Probing New Physics with Polarized Top Quark

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Based on the works in collaboration with

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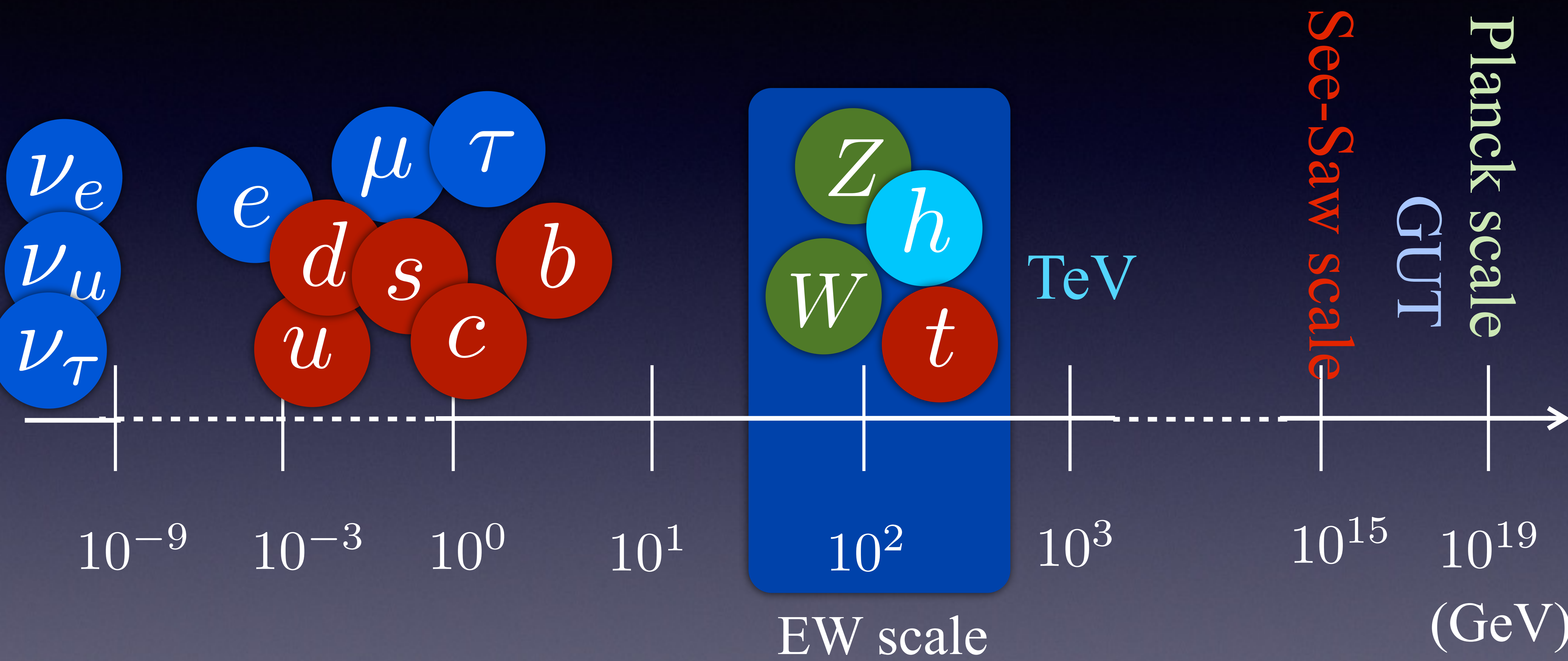
Gabe Shaughnessy, Jiang-Hao Yu, Hao Zhang

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

It appears often in the decay of NP resonances

Extra Gauge Bosons

Z' W' G'

Exotic Colored States

Color Sextet

New Heavy Quarks

Top

Vector Quark

4th Gen

Gluino

Heavy Quark Production via pQCD

Charged Higgs

$\not{CP}$

FCNC

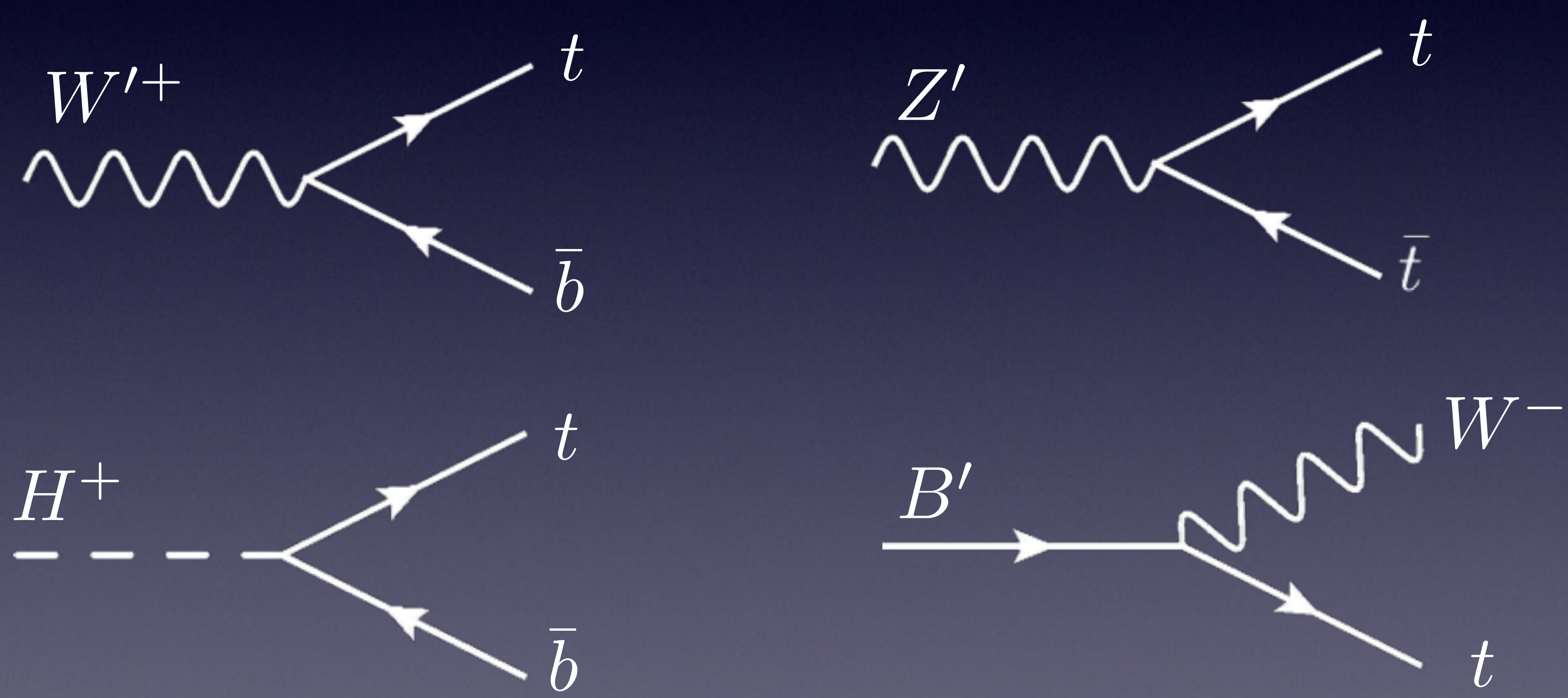
A_{FB}

Top-quark: a new physics window

Top quark is common in decays of NP resonances and

It is often polarized.

G(221), G(331), Left-Right, 2HDB, Vector-Quark, ...



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

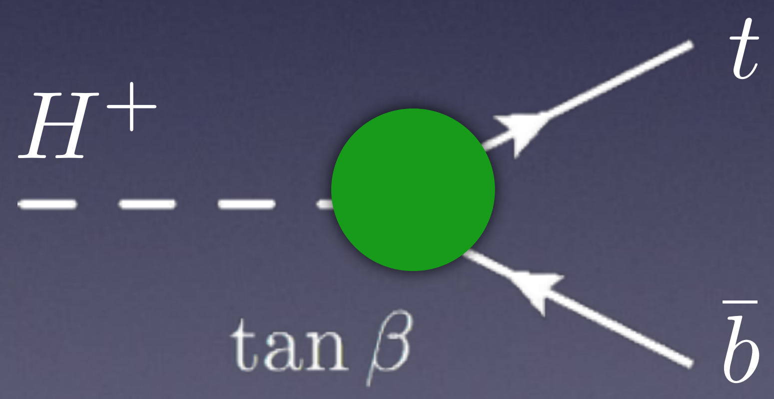
Top-quark: a new physics window

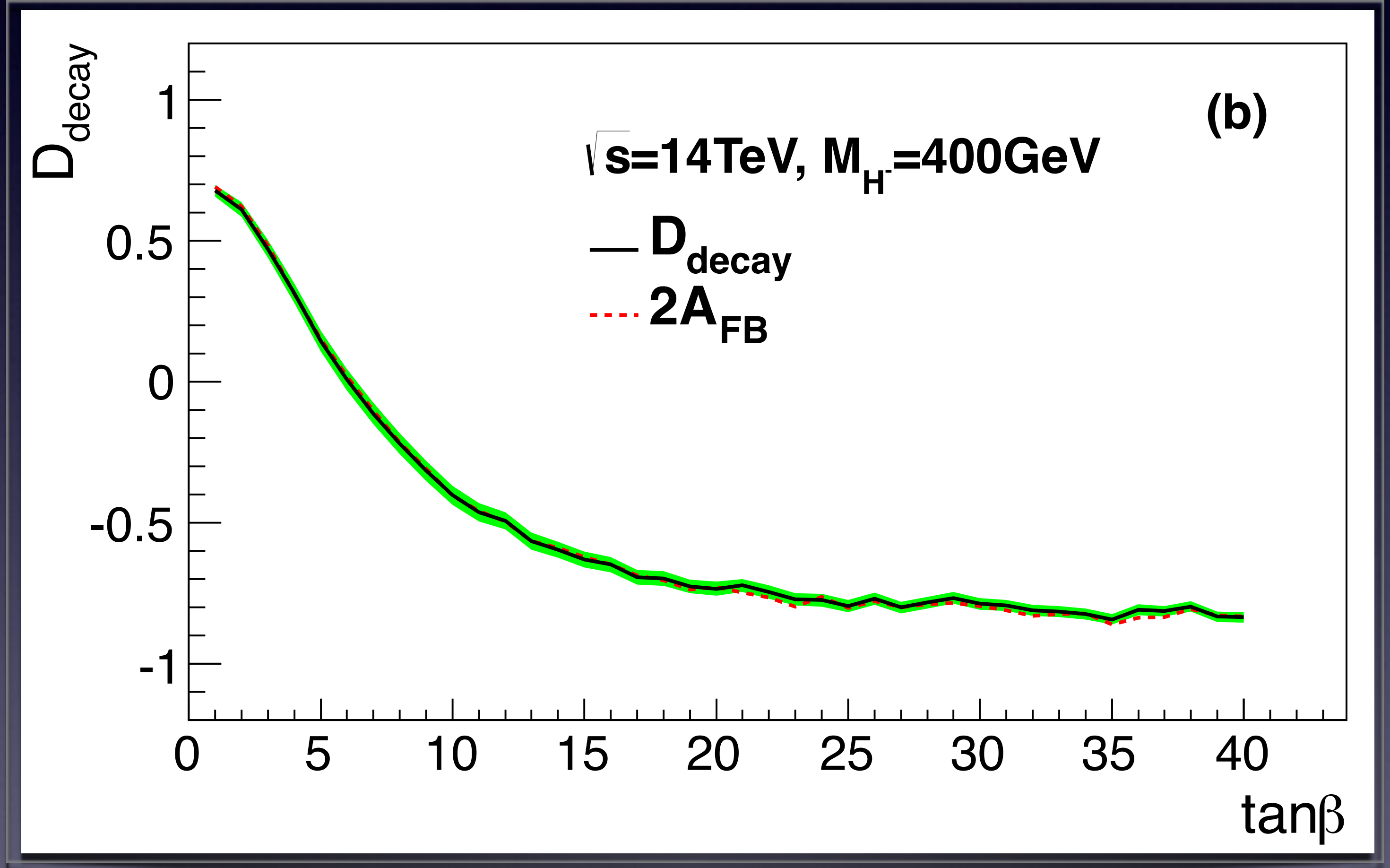
Top quark is quite common in decays of NP resonances and it is often polarized.

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

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

in Type-II 2HDB



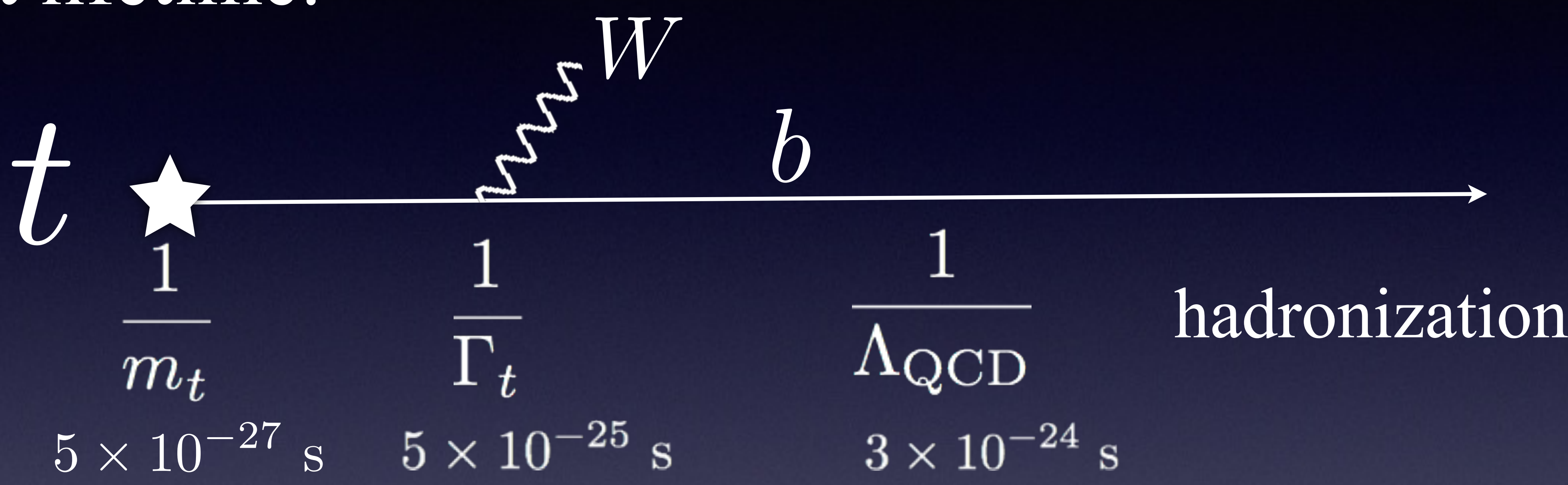


Top quark polarization can tell us the chirality structure of top quark couplings to NP Resonances

Top-quark: the only bare quark in SM

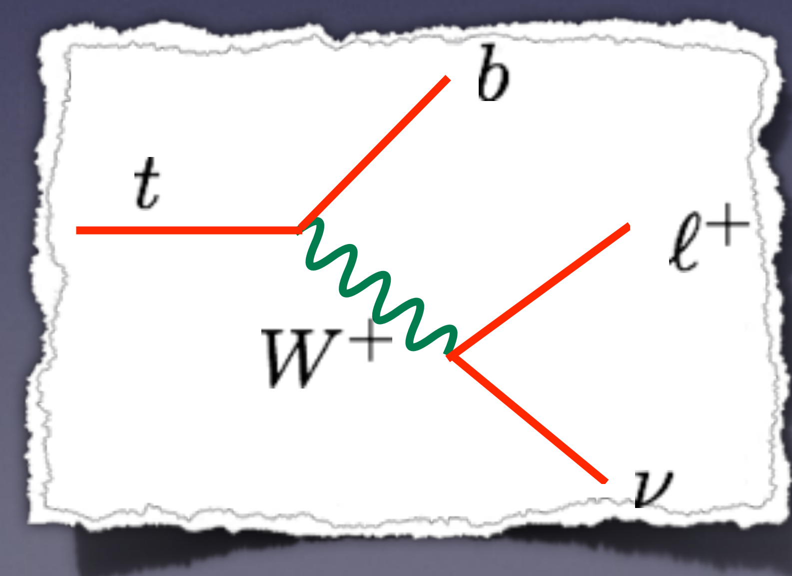
(the only bizarre quark in the SM)

- Short lifetime:



- "bare" quark :

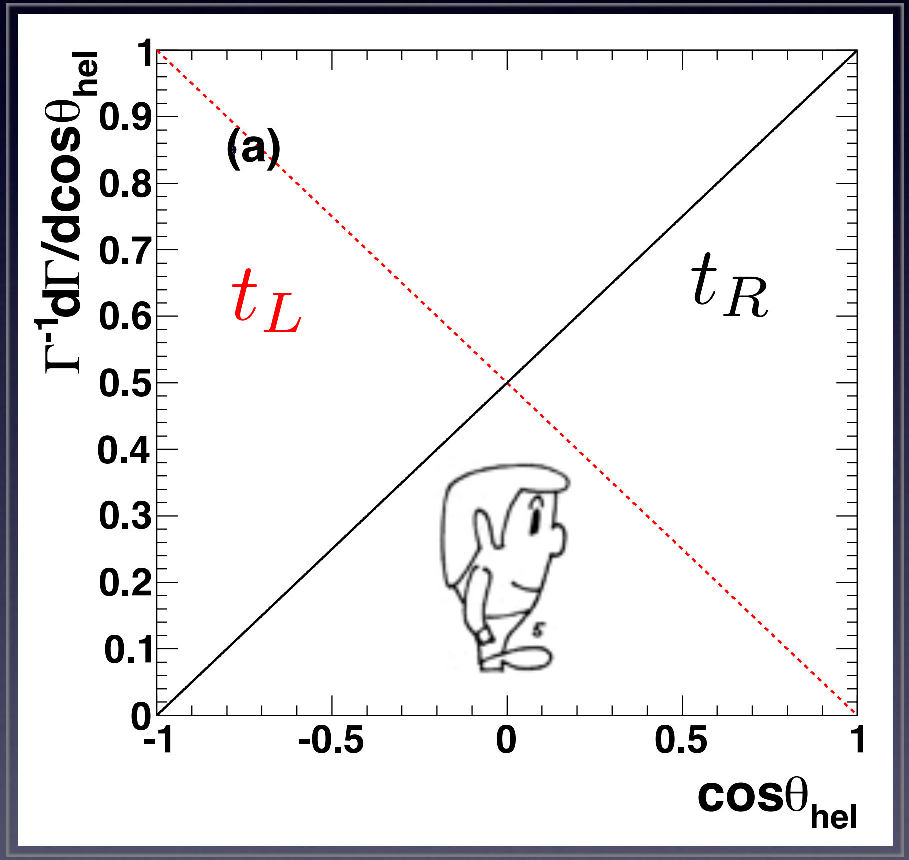
  spin info well kept
  among its decay products



Charged lepton: the top-spin analyzer

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

Czarnecki, Jezabek, Kuhn, NPB351 (1991) 70



- In top-quark rest frame

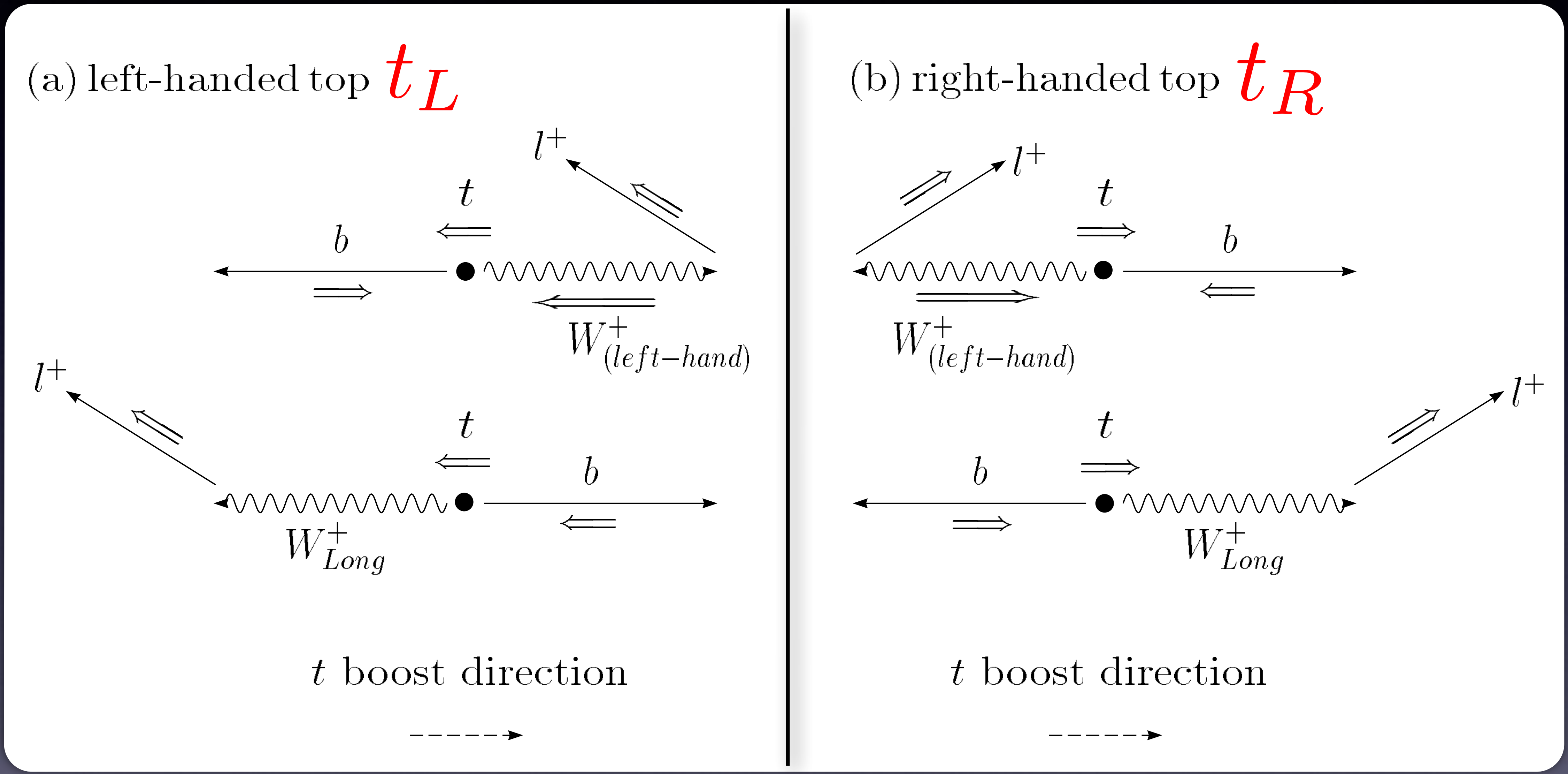
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{\rm hel}} = \frac{1+\lambda_t\cos\theta_{\rm hel}}{2}$$

$\lambda_t = +$ right-handed

$\lambda_t = -$ left-handed

reconstruction of top quark kinematics

Charged Lepton: Spin Analyzer



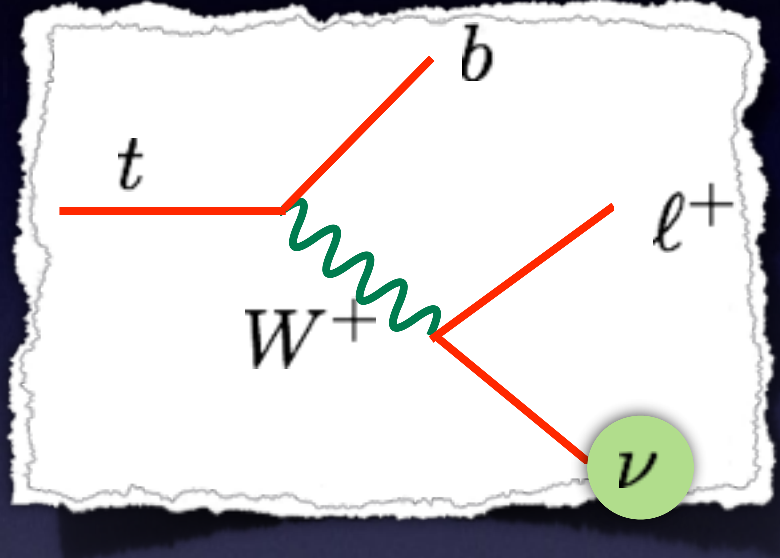
Charged Lepton tends to follow the direction of Top-quark spin.

Top quark reconstruction

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

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

p_z^ν unknown



- W-boson on-shell condition

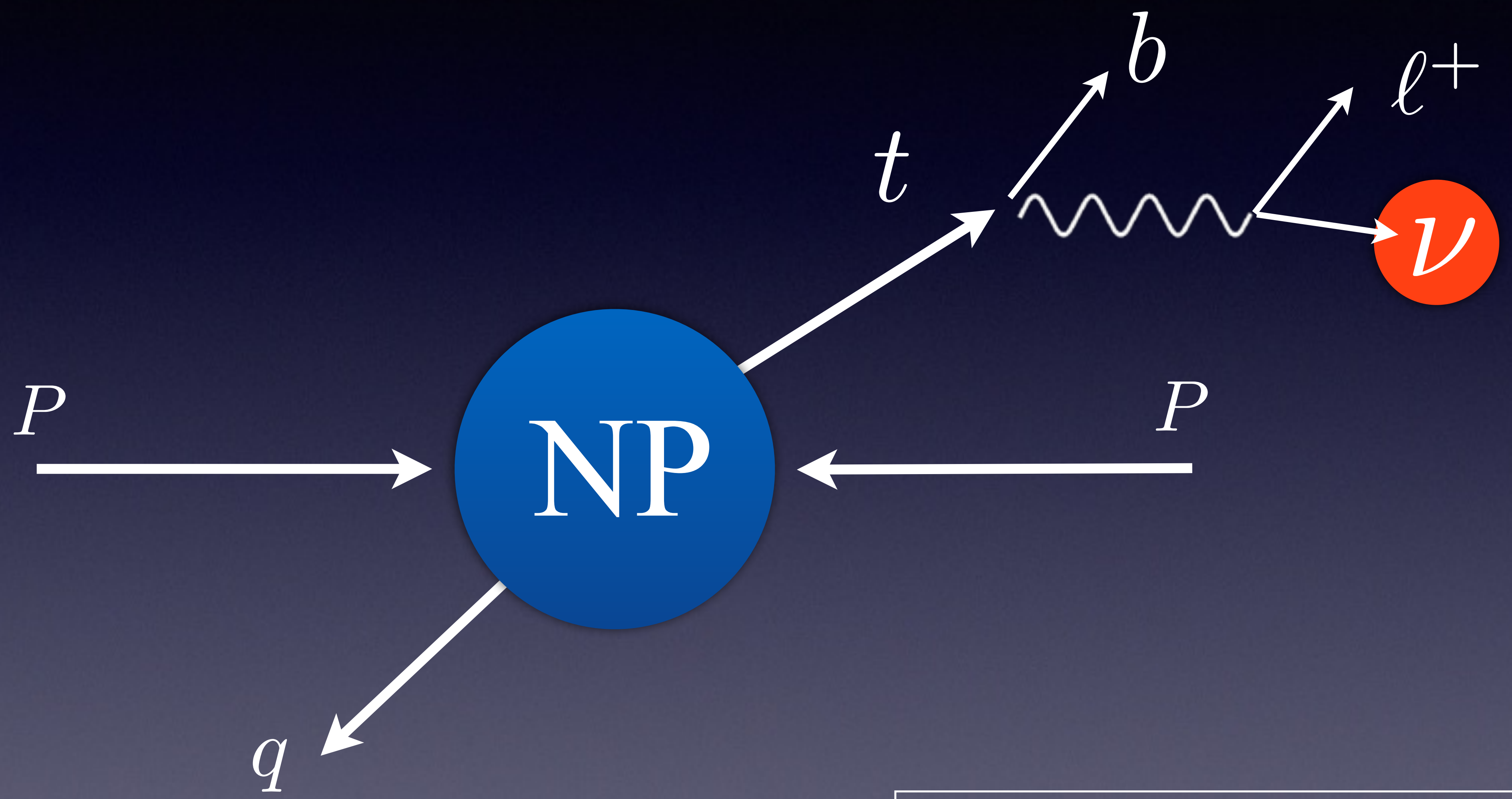
$$\boxed{m_W^2 = (p_\ell + p_\nu)^2}$$

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

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

Top quark production in NP

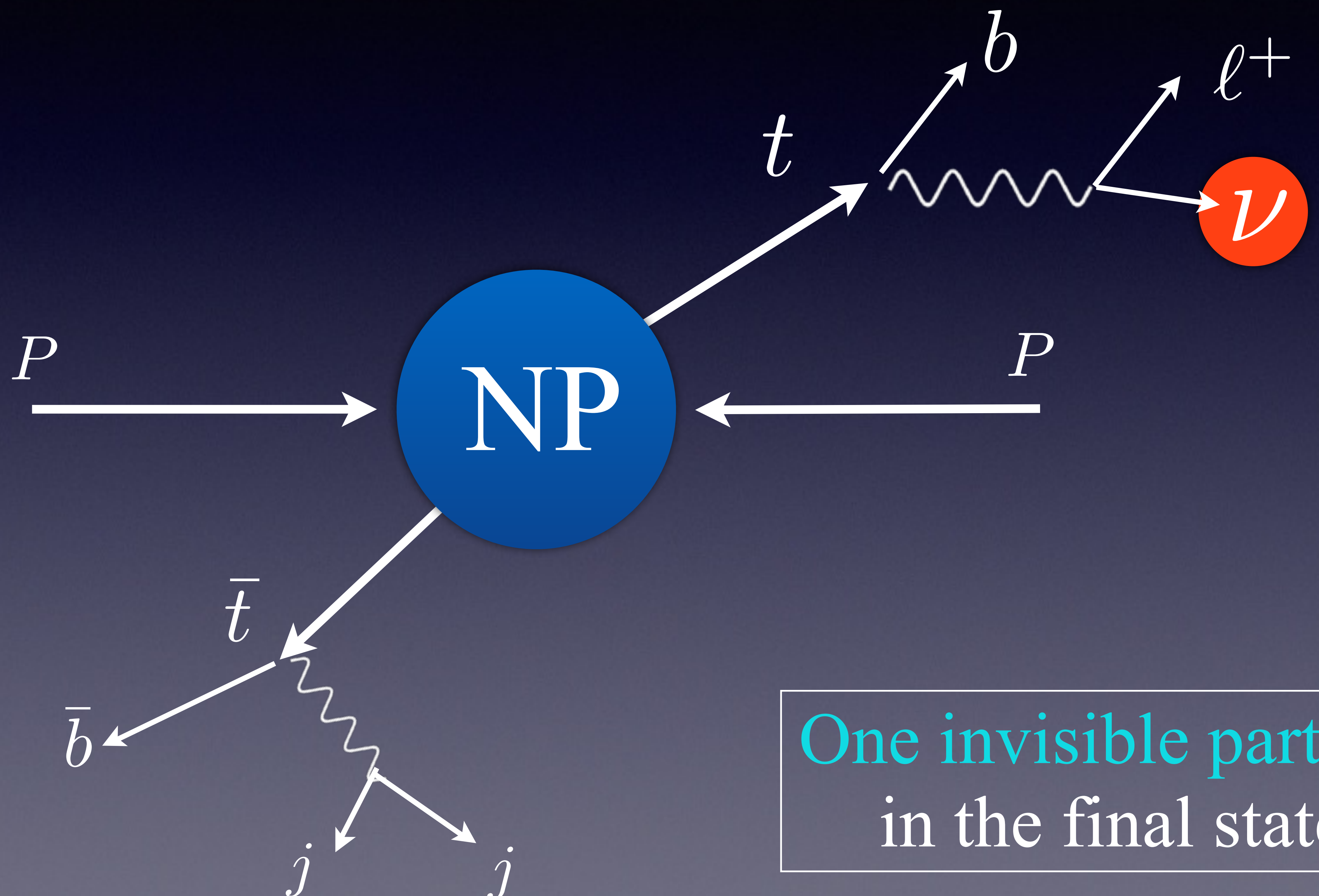
(1) Single Top-quark production + leptonic decay



One invisible particle
in the final state

Top quark production in NP

or Top-quark pair production + semi-leptonic decay

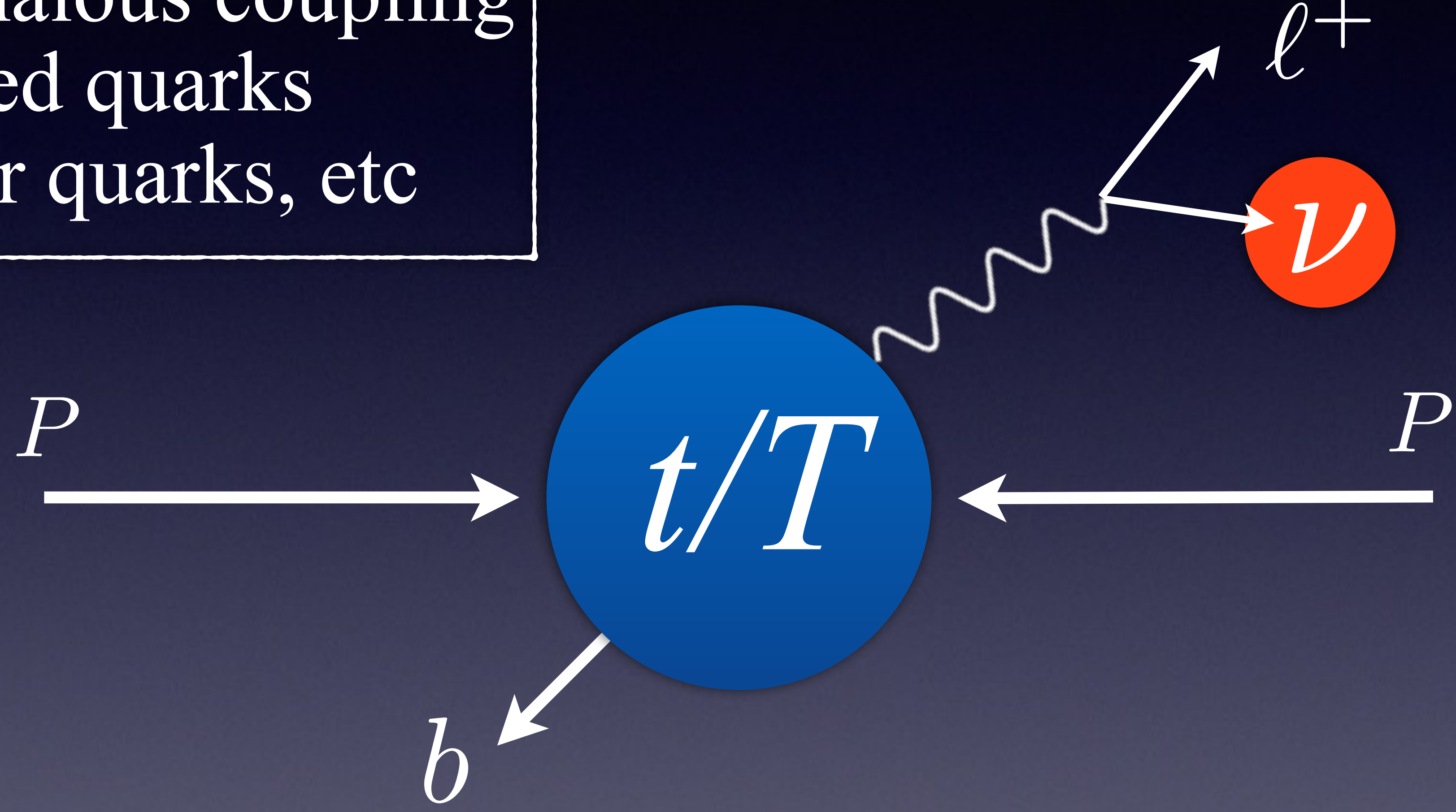


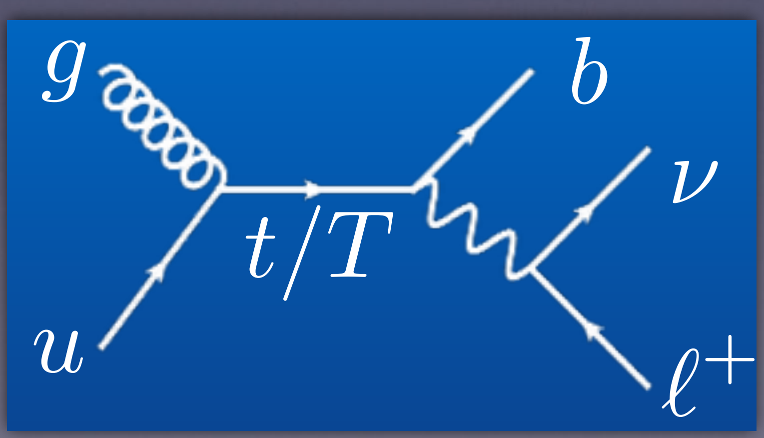
One invisible particle
in the final state

Top quark production in NP

or Direct top-quark production

Anomalous coupling
Excited quarks
Vector quarks, etc

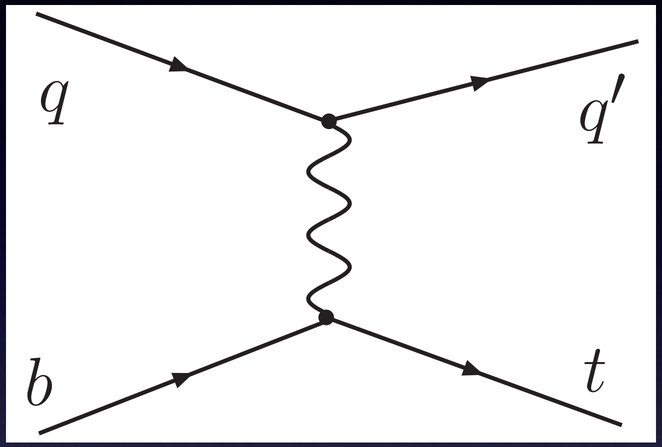


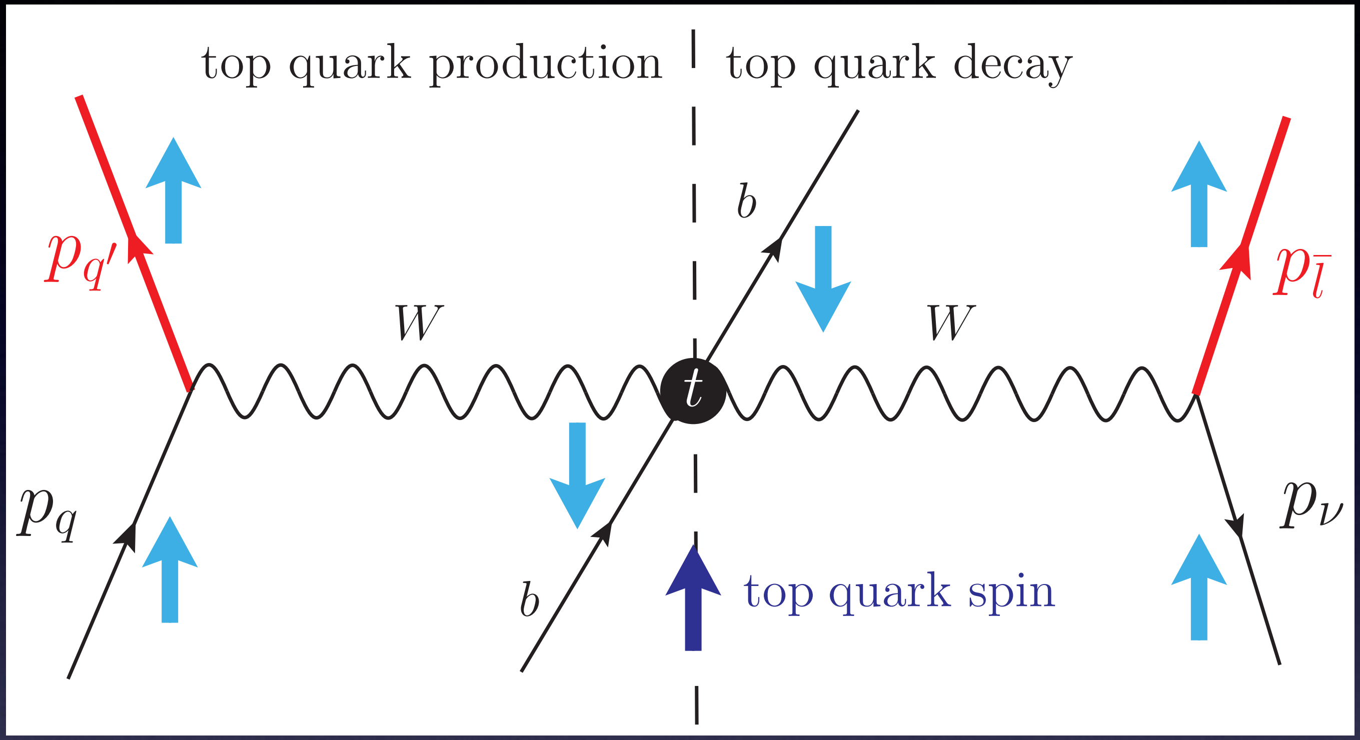


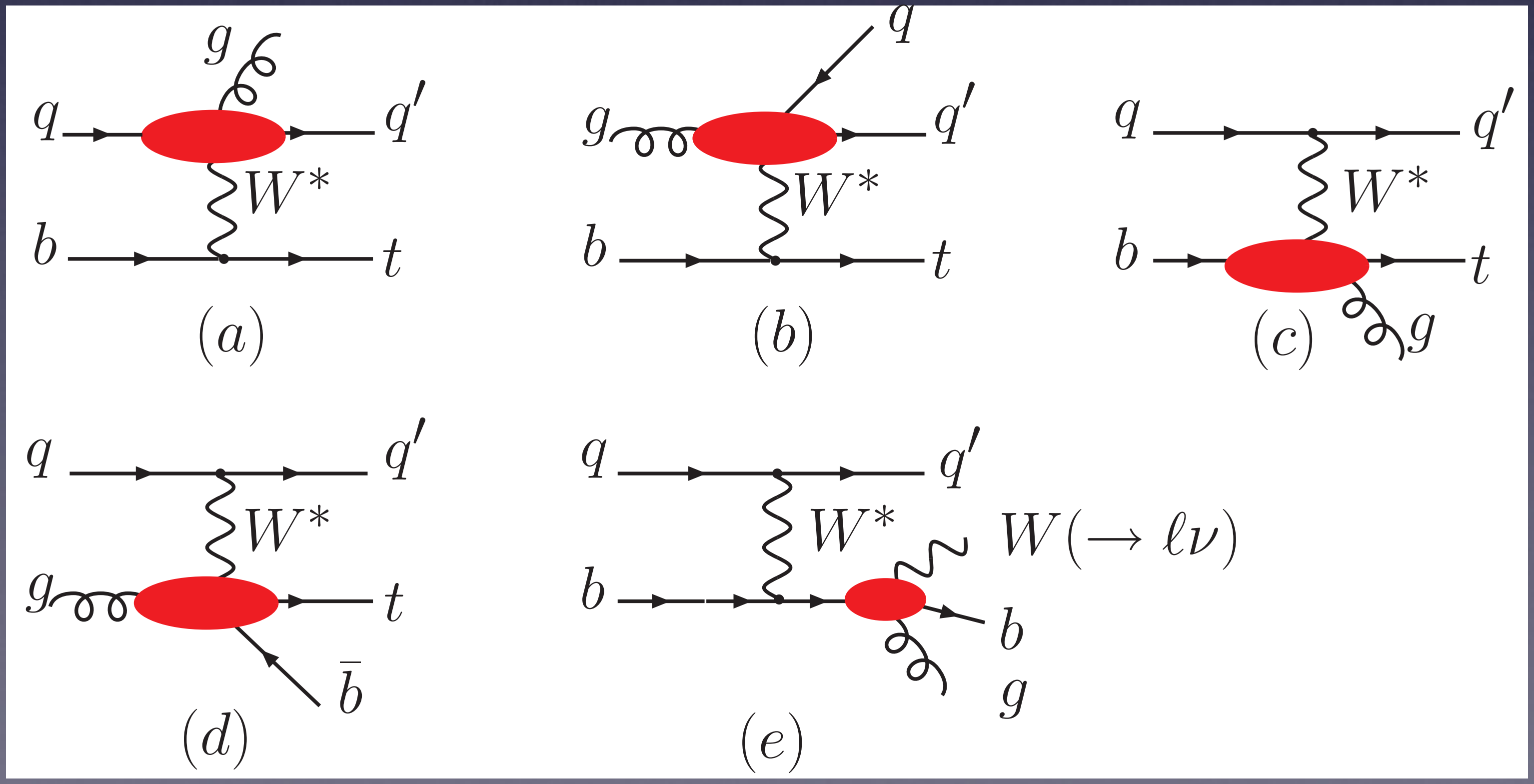
One invisible particle
in the final state

1. Single-top production @ NLO

Schwienhorst, Yuan, Muller, QHC, Phys.Rev. D83 (2011) 034019

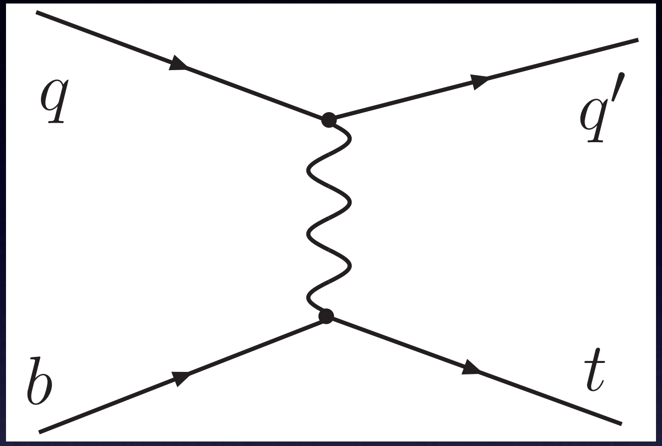


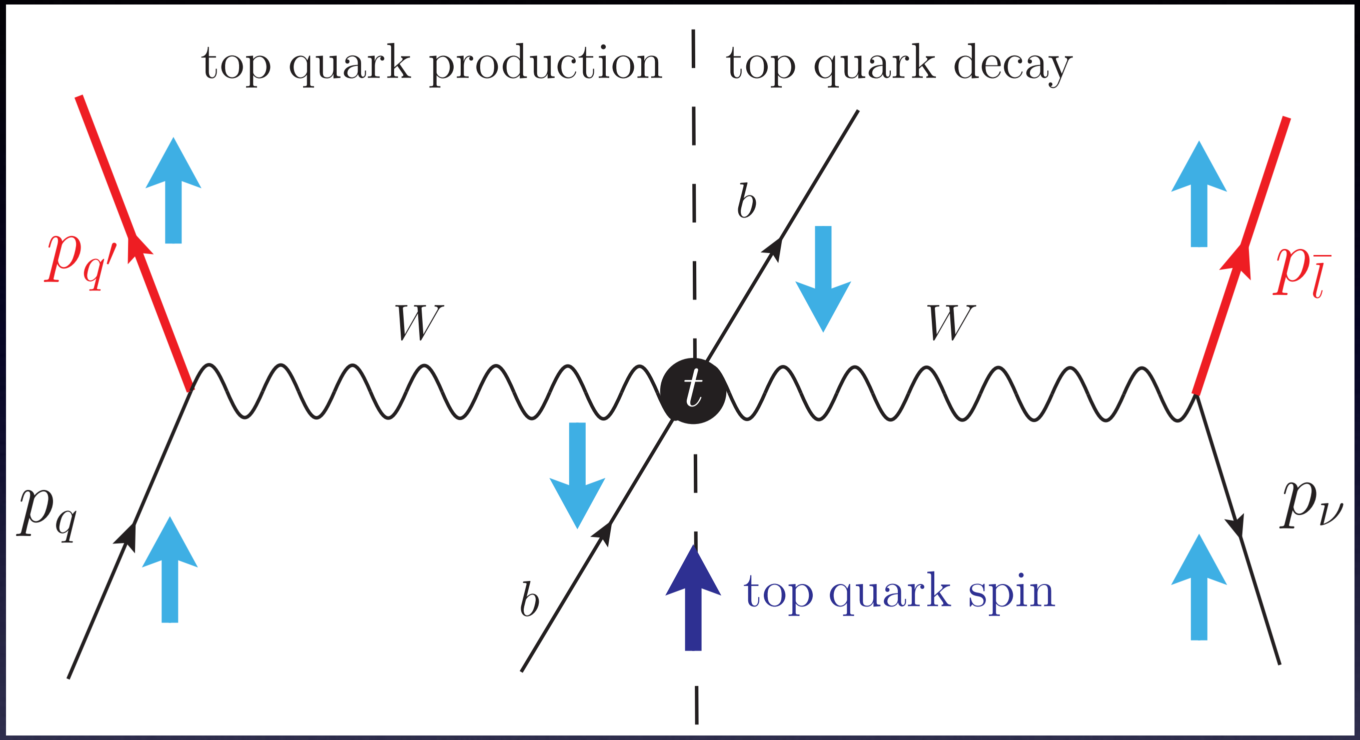


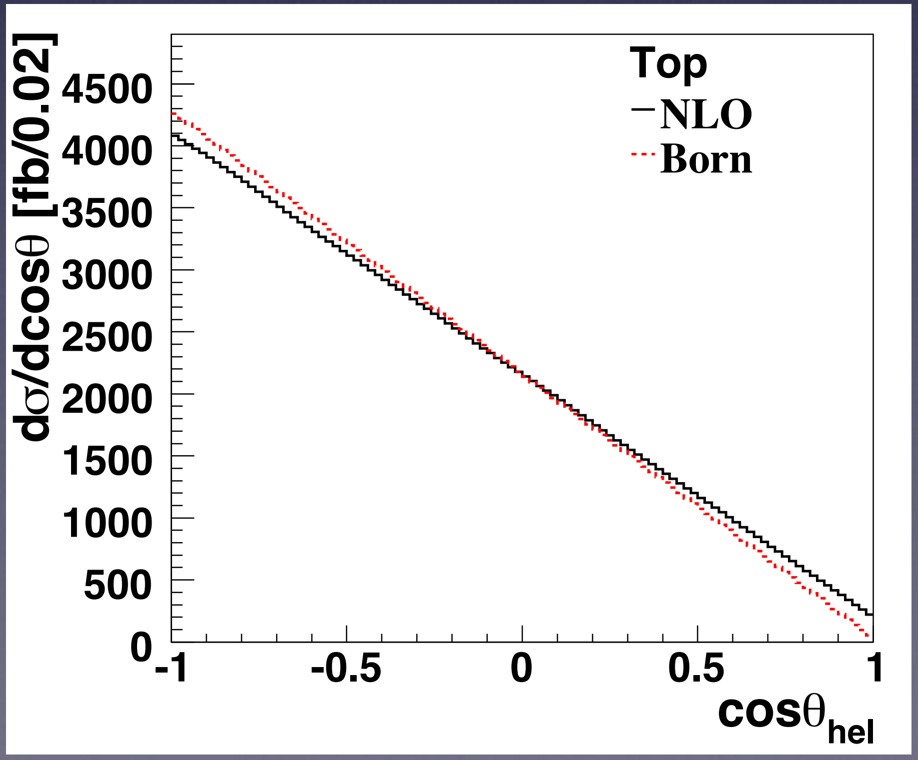


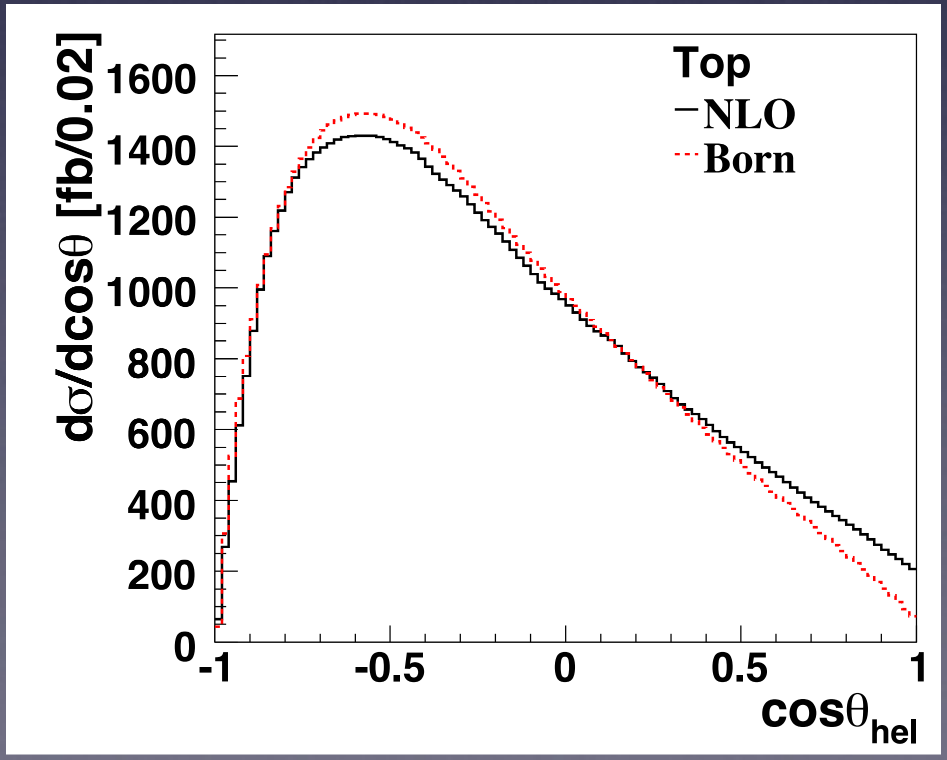
Single-top production @ NLO

Schwienhorst, Yuan, Muller, QHC, Phys.Rev. D83 (2011) 034019





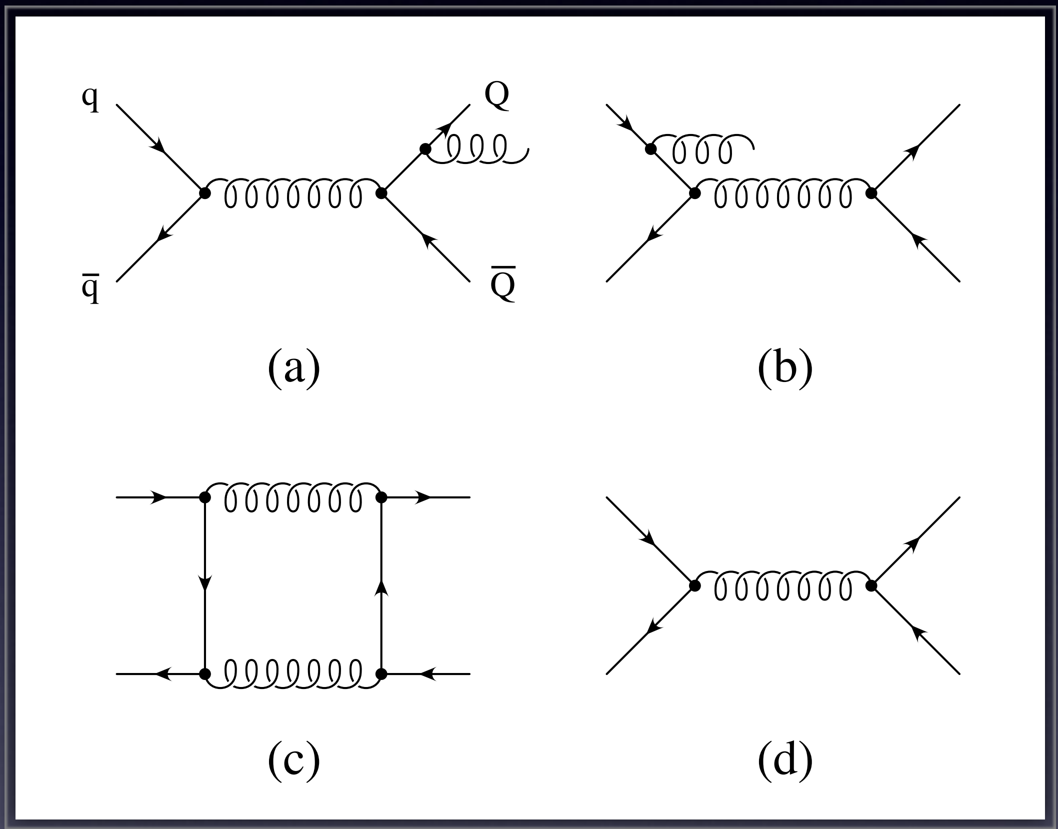


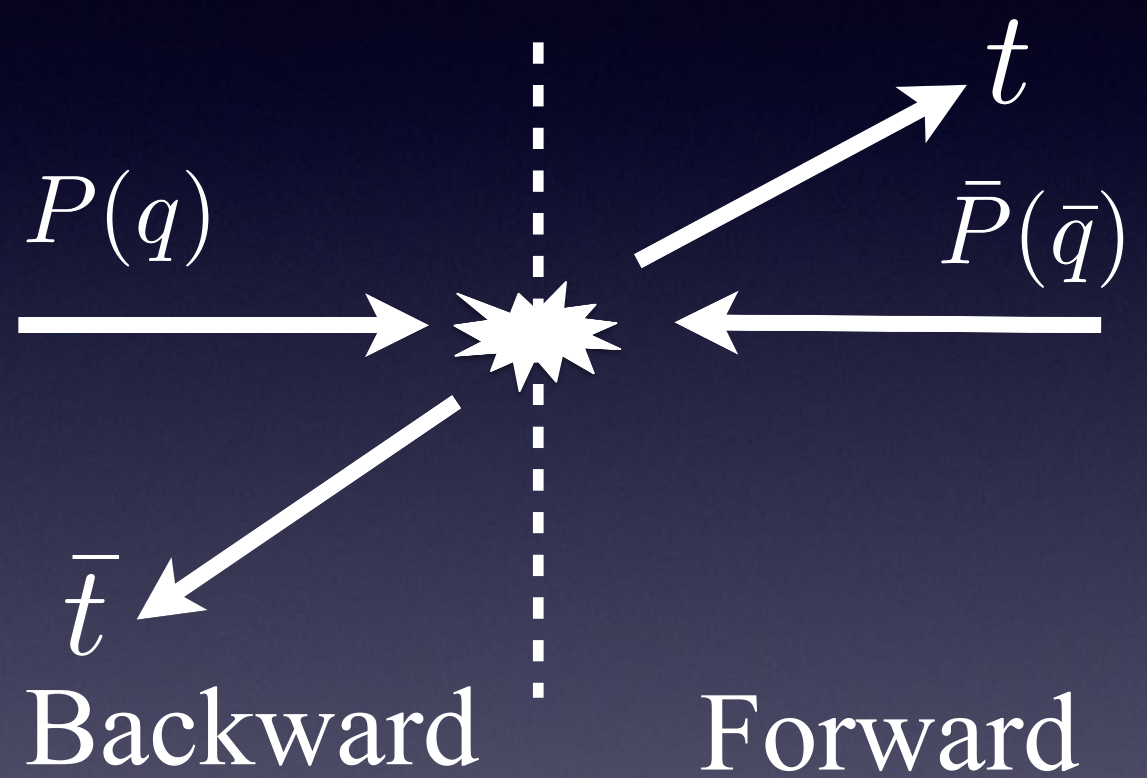


2. Top-quark Forward-backward Asymmetry at the Tevatron

It is induced at the loop level in the SM

Kuhn and Rodrigo
PRL 81 (1998) 49

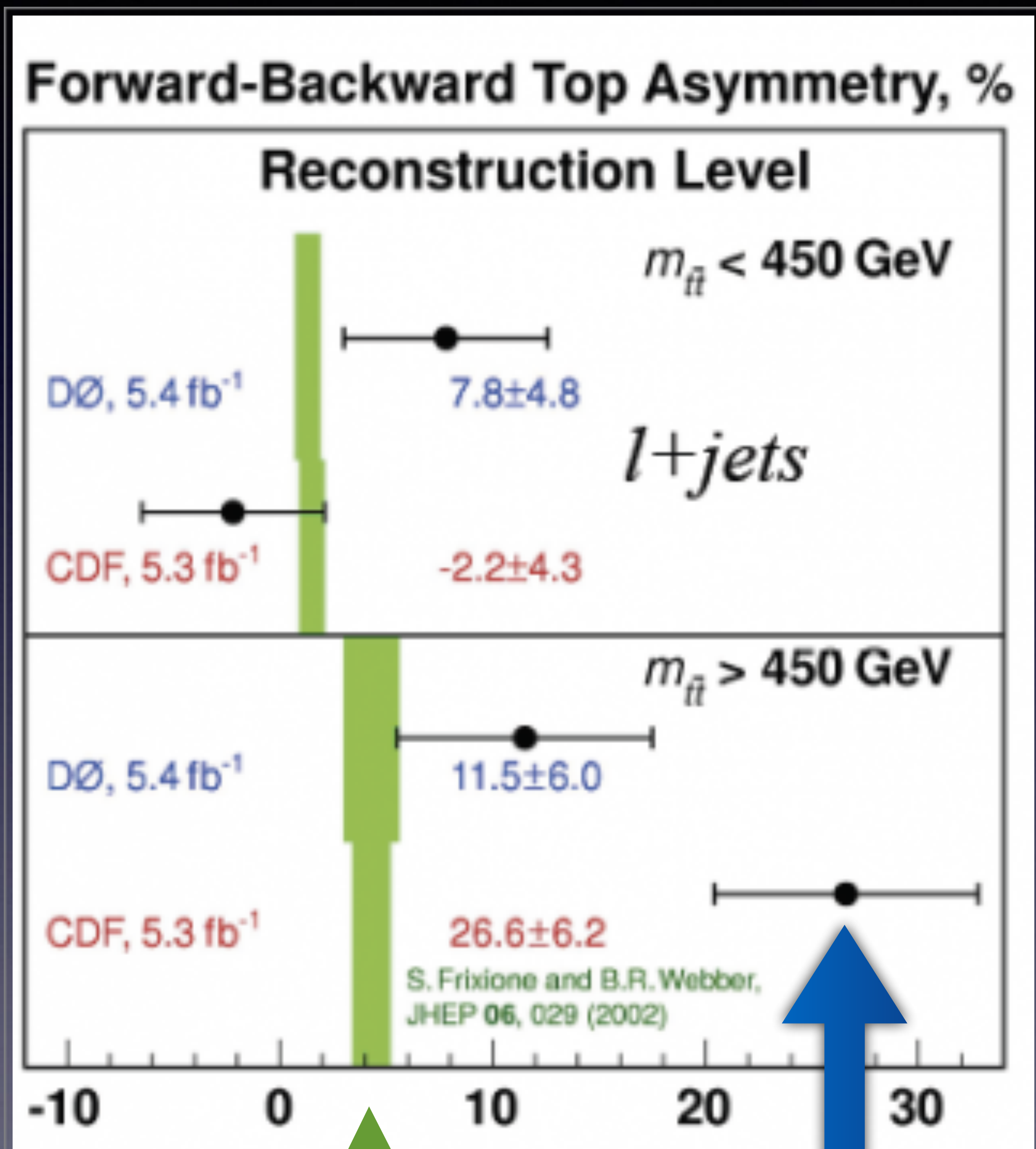




$$A^{p\bar{p}} = \frac{N_t(y>0) - N_{\bar{t}}(y>0)}{N_t(y>0) + N_{\bar{t}}(y>0)} = 0.051(6)$$

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

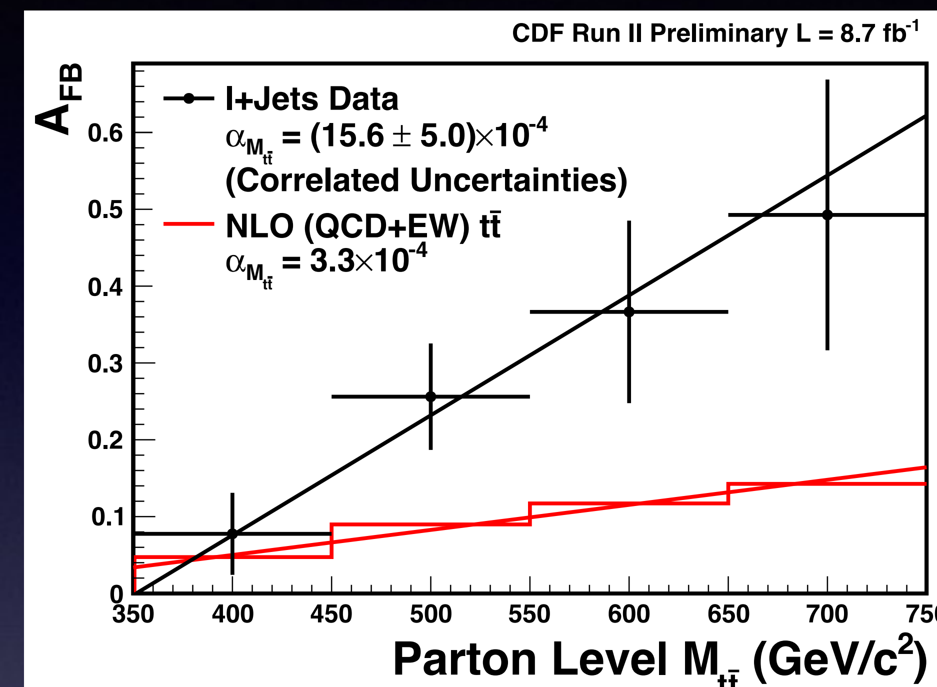
Top-quark A_{FB} at the Tevatron



SM

CDF: 1101.0034

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

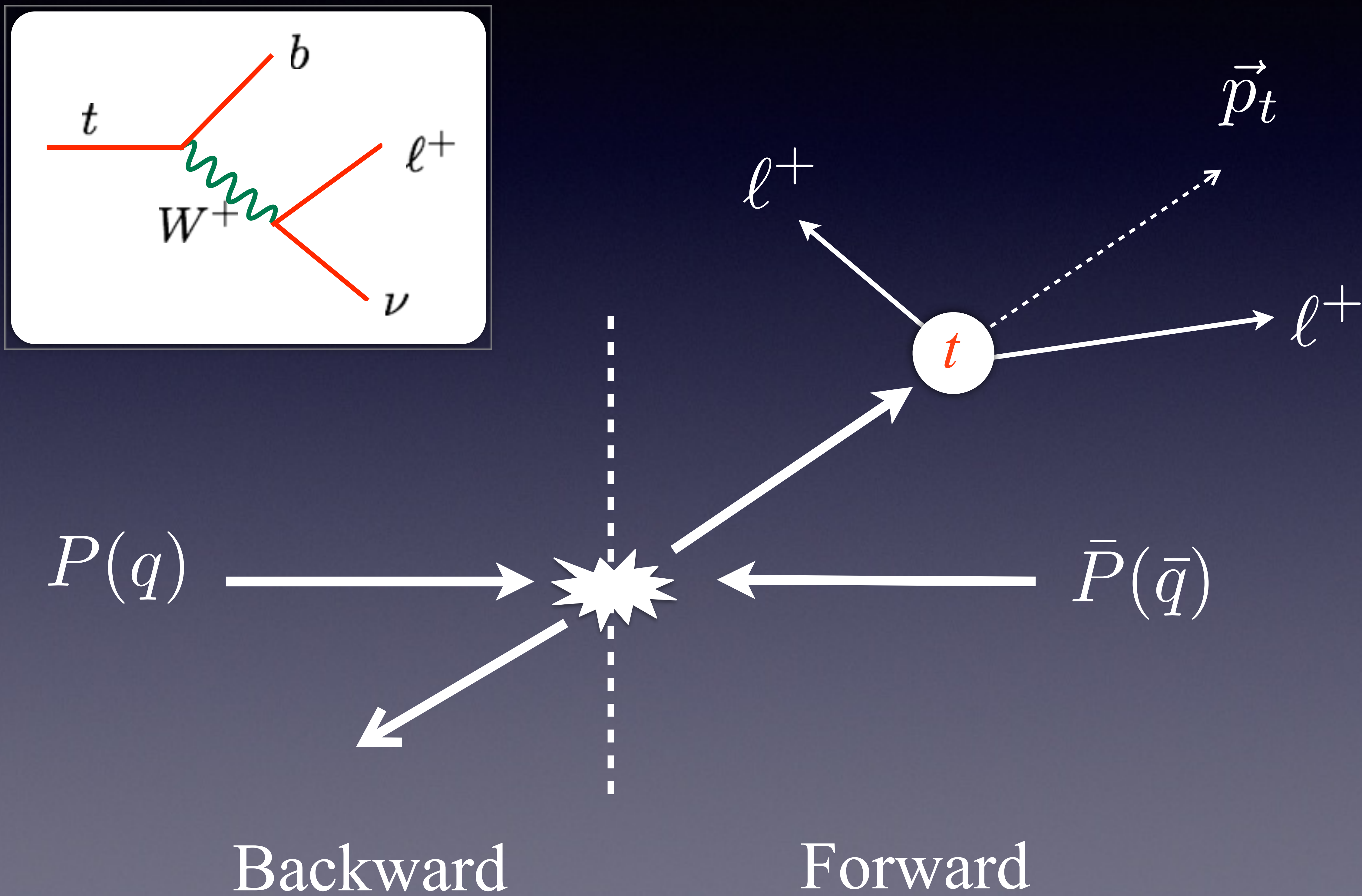


D0 new data agree well with SM prediction!
arXiv:1405.0421

$$A_{FB} = (10.6 \pm 3.0)\%$$

$$A_{FB}^{SM} = (5.0 \sim 8.0)\%$$

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



A_{FB}^t versus A_{FB}^ℓ

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

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

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

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

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

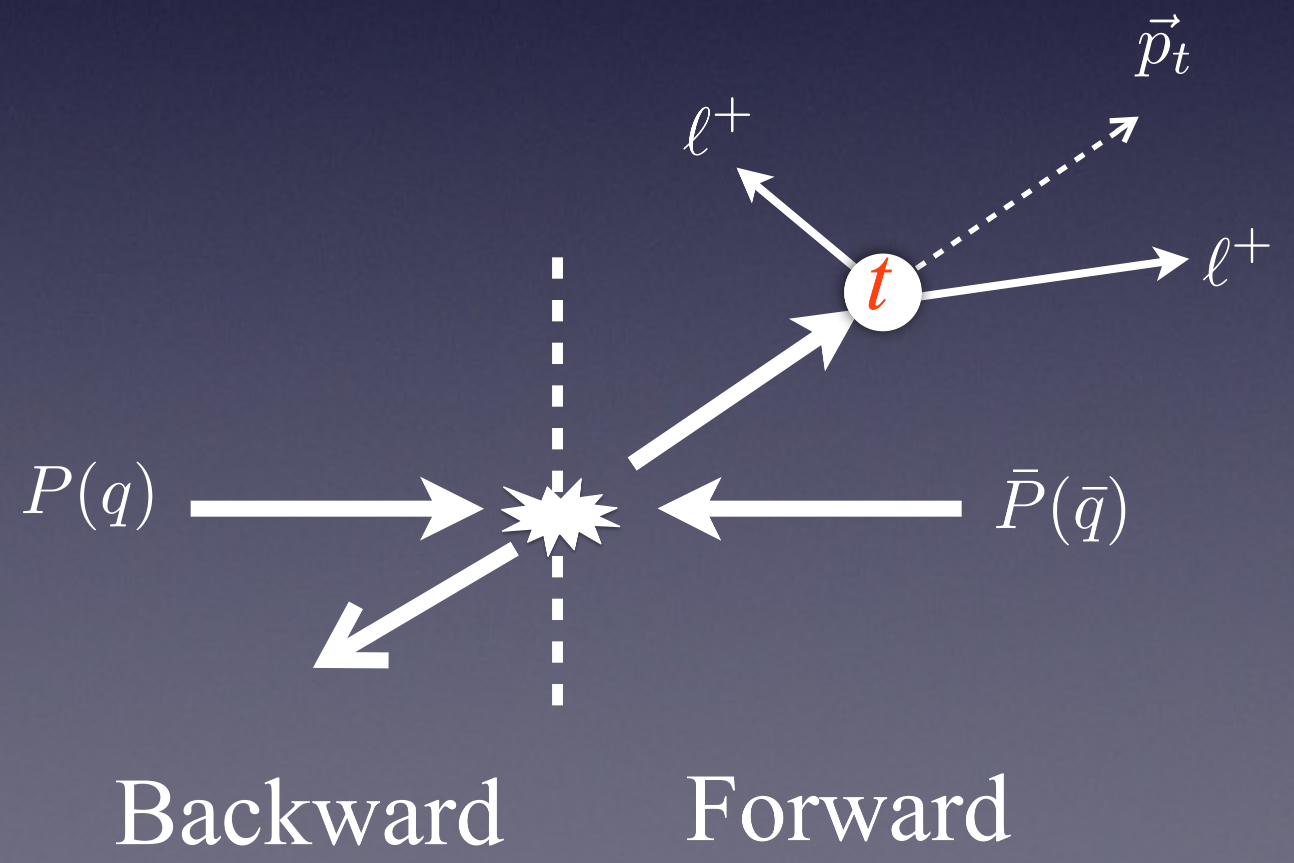
$$\left.\frac{A_{FB}^\ell}{A_{FB}^t}\right|_{\rm inc} \sim \frac{3}{4} \qquad \left.\frac{A_{FB}^\ell}{A_{FB}^t}\right|_{>450} \sim \frac{3}{5}$$

SM predictions at the NLO

$$A_{FB}^t = 0.051 \pm 0.001$$
$$A_{FB}^\ell = 0.021 \pm 0.001$$

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

Bernreuther and Si, NPB837 (2010) 90



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

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

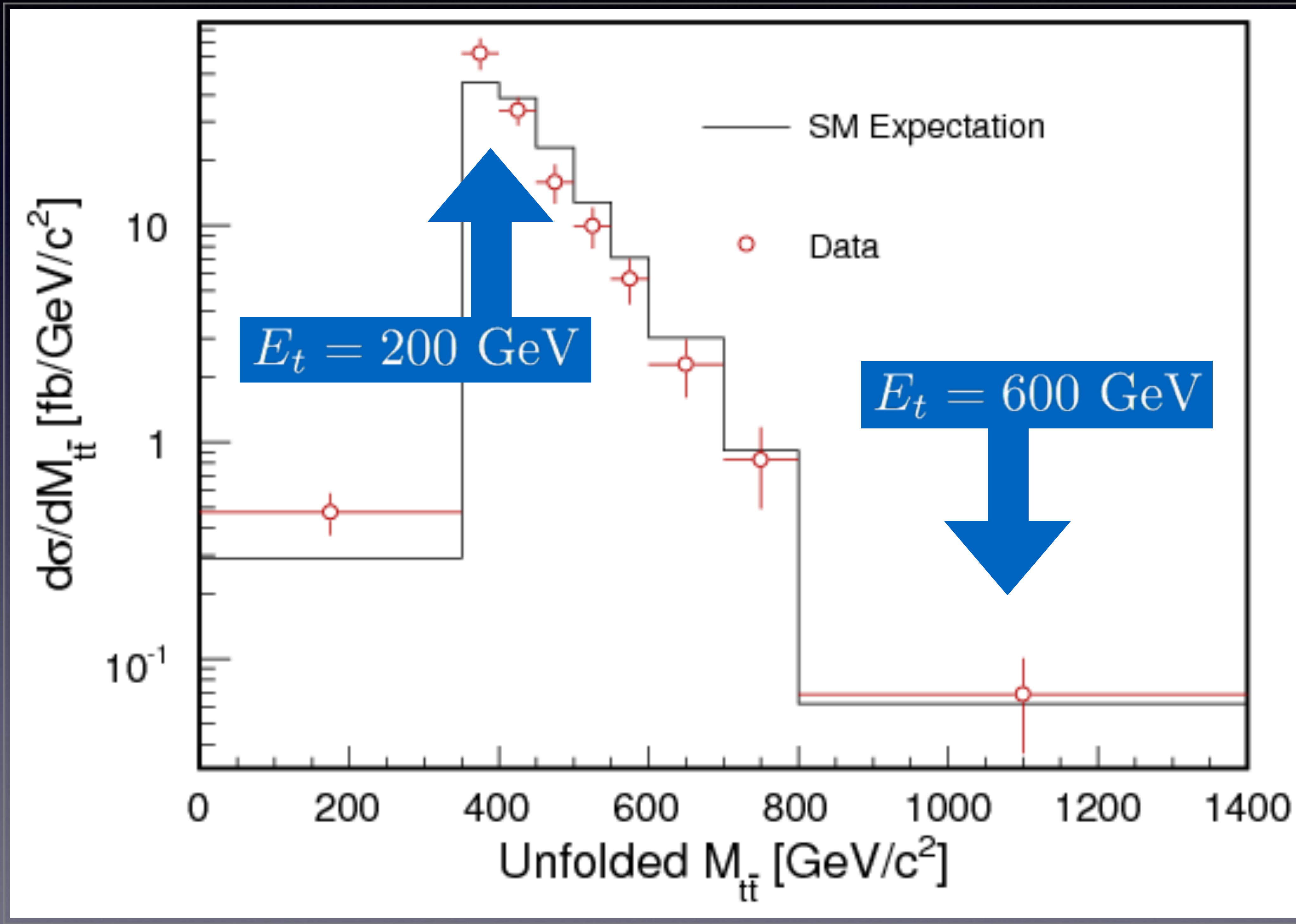
$$A^t_{FB} \approx \left[\rho_{t_L}\ A^{t_L}_{FB} + \rho_{t_R}\ A^{t_R}_{FB}\right]$$

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

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

Invariant mass spectrum of top quark pair

CDF collaboration, PRL 102 (2009) 222003

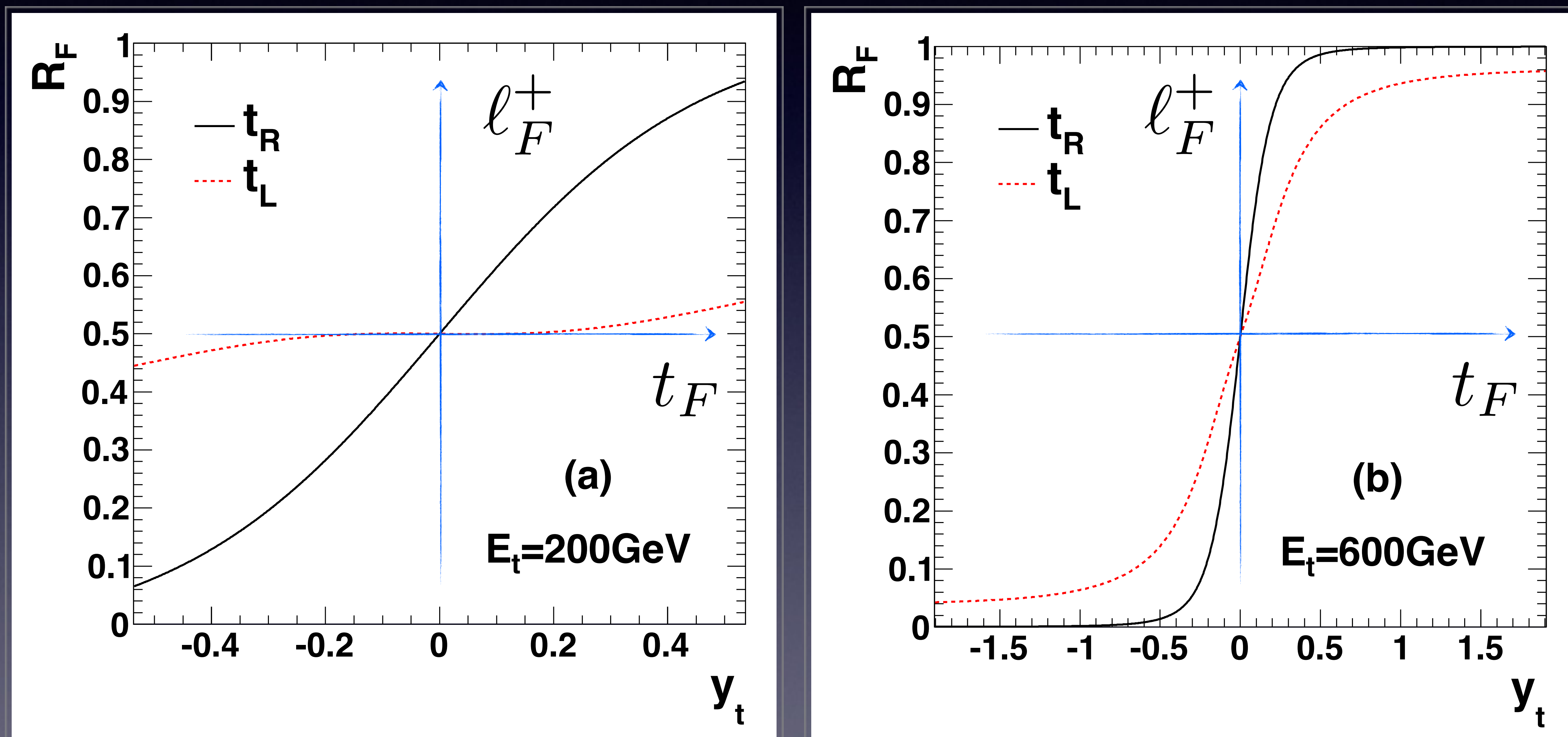


A^{ℓ}_{FB} dependence on top kinematics

Backward t Forward t

F(l)

B(l)



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

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

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

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

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

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

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

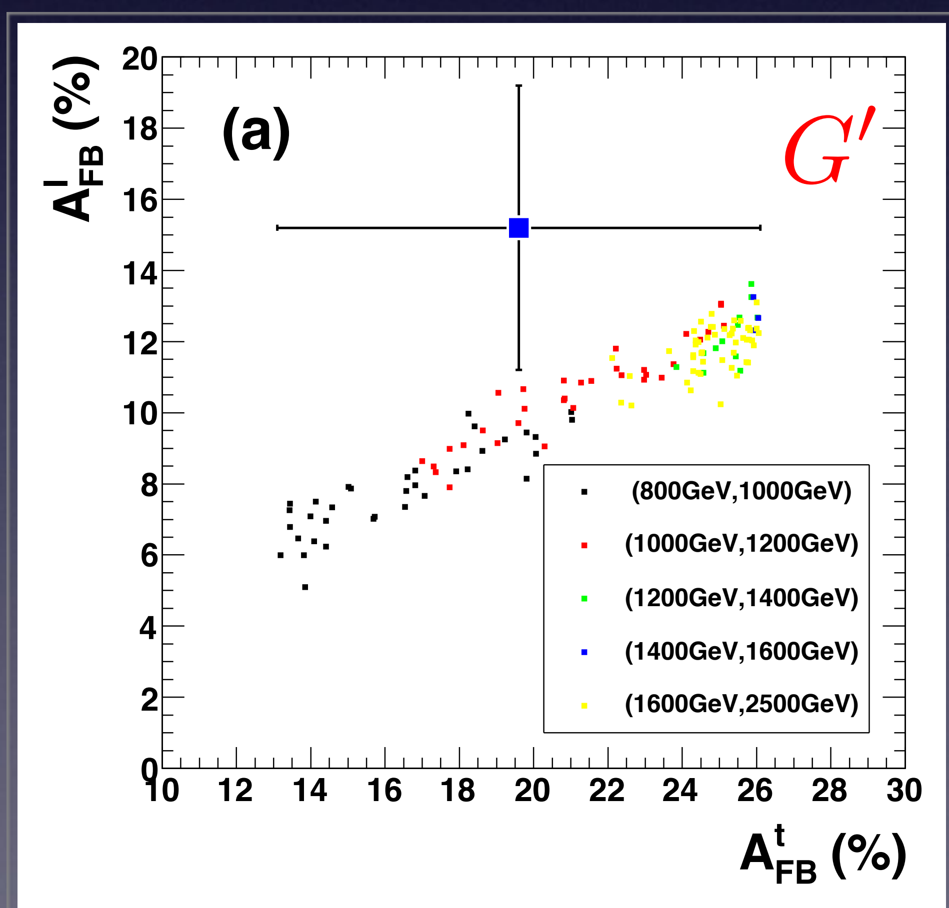
$$\rightarrow \left.\frac{A_{FB}^{\ell}}{A_{FB}^{t}}\right|_{\text{SM}} \sim \frac{1}{2} \checkmark$$

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

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

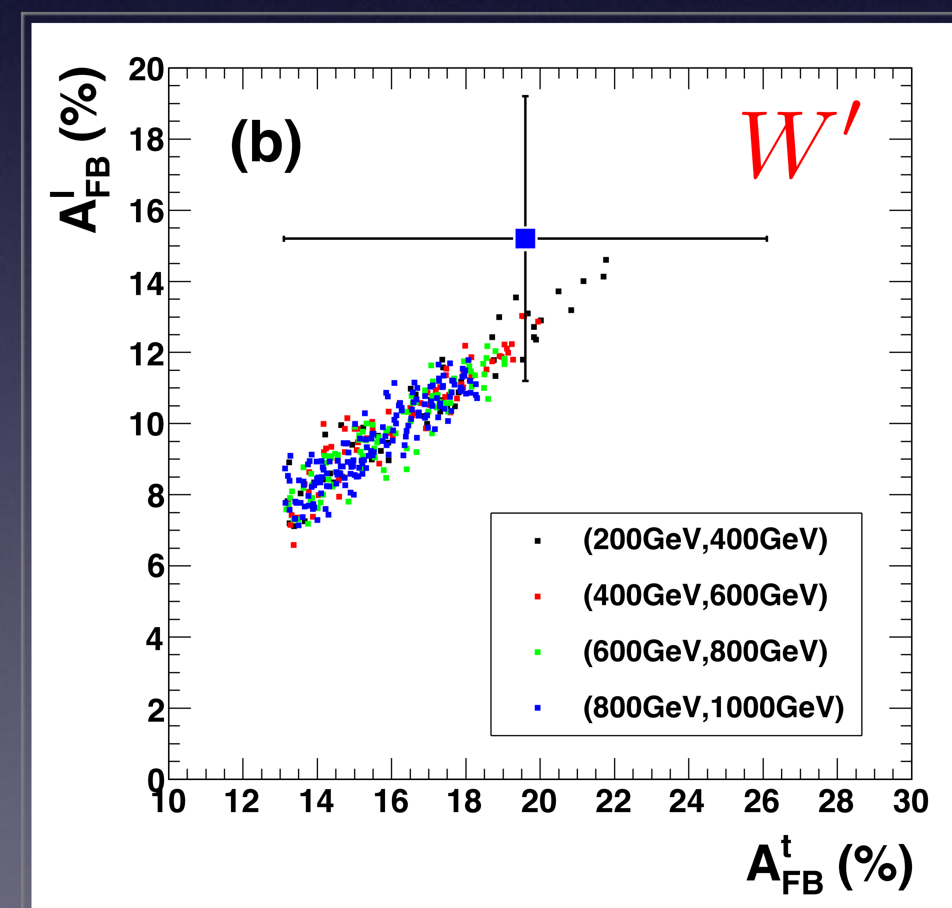
Berger, QHC, Chen, Yu, Zhang, PRL 108 (2012) 072002

Unpolarized top-quark



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

Right-handed top-quark



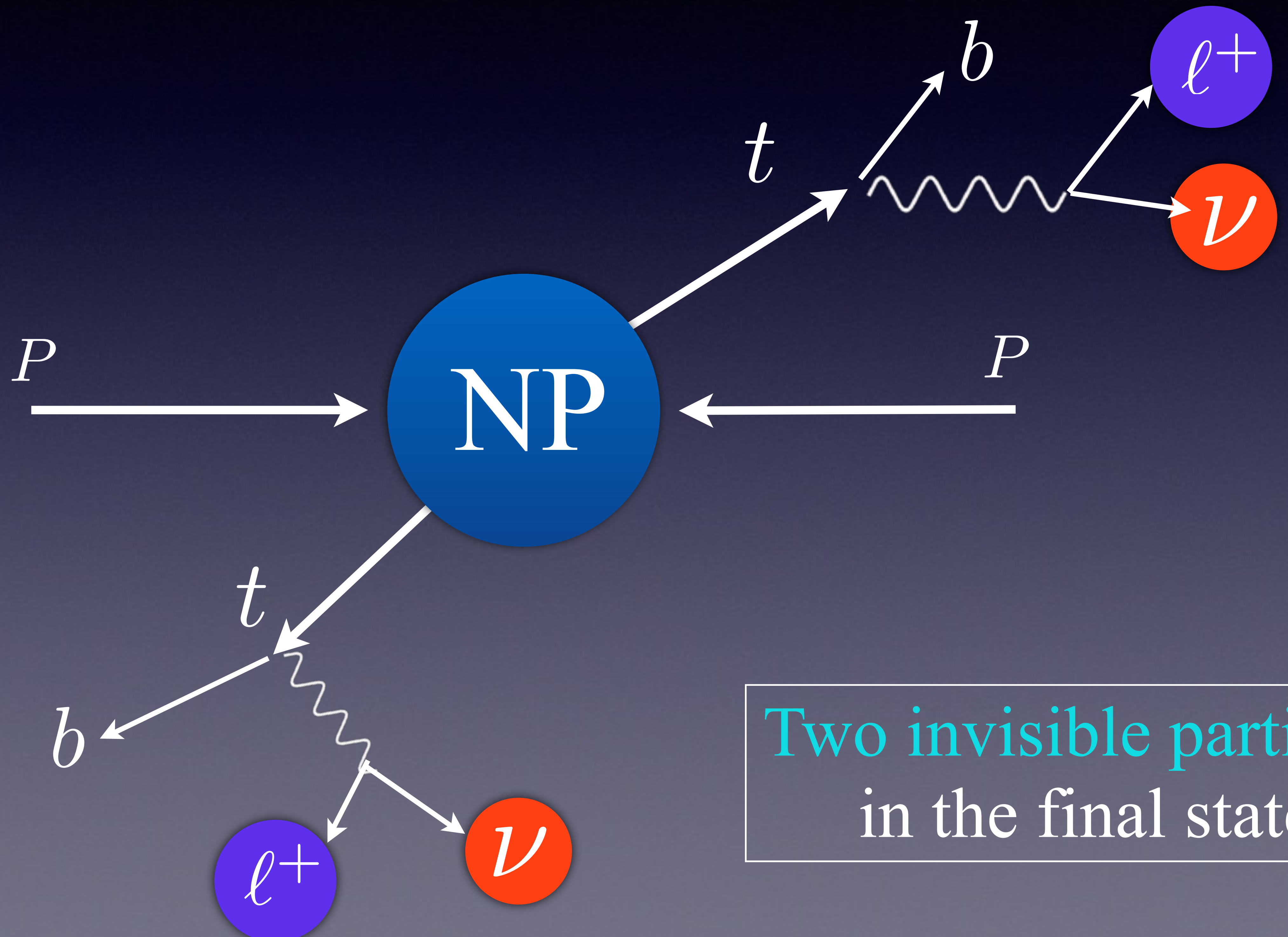
$$A^\ell_{FB} \simeq 0.75 \times A^t_{FB} - 2.1\%$$

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

Top quark production in NP

(2) Same-Sign top-quark pair production

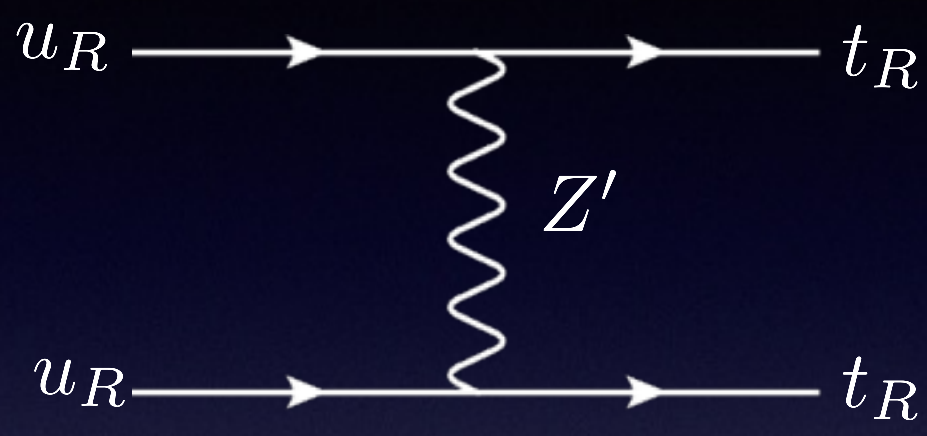
(or top-antitop pair production in dileptonic decay)



Two invisible particles
in the final state

Top quark is often polarised in NP

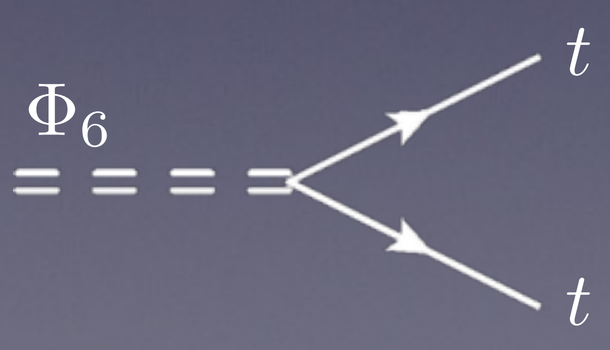
- Flavor changing gauge boson

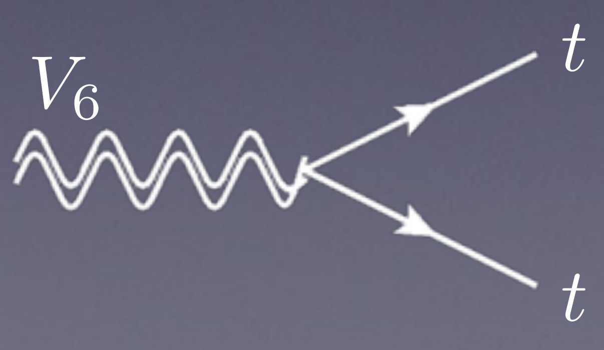


Jung, Murayama, Pierce, Wells,
PRD81 (2010) 015004

- Exotic colored particles (diquark scalar/vector)

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





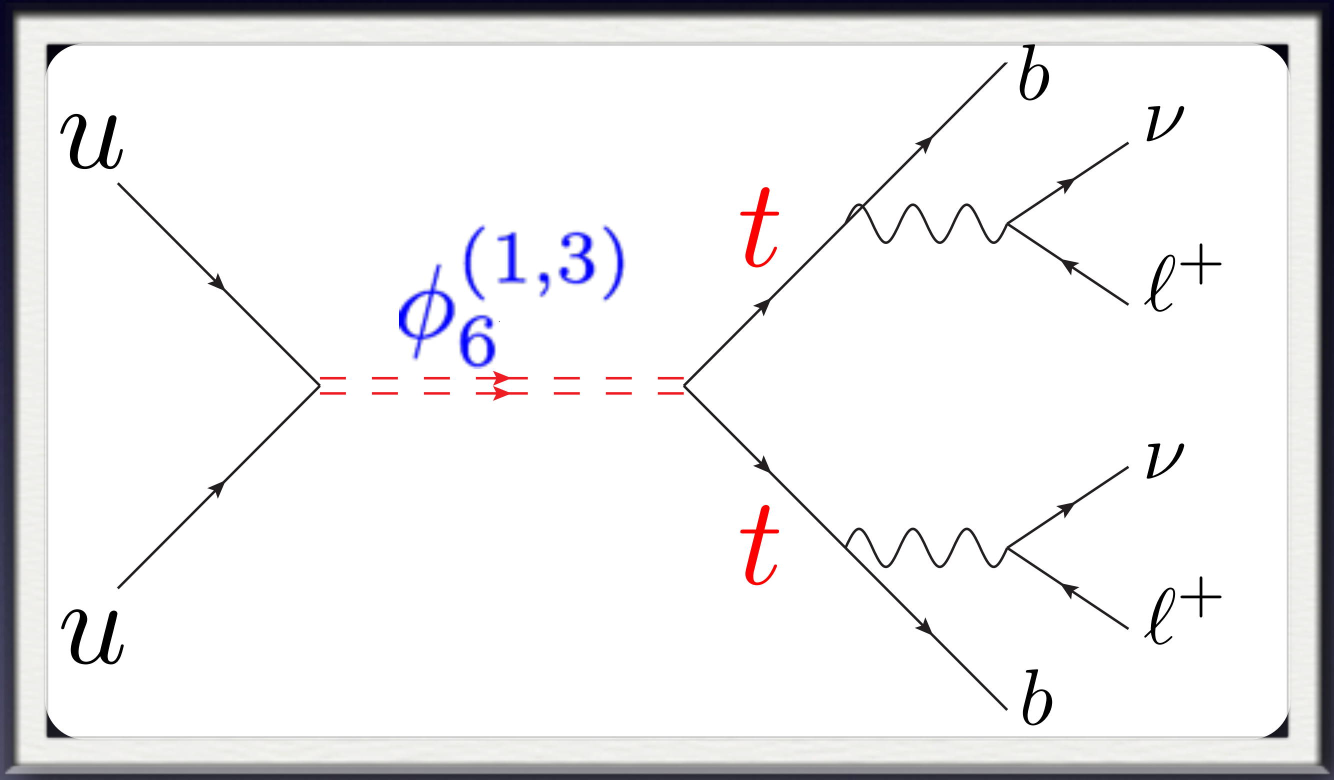
Cakir and Sahin,
PRD72 (2005) 115011

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



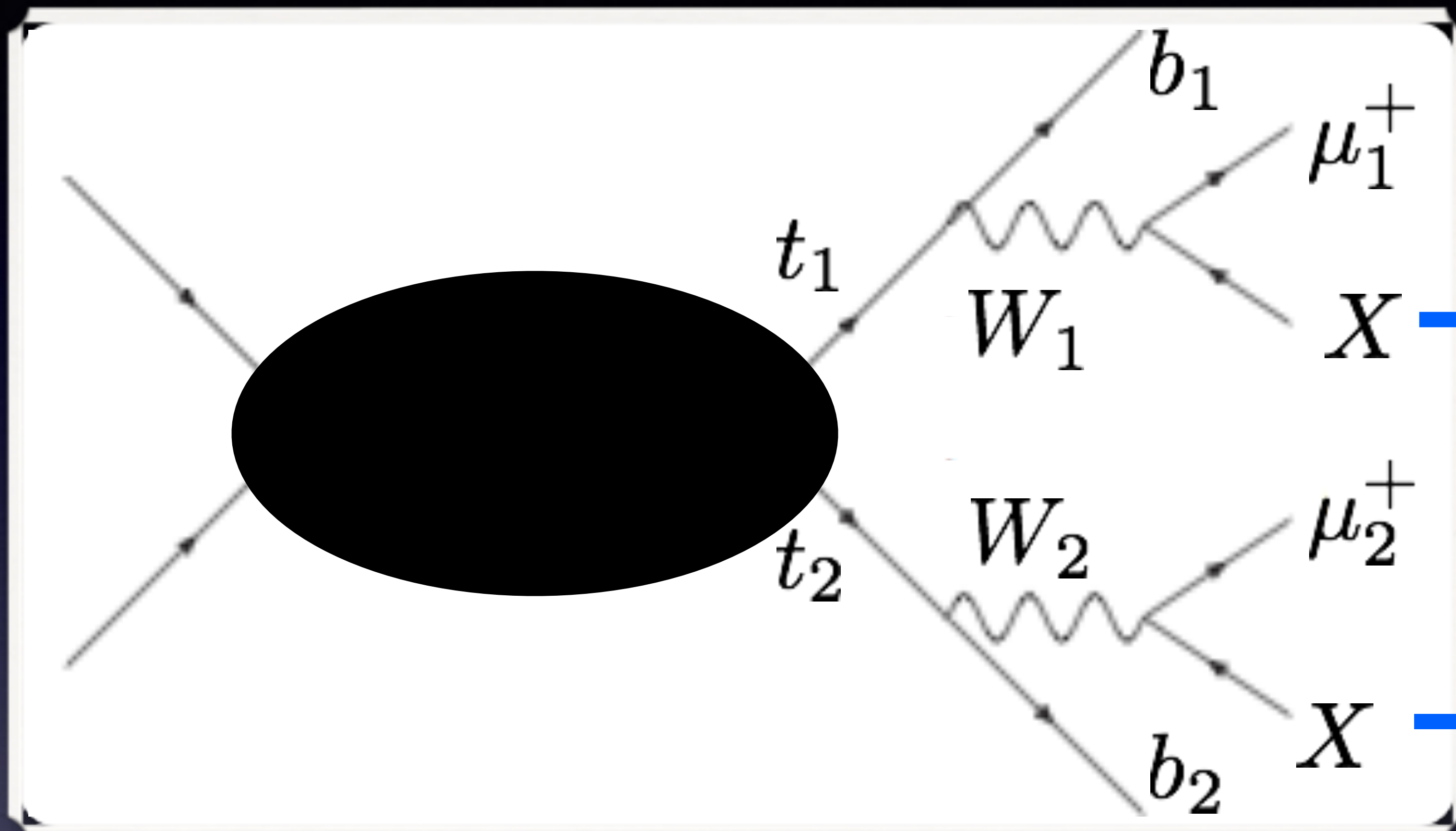
$$2\nu$$

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

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)

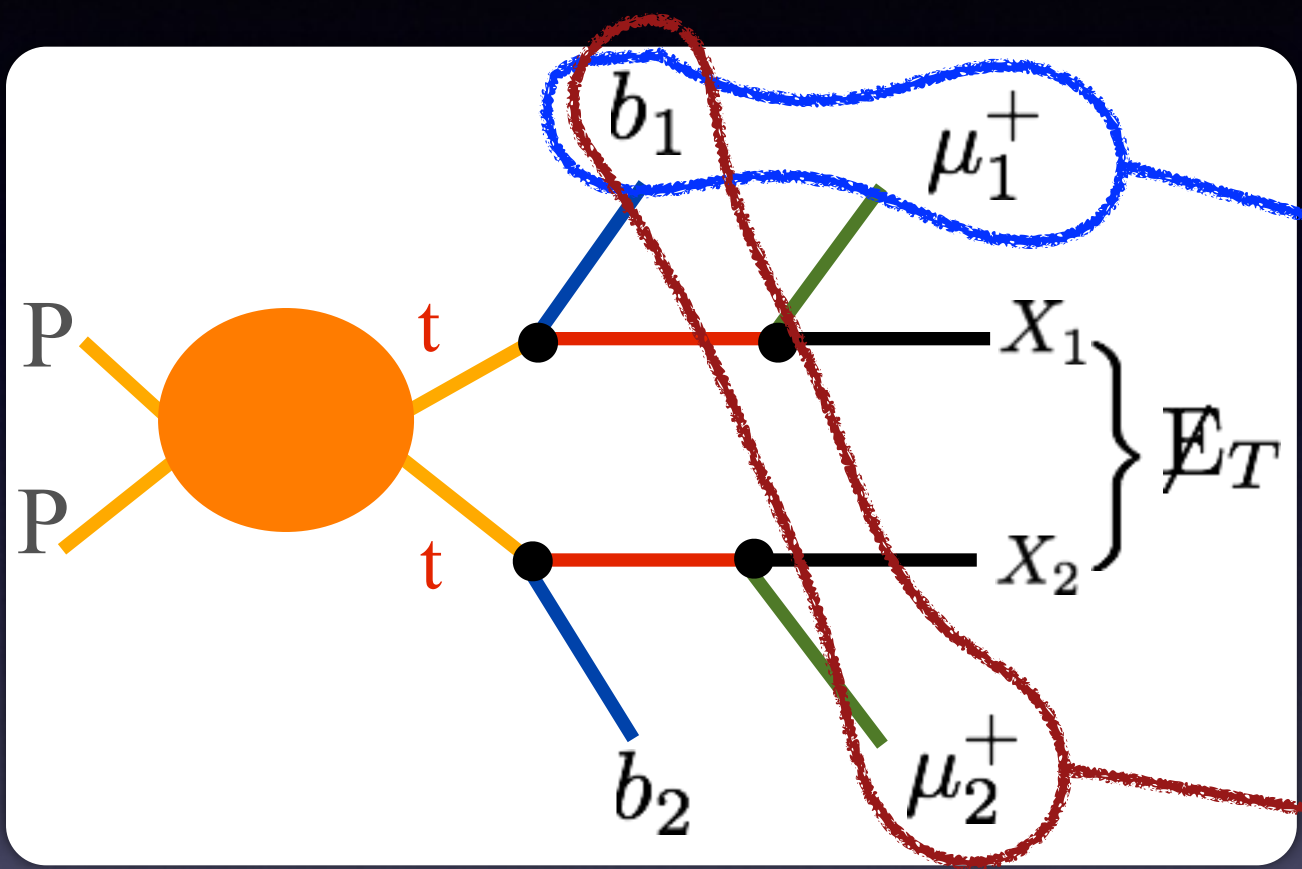
$$p_x^4(\nu_1) + a\ p_x^3(\nu_1) + b\ p_x^2(\nu_1) + c\ p_x(\nu_1) + d = 0$$

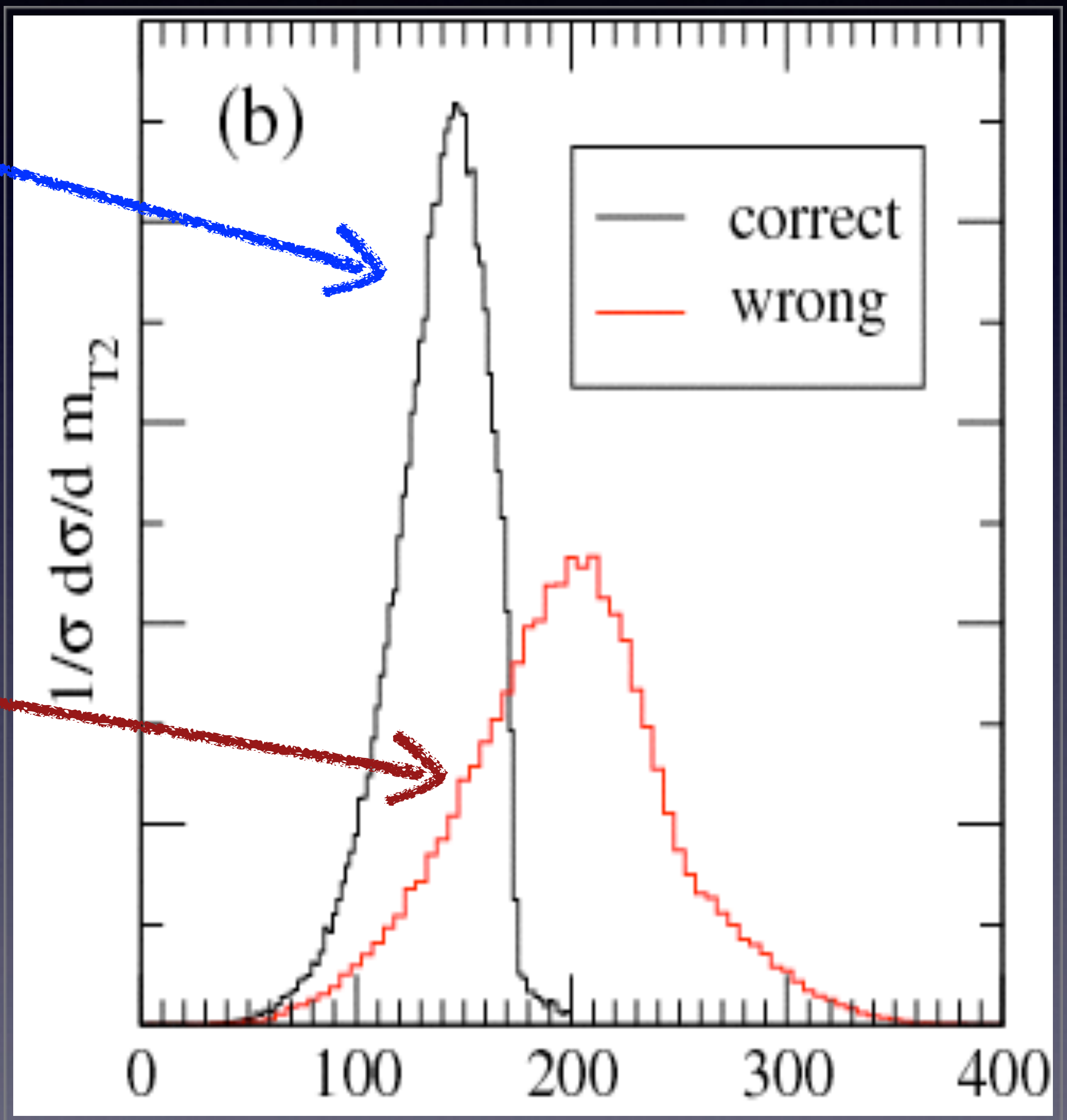
~~Two complex~~, two real solutions

Sonnenschein, PRD73 (2006) 054015

ℓ^+- b pairing: MT2-assisted method

MT2 variable of lepton-b clusters and MET





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

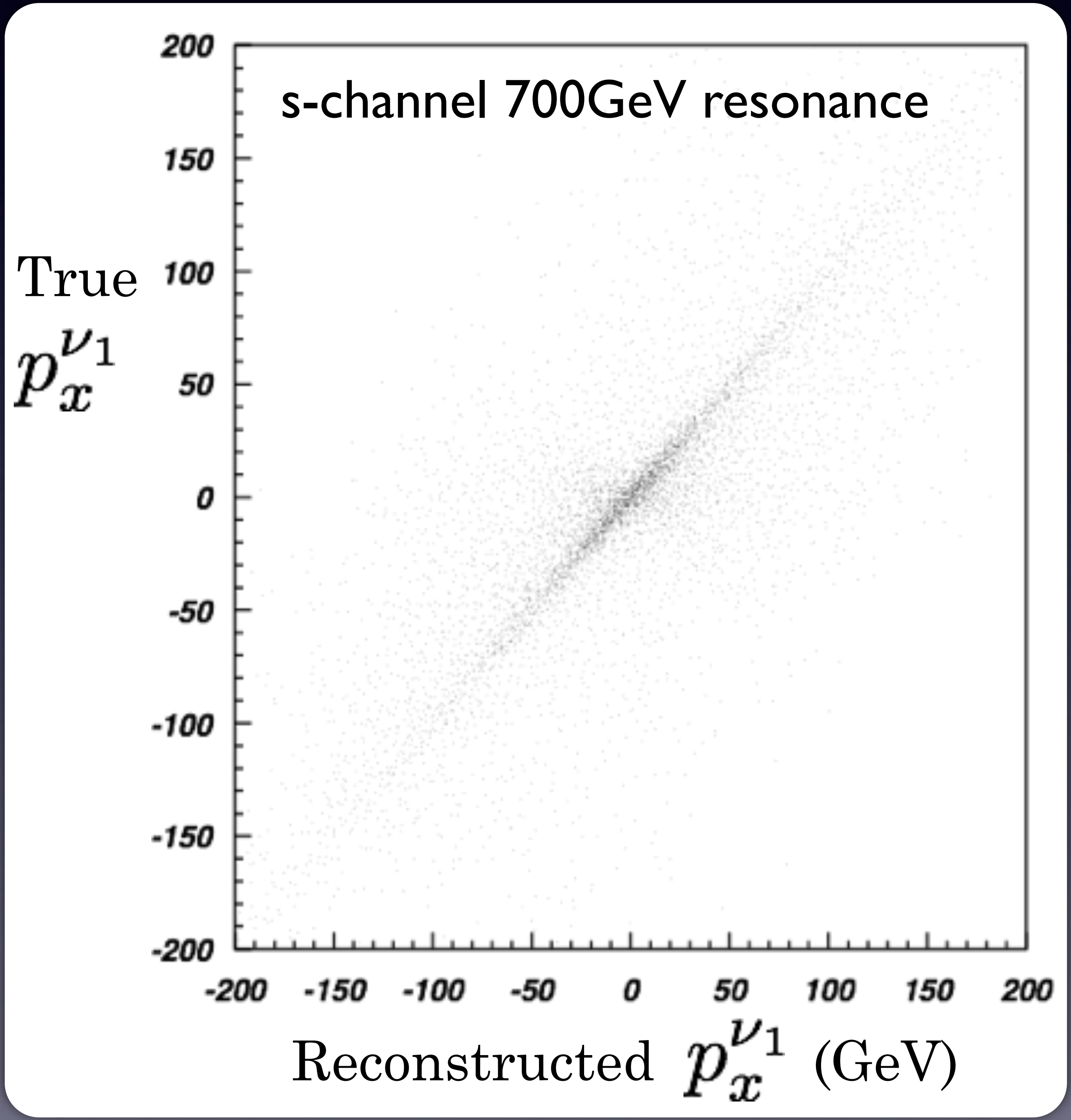
Two combinations of lepton-b clusters

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

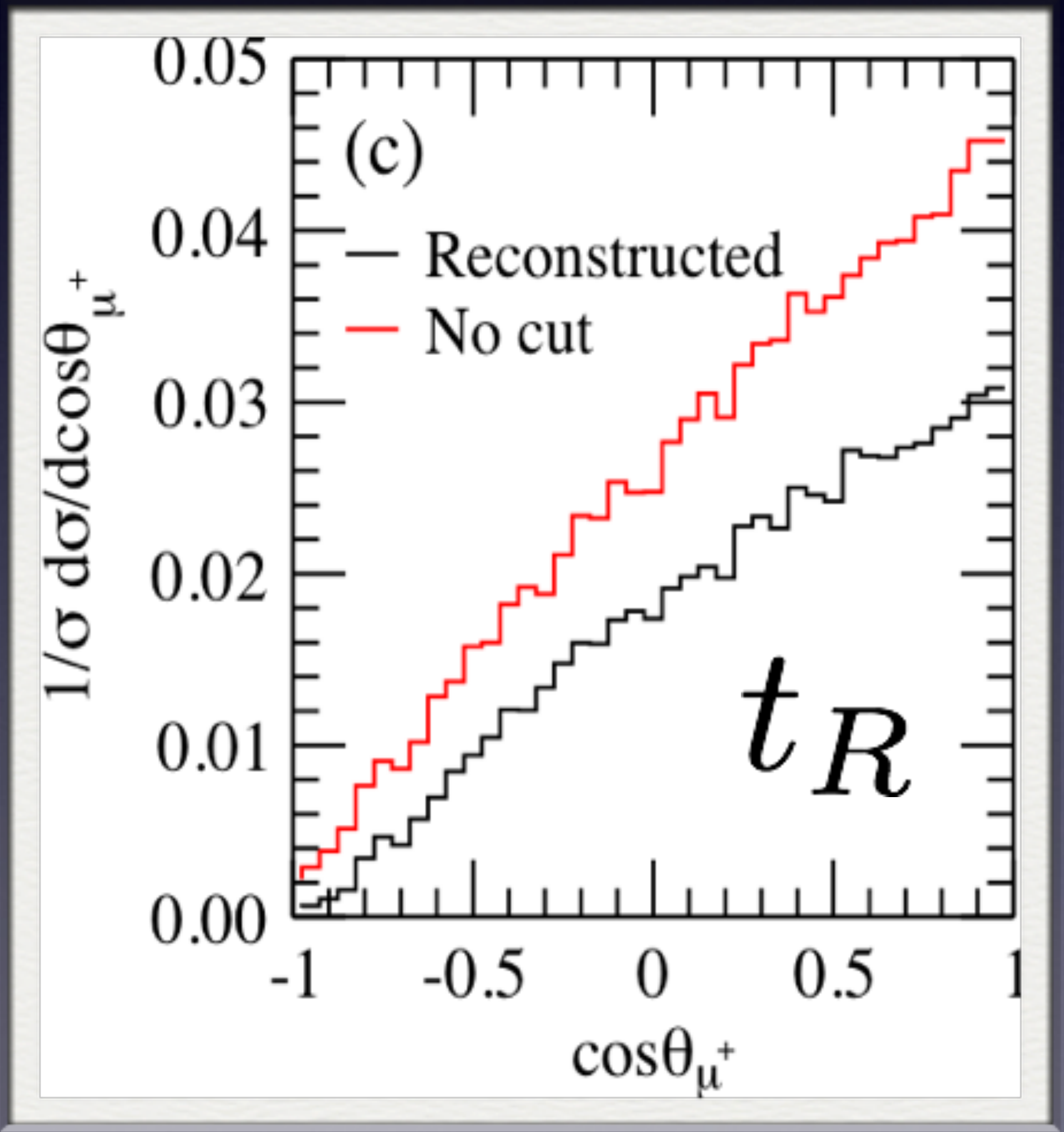
MT2 - Lester and Summers, PLB 463 (1999) 99

Neutrino momentum reconstruction

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

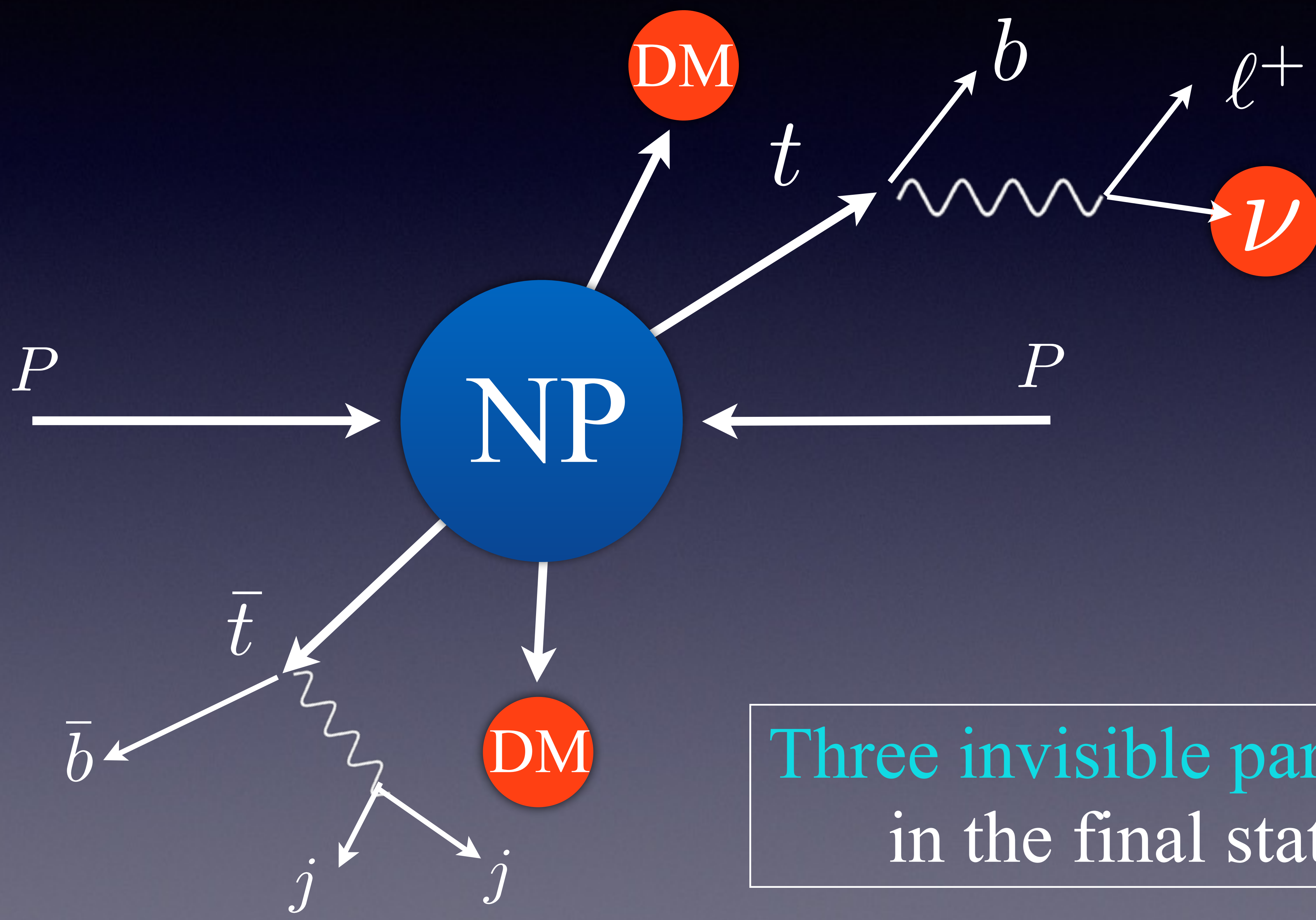


- Top quark polarisation can be measured after neutrino reconstruction.



Top quark production in NP

(3) Top-quark pair + dark matter candidates

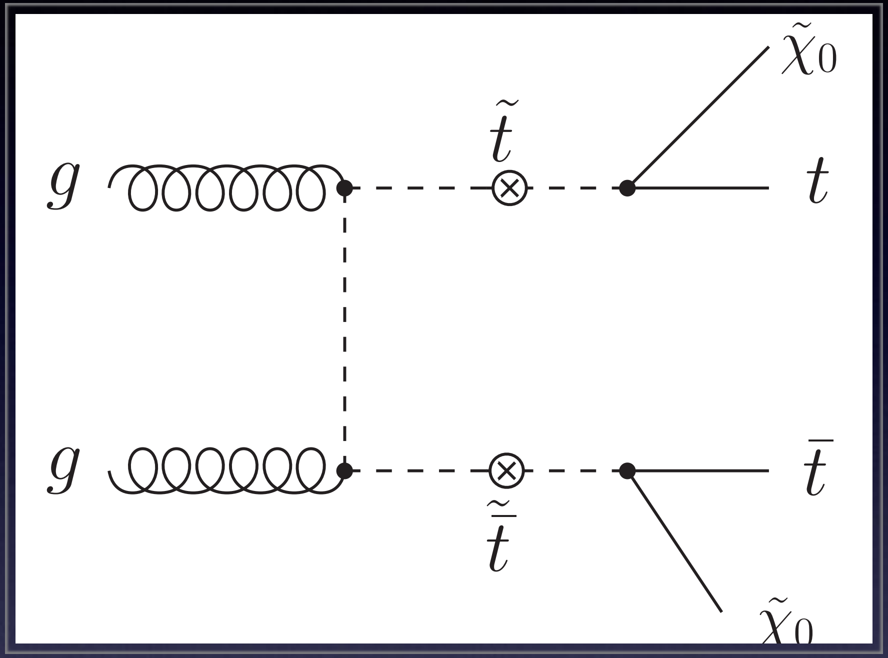


Three invisible particles
in the final state

Top-quark pair plus missing energy

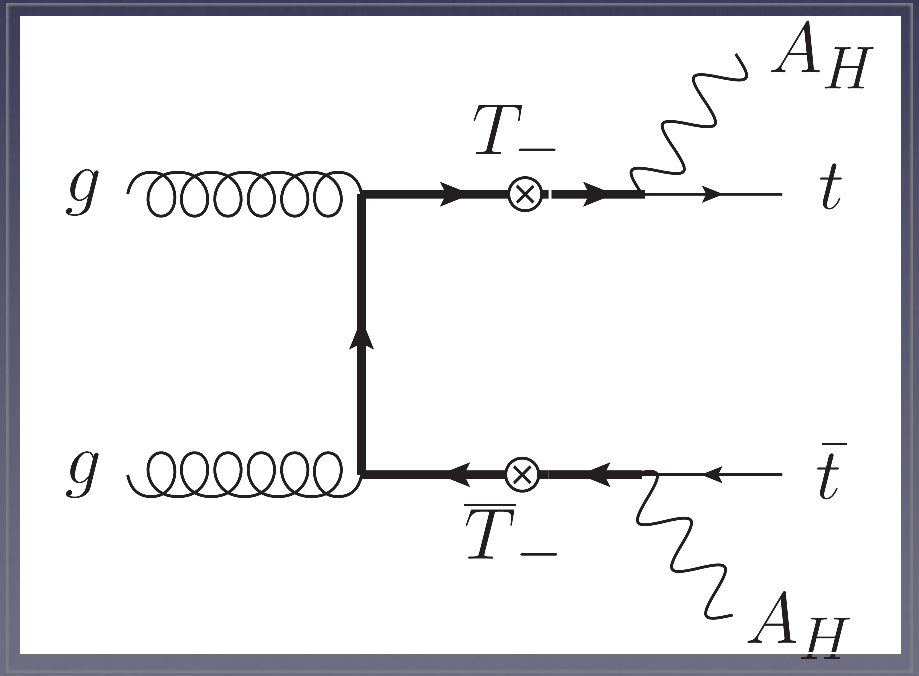
Typical collider signature in several NP models

- Minimal Supersymmetric extension of the Standard Model (MSSM)



spin 0

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



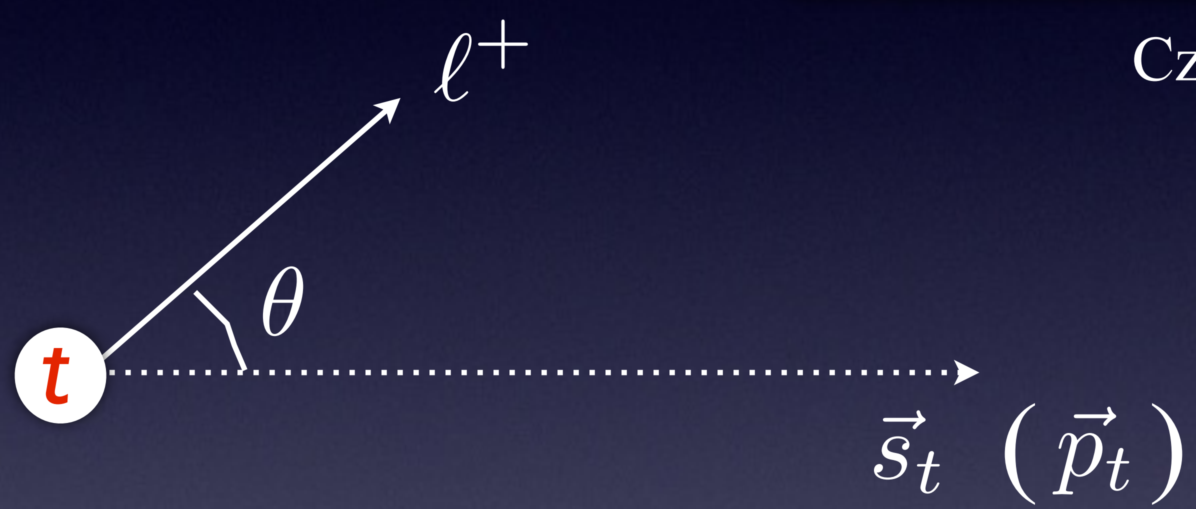
spin 1/2

Charged lepton distribution

- In the rest frame of the top-quark

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

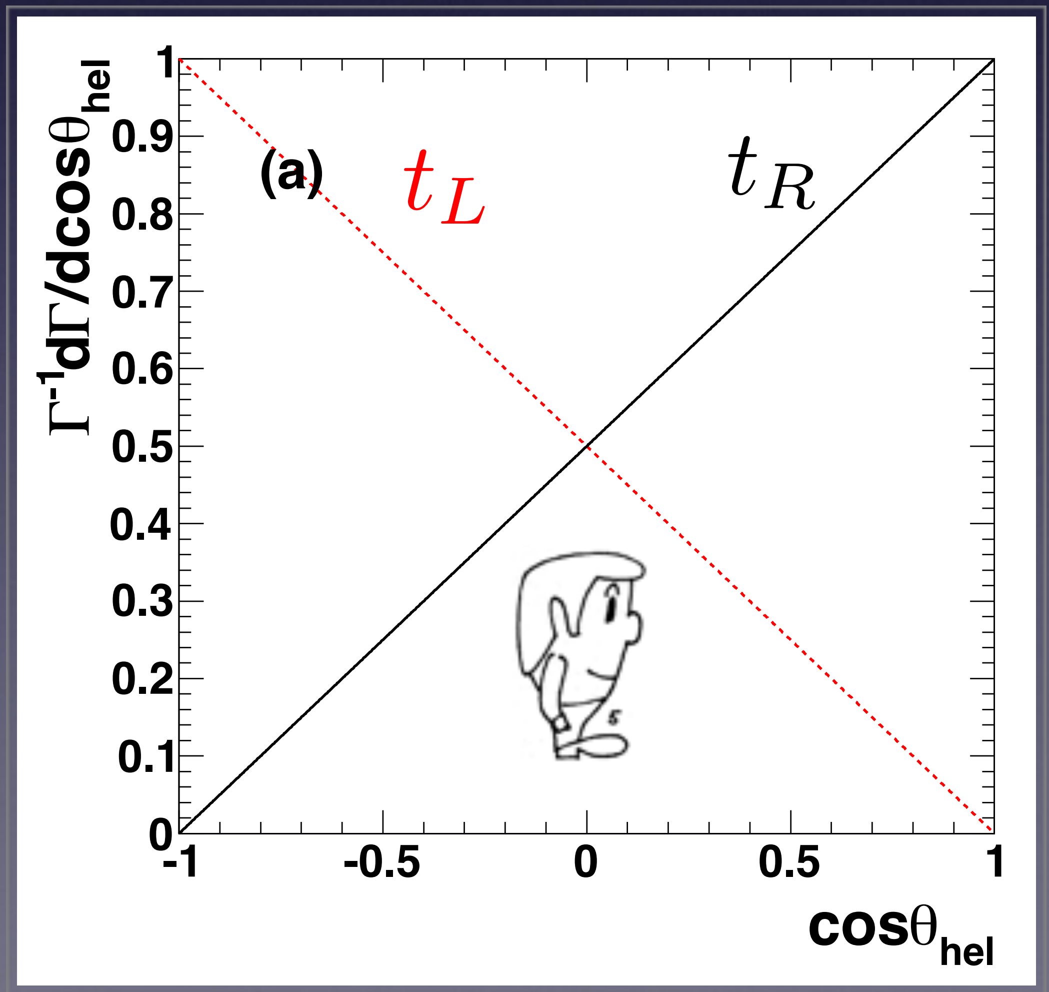
Czarnecki, Jezabek, Kuhn, NPB351 (1991) 70



$\lambda_t = +$ 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

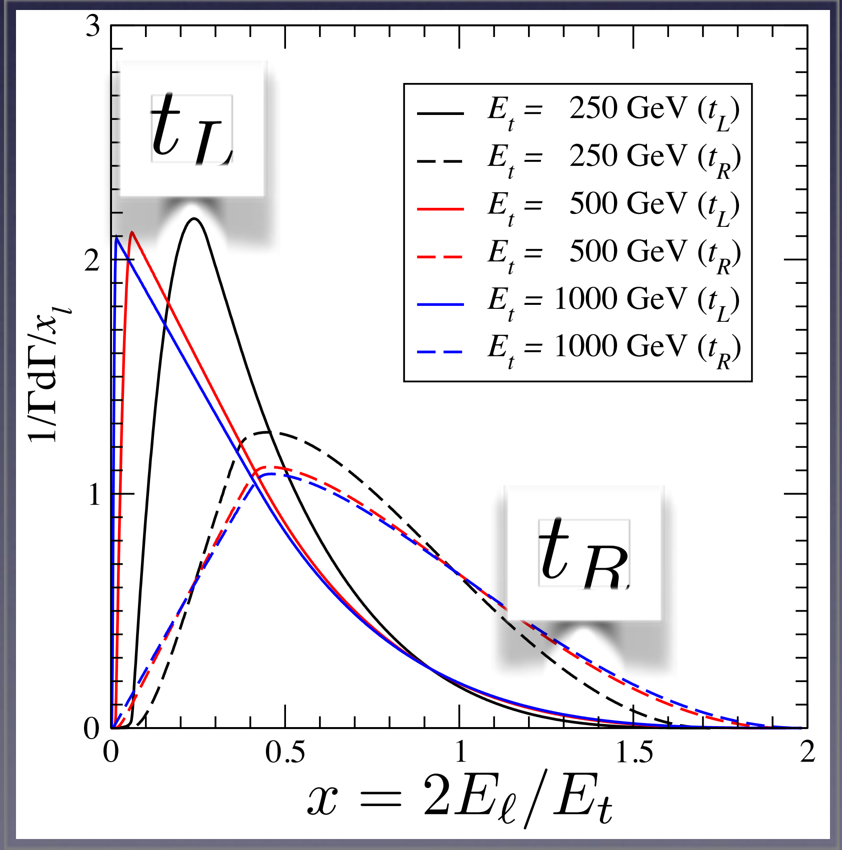
$$\frac{d\Gamma(\hat{s}_t)}{dx} = \frac{\alpha_W^2 m_t}{64\pi AB} \int_{z_{\min}}^{z_{\max}} x\gamma^2[1 - x\gamma^2(1 - z\beta)] \times \left(1 + \hat{s}_t \frac{z-\beta}{1 - z\beta}\right) \mathrm{Arctan}\left[\frac{Ax\gamma^2(1 - z\beta)}{B - x\gamma^2(1 - z\beta)}\right] dz$$

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

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

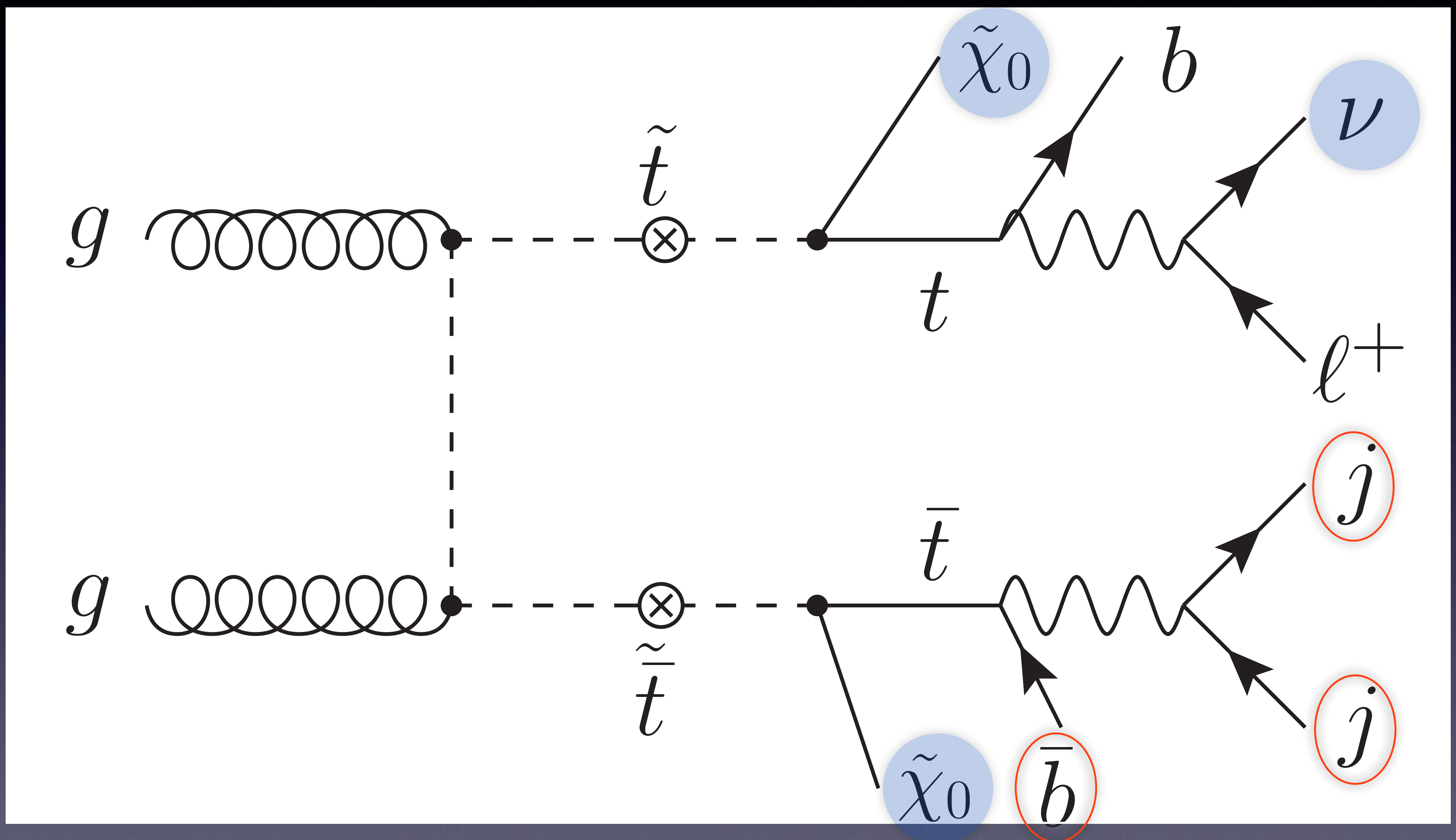
$$z_{\min} = \max[(1 - 1/\gamma^2 x)/\beta, -1]$$

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



Lepton energy and top-quark polarization

Identical decay chains



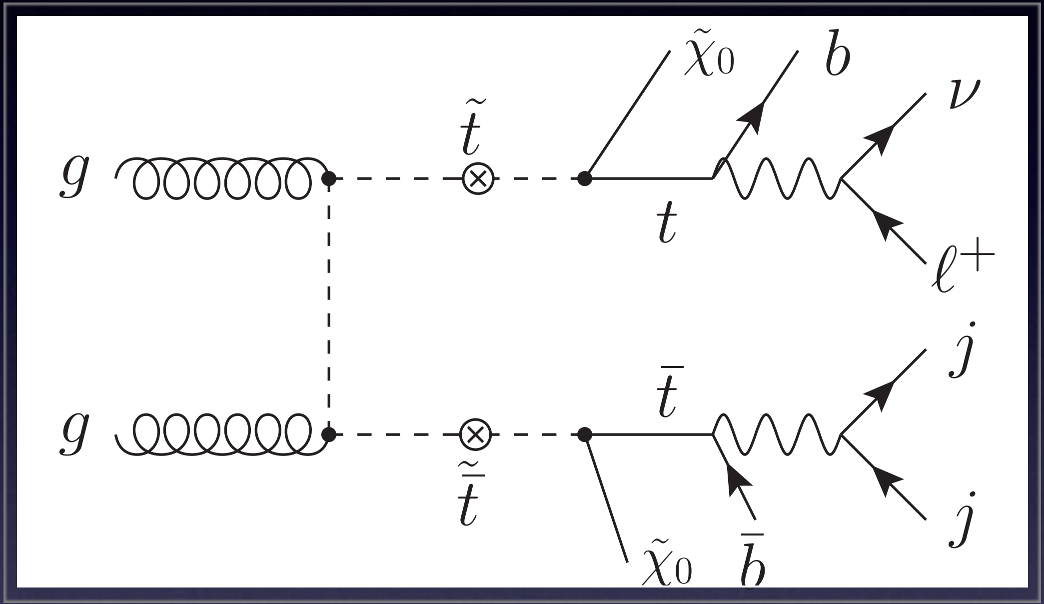
$x_\ell = 2E_{\ell^+}/E_t$ ⇒ $x'_\ell = 2E_{\ell^+}/E_{\bar{t}}$

$E_{\bar{t}} = E_{\bar{b}} + E_{j_1} + E_{j_2}$

Toy model mimicking MSSM

- MSSM like:

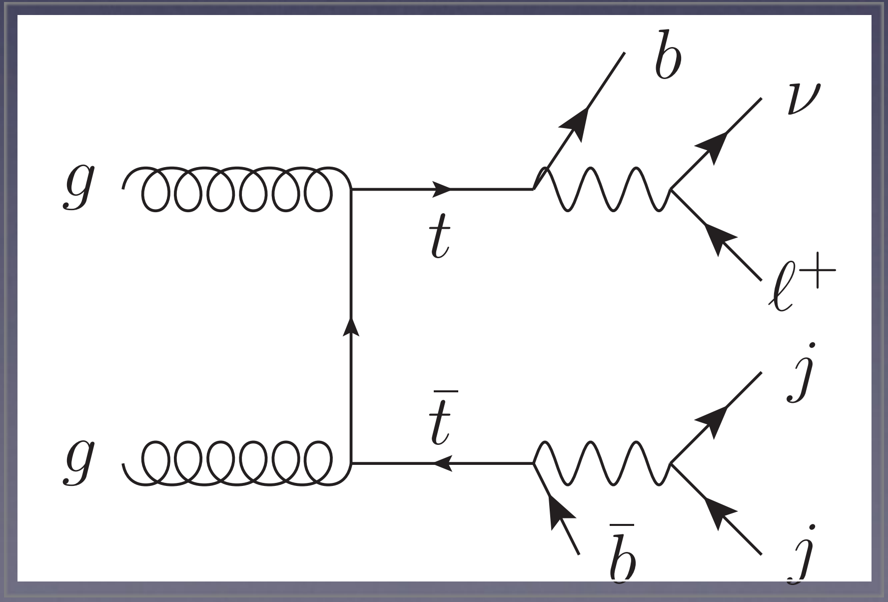
$$\mathcal{L}_{\tilde{t}t\tilde{\chi}} = g_{\text{eff}}\tilde{t}\tilde{\chi}(\cos\theta_{\text{eff}} P_L + \sin\theta_{\text{eff}} P_R)t$$

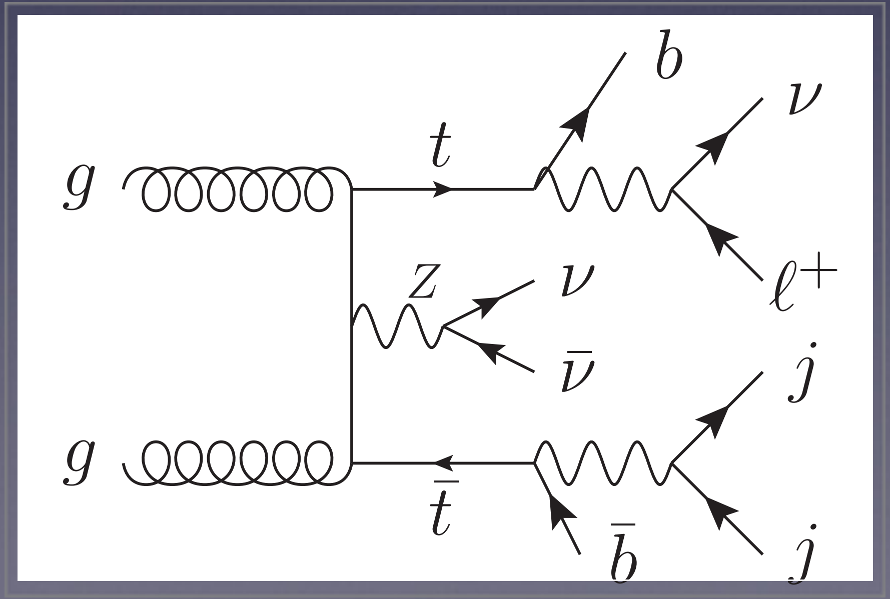


Collider signature

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

- Major SM backgrounds

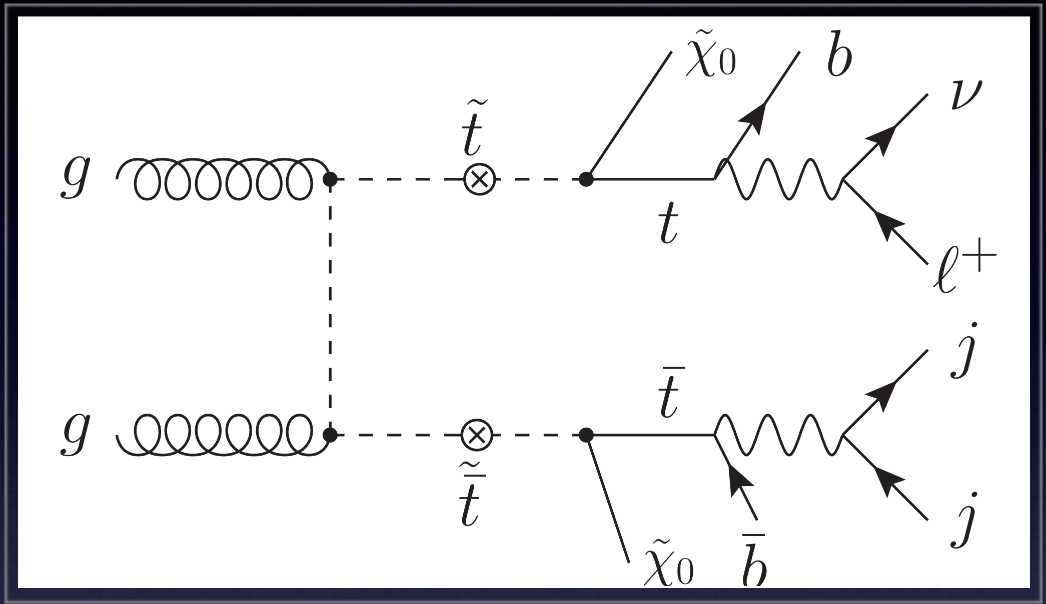




Collider simulation

- Basic selection cuts

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



$p_T^\ell > 20$ GeV $\quad p_T^j > 25$ GeV

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

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

- Hard cuts

$\not{E}_T > 100$ GeV $\quad H_T > 500$ 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 %

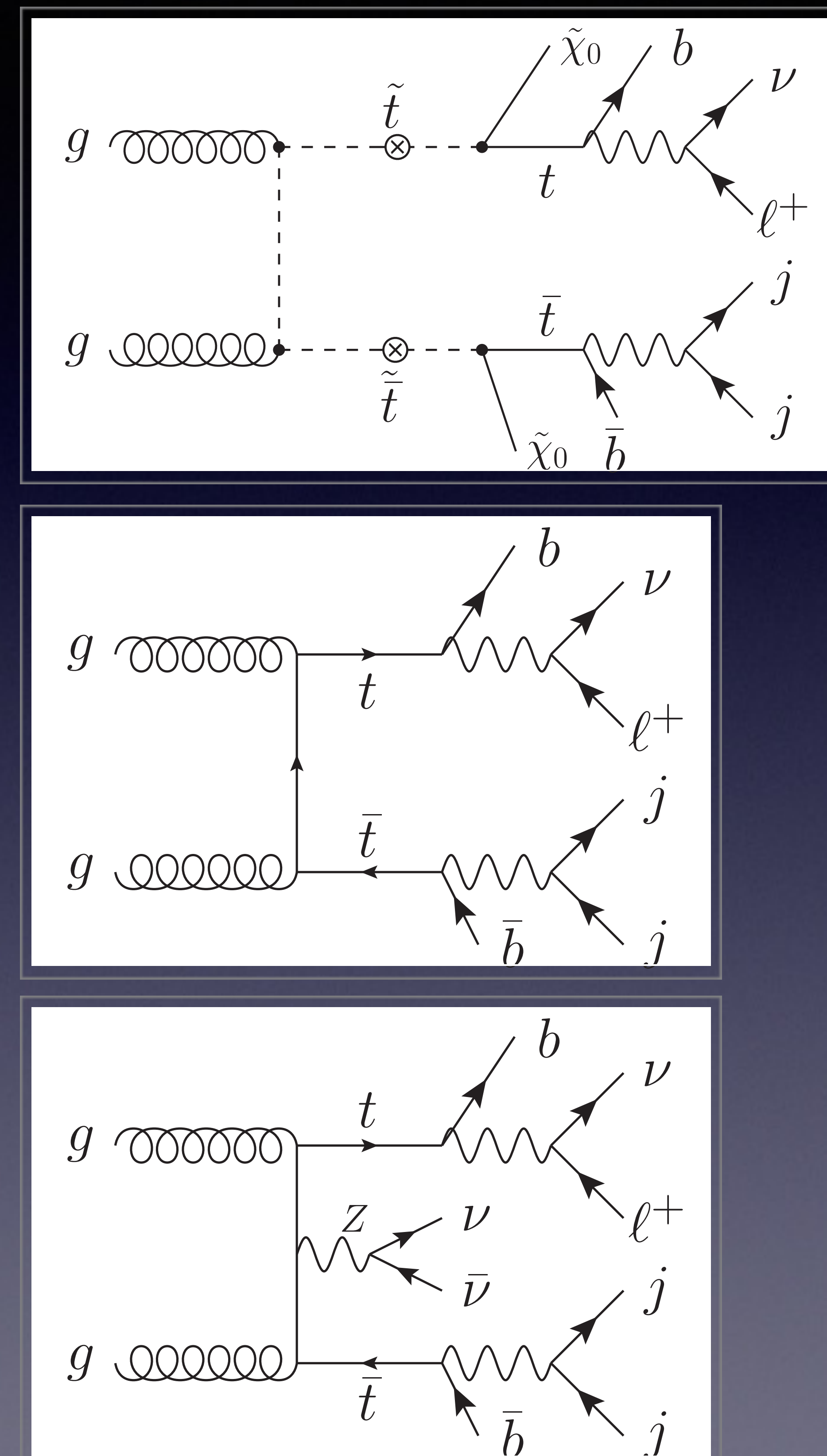
- $\not{E}_T$ solution cut

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

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

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

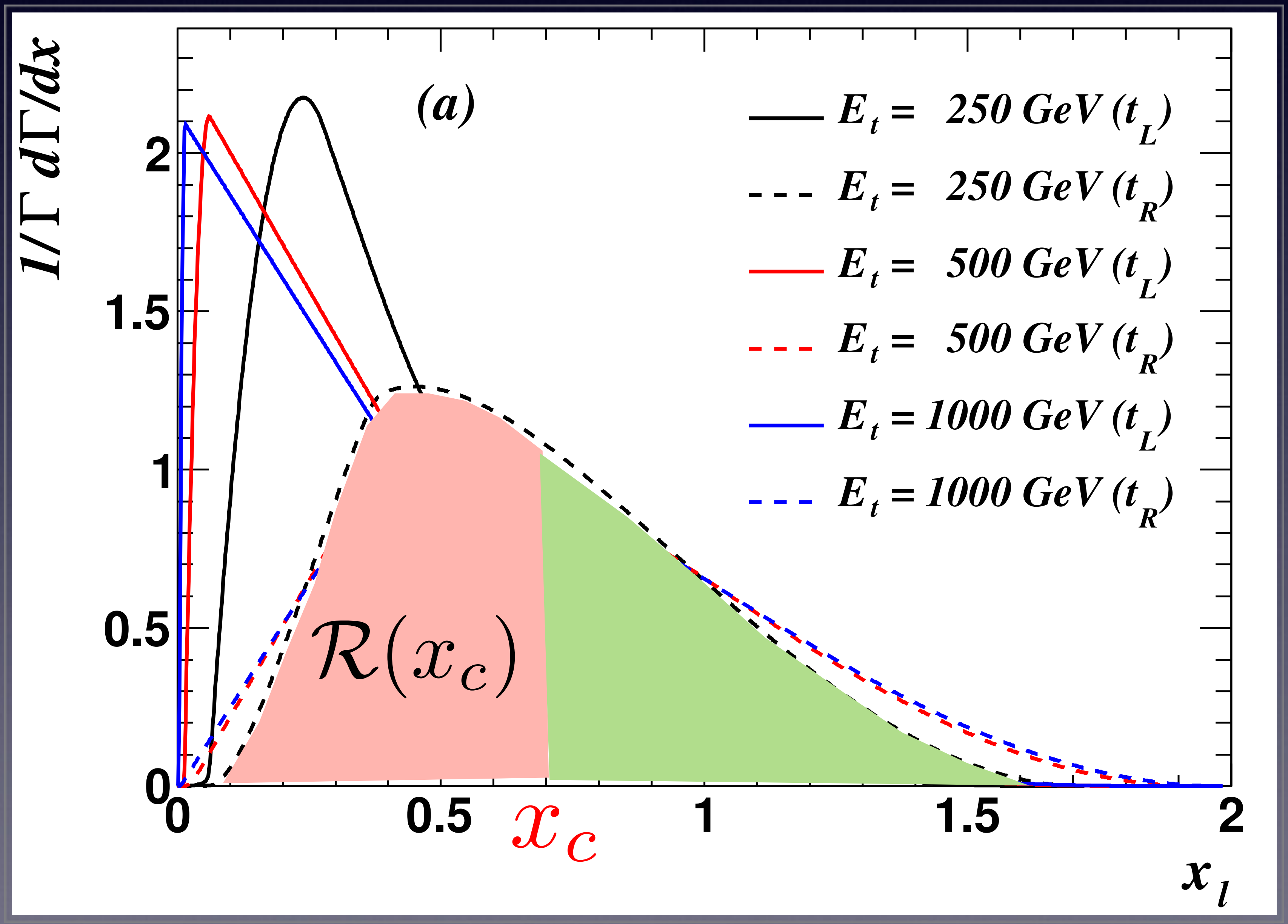
Han, Mahbubani, Walker, Wang,
JHEP 0905 (2009) 117



Lepton energy and top-quark polarization

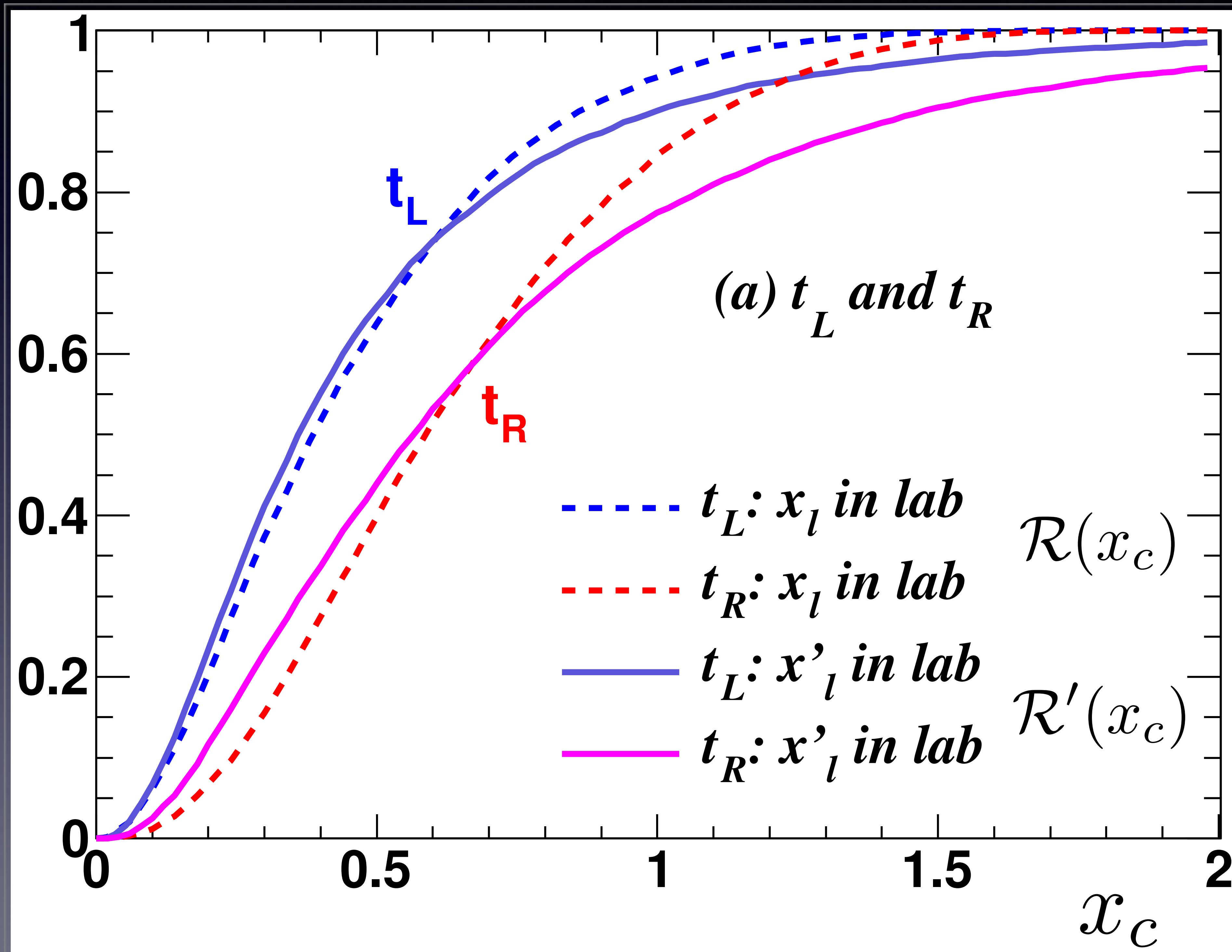
Define a variable $\mathcal{R}$ to quantify the difference between t_L and t_R

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



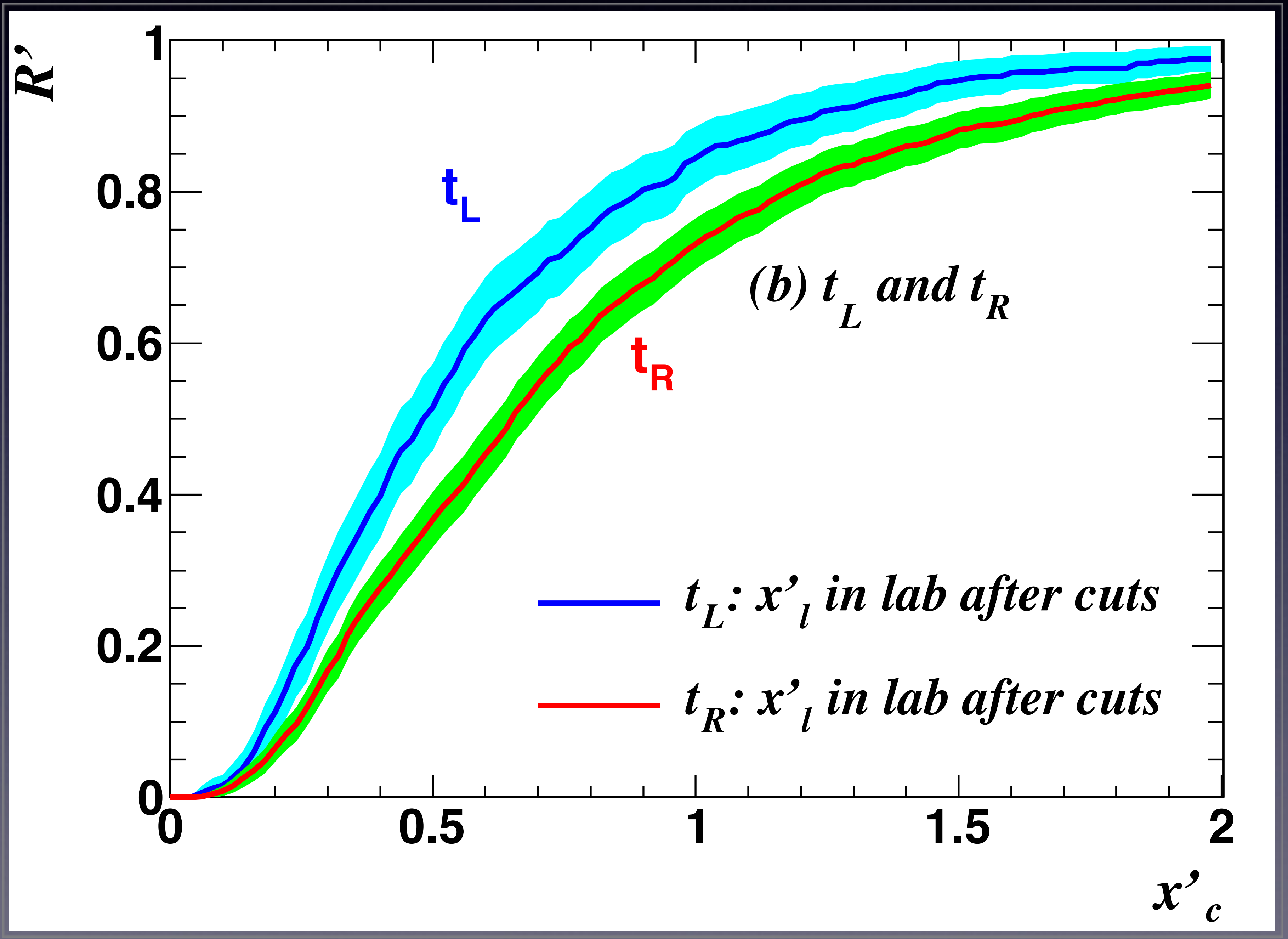
$\mathcal{R}(x_c)$ versus $\mathcal{R}'(x_c)$

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



$\mathcal{R}'$ distribution

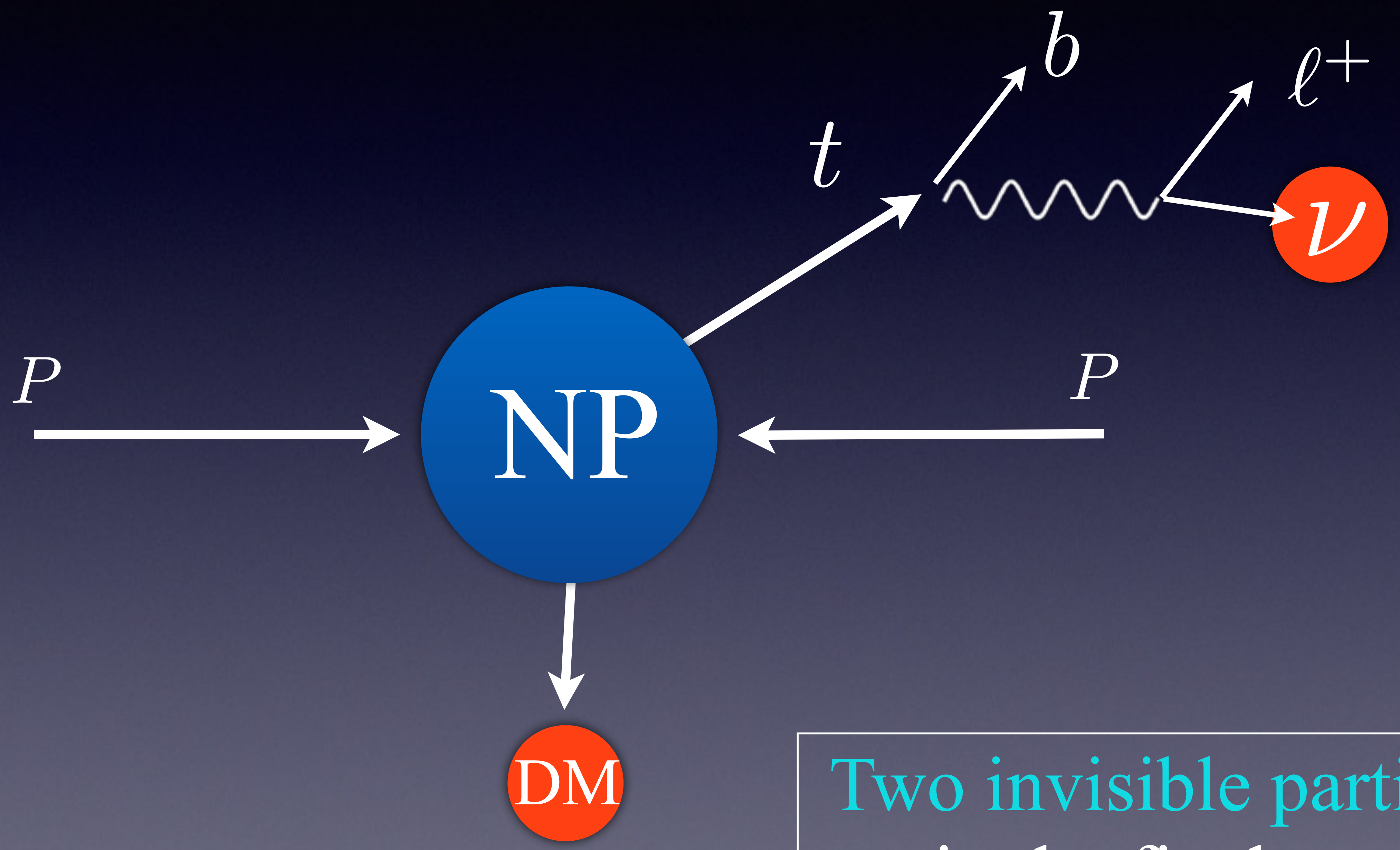
t_L and t_R are separated



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

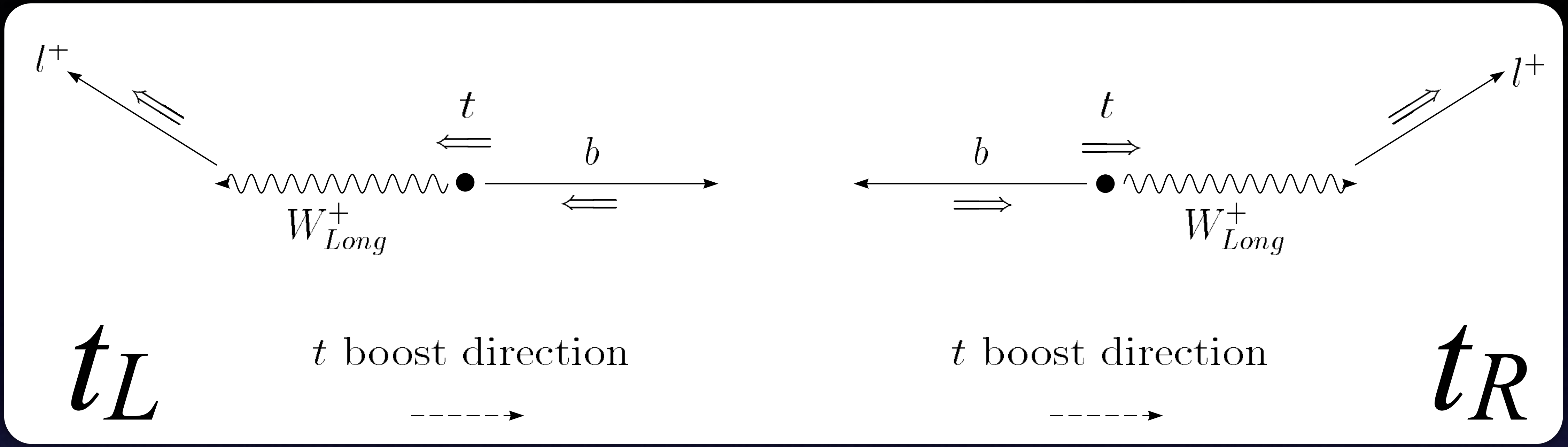
Top quark production in NP

(4) Top-quark + Dark matter candidate



Two invisible particles
in the final state

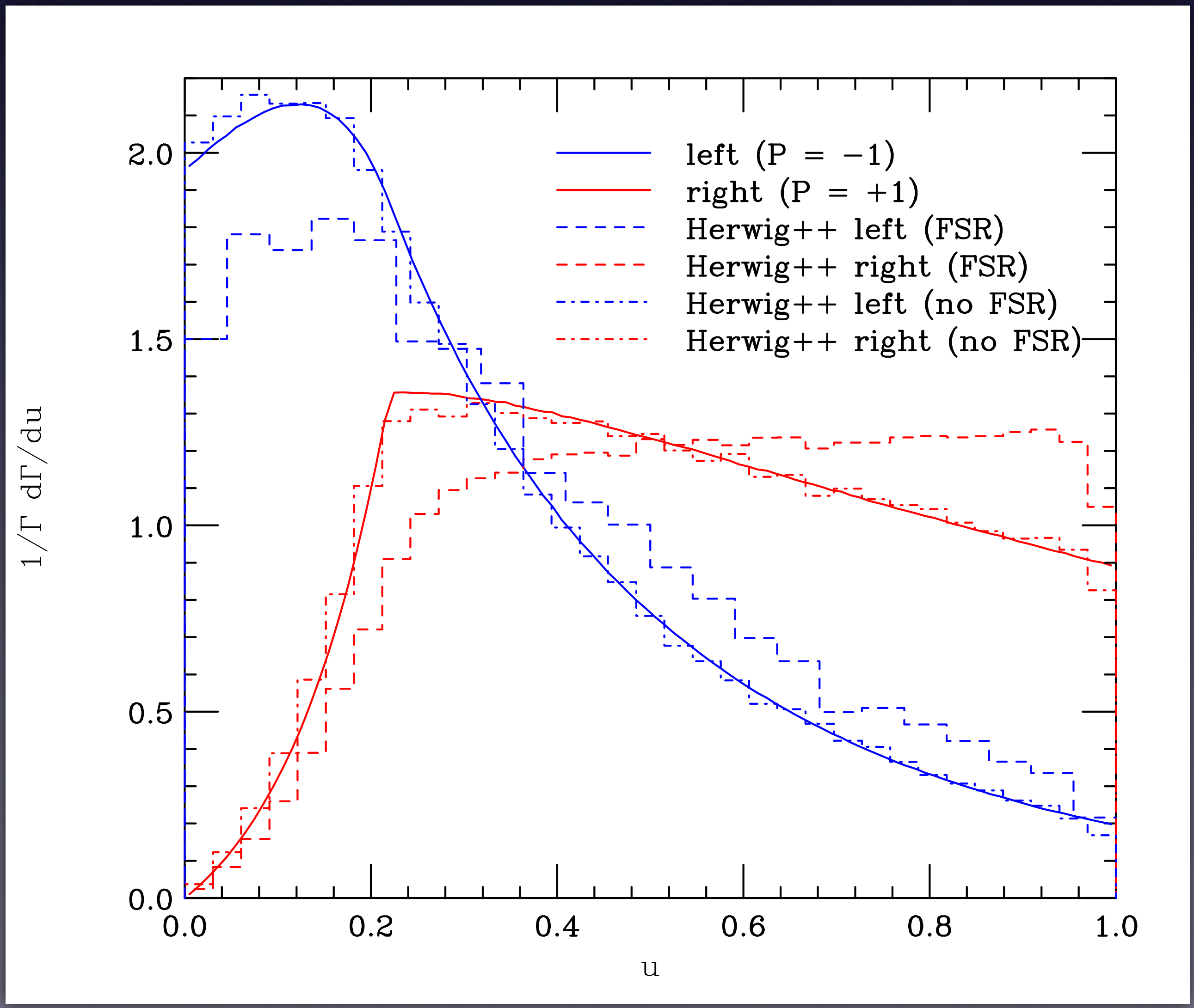
Only Two Visible Particles



New variable

$$u = \frac{E_\ell}{E_\ell + E_b}$$

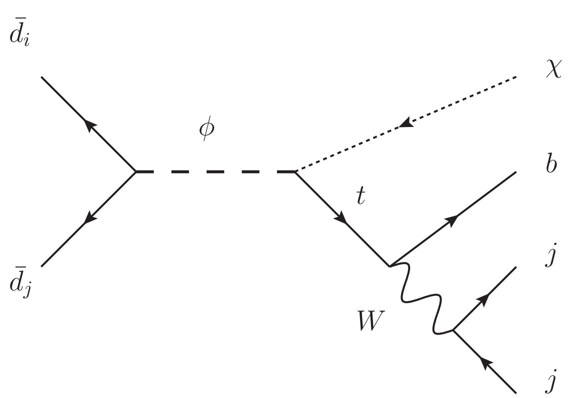
J. Shelton,
Phys. Rev. D79, 014032 (2009)
Papaefstathiou, Sakurai,
arXiv:1112.3956

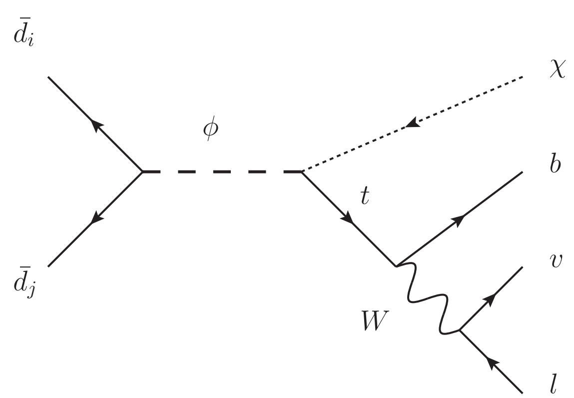


Top-quark + DM

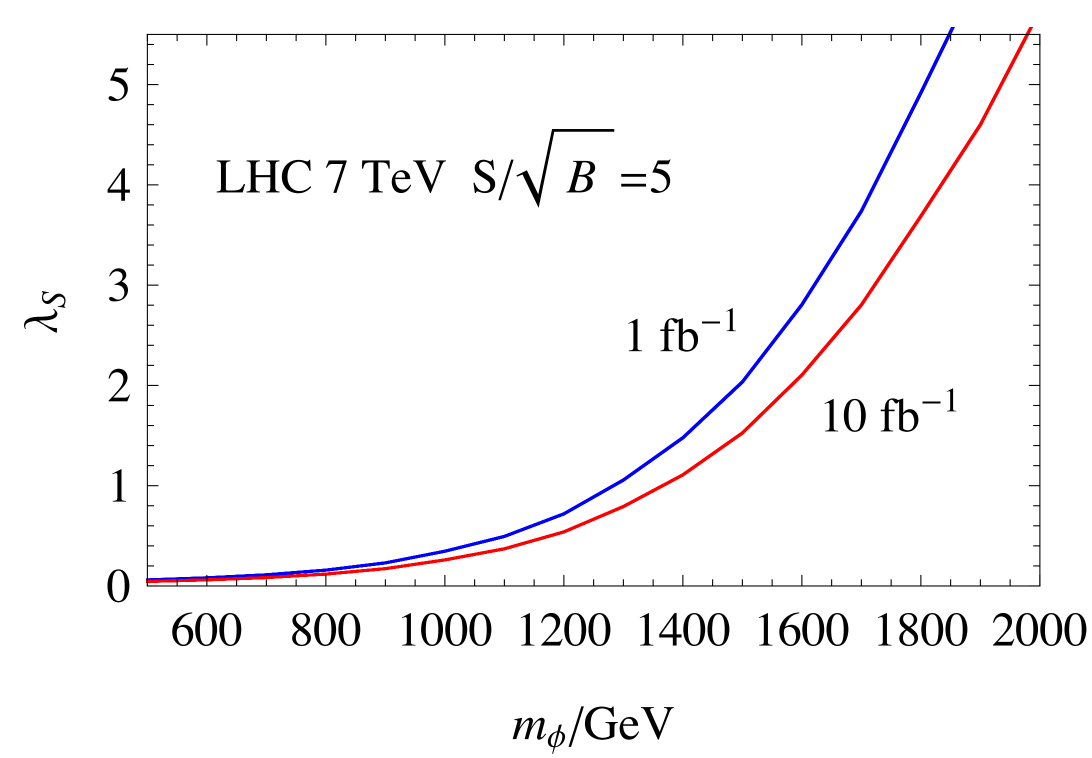
R-parity violation inspired

Andrea, Fuks, Maltoni, arxiv:1106.6199
Wang, Li, Shao, Zhang, 1109.5963

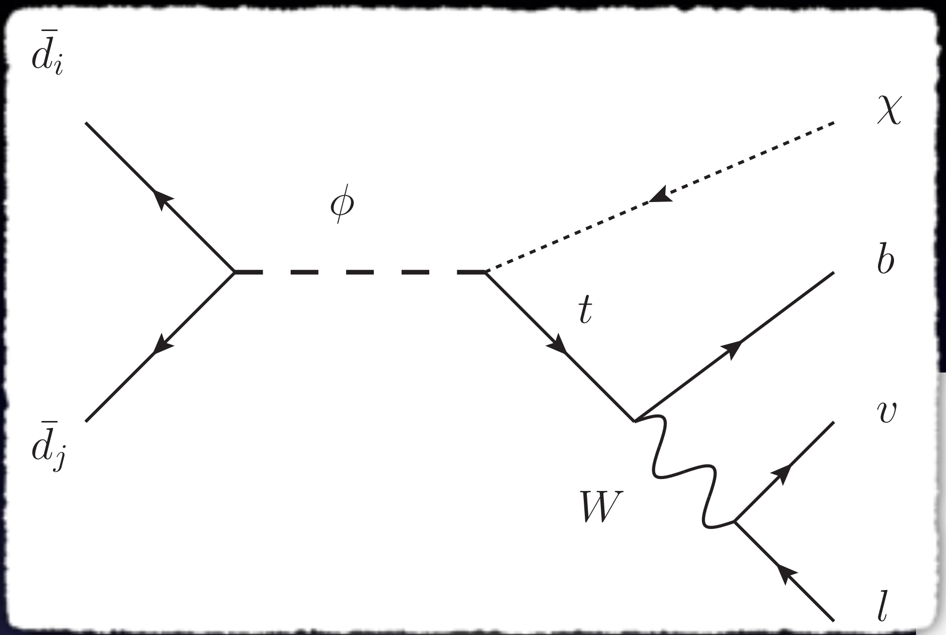




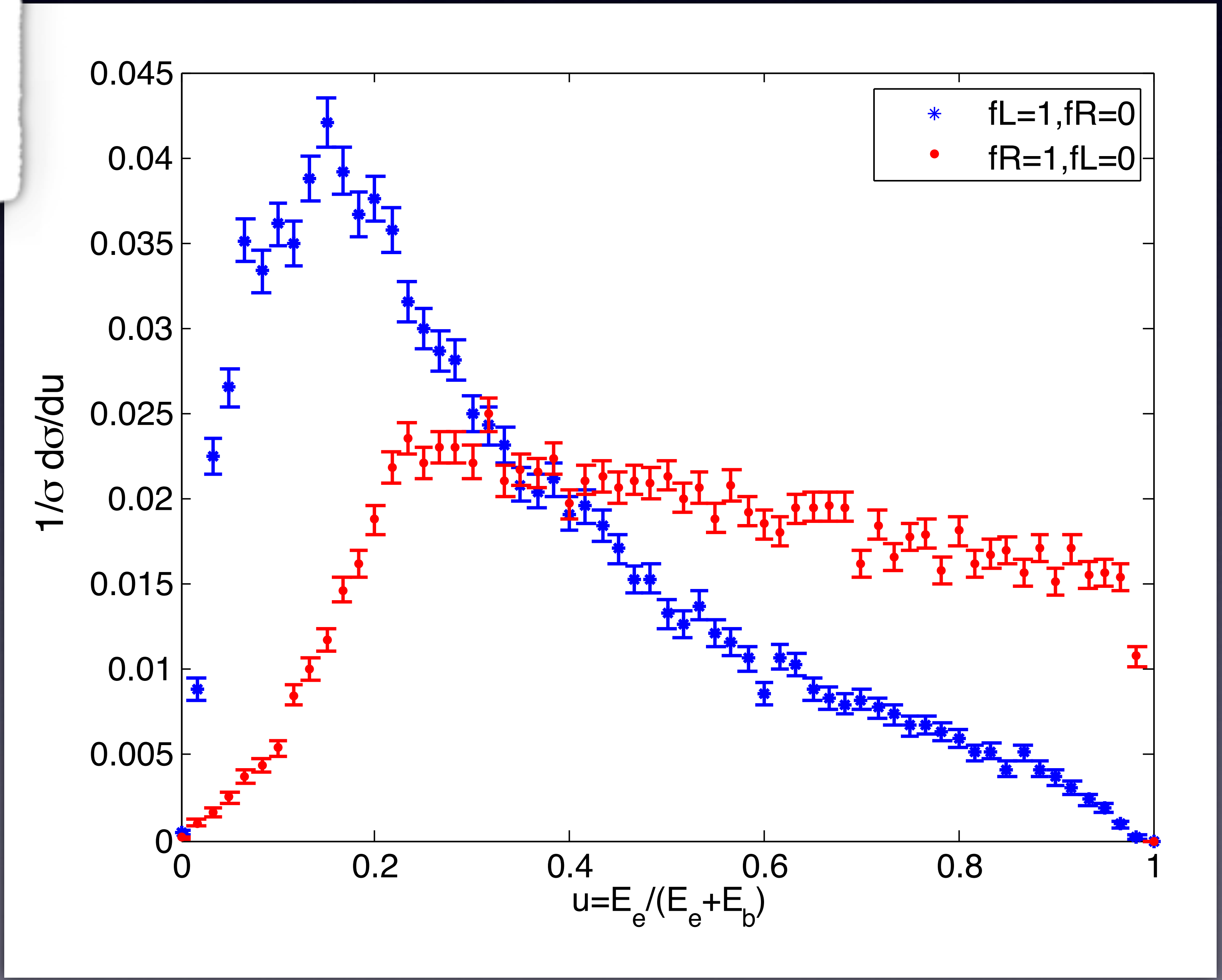
$$
\begin{aligned}
\mathcal{L} = \; & \mathcal{L}_{SM} \\
& + \phi \bar{u} \left[a^0_{FC} + b^0_{FC} \gamma_5 \right] u + V_\mu \bar{u} \left[a^1_{FC} \gamma^\mu + b^1_{FC} \gamma^\mu \gamma_5 \right] u \\
& + \epsilon^{ijk} \varphi_i \bar{d}^c_j \left[a^q_{SR} + b^q_{SR} \gamma_5 \right] d_k + \varphi_i \bar{u}^i \left[a^{1/2}_{SR} + b^{1/2}_{SR} \gamma_5 \right] \chi \\
& + \epsilon^{ijk} \tilde{\varphi}_i \bar{d}^c_j \left[\tilde{a}^q_{SR} + \tilde{b}^q_{SR} \gamma_5 \right] u_k + \tilde{\varphi}_i \bar{d}^i \left[\tilde{a}^{1/2}_{SR} + \tilde{b}^{1/2}_{SR} \gamma_5 \right] \chi \\
& + \epsilon^{ijk} X_{\mu,i} \; \bar{d}^c_j \left[a^q_{VR} \gamma^\mu + b^q_{VR} \gamma^\mu \gamma_5 \right] d_k \\
& + X_{\mu,i} \; \bar{u}^i \left[a^{1/2}_{VR} \gamma^\mu + b^{1/2}_{VR} \gamma^\mu \gamma_5 \right] \chi + \text{h.c.},
\end{aligned}
$$



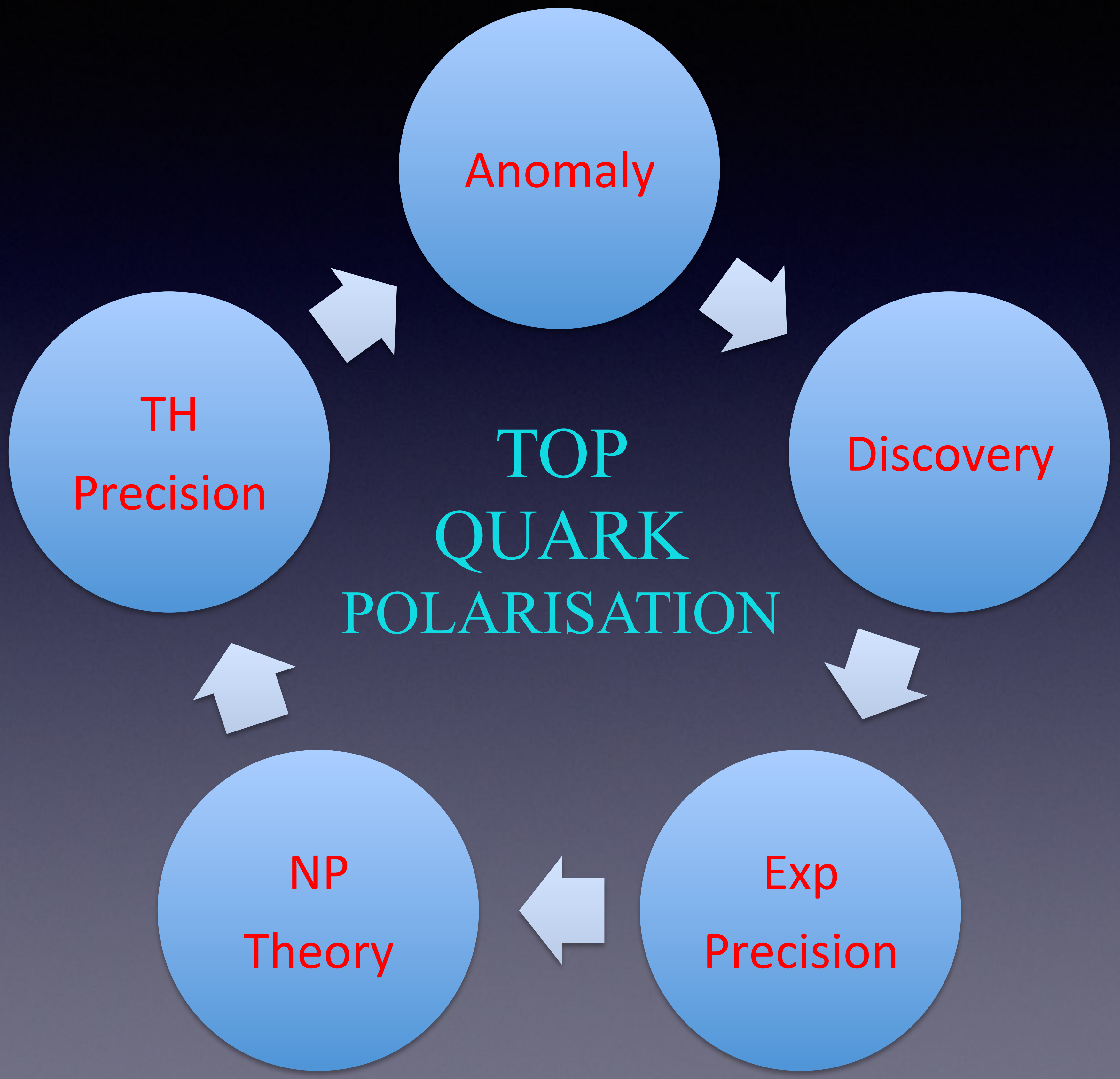
Top-quark + DM



QHC, Yan, in preparation

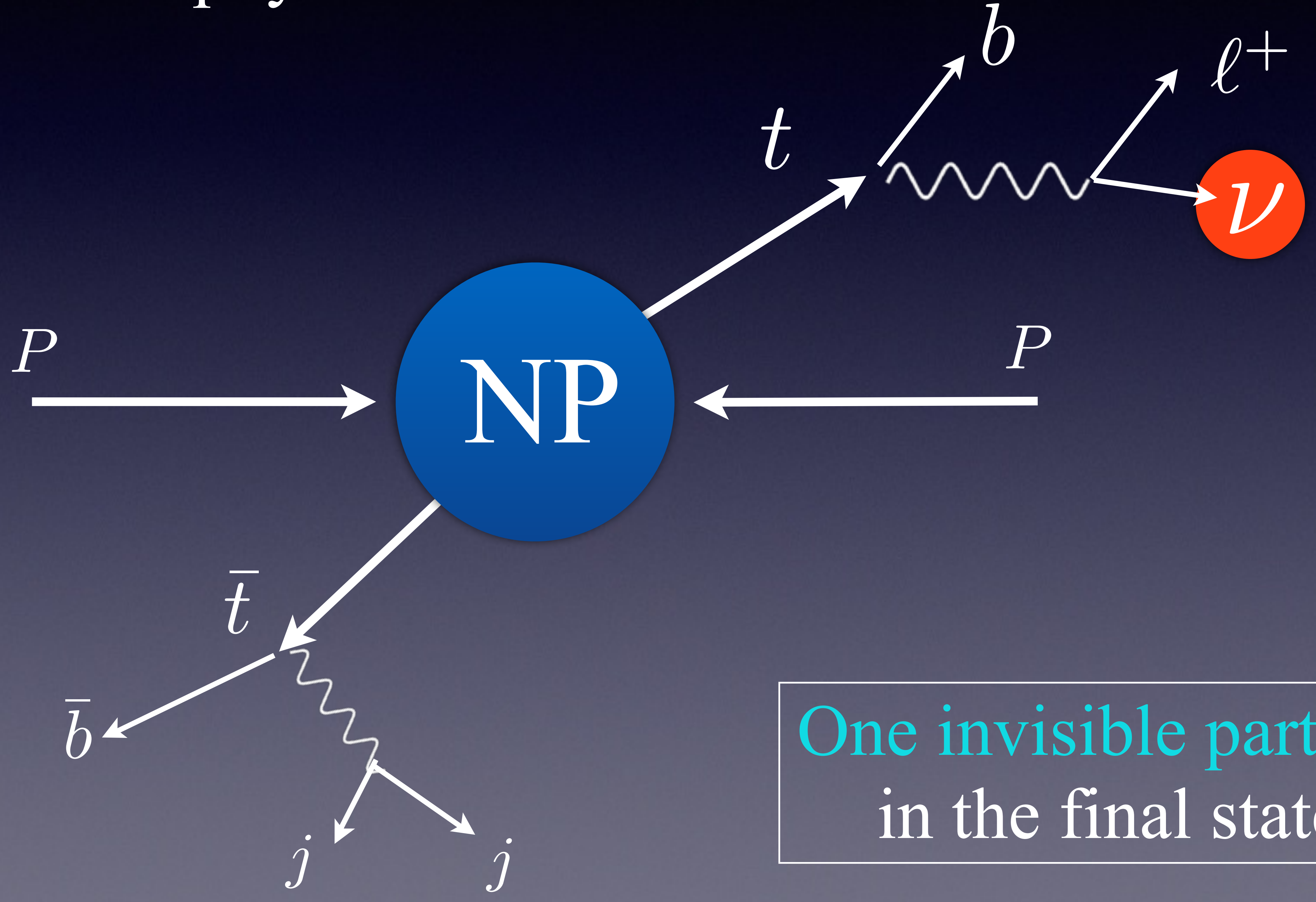


Conclusion


Anomaly
Discovery
Exp
Precision
NP
Theory
TH
Precision
TOP
QUARK
POLARISATION

Conclusion

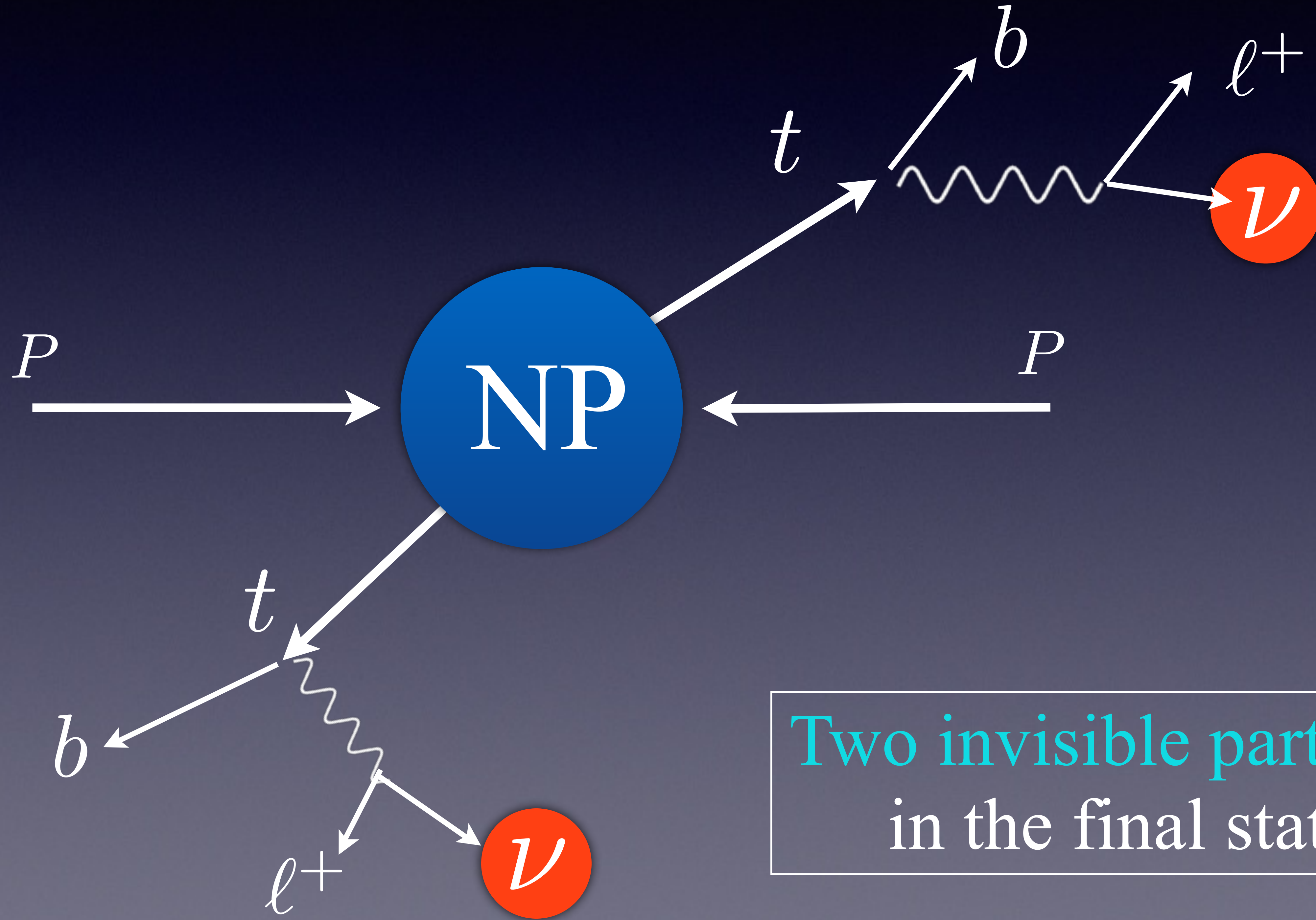
- Top-quark polarization provides additional information about new physics structure



One invisible particle in the final state

Conclusion

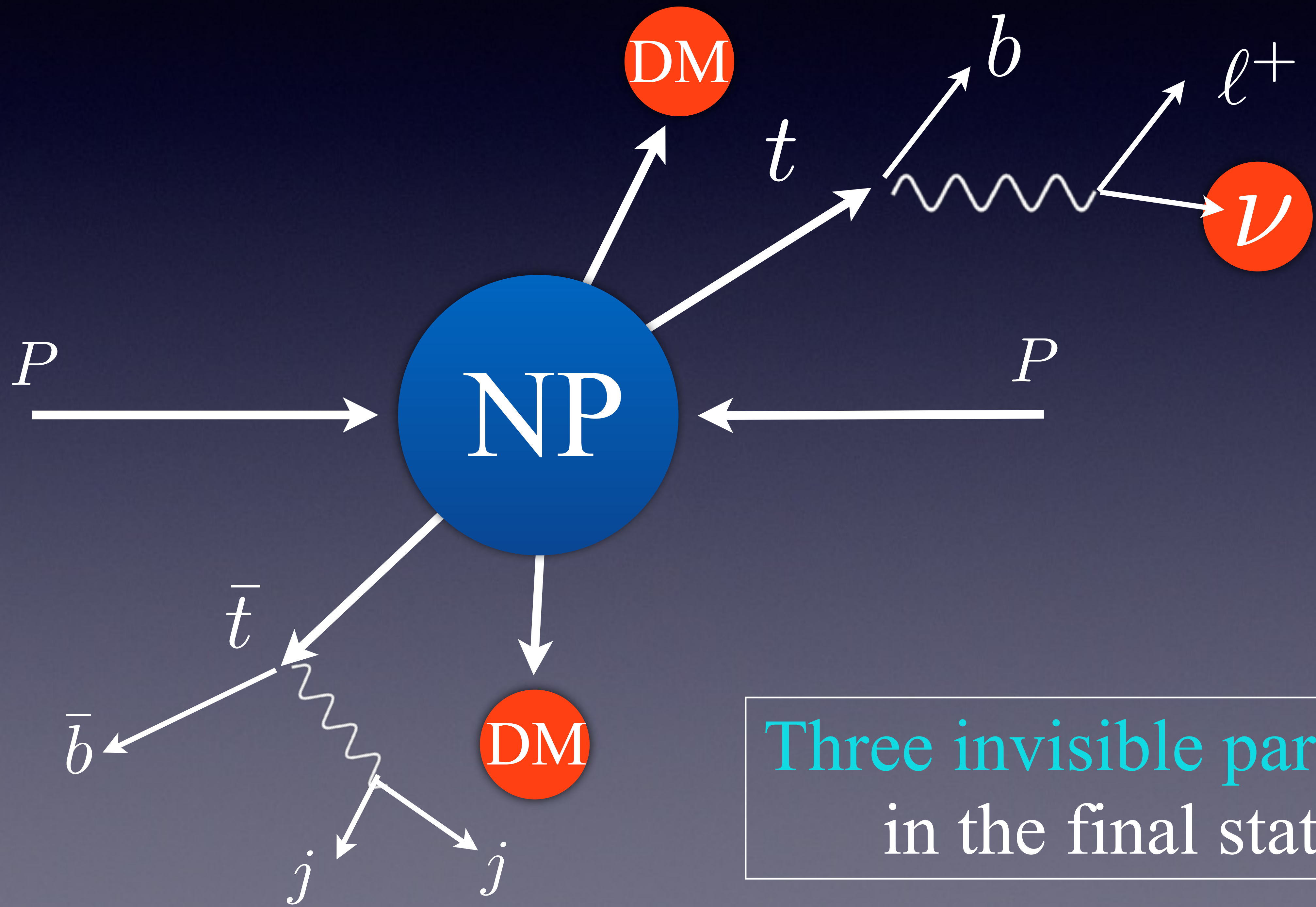
- Top-quark polarization provides additional information about new physics structure



Two invisible particles
in the final state

Conclusion

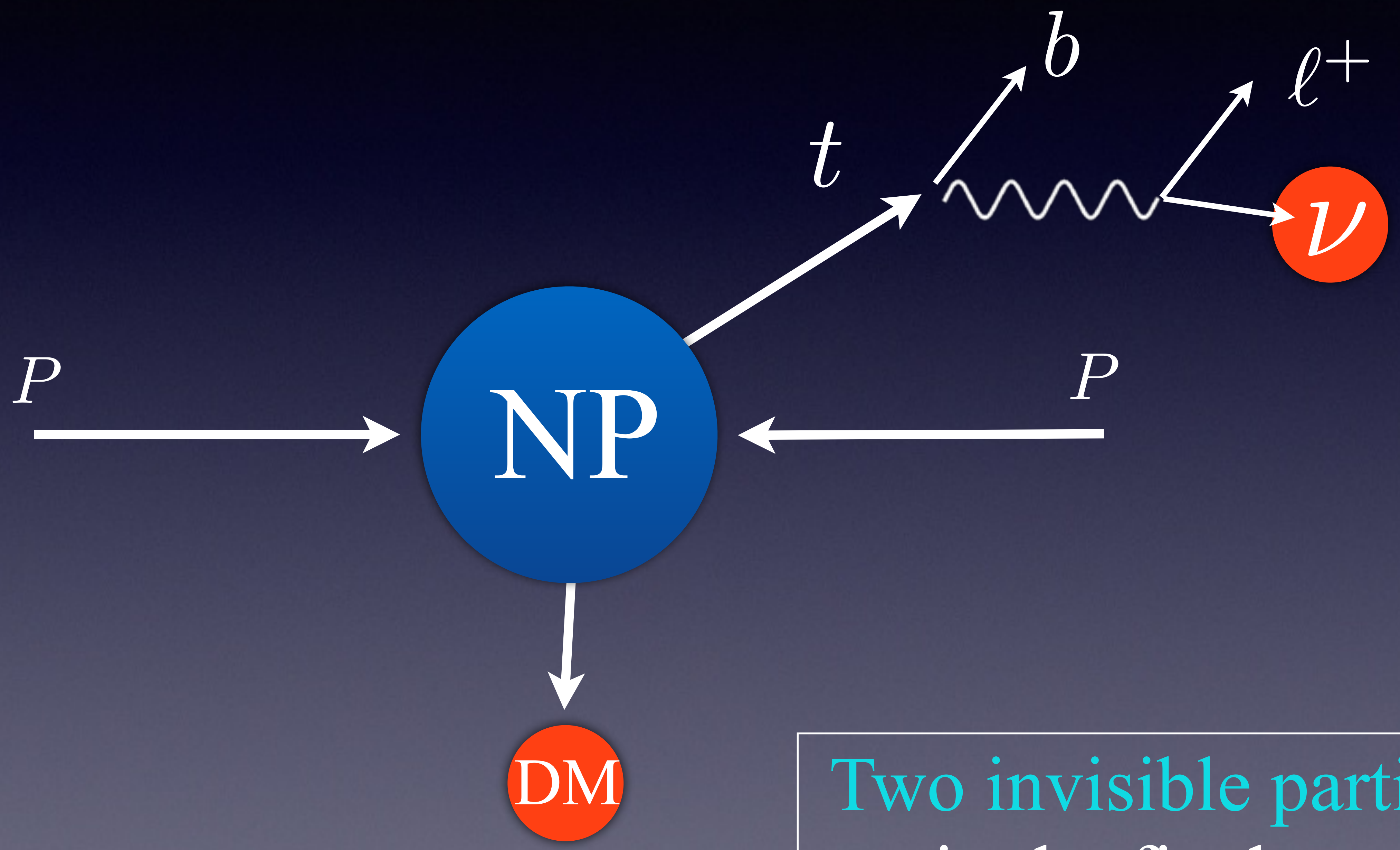
- Top-quark polarization provides additional information about new physics structure



Three invisible particles in the final state

Top quark production in NP

(4) Top-quark + dark matter candidate



Two invisible particles
in the final state

THANK YOU!