LHEP 2013, Sanya, Jan-12-2012

Probe New Physics with Polarized Top Quark

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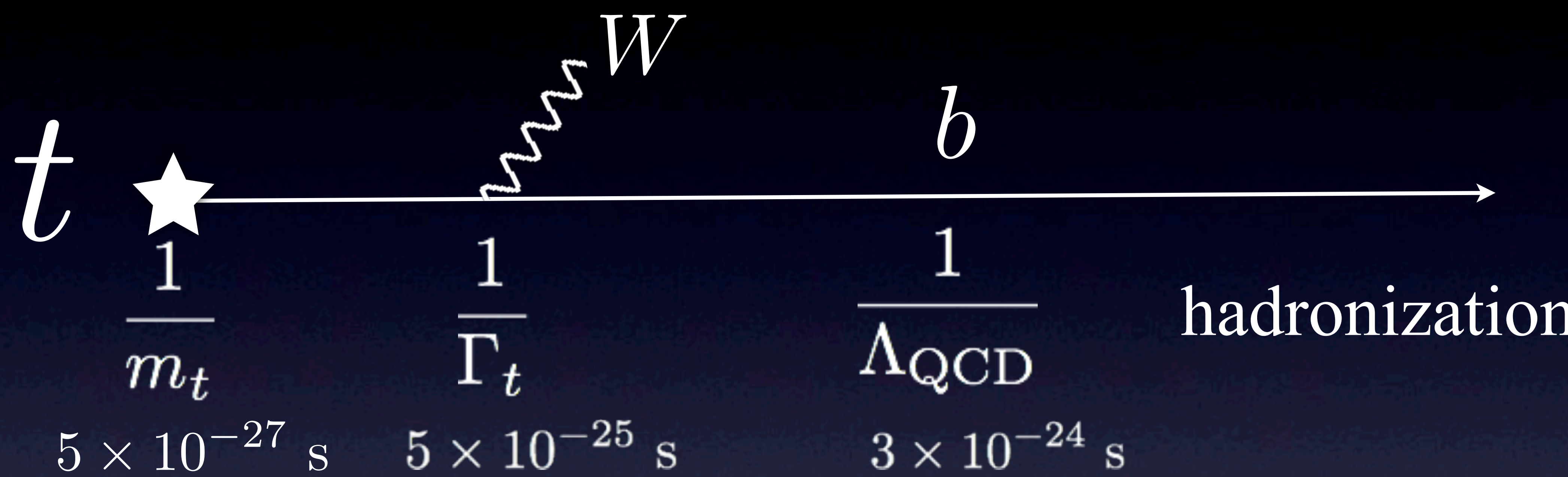
Based on the works in collaboration with

Ed Berger, Chuan-Ren Chen, Chong Sheng Li,
Gabe Shaughnessy, Jiang-Hao Yu, Hao Zhang

PRL 105 (2010) 181802; PRL 106 (2011) 201801;
PRD 83 (2011) 114026; PRL 108 (2012) 072002;
PRL 109 (2012) 152004

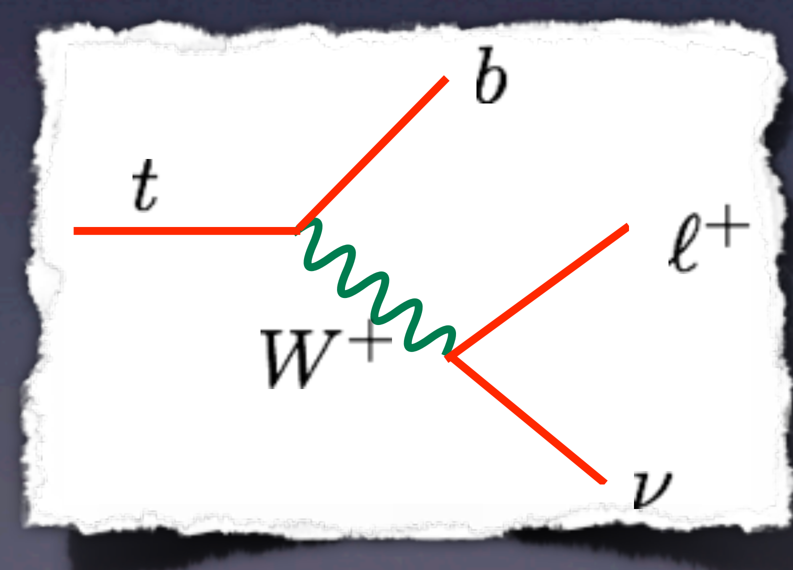
Top-quark: the only bare quark in SM

- Short lifetime:



- “bare” quark：

  spin info well kept
  among its decay products



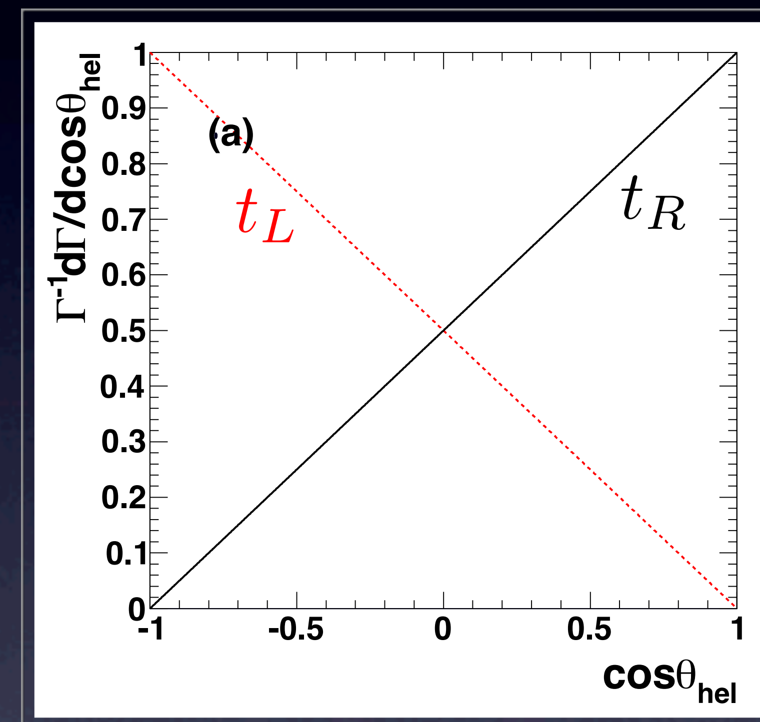
Charged lepton: the top-spin analyzer

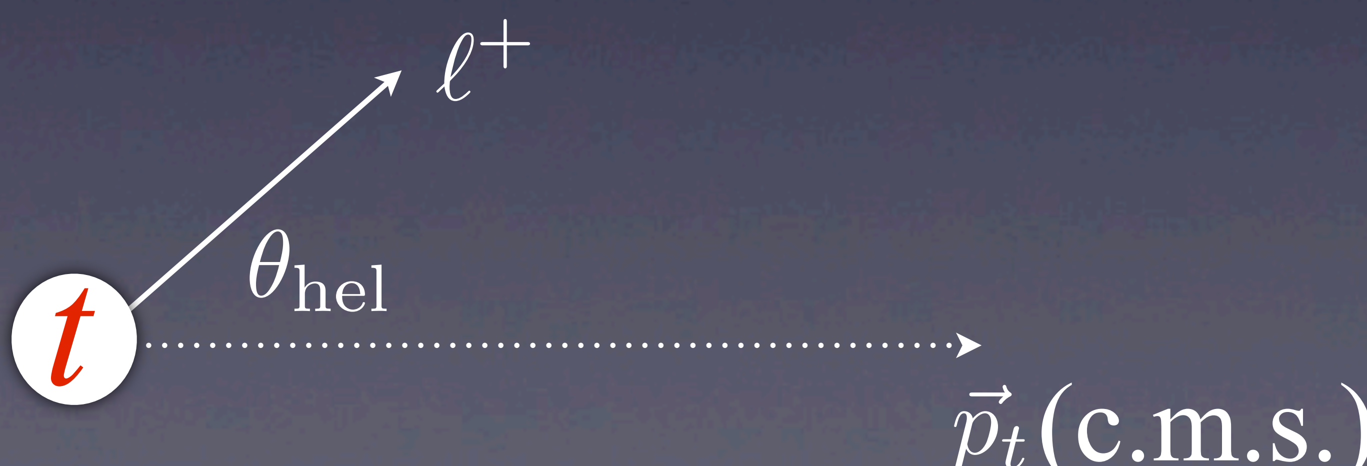
- The charged-lepton tends to *follow* the top-quark spin direction.

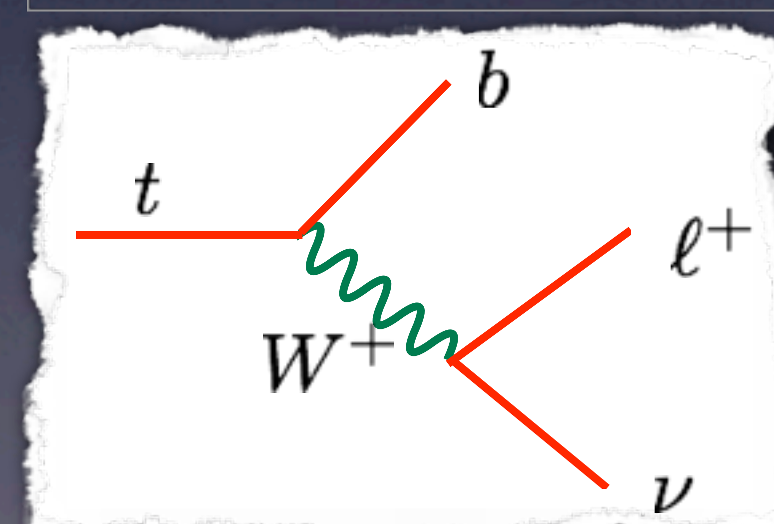
- In top-quark rest frame

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}} = \frac{1+\lambda_t\cos\theta_{\rm hel}}{2}$$

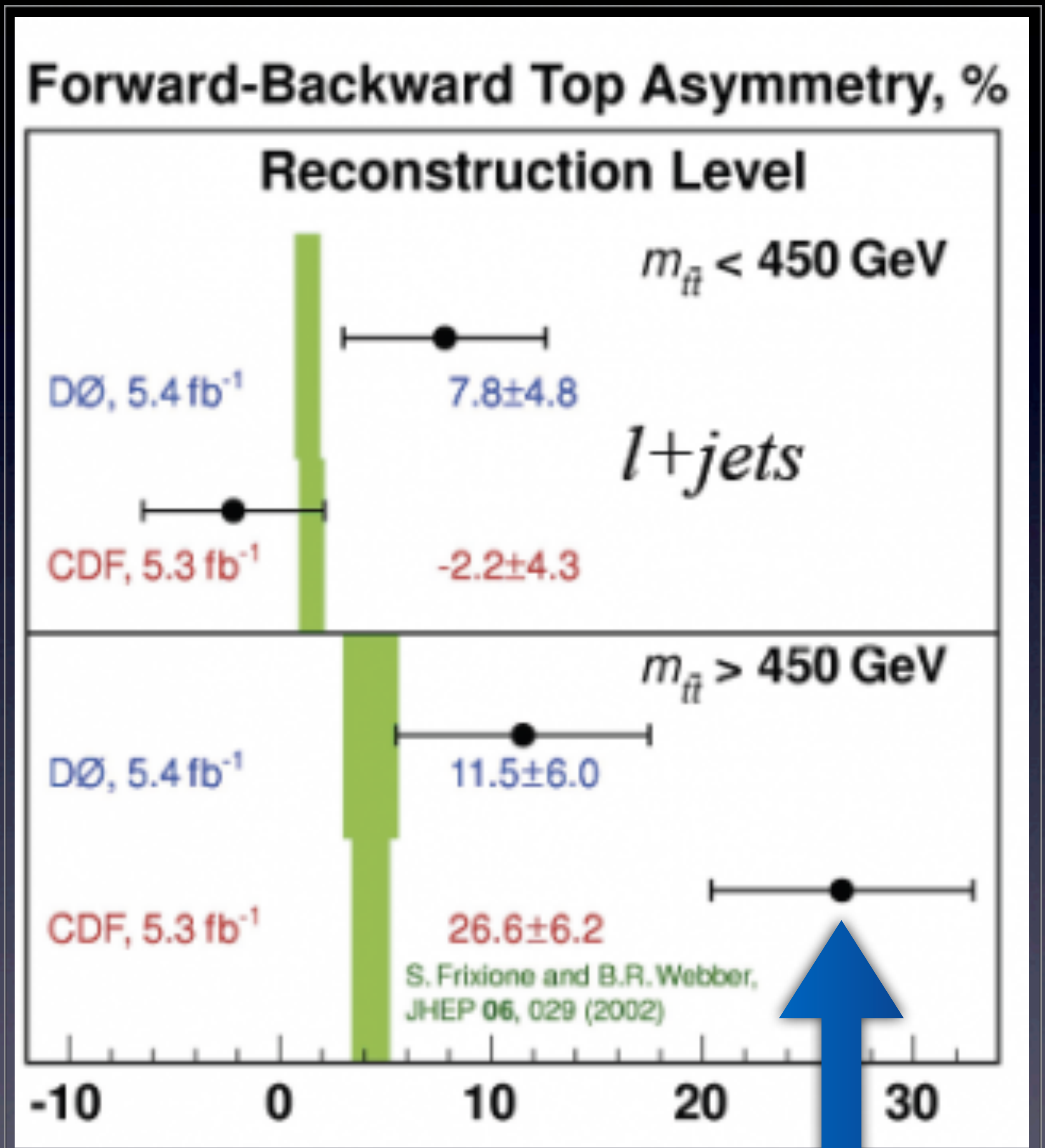
$$\begin{aligned} \lambda_t &= + \quad \text{right-handed} \\ \lambda_t &= - \quad \text{left-handed} \end{aligned}$$







Top-quark A_{FB} at the Tevatron

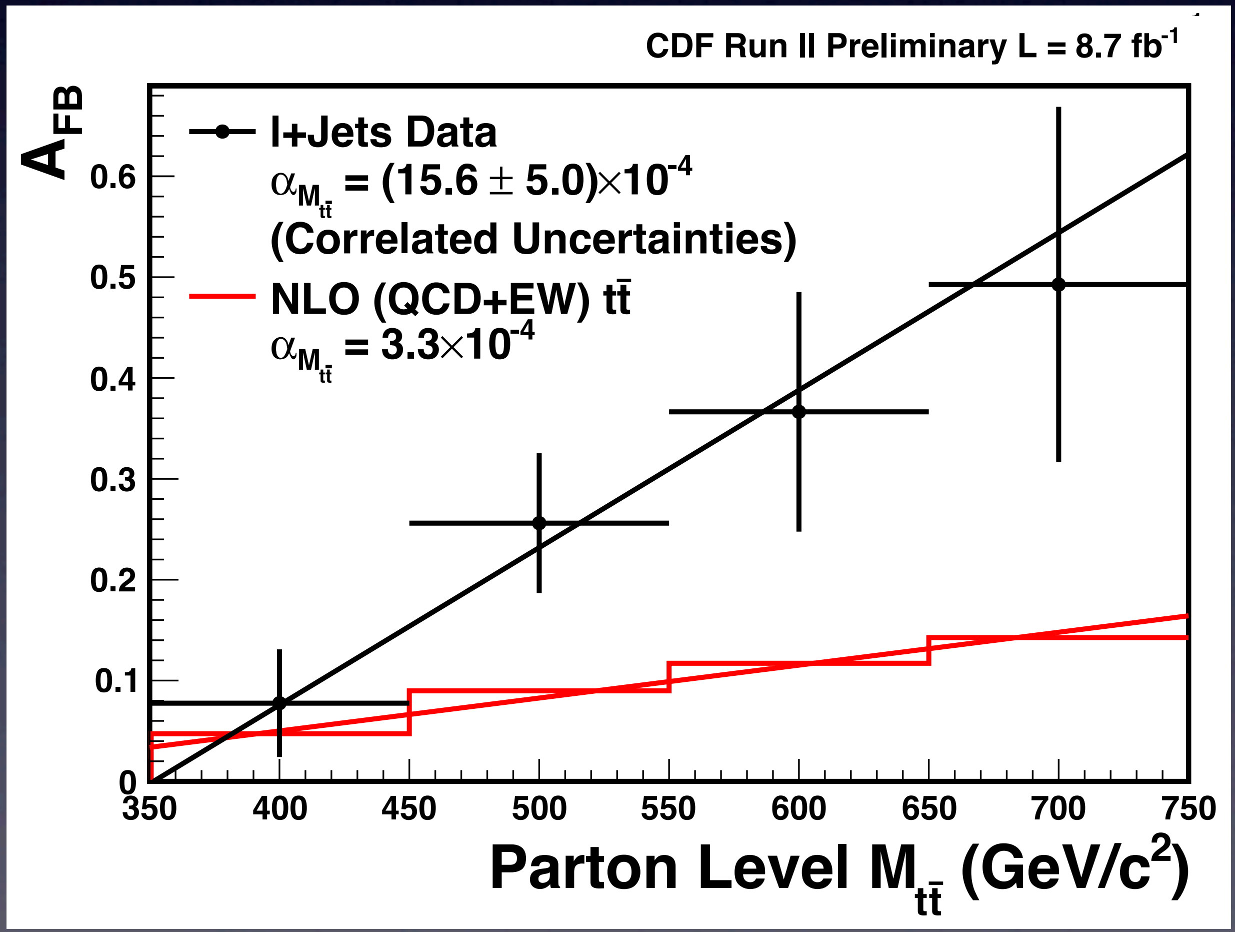


CDF: 1101.0034

CDF (8.7fb^{-1}):

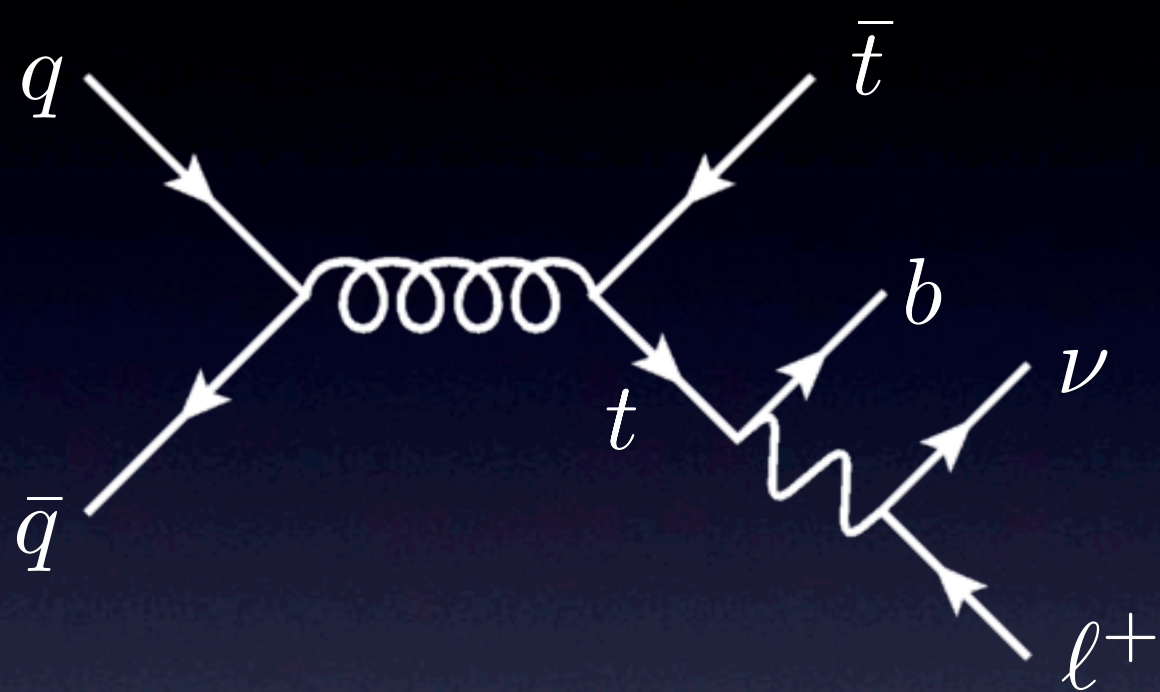
$$A_{FB}^{\text{inclusive}} = 0.162 \pm 0.041 \pm 0.022$$

$$A_{FB}^{\text{NLO+EW}} = 0.066$$



A^{ℓ}_{FB} versus A^{t}_{FB}

- Charged lepton is maximally correlated with top-spin.



Bernreuther and Si, NPB837 (2010) 90

SM: $A^{t}_{FB} = 0.051 \pm 0.001$
$A^{\ell}_{FB} = 0.021 \pm 0.001$

$$\left.\frac{A^{\ell}_{FB}}{A^{t}_{FB}}\right|_{\rm SM} \sim \frac{1}{2}$$

D0: $A^{t}_{FB} = 0.196 \pm 0.065$
$A^{\ell}_{FB} = 0.152 \pm 0.040$

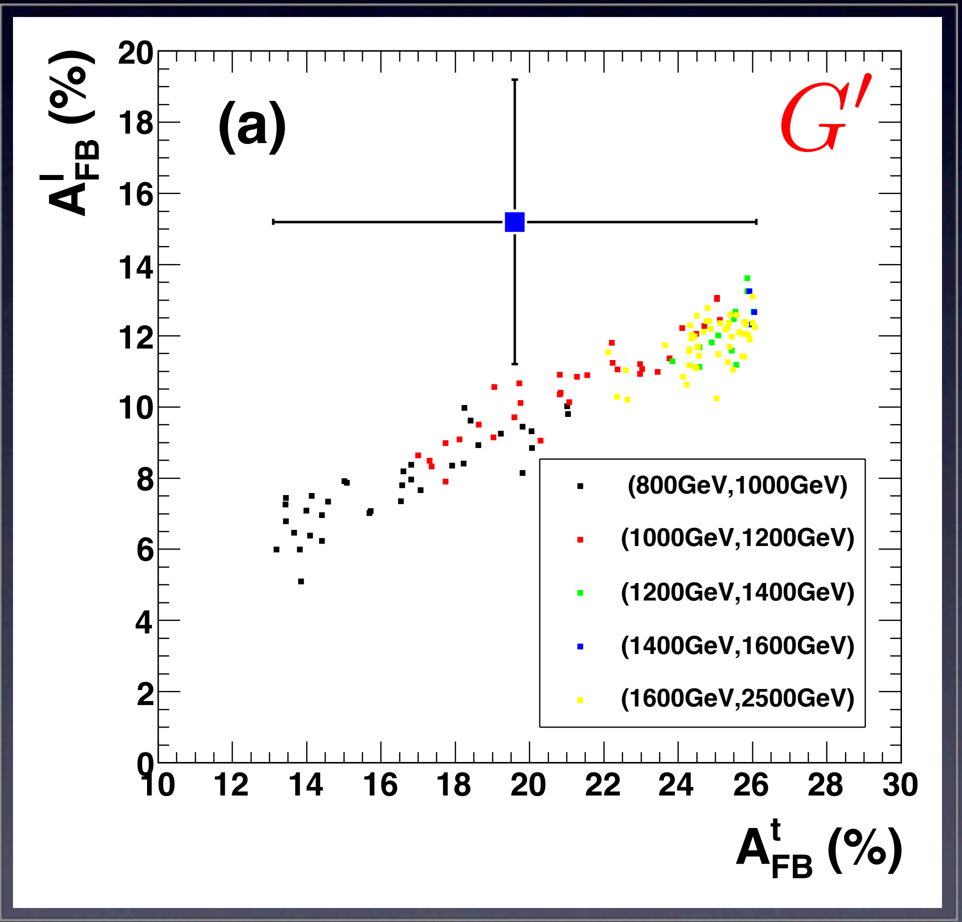
$$\left.\frac{A^{\ell}_{FB}}{A^{t}_{FB}}\right|_{\rm D0} \sim \frac{3}{4}$$

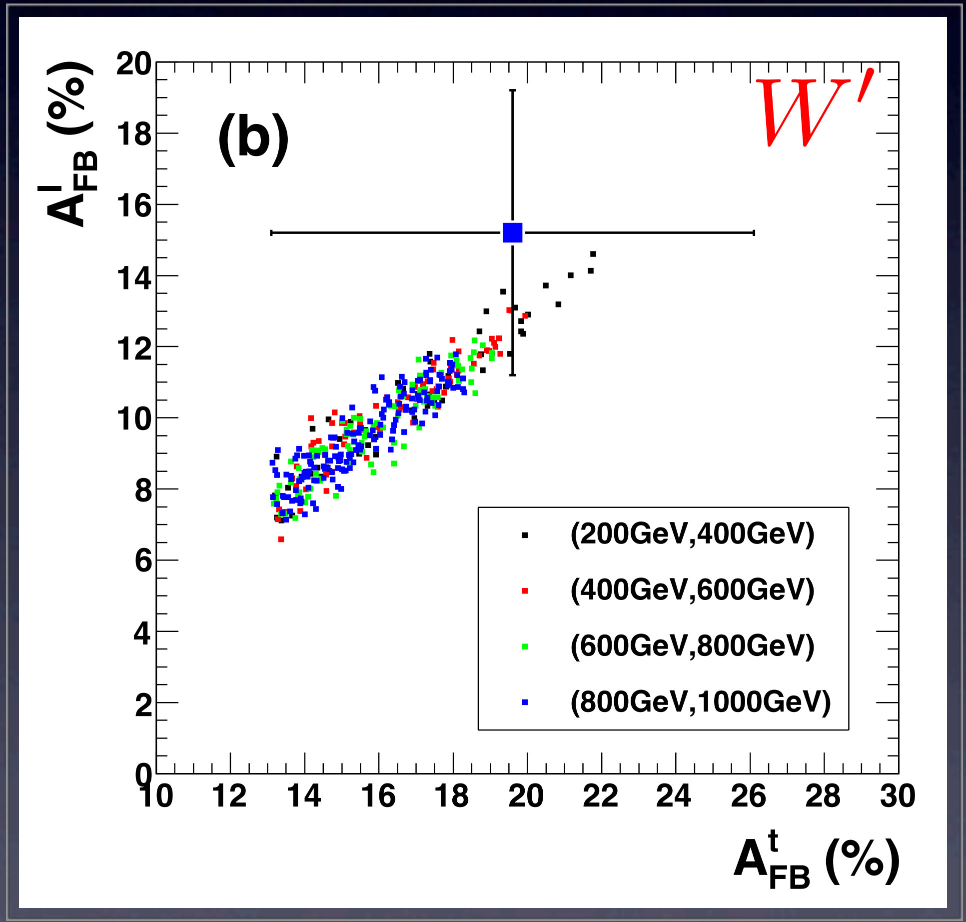
CDF: $A^{t}_{FB} = 0.085 \pm 0.025$
(8.7fb^{-1}) $A^{\ell}_{FB} = 0.066 \pm 0.025$
(Before unfolding)

$$\left.\frac{A^{\ell}_{FB}}{A^{t}_{FB}}\right|_{\rm inc} \sim \frac{3}{4} \qquad \left.\frac{A^{\ell}_{FB}}{A^{t}_{FB}}\right|_{>450} \sim \frac{3}{5}$$

A^t_{FB} and A^ℓ_{FB} are connected by the spin correlation between the top-quark and charged lepton.

Berger, QHC, Chen, Yu, Zhang,
PRL 108 (2012) 072002





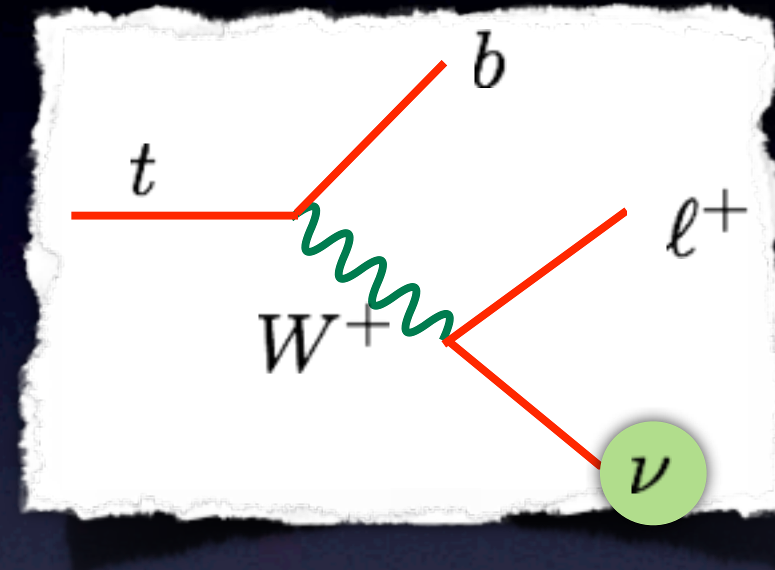
$A^\ell_{FB} \simeq 0.47 \times A^t_{FB} + 0.25\%$ $\quad$ $A^\ell_{FB} \simeq 0.75 \times A^t_{FB} - 2.1\%$

Top quark reconstruction

- The charged leptons produced always in association with an invisible neutrino

$$p_x^\nu = \not{E}_T(x) \quad p_y^\nu = \not{E}_T(y) \quad m_\nu = 0$$

p_z^ν unknown



- W-boson on-shell condition

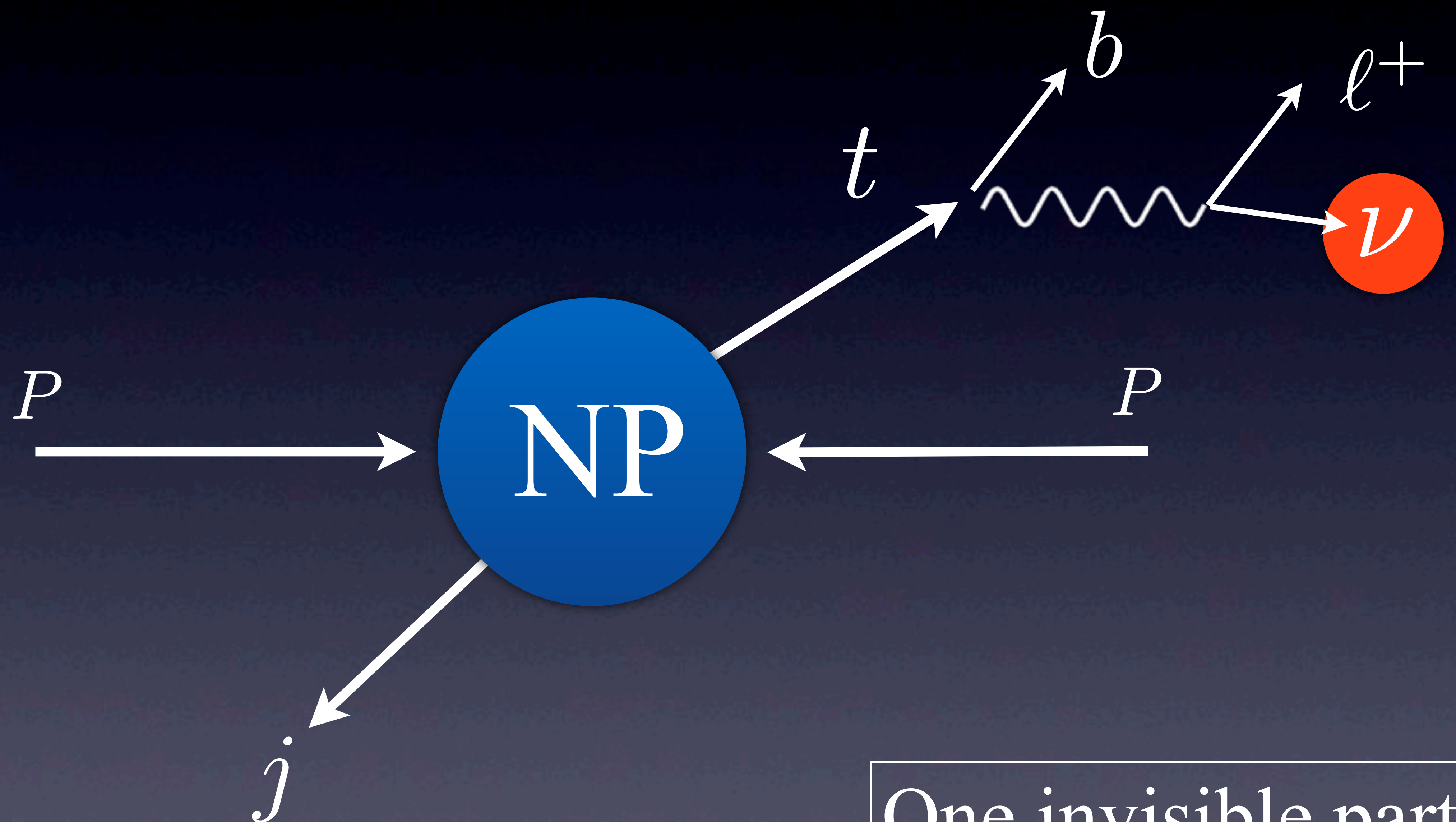
$$\boxed{m_W^2 = (p_\ell + p_\nu)^2}$$

$$\Rightarrow p_z^\nu = \frac{1}{2(p_T^e)^2}\left[A\, p_z^e \pm E_e \sqrt{A^2 - 4\,(p_T^e)^2\, \not{E}_T^2}\right]$$

$$A = m_W^2 + 2\,\vec{p}_T^{\,e} \cdot \vec{\not{E}}_T$$

Top quark production in NP

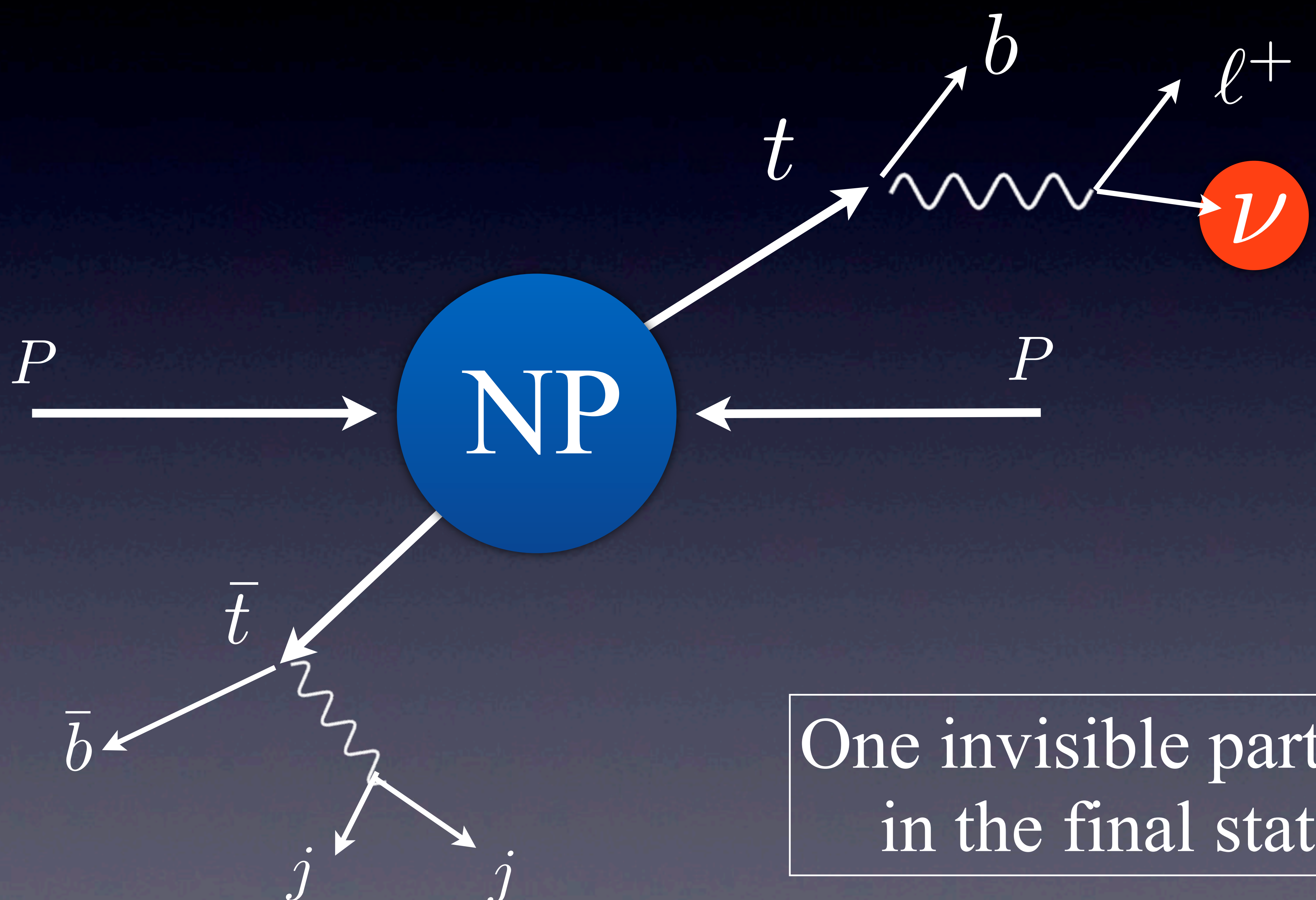
- Single top-quark production



One invisible particle in the final state

Top quark production in NP

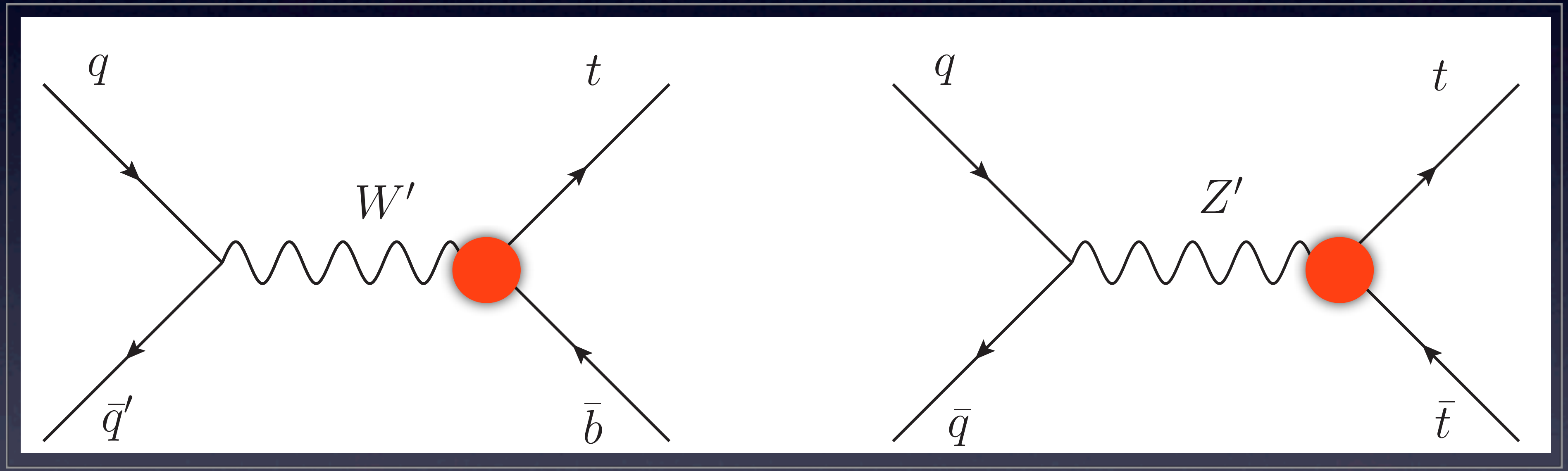
- Top-quark pair production + semi-leptonic decay



One invisible particle in the final state

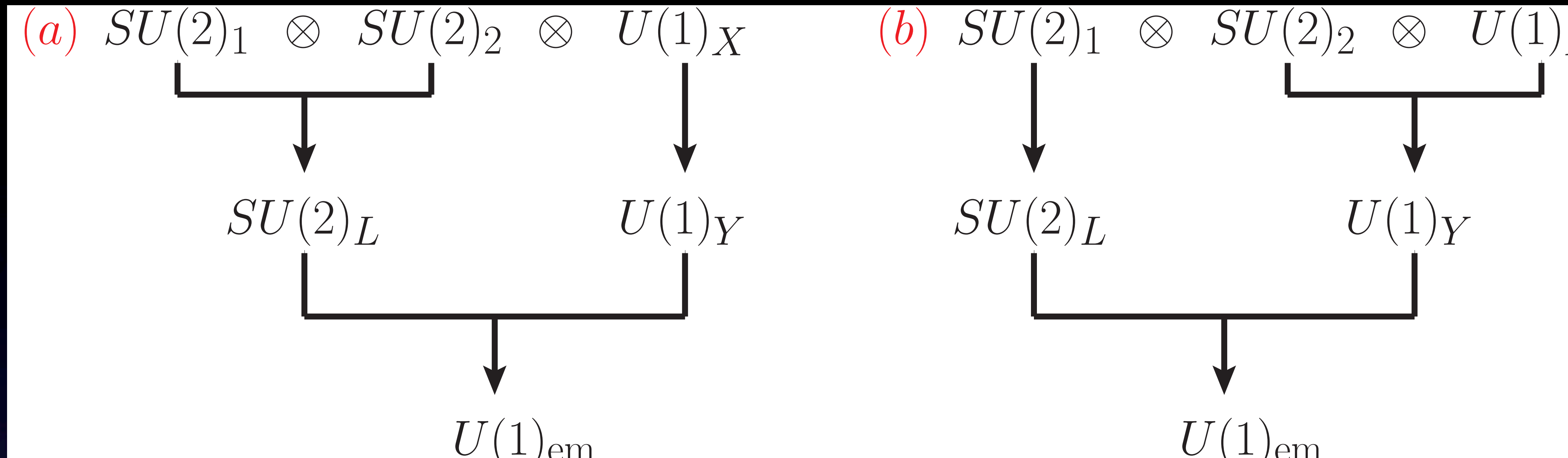
Extra gauge bosons
(W-prime and Z-prime)

Berger, QHC, Chen, Zhang, PRD83 (2011) 114026



Top-quark polarization depends on
how the top-quark is gauged under new gauge symmetry,
or, the chirality structure of W'-t-b and Z'-t-t couplings.

Effective $W'tb$ and $Z'tt$ couplings

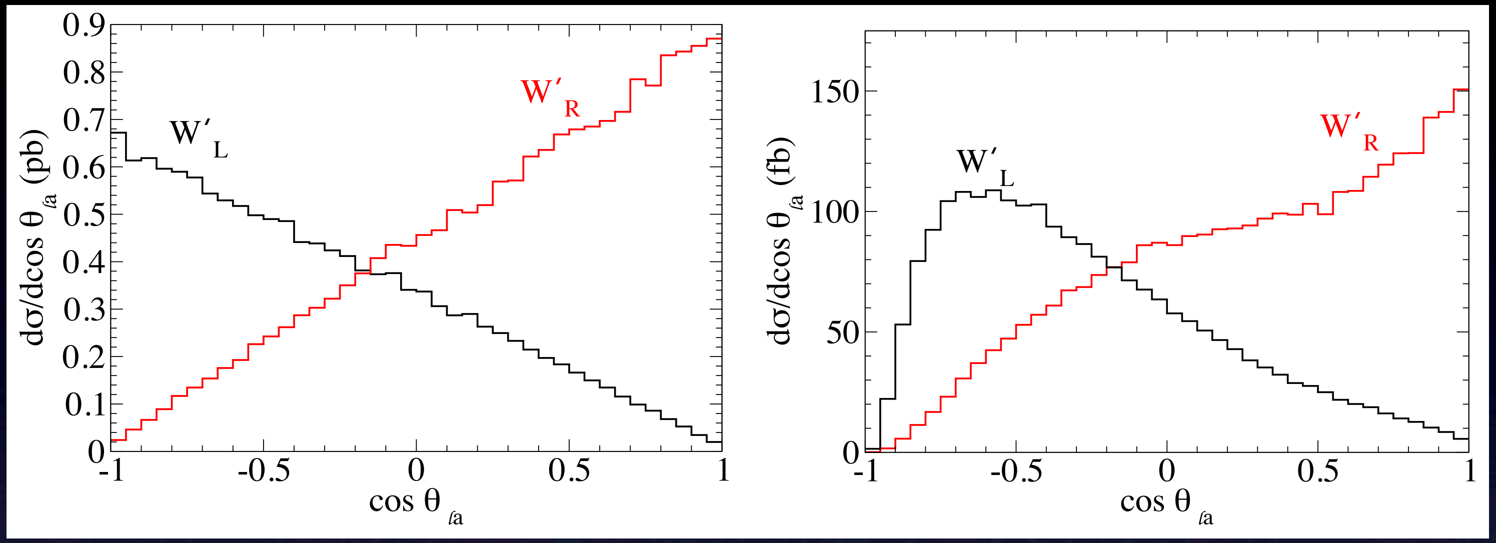


$$\mathcal{L} = \bar{q}\gamma^\mu (g_L^{Z'} P_L + g_R^{Z'} P_R) q \; Z'_\mu + \bar{q}\gamma^\mu (g_L^{W'} P_L + g_R^{W'} P_R) q' \; W'^+_\mu + h.c.$$

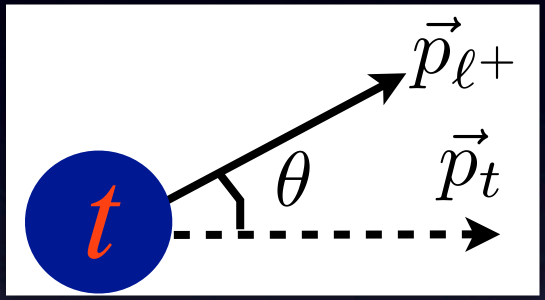
	$W'tb$	$Z't\bar{t}$
SSM	$\frac{g_2}{\sqrt{2}}\bar{b}\gamma_\mu P_L t W'^\mu$	$\frac{g_2}{6c_w}\bar{t}\gamma_\mu((-3+4s_w^2)P_L + 4s_w^2 P_R)tZ'^\mu$
LRM	$\frac{g_2}{\sqrt{2}}\bar{b}\gamma_\mu P_R t W'^\mu$	$\frac{g_2 t_w}{6}\bar{t}\gamma_\mu(\frac{1}{\alpha_{LR}}P_L + (\frac{1}{\alpha_{LR}} - 3\alpha_{LR})P_R)tZ'^\mu$
Top-Flavor	$\frac{g_2 \sin\tilde{\phi}}{\sqrt{2}}\bar{b}\gamma_\mu P_L t W'^\mu$	$\frac{g_2 \sin\tilde{\phi}}{\sqrt{2}}\bar{t}\gamma_\mu P_L t Z'^\mu$

Measuring $W'tb$ and $Z'tt$ couplings

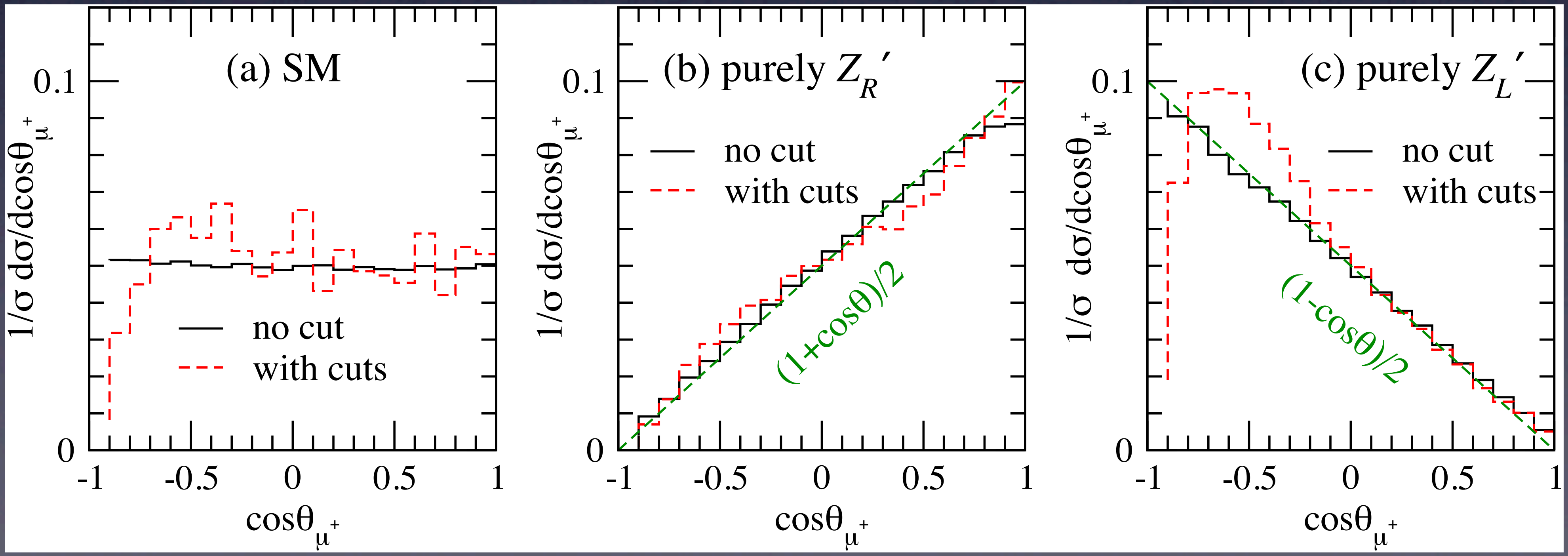
- Single-top production can probe the handness of $W'tb$ coupling



Gopalakrishna, Han, Lewis, Si, Zhou, PRD82 (2010) 115020



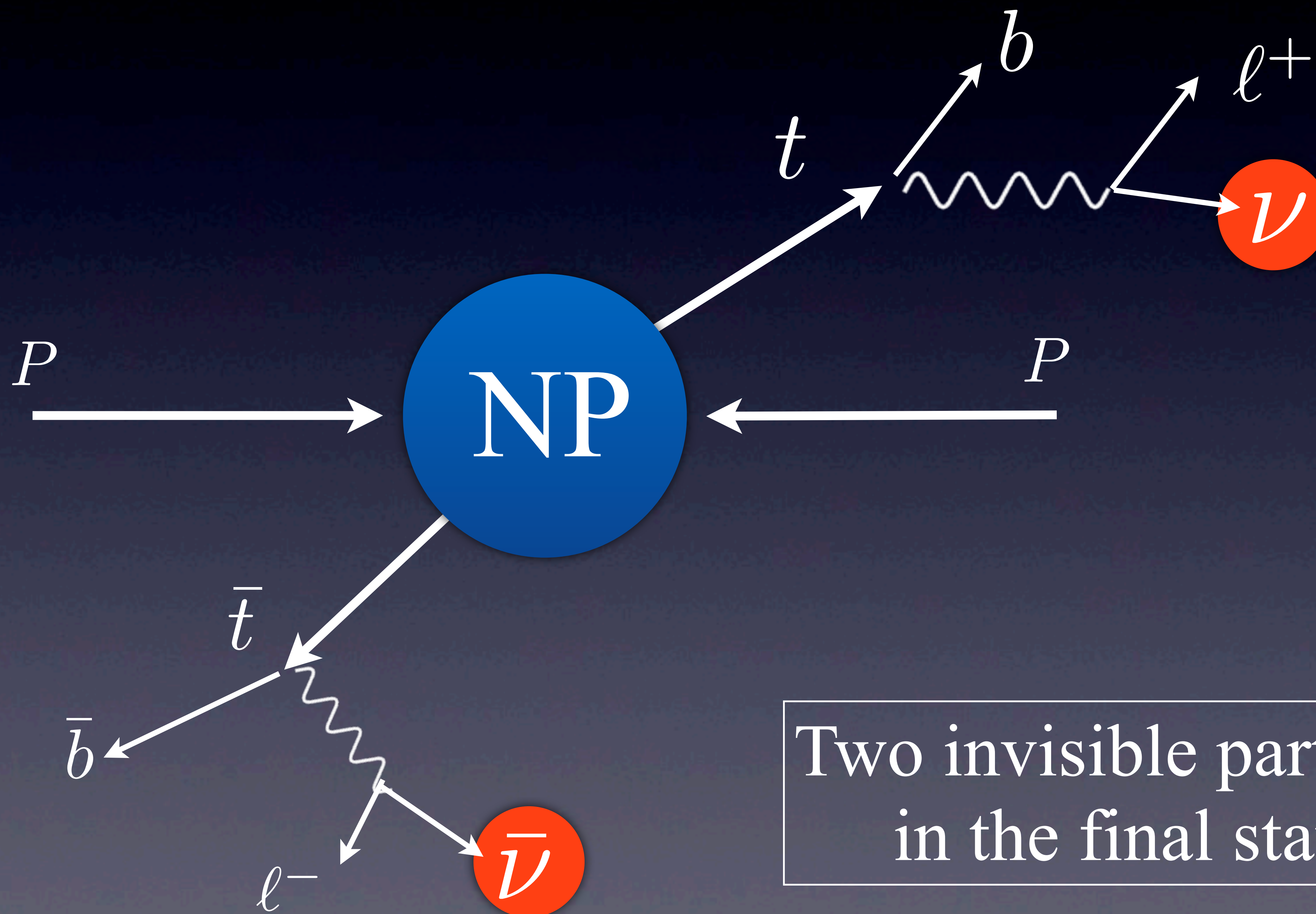
- Top-pair production can probe the handness of $Z'tt$ coupling



Berger, QHC, Chen, Zhang, PRD83 (2011) 114026

Top quark production in NP

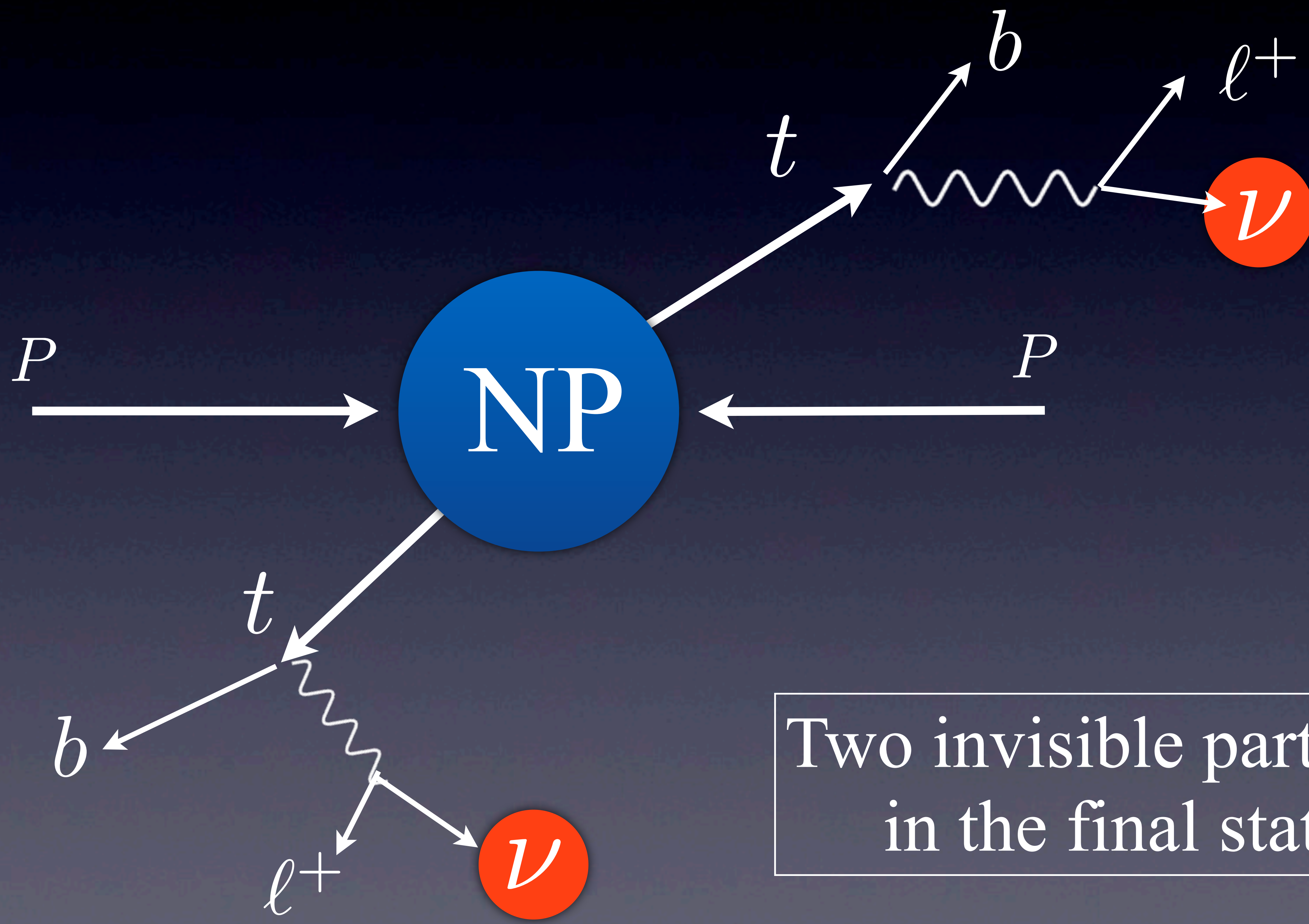
- Top-quark pair production + dileptonic decay



Two invisible particles in the final state

Top quark production in NP

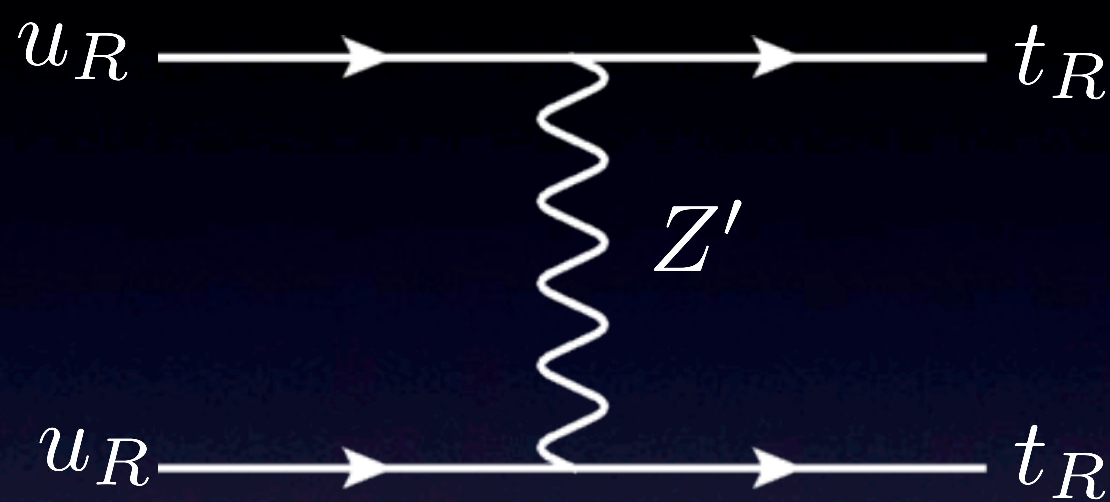
- Same-Sign top-quark pair production



Two invisible particles in the final state

Top quark is often polarized in NP

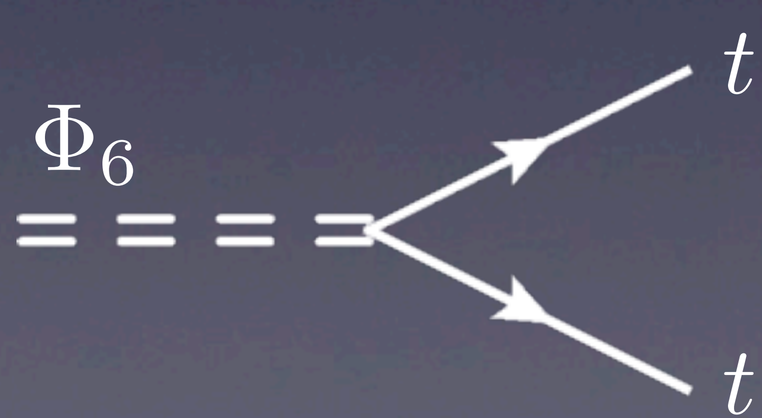
- Flavor changing gauge boson



- Exotic colored partilces (diquark scalar/vector)

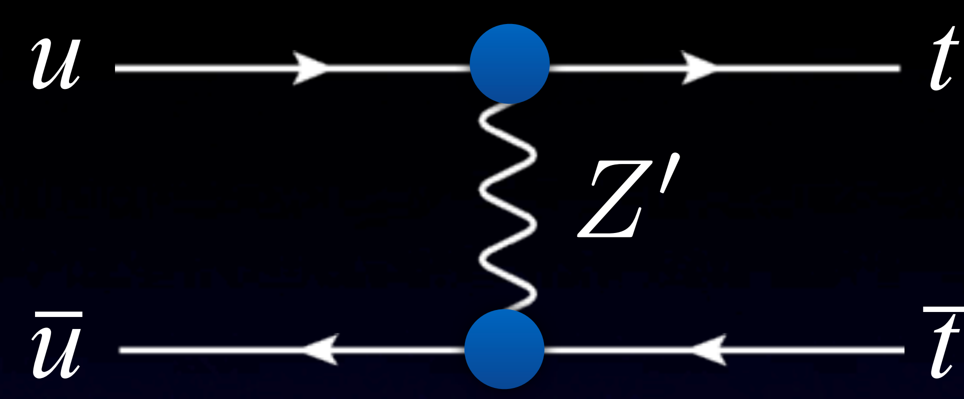
$$3 \otimes 3 = 6 \oplus \bar{3}$$

Mohapatra, Okada, Yu, PRD 77 (2008) 011701
Chen, Klemm, Rentala, Wang, PRD79 (2009) 054002



Minimal FCNC Z' cannot explain A^t_{FB}

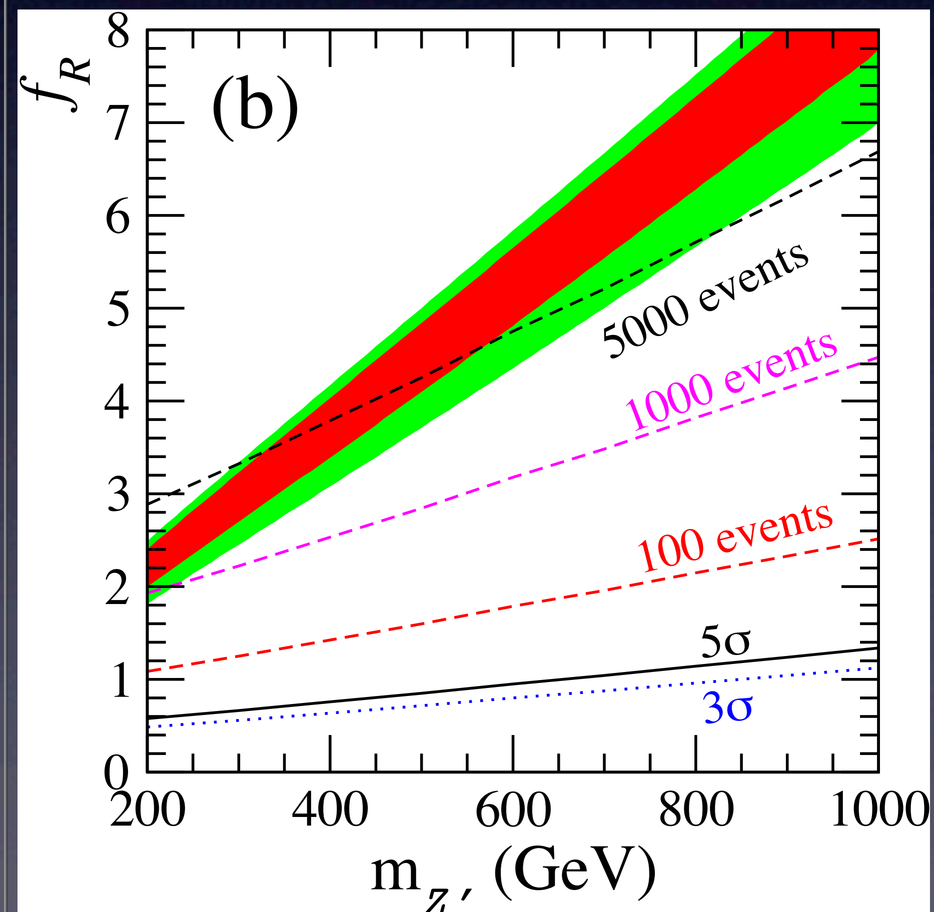
$$\mathcal{L} = g\bar{u}\gamma^\mu(f_L P_L + f_R P_R)tZ'_\mu + h.c.$$



Left-handed coupling is highly constrained by B_d - $\overline{B}_d$ mixing.

A_{FB} prefers a LARGE f_R.

Berger, QHC, Chen, Li, Zhang, PRL 106 (2011) 201801



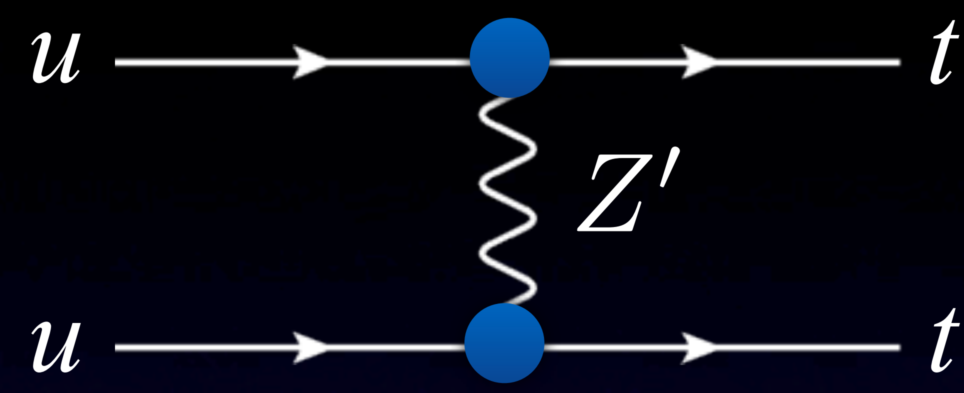
Other studies on same-sign top pair :

J. Cao et al, hep-ph/0703308, hep-ph/0409334

J. Cao, Wang, Wu, Yang, arXiv:1101.4456

Minimal FCNC Z' cannot explain A_{FB}^{t}

$$\mathcal{L} = g\bar{u}\gamma^{\mu}(f_L P_L + f_R P_R) t Z'_{\mu} + h.c.$$



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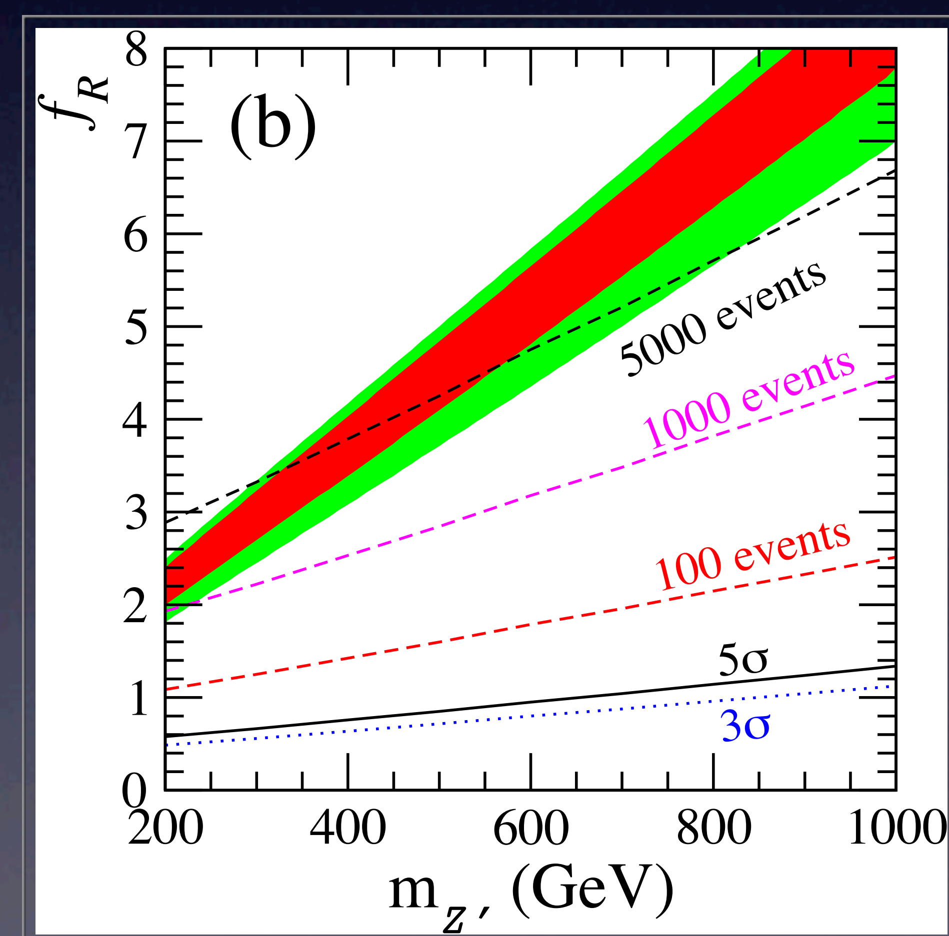

Berger, QHC, Chen, Li, Zhang, PRL 106 (2011) 201801

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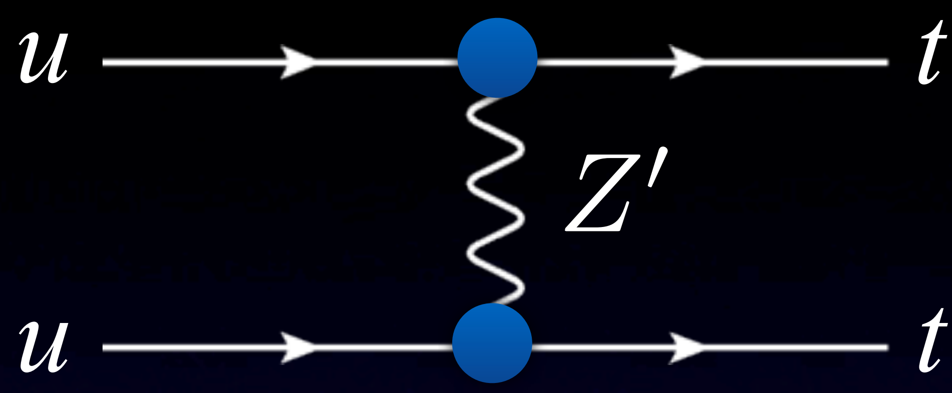

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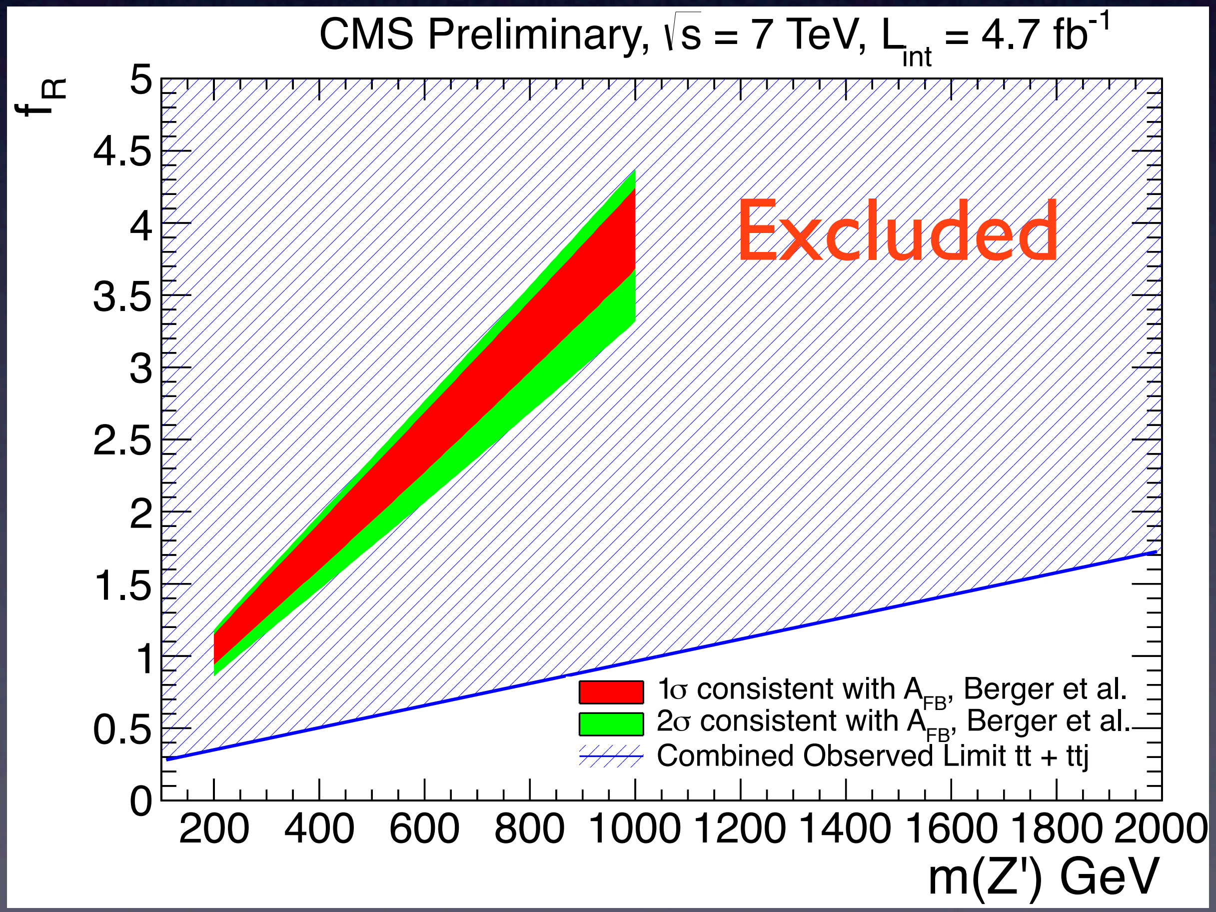


Berger, QHC, Chen, Li, Zhang, PRL 106 (2011) 201801

Other studies on same-sign top pair :

- J. Cao et al, hep-ph/0703308, hep-ph/0409334
- J. Cao, Wang, Wu, Yang, arXiv:1101.4456

Color sextet scalars and vectors

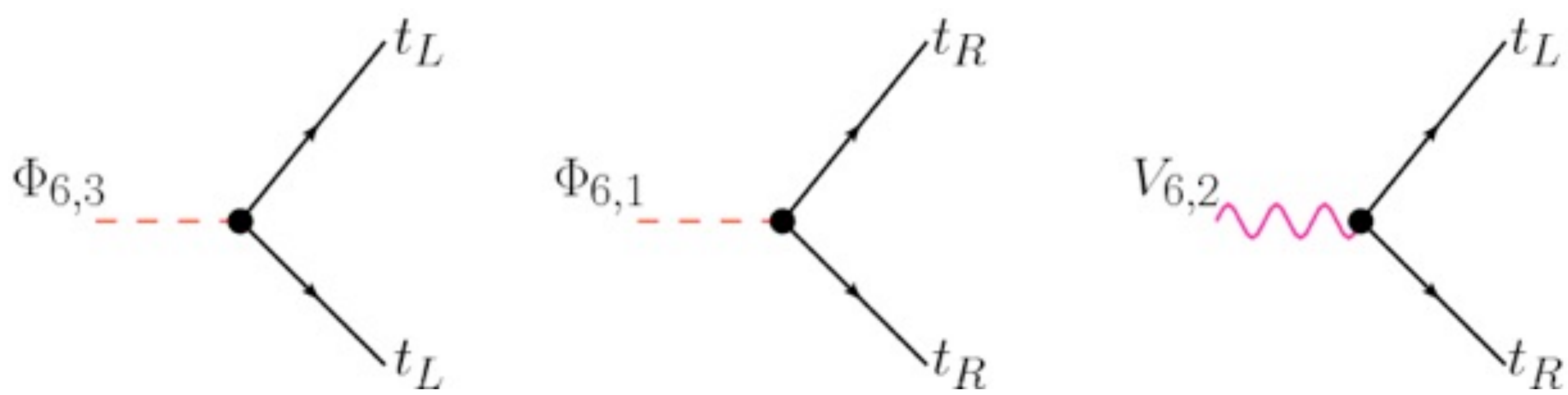
- Effective Lagrangian ($SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$)

Atag, Cakir, Sultansoy, PRD59 (1999) 015008

$$
\begin{aligned}
\mathcal{L} = & \left(g_{1L}\overline{q_L^c}\, i\tau_2 q_L + g_{1R}\overline{u_R^c} d_R\right)\Phi_{6,1,1/3} \\
& + g'_{1R}\overline{d_R^c} d_R \Phi_{6,1,-2/3} + g''_{1R}\overline{u_R^c} u_R \Phi_{6,1,4/3} \\
& + g_{3L}\overline{q_L^c}\, i\tau_2 \tau q_L \cdot \Phi_{6,3,1/3} \\
& + g_2 \overline{q_L^c}\gamma_\mu d_R V^\mu_{6,2,-1/6} + g'_2 \overline{q_L^c}\gamma_\mu u_R V^\mu_{6,2,5/6} + h.c.\,,
\end{aligned}
$$

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$$q^c = C\bar{q}^T$$



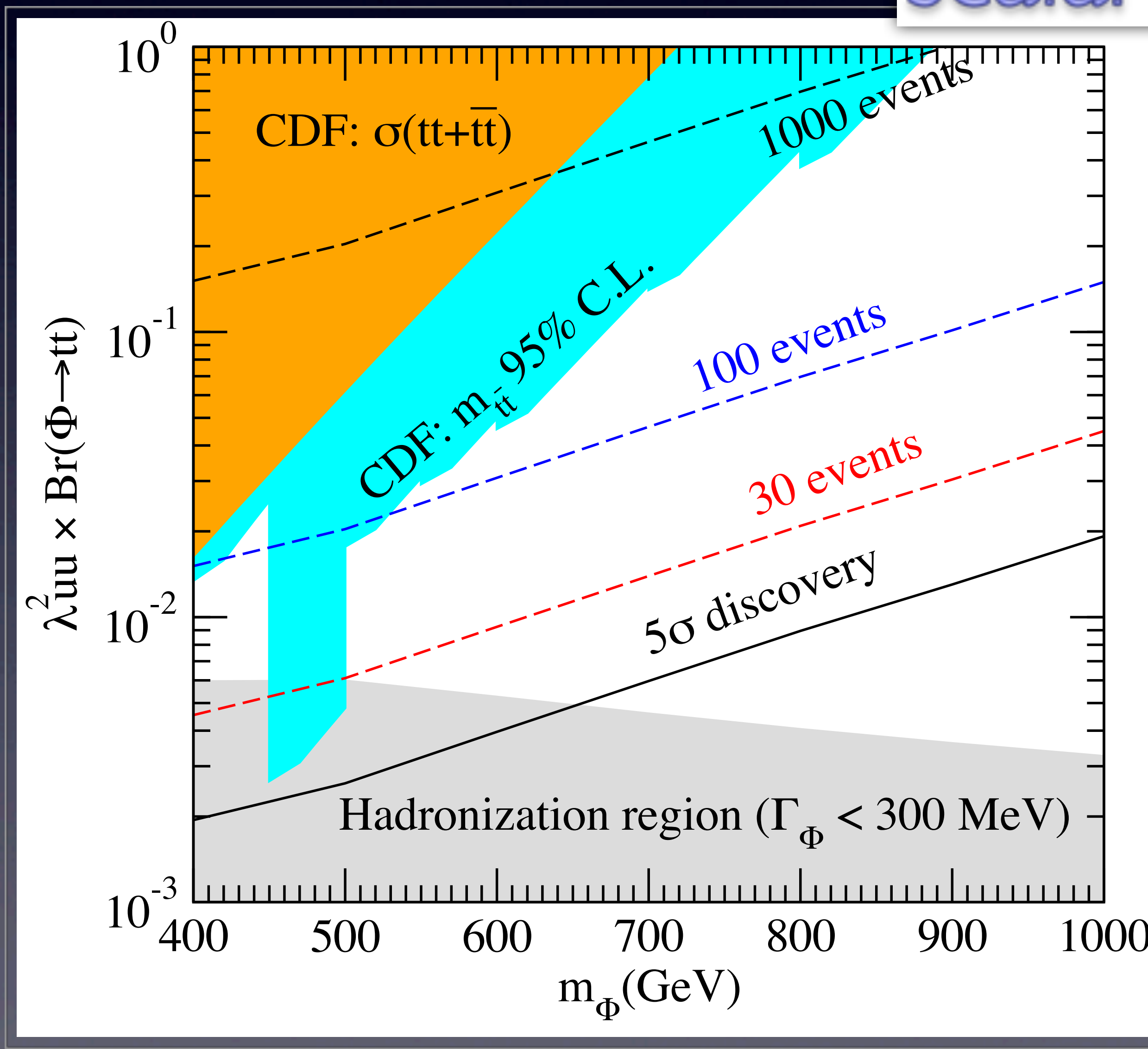
Measuring polarizations of ***both*** top quarks → Spin and gauge quantum numbers of heavy resonances

Discovery potential

- Simple cuts to extract signal:
  - Same sign di-muons
  - Two jets and leptons with P_T>50GeV

Berger, QHC, Chen, Shaughnessy, Zhang, PRL 105 (2010) 181802

7 TeV $\mathcal{L} = 1\ \mathrm{fb}^{-1}$ scalar

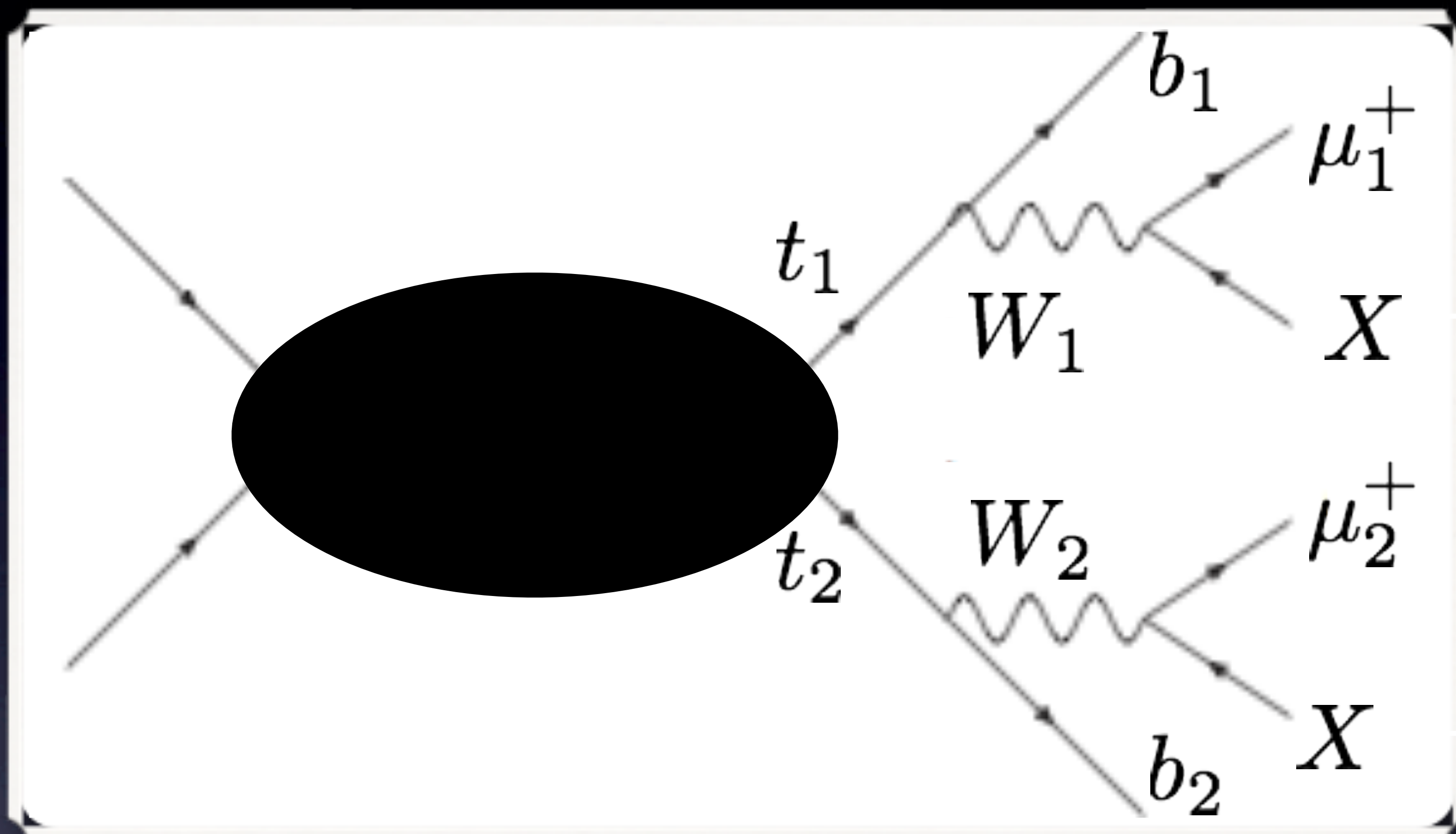


Contours shown on right are numbers of signal events

About 1 background events

Full kinematics reconstruction

★ Four unknowns and four on-shell conditions



6 unknowns
-2 from MET

$$
\begin{aligned}
m_{W_1}^2 &= (p_{\mu_1} + p_{\nu_1})^2 \\
m_{W_2}^2 &= (p_{\mu_2} + p_{\nu_2})^2 \\
m_{t_1}^2 &= (p_{W_1} + p_{b_1})^2 \\
m_{t_2}^2 &= (p_{W_2} + p_{b_2})^2
\end{aligned}
$$

Quartic equation

(correct l-b pairing is necessary)

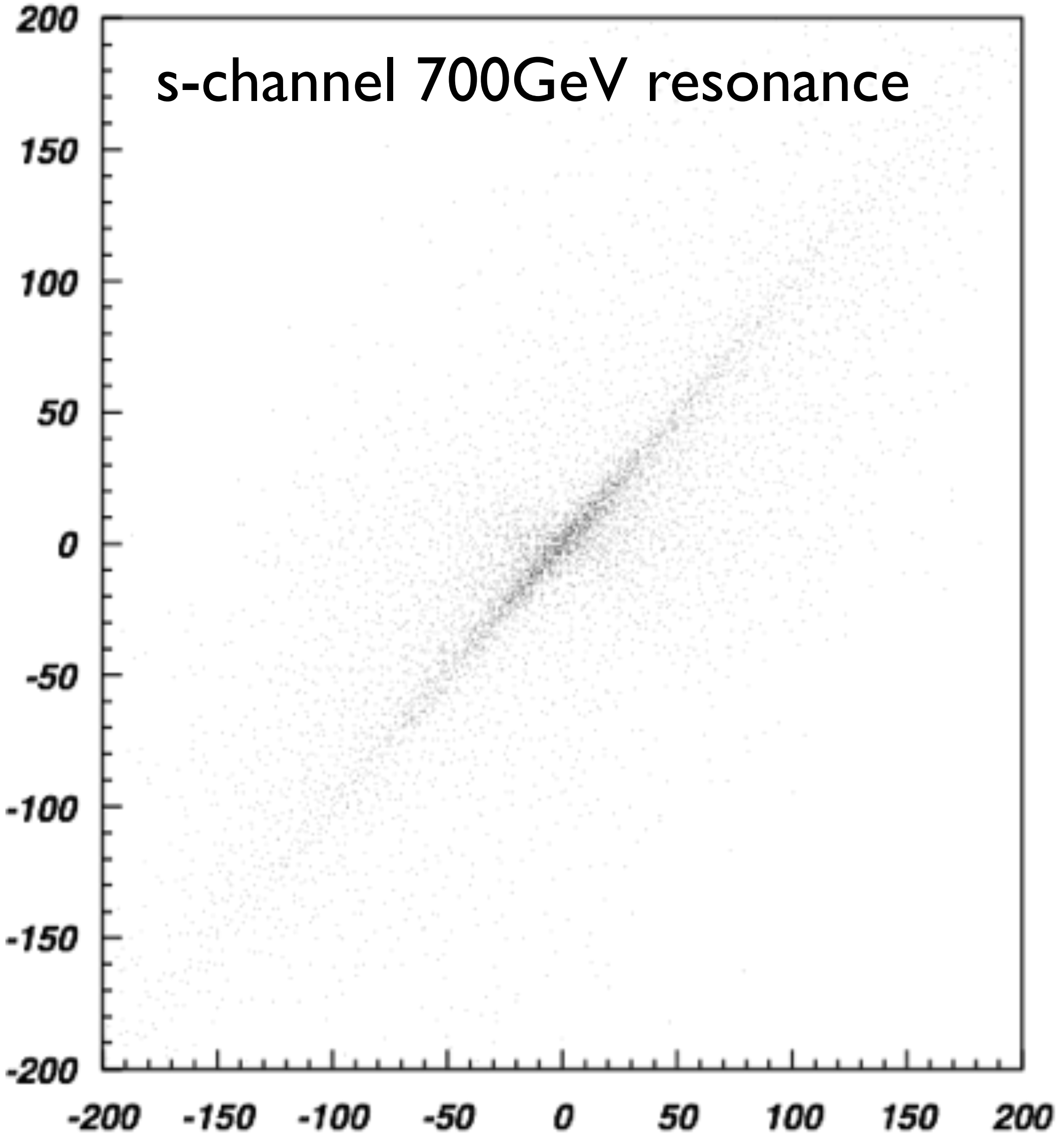
$$p_x^4(\nu_1) + a\ p_x^3(\nu_1) + b\ p_x^2(\nu_1) + c\ p_x(\nu_1) + d = 0$$

~~Two complex~~, two real solutions

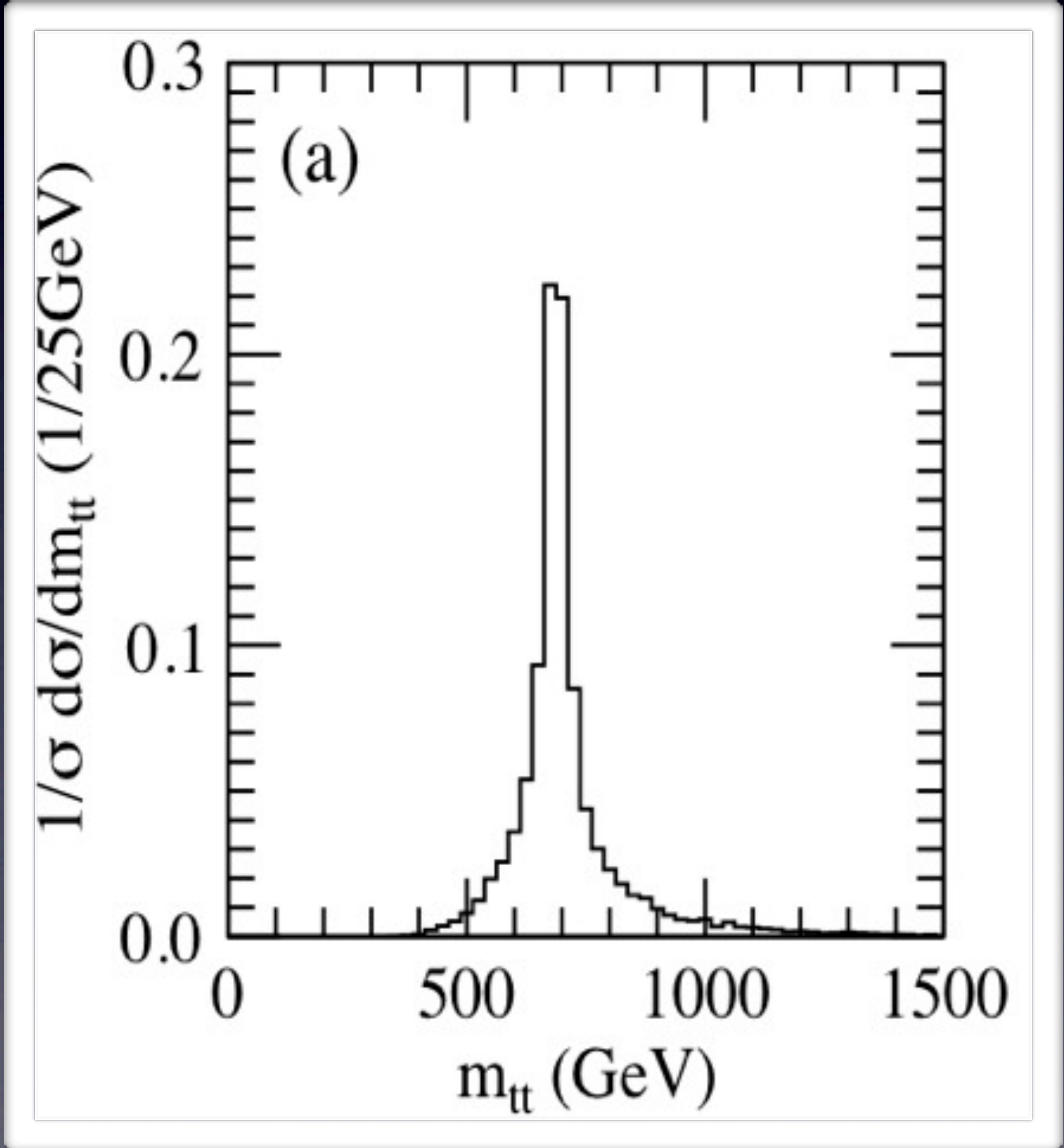
Neutrino momentum reconstruction

- Strong correlation between the true $p_x^{\nu_1}$ and reconstructed $p_x^{\nu_1}$
- The mass of heavy resonance can be determined

True $p_x^{\nu_1}$



Reconstructed $p_x^{\nu_1}$ (GeV)



Top-polarization: color sextet scalar

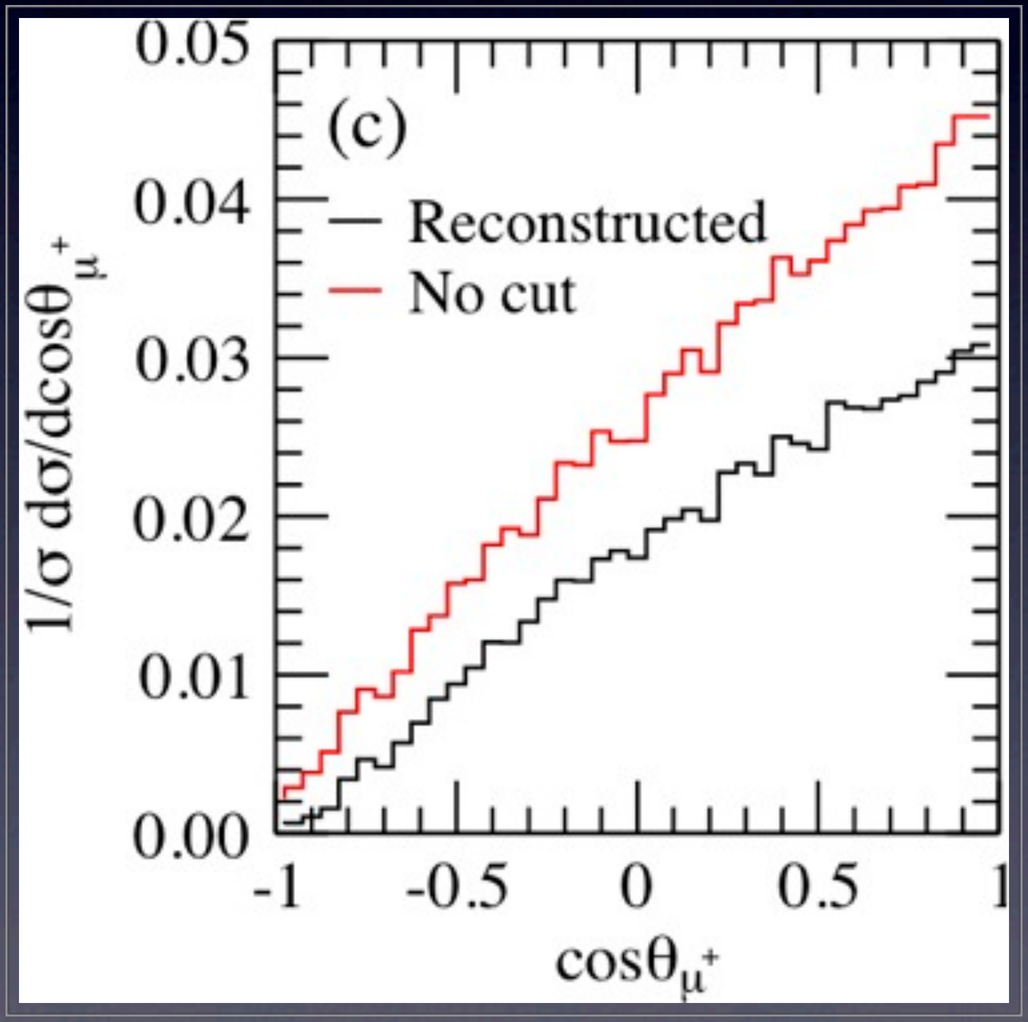
- Polarization correlates with angle between top quark spin and charged lepton momenta

$$\frac{1}{\Gamma}\frac{d\Gamma(t\to b\ell\nu)}{d\cos\theta}=\frac{1}{2}(1\pm\cos\theta)$$

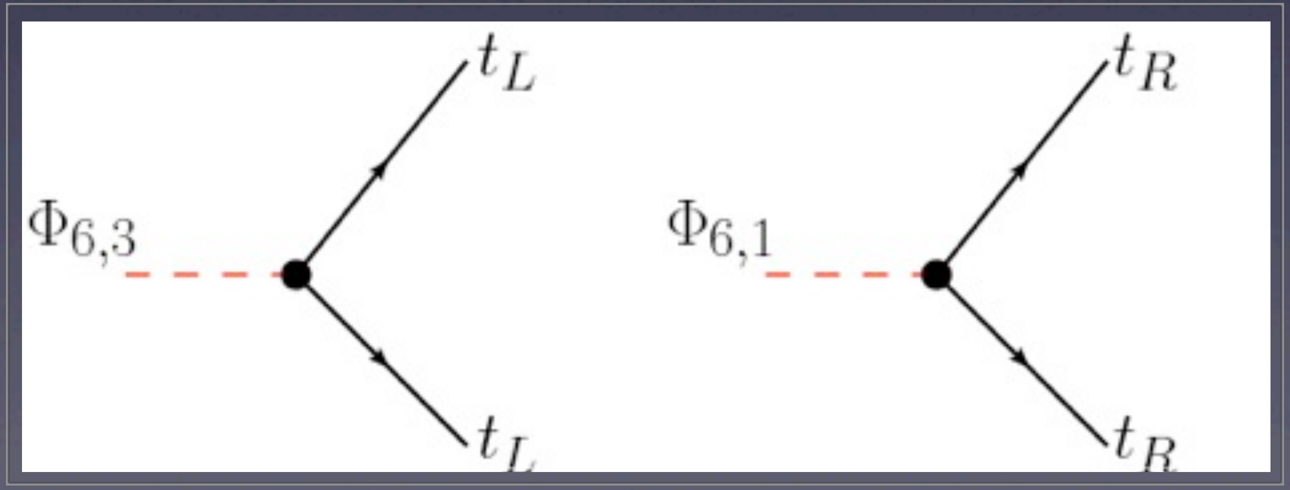
+ : right-handed

- : left-handed

Berger, QHC, Chen, Shaughnessy, Zhang, PRL 105 (2010) 181802

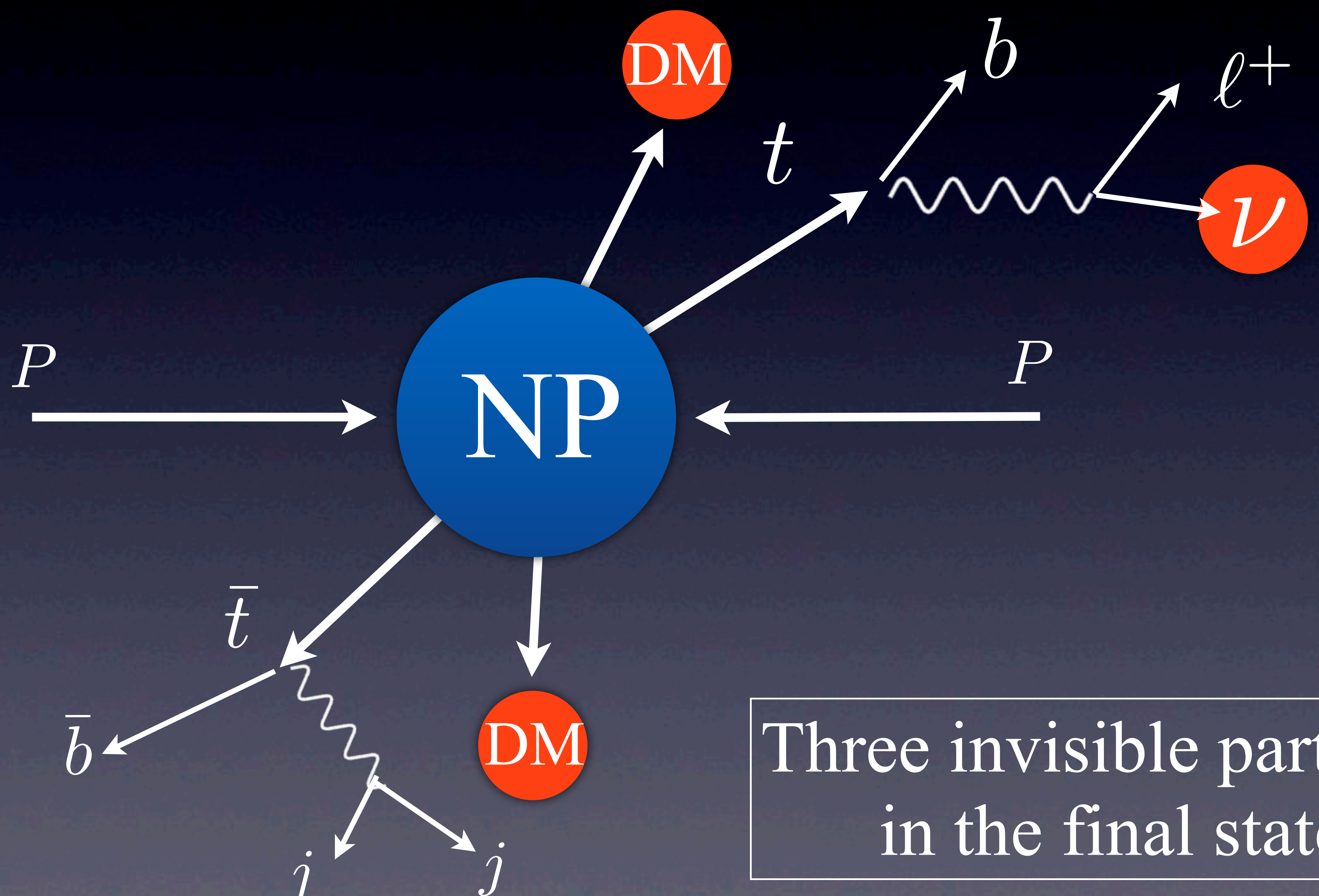


Roughly 30 events required to distinguish from unpolarized case



Top quark production in NP

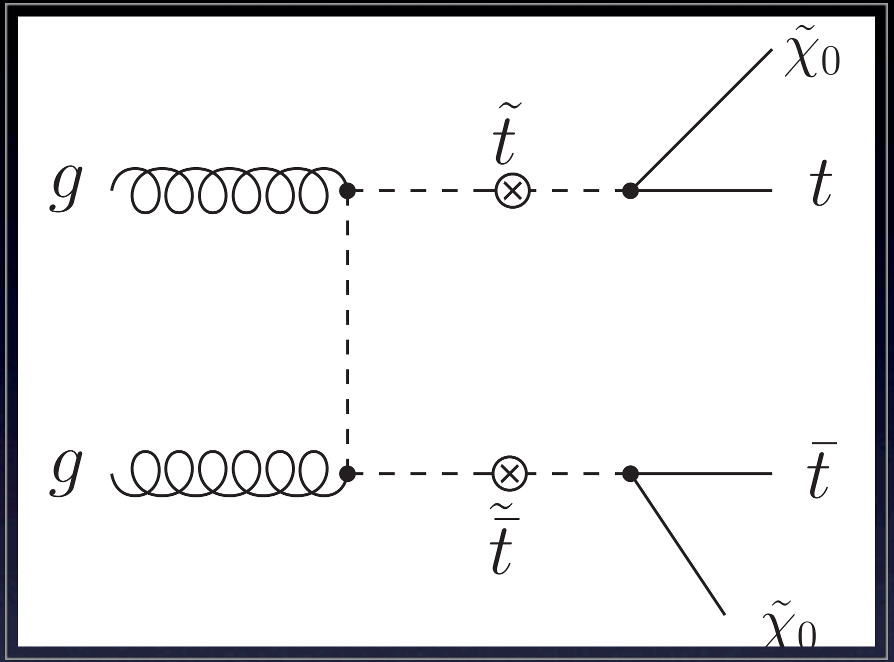
- Top-quark pair + dark matter candidates



Three invisible particles in the final state

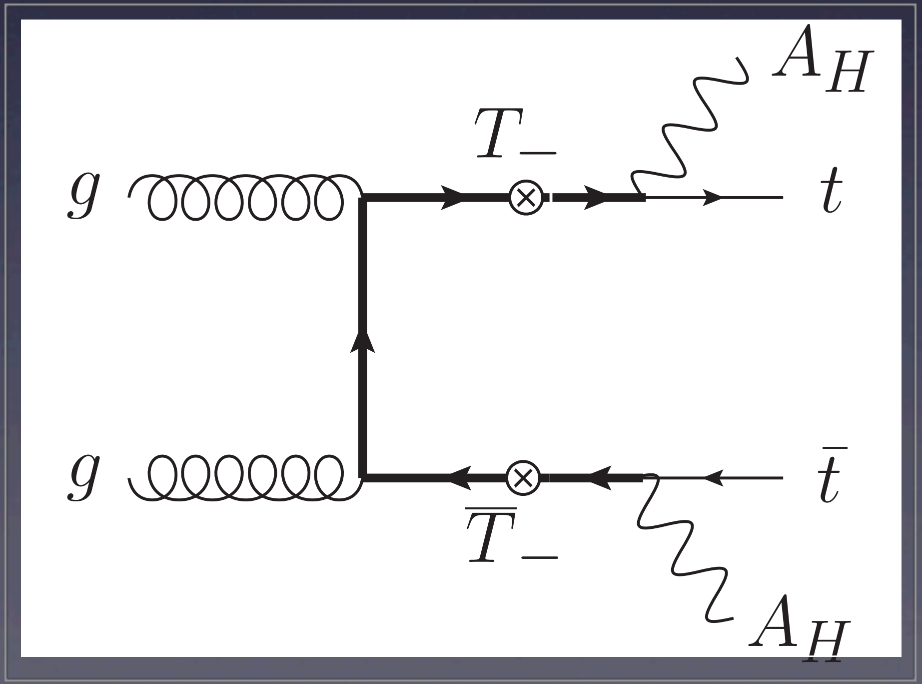
Top-quark pair plus missing energy

- Typical collider signature in several NP models
  - Minimal Supersymmetric extension of the Standard Model (MSSM)



spin 0

  - Little Higgs Model with T-parity (LHT)
  - Universal Extra Dimension Model (UED)

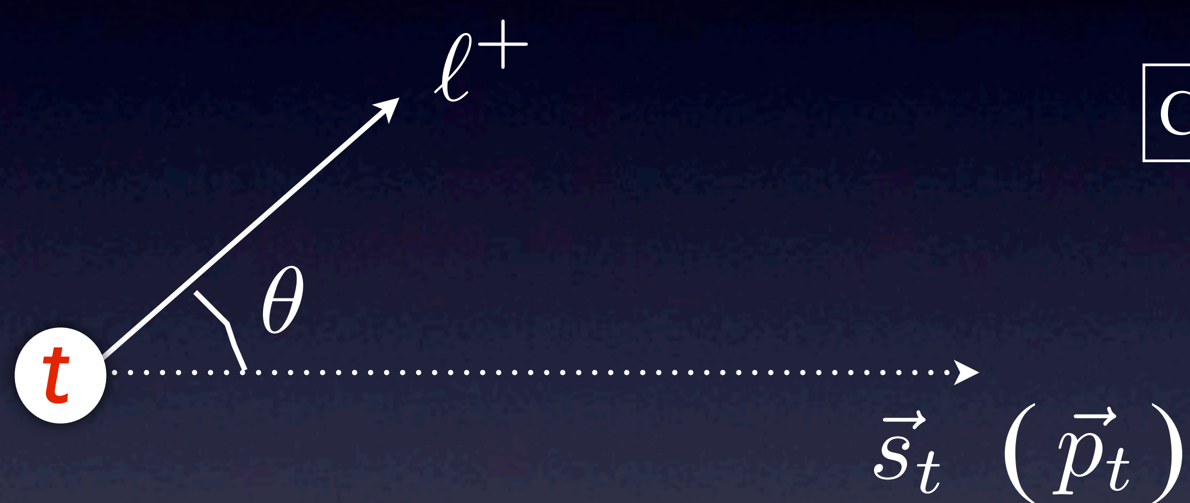


spin 1/2

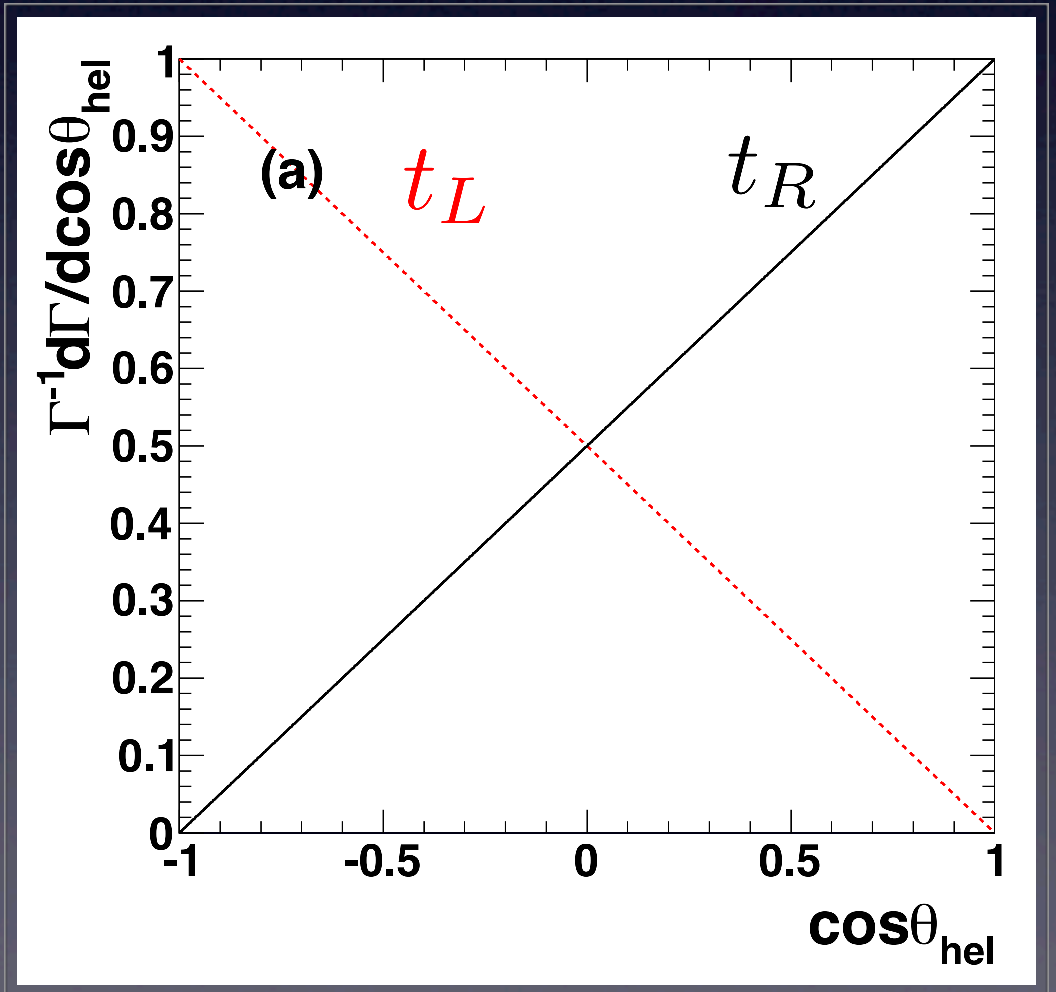
Charged lepton distribution

- In the rest frame of the top-quark

$$\frac{d\Gamma}{dx\,d\cos\theta} = \frac{\alpha_W^2 m_t}{32\pi AB}\, x(1-x)\,\mathrm{Arctan}\left[\frac{Ax}{B-x}\right] \frac{1+s_t\cos\theta}{2}$$



Czarnecki, Jezabek, Kuhn, NPB351,70 (1991)



$\lambda_t = +$ right-handed

$\lambda_t = -$ left-handed

The energy and angle are correlated when top is boosted.

Lepton energy is sensitive to top-polarization

Berger, QHC, Yu, Zhang, PRL 109 (2012) 152004

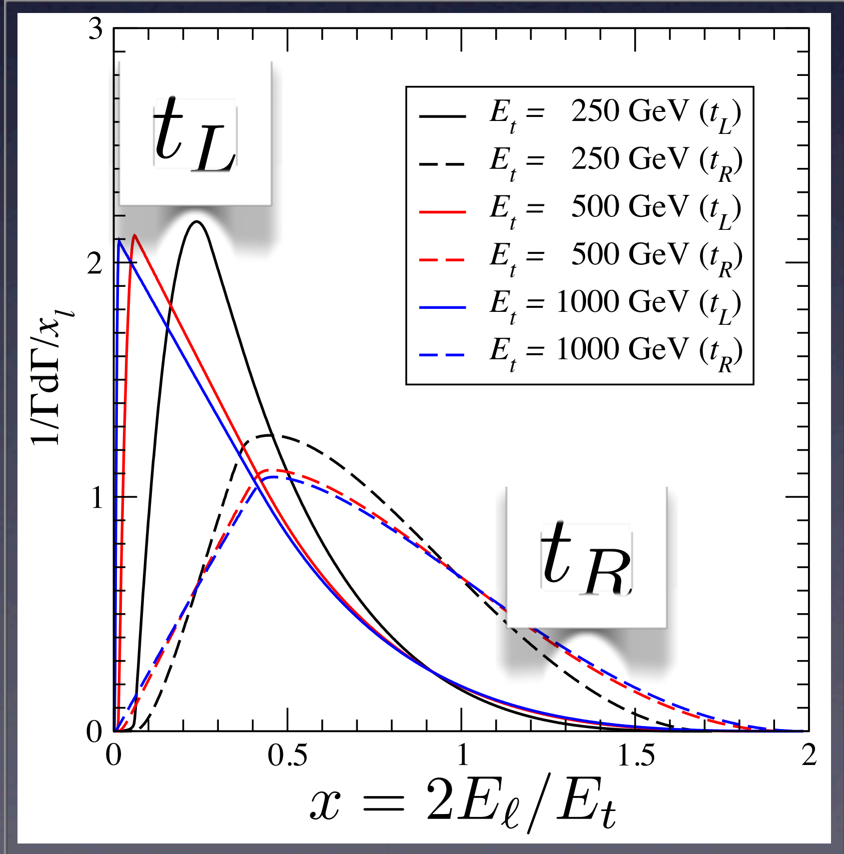
$$\frac{d\Gamma(\hat{s}_t)}{dx} = \frac{\alpha_W^2 m_t}{64\pi AB} \int_{z_{\min}}^{z_{\max}} x\gamma^2[1 - x\gamma^2(1-z\beta)] \times \left(1 + \hat{s}_t \frac{z-\beta}{1-z\beta}\right) \text{Arctan}\left[\frac{Ax\gamma^2(1-z\beta)}{B - x\gamma^2(1-z\beta)}\right] dz$$

$$A = \frac{\Gamma_W}{m_W} \qquad B = \frac{m_W^2}{m_t^2} \approx 0.216$$

$$\gamma = \frac{E_t}{m_t} \qquad \beta = \sqrt{1 - 1/\gamma^2}$$

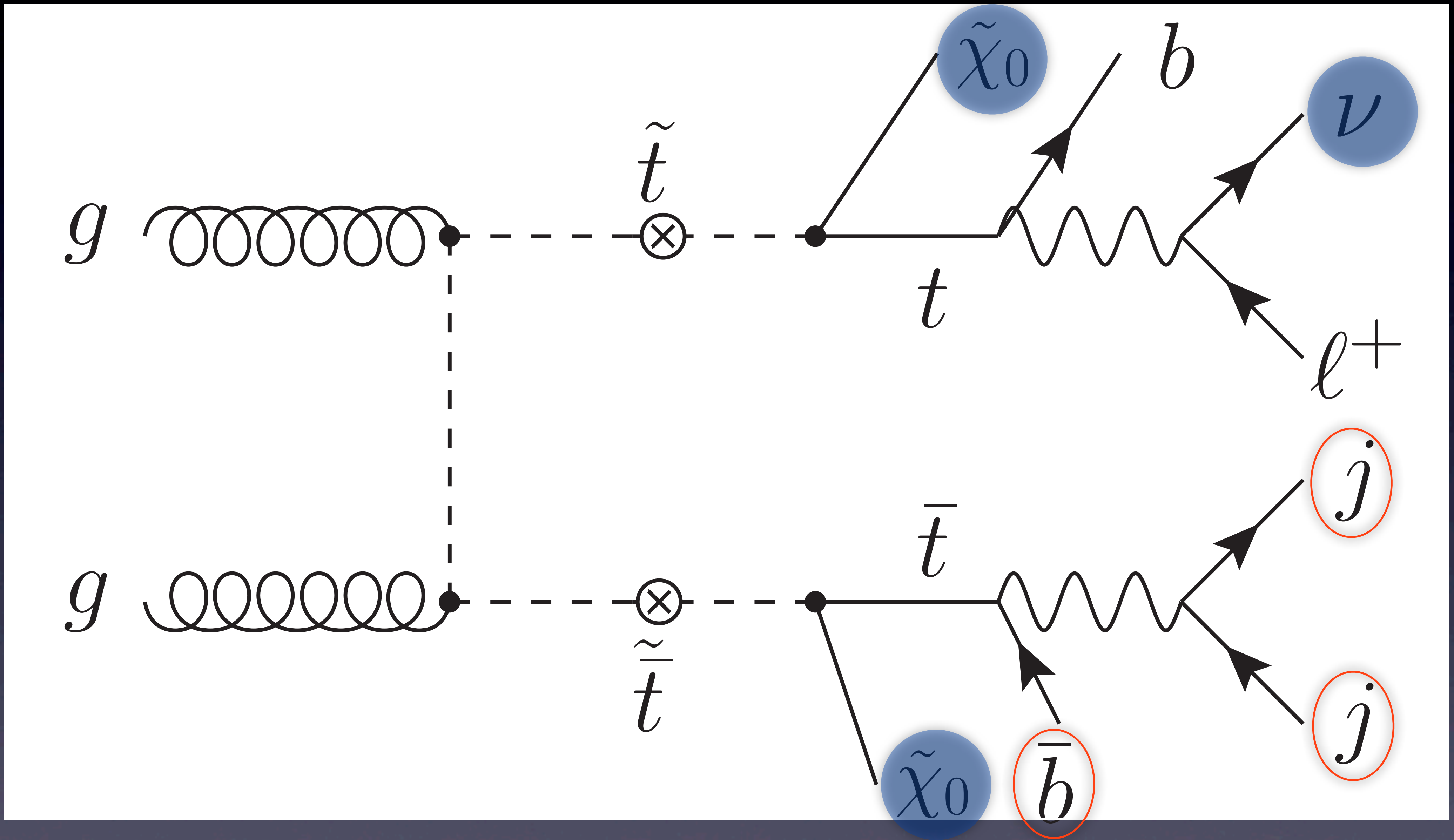
$$z_{\min} = \max[(1 - 1/\gamma^2 x)/\beta, -1]$$

$$z_{\max} = \min[(1 - B/\gamma^2 x)/\beta, 1]$$



Lepton energy and top-quark polarization

- Identical decay chains

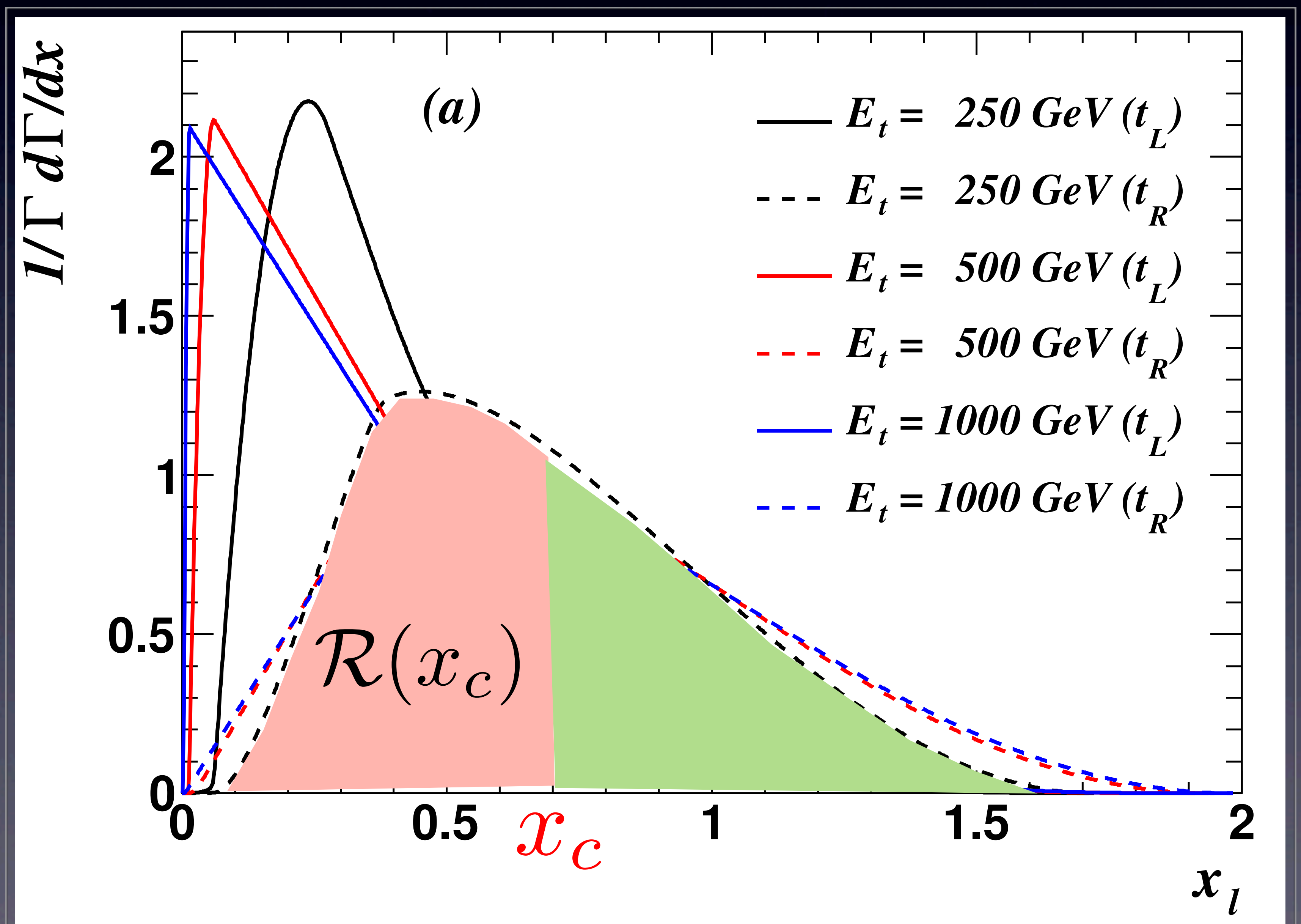


$$x'_\ell = 2E_{\ell^+} / E_{\bar{t}}$$

Lepton energy and top-quark polarization

- Define a variable $\mathcal{R}$ to quantify the difference between t_L and t_R

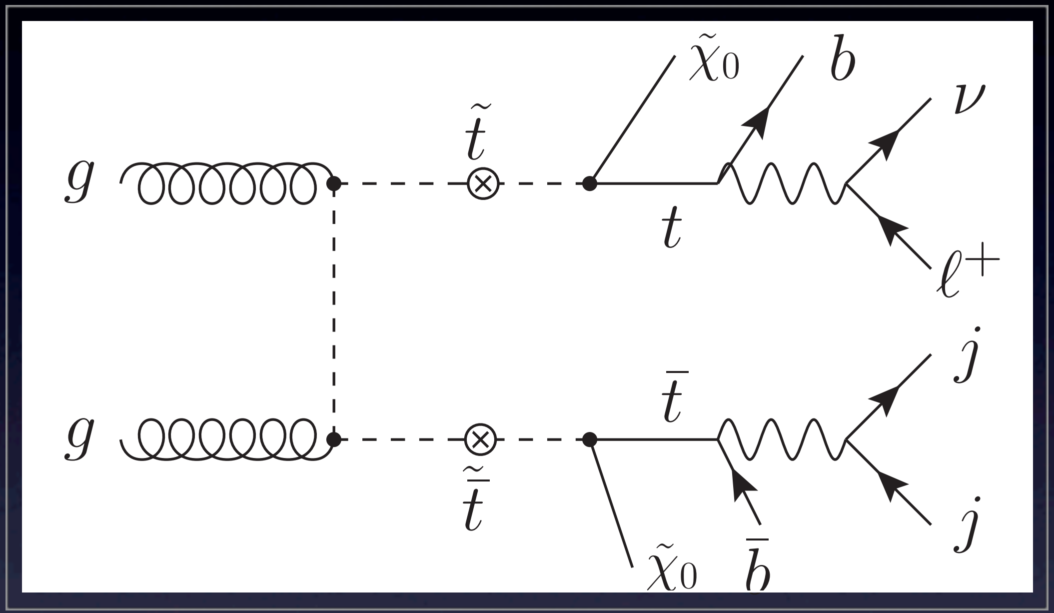
$$\mathcal{R}(x_c) \equiv \frac{\text{Area}(x_\ell < x_c)}{\text{Area(tot)}} = \text{Area}(x_\ell < x_c)$$



Toy model mimicking MSSM

- MSSM like:

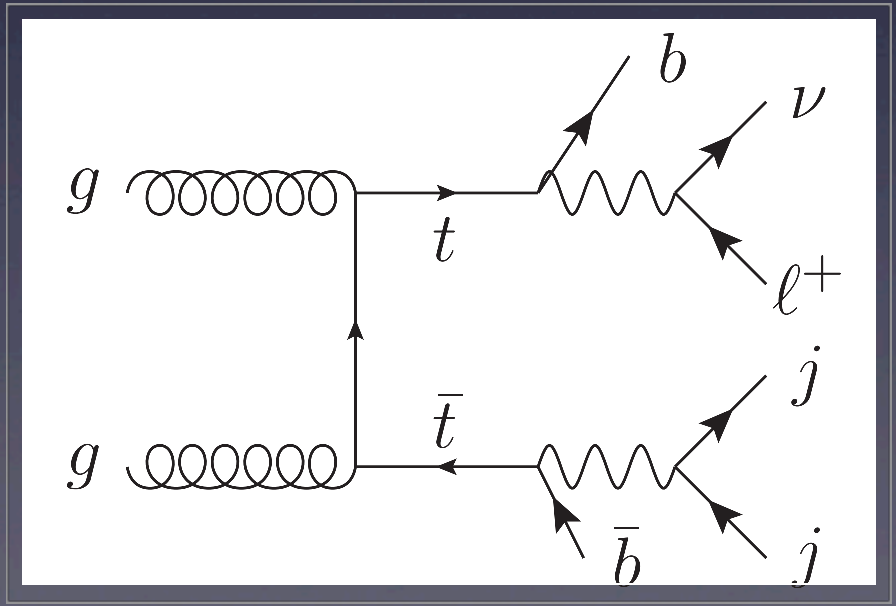
$$\mathcal{L}_{\tilde{t}t\tilde{\chi}} = g_{\text{eff}}\tilde{t}\tilde{\chi}(\cos\theta_{\text{eff}}P_L + \sin\theta_{\text{eff}}P_R)t$$

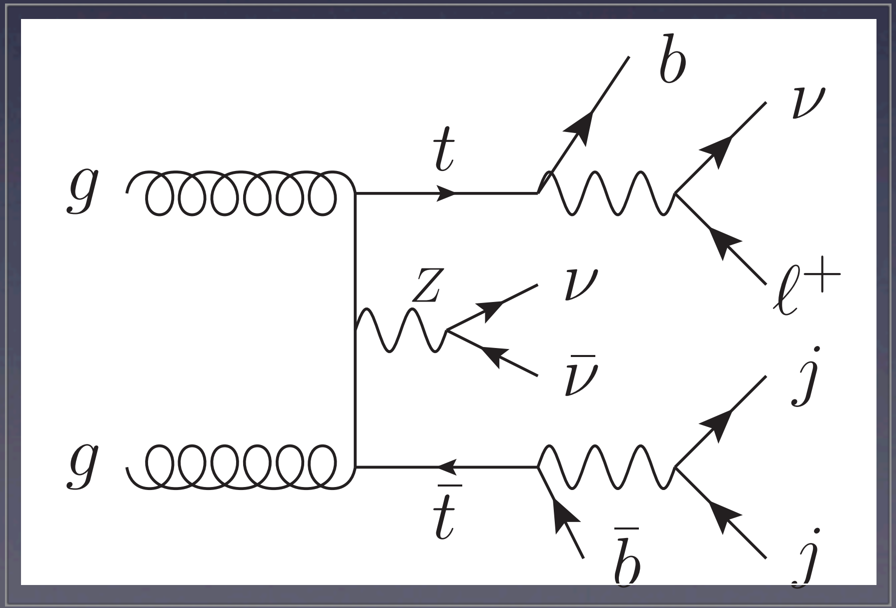


Collider signature

$b\bar{b}jj\ell^+\not{E}_T$

- Major SM backgrounds

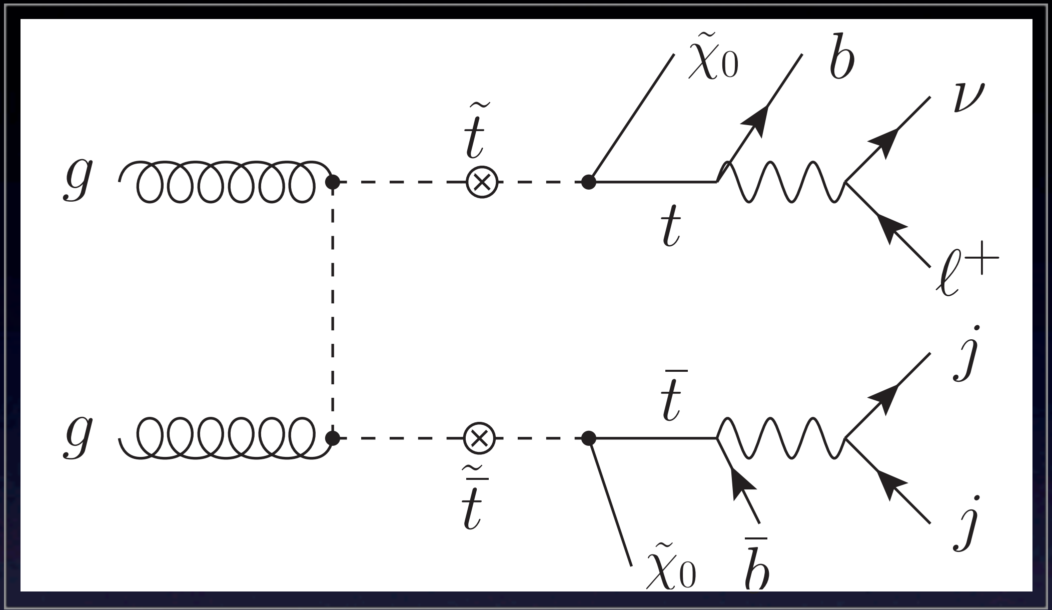




Collider simulation

- Basic selection cuts

$m_{\tilde{t}} = 360\ \text{GeV} \quad m_{\tilde{\chi}} = 50\ \text{GeV}$



$$p_T^\ell > 20\ \text{GeV} \quad p_T^j > 25\ \text{GeV}$$

$$\not{E}_T > 25\ \text{GeV} \quad \Delta R_{jj,\ell j} > 0.4$$

$$|\eta_{\ell,j}| < 2.5$$

- Hard cuts

$$\not{E}_T > 100\ \text{GeV} \qquad H_T > 500\ \text{GeV}$$

$$H_T = p_T^\ell + p_T^{j_1} + p_T^{j_2} + p_T^b + p_T^{\bar{b}} + \not{E}_T$$

- $\bar{t} \to 3j$ reconstruction (Minimal-χ^2 method)
  Loop over all jet combinations and pick up the one minimize

$$\chi^2 = \frac{(m_W - m_{jj})^2}{\Delta m_W^2} + \frac{(m_t - m_{jjj})^2}{\Delta m_t^2}$$

Signal versus Backgrounds

- Cross section (fb) of signal and backgrounds at 14TeV LHC

	Basic	t_{had} *recon.*	*Hard*	$\not{E}_T$ *sol.*	$\epsilon_{\rm cut}$
signal	22.26	18.46	8.87	6.51	11.6 %
$t\bar{t}$	4347.08	3596.75	154.47	0.91	0.00556%
$t\bar{t}Z$	1.25	1.03	0.34	0.22	5.9 %

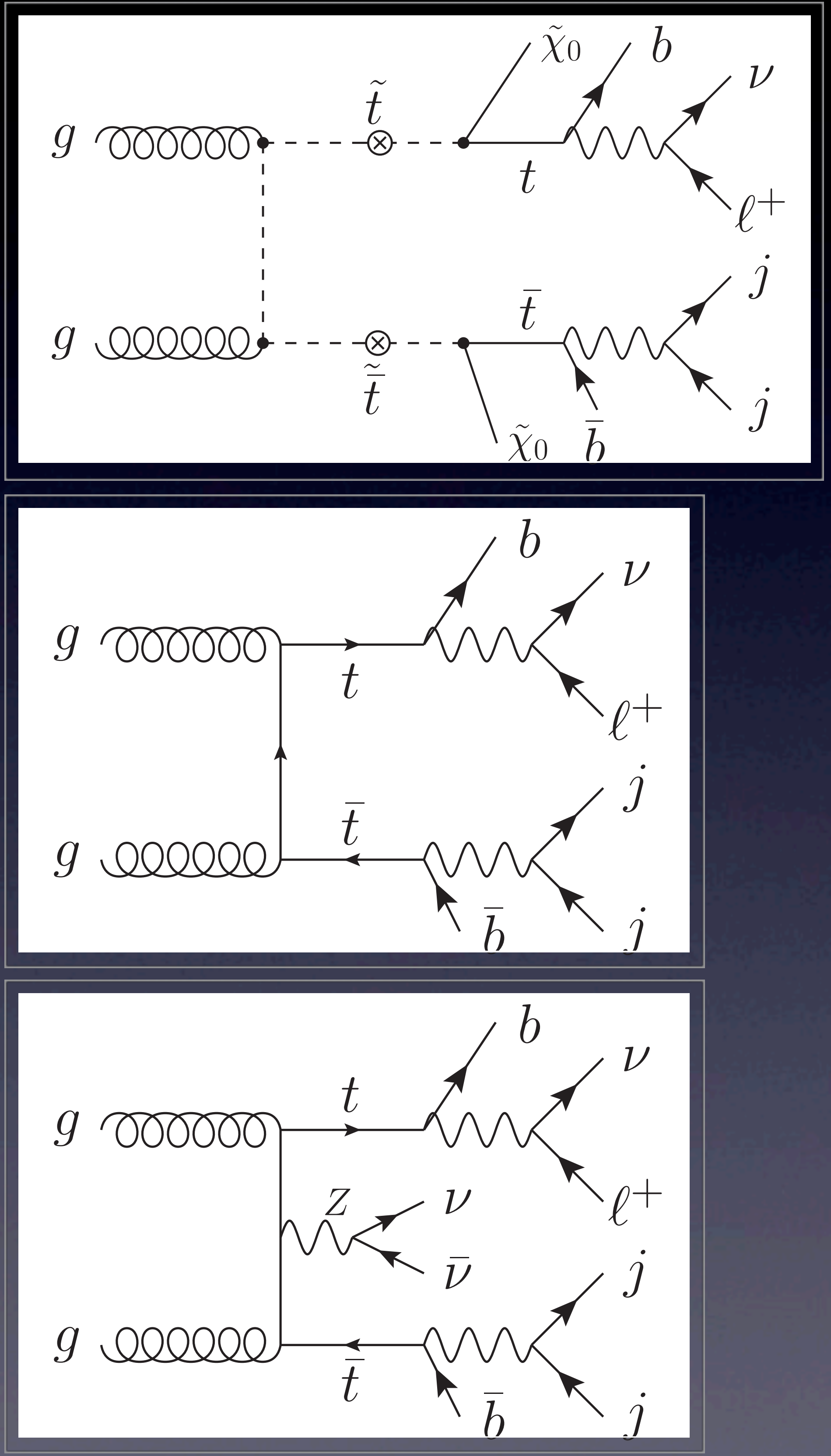
- $\not{E}_T$ solution cut

$$p_z^\nu = \frac{1}{2(p_T^e)^2}\left[A\,p_z^e \pm E_e\sqrt{A^2 - 4\,(p_T^e)^2\,\not{E}_T^2}\right]$$

$$A \equiv m_W^2 + 2\,\vec{p}_T^{\,e}\cdot\vec{\not{E}}_T$$

$$\boxed{A^2 - 4\,(p_T^e)^2\,\not{E}_T^2 \le 0}$$

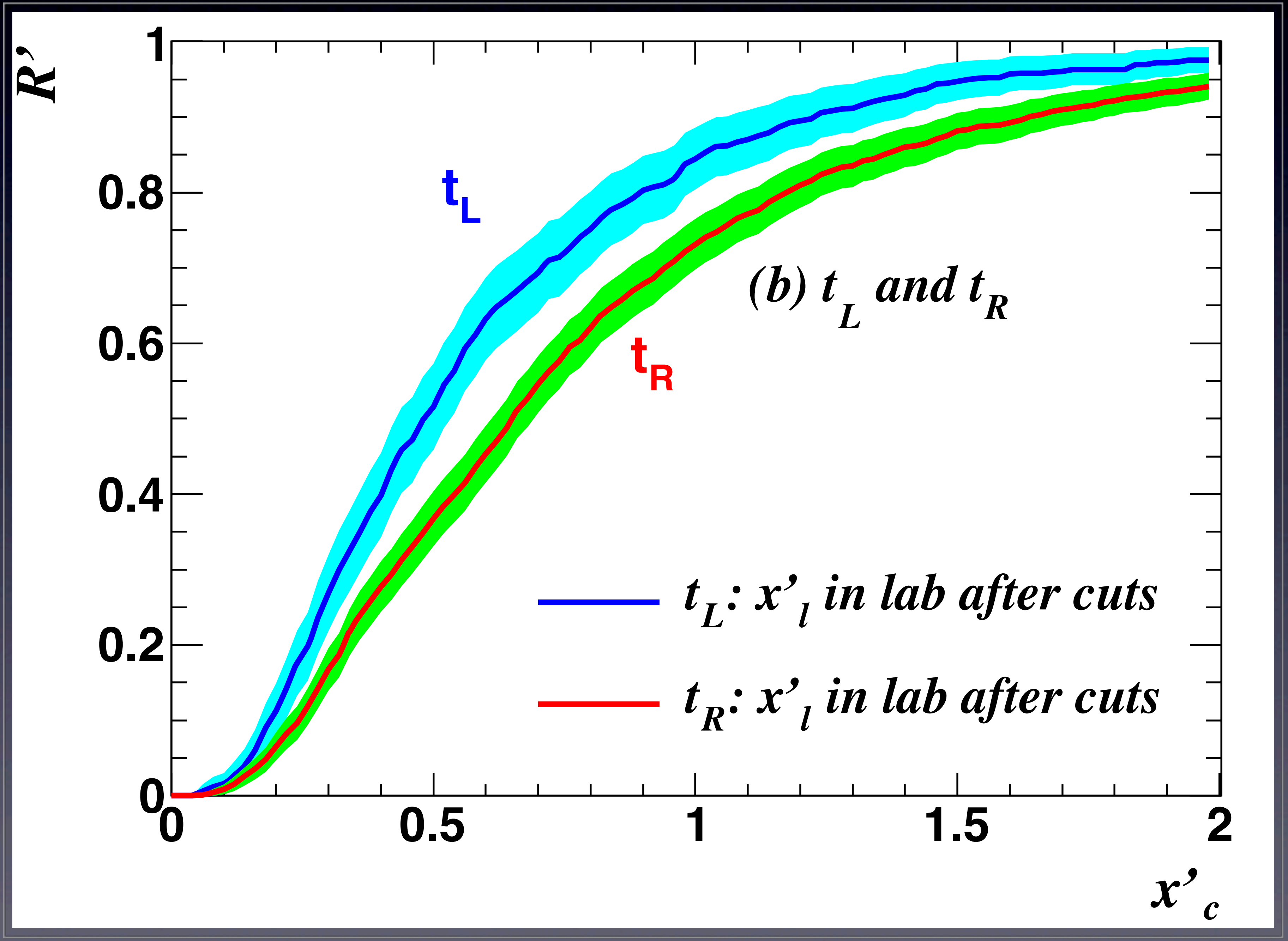
Han, Mahbubani, Walker, Wang, JHEP 0905, 117 (2009)



$\mathcal{R}'$ distribution

- t_L and t_R are separated

Berger, QHC, Yu, Zhang, PRL 109 (2012) 152004



LHC
14 TeV
$100 fb^{-1}$

Summary

Top-quark polarization is a powerful discriminator of new physics models.

1. W-prime and Z-prime bosons

   Single-top production and top-quark pair production

   1 invis

2. Color sextet scalars

   Same-sign top-quark pair production

   2 invis

3. Measuring top-polarization in $t\bar{t}+\not{E}_T$ events

   Top-squarks in MSSM and T-odd top-partners in LHT

   3 invis

THANK YOU!