A_{FB} at the Tevatron

Amnon Harel

University of Rochester

4th International Workshop on Top Quark Physics

September 25 - 30, 2011

Sant Feliu de Guixols, Spain

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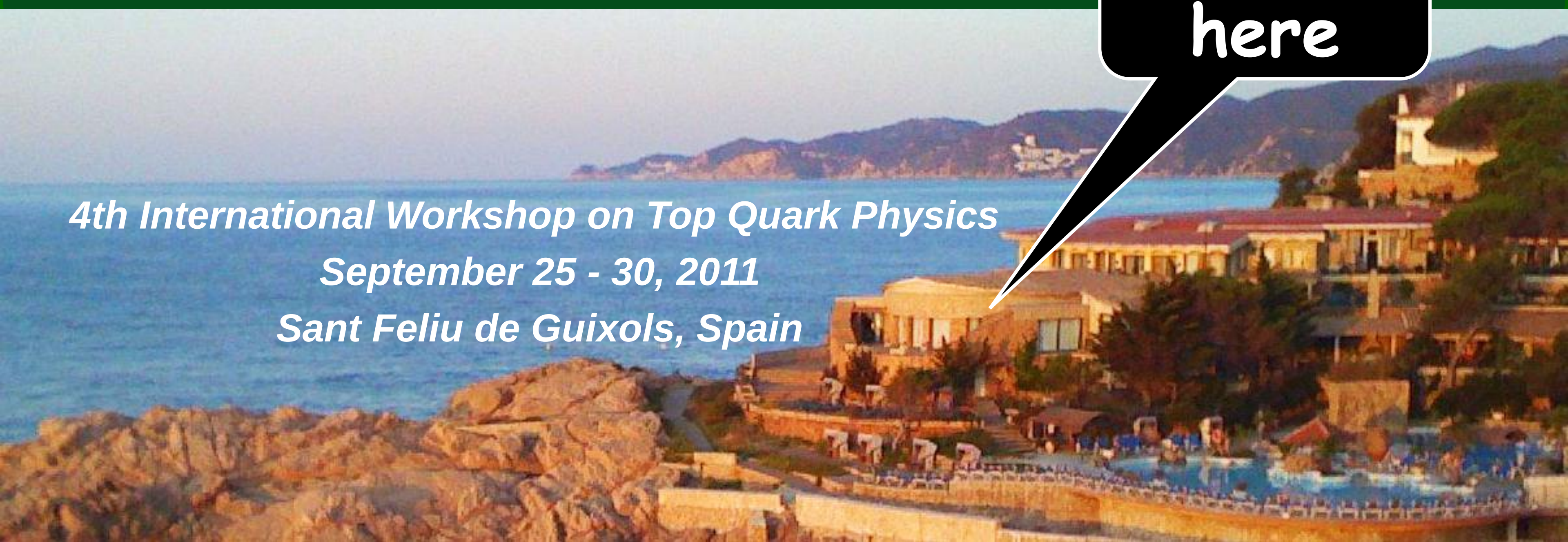

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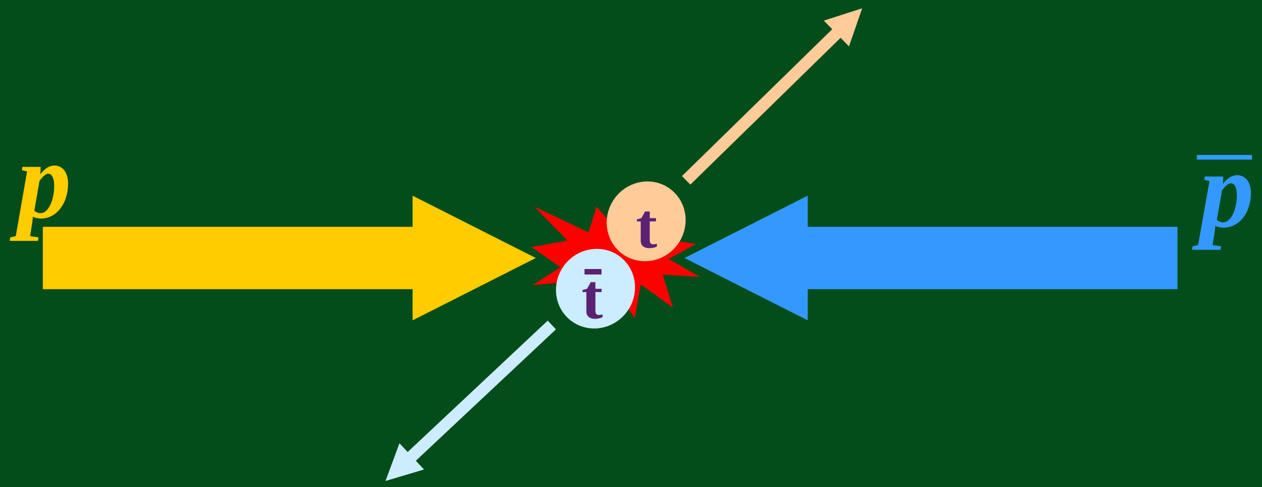
Forward-Backward?

Is it the top or the antitop that is produced preferentially in the direction of the incoming proton?



Choose an angular variable in some rest frame, and define:

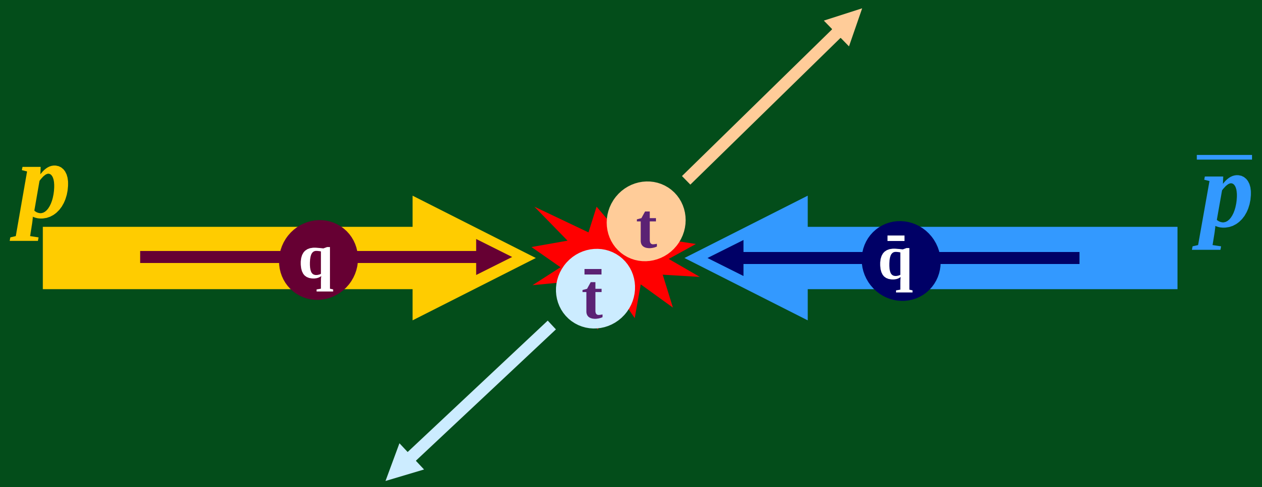
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

SM motivations

It's not about the incoming protons

It's about the incoming quarks

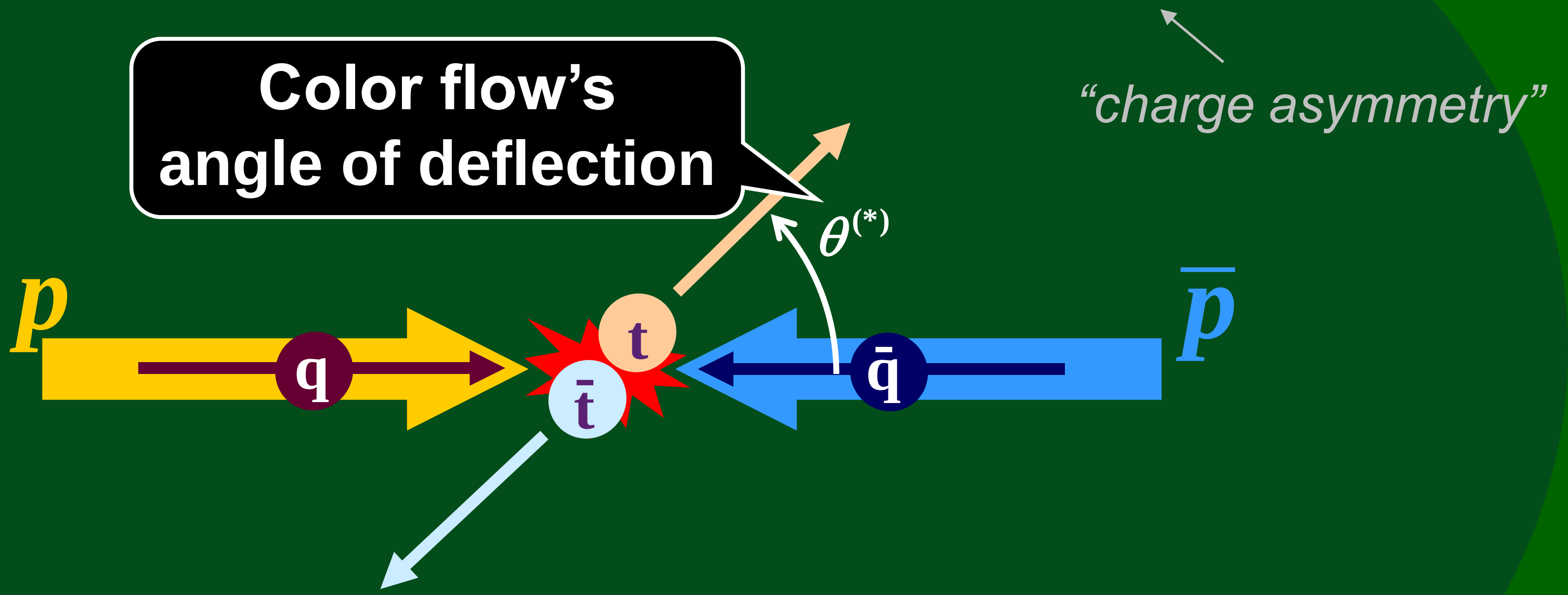
- at the Tevatron: $85\% \; q\bar{q} \rightarrow t\bar{t} + 15\% \; gg \rightarrow t\bar{t}$



SM motivations

It's not about the incoming protons

It's about the incoming quarks and their QCD charges



SM motivations

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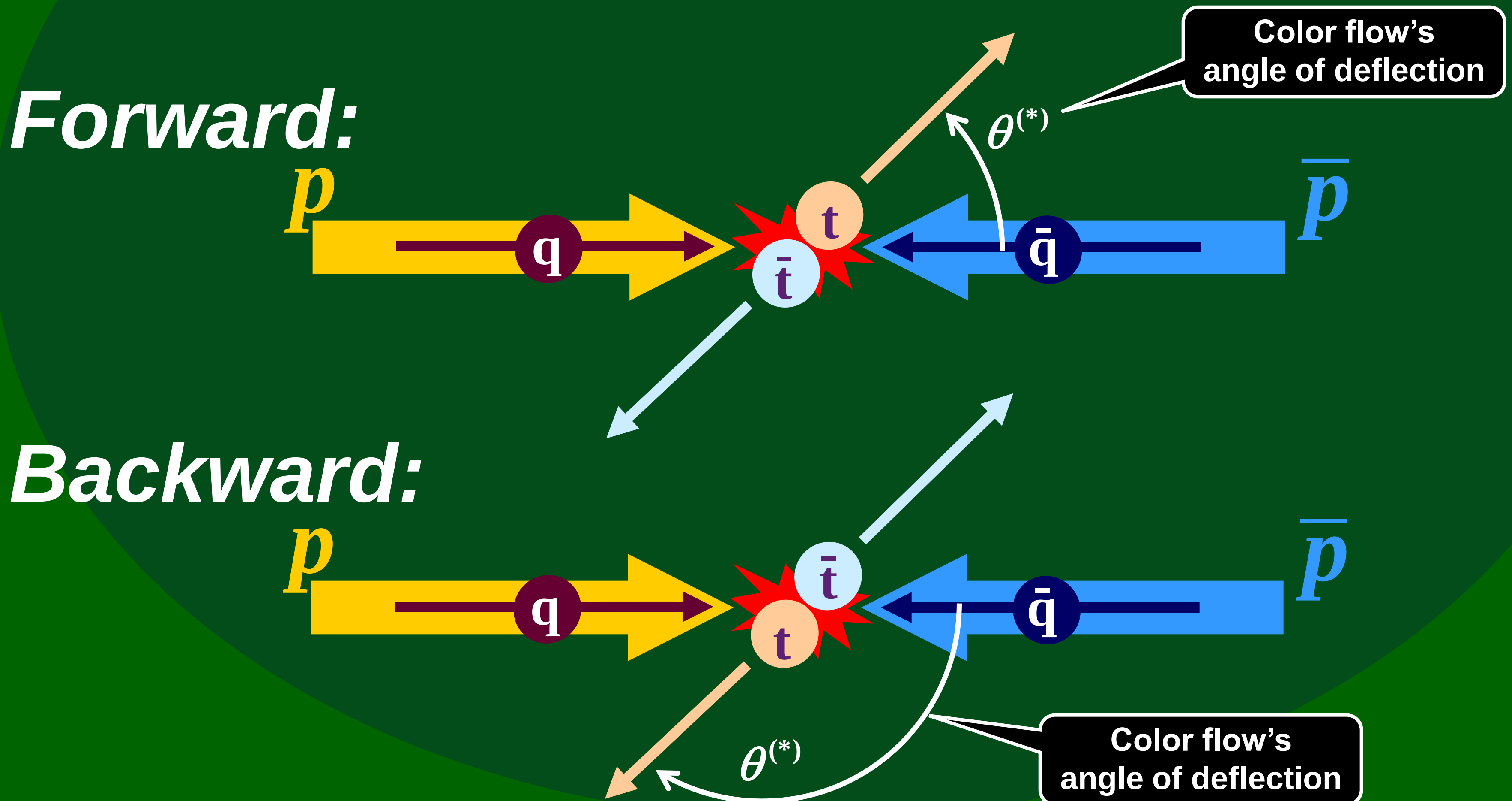
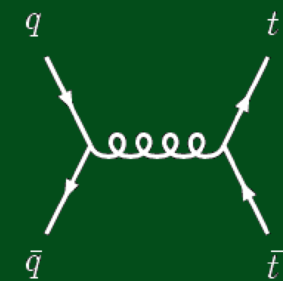


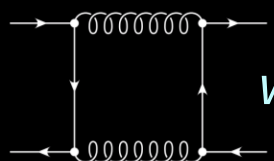
SM predictions

At order α_s^2: no preference

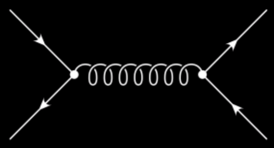


$$A_{FB}^{\alpha_s^2} = 0$$

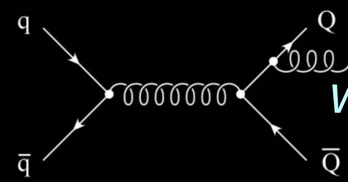
At order α_s^3: *Interference terms*



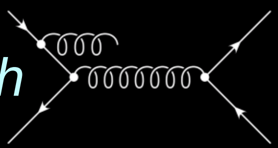
with



Enhances F



with



Enhances B

Kuhn and Rodrigo, PRL 81 (1998): $A_{FB}^{LO} = 5\%$

- incl. flavor creation, etc.
- collision frame ≈ $t\bar{t}$ frame

Ahrens et al., arXiv:1106.6051: $A_{FB}^{resum} = 7.3\%$

- LO (i.e. α_s^3 / α_s^2) + NNLL
- $t\bar{t}$ frame (also in lab frame)

Hollik and Pagani, arXiv:1107.2606: $A_{FB}^{LO+EW} \cong 9.0\%$

- $\alpha_s + \alpha_{EW} + \alpha_s^2 / \alpha_{EW}^2$
- $t\bar{t}$ frame (also in lab frame)

SM motivations

1. "Retro" style: a test of the discrete symmetries of the strong force at high energies (is QCD really the theory of the strong force?)

2. Test of challenging SM calculations
   - this is also an argument against the measurement

The above reasons got some of us into this measurement

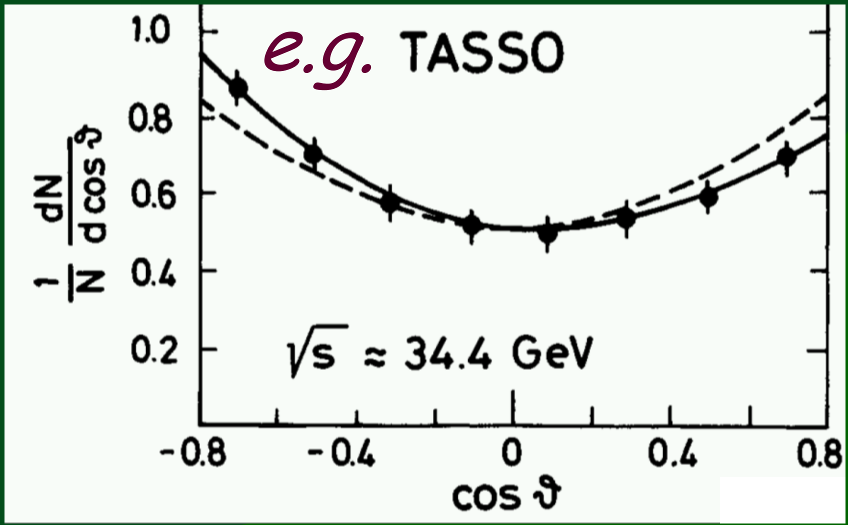
But why are you listening to this talk?

SM motivations

1. "Retro" style: a test of the discrete symmetries of the strong force at high energies (is QCD really the theory of the strong force?)

2. Test of challenging SM calculations
   - this is also an argument against the measurement

3. Small SM predictions → can identify beyond the SM physics
   - Already happened for A_{FB} and EW physics in the 80s!
     - A_{FB} in $e^+e^- \to \mu^+\mu^-$
     - $E_{c.m.}$=35GeV
     - Indication for Z resonance

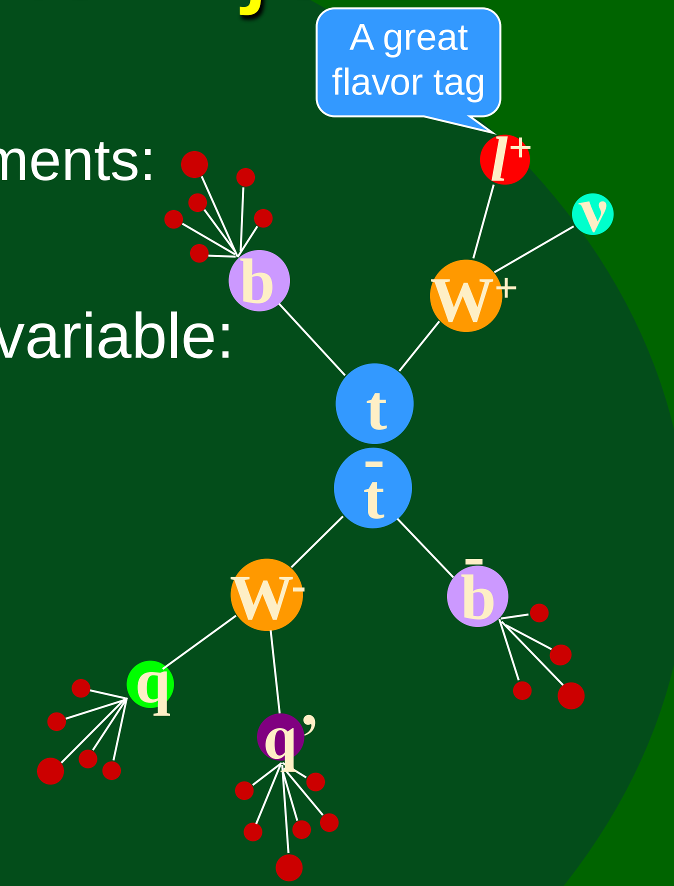


Adrian also reminded us of the LEP precedence – but little learned there

Inclusive A_{FB} in lepton+jets

Most powerful channel: lepton (e/μ) + jets

Start with the (conceptually) simplest measurements:



Inclusive measurements with the angular variable:

$$\Delta y = y_t - y_{\bar{t}} = q_l\left(y_{t,\mathrm{lep}} - y_{t,\mathrm{had}}\right)$$

- i.e. $t\bar{t}$ frame
  - Combines information from both top quarks
  - Invariant to boosts along the beam axis
- and so: $A_{\mathrm{FB}} = \frac{N(\Delta y>0)-N(\Delta y<0)}{N(\Delta y>0)+N(\Delta y<0)}$

CDF: Phys. Rev. D **83**, (2011) 112003

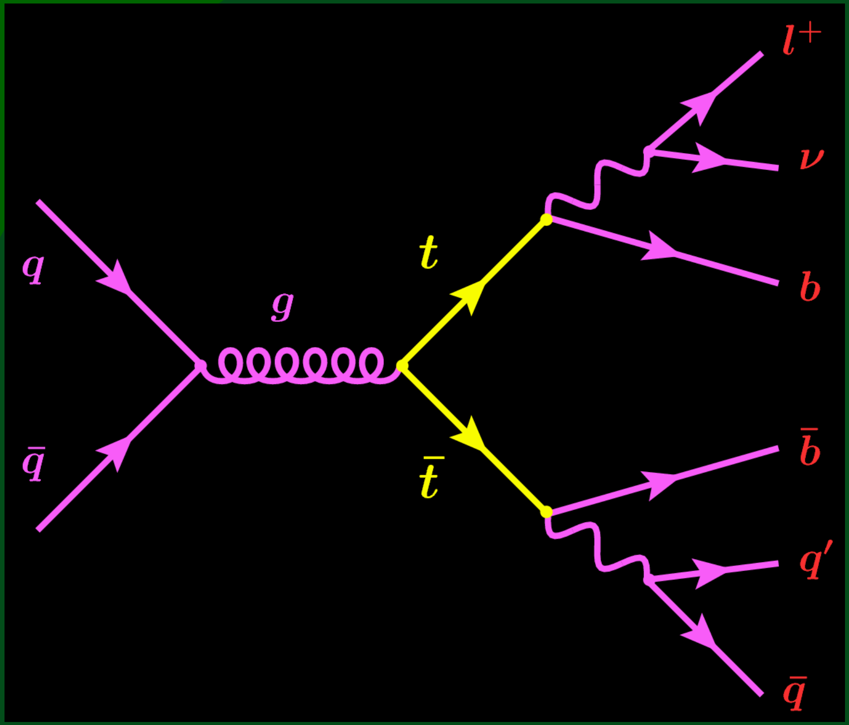
$\int \mathcal{L}\, dt = 5.3\,\mathrm{fb}^{-1}$

DØ: arXiv:1107.4995

Submitted to Phys. Rev. D

$\int \mathcal{L}\, dt = 5.4\,\mathrm{fb}^{-1}$

Selection



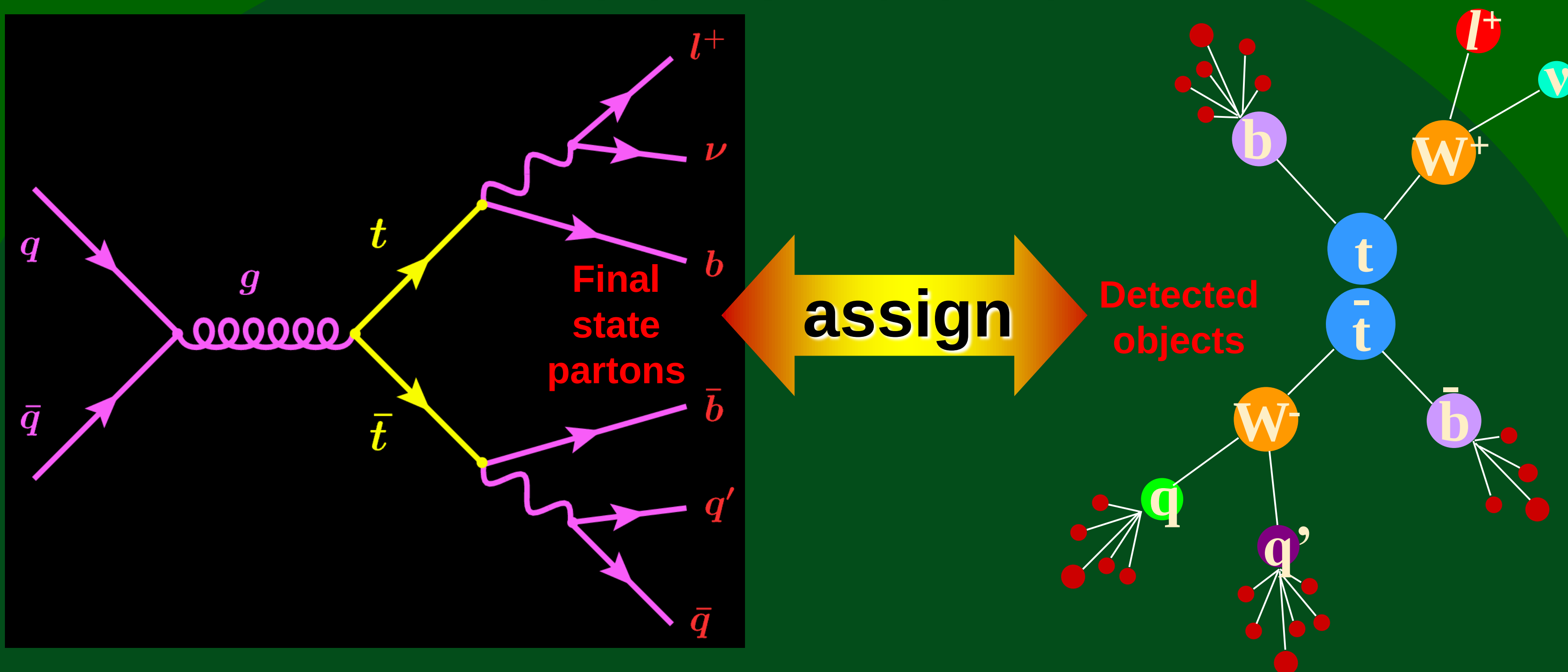
Require:

- 1 lepton with $E_T \geq 20$ GeV
  - CDF: $|\eta| < 1.1$
  - DØ: $|\eta_e| < 1.1$, $|\eta_\mu| < 2.0$
- p_T imbalance (MET) > 20 GeV
- ≥ 4 jets with $E_T \geq 20$ GeV
  - CDF: $|\eta| < 2.0$
  - DØ: $|\eta| < 2.5$
- ≥ 1 b-tagged jet

CDF:
1260 events
22% background
977 est. signal

DØ:
1581 events
29% background
1126 est. signal

Reconstruction



Assign objects to final state partons using χ^2 test statistic that accounts for experimental resolutions, *b*-tags, M_W=80.4 GeV & m_t=170 GeV

Varies object E in χ^2

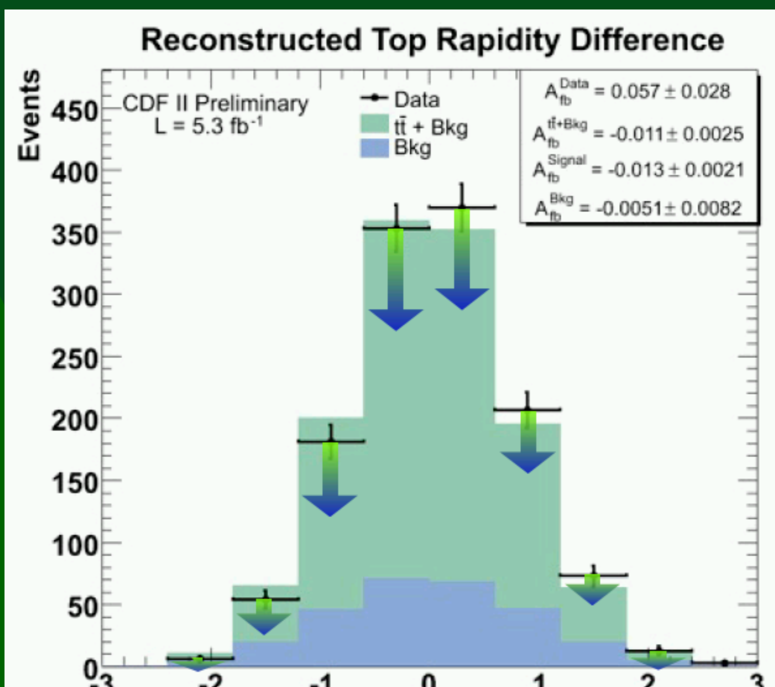
χ^2 includes Γ_W and Γ_t

Object E and direction varied and propagated into reconstruction
("kinematic fitter")

Assignment → All final state 4-vectors available. In particular, Δy

Extracting detector-level A_{FB}

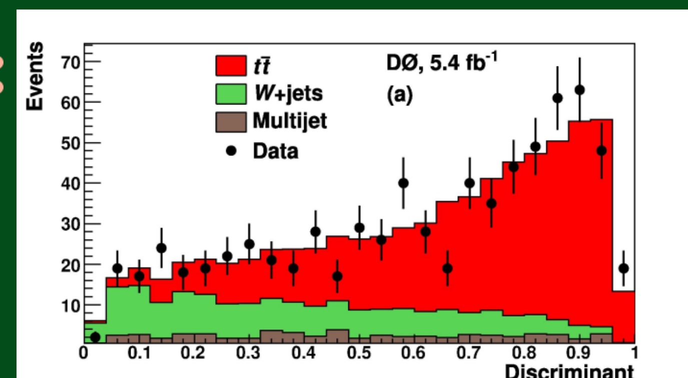
Subtract estimated background
- Estimates from x-sec measurements
  - W+jets estimated from $N_{\text{pre-}b\text{-tag}}$



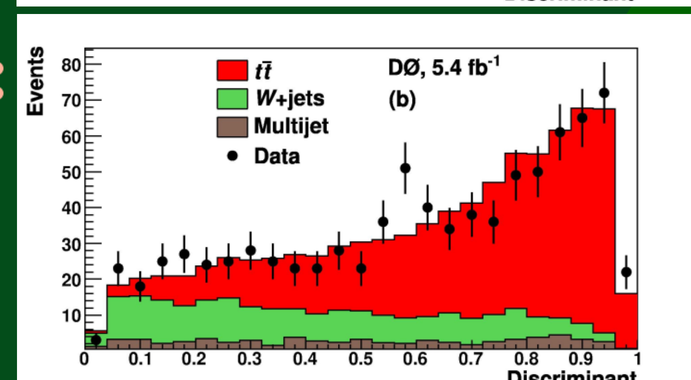
Plot from Tom Schwarz

Fit for sample composition and A_{FB}
- Discriminant for W+jets vs. signal

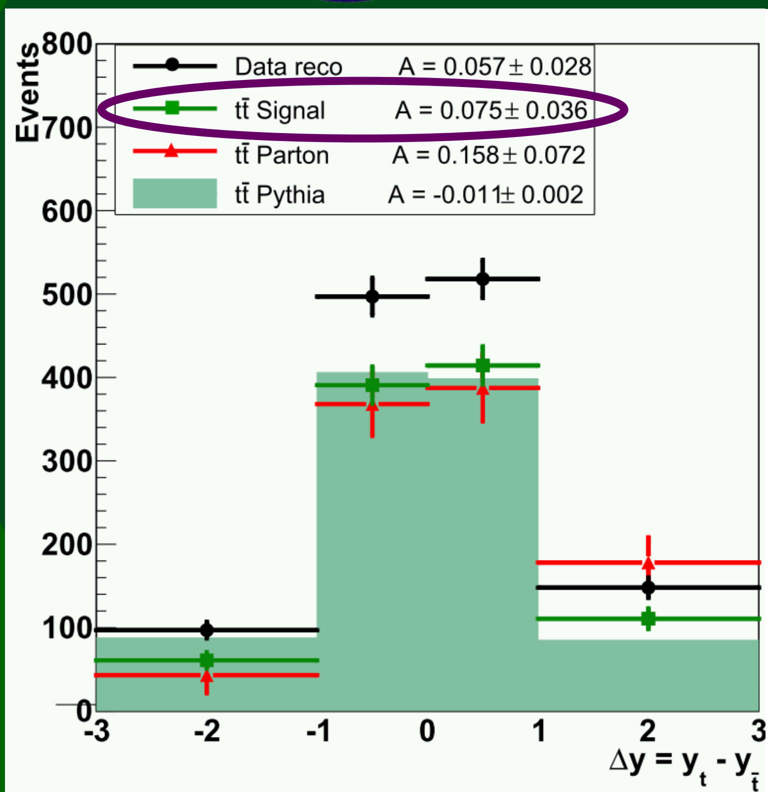
$\Delta y > 0$:

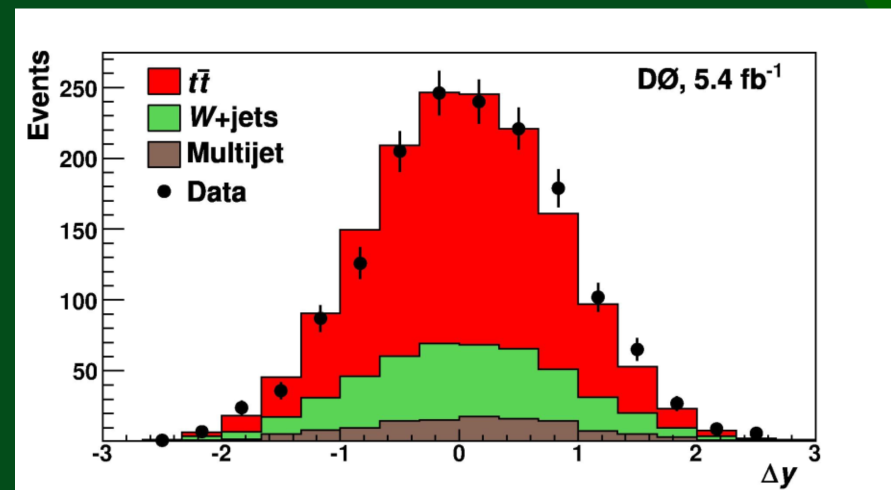


$\Delta y < 0$:



Detector-level A_{FB}s





	$l+\geq 4$ jets	$l+4$ jets	$l+\geq 5$ jets
$A_{FB}(\%)$	9.2±3.7	12.2±4.3	-3.0±7.9
MC@NLO A_{FB} (%)	2.4±0.7	3.9±0.8	-2.9±1.1

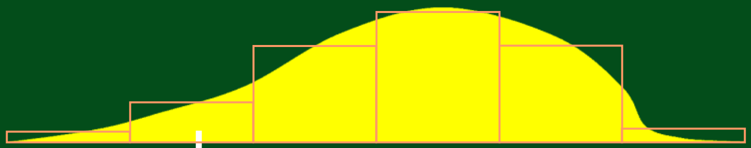
Was central to previous DØ results

Inconvenient - can't compare directly to calculations

- but possible, see PRL **100**, 142002 (2008), and PRD **83**, (2011) 114027

Unfolding inclusive A_{FB} is easy

Measure a distribution:
(in N bins)



corrections

Some components well measured, some not
→ N - dimensional info

Typical unfolding problem: how to summarize?

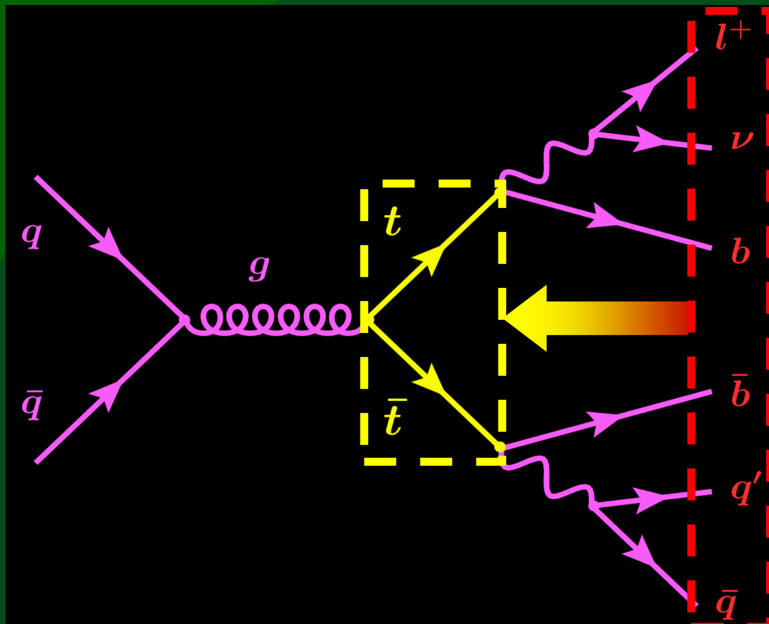
No problem: A_{FB} is the summary

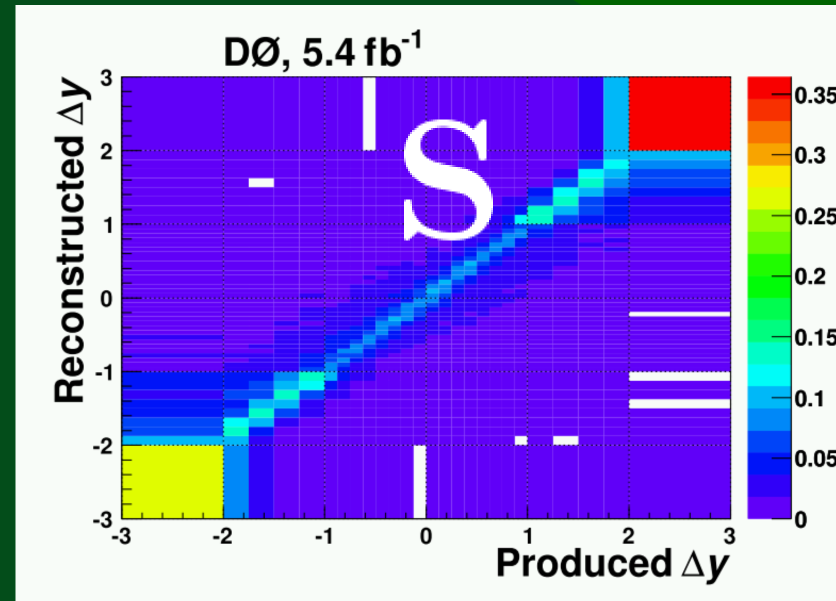
Can add regularization to suppress fluctuations

A 2D plot

$A_{\mathbf{FB}}$

Unfolding





4 bin unfolding. Δy edges: -3, -1, 0, 1, 3

$$\vec{n}_{\rm parton} = \mathbf{A}^{-1}\mathbf{S}^{-1}\left(\vec{n}_{\rm data} - \vec{n}_{\rm bkg}\right)$$

Acceptance matrix (diagonal)

Migration matrix

50→26 bin regularized unfolding

- extended TUnfold for variable binning

Improves statistical strength

- expected (if BSM)
- and observed (1.9SD → 2.4SD)

Fine-bin unfolding

Binning is crucial to unfolding (an implicit regularization)

- Narrow bins near Δy=0 boundary to fully describe migrations
- Wide bins at high |Δy| due to limited MC statistics

Regularization term based on continuous curvature of density

- Curvature → sum of absolute value of discrete 2nd derivative
- Density = diff. x-sec rather than bin counts → need to account for bin widths

Regularization strength ***balances***

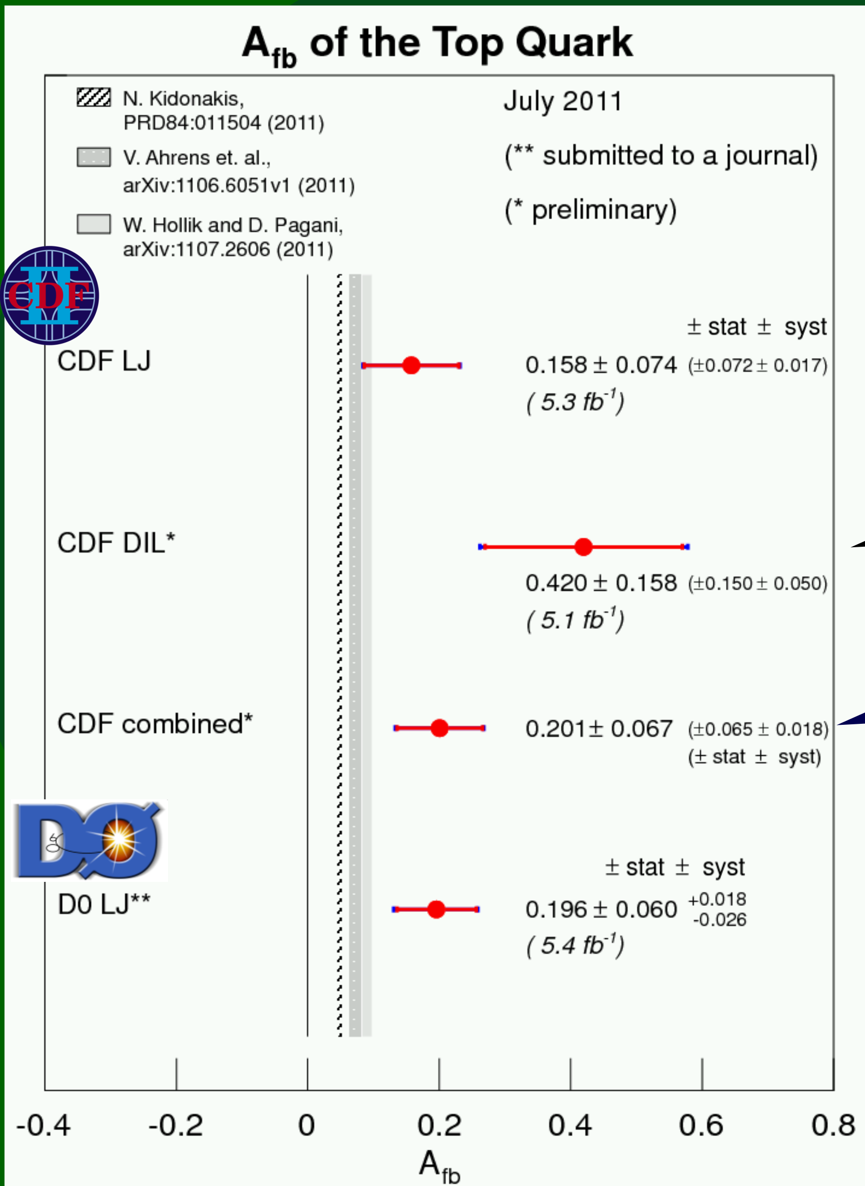
- statistical strength
- bias – we correct for bias on A_{FB}, but it's still an issue since…

Bias is model dependent

- Examines dozens of generator-level distributions (i.e. alternative models)
- Systematic uncertainties cover all realistic cases
- To invalidate systematic uncertainties: sharp bin-to-bin jumps.
  - 26 generator level bins…
  - s-channel narrow resonances have sharp edges – but already ruled out (Tuesday)

l+jets

Production-level A_{FB}s



Inclusive, Δy-based A_{FB}s

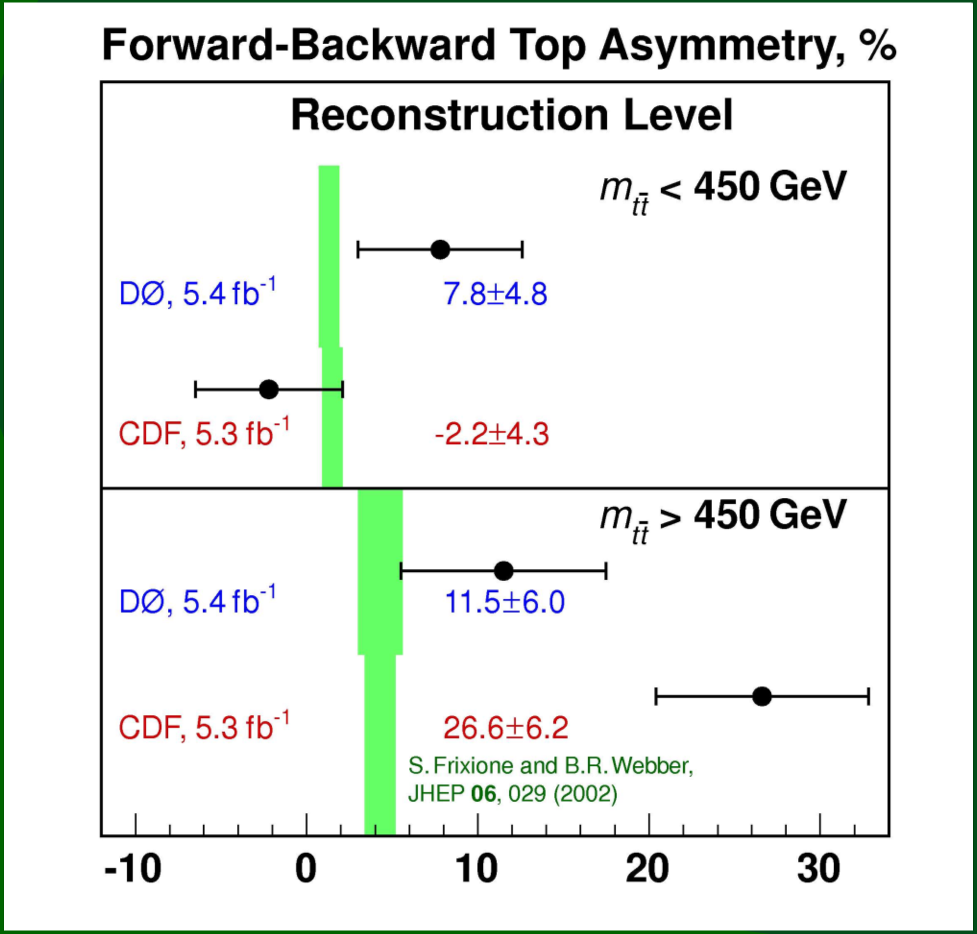
Dileptons - In a few slides…

CDF Note #10584

Mass dependence – det. level

BSM contributions to AFB will change its dependence on $m_{t\bar{t}}$

- BSM contributions often through BSM+SM interference
- CDF introduced cut at $m_{t\bar{t}} = 450\ \mathrm{GeV}$, cut value optimized on MC

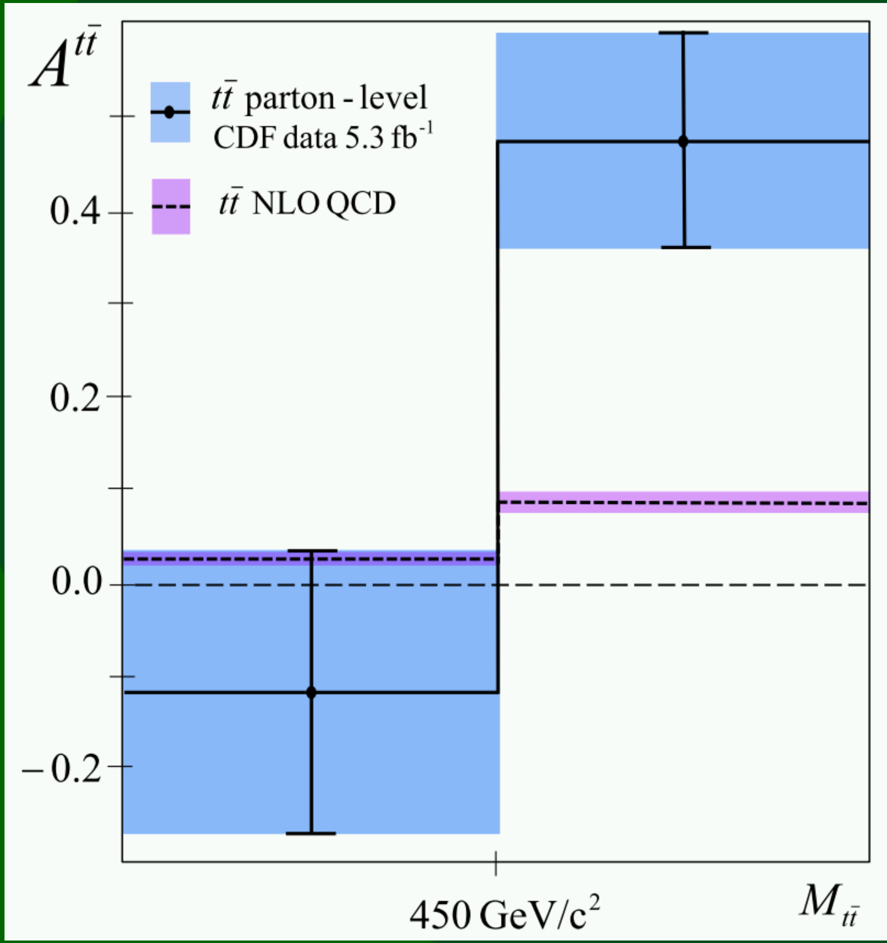


CDF di-lepton data also suggests a mass dependence:

$$\Delta A_{\mathrm{FB}}^{\mathrm{raw}} = (11 \pm 12)\%$$

Mass dependence – CDF prod.

Having observed a mass dependence, CDF reports also at production level. 4 bin unfolding



A 3σ discrepancy:

$$A_{\mathrm{FB}} = (48 \pm 11\,(\mathrm{total}))\%$$

vs.

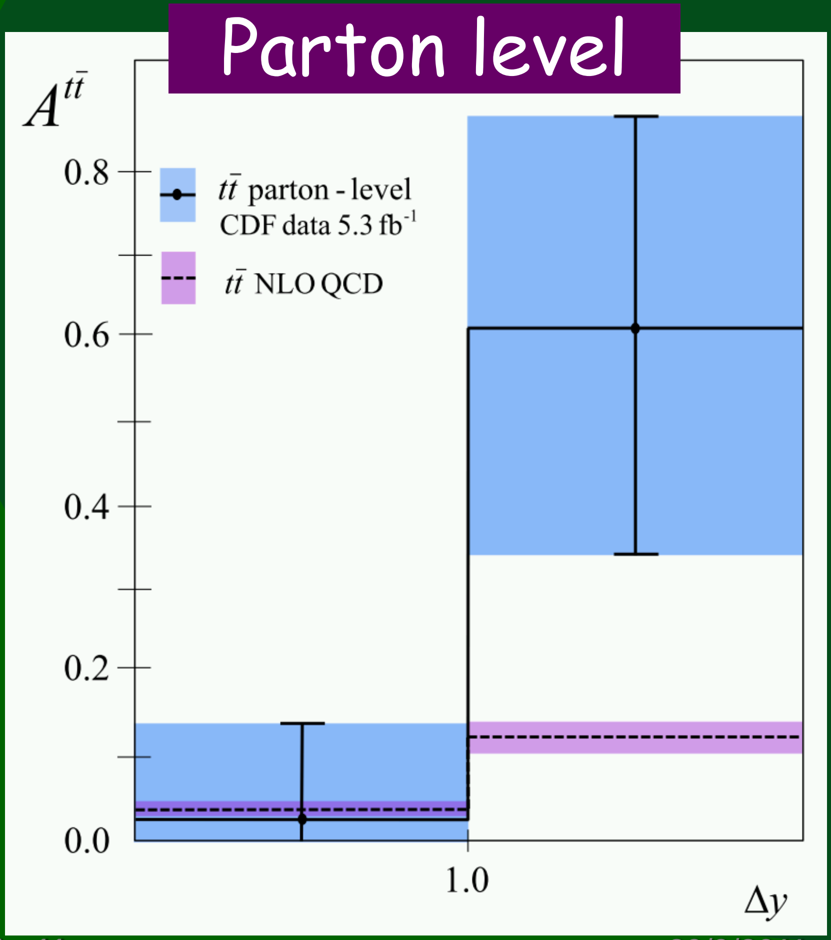
$$A_{\mathrm{FB}}^{\mathrm{MCFM}} = (9 \pm 1)\%$$

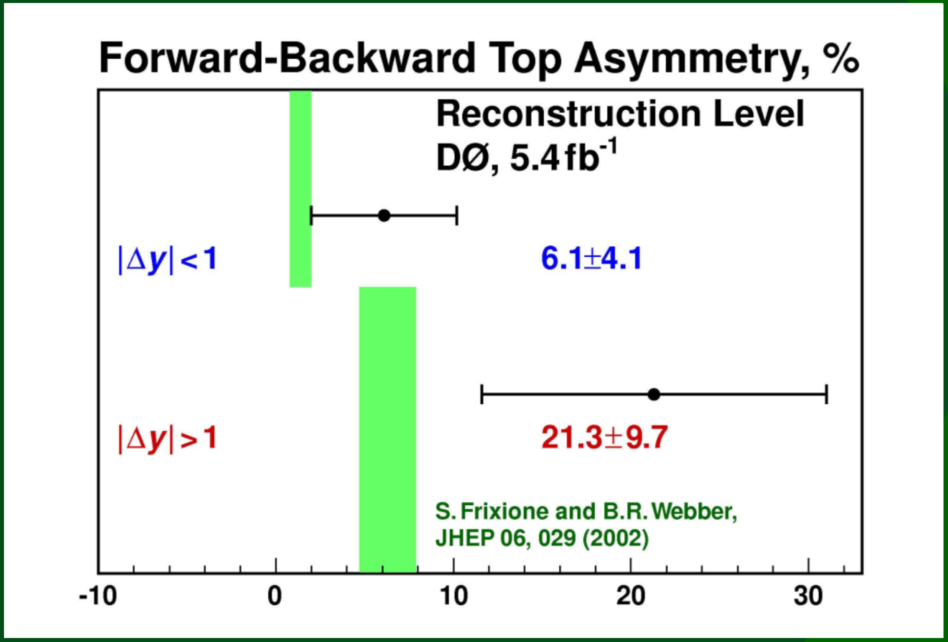
→ lots excitement

and it's at high mass
→ lots of BSM papers

Statistical significance at high mass 3.4 SD – not enhanced by unfolding

|Δy| dependence

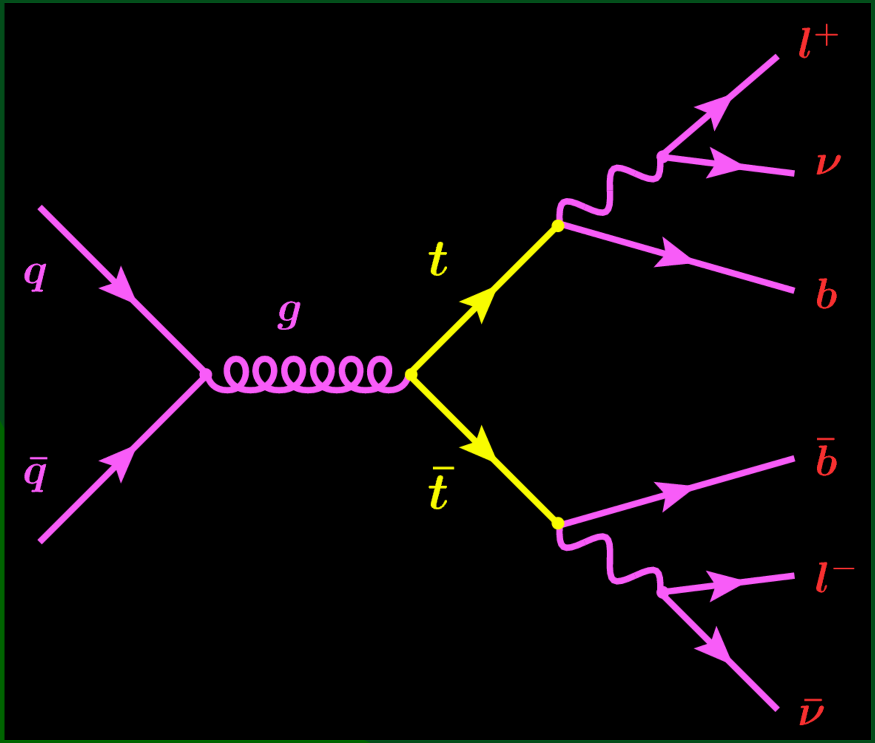




Di-lepton selection

CDF note 10436

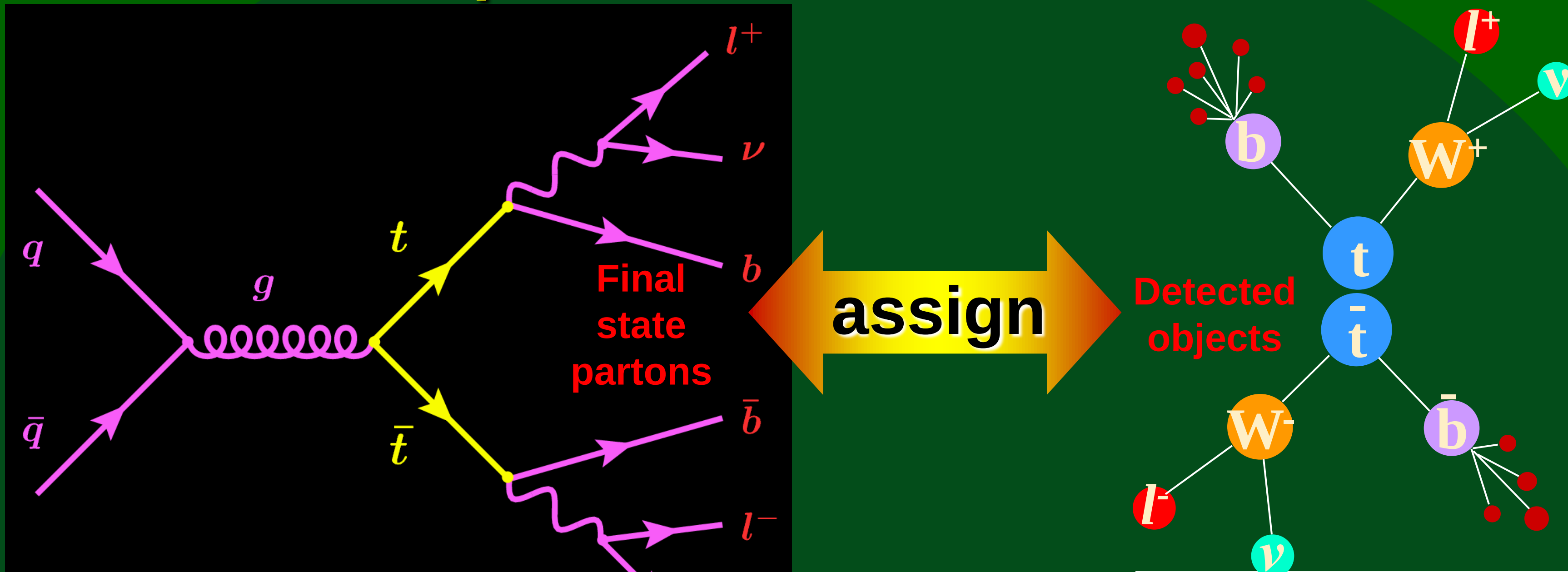
$$\int \mathcal{L}\, dt = 5.1\,\mathrm{fb}^{-1}$$

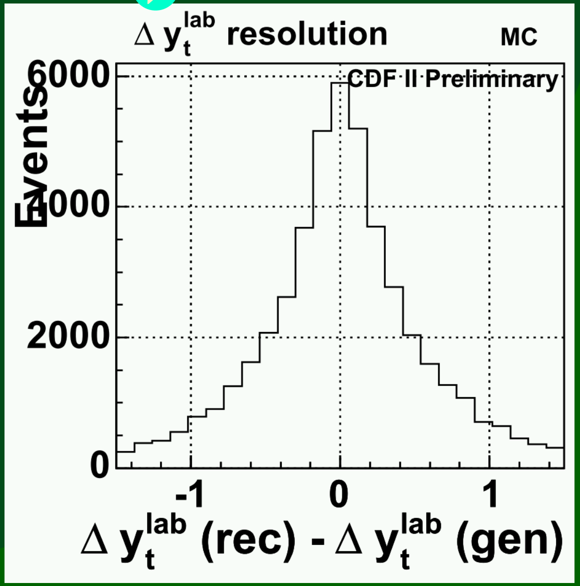


Require:

- 2 lepton with $E_T \geq 20$ GeV,
  - $|\eta_e| < 1.1$ or $1.2 < |\eta_e| < 2.8$, $|\eta_\mu| < 1.1$
- p_T imbalance (MET) > **25 or 50** GeV
  - depending on angular separation
- ≥ 2 jets with $E_T \geq 15$ GeV, $|\eta| < 2.5$
- $H_T > 200$ GeV
  - scalar sum: lepton, jet ETs + MET

Di-lepton reconstruction





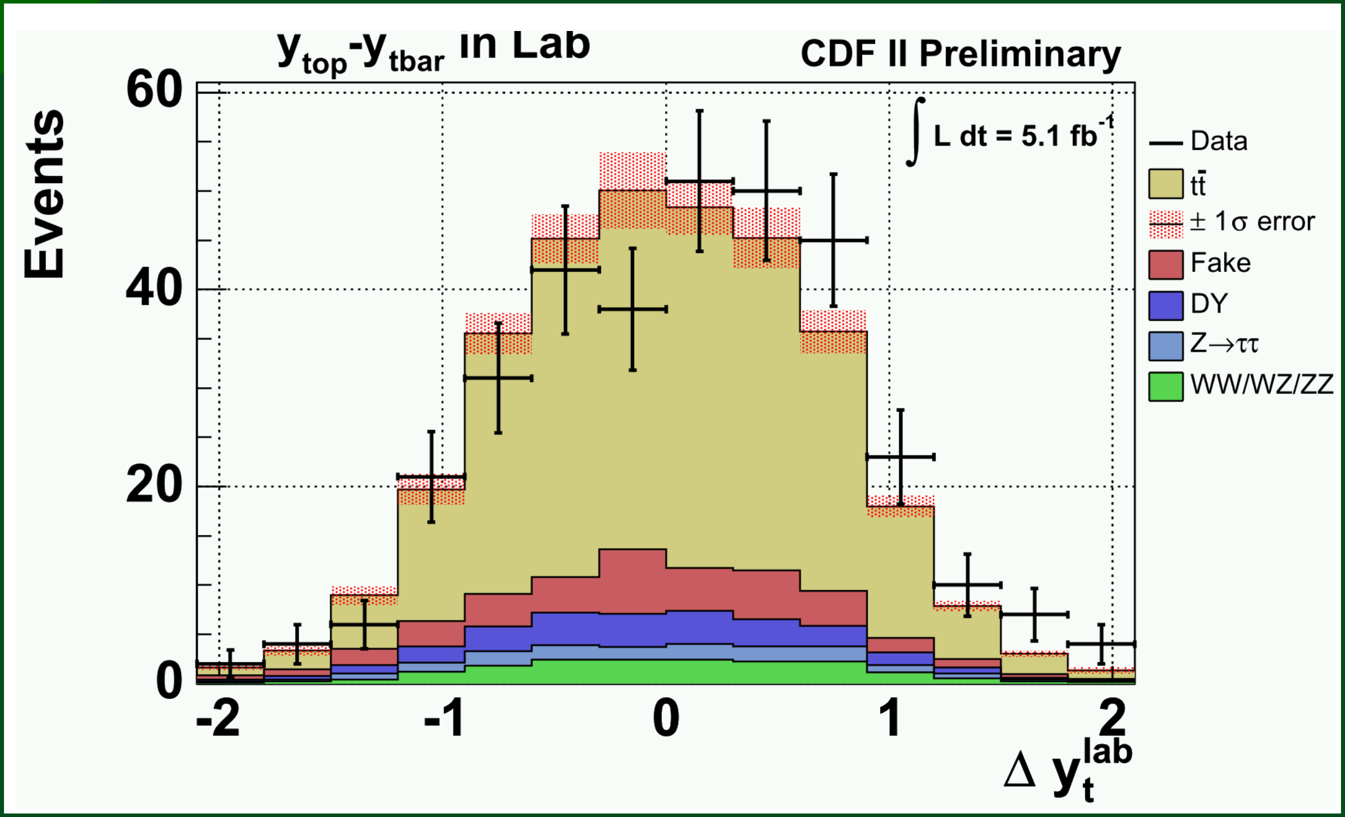
Again: kinematic fitting, χ^2 test statistic.

But fewer observables →difficult reconstruction

→also use a-priori distributions of $p_T^{t\bar{t}}, p_z^{t\bar{t}}$ and $m_{t\bar{t}}$

Excellent Δy reconstruction achieved!

A_{FB} in dileptons



A_{FB} extracted in two steps:

1. Background subtraction: $A_{\mathbf{FB}}^{\mathbf{raw}} = (14 \pm 5)\,\% \rightarrow A_{\mathbf{FB}}^{\mathbf{sub}} = (21 \pm 7)\,\%$
2. Assume A_{FB} is linear in Δy, to find $A_{\mathbf{FB}} = (42 \pm 15\,(\mathbf{stat}) \pm 4\,(\mathbf{syst}))\,\%$
   - Validated for Pythia, NLO QCD, axigluon models
   - 2.6σ from zero, 2.3 σ from prediction (A_{FB}=6%)

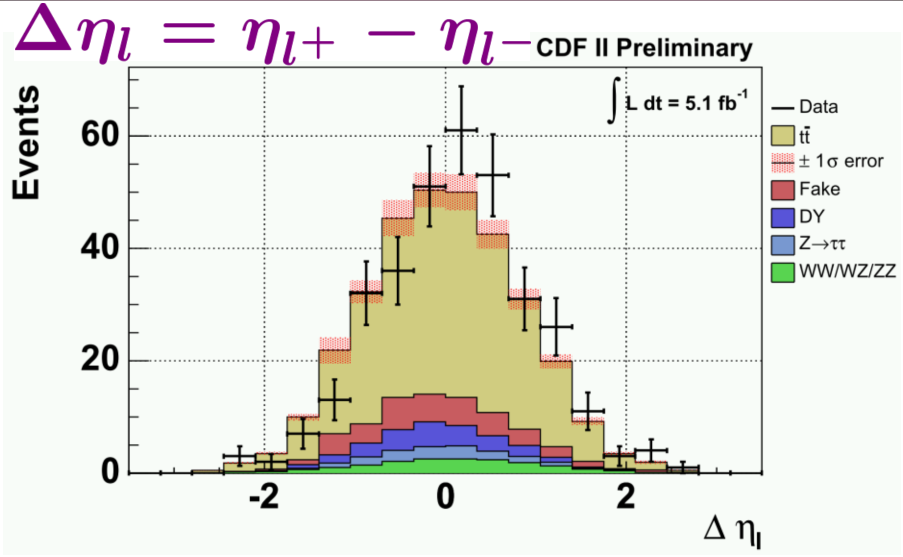
Lepton-based A_{FB}s

New angular variables → new A_{FB}s

Lepton based → Excellent resolution → Simple unfolding & interpretation

- Sensitive to the top pair A_{FB} and their polarization, but less sensitive to θ^*

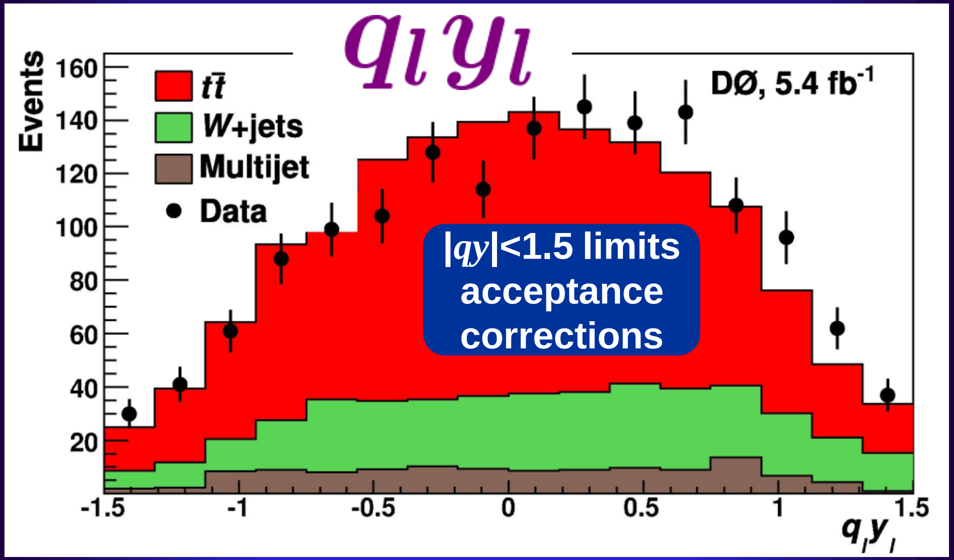
Di-lepton channel



Almost the same numbers:

$$A_{\mathrm{FB}}^{\mathrm{raw}} = (14 \pm 5)\,\% \rightarrow A_{\mathrm{FB}}^{\mathrm{sub}} = (21 \pm 7)\,\%$$

l+jets channel



	$l+\geq 4$ jets	$l+4$ jets	$l+\geq 5$ jets
A^l_{FB} (%)	14.2± 3.8	15.9± 4.3	7.0± 8.0
MC@NLO A^l_{FB} (%)	0.8± 0.6	2.1± 0.6	-3.8± 1.2

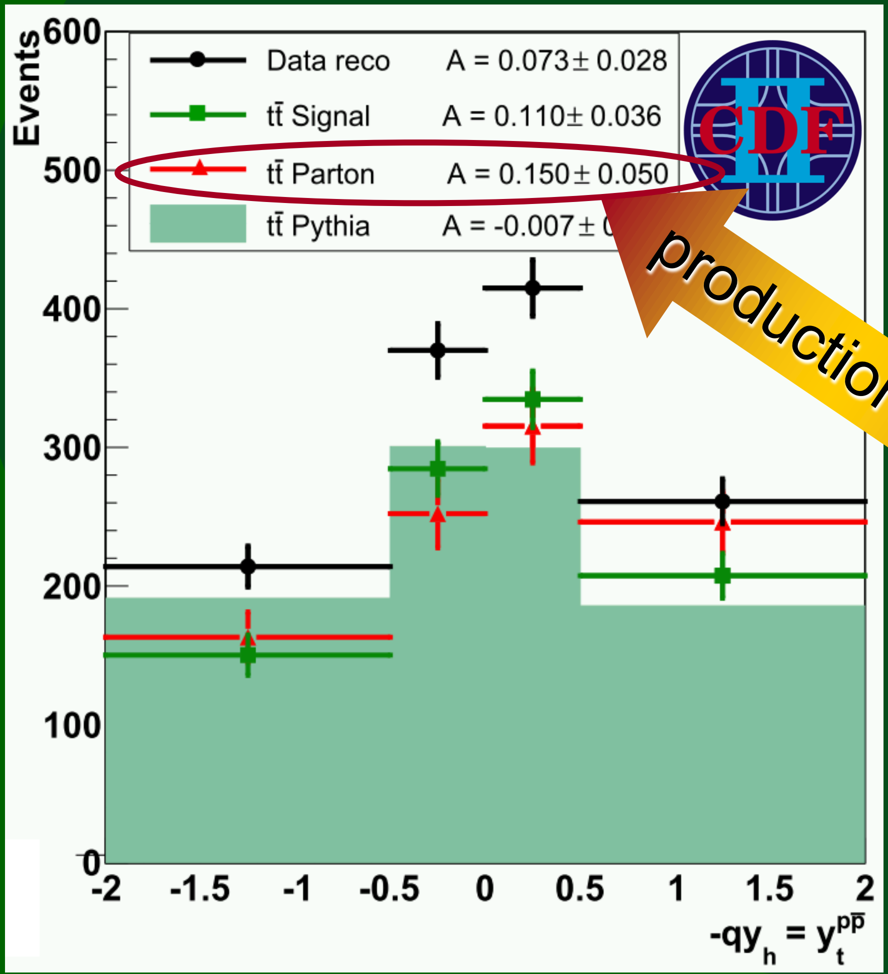
>3σ away from MC@NLO

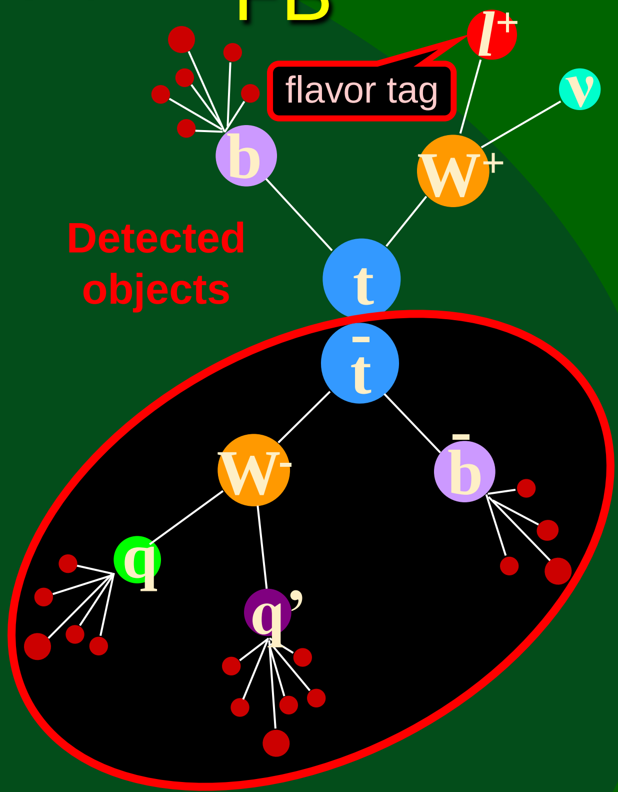
Hadronic-top based A_{FB}

New angular variables → new A_{FB}s

Use only the "hadronic" top → Better resolution

→ more stable unfolding



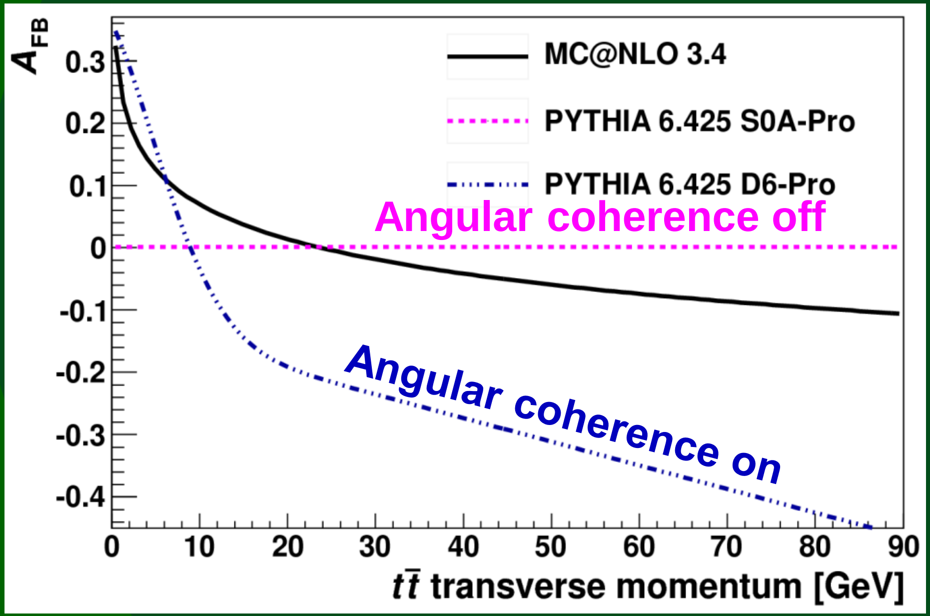


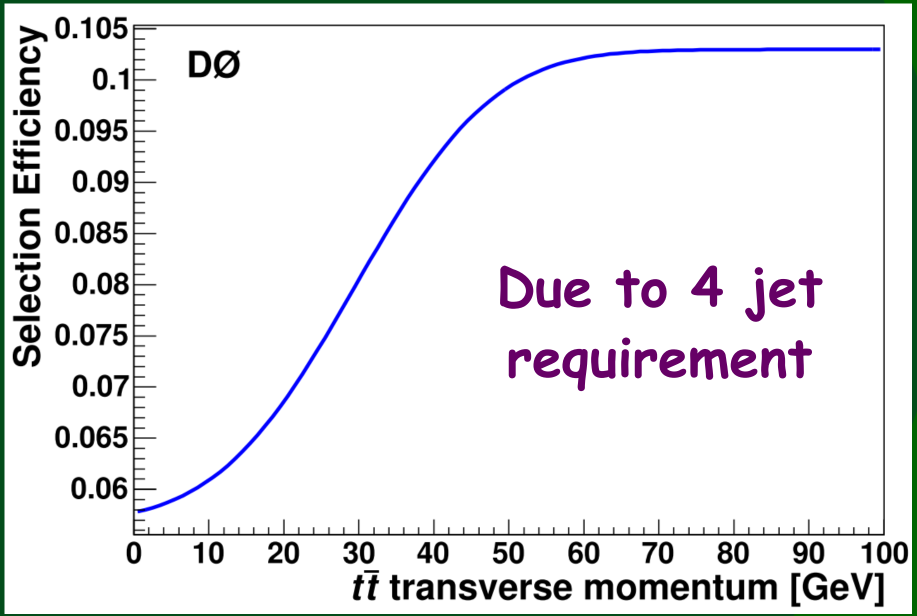
$$A_{\mathrm{FB}}^{\mathrm{MCFM}} = 3.8\%$$

- Sensitive to collision frame's boost
- Superior resolution *compensates*
- Observed less mass dependence

A related observable

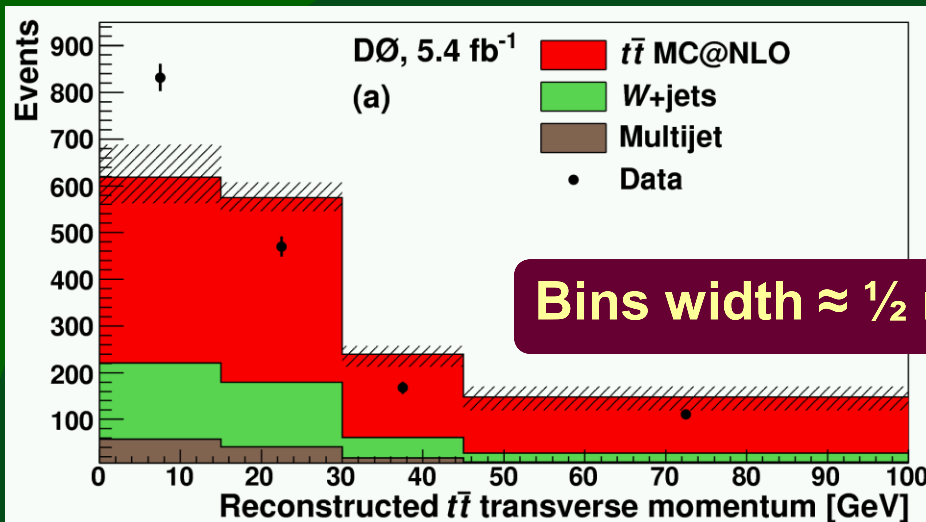
- Noted: $A_{\mathbf{FB}} \leftrightarrow p_T^{t\bar{t}}$
- Is gluon radiation the same in forward an backward events?
  - experimental constraints are few and indirect

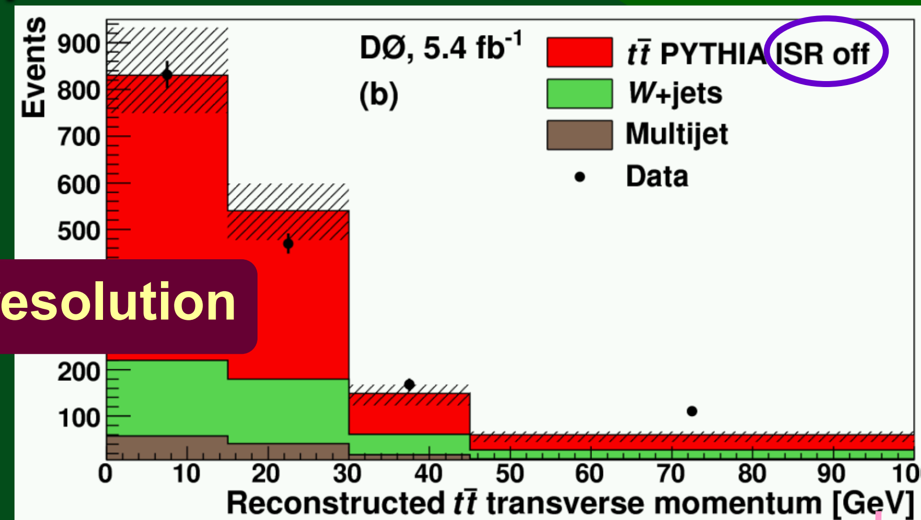




- If correlation exists, backward events selected more often than forward events
- One of the leading systematic uncertainties
  - newly identified → conservative estimate by turning dependence off → -1.6%(absolute)
  - all measurements are statistics dominated → will not invalidate any measurement

Top pair p_T modeling



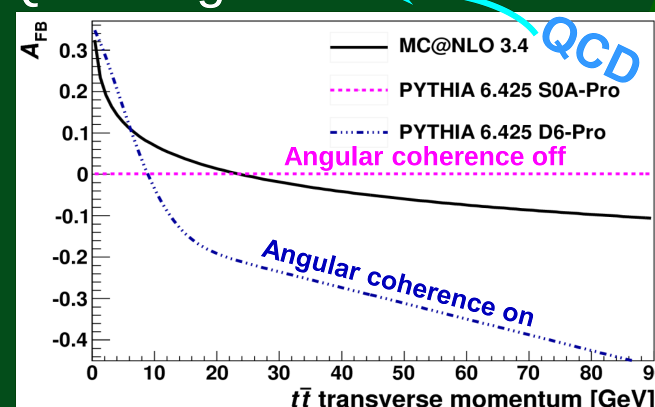


Bins width ≈ ½ resolution

- Drastic change needed to get simulation closer to data
  - → top pair p_T badly modeled (A_{FB} measurements still OK – see prev. slide)
  - → effect in the same direction as A_{FB} – hints at QCD origin?

data

QCD



- But: a check – *not a full measurement*
  - reconstruction not tweaked for observable
    - → very low resolution
  - discriminant correlated with top pair p_T
  - partial systematic uncertainties
  - no unfolding

Calls for a dedicated measurement of top pair p_T

Conclusions

- Several "top forward backward asymmetries" measured
  - they are all very correlated
- Deviations from SM predictions of ~2-3σ
- Two >3σ differences:

1) CDF: *l*+jets, high mass, Δy-based
   - exciting as indicates BSM
   - but mass dependence is marginal in DØ data

2) DØ: *l*+jets, inclusive, lepton-based
   - but less sensitive to most BSM scenarios than Δy-based A_{FB}

Conclusions

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     - exciting as indicates BSM
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  2) DØ: *l*+jets, inclusive, lepton-based
     - but less sensitive to most BSM scenarios than Δy-based A_{FB}
- SM predictions creeping upwards?
  - combining CDF & DØ on the back of an envelop:
    tension with LO prediction >3σ, but with Hollik & Pagani <3σ

Homework assignment:

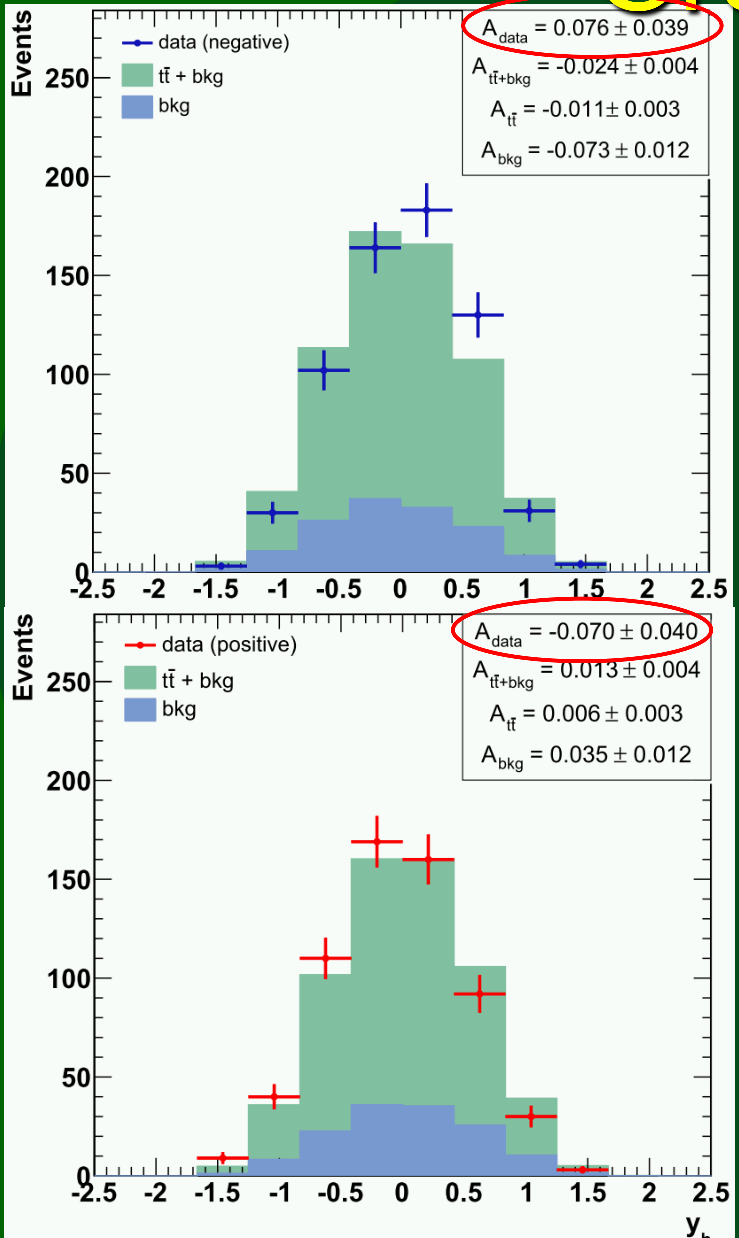
Cook up a BSM scenario where the CDF di-lepton result supports both 1&2

- More data on the way
- More channels
- Analysis improvements?

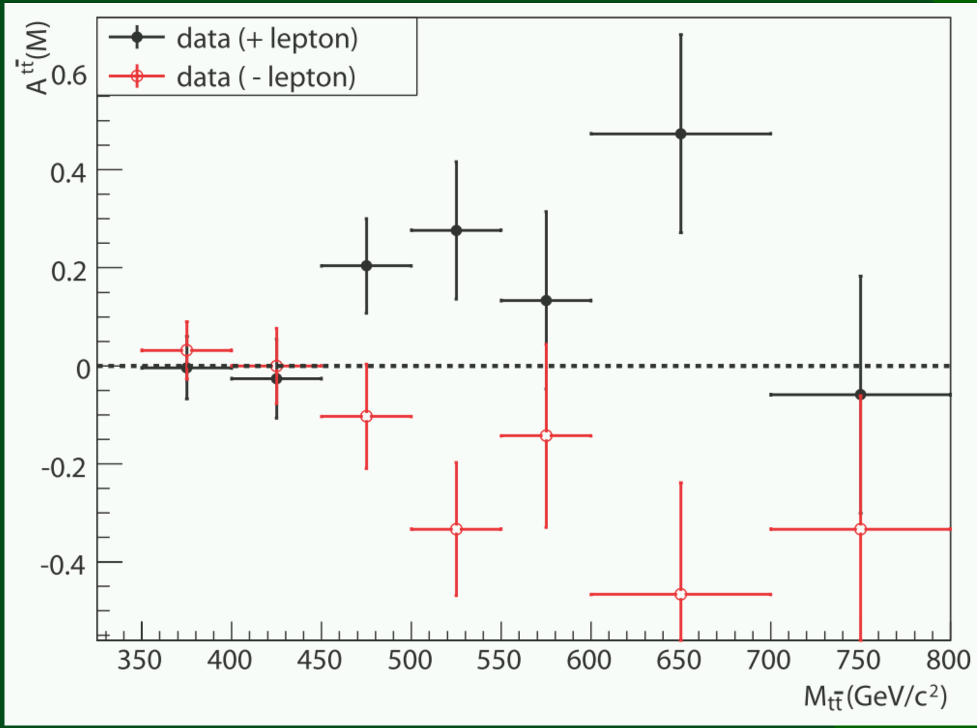
→ ***Stay tuned!***

Back up slides

Cross checks



Should we combine A_{FB}^{t} and $A_{FB}^{\bar{t}}$?



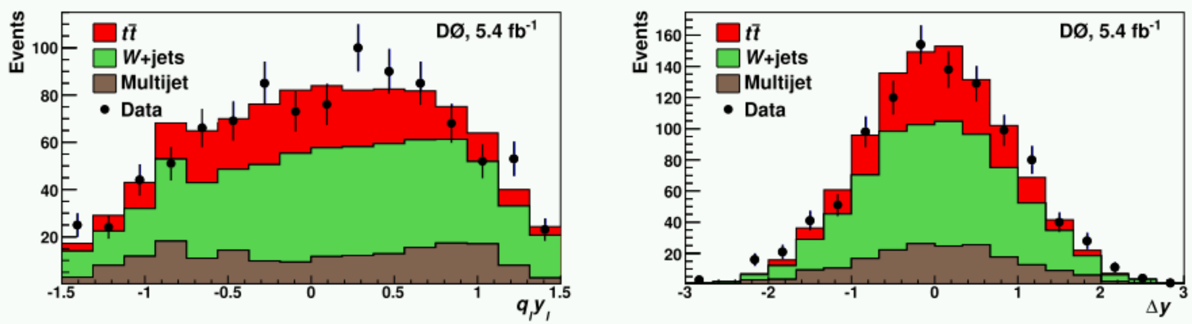
Black vs. red – a check of CP violation

- **Should be opposite in this presentation**

Cross checks

Cross checks

- Simultaneously measured A_{FB} for $t\bar{t}$ and W+jets
  - Also included events with 0 b-tags
  - Measured A_{FB} for W+jets in good agreement with simulation



- Checked A_{FB} by solenoid and toroid polarities
  - Found no significant dependence
- Checked A_{FB} by lepton charge
  - Found no significant dependence
- Good agreement between e+jets and μ+jets

CDF data (no bkg. sub.)

selection	$A^{\mathrm{t\bar{t}}}$	$A^{\mathrm{p\bar{p}}}$
inclusive	0.057 ± 0.028	0.073 ± 0.028
electrons	0.026 ± 0.037	0.053 ± 0.037
muons	0.105 ± 0.043	0.099 ± 0.043
single b-tags	0.058 ± 0.031	0.095 ± 0.032
double b-tags	0.053 ± 0.059	-0.004 ± 0.060

More on unfolding

Binning is crucial to unfolding (an implicit regularization)

- Narrow bins near Δy=0 boundary to fully describe migrations
- Wide bins at high |Δy| due to limited MC statistics

Regularization term based on continuous curvature of density

- Curvature → sum of absolute value of discrete 2nd derivative
- Density = diff. x-sec rather than bin counts → need to account for bin widths
  - introduced functionality into TUnfold

Regularization strength ***balances***

- statistical strength
- bias – we correct for bias on A_{FB}, but it's still an issue since…

Bias is model dependent

- Examines dozens of generator-level distributions (i.e. alternative models)
- Systematic uncertainties cover all realistic cases
- To invalidate systematic uncertainties: sharp bin-to-bin jumps.
  - 26 generator level bins…
  - s-channel narrow resonances have sharp edges – but already rules out (Tuesday)

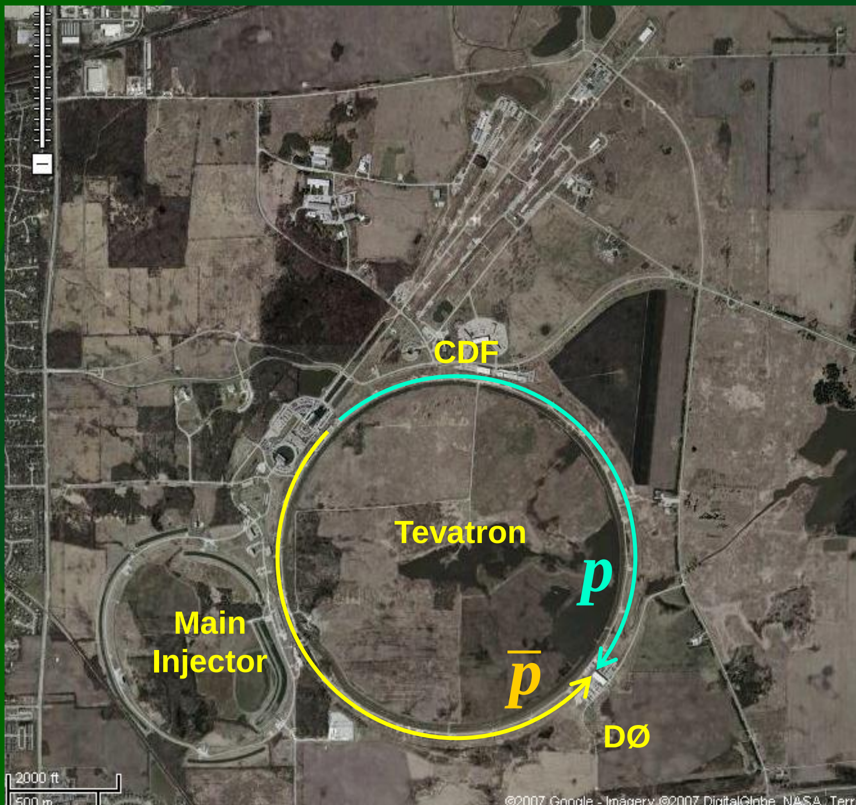
A_{FB} Tables

	$l+\geq 4$ jets	$e+\geq 4$ jets	$\mu+\geq 4$ jets	$l+4$ jets	$l+\geq 5$ jets
Raw $N_{\Delta y>0}$	849	455	394	717	132
Raw $N_{\Delta y<0}$	732	397	335	597	135
$N_{t\bar{t}}$	1126±39	622±28	502±28	902±36	218±16
N_W	376±39	173±28	219±27	346±36	35±16
N_{MJ}	79±5	56±3	8±2	66±4	13±2
A_{FB}(%)	9.2±3.7	8.9±5.0	9.1±5.8	12.2±4.3	-3.0±7.9
MC@NLO A_{FB} (%)	2.4±0.7	2.4±0.7	2.5±0.9	3.9±0.8	-2.9±1.1

	$l+\geq 4$ jets	$e+\geq 4$ jets	$\mu+\geq 4$ jets	$l+4$ jets	$l+\geq 5$ jets
Raw $N_{q\cdot y_l>0}$	867	485	382	730	137
Raw $N_{q\cdot y_l<0}$	665	367	298	546	119
A^l_{FB} (%)	14.2± 3.8	16.5± 4.9	9.8± 5.9	15.9± 4.3	7.0± 8.0
MC@NLO A^l_{FB} (%)	0.8± 0.6	0.7± 0.6	1.0± 0.8	2.1± 0.6	-3.8± 1.2

Experimental Apparatus

Fermilab Tevatron Collider



The detectors

Magnet polarities regularly flipped

The collisions

- $p\bar{p}$
- $E_{c.m.}$ = 1.96TeV

General purpose detectors

Top physics relies on tracking, calorimetry and muon detectors.

Unfolding A_{FB} is easy

Starting at the end: can check whether the unfolding works well by examining several SM MCs and viable BSM scenarios.

- same wide-bin unfolding works for all viable models
- bias from regularized unfolding (a-priori “smoothing”) can be quantified

BTW: in both cases, narrow resonances would have spoiled everything.

Typical unfolding

How much distortion is acceptable?

Showing a distribution → what bin errors?

- correlations are important
- statistical scatter vs. hypothesis testing

What additional information to supply?

Opinions differ.
I refer discussion to:

Unfolding for A_{FB}

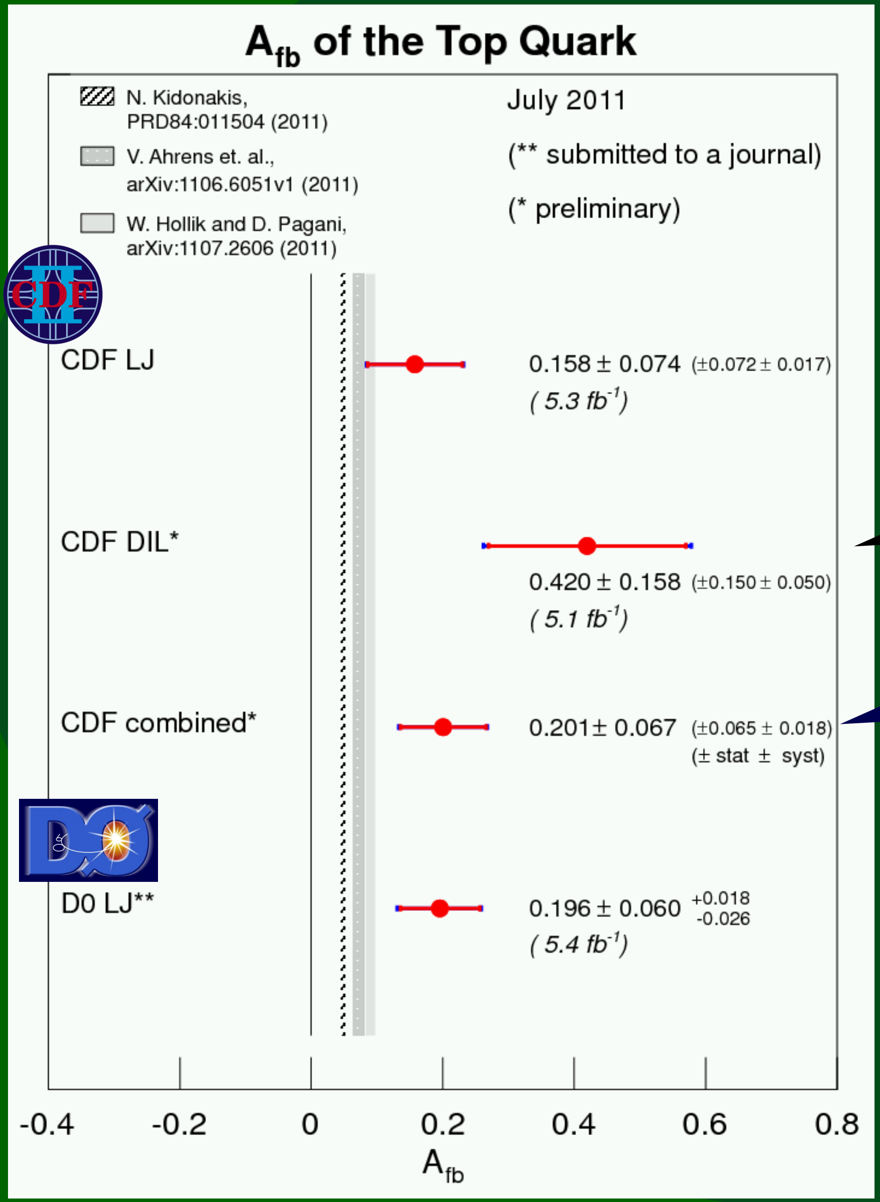
Compare to stat(A_{FB})

Not showing distribution
A_{FB} is a summary

None needed

Details on DØ unfolding in other slide

Production-level A_{FB}s



Inclusive, Δy-based A_{FB}s

$$A_{\rm FB} = (16 \pm 7.0\,({\rm stat}) \pm 2\,({\rm syst}))\%$$

Dileptons - In a few slides…

CDF Note #10584

$$A_{\rm FB} = \left(19.6 \pm 6.0\,({\rm stat})^{+1.8}_{-2.6}\,({\rm syst})\right)\%$$

Production-level A_{FB}s

CDF II

$$A_{\mathrm{FB}} = (16 \pm 7.0\,(\mathrm{stat}) \pm 2\,(\mathrm{syst}))\%$$

DØ

$$A_{\mathrm{FB}} = \left(19.6 \pm 6.0\,(\mathrm{stat})^{+1.8}_{-2.6}\,(\mathrm{syst})\right)\%$$