Probing New Physics with Polarised Top Quark

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Based on the works in collaboration with

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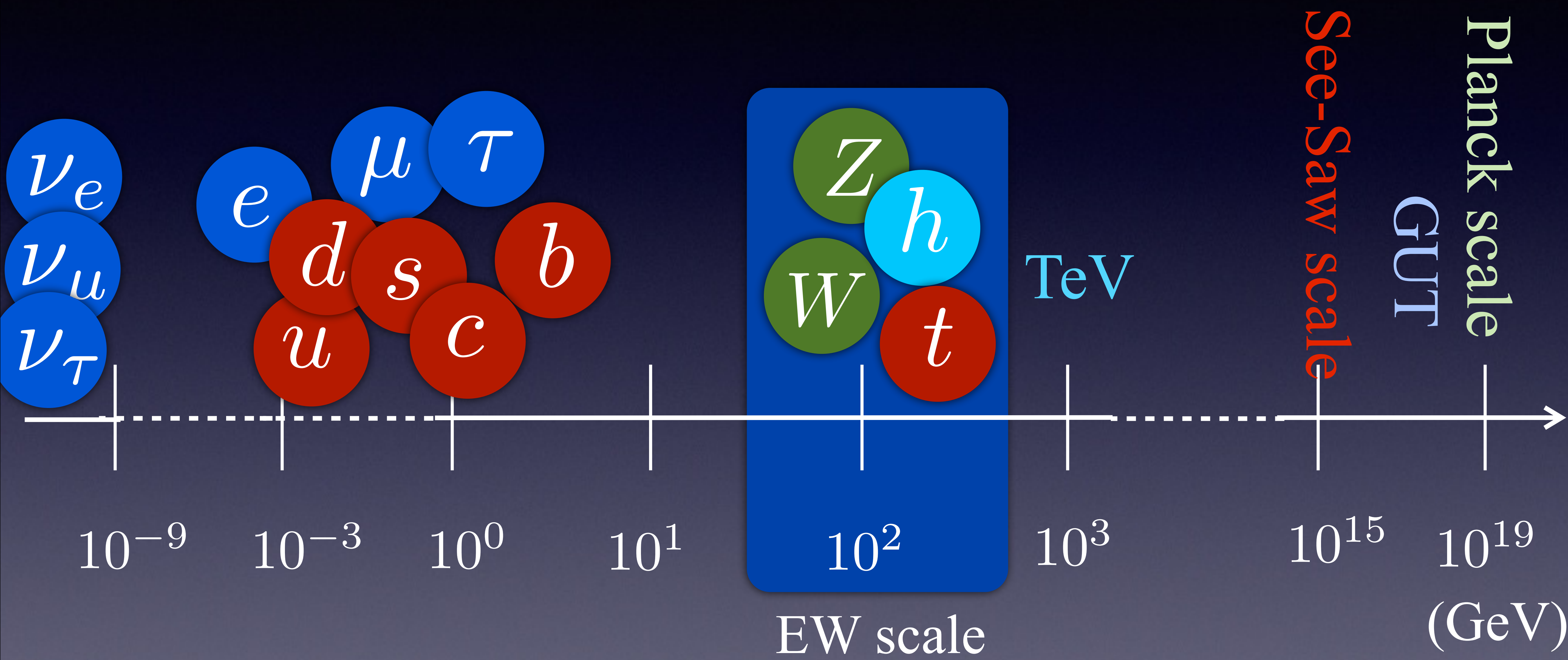
Gabe Shaughnessy, Jiang-Hao Yu, Hao Zhang

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'

Exotic Coloured States

Color Sextet

New Heavy Quarks

Top

Vector Quark

4th Gen

Gluino

Charged Higgs

Heavy Quark Production via pQCD

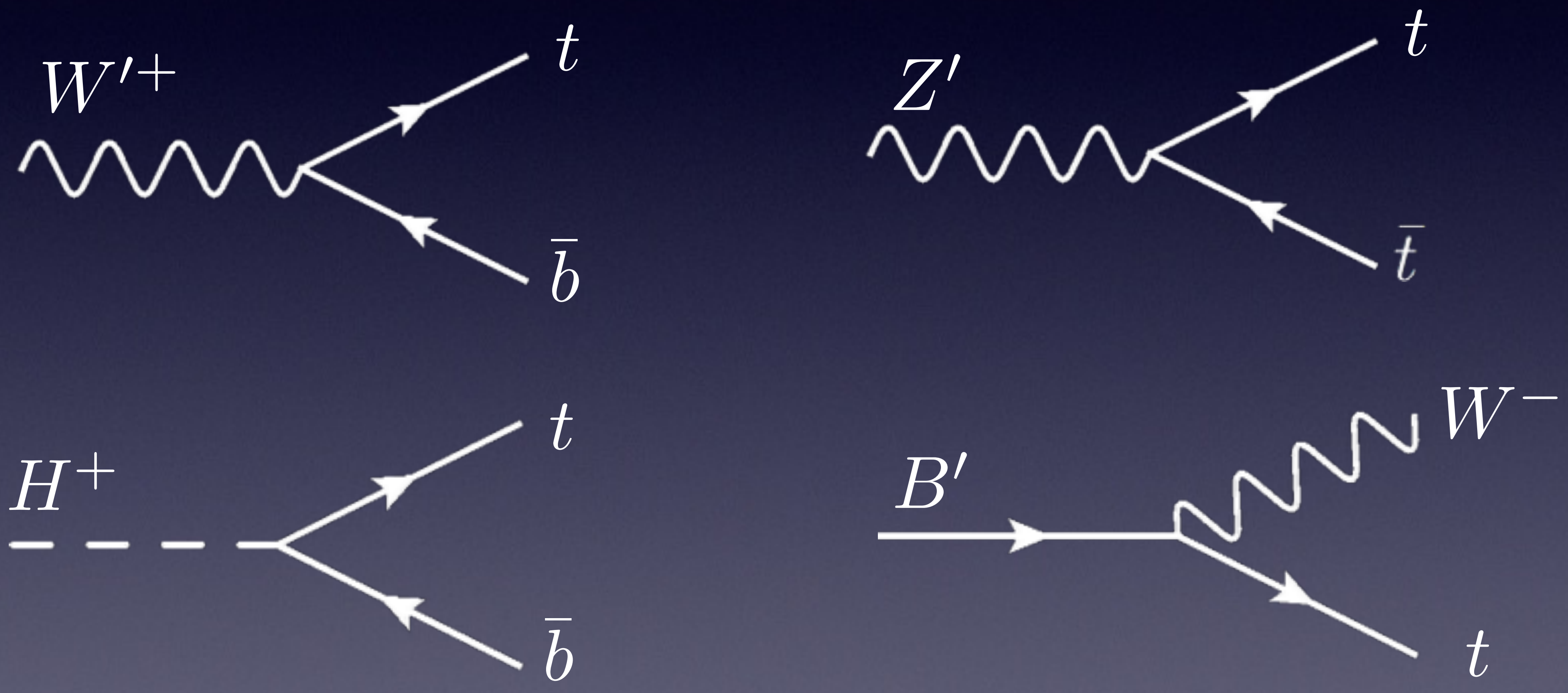
$\not{CP}$

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

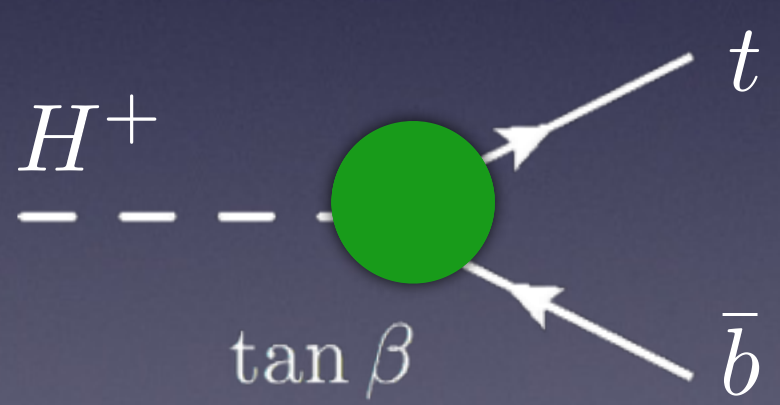
Top-quark: a new physics window

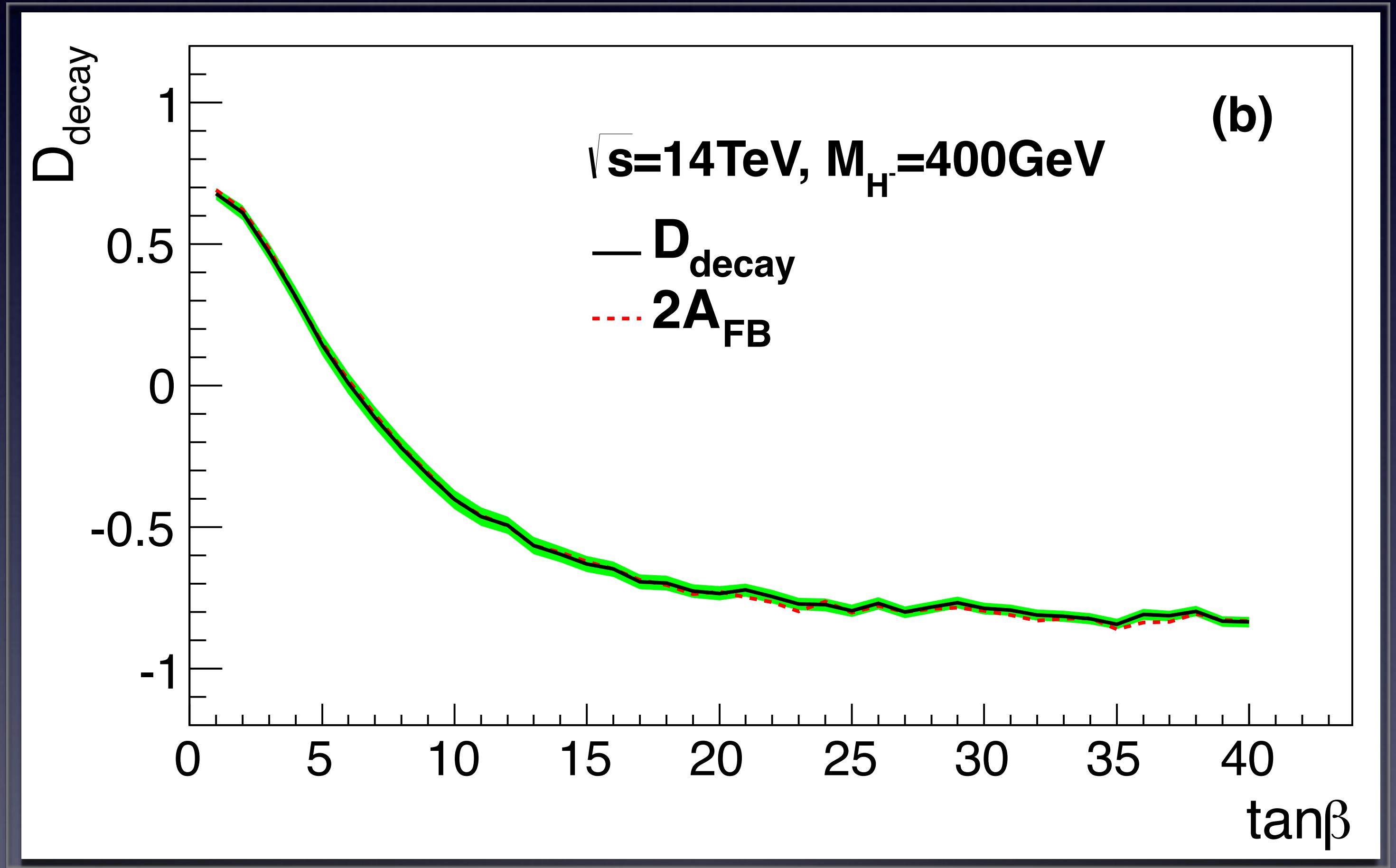
Top quark is quite common in decays of NP resonances and it is often polarised.

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

$$gb \to tH^- \to t\bar{t}b$$

in Type-II 2HDB



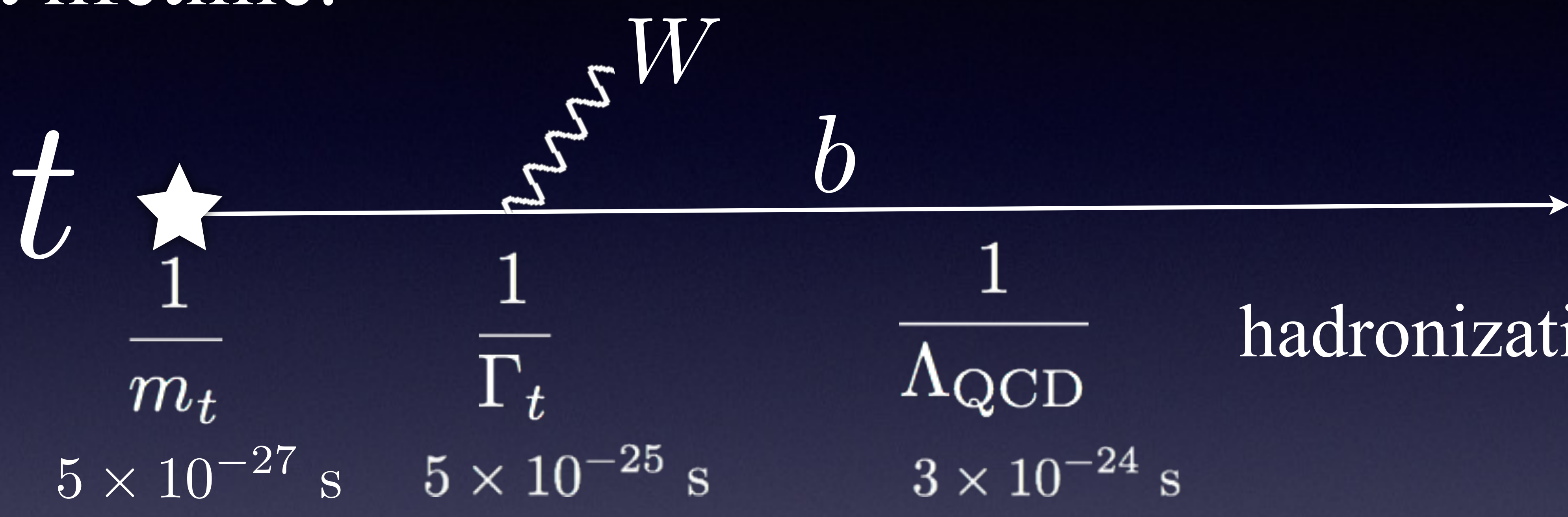


Top quark polarisation can tell us the chirality structure of top quark couplings to NP Resonances

Top-quark: the only bare quark in SM

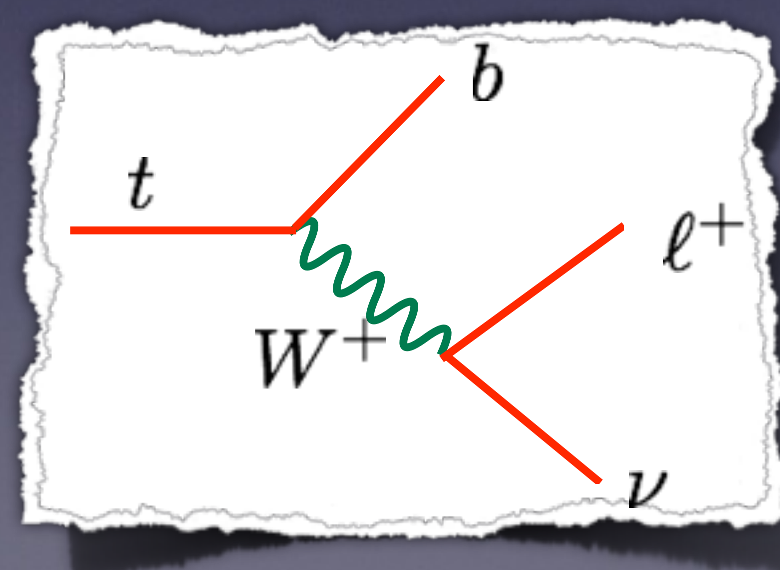
(the only “bizarre” quark in the SM)

- Short lifetime:



- “bare” quark :

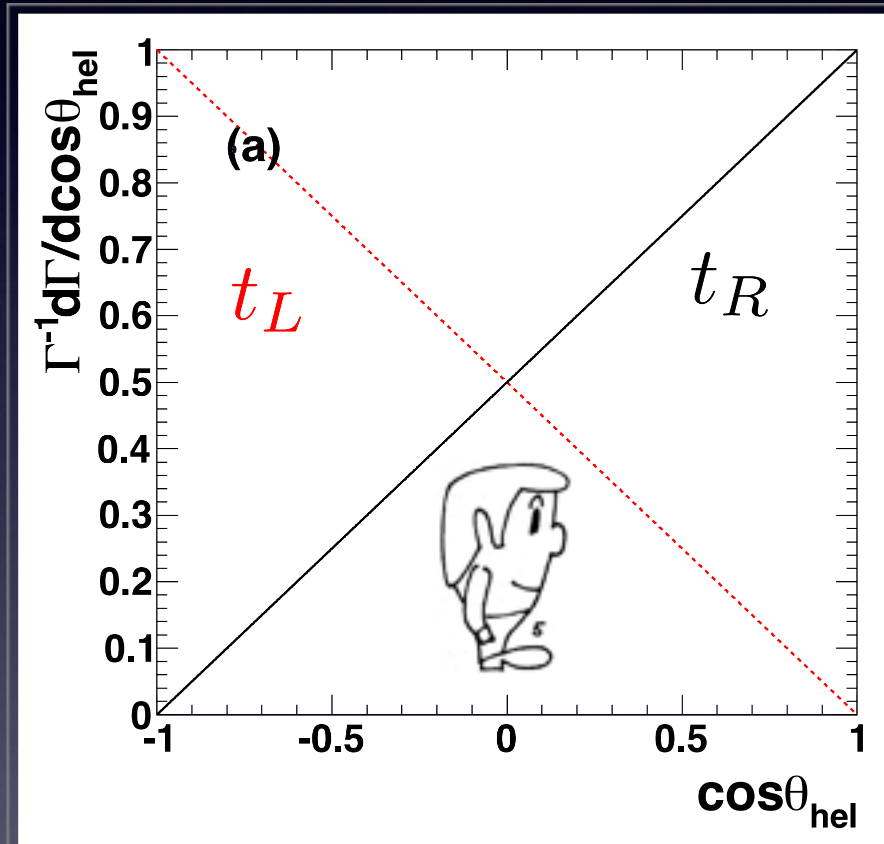
  spin info well kept
  among its decay products



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

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

$\lambda_t = +$ right-handed

$\lambda_t = -$ left-handed

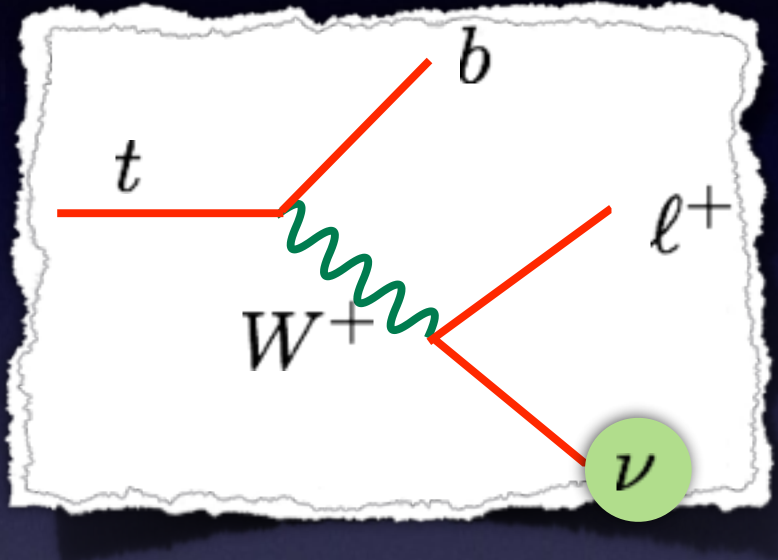
reconstruction of top quark kinematics

Top quark reconstruction

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

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

p_z^ν unknown



- W-boson on-shell condition

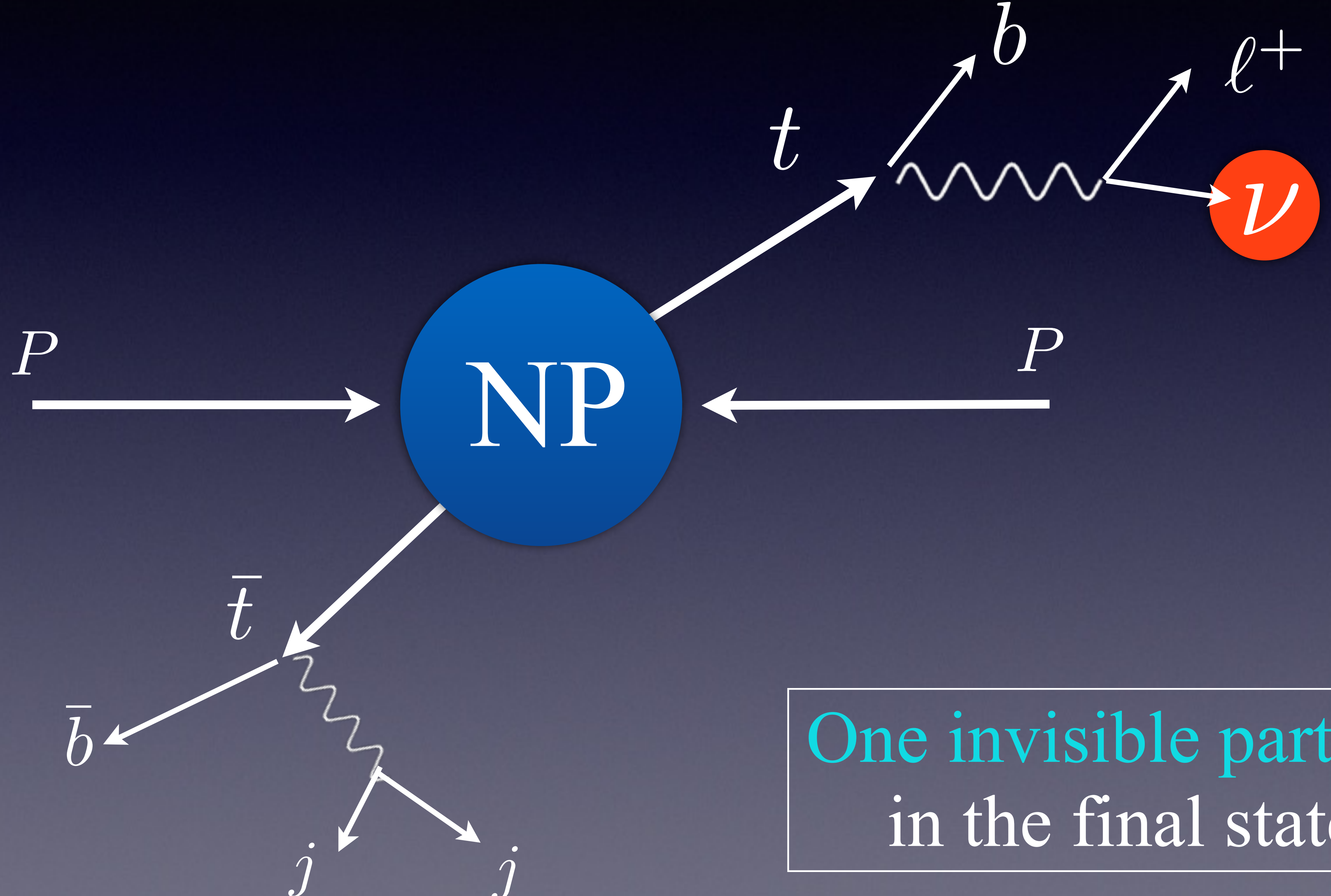
$$\boxed{m_W^2 = (p_\ell + p_\nu)^2}$$

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

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

Top quark production in NP

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

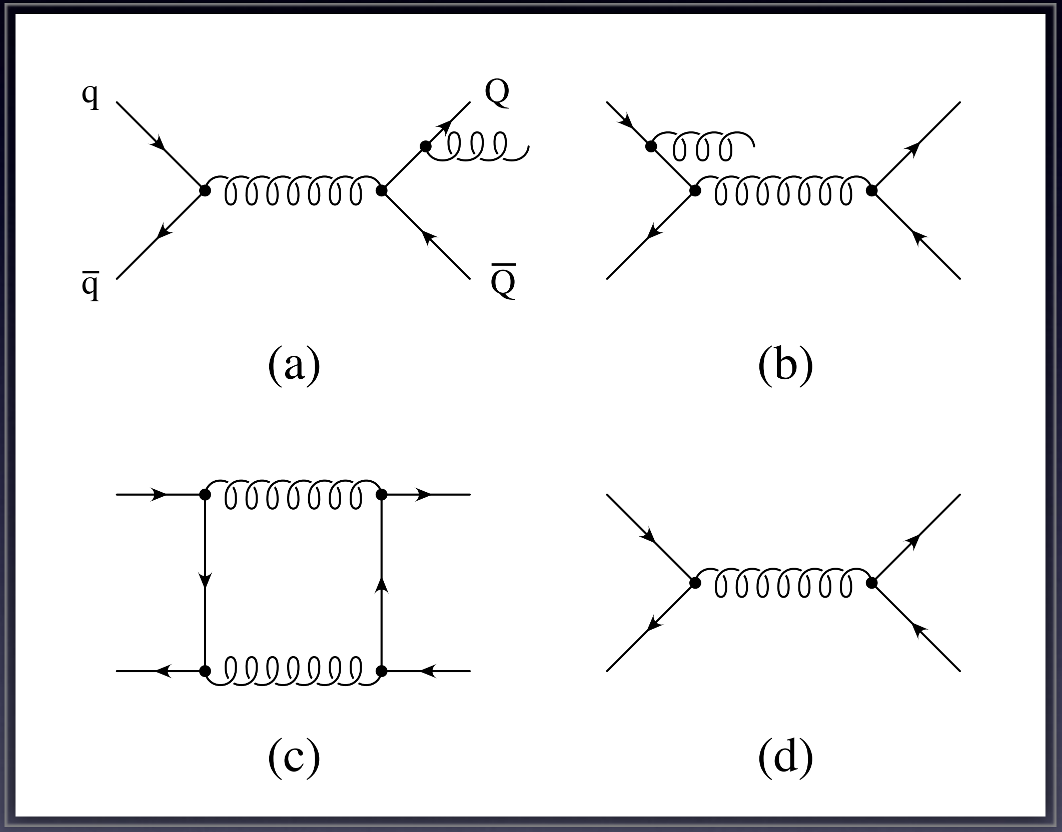


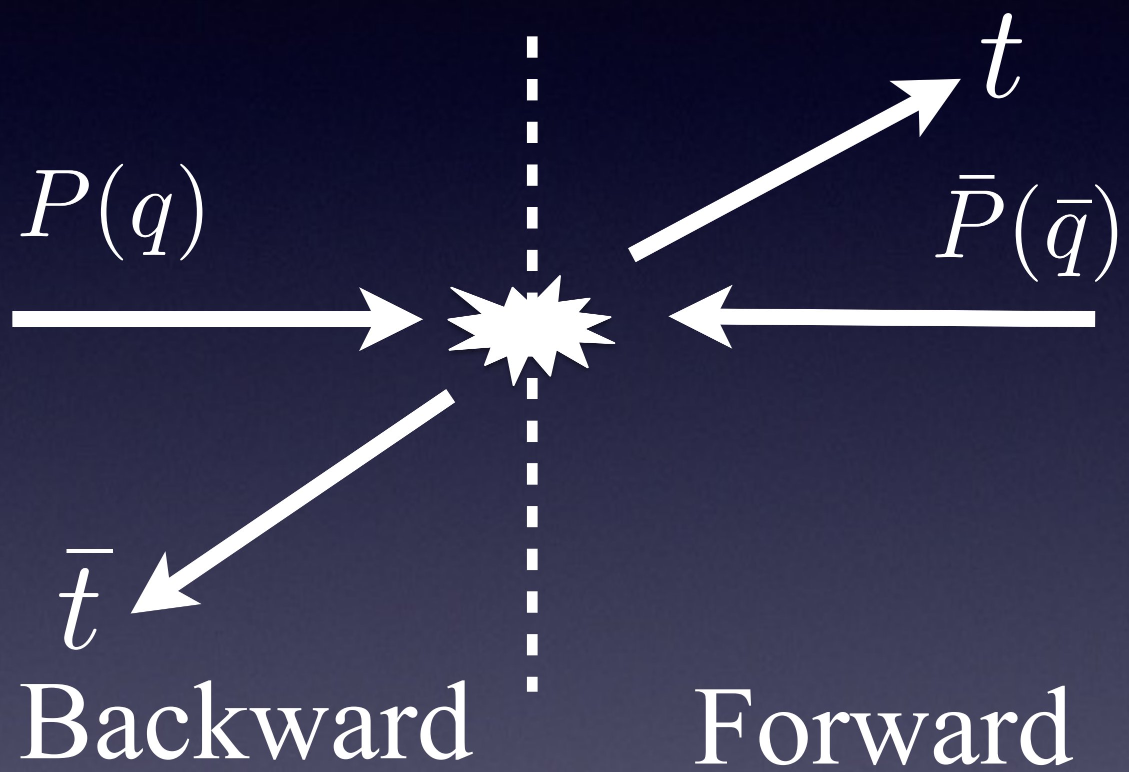
One invisible particle
in the final state

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

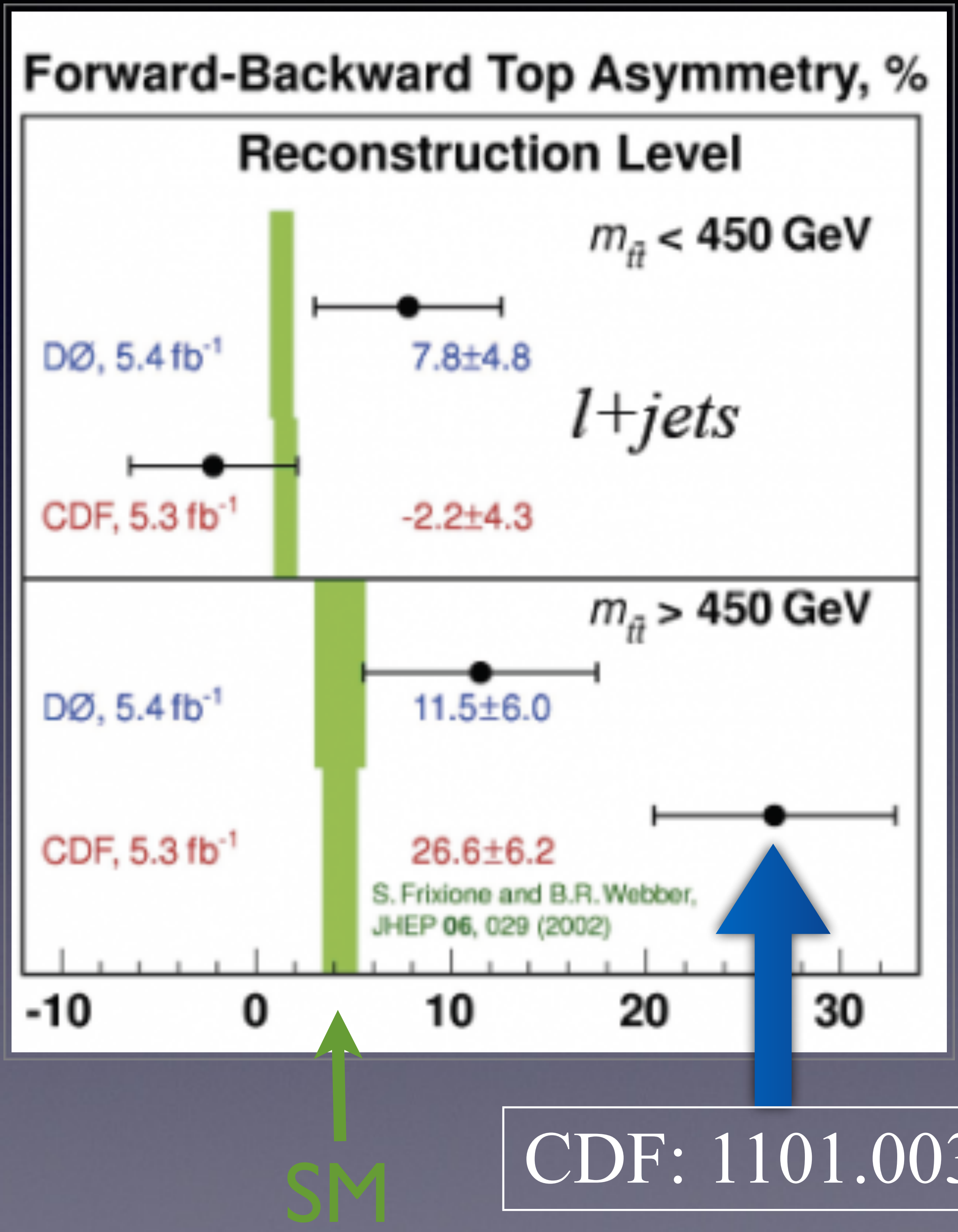




$$A^{p\bar{p}} = \frac{N_t(y>0) - N_{\bar{t}}(y>0)}{N_t(y>0) + N_{\bar{t}}(y>0)} = 0.051(6)$$

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

Top-quark A_{FB} at the Tevatron

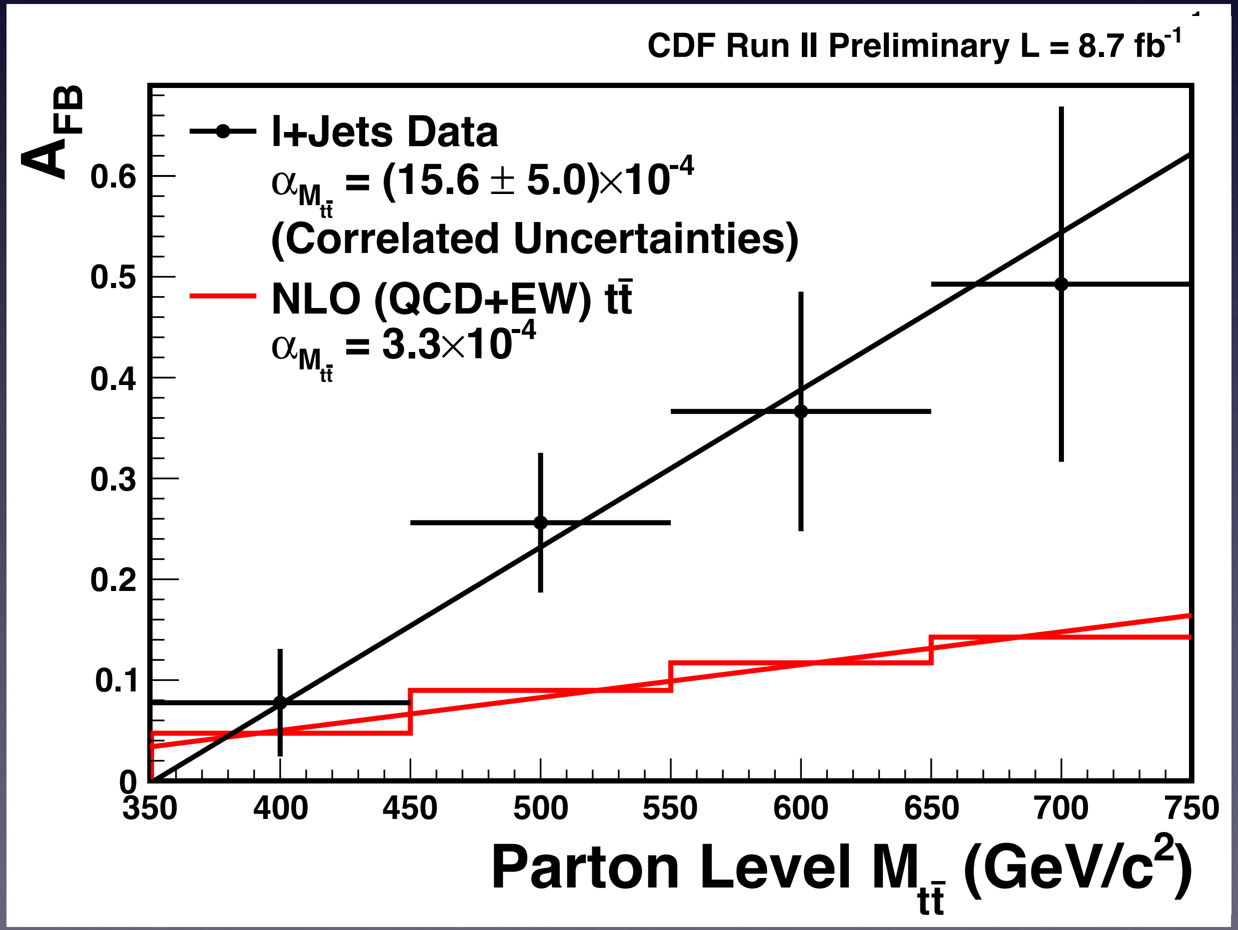


CDF: 1101.0034

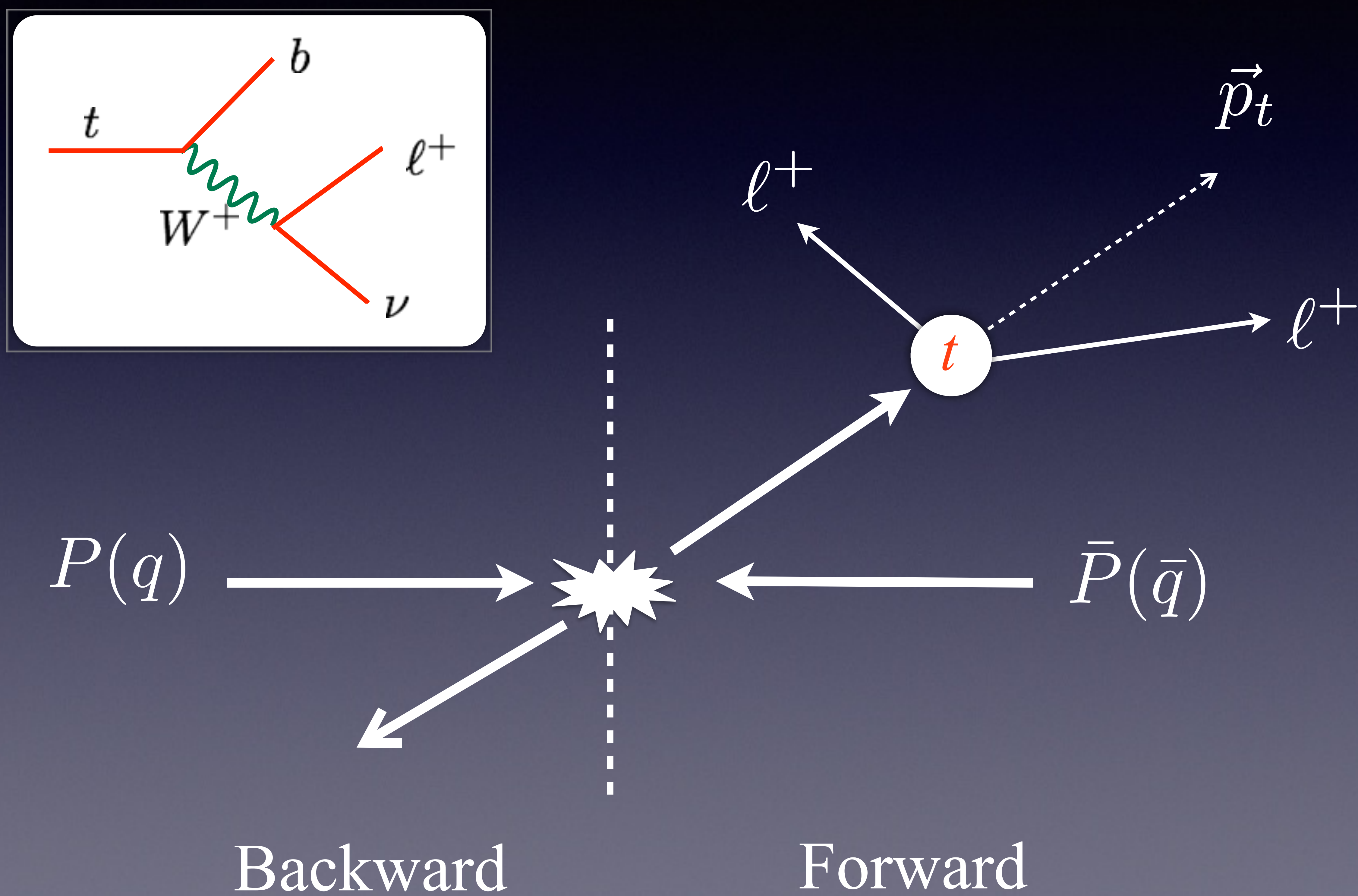
CDF ($8.7 fb^{-1}$):

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

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



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



A^t_{FB} versus A^ℓ_{FB}

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}) $A^\ell_{FB} = 0.066 \pm 0.025$

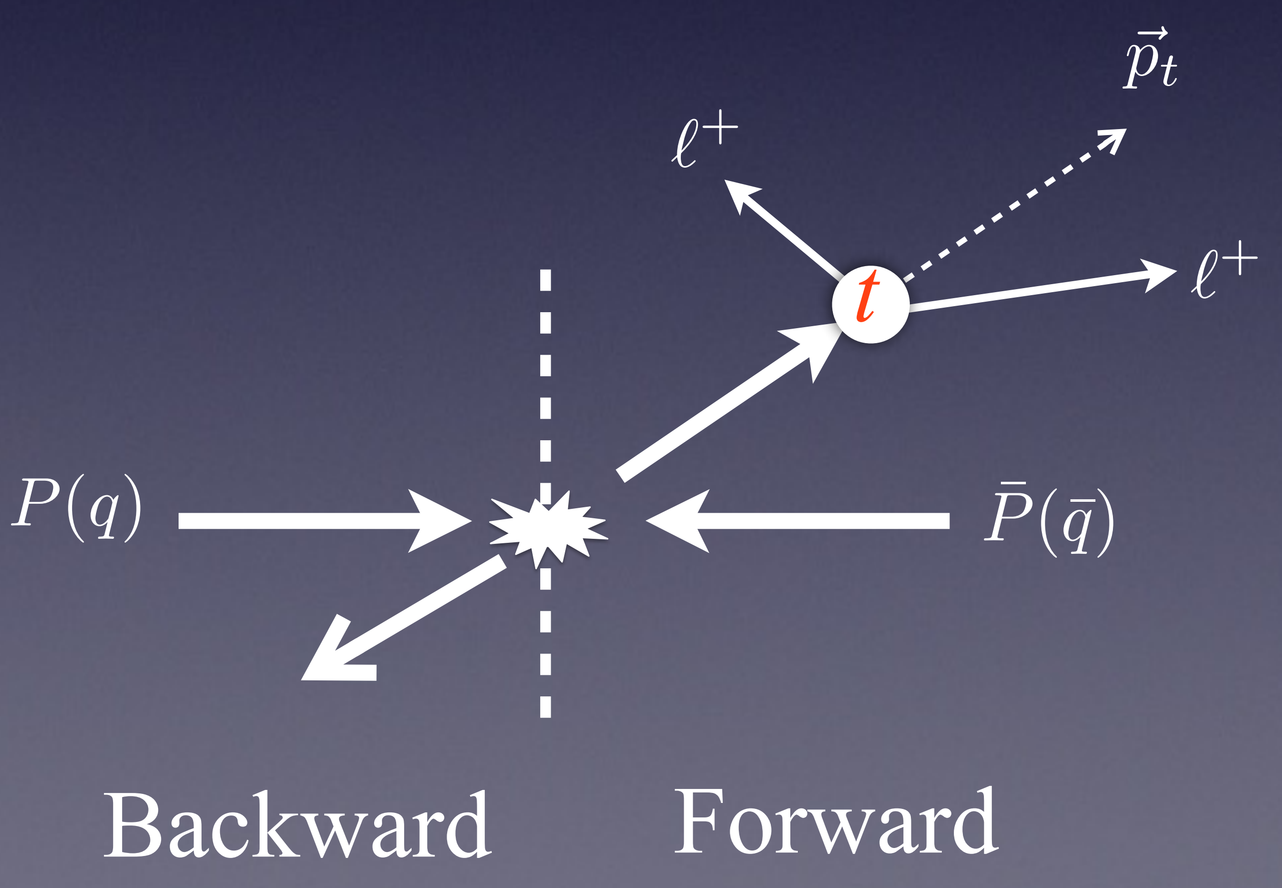
$$\left.\frac{A^\ell_{FB}}{A^t_{FB}}\right|_{\rm inc} \sim \frac{3}{4} \qquad \left.\frac{A^\ell_{FB}}{A^t_{FB}}\right|_{>450} \sim \frac{3}{5}$$

SM predictions at the NLO

$$A^t_{FB} = 0.051 \pm 0.001$$
$$A^\ell_{FB} = 0.021 \pm 0.001$$

$$\left.\frac{A^\ell_{FB}}{A^t_{FB}}\right|_{\rm SM} \sim \frac{1}{2}$$?

Bernreuther and Si, NPB837 (2010) 90



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

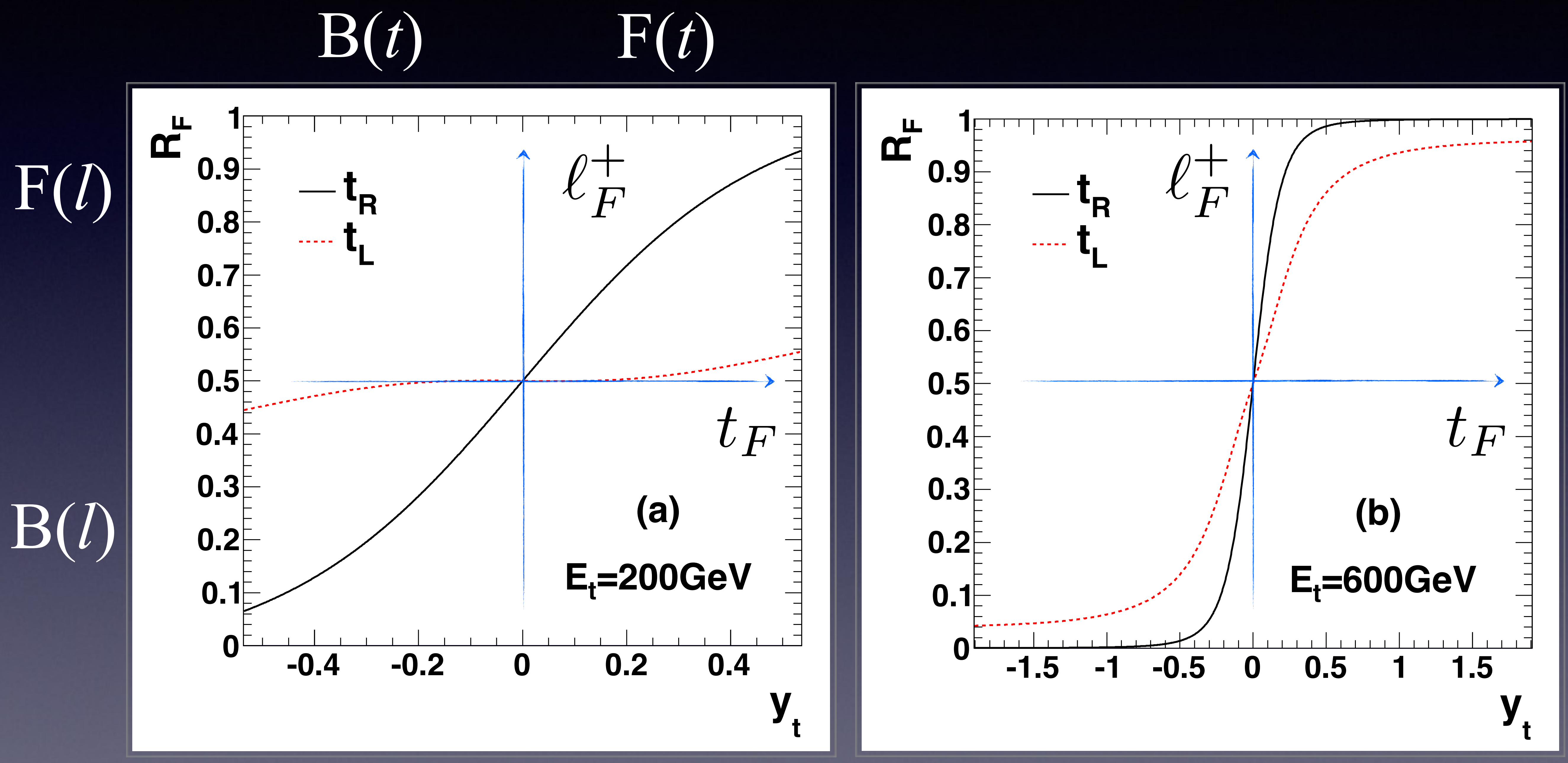
$$A_{FB}^{\ell} \approx \rho_{t_L} A_{FB}^{t_L} \times \left(2\mathcal{R}_C^{t_L} - 1\right) + \rho_{t_R} A_{FB}^{t_R} \times \left(2\mathcal{R}_C^{t_R} - 1\right)$$

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

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

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

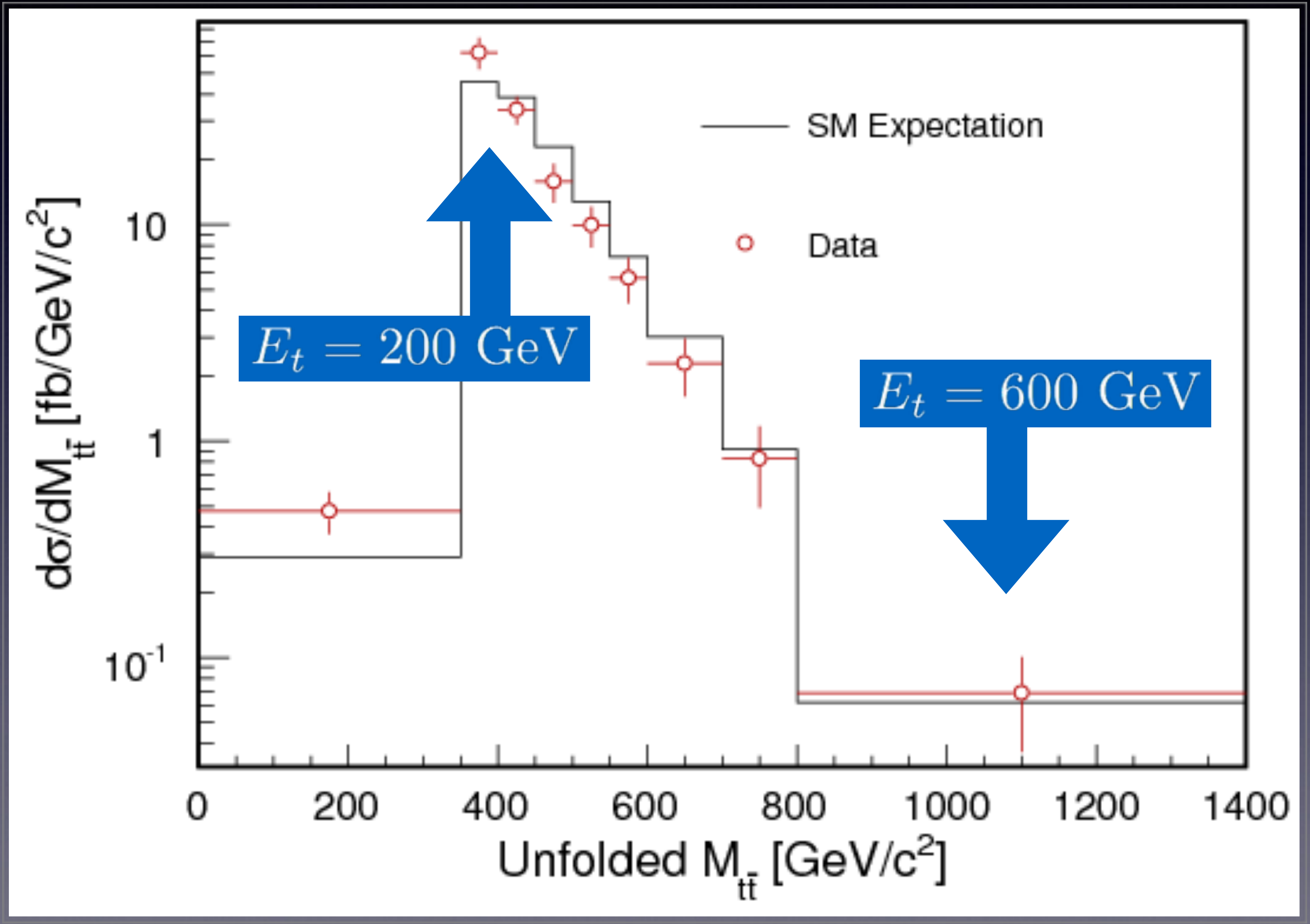
A^{ℓ}_{FB} dependence on top kinematics



$$A^{\ell,\lambda_t}_{FB}(\beta, y_t) = 2R^{\ell,\lambda_t}_{F}(\beta, y_t) - 1$$

Invariant mass spectrum of top quark pair

CDF collaboration, PRL 102 (2009) 222003



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

$$A^\ell_{FB} \approx \rho_{t_L} A^{t_L}_{FB} \times \underbrace{\left(2\mathcal{R}^{t_L}_C - 1\right)}_{0} + \rho_{t_R} A^{t_R}_{FB} \times \underbrace{\left(2\mathcal{R}^{t_R}_C - 1\right)}_{1}$$

$$A^t_{FB} \approx \left[\rho_{t_L}\ A^{t_L}_{FB} + \rho_{t_R}\ A^{t_R}_{FB}\right]$$

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

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

$A^{t_L}_{FB} = A^{t_R}_{FB}$

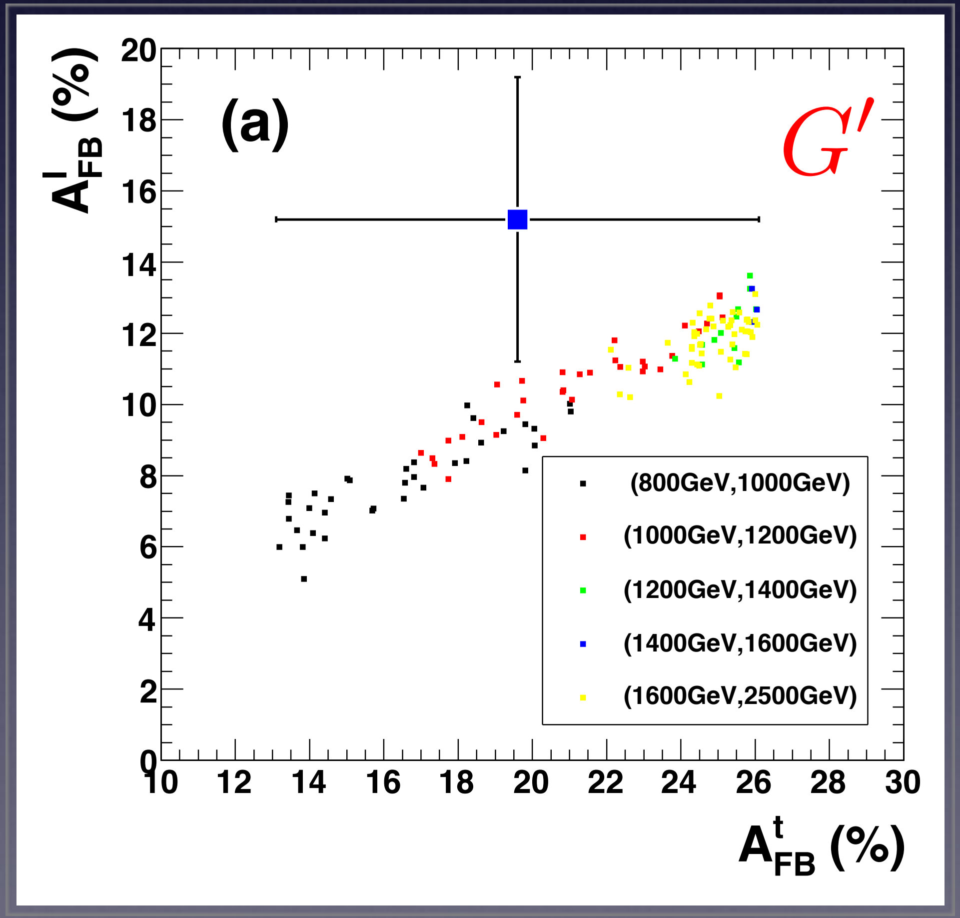
$\rightarrow \left.\frac{A^\ell_{FB}}{A^t_{FB}}\right|_{\rm SM} \sim \frac{1}{2}$

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

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

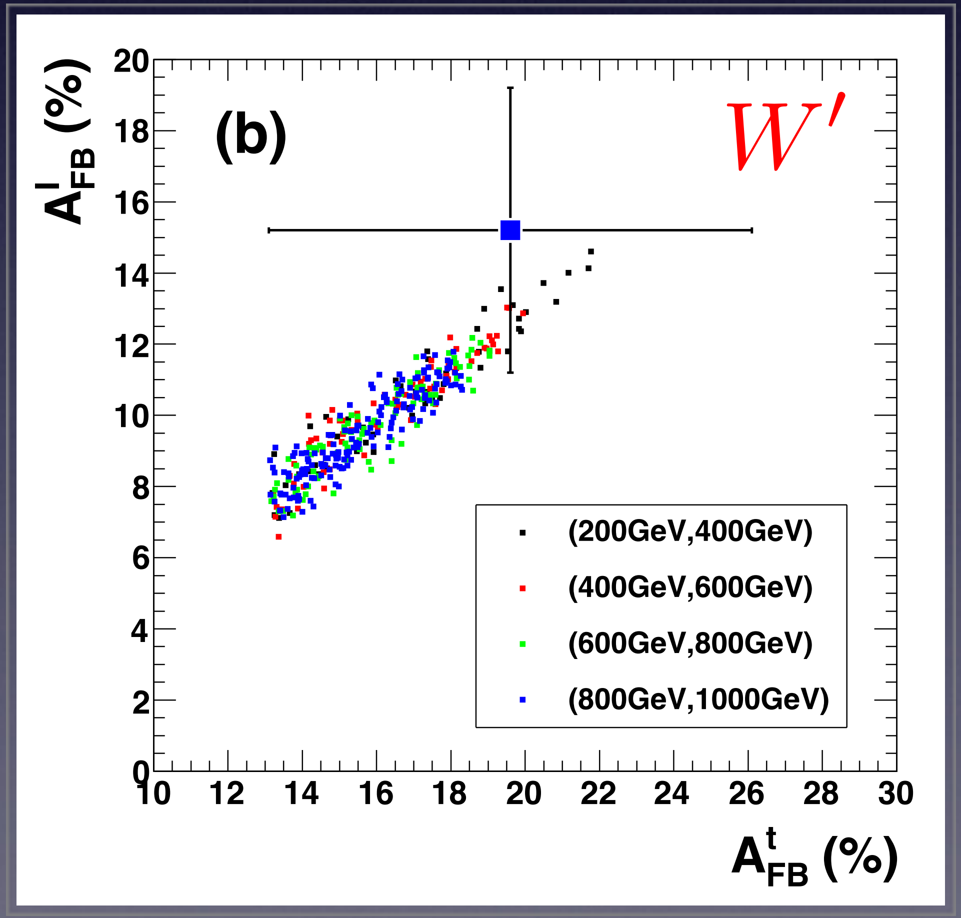
Berger, QHC, Chen, Yu, Zhang, PRL 108 (2012) 072002

Unpolarised top-quark



$$A^\ell_{FB} \simeq 0.47 \times A^t_{FB} + 0.25\%$$

Right-handed top-quark

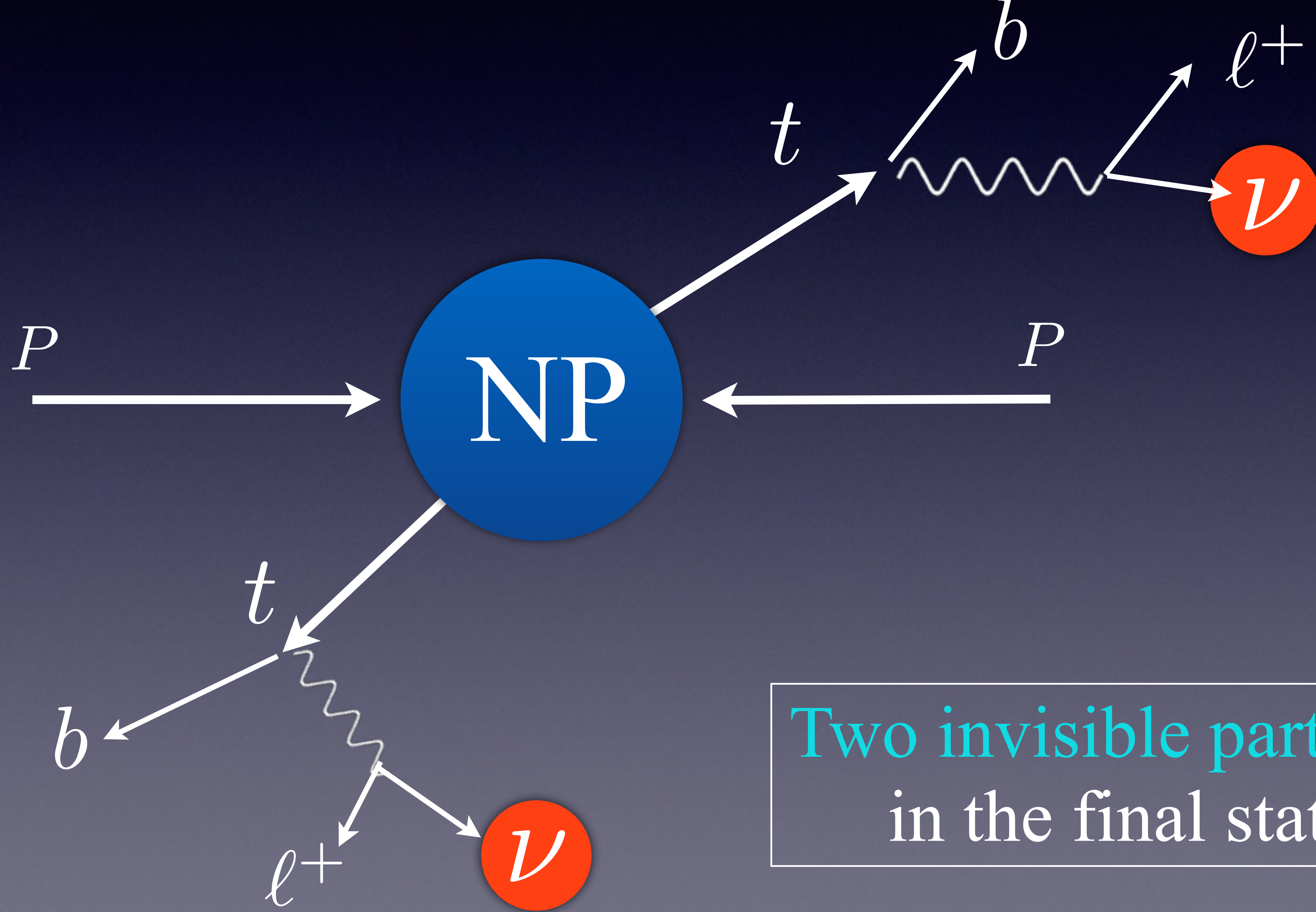


Cheung, Keung, Yuan, PLB 682 (2009) 287

$$A^\ell_{FB} \simeq 0.75 \times A^t_{FB} - 2.1\%$$

Top quark production in NP

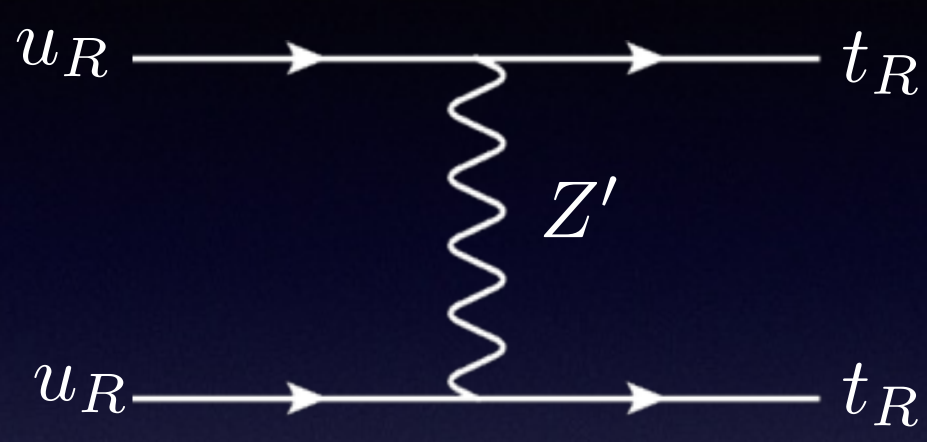
(2) Same-Sign top-quark pair production
(or top-antitop pair production in dileptonic decay)



Two invisible particles
in the final state

Top quark is often polarised in NP

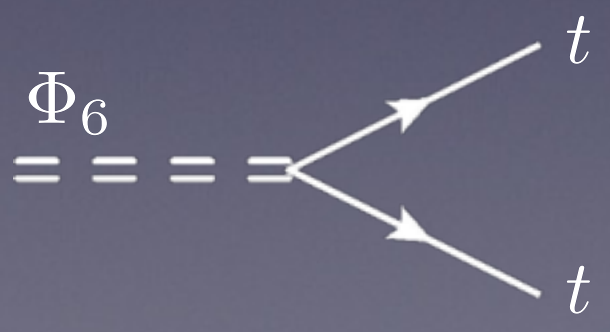
- Flavour changing gauge boson

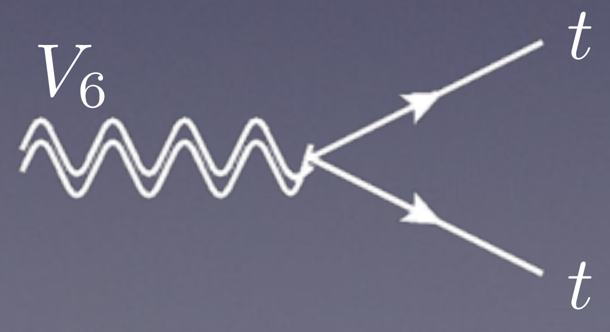


Jung, Murayama, Pierce, Wells, PRD81 (2010) 015004

- Exotic coloured particles (diquark scalar/vector)

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





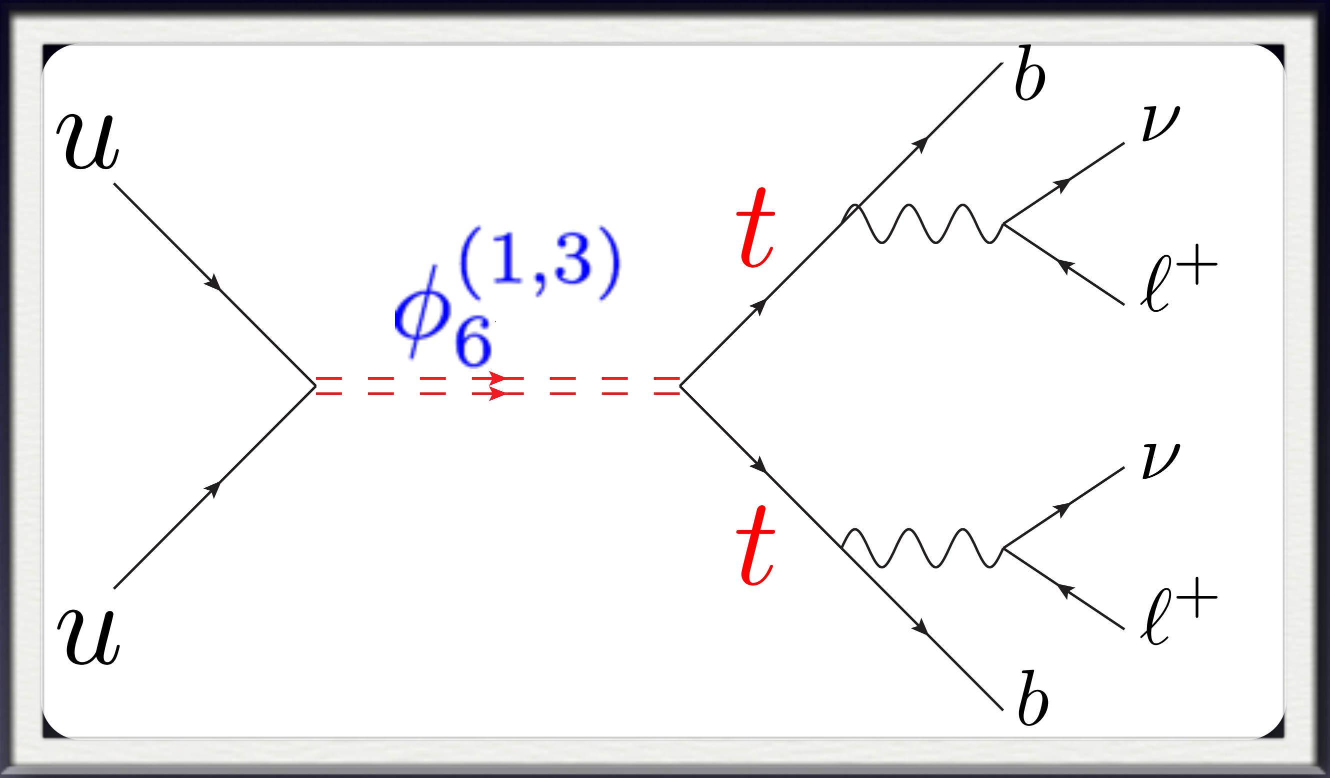
Cakir and Sahin, PRD72 (2005) 115011

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



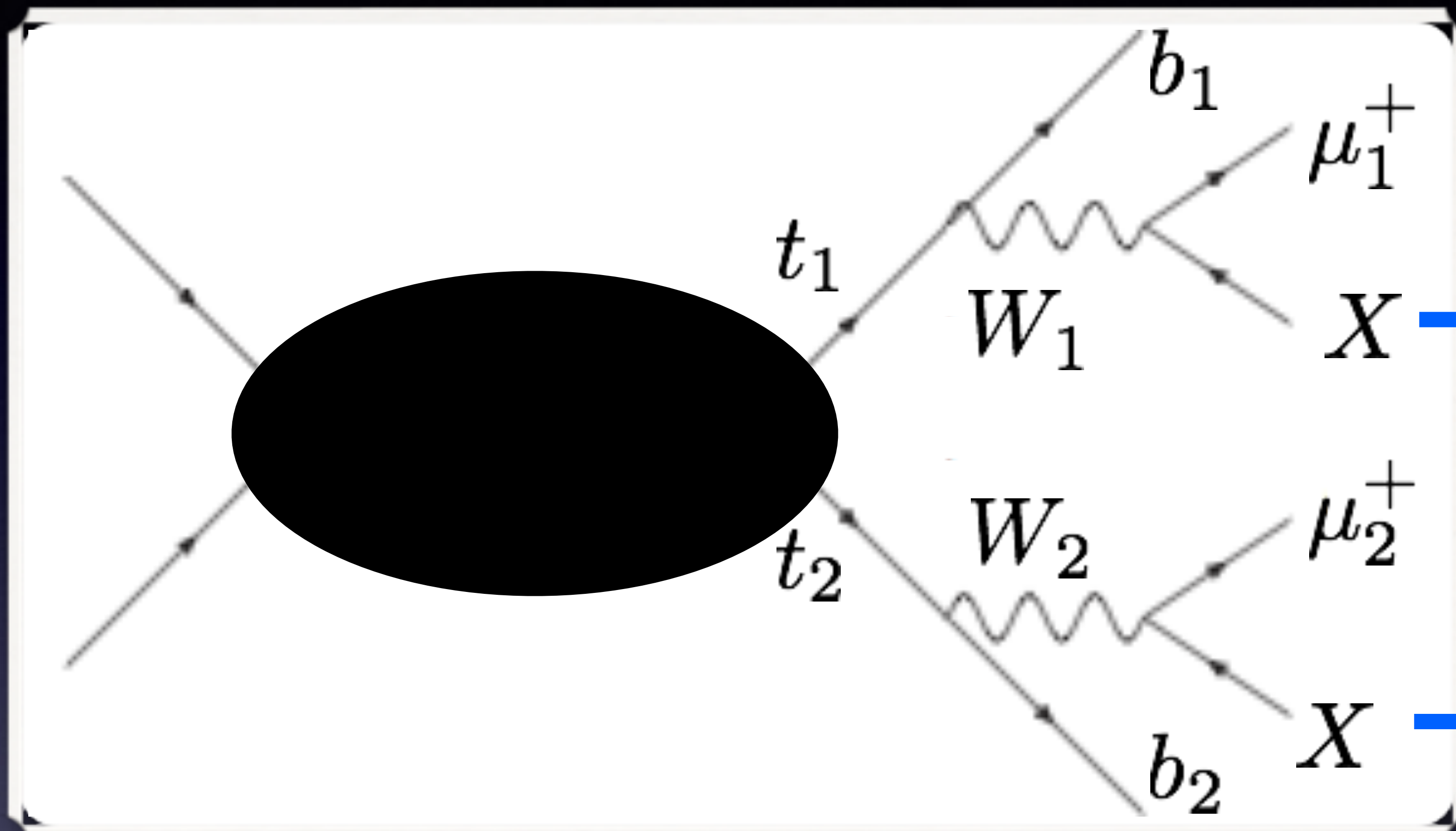
2ν

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

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

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

Quartic equation

(correct l-b pairing is necessary)

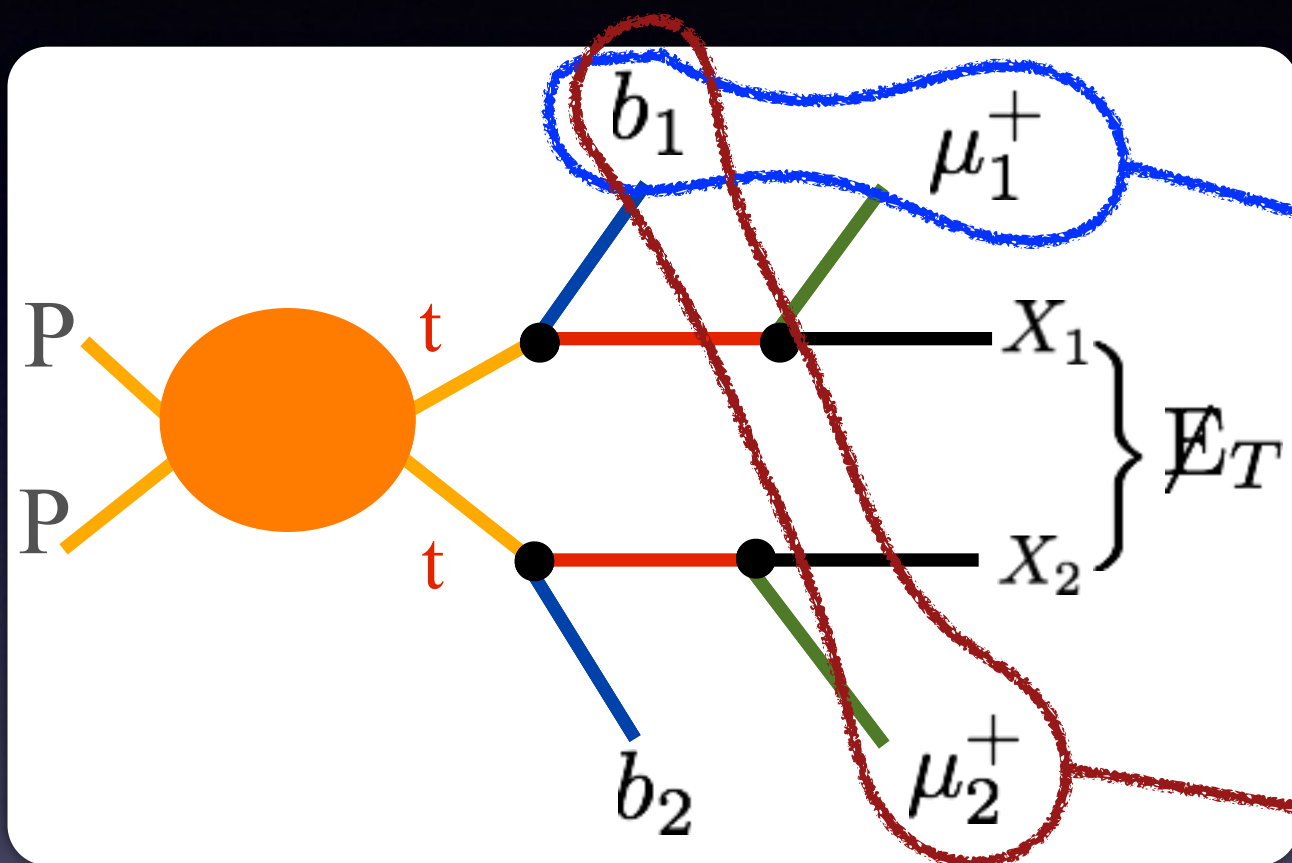
$$p_x^4(\nu_1) + a\ p_x^3(\nu_1) + b\ p_x^2(\nu_1) + c\ p_x(\nu_1) + d = 0$$

~~Two complex~~, two real solutions

Sonnenschein, PRD73 (2006) 054015

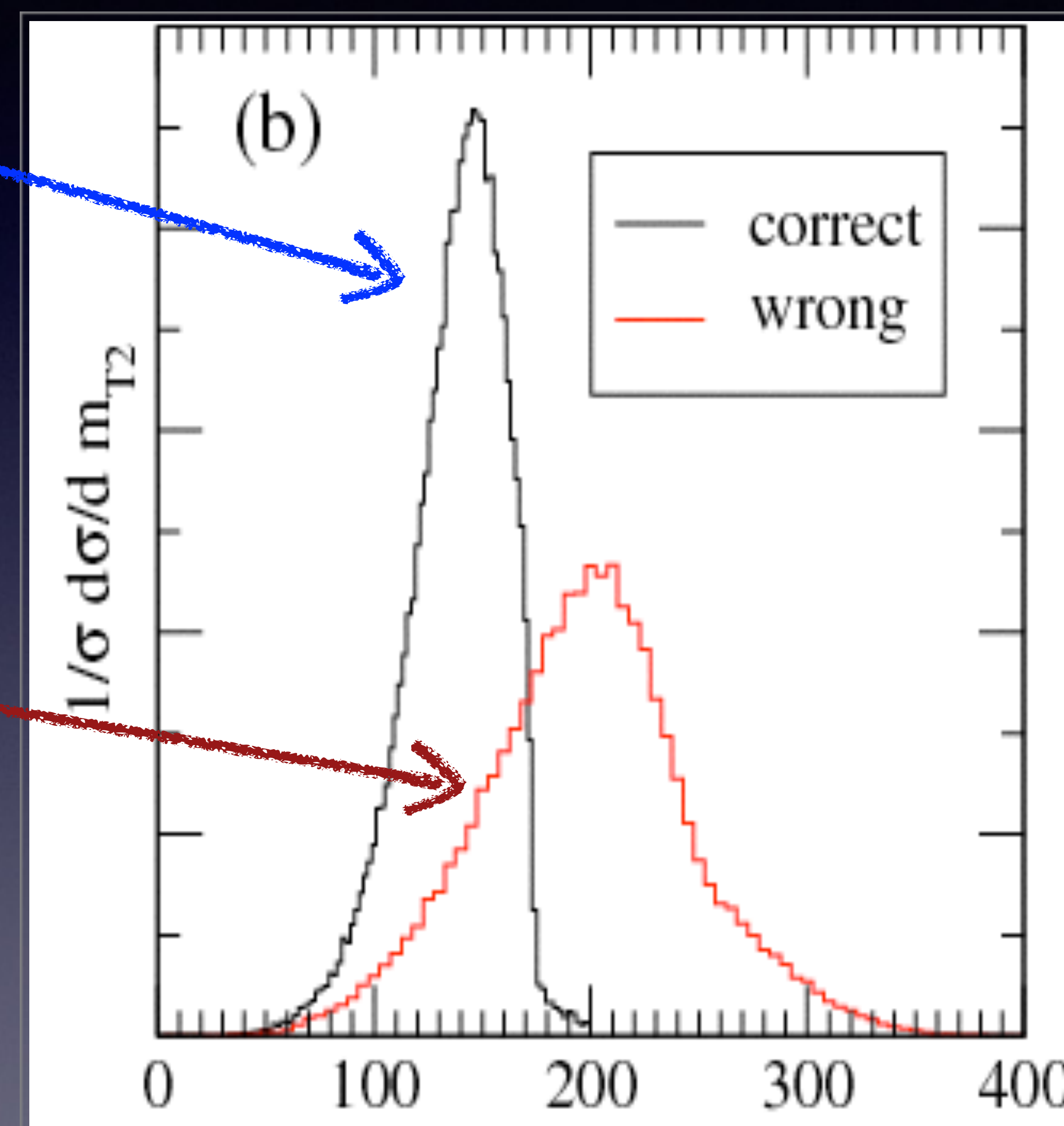
ℓ^+- b pairing: MT2-assisted method

MT2 variable of lepton-b clusters and MET



Two combinations of lepton-b clusters

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

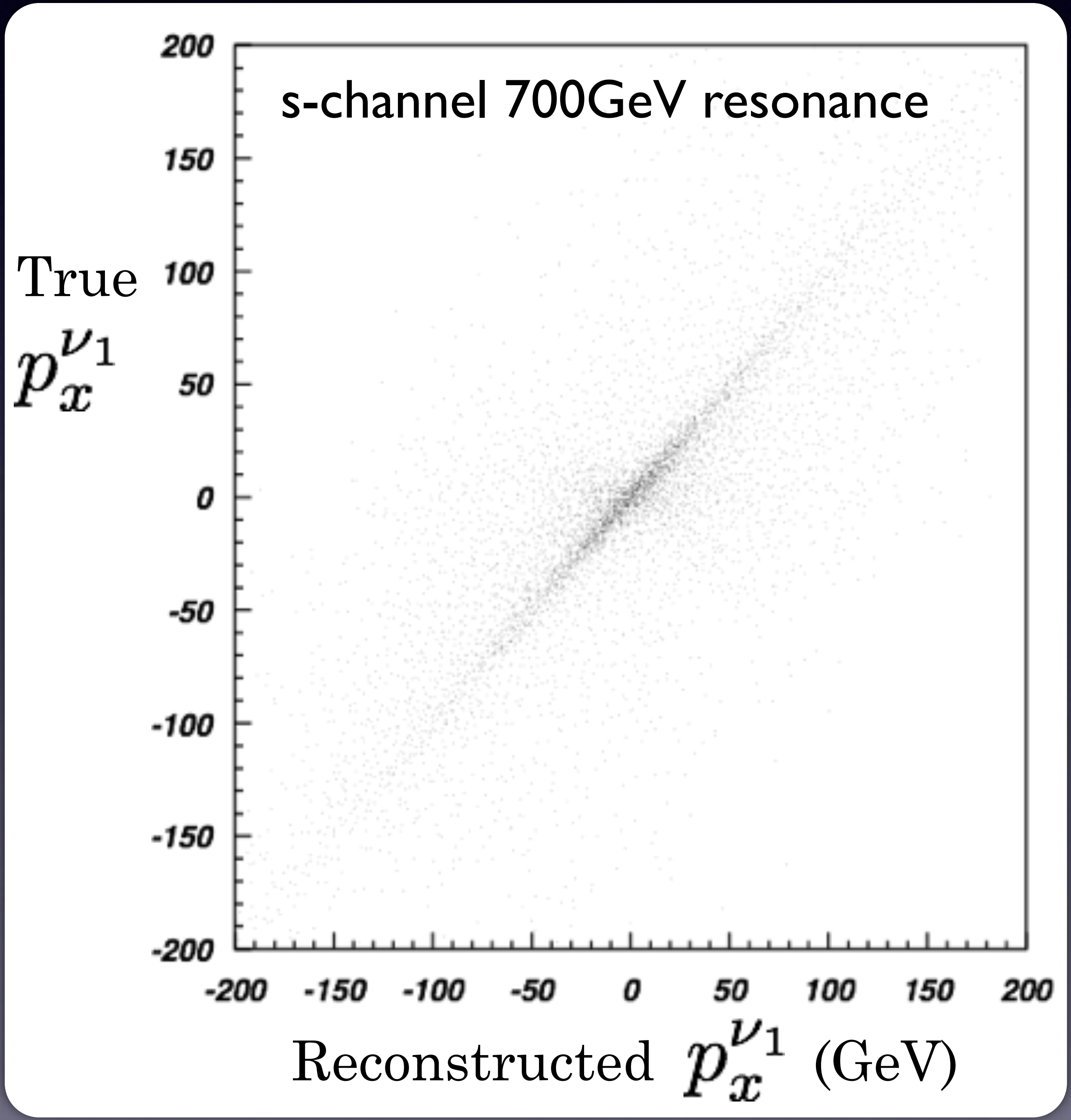


$$M_{T2}(\ell_1^+ b_1, \ell_2^+ b_2, \not{E}_T)$$

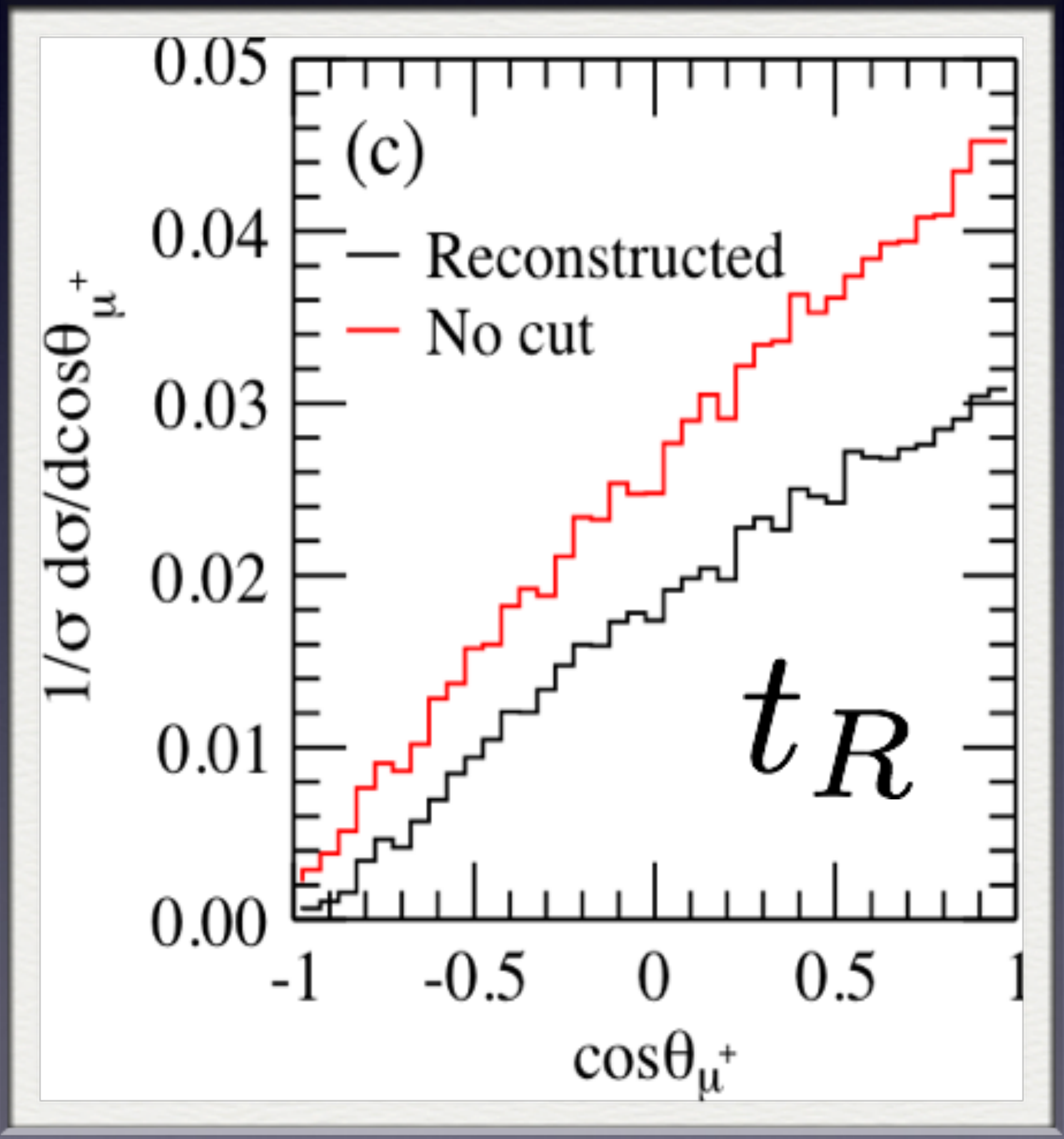
MT2 - Lester and Summers, PLB 463 (1999) 99

Neutrino momentum reconstruction

- Strong correlation between the true $p_x^{\nu_1}$ and reconstructed $p_x^{\nu_1}$

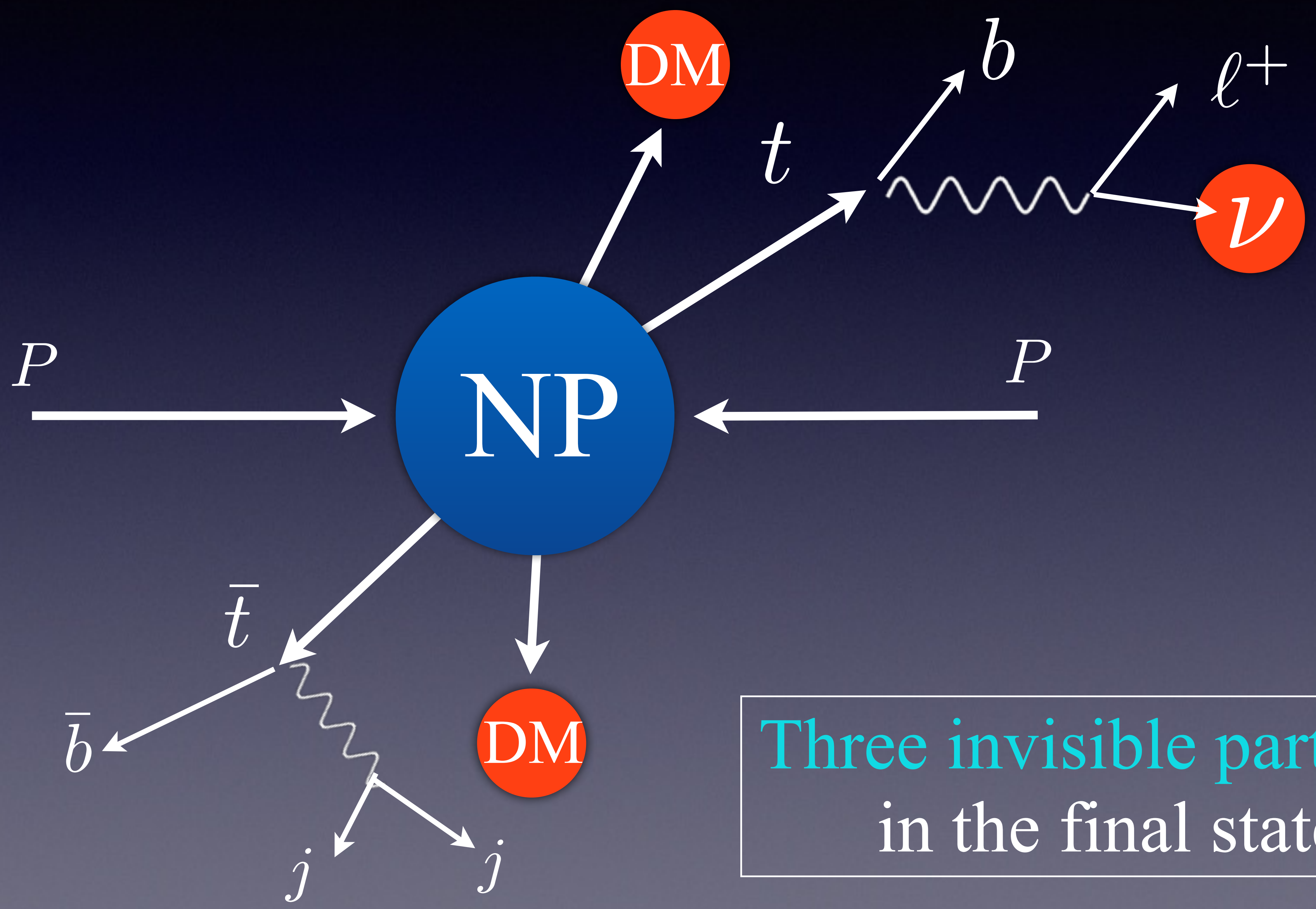


- Top quark polarisation can be measured after neutrino reconstruction.



Top quark production in NP

(3) Top-quark pair + dark matter candidates

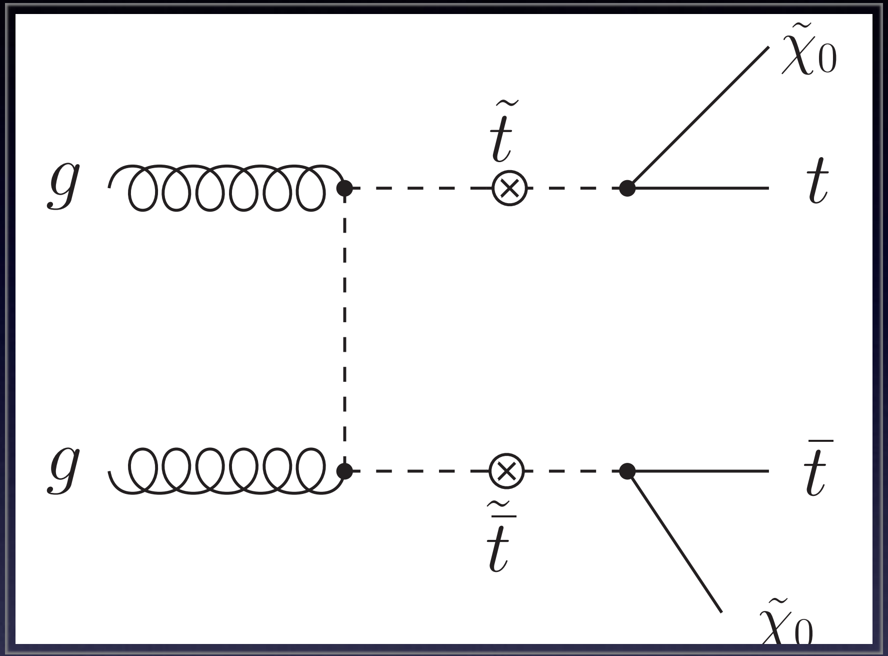


Three invisible particles
in the final state

Top-quark pair plus missing energy

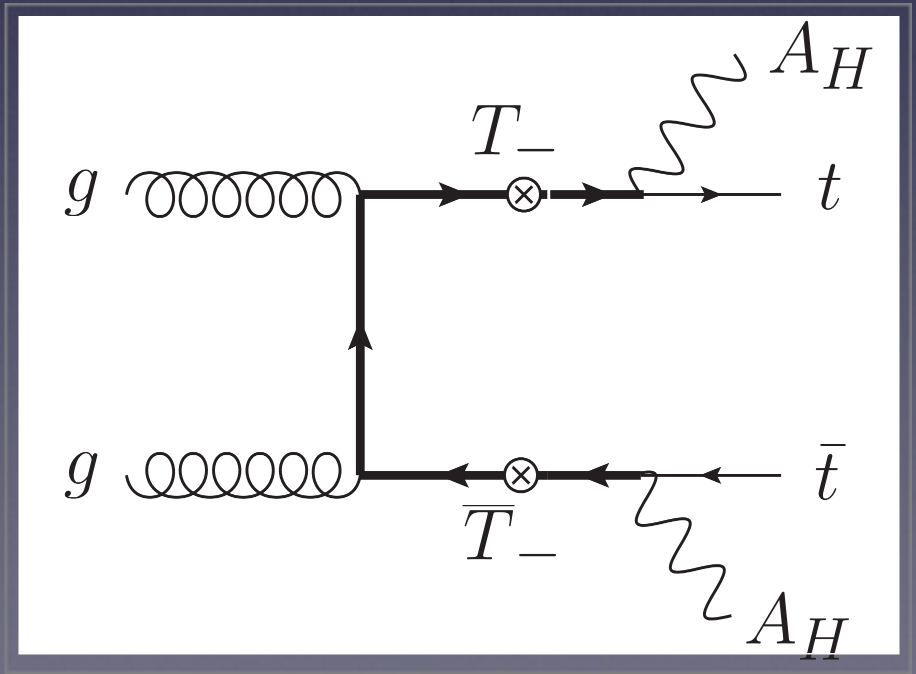
Typical collider signature in several NP models

- Minimal Supersymmetric extension of the Standard Model (MSSM)



spin 0

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



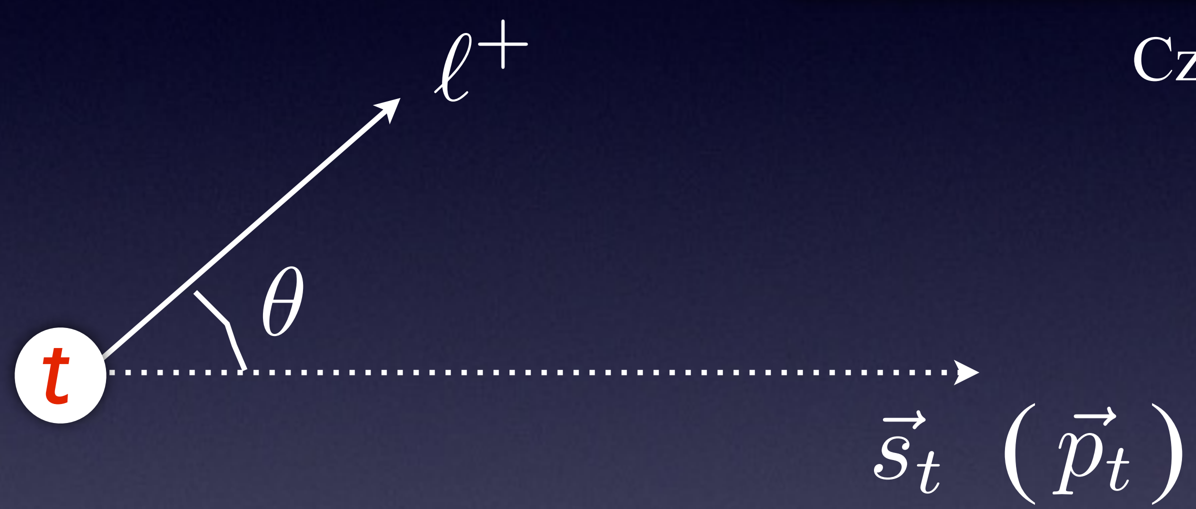
spin 1/2

Charged lepton distribution

- In the <u>rest frame</u> of the top-quark

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

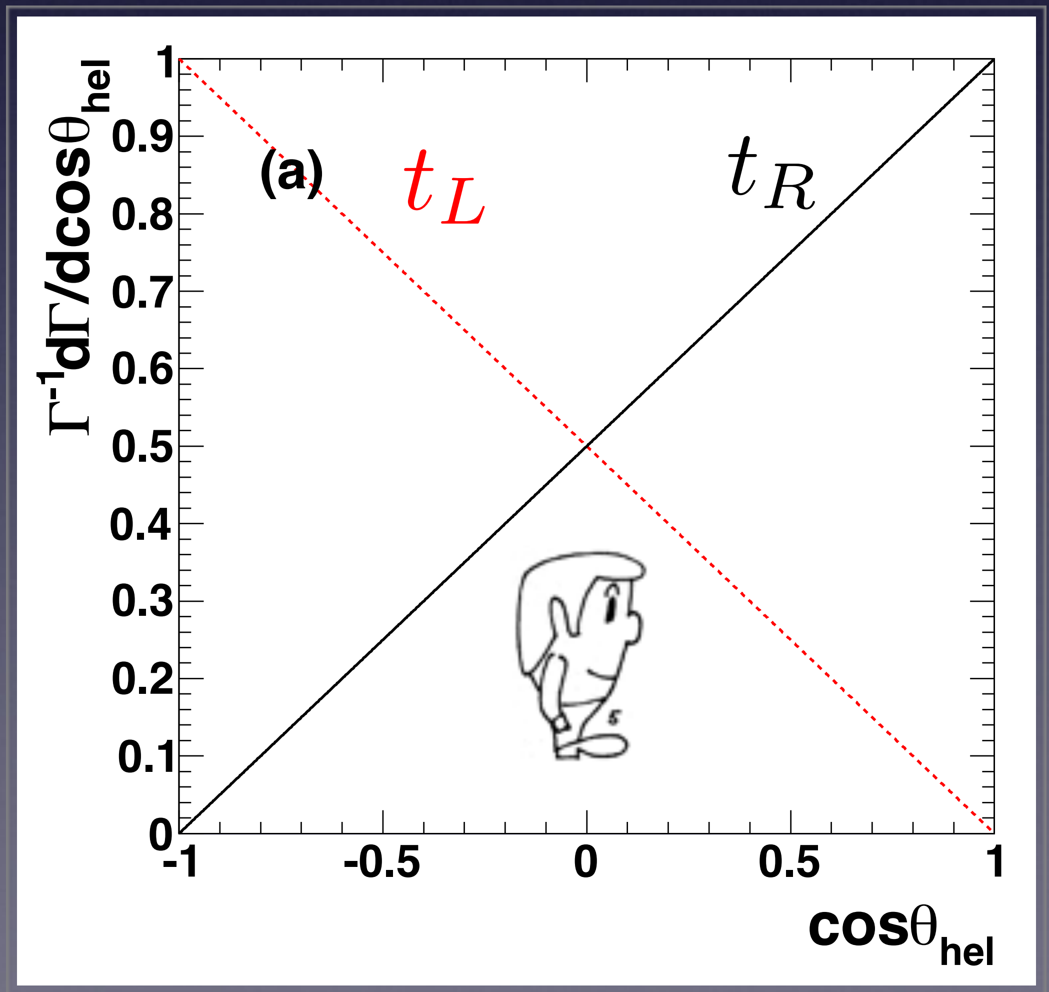
Czarnecki, Jezabek, Kuhn, NPB351 (1991) 70



$\lambda_t = +$ 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

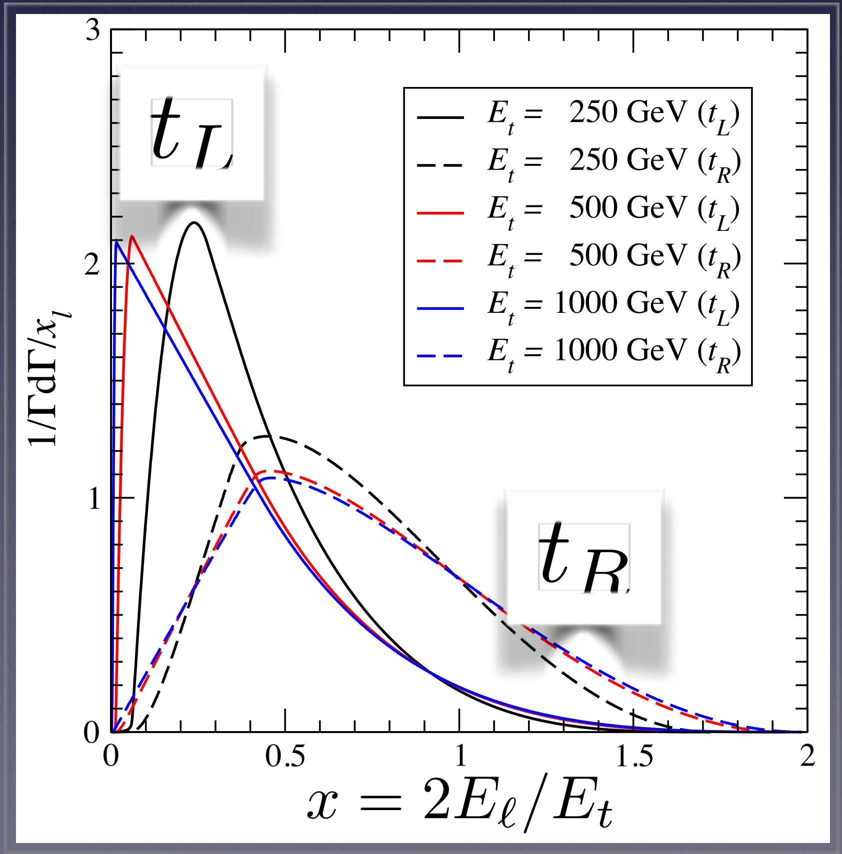
$$\frac{d\Gamma(\hat{s}_t)}{dx} = \frac{\alpha_W^2 m_t}{64\pi AB}\int_{z_{\min}}^{z_{\max}} x\gamma^2[1-x\gamma^2(1-z\beta)]$$
$$\times\left(1+\hat{s}_t\frac{z-\beta}{1-z\beta}\right)\text{Arctan}\left[\frac{Ax\gamma^2(1-z\beta)}{B-x\gamma^2(1-z\beta)}\right]dz$$

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

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

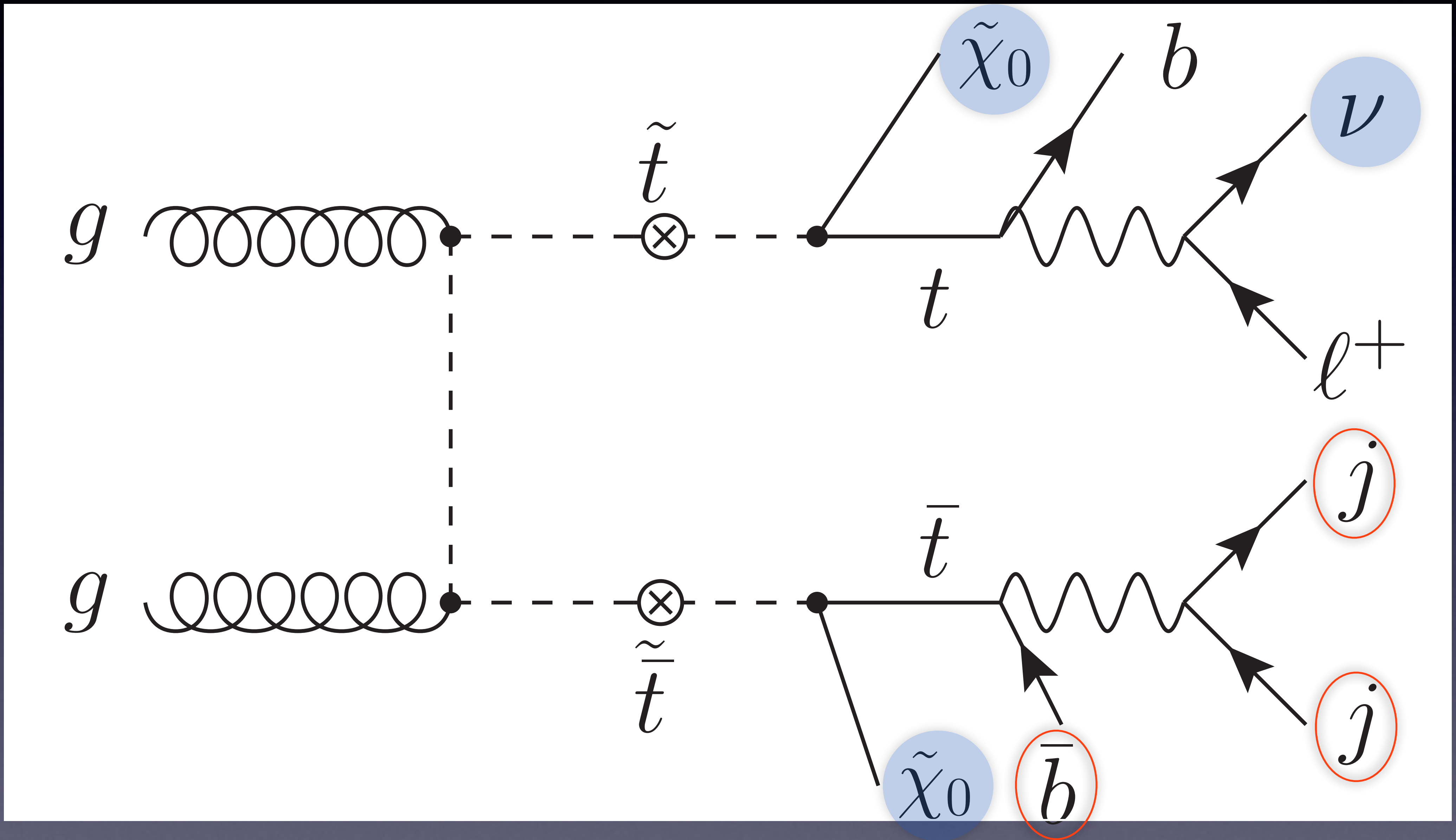
$$z_{\min} = \max[(1-1/\gamma^2 x)/\beta, -1]$$

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



Lepton energy and top-quark polarization

Identical decay chains

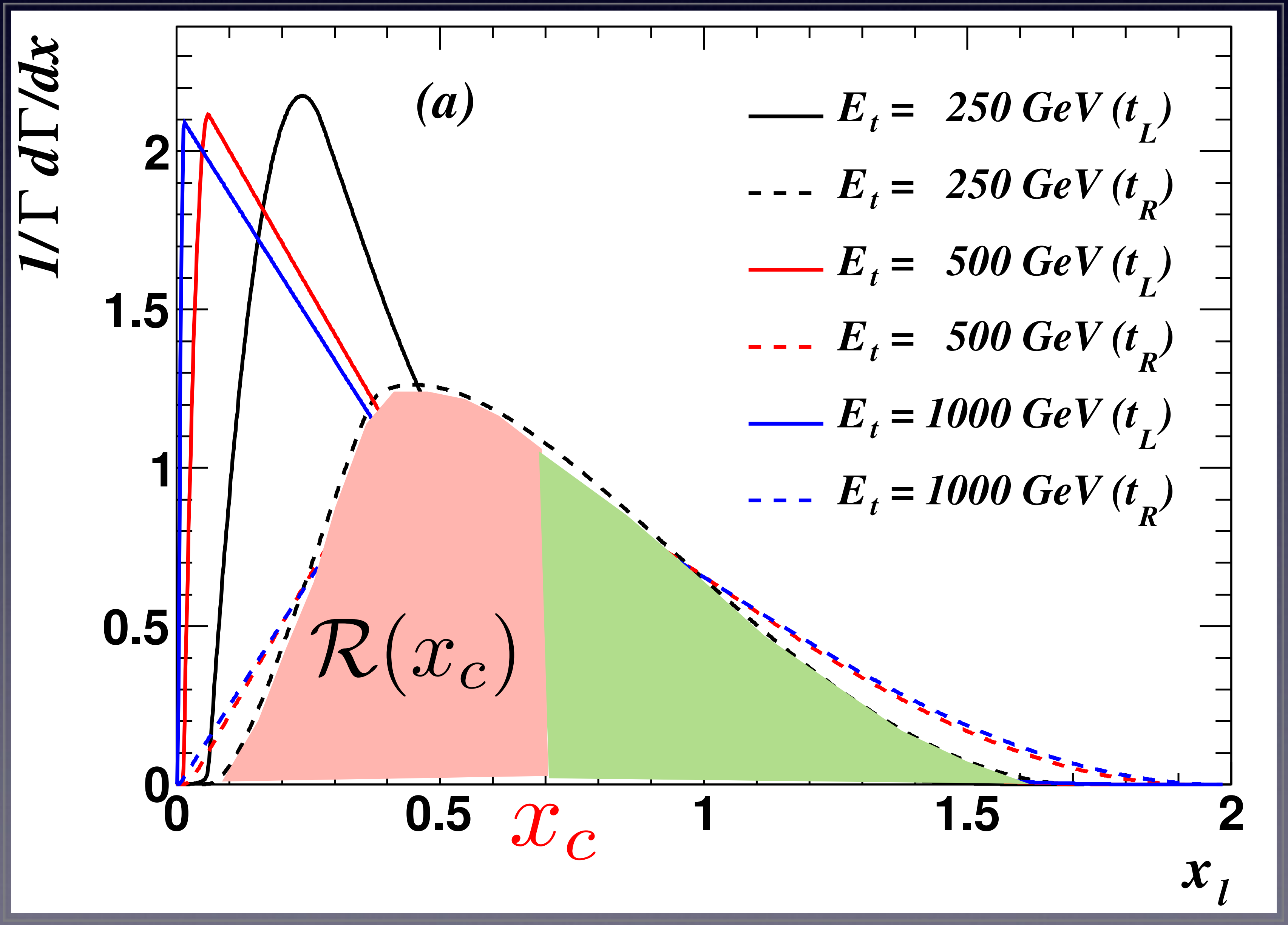


$$x'_\ell = 2E_{\ell+} / E_{\bar{t}}$$

Lepton energy and top-quark polarisation

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

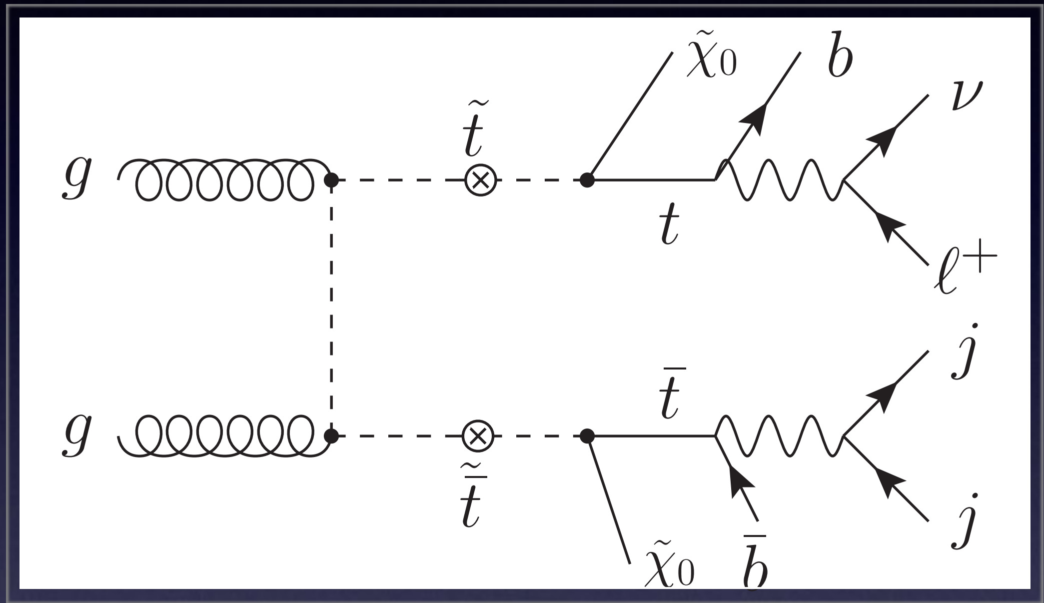
$$\mathcal{R}(x_c) \equiv \frac{\text{Area}(x_\ell < x_c)}{\text{Area(tot)}} = \text{Area}(x_\ell < x_c)$$



Toy model mimicking MSSM

- MSSM like:

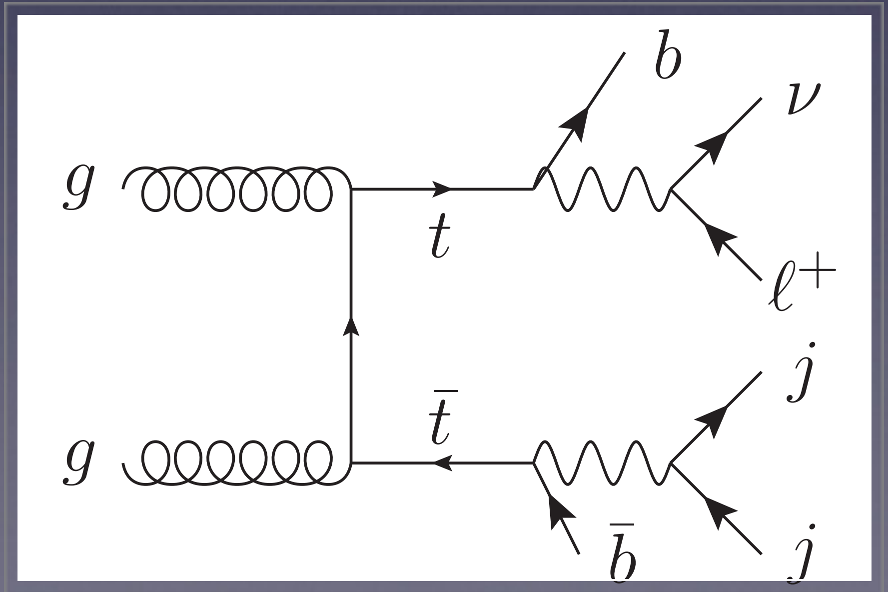
$$\mathcal{L}_{\tilde{t}t\tilde{\chi}} = g_{\rm eff}\tilde{t}\tilde{\chi}(\cos\theta_{\rm eff}P_L + \sin\theta_{\rm eff}P_R)t$$

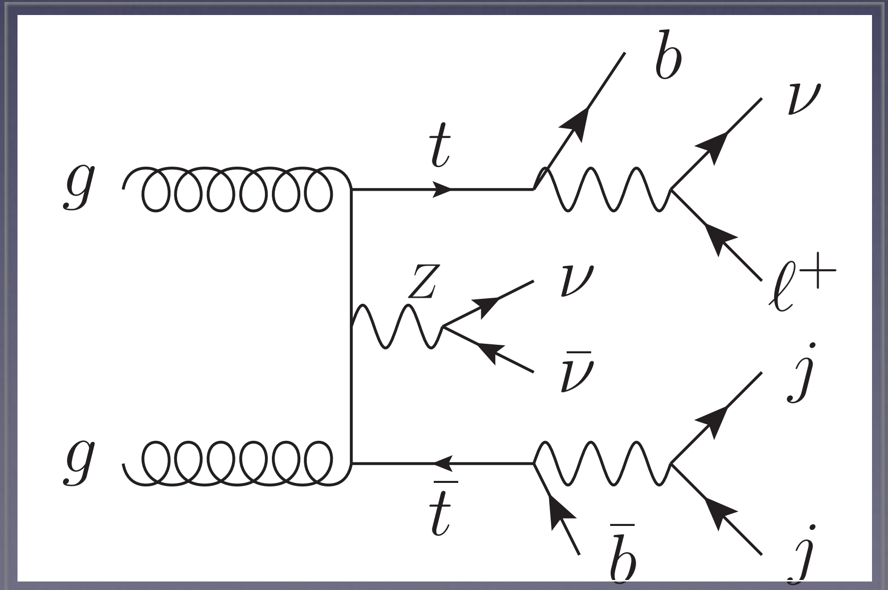


Collider signature

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

- Major SM backgrounds





Collider simulation

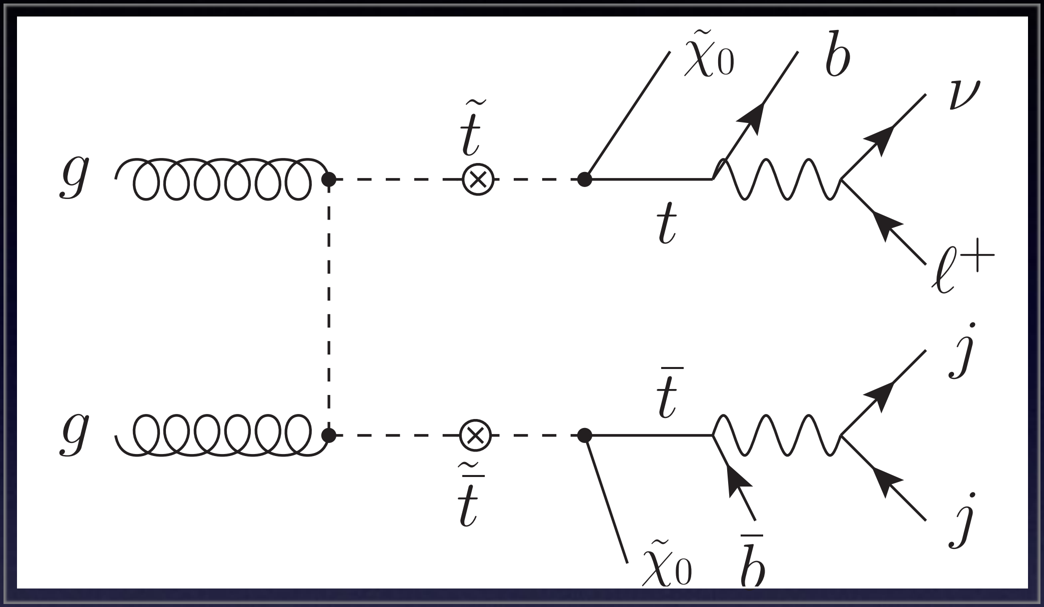
- Basic selection cuts

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

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

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

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



- 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 %

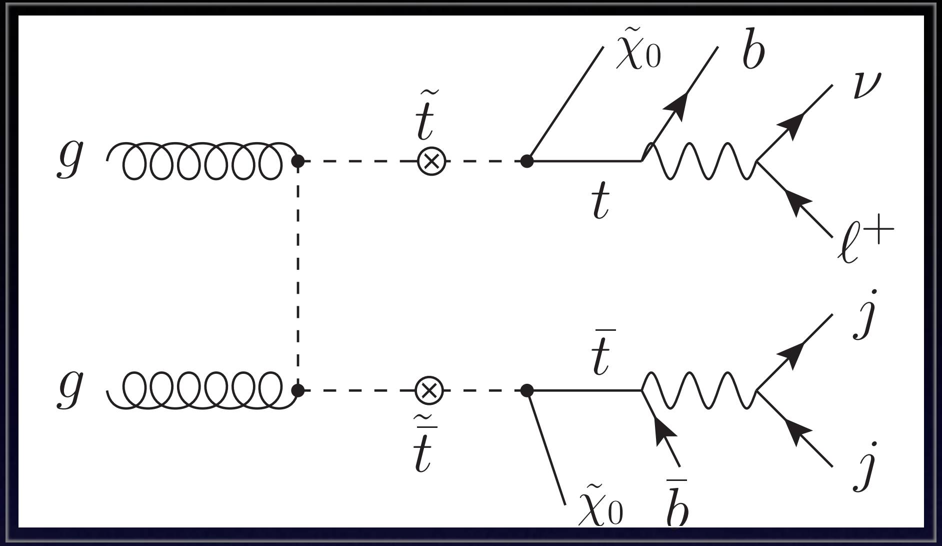
- $\not{E}_T$ solution cut

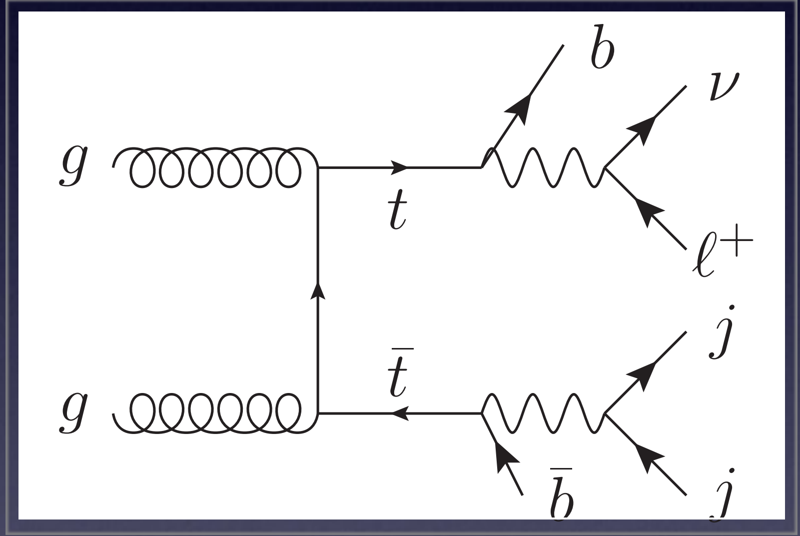
$$p_z^\nu = \frac{1}{2(p_T^e)^2}\left[A\, p_z^e \pm E_e \sqrt{A^2 - 4\,(p_T^e)^2\, \not{E}_T^2}\right]$$

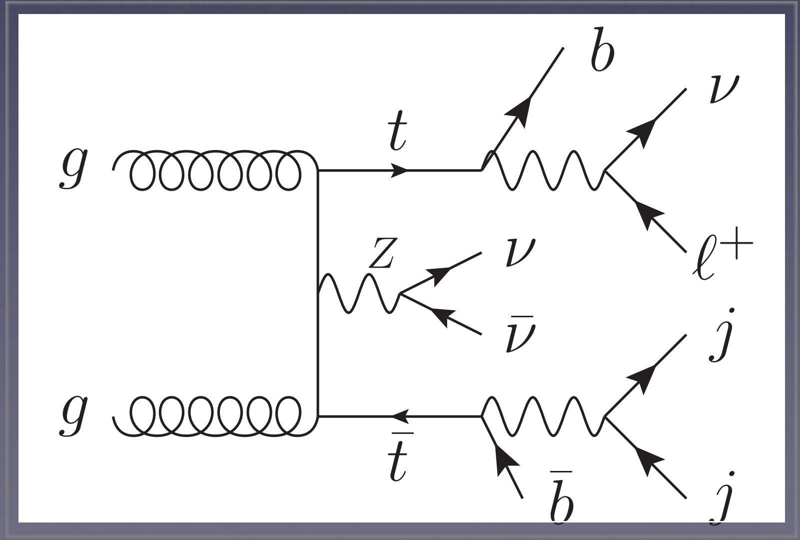
$$A \equiv m_W^2 + 2\,\vec{p}_T^{\,e} \cdot \vec{\not{E}}_T$$

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

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

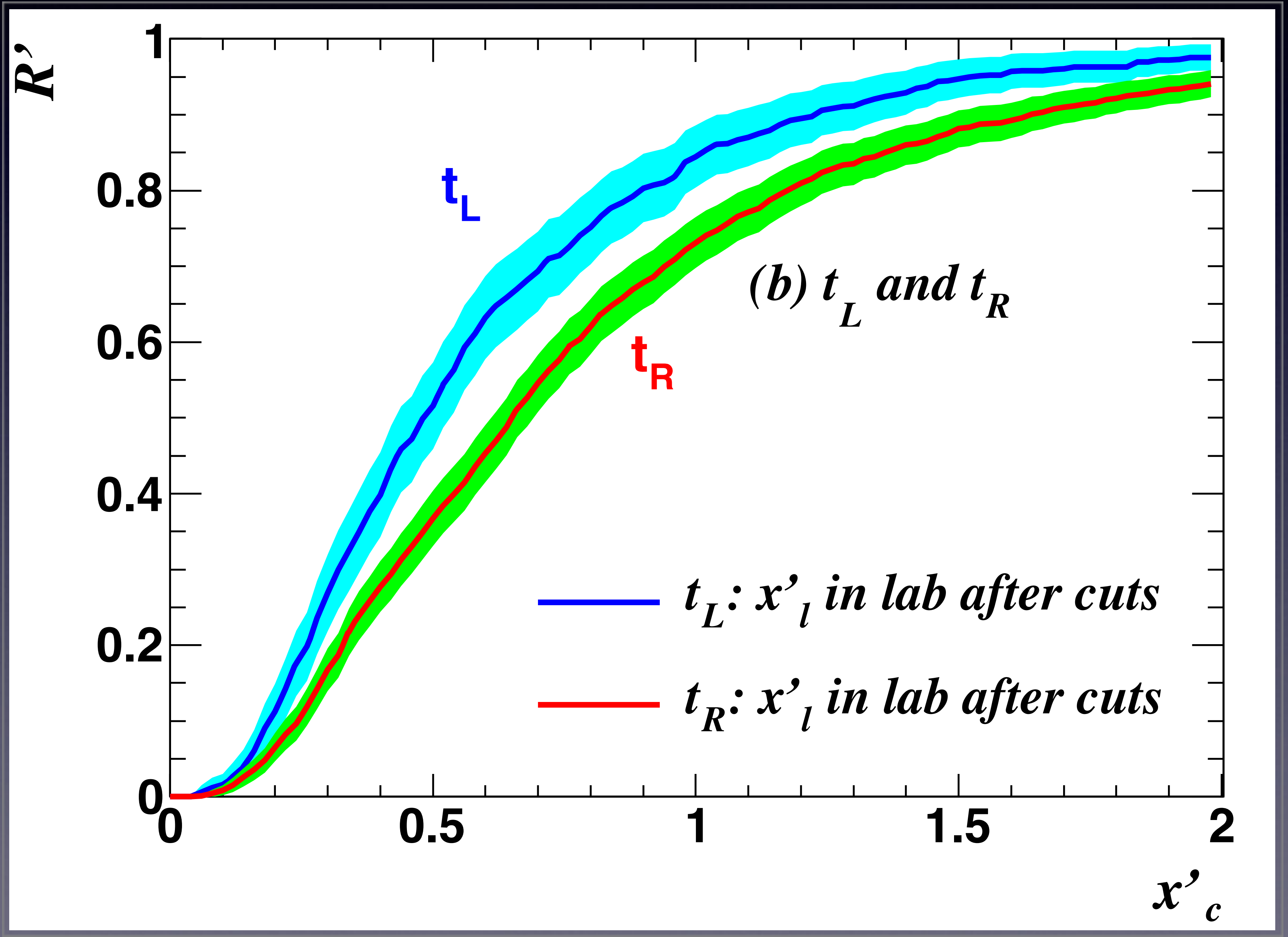






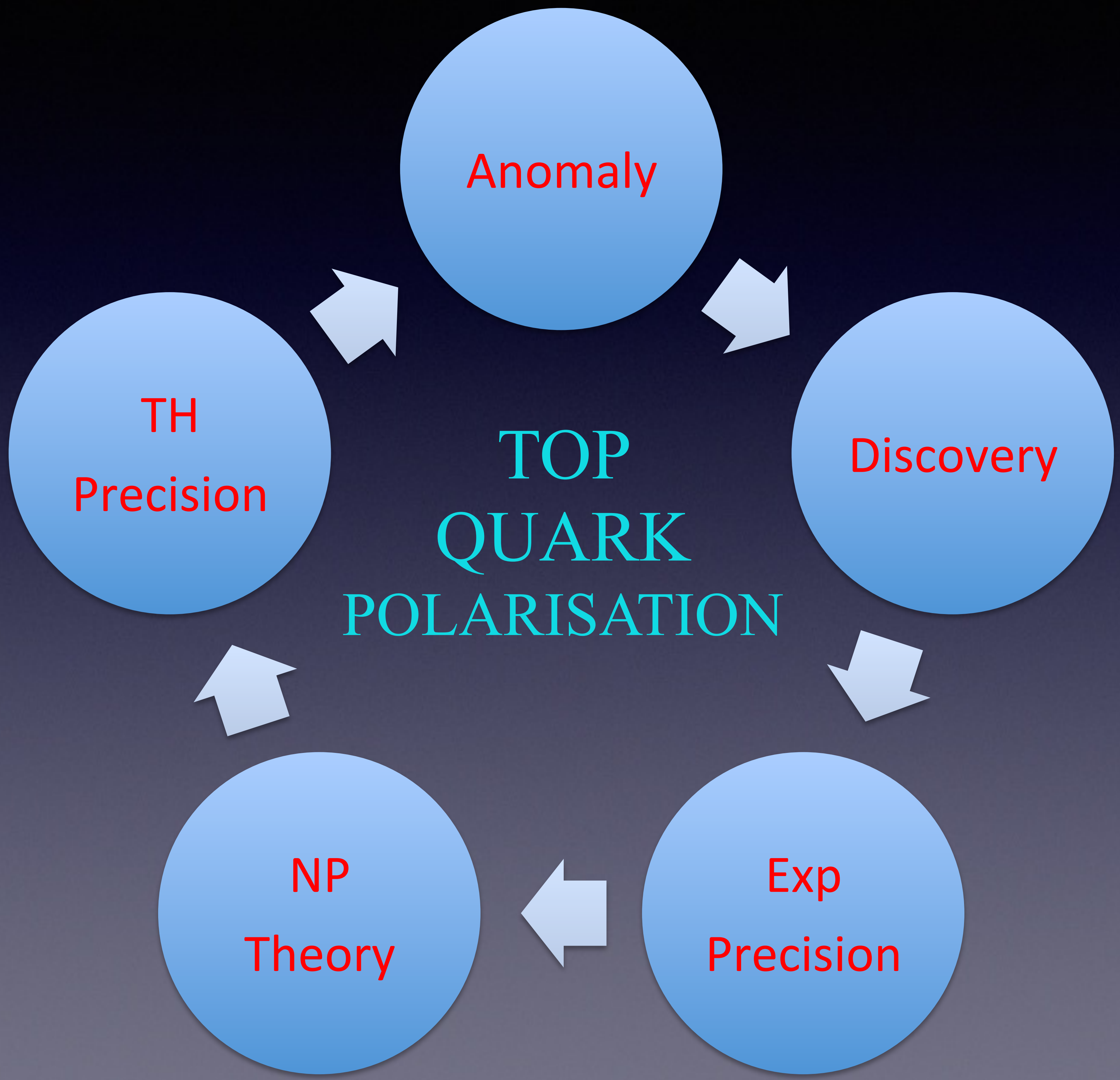
$\mathcal{R}'$ distribution

t_L and t_R are separated



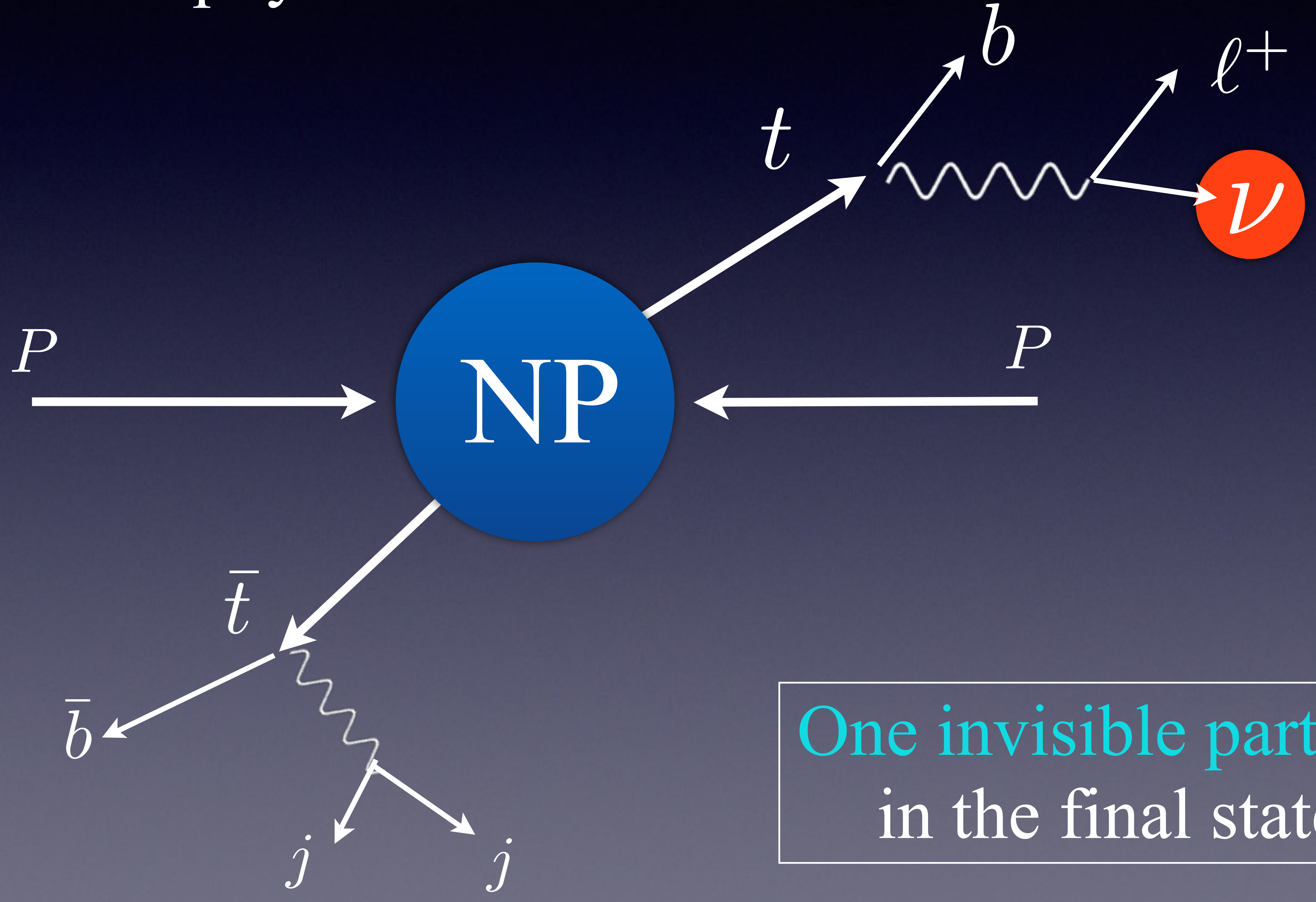
LHC
14 TeV
100fb^{-1}

Conclusion


Anomaly
Discovery
Exp
Precision
NP
Theory
TH
Precision
TOP
QUARK
POLARISATION

Conclusion

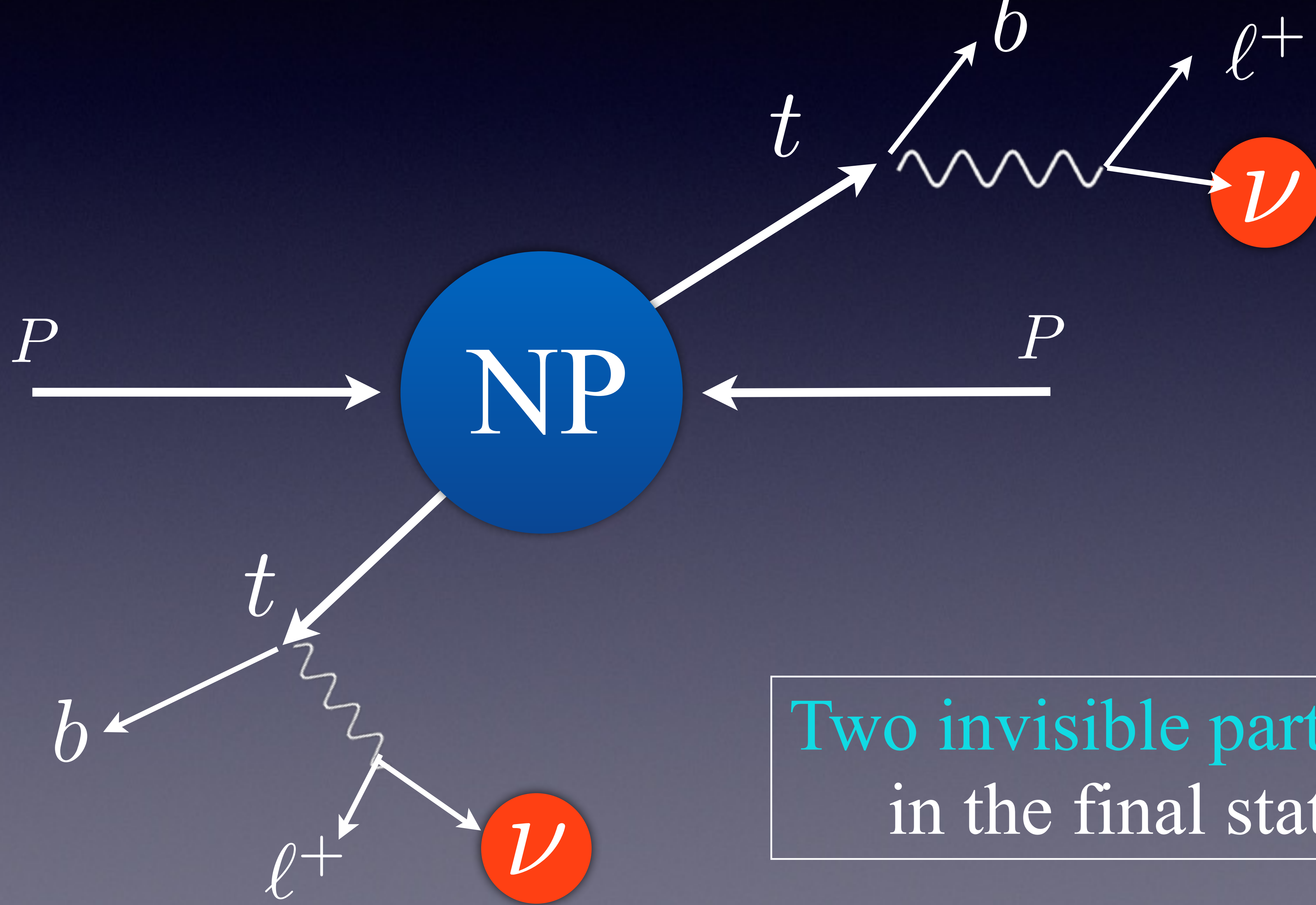
- Top-quark polarisation provides additional information about new physics structure



One invisible particle
in the final state

Conclusion

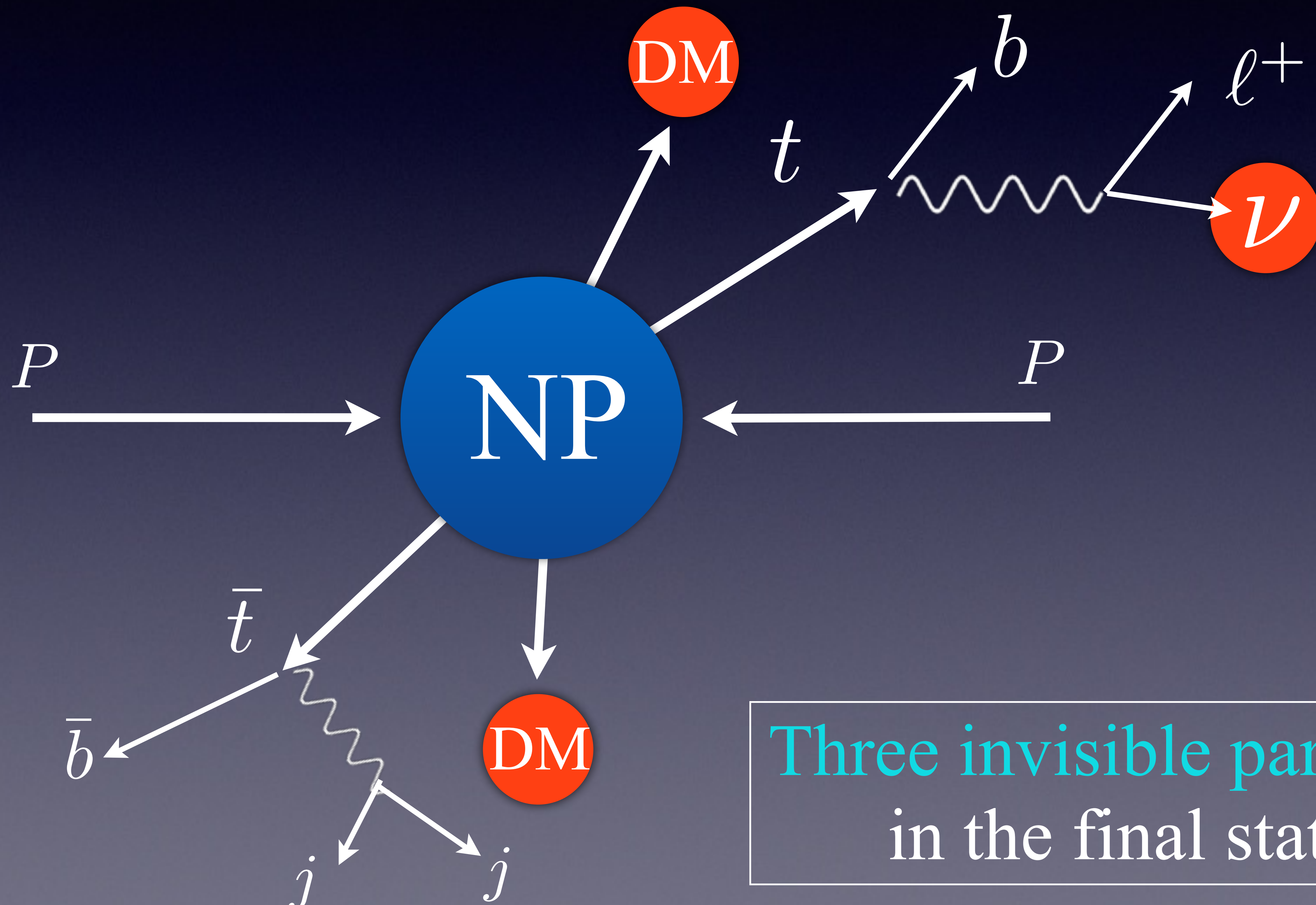
- Top-quark polarisation provides additional information about new physics structure



Two invisible particles
in the final state

Conclusion

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



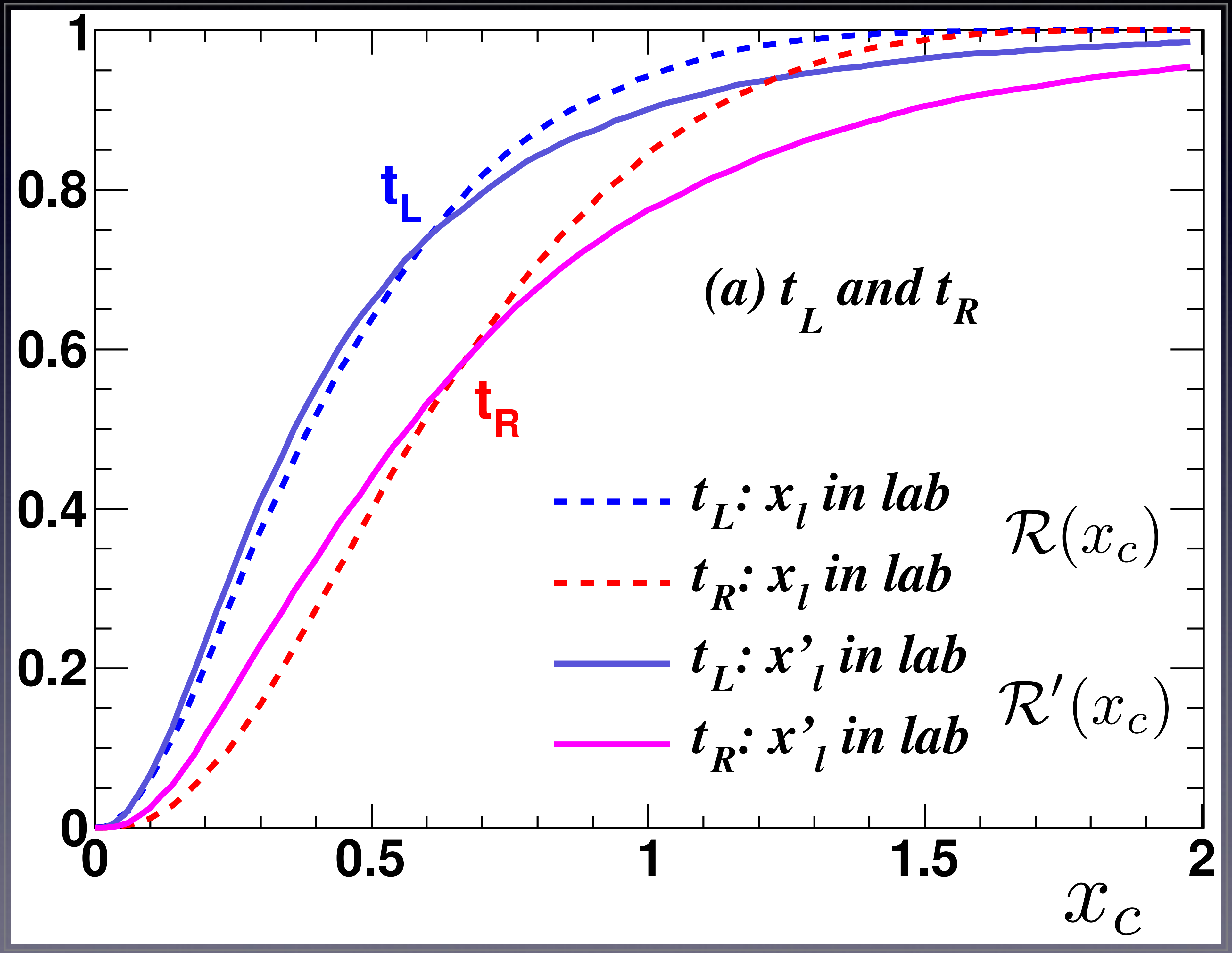
Three invisible particles in the final state

THANK YOU!

Back-up slides

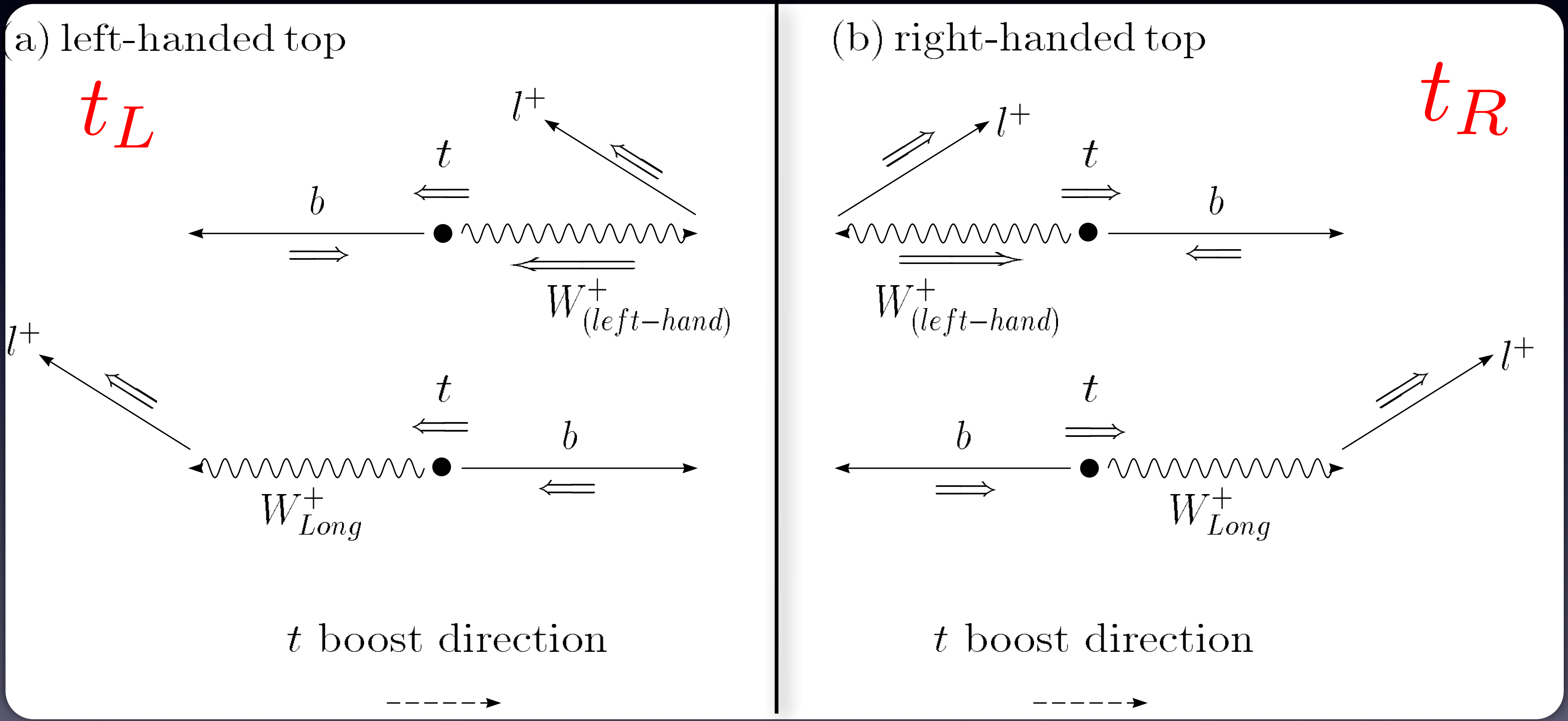
$\mathcal{R}(x_c)$ versus $\mathcal{R}'(x_c)$

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



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.