A long time ago, at a laboratory far, far away…

Top Production at the Tevatron: The Antiproton Awakens

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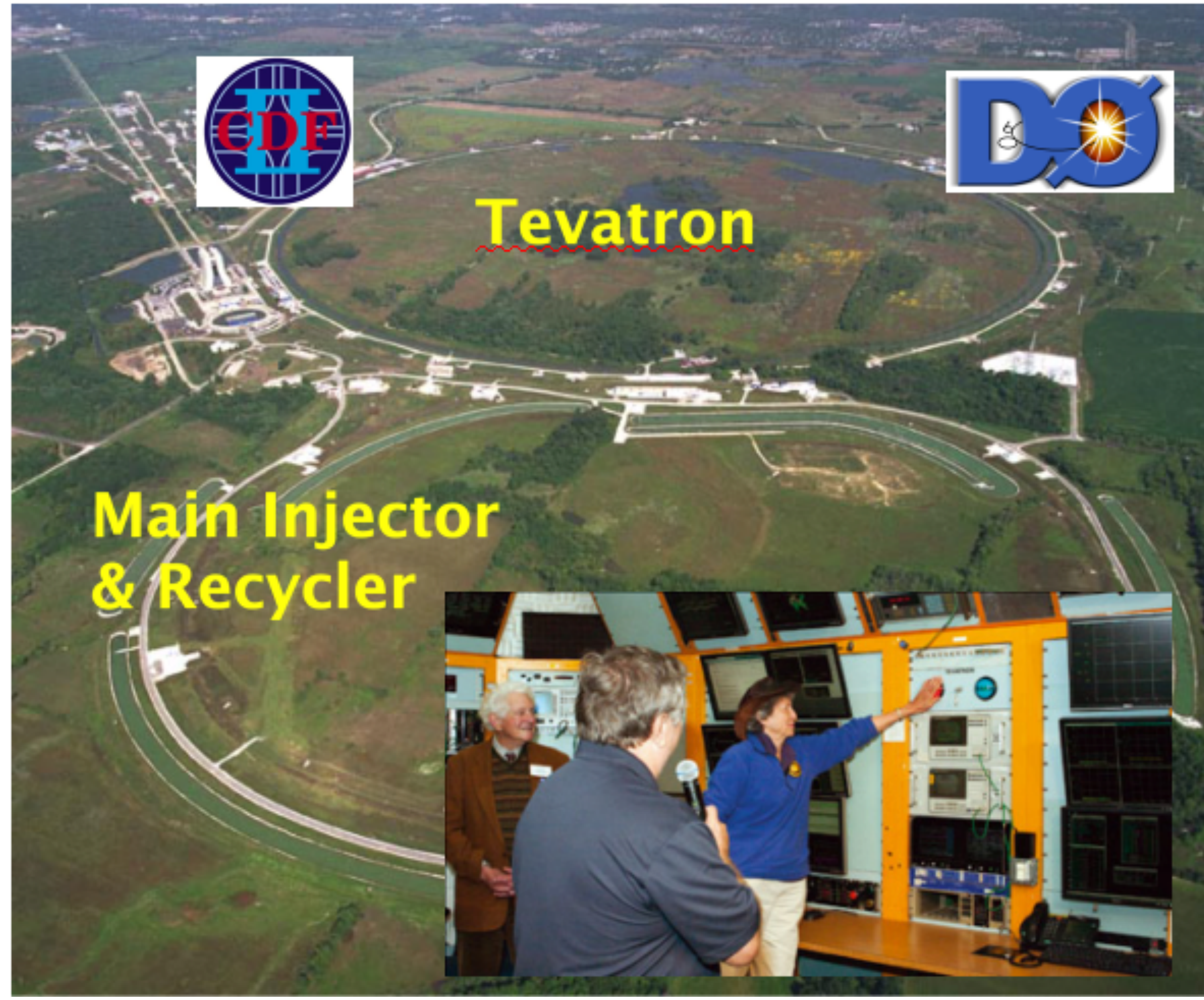
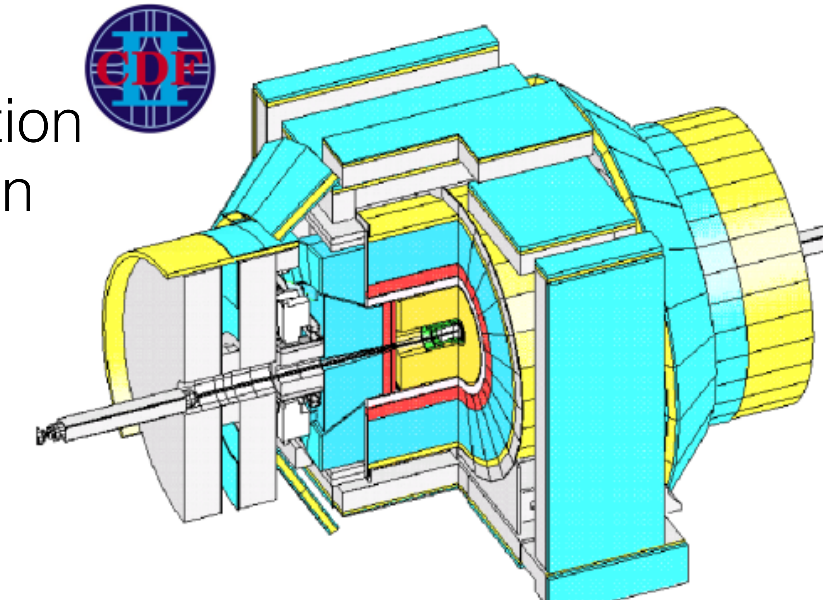
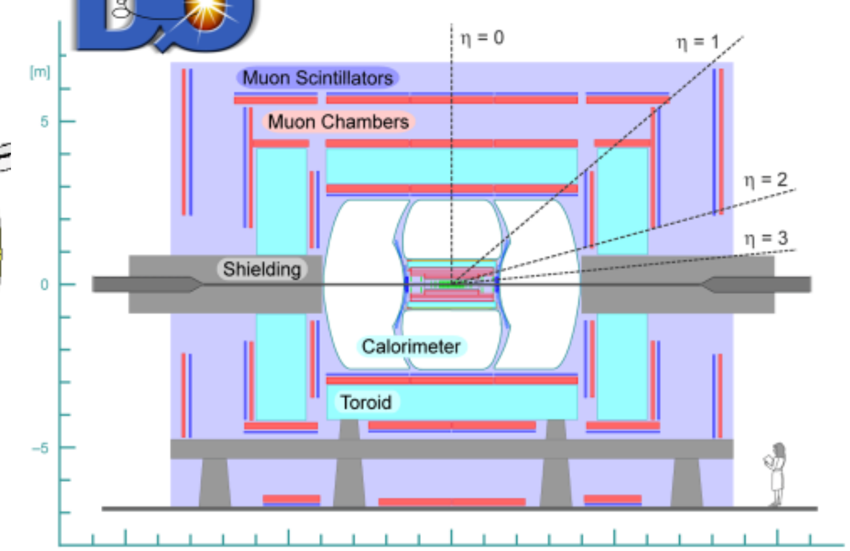
for the CDF and D0 Collaborations
10 March 2016

- The Fermilab Tevatron collided protons and antiprotons at $\sqrt{s}$ = 1.96 TeV
    - Quark-antiquark initial state (mostly)
- Two experiments recorded ~10 fb^{-1} each, concluding operations in September 2011
- It is possible that such experiments will never be repeated
    - A unique dataset for unique measurements!
    - Today’s topics: top-quark production rates, spin orientations, production asymmetries







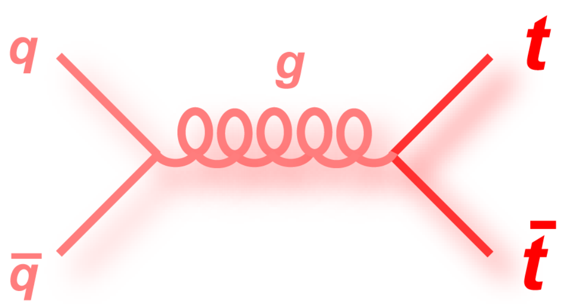
Top production modes

Cross sections from NNLO theory

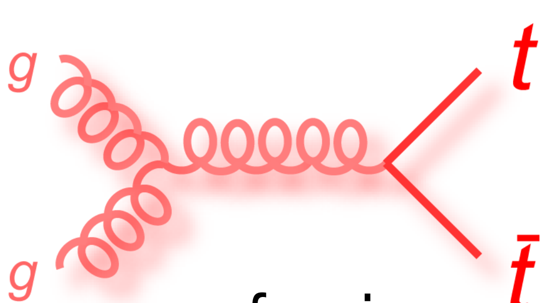
σ (pb)	$t\bar{t}$	tb	tqb	tW
TEV	7.08	1.04	2.08	0.30
LHC8	234	5.55	87.2	22.2
LHC13	816	10.32	217	71.7

$t\bar{t}$ initial state fractions

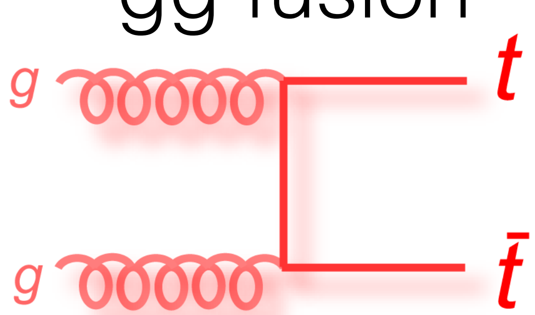
	TEV	LHC8	LHC13
$q\bar{q}$	85%	13%	10%
gg	15%	87%	90%

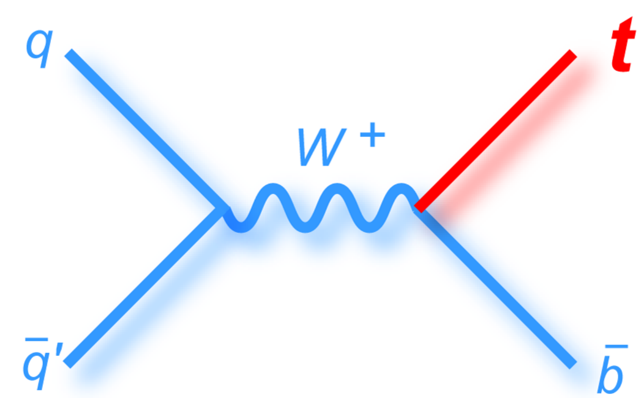


$q\bar{q}$ annihilation

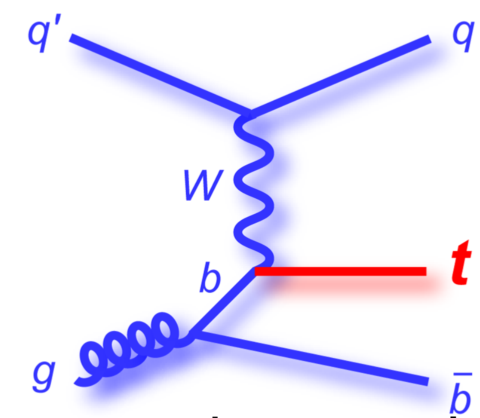


gg fusion

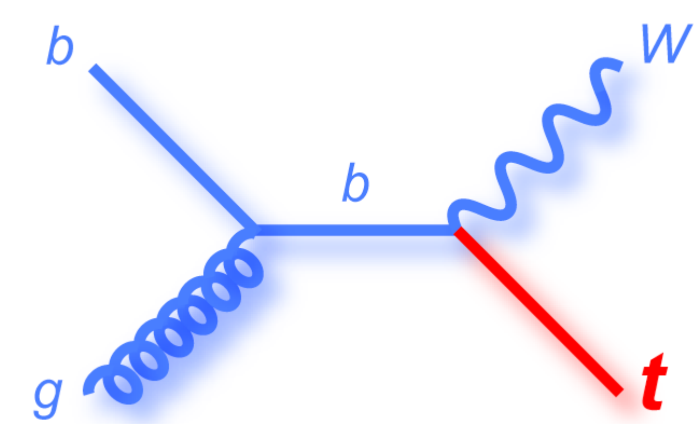




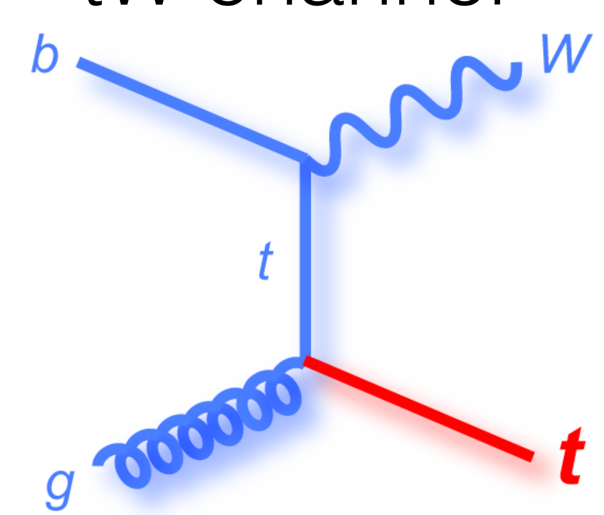
s channel



t channel



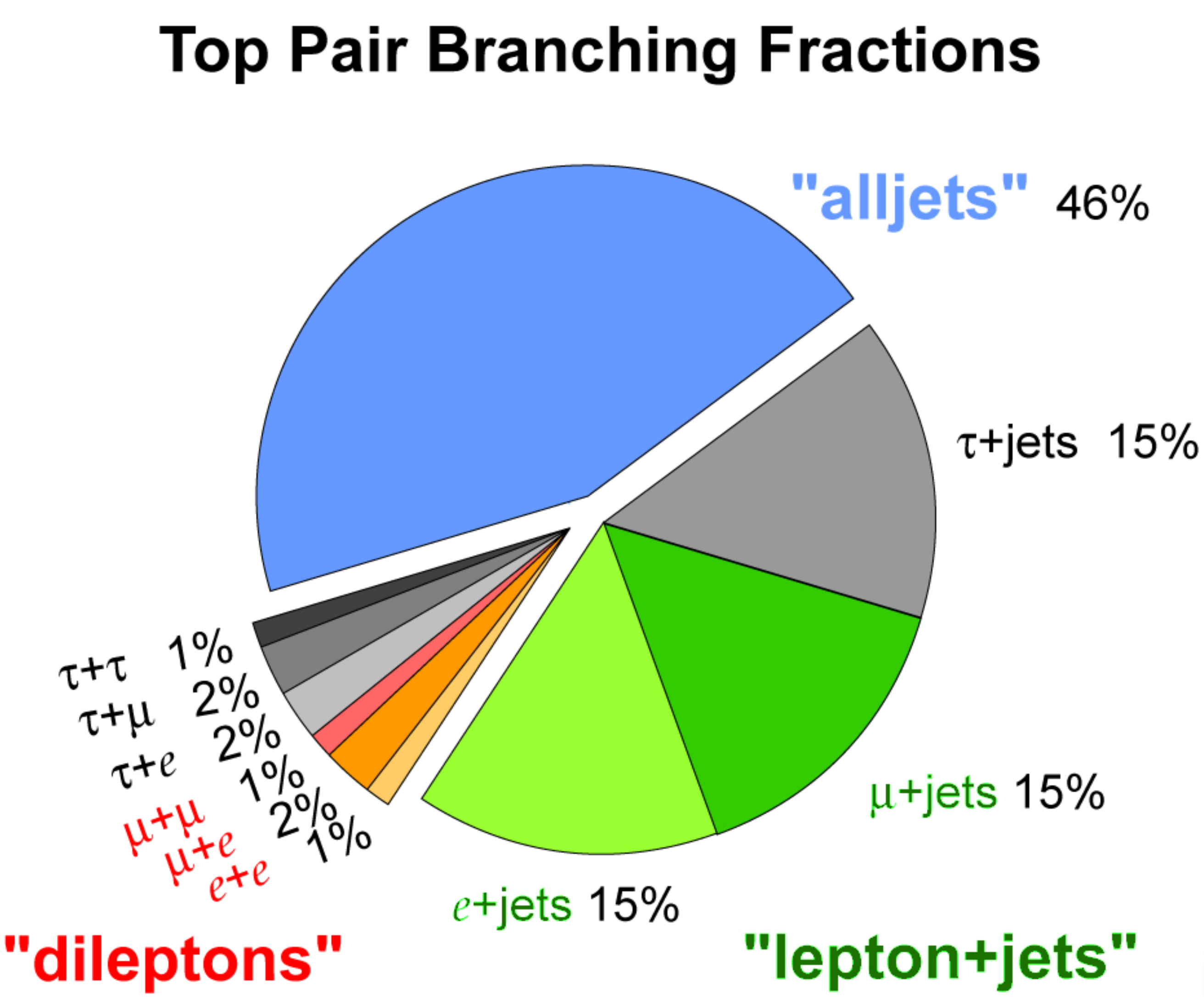
tW channel

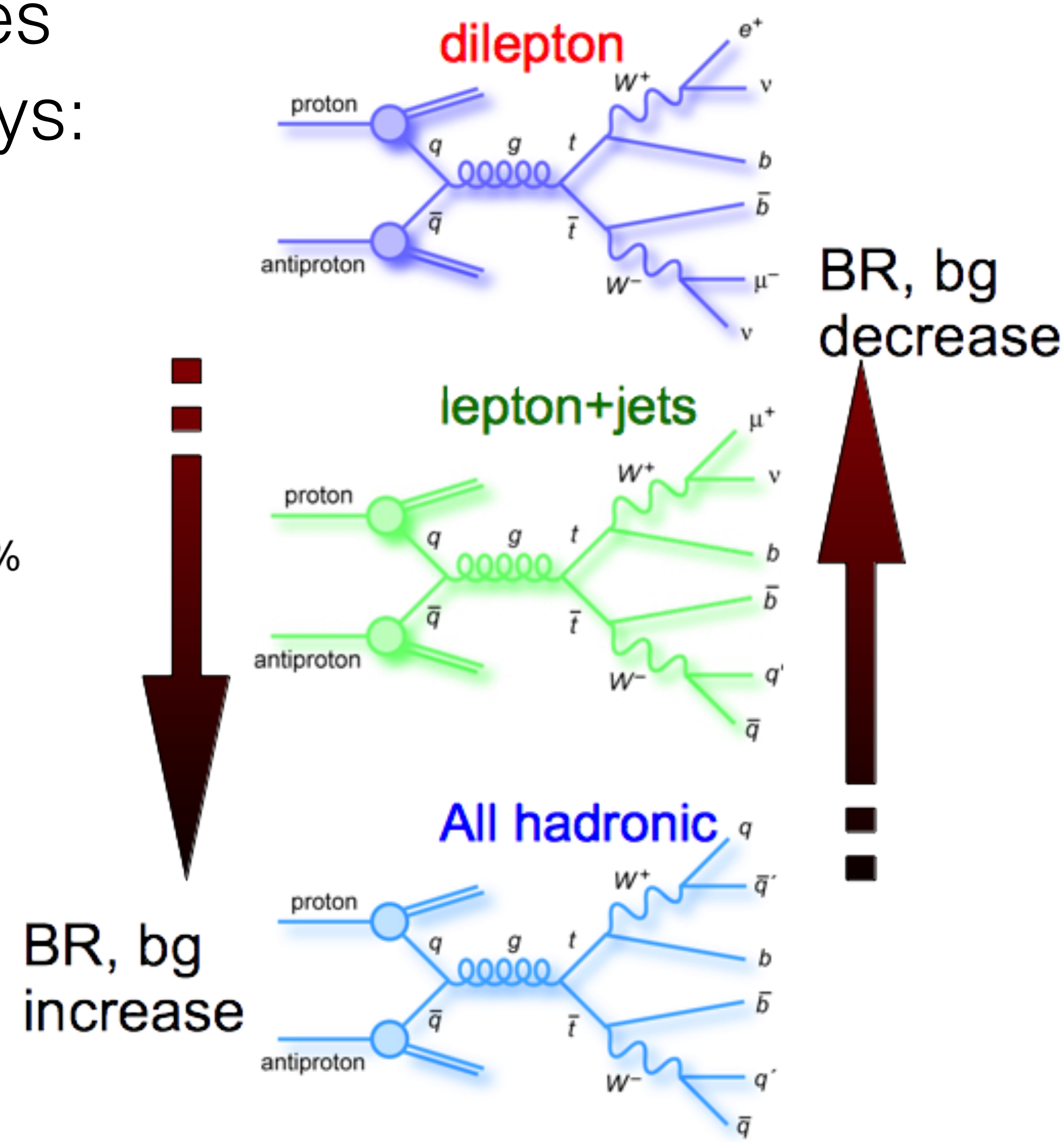


Tevatron can compete in some areas, and provides complementarity thanks to $q\bar{q}$ initial state

$t\bar{t}$ production/decay primer

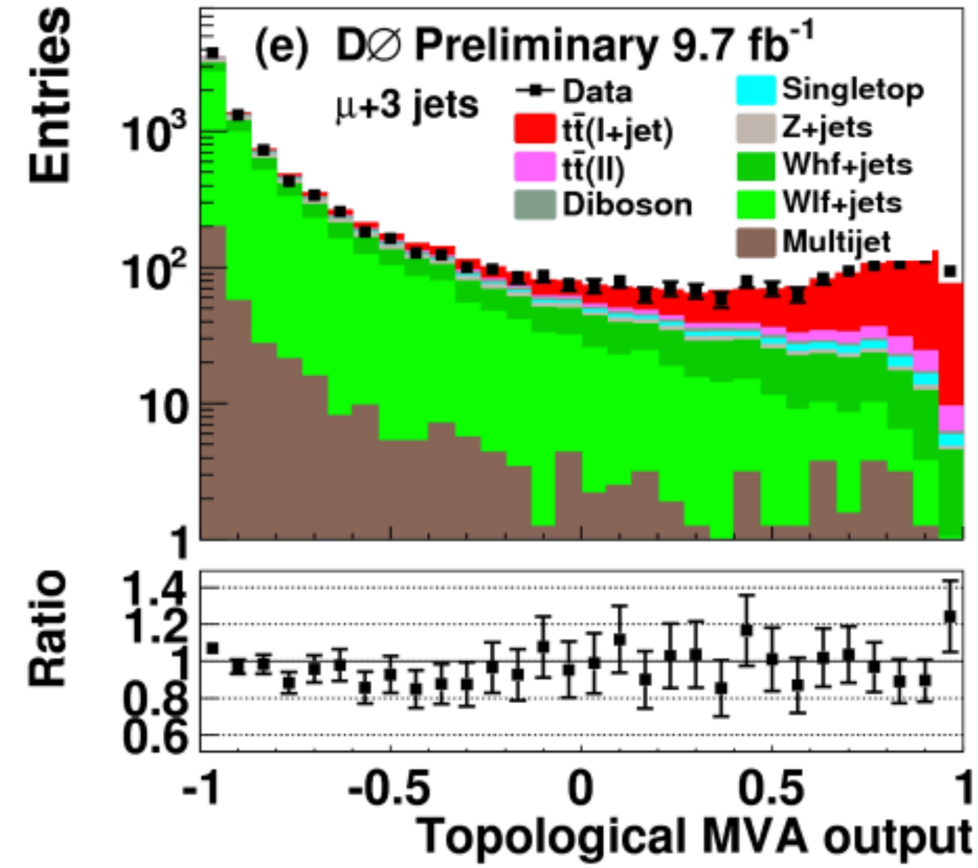
B(t → Wb) ≃100%, final states characterized by two W decays:

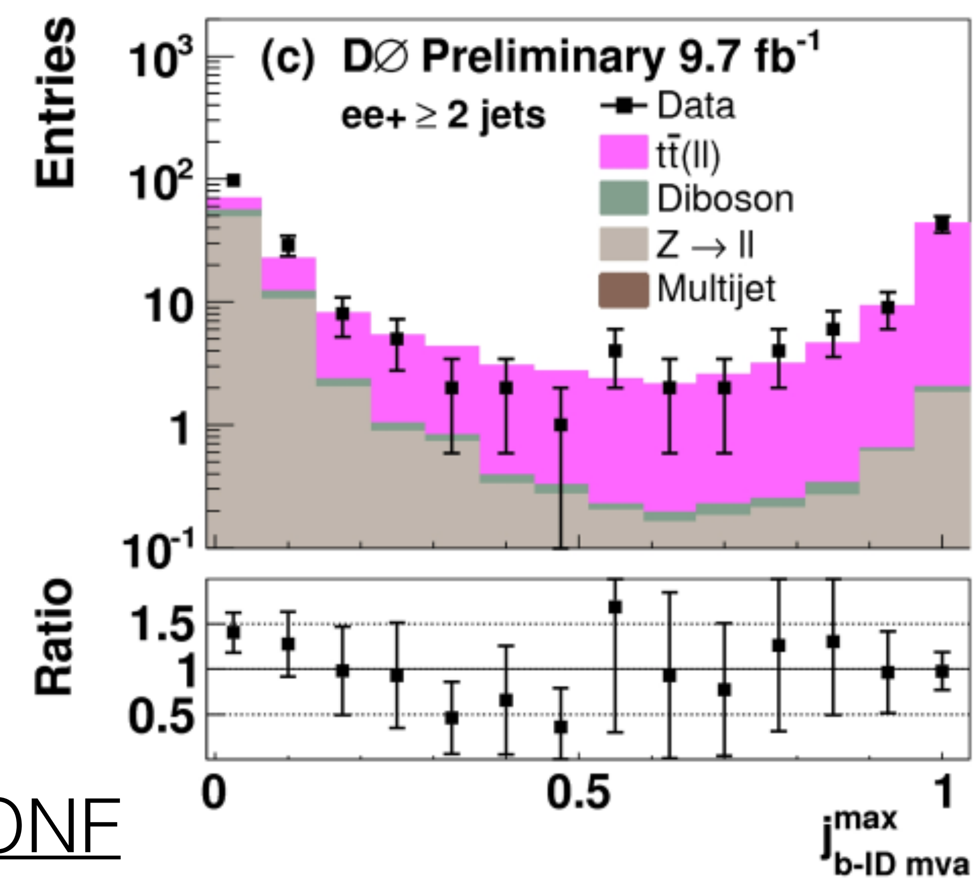




D0: Inclusive cross section

- 2x data as previous D0 measurement
- Heavy use of multivariate techniques
- Lepton plus jets channel:
  - Six subsamples based on lepton type and jet multiplicity
  - Each gets its own BDTG using ~20 kinematic variables plus b-tag MVA output for jets
- Dilepton channel:
  - Four subsamples: eμ+1 jet, eμ+≥2 jets, ee+≥2 jets, μμ+≥2 jets
  - b-tag MVA output of leading jet is used as discriminant
- Simultaneous template fits across all samples, using systematics as nuisance parameters
- σ = 7.73 ± 0.13 (stat) ± 0.55 (syst) pb
  - Relative uncertainty 7.3%!
  - Dominant systematics are from modeling, especially hadronization

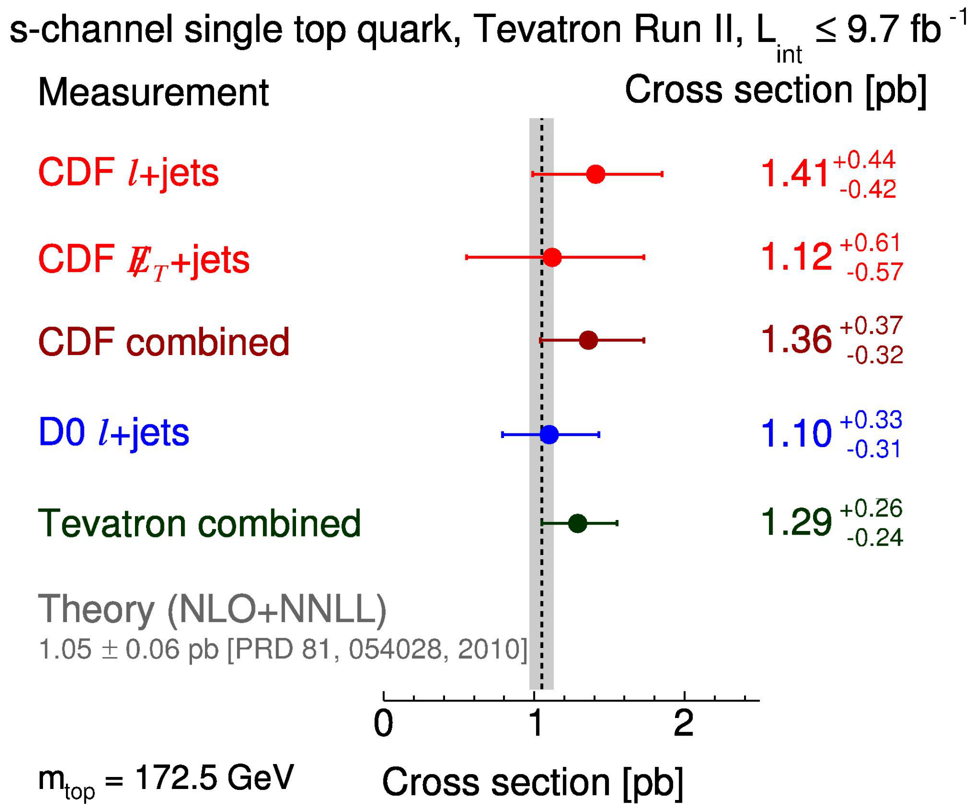


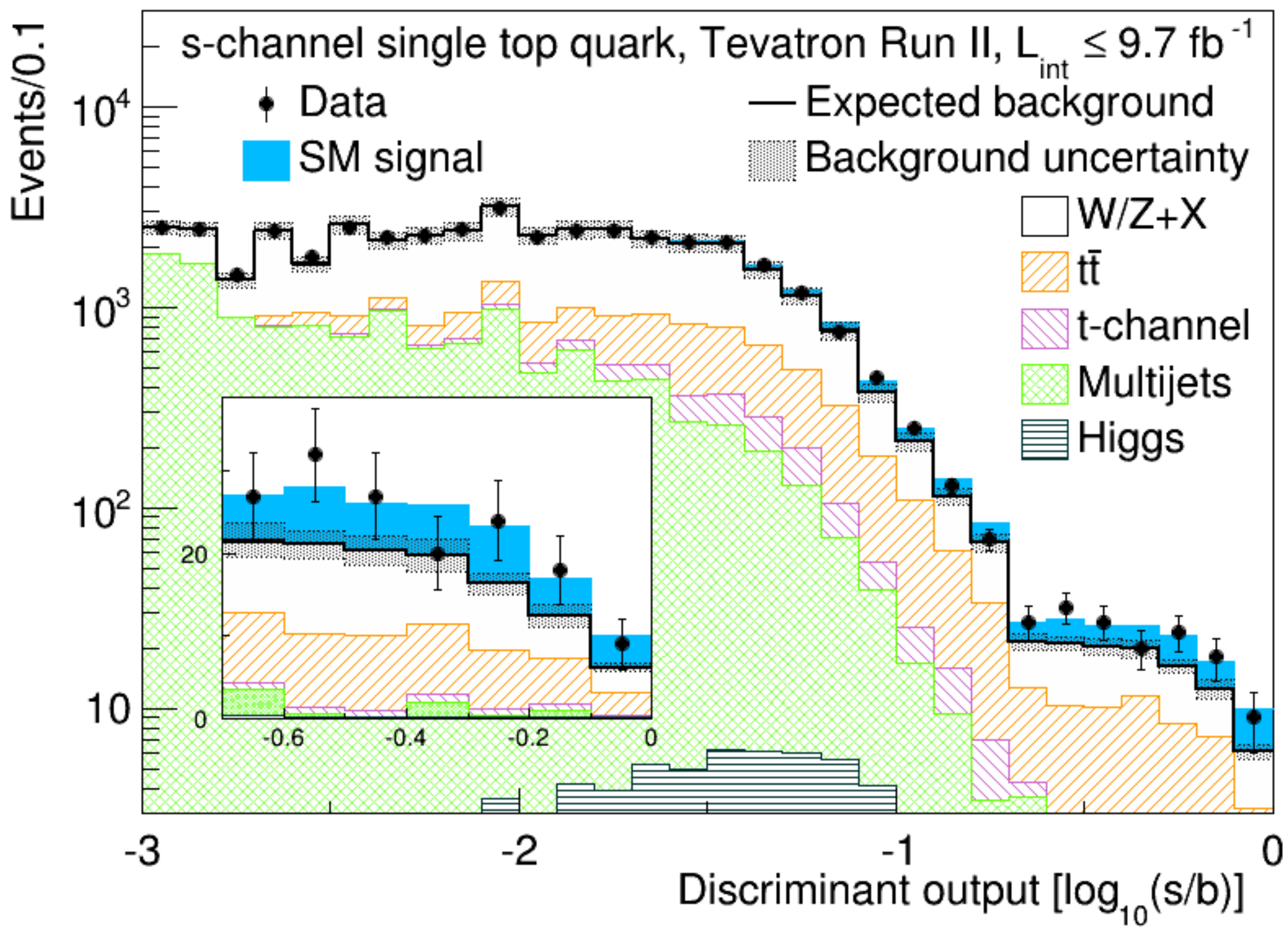


D0 6453-CONF

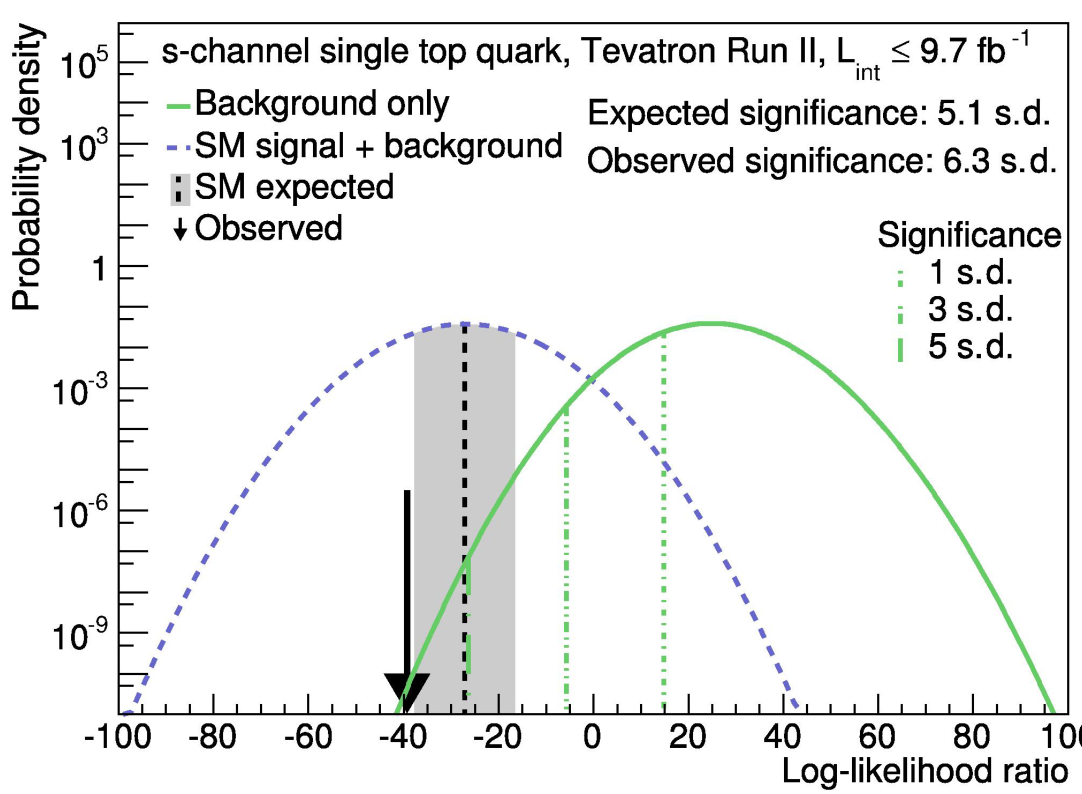
Single top production

- Combine CDF (l+jets and MET+jets) & D0 (l+jets) discriminants for s-channel production
- Include all systematic uncertainties and correlations
- First observation of s-channel single top, 6.3 SD significance



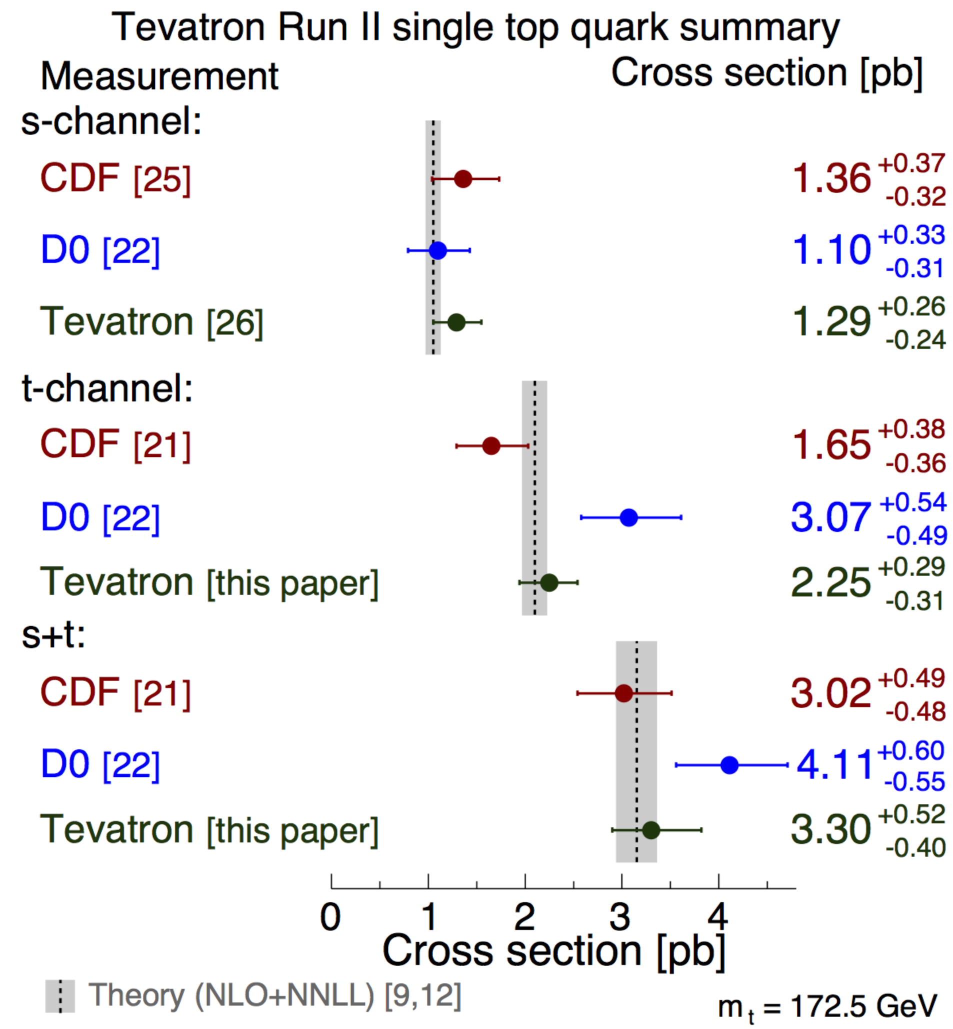


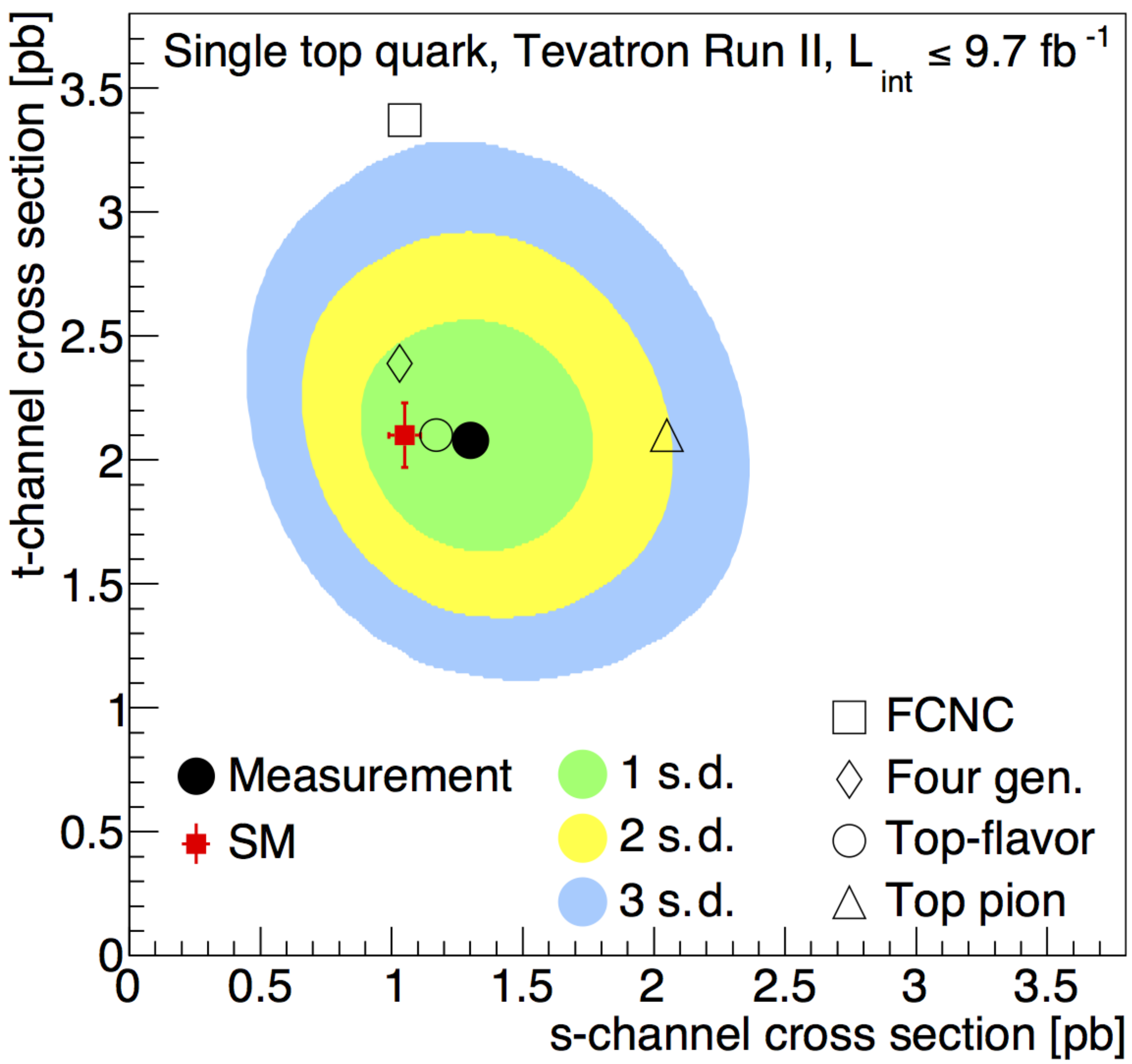
PRL 112, 231803 (2014)

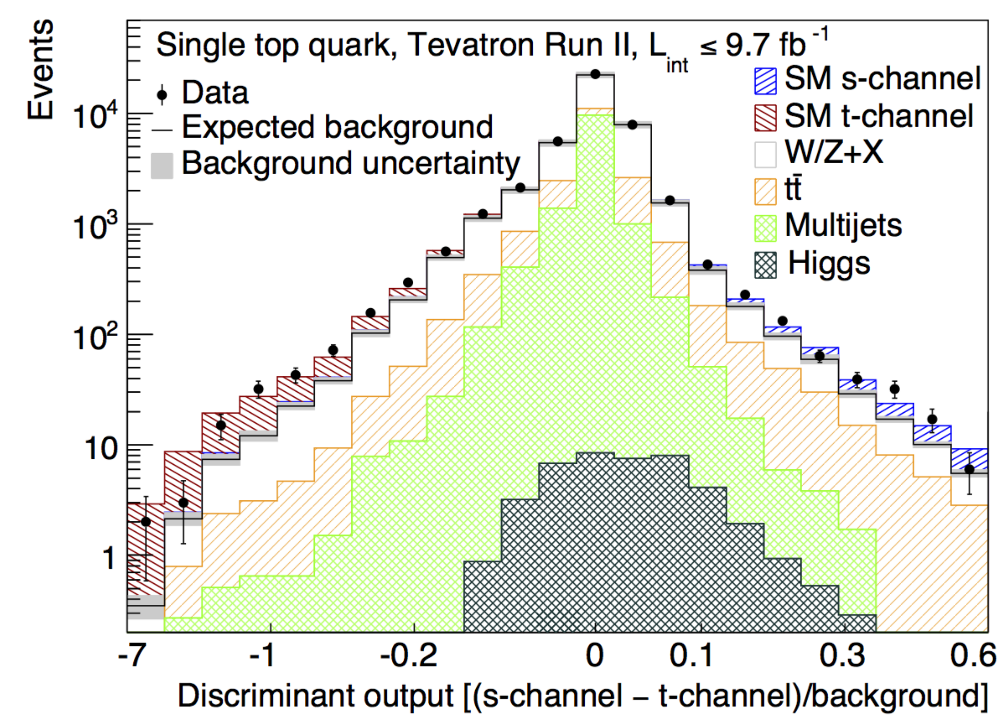


Single top production

- No assumption of σ_s/σ_t value
- Agrees with SM, no indication of non-SM contributions
- Concludes the Tevatron single-top program!







D0: top polarization

- Top quarks produced in strong interaction are (almost) entirely unpolarized
  - A search for polarization is a search for new physics
- Polarization can be measured in the top rest frame through angular distributions of decay products *i* with respect to a given axis *n*:

polarization

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{i,\hat{n}}} = \frac{1}{2}(1 + P_{\hat{n}}\kappa_i \cos\theta_{i,\hat{n}})$$

analyzing power, ~1 for leptons

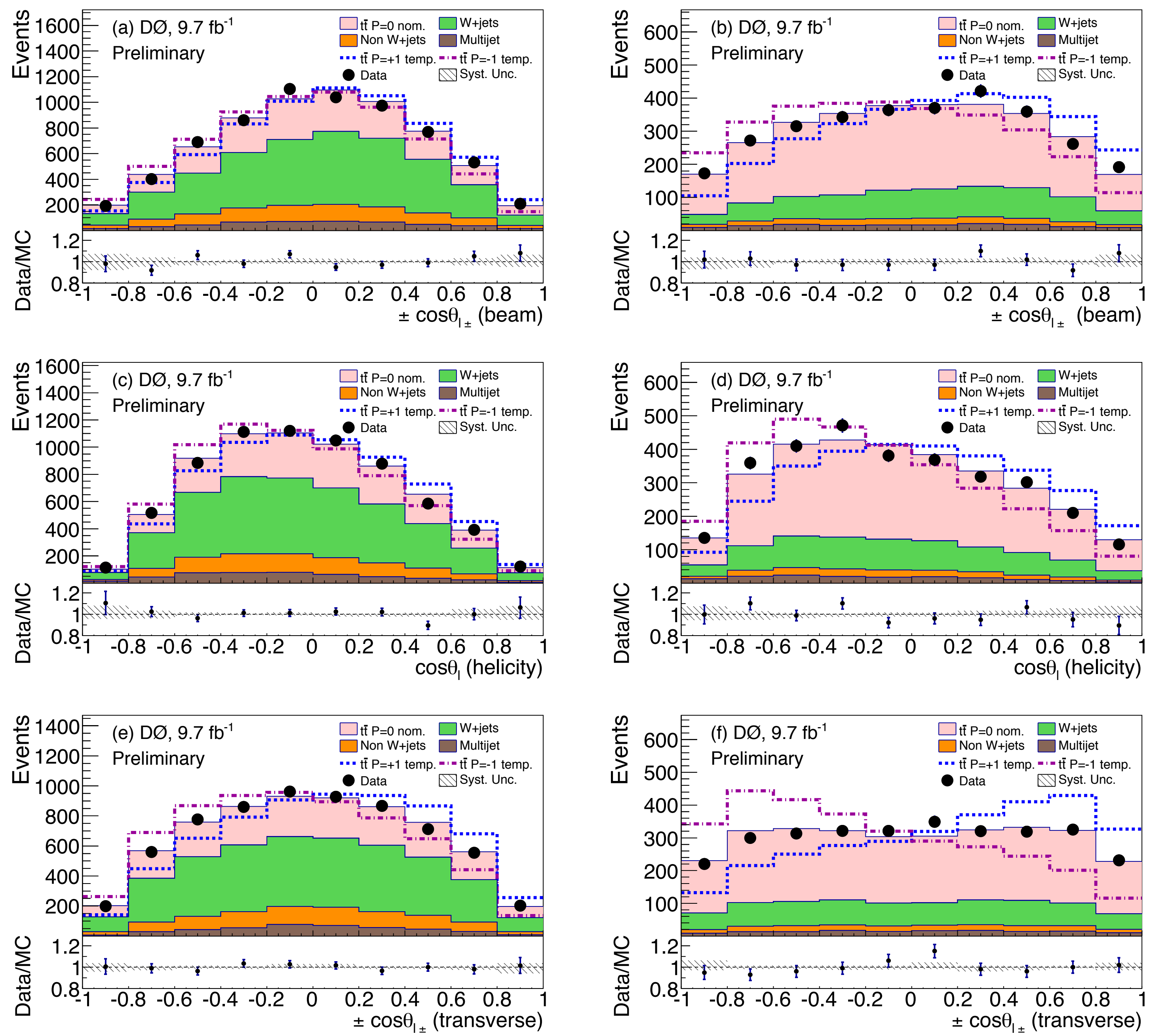
- Many axes to choose from
  - beam axis: direction of proton
  - helicity axis: direction of parent top quark
  - transverse axis: perpendicular to production plane (cross product of beam and helicity axes)
- D0 has new measurements of polarization, including the world's only measurement using the transverse axis

D0: top polarization

- Use l+3 jet and l+4 jet samples, perform kinematic reconstruction to get lepton angles
  - l+3 jet kinematic fitter developed for A_{FB} analysis increases statistics
- Develop P=+1 and P=-1 templates, extract polarization from relative fractions
- Measured polarizations consistent with both SM and 0
- First-ever measurement of transverse polarization

- Polarization also measured in dilepton events (wait 8 slides)

D0 6417-CONF



l+3 jet

l+4 jet

Axis	Measured polarization $P_{\hat{n}}$	SM prediction
Beam	$+0.070 \pm 0.055$	-0.002
Helicity	-0.102 ± 0.060	-0.004
Transverse	$+0.040 \pm 0.034$	$+0.011$

D0: spin correlation

- While tops are not produced polarized, their spins are correlated
  - Unique measurement in $t\bar{t}$ system as top lifetime is 1000x shorter than spin decorrelation time!
  - Amount of correlation depends on the initial state ($q\bar{q}$ or gg)
- Observable is $O_{ab} = \langle 4(S_t \cdot \hat{a})(S_{\bar{t}} \cdot \hat{b}) \rangle =$

$$\frac{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) - \sigma(\uparrow\downarrow) - \sigma(\downarrow\uparrow)}{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) + \sigma(\uparrow\downarrow) + \sigma(\downarrow\uparrow)}$$

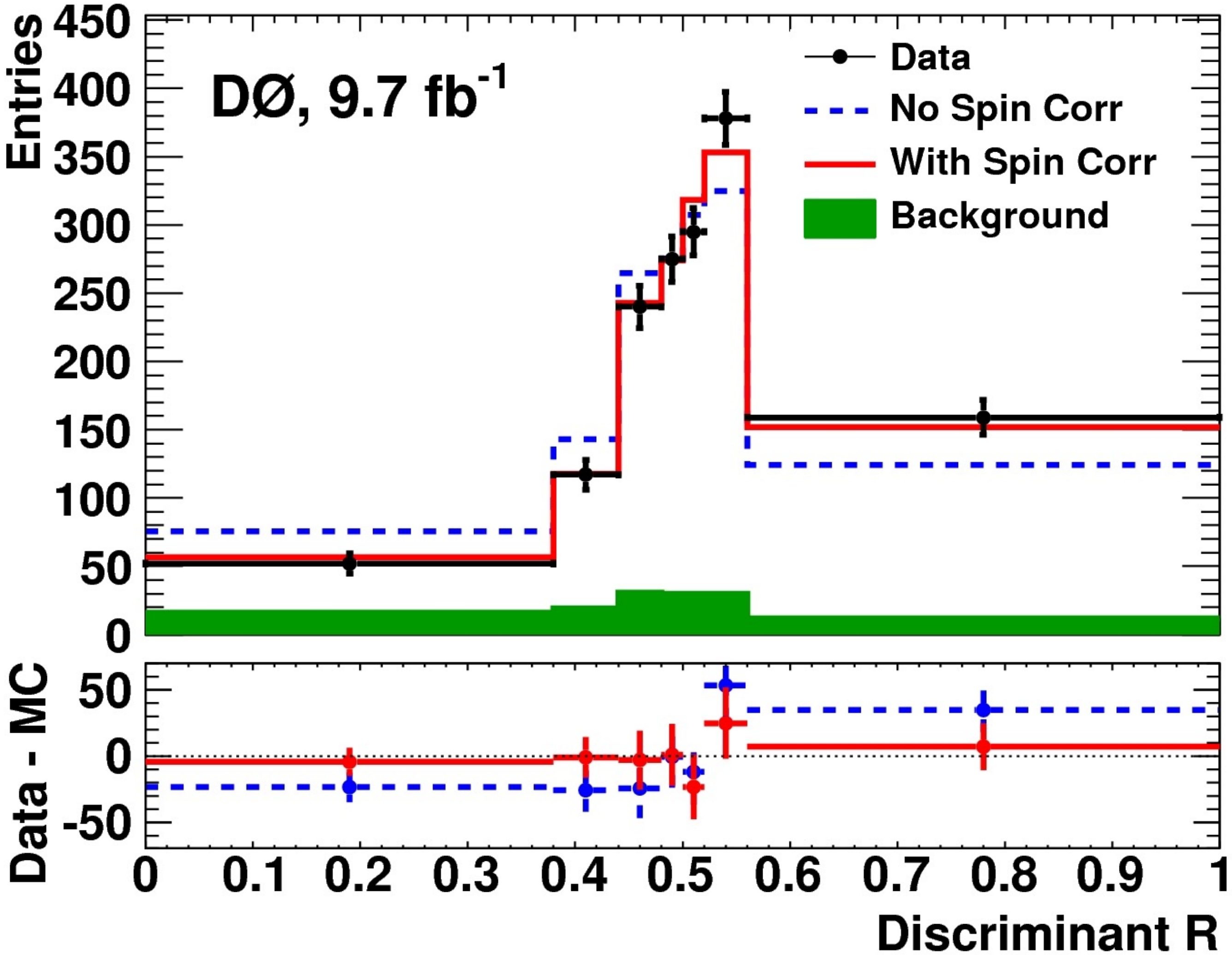
using the "off-diagonal" basis where correlation is maximized

- Reconstruct both dilepton and lepton+jets events with the matrix-element method to get spin correlation discriminant distribution

$$R(x) = \frac{P_{t\bar{t}}(x, \mathrm{SM})}{P_{t\bar{t}}(x, \mathrm{SM}) + P_{t\bar{t}}(x, \mathrm{null})}$$

where P is the probability for a given spin hypothesis (SM or null)

D0: spin correlation



arxiv.org/1512.08818
(submitted to PLB)

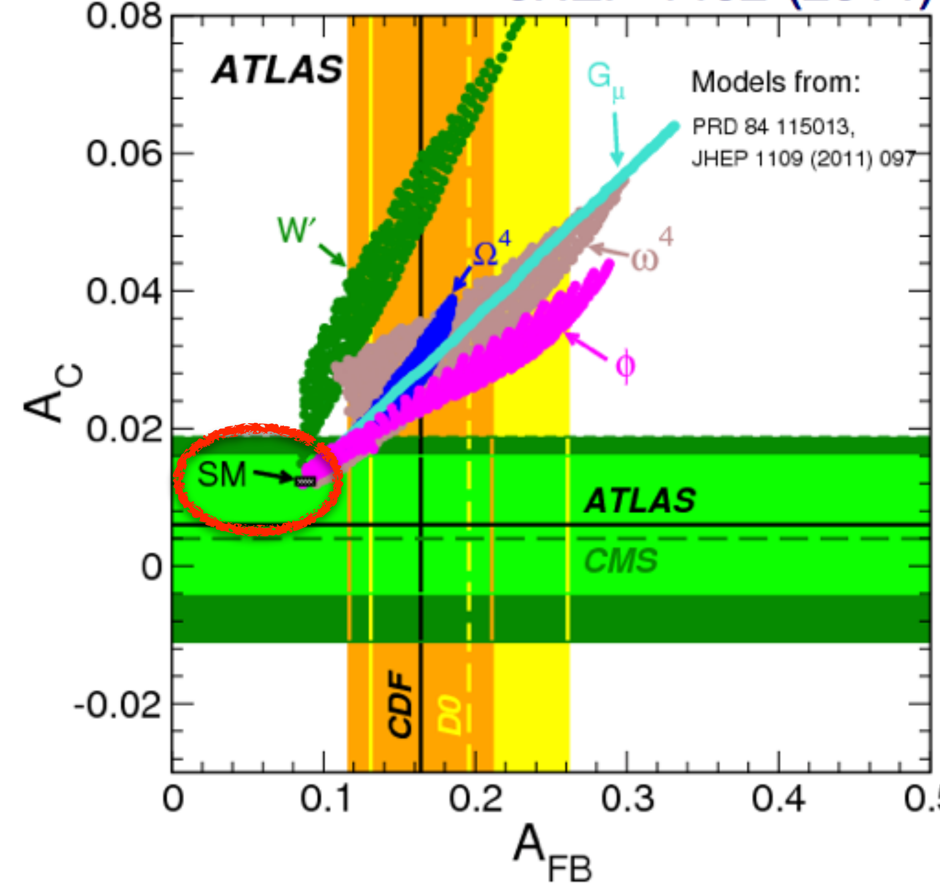
- Template fit allows for extraction of spin correlation strength
  O_{off} = 0.89 ± 0.16 (stat) ± 0.15 (syst)
  - SM value = 0.80
  - 4.2 SD significance
- Systematic uncertainties dominated by signal modeling issues

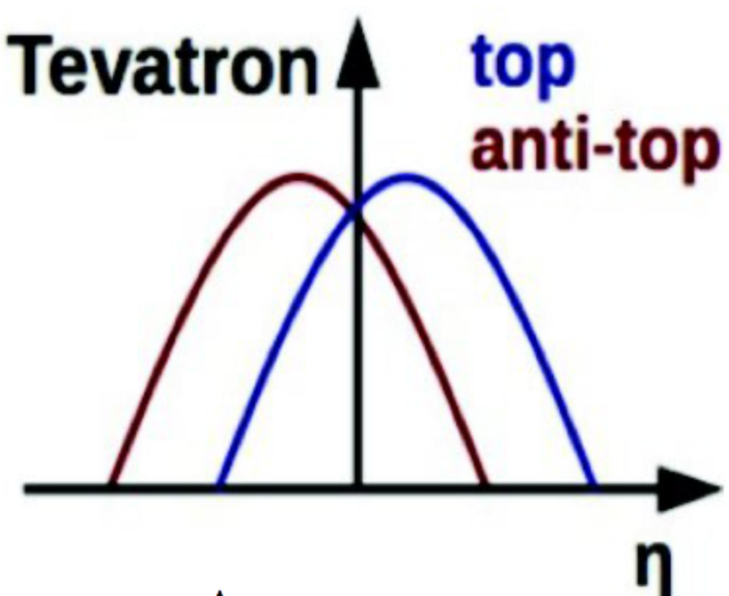
- As $p\bar{p}$ and gg initial states lead to different correlation strengths, can extract the fraction of $t\bar{t}$ from each at NLO
- f_{gg} = 0.08 ± 0.12 (stat) ± 0.11 (syst)
  - SM value = 0.135

Top production asymmetry

- Arises from interference at NLO QCD
  - Only in the $q\bar{q}$ initial state!
- ~10% forward-backward asymmetry at the Tevatron
- ~1% central-noncentral asymmetry at the LHC

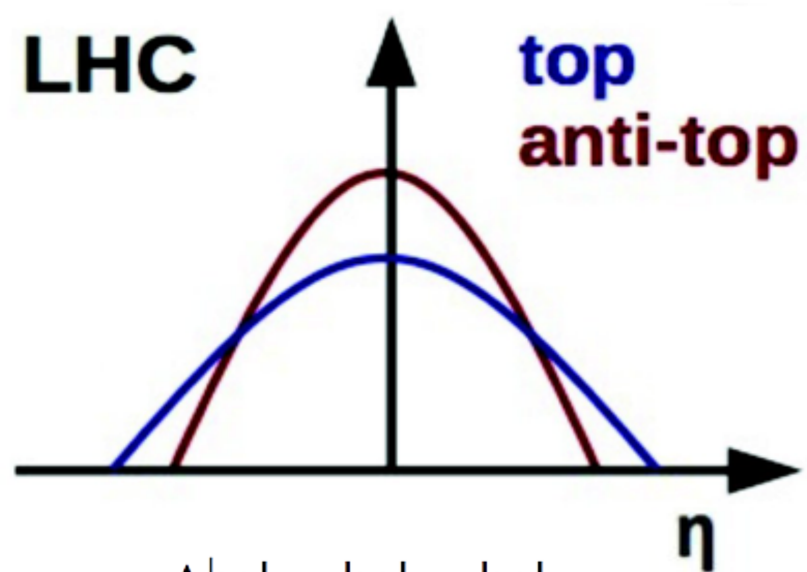
JHEP 1402 (2014)





$\Delta y = y_t - y_{\bar{t}}$

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



$\Delta|y_t| = |y_t| - |y_{\bar{t}}|$

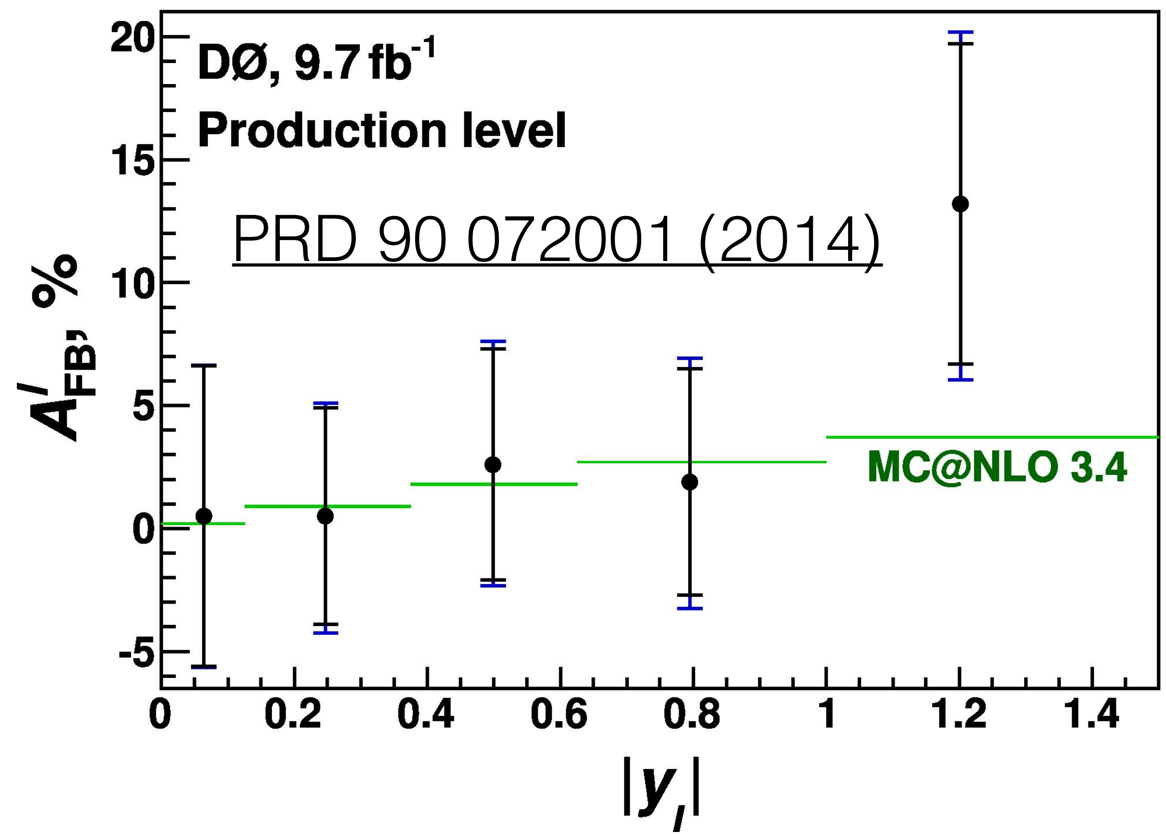
$$A_C = \frac{N(\Delta|y_t| > 0) - N(\Delta|y_t| < 0)}{N(\Delta|y_t| > 0) + N(\Delta|y_t| < 0)}$$

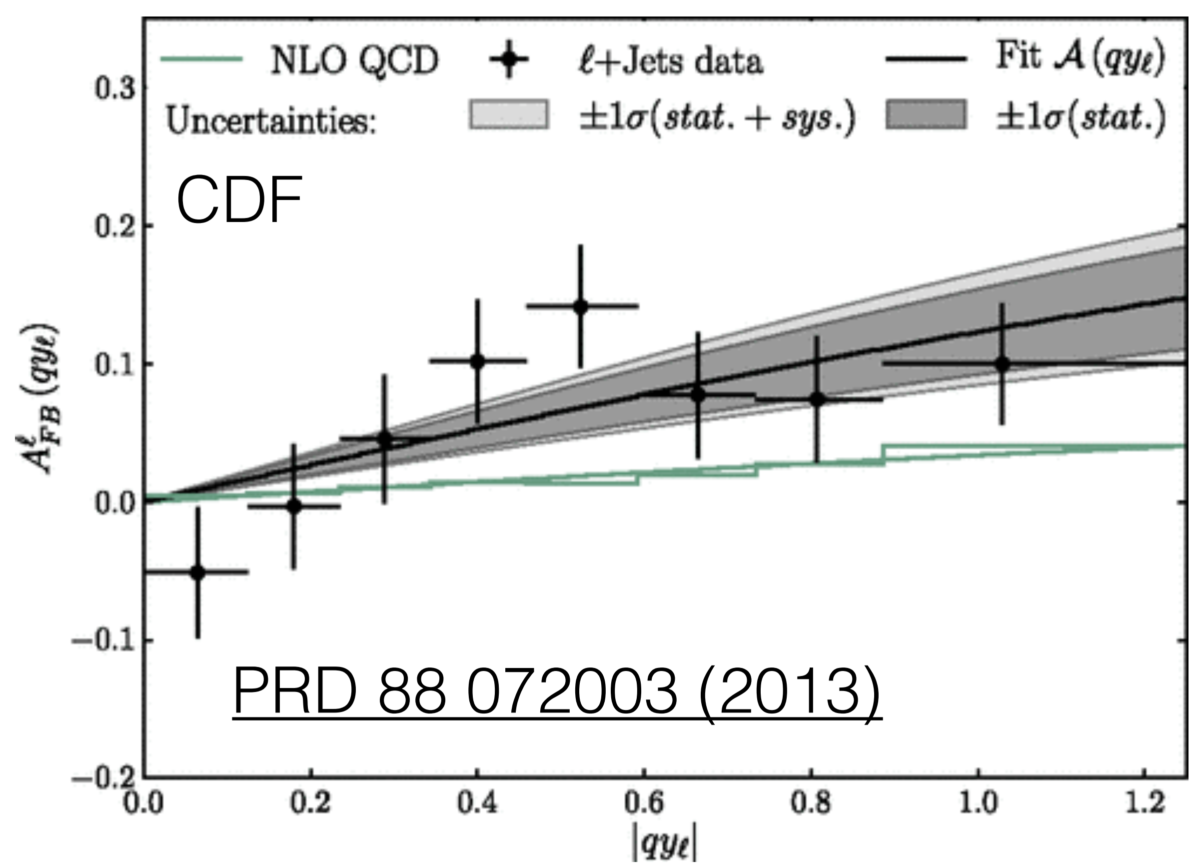
- Early Tevatron asymmetry measurements gave large values, suggesting non-SM physics!
  - (and predicted values had been smaller….)
- What happened on the road to figuring it out?

Lepton asymmetry

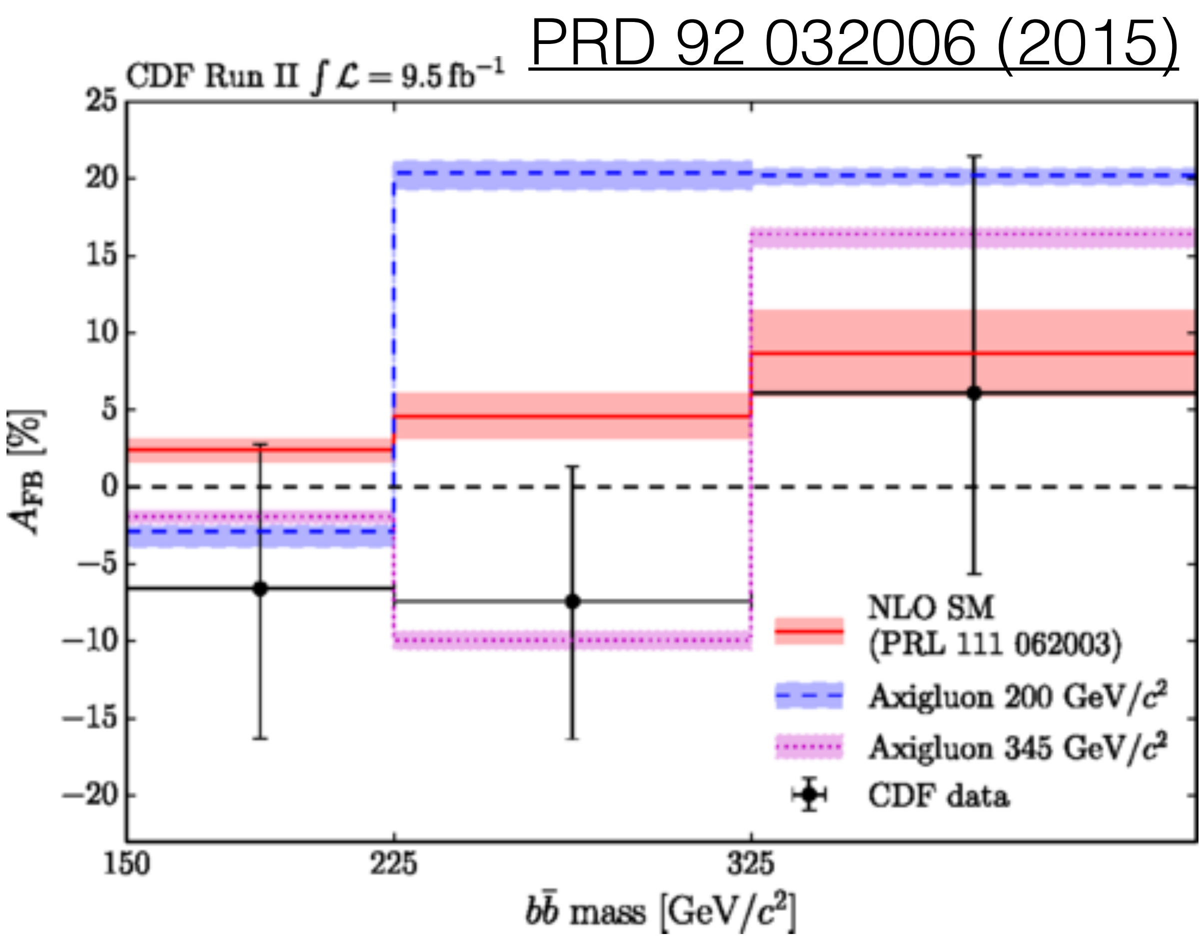
- Reconstructing top direction for asymmetry measurement is complicated, requires unfolding
- Simpler: forward-backward asymmetry of decay lepton
  - SM asymmetry only ~4%, but no unfolding required

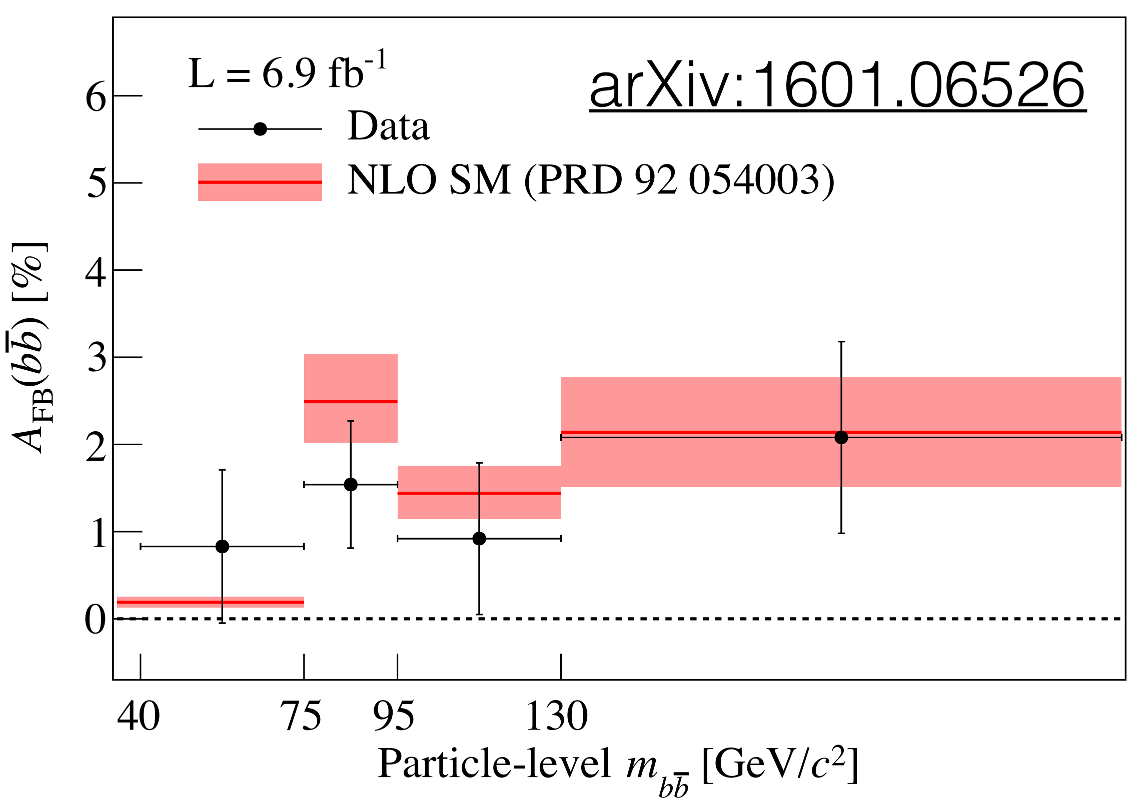
- CDF and D0 measurements in both dilepton and lepton+jet final states
  - CDF: $(9.0^{+2.8}_{-2.6})\%$
  - D0: $(4.2 \pm 2.4)\%$
- CDF result slightly above expected value with dependence on lepton rapidity





CDF: bottom asymmetry

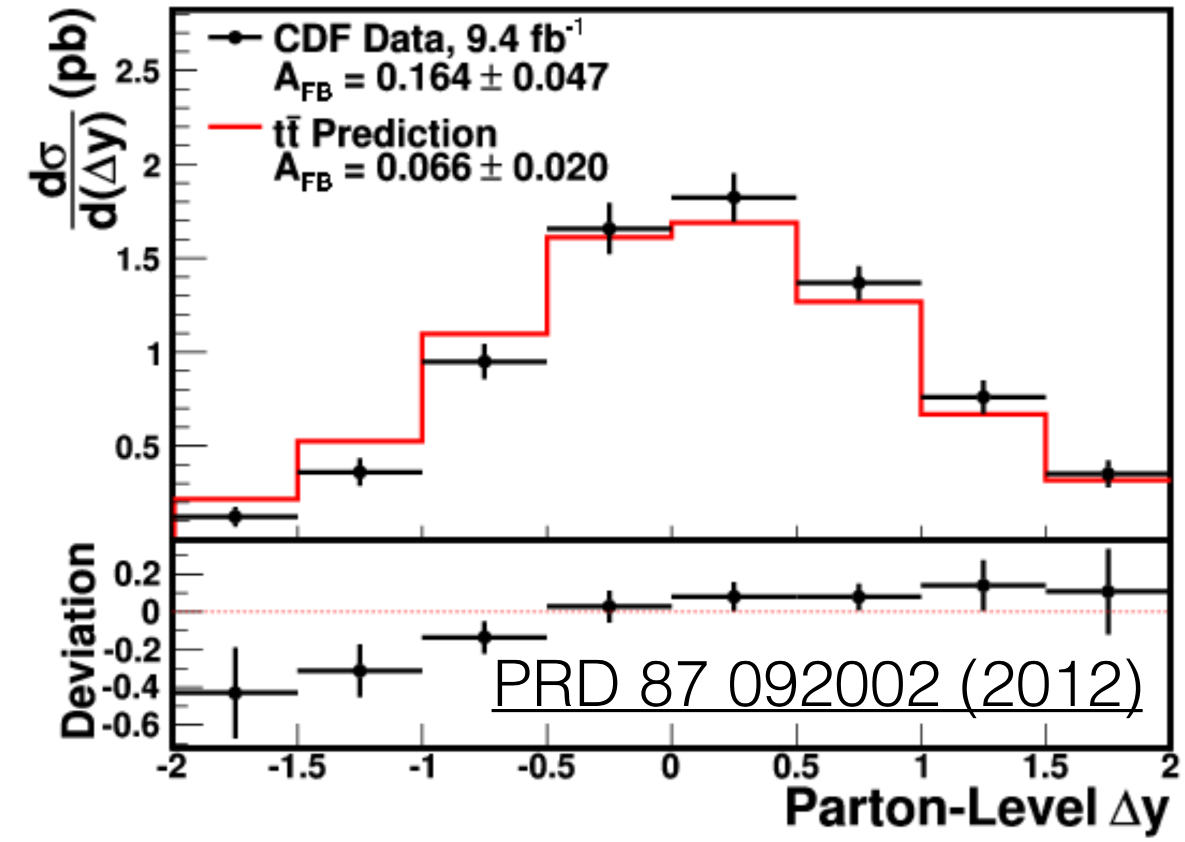




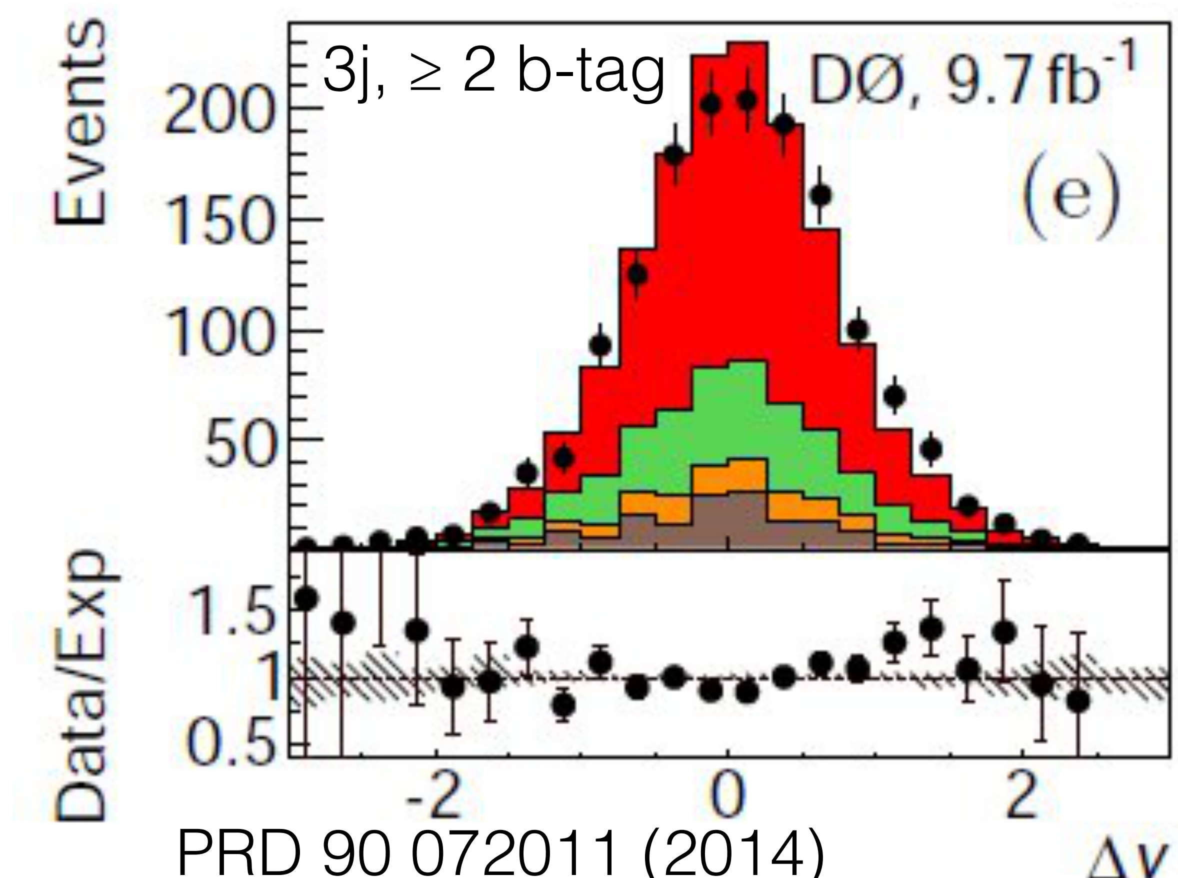
- New physics affecting the top forward-backward asymmetry would affect other quark production too. Look at bottom quarks!
- Most $b\bar{b}$ production is from gg, but enhanced $q\bar{q}$ production for high-mass pairs
- Identify b jets with secondary vertices, assign flavor with jet charge difference
- Account for mixing, secondary decays, charge mis-ID, non-b backgrounds
- Unfold and correct to particle level
- Can exclude some axigluon models
- Separate low-mass search also consistent with SM expectations

Asymmetry in l+jets

- CDF measurement well-established, with result higher than SM predictions:
  - A_{FB} = (16.4 ± 4.5)%

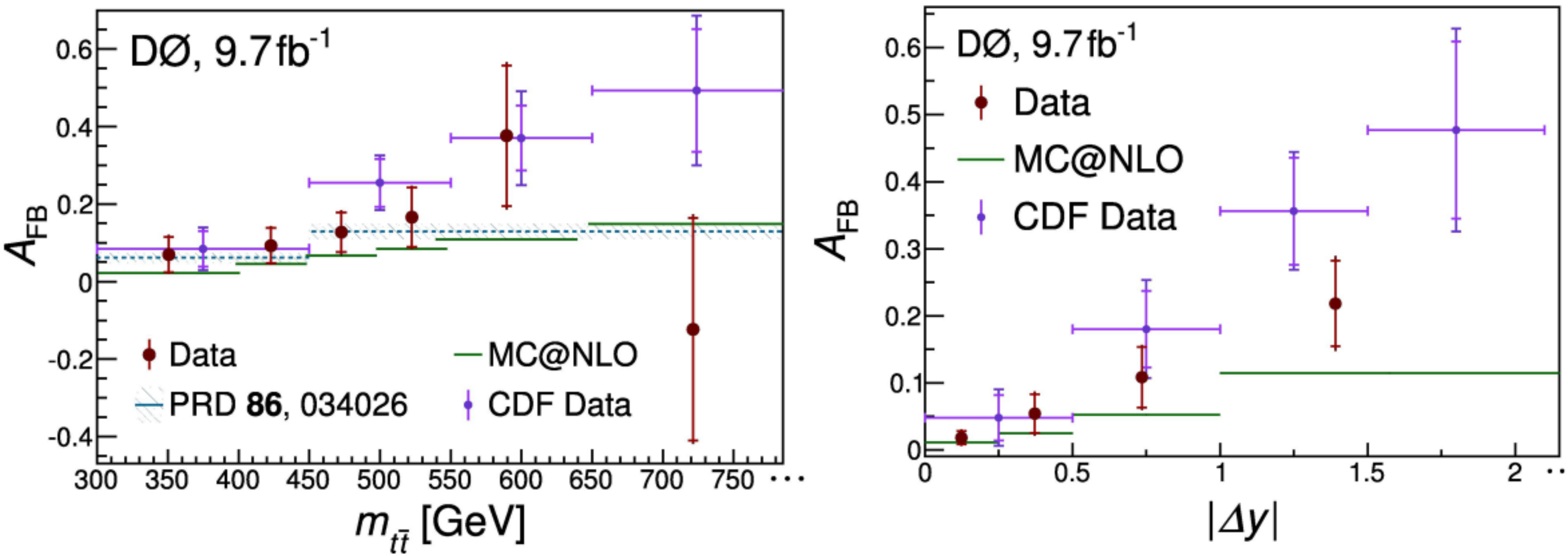


- D0 measurement includes larger phase space (with l+3 jet sample), plus new top reconstruction method and two-dimensional unfolding
  - A_{FB} = (10.6 ± 3.0)%



Asymmetry in l+jets

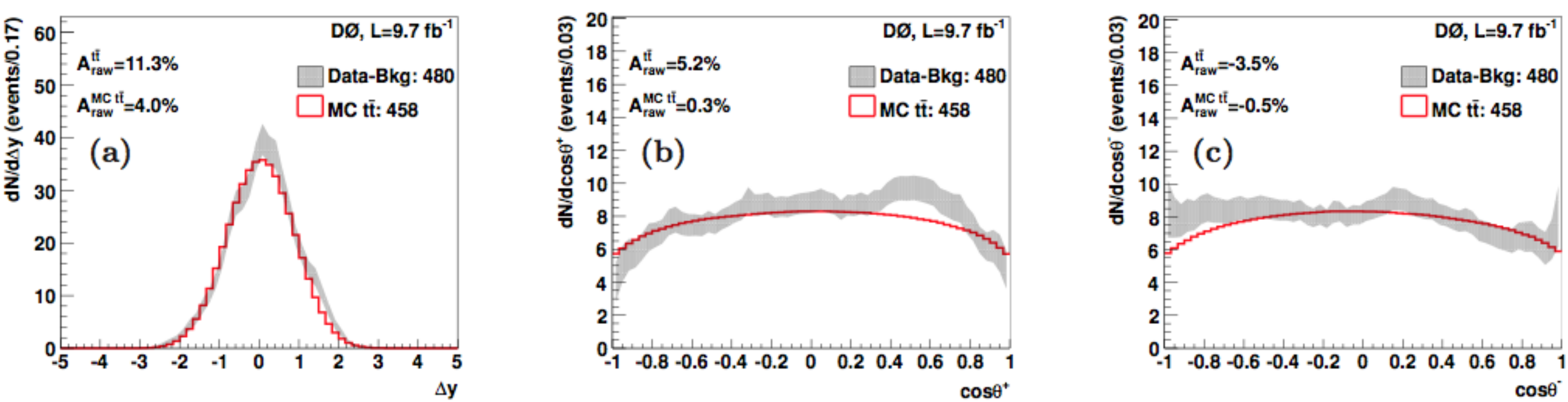
- Both experiments measure kinematic dependence of asymmetry:



- In general greater dependence on kinematic variables than predicted

D0: Asymmetry in dileptons

- Harder than l+jets because of the two neutrinos in each event!
- Simultaneous measurement of production asymmetry and top polarization in dilepton events using matrix element method
  - Novel application of matrix element techniques
- Method allows for full reconstruction of event kinematics in probabilistic fashion
- Assign a likelihood per event for both the asymmetry and the lepton decay angle for most probable kinematic value
  - Lepton angle is with respect to beam axis in $t\bar{t}$ rest frame



D0: Asymmetry in dileptons

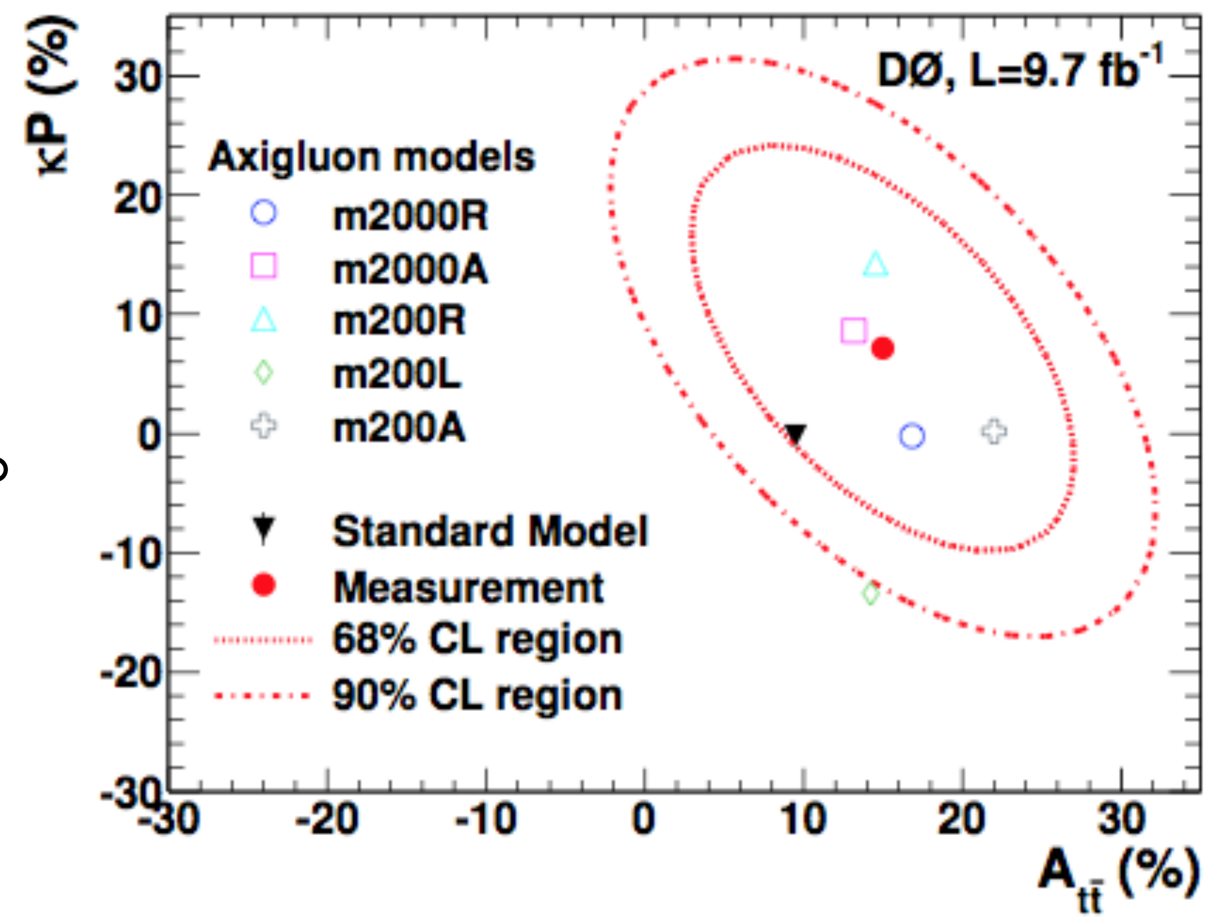
- Systematic uncertainties dominated by signal modeling, in particular hadronization and showering, and method calibration

- Results without constraining either quantity:
  - A_{FB} = (15.0 ± 6.4 (stat) ± 4.9 (syst))%
  - κP = (7.2 ± 10.5 (stat) ± 4.2 (syst))%
  - Consistent with SM, no evidence for axigluon models

- Results after constraining "other" quantity to SM value:
  - A_{FB} = (17.5 ± 5.6 (stat) ± 3.1 (syst))%
  - κP = (11.3 ± 9.1 (stat) ± 1.9 (syst))%

- Combine dilepton result with SM polarization with previous lepton+jets asymmetry measurement
  to obtain final D0 result:
  - A_{FB} = (11.8 ± 2.5 (stat) ± 1.3 (syst))%

PRD 92 052007 (2015)

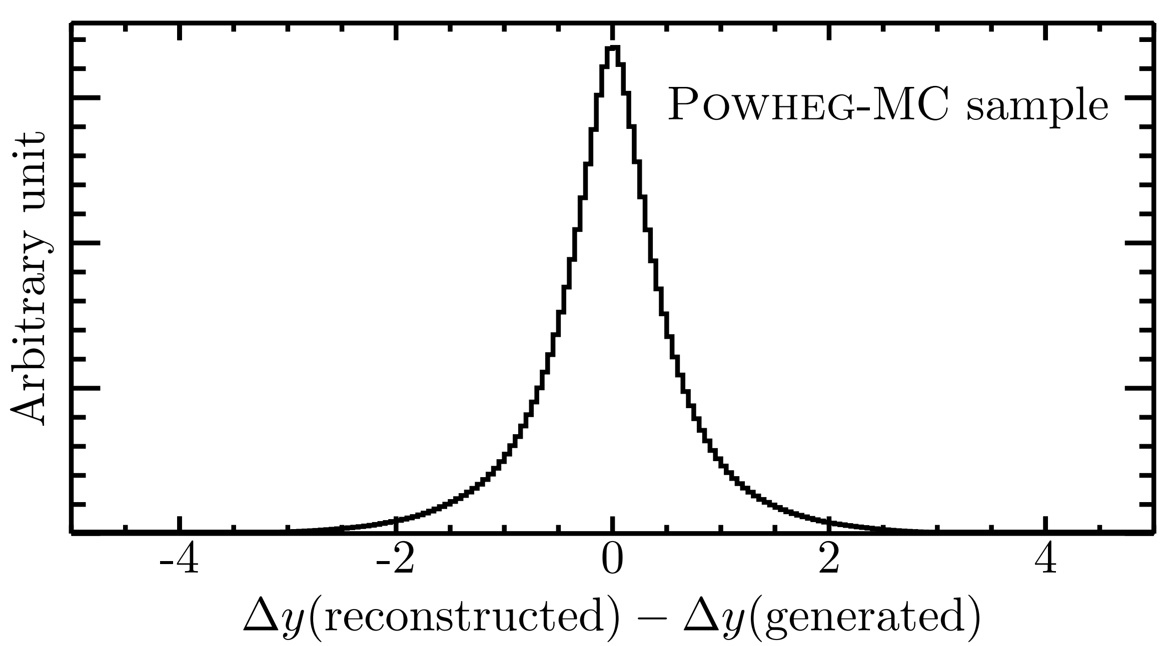


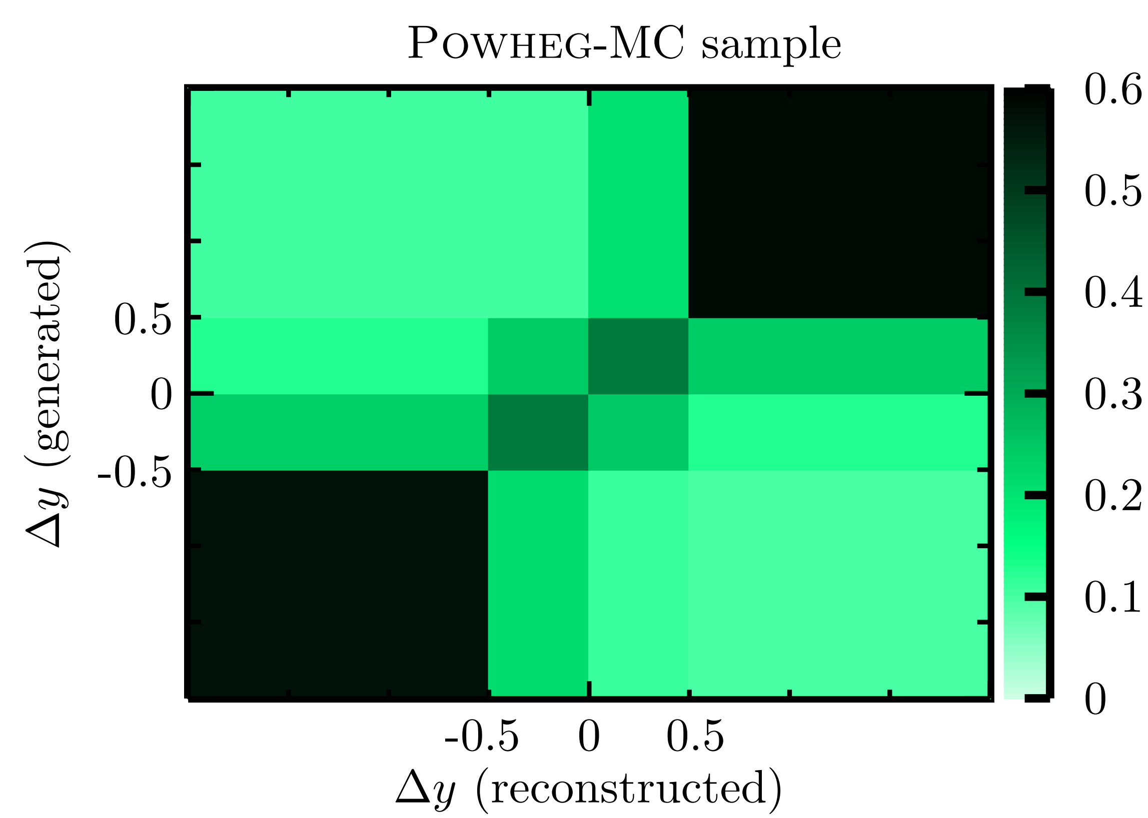
CDF: Asymmetry in dileptons

- Harder than l+jets because of the two neutrinos in each event!

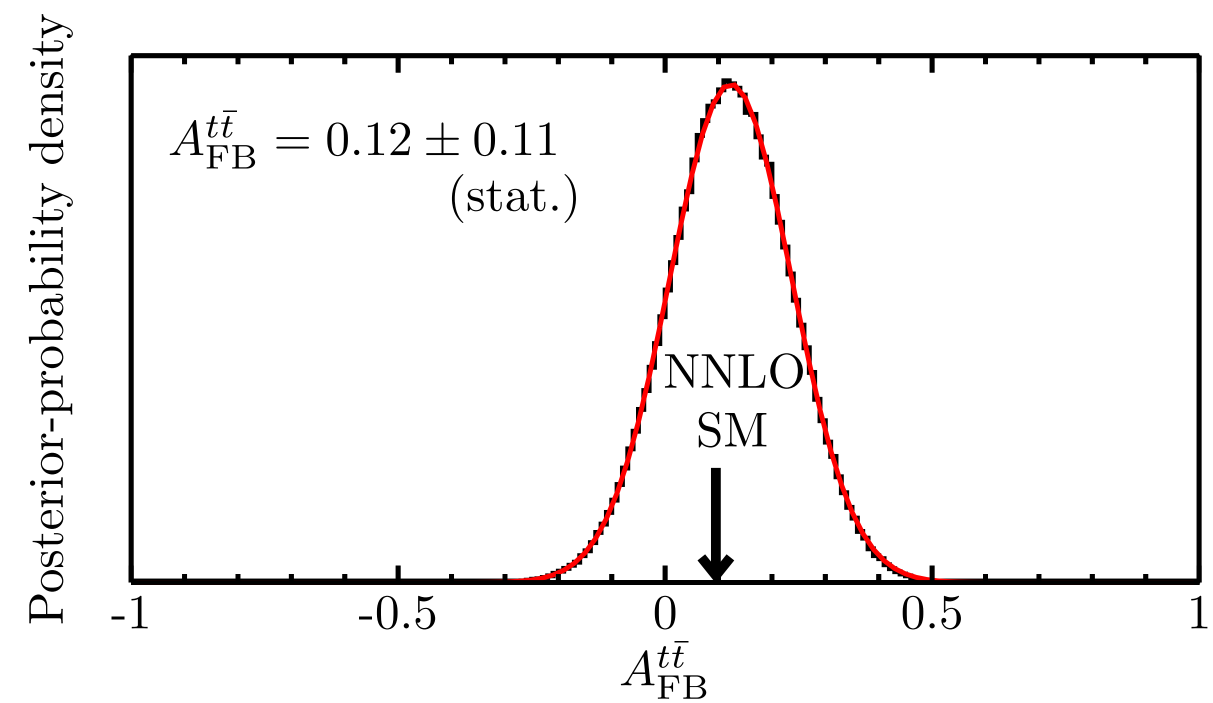
- Use a likelihood-based algorithm to reconstruct neutrino momenta (and thus top momenta) from observed kinematics in each event
  - Rather than a single solution, form a likelihood as a function of the kinematic variables, and include both possible jet-lepton pairings

- Also used a likelihood-based scheme to unfold back to parton level
- Optimize event selection to avoid poorly reconstructed events

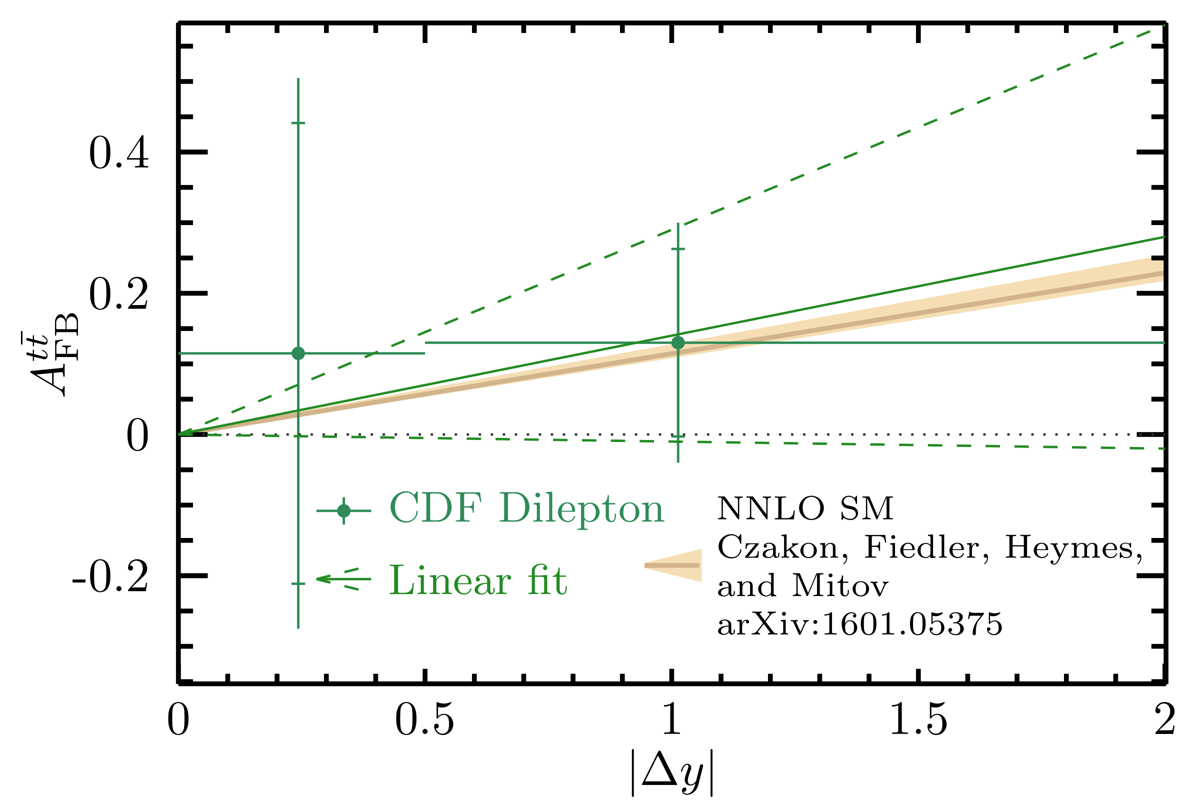




CDF: Asymmetry in dileptons

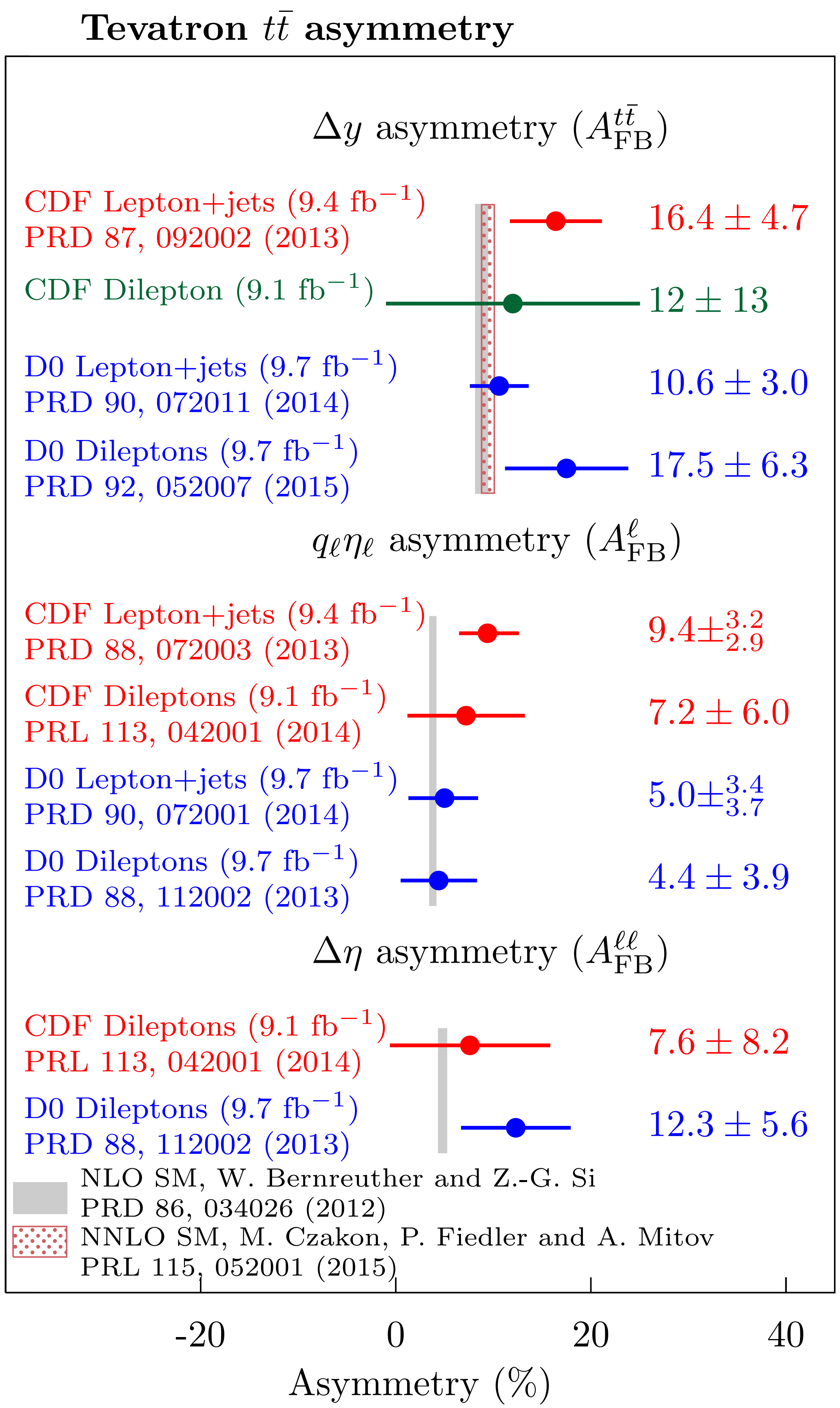


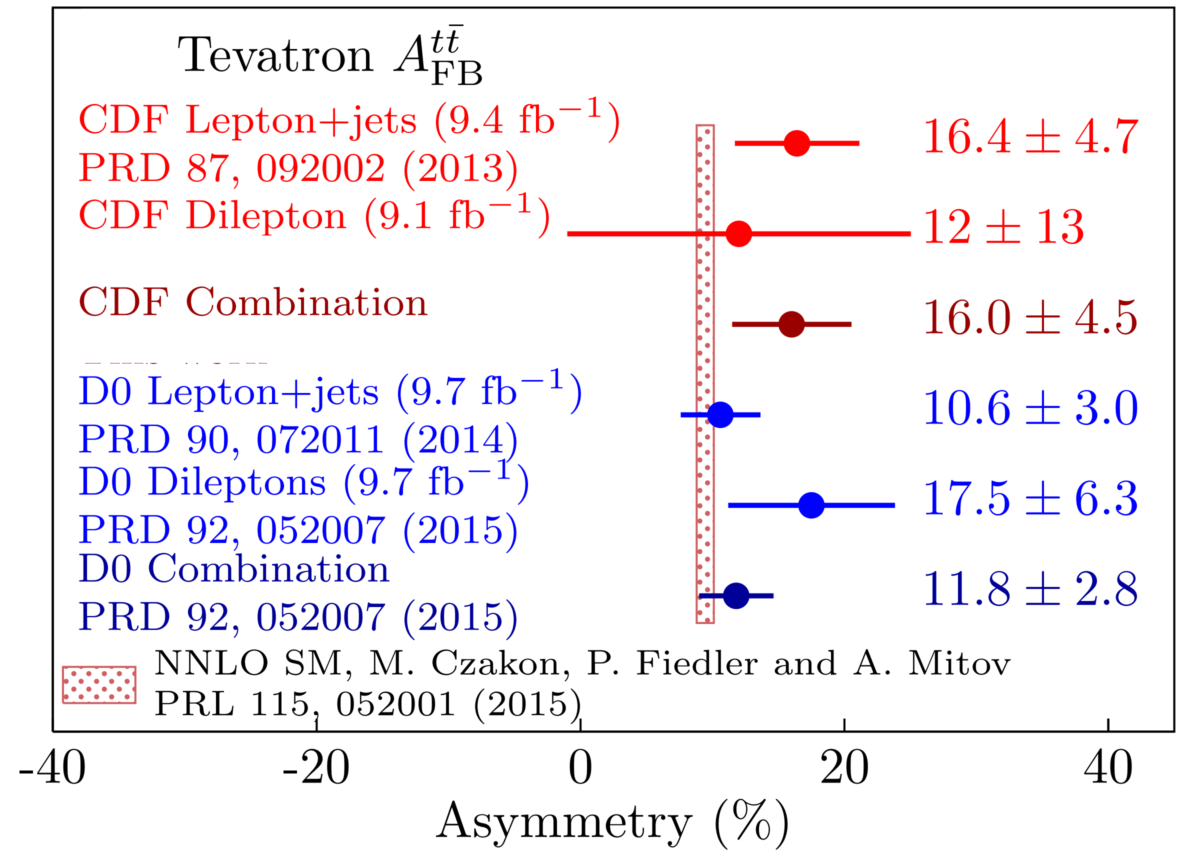
- A_{FB} = (12 ± 13 (stat) ± 7 (syst))%
- Some sensitivity to |Δy| dependence, nothing significant observed
  - Note better resolution at larger |Δy| due to less migration across y = 0
- Combine with lepton + jets result
  - A_{FB} = (16.0 ± 4.5)%
- Consistent with SM



Submitted to PRD last week! arxiv:1602.09015

Top quark asymmetries





- All Tevatron results use full datasets
- Decent agreement between results from two experiments, and with prediction from theory

Tevatron top in the LHC era

- Tevatron top physics is still interesting, even with the LHC onslaught!
- Mature experiments make for sophisticated measurements
  - Well-understood datasets, well-modeled detectors
  - Allows for significant creativity in analyses
- Complementarity of initial state provides unique opportunities
  - Production asymmetry cannot be explored as well at LHC
  - s-channel much more difficult at LHC
- Arguably LHC has much to learn from the Tevatron experience
- Last few Tevatron top production measurements coming “soon” — stay tuned!

MAY THE QUARKS BE WITH YOU