Top Quark Polarization and New Physics

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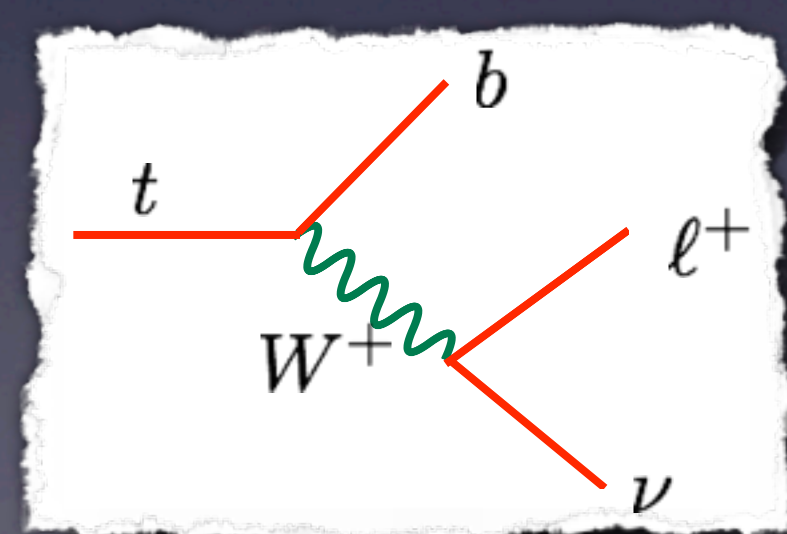
Top-quark: king of the SM

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

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

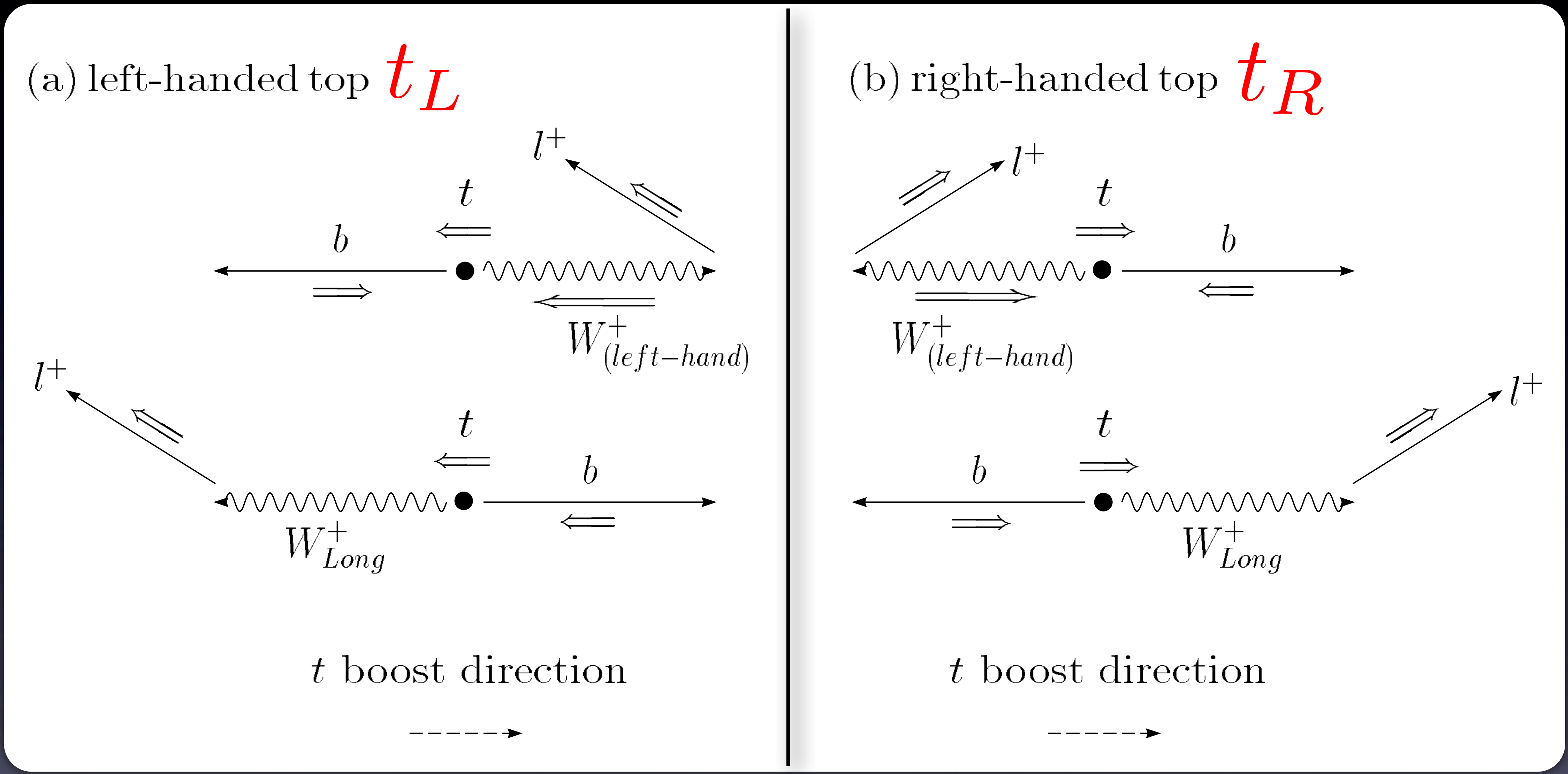
- "bare" quark：

  spin info well kept among its decay products



Top-quark leptonic decay

- Charged lepton: top-quark spin analyzer



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

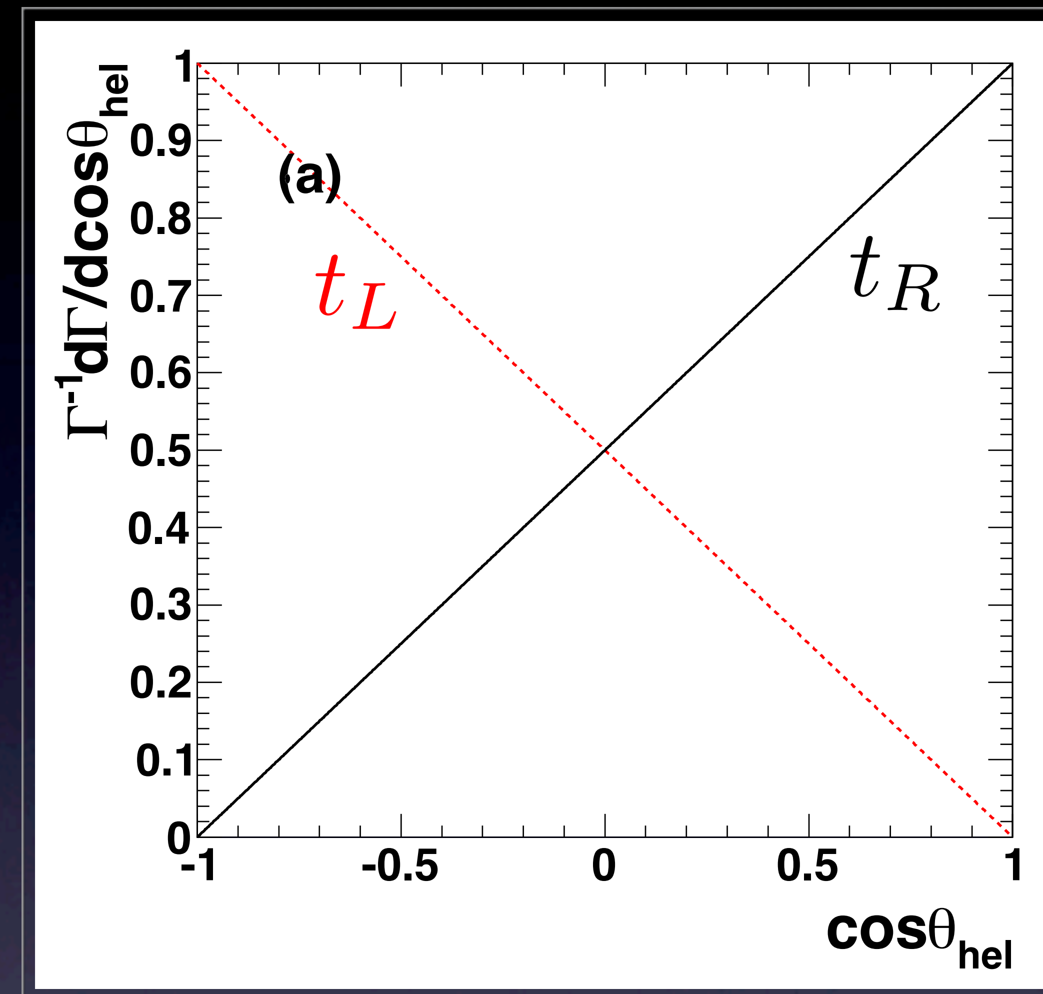
Charged lepton distribution

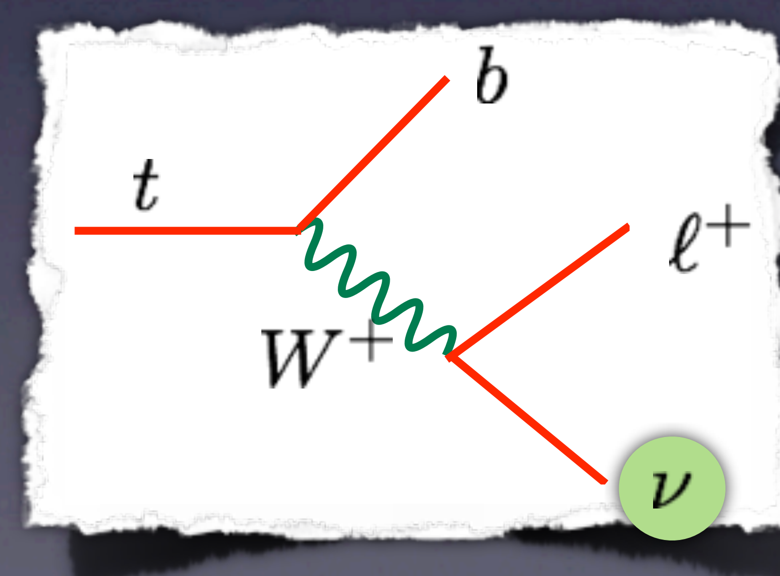
- In top-quark rest frame

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

$\lambda_t = +$ right-handed

$\lambda_t = -$ left-handed





Top-quark Polarization:
A powerful discriminator of NP models

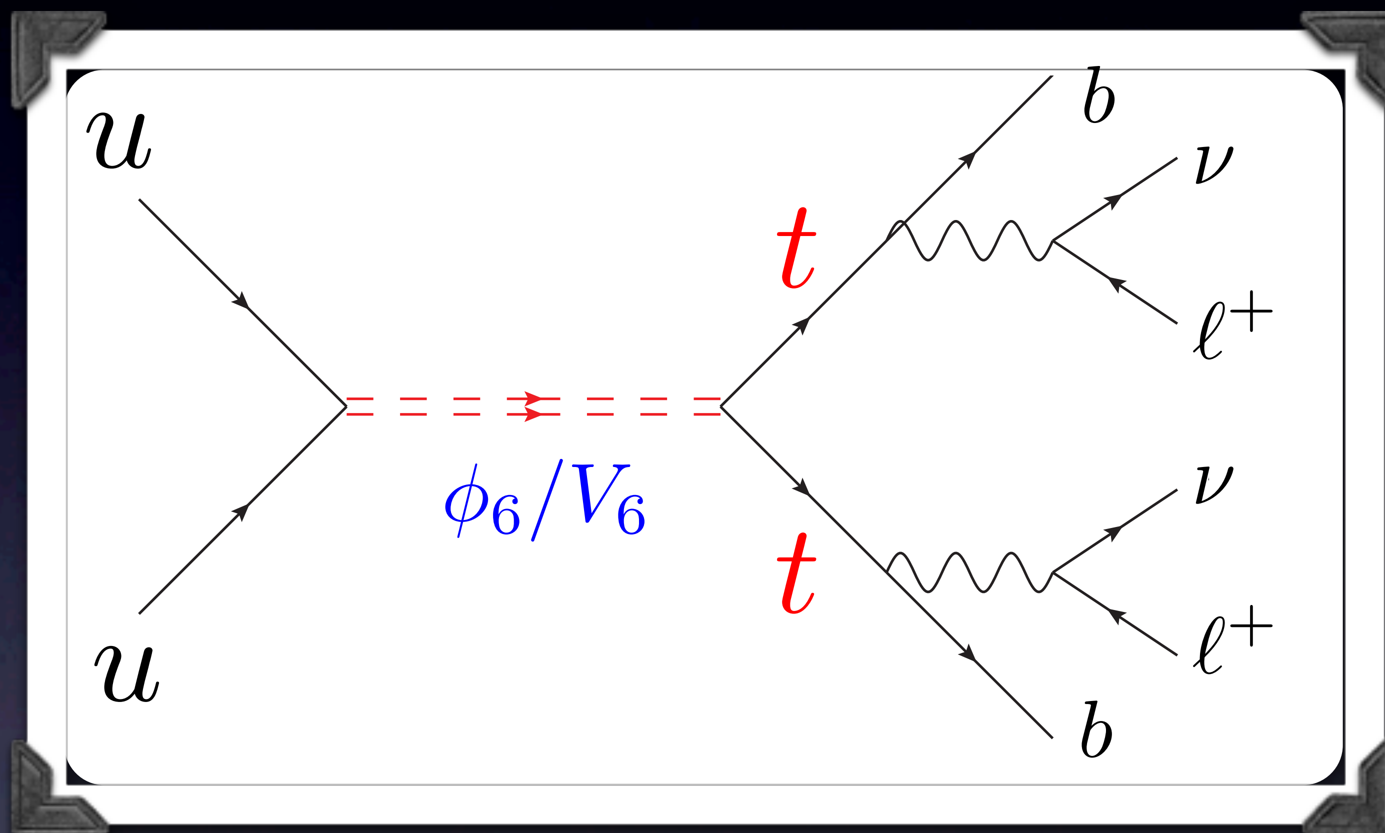
1. Color sextet scalars and vectors

   Same-sign top-quark pair production

2. Stop-quarks in MSSM and T-odd top-partners in LHT

   Top-antitop quark pair plus missing energy

New Physics Models
(I) Color sextet scalar/vector



Berger, QHC, Chen, Shaughnessy, Zhang, Phys Rev Lett **105** (2010) 181802

Zhang, Berger, QHC, Chen, Shaughnessy, Phys Lett B **696** (2001) 68

Berger, QHC, Chen, Li, Zhang, Phys Rev Lett **106** (2011) 201801

The Models

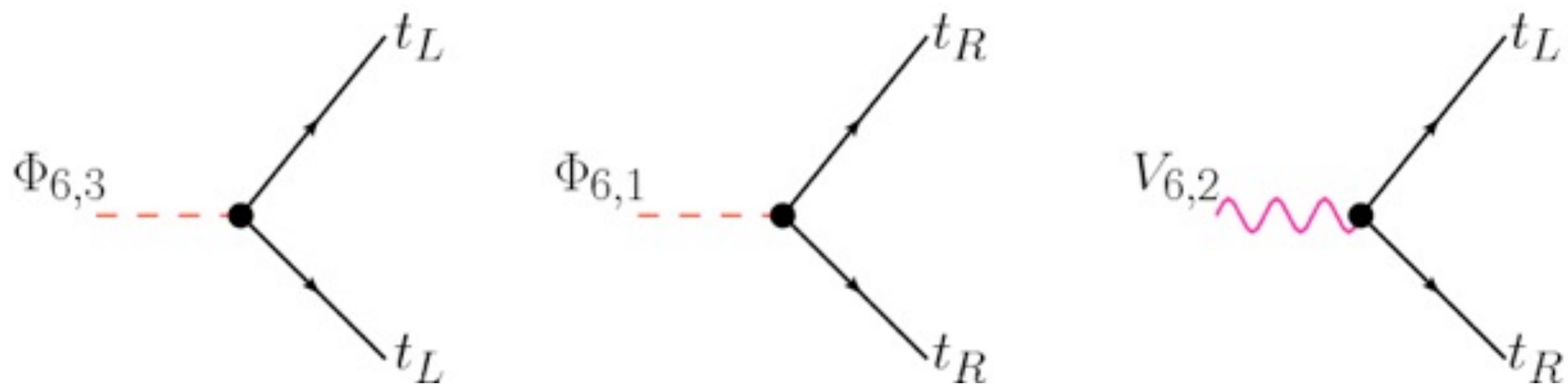
- Effective Lagrangian ($SU(3)_C \times SU(2)_L \times U(1)_Y$)

Atag, Cakir, Sultansoy, PRD59 (1999) 015008

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

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

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



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

Discovery potential

★ Simple cuts to extract signal:

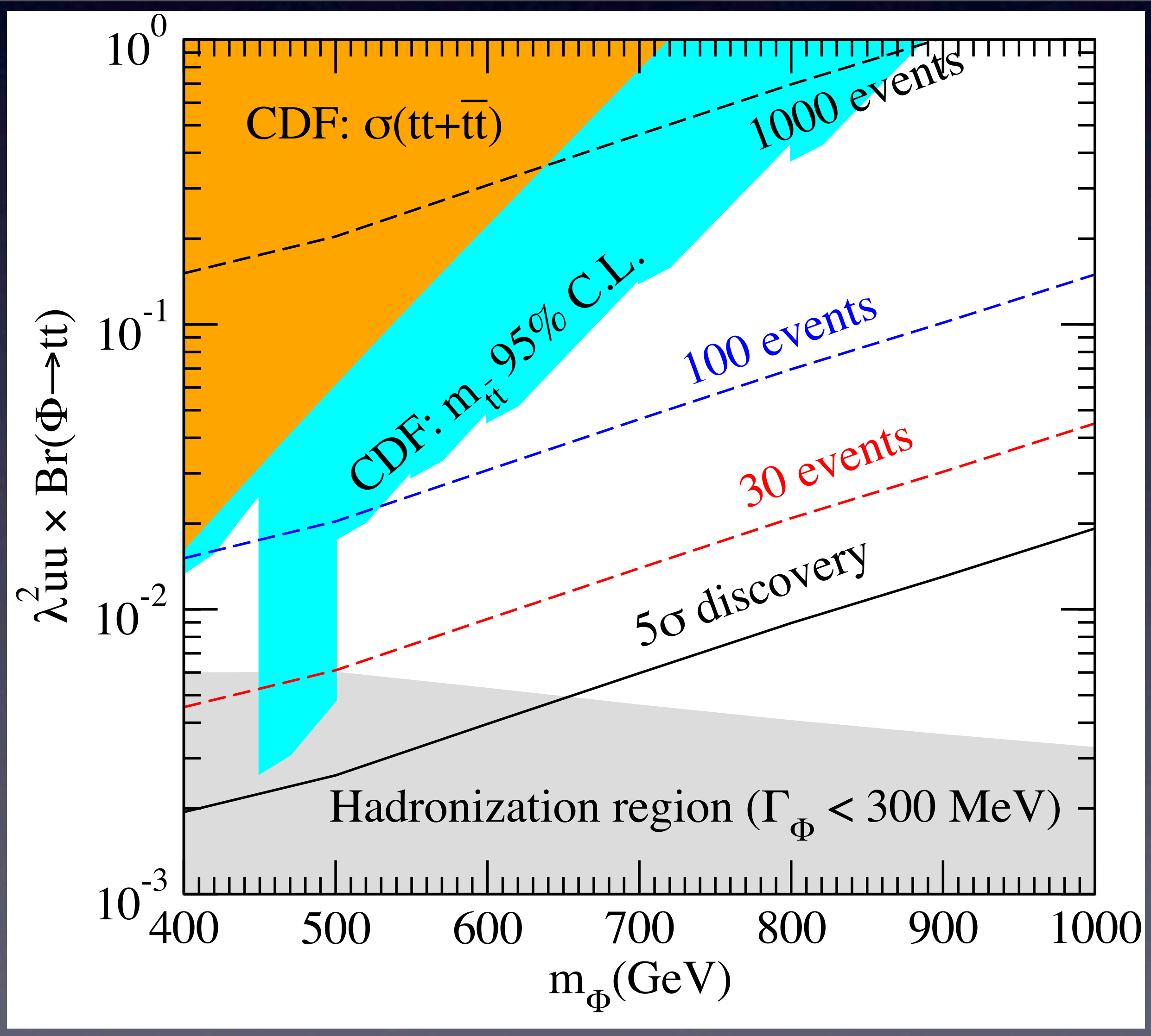
- ✳ Same sign di-muons
- ✳ Two jets and leptons with P_T>50GeV

✳ Shown are numbers of signal events;

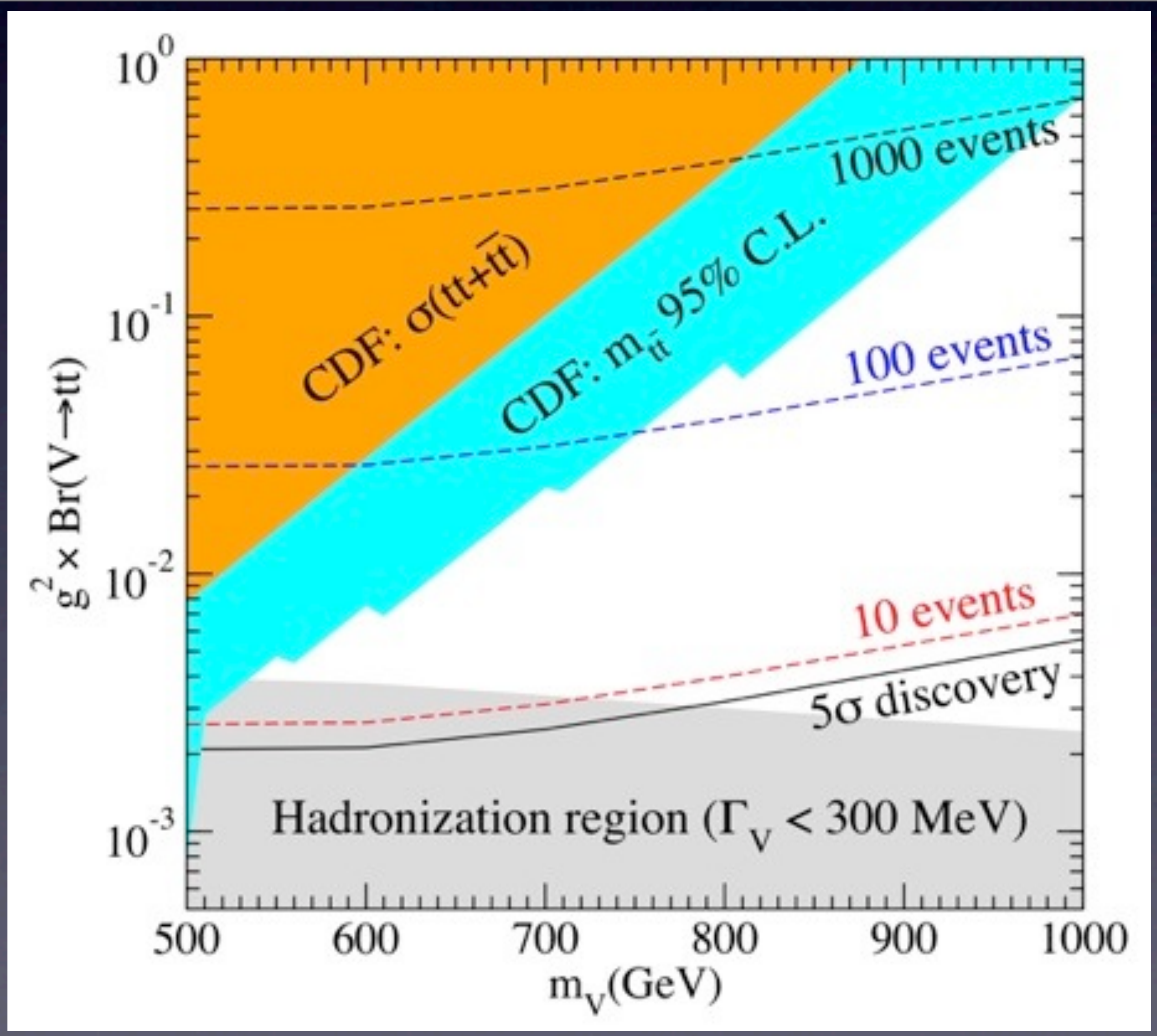
✳ about 1 background events

$$7\,\text{TeV} \quad \mathcal{L} = 1\ \text{fb}^{-1}$$

scalar



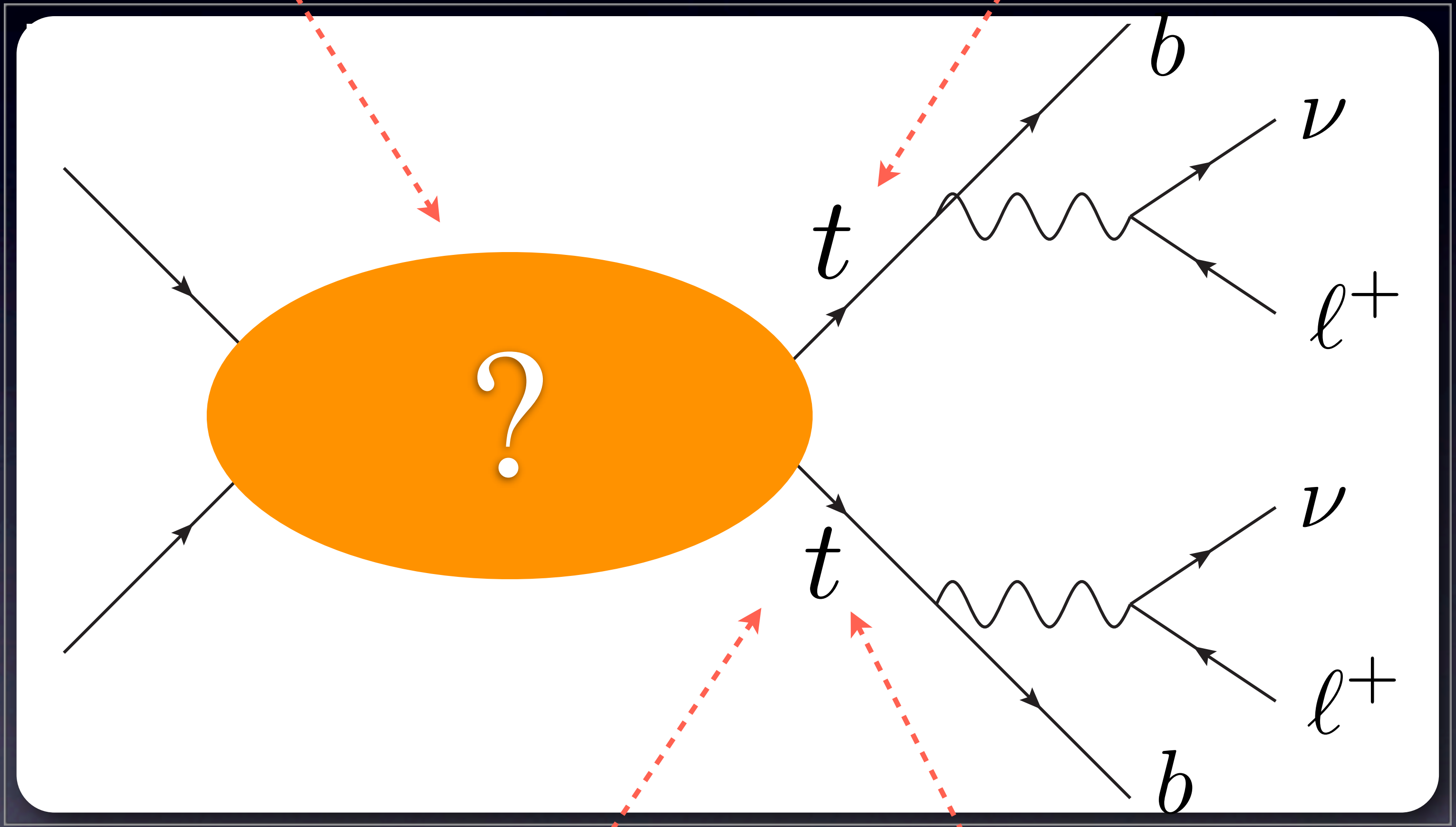
vector



Collider signature: same-sign charged leptons

(2) Is there a resonance? (*s*- or *t*-channel?)

(1) Do the pairs of jet+lepton each reconstruct a top quark?



Need full event reconstruction

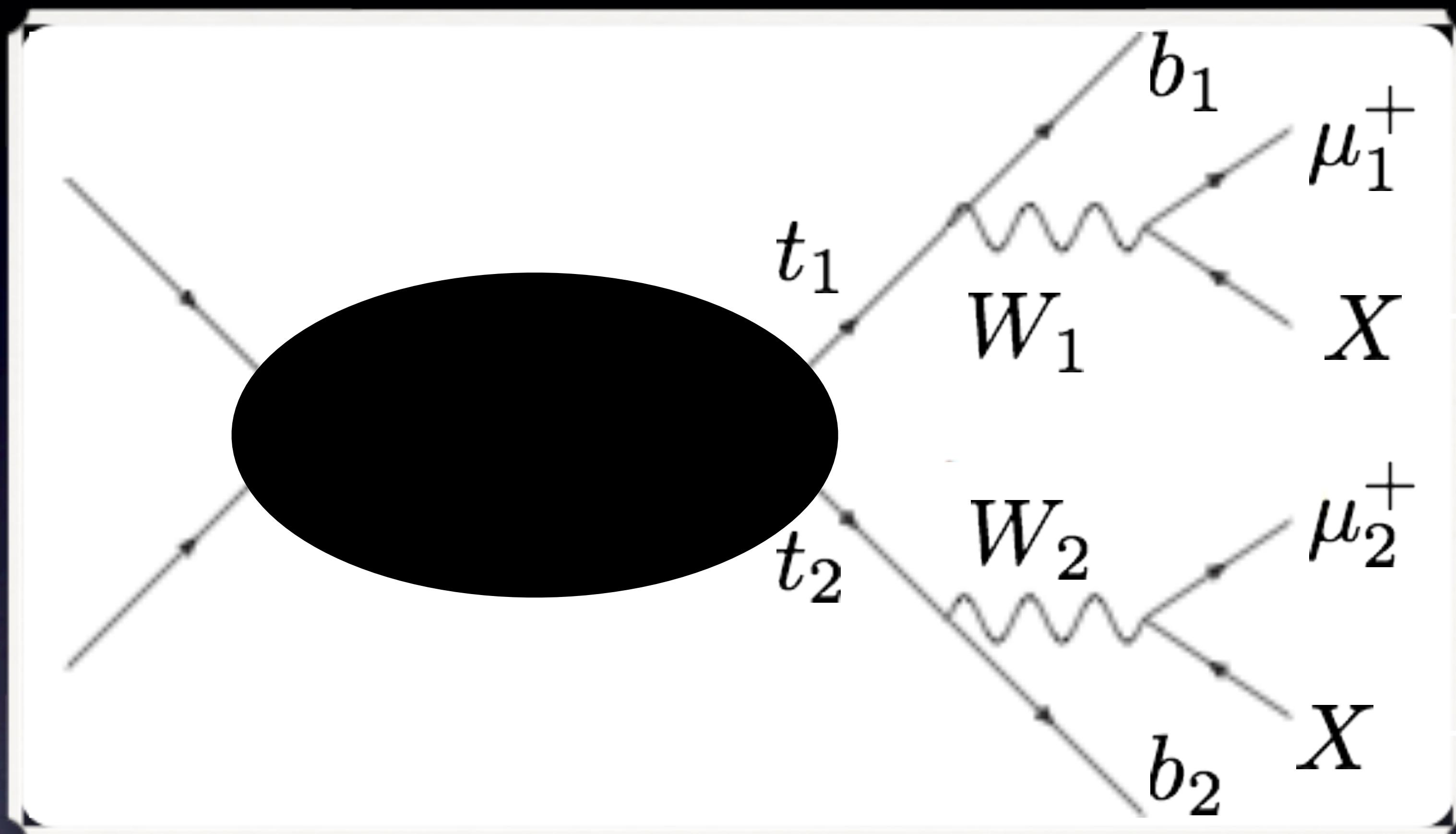
Difficulty:
identical muons and b jets

(3) What is top quark polarization?

(4) Are the top quarks from a scalar/vector decay?

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)

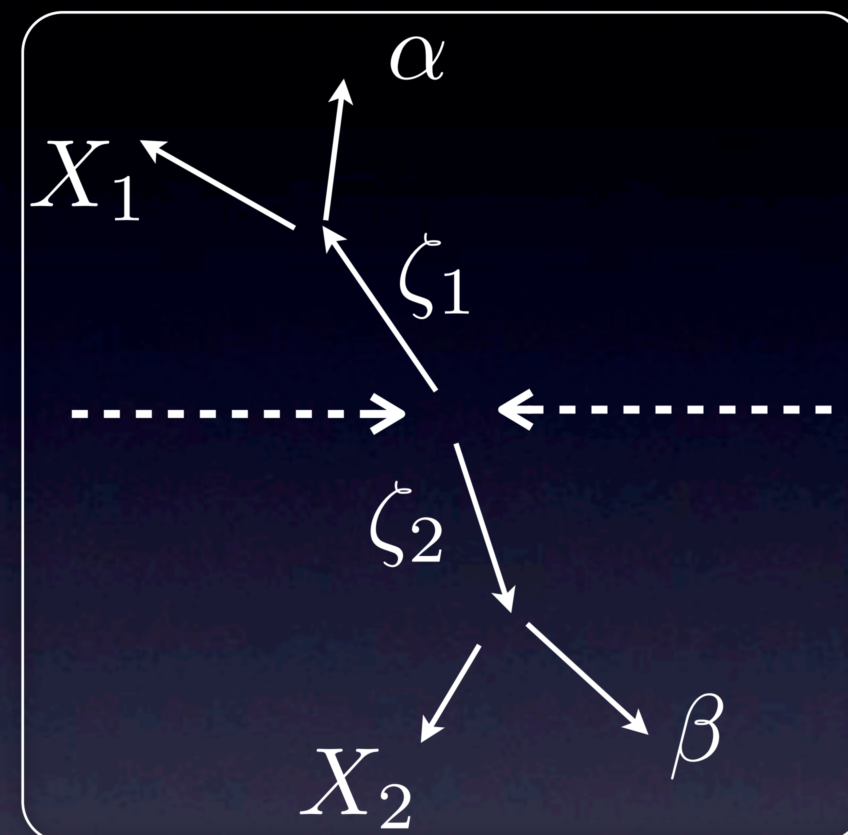
$$p_x^4(\nu_1) + a\ p_x^3(\nu_1) + b\ p_x^2(\nu_1) + c\ p_x(\nu_1) + d = 0$$

~~Two complex~~, two real solutions

$\ell^+ \; b$ - pairing: MT2

★ Question: how can one measure the mass of heavy particles if they are produced in pairs and then decay into visible and invisible particles?

Lester and Summers, hep-ph/9906349



★ The MT2 variable is a function of the momenta of visible particles (α, β) and missing transverse momentum. Its upper bound yields the mass of the parent particle (ζ).

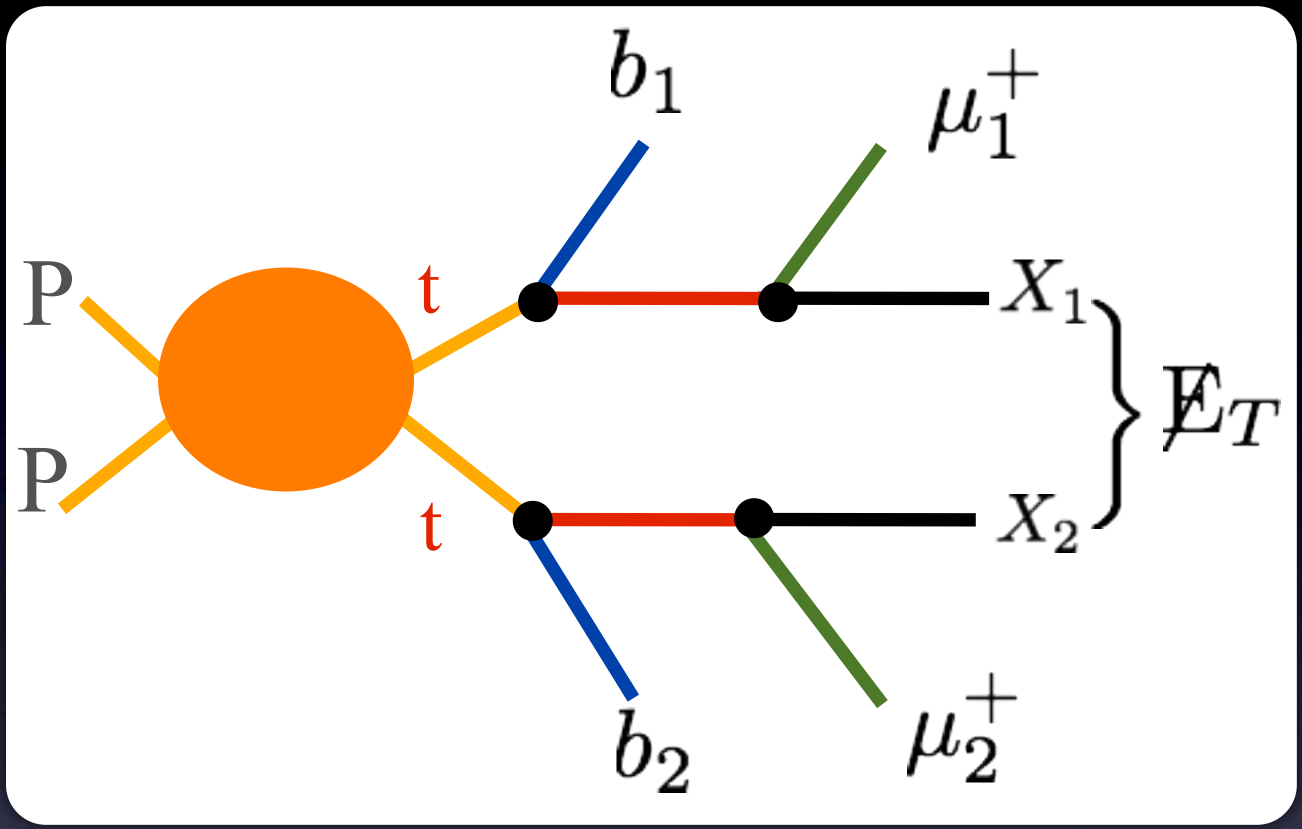
$$M_{T2} \equiv \min_{\not{\vec{p}}_{X_1} + \not{\vec{p}}_{X_2} = \not{E}_T} \left[\max\left\{ m_T(\vec{p}_T^{\,\alpha}, \not{\vec{p}}_{X_1}), m_T(\vec{p}_T^{\,\beta}, \not{\vec{p}}_{X_2}) \right\} \right]$$

$$m_T(m_{invis}; \mathbf{p}_T^{invis}) = \sqrt{m_{vis}^2 + m_{invis}^2 + 2(E_T^{vis} E_T^{invis} - \mathbf{p}_T^{vis} \cdot \mathbf{p}_T^{invis})}$$

$$p^x_{X_1} = a\, \not{E}^x_T, \quad p^x_{X_2} = (1-a)\, \not{E}^x_T$$
$$p^y_{X_1} = b\, \not{E}^y_T, \quad p^y_{X_2} = (1-b)\, \not{E}^y_T$$

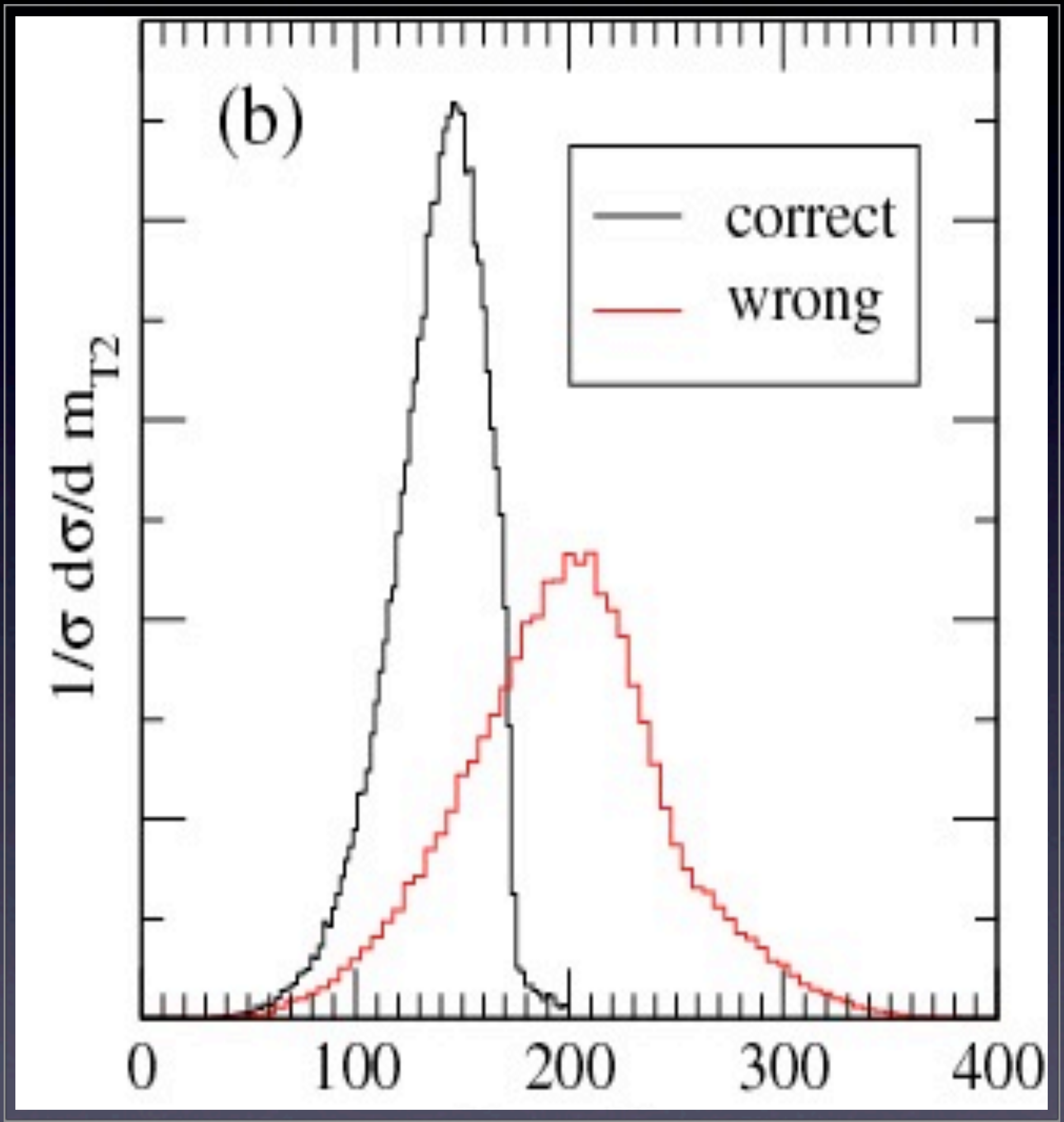
$\ell^+ \; b$ - pairing: MT2

★ MT2 of lepton-b clusters and MET



Two combinations of lepton-b clusters

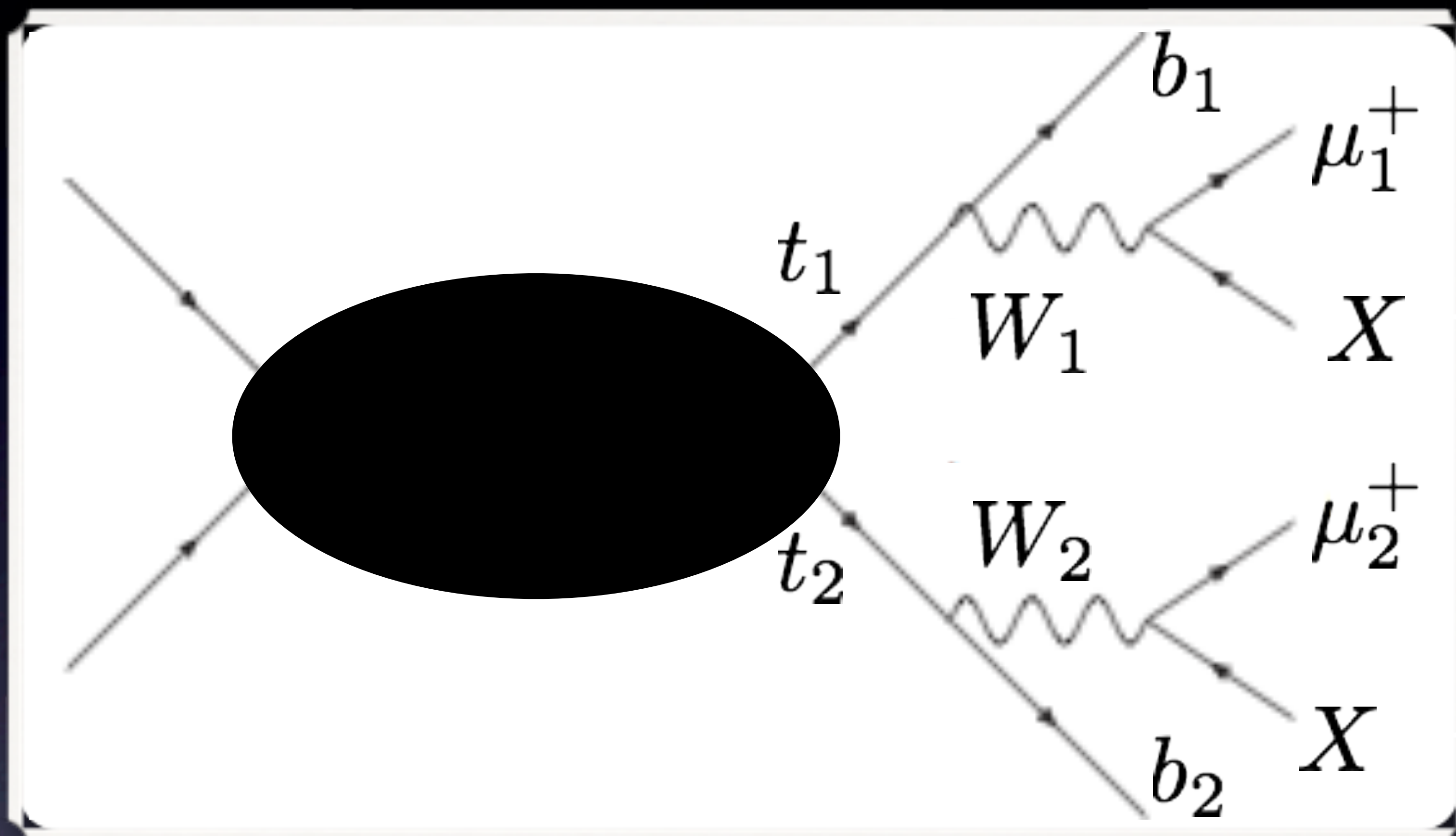
Choose smaller MT2 (correct combination found with nearly 100% probability)



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

Full kinematics reconstruction

★ Four unknowns and four on-shell conditions



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→ Quartic equation

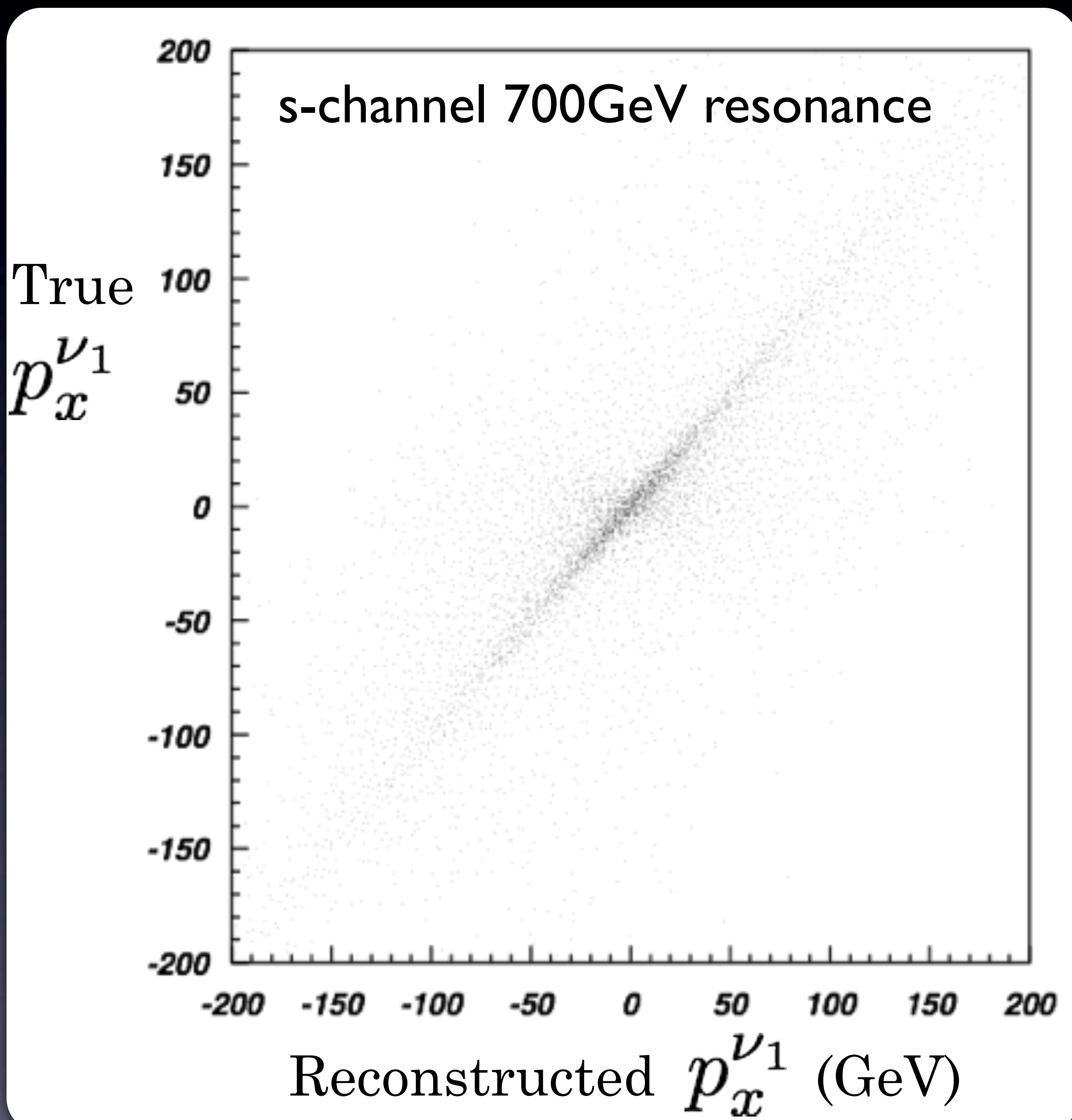
(correct l-b pairing is necessary)

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

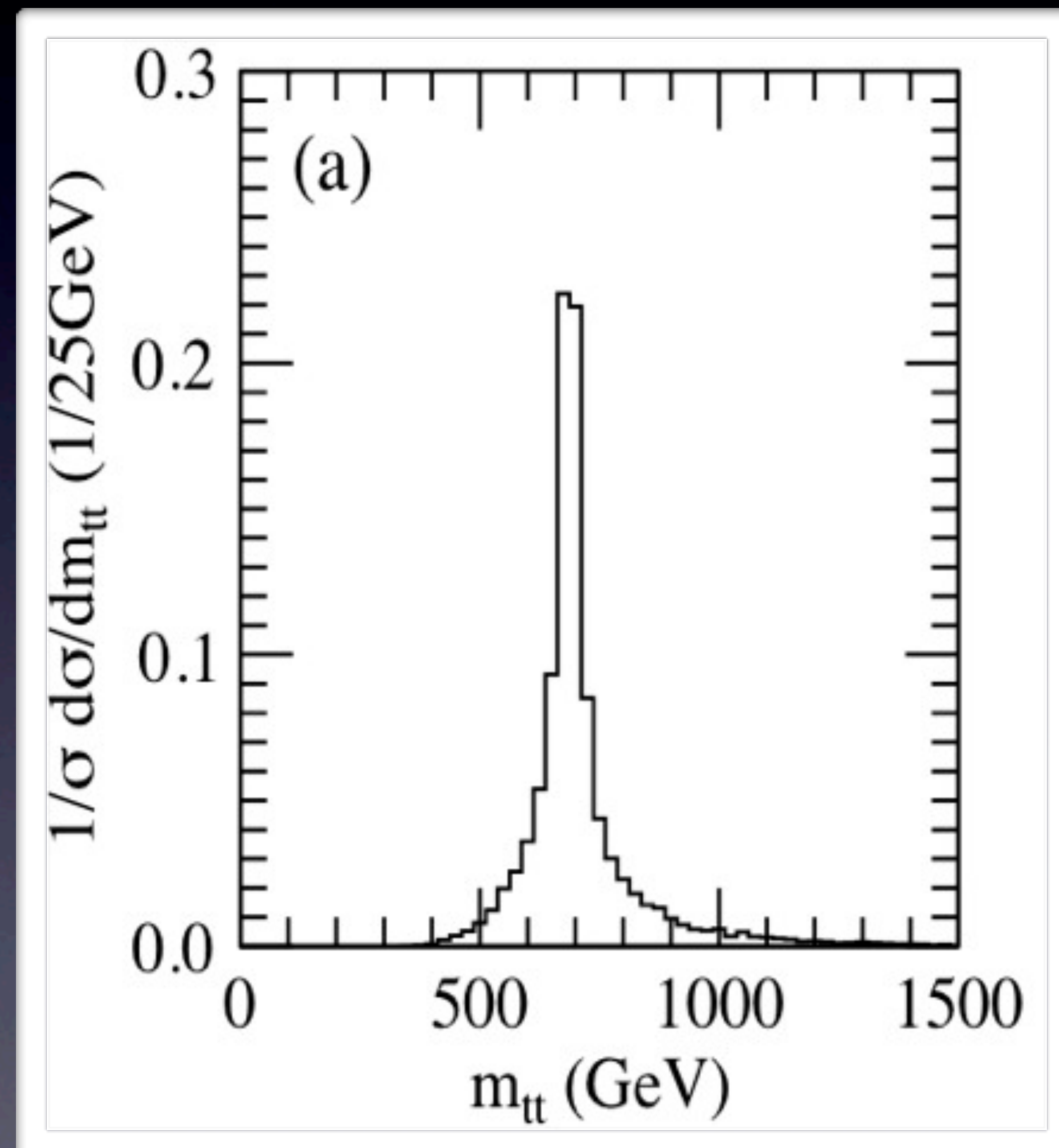
~~Two complex~~, two real solutions

Neutrino momentum reconstruction

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



★ The mass of the heavy resonance can be determined:



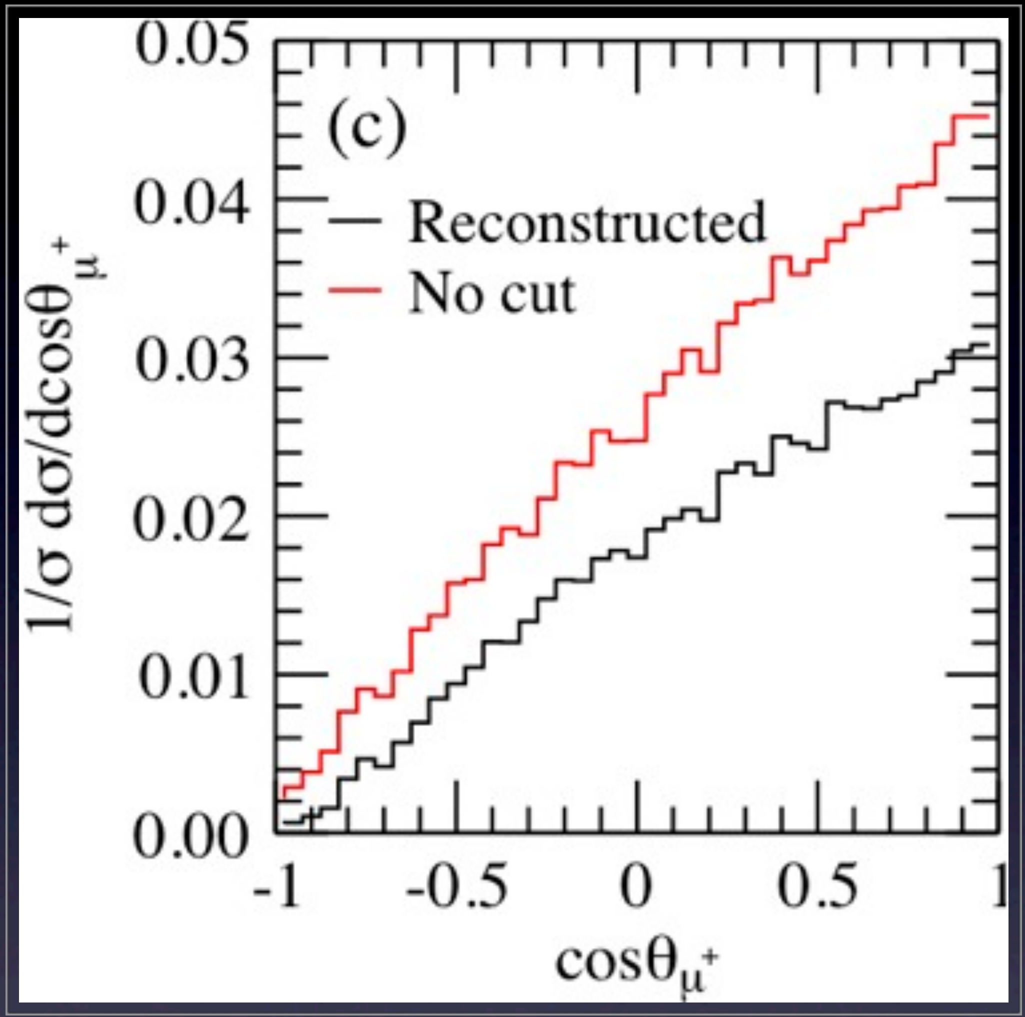
Top-polarization: color sextet scalar

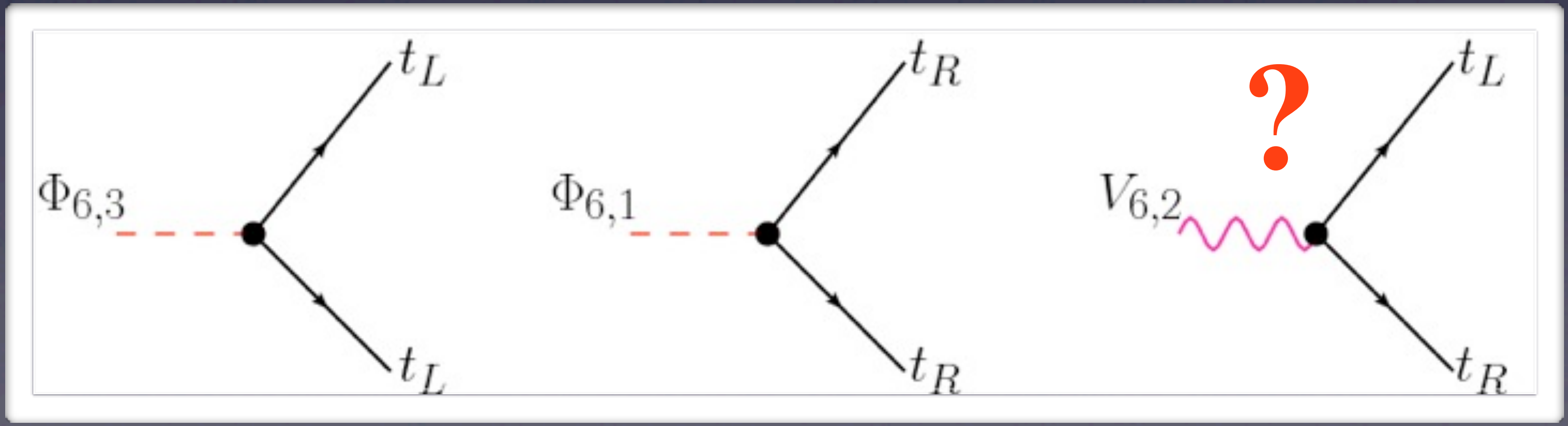
★ Polarization correlates with angle between top quark spin and charged lepton momenta

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

+ : right-handed
- : left-handed

Roughly 30 events required to distinguish from unpolarized case

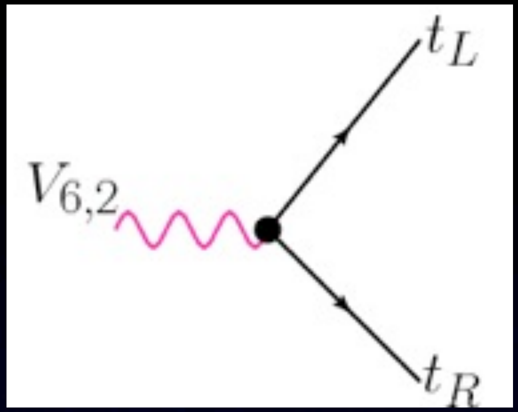




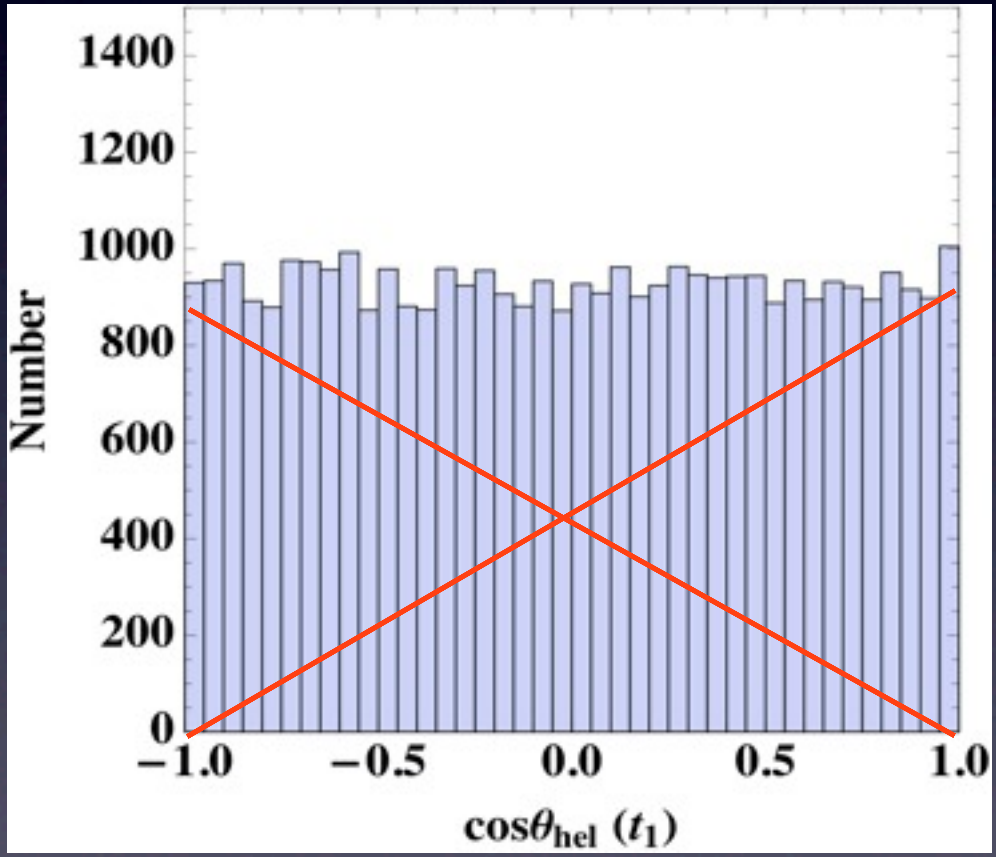
Difficulty in color sextet vector

★ The vector sextet must be a SU(2) doublet. It couples to a left-handed quark and a right-handed quark according to:

$$(6,2)_{\frac{5}{6}}\ :\ \epsilon_{ij}\bar{Q}^c_i\gamma^\mu P_R U\ V_{j\mu} + \text{h.c.}$$



★ Top quarks are oppositely polarized, but the net polarization distribution of the two identical top quarks exhibits a flat profile (i.e. like unpolarized top quarks).



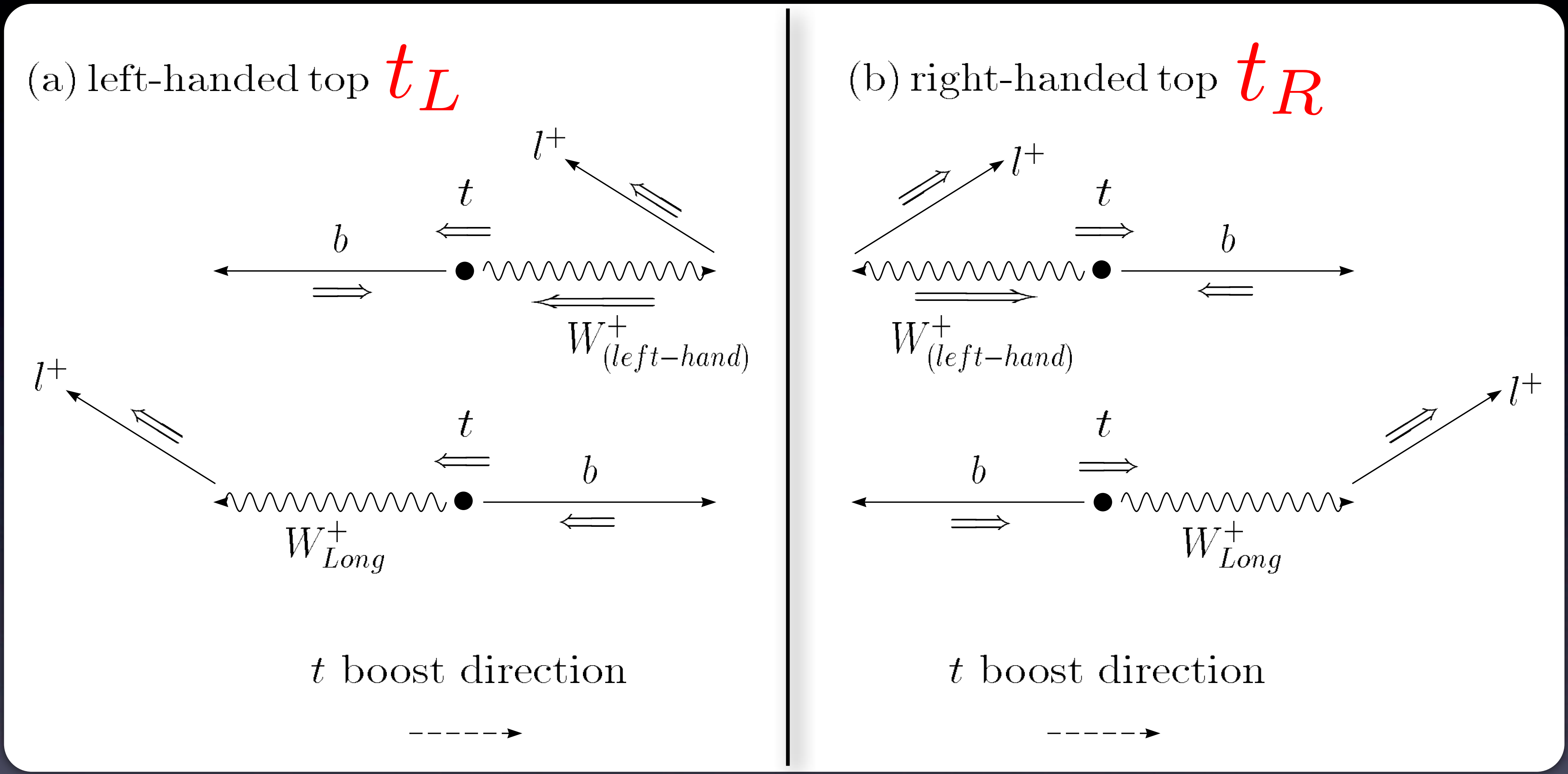
★ Even though the flat profile of sextet vectors is different from the one for scalars, it is interesting to see if we could determine that the top quarks have L and R polarizations.

★ Can we measure the polarizations of the top quarks to distinguish the color sextet vector and scalar mesons?

YES!!!

Lepton energy and top-quark polarization

★ Lepton energy distribution is sensitive to top quark polarization.



Leptons from right-handed top quark decay are more energetic than those from left-handed top quark decay.

Lepton energy and top-quark polarization

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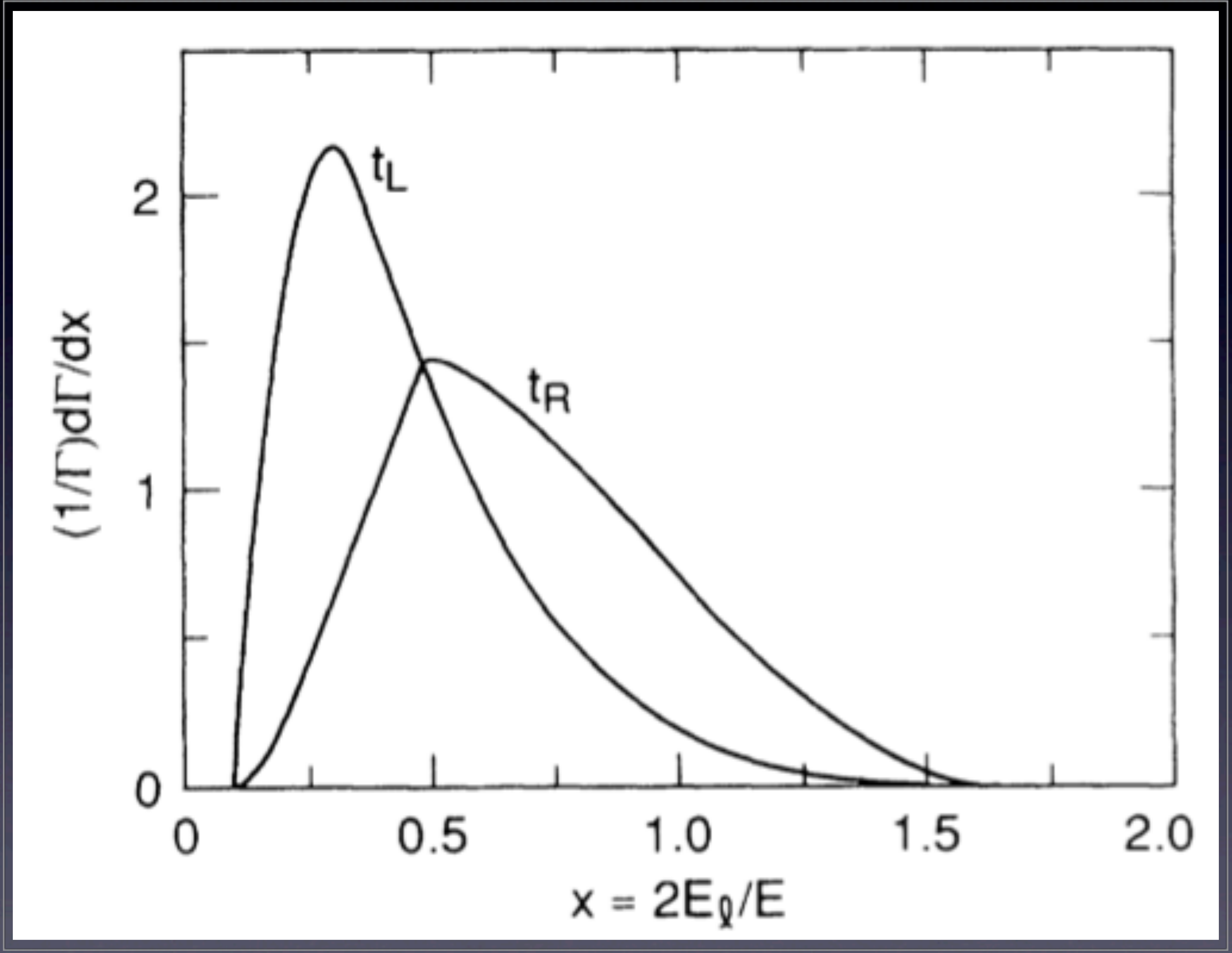
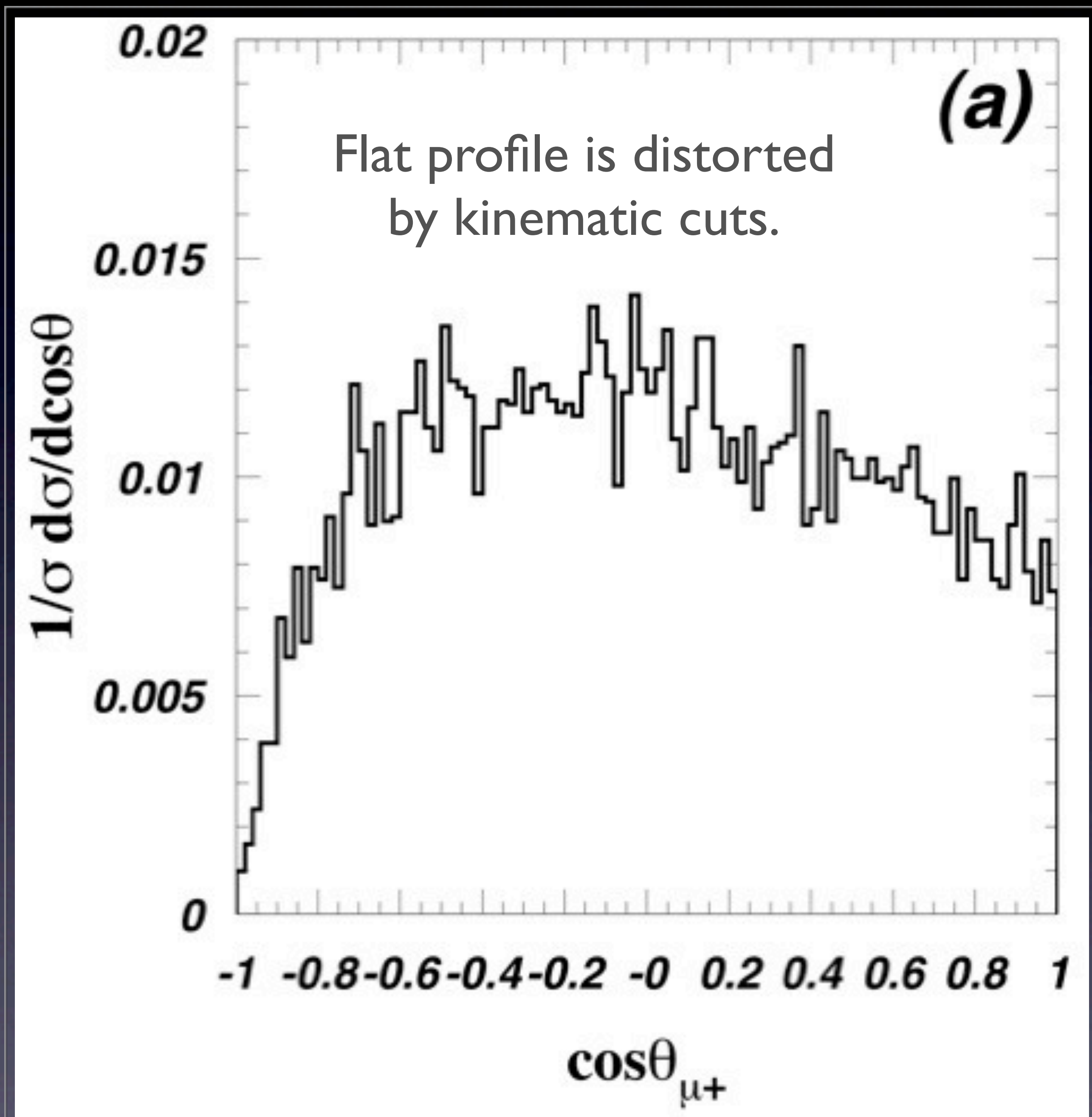


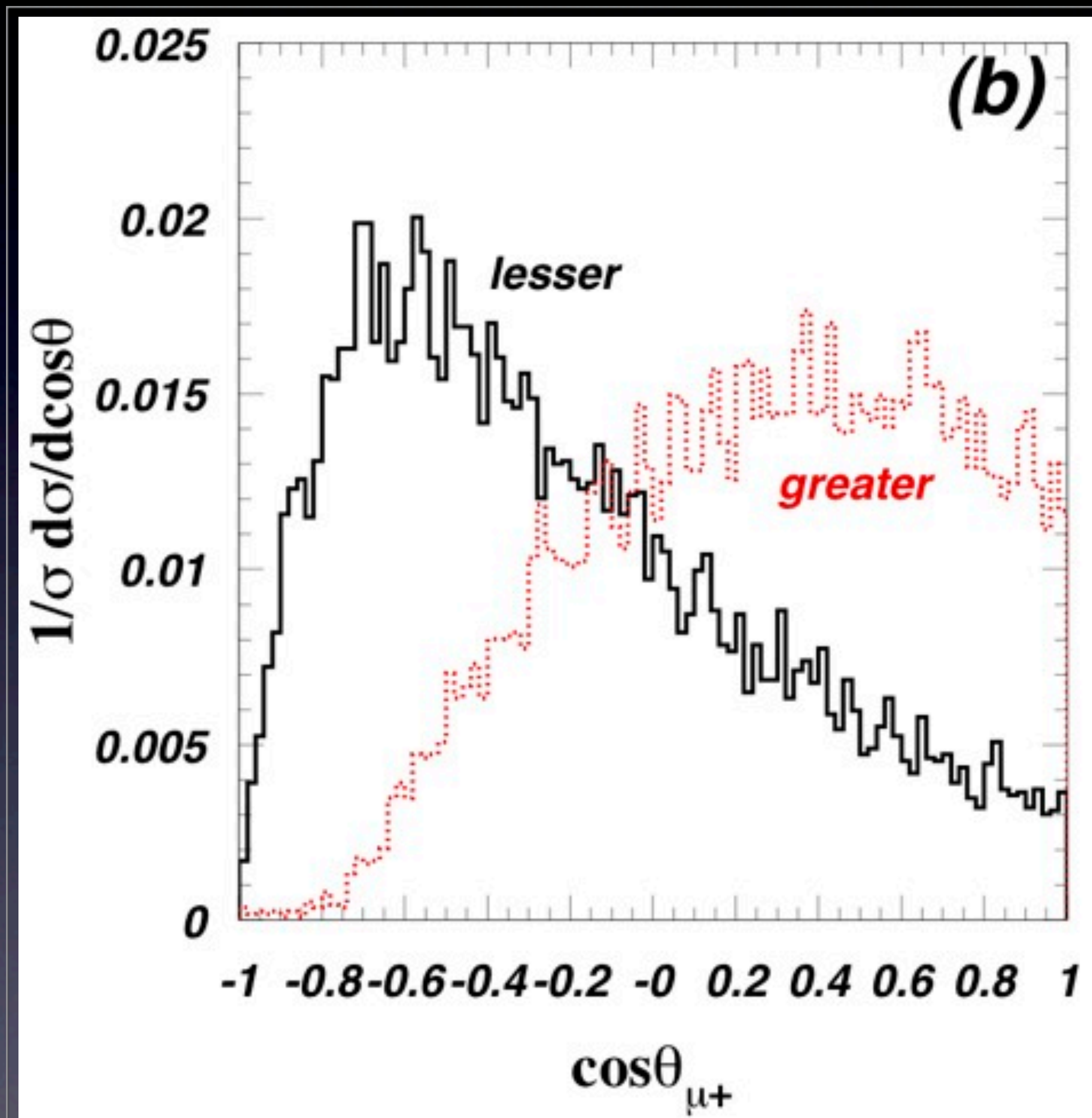
C. R. Schmidt and M. E. Peskin, Phys Rev Lett 69 (1992) 410

Top-polarization: color sextet vector

★ Before lepton energy selection



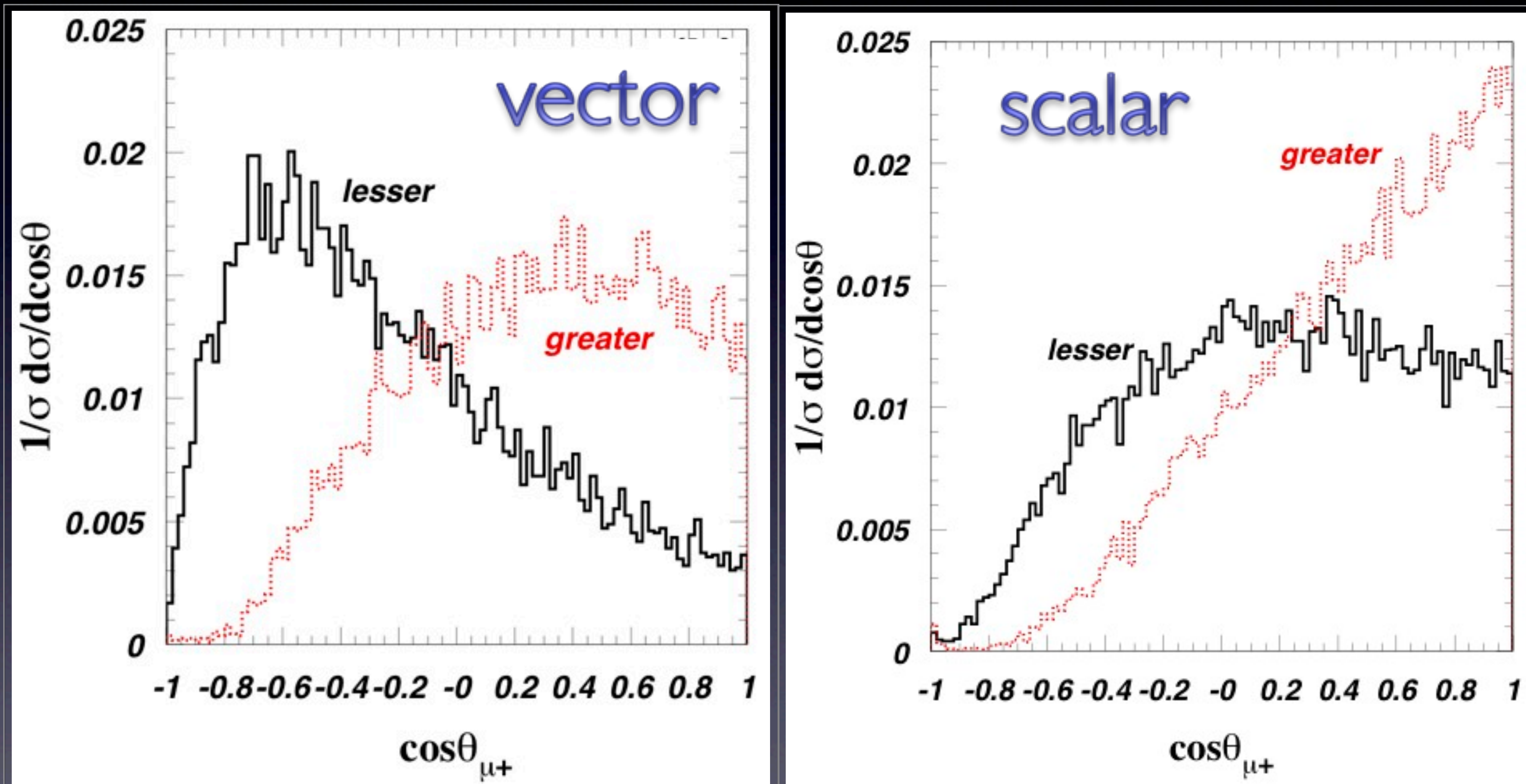
★ After lepton energy selection



Roughly 98 (67) events required to distinguish vector lesser (greater) from vector unpolarized case

Top-polarization: color sextet vector

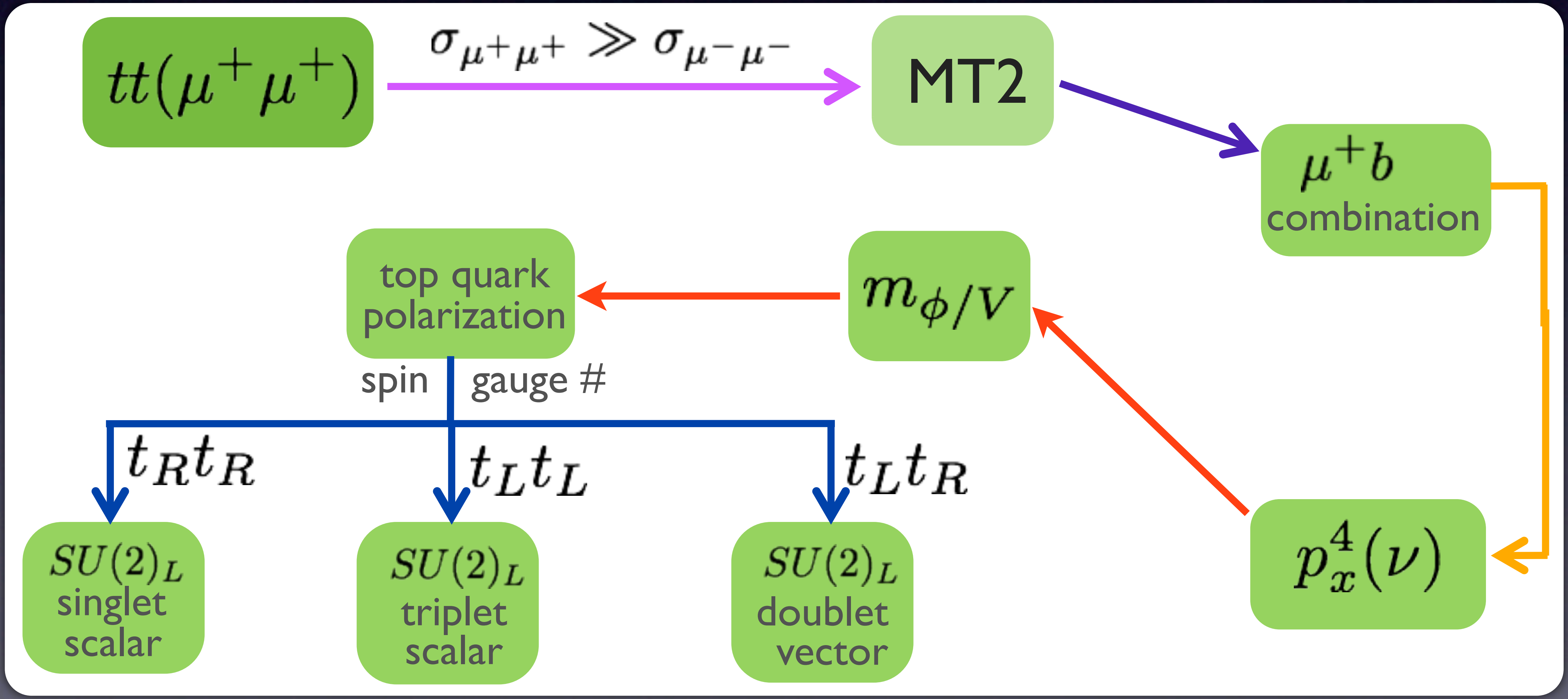
★ Apply the same analysis to sextet scalar (gauge singlet)



The $\frac{1}{2}(1+\cos\theta)$ shape of sextet scalar still remains with a moderate distortion.

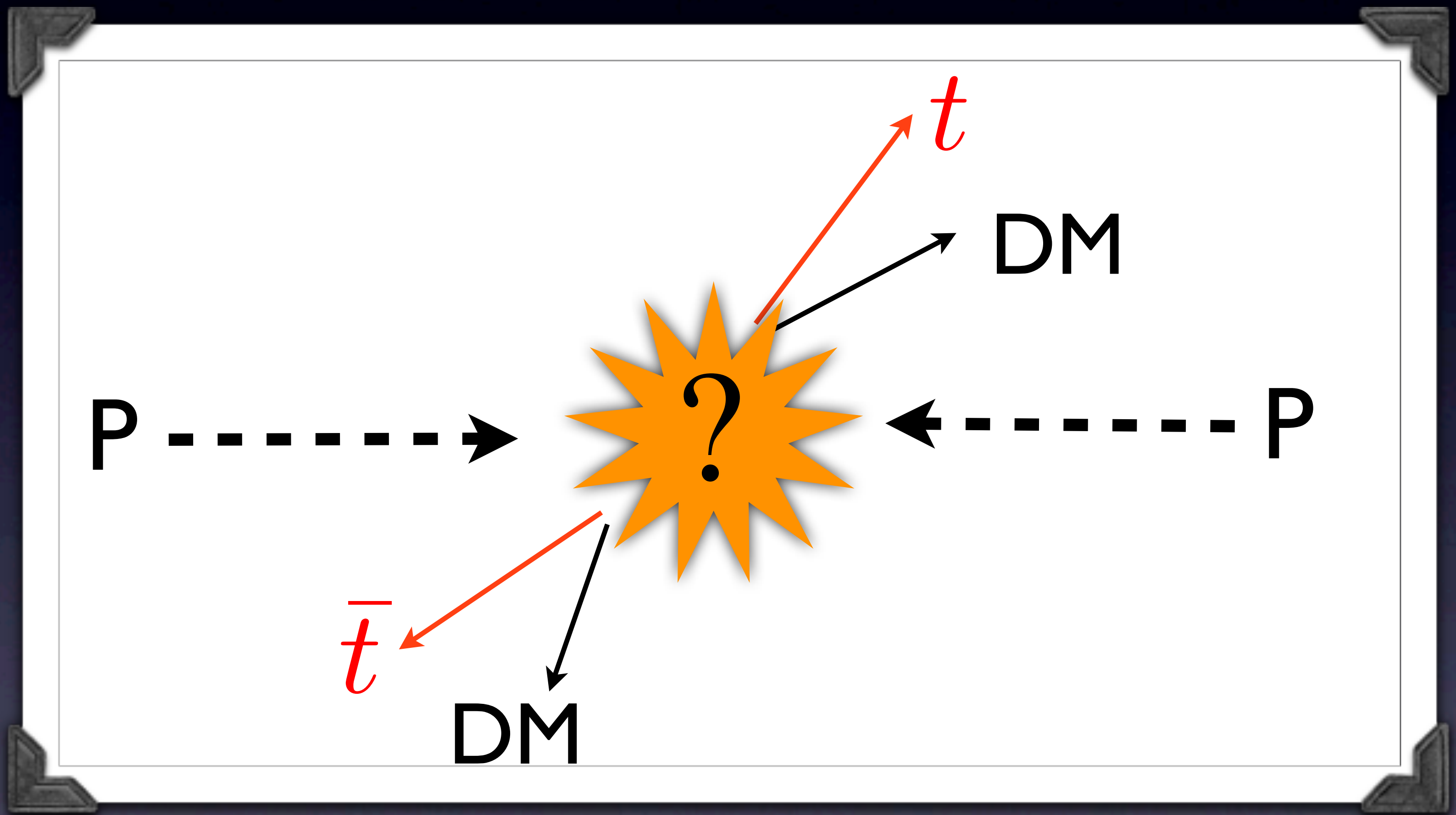
Interim summary

- ★ Color sextet scalar and vector mesons may be a long shot they offer good discovery potential in early LHC running at 7 TeV
  - ✳ Enhanced cross sections relative to EW scale new physics
  - ✳ 30 events (scalar) and 100 events (vector) sufficient
  - ✳ Naturally large same-sign dilepton rates allow background rejection
- ★ Search strategy



New Physics Models
(2) with DM candidates

Berger, QHC, Jianghao Yu and Hao Zhang, in preparation

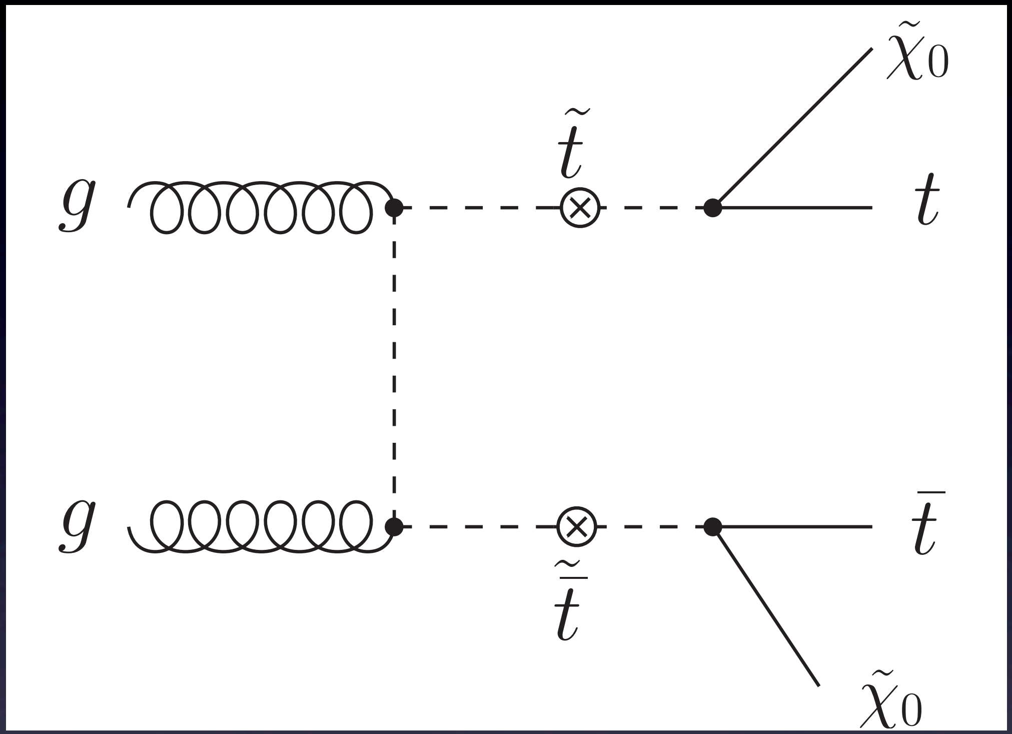


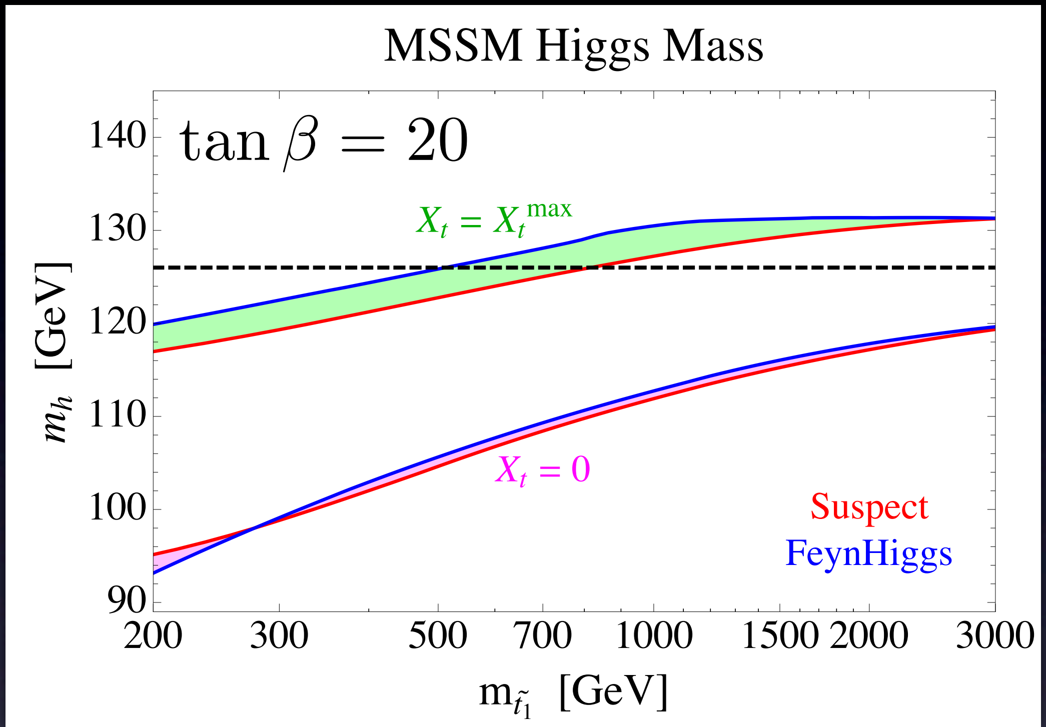
<u>Measuring top-quark polarization *without* reconstructing top-quark kinematics</u>

NP signature: Top-antitop plus MET

- Stop-quark pair production in the MSSM

Hall, Pinner and Ruderman, 1112.2703

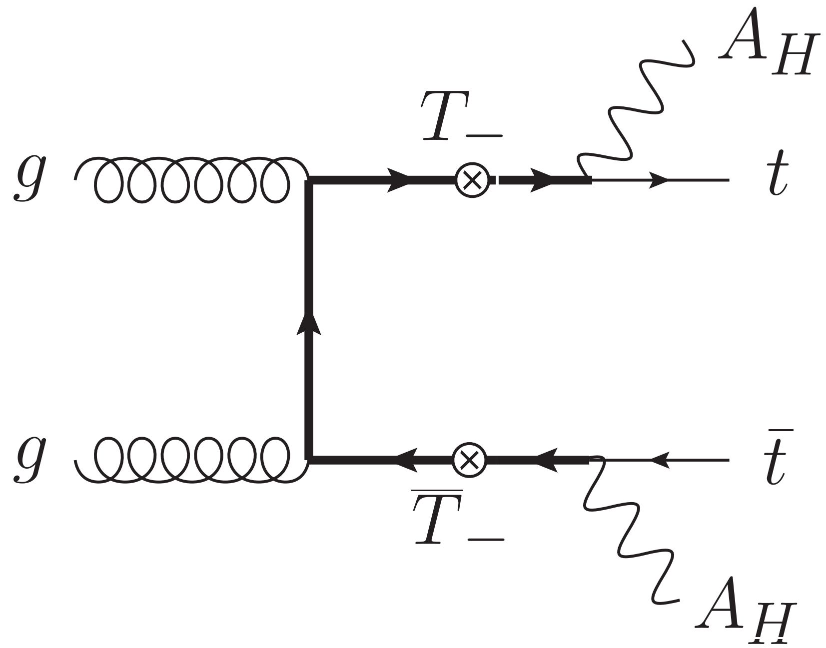


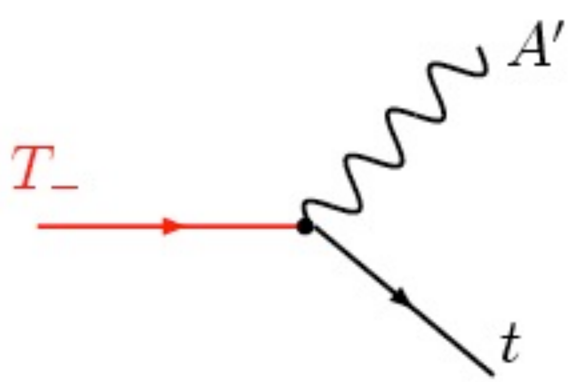


- A light stop-quark is preferred to rise m_h to 125 GeV in the maximal mixing scenario.
- Top-polarization could shed lights on the stop-quark mixing matrix.

NP signature: Top-antitop plus MET

- T-odd top-quark partner pair production in the LHT

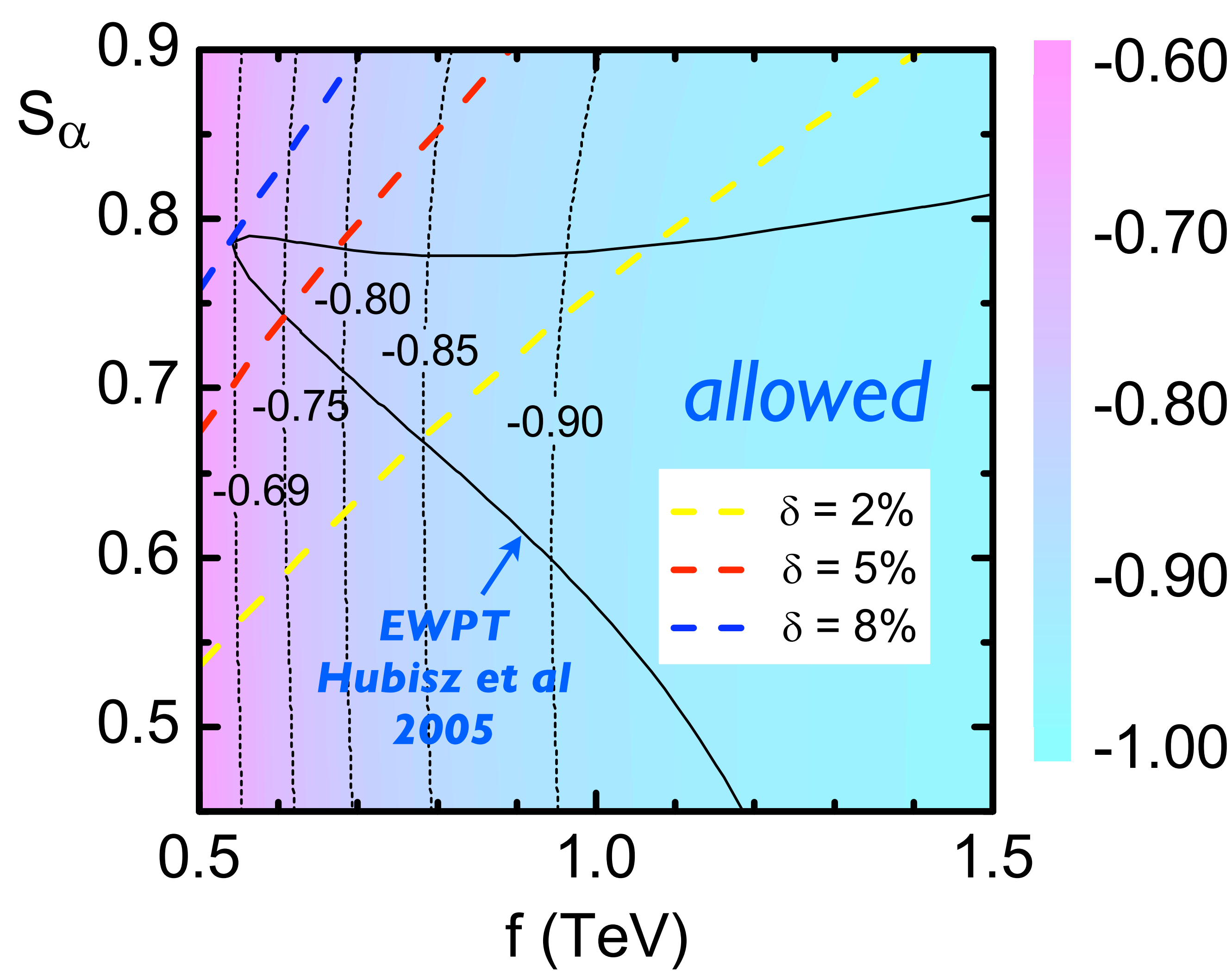




$$\frac{2}{5} g' c_\alpha \gamma_\mu \left(c_\alpha \frac{v}{f} P_L + P_R \right)$$

QHC, Li, Yuan, Phys.Lett. B668 (2008) 24

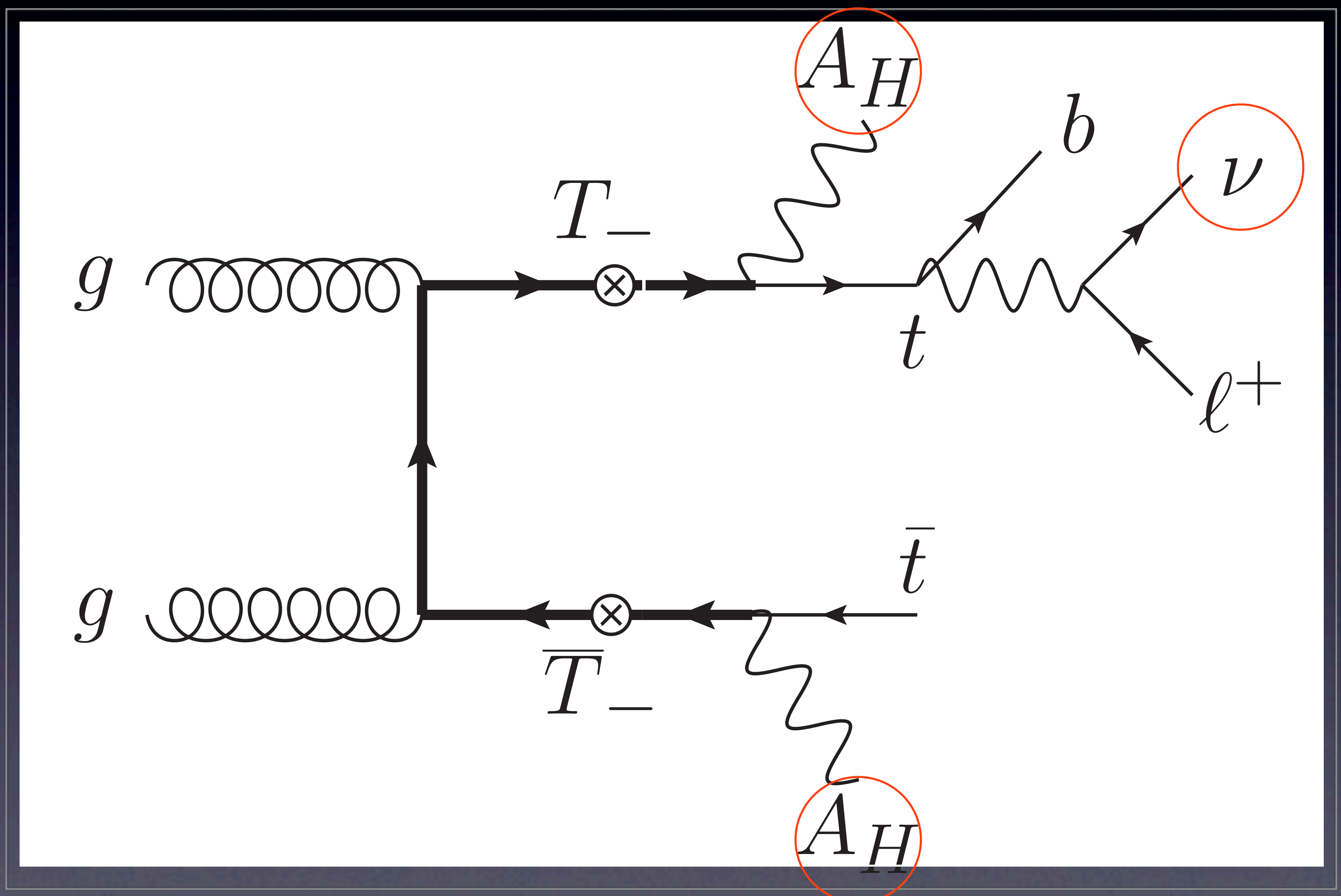
$$\mathcal{A}_{LR} \equiv \frac{\sigma(t_L) - \sigma(t_R)}{\sigma(t_L) + \sigma(t_R)}$$



Difficulty in NP signature of ttbar plus MET

- It is impossible to reconstruct a top-quark in the leptonic-decay mode.

  Angular distribution of the charged-lepton cannot be used.



assuming $p_{\bar{t}}$ is known

10 unknowns
-2 from MET

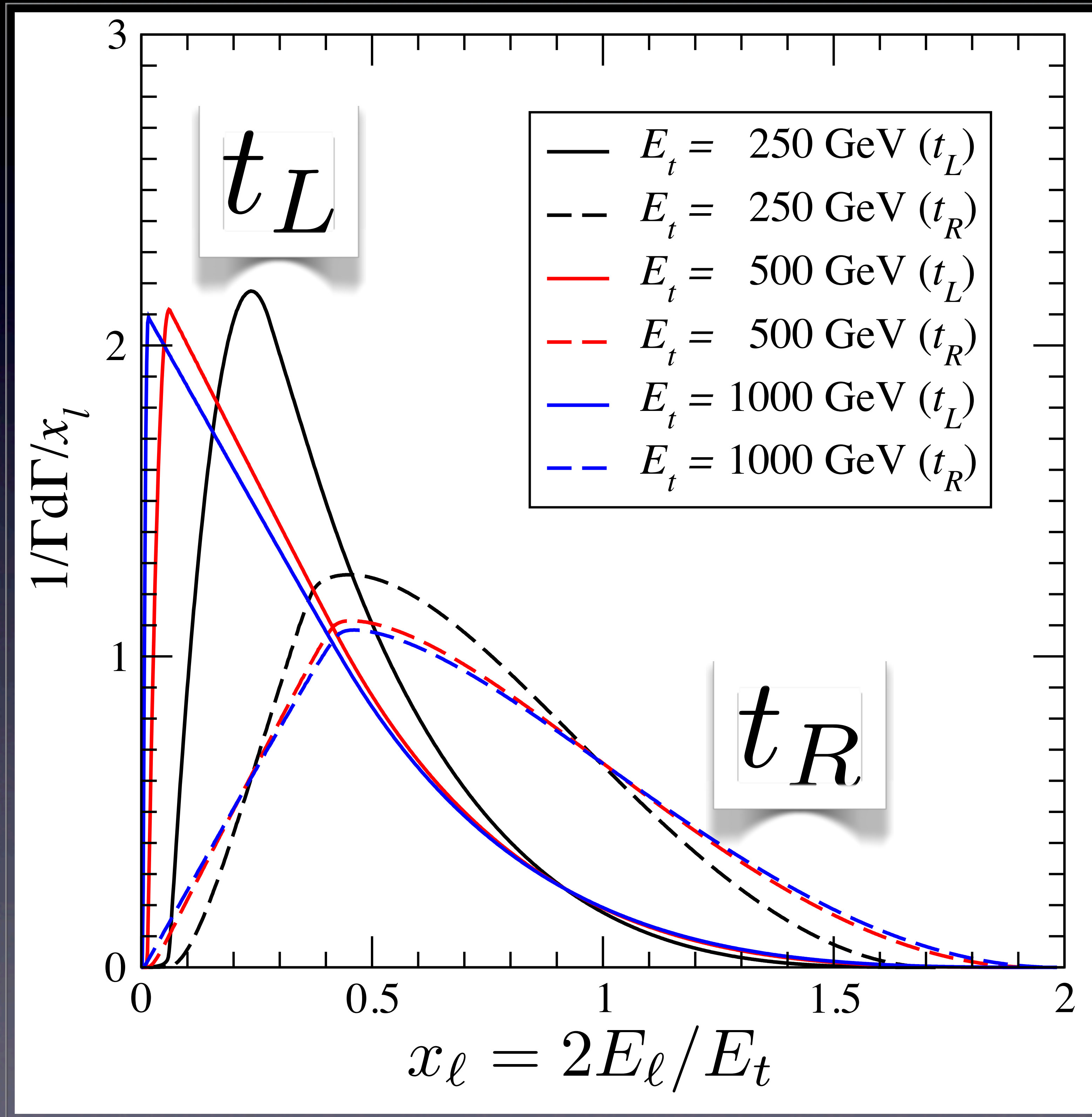
↓

No enough constraints

Can we measure top-quark polarization? Yes !!!

Lepton energy and top-quark polarization

★ Lepton energy distribution is sensitive to top quark polarization.



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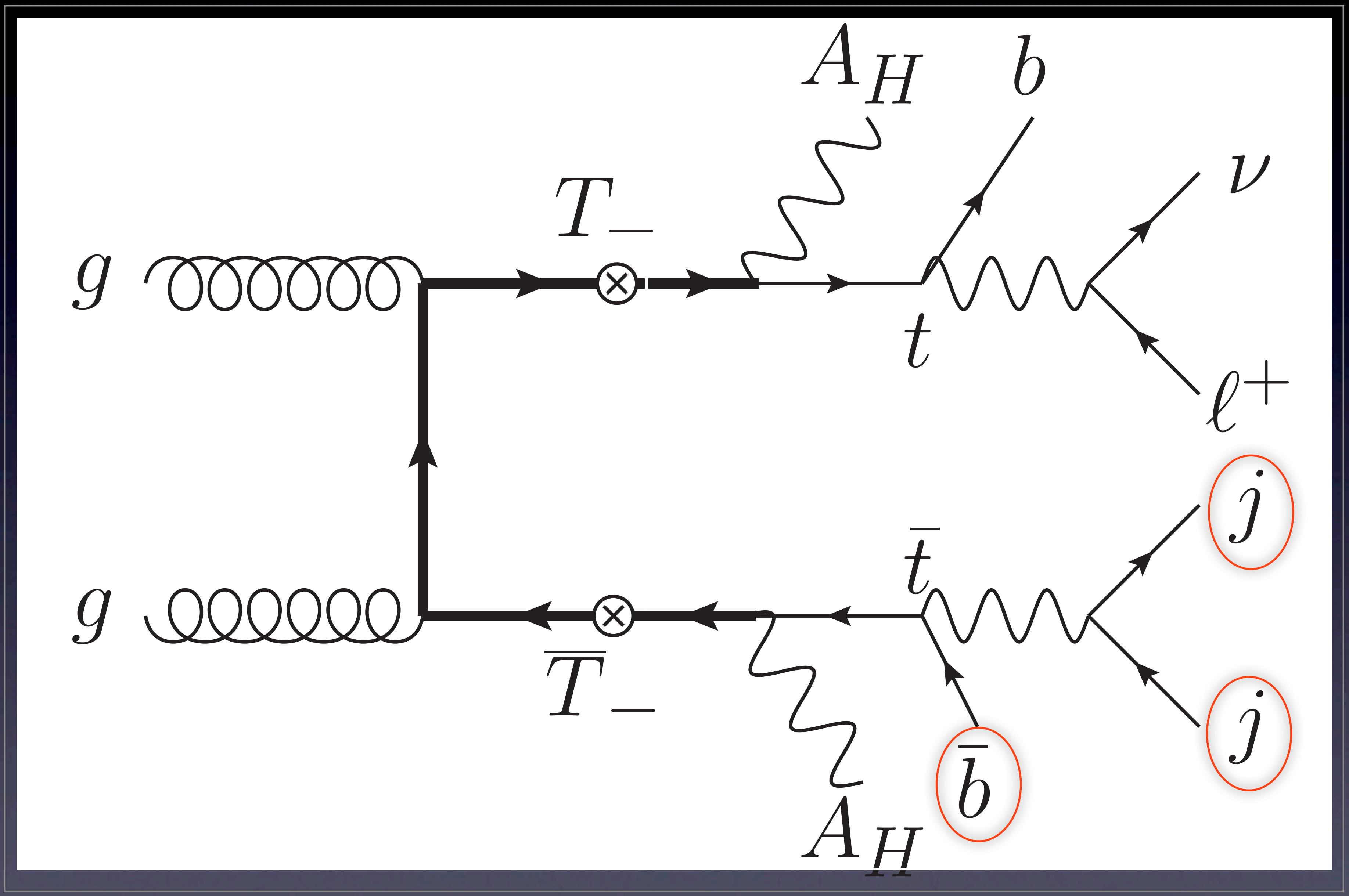


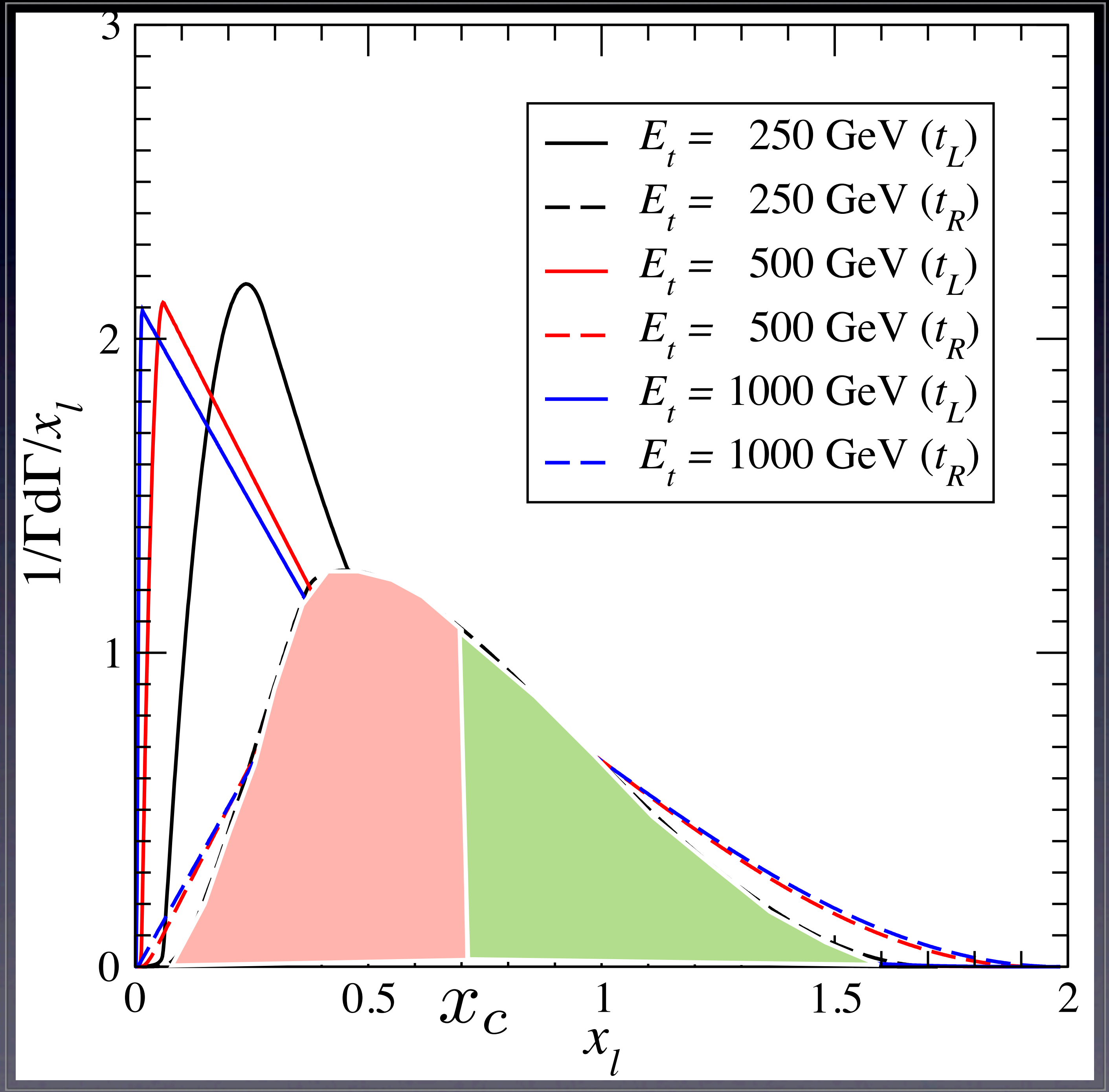
$$x'_\ell = 2E_{\ell^+} / E_{\bar{t}}$$

Lepton energy and top-quark polarization

- Define a useful variable $\mathcal{R}$:

$$\mathcal{R} = \frac{\int_0^{x_c} \frac{d\sigma}{dx_\ell} dx_\ell}{\int_{x_c}^{2} \frac{d\sigma}{dx_\ell} dx_\ell}$$

$$\equiv \frac{\sigma(x < x_c)}{\sigma(x > x_c)}$$



Toy models mimicking MSSM and LHT

★ MSSM like: $m_{\tilde{t}} = 800\ \text{GeV}, \quad m_{\tilde{\chi}} = 100\ \text{GeV}$

Purely left-handed *or* *Purely right-handed*

★ LHT like: $m_{T\_} = 1000\ \text{GeV}, \quad m_{A_H} = 100\ \text{GeV}$

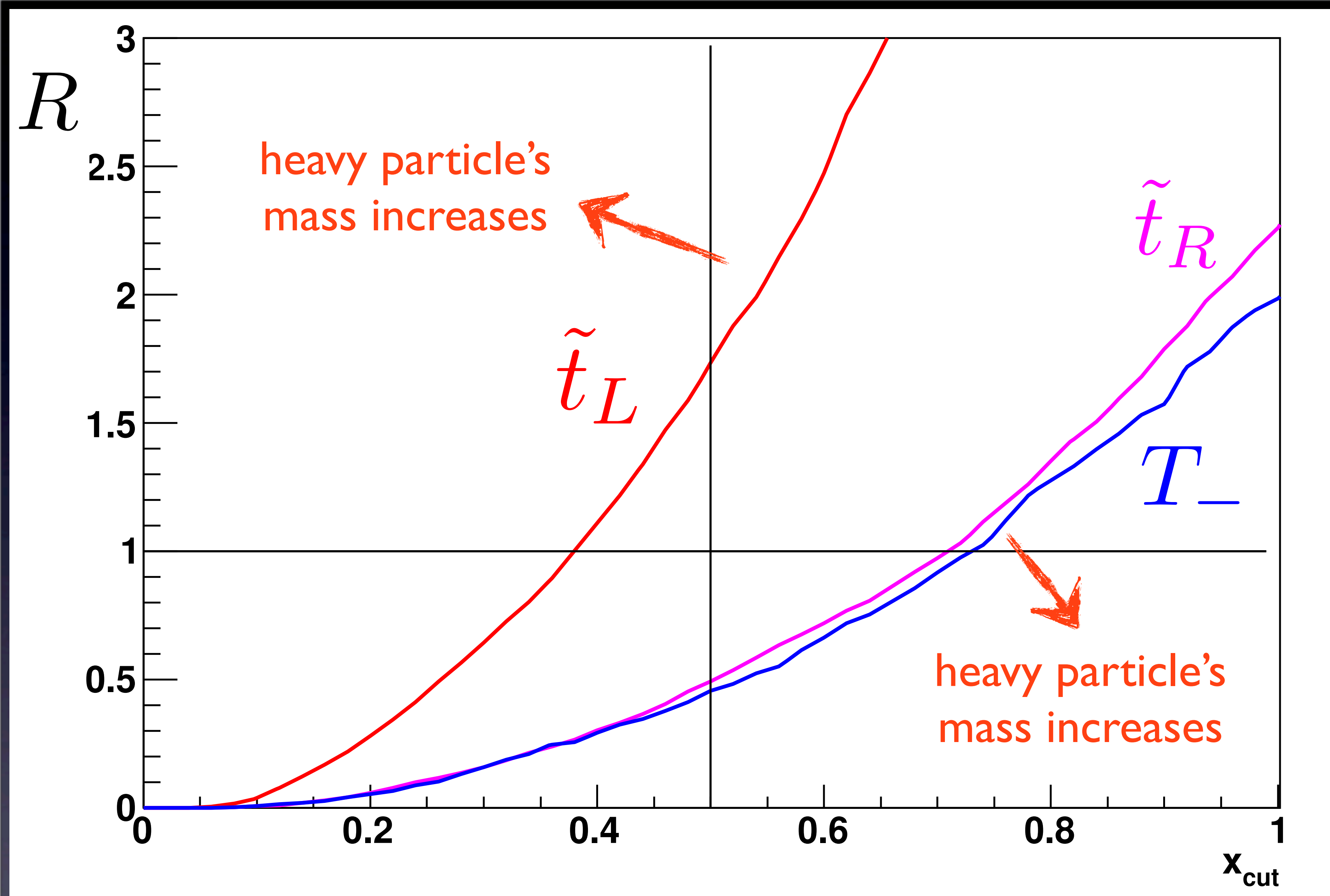
- Preliminary study of collider simulation

$p_T^{\ell} > 50\ \text{GeV} \quad p_T^{j} > 50\ \text{GeV} \quad \not{E}_T > 100\ \text{GeV}$

$|\eta_{\ell,j}| < 2.5 \quad \Delta R_{jj,\ell j} > 0.4 \quad H_T > 400\ \text{GeV}$

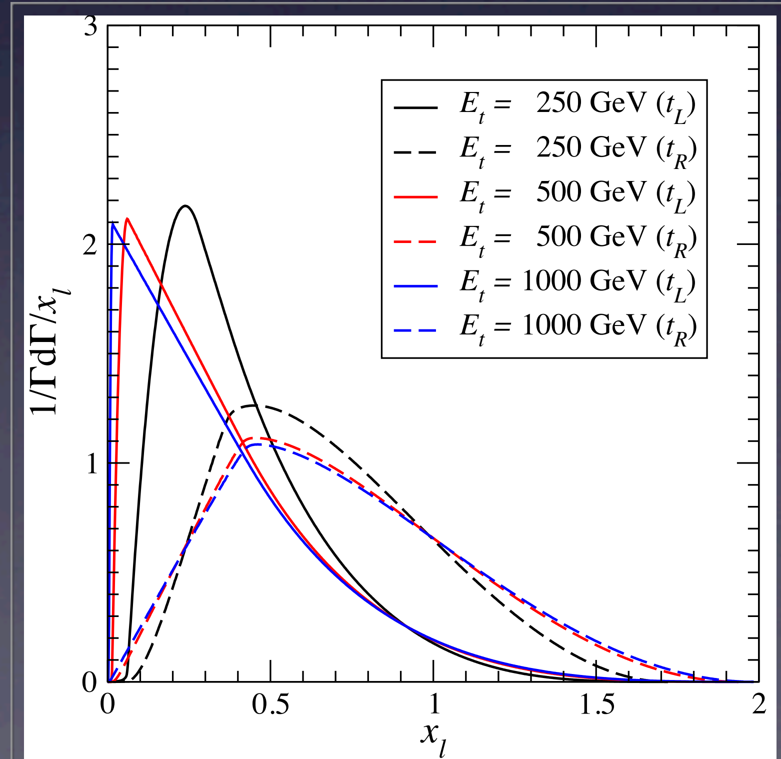
Minimal-χ^2 theme is used to pick up three jets from top-quark hadronic decay.

Preliminary results



Stat. & Sys. uncertainties and background study is needed

SPIN before MASS



Summary

- Top-quark polarization provides much richer info of new physics beyond the Standard Model.

- MT2 variable is good at solving the combinatory of multiple indistinguishable particles in the final state.

- Lepton energy (long ignored) could also be used to measure top-quark polarization, especially in NP models consisting of dark matter candidates.

THANK YOU !