Heavy Quark Asymmetries at CDF

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3. The Bottom Asymmetry
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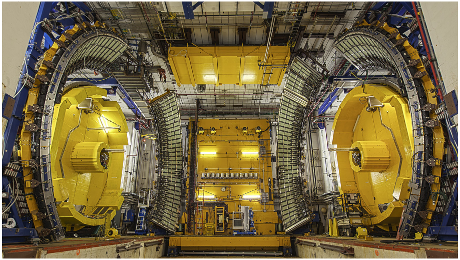
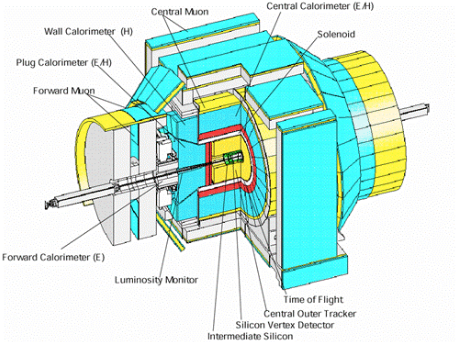
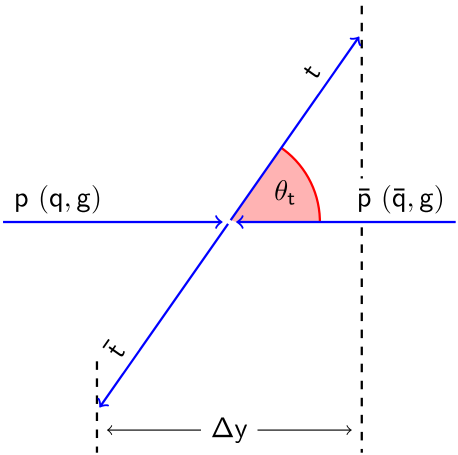


At first, the picture looks symmetric, but closer examination reveals asymmetries.

- Tevatron collided p and $\bar{p}$ at $\sqrt{s} = 1.96\,\text{TeV}$
- Run II from 2001 to 2011
- Two general-purpose experiments, CDF and D0
- Delivered $12\,\text{fb}^{-1}$ to CDF and D0
- CDF acquired $10\,\text{fb}^{-1}$
- CDF has tracking, calorimeter, muon chambers
- D0 similar – has A_{FB} measurements, not discussed in this talk

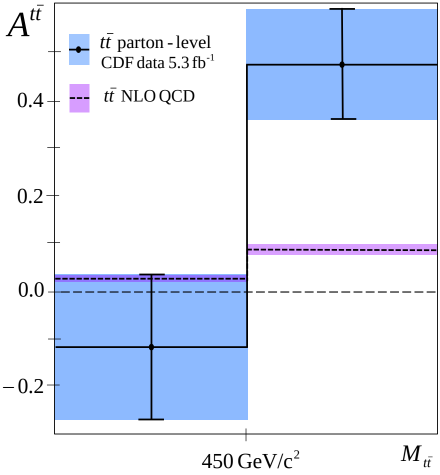




- Define $A_{FB} = \frac{N_F - N_B}{N_F + N_B}$
- In top and bottom, usually use rapidity difference to define "forward" and "backward"

$$\Delta y = y_{t,b} - y_{\bar{t},\bar{b}}$$

- This definition invariant under longitudinal boosts
- Can also use other variables, such as production angle $\cos\theta^*$
- At LHC, due to proton-proton initial state, no A_{FB}, look at forward-central asymmetry instead – not the subject of this talk



- In 2011, CDF measured the top asymmetry
- For the first time, measured as a function of top pair mass
- Two bins, $m_{t\bar{t}} < 450\,\mathrm{GeV}/c^2$ and $m_{t\bar{t}} > 450\,\mathrm{GeV}/c^2$
- A_{FB} in lower mass bin agreed with NLO SM prediction
- A_{FB} in higher bin disagreed at 3.3σ level!
- This sparked tremendous interest, with many, many new physics models proposed
- Kicked off a major program of measuring asymmetries at Tevatron and LHC

A_{FB} comes from interference between parity-even and odd $t\bar{t}$ states

The standard model:

- At leading order, zero A_{FB}
- At NLO, A_{FB} arises from interference between
  - Born and box diagrams (positive A_{FB})
  - initial- and final-state radiation (negative A_{FB})
- Tempting to think of QCD-only effect, but electroweak effects add $\sim 25\,\%$
- Recent NNLO prediction by Czakon *et al*:

$$A_{\mathrm{FB}} = (9.5 \pm 0.7)\,\%$$

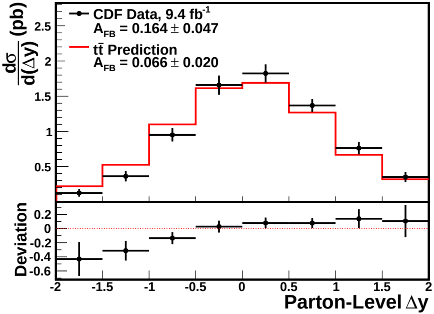
What about new physics?

- *t*-channel models include FCNCs, turn incoming light quarks into tops, scatter into forward Rutherford peak
- *s*-channel models produce A_{FB} from interference between gluon and new axial-vector particle (e.g. axigluon)
  - Can be low or high mass
  - Below top threshold, but very broad to evade dijet constraints
  - Above mass reach of LHC

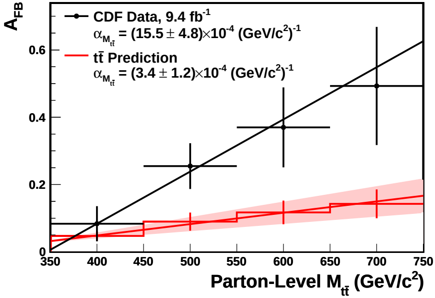
Experimental issues

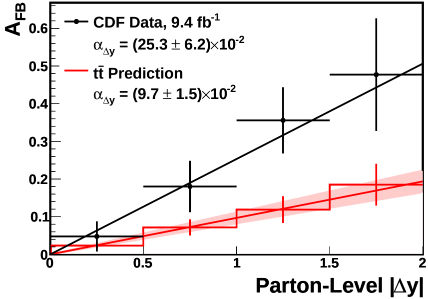
- lepton+jets: $p\bar{p} \to t\bar{t} \to W^+W^-b\bar{b} \to \ell\nu qq'b\bar{b}$
- dilepton: $p\bar{p} \to t\bar{t} \to W^+W^-b\bar{b} \to \ell^+\ell^-\nu\bar{\nu}b\bar{b}$
- (Experimental) leptons are electrons or muons
- Neutrinos are undetected, except as missing transverse energy $\not{E}_T$
- Quarks produce jets
- Bottom quarks produce jets with a displaced vertex, identified using various *b*-tagging algorithms

- A_{FB} measured in lepton+jets channel with $9.4\,\mathrm{fb}^{-1}$
- Kinematic reconstruction of top and antitop four-momenta
- Corrected to parton level using SVD unfolding
- $A_{\mathrm{FB}} = (16.4{\pm}4.7)\,\%$
- With respect to now-outdated NLO prediction, this was just over a 2σ effect
- Less than 1.5σ from new NNLO $A_{\mathrm{FB}} = (9.5{\pm}0.7)\,\%$
- New result in dilepton channel with full CDF dataset coming soon ($\sim$ weeks)

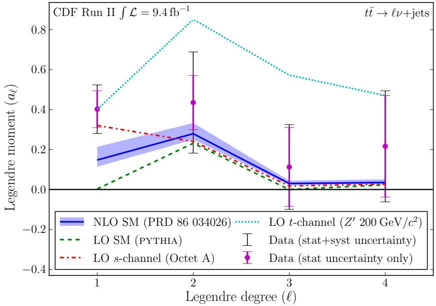


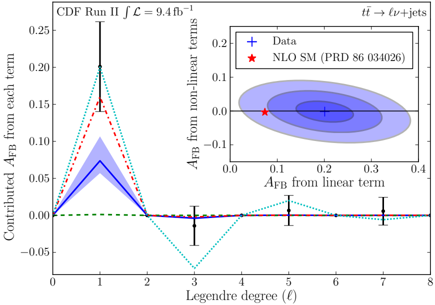
- In lepton+jets channel, measure top A_{FB} as function of $t\bar{t}$ mass and $|\Delta y|$
- Linear as function of both
- Fit lines to extract slope
- As before, NLO fails to predict data; NNLO does much better

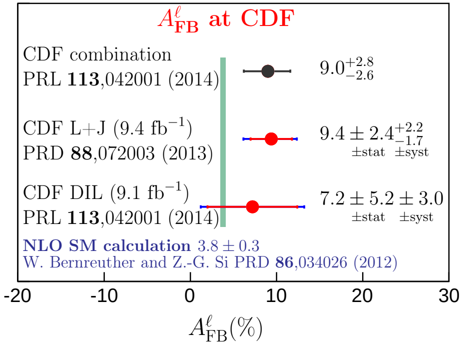




- Decompose differential XS into Legendre polynomials: $d\sigma/d\cos\theta_t = \sum_\ell a_\ell P_\ell(\cos\theta_t)$
- Measure coefficients a_ℓ, extract contribution of each to A_{FB}
- Can discriminate among SM, *s*-channel, and *t*-channel new physics
- A_{FB} entirely caused by a_1; 2σ from NLO SM, consistent with *s*-channel dynamics
- BUT: new NNLO calculation coming soon from Czakon *et al*
- Preliminary result (private comm.) agrees with CDF: $P(\chi^2) = 75\,\%$



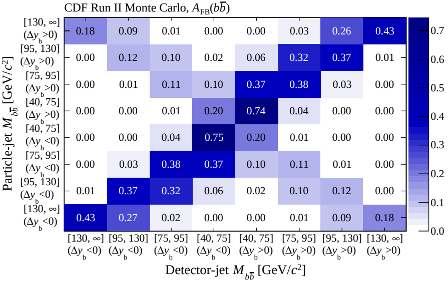




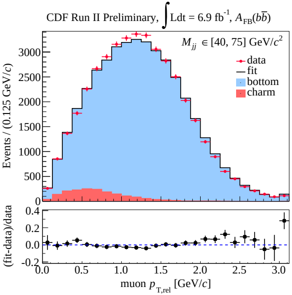
- Reconstructing top and antitop adds uncertainty
- Lepton(s) follow direction of parent top or antitop, easy to reconstruct
- Compute leptonic A^{lep}_{FB}, where "forward" defined using charge times pseudorapidity
- Use empirical model to extrapolate A^{lep}_{FB} to unmeasured regions of pseudorapidity
- About 2σ from NLO SM prediction of $A^{lep}_{FB} = (3.8 \pm 0.3)\,\%$
- No NNLO prediction yet, anticipate increase similar to that seen in $A_{FB}\,(t\bar{t})$

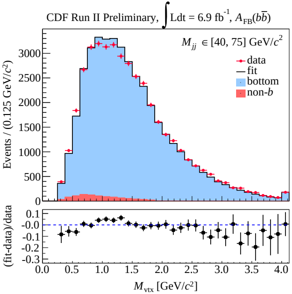
- Same dynamics that produce $t\bar{t}$ A_{FB} should impact $b\bar{b}$ A_{FB}
- Allows access to masses below $t\bar{t}$ threshold
- Search directly for low-mass axigluons – these produce a sign flip in A_{FB} as you pass the axigluon mass
- Cannot correct to parton level as in top; correct to stable-particle level instead
- SM predictions available at NLO (Grinstein and Murphy)
- No NNLO predictions yet
- At lowest masses, below few tens of GeV, A_{FB} washed out by symmetric gluon-gluon initial state
- Re-iterate: sign change in A_{FB} could be smoking gun of new physics

- To measure A_{FB}, have to know b from $\bar{b}$
- Easiest way: soft muons in jets
- Select 2-jet events (back to back jets), look for soft muon in one jet and displaced vertex in both
- Assume that charge of muon has same sign as charge of original quark
- Low efficiency – restricted to $m_{b\bar{b}} \lesssim$ few hundred GeV
- Measure rapidity difference $\Delta y = y_b - y_{\bar{b}}$ between jets
- Unfold to stable-particle level using SVD unfolding



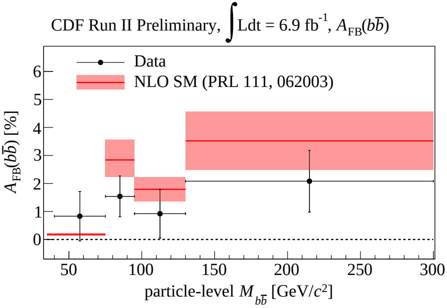
- Smearing matrix shows sometimes muon charge $\neq b$ charge
- Due to mixing and cascade decays, primarily
- This is taken into account in unfolding



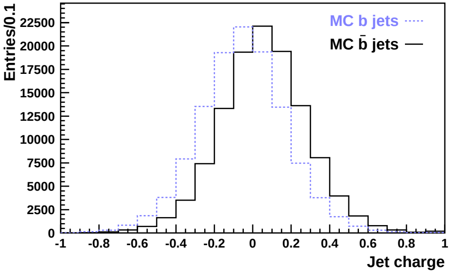


- Need to worry about backgrounds from $c\bar{c}$, bc, jb, and fake muons
- These backgrounds are primarily symmetric, only worry about rate
- On muon-jet side, use $p_{T,\mathrm{rel}}$, component of muon momentum perpendicular to jet axis
- Backgrounds and signal have different $p_{T,\mathrm{rel}}$ distributions, so do fraction fit
- Other jet, use m_{VTX}, mass of tracks associated with secondary vertex
- Signal purity ranges from 75 % to 95 % depending on $m_{b\bar{b}}$

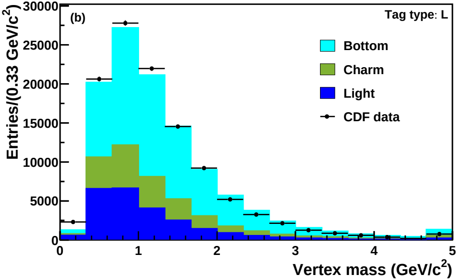
- A_{FB} consistent with SM prediction
- Can even see some sign of electroweak A_{FB} around the Z mass!
- No sign change
- No indication of axigluons or any other anomalies
- But, still a gap in mass between this and $t\bar{t}$ measurements

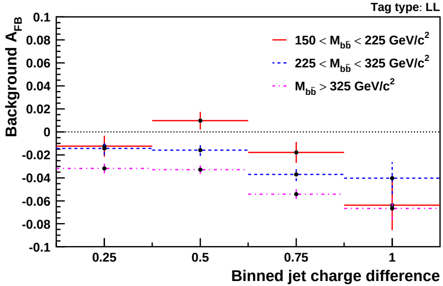


- To get to high mass, need to retain more $b\bar{b}$ events
- Can't use soft muons – not enough of them
- Have to use jet charge instead
- Momentum-weighted sum of charges of tracks associated with jet
- Use difference of jet charge between two jets
- Identification power increases with $|\Delta Q_{\text{jet}}|$
- Divide into four jet-charge-difference bins



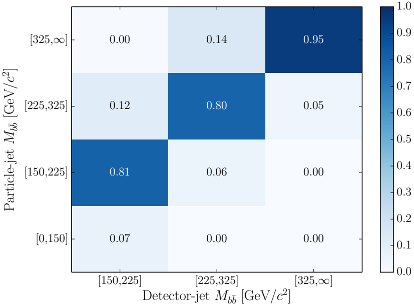
- Get data from jet triggers
- Three $m_{b\bar{b}}$ bins: $150 - 225$, $225 - 325$, $> 325\,\text{GeV}/c^2$

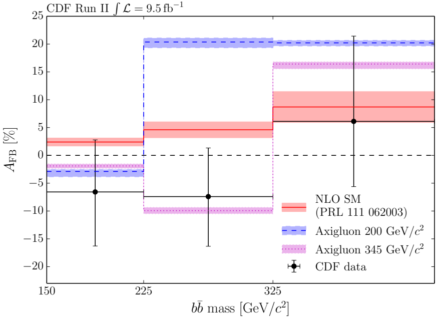




- Primary background from light-quark t-channel scattering
- Large negative A_{FB}
- Estimate background rate from m_{VTX} fits, using "negative" displaced-vertex tags
- Divide b tags into high ("H") significance and low ("L") significance, so three event categories HH, LH, LL
- Estimate background asymmetry from control region depleted in $b\bar{b}$ signal

- Unfold to stable-particle level, taking into account smearing and acceptance
- Mass reconstruction quite good, but some smearing at $\sim 10\,\%$ level
- Do this using Bayesian estimation with Markov-chain Monte Carlo
- Take into account systematics, smearing, acceptance, charge confusion, background rate and asymmetry, signal asymmetry





- A_{FB} consistent with NLO SM and with zero
- No indications of new physics
- Able to start ruling out some models
- Axigluon with mass 200 GeV/c^2 and width 50 GeV excluded at 95 % level
- Similar axigluon with mass 345 GeV/c^2 and width 80 GeV not excluded

- Top A_{FB} anomaly in 2011 created a lot of interest and effort
- It's taken us 4 years, $O(10^1)$ analyses, and $O(10^2)$ theory papers to understand this
- Eventually NNLO seems to have resolved it
- No longer appears to be hints of new physics in top A_{FB}
- No hints in bottom A_{FB} either
- D0 has had a similar program of top A_{FB}, and a very low mass bottom A_{FB} measurement – Conclusions are the same
- With no new physics, could feel disappointed
- On the other hand, this work produced tremendous advances in the theoretical capabilities for top, which is a really great outcome

Thank you

- 2011 CDF mass-dependence evidence: PRD 83 112003
- inclusive and kinematic AFB: PRD 87 092002
- $\cos\theta_t$: PRL 111 182002
- lepton AFB (lepton+jets): PRD 88 072003
- lepton AFB (dilepton): PRL 113 042001
- lepton AFB method: PRD 90 014040
- High-mass $b\bar{b}$ AFB: arXiv:1504.06888
- Low-mass $b\bar{b}$ AFB: CDF Note 11156

Theory:

- NLO+EWK $t\bar{t}$ AFB: PRD 86 034026
- NNLO $t\bar{t}$ AFB: arXiv:1411.3007
- NLO $b\bar{b}$ AFB: PRL 111 062003 and arXiv:1504.02493
- $t\bar{t}$ AFB exotica overview: PRD 83 114027
- t-channel exotica $t\bar{t}$ AFB: PRD 83 114039 (among others)
- s-channel exotica $t\bar{t}$ AFB: EPJC 72 2102 (among others)