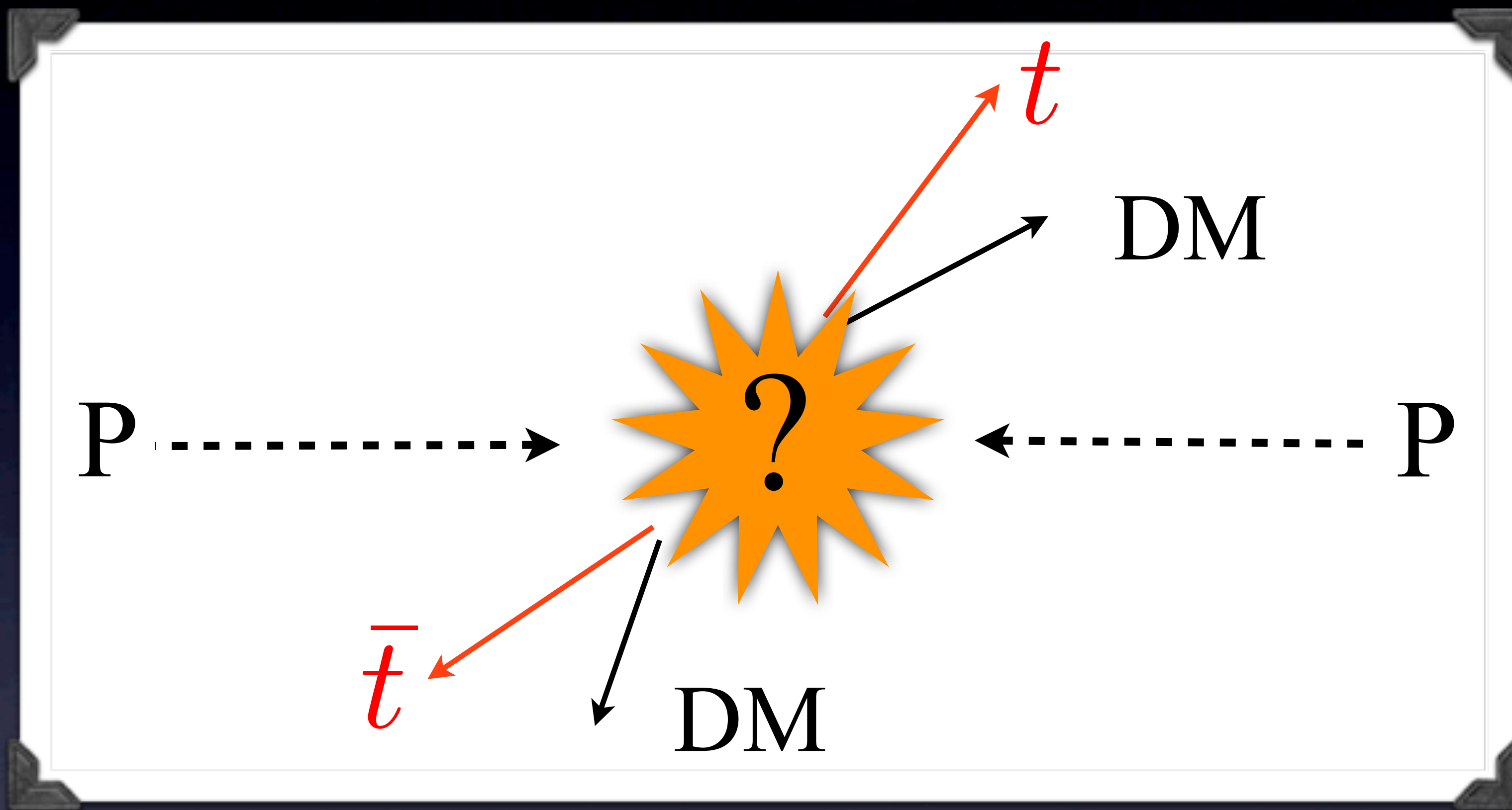
Measuring Top-Quark Polarization in Top-Pair + Missing-Energy Events



Qing-Hong Cao

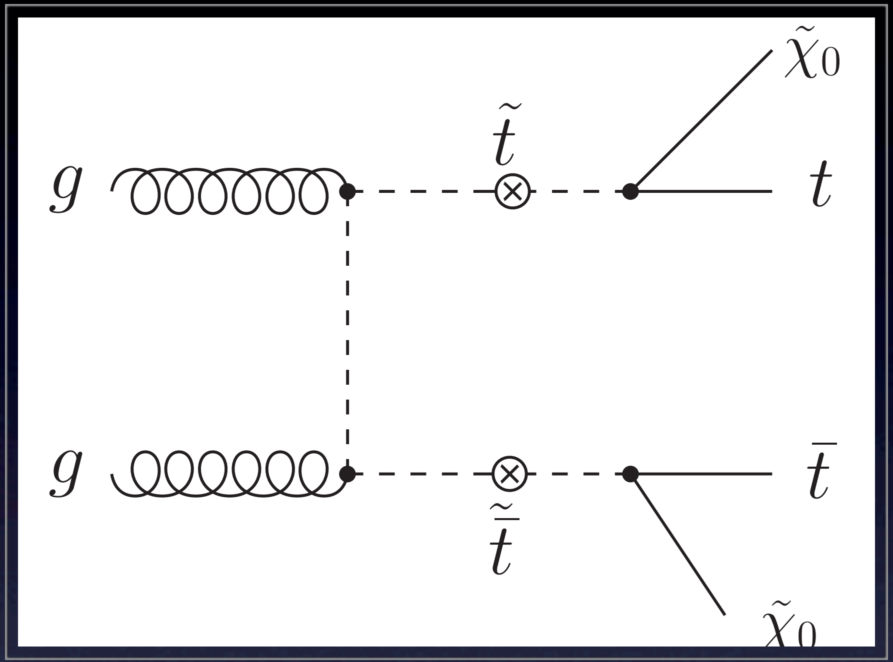
Peking University

Reference:

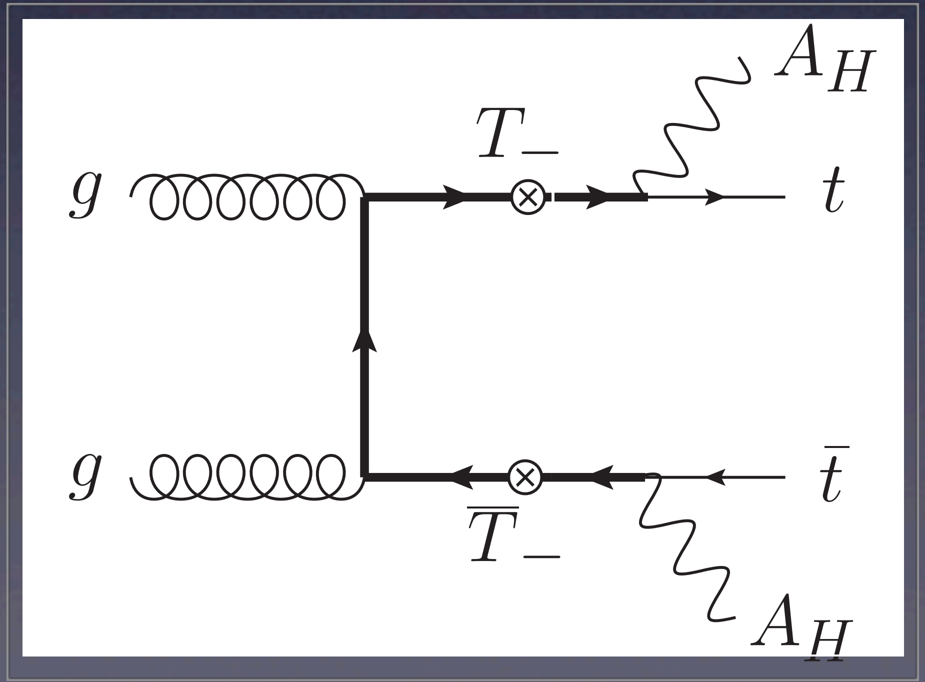
E. L. Berger, Q.-H. Cao, J.-H. Yu, H. Zhang, Phys. Rev. Lett. 109, 152004 (2012)

Top-quark pair plus missing energy

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



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



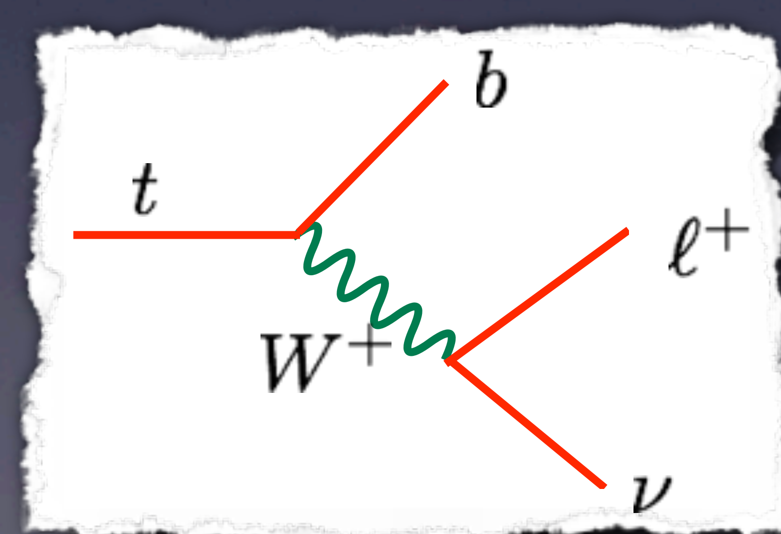
Top quark is very special

- Large mass：   173 GeV ~ VEV (246GeV) $y_t \sim O(1)$
- Short lifetime:

$\dfrac{1}{m_t}$ 5×10^{-27} s $\dfrac{1}{\Gamma_t}$ 5×10^{-25} s $\dfrac{1}{\Lambda_{\mathrm{QCD}}}$ 3×10^{-24} s   hadronization

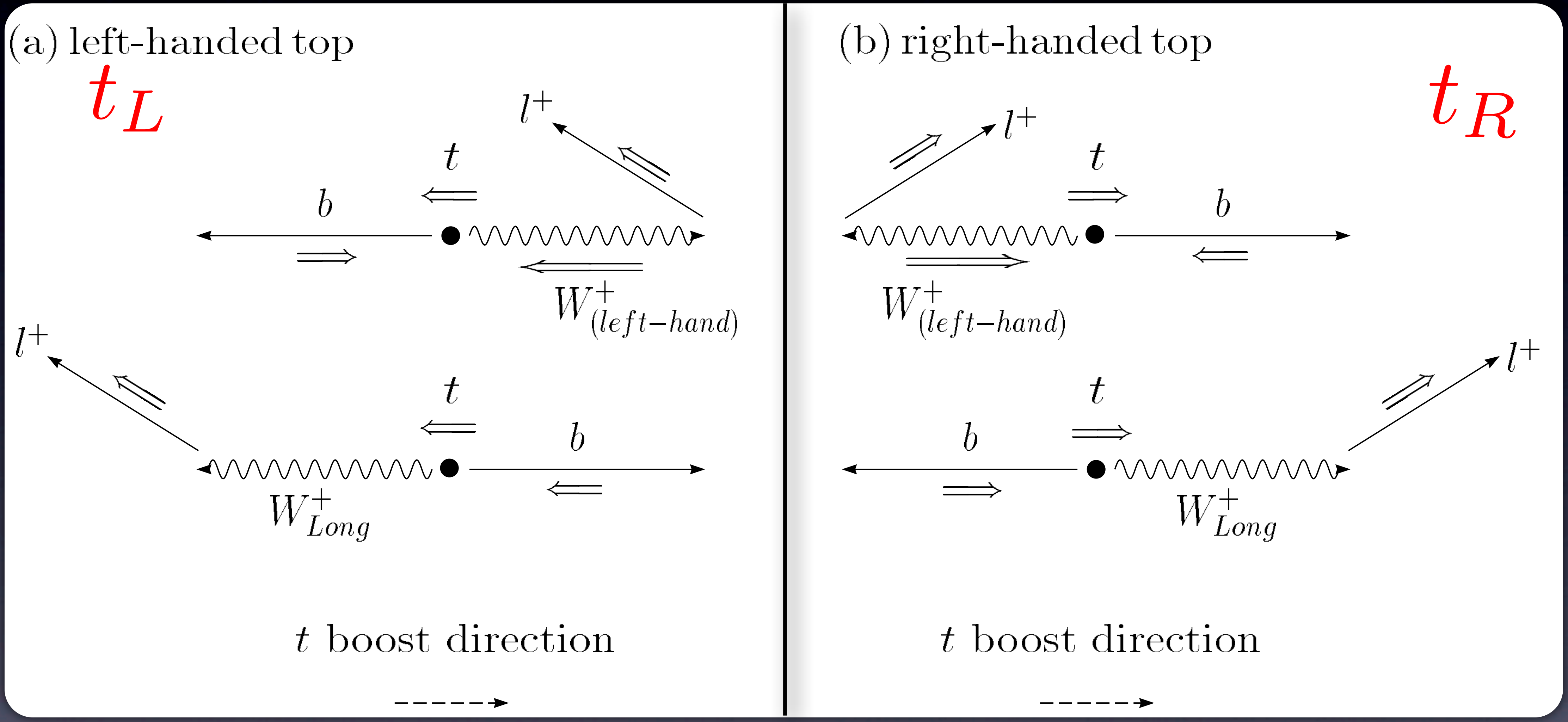
- "bare" quark：

  spin info well kept among
  its decay products



Measuring t-polarization

- Traditional method of measuring top-polarization is through the angle between the charged lepton and top-quark spin.



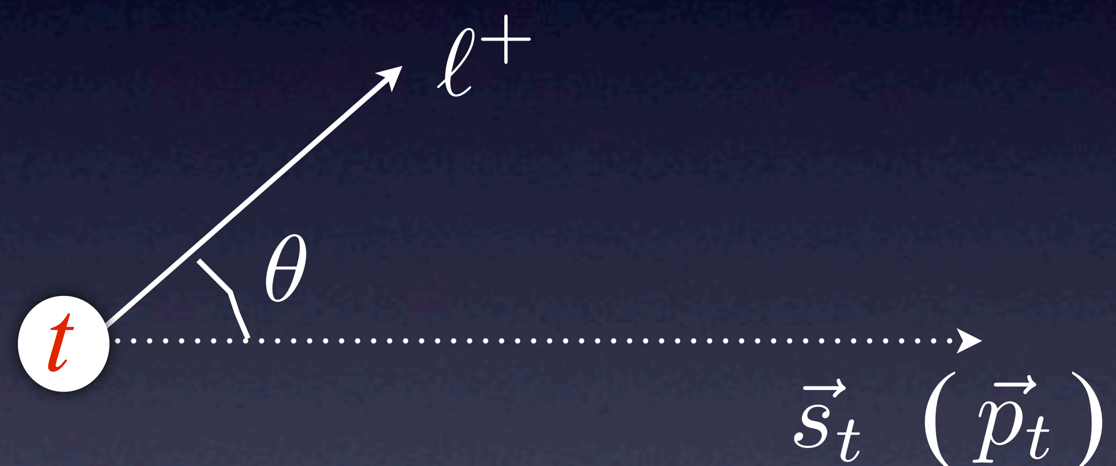
The charged-lepton tends to *follow* the top-quark spin direction.

Charged lepton distribution

- In the rest frame of the top-quark

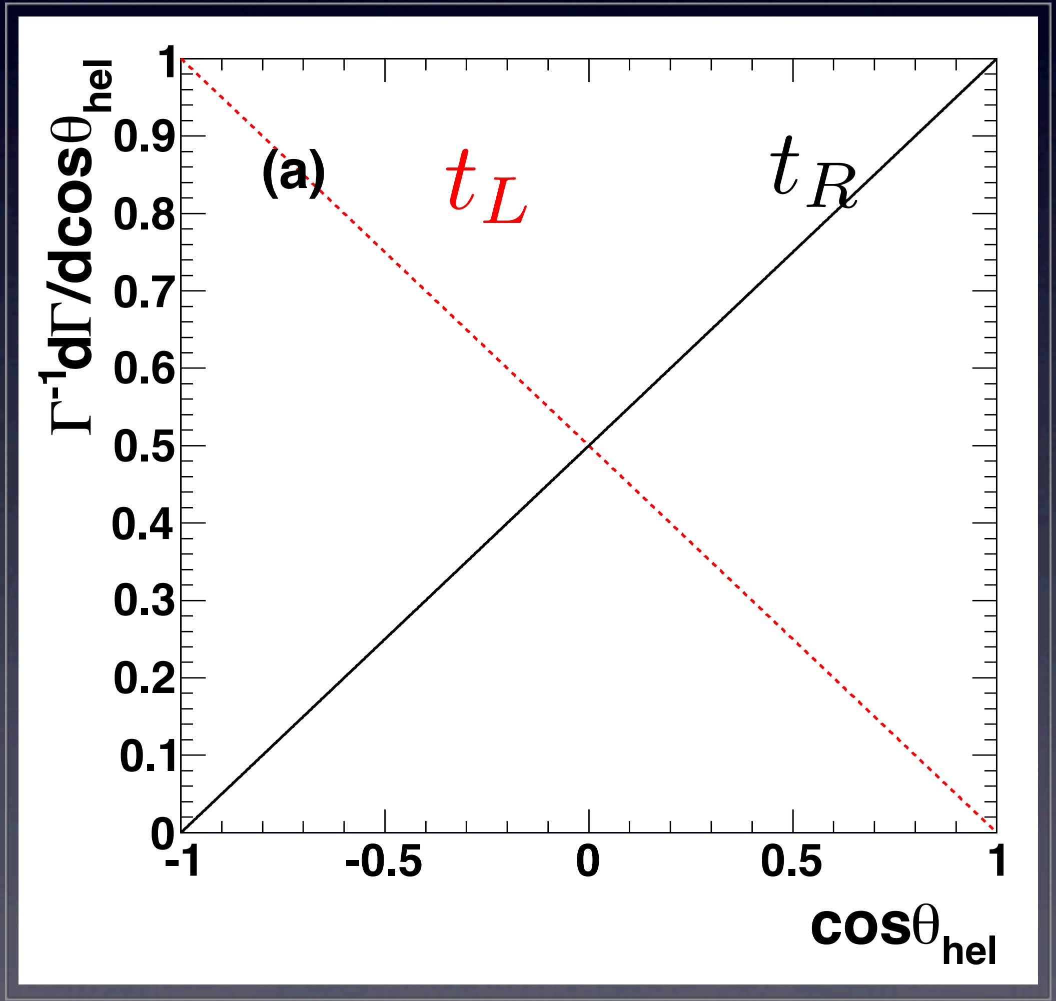
$$\frac{d\Gamma}{dx\,d\cos\theta} = \frac{\alpha_W^2 m_t}{32\pi AB} x(1-x)\,\mathrm{Arctan}\left[\frac{Ax}{B-x}\right] \frac{1+\lambda_t\cos\theta}{2}$$

$$x \equiv 2E_\ell/E_t$$



$\lambda_t = +$ right-handed

$\lambda_t = -$ left-handed

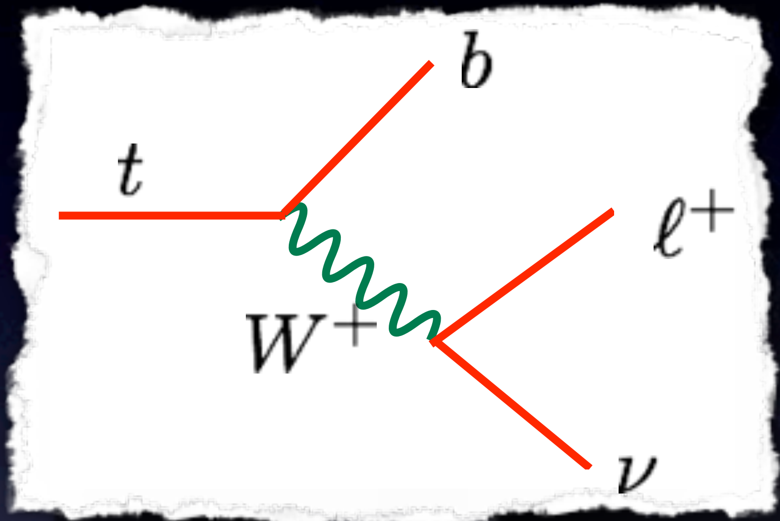


$\boxed{\text{Top-quark momentum has to be known}}$

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

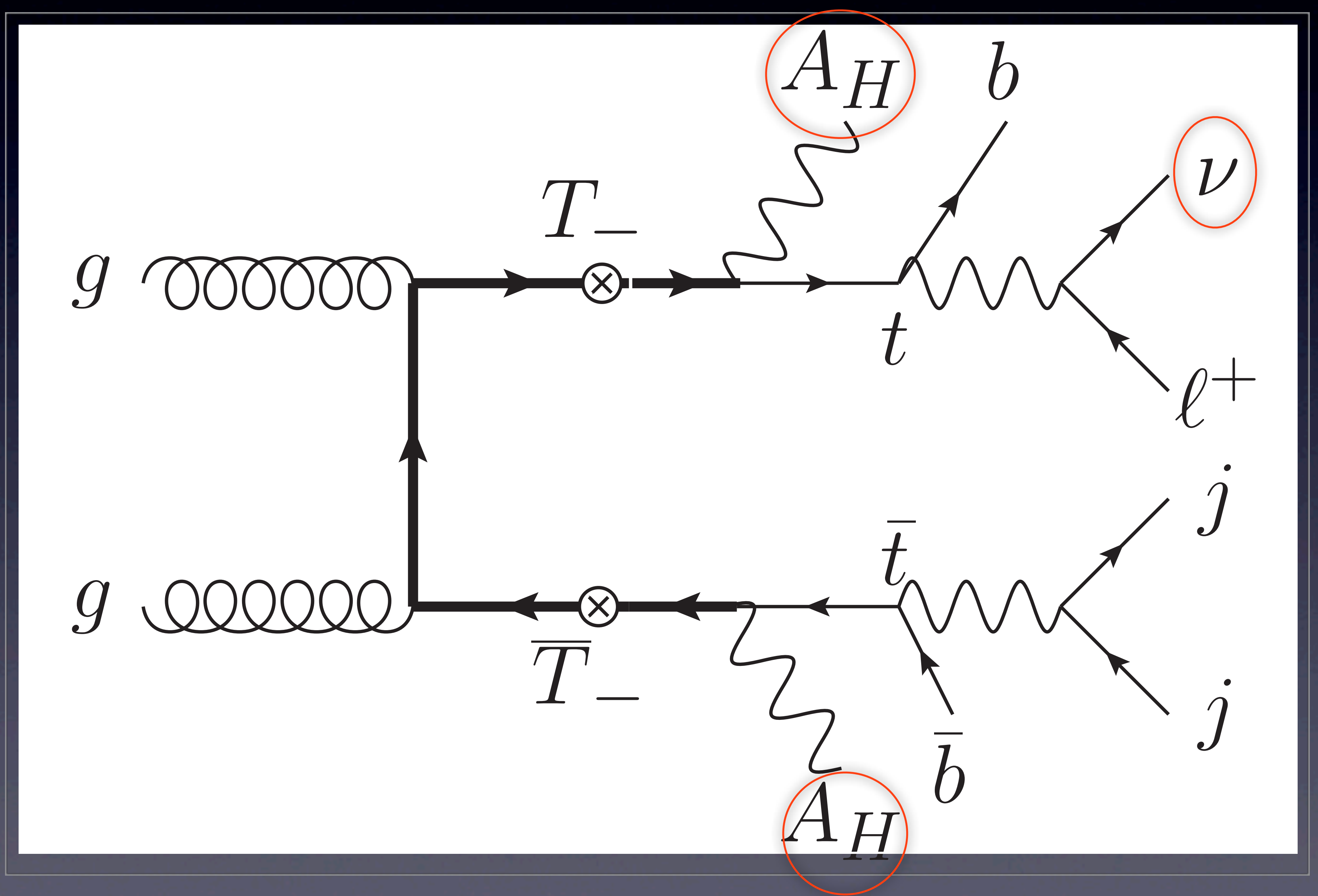
$$\boxed{m_W^2 = (p_\ell + p_\nu)^2}$$

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

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

Difficulty in $t\bar{t} + \not{E}_T$ events

- It is impossible to reconstruct a top-quark in the leptonic-decay mode. Angular distribution of the charged-lepton cannot be used.



Masses and spins of T_- and A_H are unknown.

Our goal

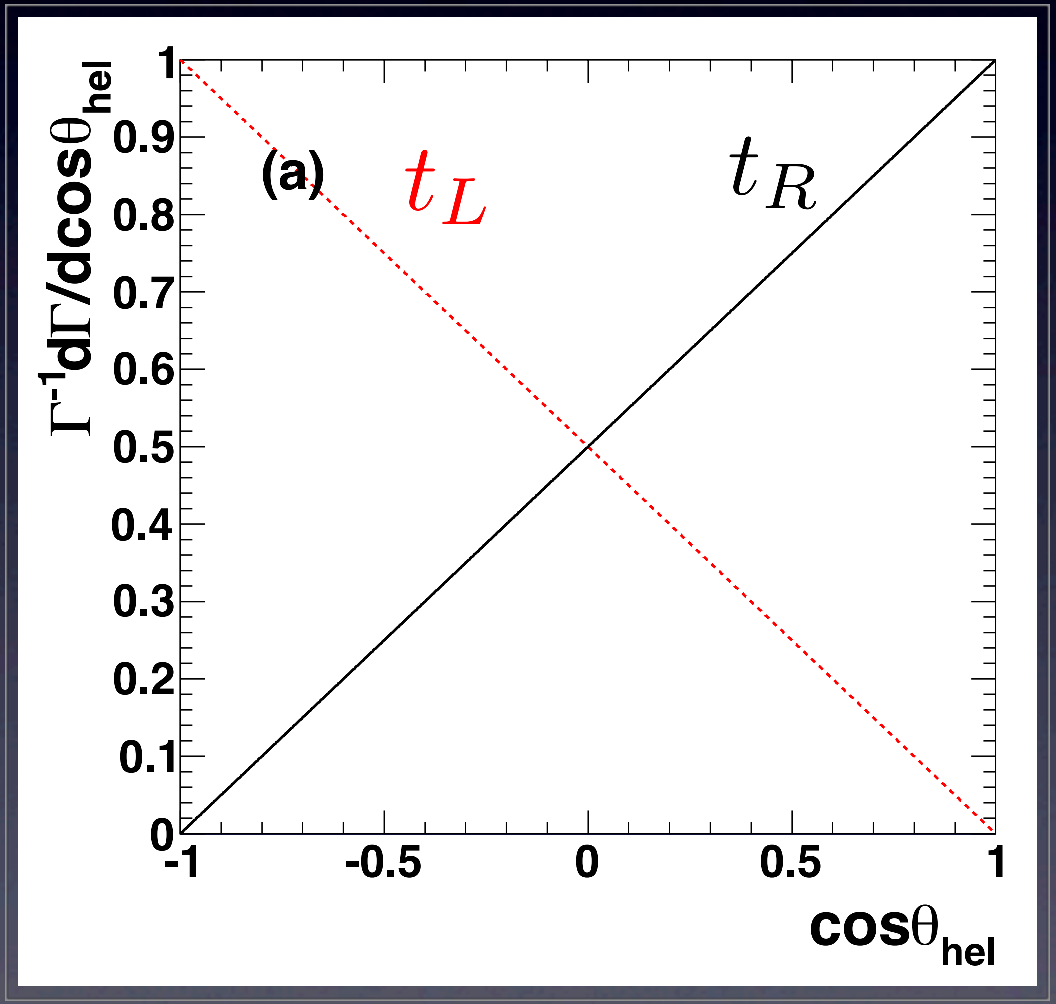
- is to find a method to measure top-quark polarization without knowing top-quark kinematics.

- Advantages of our method:
  - ✓ It is sensitive to the top-quark polarization.
  - ✓ It is not sensitive to the mass splitting between a heavy resonance parent and the DM candidate, provided that this splitting is not too small.
  - ✓ The difference between t_L and t_R is not sensitive to the spin of a heavy parent resonance *or* to the collider energy.

Charged lepton distribution

- In the rest frame of the top-quark

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



$\lambda_t = +$ right-handed

$\lambda_t = -$ left-handed

The energy and angle are correlated once top-quark is boosted in the Lab frame

Lepton energy and top-quark polarization

★ Lepton energy distribution is sensitive to top quark polarization.

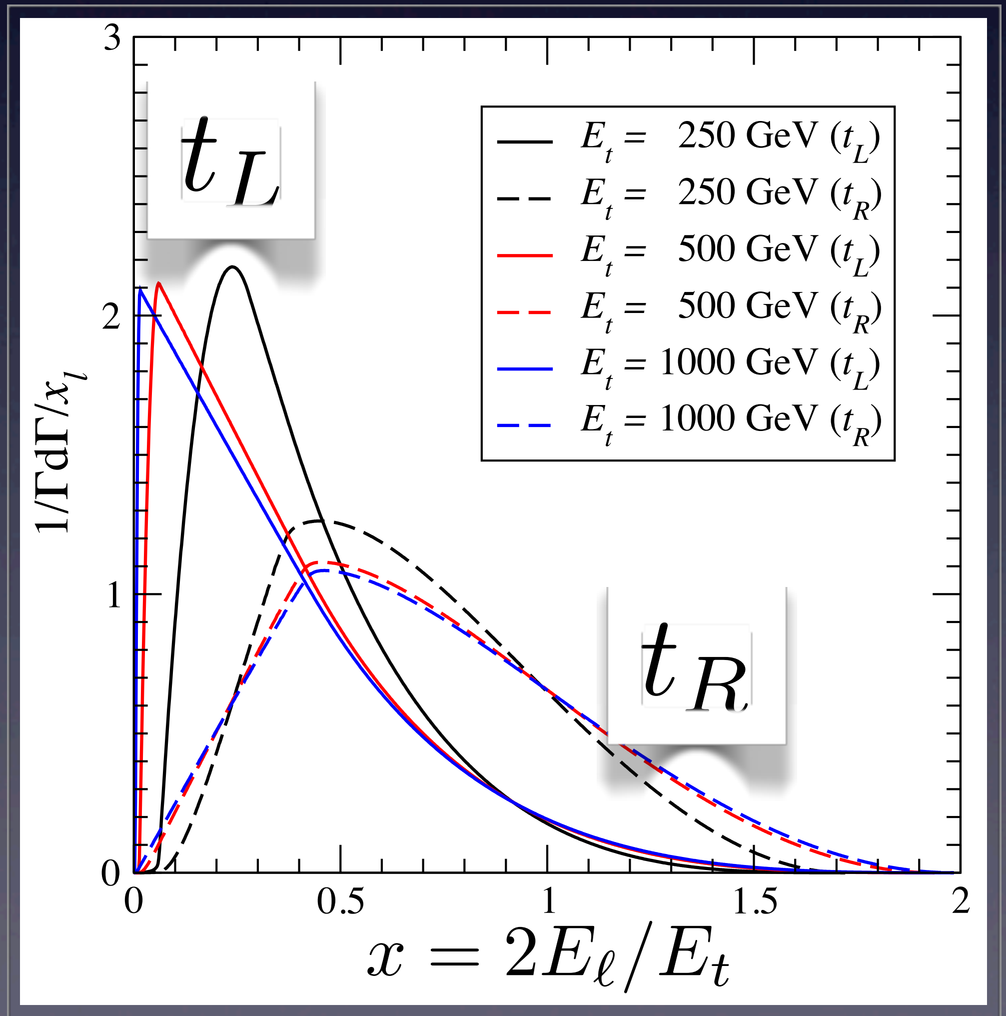
$$\frac{d\Gamma(\hat{s}_t)}{dx} = \frac{\alpha_W^2 m_t}{64\pi AB}\int_{z_{\min}}^{z_{\max}} x\gamma^2[1-x\gamma^2(1-z\beta)] \times \left(1+\hat{s}_t\frac{z-\beta}{1-z\beta}\right)\mathrm{Arctan}\left[\frac{Ax\gamma^2(1-z\beta)}{B-x\gamma^2(1-z\beta)}\right]dz$$

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

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

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

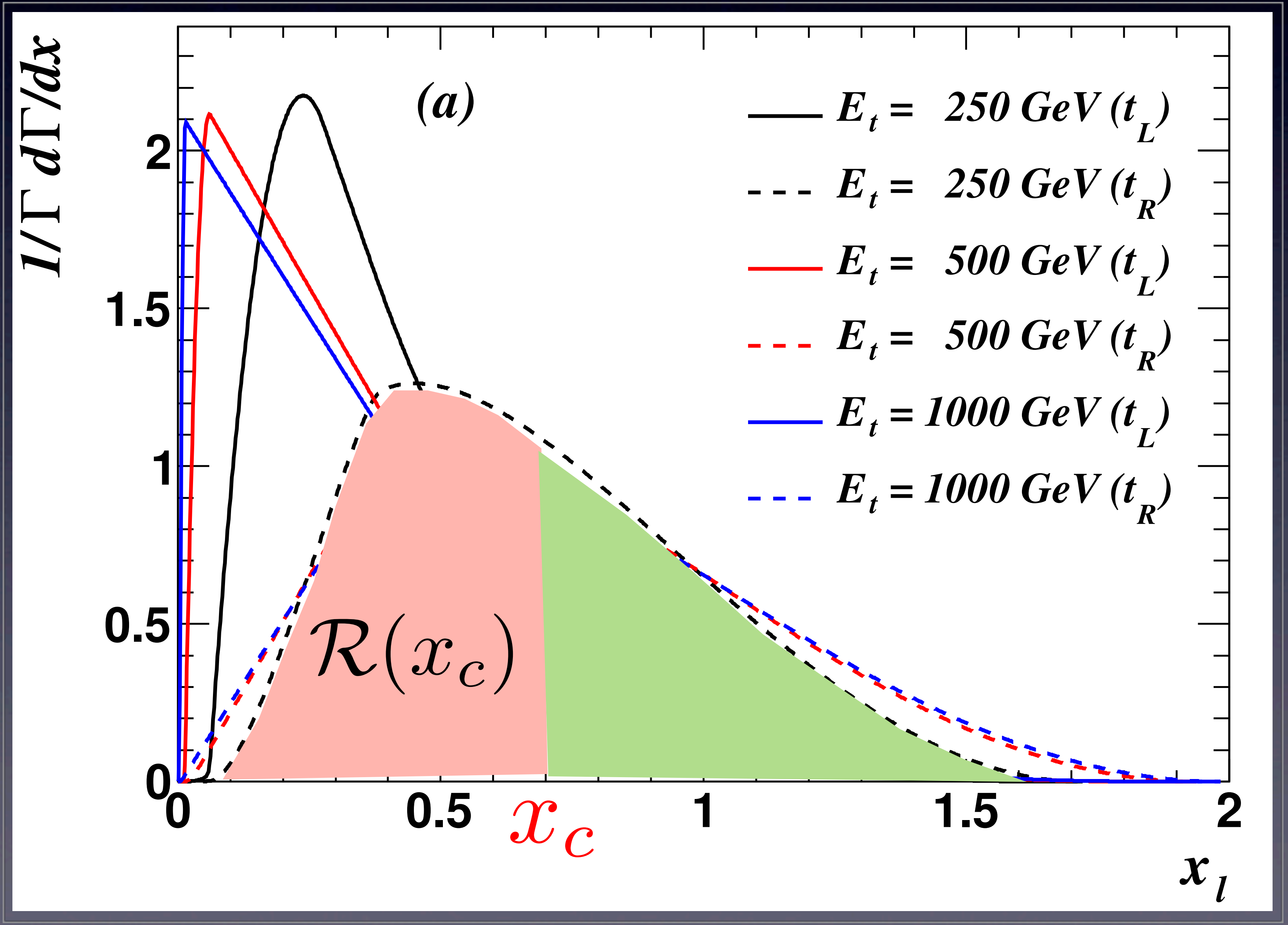
$$z_{\max} = \min[(1-B/\gamma^2 x)/\beta, 1]$$



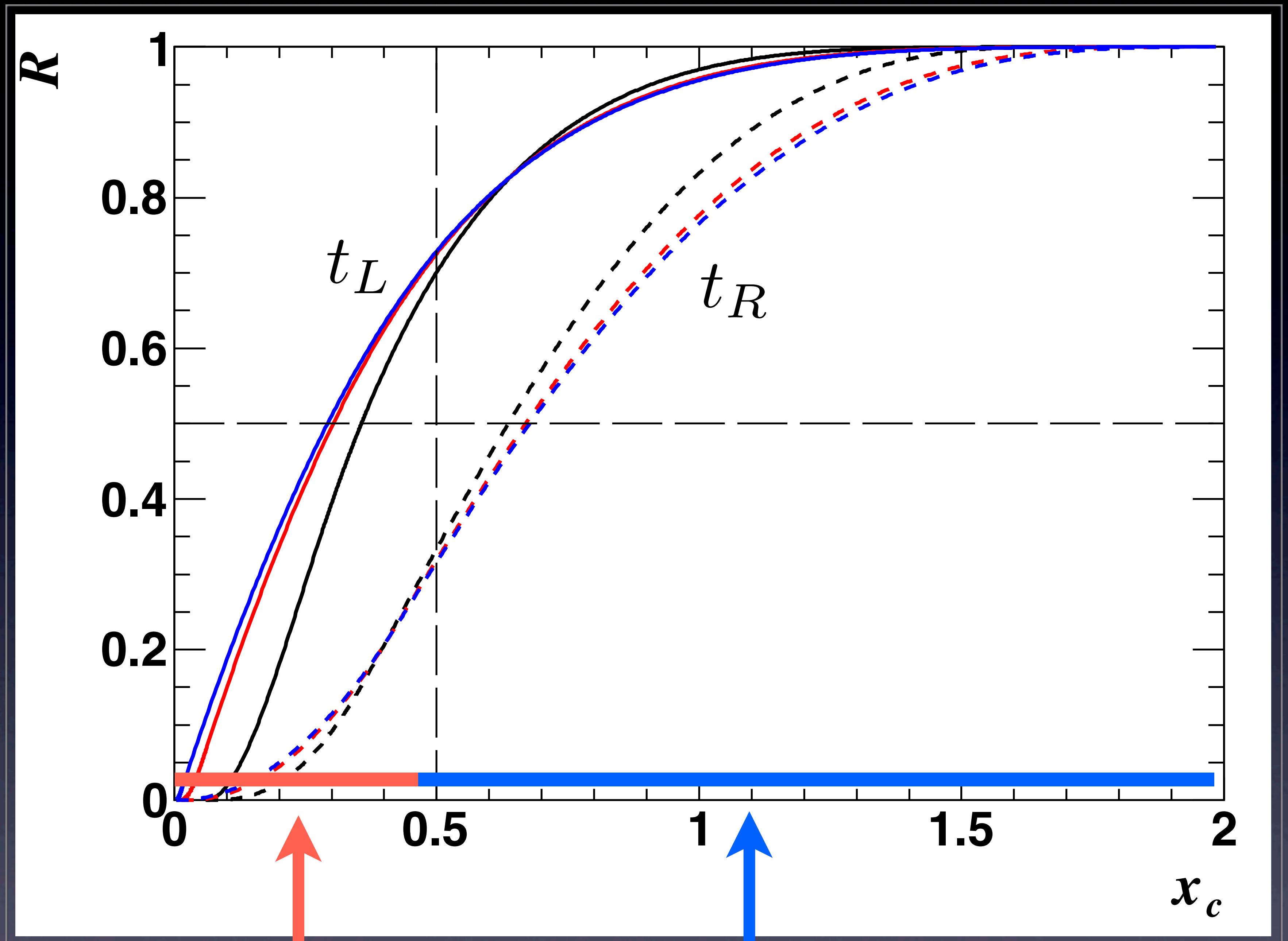
Lepton energy and top-quark polarization

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

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



R distribution

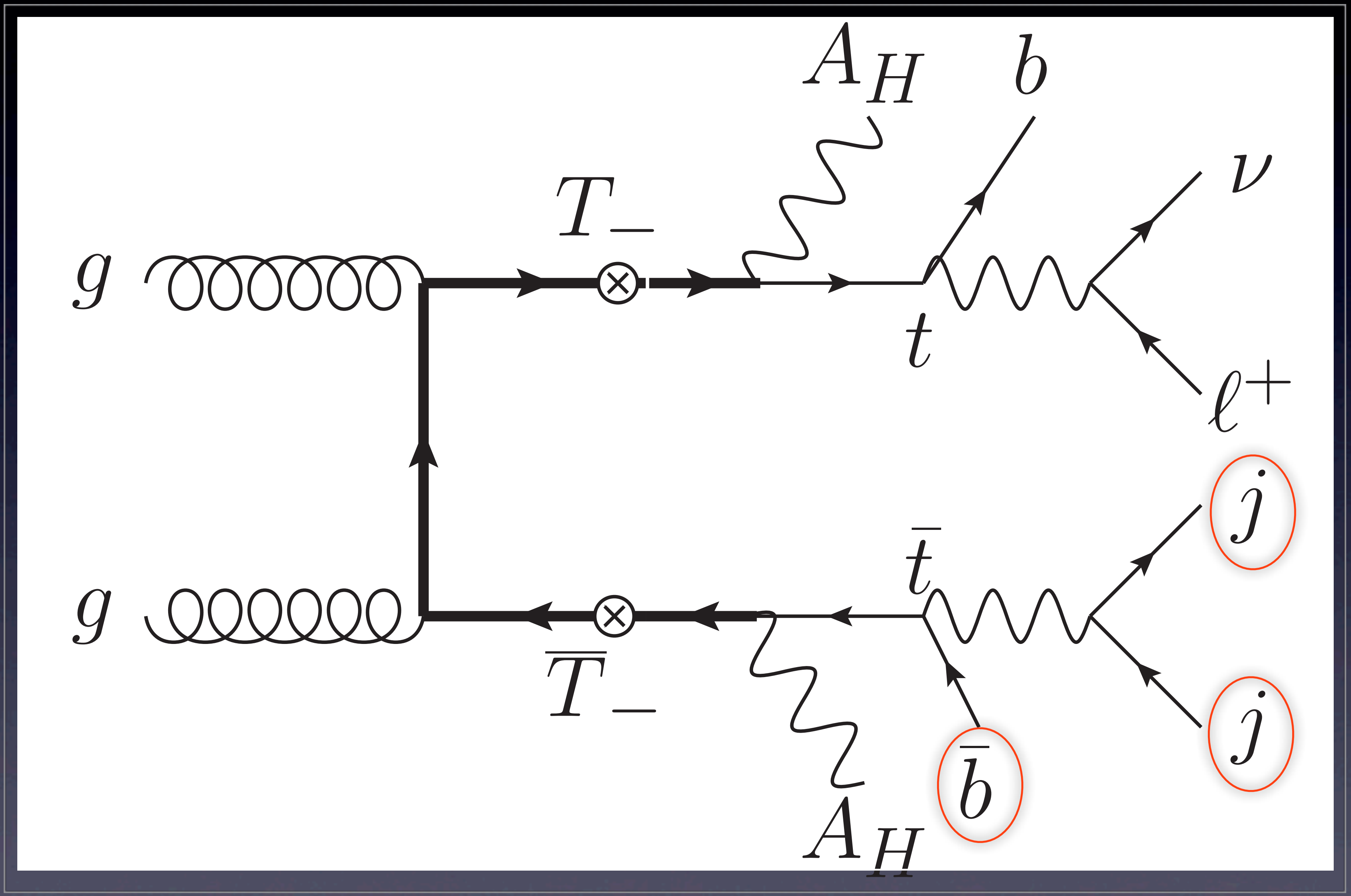


$$\mathcal{R}(x_c) = \frac{3x_c(1-\lambda_t)}{2(1+2B)} - \frac{3\lambda_t x_c^2(1-B+\ln B)}{2(1+2B)(1-B)^2}$$

$$\mathcal{R}(x_c) = \frac{B^2(2B-3)}{(1+2B)(1-B)^2} + \frac{3x_c(1-\lambda_t)}{2(1-B)^2(1+2B)} - \frac{3x_c^2[1+2\lambda_t\ln(x_c/2)]}{4(1-B)^2(1+2B)} + \frac{x_c^3(1+3\lambda_t)}{8(1-B)^2(1+2B)}$$

Lepton energy and top-quark polarization

- Identical decay chains

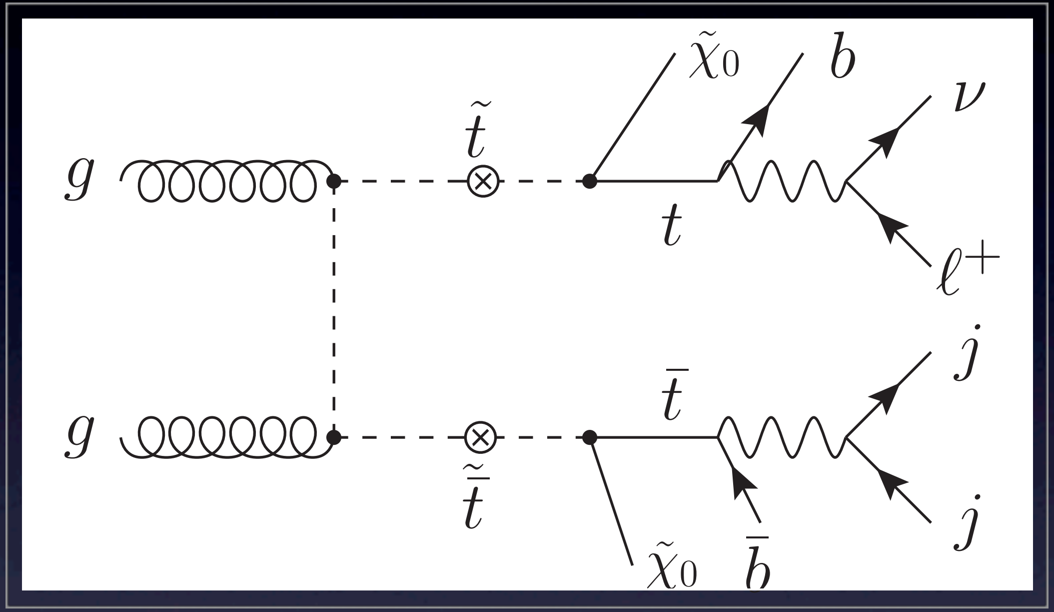


$$x'_\ell = 2E_{\ell^+} / E_{\bar{t}}$$

Toy model mimicking MSSM

- MSSM like:

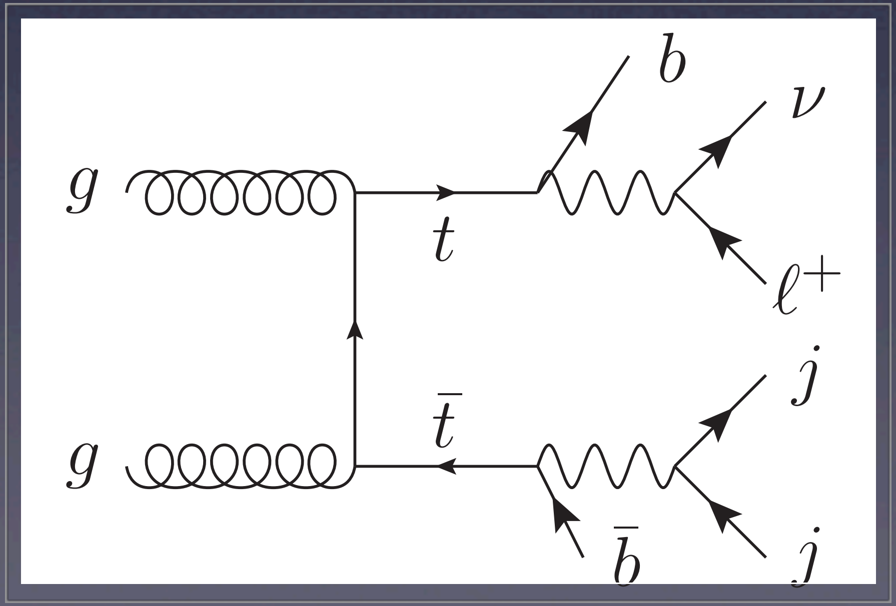
$$\mathcal{L}_{\tilde{t}t\tilde{\chi}} = g_{\text{eff}}\tilde{t}\tilde{\chi}(\cos\theta_{\text{eff}}P_L + \sin\theta_{\text{eff}}P_R)t$$

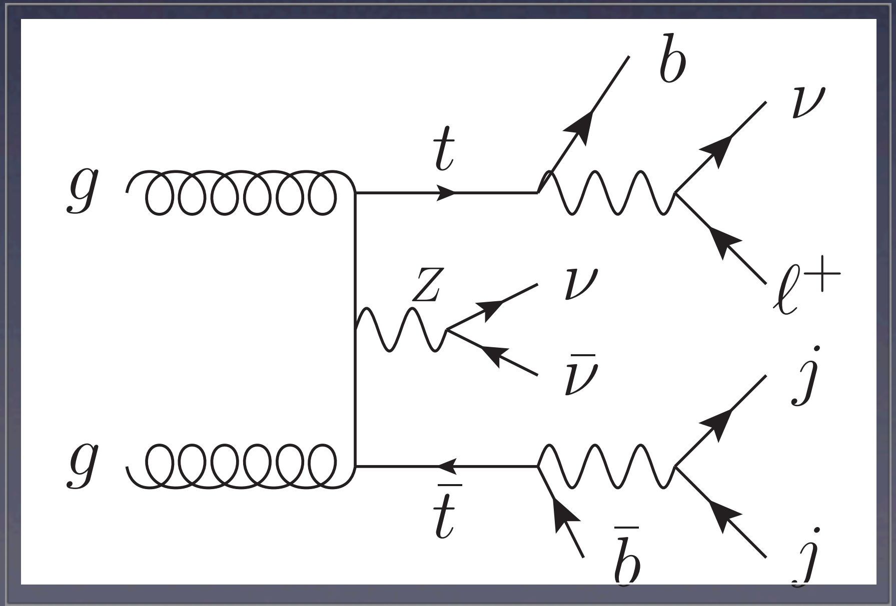


Collider signature

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

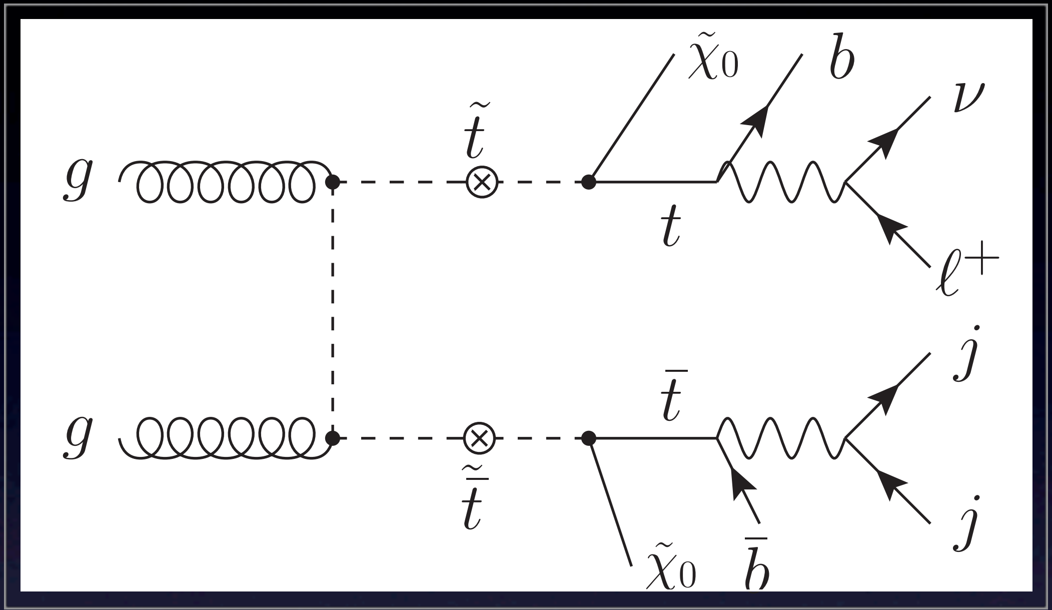
- Major SM backgrounds





Collider simulation

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



- Basic selection cuts

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

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

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

- Hard cuts

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

- $\bar{t} \to 3j$ reconstruction (Minimal-χ^2 theme)

Loop over all jet combinations and pick up the one minimize

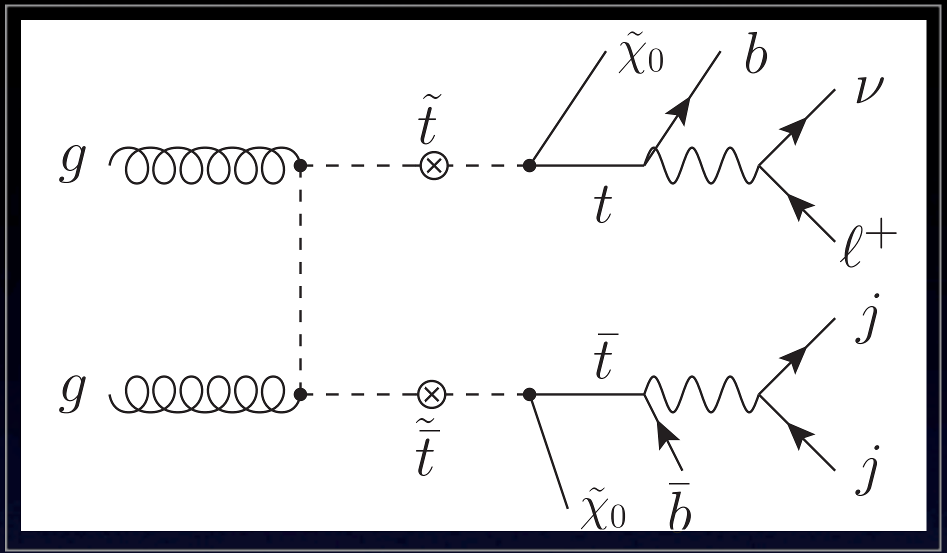
$$\chi^2 = \frac{(m_W - m_{jj})^2}{\Delta m_W^2} + \frac{(m_t - m_{jjj})^2}{\Delta m_t^2}$$

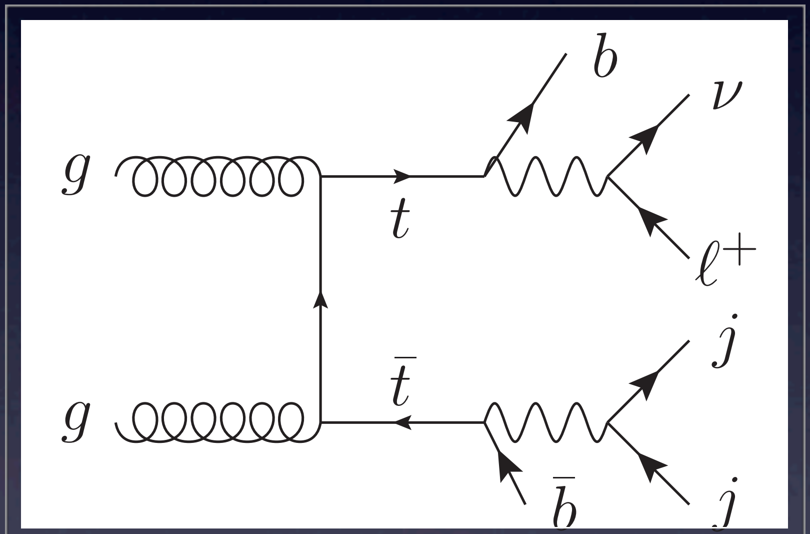
Signal versus Backgrounds

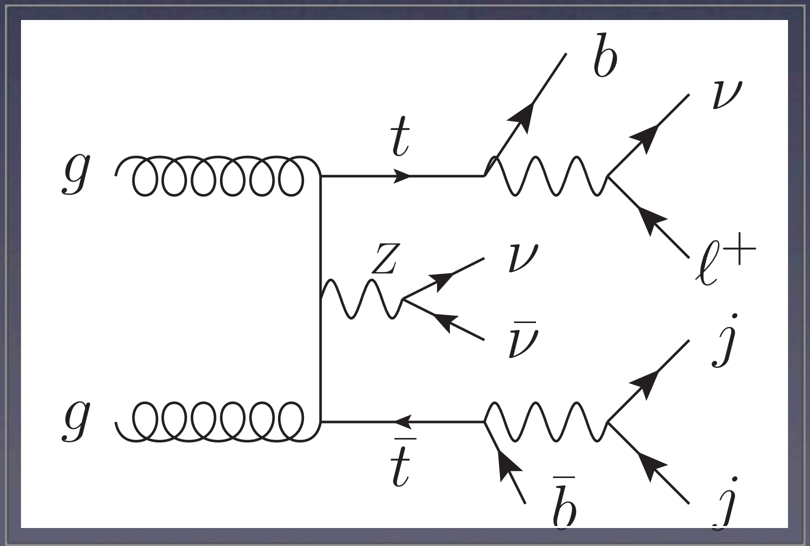
- Cross section (fb) of signal and backgrounds at 14TeV LHC

	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







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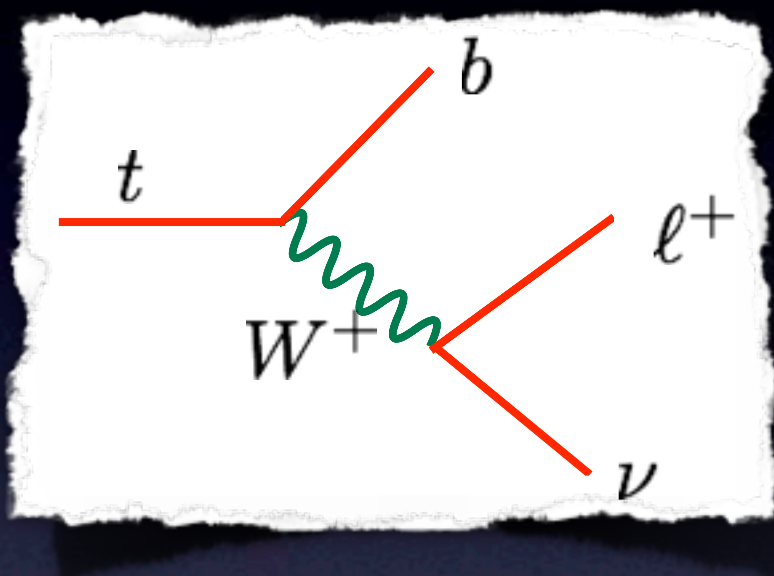

- W-boson on-shell condition

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

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

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

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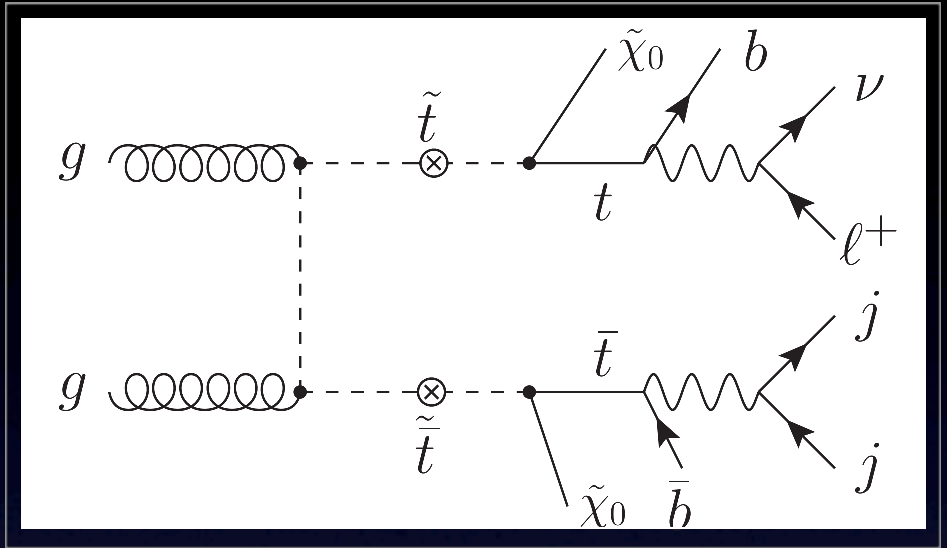
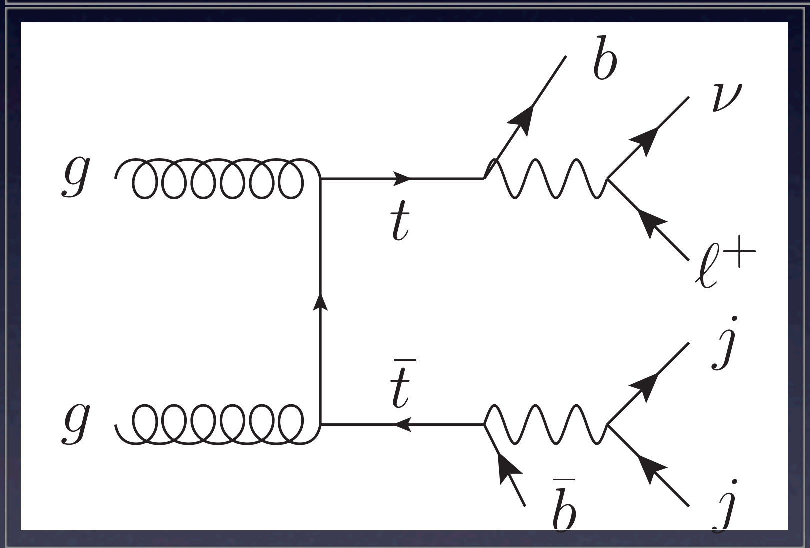
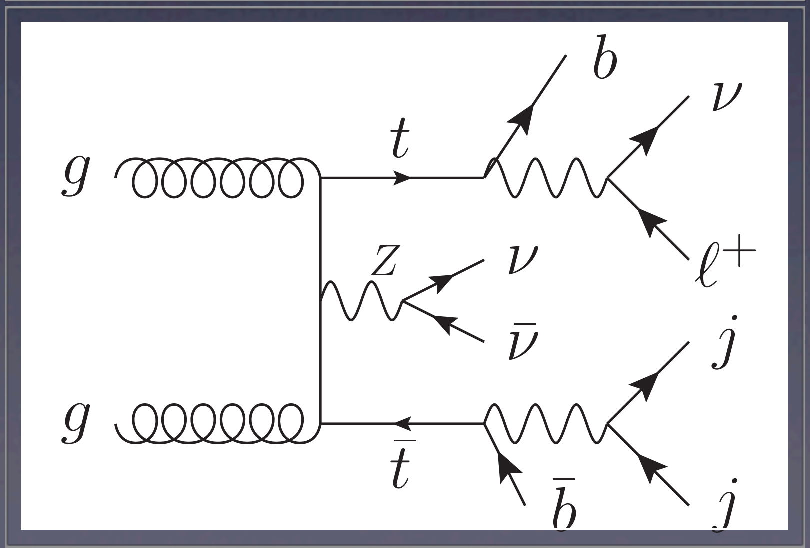
$$A \equiv m_W^2 + 2\,\vec{p}_T^{\,e}\cdot\vec{\not{E}}_T$$

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

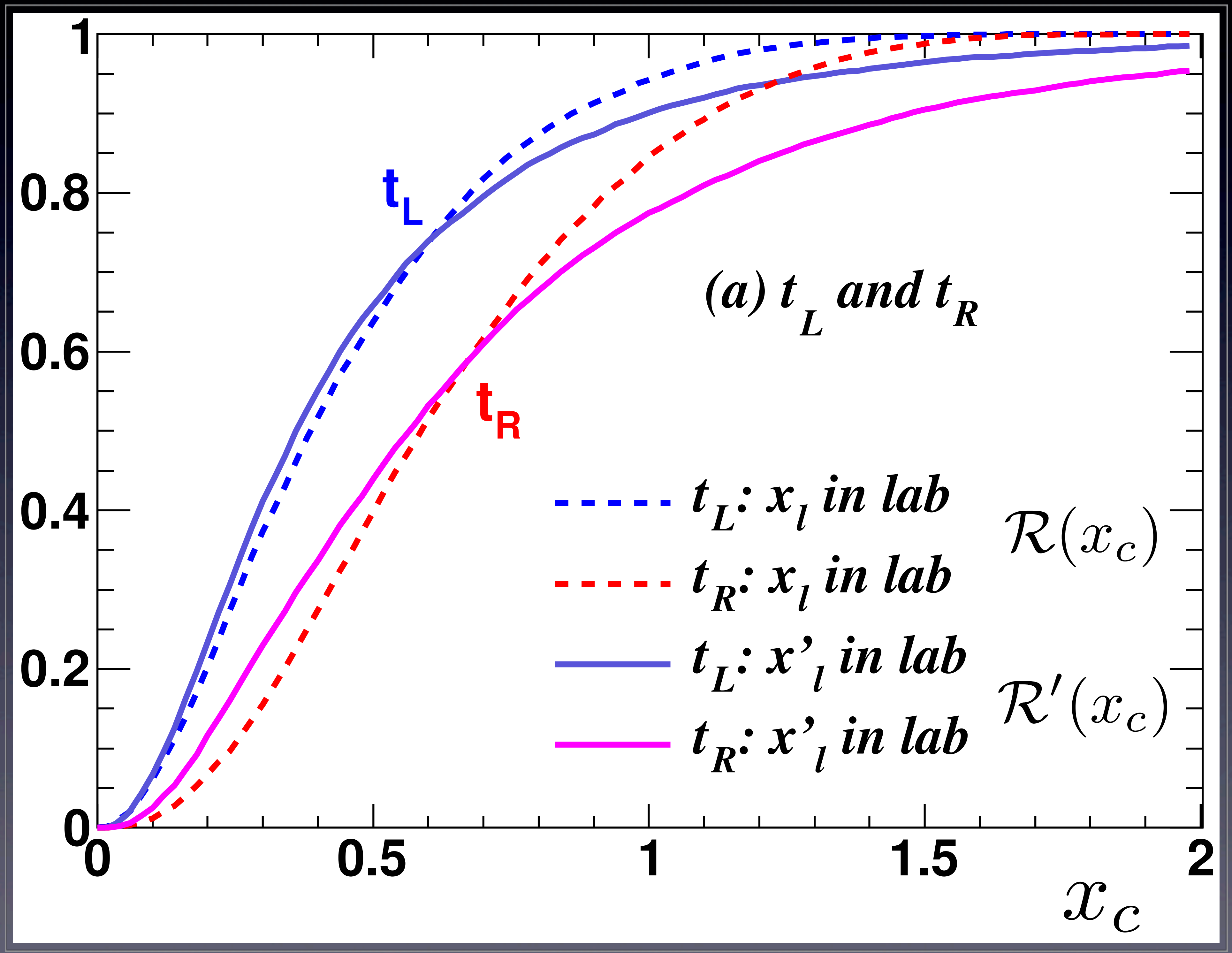






$\mathcal{R}(x_c)$ versus $\mathcal{R}'(x_c)$

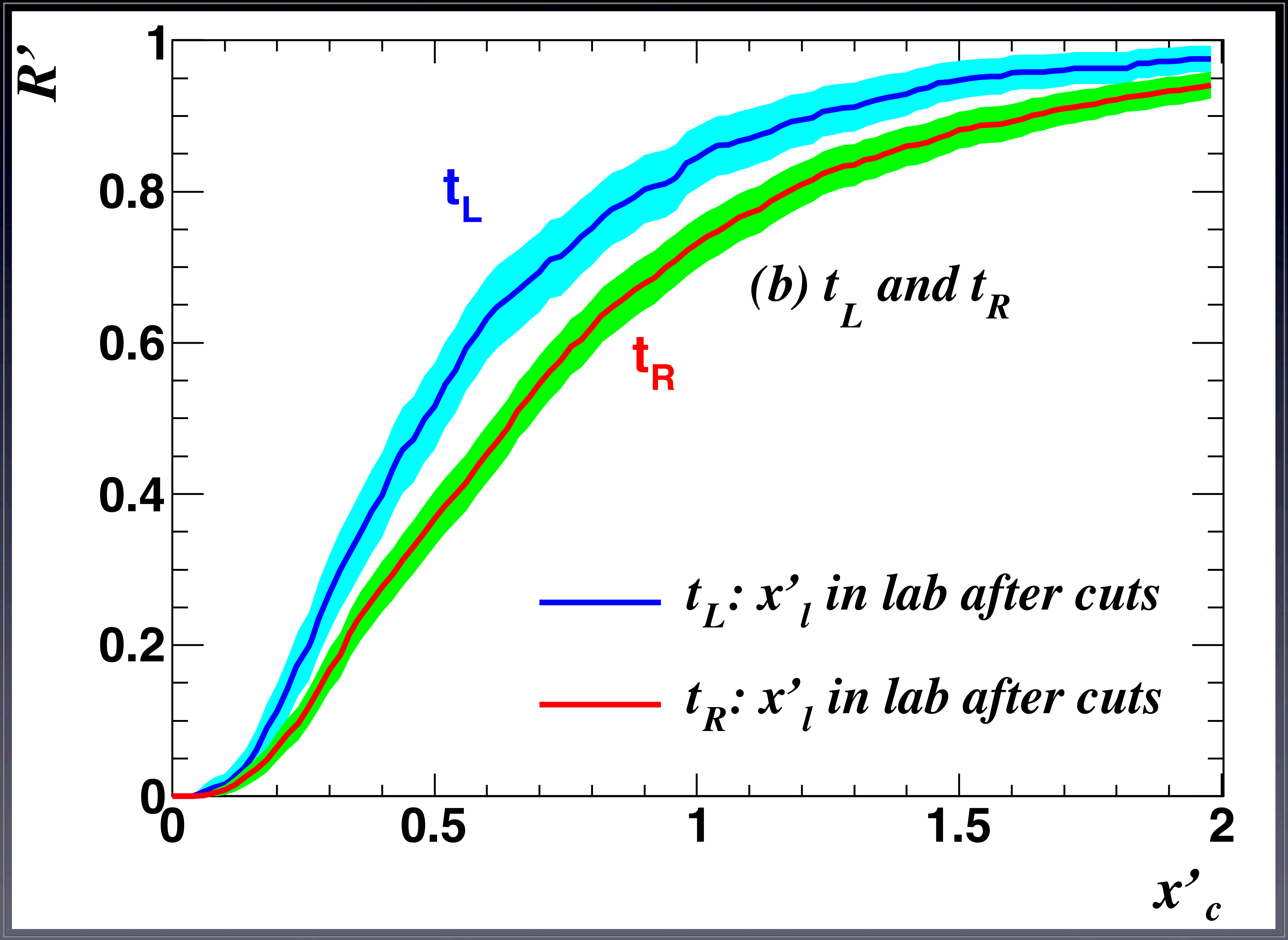
$x_\ell = 2E_{\ell+}/E_t \longrightarrow x'_\ell = 2E_{\ell+}/E_{\bar{t}}$



$\mathcal{R}'$ distribution

- t_L and t_R are separated

LHC: 14 TeV, 100fb^{-1}



Summary

- Conventional method of measuring top-quark polarization in the charged lepton angle distribution failed in $t\bar{t} + \not{E}_T$ events.

- The long ignored lepton energy could also be used to measure top-quark polarization without reconstructing the top-quark kinematics.

- The information of the mass and spin of new heavy particles in the intermediate state is no longer needed.

→ $\boxed{\text{Probe the interaction before mass and spin}}$

THANK YOU!