

Probing New Physics with Polarised Top Quark

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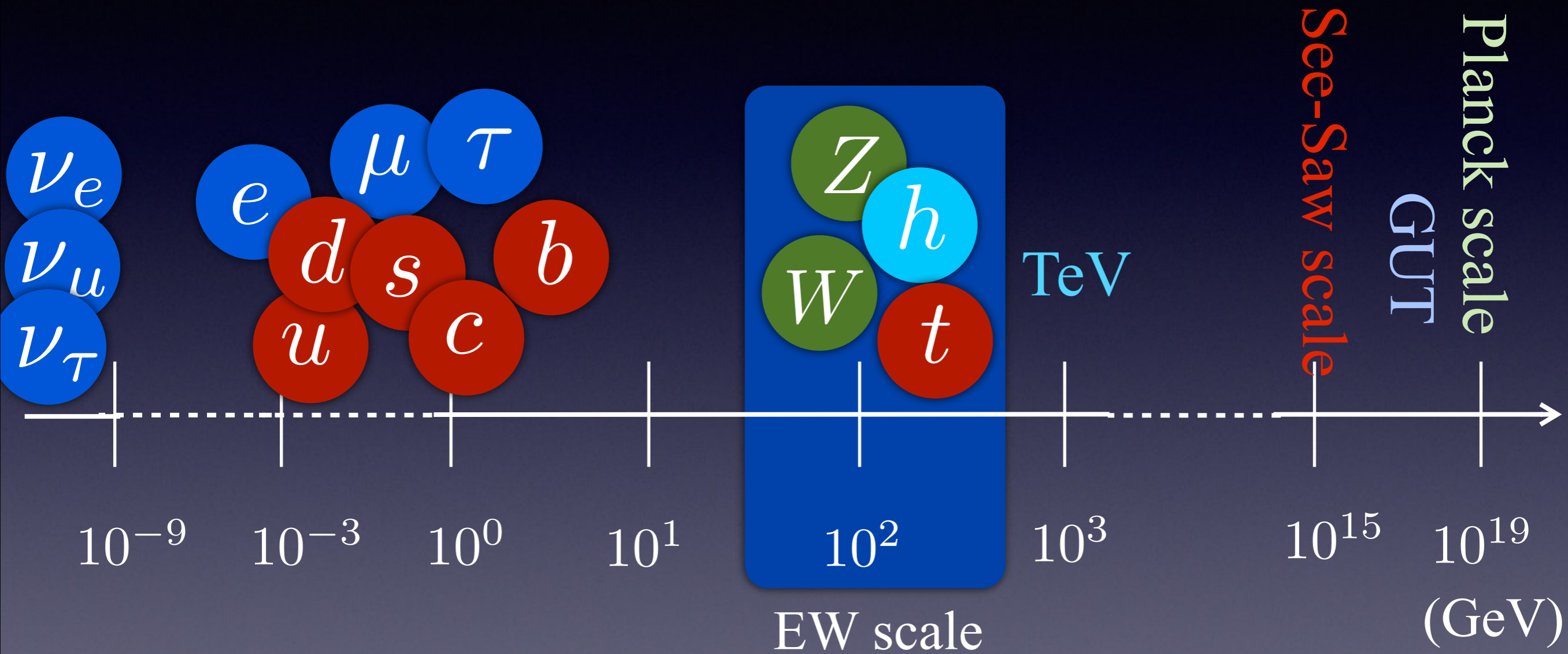
Based on the works in collaboration with

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



Top-quark: a new physics window

(The **heaviest** particle in the SM, the only “**normal**” quark)



Top quark is possibly uniquely related to unknown fundamental electroweak physics

Top quark as a probe of new physics

Extra Gauge Bosons

Z' W' G'

New Heavy Quarks

Top

Exotic Coloured States
Color Sextet

Vector Quark

4th Gen

Gluino

Heavy Quark Production
via pQCD

Charged Higgs

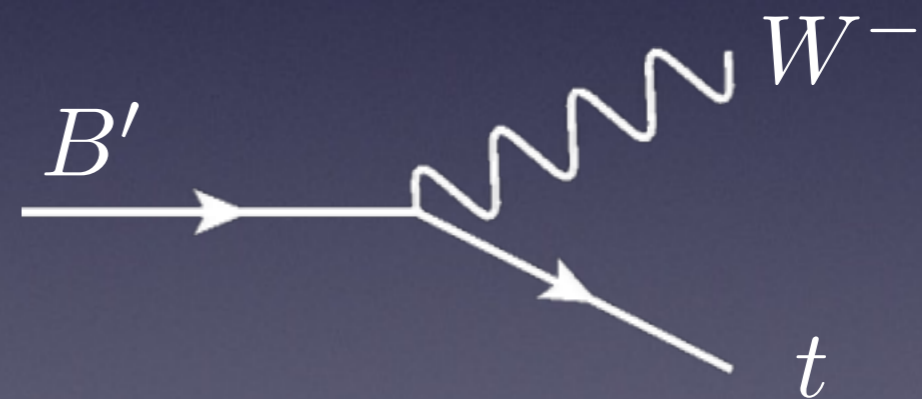
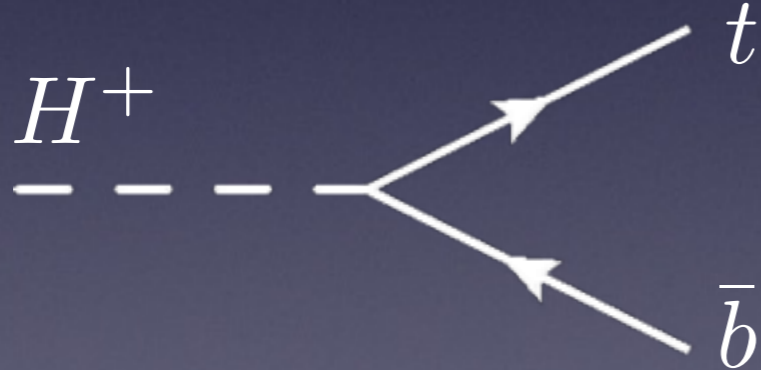
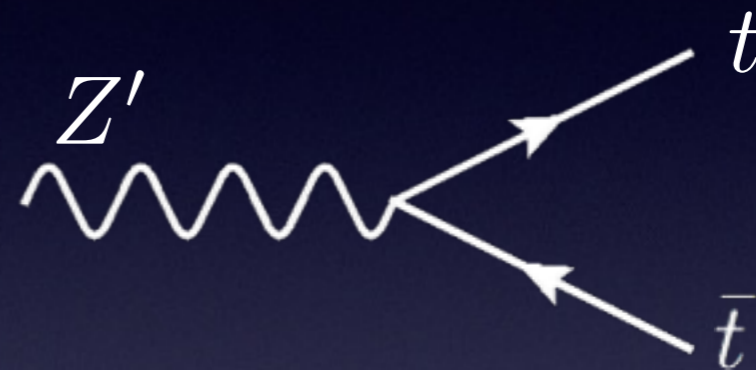
~~CP~~

FCNC

A_{FB}

Top-quark: a new physics window

Top quark is quite common in decays of NP resonances and **it is often polarised**.



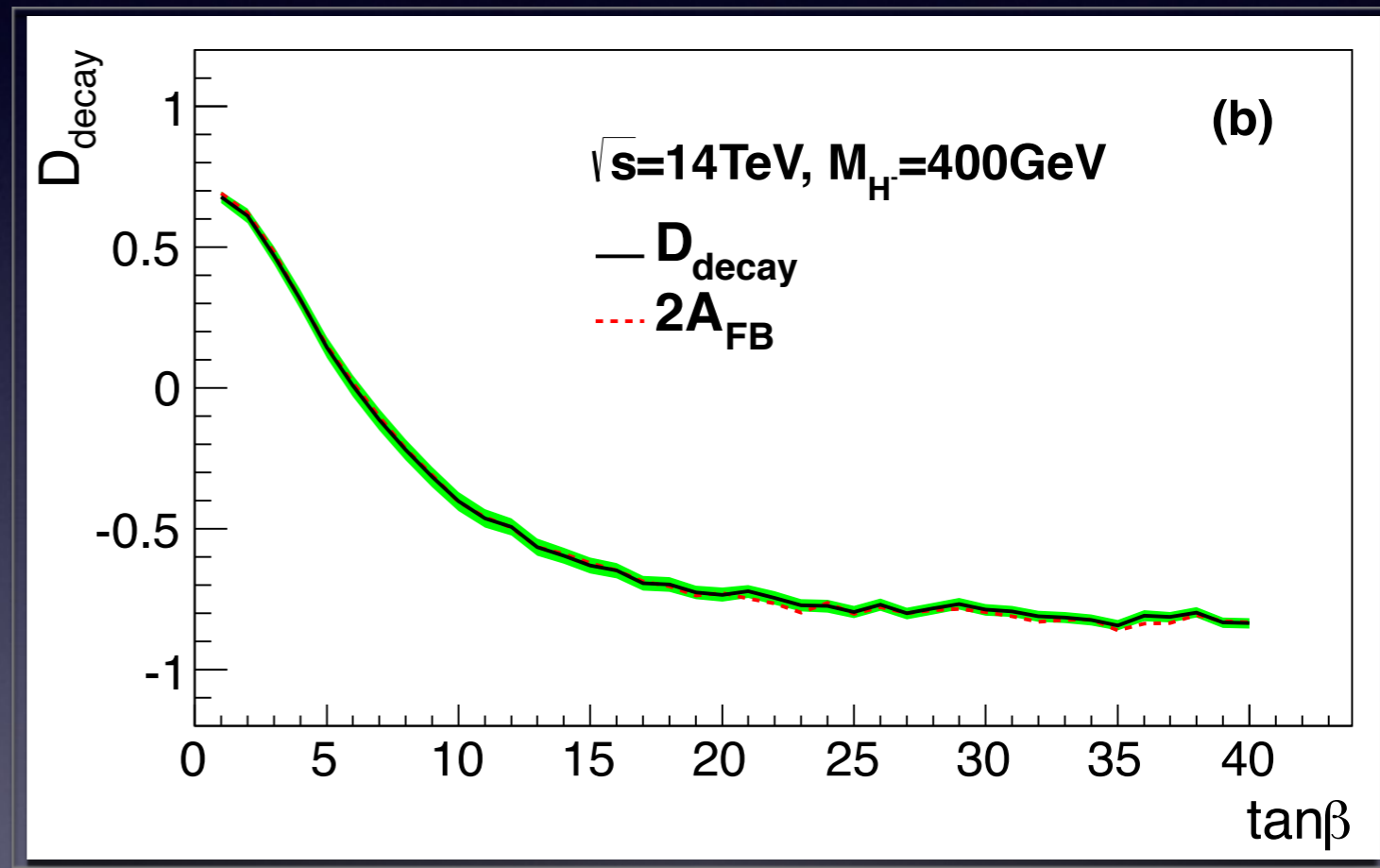
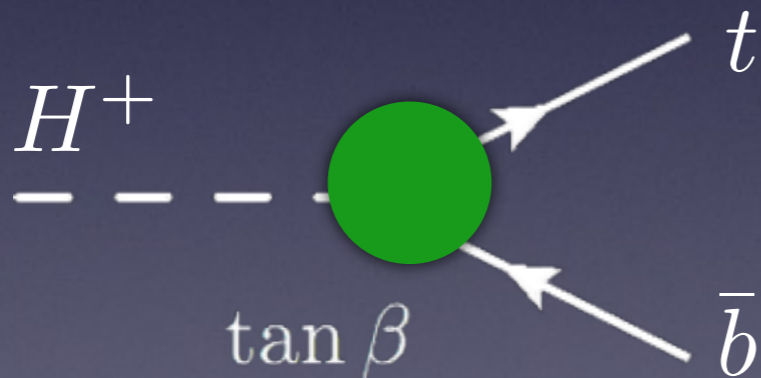
Top quark polarisation can tell us the **chirality structure** of top quark couplings to NP Resonances

Top-quark: a new physics window

Top quark is quite common in decays of NP resonances and **it is often polarised**.

QHC, Wan, Wang, Zhu,
PRD 87 (2013) 055022

$gb \rightarrow tH^- \rightarrow t\bar{t}b$
in Type-II 2HDB

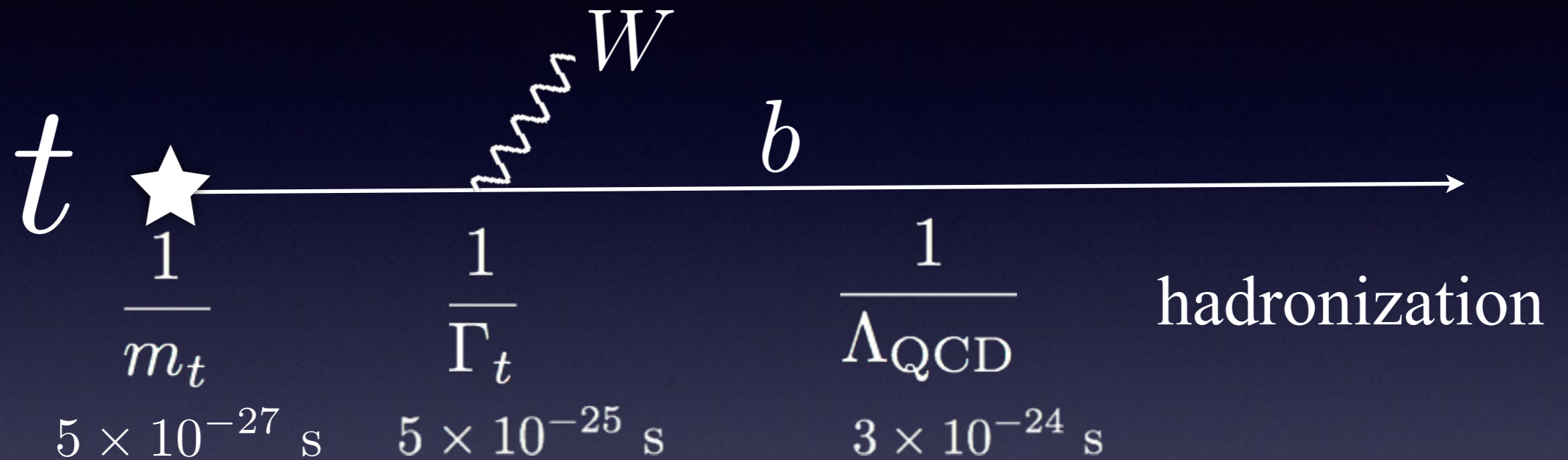


Top quark polarisation can tell us the **chirality structure** of top quark couplings to NP Resonances

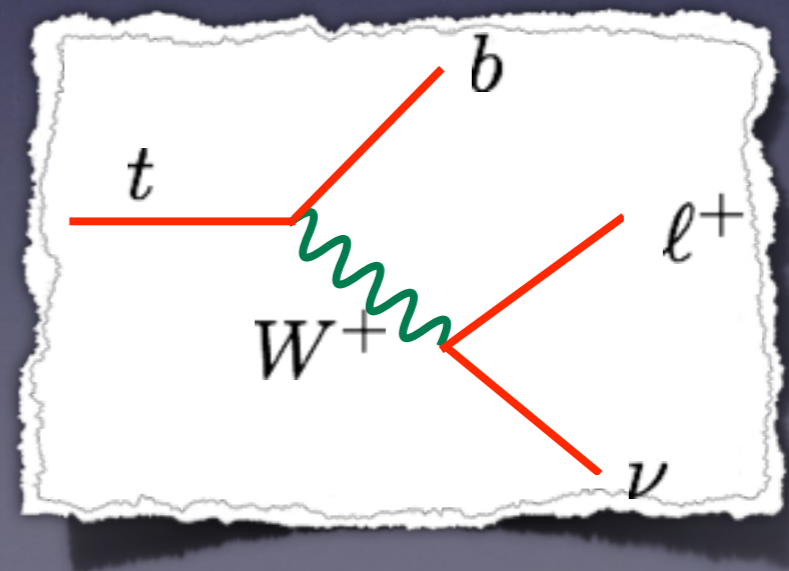
Top-quark: the only bare quark in SM

(the only “bizarre” quark in the SM)

- Short lifetime:



- “bare” quark:
spin info well kept
among its decay products



Charged lepton: the top-spin analyser

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

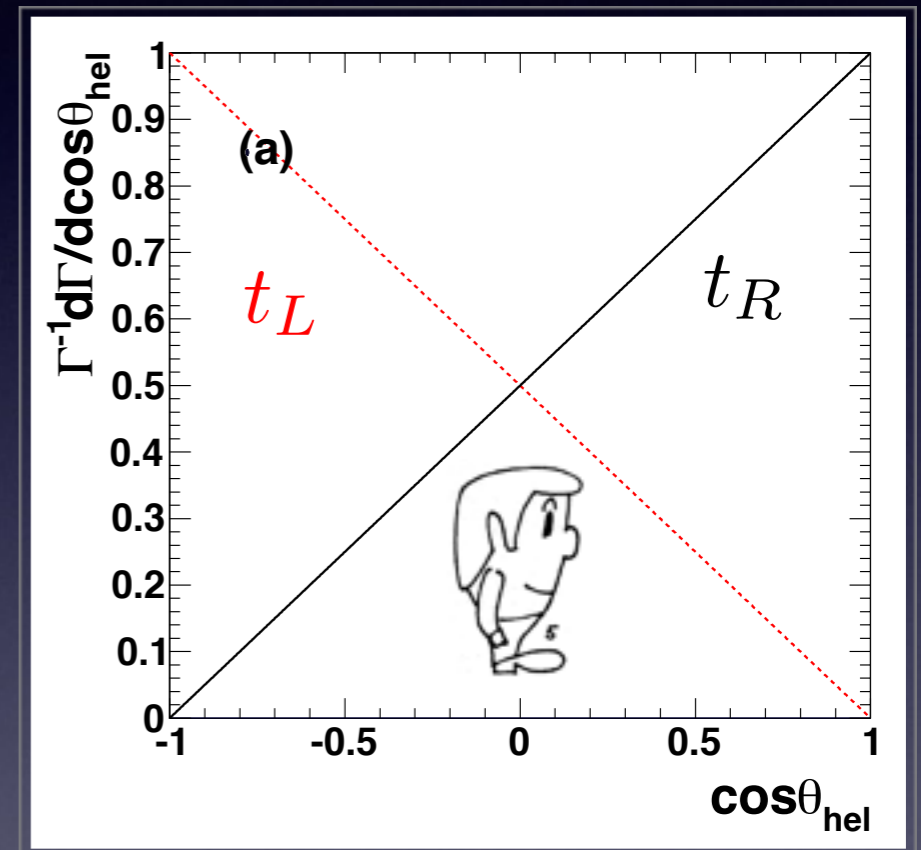
Czarnecki, Jezabek, Kuhn, NPB351 (1991) 70

- In top-quark rest frame

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

$\lambda_t = +$ right-handed

$\lambda_t = -$ left-handed



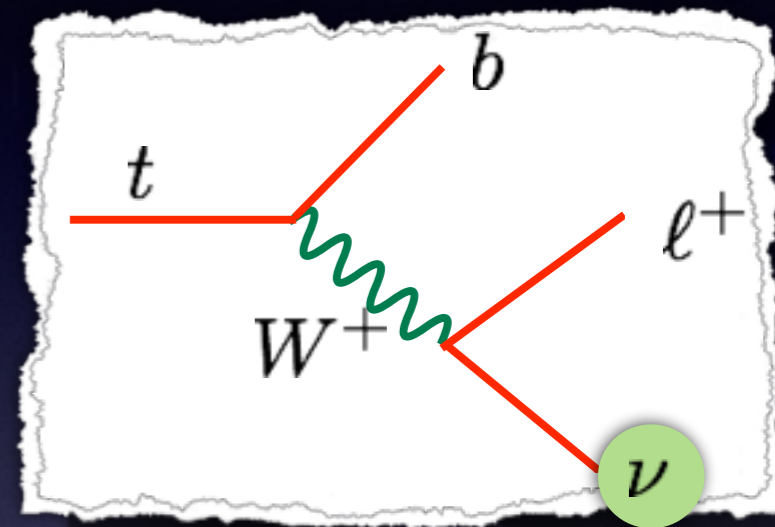
reconstruction
of top quark
kinematics

Top quark reconstruction

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

$$p_x^\nu = \cancel{E}_T(x) \quad p_y^\nu = \cancel{E}_T(y) \quad m_\nu = 0$$

p_z^ν unknown



- W -boson on-shell condition

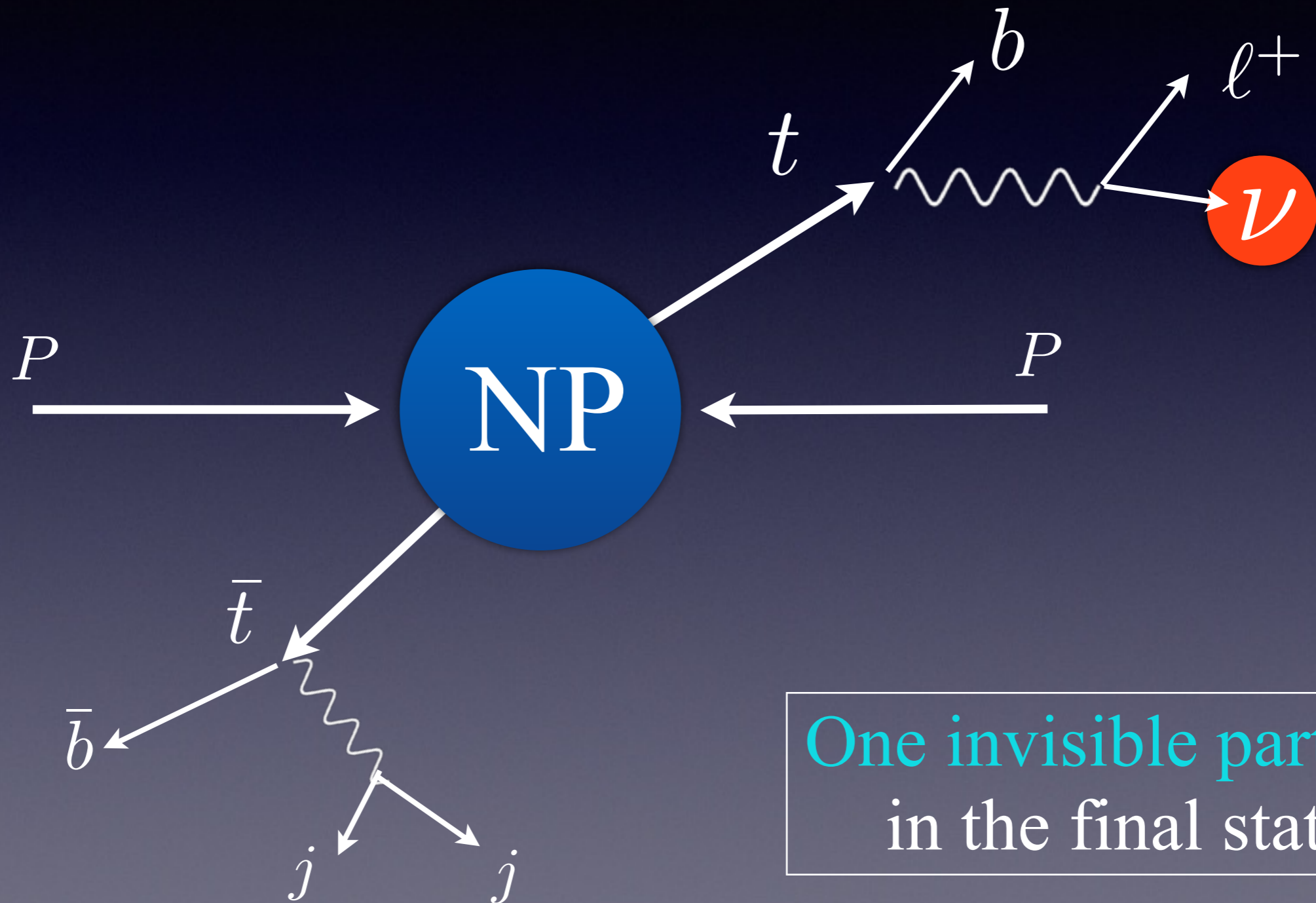
$$m_W^2 = (p_\ell + p_\nu)^2$$

$$\longrightarrow p_z^\nu = \frac{1}{2(p_T^e)^2} \left[A p_z^e \pm E_e \sqrt{A^2 - 4(p_T^e)^2 \cancel{E}_T^2} \right]$$

$$A = m_W^2 + 2\vec{p}_T^e \cdot \vec{\cancel{E}}_T$$

Top quark production in NP

(1) Top-quark pair production + semi-leptonic decay

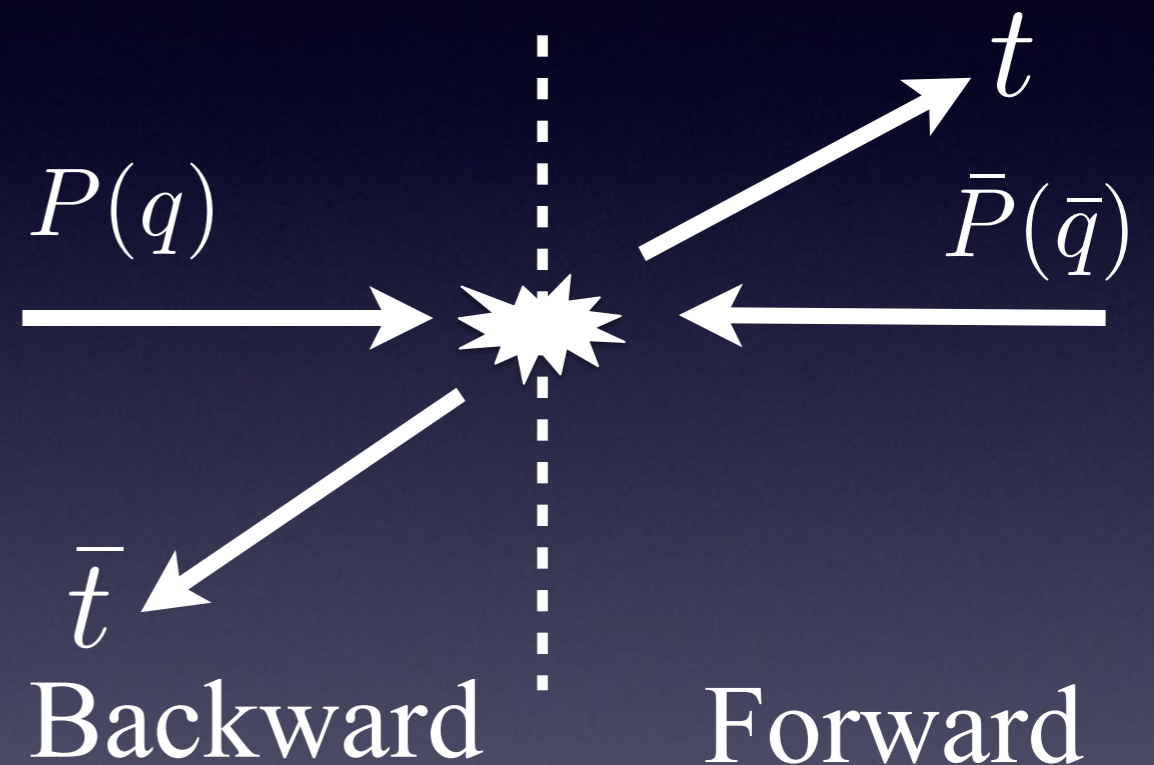
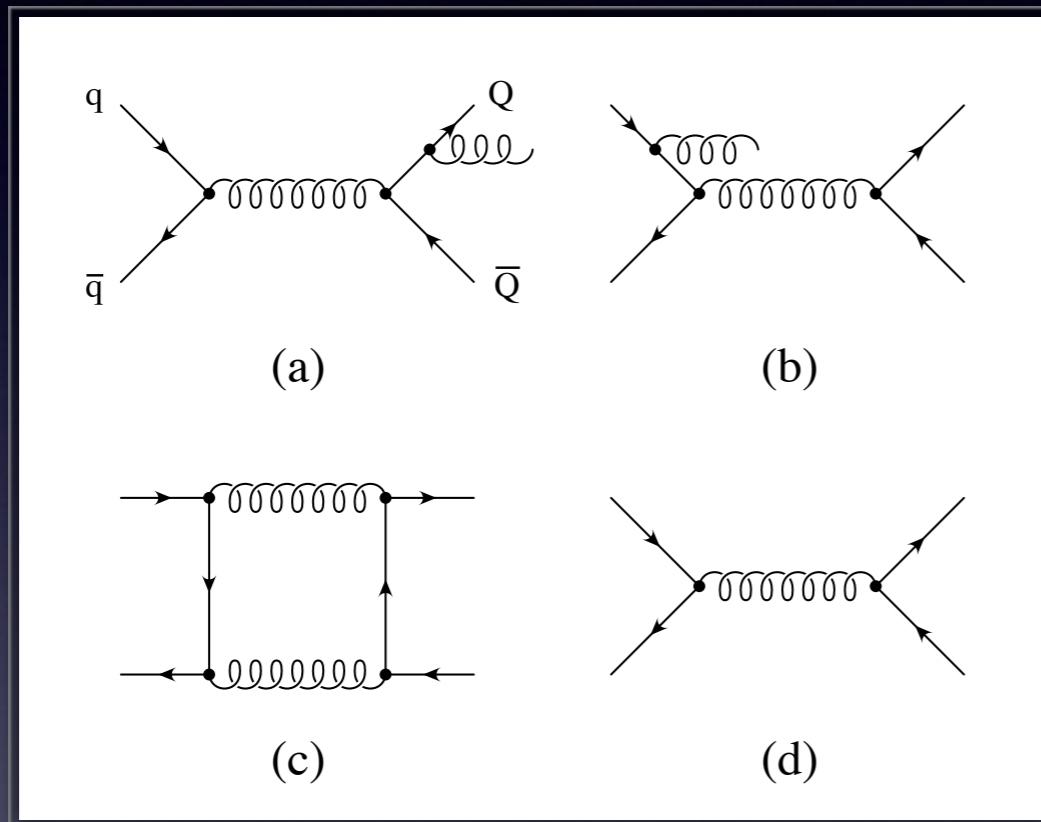


One invisible particle
in the final state

Top-quark Forward-backward Asymmetry at the Tevatron

It is induced at the loop level in the SM

Kuhn and Rodrigo
PRL 81 (1998) 49



$$A^{p\bar{p}} = \frac{N_t(y > 0) - N_{\bar{t}}(y > 0)}{N_t(y > 0) + N_{\bar{t}}(y > 0)} = 0.051(6)$$

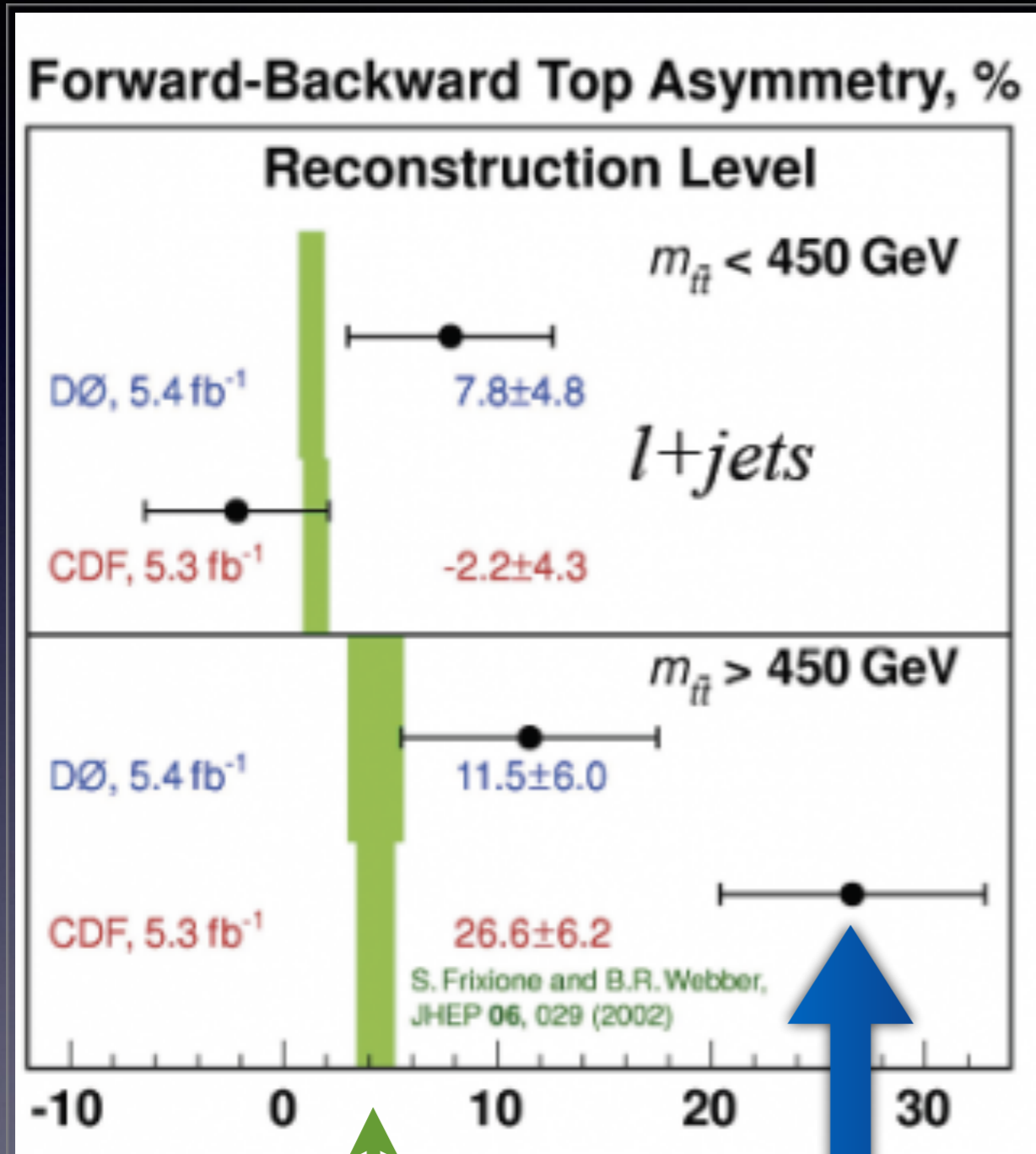
$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} = 0.078(9) \quad \Delta y = y_t - y_{\bar{t}}$$

Top-quark A_{FB} at the Tevatron

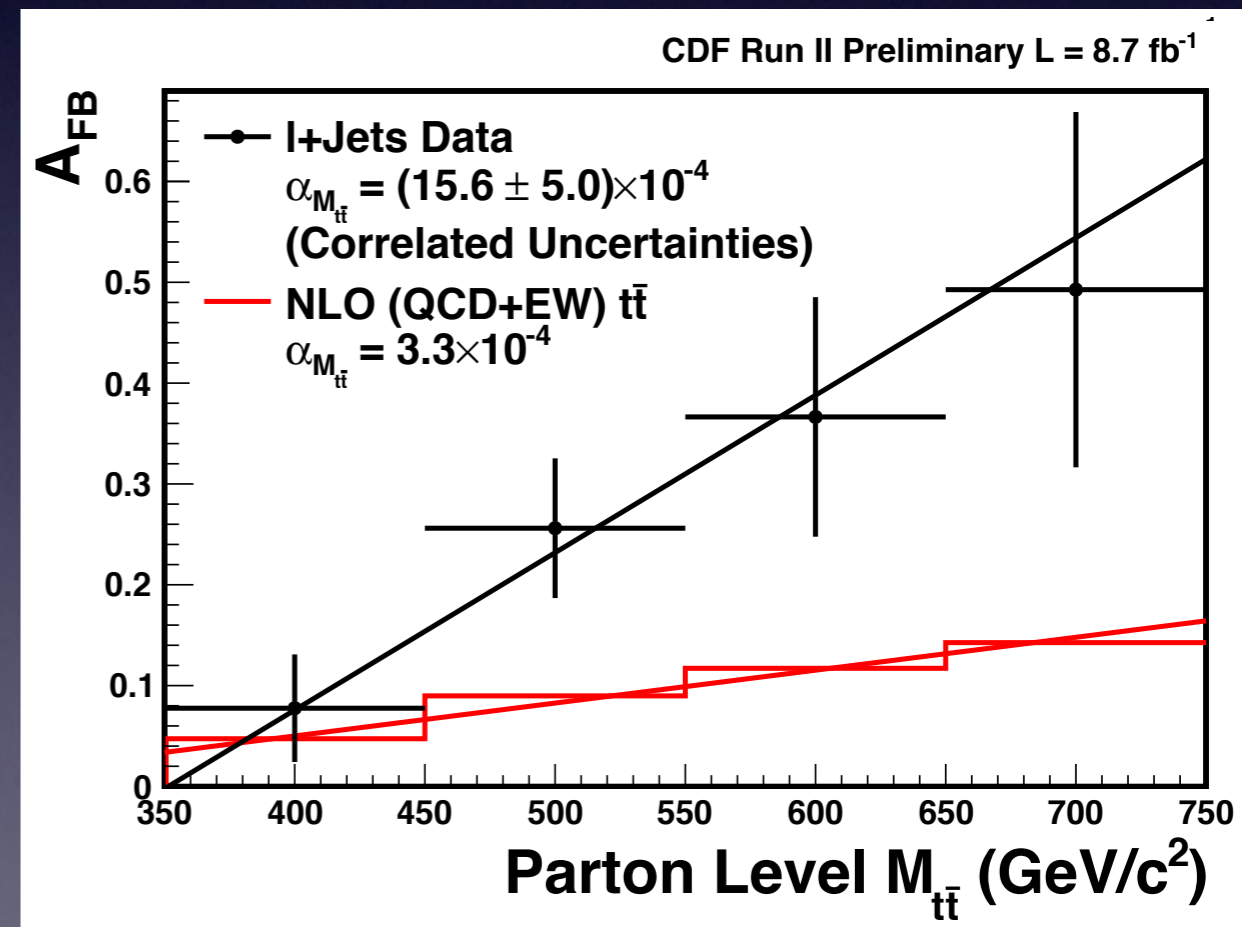
CDF (8.7 fb⁻¹):

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

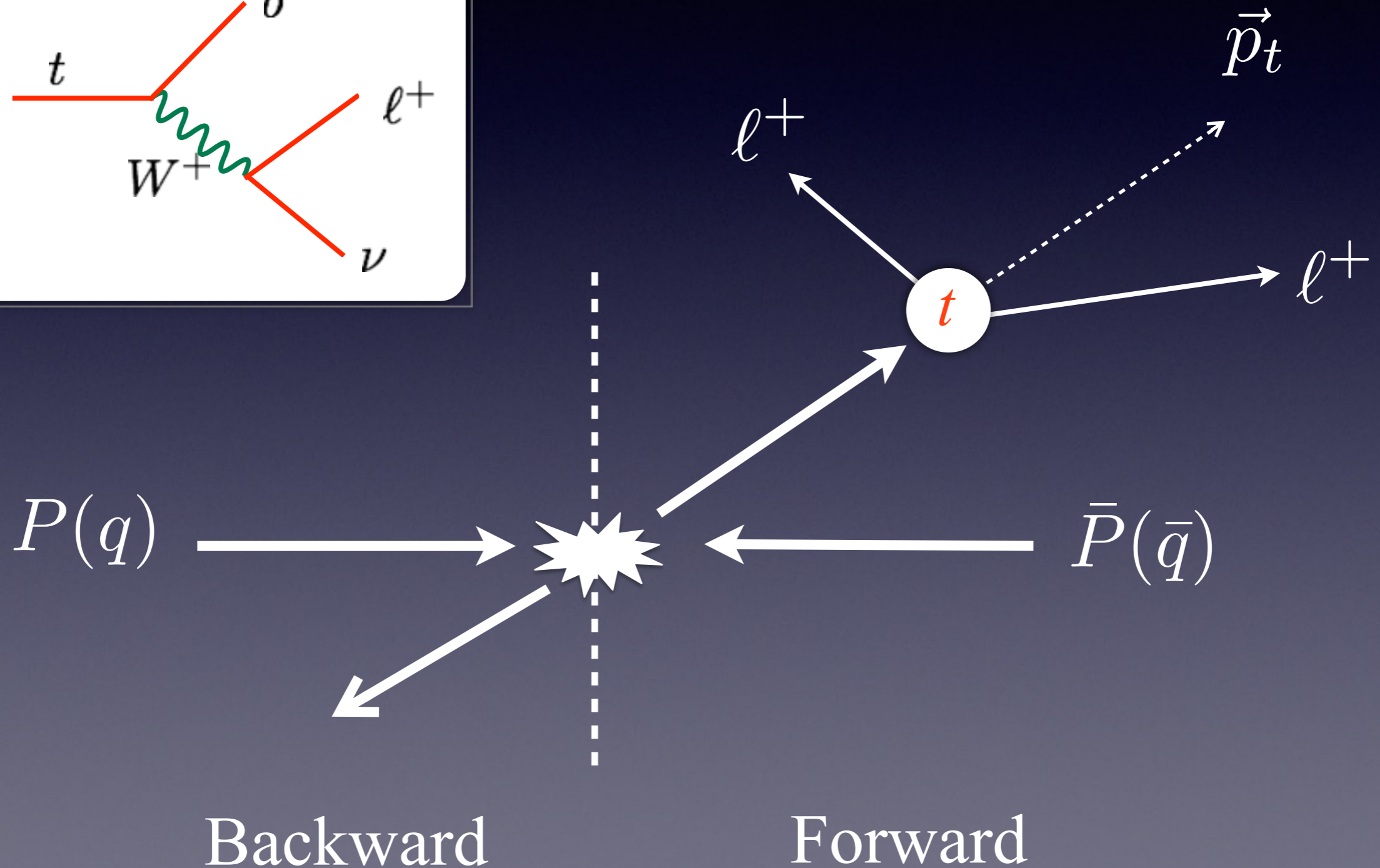
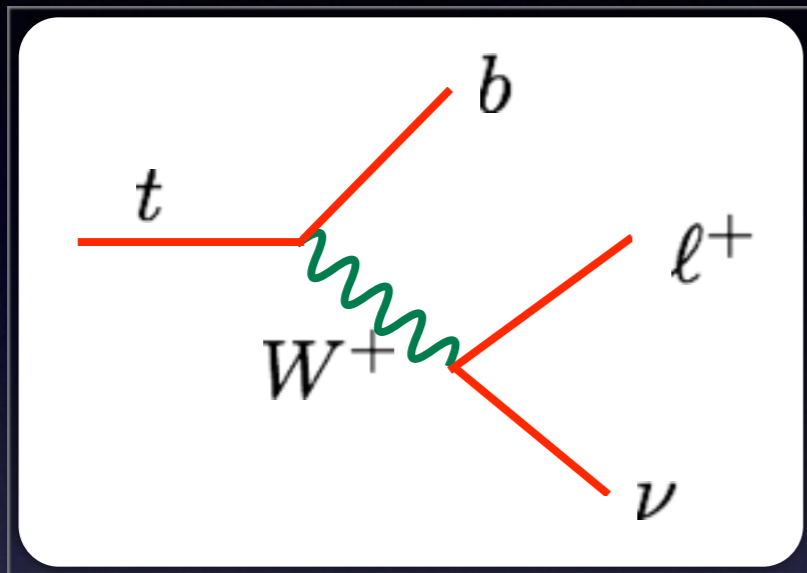
$$A_{FB}^{\text{NLO+EW}} = 0.066$$



CDF: 1101.0034



Forward-Backward asymmetry of the charged lepton from top-quark decay A_{FB}^{ℓ}



A_{FB}^t versus A_{FB}^ℓ

D0: $A_{FB}^t = 0.196 \pm 0.065$

$A_{FB}^\ell = 0.152 \pm 0.040$

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

CDF: $A_{FB}^t = 0.085 \pm 0.025$

(8.7fb⁻¹) $A_{FB}^\ell = 0.066 \pm 0.025$

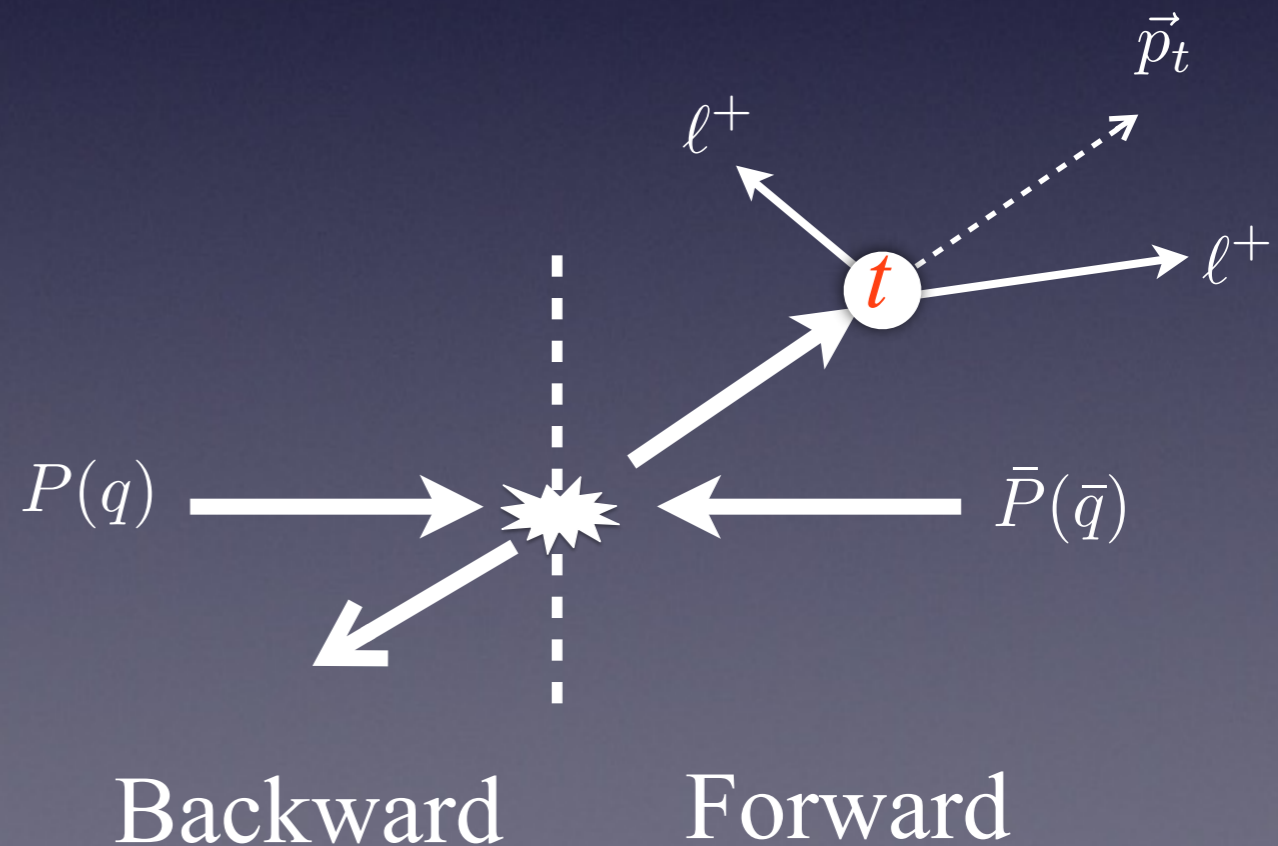
$$\left. \frac{A_{FB}^\ell}{A_{FB}^t} \right|_{\text{inc}} \sim \frac{3}{4} \quad \left. \frac{A_{FB}^\ell}{A_{FB}^t} \right|_{>450} \sim \frac{3}{5}$$

SM predictions at the NLO

$A_{FB}^t = 0.051 \pm 0.001$

$A_{FB}^\ell = 0.021 \pm 0.001$

$$\left. \frac{A_{FB}^\ell}{A_{FB}^t} \right|_{\text{SM}} \sim \frac{1}{2} \quad ?$$



A_{FB}^t and A_{FB}^ℓ are connected by the spin correlation between the top-quark and charged lepton

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

$$A_{FB}^\ell \approx \rho_{t_L} A_{FB}^{t_L} \times (2\mathcal{R}_C^{t_L} - 1) + \rho_{t_R} A_{FB}^{t_R} \times (2\mathcal{R}_C^{t_R} - 1)$$

$$A_{FB}^t \approx [\rho_{t_L} A_{FB}^{t_L} + \rho_{t_R} A_{FB}^{t_R}]$$

$$A_{FB}^\ell(t_{L/R}) = 2\mathcal{R}_C^{t_{L/R}} - 1$$

$$R_F^{\lambda_t}(\beta, y_t) = \begin{cases} \frac{1}{2} + \frac{1}{2(1 + \gamma^{-2} \coth^2 y_t)^{1/2}} + \frac{\lambda_t \coth^2 y_t}{4\beta\gamma^2 (1 + \gamma^{-2} \coth^2 y_t)^{3/2}}, & (y_t > 0) \\ \frac{1}{2} - \frac{1}{2(1 + \gamma^{-2} \coth^2 y_t)^{1/2}} - \frac{\lambda_t \coth^2 y_t}{4\beta\gamma^2 (1 + \gamma^{-2} \coth^2 y_t)^{3/2}}, & (y_t < 0) \end{cases}$$

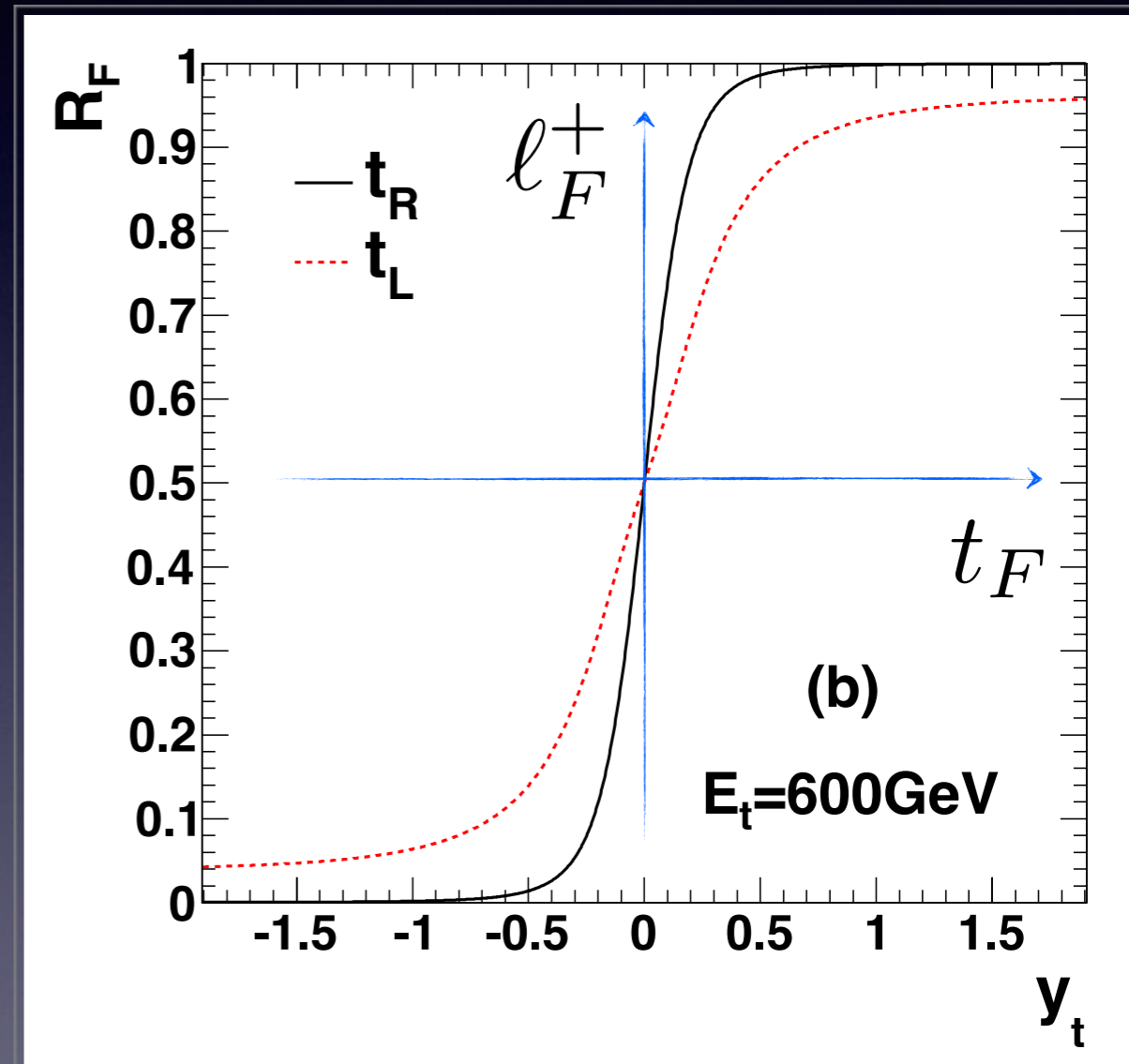
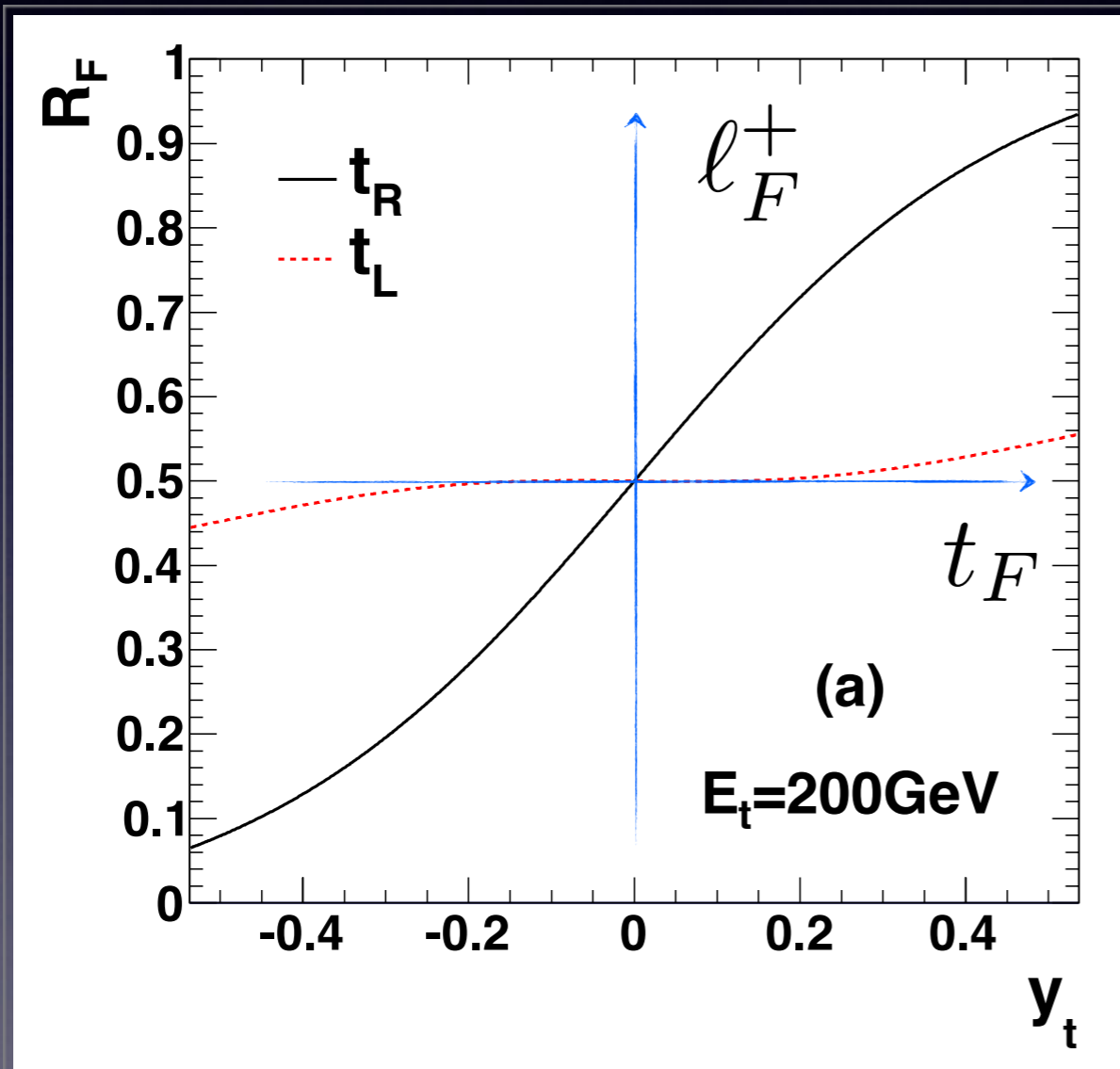
A_{FB}^{ℓ} dependence on top kinematics

B(l)

F(l)

F(l)

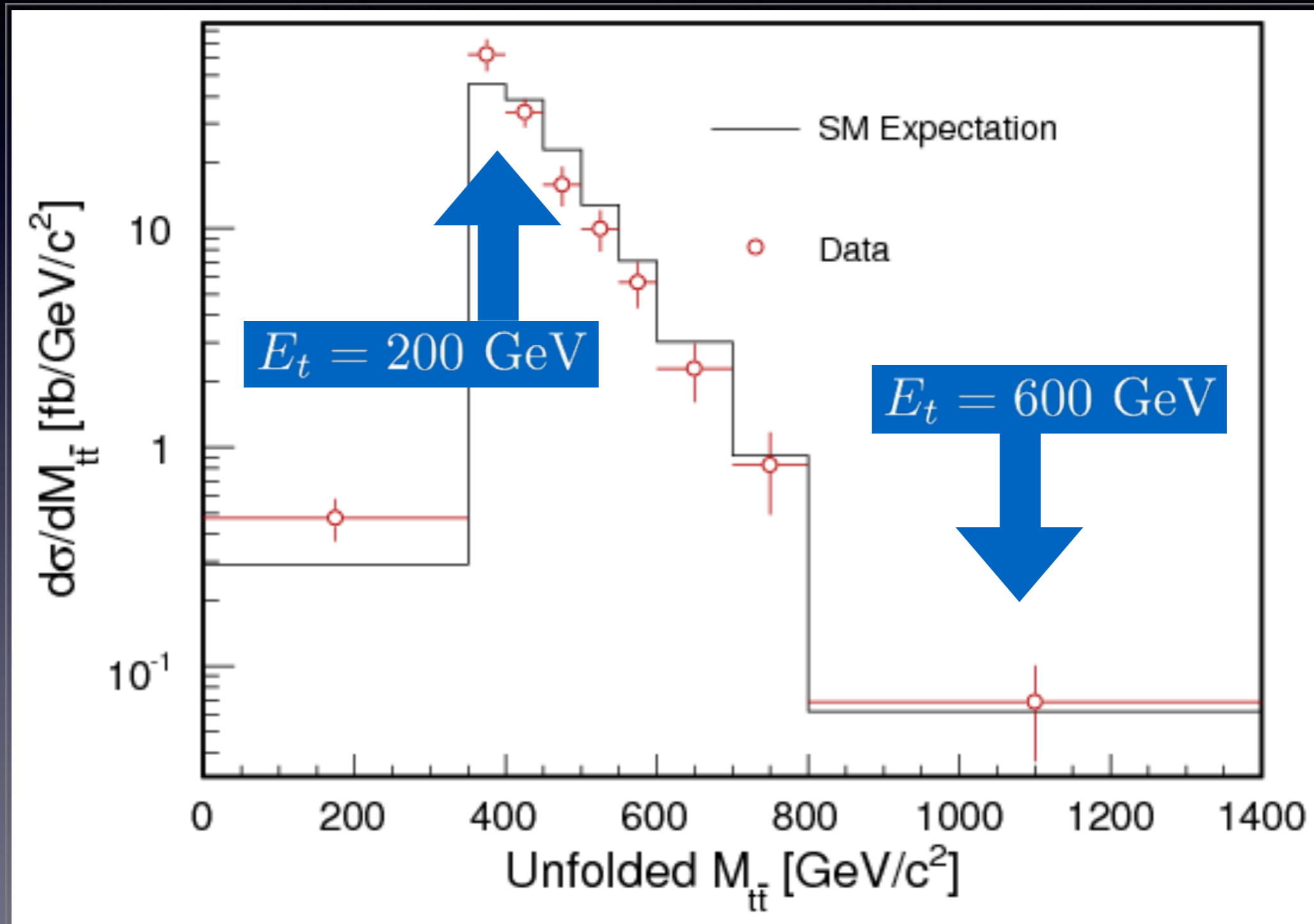
B(l)



$$A_{FB}^{\ell, \lambda_t}(\beta, y_t) = 2R_F^{\ell, \lambda_t}(\beta, y_t) - 1$$

Invariant mass spectrum of top quark pair

CDF collaboration, PRL 102 (2009) 222003



A_{FB}^t and A_{FB}^ℓ are connected by the spin correlation between the top-quark and charged lepton.

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

$$A_{FB}^\ell \approx \rho_{t_L} A_{FB}^{t_L} \times \underbrace{(2\mathcal{R}_C^{t_L} - 1)}_0 + \rho_{t_R} A_{FB}^{t_R} \times \underbrace{(2\mathcal{R}_C^{t_R} - 1)}_1$$

$$A_{FB}^t \approx [\rho_{t_L} A_{FB}^{t_L} + \rho_{t_R} A_{FB}^{t_R}]$$

$$A_{FB}^\ell(t_{L/R}) = 2\mathcal{R}_C^{t_{L/R}} - 1$$

$$\text{SM: } \rho_{t_L} = \rho_{t_R} = \frac{1}{2}$$

$$A_{FB}^{t_L} = A_{FB}^{t_R}$$

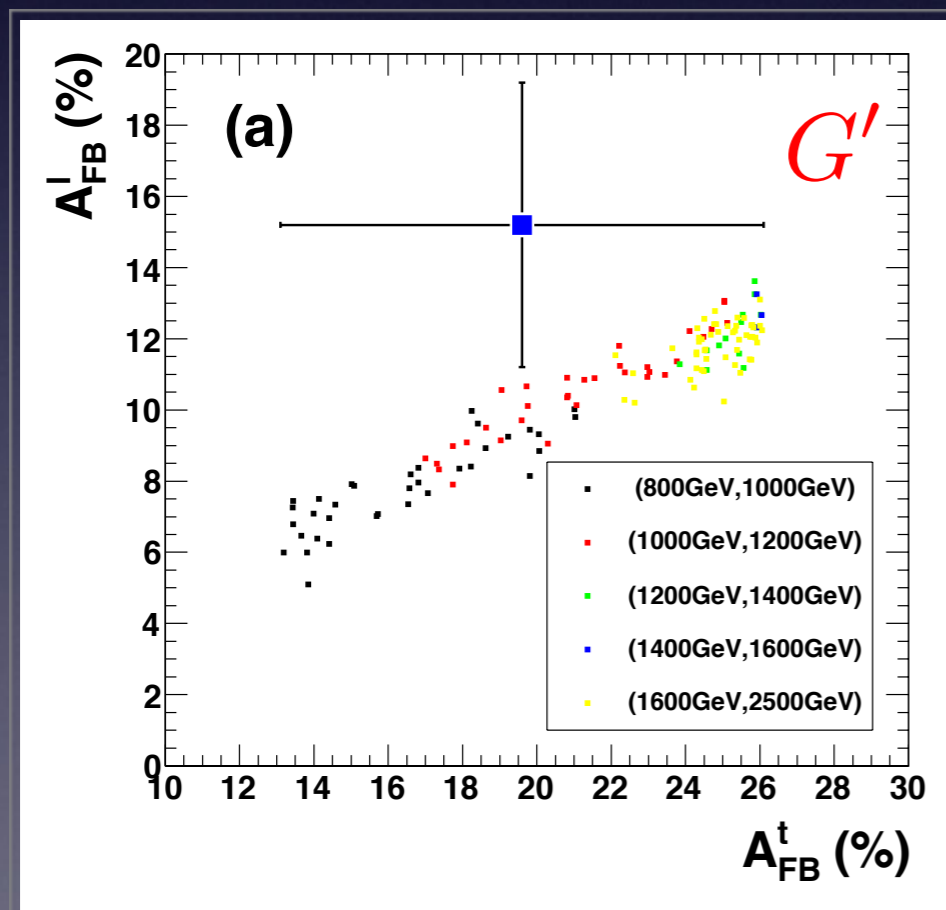
$$\rightarrow \left. \frac{A_{FB}^\ell}{A_{FB}^t} \right|_{\text{SM}} \sim \frac{1}{2}$$

$$R_F^{\lambda_t}(\beta, y_t) = \begin{cases} \frac{1}{2} + \frac{1}{2(1 + \gamma^{-2} \coth^2 y_t)^{1/2}} + \frac{\lambda_t \coth^2 y_t}{4\beta\gamma^2 (1 + \gamma^{-2} \coth^2 y_t)^{3/2}}, & (y_t > 0) \\ \frac{1}{2} - \frac{1}{2(1 + \gamma^{-2} \coth^2 y_t)^{1/2}} - \frac{\lambda_t \coth^2 y_t}{4\beta\gamma^2 (1 + \gamma^{-2} \coth^2 y_t)^{3/2}}, & (y_t < 0) \end{cases}$$

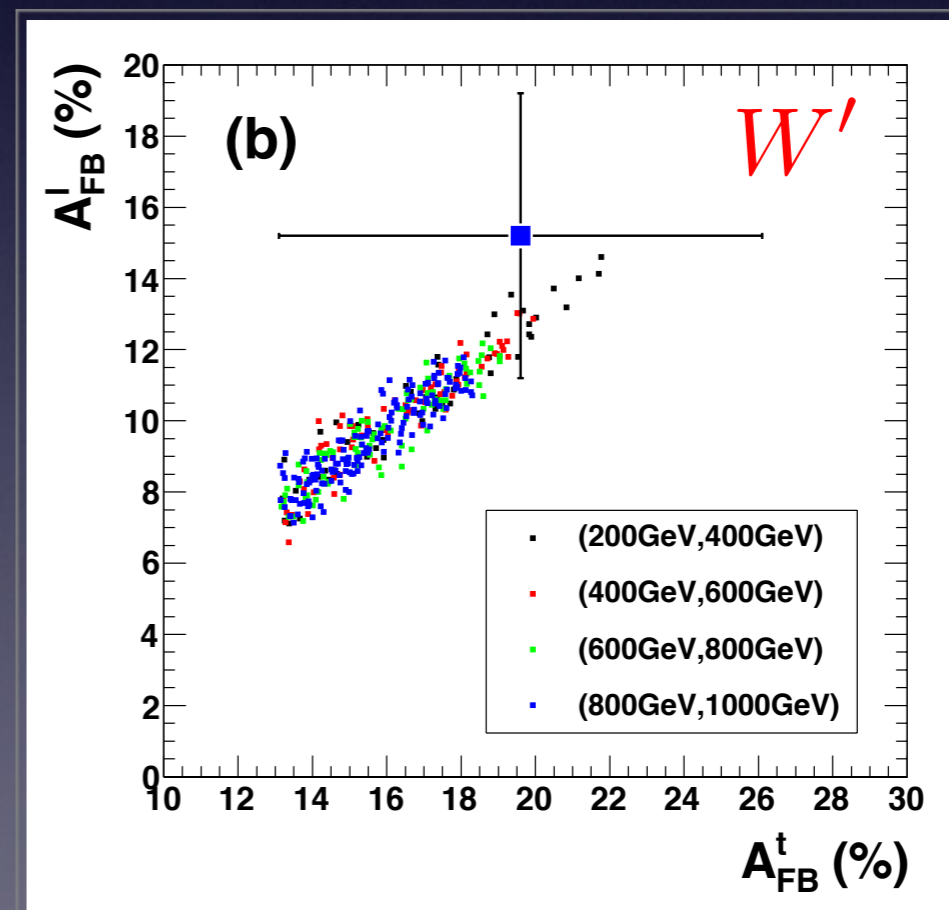
A_{FB}^t and A_{FB}^ℓ are connected by the spin correlation between the top-quark and charged lepton.

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

Unpolarised
top-quark



Right-handed
top-quark



Cheung,
Keung,
Yuan,
PLB 682
(2009) 287

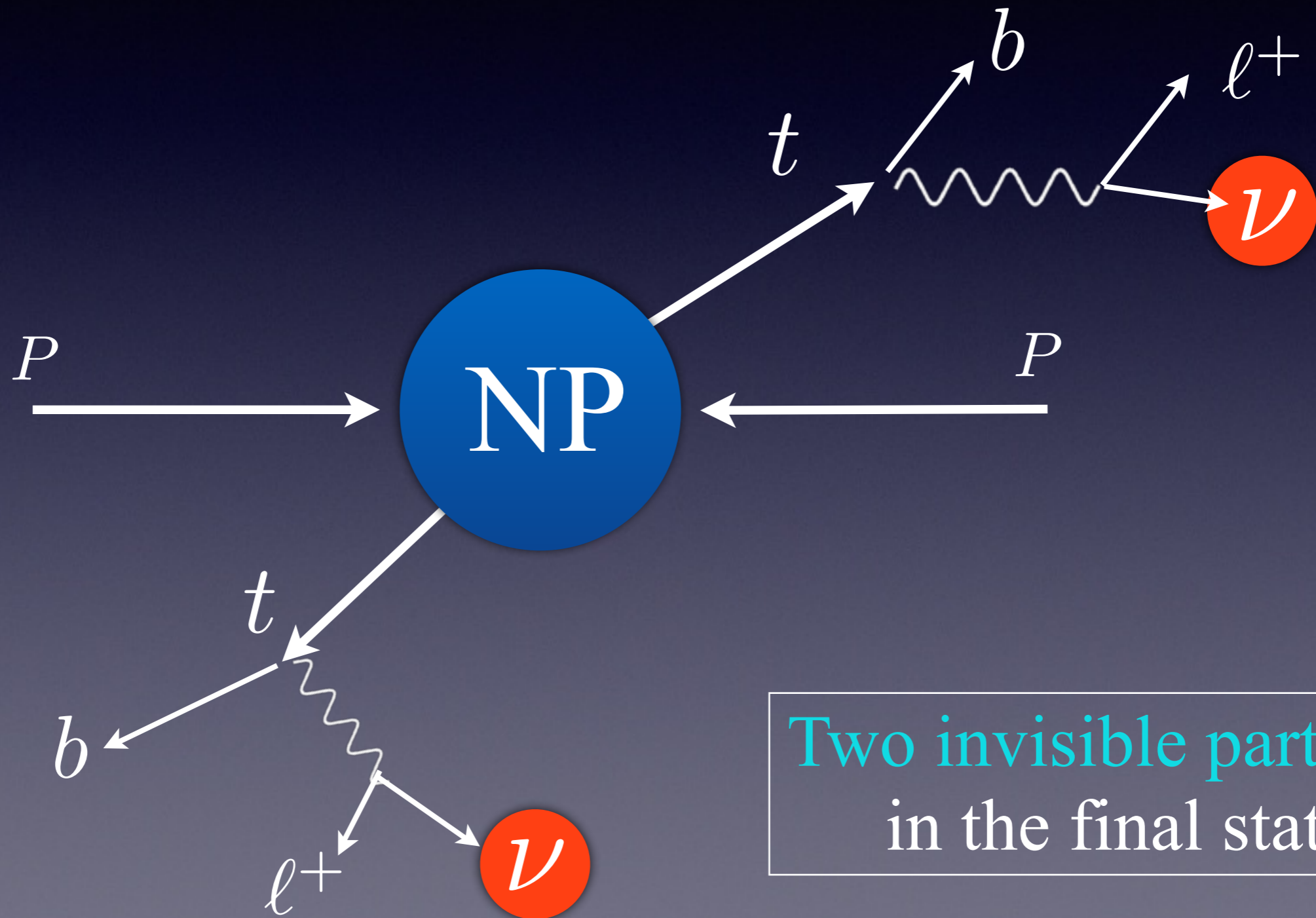
$$A_{FB}^\ell \simeq 0.47 \times A_{FB}^t + 0.25\%$$

$$A_{FB}^\ell \simeq 0.75 \times A_{FB}^t - 2.1\%$$

Top quark production in NP

(2) **Same-Sign** top-quark pair production

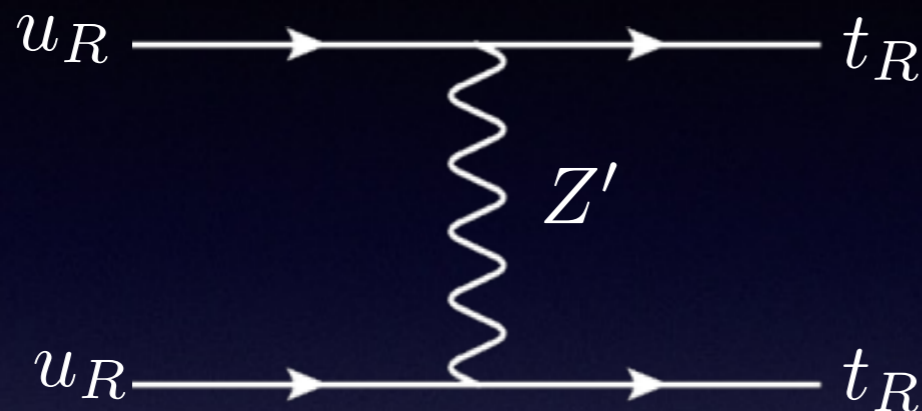
(or top-antitop pair production in dileptonic decay)



Two invisible particles
in the final state

Top quark is often polarised in NP

- Flavour changing gauge boson



Jung, Murayama, Pierce, Wells,
PRD81 (2010) 015004

- Exotic coloured particles (diquark scalar/vector)

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



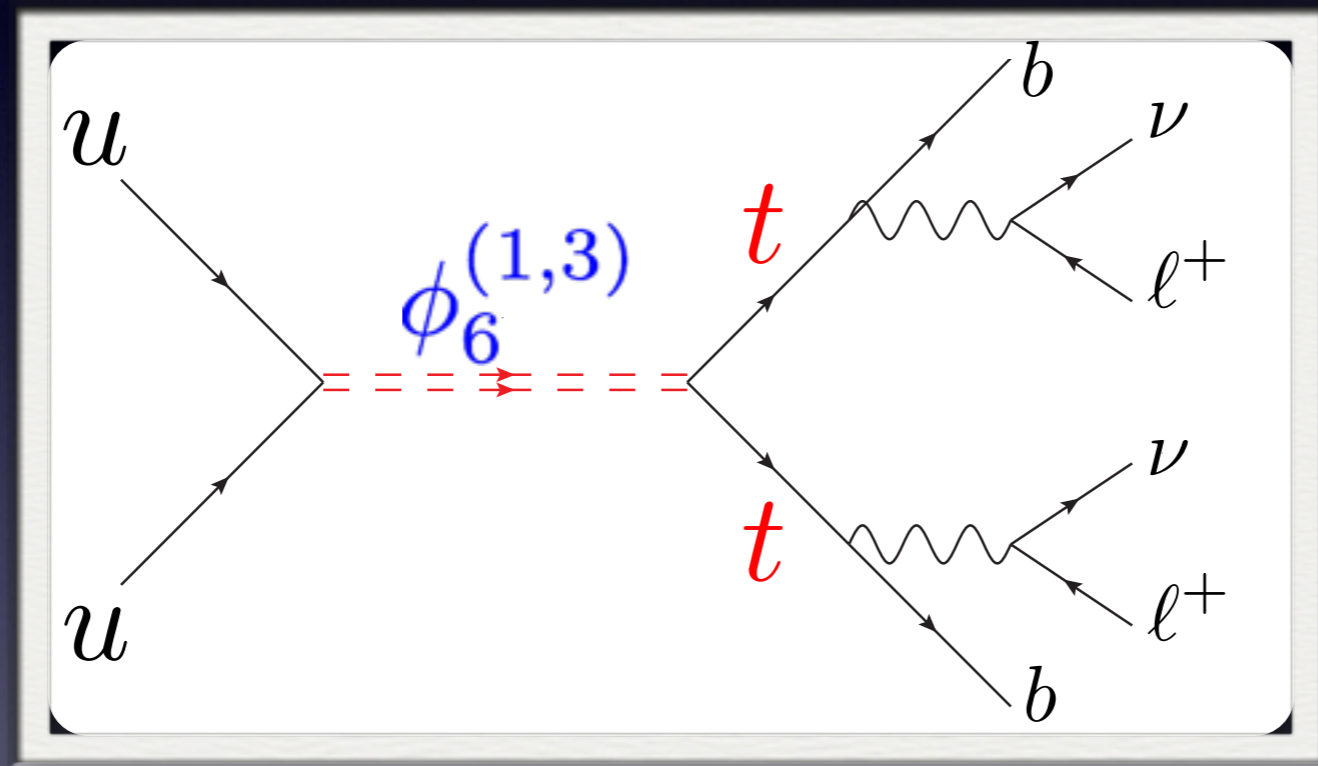
Cakir and Sahin,
PRD72 (2005) 115011

Mohapatra, Okada, Yu,
PRD77 (2008) 011701

C.-R. Chen, Klemm, Rentala, Wang,
PRD79 (2009) 054002

C.-H. Chen, PLB 680 (2009) 133

Measuring top-quark polarisation in same-sign top quark pair production in color sextet scalar/vector model



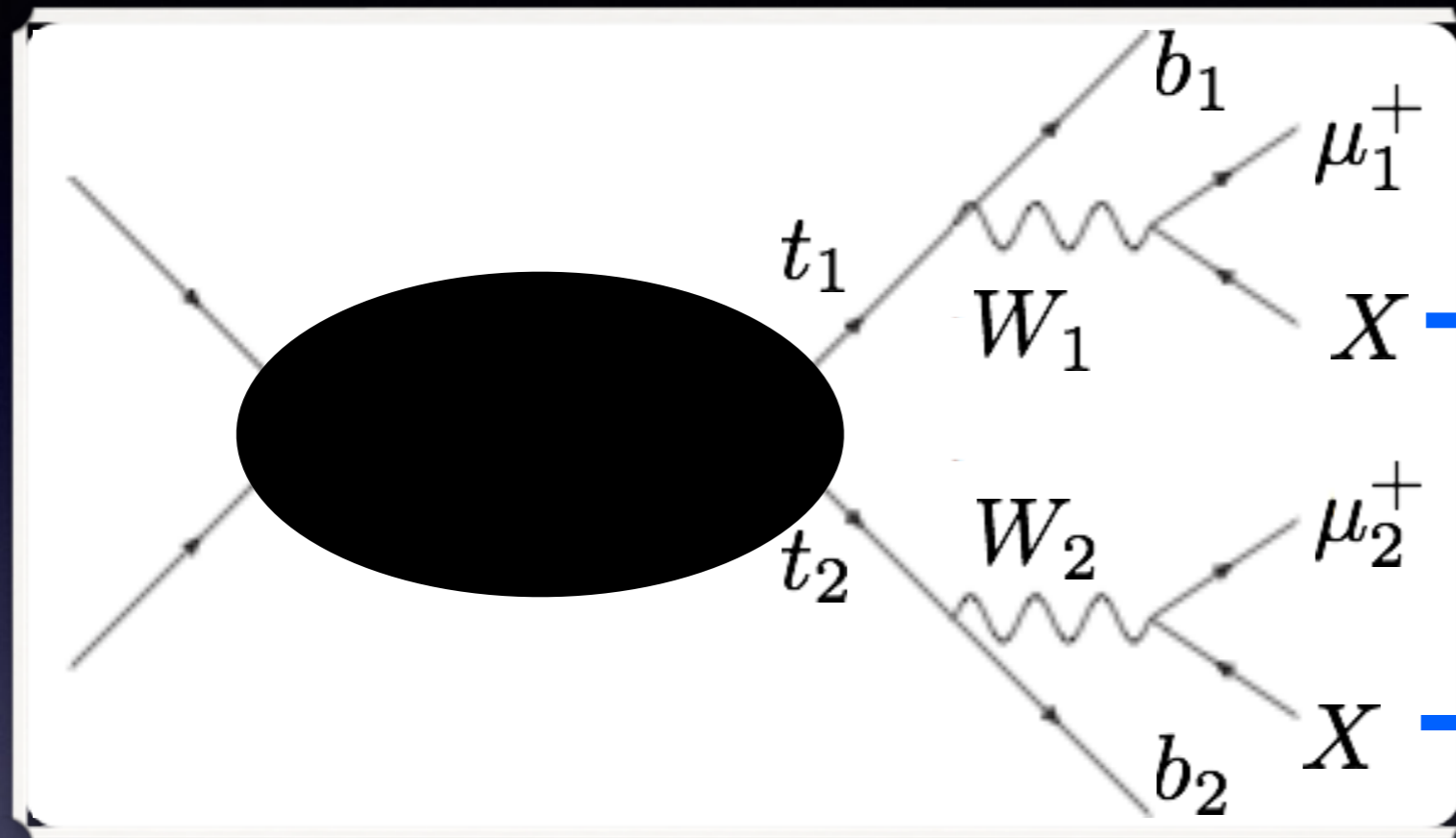
2ν

$$\phi_6^{(3)} \rightarrow t_L t_L \quad \phi_6^{(1)} \rightarrow t_R t_R$$

Berger, QHC, Chen, Shaughnessy, Zhang, PRL 105 (2010) 181802
 Zhang, Berger, QHC, Chen, Shaughnessy, PLB 696 (2011) 68

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

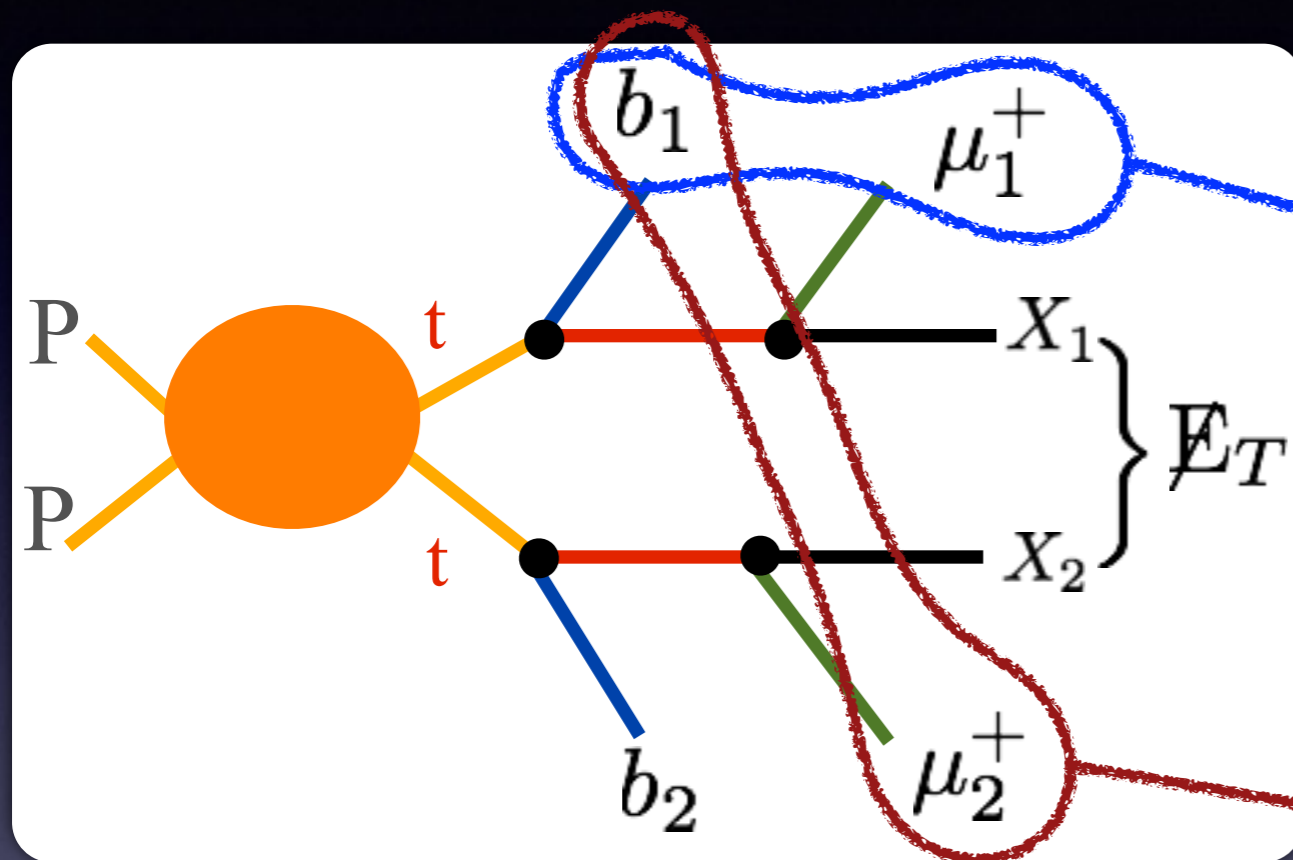
(correct l-b pairing is necessary)

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

~~Two complex~~, two real solutions

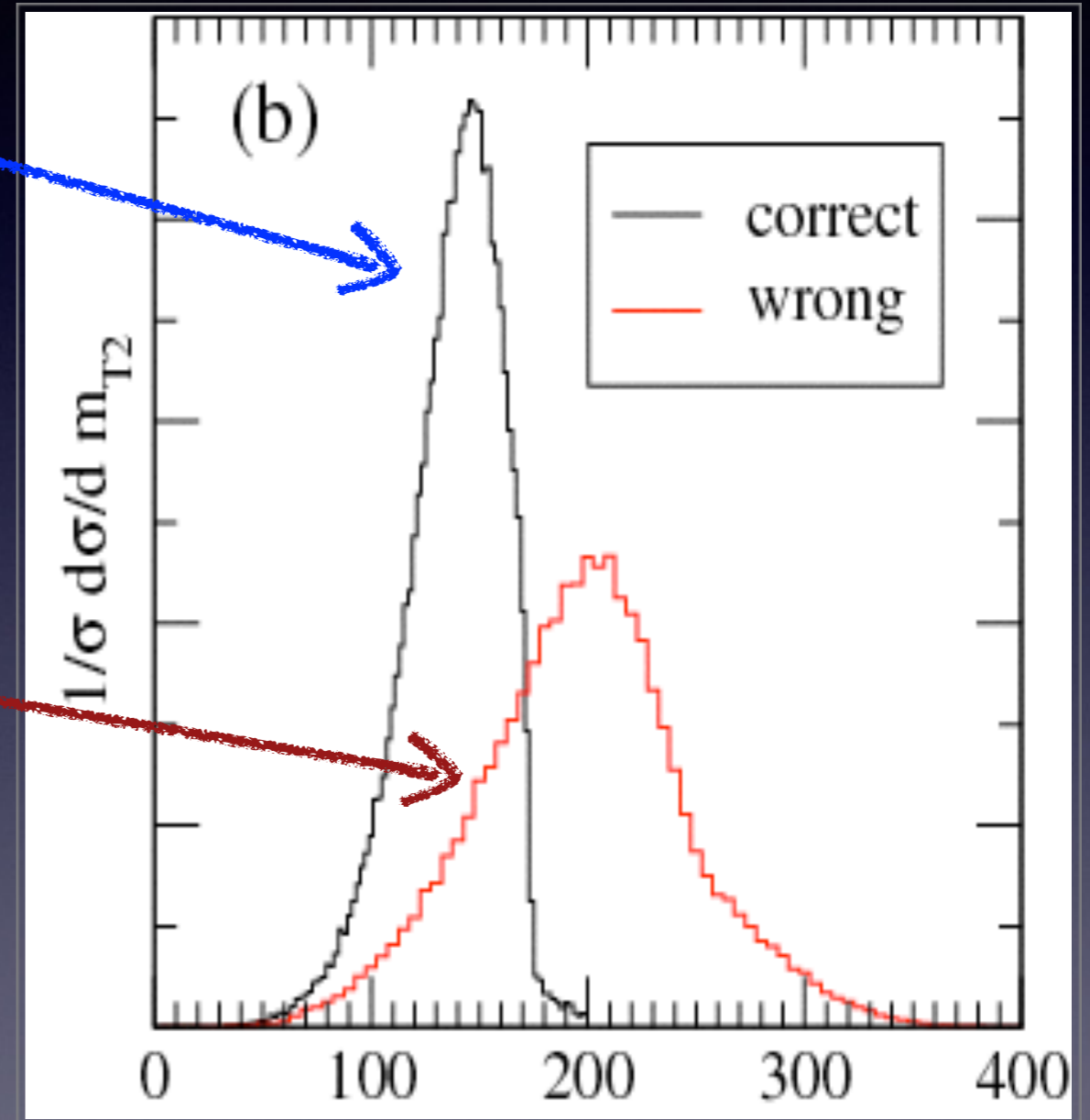
$\ell^+ - b$ pairing: MT2-assisted method

MT2 variable of lepton-b clusters and MET



Two combinations of lepton-b clusters

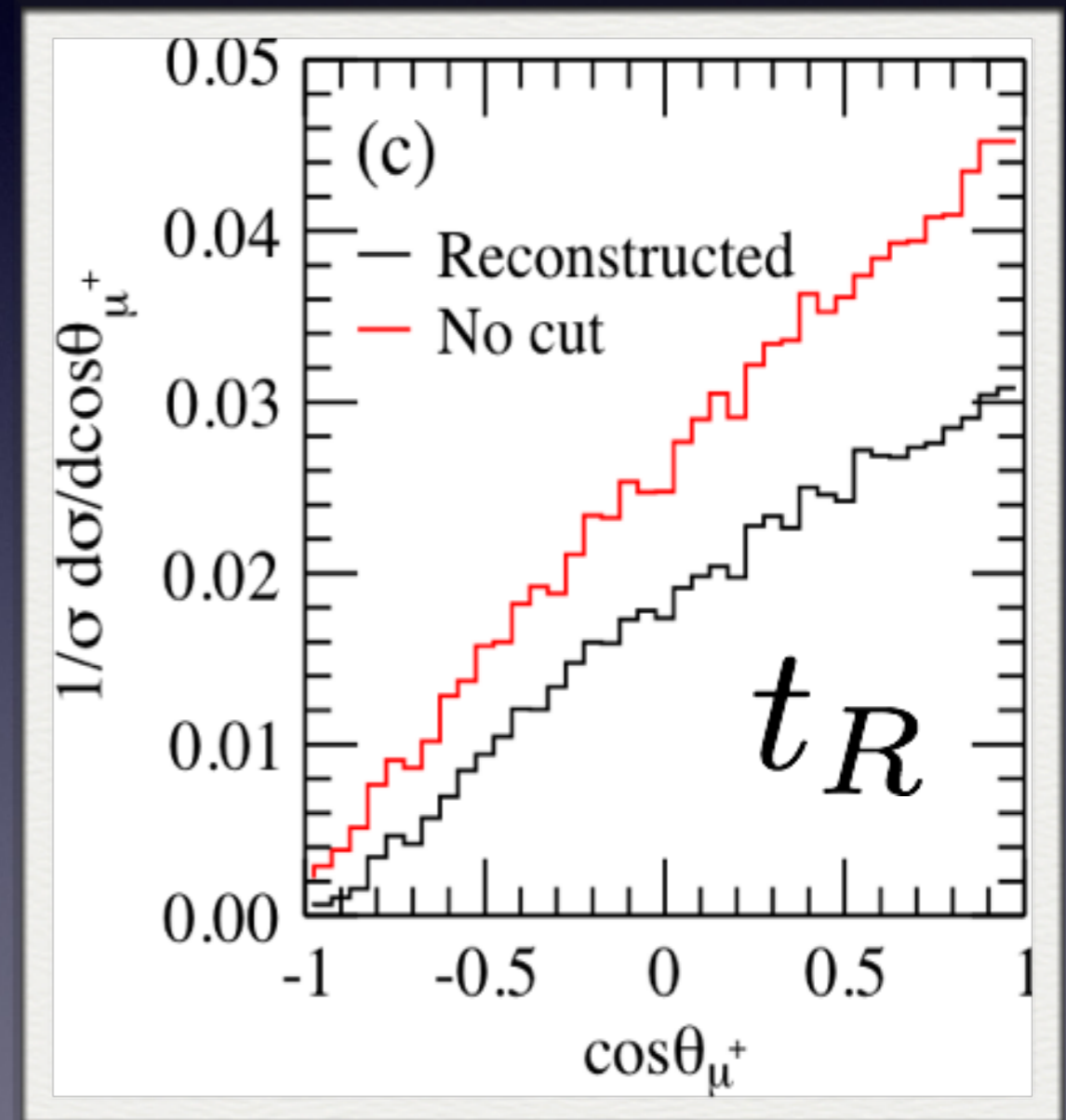
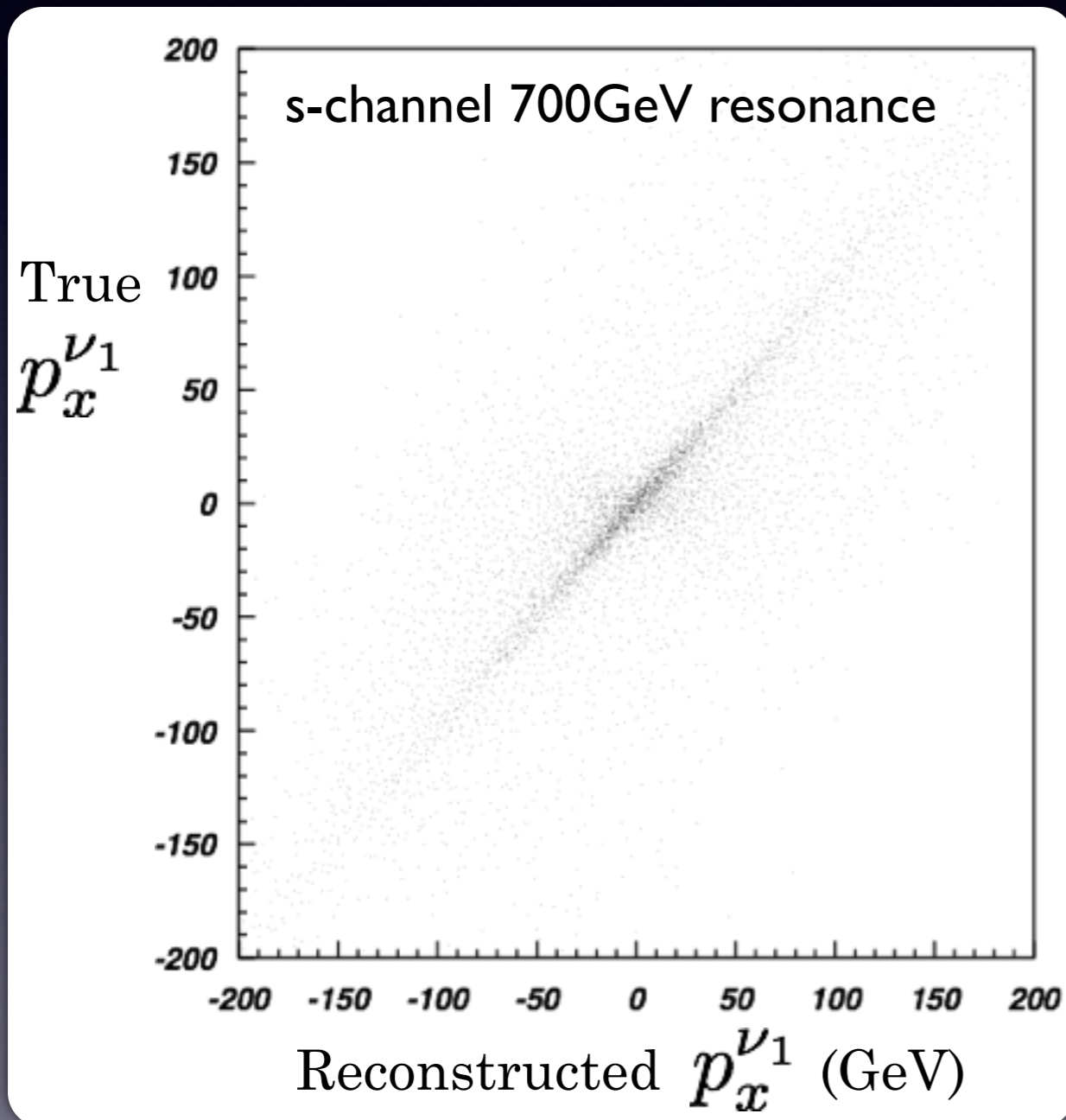
Choose smaller MT2 (correct combination found with nearly 100% probability)



$$M_{T2}(\ell_1^+ b_1, \ell_2^+ b_2, \cancel{E}_T)$$

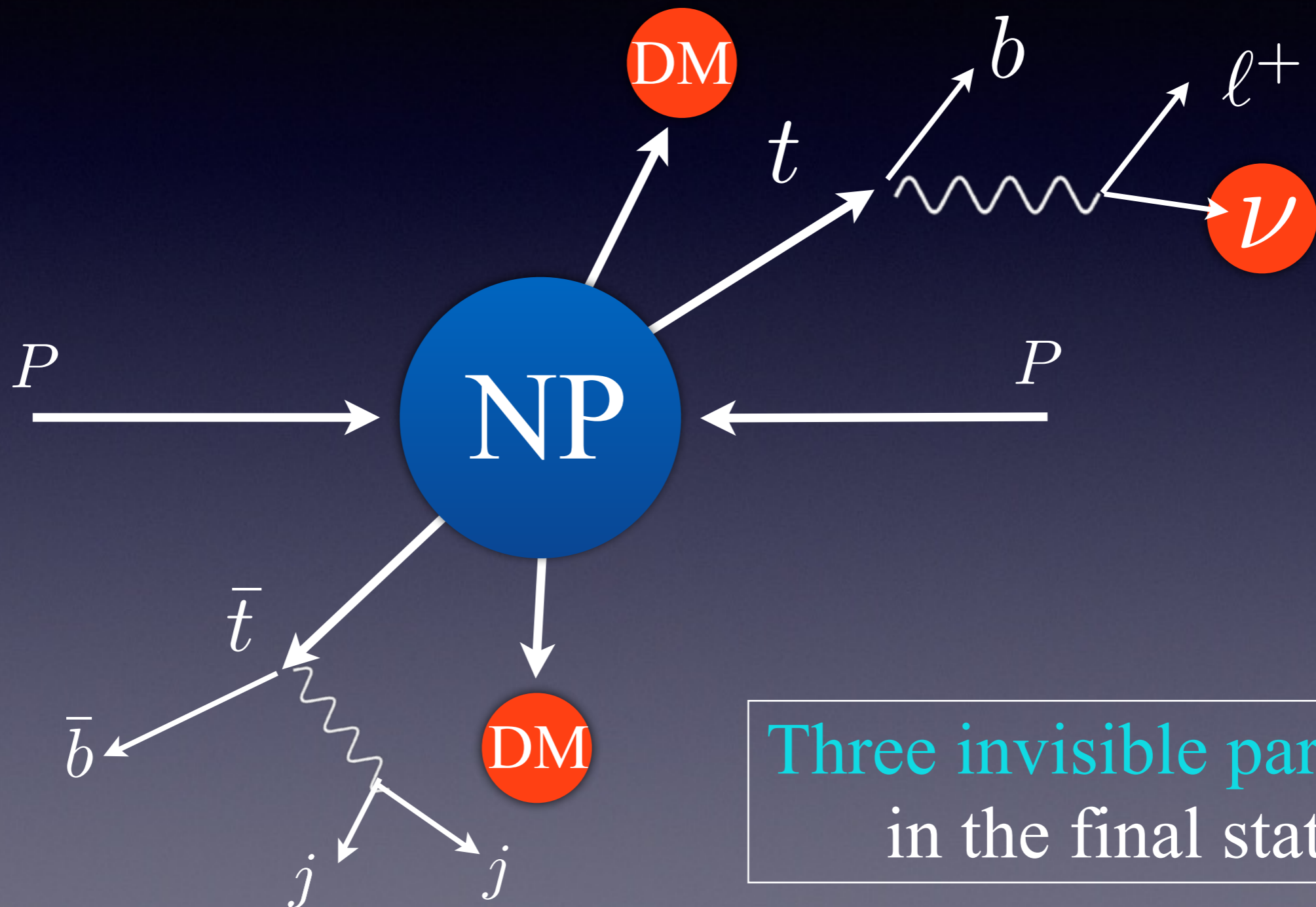
Neutrino momentum reconstruction

- Strong correlation between the true $p_x^{\nu_1}$ and reconstructed $p_x^{\nu_1}$
- Top quark polarisation can be measured after neutrino reconstruction.



Top quark production in NP

(3) Top-quark pair + dark matter candidates

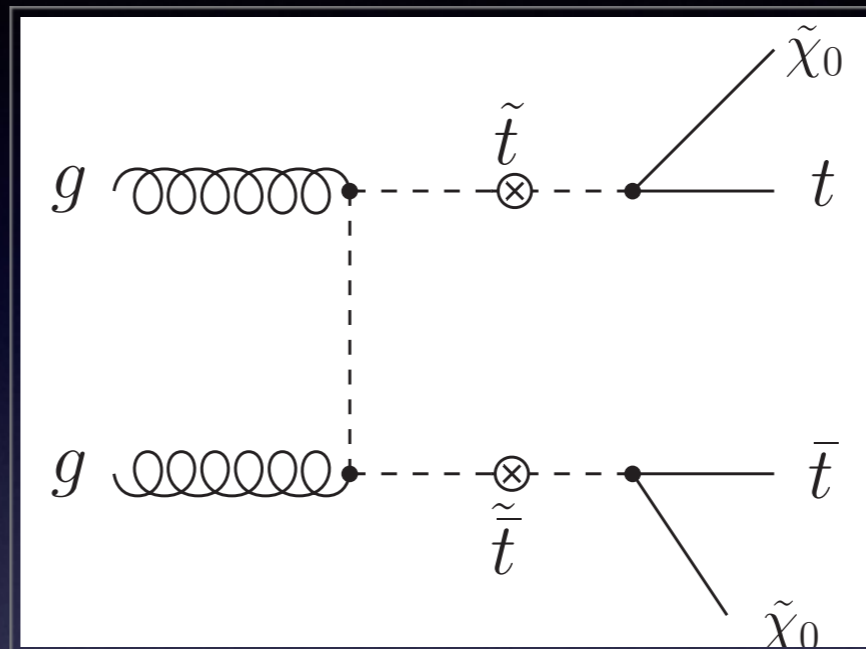


Three invisible particles
in the final state

Top-quark pair plus missing energy

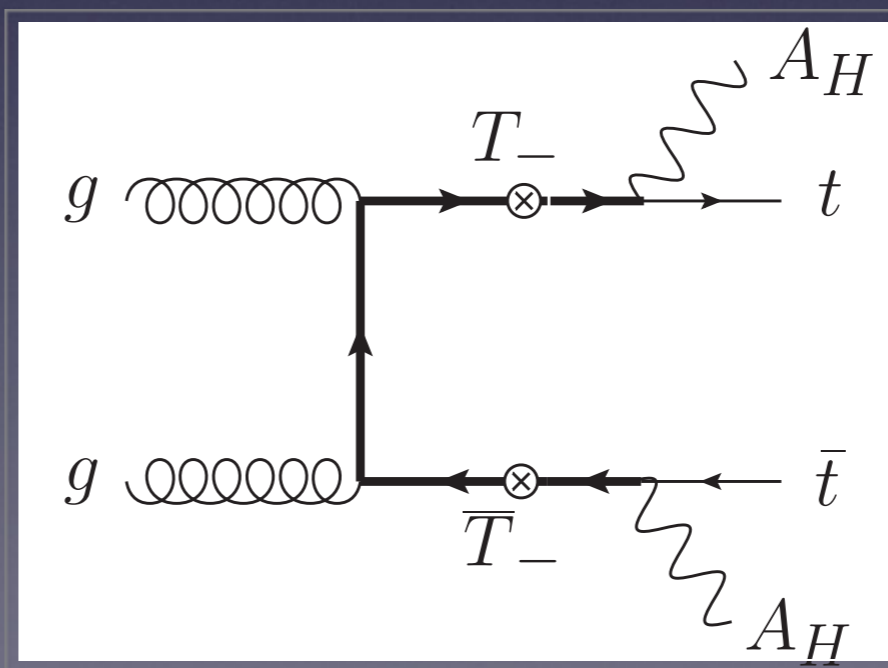
Typical collider signature in several NP models

- ▶ 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

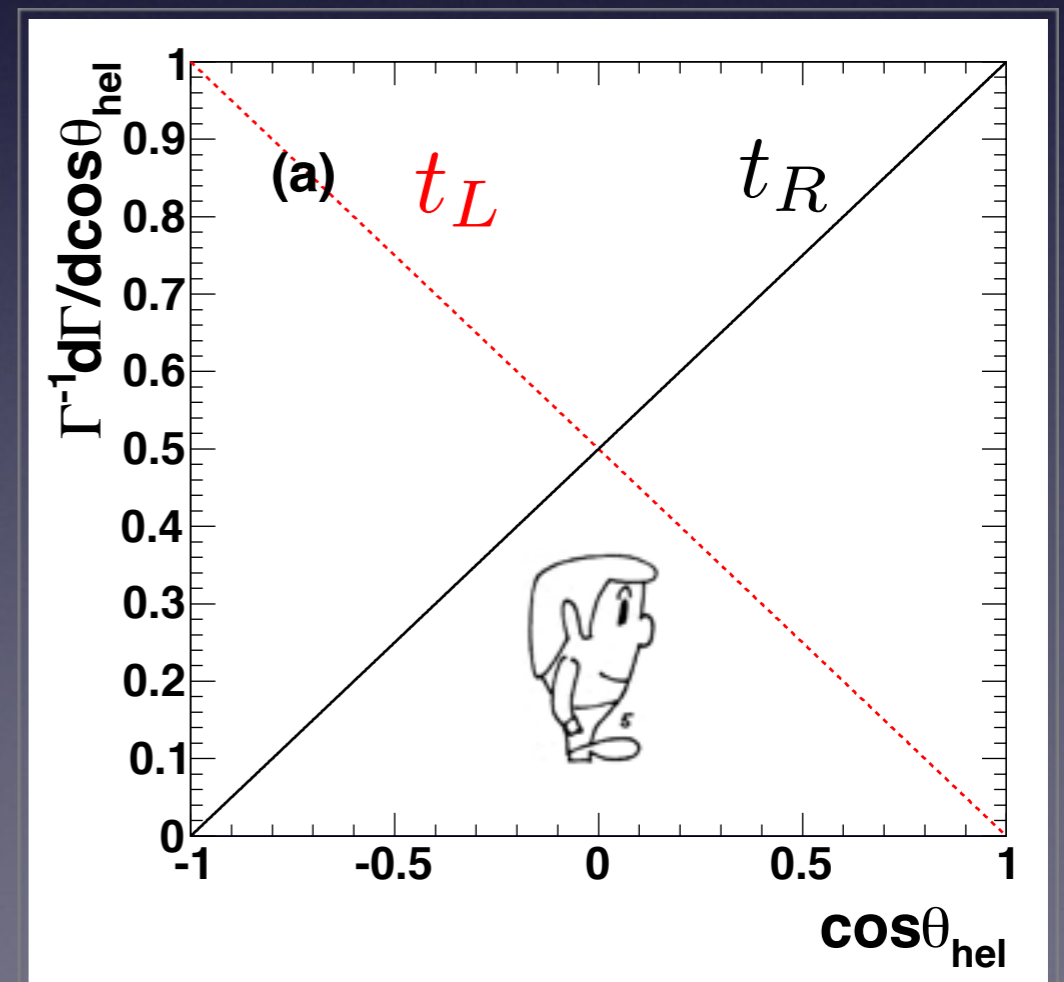
$$\frac{d\Gamma}{dx d\cos\theta} = \frac{\alpha_W^2 m_t}{32\pi AB} x(1-x) \text{Arctan} \left[\frac{Ax}{B-x} \right] \frac{1 + s_t \cos\theta}{2}$$

Czarnecki, Jezabek, Kuhn, NPB351 (1991) 70



$\lambda_t = +$ right-handed
 $\lambda_t = -$ left-handed

The energy and angle
 are correlated
 when top is boosted.



Lepton energy is sensitive to top-polarization

Schmidt and Peskin, PRL 69 (1992) 410

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

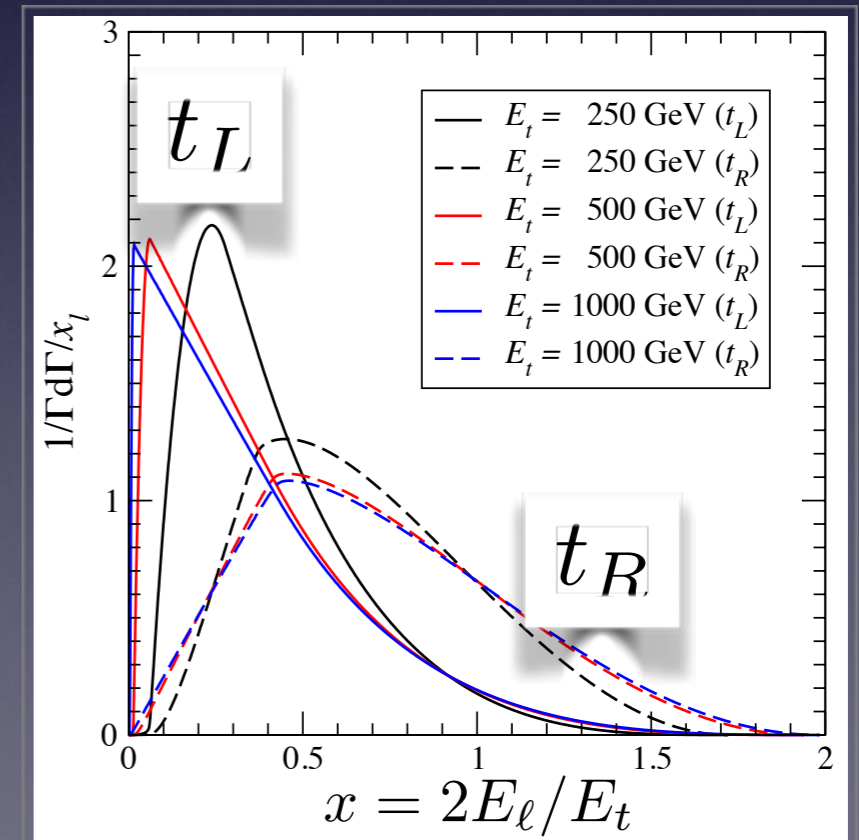
$$\frac{d\Gamma(\hat{s}_t)}{dx} = \frac{\alpha_W^2 m_t}{64\pi AB} \int_{z_{\min}}^{z_{\max}} x\gamma^2 [1 - x\gamma^2(1 - z\beta)] \times \left(1 + \hat{s}_t \frac{z - \beta}{1 - z\beta}\right) \text{Arctan} \left[\frac{Ax\gamma^2(1 - z\beta)}{B - x\gamma^2(1 - z\beta)} \right] dz$$

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

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

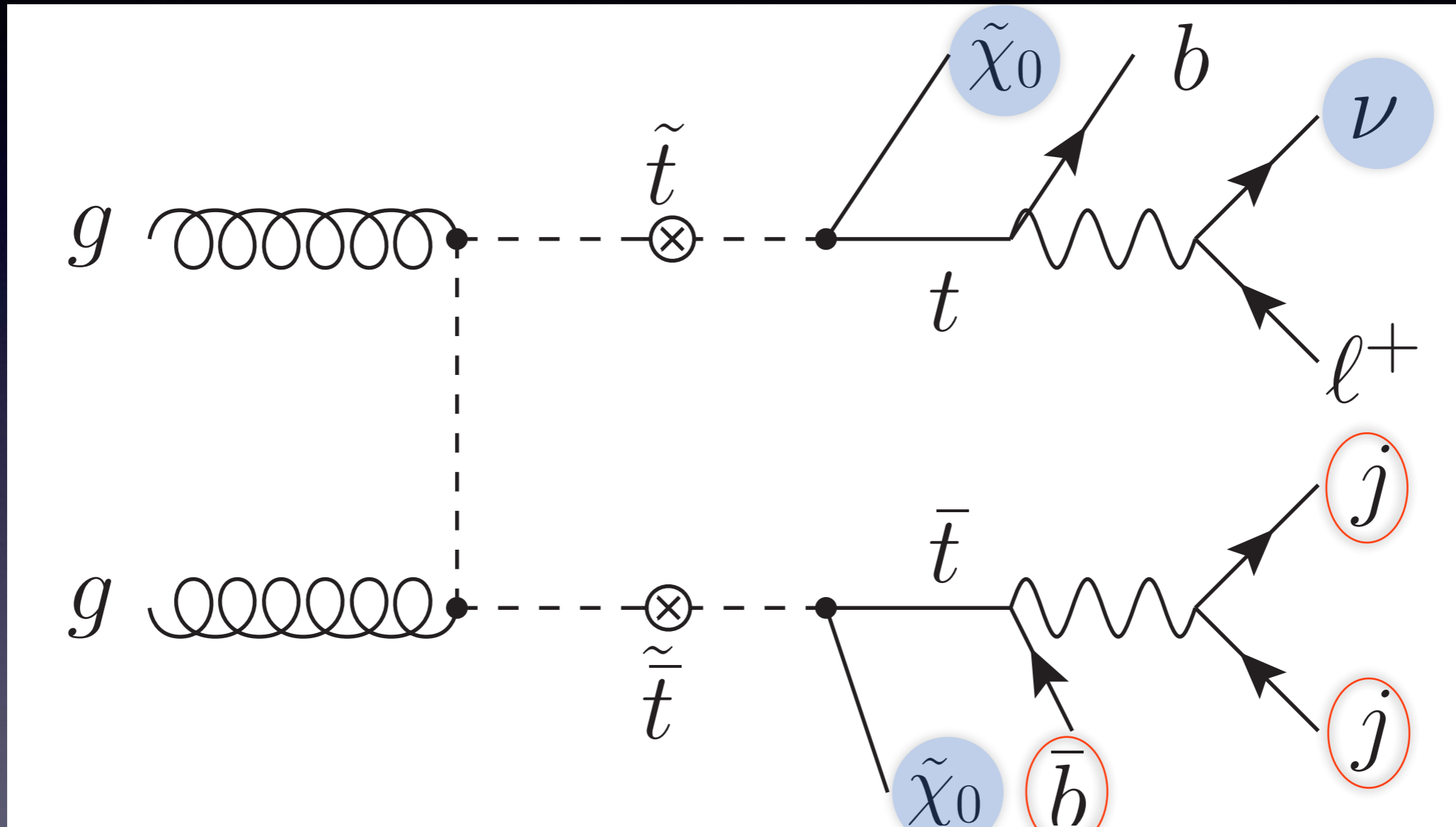
$$z_{\min} = \max[(1 - 1/\gamma^2 x)/\beta, -1]$$

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



Lepton energy and top-quark polarization

Identical decay chains

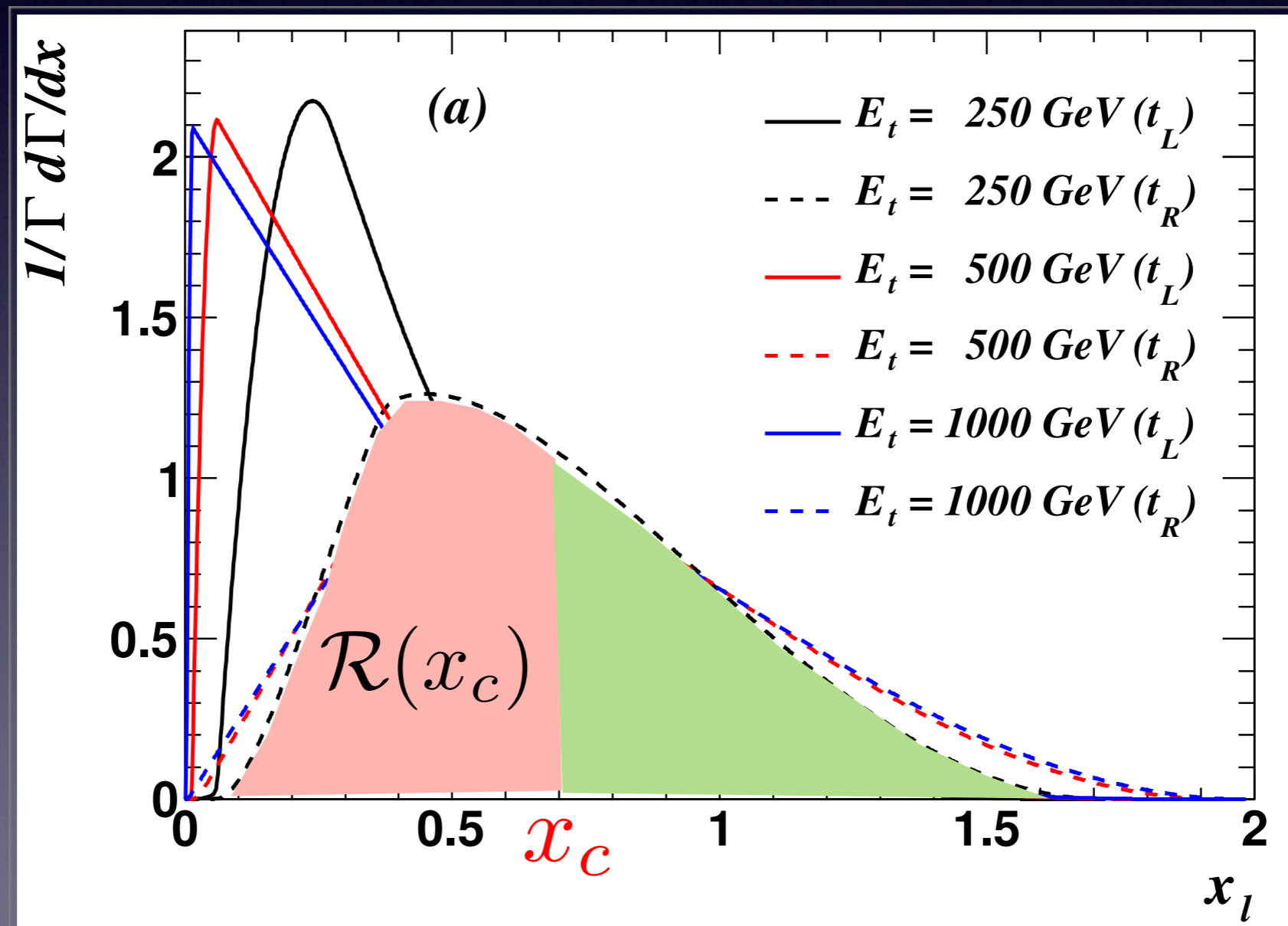


$$x'_\ell = 2E_{\ell^+} / E_{\bar{t}}$$

Lepton energy and top-quark polarisation

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

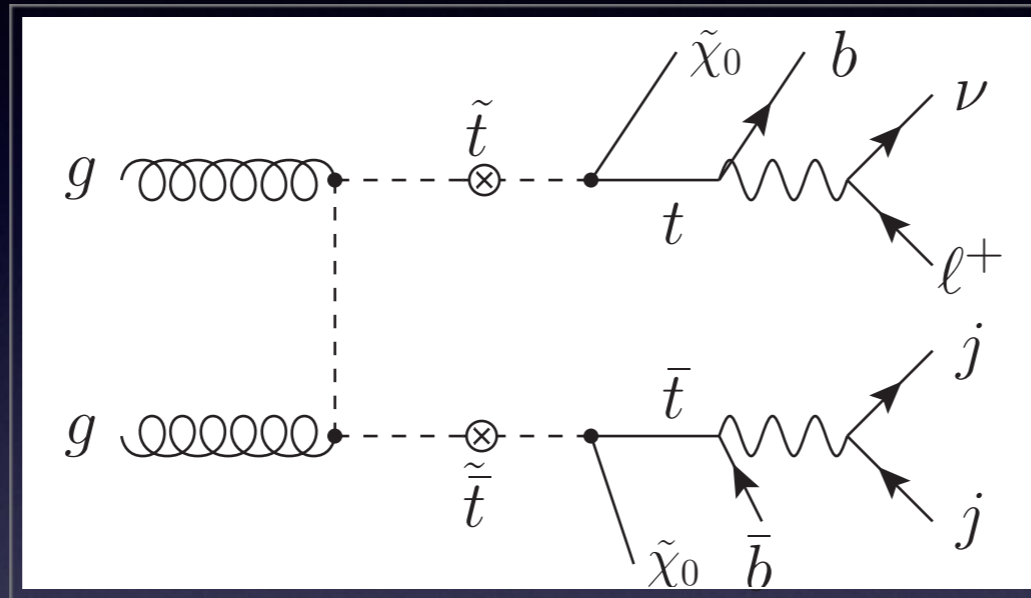
$$\mathcal{R}(x_c) \equiv \frac{\text{Area}(x_\ell < x_c)}{\text{Area}(\text{tot})} = \text{Area}(x_\ell < x_c)$$



Toy model mimicking MSSM

- MSSM like:

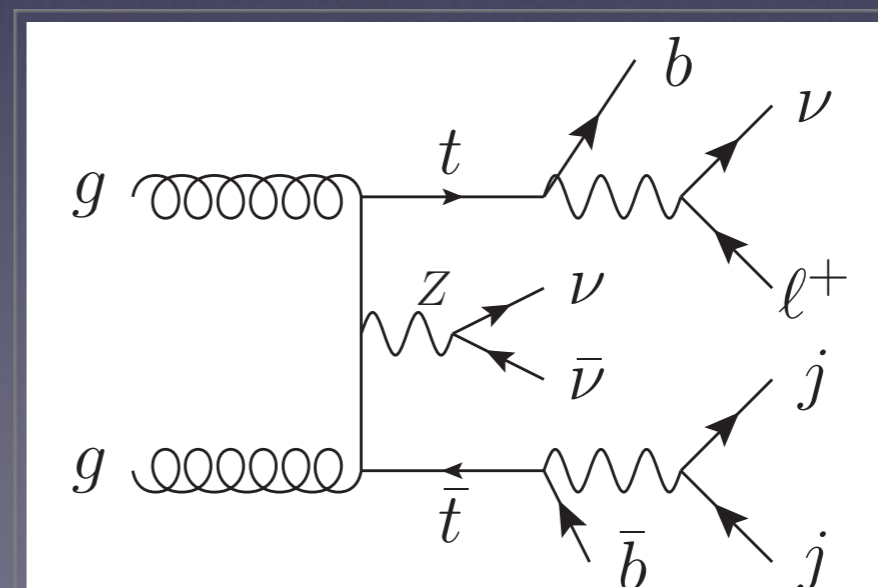
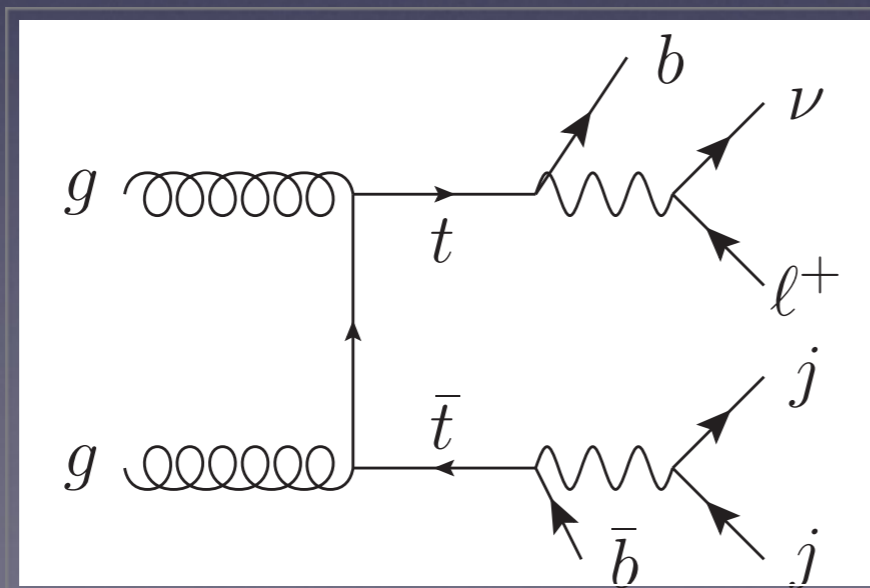
$$\mathcal{L}_{\tilde{t}t\tilde{\chi}} = g_{\text{eff}}\tilde{t}\tilde{\chi}(\cos\theta_{\text{eff}}P_L + \sin\theta_{\text{eff}}P_R)t$$



Collider signature

$$b\bar{b}jj\ell^+\ell^- \cancel{E}_T$$

- Major SM backgrounds



Collider simulation

- Basic selection cuts

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

$$\cancel{E}_T > 25 \text{ GeV} \quad \Delta R_{jj,\ell j} > 0.4$$

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

- Hard cuts

$$\cancel{E}_T > 100 \text{ GeV} \quad H_T > 500 \text{ GeV}$$

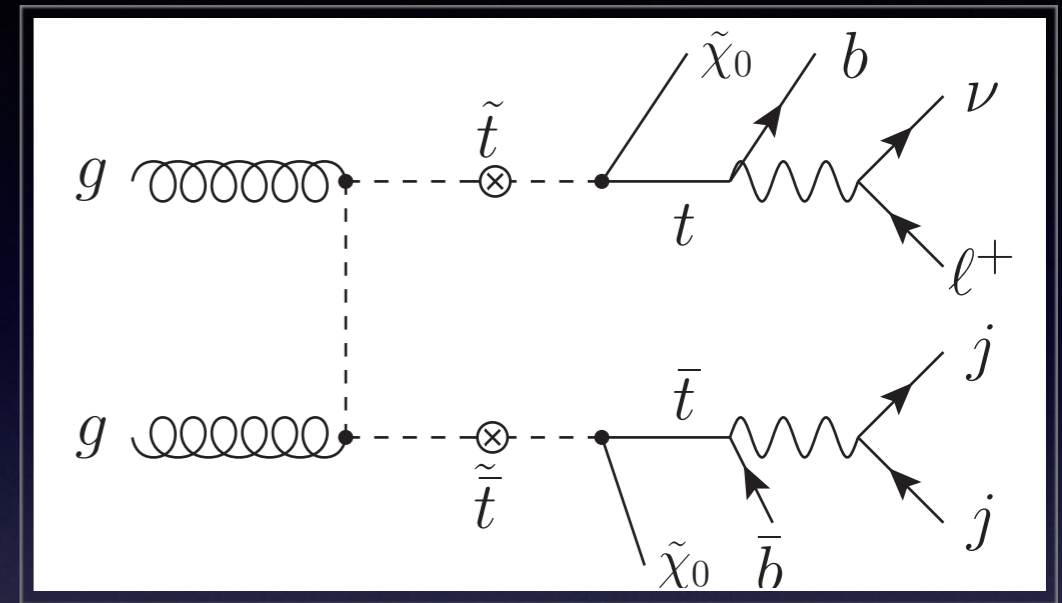
$$H_T = p_T^\ell + p_T^{j_1} + p_T^{j_2} + p_T^b + p_T^{\bar{b}} + \cancel{E}_T$$

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

Loop over all jet combinations and pick up the one minimize

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

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



Signal versus Backgrounds

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

	<i>Basic</i>	<i>t_{had} recon.</i>	<i>Hard</i>	\cancel{E}_T <i>sol.</i>	ϵ_{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 %

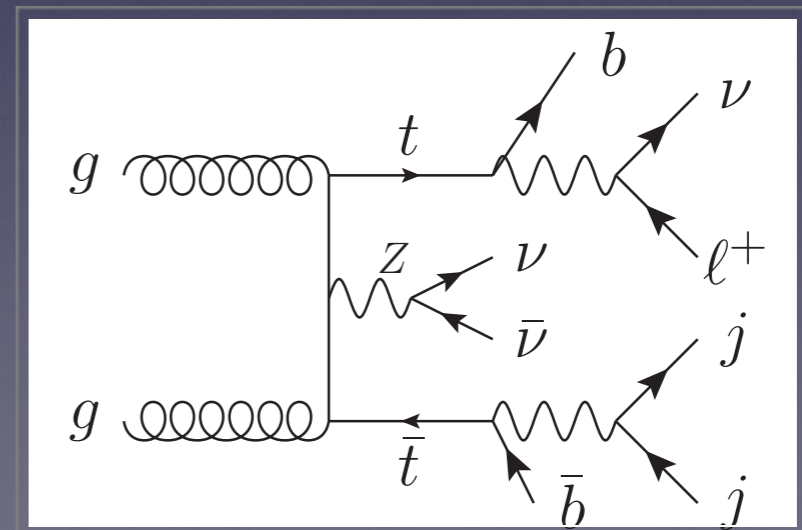
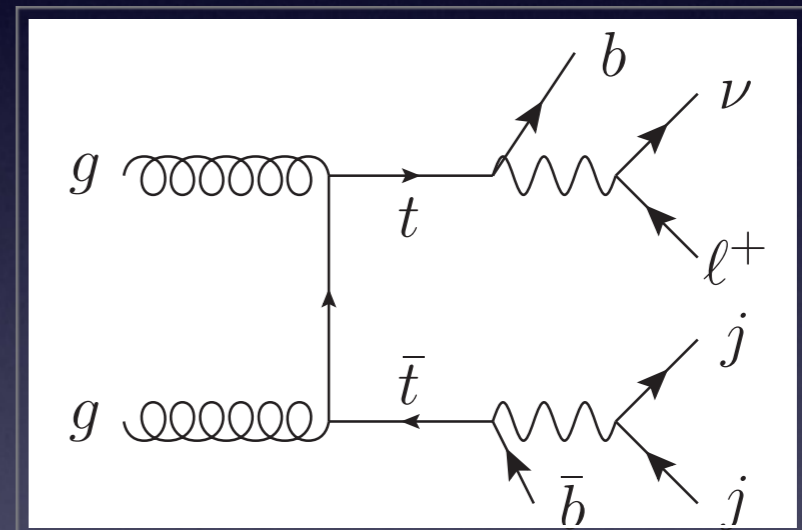
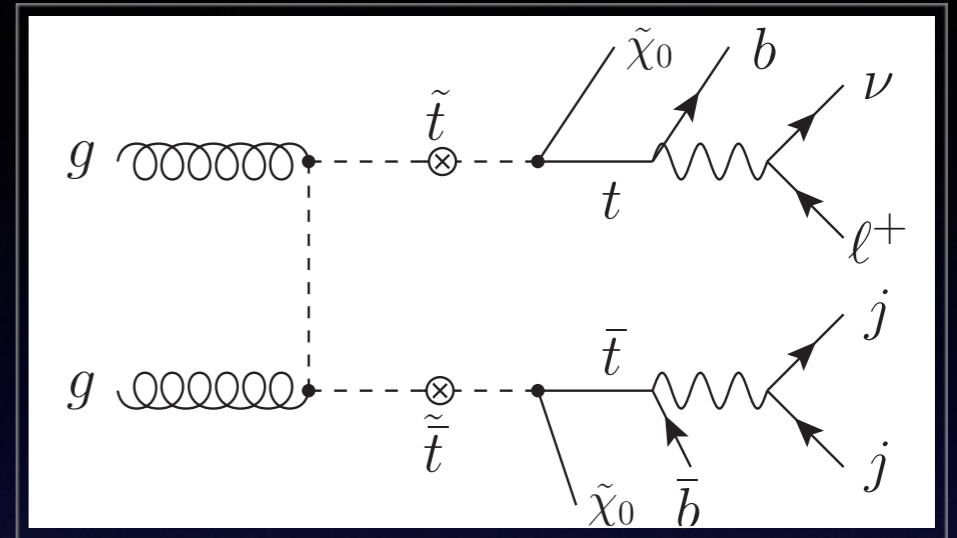
- \cancel{E}_T solution cut

$$p_z^\nu = \frac{1}{2(p_T^e)^2} \left[A p_z^e \pm E_e \sqrt{A^2 - 4 (p_T^e)^2 \cancel{E}_T^2} \right]$$

$$A \equiv m_W^2 + 2 \vec{p}_T^e \cdot \vec{\cancel{E}}_T$$

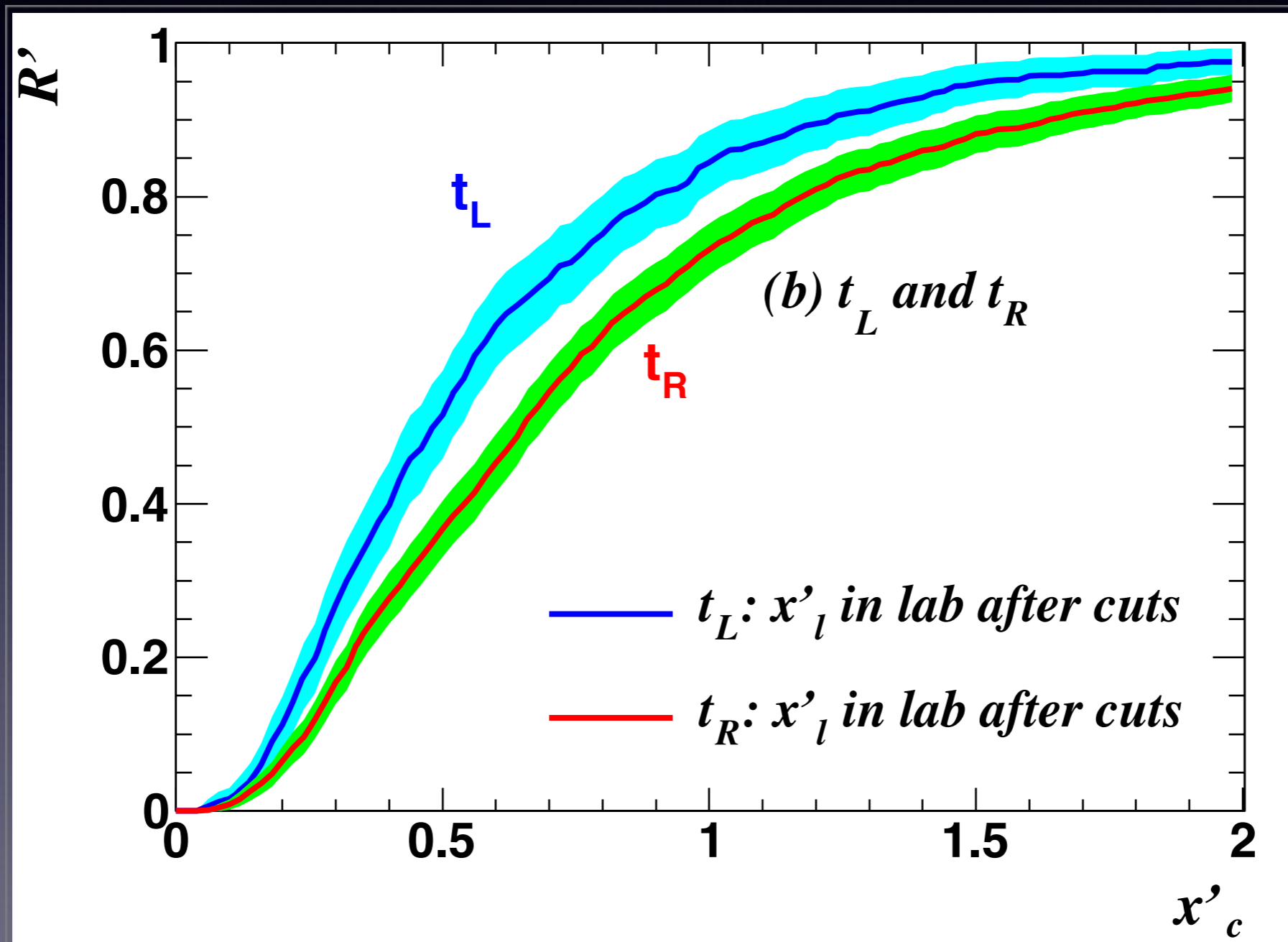
$$A^2 - 4 (p_T^e)^2 \cancel{E}_T^2 \leq 0$$

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



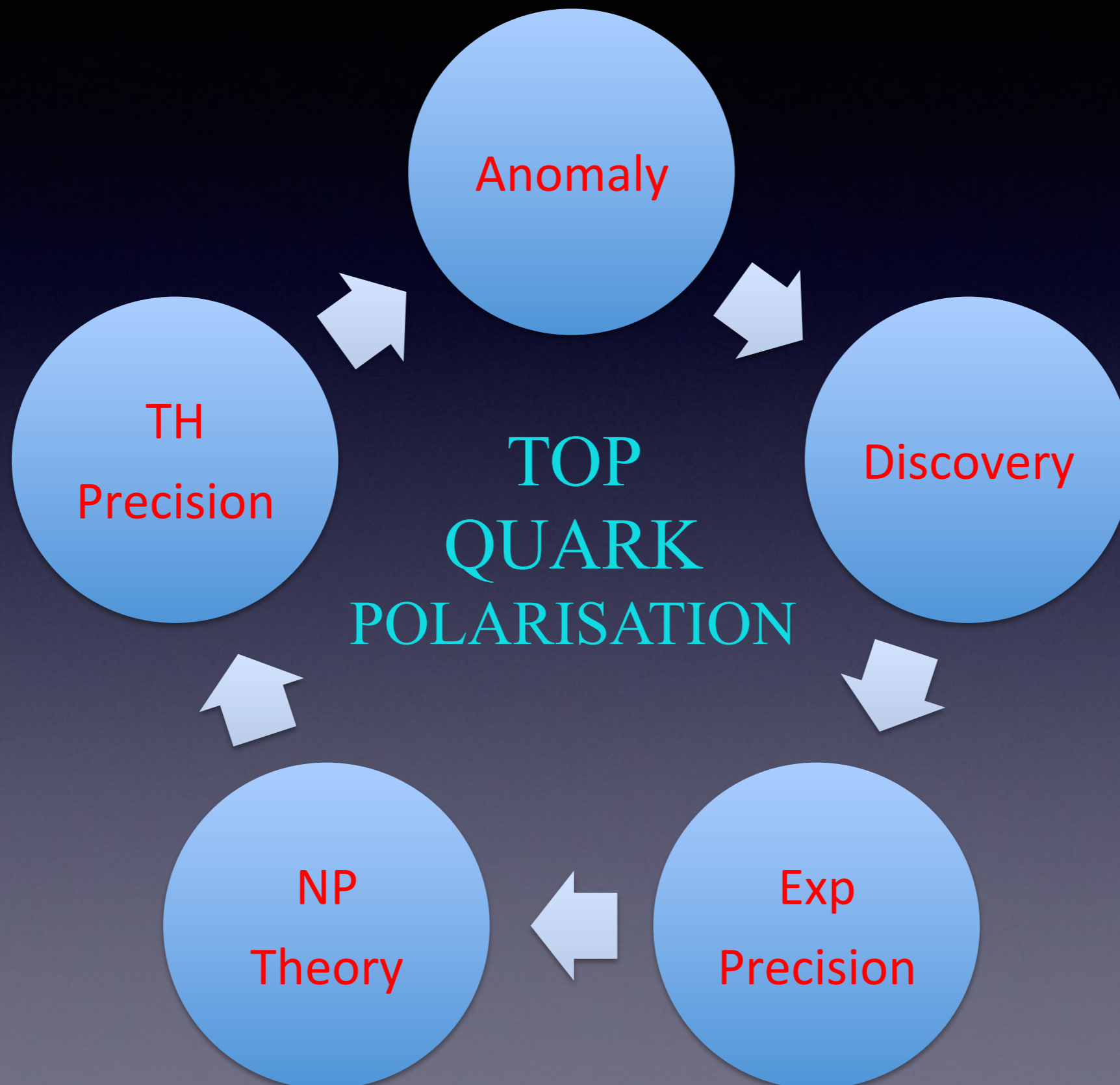
\mathcal{R}' distribution

t_L and t_R are separated



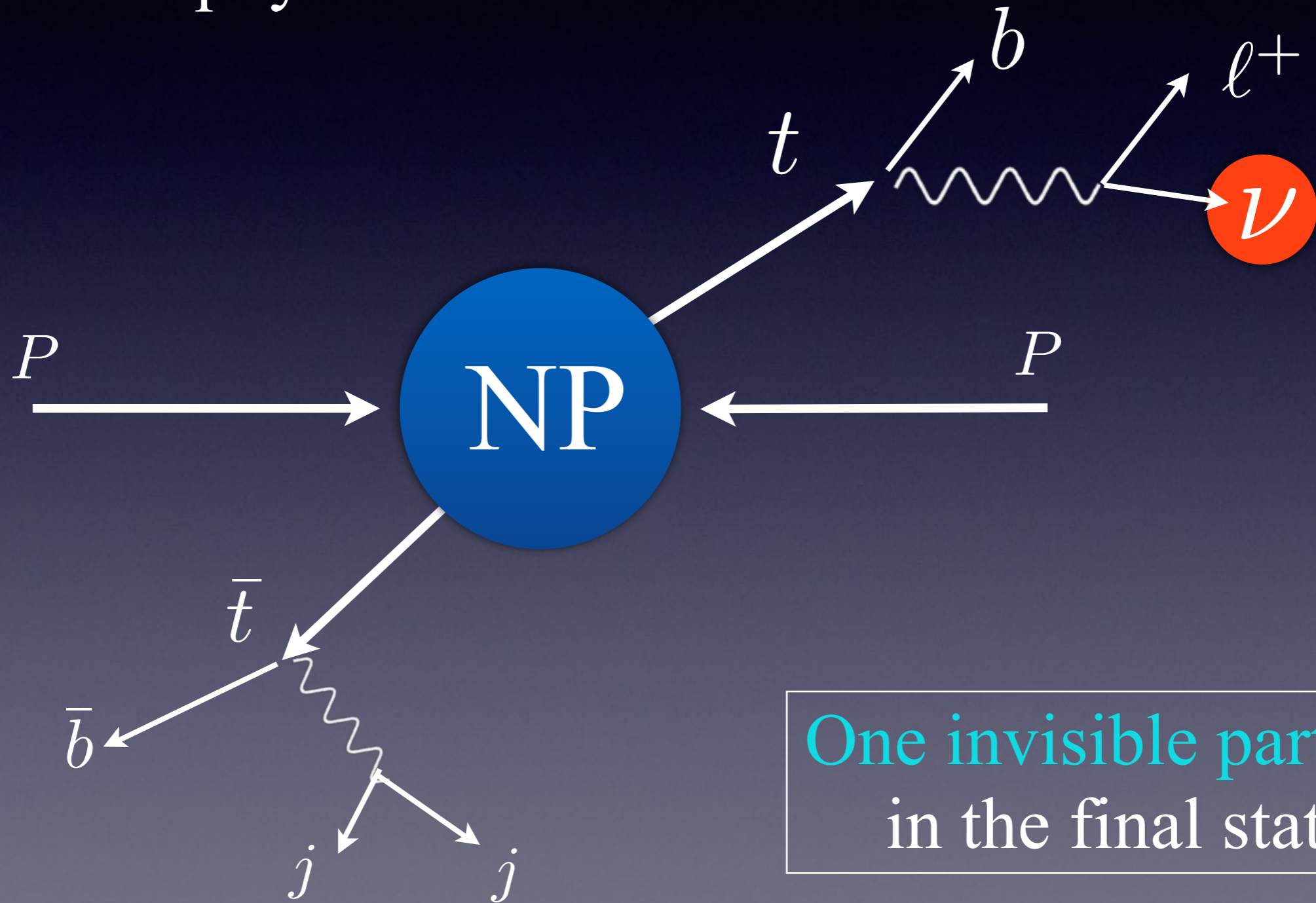
LHC
14 TeV
100fb⁻¹

Conclusion



Conclusion

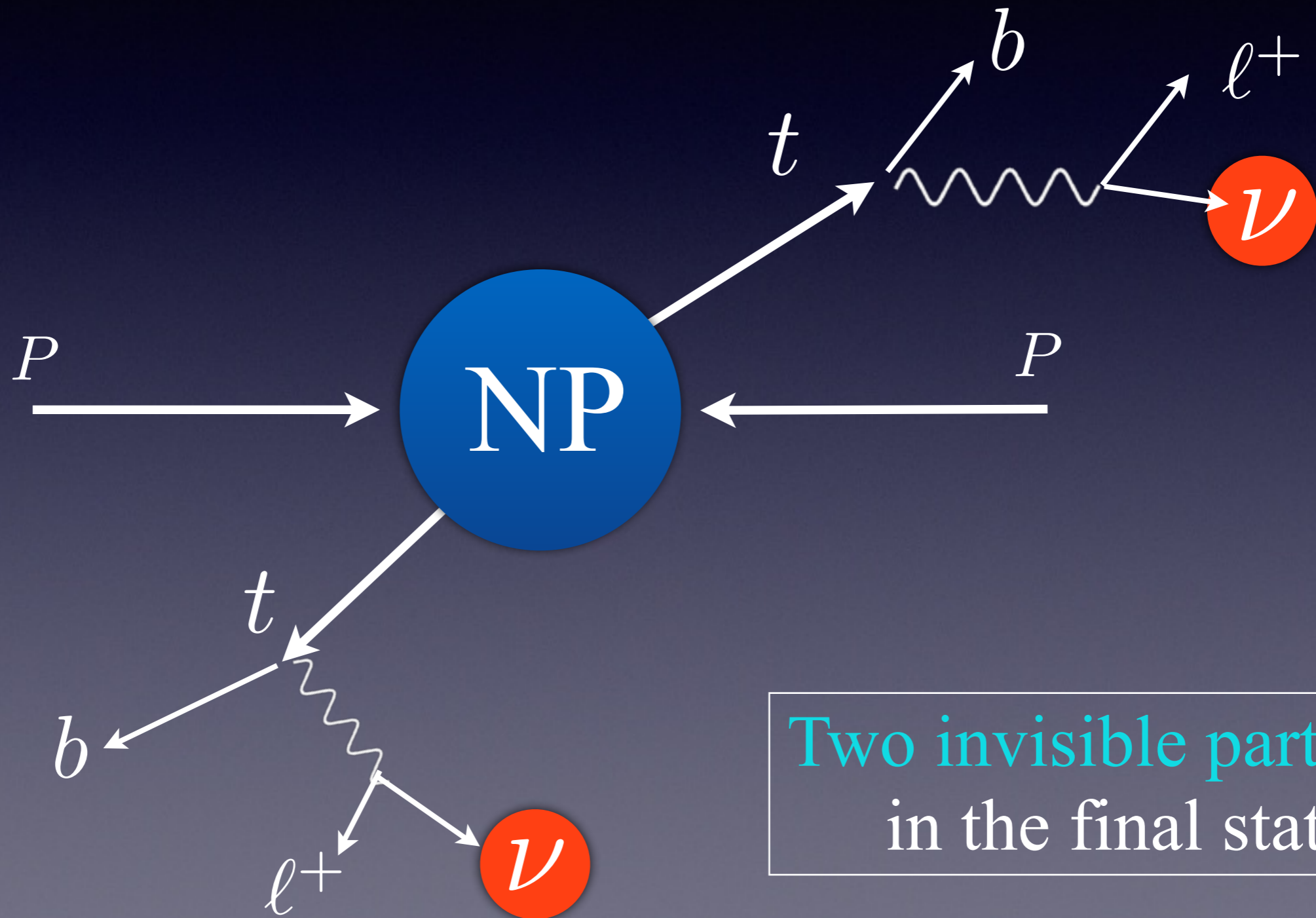
- Top-quark polarisation provides additional information about new physics structure



One invisible particle
in the final state

Conclusion

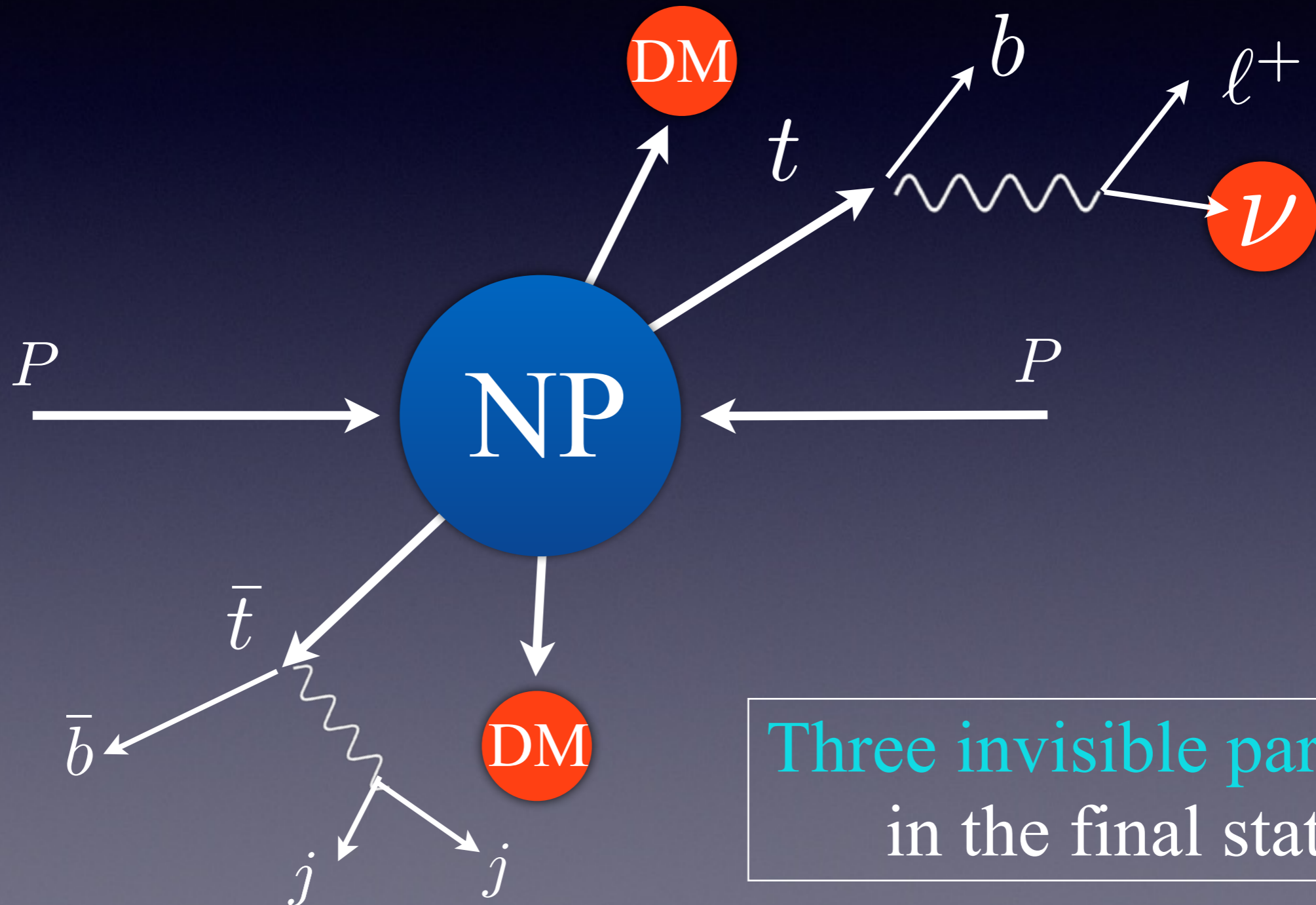
- Top-quark polarisation provides additional information about new physics structure



Two invisible particles
in the final state

Conclusion

- Top-quark polarisation provides additional information about new physics structure



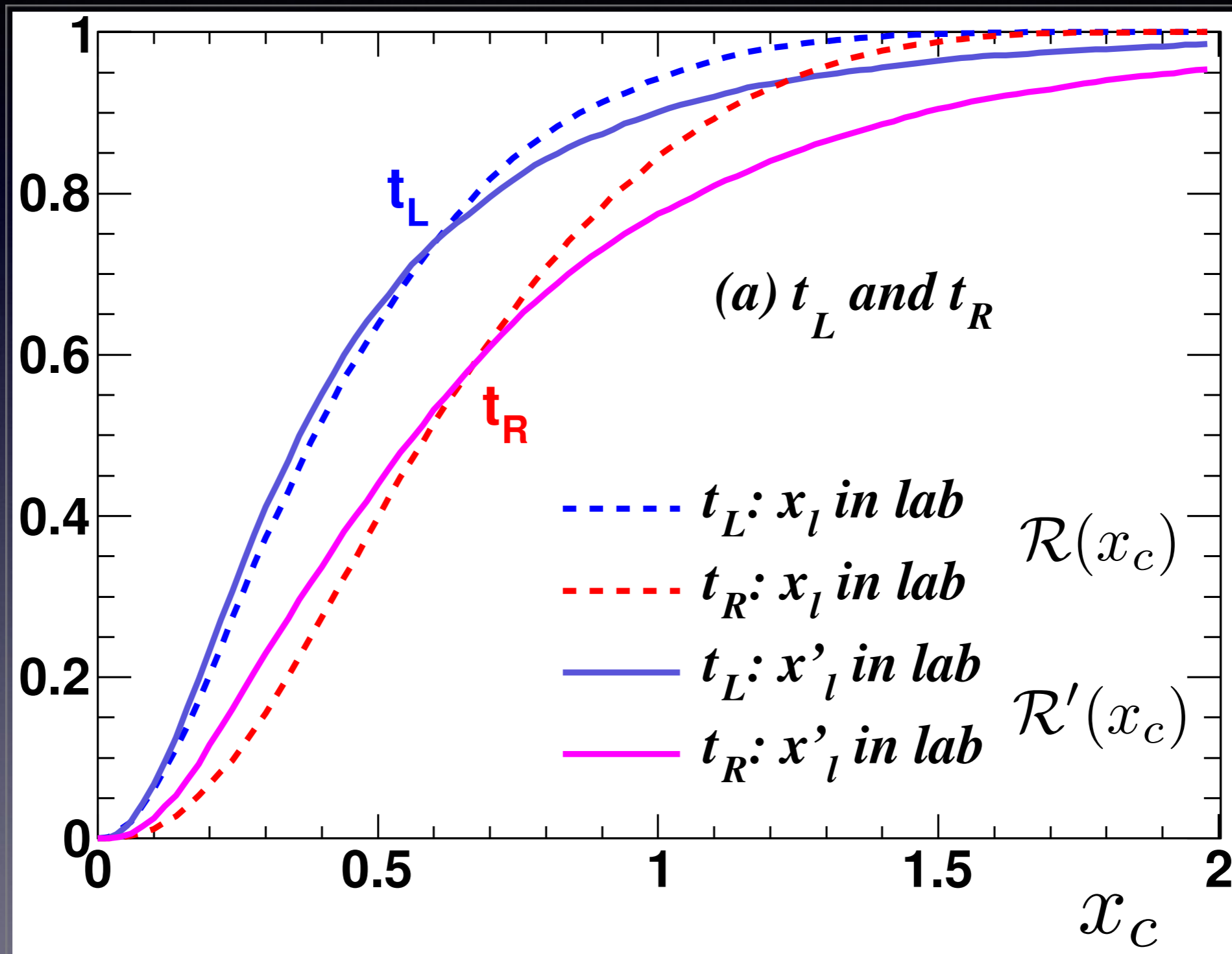
Three invisible particles
in the final state

THANK
YOU!

Back-up slides

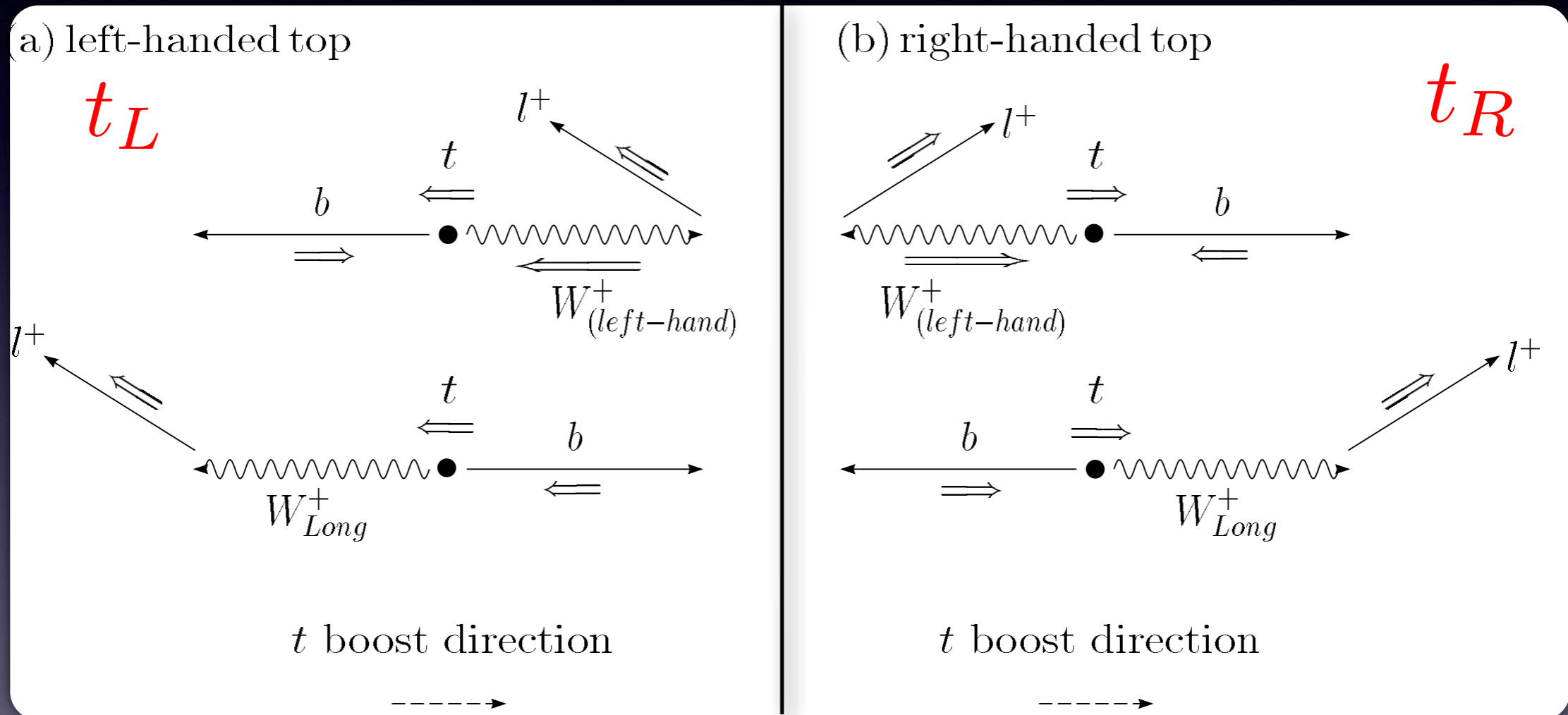
$\mathcal{R}(x_c)$ versus $\mathcal{R}'(x_c)$

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



Measuring top-quark polarisation

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



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