Z* (u_T)

Hadronic Recoil (u_T)

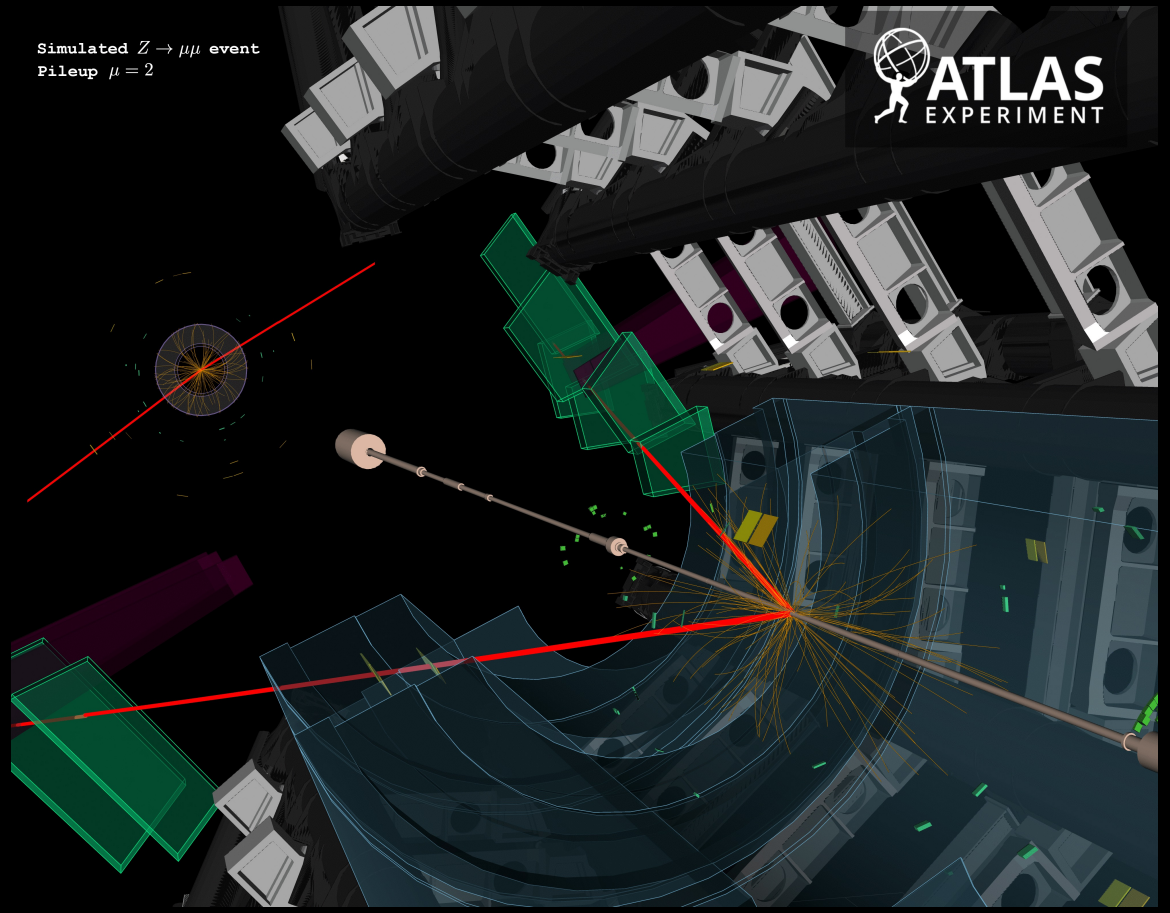


- p_T^{ll} and u_T are theoretically equal but hadronic recoil is inherently more difficult to measure
- Low pileup (μ) environment improves u_T resolution

Low Pileup Environment

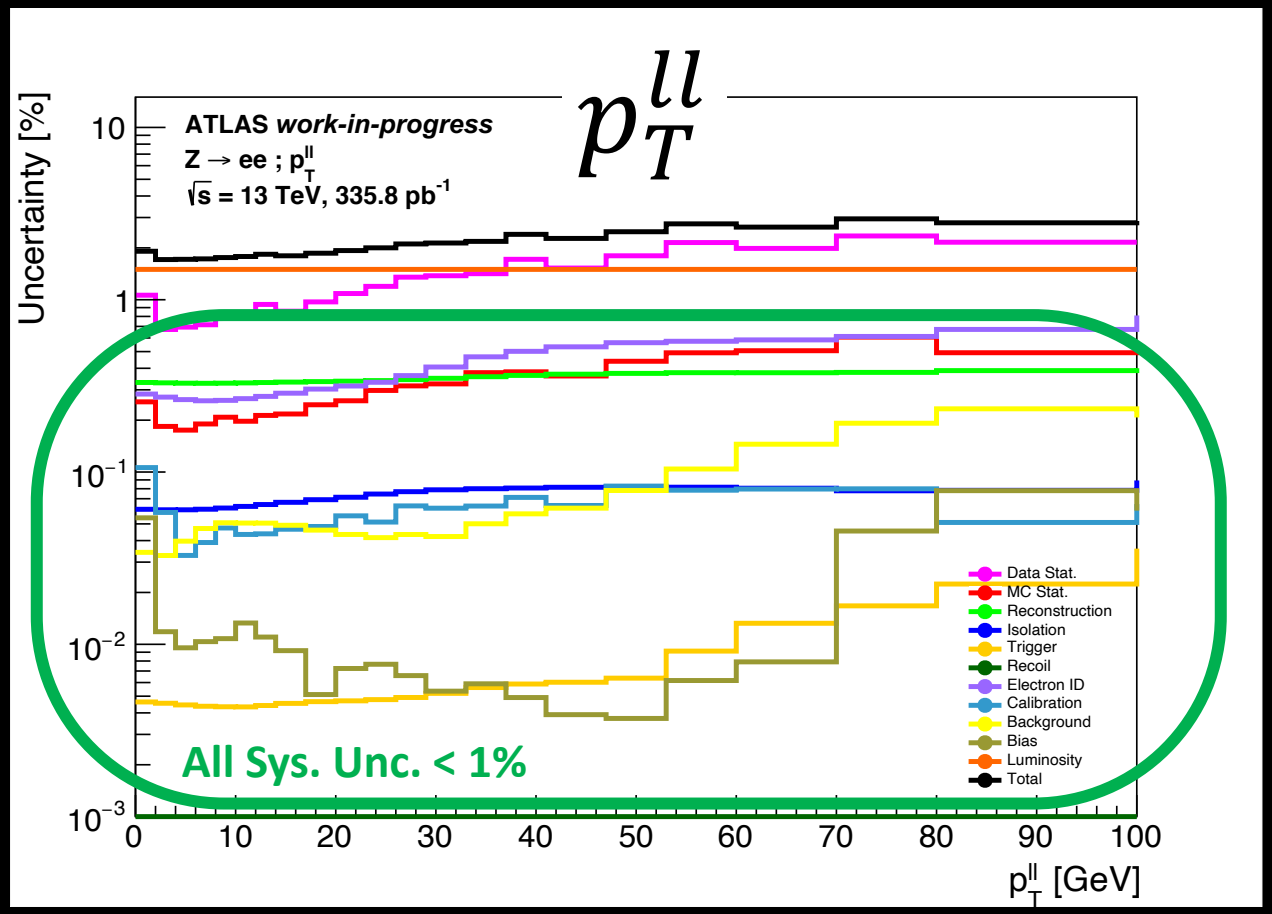


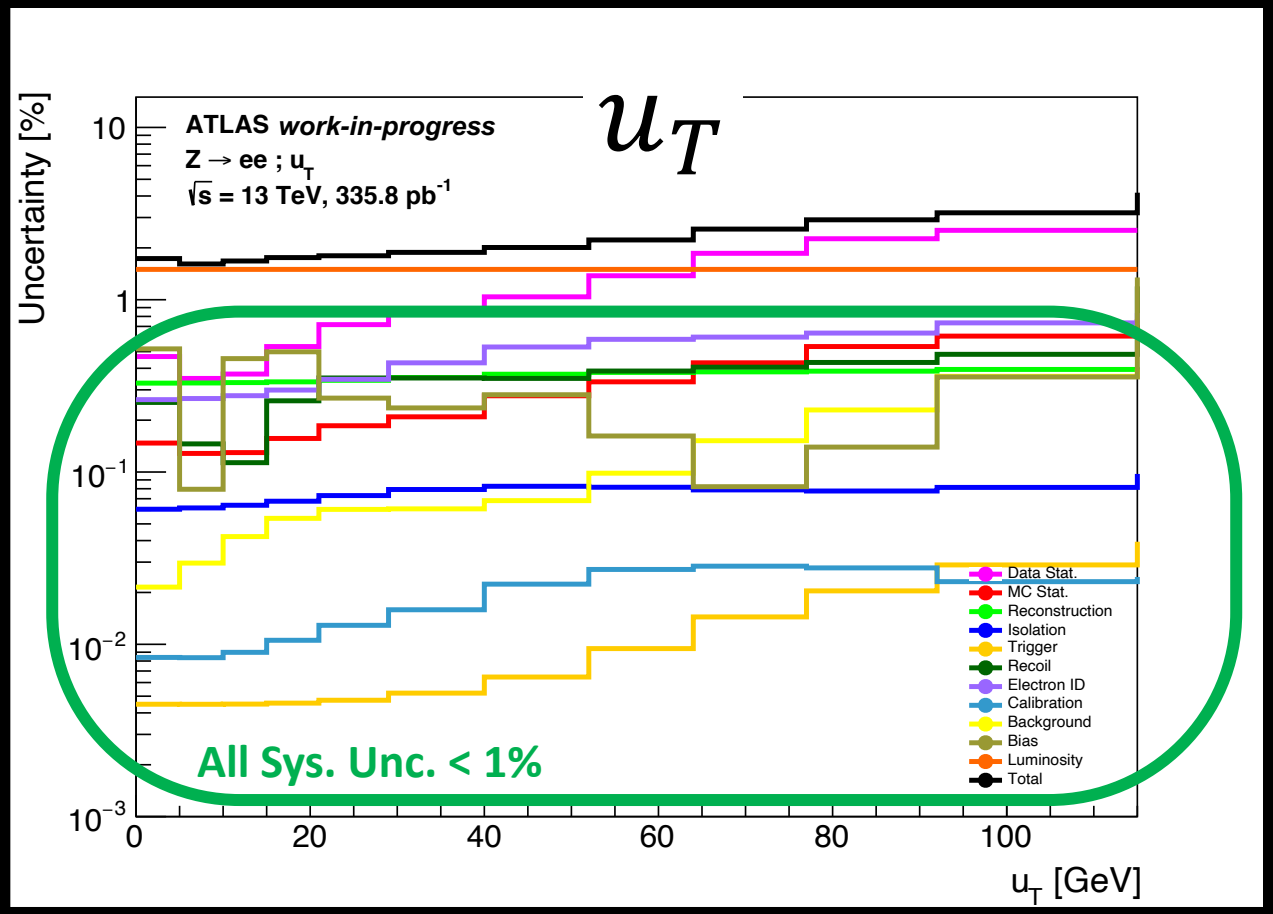
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2



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

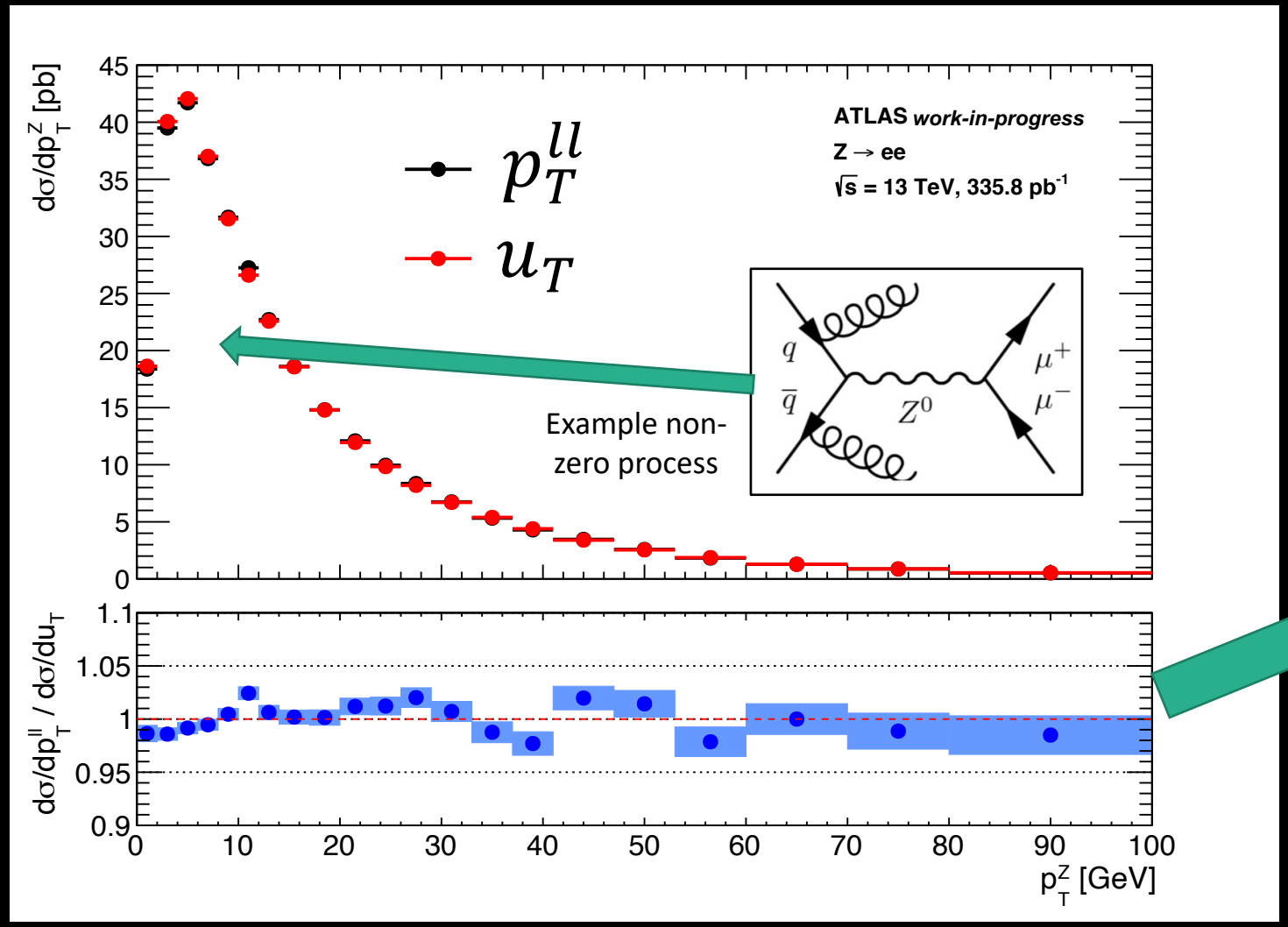
p_T^Z Measurement Uncertainties





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

Observable Cross-Section Comparison

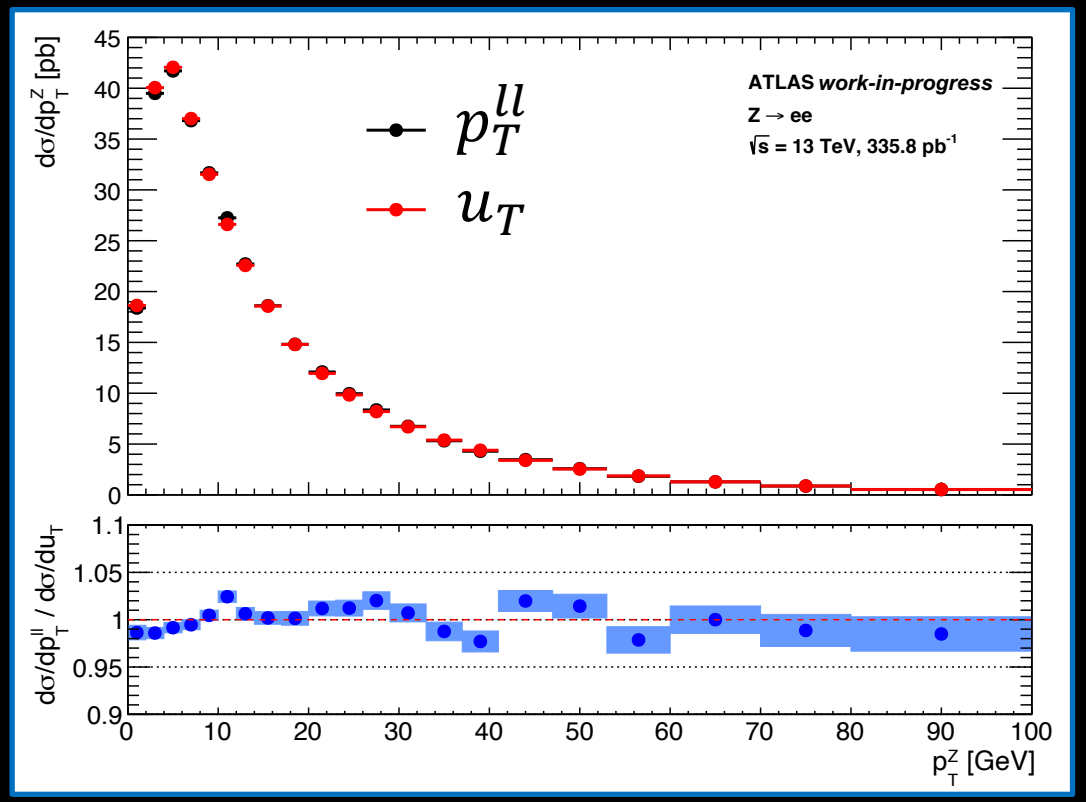


p_T^{ll}/u_T ratio

- 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

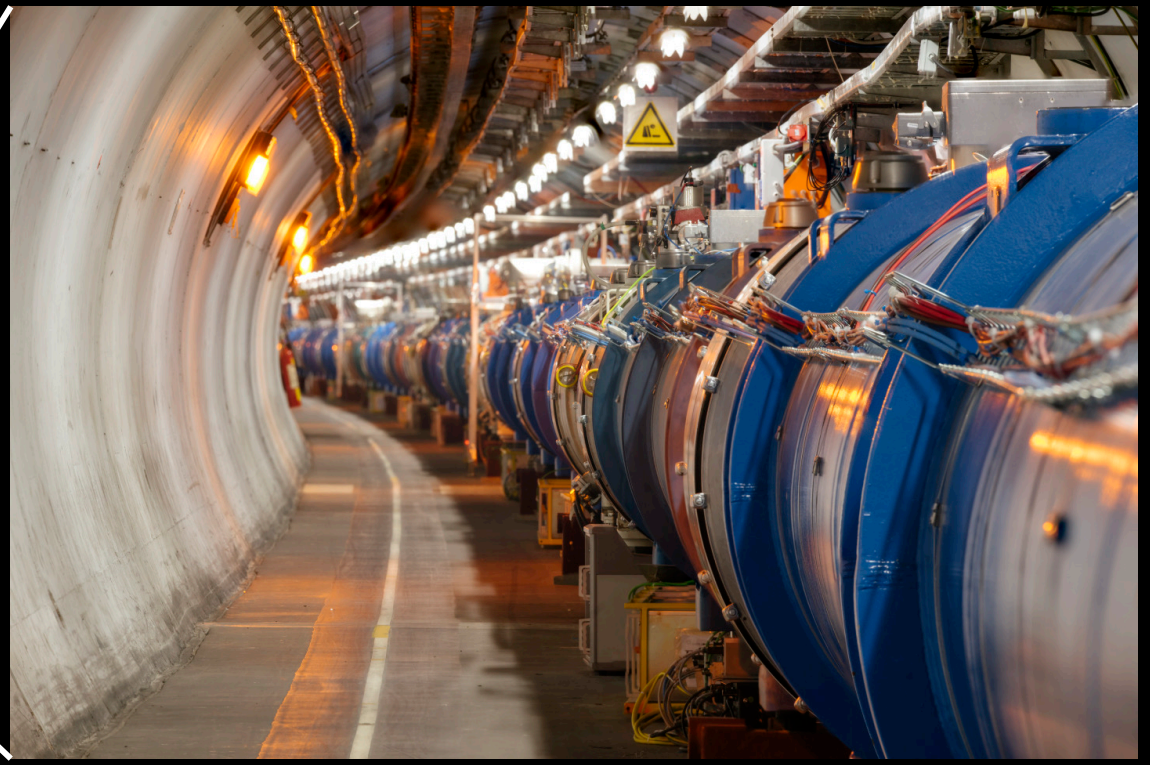
- p_T^Z differential cross-section measurement made at E_{CM} = 5, 13 TeV
- Clean low pileup environment allows for precise measurement of hadronic recoil (u_T)
- p_T^{ll} and u_T are compatible and both have systematic error below 1%
- Finalizing precision p_T^Z and p_T^W measurements with low pileup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



Backup Slides

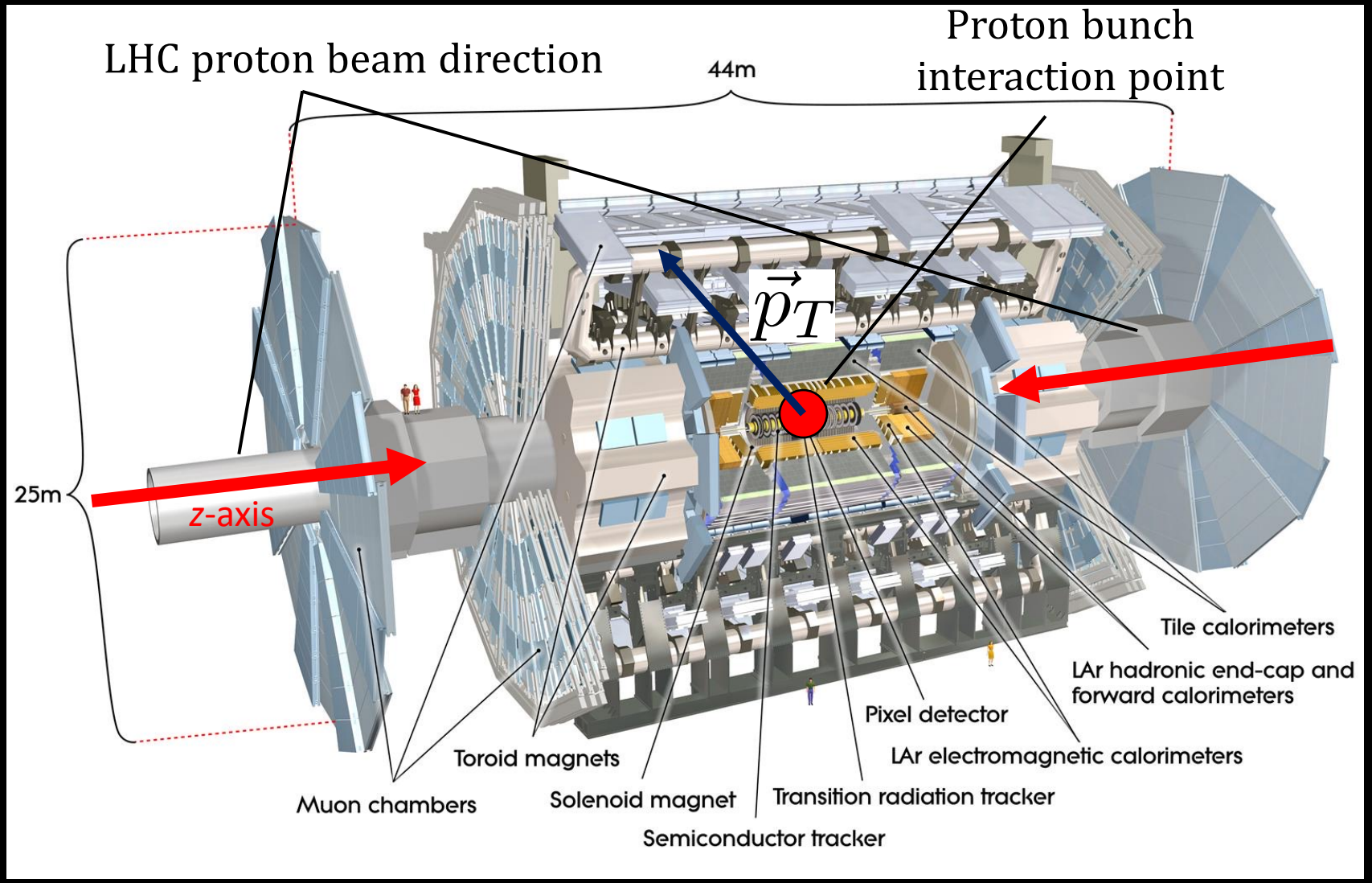
Large Hadron Collider (LHC) at CERN

- 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!



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

Measurements

"Known" Processes

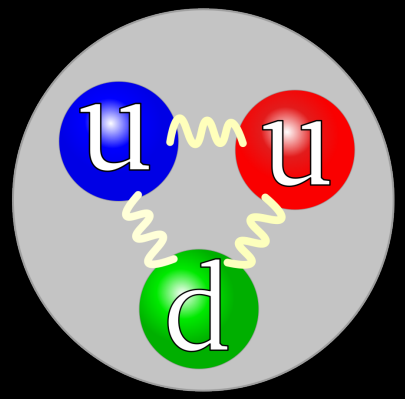
- Can we measure this for the first time?
- Example: first measurement of light-by-light scattering

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

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

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



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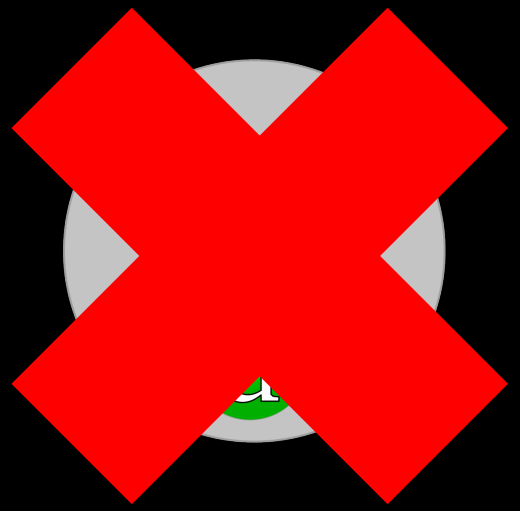

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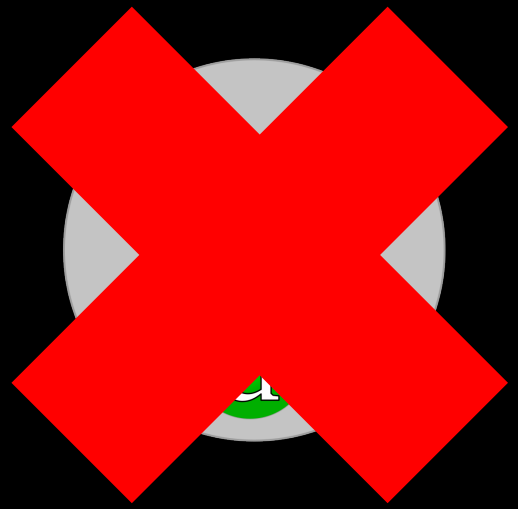

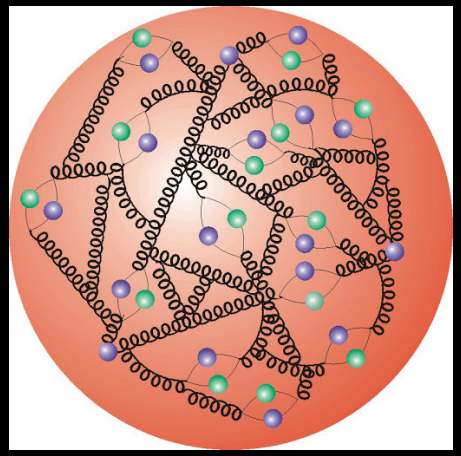

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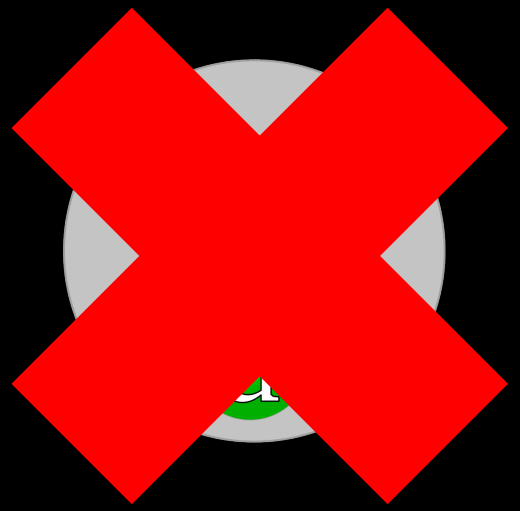
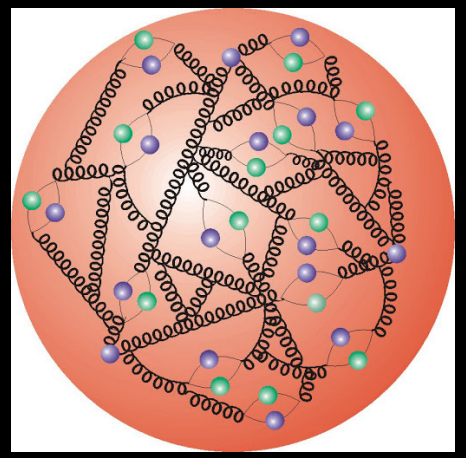
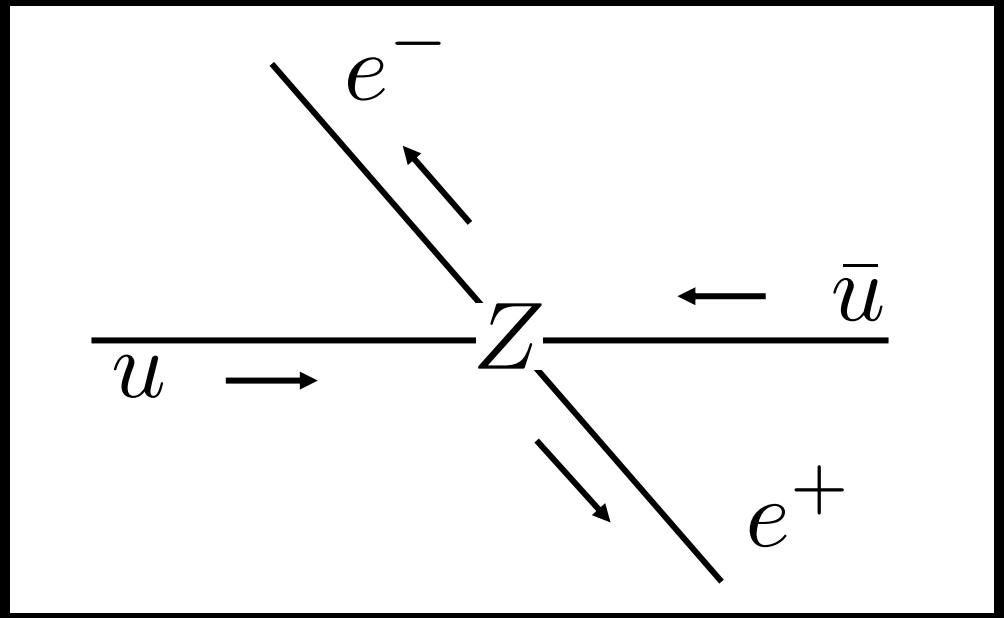
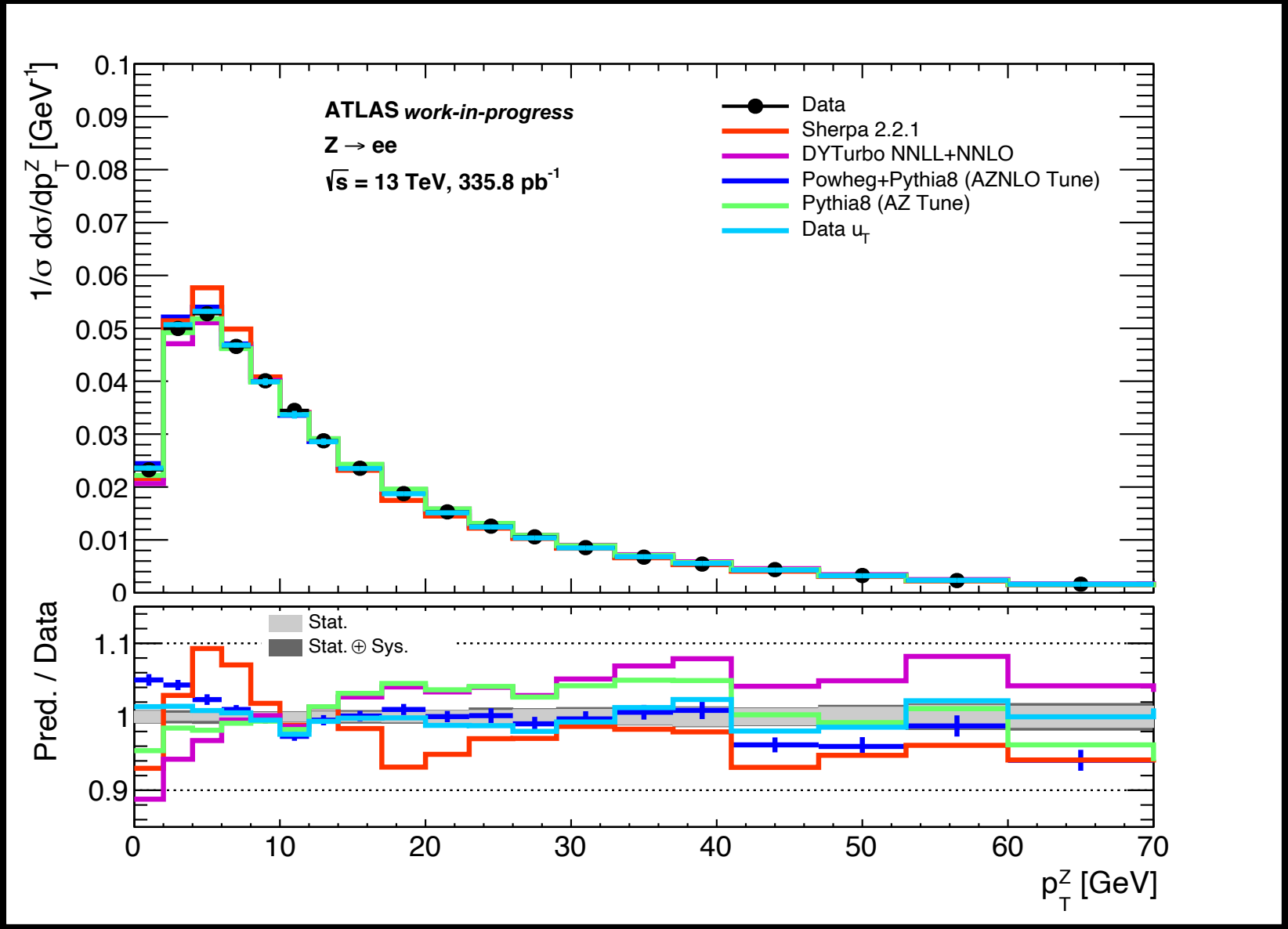




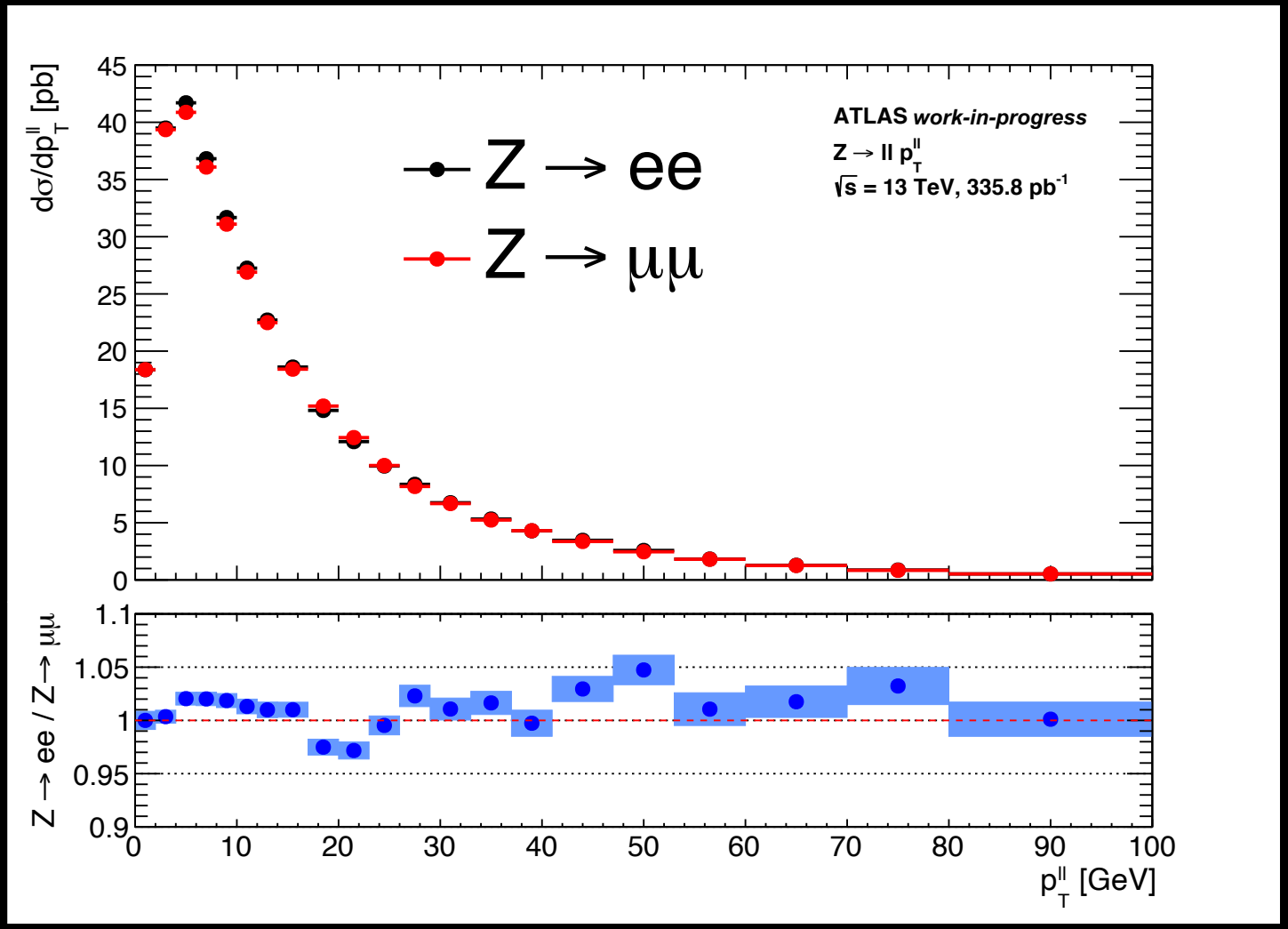


At first glance, by momentum conservation we would expect $p_T^Z = 0$!

Normalized Differential Cross-Section

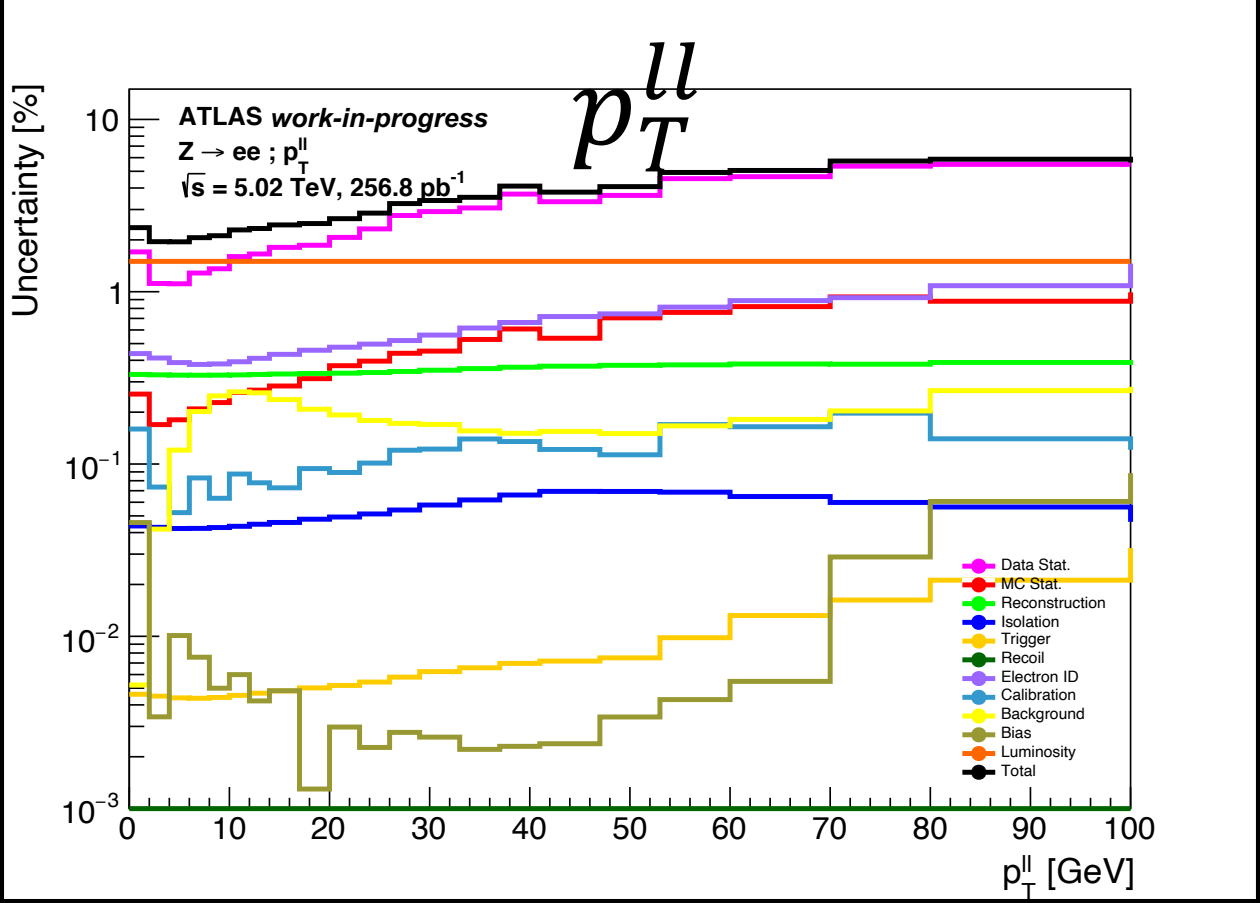


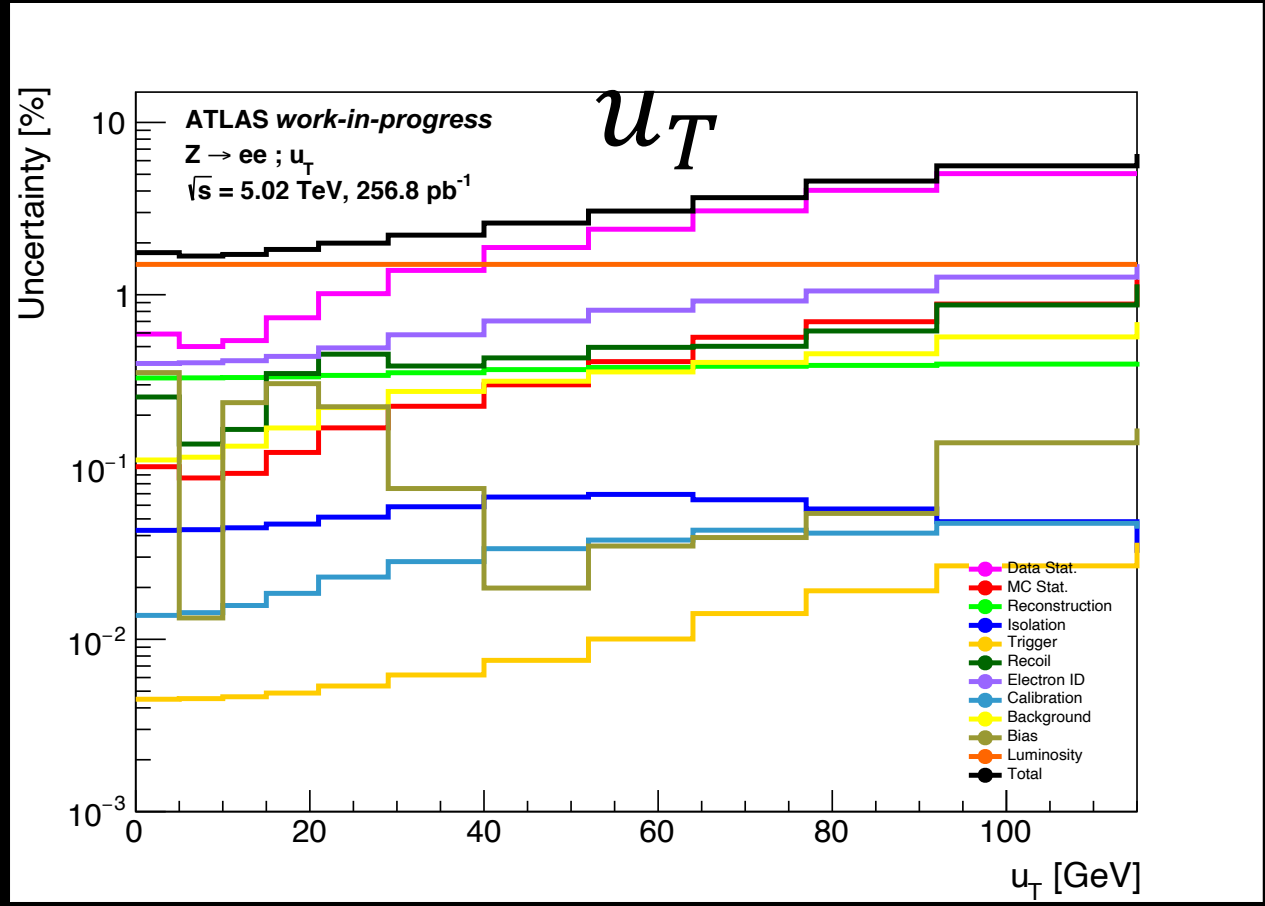
Lepton channel cross-section comparison



- 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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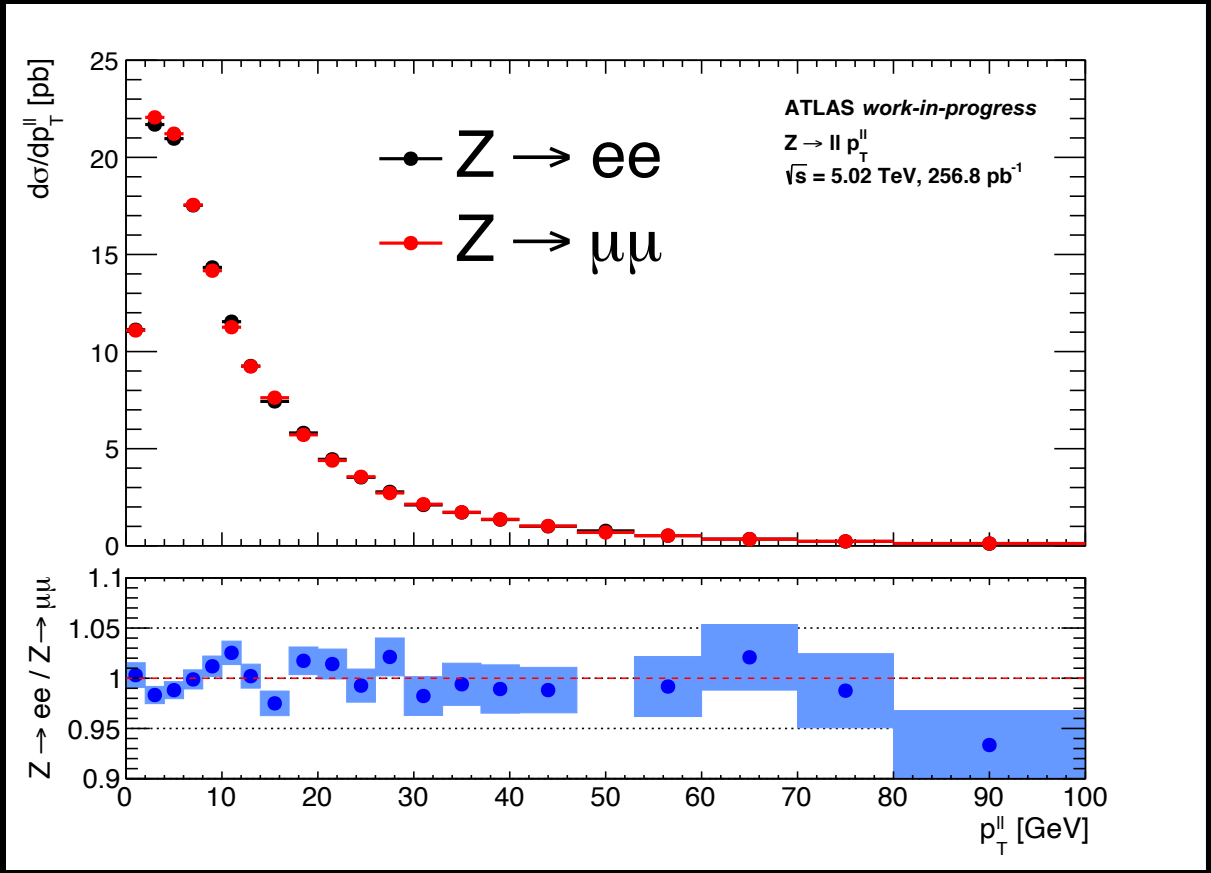
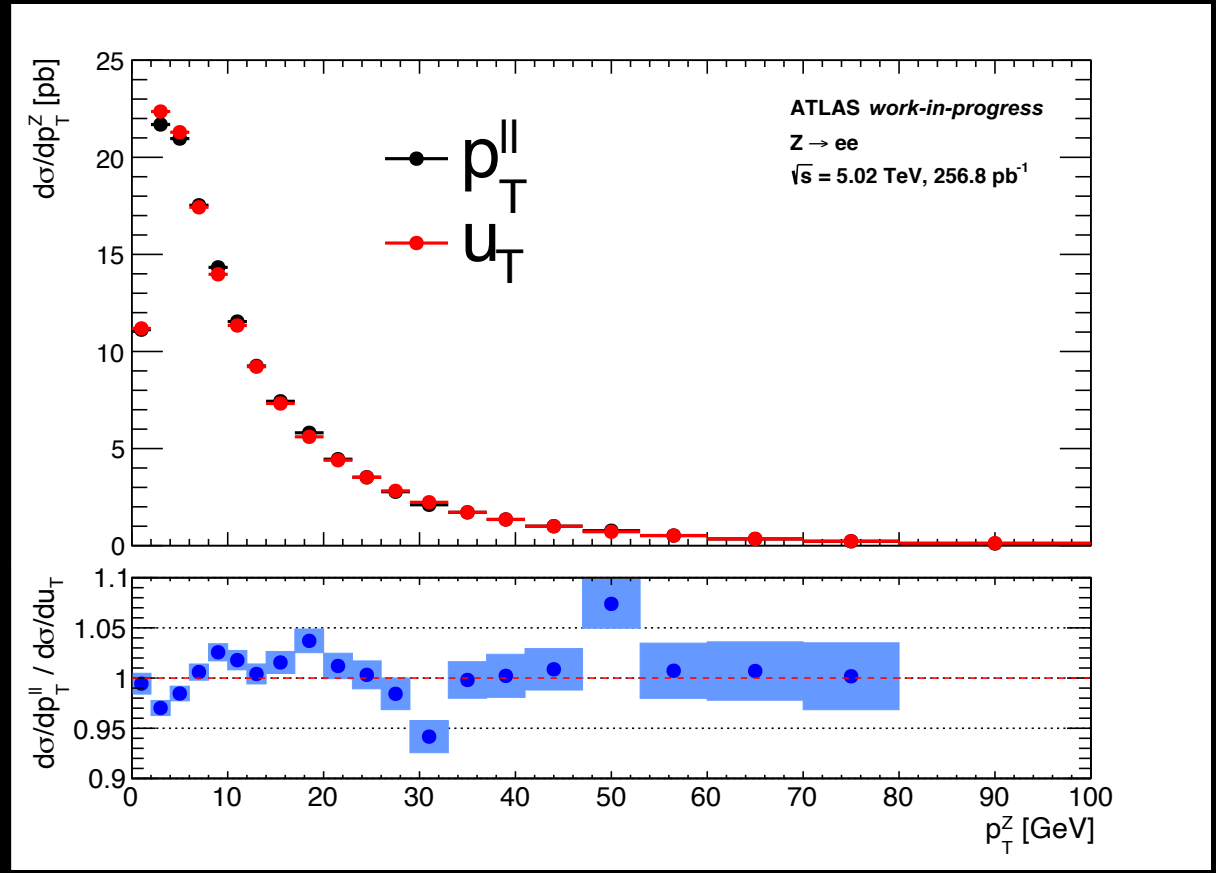


Observable cross-section comparison



E_{CM} = 5 TeV

Normalized Differential Cross-Section