Muon g-2 and LHC phenomenology in the $L_\mu - L_\tau$ gauge symmetric model

Kazuhiro Tobe (Nagoya U.)

in collaboration with K. Harigaya, T. Igari, M.M. Nojiri, M. Takeuchi

arXiv: 1311.0870

Dec. 11, 2013@KMI Symposium

muon g-2 anomaly

Difference between the experimental value

and the SM prediction Aoyama-san's talk

$a_\mu^{\rm Exp}$ $[10^{-10}]$	$\delta a_\mu = a_\mu^{\rm Exp} - a_\mu^{\rm SM}$ $[10^{-10}]$	
11659208.9 ± 6.3	26.1 ± 8.0 (3.3σ)	HLMNT11
	31.6 ± 7.9 (4.0σ)	THLMN10
	33.5 ± 8.2 (4.1σ)	BDDJ12
	28.3 ± 8.7 (3.3σ)	JS11
	29.0 ± 9.0 (3.2σ)	JN09
	28.7 ± 8.0 (3.6σ)	DHMZ12

The size ~ $a_\mu^{\rm EW} = (15.4 \pm 0.2) \times 10^{-10}$

If this anomaly is due to new physics, ...

we expect

★ new particles with EW scale mass

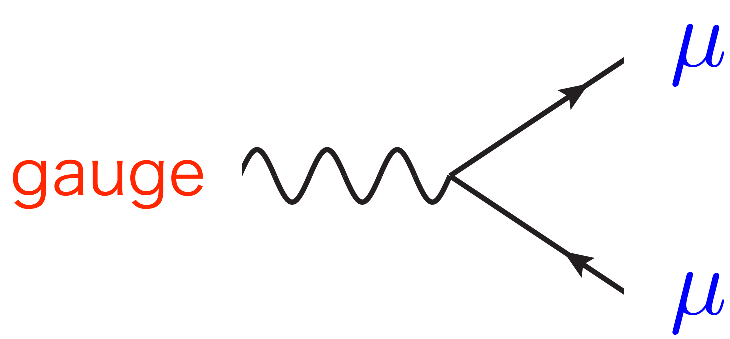
★ new coupling to muon

Good target at the LHC!

What kind of new physics ?

muon has to have new interactions...

★Gauge type



- hidden photon ~very weak int.

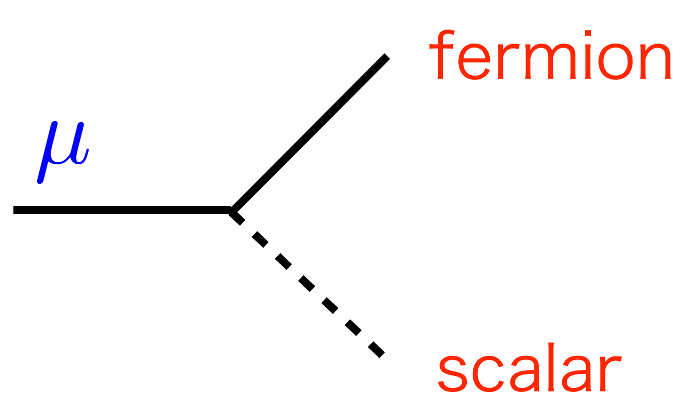
Fayet PRD75(2007), Pospelov PRD80 (2009),... Davoudiasl, Lee, Marciano PRD86 (2012), Endo, Hamaguchi, Mishima PRD86 (2012), ...

- $L_\mu - L_\tau$ model (Z" model)

He, Joshi, Lew, Volkas PRD43, 22 (1991), Baek, Deshpande, He, Ko, PRD64 (2001), Ma, Roy, Roy PLB525 (2002),Salvioni, Strumia, Villadoro, Zwirner JHEP (2010), Heeck, Rodejohann PRD84 (2011)...

★Yukawa type

S. Kanemitsu and K. Tobe
T. Igari and K. Tobe, in progress

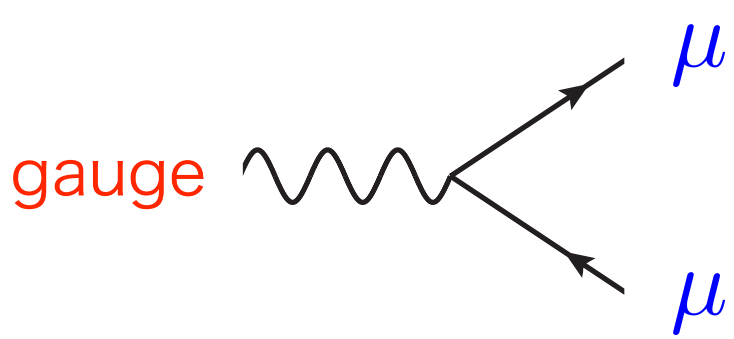


- SUSY T. Moroi PRD53 (1996), ...
- radiatively induced ν mass
  T. Hambye, K. Kannike, E. Ma, M. Raidal PRD75 (2007)

What kind of new physics ?

muon has to have new interactions...

★Gauge type



• hidden photon ~very weak int.

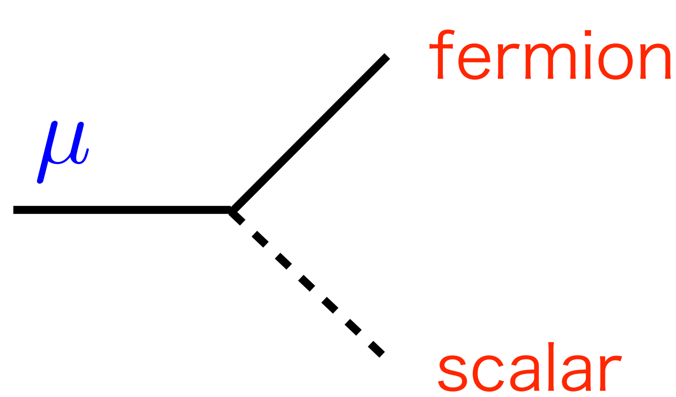
Fayet PRD75(2007), Pospelov PRD80 (2009),... Davoudiasl, Lee, Marciano PRD86 (2012), Endo, Hamaguchi, Mishima PRD86 (2012), ...

• $L_\mu - L_\tau$ model (Z" model)

He, Joshi, Lew, Volkas PRD43, 22 (1991), Baek, Deshpande, He, Ko, PRD64 (2001), Ma, Roy, Roy PLB525 (2002),Salvioni, Strumia, Villadoro, Zwirner JHEP (2010), Heeck, Rodejohann PRD84 (2011)...

★Yukawa type

S. Kanemitsu and K. Tobe
T. Igari and K. Tobe, in progress



• SUSY T. Moroi PRD53 (1996), ...

• radiatively induced ν mass

T. Hambye, K. Kannike, E. Ma, M. Raidal PRD75 (2007)

$L_\mu - L_\tau$ gauge symmetric model (Z” model)

arXiv: 1311.0870: K. Harigaya, T. Igari, M.M. Nojiri, M. Takeuchi, KT

- simple U(1) extension ~anomaly free~
- the gauge boson (Z”) does not couple to electron nor light quarks
  ~ constraints are weak ~

★ Contribution to muon g-2

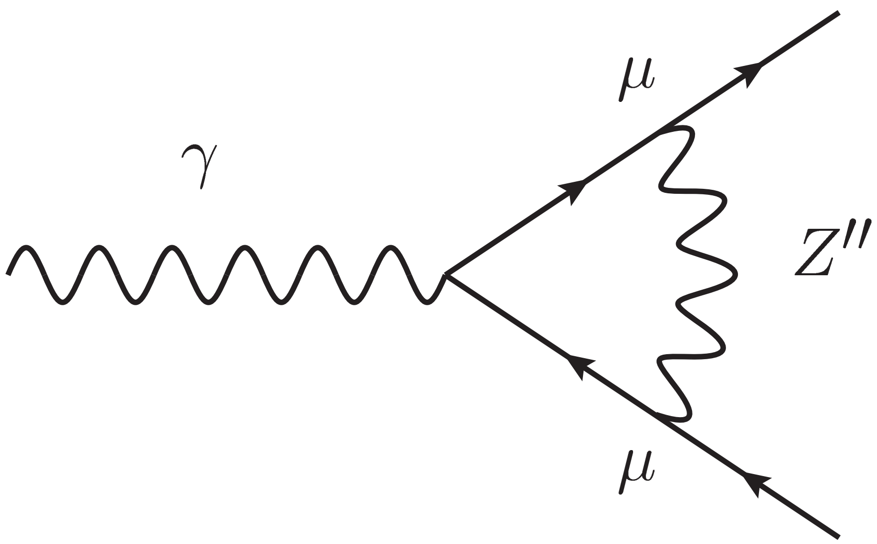
★Constraints from EW precision measurements

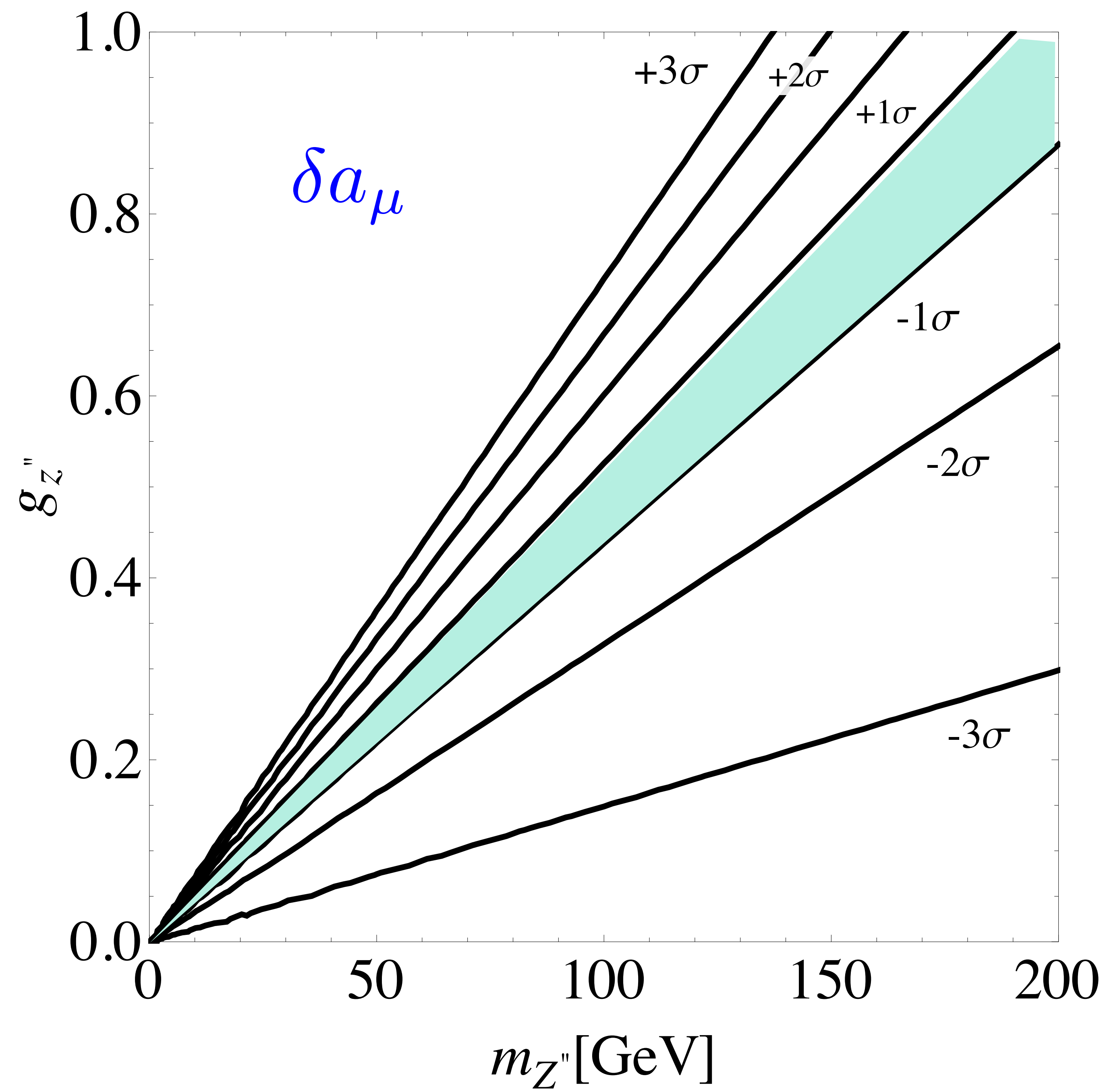
★ LHC phenomenology

★ Summary

Contribution to Muon g-2

- Z" model





Region with $g_{Z"} \sim O(1)$ and $m_{Z"} \sim O(100)$ GeV is favored

Region with $g_{Z"} \sim O(1)$ and $m_{Z"} \sim O(100)$ GeV is favored

Good target at LHC!

But it might be strongly constrained by EW precision measurements

Constraints from EW precision measurements?

$$\Gamma_Z,\ \sigma_h^0,\ R_{e,\mu,\tau},\ A_{\rm FB}^{e,\mu,\tau},\ A_{e,\mu,\tau},\ R_{b,c},\ A_{\rm FB}^{b,c},\ A_{b,c},$$

$$M_W,\ \Gamma_W,\ a_\mu,\ \Delta\alpha_{\rm had}^{(5)}(M_Z^2),\ \alpha_s(M_Z),\ m_t,\ m_h$$

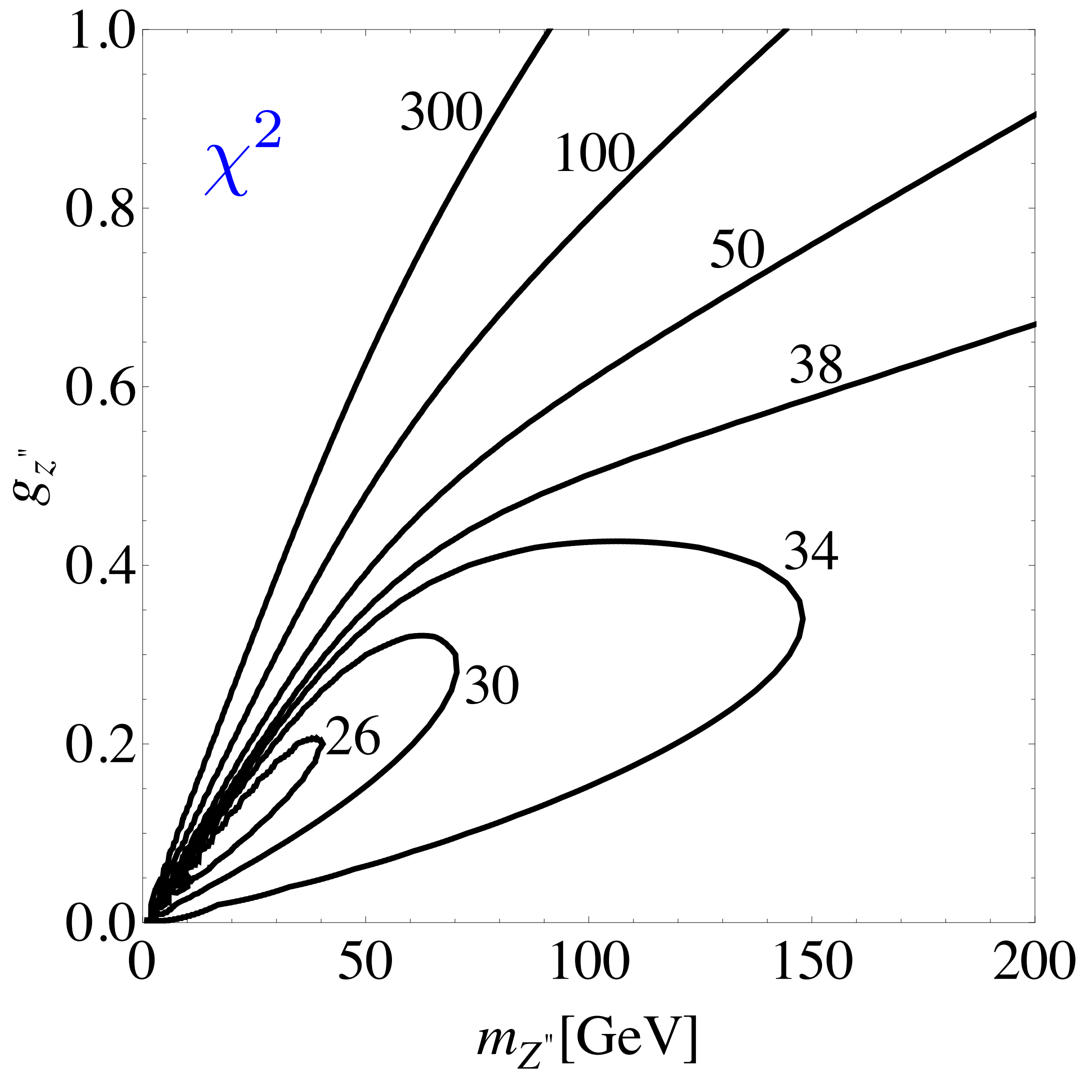


Figure 4: The total χ^2 in the $(m_{Z''}, g_{Z''})$ plane.

$\chi^2/(d.o.f) = 35/(22)$ (SM)

In region with $g_{Z"} \sim 1$

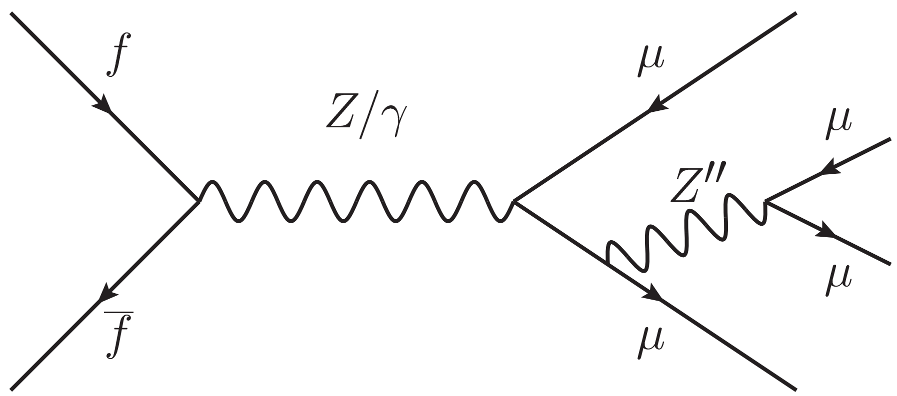
$Z\mu\mu$ vertex correction

makes fit worse. $(\sigma_h^0,\ R_\mu)$

small coupling ($g_{Z"} < 0.4$) and relatively light Z" boson ($m_{Z"} < 100$ GeV) are favored

LHC phenomenology

Z” model



only events with μ and τ (not e)

$$\sigma(Z") \sim 1 \text{ fb}$$

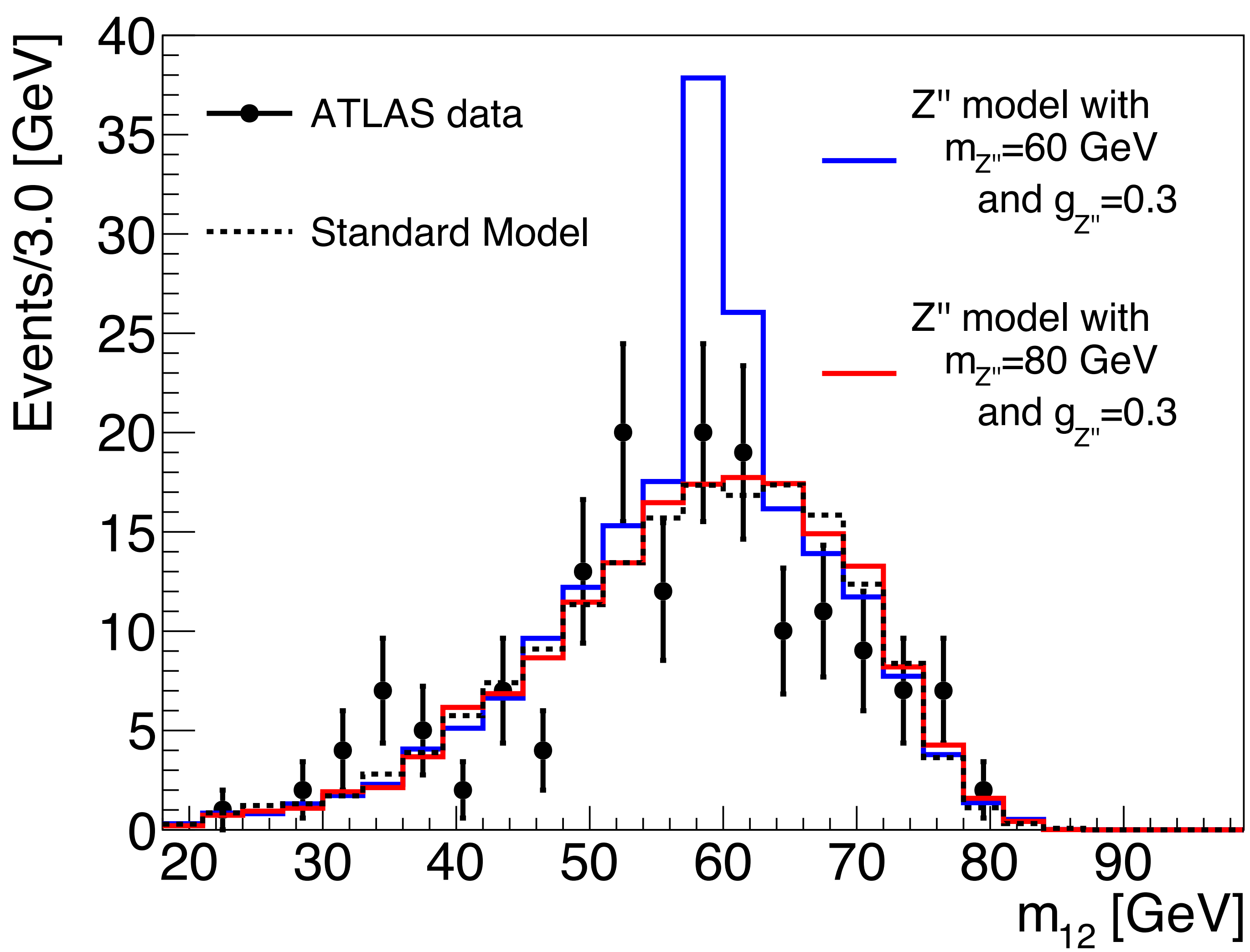
LHC is good place to look for the Z” signal

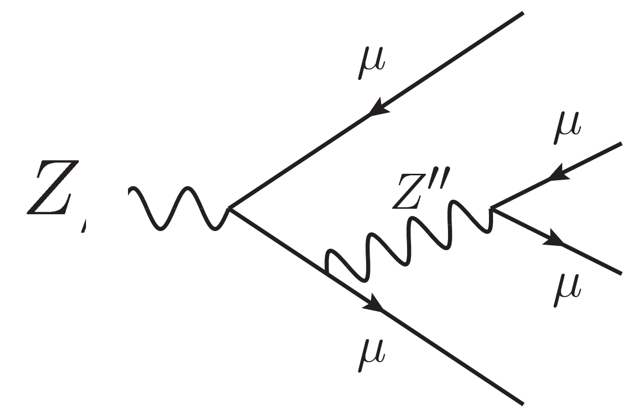
4μ channel at $\sqrt{s} = 7 - 8\ \mathrm{TeV}$

measurement of $Z \to 4e,\ 4\mu,\ 2e2\mu$ at ATLAS

ATLAS-CONF-2013-055

$$80\ \mathrm{GeV} < m_{4l} < 100\ \mathrm{GeV}$$





m_{12}: invariant mass of l^+l^-, closest to the Z boson mass

The Z” model with $m_{Z''} = 60\ \mathrm{GeV}$ is already excluded

- If only 4μ channel is taken into account, the sensitivity to this model gets better

- The ATLAS analysis is not sensitive to the heavier Z" $(m_{Z"} \geq m_Z)$

Optimized analysis for heavier Z” boson in 4μ channel

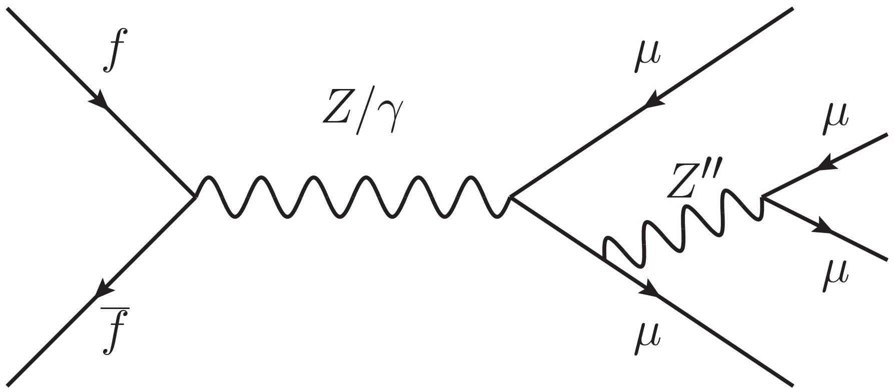
our proposal

- reject on-shell Z and Higgs

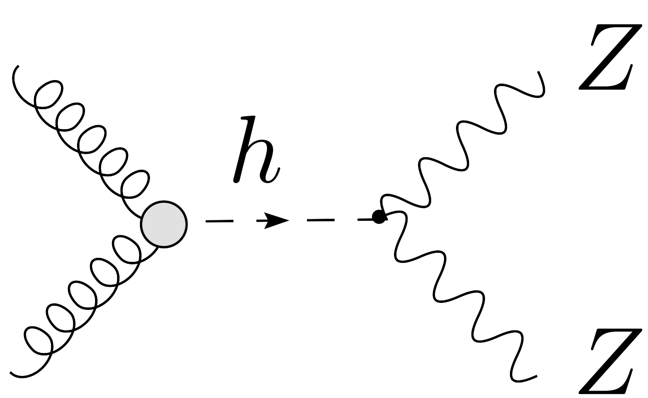
$$m_{4l} > m_Z + 10 \text{ GeV} \qquad |m_{4l} - m_h| > 10 \text{ GeV}$$

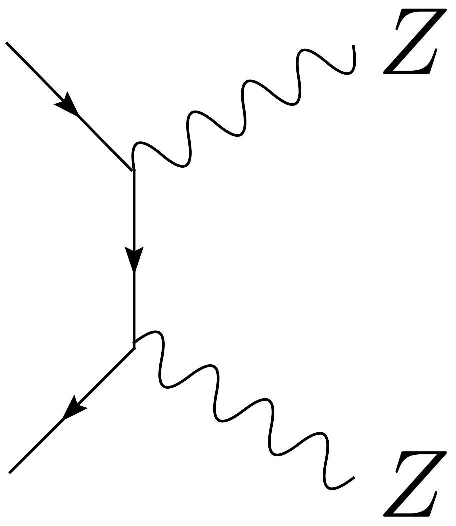
- reject ZZ production $\quad |m_{34} - m_Z| > 5 \text{ GeV}$

signal

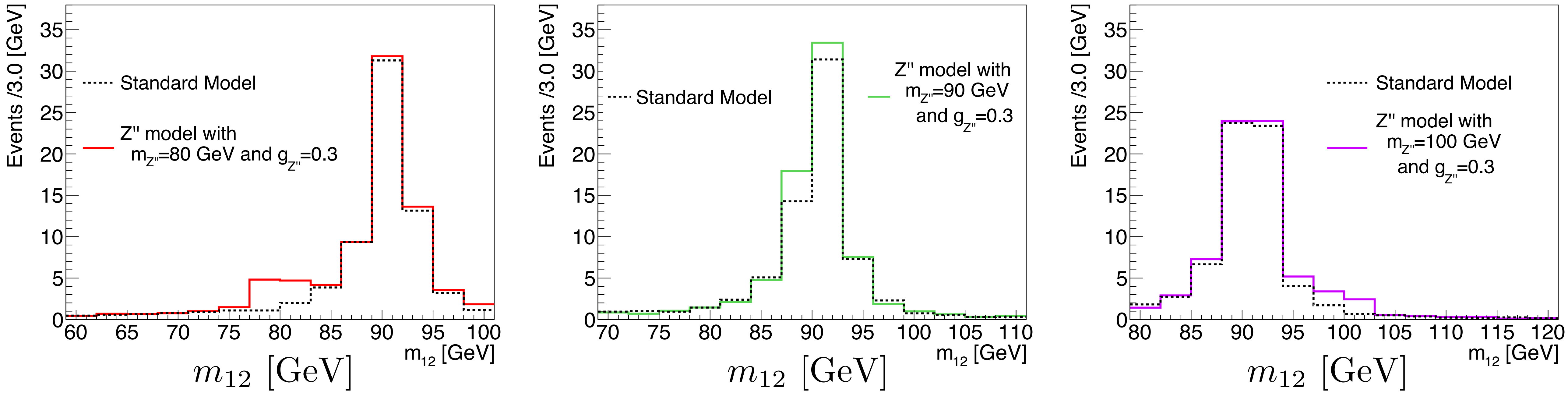


SM background

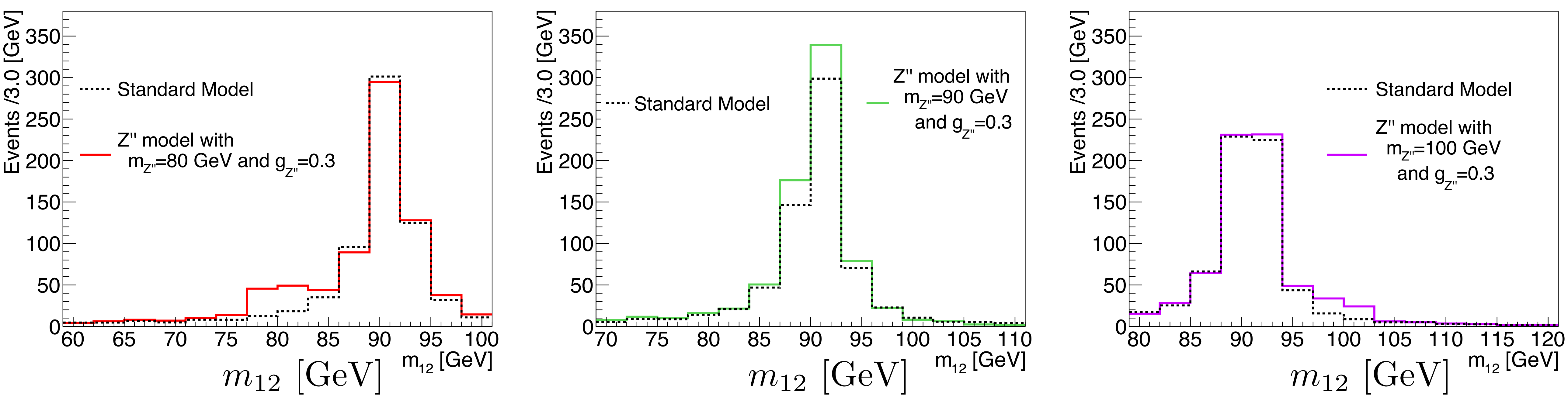




$7 + 8$ TeV $(4.6 + 20.7\ \mathrm{fb}^{-1})$



14 TeV $(300\ \mathrm{fb}^{-1})$



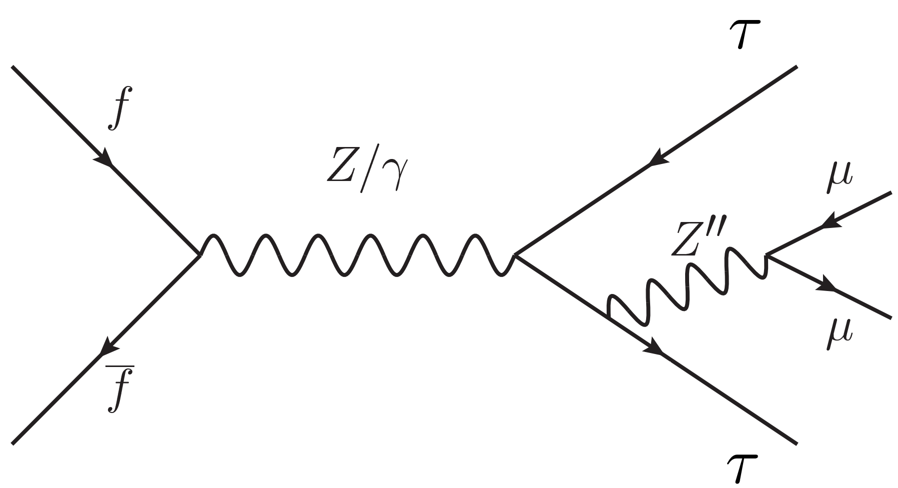
12σ 3σ 7σ

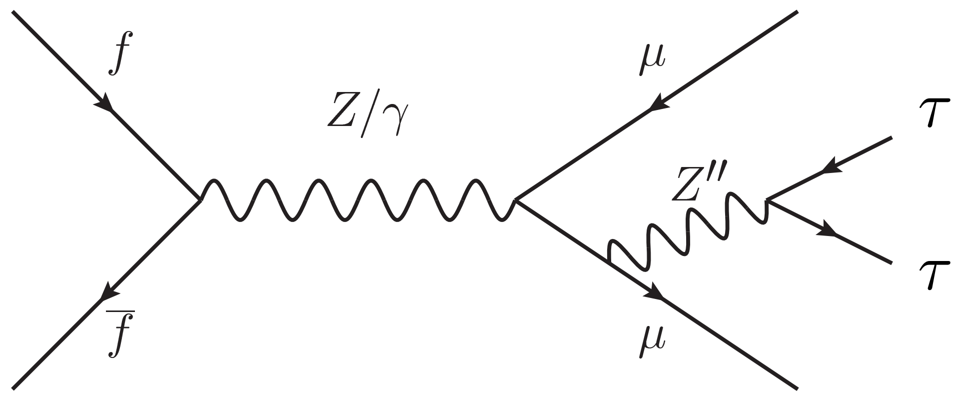
future LHC will probe Z” model in 4μ channel

$2\mu 2\tau$ channel at $\sqrt{s} = 14\ \mathrm{TeV}$

Z" boson can couple to μ and τ (but not e).

It is important to see the τ coupling as well as the μ coupling.





- 2τ jets $(p_{T,\tau} > 20\ \mathrm{GeV})$, 2μ $(p_{T,\mu} > 10\ \mathrm{GeV})$
- invariant mass cut $m_{\tau\tau} > 120\ \mathrm{GeV}$

reject the SM background (ZZ)

(collinear approximation for τ reconstruction)

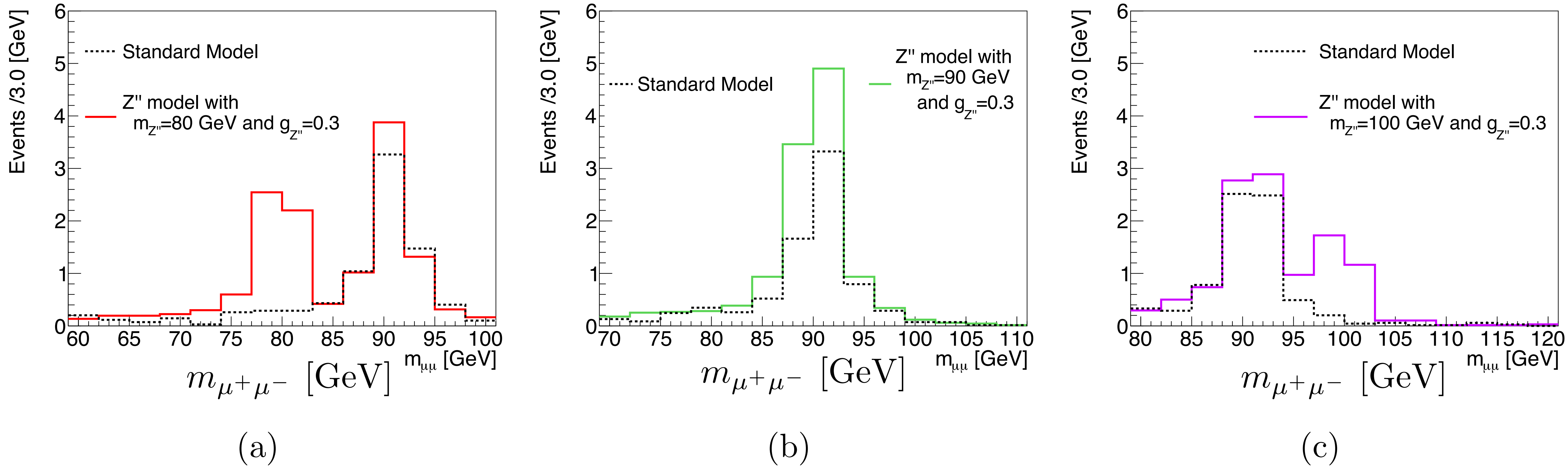


Figure 9: The ($m_{\mu\mu}$) distributions in the $2\mu2\tau$ channel at $\sqrt{s} = 14$ TeV for the SM (dashed line) and for the Z'' model with $m_{Z''} = 80,\ 90$, and 100 GeV (solid lines, from left to right). The integrated luminosity of 300 fb^{-1} is assumed.

For discovery

$> 500\ \mathrm{fb}^{-1}$ $\quad$ $> 2900\ \mathrm{fb}^{-1}$ $\quad$ $> 730\ \mathrm{fb}^{-1}$

region below $m_{Z"} < 100\ \mathrm{GeV}$ will be explored at HL-LHC

LHC will be important to test the model

for the anomaly of muon g-2

Summary

New physics for muon g-2

$L_\mu - L_\tau$ gauge symmetric model (Z" model)

- simple U(1) gauge extension of the standard model
  ~anomaly free~

- relatively light Z" boson (<100 GeV) is favored by EW precision measurements as well as muon g-2

- The interesting region will be explored at the LHC

<u>Current and future LHC data will be important to test the model responsible for the anomaly of muon g-2</u>

Backup

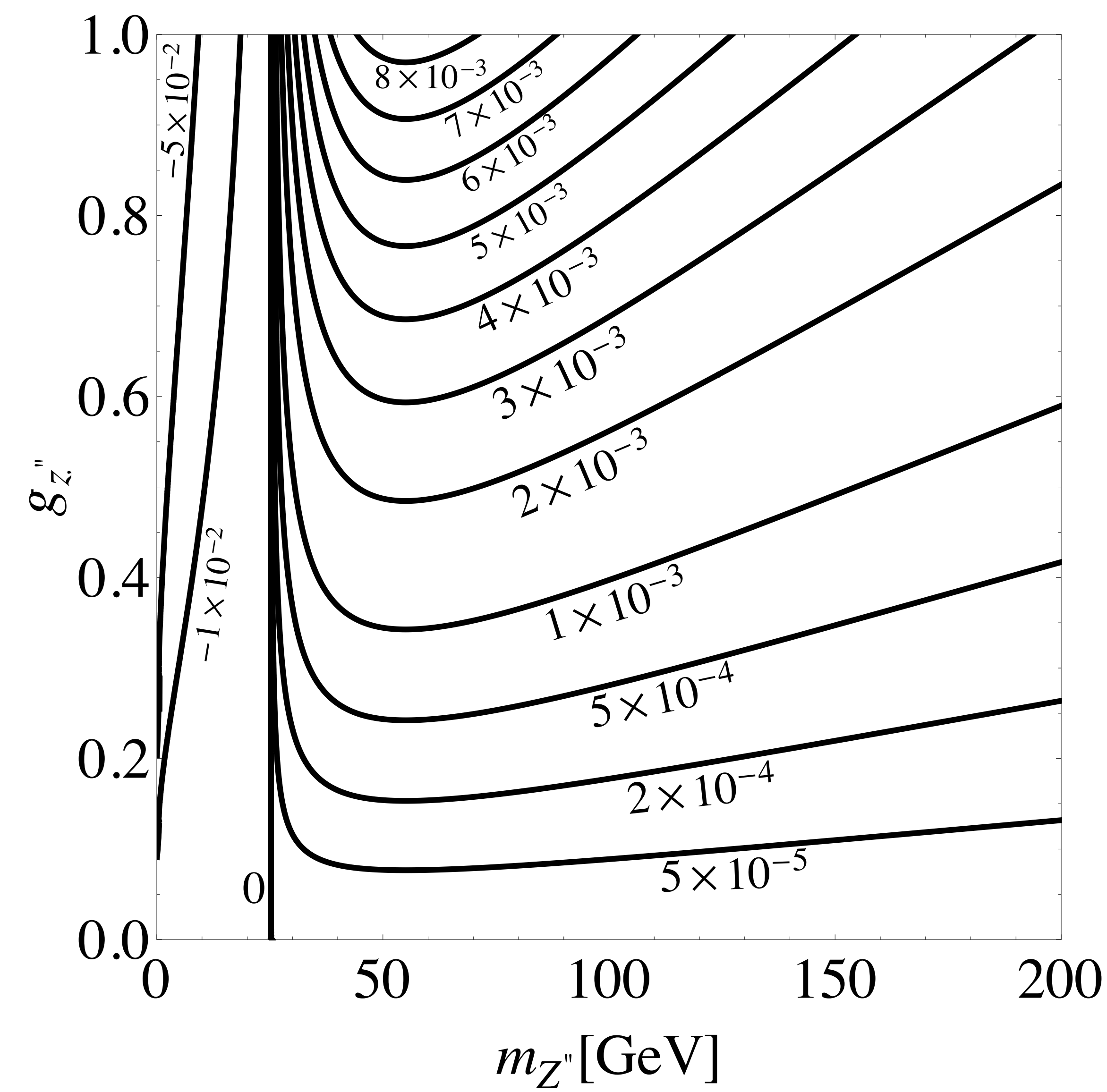


Figure 3: The vertex correction Δ at the Z-pole ($q^2 = m_Z^2$) is shown as a function of $m_{Z''}$ and $g_{Z''}$.

$$g_L^f = (T_f^3 - Q_f s_W^2)(1+\Delta), \qquad g_R^f = -Q_f s_W^2(1+\Delta).$$

	data	SM fit	pull	Z'' model	pull	Z'' model	pull
Γ_Z(GeV)	2.4952(23)	2.4953	-0.06	2.4961	-0.4	2.4960	-0.3
σ_h^0 (nb)	41.541(37)	41.480	1.7	41.454	2.3	41.457	2.3
R_e	20.804(50)	20.739	1.3	20.739	1.3	20.739	1.3
R_μ	20.785(33)	20.739	1.4	20.708	2.3	20.712	2.2
R_τ	20.764(45)	20.787	-0.5	20.755	0.2	20.759	0.1
$A_{\rm FB}^{0,e}$	0.0145(25)	0.0162	-0.7	0.0162	-0.7	0.0162	-0.7
$A_{\rm FB}^{0,\mu}$	0.0169(13)	0.0162	0.5	0.0162	0.5	0.0162	0.5
$A_{\rm FB}^{0,\tau}$	0.0188(17)	0.0162	1.5	0.0162	1.5	0.0162	1.5
τ pol.:							
A_τ	0.1439(43)	0.1472	-0.8	0.1472	-0.8	0.1472	-0.8
A_e	0.1498(49)	0.1472	0.5	0.1472	0.5	0.1472	0.5
b, c quarks:							
R_b	0.21629(66)	0.21579	0.8	0.21579	0.8	0.21578	0.8
R_c	0.1721(30)	0.1722	-0.05	0.1722	-0.05	0.1722	-0.05
$A_{\rm FB}^{0,b}$	0.0992(16)	0.1032	-2.5	0.1032	-2.5	0.1032	-2.5
$A_{\rm FB}^{0,c}$	0.0707(35)	0.0737	-0.9	0.0737	-0.9	0.0737	-0.9
A_b	0.923(20)	0.935	-0.6	0.935	-0.6	0.935	-0.6
A_c	0.670(27)	0.668	0.08	0.668	0.08	0.668	0.08
SLD:							
A_e	0.1516(21)	0.1472	2.1	0.1472	2.1	0.1472	2.1
A_μ	0.142(15)	0.1472	-0.3	0.1472	-0.3	0.1472	-0.3
A_τ	0.136(15)	0.1472	-0.7	0.1472	-0.7	0.1472	-0.7
W boson:							
M_W (GeV)	80.385(15)	80.362	1.5	80.362	1.5	80.362	1.5
Γ_W (GeV)	2.085(42)	2.091	-0.1	2.091	-0.2	2.091	-0.2
muon g-2:							
$\delta a_\mu(10^{-9})$	2.61(0.80)	0	3.3	2.36	1.1	1.33	1.1
Inputs							
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	0.02763(14)	0.02760	0.2	0.02760	0.2	0.027560	0.2
$\alpha_s(M_Z)$	0.1184(7)	0.1184	0.0	0.1184	0.0	0.1184	0.0
m_t (GeV)	173.1(0.9)	173.7	-0.6	173.7	-0.6	173.7	-0.6
m_h (GeV)	125.9 (0.4)	125.9	0	125.9	0	125.9	0
$m_{Z''}$ (GeV)	-	-	-	60	-	80	-
$g_{Z''}$	-	-	-	0.3	-	0.3	-
$\chi^2/(d.o.f)$		35.1/(22)		29.2/(22)		31.0/(22)	

Table 3: The EW precision data and theoretical predictions of EW precision observables. The experimental data are taken from Ref. [33] except that M_W, Γ_W, m_t and m_h are from Ref. [3], and δa_μ and $\Delta\alpha_{\rm had}^{(5)}$ are from Ref. [6]. The best fit values of the SM and sample points for Z'' model, $m_{Z''} = (60,\ 80)$ GeV and $g_{Z''} = 0.3$ are shown.

process		cross section [fb]	
		SM	Z'' model ($m_{Z''} = 80$ GeV)
LEP ($\sqrt{s} = 200$ GeV)	$e^+e^- \to 4\mu$	3.8	3.8
Tevatron ($\sqrt{s} = 1.96$ TeV)	$p\bar{p} \to 4\mu$	3.4	3.6
LHC ($\sqrt{s} = 8$ TeV)	$pp \to 4\mu$	14	15
	$pp \to 2\mu 2\tau$	29	30
LHC ($\sqrt{s} = 14$ TeV)	$pp \to 4\mu$	27	28
	$pp \to 2\mu 2\tau$	57	59

Table 5: Cross sections in typical processes where the Z'' boson contributes, where $p_{T,l} > 5$ GeV and $m_{l^-l^+} > 5$ GeV ($l = \mu$ and τ) are required. The numbers for the Z'' model are for $m_{Z''} = 80$ GeV and $g_{Z''} = 0.3$.

$e^+e^-e^+e^-$ ($4e$), $\mu^+\mu^-\mu^+\mu^-$ (4μ) and $e^+e^-\mu^+\mu^-$ ($2e2\mu$) at the Z resonance. We summarize the set of selection cuts they have used as follows:

1. four isolated leptons, which have two opposite sign and same-flavor di-lepton pairs, where $p_{T,\mu} > 4$ GeV and $|\eta_\mu| < 2.7$ ($p_{T,e} > 7$ GeV and $|\eta_e| < 2.47$).

2. the leading three leptons must have $p_{T,\ell} > 20,\ 15,$ and 8 GeV, and if the third (p_T-ordered) lepton is an electron it must have $p_{T,e_3} > 10$ GeV.

3. the four leptons are required to be separated as $\Delta R_{\ell\ell} > 0.1$.

4. the invariant masses of the same-flavor and opposite-sign leptons are required to have $m_{l^+l^-} > 5$ GeV.

5. $m_{12} > 20$ GeV and $m_{34} > 5$ GeV, where m_{12} is the invariant mass of the same flavor and opposite sign di-lepton pair which is the closest to the Z boson mass among the possible combinations, while the other one is called m_{34}.

6. the invariant mass of the four leptons is in the m_Z window, 80 GeV $< m_{4l} <$ 100 GeV.

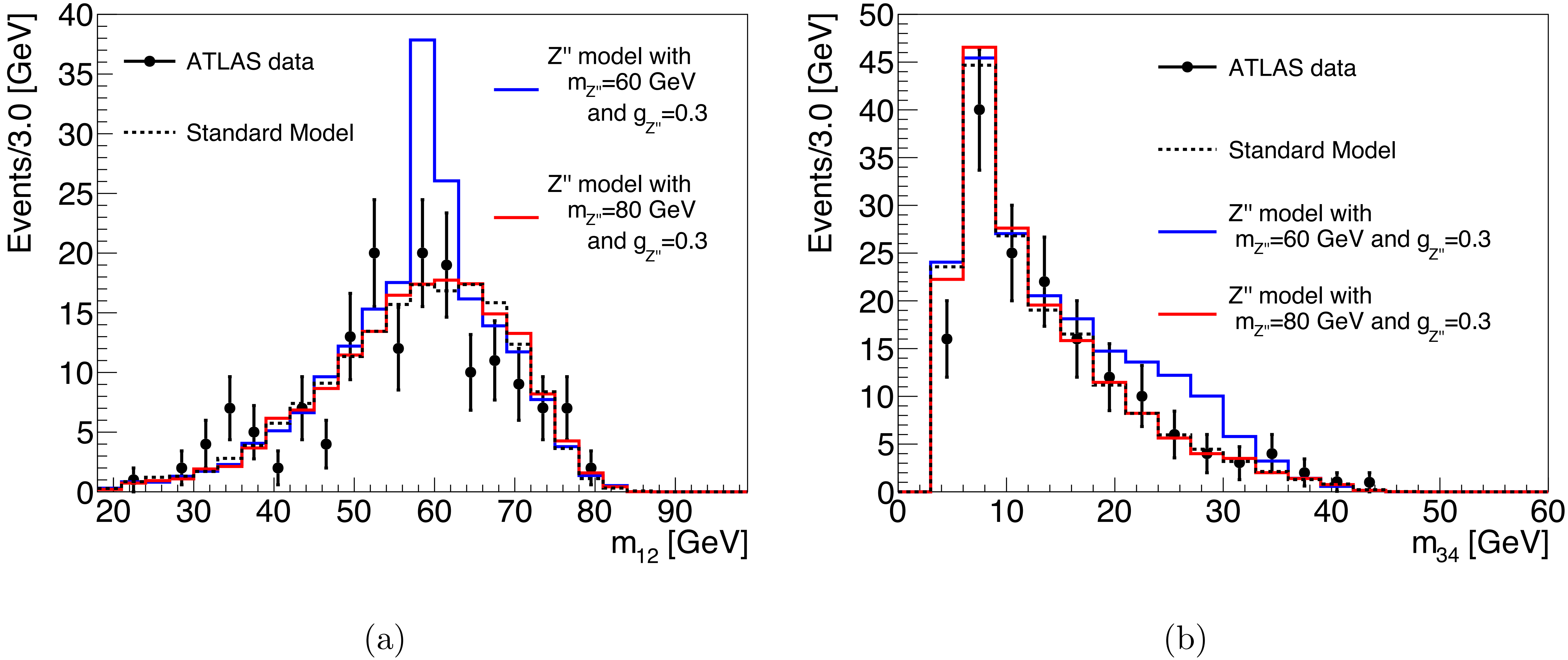


Figure 6: The m_{12} and m_{34} distributions for the SM (dashed) and for the Z'' models with $m_{Z''} = 60$ GeV (blue) and 80 GeV (red). All channels ($4e$, $2e2\mu$ and 4μ) are summed up. Combined results for the integrated luminosities of 4.6 fb^{-1} at $\sqrt{s} = 7$ TeV and 20.7 fb^{-1} at $\sqrt{s} = 8$ TeV are shown.

		$N_{\rm SM}$	$N_{Z'',60}$	$\sigma_{Z'',60}$	$N_{Z'',80}$	$\sigma_{Z'',80}$
m_{12}	(51, 57) GeV	29.1	32.8	0.7	29.9	0.1
	(57, 63) GeV	34.2	63.9	5.1	35.1	0.2
	(63, 69) GeV	33.2	30.1	-0.5	32.3	-0.2
	(69, 75) GeV	20.7	19.5	-0.3	21.5	0.2
	(75, 81) GeV	4.7	5.2	0.2	5.9	0.5
m_{34}	(3,18) GeV	130.6	135.2	0.4	131.8	0.1
	(18,33) GeV	33.0	56.4	4.1	32.8	-0.0
	(33,48) GeV	4.5	5.4	0.4	4.3	-0.1

Table 6: Event numbers in several m_{12} and m_{34} ranges. The luminosities of 4.6 fb^{-1} at $\sqrt{s} = 7$ TeV and 20.7 fb^{-1} at $\sqrt{s} = 8$ TeV are combined and event numbers in all channels ($4e$, $2e2\mu$ and 4μ) are summed up, as studied in Ref. [38]. $N_{\rm SM}$ and $N_{Z'',60}$ ($N_{Z'',80}$) are numbers of events in the SM and the Z'' model with $m_{Z''} = 60$ GeV (80 GeV), respectively. We also show the significance $\sigma_{Z''} = (N_{Z''} - N_{\rm SM})/\sqrt{N_{\rm SM}}$.

	SM	Z'' model ($m_{Z''} = 60$ GeV)	Z'' model ($m_{Z''} = 80$ GeV)
χ^2/(d.o.f) in m_{12}	33.1/(19)	47.1/(19)	34.1/(19)
χ^2/(d.o.f) in m_{34}	6.9/(14)	26.6/(14)	6.5/(14)

Table 7: χ^2 in the m_{12} and m_{34} distributions in the SM and the Z'' models with $m_{Z''} = 60$ and 80 GeV.

4μ channel		N_{SM}	$N_{Z'',60}$	$\sigma_{Z'',60}$
	$(51, 57)$ GeV	13.4	17.1	1.0
m_{12}	$(57, 63)$ GeV	17.4	47.3	7.2
	$(63, 69)$ GeV	17.5	14.1	-0.8

Table 8: Numbers of events in several m_{12} ranges in 4μ channel for the SM (N_{SM}) and Z'' model with $m_{Z''} = 60$ GeV ($N_{Z''}$). We also show $\sigma_{Z''} = (N_{Z''} - N_{\mathrm{SM}})/\sqrt{N_{\mathrm{SM}}}$.

4.2.2 $pp \to \mu^+\mu^-\tau^+\tau^-$

In our Z'' model, the Z'' boson couples to the 2nd and 3rd generation leptons. In order to test the feature, we need to see the pattern of the couplings of the Z'' boson. One of these interesting processes is $2\mu 2\tau$ channel. To study this channel, we adopt hadronic τ tagging algorithm of Delphes which roughly reproduce ATLAS and CMS data for $Z \to \tau^+\tau^-$ channel [36].

For this channel we require the following cuts:

1. two τ jets exist satisfying $p_{T,\tau} > 20$ GeV and $|\eta_\tau| < 2.3$, only hadronically decaying τ's.

2. two oppositely charged muons exist satisfying $p_{T,\mu} > 10$ GeV and $|\eta_\mu| < 2.7$, the two muons are well separated as $\Delta R > 0.1$.

3. requiring the invariant mass cut for the two τ's, $m_{\tau\tau} > 120$ GeV, where we adopt the collinear approximation for the τ momentum reconstruction, that is, the neutrino momentum from τ decay is assumed to be parallel to the τ jet direction.

$m_{Z''} = 80$ GeV		$N_{\rm SM}$	$N_{Z''}$	$N_{Z''}/N_{\rm SM}$	$\int dtL$ for discovery (fb^{-1})
	(71, 77) GeV	0.3	0.9	3.1	
$m_{\mu\mu}$	(77, 83) GeV	0.6	4.8	8.2	> 500
	(83, 89) GeV	1.5	1.4	1.0	
$m_{Z''} = 90$ GeV		$N_{\rm SM}$	$N_{Z''}$	$N_{Z''}/N_{\rm SM}$	$\int dtL$ for discovery(fb^{-1})
	(81, 87) GeV	0.8	1.3	1.7	
$m_{\mu\mu}$	(87, 93) GeV	5.0	8.4	1.7	> 2900
	(93, 99) GeV	1.1	1.3	1.2	
$m_{Z''} = 100$ GeV		$N_{\rm SM}$	$N_{Z''}$	$N_{Z''}/N_{\rm SM}$	$\int dtL$ for discovery(fb^{-1})
	(91, 97) GeV	3.0	3.7	1.3	
$m_{\mu\mu}$	(97, 103) GeV	0.3	2.9	11.8	> 730
	(103, 109) GeV	0.07	0.2	2.9	

Table 13: Number of events in several $m_{\mu\mu}$ ranges in $2\mu 2\tau$ channel at $\sqrt{s} = 14$ TeV with $\int dtL = 300$ fb^{-1} in the SM and the Z'' model with $m_{Z''} = 80$, 90, and 100 GeV.

region below $m_{Z"} < 100$ GeV will be explored at HL-LHC

LHC will be important to test the model
for the anomaly of muon g-2