SPIN CORRELATIONS OF TOP QUARK PAIR @ DZERO

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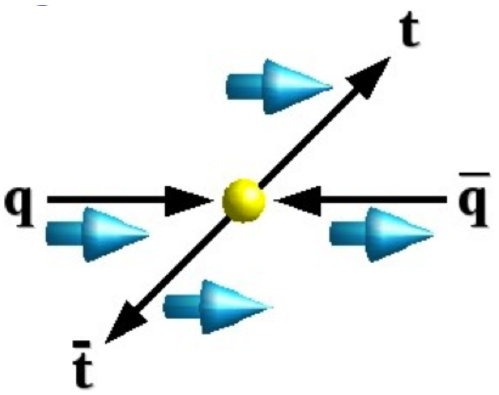
Introduction

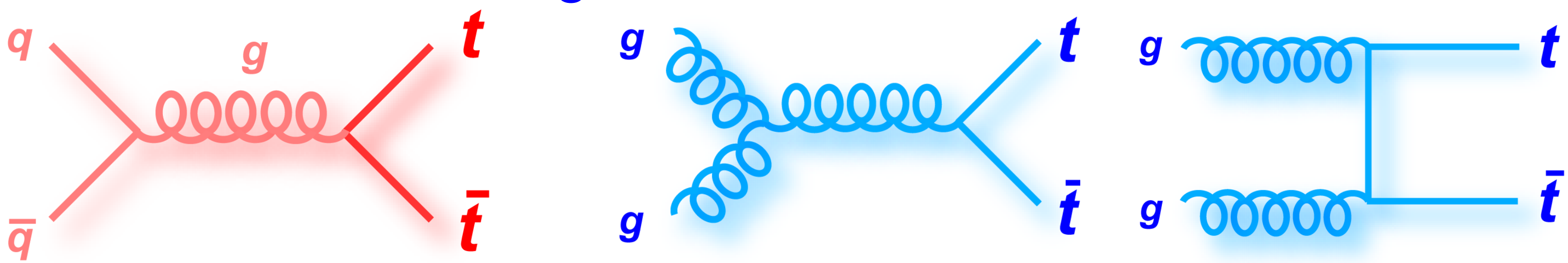
- Spin correlation in quark-pair production
  - Individual quarks are un-polarized, but spins of quark-pair are correlated
  - Not a special property of top quark!



- Top quark lifetime is short
  - Decay (~10^{-25} s) << hadronization ($1/\Lambda_{QCD}$~10^{-24} s)
  - Spin information is transferred to decay products
    - Angular distribution
- Motivation
  - Precision test of SM
    - Confirms that top quark is a spin ½ SM particle
    - Sets upper limits on lifetime, thus lower bound on decay width
  - Study of “bare” quarks free from long distance QCD effects
  - Probe of physics beyond SM
    - Neutral Higgs, stop, Z’ in production; Charged Higgs, b’ in decay

Top Pair Production and Decay

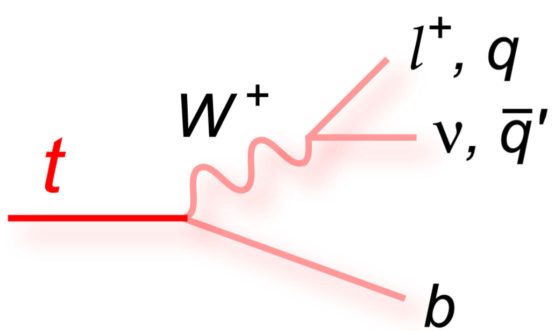
- Production via strong interaction



Tevatron (~85%) LHC (~85%)

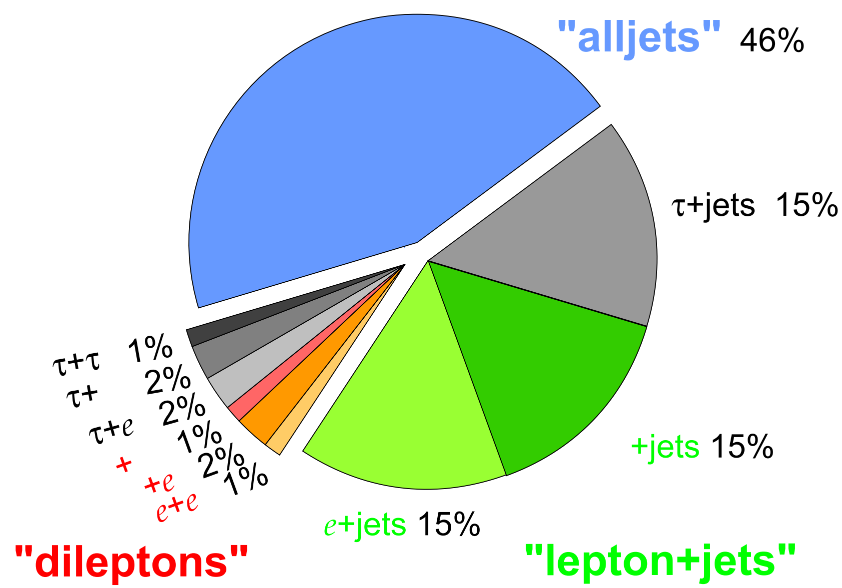
σ_{ttbar} = 7.2 pb @ m_t=173 GeV
Phys. Rev. Lett. 110, 252004

- Decay via weak interaction



In SM, BR(t→Wb) = ~100%

Top Pair Branching Fractions



Spin Correlation

- Angular distribution of the decay product
  - Top quark decays through V-A weak coupling

$$\frac{1}{\Gamma}\frac{d\Gamma}{\cos\theta} = \frac{1}{2}\left(1 \pm \alpha\cos\theta\right)$$

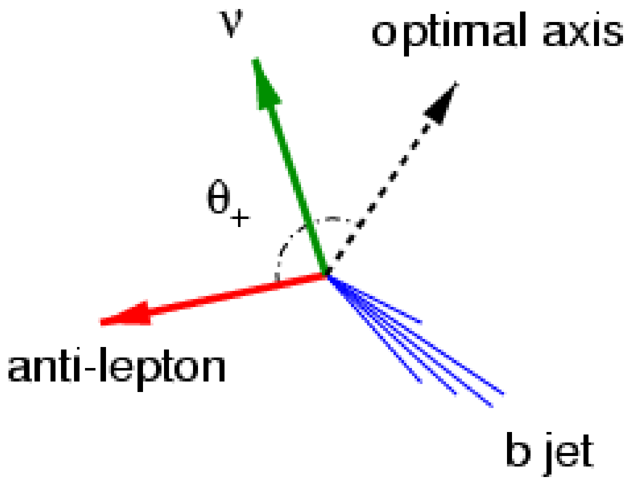
±: right-handed / left-handed

- θ: angle of the decay product w.r.t. the spin-quantization axis in the top rest frame
- α: analyzing power

  - Top pair spin correlation connects the helicity angles on both sides of decay

$$\frac{1}{\sigma}\frac{d^2\sigma}{\cos\theta_1 d\cos\theta_2} = \frac{1}{4}\left(1 + C\cos\theta_1\cos\theta_2\right)$$

  - C: correlation strength
    - Degree of spin correlation
    - $C = A\alpha_1\alpha_2$



Spin Correlation Strength

- Correlation coefficient *A*
  - Fractional difference between like and unlike spin alignments

$$A = \frac{N(\uparrow\uparrow) + N(\uparrow\uparrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\uparrow\uparrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

    - Theoretical dependencies cancels to a large extent
      - PDF, factorization, renormalization scales, and α_s
    - Experimental uncertainty (luminosity) cancels

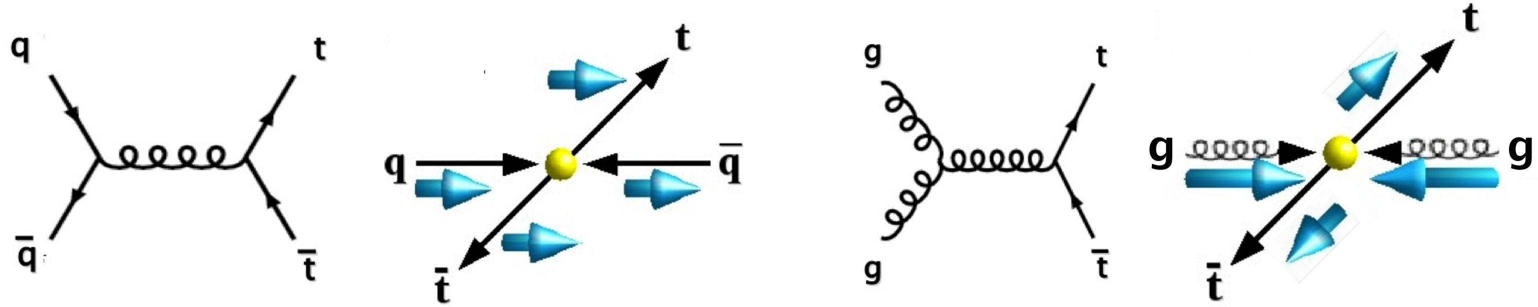
- Analyzing power of decay product, *α*
  - Amount of spin information which a daughter particle carries from the parent top
  - Charged leptons (dilepton) and down-type quarks (l+jets)

	$l^\pm$	d, s	u, c	b	$W^\pm$
α (NLO)	1.00	0.93	-0.31	-0.39	0.39

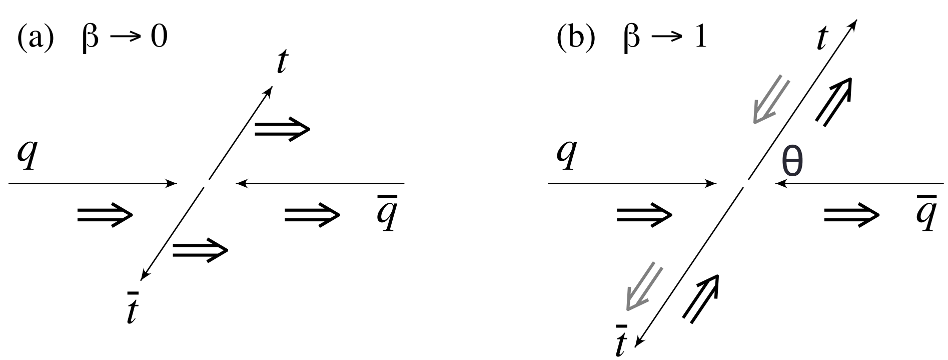
Phys.Lett. B539 235 (2002)

Strength Dependency I

- Production mode
  - qq annihilation (J=1 state): mainly likely aligned ($t_L t_R$ and $t_R t_L$)
  - gg fusion (J=0 state): unlikely aligned ($t_L t_L$ and $t_R t_R$)



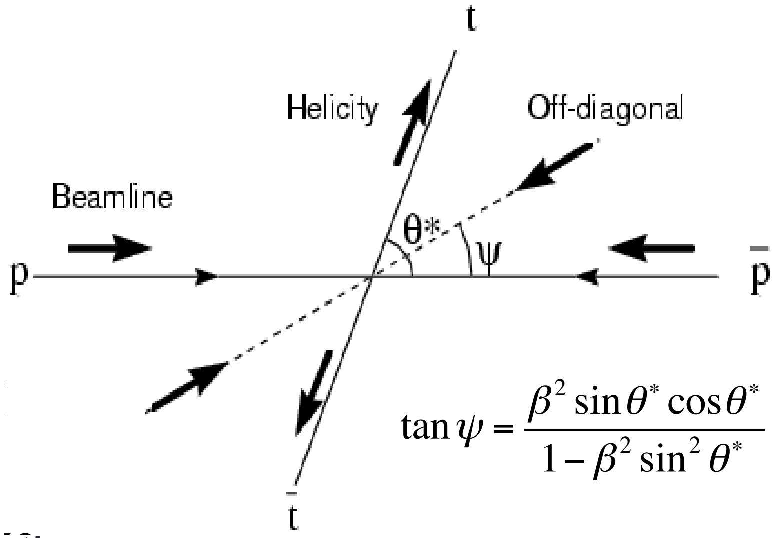
- Collision energy
  - Threshold for tt production
    - spin(t) || spin (q)
  - Large top quark momentum
    - $t_R t_L$ dominant for θ < 90



- Complementary between Tevatron and LHC

Strength Dependency II

- Spin quantization axis
  - Helicity basis
    - Top quark direction in tt rest frame
    - Sensible for LHC
  - Beam basis
    - Beam line
    - Optimal for tt produced at threshold
  - Off-diagonal basis
    - Energy dependent
    - Optimal for tt production from qq annihilation



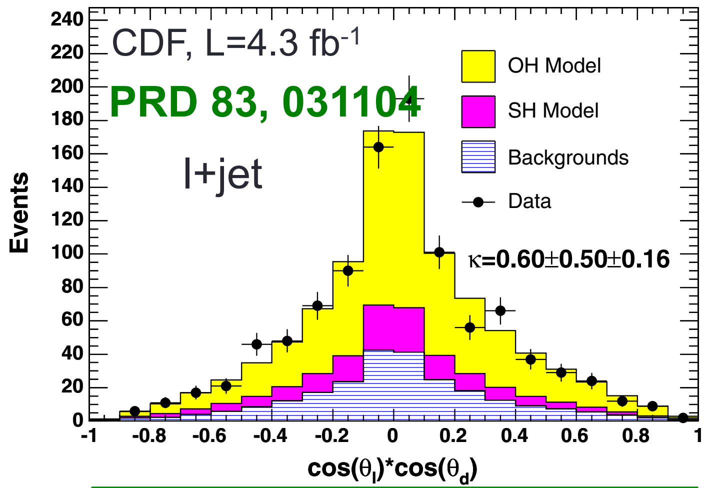
- Correlation Strength (NLO)

Nucl. Phys. B 690,81 (2004)

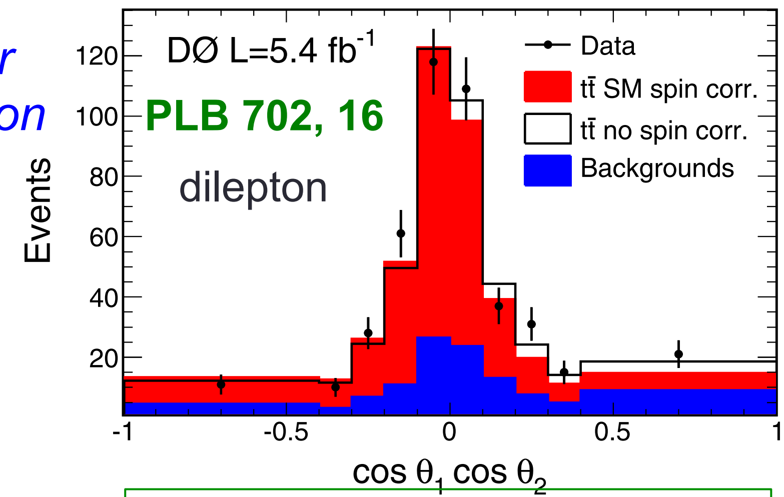
NLO	Tevatron	LHC (7 TeV)	LHC (14 TeV)
Helicity	-0.352	0.270	0.347
Beam	**0.777**	0.053	-0.051
Off-diagonal	0.782	0.034	-0.076

Measurements at Tevatron

Angular distribution

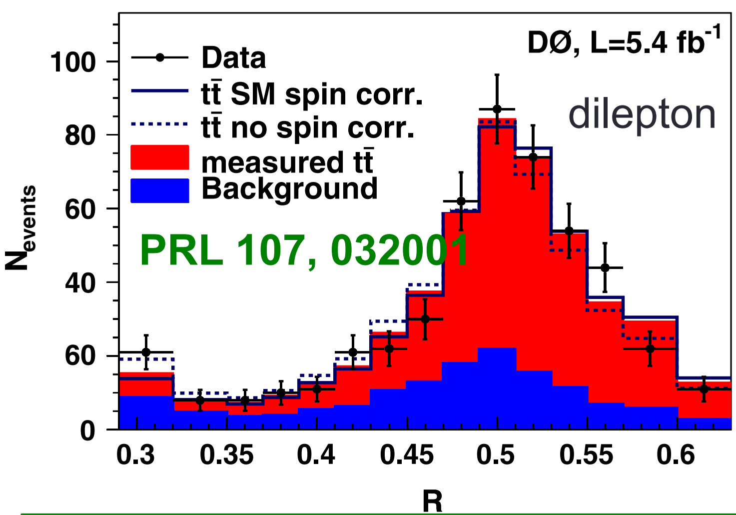


C(hel.) = -0.60 ± 0.50 ± 0.16

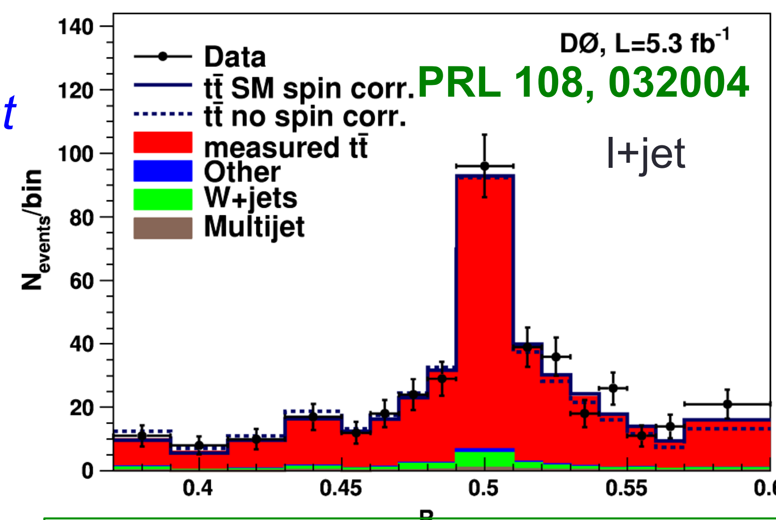


C(beam) = 0.10 ± 0.45

Matrix element



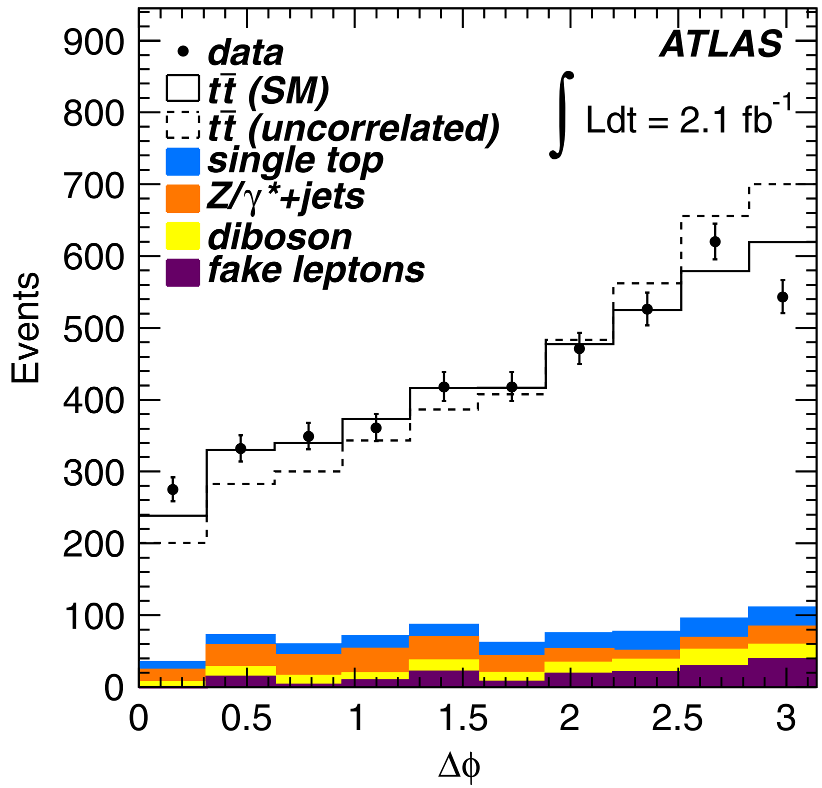
f(beam) = 0.74 ± 0.41 / C = 0.57 ± 0.31



f(beam) = 1.15 ± 0.43 / C = 0.89 ± 0.33

Measurements at LHC

PRL 108, 212001



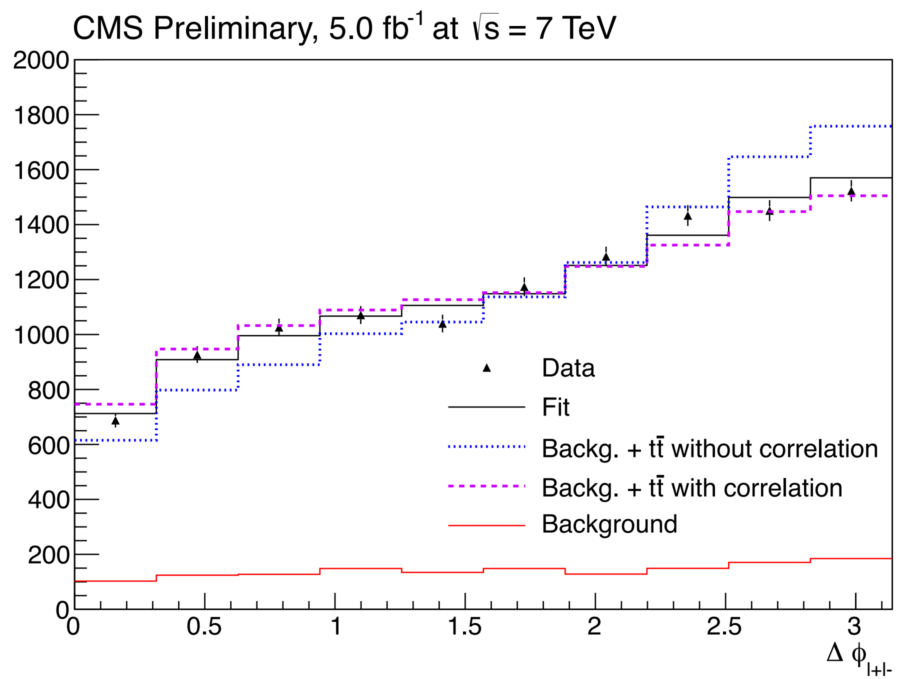
A(hel.) = $0.40^{+0.09}_{-0.08}$ (stat+syst)

Excluded H(uncorrelated) @ 5.1 SD

$\Delta\varphi = |\varphi_1 - \varphi_2|$

Dilepton channels

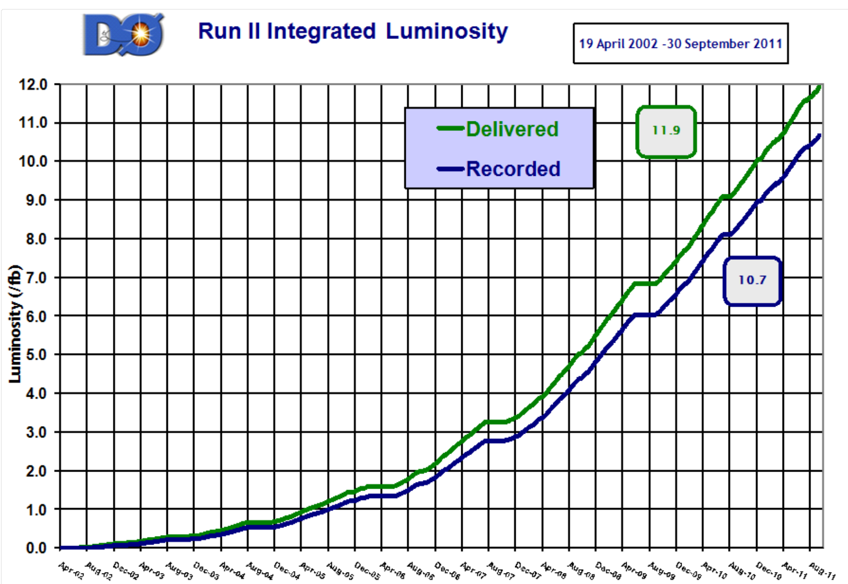
CMS PAS TOP-12-004



A(hel.) = 0.24±0.02(stat.)±0.08(syst.)

Tevatron

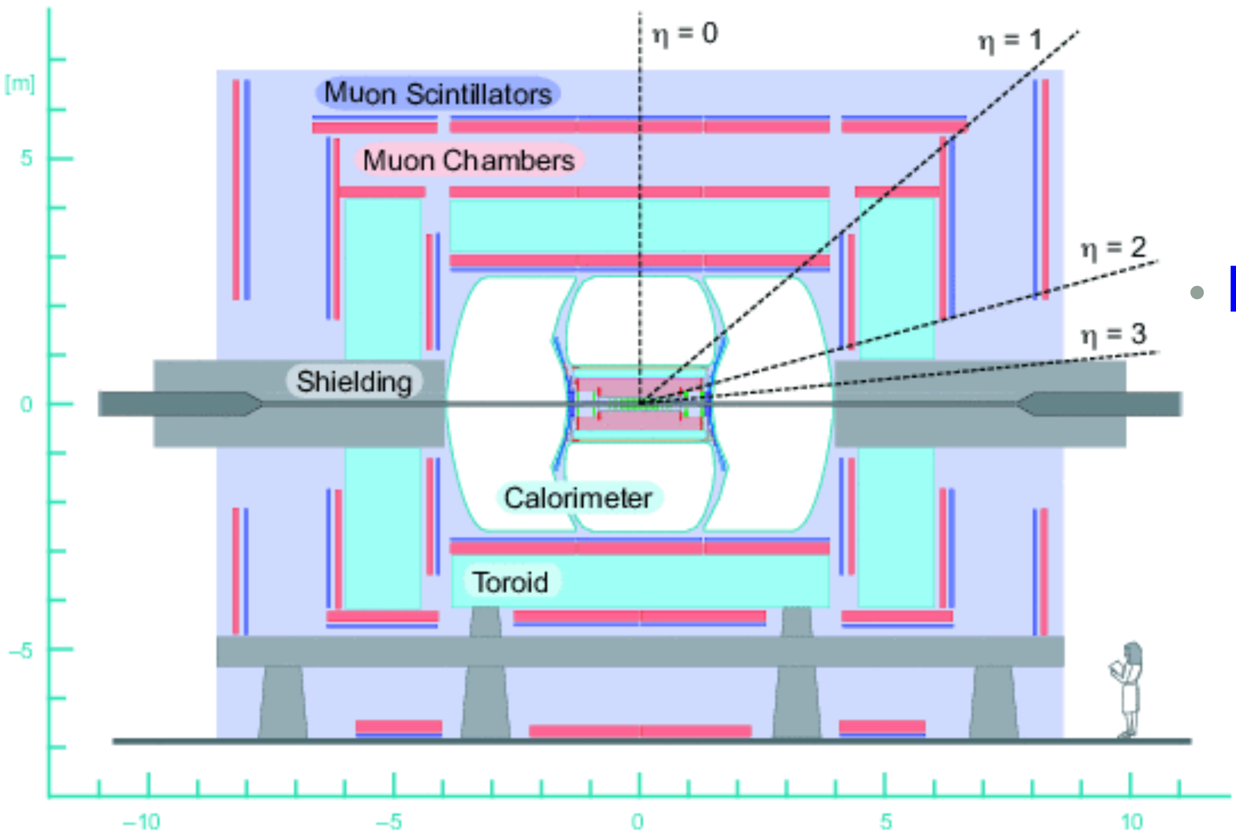
- Fermilab, IL
- Unique p-pbar collider
  - $\sqrt{s}$=1.96 TeV
  - 396 ns bunch crossing
- Two experiments
  - D0 and CDF
- RunII operation 2001 ~ 2011



- Delivered 11.9 fb^{-1}
  - Recorded 10.7 fb^{-1}
  - Analysis used 9.7 fb^{-1}
- ~100,000 top quark events
  - $\sigma(m_t=173\text{ GeV}) \sim 7.2$ pb

D0 Detector

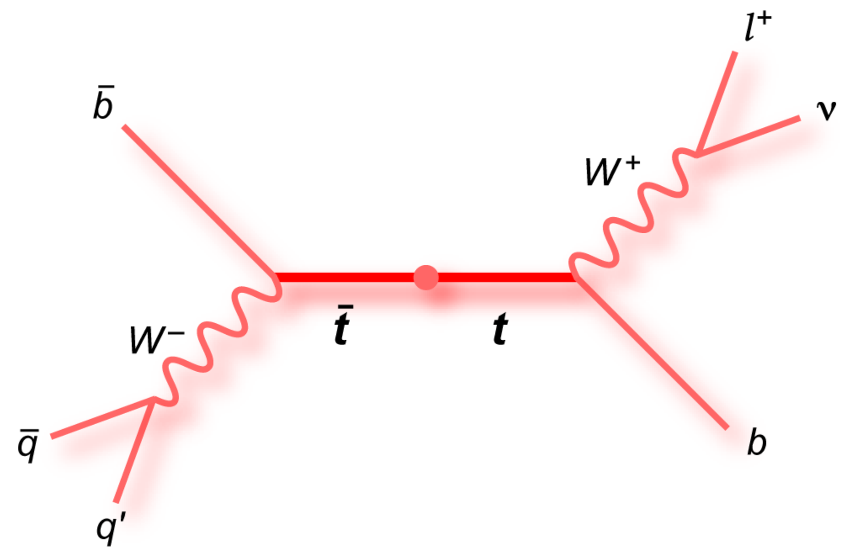
- Tracking system
  - Silicon Microstrip Tracker (SMT)
    - Upgraded with L0 in 2006
  - Central Fiber Tracker (CFT)
- Solenoid
  - 2 T
- Calorimetry
  - Uranium / liquid-argon



- Muon system
  - 3 layers of scintillators / drift chambers
  - Toroid (1.8 T)

lepton+jets Final States

- $W^+ \rightarrow l\nu$ ($l=e,\mu$) / $W^- \rightarrow qq'$



- Event characteristics
  - One isolated lepton
  - ≥ 4 jets (2 b quark + 2 light quark)
  - Momentum imbalance
- Advantages
  - (Relatively) clear events – lepton
  - Sizable statistics (BR > 30%)
    - Including leptonic tau decays
  - Top quarks can be fully reconstructed with minimal assumption
  - Large analyzing power
    - $\alpha(l) = 1.00$, $\alpha(d,s) = 0.93$

Samples

- Data
  - Full Tevatron dataset (9.7 fb^{-1})
- Signal
  - MC@NLO+HERWIG (m_t=172.5 GeV, σ_{ttbar}=7.48 pb, CTEQ6L1)
  - Spin correlation vs. no spin correlation
- Background
  - Dilepton, signle top (tb, tqb)
  - Diboson (WZ,WW,ZZ)
  - W+jets, Z+jets
  - Multijet – data driven

Event Selection

- Event selection
  - Lepton
    - One isolated lepton with $p_T > 20$ GeV, $|\eta(e)| < 1.1$, $|\eta(\mu)| < 2.1$
  - Jets
    - ≥ 4 jets with $p_T > 20$ GeV (leading jet $p_T > 40$ GeV), $|\eta| < 2.5$
    - ≥ 2 jets tagged by MVA b-tagger
  - MET > 20 GeV

Sample		e+jets	μ+jets	l+jets
Signal		647.9 ± 1.5	506.4 ± 1.2	1154.3 ± 1.9
Background	W+jets	55.8 ± 1.4	63.1 ± 1.5	118.9 ± 2.1
	Multijet	33.1 ± 2.5	4.1 ± 0.4	37.1 ± 2.5
	Others	38.6 ± 0.5	29.1 ± 0.4	67.8 ± 0.6
	Total	127.5 ± 2.9	96.3 ± 1.6	647.9 ± 3.2
Expected		775.4 ± 3.3	602.8 ± 2.2	1378.2 ± 3.9
Observed		820	731	1551

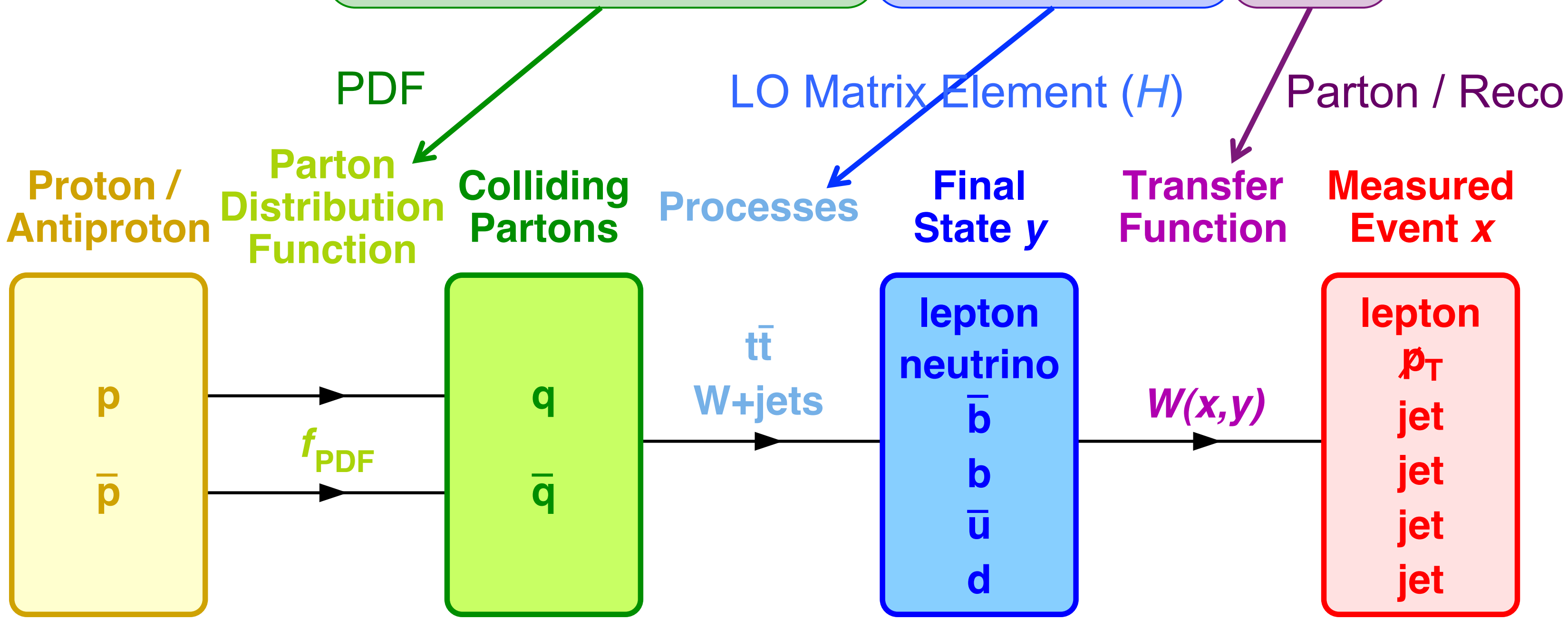
Strategy

- Matrix Element Method (next slide)
- Jet-parton assignment
  - Only 4 jets considered
    - Two b-tagged jets w/ highest MVA => b-jets
    - Two additional jets w/ highest p_T among the others => light jets
  - 4 permutations per event
- Binned maximum likelihood fit
  - Returns fraction of spin correlation (f_{meas})
- Sample splitting
  - lepton flavor / jet multiplicity / m_{jj} ($|m_{jj} – m_W|$, m_W=80.4 GeV)
  - Simultaneous fit over these 8 subsamples - enhances sensitivity
- Correlation strength *C*
  - $C_{meas} = f_{meas} \times C_{SM}$ ($C_{SM} = 0.777^{+0.027}_{-0.042}$)
  - Assume ME calculation fully reflects spins in ttbar production and decay

Matrix Element Method

- Probability of each event being signal for a given hypothesis (*H*) of interest

$$P_{\rm sgn}(x;H) = \frac{1}{\sigma} \int f_{PDF}(q_1) f_{PDF}(q_2)\, dq_1\, dq_2 \frac{(2\pi)^4 \left|M(y,H)\right|^2}{q_1 q_2 s} W(x,y)\, d\Phi_6$$



Optimal use of kinematic information => improves sensitivity by ~30%

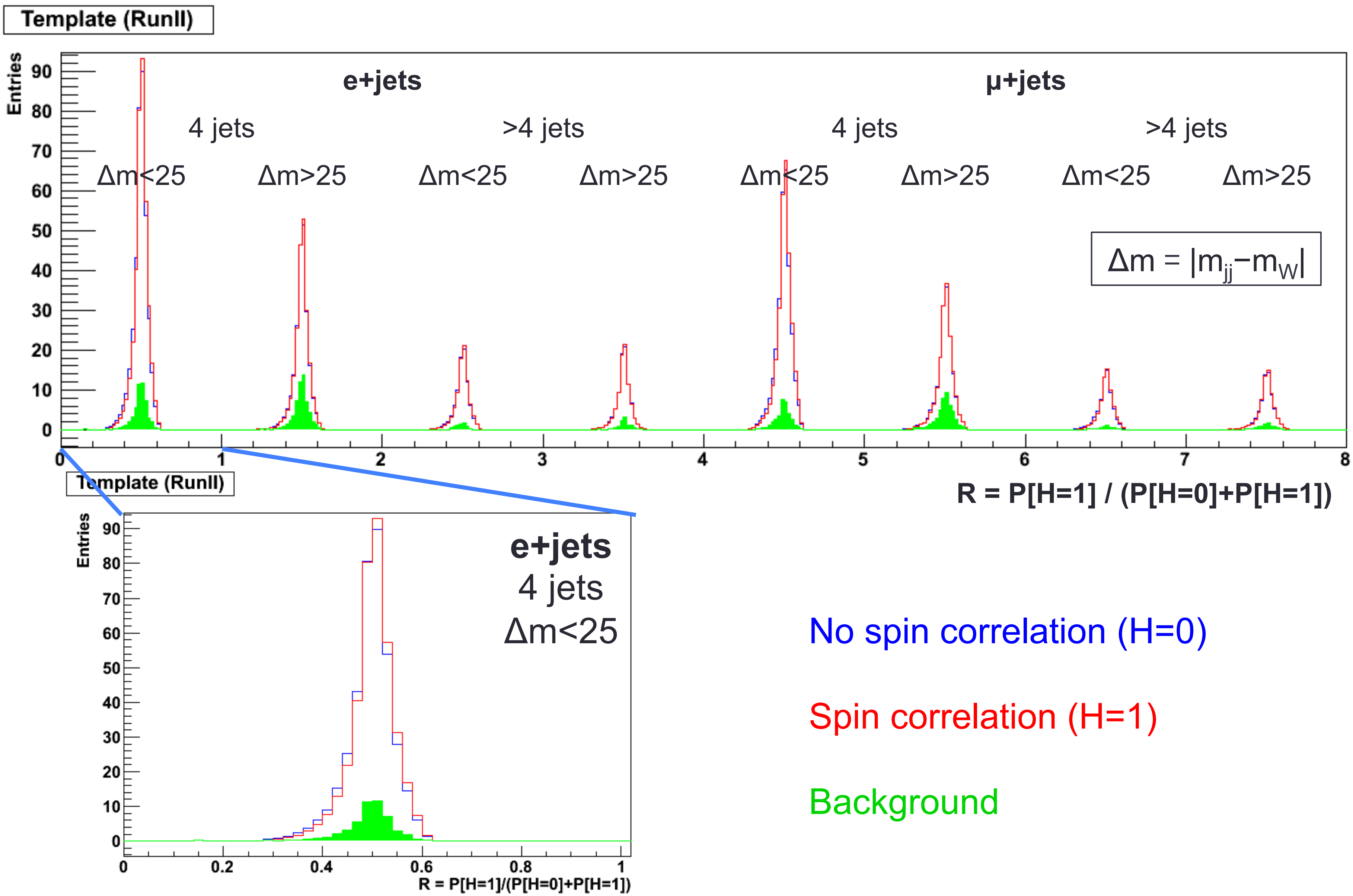
Discriminant and Templates

- Signal probabilities
  - Two probabilities per event are calculated by ME under two hypotheses
  - H=0 (spin uncorrelated) vs. H=1 (spin correlated as predicted in SM)
- Discriminant R

$$R = \frac{P_{\mathrm{sgn}}(x;H=1)}{P_{\mathrm{sgn}}(x;H=0)+P_{\mathrm{sgn}}(x;H=1)}$$

- Templates
  - Two templates (H=0 and H=1) are built from *R* distributions from signal and background
    - Background distribution is commonly used for both templates
  - Combined templates are constructed from 8 subsamples

Combined Templates



No spin correlation (H=0)

Spin correlation (H=1)

Background

Binned Maximum Likelihood Fit

- For bin *i*

$$n^i = \sigma_{norm} \cdot \left[f_{H=1} \times n^i_{H=1} + (1 - f_{H=1}) \times n^i_{H=0} \right] + n^i_{bkg}$$

  - n^i : # of events in bin *i*
  - $f_{H=1}$: fraction of spin correlation (*no constraint => Feldman-Cousins*)
  - σ_{norm} : $\sigma_{ttbar} = \sigma_{norm}$ x 7.48 pb

- Likelihood function

$$L = \prod_i^N P(m^i, n^i)$$

  - *P(m,n)* : Poisson probability to observe *m* events when *n* events are expected
  - *N*: # of bins

- LHF with systematics

$$L = \prod_i^N P(m^i, n^i) \prod_k^K G(\nu_k; 0; SD_{k,i})$$

  - $G(\nu_k;0,SD_{k,i})$: Gaussian PDF with zero mean and 1 SD width for systematic source *k*
    - ν_k : nuisance parameter
  - *K*: # of systematic sources

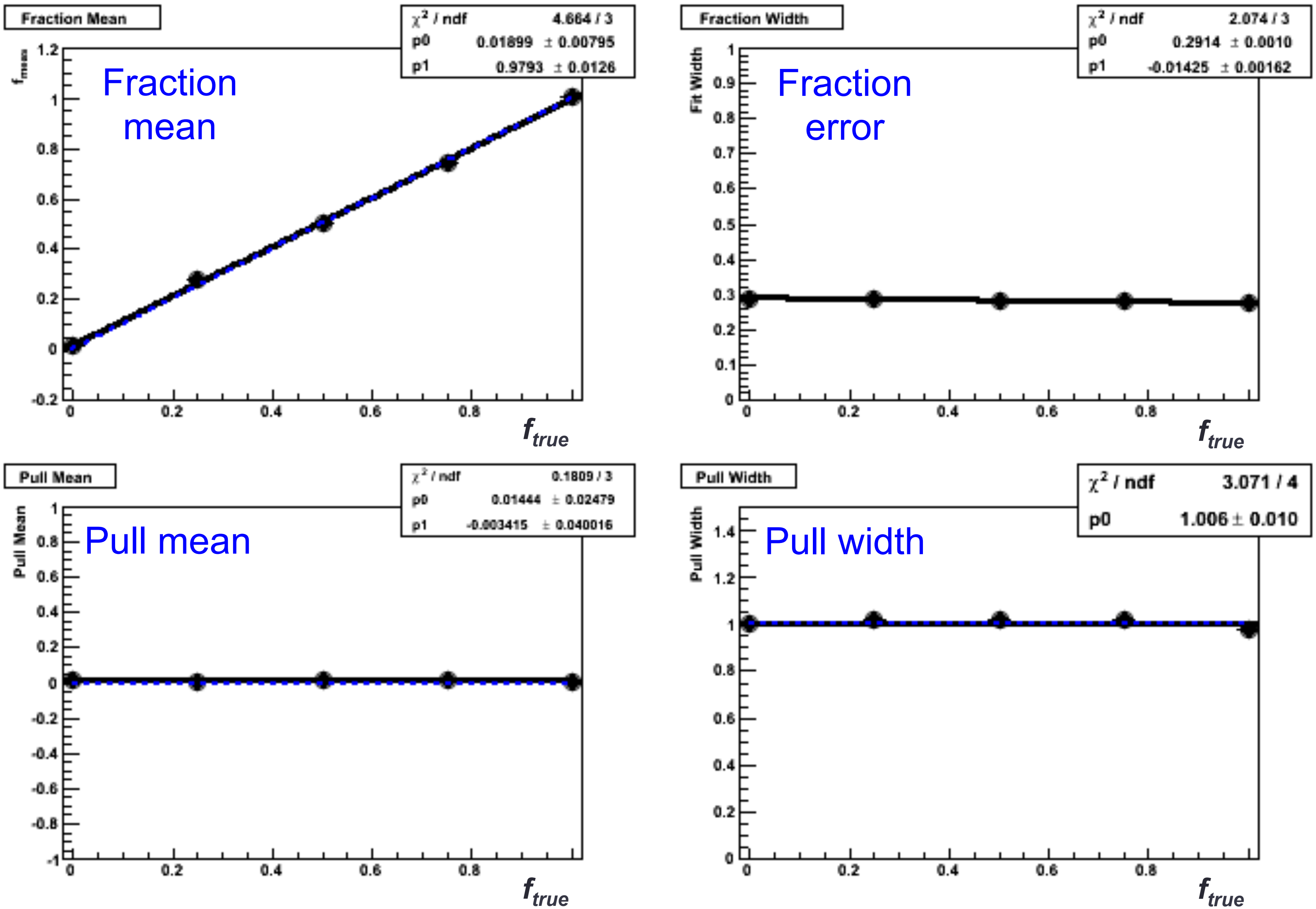
Systematic Uncertainties

Type	Source
Normalization	Lepton ID
	Trigger requirement
	Background normalization
	Multijet background
	Integrated luminosity
Shape changing	Jet energy resolution
	Jet ID
	Jet energy scale
	Flavor dependent correction
	b-tagging / fake rate
	Taggability
	PDF
	Top quark mass
	Signal modeling
	Template MC statistics

Ensemble Test

- Calibrate fitter and estimate uncertainty
- An ensemble consists of events randomly selected according to sample composition
- 5 different signal composition between H=1 and H=0
  - $f_{H=1}:f_{H=0}$ = 0.0:1.0 / 0.25:0.75 / 0.5:05 / 0.75:0.25 / 1.0:0.0
- 1000 pseudo-experiments for each mixing fraction point
- Pull distribution
  - $(f_{obs} - \langle f_{obs} \rangle) / \sigma_{obs}$ per pseudo-experiment
  - Non-bias sampling generates a Gaussian with zero mean and unity width

Ensemble Test (Statistics only)



Results (Expected)

- Based on ensemble test (@ f_{true}=1.0)

$$f_{meas} = x.xx \pm 0.28\ (stat.) \pm x.xx\ (syst.)$$

$$\sigma_{ttbar} = x.xx \pm 0.26\ (stat.) \pm x.xx\ (syst.)$$

$$C_{meas} = x.xx \pm 0.22\ (stat.) \pm x.xx\ (syst.)$$

- "x.xx" will be filled soon

- Previous measurement (5.4 fb^{-1})

$$f_{meas} = 0.85 \pm 0.39\ (stat.) \pm 0.21\ (syst.)$$

$$(1.15 \pm 0.43\ (nuisance))$$

$$\sigma_{ttbar} = 8.31 \pm 0.32\ (stat.) \pm 0.86\ (syst.)$$

$$(8.30 \pm 0.87\ (nuisance))$$

- *Statistically dominated*

Feldman Cousins C.L.

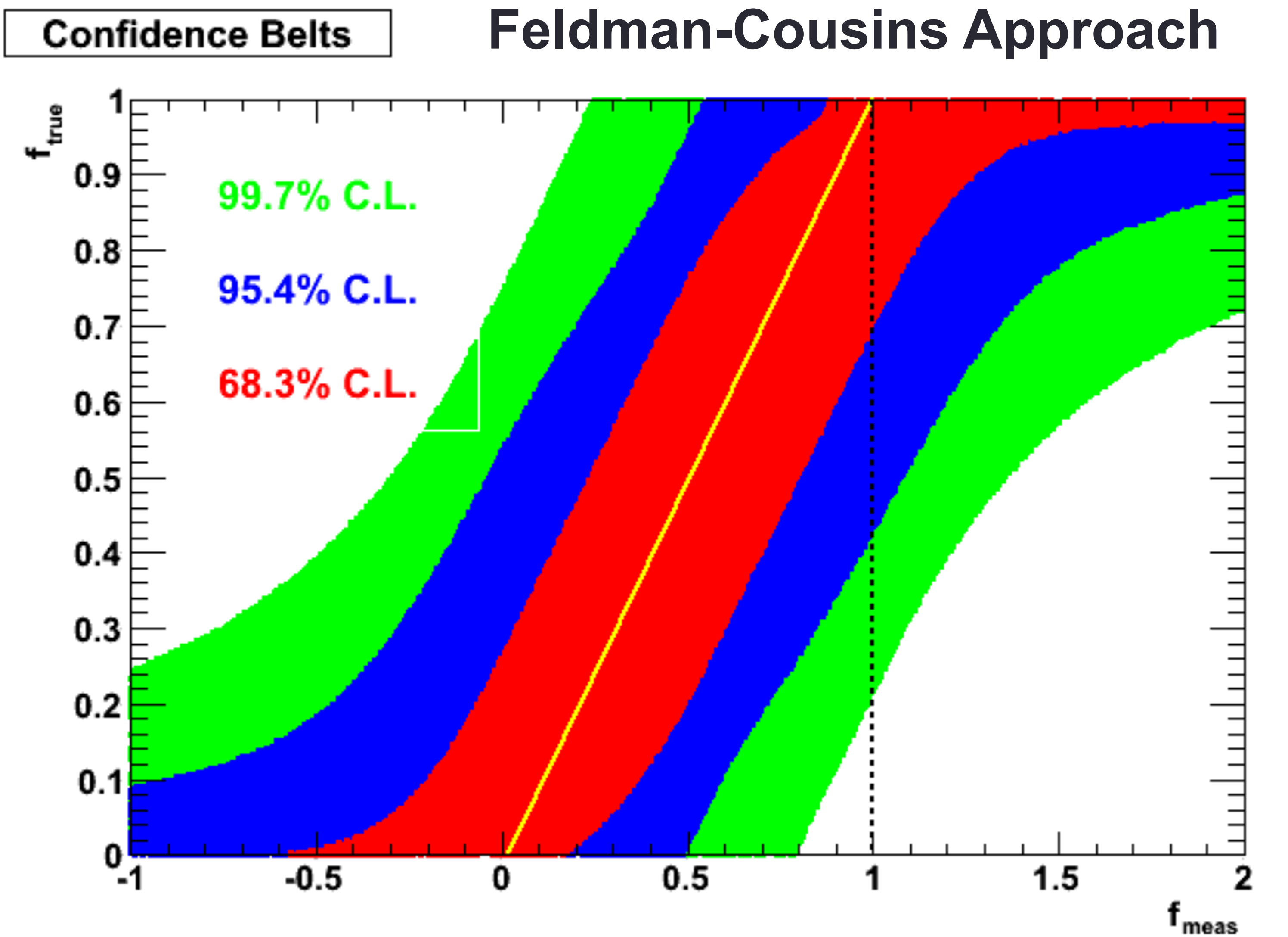
- General approach to (classical) statistical analyses with small signals or physical boundary
  - Construction of confidence belts using frequentist method
  - Restrict measurements into physical region
- Original (Neyman) way has some issues
  - Flip-flopping (interval or limit?) based on data
  - Under(over)coverage => serious flaw (too conservative)
- Ordering principle
  - Ranking strategy based on likelihood ratios

$$R = P(x|\mu) / P(x|\mu_{best})$$

  μ: parameter of interest, x: measured value of μ

  - Natural transition from two-sided intervals to one-sided limits (unified approach)
  - Appropriate coverage

Confidence Limit (Expected)



Exclusion of $f_{true} < 0.21$ for $f_{meas} = 1.0$ @ 3 S.D. (Statistics only)

Summary

- Spin correlation measurement is a legacy at Tevatron and complementary to LHC
- Utilize Full RunII data (9.7 fb^{-1}) to measure the fraction in l+jets final states
- Results (expected & statistics only)

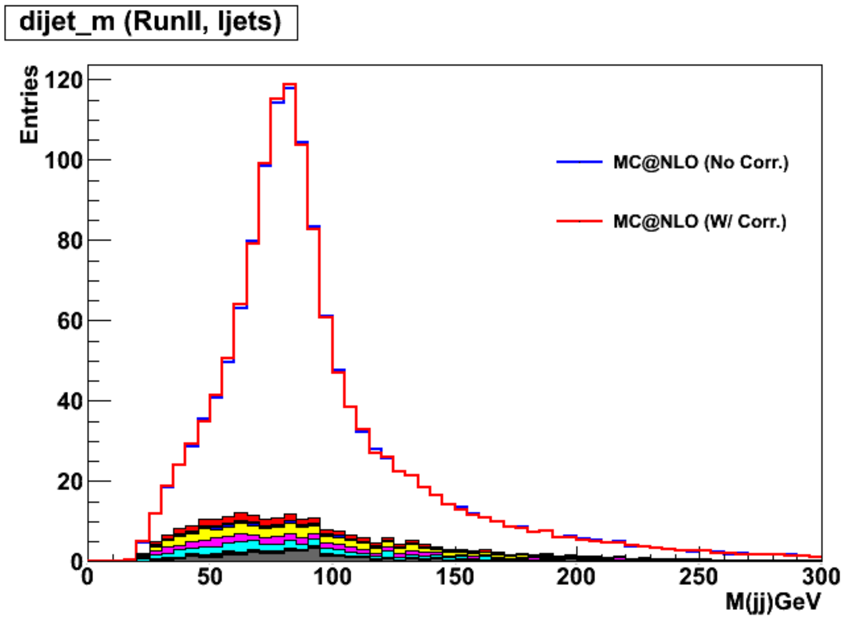
$$f_{meas} = x.xx \pm 0.28\,(stat.) \pm x.xx\,(syst.)$$
$$\sigma_{ttbar} = x.xx \pm 0.26\,(stat.) \pm x.xx\,(syst.)$$
$$C_{meas} = x.xx \pm 0.22\,(stat.) \pm x.xx\,(syst.)$$

  - Exclusion of $f_{H=1} < 0.21$ @ 3 SD
  - Statistically dominated
- Prospects
  - Expect 3~4 SD with single channel
  - Combination with dilepton channel expects ~5 SD

Back-Up

Sample Splitting (l+jets)

- Capability of full reconstruction with minimal assumption
  - Invariance mass of two non-tagged jets should be close to W mass
- Two subsamples
  - |M(jj)| < Δm and |M(jj)| > Δm
- Scanning over Δm for minimum sensitivity (combined) from ensemble tests
  - Δm = 25 GeV
- Improves sensitivity

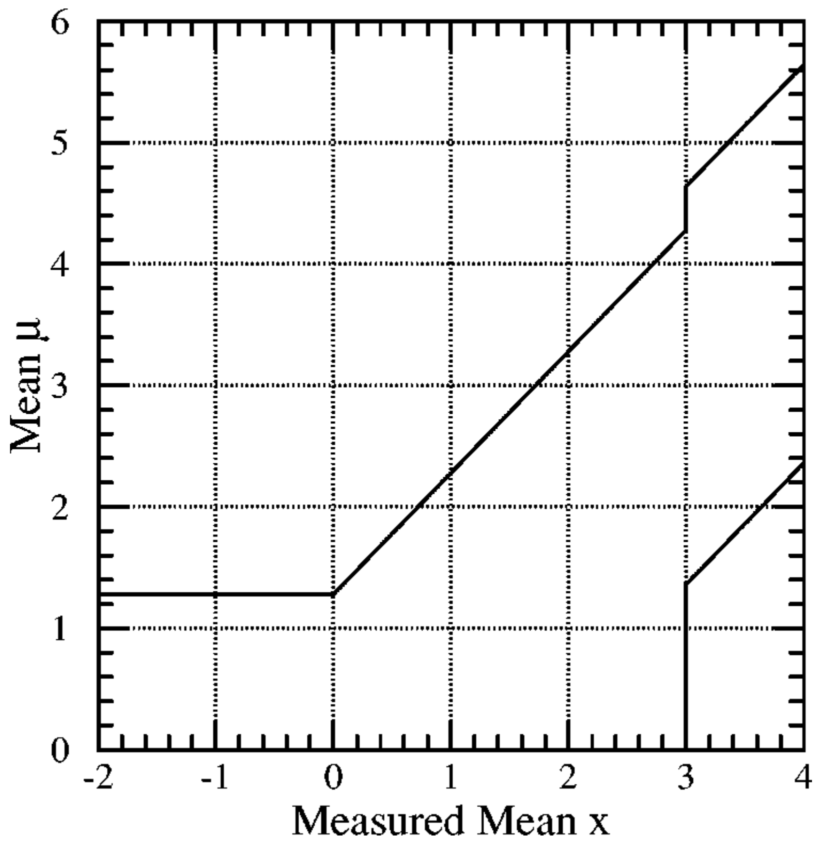


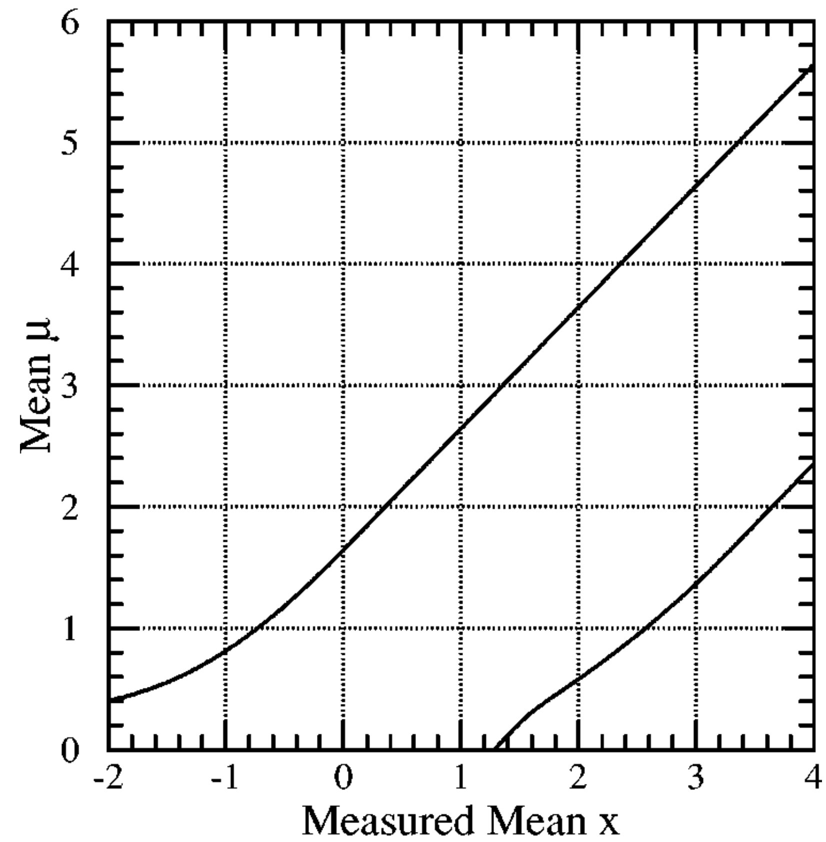
Separation Power

$$S.P. = \frac{\left|\mu_{H=1} - \mu_{H=0}\right|}{\sqrt{\sigma_{H=1}^2 + \sigma_{H=0}^2}}$$

	e+jets				μ+jets			
jets	=4		>4		=4		>4	
$\lvert m_{jj}-80.4\rvert$	<25	>25	<25	>25	<25	>25	<25	>25
Signal only	0.074	0.033	0.042	0.023	0.081	0.032	0.071	0.029
Signal+Bkg	0.065	0.025	0.039	0.021	0.072	0.023	0.066	0.025

Neyman vs. F-C





P(x|μ) = Gaus(μ,1)

PRD 57, 3873

$$P(x \in [x_1, x_2] \mid \mu) = 0.9$$

Ensemble Distributions