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

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November 2015

Prologue

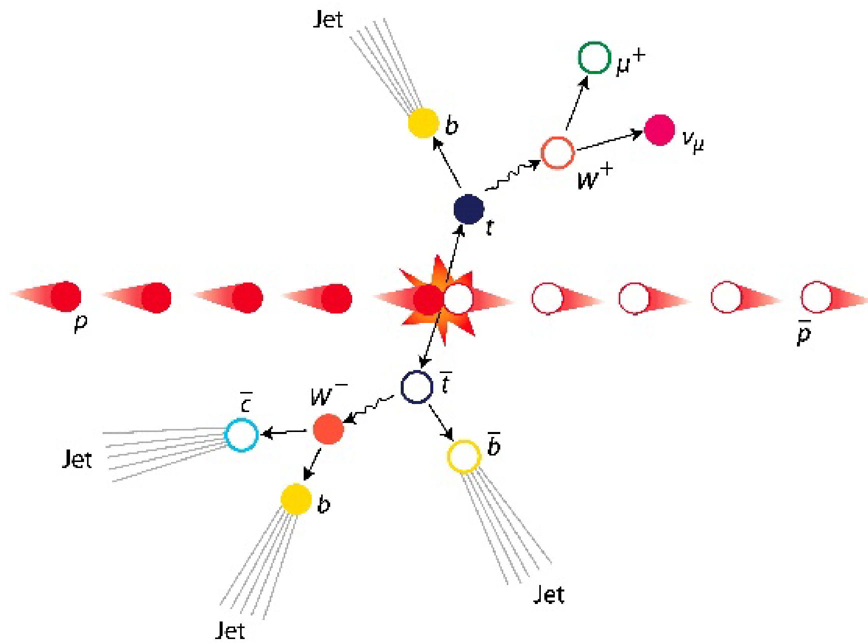
- What you might know… "*Didn't there used to be an excess in $t\bar{t}$ asymmetry at the Tevatron? But then it went away?*"
- This is THAT talk. Want to get the facts, story and details out
- Will focus on the parts that are most interesting, not the gory details to convine you that we did it right
- Description will be partly historical since its been a fun chase, and partly focused on some of the new the tools that have evolved

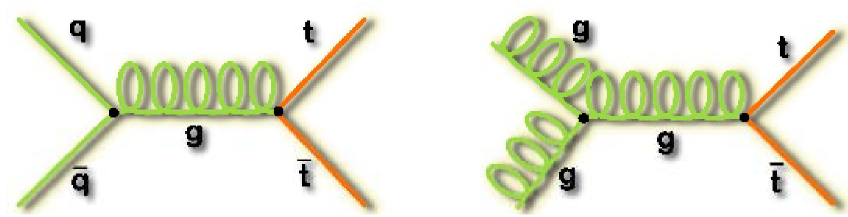
Outline

- Start with the basics of A_{FB} for $t\bar{t}$ predictions
- Then tell you about the interesting results (Lep+Jets) that CDF got which started a lot of excitement
- The set of stuff that came afterwards: better SM predictions, other observables, better MC, other final states, new methods, etc.
- Emphasis in this talk: the dilepton results
  - Leptonic Asymmetry
  - Fully Reconstructed A_{FB}
- Current State-of-the-World-Understanding

Top Production at the Tevatron

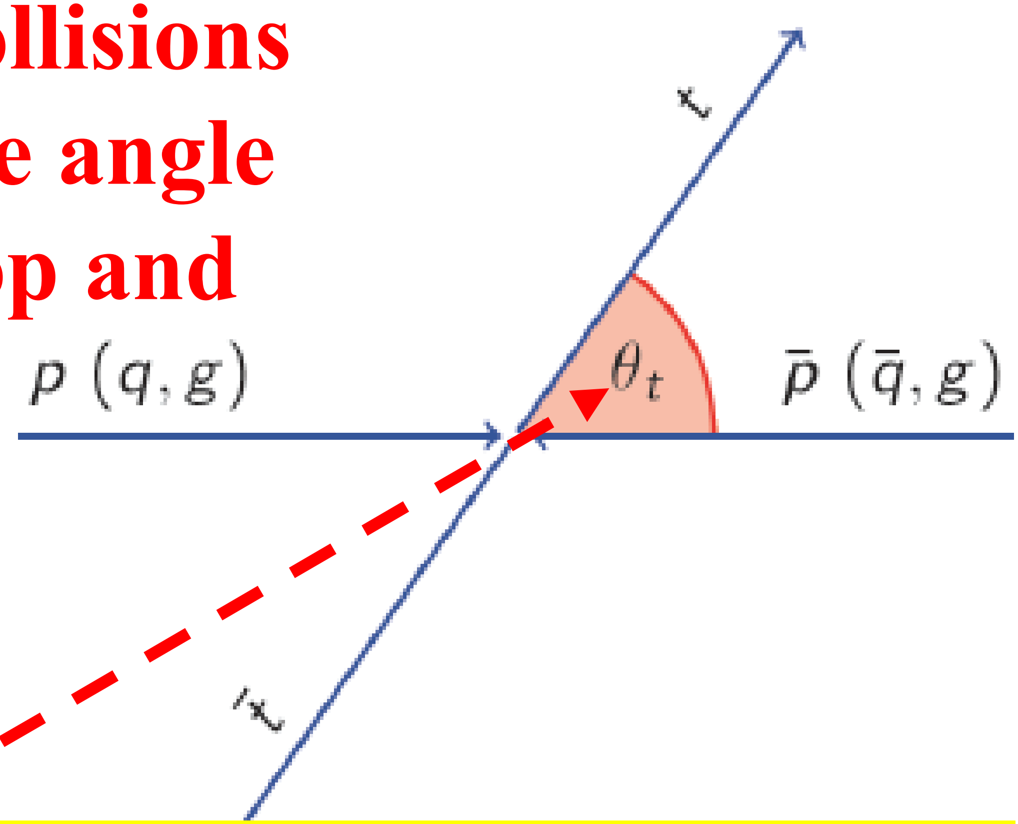
- $p\bar{p}$ collision at Tevatron
  - Asymmetric initial state
- Dominant process is top quark pair production
  - 85% quark annihilation
  - 15% gluon fusion
- ~70,000 $t\bar{t}$ produced
  - ~3,000 reconstructed





Definition of A_{FB}

In proton-antiproton collisions can measure the relative angle between the outgoing top and the proton direction



This is a forward event… If the top was going in the direction of the anti-proton →backward event

Forward-Backward Asymmetry:

A_{FB} = Fraction(Forward) – Fraction(Backward)

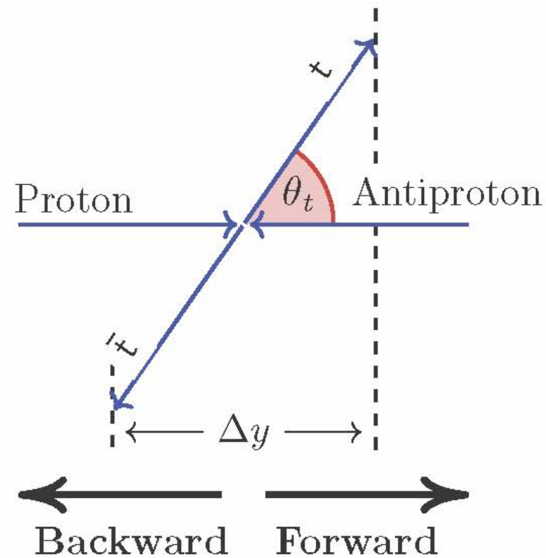
Quick Aside on Variable Choice Δy

Transform from Θ_t to *rapidity* (y)

Rapidity difference is a good proxy for production angle

Invariant under longitudinal boosts

Asymmetry in Δy is bigger than in Θ_t, easier to distinguish from 0



$$A_{\mathrm{FB}} \equiv \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

Measure $\Delta y = y_t - y_{\bar{t}}$, where $y = \frac{1}{2} ln\left(\frac{E+p_z}{E-p_z}\right)$

Note: *y* doesn't have the usual geometric angle many of us are used to.

At hadron colliders we usually use pseudo-rapidity which assumes *m*=0

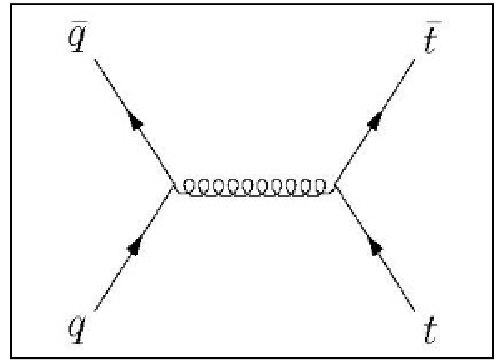
→ Here *E* and *p* not close to equal because of the top mass

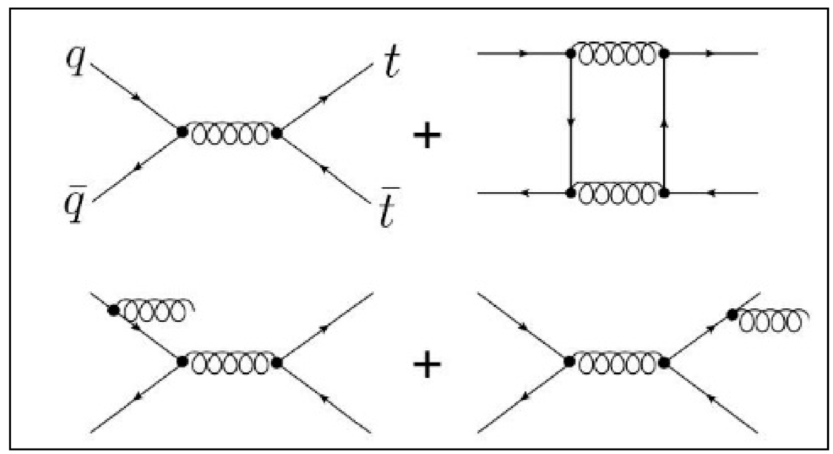
Tevatron VS. LHC

- *Isn't the LHC better for this?*
- **Tevatron is proton-antiproton while LHC is proton-proton**
- **Tevatron provides a direction in space, while LHC only provides a line in space**
- **Can directly use the opening angle relative to learn about Feynman diagrams**
  - **Can get at the same diagrams at LHC, but takes much larger statistics and more indirect methods**

Asymmetry Predictions

- First SM predictions of A_{FB} after top discovery (~1995)
- No A_{FB} at LO, all asymmetry comes from NLO diagrams. Took many years to get decent predictions
  - Interference among diagrams
  - Larger-than-expected EW correction and higher order QCD corrections complicate the calculation
- Note: Process has been a harbinger of things to come: We have learned during the process that LO MC's are simply not good enough to measure properties of the top quark





Lots of Predictions

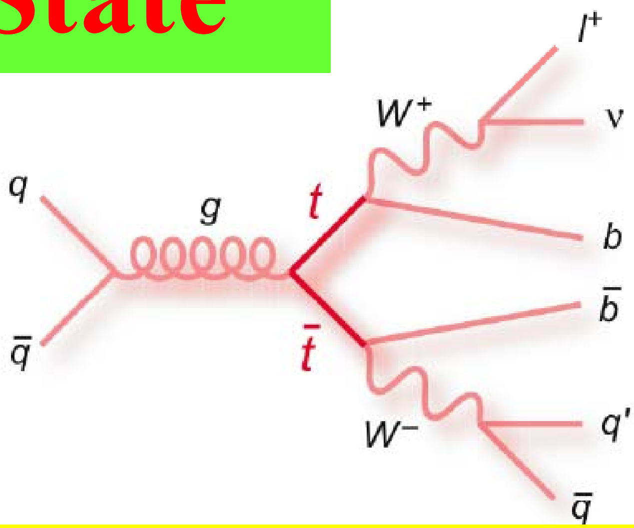
- Original prediction suggests an asymmetry of 0.05
- Different SM calculation gives different answers (0.050-0.125)
- Benchmark NLO SM: $A_{FB}^{t\bar{t}} = 0.088 \pm 0.006$
  (PRD **86**,034026 (2012))
- Recent NNLO prediction: $A_{FB}^{t\bar{t}} = 0.095 \pm 0.007$
  (PRL **115**, 052001 (2015))
- aN^{3}LO: $A_{FB}^{t\bar{t}} = 0.100 \pm 0.006$
  (PRD **91**, 071502 (2015)(R))
- **SM calculation has been pushed forward by this measurement**

Comments on Systematics & Biases

- The measurements presented today are statistics limited, so focus on techniques which make the most of the data
- Spent a lot of time worrying that our methods aren't biased
- Won't rehash the results from Lep+Jets analysis as those were published a few years ago…

Selecting Top Quark Events

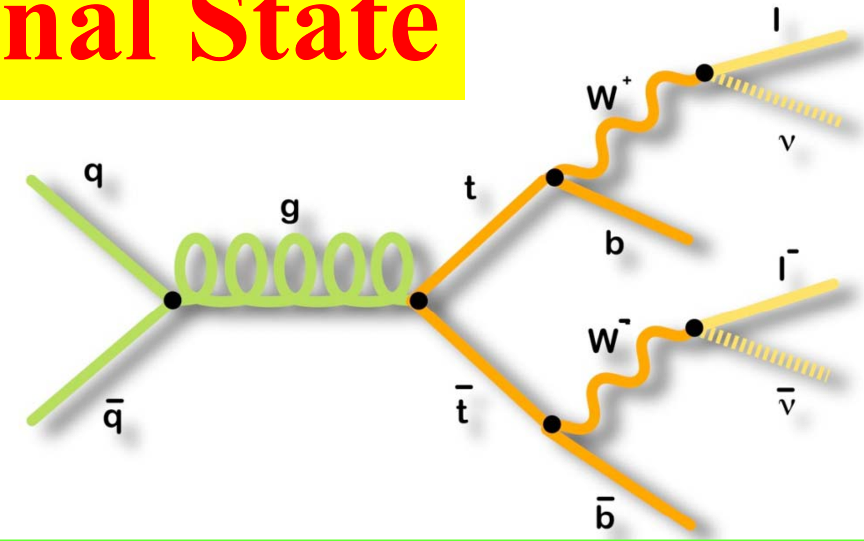
Lepton+Jets Final State



- 1 reconstructed lepton
- Missing transverse energy
- ≥4 jets (1 *b*-tag)
- $\Sigma E_T > 220$ GeV

Bigger branching fraction, more final state particles to measure, bigger backgrounds

Dilepton Final State



- 2 reconstructed leptons
- Missing transverse energy
- ≥2 jets
- $\Sigma E_T > 200$ GeV
- **Higher purity sample, but smaller branching fraction, two leptons have better angles, but two neutrinos cause reconstruction ambiguities**

Inclusive A_{FB} Results

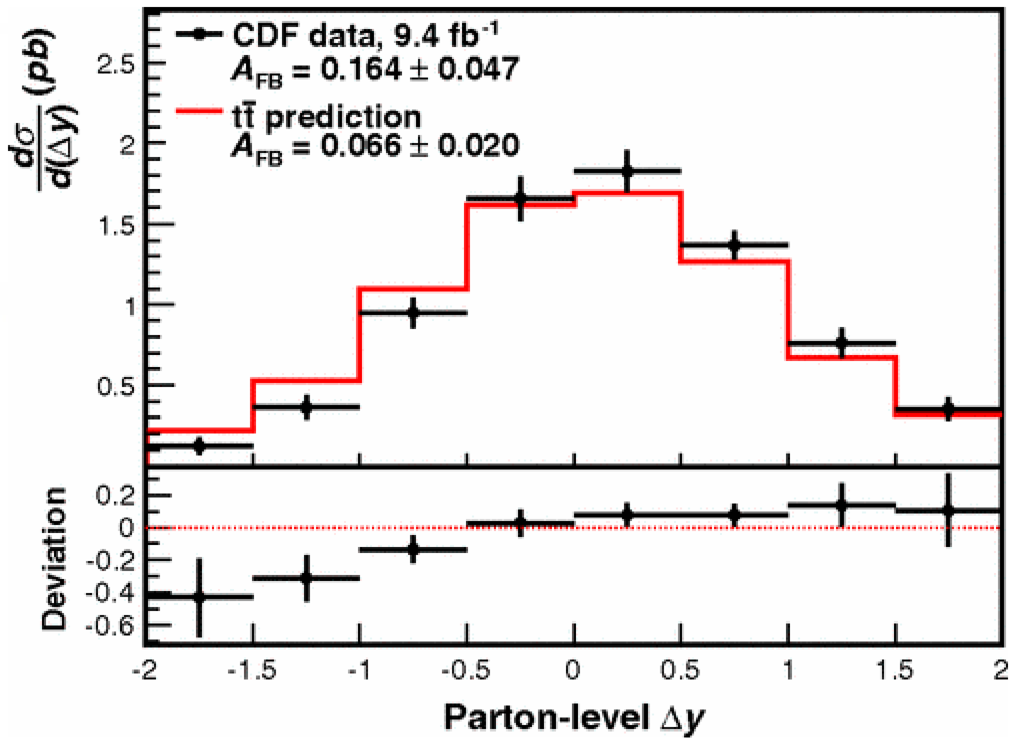
- CDF: $A_{FB}^{t\bar{t}} = 0.164 \pm 0.047$

  (Lep+jets, PRD **87**, 092002 (2013))
- D0: $A_{FB}^{t\bar{t}} = 0.106 \pm 0.030$

  (Lep+jets, PRD **90**, 072011 (2014))

  $A_{FB}^{t\bar{t}} = 0.175 \pm 0.064$

  (Dilepton, PRD **92**, 052007 (2015))
- Final result from CDF in tension with aN^{3}LO SM calculation (0.100), with both results from D0 consistent with calculation



Prediction in plot is old so one can see where the excitement came from

Can already tell that the asymmetry is larger than expected for large |Δy|

CDF Dilepton Result with 5.1fb^{-1}

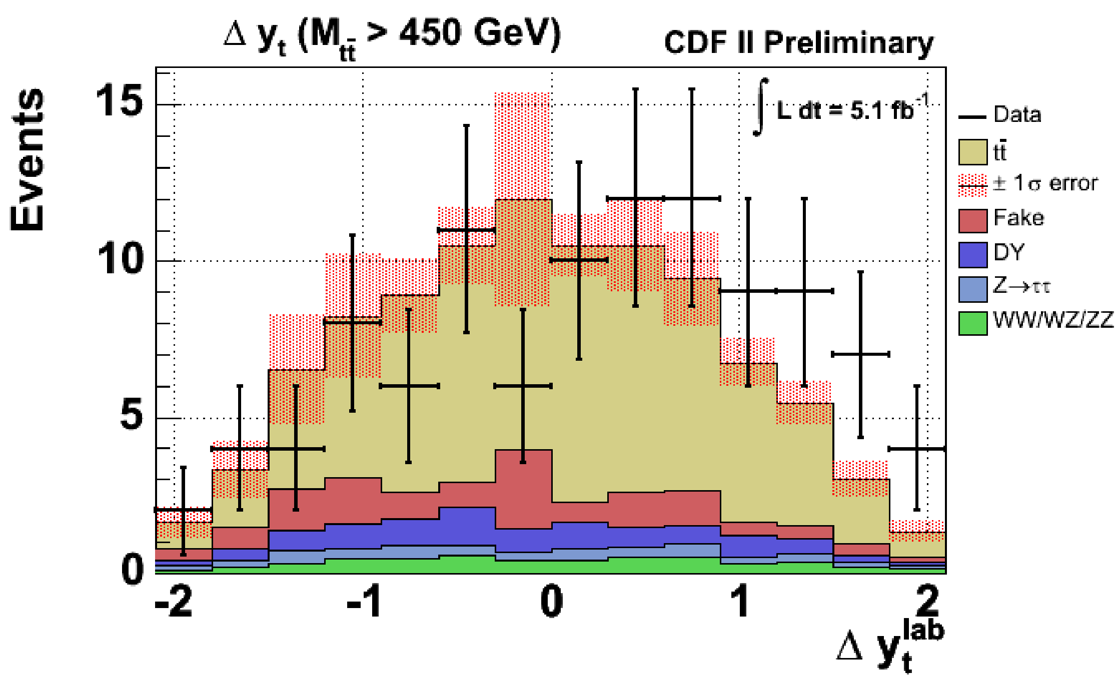
- **Blessed-but-not-published result:**

$$A_{FB} = 0.417 \pm 0.148\ (\text{stat}) \pm 0.053\ (\text{sys})$$

- **Also appeared to be bigger for large $M_{t\bar{t}}$**

(N.B. Now know it wasn't a clean measurement)

  - Back then fueled the fire



Moving Forward

- Adopt a quasi-historical approach from here on out
- **For awhile there was a the real sense that there was a significant discrepancy between the data and the SM predictions**
- Goals:
  - Improve SM prediction
  - Consider other ways to look at the data
  - *New physics models?*

Recurring Theme:
Lots of Ways to Measure and/or Compare to predictions

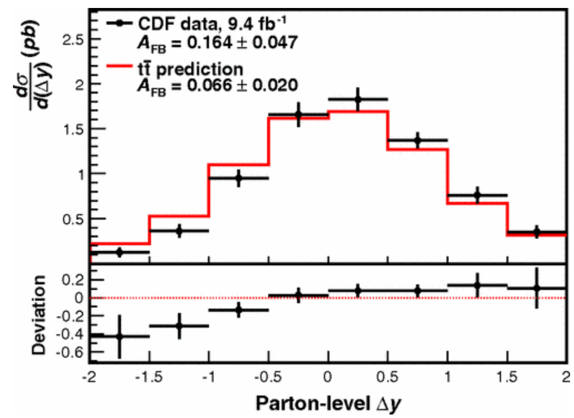
- Lepton+Jets vs. Dileptons
- Reconstructed A_{FB} vs. Leptonic A_{FB}
- Reconstructed Asymmetry vs. $|\Delta y|$
- Reconstructed Asymmetry vs. $M_{t\bar{t}}$
- CDF Vs. DZero

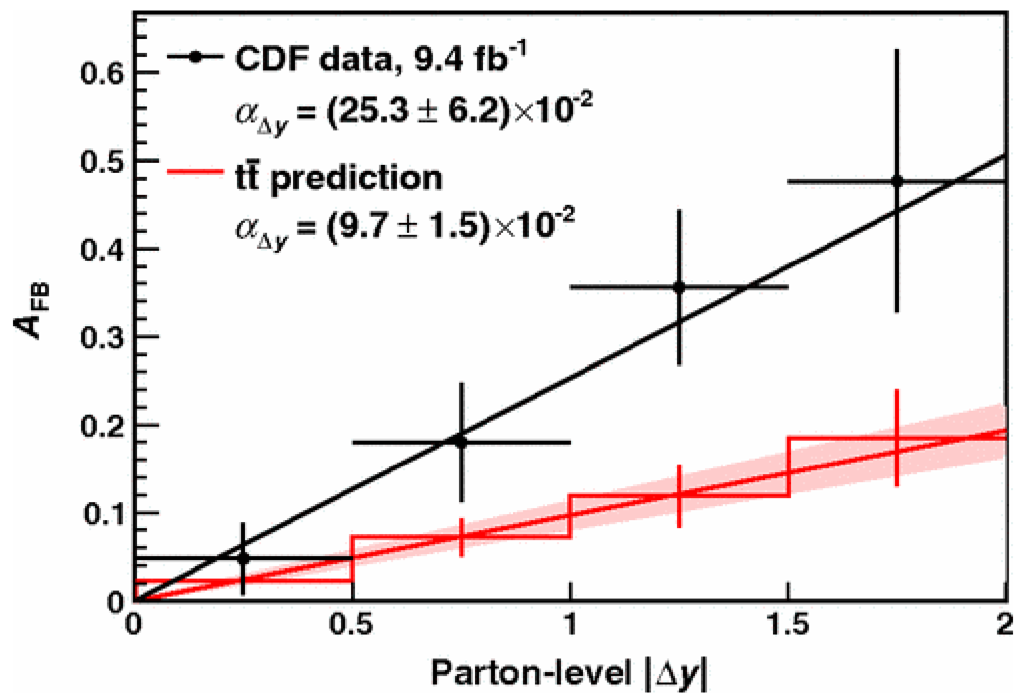
A_{FB} as a function of Δy

Observe larger asymmetry at larger values of Δy

Differential values of A_{FB} well described by a linear relationship

- Not clear to theorists why this should be so…

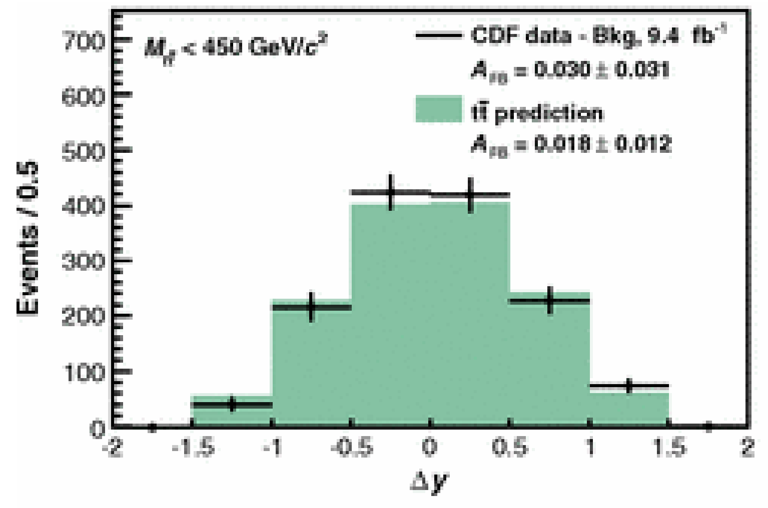




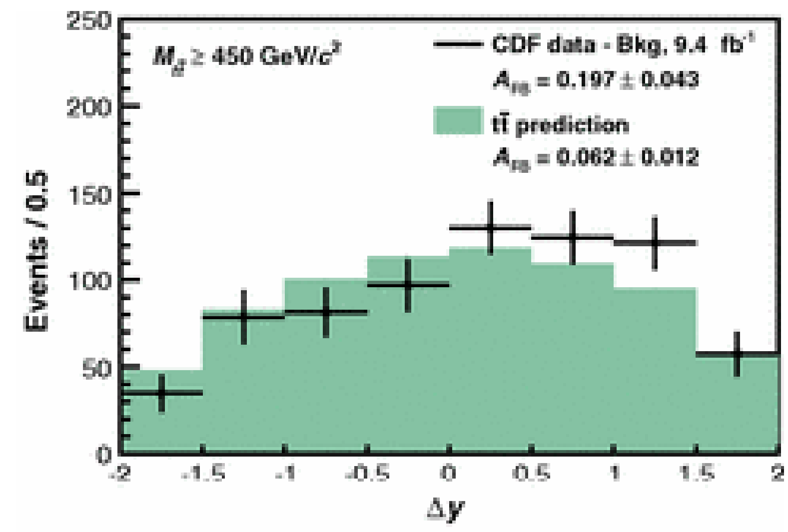
- Slope: 0.253±0.062
  - PRD 87, 092002 (2012)
- 2.2 higher than NNLO SM prediction
  - Slope: $0.114^{+0.005}_{-0.012}$
  - PRL 115, 052001 (2015)

A_{FB} vs. $M_{t\bar{t}}$

- Can break the data into low values of $M_{t\bar{t}}$ and large values of $M_{t\bar{t}}$



- Can see by eye that the data doesn't agree with predictions



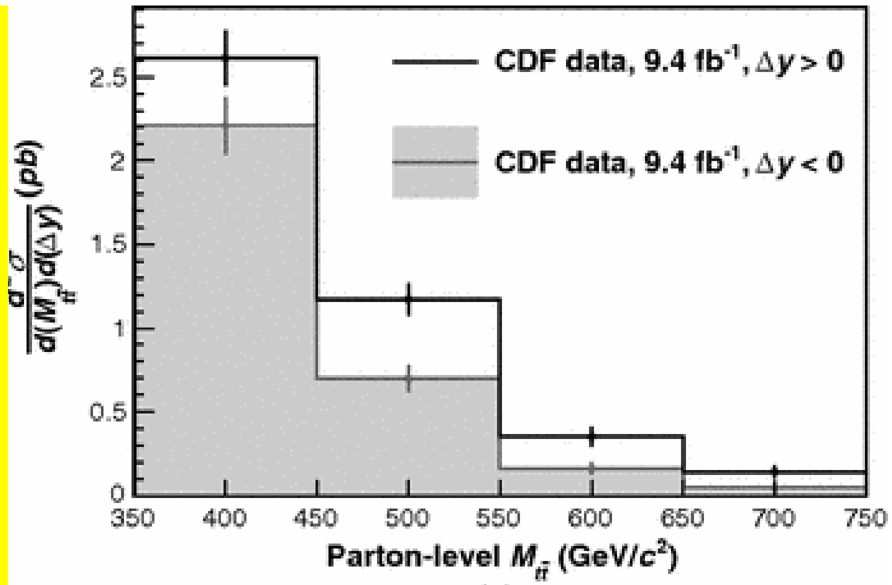
A_{FB} vs. $M_{t\bar{t}}$ Cont…

Quantify with a Slope:

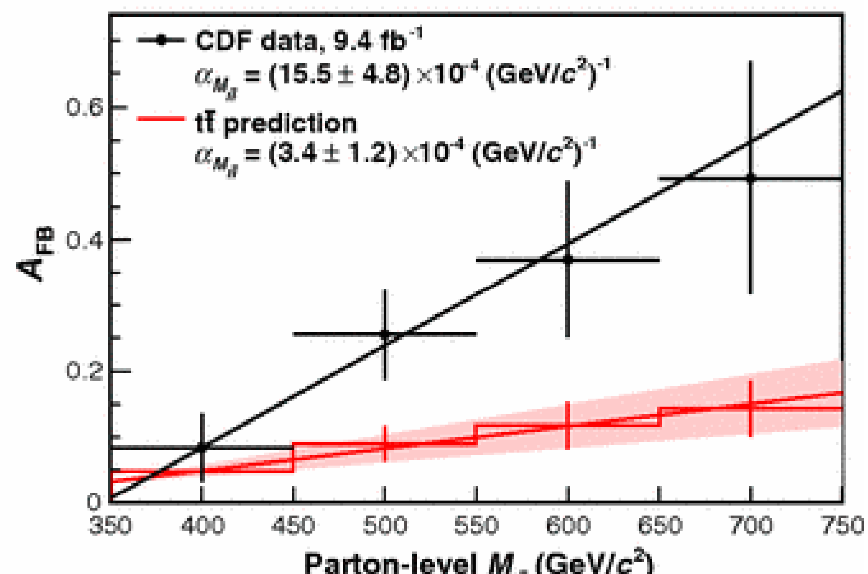
- **$(15.5\pm4.8)\times10^{-4}$ Observed**
- **$(3.4\pm1.2)\times10^{-4}$ NLO**

Not a huge anomaly, but certainly we notice it and push forward…

Can the numerical values of these slopes be useful to model builders?



(a)

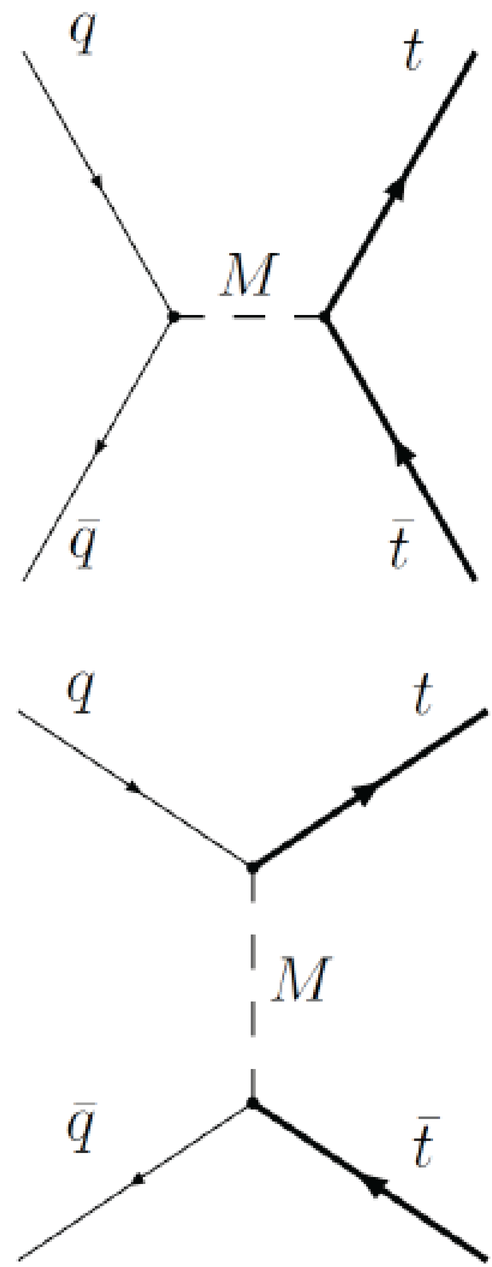


(b)

Examples of New Physics that could give a Large A_{FB}

Two main classes of models

- **S-channel mediator**
  - e.g. axigluon
- **T-channel flavor changing mediator**
  - e.g. W' or Z'



Although many of these have strong constraints (and many are now excluded), they provide a good model for searches

For a review see:

M. Gresham, I.-W. Kim and K. Zurek,

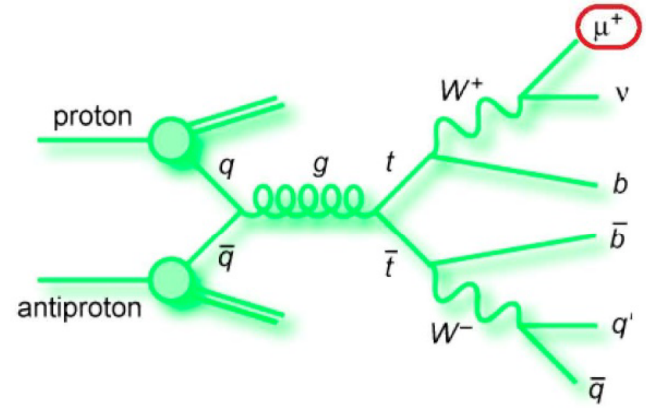
Phys. Rev. D83 114027 (2011)

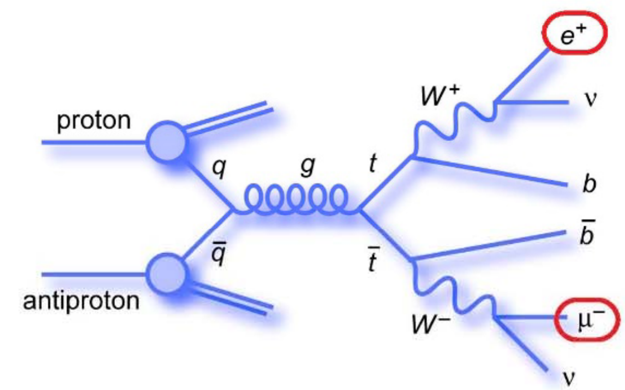
Fun historical aside…

- This is when my team joined the hunt
- Before we joined: UChicago tie-in Amidei and his group led Lep+Jets
  - His postdoc Jon Wilson now works with me
- Top→Dileptons datasets were a mess
- Ziqing Hong, student who worked with me, cleaned up dilepton datasets, then systematically did all the measurements
- Start picking them off one-by-one…

Leptonic A_{FB} Definition

- Besides $A_{FB}^{t\bar{t}}$, two equally important observables with leptons
- Leptonic A_{FB}
  - $$A_{FB}^{\ell} = \frac{N(q_\ell \eta_\ell > 0) - N(q_\ell \eta_\ell < 0)}{N(q_\ell \eta_\ell > 0) + N(q_\ell \eta_\ell < 0)}$$
- Also lepton pair A_{FB} defined with lepton η difference, only in dilepton
  - Details in backup.
- Why consider A_{FB}^{ℓ}?
  - Lepton angles precisely measured
  - Tend to follow direction of parent tops
  - Also carries top spin information



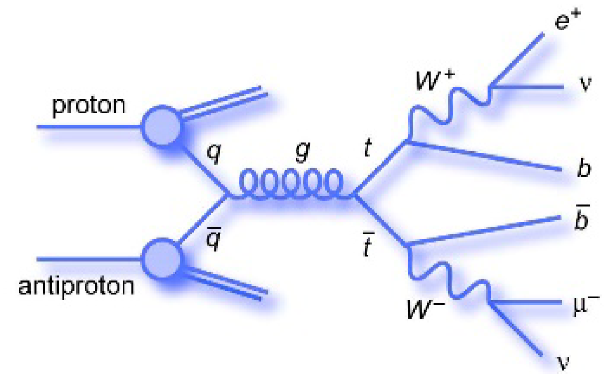


SM: A_{FB} = 3.8%, specific ratio for Reconstructed/Leptonic

Various BSM Models: -5% < A_{FB} < 15%, ratio can vary significantly

Dilepton-only Observable

- Lepton pair A_{FB}
  - $$\boxed{A_{\mathrm{FB}}^{\ell\ell} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)}}$$
- NLO SM prediction: $A_{\mathrm{FB}}^{\ell\ell} = 0.048 \pm 0.004$
- Larger expectations
- Only defined in dilepton, smaller statistics
- Provide extra information to help constraining new physics models



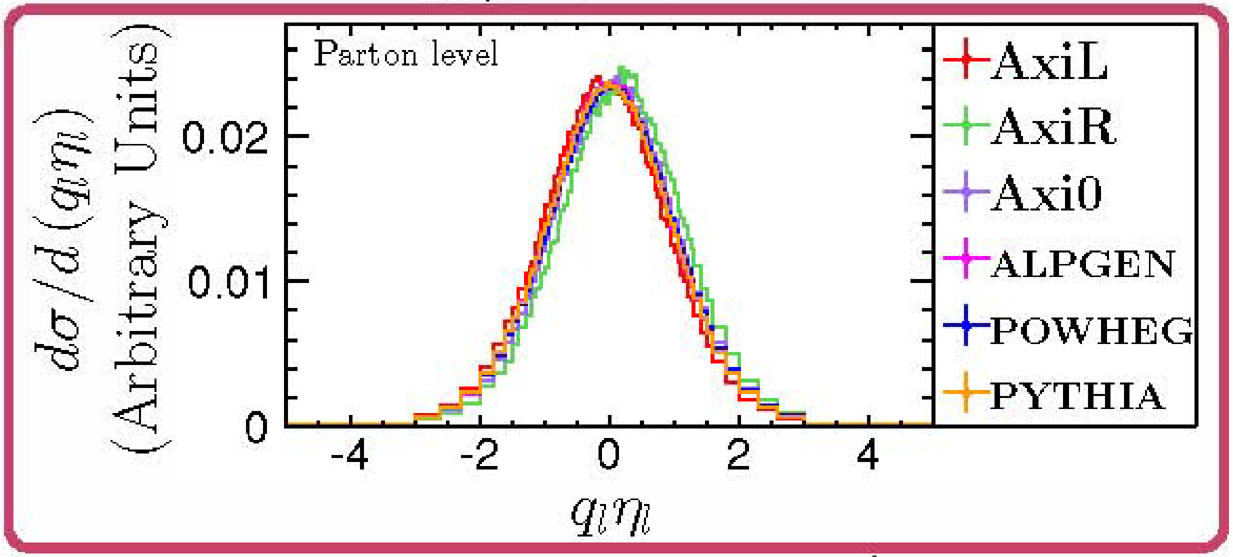
Same BSM models: -9% < A_{FB} < 22%

Quick Aside on the Method

- The methodology for measuring the Leptonic asymmetry turned out to be both simple and complicated
- Not sure why it worked
- Spent some real time trying to understand why
- Turned out to be so simple that I thought I'd share what we learned

Leptonic Methodology

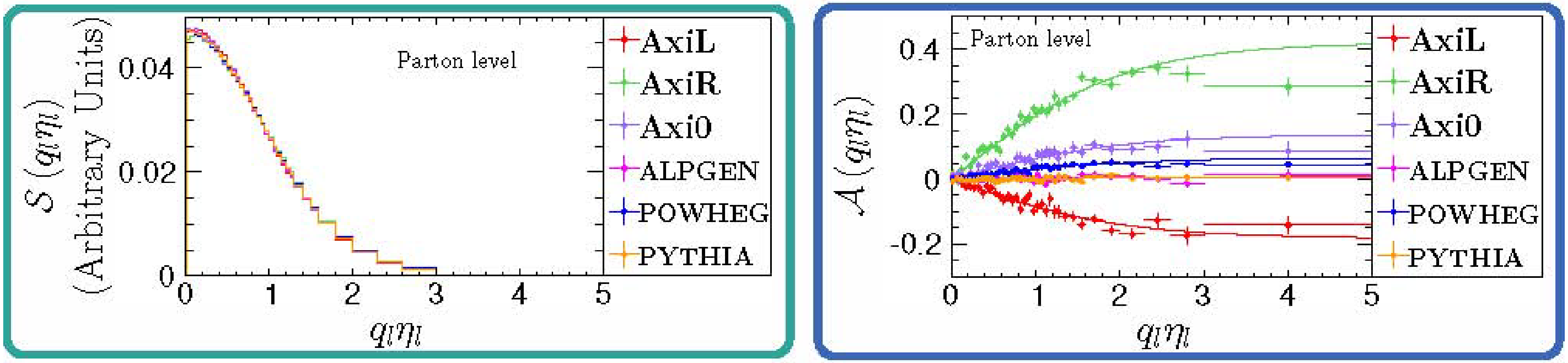
$q_\ell \eta_\ell$ spectrum



- Benchmark models with $-0.06 < A^\ell_{\mathrm{FB}} < 0.15$
- Difference among models are small
  - Shapes almost identical, tiny shift in the mean
- Acceptance in detector limited
  - No acceptance beyond $|q_\ell \eta_\ell| = 2$
- Need a clever way to measure the subtle difference

Clever idea: Break into parts

$$\mathcal{S}(q_\ell\eta_\ell) = \frac{\mathcal{N}(q_\ell\eta_\ell) + \mathcal{N}(-q_\ell\eta_\ell)}{2};\ \mathcal{A}(q_\ell\eta_\ell) = \frac{\mathcal{N}(q_\ell\eta_\ell) - \mathcal{N}(-q_\ell\eta_\ell)}{\mathcal{N}(q_\ell\eta_\ell) + \mathcal{N}(-q_\ell\eta_\ell)}$$



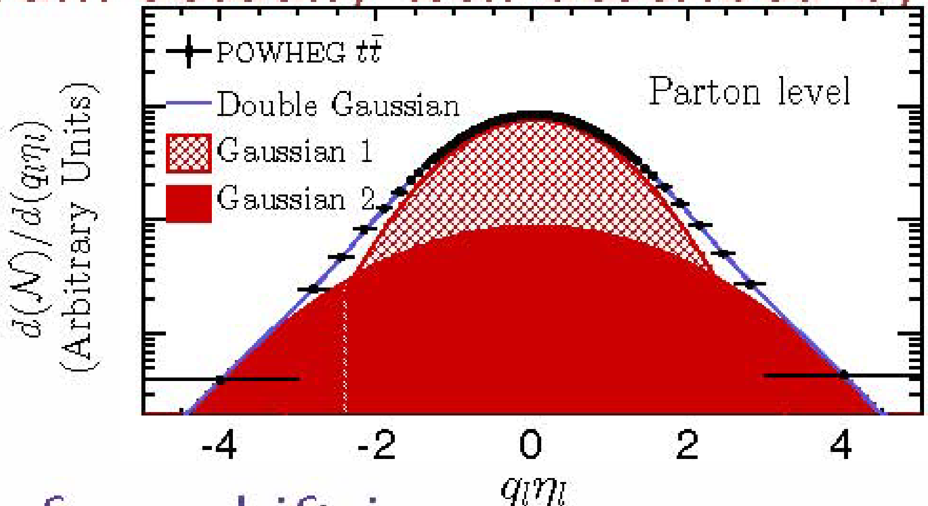
- $\mathcal{S}(q_\ell\eta_\ell)$ consistent among models
- $\mathcal{A}(q_\ell\eta_\ell)$ sensitive to different A_{FB}^{ℓ}
  - Well modeled with $a \cdot \tanh(\frac{1}{2}q_\ell\eta_\ell)$
- A_{FB}^{ℓ} rewritten as

$$A_{\mathrm{FB}}^{\ell} = \frac{\int_0^\infty \mathrm{d}q_\ell\eta_\ell \mathcal{A}(q_\ell\eta_\ell)\mathcal{S}(q_\ell\eta_\ell)}{\int_0^\infty \mathrm{d}q'_\ell\eta'_\ell \mathcal{S}(q'_\ell\eta'_\ell)}$$

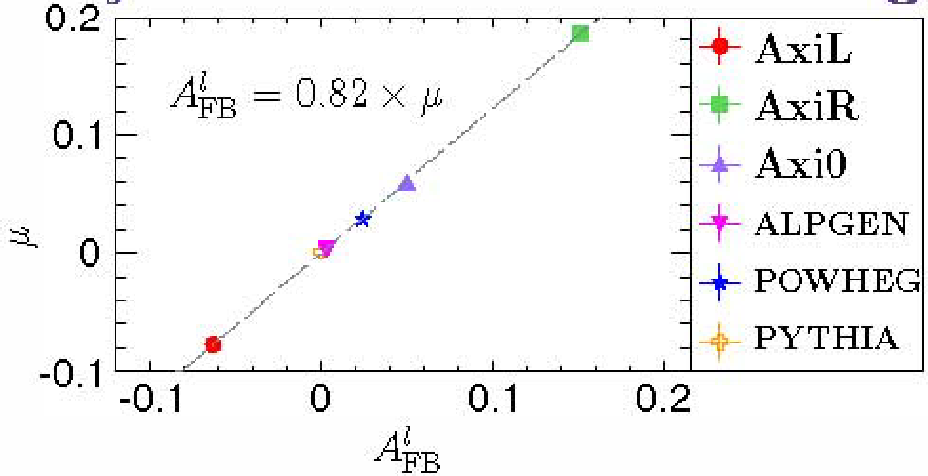
Validation summarized as PRD **90**, 014040 (2014)
Hong, Edgar, Henry, Toback, Wilson, Amidei

Why does it work?

- $q_\ell \eta_\ell$ spectrum actually well described by a double-Gaussian

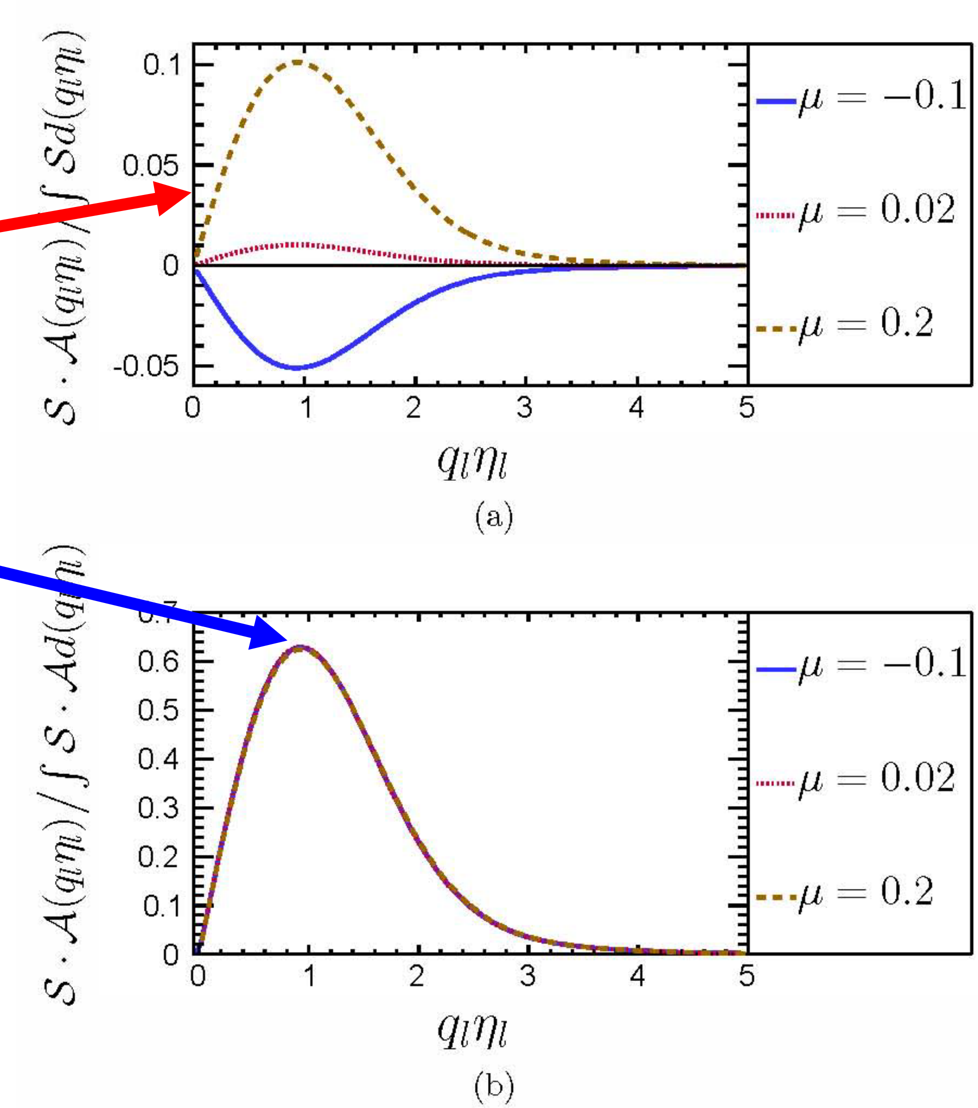


- A^ℓ_{FB} comes from shift in mean
  $\rightarrow A^\ell_{\mathrm{FB}}$ linearly related with mean in regime of interest

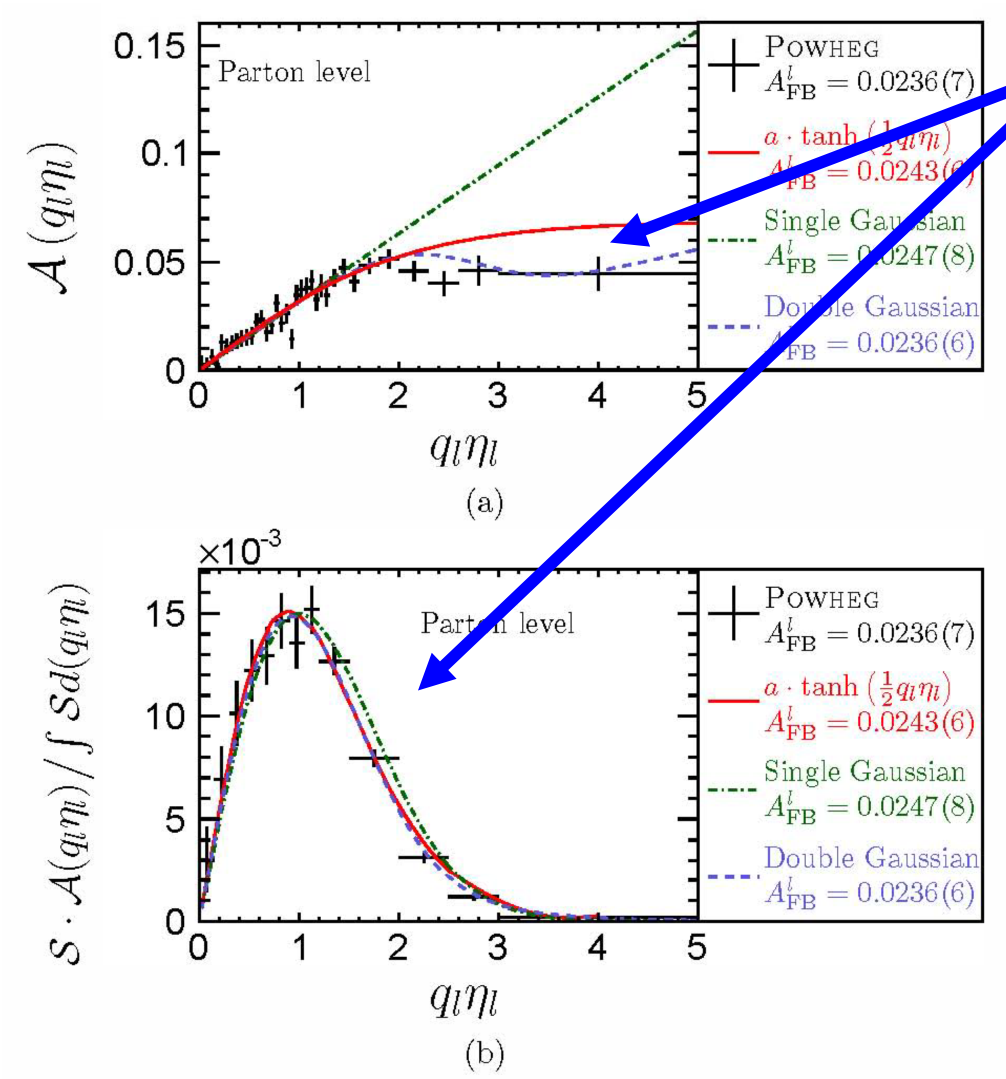


Fun details

- If we look at the <u>contribution</u> to the asymmetry as a function of η, we see that for different means (total A_{FB}) we get very different shapes
- However, the shapes basically look the same, just with a different overall normalization
  - Gives us a robust way to measure things
- Interesting:
  - Very little sensitivity at the center of the detector/where most of the events are
  - Most of the sensitivity comes around |η|=1

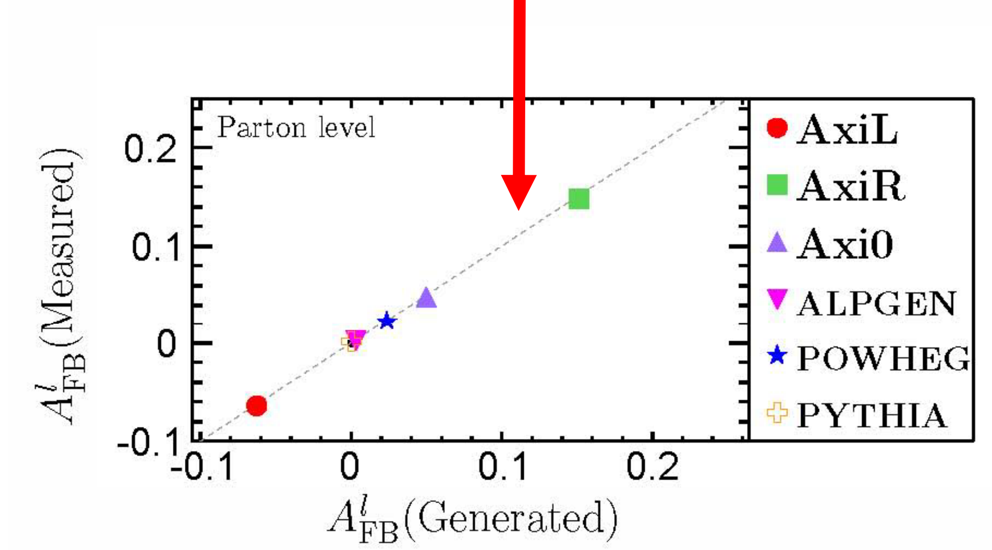


More on how well it worked



Works well as a function of qη

Works well for many different input values of A_{FB}

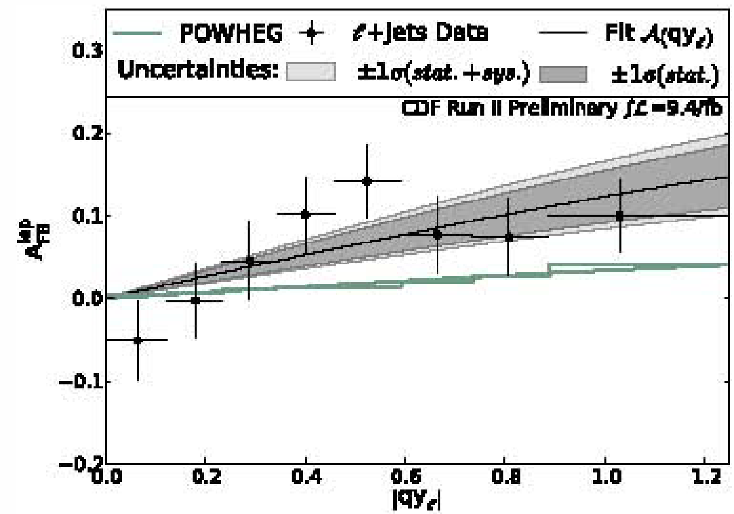


Leptonic A_{FB} from Lepton+Jets

- A^{ℓ}_{FB} measurement in lepton+jets based on this decomposition and $a \cdot \tanh(\frac{1}{2} q_{\ell}\eta_{\ell})$ modeling

$$A^{\ell}_{\mathrm{FB}} = 0.094^{+0.032}_{-0.029}$$

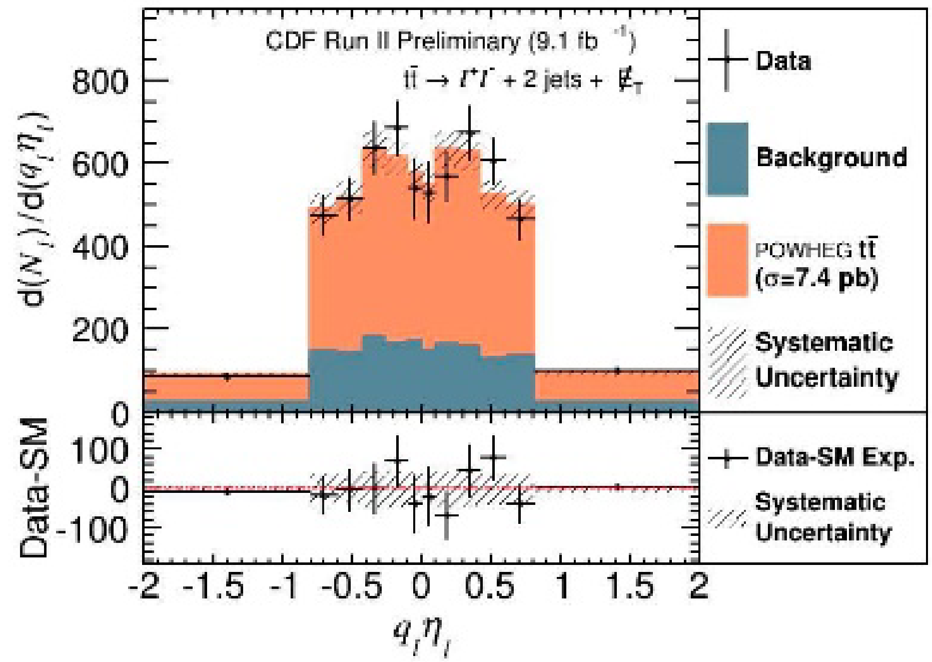
- 1.9σ larger than NLO SM

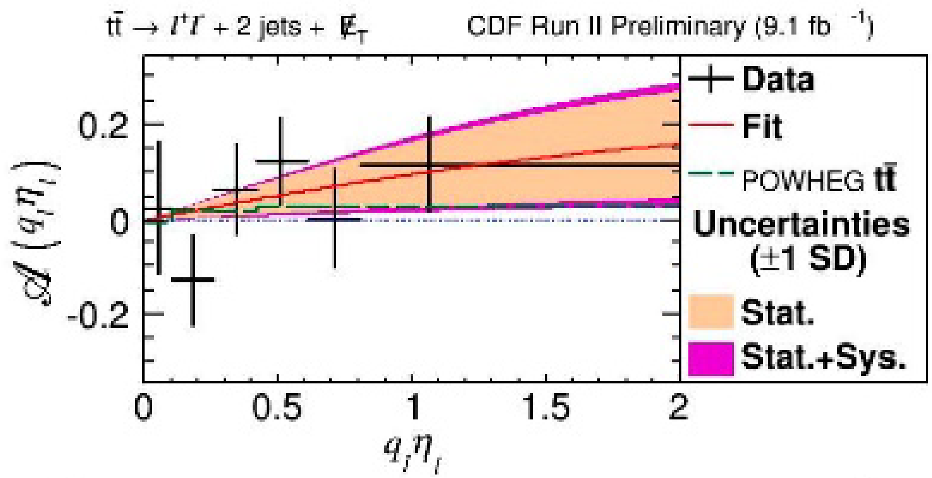


PRD **88** 072003 (2013), CDF

Leptonic A_{FB} from Dileptons

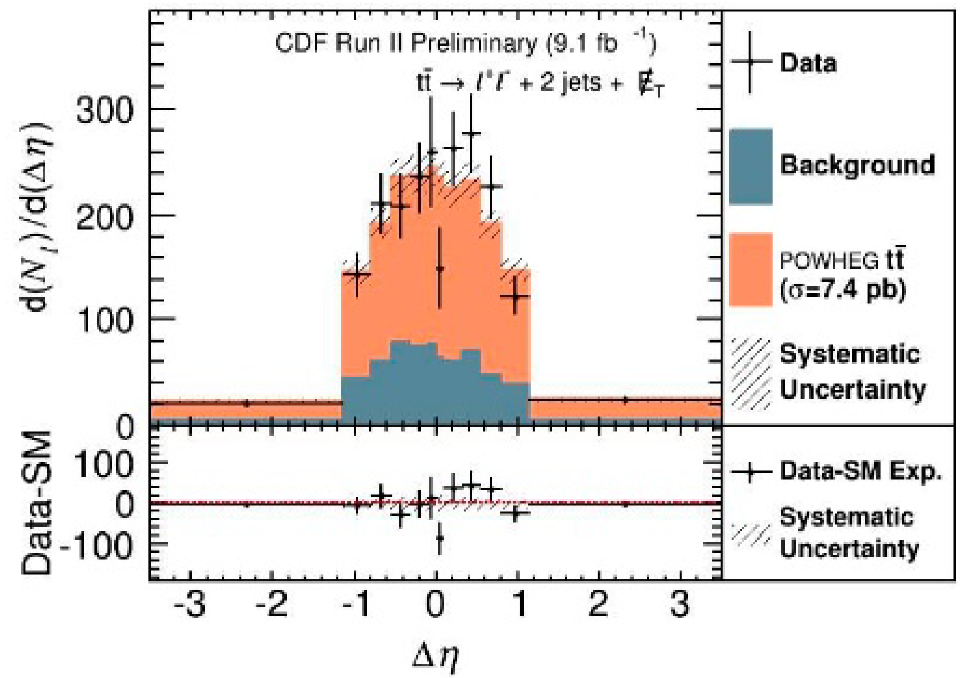
- **Measure A_{FB} with CDF full dataset in dilepton (9.1 fb^{-1})**
- **A_{FB} = 0.072±0.060**
  - **A_{FB}(SM,NLO) = 0.038 ±0.003**
- **Combine CDF measurements →Result is 2σ larger than NLO SM prediction:**
  - **A_{FB} = 0.090 ± 0.028**
- **Published as PRL 113, 042001 (2014) (CDF)**

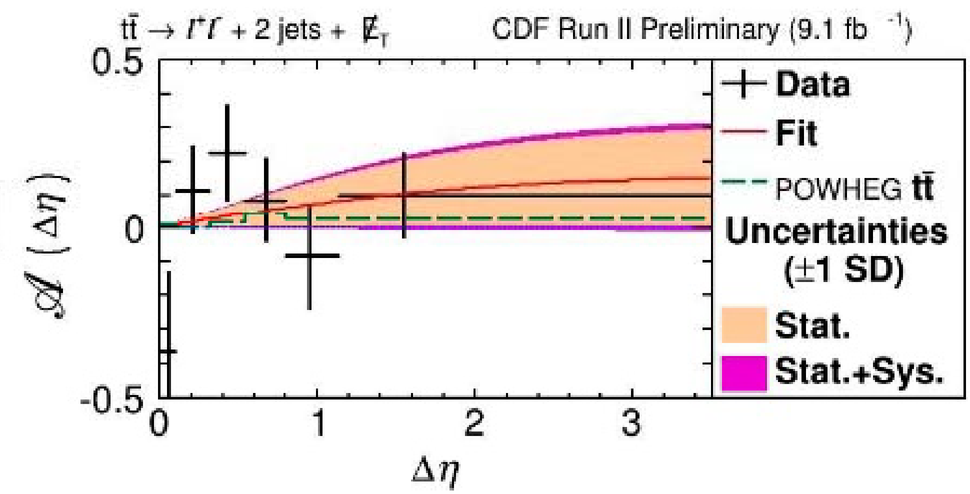




Leptonic Δη Results (Dileptons only)

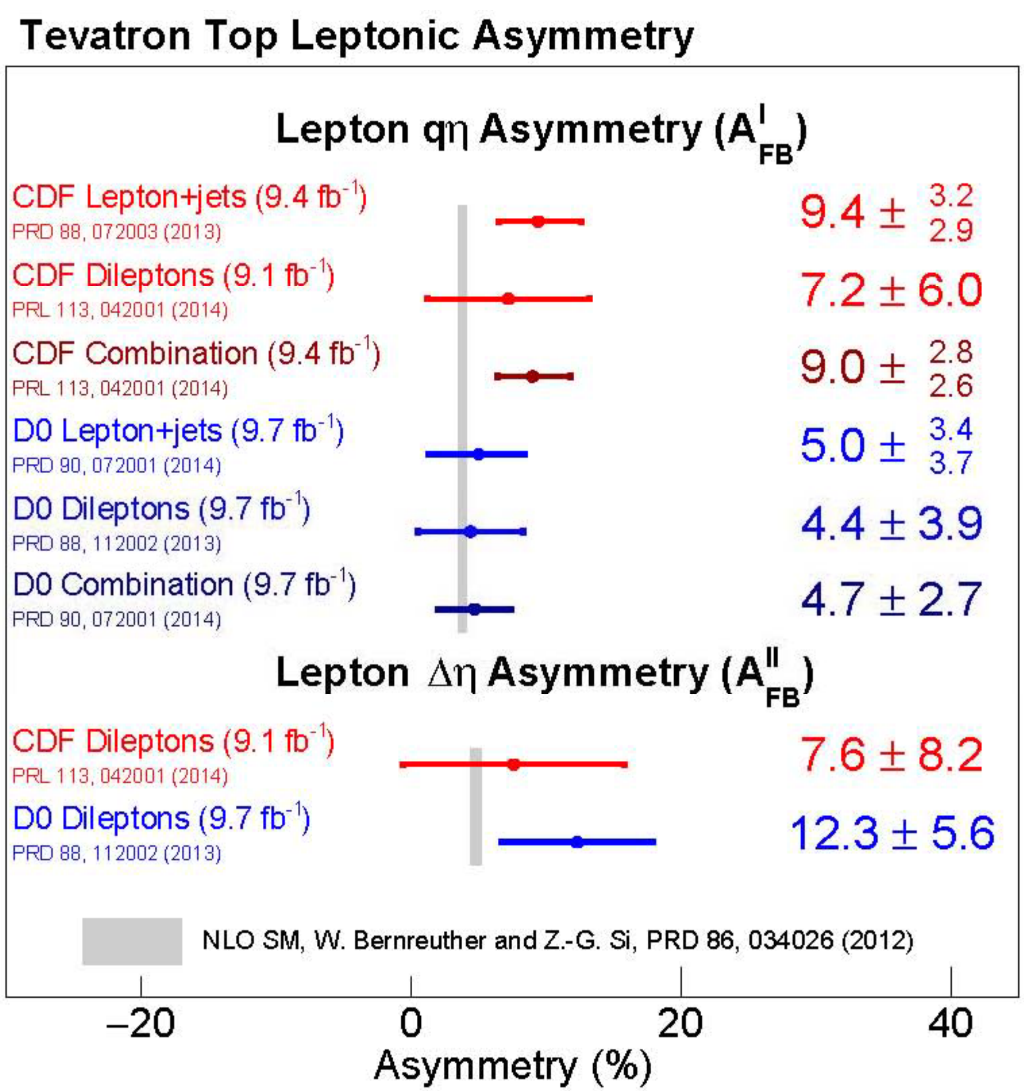
- **Measurement techniques works equally well for A_{FB} in Δη**
  - A_{FB} =0.076±0.072(st)±0.039(sys) = 0.076± 0.081
- **Result consistent with SM**
  - A_{FB}(SM,NLO) = 0.048 ±0.004
  - PRL 113, 042001 (2014)





State of the Art for Leptonic A_{FB}

- All the results, including from DZero, are consistent with SM predictions
- Notice that all of them are above…



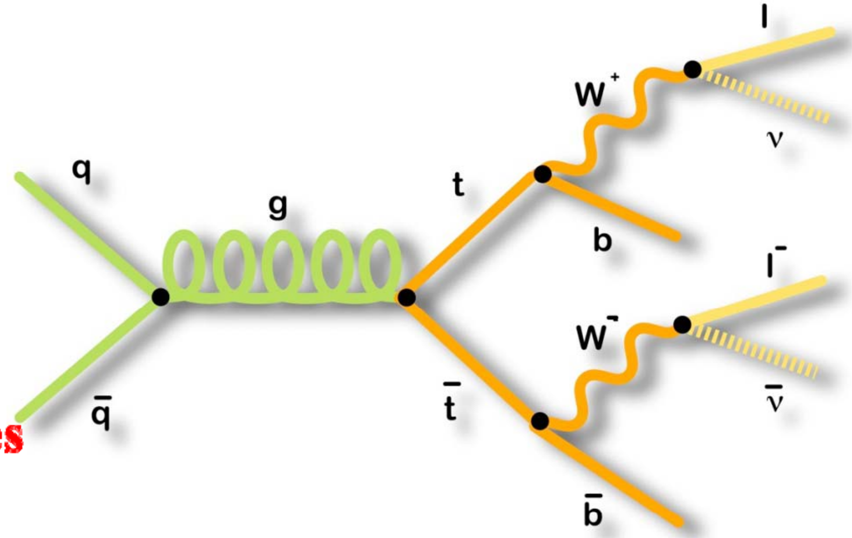
Transition to Reconstructed A_{FB}

Taking Stock of where we are, and looking forward

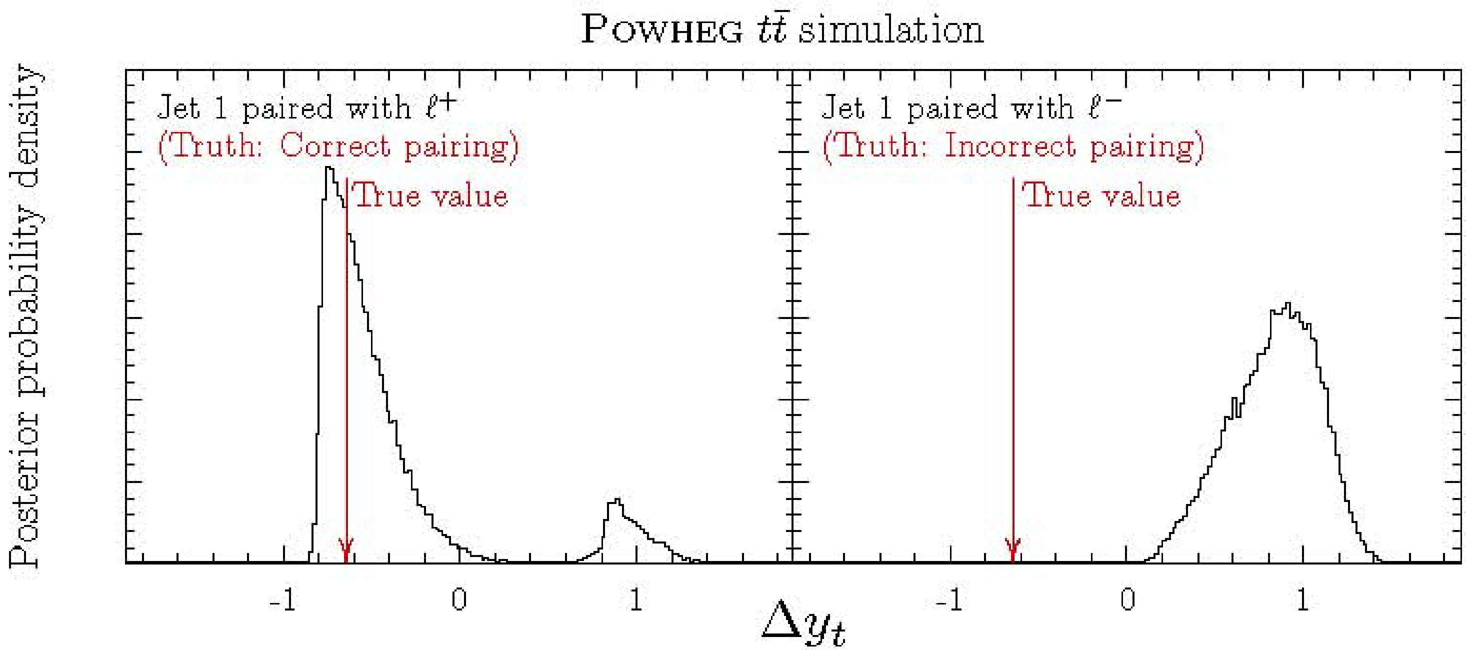
- **Observed large A_{FB} in reconstructed Lep+Jets, but only big in differential measurements**
- **Looked at Leptonic A_{FB}: Still above predictions, but not anomalously so**
- **Next: Even though we won't have enough statistics to say anything conclusive we measure the full reconstructed A_{FB} in dileptons**

Reconstruction in Dileptons

- A full reconstruction of the 4-momenta of the t and $\bar{t}$ is a pain
  - Quadratic energy-momentum conservation equations
  - Two neutrinos undetected, 6 unknown variables
  - 6 constraints (2 m_W, 2 m_t , Measured Met)
  - 2 lepton-jet pairings (b and $\bar{b}$ ambiguity):
  - Large jet energy and Met resolutions
- Under-constrained system, 4-dimensional parameter space with 2 lepton-jet pairing choices
- Do a likelihood fit where we map out the full probability distribution of solutions using Markov-Chain Monte Carlo
- Let all variables float within their uncertainties and consider both lepton-jet pairings
- Computationally intensive algorithm (2 mins/event)



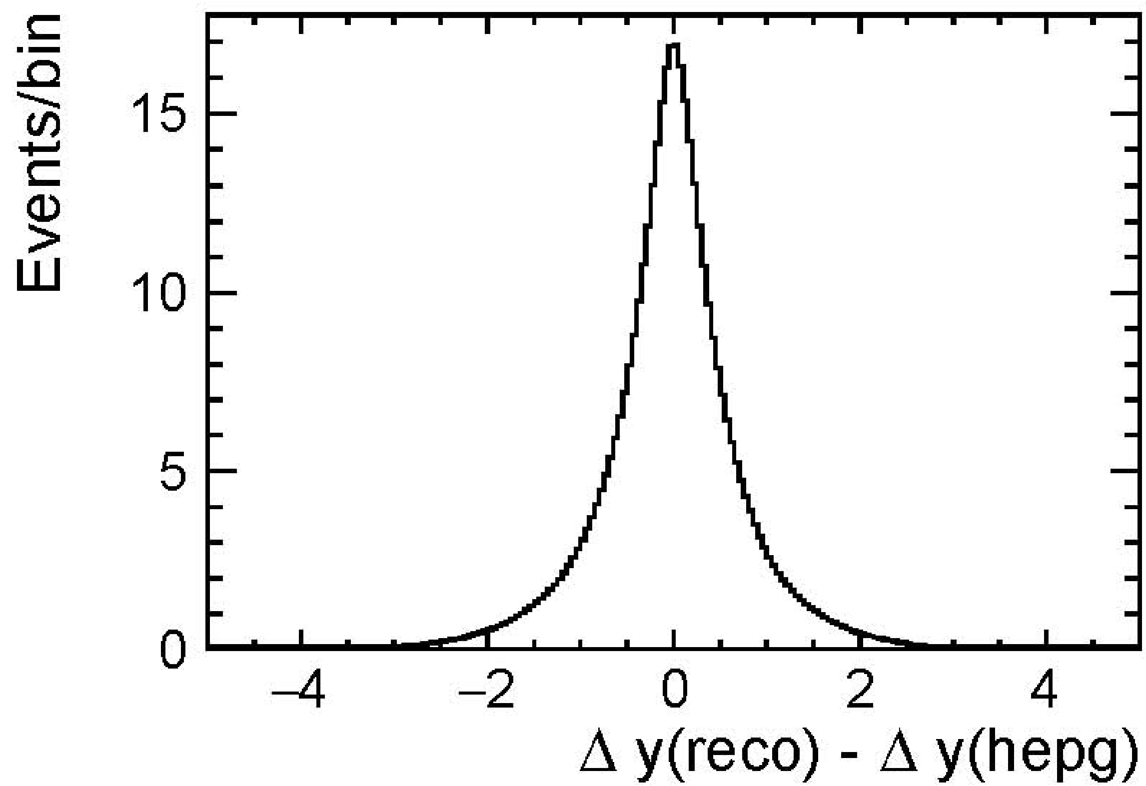
How well does the Reconstruction Do?



- Δy_t probability distribution from one (well-measured) event from simulation
- Two lep-jet pairings, multiple solution structure
- Use the full distribution in the measurement
  - It contains the maximum amount of information

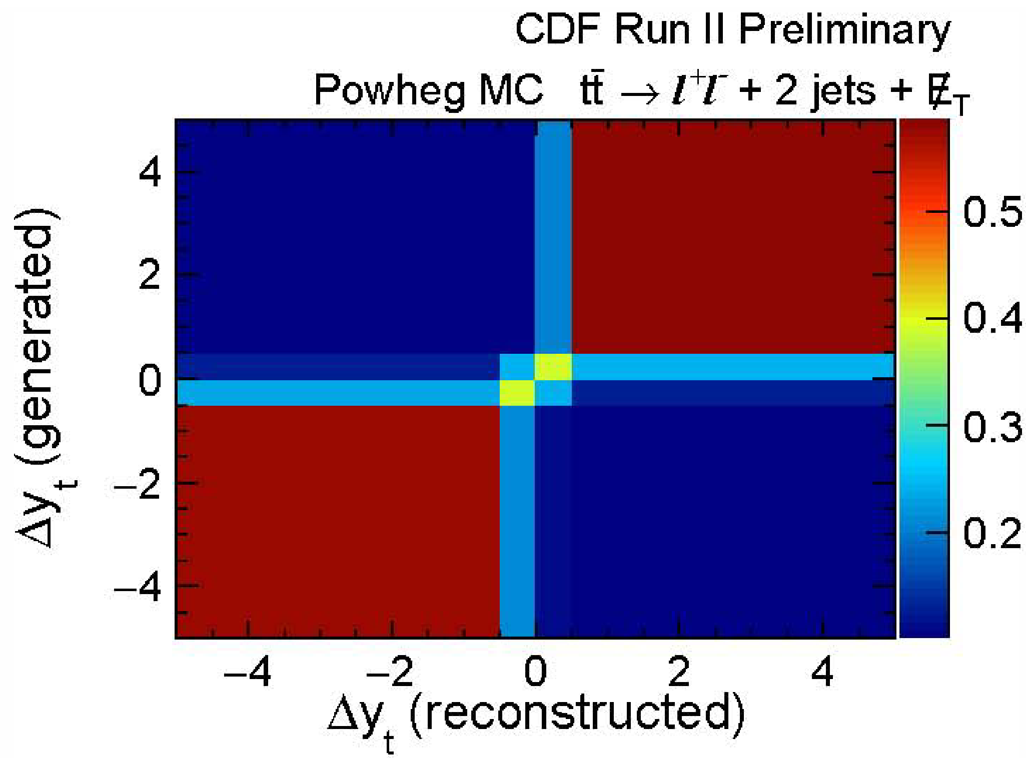
Resolution Continued

- Consider all solutions and weight them according to their probability from the fit
- Find 61% have a y_t measured within 0.5 of truth value



Going from Reconstruction to a Measurement of A_{FB}

- Need a sophisticated methodology to turn reconstructed Δy measurement into a measurement of Δy at the parton level
- Want to measure the inclusive A_{FB} as well as the differential A_{FB} vs. Δy.
- Correct for two effects:
  1) Not able to measure all events
     - Limited detector coverage
     - Imperfect event selection efficiency
  2) Not able to measure y_t correctly for events we do have a measurement
     - Finite detector response resolution
     - Imperfect tt momenta reconstruction

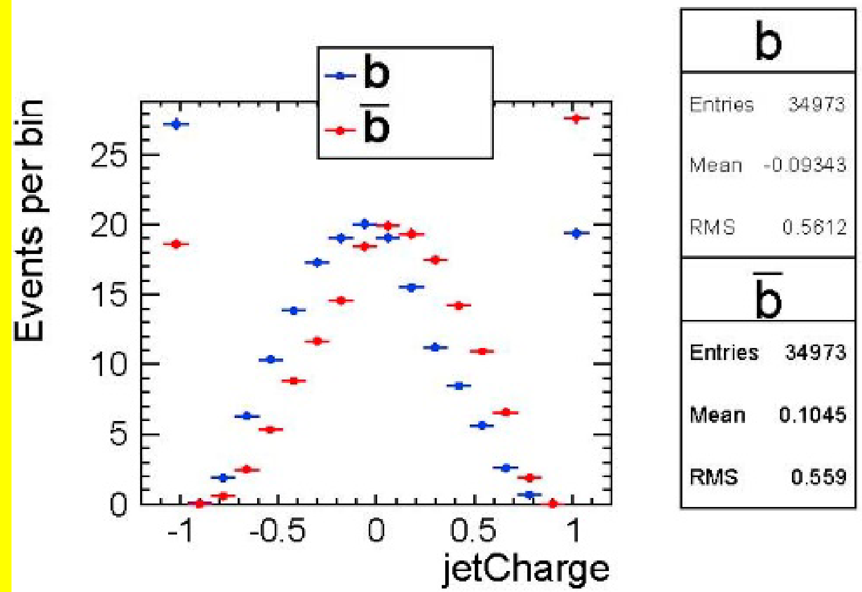


Optimization Slide 1

- Tried to do something state-of-the-art since this is a legacy measurement
- Optimize before looking at data
- Minimize the expected uncertainty on A_{FB}

1) Use more information in the measurement

  – Keep full probability distribution rather than pick the most probable solution
  – Weight both lep-jet pairings with likelihoods
  – Add information from *b*-jet charge



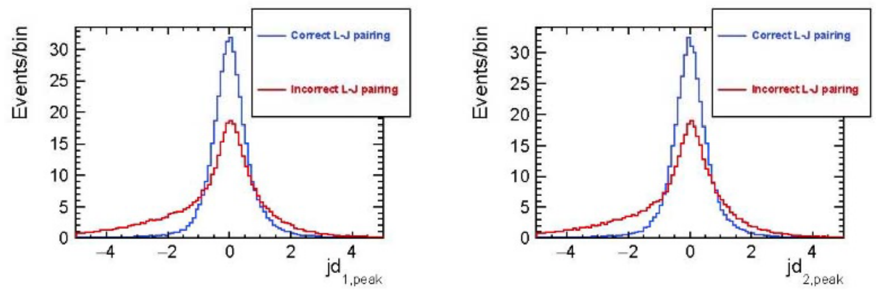
σ(tot.)/σ(sig.only)	Pick L-J pairing	Weight both
Max-likelihood	0.144/0.133	0.137/0.126
Full probability	0.131/0.114	0.122/0.106

Optimization Slide 2

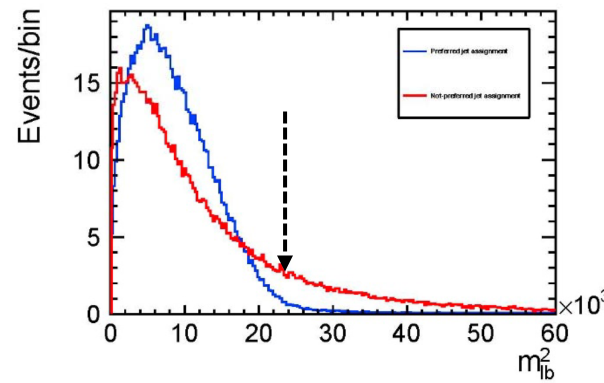
2) Reject tt with low reconstruction quality

- Jet energy dragged too far from measured values to make a tt
- m^2_{lb} too high, not likely a good top
- Lepton lying on top of a jet, most likely a W+Jets

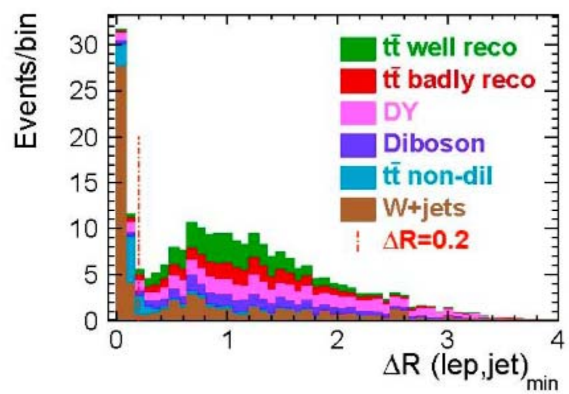
- Expected uncertainty goes from 0.144 before optimization and 0.122 after



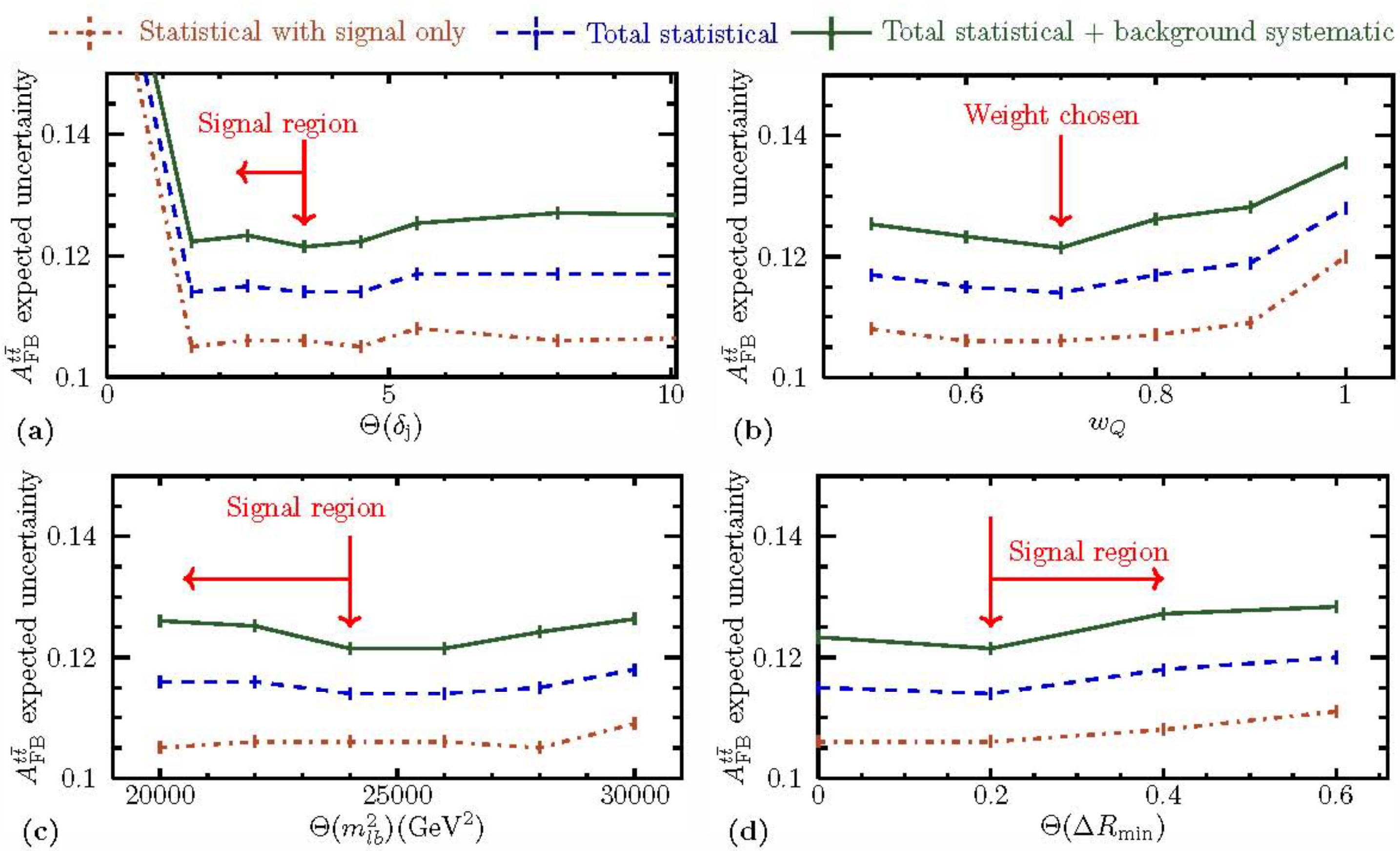
(a) $jd_{1,peak}$ (b) $jd_{2,peak}$



Distribution of m^2_{lb} for the correct and incorrect lepton-jet pairings taken from the POWHEG sample. The blue curve is from the correct lepton-jet pairing, and the red curve is from the incorrect lepton-jet pairing.



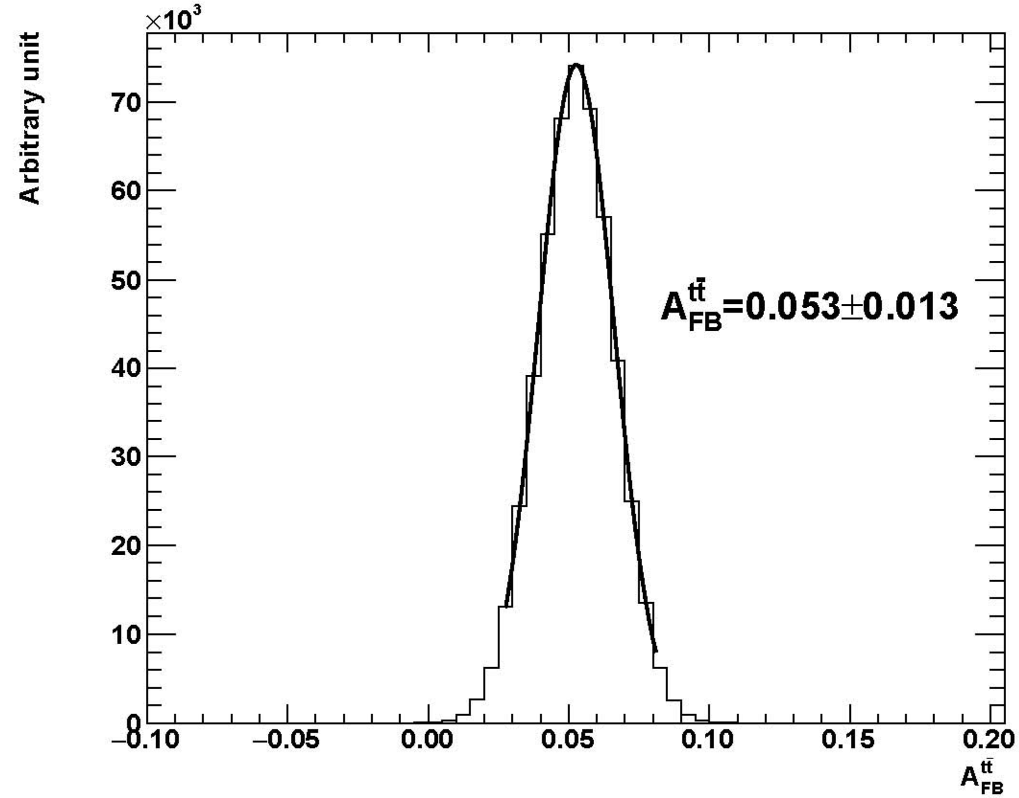
Optimization Results



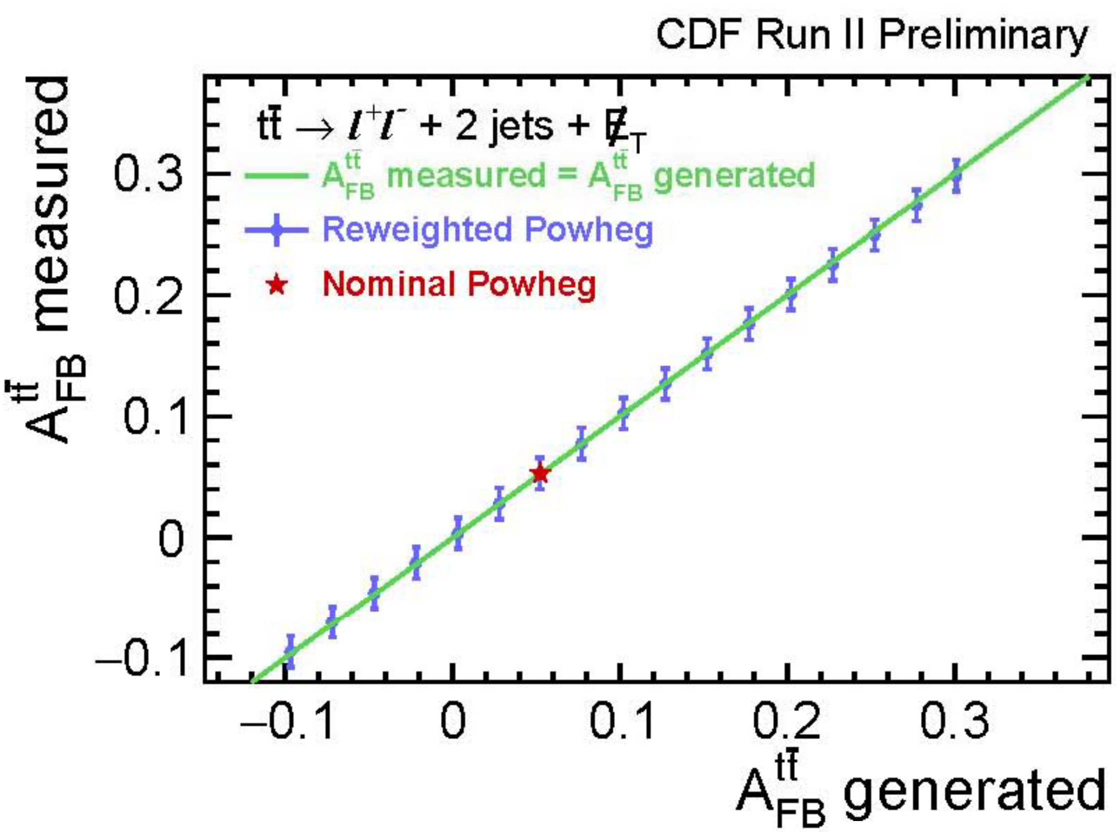
The expected statistical uncertainty with signal only (brown dot-dashed line), the total statistical uncertainty (with signal + background, blue dashed line), and the total statistical + background systematic uncertainty (the expected uncertainty in the text, green solid line), as functions of various cut and weight values. The optimum values are based on the minimum point of the green line, as marked with the red arrows on the plots, and summarized in Table 6.2. All other values are held at their optimal values for each plot. The expected uncertainty, after optimization, is 0.122.

Validation/Unfolding Results

- To extract parton-level A_{FB}, run MCMC to find most probable parameters that match observation
- Extract A_{FB} from marginalized posterior distribution
- POWHEG sample with 10M events gives 0.053±0.013 with 0.0524 generated



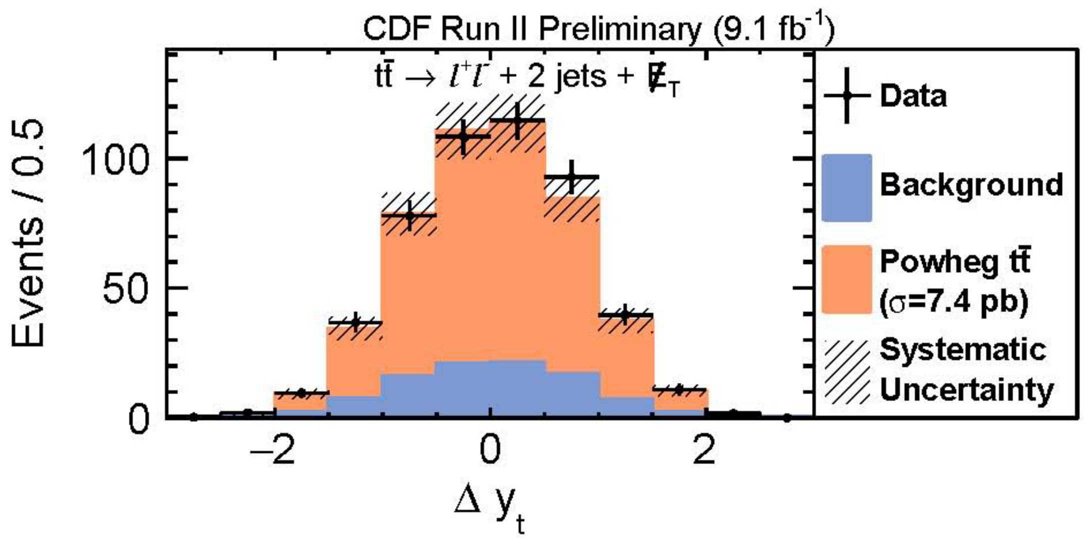
Comparing MC to Truth



A comparison of the $A_{\mathrm{FB}}^{t\bar{t}}$ measured with the unfolding algorithm compared with the $A_{\mathrm{FB}}^{t\bar{t}}$ generated, for the reweighted POWHEG MC samples, with $-0.1 < A_{\mathrm{FB}}^{t\bar{t}} < 0.3$. No bias observed. We note that all the data points are correlated.

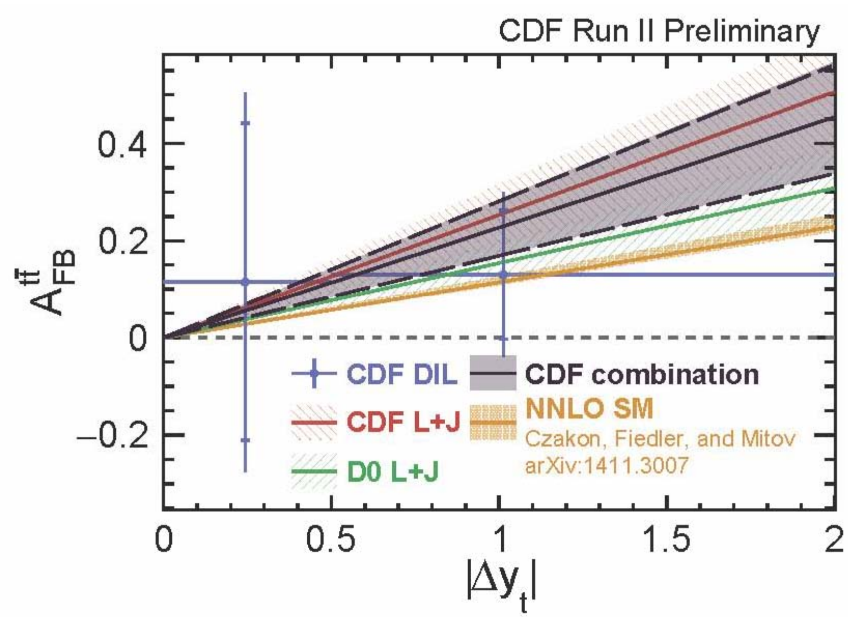
Reconstruct/Unfolding Results

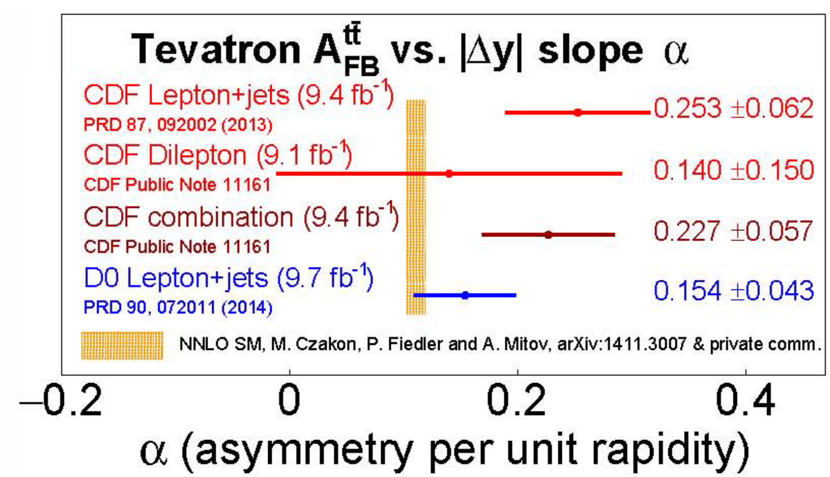
- Results with dilepton data:
  - A_{FB} = 0.12±0.11(stat) ±0.07(syst) = 0.12±0.13
- Combined with CDF result in lepton+jets
  - A_{FB}(CDF) = 0.160±0.045
- Consistent with prediction
  - A_{FB} (N^3LO SM) = 0.100±0.006 within 1.5σ
- Manuscript in preparation, to be submitted to PRD



A_{FB} Reconstructed Results

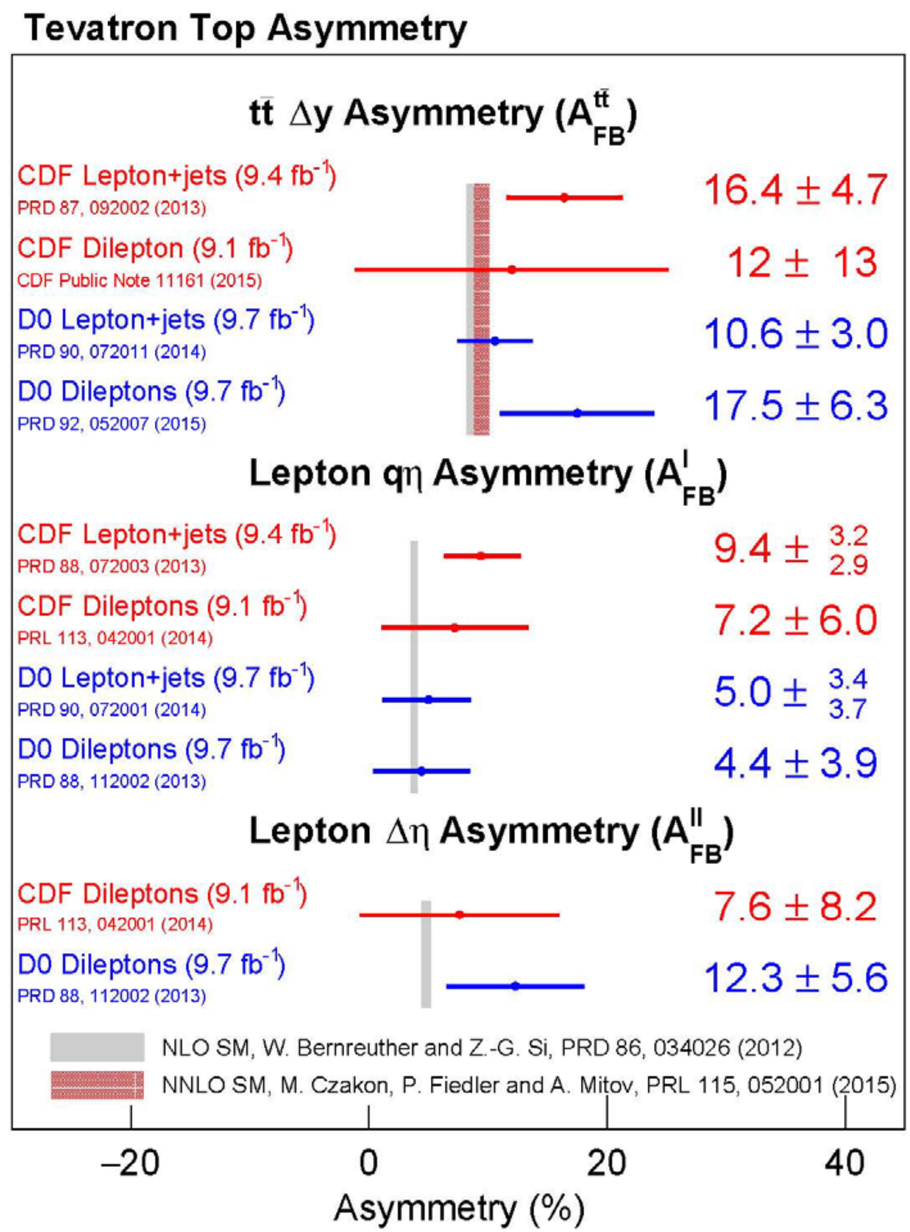
- Can extract A_{FB} vs. $|\Delta y|$ with a slope, as in Lep+Jets
  - Slope = 0.14± 0.16
- Combine with Lep+Jets results
  - Slope = 0.227± 0.057
  - 2.0σ from NNLO SM
- (Not enough statistics to make a meaningful slope vs. $M_{t\bar{t}}$ measurement)





Tevatron Results

- **Final individual results on A_{FB} from Tevatron**
- **All results consistent but higher than NLO (and NNLO) SM predictions**
- **A combination of CDF+DZero results is in the works**



Summary and Conclusions

- The A_{FB} of top-quark pairs at the Tevatron has been a hot topic for years, mostly based on early results from the CDF Lep+Jets measurement
- Have completed measurements in Lepton+Jets and Dilepton Final states with the full dataset
- Legacy measurements of the reconstructed A_{FB}, A_{FB} vs. $M_{t\bar{t}}$, A_{FB} vs. $|\Delta y|$ as well as the Leptonic asymmetry and the dilepton asymmetry are now done
- The SM calculations in the NLO+ era explain much, and an apparent fluctuations high appear to account for the rest
- Either way it has been an exciting chase for new physics

Backups