Top Quark Production Asymmetry at CDF

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For the CDF collaboration

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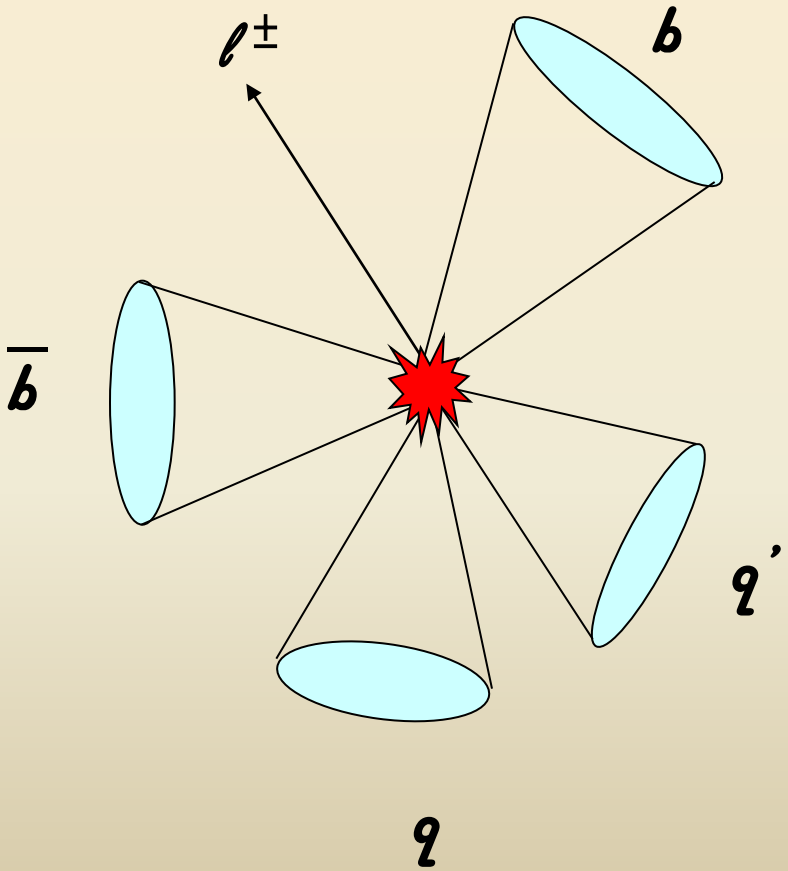
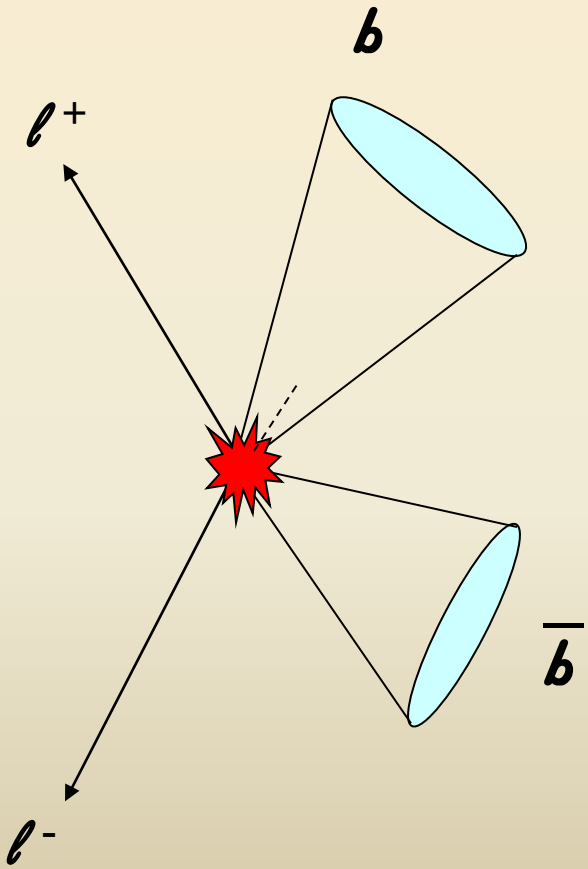
$t\bar{t}$ decay channels used

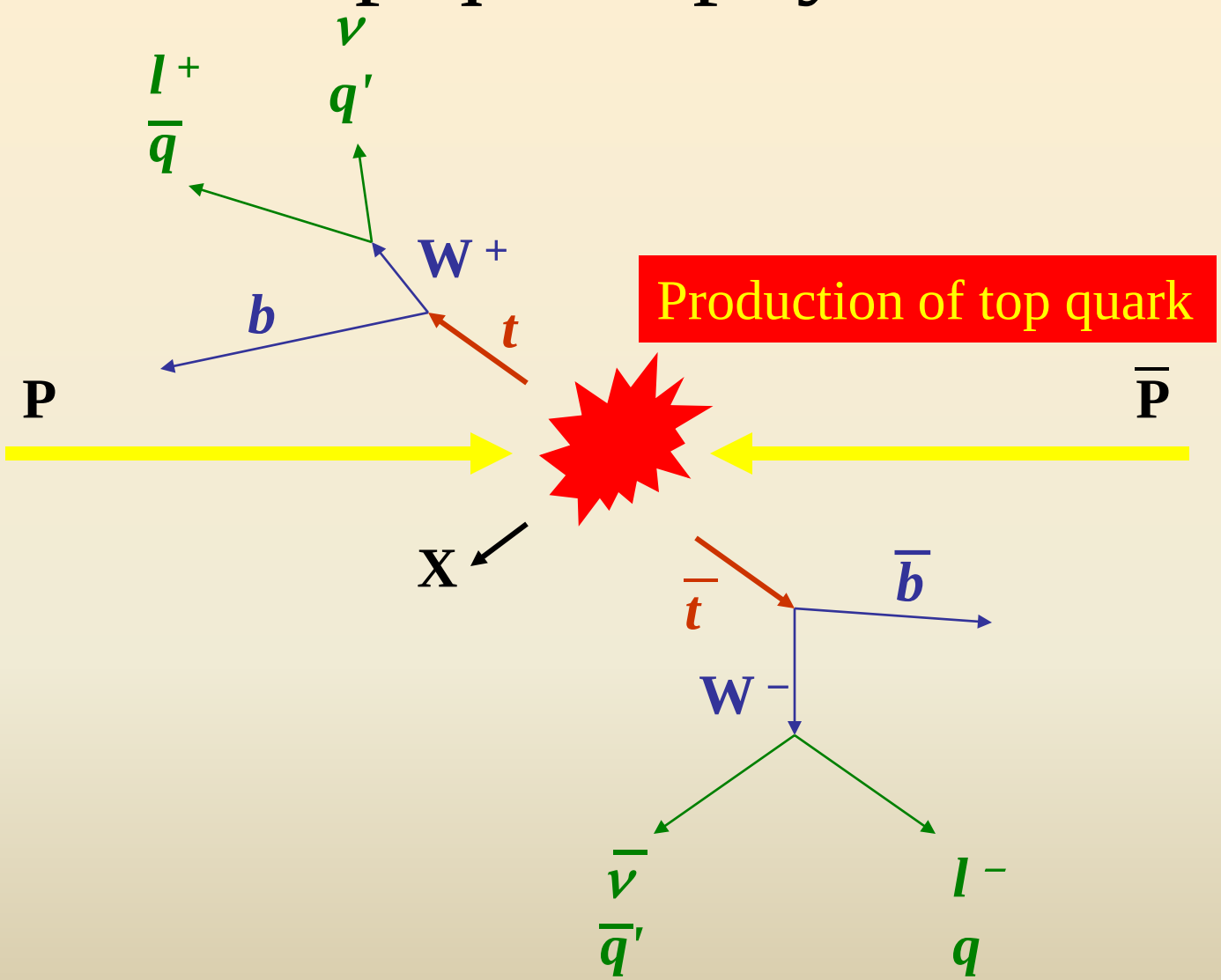
Lepton + Jets, LJ



Di-lepton, DIL

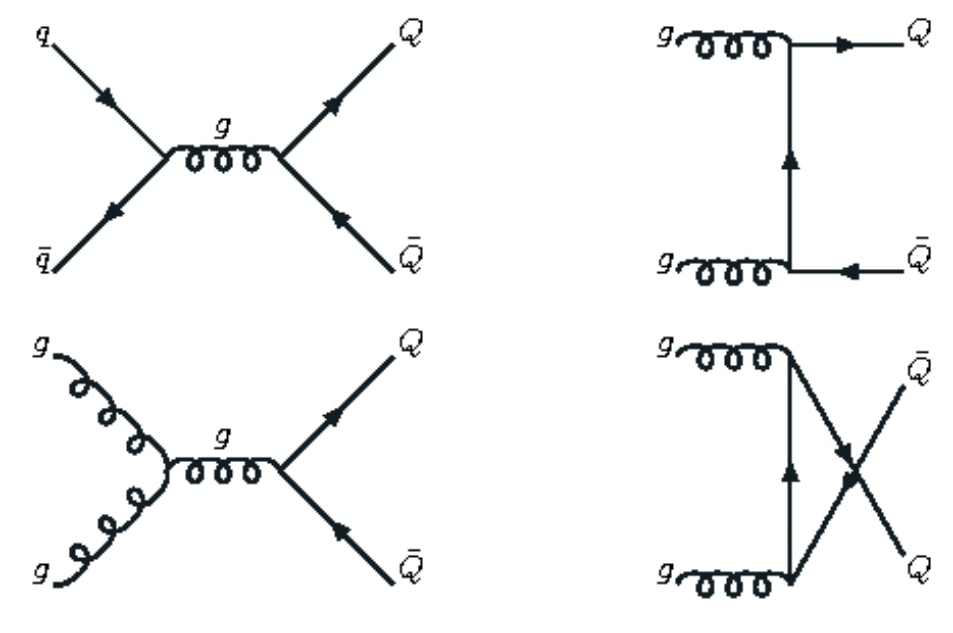


Top quark physics



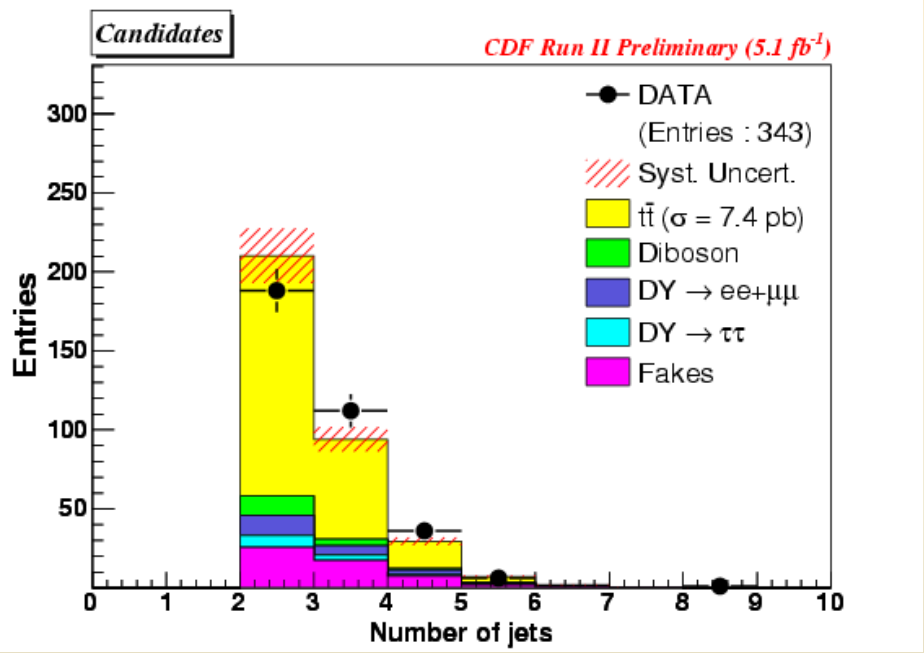
Top quark production

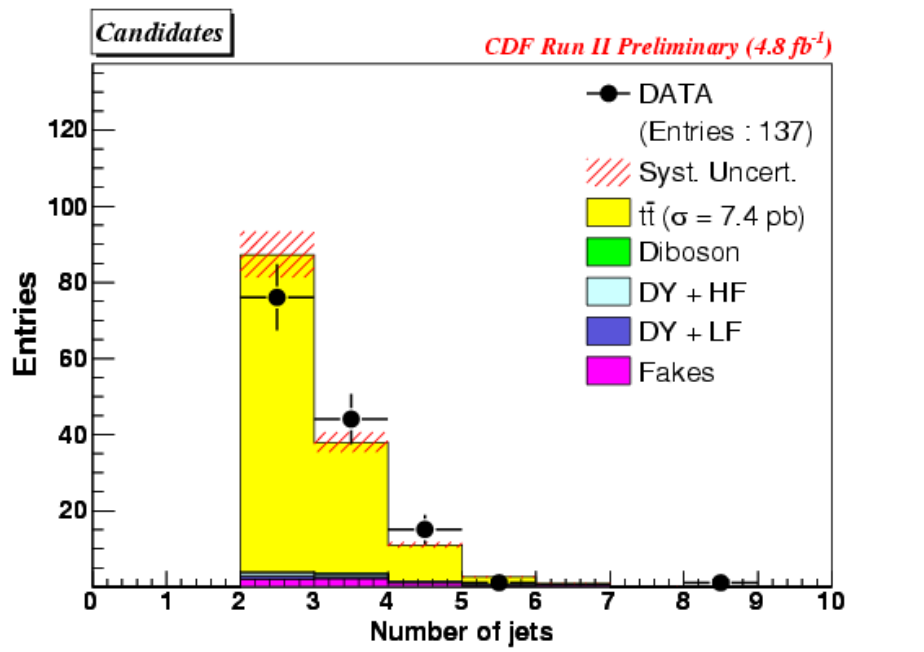
- $p\bar{p} \rightarrow t\bar{t}$
  - $\sigma \sim 7.4$ pb at $\sqrt{S} = 1.96$ TeV:
    - 85% $q\bar{q} \rightarrow t\bar{t}$
    - 15% $gg \rightarrow t\bar{t}$



Cross section using Di-lepton events

Blessed at 5/23/2010

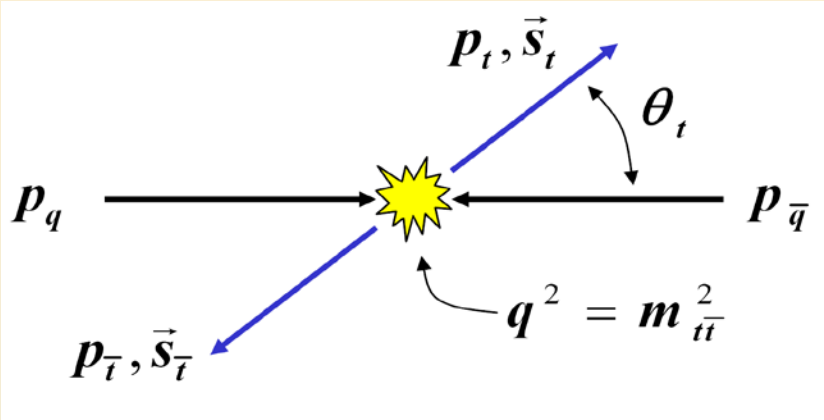




$\sigma_{pretag} = 7.40 \pm 0.58_{stat} \pm 0.63_{syst} \pm 0.45_{lumi}$ pb

$\sigma_{btag} = 7.25 \pm 0.66_{stat} \pm 0.47_{syst} \pm 0.44_{lumi}$ pb

Top production
differential cross section



$$\frac{d\sigma}{d\cos\theta} \propto \frac{\alpha_s^2}{q^2}\left[1+\cos^2\theta^* + (1-\beta^2)\sin^2\theta^* + \frac{q^2}{q^2-M^2}\cos\theta^*\right]$$

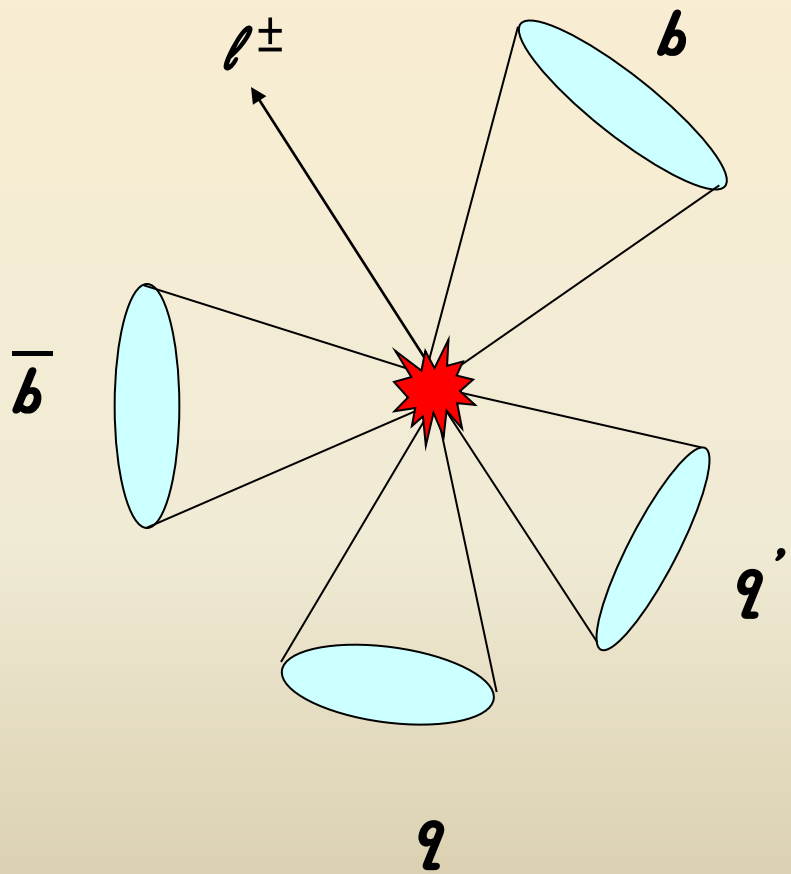
- Dependent on q^2 and $\theta^* \rightarrow M_{tt}$ and Δy
- There is asymmetry with respect to beamline

Theoretical interest

- Exotic gluons
  - massive chiral color
  - RS gluon
  - color sextets, anti-triplets
- Intermediate Vector B´
  - Z´, …
- …
- Nice theoretical review by Cao et al. PRD 81,014016, arXiv:1003.3461

- Model building must contend with
  - total σ in good agreement with SM
  - $d\sigma/dM_{tt}$ in good agreement with SM

Using the lepton + jets events
up to 5.3 fb^{-1}



- high p_t lepton (e/μ)
  - $E_t/p_t > 20$ GeV (/c)
  - $|\eta| < 1.0$
- missing $E_t > 20$ GeV
- four jets
  - $E_t > 20$ GeV
  - $|\eta| < 2.0$
- at least one b-tagged jet
  - $|\eta| < 1.0$

- 1260 events
- 283±50 non-tt background
  - established in precision cross section measurement
  - mostly W+jets

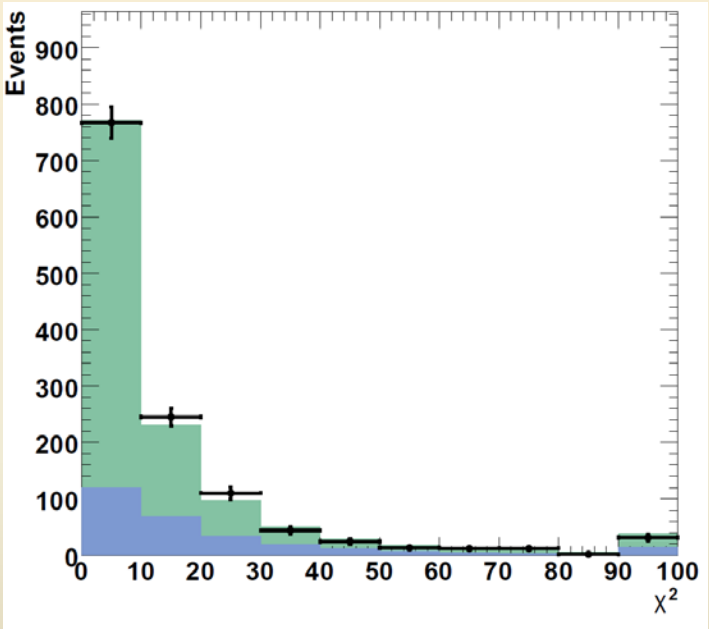
Top reconstruction

$$\chi^2 = \sum_{lep,\,jets} \frac{\left(p_t^{i,\,meas} - p_t^{i,\,fit}\right)^2}{\sigma_i^2} + \sum_{j=x,\,y} \frac{\left(p_j^{UE,\,meas} - p_j^{UE,\,fit}\right)^2}{\sigma_j^2} +$$

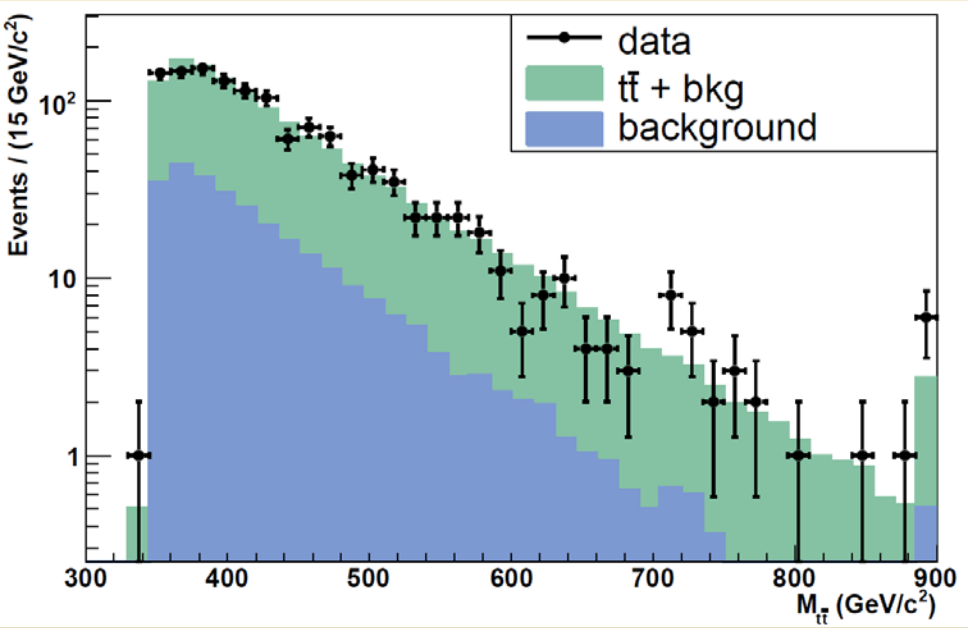
$$\frac{\left(M_{jj} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(M_{l\nu} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(M_{bjj} - M_{top}\right)^2}{\Gamma_t^2} + \frac{\left(M_{bl\nu} - M_{top}\right)^2}{\Gamma_t^2}$$

Top reconstruction

χ^2



$M_{t\bar{t}}$



tt rest frame asymmetry

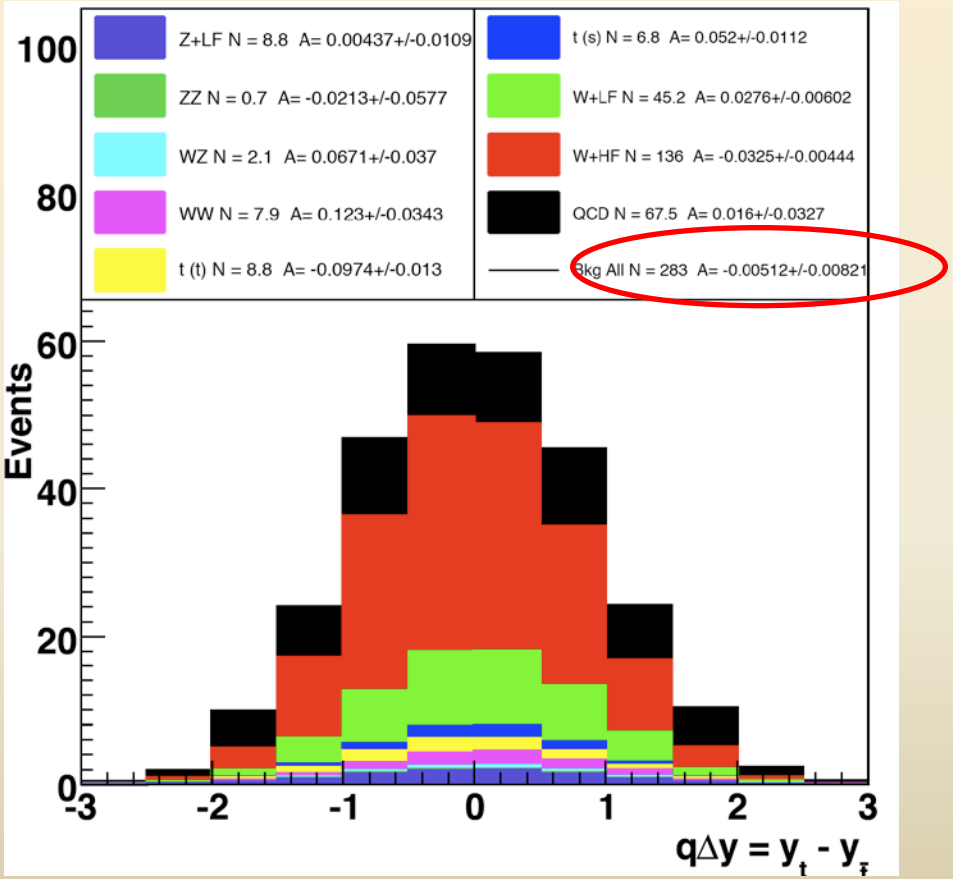
Δy_{tt}

$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

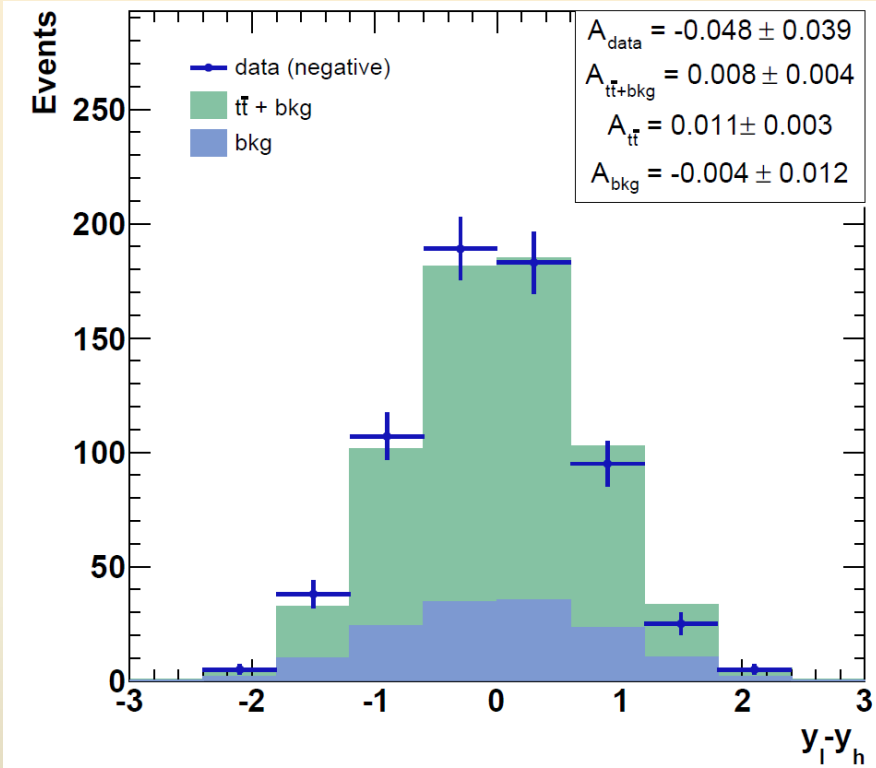
$$= \frac{N(y_t^{t\bar{t}} > 0) - N(y_t^{t\bar{t}} < 0)}{N(y_t^{t\bar{t}} > 0) + N(y_t^{t\bar{t}} < 0)}$$

Asymmetry from background is small but not zero!

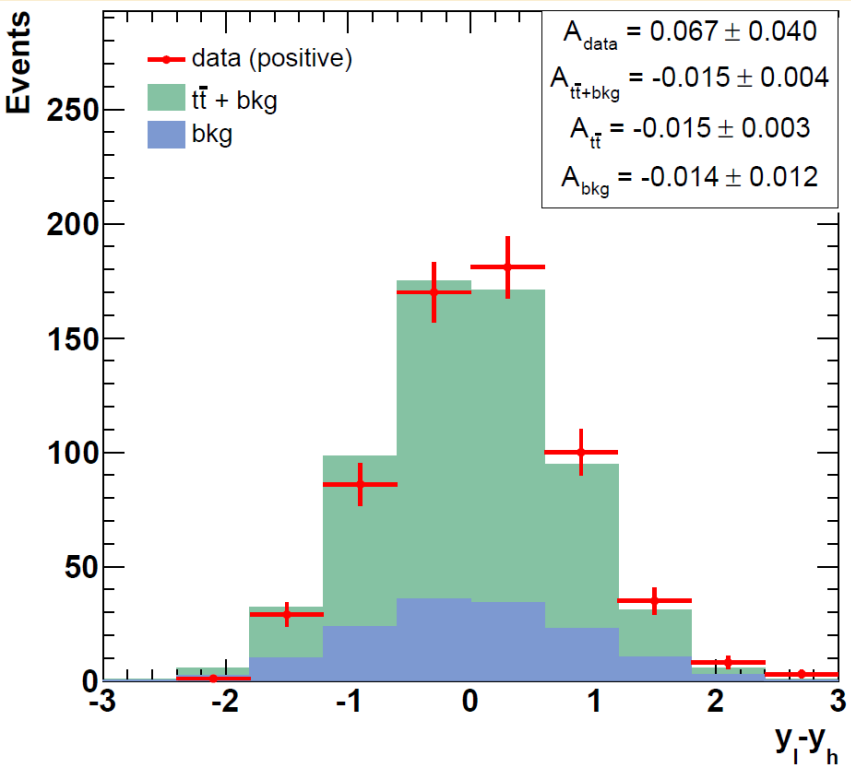
tt rest frame



negative leptons **positive leptons**

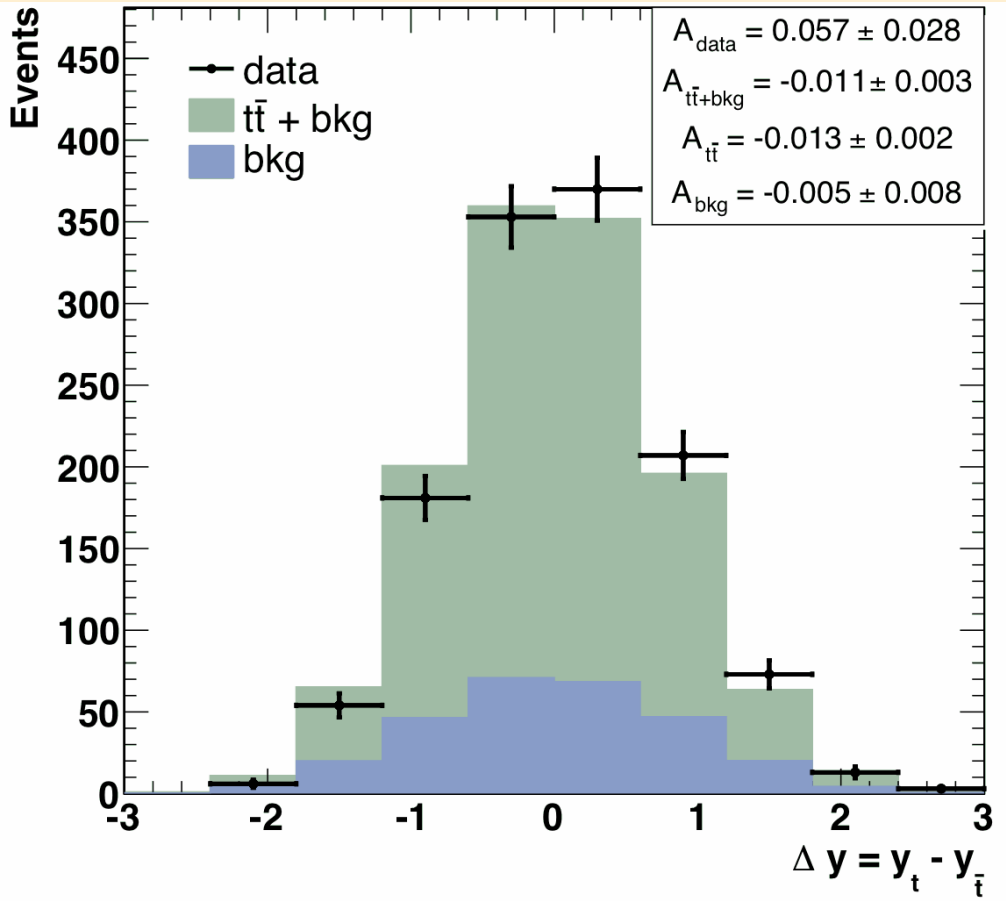


A_{FB} = -0.048 ±0.039



A_{FB} = 0.067±0.040

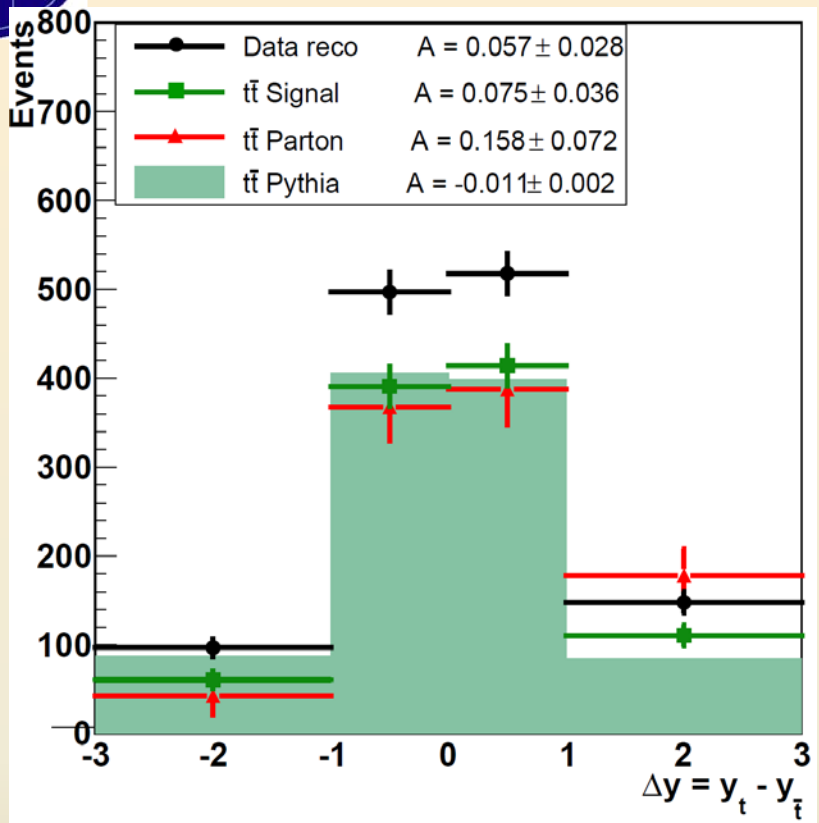
It's 1) a charge asymmetry 2)CP conserving

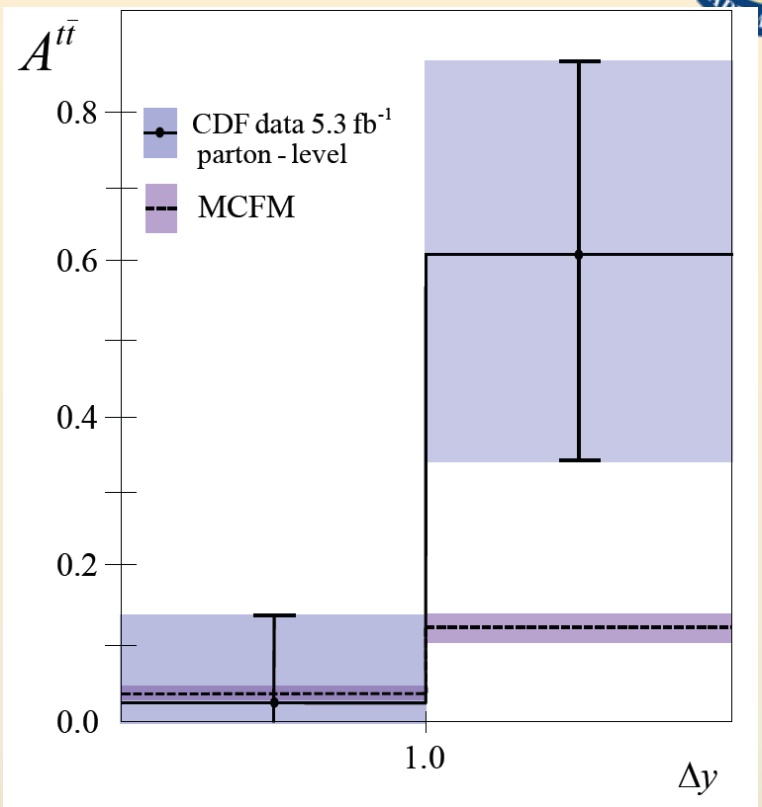


sample	level	$A^{t\bar{t}}$
data	data	0.057 ± 0.028
MC@NLO	$t\bar{t}$+bkg	0.017 ± 0.004
data	signal	0.075 ± 0.037
MC@NLO	$t\bar{t}$	0.024 ± 0.005
data	parton	0.158 ± 0.074
MCFM	parton	0.058 ± 0.009

Note:
D0 signal level 4.3 fb^{-1}
Yields 0.08±0.04.
We agree!

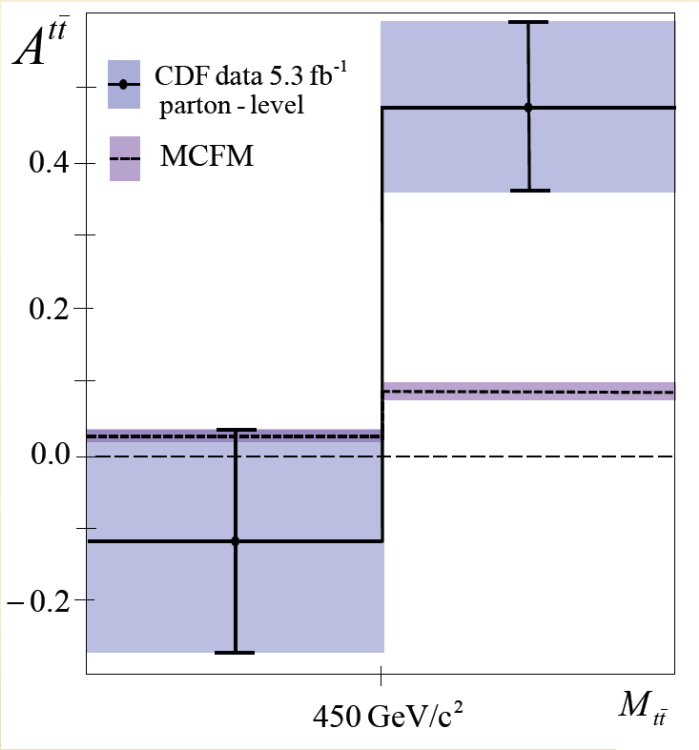
Dependence on Δy_{tt}





sample	level	$\lvert\Delta y\rvert < 1.0$	$\lvert\Delta y\rvert \geq 1.0$
data	data	0.021 ± 0.031	0.208 ± 0.062
data	parton	$0.026 \pm 0.104 \pm 0.056$	$0.611 \pm 0.210 \pm 0.147$
MCFM	parton	0.039 ± 0.006	0.123 ± 0.018

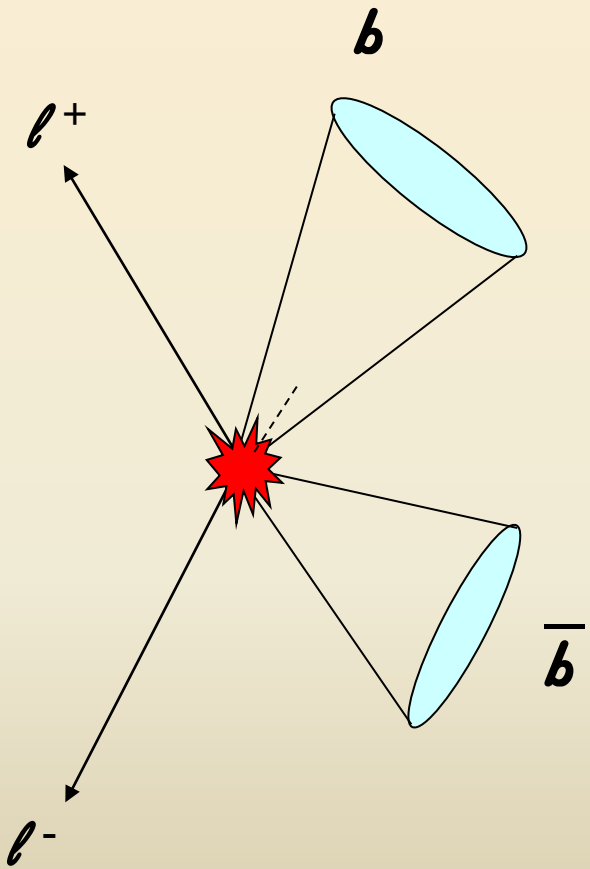
Dependence on M_{tt}



selection	$M < 450$ GeV/c^2	$M \geq 450$ GeV/c^2
data	-0.016 ± 0.034	0.210 ± 0.049
MC@NLO $t\bar{t}$+bkg	$+0.012 \pm 0.006$	0.030 ± 0.007
data signal	$-0.022 \pm 0.039 \pm 0.017$	$0.266 \pm 0.053 \pm 0.032$
MC@NLO $t\bar{t}$	$+0.015 \pm 0.006$	0.043 ± 0.009
data parton	$-0.116 \pm 0.146 \pm 0.047$	$0.475 \pm 0.101 \pm 0.049$
MCFM	$+0.040 \pm 0.006$	0.088 ± 0.013

TABLE XIII: Asymmetry $A^{t\bar{t}}$ at high and low mass compared to prediction.

Using di-lepton events up to 5.1 fb^{-1}



- two high p_t lepton (e/μ)
  - $E_t/p_t > 20$ GeV (/c)
  - $|\eta| < 2.8$
- missing $E_t > 25$ GeV
  - missing $E_t > 50$ GeV, if $\Delta\theta$ (ℓ or j vs missing Et) $< 20^0$
- two or more jets
  - $E_t > 15$ GeV
  - $|\eta| < 2.5$
- Ht > 200 GeV
- $|\Delta Z_{\ell\ell}| < 4$ cm
- no b-tagging required

- 343 events
- 106±17 non-tt background
  - mostly FAKES and DY

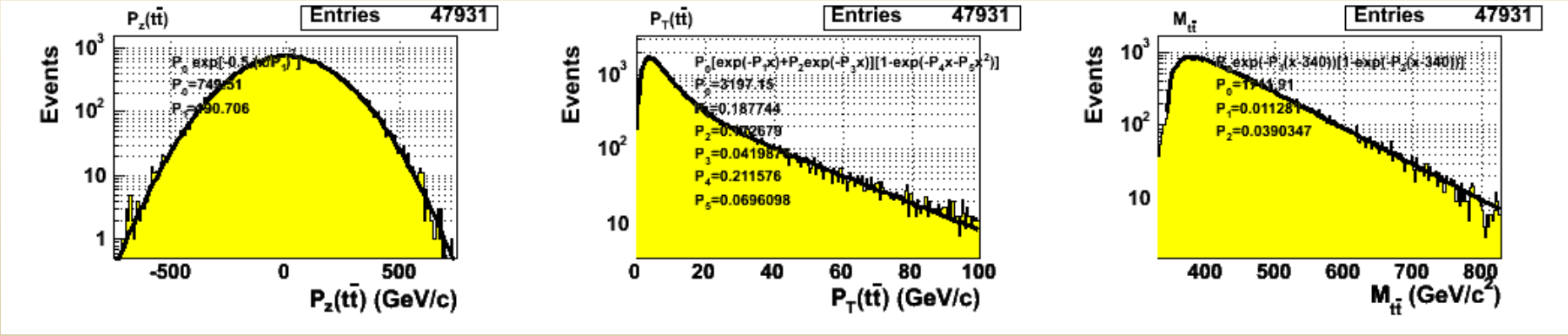
DIL reconstruction

$$\mathcal{L}(\vec{p}_\nu, \vec{p}_{\bar{\nu}}, E_b^{\text{guess}}, E_{\bar{b}}^{\text{guess}}) = P(p_z^{t\bar{t}})P(p_T^{t\bar{t}})P(M_{t\bar{t}})\times$$

$$\frac{1}{\sigma_{\text{jet1}}}\exp\left[-\frac{1}{2}\left\{\frac{E_{\text{jet1}}^{\text{meas}} - E_{\text{jet1}}^{\text{guess}}}{\sigma_{\text{jet1}}}\right\}^2\right]\times\frac{1}{\sigma_{\text{jet2}}}\exp\left[-\frac{1}{2}\left\{\frac{E_{\text{jet2}}^{\text{meas}} - E_{\text{jet2}}^{\text{guess}}}{\sigma_{\text{jet2}}}\right\}^2\right]\times$$

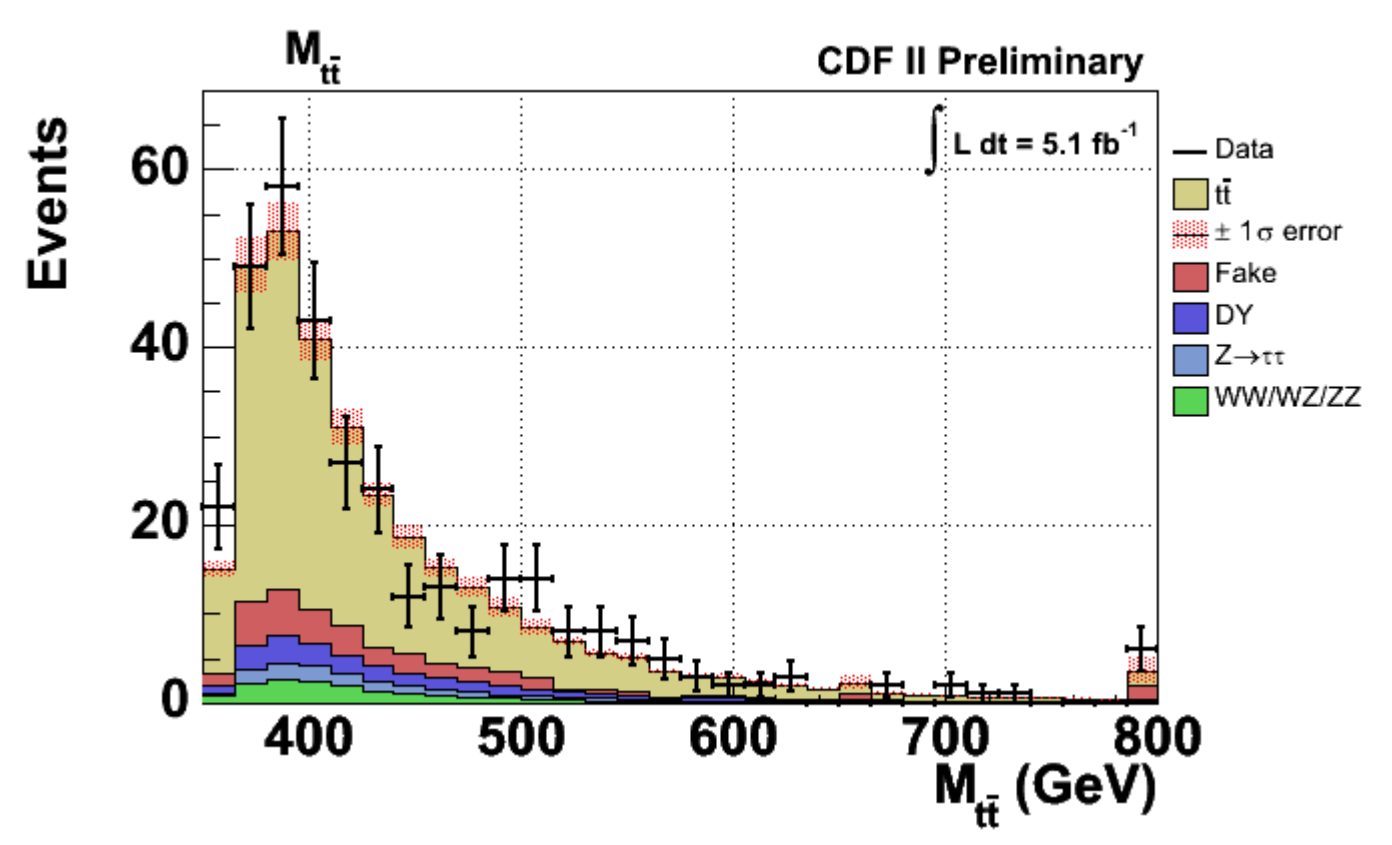
$$\frac{1}{\sigma_x^{\text{MET}}}\exp\left[-\frac{1}{2}\left\{\frac{\not{E}_x^{\text{meas}} - \not{E}_x^{\text{guess}}}{\sigma_x^{\text{MET}}}\right\}^2\right]\times\frac{1}{\sigma_y^{\text{MET}}}\exp\left[-\frac{1}{2}\left\{\frac{\not{E}_y^{\text{meas}} - \not{E}_y^{\text{guess}}}{\sigma_y^{\text{MET}}}\right\}^2\right]$$

$P(p_z^{t\bar{t}})$, $P(p_T^{t\bar{t}})$, and $P(M_{t\bar{t}})$ are obtained from DIL candidates in PYTHIA MC

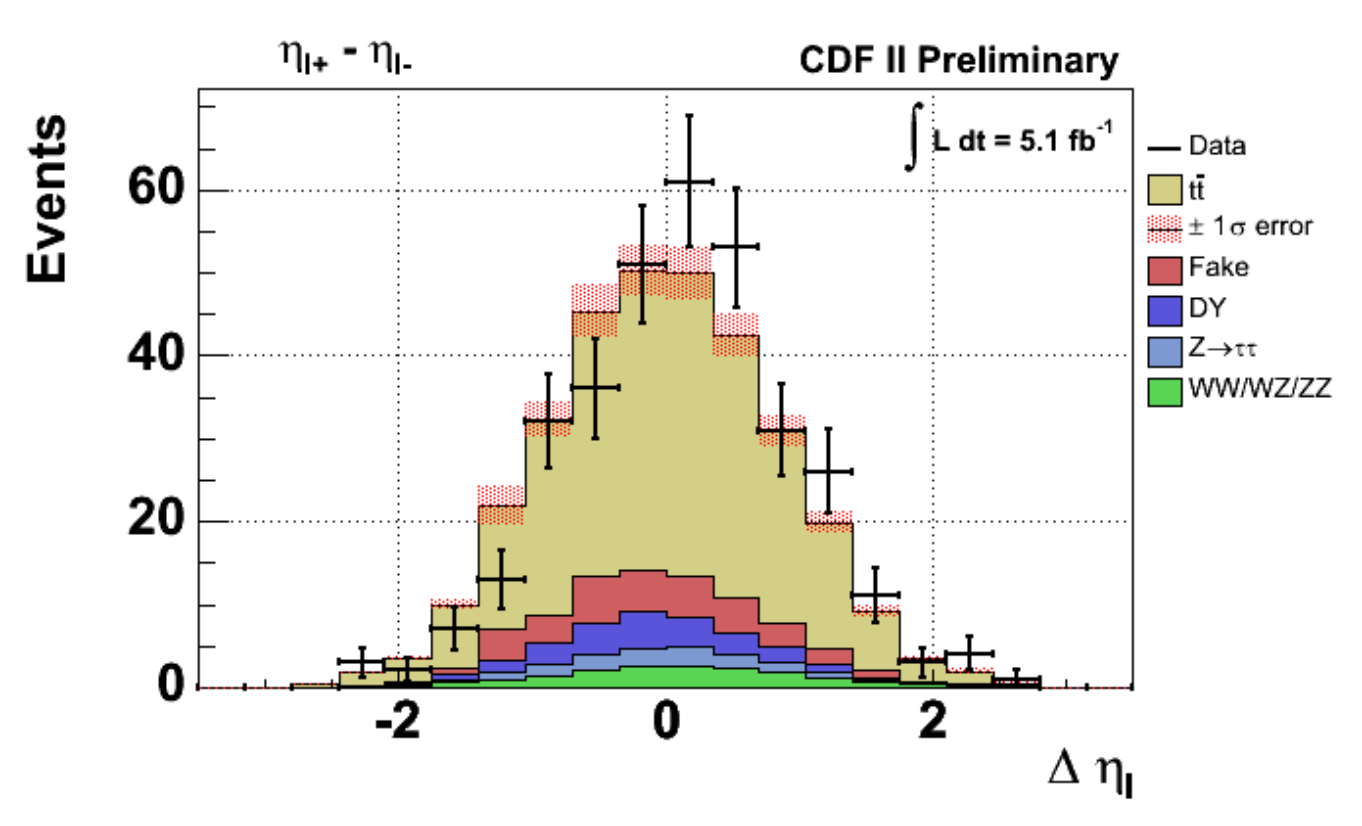


We take one representative $(\vec{p}_\nu, \vec{p}_{\bar{\nu}}, E_b^{\text{guess}}, E_{\bar{b}}^{\text{guess}})$ which gives maximum likelihood in an event.

Reconstructed $M_{t\bar{t}}$



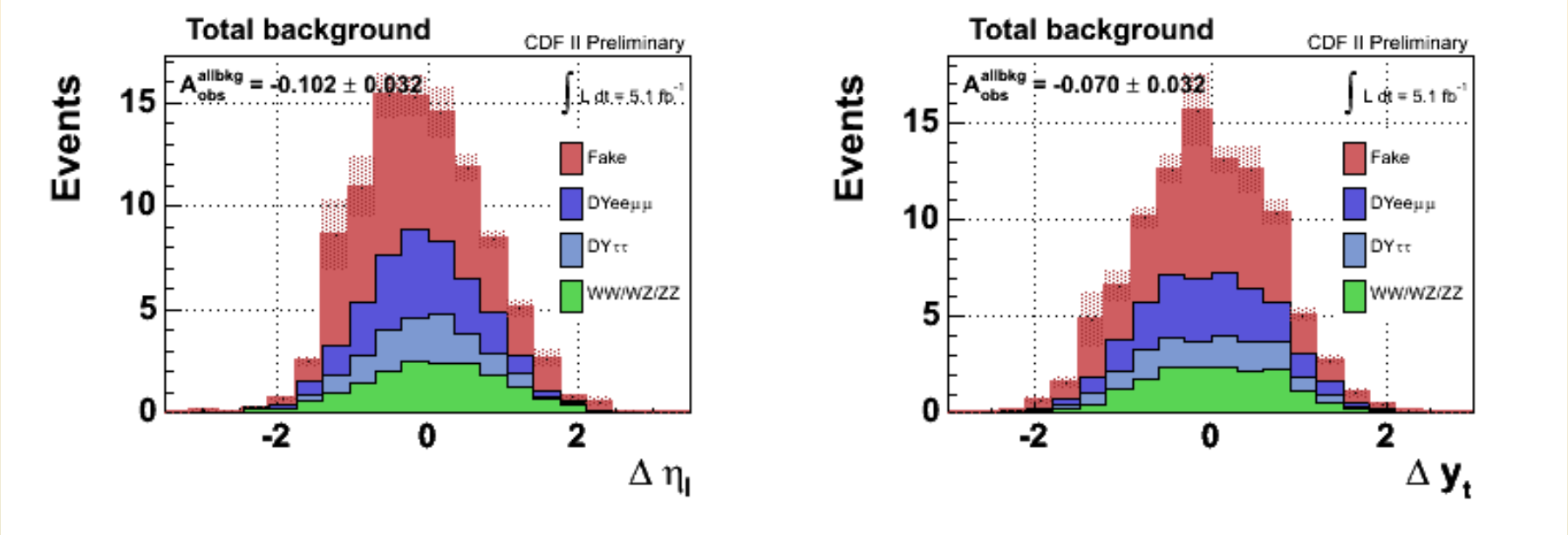
$\Delta\eta_\ell$

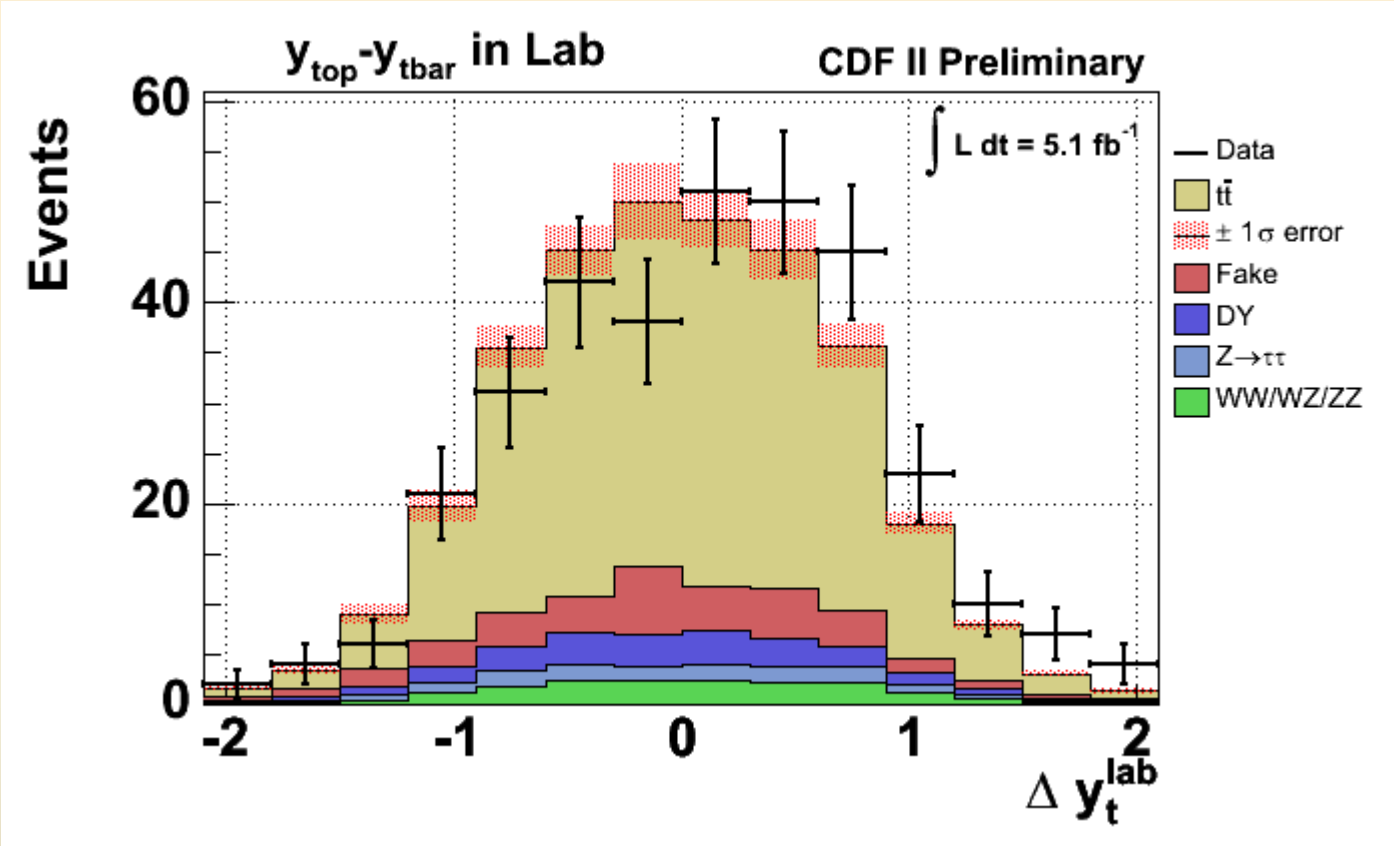


$$A_{\rm obs}^{\Delta\eta_\ell} = 0.14 \pm 0.05(\text{stat.})$$

$$A_{\rm sub}^{\Delta\eta_\ell} = 0.21 \pm 0.07(\text{stat.}) \pm 0.02(\text{bkg. shape})$$

Afb from background is not zero

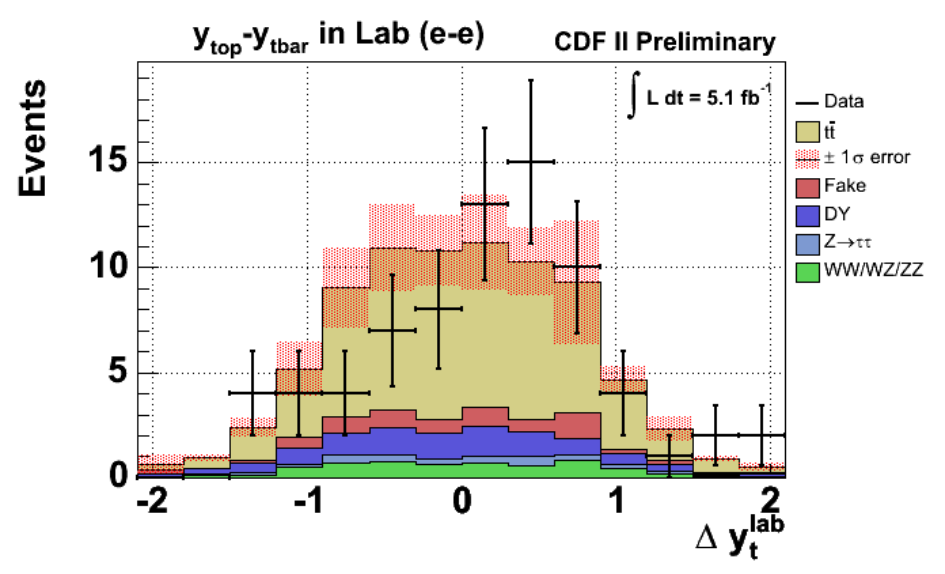


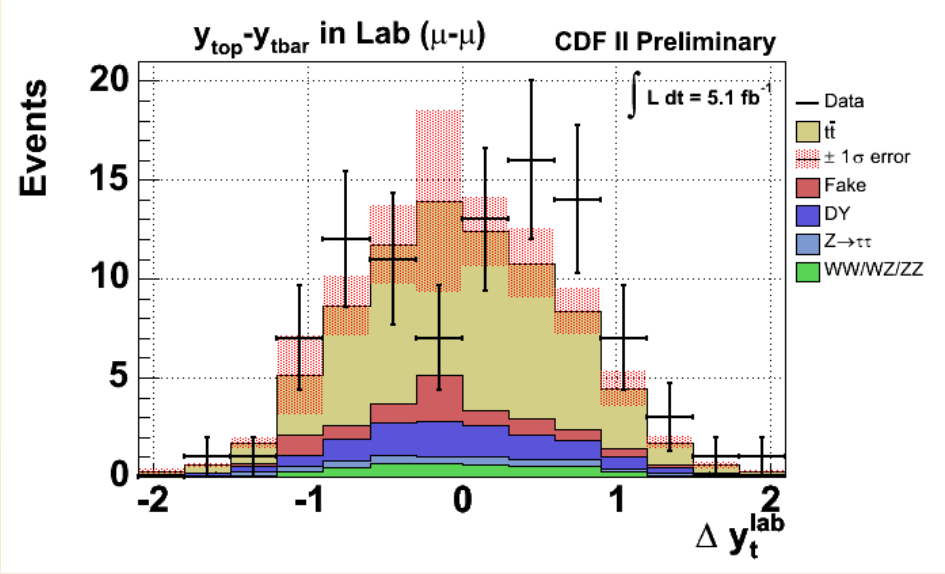


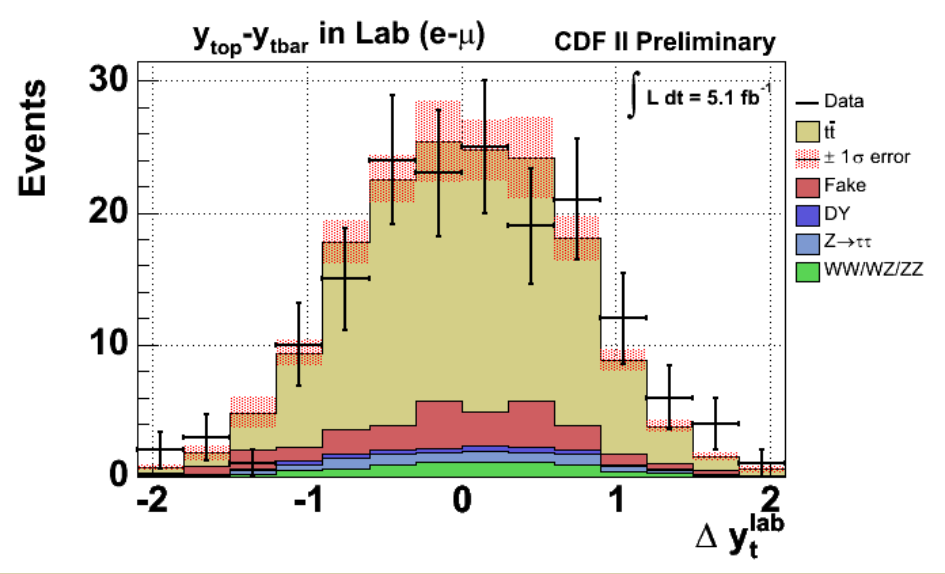
$$A_{obs} = 0.14 \pm 0.05(\text{stat.})$$

$$A_{sub} = 0.21 \pm 0.07(\text{stat.}) \pm 0.02(\text{bkg. shape})$$

$$A_{true} = 0.42 \pm 0.15(\text{stat.}) \pm 0.05(\text{syst.})$$
$$= 0.42 \pm 0.16$$





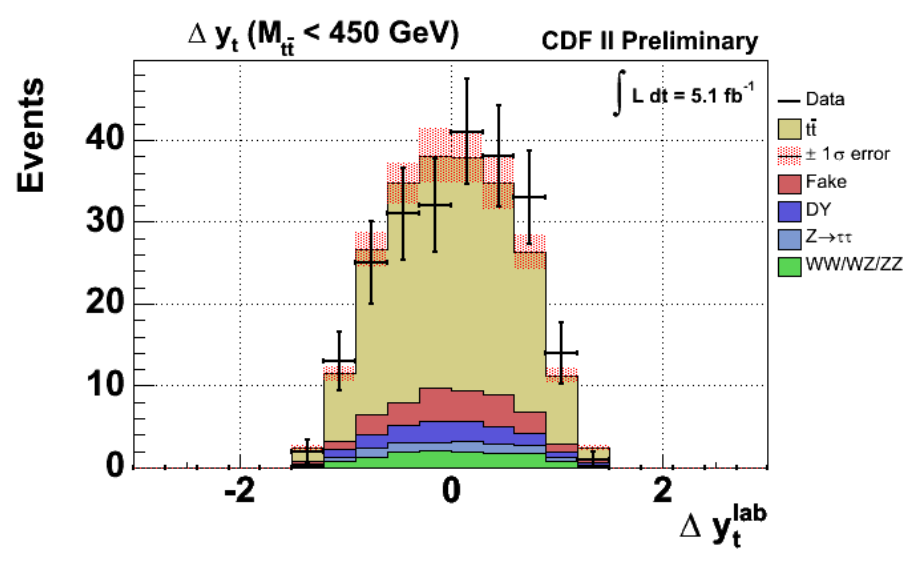


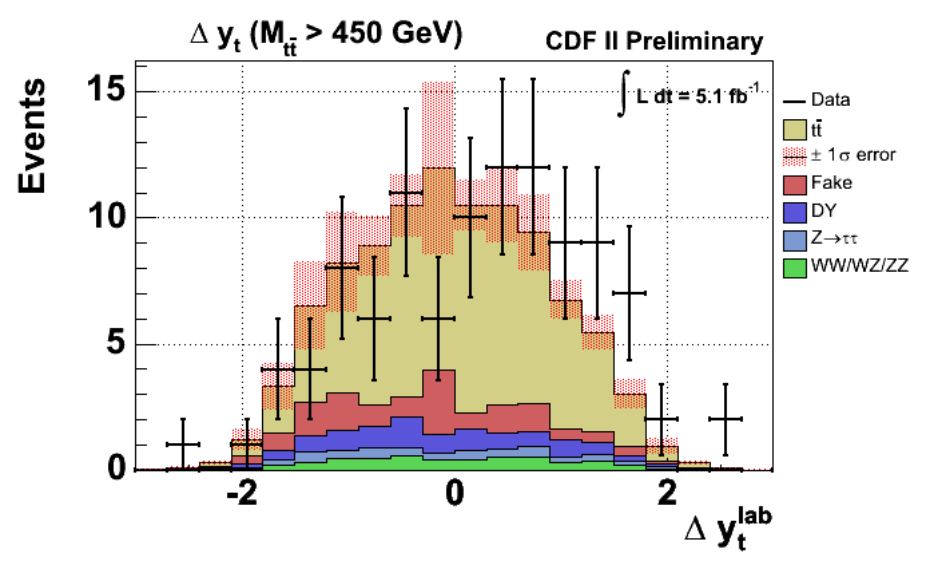
ee :
A_{obs} = 0.270 ± 0.112(stat.) (Pred. : − 0.010 ± 0.070)

eμ :
A_{obs} = 0.060 ± 0.077(stat.) (Pred. : − 0.004 ± 0.037)

μμ :
A_{obs} = 0.170 ± 0.102(stat.) (Pred. : − 0.039 ± 0.078)

$M_{t\bar{t}}$ dependence





Aobs = 0.104 +- 0.066(stat.)

Asub = 0.134 +- 0.088(stat.)

Aobs = 0.212 +- 0.096(stat.)

Asub = 0.368 +- 0.137(stat.)

A_{fb} summary, LJ

- Inclusive A in lab and tt frames in 2 sigma excess over SM

- Consistent with CP conservation
  - consistency between positive and negative lepton samples

- A^{tt} has a strong dependence on Δy, M_{tt}
- For $M_{tt} > 450$ GeV/c^2

$$A^{tt}_{reco} = 0.210 \pm 0.049, \quad A^{tt}_{parton} = 0.475 \pm 0.112$$

$$A^{tt}_{NLO\ reco} = 0.043 \pm 0.006\ , \quad A^{tt}_{MCFM} = 0.088 \pm 0.013$$

Afb summary, DIL

- A_{sub} = 0.21 ± 0.07(stat.) ± 0.02(bkg. shape)

  A_{true} = 0.42 ± 0.15(stat.) ± 0.05(syst.)

  = 0.42 ± 0.16

- Consistency between ee, eμ, μμ

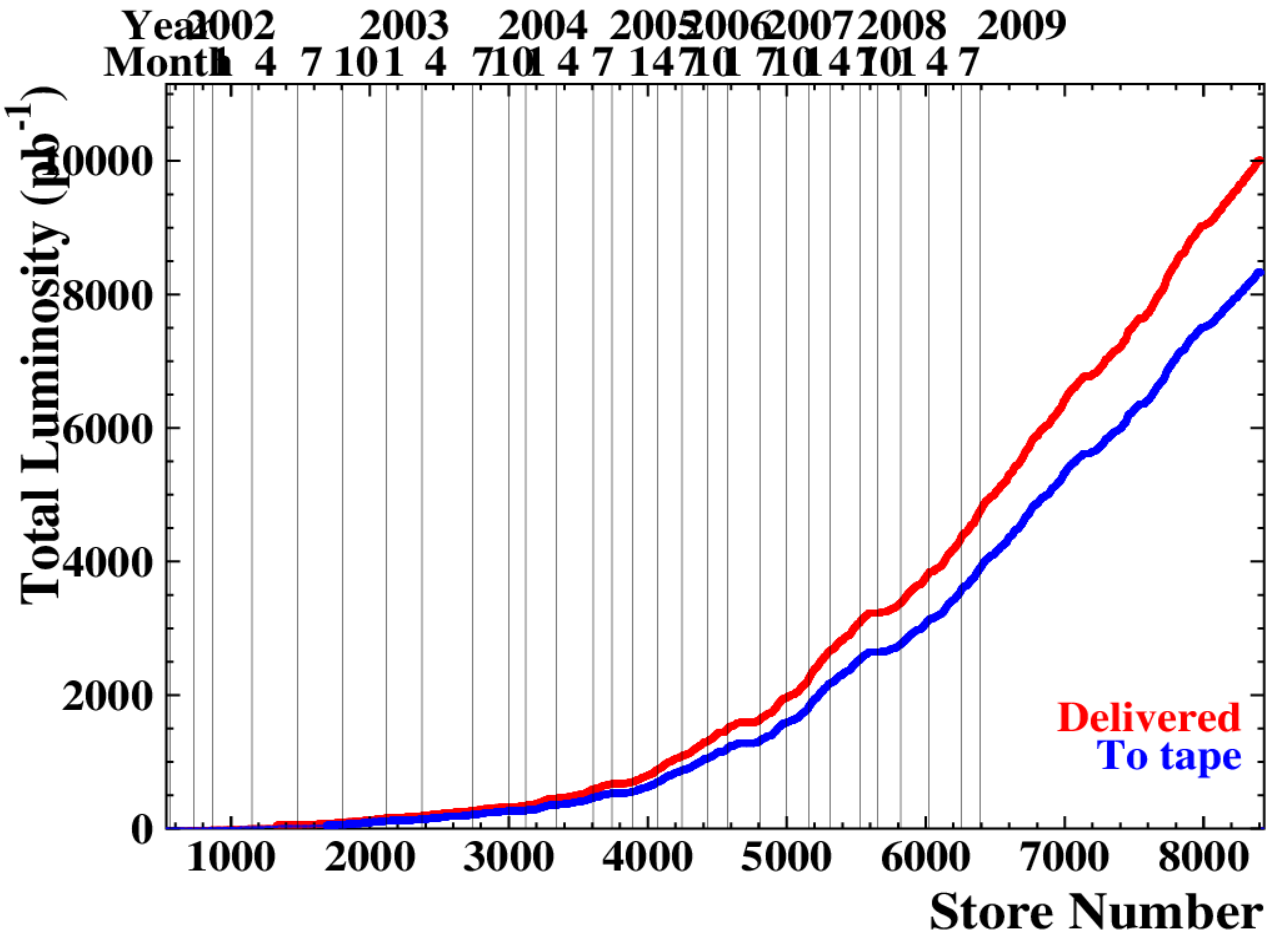
- A^{tt} has dependence on M_{tt}

Will update the results with more studies and more data!

The result with b tagging is coming soon!

Thanks!

Integrated luminosity

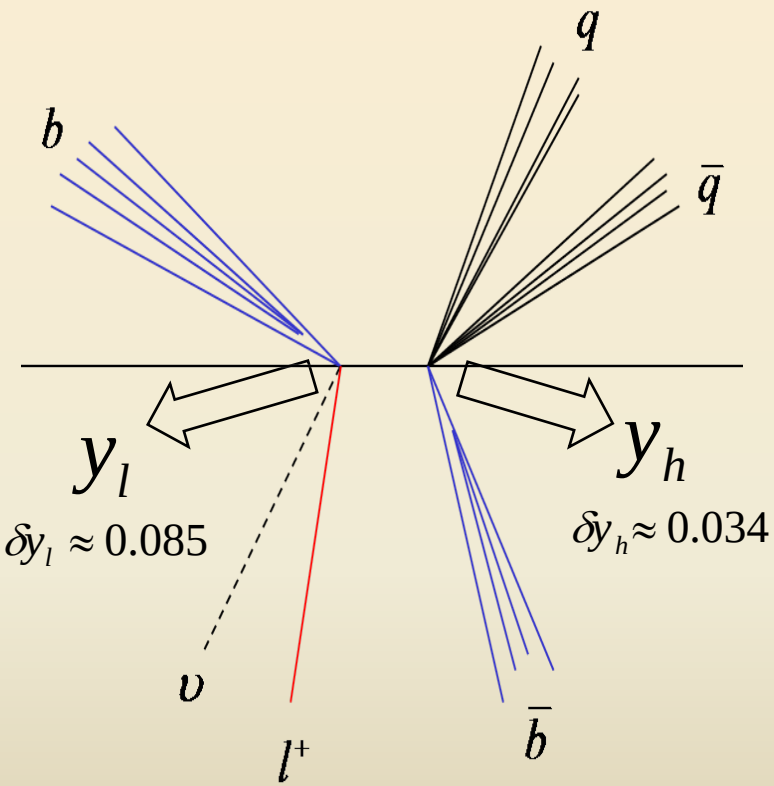


Top quarks reconstructed

- Reconstructed top quarks are called "leptonic top" and "hadronic top"
  - t_l and t_h
  - Lead to y_l and y_h.
  - Resolution

$$\delta y_l \approx 0.085$$

$$\delta y_h \approx 0.034$$



Rapidity of top quarks

- From charge of lepton the flavor of t_l and t_h can be identified, top or anti-top.

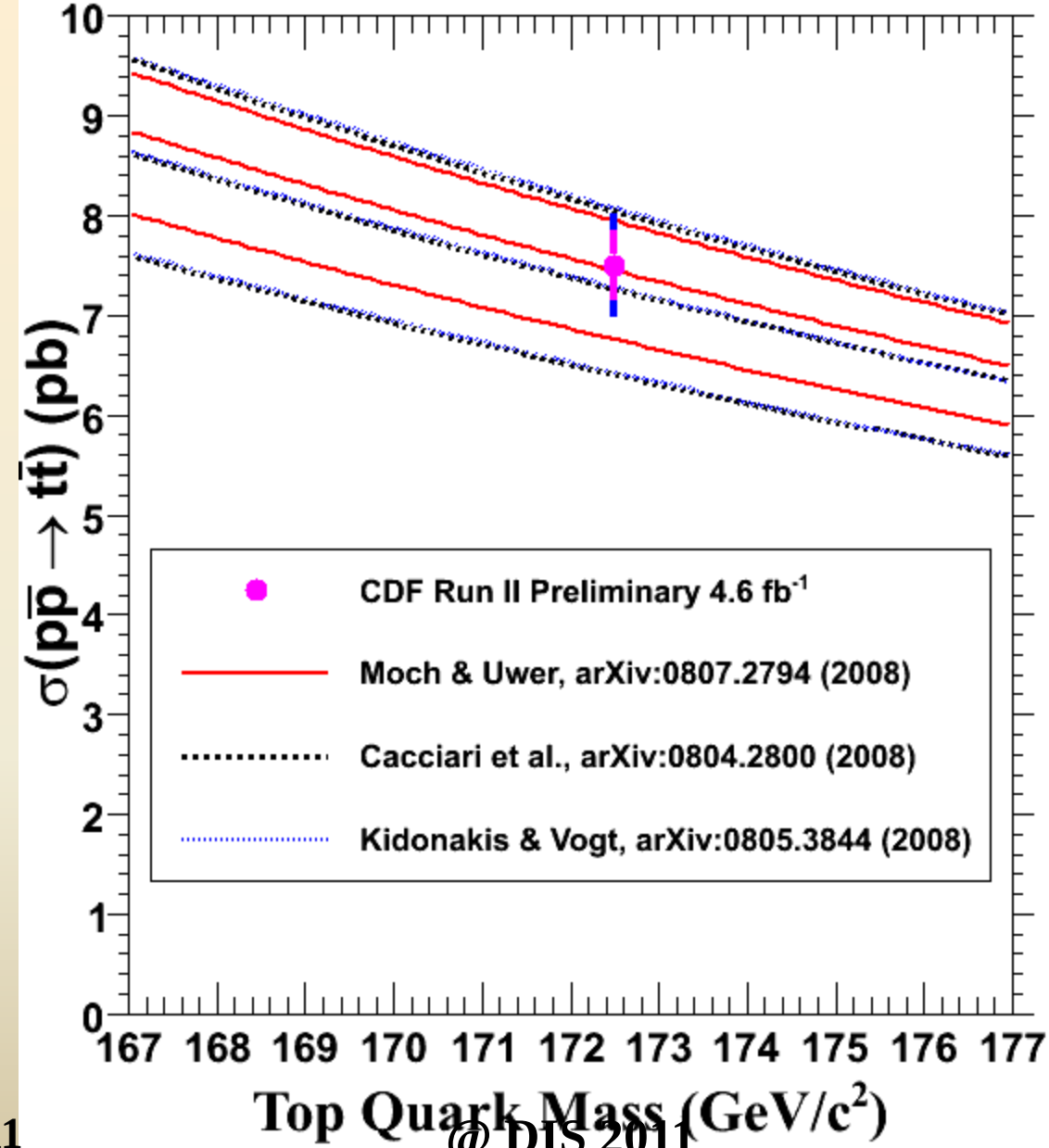
q_l	t_l	t_h
+	top	anti-top
-	anti-top	top

- If CP is conserved:
  - Diluted by production boost

$$-q \cdot y_h = y_t^{p\bar{p}}$$

- Rapidity difference:
  - least affected by boost
  - Resolution is worse, $\delta\Delta y \approx 0.100$

$$\Delta y_{t\bar{t}} = q \cdot (y_l - y_h)$$
$$= y_t - y_{\bar{t}}$$
$$\Delta y_{t\bar{t}} = 2 y_t^{t\bar{t}}$$


CDF Run II Preliminary 4.6 fb^{-1}
Moch & Uwer, arXiv:0807.2794 (2008)
Cacciari et al., arXiv:0804.2800 (2008)
Kidonakis & Vogt, arXiv:0805.3844 (2008)
$\sigma(p\bar{p} \to t\bar{t})$ (pb)
Top Quark Mass (GeV/c^2)
0
1
2
3
4
5
6
7
8
9
10
167
168
169
170
171
172
173
174
175
176
177

Lab frame asymmetry

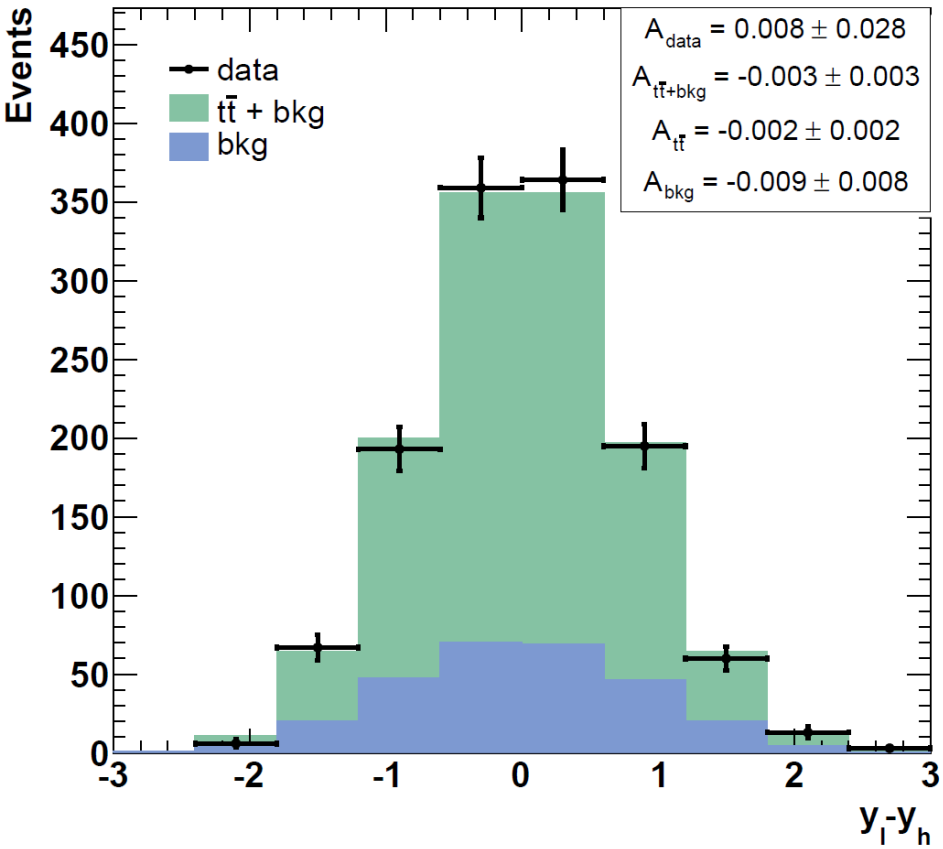
$-q.y_h$

$$A_{FB}^{p\bar{p}} = \frac{N(-qy_h > 0) - N(-qy_h < 0)}{N(-qy_h > 0) + N(-qy_h < 0)}$$

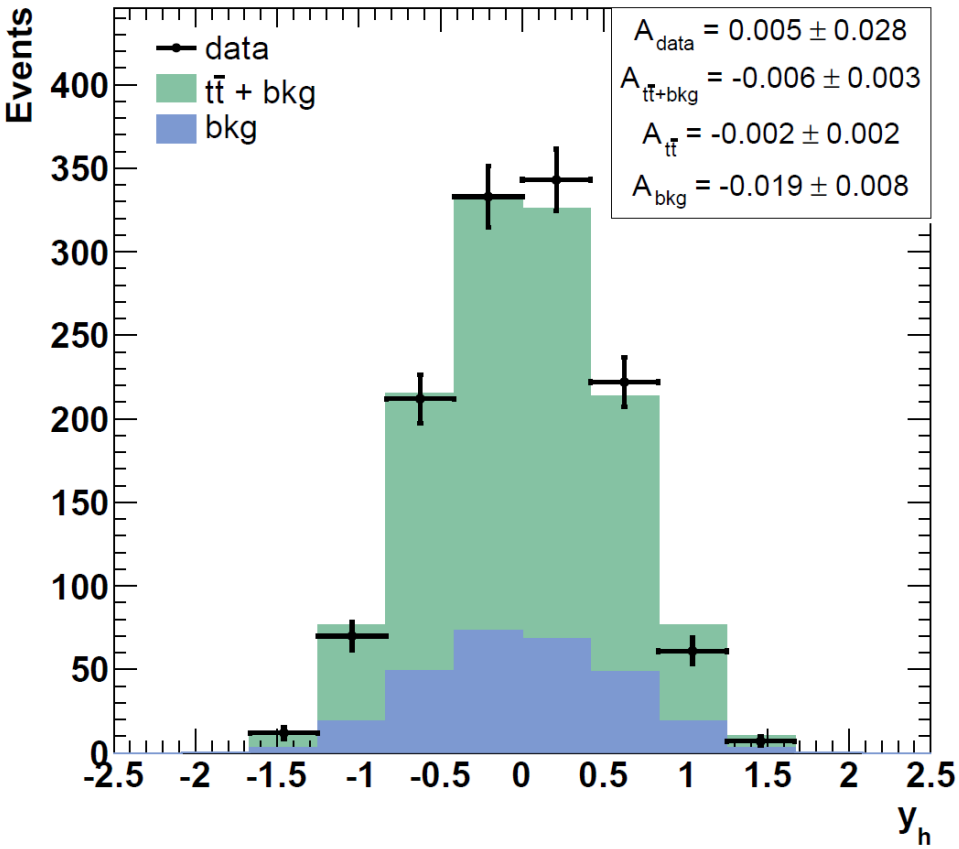
$$= \frac{N(y_t^{p\bar{p}} > 0) - N(y_t^{p\bar{p}} < 0)}{N(y_t^{p\bar{p}} > 0) + N(y_t^{p\bar{p}} < 0)}$$

Inclusive asymmetry

Δy



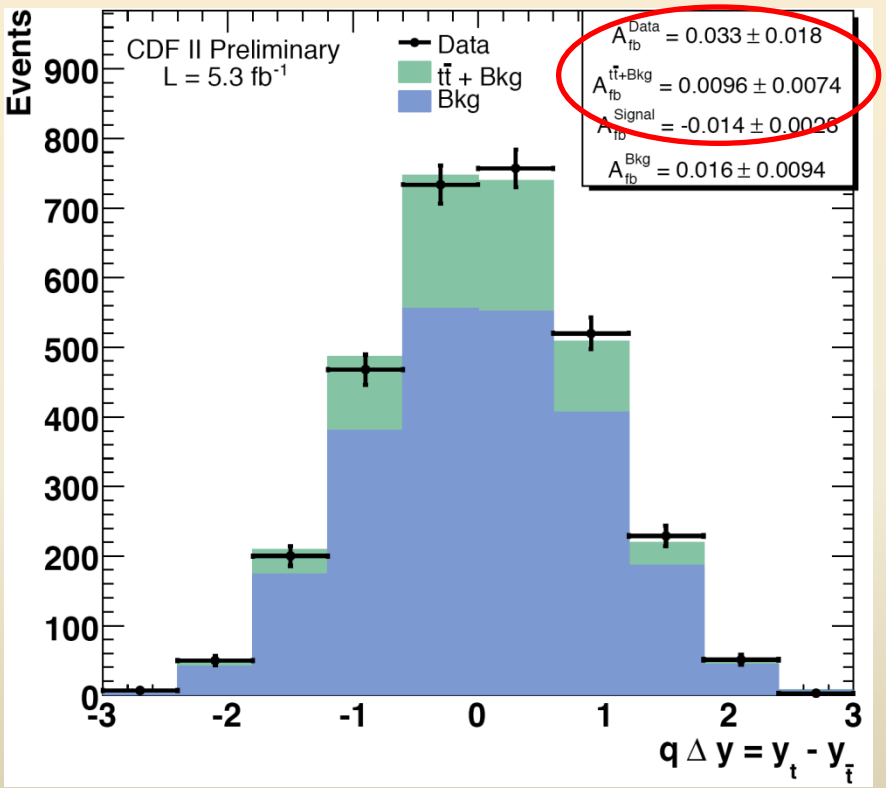
y_h



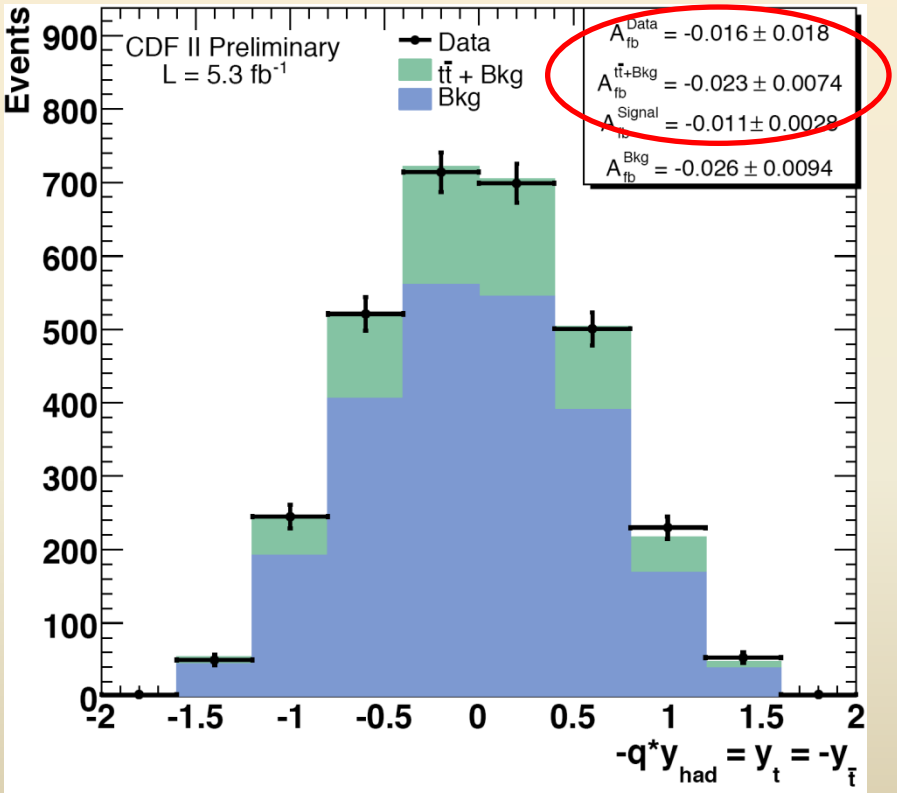
Apply to not b tagged sample

S:B = 0.3

tt frame

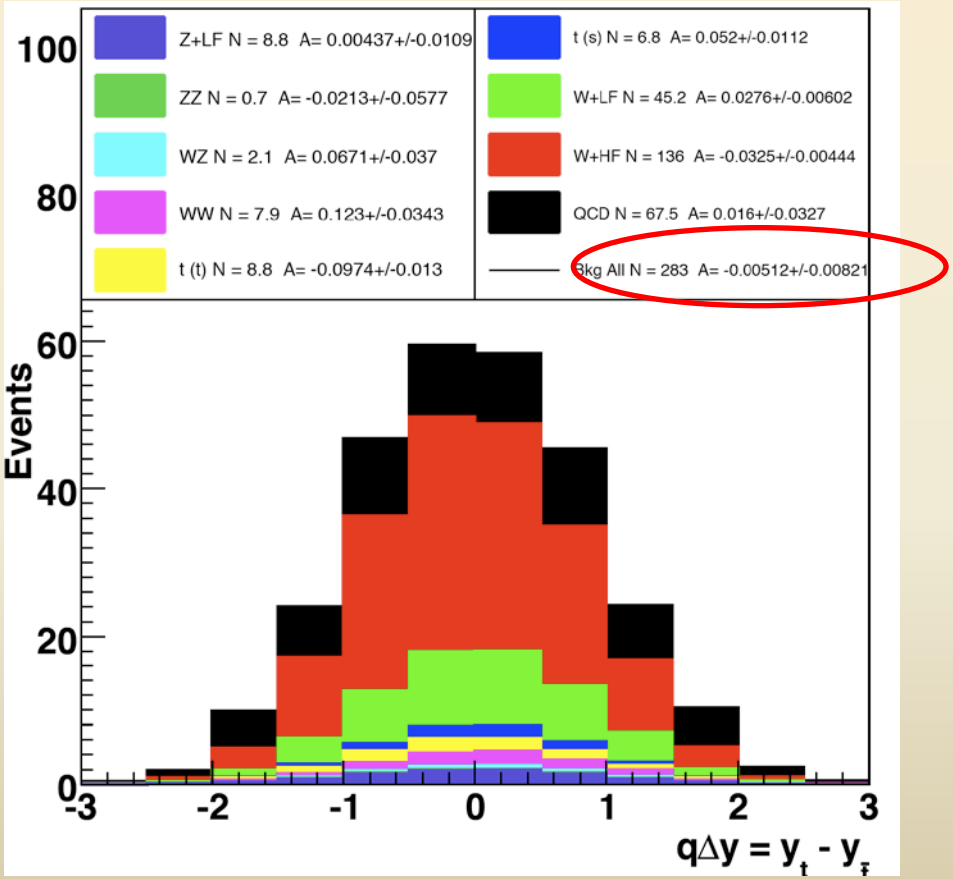


lab frame

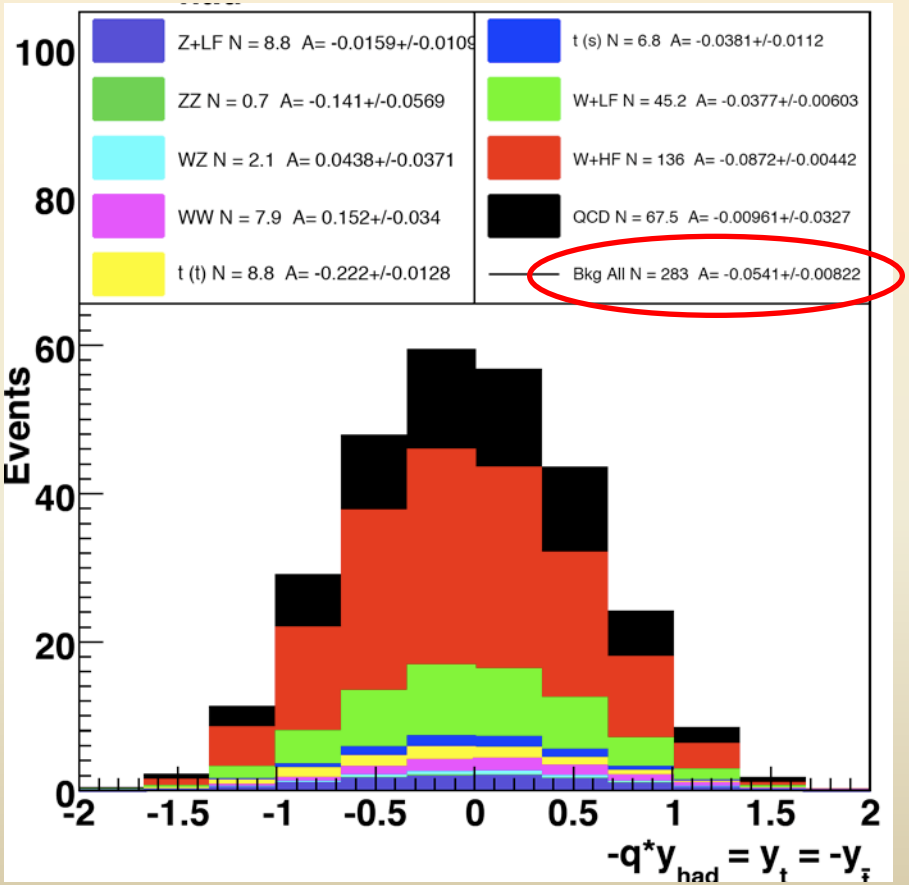


Asymmetry from background is small but not zero!

tt rest frame



lab frame



A_{fb} from di-lepton channel

- In progress of blessing
- Shows also strong asymmetry
- Combining with the result from the lepton + jets channel and using full dataset we could reach 5 sigma, if this asymmetry is true.
- Also some puzzles similar to lepton + jets result!
  - Such as smaller asymmetry in the not b tagged sample
  - Is this just statistical or is it telling us something that we are not aware of?

Asymmetry categorized

selection	N events	all M	$M < 450$ GeV/c^2	$M \geq 450$ GeV/c^2
standard	1260	0.057±0.028	-0.016±0.034	0.212±0.049
electrons	735	0.026±0.037	-0.020±0.045	0.120±0.063
muons	525	0.105±0.043	-0.012±0.054	0.348±0.080
data $\chi^2 < 3.0$	338	0.030±0.054	-0.033 ± 0.065	0.180 ± 0.099
data no-b-fit	1260	0.062±0.028	0.006 ± 0.034	0.190 ± 0.050
data single b-tag	979	0.058±0.031	-0.015±0.038	0.224±0.056
data double b-tag	281	0.053±0.059	-0.023±0.076	0.178±0.095
data anti-tag	3019	0.033±0.018	0.029±0.021	0.044±0.035
pred anti-tag	-	0.010±0.007	0.013±0.008	0.001±0.014
pre-tag	4279	0.040±0.015	0.017±0.018	0.100±0.029
pre-tag no-b-fit	4279	0.042±0.015	0.023±0.018	0.092±0.029

Separated by number of jets

- data: the high mass asymmetry is significantly reduced for 5 jet events

selection	N events	all M	$M < 450$ GeV/c^2	$M \geq 450$ GeV/c^2
data 4-jet	939	0.065±0.033	-0.023±0.039	0.26±0.057
data 5-jet	321	0.034±0.056	0.0049±0.07	0.086±0.093

- the NLO QCD asymmetry has a strong N_{jet} dependence

selection	all M	$M < 450$ GeV/c^2	$M \geq 450$ GeV/c^2
inclusive	0.024 ± 0.004	0.015 ± 0.005	0.043 ± 0.007
4-jet	0.048 ± 0.005	0.033 ± 0.006	0.078 ± 0.009
5-jet	-0.035 ± 0.007	-0.032 ± 0.009	-0.040 ± 0.012

In the lab frame

- Cross check using $-qy_h = y_t^{p\bar{p}}$

selection	all M	$M < 450$ GeV/c^2	$M \geq 450$ GeV/c^2
data reco	0.073±0.028	0.059±0.034	0.103±0.049
MC@NLO	0.017±0.004	-0.008±0.005	0.022±0.007
A_h^+	-0.076±0.039	-0.085±0.047	-0.053±0.072
A_h^-	0.070±0.040	0.028±0.050	0.148±0.066
single b-tags	0.095±0.032	0.079±0.034	0.130±0.057
double b-tags	-0.004±0.060	-0.023±0.076	0.028±0.097

?

Production asymmetry

- "Evidence for a Mass Dependent Forward-Backward Asymmetry in Top Quark Pair Production",
  - "Wine & Cheese" at Fermilab, Jan. 7, 2011.
- Paper submitted to PRD.
- D0 also see similar effect.

prior measurements

- CDF, 1.9 fb^{-1} , inclusive, corrected to "parton-level"
  - tt rest frame $A^{t\bar{t}} = 0.24 \pm 0.14$
  - NLO QCD $A^{t\bar{t}} = 0.06 \pm 0.01$

PRL 101, 202001 (2008)

  - lab (pp) frame $A^{p\bar{p}} = 0.17 \pm 0.08$
  - NLO QCD $A^{p\bar{p}} = 0.04 \pm 0.01$

prior measurements

- D0, inclusive, background subtracted "data-level"
  - tt rest frame $A^{t\bar{t}} = 0.12 \pm 0.08$ 0.9 fb^{-1}

    PRL 100, 142002 (2008)

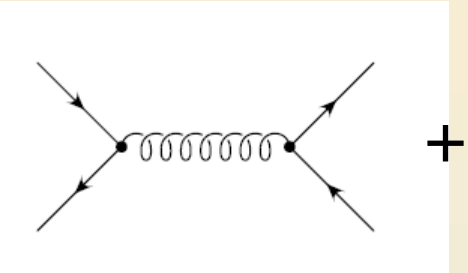
$A^{t\bar{t}} = 0.08 \pm 0.04$ 4.3 fb^{-1}

ICHEP 2010

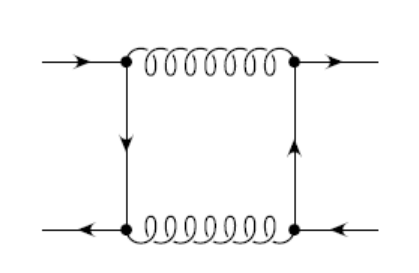
Top charge asymmetry in QCD

- Halzen, Hoyer, Kim; Brown, Sadhev, Mikaelian; Kuhn, Rodrigo; Ellis, Dawson, Nason; Almeida, Sterman, Vogelsang; Bowen, Ellis, Rainwater

$t\bar{t}$

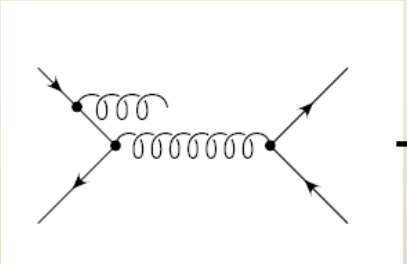


+

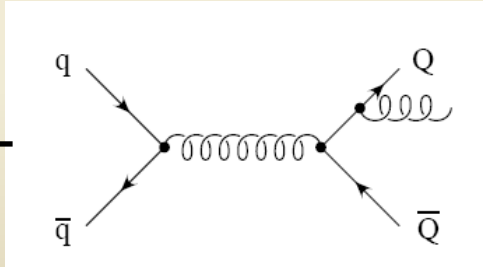


C = - 1 C = +1

$t\bar{t}j$



+



C = + 1 C = -1

In t t rest frame:

A_{FB} ~ +10-12 % NLO

A_{FB} ~ -7 % NLO

A_{FB} ~ 6 ± 1 % NLO

Asymmetry in $t\bar{t}$ and $p\bar{p}$ frame

- The asymmetry in the lab. Frame is reduced by the uncontrolled boost along the beamline:

$$A_{FB}^{t\bar{t}} \approx 1.5 \times A_{FB}^{p\bar{p}}$$

MC NLO study

- MCFM NLO calculation at "parton level"
- MC@NLO + CDFSIM

model	level	$A^{p\bar{p}}$	$A^{t\bar{t}}$
MCFM	parton	0.038 ± 0.006	0.058 ± 0.009
MC@NLO	parton	0.032 ± 0.005	0.052 ± 0.008
MC@NLO	$t\bar{t}$	0.018 ± 0.005	0.024 ± 0.005
MC@NLO	$t\bar{t}$+bkg	0.001 ± 0.003	0.017 ± 0.004

truth

sim + reco

sim + reco +bkg

- Pythia remains good approximation of SM

Correction to parton level

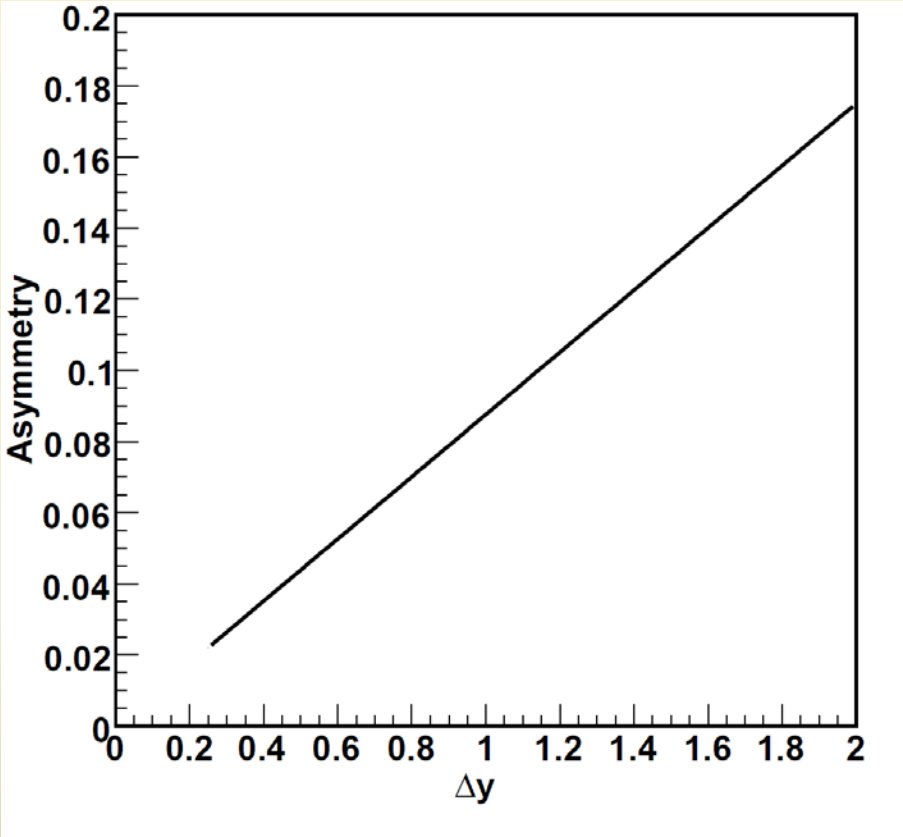
- Bin by bin in the histogram
  - P_j : parton level distribution
  - A_j: acceptance of the analysis
  - S_{ij}: smearing of the reconstruction
  - T_i: top signal

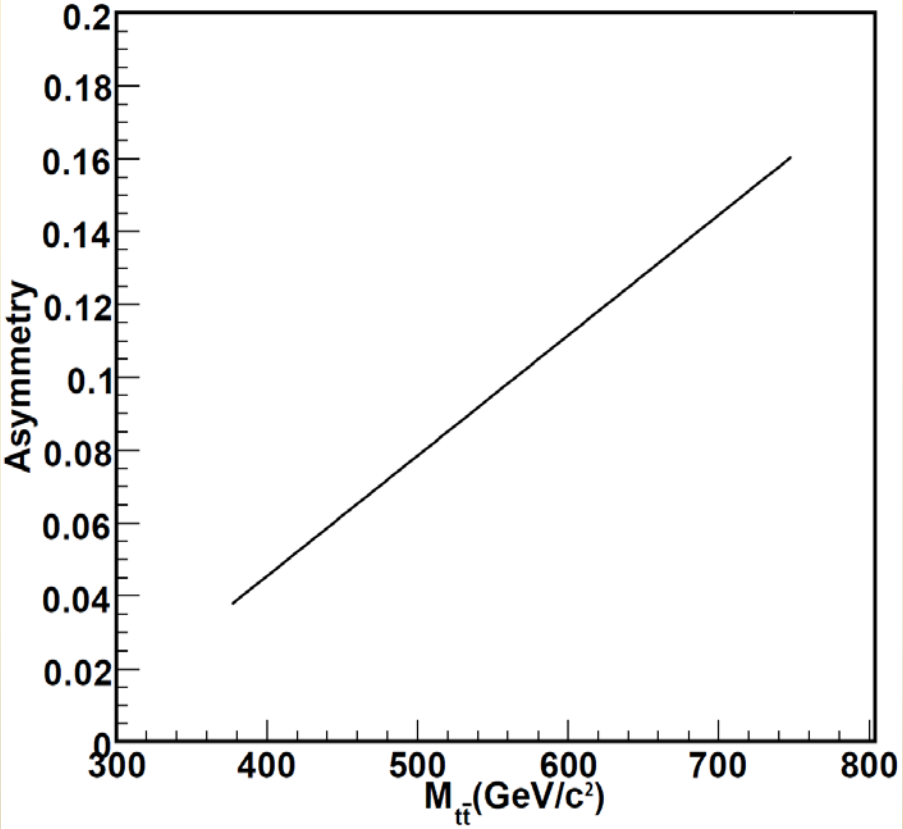
$$T_i = S_{ij} \times A_j \times P_j$$

  - B_i: background
  - D_i: data distribution

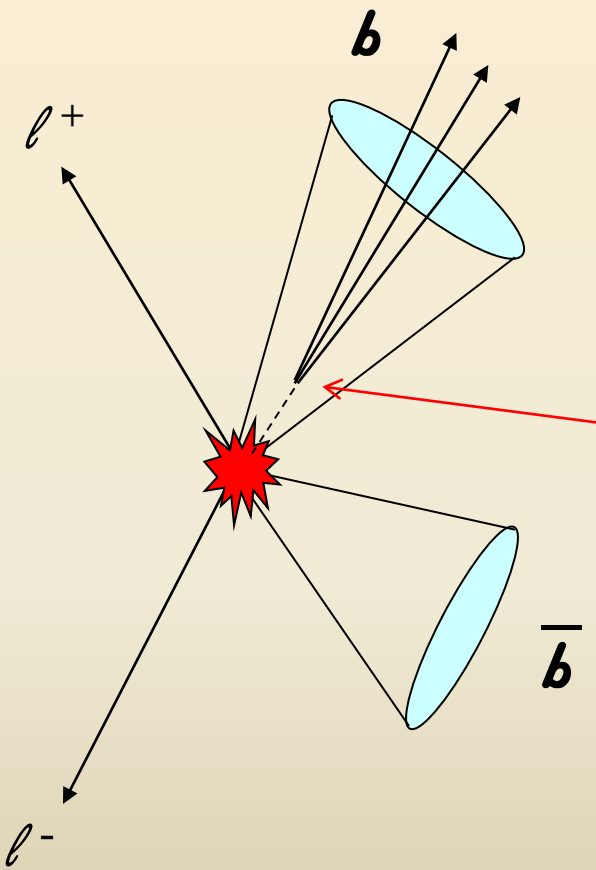
$$P_j = A_j^{-1} \times S_{ij}^{-1} \times (D_i - B_i)$$

Asymmetry is a function of Δy_{tt} and M_{tt}





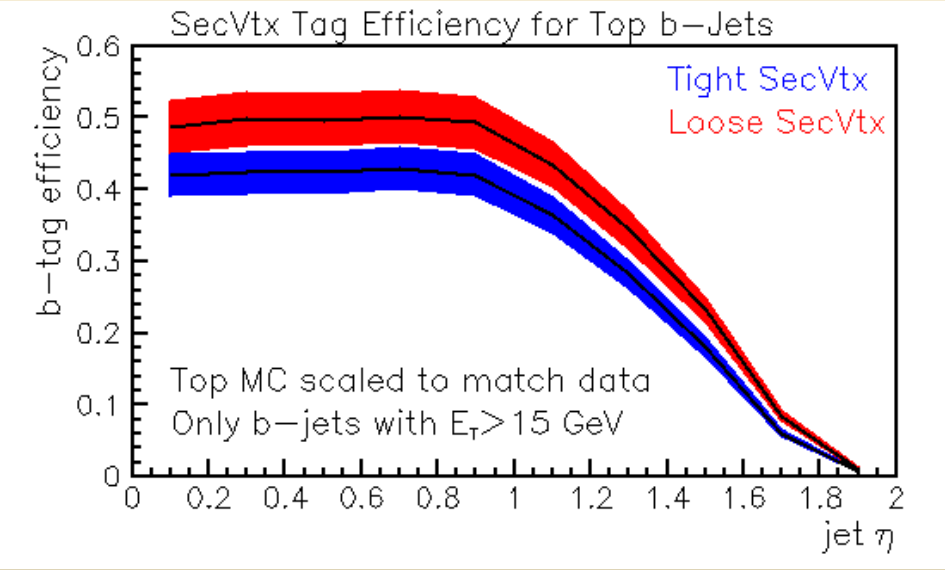
To reject the background - tagging of b quark jets



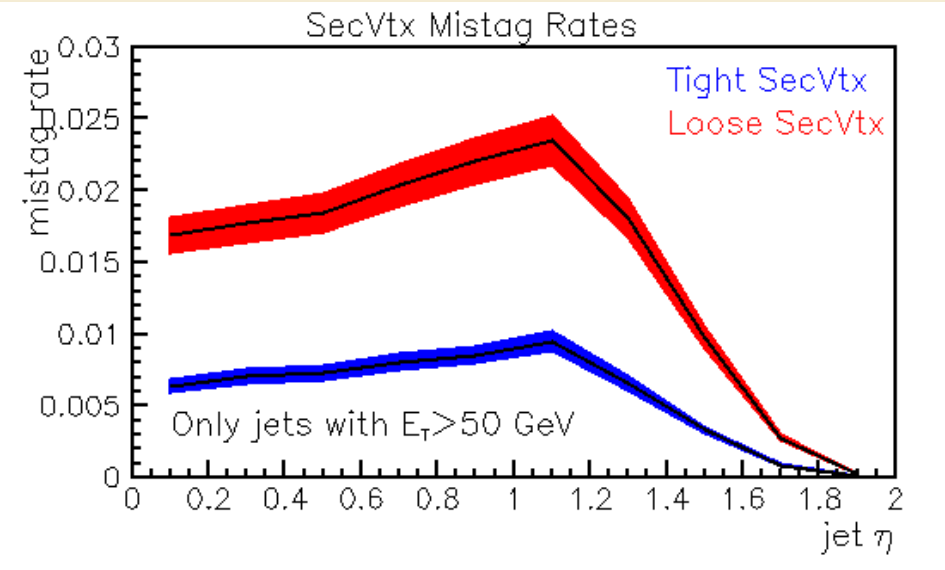
Looking for *secondary vertex*

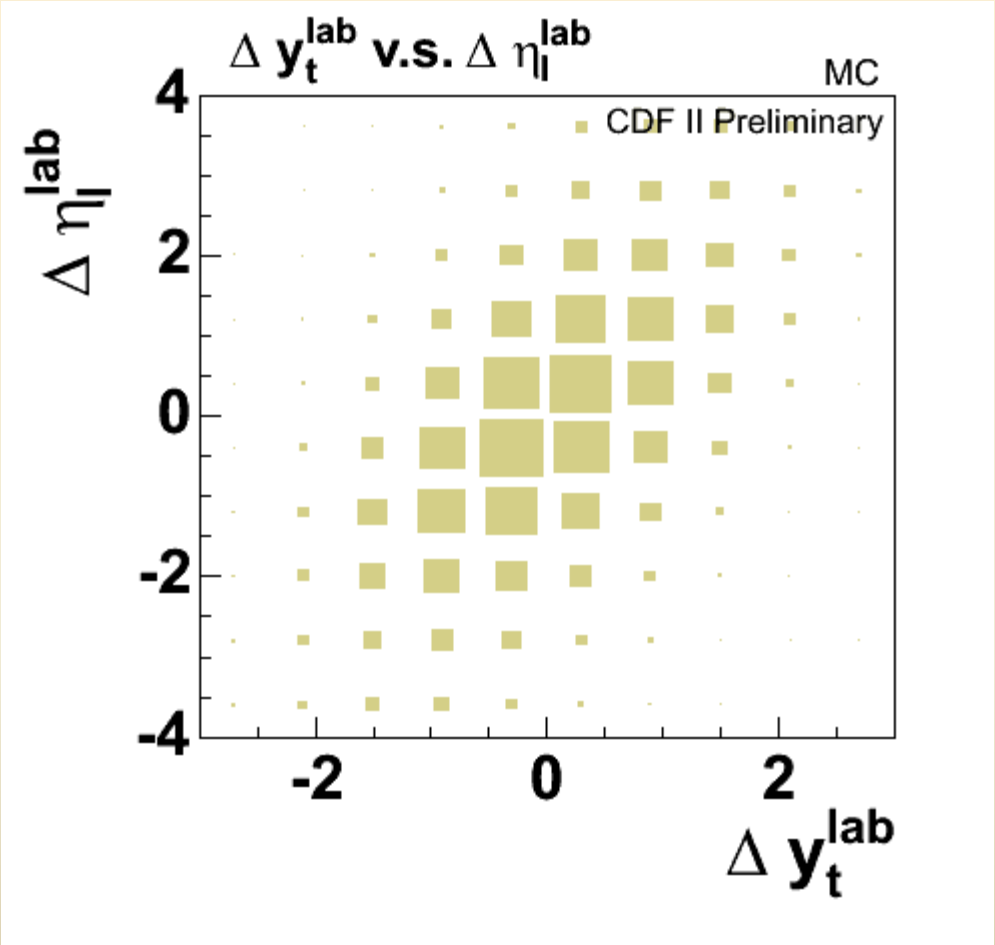
B tagging via Secondary vertex (SVX)

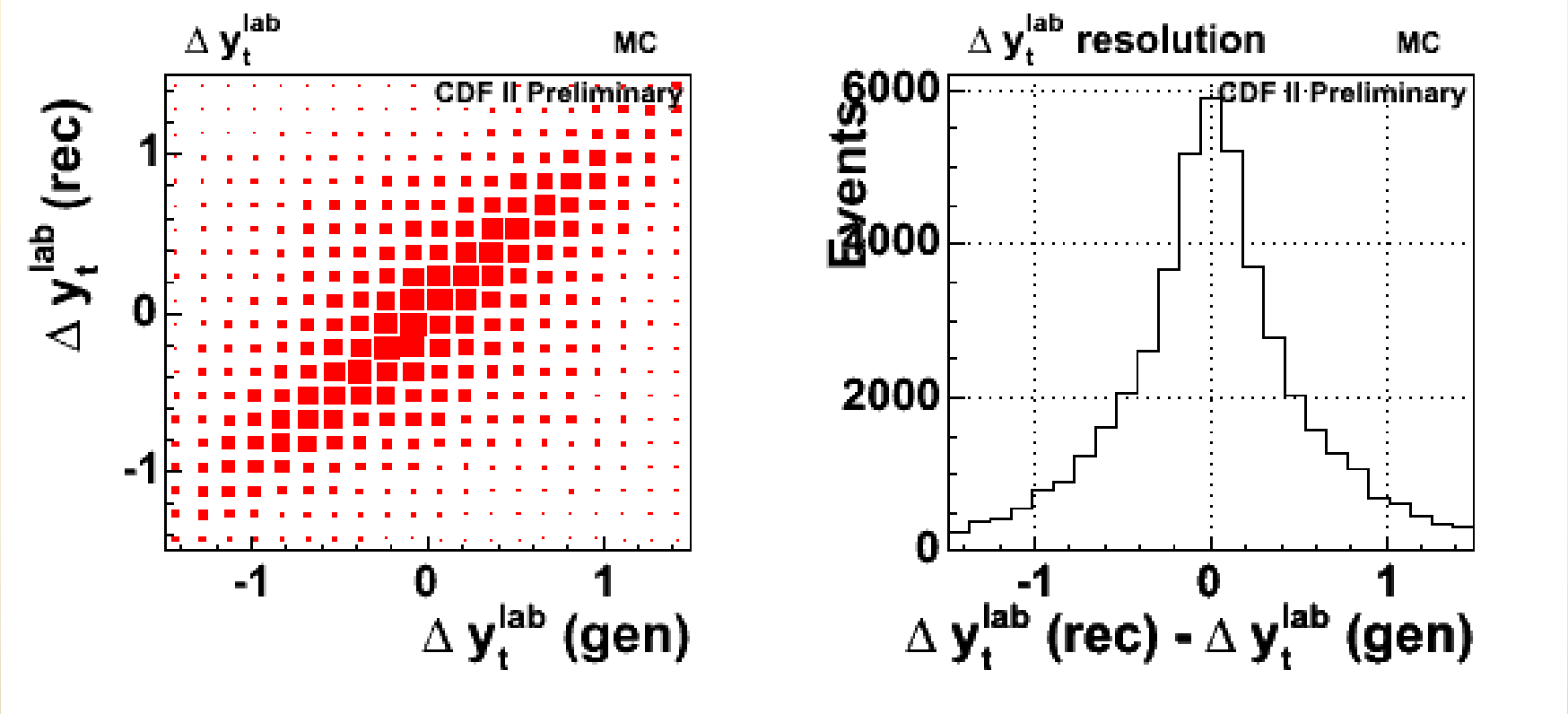
Efficiency

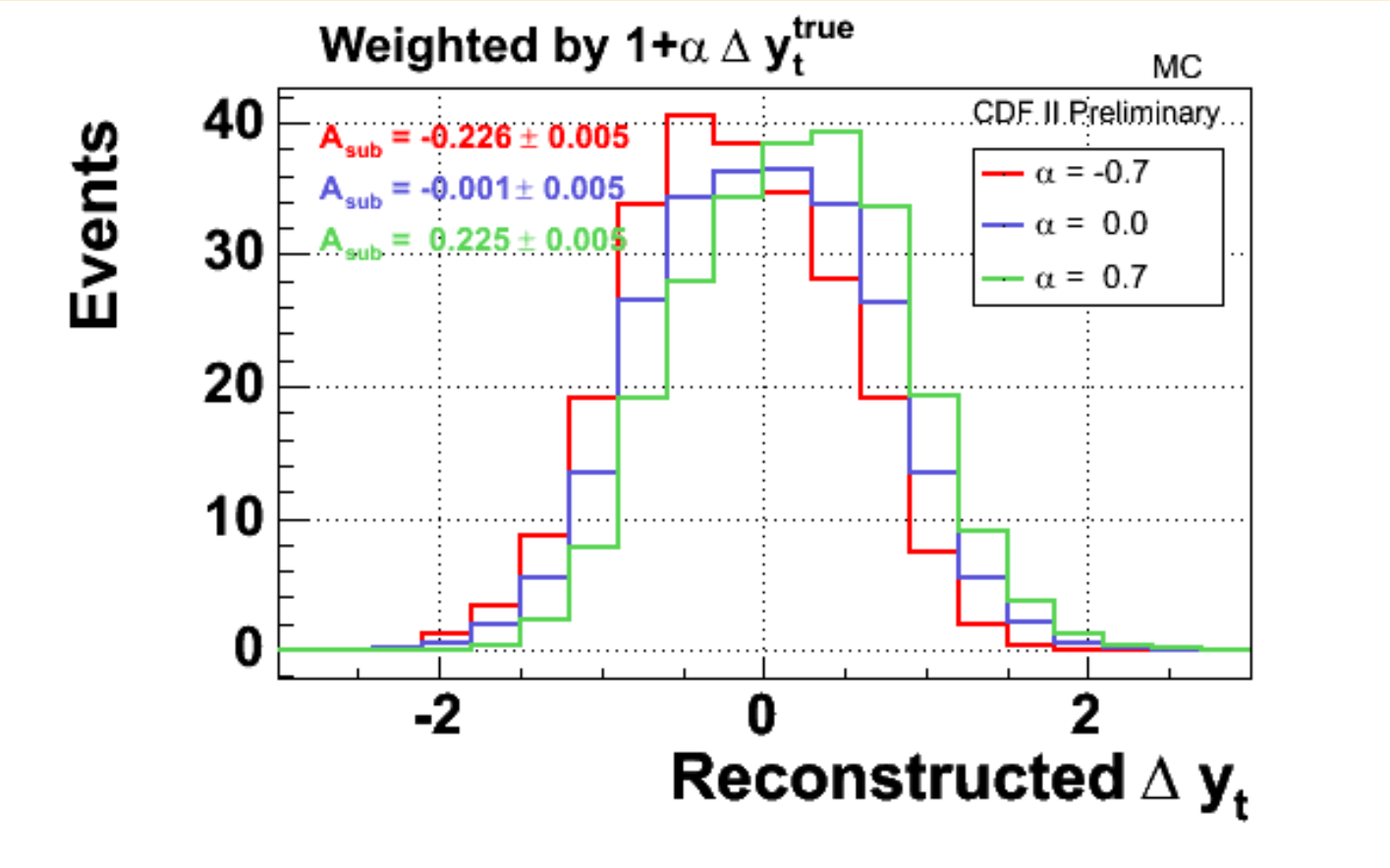


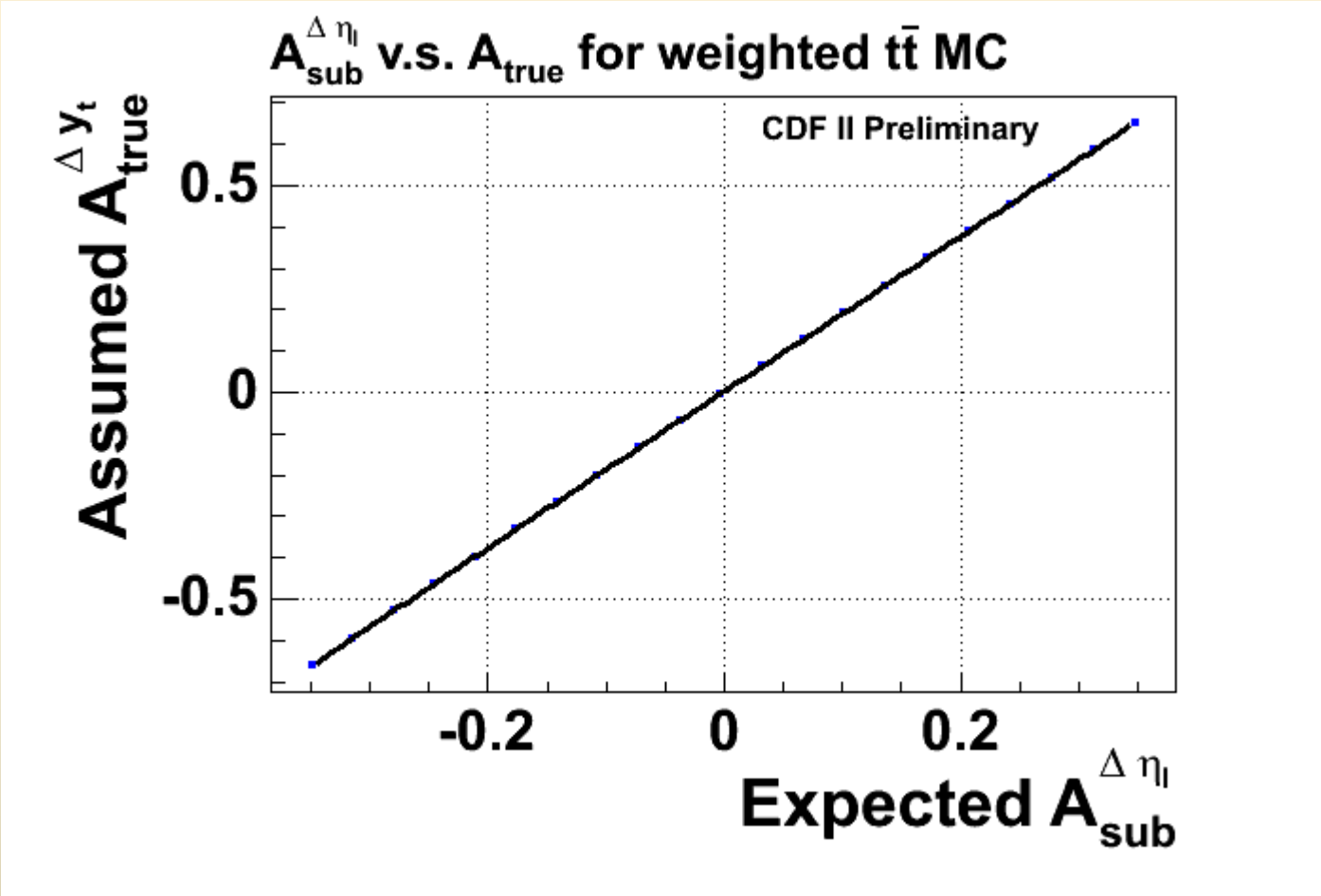
Miss tagging

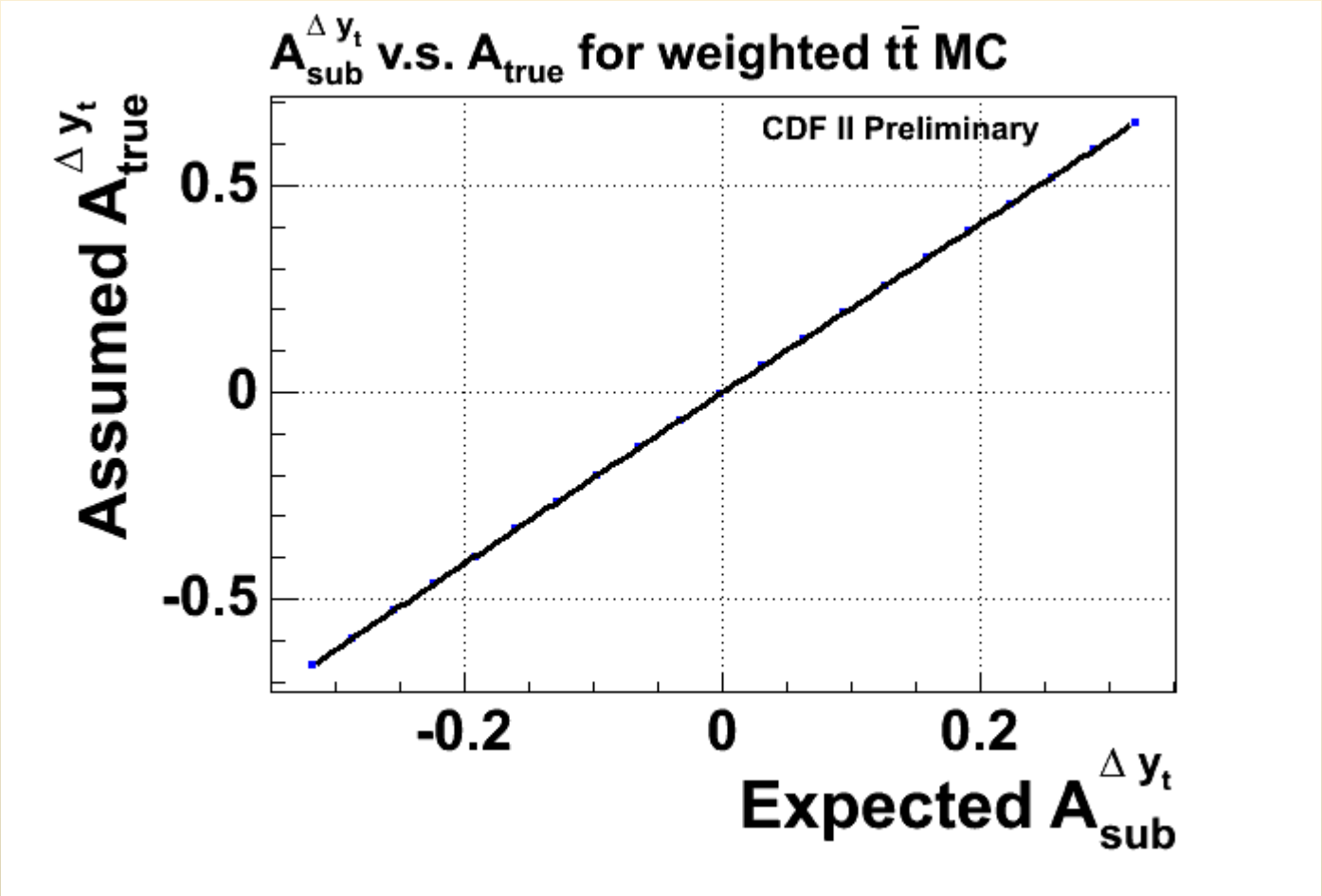



Δy_t^{lab} v.s. $\Delta \eta_l^{lab}$
MC
CDF II Preliminary
$\Delta \eta_l^{lab}$
4
2
0
-2
-4
-2
0
2
Δy_t^{lab}

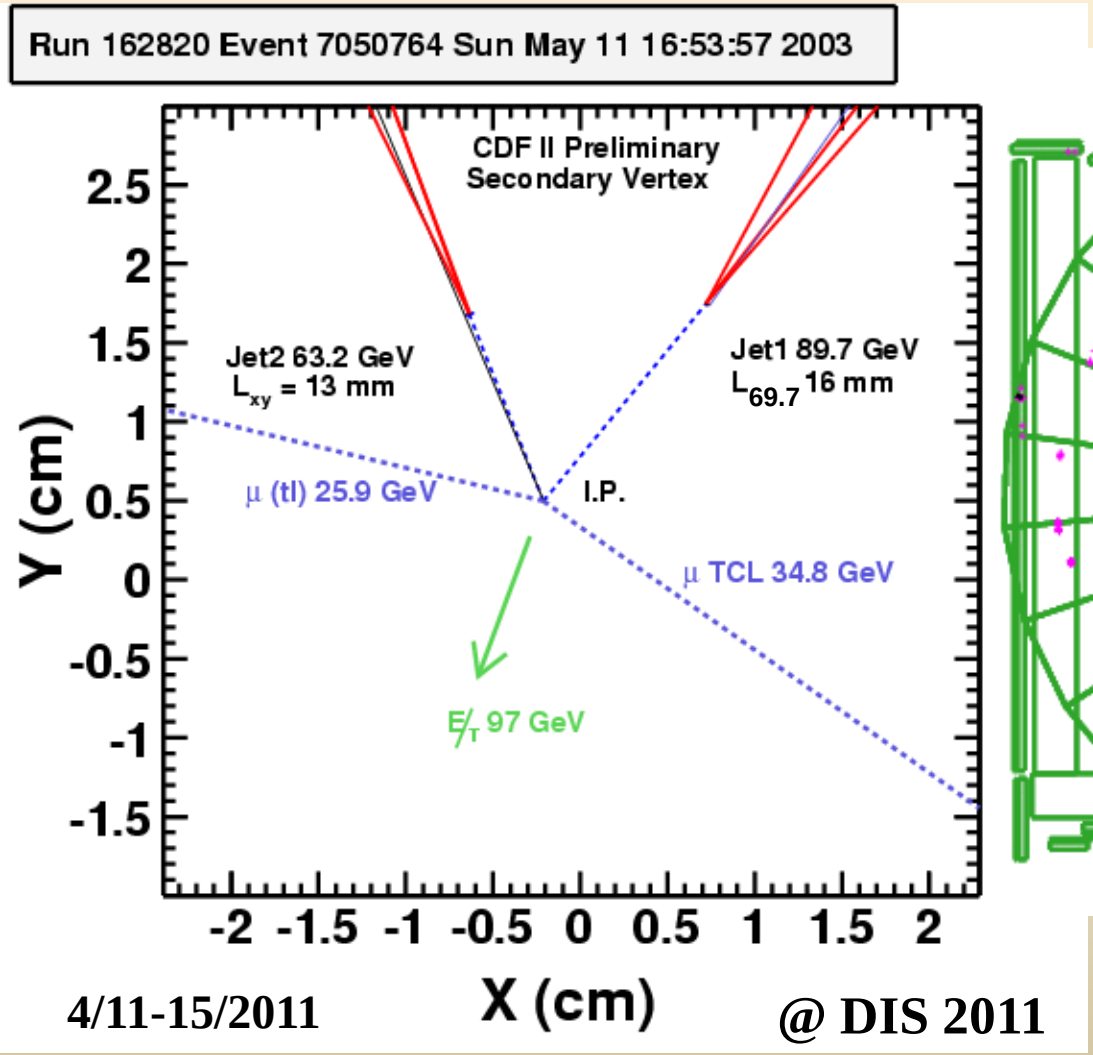

Δy_t^{lab}
MC
CDF II Preliminary
Δy_t^{lab} (rec)
Δy_t^{lab} (gen)
Δy_t^{lab} resolution
MC
CDF II Preliminary
Events
Δy_t^{lab} (rec) - Δy_t^{lab} (gen)

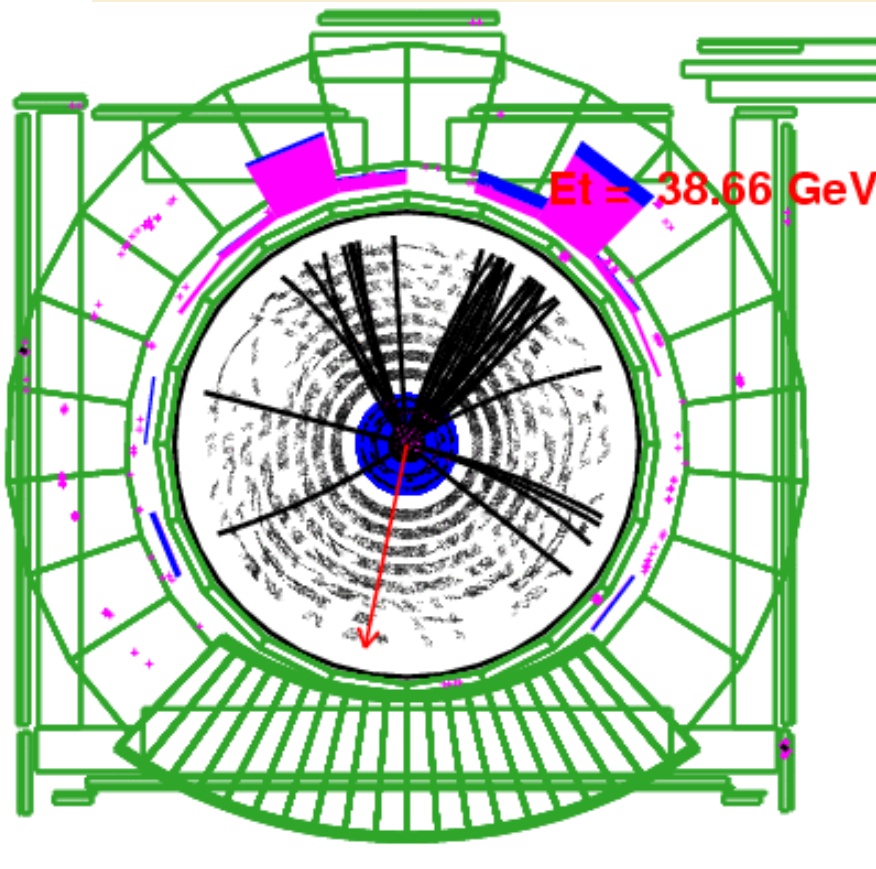
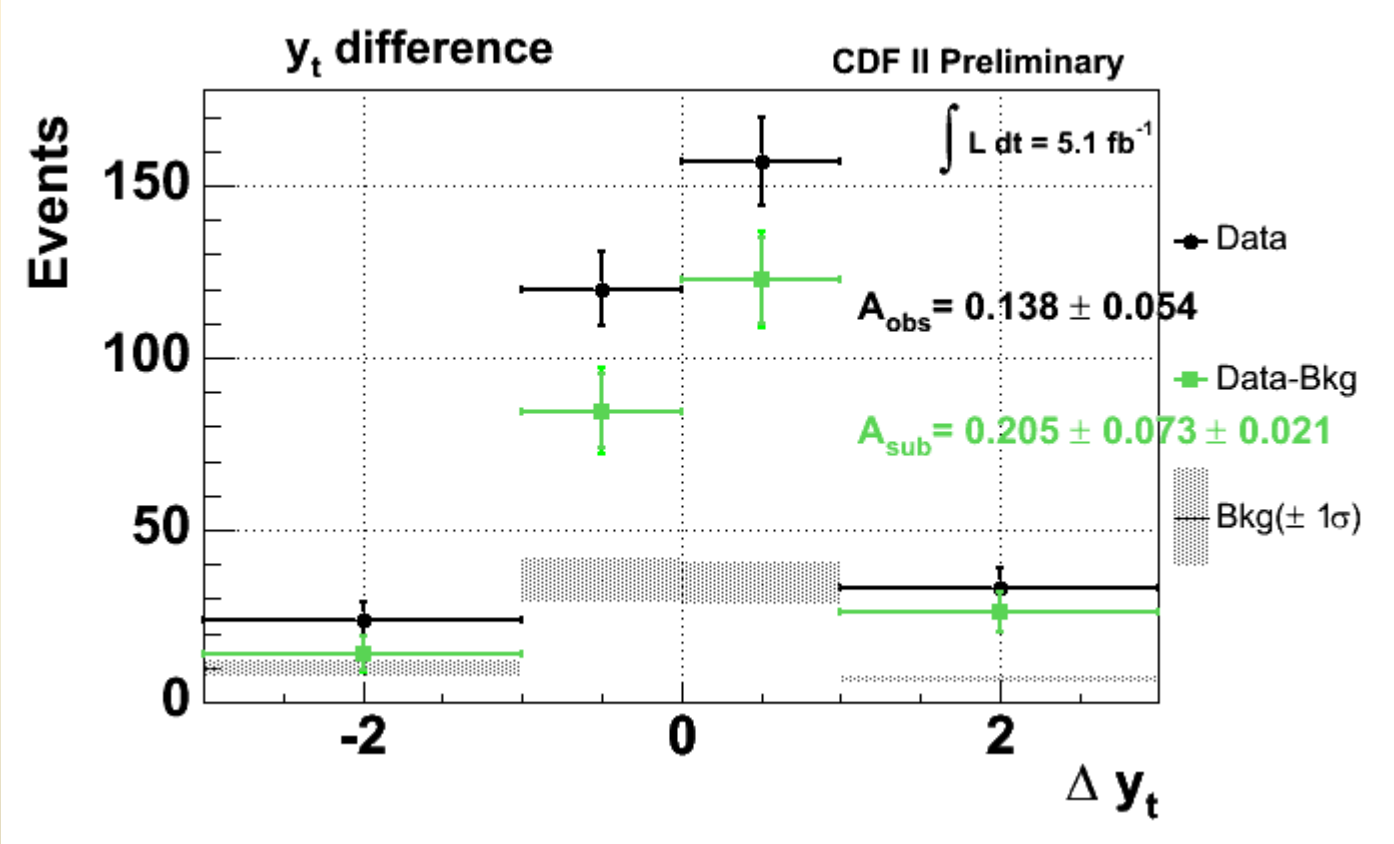

Weighted by 1+α Δ y_t^true
MC
CDF II Preliminary
A_sub = -0.226 ± 0.005
A_sub = -0.001 ± 0.005
A_sub = 0.225 ± 0.005
α = -0.7
α = 0.0
α = 0.7
Events
40
30
20
10
0
-2
0
2
Reconstructed Δ y_t


$A_{sub}^{\Delta\eta_l}$ v.s. A_{true} for weighted $t\bar{t}$ MC
CDF II Preliminary
Assumed $A_{true}^{\Delta y_t}$
0.5
0
-0.5
-0.2
0
0.2
Expected $A_{sub}^{\Delta\eta_l}$


$A_{sub}^{\Delta y_t}$ v.s. A_{true} for weighted $t\bar{t}$ MC
CDF II Preliminary
Assumed $A_{true}^{\Delta y_t}$
0.5
0
-0.5
-0.2
0
0.2
Expected $A_{sub}^{\Delta y_t}$

Top di-lepton event candidate





Background subtracted