Measurement of the Z/γ^* transverse momentum distribution in pp collisions at $\sqrt{s}$ = 7TeV with the ATLAS detector

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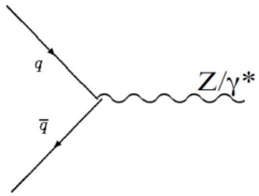
Outline

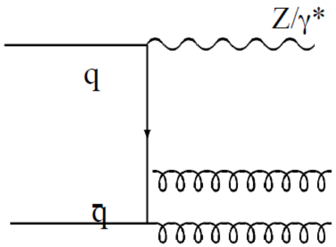
- Introduction
- Collision data and Simulation
- Analysis
  - Event selection
  - Background estimation
  - Unfolding
  - Systematics
- Results
- Summary and Conclusions

Introduction (1/2)

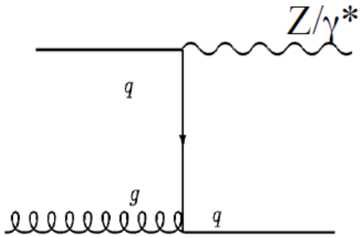
- The transverse momenta of Z/γ* bosons (P_T^Z) produced in pp collisions are a result of the QCD initial state radiation.



P_T^Z = 0 at LO



Multiple soft gluon emission (low P_T^Z)



Radiation of a single parton (high P_T^Z)

- P_T^Z is sensitive to the nature of the QCD radiation.
  - An excellent testing ground for QCD predictions
    - Soft gluon resummation in low P_T^Z
    - Fixed order pQCD in high P_T^Z
  - An ideal laboratory for evaluating the phenomenology of vector boson production (e.g. event generators).

Introduction (2/2)

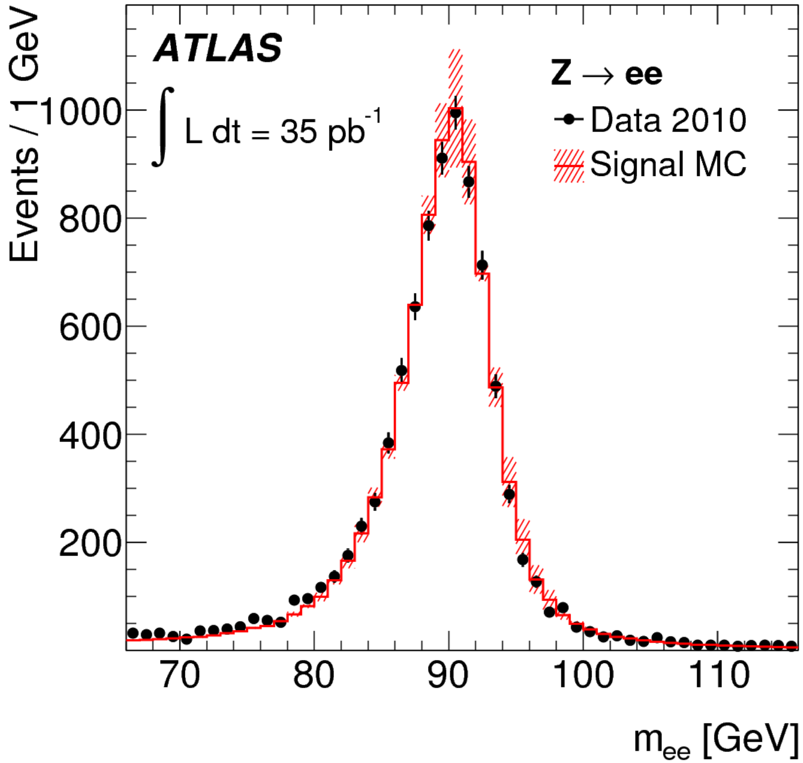
- We measure the normalized P_T^Z distribution within the fiducial phase space using the Z->μμ and Z->ee decays.
  - **"normalized" measurement** $\frac{1}{\sigma}\frac{d\sigma(Z)}{dp_T(Z)}$
    - A lot of systematic uncertainties cancel out leading to a better precision.
  - **Fiducial phase space**
    - $P_t^{e/\mu}>20$ GeV, $|\eta|<2.4$, 66 GeV$<M_{ll}<$116 GeV
    - Very close to the phase space defined by the event selection -> minimal model-dependent extrapolation
  - **Leptonic decays**
    - well reconstructed final states with little background making a precision measurement possible.
- We also produce correction factors to extrapolate the fiducial P_T^Z to the full phase space.

Event Samples and Selection

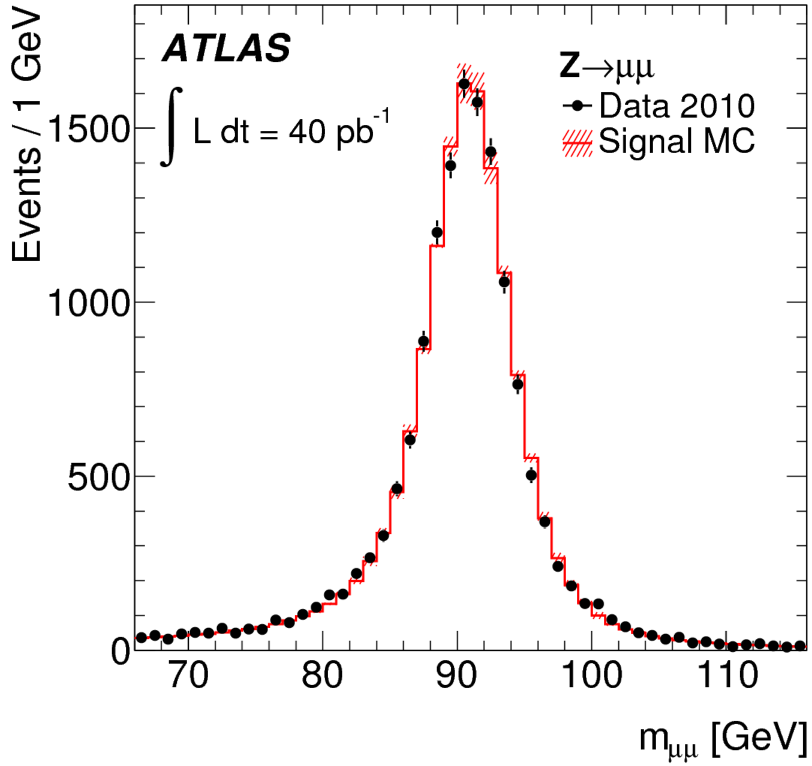
- **Event samples**
  - Collision data
    - 7 TeV pp collisions recorded with ALTAS in 2010
    - ee channel : $35\ pb^{-1}$, $\mu\mu$ channel : $40\ pb^{-1}$
  - Simulation
    - Pythia Z->$\mu\mu$ and Z->ee with pileup simulated
- **Event selection**
  - A good primary vertex
  - Lepton Selection
    - Muon: P_T>20GeV, $|\eta|$<2.4, isolated
    - Electron: E_T>20GeV, $|\eta|$<1.37 or 1.52<$|\eta|$< 2.4
  - *Z->ll* (*l*=e/μ) selection
    - two good electrons or two good muons
    - Oppositely charged
    - 66 GeV < M_{ll} < 116 GeV

M_{ll} after final selection

M(e⁺e⁻)



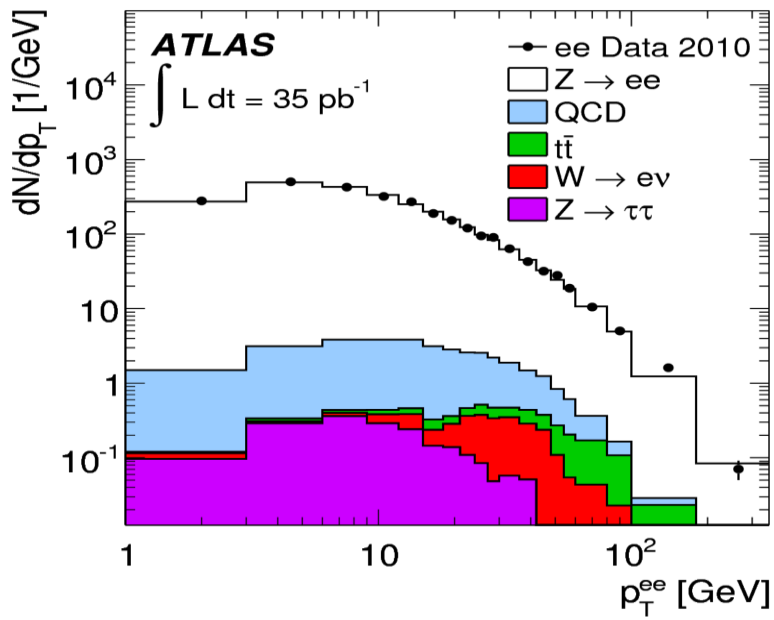
M(μ⁺μ⁻)



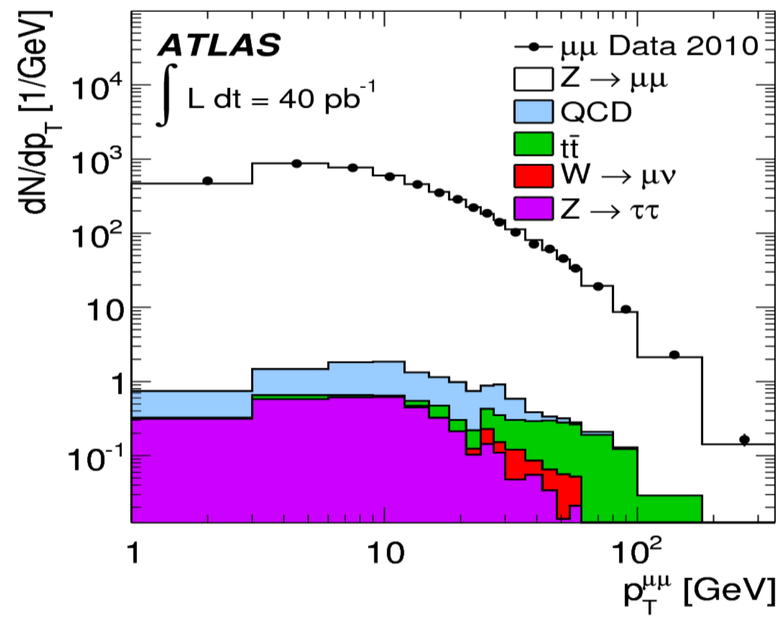
- Good data and MC agreement in the di-lepton invariant mass distributions

P_T(ll) after final selection

$P_T(e^+e^-)$



$P_T(\mu^+\mu^-)$



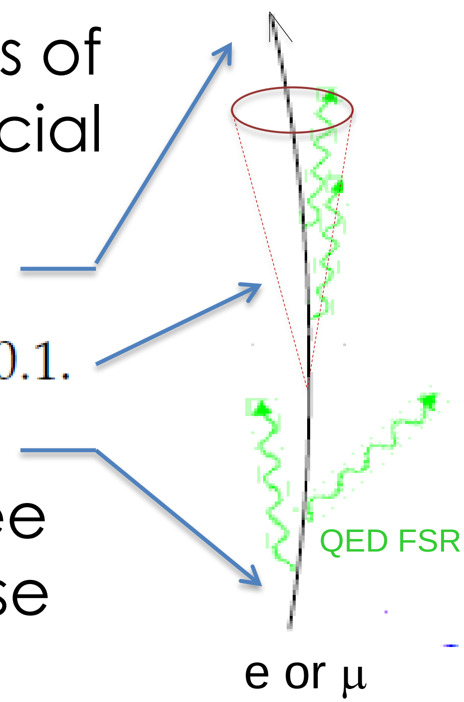
- Observed P_T(ll) is well described by the simulation.
- Very low level of background with slight P_T^Z dependence
  - Background estimation
    - Z->tautau, W->lv and ttbar: simply using MC
    - QCD: data driven approach
  - Total background
    - ee channel : 1.5%±0.6% , μμ channel : 0.4%±0.2%

P_T^Z Unfolding

- Bin-by-bin unfolding is used to correct the observed P_T^Z for detector effects and QED FSR.
  - 0-350 GeV with 19bins
  - Bin purity >60% at low P_T^Z and >90% at P_T^Z
- Bayesian/Matrix unfolding methods are tried as well for cross-check and systematics.
- Observed P_T^Z is unfolded to different levels of lepton QED FSR corrections within the fiducial phase space.

bare:	after QED FSR radiation.
dressed:	"bare" + photons in cone with $\Delta R < 0.1$.
propagator:	before QED FSR.

- The "propagator" unfolded P_T^Z from the ee and $\mu\mu$ channels are combined to increase the measurement sensitivity.



Systematics

- Lepton efficiencies
  - 1%-3% in most of the P_T^Z bins
- Lepton energy/momentum scale and resolution
  - Scale: 0.2%-4% (ee), ~0.4% (μμ)
  - Resolution: ~0.5% (ee), 0.1%-0.7% (μμ)
- Unfolding bias
  - P_T^Z<6 GeV: 3.6% (ee), 4.7% (μμ)
  - 6 GeV<P_T^Z<100 GeV: 2.0% (ee), 1.3% (μμ)
  - P_T^Z>100 GeV: 4.2% (ee), 2.9% (μμ)
- Others
  - Background estimation: 0.5% (ee), 0.6% (μμ)
  - Pileup modeling: 0.3%
  - QED FSR corrections: 0.6%

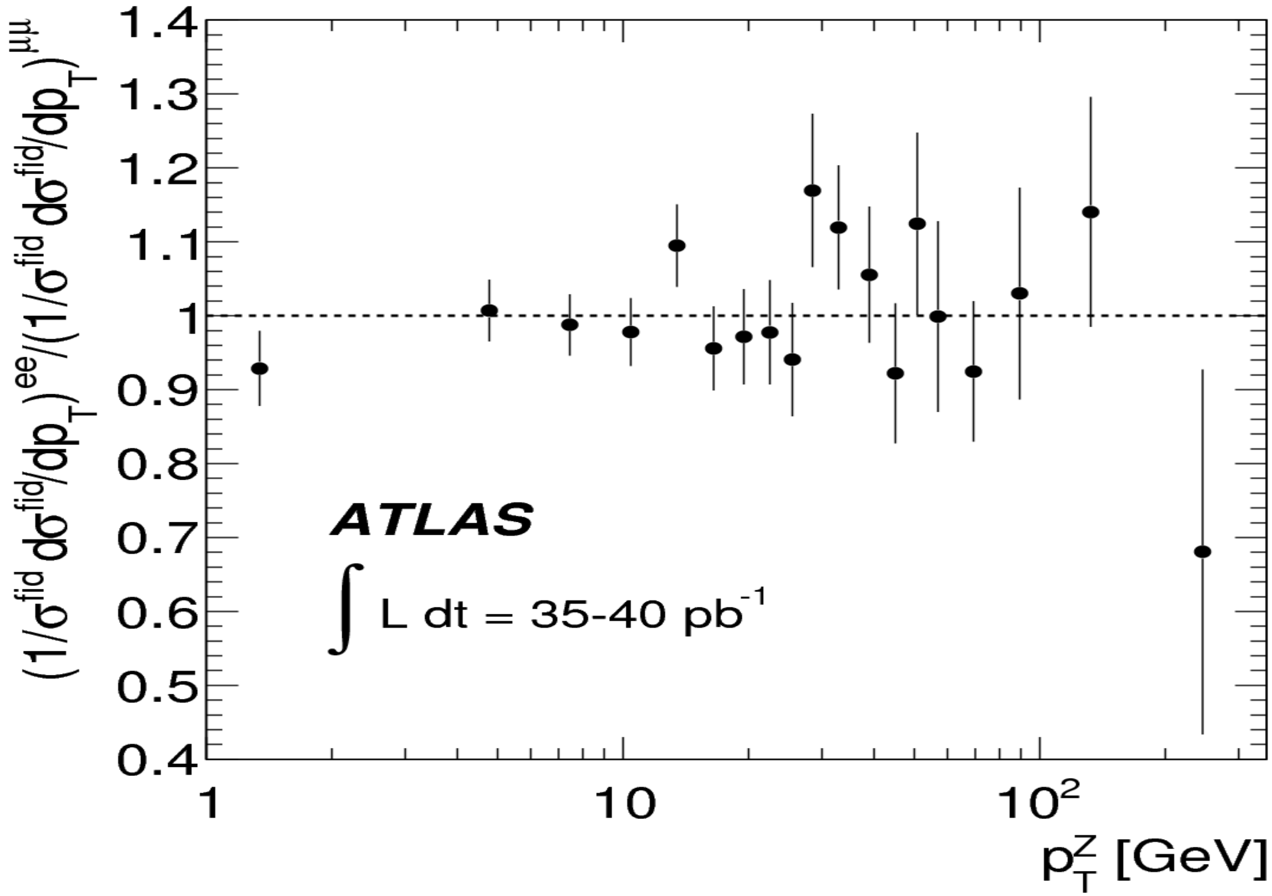
normalized P_T^Z distribution

p_T^Z bin (GeV)	$1/\sigma^{\rm fid}_{\rm ref} d\sigma^{\rm fid}_{\rm ref}(pp \to Z/\gamma^* \to \ell^+\ell^-)/dp_T^Z$ (GeV^{-1}) $Z/\gamma^* \to e^+e^-$				uncert. (%)		$Z/\gamma^* \to \mu^+\mu^-$				uncert. (%)	
	propag.	dressed	bare	k	stat.	syst.	propag.	dressed	bare	k	stat.	syst.
0 - 3	3.48	3.40	3.21	$\cdot 10^{-2}$	3.3	4.7	3.75	3.66	3.58	$\cdot 10^{-2}$	2.6	5.0
3 - 6	5.85	5.78	5.60	$\cdot 10^{-2}$	2.4	3.3	5.81	5.74	5.68	$\cdot 10^{-2}$	2.0	4.0
6 - 9	4.61	4.62	4.64	$\cdot 10^{-2}$	2.7	2.3	4.67	4.68	4.69	$\cdot 10^{-2}$	2.1	1.6
9 - 12	3.43	3.46	3.56	$\cdot 10^{-2}$	3.1	2.4	3.50	3.54	3.58	$\cdot 10^{-2}$	2.4	1.6
12 - 15	2.93	2.97	3.09	$\cdot 10^{-2}$	3.3	2.7	2.67	2.72	2.76	$\cdot 10^{-2}$	2.8	1.7
15 - 18	2.04	2.08	2.16	$\cdot 10^{-2}$	3.9	3.0	2.13	2.17	2.20	$\cdot 10^{-2}$	3.1	1.7
18 - 21	1.64	1.67	1.73	$\cdot 10^{-2}$	4.4	3.3	1.69	1.72	1.74	$\cdot 10^{-2}$	3.5	1.8
21 - 24	1.32	1.33	1.37	$\cdot 10^{-2}$	4.8	3.6	1.35	1.36	1.37	$\cdot 10^{-2}$	4.0	1.8
24 - 27	1.08	1.08	1.11	$\cdot 10^{-2}$	5.5	3.8	1.15	1.16	1.17	$\cdot 10^{-2}$	4.3	1.9
27 - 30	1.02	1.03	1.03	$\cdot 10^{-2}$	6.5	4.0	0.87	0.88	0.88	$\cdot 10^{-2}$	5.0	2.0
30 - 36	7.22	7.24	7.26	$\cdot 10^{-3}$	4.8	4.2	6.45	6.46	6.45	$\cdot 10^{-3}$	4.1	2.1
36 - 42	4.89	4.88	4.85	$\cdot 10^{-3}$	5.8	4.5	4.63	4.63	4.62	$\cdot 10^{-3}$	4.9	2.2
42 - 48	3.66	3.64	3.59	$\cdot 10^{-3}$	7.0	4.8	3.97	3.95	3.94	$\cdot 10^{-3}$	5.3	2.4
48 - 54	3.26	3.25	3.20	$\cdot 10^{-3}$	7.8	5.0	2.90	2.88	2.86	$\cdot 10^{-3}$	6.2	2.6
54 - 60	2.14	2.13	2.08	$\cdot 10^{-3}$	9.2	5.4	2.14	2.13	2.11	$\cdot 10^{-3}$	7.2	2.7
60 - 80	1.21	1.20	1.17	$\cdot 10^{-3}$	6.5	5.7	1.31	1.30	1.28	$\cdot 10^{-3}$	5.1	3.0
80 -100	5.69	5.63	5.44	$\cdot 10^{-4}$	9.8	5.9	5.52	5.47	5.40	$\cdot 10^{-4}$	7.8	3.5
100-180	1.74	1.73	1.67	$\cdot 10^{-4}$	9.6	6.1	1.52	1.51	1.49	$\cdot 10^{-4}$	7.5	4.4
180-350	0.78	0.77	0.73	$\cdot 10^{-5}$	27.0	7.8	1.14	1.14	1.11	$\cdot 10^{-5}$	18.9	6.6

- Acceptance and lepton efficiency: μμ > ee, so more statistics in μμ, thus for statistical uncertainties: μμ < ee
- Electron energy scale contributes a lot to the systematic uncertainties in ee in most of the bins.

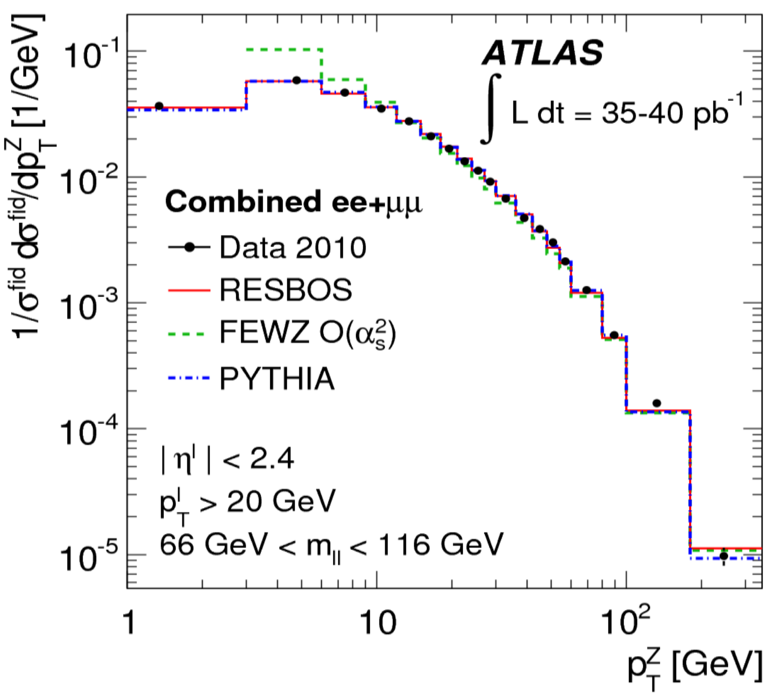
Comparison between channels

$$\frac{1}{\sigma}\frac{d\sigma(Z)}{dp_T(Z)} \text{ (ee, propagator) } / \frac{1}{\sigma}\frac{d\sigma(Z)}{dp_T(Z)} \text{ } (\mu\mu\text{, propagator})$$



- *Good agreement between the two channels within uncertainties*

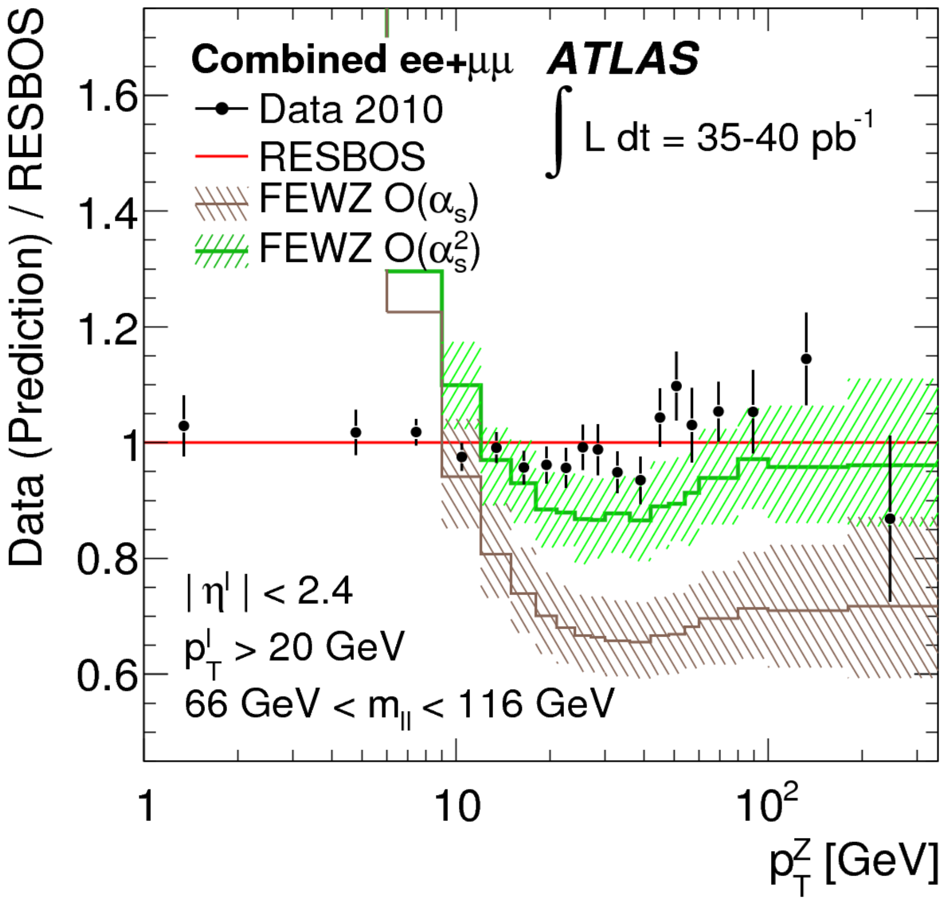
Combined P_T^Z distribution



$\langle p_T^Z \rangle$ (GeV)	$\frac{1}{\sigma^{fid}}\frac{d\sigma^{fid}}{dp_T^Z}$ (GeV^{-1})	stat. (%)	syst. (%)	A_c^{-1}	unc. (%)
0 - 3	0.0366	2.0	4.7	1.047	3.7
3 - 6	0.0586	1.5	3.6	1.029	1.8
6 - 9	0.0466	1.7	1.5	1.014	1.5
9 - 12	0.0348	1.9	1.6	0.999	1.5
12 - 15	0.0277	2.2	1.7	0.999	1.4
15 - 18	0.0210	2.5	1.7	0.990	1.5
18 - 21	0.0167	2.8	1.8	0.989	1.5
21 - 24	0.0133	3.1	1.9	0.990	1.5
24 - 27	0.0112	3.4	2.0	0.994	2.3
27 - 30	0.0092	4.0	2.1	0.988	2.3
30 - 36	0.0067	3.2	2.1	0.987	3.2
36 - 42	0.0047	3.8	2.3	0.979	3.9
42 - 48	0.0038	4.2	2.4	0.965	4.3
48 - 54	0.0030	4.9	2.5	0.950	4.4
54 - 60	$2.1 \cdot 10^{-3}$	5.7	2.7	0.938	5.3
60 - 80	$1.3 \cdot 10^{-3}$	4.0	2.8	0.910	5.3
80 -100	$5.5 \cdot 10^{-4}$	6.1	3.1	0.894	5.3
100-180	$1.6 \cdot 10^{-4}$	5.9	3.7	0.826	5.4
180-350	$9.8 \cdot 10^{-6}$	15.6	5.4	0.672	5.6

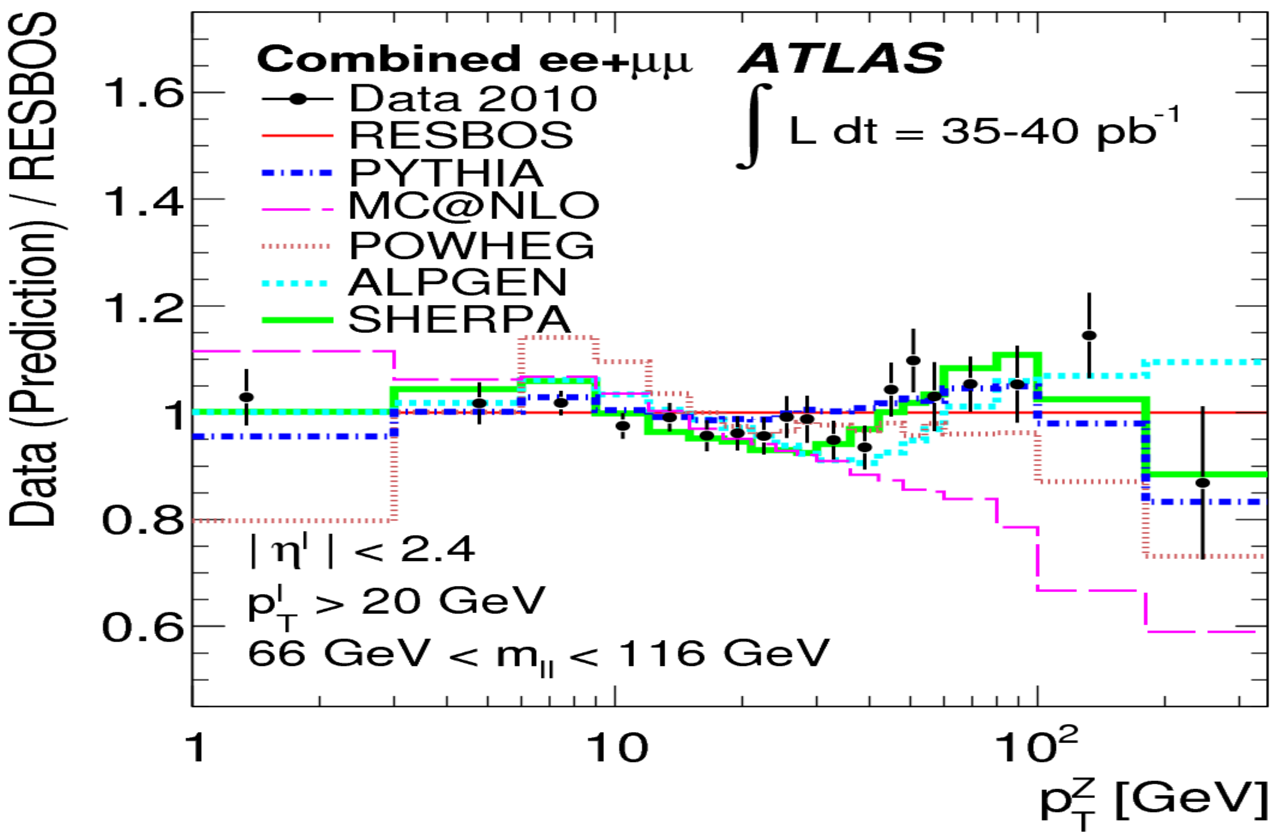
- The two channels are combined using a χ^2 minimization method that takes into account the correlated systematic uncertainties.
  - χ^2 /d.o.f = 17.0/19 -> good compatibility of the measurements in the two channels
- A_c^{-1} = correction factor needed to extrapolate the fiducial measurement to the full phase space.

Comparison with theoretical predictions



- FEWZ (fixed order pQCD prediction)
  - Diverging in low P_T^Z region.
  - Its $O(\alpha_s^2)$ prediction is lower than data by ~10%. But still comparable with uncertainty.
  - 26-36% $O(\alpha_s^2)$ correction s for P_T^Z >18GeV with significant uncertainties indicate non-negligible missing higher order corrections.
- RESBOS (combination of resummed and fixed order pQCD calculation)
  - In good agreement with data over the entire P_T^Z range indicating the importance of resummation even at relatively large P_T^Z.
  - Slightly higher than data in P_T^Z of [10,40] GeV and slightly lower than data when P_T^Z above 40 GeV

Comparison with Generators



- ALPGEN and SHERPA implement tree-level diagrams up to 5 additional hard partons. So they both give good description of data up to large P_T^Z .
- MC@NLO and POWHEG deviate from data at low and high P_T^Z .
- PYTHIA describes data very well over the entire P_T^Z range.

Summary and Conclusions

- Normalized P_T^Z distribution has been measured up to P_T^Z=350 GeV in both Z->ee and Z->$\mu\mu$ channels.
- The measurements in the two channels at the "propagator" level are quite compatible , and are combined to increase the measurement sensitivity.
- RESBOS agrees with the measurement. FEWZ is below the measurement by about 10%.
- The measurement is found to be in good agreement with SHERPA, ALPGEN and PYTHIA.
- A better measurement is expected with more data available and novel techniques (e.g. ϕ^*_η) to be used.

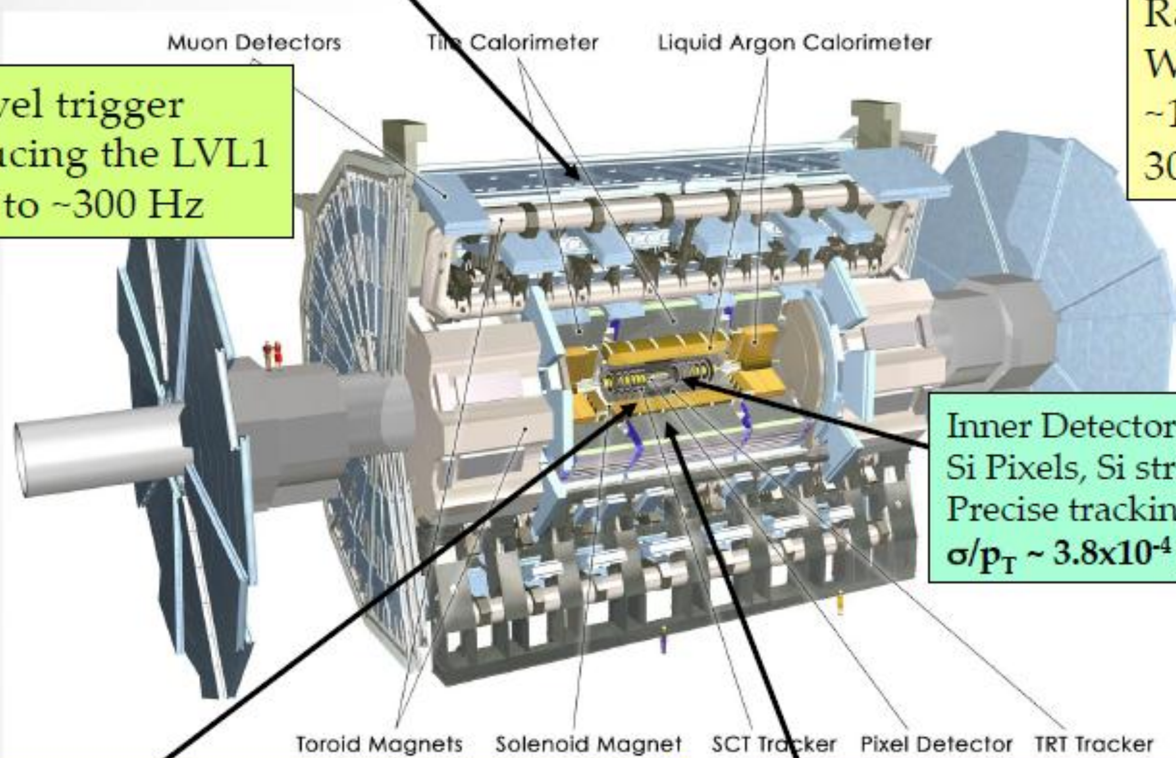
Backup

ATLAS Detector

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers **(MS)**
Muon trigger and measurement with momentum resolution **< 10% up to E_μ ~ 1 TeV**

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger reducing the LVL1 rate to ~300 Hz



Inner Detector ($|\eta|<2.5$, B=2T): **(ID)**
Si Pixels, Si strips, TRT
Precise tracking and vertexing,
σ/p_T ~ 3.8×10^{-4} p_T (GeV) $\oplus$ 0.015

EM calorimeter: Pb-LAr Accordion **(ECal)**
e/γ trigger, identification and measurement
E-resolution: σ/E ~ $10\%/\sqrt{E} \oplus 0.007$
High granularity

Hadron calorimetry ($|\eta|<4.9$) **(HCal)**
Fe/scintillator Tiles (central), Cu-LAr (endcap)
E-resolution: **σ/E ~ $50\%/\sqrt{E} \oplus 0.03$**
FWD calorimetry:Cu/W-LAr **σ/E ~ $90\%/\sqrt{E} \oplus 0.07$**

Collision data and MC

- **Collision data**
  - Triggered on single leptons (E_T^e>15GeV or P_T^μ>13GeV)
  - 7TeV pp data recorded in 2010 with all relevant sub-detectors fully operational
  - 35pb^{-1} for ee channel and 40pb^{-1} for $\mu\mu$ channel
- **MC samples**
  - Signal (Z->mm and Z->ee) generation
    - Pythia (MRST2007LO*) as default, MC@NLO(CTEQ6.6)/HERWIG/Jimmy
  - Background generation
    - W->lv: Pythia;
    - Z->tautau: Pythia, MC@NLO
    - Dijet: Pythia
    - ttbar: MC@NLO, PowHeg;
  - Detector simulation based on GEANT4
  - Pileup simulated by overlaying minimum bias MC events

Event Selection

- **A good primary vertex (PV)**
- **Lepton selection**
  - **Muon**
    - Reconstructed by associating a track in the Muon spectrometer track with an track in the inner detector .
    - P_T>20GeV, $|\eta|<2.4$
    - Isolated: $\Sigma P_T(\text{cone}0.2)/P_T^{\mu}<0.2$
    - Originated from PV: $|z_{w.r.t.\ PV}|<5mm$ && $|d_{w.r.t.\ PV}|<1mm$
  - **Electron**
    - Electron identification based on the information from the sub-detectors of ID/ECal/HCal
    - E_T>20GeV, $|\eta|<1.37$ or $1.52<|\eta|< 2.47$
- **Z->ll selection**
  - Exactly two good electrons or at least two good muons
  - Oppositely charged
  - $66GeV < M_{ll} < 116GeV$

Background Estimation

- Contributions from Z->tautau, W->lv and ttbar are estimated using MC and normalized to the data integrated luminosities using NNLO or NLL-NLO cross sections.
- Data driven methods are used for QCD multiple-jet

ee channel

- Total contribution
  - fit signal and QCD templates to the Mll with loosened electron identification requirements.
  - scale the result from the fit.
- Background shape in P_T^Z is determined using a QCD- enriched di-electron sample with inverted electron identification criteria and Mll cut

μμ channel

	40…60 GeV	66…116 GeV
isolated	B	A (Signal)
inverted-isolation	D	C

- ABCD method for total contribution.
- Background shape from region C.

Details of Generators

- ALPGEN
  - v2.13,
  - interfaced to HERWIG-v6.510 for parton shower and to JIMMY-v4.31 for underlying events
  - CTEQ6L1
  - tree-level diagrams up to 5 additional hard partons implemented
- SHERPA
  - v1.2.3,
  - CTEQ66
  - tree-level diagrams up to 5 additional hard partons implemented
- MC@NLO
  - interfaced to HERWIG and JIMMY
  - CTEQ66
- POWHEG
  - interfaced to PYTHIA
  - CTEQ66
- PYTHIA
  - v6.4 with pt-ordered parton shower
  - MRST2007LO*
  - underlying event parameters tuned to Tevatron data