Searching $W \to \ell\ell\ell\nu$ decay channel at LHC

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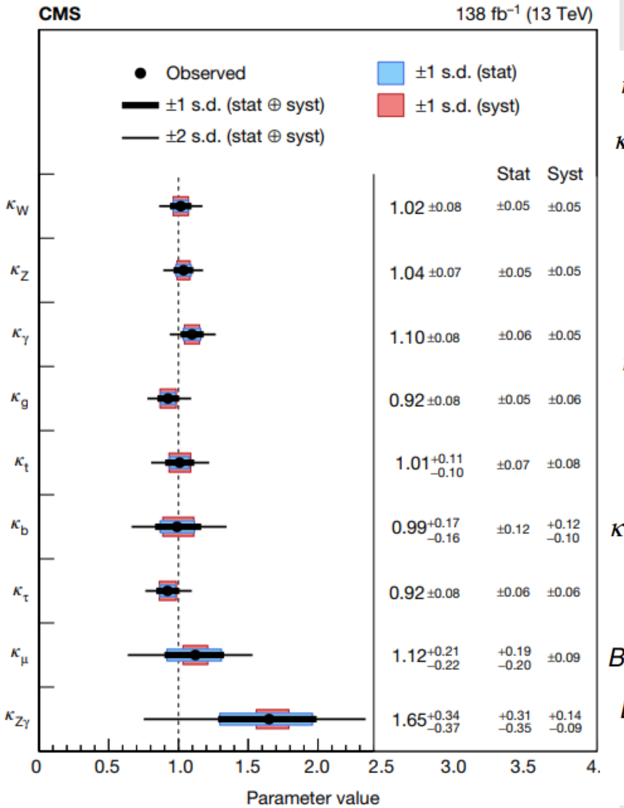
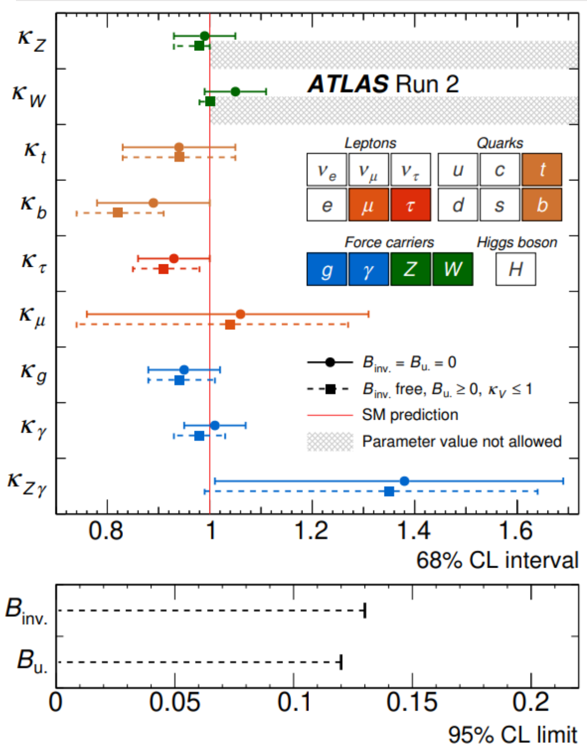
Electroweak boson measurement

- Higgs Discovery: $h \to \gamma\gamma, h \to b\bar{b}$, $h \to \ell\ell\ell\ell, \ldots$
- Precision measurement





	H DECAY MODES		
	Mode		Fraction (Γ_i/Γ)
Γ_1	WW^*		$(25.7 \pm 2.5)\%$
Γ_2	ZZ^*		$(2.80 \pm 0.30)\%$
Γ_3	$\gamma\gamma$		$(2.50 \pm 0.20) \times 10^{-3}$
Γ_4	$b\bar{b}$		$(53 \pm 8)\%$
Γ_5	e^+e^-		$< 3.6 \times 10^{-4}$
Γ_6	$\mu^+\mu^-$		$(2.6 \pm 1.3) \times 10^{-4}$
Γ_7	$\tau^+\tau^-$		$(6.0^{+0.8}_{-0.7})\%$
Γ_8	$Z\gamma$		$(3.2 \pm 1.5) \times 10^{-3}$
Γ_9	$Z\rho(770)$		$< 1.21\%$
Γ_{10}	$Z\phi(1020)$		$< 3.6 \times 10^{-3}$
Γ_{11}	$Z\eta_c$		
Γ_{12}	ZJ/ψ		
Γ_{13}	$J/\psi\gamma$		$< 3.5 \times 10^{-4}$
Γ_{14}	$J/\psi J/\psi$		$< 1.8 \times 10^{-3}$
⋮			
Γ_{22}	$e\mu$	LF	$< 6.1 \times 10^{-5}$
Γ_{23}	$e\tau$	LF	$< 2.2 \times 10^{-3}$
Γ_{24}	$\mu\tau$	LF	$< 1.5 \times 10^{-3}$
Γ_{25}	invisible		$< 13\%$
Γ_{26}	γ invisible		$< 2.9\%$

26 Higgs decay channels

Z boson also has been well studied from LEP, LHC, etc.

Z DECAY MODES

Mode				Fraction (Γ_i/Γ)
Γ_1	e^+e^-		[1]	$(3.3632 \pm 0.0042)\%$
Γ_2	$\mu^+\mu^-$		[1]	$(3.3662 \pm 0.0066)\%$
Γ_3	$\tau^+\tau^-$		[1]	$(3.3696 \pm 0.0083)\%$
Γ_4	$\ell^+\ell^-$		[2][1]	$(3.3658 \pm 0.0023)\%$
Γ_5	$\mu^+\mu^-\mu^+\mu^-$			
Γ_6	$\ell^+\ell^-\ell^+\ell^-$		[3]	$(4.55 \pm 0.17) \times 10^{-6}$
Γ_7	invisible		[1]	$(20.000 \pm 0.055)\%$
Γ_8	hadrons		[1]	$(69.911 \pm 0.056)\%$
Γ_9	$(u\bar{u} + c\bar{c})/2$			$(11.6 \pm 0.6)\%$
Γ_{10}	$(d\bar{d} + s\bar{s} + b\bar{b})/3$			$(15.6 \pm 0.4)\%$
Γ_{11}	$c\bar{c}$			$(12.03 \pm 0.21)\%$
Γ_{12}	$b\bar{b}$			$(15.12 \pm 0.05)\%$
Γ_{13}	$b\bar{b}b\bar{b}$			$(3.6 \pm 1.3) \times 10^{-4}$
Γ_{14}	ggg			$< 1.1\%$
Γ_{15}	$\pi^0\gamma$			$< 2.01 \times 10^{-5}$
Γ_{16}	$\eta\gamma$			$< 5.1 \times 10^{-5}$
⋮				
Γ_{65}	$e^\pm\tau^\mp$	LF	[4]	$< 5.0 \times 10^{-6}$
Γ_{66}	$\mu^\pm\tau^\mp$	LF	[4]	$< 6.5 \times 10^{-6}$
Γ_{67}	pe	B, L		$< 1.8 \times 10^{-6}$
Γ_{68}	$p\mu$	B, L		$< 1.8 \times 10^{-6}$

68 Z boson decay channels has been studied.

W boson measurement

W^+ DECAY MODES

W^- modes are charge conjugates of the modes below.

Mode			Fraction (Γ_i / Γ)
Γ_1	$\ell^+\nu$	[1]	$(10.86 \pm 0.09)\%$
Γ_2	$e^+\nu$		$(10.71 \pm 0.16)\%$
Γ_3	$\mu^+\nu$		$(10.63 \pm 0.15)\%$
Γ_4	$\tau^+\nu$		$(11.38 \pm 0.21)\%$
Γ_5	hadrons		$(67.41 \pm 0.27)\%$
Γ_6	$\pi^+\gamma$		$< 7 \times 10^{-6}$
Γ_7	$D_s^+\gamma$		$< 1.3 \times 10^{-3}$
Γ_8	c X		$(33.3 \pm 2.6)\%$
Γ_9	$c\bar{s}$		$(31^{+13}_{-11})\%$
Γ_{10}	invisible	[2]	$(1.4 \pm 2.9)\%$
Γ_{11}	$\pi^+\pi^+\pi^-$		$< 1.01 \times 10^{-6}$

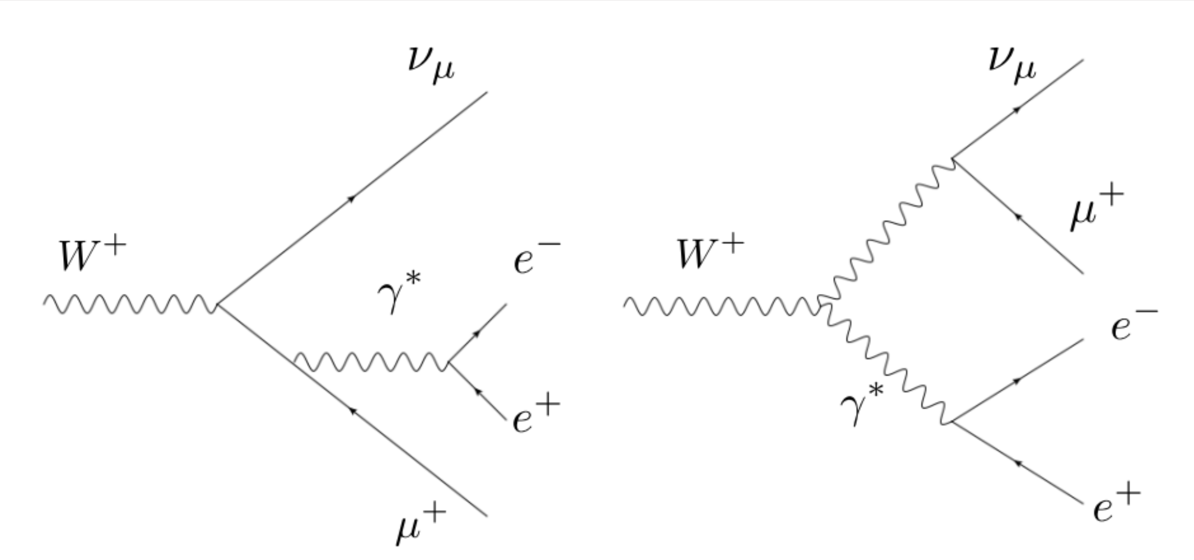
11 channels…

Total cross section at 13 TeV pp collision

- Z boson: 58 nb for single Z boson production
  - Number of single Z boson for LHC run-2: ~8 billions
- W boson: 190 nb for single W boson production
  - Number of single W boson for LHC run-2: ~27 billions

Maybe we can look into W boson more.
As a first example, we propose to study the W exotic decay into $3\ell + \nu$.

$W \to \ell\ell\ell\nu$ precision measurement at LHC



Signal process	cross section [pb]
$pp \to \ell^+\ell^-\ell^+\nu_\ell + (j),\ \mathrm{M}_{\ell\ell\ell\nu} \in \mathrm{OR}$	0.36
$pp \to \ell^+\ell^-\ell^-\bar{\nu}_\ell + (j),\ \mathrm{M}_{\ell\ell\ell\nu} \in \mathrm{OR}$	0.25

On-shell Region (OR) defined as: $m_W \pm 2\Gamma_W$

With parton level pre-selection

$$p_T(j) > 20 \text{ GeV},\ p_T(\ell) > 3 \text{ GeV},\ \eta(\ell) < 5.0(2.5),$$
$$\eta(j) < 5.0,\ \Delta R(\ell\ell) > 0.2,\ \mathrm{M}_{\ell\ell} > 1 \text{ GeV},$$

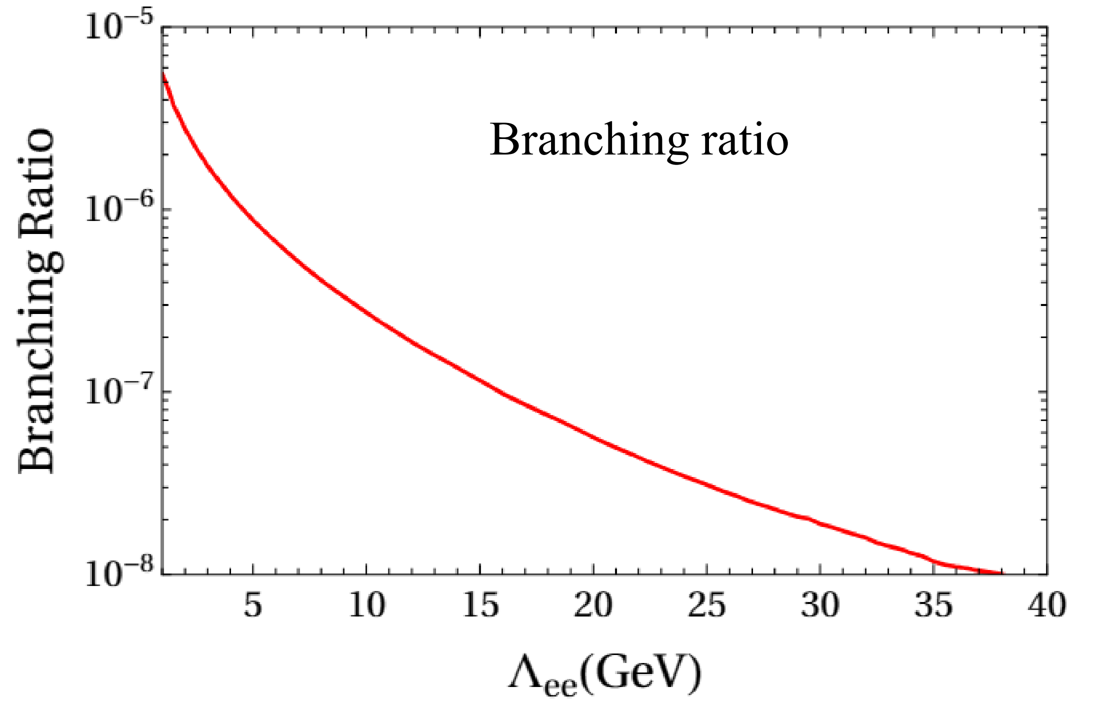


FIG. 2. The branching ratio of the decay channel $W^+ \to \mu^+\nu_\mu e^+e^-$ as the function of the electron pair invariant mass M_{ee} thresh-hold value.

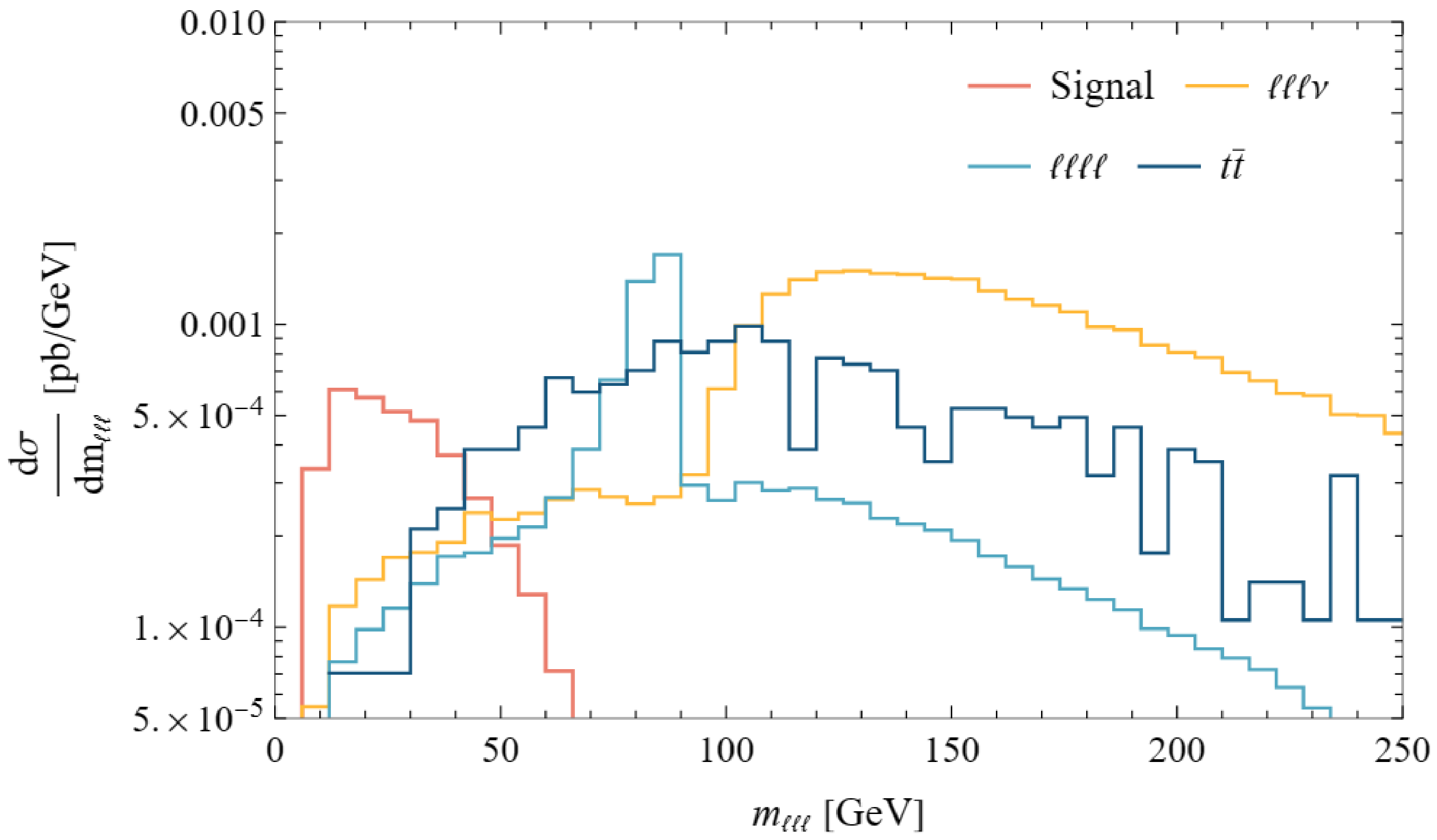
SM background

Parton level pre-selection

$p_T(j) > 20$ GeV, $p_T(\ell) > 3$ GeV,
$\eta(\ell) < 5.0(2.5)$, $\eta(j) < 5.0$, $\Delta R(\ell\ell) > 0.2$.

Background process	cross section [pb]
$pp \to \ell\ell\ell\nu_\ell + (j)$, $M_{\ell\ell\ell\nu} \notin$ OR	0.95
$pp \to \ell\ell\ell\ell + (j)$	0.34
$pp \to t\bar{t} + (j)$	6.88×10^2

Trilepton invariant mass



← Detector level

Projective sensitivity

Detector level cuts →

Cross-section [pb]	Parton-level	$n(\ell) = 3$	$n(j) \leq 2$, $M_{\ell\ell} > 4$ GeV	$M_{\ell\ell\ell} < 80$ GeV	Cut-based result	ML result
					$M_{\ell\ell\ell} < 60$ GeV	DNN selection
Signal	0.61(100%)	0.036(5.9%)	0.021(3.5%)	0.021(3.5%)	0.021(3.4%)	0.017(2.7%)
$pp \to \ell\ell\ell\nu$, $M_{\ell\ell\ell\nu} \notin$ OR	0.95(100%)	0.22(23%)	0.2(21%)	0.013(1.4%)	8×10^{-3}(0.87%)	3.3×10^{-3}(0.3%)
$pp \to \ell\ell\ell\ell$	0.34(100%)	0.068(20%)	0.061(18%)	0.017(5%)	7.2×10^{-3}(2.1%)	3.2×10^{-3}(0.95%)
$pp \to t\bar{t} + (j)$	688(100%)	0.19(0.027%)	0.11(0.016%)	$0.023(3 \times 10^{-5})$	$0.01(1 \times 10^{-5})$	$2.1 \times 10^{-3}(3 \times 10^{-6})$

The Br of $W \to \ell\ell\ell\nu$ is at 10^{-6} level.

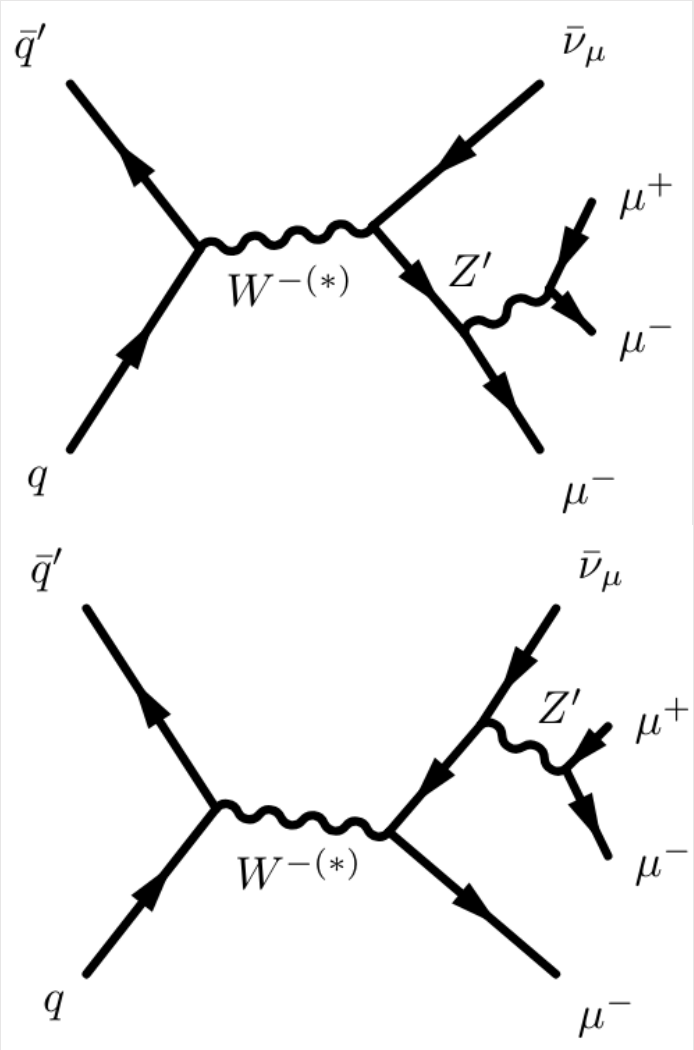
Current LHC (with current trigger and selection)

$$\frac{\delta Br}{Br}(W \to 3\ell + \nu) = 4.4\%$$

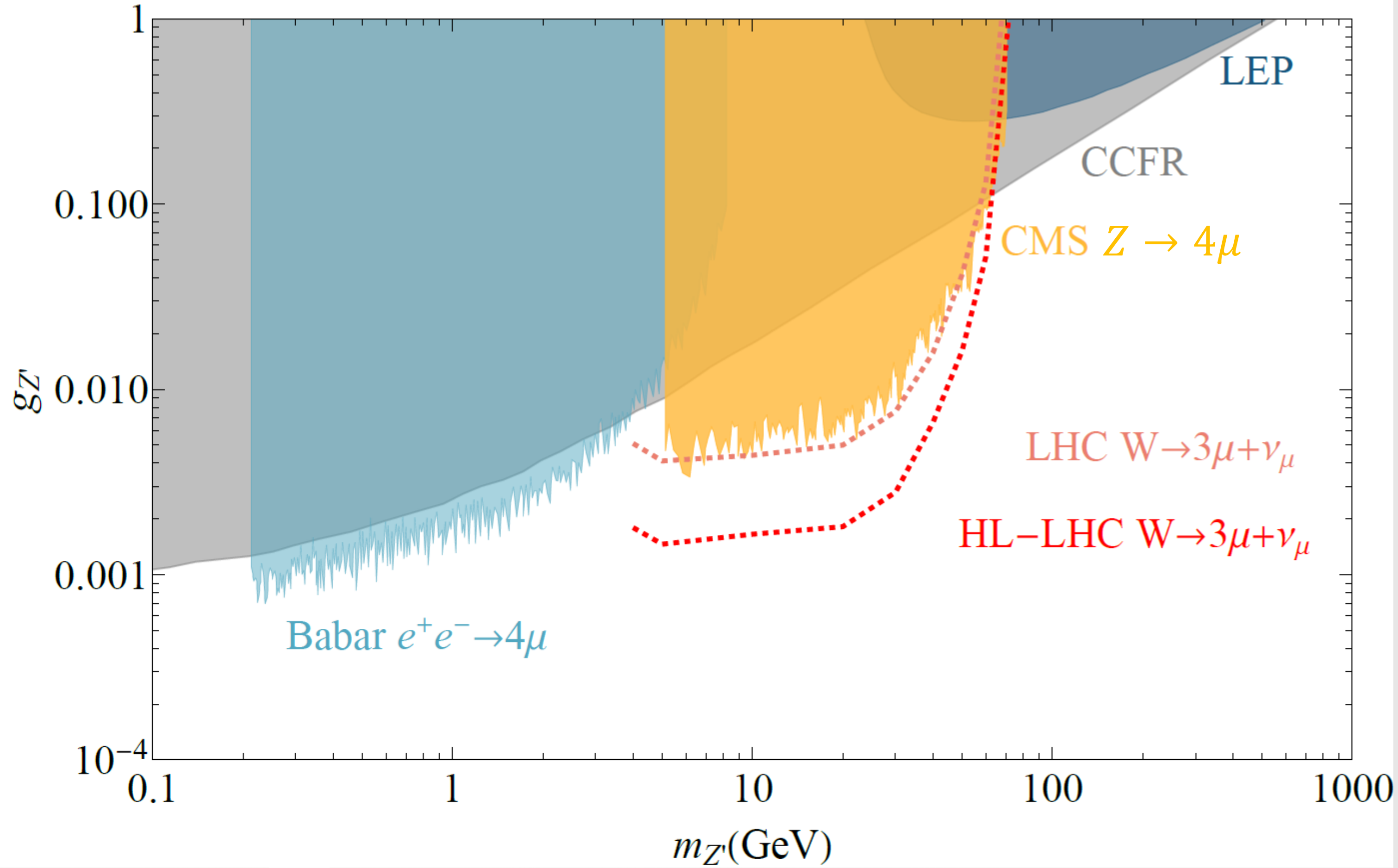
HL-LHC (with improved trigger on multileptons)

$$\frac{\delta Br}{Br}(W \to 3\ell + \nu) = 0.6\%$$

Constrain on $L_\mu - L_\tau$ model

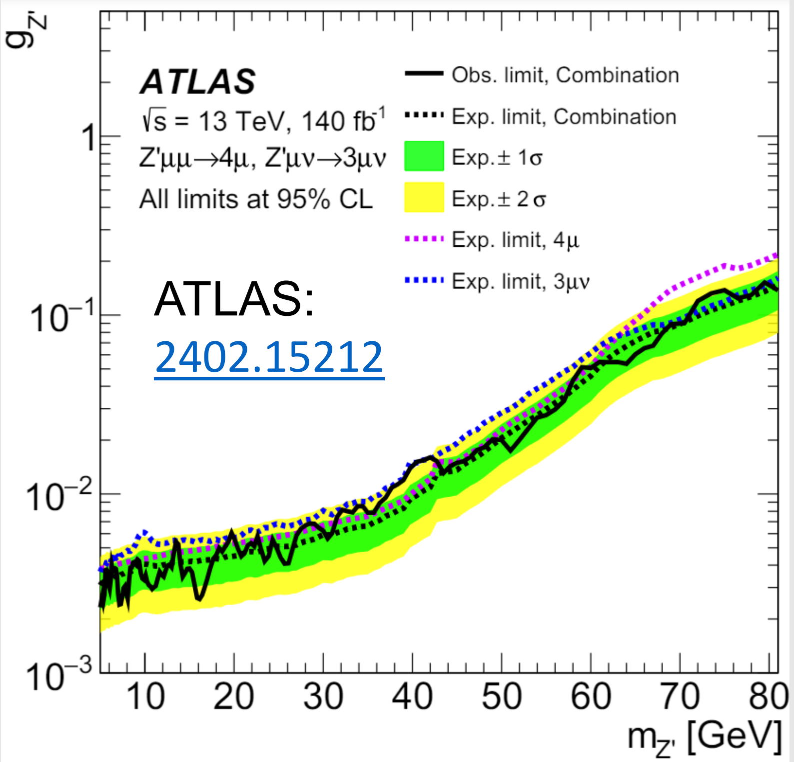


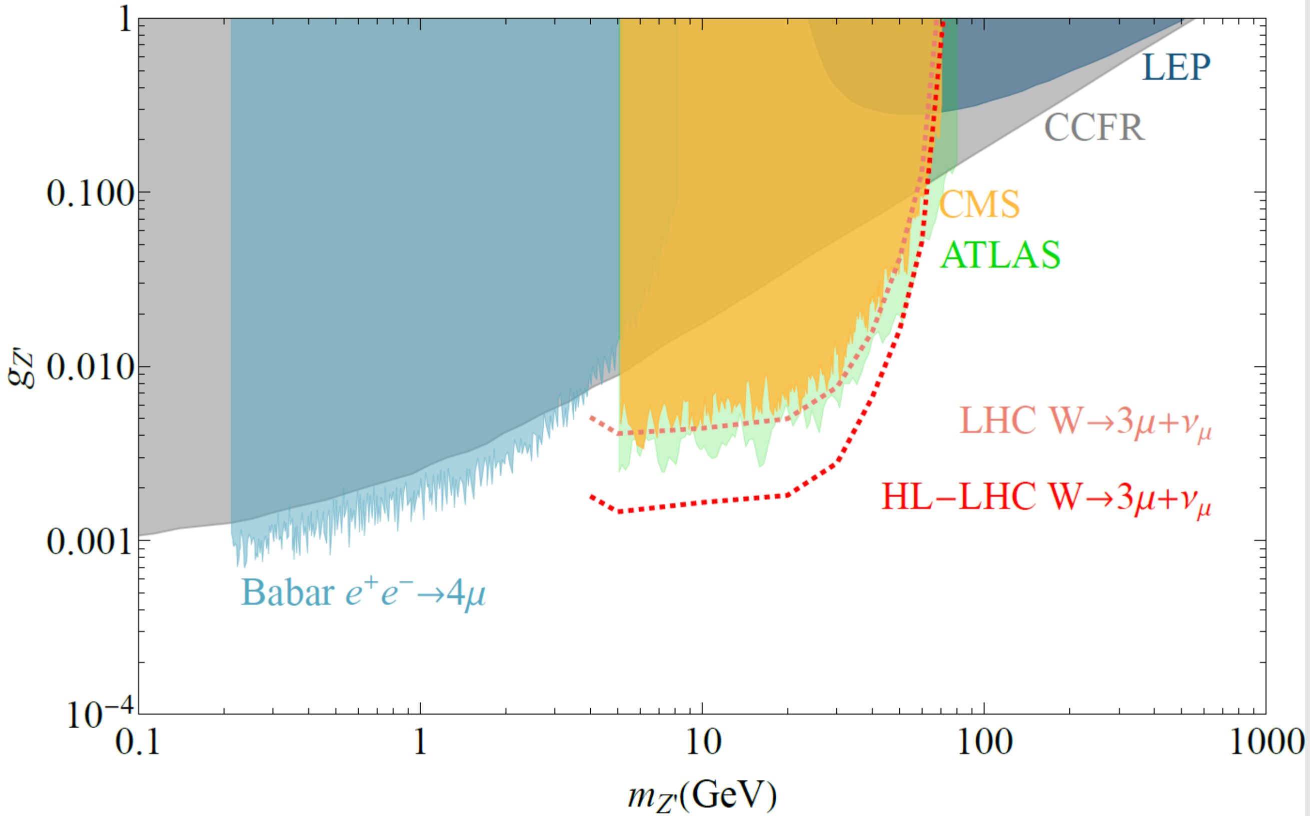
- $\mathcal{L} \supset g' Z' (\bar{\mu}\gamma\mu - \bar{\tau}\gamma\tau + \bar{\nu}_\mu \gamma P_L \nu_\mu - \bar{\nu}_\tau \gamma P_L \nu_\tau)$



However, ATLAS just explored this BSM study 3 month ago.

- Our results are compatible
- But the SM value was never extracted.
- More new physics:
  - Anomalous Z'
  - SMEFT
  - Flavor universality





Conclusion

- There are still some channels that we can but haven't discovered at LHC.
- $W \to 3\ell + \nu$ can be measured to a precision of 4%.
- Can also be exploited to search on BSM models.

Thank you

Backup

Precision

- HL-LHC
  - Extend rapidity coverage: $\eta(e, j) < 5, \eta(\mu) < 2.8$
  - High luminosity: $L = 3000 \text{ fb}^{-1}$
  - Better resolution and reconstructed efficiency at low p_T

$$\frac{\delta \mathrm{Br}^{\mathrm{fid}}(W \to \ell\ell\ell\nu_\ell)}{\mathrm{Br}^{\mathrm{fid}}(W \to \ell\ell\ell\nu_\ell)} = 0.62\%$$

- Run-2
  - Current status: $\eta(\ell, j) < 2.5$
  - $L = 140 \text{ fb}^{-1}$

$$\frac{\delta \mathrm{Br}^{\mathrm{fid}}(W \to \ell\ell\ell\nu_\ell)}{\mathrm{Br}^{\mathrm{fid}}(W \to \ell\ell\ell\nu_\ell)} = 4.4\%$$

How we extract the branching ratio from signal

$$\mathrm{Br}^{\text{fid}} = \frac{\sigma^{\text{fid}}_{\text{signal}}}{\sigma_W} \times f_W$$

Signal: $pp \to lllv$ $(M_{lllv} \in M_W \pm 2\Gamma)$

- $f_W = \frac{\sigma_{pp \to W^+ \to lllv}}{\sigma_{pp \to lllv}}$