

General analysis of the signal with two leptons and missing energy at the LHC

Chien-Yi Chen
Carnegie Mellon University

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Outline

- Purpose and setup
- Spin determination
- Coupling determination
- Conclusions

Purpose

- Properties of new heavy particles beyond the standard model.

e.g.

- Mass
 - Spin
 - Coupling
-
- Model independent approach.
 - Consider all possible assignments of spins and SU(2) representations of new particles.

Purpose

- Properties of new heavy particles beyond the standard model.

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- Spin

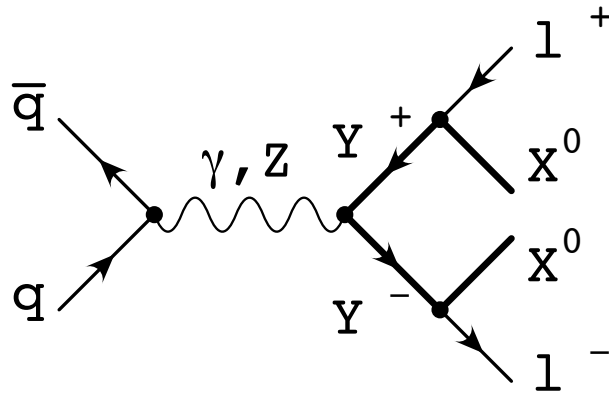
- Coupling



- Model independent approach.
- Consider all possible assignments of spins and SU(2) representations of new particles.

Setup

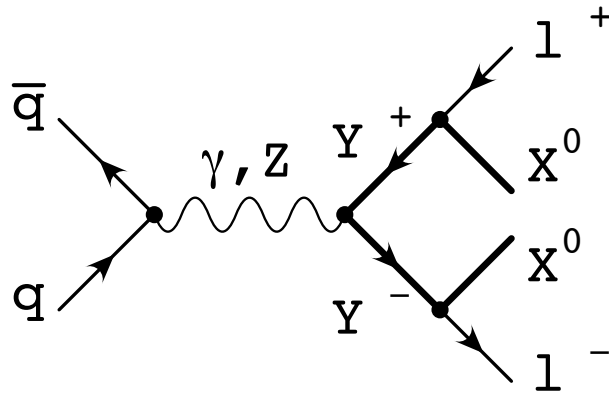
$$pp \rightarrow Y^+ Y^- \rightarrow \ell^+ \ell^- X^0 \bar{X}^0, \quad (\ell = e, \mu).$$



- Y : Charged massive particles.
- X : Missing energy signal; neutral massive particle. It can be a dark matter candidate.

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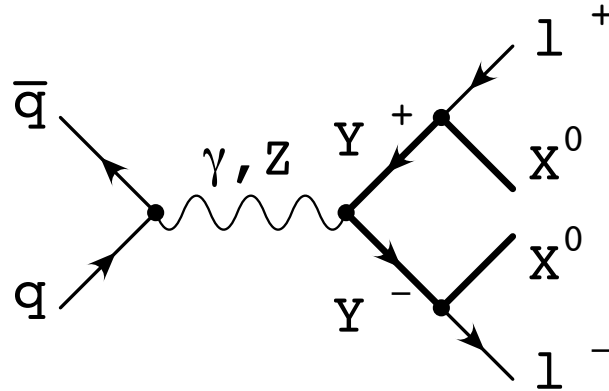


- Y : Charged massive particles.
- X : Missing energy signal; neutral massive particle. It can be a dark matter candidate.
- Assume a discrete symmetry to ensure X is pair produced:

e.g.

- R-parity in supersymmetry
- KK parity in universal extra dimensions

Spins of the X and Y



- Angular momentum conservation

Y	0	1/2	1
X	1/2	0 or 1	1/2
L	1/2	1/2	1/2

SU(2) representations of X and Y

- Singlet: **1** e.g. $e_R(x)$
- Doublet: **2** e.g. $L(x) = \begin{pmatrix} \nu_L(x) \\ E_L(x) \end{pmatrix}$
- Triplet (adjoint rep.): **3**, $[T_a, T_b] = i f_{abc} T_c$
 $[T_a]_{bc} = -i f_{abc}$

e.g. $W^\pm W^0$

[Doublet] 1x2	[Doublet] 2x1	[Singlet] 1x1
[Singlet] 1x1	[Singlet] 1x1	[Singlet] 1x1
[Doublet] 1x2	[Triplet] 2x2	[Doublet] 2x1

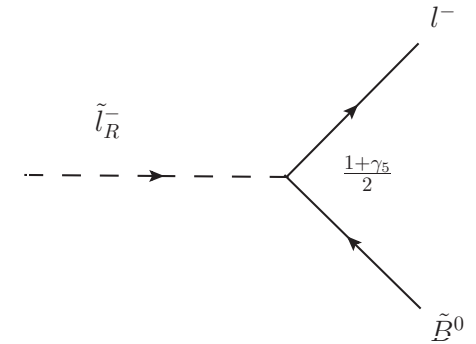
	Y $s, I_{\text{SU}(2)}$	X $s, I_{\text{SU}(2)}$	ℓ $I_{\text{SU}(2)}$	ZYY coupling	$XY\ell$ coupling
1	0, 1	$\frac{1}{2}$, 1	1	$Z^\mu Y^* \overleftrightarrow{\partial}_\mu Y$	$\bar{X}^{\frac{1+\gamma_5}{2}} \ell Y^*$
2	0, 2	$\frac{1}{2}$, 1	2	$Z^\mu Y^* \overleftrightarrow{\partial}_\mu Y$	$\bar{X}^{\frac{1-\gamma_5}{2}} \ell Y^*$
3	0, 3	$\frac{1}{2}$, 2	2	$Z^\mu Y^* \overleftrightarrow{\partial}_\mu Y$	$\bar{X}^{\frac{1-\gamma_5}{2}} \ell Y^*$
4	$\frac{1}{2}$, 1	0, 1	1	$\bar{Y} \not{Z} Y$	$\bar{Y}^{\frac{1+\gamma_5}{2}} \ell X$
5	$\frac{1}{2}$, 1	0, 2	2	$\bar{Y} \not{Z} Y$	$\bar{Y}^{\frac{1-\gamma_5}{2}} \ell X$
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10	$\frac{1}{2}$, 3	0, 2	2	$\bar{Y} \not{Z} Y$	$\bar{Y}^{\frac{1-\gamma_5}{2}} \ell X$
11	1, 3	$\frac{1}{2}$, 2	2	$S[Z, Y, Y^*]$	$\bar{X} Y^* \frac{1-\gamma_5}{2} \ell$

$$\overleftrightarrow{A} \partial_\mu B \equiv A(\partial_\mu B) - (\partial_\mu A)B,$$

$$S[Z, Y, Y^*] \equiv Z_\mu Y_\nu^* \overleftrightarrow{\partial}^\mu Y^\nu + Y_\mu Z_\nu \overleftrightarrow{\partial}^\mu Y^{*\nu} + Y_\mu^* Y_\nu \overleftrightarrow{\partial}^\mu Z^\nu$$

	Y $s, I_{\text{SU}(2)}$	X $s, I_{\text{SU}(2)}$	ℓ $I_{\text{SU}(2)}$	ZYY coupling	$XY\ell$ coupling
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Example: in supersymmetry



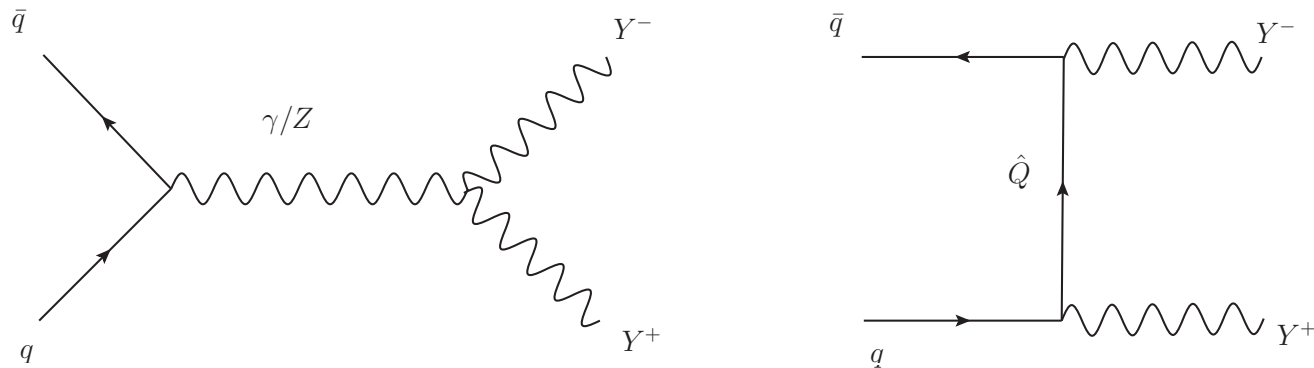
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Combination I I

	Y $s, I_{\text{SU}(2)}$	X $s, I_{\text{SU}(2)}$	ℓ $I_{\text{SU}(2)}$	ZYY coupling	$XY\ell$ coupling
11	1, 3	$\frac{1}{2}$, 2	2	$S[Z, Y, Y^*]$	$XY^*\frac{1-\gamma_5}{2}\ell$

$$S[Z, Y, Y^*] \equiv Z_\mu Y_\nu^* \overleftrightarrow{\partial}^\mu Y^\nu + Y_\mu Z_\nu \overleftrightarrow{\partial}^\mu Y^{*\nu} + Y_\mu^* Y_\nu \overleftrightarrow{\partial}^\mu Z^\nu$$



- s-channel contribution alone grows monotonically with the center-of-mass energy. t-channel diagram must be considered due to unitarity.
- s- and t-channel interfere negatively.
- In the t-channel, heavy \hat{Q} for the masses 500GeV and 1000GeV are considered in the simulation.
- If \hat{Q} is light, it has larger cross section and might be observed directly.

Variables for spin determination

Effective mass

$$M_{\text{eff}} = p_{T,\ell^+} + p_{T,\ell^-} + \cancel{p}_T,$$

Azimuthal angle difference
of the two leptons

$$\Delta\phi_{\ell\ell} = |(\phi_{\ell^+} - \phi_{\ell^-}) \bmod 2\pi|.$$

Barr's variable

$$\cos\theta_{\ell\ell}^* = \tanh \frac{|\eta_{\ell^+} - \eta_{\ell^-}|}{2} = \tanh \frac{\Delta\eta_{\ell\ell}}{2}$$

A. Barr, JHEP 0602, 042(2006)

- η_{ℓ^-} : The pseudorapidity of the lepton

$$\text{Pseudorapidity: } \eta = \frac{1}{2} \log \left[\frac{p + p_z}{p - p_z} \right] = -\log[\tan(\theta/2)]$$

- $\theta_{\ell\ell}^*$ is strongly correlated to the production angle.
- They are all Lorentz invariant along the boost direction.

Numerical results for spin determination

	Y $s, I_{\text{SU}(2)}$	X $s, I_{\text{SU}(2)}$	ℓ $I_{\text{SU}(2)}$	ZYY coupling	$XY\ell$ coupling
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$\sqrt{\chi^2}$ value for a 5-bin χ^2 – test , 5000 parton-level events. $m_Y = 300$ GeV and $m_X = 100$ GeV.

Variable	(model A, model B)				
	(3,10)	(3,11) [$M_{\hat{Q}}=1$ TeV]	(3,11) [$M_{\hat{Q}}=0.5$ TeV]	(10,11) [$M_{\hat{Q}}=1$ TeV]	(10,11) [$M_{\hat{Q}}=0.5$ TeV]
$\tanh(\Delta\eta_{\ell\ell}/2)$	19.0	18.6	26.0	2.4	8.0
M_{eff}	37.5	3.9	25.1	30.7	9.5
$\Delta\phi_{\ell\ell}$	16.3	21.4	10.7	41.1	29.0
All combined	37.5	21.4	26.0	41.1	29.0

Coupling determination

- Definition of the charge asymmetry:

$$A_{\ell^+\ell^-} = \frac{N(E_{\ell^-} > E_{\ell^+}) - N(E_{\ell^+} > E_{\ell^-})}{N(E_{\ell^-} > E_{\ell^+}) + N(E_{\ell^+} > E_{\ell^-})}$$

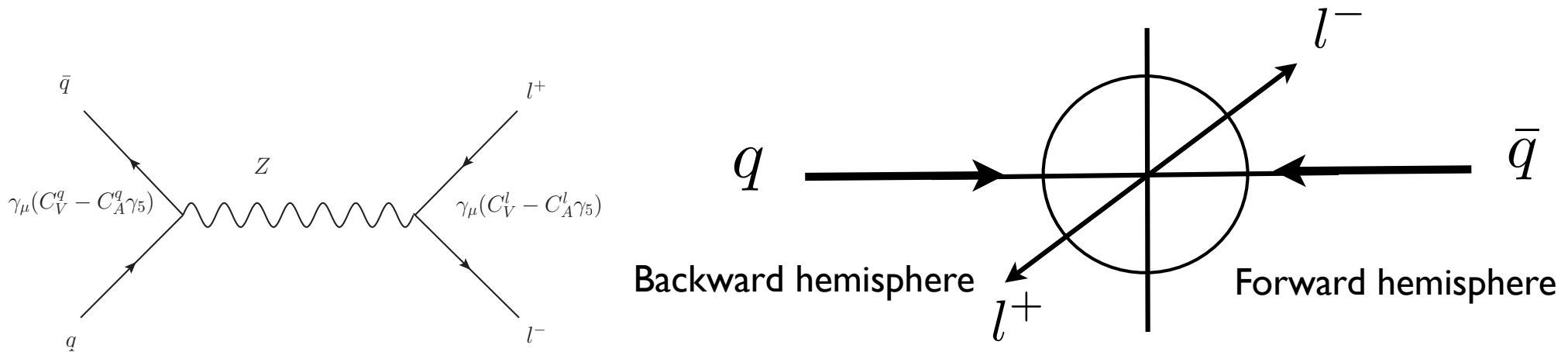
$N(E_{\ell^-} > E_{\ell^+})$ denotes the number of events for which ℓ^- has a larger energy than ℓ^+ .

- It is well correlated with the forward and backward asymmetry at the LHC.

Coupling determination

e.g. $q\bar{q} \rightarrow l^+l^-$

In the center of mass frame:



- Definition of forward-backward asymmetry:

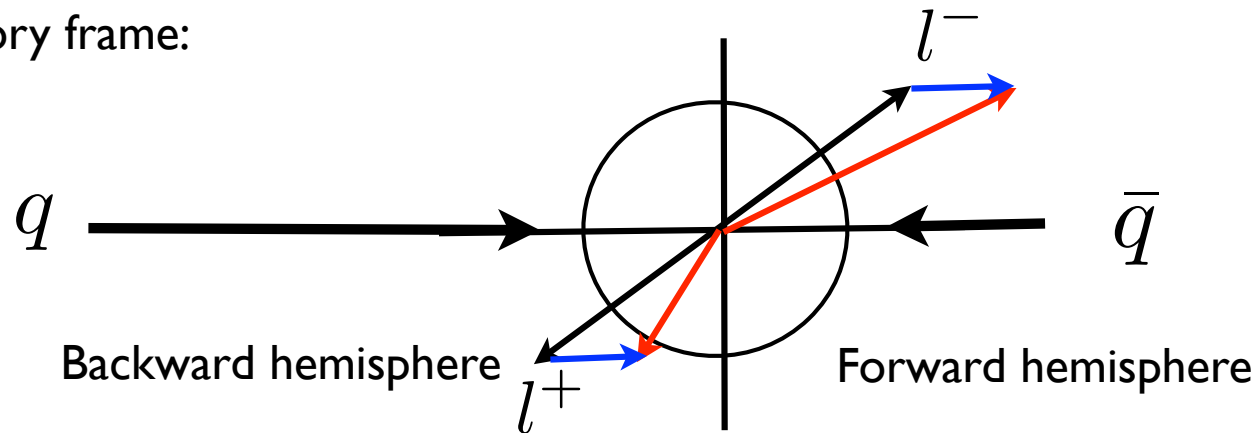
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

$$F = \int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta, \quad B = \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta$$

Coupling determination

Center of mass frame: $E_{\ell^-} = \sqrt{m^2 + p_x^2 + p_y^2 + p_z^2} = E_{\ell^+}$ $A_{FB} = \frac{N_F - N_B}{N_F + N_B}$

Laboratory frame:



- Define charge asymmetry:

$$E_{\ell^-} = \sqrt{m^2 + p_x^2 + p_y^2 + (p_z + p'_z)^2}$$

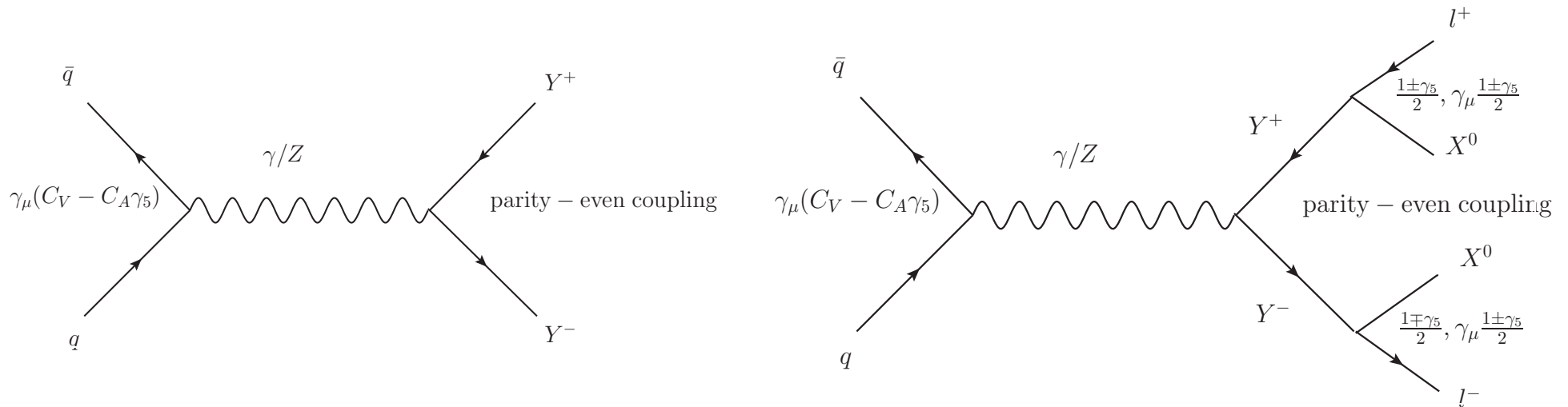
$$E_{\ell^+} = \sqrt{m^2 + (-p_x)^2 + (-p_y)^2 + (-p_z + p'_z)^2}$$

$$A_{\ell^+\ell^-} = \frac{N(E_{\ell^-} > E_{\ell^+}) - N(E_{\ell^+} > E_{\ell^-})}{N(E_{\ell^-} > E_{\ell^+}) + N(E_{\ell^+} > E_{\ell^-})}$$

$N(E_{\ell^-} > E_{\ell^+})$ denotes the number of events for which ℓ^- has a larger energy than ℓ^+ .

- In hadron colliders, the center-of-mass energy of partons is unknown. The incoming quark are more energetic than incoming anti-quark because the valence quarks are on average more energetic than sea quarks.

Coupling determination



- Charge asymmetry does not work for scalar Y cases due to the absence of spin correlations between the production and decay parts of the process.
- For fermion Y cases, the V-A structure still exists.

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Indistinguishable by using charge asymmetry.

Most of them are distinguishable by using charge asymmetry!

$$\overleftrightarrow{\partial}_\mu B \equiv A(\partial_\mu B) - (\partial_\mu A)B,$$

$$S[Z, Y, Y^*] \equiv Z_\mu Y_\nu^* \overleftrightarrow{\partial}^\mu Y^\nu + Y_\mu Z_\nu \overleftrightarrow{\partial}^\mu Y^{*\nu} + Y_\mu^* Y_\nu \overleftrightarrow{\partial}^\mu Z^\nu$$

Numerical results for coupling determination

		model A					
		4	5	6	7	8	9
model B	5	36					
	6	4.9	29				
	7	1.6	33	2.9			
	8	32	3.5	26	29		
	9	6.7	27	1.5	4.7	23	
	10	0.3	37	5.8	2.2	33	7.6

- Statistical significance, in units of standard deviations.
- 5000 parton-level events without cut and detector effects.
- The differential asymmetry $dA_{e^+e^-}/d \tanh(\Delta\eta_{ee}/2)$ is used.

Conclusions

- Two new variables for spin determination and one new variables for coupling determination are introduced.
- $s_Y = 0$: It is generally not possible to discriminate between cases with different couplings.
- $s_Y = 1/2$, only some pairs cannot achieve a 3 sigma discrimination with a realistic number of a few thousand events.
- Fast detector simulation with selection cuts are performed and we found our conclusion still hold.

Thank you.