Santa Fe 2012 Summer Workshop, "LHC Now"
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Top Quark Forward-Backward Asymmetry and Its Polarization

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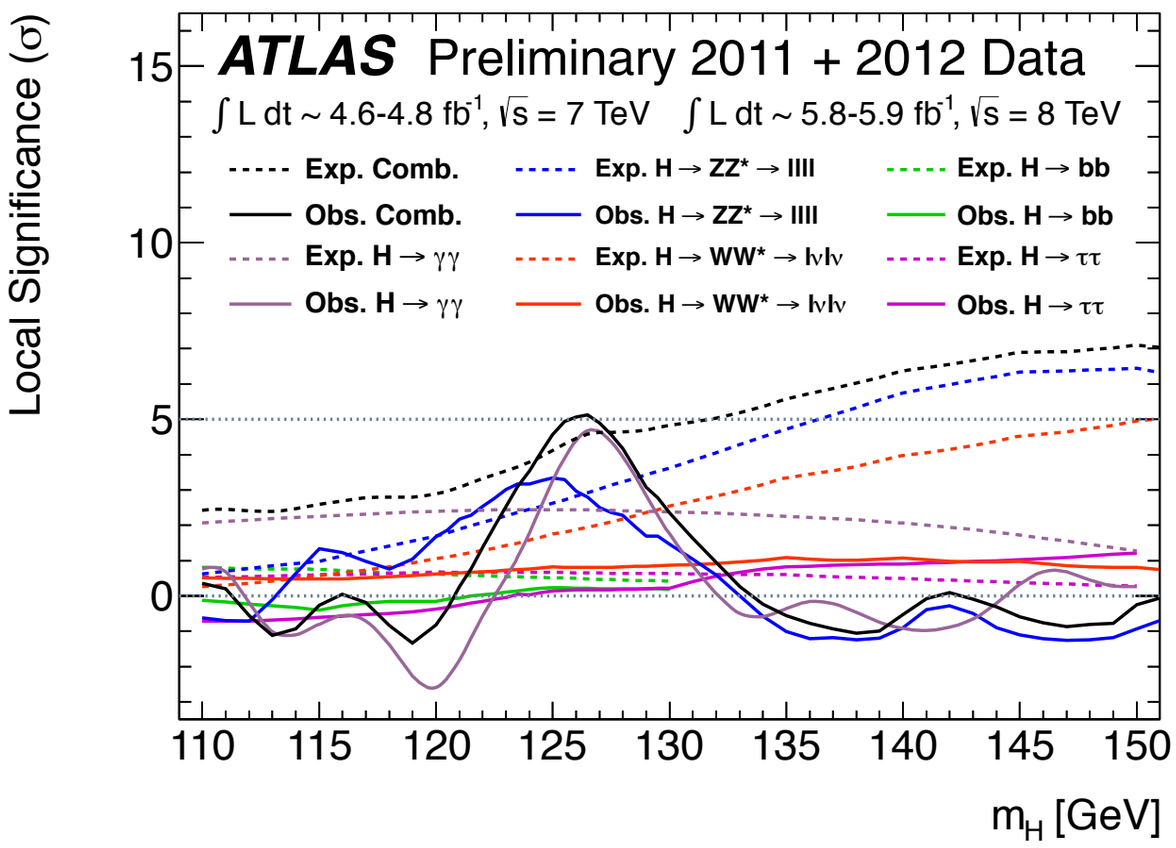
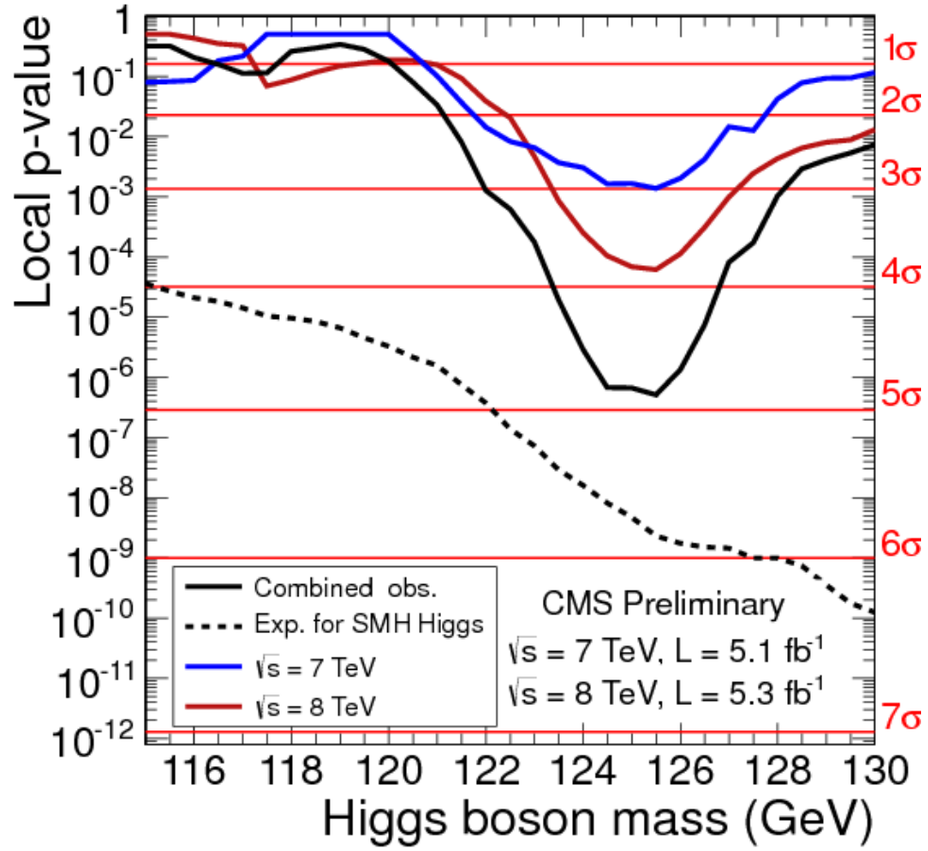
Based on works in collaboration with:
Edmond L. Berger, Qing-Hong Cao, Chuan-Ren Chen and Jianghao Yu,
Phys. Rev. Lett. 108, 072002, and arXiv: 1207.xxxx

LHC Now?

Observation of the Higgs-like particle ?!!





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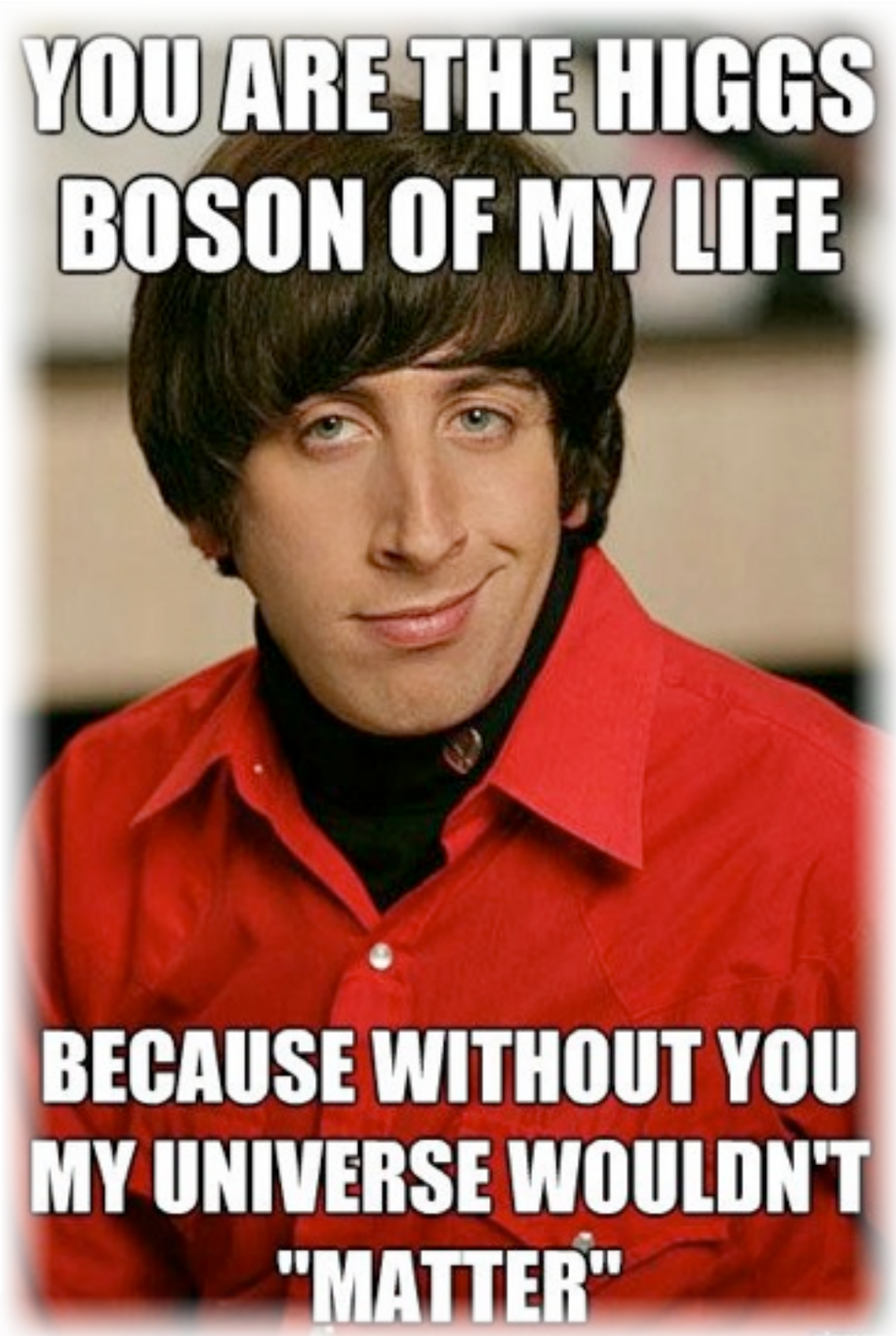
LHC Now?

- If the Higgs boson is a SM-like one, it gives more to a guy than itself. That is ...

LHC Now?

- If the Higgs boson is a SM-like one, it gives more to a guy than itself. That is ...

TOP quark



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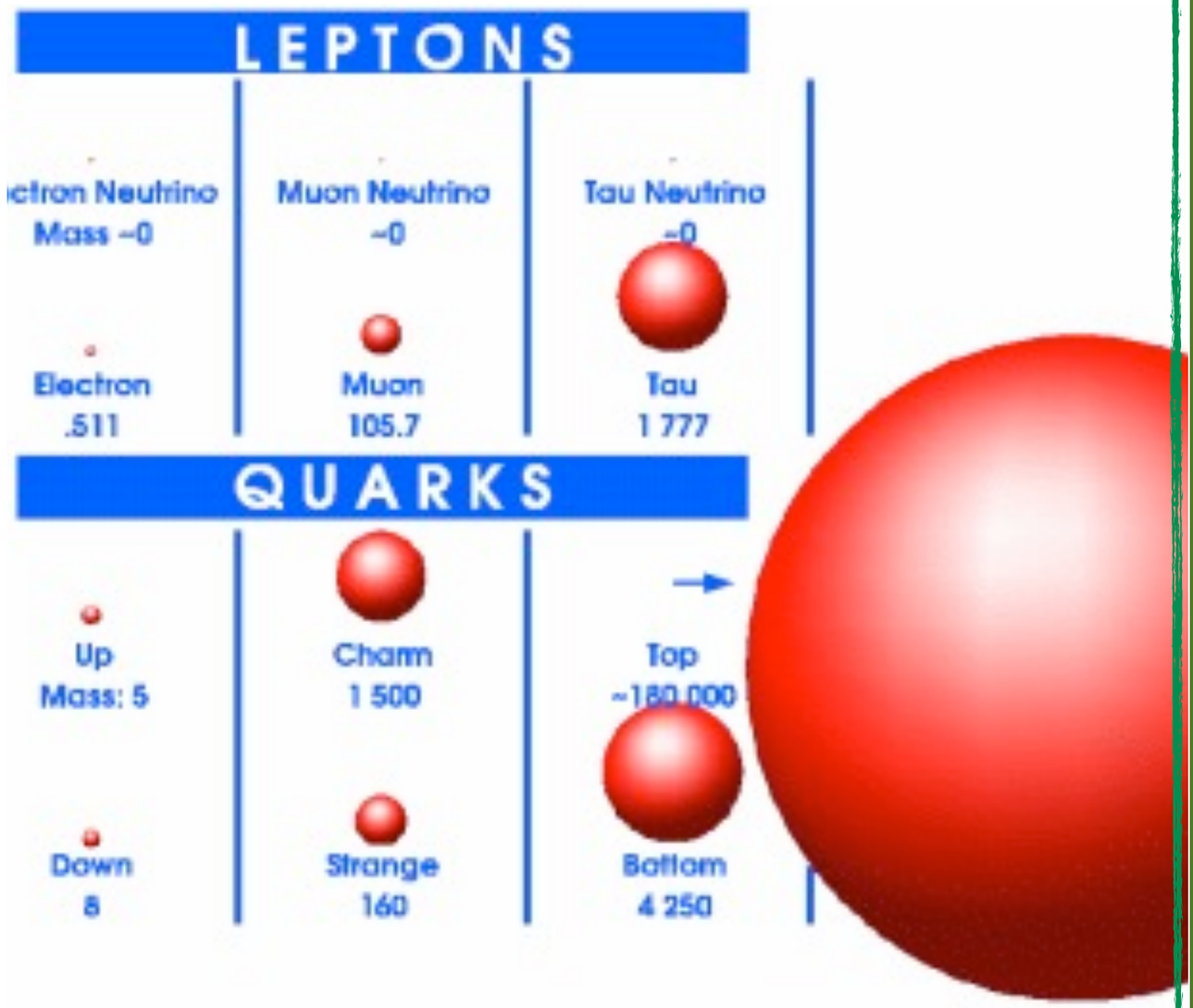
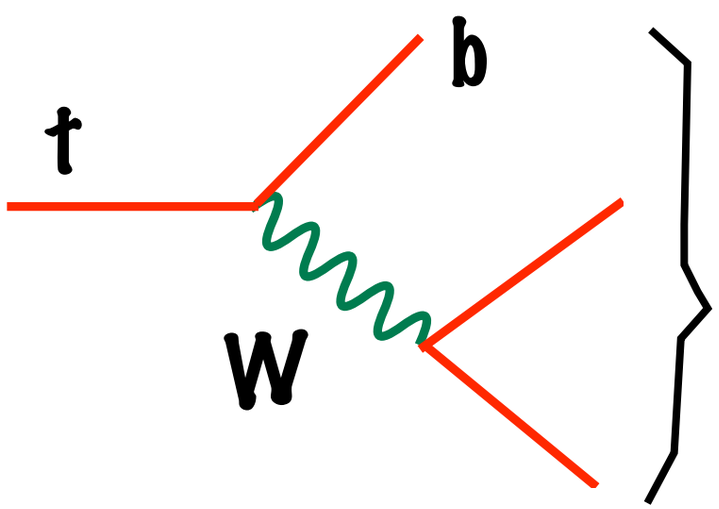
Top quark: King of the Standard Model

- Heaviest quark in the SM :
  sensitive to symmetry breaking
- Only fermion with "natural"
  Yukawa coupling
- "Bare" quark: decay rapidly via
  EW interaction





- Top quark spin information is well retained among its decay products

Outline

Outline

Top quark forward-backward asymmetry

1

End

Outline

Top quark forward-backward asymmetry

1

2

End

Top quark leptonic decay and spin information

Outline

Top quark forward-backward asymmetry

From top AFB to lepton AFB

1

2

3

End

Top quark leptonic decay and spin information

Outline

Top quark forward-backward asymmetry

From top AFB to lepton AFB

1 2 3 4 End

Top quark leptonic decay and spin information

Two examples of new physics models

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Outline

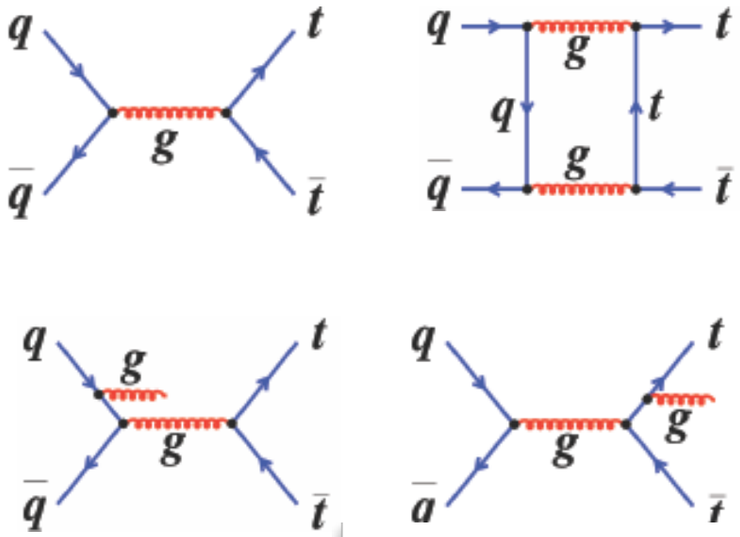
1. Top quark forward-backward asymmetry
2. Top quark leptonic decay and spin information
3. From top AFB to lepton AFB
4. Two examples of new physics models
5. Conclusion and Outlook

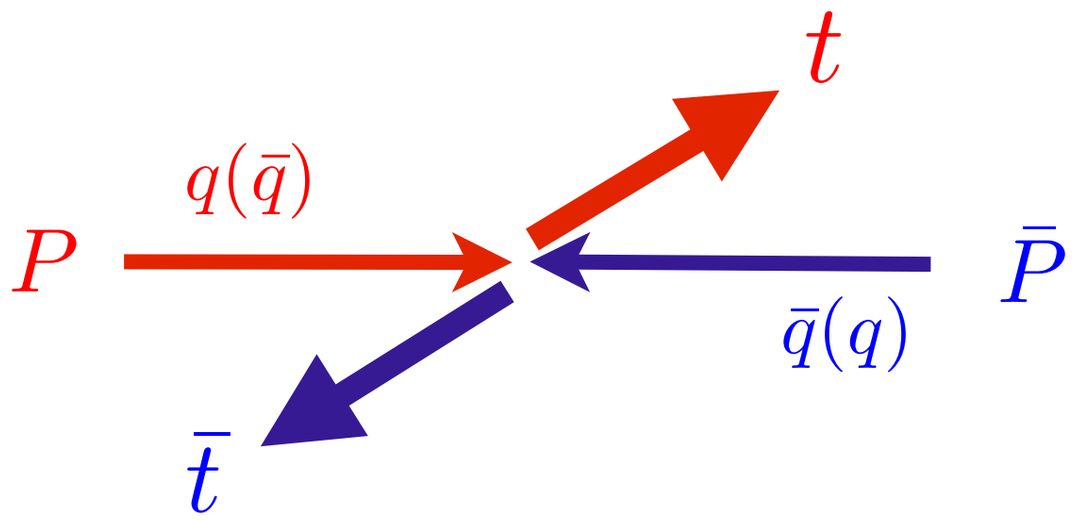
Top quark forward-backward asymmetry

Great TOPatron

Top AFB from Tevatron

- A charge asymmetry from NLO correction in the SM
- Is there any intuitive physical picture to understand it? (PRD83, 112003)





intuitive picture of the first effect is that the QCD soft gluon field of an incoming light quark "repels" the t quark to larger (more positive) rapidities, while "attracting" the $\bar{t}$ to smaller (more negative) rapidities, thus creating a positive asymmetry at large y, as defined by the quark direction [25]. (Of course, the pushing and pulling refers to corrections to the amplitude and not to actual momentum transfers.) The second effect can be pictured in terms of color flow: if the top (antitop) quark is produced in the backward (forward) region, this corresponds to a large acceleration of the color charges, leading to a greater probability of gluon bremsstrahlung and thus the production of a $t\bar{t}$ + jet event.

Top AFB from Tevatron

The CDF collaboration's results (CDF Note 10807)

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

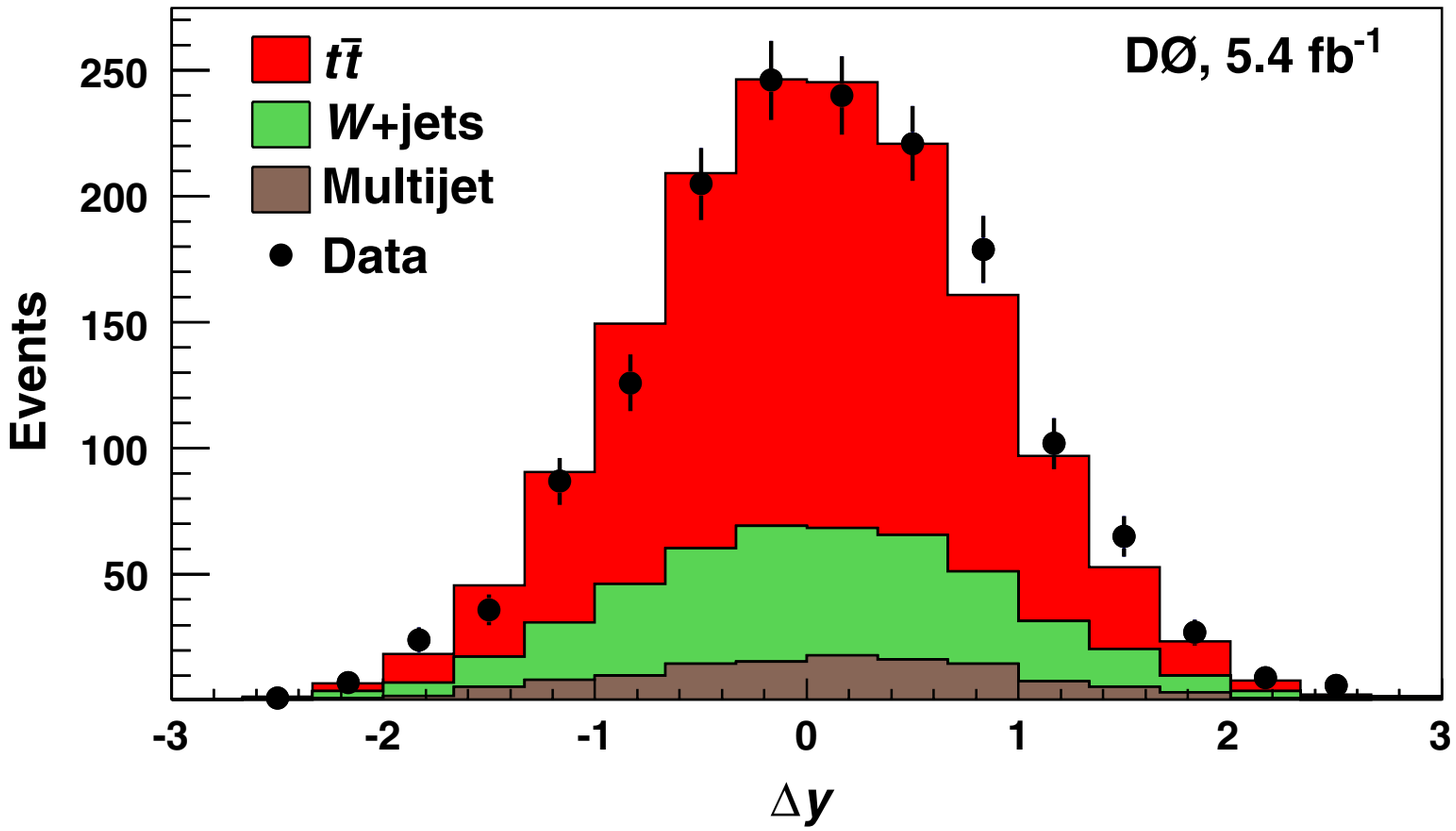
Parton Level $\lvert\Delta y\rvert$	NLO (QCD+EW) $t\bar{t}$ A_{FB}	5.3 fb^{-1} A_{FB} (±[stat.+syst.])	8.7 fb^{-1} A_{FB} (±[stat.+syst.])
Inclusive	0.066	0.158 ± 0.074	0.162 ± 0.047
< 1.0	0.043	0.026 ± 0.118	0.088 ± 0.047
≥ 1.0	0.139	0.611 ± 0.256	0.433 ± 0.109
Parton Level $M_{t\bar{t}}$	NLO (QCD+EW)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

- There is still nearly 3σ discrepancy from the SM prediction.

Top AFB from Tevatron

- D0 collaboration top asymmetry (PRD84, 112005)

	A_{FB} (%)	
	Reconstruction level	Production leve
Data	9.2 ± 3.7	19.6 ± 6.5
MC@NLO	2.4 ± 0.7	5.0 ± 0.1



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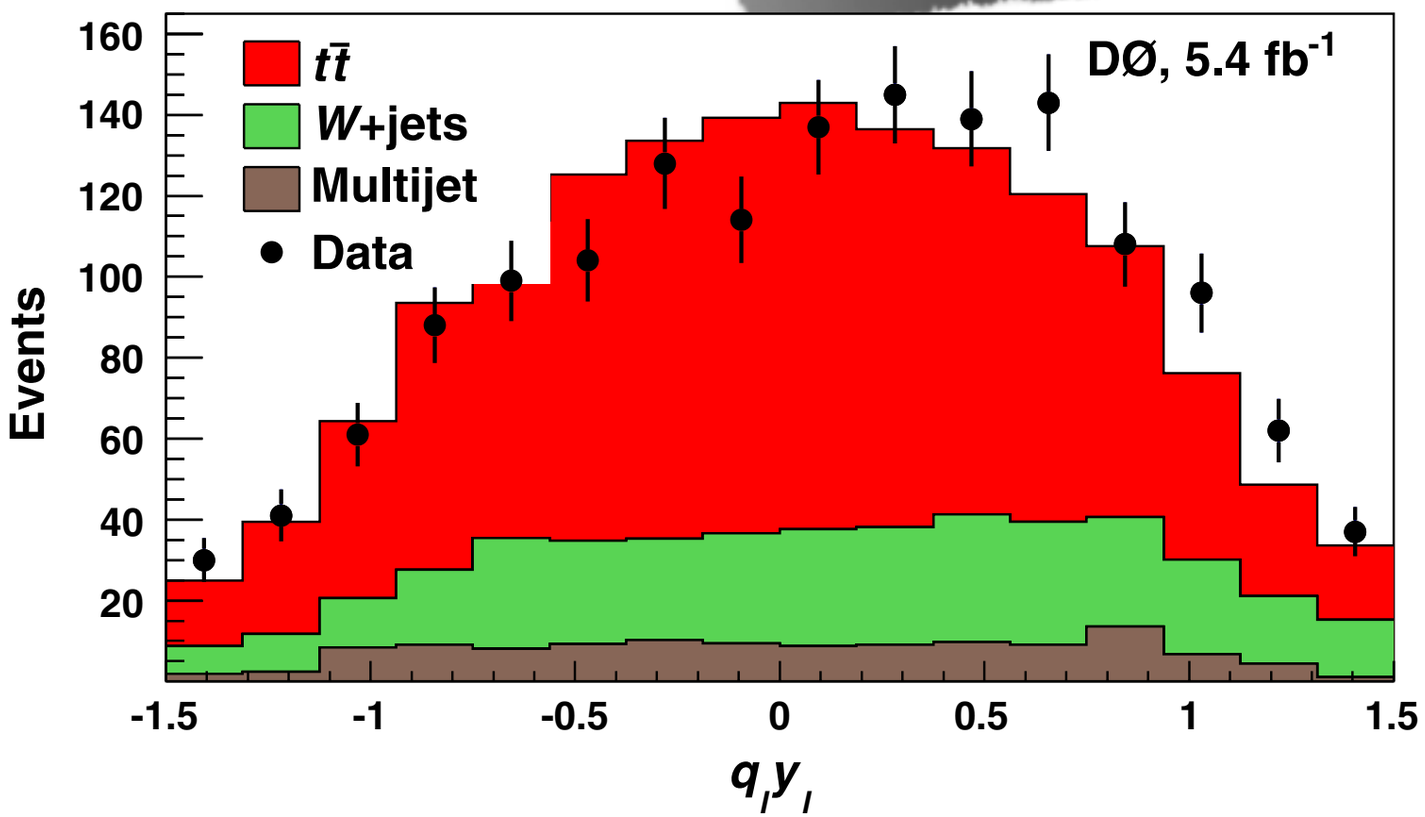
Top AFB from Tevatron

- **D0 collaboration also measures the lepton charge asymmetry! (PRD84, 112005)**

$$A_{\mathrm{FB}}^{l} = \frac{N_{\mathrm{F}}^{l} - N_{\mathrm{B}}^{l}}{N_{\mathrm{F}}^{l} + N_{\mathrm{B}}^{l}}, \qquad (3$$

where N_{F}^{l} is the number of events that have $q_l y_l > 0$, and N_{B}^{l} is the number of events with $q_l y_l < 0$

	A_{FB}^{l} (%)	
	Reconstruction level	Production leve
Data	14.2 ± 3.8	15.2 ± 4.0
MC@NLO	0.8 ± 0.6	2.1 ± 0.1



Top AFB from Tevatron

Top AFB from Tevatron

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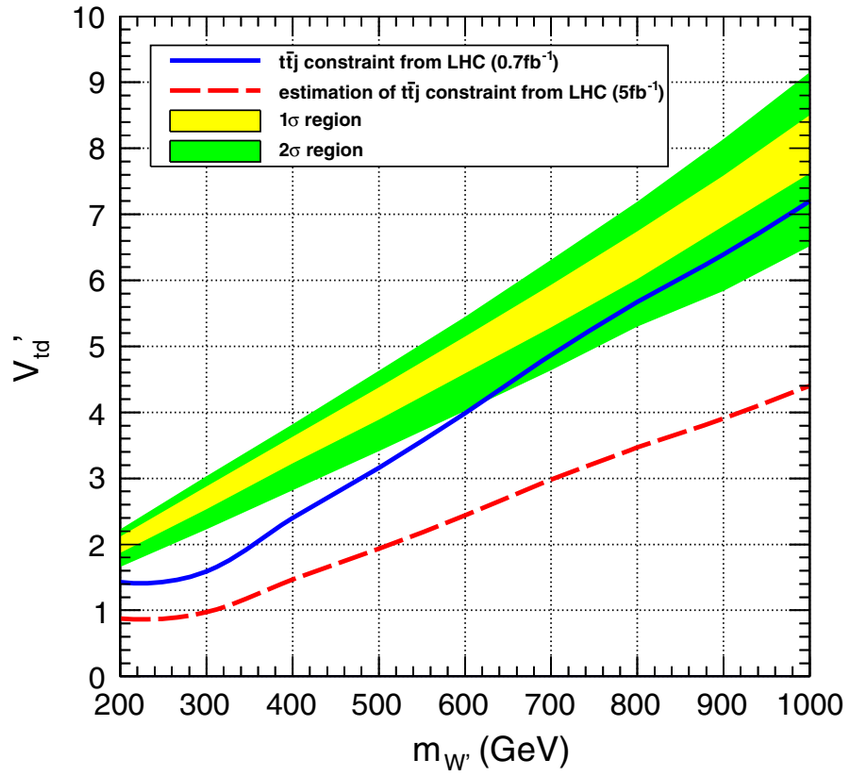
How to check these models?

- They could be checked at the LHC
- Some examples
  - FCNC Z' model (PRL106, 201801, E Berger, Q-H Cao, C-R Chen, CS Li and HZ, JHEP08(2011)005, CMS collaboration)
  - FC W' model (PRD85, 094027, D Duffty, Z Sullivan and HZ)



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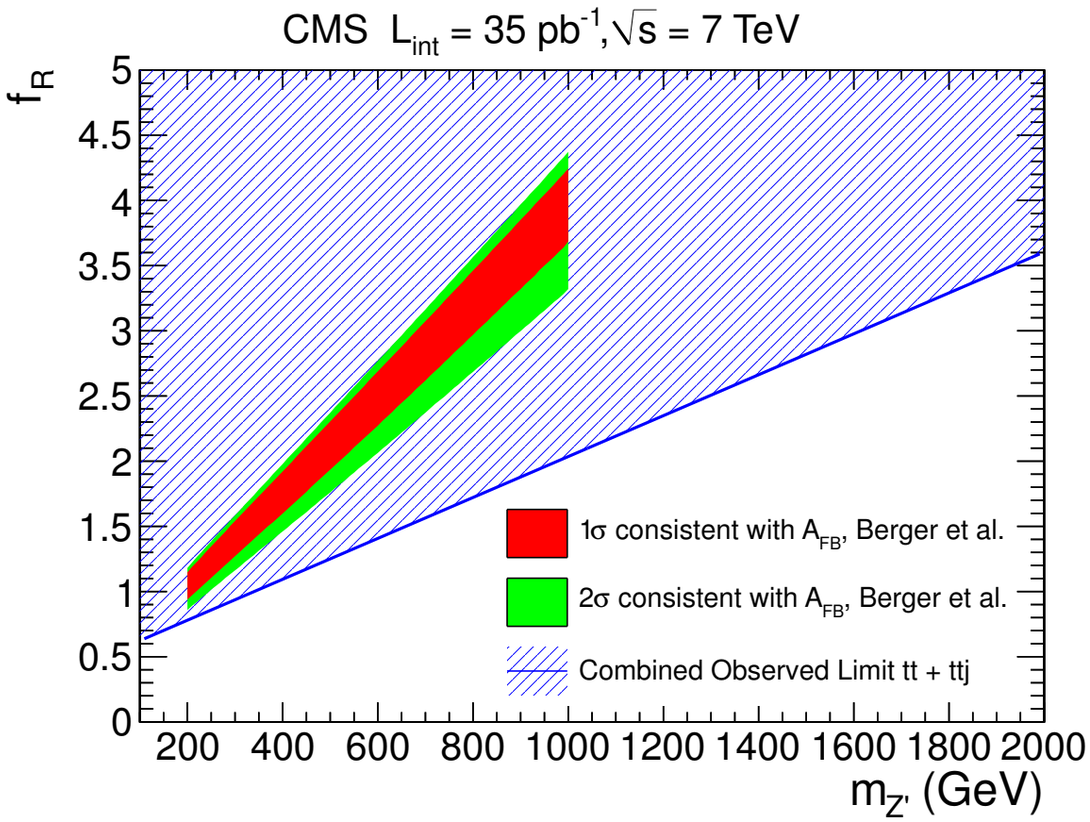

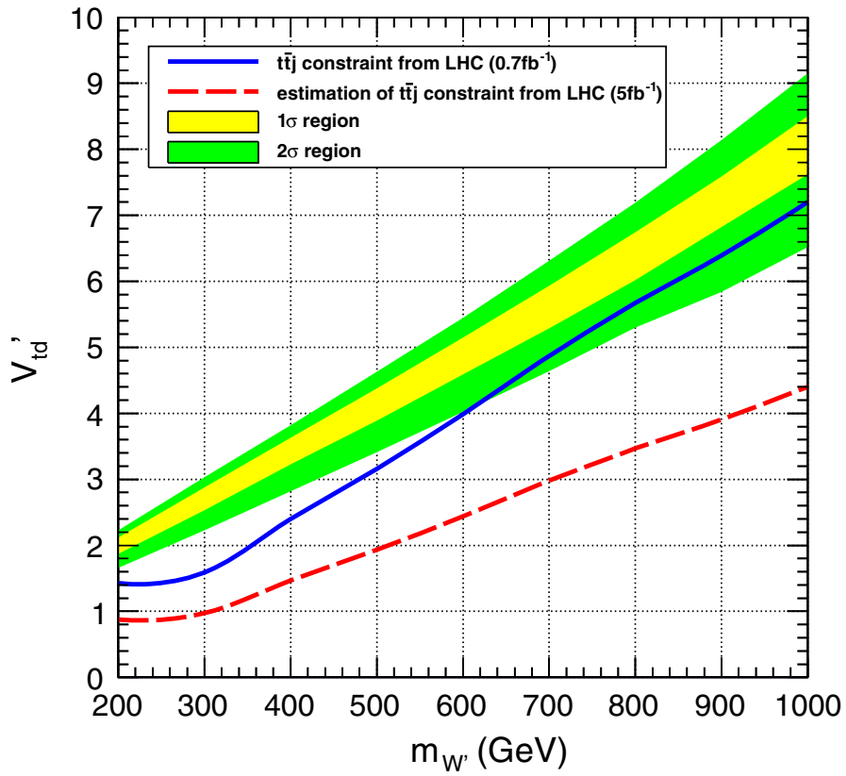

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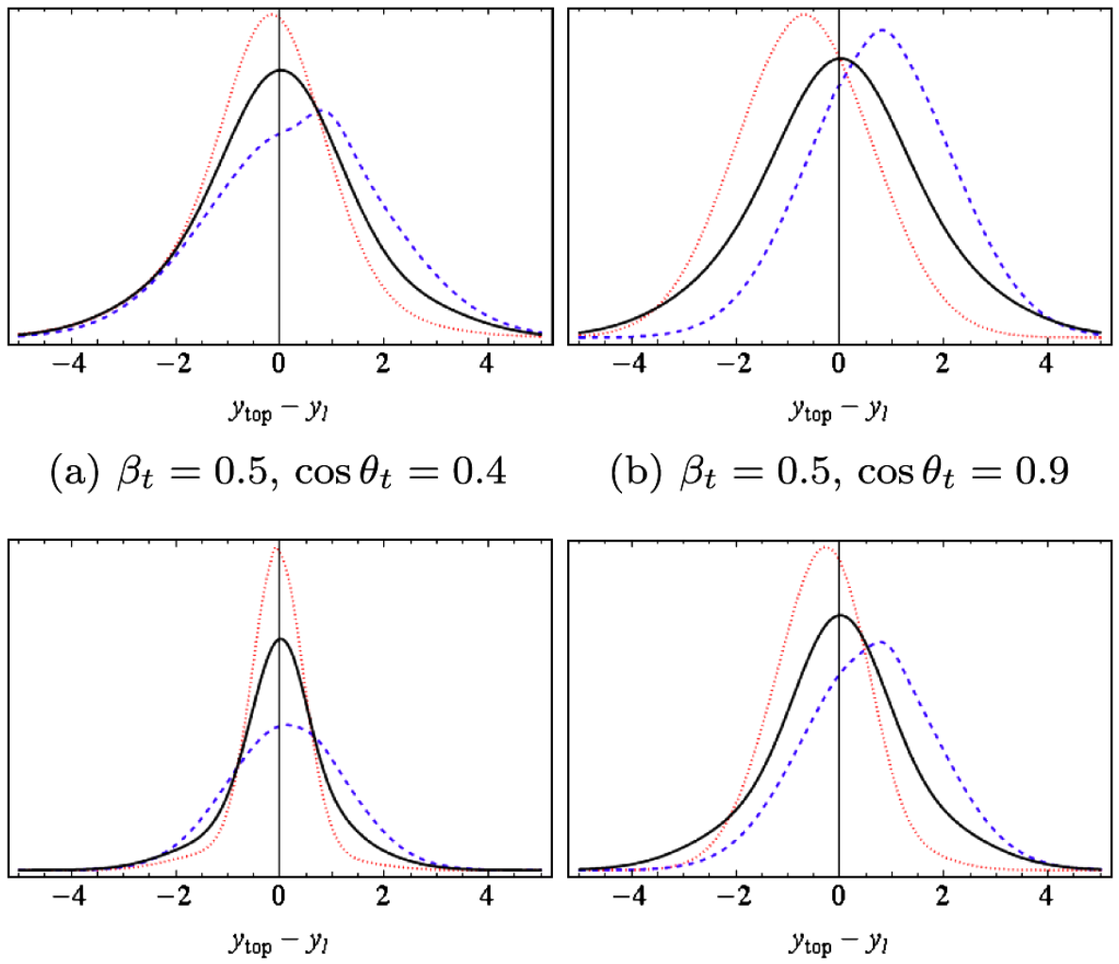
How to check these models?

- Which kind of new physics model is favored by Tevatron?
- It was suggested to measure the lepton forward backward asymmetry from top quark decay. (PRD84, 074034, D. Krohn, T. Liu, J. Shelton and L.-T Wang)

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

Qualitatively, there are more lepton in forward region due to the top decay spin correlation.



(a) $\beta_t = 0.5$, $\cos\theta_t = 0.4$ (b) $\beta_t = 0.5$, $\cos\theta_t = 0.9$

(c) $\beta_t = 0.9$, $\cos\theta_t = 0.4$ (d) $\beta_t = 0.9$, $\cos\theta_t = 0.9$

How to check these models?

- Which kind of new physics model is favored by Tevatron?
- D0 collaboration gives the lepton charge asymmetry!

- For the same top quark distribution, left-handed top quark and right-handed top quark will lead to different lepton charge asymmetry.

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

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

$\frac{A_{FB}^{\ell}}{A_{FB}^{t}} \sim 40\%$

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

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

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

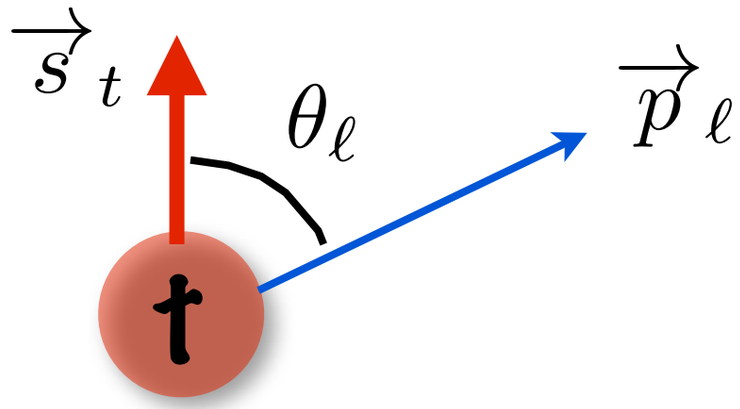
- I will explain how the lepton AFB provides new insight to new physics.

Top quark leptonic decay and spin information

Top Leptonic Decay

- In the top quark rest frame

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

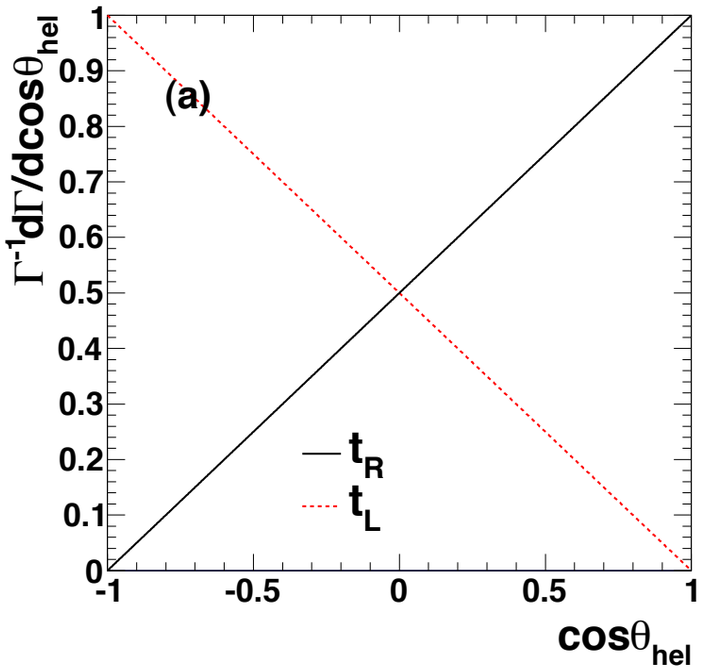


- In helicity basis, the momentum direction of left(right)-handed top quark is opposite (same) to the top quark spin direction

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

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

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



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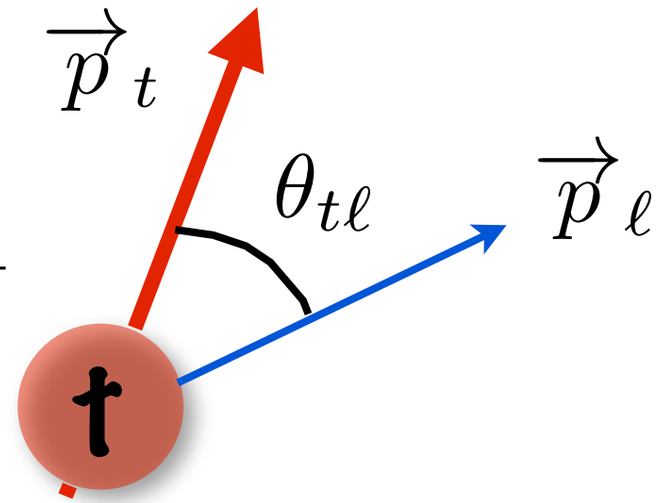
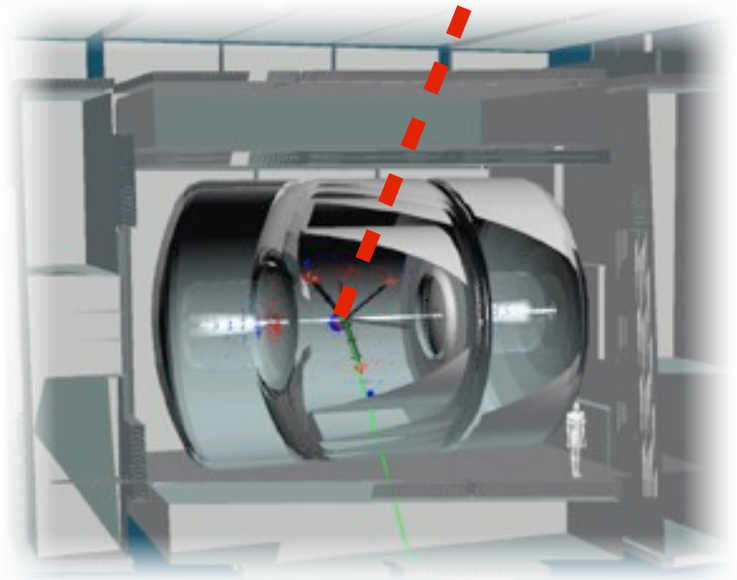
Top Leptonic Decay

- When top quark is boosted, the differential decay spectrum according to the angle between the top quark moving direction and the lepton momentum in the LAB frame is (β = v/c)

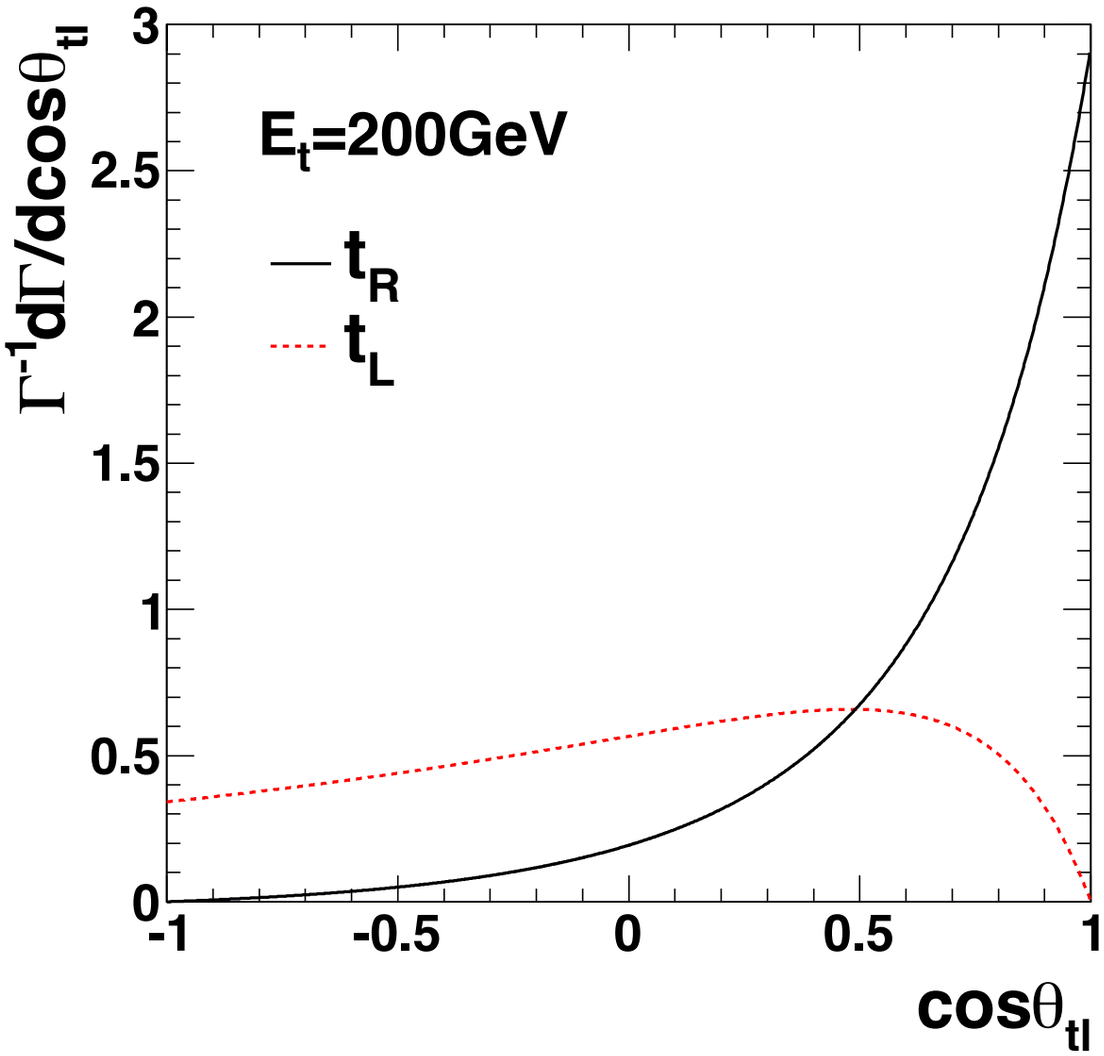
$$\frac{d\Gamma}{\Gamma d\cos\theta_{t\ell}} = \frac{\left[1-\beta\cos\theta_{t\ell}+\lambda_t\left(\cos\theta_{t\ell}-\beta\right)\right]}{2\gamma^2\left(1-\beta\cos\theta_{t\ell}\right)^3}$$





Top Leptonic Decay

- When top quark is boosted, the differential decay spectrum according to the angle between the top quark moving direction and the lepton momentum in the LAB frame is ($\beta = v/c$)



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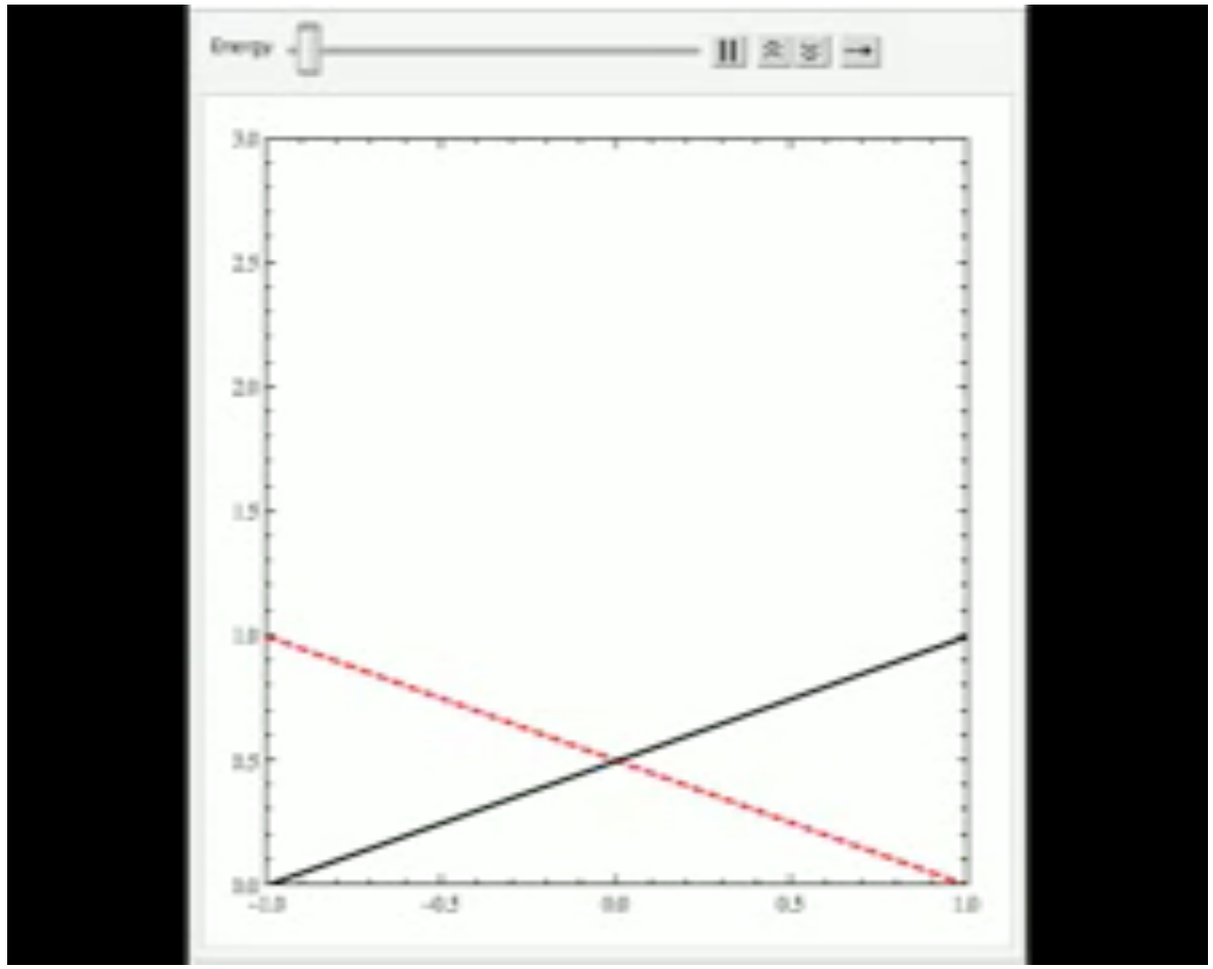
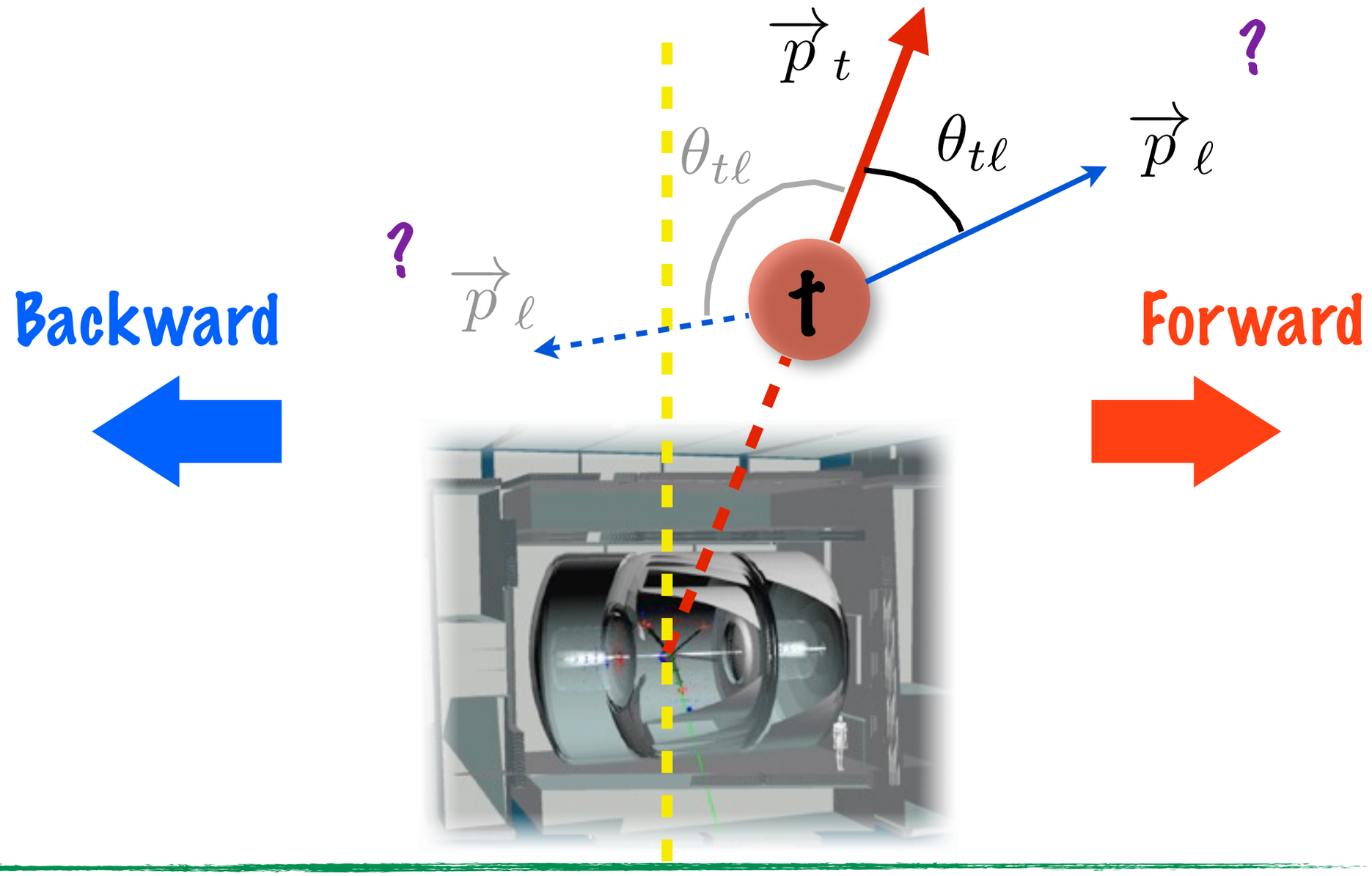


Top Leptonic Decay

- The question is: when we know the configuration of the top quark, what is the probability of the lepton in the forward (backward) region?



Top Leptonic Decay

- We can define a probability density function (p.d.f) of the lepton distribution

$$R_F\left(\overrightarrow{p}_t, \lambda_t\right) = \frac{n_\ell^F}{n_\ell^F + n_\ell^B}$$

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- General properties of the p.d.f

$$\begin{aligned}
&(1)\ R_F|_{y_t=0} = 0.5, \\
&(2)\ R_F\left(-y_t\right) = 1 - R_F\left(y_t\right), \\
&(3)\ R_F|_{E_t\to\infty} \to \Theta\left(y_t\right), \\
&(4)\ R_F|_{\lambda_t=+} \geqslant R_F|_{\lambda_t=-}, \quad \text{for } y_t \geqslant 0.
\end{aligned}$$

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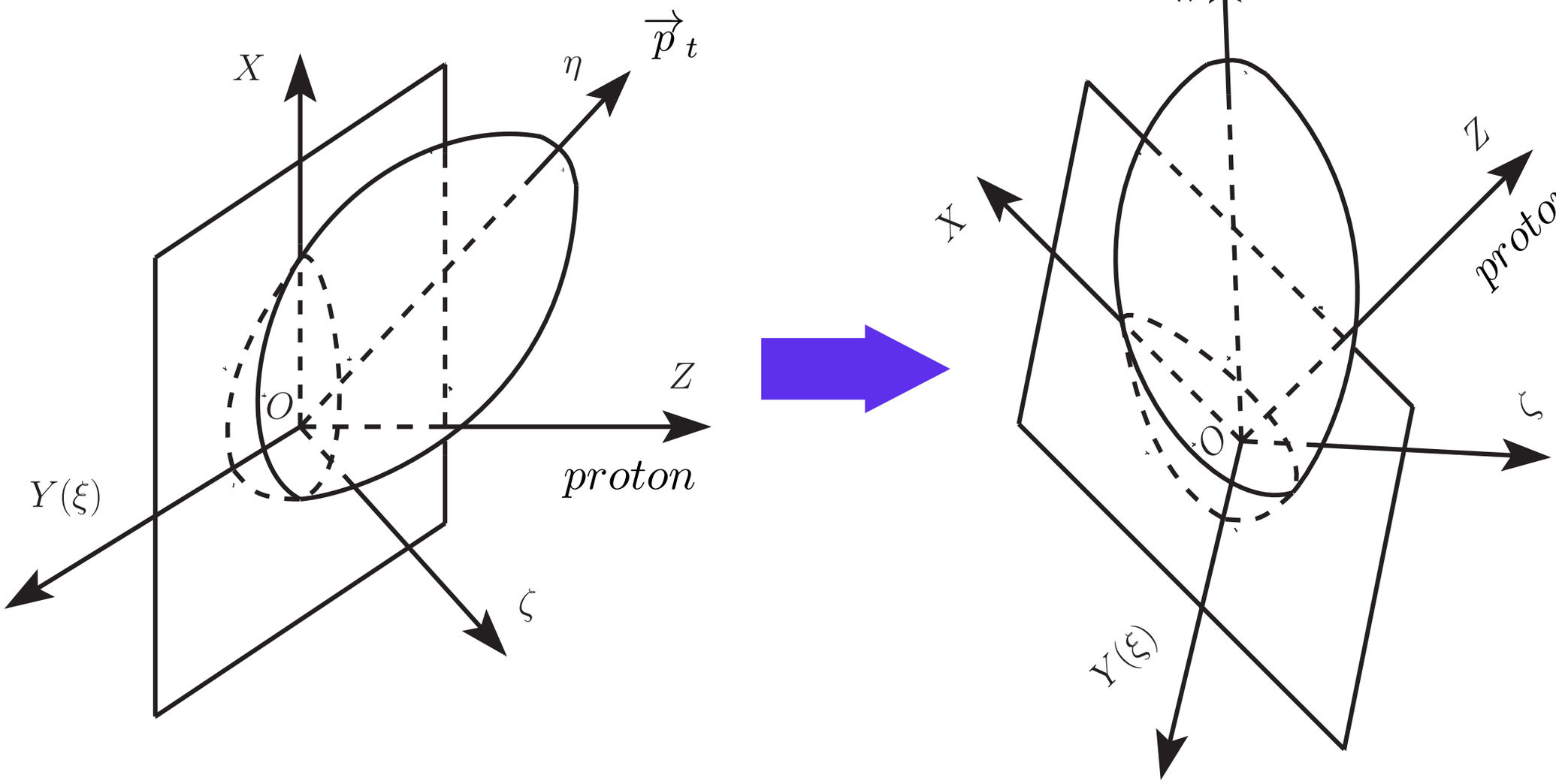

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$$R_F\left(\beta, y_t, \lambda_t\right) = \frac{1}{2} + \frac{1}{2\left(1+\gamma^{-2}\coth^2 y_t\right)^{1/2}} + \frac{\lambda_t \coth^2 y_t}{4\beta\gamma^2\left(1+\gamma^{-2}\coth^2 y_t\right)^{3/2}}$$

$$R_F\left(\beta, -y_t\right) = 1 - R_F\left(\beta, y_t\right)$$

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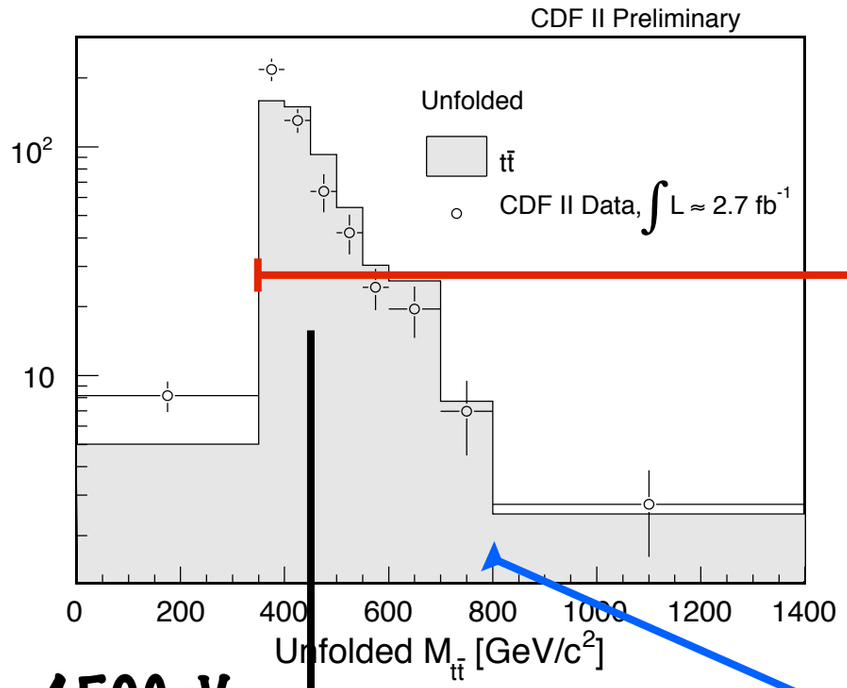
Top Leptonic Decay



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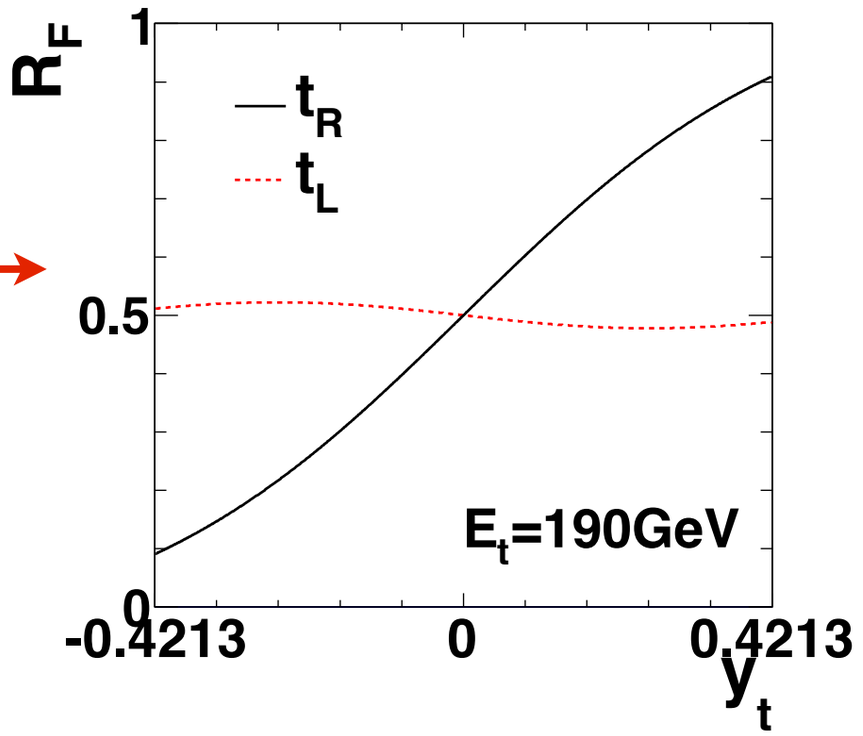
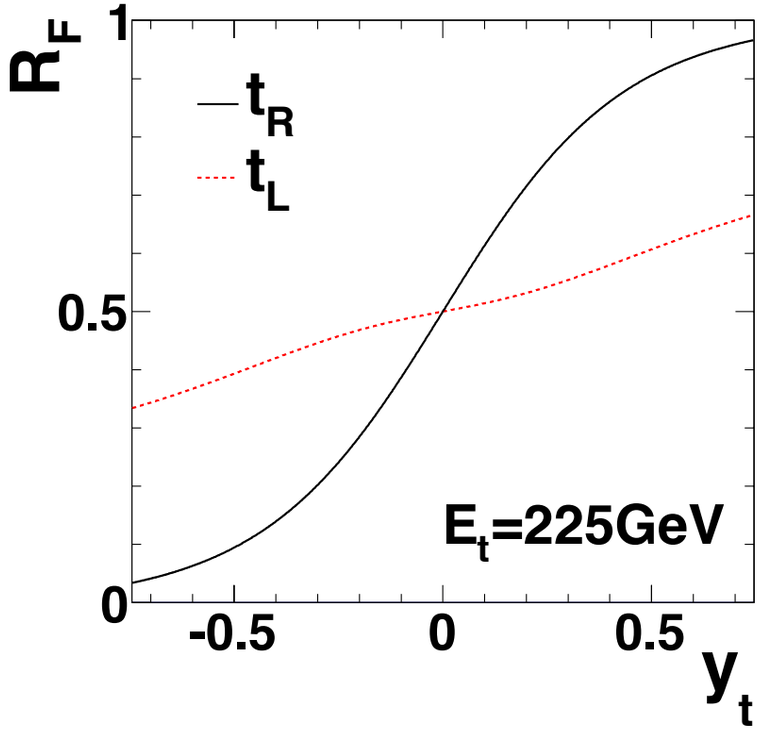
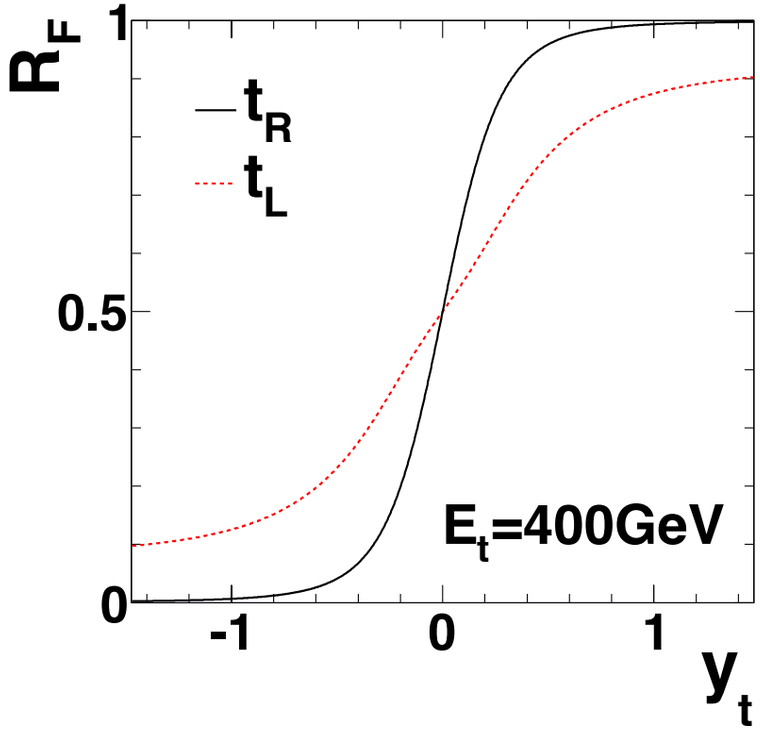


M_{tt} ~ 450GeV

Highly boosted





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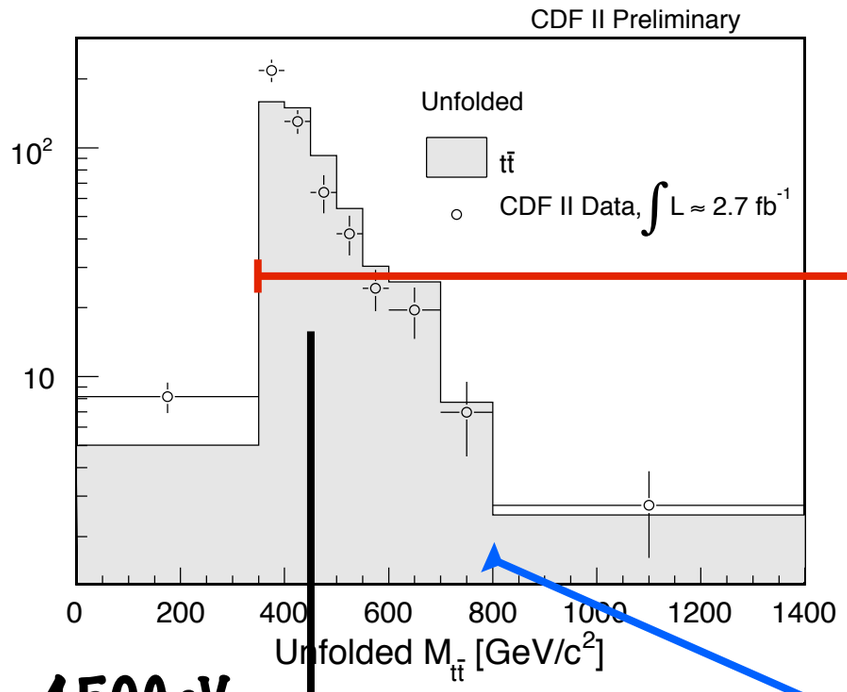

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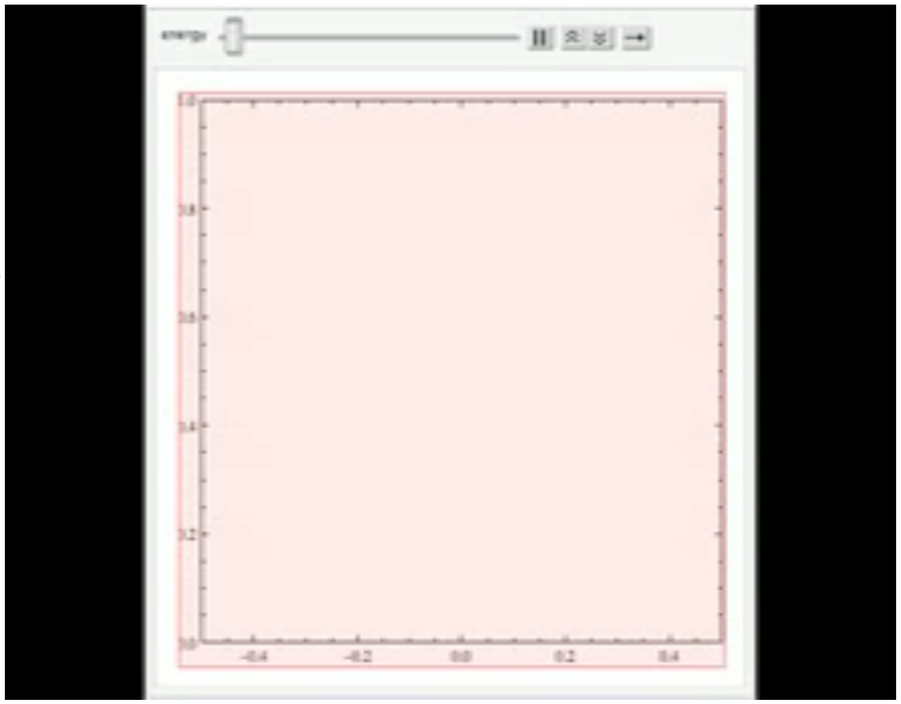

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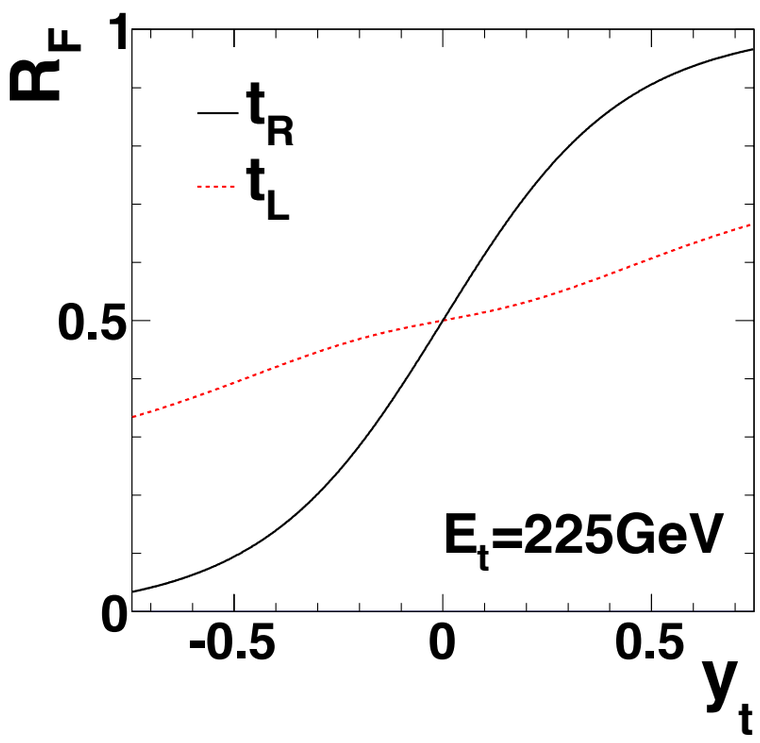

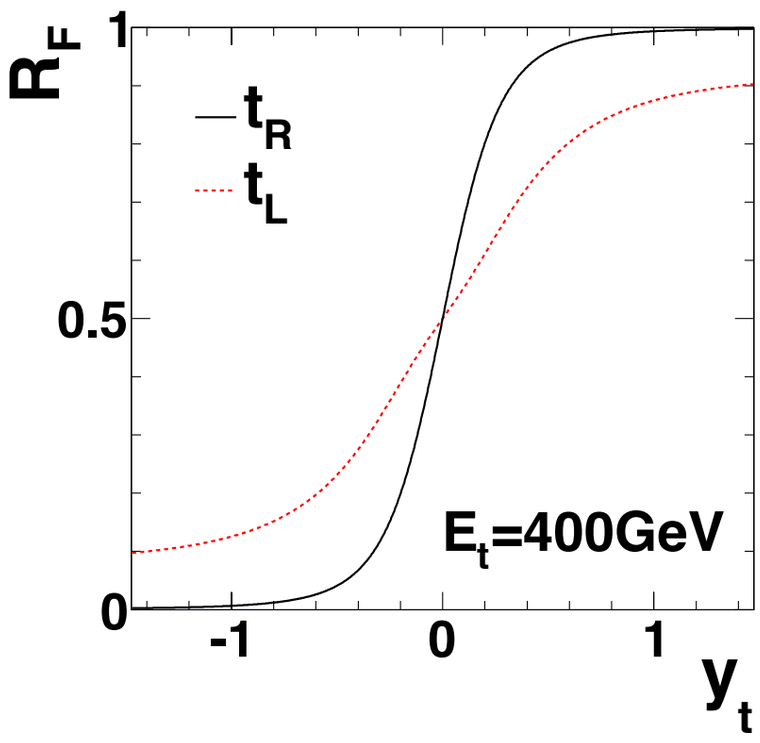

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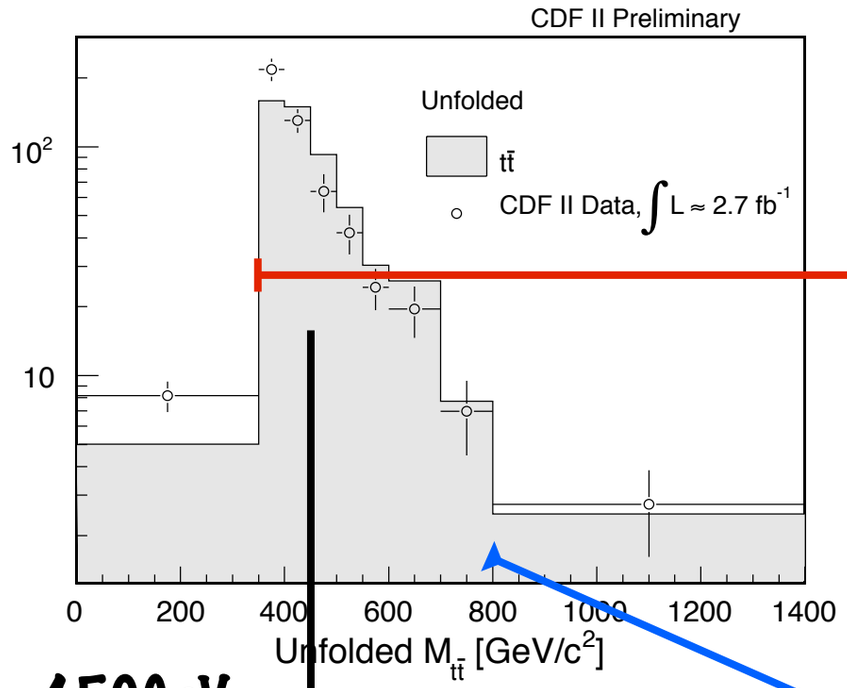

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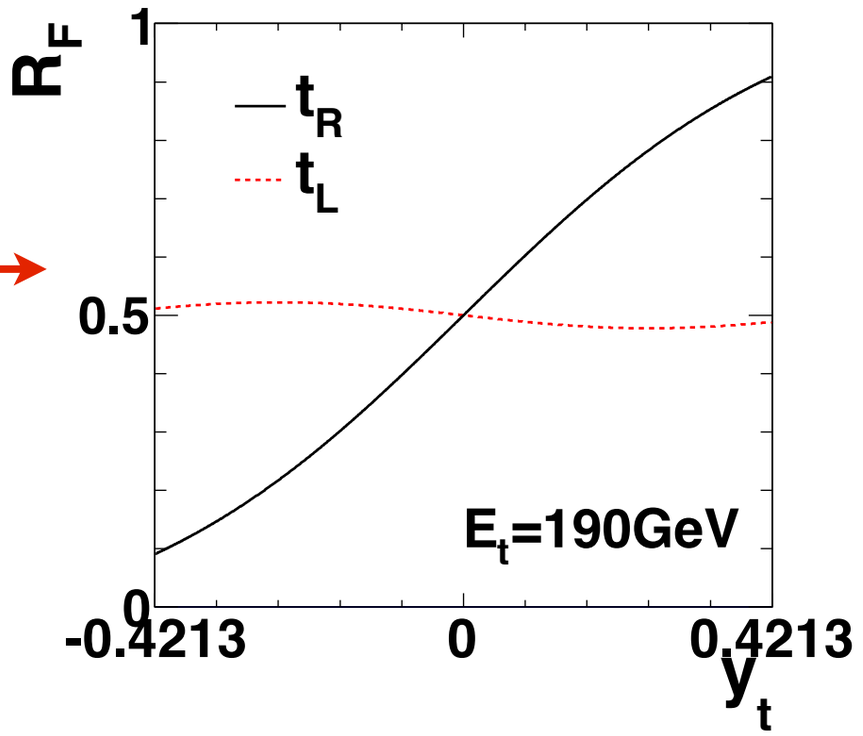

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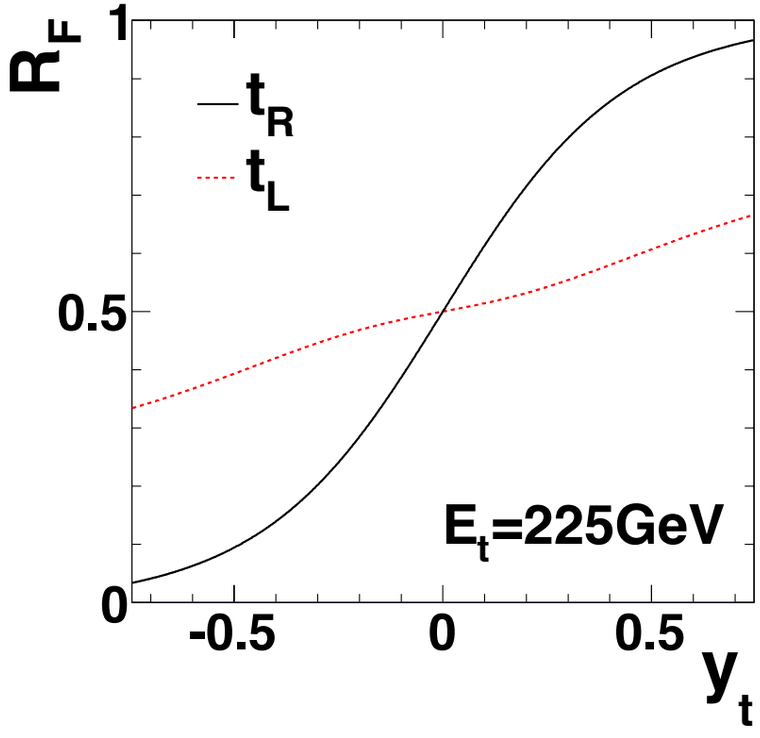

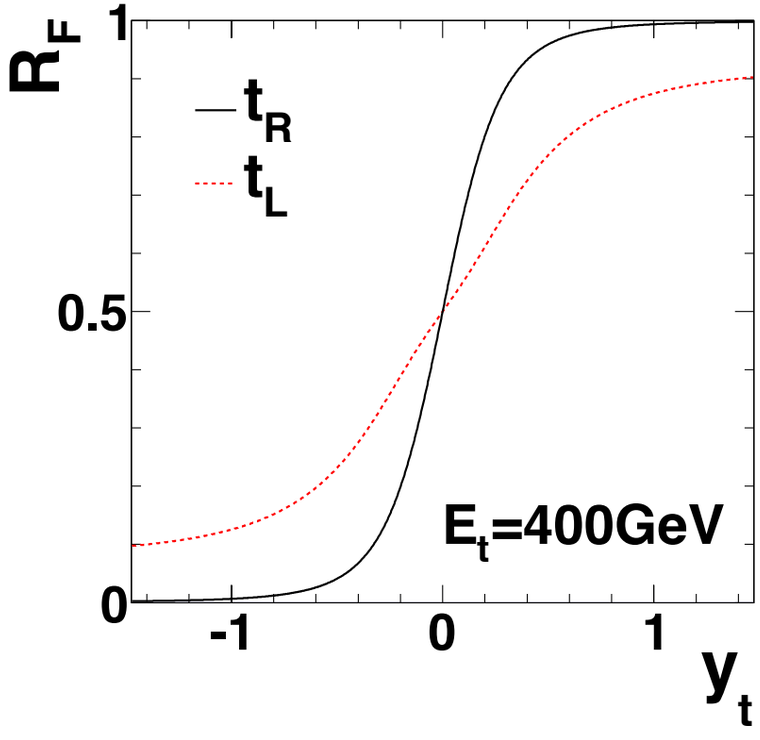

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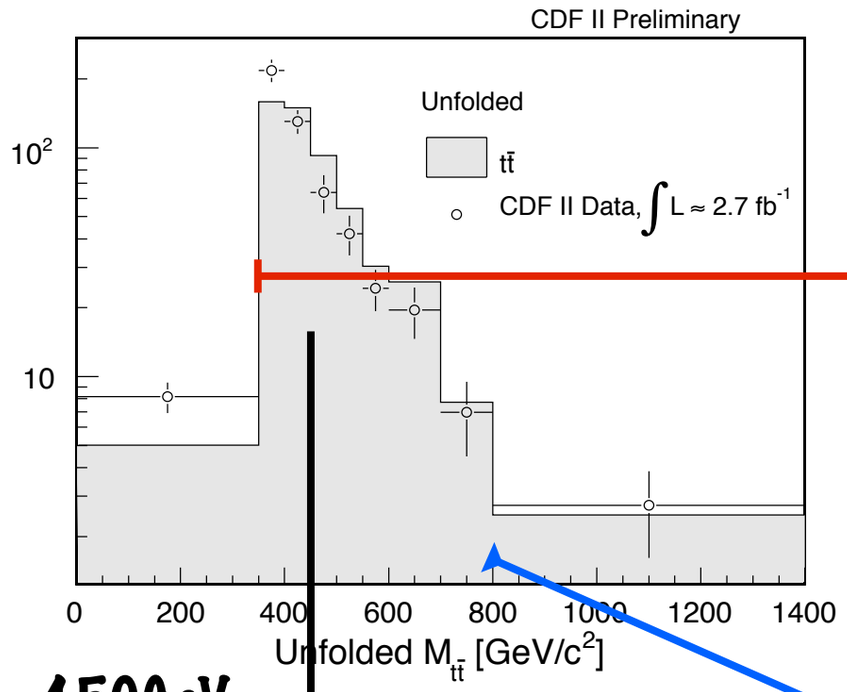

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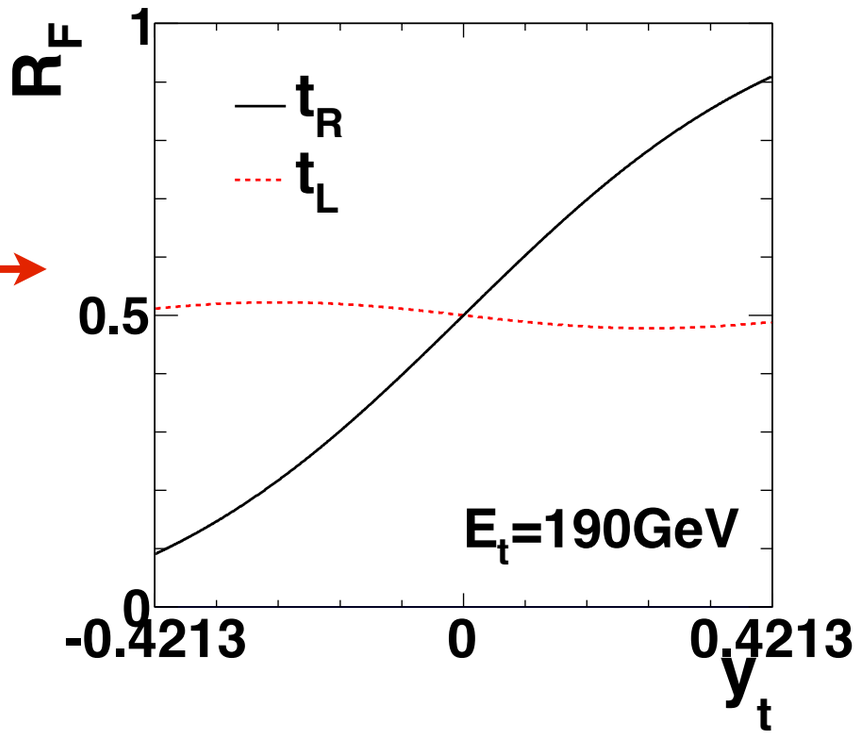

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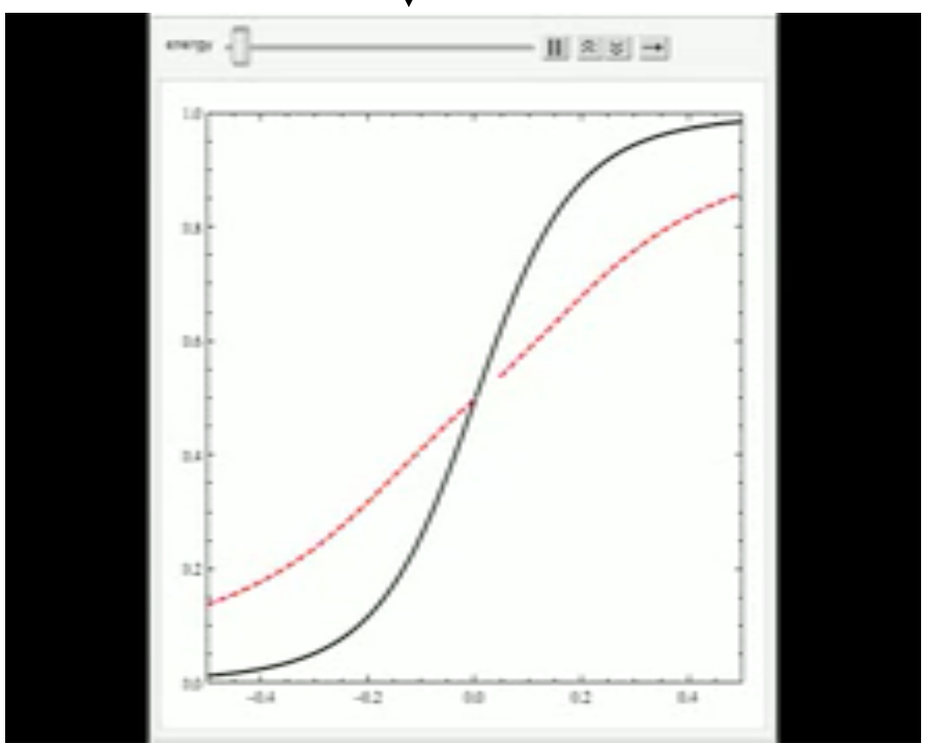

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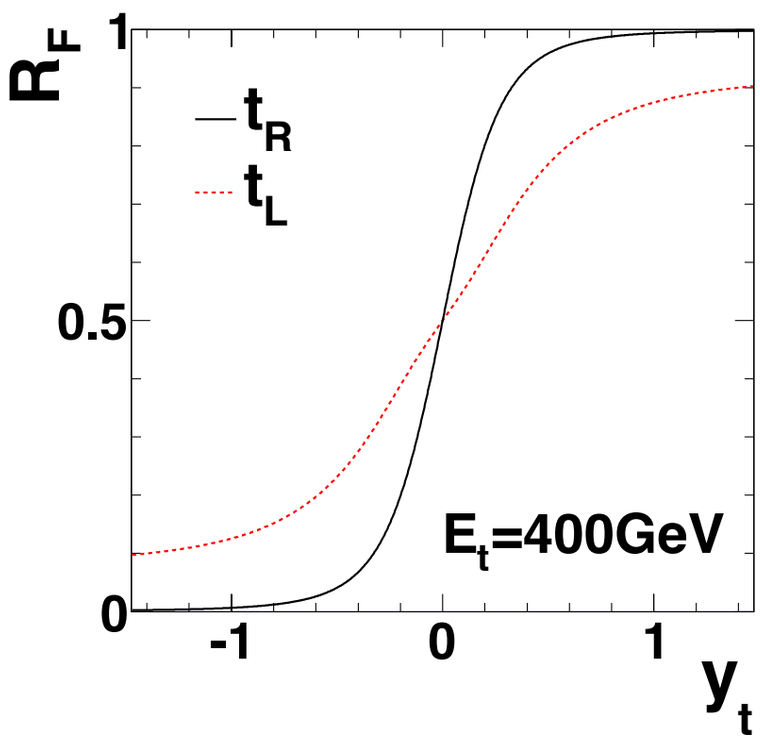

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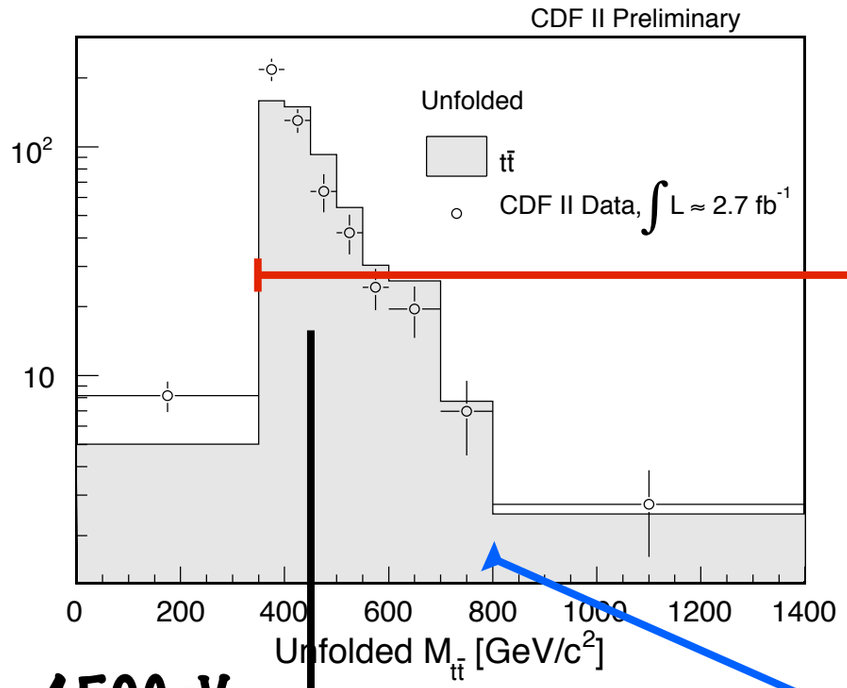

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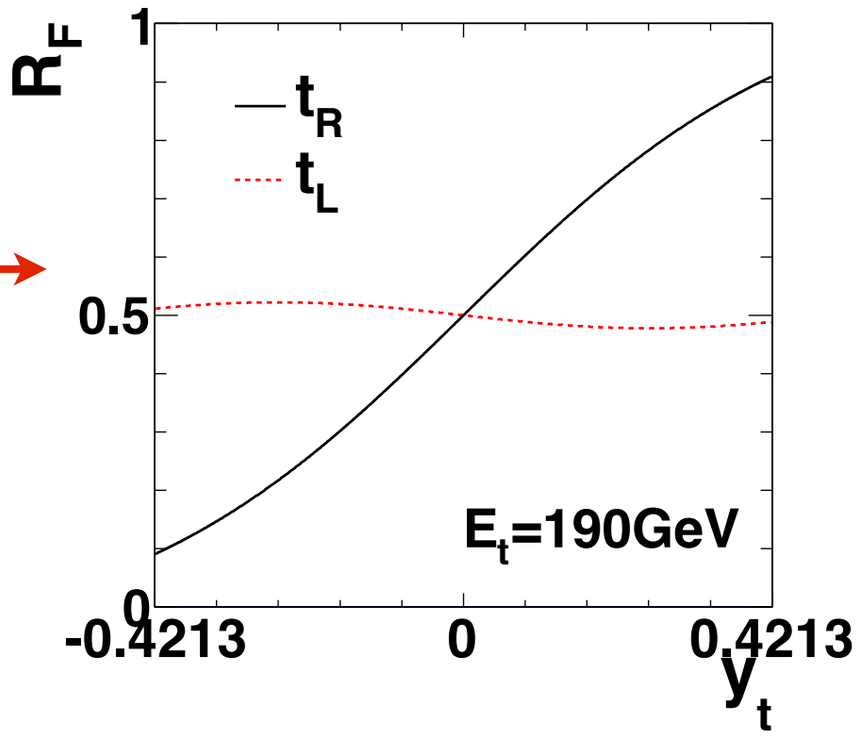

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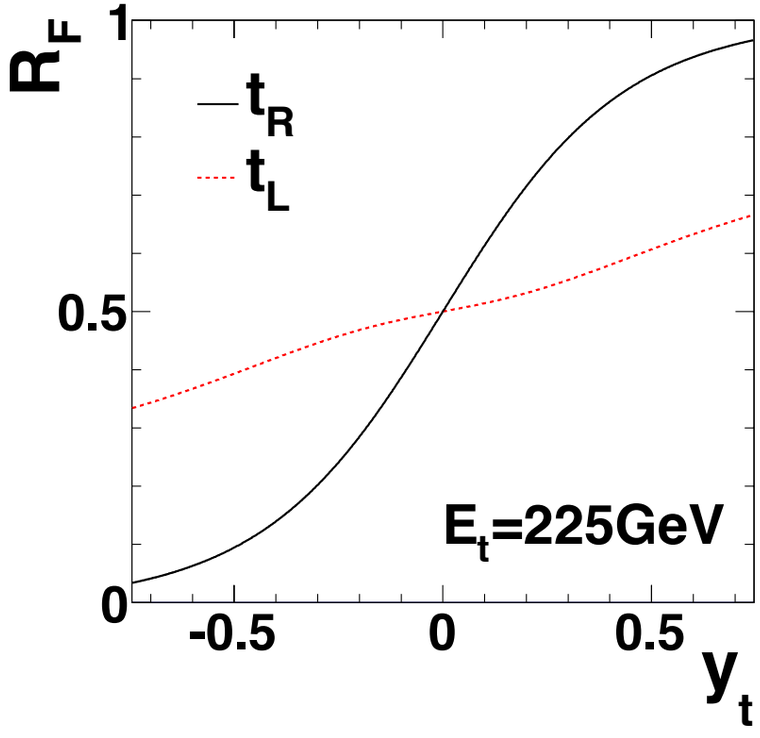

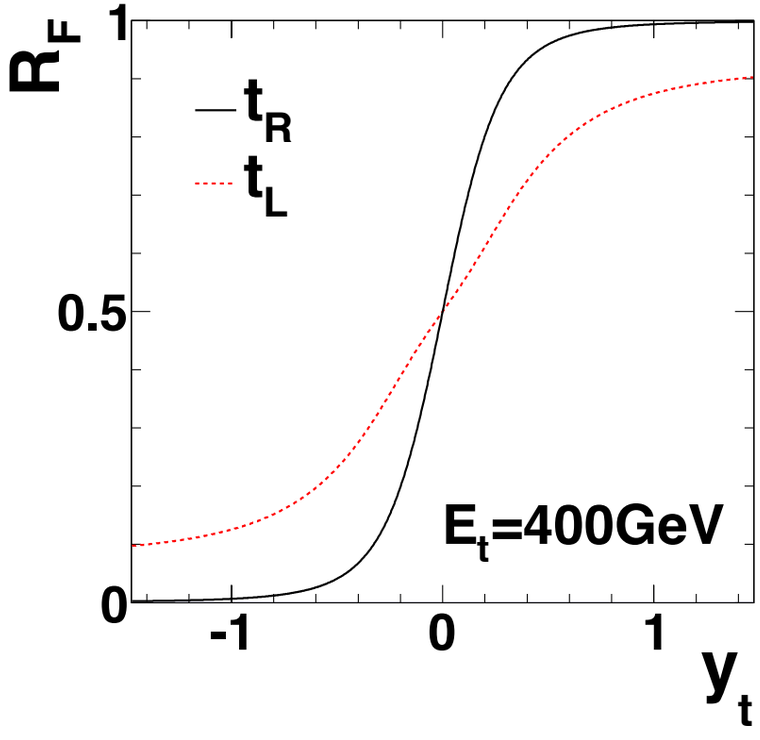

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From top AFB to lepton AFB

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?

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

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

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

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From Top AFB to Lepton AFB

- The integration over rapidity can be separated into two parts:

$$\int_{-\infty}^{\infty} dy = \int_{0}^{\infty} dy + \int_{-\infty}^{0} dy$$

- By definition $R_F\left(\beta, -y_t\right) = 1 - R_F\left(\beta, y_t\right)$

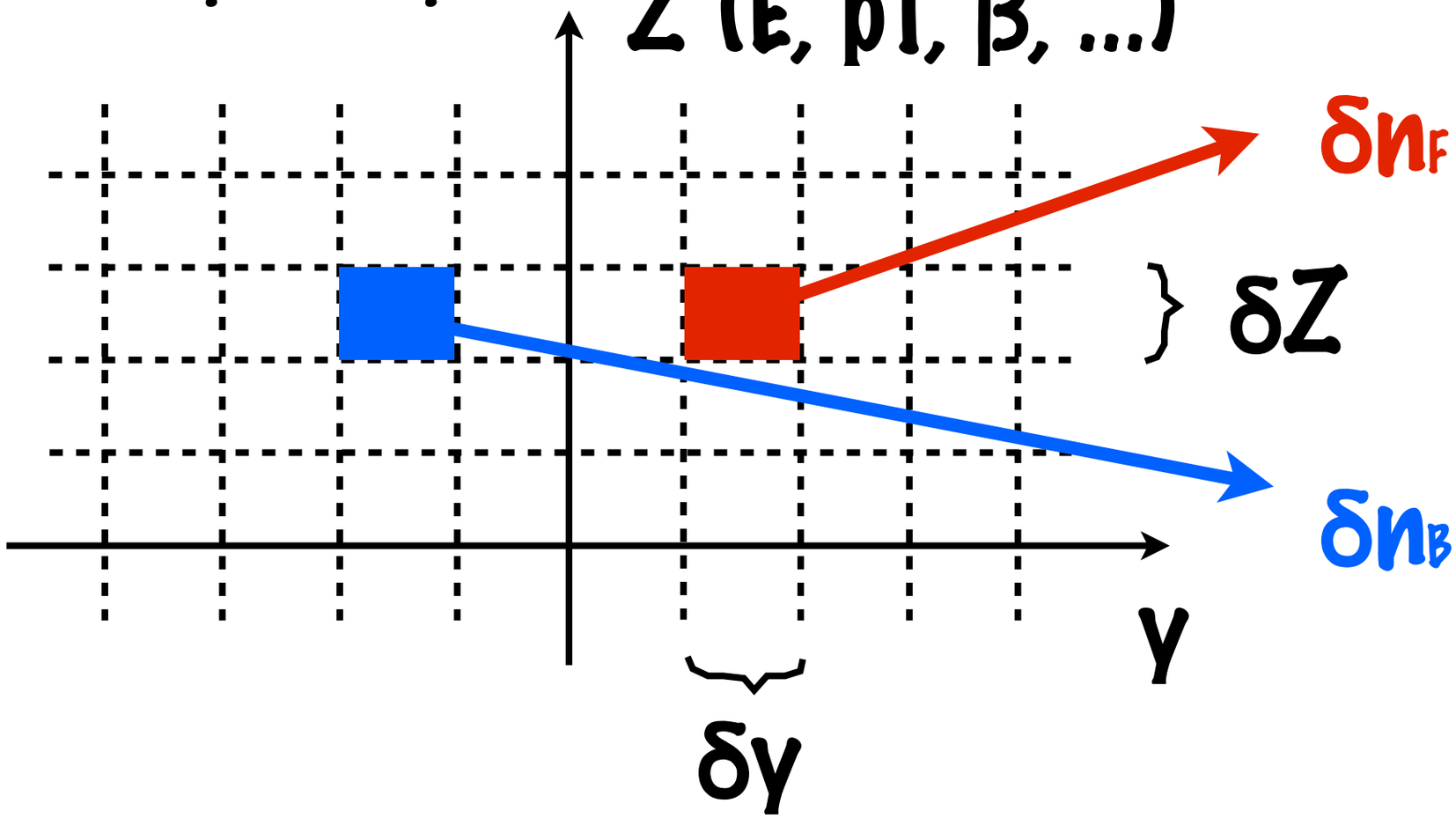
- So we have

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

$$= \sum_{\lambda=+,-} \int \Theta\left(y_t\right) \left[2R_F^{\lambda}\left(\beta, y_t\right) - 1\right] \Delta^{\lambda}\left(\beta, y_t\right) d\beta \wedge dy_t$$

From Top AFB to Lepton AFB

- Top quark in phase space



$$\Delta(Z, y) = \lim_{\delta y \to 0,\ \delta Z \to 0} (\delta n_F - \delta n_B)/(n\ \delta y\ \delta Z)$$

- Normalized differential forward-backward asymmetry for the top!

From Top AFB to Lepton AFB

- Without the weight function $2R_F-1$

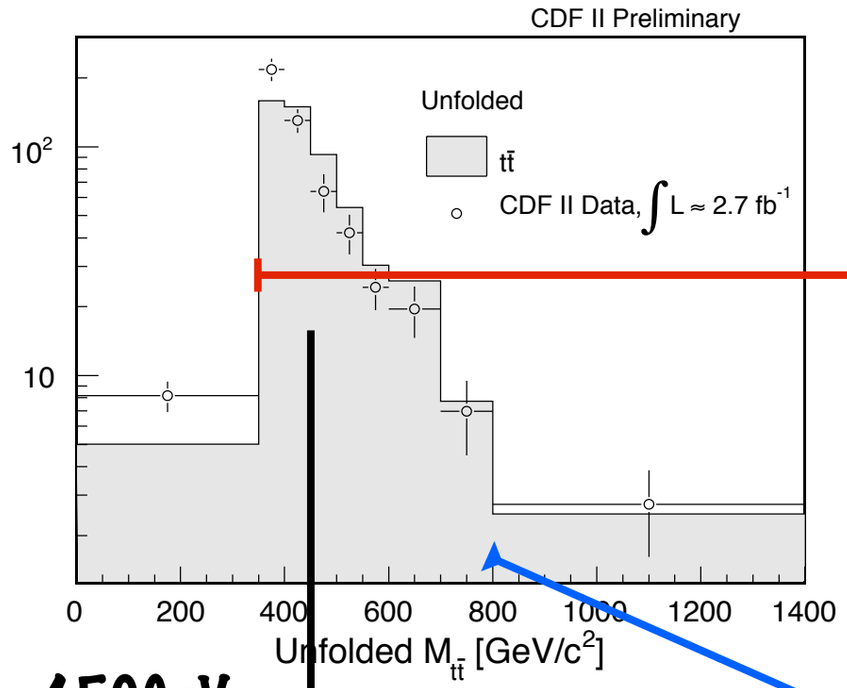
$$\sum_{\lambda=+,-} \int \Theta\left(y_t\right) \Delta^{\lambda}\left(\beta, y_t\right) d\beta \wedge dy_t$$

is "the top quark AFB".

- If the dominant contribution to Δ is from large boost region, $2R_F-1 \rightarrow 1$, lepton AFB ≈ top AFB.

- Right-handed top quarks will give larger lepton AFB. The difference from the left-handed top quarks is larger if the dominant contribution to Δ is from threshold region.

From Top AFB to Lepton AFB



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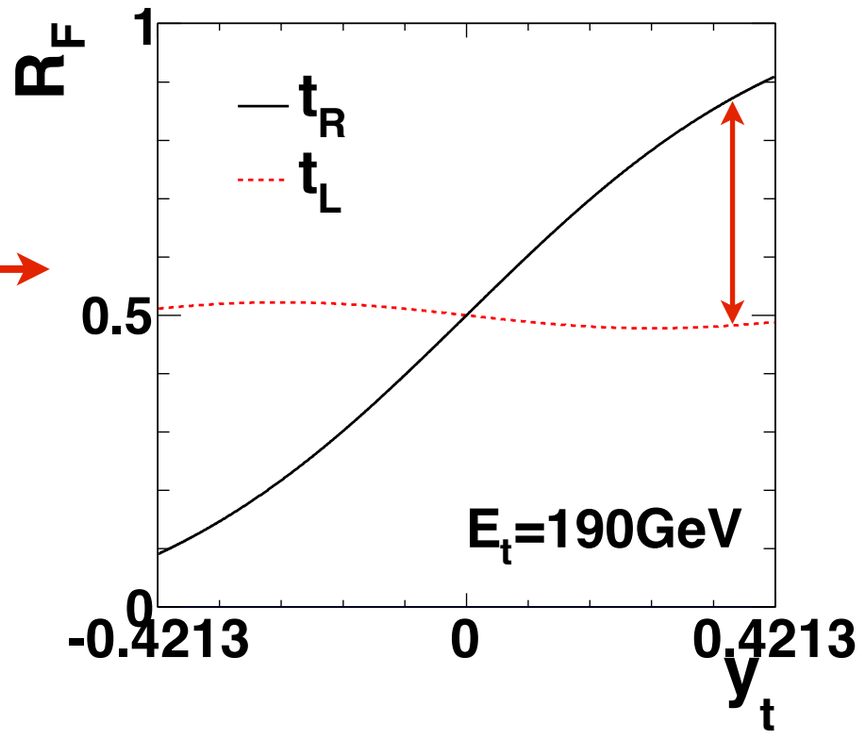
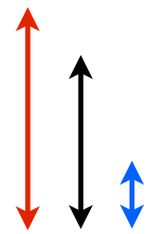
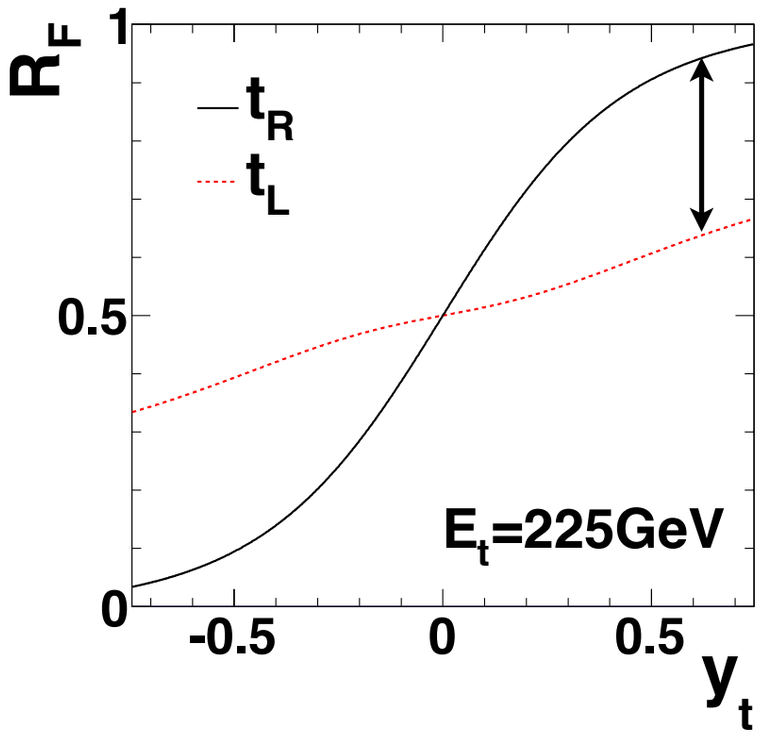
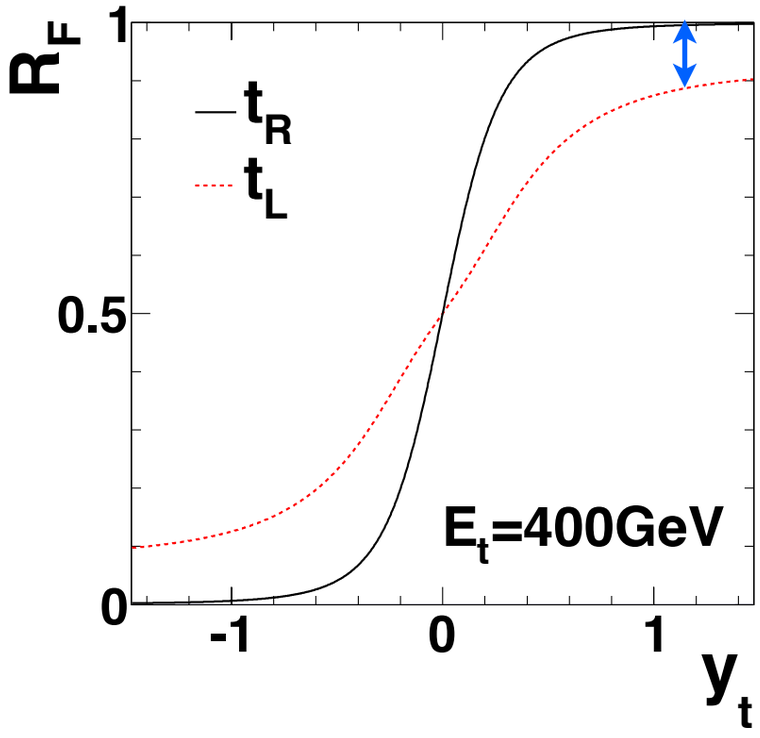




M_{tt} ~ 450GeV



Highly boosted



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From Top AFB to Lepton AFB

- Without the weight function $2R_F-1$

$$\sum_{\lambda=+,-} \int \Theta\left(y_t\right) \Delta^{\lambda}\left(\beta, y_t\right) d\beta \wedge dy_t$$

is "the top quark AFB".

- If the dominant contribution to Δ is from large boost region, $2R_F-1 \rightarrow 1$, lepton AFB ≈ top AFB.

- Right-handed top quarks will give larger lepton AFB. The difference from the left-handed top quarks is larger if the dominant contribution to Δ is from threshold region.

- Special case, if the dominant contribution to Δ is from threshold region and the top quarks are nearly all left-handed, a "+" top quark AFB will lead to a "-" lepton AFB.

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 could we learn?

- The D0 result

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

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

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

Data needs larger $2R_F$-1 than the SM !!

- Two possibilities:

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

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

Two examples of New Physics Models

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 the new physics

Two Examples (I). Axigluon

- Assuming $-g_l = g_h$, we scan the parameter space using MadGraph5 and BRIDGE to fit the total cross section and the top AFB.
- D0 gives the unfolded result.
- We combine the new physics contribution and the NLO SM contribution:

$$
\begin{aligned}
A_{FB}^t =& \frac{n_F - n_B}{n_F + n_B} \\
=& \frac{n_F^{SM\ NLO} + n_F^{with\ NP} - n_B^{SM\ NLO} - n_B^{with\ NP}}{n^{SM\ NLO} + n^{with\ NP}} \\
=& \frac{n_F^{SM\ NLO} + n_F^{NP} - n_B^{SM\ NLO} - n_B^{NP}}{n^{SM\ NLO} + n^{NP} - n^{SM\ LO}} \\
=& A_{FB}^t|_{SM} \times \frac{\sigma^{SM\ NLO}}{\sigma^{SM\ NLO} + \sigma^{NP} - \sigma^{SM\ LO}} \\
&+ A_{FB}^t|_{NP} \times \frac{\sigma^{NP}}{\sigma^{SM\ NLO} + \sigma^{NP} - \sigma^{SM\ LO}}
\end{aligned}
$$

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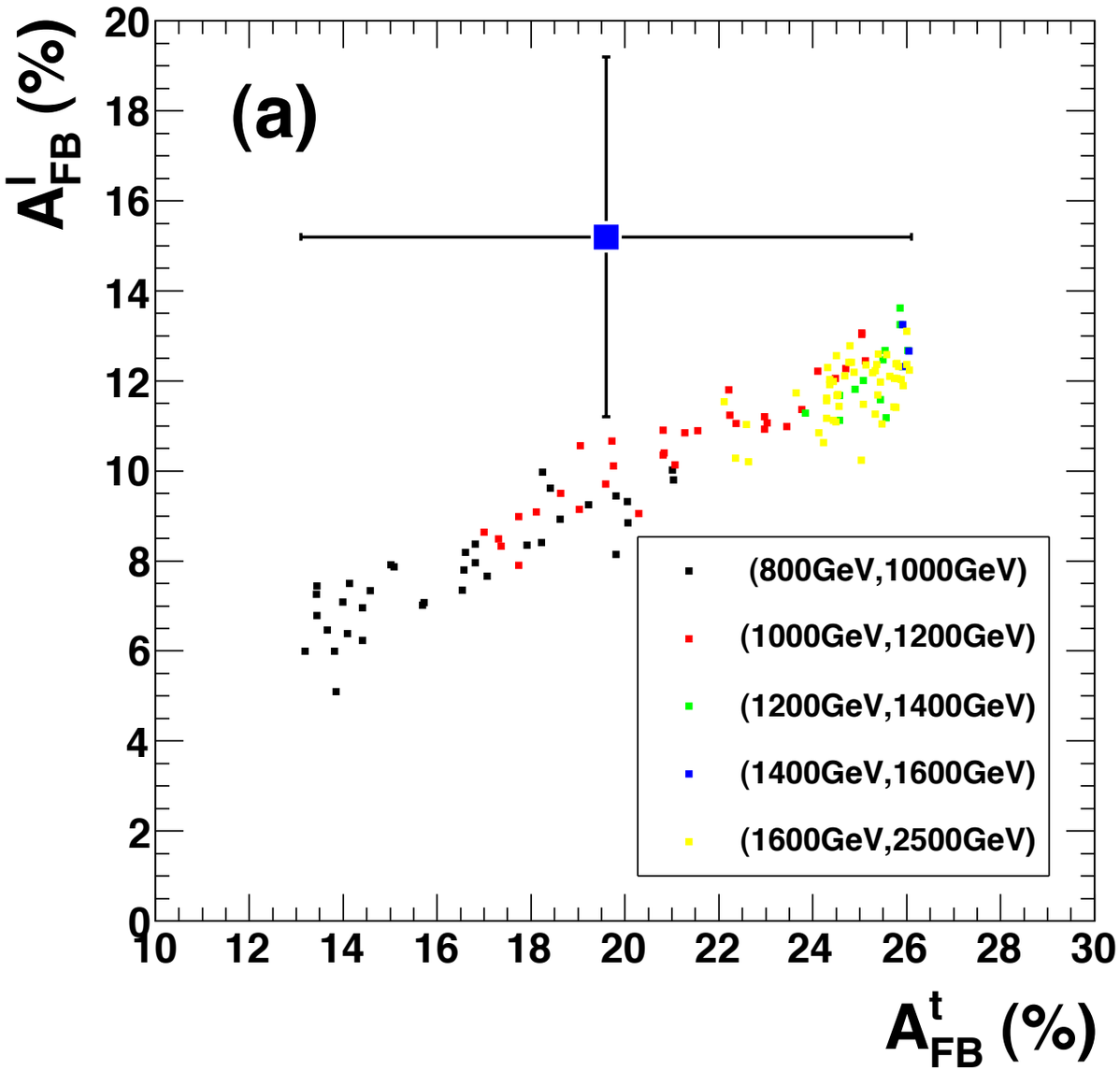
Two Examples (I). Axigluon

- Requiring both the top AFB and the total cross section within 1σ, we show the correlation between top and lepton AFB

- Large mass axigluon can fit the data better, because the contribution from boosted tops is larger.
- Basically, an axigluon will give a small increase in the lepton AFB.

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



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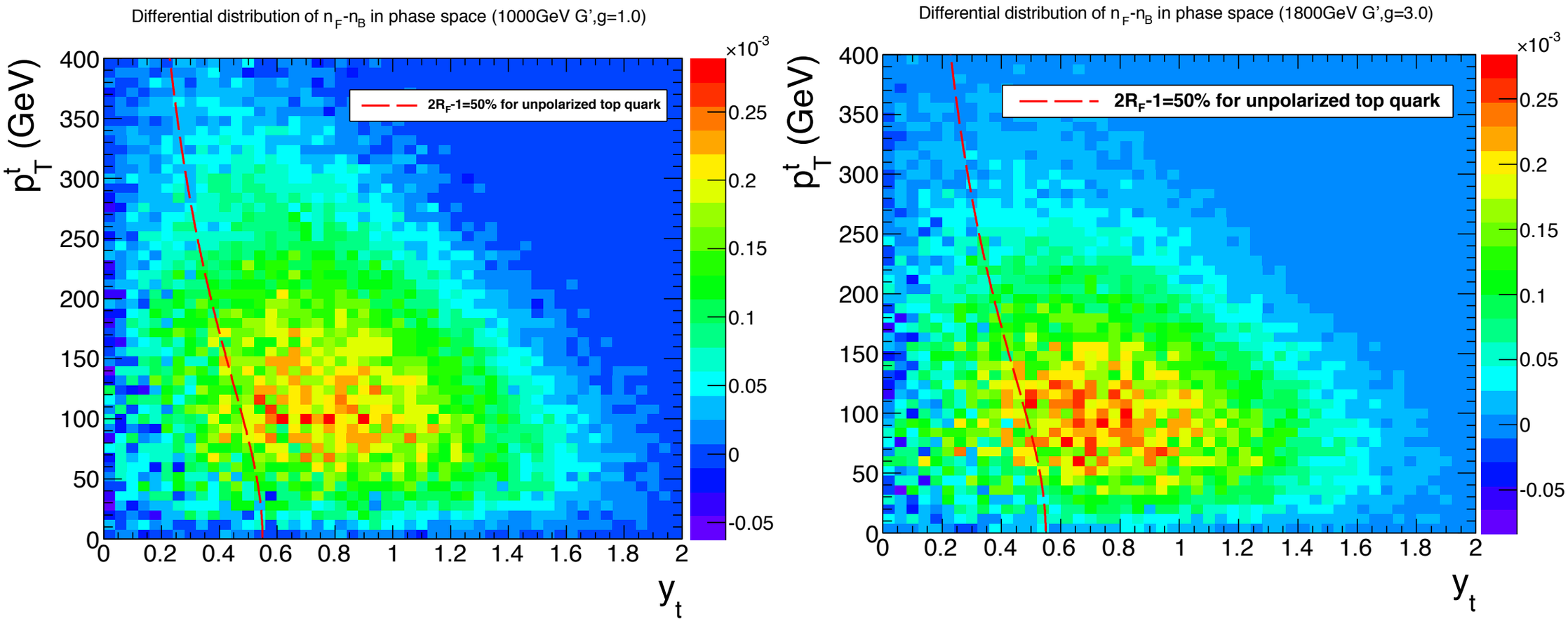
Two Examples (I). Axigluon

The distribution function Δ



- In order to get the lepton AFB, we have to convolute this distribution with $2R_F$-1
- On the right-hand side of the dashed red line, the weight function $2R_F$-1>50%

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

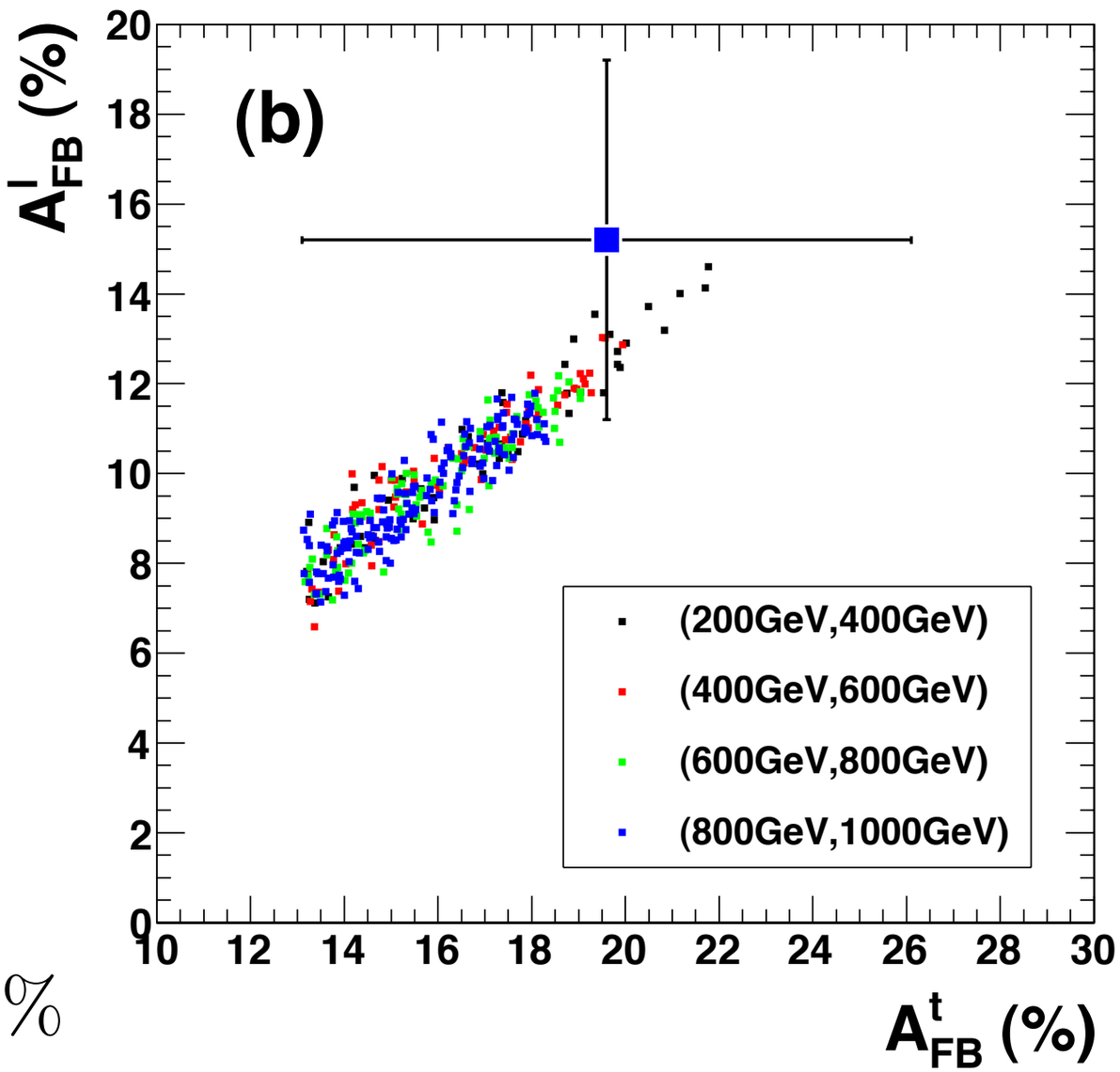
Two Examples (III). W'

- Requiring both the top AFB and the total cross section within 1σ, we show the correlation between top and lepton AFB

- Low mass W' can fit the data better, because the contribution from NP is larger.

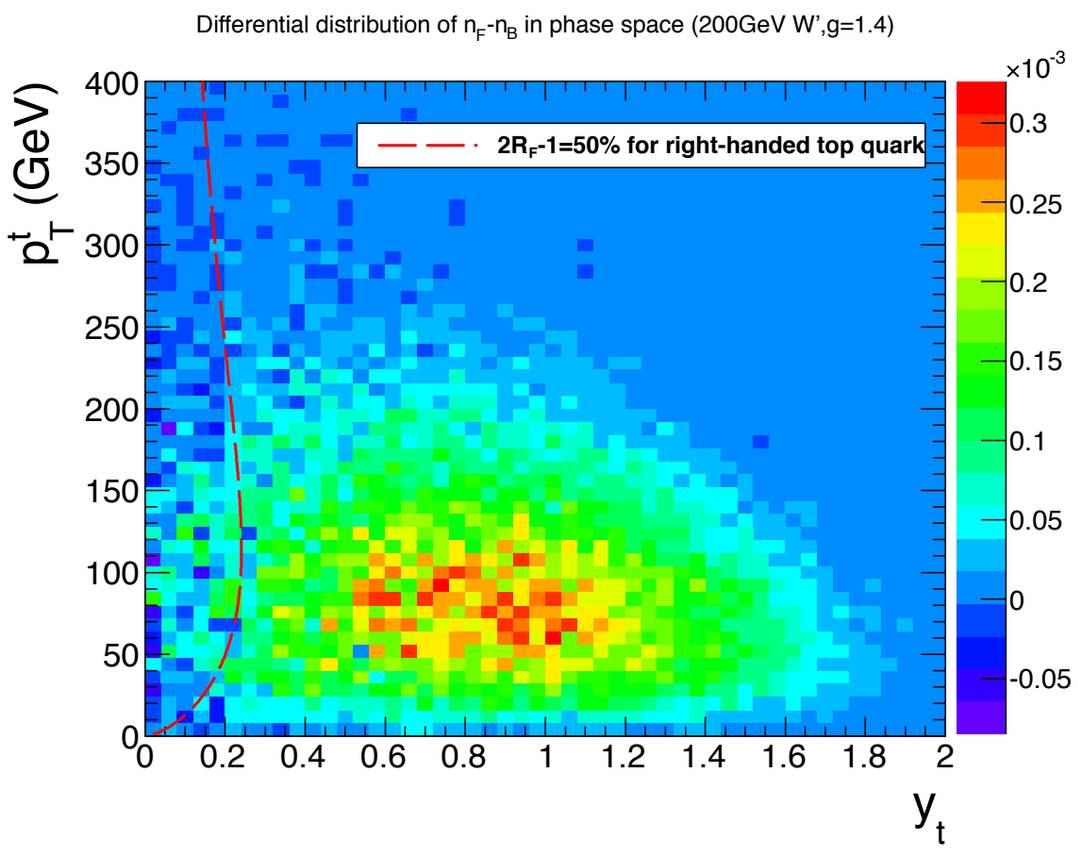
- W' model will give a large increase in the lepton AFB.

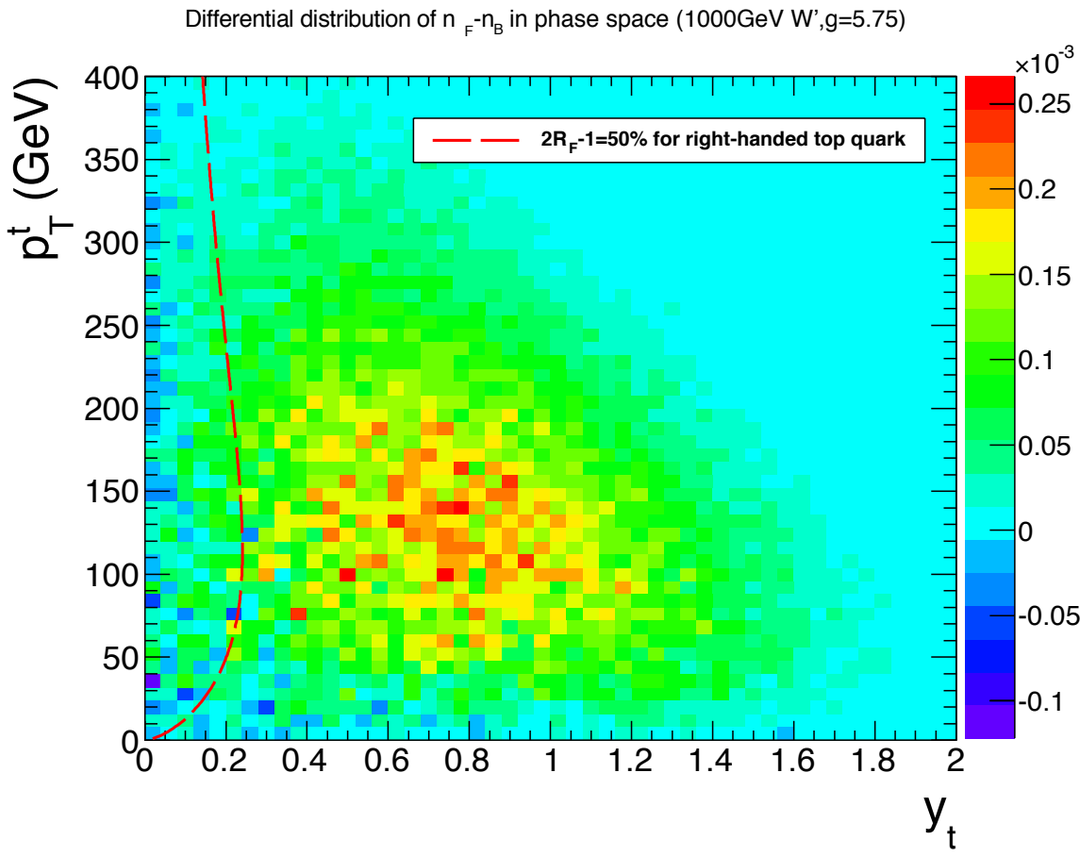
$$A_{FB}^{\ell} \simeq 0.75 \times A_{FB}^{t} - 2.1\%$$



Two Examples (II). W'

The distribution function Δ





- On the right-hand side of the dashed red line, the weight function $2R_F-1>50\%$
- Comparing with the unpolarized case, the red dashed line moves to the left

Conclusion and Outlook

Conclusion

- We study the kinematic and dynamic aspects of the relationship between the top AFB and lepton AFB based on the spin correlation between charged leptons and the top quark with different polarization states.
- Owing to the spin correlation in top quark decay, they 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 D0 collaboration shows a relatively large positive correlation.
- So a new physics model that predicts more right-handed top quarks is favored by this new result!

Phys. Rev. Lett. 108, 072002

Outlook

- The error bar is still large

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

- It is necessary to analyze more data from the Tevatron to reduce this uncertainty.

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How about the LHC?

LHC Now

- It is more difficult to measure the top AFB at the LHC

  (1) pp collider

  (2) gg initial state dominant

  (3) for qqbar initial state process, the c.m.s and then the top quark is boosted. The difference between left-handed and right-handed top is smaller at the LHC

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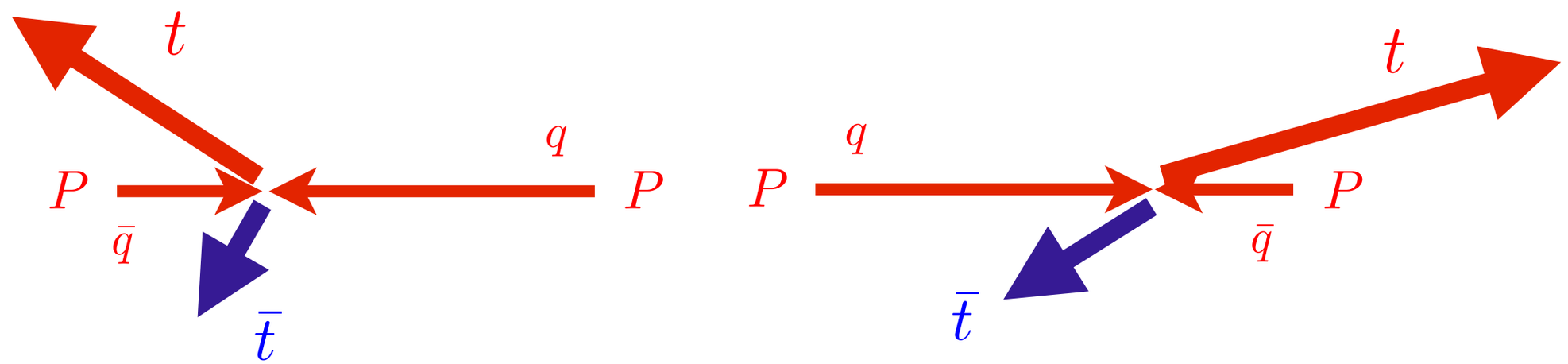

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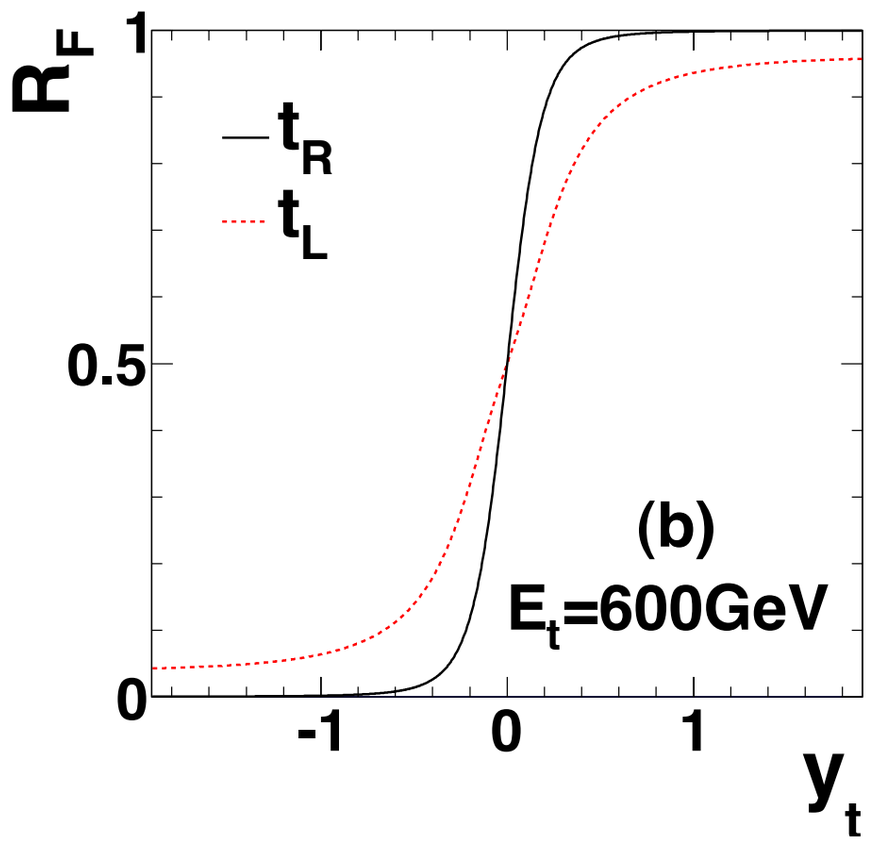

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$$A_C^{\ell\ell} = 0.023 \pm 0.012(\text{stat.}) \pm 0.008(\text{syst.})$$

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

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

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

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CMS Collaboration, arXiv: 12070065

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

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- It is possible to obtain an estimation of AFB at the LHC by extrapolating from the Tevatron result and applying the gg dilution.
- Estimate this way is about 10%, in agreement with ATLAS.

Thank you!