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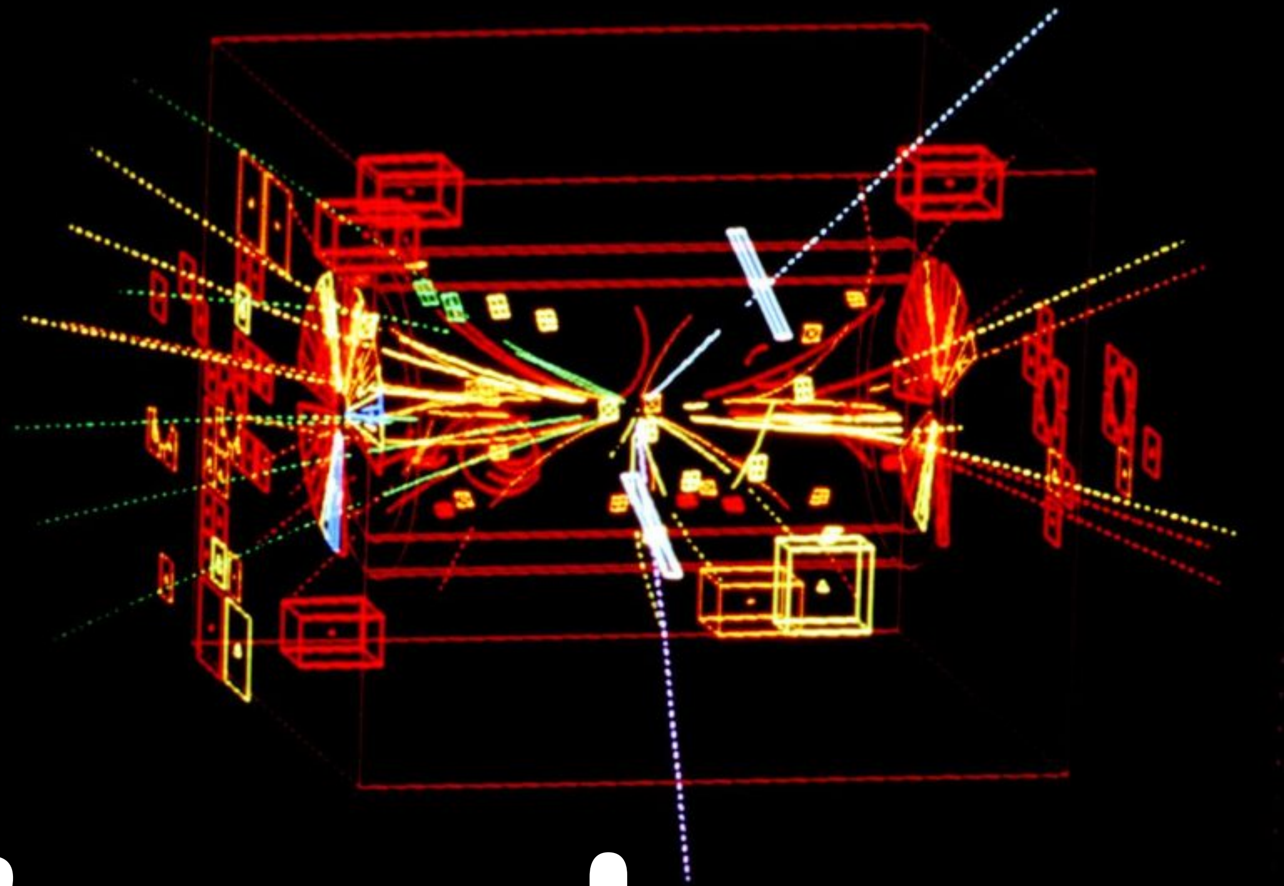
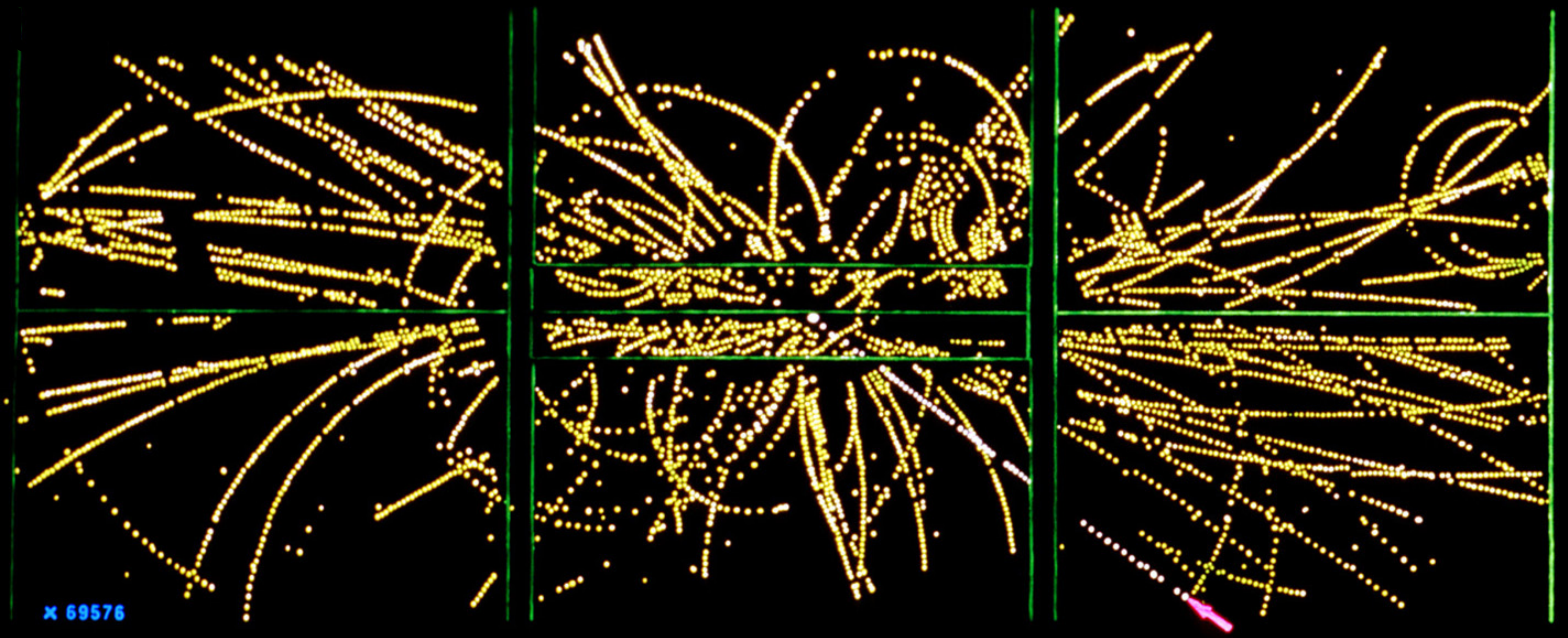
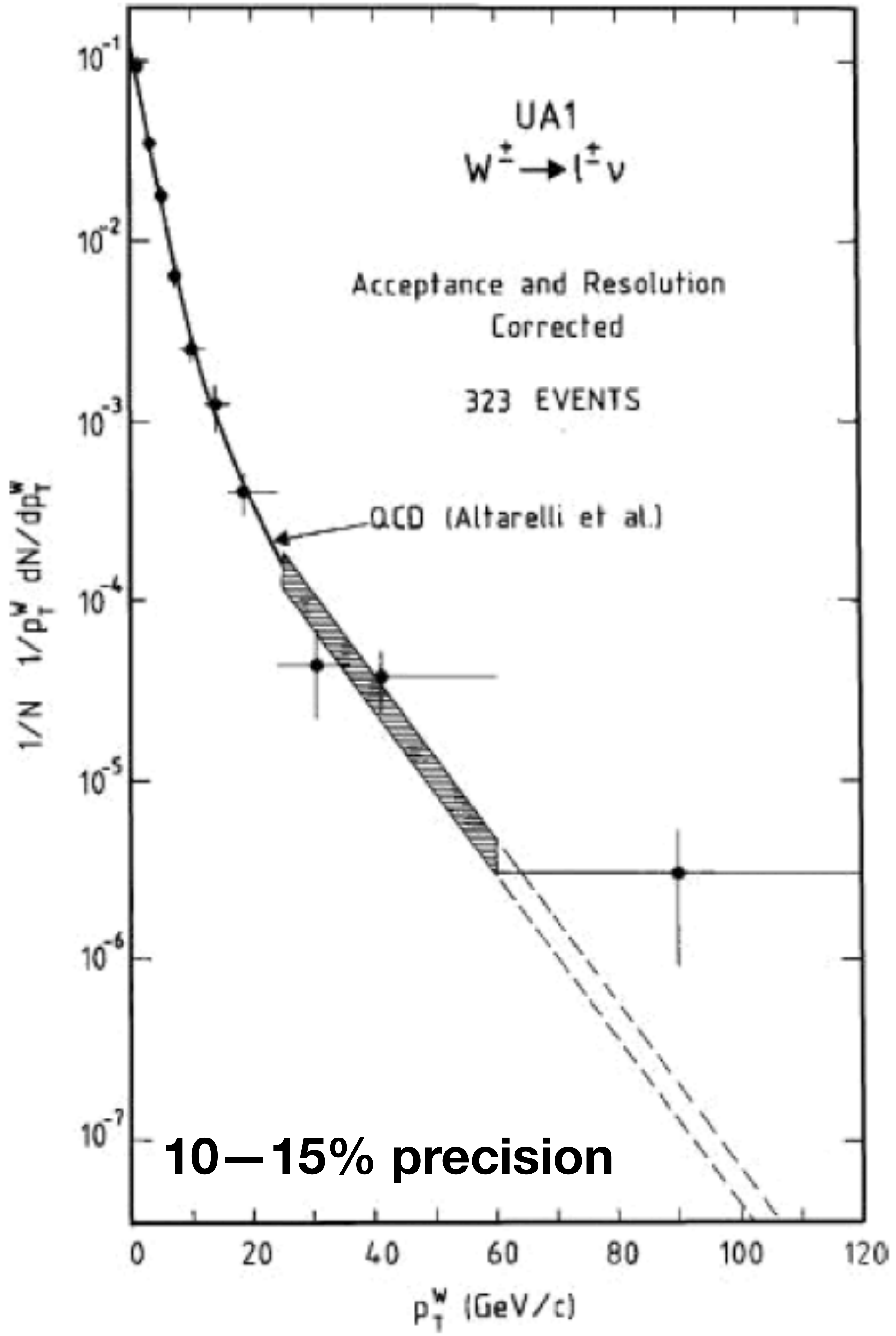


Measurements of W, Z and Drell-Yan processes in ATLAS

Xuewei Jia
on behalf of the ATLAS Collaboration
18. Jul, Prague, ICHEP2024



W, Z and Drell-Yan measurements



Albajar et al. (UA1 Collaboration), Z. Phys. C 44, 15 (1989).

Long history of W, Z measurements

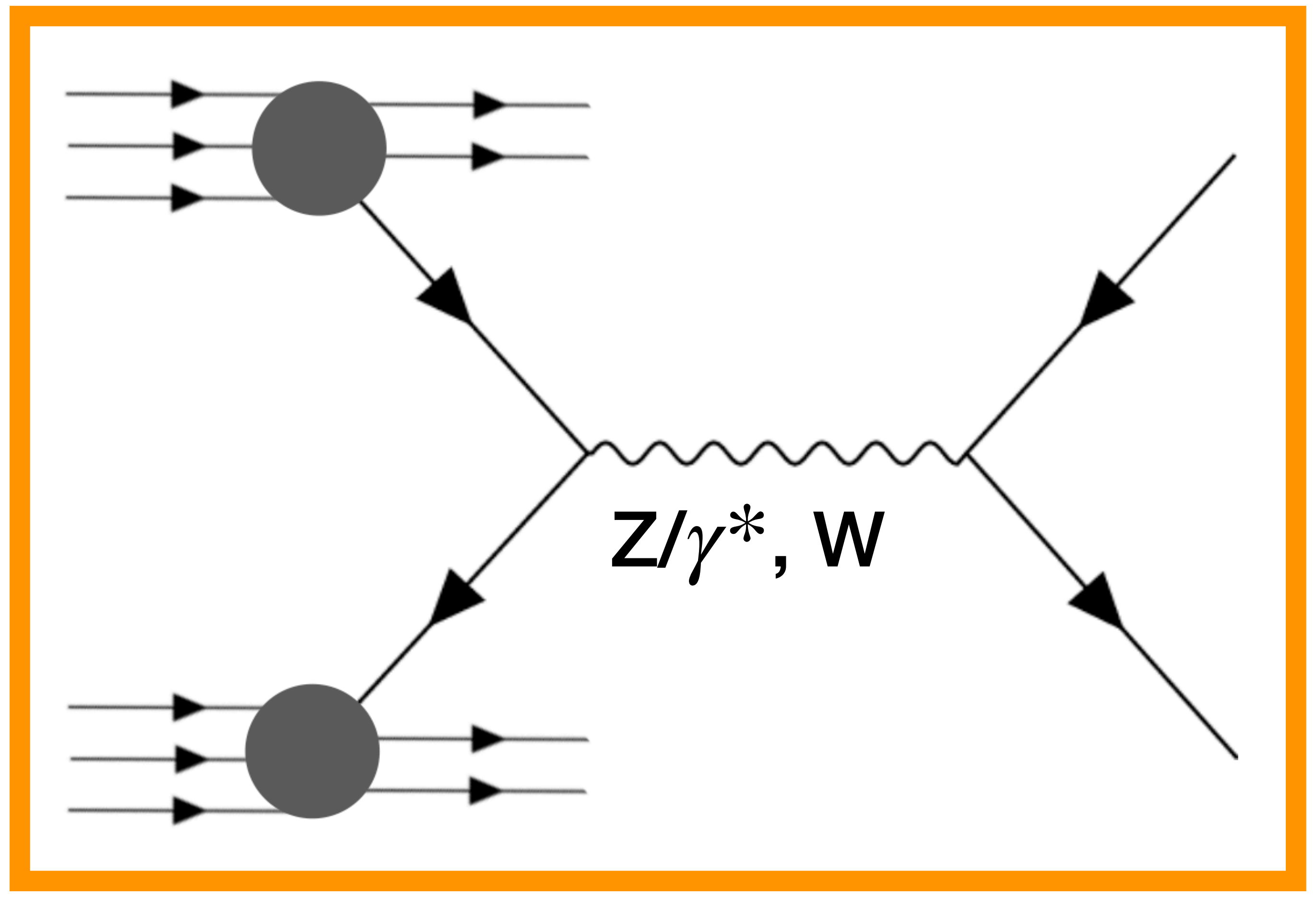
- Stringent tests of the electroweak theory and perturbative and non-perturbative QCD
- Provides important information on the partonic structure
- Set limit to new physics
- Milestone for more precision fundamental parameters measurements, e.g. W mass

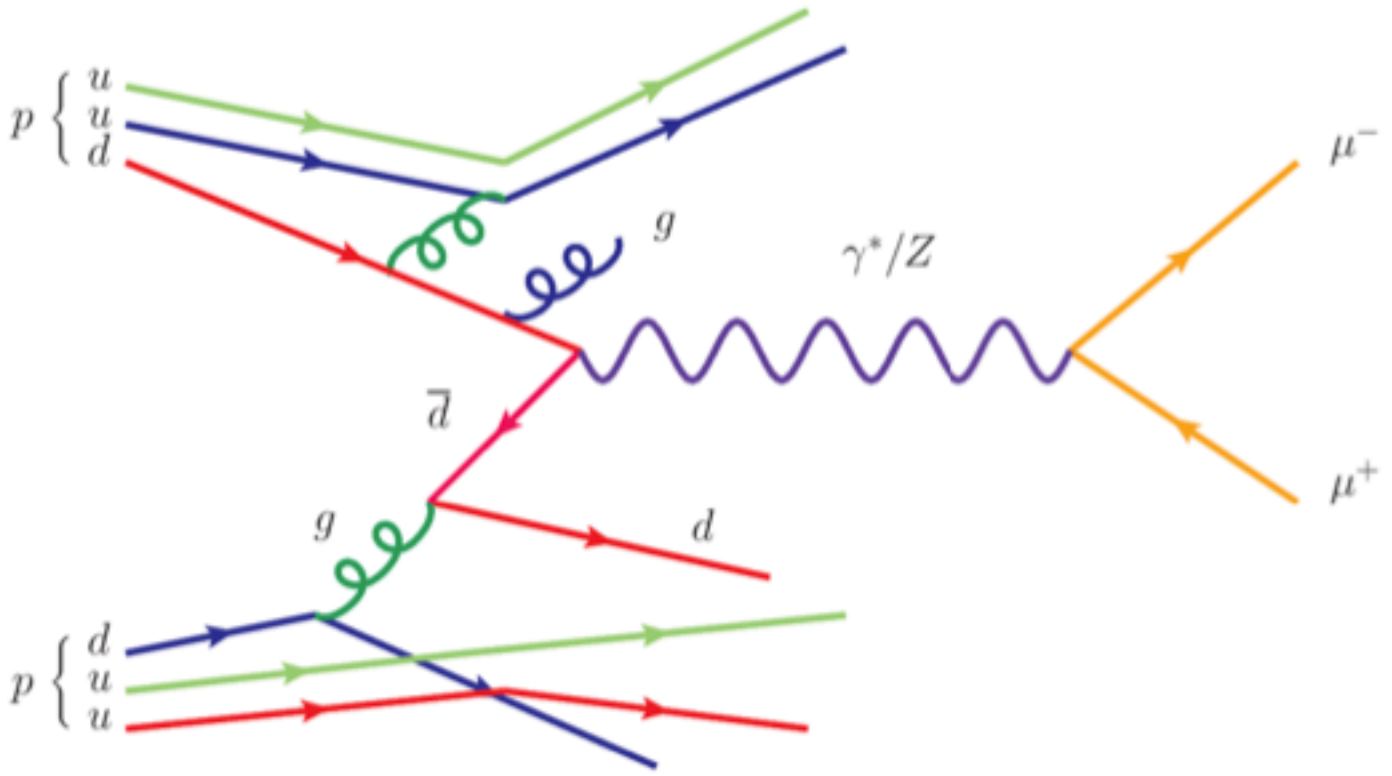
ATLAS miscellanea for this talk:

- W, Z cross section measurement
- Low- and high-mass Drell-Yan
- W hadronic decay mode search
- W, Z transverse momentum measurement

Drell-Yan Process

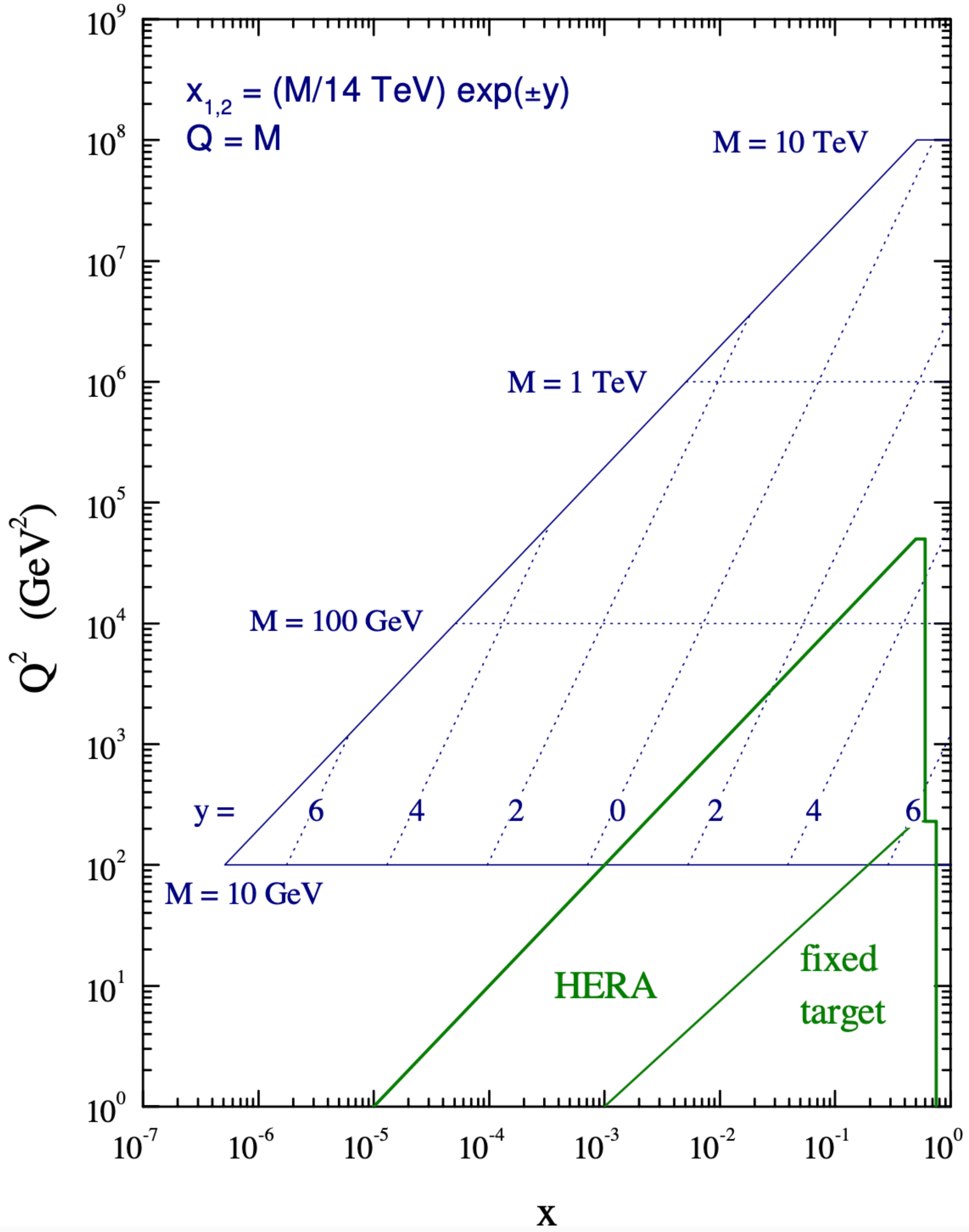
Low-order Drell-Yan process





(b) More realistic Drell-Yan diagram.

LHC parton kinematics



LHC explore higher energy scale

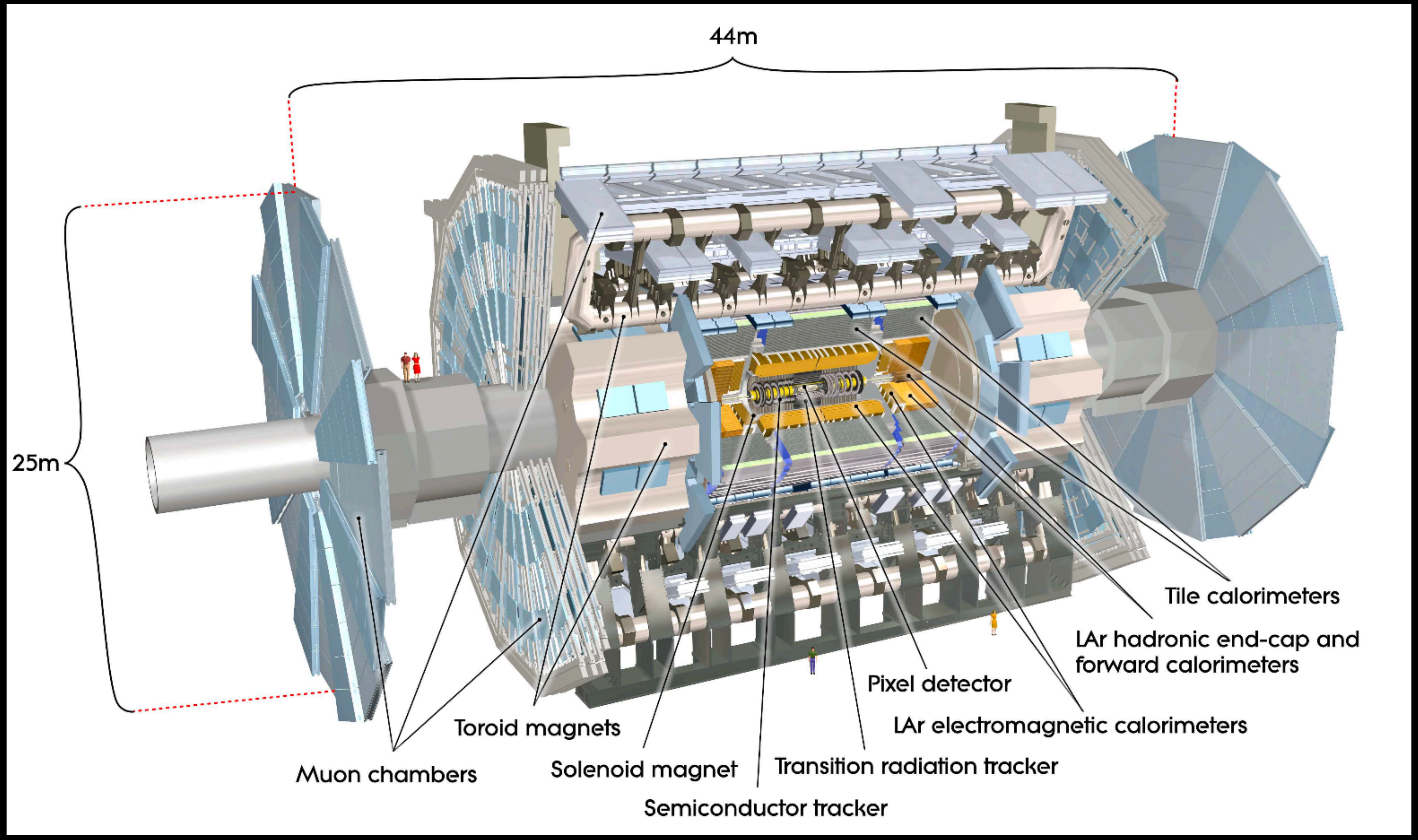
W, Z topology at ATLAS

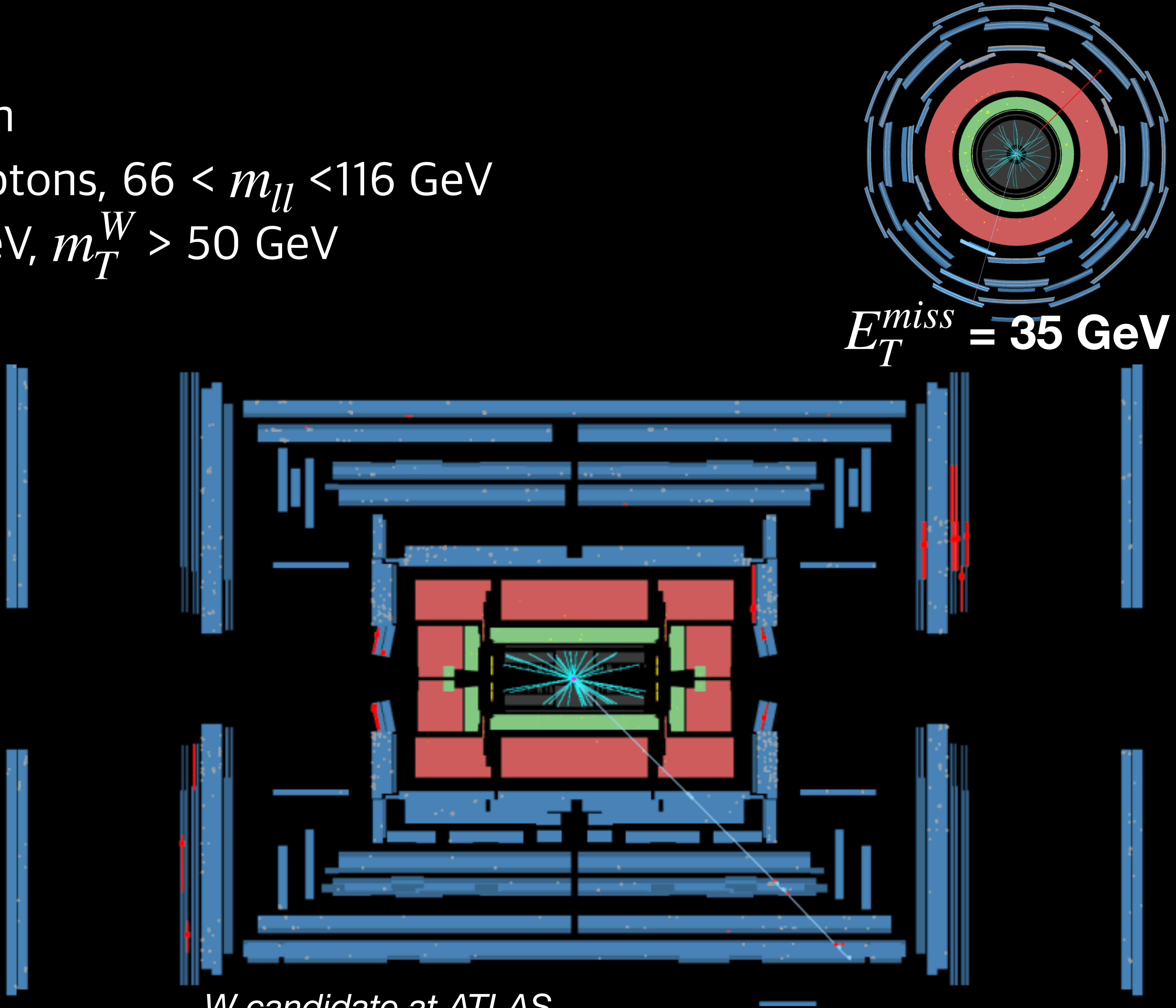
Typical W, Z selection:

Electron and muon: $p_T^l > 25$ GeV, tight isolation

Z-boson event: 2 opposite sign, same flavor leptons, $66 < m_{ll} < 116$ GeV

W-boson event: exactly 1 lepton, $E_T^{miss} > 25$ GeV, $m_T^W > 50$ GeV

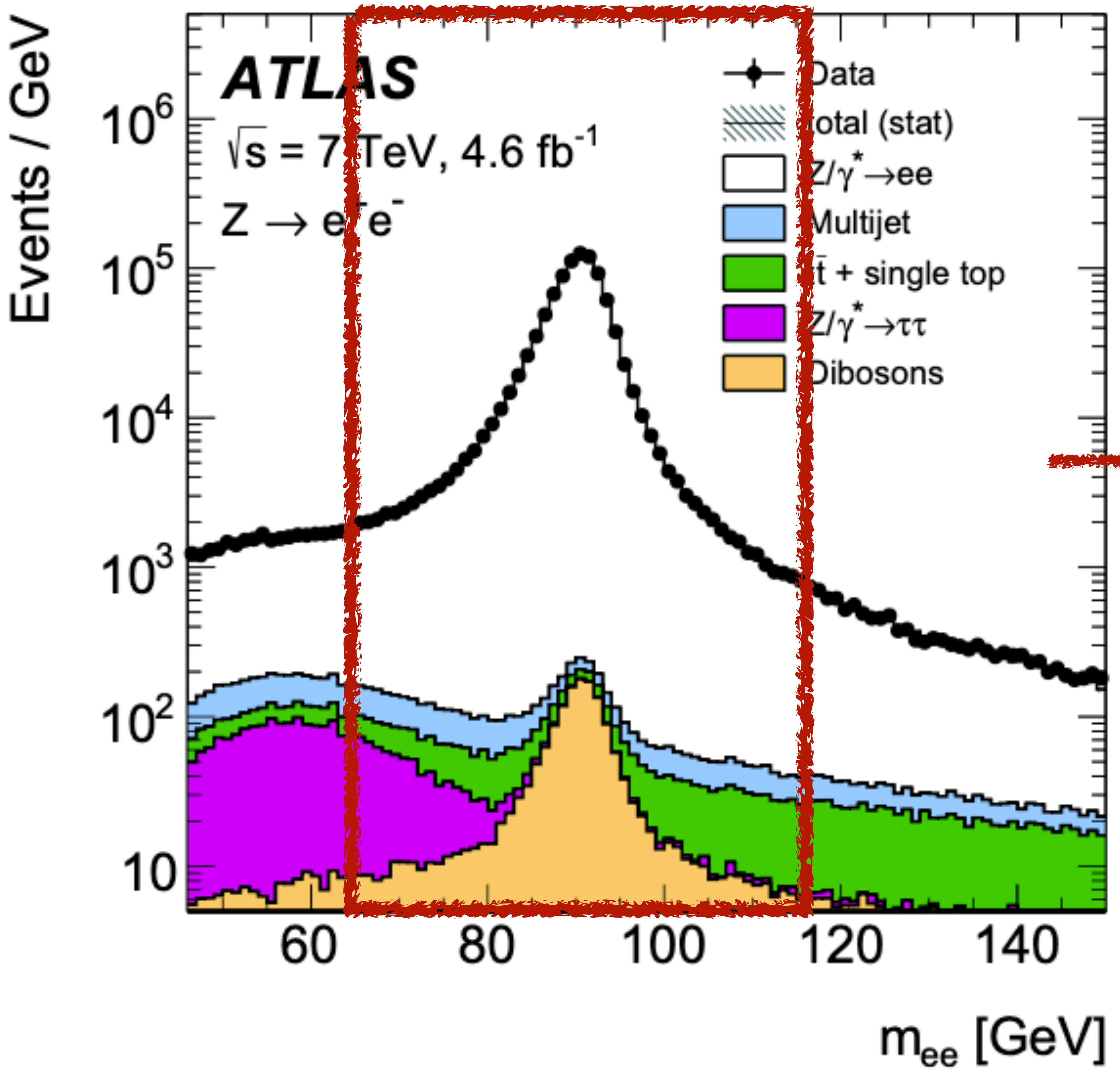




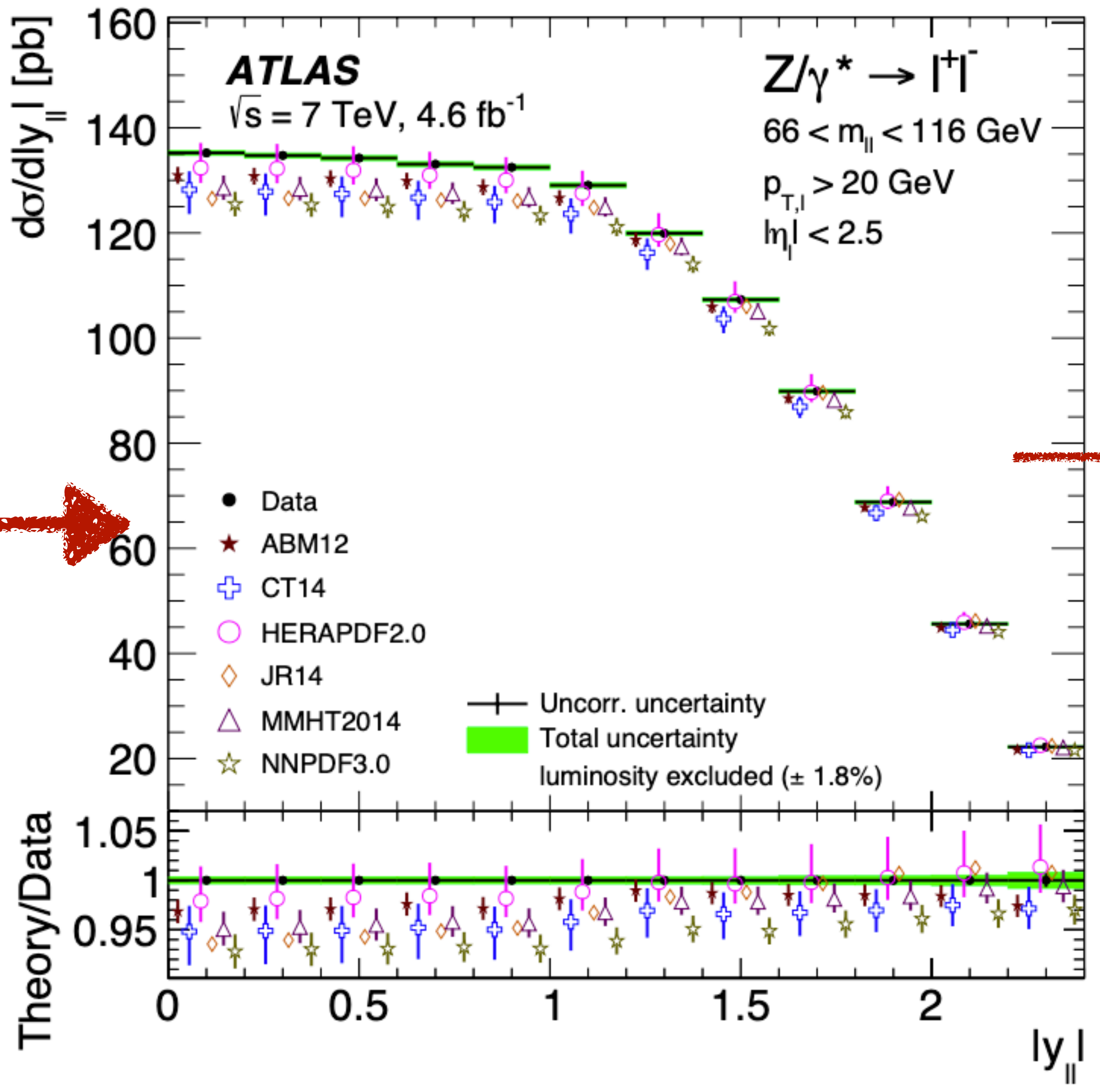
W candidate at ATLAS

Drell-Yan cross section measurements

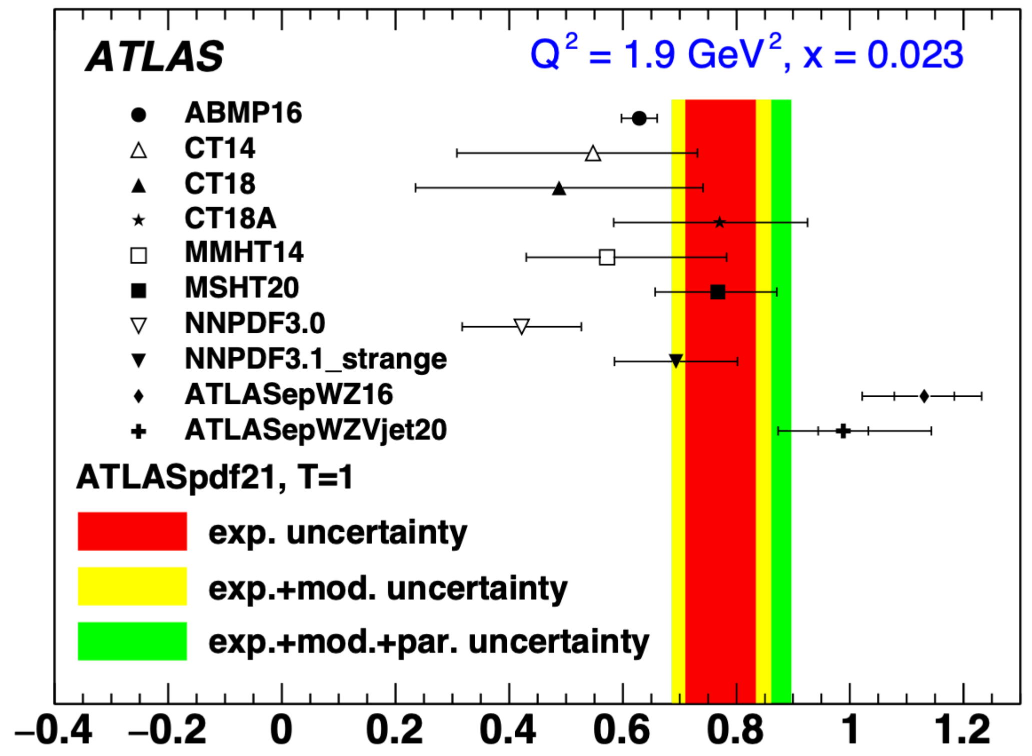
Very precise measurement around Z-resonance



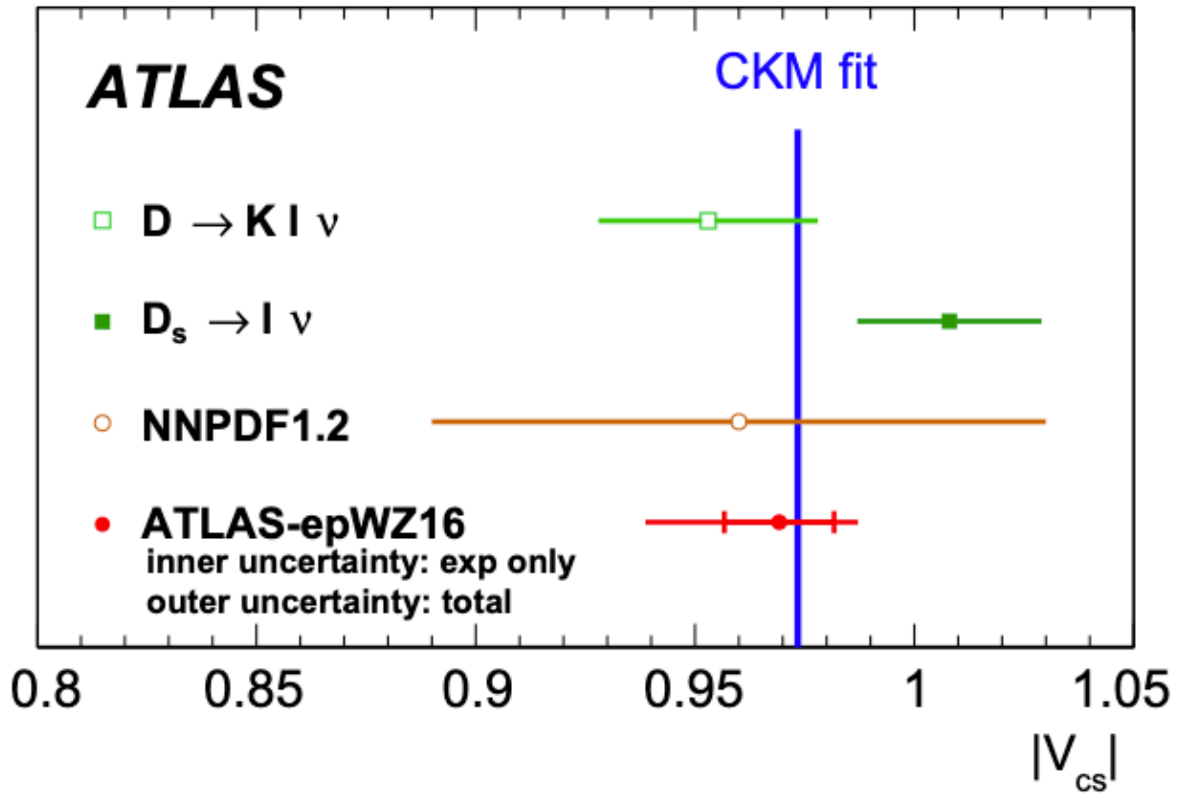
Give you understanding of QCD theory



strange quark density



Evolute from x=0.013, $Q^2 = m_Z^2$



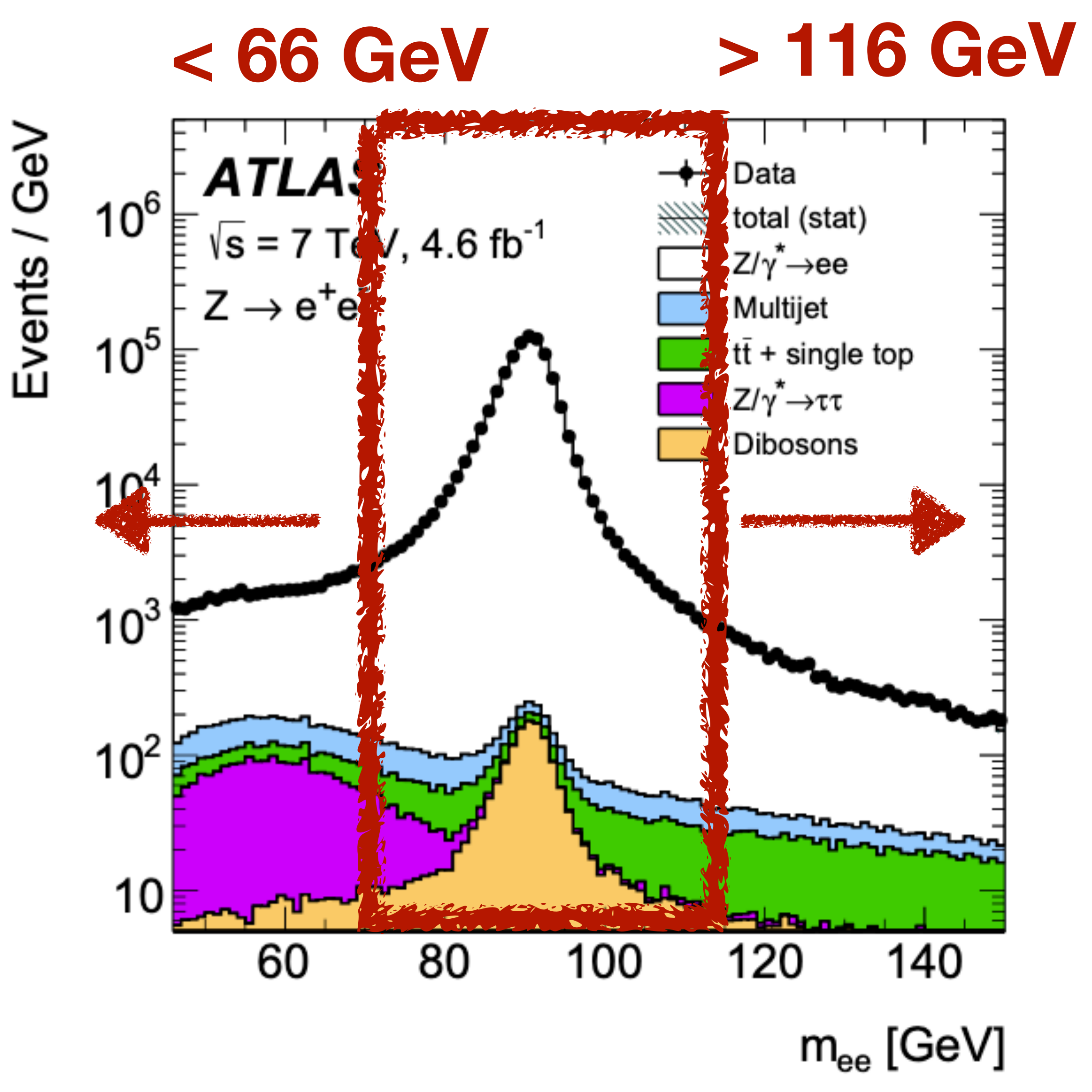
Eur. Phys. J. C 77 (2017) 367
Eur. Phys. J. C 82 (2022) 438

Drell-Yan cross section measurements

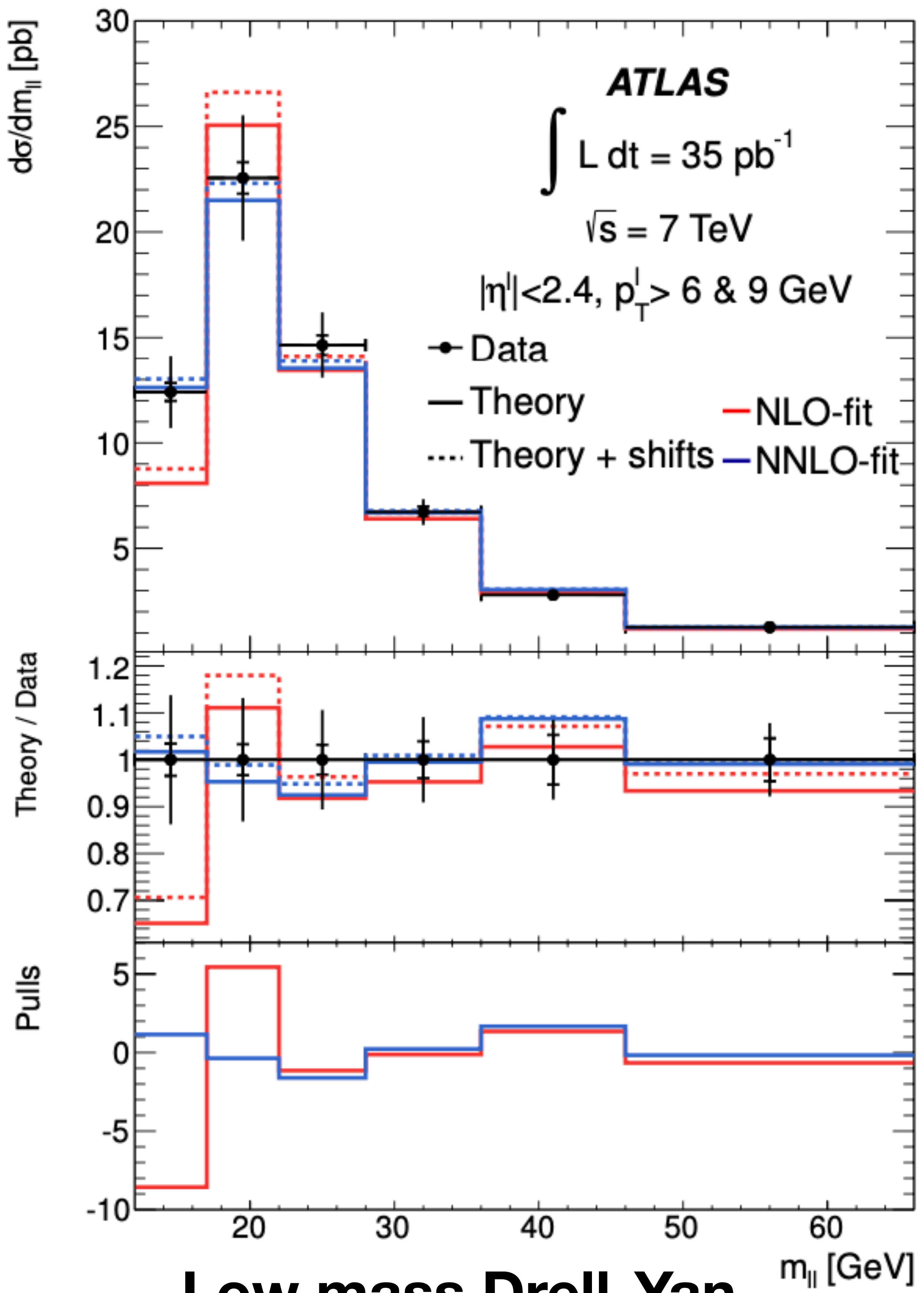
Low- and high-mass Drell-Yan

- off-shell m_{ll}, dominant by electromagnetic coupling of quark to the virtual photon (γ_*)
- different sensitivity to the up- and down-type quarks

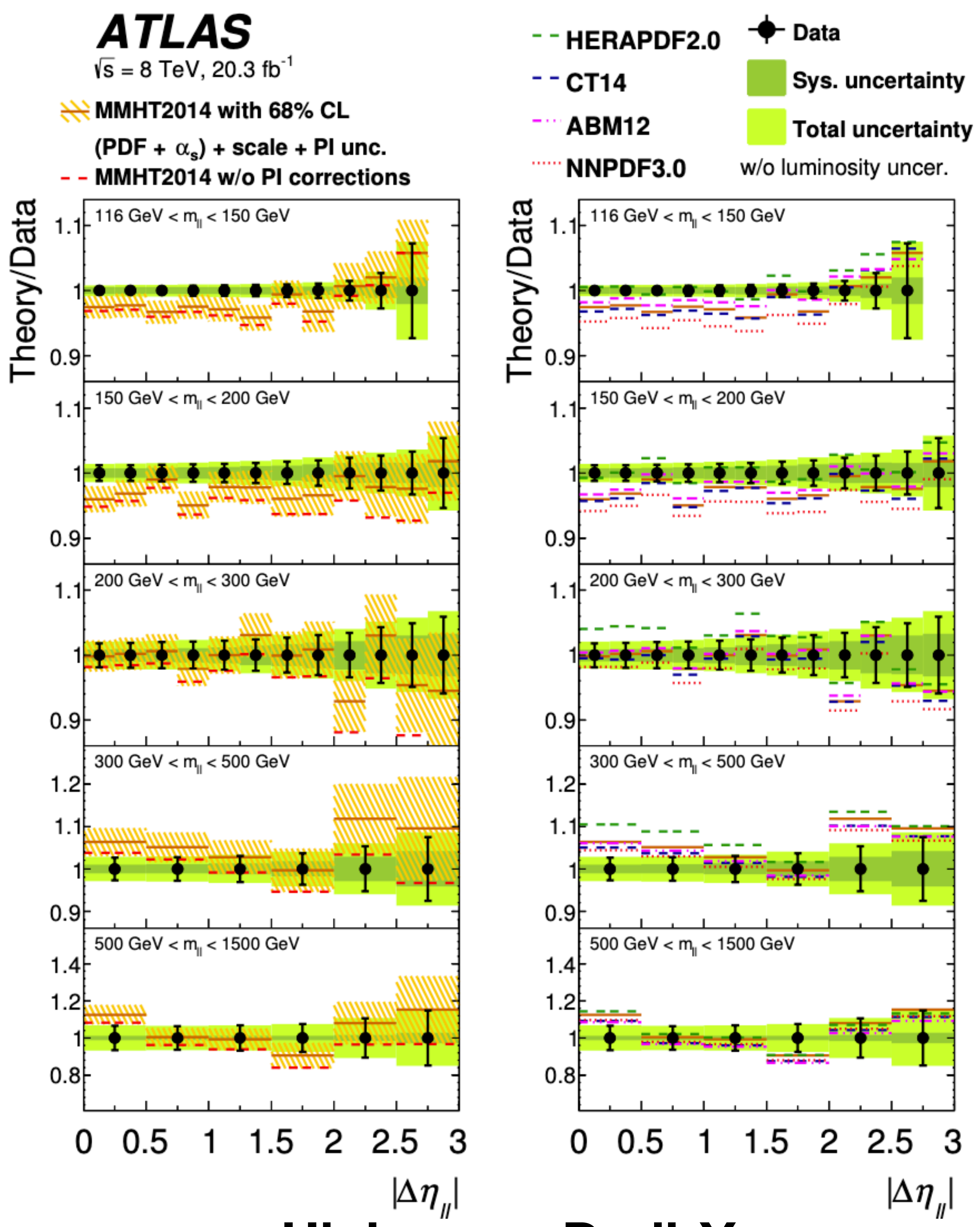
JHEP 08 (2016) 009
JHEP 06 (2014) 112



Low mass and high mass Drell-Yan



Low mass Drell-Yan



High mass Drell-Yan

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Drell-Yan cross section measurements

ATLAS EXPERIMENT

Low mass and high mass Drell-Yan

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JHEP 08 (2016) 009
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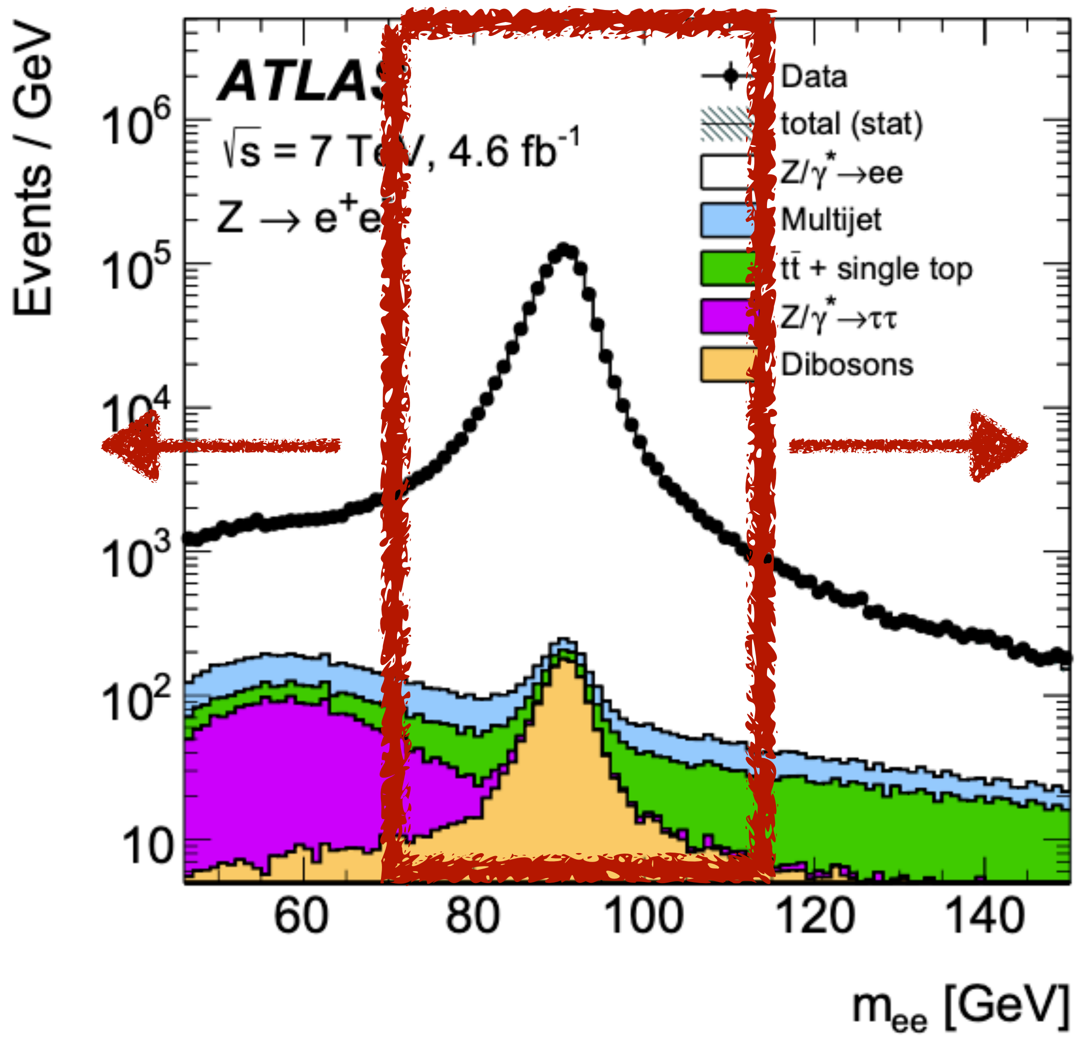
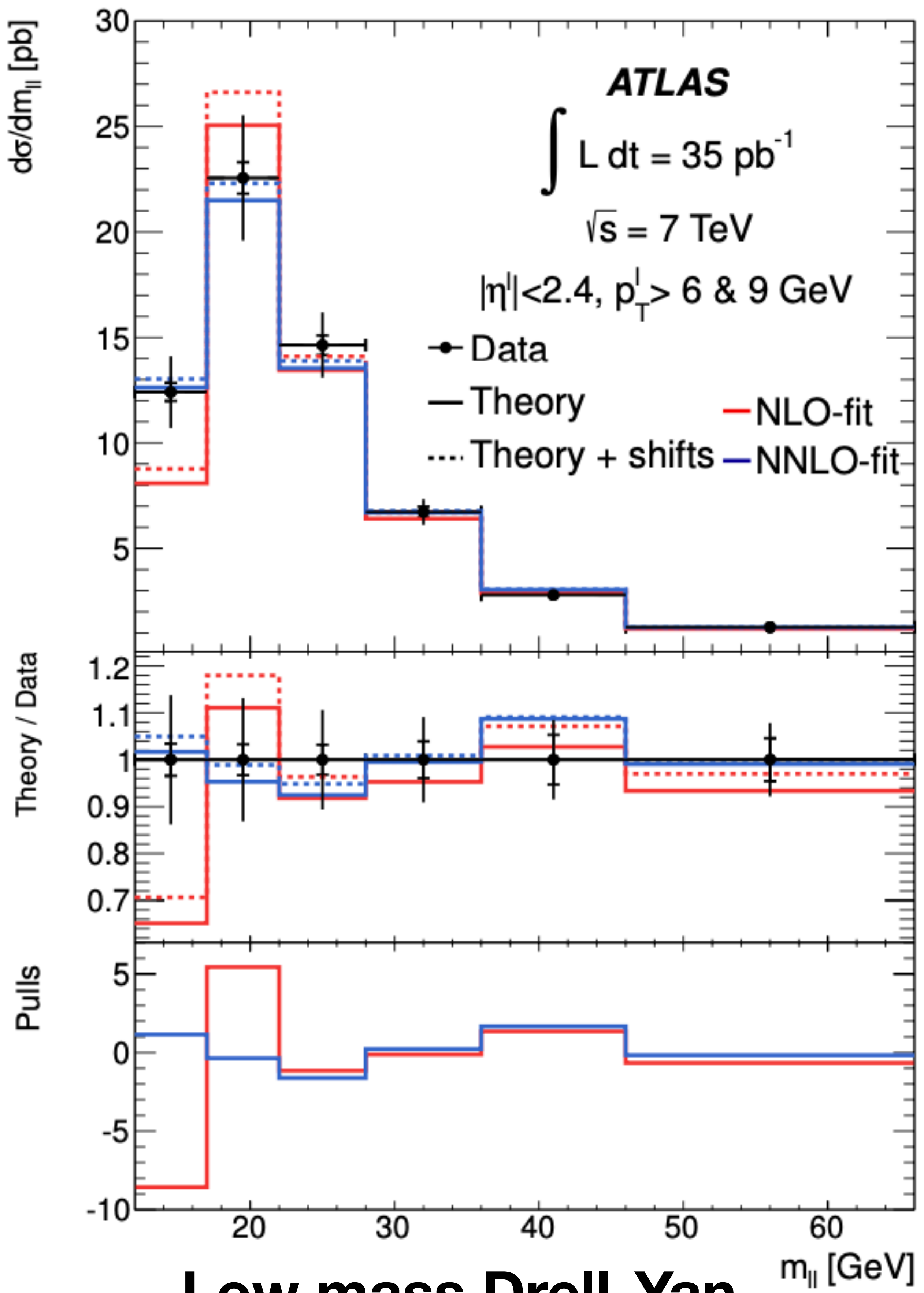
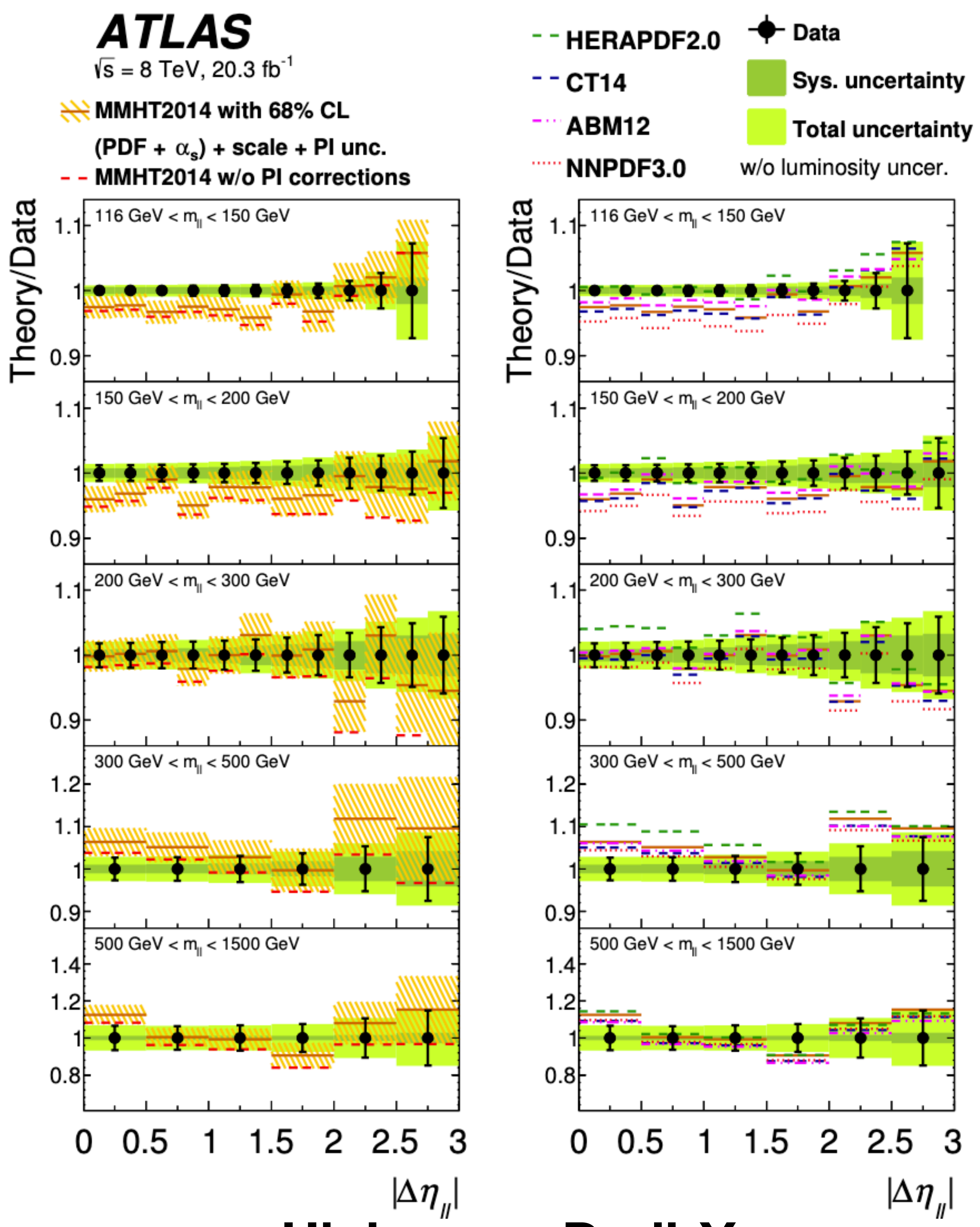


Low mass and high mass Drell-Yan



Low mass Drell-Yan



High mass Drell-Yan

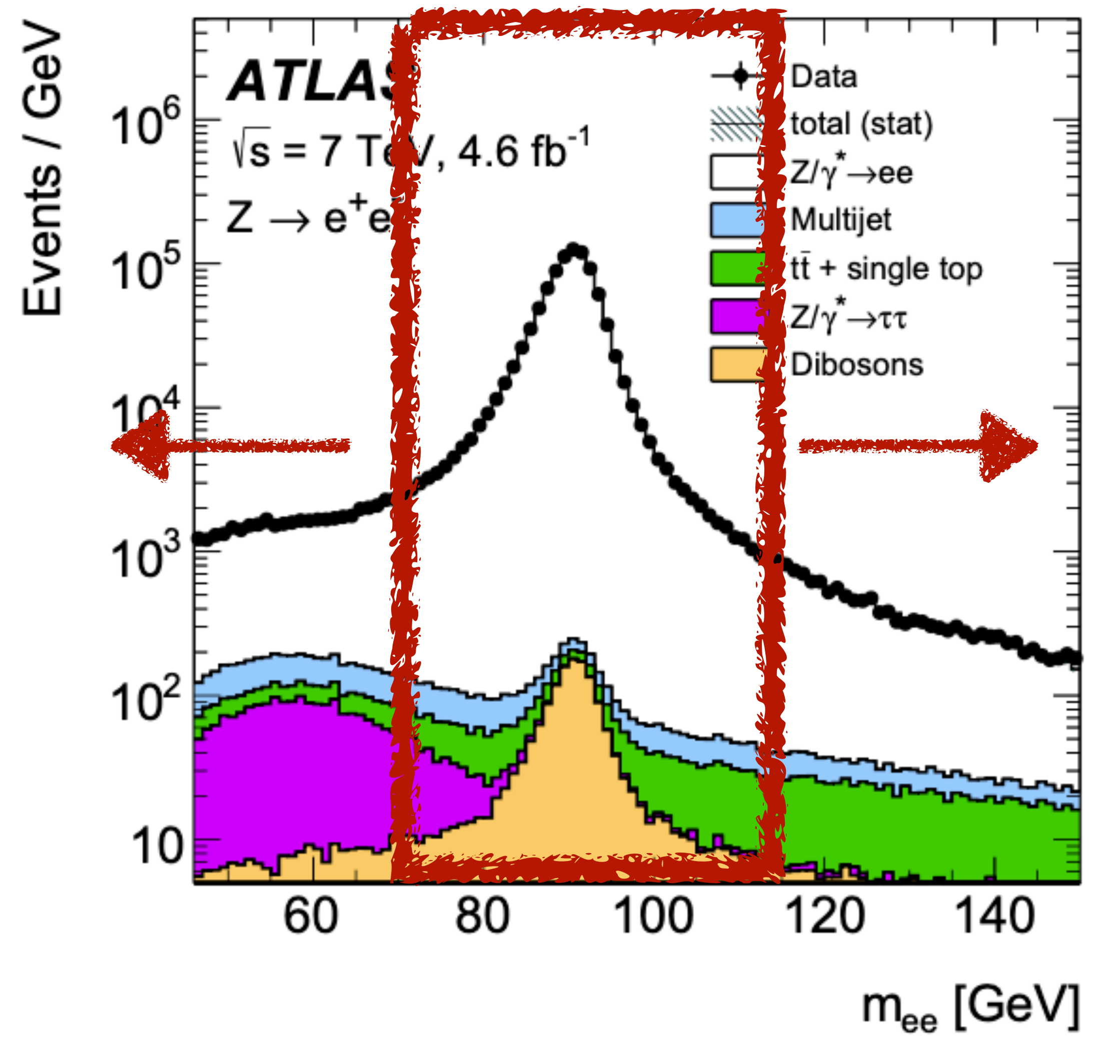
Compare to NNLO QCD+ HOEW

Drell-Yan cross section measurements

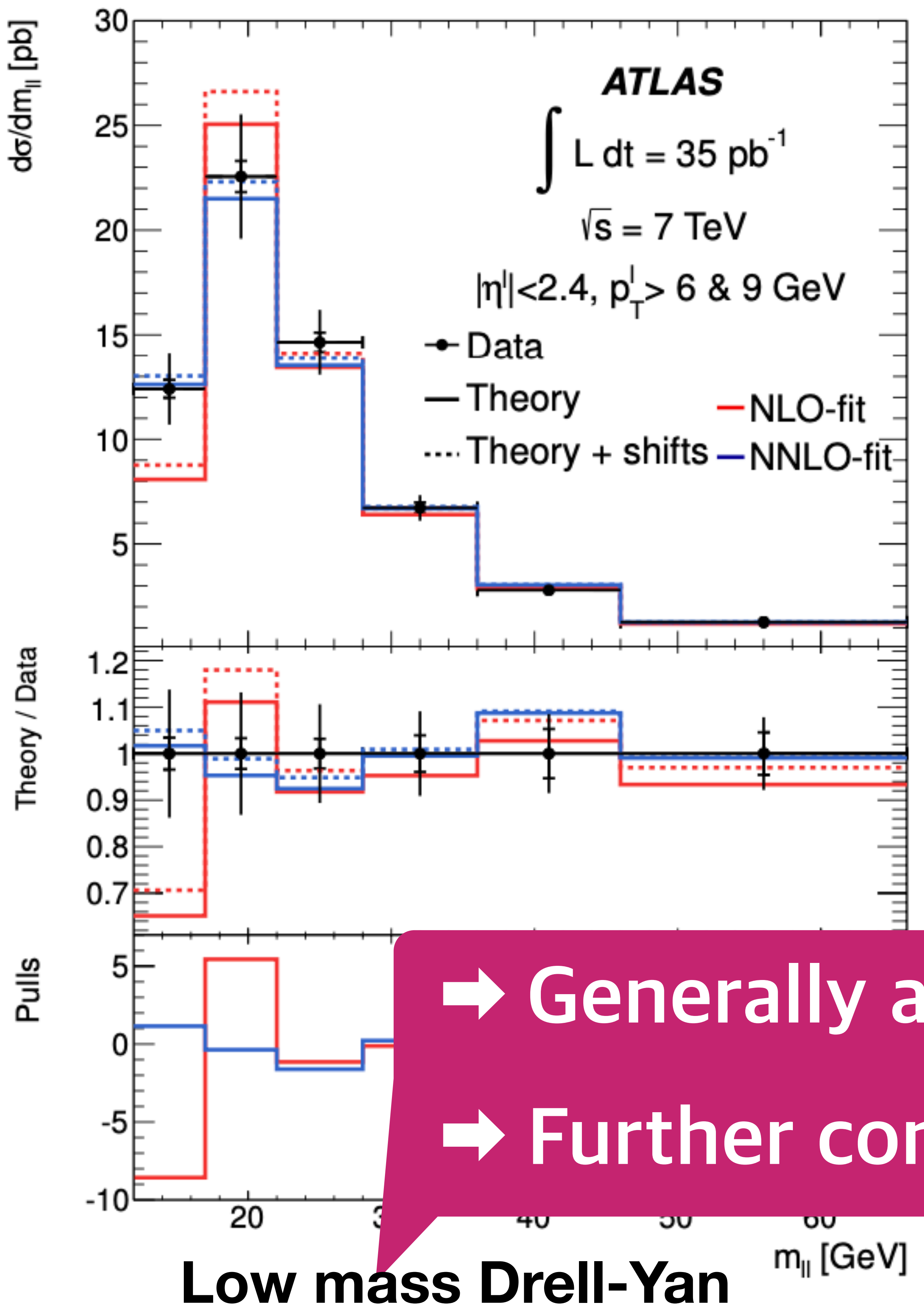
Low mass and high mass Drell-Yan

- off-shell m_{ll}, dominant by electromagnetic coupling of quark to the virtual photon ($\gamma*$)
- different sensitivity to the up- and down- type quarks

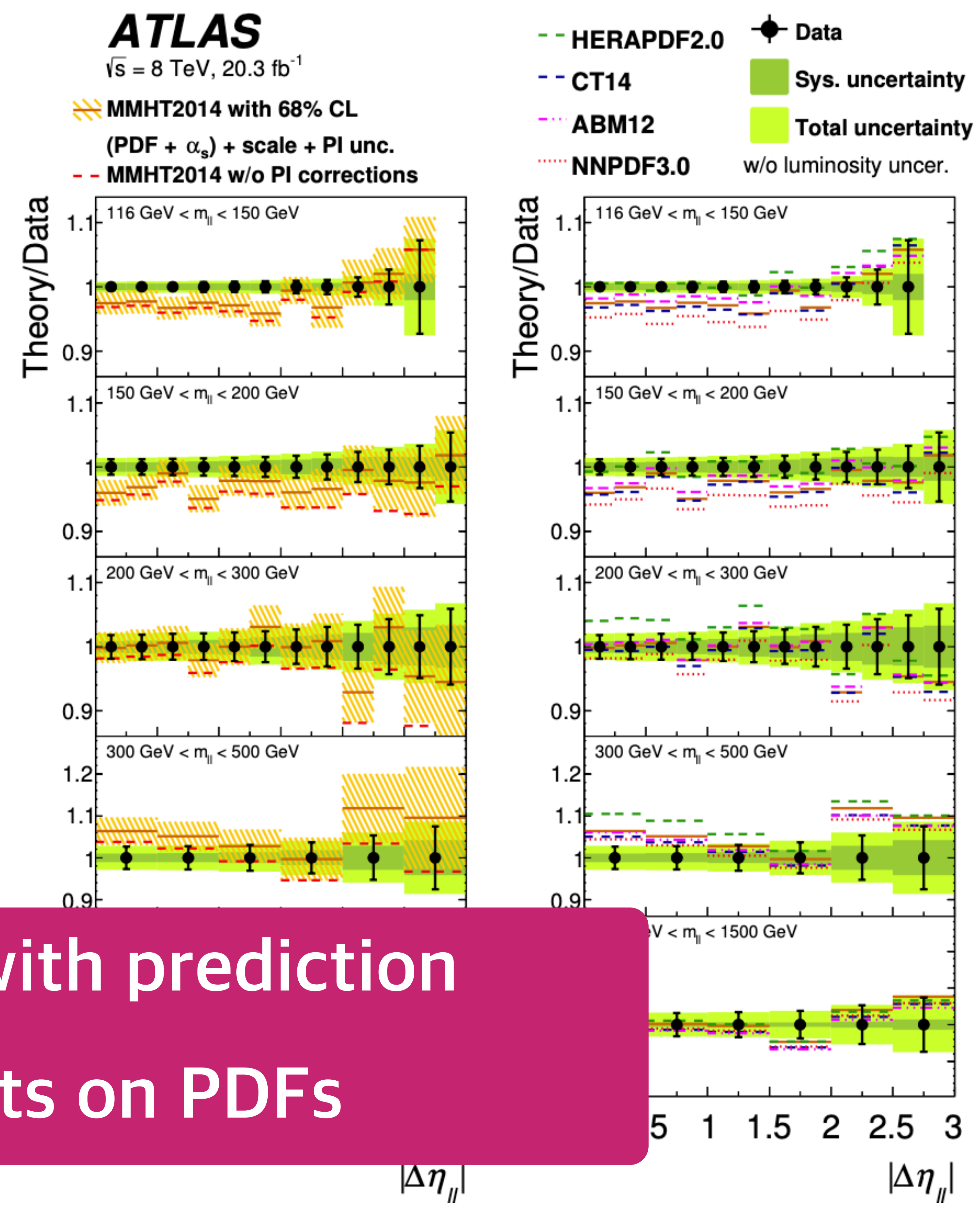
JHEP 08 (2016) 009
JHEP 06 (2014) 112



Low mass and high mass Drell-Yan



Low mass Drell-Yan



High mass Drell-Yan

➡ Generally agree with prediction

➡ Further constraints on PDFs

Compare to NNLO QCD+ HOEW

First ATLAS Run-3 W and Z boson production measurement

NEW Phys. Lett. B 854 (2024) 138725

New centre-of-mass energy 13.6 TeV, 29 ± 2% fb^{-1} of data collected in 2022

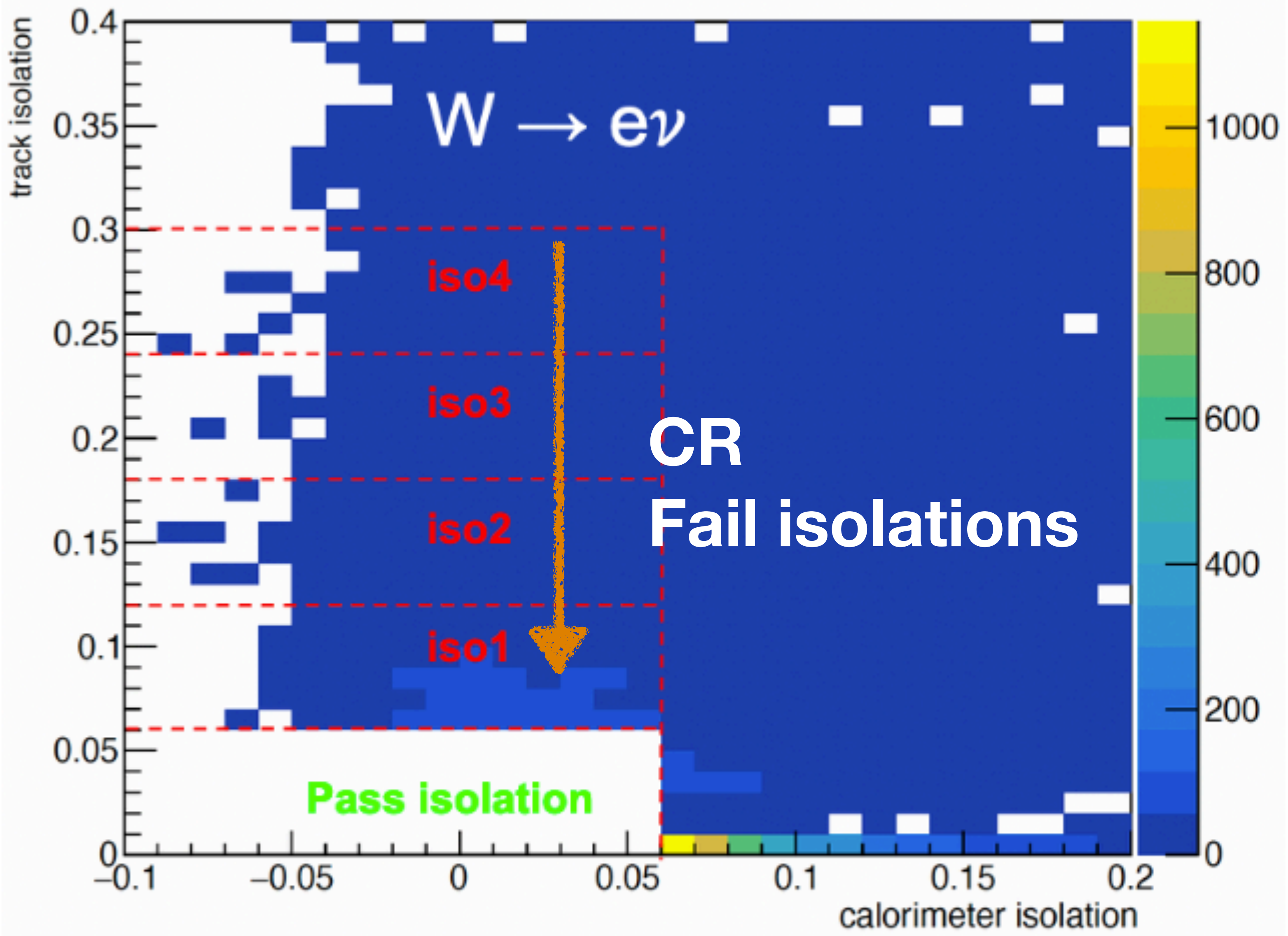
Event Selection: Standard WZ selection, slightly higher momentum (higher pileup)

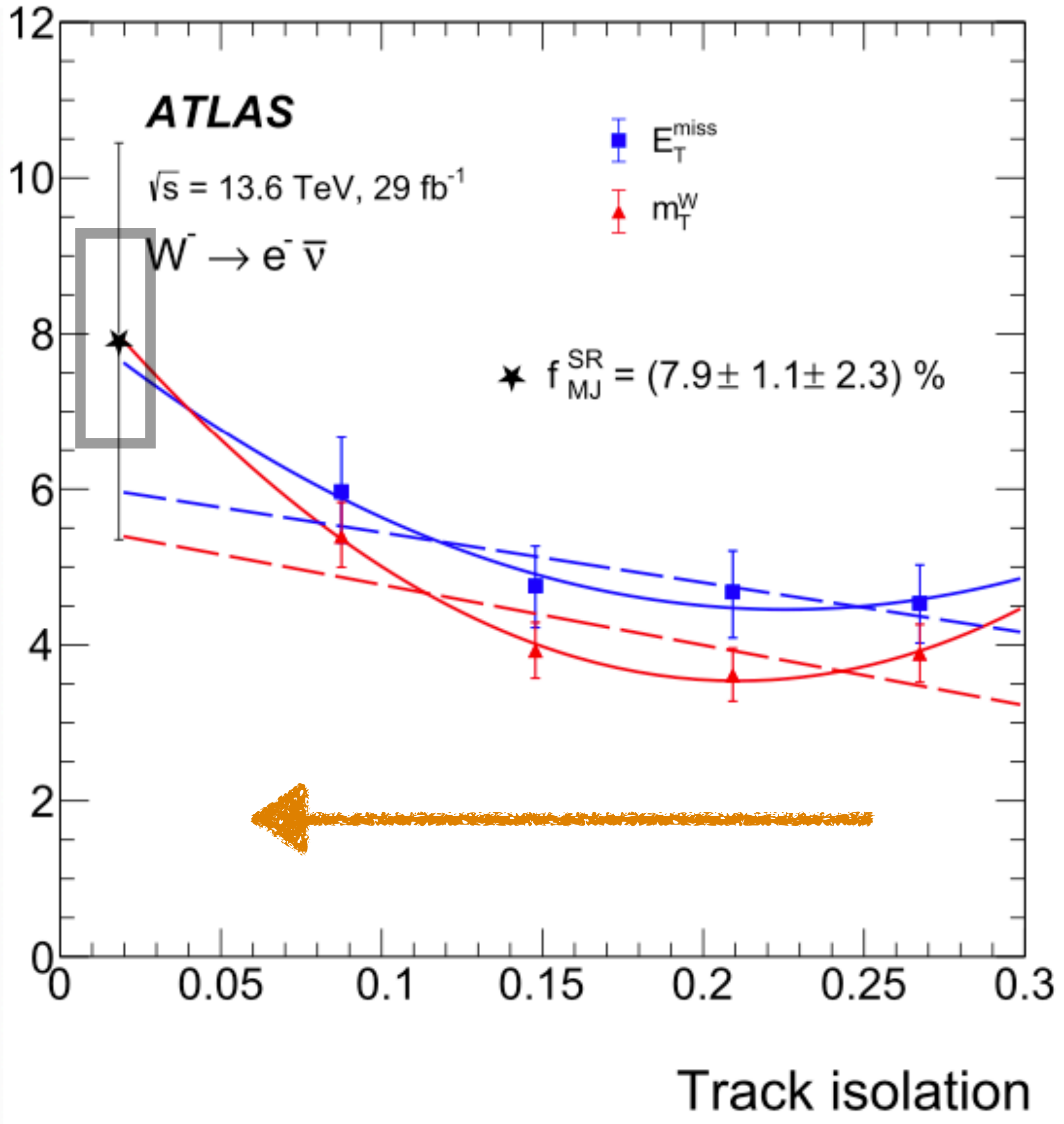
Background estimation

EW and top-quark process: MC simulation

Multi-jet: data driven

- Fit Region (FR): Perform PLH fit using template obtained in control region(CR) isolation slices
- Signal region (SR): Extrapolate from FR to SR using CR2/CR1





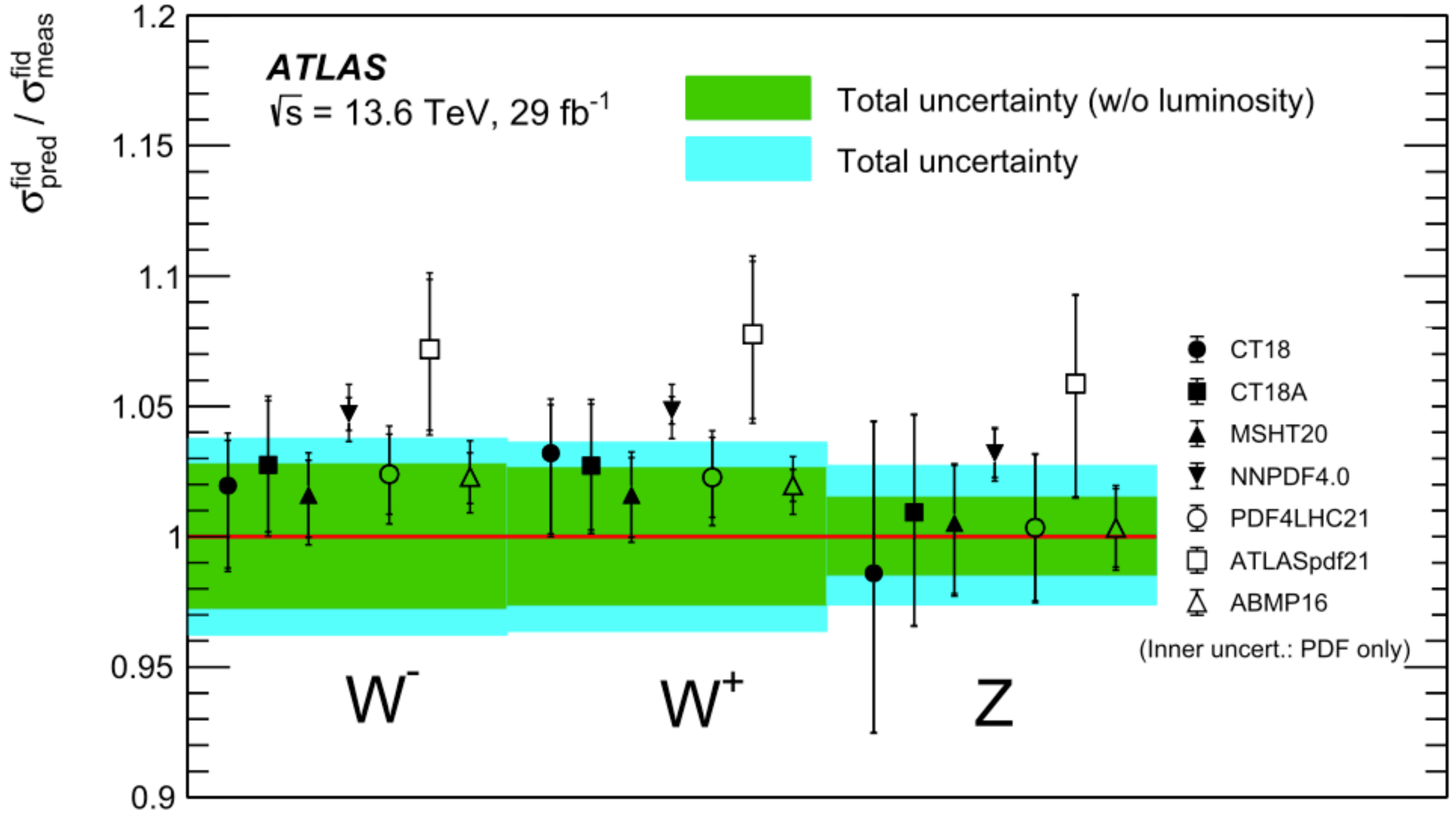
- Combine from two discriminating variables E_T^{miss} and m_T^W
- Compare linear fit and quadratic fit as systematics

First ATLAS Run-3 W and Z boson production measurement

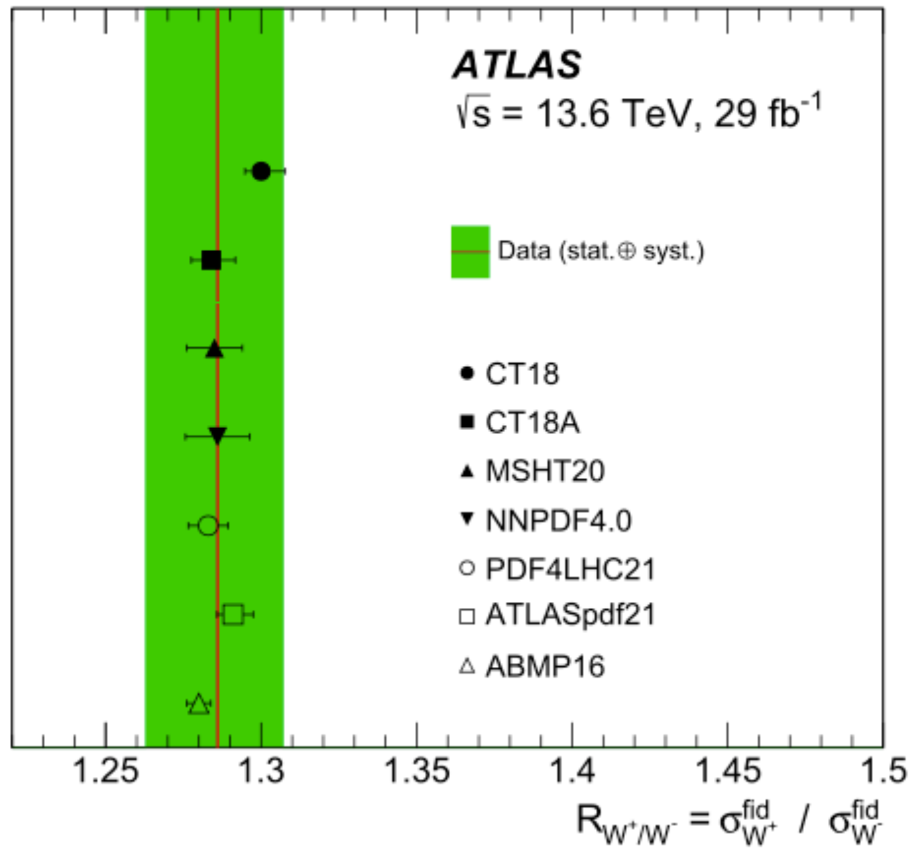
Measurement Strategy:

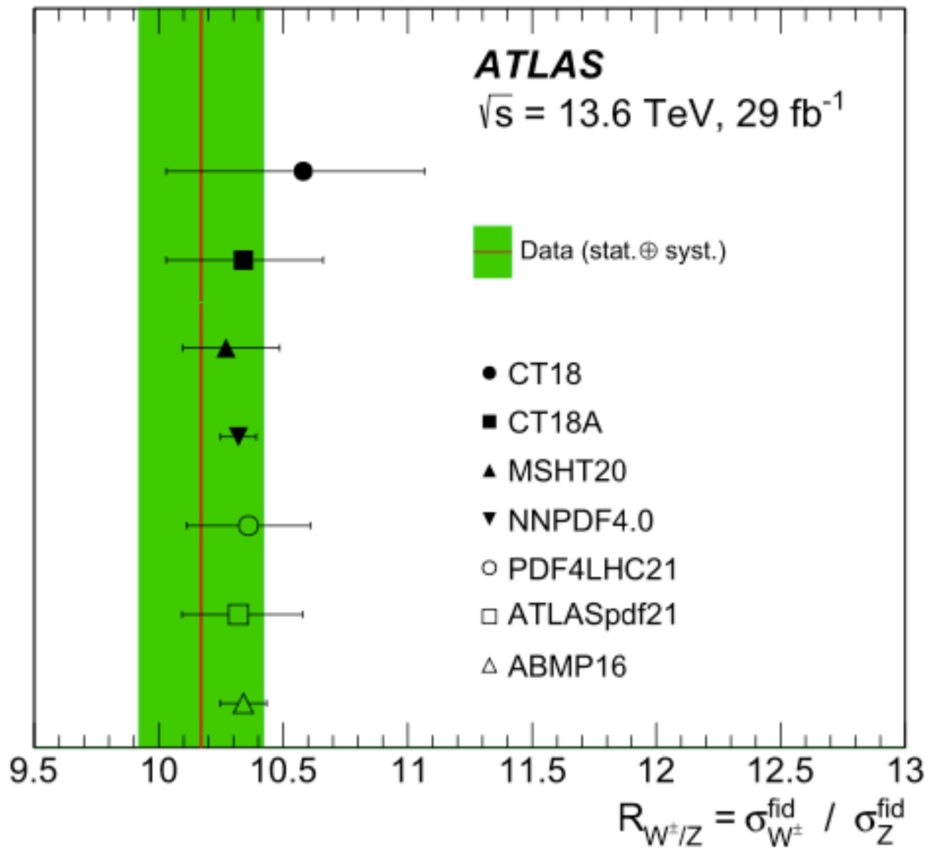
- Fiducial cross sections are extracted with **binned profile likelihood fits using all channels**: 2 Z-boson channels (ee and μμ) and 4 W-boson channels (e+ν, e−ν, μ+ν and μ−ν)
- Cross section ratio extracts as well by fitting with different parameterizations
- The total cross section: Fiducial / Acceptance

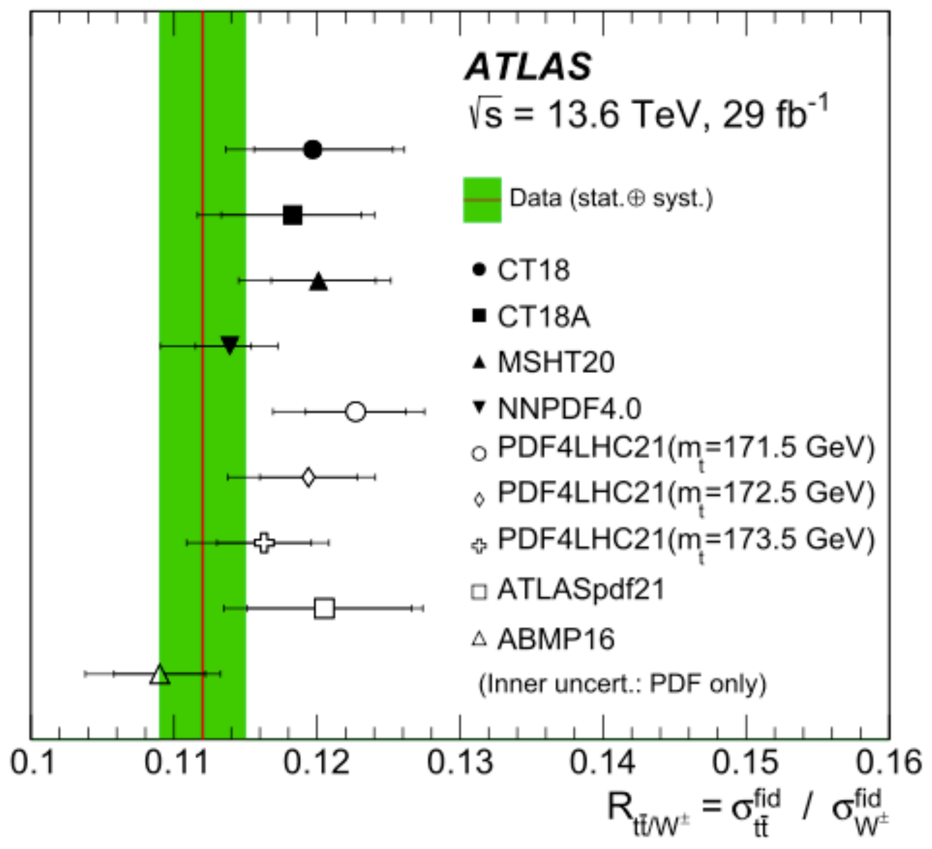
Dominant Uncertainty:
W: Luminosity, jet and MJ background
Z : Luminosity, lepton reconstruction



Good agreement with theory prediction (NNLO+NNLL QCD+ NLO EW)







Dominant Uncertainty: MJ background, jet, ttbar modeling

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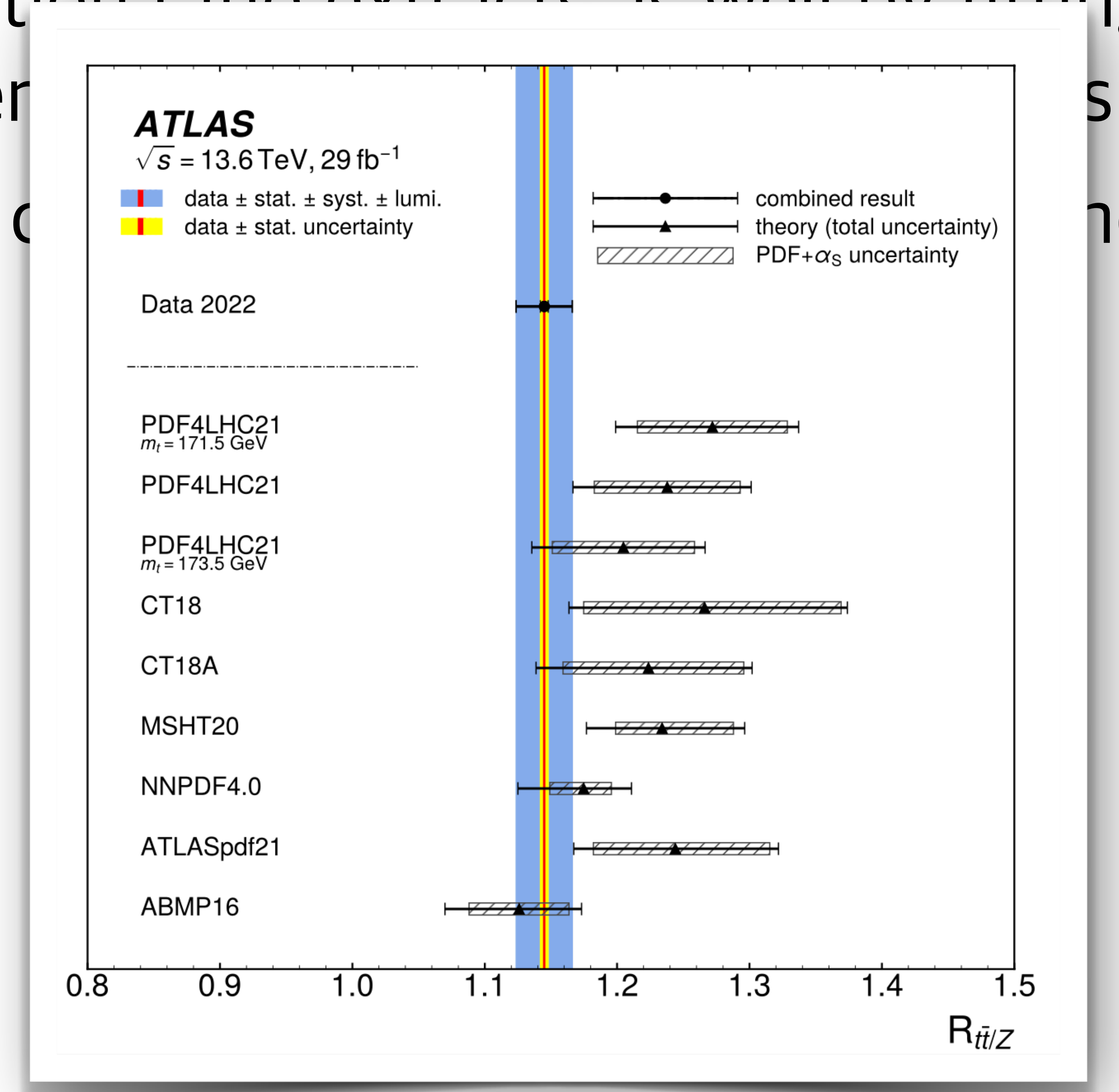
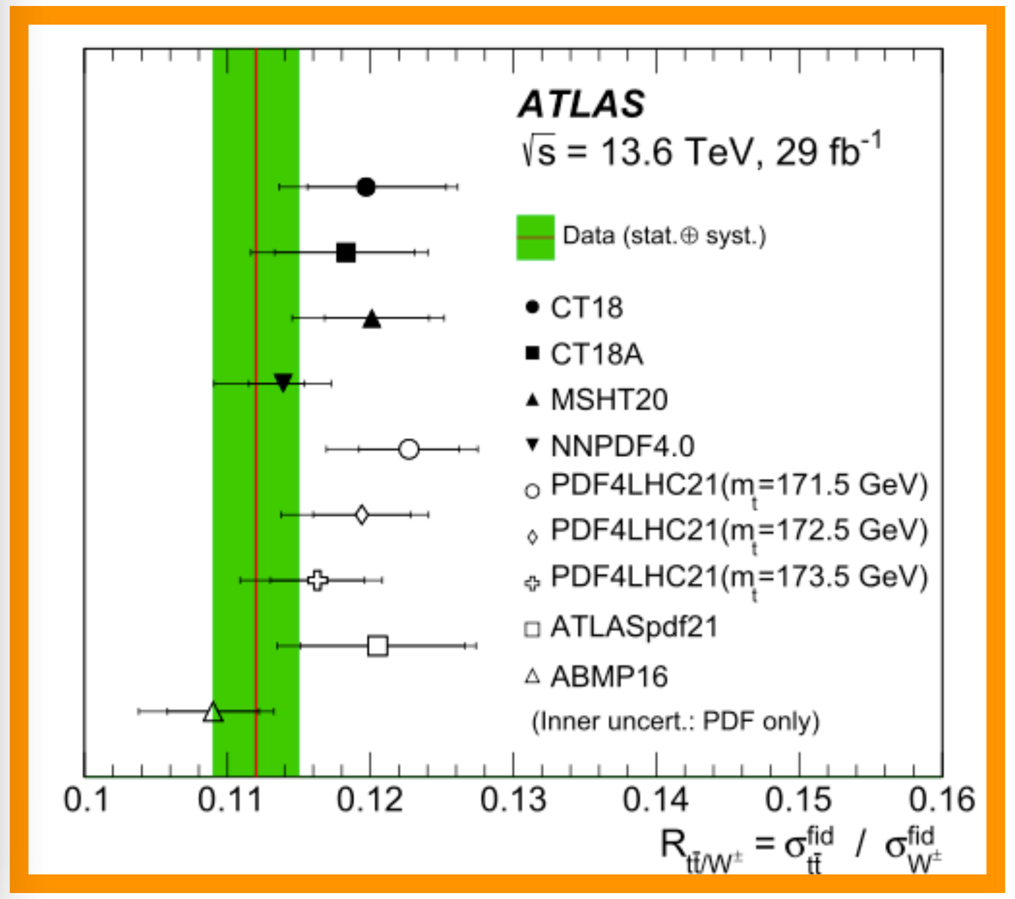
First ATLAS Run-3 W and Z boson production measurement

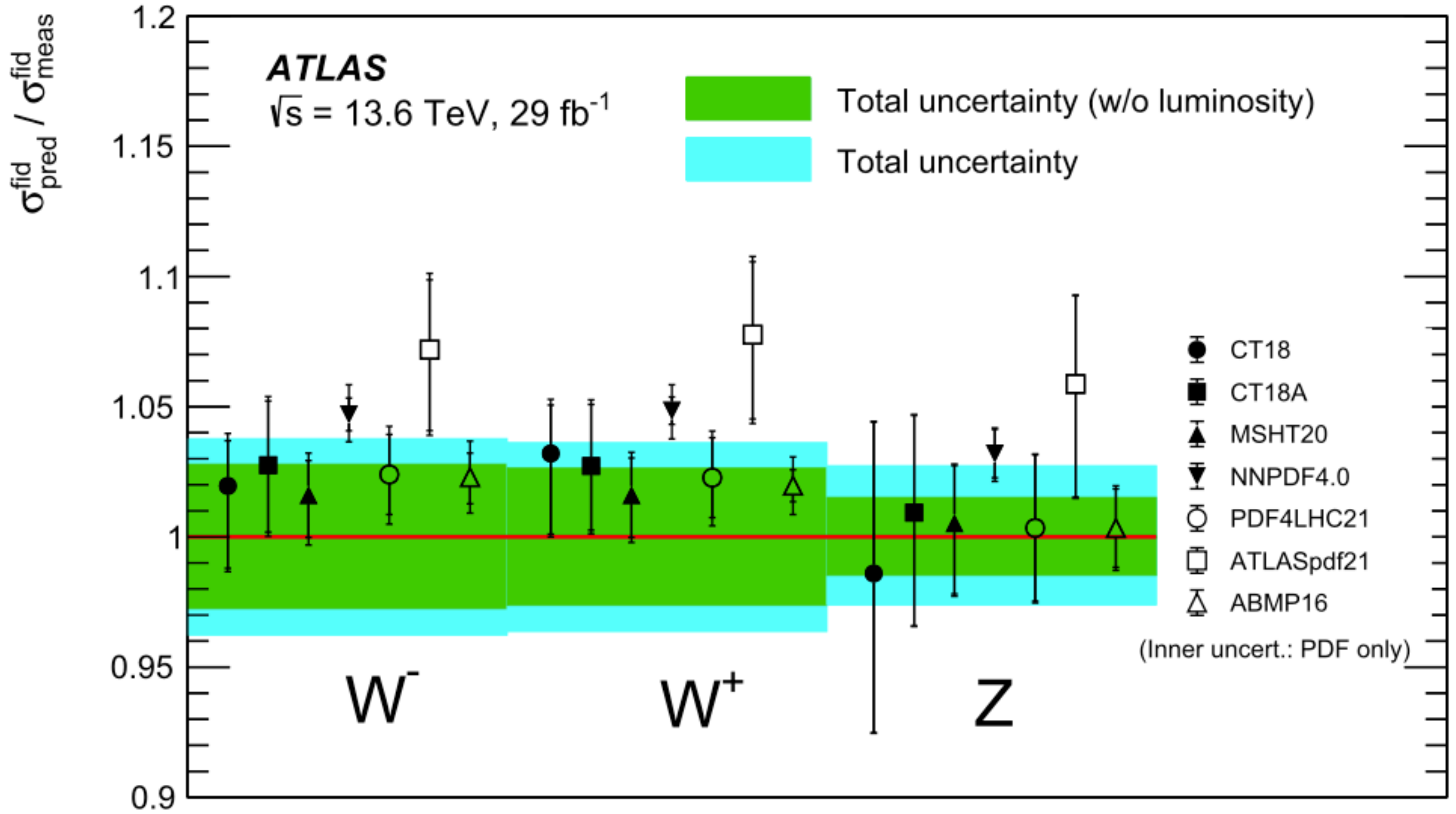
ATLAS EXPERIMENT

Measurement Strategy:

- Fiducial cross sections are extracted with **binned profile likelihood fits using all channels**: 2 Z-boson channels (ee and μμ) and 4 W-boson channels (e+ν, e−ν, μ+ν and μ−ν)
- Cross section ratio extracts as well by fitting with different parameter … signal strengths
- The total c… …nce







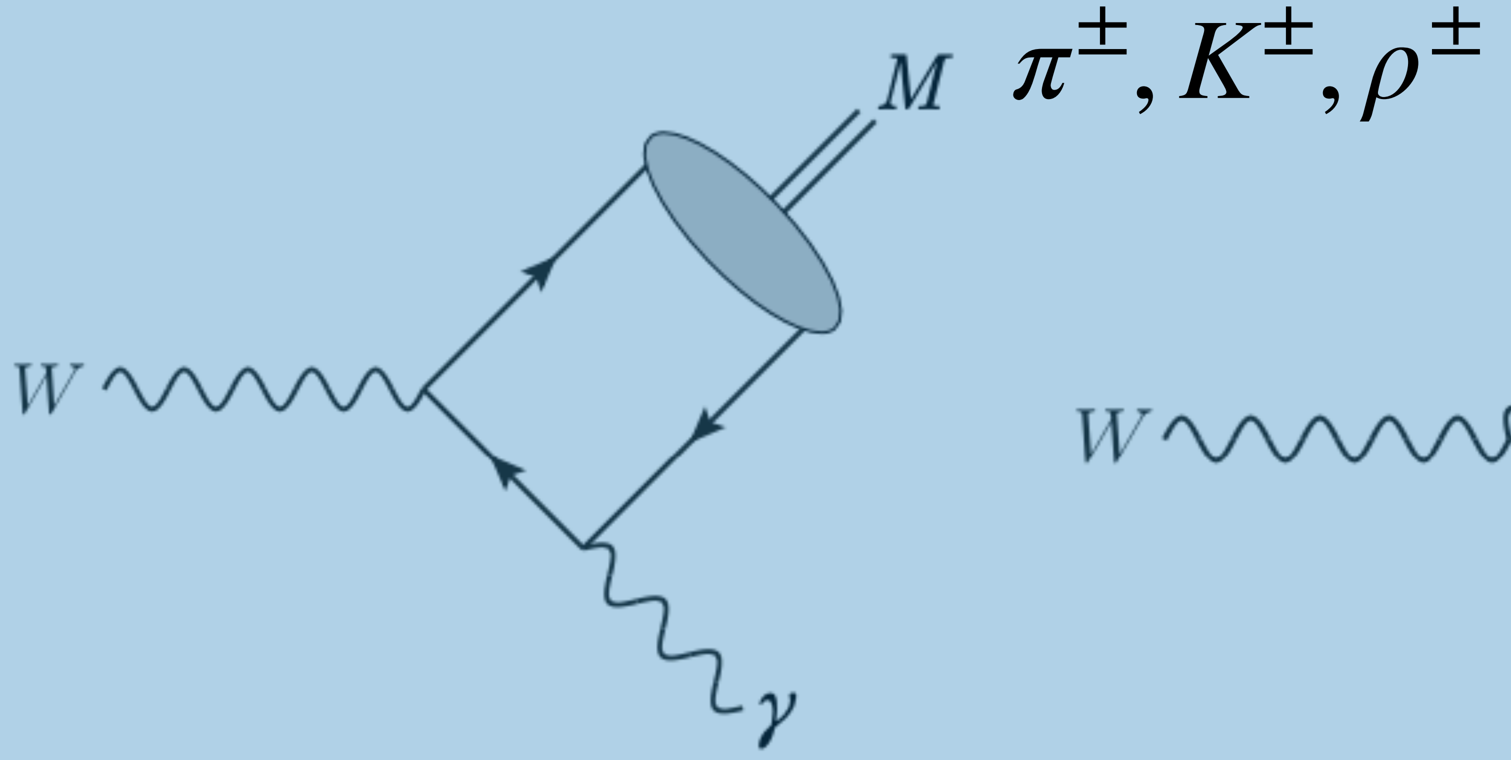
Good agreement with theory prediction (NNLO+NNLL QCD+ NLO EW)

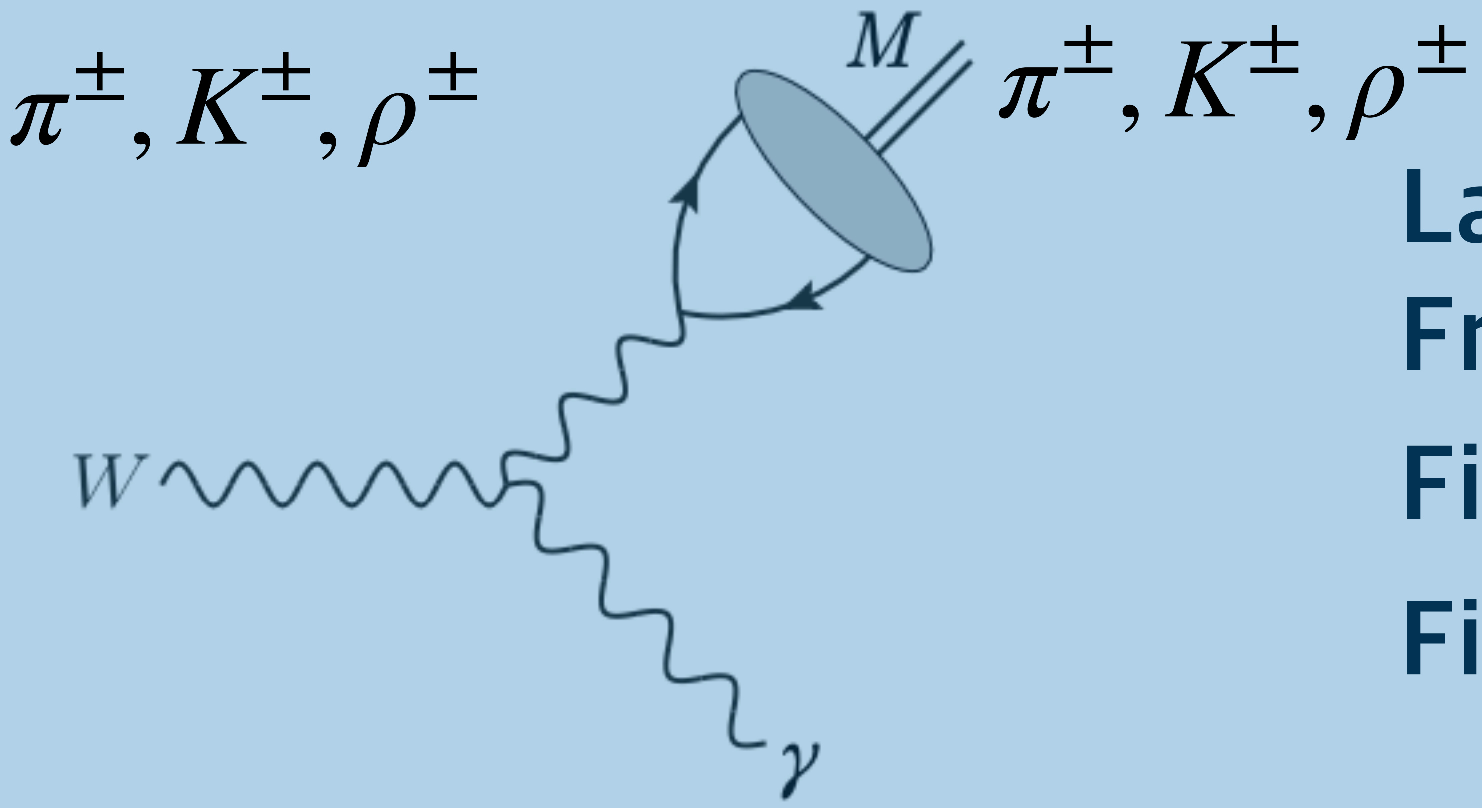
Same data/prediction agreement found in tt/Z measurement

Phys. Lett. B 848 (2024) 138376

Search for the exclusive W boson hadronic decays

Search for $W^{\pm} \to \pi^{\pm}\gamma$, $W^{\pm} \to K^{\pm}\gamma$, $W^{\pm} \to \rho^{\pm}\gamma$ at $\sqrt{s}$= 13 TeV, 140 fb^{-1}





Larger integrated luminosity and CME w.r.t. CDF
From pQCD to strongly-coupled QCD regime
First ATLAS $W^{\pm} \to \pi^{\pm}\gamma$ search
First $W^{\pm} \to K^{\pm}\gamma$, $W^{\pm} \to \rho^{\pm}\gamma$ search

Event selection:

$W^{\pm} \to \pi^{\pm}\gamma$, $W^{\pm} \to K^{\pm}\gamma$: track+ photon

$W^{\pm} \to \rho^{\pm}\gamma$: $\tau_{1-prong}$ + photon

- $\rho^{\pm} \to \pi^{\pm}\pi^{0}$ indistinguishable to tau, except impact parameter
- benefit from ATLAS refined algorithms

Background:

- $Z \to e^{+}e^{-}$ background rejected with TRT track information and hadronic leakage
- Multijet: data driven method, sample from template that mimicking the data correlations

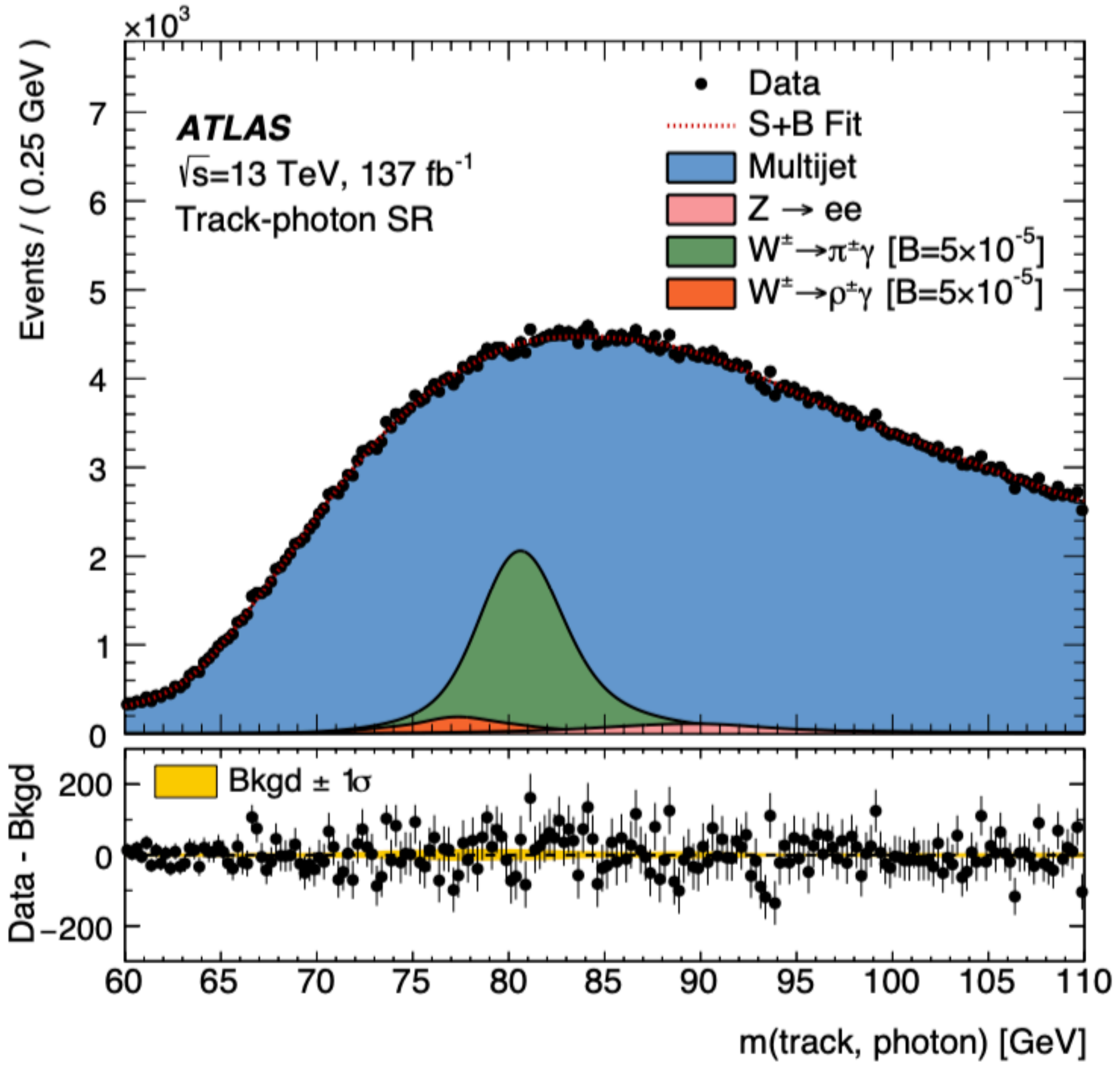
Submitted to PRL
https://arxiv.org/abs/2309.15887 009

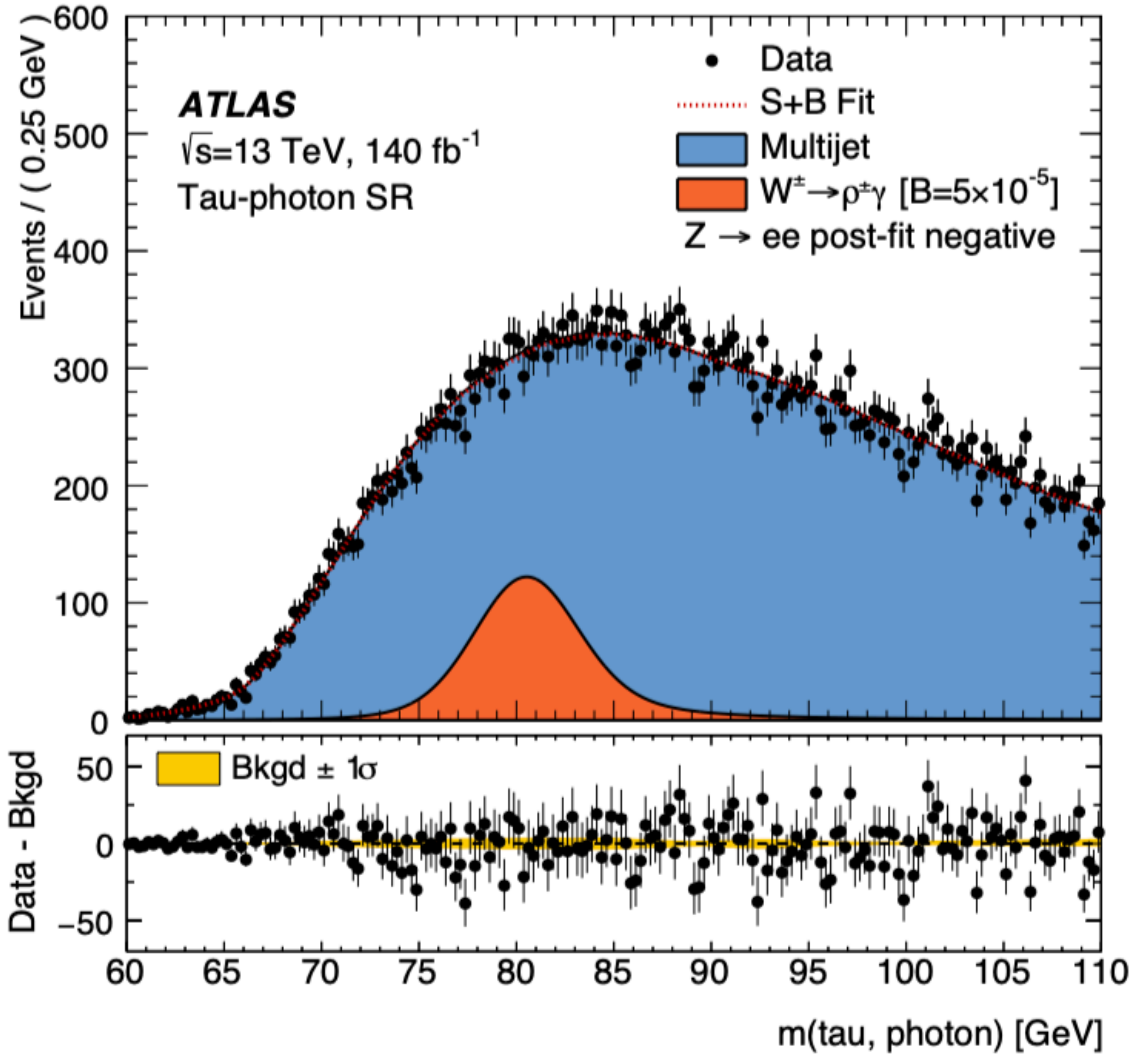
Search for the exclusive W boson hadronic decays

Joint fit across all channels with binned maximum likelihood fit S+B at W invariant mass region [60,110] GeV

- No significant excess found
- Improve the previous upper limit on B($W^{\pm} \rightarrow \pi^{\pm}\gamma$)~ a factor of four
- First upper limits on $W^{\pm} \rightarrow K^{\pm}\gamma$, $W^{\pm} \rightarrow \rho^{\pm}\gamma$.
- Constrain theoretical predictions based on the QCD factorization approach

	Number of events	
	Track-photon SR	Tau-photon SR
Multijet	632000 ± 2200	43200 ± 600
$Z \rightarrow e^{+}e^{-}$	6100 ± 1500	-200 ± 400
$W^{\pm} \rightarrow \pi^{\pm}/K^{\pm}\gamma$	1000 ± 800	–
$W^{\pm} \rightarrow \rho^{\pm}\gamma$	-100 ± 400	-90 ± 240
Data	638962	42918





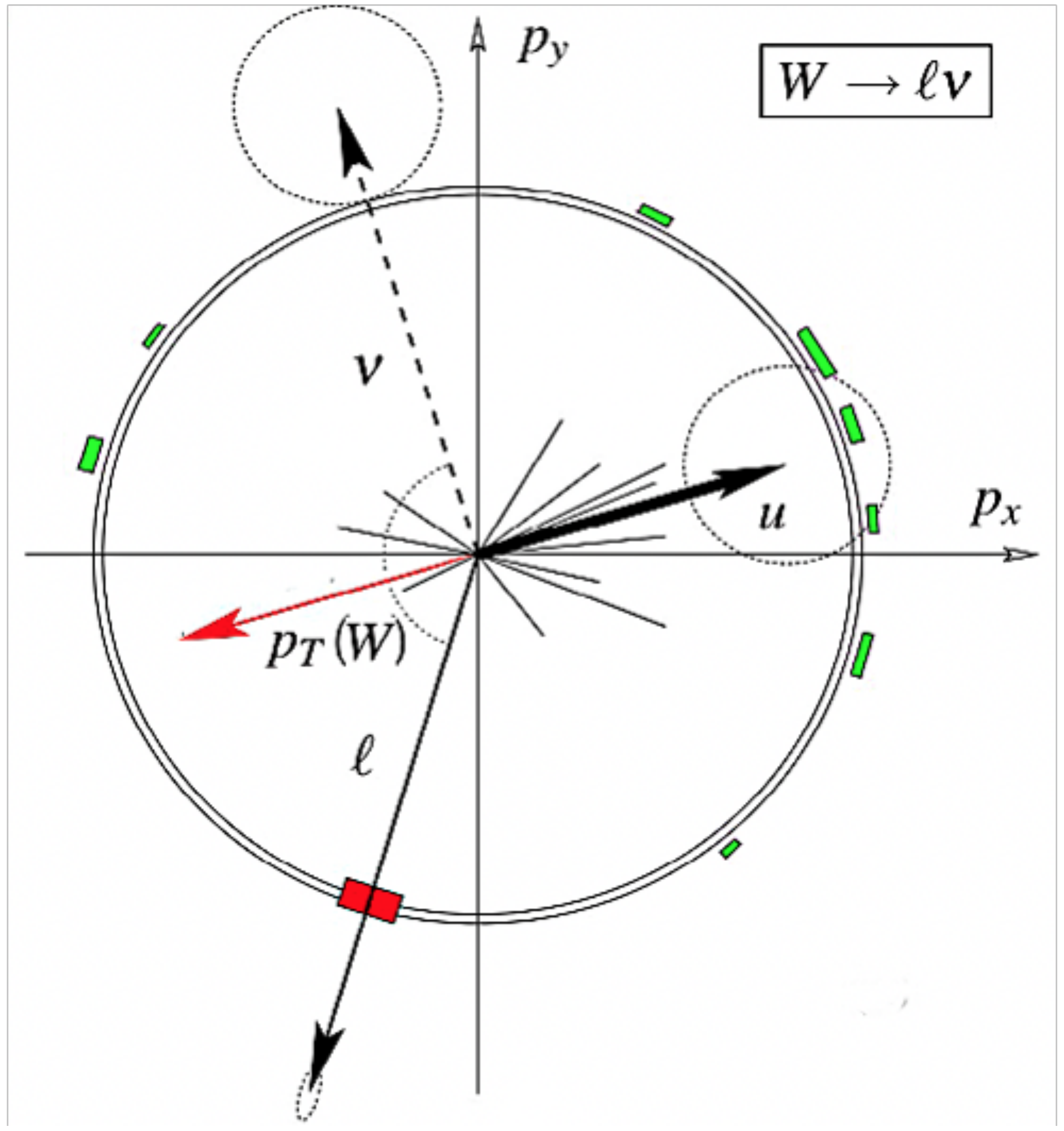
	95% CL upper limits	
Branching fraction	Expected $\times 10^{-6}$	Observed $\times 10^{-6}$
$\mathcal{B}(W^{\pm} \rightarrow \pi^{\pm}\gamma)$	$1.2^{+0.5}_{-0.3}$	1.9
$\mathcal{B}(W^{\pm} \rightarrow K^{\pm}\gamma)$	$1.1^{+0.4}_{-0.3}$	1.7
$\mathcal{B}(W^{\pm} \rightarrow \rho^{\pm}\gamma)$	$6.0^{+2.3}_{-1.7}$	5.2

W and Z pT with low-pileup data

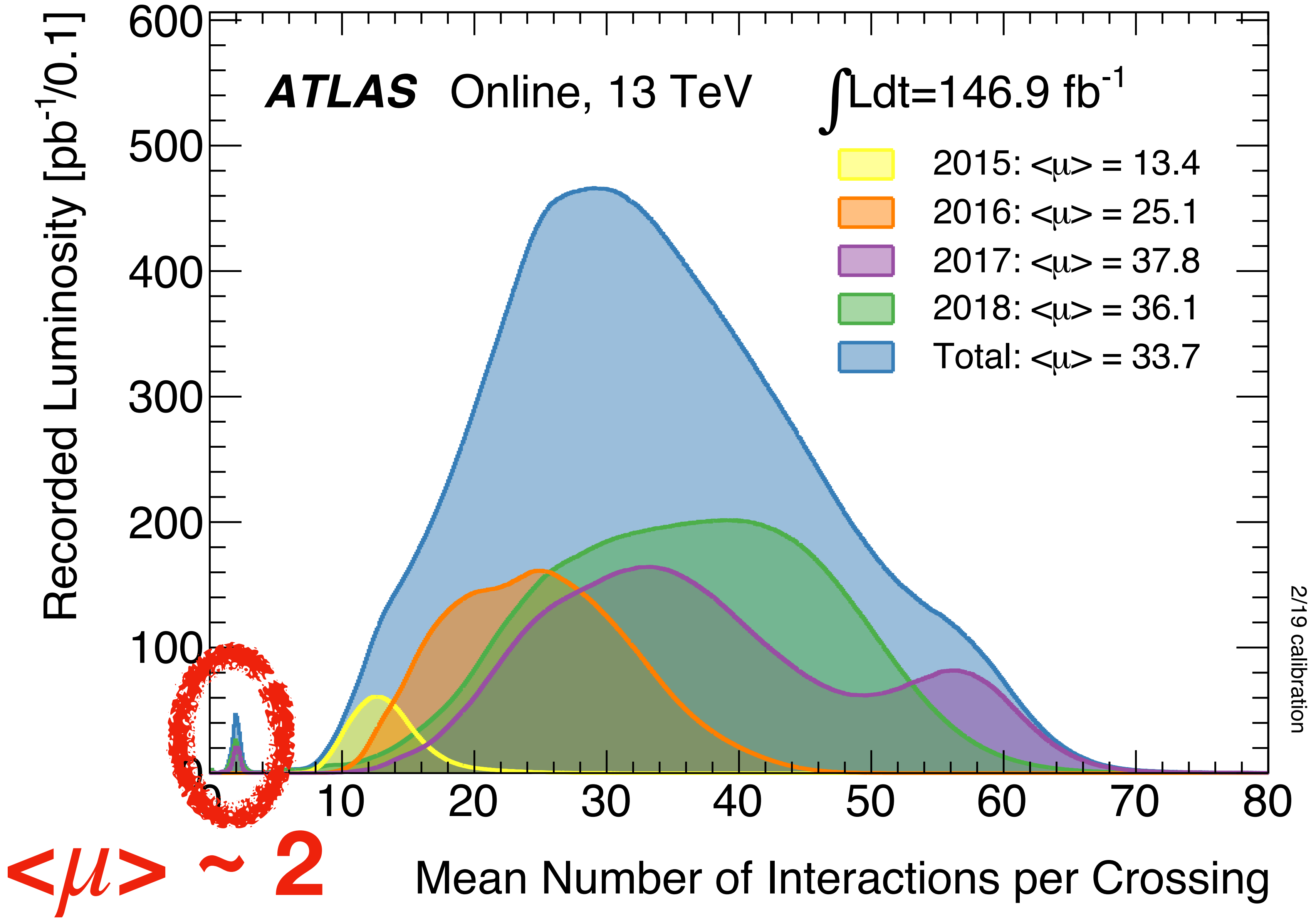
Submitted to EPJC
https://arxiv.org/abs/2404.06204

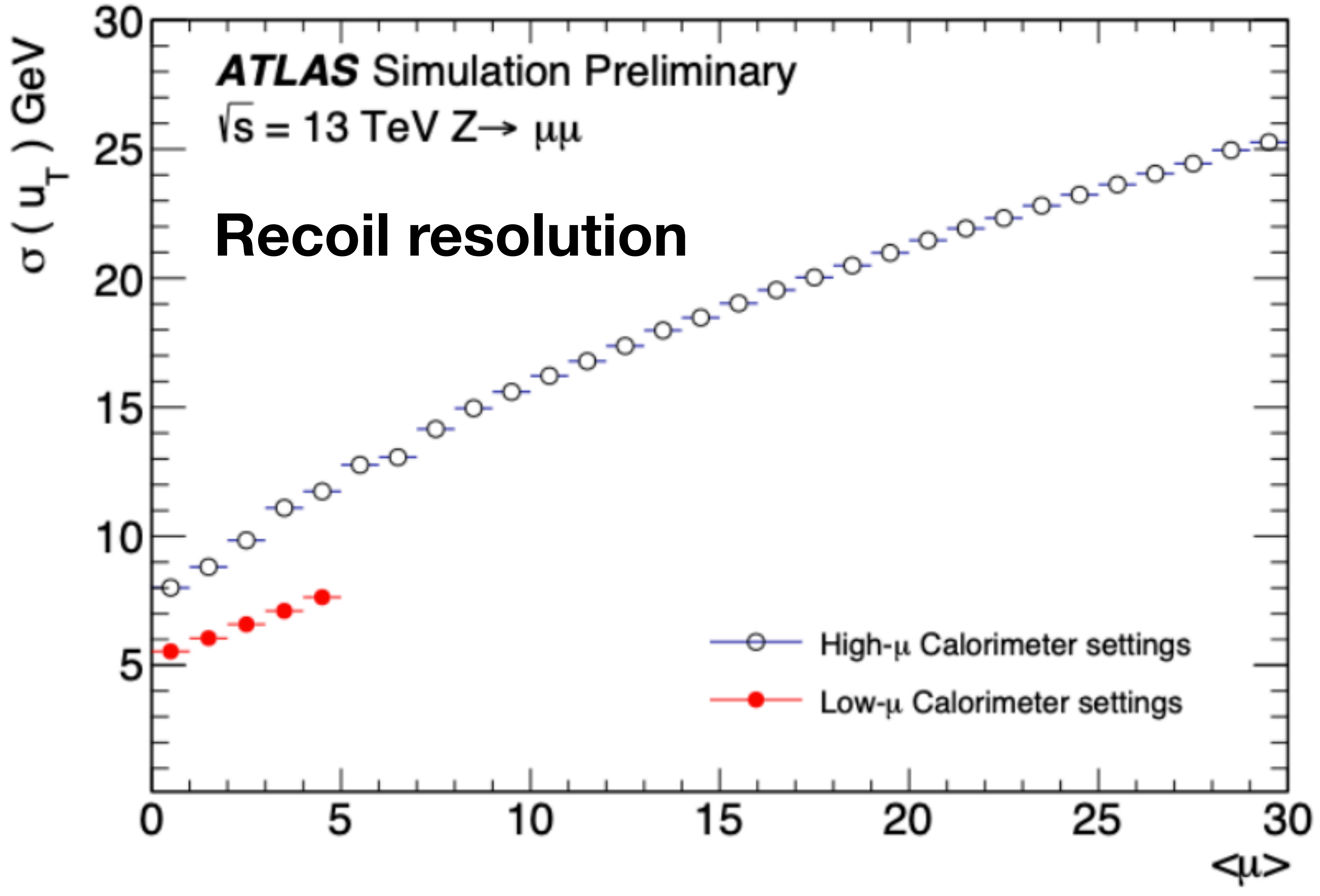
Low pile-up data:

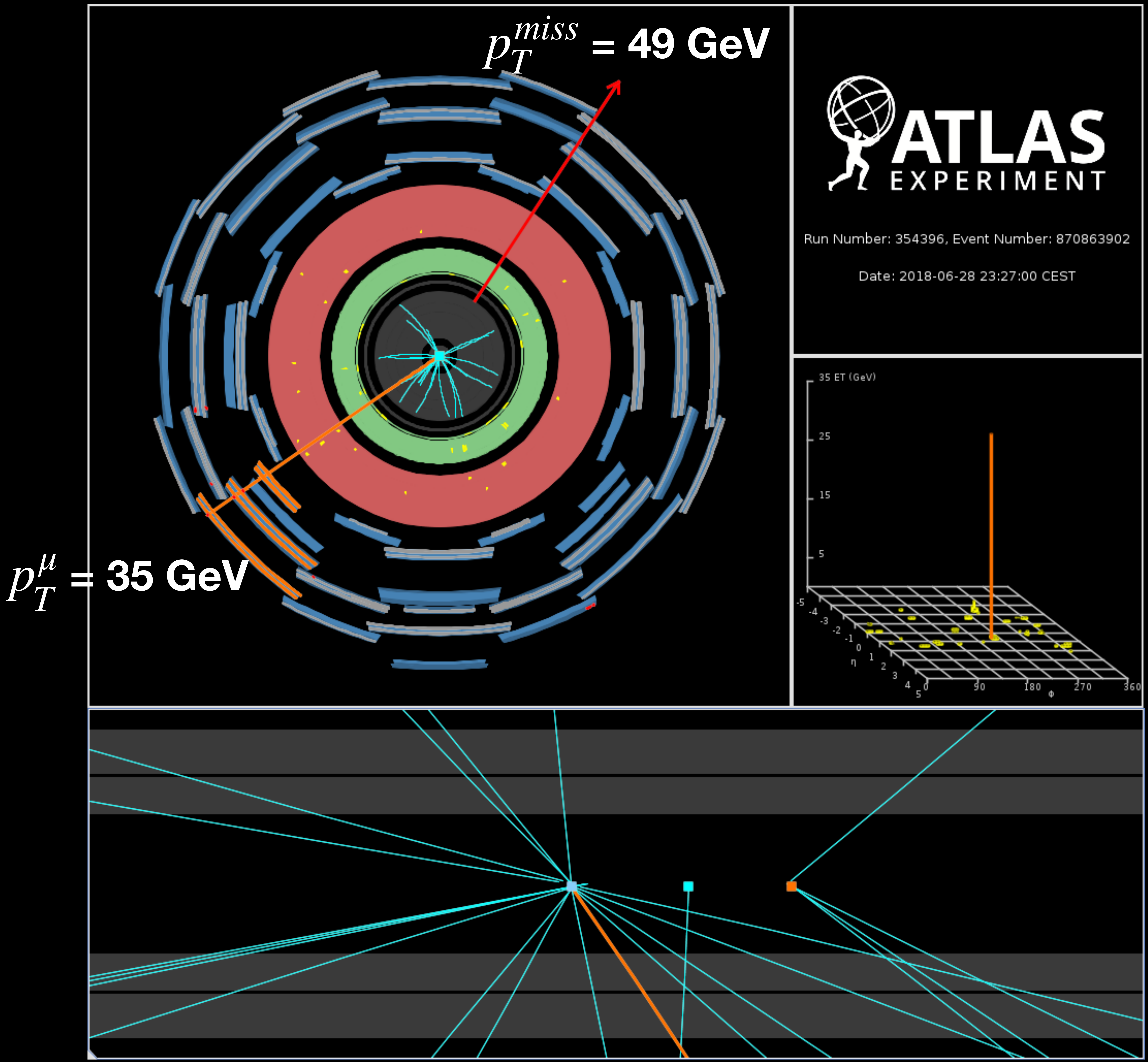
- $\sqrt{s}$= 5.02 TeV: Nov 2017, 255 ± 1% pb^{-1}
- $\sqrt{s}$= 13 TeV: Nov 2017 + Jun 2018, 335 ± 0.92% pb^{-1}
- Standard W and Z selection
  1.45 M (5 TeV) and 4.35 M (13 TeV) W events
  111 K (5 TeV) and 366 K (13 TeV) Z events



Boson transverse momentum reconstruction







13 TeV W—>$\mu\nu$ candidate

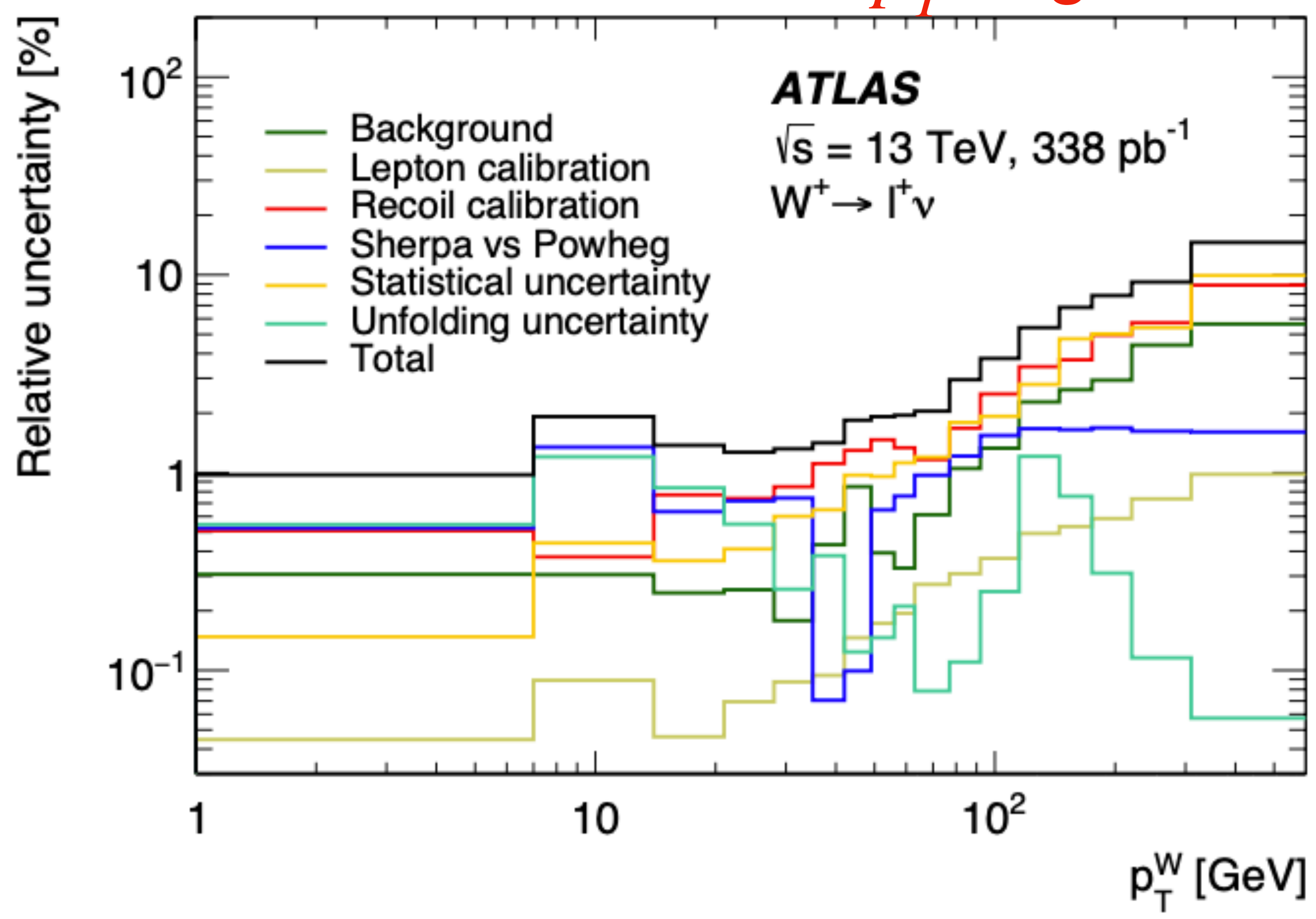
m_T = **77 GeV**

u_T = **16 GeV**

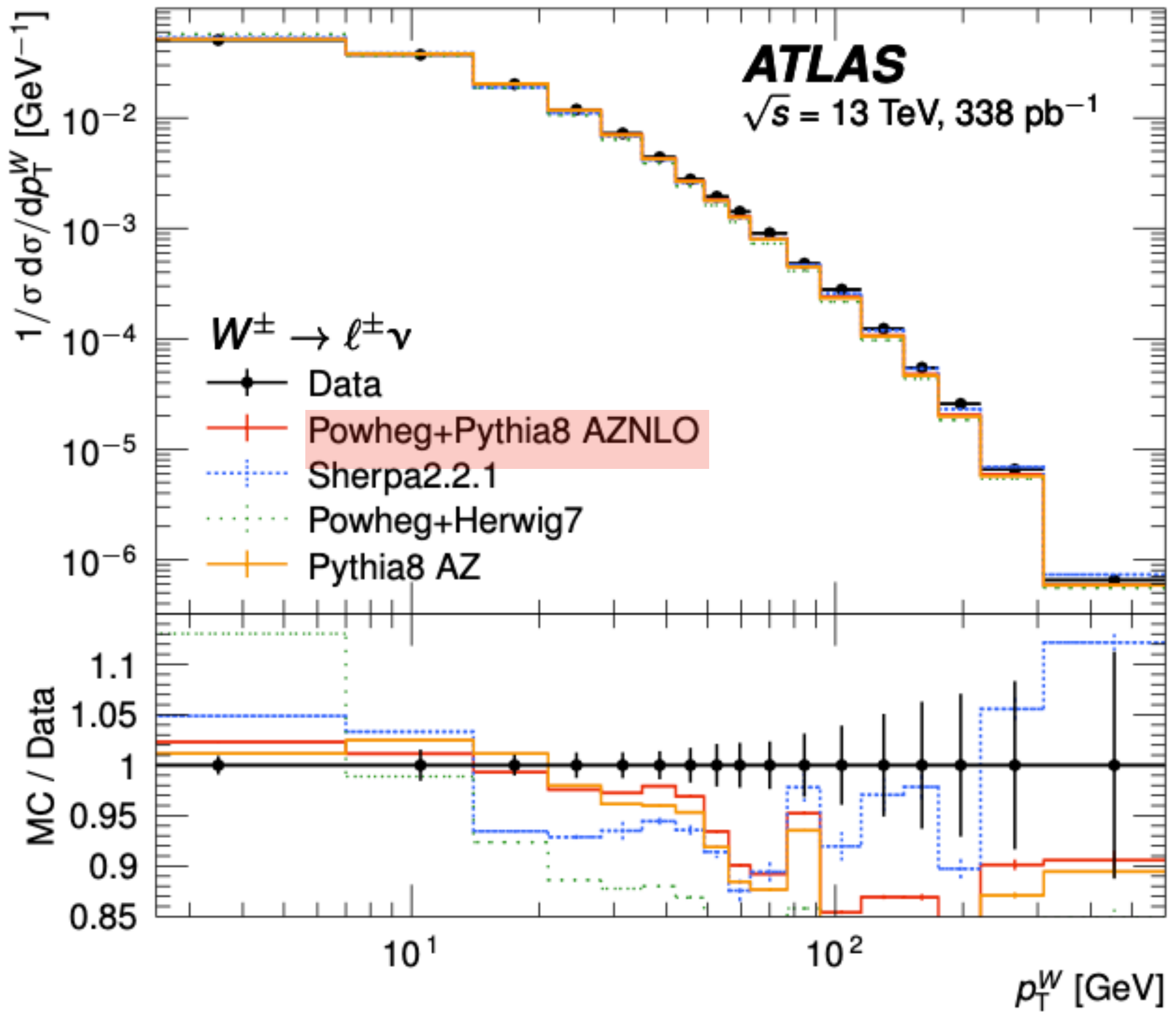
W and Z pT with low-pileup data

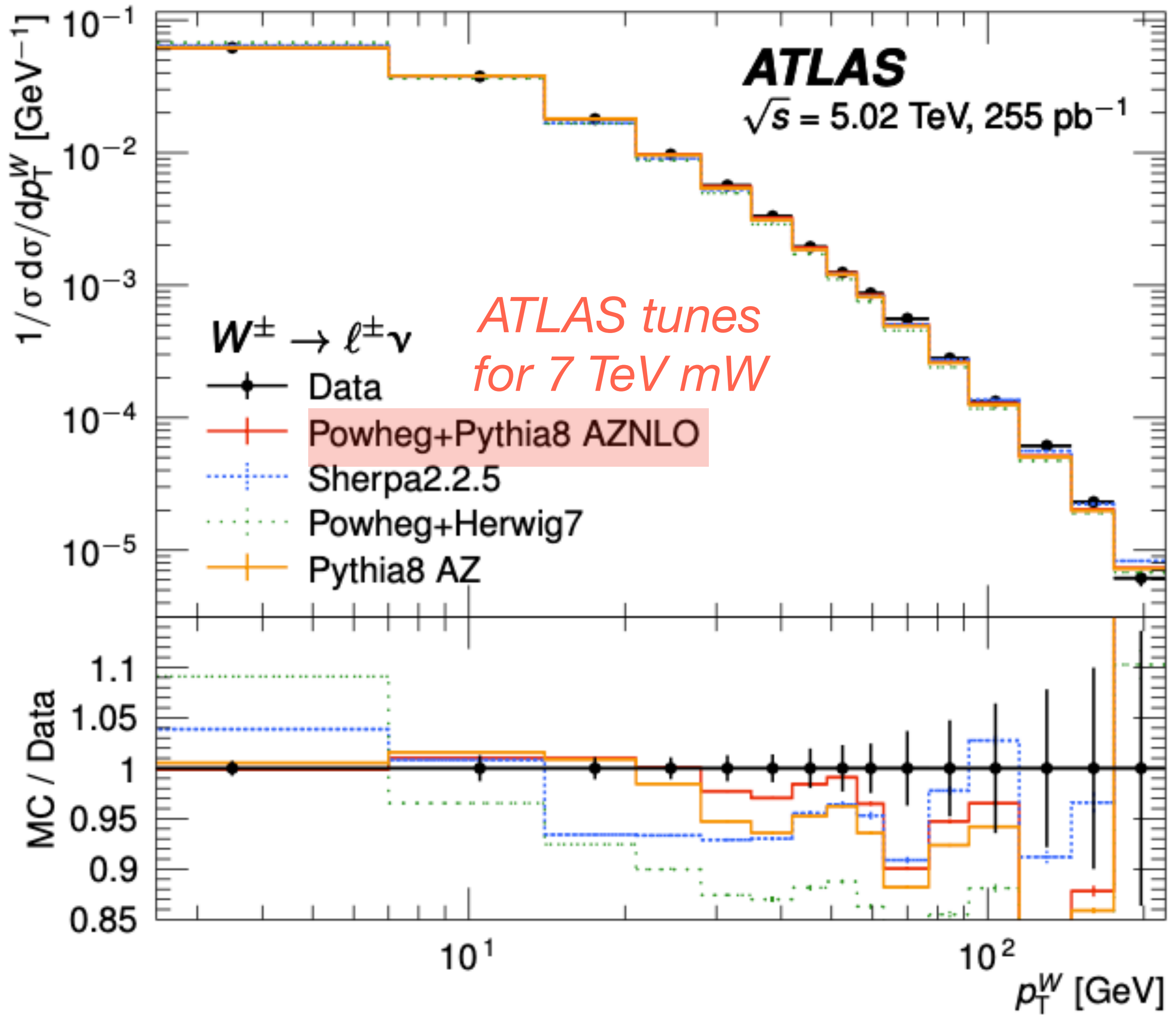
- Lepton and recoil calibration and MC dedicated to special low pile-up data conditions
- Standard background: EW and top background estimated from MC, Multijet estimated with data-driven method
- Bayesian unfolding of u_T in the W and $p_T(\ell\ell)$ in the Z
- Electron and muon channels combined with BLUE, good χ^2

~1 % unc at low p_T^W region



Z acts as a cross check of recoil measurement





- ➡ General agree with prediction
  - Further validation of the AZNLO
- ➡ Provide test and constrains for theory
- ➡ *Milestone for future next ATLAS low pile-up W mass measurement
  - ➡ Save extrapolate WpT from Z. Reduce modelling uncertainty

Latest mW measurement in Jakub Kremer's talk

Summary

- Precision measurement of W, Z properties at ATLAS
  - Low- and high-mass Drell-Yan
  - First 13.6 TeV W, Z cross section measurement and their ratios
  - W exclusive decay search
  - Precision W, Z pT of low pile-up data
- They all provide stringent tests of the electroweak and QCD theory
- Key input and facilitating future ATLAS W mass measurement.

Extra

First ATLAS Run-3 W and Z boson production measurement

NEW Phys. Lett. B 854 (2024) 138725

New centre-of-mass energy 13.6 TeV, $29 \pm 2\%\ fb^{-1}$ of data collected in 2022

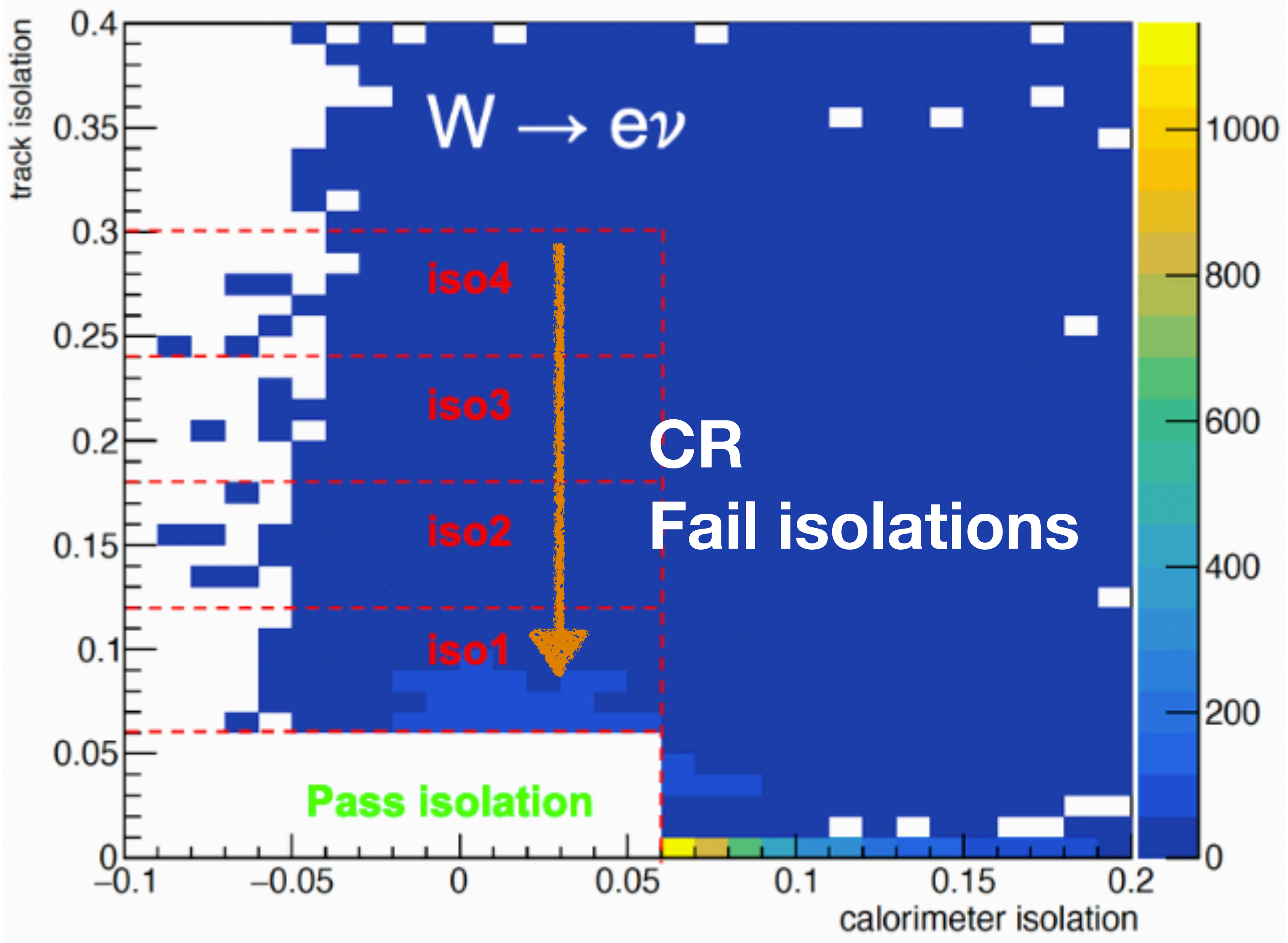
Event Selection: Standard WZ selection, slightly higher momentum

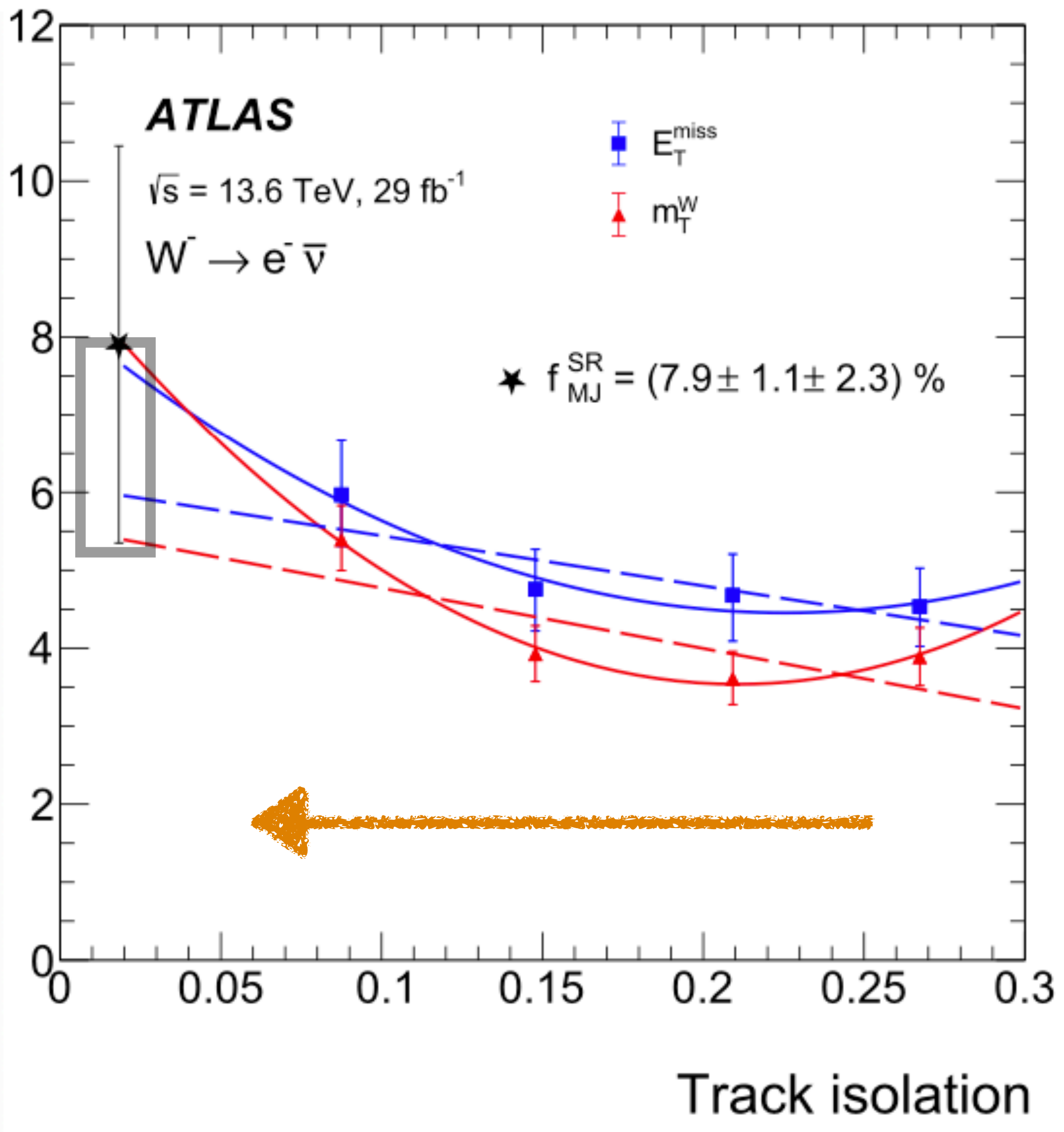
Background estimation

EW and top-quark process: MC simulation

Multi-jet: data driven

- FR: Perform PLH fit using template obtained in CR isolation slices
- SR: Extrapolate from FR to SR using CR2/CR1



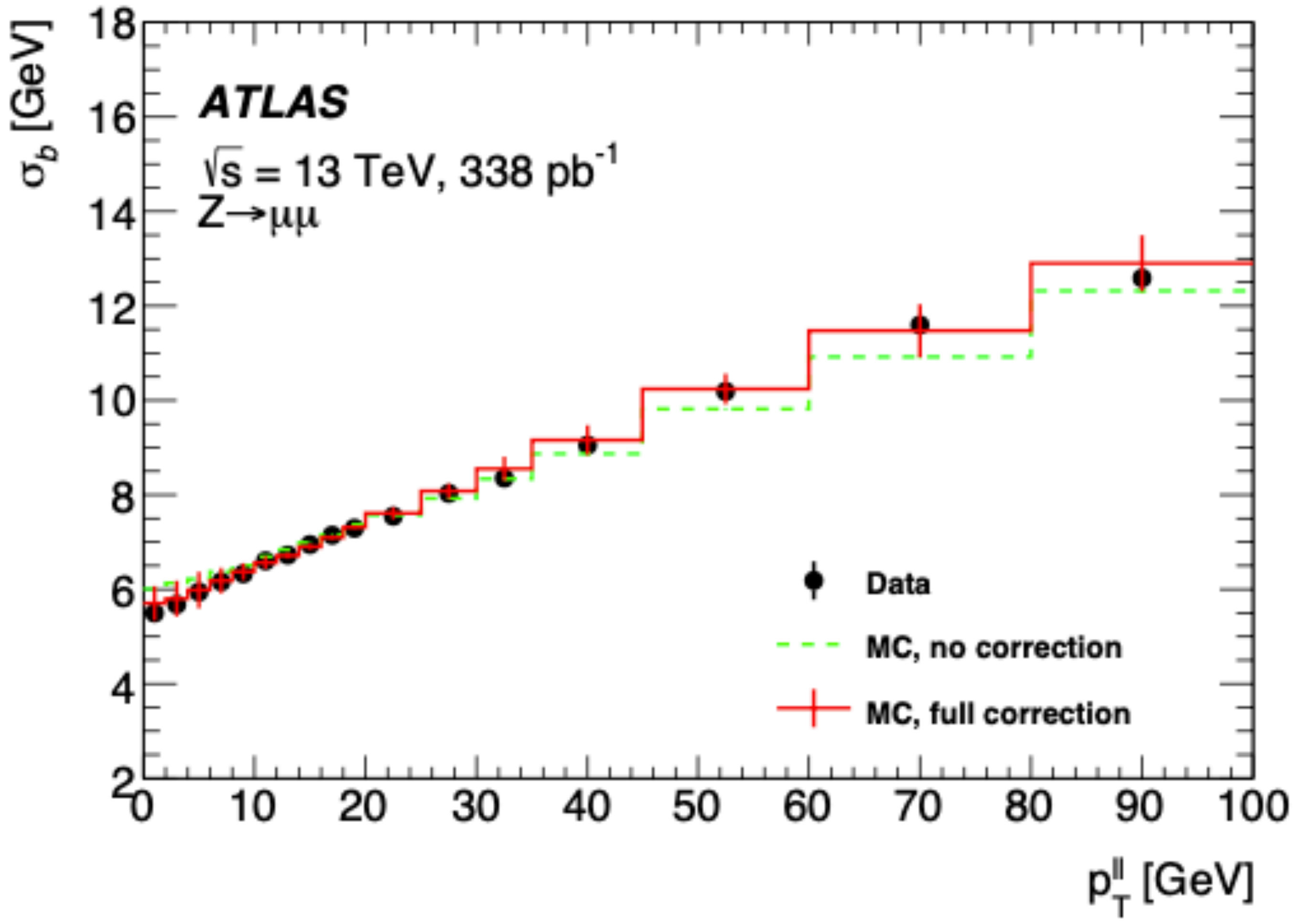


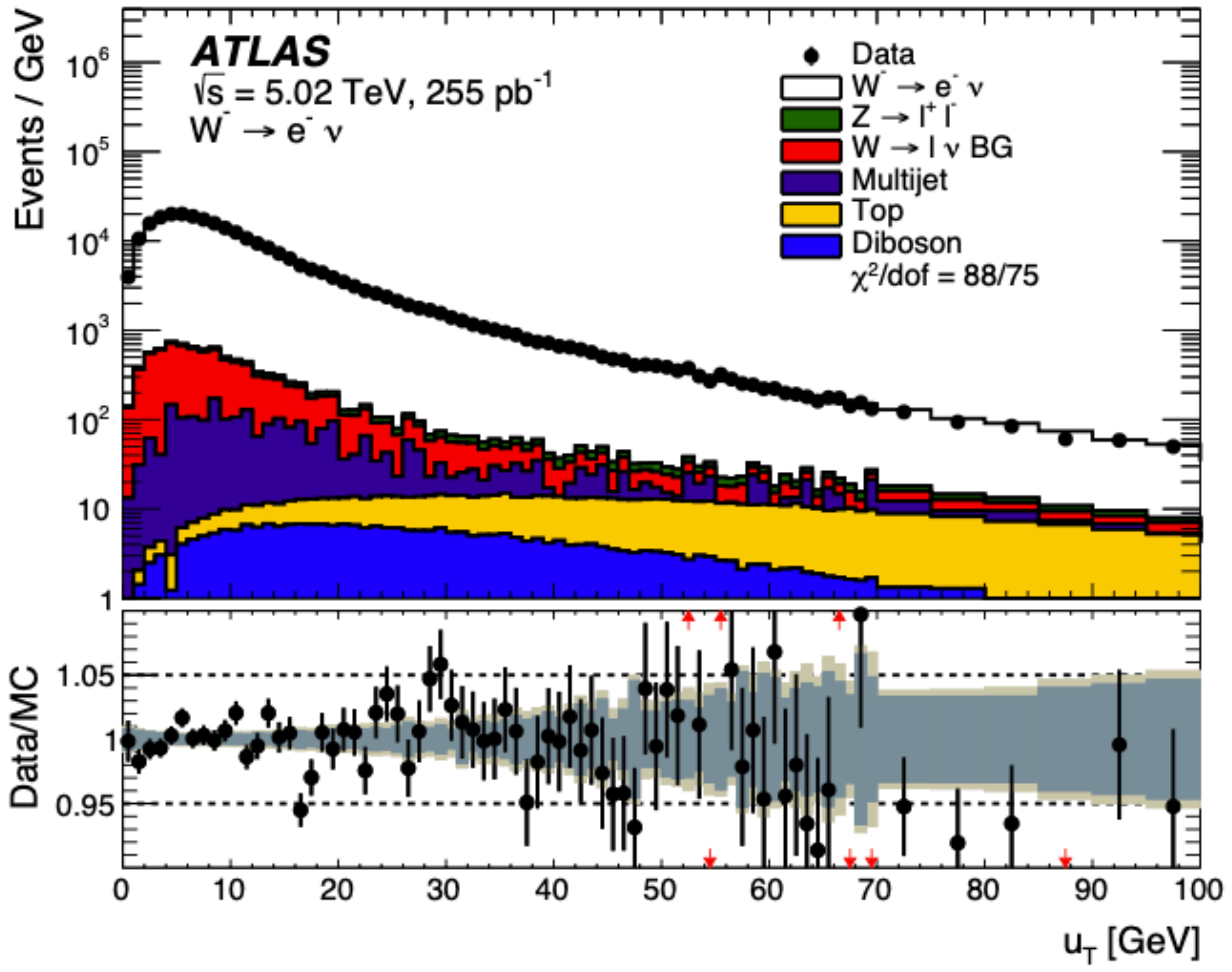
Fit region (FR)	Signal region (SR)
• Lepton p_T > 27 GeV • E_T^{miss} < 25 GeV • m_T^W < 50 GeV • Pass isolation	• Lepton pT > 27 GeV • E_T^{miss} > 25 GeV • m_T^W > 50 GeV • Pass isolation
Control region 1 (CR1) • Lepton p_T > 27 GeV • E_T^{miss} < 25 GeV • m_T^W < 50 GeV • Fail isolation	**Control region 2 (CR2)** • Lepton pT > 27 GeV • E_T^{miss} > 25 GeV • m_T^W > 50 GeV • Fail isolation

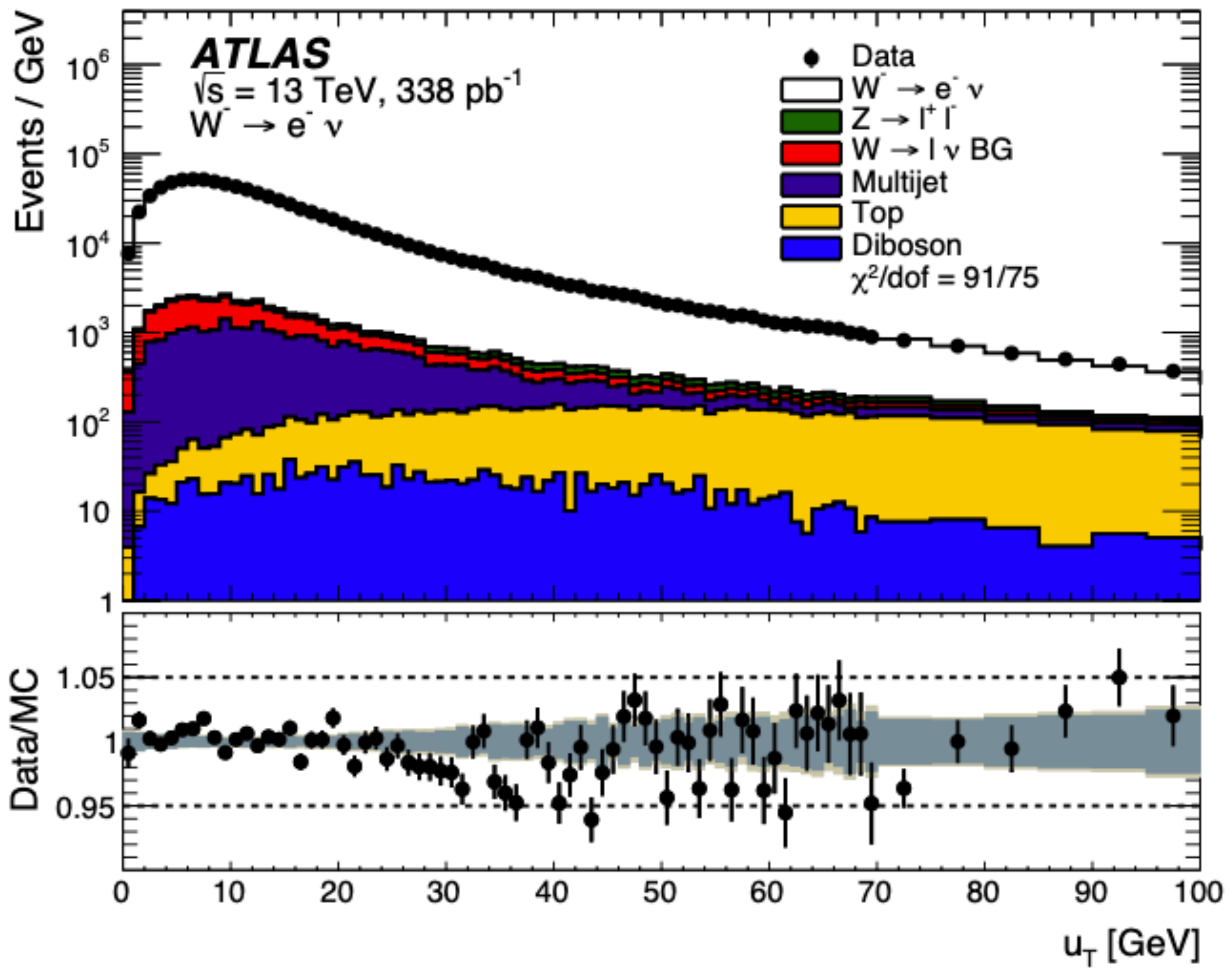
- Combine from two discriminating variables E_T^{miss} and m_T^W
- Compare linear fit and quadratic fit as systematics

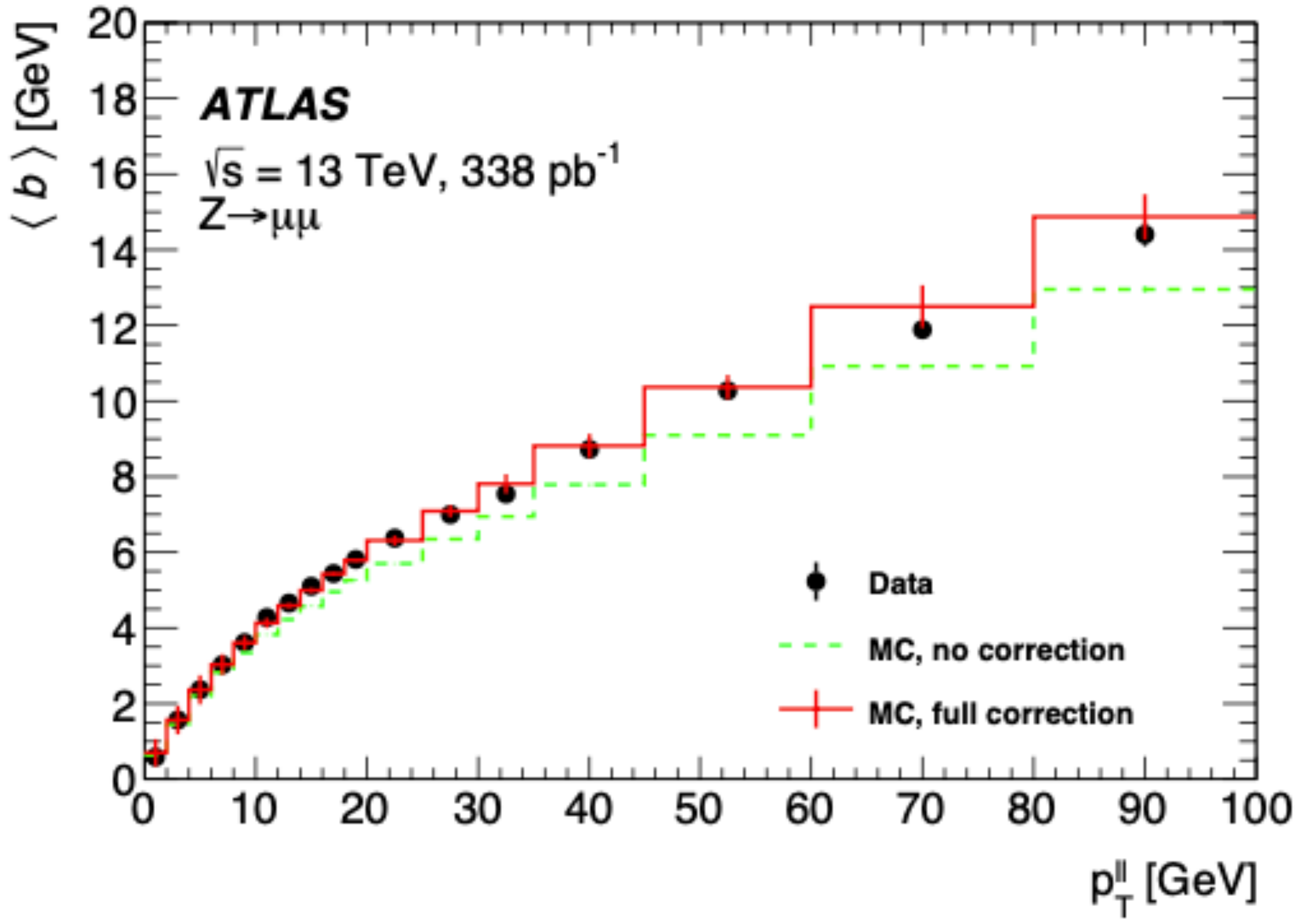
W and Z pT with low-pileup data

- **Lepton calibration:** uses standard high-pileup data extrapolate to low-pileup wherever possible, otherwise in-situ calibrations with Z events.
- **Hadronic recoil:**
  - Reconstructed with particle flow objects(PFOs), better resolution than calorimeter reconstruction.
  - Calibrated with in-situ Z events
    - Modeling of underlying events, response and resolution correction, azimuthal angle etc addressed









Category	$\sigma(Z \to ee)$	$\sigma(Z \to \mu\mu)$	$\sigma(Z \to \ell\ell)$	$\sigma(W^- \to e^-\bar{\nu})$	$\sigma(W^+ \to e^+\nu)$	$\sigma(W^- \to \mu^-\bar{\nu})$	$\sigma(W^+ \to \mu^+\nu)$
Luminosity	2.2	2.2	2.2	2.5	2.5	2.5	2.4
Pile-up	1.2	0.3	0.8	1.1	1.1	0.3	0.4
MC statistics	< 0.2	< 0.2	< 0.2	< 0.2	0.4	< 0.2	0.4
Lepton trigger	0.2	0.4	0.2	1.2	1.3	1.0	1.0
Electron reconstruction	1.4	–	0.9	0.7	0.8	–	–
Muon reconstruction	–	2.1	1.4	–	–	1.0	1.0
Multi-jet	–	–	–	2.9	2.4	1.3	1.1
Other background modelling	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	0.5	0.4
Jet energy scale	–	–	–	1.4	1.4	1.3	1.4
Jet energy resolution	–	–	–	< 0.2	0.3	0.2	0.2
NNJVT	–	–	–	1.6	1.5	1.3	1.3
$E_{\mathrm{T}}^{\mathrm{miss}}$ track soft term	–	–	–	< 0.2	0.4	< 0.2	< 0.2
PDF	0.2	0.2	< 0.2	0.8	0.8	0.6	0.5
QCD scale (ME and PS)	0.6	< 0.2	0.3	1.3	1.2	0.6	0.6
Flavour tagging	–	–	–	–	–	–	–
$t\bar{t}$ modelling	–	–	–	–	–	–	–
Total systematic impact [%]	3.0	3.1	2.7	5.0	4.5	3.8	3.6
Statistical impact [%]	0.04	0.03	0.02	0.02	0.01	0.01	0.01

Category	$\sigma(W^- \to \ell^- \bar{\nu})$	$\sigma(W^+ \to \ell^+ \nu)$	$\sigma(W^\pm \to \ell \nu)$	R_{W^+/W^-}	$R_{W^\pm/Z}$	$R_{t\bar{t}/W^\pm}$
Luminosity	2.5	2.4	2.4	< 0.2	0.3	< 0.2
Pile-up	0.5	0.7	0.6	< 0.2	< 0.2	< 0.2
MC statistics	< 0.2	0.2	< 0.2	< 0.2	< 0.2	< 0.2
Lepton trigger	1.0	0.9	0.9	< 0.2	0.7	0.8
Electron reconstruction	0.4	0.5	0.4	< 0.2	0.5	0.4
Muon reconstruction	0.6	0.6	0.6	0.2	0.8	0.6
Multi-jet	1.2	1.2	1.2	1.6	1.1	1.0
Other background modelling	0.4	0.4	0.4	< 0.2	0.3	0.9
Jet energy scale	1.3	1.3	1.3	< 0.2	1.3	1.3
Jet energy resolution	< 0.2	0.2	< 0.2	< 0.2	< 0.2	< 0.2
NNJVT	1.4	1.3	1.3	< 0.2	1.3	< 0.2
E_T^{miss} track soft term	< 0.2	0.3	0.3	< 0.2	0.3	0.3
PDF	0.5	0.5	0.3	0.5	0.2	0.4
QCD scale (ME and PS)	0.8	0.7	0.6	< 0.2	0.7	0.7
Flavour tagging	–	–	–	–	–	< 0.2
$t\bar{t}$ modelling	–	–	–	–	–	1.1
Total systematic impact [%]	3.7	3.5	3.5	1.7	2.4	2.5
Statistical impact [%]	0.01	0.01	0.01	0.01	0.02	0.32