$Z \rightarrow 4l$ Measurement

Yusheng Wu
Modern Physics Department & State Key Laboratory for Particle Detection and Electronics, USTC

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Introduction

- Rare decays of Z bosons are important channels to look for BSM physics

- CEPC will offer a huge amount of Z bosons (in only 2-years dedicated running), ~ 10^{12} (which is actually larger than the number produced at the LHC: 50nb x $3ab^{-1}$ ~ 1.5 x 10^{11}

- Rare decays can be investigated with unprecedented precision, and Z → four or more leptons is one of these channels

- This talk will briefly review the measurement strategy and results at the LHC, and then comment on the potentials with CEPC

The BR(Z→4l)

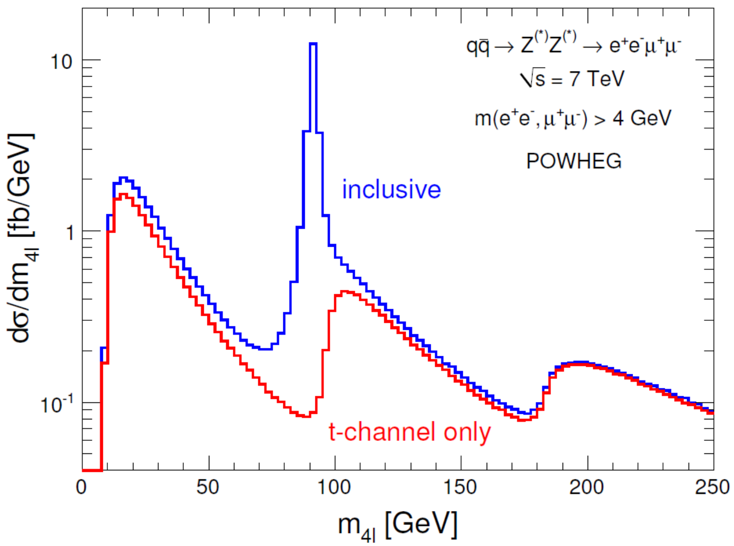
From PDG

Z DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	e^+e^-	[a]	(3.3632 ± 0.0042) %	
Γ_2	$\mu^+\mu^-$	[a]	(3.3662 ± 0.0066) %	
Γ_3	$\tau^+\tau^-$	[a]	(3.3696 ± 0.0083) %	
Γ_4	$\ell^+\ell^-$	[a,b]	(3.3658 ± 0.0023) %	
Γ_5	$\mu^+\mu^-\mu^+\mu^-$			
Γ_6	$\ell^+\ell^-\ell^+\ell^-$	[c]	$(4.58 \pm 0.26) \times 10^{-6}$	
Γ_7	invisible	[a]	(20.000 ± 0.055) %	
Γ_8	hadrons	[a]	(69.911 ± 0.056) %	
Γ_9	$(u\bar{u}+c\bar{c})/2$		(11.6 ± 0.6) %	
Γ_{10}	$(d\bar{d}+s\bar{s}+b\bar{b})/3$		(15.6 ± 0.4) %	
Γ_{11}	$c\bar{c}$		(12.03 ± 0.21) %	
Γ_{12}	$b\bar{b}$		(15.12 ± 0.05) %	
Γ_{13}	$b\bar{b}b\bar{b}$		$(3.6 \pm 1.3) \times 10^{-4}$	
Γ_{14}	ggg		< 1.1 %	CL=95%
Γ_{15}	$\pi^0\gamma$		$< 2.01 \times 10^{-5}$	CL=95%
Γ_{16}	$\eta\gamma$		$< 5.1 \times 10^{-5}$	CL=95%
Γ_{17}	$\rho^0\gamma$		$< 2.5 \times 10^{-5}$	CL=95%
Γ_{18}	$\omega\gamma$		$< 6.5 \times 10^{-4}$	CL=95%
Γ_{19}	$\eta'(958)\gamma$		$< 4.2 \times 10^{-5}$	CL=95%

One of the rare channels, which have been established, but without a perfect precision

Example with Details: A Previous ATLAS Measurement



qq → Z/Z*Z* → 4ℓ modeled by Powheg MC for

- Cross section calculations (NLO QCD)
- Event generations (interfaced to PYTHIA)

gg → ZZ → 4ℓ modeled by GG2ZZ MC for

- Cross section calculations (LO QCD)
- Event generations (interfaced to Herwig/Jimmy)

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NLO Calculation by Powheg (CT10 PDF, Scales = $m_{4\ell}$)

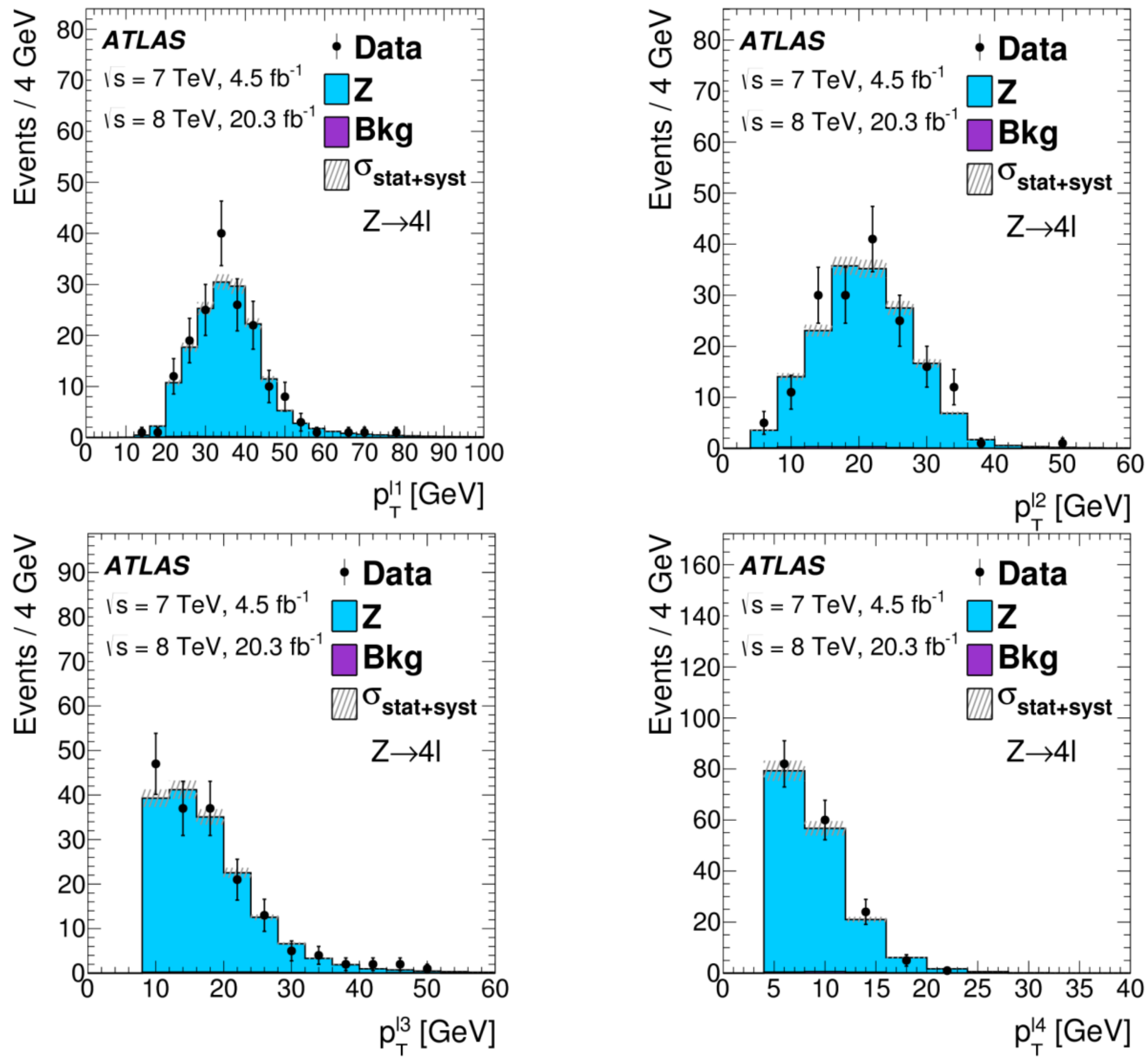
Phase space: $80 < m_{4\ell} < 100$ GeV and $m_{\ell^+\ell^-} > 5$ GeV

Expected quantity	7 TeV	8 TeV
Total inclusive cross-section of $pp \to Z$	26.0 ± 0.6 nb	30.3 ± 0.8 nb
Total cross-section of $pp \to Z/ZZ^* \to 4\ell(e,\mu)$	89.97 ± 2.06 fb	104.84 ± 2.50 fb
Cross-section of $pp \to Z/ZZ^* \to 4e, 4\mu$	45.78 ± 1.10 fb	53.35 ± 1.24 fb
Cross-section of $pp \to Z/ZZ^* \to 2e2\mu$	44.19 ± 1.04 fb	51.49 ± 1.26 fb
Total t-ch. cross-section of $pp \to ZZ^* \to 4\ell(e,\mu)$)	3.28 ± 0.08 fb	3.80 ± 0.09 fb
t-ch. cross-section of $pp \to ZZ^* \to 4e, 4\mu$	1.55 ± 0.04 fb	1.79 ± 0.04 fb
t-ch. cross-section of $pp \to ZZ^* \to 2e2\mu$	1.73 ± 0.04 fb	2.01 ± 0.05 fb
Branching ratio of $Z \to 4\ell(e,\mu)$	$(3.33 \pm 0.01) \times 10^{-6}$	

Phase space σ

Z→4l is a rare decay

Example with Details: A Previous ATLAS Measurement



3rd and 4th leptons are pretty soft

Example with Details: A Previous ATLAS Measurement

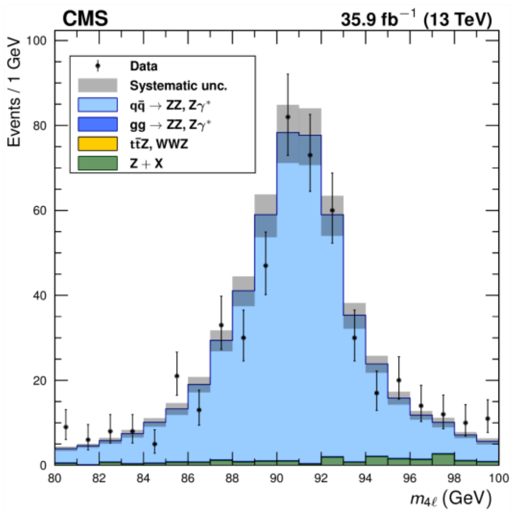
$$\mathrm{BR}(Z \to 4\ell) = \mathrm{BR}(Z \to 2\mu)(1-f_t)\frac{\left(N_{\mathrm{obs.}} - N_{\mathrm{bkg.}}\right)^{4\ell}(C \times A)^{2\mu}}{\left(N_{\mathrm{obs.}} - N_{\mathrm{bkg.}}\right)^{2\mu}(C \times A)^{4\ell}}$$

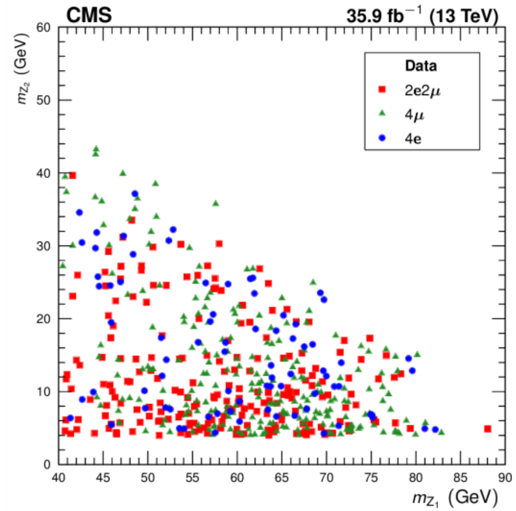
Uncertainty on $\mathrm{BR}(Z \to 2\mu)$ is small. f_t = fraction of t-channel in phase-space.

Quantity	$\sqrt{s}$	Value
Measured	7 TeV	$(2.67 \pm 0.62\ (\mathrm{stat}) \pm 0.14\ (\mathrm{syst})) \times 10^{-6}$
	8 TeV	$(3.33 \pm 0.27\ (\mathrm{stat}) \pm 0.11\ (\mathrm{syst})) \times 10^{-6}$
	Combined	$(3.20 \pm 0.25\ (\mathrm{stat}) \pm 0.12\ (\mathrm{syst})) \times 10^{-6}$
Expected		$(3.33 \pm 0.01) \times 10^{-6}$

Relied on the ratio of Z→4l and Z→2l to cancel the theoretical and experimental uncertainties

Current Results from the LHC - CMS





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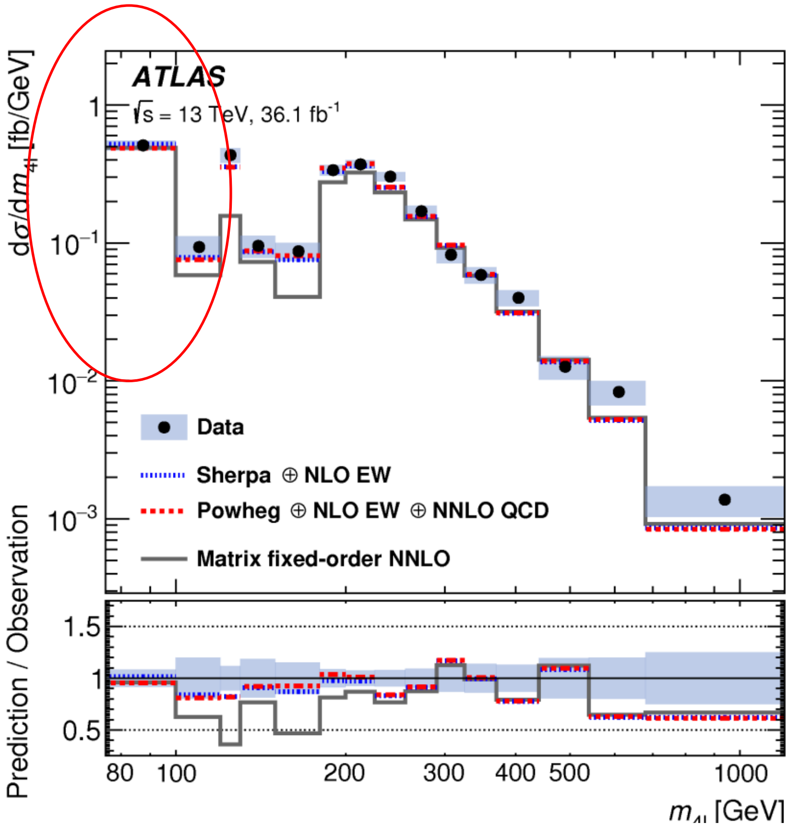
Cross section measurement	Fiducial requirements
Common requirements	$p_T^{\ell_1} > 20\,\text{GeV}$, $p_T^{\ell_2} > 10\,\text{GeV}$, $p_T^{\ell_{3,4}} > 5\,\text{GeV}$, $\lvert\eta^\ell\rvert < 2.5$, $m_{\ell\ell} > 4\,\text{GeV}$ (any opposite-sign same-flavor pair)
$Z \to 4\ell$	$m_{Z_1} > 40\,\text{GeV}$ $80 < m_{4\ell} < 100\,\text{GeV}$

Uncertainty	$Z \to 4\ell$
Lepton efficiency	6–10%
Trigger efficiency	2–4%
Statistical (simulation)	1–2%
Background	0.6–1.3%
Pileup	1–2%
PDF	1%
μ_R, μ_F	1%
Integrated luminosity	2.5%

$B(Z \to 4\ell) = 4.8 \pm 0.2\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.1\,(\text{theo}) \pm 0.1\,(\text{lumi}) \times 10^{-6}$

Current Results from the LHC - ATLAS



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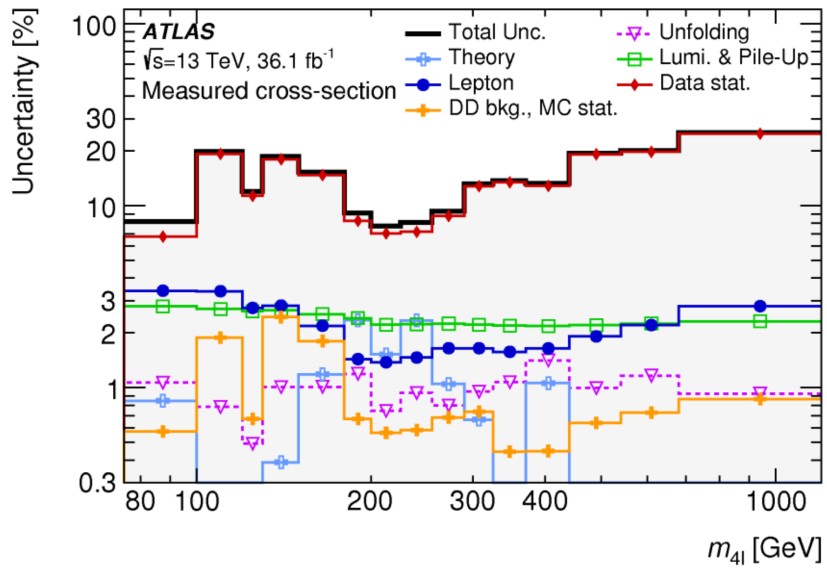
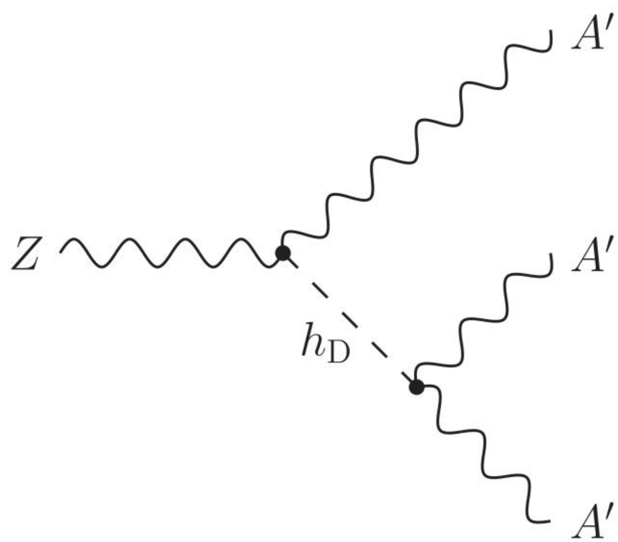


Table 3: Comparison of measurements for the $Z \to 4\ell$ branching fraction in the phase-space region 80 GeV $< m_{4\ell} <$ 100 GeV, $m_{\ell\ell} >$ 4 GeV.

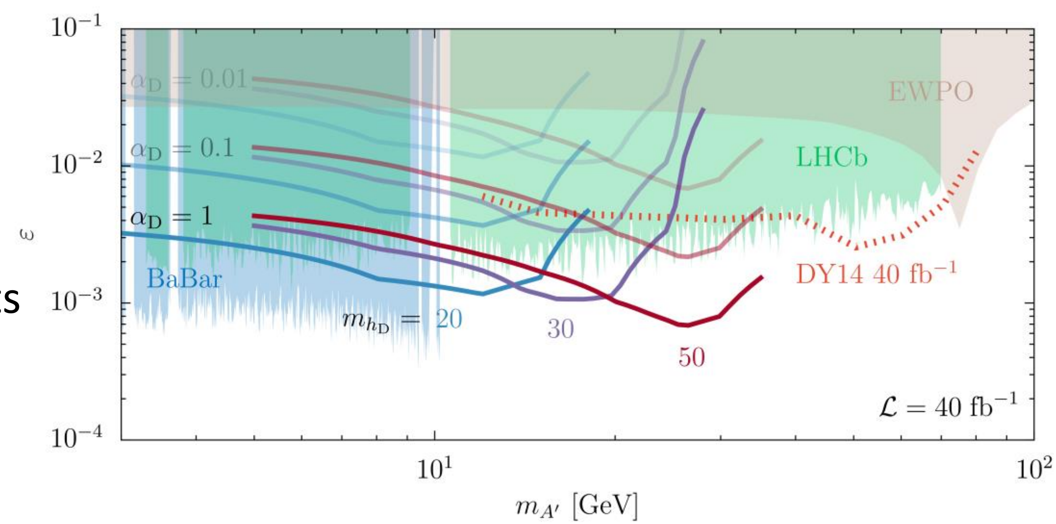
Measurement	$\mathcal{B}_{Z\to 4\ell}/10^{-6}$
ATLAS, $\sqrt{s}$ = 7 TeV and 8 TeV [8]	4.31±0.34(stat)±0.17(syst)
CMS, $\sqrt{s}$ = 13 TeV [6]	4.83 $^{+0.23}_{-0.22}$(stat) $^{+0.32}_{-0.29}$(syst)±0.08(theo)±0.12(lumi)
ATLAS, $\sqrt{s}$ = 13 TeV	**4.70 ± 0.32(stat) ± 0.21(syst) ± 0.14(lumi)**

Ideas of Using Z→ 4l decays to Search for BSM

For instance arXiv:1710.07635v2



Rare decays of Z to multiple leptons can have good sensitivity to its portal to dark / hidden sector



LHC could give sensitive constraints of dark photon with O(10) GeV mass range

CEPC can do better with large amount of Zs and precise detector?

Discussions

Z rare decays are important physics channels for CEPC, especially given the large number of Zs

Z→4l, 6l, … can be a precise channel to study and have good sensitivity to BSM physics

At CEPC, Z bosons are produced at rest, lepton pT would be even lower, this requires some care about low momentum measurement

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