Model-independent analysis of processes with invisible particles

A. Freitas

University of Pittsburgh

C.-Y. Chen & A. Freitas, JHEP 1102, 002 (2011)
C.-Y. Chen, A. Freitas, T. Han & K. Lee, arXiv:1206.xxxx

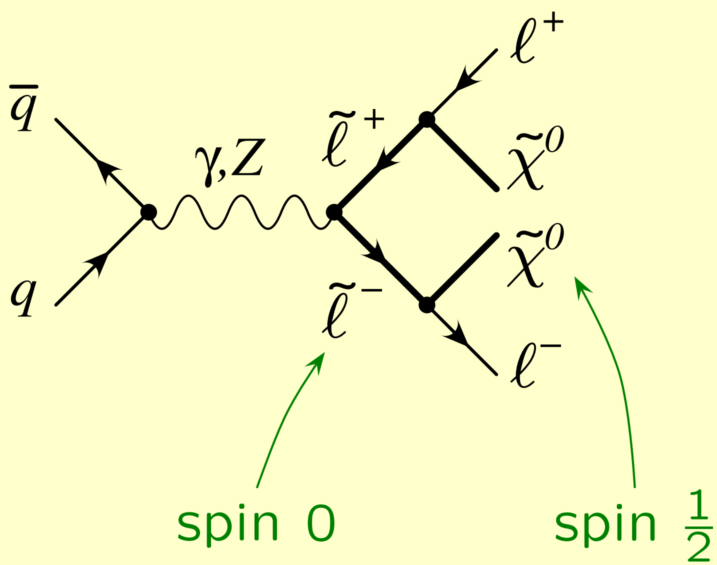
1. **New physics at LHC and model dependence**
2. **Leptonic signatures:** $\ell^+\ell^- + \not{E}$
3. **Top-quark signatures:** $t\bar{t} + \not{E}$
4. **Summary and discussion**

New physics at LHC and model dependence

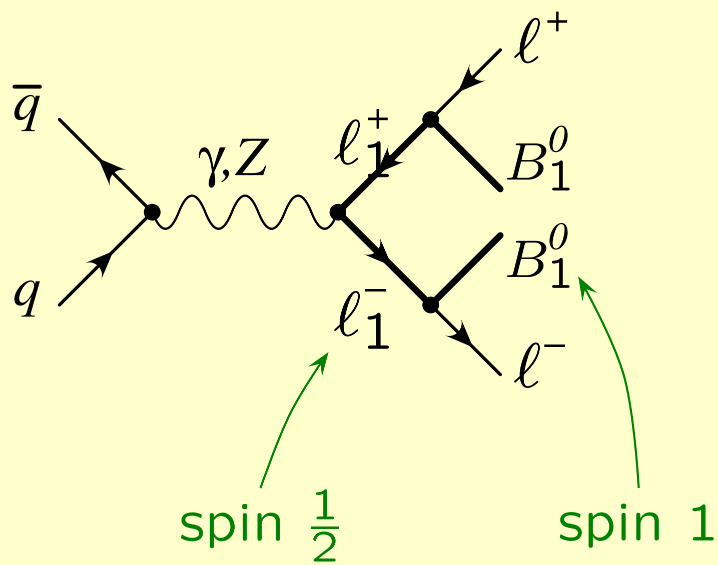
Many models predict **missing-momentum signatures** from stable (dark matter) particles: **SUSY, UED, ...**

Spin determination important for distinction:

SUSY:



UED:

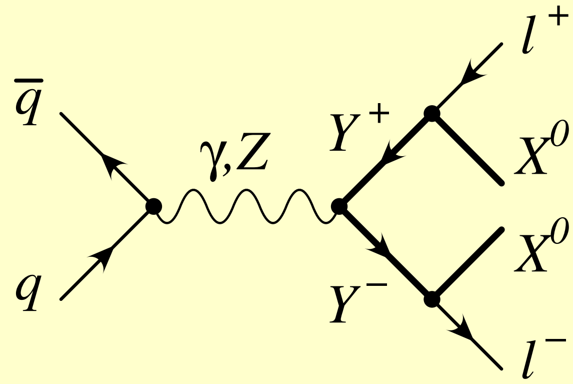


Spins and couplings

Suppose we measure

$\text{spin}(Y) = \frac{1}{2}$

Is it a KK-lepton in UED?

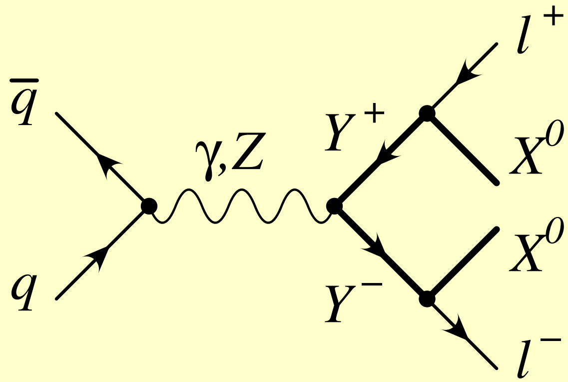


Spins and couplings

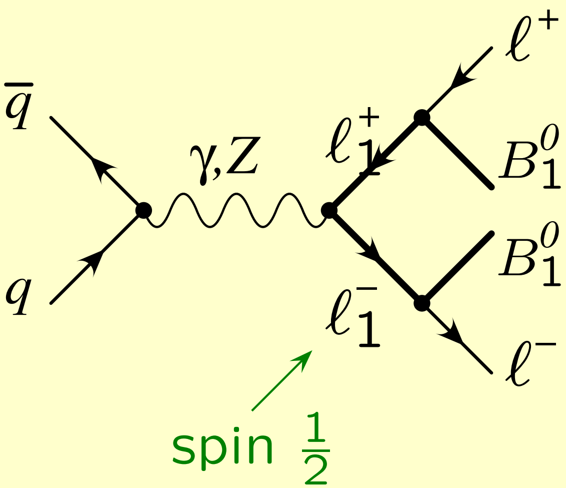
Suppose we measure

spin$(Y) = \frac{1}{2}$

Is it a KK-lepton in UED?



maybe ...

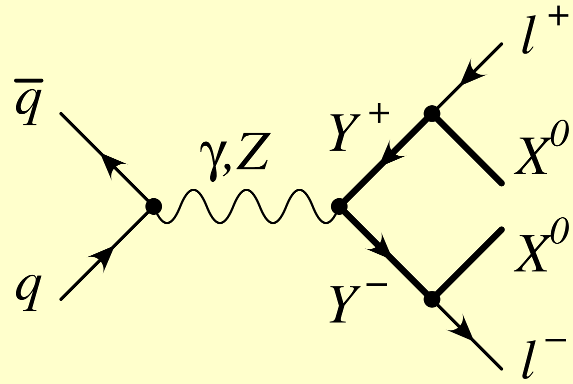


Spins and couplings

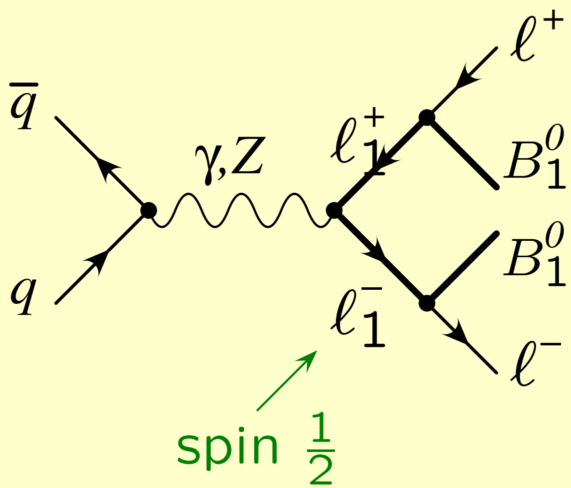
Suppose we measure

spin$(Y) = \frac{1}{2}$

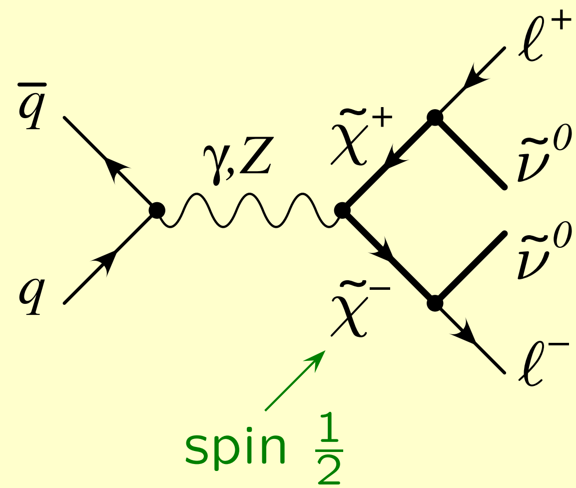
Is it a KK-lepton in UED?



maybe ...



... or maybe not



$\longrightarrow$ Need also coupling determination to obtain clear picture!

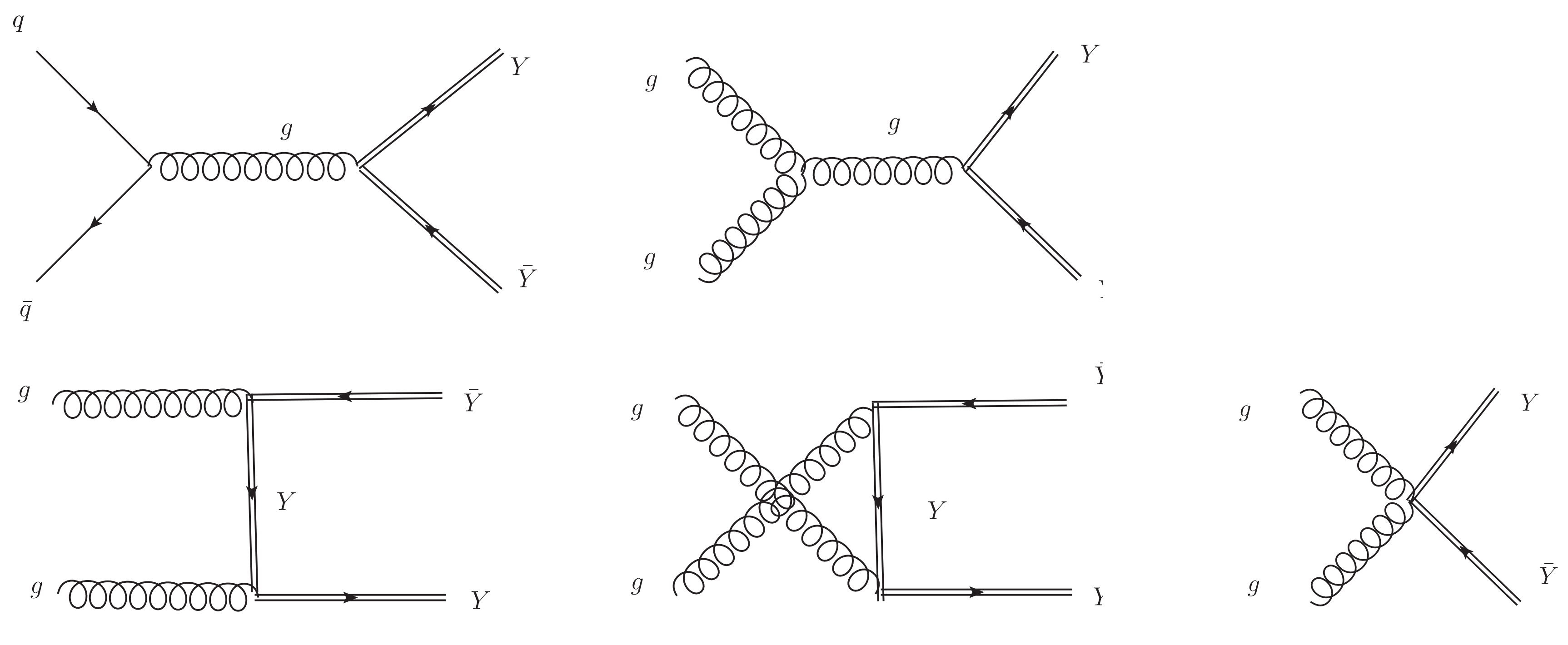
Top-quark signatures: $t\bar{t} + \not{E}$

Processes with **top partner Y** and **neutral DM candidate X**

$pp \to Y\bar{Y}, \quad Y \to tX$

$\longrightarrow$ Charged under $\mathbb{Z}_2$ symmetry

$\longrightarrow$ Signature $t\bar{t} + \not{E}$

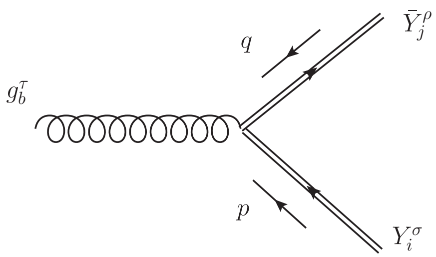


Consider all combinations of Y/X with spin 0, $\frac{1}{2}$, 1

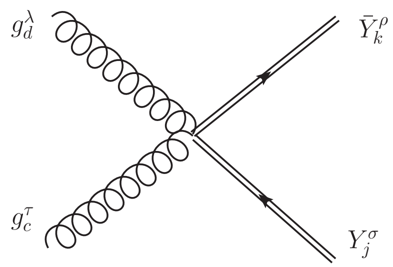
	Y s, $I_{\mathrm{SU(3)}}$	X s, $I_{\mathrm{SU(3)}}$	GYY coupling	XYt coupling	sample model and decay $Y \to tX$
i	0, **3**	$\frac{1}{2}$, **1**	$Y^* \overleftrightarrow{\partial_\mu} G^\mu Y$	$\overline{X}(a_L P_L + a_R P_R) t\, Y^*$	MSSM $\tilde{t} \to t\, \tilde{\chi}^0_1$
ii	$\frac{1}{2}$, **3**	0, **1**	$\overline{Y} \not{G} Y$	$\overline{Y}(a_L P_L + a_R P_R) t\, X$	UED $t_{(1)} \to t\, B^0_{H,(1)}$
iii	$\frac{1}{2}$, **3**	1, **1**	$\overline{Y} \not{G} Y$	$\overline{Y} \not{X}(a_L P_L + a_R P_R) t$	UED $t_{(1)} \to t\, B^0_{(1)}$
iv	1, **3**	$\frac{1}{2}$, **1**	$S[Z, Y, Y^*]$	$\overline{X} \not{Y}^*(a_L P_L + a_R P_R) t$	Cai et al. '08 $\vec{Q} \to t\tilde{\chi}_0$

Vector top partners:

$$\mathcal{L}_{\mathrm{kin}} = -\frac{1}{2}(F_{\mu\nu})^\dagger F^{\mu\nu}, \qquad F_{\mu\nu} = D_\mu Y_\nu - D_\nu Y_\mu\,, \qquad D_\mu = \partial_\mu - igT_a G^a_\mu$$



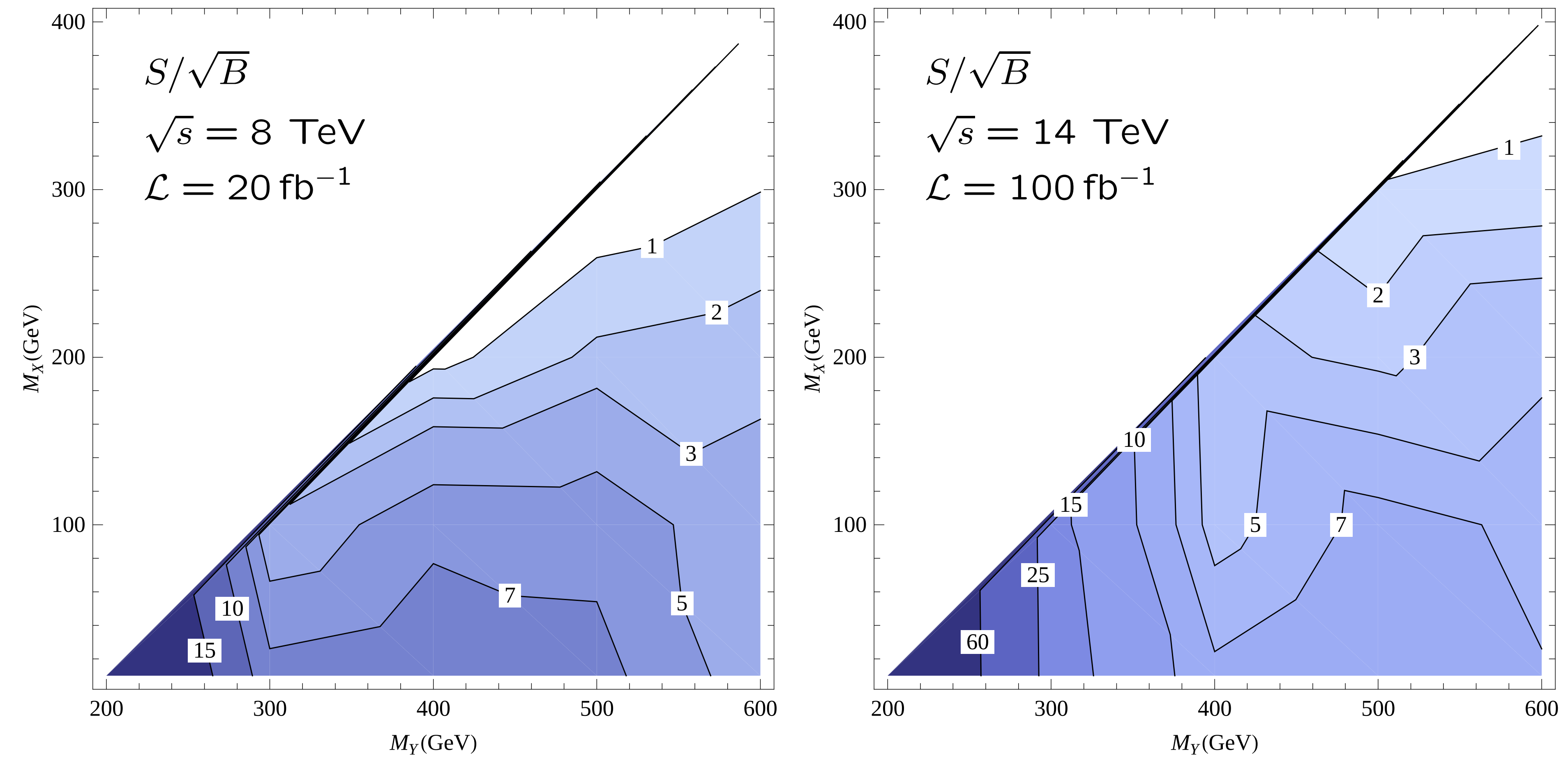
$$= ig(T_b)_{ji}\left((q-p)^\tau g^{\sigma\rho} + p^\rho g^{\sigma\tau} - q^\sigma g^{\rho\tau}\right)$$



$$= -ig^2\Big[(T_c T_d + T_d T_c)_{kj} g^{\tau\lambda} g^{\rho\sigma} - (T_c T_d)_{kj} g^{\tau\sigma} g^{\lambda\rho} - (T_d T_c)_{kj} g^{\tau\rho} g^{\lambda\sigma}\Big]$$

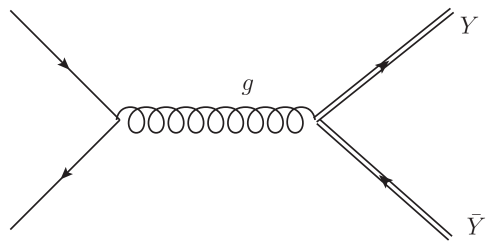
Signal reach

- $pp \to Y\bar{Y} \to tX\bar{t}X \to bj_1j_2X\bar{b}\ell^-\bar{\nu}_\ell X$ + h.c. , $(\ell = e, \mu)$.
- Generate events with *CalcHEP+Pythia* Pukhov, Belyaev, Christensen '11
  Sjöstrand, Mrenna, Skands '06
- Selection cuts, optimized for different values of m_Y



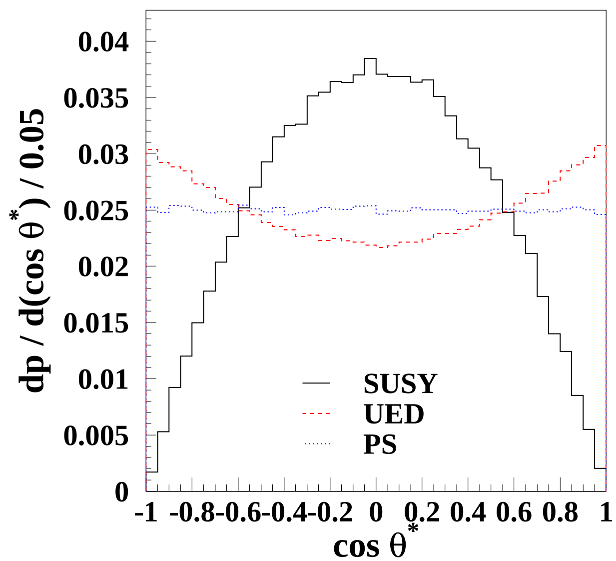
Spin determinaton: tanh$(\Delta y_{t\bar{t}}/2)$

$q\bar{q}$ channel:



scalar Y: $$\frac{d\sigma}{d\cos\theta^*} \propto 1 - \cos^2\theta^*$$

fermion Y: $$\frac{d\sigma}{d\cos\theta^*} \propto 2 + \beta_Y^2(\cos^2\theta^* - 1)$$



Barr '05

For $m_Y \sim$ few 100 GeV: $Y, \bar{Y}$ produced with boost

$\longrightarrow$ $t, \bar{t}$ mostly go in same direction as $Y, \bar{Y}$

$\longrightarrow$ $\cos\theta^*_{t\bar{t}} \approx \tanh\frac{|y_{bjj} - y_{b\ell}|}{2} \equiv \tanh\frac{\Delta y_{t\bar{t}}}{2}$ correlated to $\cos\theta^*$

top polar angle in frame where $|y_t| = |y_{\bar{t}}|$

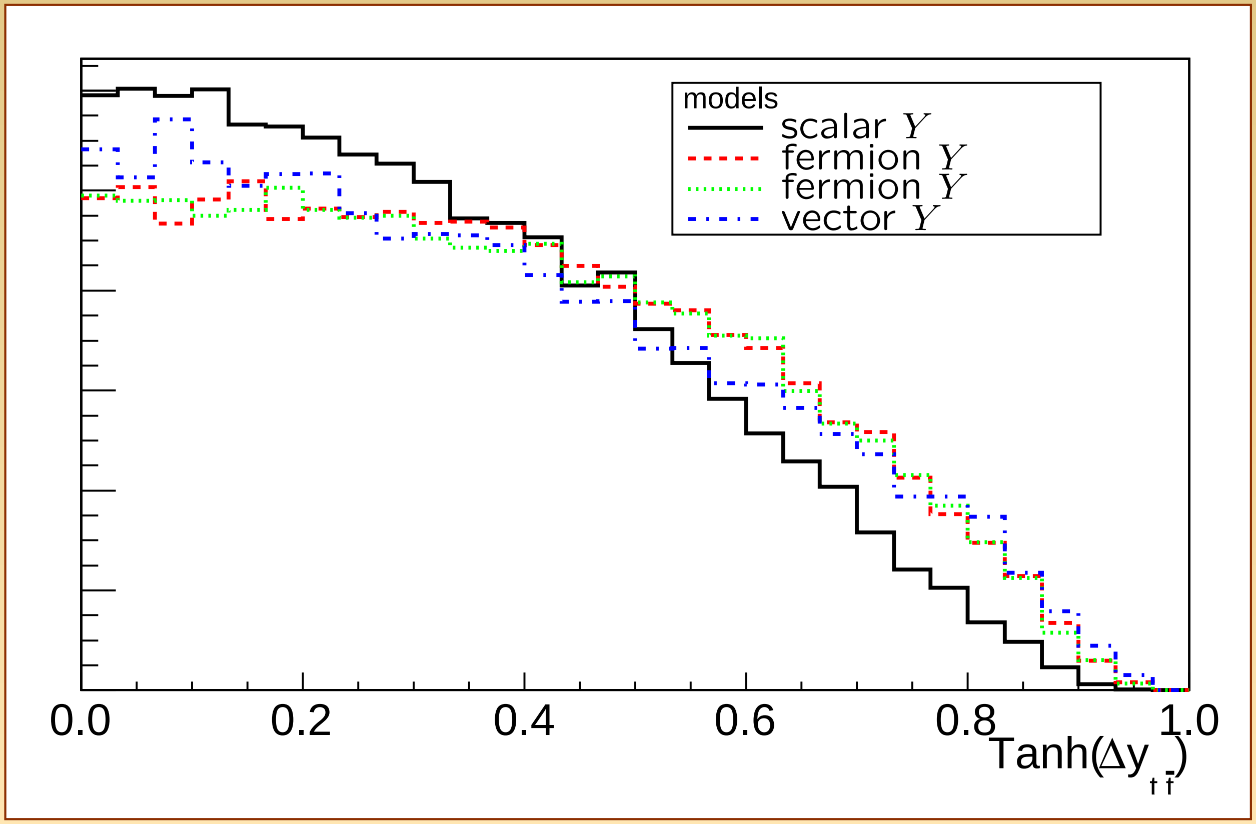
Y polar angle in CM frame

Spin determinaton: $\tanh(\Delta y_{t\bar{t}}/2)$

$\rightarrow$ $\cos\theta^*_{t\bar{t}} \approx \tanh\frac{|y_{bjj}-y_{b\ell}|}{2} \equiv \tanh\frac{\Delta y_{t\bar{t}}}{2}$ correlated to $\cos\theta^*$

top polar angle in frame
where $|y_t| = |y_{\bar{t}}|$

Y polar angle in CM frame



Spin determinaton: M_{eff}

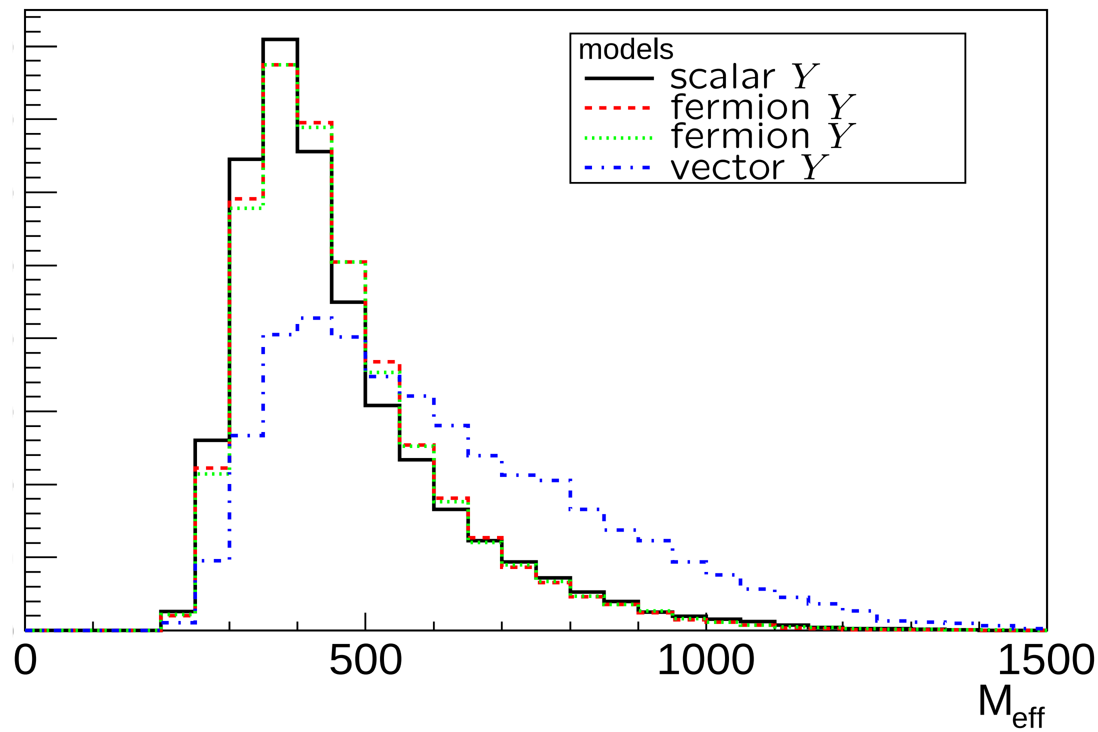
Invariant mass distribution $\frac{d\sigma[q\bar{q}\to Y^+Y^-]}{dm_{YY}}$:

scal./ferm. Y: $\sigma \sim 1/m_{YY}^2$ for $m_{YY} \to \infty$

vector Y: σ grows indefinitely for $m_{YY} \to \infty$
(until new resonances enter)

$$M_{\text{eff}} = \sum_{i\in\text{vis.}} p_{\perp,i} + \not{p}_\perp$$

correlated to m_{YY}



Spin determinaton: Results

- $m_Y = 300$ GeV, $m_X = 100$ GeV
- Cross section for scalar Y
- Selection cuts as before

Lumin. to reach
5σ discrimination:
[in fb^{-1}]

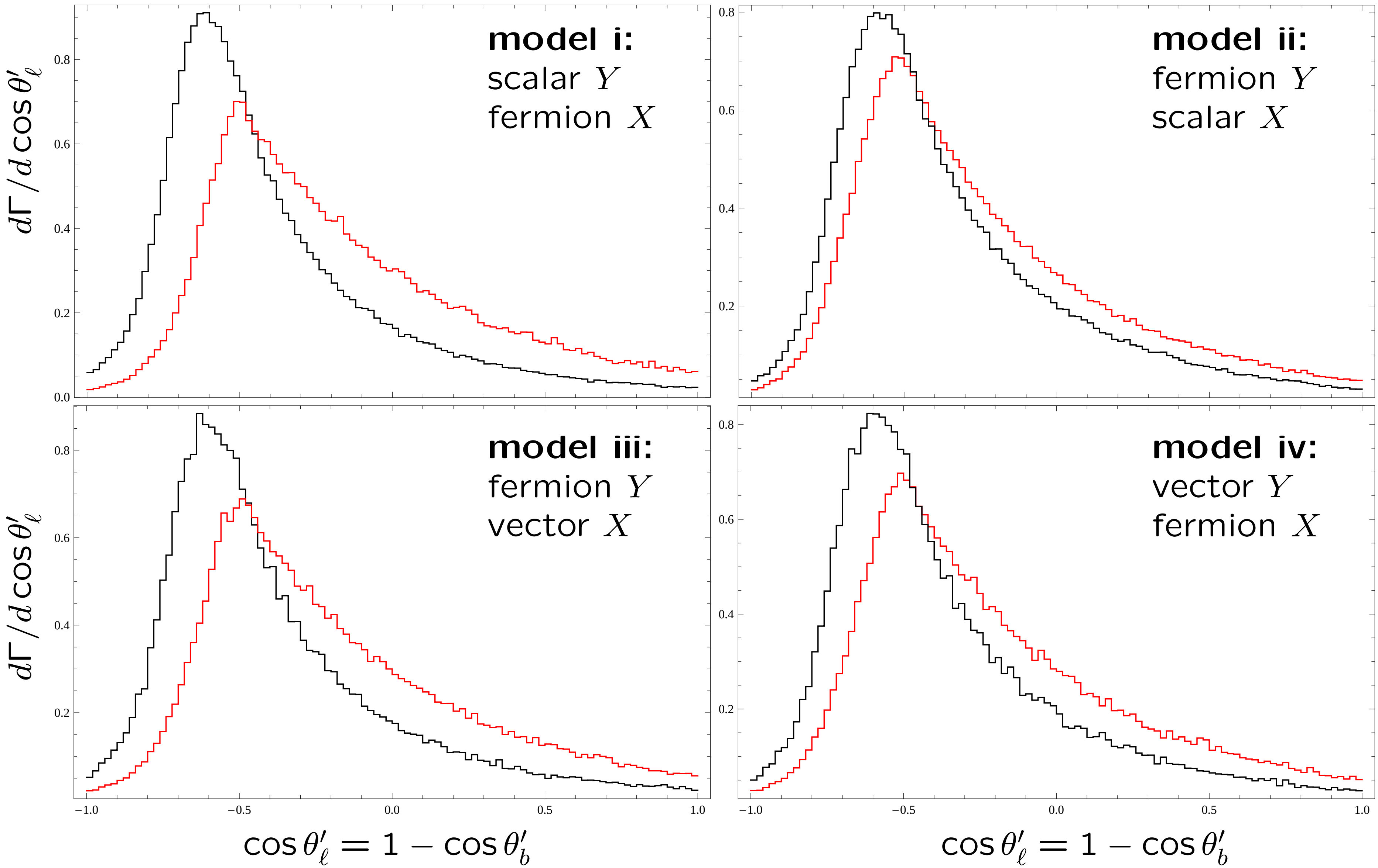
	Variable	(S,F)	(S,V)	(F,V)
8 TeV	$\tanh(\Delta\eta_{t\bar{t}}/2)$	35	—	—
	M_{eff}	—	4.0	2.6
14 TeV	$\tanh(\Delta\eta_{t\bar{t}}/2)$	4.7	—	80
	M_{eff}	160	0.4	0.35

$\longrightarrow$ good identification with moderate amounts of data!

Coupling determinaton: top polarization

- QCD dicated form of production amplitudes
- Decay amplitudes can have L/R parts: $\overline{Y}(a_L P_L + a_R P_R)t\, X$
  $\longrightarrow$ Probe through top polarization
- Observable: angle θ'_b of b-quark with respect to t boost direction in t rest frame
  - **left**-handed top-quark: $\cos\theta'_b > 0$
  - **right**-handed top-quark: $\cos\theta'_b < 0$
- For $t \to b\ell\nu$: angle θ'_b of b-quark with respect to $b\ell$ boost direction in $b\ell$ rest frame

Coupling determinaton: Results

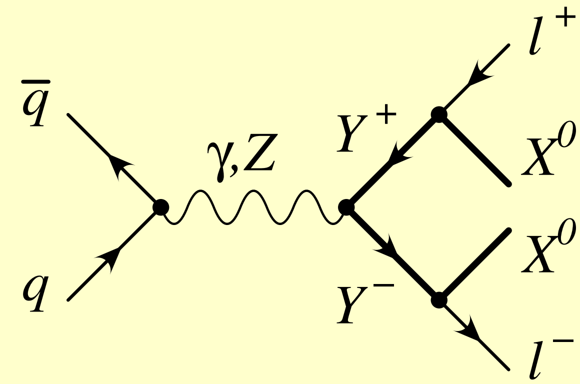


Leptonic signatures: $\ell^+\ell^- + \not{E}$

Processes with **lepton partner $\boldsymbol{Y}$** and **neutral DM candidate $\boldsymbol{X}$**

$\longrightarrow$ Charged under $\mathbb{Z}_2$ symmetry

$\longrightarrow$ Signature $\ell^+\ell^- + \not{E}, \quad \ell = e, \mu$



Consider all combinations of Y/X with:

- Spin 0, $\frac{1}{2}$, 1
- SU(2) singlets, doublets, (adjoint/real) triplets

- Spin determination similar to top-partner scenario

	Y s, $I_{\mathrm{SU}(2)}$	X s, $I_{\mathrm{SU}(2)}$	ℓ $I_{\mathrm{SU}(2)}$	ZYY coupling	$XY\ell$ coupling	sample model and decay $Y^- \to \ell^- X$
1	0, **1**	$\frac{1}{2}$, **1**	**1**	$Z^\mu Y^* \overleftrightarrow{\partial_\mu} Y$	$\overline{X}\frac{1+\gamma_5}{2}\ell\, Y^*$	MSSM $\tilde{\ell}^-_{\mathrm{R}} \to \ell^- \tilde{B}^0$
1a	0, **1**	$\frac{1}{2}$, **2**	**2**	$Z^\mu Y^* \overleftrightarrow{\partial_\mu} Y$	$\overline{X}\frac{1-\gamma_5}{2}\ell\, Y^*$	MSSM $\tilde{\ell}^-_{\mathrm{R}} \to \ell^- \tilde{H}^0$
2	0, **2**	$\frac{1}{2}$, **1**	**2**	$Z^\mu Y^* \overleftrightarrow{\partial_\mu} Y$	$\overline{X}\frac{1-\gamma_5}{2}\ell\, Y^*$	MSSM $\tilde{\ell}^-_{\mathrm{L}} \to \ell^- \tilde{B}^0$
2a	0, **2**	$\frac{1}{2}$, **2**	**1**	$Z^\mu Y^* \overleftrightarrow{\partial_\mu} Y$	$\overline{X}\frac{1+\gamma_5}{2}\ell\, Y^*$	MSSM $\tilde{\ell}^-_{\mathrm{L}} \to \ell^- \tilde{H}^0$
2b	0, **2**	$\frac{1}{2}$, **3**	**2**	$Z^\mu Y^* \overleftrightarrow{\partial_\mu} Y$	$\overline{X}\frac{1-\gamma_5}{2}\ell\, Y^*$	MSSM $\tilde{\ell}^-_{\mathrm{L}} \to \ell^- \tilde{W}^0$
3	0, **3**	$\frac{1}{2}$, **2**	**2**	$Z^\mu Y^* \overleftrightarrow{\partial_\mu} Y$	$\overline{X}\frac{1-\gamma_5}{2}\ell\, Y^*$	UED6 $W^-_{H,(1)} \to \ell^- \nu_{(1)}$
4	$\frac{1}{2}$, **1**	0, **1**	**1**	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1+\gamma_5}{2}\ell\, X$	UED6 $\ell^-_{S,(1)} \to \ell^- B^0_{H,(1)}$
5	$\frac{1}{2}$, **1**	0, **2**	**2**	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1-\gamma_5}{2}\ell\, X$	UED $\ell^-_{S,(1)} \to \ell^- H^0_{(1)}$
6	$\frac{1}{2}$, **1**	1, **1**	**1**	$\overline{Y}\not{Z}Y$	$\overline{Y}\not{X}\frac{1+\gamma_5}{2}\ell$	UED $\ell^-_{S,(1)} \to \ell^- B^0_{\mu,(1)}$
7	$\frac{1}{2}$, **2**	0, **1**	**2**	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1-\gamma_5}{2}\ell\, X$	UED6 $\ell^-_{D,(1)} \to \ell^- B^0_{H,(1)}$
7a	$\frac{1}{2}$, **2**	0, **3**	**2**	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1-\gamma_5}{2}\ell\, X$	UED6 $\ell^-_{D,(1)} \to \ell^- W^0_{H,(1)}$
8	$\frac{1}{2}$, **2**	0, **2**	**1**	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1+\gamma_5}{2}\ell\, X$	MSSM $\tilde{H}^- \to \ell^- \tilde{\nu}$
9	$\frac{1}{2}$, **2**	1, **1**	**2**	$\overline{Y}\not{Z}Y$	$\overline{Y}\not{X}\frac{1-\gamma_5}{2}\ell$	UED $\ell^-_{D,(1)} \to \ell^- B^0_{\mu,(1)}$
9a	$\frac{1}{2}$, **2**	1, **3**	**2**	$\overline{Y}\not{Z}Y$	$\overline{Y}\not{X}\frac{1-\gamma_5}{2}\ell$	UED $\ell^-_{D,(1)} \to \ell^- W^0_{\mu,(1)}$
10	$\frac{1}{2}$, **3**	0, **2**	**2**	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1-\gamma_5}{2}\ell\, X$	MSSM $\tilde{W}^- \to \ell^- \tilde{\nu}$
11	1, **3**	$\frac{1}{2}$, **2**	**2**	$S[Z, Y, Y^*]$	$\overline{X}\not{Y}^*\frac{1-\gamma_5}{2}\ell$	UED $W^-_{\mu,(1)} \to \ell^- \nu_{(1)}$

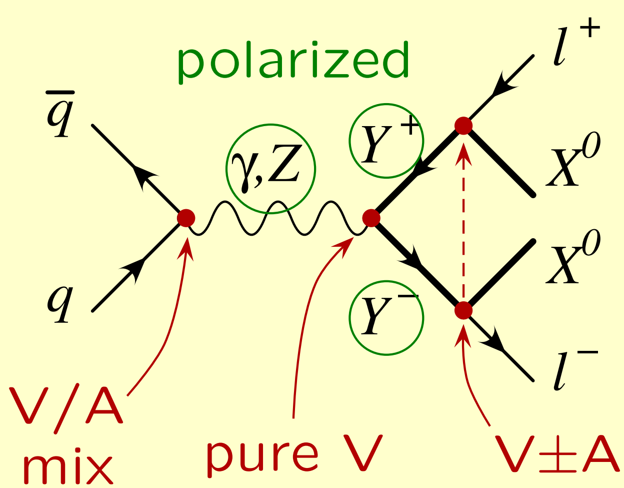
	Y $s,\ I_{\mathrm{SU(2)}}$	X $s,\ I_{\mathrm{SU(2)}}$	ℓ $I_{\mathrm{SU(2)}}$	ZYY coupling	$XY\ell$ coupling	sample model and decay $Y^- \to \ell^- X$
1	$0,\ \mathbf{1}$	$\frac{1}{2},\ \mathbf{1}$	$\mathbf{1}$	$Z^\mu Y^* \overleftrightarrow{\partial}_\mu Y$	$\overline{X}\frac{1+\gamma_5}{2}\ell\, Y^*$	MSSM $\tilde{\ell}_R^- \to \ell^- \tilde{B}^0$
1a	$0,\ \mathbf{1}$	$\frac{1}{2},\ \mathbf{2}$	$\mathbf{2}$	$Z^\mu Y^* \overleftrightarrow{\partial}_\mu Y$	$\overline{X}\frac{1-\gamma_5}{2}\ell\, Y^*$	MSSM $\tilde{\ell}_R^- \to \ell^- \tilde{H}^0$
2	$0,\ \mathbf{2}$	$\frac{1}{2},\ \mathbf{1}$	$\mathbf{2}$	$Z^\mu Y^* \overleftrightarrow{\partial}_\mu Y$	$\overline{X}\frac{1-\gamma_5}{2}\ell\, Y^*$	MSSM $\tilde{\ell}_L^- \to \ell^- \tilde{B}^0$
2a	$0,\ \mathbf{2}$	$\frac{1}{2},\ \mathbf{2}$	$\mathbf{1}$	$Z^\mu Y^* \overleftrightarrow{\partial}_\mu Y$	$\overline{X}\frac{1+\gamma_5}{2}\ell\, Y^*$	MSSM $\tilde{\ell}_L^- \to \ell^- \tilde{H}^0$
2b	$0,\ \mathbf{2}$	$\frac{1}{2},\ \mathbf{3}$	$\mathbf{2}$	$Z^\mu Y^* \overleftrightarrow{\partial}_\mu Y$	$\overline{X}\frac{1-\gamma_5}{2}\ell\, Y^*$	MSSM $\tilde{\ell}_L^- \to \ell^- \tilde{W}^0$
3	$0,\ \mathbf{3}$	$\frac{1}{2},\ \mathbf{2}$	$\mathbf{2}$	$Z^\mu Y^* \overleftrightarrow{\partial}_\mu Y$	$\overline{X}\frac{1-\gamma_5}{2}\ell\, Y^*$	UED6 $W^-_{H,(1)} \to \ell^- \nu_{(1)}$
4	$\frac{1}{2},\ \mathbf{1}$	$0,\ \mathbf{1}$	$\mathbf{1}$	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1+\gamma_5}{2}\ell\, X$	UED6 $\ell^-_{S,(1)} \to \ell^- B^0_{H,(1)}$
5	$\frac{1}{2},\ \mathbf{1}$	$0,\ \mathbf{2}$	$\mathbf{2}$	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1-\gamma_5}{2}\ell\, X$	UED $\ell^-_{S,(1)} \to \ell^- H^0_{(1)}$
6	$\frac{1}{2},\ \mathbf{1}$	$1,\ \mathbf{1}$	$\mathbf{1}$	$\overline{Y}\not{Z}Y$	$\overline{Y}\not{X}\frac{1+\gamma_5}{2}\ell$	UED $\ell^-_{S,(1)} \to \ell^- B^0_{\mu,(1)}$
7	$\frac{1}{2},\ \mathbf{2}$	$0,\ \mathbf{1}$	$\mathbf{2}$	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1-\gamma_5}{2}\ell\, X$	UED6 $\ell^-_{D,(1)} \to \ell^- B^0_{H,(1)}$
7a	$\frac{1}{2},\ \mathbf{2}$	$0,\ \mathbf{3}$	$\mathbf{2}$	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1-\gamma_5}{2}\ell\, X$	UED6 $\ell^-_{D,(1)} \to \ell^- W^0_{H,(1)}$
8	$\frac{1}{2},\ \mathbf{2}$	$0,\ \mathbf{2}$	$\mathbf{1}$	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1+\gamma_5}{2}\ell\, X$	MSSM $\tilde{H}^- \to \ell^- \tilde{\nu}$
9	$\frac{1}{2},\ \mathbf{2}$	$1,\ \mathbf{1}$	$\mathbf{2}$	$\overline{Y}\not{Z}Y$	$\overline{Y}\not{X}\frac{1-\gamma_5}{2}\ell$	UED $\ell^-_{D,(1)} \to \ell^- B^0_{\mu,(1)}$
9a	$\frac{1}{2},\ \mathbf{2}$	$1,\ \mathbf{3}$	$\mathbf{2}$	$\overline{Y}\not{Z}Y$	$\overline{Y}\not{X}\frac{1-\gamma_5}{2}\ell$	UED $\ell^-_{D,(1)} \to \ell^- W^0_{\mu,(1)}$
10	$\frac{1}{2},\ \mathbf{3}$	$0,\ \mathbf{2}$	$\mathbf{2}$	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1-\gamma_5}{2}\ell\, X$	MSSM $\tilde{W}^- \to \ell^- \tilde{\nu}$
11	$1,\ \mathbf{3}$	$\frac{1}{2},\ \mathbf{2}$	$\mathbf{2}$	$S[Z, Y, Y^*]$	$\overline{X}\not{Y}^*\frac{1-\gamma_5}{2}\ell$	UED $W^-_{\mu,(1)} \to \ell^- \nu_{(1)}$

Coupling determinaton: $A_{\ell+\ell-}$

Analyze FB asymmetry:

New physics models have **P-even** ZYY coupling:

$\longrightarrow$ $\mathcal{A}^{YY}_{\mathrm{FB}} = 0$, but $\mathcal{A}^{\ell\ell}_{\mathrm{FB}} \neq 0$



- resulting FB asymmetry of $\ell^\pm$
- on average $E_q > E_{\bar{q}}$
  $\longrightarrow$ forward direction = direction of long. boost of event
- $A_{\ell+\ell-} \equiv \frac{N(E_{\ell-}>E_{\ell+})-N(E_{\ell+}>E_{\ell-})}{N(E_{\ell-}>E_{\ell+})+N(E_{\ell+}>E_{\ell-})}$

	Y $s,\ I_{\mathrm{SU(2)}}$	X $s,\ I_{\mathrm{SU(2)}}$	ℓ $I_{\mathrm{SU(2)}}$	ZYY coupling	$XY\ell$ coupling	sample model and decay $Y^- \to \ell^- X$
1	0, **1**	$\frac{1}{2}$, **1**	**1**	$Z^\mu Y^* \overleftrightarrow{\partial_\mu} Y$	$\overline{X}\frac{1+\gamma_5}{2}\ell\, Y^*$	MSSM $\tilde{\ell}^-_{\mathrm{R}} \to \ell^- \tilde{B}^0$
2	0, **2**	$\frac{1}{2}$, **1**	**2**	$Z^\mu Y^* \overleftrightarrow{\partial_\mu} Y$	$\overline{X}\frac{1-\gamma_5}{2}\ell\, Y^*$	MSSM $\tilde{\ell}^-_{\mathrm{L}} \to \ell^- \tilde{B}^0$
3	0, **3**	$\frac{1}{2}$, **2**	**2**	$Z^\mu Y^* \overleftrightarrow{\partial_\mu} Y$	$\overline{X}\frac{1-\gamma_5}{2}\ell\, Y^*$	UED6 $W^-_{H,(1)} \to \ell^- \nu_{(1)}$
4	$\frac{1}{2}$, **1**	0, **1**	**1**	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1+\gamma_5}{2}\ell\, X$	UED6 $\ell^-_{S,(1)} \to \ell^- B^0_{H,(1)}$
5	$\frac{1}{2}$, **1**	0, **2**	**2**	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1-\gamma_5}{2}\ell\, X$	UED $\ell^-_{S,(1)} \to \ell^- H^0_{(1)}$
6	$\frac{1}{2}$, **1**	1, **1**	**1**	$\overline{Y}\not{Z}Y$	$\overline{Y}\not{X}\frac{1+\gamma_5}{2}\ell$	UED $\ell^-_{S,(1)} \to \ell^- B^0_{\mu,(1)}$
7	$\frac{1}{2}$, **2**	0, **1**	**2**	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1-\gamma_5}{2}\ell\, X$	UED6 $\ell^-_{D,(1)} \to \ell^- B^0_{H,(1)}$
8	$\frac{1}{2}$, **2**	0, **2**	**1**	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1+\gamma_5}{2}\ell\, X$	MSSM $\tilde{H}^- \to \ell^- \tilde{\nu}$
9	$\frac{1}{2}$, **2**	1, **1**	**2**	$\overline{Y}\not{Z}Y$	$\overline{Y}\not{X}\frac{1-\gamma_5}{2}\ell$	UED $\ell^-_{D,(1)} \to \ell^- B^0_{\mu,(1)}$
10	$\frac{1}{2}$, **3**	0, **2**	**2**	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1-\gamma_5}{2}\ell\, X$	MSSM $\tilde{W}^- \to \ell^- \tilde{\nu}$
11	1, **3**	$\frac{1}{2}$, **2**	**2**	$S[Z, Y, Y^*]$	$\overline{X}\not{Y}^*\frac{1-\gamma_5}{2}\ell$	UED $W^-_{\mu,(1)} \to \ell^- \nu_{(1)}$

Combination	4	5	6	7	8	9	10
$A_{\ell^+\ell^-}$	0.20	−0.22	0.13	0.17	−0.18	0.10	0.20

	Y $s,\ I_{SU(2)}$	X $s,\ I_{SU(2)}$	ℓ $I_{SU(2)}$	ZYY coupling	$XY\ell$ coupling	sample model and decay $Y^- \to \ell^- X$
1	0, **1**	$\frac{1}{2}$, **1**	**1**	$Z^\mu Y^* \overleftrightarrow{\partial_\mu} Y$	$\overline{X}\frac{1+\gamma_5}{2}\ell Y^*$	MSSM $\tilde{\ell}^-_R \to \ell^- \tilde{B}^0$
2	0, **2**	$\frac{1}{2}$, **1**	**2**	$Z^\mu Y^* \overleftrightarrow{\partial_\mu} Y$	$\overline{X}\frac{1-\gamma_5}{2}\ell Y^*$	MSSM $\tilde{\ell}^-_L \to \ell^- \tilde{B}^0$
3	0, **3**	$\frac{1}{2}$, **2**	**2**	$Z^\mu Y^* \overleftrightarrow{\partial_\mu} Y$	$\overline{X}\frac{1-\gamma_5}{2}\ell Y^*$	UED6 $W^-_{H,(1)} \to \ell^- \nu_{(1)}$
4	$\frac{1}{2}$, **1**	0, **1**	**1**	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1+\gamma_5}{2}\ell X$	UED6 $\ell^-_{S,(1)} \to \ell^- B^0_{H,(1)}$
5	$\frac{1}{2}$, **1**	0, **2**	**2**	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1-\gamma_5}{2}\ell X$	UED $\ell^-_{S,(1)} \to \ell^- H^0_{(1)}$
6	$\frac{1}{2}$, **1**	1, **1**	**1**	$\overline{Y}\not{Z}Y$	$\overline{Y}\not{X}\frac{1+\gamma_5}{2}\ell$	UED $\ell^-_{S,(1)} \to \ell^- B^0_{\mu,(1)}$
7	$\frac{1}{2}$, **2**	0, **1**	**2**	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1-\gamma_5}{2}\ell X$	UED6 $\ell^-_{D,(1)} \to \ell^- B^0_{H,(1)}$
8	$\frac{1}{2}$, **2**	0, **2**	**1**	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1+\gamma_5}{2}\ell X$	MSSM $\tilde{H}^- \to \ell^- \tilde{\nu}$
9	$\frac{1}{2}$, **2**	1, **1**	**2**	$\overline{Y}\not{Z}Y$	$\overline{Y}\not{X}\frac{1-\gamma_5}{2}\ell$	UED $\ell^-_{D,(1)} \to \ell^- B^0_{\mu,(1)}$
10	$\frac{1}{2}$, **3**	0, **2**	**2**	$\overline{Y}\not{Z}Y$	$\overline{Y}\frac{1-\gamma_5}{2}\ell X$	MSSM $\tilde{W}^- \to \ell^- \tilde{\nu}$
11	1, **3**	$\frac{1}{2}$, **2**	**2**	$S[Z, Y, Y^*]$	$\overline{X}\not{Y}^*\frac{1-\gamma_5}{2}\ell$	UED $W^-_{\mu,(1)} \to \ell^- \nu_{(1)}$

Combination	4	5	6	7	8	9	10
$A_{\ell^+\ell^-}$	0.20	−0.22	0.13	0.17	−0.18	0.10	0.20

	Y s, $I_{\mathrm{SU(2)}}$	X s, $I_{\mathrm{SU(2)}}$	ℓ $I_{\mathrm{SU(2)}}$	ZYY coupling	$XY\ell$ coupling	sample model and decay $Y^- \to \ell^- X$	
1	0, **1**	$\frac{1}{2}$, **1**	**1**	$Z^\mu Y^* \overleftrightarrow{\partial_\mu} Y$	$\overline{X}\frac{1+\gamma_5}{2}\ell\, Y^*$	MSSM	$\tilde{\ell}^-_{\mathrm{R}} \to \ell^- \tilde{B}^0$
2	0, **2**	$\frac{1}{2}$, **1**	**2**	$Z^\mu Y^* \overleftrightarrow{\partial_\mu} Y$	$\overline{X}\frac{1-\gamma_5}{2}\ell\, Y^*$	MSSM	$\tilde{\ell}^-_{\mathrm{L}} \to \ell^- \tilde{B}^0$
3	0, **3**	$\frac{1}{2}$, **2**	**2**	$Z^\mu Y^* \overleftrightarrow{\partial_\mu} Y$	$\overline{X}\frac{1-\gamma_5}{2}\ell\, Y^*$	UED6	$W^-_{H,(1)} \to \ell^- \nu_{(1)}$
4	$\frac{1}{2}$, **1**	0, **1**	**1**	$\overline{Y} \not{Z} Y$	$\overline{Y}\frac{1+\gamma_5}{2}\ell\, X$	UED6	$\ell^-_{S,(1)} \to \ell^- B^0_{H,(1)}$
5	$\frac{1}{2}$, **1**	0, **2**	**2**	$\overline{Y} \not{Z} Y$	$\overline{Y}\frac{1-\gamma_5}{2}\ell\, X$	UED	$\ell^-_{S,(1)} \to \ell^- H^0_{(1)}$
6	$\frac{1}{2}$, **1**	1, **1**	**1**	$\overline{Y} \not{Z} Y$	$\overline{Y}\not{X}\frac{1+\gamma_5}{2}\ell$	UED	$\ell^-_{S,(1)} \to \ell^- B^0_{\mu,(1)}$
7	$\frac{1}{2}$, **2**	0, **1**	**2**	$\overline{Y} \not{Z} Y$	$\overline{Y}\frac{1-\gamma_5}{2}\ell\, X$	UED6	$\ell^-_{D,(1)} \to \ell^- B^0_{H,(1)}$
8	$\frac{1}{2}$, **2**	0, **2**	**1**	$\overline{Y} \not{Z} Y$	$\overline{Y}\frac{1+\gamma_5}{2}\ell\, X$	MSSM	$\tilde{H}^- \to \ell^- \tilde{\nu}$
9	$\frac{1}{2}$, **2**	1, **1**	**2**	$\overline{Y} \not{Z} Y$	$\overline{Y}\not{X}\frac{1-\gamma_5}{2}\ell$	UED	$\ell^-_{D,(1)} \to \ell^- B^0_{\mu,(1)}$
10	$\frac{1}{2}$, **3**	0, **2**	**2**	$\overline{Y} \not{Z} Y$	$\overline{Y}\frac{1-\gamma_5}{2}\ell\, X$	MSSM	$\tilde{W}^- \to \ell^- \tilde{\nu}$
11	1, **3**	$\frac{1}{2}$, **2**	**2**	$S[Z, Y, Y^*]$	$\overline{X}\not{Y}^*\frac{1-\gamma_5}{2}\ell$	UED	$W^-_{\mu,(1)} \to \ell^- \nu_{(1)}$

Combination	4	5	6	7	8	9	10
$A_{\ell^+\ell^-}$	0.20	−0.22	0.13	0.17	−0.18	0.10	0.20

Summary and discussion

- Independent determinaton of particle masses, spins and couplings important for pinning down new physics at LHC

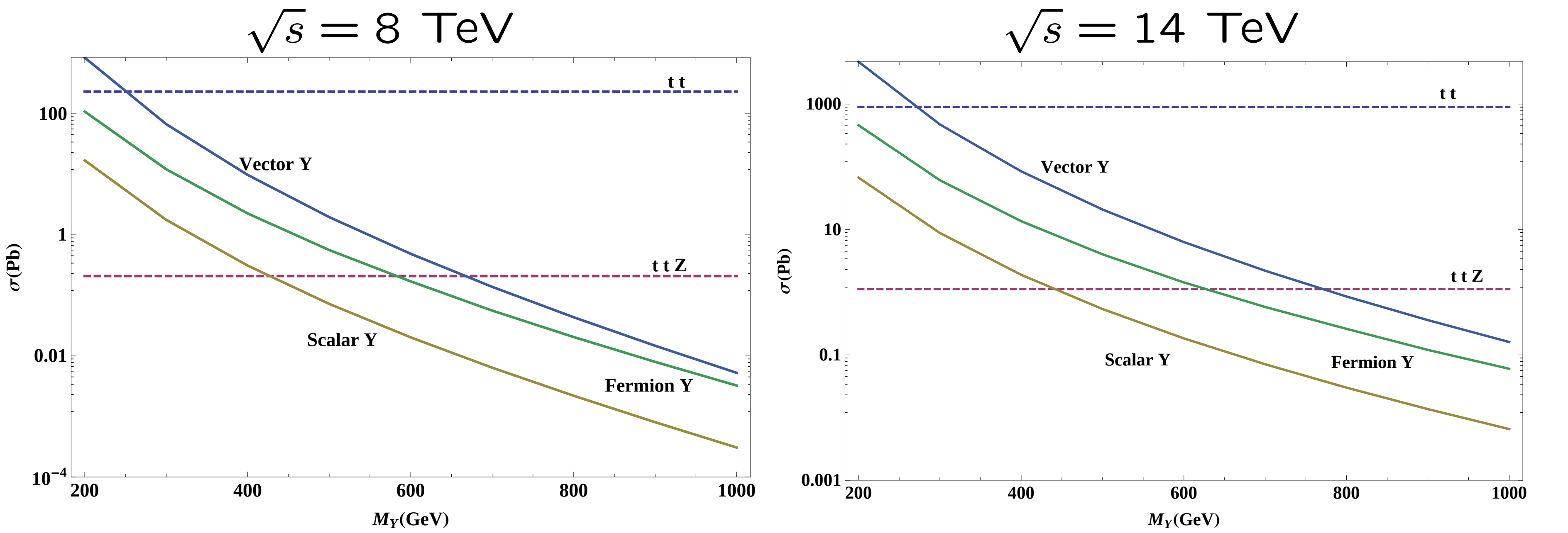
- Model-independent study of $pp \to Y^+Y^- \to \ell^+\ell^-\, X^0X^0$,
  $pp \to Y^+Y^- \to t\bar{t}\, X^0X^0$:
  - include all combinations with spin-0/$\frac{1}{2}$/1 particles
  - consider SU(2)-singlet/doublet/triplet reps. (for the leptonic case)
  - investigate variables for spin and coupling determination

- Most particle properties can be independently determined, although some ambiguity remains in some cases

- Systematic uncertainties could be important, in particular for the masses m_Y and m_X

Backup slides

Model cross sections



Model cross sections

Combination	σ_{prod} [fb]	σ_{meas} [fb]	sample model	
1	3.62	1.45	MSSM	$\tilde{\ell}^-_{\mathrm{R}} \to \ell^- \tilde{B}^0$
2	8.50	3.36	MSSM	$\tilde{\ell}^-_{\mathrm{L}} \to \ell^- \tilde{B}^0$
3	9.65	3.11	UED6	$W^-_{H,(1)} \to \ell^- \nu_{(1)}$
4	41.4	11.45	UED6	$\ell^-_{S,(1)} \to \ell^- B^0_{H,(1)}$
5	41.4	11.70	UED	$\ell^-_{S,(1)} \to \ell^- H^0_{(1)}$
6	41.4	14.05	UED	$\ell^-_{S,(1)} \to \ell^- B^0_{\mu,(1)}$
7	89.6	25.0	UED6	$\ell^-_{D,(1)} \to \ell^- B^0_{H,(1)}$
8	29.9	8.47	MSSM	$\tilde{H}^- \to \ell^- \tilde{\nu}$
9	89.6	31.4	UED	$\ell^-_{D,(1)} \to \ell^- B^0_{\mu,(1)}$
10	112	31.2	MSSM	$\tilde{W}^- \to \ell^- \tilde{\nu}$
11 [$M_{\hat{Q}}$=0.5 TeV]	179	48.3	UED	$W^-_{\mu,(1)} \to \ell^- \nu_{(1)}$
11 [$M_{\hat{Q}}$=1 TeV]	445	137		

Simulation for $\ell^+\ell^- + \not{E}$

Pass *CompHEP* events through *Pythia 6.4* Sjöstrand, Mrenna, Skands '06
and fast detector simulation *PGS4* Conway '06

$\longrightarrow$ include acceptance, smearing, and initial-state p_{T} kick

Cuts: Barr '05

$$N(\ell^+) = N(\ell^-) = 1, \qquad m_{\ell\ell} > 150 \text{ GeV},$$
$$\max\{p_{\mathrm{T},\ell^\pm}\} > 40 \text{ GeV}, \qquad \min\{p_{\mathrm{T},\ell^\pm}\} > 30 \text{ GeV},$$
$$\not{p}_{\mathrm{T}} > 100 \text{ GeV}, \qquad M_{\mathrm{T2}} > 100 \text{ GeV},$$
$$|\not{\mathbf{p}}_{\mathrm{T}} + \mathbf{p}_{\mathrm{T},\ell^+} + \mathbf{p}_{\mathrm{T},\ell^-}| < 100 \text{ GeV},$$
$$p_{\mathrm{T,j}} < 100 \text{ GeV}, \qquad N_b = 0$$

$\longrightarrow$ reduce the SM background rate to about 1.6 fb

$\longrightarrow$ signal efficiency for $pp \to Y^+Y^- \to \ell^+\ell^- XX$: 27%–40%

Typical (model-dependent) example: $\sigma_{\text{parton}} \sim 90$ fb, $\sigma_{\text{det}} \sim 25$ fb

$\longrightarrow$ $N_{\text{ev}} = 5000$ for $\mathcal{L} = 200 \text{ fb}^{-1}$

Simulation $t\bar{t} + \not{E}$

Pass *CompHEP* events through *Pythia 6.4* for showering and clustering

Basic cuts:

$$N_b = 2,\ \ E_\perp^b > 30\ \text{GeV} \qquad \Delta R_{jj}, \Delta R_{bj}, \Delta R_{bb} > 0.4,$$
$$N_j = 2,\ \ E_\perp^j > 25\ \text{GeV}, \qquad \Delta R_{\ell j}, \Delta R_{\ell b} > 0.3,$$
$$N_\ell = 1,\ \ E_\perp^\ell > 20\ \text{GeV},$$
$$70\ \text{GeV} < m_{jj} < 90\ \text{GeV}, \qquad 120\ \text{GeV} < m_{bjj} < 180\ \text{GeV}$$

Additional cuts:

	low $m_Y \sim 200$ GeV	interm. $m_Y \sim 400$ GeV	large $m_Y \sim 600$ GeV
$\sqrt{s} = 8$ TeV	—	$\not{E} > 200$ GeV $M_\perp^{\ell,\text{miss}} > 145$ GeV	$\not{E} > 300$ GeV $M_\perp^{\ell,\text{miss}} > 185$ GeV
$\sqrt{s} = 14$ TeV	—	—	$\not{E} > 350$ GeV $M_\perp^{\ell,\text{miss}} > 90$ GeV

Alternative approach: automated likelihood analysis

Matrix Element Method (MEM):

Kondo '88,'91
Dalitz, Goldstein '92
DØ collaboration '99,'04

Likelihood that measured event, $\mathbf{p}_i^{\text{vis}}$, agrees with theoretical matrix element M_α:

$$\mathcal{P}(\mathbf{p}_i^{\text{vis}}|\alpha) = \frac{1}{\sigma_\alpha} \int dx_1 dx_2 \, \frac{f_1(x_1) f_2(x_2)}{2 s x_1 x_2} \times \left[\prod_{i \in \text{final}} \int \frac{d^3 p_i}{(2\pi)^3 2E_i} \right] |M_\alpha(p_i)|^2 \prod_{i \in \text{vis}} \delta(\mathbf{p}_i - \mathbf{p}_i^{\text{vis}})$$

For sample of N events:

$$\chi^2 = -2 \ln(\mathcal{L}) = -2 \sum_{n=1}^{N} \ln \mathcal{P}(\mathbf{p}_{n,i}^{\text{vis}}|\alpha)$$

(+) Uses complete event information
(−) "Black box", no separation of properties like spin and couplings

MEM results (parton level)

$\sqrt{\chi^2}$ values for spin determinaton:

(model A, model B)				
(S,F)	(S,V) $[M_{\hat{Q}}=1]$	(S,V) $[M_{\hat{Q}}=0.5]$	(F,V) $[M_{\hat{Q}}=1]$	(F,V) $[M_{\hat{Q}}=0.5]$
60	59	61	85	87

Discrimination between models with fermion Y in standard deviations:

		model A					
		4	5	6	7	8	9
model B	5	**23**					
	6	3.3	**20**				
	7	*2.0*	**22**	*1.6*			
	8	**22**	*2.1*	19	**21**		
	9	3.7	19	*1.7*	3.3	17	
	10	*1.3*	**25**	4.1	*2.1*	**23**	5.3

- Significance for spin determination 60–85 (compared to 20–40 before)
- Significance for coupling determinaton similar to $A_{\ell^+\ell^-}$

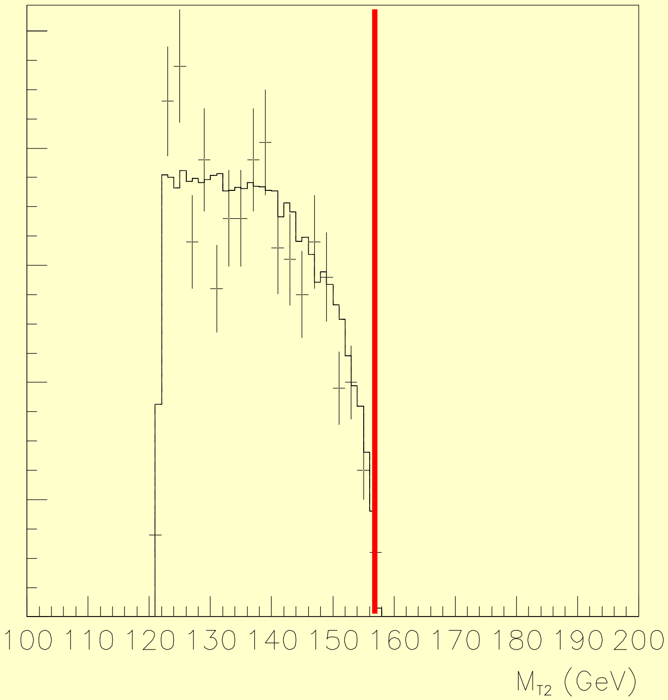
Mass determination

$$M_{\mathrm{T}2} = \min_{\mathbf{p}_{\mathrm{T},X_1}+\mathbf{p}_{\mathrm{T},X_2} = \not{p}_{\mathrm{T}}} \left\{ \max\left(m_{\mathrm{T}}^{\ell^+,X_1}, m_{\mathrm{T}}^{\ell^-,X_2} \right) \right\}$$

endpoint at m_Y if m_X known

Lester, Summers '99

Barr, Lester, Stephens '03



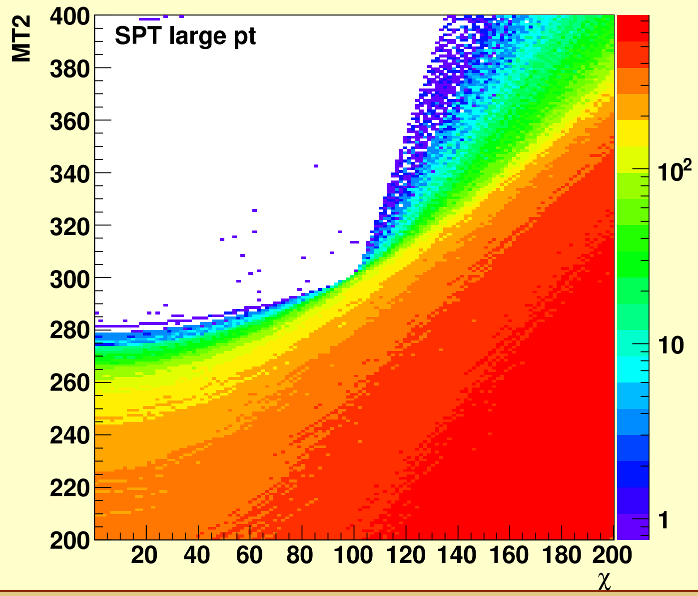
"Kink" for $M_{\mathrm{T}2}$ endpoints at tue m_X

Cho, Choi, Kim, Park '07,'08

Barr, Gripaios, Lester '07,'09

Tovey '08

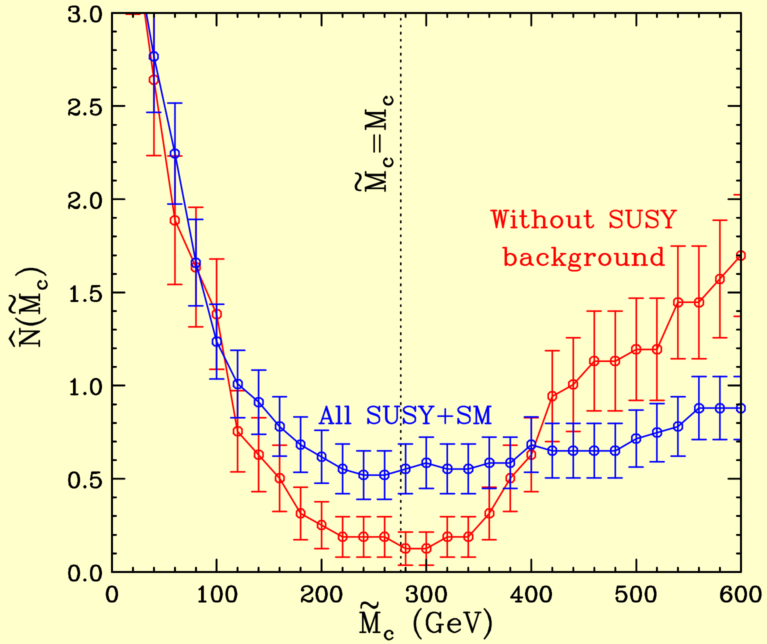
Cheng, Han '08



Mass determination

Variantes of M_{T2} using information from ISR

$\longrightarrow$ Determination of both m_X and m_Y possible



Matchev, Park ’09

Konar, Kong, Matchev, Park ’09

Polesello, Tovey ’09

Cohen, Kuflik, Zurek ’10

Spin determinaton: Results

- $\sqrt{s} = 14$ TeV, $m_Y = 300$ GeV, $m_X = 100$ GeV
- Generate events with *CompHEP* — Boos et al. '04
  pass through *Pythia 6.4* — Sjöstrand, Mrenna, Skands '06
  and fast detector simulation *PGS4* — Conway '06
- Selection cuts $\longrightarrow$ $N_{\text{ev}} = 300$–$27,000$ for $\mathcal{L} = 200$ fb^{-1}
  $\longrightarrow$ Assume $N_{\text{ev}} = 5000$ — Barr '05

Compare:
- Combination 3: scalar Y **(S)**
- Combination 10: fermion Y **(F)**
- Combination 11: vector Y **(V)**

$\sqrt{\chi^2}$ values from 5-bin test:

Variable	(S,F)	(S,V) $[M_{\hat{Q}}=1]$	(F,V) $[M_{\hat{Q}}=1]$
$\tanh(\Delta\eta_{\ell\ell}/2)$	23	**20**	6.3
M_{eff}	**40**	10	**37**