Fingerprinting natural new top quark physics at the LHC

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1. New physics at LHC and model dependence
2. Direct top partner production: $t\bar{t} + \not{E}$
3. Determination of particle properties
4. Top partner production via gluon partners: $t\bar{t}t\bar{t} + \not{E}$
5. Summary

New physics at LHC and model dependence

New physics at LHC and model dependence

Top sector is likely place for new physics:

- Yukawa coupling $y_t \gg y_{f \neq t}$
- New physics required to make Higgs mass parameter $\mu^2(\Lambda)$ natural until $\Lambda \gtrsim 10$ TeV

Generally need new (discrete) symmetry to avoid constraints from EW precision tests and flavor physics

$\longrightarrow$ Dark matter candidate

Examples:

SUSY:	R-parity	stop $\tilde{t}_{L,R}$	neutralino $\tilde{\chi}_1^0$
UED:	KK parity	KK-top $t_{L,R}^{(1)}$	KK-hyperboson $B^{(1)}$
Little Higgs:	T-parity	top partner $T^{(\prime)}$	T-odd hyperboson B_H

- many other conceivable and inconceivable possibilities...

Bottom-up approach

If new physics discovered:

$\longrightarrow$ Need to determine **all** particle properties:

- Masses
- Spins
- Gauge interactions:
  - electromagnetic charge
  - color charge
  - weak charge
- Flavor structure

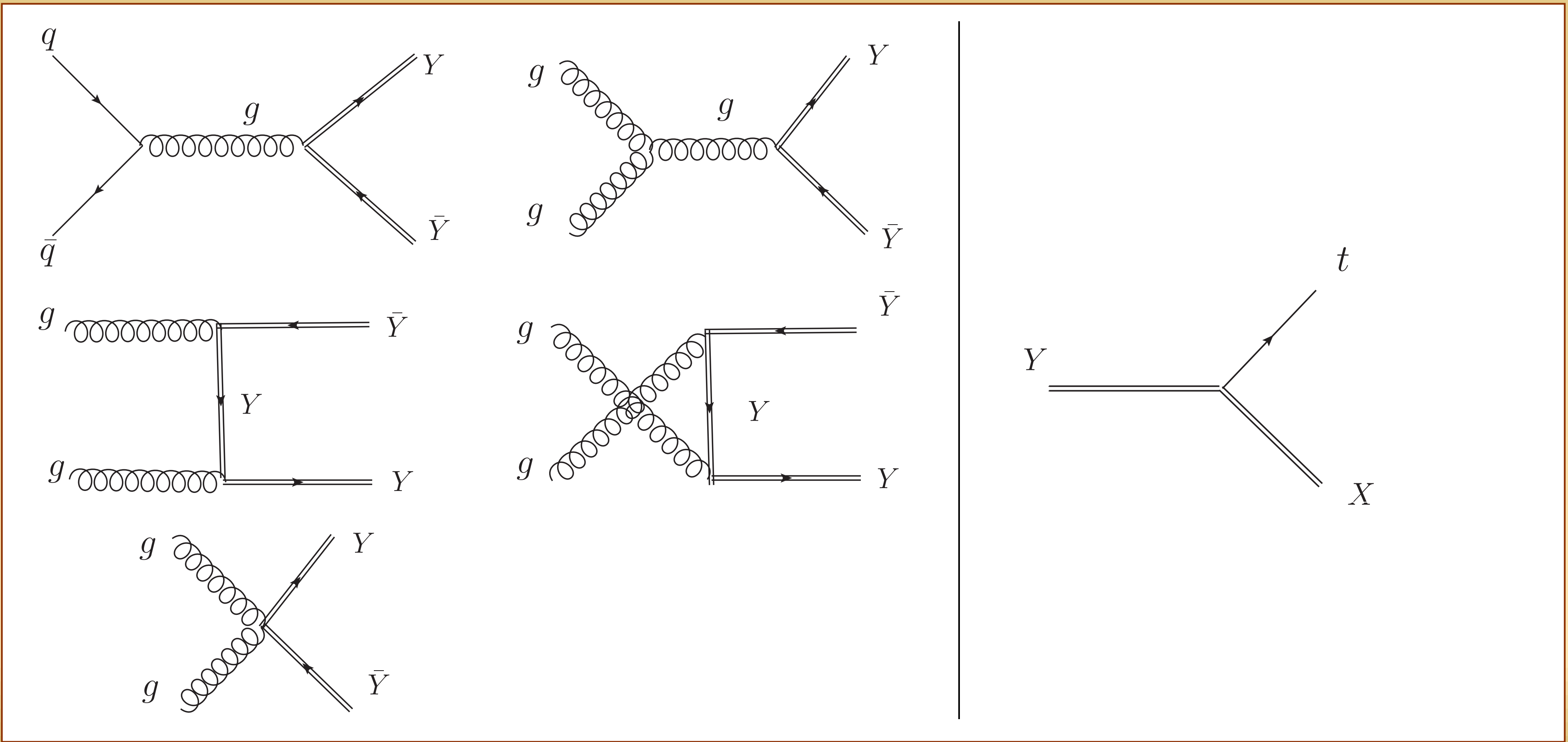
Framework

Simplified model class A:

Top partner Y and **neutral DM candidate X**

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

→ Signature $t\bar{t} + \not{E}$



Framework

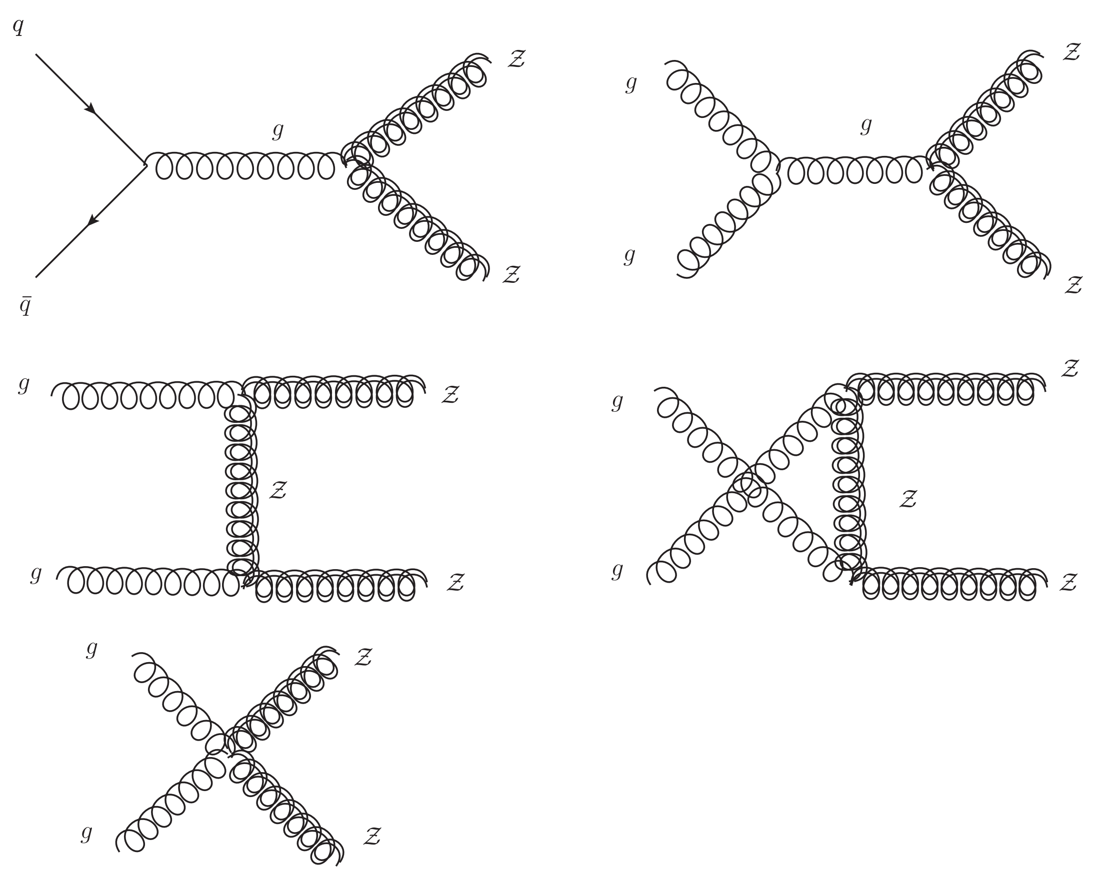
Simplified model class B:

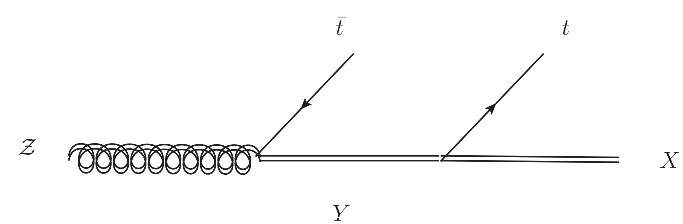
Gluon partner $\mathcal{Z}$, Top partner Y and **neutral DM candidate X**

→ Motivated by naturalness to cancel 2-loop correction to M_{H}

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

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





Framework

Consider all spin assignments $(0, \frac{1}{2}, 1)$ for X and Y

	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 $\tilde{t} \to t\, \tilde{\chi}_1^0$
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**	$S_3[G, Y, Y^*]$	$\overline{X} \not{Y}^*(a_L P_L + a_R P_R) t$	SUSY $\vec{Q} \to t\tilde{\chi}_0$

Cai, Cheng, Terning '08

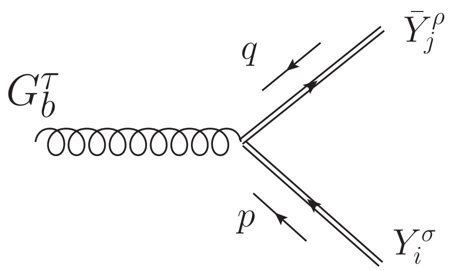
Chirality of decay coupling depends on weak charge: SU(2) singlet/doublet/mixed

$$S_3[G, Y, Y^*] \equiv G_\mu\, Y^*_\nu \overleftrightarrow{\partial^\mu} Y^\nu + Y_\mu\, G_\nu \overleftrightarrow{\partial^\mu} Y^{*\nu} + Y^*_\mu\, Y_\nu \overleftrightarrow{\partial^\mu} G^\nu$$

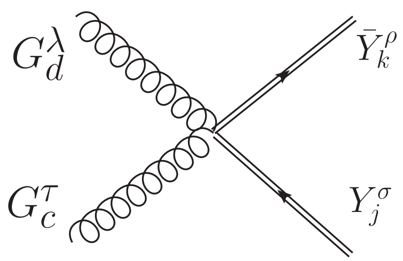
Framework

Vector top partners:

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



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



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

Framework

Consider all spin assignments (0, $\frac{1}{2}$, 1) for $\mathcal{Z}$

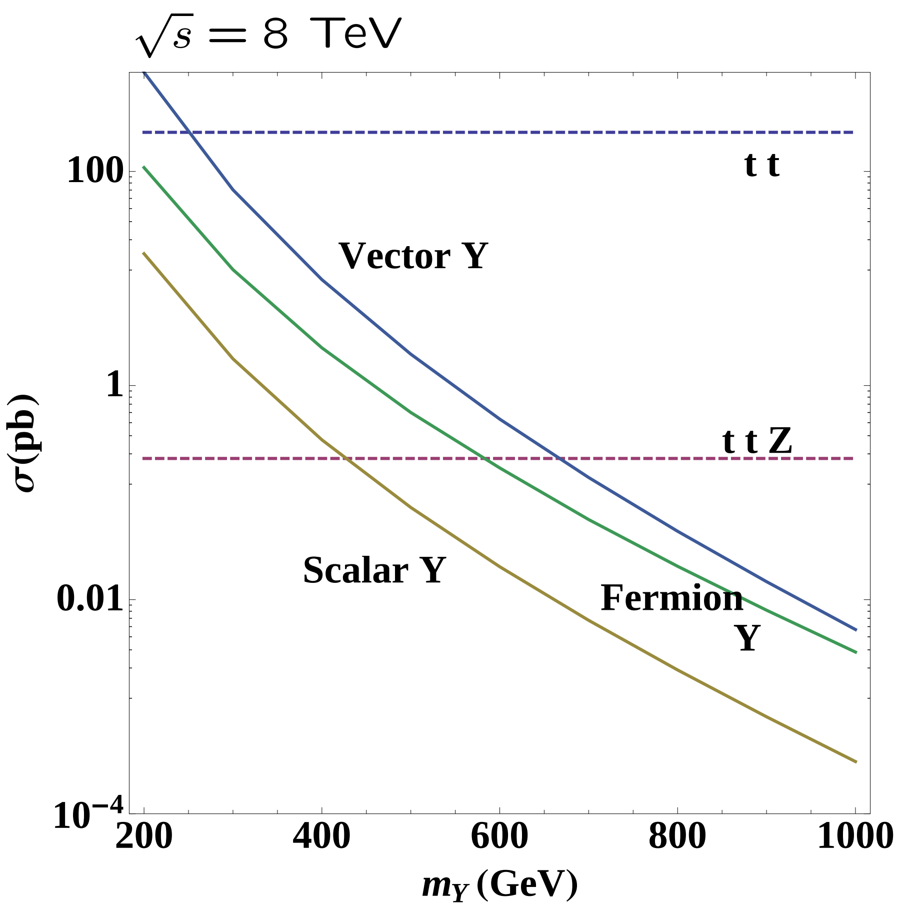
	$\mathcal{Z}$ $s, I_{\mathrm{SU(3)}}$	Y $s, I_{\mathrm{SU(3)}}$	$G\mathcal{Z}\mathcal{Z}$ coupling	$\mathcal{Z}Yt$ coupling	sample model and decay $\mathcal{Z} \to tX$
v	0, **8**	$\frac{1}{2}$, **3**	$G^a_\mu \mathcal{Z}^c \overleftrightarrow{\partial}^\mu \mathcal{Z}^b f^{abc}$	$\overline{Y}\frac{\lambda^a}{2}(b_L P_L + b_R P_R)t\, \mathcal{Z}^a$	UED $g_{H,1} \to t_1 \bar{t}$
vi	$\frac{1}{2}$, **8**	0, **3**	$\overline{\mathcal{Z}}^c \not{G}^a \mathcal{Z}^b f^{abc}$	$\overline{\mathcal{Z}}^a Y^* \frac{\lambda^a}{2}(b_L P_L + b_R P_R)t$	SUSY $\tilde{g} \to \tilde{t}\bar{t}$
	$\frac{1}{2}$, **8**	0, **3**	$\overline{\mathcal{Z}}^c_D \not{G}^a \mathcal{Z}^b_D f^{abc}$	$(\overline{\mathcal{Z}}^a_D)^* Y^* \frac{\lambda^a}{2} b_L P_L t + \overline{\mathcal{Z}}^a_D Y^* \frac{\lambda^a}{2} b_R P_R t$	N=2 SUSY $\tilde{g}_D \to \tilde{t}\bar{t}$
vii	$\frac{1}{2}$, **8**	1, **3**	$\overline{\mathcal{Z}}^c \not{G}^a \mathcal{Z}^b f^{abc}$	$\overline{\mathcal{Z}}^a \not{Y}^* \frac{\lambda^a}{2}(b_L P_L + b_R P_R)t$	SUSY $\tilde{g} \to \vec{Q}\bar{t}$
viii	1, **8**	$\frac{1}{2}$, **3**	$S_8[G, \mathcal{Z}, \mathcal{Z}]$	$\overline{Y}\not{\mathcal{Z}}^a \frac{\lambda^a}{2}(b_L P_L + b_R P_R)t$	UED $g_1 \to t_1 \bar{t}$

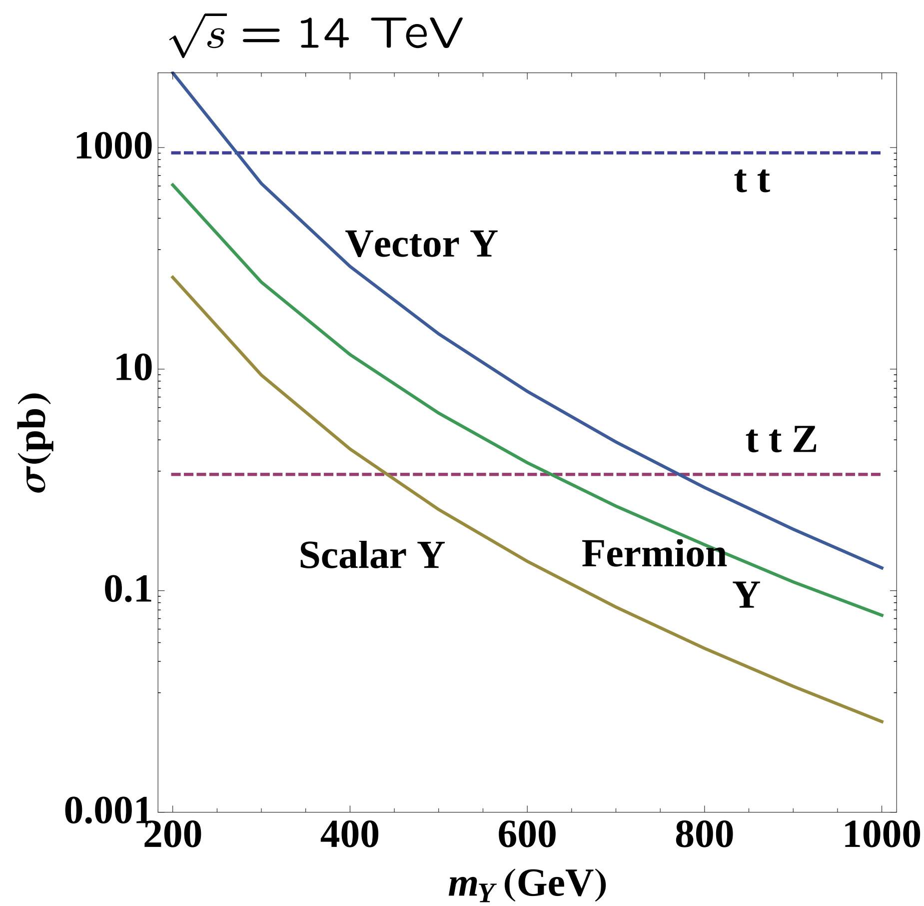
$$S_8[G, Y, Y^*] \equiv f^{abc}\left[G^a_\mu \mathcal{Z}^{c*}_\nu \overleftrightarrow{\partial}^\mu \mathcal{Z}^{b\nu} + \mathcal{Z}^b_\mu G^a_\nu \overleftrightarrow{\partial}^\mu \mathcal{Z}^{c\nu*} + \mathcal{Z}^{c*}_\mu \mathcal{Z}^b_\nu \overleftrightarrow{\partial}^\mu G^{a\nu}\right]$$

Case vi: option with Majorana or Dirac octet fermion

Direct top partner production: $t\bar{t} + \not{E}$

Production cross sections:





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

- $pp \to Y\bar{Y} \to tX\bar{t}X \to bj_1j_2\bar{b}\ell^-\bar{\nu}_\ell XX + \text{h.c.}\,, \qquad (\ell = e, \mu).$
- Generate events with *CalcHEP*+*Pythia* Pukhov, Belyaev, Christensen '11
  Sjöstrand, Mrenna, Skands '06

Basic cuts:

$$N_b = 2,\quad E_\perp^b > 30 \text{ GeV} \qquad \Delta R_{jj}, \Delta R_{bj}, \Delta R_{bb} > 0.4,$$
$$N_j = 2,\quad E_\perp^j > 25 \text{ GeV}, \qquad \Delta R_{\ell j}, \Delta R_{\ell b} > 0.3,$$
$$N_\ell = 1,\quad E_\perp^\ell > 20 \text{ GeV},$$

$\not{E} > 25$ GeV, $\quad 70 \text{ GeV} < m_{jj} < 90 \text{ GeV}, \quad 120 \text{ GeV} < m_{bjj} < 180$ GeV

Additional cuts for large $m_Y \gtrsim 600$ GeV ($\sqrt{s} = 14$ TeV):

$\not{E} > 350$ GeV, $\qquad M_\perp^{\ell,\text{miss}} > 90$ GeV

Signal reach

- $pp \to Y\bar{Y} \to tX\bar{t}X \to bj_1j_2\bar{b}\ell^-\bar{\nu}_\ell XX$ + h.c. , $\quad (\ell = e, \mu)$.
- Generate events with *CalcHEP+Pythia* Pukhov, Belyaev, Christensen '11
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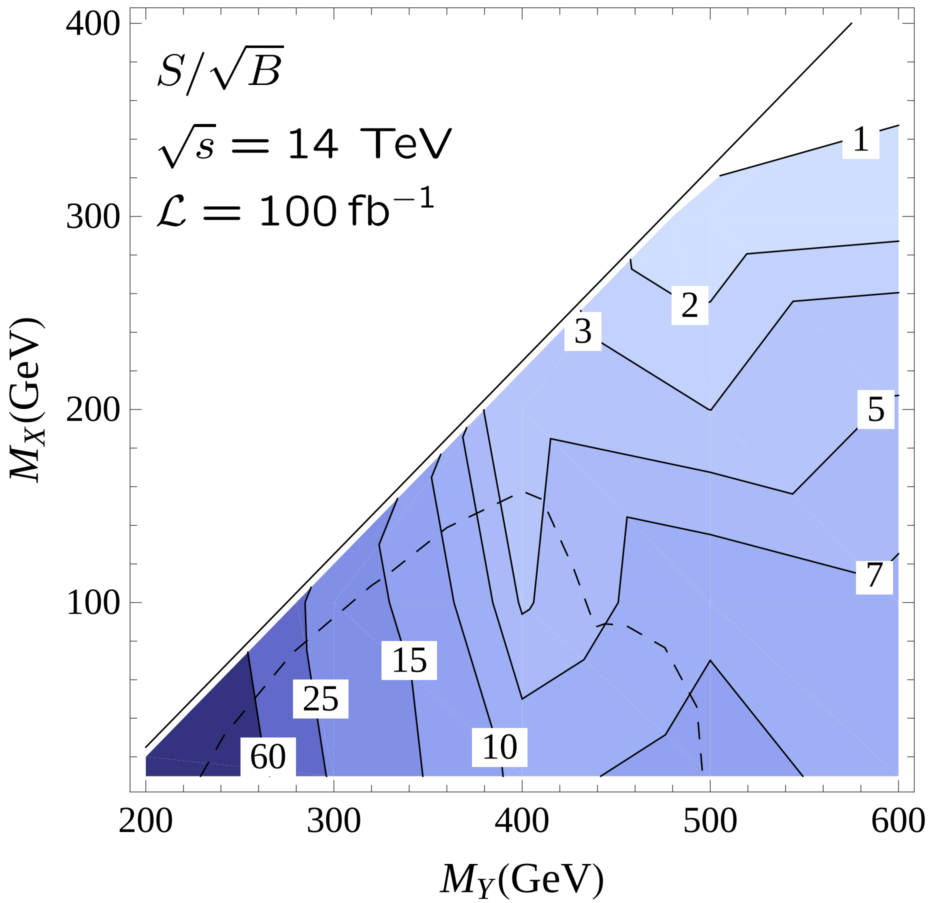


Discovery reach
(14 TeV, 100 fb^{-1}):

scalar Y: $m_Y < 675$ GeV
fermion Y: $m_Y < 945$ GeV

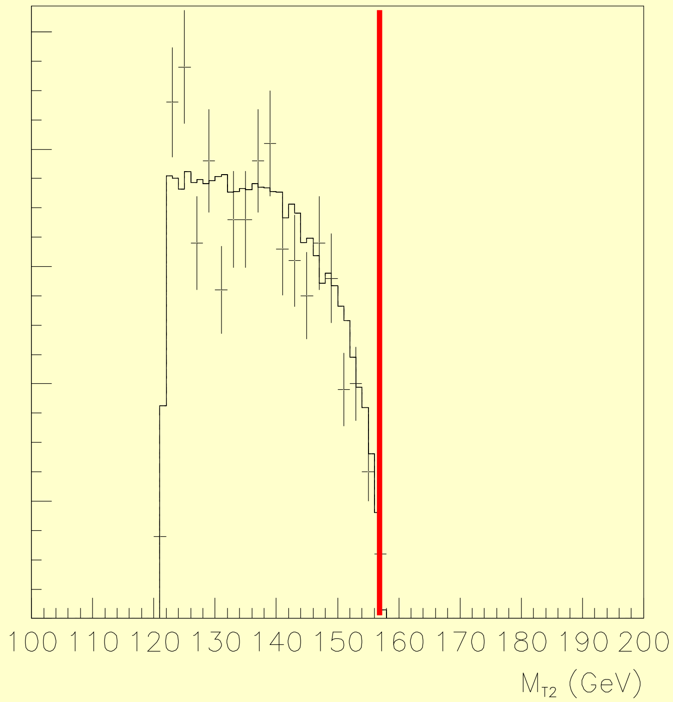
See also:
Han, Mahbubani, Walker, Wang '09
Plehn, Spannowsky, Takeuchi '11,12
Bai, Cheng, Gallicchio, Gu '12
Alves, Buckley, Fox, Lykken, Yu '12
Han, Katz, Krohn, Reece '12
Kaplan, Rehermann, Stolarski '12
Cao, Han, Wu, Yang, Zhang '12
ALTAS, CMS '12,14
etc...

Determination of particle properties

Mass determination

$$M_{\mathsf{T2}} = \min_{\substack{\mathbf{p}_{\mathsf{T},\mathsf{X}_1} + \mathbf{p}_{\mathsf{T},\mathsf{X}_2} \\ = \not{\mathbf{p}}_{\mathsf{T}}}} \left\{ \max\left(m_{\mathsf{T}}^{t,X_1}, m_{\mathsf{T}}^{\bar{t},X_2} \right) \right\}$$

endpoint at m_Y if m_X known



Lester, Summers '99

Barr, Lester, Stephens '03

$\longrightarrow$ $\mathcal{O}(\%)$ determination of $m_Y - m_X$

$\longrightarrow$ No reliable determination of overall mass scale

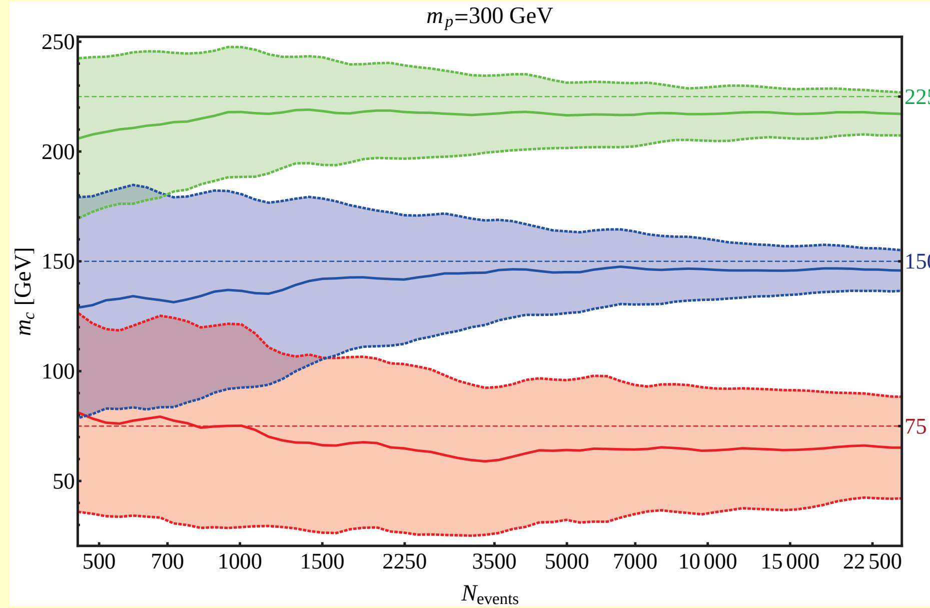
Mass determination

Variants of M_{T2} using ISR

$\longrightarrow$ Determine m_X **and** m_Y

$\longrightarrow$ For $m_Y \sim \mathcal{O}(300~\text{GeV})$: $\delta m_Y \sim 20\text{–}30\%$

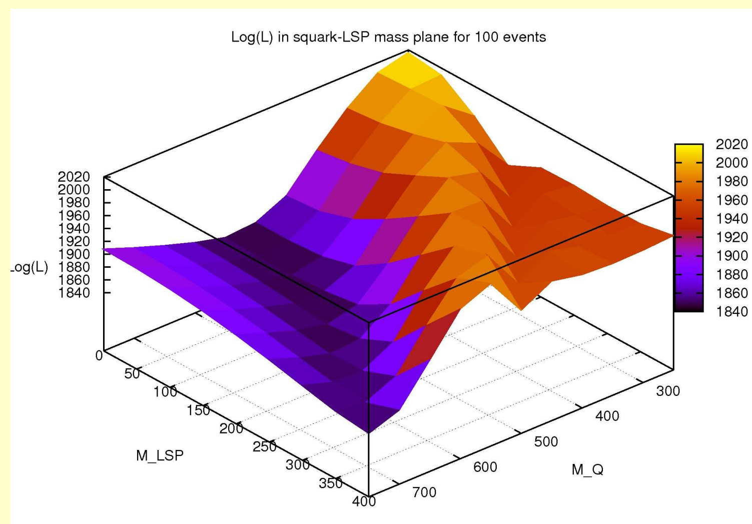
Matchev, Park '09
Konar, Kong, Matchev, Park '09
Polesello, Tovey '09
Cohen, Kuflik, Zurek '10



Likelihood fit to all event information in a sample (Matrix Element Method), ignoring ISR

$\longrightarrow$ For $m_Y \sim \mathcal{O}(300~\text{GeV})$: $\delta m_Y \sim 20\text{–}30\%$

Kondo '88,91; DØ '99,04
Alwall, Freitas, Mattelaer '09



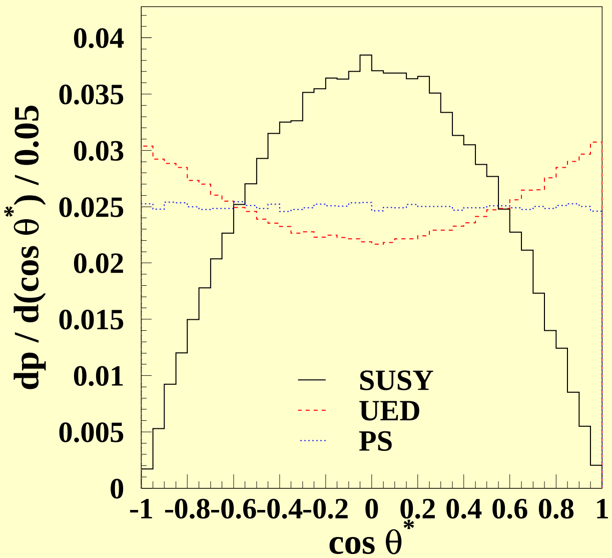
Spin determinaton: $\tanh(\Delta y_{t\bar{t}}/2)$

For $q\bar{q} \to Y\bar{Y}$ channel:

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

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

vector Y: (dominant) partial S-wave
$\longrightarrow$ similar to fermion



Barr '05

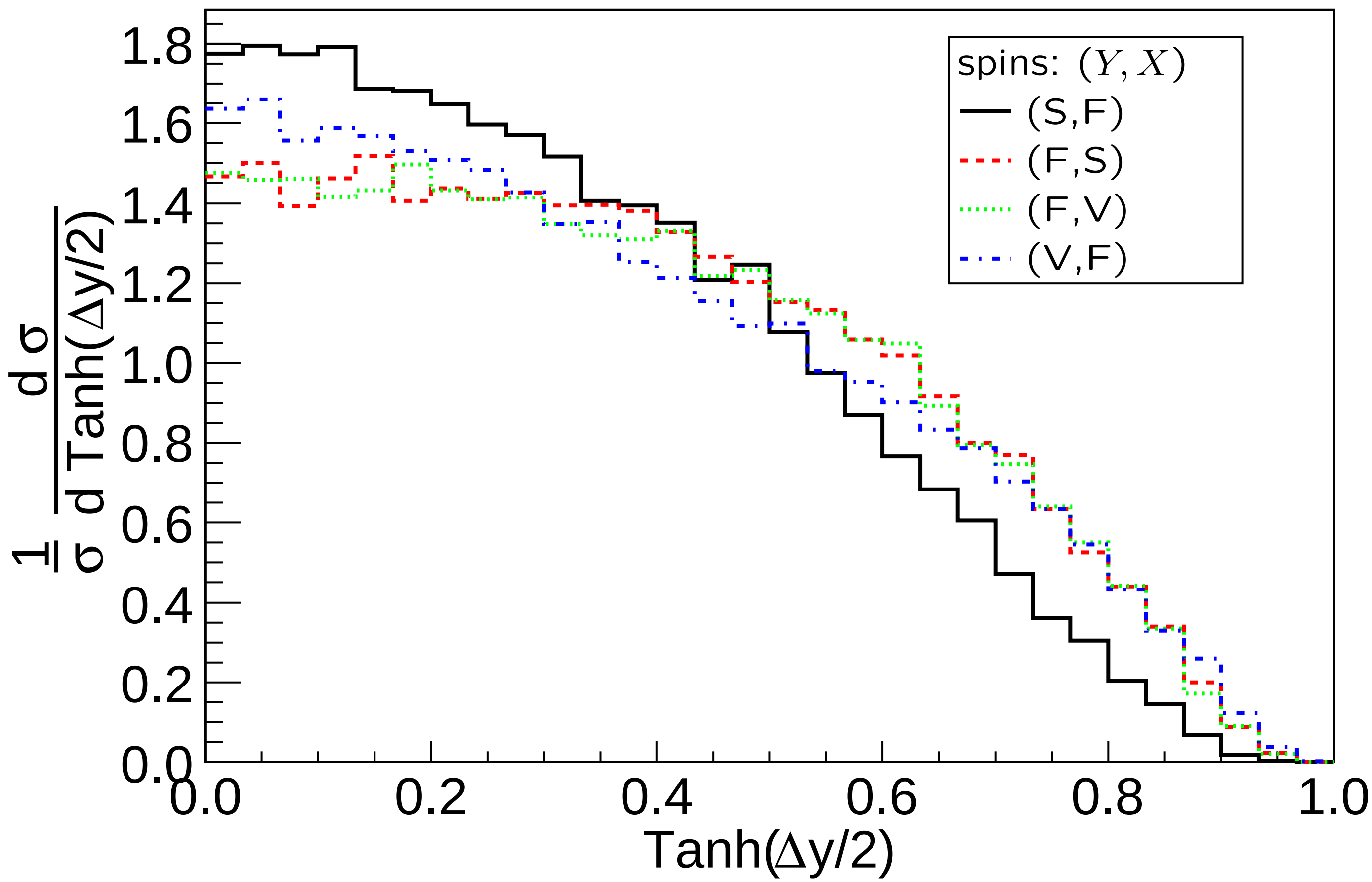
For $m_Y \sim$ few 100 GeV: $Y^\pm$ produced with boost
$\longrightarrow$ vis. decay products mostly go in same direction as $Y^\pm$

$$\longrightarrow \quad \tanh\frac{\Delta y_{t\bar{t}}}{2} \equiv \tanh\frac{|y_{bjj} - y_{bl}|}{2} \quad \text{correlated to} \quad \tanh\frac{|y_Y - y_{\bar{Y}}|}{2} = \cos\theta^*$$

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

Observable:

$\tanh(\Delta y_{t\bar{t}}/2)$, $\Delta y_{t\bar{t}} \equiv |y_{bjj} - y_{b\ell}|$ correlated to prod. angle



$m_Y = 300$ GeV

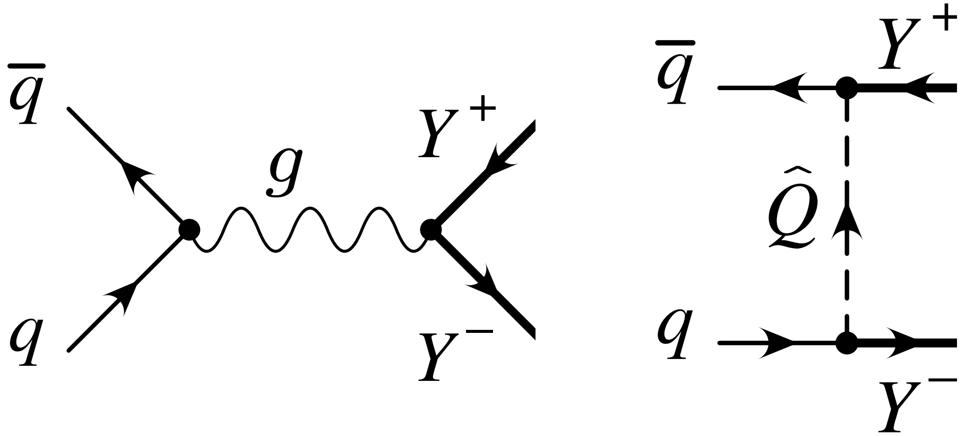
$m_X = 100$ GeV

Spin determinaton: $M_{\rm eff}$

vector Y: $\sigma(m_{YY})$ grows indefinitely if $m_{YY} \to \infty$

perturbative unitarity: t-channel particle $\hat{Q}$ required with $m_{\hat{Q}} \lesssim$ 5 TeV
$\longrightarrow$ may be beyond LHC reach

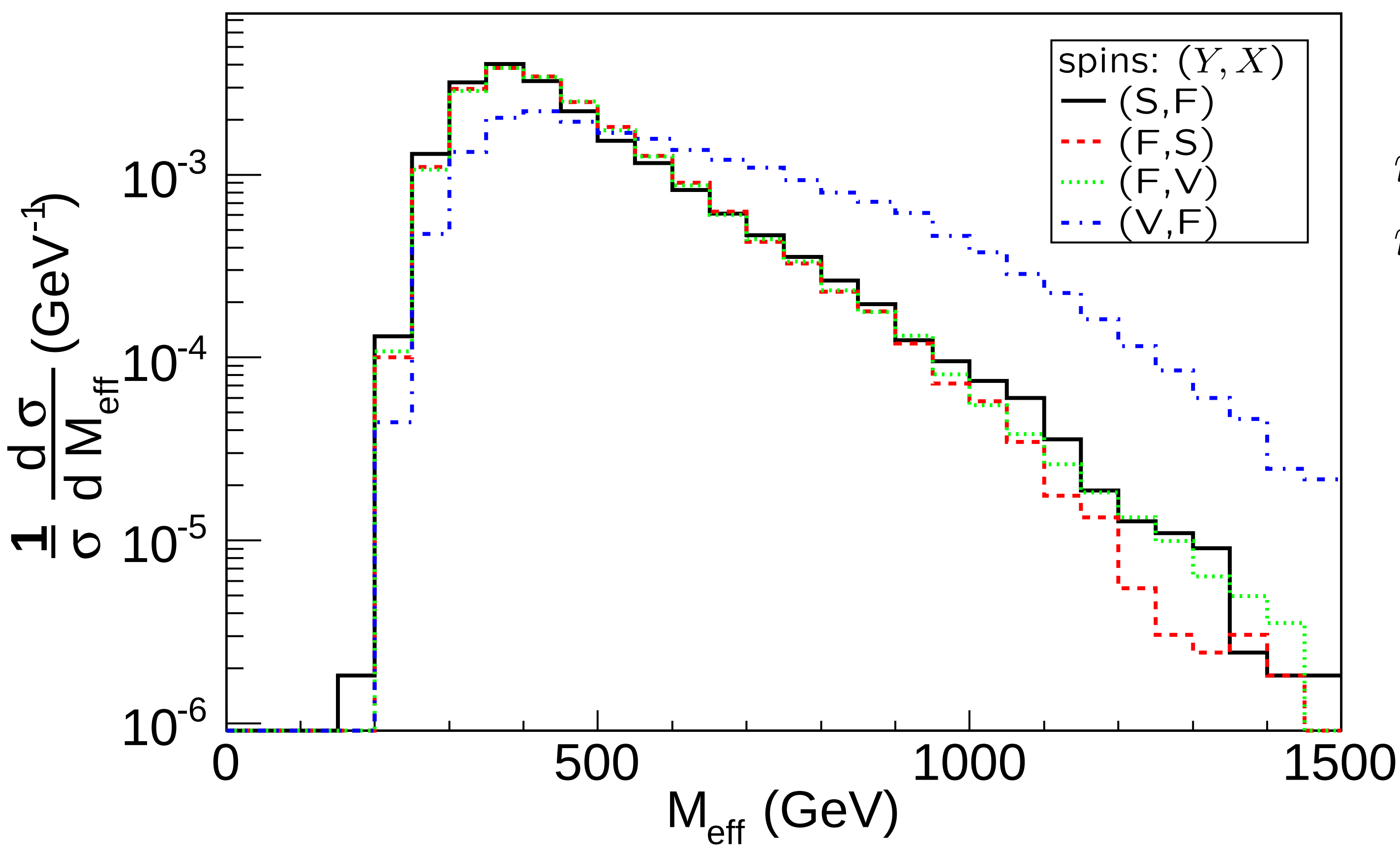
$\longrightarrow$ long tail for large m_{YY}



Spin determinaton: M_{eff}

vector Y: long tail for large m_{YY}

Observable: $M_{\text{eff}} = \sum_{i \in \text{vis.}} p_{\text{T},i} + \not{p}_{\text{T}}$ correlated to m_{YY}



$m_Y = 300$ GeV

$m_X = 100$ GeV

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 at 14 TeV [in fb^{-1}]:

Variable	(S,F)	(S,V)	(F,V)
$\tanh(\Delta y_{t\bar{t}}/2)$	9.4	160	9.9
M_{eff}	330	0.8	0.7

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

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- Including mass uncertainty: $\delta(m_Y - m_X) \lesssim 5\%$, $\delta m_Y \approx 30\%$

  $\longrightarrow$ increase $\mathcal{L}_{5\sigma}$ by roughly 50%

Spin determinaton: Results

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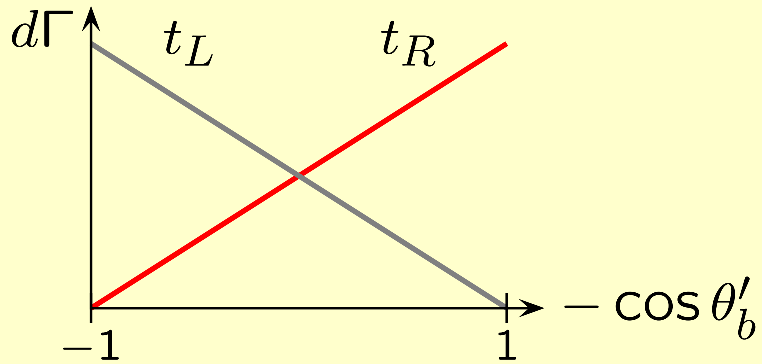
- No good handle on spin of DM candidate X — Chen, Freitas '10

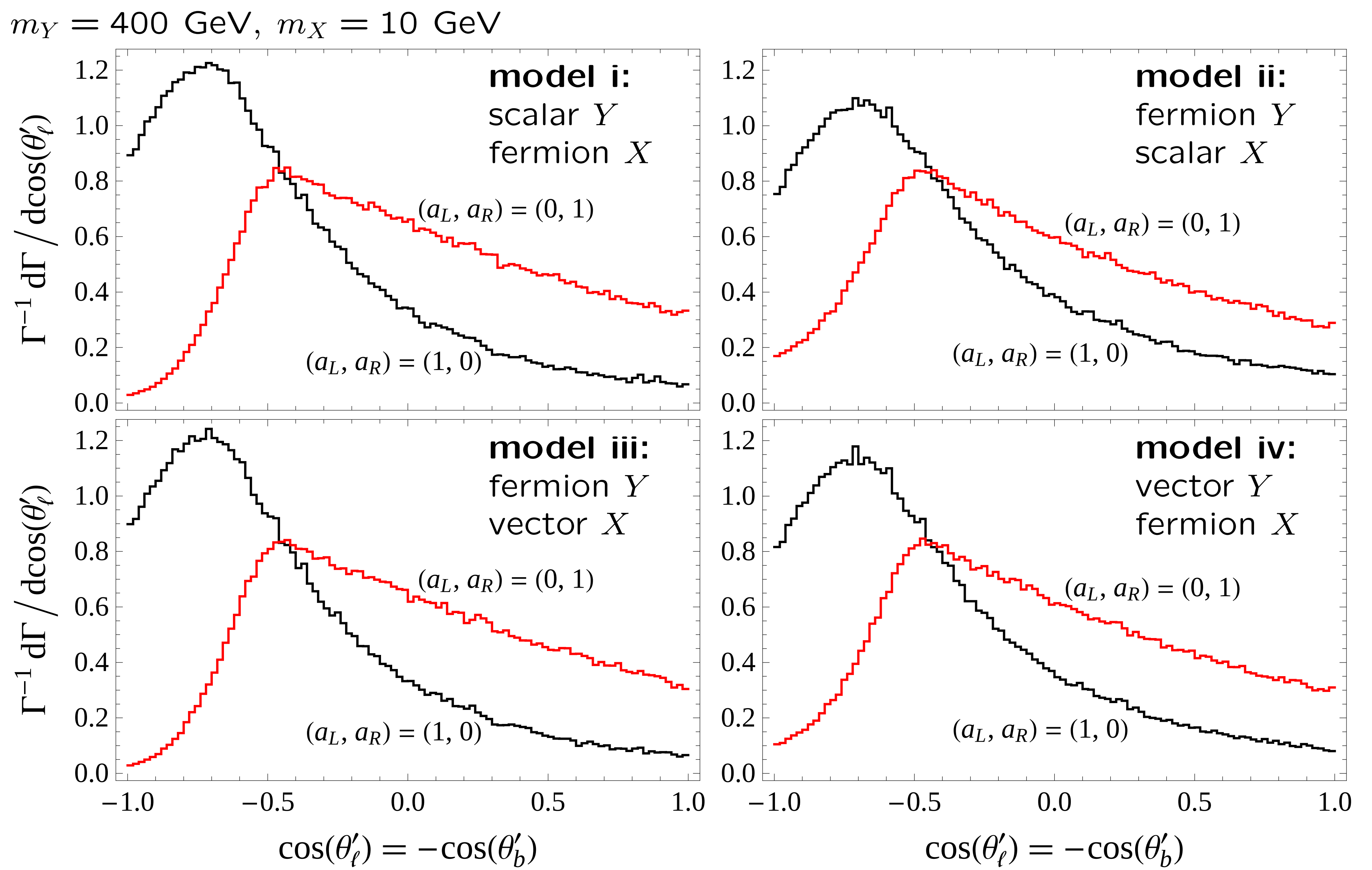
Coupling determinaton: top polarization

- QCD dictates 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



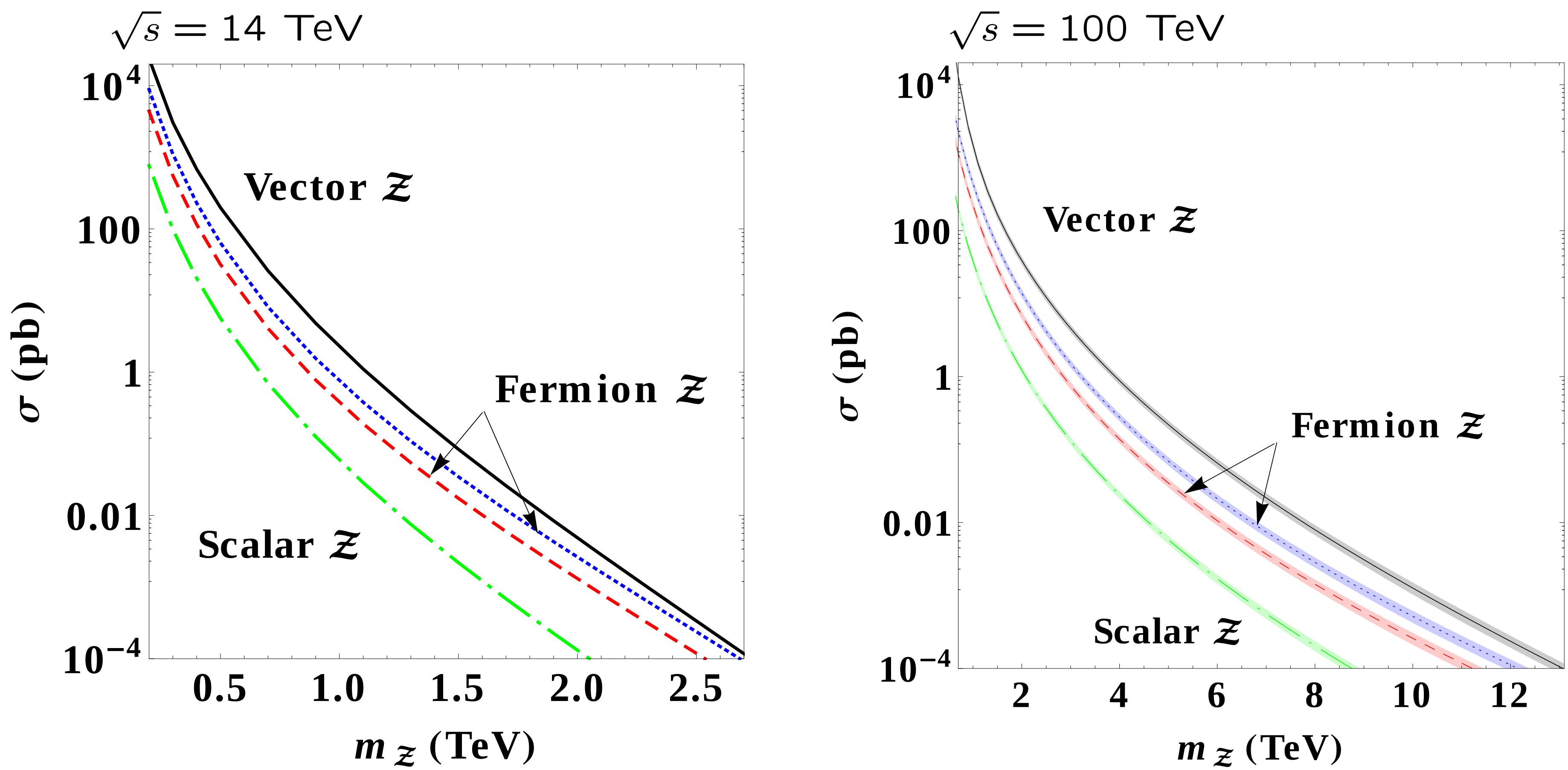
- For $t \to b\ell\nu$: angle θ_b' of b-quark with respect to $b\ell$ boost direction in $b\ell$ rest frame
- Distortion due to imperfect reconstruction and possible helicity flip

Coupling determinaton: Results



Top partner production via gluon partners: $t\bar{t}t\bar{t} + \not{E}$

Production cross sections:



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

- $pp \to \mathcal{Z}\bar{\mathcal{Z}} \to t\bar{Y}\bar{t}Y \to t\bar{t}t\bar{t}XX \to 4b + \text{jets} + \ell^{\pm}\ell'^{\pm}\nu\nu XX\,,\qquad (\ell = e, \mu).$
- Generate events with *CalcHEP+Pythia* Pukhov, Belyaev, Christensen '11
  Sjöstrand, Mrenna, Skands '06

Basic cuts:

$N_b \geq 2,\ \ E_\perp^b > 30$ GeV $\qquad \Delta R_{jj}, \Delta R_{bj}, \Delta R_{bb} > 0.4,$

$N_j \geq 2,\ \ E_\perp^j > 25$ GeV, $\qquad \Delta R_{\ell\ell}, \Delta R_{\ell j}, \Delta R_{\ell b} > 0.3,$

$N_\ell = 2,\ \ E_\perp^\ell > 20$ GeV, same charge

Additional cuts:

SR A: $\not{E} > 150$ GeV, $\quad m_T(\ell_1, \not{p}_T) > 700$ GeV, $\quad m_{\text{eff}} > 700$ GeV

SR B: $N_j \geq 4, \quad N_b \geq 3$

Signal reach

- $pp \to \mathcal{Z}\bar{\mathcal{Z}} \to t\bar{Y}\bar{t}Y \to t\bar{t}t\bar{t}XX \to 4b + \text{jets} + \ell^{\pm}\ell'^{\pm}\nu\nu XX\,, \qquad (\ell = e, \mu).$
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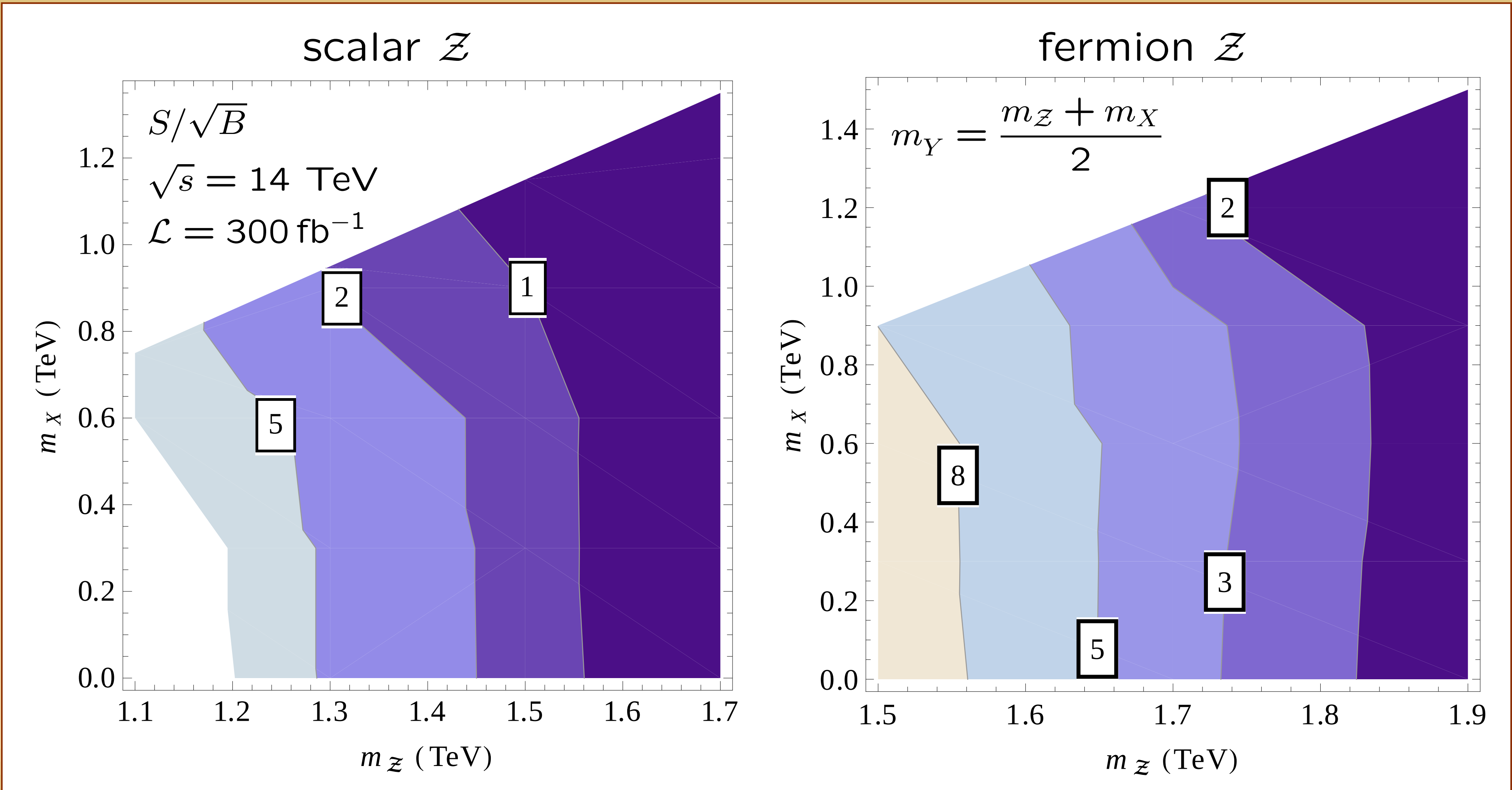

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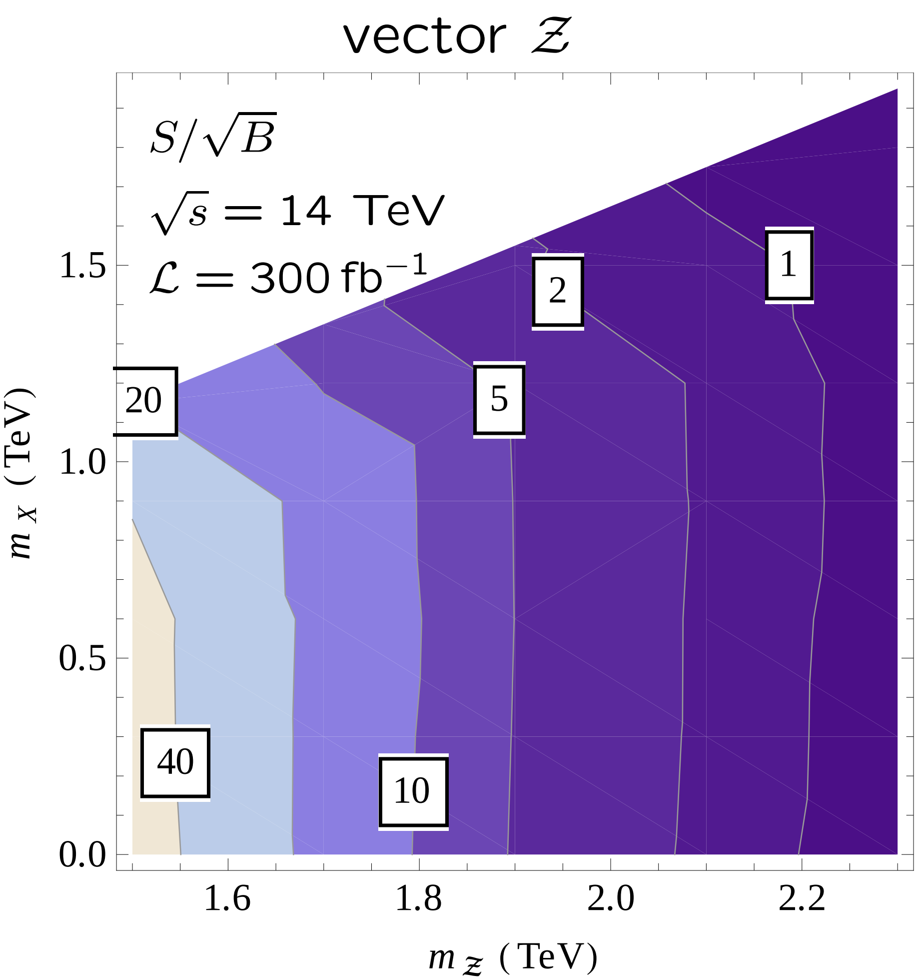
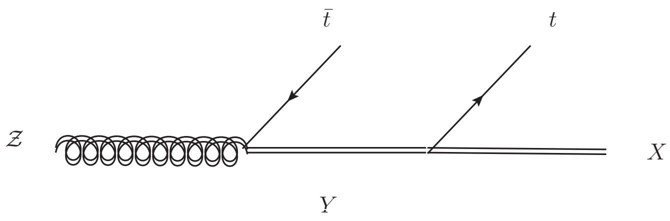


Discovery reach for gluon partner at 14 TeV [in TeV]: (assuming $m_X < 300$ GeV)

	spin 0	spin $\frac{1}{2}$	spin 1
$300\ \text{fb}^{-1}$	1.28	1.65	1.9
$3000\ \text{fb}^{-1}$	1.48	1.86	2.1

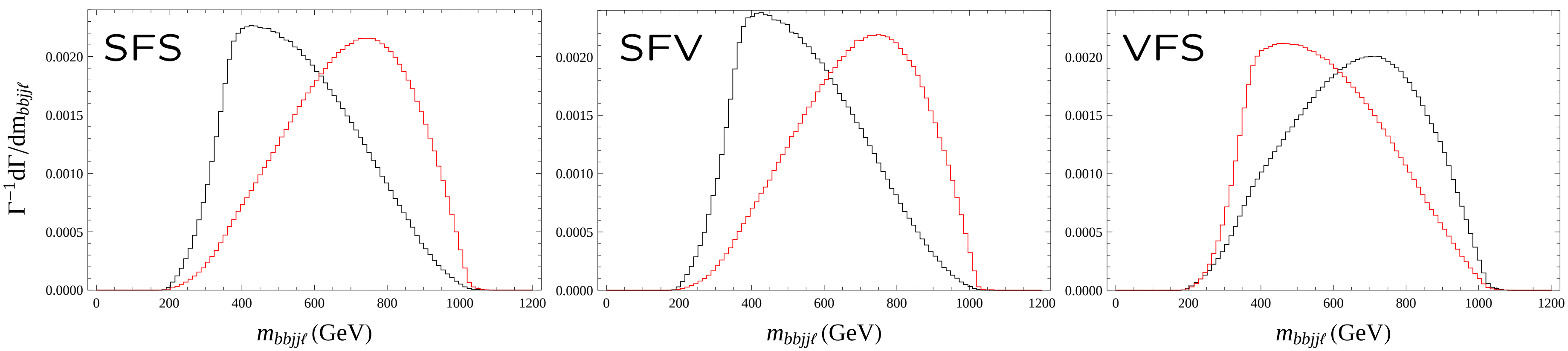
Spin determination

- m_{tt} inv. mass in $\mathcal{Z} \to t\bar{t}X$ sensitive to spins of $X, Y, \mathcal{Z}$



Smillie, Webber '05
Athanasiou, Lester, Smillie, Webber '06
Kilic, Wang, Yavin '07
Burns, Kong, Matchev, Park '08

- For $t\bar{t} \to bbjj\ell\nu$, m_{tt} cannot be reconstructed due to missing neutrino
  $\longrightarrow$ Use visible system $m_{bbjj\ell}$ instead



Black: $\mathcal{Z} \to t_{L/R}\bar{t}_{R/L}X$ Red: $\mathcal{Z} \to t_{L/R}\bar{t}_{L/R}X$
(chirality from top polarization measurement)

Spin determination

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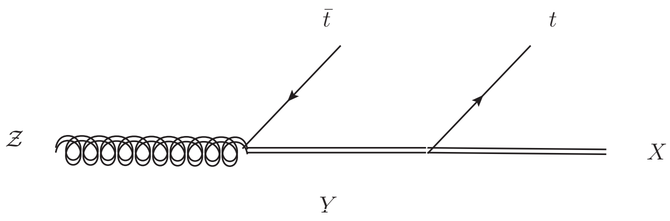

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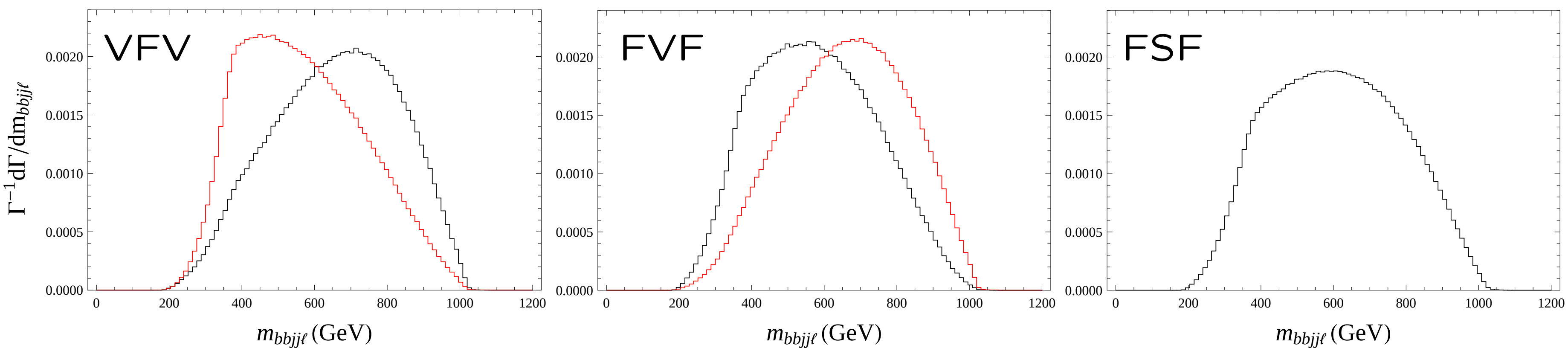

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(chirality from top polarization measurement)

Spin determinaton: Results

- $m_{\mathcal{Z}} = 1200$ GeV, $m_Y = 600$ GeV, $m_X = 100$ GeV
- Cross section for fermion $\mathcal{Z}$
- Selection cuts as before

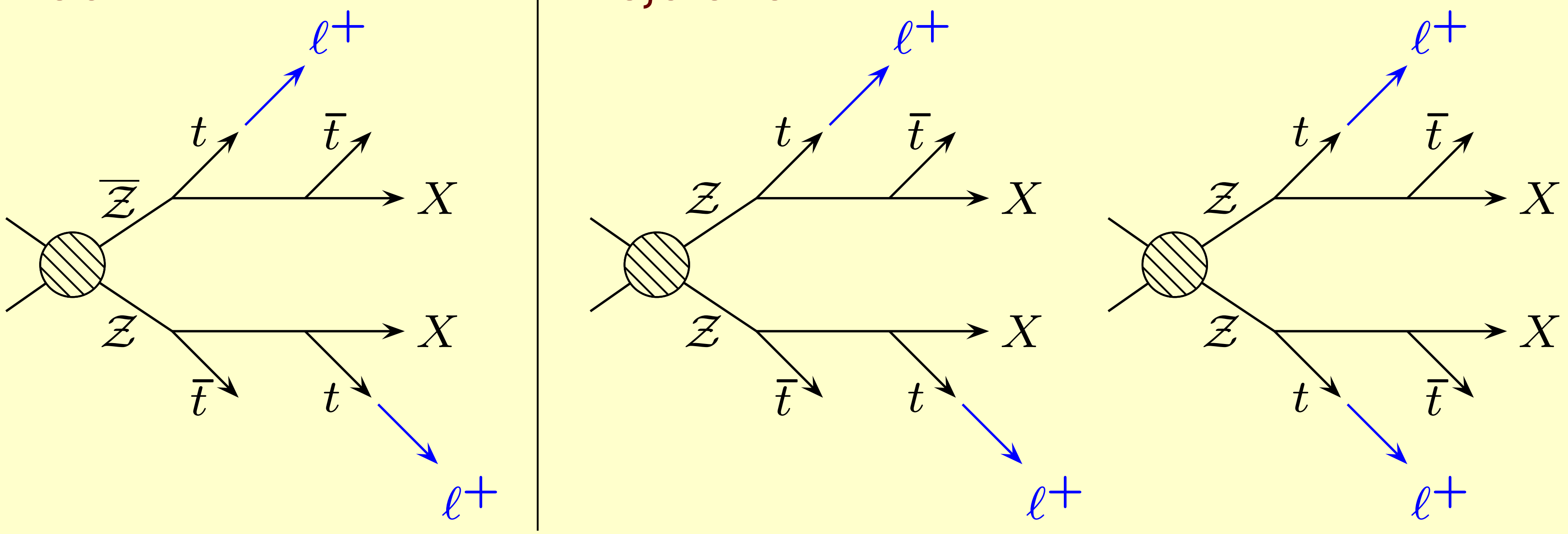
Significance with 300 fb^{-1} at 14 TeV:

	Spin combinations				
	SFV	VFS	VFV	FVF	FSF
SFS	1.3	10.3	10.6	2.4	5.3
SFV		11.4	11.8	3.5	6.4
VFS			0.35	9.6	4.7
VFV				9.6	4.8
FVF					3.6

Distinction Majorana–Dirac gluon partners

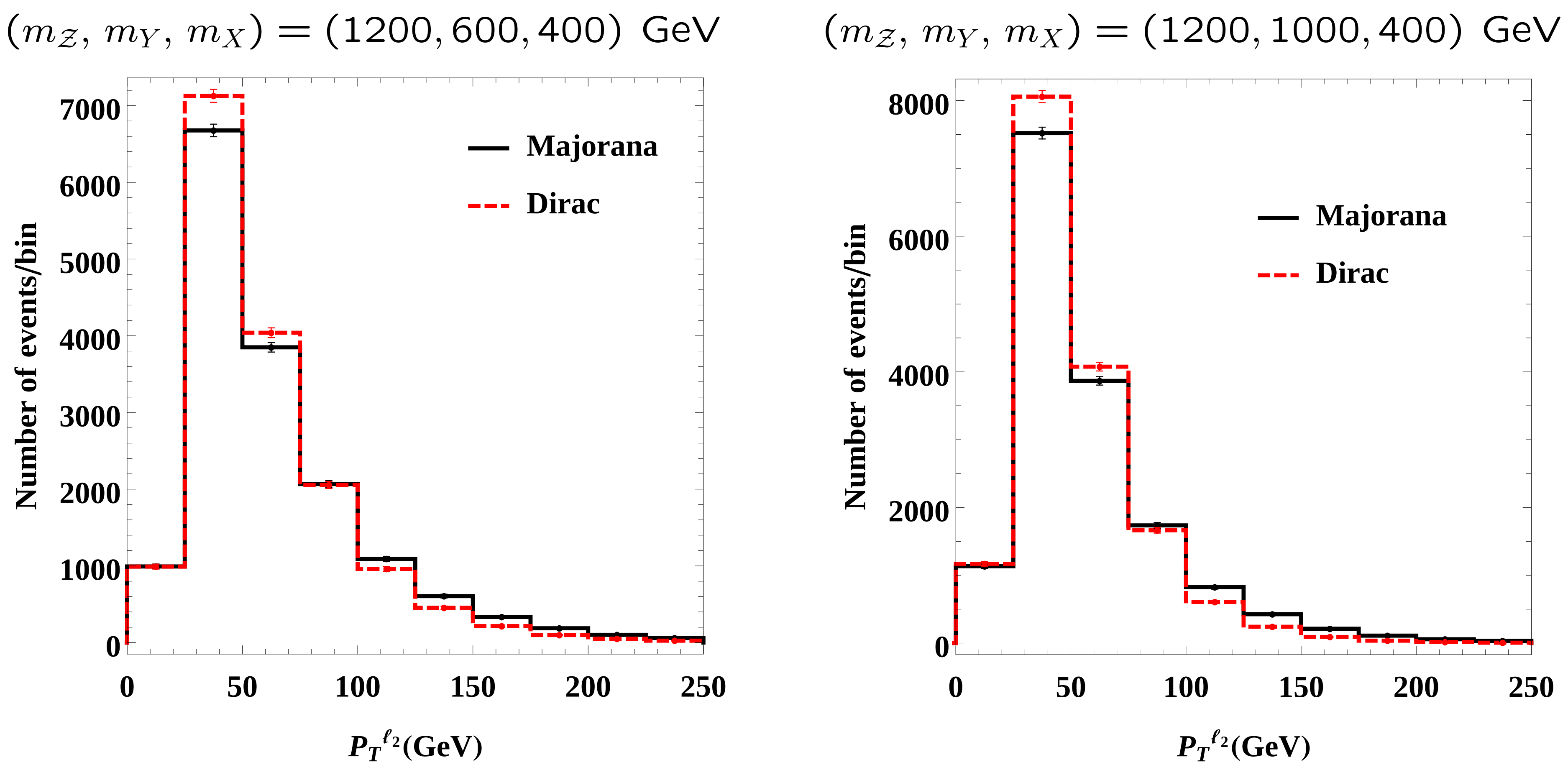
1. Prod. cross-section $\sigma^{\text{Dirac}}_{\mathcal{Z}\mathcal{Z}} \approx 2\sigma^{\text{Maj}}_{\mathcal{Z}\mathcal{Z}}$ Choi, Drees, Freitas, Zerwas '08
   $\longrightarrow$ Depends on knowledge of BRs and masses
2. Differences in decay distributions

Dirac Z: Majorana Z:



In Dirac case: If $|m_{\mathcal{Z}} - m_Y|$ and $|m_Y - m_X|$ are sufficiently different one lepton tends to be always softer

Distinction Majorana–Dirac gluon partners



$\longrightarrow$ Effect is relatively small, but visible

Summary

- Independent determinaton of particle masses, spins and couplings important for pinning down new physics at LHC
- Heavy top and gluon partners motivated by naturalness
  $\longrightarrow$ Sizeable production rates at LHC14
- Model-independent study of $pp \to Y^+Y^- \to t\bar{t}\,X^0X^0$
  and $pp \to \mathcal{Z}\mathcal{Z} \to t\bar{t}t\bar{t}\,X^0X^0$ $(m_{\mathcal{Z}} > m_Y > m_X)$
  - include all combinations with spin-0/$\frac{1}{2}$/1 particles
  - consider arbitrary chiral interactions
  - investigate LHC observables for spin and coupling determination
- $\mathcal{Z}/Y$ spin and coupling chirality can be independently determined, X spin and self-conjugate nature of $\mathcal{Z}$ more difficult to probe
- Many experimental aspects (systematic uncertainty, more detailed backgrounds, ...) need further study

Backup slides

Coupling determinaton: Results

Essential features captured by single quantity

$$A(x) = \frac{\sigma(\cos\theta'_\ell > x) - \sigma(\cos\theta'_\ell < x)}{\sigma(\cos\theta'_\ell > x) + \sigma(\cos\theta'_\ell < x)}\,.$$

$\longrightarrow$ Useful for limited statistics

For $x = -0.5$:

	$m_Y = 400$ GeV, $m_X = 10$ GeV				$m_Y = 300$ GeV, $m_X = 100$ GeV			
	Model				Model			
$a_L,\ a_R$	i	ii	iii	iv	i	ii	iii	iv
1, 0	−0.10	0.02	−0.10	−0.03	0	0.15	0.04	0.10
0, 1	0.68	0.55	0.68	0.61	0.54	0.39	0.50	0.45
1, 1	0.29	0.28	0.29	0.29	0.28	0.27	0.28	0.27

$(a_L, a_R) = (1,0)$: $A(-0.5) = -0.10 \dots 0.15$

$(a_L, a_R) = (1,1)$: $A(-0.5) = 0.27 \dots 0.29$

$(a_L, a_R) = (0,1)$: $A(-0.5) = 0.39 \dots 0.68$