Angular distributions at the Tevatron

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Photo by Justin Eure

Day 4 of Top 2012

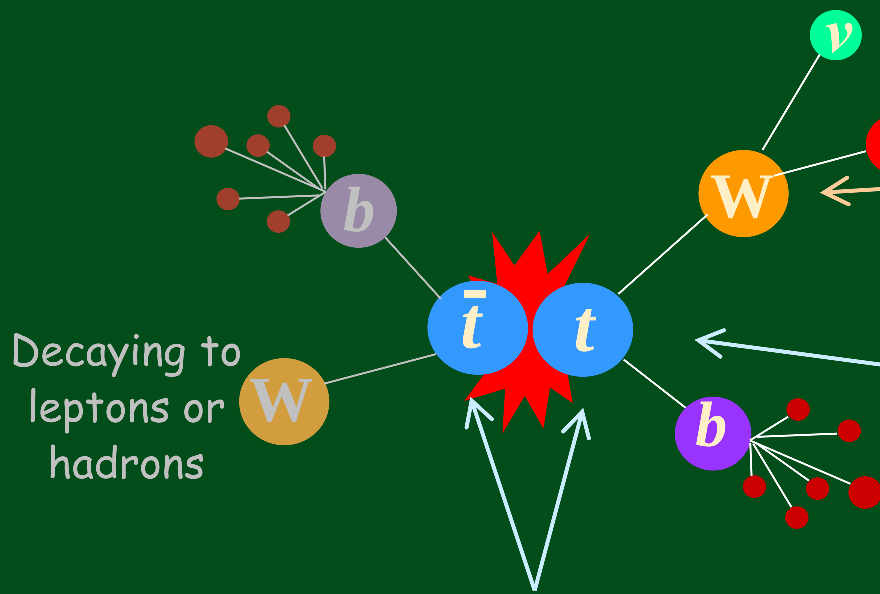
Previous talks already covered:

- Selections
- Estimations of sample composition
- Background modeling
- Signal modeling

I mostly avoid these aspects of the analyses in this talk.

- This is often in the spirit of the notes / papers which defer such details to the relevant cross-section measurements.

Overview



1. What is the W polarization?

2. Is the top quark polarized?

3. Are the top pair spins correlated?

Measurements of
W helicity
in top decays

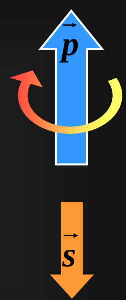
- Combination with ≤5.4fb^{-1} – Phys. Rev. D 85, 071106 (2012)
- Latest and greatest from each collaboration:
  - CDF lepton+jets, matrix element with 8.7fb^{-1} – CDF note 10855
  - D0 with 5.4fb^{-1} - Phys. Rev. D 83, 032009 (2011)

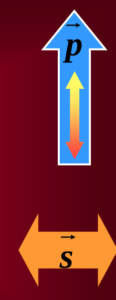
W helicity

So far measurements support the SM prediction: f(*t*→*Wb*) = ~100%

Breaking it down by W helicity states:

Left handed	Longitudinal	Right handed
λ=-1	λ=0	λ=1
$f_- = \frac{\Gamma(t \to W_- b)}{\Gamma(t \to W b)}$	$f_0 = \frac{\Gamma(t \to W_0 b)}{\Gamma(t \to W b)}$	$f_+ = \frac{\Gamma(t \to W_+ b)}{\Gamma(t \to W b)}$
SM: 30.3%	SM: 69.6%	SM: 0.1%

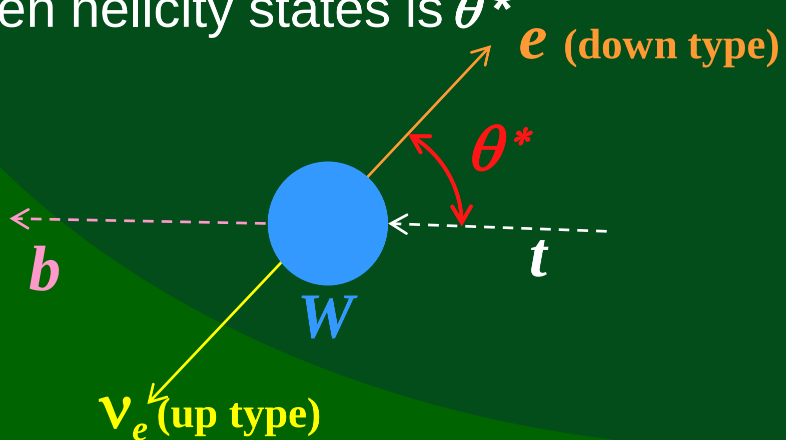


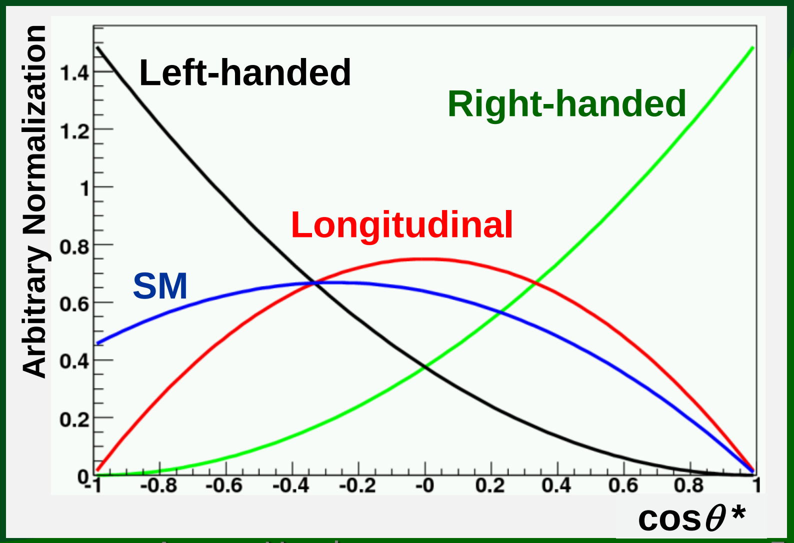


SM uncertainties << Experimental uncertainties → can't constrain SM parameters

Firm SM prediction, in particular: tiny f_+ → looking for new physics

Most relevant observable to distinguish between helicity states is θ^*

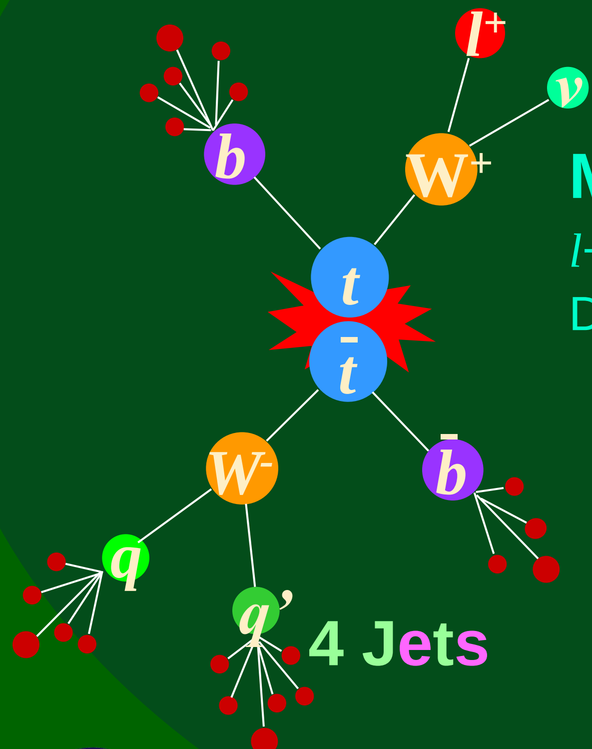




Samples

Lepton+jets

(lepton=e/μ)



isolated, p_T>20 GeV

MET:

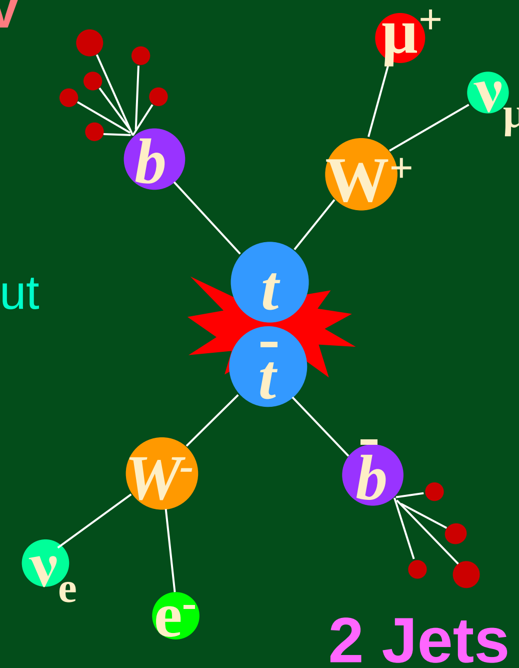
l+jets: >20GeV

Dileptons: discriminant input in $ee/e\mu$

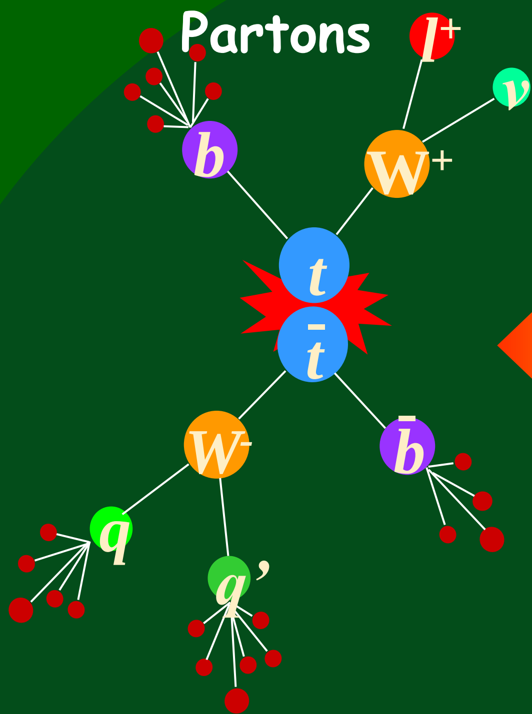
***b* tags**

Dilepton

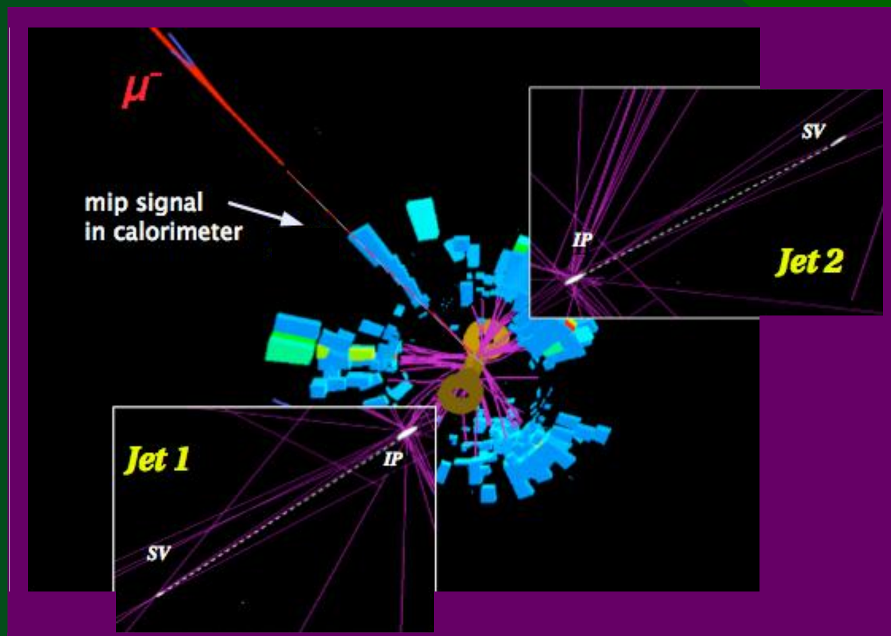
(lepton=e/μ)



l+jets reconstruction



Observed objects



Parton-level ⟷ **Particle-level** ⟷ **Detector-level**

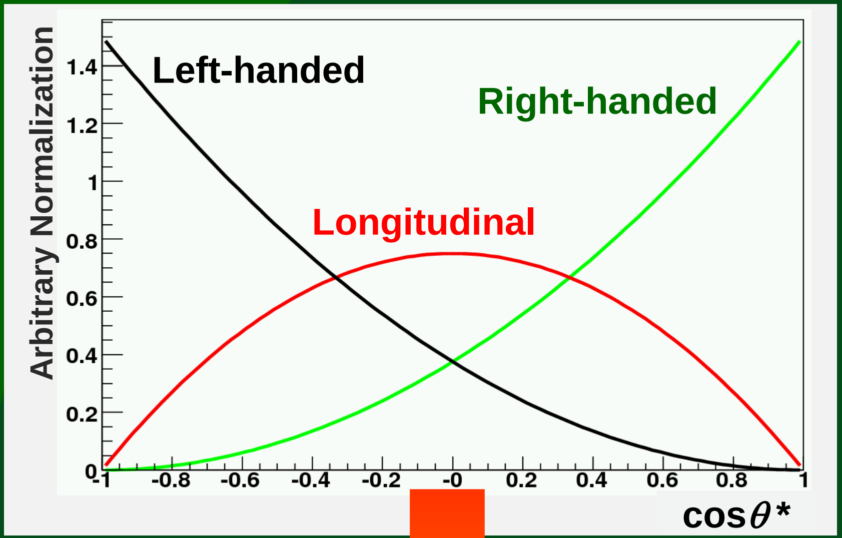
QCD Simulation

Experimental resolutions & *b*-ID probabilities

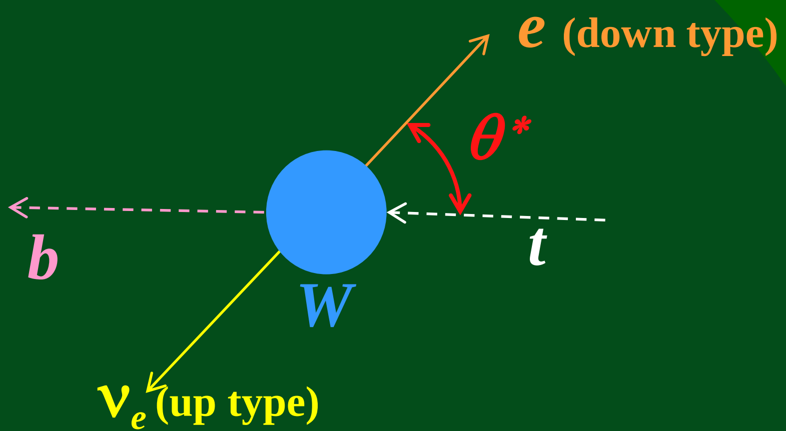
- fit parton energies to the measured objects, minimizing a χ^2
- Constraints: $m_{t1} = m_{t2} = 172.5$ GeV; $m_{W1} = m_{W2} = 80.4$ GeV
- Do the fit for every combination of assigning a jet to a parton

l+jets reconstruction gives…

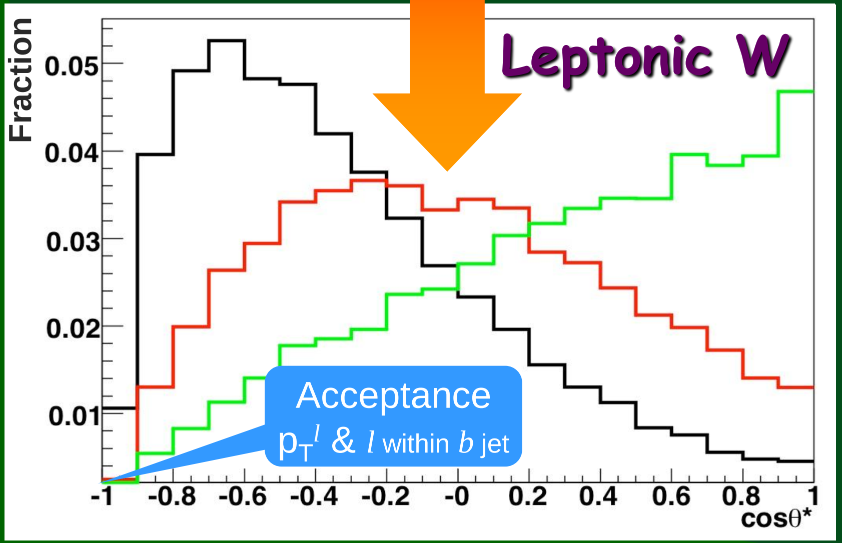
Parton level



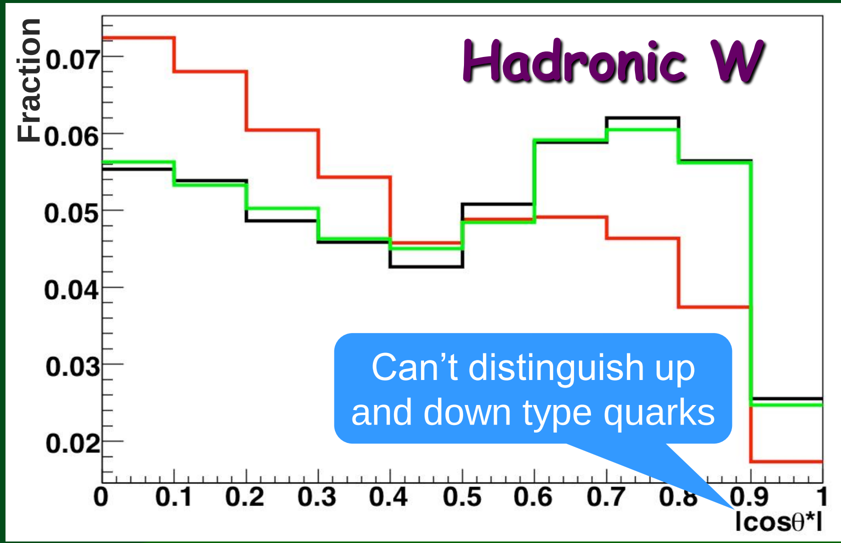
excellent cos θ* reconstruction!



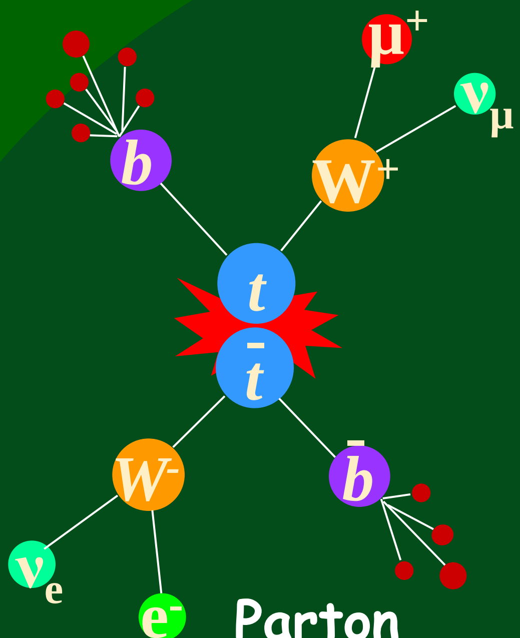
Reconstructed



The hadronic W helps measure f_0



Dilepton reconstruction

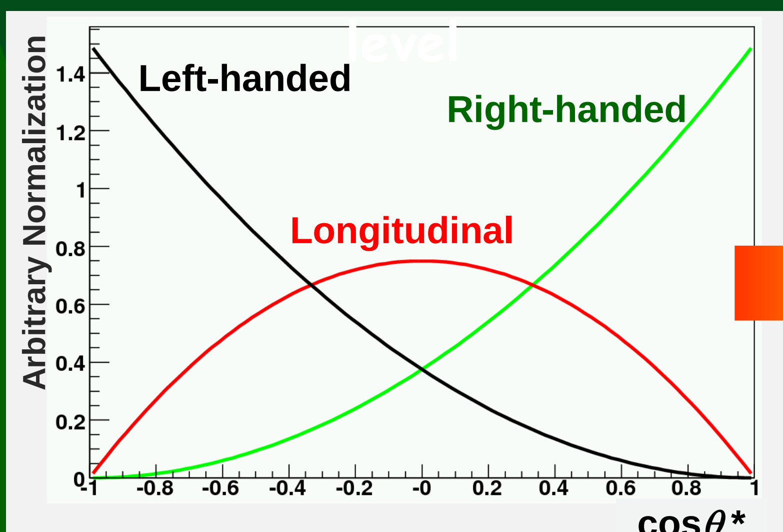


With two *ν*s, reconstruction is harder.

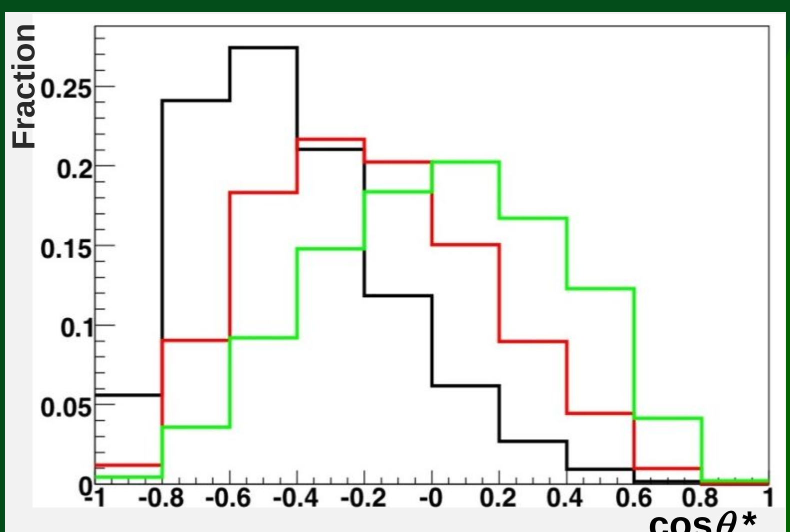
"resolution sampling"

- smear objects within their resolution
  - 500 times per event
- for each *b*-jet & *l* combination and smearing, solve algebraically for $\cos\theta^*$
  - use the 2 MET components + 4 mass constraints
  - 0-8 solutions
- average all solutions

Parton level

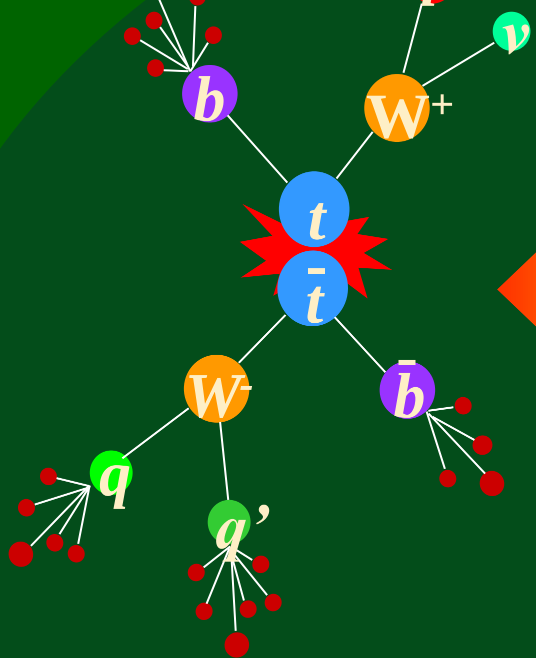


Reconstructed

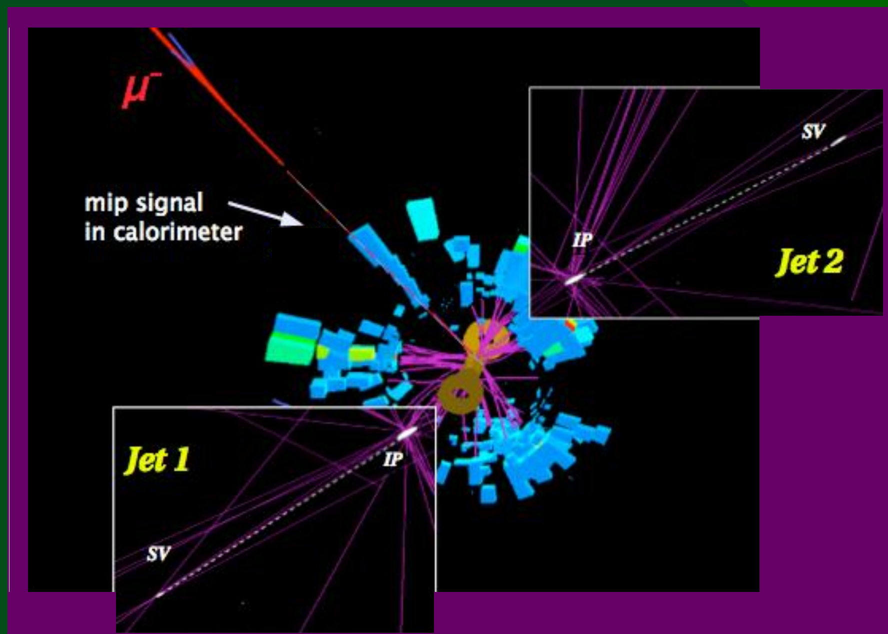


Without reconstruction

Partons



Observed objects



Parton-level ⟷ **Particle-level** ⟷ **Detector-level**

QCD Simulation (Parton-level ⟷ Particle-level)

Experimental resolutions & *b*-ID probabilities (Particle-level ⟷ Detector-level)

- Instead of reconstructing θ^*, calculate a likelihood P (data | parameters)
- Many observables per event → summarize
  - *2010s approach: machine learning? If so, fortunate this was tackled earlier…*

Matrix element method

- Calculate the likelihood using the SM (manual learning?)
  - with leading order calculations of the matrix elements
- Likelihood accounts for all jet-parton assignments
- makes use of hadronic side & of all jet kinematics, not just θ*

  → 20% than previous CDF technique (for same dataset)
- Likelihood accounts for backgrounds
  - $L(f_0, f_+, C_s) = \prod_{i=1}^{N} \left[C_s \frac{P_s(x; f_0, f_+)}{\langle A(x; f_0, f_+) \rangle} + (1 - C_s) \frac{P_b(x)}{\langle A_b(x) \rangle} \right]$
  - P_b and P_s convolute the differential partonic cross-section (proportional to the matrix element) with the PDFs and the transfer functions
  - using W+jets matrix elements from VECBOS

Matrix element method

- The ME-based likelihood does not model everything:
  - Missing diagrams, beyond LO
  - Events without a correct assignment
  - Effect of other backgrounds

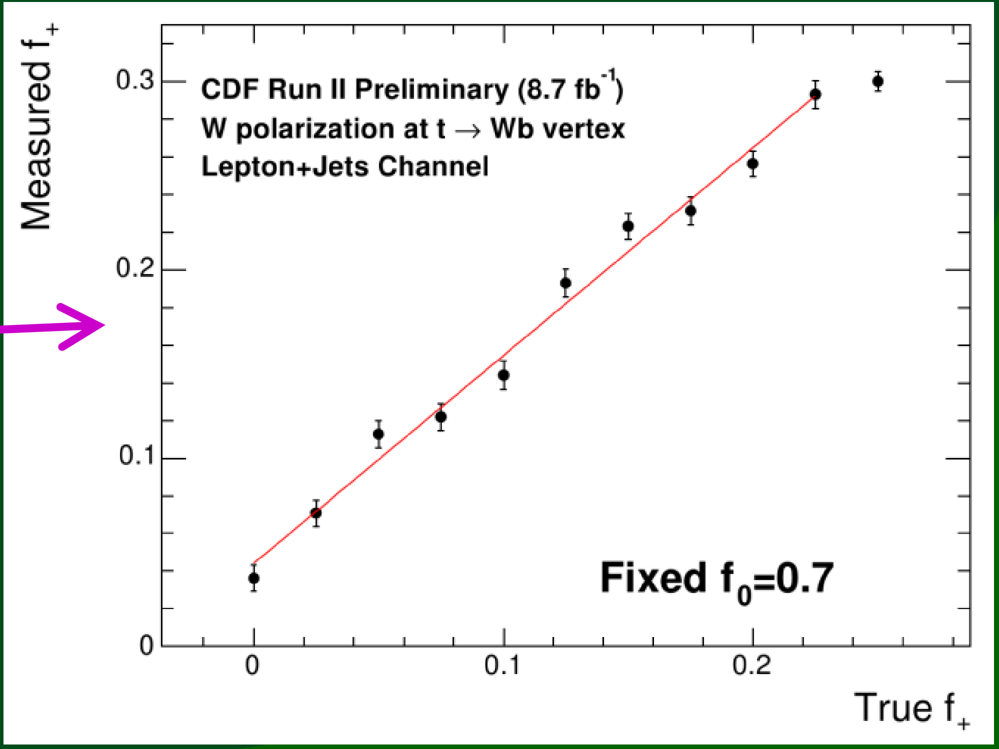
  → In general, we expect the fitted fractions to be biased

→ Calibrate using ensemble tests

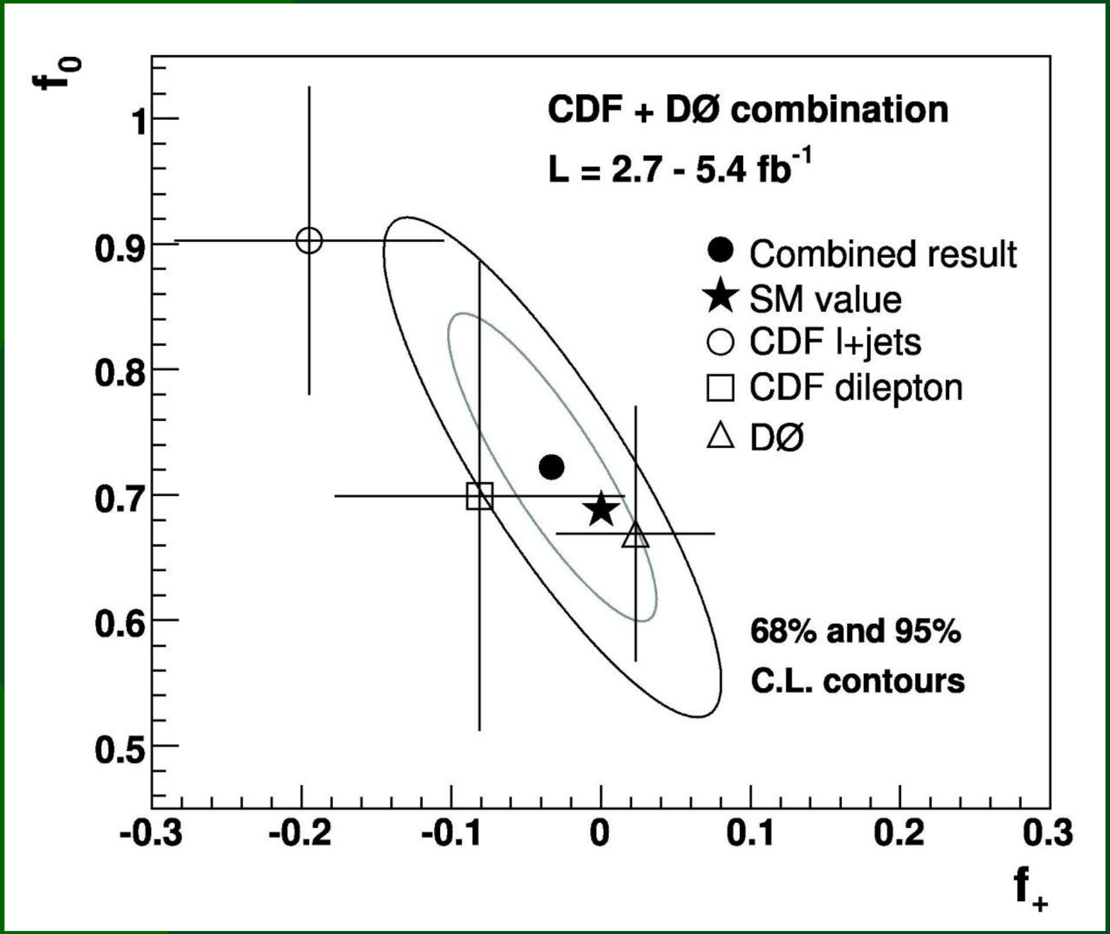
Separate calibrations for 1D and 2D fits

- Example of 1D calibration
- Found linear dependences

  → simplifies interpretation ☺



Combination results



Results of 2D fit:

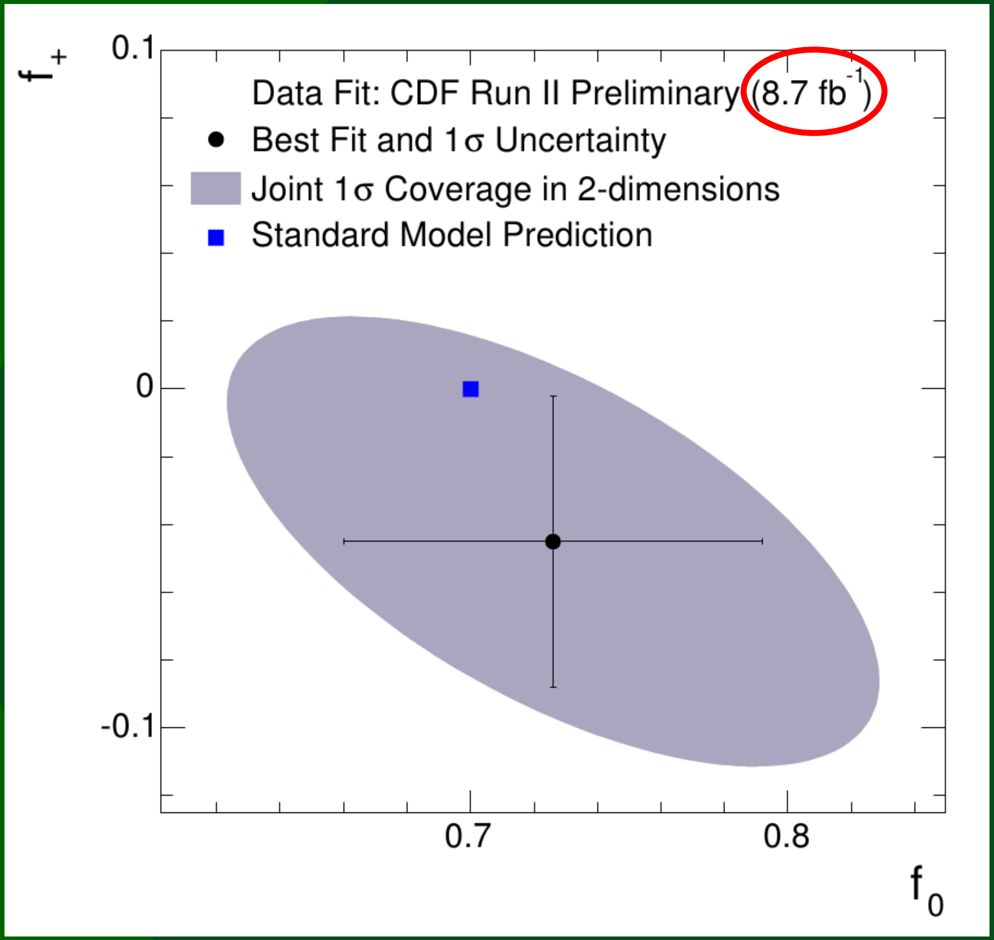
$$f_0 = 0.722 \pm 0.081$$

$$f_+ = -0.033 \pm 0.046$$

Results of 1D fits: $f_0 = 0.682 \pm 0.057$ **with SM** f_+

$f_+ = -0.015 \pm 0.035$ **with SM** f_0

New CDF results



For maximal confusion:
x and y-axis are flipped…

Results of 2D fit:

$$f_0 = \quad 0.726 \pm 0.066 \pm 0.067$$
$$f_+ = -0.045 \pm 0.043 \pm 0.058$$

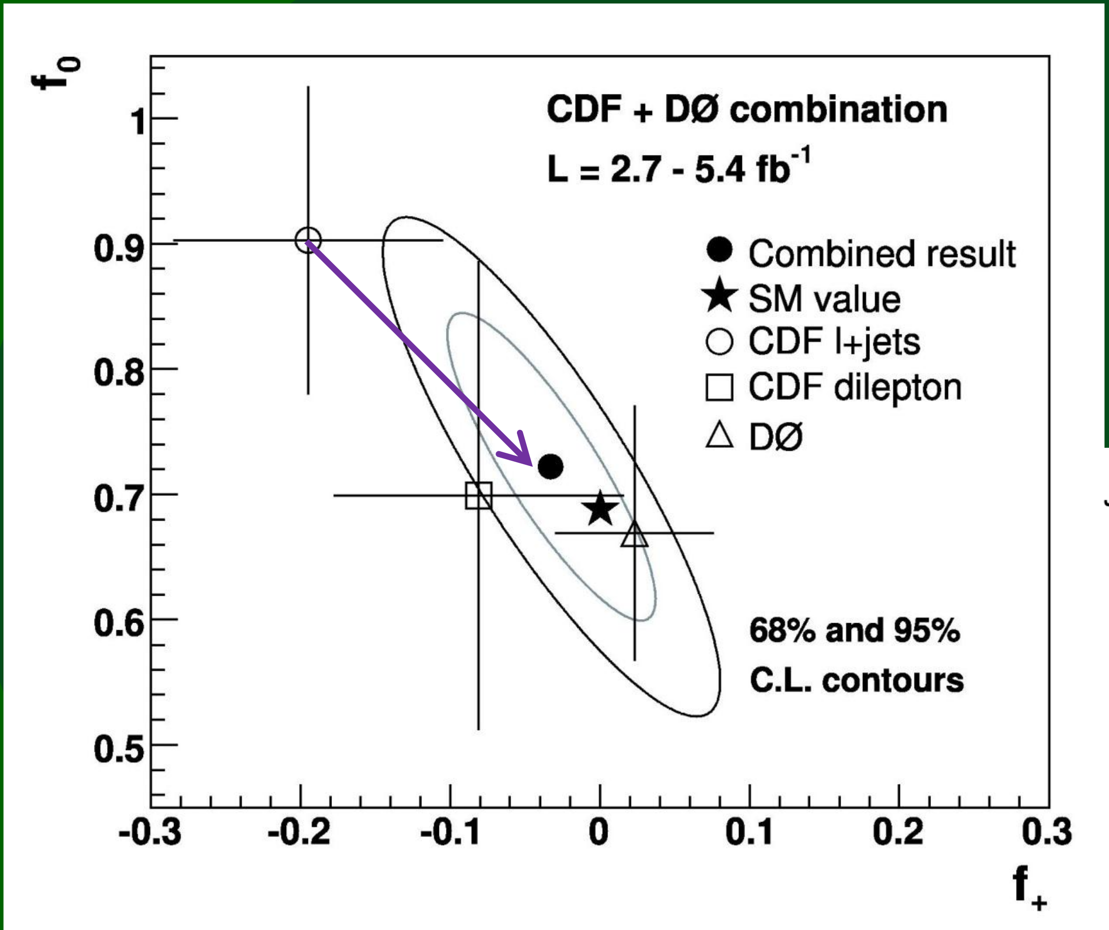
stat. *syst.*

Results of 1D fits:

$f_0 = \quad 0.683 \pm 0.042 \pm 0.040$ with SM f_+

$f_+ = -0.025 \pm 0.024 \pm 0.040$ with SM f_0

Putting them together



For maximal confusion:
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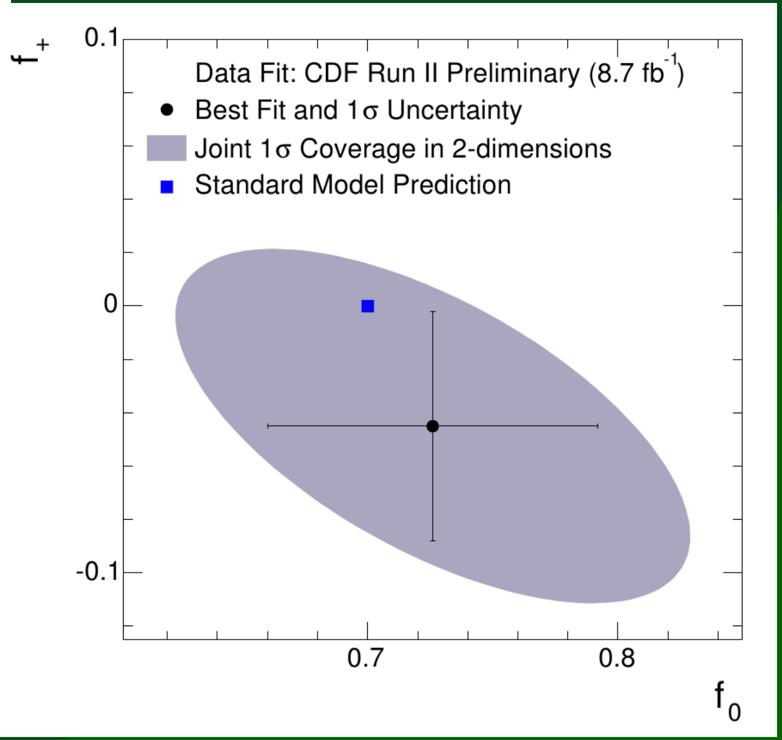


Results in good agreement with the SM

Checks for

top polarization

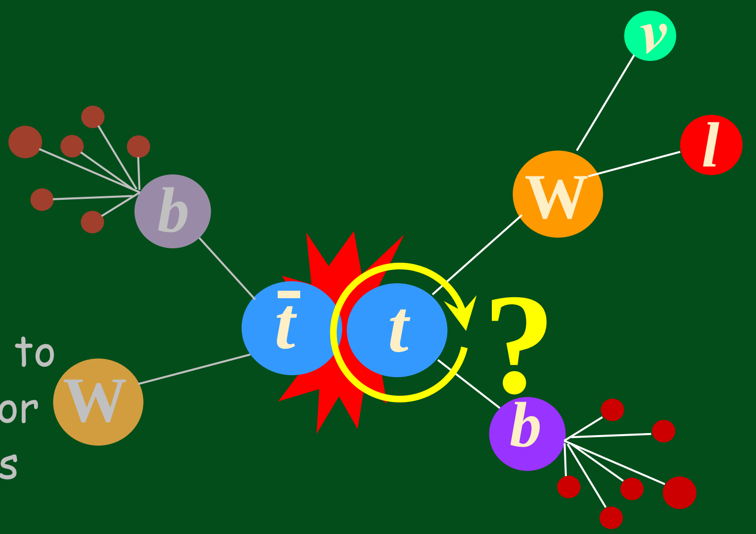
in top pair production

Analyzing top spin

Top lifetime (~3·10^{-25}s)

$$\tau_t \ll \frac{m_t}{\Lambda^2_{QCD}}$$

Spin flip time scale (~3·10^{-21}s)



Decaying to leptons or hadrons

Production @ Tevatron != production @ LHC – best measure both

No measurements of the polarization from the Tevatron.
But there is some relevant public data…

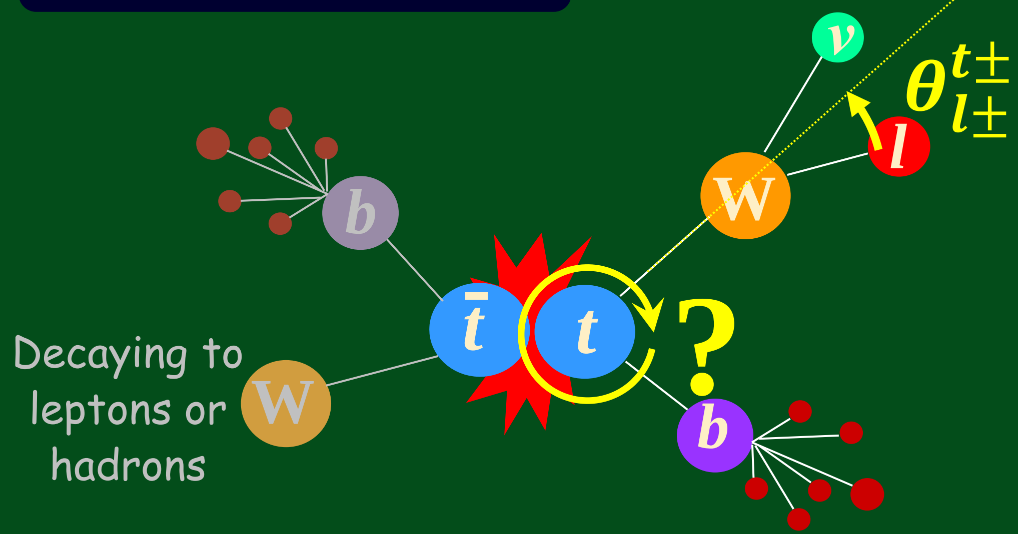
Analyzing top spin

Polarization vector

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1}{2}\left(1 + \left|\vec{P}\right| \kappa_p \cos\theta\right)$$

Angle between polarization axis and decay product (***l***) in the top's rest frame

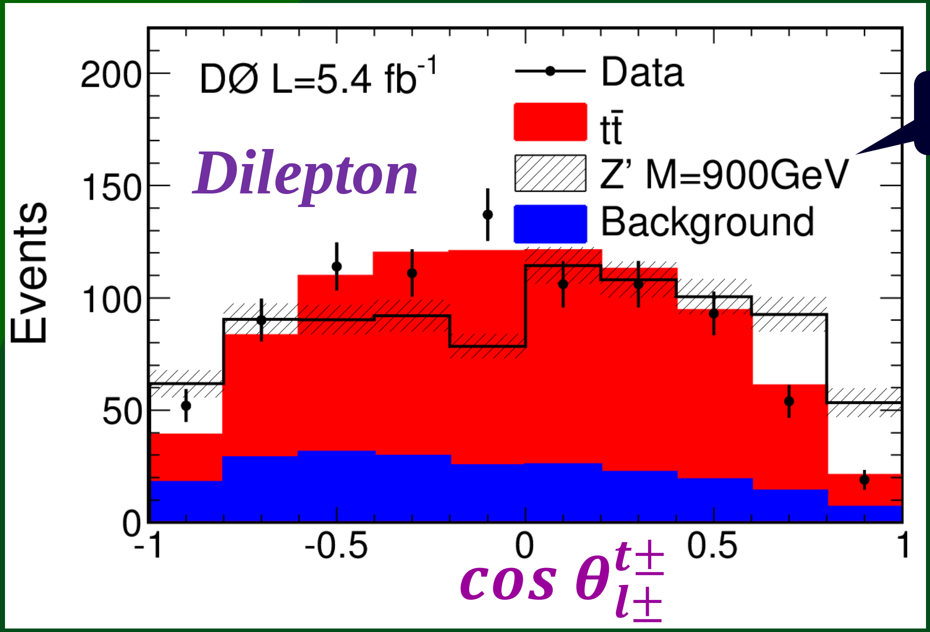
Analyzing strength, κ_l=1



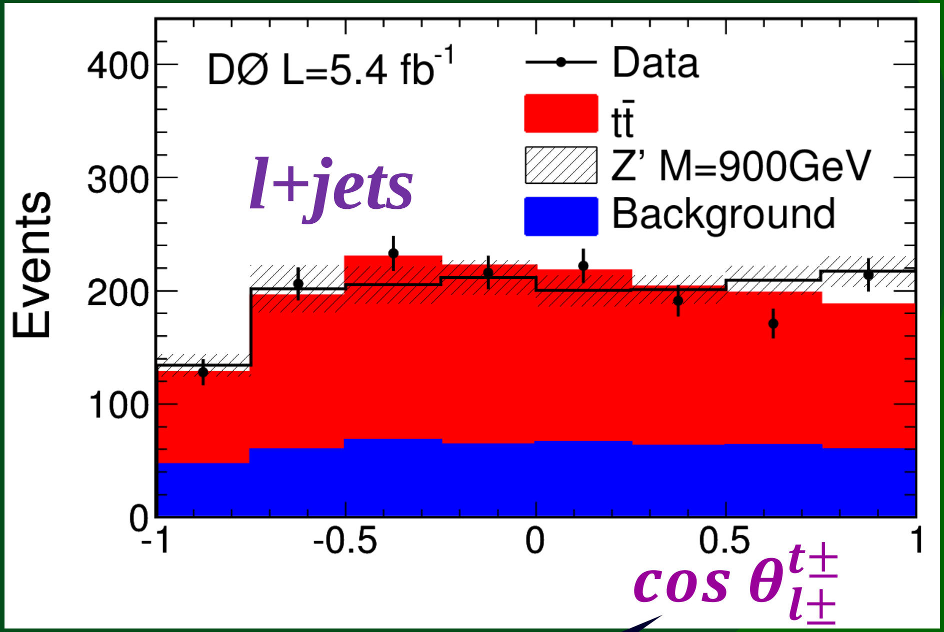
e.g. for longitudinal polarization

Longitudinal polarization?

arXiv:1207.0364 (2012)



Z' model with Z-like coupling to quarks



From CP:
PDF(cos θ^+)+PDF(cos θ^-)

Reconstruction in dilepton channel uses the neutrino-weighting method.

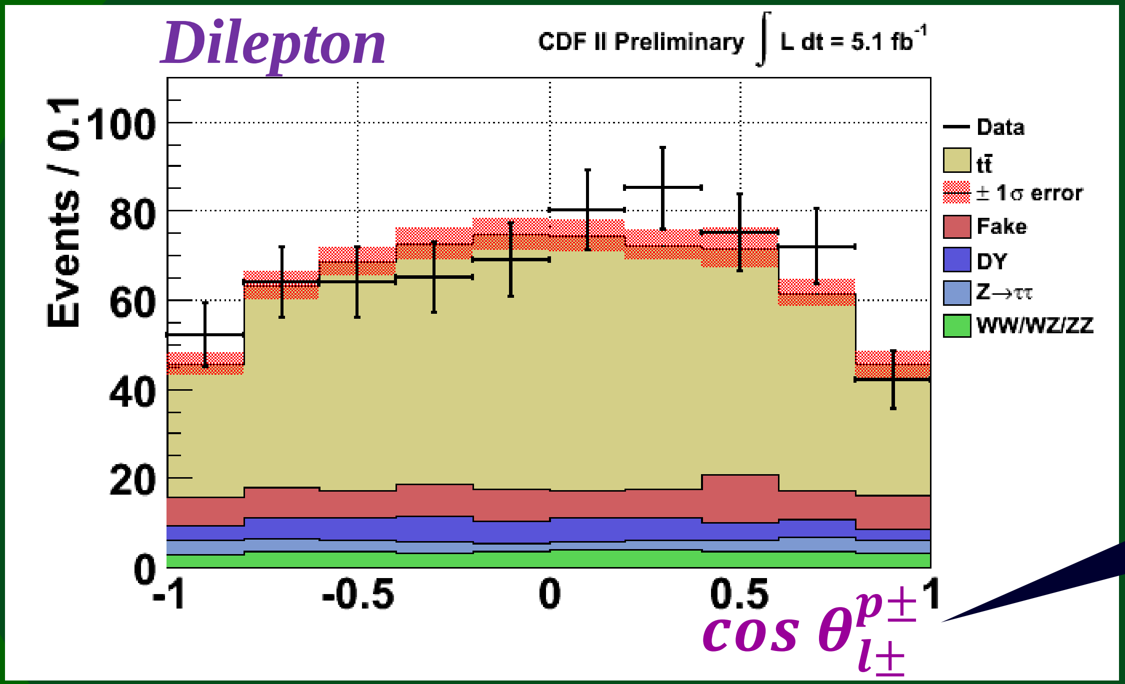
Sum possible neutrino ηs, each one:

- weighted by compatibility with MET
  - Statistical sample for jet resolutions, etc.
- solved analytically using known m_t

Hints at SM-like, unpolarized top pair production

Related plot

From CDF note 10719, which presents this as a check of data modeling. My apologies for reinterpreting…



From CP:
PDF(cos θ^{+})+PDF(-cos θ^{-})

$\theta_{l\pm}^{p\pm}$ from lepton$^{\pm}$'s direction in t$^{\pm}$ frame, to p$^{\pm}$'s in the $t\bar{t}$ frame (i.e. the beam axis)

Hints at SM-like, unpolarized top pair production

Measurements of
spin correlation
in top pair production

- CDF note 10719 – dilepton (2011)
- D0: Phys. Rev. Lett. 108, 032004 (2012)
  - Combined with Phys. Reb. Lett. 107, 032001 (2011)
- CDF note 10211 – l+jets (2010)

Analyzing spin correlations

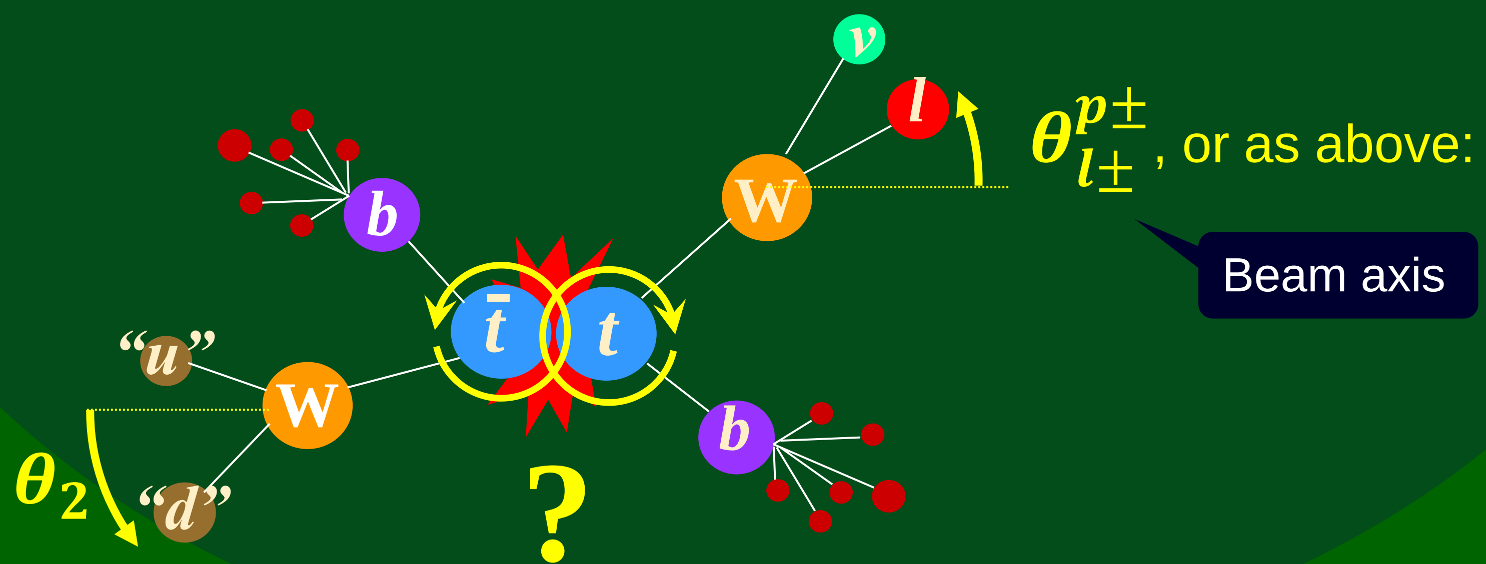
$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2} = \frac{1}{4}\left(1 - \overbrace{A\alpha_1\alpha_2}^{C}\cos\theta_1\cos\theta_2\right)$$

Correlation strength (in production)

$A_{\mathrm{SM}}^{\mathrm{beam}} = 0.78$ (@NLO QCD)

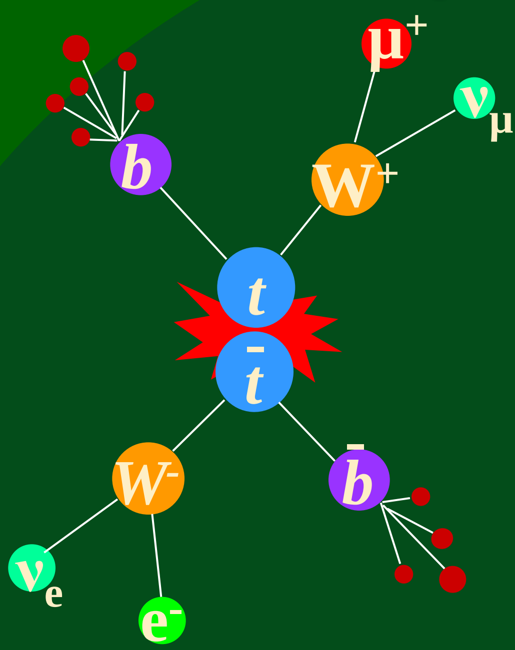
Analyzing strength:

$\alpha_l = 1,\ \alpha_b = -0.41,\ \alpha_d = 0.97$



Again: Production @ Tevatron != production @ LHC – measure both

Dilepton reconstruction



With two *ν*s, reconstruction is harder.

Assuming "true" lepton and jet 4-vectors and a "true" MET, we have

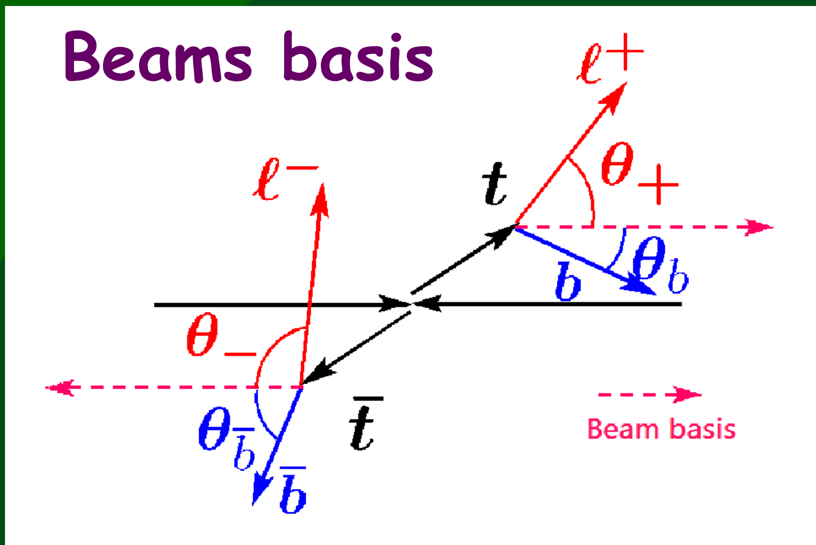
- 6 unknowns (*ν*s momenta)
- 6 constraints (4 masses, "true" MET)

→Algebraic solution

Kinematic fit:

- Fit for *b*-jet energies, MEX, & MEY and best jet-parton assignment
- Minimize a likelihood with
  - χ^2 terms for each parameter
  - A-priori probability densities for $p_z^{t\bar{t}}$, $p_T^{t\bar{t}}$, and $M_{t\bar{t}}$
    - As simulated with Pythia

Template construction



Signal simulated with Pythia, i.e., without spin correlations.

Spin correlations modeled by reweighting of: $1 + C\cos\theta_+^{true}\cos\theta_-^{true}$

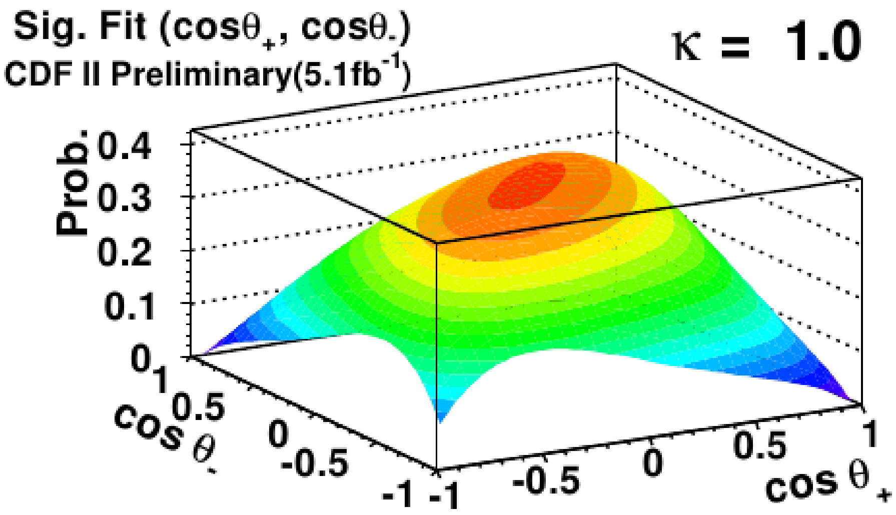
- See also backup slide

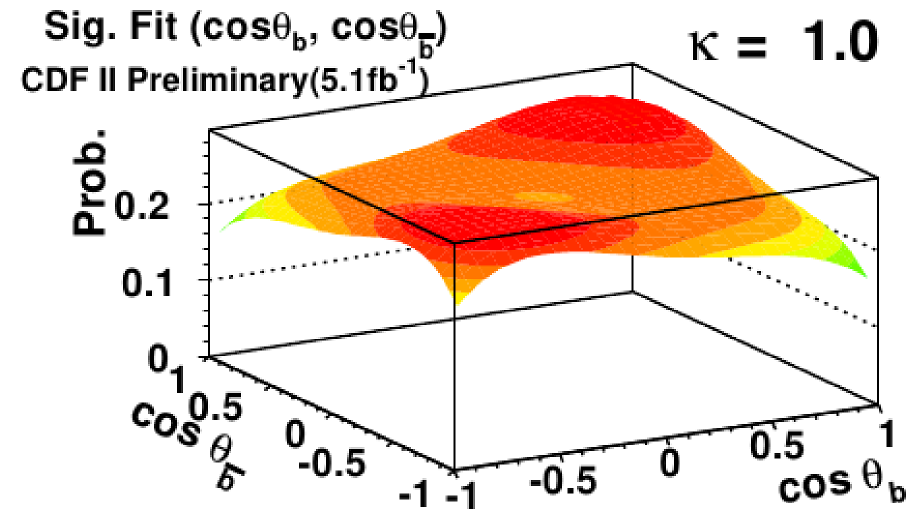
Templates fit to 2D polynomials (up to order 4, constrained by P & CP):

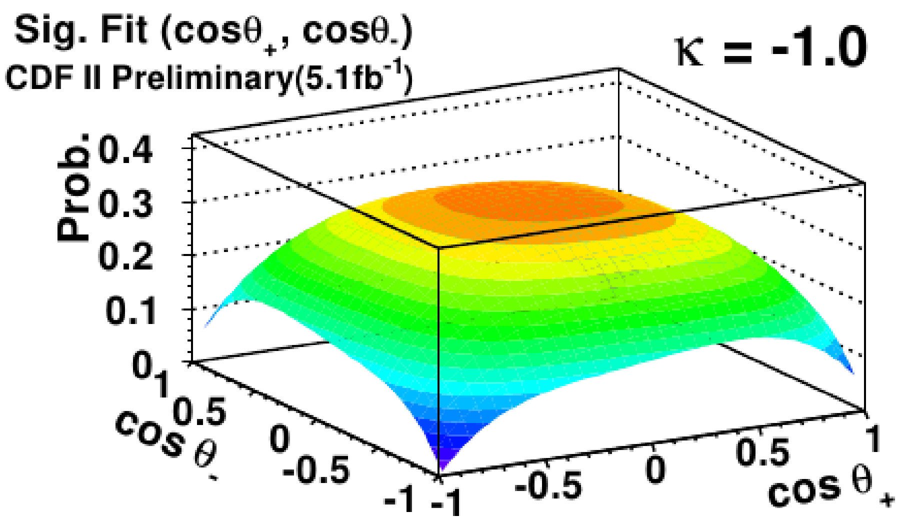
$$f(x,y) = \frac{C_0}{4}\left\{1 + C_1\left[\tfrac{3}{2}\left(x^2+y^2\right)-1\right] + C_2xy + C_3\left[\tfrac{5}{2}\left(x^4+y^4\right)-1\right] + \ldots\right.$$
$$\left.\ldots C_4\left[\tfrac{1}{2}\left(x^3y+xy^3\right)\right] + C_5\left[9x^2y^2-1\right]\right\}$$

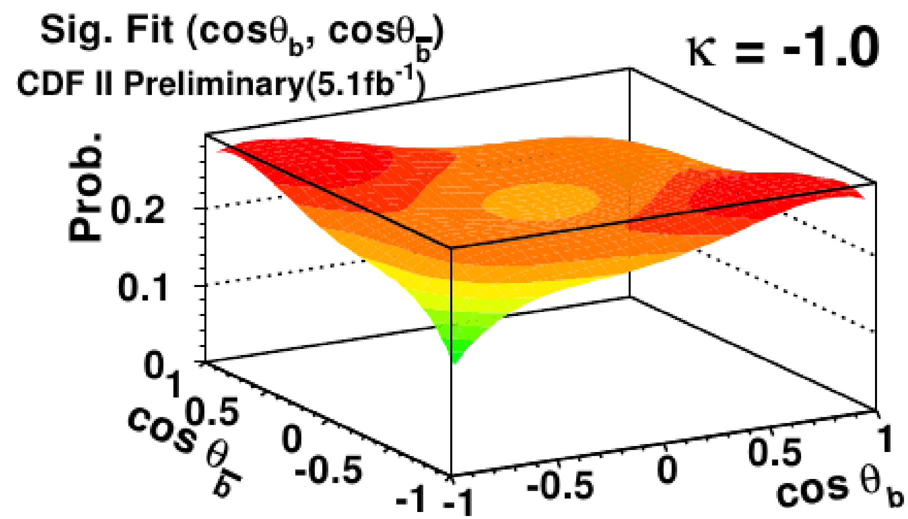
- Templates fit for correlation strengths -1, -0.8, -0.6, … 1
- Templates for $\cos\theta_+^l, \cos\theta_-^l$ and for $\cos\theta_+^b, \cos\theta_-^b$
- Also derived for backgrounds
  - dibosons w. Pythia, Z+jets w. Alpgen, fakes from data

Extreme templates







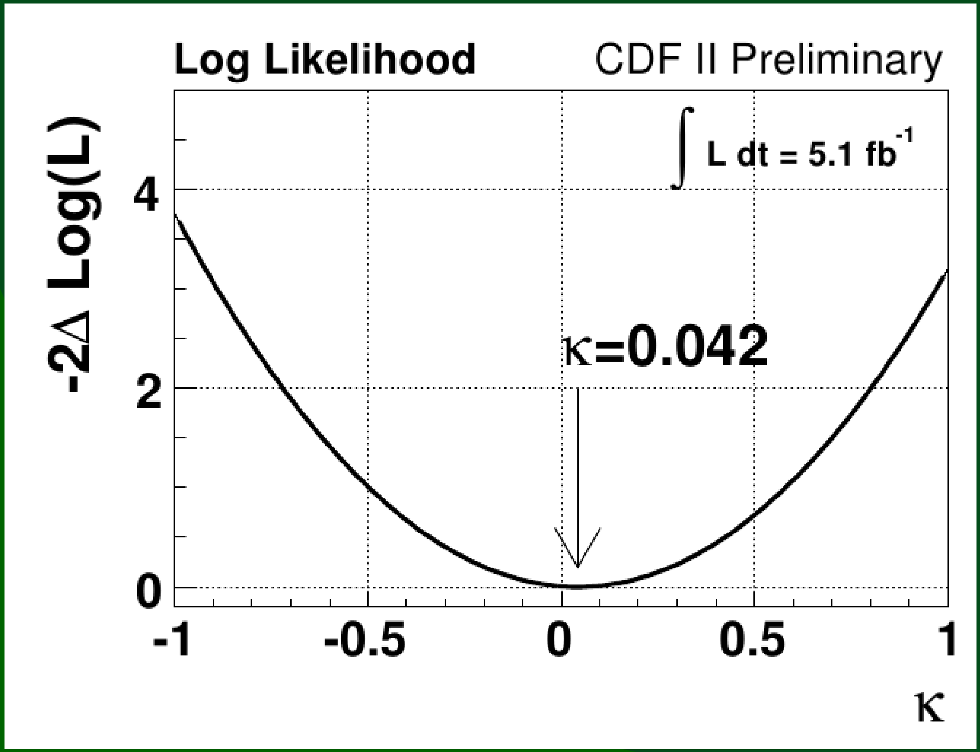


Fit to data

Maximal likelihood fit

- Simultaneous fit for $\cos\theta_+^l, \cos\theta_-^l$ and for $\cos\theta_+^b, \cos\theta_-^b$.
- Using the expected sample composition.

Calibration checked with ensemble tests: no calibration needed



Measured correlation strength ("*C*" in previous slide):

$$\kappa = 0.042^{+0.563}_{-0.562}$$

Matrix element method

Used both in dilepton channel (shown in Top11),

and in l+jet channel (preliminary version shown in Top11).

Again, efficiently summarizes all event kinematics. But here, following Melnikov & Schulze (PLB 700, 17 (2011), they are summarized into a discriminant:

$$R(data) = \frac{P_c(data)}{P_c(data) + P_u(data)}$$

- P_c is the probability assuming SM signal (including spin correlations)
- P_u is the probability assuming signal without spin correlations

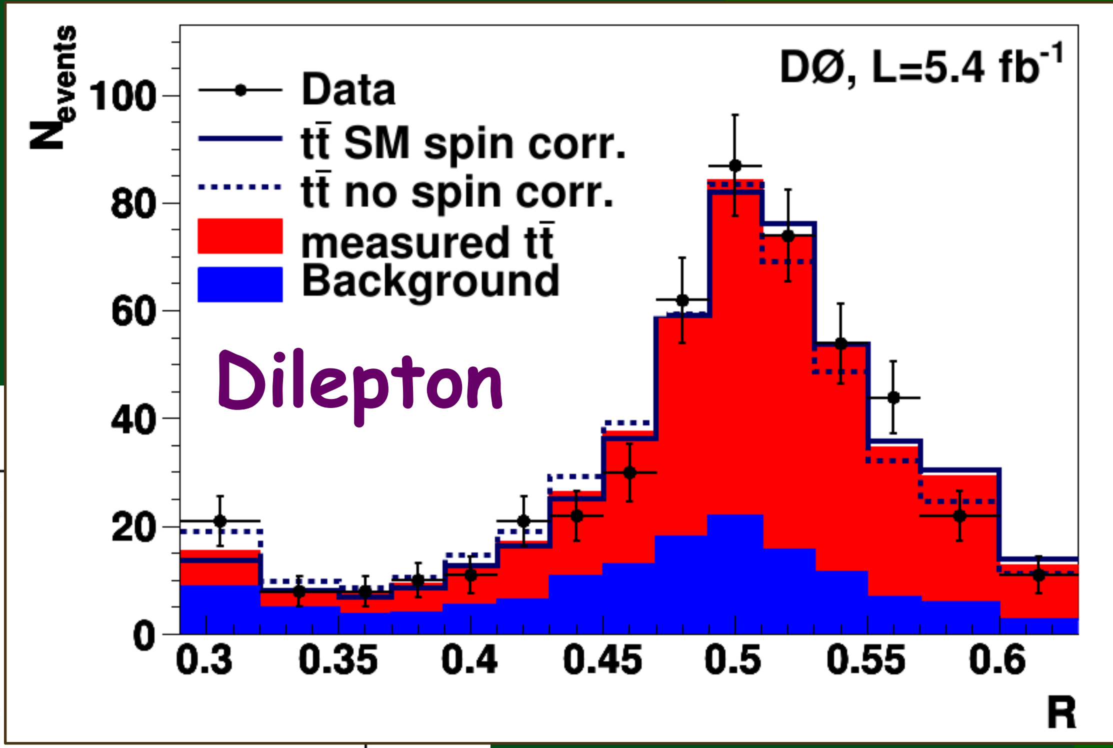
Calculating with LO matrix-elements taken from Mahlon and Parke.

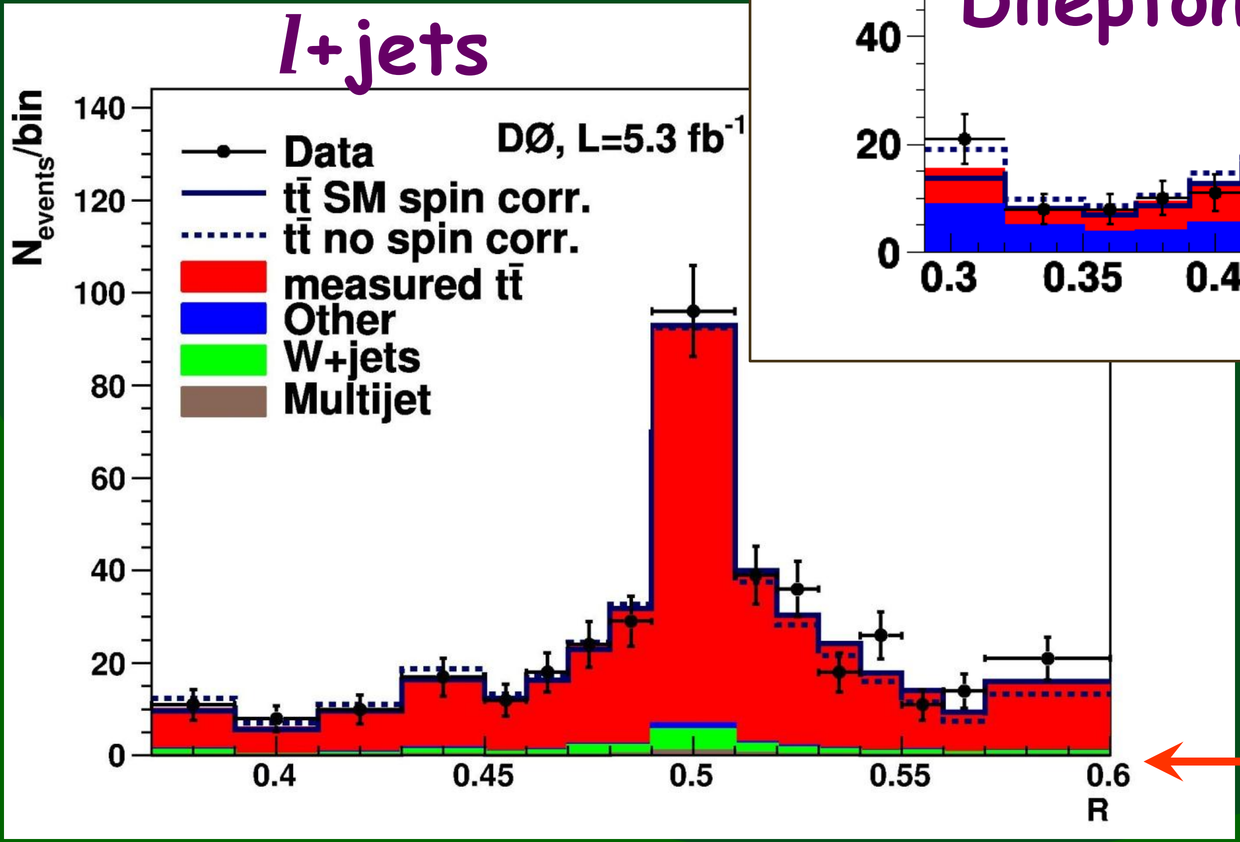
- l+jets: 5D integration, 4 jet-parton assignments (u-jet distinct from d-jet)
- Dilepton: 4-6D integration (but weakly constrained), 2 assignments

Fit to data

Fit for f the fraction of events with spin correlations

Templates generated with MC@NLO



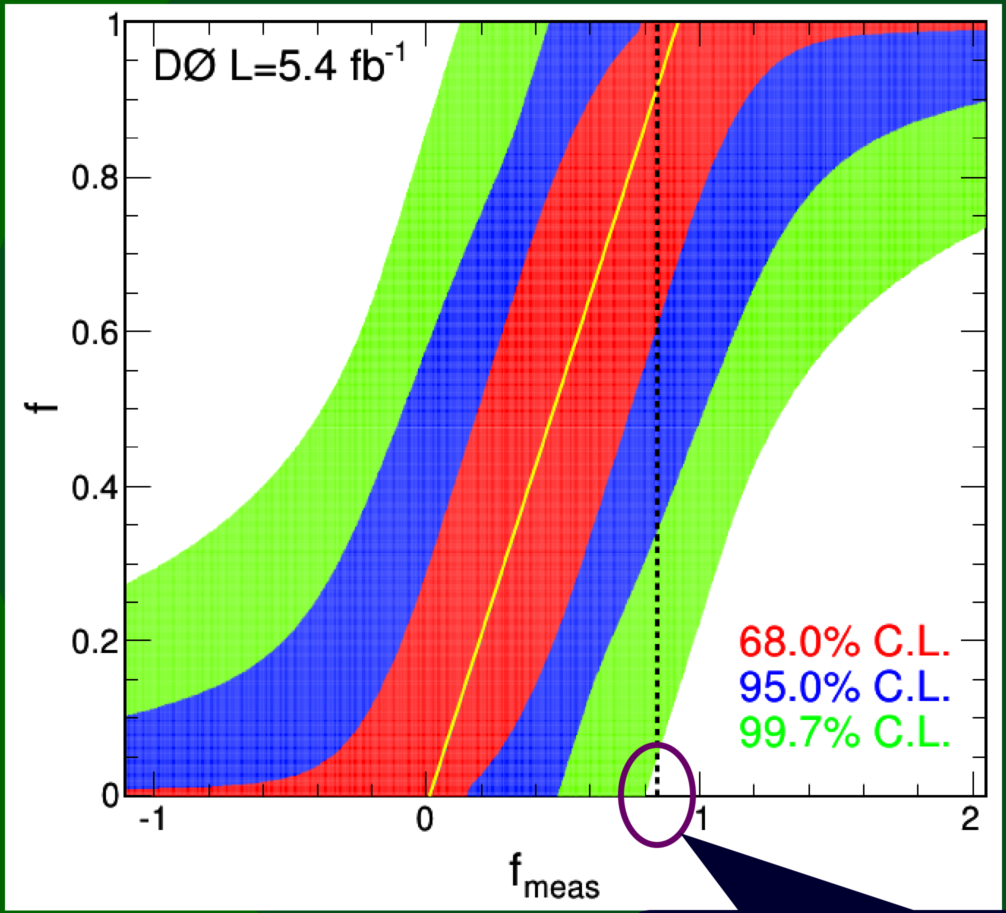


4 *l*+jets subchannels:

- 4 or ≥5 jets
- $M_{jj} \approx M_W$

Only the best one shown

Results



Dilepton: $f = 0.74 \pm 0.41$

l+jets: $f = 1.15 \pm 0.43$

Combined: $f = 0.85 \pm 0.29$

"No spin correlation" excluded at 3σ, i.e., evidence

Summary

The Tevatron experiments measured

- W helicity fractions in top pair decays
  - To better than 10%
- Spin correlations in top pair production
  - Evidence for spin correlation from D0

Not all results included in this talk

Many measurements still using ~half of the Tevatron data

No full measurements, but some indications from Tevatron data that top quarks in top pair production are not 100% polarized…

Good agreement with the standard model

Back up slides

Claimer / Disclaimer

Claimer:

Following long discussion with the authors, or at least, the current experts in the collaboration, a few definitions & descriptions in this talk knowingly do not follow the corresponding documentation.

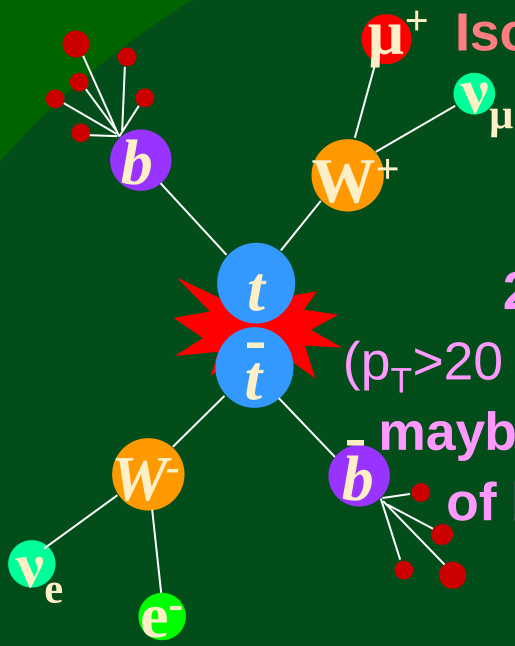
Can discuss as needed after the talk…

Disclaimer:

But as always, I might have introduced silly mistakes, which should not reflect on the excellent work reported here.

$e\mu$ sample

Isolated μ, p_T>15 GeV, |η|<2.0

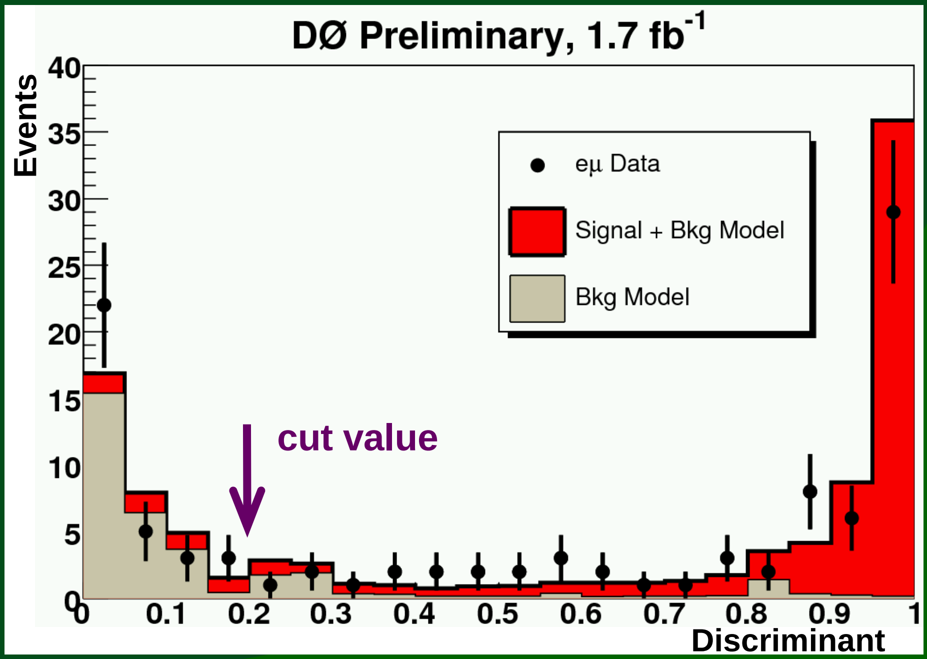


2 Jets
(p_T>20 GeV, |η|<2.5)
- maybe a couple of b-tags…

Isolated e, p_T>15 GeV, |η|<1.1 / 1.5<|η|<2.5

A strong experimental signature
→ no MET requirements
→ looser lepton ID requirements

Discriminant construction and fit procedures similar to those in *l*+jets



Signal modeling

Signal without spin correlations taken from Pythia.

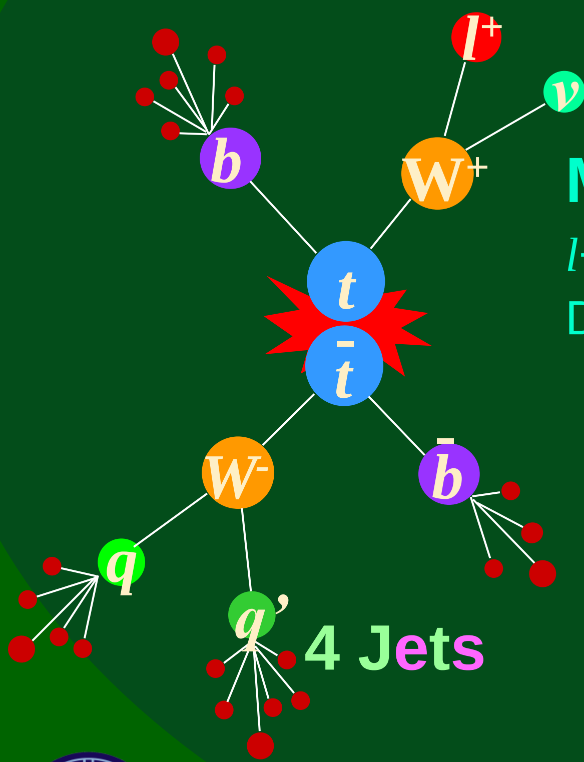
Signal with spin correlations is modeled by reweighting the Pythia events by $1 + C\cos\theta_{+}^{true}\cos\theta_{-}^{true}$, where the angles and C are in the beam basis.

- Based on the LO matrix element of the decay
- Exact for a pure state that is a spin eigenstate for this quantization axis
  - For mixed states, C=1-2p<1
  - “top-tbar spin state is approximately in the eigen-state in beamline basis and weighting method works fairly fine.”

Samples

Lepton+jets

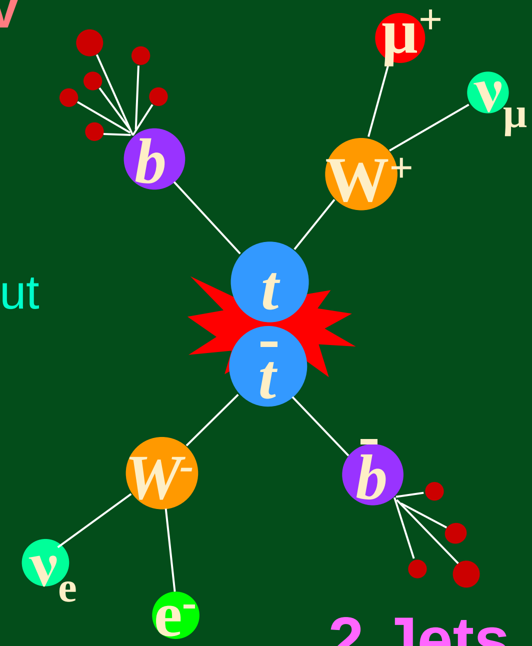
(lepton=e/μ)



4 Jets

Dilepton

(lepton=e/μ)



2 Jets

isolated, p_T>20 GeV

MET:

l+jets: >20GeV

Dileptons: discriminant input in *ee/eμ*

***b* tags**

CDF: **Helicity basis Templates**

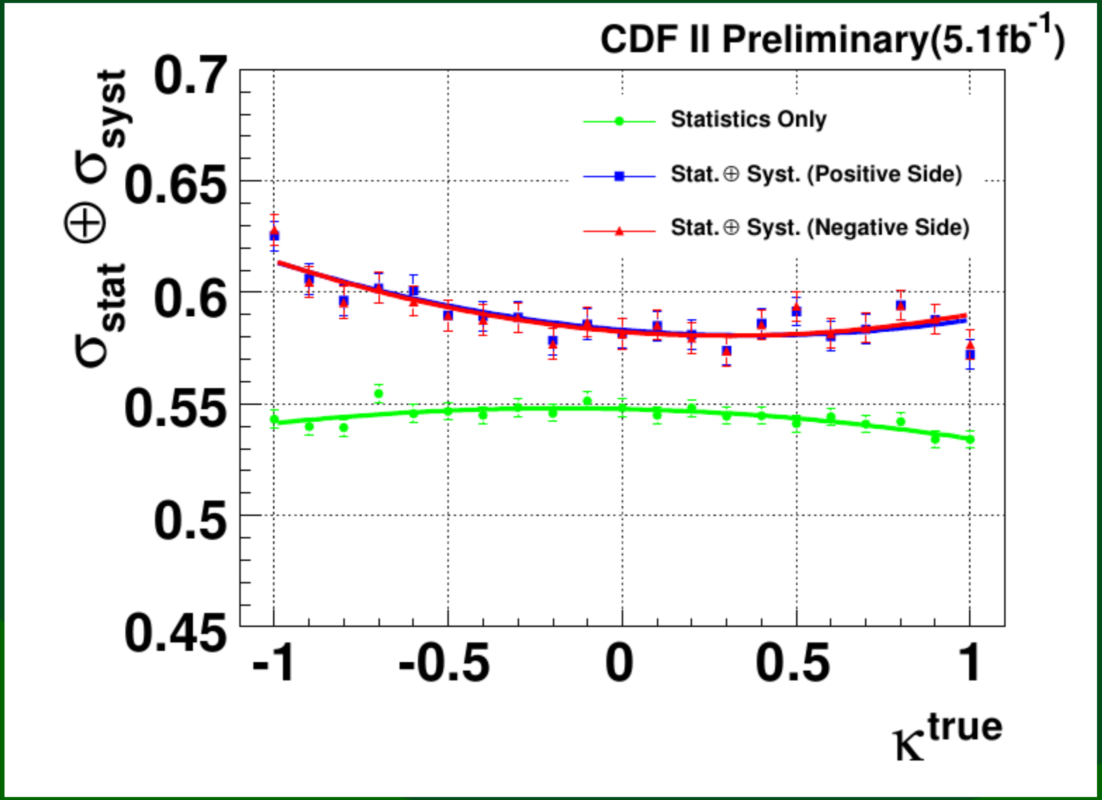
DØ: **Beam Basis Matrix element**

DØ: **Beam basis Templates** (CDF)

CDF systematics

Leading sources:

- Up to 0.21 from higher order terms, evaluated with MC@NLO
- Up to 0.19 from ISR/FSR simulation
- Up to 0.17 from sample composition & instrumental fakes sample
- Up to 0.13 from color reconnection



D0 systematics

TABLE 1: Summary of uncertainties on f_{meas} for the combined fit in dilepton and ℓ+jets channels.

Source	+1SD	−1SD
Muon identification	0.003	−0.003
Electron identification and smearing	0.009	−0.008
PDF	0.058	−0.051
m_t	0.024	−0.040
Triggers	0.007	−0.008
Opposite charge selection	0.002	−0.002
Jet energy scale	0.005	−0.028
Jet reconstruction and identification	0.007	−0.035
b-tagging	0.012	−0.012
Normalization	0.039	−0.043
MC statistics	0.015	−0.015
Instrumental background	0.003	−0.003
Luminosity	0.023	−0.023
Multijet background	0.007	−0.007
Other	0.007	−0.007
MC statistics for template fits	0.156	−0.156
Total systematic uncertainty	0.176	−0.184
Statistical uncertainty	0.251	−0.258

Matrix method

$$\pi(p|m_t) = \frac{1}{\sigma(m_t)} \int dz_a dz_b f_k(z_a) f_l(z_b) d\sigma_{kl}(p|m_t, z_a, z_b)$$

4-vectors of quarks, lepton, ν

PDFs

Diff. x-sec. Proportional to ME

Jet-quark assignments

Transfer functions

- QCD modeling
- Detector modeling

$$\rho(x) \equiv \int \sum_k \pi(p_k|m_t) W(j, \ell, \nu|p_k) \delta(x - \mathbb{M}(p_k)) dp_k$$

Observable as a function of the 4-vectors

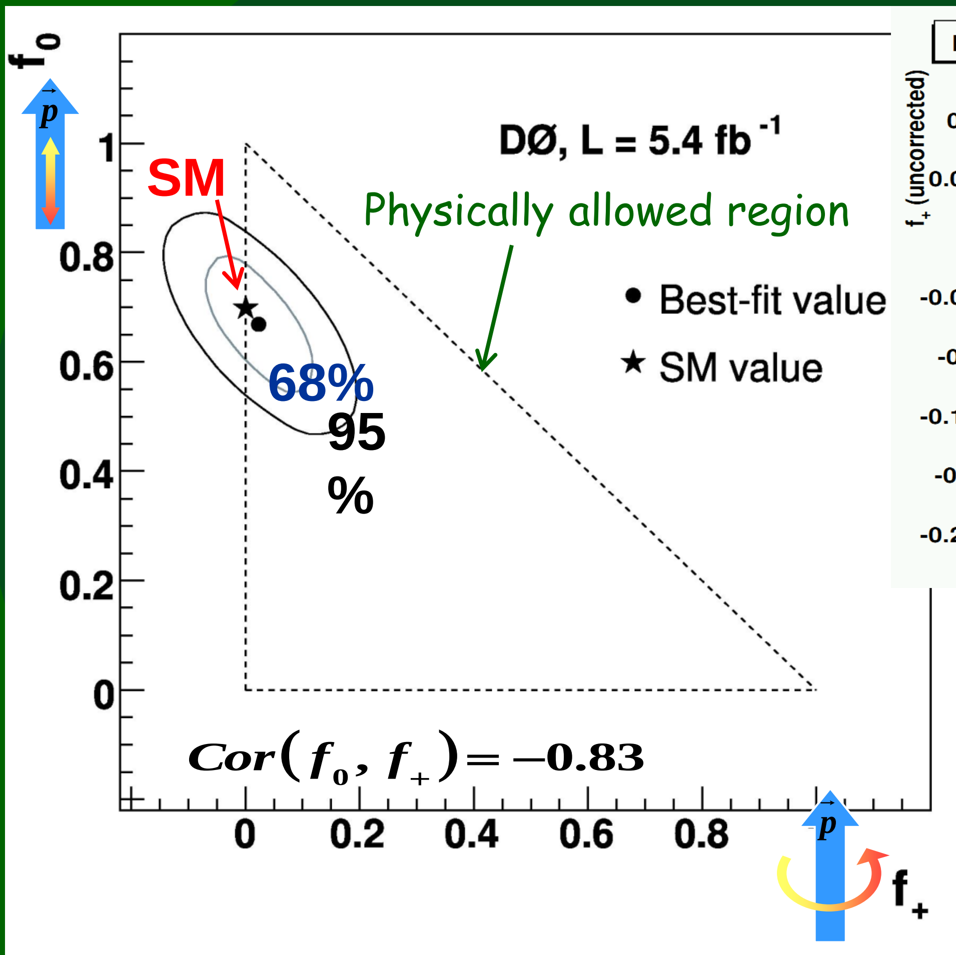
Phys. Rev. **D** 83, 032009 (2011)

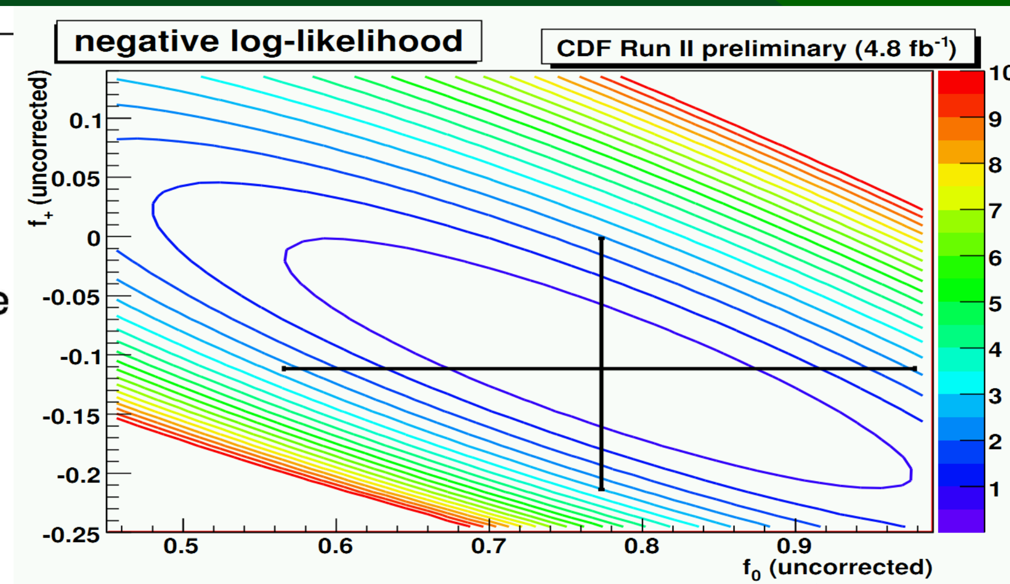
CDF Note 10333

Older W helicity results

Lepton+jets and dilepton channels

Dilepton channels





Corrections are small

For maximal confusion:
x and y-axis are flipped…

Longitudinal: f_0 **= 0.67± 0.10**

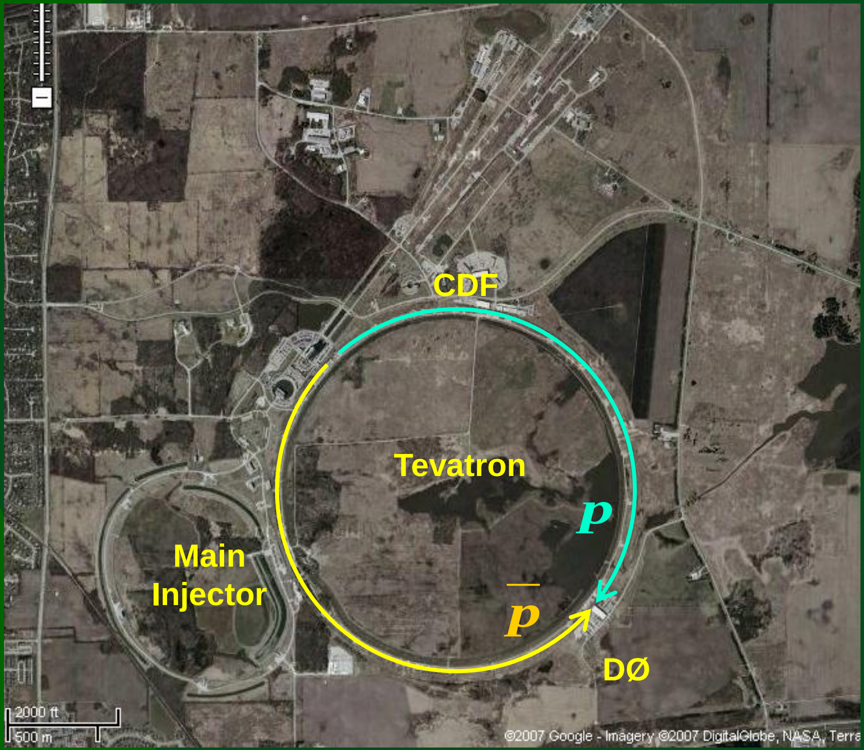
Right handed: f_+ **= 0.02 ± 0.05**

f_0 **= 0.78 ± 0.20**

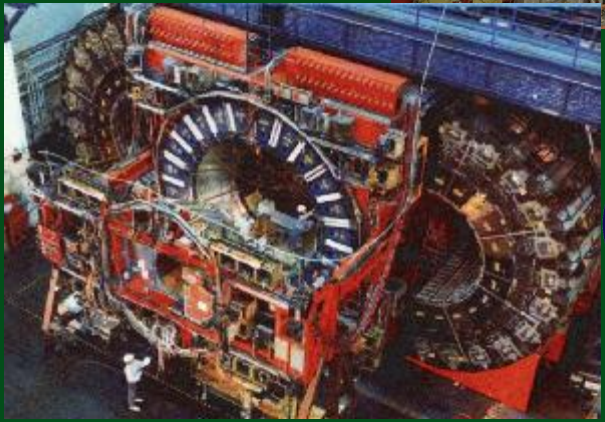
f_+ **= -0.12 ± 0.10**

Experimental Apparatus

Fermilab Tevatron Collider
Run II 2002-2011



The detectors



The collisions

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

General purpose detectors

Top physics relies on tracking, calorimetry and muon detectors.

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