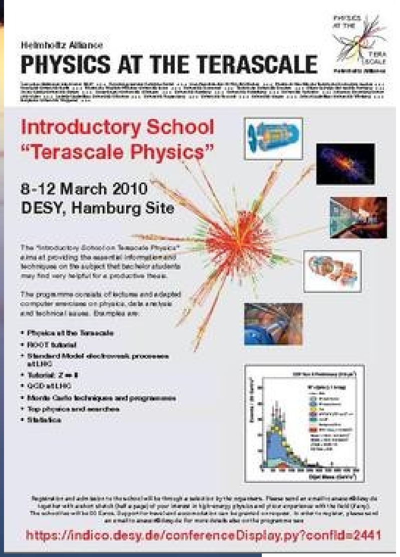
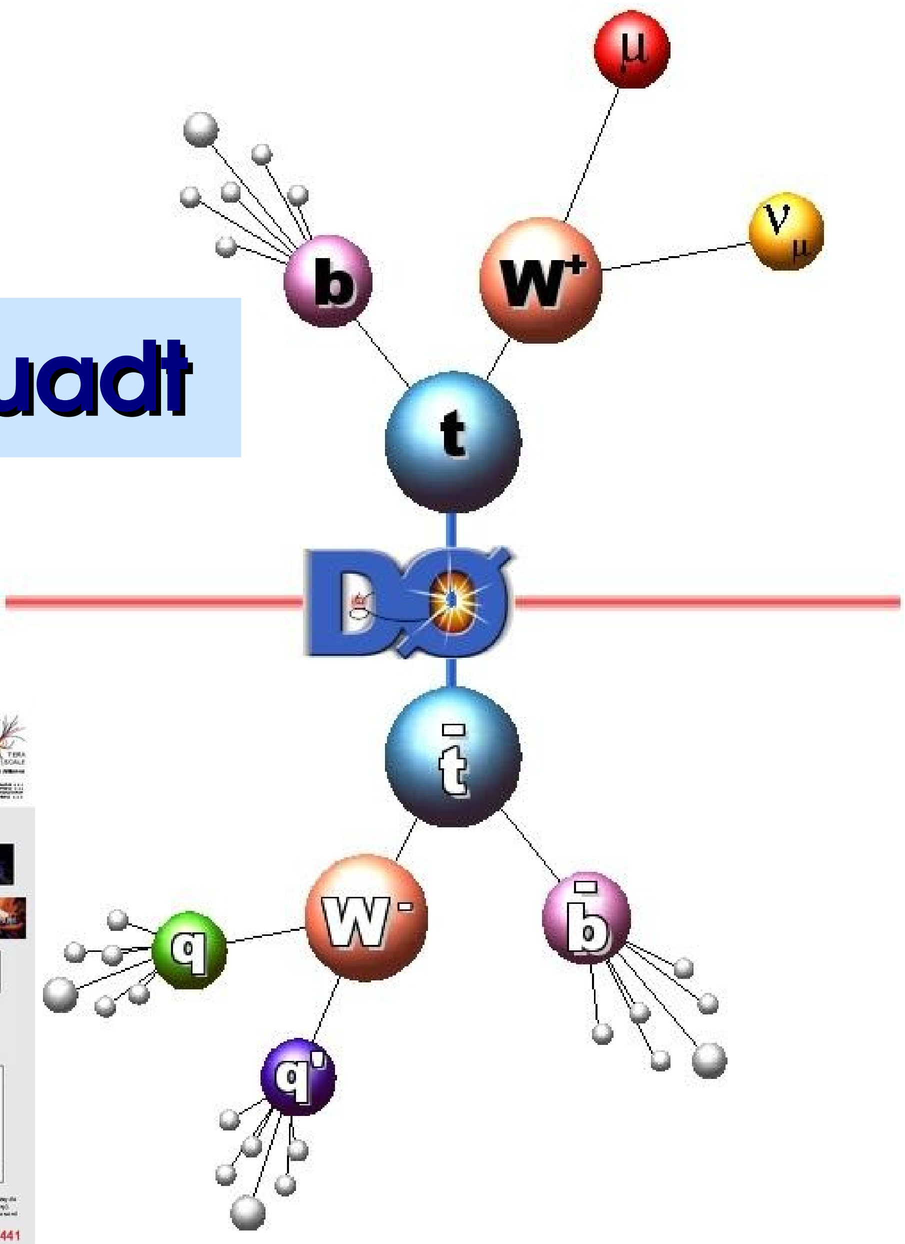
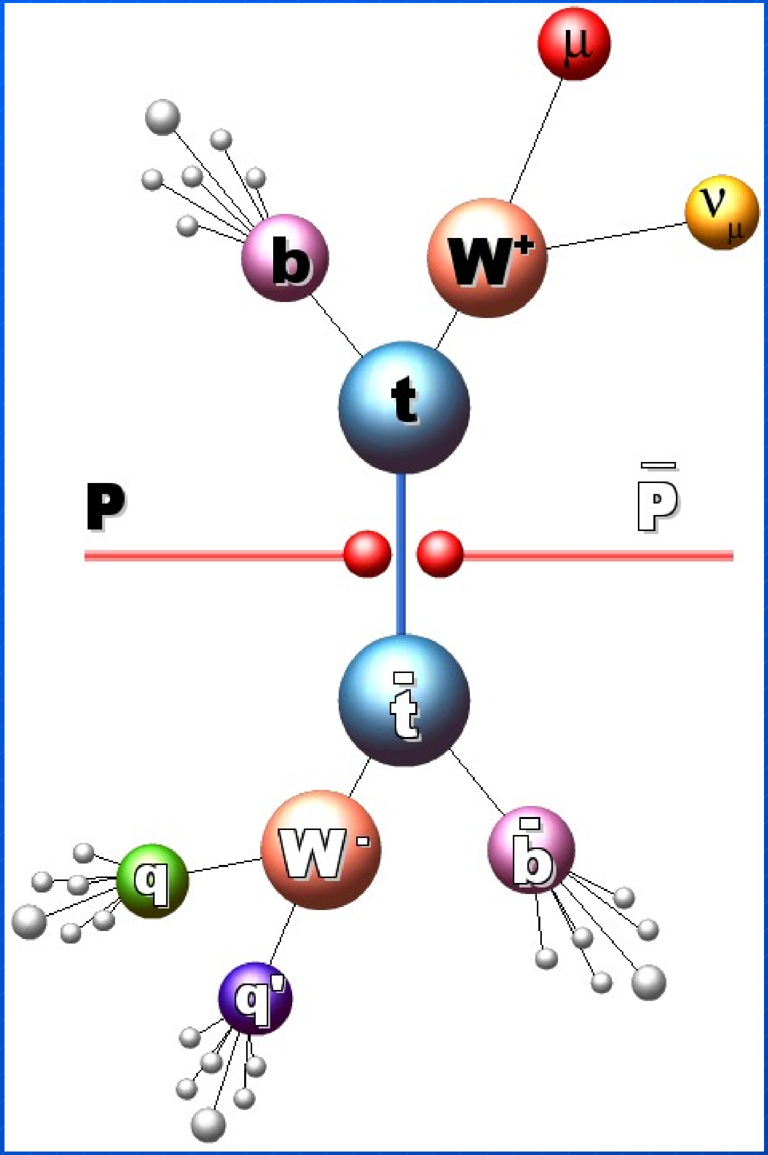
Physics of the Top Quark
Lecture 2

Arnulf Quadt





Top Quark Physics



Part 1

- Introduction
- discovery of the top quark
- experimental tools

Part 2

- top-antitop quark production (strong)
- ttbar Xsec (experimental)
- single-top quark production (weak)
- top quark mass
- top quark charge and spin
- W helicity in top quark decays

Strong Coupling

Top-Antitop Cross Section (1)

Question 4: Top Quark Production

Consider the top quark pair production process $p\bar{p} \to t\bar{t} + X$

In order to calculate the $t\bar{t}$ production cross-section in proton-antiproton collisions it is very helpful to recall the cross-section for the process $e^+e^- \to \mu^+\mu^-$, only mediated via photon exchange, i.e. the pure QED contribution:

$$\frac{d\sigma^{(e^+e^-\to\mu^+\mu^-)}}{d\Omega} = \frac{\alpha^2\beta_\mu}{16E^2}\left(1 + \frac{M^2}{E^2} + \beta_\mu^2 \cdot \cos^2\Theta\right) \quad (5)$$

$$\beta_\mu = \sqrt{1 - \frac{M^2}{E^2}} \text{ muon velocity} \quad (6)$$

$$M = \text{muon mass} \quad (7)$$

$$E = \text{muon energy} \quad (8)$$

$$\Theta = \text{muon scattering angle} \quad (9)$$

$$\frac{d\sigma^{(e^+e^-\to\mu^+\mu^-)}}{d\Omega} = \begin{cases} 0 \text{ for } E = M \\ \frac{\alpha^2}{16E^2}(1 + \cos^2\Theta) \text{ for } E \gg M \end{cases} \quad (10)$$

The two processes differ in

- that the electromagnetic coupling α has to be replaced by the strong coupling α_s.
- we have to consider that the exchanged gluons can come in different colour states, i.e. we need to include a colour factor.
- we need to know how many quarks of which energy in the proton can participate in the t-tbar production.

Top-Antitop Cross Section (2)

- The colour factor C_F of a reaction is given by $C_F = \frac{1}{2} C_1 C_2$ where C_1 and C_2 are the Clebsch-Gordan coefficients for coupling of quarks with the gluon octett. Complete the following table for the different colour states involved in the quark-antiquark annihilation, using the table of the gluon octet colour wave functions.

gluon colour states	quark colour combination	colour factor C_F
$(\bar{R}R) \cdot (\bar{B}B)$	$q_B \bar{q}_B \rightarrow q_B \bar{q}_B$	$\frac{1}{2} \cdot (\frac{1}{\sqrt{6}}) \cdot (\frac{-2}{\sqrt{6}}) = -\frac{1}{6}$
	$q_B \bar{q}_R \rightarrow q_B \bar{q}_R$	
	$q_B \bar{q}_R \rightarrow q_R \bar{q}_B$	
	$q_B \bar{q}_G \rightarrow q_B \bar{q}_G$	
	$q_B \bar{q}_G \rightarrow q_G \bar{q}_B$	
	.	
	.	
	.	
	permutations	

singlet	$\frac{1}{\sqrt{3}}(\vert R\bar{R} > + \vert G\bar{G} > + \vert B\bar{B} >)$
octet	$\vert G\bar{B} >$
	$\vert R\bar{B} >$
	$-\vert G\bar{R} >$
	$\frac{1}{\sqrt{2}}(\vert G\bar{G} > - \vert R\bar{R} >)$
	$\frac{1}{\sqrt{6}}(\vert R\bar{R} > + \vert G\bar{G} > -2\vert B\bar{B} >)$
	$\vert R\bar{G} >$
	$-\vert B\bar{R} >$
	$\vert B\bar{G} >$

  Taking all the permutations into account we need to calculate $3 \times \sum_i (C_F)_i^2$. Explain why.

  Equivalently to the argument of spin summation and averaging in lepton scattering we now need to average over the the colours of the incoming quarks. Show that the total colour factor is $\frac{2}{9}$.

- Let's now calculate the cross-section $\sigma(q\bar{q} \rightarrow t\bar{t})$ by integrating (5) over the solid angle. Show that this integration yields

  $\sigma(q\bar{q} \rightarrow t\bar{t}) = \frac{\pi \alpha_s^2}{27 m_t^2} \rho_t (2 + \rho_t) \sqrt{1 - \rho_t}$

  where $\rho_t = \frac{4m_t^2}{\hat{s}}$ and $\hat{s}$ is the centre-of-mass energy in the quark-antiquark system.

- Only considering valence quarks how many combinations of quark-antiquark pairs can we get in the initial state ?

- Estimate the quark-antiquark centre-of-mass energy squared, $\hat{s}$, for the Tevatron Run-I, i.e. for proton-antiproton collisions with centre-of-mass energy $\sqrt{s} = 1.8$ TeV.

- Approximate $\alpha_s(m_t) \approx 0.1$ and plug in all numbers to calculate $\sigma_{(p\bar{p} \rightarrow t\bar{t})}^{\sqrt{s}=1.8\ \mathrm{TeV}}$.

Top-Antitop Cross Section (4)

partonic to hadronic ttbar cross section:

$$\frac{d\sigma_{p\bar{p}}}{dz} = \sigma_{q\bar{q}}(z s)\ \ L_{q\bar{q}}(z)$$

$$\text{Def.:}\quad z = z_1 z_2 \qquad r = z_1 / z_2$$

$$L_{q_i \overline{q_j}}(z) = \int_z^{1/z} q_i(\underbrace{\sqrt{zr}}_{z_1})\ \ q_j(\underbrace{\sqrt{z/r}}_{z_2}) \frac{1}{2r} dr$$

PDF parametrisation:

$$x u_v(x) = 1.78\, x^{0.5} (1 - x^{1.51})^{3.5}$$

$$x d_v(x) = 0.67\, x^{0.4} (1 - x^{1.51})^{4.5}$$

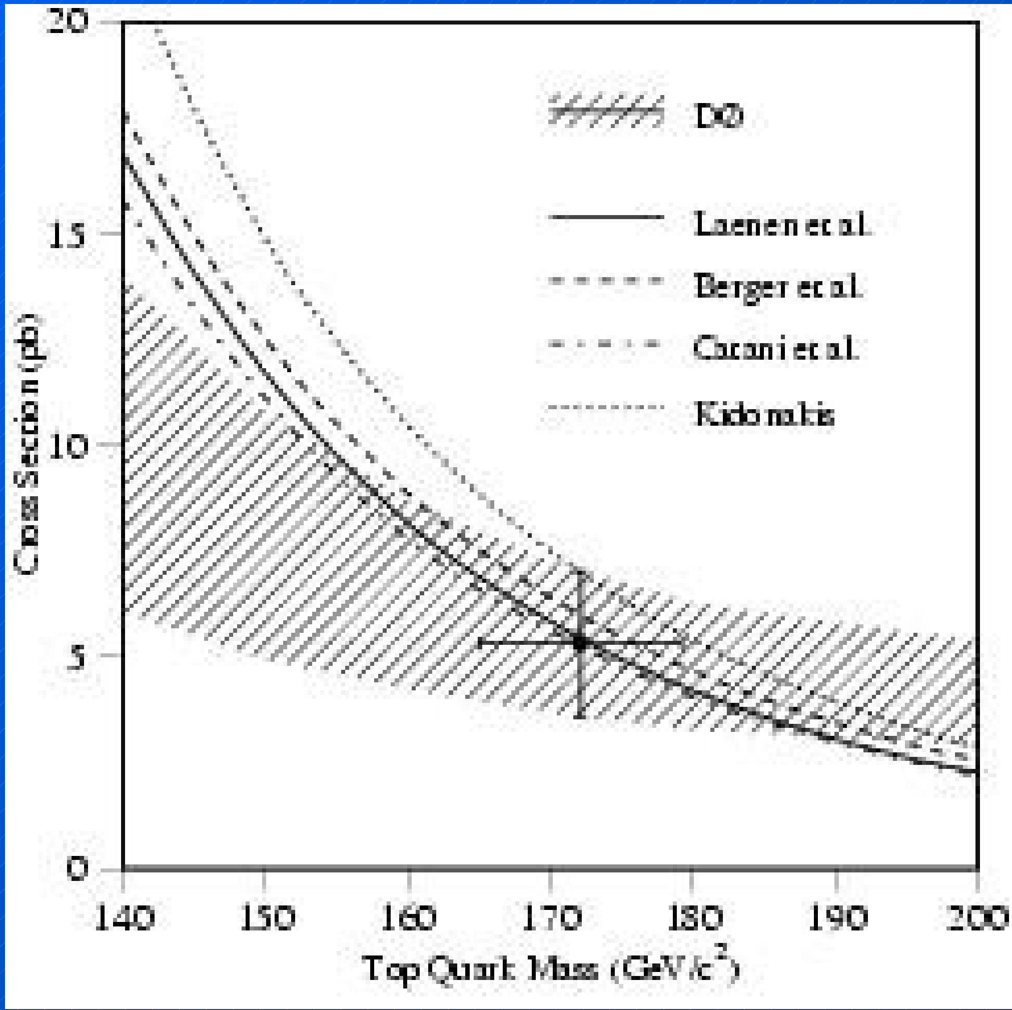
$$x u_s(x) = 0.182 (1 - x)^{8.54}$$

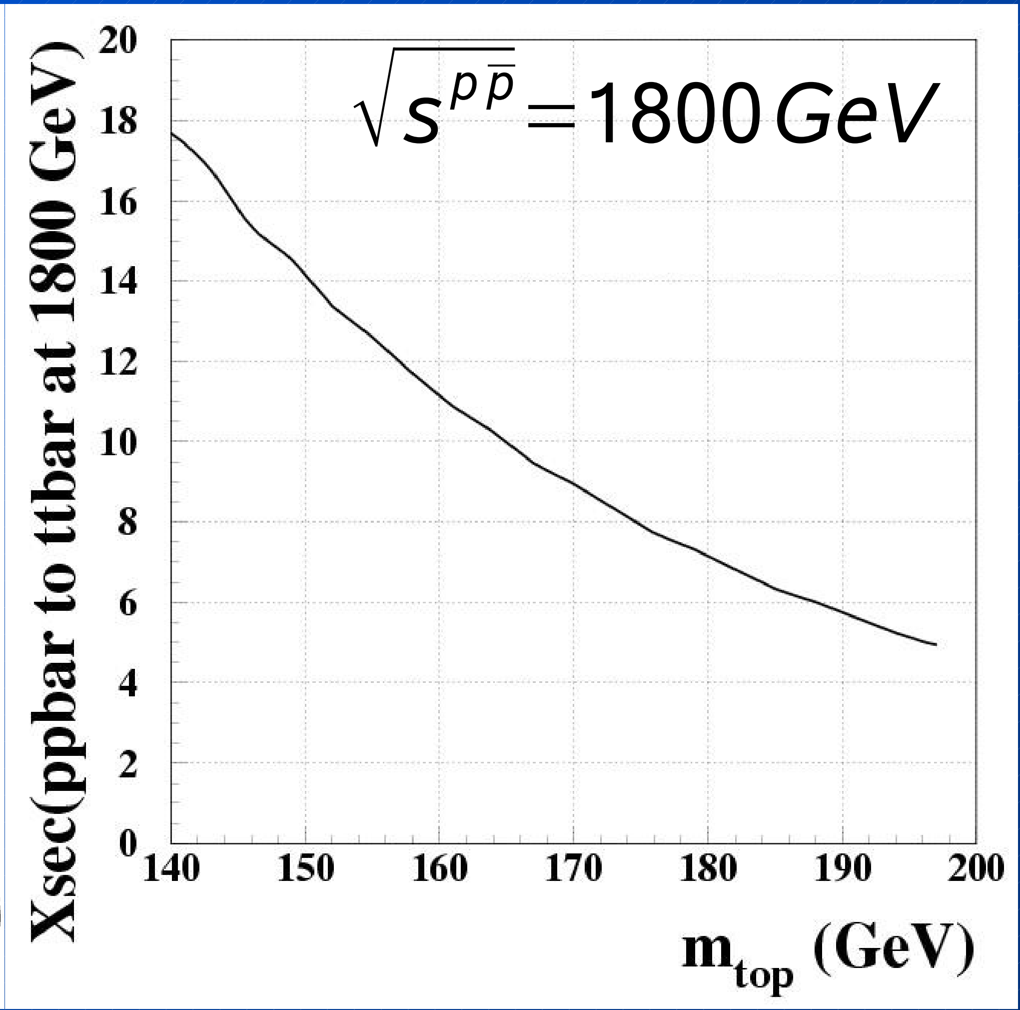
$$x d_s(x) = x u_s(x)$$

$$x s_s(x) = 0.081 (1 - x)^{8.54}$$

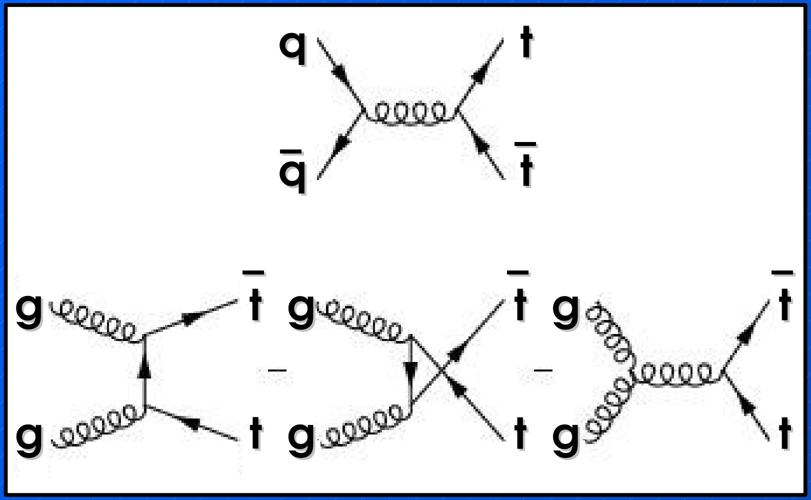
Top-Antitop Cross Section (5)

result of numerical integration from previous page:

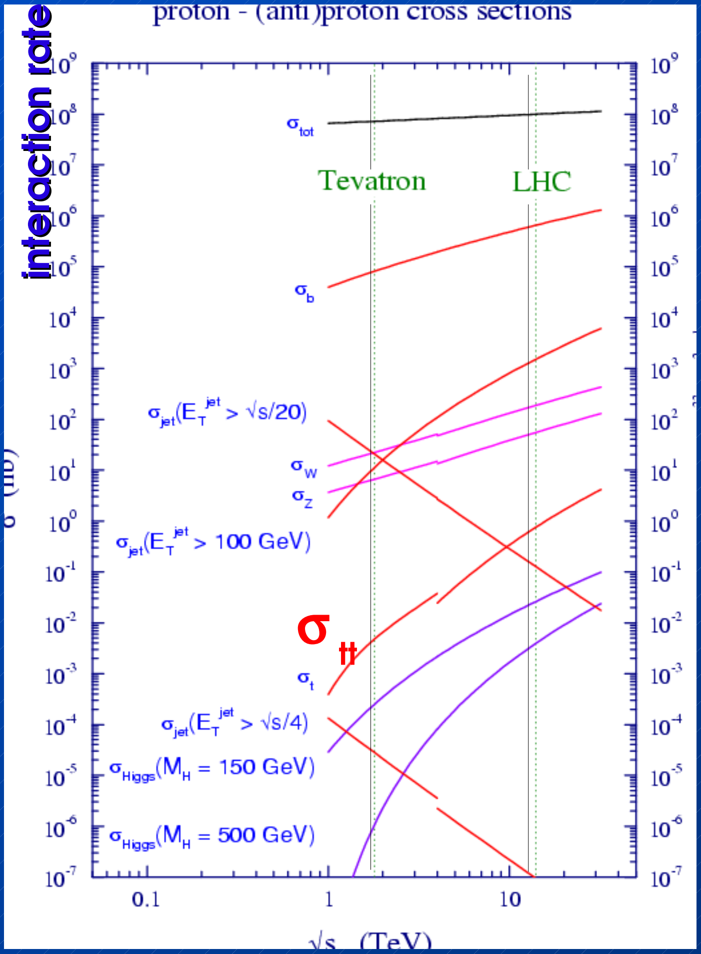




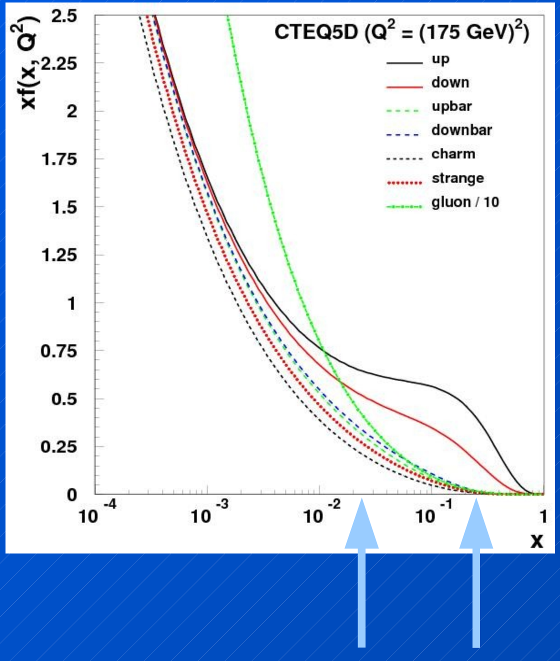
Strong Top Quark Production



	Tevatron	LHC
$q\bar{q}$ ~ 85 %		15%
gg ~ 15 %		85%



	Run I	Run II (2 fb^{-1})	LHC (10 fb^{-1})
nr ttbar (m_t sample ≥ 1 b-tag)	20	800	8 * 10^6



LHC Tevatron

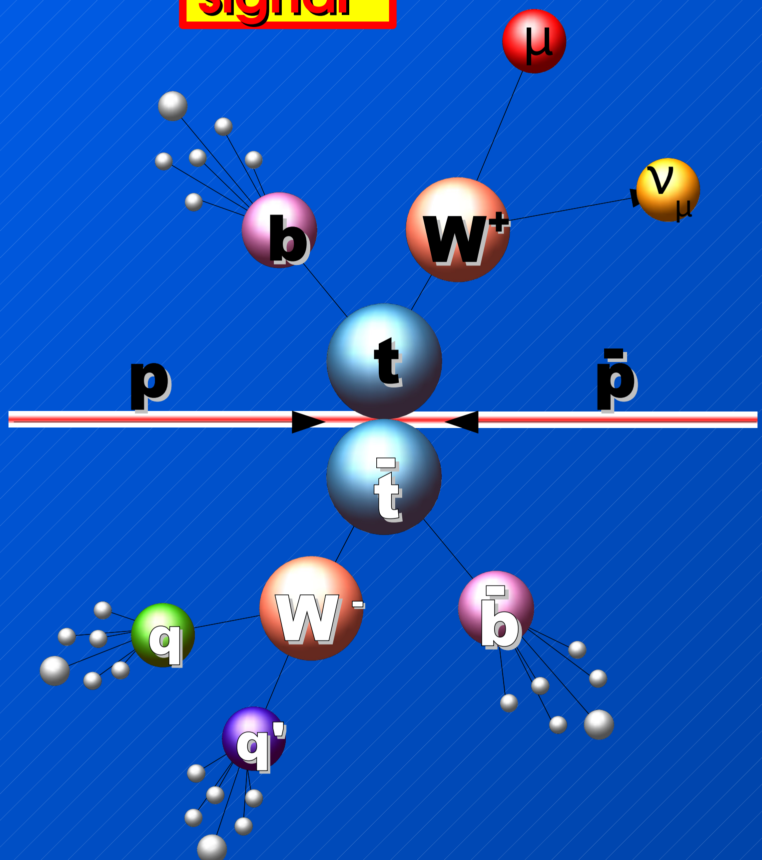
Ttbar Xsec Measurements at Tevatron

dilepton	Topological selection (lepton p_T, MET, Njets)	➪ counting experiment
	b-tag selection (lepton p_T, MET, SVX-tag, Njets)	➪ counting experiment
	lepton+track (lepton p_T, MET, isolated track, Njets)	➪ counting experiment
	dilepton 2-dim. (MET,Njet) fit for ttbar, WW, $Z\to\tau\tau$	➪ 2-dim. fit
l+jets	Topological selection (e/μ+jets, lepton p_T, MET, Njets), topological & kinematic variables, 1-dim. fit	➪ 1-dim. fit
	b-tag selection (e/mu+jets, lepton pT, MET, Njets), b-tag (SVX, IP, jet-prob., soft-μ)	➪ counting experiment
	kinematic fit (MET or jet ET) in b-tagged events	➪ 1-dim. fit
	combined fit of 0, 1, 2-tag sample and $B(t\to Wb)/B(t\to Wq)$	➪ 2-dim. fit
alljets	Kinematic & topological selection, Njet distribution	➪ 1-dim. fit
	Kinematic & topological selection, ANN-output	➪ counting experiment

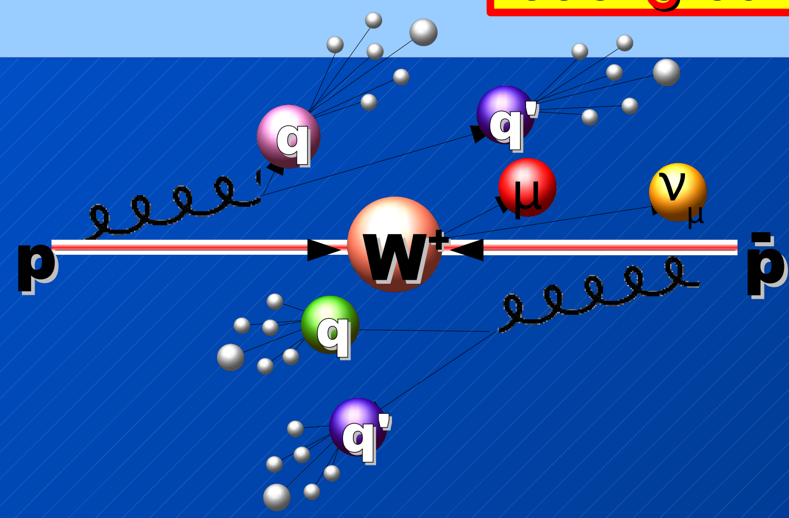
Event Topology in Lepton+Jets

- 1 lepton with high p_T
- 1 ν (reconstructed as transverse energy (met))
- ≥ 4 jets

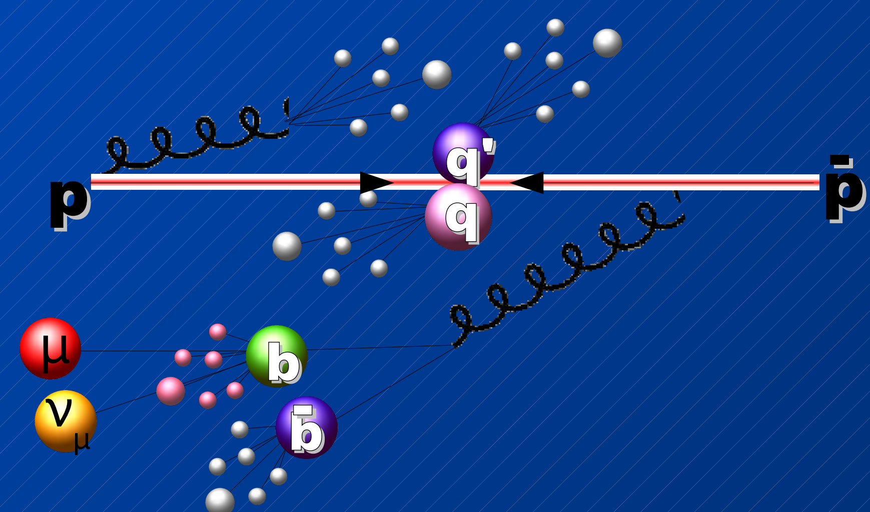
signal



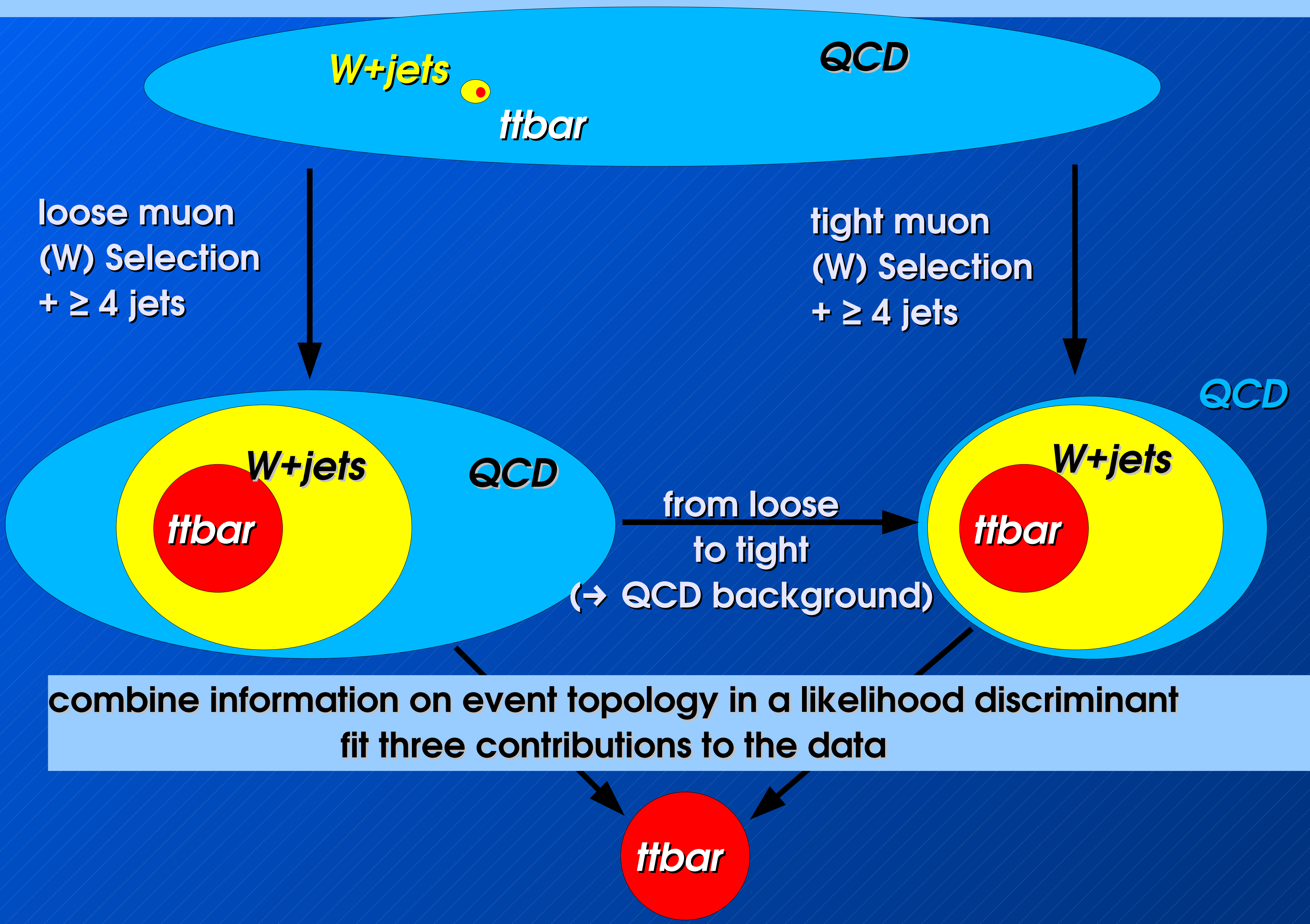
background



multijet background (QCD)
+ misreconstructed met
+ fake isolated μ or e



Overview over μ+Jets Analysis



Topological Xsec in L+Jets (I)

Select l+ ≥ 4 jet events in 230 pb^{-1}
choose topological variables:

- with **strong separation** potential
- with **small sensitivity** to **jet energy scale**

use the following 6 variables:

angular dependent:

- sphericity
- aplanarity
- centrality

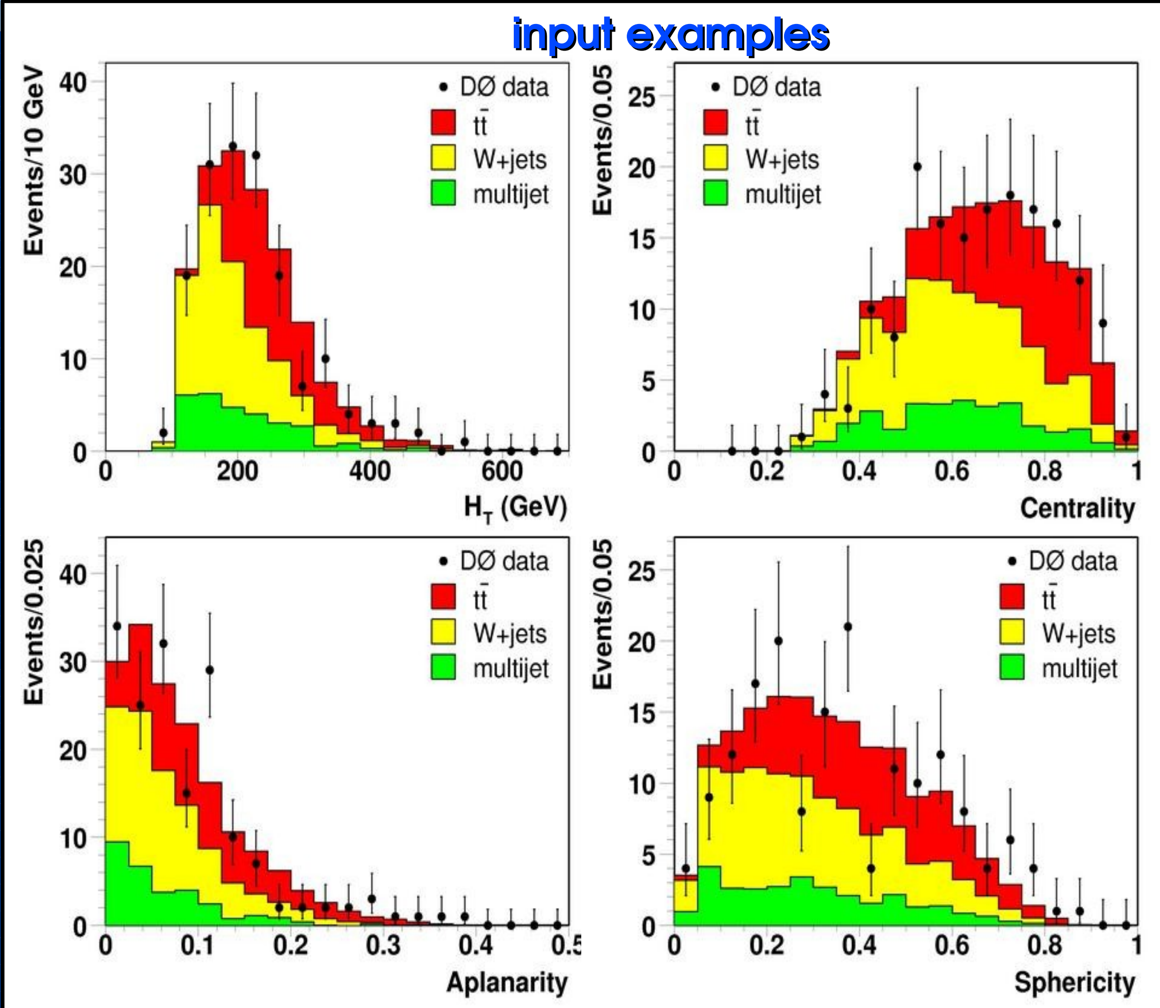
energy-dependent quantities:

- H_T
- $K_{t,min}$

Background sensitive quantities:

- $\Delta\ \varphi(l,MET)$

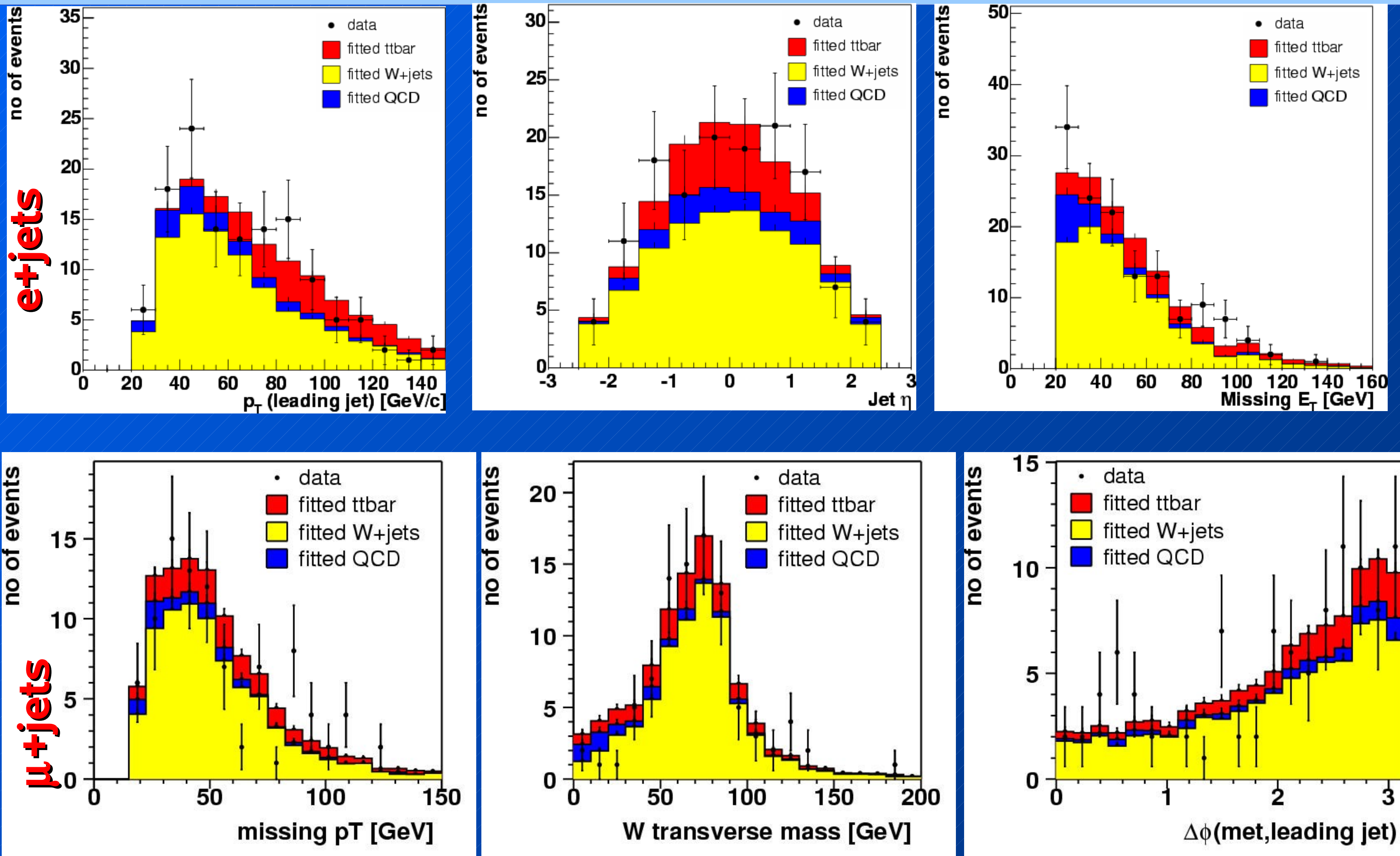
topological likelihood:



$$P = \frac{\prod_i S_i}{\prod_i S_i + \prod_i B_i}$$

i=1..6,
S = tt̄-distribution,
B = Wjjjj-distribution

Kinematic Distributions in l+jets Channel



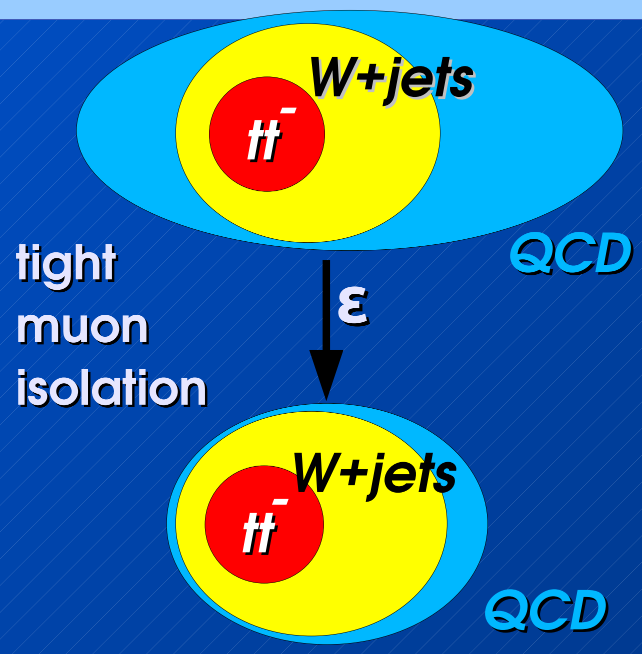
Determination of Multijet Background

μ+jets

$$N_{loose} = N_{QCD} + N_{W+ttbar}$$

$\downarrow \varepsilon$ $\quad \varepsilon_{QCD} = 8\% \downarrow$ $\quad \varepsilon_{W+ttbar} = 82\% \downarrow$

$$N_{tight} = \varepsilon_{QCD} * N_{QCD} + \varepsilon_{W+ttbar} * N_{W+ttbar}$$



- N_{loose} und N_{tight}: Signal-Datensatz

- ε_{QCD} : independent multijet (QCD) data set (met < 10 GeV)
- $\varepsilon_{W+ttbar}$: W+Jets Monte Carlo simulation
  (Monte Carlo to Data calibration from Z+Jets events)

→ solve equations for N_{QCD} and $N_{W+ttbar}$
→ determine multijet (QCD) background entirely from data

Topological Event Likelihood

choose topological variables:

- with **strong separation** potential
- with **small sensitivity to jet energy scale**

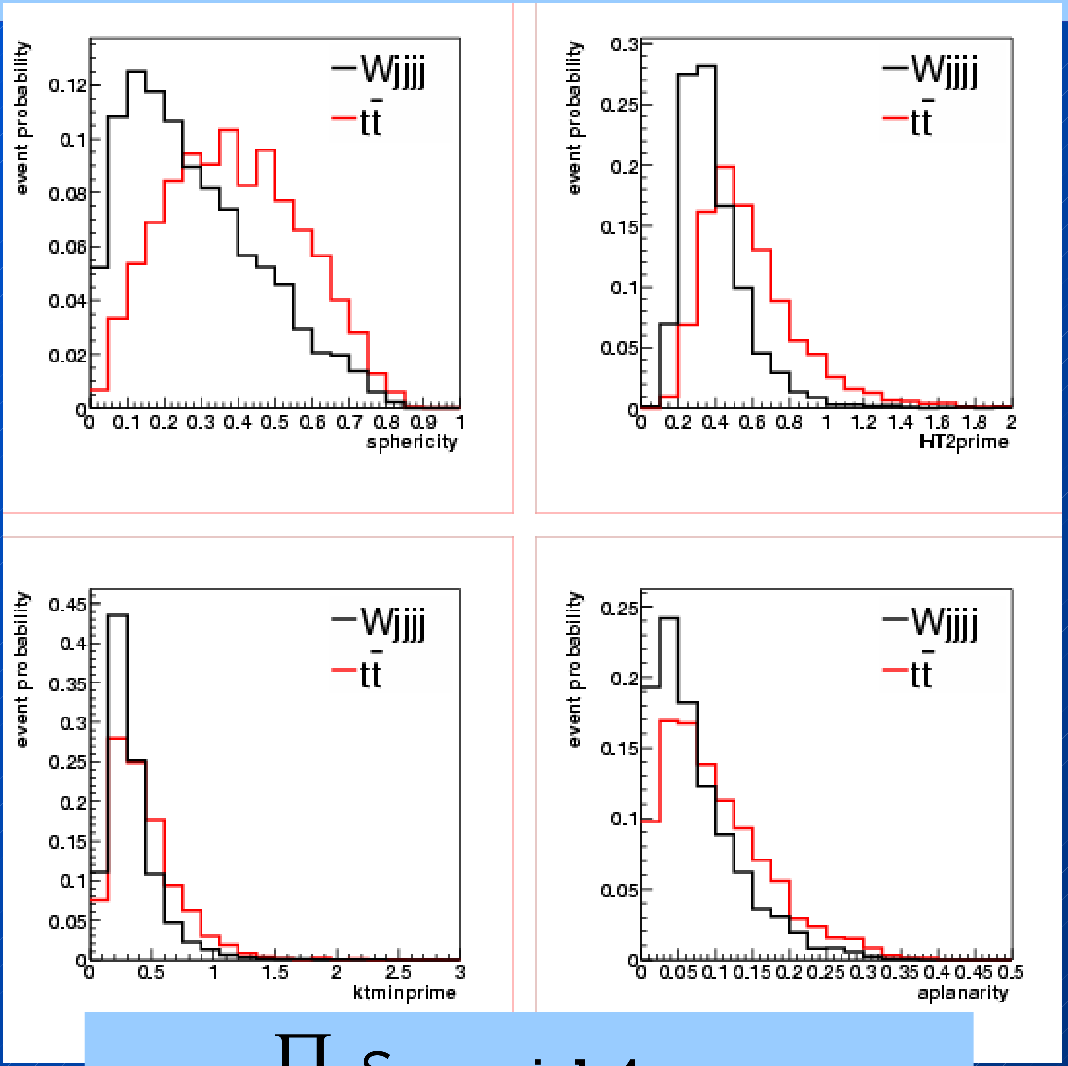
use the following variables:

angular dependent:

- sphericity
- aplanarity

ratio of energy-dependent quantities:

- HT2prime
- ktminprime



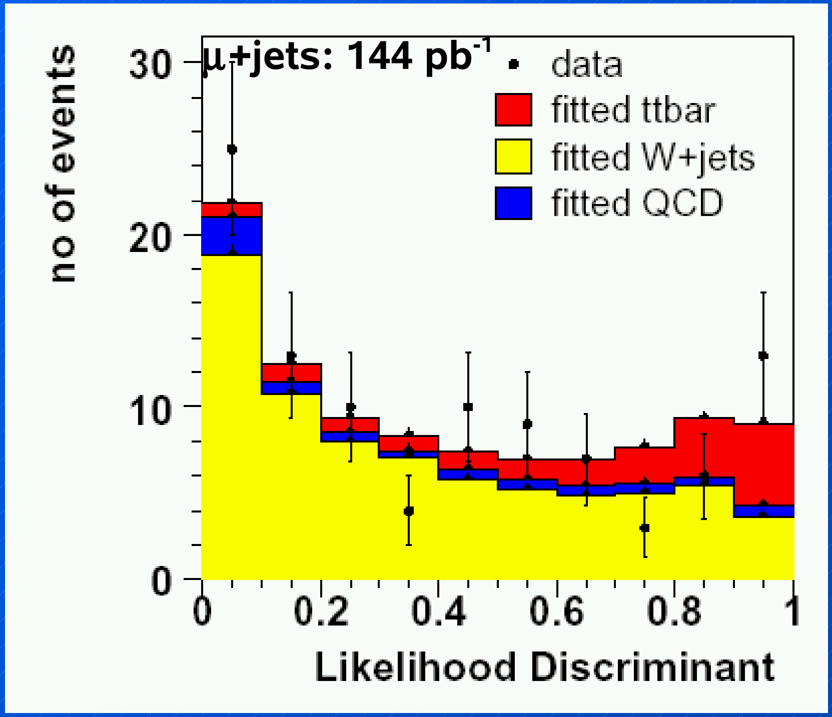
topological likelihood:

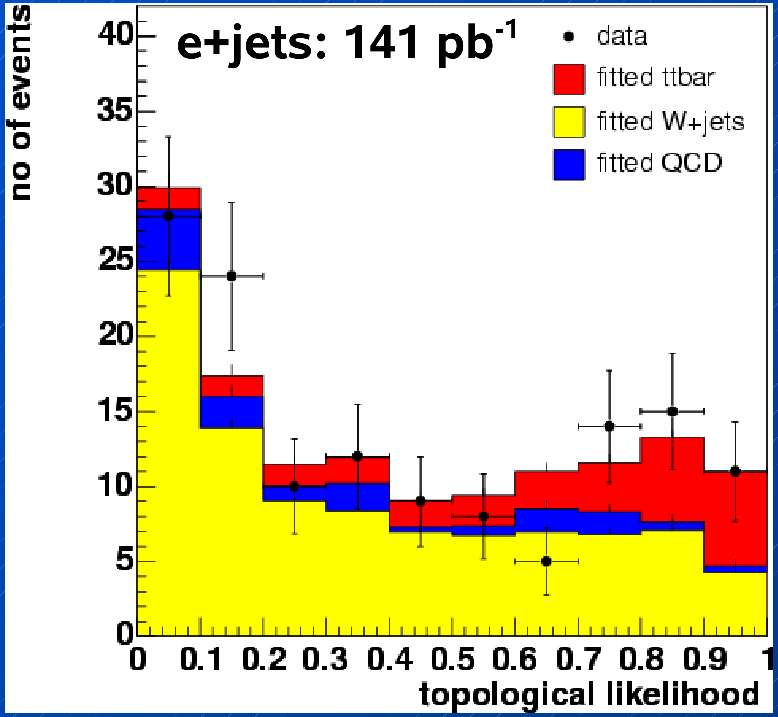
$$P = \frac{\prod_i S_i}{\prod_i S_i + \prod_i B_i}$$

i=1..4,
S = tt̄-distribution,
B = Wjjjj-distribution

Likelihood Fits in l+jets Channel

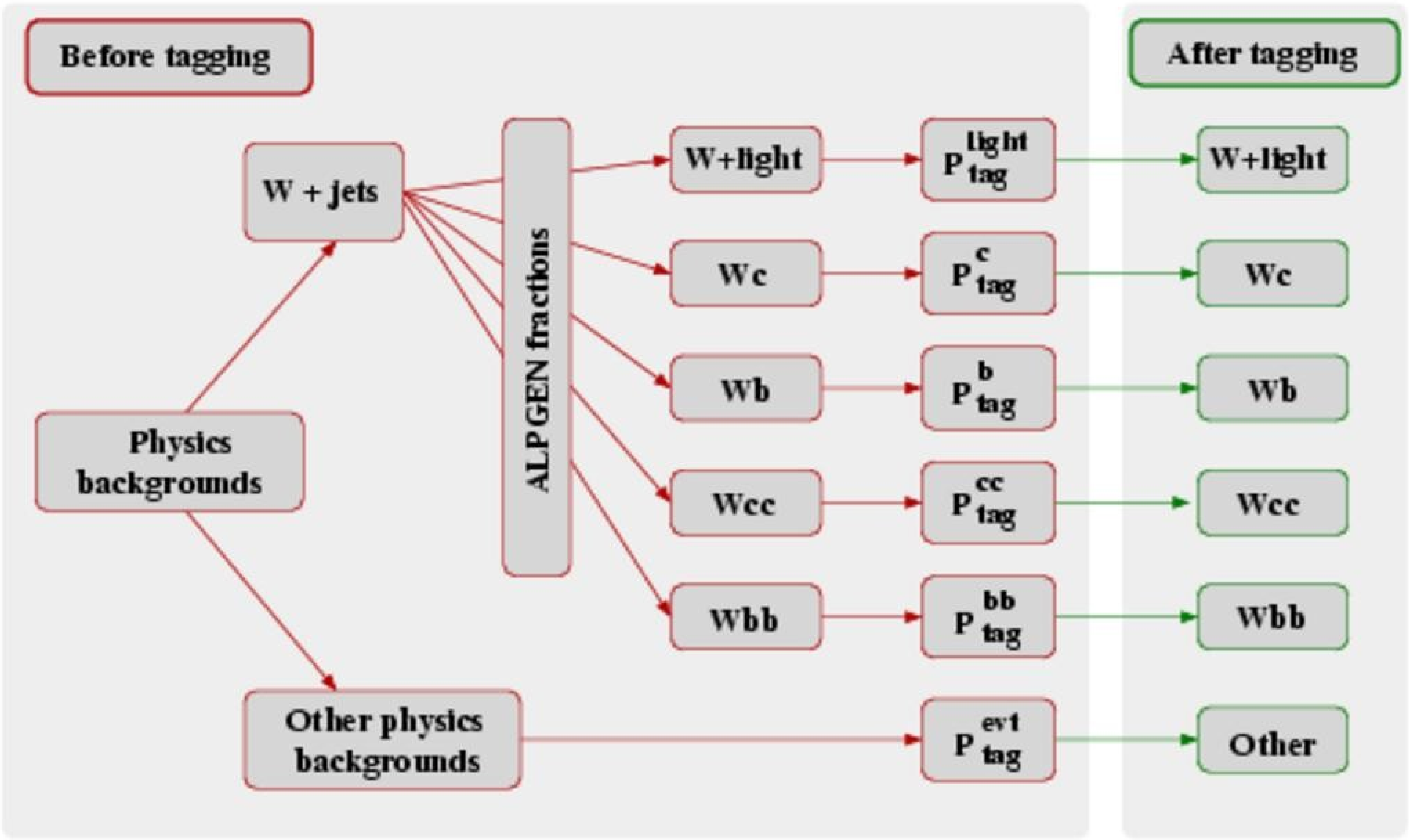
fit linear combination of QCD (inverted tight selection in data), W+4jet and ttbar to data





	muons	*electrons*
Nev	*100*	*136*
fitted N^W	*74.7 + 12.7 – 12.0*	*94.6 + 15.8 - 15.0*
fitted N^{QCD}	*7.1 + 0.9 – 0.9*	*14.1 + 1.2 - 1.2*
fitted N^{tt}	*17.8 + 9.9 – 8.7*	*27.5 + 12.7 - 11.7*

B-Tag Xsec in L+Jets



$$N_{expected}^{tag} = N_{t\bar{t}}^{untagged}(\sigma_{t\bar{t}}) \times P_{tag}^{t\bar{t}} + \sum_{bgd} N_{bgd}^{untagged} \times P_{tag}^{bgd}$$

SecVtx tagger

Single Tag:

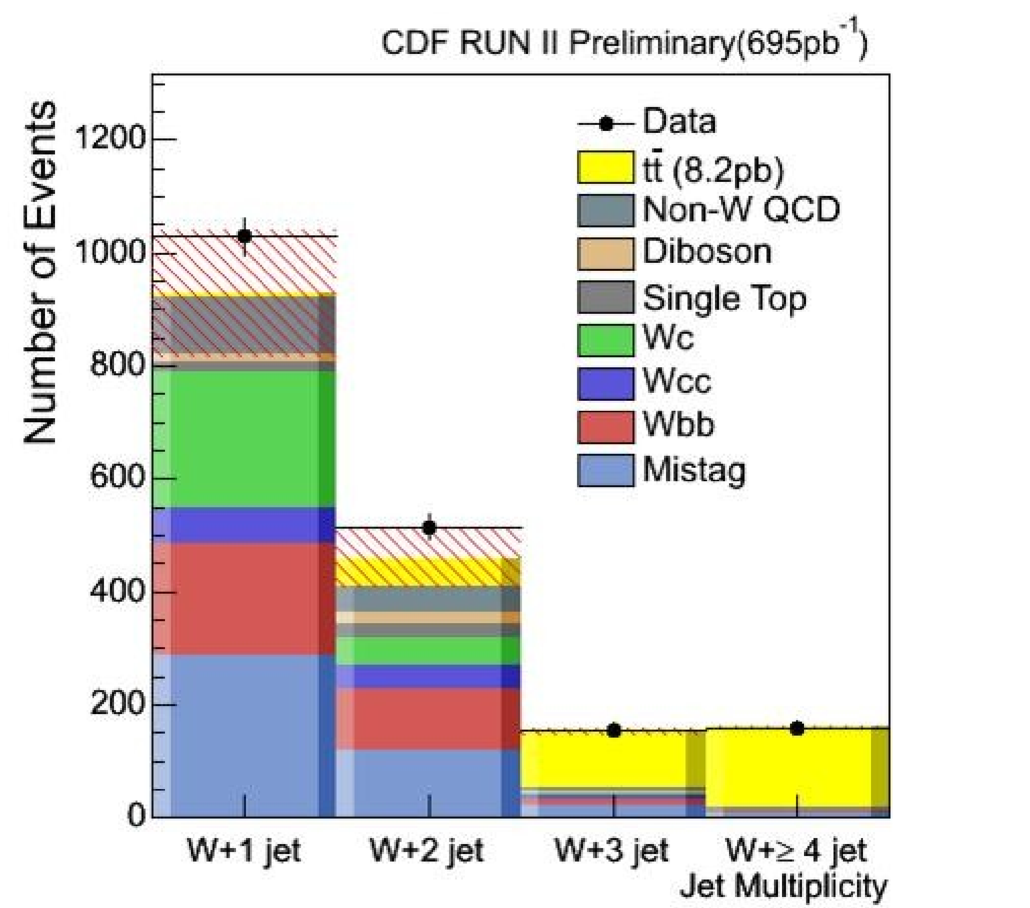
$$P_{tag}^{t\bar{t}} = 53.4\,\%$$

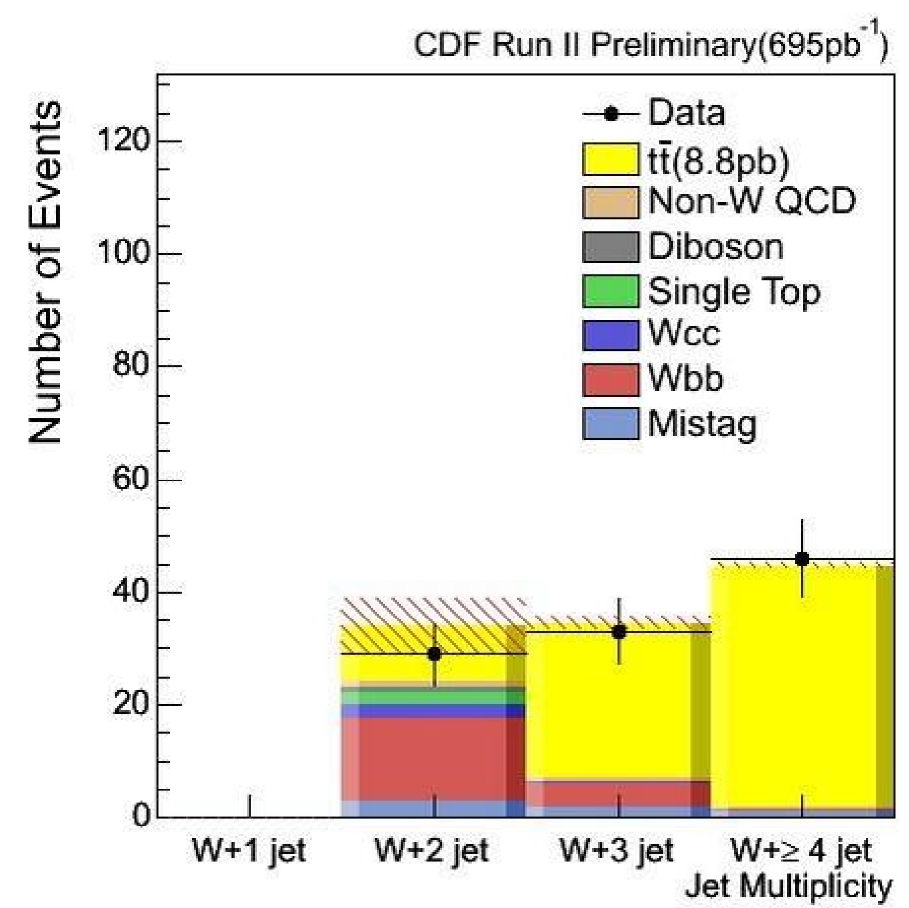
$$P_{tag}^{W+light} = 1.7\,\%$$

Double Tag:

$$P_{Dtag}^{t\bar{t}} = 16\,\%$$

B-Tag Xsec in L+Jets





$$\sigma_{tt} = 8.2 \pm 0.6 (stat.) \pm 1.0 (syst.)\, pb$$

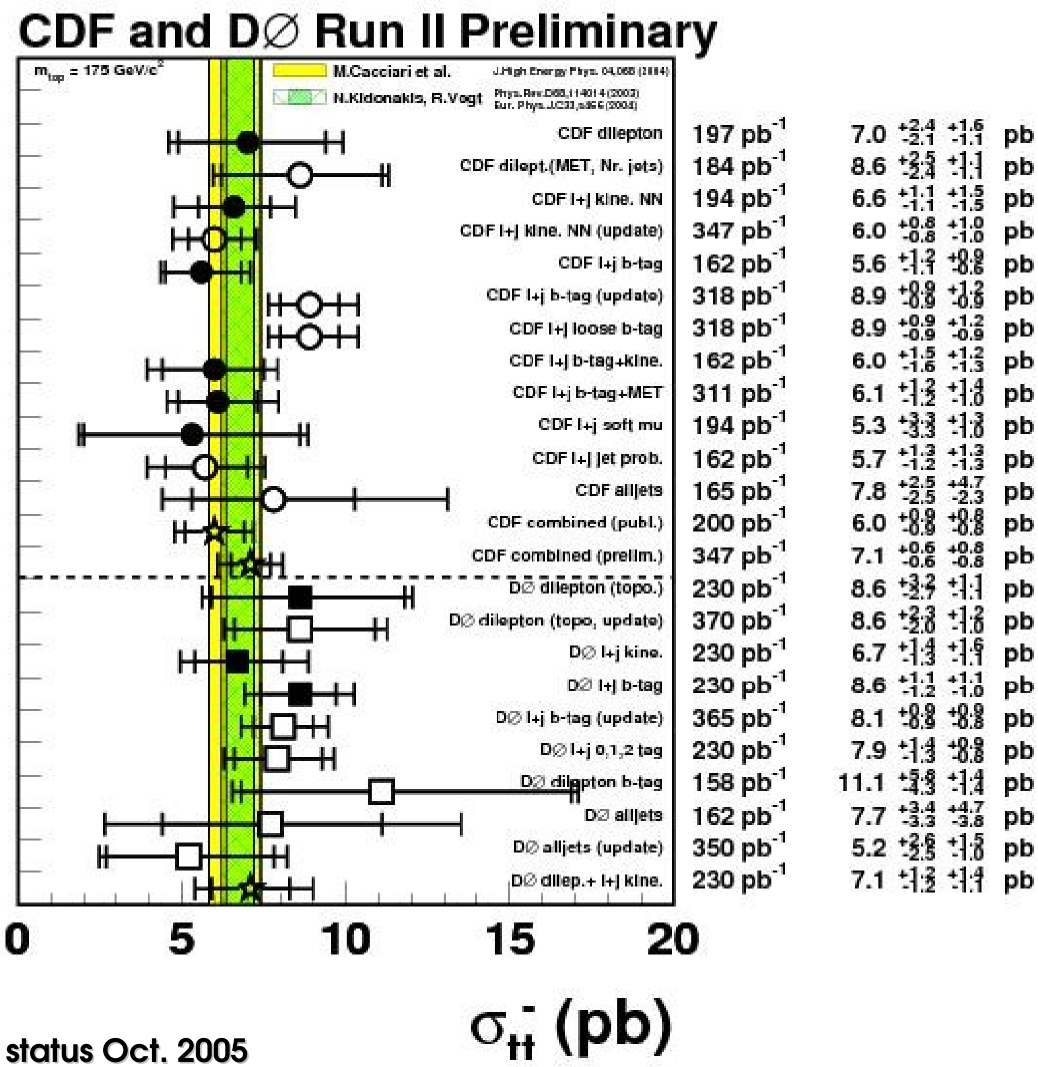
$$\sigma_{tt} = 8.8^{+1.2}_{-1.1} (stat.)^{+2.0}_{-1.3} (syst.)\, pb$$

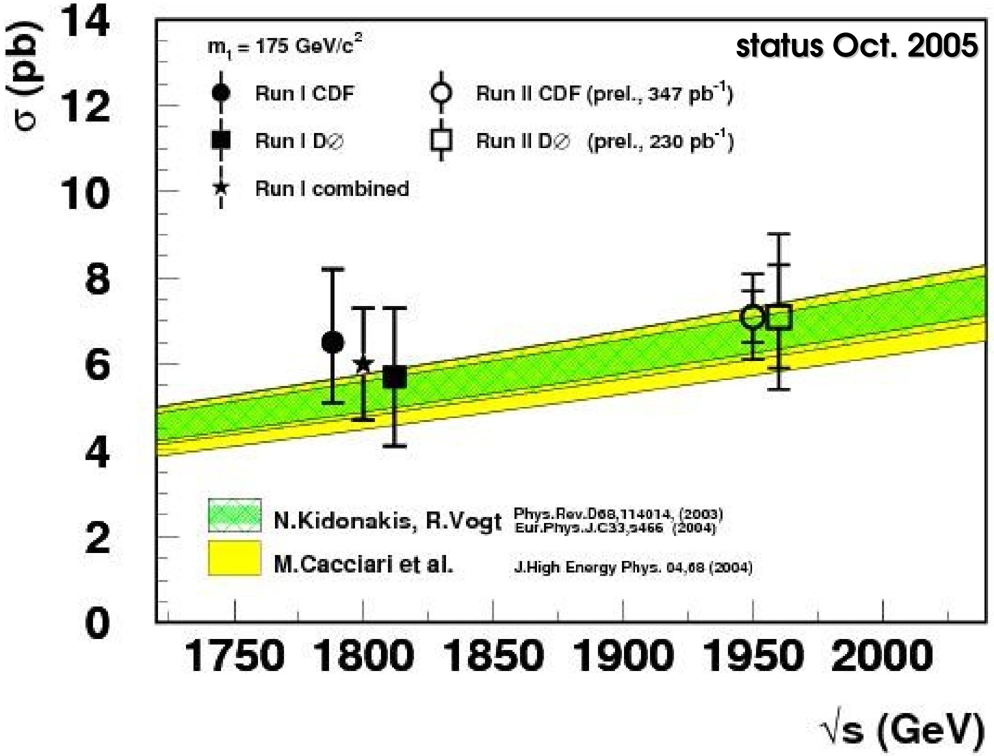
Systematics dominated by b-tagging ...

Similar analysis by DØ (365 pb^{-1}):

$$\sigma_{tt} = 8.1^{+1.3}_{-1.2} (stat. + syst.) \pm 0.5 (lumi)\, pb$$

Run II Top Cross Section - Summary

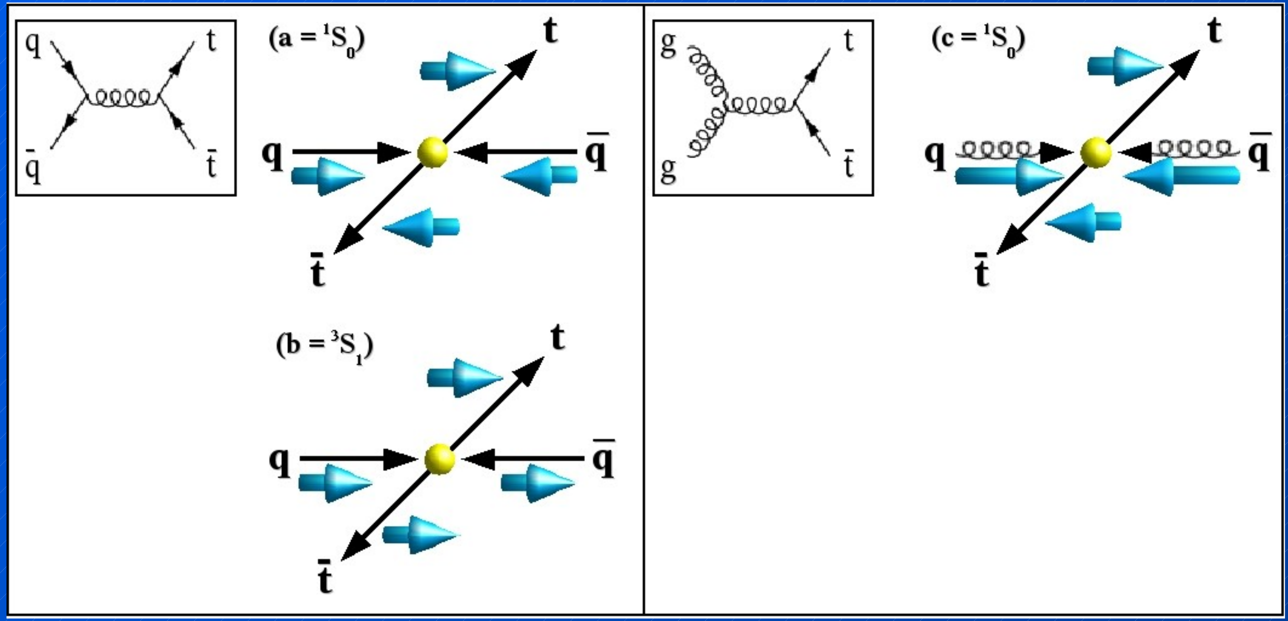




errors between different channels
are correlated

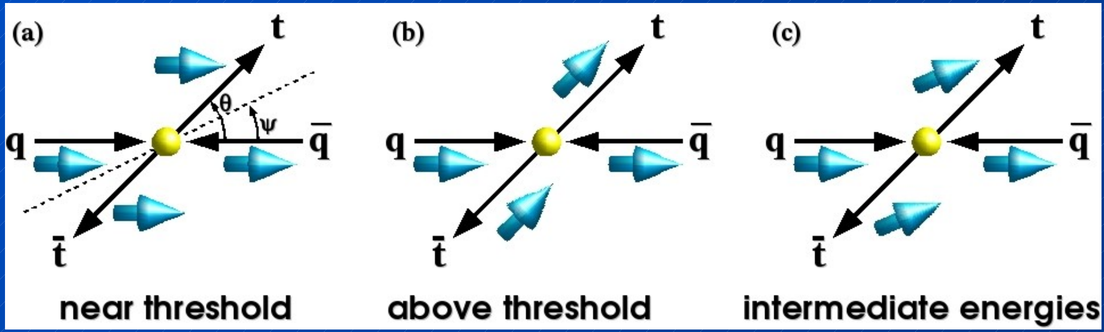
Spin Correlations in $t\bar{t}$

Test production mechanism and QCD predictions:



in qq annihilation, opposite-helicity (b) production dominates
in gg annihilation, equal-helicity (c) production dominates

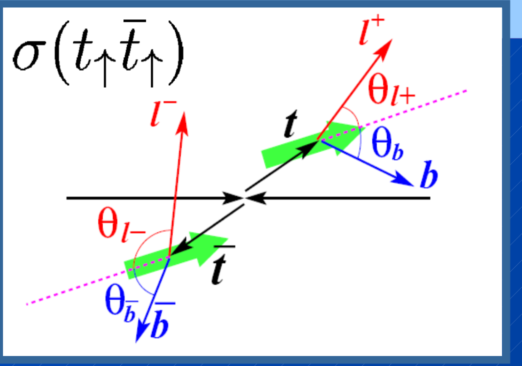
Three helicity basis:



Spin Correlations at LHC

The best way to access the **top spin** is to study the angular distribution of its decay products:

$$t \rightarrow Wb \rightarrow l\nu(j_1 j_2)b$$

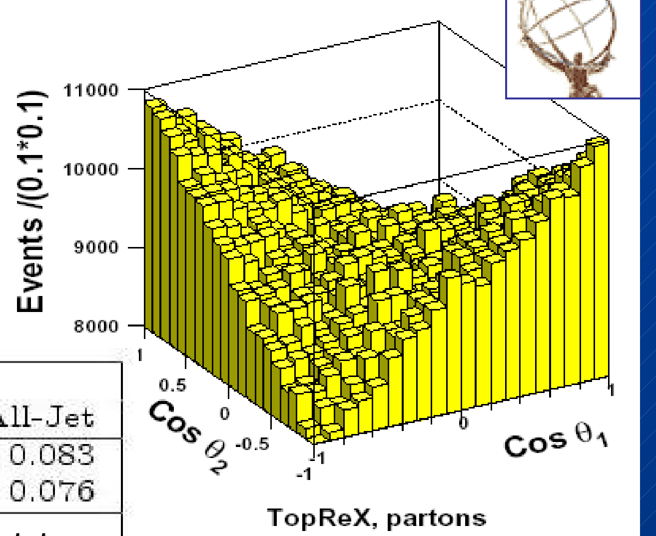


$$\mathcal{A} = \frac{N(t_L\bar{t}_L + t_R\bar{t}_R) - N(t_L\bar{t}_R + t_R\bar{t}_L)}{N(t_L\bar{t}_L + t_R\bar{t}_R) + N(t_L\bar{t}_R + t_R\bar{t}_L)}$$ → *measure asymmetries*

$$\frac{1}{N}\frac{d^2N}{d\cos\theta_l\, d\cos\theta_q} = \frac{1}{4}(1 - \mathcal{A}\kappa_l\kappa_q \cos\theta_l \cos\theta_q)$$

κ_i **spin analyzing power**

TeVatron result (DØ)
κ>-0.25 @ 68% CL



		$p\bar{p}$ at $\sqrt{s} = 1.96$ TeV			pp at $\sqrt{s} = 14$ TeV		
		Dilepton	Lepton-Jet	All-Jet	Dilepton	Lepton-Jet	All-Jet
$\kappa_{heli.}$	LO	-0.471	-0.240	-0.123	0.319	0.163	0.083
	NLO	-0.352	-0.168	-0.080	0.326	**0.158**	0.076
κ_{beam}	LO	0.928	0.474	0.242	(-0.005)		
	NLO	0.777	0.370	0.176	(-0.072)		
$\kappa_{off-diag.}$	LO	0.937	0.478	0.244	(-0.027)		
	NLO	0.782	0.372	0.177	(-0.089)		

W.Bernreuther *et al.*, Nucl.Phys. B690 (2004) 81

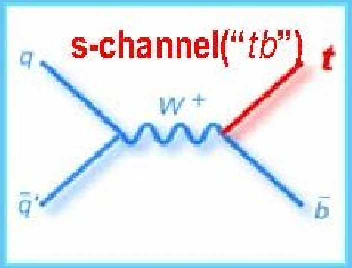
TopRex, S.R.Slabospitsky and L.Sonnenschein, Comp.Phys.Commun. 148 (2002) 87

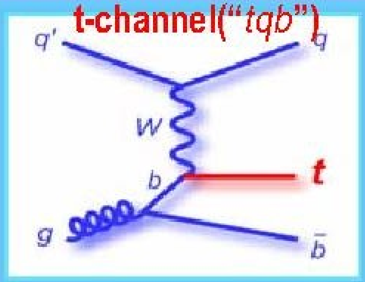
Main systematic uncertainties: parton generation (PDFs and Q² scale), FSR, b-jet energy scale and top quark mass uncertainty

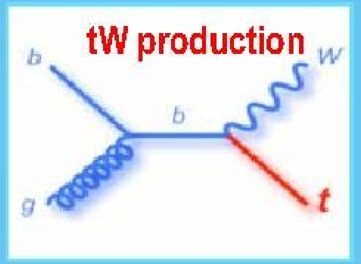
Both CMS and ATLAS have sensitivity for observing spin correlations after 10 fb⁻¹

Weak Coupling

Single Top Production



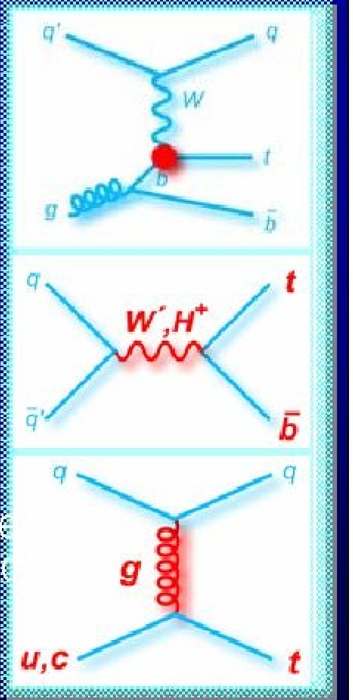




	s-channel	t-channel	tW production
Tev:	σ ~1 pb	σ ~ 2pb	σ ~0.25 pb
LHC:	σ ~11 pb	σ ~ 235pb	σ ~95 pb

Motivation:

- **Prediction of SM not observed so far**
- **Study *Wtb* coupling in top production**
  Measure $|V_{tb}|$ directly: $\sigma \propto |V_{tb}|^2$
- **Cross sections sensitive to new physics**
  s-channel: resonances (heavy W' boson, charged Higgs boson, Kaluza-Klein excited W_{KK}, technipion, etc.), t-channel: flavor-changing neutral currents ($t - Z/\gamma/g - c/u$ couplings), Fourth generation of quarks
- **Top properties**
  Polarized top quarks – spin correlations measurable in decay products, Measure top quark partial decay width and lifetime, CP violation (same rate for top and antitop?)
- **Similar search for *WH* associated Higgs production**

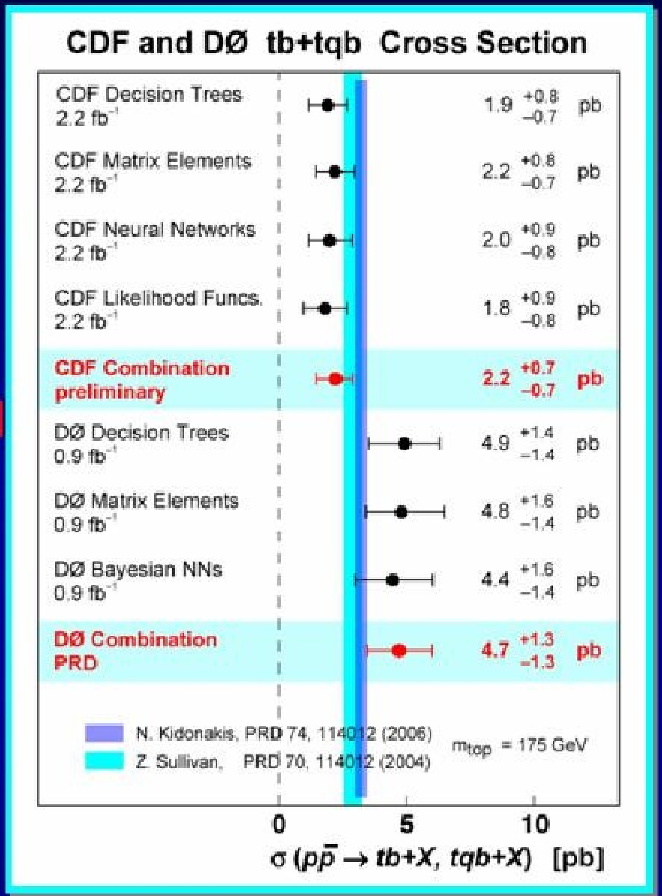


Conclusion / Outlook

- **First Evidence for Single Top Production**
- **First direct measurement of $|V_{tb}|$**

$$0.68 < |V_{tb}| \leq 1 \quad \text{at 95\% C.L.}$$

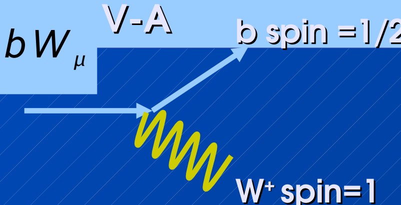
- **First search for charged Higgs decaying to *tb* final state**
  Complementary to other charged Higgs searches
  Exclusion region of parameter space for 2HDM Type-I
- **Search for W' decaying to *tb* final state**
  limits on left and right W' masses and couplings
- **We are working on (along with 5σ discovery) making this list a little bit longer and plan to repeat these measurements with more data**

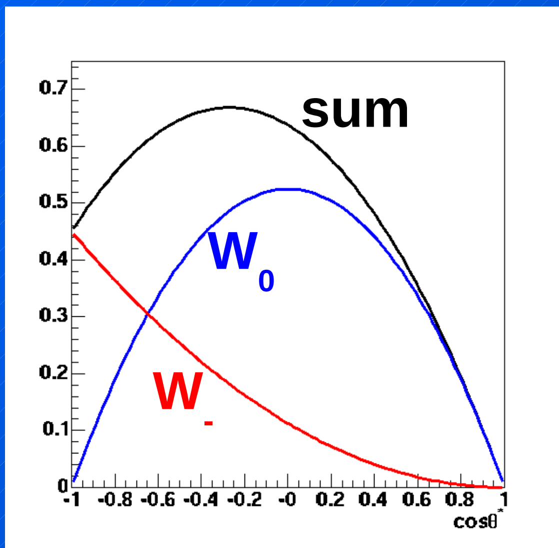


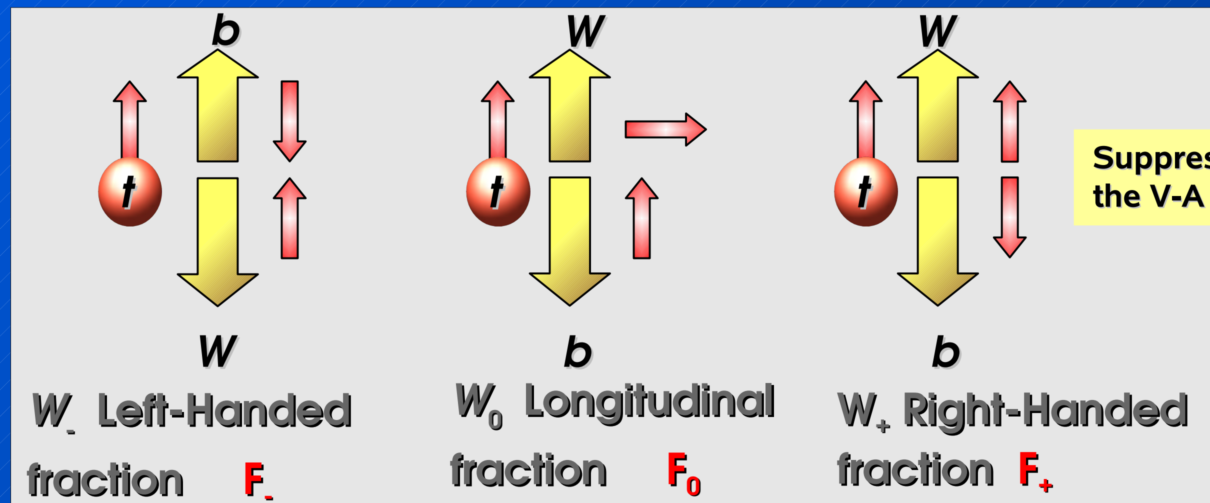
….single top search is a gold mine and we are digging deeper than ever …

Helicity of the W in ttbar Events

$$\frac{-i\,g}{2\sqrt{2}}\,\bar{t}\,\gamma^{\mu}\left(1-\gamma^{5}\right)V_{tb}\,b\,W_{\mu}$$







$$w(\cos\phi_{l\bar{b}})=F_{-}\cdot\frac{3}{8}(1-\cos\phi_{l\bar{b}})^2+F_{0}\cdot\frac{3}{8}(1-\cos^2\phi_{l\bar{b}})+F_{+}\cdot\frac{3}{8}(1+\cos\phi_{l\bar{b}})^2$$

In SM (with m_b=0, M_{top} = 175 GeV and m_W = 80.4 GeV),

$$F_{-}=\frac{2\frac{m_W^2}{M_{top}^2}}{1+2\frac{m_W^2}{M_{top}^2}}\approx 0.30$$

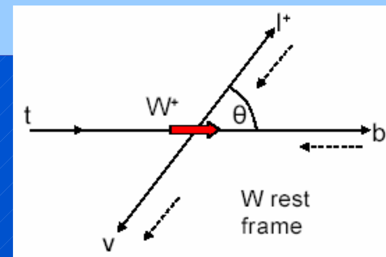
$$F_{0}=\frac{1}{1+2\frac{m_W^2}{M_{top}^2}}\approx 0.70$$

$$F_{+}=0$$

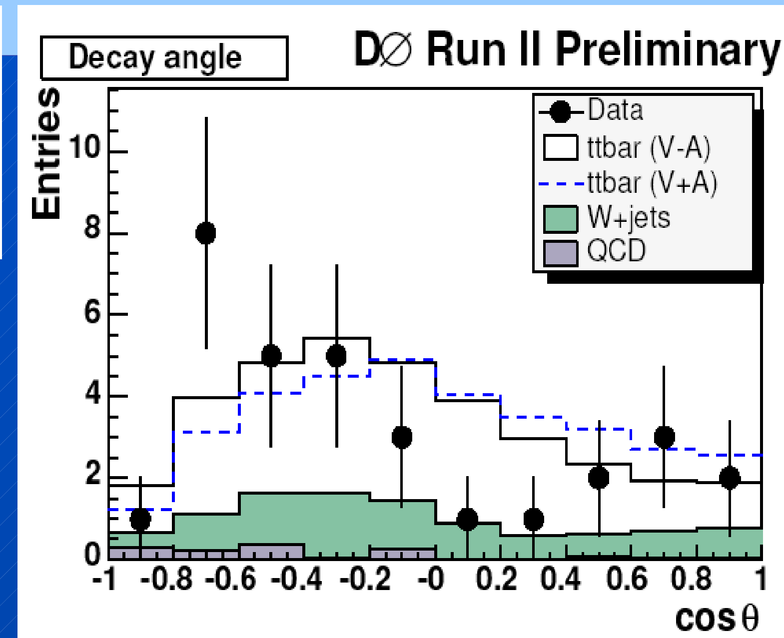
Helicity of W manifests itself in decay product kinematics

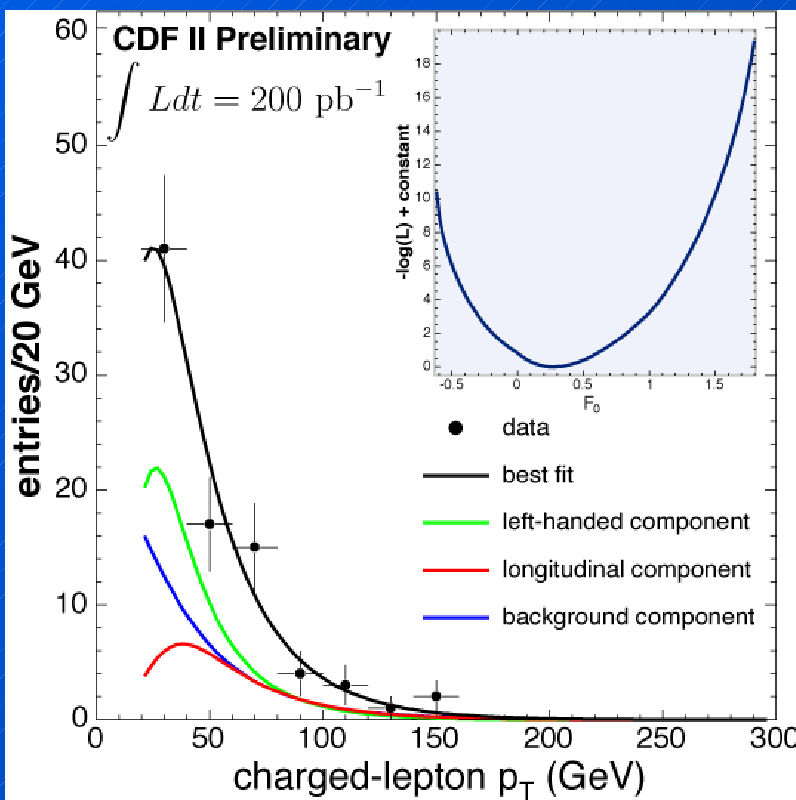
Helicity of the W in ttbar Events (Run II)

- DØ (l+jets, 160 pb^{-1})
- b-tag or topol. selection
- kinematic ttbar fit → boost into W rest frame
- decay angle distribution



$F_+ < 0.24$ @ 90% CL





- CDF (l+jets and dilepton, 200 pb^{-1})
- charged lepton p_T in lab. frame

$F_0 = 0.27^{+0.35}_{-0.24}$

... no deviations from SM predictions
eventually simultaneous fit for F_0 and F_+ ...

Properties

Top Quark Mass – Direct Measurements

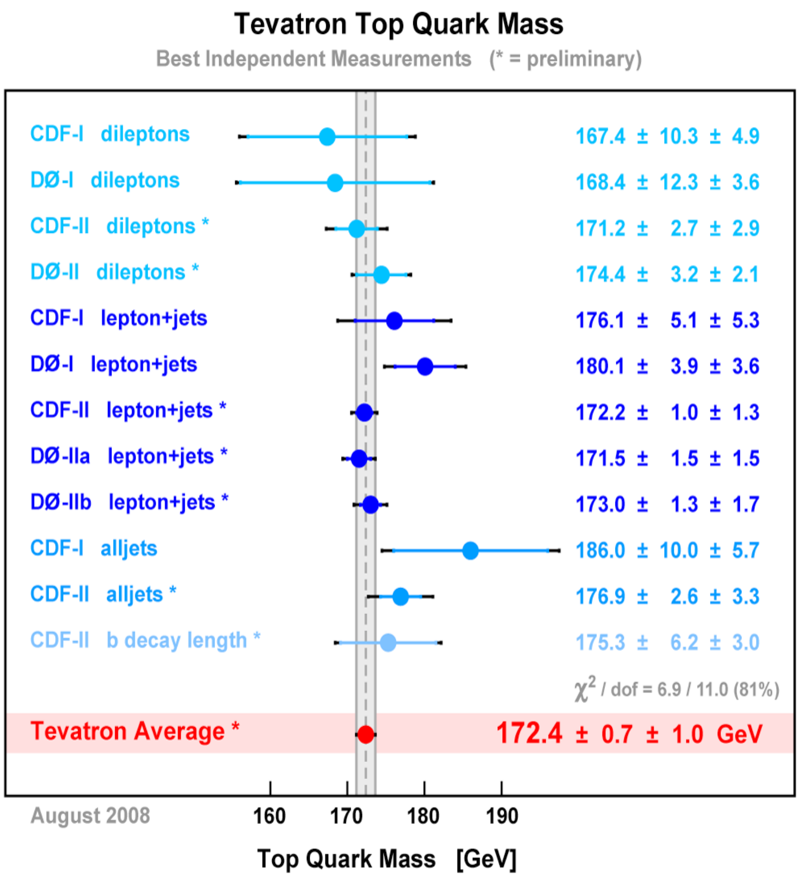
- Fundamental parameter of the SM
- Important ingredient for EW precision analyses
  - incisive consistency checks
  - constrain/rule out models

- Sophisticated techniques to minimize statistical and dominant systematic uncertainties.

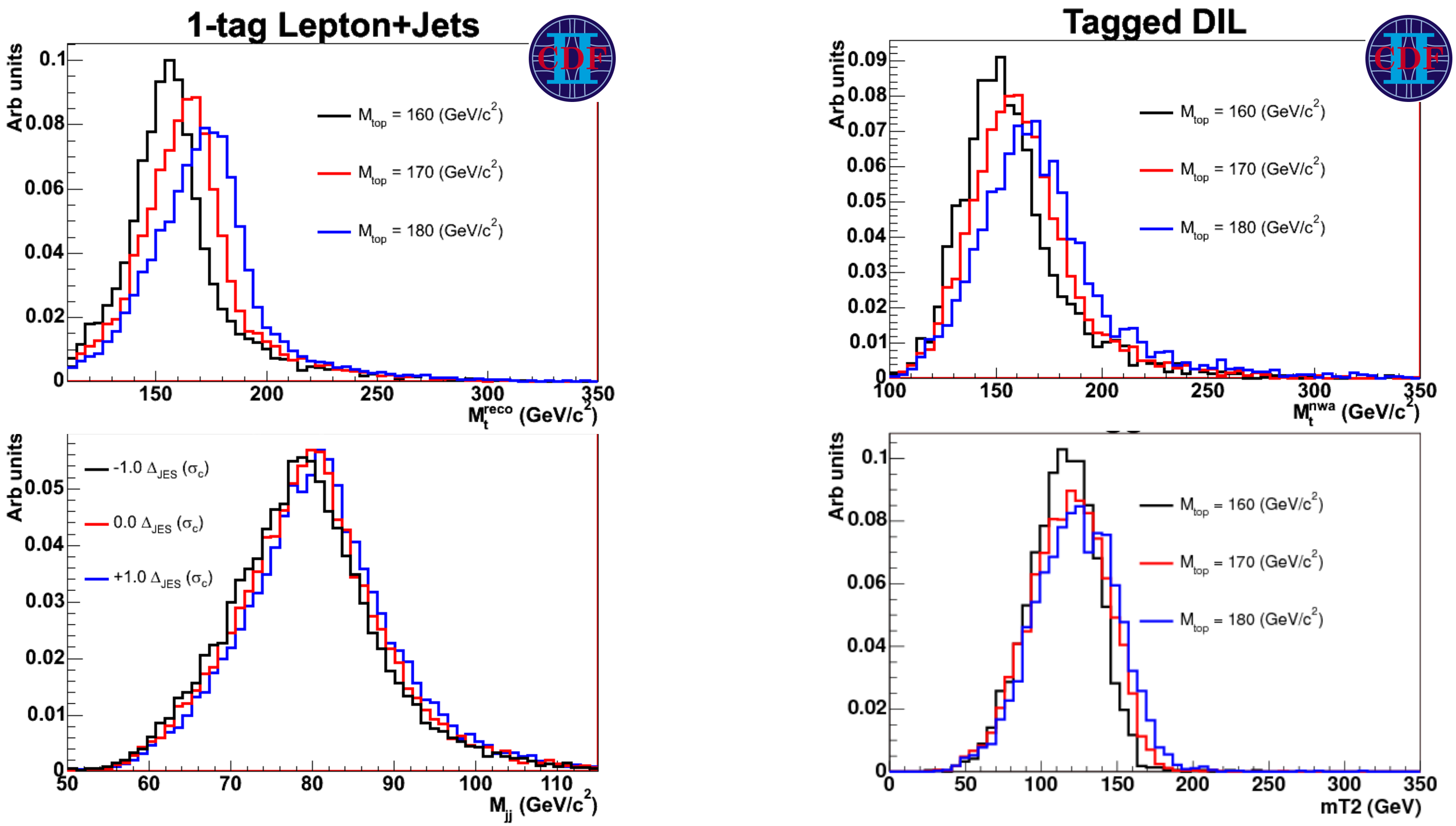
- Current world-average (most sensitive channels use up to 2.7 fb-1):

$$m_t = 172.4 \pm 0.7(stat) \pm 1.0(syst)\ GeV$$

Measurements are limited by systematic uncertainties (signal modeling, b-jet response).

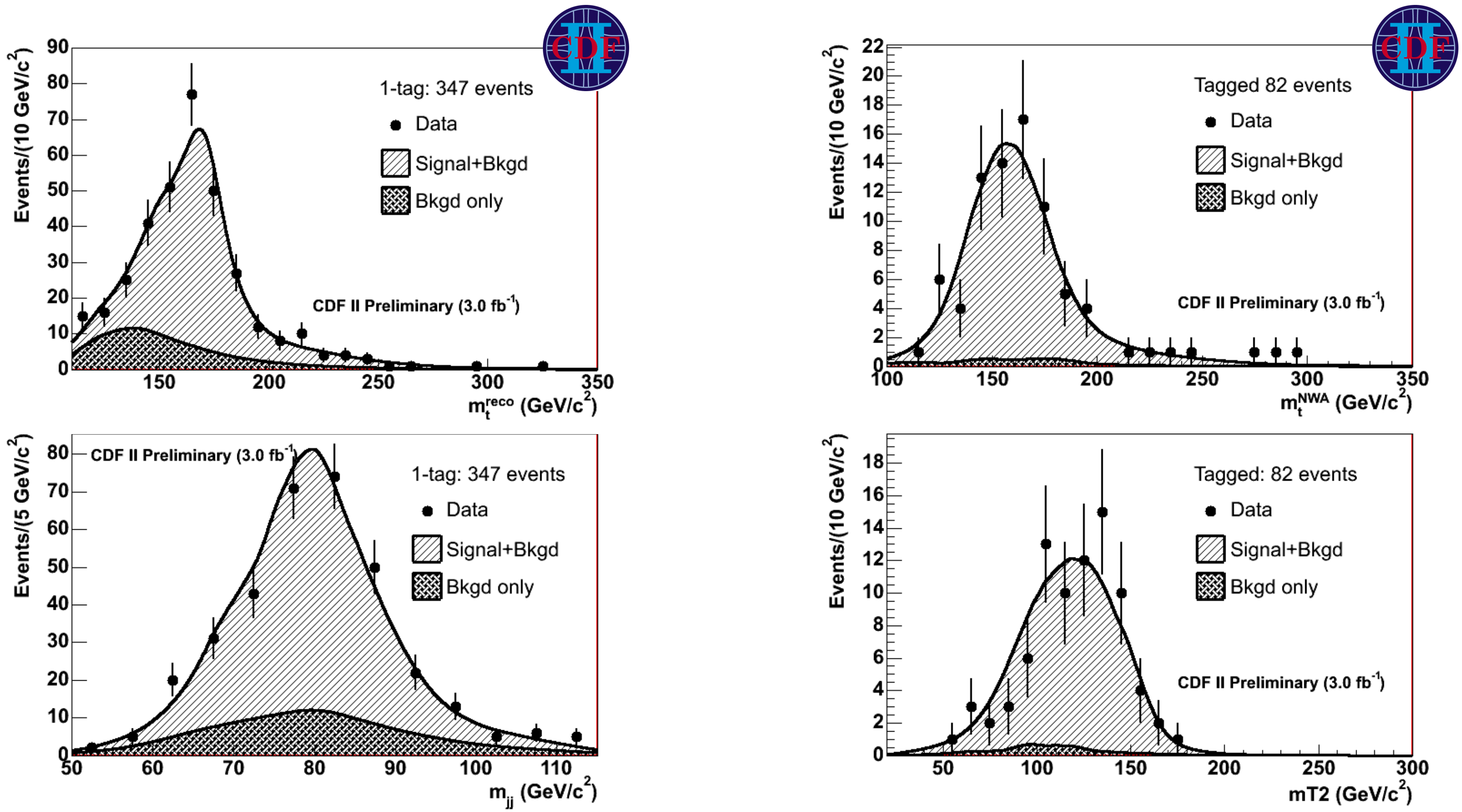


Top Quark Mass – Template Method



$$\mathcal{L}_k = \exp\left(-\frac{(n_b - n_b^0)^2}{2\sigma_{n_b}^2}\right) \times \prod_{i=1}^{N} \frac{n_s P_{sig}(m_i, y_i; M_{top}, \Delta_{JES}) + n_b P_{bg}(m_i, y_i)}{n_s + n_b}$$

Top Quark Mass – Template Method



172.5 ±1.6 (stat.+JES) ± 1.1 (syst) GeV/c2

169.0 ±2.7 (stat.) ± 3.2 (syst) GeV/c2

Combined: 171.8 ± 1.5 (stat.+JES) ± 1.1 (syst) GeV/c2

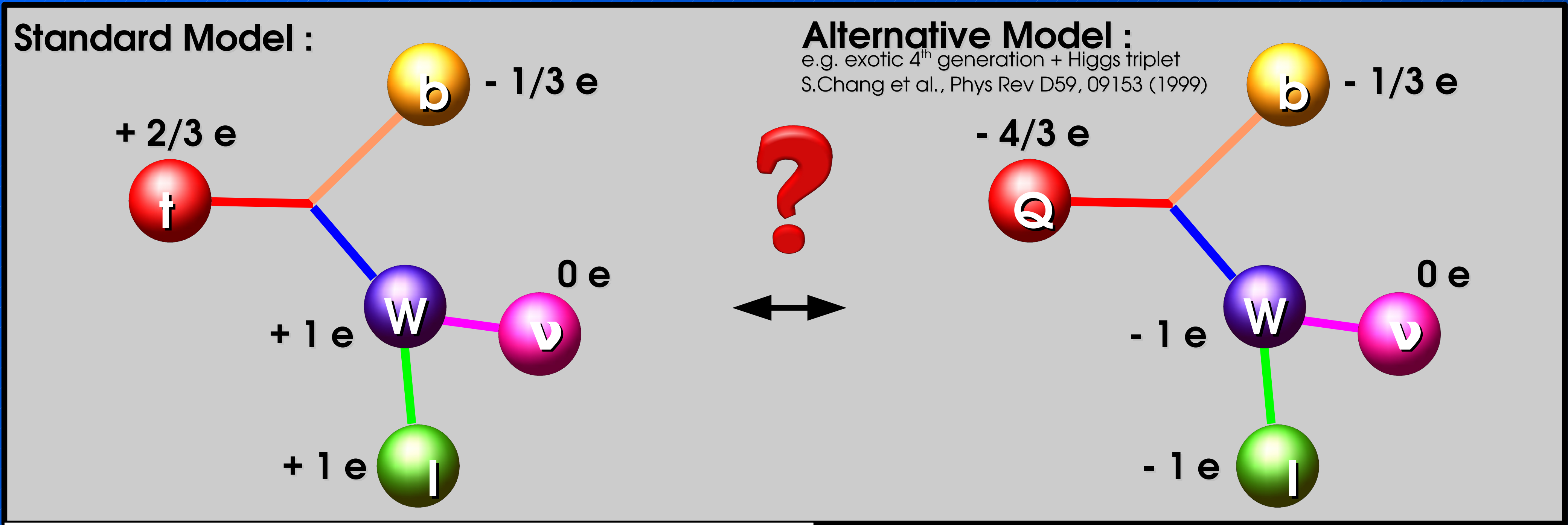
Top Quark Charge

SM: Top Charge +2/3 e

Other models predict -4/3 e

Strategy:

- measure $\sigma(t+\gamma)$ @ LHC (10 fb^{-1})
- b-jet charge @ Tevatron



Analysis :

a) associate lepton and b-quark to top quark

use a kinematic fit for ttbar hypothesis

b) determine charge of b-jet

p_T weighted sum of charged tracks associated to a b-jet

Present Z→ll and Z→bb data not inconsistent with -4/3 e top quark of mass 270 GeV/c^2

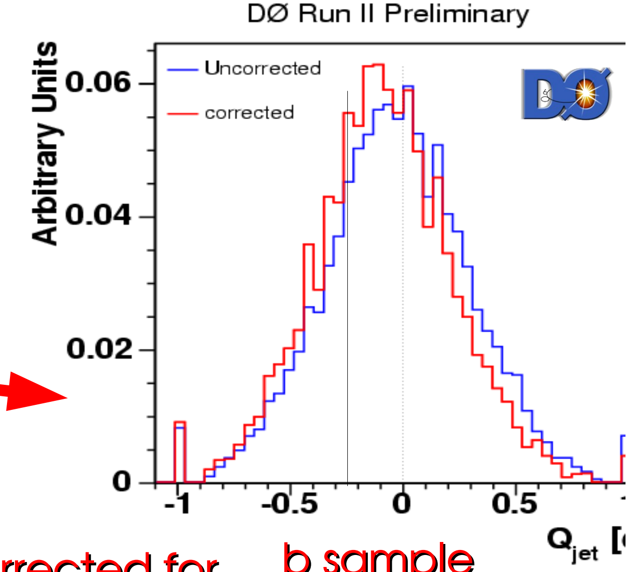
Top Quark Charge at Tevatron

- discriminate b and bbar with jet charge algorithm

$$q_{jet} = \frac{\sum_i q_i \, p_{T\,i}^{0.6}}{\sum_i P_{T\,i}^{0.6}}$$, $p_T > 0.5$ GeV & $\Delta R > 0.5$

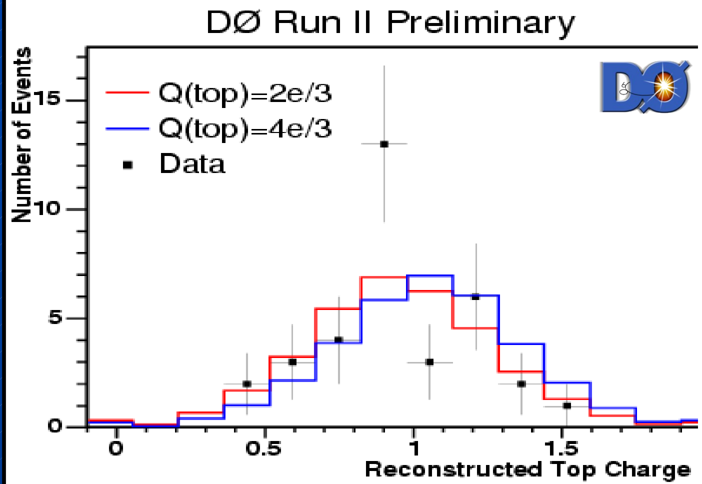
- calibrate Monte Carlo with data using two jet heavy flavor sample with opposite jet tagged with μ flavor

⇨ exclude the hypothesis of an exotic quark with charge = -4/3 e ...



corrected for B mixing and charm fraction

b sample q=-1/3



CDF (1.5 fb^{-1}, l+jets and dilepton)

exclusion at 87% CL, at 94%, sensitivity b=99.9%

DØ (365 pb^{-1}, l+jets, double-tag)

p-value(exotic model) = 7.8%, sensitivity 91.2%

Top Quark Charge at LHC

- Q_{top}=-4/3 ($t \to W^- b$ instead of $t \to W^+ b$) ?

- **Method 1**: Measurement of radiative top production and/or decay
  - σ ($pp \to t\bar{t}\gamma$) is proportional to Q_{top}^2
  - After selection+reconstruction (10 fb^{-1})

    σ (Q=-4/3) > σ (Q=2/3)

nr. events

	Q=2/3	Q=-4/3
$pp \to t\bar{t}\gamma$	80	250
Background	70	70

- **Method 2**: Measurement of daughter particle charge
  - Associate b-lepton pair from the same top
  - Compute the charge of b on a statistical basis:

$$q_{\text{bjet}} = \frac{\sum_i q_i |\vec{j} \cdot \vec{p}_i|^{\kappa}}{\sum_i |\vec{j} \cdot \vec{p}_i|^{\kappa}}, \kappa = 0.6$$

  - Separate the 2 Q_{top} hypothesis needs less data than Method 1 (~1 fb^{-1})