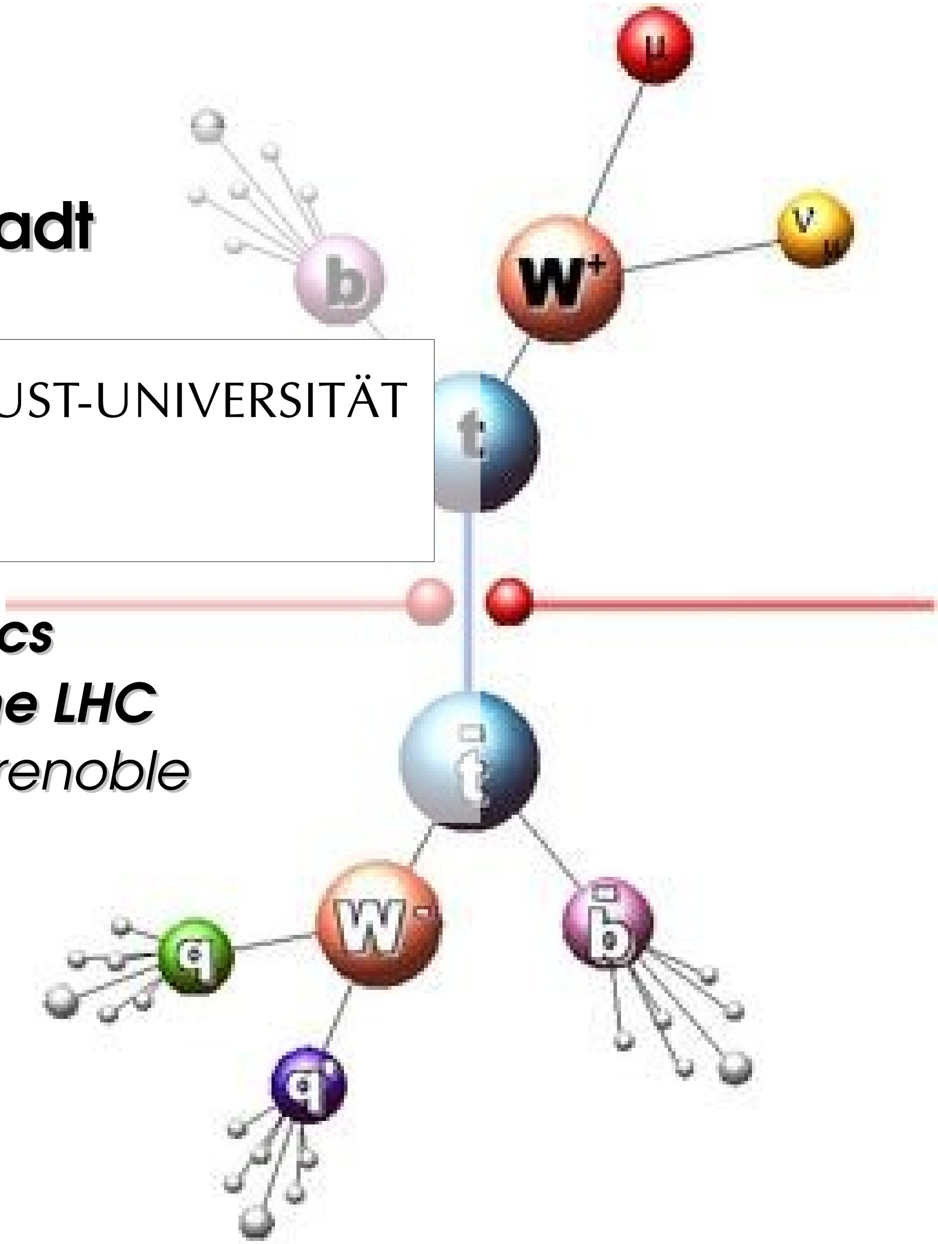
A brief history of the Top Quark
- an overview -

Arnulf Quadt

GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

Workshop on Top Physics
From the TeVatron to the LHC
18-20 October 2007, Grenoble



Outline

- Introduction
- Strong interaction of the top quark
  - Production (SM, anomalous) & spin correlations
- Weak interaction of the top quark
  - single top production & W-helicity in top decays
- Electromagnetic interaction of the top quark
- Top Quark Properties
  - Mass, charge, spin, lifetime
- Conclusion

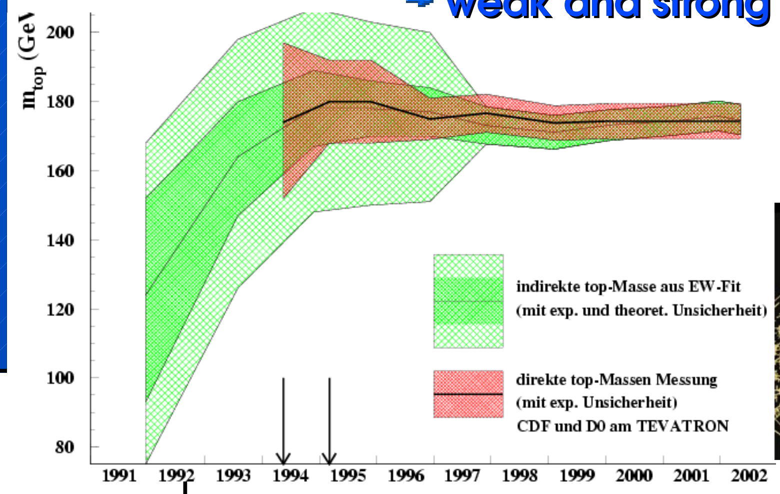
Introduction

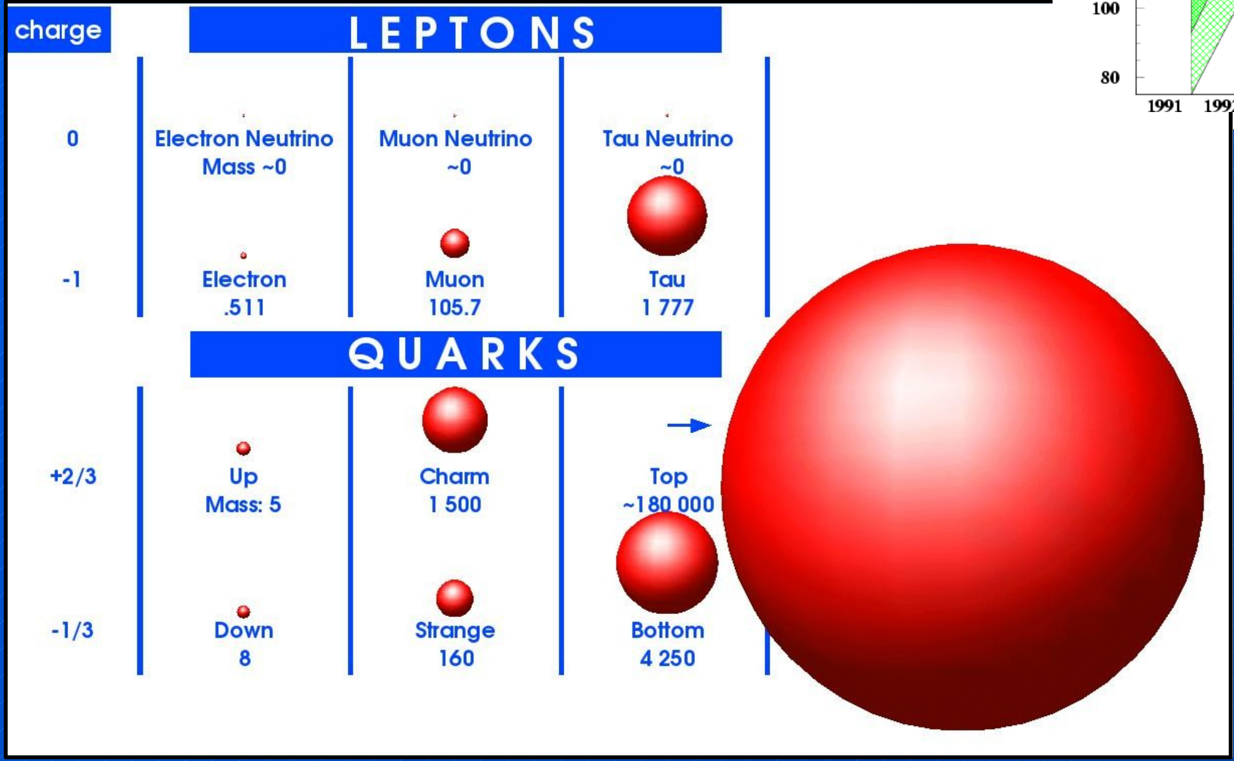
Top Quark in the Standard Model

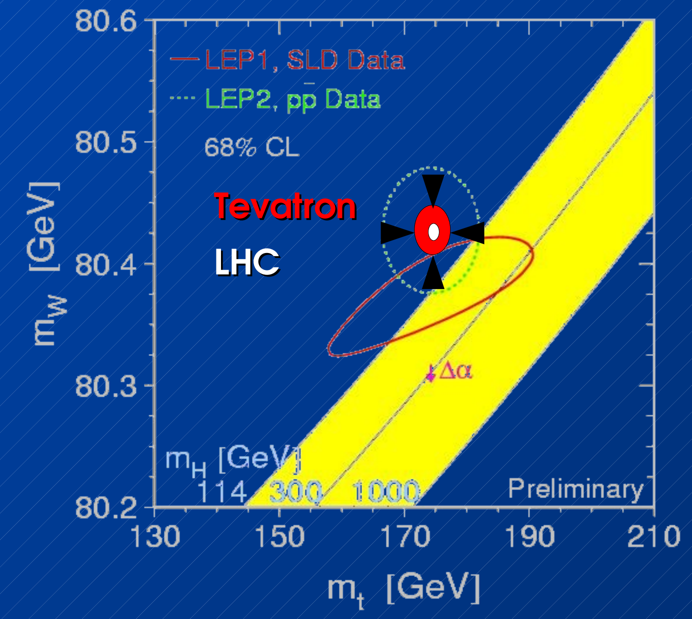
Why is the Top Quark so interesting ?

- completes the quark sector
- large mass $m_{top} \sim 170$ GeV / c^2
- short lifetime $\tau \sim 5 \cdot 10^{-25}$s $\ll \Lambda^{-1}_{QCD}$
- sensitive to physics beyond the Standard Model
- Higgs-Boson coupling to fermions : $g \sim m_f$
- $m_t \sim v/\sqrt{2}$, Yukawa coupling $\lambda_t \sim 1$
- `standard candle' at the LHC ⇨ commissioning

Only `recent' discovery ⇨
- ➜ charge, mass, ... ?
- ➜ weak and strong top physics







Top Quark Properties

	Tevatron results
It´s massive	$\delta m/m \sim 1\%$
Spin=1/2	Not directly, spin correlations
Charge=+2/3	-4/3 excluded by DØ (p = 0.78%) and CDF (87%CL)
Isospin =+1/2	Not directly
$t \rightarrow bW$	~100%, first V_{tb} measurement
V-A decay	at 20%
FCNC	at 10%
Large Γ=1.42GeV (m_b,M_W,α_s,EW corr.) ⇨ short lifetime, observe \`free quark decay'	$c\tau$<52.5μm @95%C.L.(CDF) Γ_t < 12.7 GeV/c^2 (CDF)
Yukawa coupling ?	first discover the Higgs

The TEVATRON is probing better than ever the top sector…
The LHC will allow precision measurements of Top Quark Physics

Top Quark Physics

Tevatron Run I : top quark discovery (1995) **Run II &LHC :** with high precision answer ...

- Why is top so heavy ?
- Is top/third generation special ?
- Is top involved in EWSB ?
- Is it connected to new physics ?
- Precision measurement of couplings

tt Production Cross-Section
tt Production via interm. Resonances
EW single-top production
Production Kinematics (SUSY, FCNC)
Spin Polarization, spin correlations

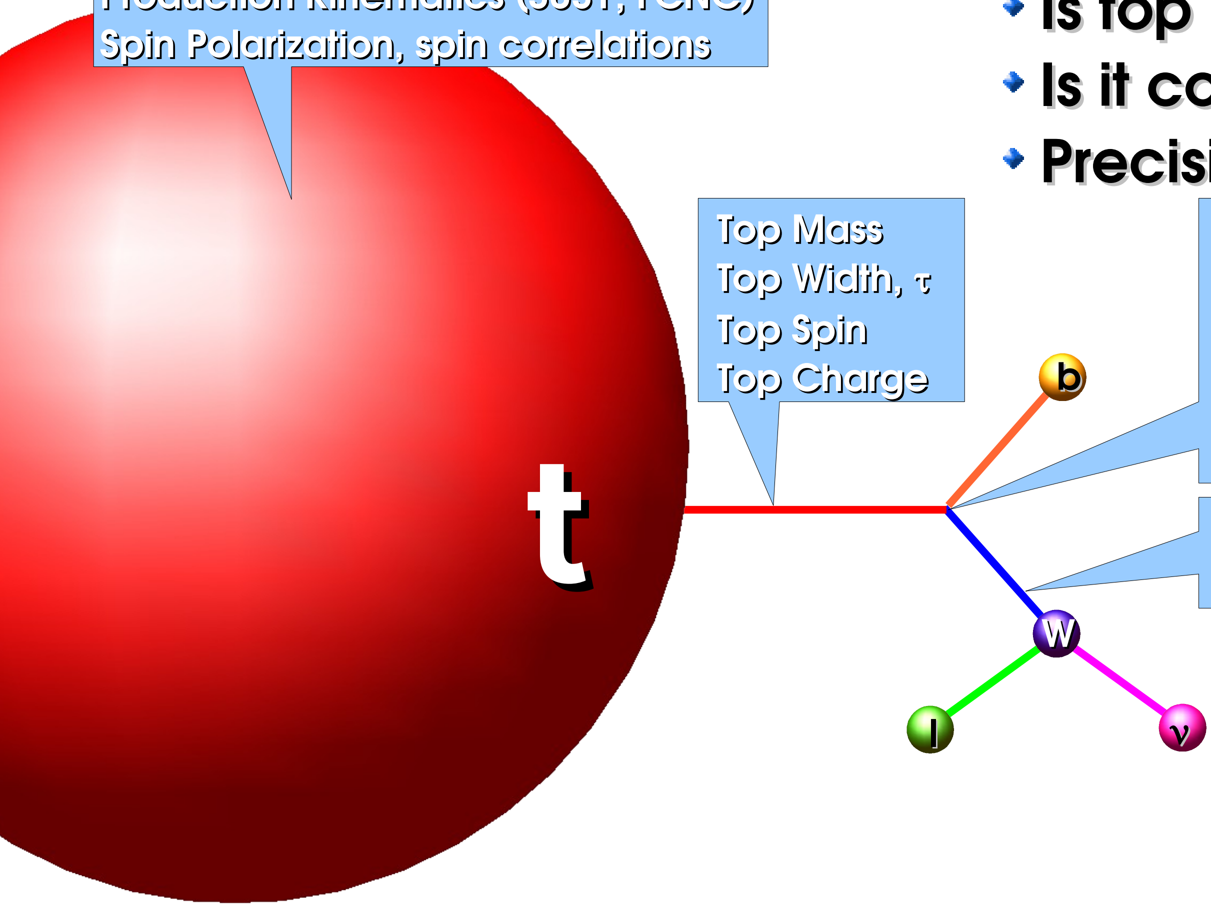
Top Mass
Top Width, τ
Top Spin
Top Charge

Anomalous Couplings
CP Violation
Rare/non-SM Decays
Branching Ratios
$|V_{tb}|$

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

$g \simeq 0.67$
$V_{tb} \simeq 1$
$m_{top} > m_W$ (phase space)

W helicity
charged Higgs ?



Commissioning: trigger studies
jet enery scale
b-tagging effi.

The TEVATRON at Fermilab

p $\bar{p}$

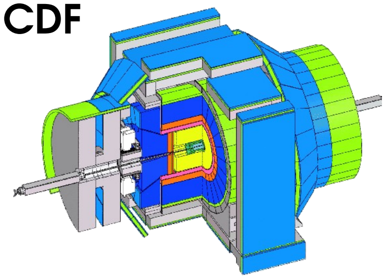
$\sqrt{s}$ =1.8 - 1.96 TeV, Δt = 396 ns

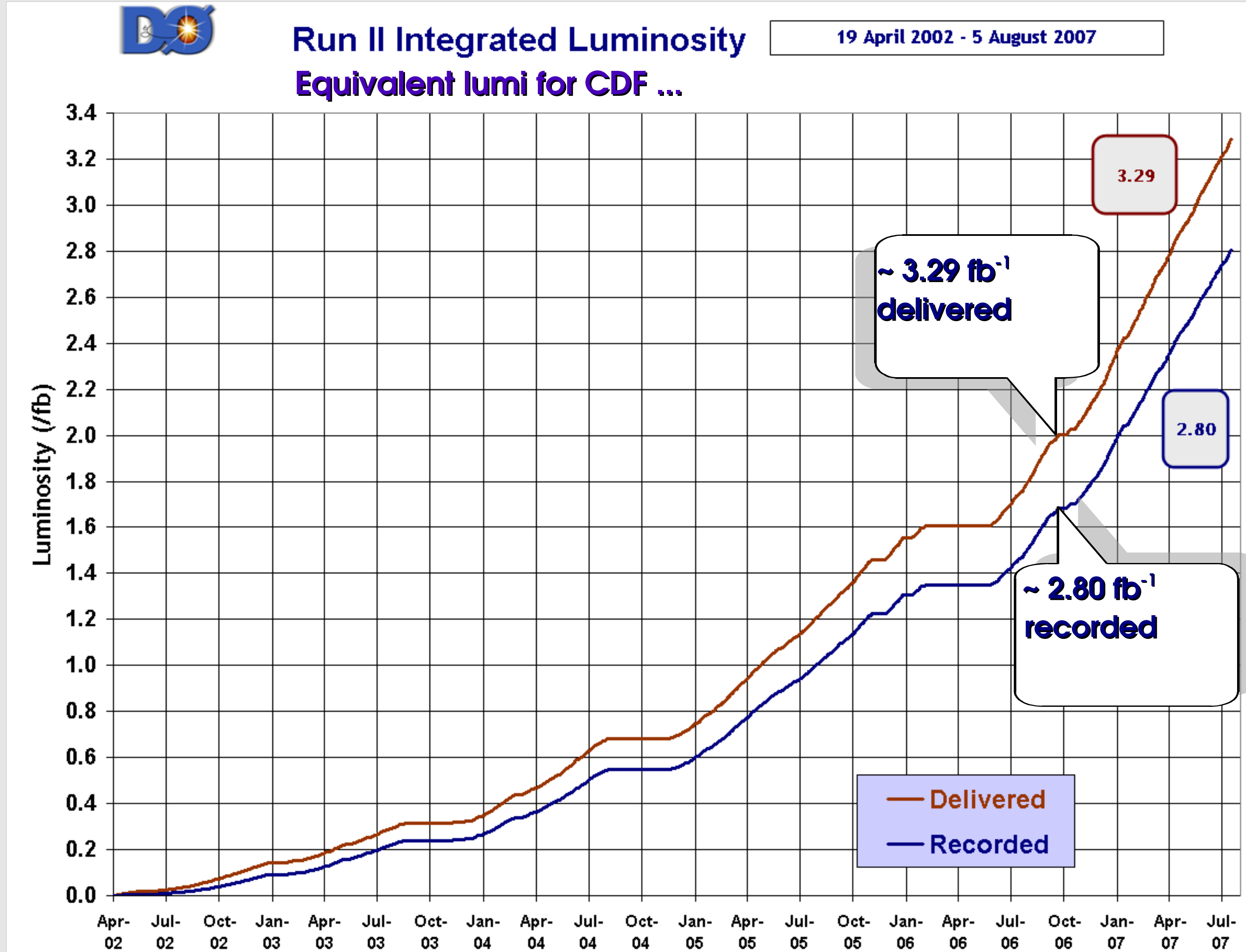
Run I 1987 (92)-95 L_{int} ~ 125 pb^{-1}

Run II 2001-09(?) 4-9 fb^{-1}

The TEVATRON at Fermilab

CDF





CDF & DØ data taking ε ~90%

p 

$\sqrt{s}$ =1.8 - 1.96 TeV, Δt = 3

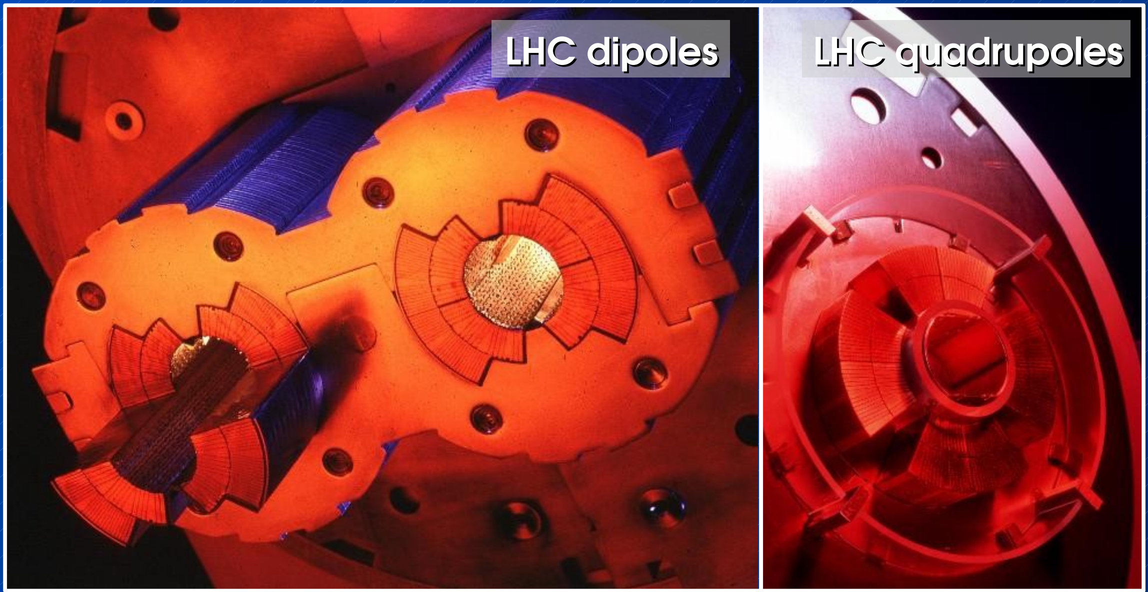
Run I 1987 (92)-95 L_{int} ~ 12

Run II 2001-09(?) 4

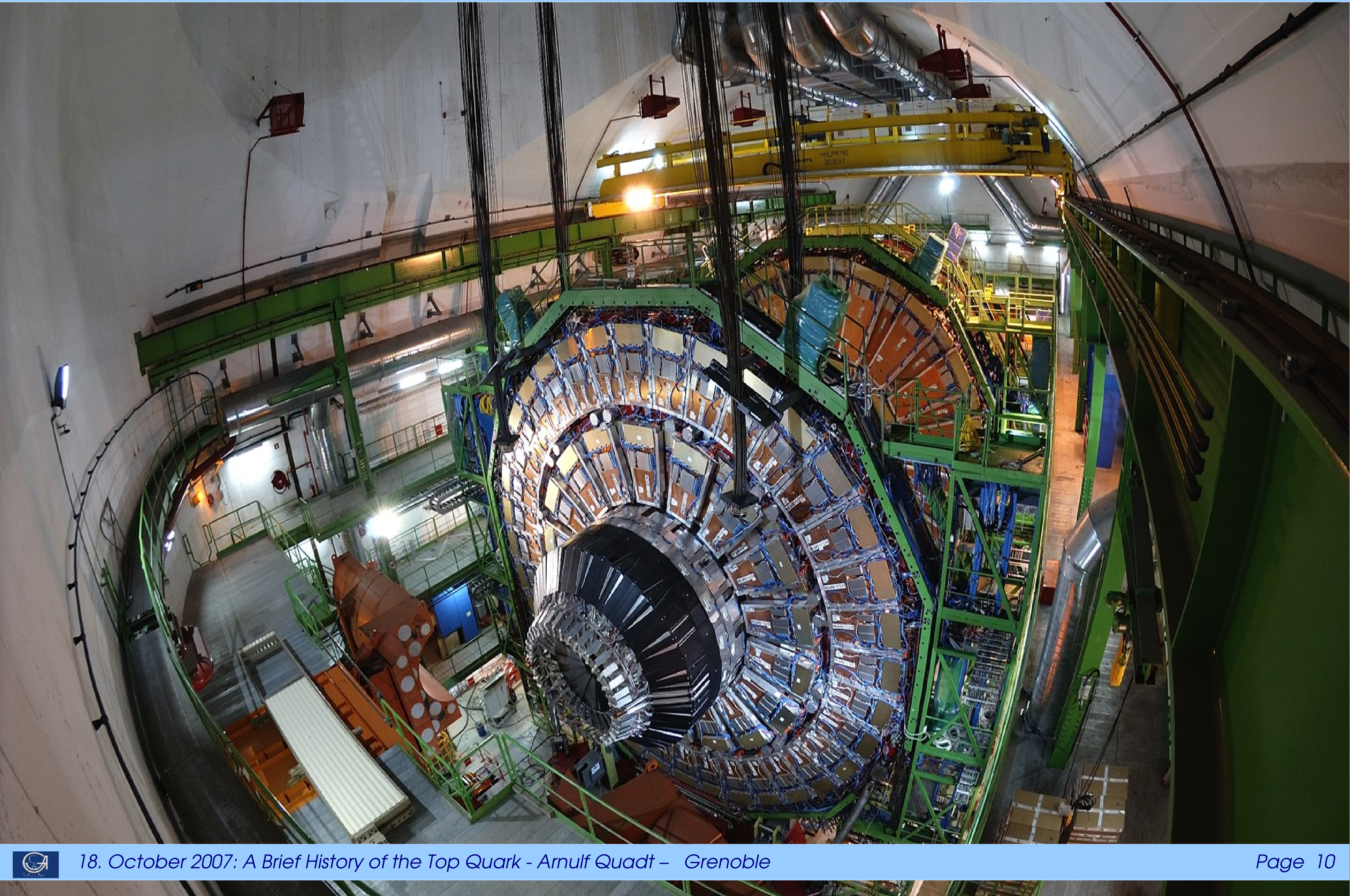
The Large Hadron Collider - LHC

The Large Hadron Collider:

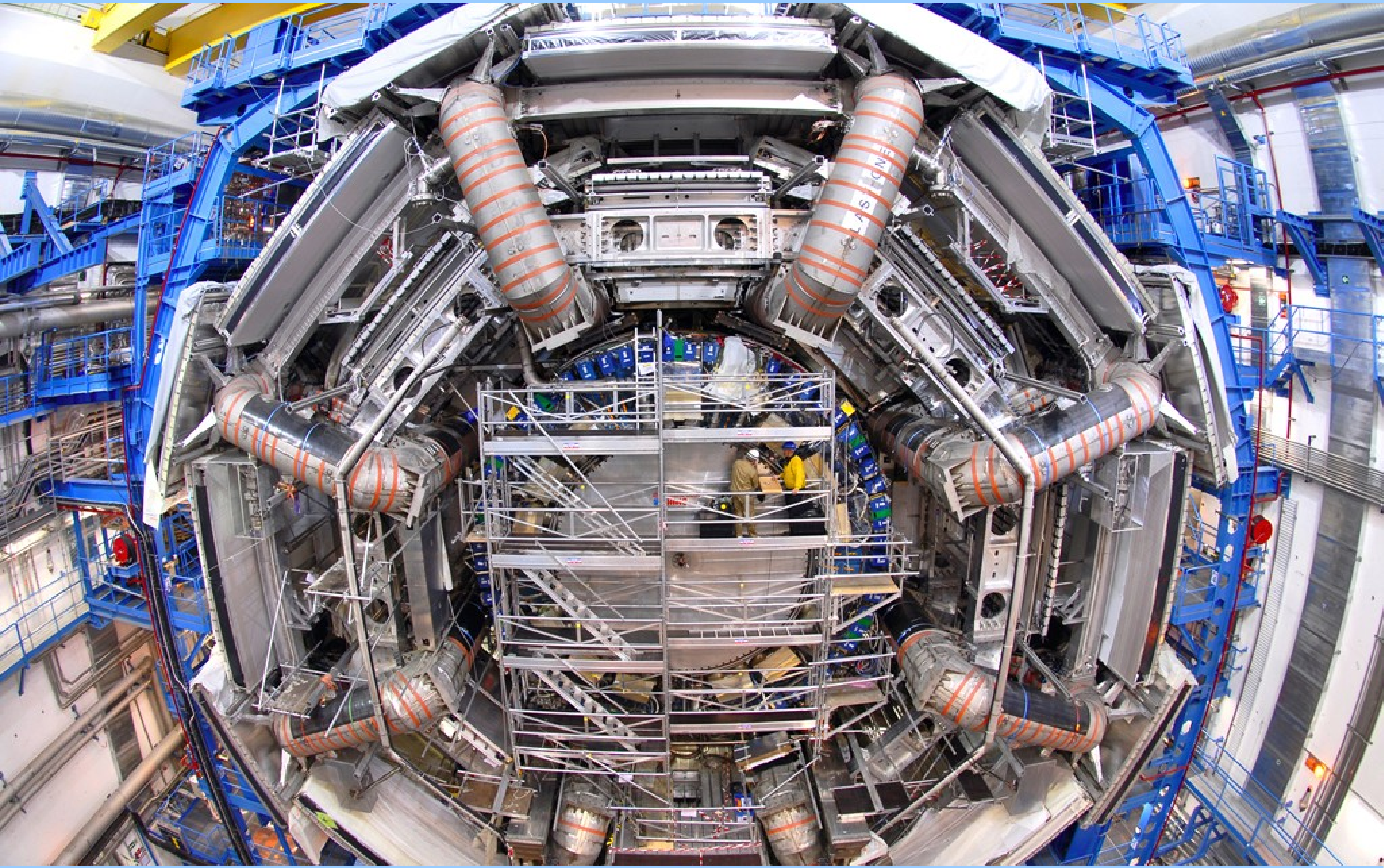
- proton-proton collider (no $\bar{p}$)
  ⇨ 2 separate beampipes
- first collisions in 2008
- high energy: $\sqrt{s}$ = 14 TeV
- 40 Mio. collisions per second
- 4 experiments:
- ATLAS, CMS, ALICE, LHC-B
- 10 fb^{-1} per year



The Large Hadron Collider - CMS



The Large Hadron Collider - ATLAS

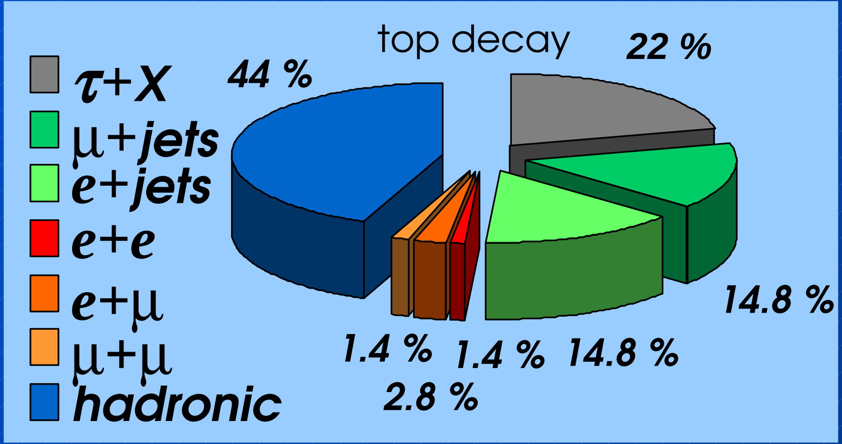


Strong Coupling of the Top Quark

- ttbar production
  (total Xsec, differential Xsec, gg→tt fract., forw.-backw. asymmetry)
- spin correlations
- possible admixture to tt via $H^{\pm}$, stop, narrow resonances ...
- study of ttj, ttjj, ttb, ttbb
  ⇨ QCD (m_t via τ_t) as well as background for tth(h→bb)

Decay Topology in $t\,\bar{t}$

Top quarks decay predominantly (~100%) to a W-Boson and a b-quark



Top-Antitop Signatures:

`dilepton channel'

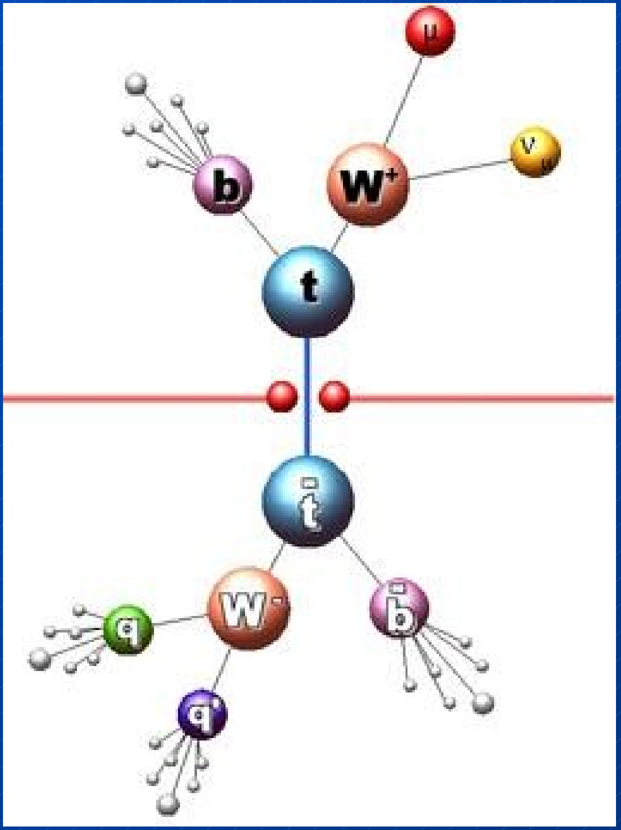
5% : 2 jets, 2 charged leptons, 2 ν

'lepton+jets channel'

30%: 4 jets, 1 charged lepton, 1 ν

'all-jets channel'

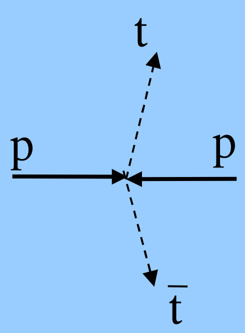
40%: 6 jets



always 2 jets are b-jets

Top Quark Production

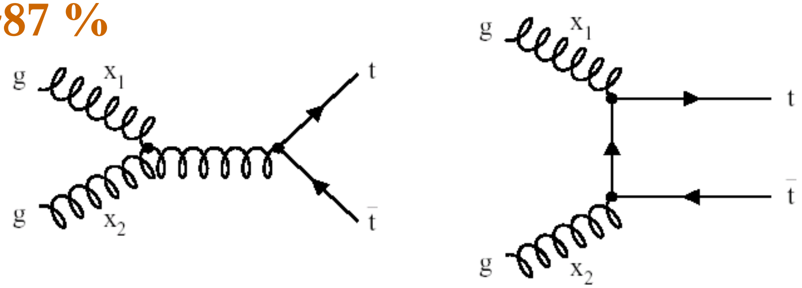
top pairs

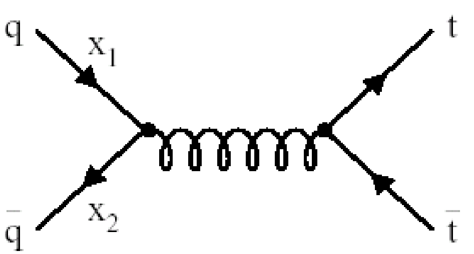


10 tt pairs per day @ Tevatron ↔ 1 tt pair per second @ LHC

qq → tt : 85% *gg→ tt : 87%*

~87 %

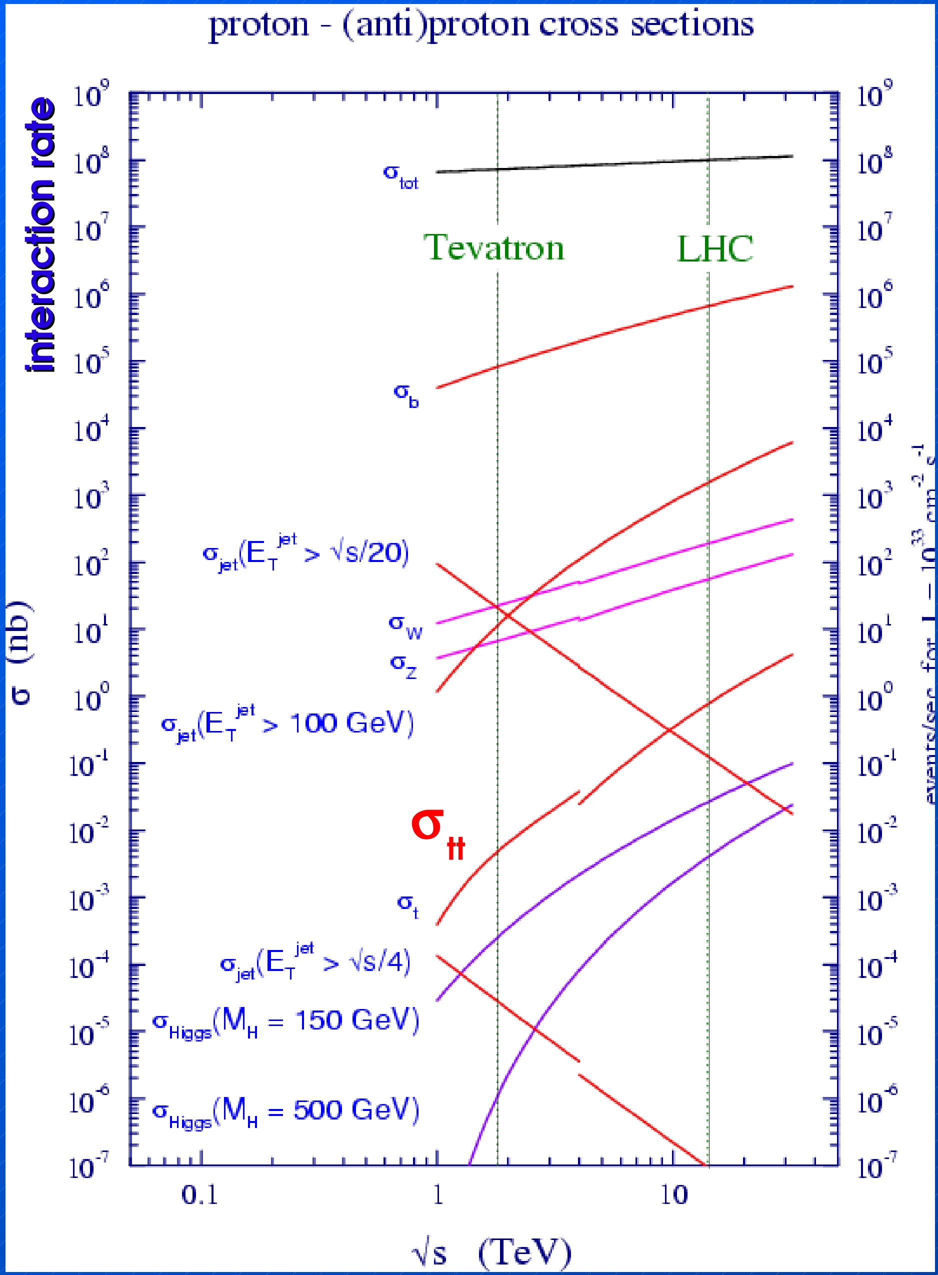




- NLO cross-section σ^{NLO} = **833** pb ~8M events/10fb^{-1}

Some references (not a complete list!): (top pairs) N.Nason *et al.* Nucl.Phys. B303 (1988) 607, S.Catani *et al.* Nucl.Phys. B478 (1996) 273, M.Beneke *et al.* hep-ph/0003033, N.Kidonakis and R.Vogt, Phys.Rev. D68 (2003) 114014, W.Bernreuther et al. Nucl.Phys. B690 (2004) 81-137 (single-top) T.Stelzer et al. Phys.Rev. D56 (1997) 5919, M.C.Smith and S.Willenbrock Phys.Rev. D54 (1996) 6696, T.M.Tait Phys.Rev. D61 (2000) 034001

Top Quark Production Rates



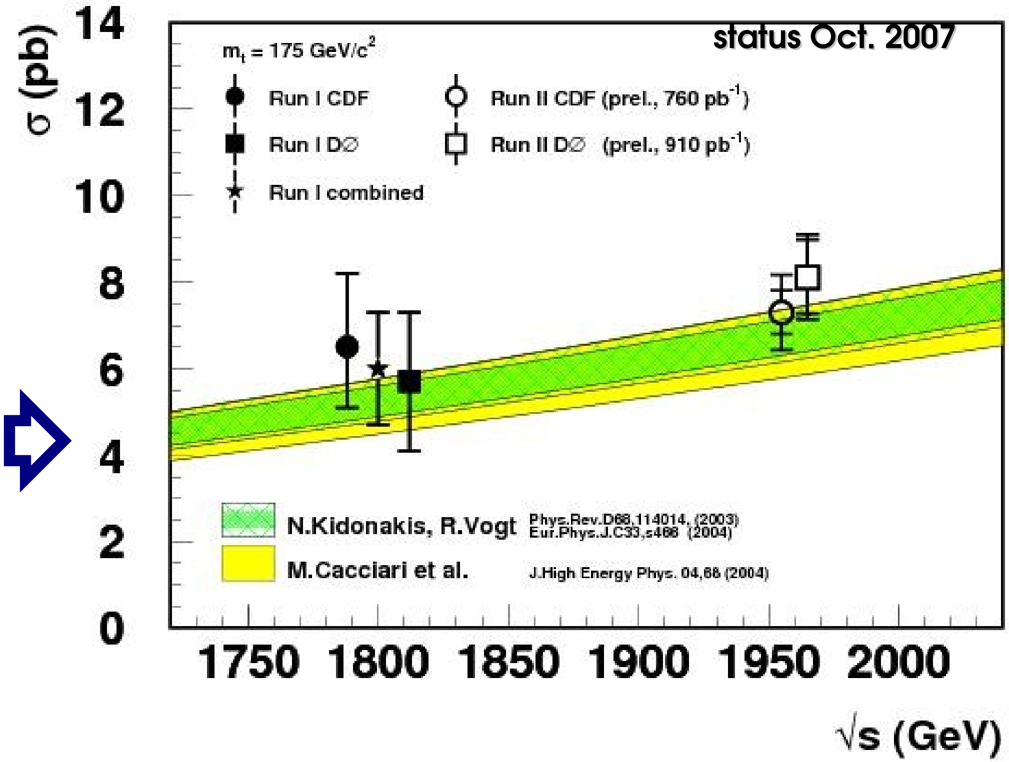
process	σ(pb)	ev/s	ev/y Low L	Comparison with other experiments
bb	5×10^8	10^6	10^{13}	10^9 Belle/Babar
$Z \rightarrow ee$	1.5×10^3	~3	10^7	10^7 LEP
$W \rightarrow e\nu, \mu\nu$	3×10^4	~60	10^8	10^5 LEP 10^8 FNAL
$WW \rightarrow e\nu X$	6	10^{-2}	10^5	
tt	830	~1.7	10^7	10^4 Tevatron
H(130GeV/c²)	2	4×10^{-3}	10^5	?
H(700GeV/c²)	1	2×10^{-3}	10^4	?

Year	Max Lumi	Top pairs Produced /day	Top pairs(l+j) after selection /day
2007	10^{32}	7 000	~20-100
2008	10^{33}	70 000	~200-1 000
2009- -2010	10^{34}	70 0000	~2 000-10 000

- establish top signal
- measure cross section as QCD test
- cross section & topology close to Higgs physics

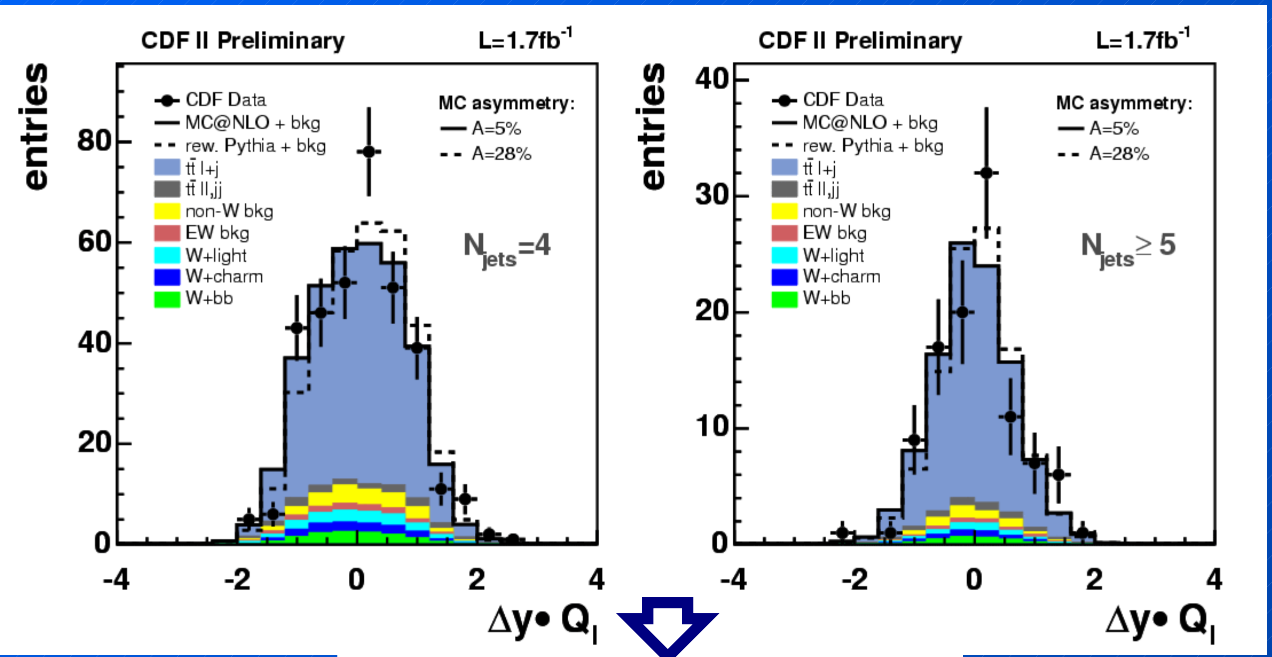
Run II Top Cross Section - Summary

$\sigma_{t\bar{t}}(pb)$	Source	$\int \mathcal{L}dt$ (pb^{-1})	Ref.	Method
8.3 ± 1.3	DØ	910	[30]	ℓ + jets/vtx b-tag
8.1 ± 1.0	DØ	910	[31]	ℓ + jets/0-2 vtx b-tags
7.3 ± 2.0	DØ	430	[32]	ℓ + jets/soft μ b-tag
6.3 ± 1.2	DØ	910	[33]	ℓ + jets/kinematics
5.1 ± 4.4	DØ	350	[17]	τ + jets
6.2 ± 1.2	DØ	1050	[34]	$\ell\ell$ + ℓ+track/vtx b-tag
$11.1^{+6.0}_{-4.6}$	DØ	160	[35]	$e\mu$/vtx b-tag
$8.6^{+2.3}_{-2.1}$	DØ	370	[36]	ℓ+track/vtx b-tag + $e\mu$
8.3 ± 2.3	DØ	1000	[16]	$\ell\tau$/vtx b-tag
12.1 ± 6.7	DØ	360	[9]	all-jets/vtx b-tags
$7.1^{+1.9}_{-1.7}$	DØ	220-240	[37]	combined
8.2 ± 1.1	CDF	1120	[38]	ℓ + jets/vtx b-tag
7.8 ± 2.0	CDF	760	[39]	ℓ + jets/soft μ b-tag
6.0 ± 1.1	CDF	760	[40]	ℓ + jets/kinematics
6.2 ± 1.4	CDF	1200	[41]	$\ell\ell$
8.3 ± 1.6	CDF	1100	[42]	ℓ+track
10.1 ± 2.2	CDF	1000	[43]	ℓ+track+b-tag
$8.3^{+2.3}_{-1.9}$	CDF	1020	[44]	all-jets/kin+vtx b-tags
7.3 ± 0.9	CDF	760	[45]	combined

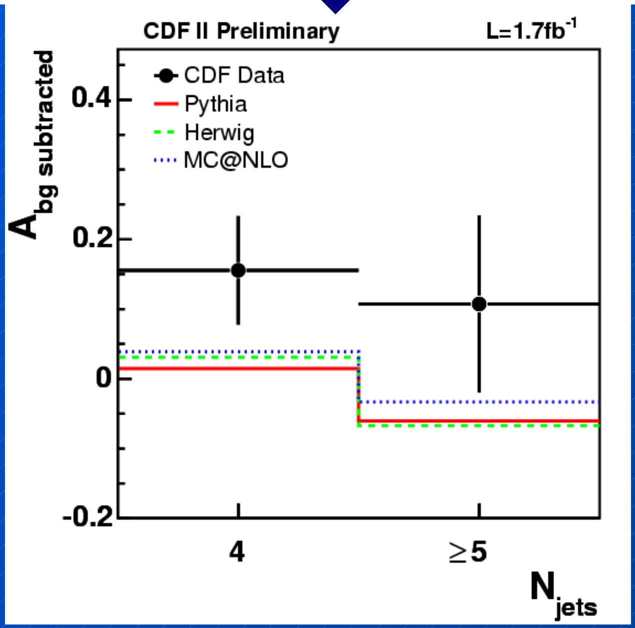


- Many channels, both exp.s consistent (> 1fb^{-1})
- ... with NLO SM prediction for 1.96 TeV of ~7 pb^{-1}
- approaching ~12% precision, syst. dominated
- Forward-backward charge asymmetry (8%)
  ⇨ first results (CDF & DØ)

Ttbar Charge Asymmetry



- expect about A_{fb} ~ 5-10% at NLO
- l+jets in 1.7 fb^{-1}
- study Δrapidity * lepton charge



Inclusive asymmetry (corrected) :

A = 0.28 +-0.13 (stat.) +-0.05 (syst.)

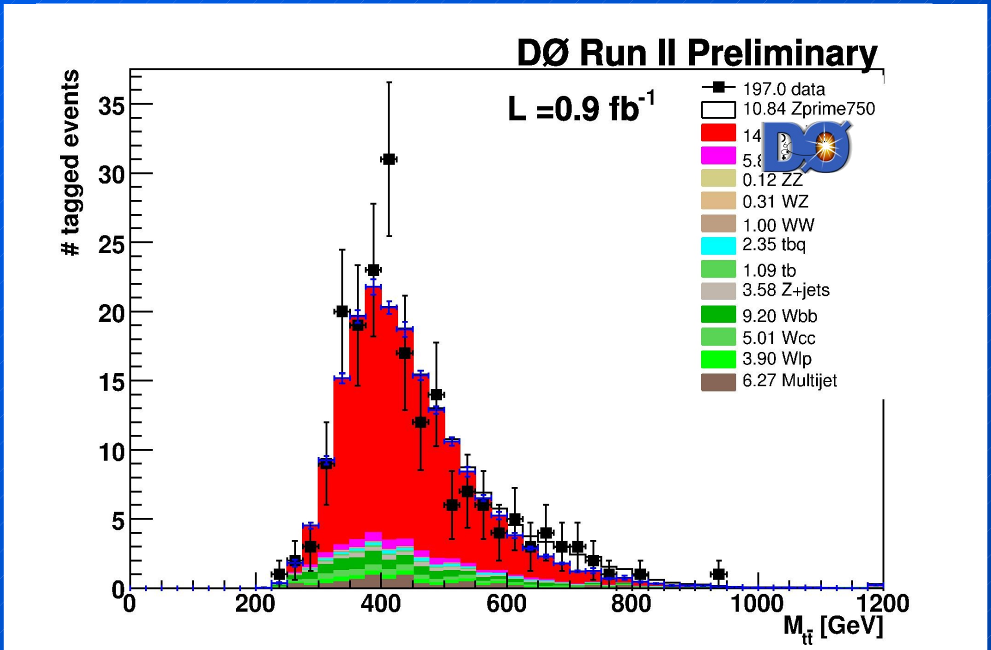
DØ uncorr.: 0.12 +- 0.08 (0.9 fb^{-1})

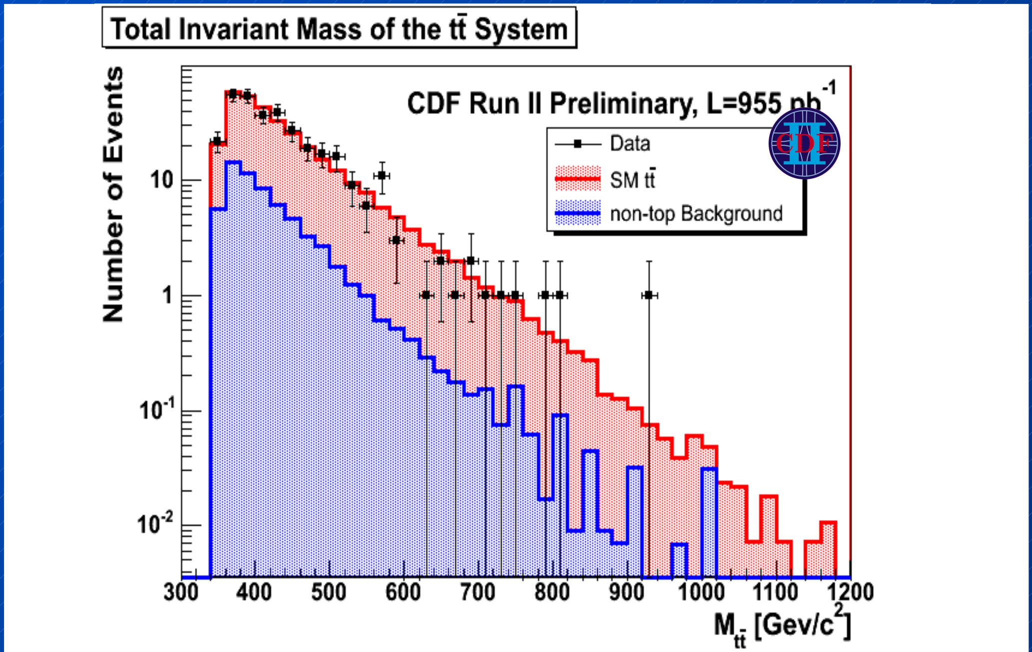
Ttbar Production via Resonances

Does something new (narrow resonance) produce ttbar pairs ?

- Lepton + ≥ 4 jets with ≥ 1 b-tag in 900 pb^{-1}
- kinematic fit to ttbar hypothesis
- assume SM rate for SM ttbar production
- no significant excess observed

- Lepton + ≥ 4 jets (with b-tagging) in 1 fb^{-1}
- χ^2 kinematic fit
- SM ttbar, diboson, QCD rates free param.
- no significant excess observed





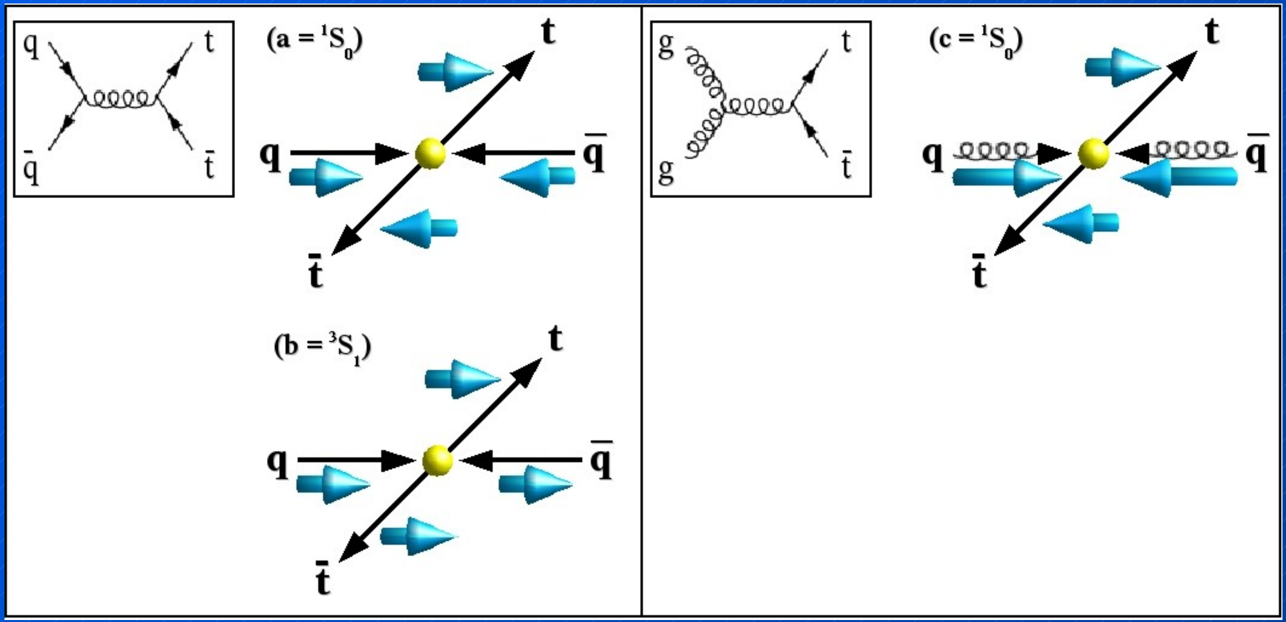
Interpretation of $\sigma_X \cdot BR(X \rightarrow tt)$ limit in terms of mass limit of a Z' in topcolor assisted technicolor (hep-ph/9911288)

CDF: m_X > 720 GeV @95% C.L.

DØ: m_X > 680 GeV @95% C.L.

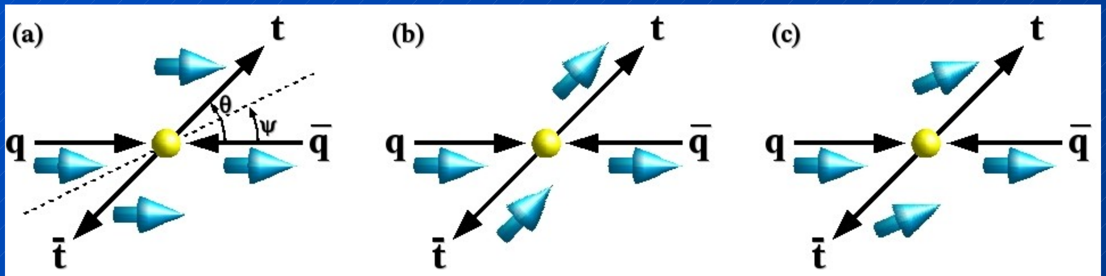
Spin Correlations in $t\bar{t}$

Test production mechanism and QCD predictions:



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

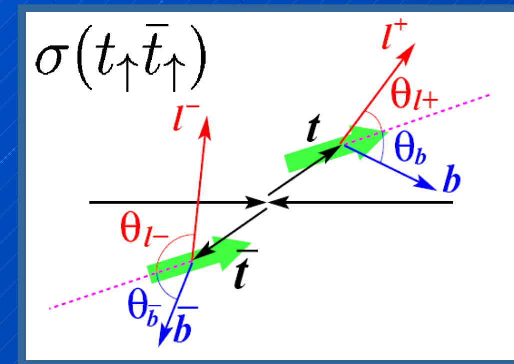
Three helicity basis:



Spin Correlations at LHC

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

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



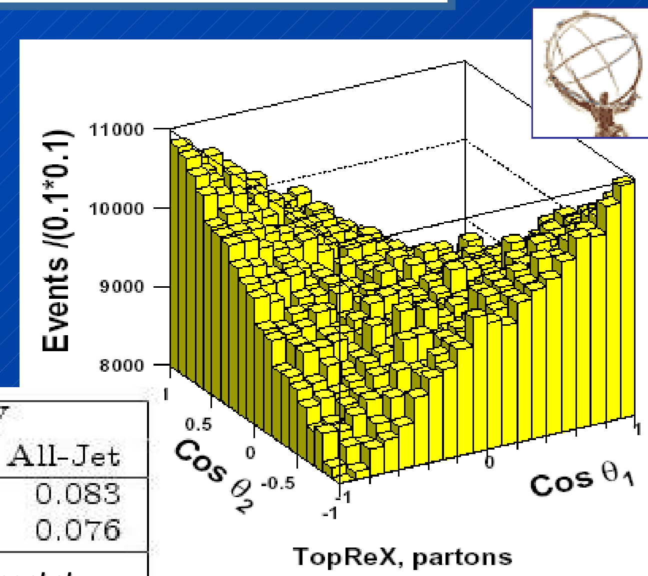
$$\mathcal{A} = \frac{N(t_L\bar{t}_L + t_R\bar{t}_R) - N(t_L\bar{t}_R + t_R\bar{t}_L)}{N(t_L\bar{t}_L + t_R\bar{t}_R) + N(t_L\bar{t}_R + t_R\bar{t}_L)}$$

→ *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
$\kappa_{\text{heli.}}$	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)		
$\kappa_{\text{off-diag.}}$	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

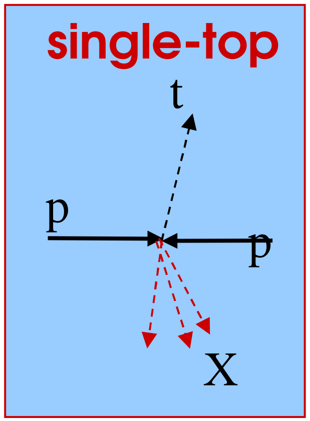
Main systematic uncertainties: parton generation (PDFs and Q^2 scale), FSR, b-jet energy scale and top quark mass uncertainty

Both CMS and ATLAS have sensitivity for observing spin correlations after 10 fb^{-1}

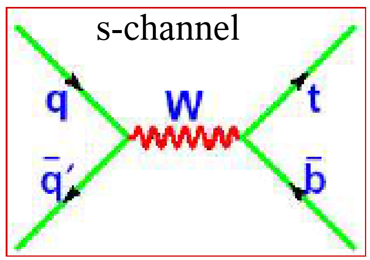
Weak Coupling of the Top Quark

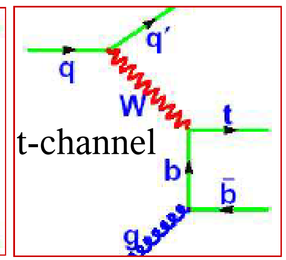
- Electroweak single top quark production (“evidence”)
  - in SM
  - in alternative models (W' (m>630-790 GeV), FCNC, ...)
- W-helicity in top quark decays

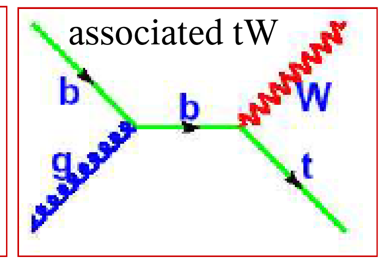
Electroweak Single Top Quark Production



4 single-tops per day @ Tevatron ↔ 30 single-tops per minute @ LHC







σ_{top} & $\sigma_{anti\text{-}top}$ not equal

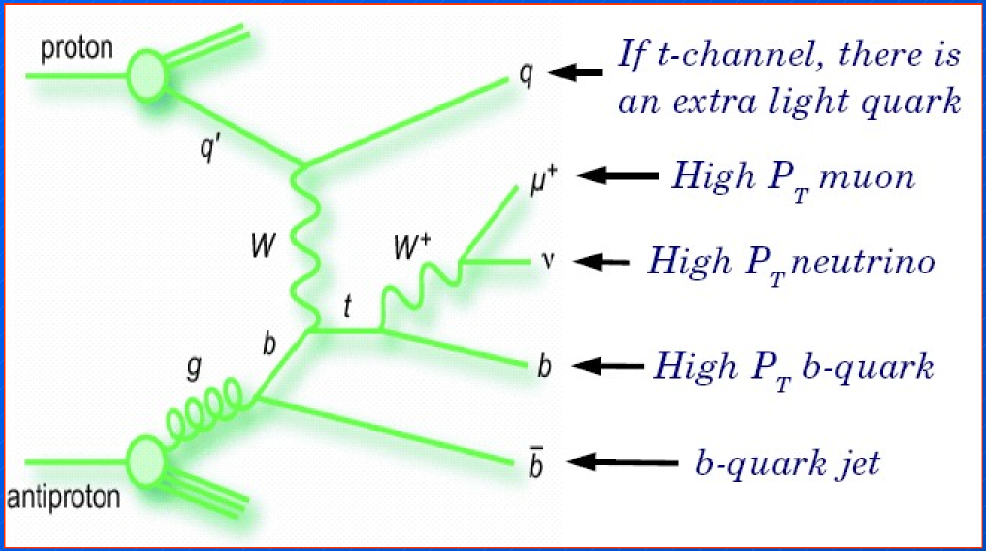
σ^{NLO}(total) = 373 pb

□ ~3.7M events/10fb^{-1}

	s-channel	t-channel	associated tW	
LHC	σ^{NLO} = 6.6 pb σ^{NLO} = 4.1 pb	σ^{NLO} = 153 pb σ^{NLO} = 90 pb	σ^{NLO} = 60 pb σ^{NLO} = 60 pb	→ top production → anti-top production
TeV	σ^{NLO} = 0.75 pb	σ^{NLO} = 1.47 pb	σ^{NLO} = 0.15 pb	

Some references (not a complete list!): (top pairs) N.Nason *et al.* Nucl.Phys. B303 (1988) 607, S.Catani *et al.* Nucl.Phys. B478 (1996) 273, M.Beneke *et al.* hep-ph/0003033, N.Kidonakis and R.Vogt, Phys.Rev. D68 (2003) 114014, W.Bernreuther et al. Nucl.Phys. B690 (2004) 81-137 (single-top) T.Stelzer et al. Phys.Rev. D56 (1997) 5919, M.C.Smith and S.Willenbrock Phys.Rev. D54 (1996) 6696, T.M.Tait Phys.Rev. D61 (2000) 034001

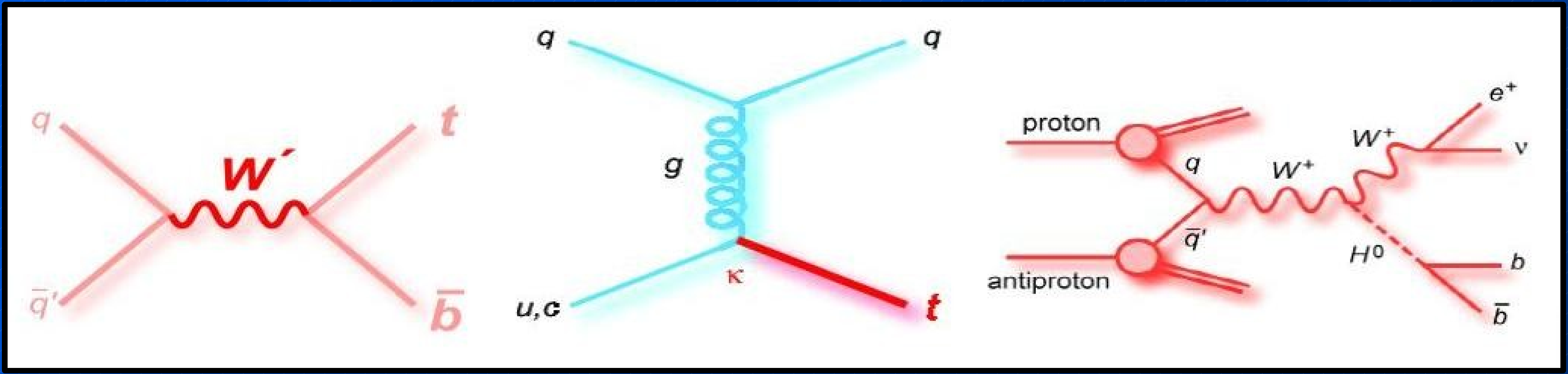
EW Single-Top Production



Each channel sensitive to different signals

- heavy W' → s-channel
- FCNC → t-channel
- $H^{\pm}$ → Wt-channel
- $W(H^0 \rightarrow bb)$ → s-channel

Also directly related to $|V_{tb}|$ to percent level (s-channel preferred, t-channel dominated by PDF scale uncertainties of ~10%)

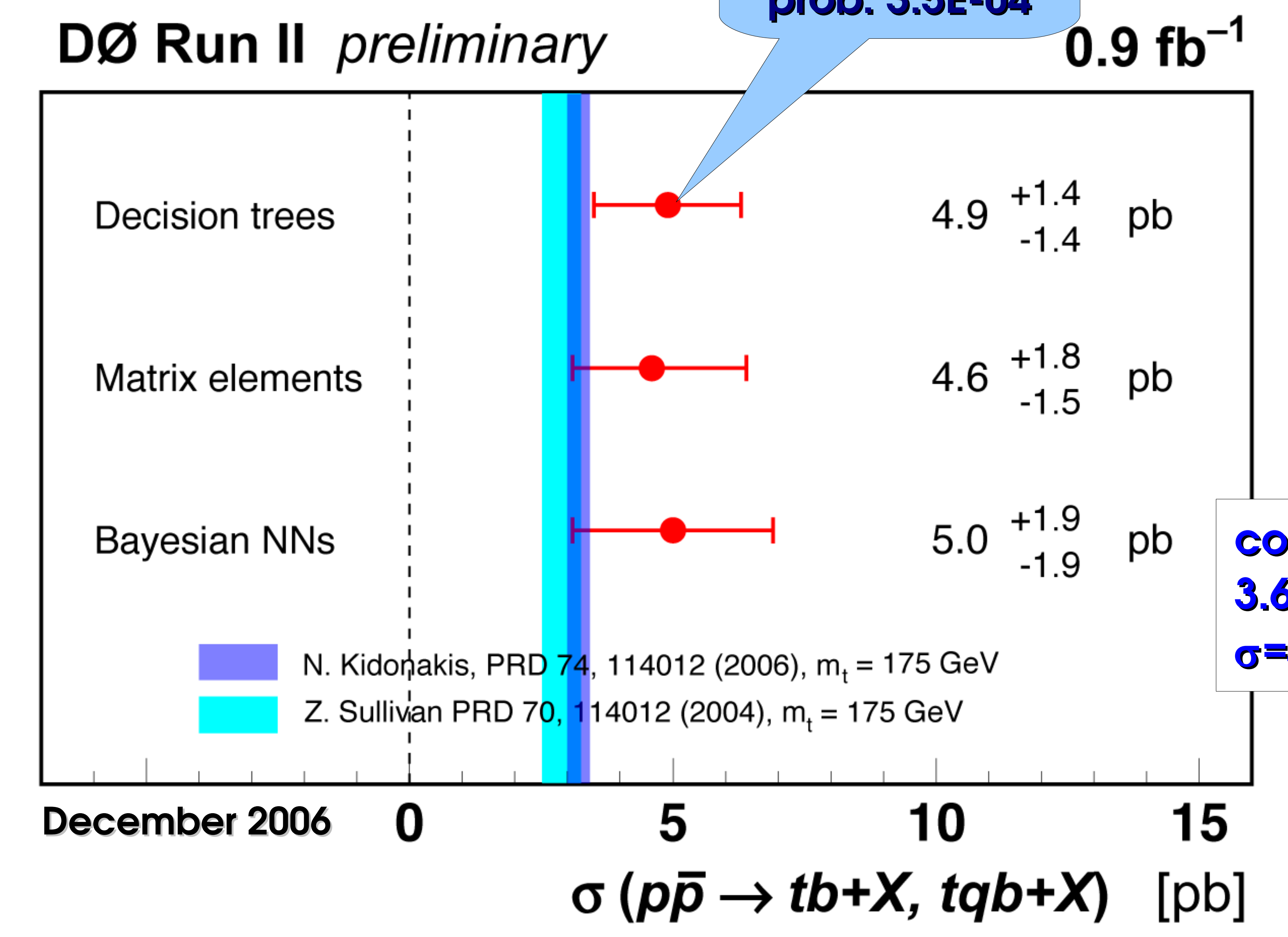


Evidence for Single-Top

Dec.2006

1 fb^{-1}

3.4σ excess
prob. 3.5E-04

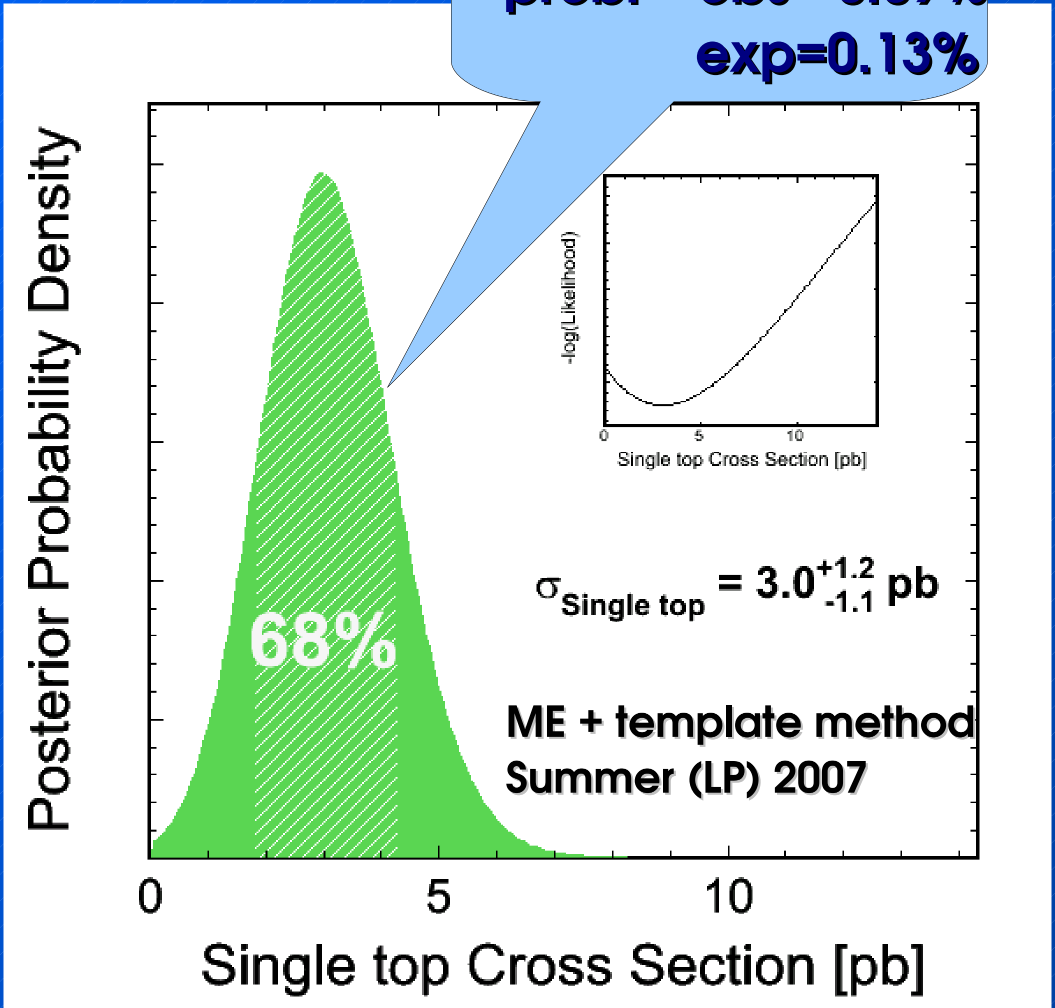


combination ('07):
3.6σ, prob.=0.014%
σ=4.7 ± 1.3 pb

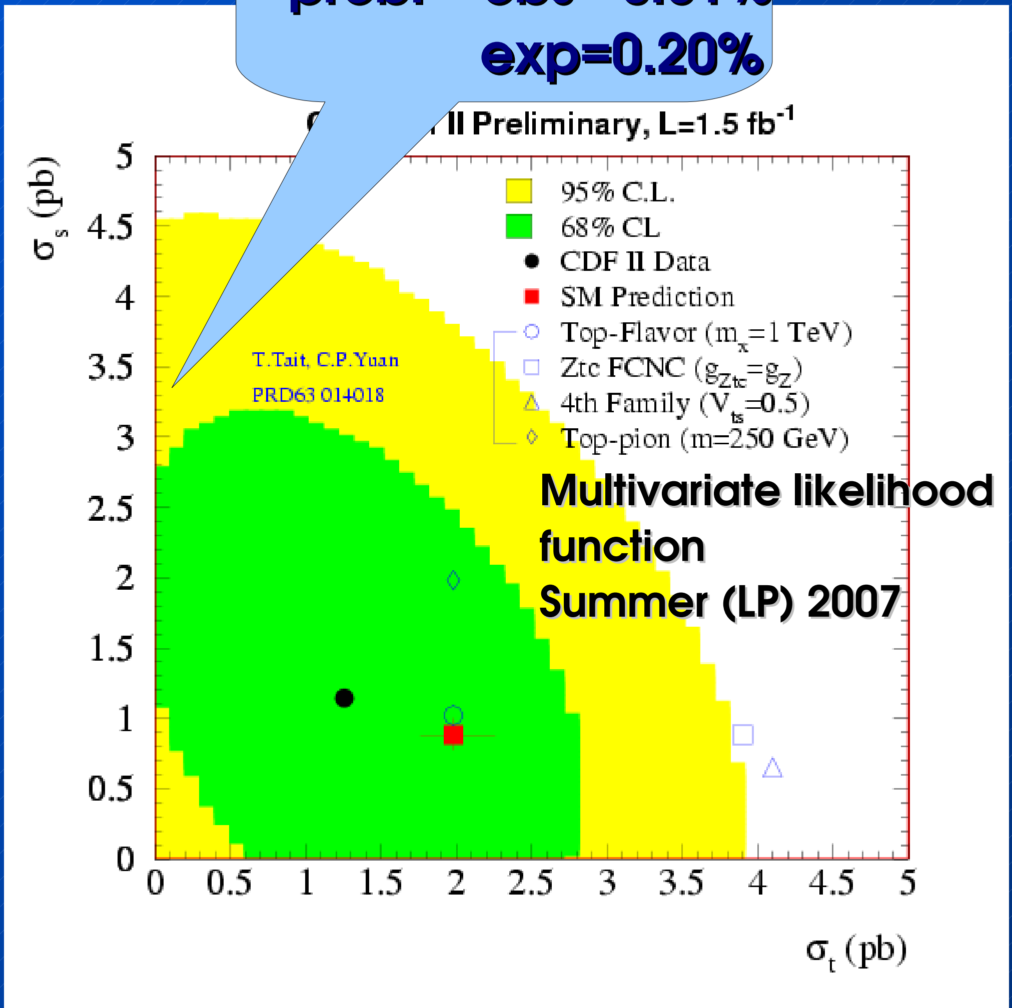
Evidence for Single-Top

15 fb^{-1}

3.1σ excess
prob. obs= 0.09%
exp=0.13%



2.7σ excess
prob. obs= 0.31%
exp=0.20%



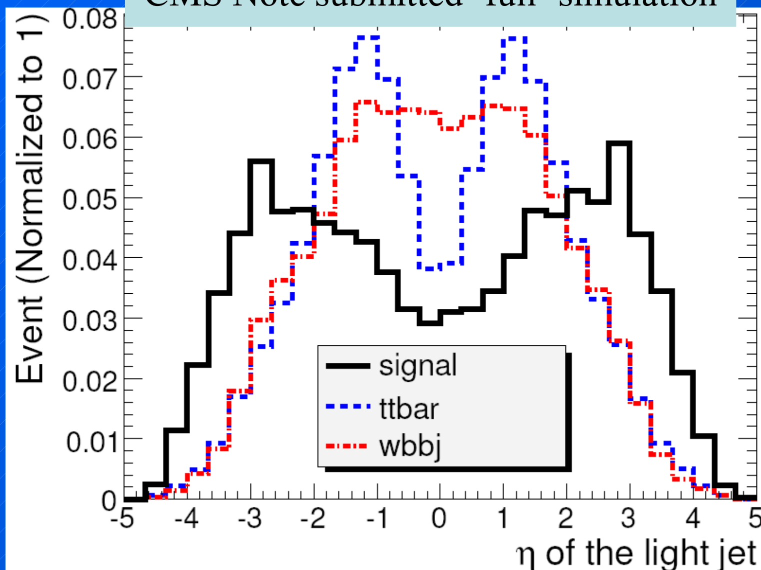
$|V_{tb}| = 1.02 \pm 0.18$ (exp) ± 0.07 (theory)

$|V_{tb}| = 0.97 \pm 0.2$ (exp) ± 0.07 (theory)

Single-Top Xsec at LHC

S-channel (10 fb^{-1})

CMS Note submitted ‘full’ simulation

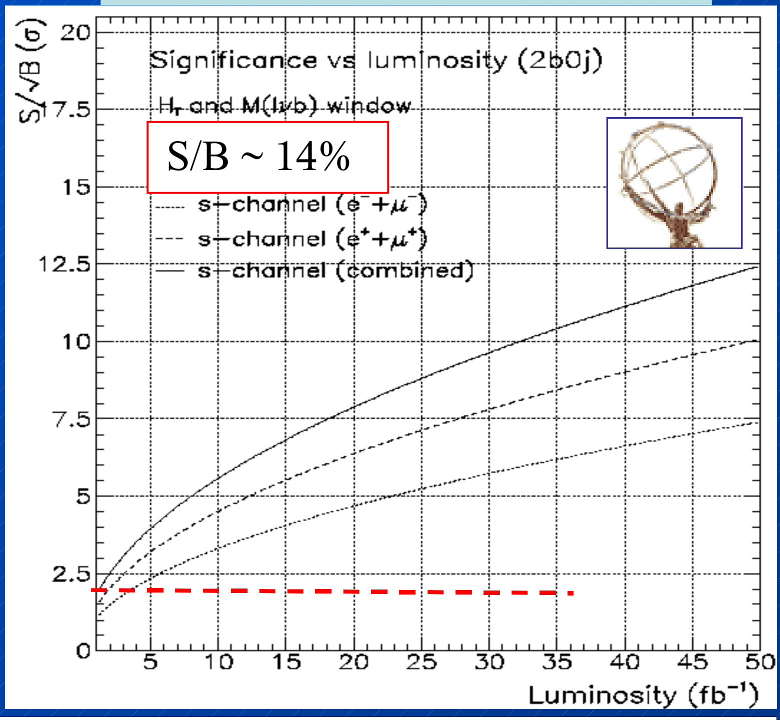


$$\frac{\Delta\sigma_t}{\sigma_t} = 2.7\%(stat) \oplus 8.1\%(syst) \oplus 3\%(lumi) = 9.$$

theory, JES, b-tagging

t-channel

ATLAS ATL-PHYS-PUB-2006-014
CMS Note submitted ‘full’ simulation



$$\frac{\Delta\sigma}{\sigma} = 12\%_{\mathrm{stat}} \pm 10.1\%_{\mathrm{exp}} \pm 8\%_{\mathrm{bckgd\ theo}} \pm 5\%_{\mathrm{lumi}}$$ **ATLAS (30fb^{-1})**

$$\frac{\Delta\sigma_s}{\sigma_s} = 18\%(stat) \oplus 31\%(syst) \oplus 3\%(lumi) = 36\%$$ **CMS (10fb^{-1})**

different treatment of bck uncertainties

Wt-channel (10 fb^{-1})

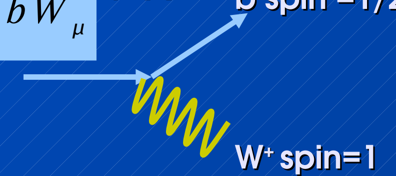
- Δσ/σ (di-lepton): 8.8 (stat) ± 23.9 (syst) ± 9.9 (MC stat) %
- Δσ/σ (semi-lepton): 7.4 (stat) ± 17.7 (syst) ± 15.2 (MC stat) %

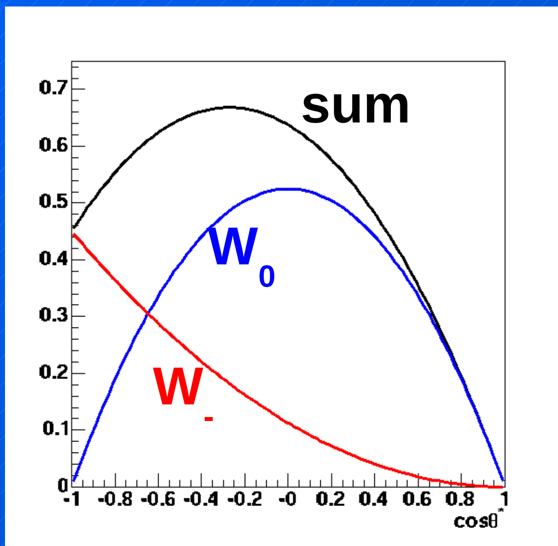
Weak Top Decay - Helicity of the W

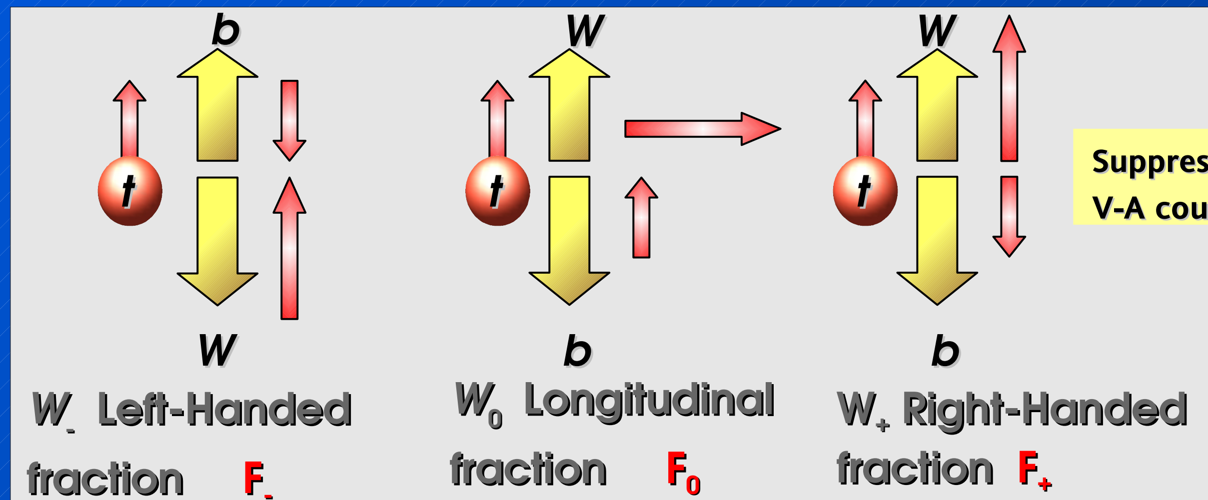
Top Standard Model weak decay →

V-A coupling as it is for all the other fermions

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







$$w(\cos\phi_{l\bar{b}})=F_{-}\cdot\frac{3}{8}(1-\cos\phi_{l\bar{b}})^2+F_0\cdot\frac{3}{4}(1-\cos^2\phi_{l\bar{b}})+F_{+}\cdot\frac{3}{8}(1+\cos\phi_{l\bar{b}})^2$$

In SM

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

$$F_0=\frac{1}{1+2\frac{m_W^2}{M_{top}^2}}\approx 0.70$$

... for any V, A combinations ...

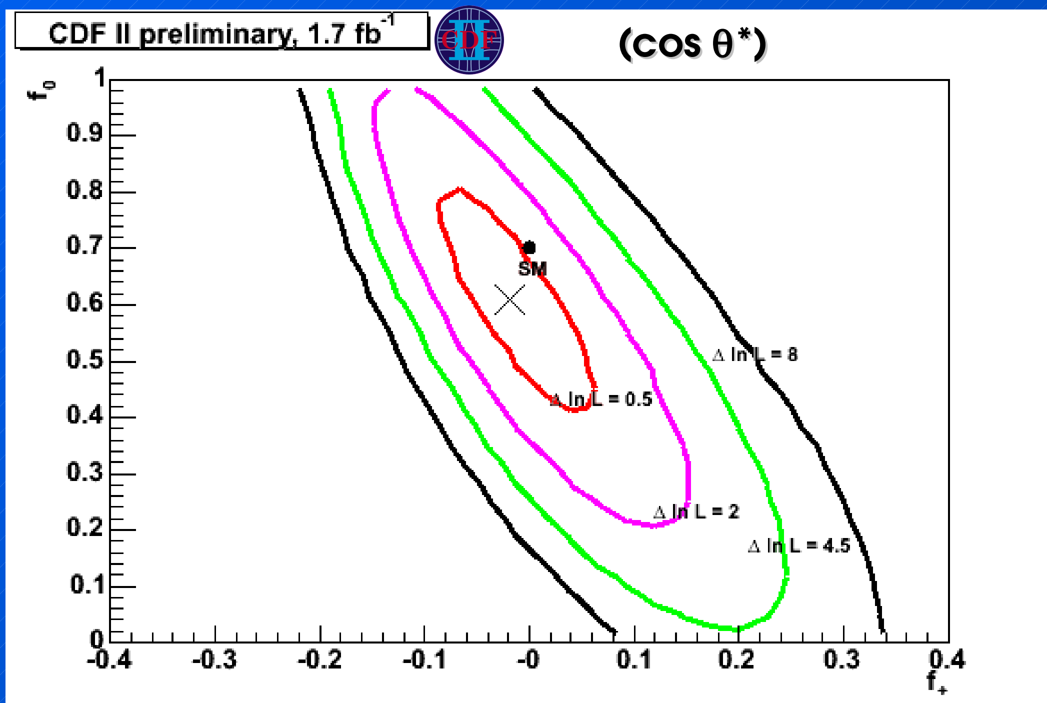
$$F_{+}\propto(m_b/m_t)^2 \approx 0$$

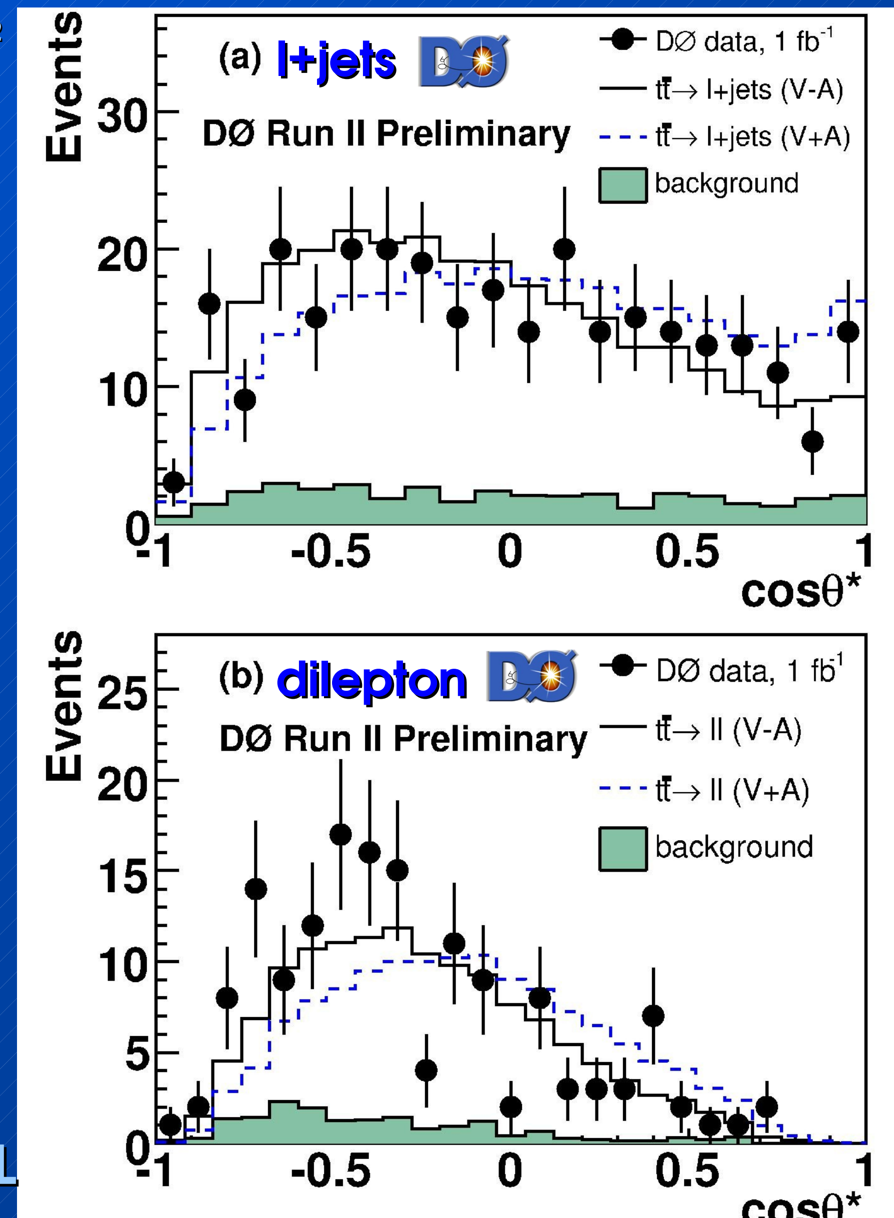
Helicity of W manifests itself in decay product kinematics

W-helicity in Top Quark Decays

- Charged leptons from ...
  ... left-handed W opposite to W ⇨ soft p_T
  ... longitudinal W transverse to W ⇨ hard p_T

- kinematic fit + cos θ* reconstr.
- M_{lb}^2





First simultaneous fit:

f_0 = 0.61 ± 0.20 ± 0.03 and

f_+ = -0.02 ± 0.08 ± 0.03

f_+<0.07 @ 95%CL

f_+<0.14 @ 95%CL

Electromagnetic Coupling of the Top Quark

- $e^+e^- \rightarrow \gamma^* \rightarrow t\bar{t}$ ⇨ ILC ...
- $t\bar{t}\gamma$ production @ LHC with 10 fb^{-1} (coupling $\otimes$ charge)

Top Quark Properties

... Charge & Mass ...

Top Quark Mass Measurements at Tevatron

dilepton	Neutrino weighting ($\eta \rightarrow \phi$)	➩ 1-dim. fit
	Phi-weighting ($\phi \rightarrow \eta$)	➩ 1-dim. fit
	P_z(tt) method	➩ 1-dim. fit
	ME weighting	➩ 1-dim. fit
	ME method	➩ 1-dim. fit
l+jets	Template method in m_{top} after kinematic fit, topological or b-tag, with internal or external JES constraint	➩ 1- or 2-dim. fit
	Matrix Element/Dynamical Likelihood Method, topological or b-tag, with internal or external JES constraint, complex analysis	➩ 1- or 2-dim. fit
	Ideogram method (W-mass @ LEP), compare signal and background mass spectrum, χ^2 weighting (kine fit), with internal/external JES constraint	➩ 1- or 2-dim. fit
	Decay Length Method, compare transv. Decay length spectrum with expecation from $c\tau(B) \cdot \beta(m_{top})\gamma(m_{top})$	➩ 1-dim. fit
alljets	Kinematic fit & ideogram, little sensitivity	➩ 1-dim. fit

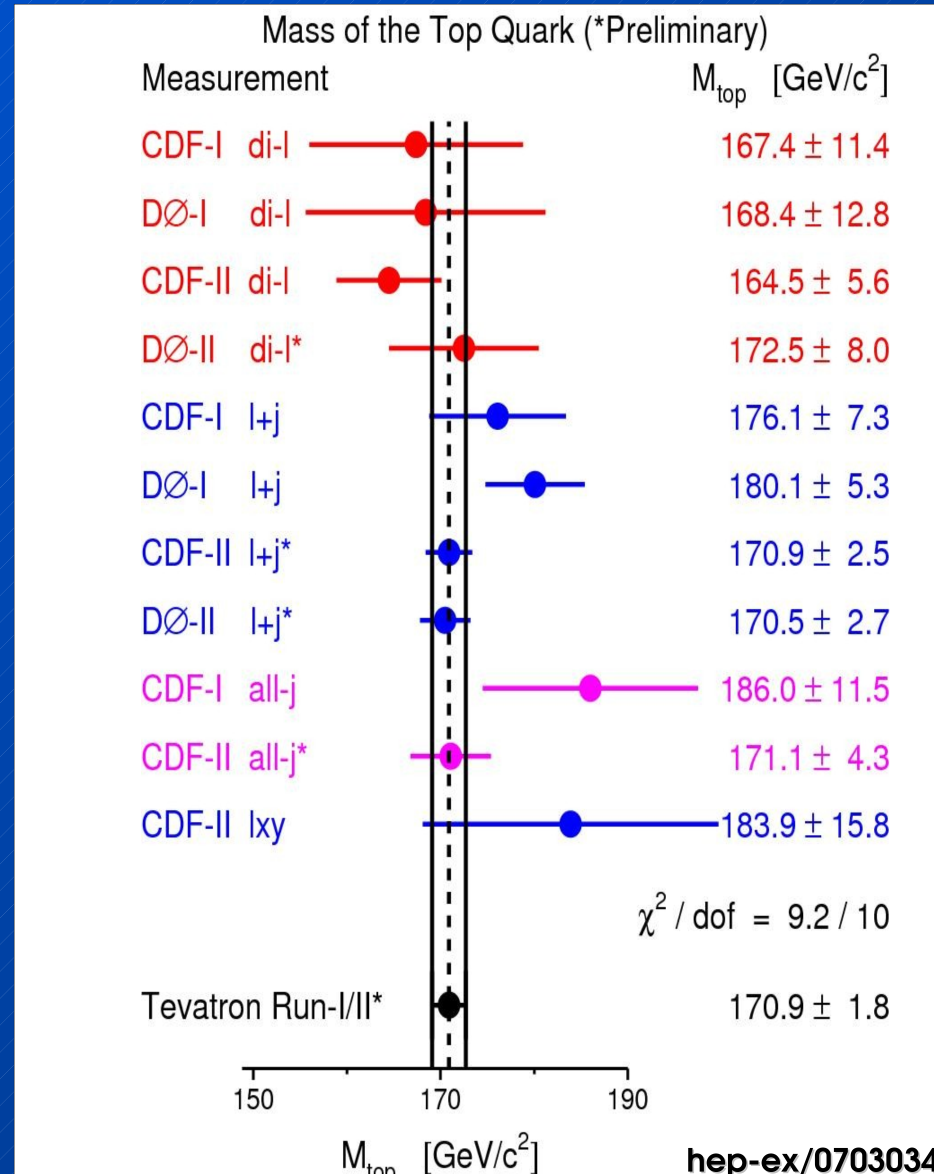
Top Mass Summary/Combination

systematics limited: JES, ttbar/W+j modelling, ...

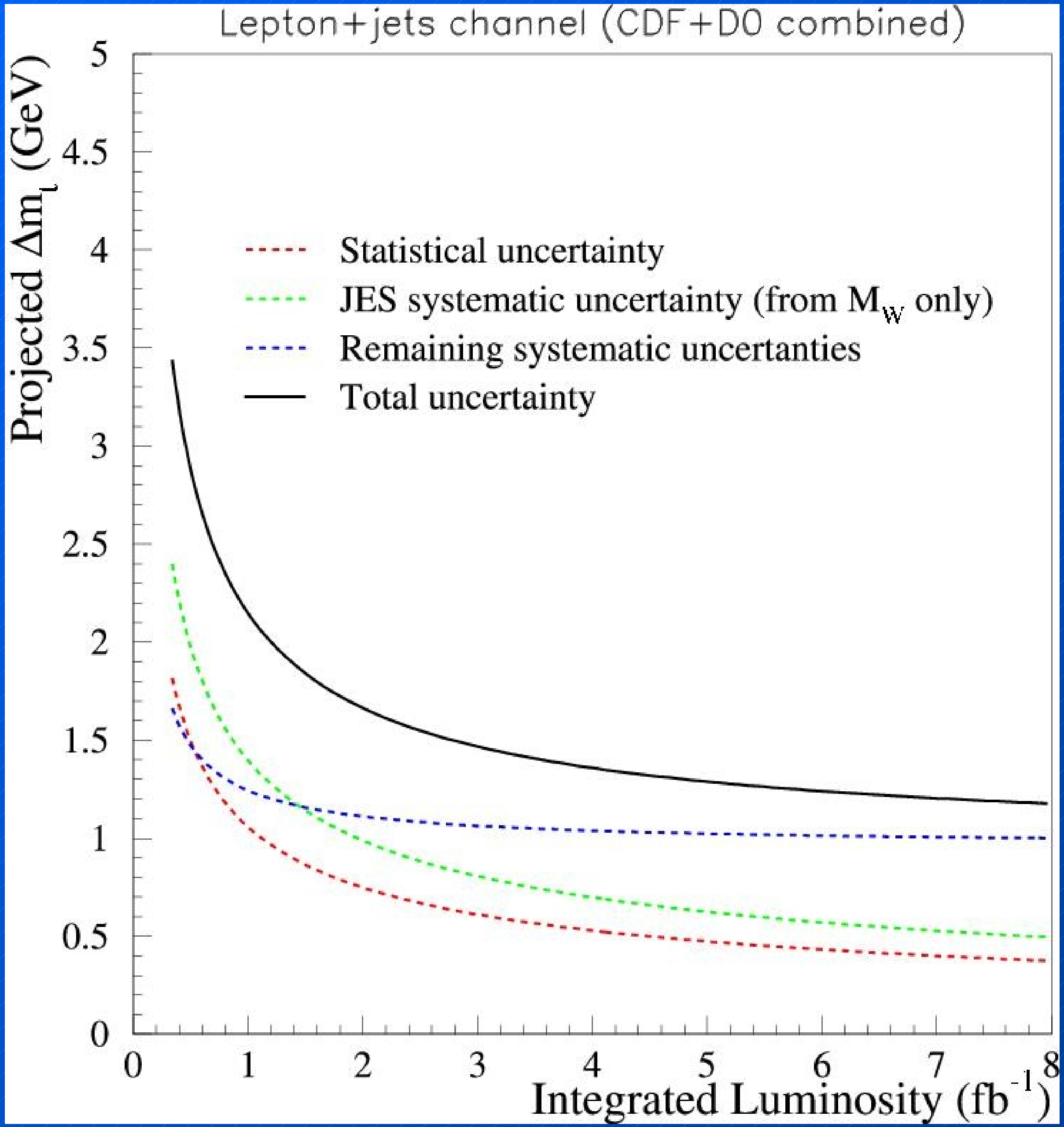
1 fb^{-1}

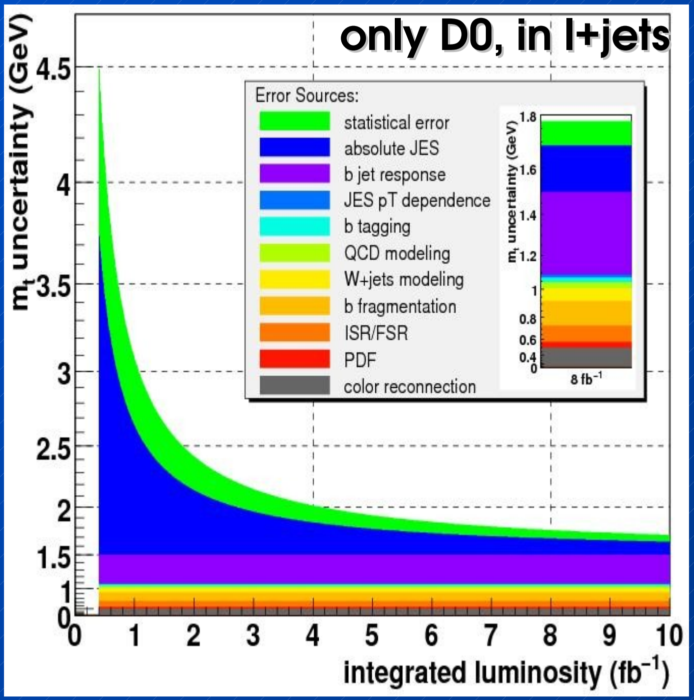
m_t (GeV/c^2)	Source		$\int \mathcal{L}dt$	Ref.	Method
179.0 ± 5.1	DØ	Run I	110-125	[70]	DØ combined
$169.9 \pm 5.8^{+7.8}_{-7.1}$	DØ	Run II	230	[73]	ℓ+jets/topo, TM
$170.6 \pm 4.2 \pm 6.0$	DØ	Run II	230	[73]	ℓ+jets/b-tag, TM
$170.5 \pm 2.5 \pm 1.4$	DØ	Run II	910	[74]	ℓ+jets/topo, ME($W \to jj$)
$170.5 \pm 2.4 \pm 1.2$	DØ	Run II	910	[74]	ℓ+jets/b-tag, ME($W \to jj$)
$176.6 \pm 11.2 \pm 3.8$	DØ	Run II	370	[75]	$\ell\ell$/b-tag, $\mathcal{MWT}$
$177.7 \pm 8.8 \pm 4.5$	DØ	Run II	835	[76]	$e\mu$, $\mathcal{MWT}$
$173.7 \pm 5.4 \pm 3.4$	DØ	Run II	1000	[77]	$\ell\ell$, $\eta(\nu) + \mathcal{MWT}$
$166.1 \pm 5.7 \pm 5.8(th)$	DØ	Run II	1000	[66]	$\sigma_{t\bar{t}}^{\ell+jets}$
$174.1 \pm 9.1 \pm 5.1(th)$	DØ	Run II	1000	[66]	$\sigma_{t\bar{t}}^{\ell\ell}$
$172.1 \pm 1.5 \pm 1.9$	DØ	Run I+II	1000	[67]	DØ combined
$170.9 \pm 2.2 \pm 1.4$	CDF	Run II	940	[81]	ℓ+jets/b-tag, ME($W \to jj$)
$169.8 \pm 1.6 \pm 2.2$	CDF	Run II	955	[82]	ℓ+jets/b-tag, ML
$171.6 \pm 2.1 \pm 1.1$	CDF	Run II	1700	[83]	ℓ+jets/b-tag, TM($W \to jj$)
$170.4 \pm 3.1 \pm 3.0$	CDF	Run II	1800	[84]	$\ell\ell$, ME
$169.7^{+5.2}_{-4.9} \pm 3.1$	CDF	Run II	1200	[85]	$\ell\ell$, $p_z(t\bar{t})$
$170.7^{+4.2}_{-3.9} \pm 2.6 \pm 2.4(th)$	CDF	Run II	1200	[85]	$\ell\ell$, $p_z(t\bar{t}) + \sigma(t\bar{t})$
$172.0^{+5.0}_{-4.9} \pm 3.6$	CDF	Run II	1800	[86]	$\ell\ell$, $\eta(\nu)$
$156 \pm 20 \pm 4.6$	CDF	Run II	1800	[65]	$\ell\ell$, $P_T(\ell)$
$174.0 \pm 2.2 \pm 4.8$	CDF	Run II	1020	[87]	all jets, TM
$171.1 \pm 3.7 \pm 2.1$	CDF	Run II	943	[88]	all jets, TM+ME($W \to jj$)
$170.5 \pm 1.3 \pm 1.8$	CDF	Run I+II	110-1000	[89]	CDF Combined
$172.5 \pm 1.5 \pm 2.3$ *	CDF,DØ	(I+II)	110-1000		publ. results, PDG best
$170.9 \pm 1.1 \pm 1.5$ **	CDF,DØ	(I+II)	110-1000	[68]	publ. or prelim. results

TevEWWG (Mar/2007):



Top Mass Outlook at Tevatron





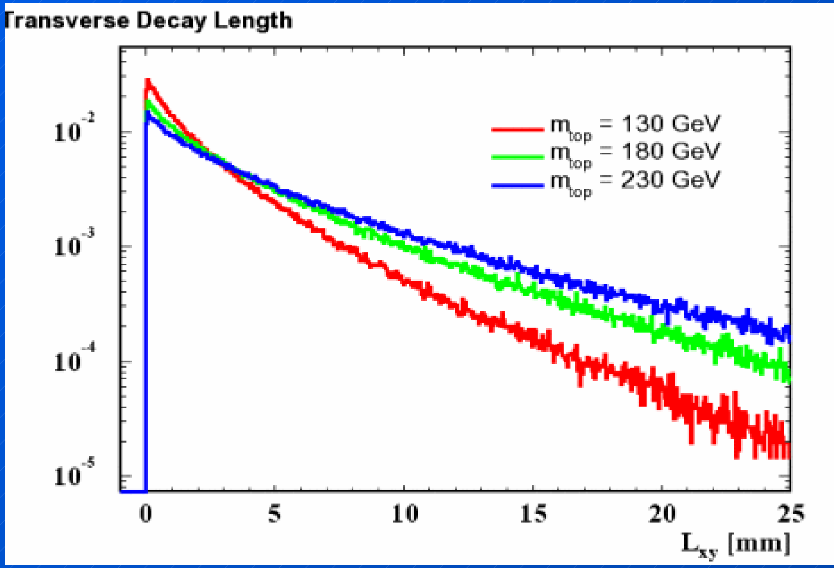
- Tevatron could reach Δm_{top}=1 GeV/c^2 in combination of all channels and both experiments if ...
- in-situ calib. → correl. with m_W
- ultimate precision in top mass from LHC and Tevatron expected to be comparable; limited by mapping exp. ⇨ mass

Decay Length Technique

- Top quarks at Tevatron produced nearly at rest
  ⇨ boost of the b-quark a function of m_{top}

$$\gamma_b = \frac{m_t^2 + m_b^2 - m_W^2}{2\, m_t\, m_b} \approx 0.4 \frac{m_t}{m_b}$$

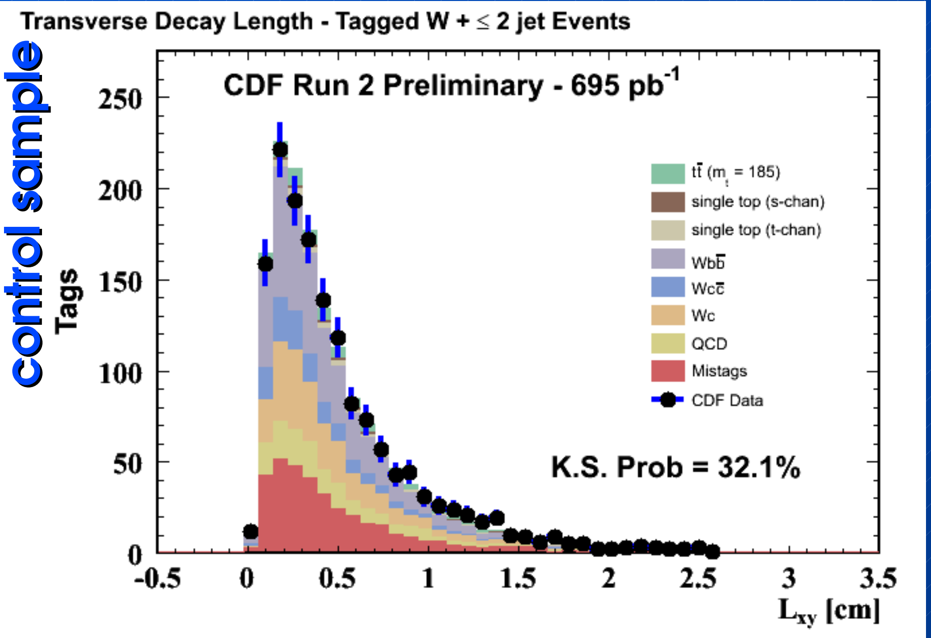
- Measure transverse decay length of B-hadrons from top decay ⇨ infer on top quark mass



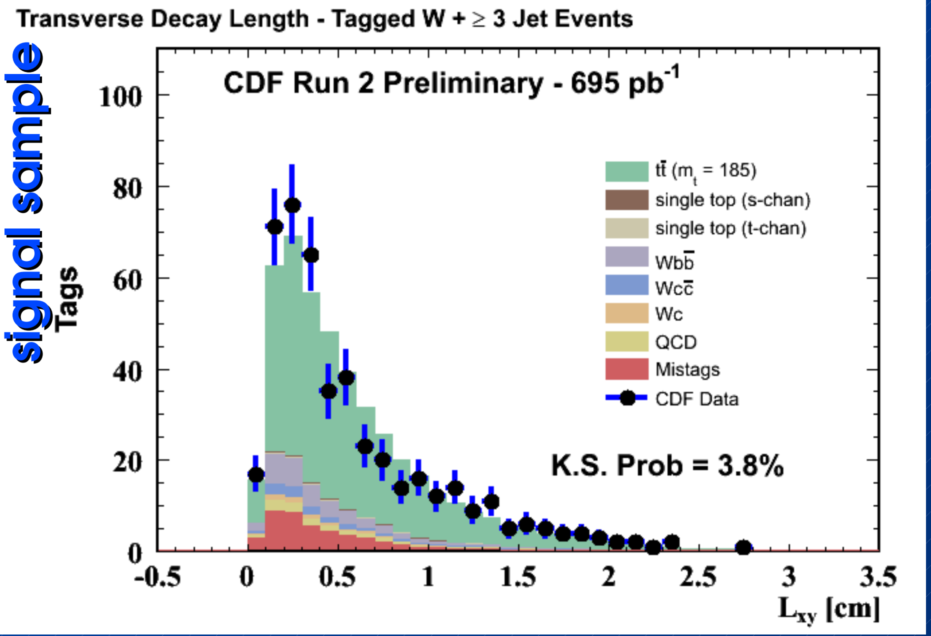
- Select l + ≥ 3 jets events with ≥ 1 SecVtx tag in 695 pb^{-1} ⇨ 456 pos. SecVtx tags in 375 events

$$m_{top} = 183.9\, ^{+15.7}_{-13.9}\,(stat.) \pm 5.6\,(syst.)\, GeV/c^2$$
$$\Delta m_{top}(JES) = 0.3\, GeV/c^2$$

control sample



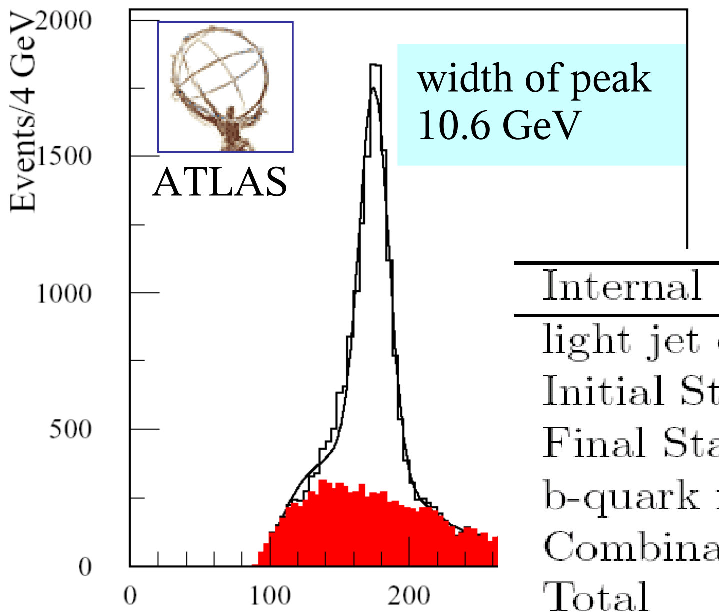
signal sample



Top Mass in L+Jets Channel

ATLAS Eur.Phys.J C39 (2005) 63

- Based on 'fast'(`full') simulation
- Jet pairing via angle (b,lepton) → ~82%
- In-situ jet energy calibration (W→jj)
- Mass estimator via fit on spectrum
- Alternative: kinematic fit (m_W & m_t=$m_{anti\text{-}t}$)
- Reduces systematics due to radiation



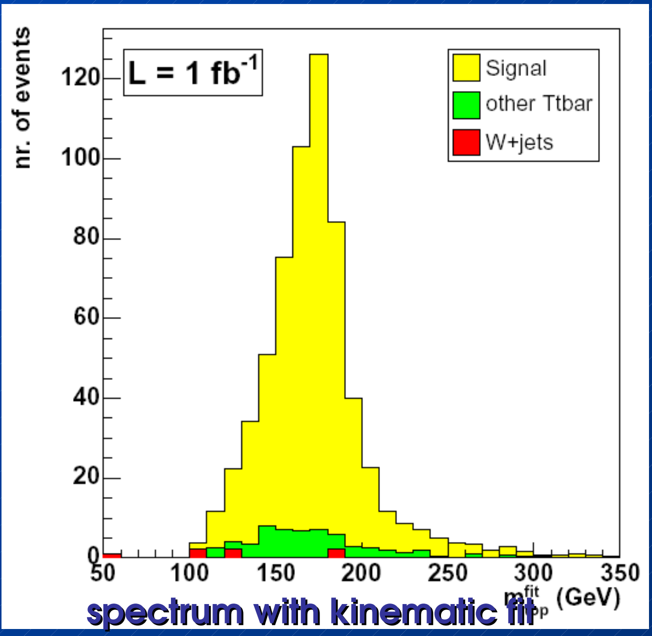
δm_t(stat) ~ 100 MeV (10fb^{-1})

Internal Systematics ATLAS	δm_t (GeV)
light jet energy scale	0.2
Initial State Radiation	0.1
Final State Radiation	$\leq$ 0.5
b-quark fragmentation	0.1
Combinatorial background	0.1
Total	$\leq$ 0.6
Statistical error	0.1
b jet energy scale	$0.7\times x\%$

also: pileup, JES, ...

CMS Note 2006/066

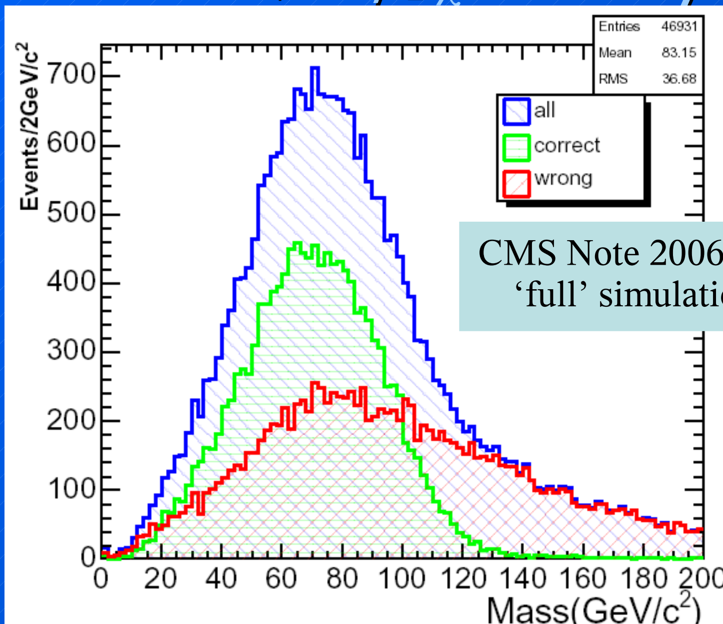
- Three top quark mass estimators :
  - ☆ *Gaussian fit (CMS Note 2006/023) on m_t^{reco} spectrum* → m_t^{Simple}
  - ☆ *convolution with Gaussian parametrized ideogram* → $m_t^{ParamIdeo}$
  - ☆ *convolution with full scanned ideogram* → $m_t^{FullIdeo}$



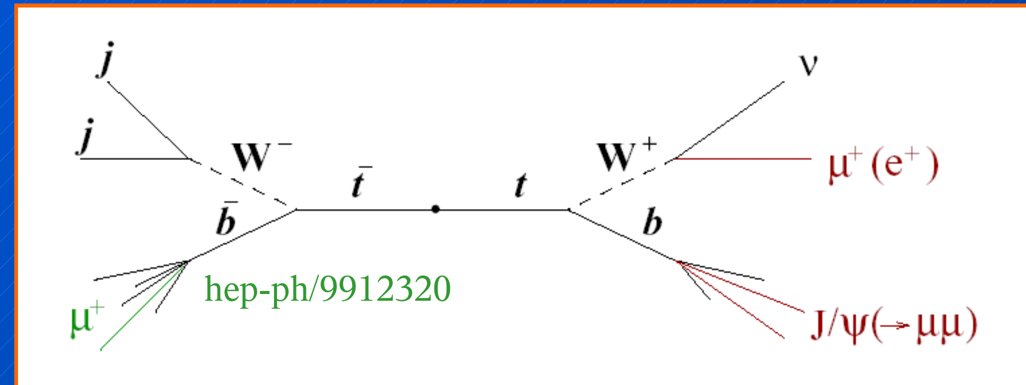
spectrum with kinematic fit

Top Mass in $t \to \ell\nu + J/\Psi + X$ Channel

- from $t \to \ell\nu + J/\Psi + X$ decays :



CMS Note 2006/058
'full' simulation



- ➔ *100 fb^{-1} gives after selection*

  ~ 1,000 signal events (S/B > 100)
- ➔ *large mass of J/Ψ induces strong correlation with top mass*
- ➔ *easy to identify, clean sample*
- ✶ *BR(overall in tt) ~ 5.3 x 10^{-5}*

- no jet related systematics
- 2 GeV uncertainty after 2 years of LHC running
- conservative estimate; most syst. Uncertainties related to theoretical modeling of events
- ultimately, a **1-1.5 GeV uncertainty** feasible

ATLAS Eur.Phys.J C39 (2005) 63
'fast' simulation

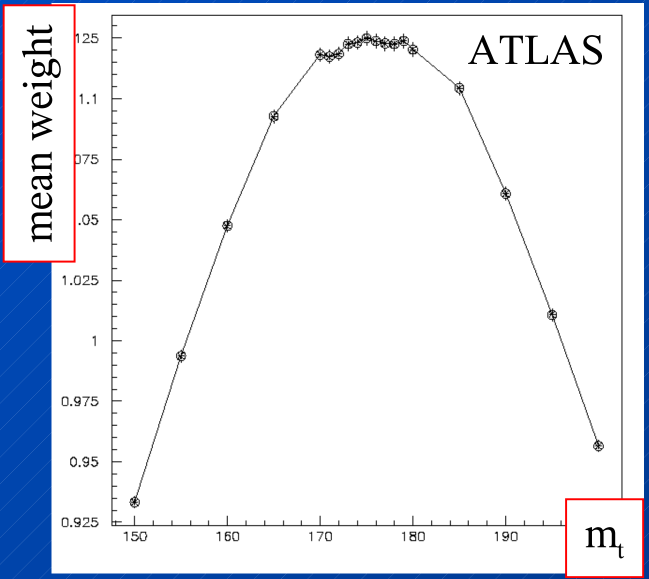
Systematic uncertainties	$\delta M_{\ell-J/\psi}^{peak}$(GeV/c^2)
Final State Radiation	0.15
PDF	0.1
b-quark fragmentation	0.3
Background	0.1
Statistical error	0.5

Top Mass in Dilepton Channel

full event reconstruction via χ^2 technique
- *set of equations from kinematic constraints*

- *solution is found in 98% of the selected events*
- *σm_t(stat) ~ 300 MeV (10fb^{-1})*

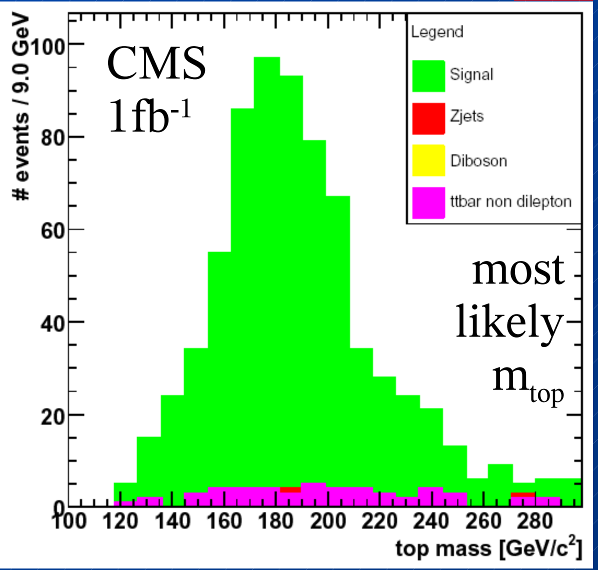
- *small systematics due to radiation (switching on/off ISR/FSR)*



ATLAS Eur.Phys.J C39 (2005) 63 = 'fast' simulation
CMS Note 2006/077 = 'full' simulation

source of uncertainty ATLAS	$\|\Delta m_t\|$ (GeV)	δm_t (GeV)
Statistics and reconstruction method		0.3
b-jet energy scale	0.6	0.6
b-quark fragmentation	0.7	0.7
Initial state radiation	0.4	0.1
Final state radiation	2.7	0.6
Parton distribution function	1.2	1.2

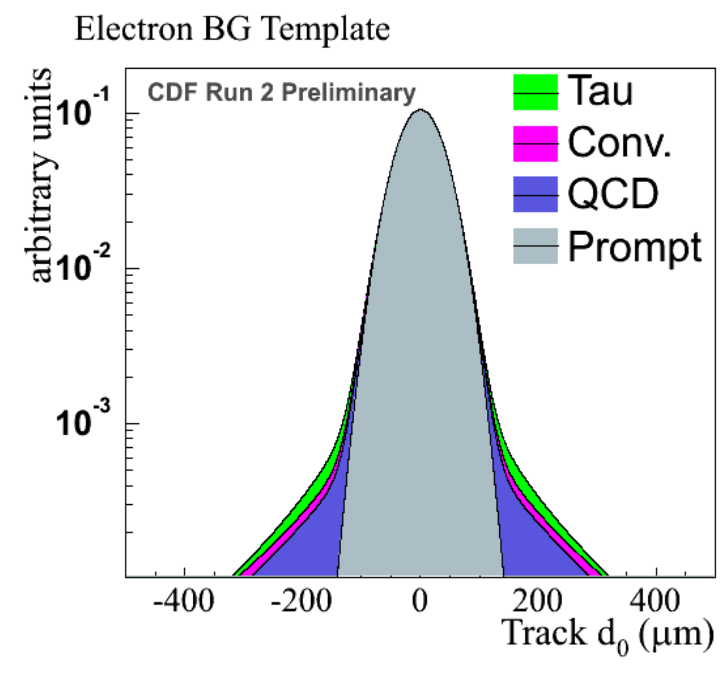
(ISR/FSR: 20% →)

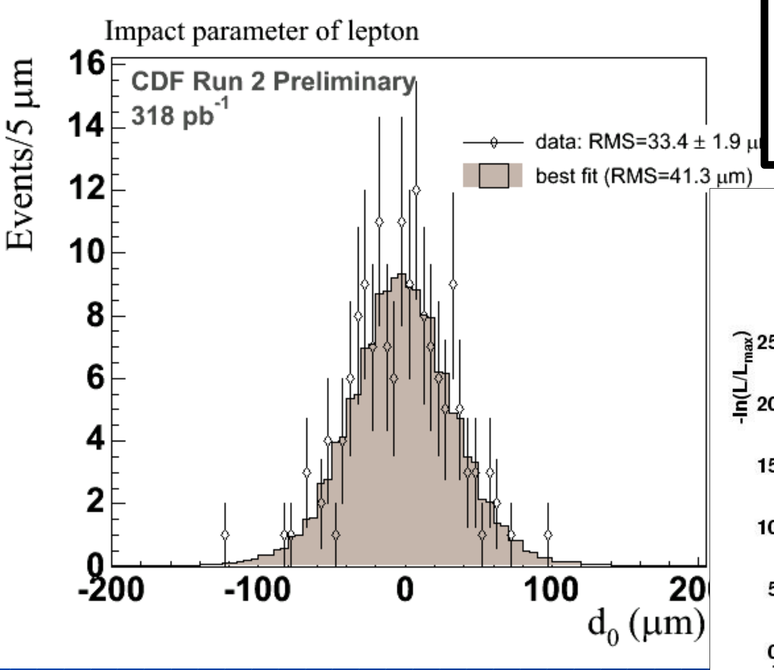


≤ 1 GeV/c^2 total precision appears feasible @ 10 fb^{-1}

Top Quark Lifetime

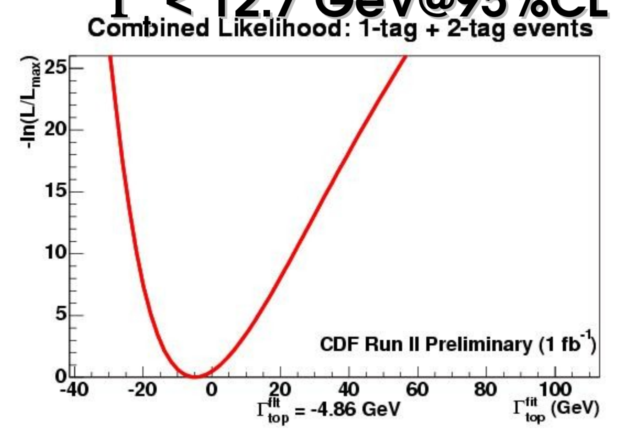
- First direct limit on the lifetime of the top quark
- top quark lifetime in SM $5 \cdot 10^{-25}$ s ($c\tau = 3 \cdot 10^{-10}$ μm)
- search for anomalous top production via new, long-lived particle
- lepton + ≥ 3 jets with ≥1 b-tag in 318 pb-1
  - 97 e+jets candidates
  - 60 μ+jets candidates
- measure impact parameter d0 for lepton tracks
- use max. likelihood fit with templates of arbitrary lifetime (incl. track resolution)





Best fit: $c\tau = 0$ μm
upper limit: $c\tau < 53$ μm
(@ 95% CL)

kine.fit (1 fb^{-1}):
$\Gamma_t < 12.7$ GeV@95%CL



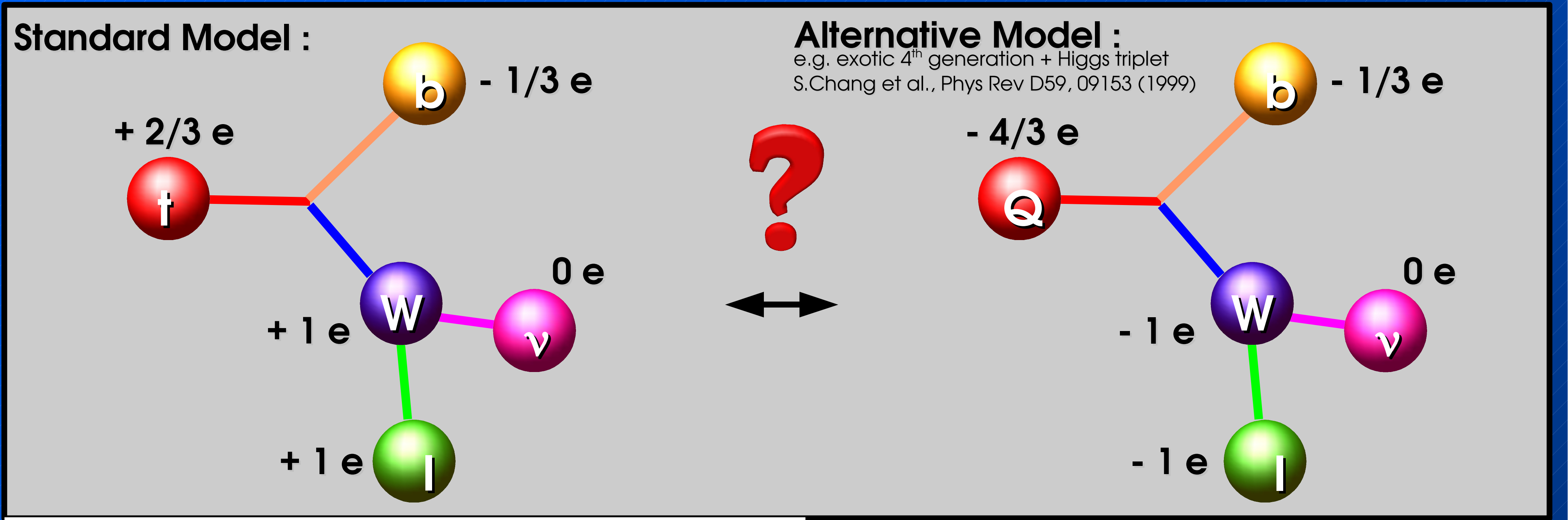
Top Quark Charge

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

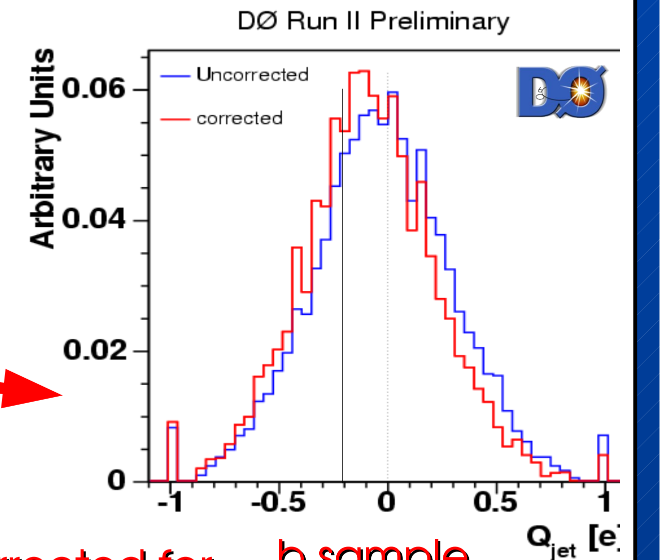
Top Quark Charge at Tevatron

- 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

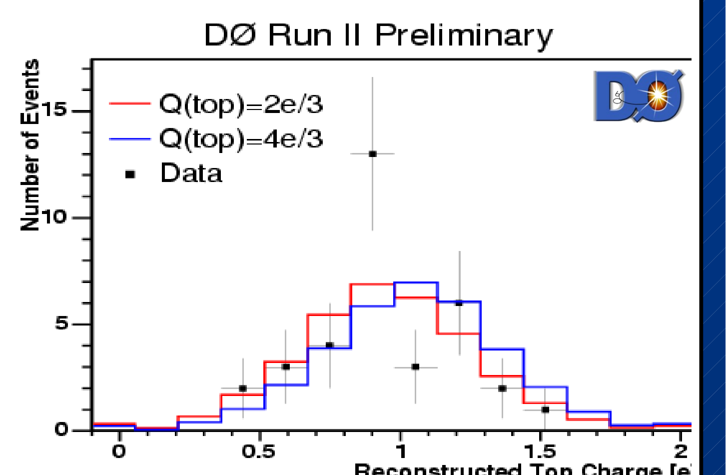
b sample q=-1/3

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
  - $\sigma(pp \to t\bar{t}\gamma)$ 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

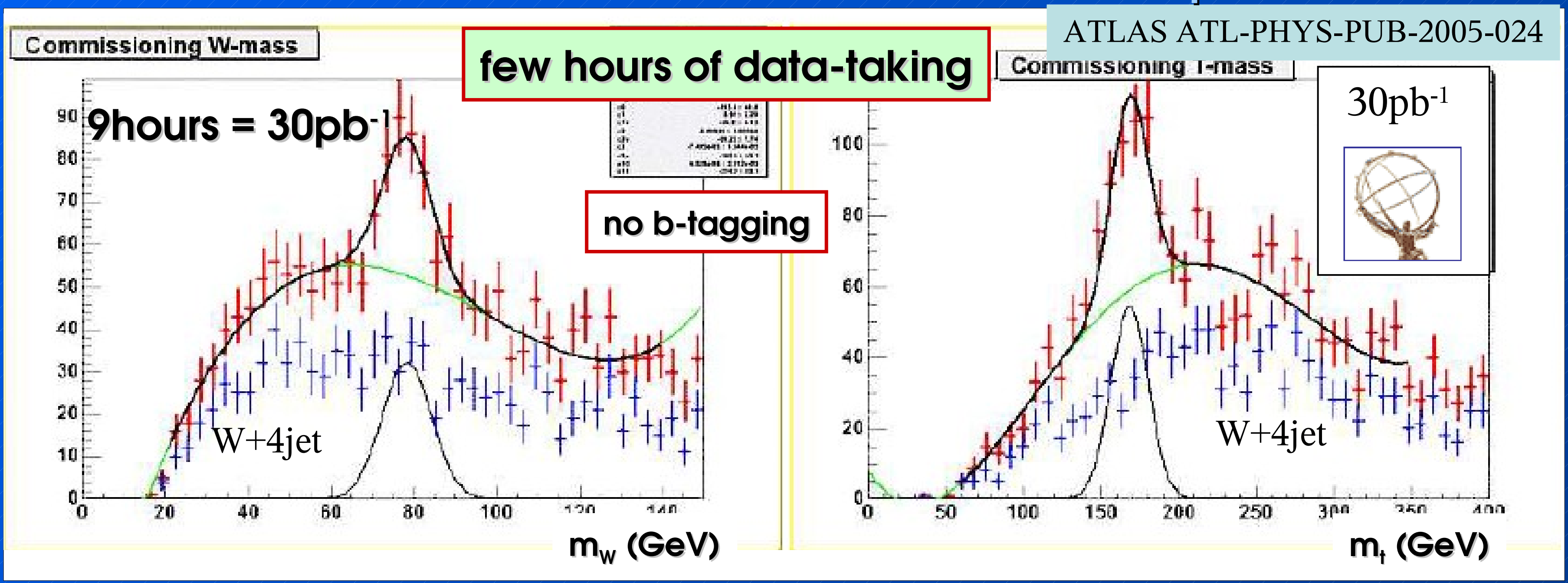
- **Method 2**: Measurement of daughter particle charge
  - Associate b-lepton pair from the same top
  - Compute the charge of b on a statistical basis:

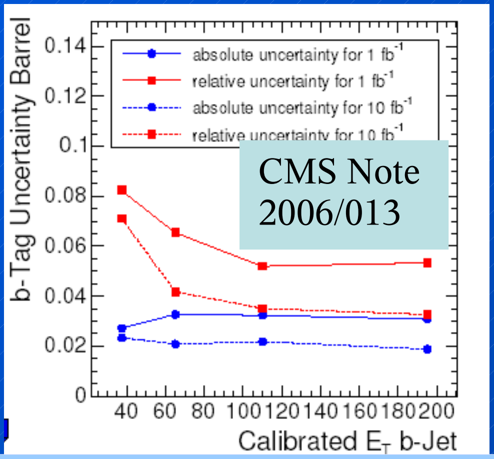
$$q_{\text{bjet}} = \frac{\sum_i q_i |\vec{j} \cdot \vec{p}_i|^\kappa}{\sum_i |\vec{j} \cdot \vec{p}_i|^\kappa}, \kappa = 0.6$$

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

Top Quarks as `Standard Candle'

The top mass peak will be one of the first signals to detect and the cross section one of the first relevant measurement to be performed.





First day results with 30pb^{-1} : $\sigma(m_t)$ ~ 3 GeV and $\sigma(m_W)$ ~ 1 GeV

ΔJES = 2-3% in first year

$\Delta\varepsilon$(b-tag) = 3-4% with 1fb^{-1}

Conclusion

- Top quark physics at TeVatron a large field
  - already now many analyses systematics limited
  - SM measurements and many tests fro new physics

- Top quark physics at LHC ⇨ high precision SM measurements
  ⇨ high sensitivity for new physics
  ⇨ much wider range of topics

  - Top in `year 1': Commissioning detector and physics
  - Top in `year 2': Standard Model Processes and Phenomena
  - Top in `year 3': Exploit Sensitivity to New Physics

Backup Slides

Further Studies on Top Quark Pair Production

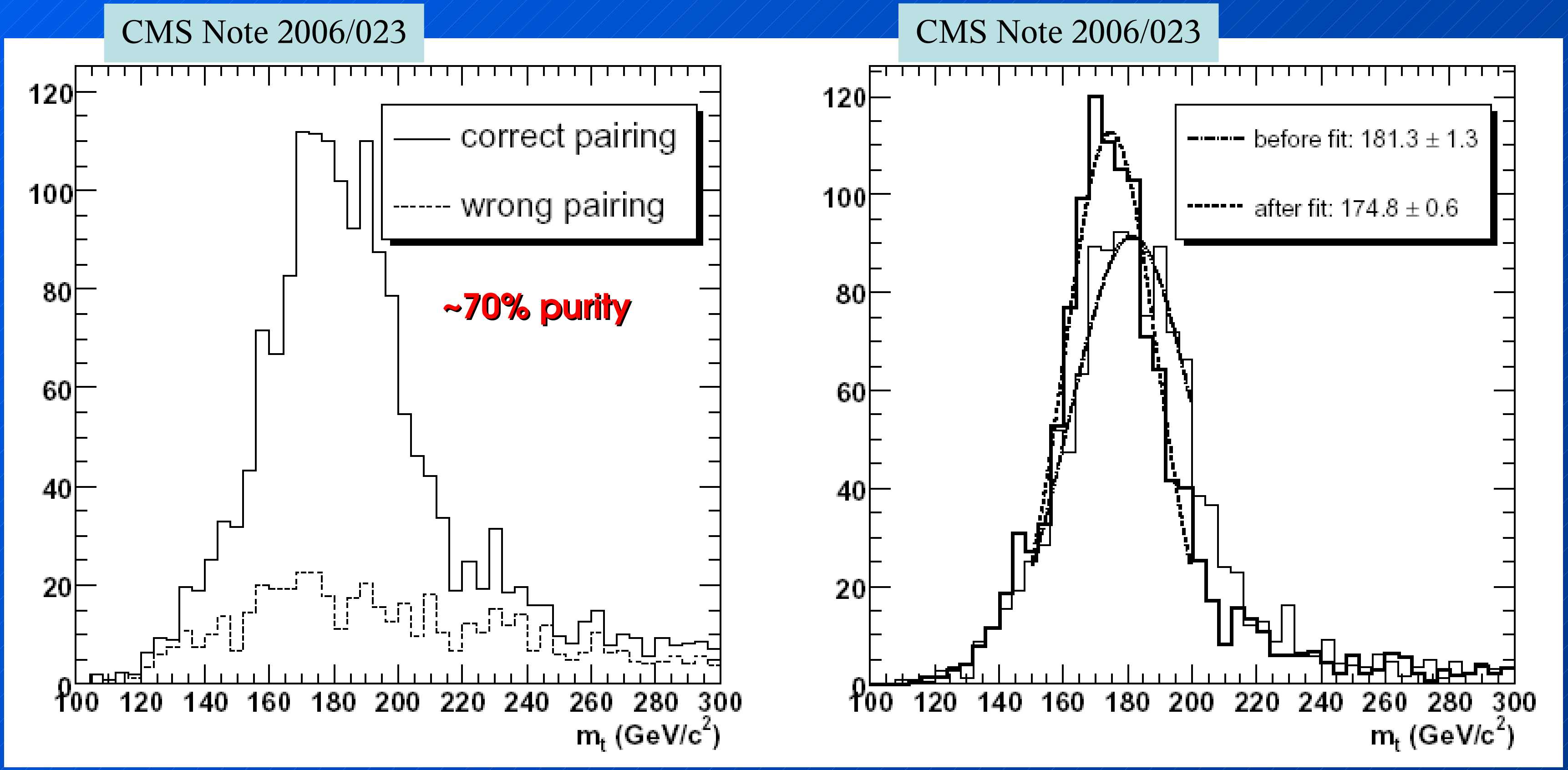
ttj and ttjj Xsec measurements are very important ...

- as QCD tests
- probe suppressed t → tg radiation due to large top mass
- determine mass from σ_{ttj}/σ_{tt} ...?
- study/understand tt(H → bb) background from data

spin correlations ...

Object & Event Reconstruction (l+jets)

Kinematic fit techniques (Least-Square methods with mass constraints)
... here hard m_W constraint ...

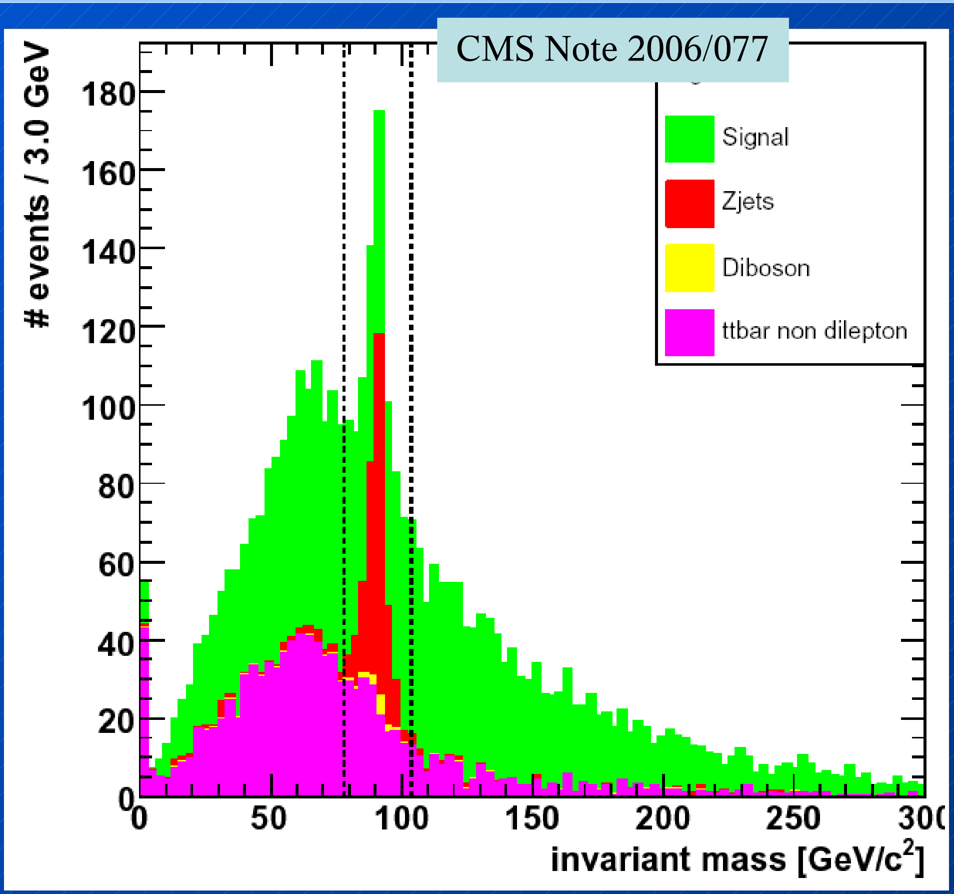


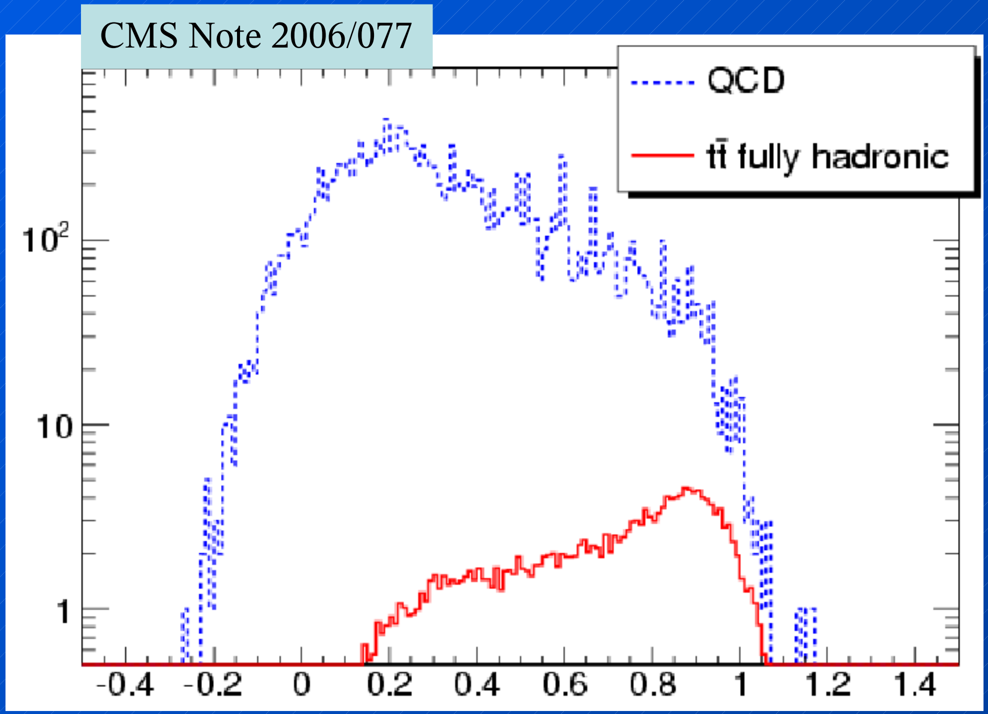
precision equivalent to ...
... no fit with 5 times more data ...

Object & Event Reconstruction (ll & all-jets)

Di-leptonic channel:

Mass window around the Z boson mass rejects basically all Z+jet events





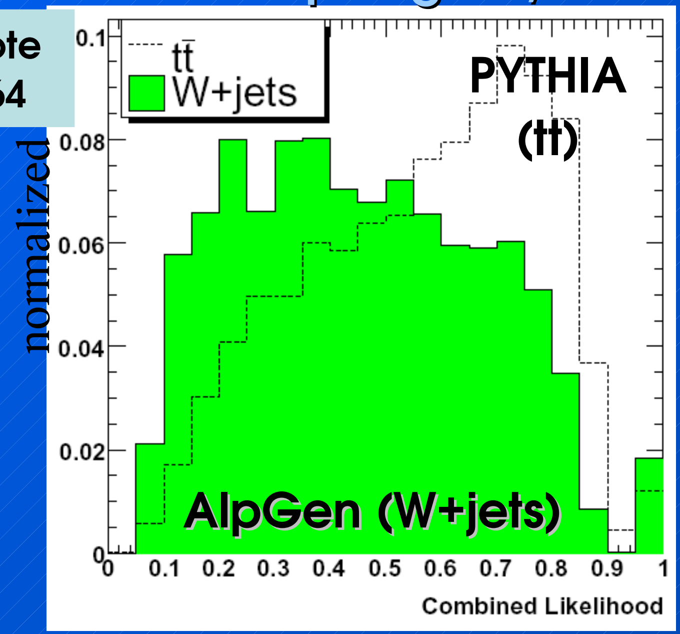
Fully hadronic channel:

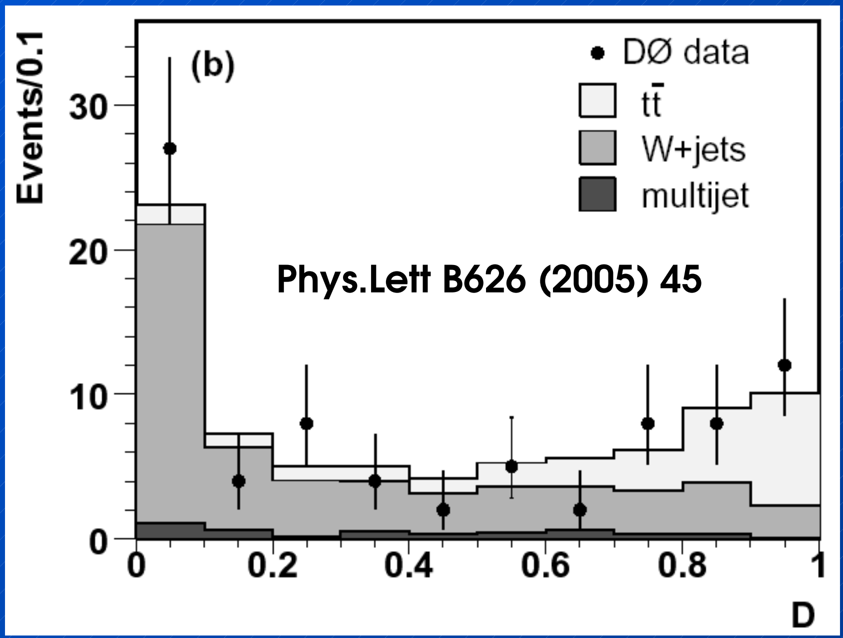
Neural Network output combining the information of several topological obervables (scaled to effective cross section)

Top Quark Pair Cross Section

- Shape analysis (identical á la D0 in Phys.Lett. B626 (2005) 45)
  - combine the topological/kinematic information of several event observables

CMS Note 2006/064





  - not as powerful as at the Tevatron (CMS Note 2006/064 & ATLAS Eur.Phys.J.C39(2005)63)

- Simple counting experiment (high S/N) ➪ precision:

• di-lepton :	(e/μ)	0.9 (stat) ± 11	(syst)	± 3 (lumi) %	($10fb^{-1}$)
	(τ)	1.3 (stat) ± 16	(syst)	± 3 (lumi) %	($10fb^{-1}$)
• lepton+jet :	(e/μ)	0.4 (stat) ± 9.2	(syst)	± 3 (lumi) %	($10fb^{-1}$)
• fully hadronic :		3 (stat) ± 18	(syst)	± 3 (lumi) %	($10fb^{-1}$)

Top Quark Pair Cross Section

- Breakdown of total uncertainty (CMS Note 2006/064)
  - example in the semi-leptonic muon channel

	$\Delta\hat{\sigma}_{t\bar{t}(\mu)}/\hat{\sigma}_{t\bar{t}(\mu)}$		
	1 fb^{-1}	5 fb^{-1}	10 fb^{-1}
Simulation samples (ϵ_{sim})	0.6%	0.6%	0.6%
Simulation samples (F_{sim})	0.2%	0.2%	0.2%
Pile-Up (30% On-Off)	3.2%	3.2%	3.2%
Underlying Event	0.8%	0.8%	0.8%
Jet Energy Scale (light quarks) (2%)	1.6%	1.6%	1.6%
Jet Energy Scale (heavy quarks) (2%)	1.6%	1.6%	1.6%
Radiation (Λ_{QCD}, Q_0^2)	2.6%	2.6%	2.6%
Fragmentation (Lund b, σ_q)	1.0%	1.0%	1.0%
b-tagging (5%) → Tevatron ~2%	7.0%	7.0%	7.0%
Parton Density Functions	3.4%	3.4%	3.4%
Integrated luminosity	10%	5%	3%
Background level	0.9%	0.9%	0.9%
Statistical Uncertainty	1.2%	0.6%	0.4%
Total Systematic Uncertainty	13.6%	10.5%	9.7%
Total Uncertainty	13.7%	10.5%	9.7%

Pile-Up → conservative

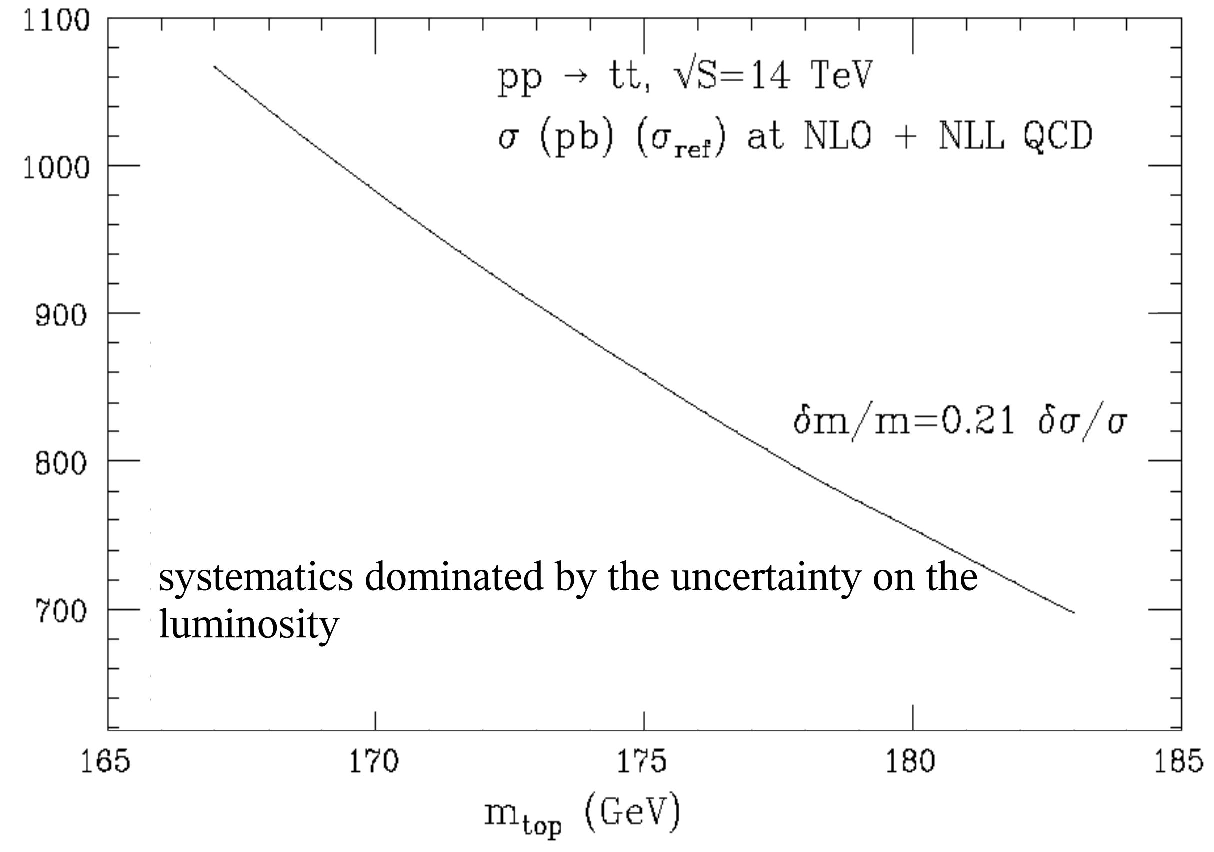
b-tagging (7.0%) → conservative

~10% @ 10 fb^{-1}

- dominated by uncertainty on b-tagging efficiency which is conservative
  when assuming 2% (rather than 5%) i *total uncertainty ~ 7% (10fb^{-1})*
- 2-3 GeV uncertainty on m_t is feasible via cross section measurement

Top Quark Pair Cross Section

- Sensitive to top mass : $\Delta\sigma/\sigma \sim 5\ \Delta m_t/m_t$ ⇨ 5% on σ gives **2 GeV on m_t**



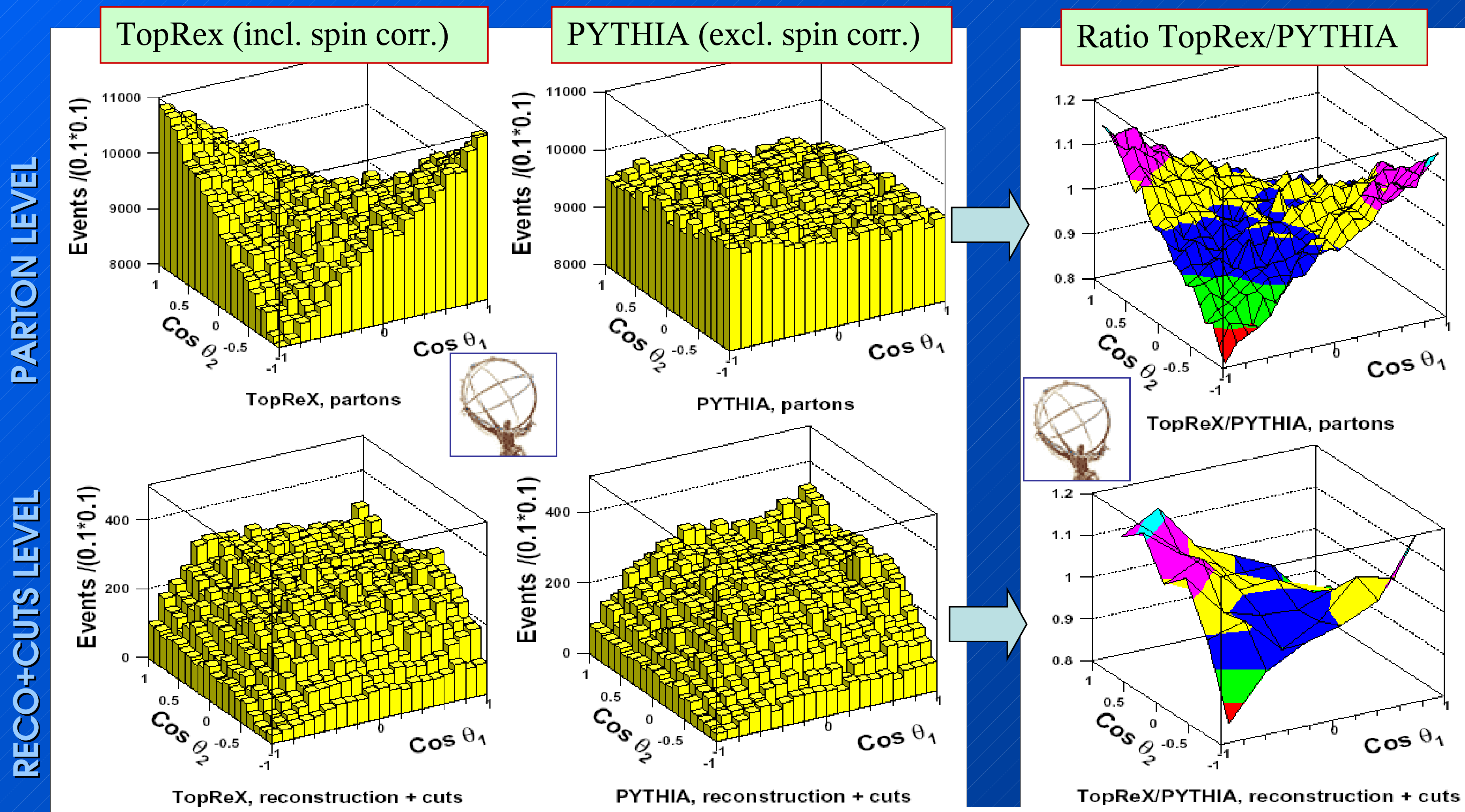
ATLAS ATL-PHYS-PUB-2005-024

Time	Number of events at 10^{33}	$\Delta\sigma/\sigma$ (stat)
1 "week"	2×10^3	2.5%
1 "month"	7×10^4	0.4%
1 "year"	3×10^5	0.2%

Cross-section sensitive to renormalisation and factorisation **scale**, and to the choice of **PDF** (Parton Density Function)

Spin Correlations at LHC

ATLAS Eur.Phys.J. C44 (2005) 13-33 = ‘fast’ simulation
CMS Note submitted = ‘full’ simulation

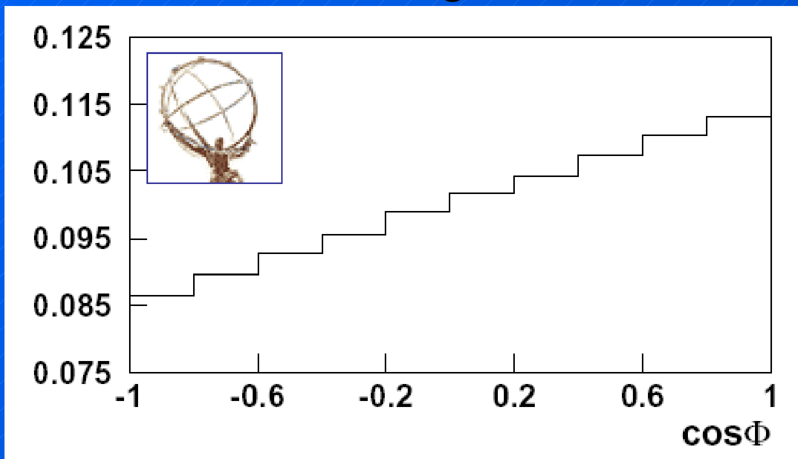


results (CMS, 10fb^{-1}) :
good agreement with TopRex inp

$$\mathcal{A}_{b-t1-t} = 0.375 \pm 0.027\,(\text{stat.})^{+0.055}_{-0.084}\,(\text{syst.})$$
$$\mathcal{A}_{q-t1-t} = 0.346 \pm 0.021\,(\text{stat.})^{+0.026}_{-0.055}\,(\text{syst.})$$

Spin Correlations at LHC

- also fit the single differential distribution of the opening angle between two spin analyzers



ATLAS definition of C and D (incl. κ_i factors):

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

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

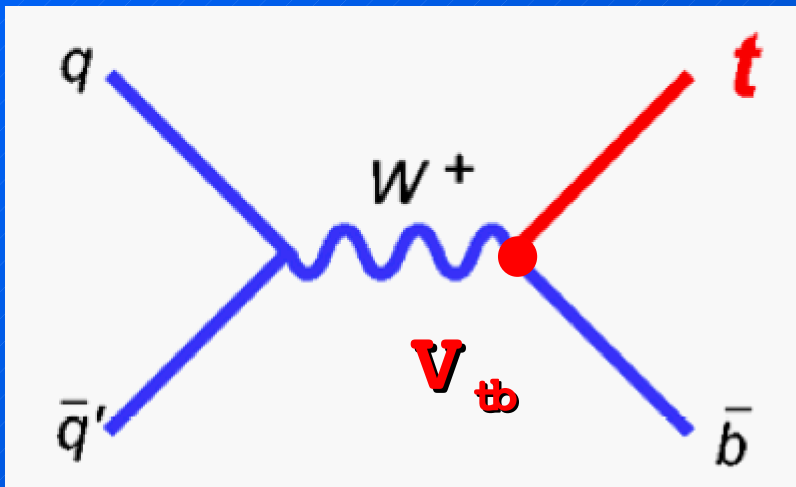
Results (ATLAS, 10fb^{-1})

	Standard Model result	Sensitivity	Precision
C_{l-lej}	0.181 ± 0.010 (stat) ± 0.040 (syst)	4.4 σ	23%
C_{l-W}	0.168 ± 0.010 (stat) ± 0.034 (syst)	4.7 σ	21%
D_{l-lej}	-0.142 ± 0.006 (stat) ± 0.018 (syst)	7.5 σ	13%
D_{l-W}	-0.127 ± 0.006 (stat) ± 0.024 (syst)	5.1 σ	19%

Main systematic uncertainties: parton generation (PDFs and Q^2 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}

First Direct Measurement of V_{tb}



$1\ fb^{-1}$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- previously only indirect limits: $|V_{tb}| = 0.999127 \pm 0.00026$ (1σ CL)
  CKM Fitter Group for Beauty 2006

- assume: $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$
- assume: pure V-A and CP-conserving Wtb interaction

- no assumption on quark families or CKM matrix unitarity

$$0.68 < |V_{tb}| \leq 1 \quad (95\%\ CL)$$

Further Single-Top Interpretations at LHC

Tait,Yuan PRD63 (2001) 014018

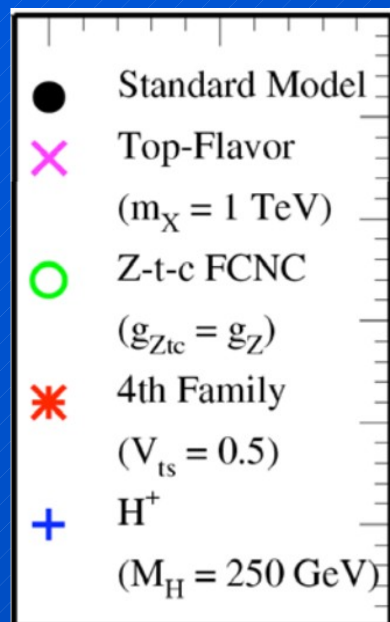


Illustration of the Physics Potential: