Quy Nhon, Vietnam July 15 - 21, 2012

Top Quark Polarization and the Search for New Physics

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Based on work in collaboration with:

Qing-Hong Cao, Chuan-Ren Chen. Jianghao Yu, and Hao Zhang

arXiv: 1101.5625 Phys. Rev. Lett. 106, 201801 (2011);

arXiv: 1111.3641, Phys. Rev. Lett. 108, 072002 (2012);

arXiv: 1207.1101 (July 2012)

Outline

- **Semi-leptonic top quark decay.** Methods to measure the top quark polarization
- **New physics interpretations of the top quark rapidity asymmetry** at the Tevatron -- what, in addition, do we learn from the decay lepton asymmetry

$$\mathcal{A}^{\ell}_{\rm FB} = \frac{N(q_\ell y_\ell > 0) - N(q_\ell y_\ell < 0)}{N(q_\ell y_\ell > 0) + N(q_\ell y_\ell < 0)}$$

- **Models** (axigluon model and right-handed W' model) and the decay lepton asymmetry
- **Implications for the LHC**: same sign top pairs; rapidity asymmetry
- **Models with dark matter candidates** -- added information from top quark polarization

Top quark: most massive of the SM

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

- Large mass suggests sensitivity to symmetry breaking and BSM effects

- Experiment -- Tevatron deviation from SM expectations of the F/B rapidity asymmetry for top

- Various models of new physics proposed to interpret the asymmetry data (e.g, W', Z', ...) invoke right-handed couplings of the top quark

- Other new physics schemes -- unrelated to the asymmetry -- also favor right-handed couplings; valuable to measure polarization of top quarks

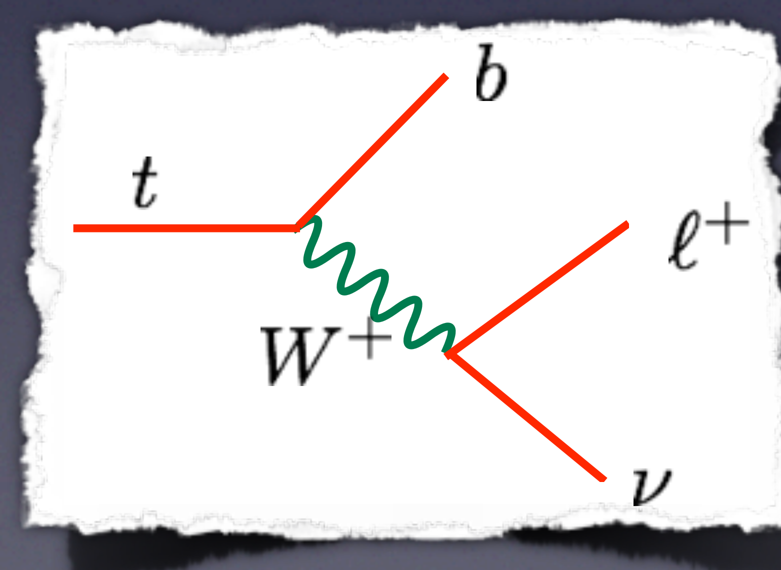
Top quark

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

$\frac{1}{m_t}$ $\frac{1}{\Gamma_t}$ $\frac{1}{\Lambda_{QCD}}$ hadronization

5×10^{-27} s 5×10^{-25} s 3×10^{-24} s

- "bare" quark： spin info retained among decay products in (V-A) interaction



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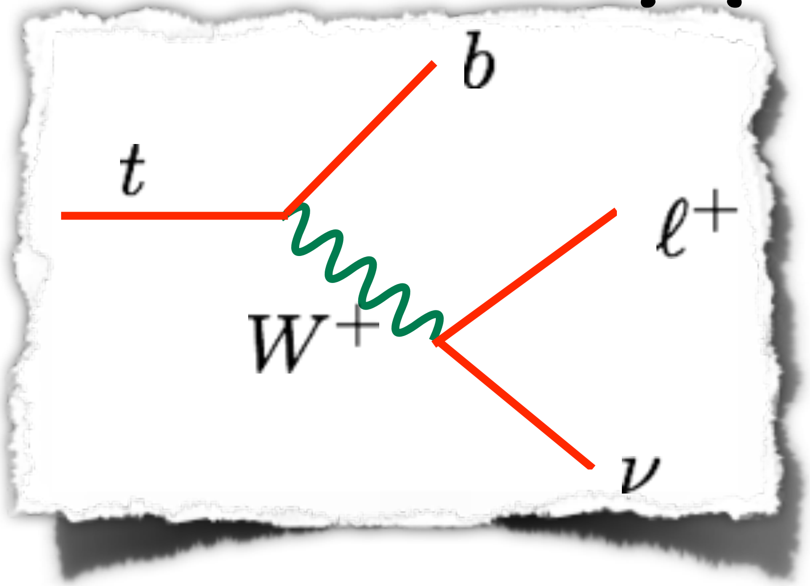
Two Methods to Measure Top Polarization

- A. Lepton angular distribution in top quark rest frame -- maximally correlated with the top quark spin orientation.



  - Method requires full reconstruction of the top quark kinematics, e.g., with MT2 method

- B. Lepton momentum distribution -- useful for more complex final states, e.g., when missing energy from dark matter candidates is present (arXiv:1207.1101)

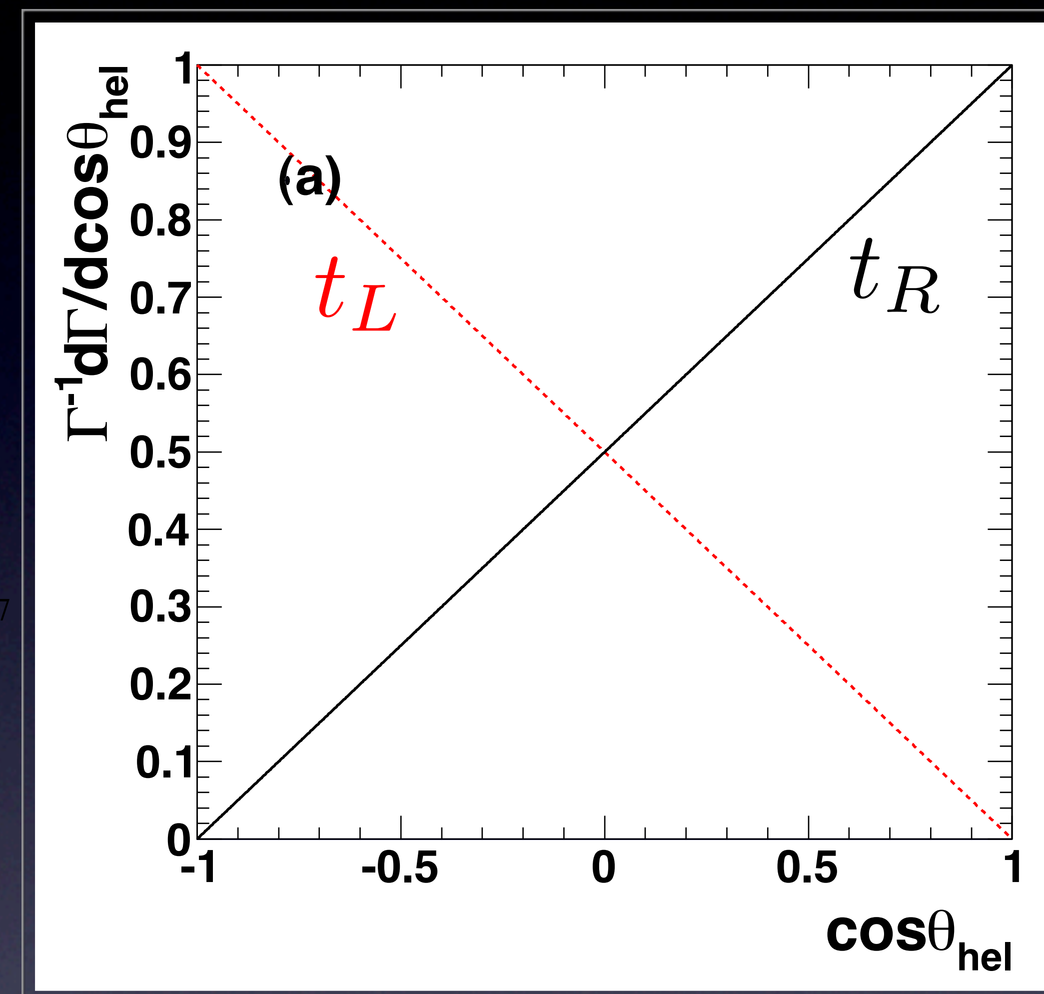
Angular distribution of decay lepton is a top quark spin analyzer

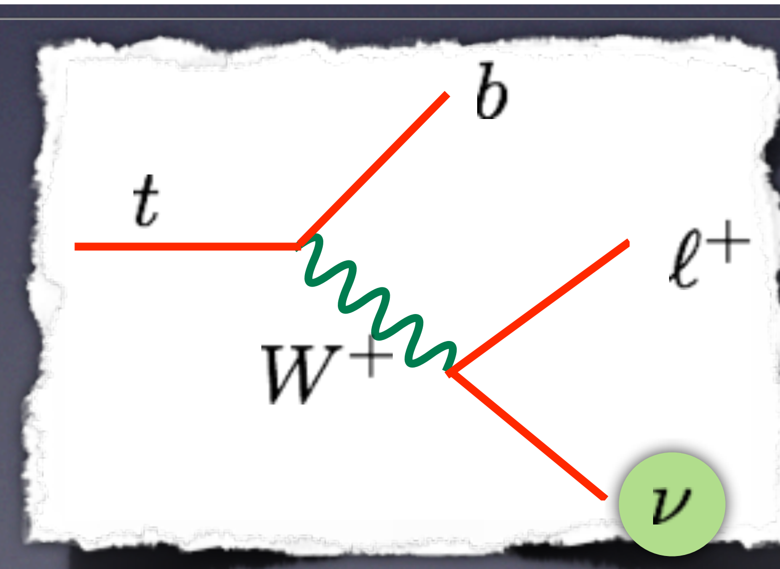
- In the top-quark rest frame

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

$\lambda_t = +$ right-handed

$\lambda_t = -$ left-handed

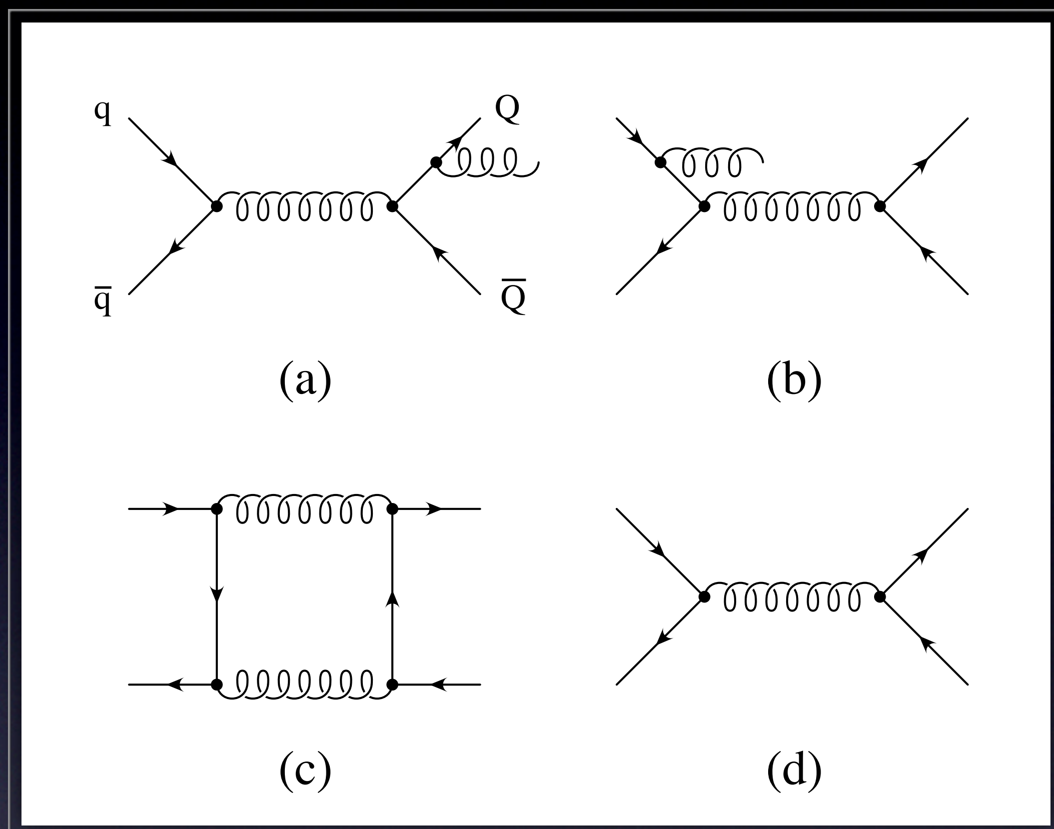


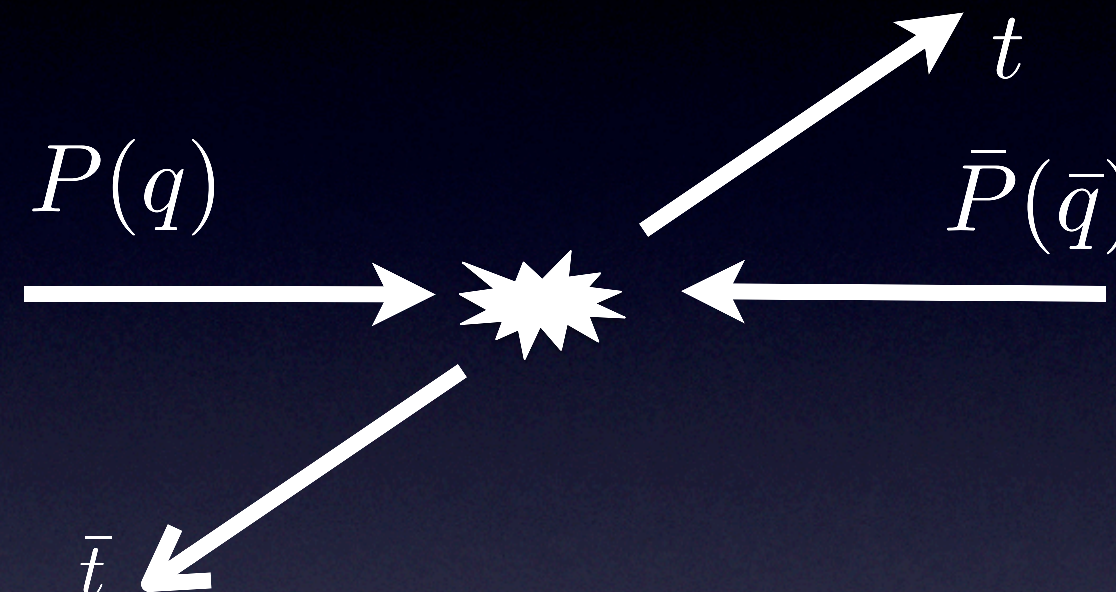


II. Top quark forward-backward asymmetry

Top-quark F-B asymmetry in the SM

- A charge asymmetry arises at NLO





Top quarks are produced along the direction of the incoming quark

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

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

Top AFB from Tevatron

- CDF collaboration (CDF Note 10807)

CDF Run II Preliminary L = 8.7 fb^{-1}

Parton Level	NLO (QCD+EW) $t\bar{t}$	5.3 fb^{-1}	8.7 fb^{-1}
$\|\Delta y\|$	A_{FB}	A_{FB} (±[stat.+syst.])	A_{FB} (±[stat.+syst.])
Inclusive	0.066	0.158 ± 0.074	0.162 ± 0.047
< 1.0	0.043	0.026 ± 0.118	0.088 ± 0.047
≥ 1.0	0.139	0.611 ± 0.256	0.433 ± 0.109

Parton Level	NLO (QCD+EW) $t\bar{t}$	5.3 fb^{-1}	8.7 fb^{-1}
$M_{t\bar{t}}$	A_{FB}	A_{FB} (±[stat.+syst.])	A_{FB} (±[stat.+syst.])
$< 450 GeV/c^2$	0.047	-0.116 ± 0.153	0.078 ± 0.054
$\geq 450 GeV/c^2$	0.100	0.475 ± 0.112	0.296 ± 0.067

- After the increase in luminosity, the discrepancy from the SM prediction is still nearly 3σ

A_{FB}^{t} and Some NP models

s-channel

Ferrario, Rodrigo
Axigluon
0809.3353

Antunan, Kuhn, Rodrigo
Axigluon
0709.1652

Frampton, Shu, Wang
Axigluon
0911.2955

Ferrario, Rodrigo
chiral G'
0906.5541

Djouadi, Moreau, Richard, singh
KK Gluon
0906.0604

EFT

Q-H.Cao et al
Effective coupling
(G', Z', W', H^0, H^+)
1003.3461

Jung, Ko, Lee, Nam
EFT
0912.1105

2007, 2008 → 2009 → 2010, 2011

t-channel

Jung, Murayama, Pierce, Wells
FCNC Z-prime
0907.4112

Cheung, Keung, Yuan
FC W-prime
0908.2589

Shu, Tait, Wang
Color Sextet/triplet scalar
0911.3237

Arhrib, Benbrik, Chen
Color Sextet/triplet scalar
0911.4875

J. Cao, Heng, Wu, Yang
$\not{R}$-SUSY and TC2
0912.1447

NLO QCD

Xiao, Wang, Zhu,
NLO QCD to Z-prime
1006.2510

Yan, Wang, Shao, Li
NLO QCD to W-prime
1110.6684

Shao, Li, et al
NLO QCD to EFT
1107.4012

More insight (into these models) from Tevatron?

- D0 collaboration measured the lepton charge asymmetry

SM:

$$A^t_{FB} = 0.051 \pm 0.001$$
$$A^\ell_{FB} = 0.021 \pm 0.001$$
$$\frac{A^\ell_{FB}}{A^t_{FB}} \sim 40\%$$

D0:

$$A^t_{FB} = 0.196 \pm 0.065$$
$$A^\ell_{FB} = 0.152 \pm 0.040$$
$$\frac{A^\ell_{FB}}{A^t_{FB}} \sim 75\%$$

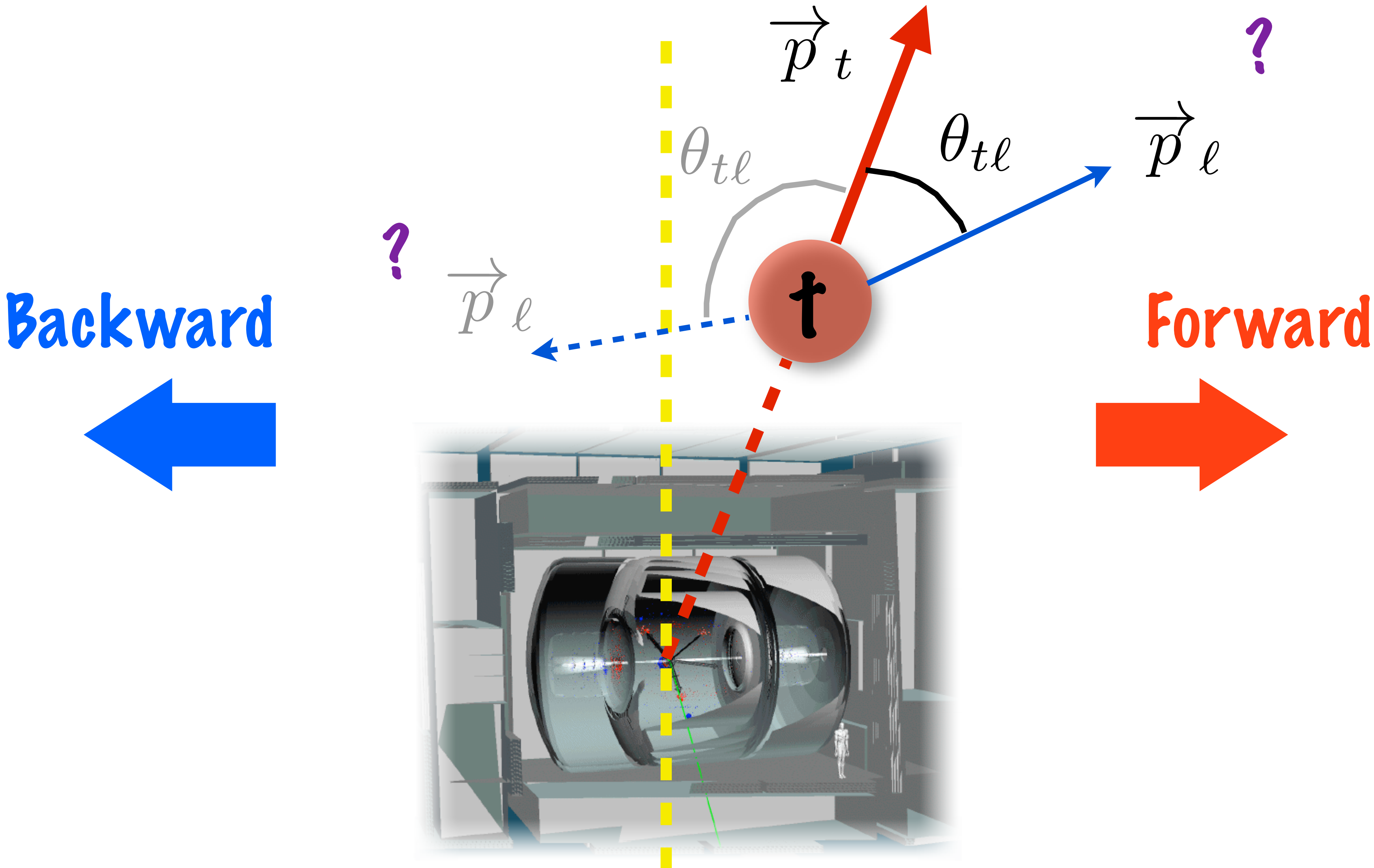
- Theoretically - for the same top quark momentum distribution, a left-handed top quark and a right-handed top quark leads to a different lepton charge asymmetry

- How can we relate AFB(lepton) and AFB(top)? Show here that AFB(lepton) provides independent insight into new physics models

From top AFB to lepton AFB

Top Leptonic Decay

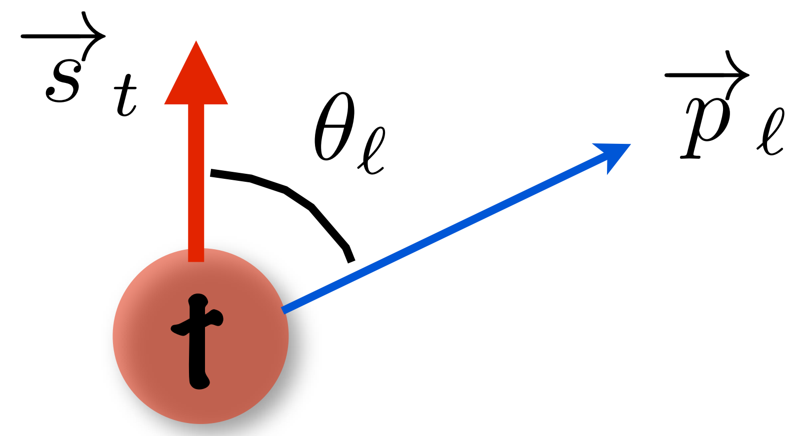
- If we know the momentum and spin direction of the top quark, what is the probability that the decay lepton is in the forward (backward) region in the laboratory frame?



Top Leptonic Decay

- Recall - in the top quark rest frame

$$\frac{d\Gamma}{\Gamma d\cos\theta_\ell} = \frac{1+\cos\theta_\ell}{2}$$

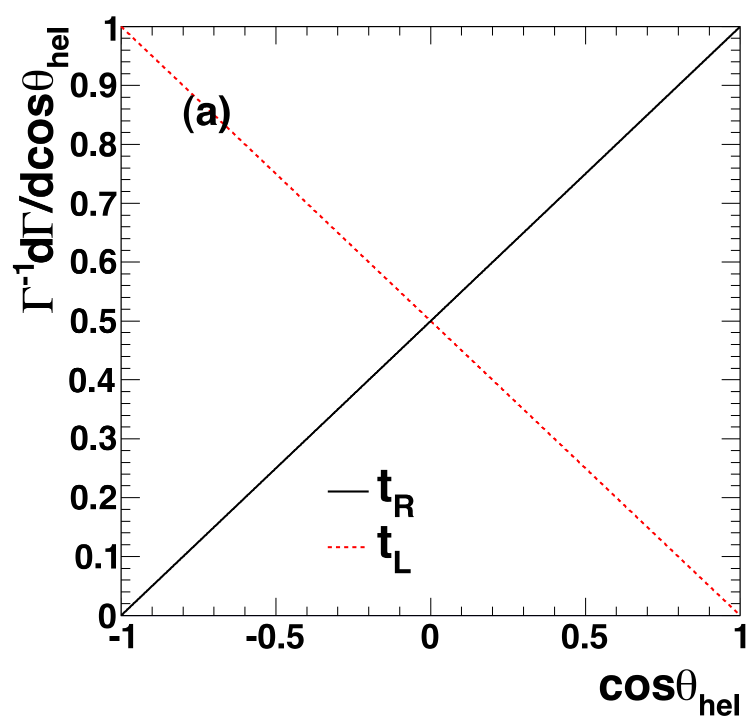


- In the helicity basis, the momentum direction of the lepton from a left(right)-handed top quark is opposite (same) as the top quark spin direction

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

$\lambda_t = +1$ — positive helicity, right-handed

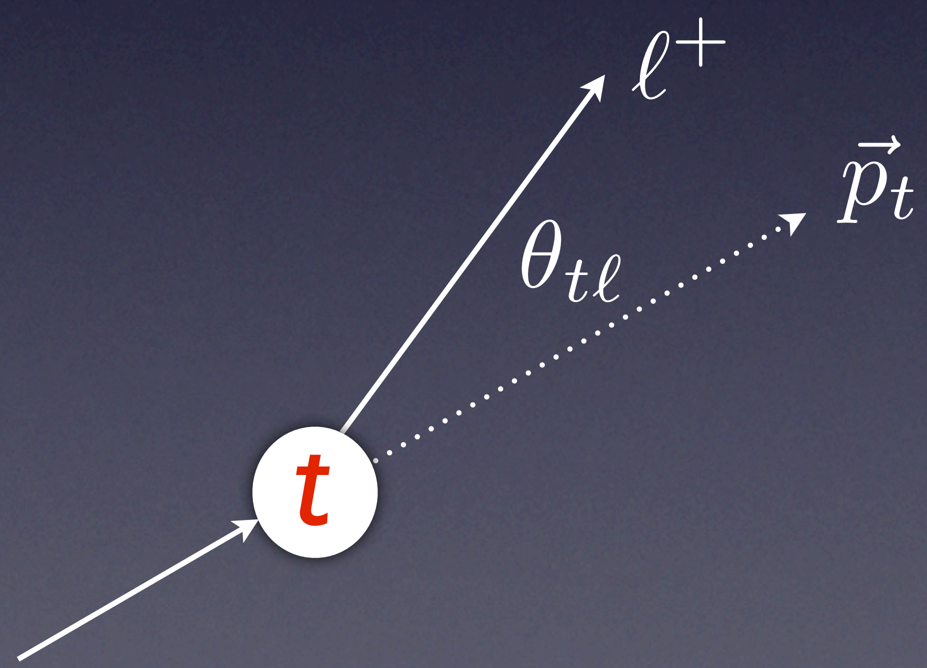
$\lambda_t = -1$ — negative helicity, left-handed

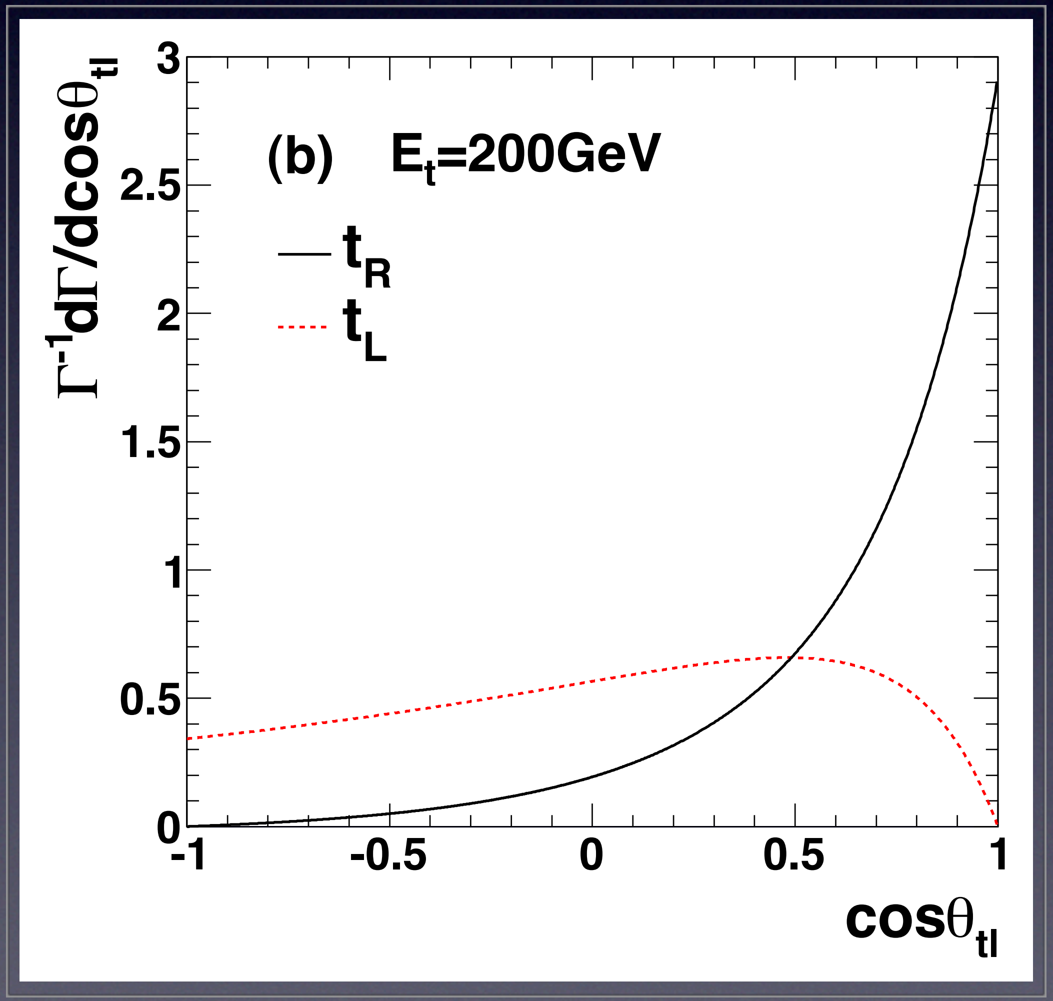


Charged lepton distribution

- When the top quark is boosted along the spin direction, the angular distribution becomes

$$\frac{d\Gamma}{\Gamma d\cos\theta_{t\ell}} = \frac{1-\beta\cos\theta_{t\ell}+\lambda_t\left(\cos\theta_{t\ell}-\beta\right)}{2\gamma^2\left(1-\beta\cos\theta_{t\ell}\right)^3}$$





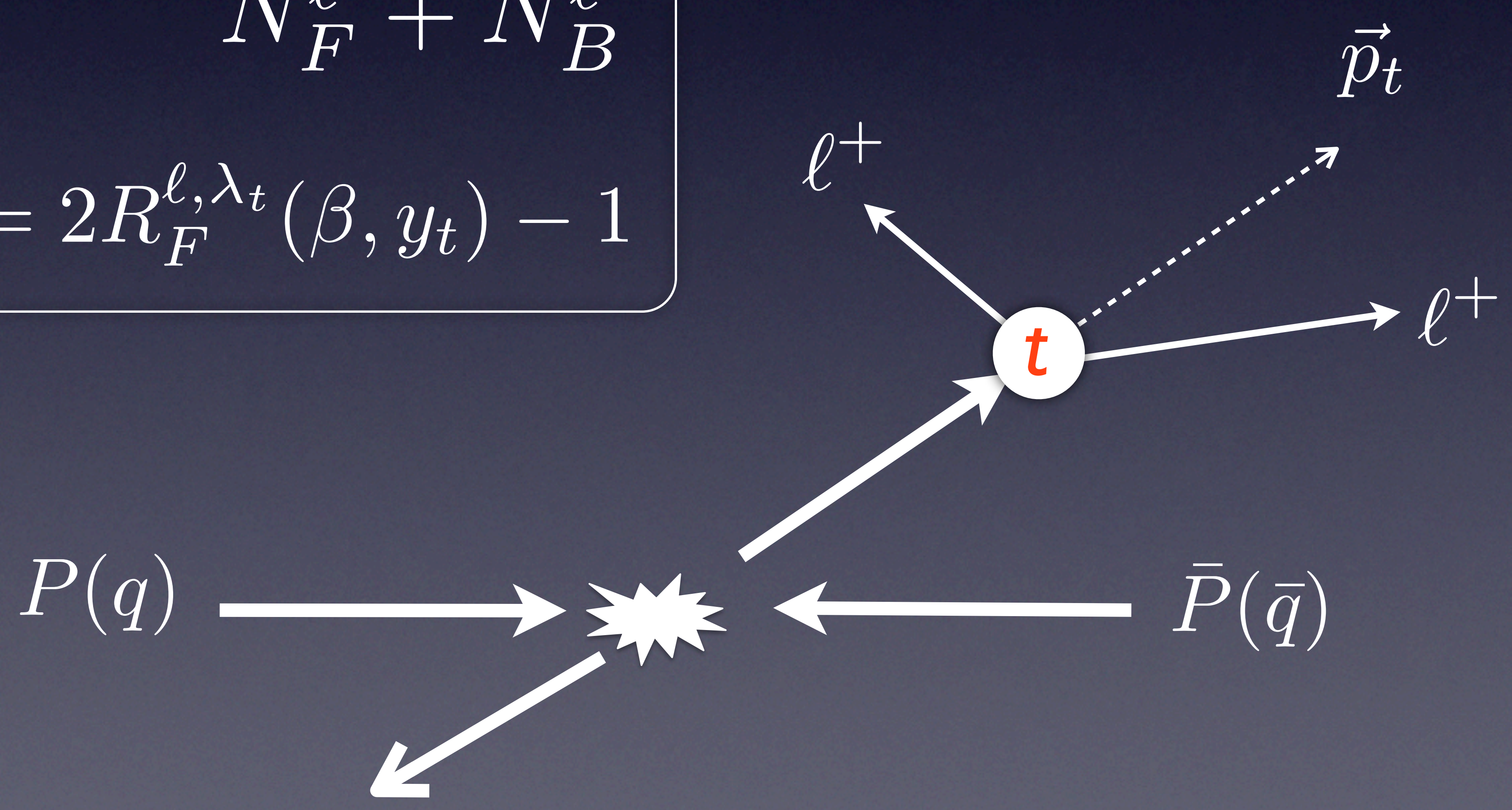
Next: rotate to the laboratory frame

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

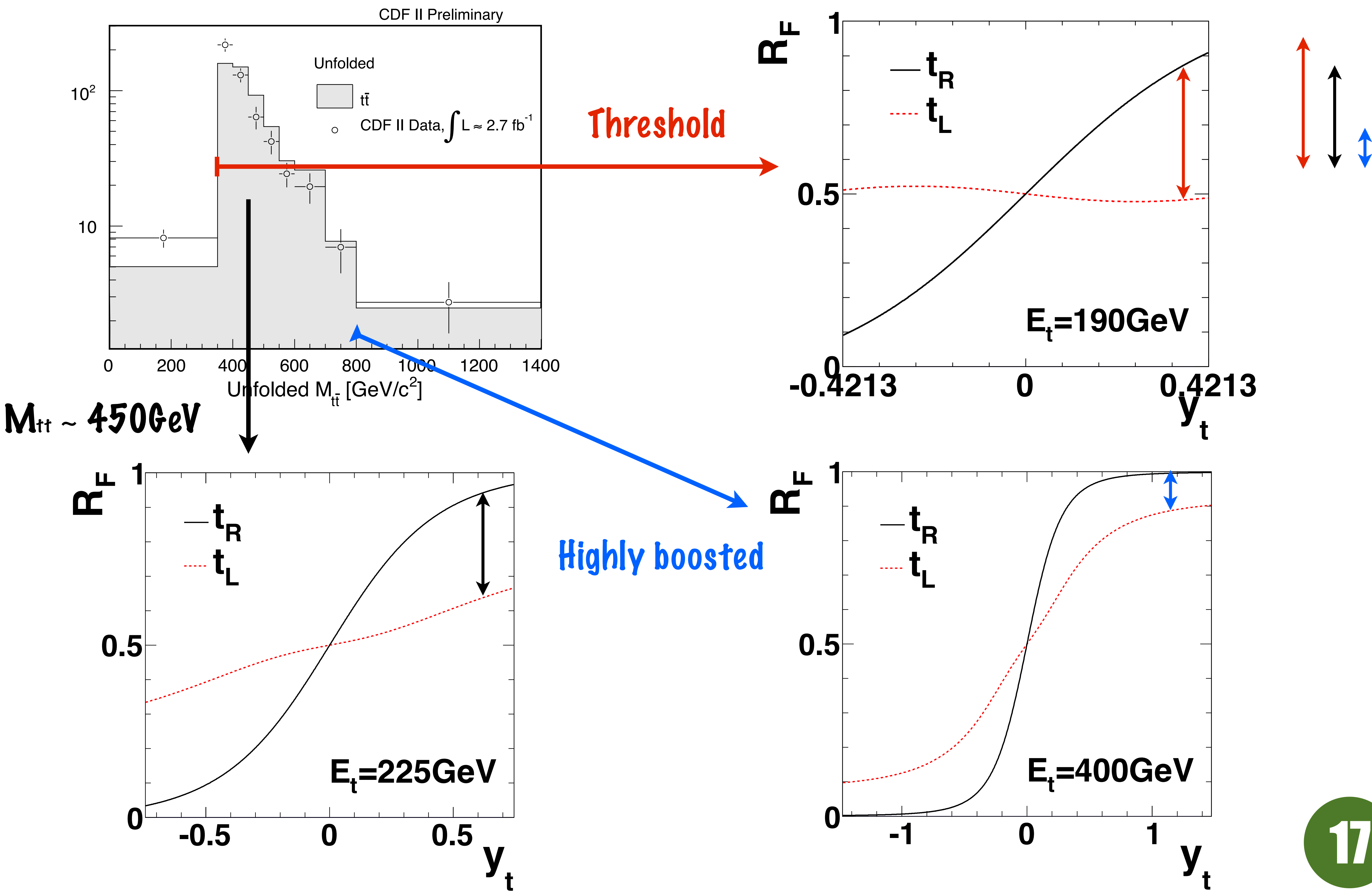
- Probability that the decay lepton is in the forward region of detector for a top-quark (β , y_t , λ_t) is encoded in an analytic expression arXiv:1201.1790

$$R_F^{\ell,\ \lambda_t}(\beta, y_t) = \frac{N_F^{\ell}}{N_F^{\ell} + N_B^{\ell}}$$

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



Top Leptonic Decay



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From Top AFB to Lepton AFB

- When we know the top quark AFB and the final state ttbar distribution, how to estimate the lepton AFB? Convolution of the function R with the top quark momentum spectrum is required

$$n_\ell^F = \frac{1}{\sigma}\sum_{\lambda=+,-}\int R_F^\lambda(\beta, y_t)\,\frac{d^2\sigma|_{\lambda_t=\lambda}}{d\beta dy_t} d\beta \wedge dy_t$$

$$n_\ell^B = \frac{1}{\sigma}\sum_{\lambda=+,-}\int \left[1 - R_F^\lambda(\beta, y_t)\right]\frac{d^2\sigma|_{\lambda_t=\lambda}}{d\beta dy_t} d\beta \wedge dy_t$$

$$\begin{aligned} A_{FB}^\ell =& n_\ell^F - n_\ell^B \\ =& \frac{1}{\sigma}\sum_{\lambda=+,-}\int \left[2R_F^\lambda(\beta, y_t) - 1\right]\frac{d^2\sigma|_{\lambda_t=\lambda}}{d\beta dy_t} d\beta \wedge dy_t \end{aligned}$$

From Top AFB to Lepton AFB

- For the SM, we have equal number of left-handed and right-handed top quarks in the final state.

- The dominant contribution is from the top quarks with energy around 200GeV,

  left-handed: $2R_F-1 \approx 0$

  right-handed: $2R_F-1 \approx 0.8$

$$\frac{A^{\ell}_{FB}}{A^{t}_{FB}} \approx \frac{0+0.8}{2} = 40\%$$

What do we learn from D0 Lepton AFB data?

- The D0 result

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

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

$$\frac{A_{FB}^{\ell}}{A_{FB}^{t}} \sim 75\%$$

Data require larger $2R_F-1$ than the SM

- Two possibilities:

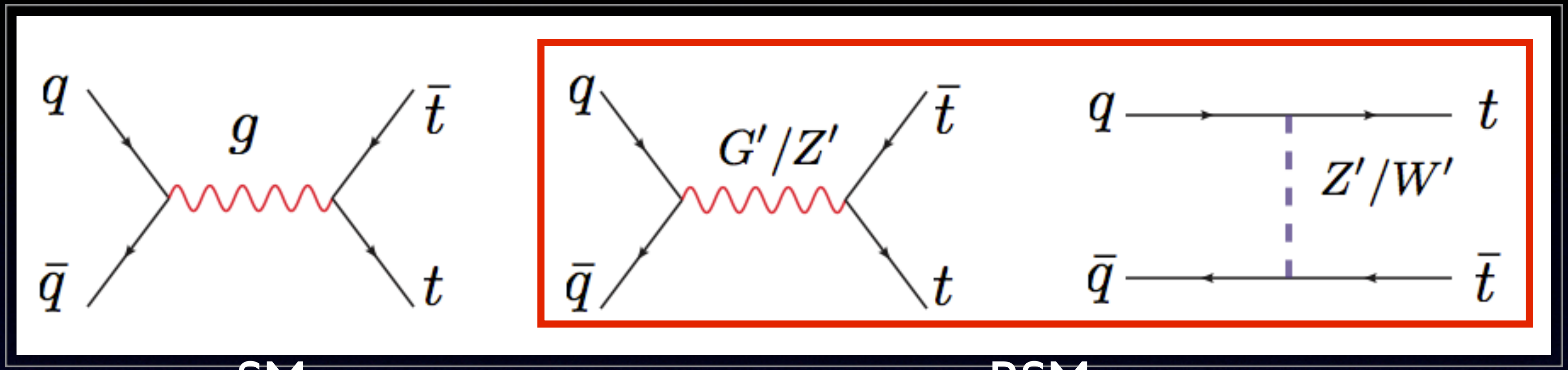
(1) If the contribution to AFB is dominated by the threshold region, the new physics must produce more right-handed top quarks

(2) Or the contribution to AFB must be from highly boosted region. But...

III. Two examples of New Physics Models

New physics models

NP models are divided into two classes



SM BSM

- *s*-channel: extra octet vector gluon (axigluon is an example)

  Small couplings to the first two generations: dijet constraints at 7 TeV
  Large couplings to third generation: to generate large A_{FB}
  Heavy resonances: ttbar invariant mass spectrum
  Very broad width: to interfere with the SM channel

- *t*-channel: flavor changing interaction

  color singlet: Z'-u-t (ϕ-u-t)
  W'$^{+}$-d-t (ϕ^{+}-d-t)

  color sextet or triplet

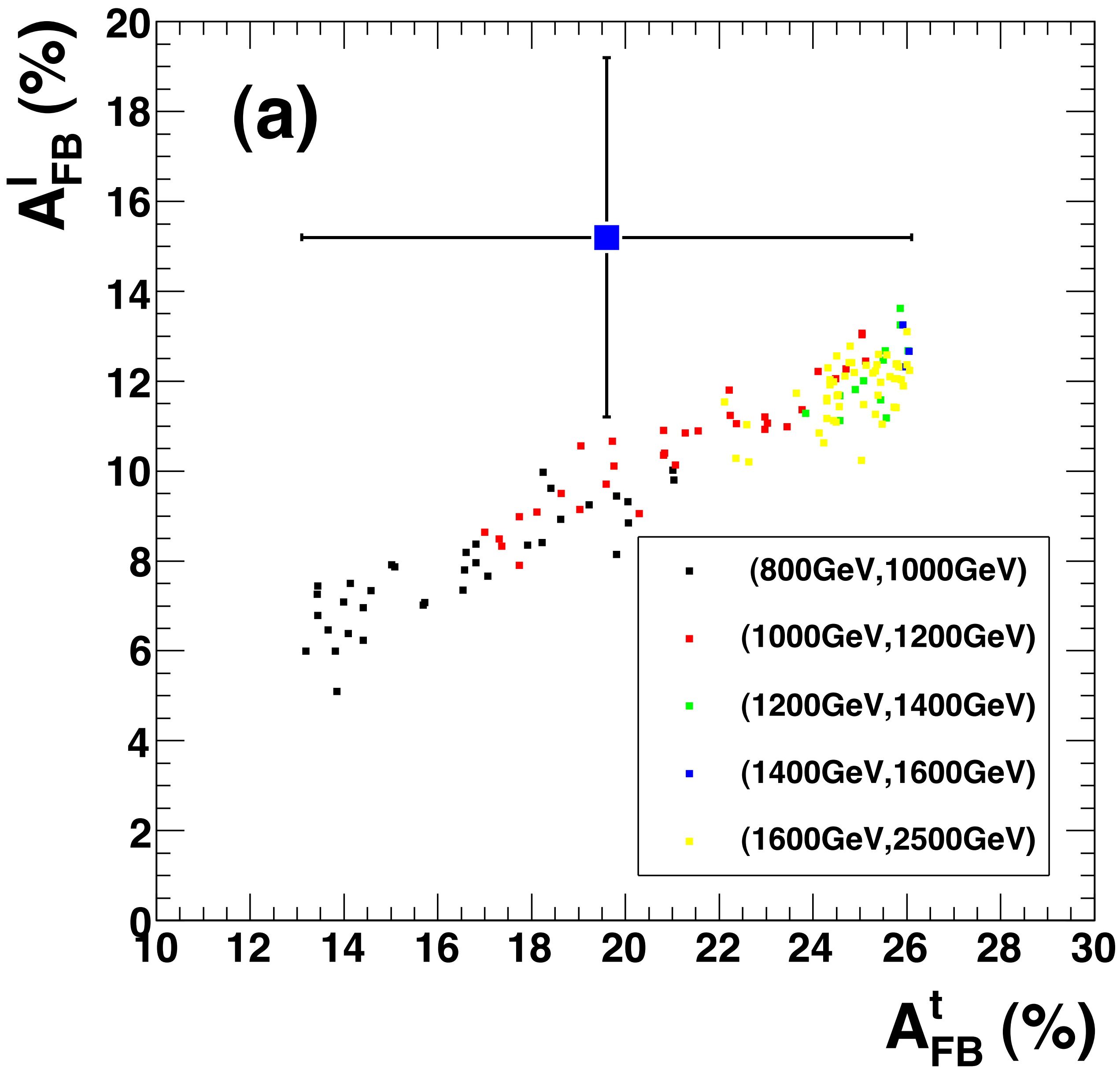
(I). Axigluon

- To determine parameters, require top AFB and the total cross section to fit within 1σ. Compute the correlation between top and lepton AFB:

- Pure pseudo-vector interaction (equal left and right tops)

- An axigluon produces a small increase in the

$$A^{\ell}_{FB} \simeq 0.47 \times A^{t}_{FB} + 0.25$$



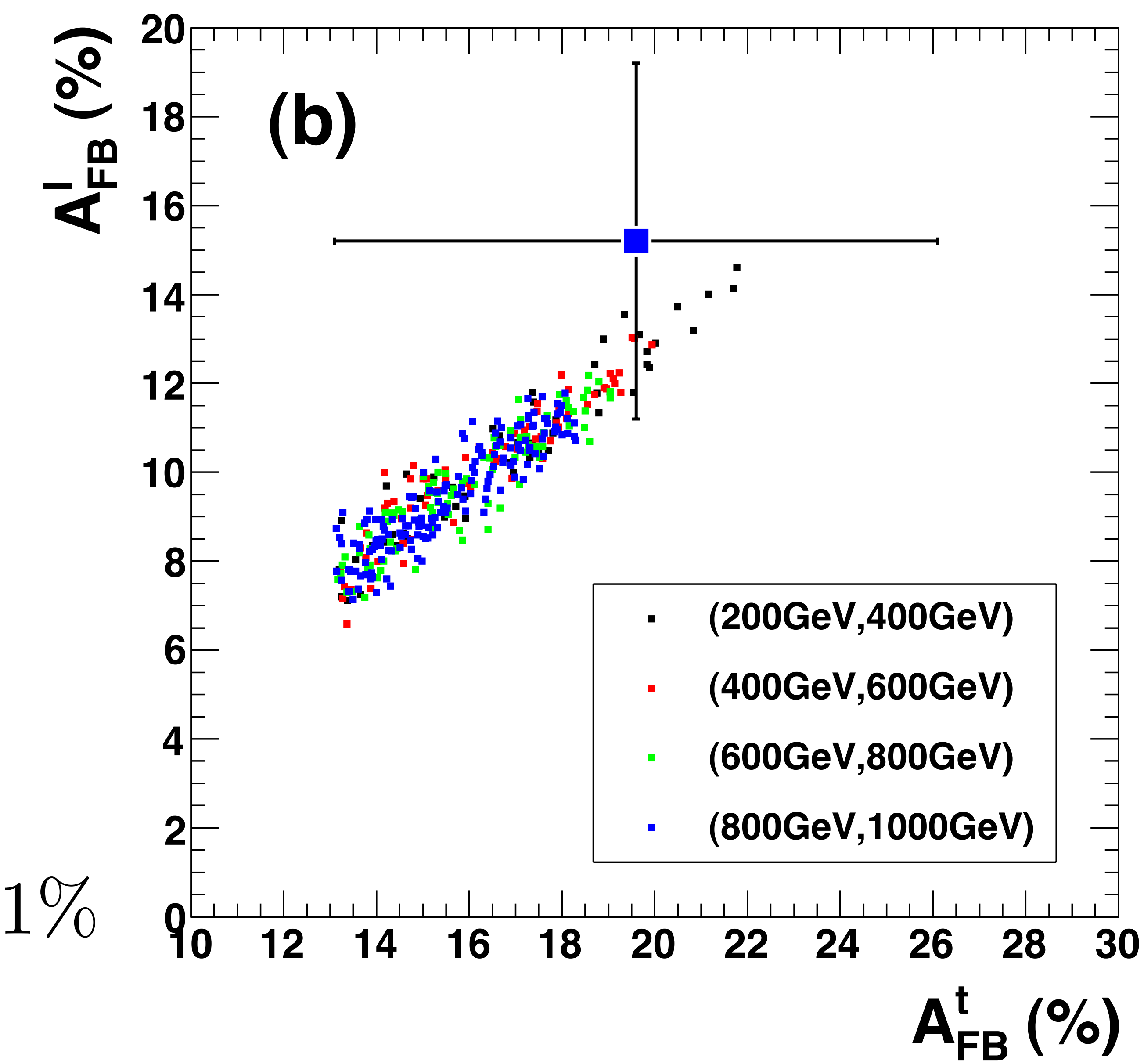
(II). W'

- To determine parameters, require top AFB and the total cross section to fit within 1σ. Compute the correlation between top and lepton AFB:

- Purely right-handed FC interaction

- W' model produces a large increase in the lepton AFB.

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



SUMMARY ON top AFB and lepton AFB

- Owing to the spin correlation in top quark decay, the top AFB and lepton AFB are strongly positively correlated for right-handed top quarks.
- For left-handed top quarks, the correlation depends on the energy of the top quark.
- Data from the D0 collaboration show a relatively large positive correlation.
- A model of new physics that predicts more right-handed top quarks is favored
- * Important to measure both top and lepton AFB *

Phys. Rev. Lett. 108, 072002 (2012)

Outlook

- The D0 experimental uncertainty is large

$$\left.\frac{A^{\ell}_{FB}}{A^{t}_{FB}}\right|_{D0} = 78 \pm 33\%$$

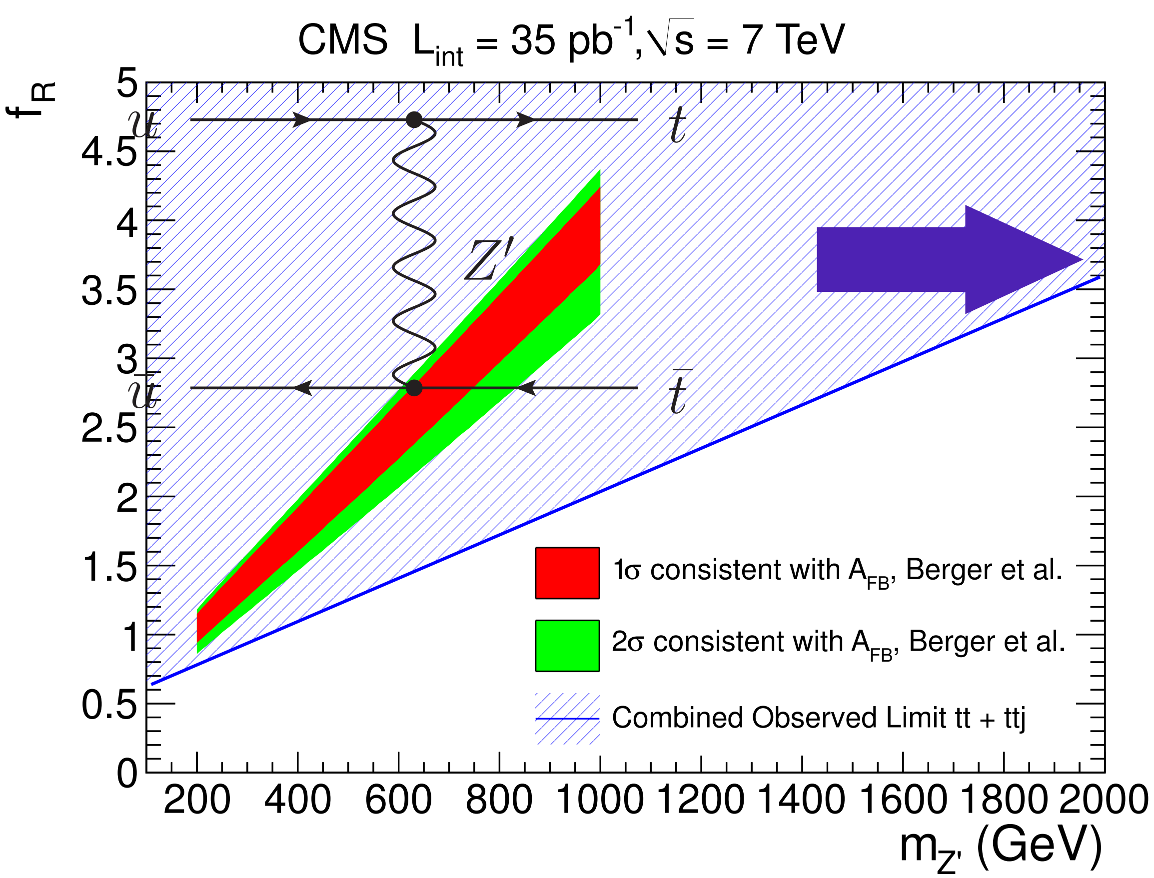
- Analysis of more data from the Tevatron could reduce this uncertainty

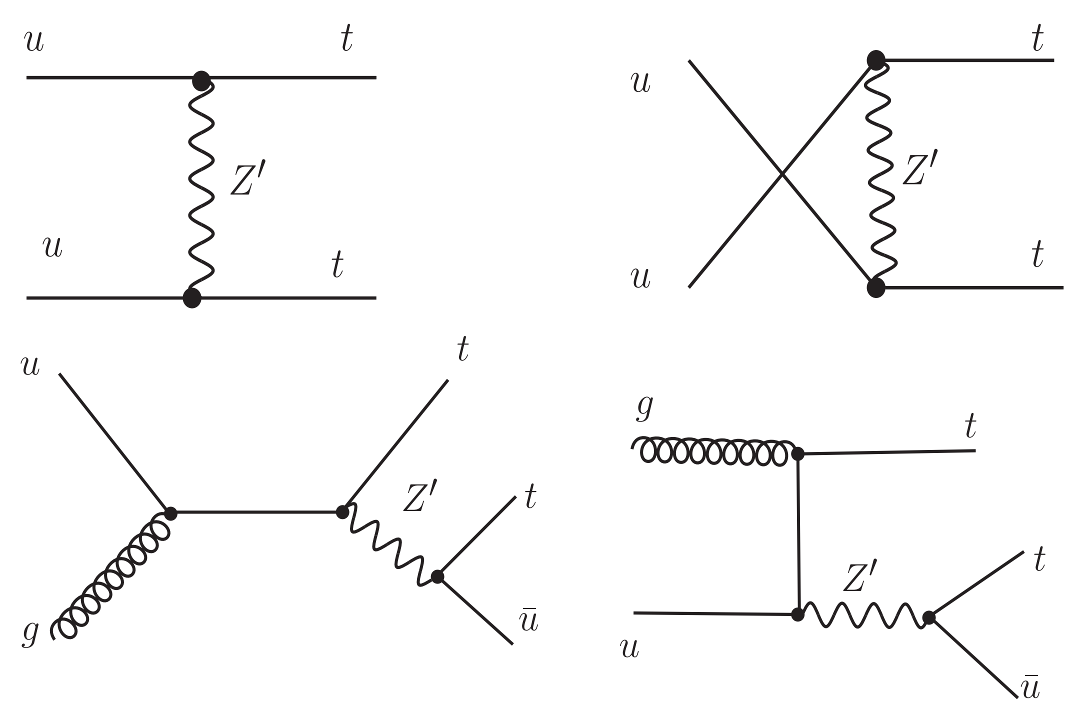
What about the LHC?

IV. LHC Implications

IMPLICATIONS OF MODELS AT THE LHC?

- Same sign top pair production
- Prediction based on Tevatron analysis; checked by CMS
- Minimal FCNC Z' model is disfavored (PRL 106, 201801, E Berger, Q-H Cao, C-R Chen, CS Li and Hao Zhang; JHEP08(2011) 005, CMS collaboration)





LHC Rapidity Asymmetries

- It is more difficult to measure AFB at the LHC

  (1) pp collider

  (2) gg initial state dominant -- yields no asymmetry

  (3) for the qqbar initial state process, an asymmetry persists, but its effect is diluted by the large gg contribution

- Define LHC asymmetries:

$$A_C^{t\bar{t}} \equiv \frac{N(|y_t| - |y_{\bar{t}}| > 0) - N(|y_t| - |y_{\bar{t}}| < 0)}{N(|y_t| - |y_{\bar{t}}| > 0) + N(|y_t| - |y_{\bar{t}}| < 0)}$$

$$A_C^{\ell\ell} \equiv \frac{N(|y_{\ell^+}| - |y_{\ell^-}| > 0) - N(|y_{\ell^+}| - |y_{\ell^-}| < 0)}{N(|y_{\ell^+}| - |y_{\ell^-}| > 0) + N(|y_{\ell^+}| - |y_{\ell^-}| < 0)}$$

LHC Rapidity Asymmetry Data

The results from the two collaborations are different, even if they are consistent within the quoted uncertainties

$$A_C^{t\bar{t}} = 0.029 \pm 0.018(\text{stat.}) \pm 0.014(\text{syst.})$$

$$A_C^{\ell\ell} = 0.023 \pm 0.012(\text{stat.}) \pm 0.008(\text{syst.})$$

ATLAS-CONF-2012-057

$$A_C^{t\bar{t}} = 0.004 \pm 0.010(\text{stat.}) \pm 0.011(\text{syst.})$$

CMS Collaboration, arXiv: 1207.0065

$$A_C^{t\bar{t}\ \text{SM}} = 0.006, \ \ A_C^{\ell\ell\ \text{SM}} = 0.004$$ MC@NLO

- We can obtain an estimate of AFB (ttbar) at the LHC by extrapolating from the Tevatron and applying the gg dilution
- The LHC value should be about 10% of the Tevatron
- ATLAS value agrees with the Tevatron asymmetry

LHC Rapidity Asymmetry Data

CMS result on AFB (ttbar) agrees with SM; no need for NP.
ATLAS data exceed SM

$$A_C^{t\bar{t}} = 0.029 \pm 0.018(\text{stat.}) \pm 0.014(\text{syst.})$$

$$A_C^{\ell\ell} = 0.023 \pm 0.012(\text{stat.}) \pm 0.008(\text{syst.})$$

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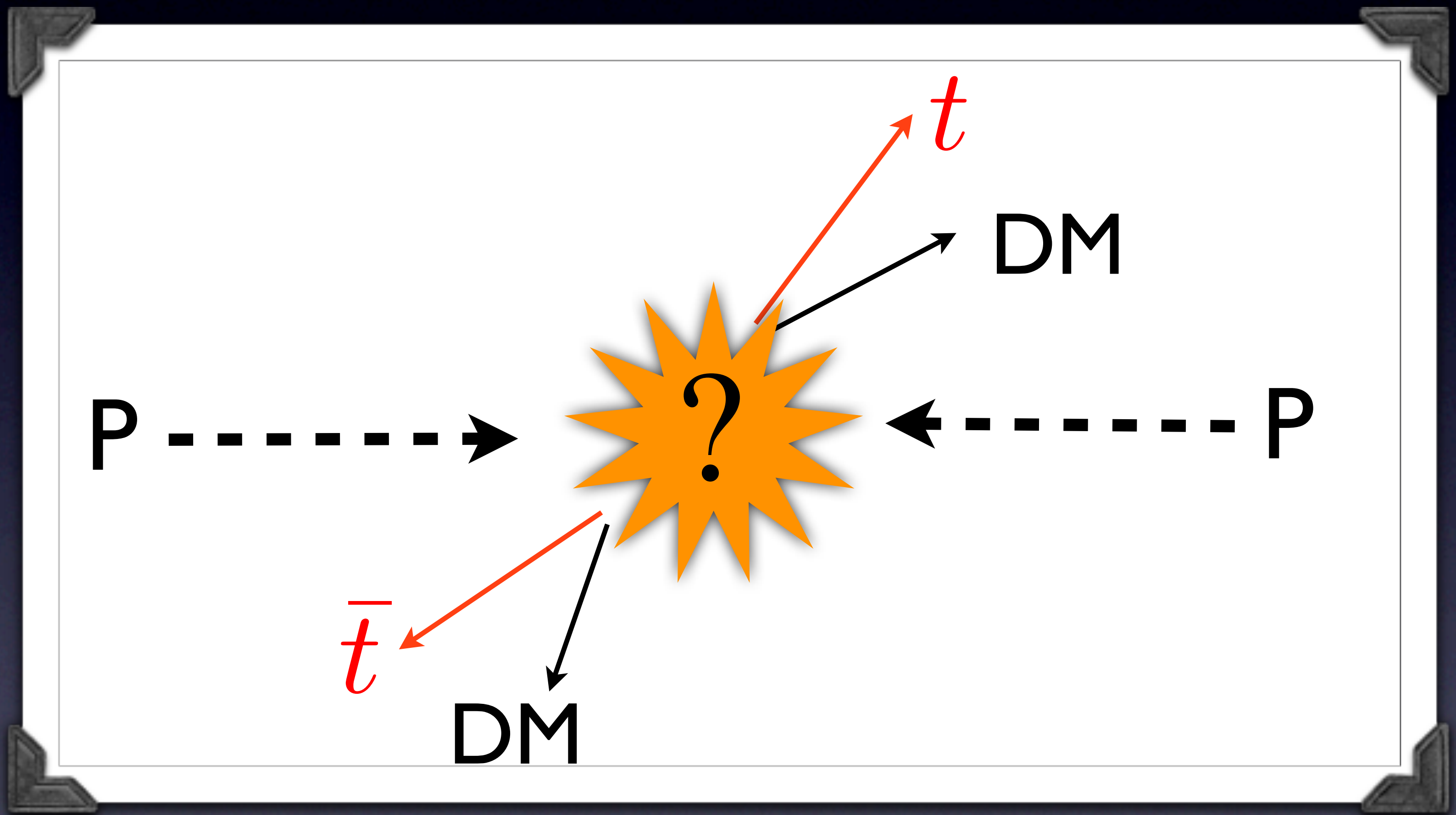
CMS Collaboration, arXiv: 1207.0065

$$A_C^{t\bar{t}\ \text{SM}} = 0.006, \ \ A_C^{\ell\ell\ \text{SM}} = 0.004$$ MC@NLO

- We can obtain an estimate of AFB (ttbar) at the LHC by extrapolating from the Tevatron and applying the gg dilution
- The LHC value should be about 10% of the Tevatron
- ATLAS value agrees with the Tevatron asymmetry

V. New Physics Models
with DM candidates

Berger, Qing-Hong Cao, Jianghao Yu, and Hao Zhang, arXiv:1207.1101

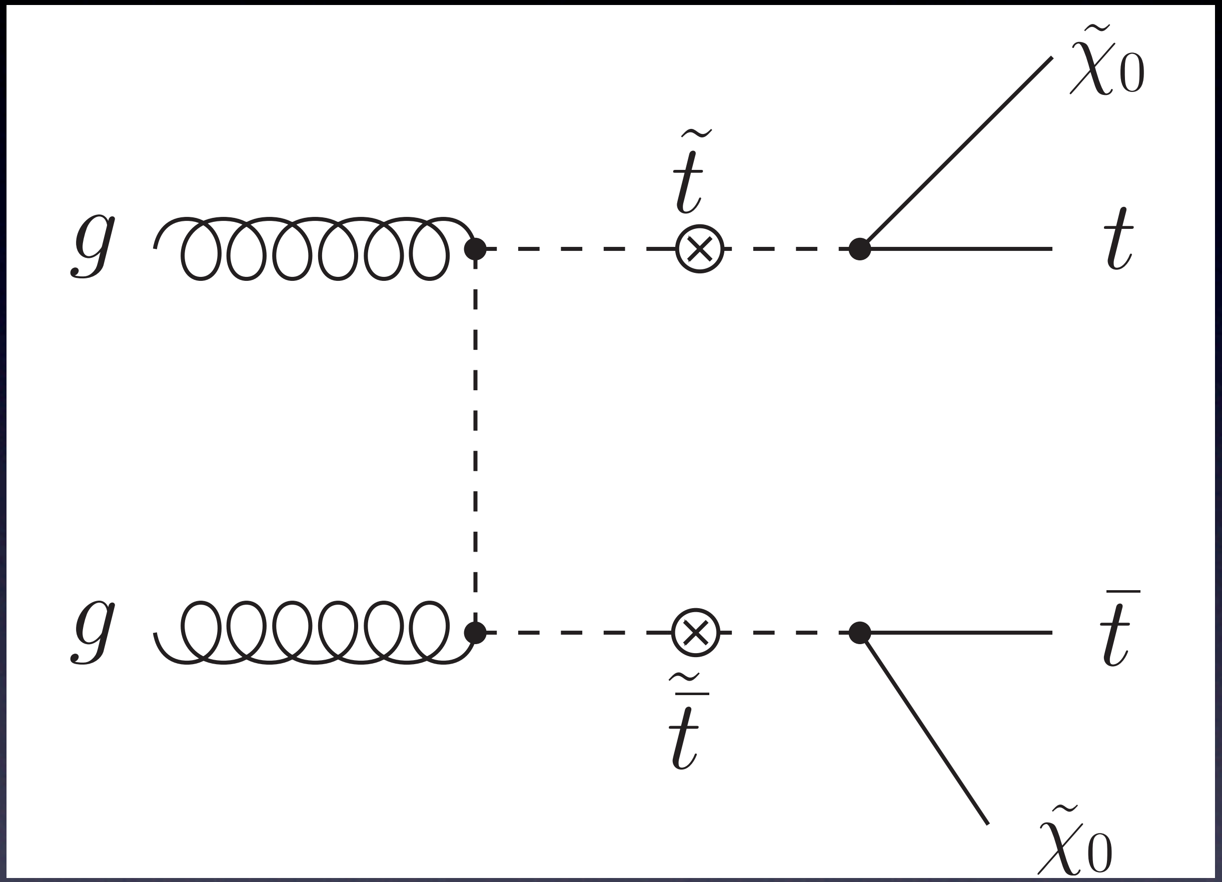


Measuring top-quark polarization *without* reconstructing top-quark kinematics

NP signature: Top antitop pair plus MET

- top squark pair production in the MSSM

Hall, Pinner and Ruderman, 1112.2703



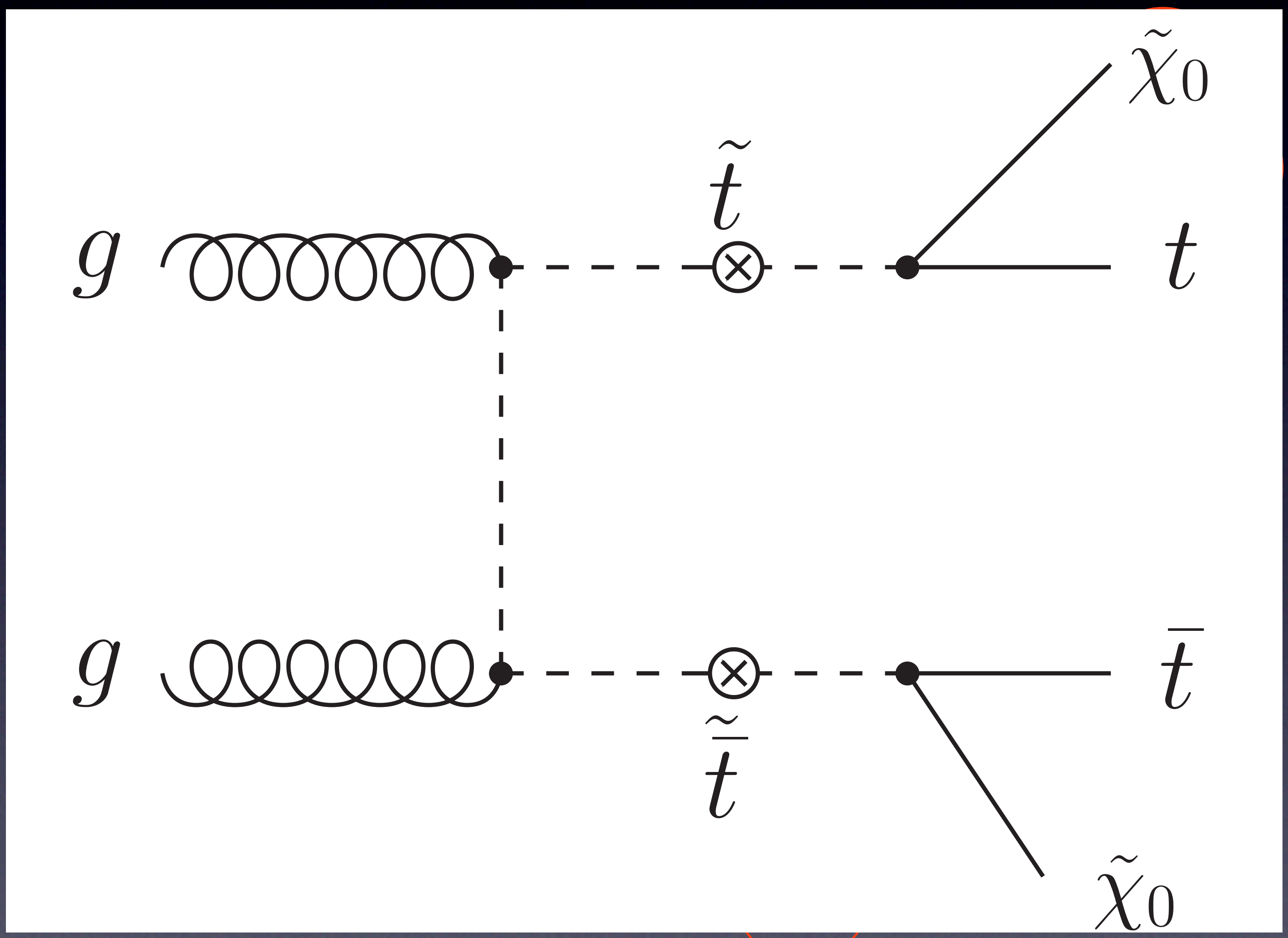
- Light top squark is "preferred" to raise m_h *to* 125 GeV in the maximal mixing scenario.

- Top quark polarization could shed light on the top squark mixing matrix.

Difficulty in NP signature of ttbar plus MET

- Not possible to reconstruct top quark in the leptonic-decay mode.

  Angular distribution of the charged-lepton cannot be used.



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

10 unknowns (neutrino from top decay, 2 DM) -2 from MET

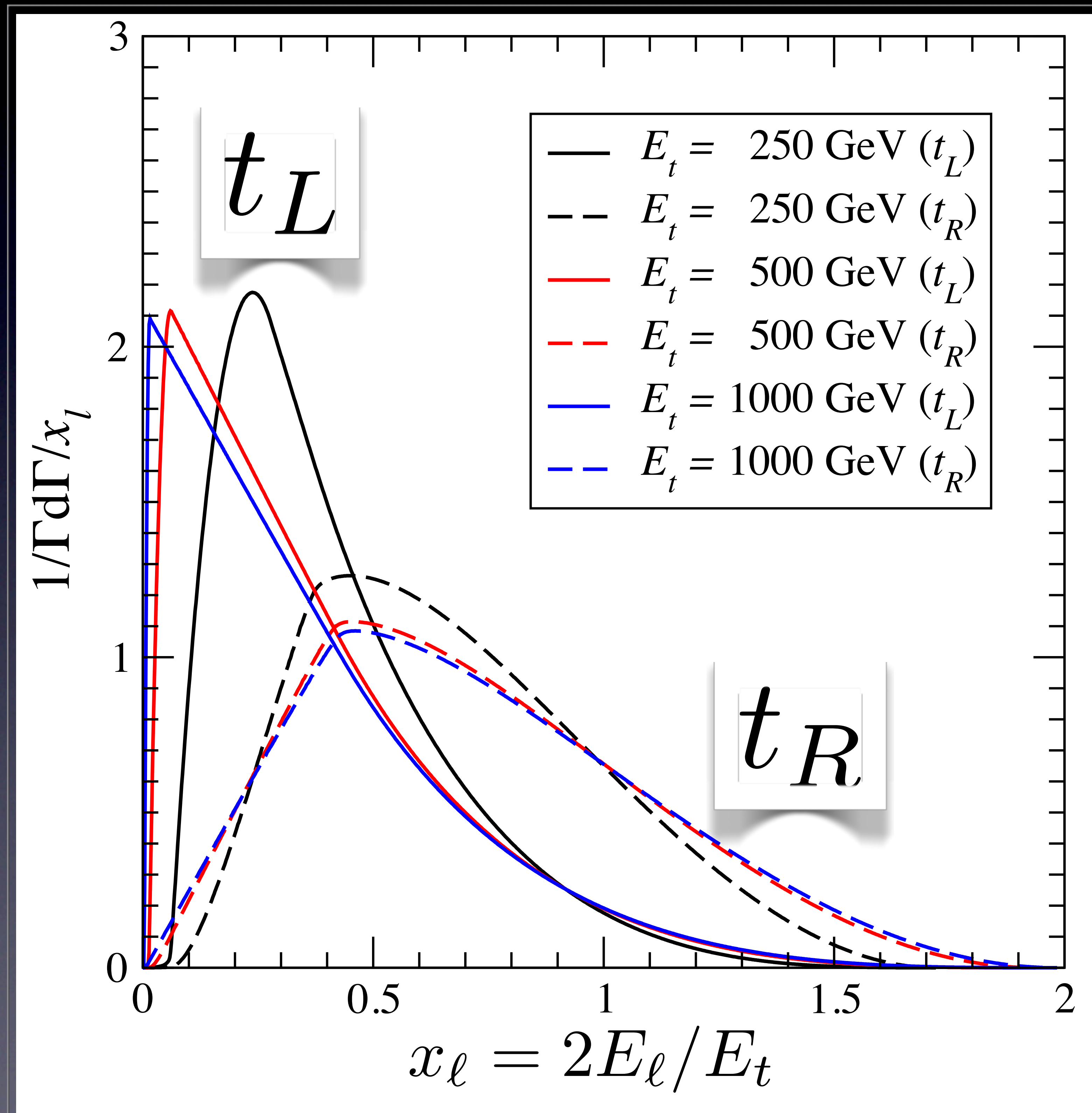
↓

Not enough constraints

Still possible to measure the top quark polarization

Lepton energy and top quark polarization

★ Lepton energy distribution is sensitive to top quark polarization.

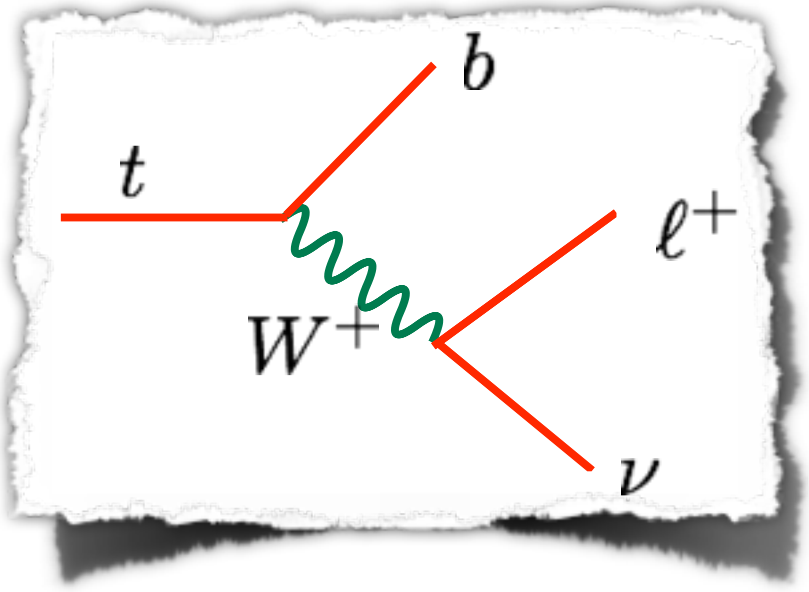


Conclusion

Summary

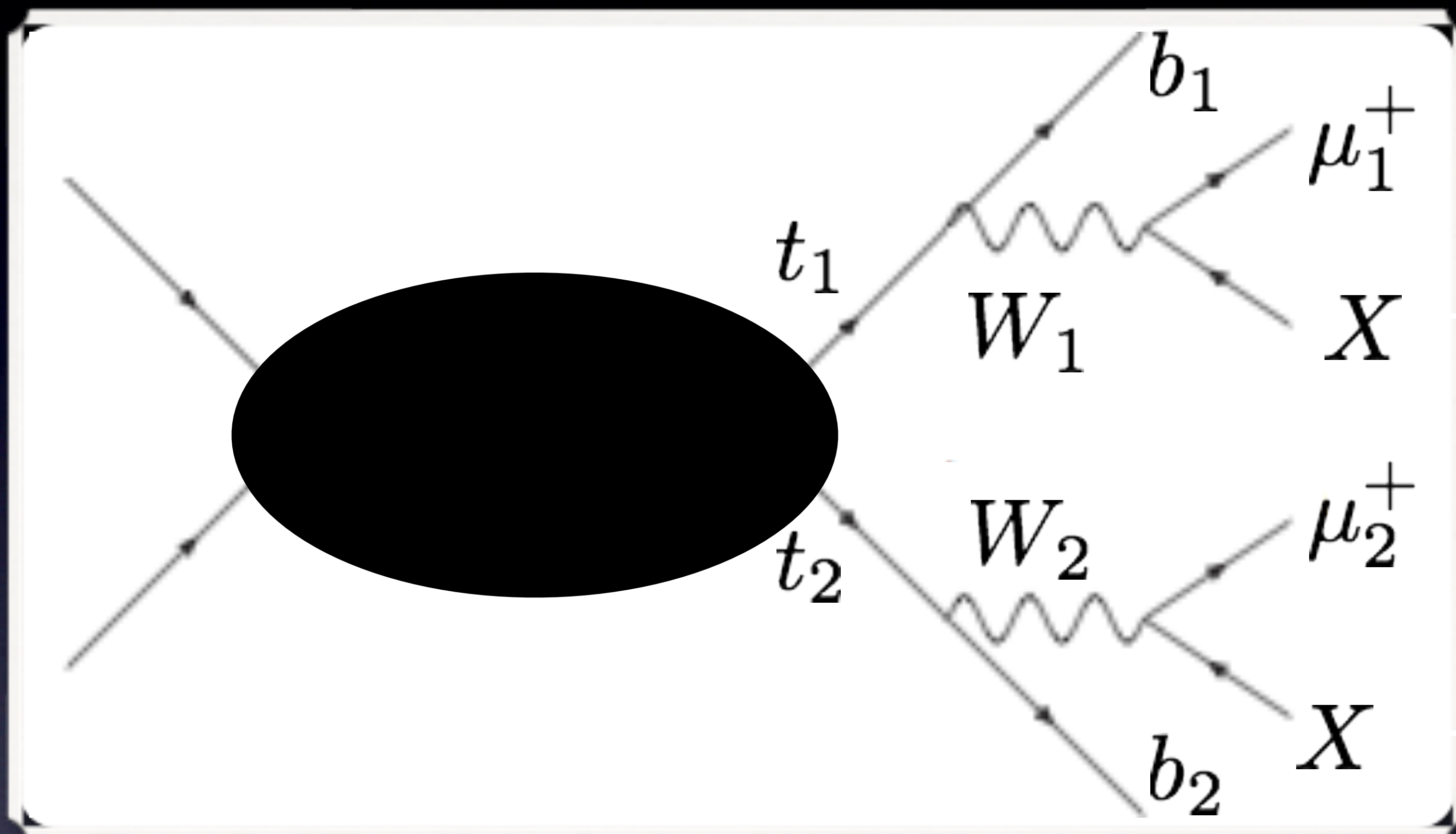
- Top-quark polarization provides richer insight into BSM physics
- Lepton AFB and top AFB are connected by the top quark and charged lepton spin correlation; D0 data suggest BSM with right-handed couplings. Data need confirmation
- LHC CMS data on the asymmetry show evidence of tension with the Tevatron, independent of models, but ATLAS data are consistent with the Tevatron
- Lepton energy distribution can be exploited to measure top quark polarization, especially in new physics models with dark matter candidates

Back up



Full kinematic reconstruction

★ <u>Four</u> unknowns and <u>four</u> 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

It is "easy" to show ...

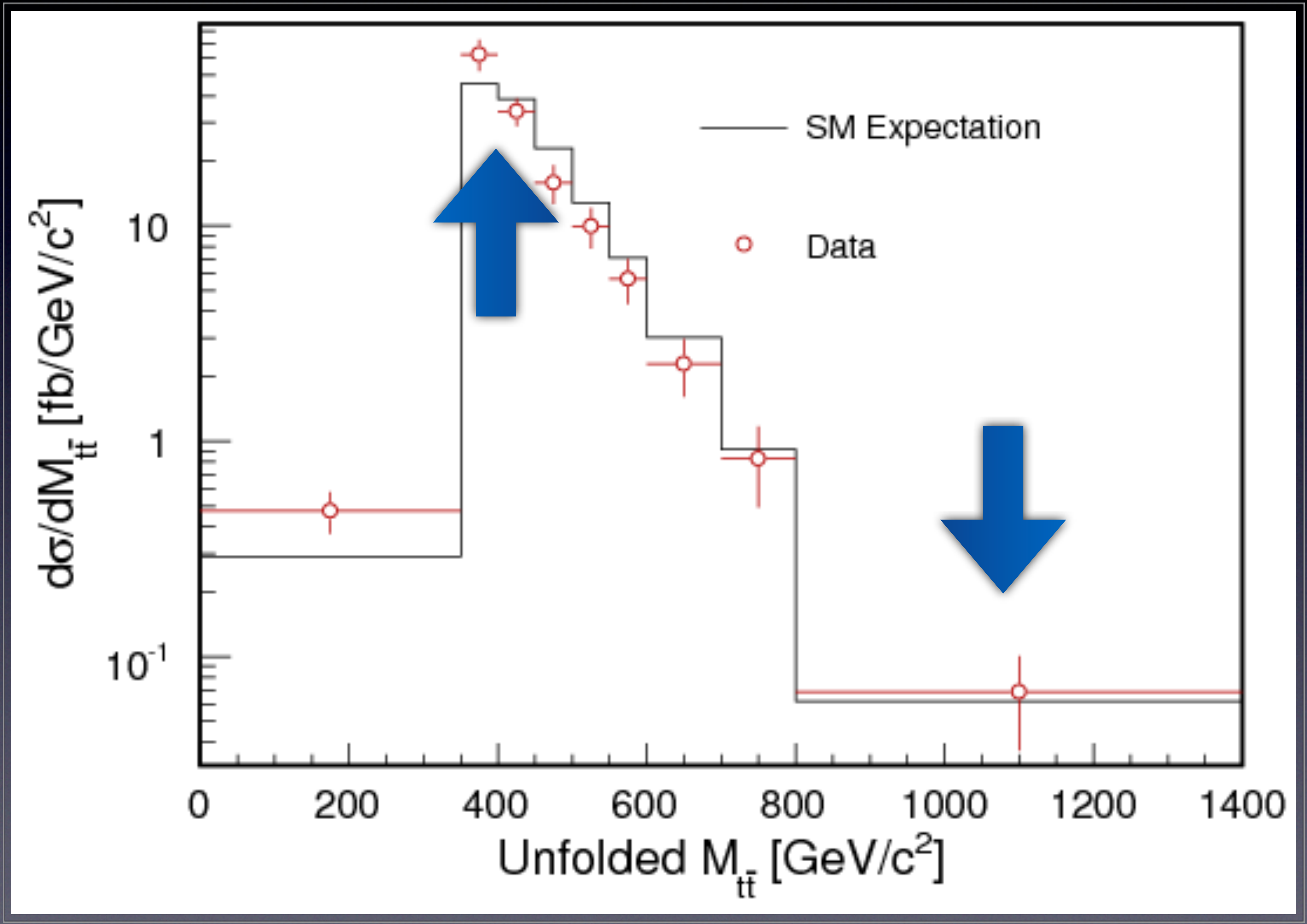
- After rotation of frames, derive the probabilty that lepton is in the forward region of the detector for a top quark top quark with (β , y_t , λ_t) is

$$R_F^{\ell,\lambda_t}(\beta, y_t)$$

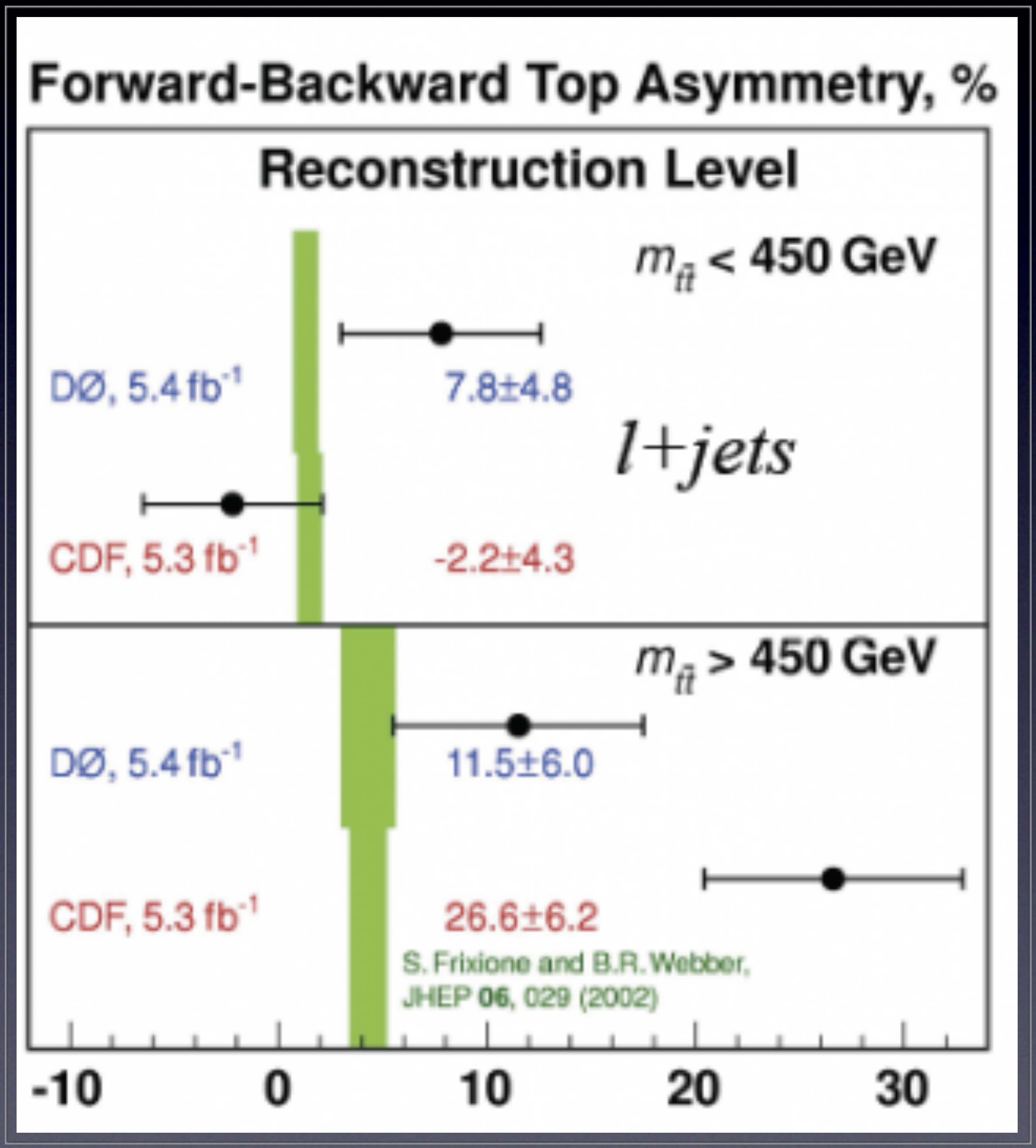
$$= \begin{cases} \dfrac{1}{2} + \dfrac{1}{2\left(1+\gamma^{-2}\coth^2 y_t\right)^{1/2}} + \dfrac{\lambda_t \coth^2 y_t}{4\beta\gamma^2\left(1+\gamma^{-2}\coth^2 y_t\right)^{3/2}}, & (y_t > 0) \\ \dfrac{1}{2} - \dfrac{1}{2\left(1+\gamma^{-2}\coth^2 y_t\right)^{1/2}} - \dfrac{\lambda_t \coth^2 y_t}{4\beta\gamma^2\left(1+\gamma^{-2}\coth^2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

Invariant mass spectrum of top quark pair

CDF, Phys.Rev.Lett. 102 (2009) 222003



A^ℓ_{FB} versus A^t_{FB}



D0: $A^t_{FB} = 0.196 \pm 0.065$

$A^\ell_{FB} = 0.152 \pm 0.040$

$$\left.\frac{A^\ell_{FB}}{A^t_{FB}}\right|_{\mathrm{D0}} \sim \frac{3}{4}$$

SM: $A^t_{FB} = 0.051 \pm 0.001$

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

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

Bernreuther, Zong-Guo Si, arXiv:1003.3926

Two Examples (I). Axigluon

- The interaction of the axigluon is chosen to be

$$\mathcal{L} = g_s \left(g_l \bar{q} \gamma^\mu \gamma_5 q + g_h \bar{Q} \gamma^\mu \gamma_5 Q \right) G'_\mu$$

- Some properties of axigluon model

(1) Interference term (INT) gives top AFB $\propto -g_l g_h$, does not change the total xsec

(2) Should be heavy to satisfy the ttbar invariant mass spectrum and total cross section

(3) Pure new physics contribution (NP) is suppressed by the propagator

(4) Equal number of left-handed and right-handed top quarks in final state from this new physics

Two Examples (II). W'

- The interaction of the pure right-handed W' is chosen to be

$$\mathcal{L} = g_2 g_R \bar{d}\gamma^\mu P_R t W'_\mu + h.c.$$

- Some properties of W' model

  (1) Both interference term and pure new physics term contribute to the AFB

  (2) There is a cancellation between the contribution to the ttbar total cross section from interference term and pure new physics term

  (3) More right-handed top quarks in final state

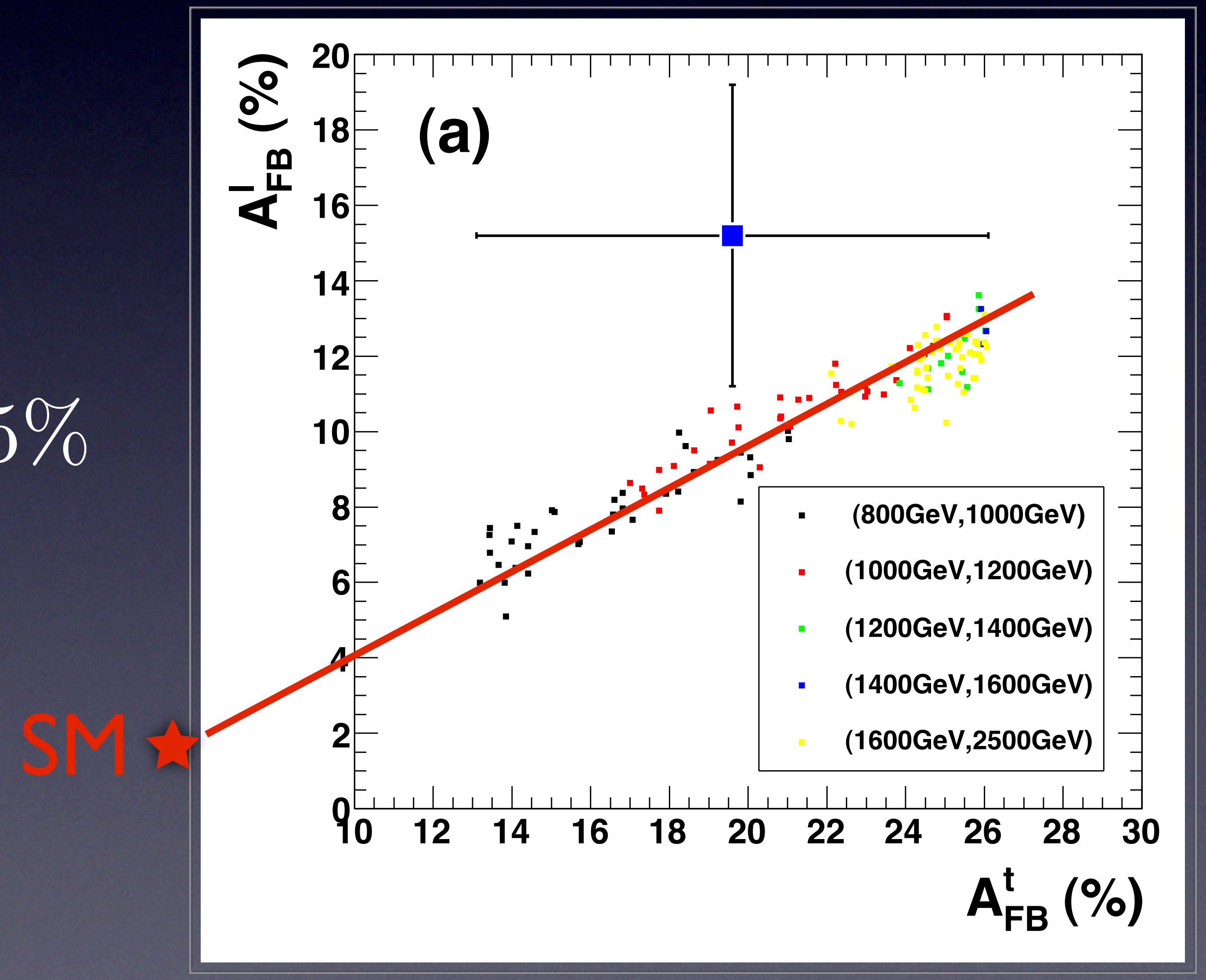
Axigluon: *s*-channel

- Purely pesudo-vector coupling

$$\mathcal{L} = g_s \left(g_l \; \bar{q}\gamma^\mu\gamma_5 q + g_h \; \bar{Q}\gamma^\mu\gamma_5 Q \right) G'_\mu$$

- Best-fit

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



FC W-prime: *t*-channel

- Purely right-handed flavor changing interaction

$$\mathcal{L} = g_2 g_R \bar{d} \gamma^\mu P_R t W'_\mu + h.c.$$

$$\rho_{t_R} > \rho_{t_L}$$

- Best-fit

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

SM ★