# トップ対生成におけるスピン相関と前後方非対称性

武内勇司 (筑波大)
for CDF collaboration

特定領域「フレーバー物理の新展開」研究2012
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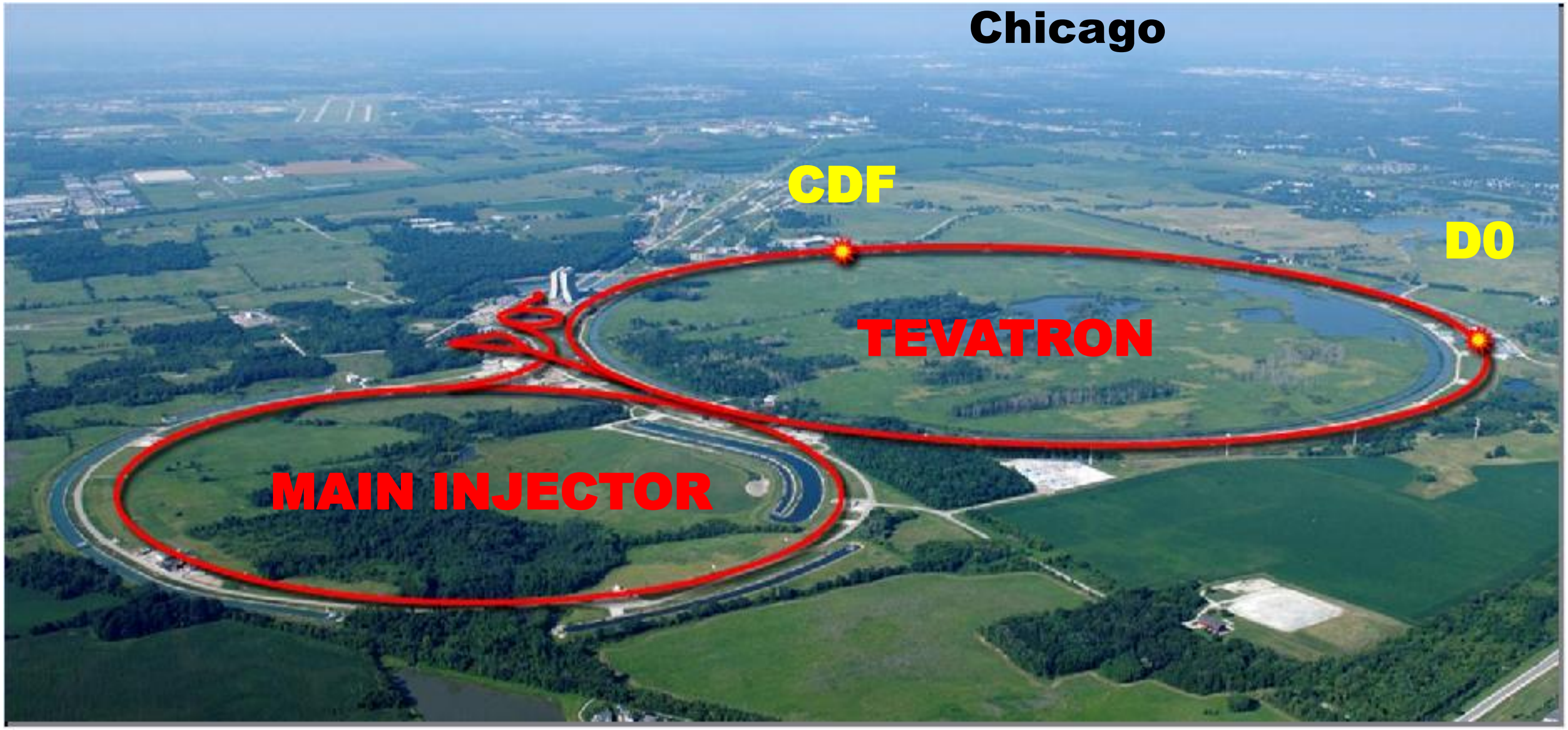
Jul. 7th, 2012

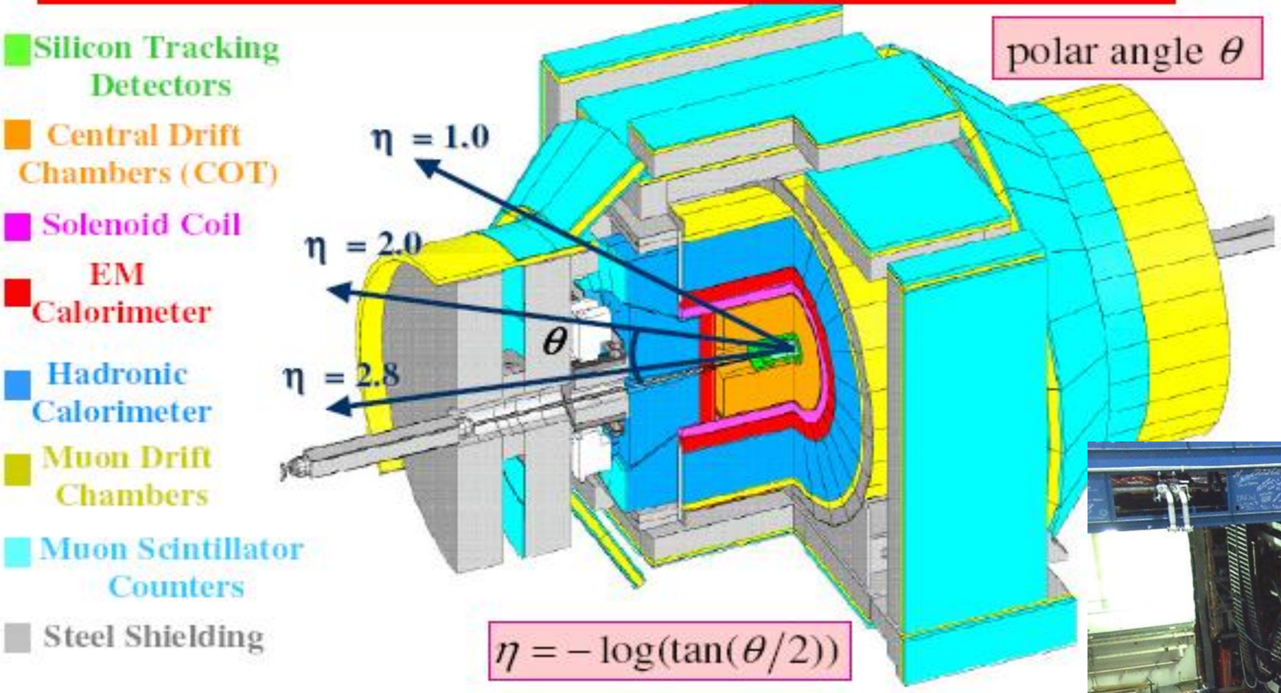
# Tevatron Run II

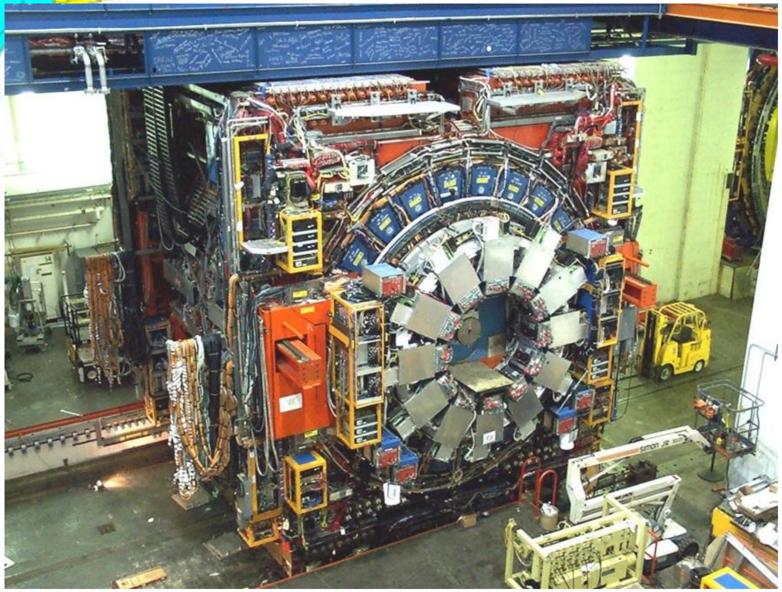



Tevatron

- Proton-antiproton collisions at $\sqrt{s}$ = 1.96 TeV
- Shutdown on Sep. 30, 2011
- Final dataset: ~10 $fb^{-1}$ for physics

# The CDF II Detector

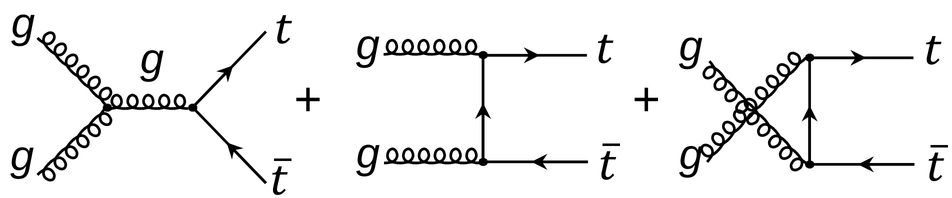


- Silicon vertex detector (1+5+2 layers)
- Central drift chamber (8 super layers)
- 1.4T solenoid
- Good particle identification (K,$\pi$)
- Central/Wall/Plug calorimeters
- Scintillator+drift chamber muon detectors

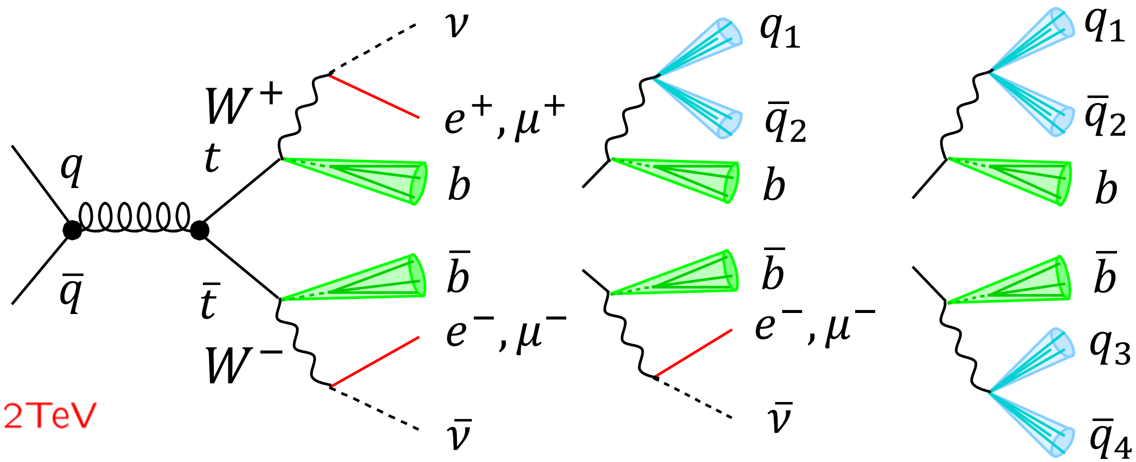
# TEVATRONにおける$t\bar{t}$ 生成と崩壊

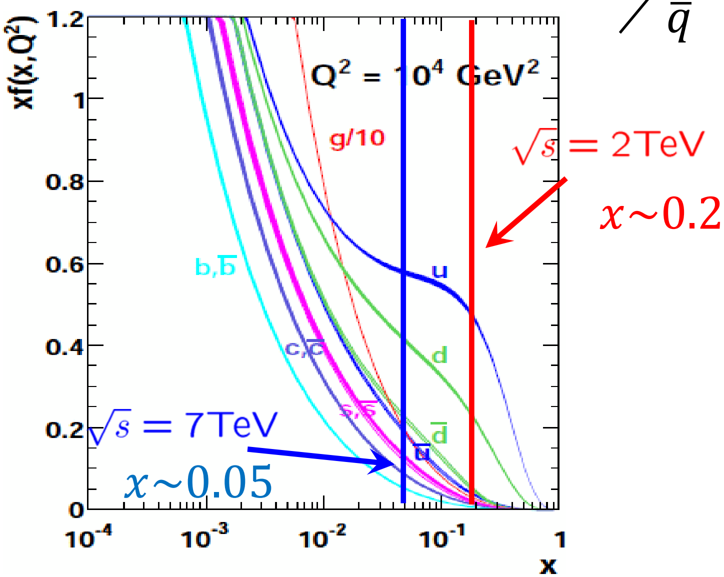
15%




$Br(t \rightarrow W^{+}b)$~100%

85%




Dilepton
- 2 lepton
- 2 *b*-jet
- MET

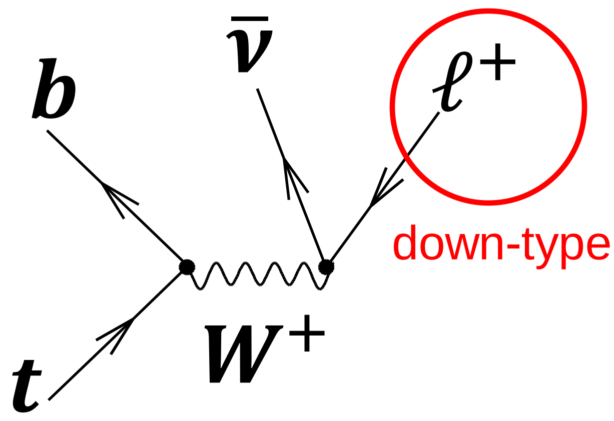
Lepton+Jet
- 1 lepton
- 4 jet(2 *b*-jet)
- MET

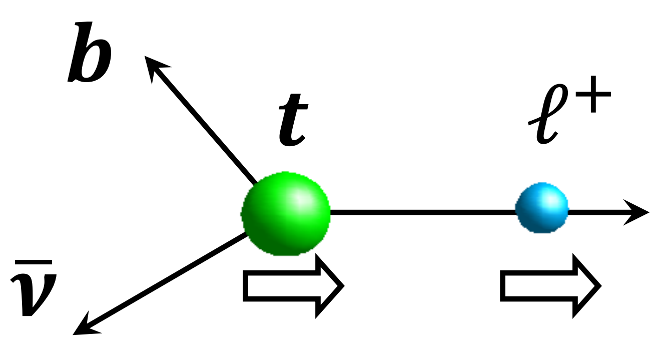
All Hadronic
- 6 jet(2 *b*-jet)

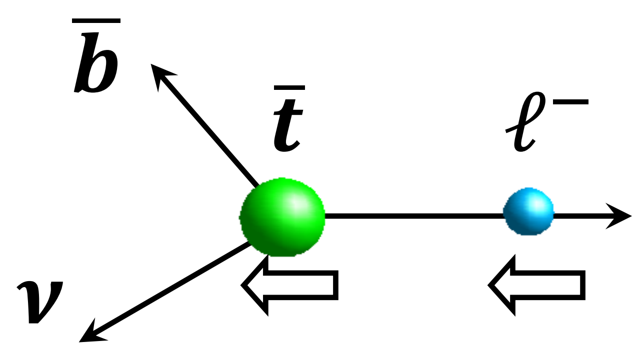
Categorize $t\bar{t}$ events into 3 decay types according to W decay mode

# トップクォークの崩壊

- 弱い相互作用(V-A)で崩壊
  - W helicity 測定により，実験的にも既に確立している
  - トップクォークの静止系において荷電レプトンの飛んでいく方向がトップの偏極方向
  - トップクォークのスピンは，測ることが可能！



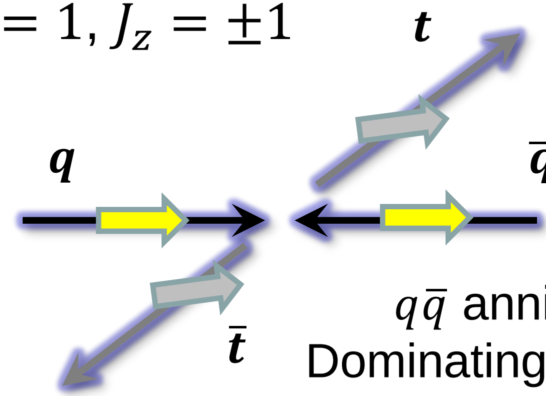



# $t\bar{t}$ 生成におけるSpin Correlation

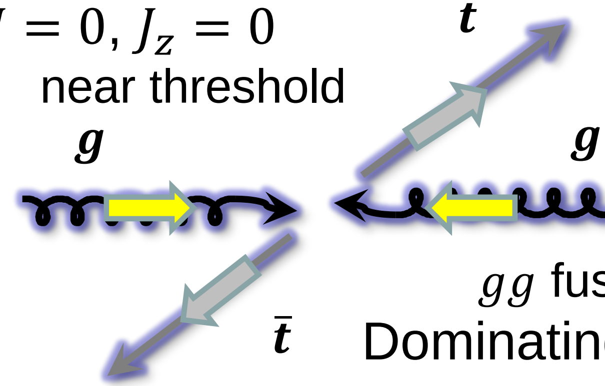
- Top and anti-top spins are correlated at production
  - in different ways at Tevatron and LHC
- Top quark spin at the production can be measured
  - decays before losing polarization
  - decays via V-A interaction (charged lepton has 100% information on top spin)
  - Spin correlation can be measured as angular correlations of decay products: $d\sigma \propto 1 - C\cos\theta_{+}\cos\theta_{-}$

$J = 1, J_z = \pm 1$




$q\bar{q}$ annihilation
Dominating@**Tevatron**

$J = 0, J_z = 0$
near threshold

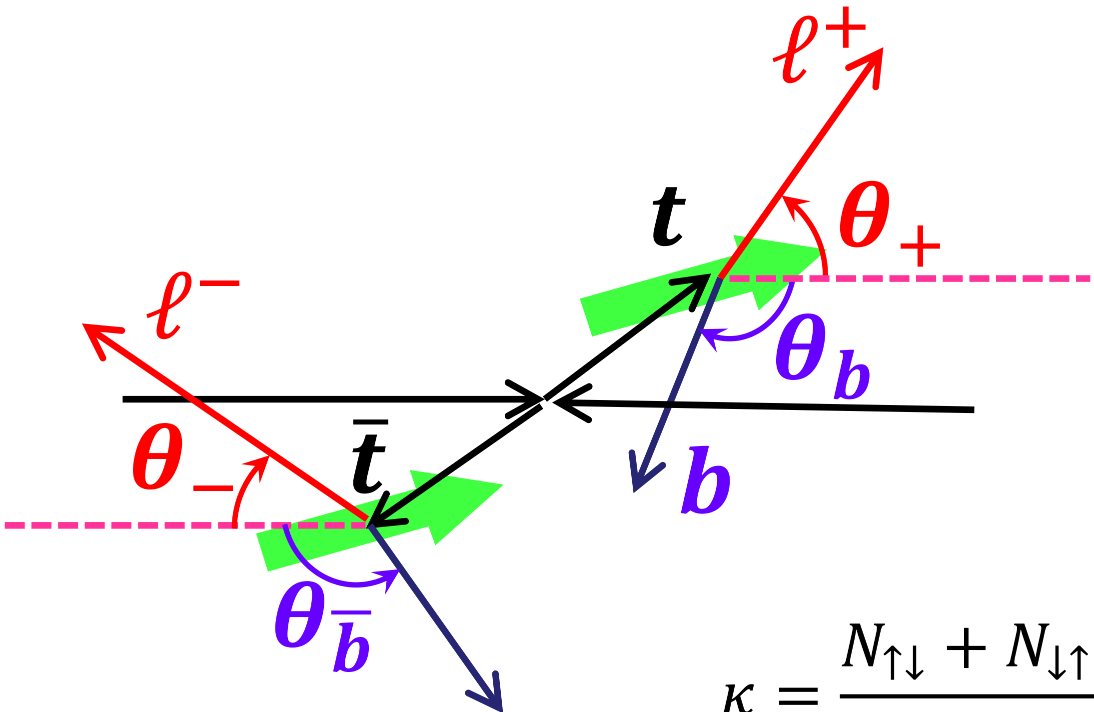



$gg$ fusion
Dominating@**LHC**

$J_z = 0$がないのは helicity conservation

- Experimental verification of
  top decaying before losing polarization
- Sensitive to anomalous coupling at $t\bar{t}$ production

# Spin-spin 相関係数κ




量子化軸 : $t\bar{t}$重心系における proton方向, antiproton方向

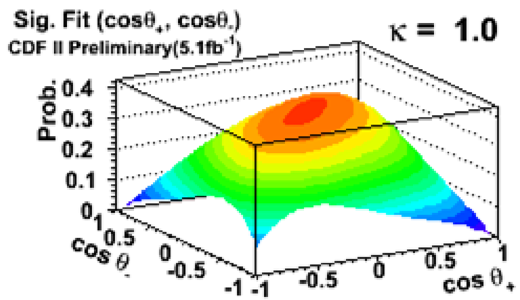
$$\kappa = \frac{N_{\uparrow\downarrow} + N_{\downarrow\uparrow} - N_{\uparrow\uparrow} - N_{\downarrow\downarrow}}{N_{\uparrow\downarrow} + N_{\downarrow\uparrow} + N_{\uparrow\uparrow} + N_{\downarrow\downarrow}}$$

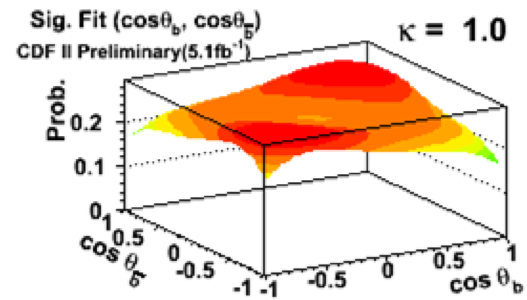
$N_{ss}$ : $t\bar{t}$対のスピン状態の数

$$\Rightarrow \frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1 + \kappa\cos\theta_+\cos\theta_-}{4}$$

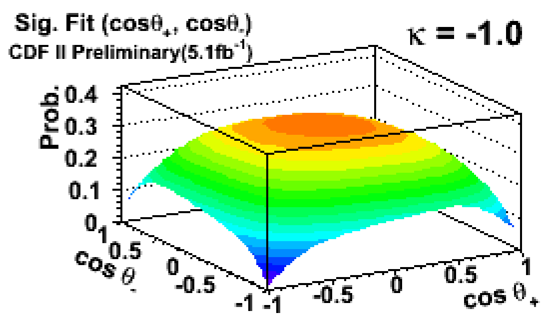
# Expected $(\cos\theta_+, \cos\theta_-)$, $(\cos\theta_b, \cos\theta_{\bar{b}})$, distributions

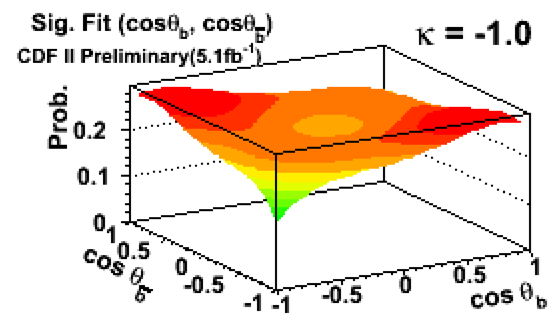
$t\bar{t}$ MC $(\kappa = 1.0)$



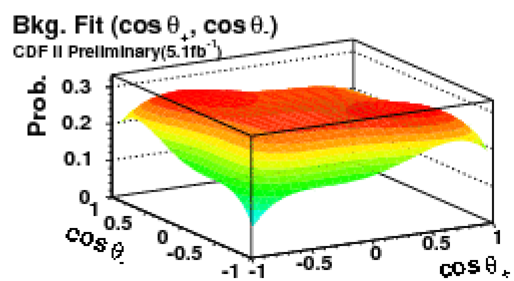



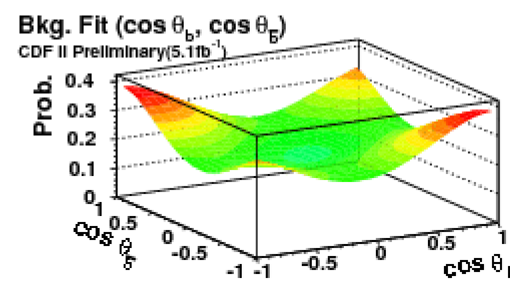

$t\bar{t}$ MC $(\kappa = -1.0)$



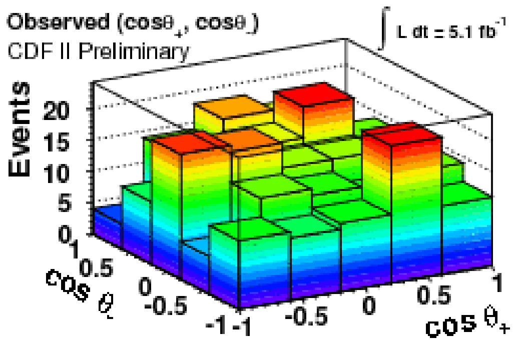



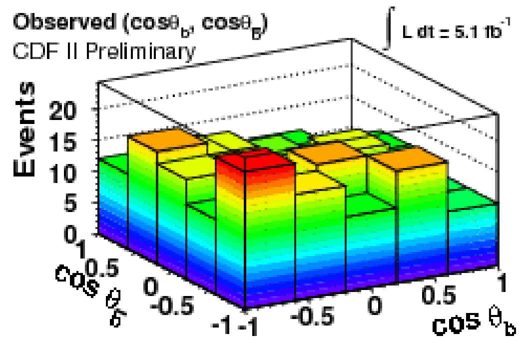

background

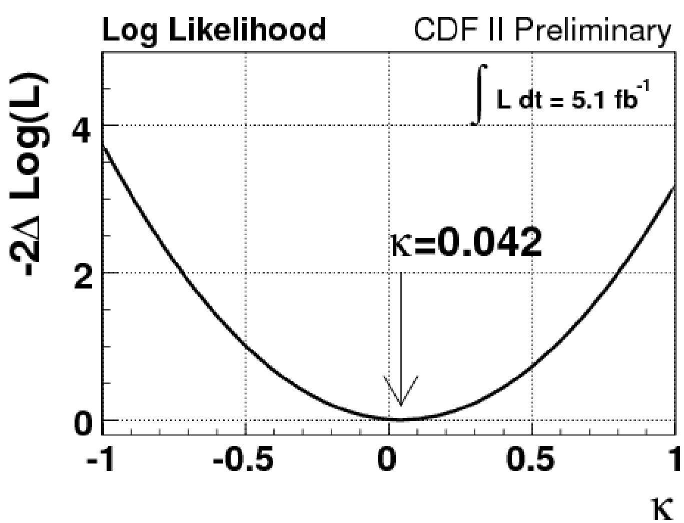


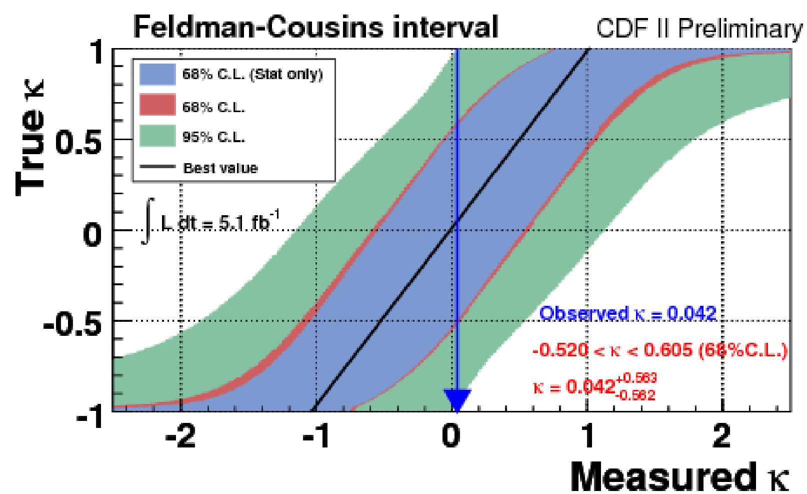



# $\kappa$ measurement result (5.1fb$^{-1}$)



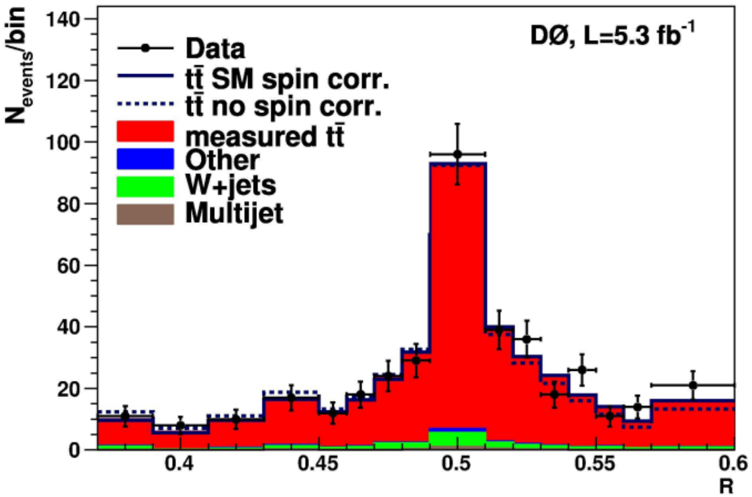



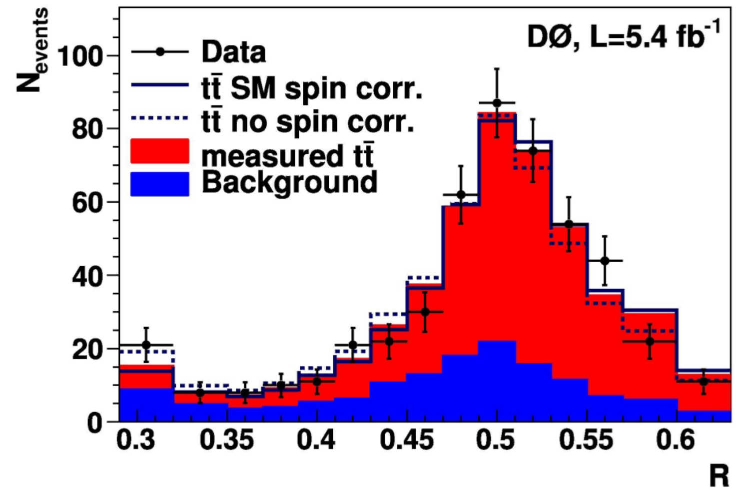

$-0.520 < \kappa < 0.605$ (68%CL)

SMの予想は, $\kappa \sim 0.78$

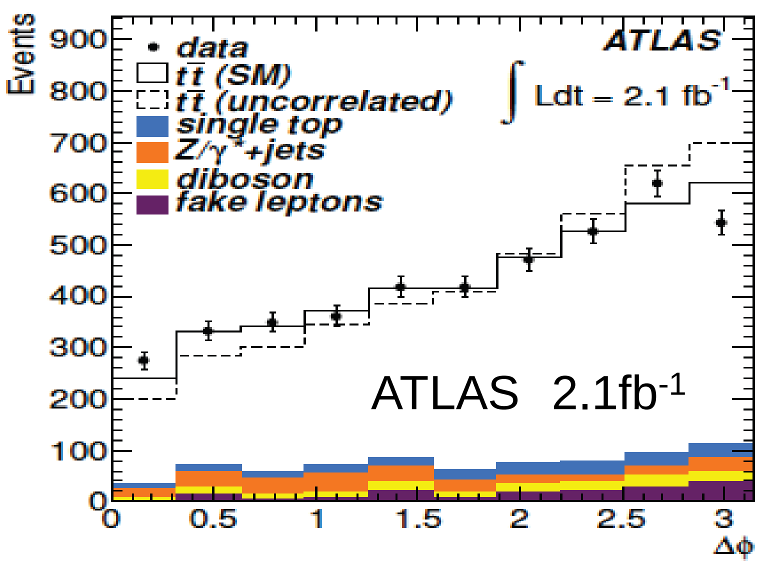
- SMとはconsistent(しかし$\kappa = 0$とも矛盾しない)

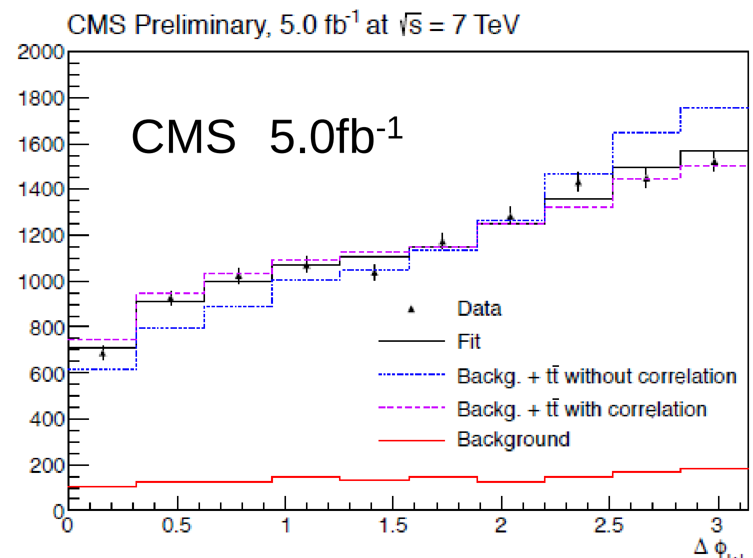
# 他の実験でのspin correlation 測定




l+jet ⊕ dilepton: $\kappa = 0.66 \pm 0.23$ ($\kappa > 0$ @>3σ CL)

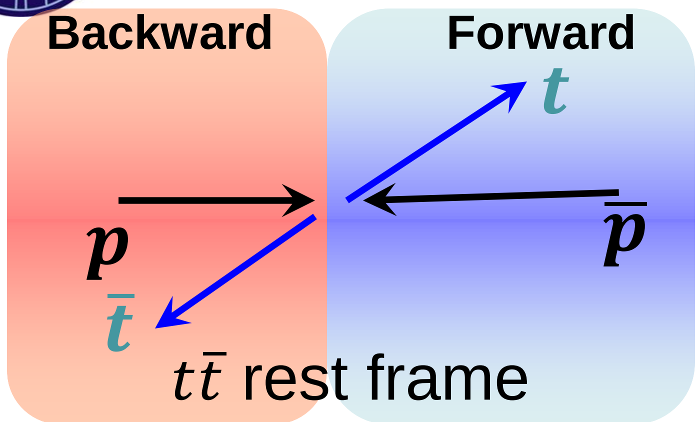



$\kappa = 0.40 \pm 0.04^{+0.06}_{-0.07}$ ($\kappa > 0$ @>5σ)

$\kappa = 0.24 \pm 0.02 \pm 0.08$ ($\kappa_{SM} = 0.33$)

# $t\bar{t}$ Forward Backward Asymmetry




$$A_{\mathrm{fb}} = \frac{F - B}{F + B}$$

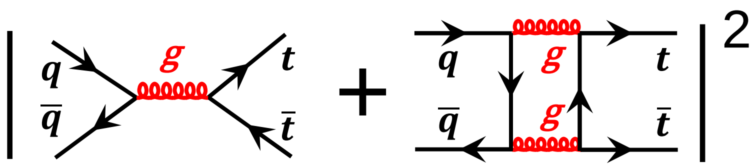
F: $\cos\theta_t > 0 \approx \Delta y_t \equiv y_t - y_{\bar{t}} > 0$

B: $\cos\theta_t < 0 \approx \Delta y_t < 0$

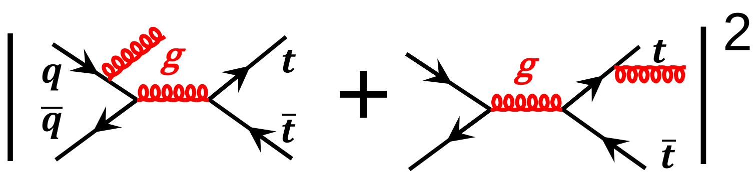
$\Delta y_t$: Invariant for a boost along beam dir.

NLO prediction: $A_{\mathrm{fb}} = 0.06 \pm 0.01$

$|\mathcal{M}|^2 \propto$

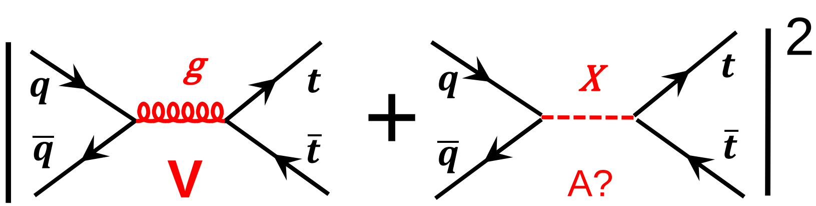


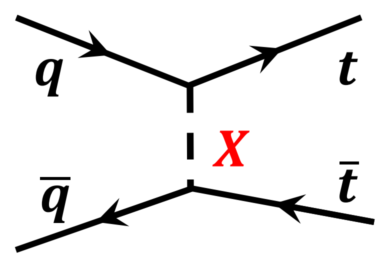

LO and NLO: positive asym.




ISR and FSR: negative asym.

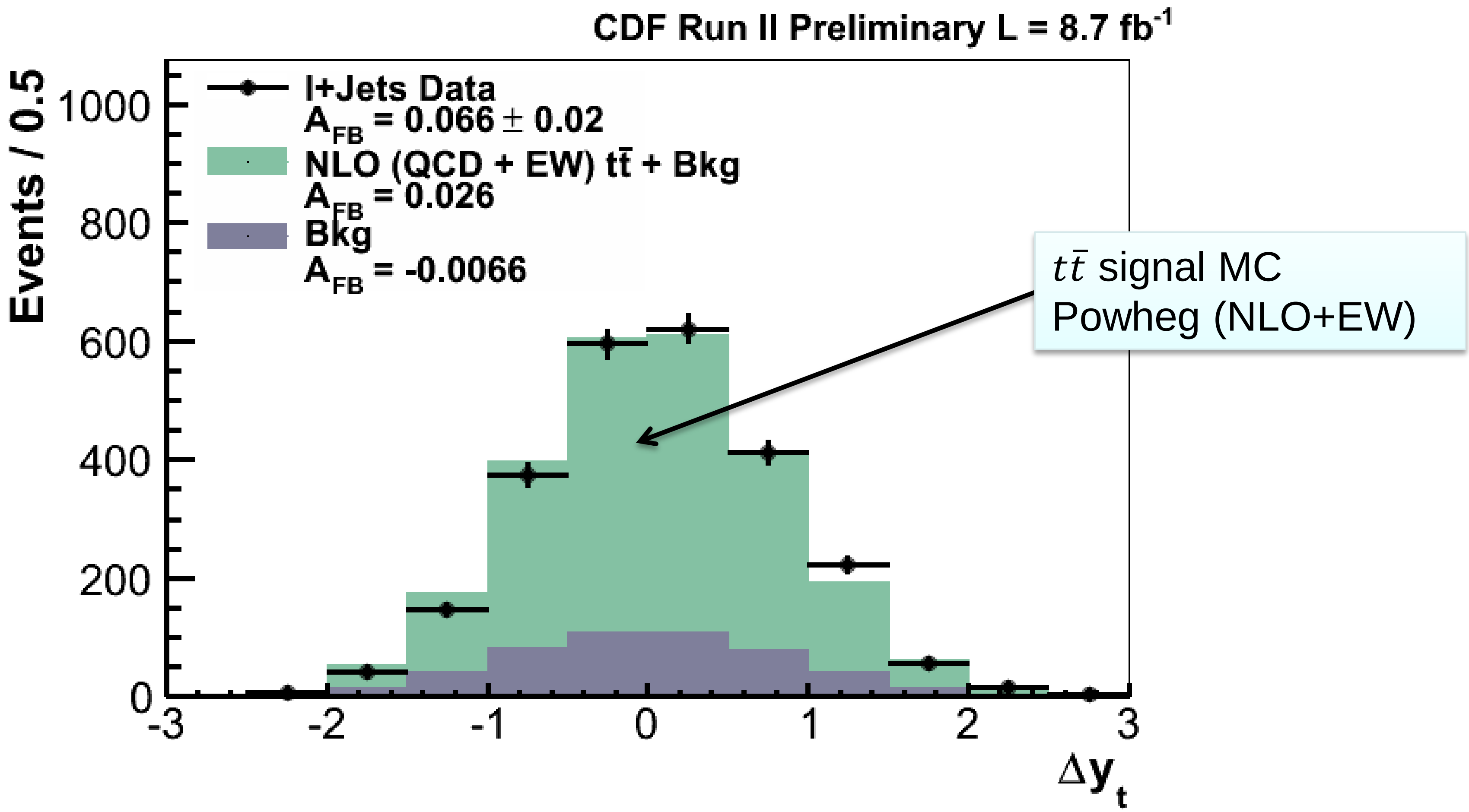
Also presence of new physics could make asymmetry



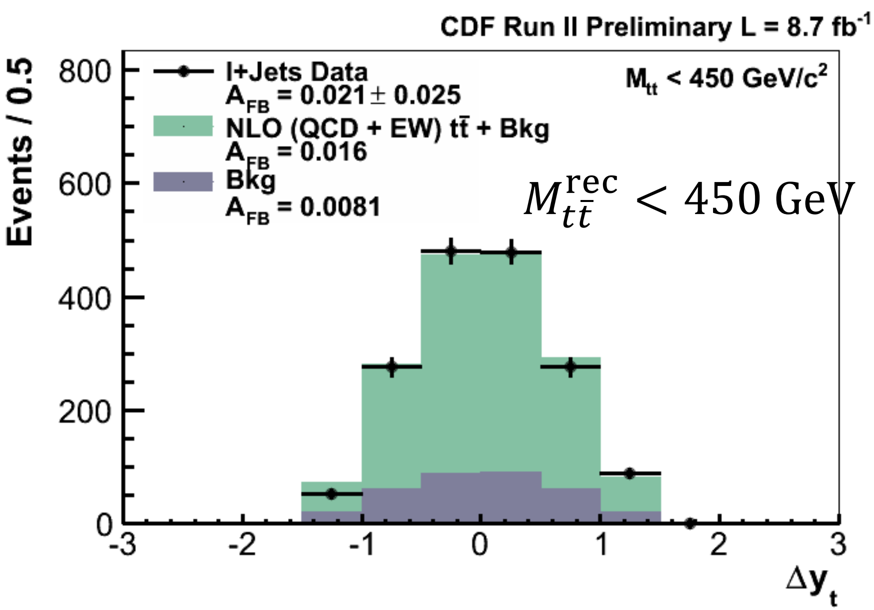
# $\ell$+jets results (8.7fb$^{-1}$)

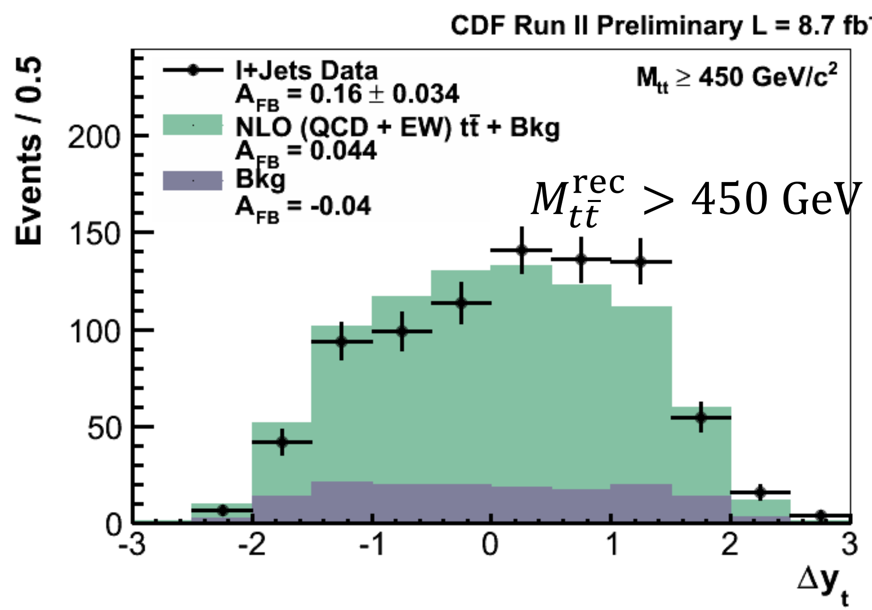
- $\Delta y_t = y_t - y_{\bar{t}}$
- A$^{raw}$(data)= 0.066±0.020 ⇔A$^{raw}$($t\bar{t}$ MC + bkg)=0.026



# $\ell$+jets results (8.7fb$^{-1}$)

- Reconstructed $\Delta y_t$ distributions for reconstructed $M_{t\bar{t}}^{\mathrm{rec}}$ < or > 450 GeV
- $A^{\mathrm{raw}}(M_{t\bar{t}}^{\mathrm{rec}}$ <450GeV) = 0.021 $\pm$ 0.025 ⇔$A^{\mathrm{raw}}(t\bar{t}$ MC + bkg)=0.016
- $A^{\mathrm{raw}}(M_{t\bar{t}}^{\mathrm{rec}}$ >450GeV) = 0.160 $\pm$ 0.034 ⇔$A^{\mathrm{raw}}(t\bar{t}$ MC + bkg)=0.044



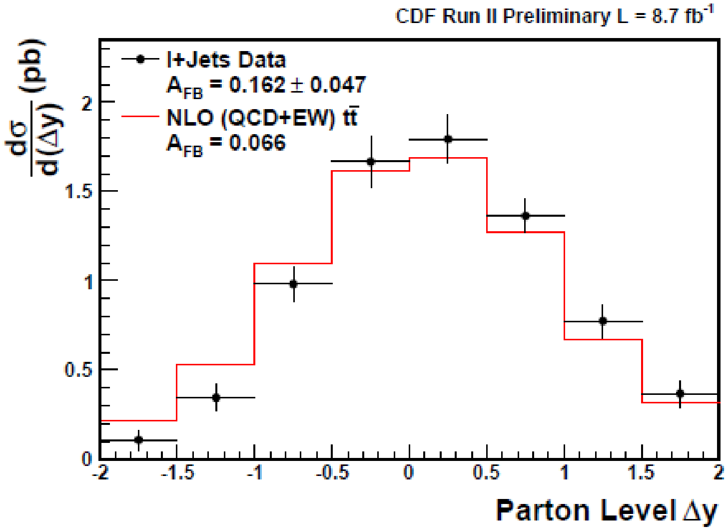



# $\ell$+jets results (8.7fb$^{-1}$)

- Unfolding technique

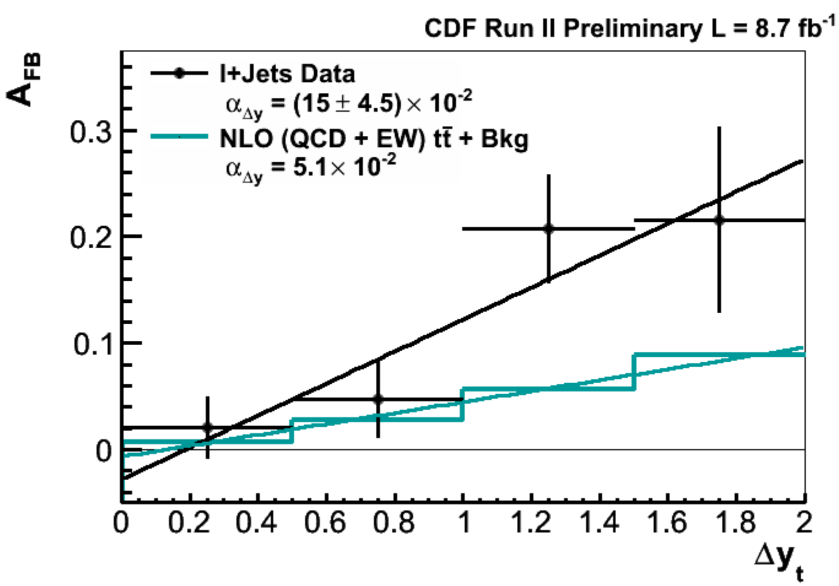
$$\begin{bmatrix} N_1^{\text{obs}} \\ \vdots \\ N_n^{\text{obs}} \end{bmatrix} = \begin{bmatrix} R_{11} & \cdots & R_{1m} \\ \vdots & \ddots & \vdots \\ R_{n1} & \cdots & R_{nm} \end{bmatrix} \begin{bmatrix} A_1 & & \\ & \ddots & \\ & & A_m \end{bmatrix} \begin{bmatrix} N_1^{\text{truth}} \\ \vdots \\ N_m^{\text{truth}} \end{bmatrix}$$

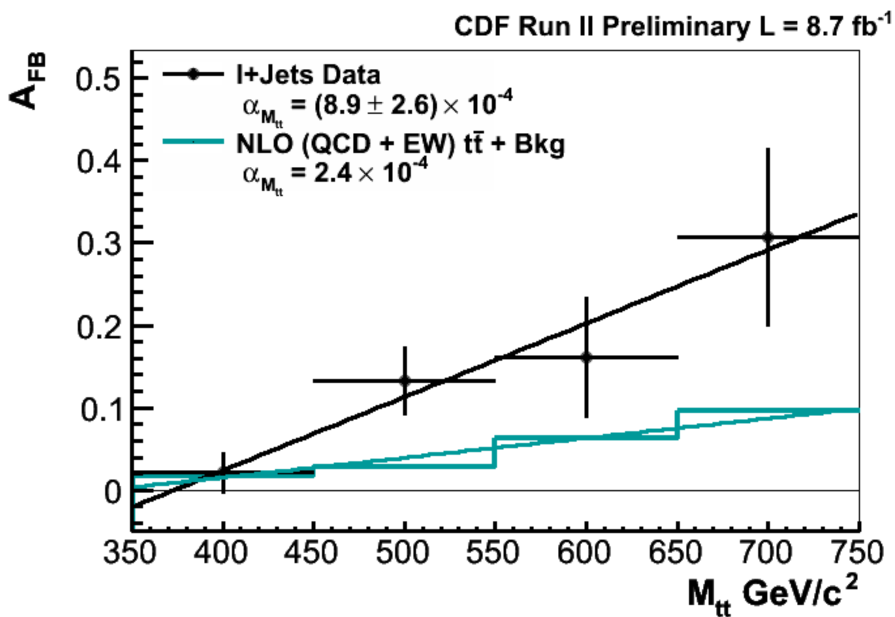
$$\Rightarrow N^{\text{truth}} = A^{-1} R^{-1} N^{\text{obs}}$$




$$\Delta y_t = 0.162 \pm 0.041 \pm 0.022$$

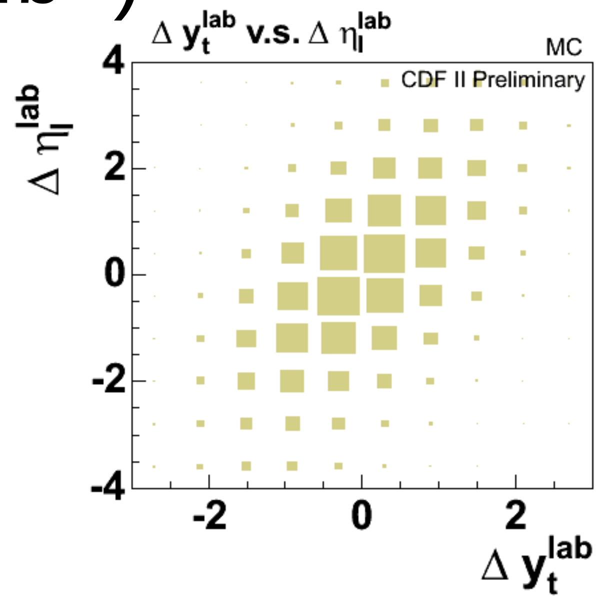
Parton-level asymmetry as functions of $\Delta y_t$ and $M_{t\bar{t}}$

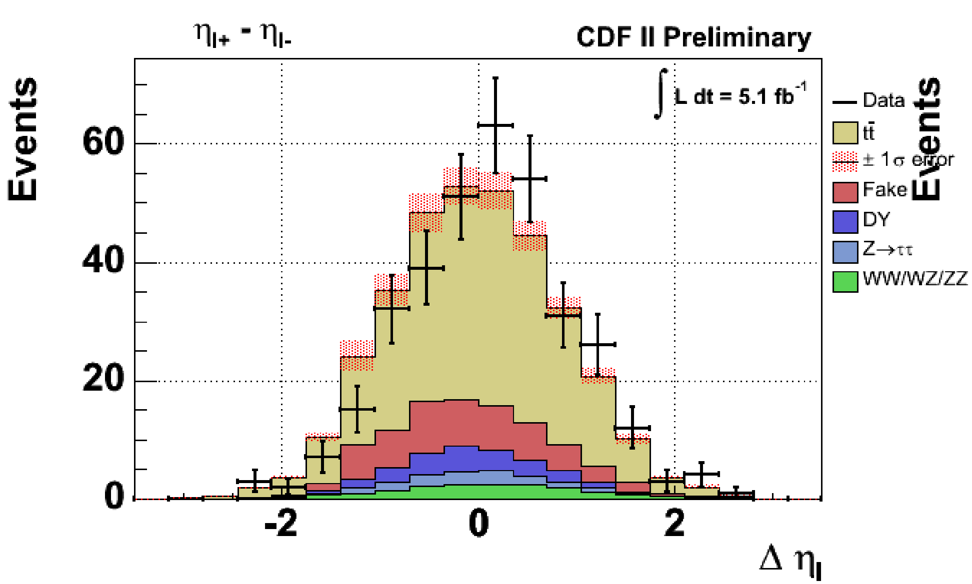


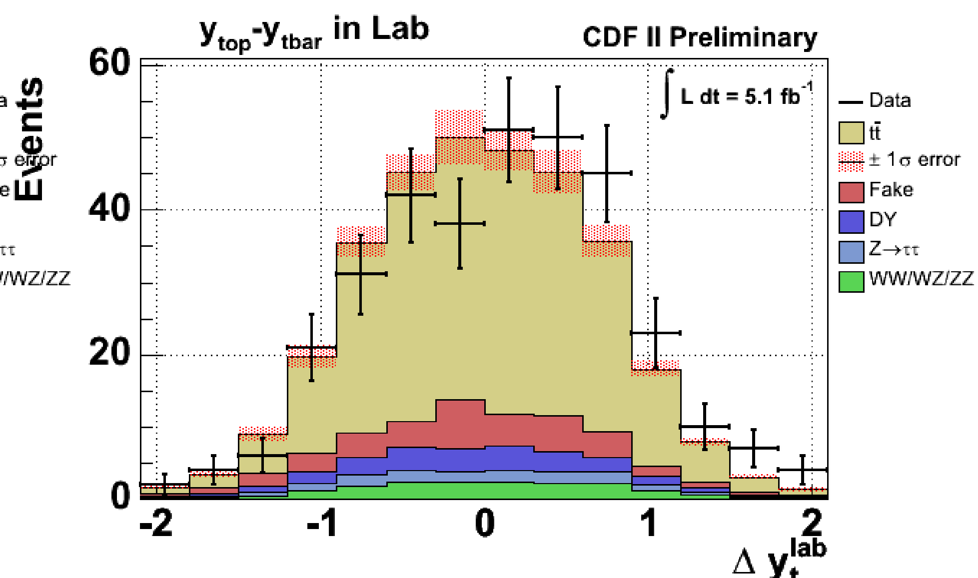



# dilepton results ($5.1\mathrm{fb}^{-1}$)

- $\Delta y_t = y_t - y_{\bar{t}}$ & $\Delta\eta_\ell = \eta_{\ell^+} - \eta_{\ell^-}$
  - $\ell^+$ はトップクォーク，$\ell^-$は反トップクォークから
    ➔$\Delta\eta_\ell$と$\Delta y_t$に相関
- $\mathrm{A^{raw}}(\Delta\eta_\ell) = 0.14 \pm 0.05$
  ⇔ $\mathrm{A^{raw}}(t\bar{t}$ MC+bkg$) = -0.02 \pm 0.02$
- $A^{\mathrm{raw}}(\Delta y_t) = 0.14 \pm 0.05_{\mathrm{stat}}$
  ⇔$\mathrm{A^{raw}}(t\bar{t}$ MC+bkg$) = -0.02 \pm 0.02$

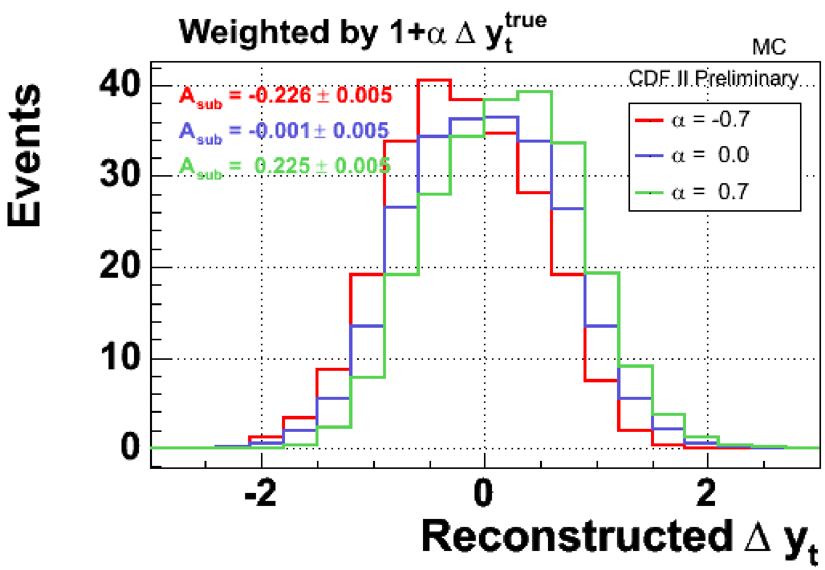


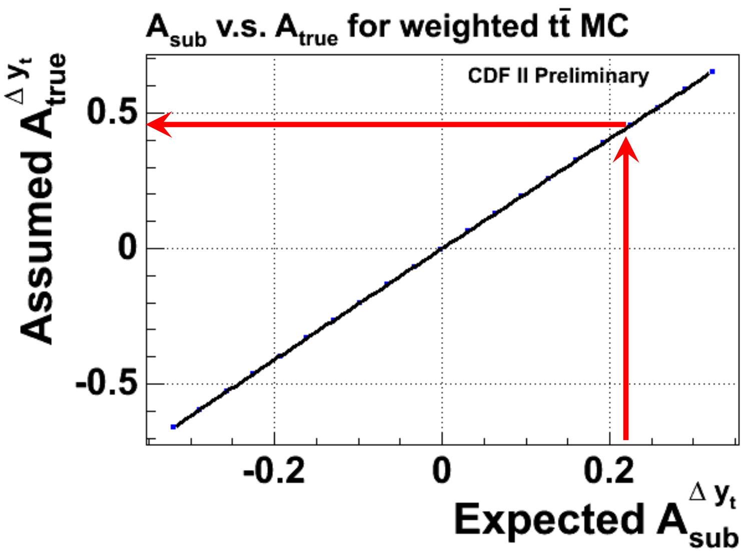



# dilepton results (5.1fb$^{-1}$)

- $t\bar{t}$ Pythia MC with event-by-event weight of $(1+\alpha\Delta y_t^{true})$ to implement non-zero asymmetry into MC



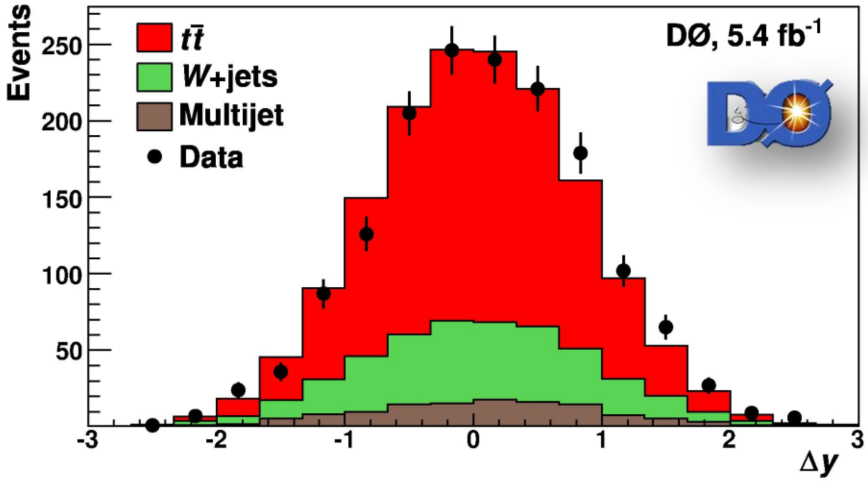



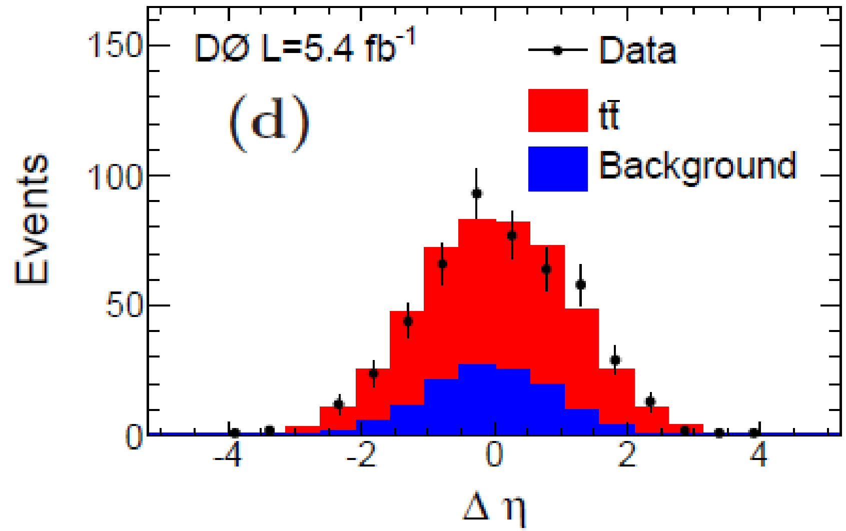

- Extract $A^{parton}$ from $A^{subt}$

$$A^{\mathrm{subt}} = 0.21 \pm 0.07_{\mathrm{stat}} \quad \Rightarrow \quad A^{\mathrm{parton}} = 0.42 \pm 0.15_{\mathrm{stat}}$$

$A^{parton} = 0.42 \pm 0.15_{stat.} \pm 0.05_{syst.}$.

# $A_{fb}$ at DØ




- Unfolded asymmetry from $\Delta y_t$ distribution

$$A_{\mathrm{fb}} = 0.196 \pm 0.060^{+0.018}_{-0.026}$$

- Unfolded asymmetry from $\Delta\eta_\ell$ distribution

$$A_{\mathrm{fb}} = 0.053 \pm 0.079 \pm 0.029$$

- Unfolded asymmetry from $\mathrm{Q} \cdot \eta_\ell$ distribution

$$A^{\ell}_{\mathrm{fb}} = 0.152 \pm 0.040$$

$$A^{\ell}_{\mathrm{fb}} = 0.058 \pm 0.053 \pm 0.013$$

combined $A^{\ell}_{\mathrm{fb}} = 0.118 \pm 0.032 \Leftrightarrow$ prediction: $0.047 \pm 0.001$

# Summary

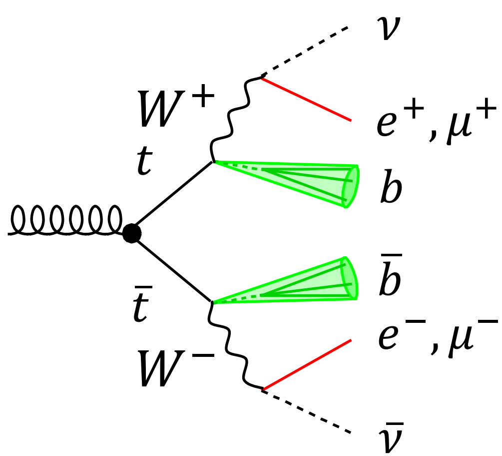
- Top quark対生成の機構は,Tevatron とLHCで異なる
  - $t\bar{t}$ forward-backward asymmetry, $t\bar{t}$ spin correlation などは，対生成の機構に依存
  - ➔ Tevatronで固有な解析，LHCでの実験と相補的

- CDF full data を用いた $t\bar{t}$ spin correlation の解析 (dilepton)，$t\bar{t}$ forward-backward asymmetry (dilepton)の解析は，現在進行中
  - top polarizationまで含めたforward-backward asymmetryの原因解明が最終目標

- $t\bar{t}$ forward-backward asymmetry
  - CDF $\ell$+jet: SMより 2σ level で大きな値, 大きな$M_{t\bar{t}}$ dependence
  - D0 $\ell$+jet: SM より2σ level で大きな値, $M_{t\bar{t}}$ dependenceは，むしろCDF $\ell$+jet と逆
  - CDF dilepton: SMより 2σ level で大きな値, 顕著な$M_{t\bar{t}}$ dependenceは見られない
  - D0 dilepton: SM と consistent ($A_{fb}$=0とも consistent)
  - LHC: SM と consistent ($A_{fb}$=0とも consistent)，$M_{t\bar{t}}$ dependenceは見られない
    - LHCの最新結果はICHEPで7/6に発表?

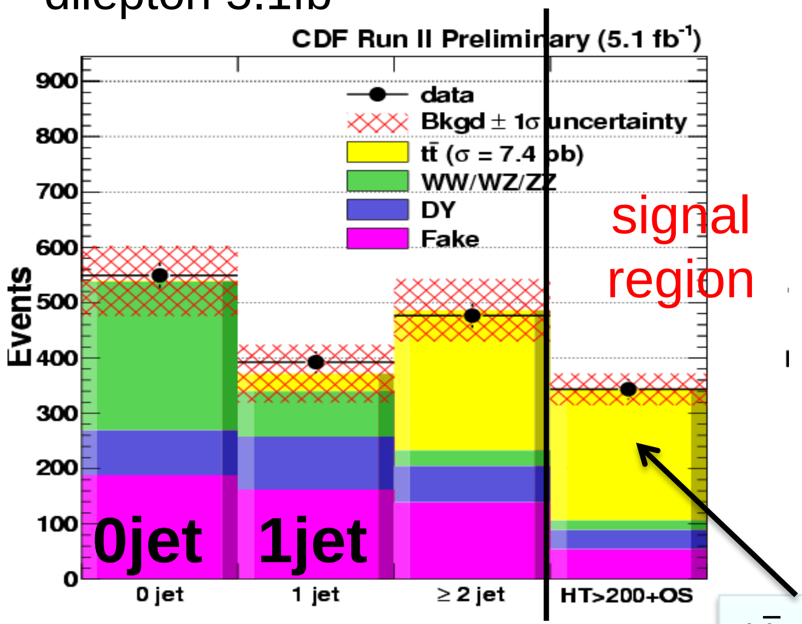
# Backup

# Dilepton candidates (5.1fb$^{-1}$)




- Selection
  - 2 lepton $(e/\mu)$ $E_{\mathrm{T}}(p_{\mathrm{T}}) > 20$ GeV
  - 2 or more jets
  - pre-tag
  - Missing $E_{\mathrm{T}} > 25$ GeV
  - $Z$ veto, $H_{\mathrm{T}}$, Opposite charge
- 334 candidates w/ 87±17 bkg.

dilepton 5.1fb$^{-1}$




$t\bar{t}$ signal MC

6+1 unknonwns

- $\vec{p}_\nu, \vec{p}_{\bar{\nu}}$ : 6 components
- $b, \bar{b}$ ambiguity

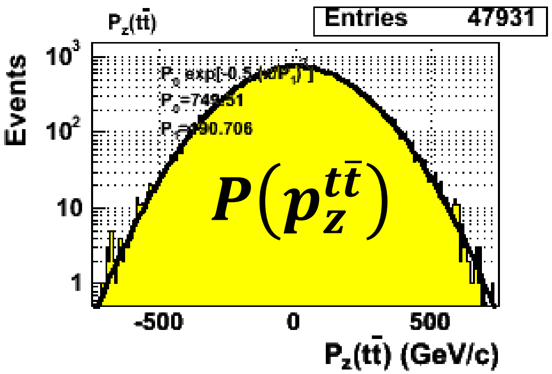
6 constraints → quartic equation

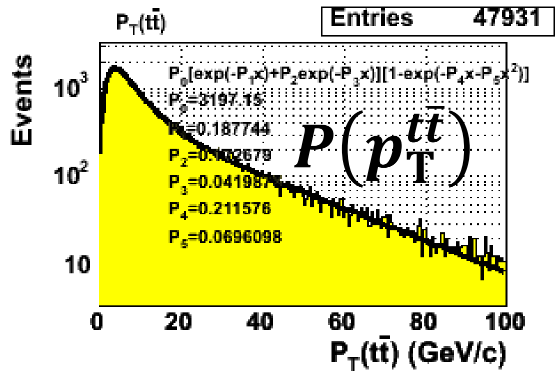
- $M(\ell^+ + \nu) \to M_W$ and c.c.
- $M(\ell^+ + \nu + b) \to M_t$ and c.c.
- $(\vec{p}_{\bar{\nu}})_{x,y} = E^{\mathrm{miss}}_{x,y}$

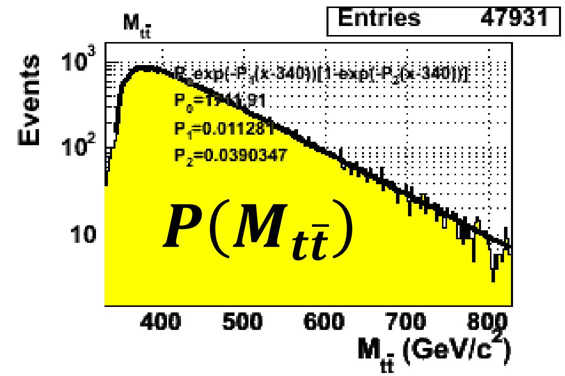
**$\vec{p}_\nu, \vec{p}_{\bar{\nu}}$ is solvable, but 8 solutions in maximum**

# Likelihood function w/ jet and MET resolutions

$P\left(p_z^{t\bar{t}}\right)$, $P\left(p_{\mathrm{T}}^{t\bar{t}}\right)$, and $P(M_{t\bar{t}})$ are obtained from the signal candidates in $t\bar{t}$ Pythia MC




We choose the best solution of $(\vec{p}_\nu, \vec{p}_{\bar{\nu}}, E_b, E_{\bar{b}})$ which gives maximum likelihood in an event

$$\mathfrak{L}(\vec{p}_\nu, \vec{p}_{\bar{\nu}}, E_b, E_{\bar{b}}) = P\left(p_z^{t\bar{t}}\right) P\left(p_T^{t\bar{t}}\right) P(M_{t\bar{t}})$$

$$\times \frac{1}{\sigma_{\mathrm{jet1}}} \exp\left[-\frac{1}{2}\left\{\frac{E_{\mathrm{jet1}} - E_b}{\sigma_{\mathrm{jet1}}}\right\}^2\right] \times \frac{1}{\sigma_{\mathrm{jet2}}} \exp\left[-\frac{1}{2}\left\{\frac{E_{\mathrm{jet2}} - E_{\bar{b}}}{\sigma_{\mathrm{jet2}}}\right\}^2\right]$$

$$\times \frac{1}{\sigma_x^{\mathrm{MET}}} \exp\left[-\frac{1}{2}\left\{\frac{E_x^{\mathrm{miss}} - (\vec{p}_\nu + \vec{p}_{\bar{\nu}})_x}{\sigma_x^{\mathrm{MET}}}\right\}^2\right] \times \frac{1}{\sigma_y^{\mathrm{MET}}} \exp\left[-\frac{1}{2}\left\{\frac{E_y^{\mathrm{miss}} - (\vec{p}_\nu + \vec{p}_{\bar{\nu}})_y}{\sigma_y^{\mathrm{MET}}}\right\}^2\right]$$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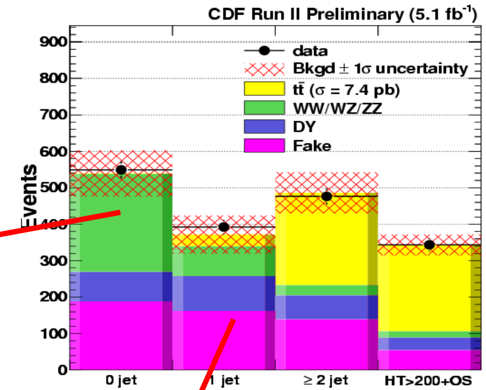
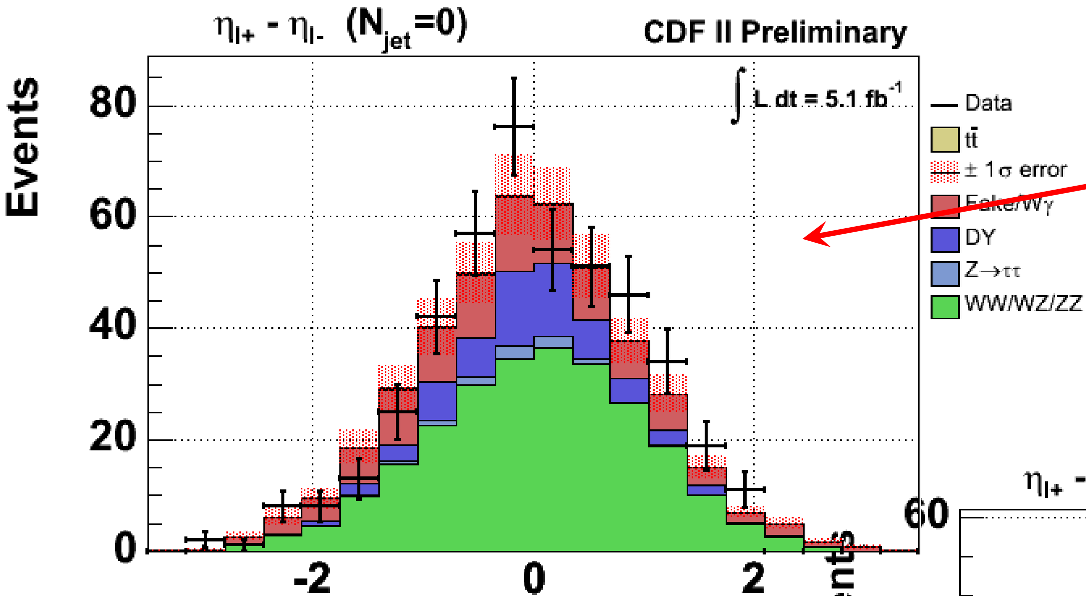
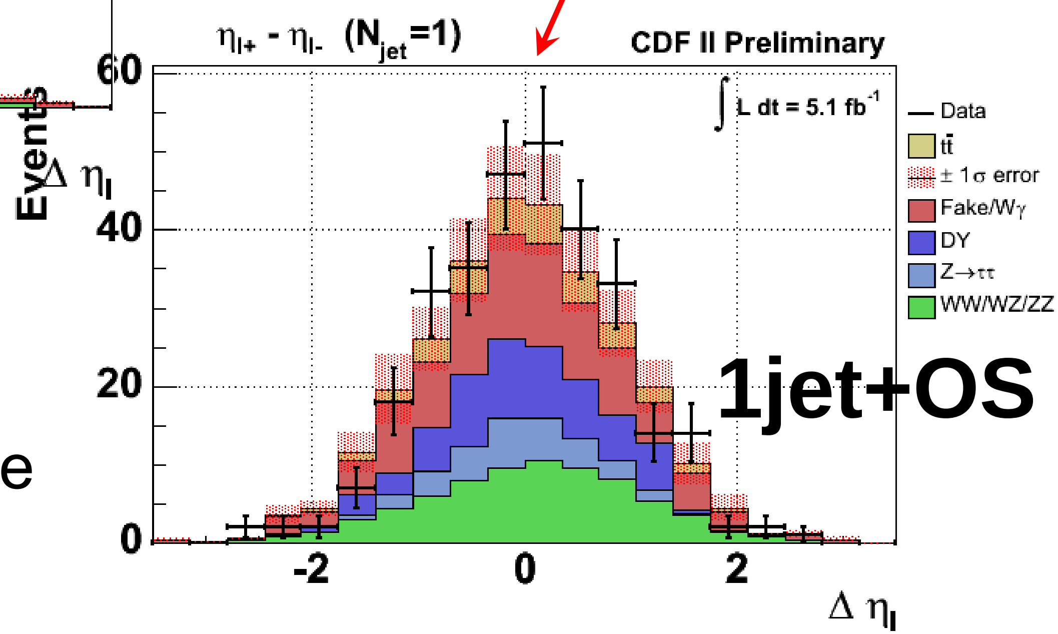
# $\Delta\eta_\ell$ in control region

## $\Delta\eta_\ell$ in control sample




**0jet+OS**




**1jet+OS**

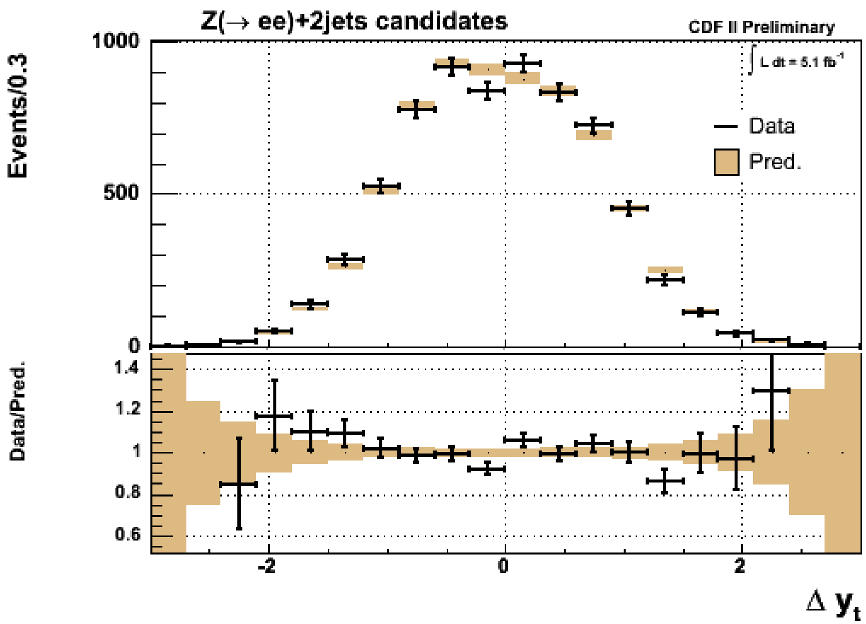
- Bkg model is OK
- Bkg doesn't cause a large positive asymmetry.

# $\Delta y_t$ in Z+2jets candidates

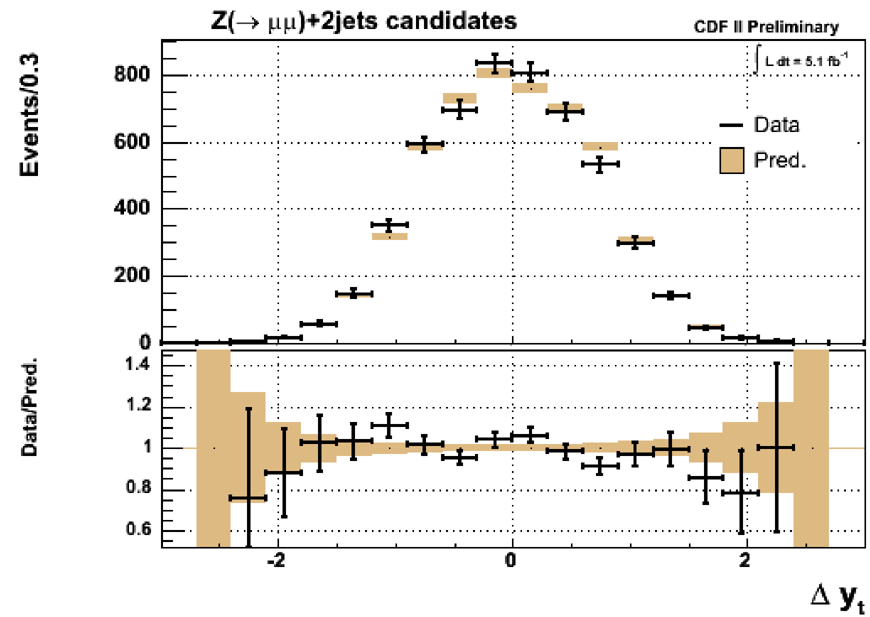
$\Delta y_t$ in Z+2jets candidates

- Same flavor, OS($e^+e^-$, $\mu^+\mu^-$)
- 2 or more jets

- No MET ($E_{\mathrm{T}}^{\mathrm{miss}}$<25 GeV)
- $M_{\ell\ell}$ in Z mass window
  - 76 < $M_{\ell\ell}$ < 106 GeV




$Z(\rightarrow e^+e^-)$+2jets




$Z(\rightarrow \mu^+\mu^-)$+2jets

$\Delta y_t$ reconstruction doesn't introduce a fake asymmetry.

# Dilepton results (5.1fb$^{-1}$)

## $Mt\bar{t}$ dependence

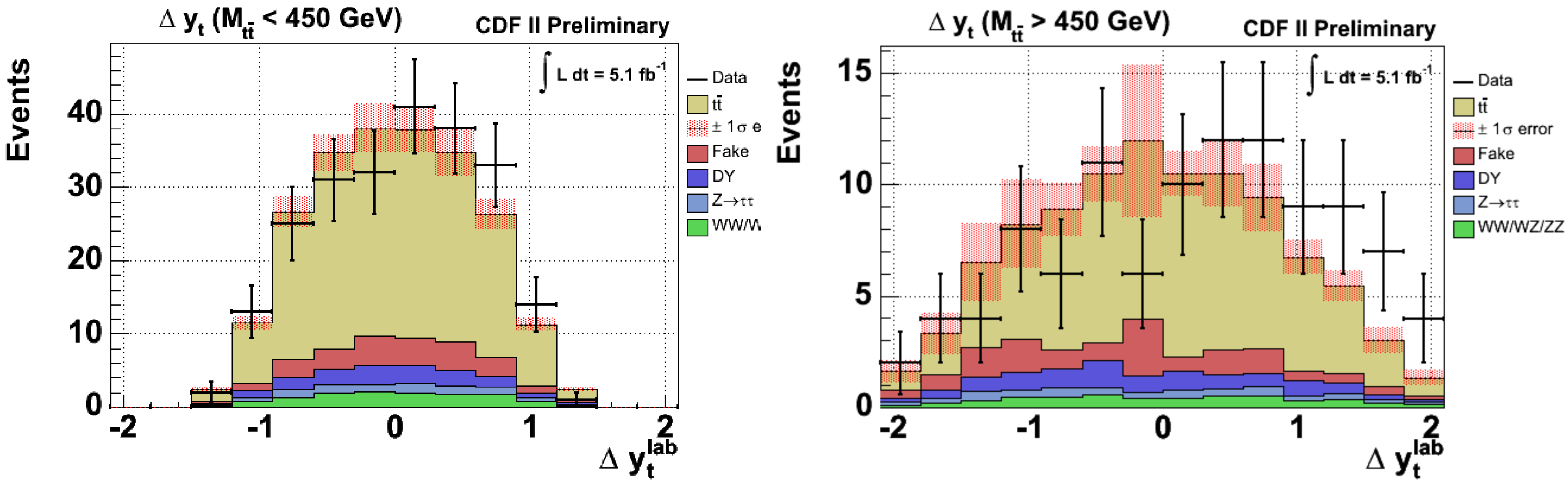
- $M_{t\bar{t}}^{\rm rec}$ < or >450GeV

$$A^{\rm raw}(M_{t\bar{t}}^{\rm rec} < 450{\rm GeV}) = 0.10 \pm 0.07_{\rm stat}$$

⇔ pred: -0.003 ± 0.031

$$A^{\rm raw}(M_{t\bar{t}}{}^{\rm rec} > 450{\rm GeV}) = 0.21 \pm 0.10_{\rm stat}$$

⇔ pred: -0.040 ± 0.055




## Caveat

- Based on "Reconstructed $M_{t\bar{t}}$" cut
  - Poor resolution, bias toward lower $M_{t\bar{t}}$
- Not parton level asymmetries