ATLAS sensitivity to W polarization and top spin correlation in $t\bar{t}$ events

TEV4LHC Workshop, CERN, April 28-30, 2005

F. Hubaut, E. Monnier, P. Pralavorio

CPPM/IN2P3 – Université de la Méditerranée
Marseille, FRANCE
hubaut@in2p3.fr

1. **Introduction, Motivations**
2. **W polarization and sensitivity to tWb anomalous couplings**
3. **Spin correlation**
4. **Conclusions and perspectives**

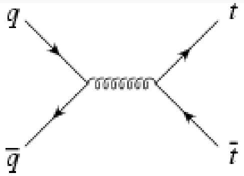
Top production and decay

Strong Interaction → $t\bar{t}$

LHC

σ ~850 pb

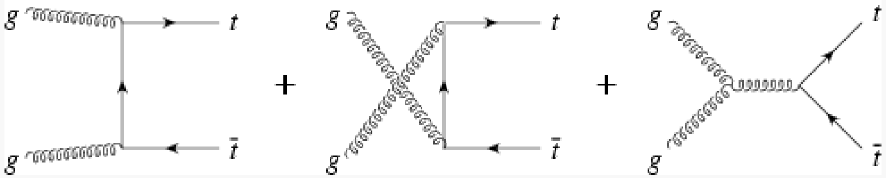
10% $q\bar{q}$, 90% gg



Tevatron

σ ~7 pb

85% $q\bar{q}$, 15% gg



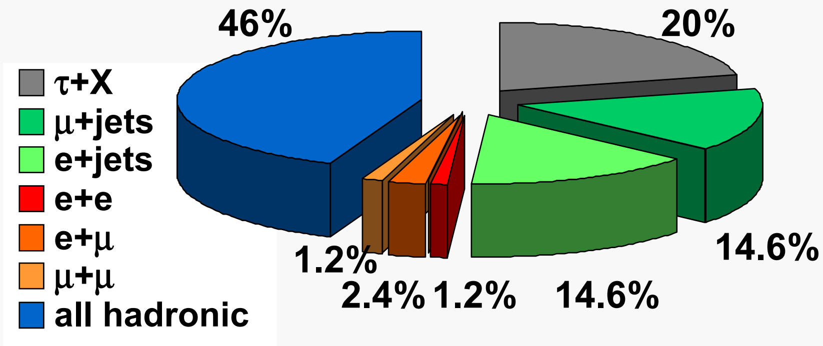
Weak Interaction → single top

LHC

σ ~300 pb

Tevatron

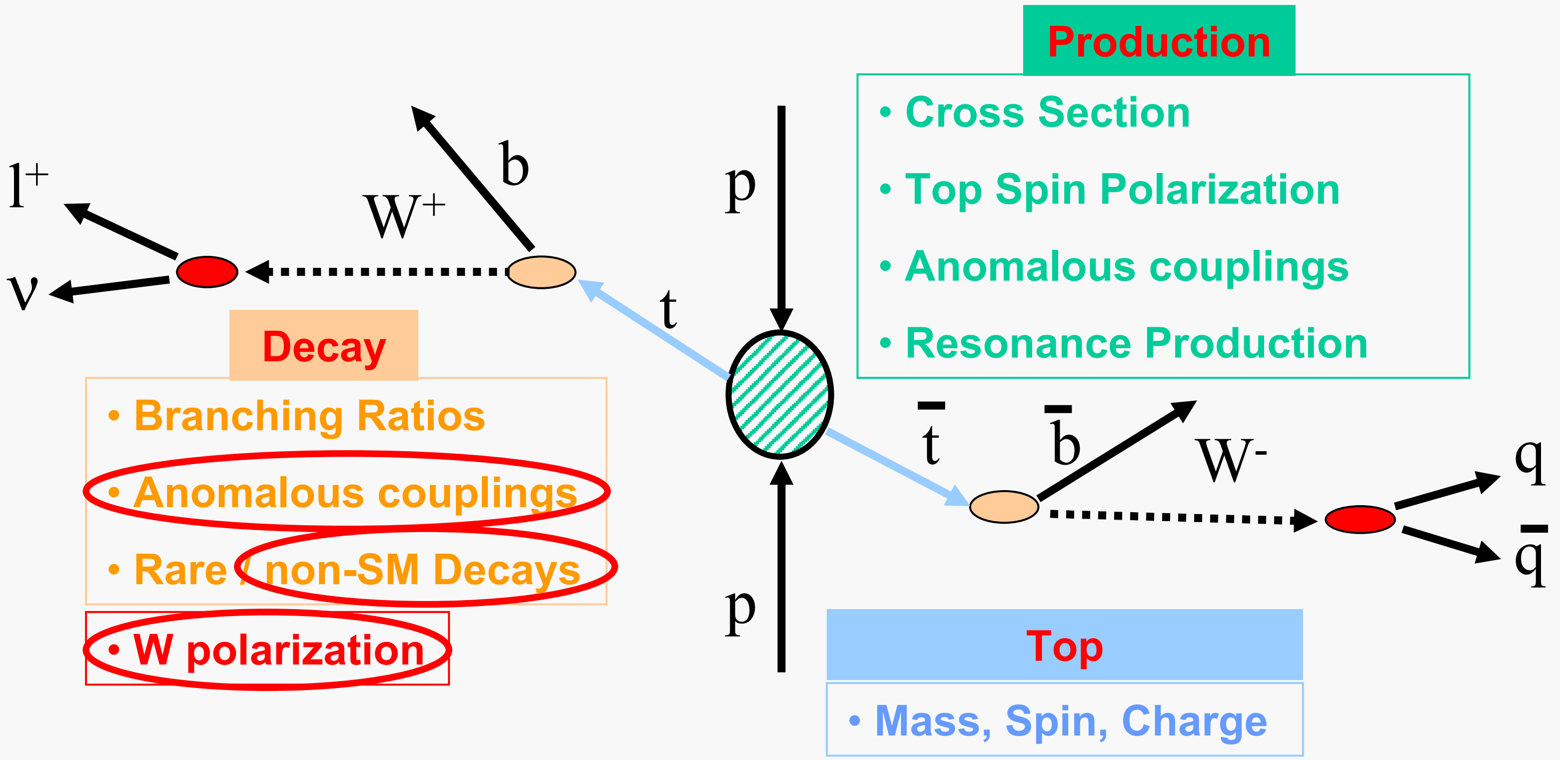
σ ~3 pb



- BR (t→Wb) ~ 100 % in SM
- $t\bar{t}$ final states (LHC, 1 year initial lumi.)
  - Full hadronic (3.7M): jets
  - Dileptonic (0.4M): ee, eμ, μμ
  - Semileptonic (2.5M): e+jets, μ +jets →

- *~ easy reconstruction*
- *High statistics*
- *High S/B*

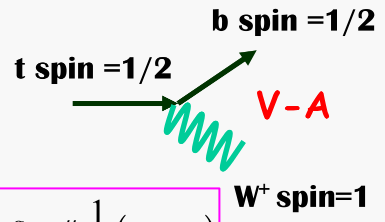
W polarization in top decay



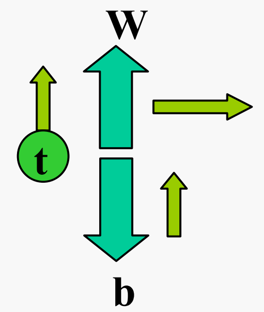
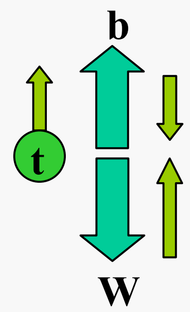
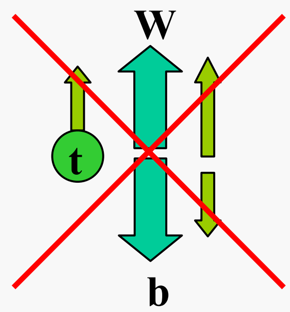
- Direct test of the V-A structure of the Wtb decay vertex
- Search for anomalous couplings and new physics (e.g. V+A component)
- Top decay: only significant source of longitudinal W bosons ➔ EWSB

SM expectations and actual meas./limits

Top Standard Model weak decay ➔ V-A coupling as for all fermions



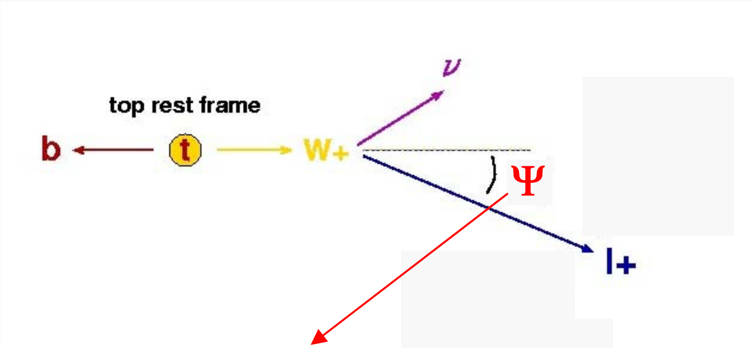
$$-i\frac{g}{\sqrt{2}}\gamma^{\mu}\frac{1}{2}(1-\gamma_5)$$

			
	Longitudinal W^+ Fraction F_0	Left-handed W^+ Fraction F_L	Right-handed W^+ Fraction F_R
Standard Model (M_{top}=175 GeV) NLO	0.703 $\left(=\frac{M_t^2}{M_t^2+2M_W^2}\right)$ 0.695	0.297 $\left(=\frac{2M_W^2}{M_t^2+2M_W^2}\right)$ 0.304	0.000 0.001
Measurement or actual limit	F_0=0.89 ± 0.30 ± 0.17 (stat) (syst) (Tev. run II, 162 pb^{-1})	F_R < 0.18 @ 95% CL (Tev. run I , 109 pb^{-1}) F_R < ~ 0.01 from b→s γ (CLEO, BELLE, BABAR) ➔ indirect limit, SM dependent	

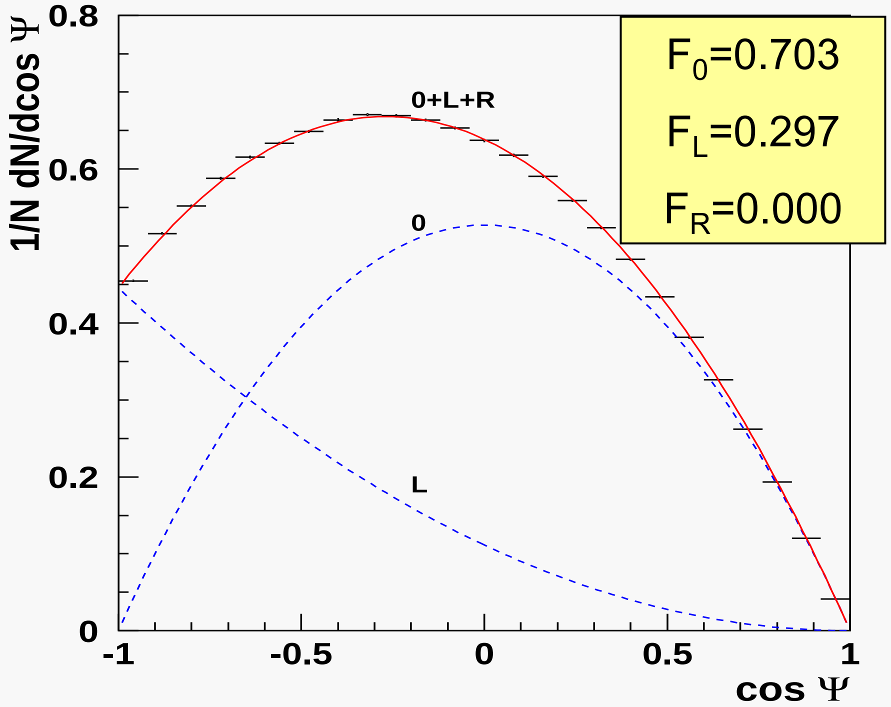
W helicity Observable

W polarization is measured through angular distribution of charged lepton:

$$\frac{1}{N}\frac{dN}{d\cos\Psi} = \frac{3}{2}\left[F_0 \cdot \left(\frac{\sin\Psi}{\sqrt{2}}\right)^2 + F_L \cdot \left(\frac{1-\cos\Psi}{2}\right)^2 + F_R \cdot \left(\frac{1+\cos\Psi}{2}\right)^2\right]$$



angle between lepton in W rest frame and W direction in top rest frame



Semileptonic $t\bar{t}$ event simulation

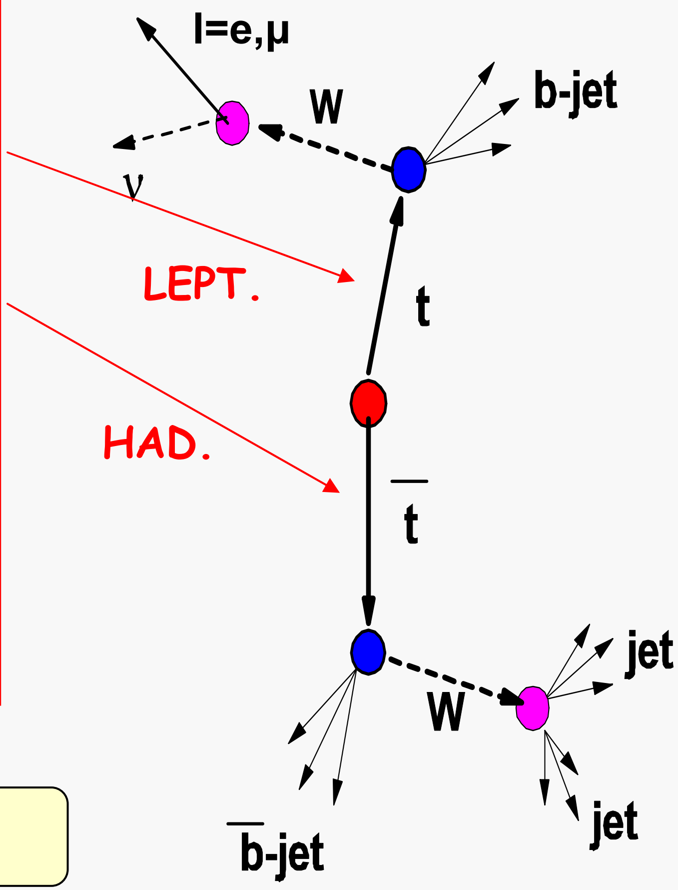
Event simulation is performed using:

- TopReX 4.05 or AcerMC 2.2 or AlpGen 1.33 : LO density matrix for production and decay of $t\bar{t}$ pairs including spin effects
- Pythia 6.2 or Herwig 6.5 : hadronisation, fragmentation and decay
- Tauola + Photos : τ lepton decay and radiative corrections
- ATLAS fast simulation + reconstruction
  - b-tagging parametrization (p_T,η): ε_b=60%, R_{uds}=100, R_c=10
  - Jet cone algorithm: size ΔR=0.4
- Default: M_{top}=175 GeV, CTEQ5L structure function, ISR-FSR

→ 1 year of statistics (10 fb^{-1}, 3.8 Mevents) simulated for each generator and each hadronization scheme

Event selection and reconstruction

- p_T and η cuts
  - 1 lepton $p_T > 20GeV$ ($|\eta|<2.5$) + $P_T^{miss} > 20GeV$ + 1 b-jet $p_T > 30GeV$ ($|\eta|<2.5$)
  - 2 non b-jets $p_T > 30GeV$ ($|\eta|<2.5$) + + 1 b-jet $p_T > 30GeV$ ($|\eta|<2.5$)
  - ➔ double b-tag
- Event topology reconstruction
- Quality cuts
  - $|M_w^{REC} - M_w| < 20GeV$ and $|M_t^{REC} - M_t| < 35$ GeV



ε(sig)=4.5%, 115 000 events per 10 fb^{-1}

~ easy event reconstruction, high statistics

Background

1 LHC year of statistics (10 fb^{-1}) simulated for each background, except

Signal and background for 1 LHC year (10 fb^{-1})		
	Expected events ($x10^6$)	Events after selection + recons.
W($\to l\nu$) **+4jets** (AlpGen)	**~20** (p_T^{jets}>10 GeV)	**[500,1400]***
$b\bar{b}$ (Pythia)	6000 ($\sqrt{\hat{s}}$>120 GeV)	250*
Z($\to l^+l^-$) +jets (Pythia)	50	17
ZZ+ZW+WW (Pythia)	1	6
W($\to l\nu$) $b\bar{b}$ (AcerMC)	0.7	4
Single top (TopReX)	0.7	300
$t\bar{t} \to \tau$+X (TopReX)	**1.3**	**8500**
$t\bar{t} \to$ all had (TopReX)	3.7	90
SIGNAL (TopReX)	**2.5**	**115000**

S/B~12; main background $t\bar{t} \to \tau$ + X

* Poisson stat. rescaled by 63

* Stat. rescaled by 8

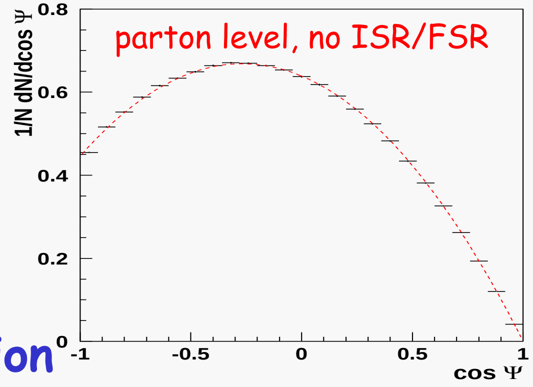
Non $t\bar{t}$: 60 < S/B < 100

$t\bar{t} \to \tau$+X: S/B=13

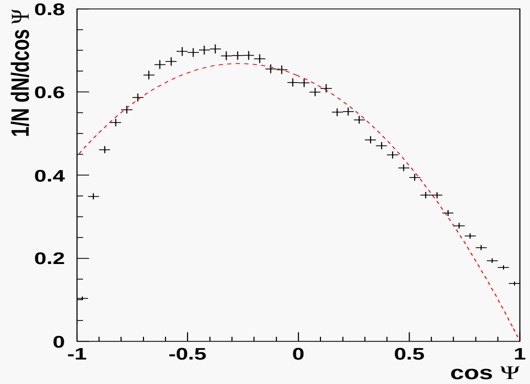
Normalization and shape under control

Measurement method (1)

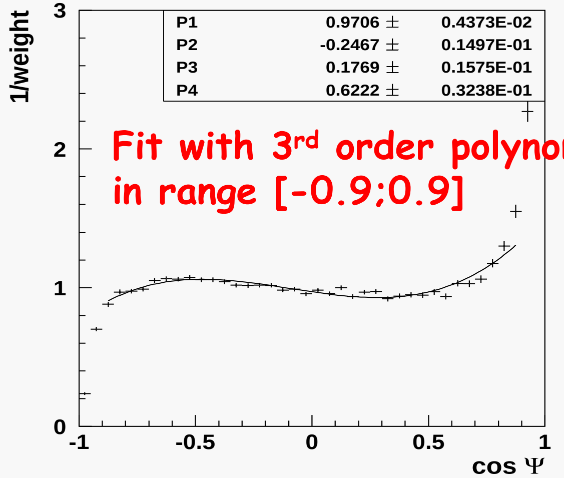
- Selection cuts and reconstruction distord the parton level distribution
- use MC generator on an independent sample to parametrize these effects



Reconstruction and cuts



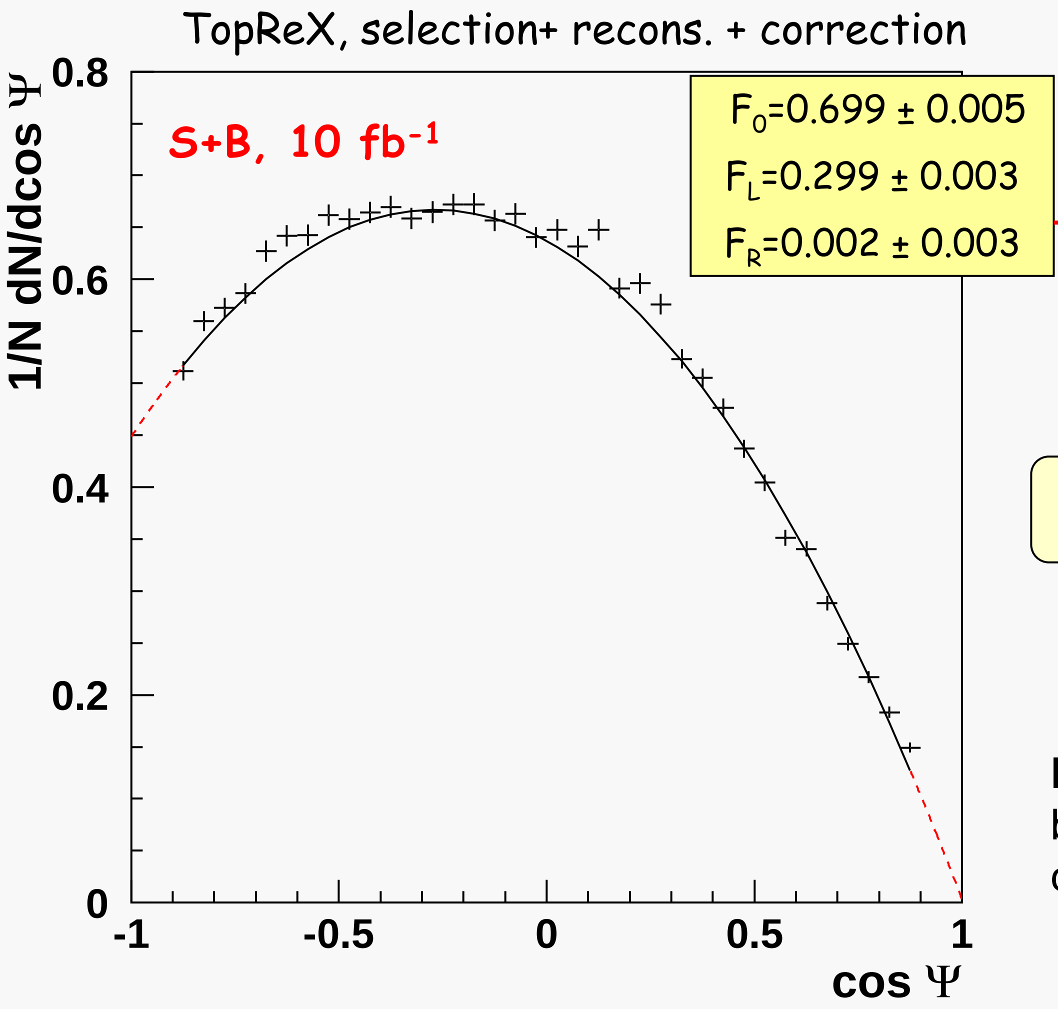
Correction function :



apply weights event by event

→ Use this unique weight parametrization everywhere in the following

Measurement method (2)



Fit results with 2 parameters (constraint $F_0+F_L+F_R=1$)

Compatible with parton level

Robustness of the method assessed by varying number of bins, fit limits, correction polynom order, …

Systematic uncertainties

MC level

1. Parton generation
2. Hadronization scheme
3. Structure function
4. ISR, FSR
5. b-fragmentation

Reconstruction level

1. Input top mass
2. b-jet mis-calibration
3. Light jet mis-calibration
4. b-tagging efficiency (p_T,η)

Tevatron data can help to decrease these uncertainties

Others

1. Pile-up
2. Background normalization

Systematics: Monte Carlo Generators

Generate 3 LHC year statistics in semileptonic channel with :

- different Monte-Carlo generators
- Pythia for hadronisation, fragmentation and decays (+Tauola, Photos)

Generator	F_0 (±0.003)	F_L (±0.002)	F_R (±0.002)
TopReX 4.05	0.699	0.299	0.002
AlpGen 1.33	0.698	0.299	0.003
AcerMC 2.2	0.705	0.287	0.008

after selection
+ reconstruction
+ correction

- Very good agreement TopRex-AlpGen
- AcerMC harder p_T spectrum induces a significant (5 σ_{stat}) variation

Systematics: Hadronization scheme

Generate 3 LHC year statistics in semileptonic channel with :

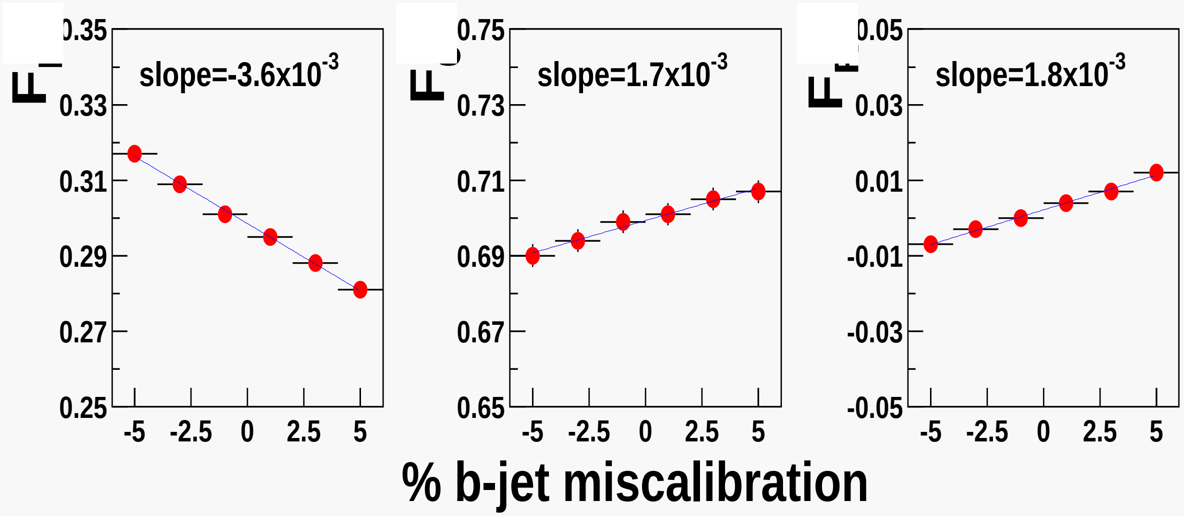
- ACERMC 2.2 to generate partons
- Pythia or Herwig for hadronization

Hadronization scheme	F_0 (±0.003)	F_L (±0.002)	F_R (±0.002)
Pythia 6.2	0.705	0.287	0.008
Herwig 6.5	0.689	0.297	0.014

after selection
+ reconstruction
+ correction

➢ Significant (5 σ_{stat}) impact of hadronization scheme

Systematics: b-jet calib. and top mass



b-jet miscalibration

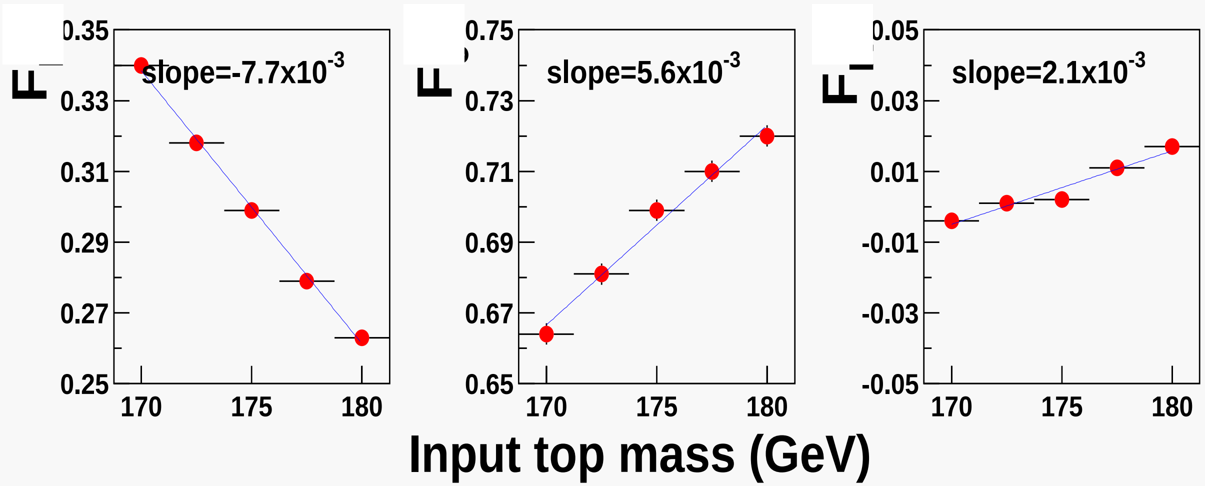
expected behaviour :

$$\cos\Psi = \frac{2M_{lb}^{2}}{M_t^{2} - M_W^{2}} - 1$$

positive miscalibration

➔ M_{lb} ↗ ➔ cos Ψ ↗ ➔ F_R ↗

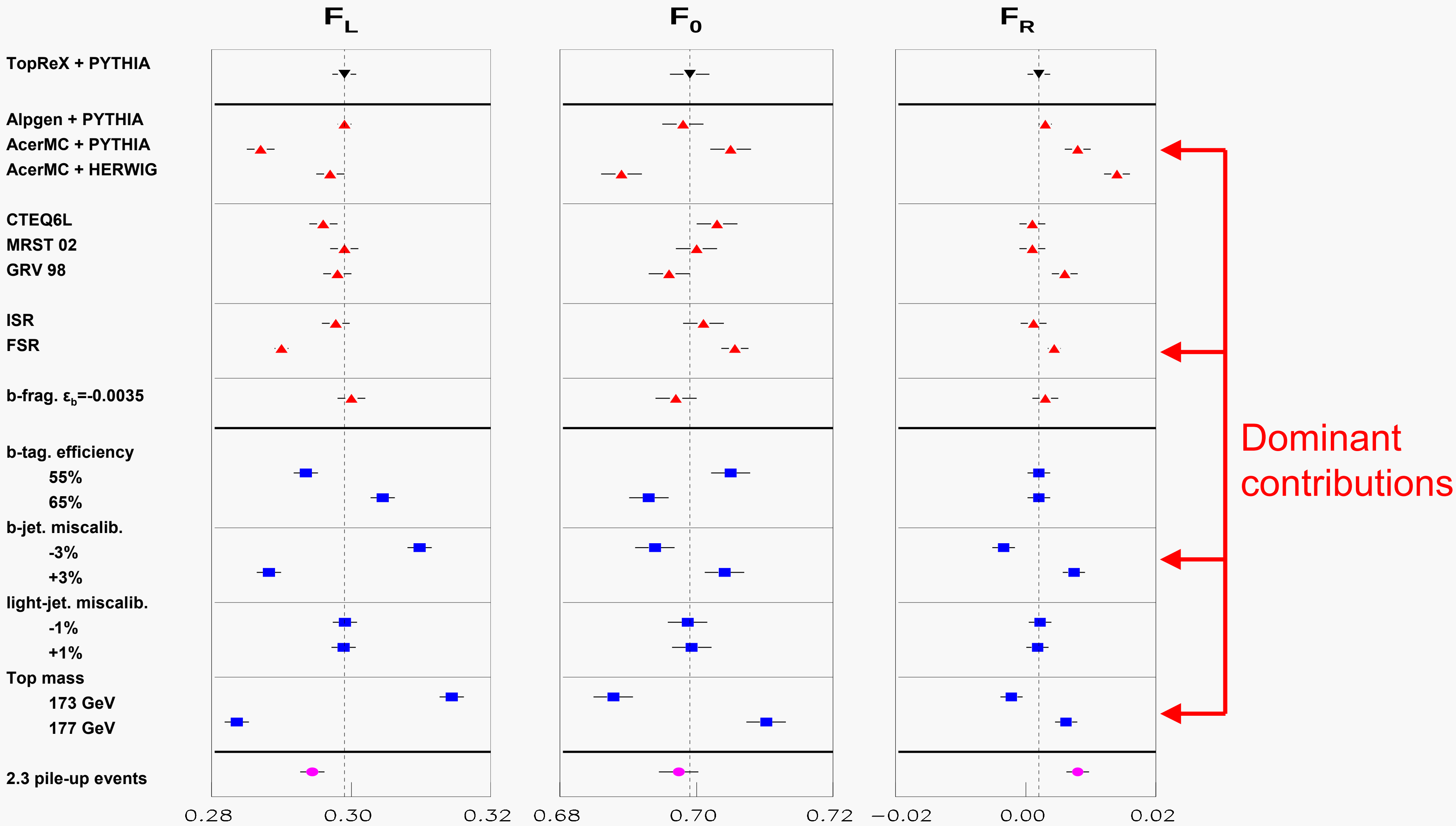
F_L ↘



Top mass uncertainty

expected behaviour

Systematics: summary



Results

W polarization with semileptonic $t\bar{t}$ events for S+B at 10 fb^{-1} (±stat ±syst)

	Results (±stat ±syst)	Standard Model
F_0	0.699 ± 0.005 ± 0.023	0.703 + 0.002 (M_{top}-175)
F_L	0.299 ± 0.003 ± 0.028	0.297 - 0.002 (M_{top}-175)
F_R	0.002 ± 0.003 ± 0.013	0.000

- In 1 LHC year (10 fb^{-1}), ATLAS can measure F_0 with an accuracy ~3% and F_R with a precision ~1.3%
- Measurements largely dominated by systematic uncertainties
- Tevatron expectations with 2 fb^{-1}: δF_0^{stat}~0.09 and δF_R^{stat}~0.03

Sensitivity to tWb anomalous couplings (1)

One of the main motivation for top physics: search for anomalous interactions

- BR (t→Wb) ~ 100 % in SM
- Many models beyond SM ➔ study the tWb vertex in a model independent approach, i.e. effective Lagrangian

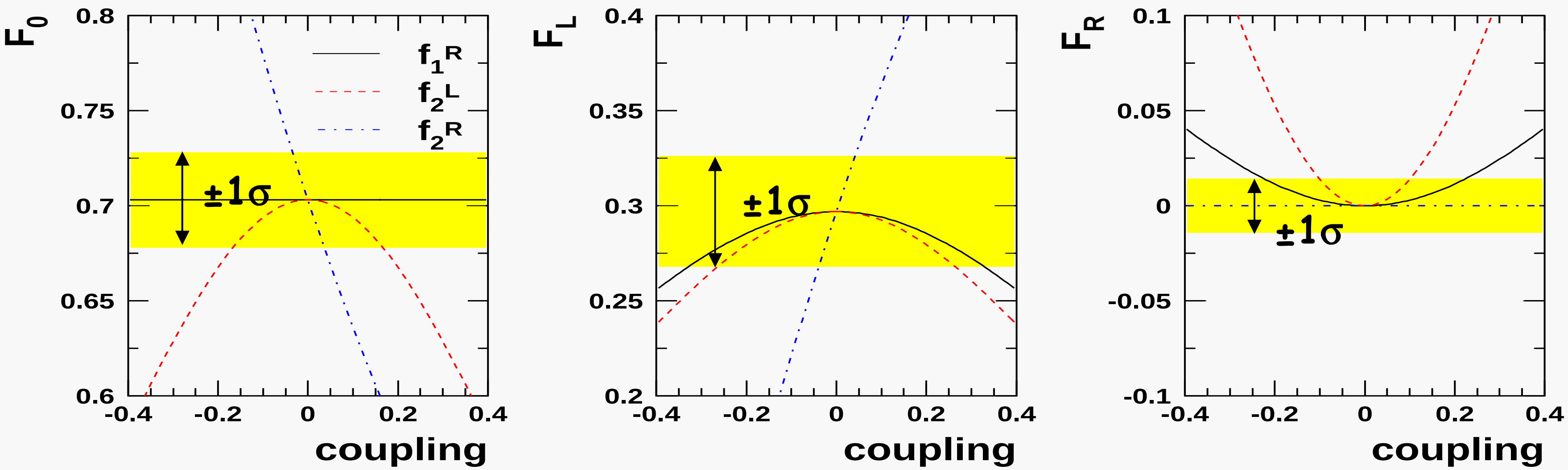
$$L = \frac{g}{\sqrt{2}} W_\mu b \gamma^\mu (f_1^L P_L + f_1^R P_R) t - \frac{g}{\sqrt{2}\Lambda} \partial_\nu W_\mu b \sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) t + h.c.$$

$P_{R/L} = \frac{1}{2}(1 \pm \gamma_5)$ and 4 couplings (in SM LO $f_1^L = V_{tb} \approx 1, f_1^R = f_2^L = f_2^R = 0$)

→ Determine sensitivity to f_1^R, f_2^L and f_2^R using W polarization measurement (insensitive to f_1^L)

Sensitivity to tWb anomalous couplings (2)

Assume a variation of each coupling f_1^R, f_2^L and f_2^R independently:

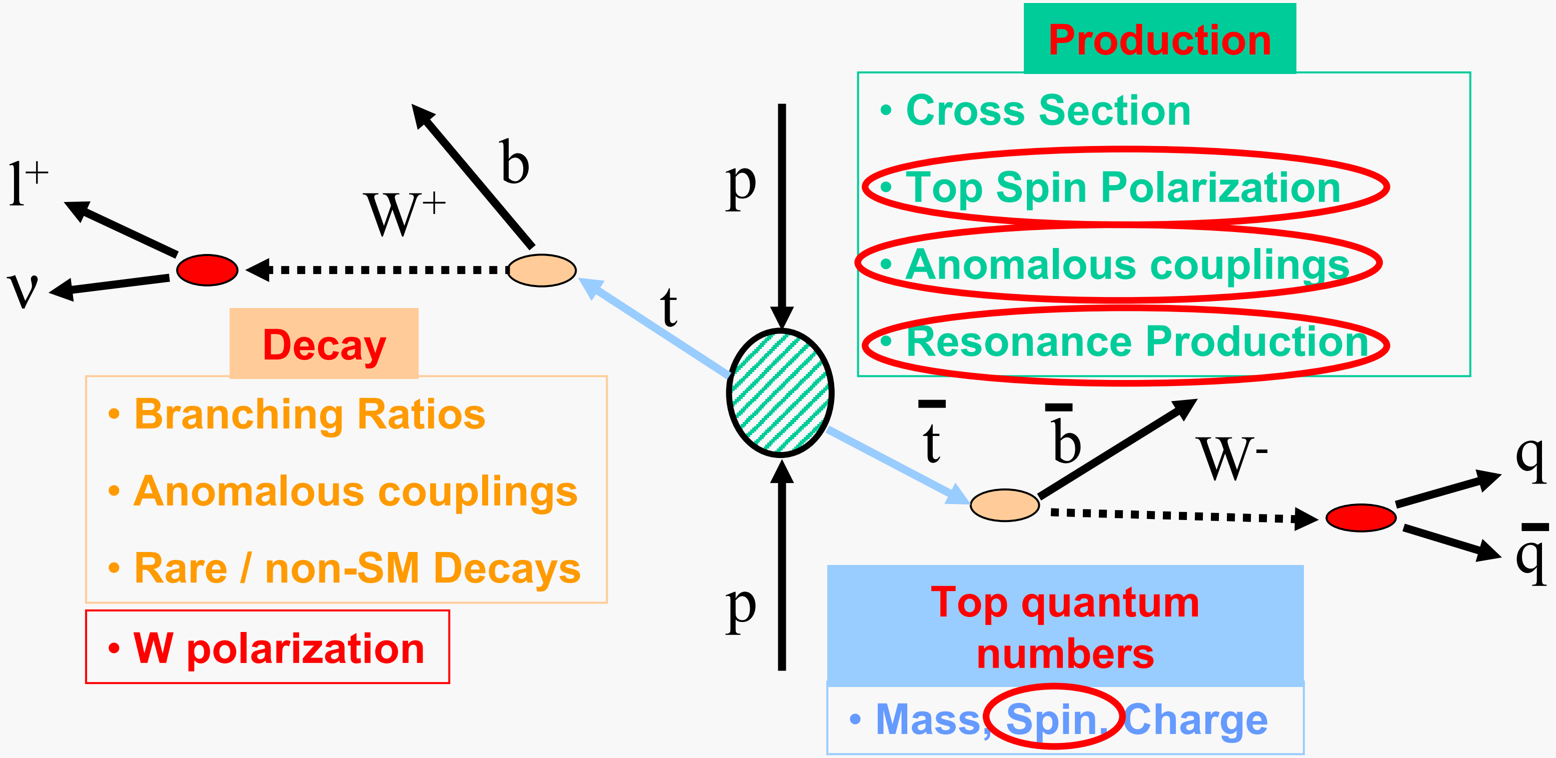


Uncertainties on F_R and F_0 with 10 fb^{-1} ➔

Coupling	f_1^R	f_2^L	f_2^R
2σ limit (stat⊕syst)	0.31	0.14	0.07

Best sensitivity to f_2^R (linear behavior)

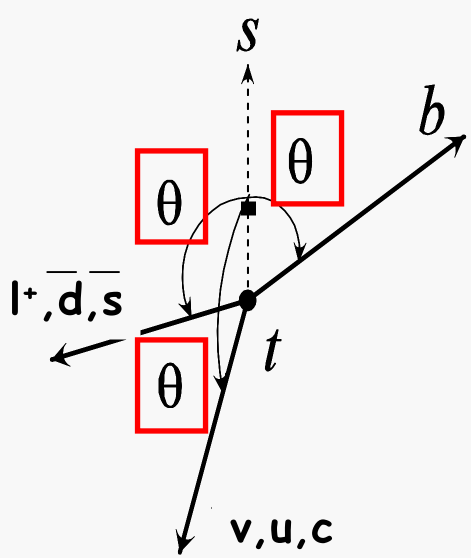
$t\bar{t}$ spin correlation



➢ Sensitivity to new physics : anomalous $gt\bar{t}$ interaction (chromomagnetic or/and chromoelectric dipole moment), new production mechanisms, discrete symmetry tests (CP), ...

Top spin

- Top decays before hadronisation ($t \sim 3 \times 10^{-25}$ s) due to high mass: «bare» quark
  - Top production and decay : perturbative QCD and NLO computation
  - No spin flip between production and decay …
  - … direct transmition to decay products
- In top rest frame, polarisation effects (S) observed by measuring angular distributions of daughter particles:



$$\frac{1}{N}\frac{dN}{d\cos\theta_i} = \frac{1}{2}(1 + S\alpha_i \cos\theta_i)$$

- θ_i angle between decay particle of the top and top spin quantization axis **s**
- α_i degree to which its direction is correlated with the top spin (**spin analyzing power**)

	W	b	l^+,d,s	ν,u,c	lej*
α (NLO)	0.40	-0.40	1.	-0.31	0.47

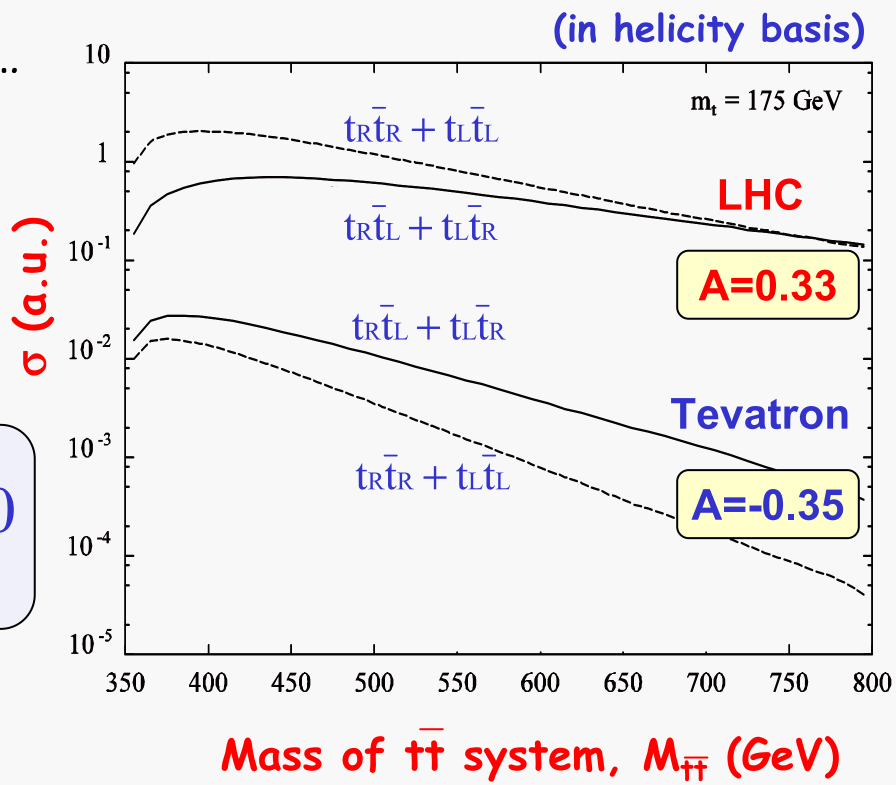
* lej = least energetic jet in top rest frame

$t\bar{t}$ spin correlation

$t\bar{t}$ pairs not polarised (< 1% at NLO) but …

Correlations between spins of t and $\bar{t}$

$$A = \frac{\sigma(t_L\bar{t}_L) + \sigma(t_R\bar{t}_R) - \sigma(t_L\bar{t}_R) - \sigma(t_R\bar{t}_L)}{\sigma(t_L\bar{t}_L) + \sigma(t_R\bar{t}_R) + \sigma(t_L\bar{t}_R) + (t_R\bar{t}_L)} \neq 0$$



Applying a cut on $M_{t\bar{t}}$ (e.g. **<** 550 GeV) increases the asymmetry at LHC and reduces systematics coming from high p_T tails

$t\bar{t}$ spin correlation observables

Tevatron

- An optimal basis (i.e. A(qq)=1 at LO) exists = « off-diagonal » basis: A~0.8 NLO
- First measurement by D0 (run I, 125 pb^{-1}) : A>-0.25 at 68% C.L.

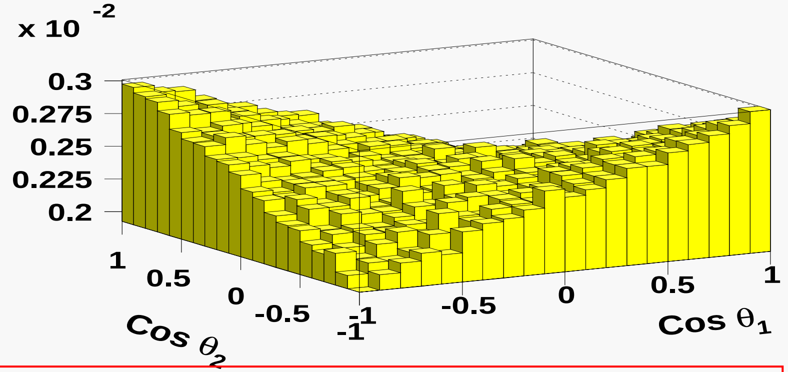
LHC

- No optimal basis, asymmetry in helicity basis A=0.33
- Smaller QCD corrections (a few %), theoretical uncertainties under control

Measurement of $t\bar{t}$ spin correlation → Angular distribution of decay particles (i.e. 'spin analyzer') on each side (t, $\bar{t}$)

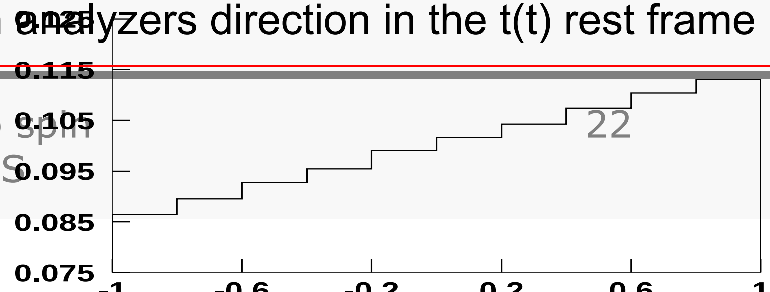
$$\frac{1}{N}\frac{d^2N}{d(\cos\theta_1)\,d(\cos\theta_2)} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$$

$C \rightarrow A\cdot\alpha_1\cdot\alpha_2$



$$\frac{1}{N}\frac{dN}{d\cos\Phi} = \frac{1}{2}(1 - D\cos\Phi)$$

Φ → angle bwn spin analyzers direction in the t($\bar{t}$) rest frame



$t\bar{t}$ spin correlation measurement

✓ Event selection and reconstruction exactly the same as for W polarization

➢ except, add cut on $t\bar{t}$ invariant mass to enhance spin correlation: $M_{tt} < 550$ GeV ($\varepsilon = 75\%$)

✓ Measure C and D with simple unbiased estimators

$C = -9 < \cos\theta_1 \cos\theta_2 >$

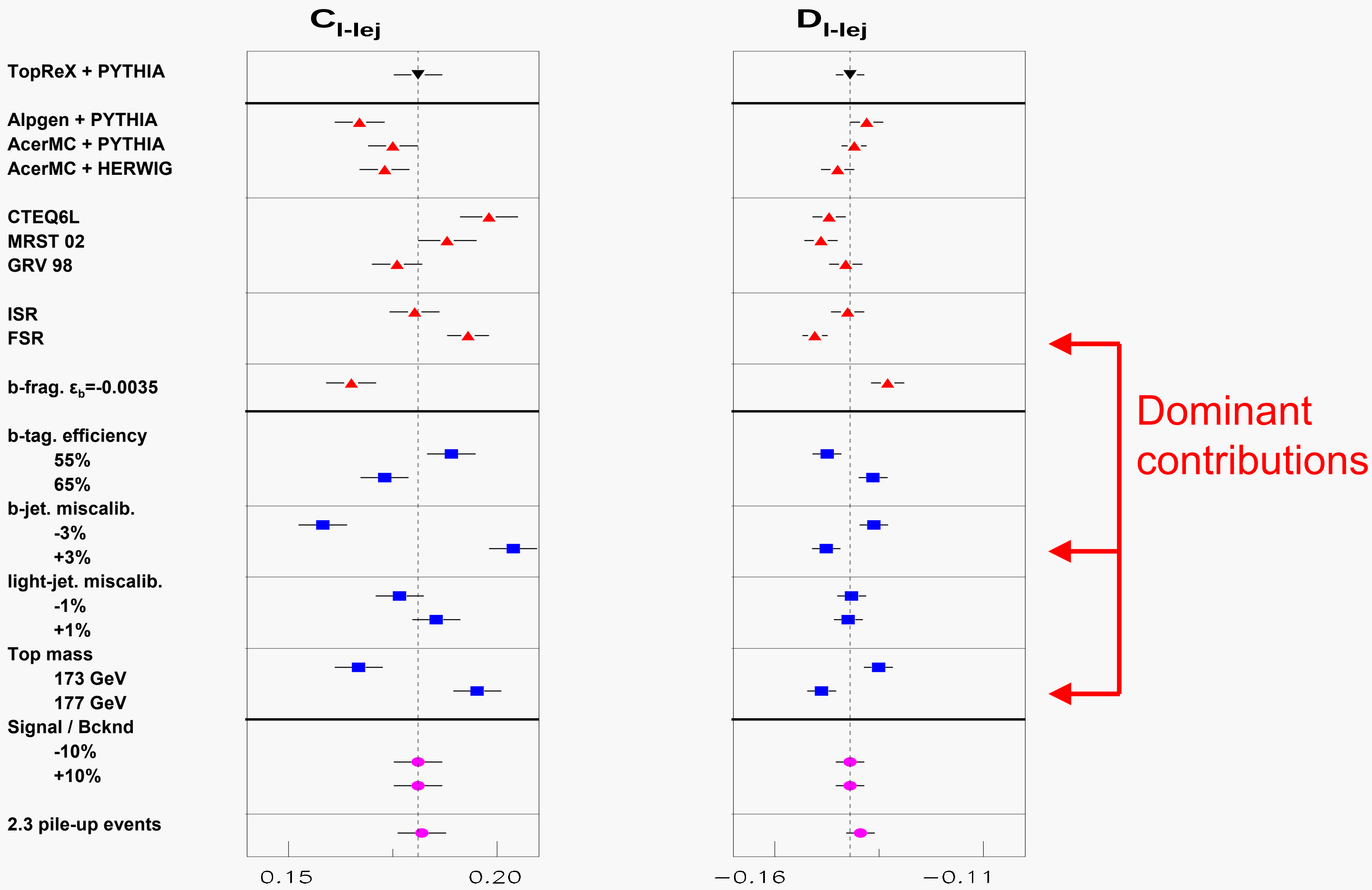
$D = -3 < \cos\Phi >$

✓ Selection cuts distord the parton level distribution

➢ Unique correction function, apply weights event by event

✓ Redo the complete study of systematic uncertainties

Systematics: summary



Results

Spin correlation with semileptonic $t\bar{t}$ events for S+B at 10 fb^{-1} (±stat ±syst)

	Results (±stat ±syst)	Precision	Standard Model (M_{tt} cut included)
C	0.18 ± 0.01 ± 0.04	**23%**	0.22
D	-0.14 ± 0.006 ± 0.02	**13%**	-0.15

- In 1 LHC year (10 fb^{-1}), ATLAS can measure spin correlation ~15%
- D observable can be measured more precisely than C
- Measurements largely dominated by systematic uncertainties
- Tevatron expectations with 2 fb^{-1}: $\delta C^{stat}/C$~40%
- Need input from theoreticians to derive sensitivity to anomalous $gt\bar{t}$ couplings

Conclusions - Perspectives

- LHC will produce a high top statistics during the first year (10 fb^{-1})
  ➔ precise measurements with $t\bar{t}$ semilep. events (clean signature, high stat, high S/B)

- Measurements dominated by systematics, complete study performed

- In 1 LHC year (10 fb^{-1}), ATLAS can measure W polarization in top decay precisely ~1-3% and spin correlation ~15% (> 5σ sensitivity on SM)

- ~2-4 times better than Tevatron statistical expectations with 2 fb^{-1}

➢ Search for anomalous couplings in a model independent approach

➢ 2 ATLAS notes written: ATL-PHYS-PUB-2005-001 and ATL-COM-PHYS-2005-015

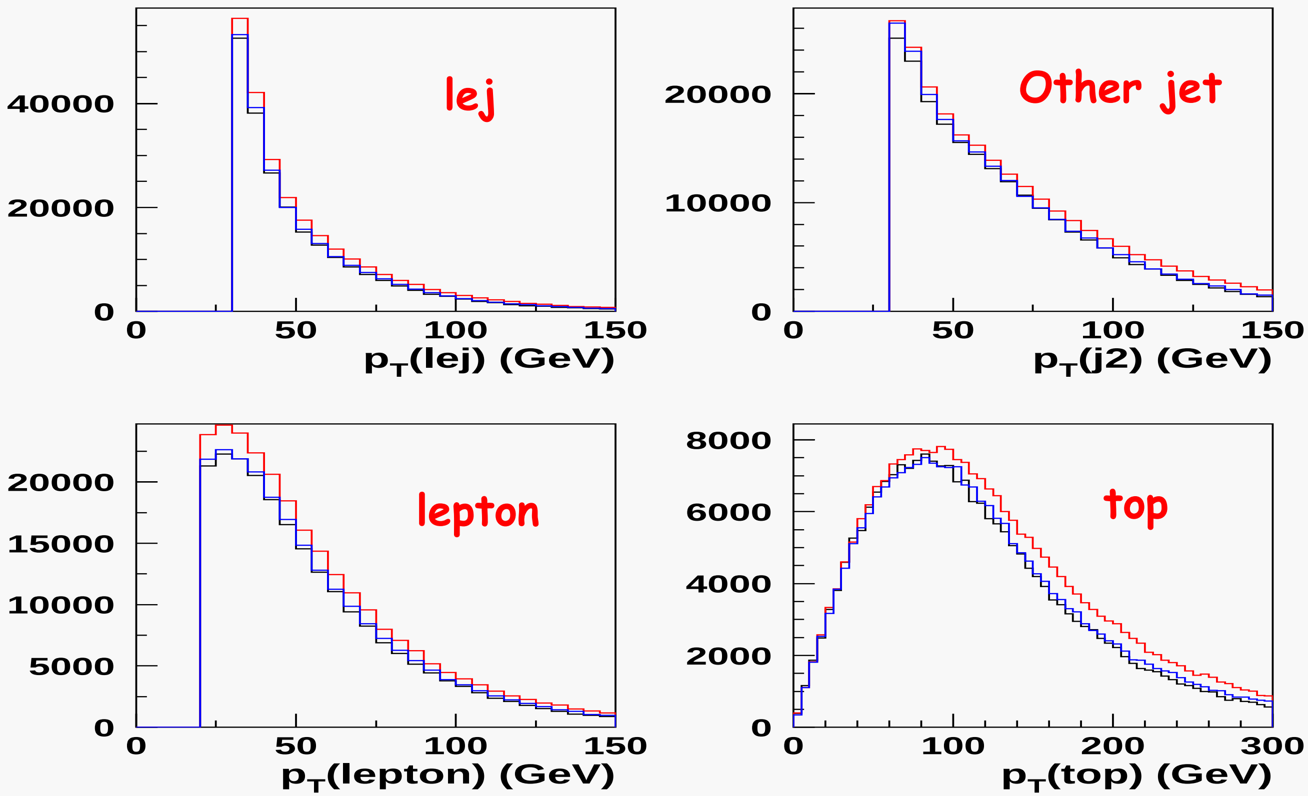
➢ Combine with dileptonic $t\bar{t}$ results (analysis done by Prague) ➔ publication

SPARE SLIDES

Spare: Monte Carlo Generators

Generator	Q^2	σ (pb) $t\bar{t}$ LO	$gg / q\bar{q}$
AcerMC 2.2	$\hat{s}$	380	85/15
AlpGen 1.33	m_t^2	530	86/14
TopReX 4.05	$m_t^2+p_T(t)^2$	370	86/14

Spare : pT comparison between MC



Kinematical cuts (p_T and η cuts) applied

— TopReX

— AcerMC

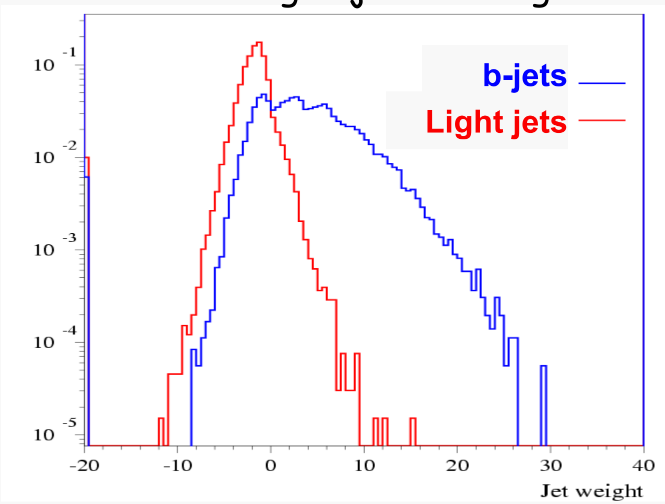
— AlpGen

- TopRex~AlpGen
- AcerMC harder p_T (top) spectrum compared to TopReX, AlpGen

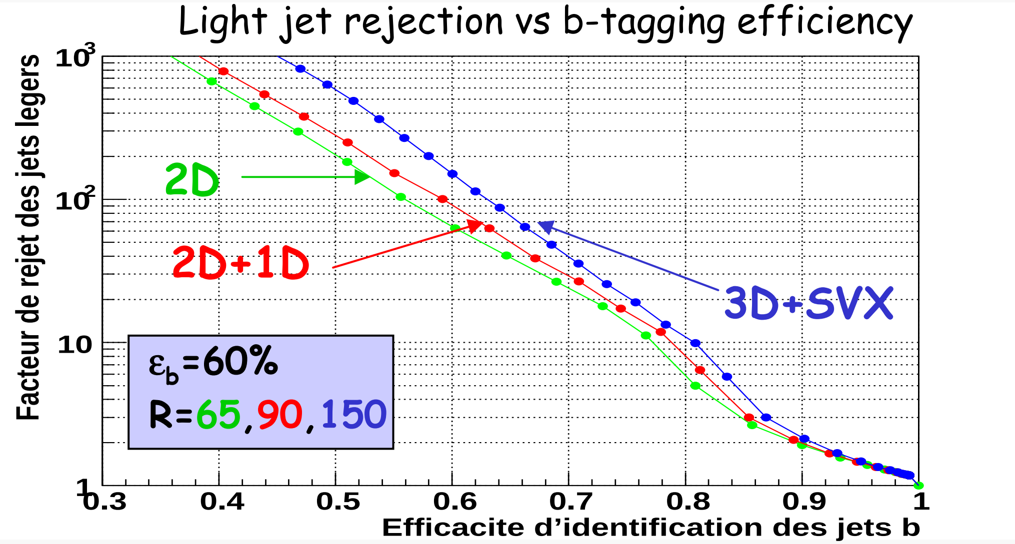
Spare: *b-tagging*

- Complete revisiting of ATLAS potential with latest inner detector designs and refined simulations
- Improvement of algorithms: weight jets by combining signed impact parameter (2D+3D) and secondary vertices reconstruction (mass, number of vertices, …)

b and light jet 2D weight

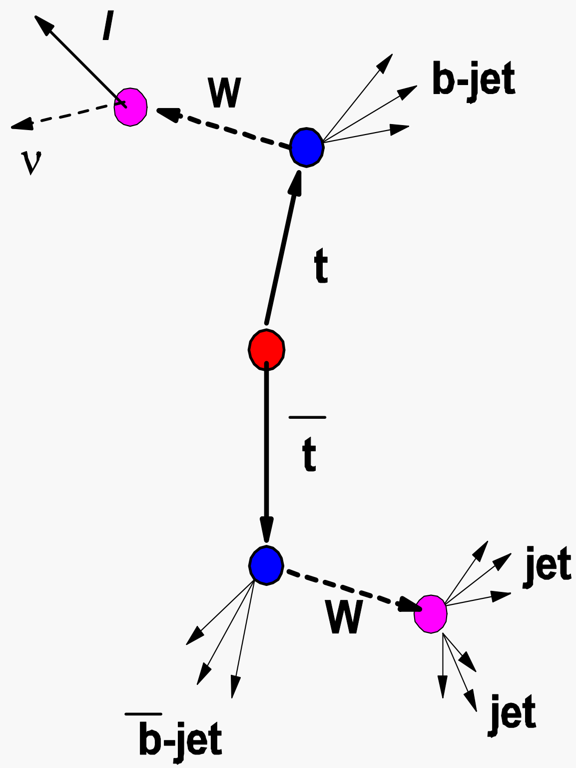


Light jet rejection vs b-tagging efficiency



Spare : Event reconstruction

- Jet calibration, b-tagging
- Select the 2 non-b jets with M_{jj} closest to M_W
- Select the b jet with M_{jjb} closest to M_t
- P_T^{miss} for P_T^ν and P_z^ν by constraining $M_{l\nu}$ to M_w
- Select the b jet closest to the lepton
- Select the ν with $M_{l\nu b}$ closest to M_t

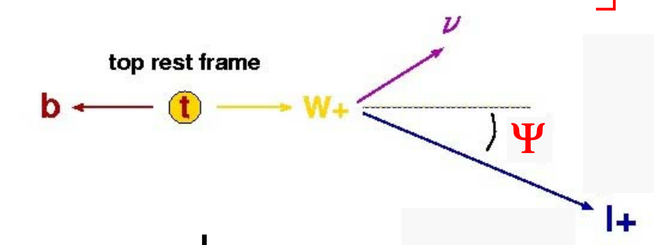


Spare: W helicity Observable

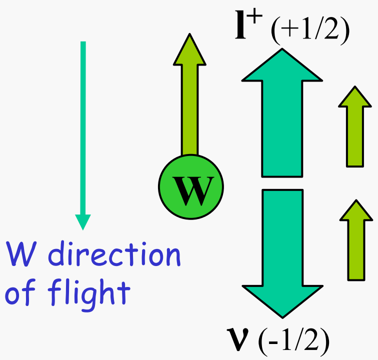
W polarization is measured through angular distribution of charged lepton:

$$\frac{1}{N}\frac{dN}{d\cos\Psi} = \frac{3}{2}\left[F_0 \cdot \left(\frac{\sin\Psi}{\sqrt{2}}\right)^2 + F_L \cdot \left(\frac{1-\cos\Psi}{2}\right)^2 + F_R \cdot \left(\frac{1+\cos\Psi}{2}\right)^2\right]$$

Ψ : angle between lepton in W rest frame and W direction in top rest frame

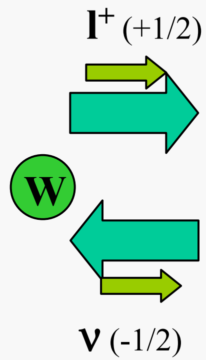


Left-handed W^+



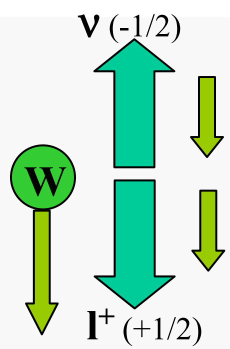
l^+ opposite to W (Ψ ~ π)

Longitudinal W^+



l^+ transverse to W (Ψ ~ π/2)

Right-handed W^+



l^+ same as W (Ψ ~ 0)

Spare: Related observables

- **cos Ψ** → have to reconstruct the whole event topology

In the M_b=0 approx. : $$\cos\Psi = \frac{2M_{lb}^2}{M_t^2 - M_W^2} - 1$$

- **M_{lb}^2** (lepton-b invariant mass): simpler
  - assume M_t=175 GeV in the formula
  - can even look at the lepton P_T

  → + not necessary to reconstruct the whole event topology
  - high systematics due to jet energy scale and top mass

Tevatron studies
LHC dilep. events

→ We tested both observables for **ATLAS semilep. events**

The first one gives a final total systematics ~2 times lower

Spare: Measurement of α_W, A_{FB}

Information which can be derived from the W polarization:

1. Spin analyzing power of the W (α_W) in the polarized top decay

$$\frac{1}{N}\frac{dN}{d\cos\theta_W} = \frac{1}{2}(1+\alpha_W\cos\theta_W)$$ with θ_W angle between W and top spin polarization

$$\alpha_W \equiv F_0 - F_L = 0.400 \pm 0.007\,(stat) \pm 0.050\,(syst)$$ **(12% accuracy)**

2. Forward Backward Assymetry (A_{FB}), related to the angle between the charged lepton and the b-jet in W rest-frame

$$A_{FB} = \frac{3}{4}(F_L - F_R) = 0.223 \pm 0.003\,(stat) \pm 0.019\,(syst)$$ **(9% accuracy)**

Spare: dileptonic results, W polarization

➔ V. Simak and K. Smolek

W polarization with dileptonic $t\bar{t}$ events for S+B at 10 fb^{-1} (±stat ±syst)

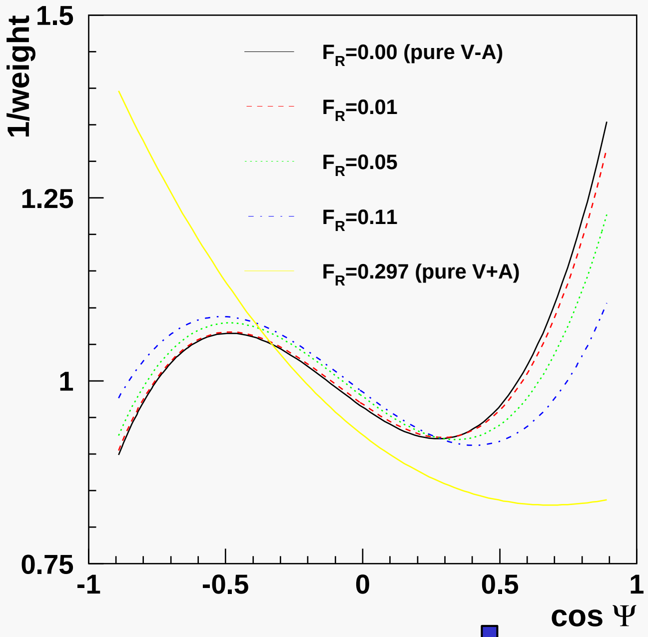
	Results (±stat ±syst)	Standard Model
F_0	0.706 ± 0.010 ± 0.019	0.703 + 0.002 (M_{top}-175)
F_L	0.296 ± 0.007 ± 0.038	0.297 - 0.002 (M_{top}-175)
F_R	-0.002 ± 0.012 ± 0.029	0.000

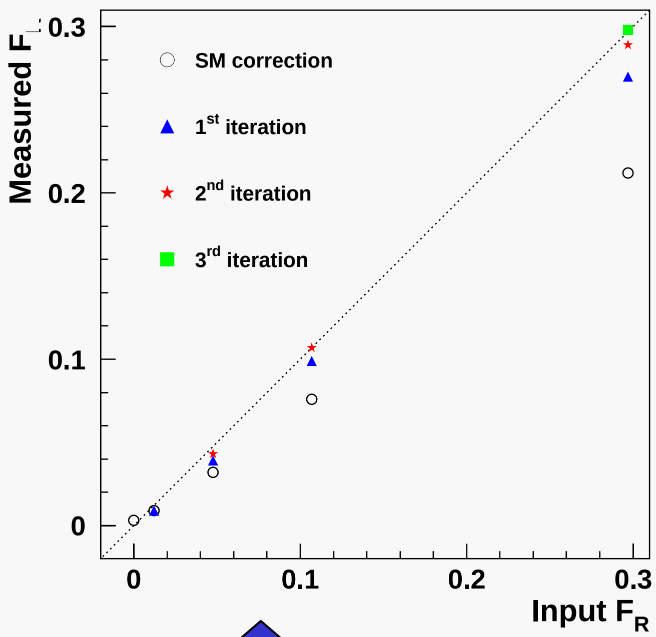
- Same precision as semileptonic channel for F_0
- ~2-3 times worse for F_L and F_R than for semileptonic channel

Spare: Beyond SM - V+A component

The correction used is extracted from a V-A hypothesis (70% F_0 - 30% F_L)

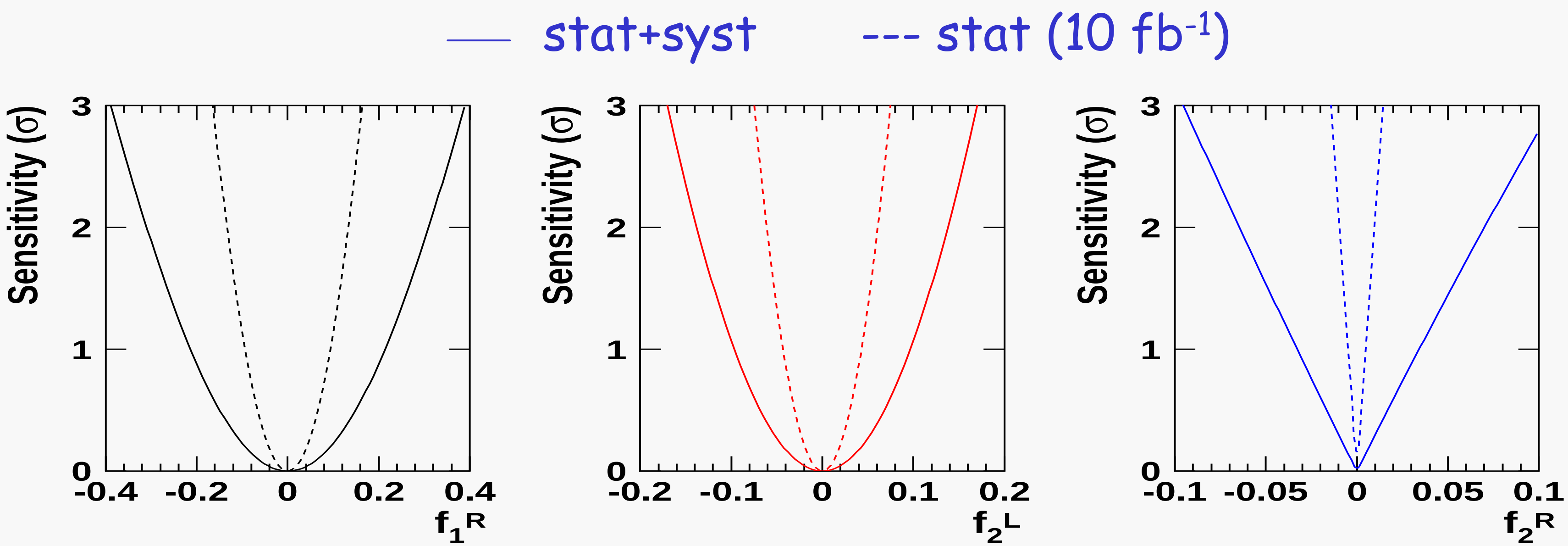
➡ Correction changes in case of V+A component ➔ bias expected





Iterative process

Spare: Sensitivity to tWb anomalous couplings



10 fb^{-1} →

Coupling	f_1^R	f_2^L	f_2^R
2σ limit (stat⊕syst)	0.31	0.14	0.07

→ Best sensitivity to f_2^R (linear behavior)

Spare: Sensitivity to tWb anomalous couplings

Comparison with other expectations (2σ limit):

	f_1^R	f_2^L	f_2^R
Our study (low lumi, $t\bar{t}$)	0.31	0.14	0.07
Tev (Run II, $t\bar{t}$)	0.5	0.3	0.3
Tev (Run II, single top)*1	??	~0.35	~0.25
LHC (High Lumi, single top)*2	??	~0.07	~0.13

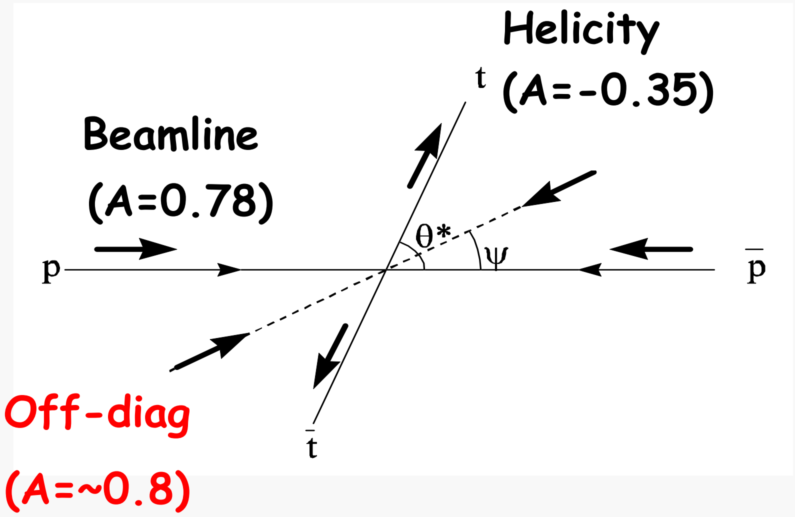
*1: 2 fb^{-1}, assuming a 10% systematic uncertainty
*2: 100 fb^{-1}, assuming a 5% systematic uncertainty

} **Preliminary studies**

→ Sensitivity 2-4 times better than Tev. expectations with 2 fb^{-1} and competitive with single top at LHC (100 fb^{-1}, high luminosity)

Spare: off-diagonal basis

Tevatron: « off-diagonal » = optimal basis (i.e. A(qq)=1 at LO)



$$\tan\psi = \frac{\beta^2 \sin\theta^* \cos\theta^*}{1-\beta^2 \sin^2\theta^*}$$

- β top velocity
- θ^* top scattering angle wrt $p\bar{p}$ ZMF

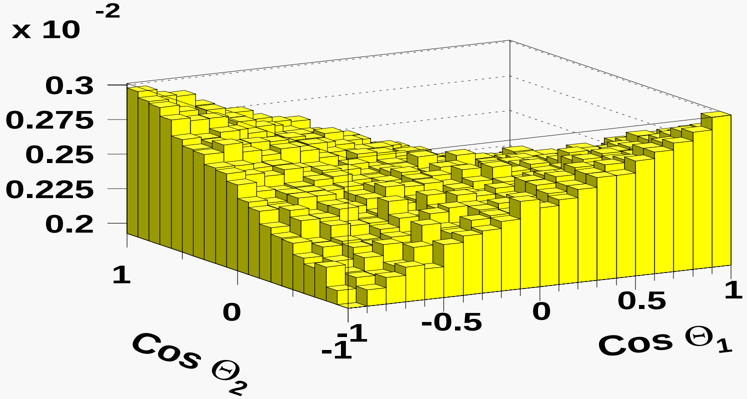
- near treshold: « off-diagonal » ≡ beamline basis
- Far above treshold: « off-diagonal » ≡ helicity basis

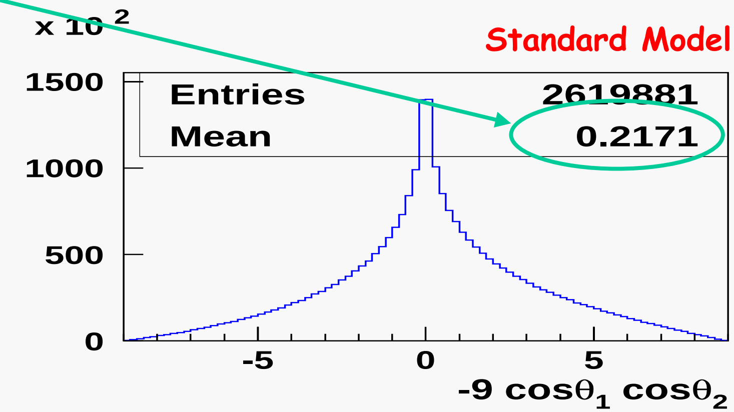
Spare: Top spin correlation observable

Two spin correlation observables C and D (hep-ph/0403035) :

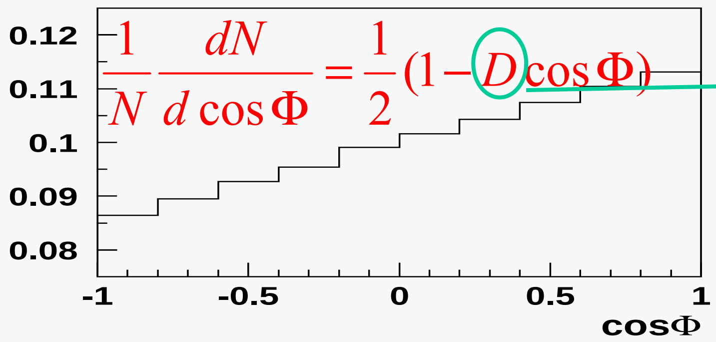
$$\frac{1}{N}\frac{d^2N}{d(\cos\theta_1)d(\cos\theta_2)} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$$

C and D unbiased estimators

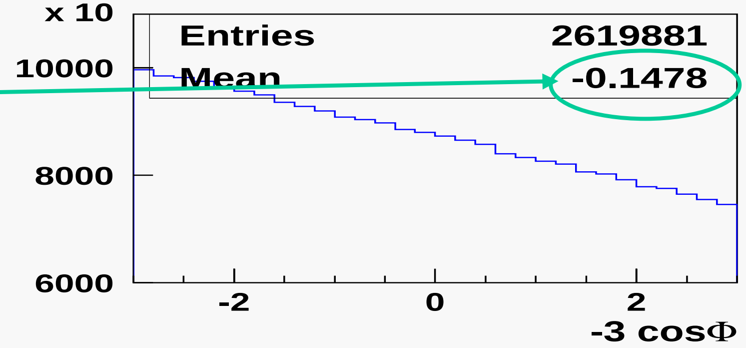




C=0
(No spin correlation)



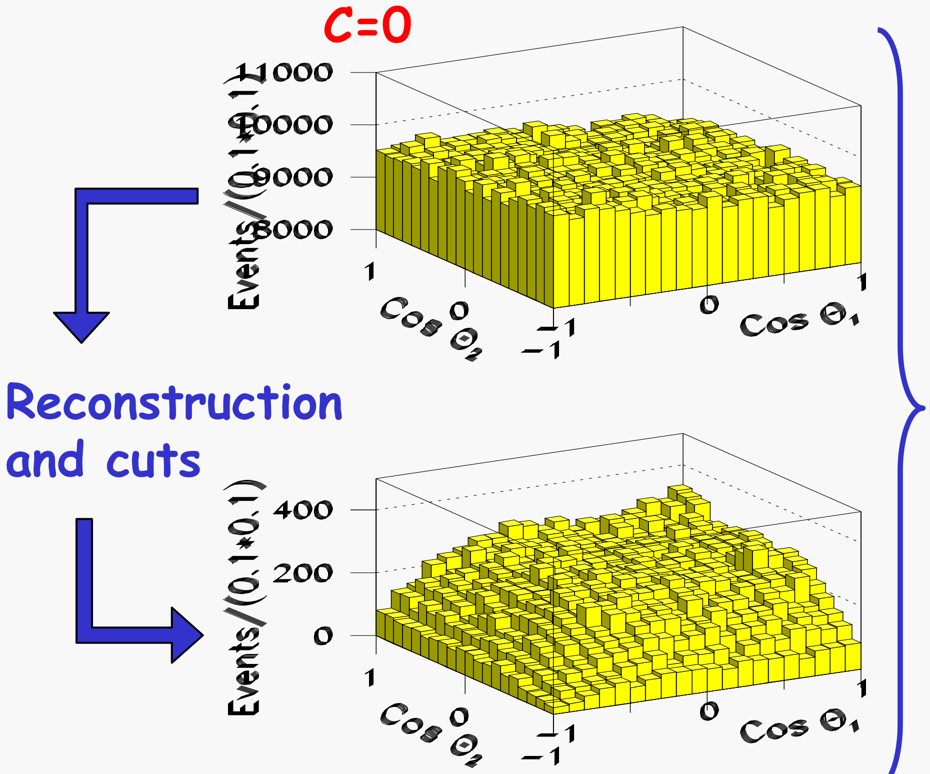
$$\frac{1}{N}\frac{dN}{d\cos\Phi} = \frac{1}{2}(1 - D\cos\Phi)$$

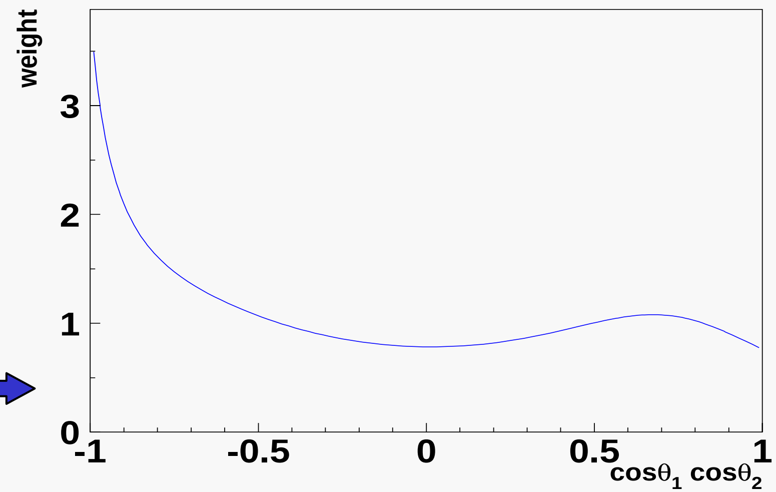


D=0
(No spin correlation)

Spare: Measurement method

Spin correlation: use a Non Correlated MC generator (PYTHIA) to parametrize reconstruction + cuts effects :





apply weights event by event

Spare: dileptonic results, spin correlation

➔ V. Simak and K. Smolek

Spin correlation with dileptonic $t\bar{t}$ events for S+B at 10 fb^{-1} (±stat ±syst)

	Results (±stat ±syst)	Precision	Standard Model (M$_{tt}$ cut included)
C	0.26 ± 0.02 ± 0.04	**17%**	0.46
D	-0.24 ± 0.01 ± 0.02	**10%**	-0.31

- ~ same precision as semileptonic channel
- Large dilution due to reconstruction effects

Systematics: Monte Carlo Generators and hadronization scheme

Compare results obtained with:

- different Monte-Carlo generators including spin correlation
- Pythia or Herwig for hadronisation, fragmentation and decays

Generator	C (±0.006)	D (±0.004)
TopReX 4.05	0.181	-0.142
AlpGen 1.33	0.167	-0.138
AcerMC 2.2 + Pythia 6.2	0.175	-0.141
AcerMC 2.2 + Herwig 6.5	0.174	-0.144

after selection
+ reconstruction
+ correction

- Very good agreement
- Better agreement than for W polarization

Systematics: jet calibration and top mass