Spin correlation in the dileptonic decay of top quark pairs at ATLAS

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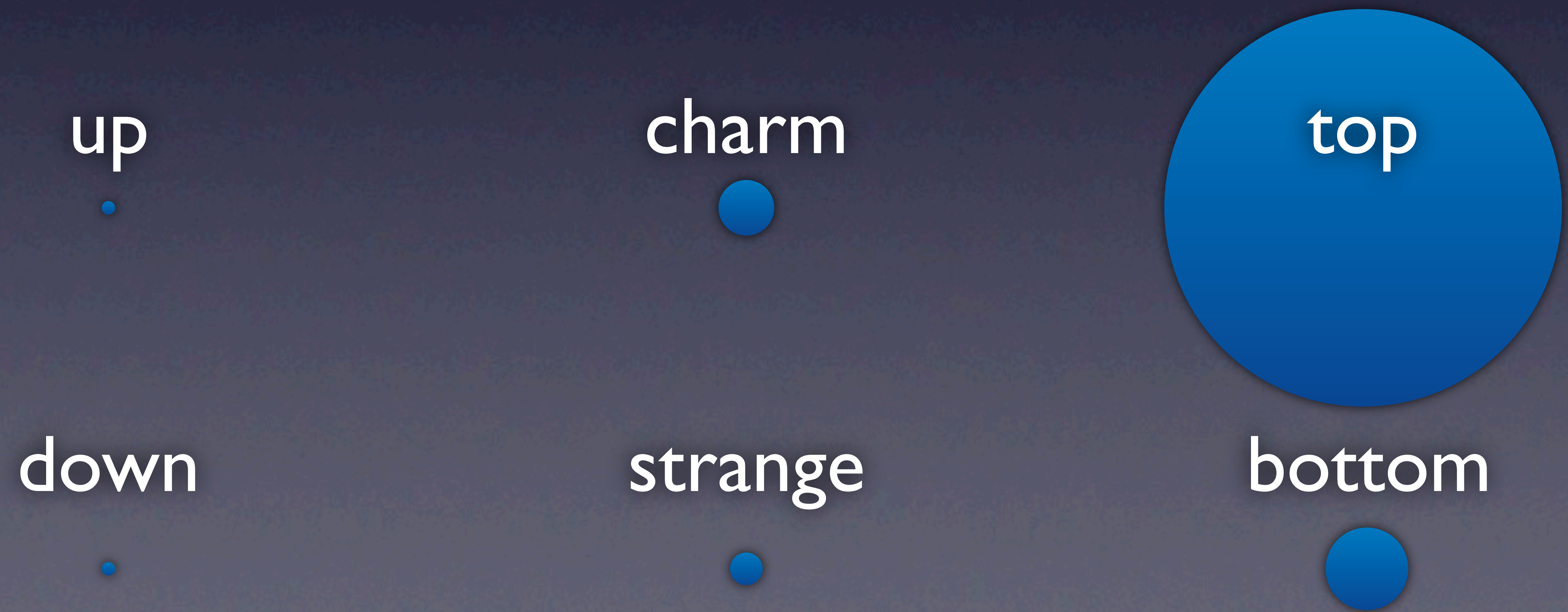
Birmingham Group Seminar

Introduction

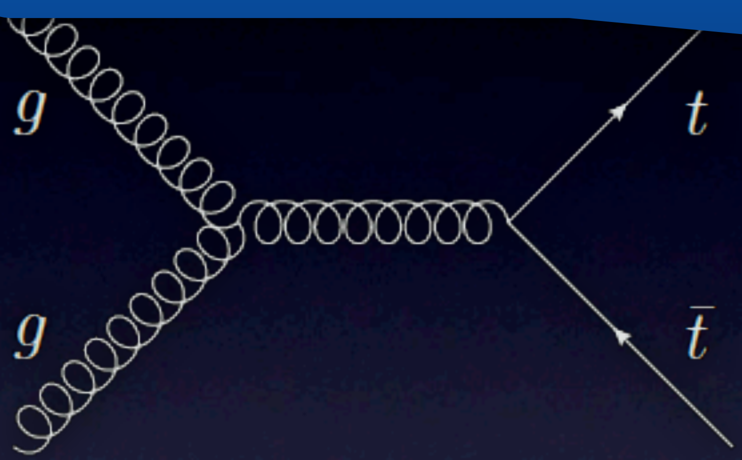
The top quark

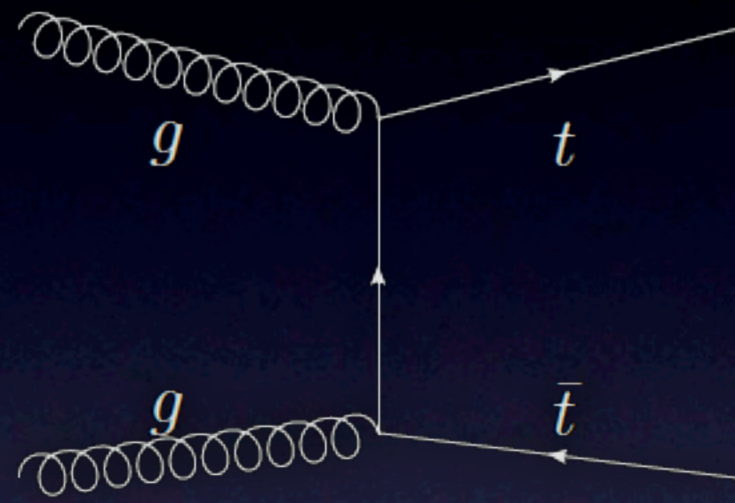
- Discovered in 1995 at the Tevatron
- Heaviest Standard Model particle*
- Strong coupling to Higgs and new physics
- Lifetime of 5×10^{-25} s
- Decays before hadronising
- Mainly produced in pairs via strong interaction
- LHC is a top factory

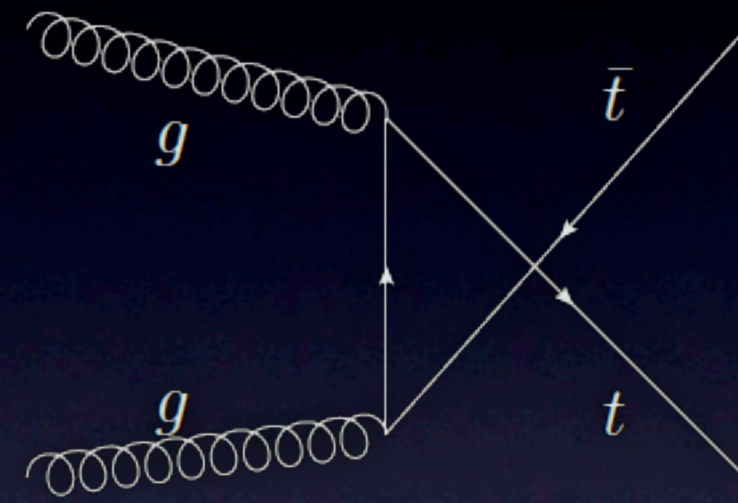


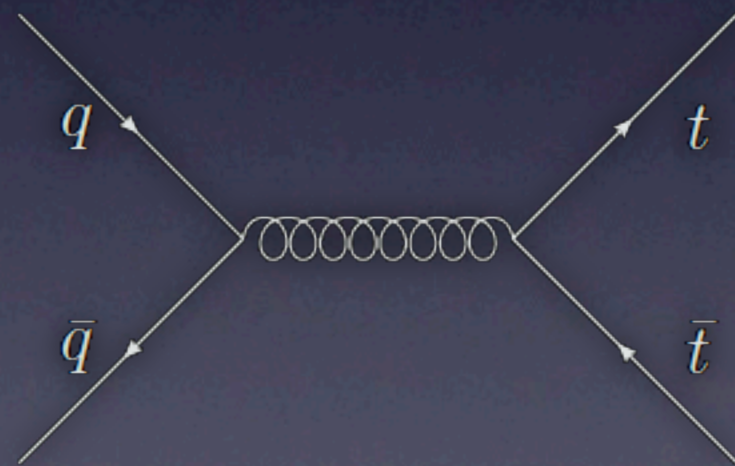
Top quark pair production

Dominates at the LHC (90 %) of ttbar pairs









Dominates at the Tevatron (90 %) of ttbar pairs

QCD causes top quark spins to be correlated

Can be modified by resonances decaying to tops

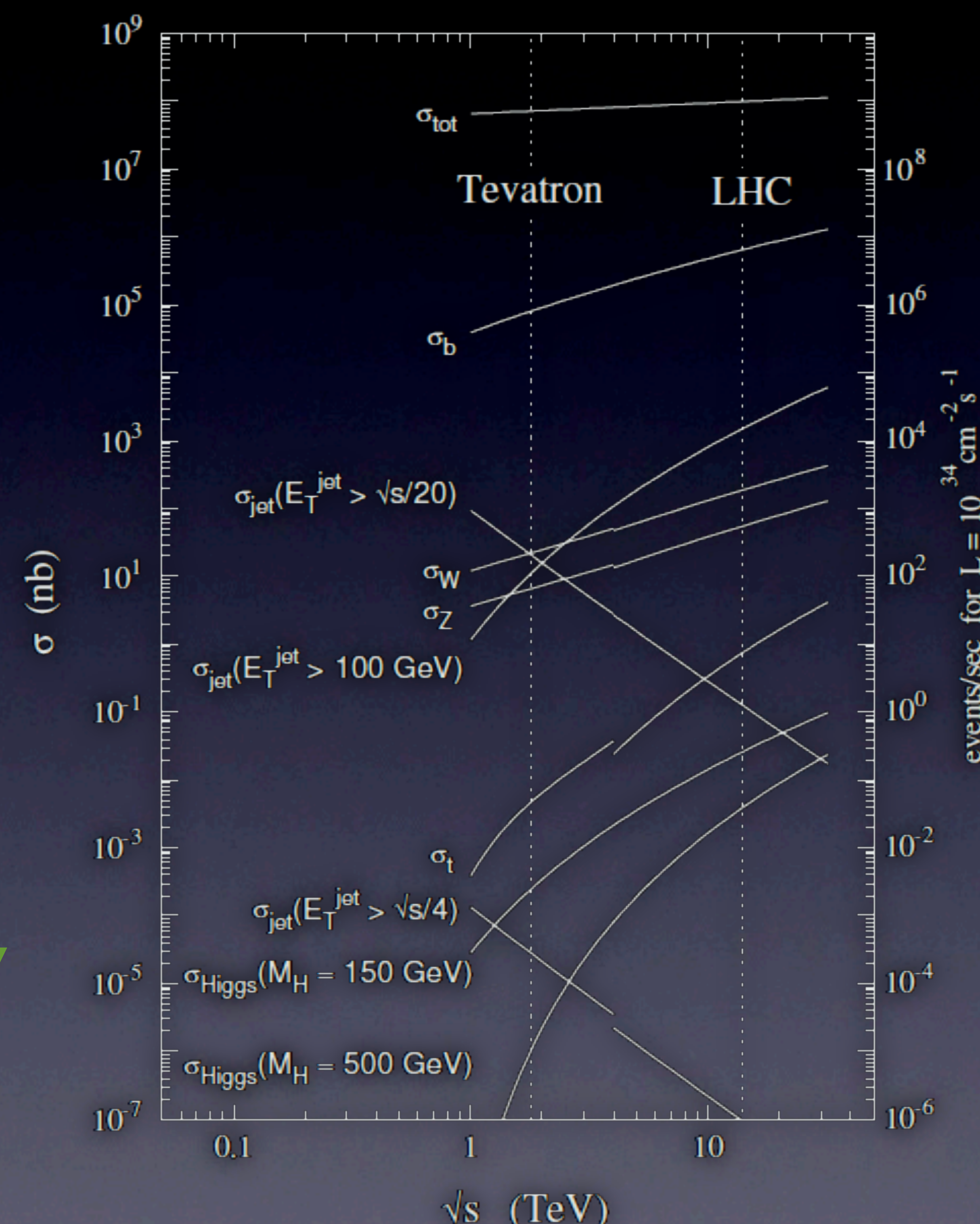
Production cross section

Standard Model
cross sections

LHC:
14 TeV = 830 pb
10 TeV = 420 pb
7 TeV = 160 pb

Tevatron = 8 pb

consider 200 pb^{-1} of data at 10 TeV



Tevatron run i: spin correlation limit with 6 events

Why measure the spin correlation?

- Top quarks produced by the strong interaction are unpolarised but have correlated spins
- Test of top quark production and decay
- Probe of a quark free of confinement effects
- Observation would place an upper limit on the top quark lifetime
- New physics could affect the spin correlation
- Precision test of the Standard Model

Spin correlation

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

- PDF, factorisation and renormalisation scales, and α_s dependencies cancel to a large extent
- NLO corrections to *A* are small at the LHC (smaller than Tevatron)
- Experimental uncertainty for the luminosity cancels

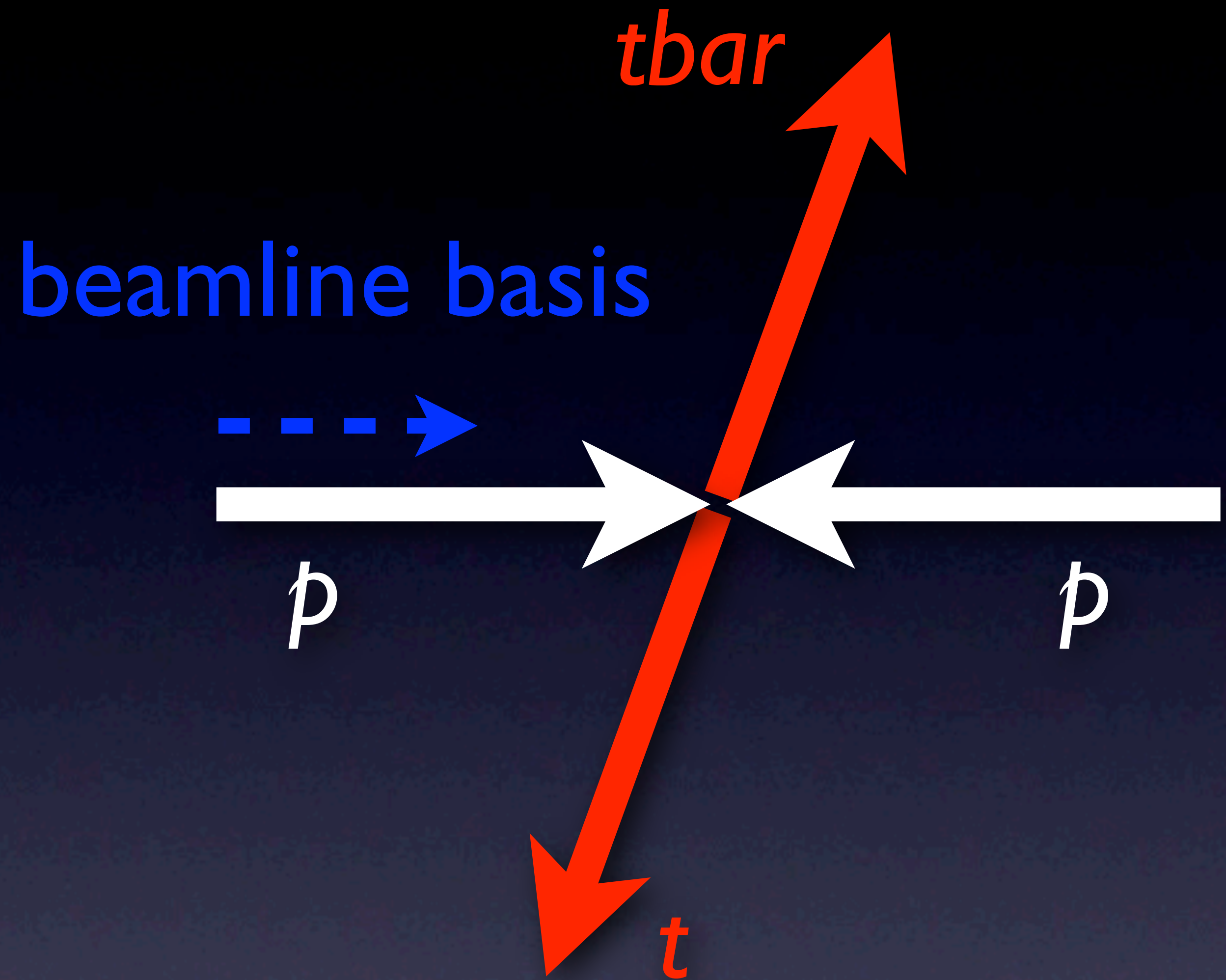
Strength of measured correlation depends on quantisation axis

Defining a basis

- To measure the direction in which the spins (of the top and antitop quarks) are pointing we need a quantisation axis

- Consider four different bases
  - Beamline
  - Helicity
  - Off-diagonal
  - and a 4th basis (with a name that shall remain a mystery for three more slides)

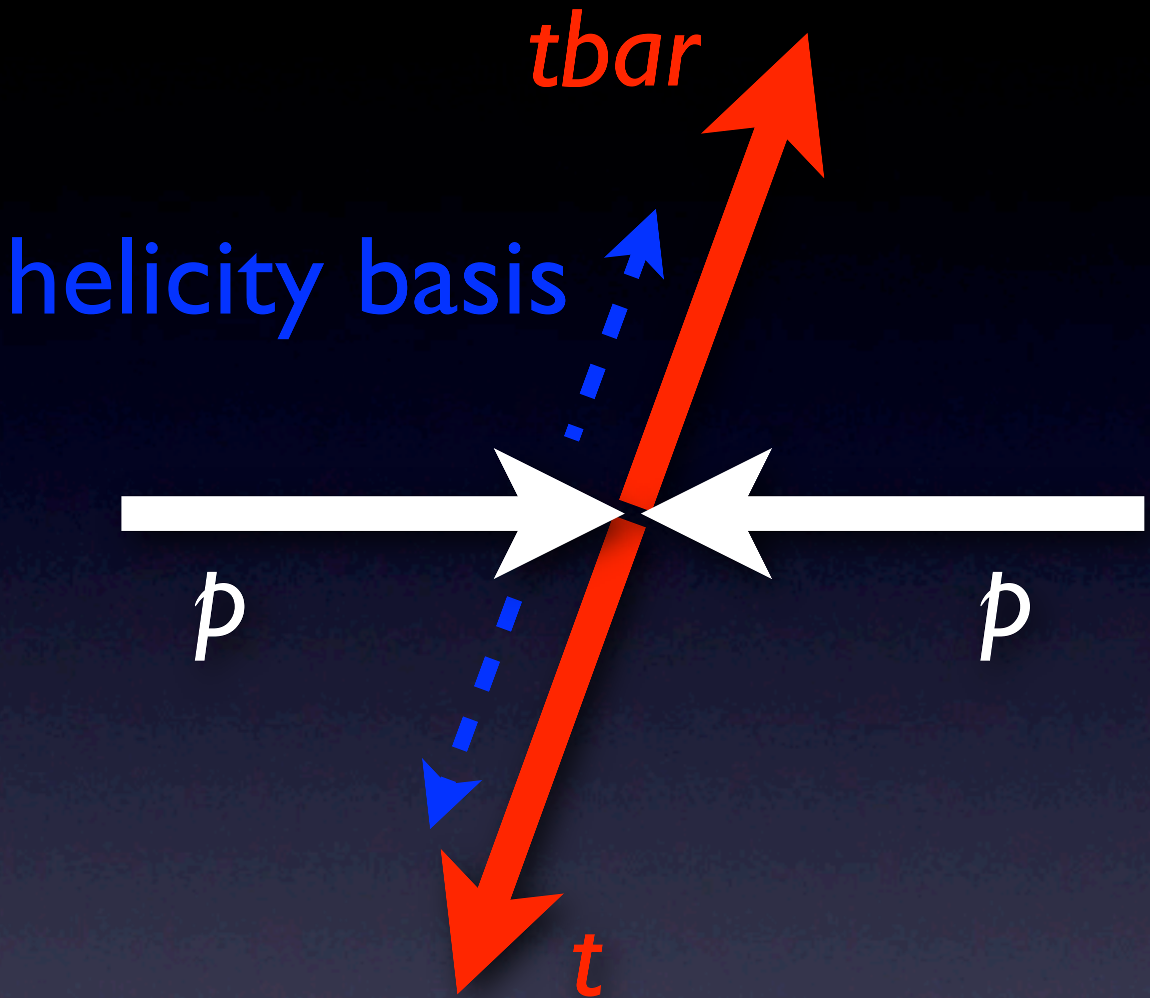
Beamline basis



Tevatron (NLO)	0.777
LHC 7 TeV (Herwig++)	0.053
LHC 10 TeV (Herwig++)	-0.004
LHC 14 TeV (Herwig++)	-0.051

- Use direction of one of the incoming beams (approximately the direction of an incoming proton)
- Simple to construct
- Optimal for ttbar pairs produced at threshold

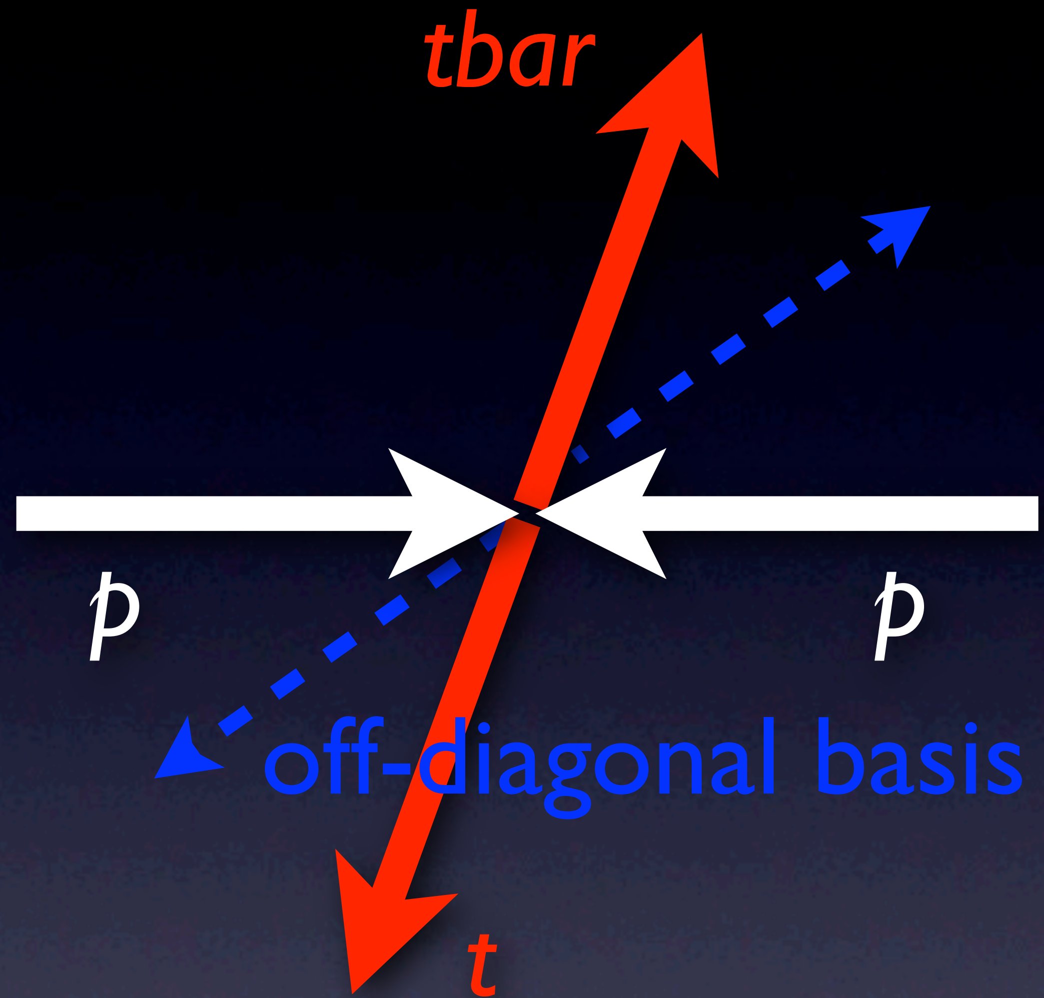
Helicity basis



Tevatron (NLO)	-0.352
LHC 7 TeV (Herwig++)	0.270
LHC 10 TeV (Herwig++)	0.299
LHC 14 TeV (Herwig++)	0.347

- Use direction of one of the top / antitop quark in the ttbar rest frame
- Looks promising for the LHC

Off-diagonal basis

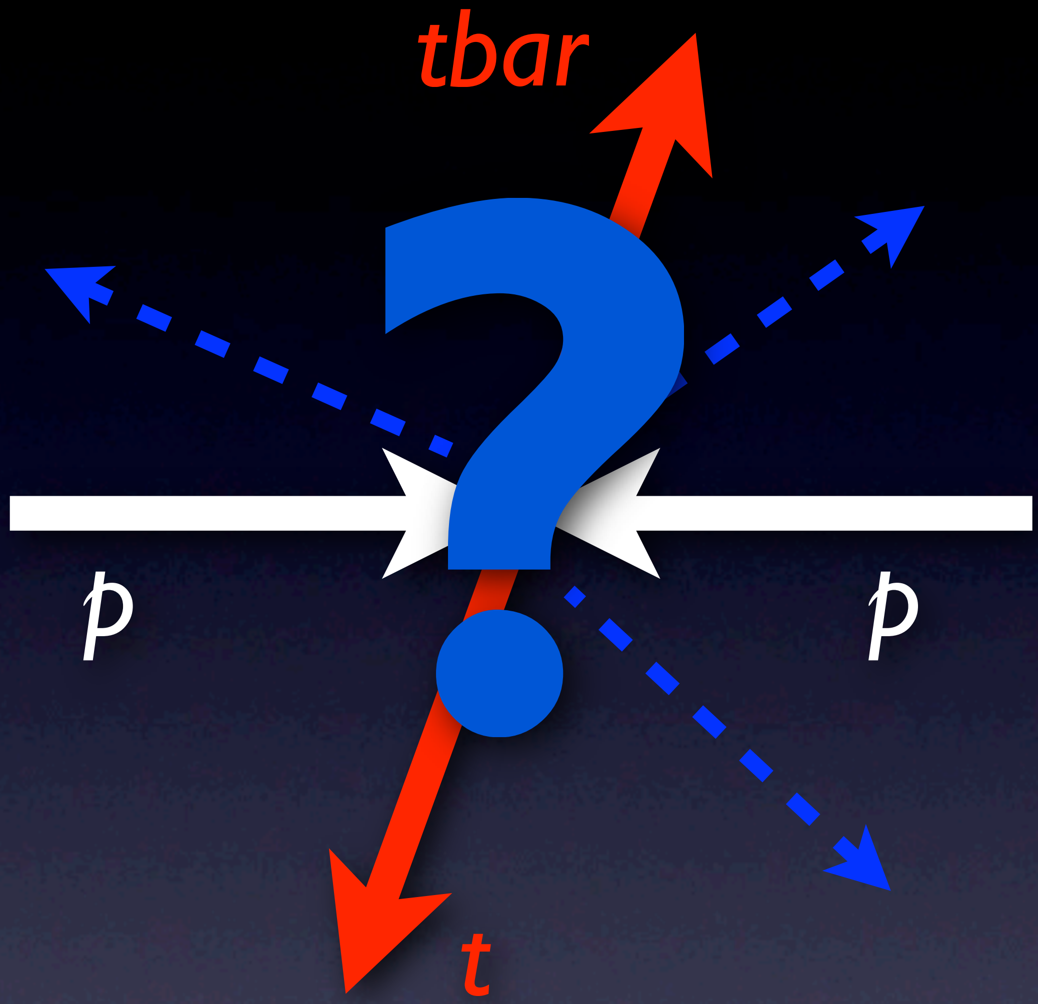


Tevatron (NLO)	0.782
LHC 7 TeV (Herwig++)	0.034
LHC 10 TeV (Herwig++)	-0.023
LHC 14 TeV (Herwig++)	-0.076

- Interpolate between beam line basis and helicity basis
- Works for top quark pairs produced above threshold
- Optimised for ttbar from qqbar annihilation (not at all optimised for the LHC!)

LHC maximal basis

P. Uwer
hep-ph/0412097



Tevatron (NLO)	---
LHC 7 TeV (Herwig++)	0.420
LHC 10 TeV (Herwig++)	0.458
LHC 14 TeV (Herwig++)	0.479

- Create a basis optimised for top quarks produced by gg fusion (LHC)
- Requires information from the event (kinematics and angles for top quarks)
- Essentially an eigenvector problem based on the spin density matrix

LHC maximal basis

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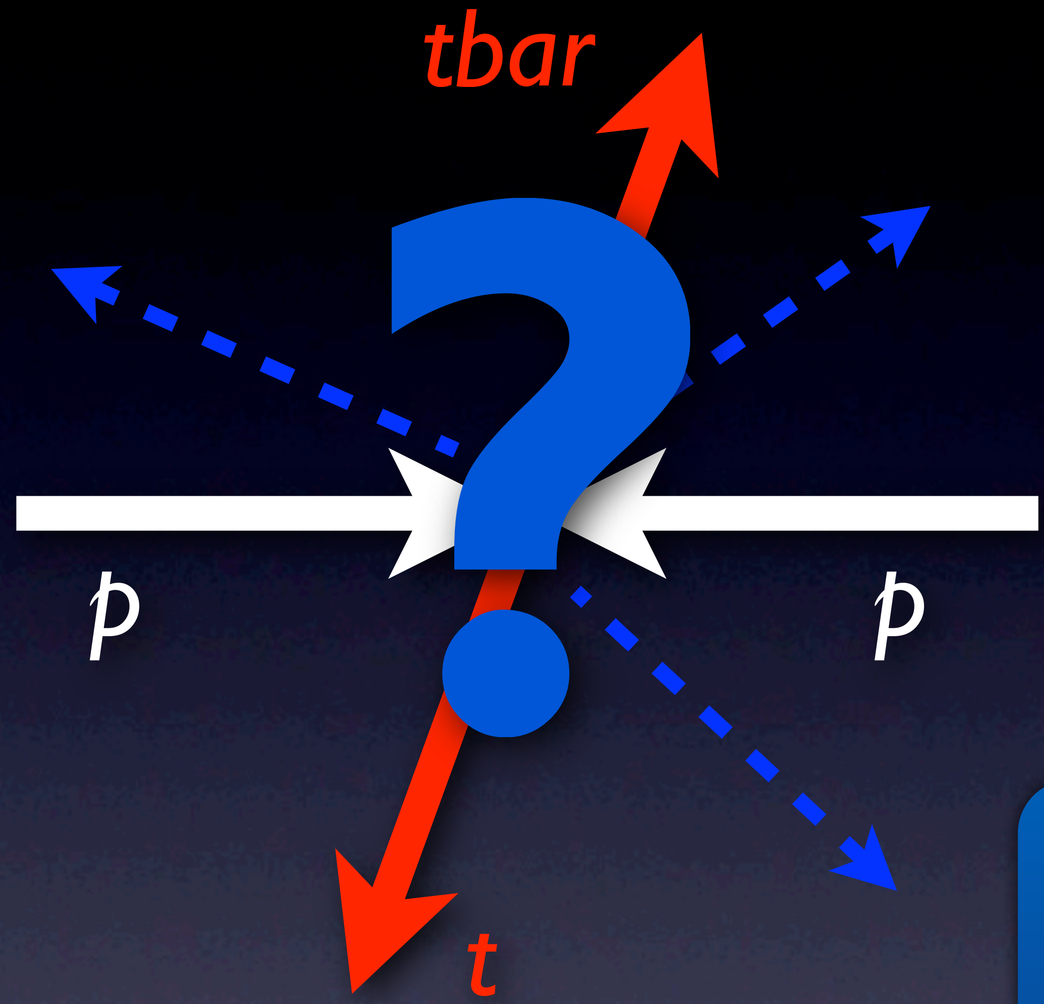
hep-ph/0412097



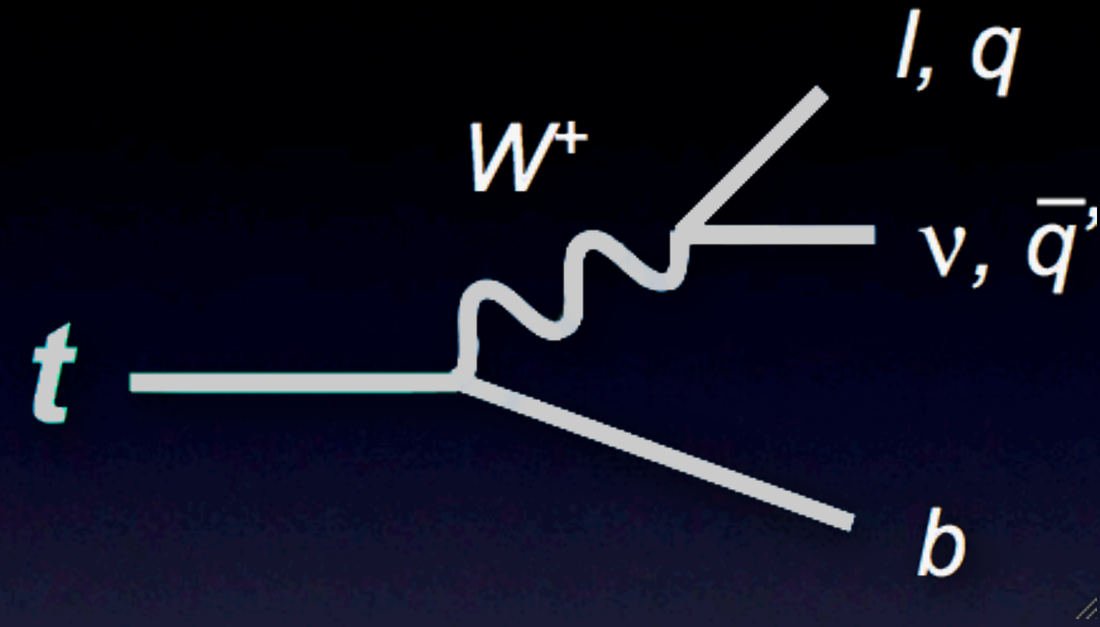
Tevatron (NLO)	---
LHC 7 TeV (Herwig++)	0.420
LHC 10 TeV (Herwig++)	0.458
[illegible]	0.479

Increase from 0.299 in the Helicity basis at 10 TeV

- Create a basis optimised for to[illegible]sion (LHC)
- Requires information from the event (kinematics and angles for top quarks)
- Essentially an eigenvector problem based on the spin density matrix

The top quark decay

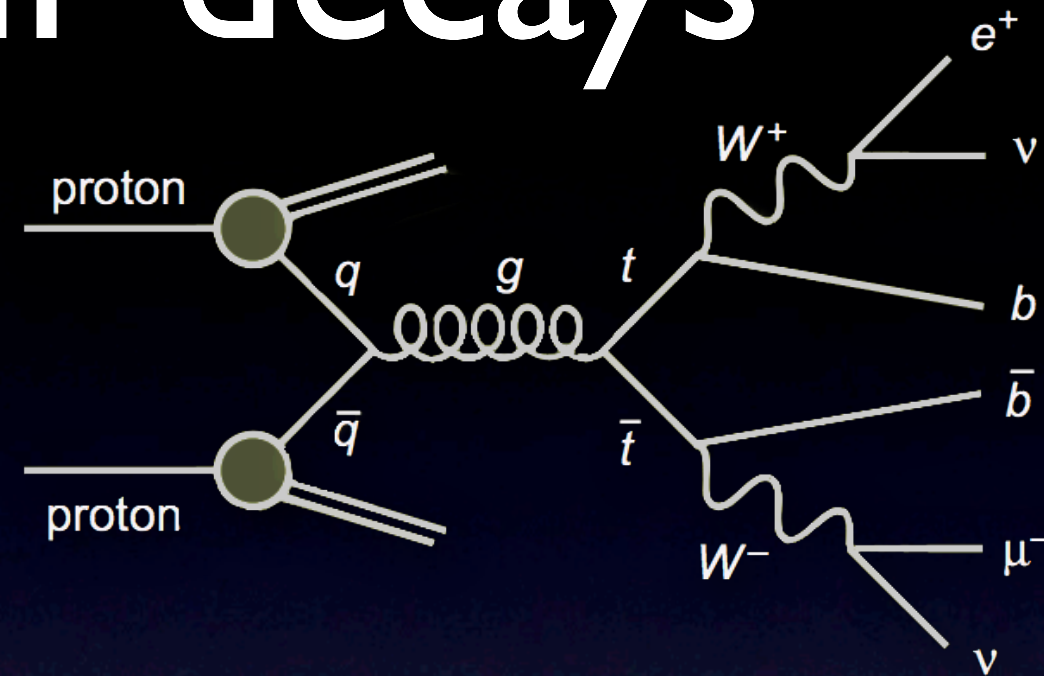
- Top quark decay via t→Wb almost always (99.9 %)
- Short lifetime: decays before it hadronises
- Spin information is preserved in decay products
- Decay products determined by the W boson decay
- ttbar decays have two W bosons



	Branching ratio
$W \to e\nu$	1/9
$W \to \mu\nu$	1/9
$W \to \tau\nu$	1/9
$W \to$ hadrons	2/3

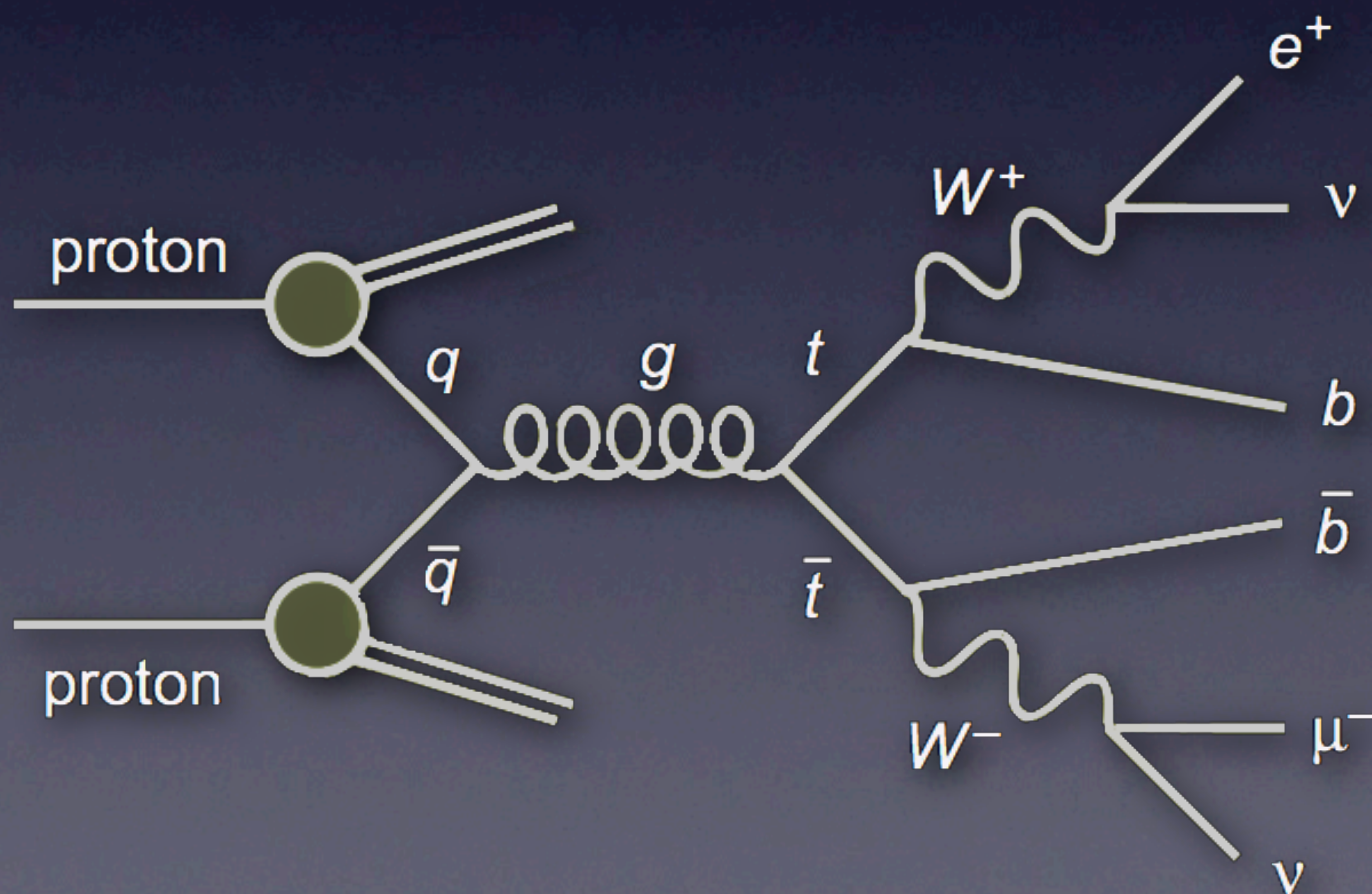
Top quark pair decays

- Traditionally three channels:
  - **dilepton:**
    - both W bosons decay to leptons
    - 2 leptons + 2 jets + missing E_T
  - **lepton + jets:**
    - one W boson decays leptonically, the other hadronically
    - 1 lepton + 4 jets + missing E_T
  - **fully hadronic**
    - both W bosons decay to hadrons
    - 6 jets



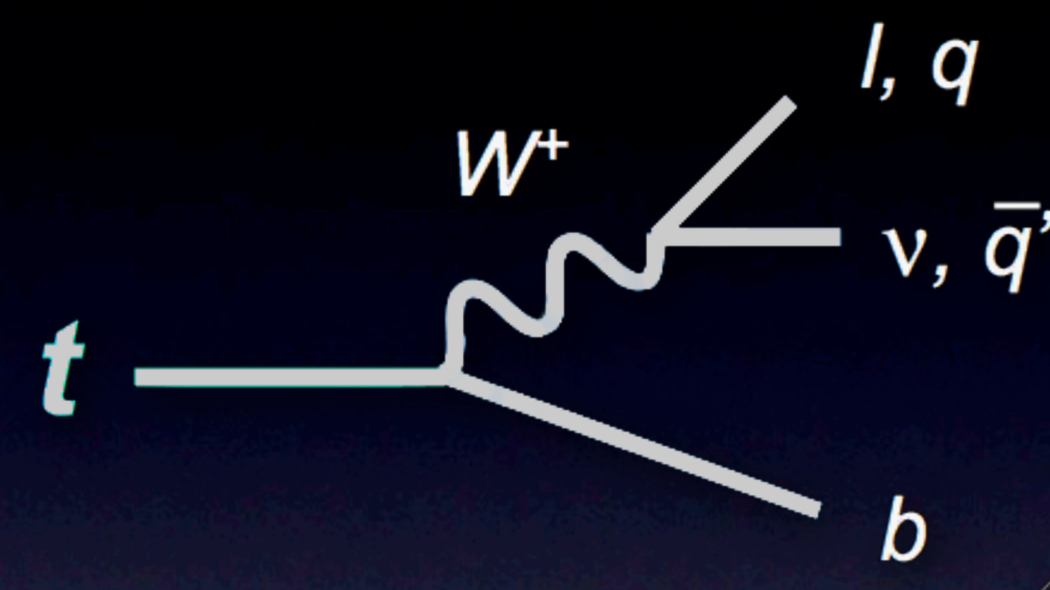
Dileptonic decays

- Events with electrons, and muons easily identifiable
- Look for events that contain only those
- 6.4 % of ttbar events (including leptonic τ decays)



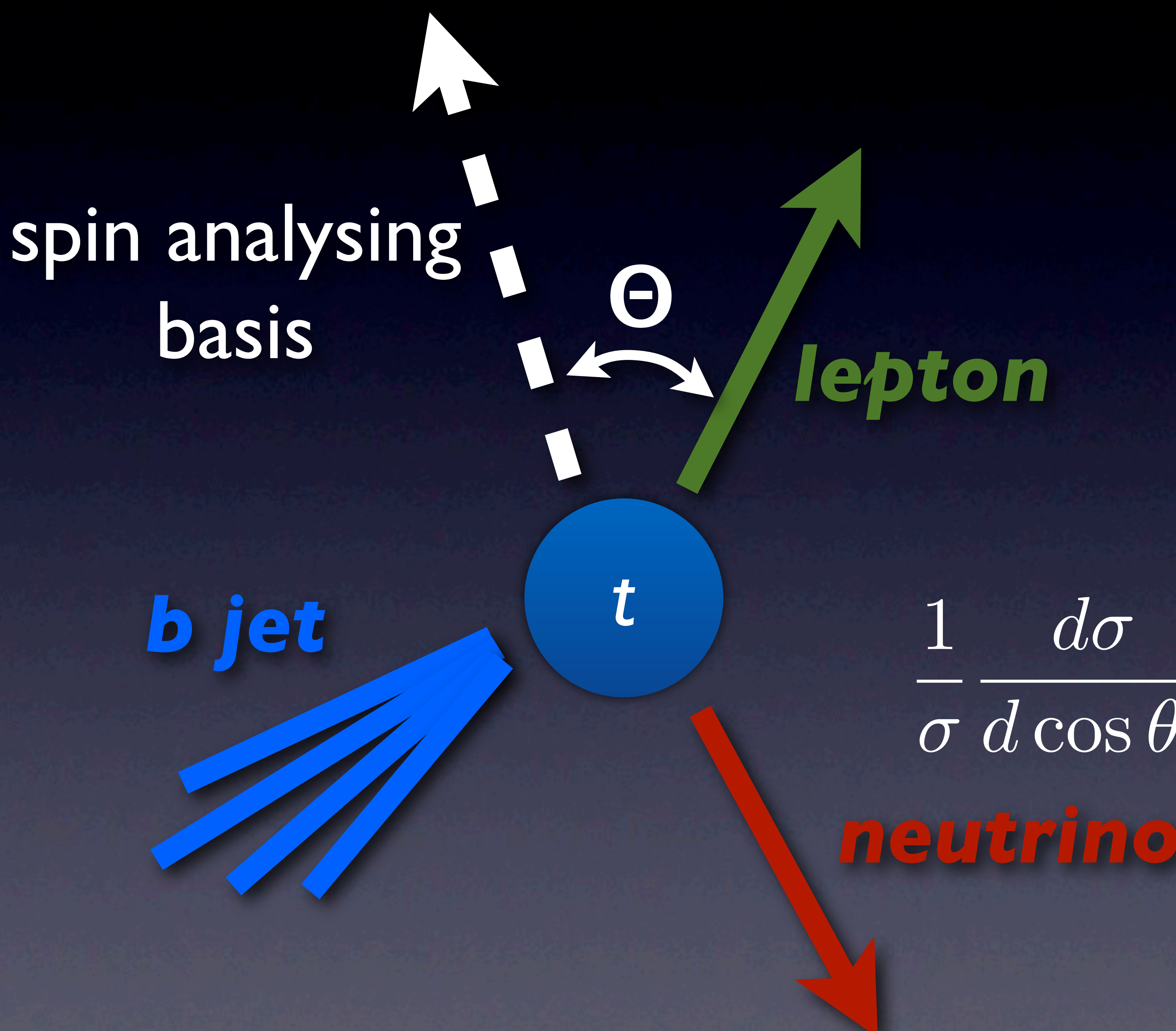
Spin analysing power

- Spin information can be accessed via the angular momentum of the top quark decay products
- Amount of spin information a daughter particle carries from the parent top is encoded in α_i
- Charged leptons and down type quarks



	b quark	W	lepton	d or s quark	u or c quark
α_i (LO)	-0.41	0.41	1	1	-0.31
α_i (NLO)	-0.39	0.39	0.998	0.93	-0.31

Measuring the top spin



Information about the direction of the top quark spin is passed on to its decay products

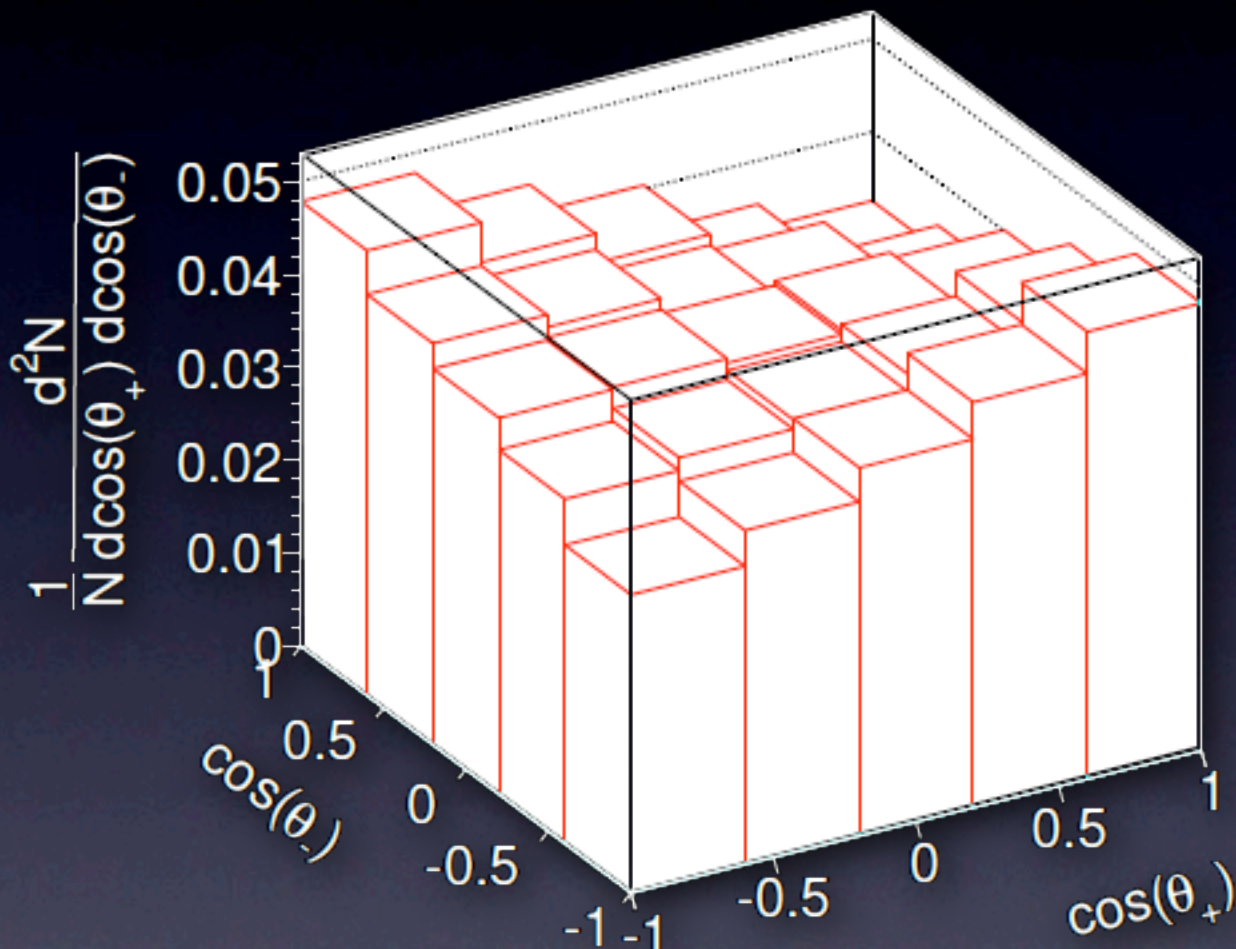
modulus of top polarisation

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

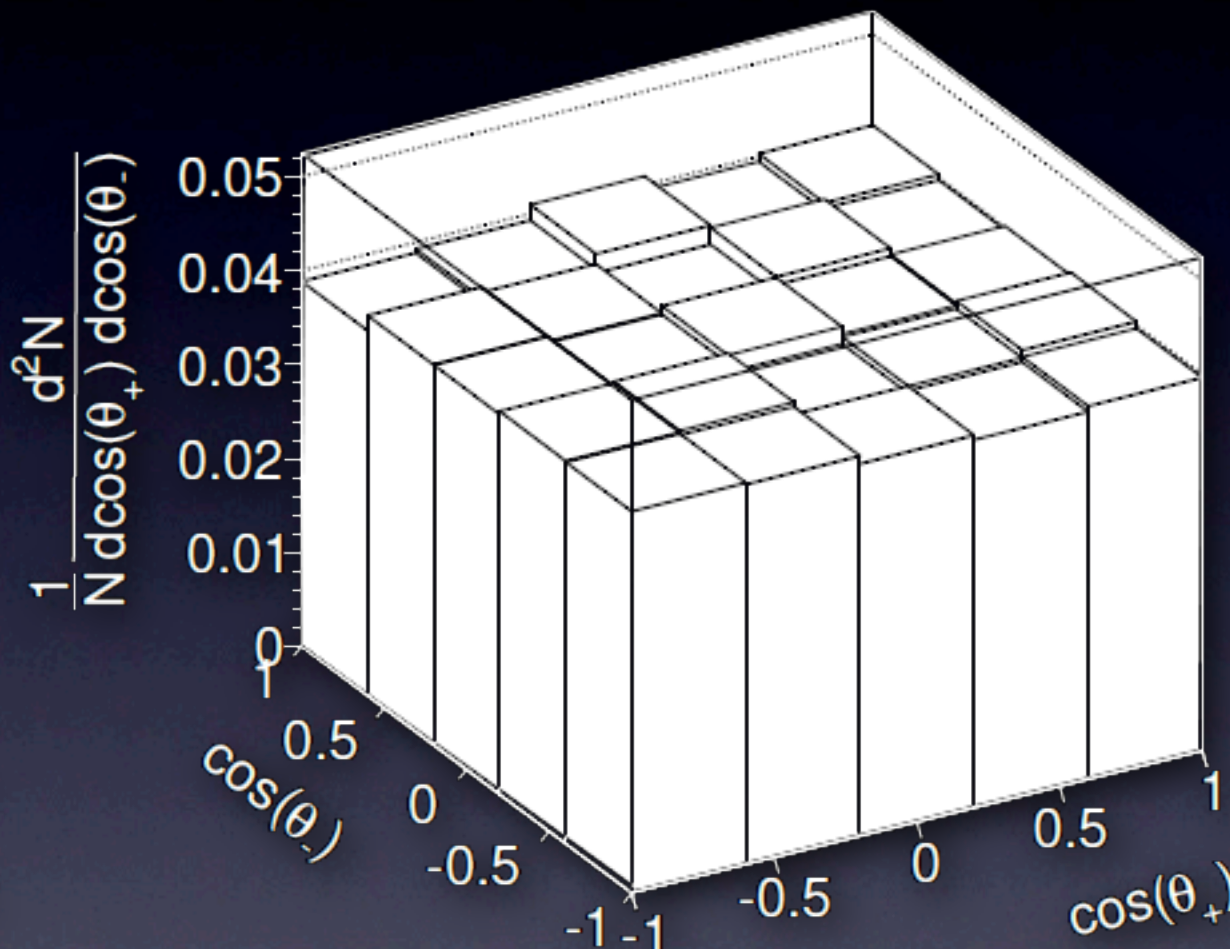
spin analysing power

in top quark rest frame

2D distributions



Standard Model
(Helicity basis)

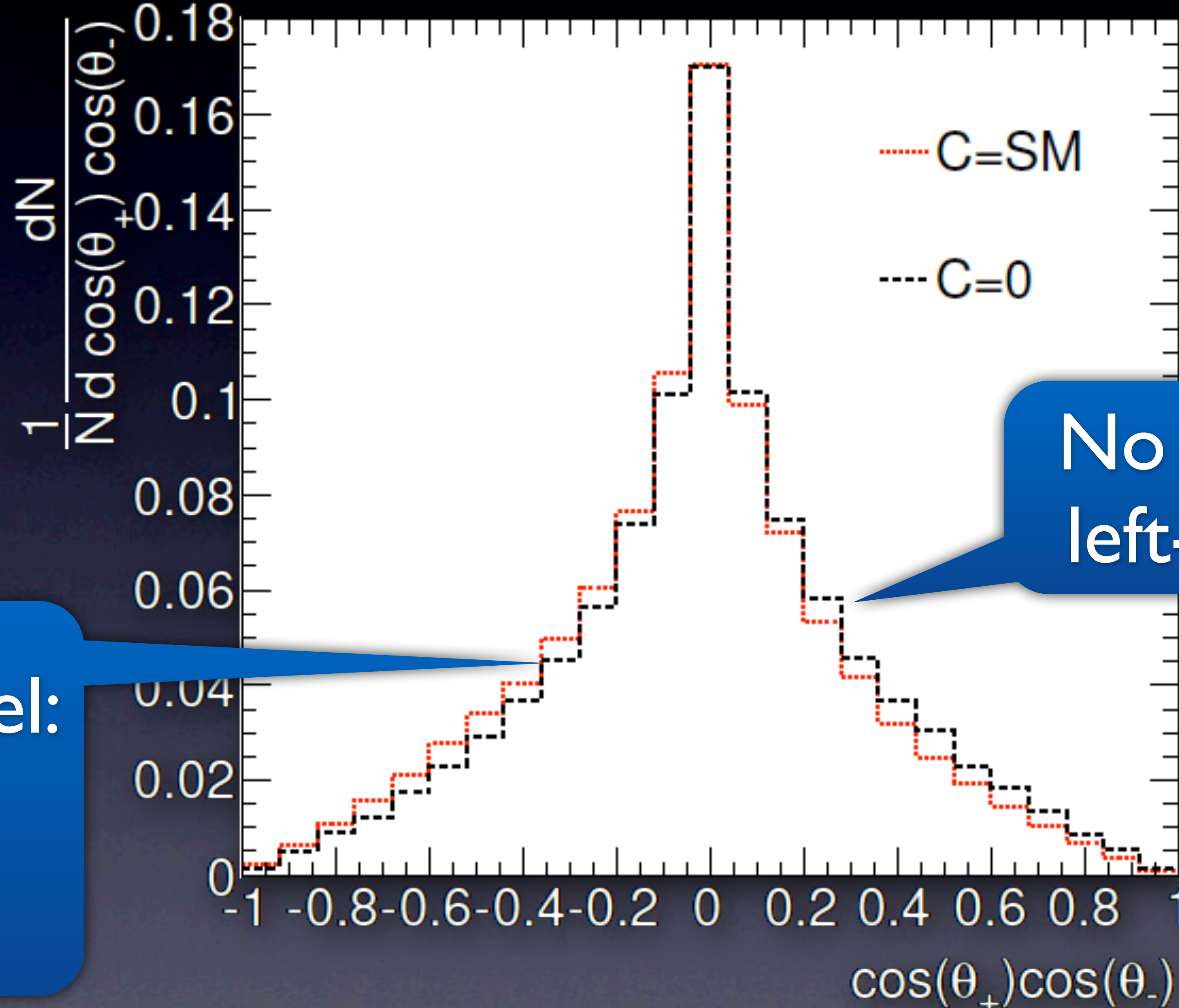


no spin
correlation

Herwig++ Monte Carlo 10 TeV

Spin correlation

Herwig++ Monte Carlo 10 TeV



No spin correlation: left-right symmetric

Standard Model: left-right asymmetric

Helicity basis

Linear extraction

$$A = \frac{N_{like} - N_{unlike}}{N_{like} + N_{unlike}}$$

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos(\theta_+)d\cos(\theta_-)} = \frac{1}{4}\left[1 - A|\alpha_+\alpha_-|\cos(\theta_+)\cos(\theta_-)\right]$$

Spin analysing power:
for charged leptons =1 x 1

Results from the Tevatron

- Run i
  - DØ: A > -0.25 at 68 % confidence level using 125 pb^{-1} at centre-of-mass energy of 1.8 TeV

0.777

- Run ii
  - DØ: A = $-0.17^{+0.64}_{-0.53}$ using up to 4.2 fb^{-1} in the beam line basis at 1.96 TeV
  - CDF: A= $0.320^{+0.545}_{-0.775}$ using 2.8 fb^{-1} in the off-diagonal basis at 1.96 TeV

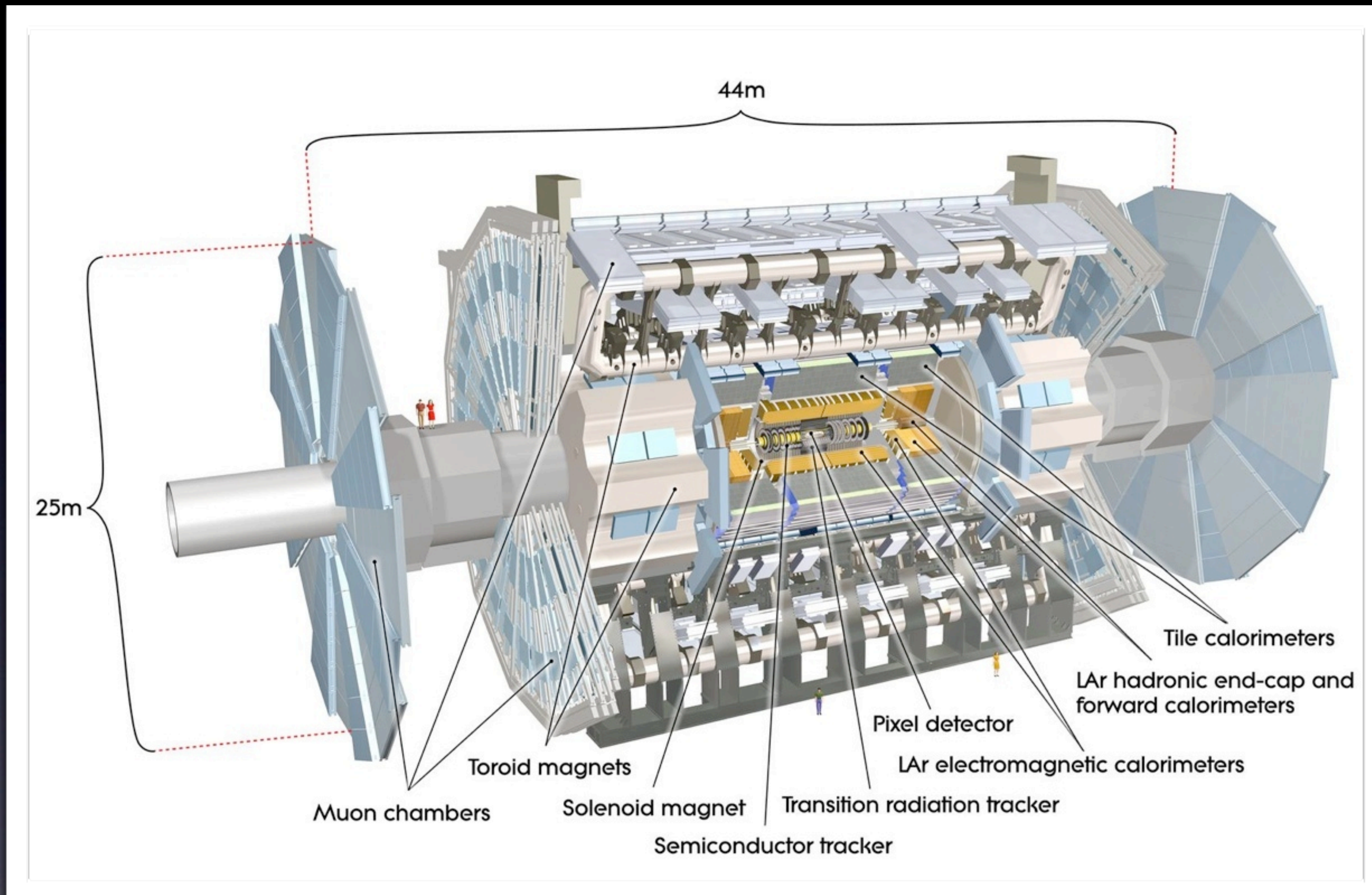
0.782

Expectations for the LHC

E_{CM}	14 TeV (LO Calc)	14 TeV Herwig++	10 TeV Herwig++	7 TeV Herwig++
$A_{helicity}$	0.33	0.35	0.30	0.27
$A_{maximal}$	0.48	0.48	0.46	0.42

Event selection

The ATLAS detector

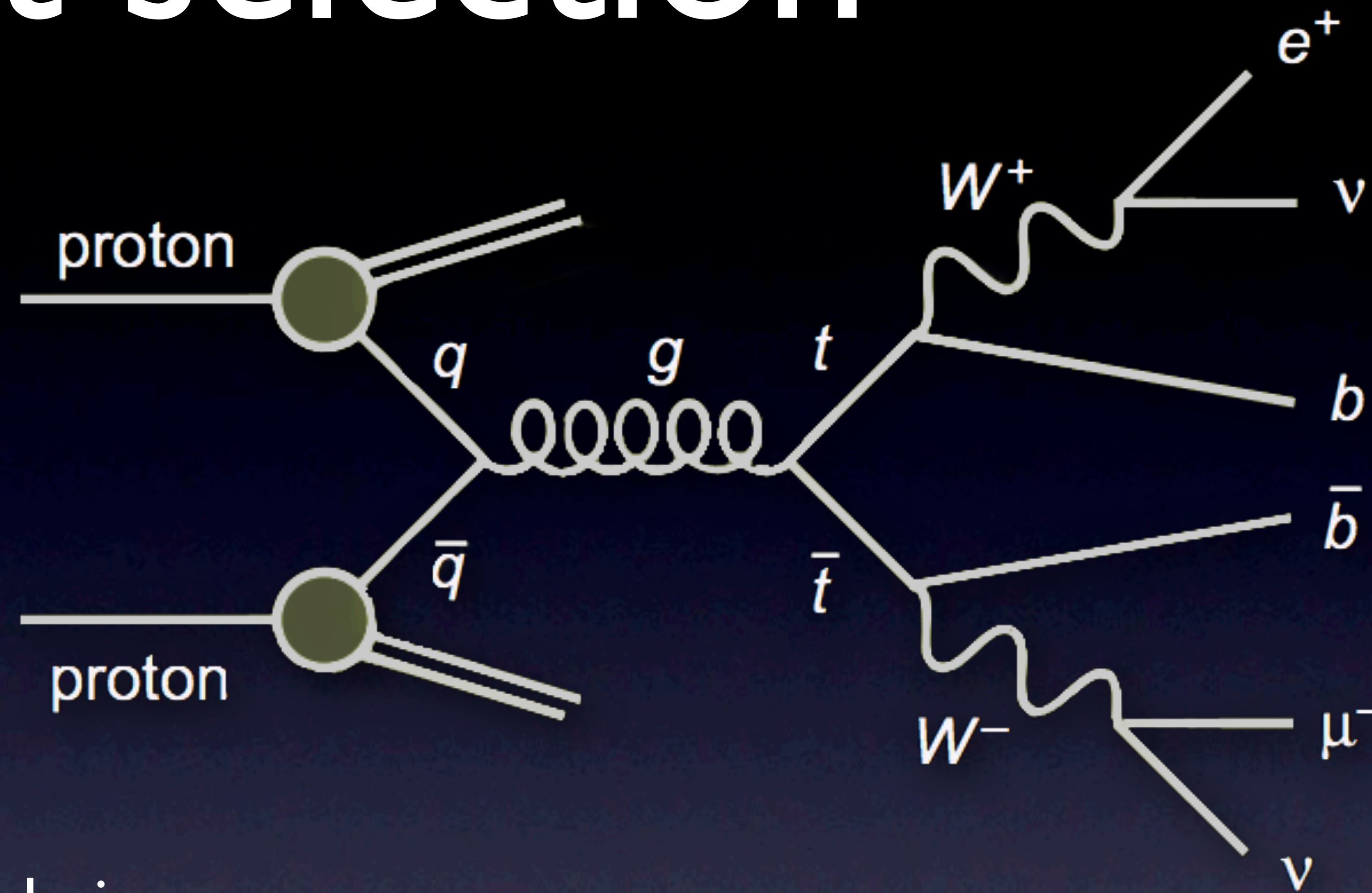


Event selection

- Dilepton channels:
    - ee, eμ, μμ

- Advantages:
    - Small background
    - Clear signal
    - No ambiguities in spin analysing power (e.g. due to the down quark)

- Disadvantages:
    - Two neutrinos in the final state
    - Lepton + Jet channel has higher statistics

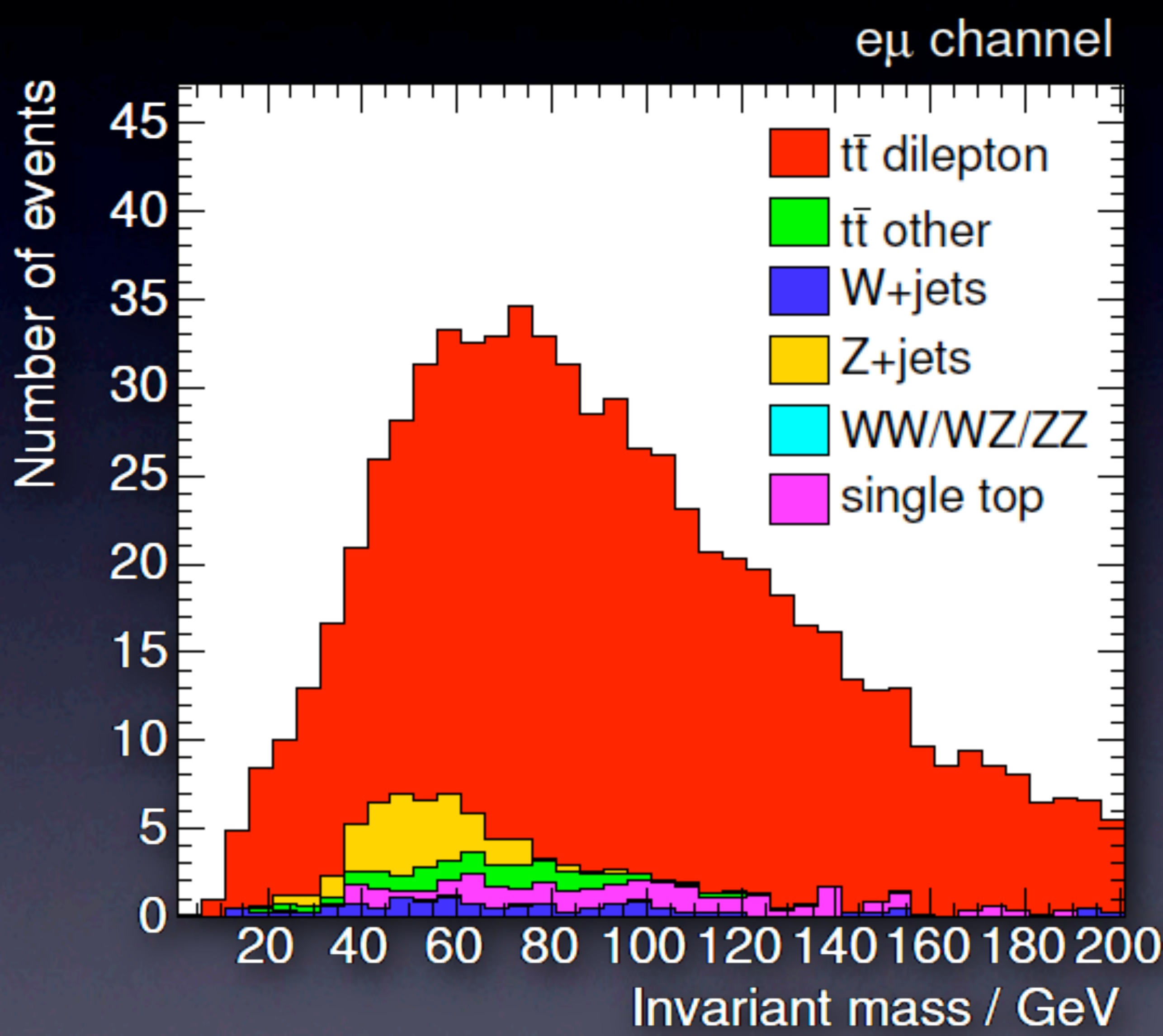


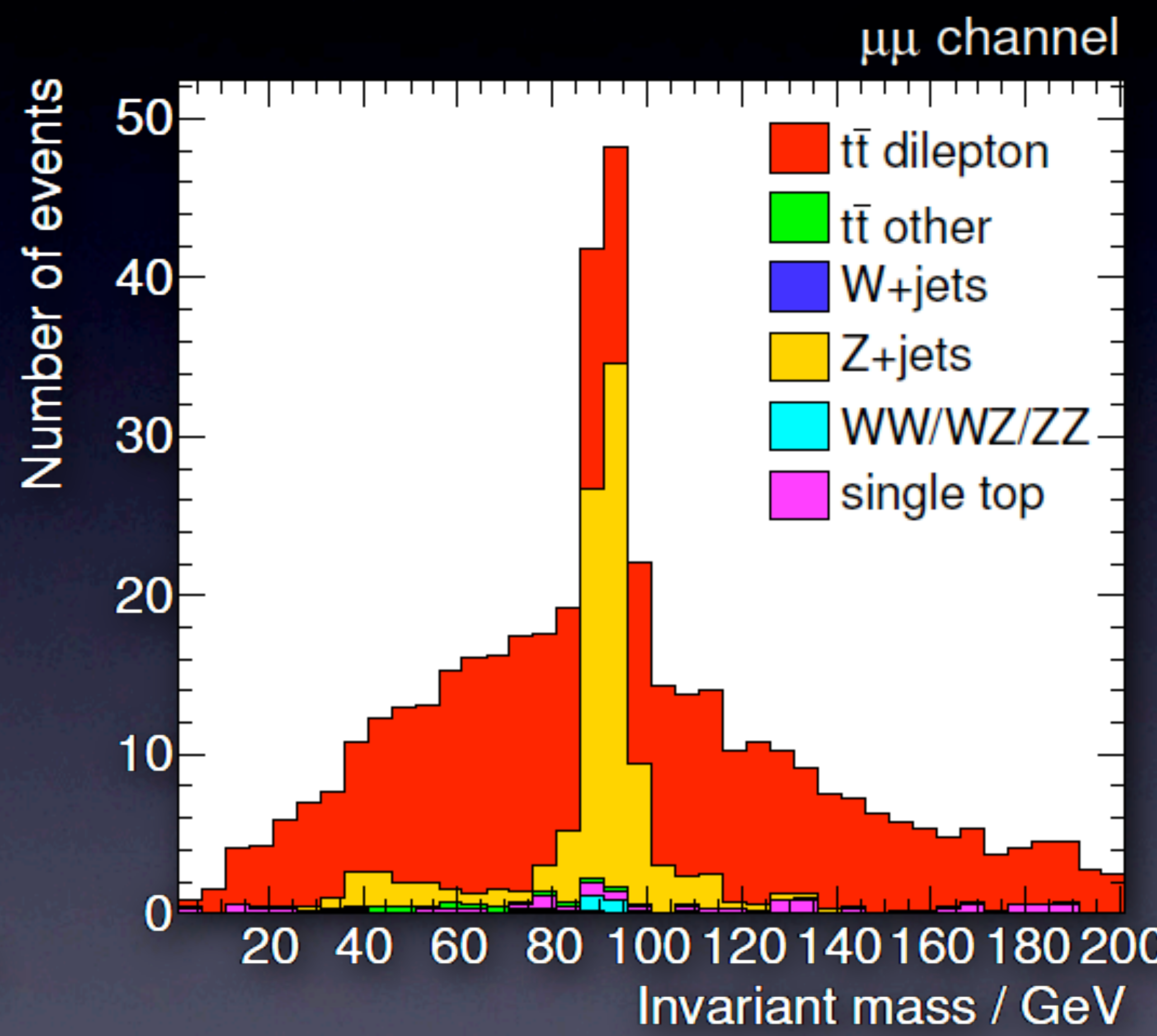
- High efficiency from single lepton (e, μ) trigger, $p_T > 15$ GeV
- Exactly 2 leptons $p_T > 20$ GeV, opposite charge
- At least 2 jets $p_T > 25$ GeV
- Veto events with lepton invariant mass near Z peak (ee and μμ channels)
- Missing $E_T > 35$ GeV (20 GeV for eμ channel)

	signal	background
eμ	645	93
ee	215	39
μμ	301	55
combined	1161	187

Expected number of selected events in 200 pb^{-1} at 10 TeV (MC@NLO)

Invariant mass of the two leptons in the event

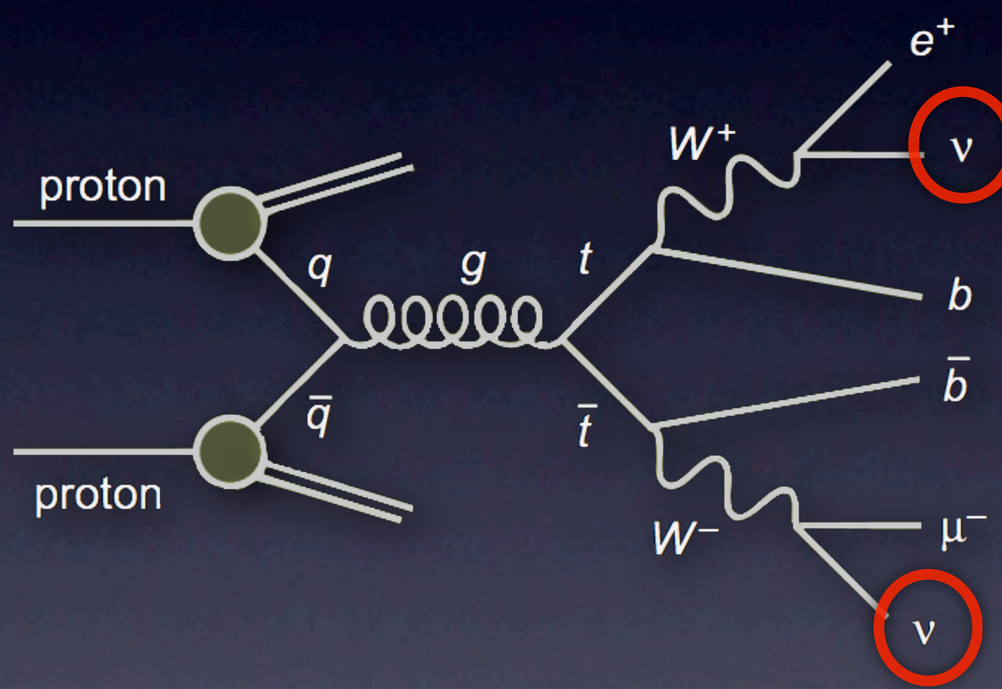




Event reconstruction

Neutrino weighting

- Need full event topology for spin correlation measurement
- Kinematics under-constrained due to two neutrinos in the final state
- Each neutrino contributes three unknowns
- Use top mass and W mass constraints: (4 quantities)
- Reconstruction based on technique from DØ

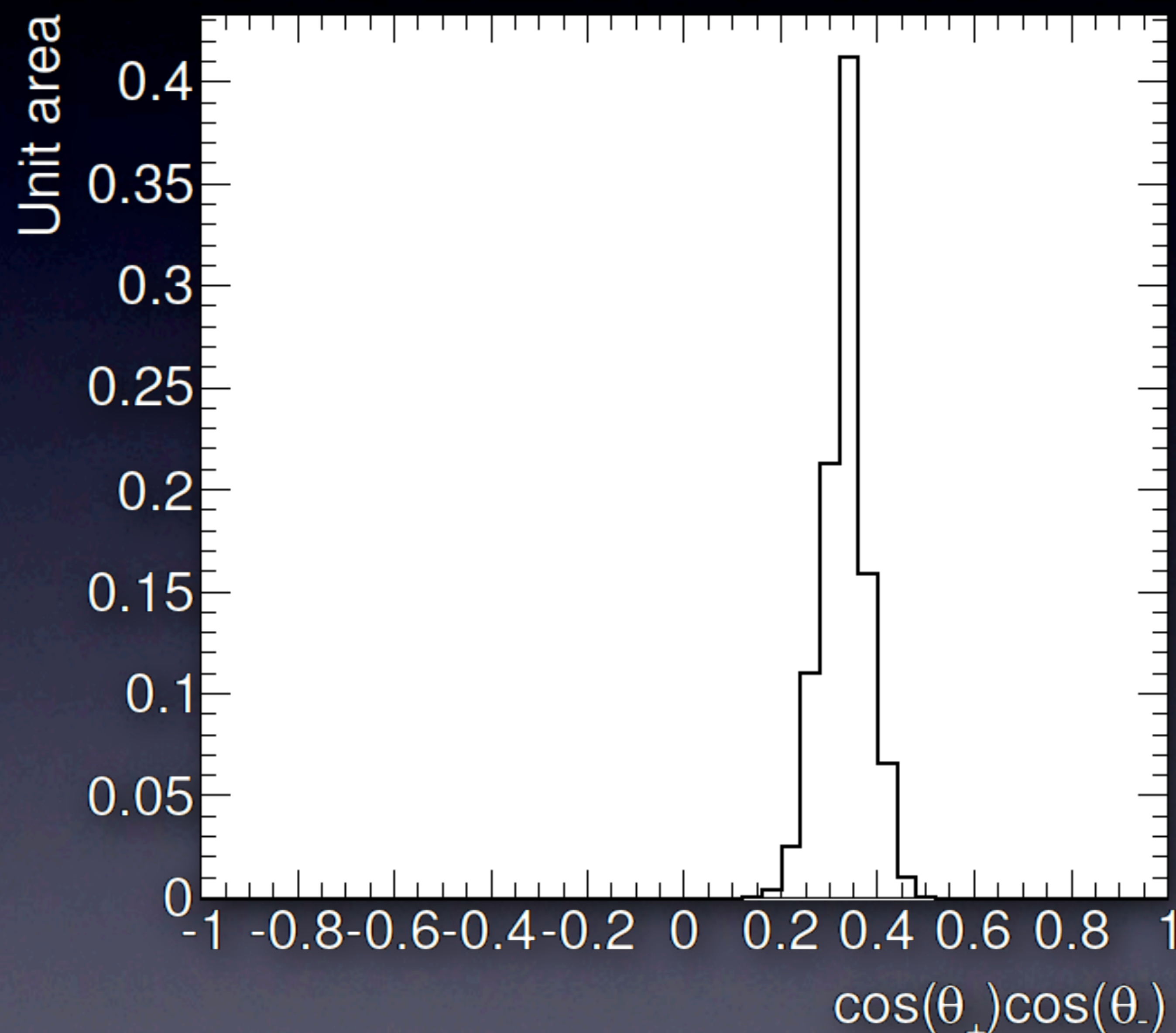


Neutrino weighting

- Do not use the missing E_T *x* and *y* components to solve the event kinematics
- Instead test many different assumptions for the neutrino and antineutrino η's
- Multiple solutions per event
- Calculate p_x and p_y for the neutrino and antineutrino in the solution
- Weight the solution by the agreement with measured missing E_T in the event

$$w_i = \exp\left(\frac{-\left(E_x^{miss} - p_x^{\nu} - p_x^{\bar{\nu}}\right)^2}{2\sigma_x^2}\right) \cdot \exp\left(\frac{-\left(E_y^{miss} - p_y^{\nu} - p_y^{\bar{\nu}}\right)^2}{2\sigma_y^2}\right)$$

Distribution for one event



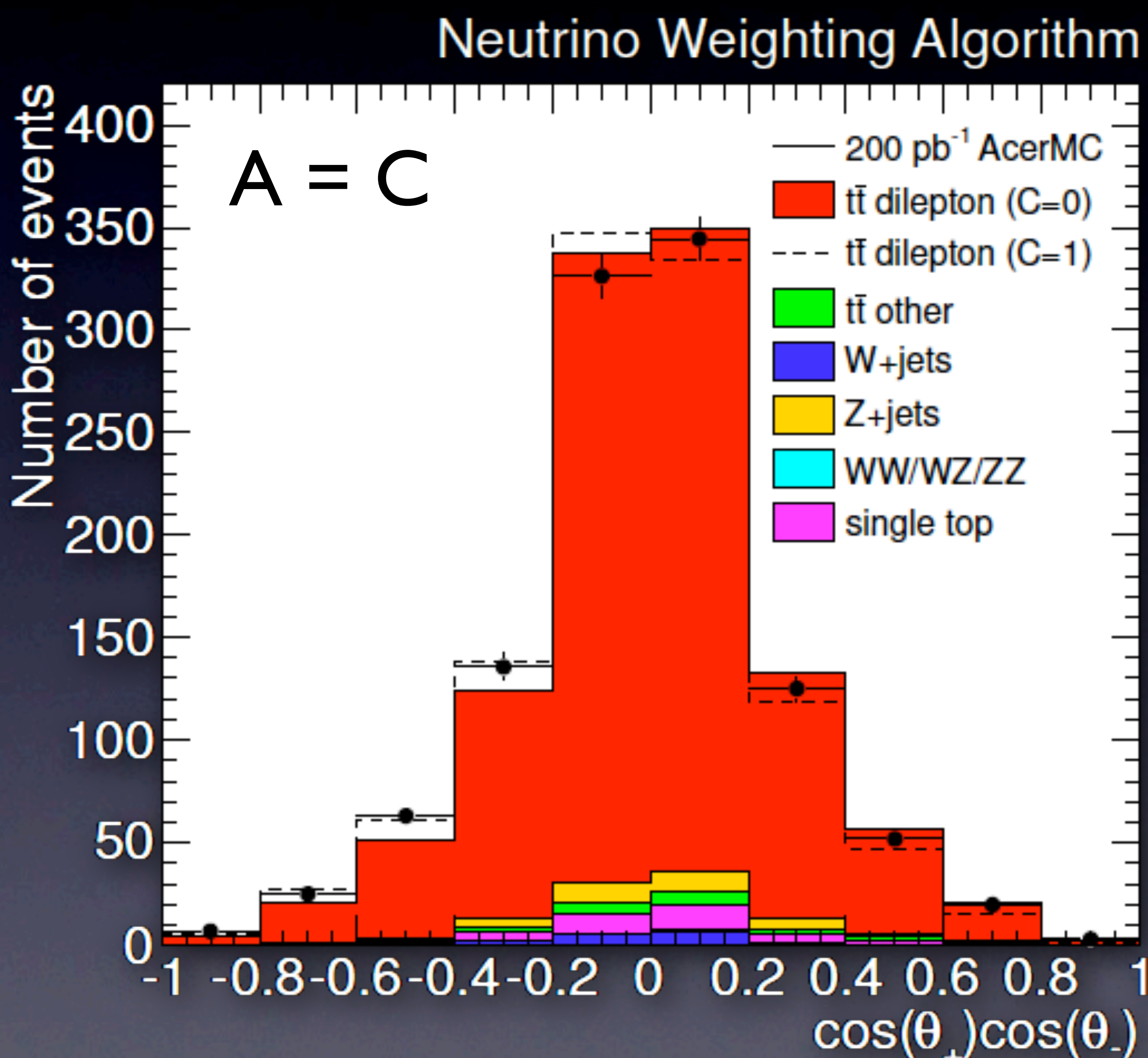
- Results from the neutrino weighting algorithm for a single event
- Probability density of solutions

Results

Template fits

- Distributions are distorted by the selection and reconstruction → template fits
- Make templates for the background processes
- Make templates for the signal process with different amounts of spin correlation
- Pseudo experiments for the uncertainties

LHC maximal basis

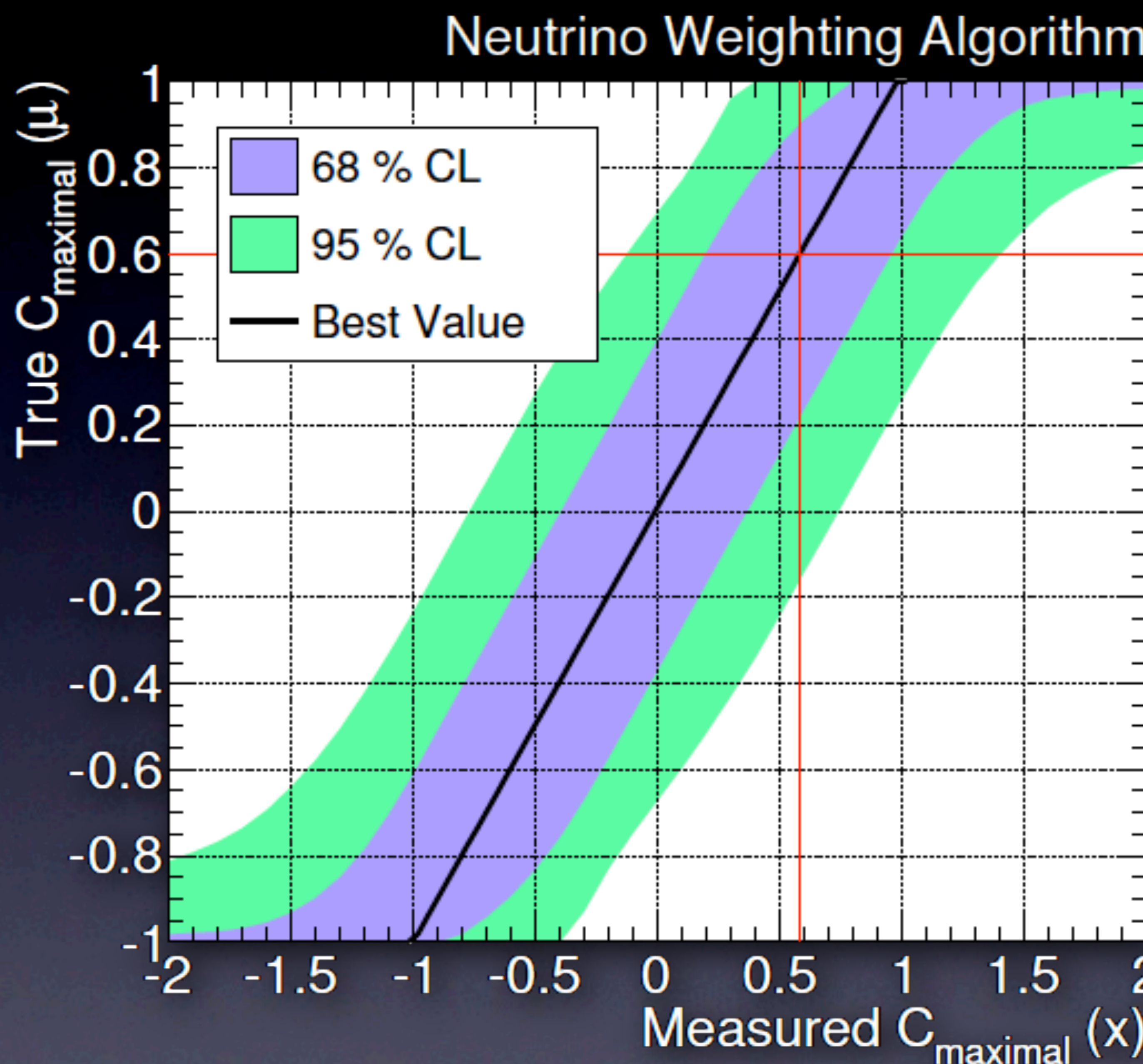


'Data' points represent $200\ pb^{-1}$ of AcerMC Monte Carlo contains correlation A = SM (0.46?)

MC@NLO Monte Carlo:
A = 0: red (no correlation)
A = 1: dashed, hollow

A = C

- Confidence interval
- Maps measured value of A to parton level value (diagonal line)
- Uncertainty is systematic and statistical for 200 pb^{-1}
- Takes into account that only $-1 < A < 1$ are physically allowed
- Draw vertical line at measured A and read off horizontal value + limits



200 pb^{-1}

$A = 0.60^{+0.30}_{-0.39}$

Conclusions

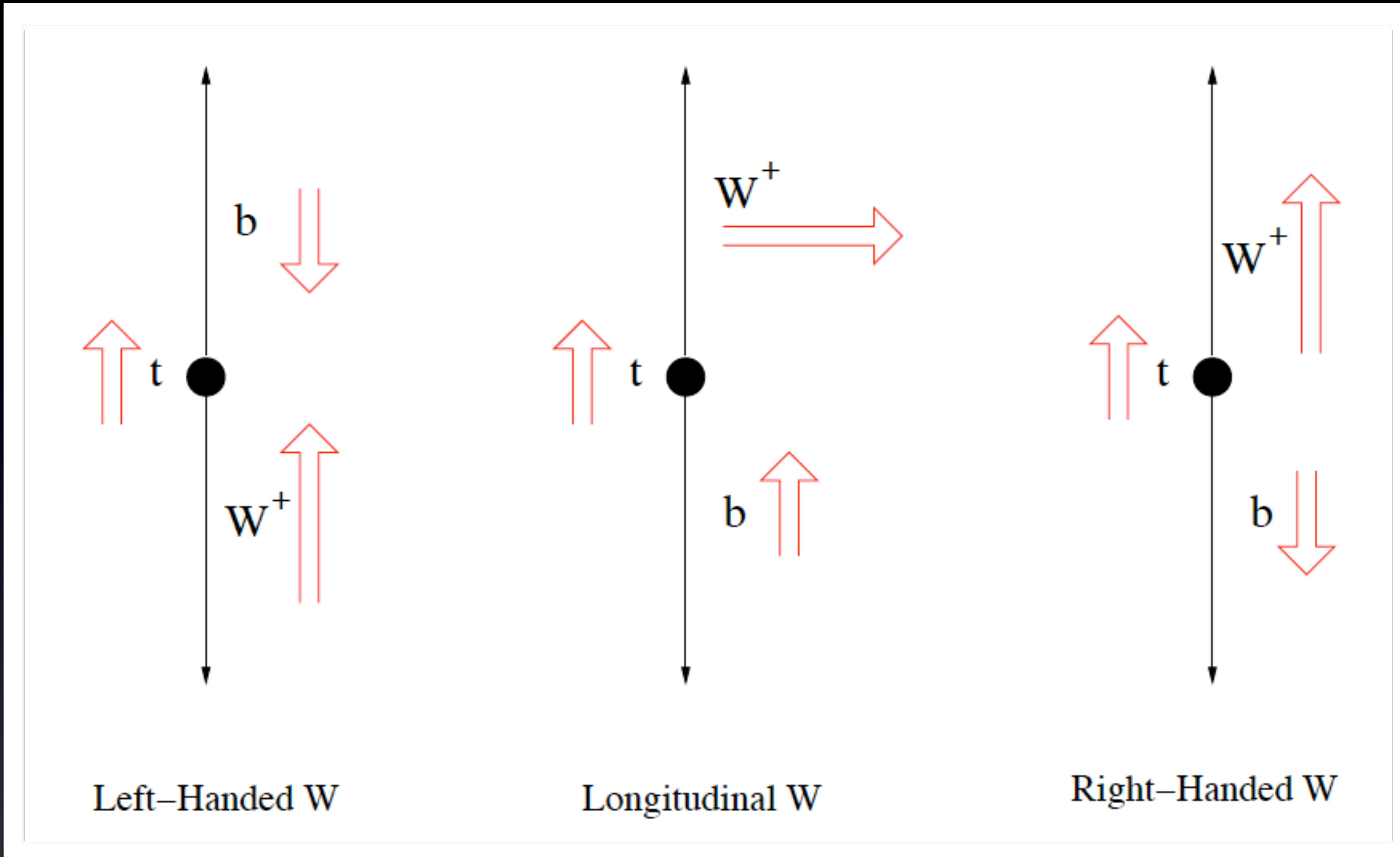
- Even though a measurement looks impossible, it isn't!
- First study using a 'small-ish' amount of data (i.e. not 10 fb^{-1} at 14 TeV)
- 200 pb^{-1} uncertainty is ±0.35, D∅ has ±0.59 with 4.2 fb^{-1}
- Maximal basis better than Helicity basis (A=0.46 vs 0.30)
- Template method more sensitive than unbiased estimators

- To-do:
  - Repeat analysis in easier (to reconstruct) lepton + jets channel
  - Update for 7 TeV

Slides inspired by those of Tim Head

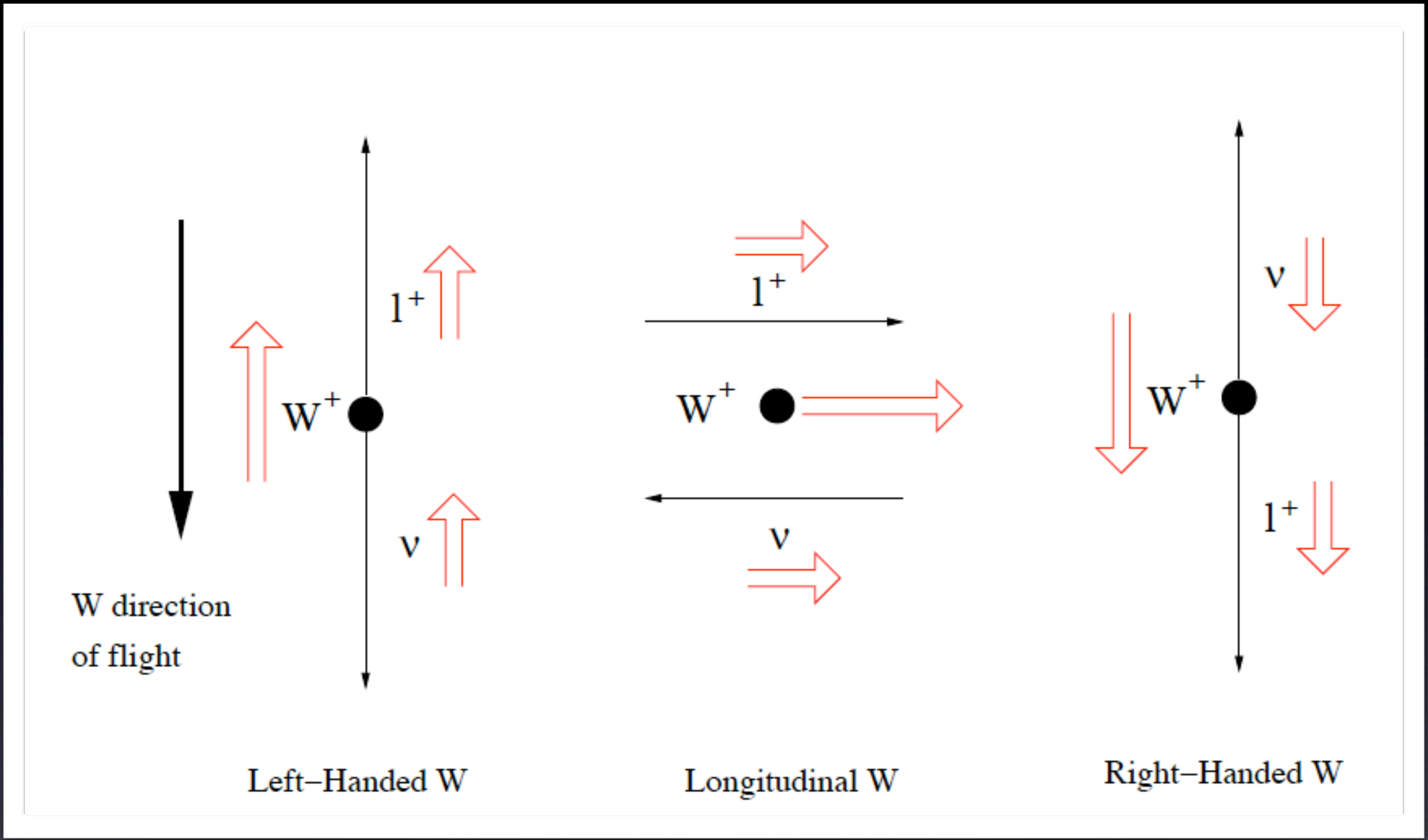
Didn't talk about

- LHC Maximal basis implementation in detail
- Alternative dilepton reconstruction method
    - Can write the equations describing ttbar system as a single quartic polynomial and solve analytically (no numerical methods)
- Measurements in the helicity basis
- Unbiased estimators
- Feldman Cousins confidence Interval



0.304 0.695

$$0.695 - 0.304 = \alpha_i(W)$$


W direction
of flight
W^+
l^+
ν
W^+
l^+
ν
W^+
ν
l^+
Left–Handed W
Longitudinal W
Right–Handed W