Top Quark properties at CDF

Is there production asymmetry?

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Jan. 18, 2011 @ NCTS

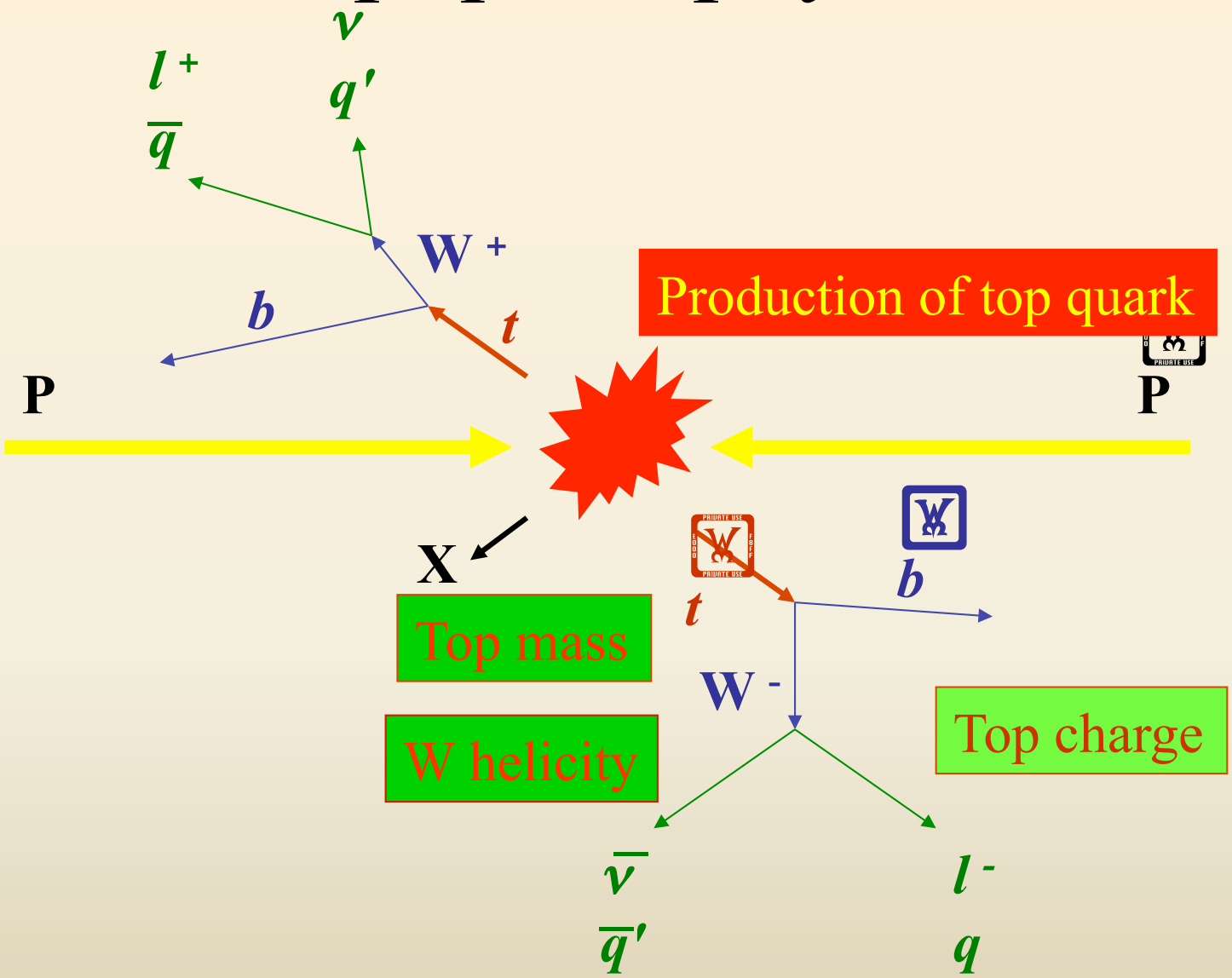
Outline

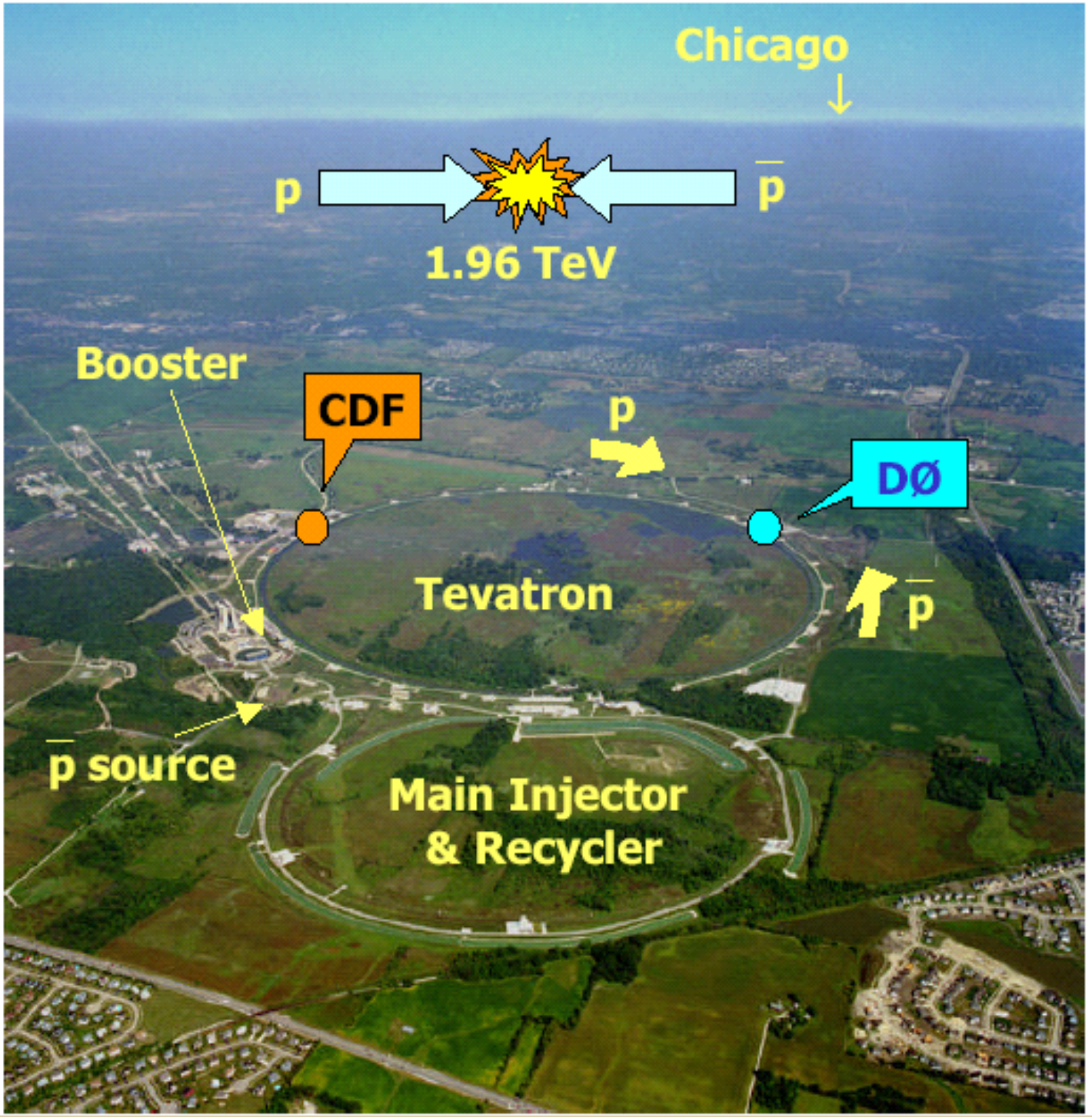
- **The Top quark**
- **The CDF experiment**
- **Top quark production**
- **Top quark properties**
  - **Top quark mass measurement**
    - Implication to Higgs search
  - **W helicity in the top decay**
- **Production asymmetry**
- **Toward the end of TEVATRON**
- **Conclusion**

The Top quark

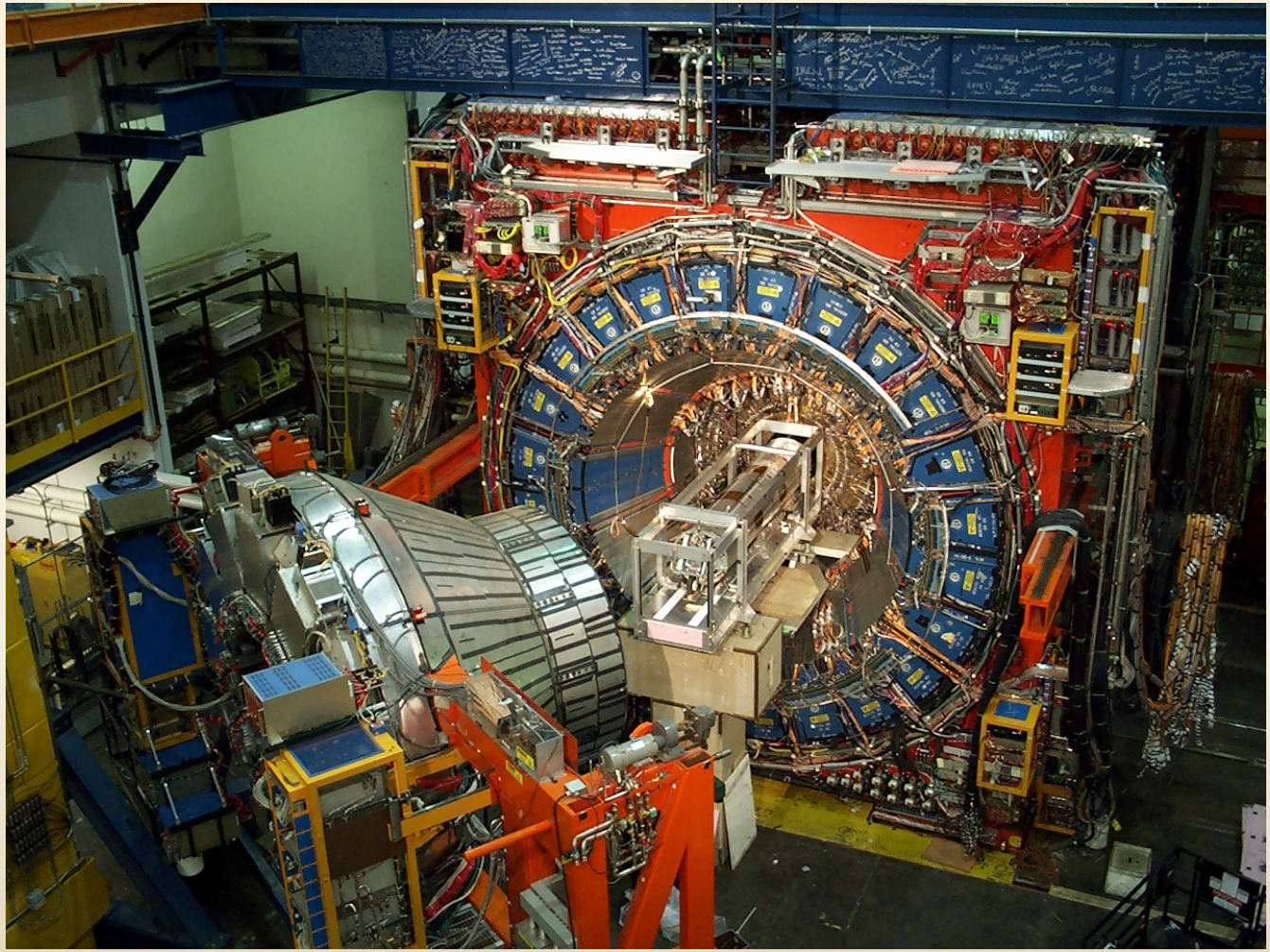
- Properties
  - ➢ Standard Model
    - Charge : + 2/3
    - Spin : 1/2
    - Mass : A free parameter
    - Life time: $\sim 10^{-25}$ s
- Are we seeing the top quark of the Standard Model?
  - ➢ Need to measure the properties!

Top quark physics

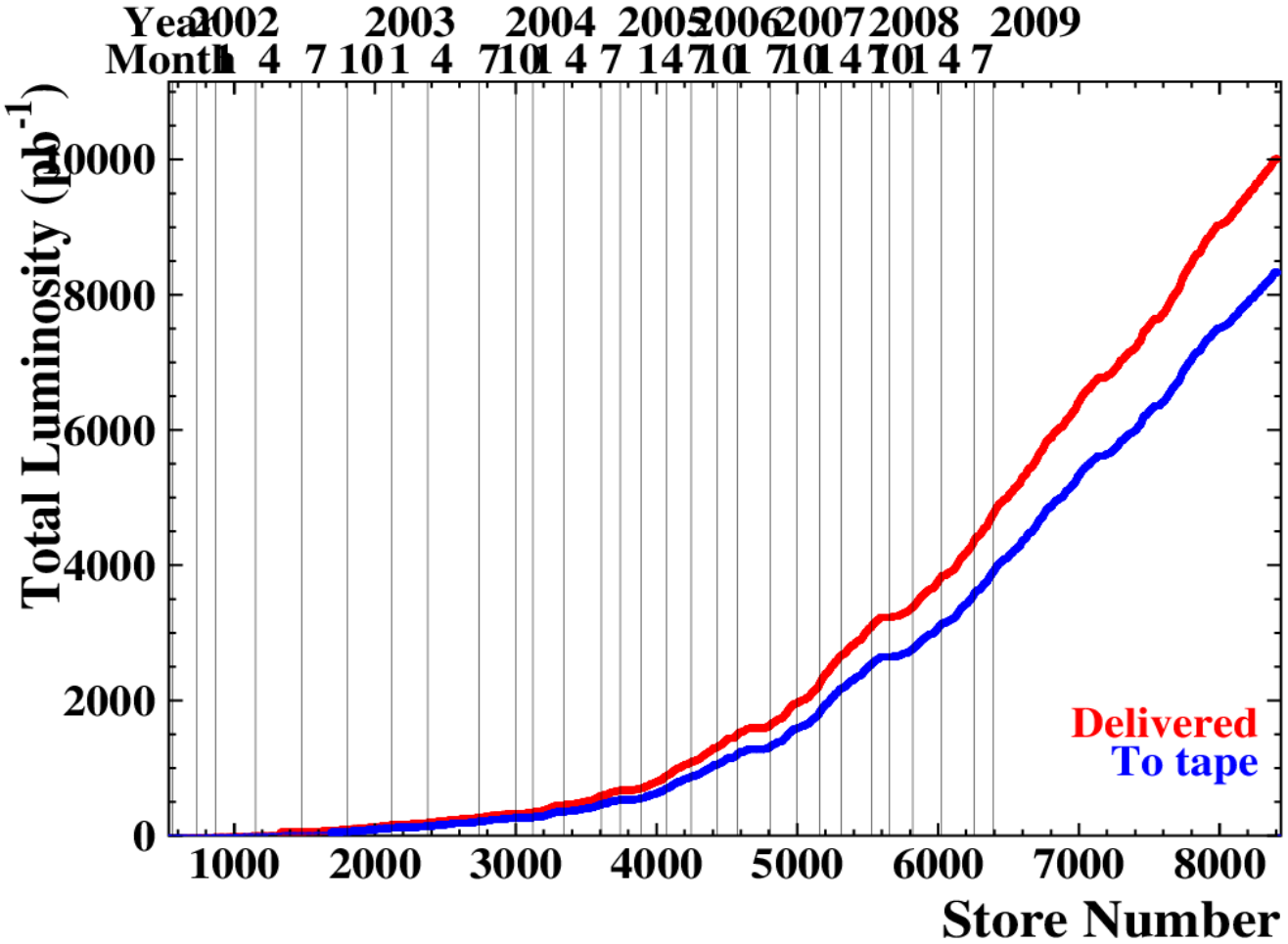



Chicago
p
p̄
1.96 TeV
Booster
CDF
p
DØ
Tevatron
p̄
p̄ source
Main Injector
& Recycler

CDF detector

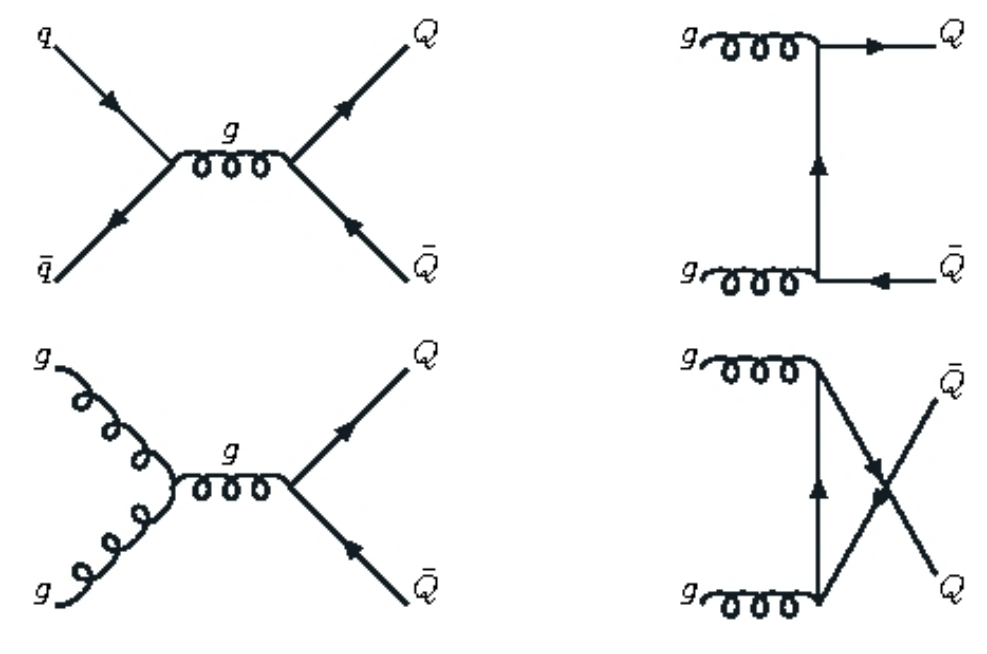


Integrated luminosity



Top quark production

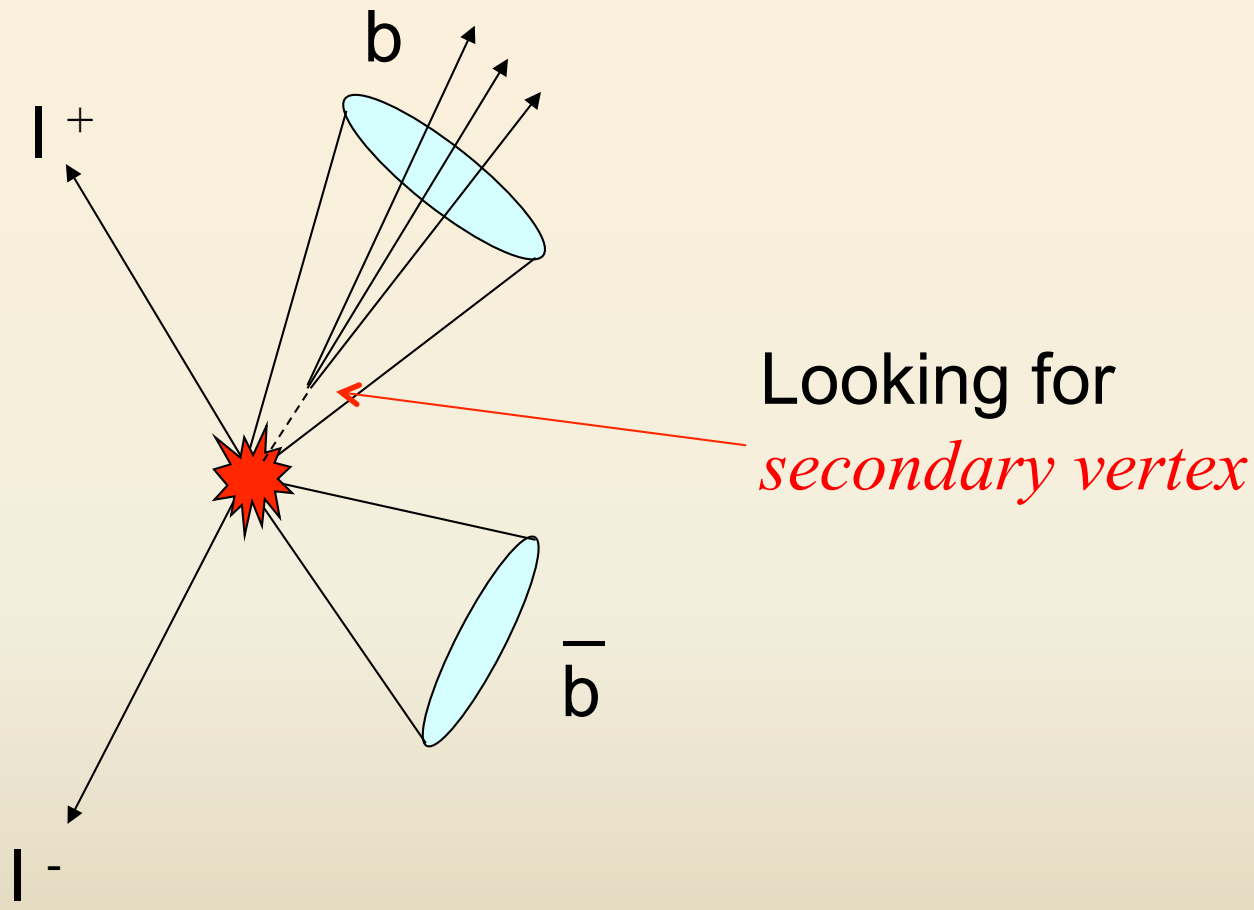
- $p\bar{p} \rightarrow t\bar{t}$
  - $\sigma \sim 6.7$ pb at $\sqrt{S} = 1.96$ TeV:
    - 85% $q\bar{q} \rightarrow t\bar{t}$
    - 15% $gg \rightarrow t\bar{t}$



t t decay modes

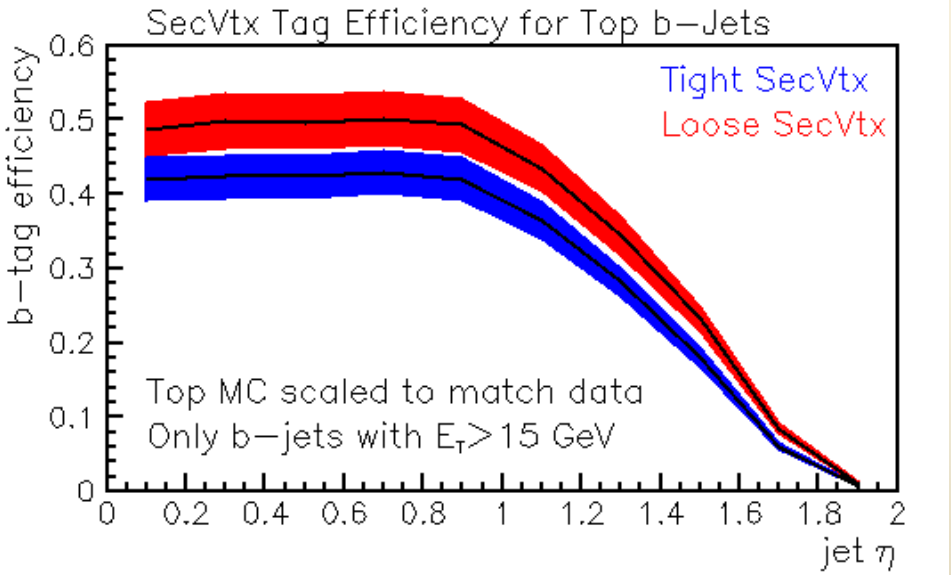
- Di-lepton: $t\,t \rightarrow W^{+}bW^{-}b \rightarrow l^{+}\nu b\, l^{-}\nu b$
  - Two high pt leptons, high missing energy, b-tagging
- Lepton + jet: $t\,t \rightarrow W^{+}bW^{-}b \rightarrow l\nu b\, qqb$
  - One high pt lepton, high missing energy, b-tagging
- All jet: $t\,t \rightarrow W^{+}bW^{-}b \rightarrow qqb\, qqb$
  - b-tagging, number of jets, small missing energy, no high pt lepton, kinematical requirement, etc.

Tagging of b quark jets

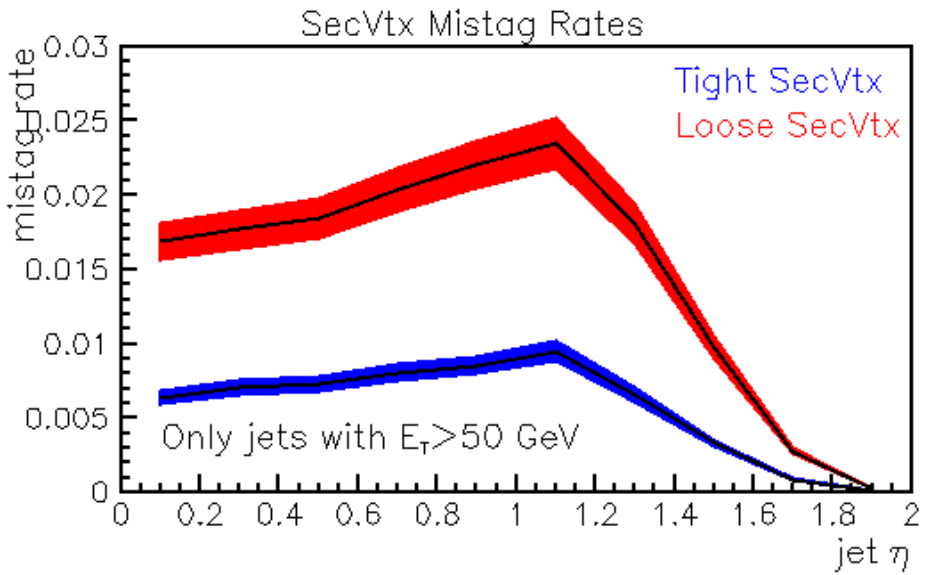


B tagging via Secondary vertex (SVX)

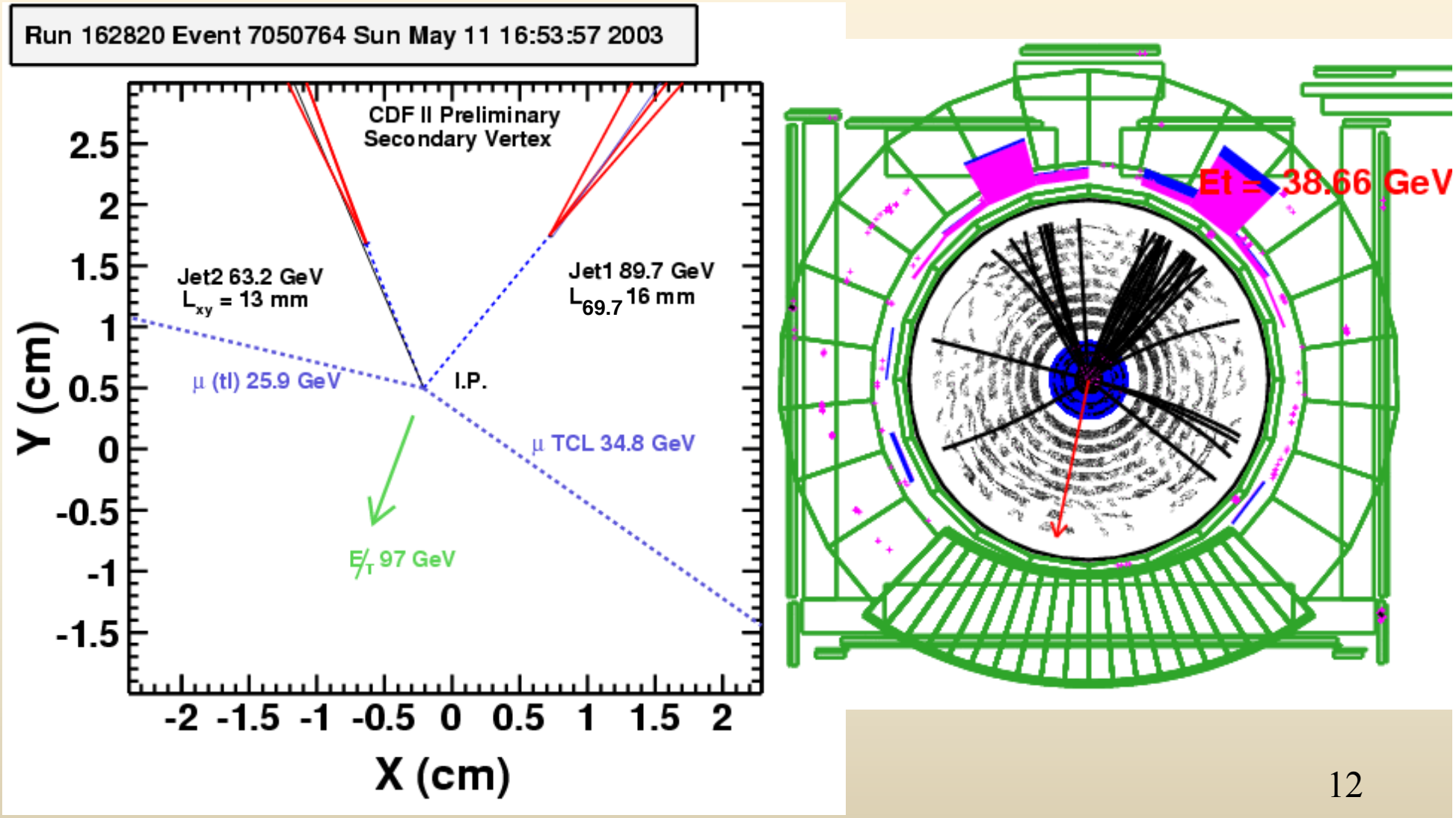
Efficiency



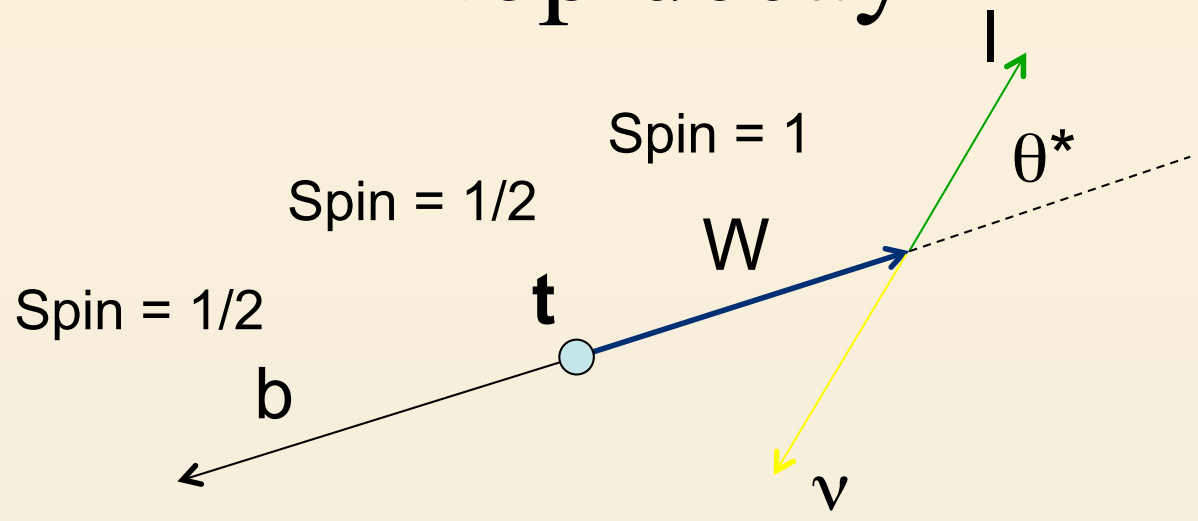
Miss tagging

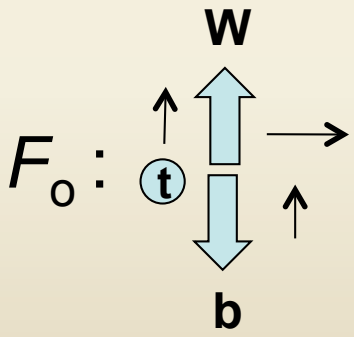


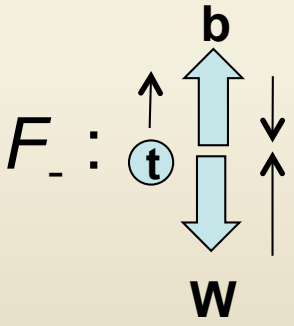
Top di-lepton event candidate

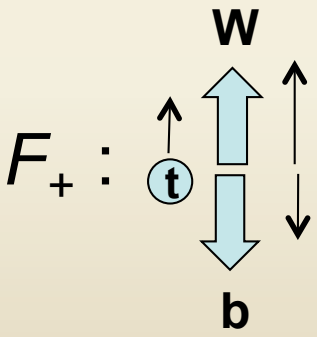


W helicity in the top decay

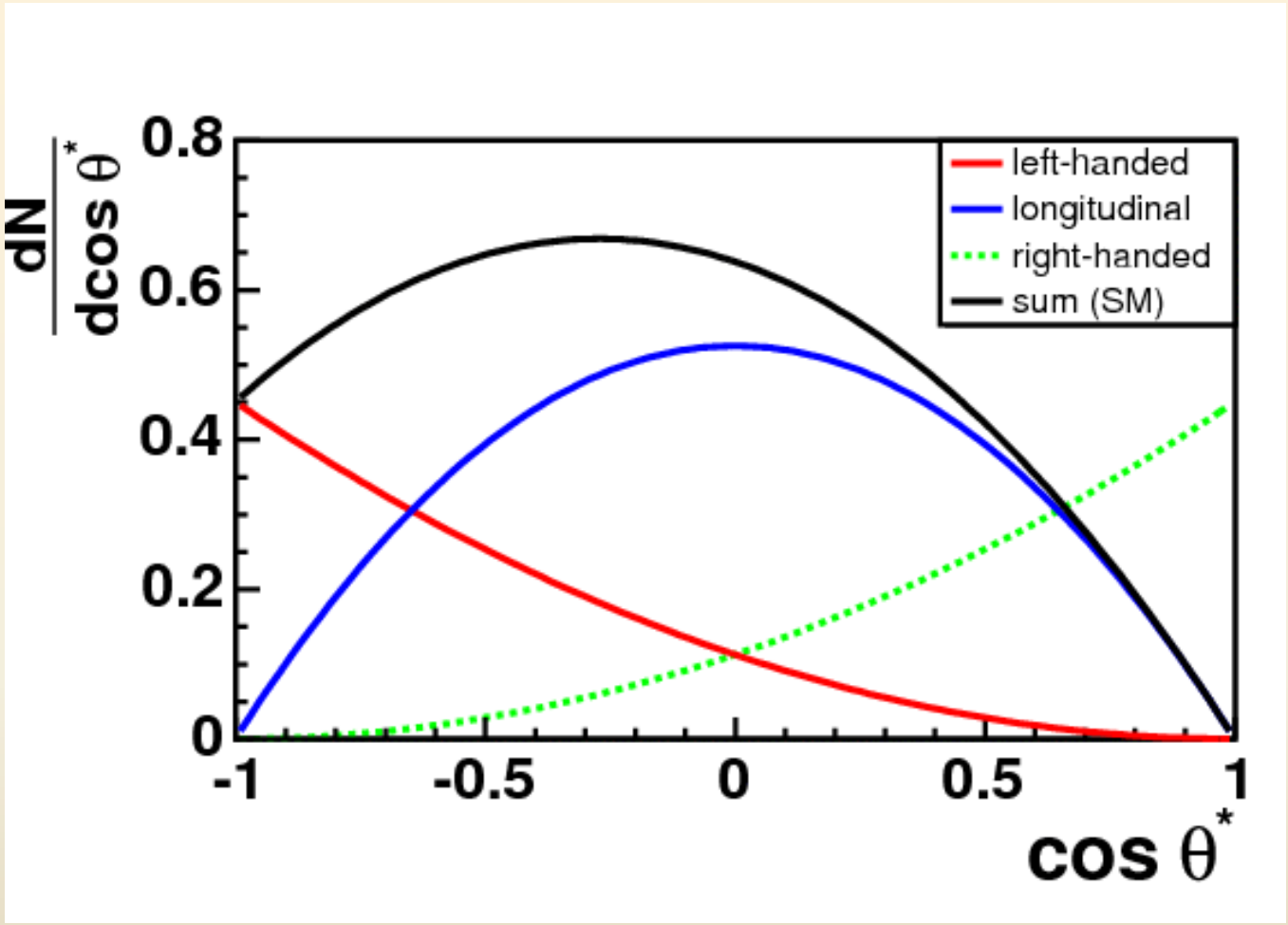




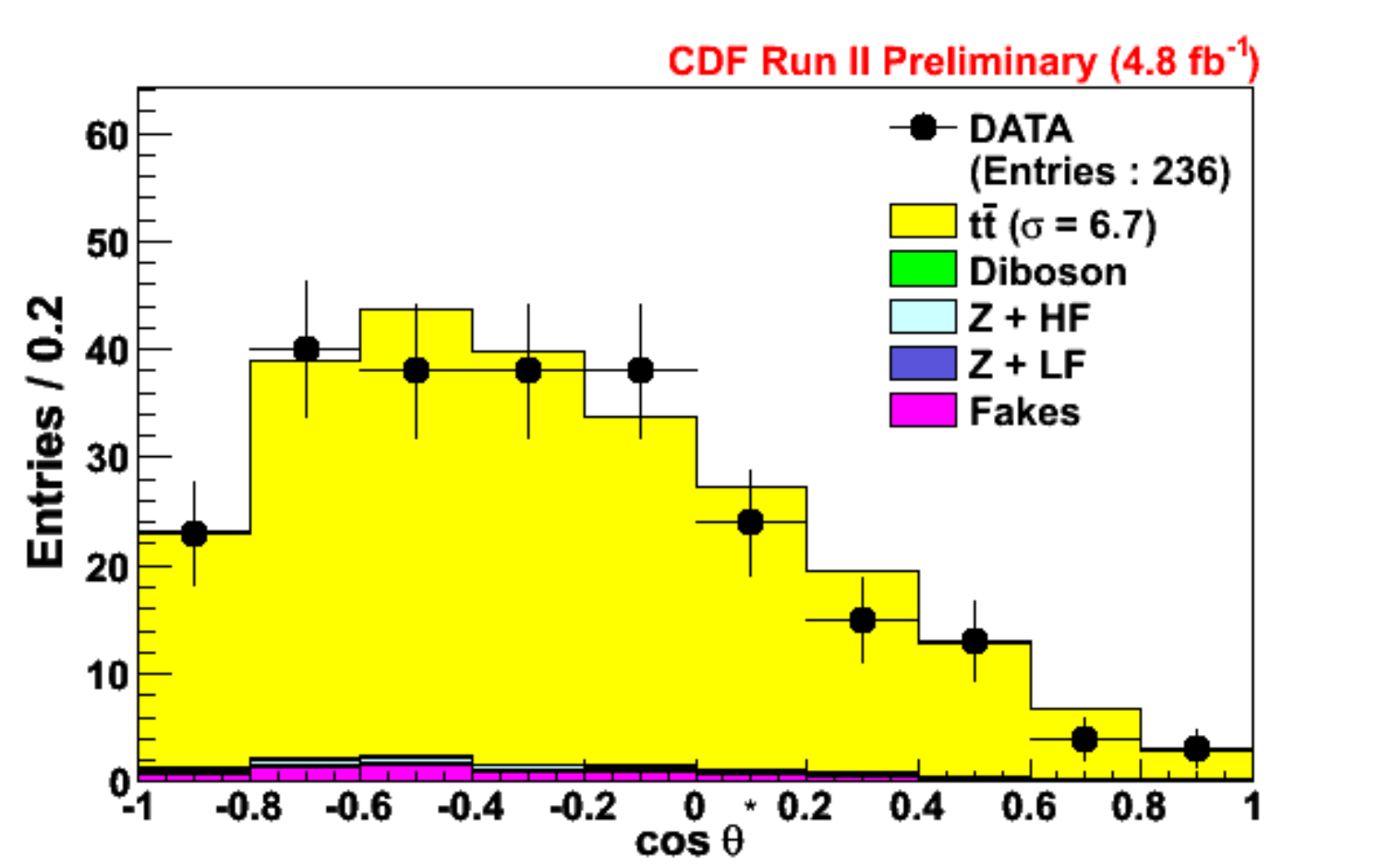


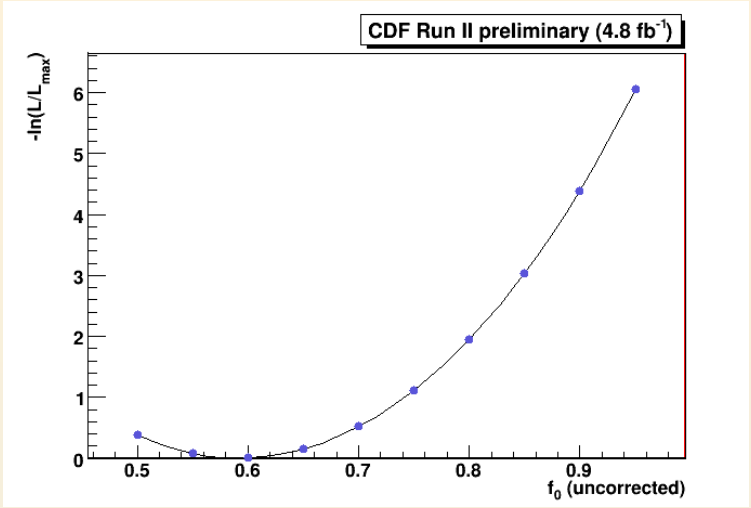


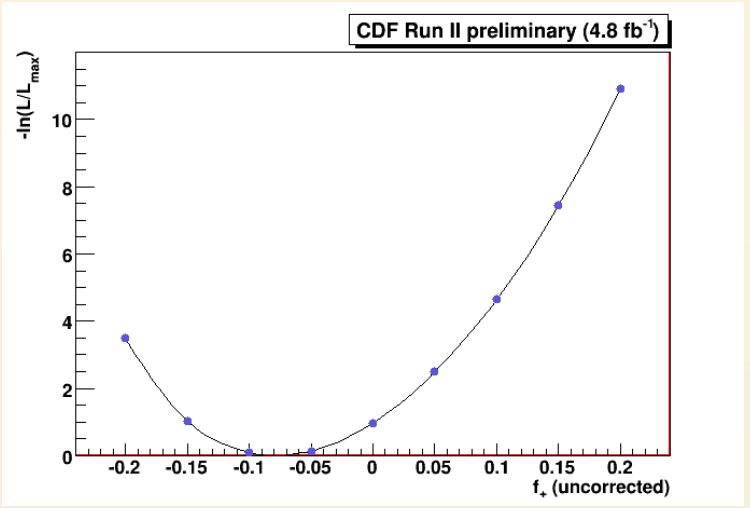
Longitudinal, 70% Left-handed, 30% Right-handed, 0%

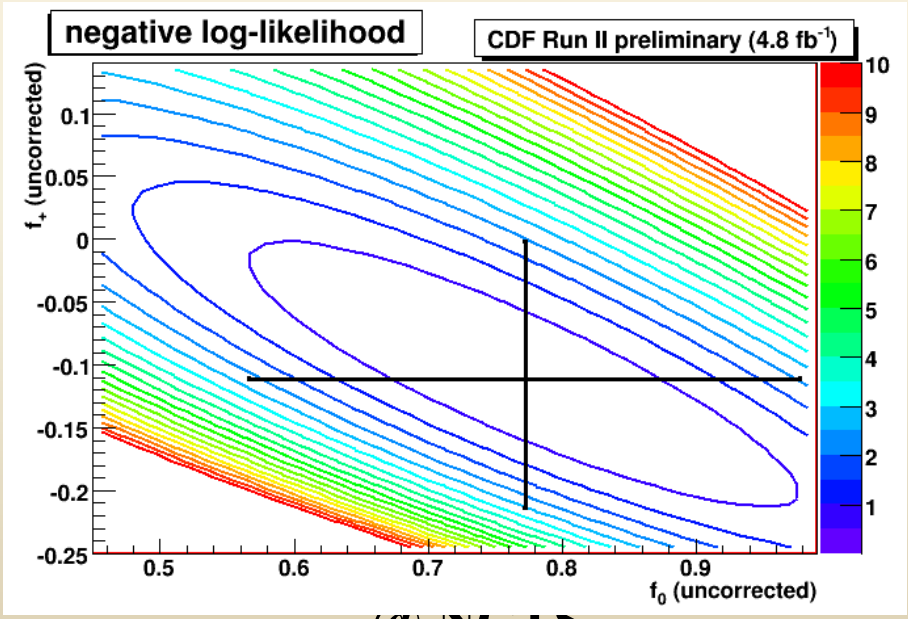

left-handed
longitudinal
right-handed
sum (SM)
dN/dcos θ*
0.8
0.6
0.4
0.2
0
-1
-0.5
0
0.5
1
cos θ*

W helicity
b tagged sample




CDF Run II preliminary (4.8 fb^{-1})
-ln(L/L$_{max}$)
f$_0$ (uncorrected)


CDF Run II preliminary (4.8 fb^{-1})
-ln(L/L$_{max}$)
f$_+$ (uncorrected)


negative log-likelihood
CDF Run II preliminary (4.8 fb^{-1})
f$_+$ (uncorrected)
f$_0$ (uncorrected)

1-parameter fit:

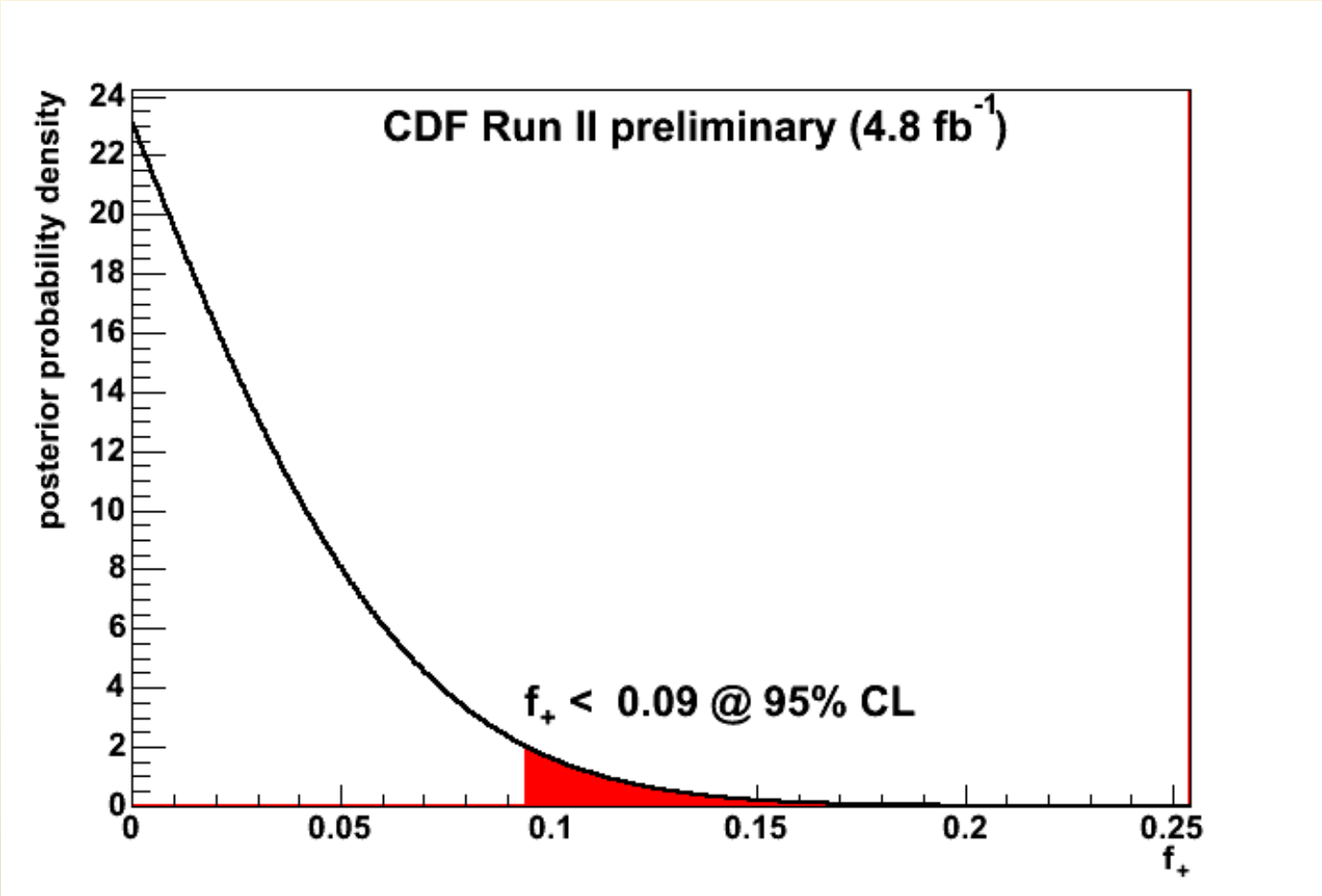
$F_0 = 0.62 \pm 0.11(\text{stat}) \pm 0.06(\text{syst})$

$F_+ = -0.07\ ^{+0.06}_{-0.05}\ (\text{stat}) \pm 0.03(\text{syst})$

2-parameter fit:

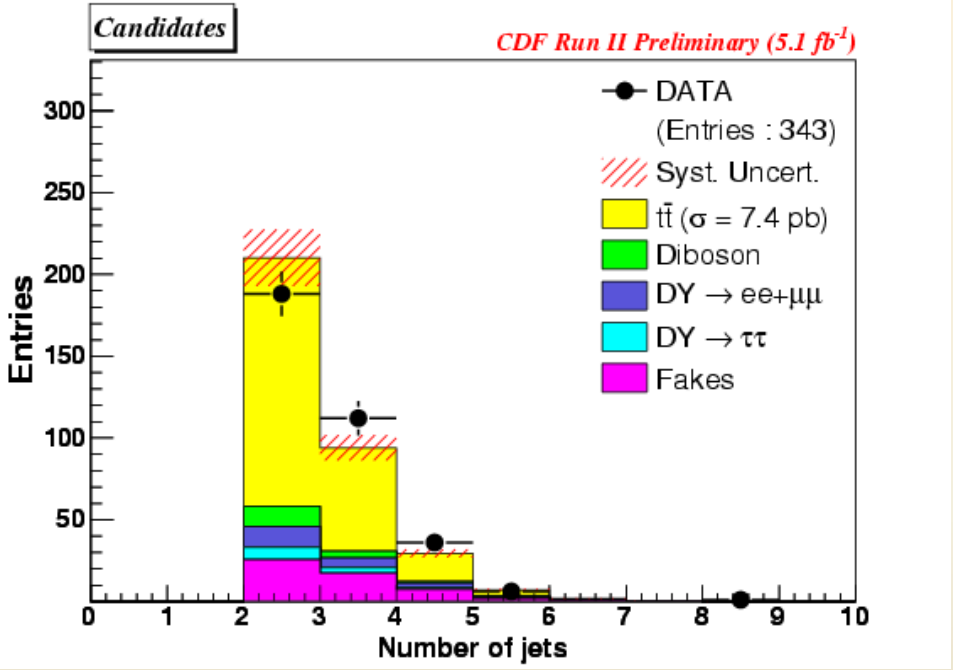
$F_0 = 0.78\ ^{+0.19}_{-0.20}\ (\text{stat}) \pm 0.06\ (\text{syst})$

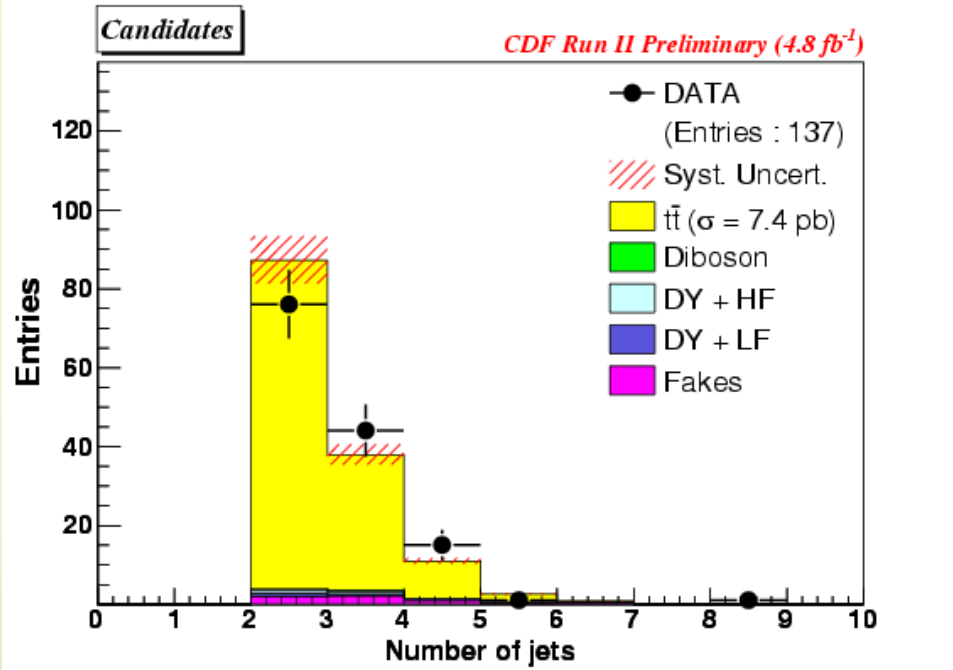
$F_+ = -0.11\ ^{+0.11}_{-0.10}\ (\text{stat}) \pm 0.04(\text{syst})$


CDF Run II preliminary (4.8 fb^{-1})
posterior probability density
$f_+ < 0.09$ @ 95% CL
f_+
0
2
4
6
8
10
12
14
16
18
20
22
24
0
0.05
0.1
0.15
0.2
0.25

Cross section using Di-lepton events

Blessed at 5/23/2010

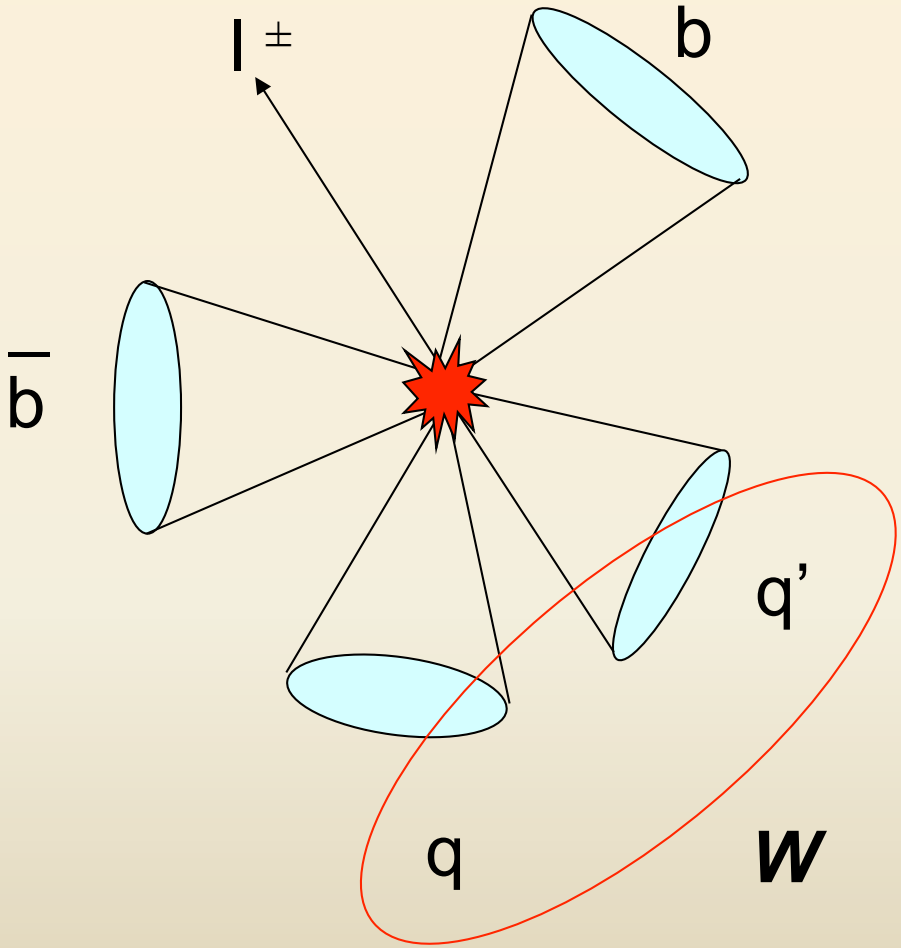




$\sigma_{pretag} = 7.40 \pm 0.58_{stat} \pm 0.63_{syst} \pm 0.45_{lumi}$ pb

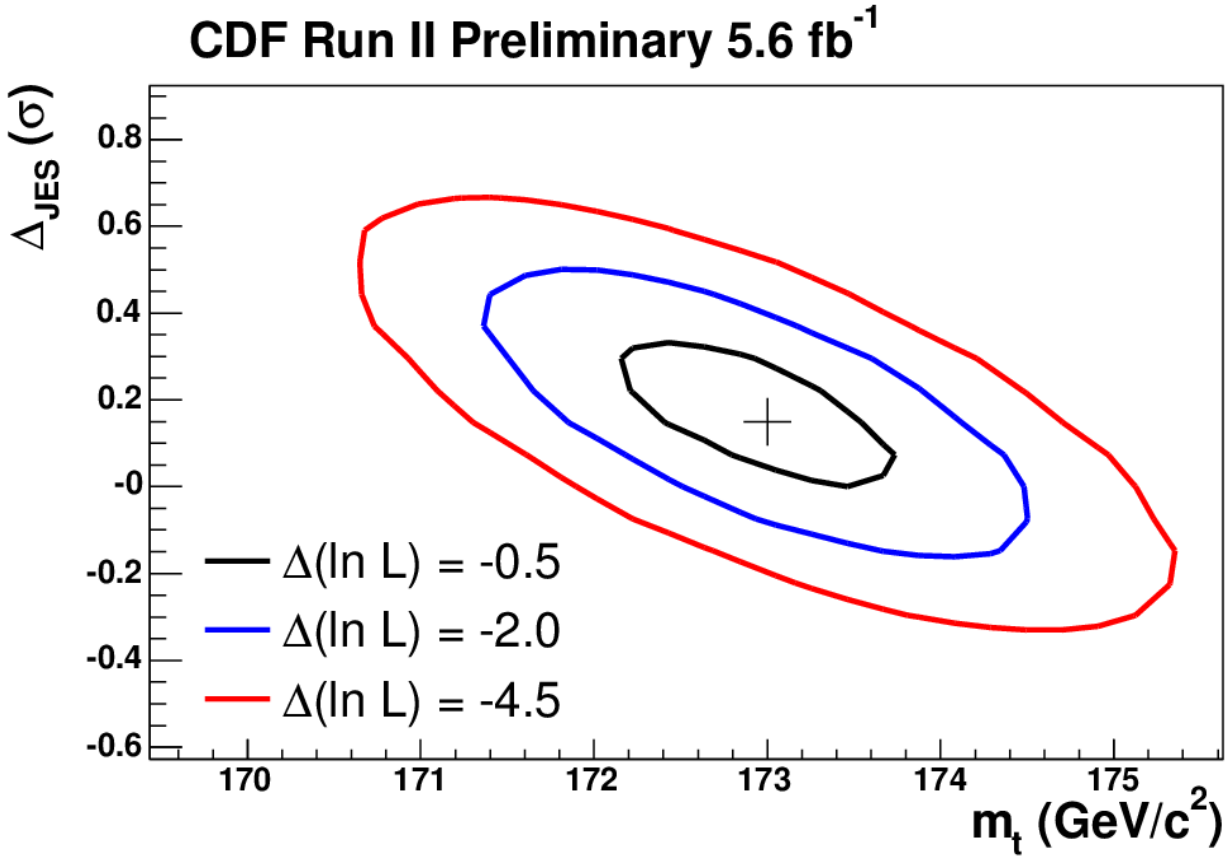
$\sigma_{btag} = 7.25 \pm 0.66_{stat} \pm 0.47_{syst} \pm 0.44_{lumi}$ pb

Top mass
using lepton + jets events



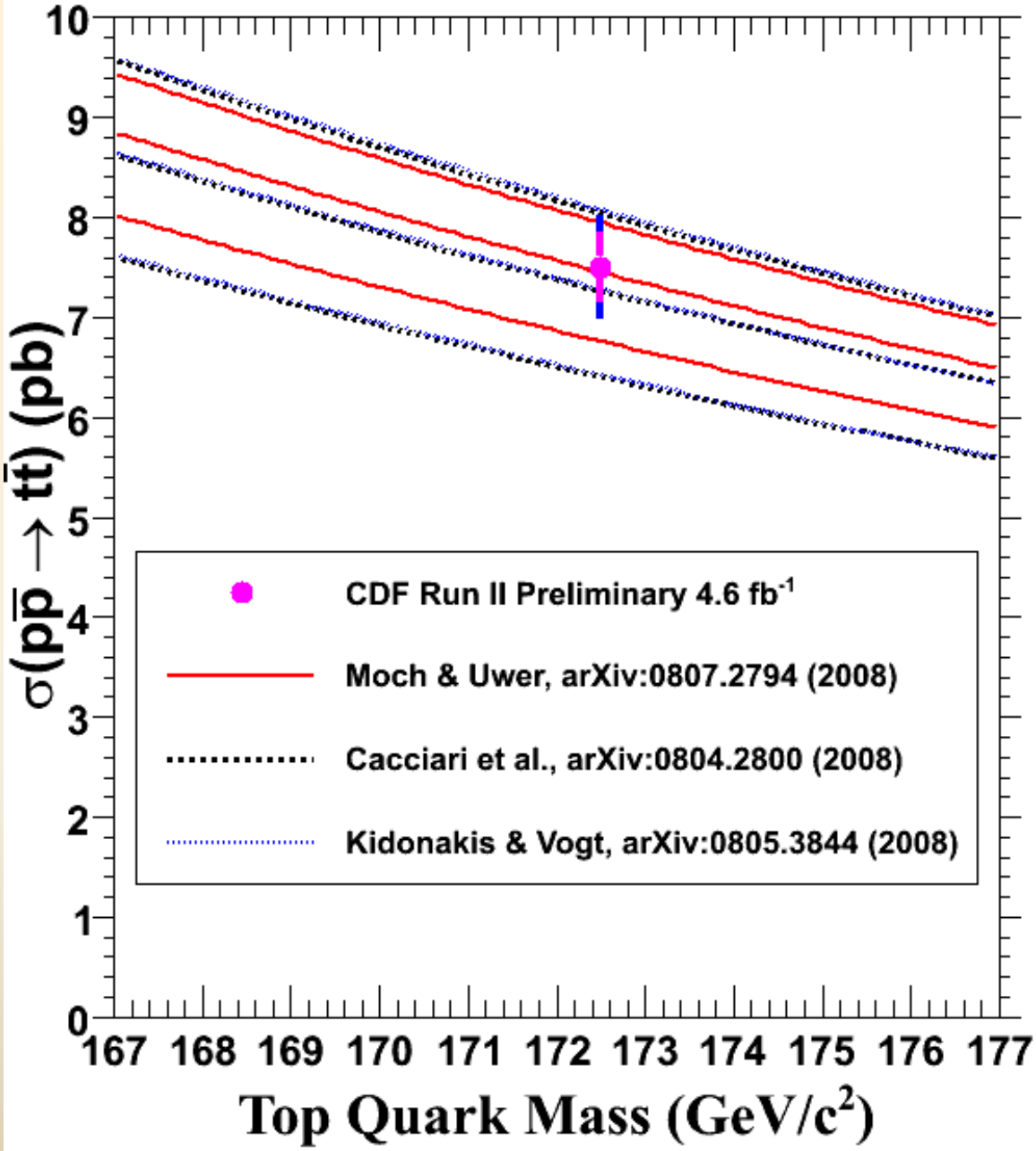
Constrained to ***W*** boson mass
→ update the jet energy scale

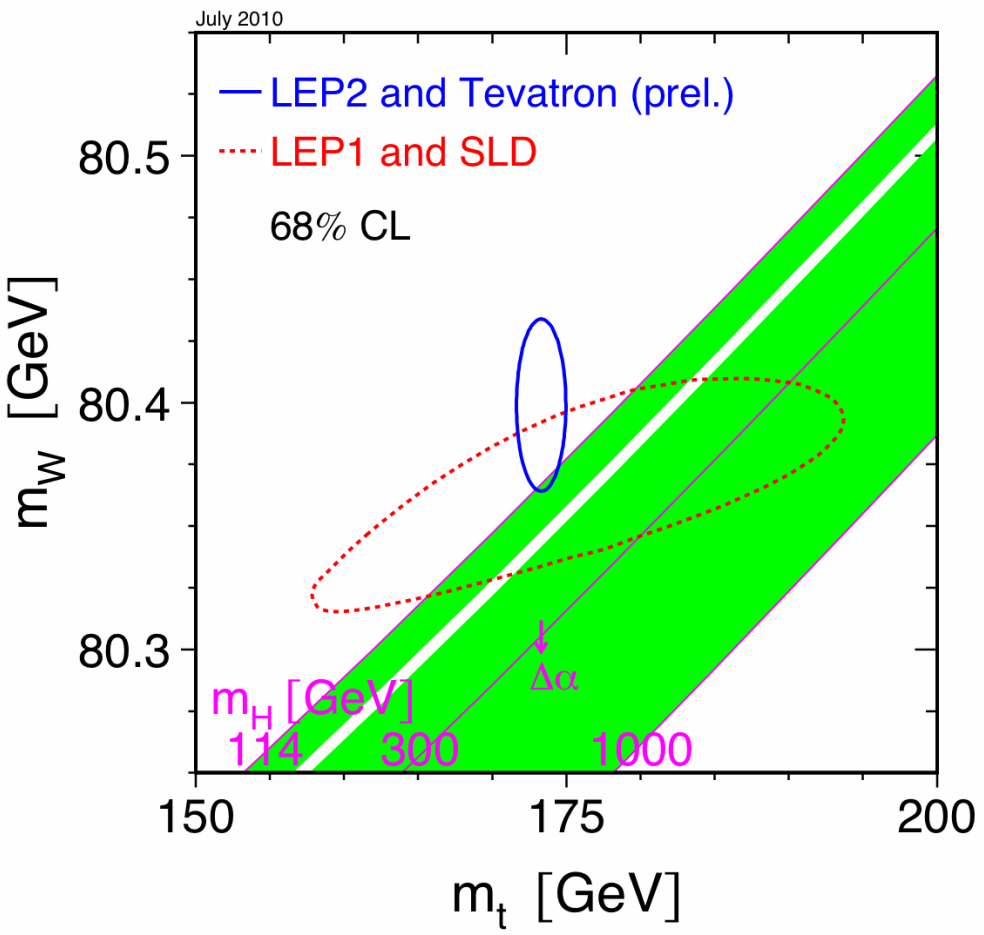
Top mass



m_t = 173.0 ± 0.7 (stat.) ± 0.6 (JES) ± 0.9 (syst.) GeV/c^2

= 173.0 ± 1.2 (total) GeV/c^2


$\sigma(p\bar{p} \rightarrow t\bar{t})$ (pb)
Top Quark Mass (GeV/c^2)
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)
0
1
2
3
4
5
6
7
8
9
10
167
168
169
170
171
172
173
174
175
176
177



Strong indication of low mass Higgs!

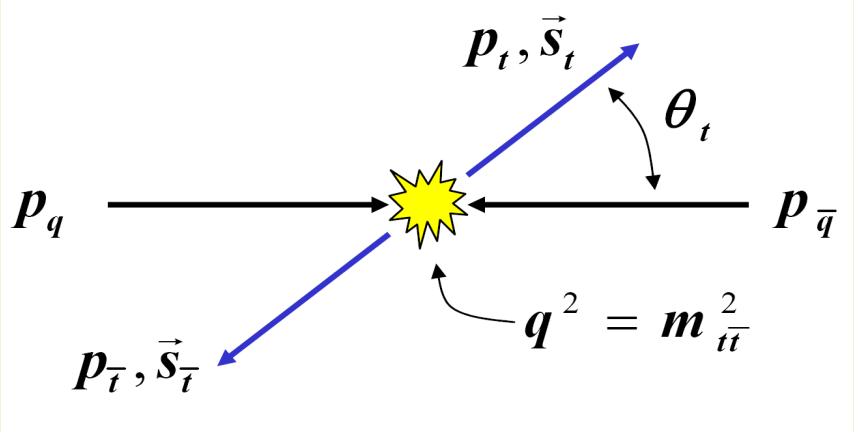
So far so good …

But that is not all …

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.

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
- Asymmetry with respect to beamline

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}

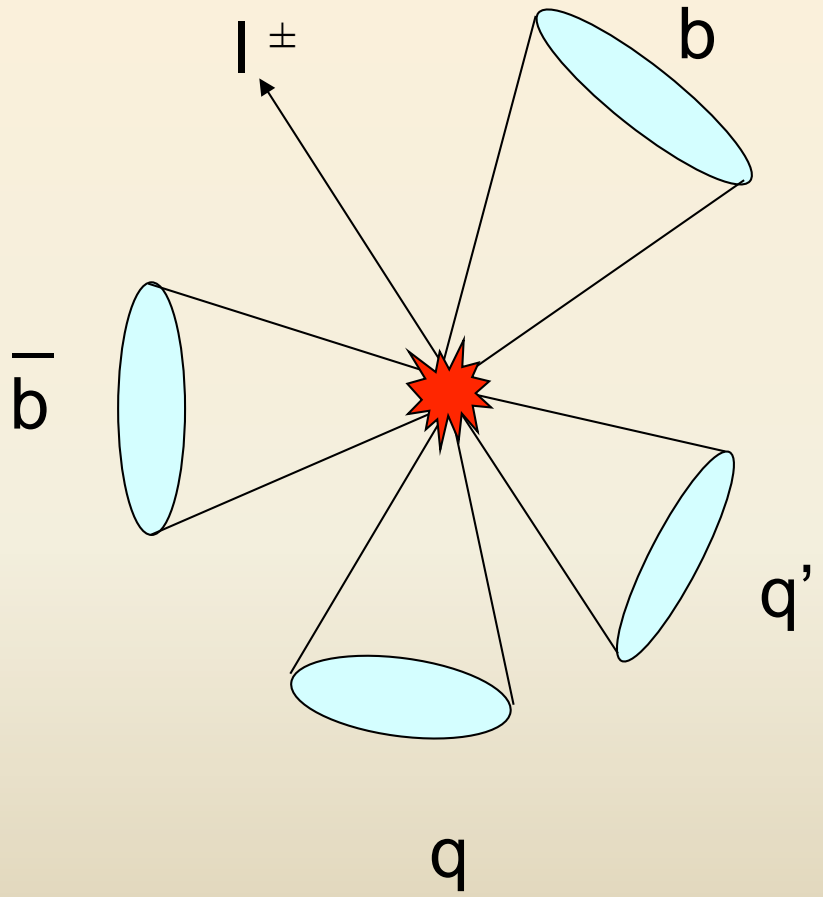
    ICHEP 2010

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

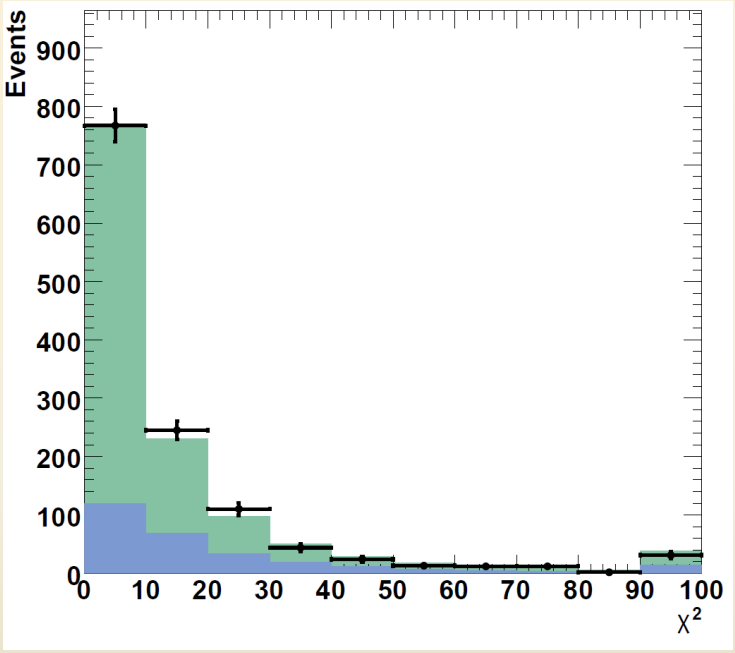
Top reconstruction

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

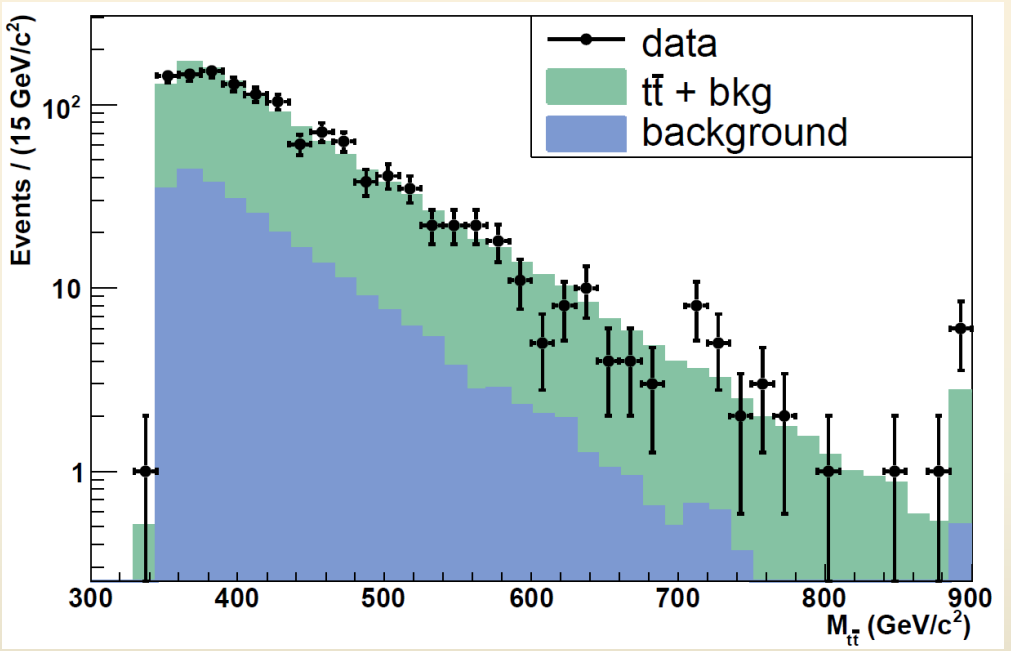
$$\frac{\left(M_{jj} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(M_{l\nu} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(M_{bjj} - M_{top}\right)^2}{\Gamma_t^2} + \frac{\left(M_{blv} - M_{top}\right)^2}{\Gamma_t^2}$$

Top reconstruction

χ^2



$M_{t\bar{t}}$

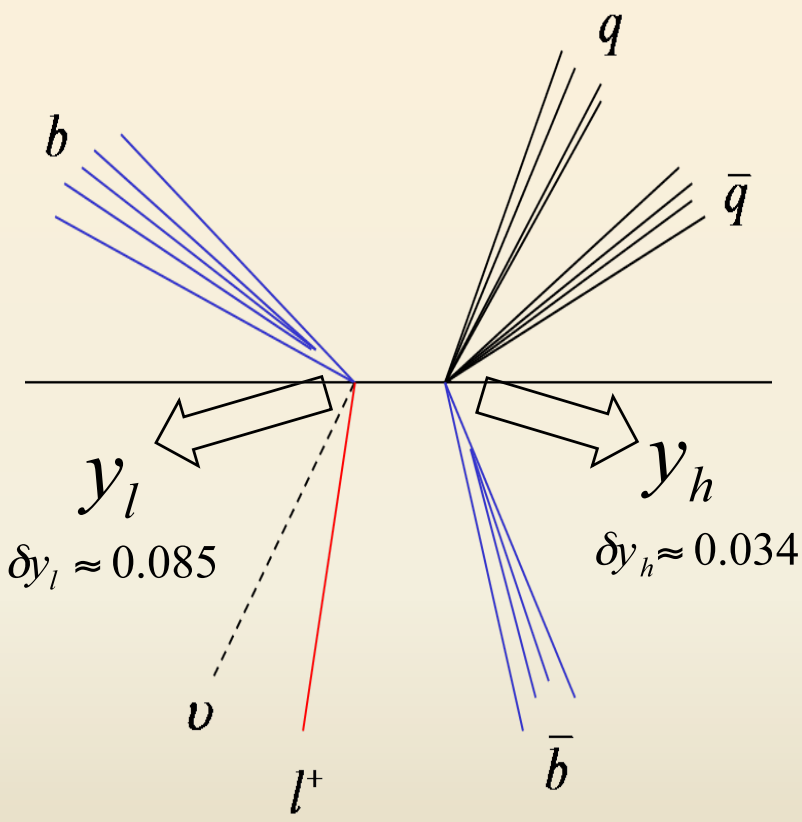


Top reconstruction

- 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

- 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, $\delta\Delta y \approx 0.100$

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

Lab frame asymmetry

$$-q \cdot y_h$$

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

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

tt rest frame asymmetry

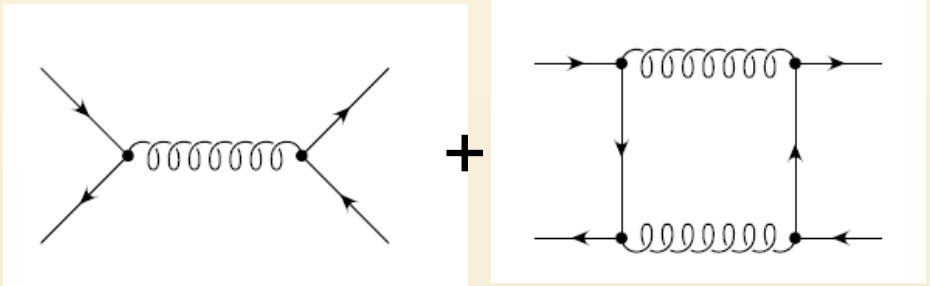
$$\Delta y_{tt}$$

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

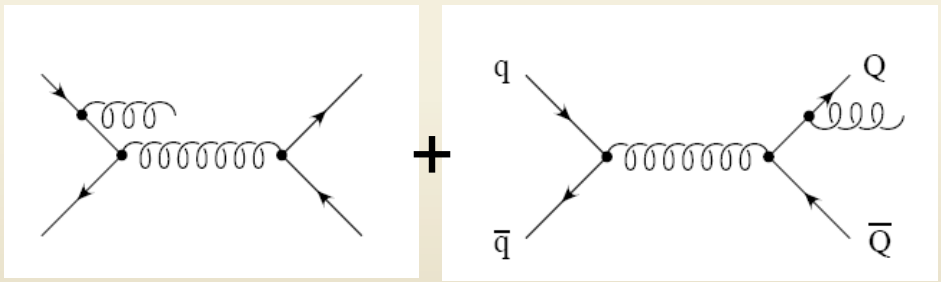
$$= \frac{N(y_t^{t\bar{t}} > 0) - N(y_t^{t\bar{t}} < 0)}{N(y_t^{t\bar{t}} > 0) + N(y_t^{t\bar{t}} < 0)}$$

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

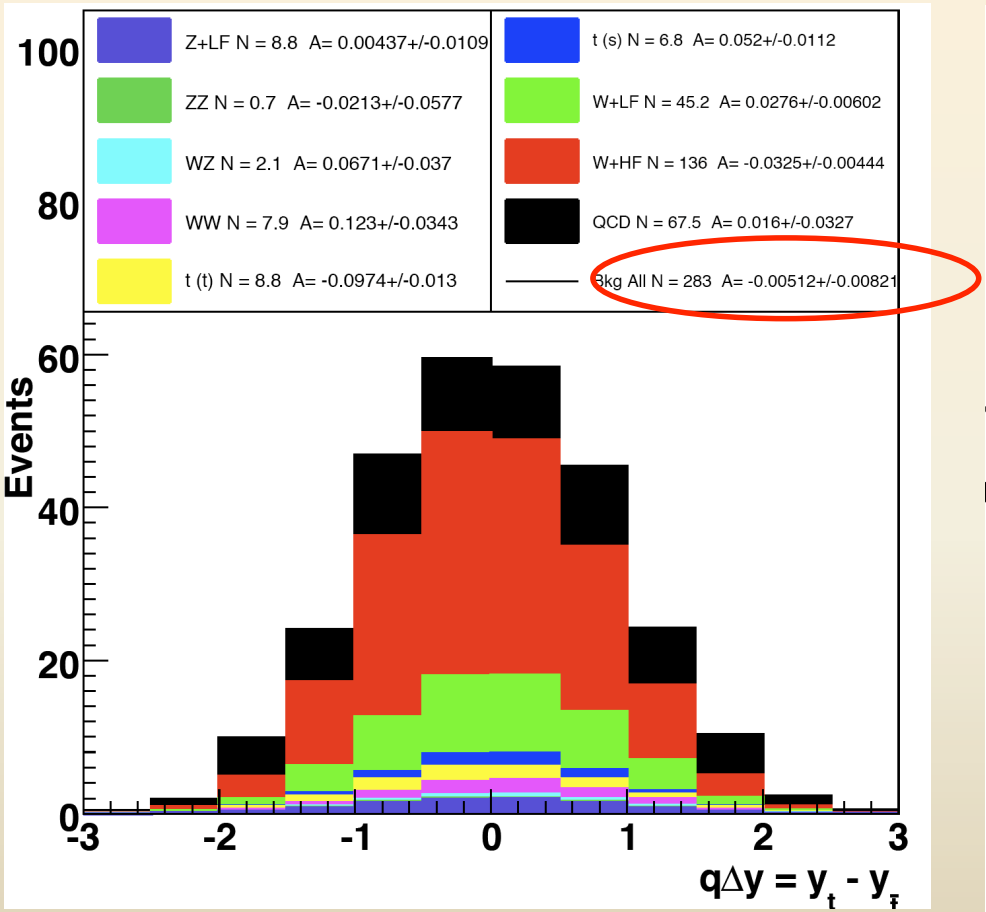
sim + reco

sim + reco +bkg

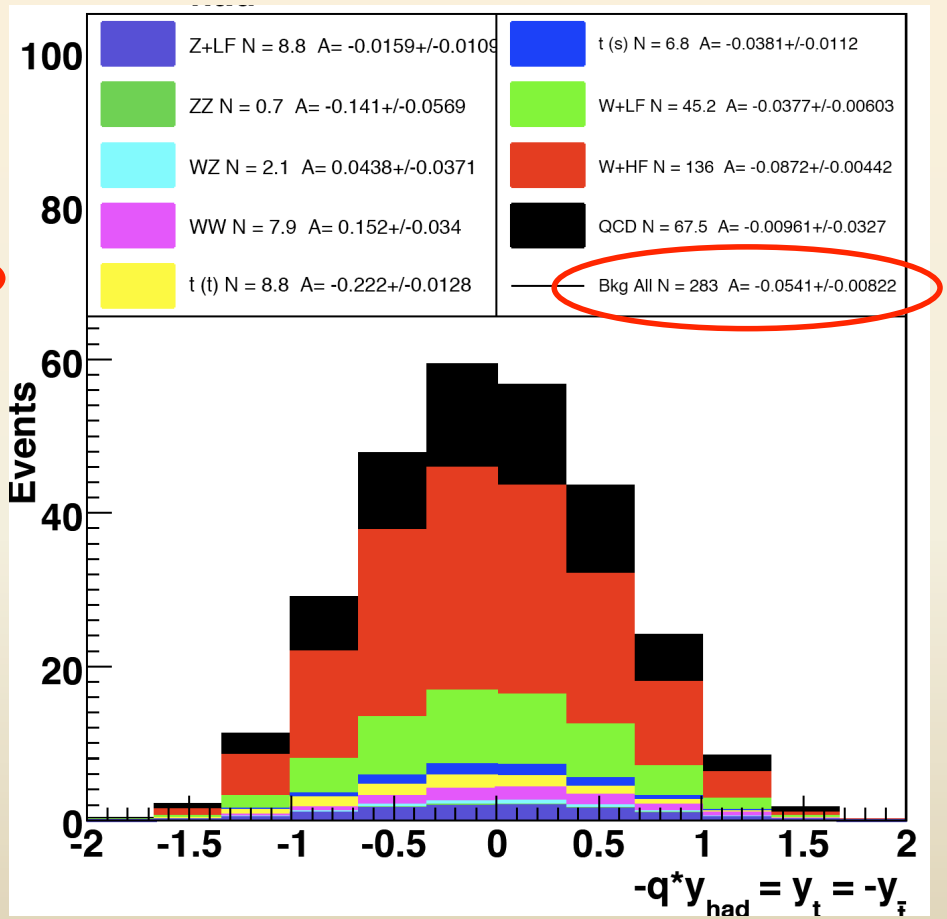
- Pythia remains good approximation of SM

Asymmetry from background is small but not zero!

tt rest frame



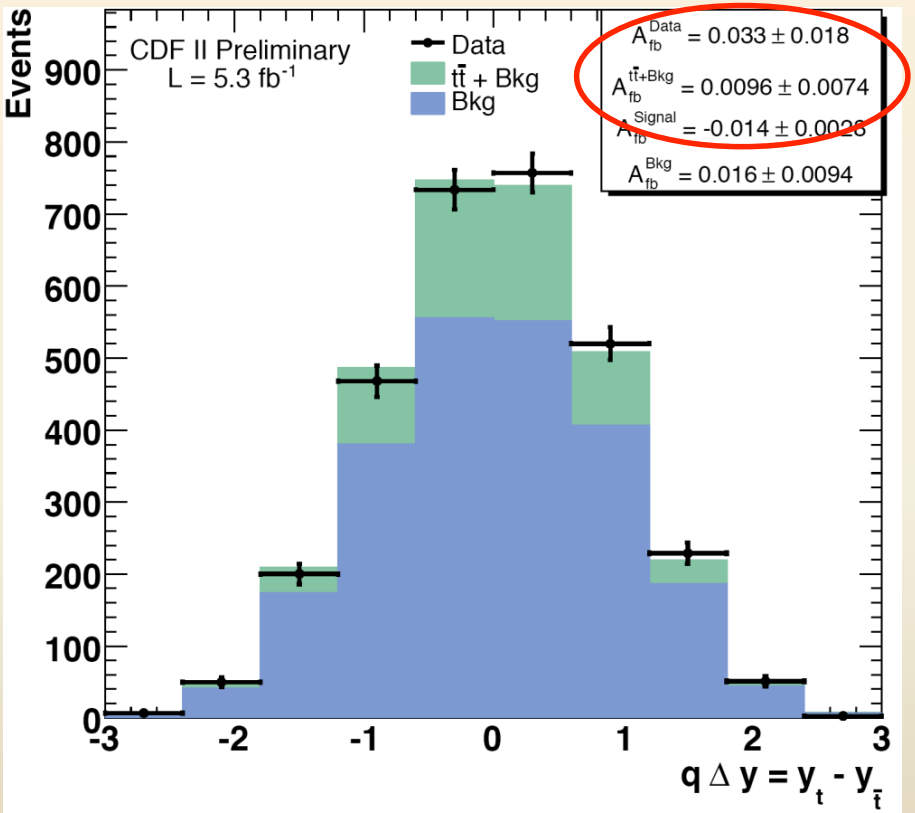
lab frame



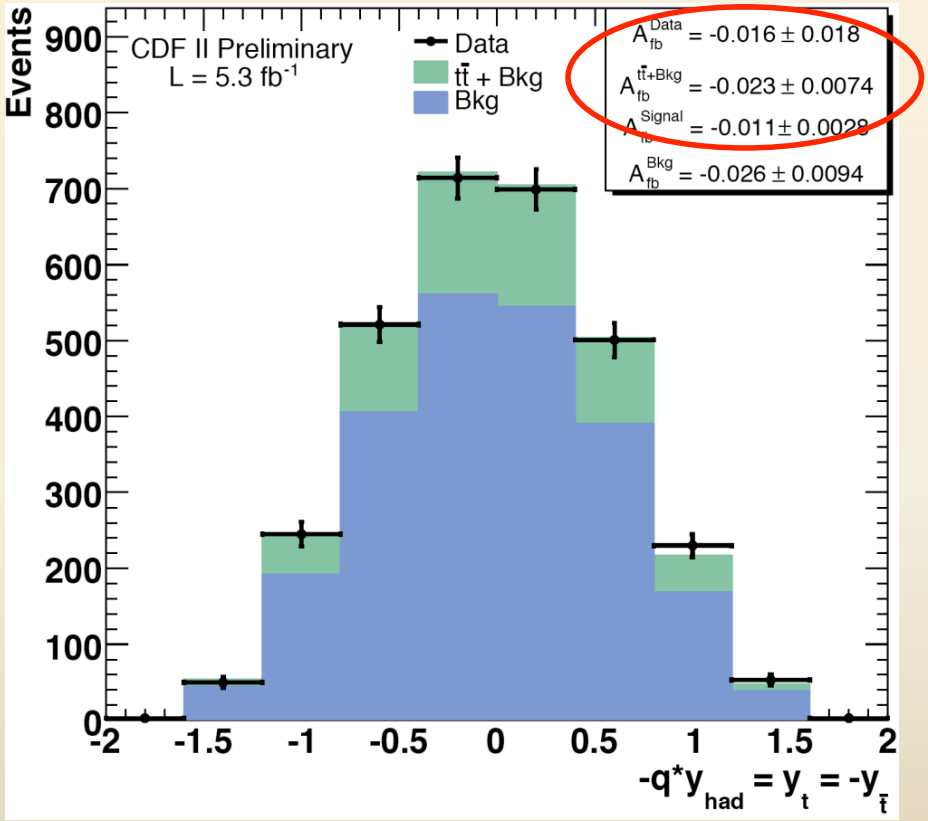
Apply to not b tagged sample

S:B = 0.3

tt frame

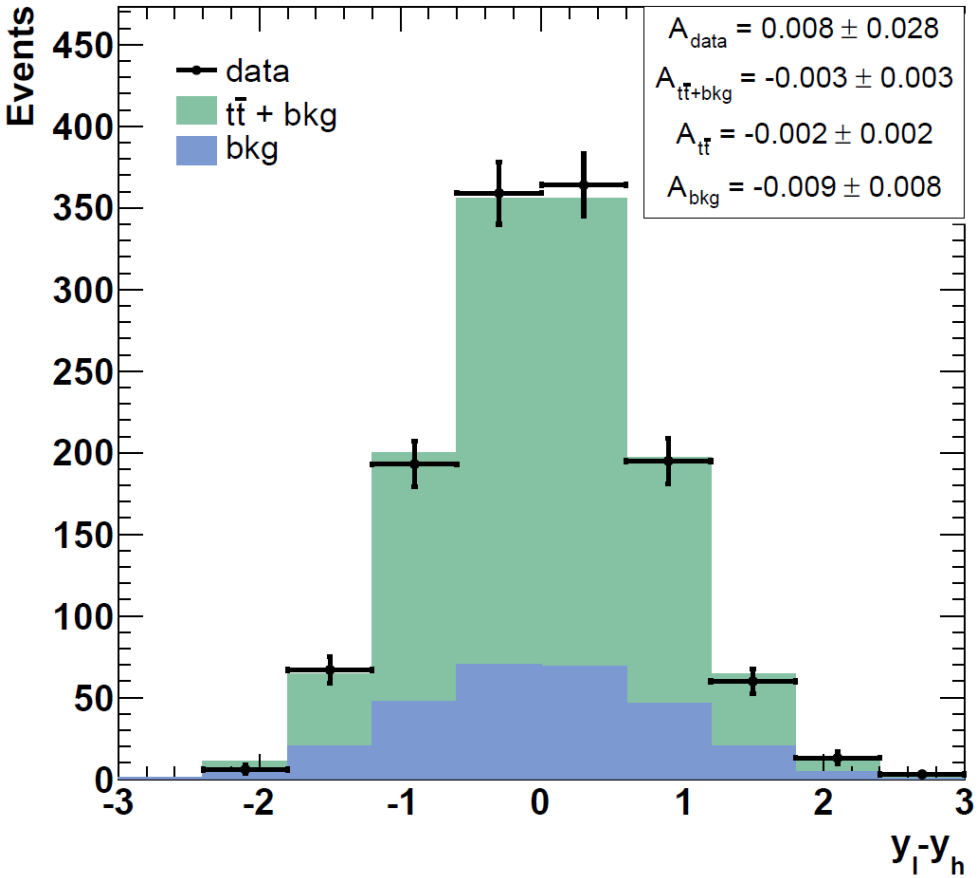


lab frame

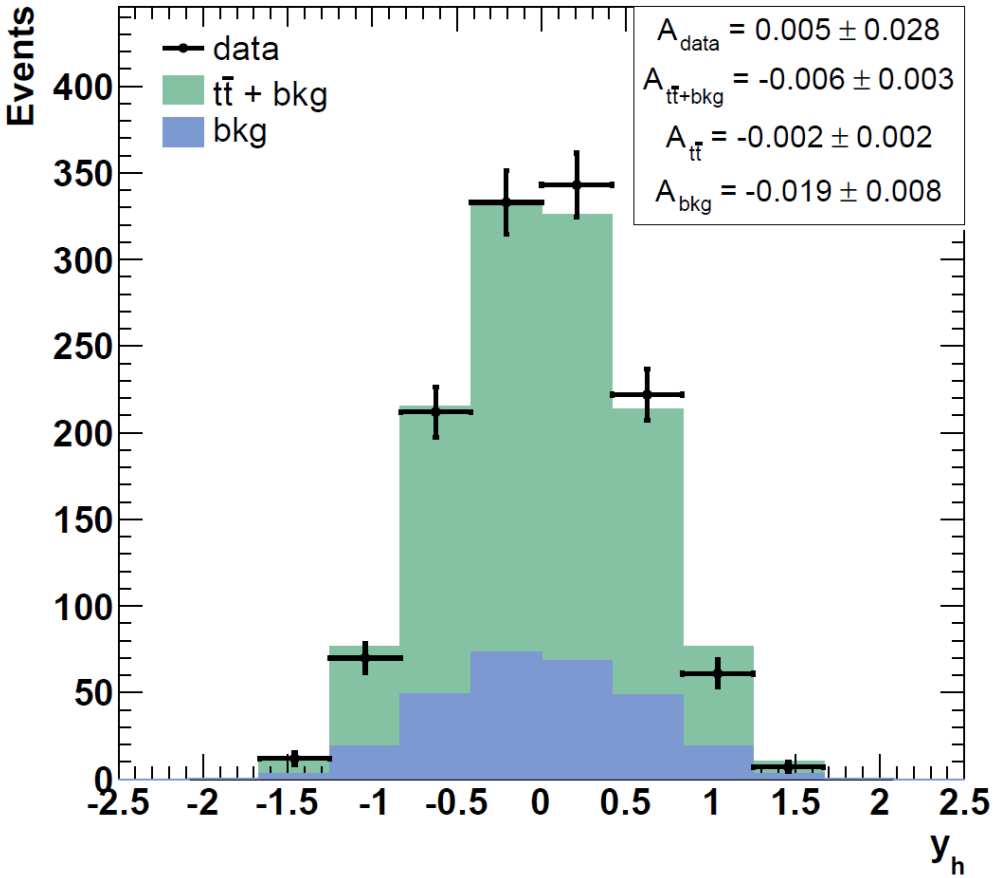


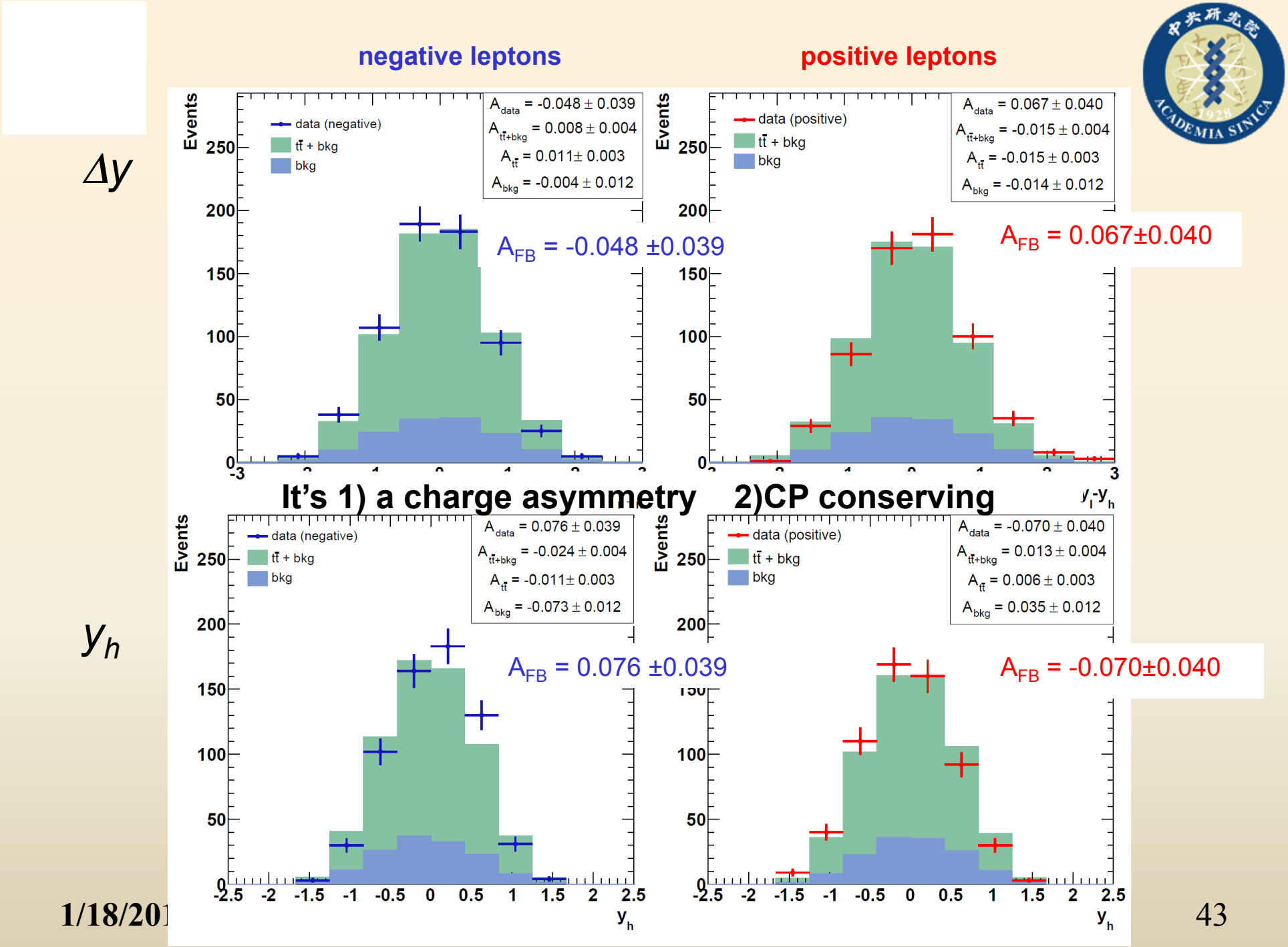
Inclusive asymmetry

Δy



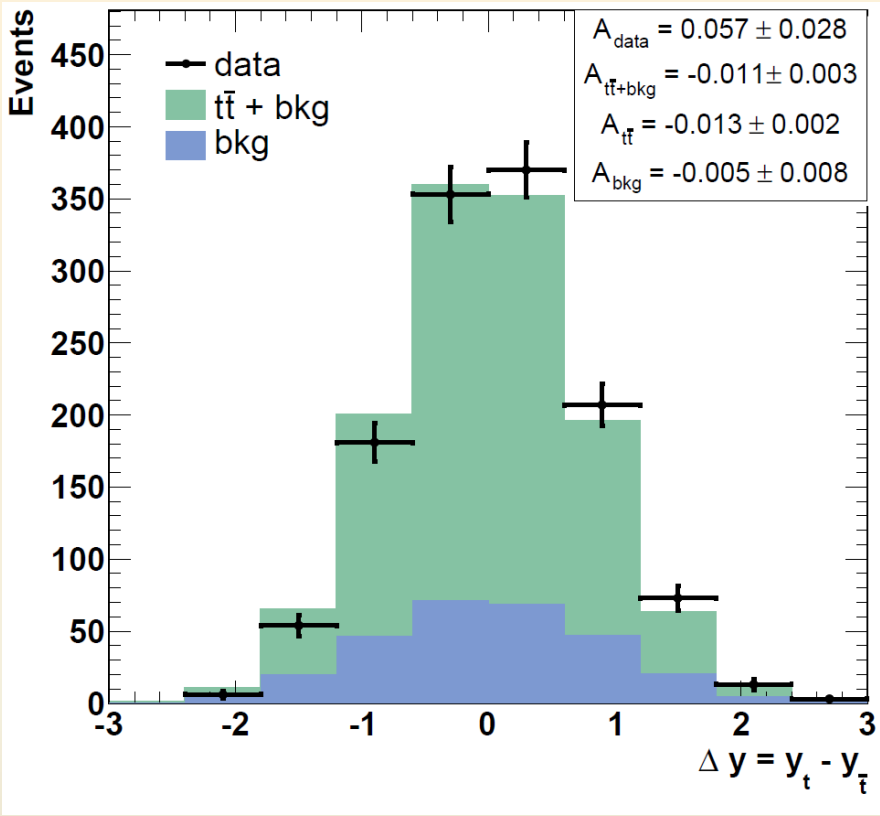
y_h



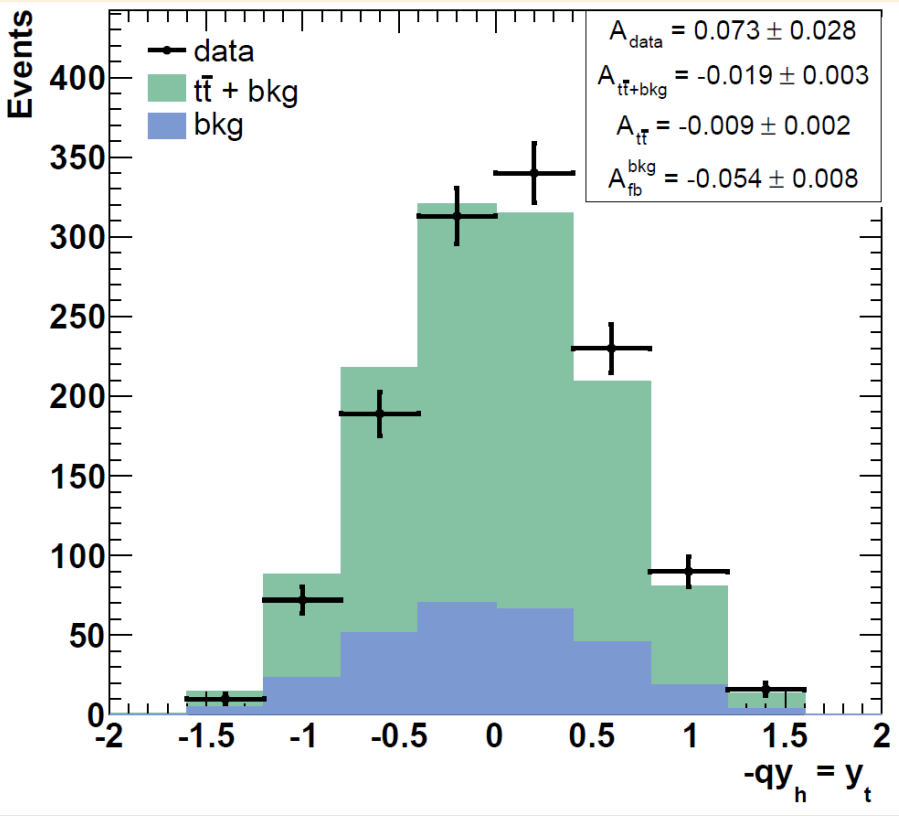

negative leptons
positive leptons
Δy
y_h
Events
data (negative)
$t\bar{t}$ + bkg
bkg
A_{data} = -0.048 ± 0.039
$A_{t\bar{t}+bkg}$ = 0.008 ± 0.004
$A_{t\bar{t}}$ = 0.011± 0.003
A_{bkg} = -0.004 ± 0.012
A_{FB} = -0.048 ±0.039
data (positive)
A_{data} = 0.067 ± 0.040
$A_{t\bar{t}+bkg}$ = -0.015 ± 0.004
$A_{t\bar{t}}$ = -0.015 ± 0.003
A_{bkg} = -0.014 ± 0.012
A_{FB} = 0.067±0.040
y_l-y_h
It's 1) a charge asymmetry 2)CP conserving
A_{data} = 0.076 ± 0.039
$A_{t\bar{t}+bkg}$ = -0.024 ± 0.004
$A_{t\bar{t}}$ = -0.011± 0.003
A_{bkg} = -0.073 ± 0.012
A_{FB} = 0.076 ±0.039
A_{data} = -0.070 ± 0.040
$A_{t\bar{t}+bkg}$ = 0.013 ± 0.004
$A_{t\bar{t}}$ = 0.006 ± 0.003
A_{bkg} = 0.035 ± 0.012
A_{FB} = -0.070±0.040
y_h

Combine charges

tt frame



lab frame



- Combined Δy:
  A_{FB} = 0.057 ±0.028
- Compare to mc@nlo
  A_{FB} = 0.024

- Combined $-q*y_h$:
  A_{FB} = 0.073 ±0.028
- Compare to mc@nlo
  A_{FB} = 0.001

Correction to parton level

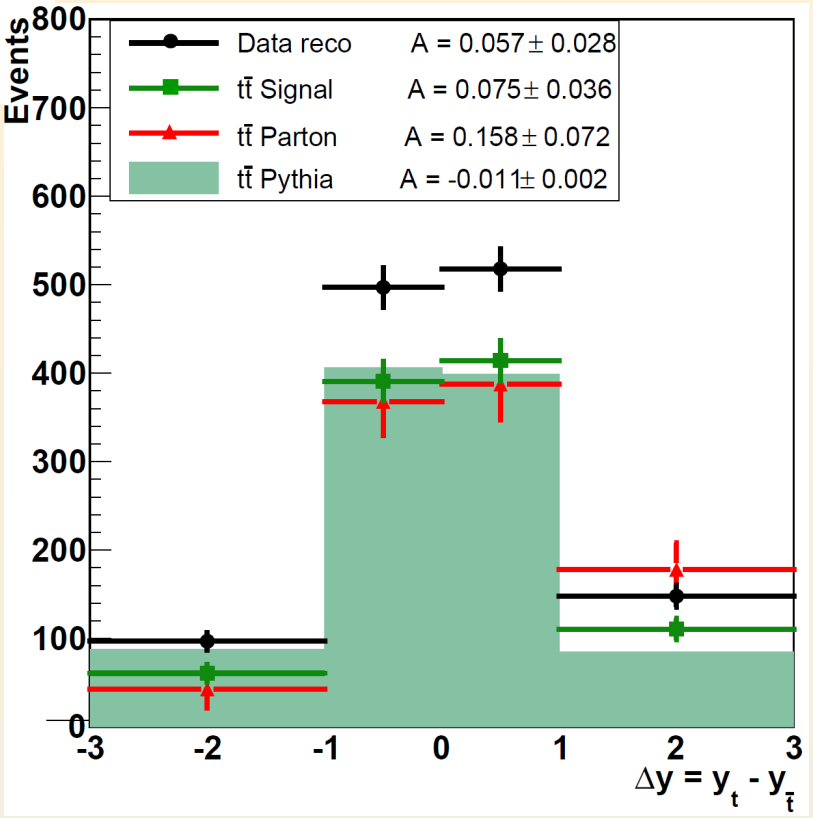
- Bin by bin in the histogram
  - P_j : parton level distribution
  - A_j: acceptance of the analysis
  - S_{ij}: smearing of the reconstruction
  - T_i: top signal

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

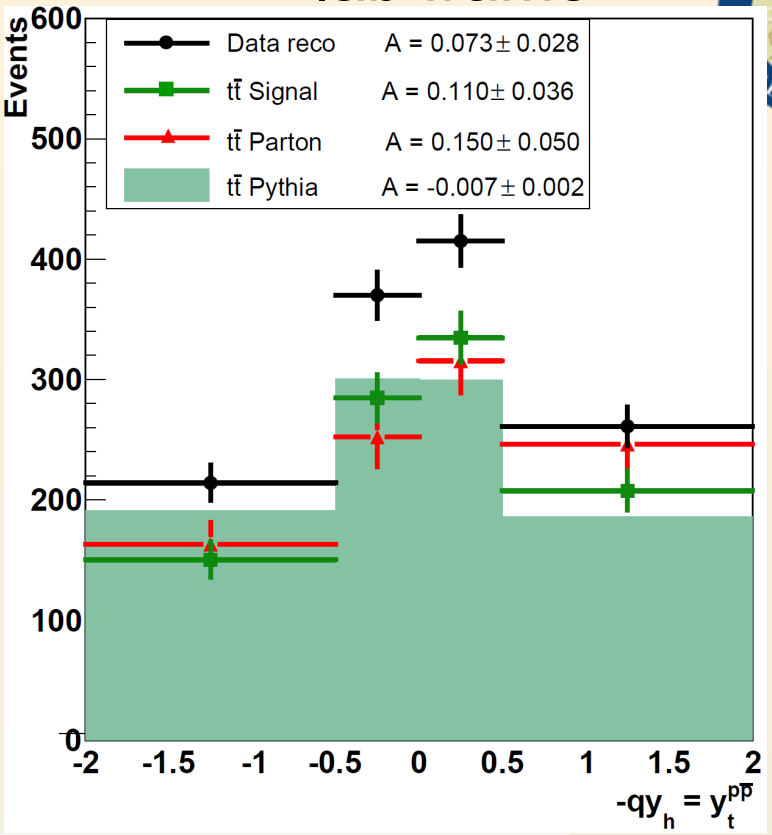
  - B_i: background
  - D_i: data distribution

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

tt frame

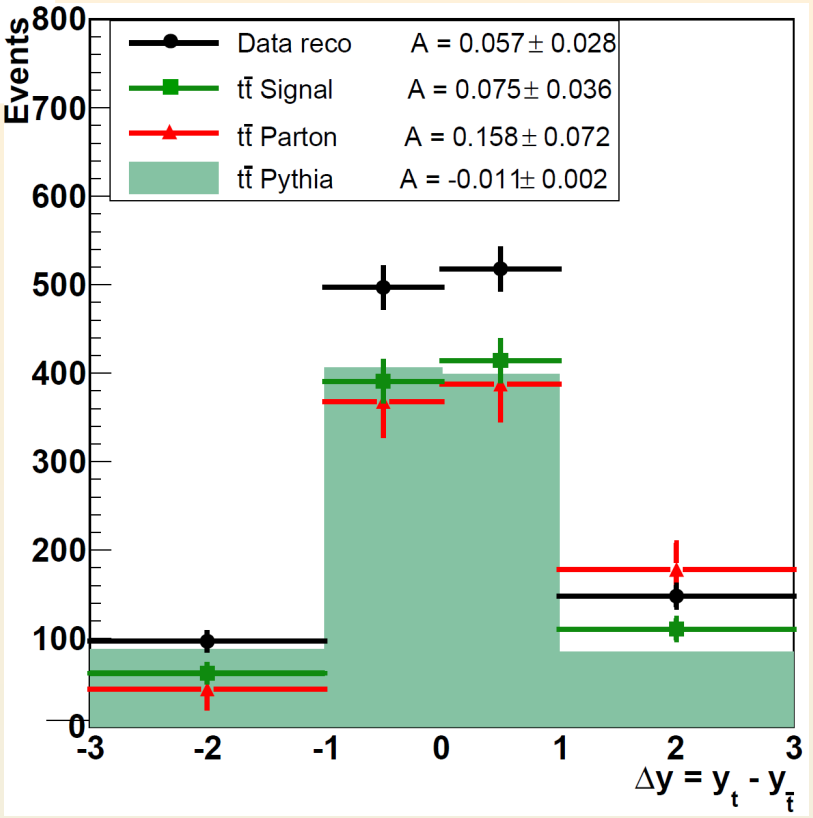


lab frame

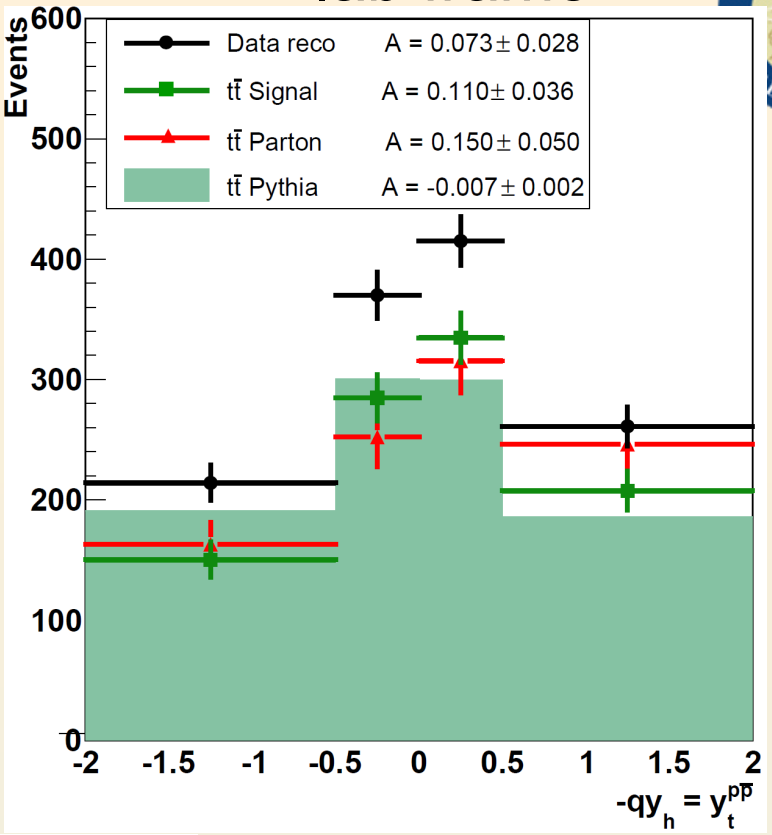


sample	level	$A^{\mathrm{t\bar{t}}}$	$A^{\mathrm{p\bar{p}}}$
data	data	0.057 ± 0.028	0.073 ± 0.028
MC@NLO	$t\bar{t}$+bkg	0.017 ± 0.004	0.001 ± 0.003
data	signal	0.075 ± 0.037	0.110 ± 0.039
MC@NLO	$t\bar{t}$	0.024 ± 0.005	0.018 ± 0.005
data	parton	0.158 ± 0.074	0.150 ± 0.055
MCFM	parton	0.058 ± 0.009	0.038 ± 0.006

tt frame



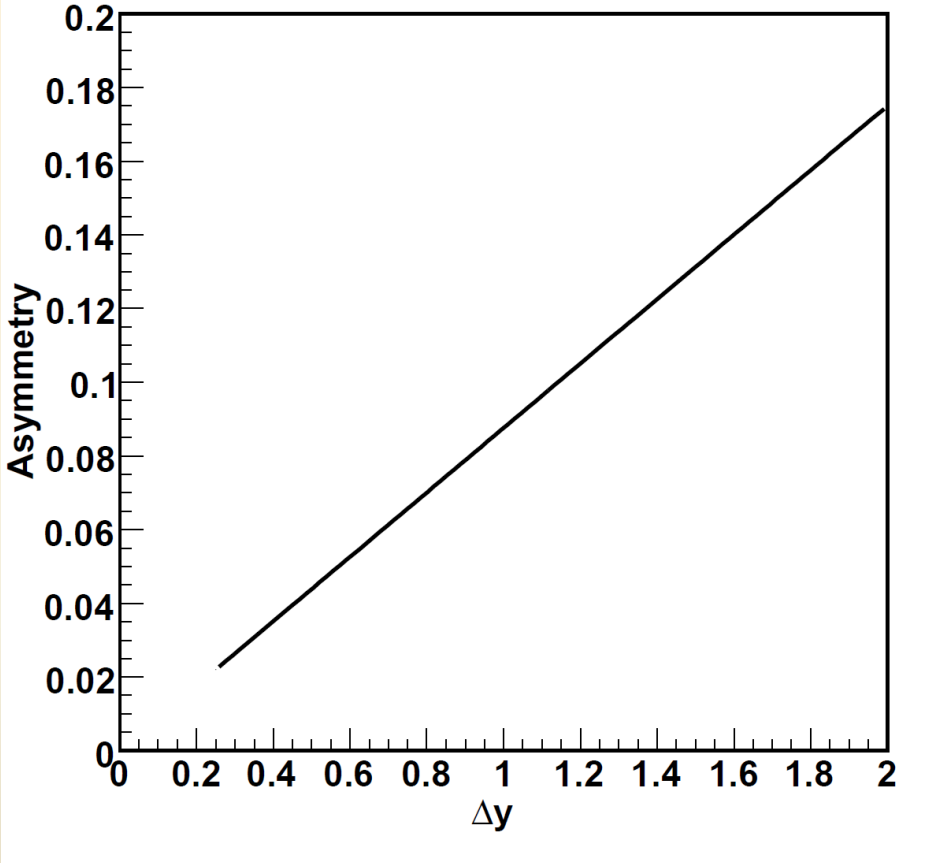
lab frame

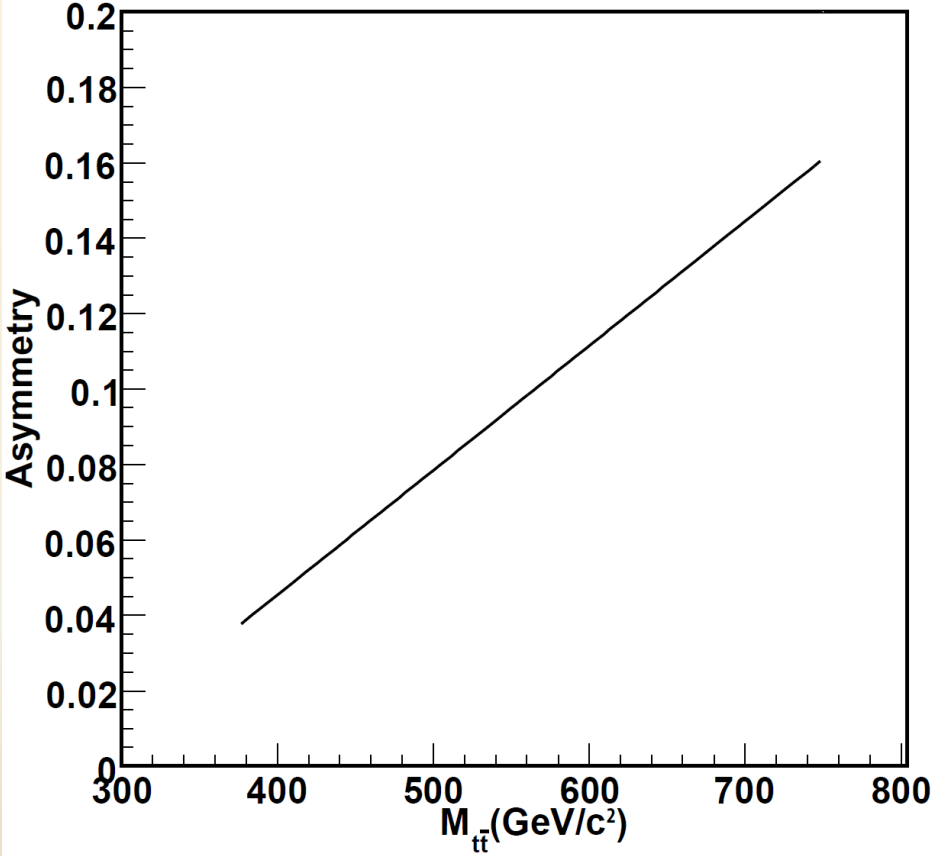


sample	level	$A^{t\bar{t}}$
data	data	0.057 ± 0.028
MC@NLO	$t\bar{t}$+bkg	0.017 ± 0.004
data	signal	0.075 ± 0.037
MC@NLO	$t\bar{t}$	0.024 ± 0.005
data	parton	0.158 ± 0.074
MCFM	parton	0.058 ± 0.009

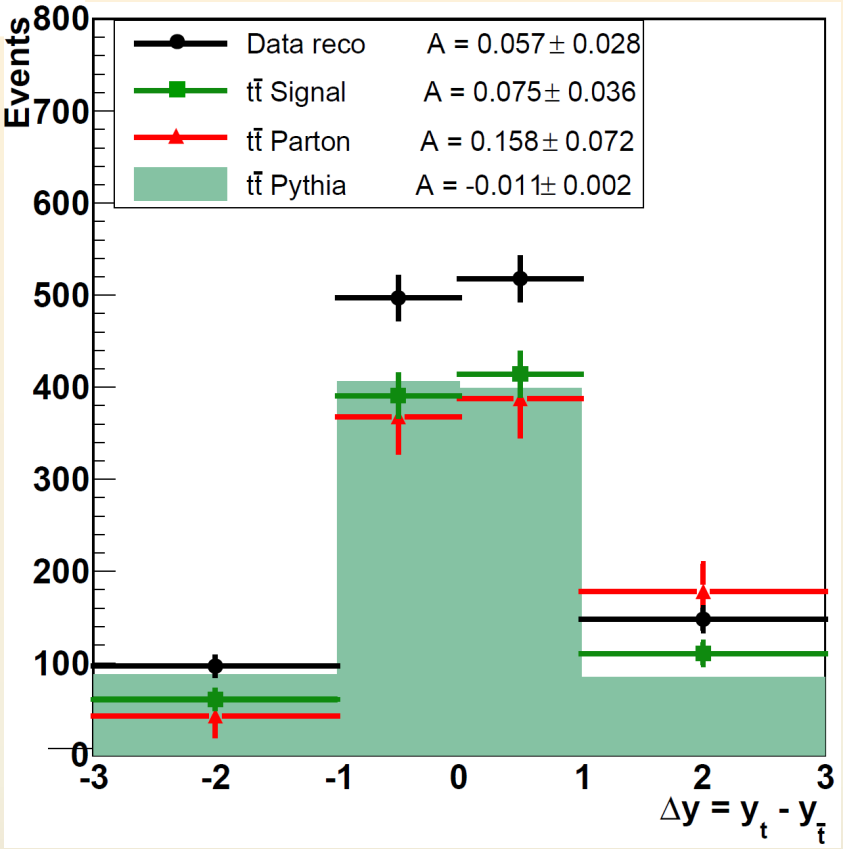
Note:
D0 signal level 4.3 fb^{-1}
Yields 0.08±0.04.
We agree!

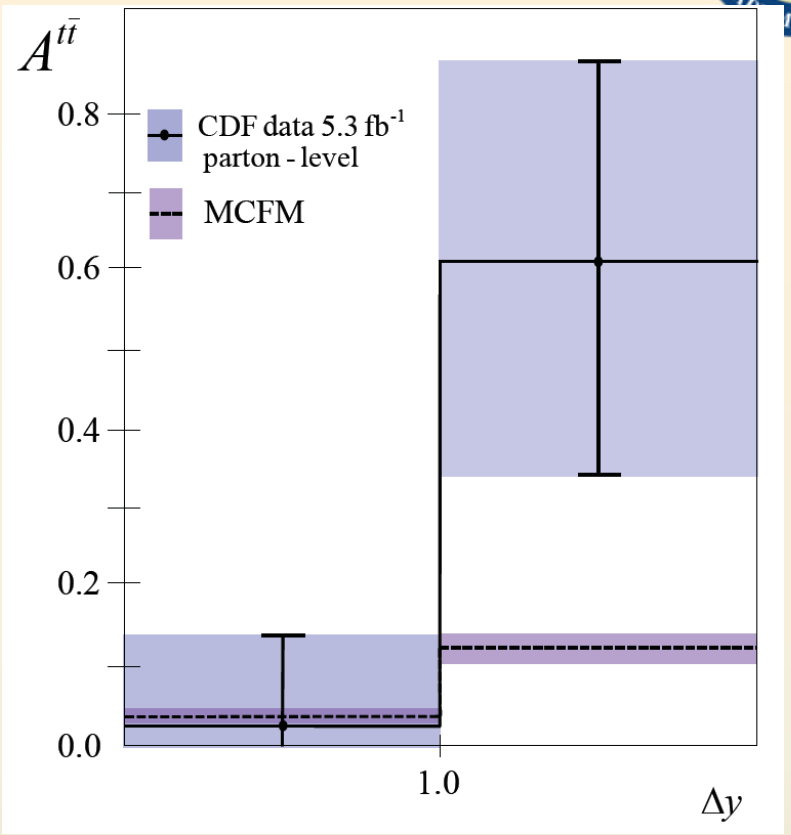
Asymmetry is a function of Δy_{tt} and M_{tt}





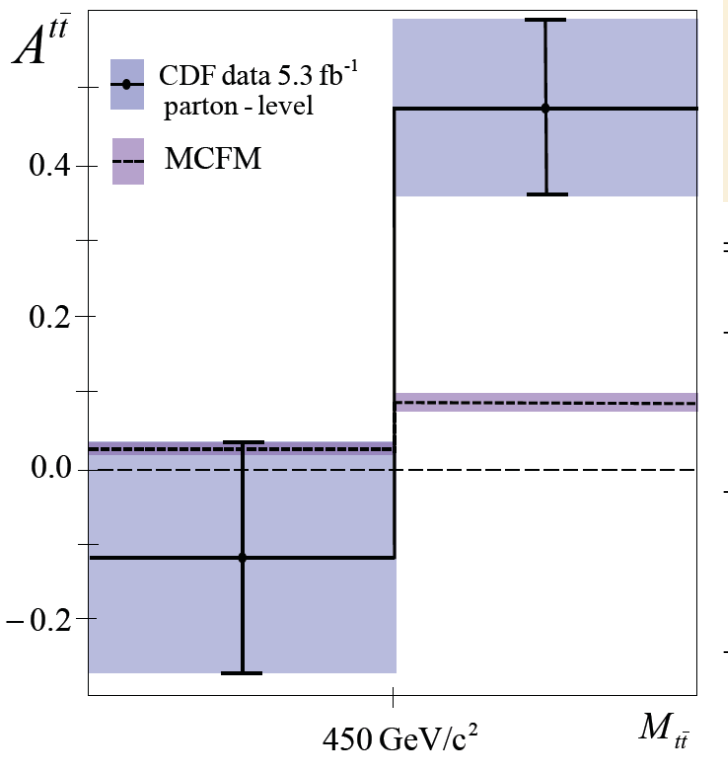
Dependence on Δy_{tt}





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.

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

?

A_{fb} summary

- Inclusive A in lab and tt frames in 2 sigma excess over SM
- Consistent with CP conservation

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

$$A^{tt}_{reco} = 0.210 \pm 0.049, \quad A^{tt}_{parton} = 0.475 \pm 0.112$$
$$A^{tt}_{NLO\ reco} = 0.043 \pm 0.006 \quad A^{tt}_{MCFM} = 0.088 \pm 0.013$$

- The asymmetry at high mass is consistent with CP conservation
- Most cross-checks rule out non-physics, although a few puzzles
- More work to do!

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?

A_{fb} to be continued

- One thing to note, this study is not doable at LHC!!!
  - There is proton-proton collision at LHC. Can't define a reference to call Forward/Backward.
  - If we understood what is the physics beyond the fact, if this asymmetry is true, then one could think about how to verify it at LHC. But until then this is a game at TEVATRON only!

Toward the end of TEVATRON

- There is no RUN III!
  - No extra fund for extending the run despite the strong physics reason.
- Data taking ends at the end of Sep. 2011.
- Could have 9 fb^{-1} good samples for analysis requiring b tagging.

Two main goals

- Asymmetry in the top production
  - Combine LJ and DIL to enhance the significance.
  - It is possible to reach 5 sigma with full dataset.
- Low mass Higgs search at TEVATRON
  - IPAS is on all hadronic channel (ZH/WH, VBF); QCD and top are the major background.
  - W/Z boson identification is important; rejecting QCD and top events at the same time. But has no help to VBF.

Schedule

- An update in the summer of 2011
- Full analysis completed in the summer of 2012.

Thank you!!!

Expecting Higgs at LHC/ATLAS