XVI International Workshop on
Deep-Inelastic Scattering
and Related Subjects

Measurement of the Forward-Backward Asymmetry in $t\bar{t}$ Production at the Tevatron

On behalf of CDF and DØ collaborations

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Outline

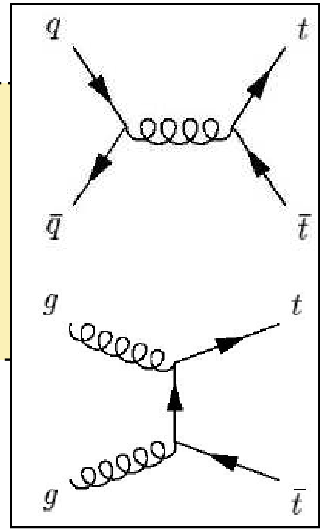
- Theoretical framework :
  - Charge conjugation symmetry
  - Forward-backward asymmetry
- Analysis strategies in top pair events :
  - 2 measurements from CDF, 1 from DØ
- NLO predictions vs Tevatron measurements
  - CDF / DØ comparison (?)

1^{st} measurements
New results (2007)

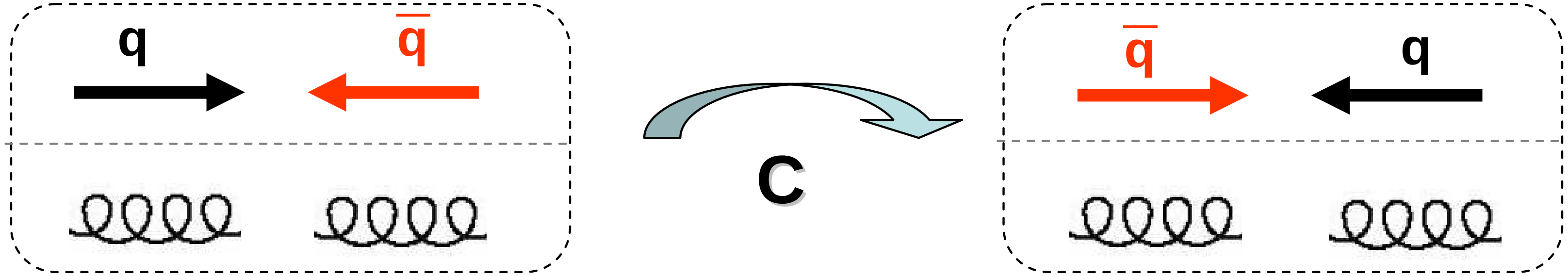
C symmetry @ p$\bar{\text{p}}$ collider

At the Tevatron : top pair production involves ~ 85 % q$\bar{\text{q}}$ and 15 % gg

p$\bar{\text{p}}$ initial state : **not eigenstate for charge conjugation C**



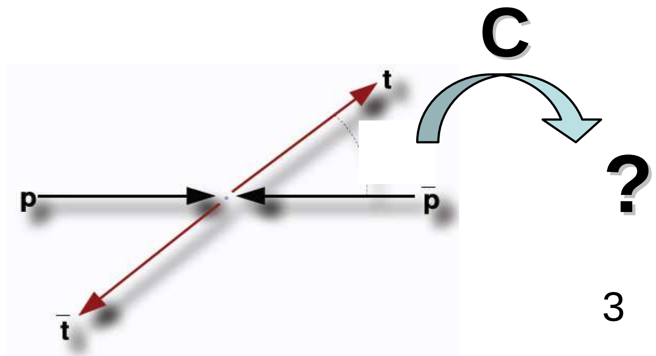
Initial state



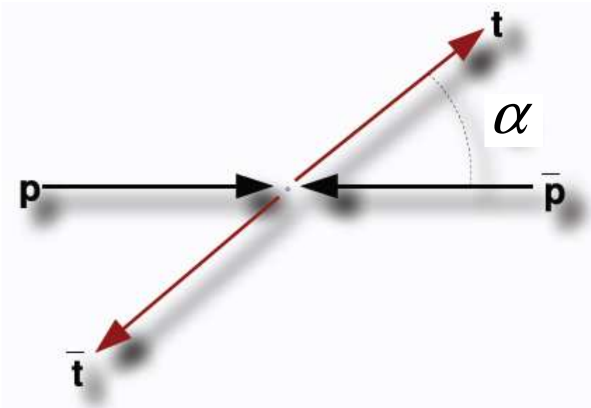
$$\left|p\bar{p}\right\rangle = \alpha\left|q\bar{q}\right\rangle + \beta\left|gg\right\rangle$$

$$C\left|p\bar{p}\right\rangle = \alpha(-1)^{L+S}\left|q\bar{q}\right\rangle + \beta\left|gg\right\rangle$$

Even if the strong interaction is assumed to respect the **charge conjugation symmetry C**, *the final state not expected to be symmetric under C*



Forward-backward asymmetry



Polar angle between top quark and beam axis
in the $(q,\bar{q})$ rest frame **or** in the lab frame

Assuming CP symmetry

$$A(\cos\alpha) = \underbrace{\frac{N_t(\cos\alpha) - N_{\bar{t}}(\cos\alpha)}{N_t(\cos\alpha) + N_{\bar{t}}(\cos\alpha)}}_{\text{Charge asymmetry}} = \underbrace{\frac{N_t(\cos\alpha) - N_t(-\cos\alpha)}{N_t(\cos\alpha) + N_t(-\cos\alpha)}}_{\text{Forward-backward asymmetry}} \neq 0$$

Total asymmetry : **integrated over α**
(not enough data for a differential measurement)

"Forward" event : cos α > 0

Parton rest frame : $\Delta y = y_t - y_{\bar{t}} > 0$

Lab frame : $y_t > 0$

$$A_{fb} = \frac{N_f - N_b}{N_f + N_b}$$

N_f : number of "forward" events

N_b : number of "backward" events

Theoretical framework

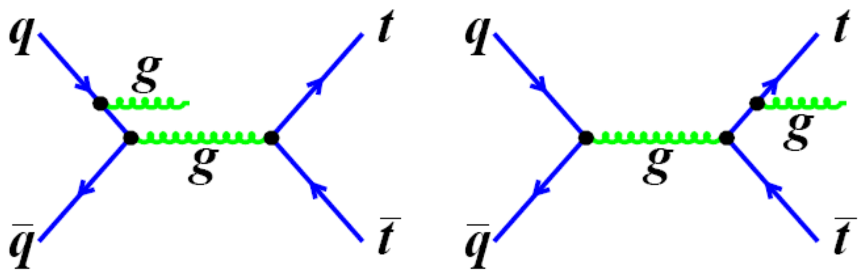
Each single diagram gives a charge symmetric production

strong interaction indifferent to electric charge

At LO, differential cross-section symmetric under the exchange $t \leftrightarrow \bar{t}$

At NLO, asymmetry appears through **interferences in $q\bar{q}$** diagrams between

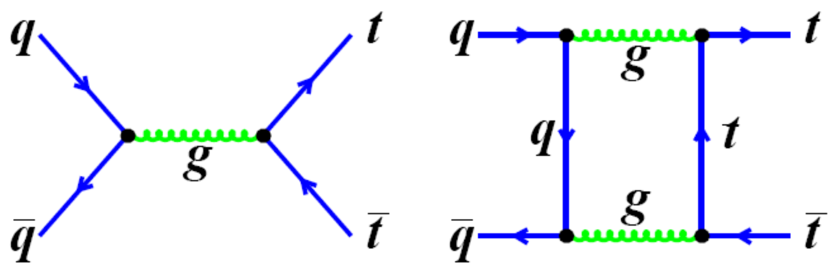
ISR / FSR



Negative contribution to A_{fb}

"≥5 jets"

Born amplitude / Box diagram



Positive contribution to A_{fb}

"4 jets"

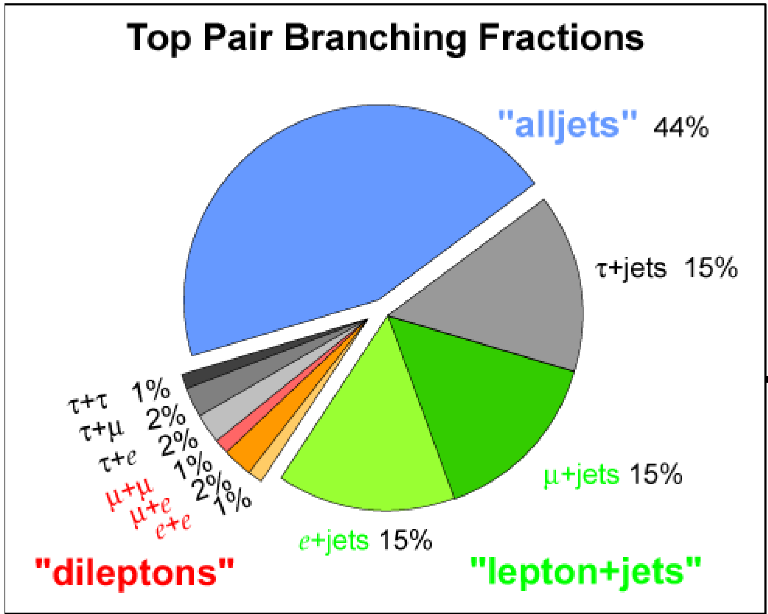
Recent A_{fb} calculation for $t\bar{t}$+g
–(0-2)% @ NLO (~ α_s^4) vs –(9-10)% @ LO (~ α_s^3)

Dittmaier *et al.*

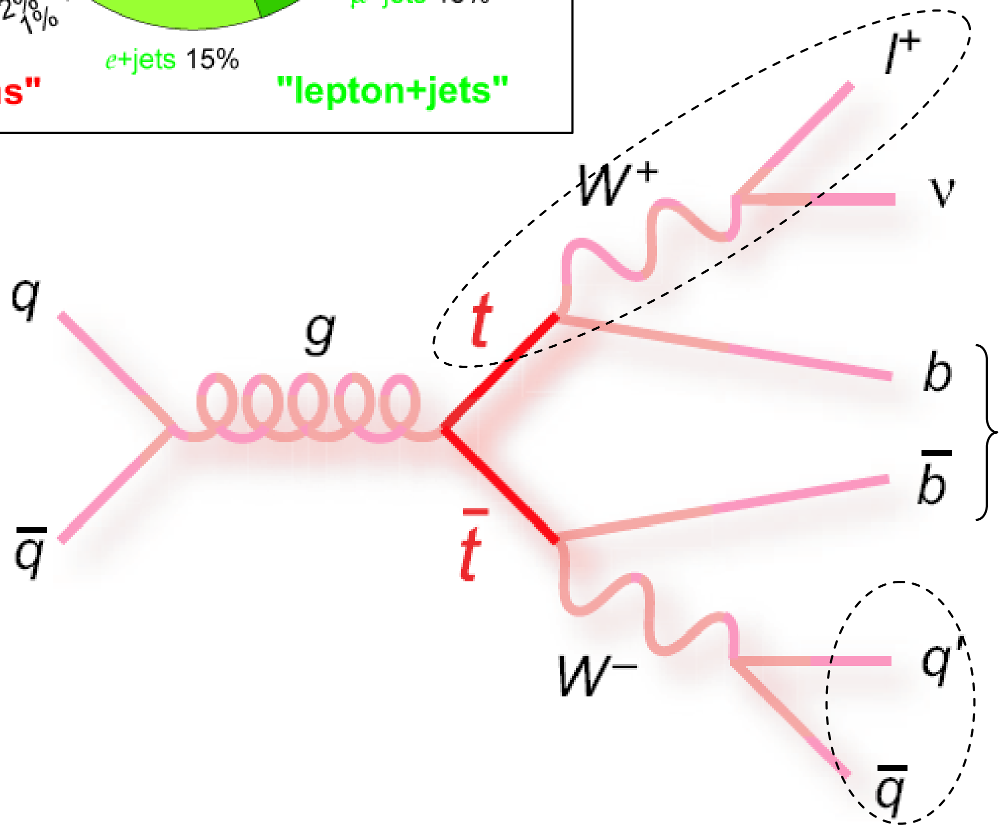
Split measurements
between 4 and ≥ 5 jets

Total asymmetry is positive ~ **5 %** Kühn et al. (LO) / Bowen *et al.*

The l+jets final state



Asymmetry probed in top pair production, in the lepton + jets decay mode



1 high p_T isolated lepton
same sign as top quark

Missing E_T

2 b-jets

2 light jets

Main backgrounds
W+jets , QCD

Kinematics : minimize χ^2 with mass constrains

Analysis strategy

Select top pair events

estimate signal / background composition

Reconstruct the full event kinematics, and compute the asymmetry

either in the parton rest frame (Δy) , or the lab frame (y_t)

The raw measurement is the A_{fb} **visible within** detector **acceptance**, distorted by reconstruction effects

Estimate biases, and "deal with them" :

o DØ provides a raw A_{fb} , uncorrected for dilution *(next slide)*

generator predictions must be "folded" with the parameterized detector effects to be compared with DØ observations

o both CDF analyses "unfold" A_{fb} from reconstruction effects only one result is corrected back to particle-level (acceptance)

Difficult to compare DØ and CDF results

DØ analysis (0.9 fb^{-1})

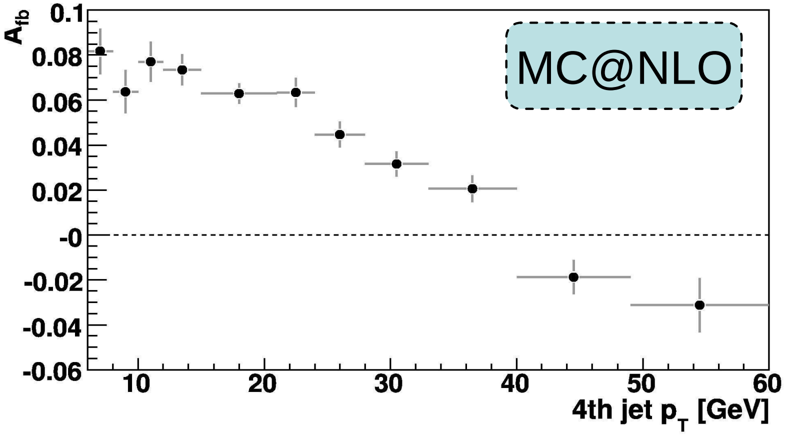
Acceptance :

Parton rest frame

the integrated asymmetry strongly depends on the <u>phase space being probed</u> :

- jet p_T cut , number of jets
- **NO acceptance correction** back to particle level (MC@NLO ≠ "truth")

Analysis designed so that simple approximation on acceptance cuts works !



Dilution :

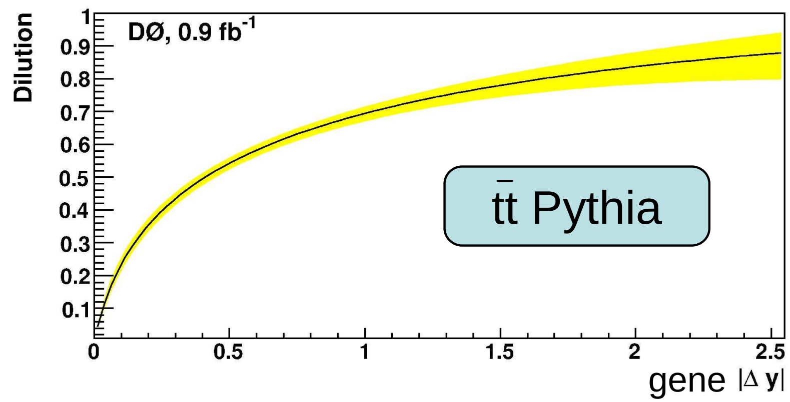
"forward" event : $\Delta y = y_t - y_{\bar{t}} > 0$

how well is measured the asymmetry at reconstructed level ?

wrong lepton charge (= top charge) or **wrong kinematics dilute A_{fb}**

If the sign of Δy is correctly reconstructed for a fraction p of $t\bar{t}$ candidates, the fraction of visible asymmetry is :

$$\mathcal{D} = 2p - 1$$



Predicted asymmetry

Now that the accessible phase space and the geometric dilution are described, the "raw asymmetry" predicted by MC@NLO is :

$$A_{fb}^{pred} = \int_0^{\infty} A_{fb}\left(\left|\Delta y\text{gen}\right|\right) \mathcal{D}\left(\left|\Delta y\text{gen}\right|\right) f\left(\left|\Delta y\text{gen}\right|\right) d\left|\Delta y\text{gen}\right|$$

particle-level A_{fb} (MC@NLO here)

probability density within geometrical acceptance

MC@NLO predictions (or ANY model) can be compared to A_{fb} observed in data

Fitting procedure for A_{fb} measurement in data :

Likelihood discriminant built to separate $t\bar{t}$ from W+jets

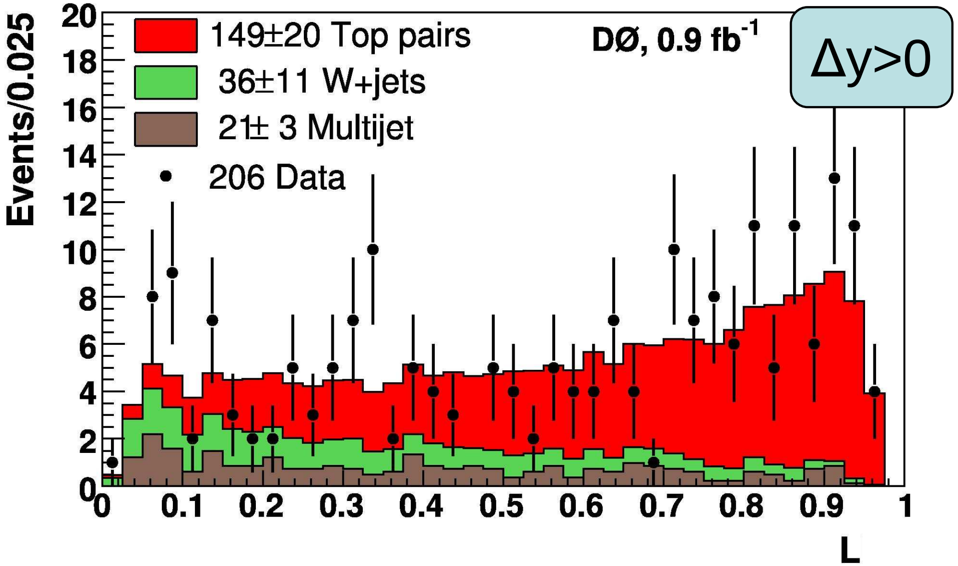
intrinsic A_{fb} reduced when reconstructed with $t\bar{t}$ kinematics

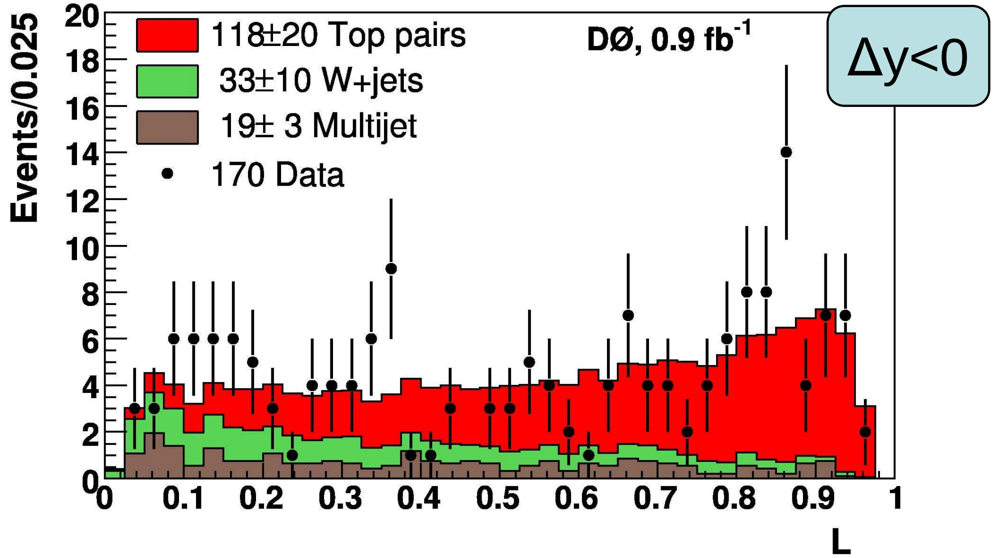
QCD : from data, same selection as $t\bar{t}$, but fail tight lepton ID

Asymmetry extraction

Extract both asymmetry and data sample composition with a maximum likelihood fit

Likelihood discriminant templates for : forward signal, backward signal, W+jets, QCD





	$D\varnothing$	$MC@NLO$
≥ 4 *jets*	$A_{fb} = 12 \pm 8(stat) \pm 1(syst)\%$	$A_{fb} = 0.8 \pm 0.2(stat) \pm 1(accep)\%$
$= 4$ *jets*	$A_{fb} = 19 \pm 9(stat) \pm 2(syst)\%$	$A_{fb} = 2.3 \pm 0.2(stat) \pm 1(accep)\%$
≥ 5 *jets*	$A_{fb} = -16^{+15}_{-17}(stat) \pm 3(syst)\%$	$A_{fb} = -4.9 \pm 0.4(stat) \pm 1(accep)\%$

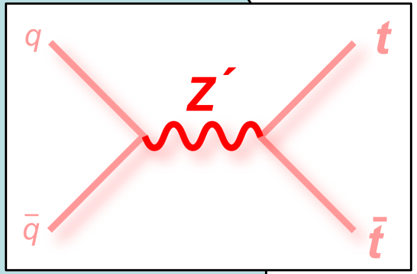
Beyond A_{fb} measurement

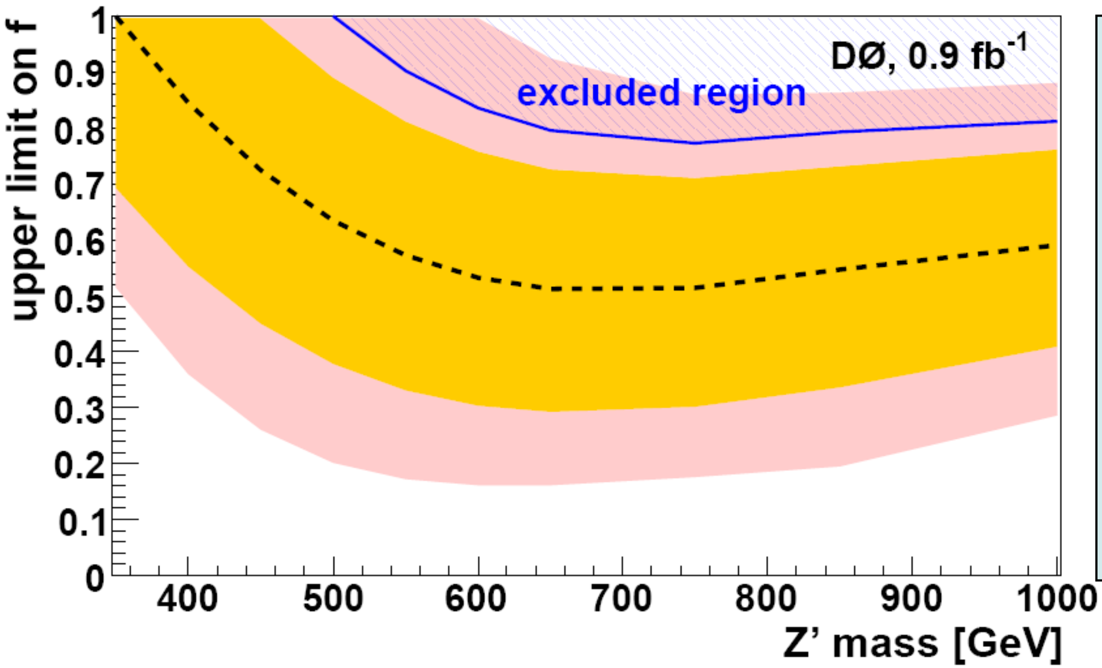
- Test of perturbative QCD calculation
- Asymmetry sensitive to new physics :

  $t\bar{t}$ production via a massive gauge boson Z'

  "*lepto-phobic*" Z' scenario, predicting V-A left-handed decays

  → CP-asymmetric Z' decay = large positive asymmetry





Put limits on the fraction **f** of top pairs produced via a Z'

Complementary to direct Z' searches (sensitive to a wide resonance)

Heavy axigluon can predict $A_{fb} < 0$ due to

$$\left\{ \begin{array}{l} q\bar{q} \to g \to t\bar{t} \\ q\bar{q} \to A \to t\bar{t} \end{array} \right. \quad \text{interference}$$

arXiv:0709.1652

CDF : analysis I (1.9 fb^{-1})

Parton rest frame

Same observable (Δy) , different strategy

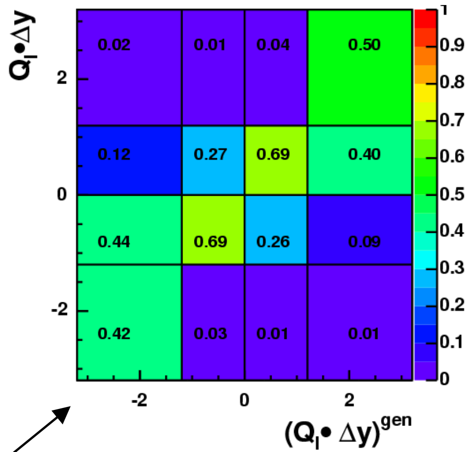
	DØ	CDF (analysis I)
Predicted A_{fb}	MC@NLO in visible phase space	
Detector effects	Fold MC@NLO prediction with dilution when ∫dΔy	Unfold data distribution from smearing and reconstruction
Background	Included in maximum likelihood fit	Subtracted from data distribution

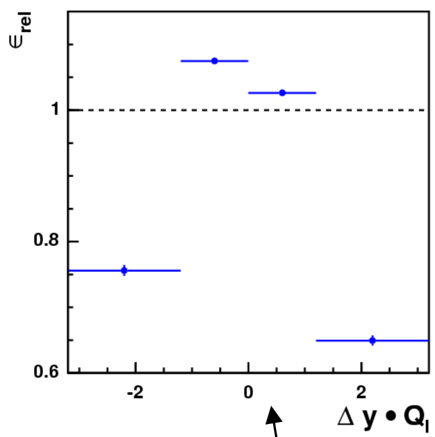
Correcting the raw A_{fb}

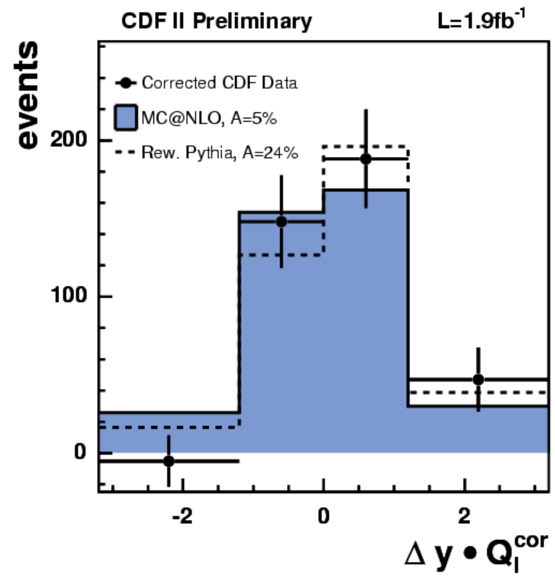
Backgrounds dilute A_{fb}, and can bias the measurement if they intrinsically contain an asymmetry (EW : parity violating)

Background contribution subtracted bin per bin from the raw $\Delta y.Q_l$ data distribution

$$\begin{pmatrix} N_1^{bg\,sub} \\ N_2^{bg\,sub} \\ N_3^{bg\,sub} \\ N_4^{bg\,sub} \end{pmatrix} = \underbrace{\begin{pmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{pmatrix} \cdot \begin{pmatrix} \epsilon_{11} & 0 & 0 & 0 \\ 0 & \epsilon_{22} & 0 & 0 \\ 0 & 0 & \epsilon_{33} & 0 \\ 0 & 0 & 0 & \epsilon_{44} \end{pmatrix}} \cdot \begin{pmatrix} N_1 \\ N_2 \\ N_3 \\ N_4 \end{pmatrix}$$



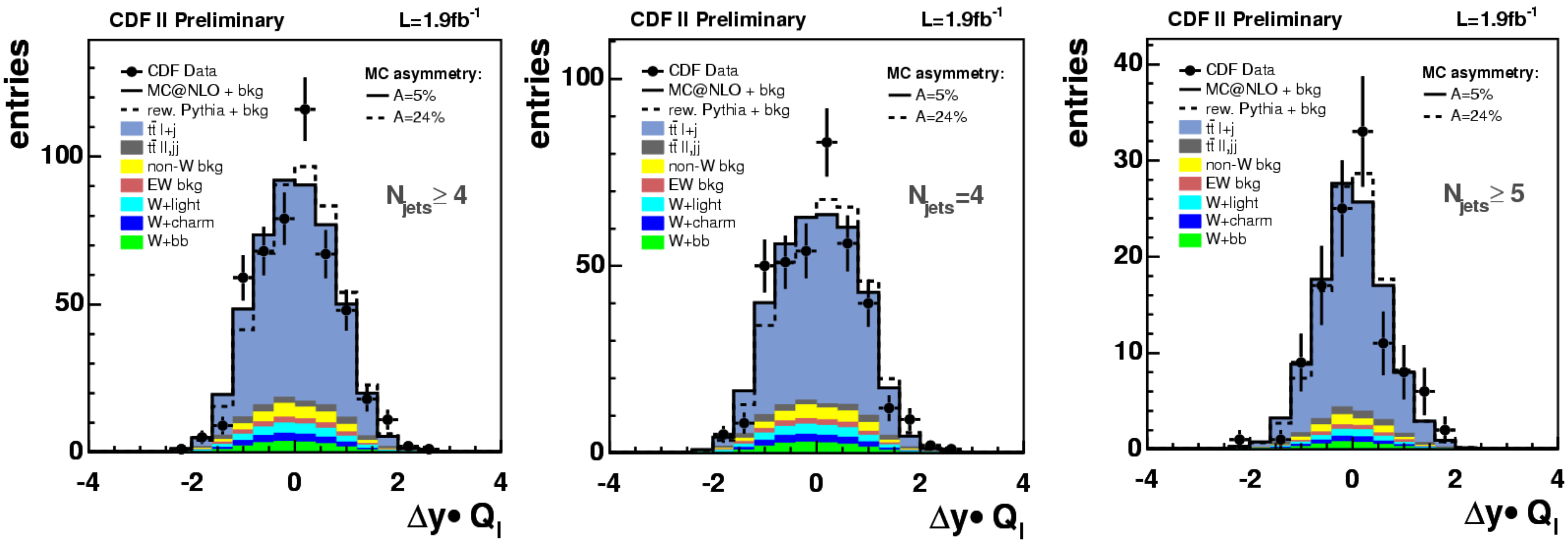




Smearing : event generated in a given $\Delta y.Q_l$ bin migrate to a different bin after reconstruction

Different **relative** reconstruction **efficiencies** within $\Delta y.Q_l$ bins

Corrected A_{fb}



The A_{fb} **corrected** for reconstruction effects, measured **within detector acceptance** in the inclusive ≥ 4 jets bin, is

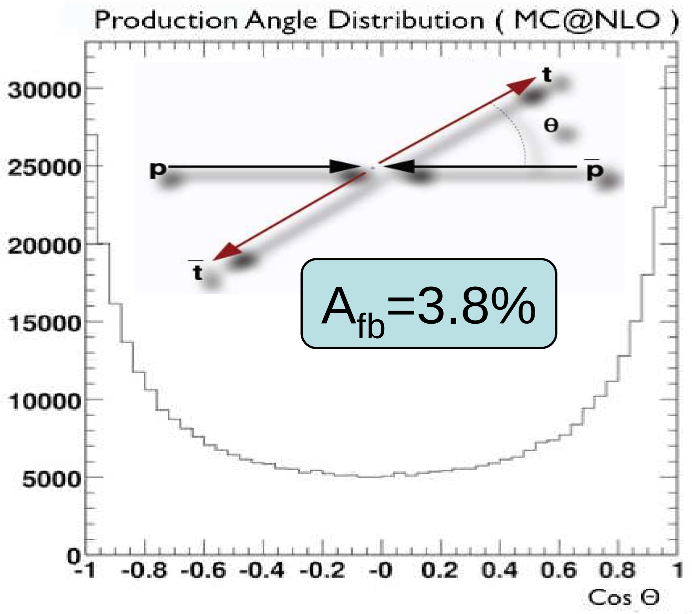
$$A^{\Delta y \cdot Q_l} = 0.24 \pm 0.13\,(\text{stat.}) \pm 0.04(\text{syst.})$$

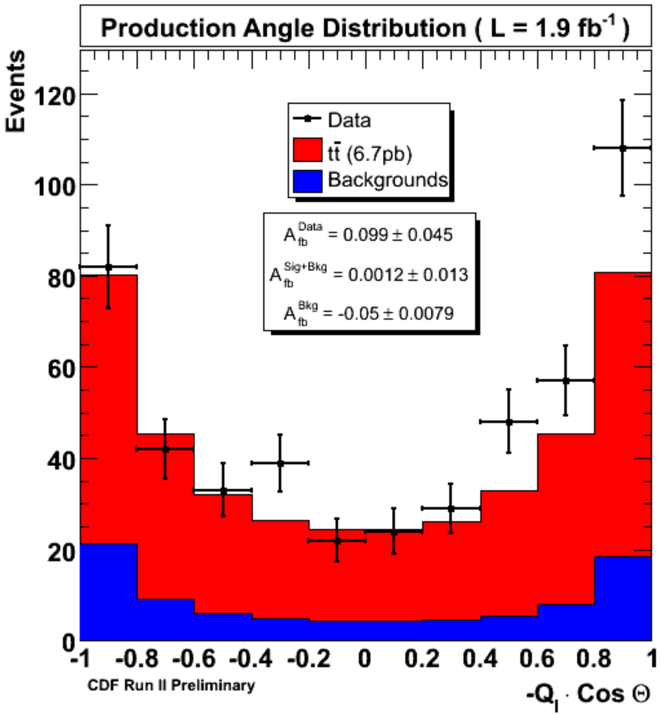
MC@NLO
0.04 – 0.07

High asymmetry in both 4th exclusive and 5th inclusive jet bins, difficult to interpret in terms of $t\bar{t}$ vs $t\bar{t}g$ contributions

CDF : analysis II (1.9 fb^{-1})

Lab frame





top quark production angle defined as :

$$\Theta = \tan^{-1}\left(\frac{p_T}{p_z}\right)$$

Corresponding definition of A_{fb} :

$$A_{fb} = \frac{N_{(-Q_l)\cdot Cos(\Theta)>0} - N_{(-Q_l)\cdot Cos(\Theta)<0}}{N_{(-Q_l)\cdot Cos(\Theta)>0} + N_{(-Q_l)\cdot Cos(\Theta)<0}}$$

Θ : angle of **hadronic decay of the top quark**

(more accurate reconstruction)

$$A_{fb}^{data} = 0.099 \pm 0.045$$

$$A_{fb}^{MC} = 0.003 \pm 0.013$$

After reconstruction
Before bkg sub.
Before acceptance correction

Corrected A_{fb} measurement

$$N_{corrected} = A^{-1} \cdot S^{-1} \cdot N_{bkg-sub}$$

Unfolded from **acceptance** and reconstruction

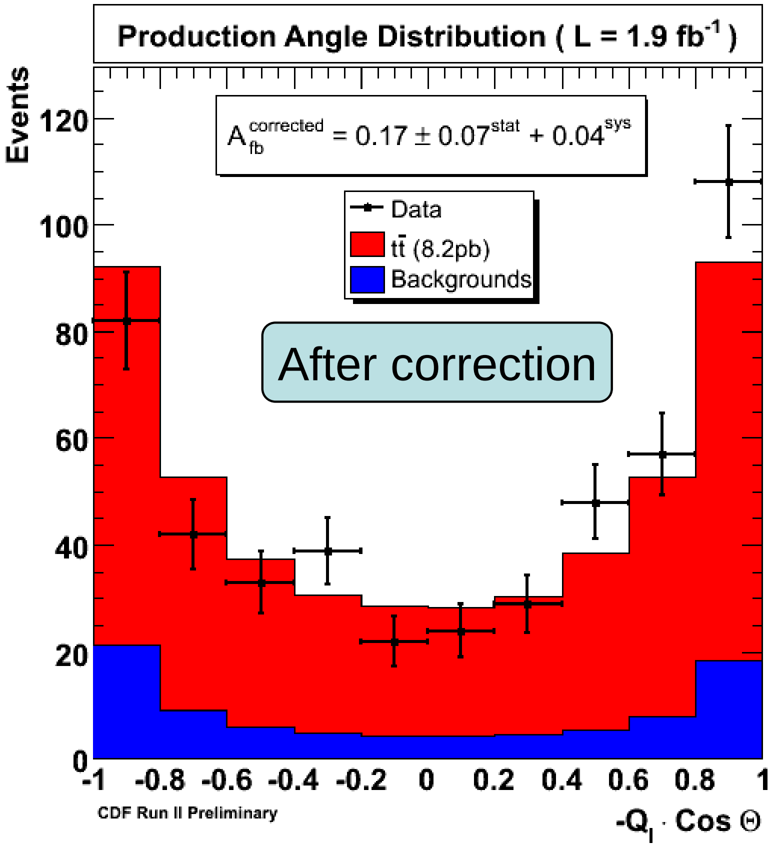
acceptance

smearing

Acceptance matrix

$$A = \begin{pmatrix} \varepsilon_0 = \frac{N_0^{sel}}{N_0^{gene}} & & & \\ & \varepsilon_1 & & \\ & & \varepsilon_2 & \\ & & & \varepsilon_3 \end{pmatrix}$$

Invert A = "*probe* ***all phase space***"



$$A_{fb}^{data} = 0.099 \pm 0.045$$

$$A_{fb}^{bkg-sub} = 0.13 \pm 0.06$$

$$A_{fb}^{measured} = 0.17 \pm (0.07)_{stat} + (0.04)_{sys}$$

2σ higher than theory
0.04 ± 0.01

Summary

DØ and CDF measurements of the forward-backward asymmetry $\mathbf{A_{fb}}$ in top pair production have been presented, testing perturbative QCD predictions @ **NLO**

Integrated A_{fb} strongly depends on the probed phase space

A_{fb} sensitive to new physics

= 4 jets   vs   ≥ 5 jets

Results for ≥ 4 jets

DØ (0.9 fb^{-1}) :

$$A_{fb} = 12 \pm 8(stat) \pm 1(syst)\% \qquad A_{fb}^{MC@NLO} = 0.8 \pm 0.2(stat) \pm 1.0(syst)\%$$

CDF (1.9 fb^{-1}) analysis I :

$$A_{fb} = 24 \pm 13(stat) \pm 4(syst)\% \qquad A_{fb}^{MC@NLO} = 4-7\%$$

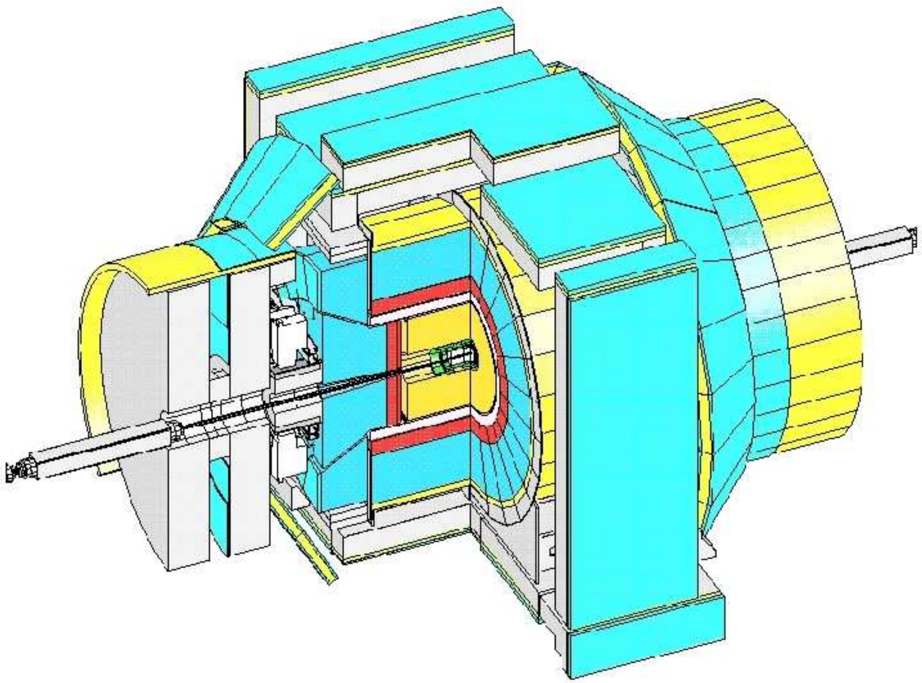
CDF (1.9 fb^{-1}) analysis II :

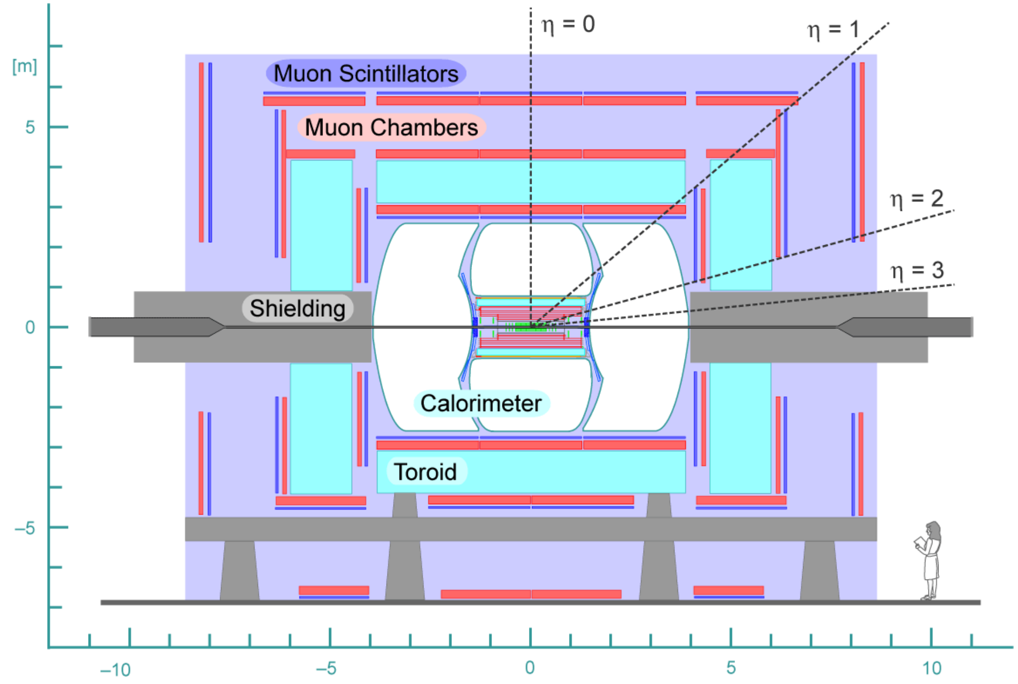
$$A_{fb} = 17 \pm 7(stat) \pm 4(syst)\% \qquad A_{fb}^{\text{Kühn and Rodrigo}} = 4 \pm 1\%$$

Still consistent with SM expectations, for now…

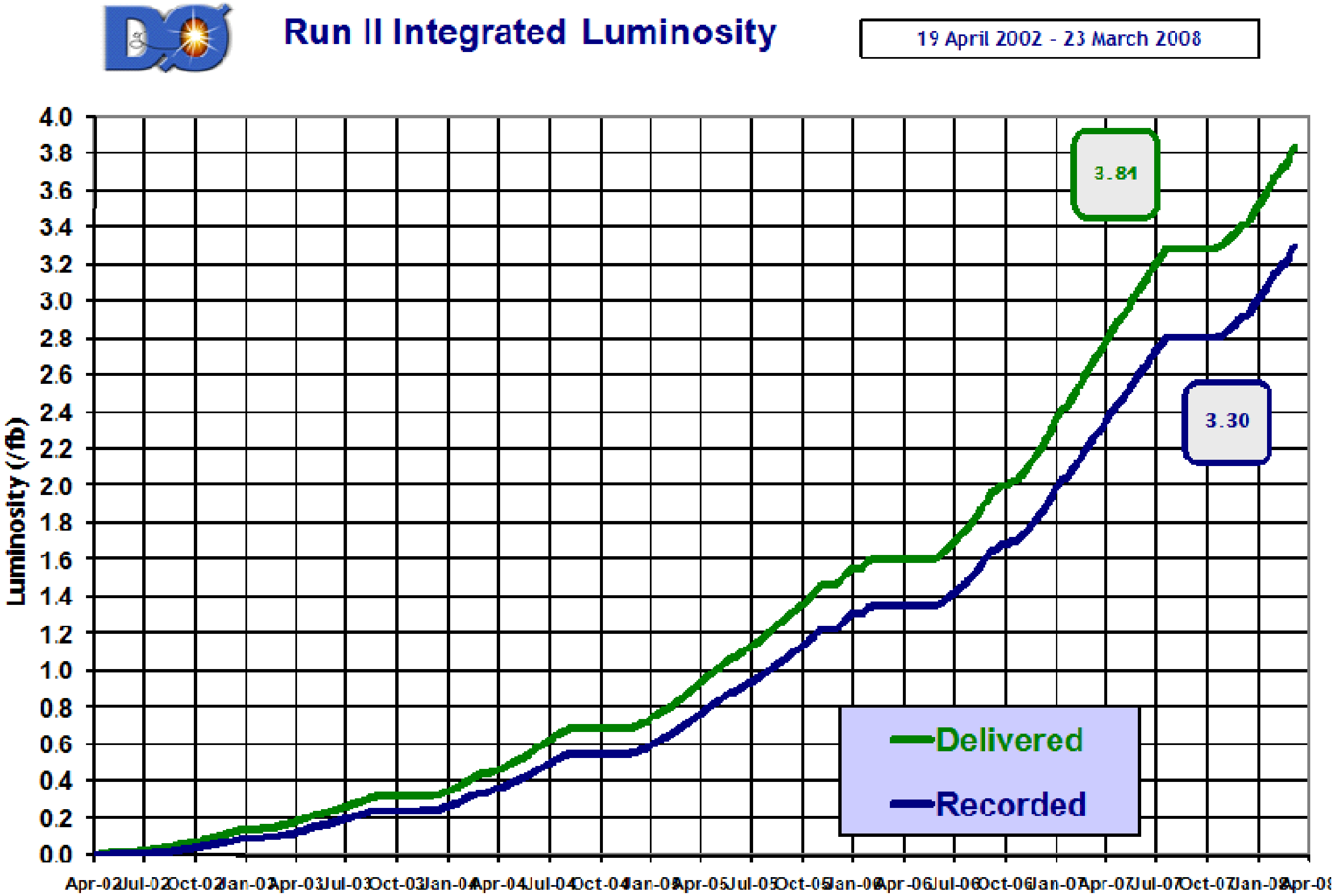
Backup

CDF and DØ detectors





Tevatron

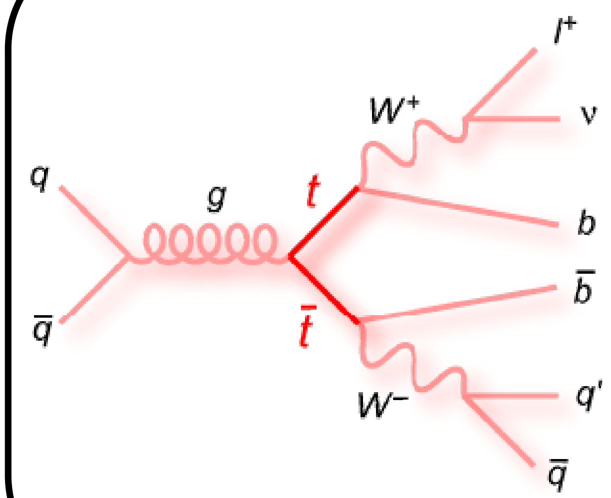

Run II Integrated Luminosity
19 April 2002 - 23 March 2008
Luminosity (/fb)
3.84
3.30
Delivered
Recorded

Kinematics reconstruction

General approach for l+jets :

Minimize a χ^2 , trying different jet-to-parton assignments, with constrains on reconstructed W masses and top masses

Can make use of b-tagging information to reduce the number of combinations



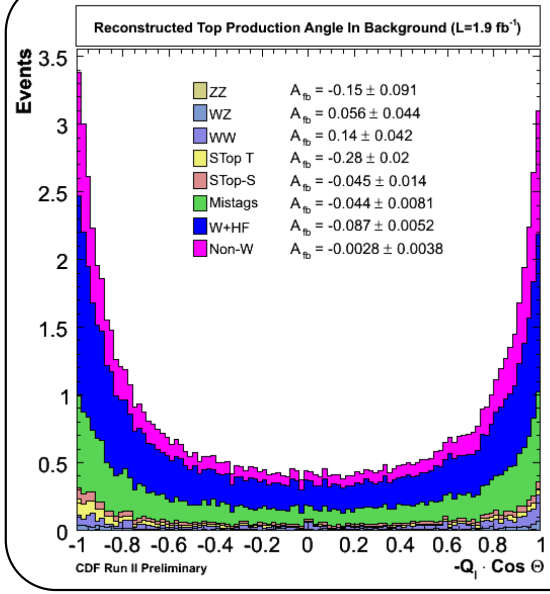
One example :

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

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

Corrections to raw A_{fb}

Bkg sub.



Bkg subtracted from the **$-Q_l$.cosΘ** data distribution

$$A_{fb}^{Total\ Bkg} = -0.05 \pm 0.01$$

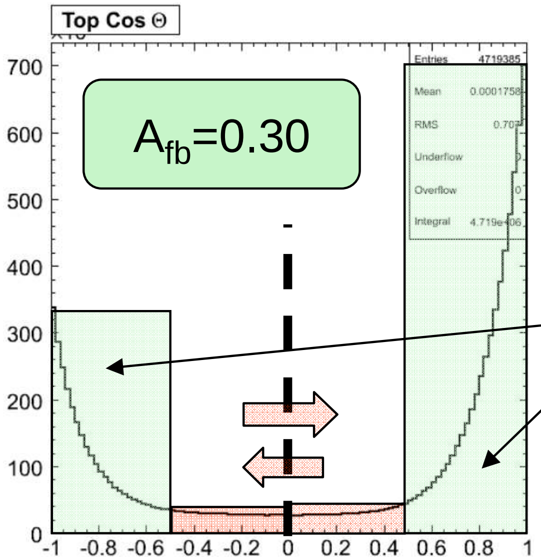
$$N_{corrected} = A^{-1} \cdot S^{-1} \cdot N_{bkg-sub}$$

Acceptance

A = ε (after selection / generator-level)

→ Invert A = “*probe all phase space*”

Smearing



Most events unlikely to cross the forward/backward limit

Why a 4x4 matrix ?

Smearing matrix derived with symmetric MC

→ relatively more events in bin

i.e. larger smearing effects

Choose a “fine binning” not to overestimate corrections

A_{fb}^{True}	2x2	4x4	10x10
0.3	0.35 ± 0.01	0.31±0.01	0.31 ±0.01