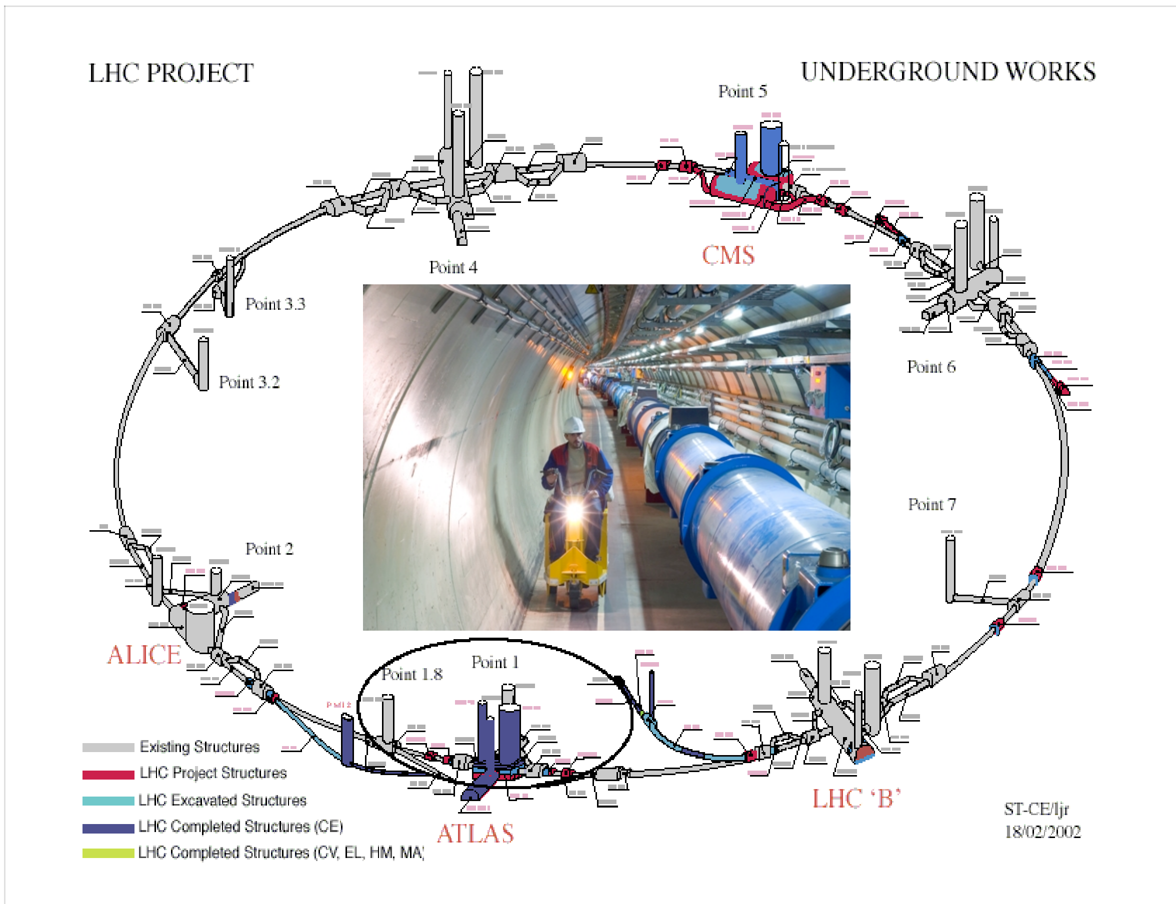
Top Physics at the LHC



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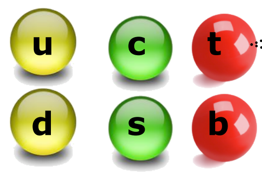
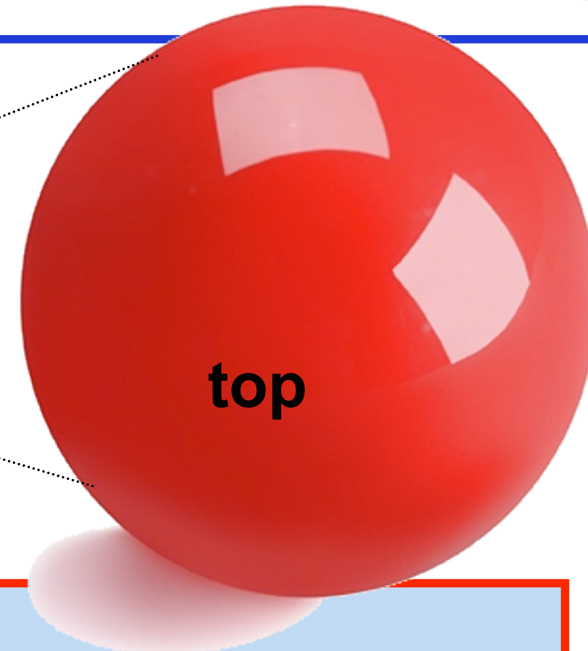
The Top Quark in the Standard Model

Discovered in 1995 at the TeVatron,
flurry of measurements
We still don't know all about it





- Mass	Precision <2%
- Top width ~1.5 GeV	?
- Electric charge ⅔	-4/3 excluded @ 94% C.L. (preliminary)
- Spin ½	Not really tested – spin correlations
- BR($t \rightarrow Wb$) ~ 100%	At 20% level in 3 generations case
	FCNC: probed at the 10% level
- Production mechanisms	Single Top : not yet observed

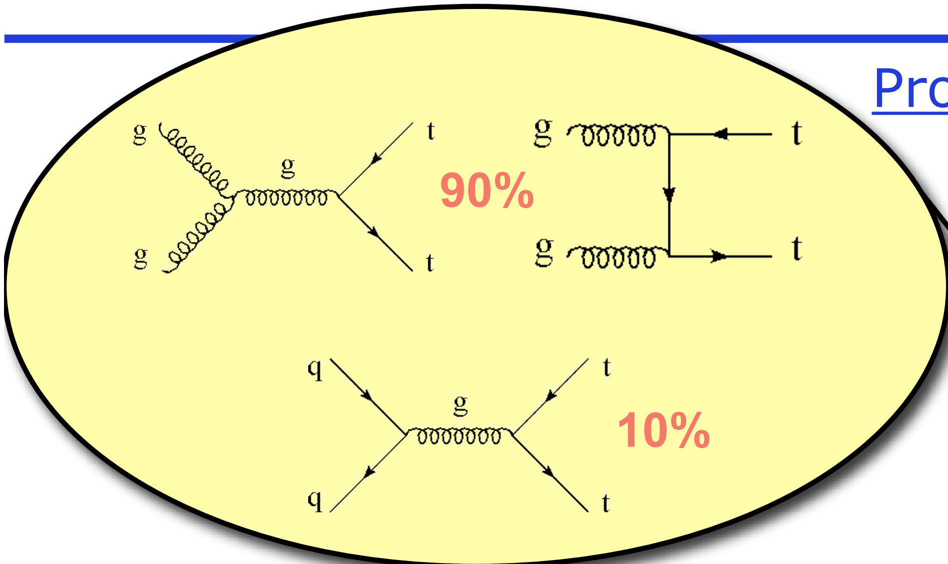
The LHC offers opportunity for further testing and **<u>precision measurements</u>**

Talk Outlook

- Strong pair production
  - Standard top physics
  - Early top physics
- Top Properties
  - Mass,Charge,W polarization,top polarization
- Electroweak single top production
  - Analysis strategies
  - Vtb measurements
- Using top for calibration purposes
  - Jet energy corrections, b-jets, missing energy
- A window to new physics
- Conclusions

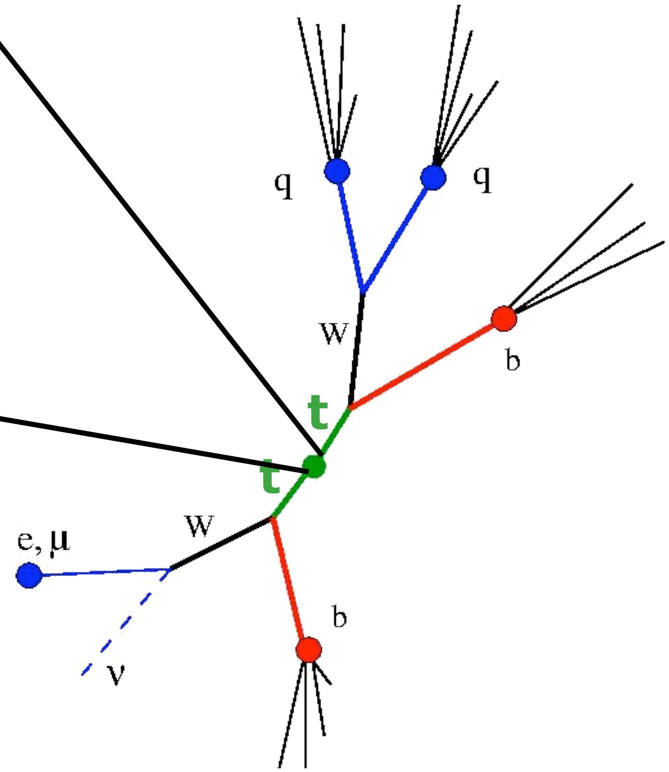
Most of the results presented are based on ATLAS studies

Strong Pair production at the LHC

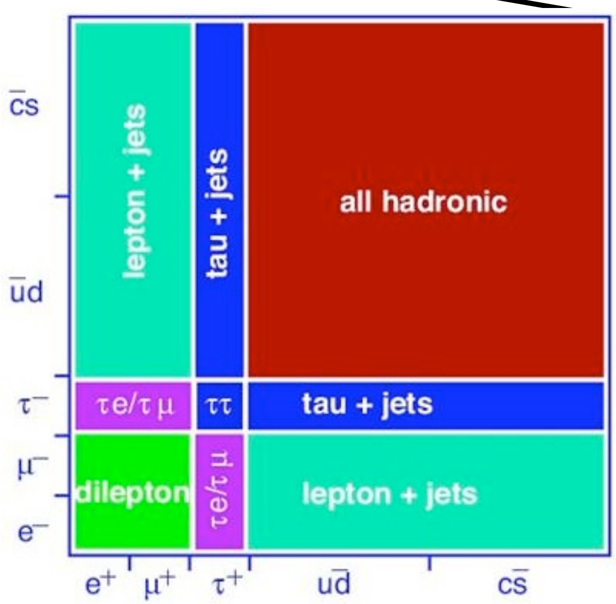


Production: σ_{tt}(LHC) ~ 830 ± 100 pb

Cross section LHC = 100 x Tevatron
Background LHC = 10 x Tevatron



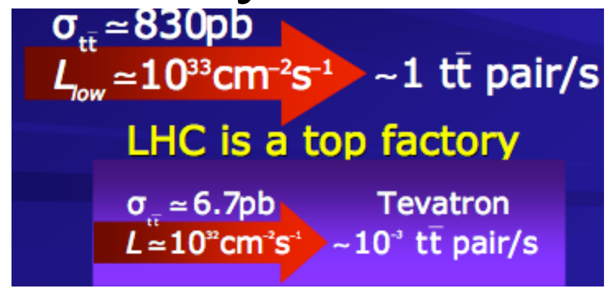
Decay



L+jets (l=e,μ) *is the Golden channel*
→ 2.5 million events/year

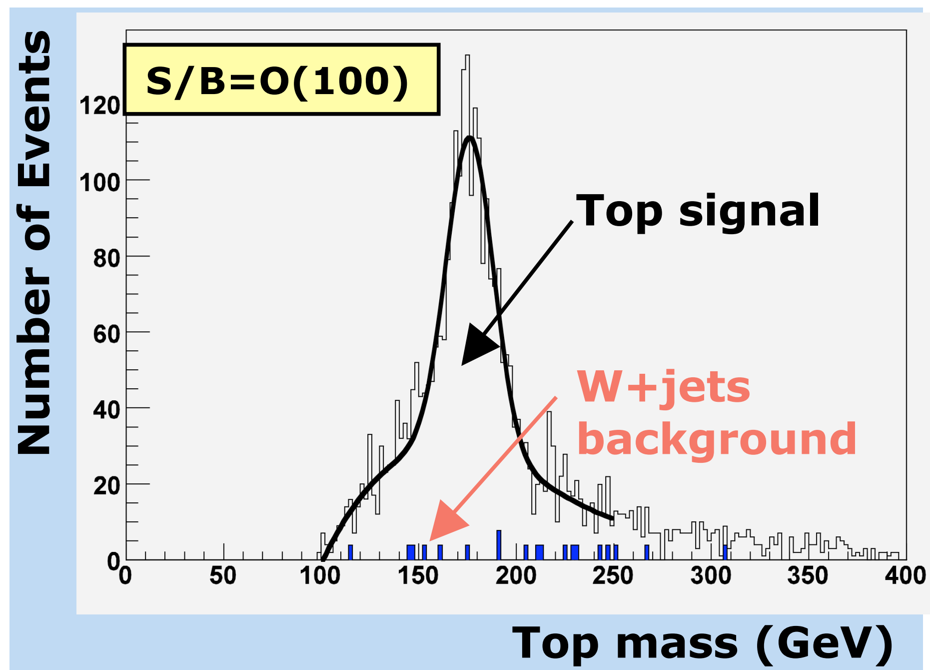
Top quark physics with b-tag

LHC is a top factory → Seeing top is easy



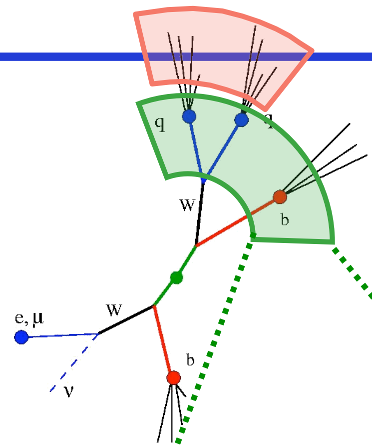
Selection: High P_T Lepton
Large Missing E_T
4 high-P_T jets (2 b-jets)

→ signal efficiency few %
→ *very* small SM background



- 'Standard' Top physics at the LHC:
  - b-tag is important in selection
  - Most measurements limited by systematic uncertainties
- 'Early' top physics at the LHC:
  - Cross-section measurement (~ 20%)
  - Decay properties

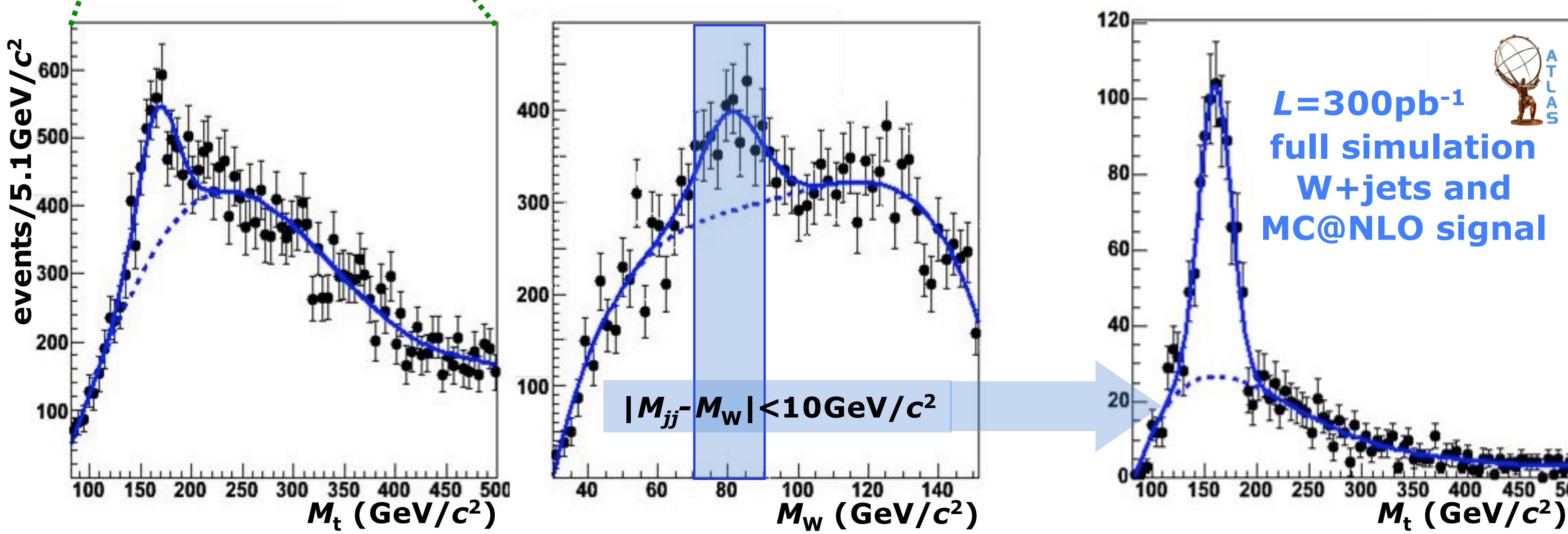
Top quark physics **without** b-tag (early phase)



Selection

- semileptonic top: p_T(lepton)>20GeV/c, missing E_T>20GeV
  - no b-tagging required
- hadronic top: N_{jet}>4, p_T(jet)>40GeV/c (0.4 cone algorithm)
- 3 jets with highest vector-sum p_T identified as top
  - of these, 2 leading jets in 3-jet rest frame identified as W

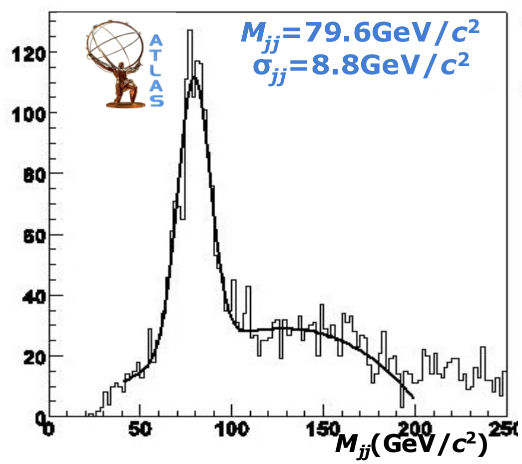
A top peak can be seen without b-tag requirement

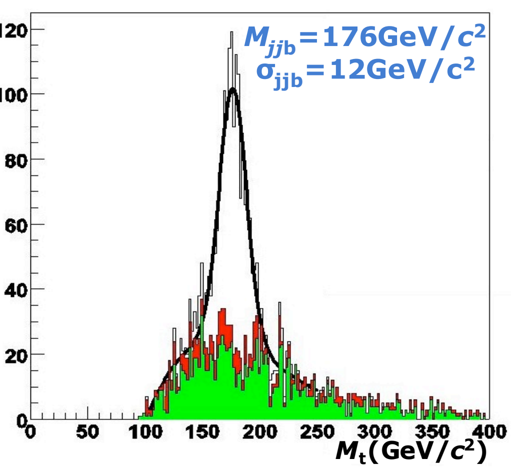


Top Properties: Mass

Lepton+jets

- isolated lepton (e,μ): p_T>20GeV/c, $|\eta|$<2.5
- missing E_T>20GeV
- at least 4 jets: p_T>20GeV/c (corrected), $|\eta|$<2.5
  - at least 2 light jets to reconstruct hadronic W
  - 2 b-tagged jets to select the bjj system with highest P_T
- very effective in background rejection ($S/B=10^{-4}\rightarrow 30$)
  - mainly from bb, W/Z+jets and Wbb

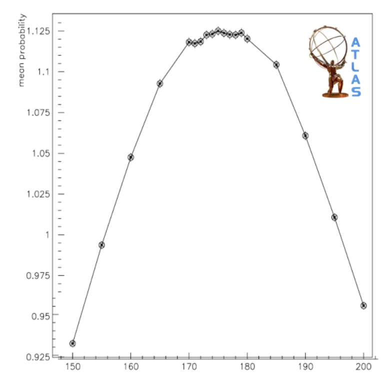




full simulation, L=10fb^{-1}
δM_t(stat)=0.05GeV/c^2
δM_t(sys)=1.3GeV/c^2

Dileptons:

- two opposite-signed leptons: p_T(lepton)>20GeV/c, $|\eta|$<2.5
- missing E_T>40GeV
- 2 b-jets: p_T>25GeV/c (corrected), $|\eta|$<2.5
- Final state reconstruction
- 6 unknowns (neutrinos' momenta), M_t hypothesis
  - conservation of transverse momentum
  - mass-constrain each l–ν pair to M_W
  - mass-constrain each l–ν–b-jet system to M_t
- weight assigned to each solution
  - based on comparison with MC
  - average weight over whole event sample
- M_t from solution with highest mean weight

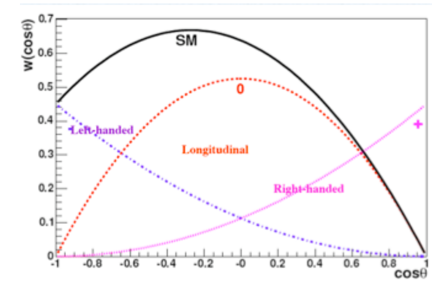


fast simulation
L=10fb^{-1}
δM_t(stat)=0.04GeV/c^2
δM_t(sys)=1.7GeV/c^2

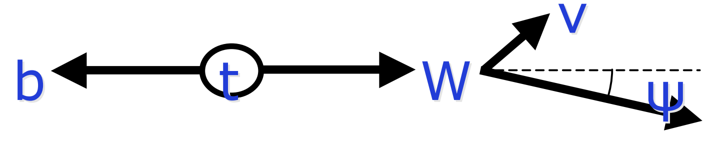
Top Properties: W Polarization

Top decays before hadronization

- spin information passed directly onto Wb
- SM predicts 70% longitudinal W and 30% left-handed W
  - depending on M_t and M_W only $f_0 = \frac{m_t^2}{2m_W^2 + m_t^2}$

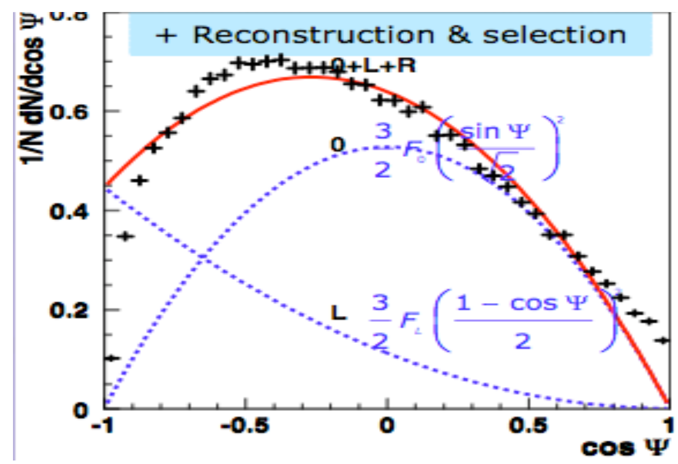


- parametrize in terms of angle between
  - direction of W in top rest frame
  - direction of lepton in W rest frame



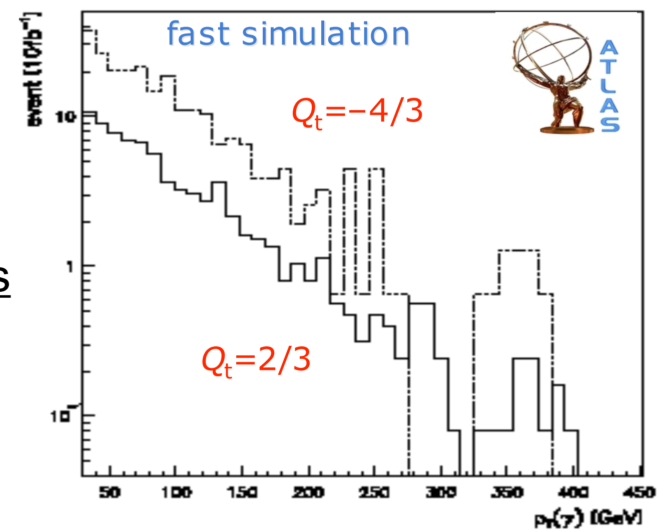
- Precision in measurements of the fractions F_0(longitudinal) and F_R
- Unfold selection and detector effects

fast simulation L=10fb^{-1}		F_0	F_R
Stat	CMS (SL)	±0.023	±0.015
	ATLAS (SL+DL)	±0.004	±0.003
Sys	CMS (SL)	±0.022	±0.053
	ATLAS (SL+DL)	±0.016	±0.012



Top Properties: Charge

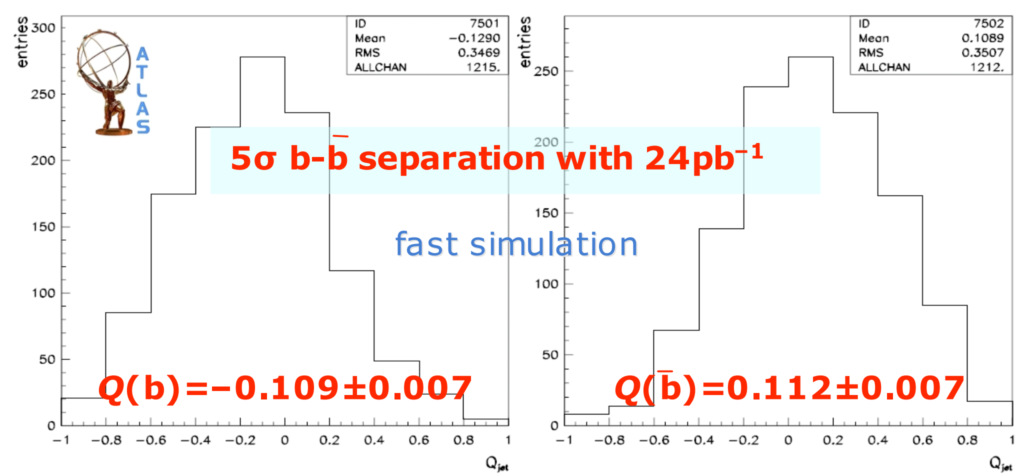
- Aimed at confirming Q_t=2/3 SM hypothesis
  - non standard value Q_t=–4/3 not yet excluded
    - can arise from wrong W-b association
- Two procedures for direct measurement
  - <u>Top e.m. coupling through photon radiation in tt events</u>
    - gg initial state dominance at LHC reduces ISR
    - radiative tt production & (interfering) decay: x-section
    - radiative tt decay: reduced by requiring high M(bjjγ) or M_T(lνbγ)



  - <u>reconstruct charge of decay products</u> (lepton/dilepton+jets)
    - easy for W boson (Q_l)
    - challenging for b-jets

$$Q_{jet} = \frac{\Sigma_i Q_i \left|\bar{p}_{jet} \cdot \vec{p}_i\right|^2}{\Sigma_i \left|\bar{p}_{jet} \cdot \vec{p}_i\right|^2}$$

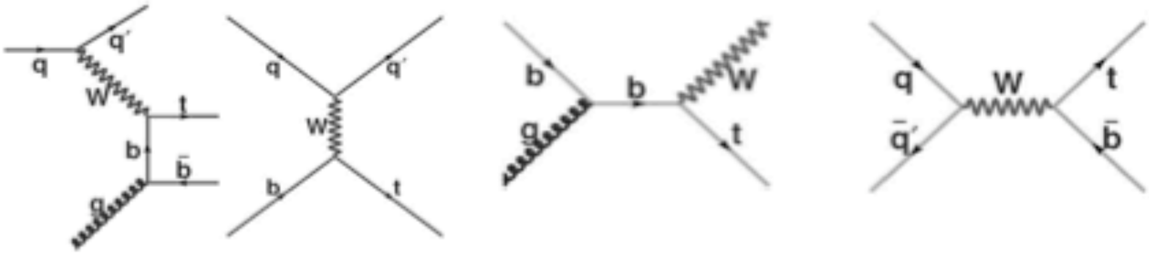
    - l-b association: $M_{lb} < M_t$
    - Systematics underway



Single Top at LHC

- **All 3 contributing mechanisms in SM:**

W-g (t-channel) W+t W* (s-channel)



- **Computation at NLO available for W* and W-g :**
  - Increase of σ(W*) by ~30 %
  - Affect p_T(jet) distribution, H_T etc…

Channel	σ x BR(pb)
W-g	54.2
W+t	17.8
W*	2.2
ttbar	246
Wbb	66.7
W+jets	3,850

Decay modes:

- W* : W* → t bbar → ($l^+\nu$b) bbar
- Wg: q'g → t q bbar → ($l^+\nu$b) q bbar
- W+t: bg → t W → ($l^+\nu$b) qq'

1 leptons + MET
+ ≥ 2 jets
+ 1(2) b-tags

Common selection for all 3 single-top samples :

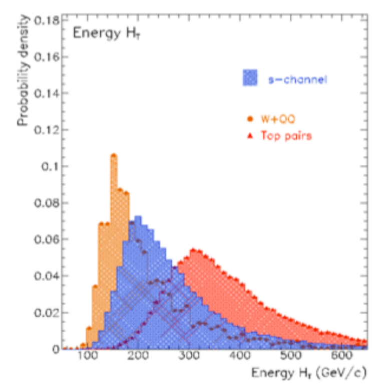
- 1 High pT Lepton + mET

→ reduce non-W events

- At least two high-p_T jets

→ reduce W+jets events

- Single-top ~22-26%
- ttbar ~ 38%
- WQQ ~ 1.5% , W+njets < 1/1000



Why Single Top ?

Motivations

- Properties of the Wtb vertex :
  - Determination of $\sigma(pp \to tX)$, $\Gamma(t \to Wb)$
  - Direct determination of $|V_{tb}|$
  - Top polarization
- Precision measurements → probe to new physics
  - Anomalous couplings
  - FCNC

  } t-channel,Wt
  - Extra gauge-bosons W' (GUT, KK)
  - Extra Higgs boson (2HDM)

  } s-channel
- Single-top is one of the main background to …

  … Higgs physics…

M(top) = 175 GeV/c^2	s-channel	t-channel	Associated tW	Combined (s+t)
TeVatron σ_{NLO}	0.88 ± 0.11 pb	1.98 ± 0.25 pb	0.1 pb	
LHC σ_{NLO}	10.6 ± 1.1 pb	247 ± 25 pb	62 $^{+17}_{-4}$ pb	
Run II 95% CL — CDF	<3.2 pb	< 3.1pb	NA	< 3.5
Run II 95% CL — D0	< 5 pb	< 4.4 pb	NA	NA

σ_{t+s} = 2.9 pb for m(top) = 175 GeV/c^2

B.W. Harris et al.:Phys.Rev.D66,054024 T.Tait: Phys.Rev.D61,034001
Z.Sullivan Phys.Rev.D70:114012 A.Belyaev,E.Boos: Phys.Rev.D63,034012

ATLAS analysis strategies

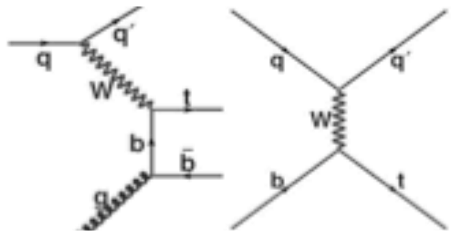
In the late '90 several studies were conducted to produce a physics TDR. Current studies are meant to devise analysis strategies for early data taking and the full statistics, using the latest software tools.

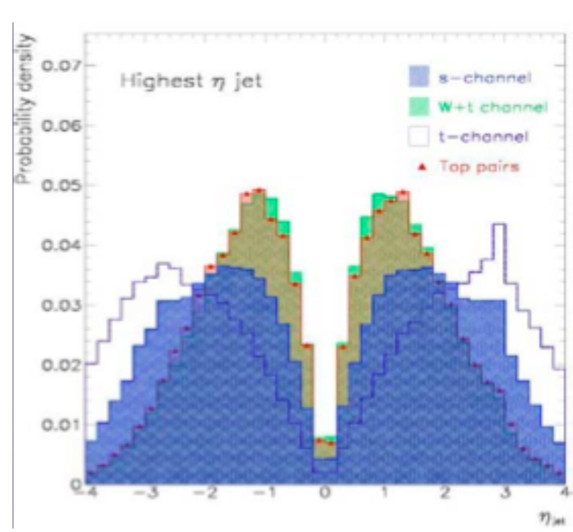
Description of cuts	Cumulative Selection Efficiency (%)			
	W-g fusion	$t\bar{t}$	$Wb\bar{b}$	Wjj
Pre-selection cuts	20.0	44.4	2.49	0.667
Njets = 2; p_T>30GeV	13.2	0.95	0.99	0.37
Forward jet; p_T>50, $\lvert\eta\rvert$>2.5	4.3	0.046	0.072	0.06
m_{tot}>300 GeV	3.58	0.025	0.043	0.048
H_T > 200 GeV	2.08	0.019	0.036	0.027
150 < m_t < 200 veto	1.64	0.01	0.0052	0.0066
Events/30 fb^{-1}	26 800 ± 1000	720 ± 160	104 ± 60	7900 ± 1600

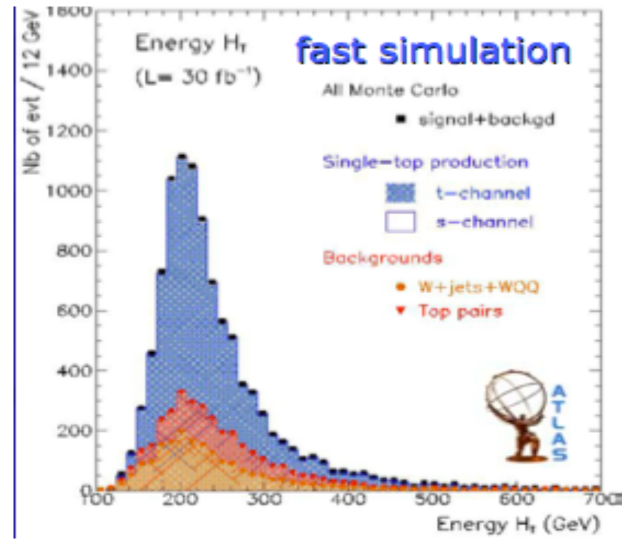
Description of cuts	Cumulative Selection Efficiency (%)		
	Wt	$t\bar{t}$	$Wb\bar{b}$
Pre-selection cuts	25.5	44.4	2.49
njets = 3; p_T > 50 GeV	3.41	4.40	0.05
nb-jet = 1	3.32	3.24	0.037
m_{tot} < 300 GeV	1.43	0.71	0.008
65 < m_{jj} < 95 GeV	1.27	0.41	0.003
Events/30 fb^{-1}	6828 ± 269	30408 ± 742	58 ± 19

Description of cuts	Cumulative Selection Efficiency (%)					
	W^*	W-g fusion	Wt	$t\bar{t}$	$Wb\bar{b}$	Wjj
Pre-selection cuts	27.0	20.0	25.5	44.4	2.49	0.667
njets = 2; p_T > 30 GeV	15.7	6.8	3.79	0.93	1.35	0.201
nb-jet = 2; p_T > 75 GeV	2.10	0.05	0.018	0.023	0.038	0.0005
scalar sum of p_T >175 GeV	1.92	0.036	0.016	0.021	0.030	0.0004
m_{tot}>200GeV	1.92	0.036	0.014	0.021	0.025	0.0003
150<$m_{l\nu b}$<200 GeV	1.67	0.031	0.008	0.017	0.016	0.0002
Events/30 fb^{-1}	1106 ± 40	510 ± 148	42 ± 21	1290 ± 228	328 ± 61	226 ± 113

Wg channel







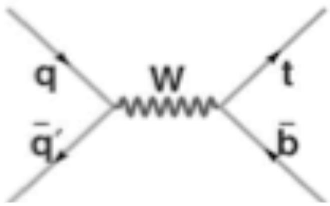
Selection criteria

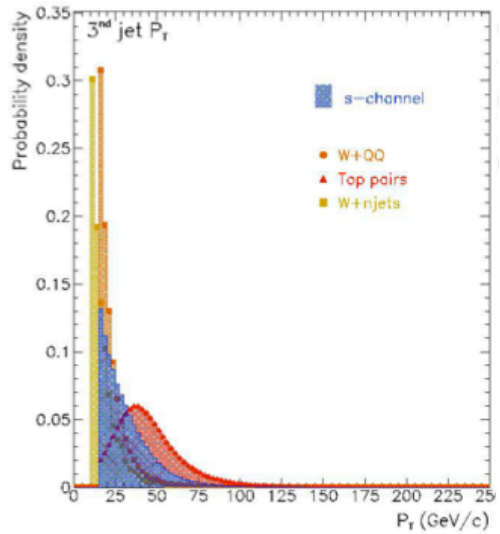
- Number of jets : N(jet) = 2
- Presence of a high-p_T b-tagged jets (p_T>40GeV/c)
  Wg evts have 1 b-jet escaping the acceptance
  → requires **only** 1 b-tagged jet
- Presence of a high-p_T forward jet
  → 1 jet with $|\eta|$>2.5 and $p_T \geq$ 50GeV/c
- Reconstruct $M_{l\nu b}$ within ±25 GeV/c^2
- Window in H_T

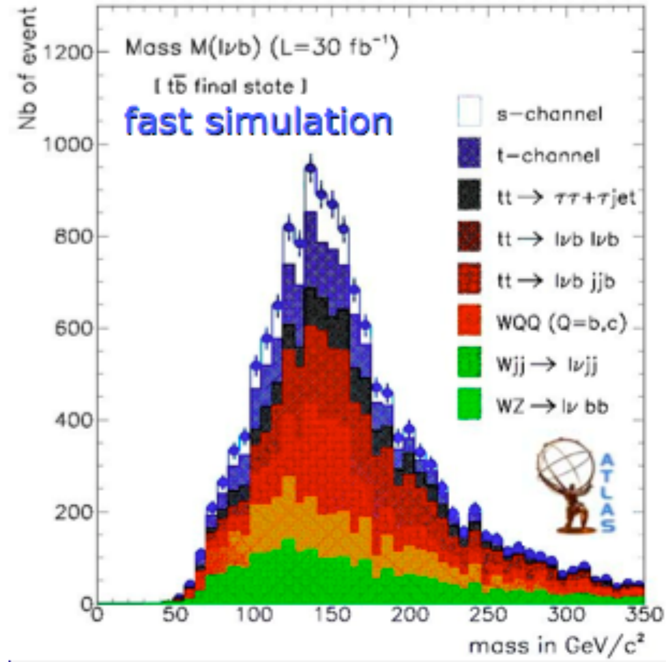
	W*	Wg	W+t	tt	WQQ	W+jets
Pre-Selection (%)	26.2	23.7	22.4	38.3	1.46	0.05
Selection ε(%)	0.22	0.44	0.023	0.007	0.006	0.0013
N^{event}(30 fb^{-1}) ± MC stat.	150 ± 6	7,080 ± 160	125 ± 13	500 ± 150	130 ±40	1,500 ± 750

- N(jet) = 2 → reduces tt by ~6 vs Wg
- 1 high-p_T fwd jet → reduce tt (by ~5), Wt(~10), Wjj(~2)
- Great uncertainty on WQQ / W+jets backgrounds

s-channel







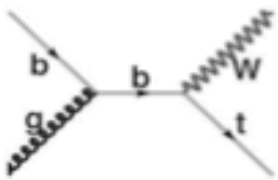
Selection criteria

- Number of jets : N(jet) = 2
- Presence of two high p_T jets
- Presence of two central, high-p_T b-tagged jets
  → Wg usually have 1 b-jet escaping the acceptance
- Reconstruct $M_{l\nu b}$ within $m_{top} \pm 25$ GeV/c²
- Window in H_T

	W*	Wg	W+t	tt	WQQ	W+jets
Pre-Selection ε(%)	26.2	23.7	22.4	38.3	1.46	0.05
Selection ε(%)	1.73	0.105	0.002	0.035	0.059	0.0001
N^{event}(30 fb^{-1}) ± MC stat.	1,141 ± 7	1,680 ± 48	10 ± 3	2,580 ± 150	1,148 ± 38	170 ± 85

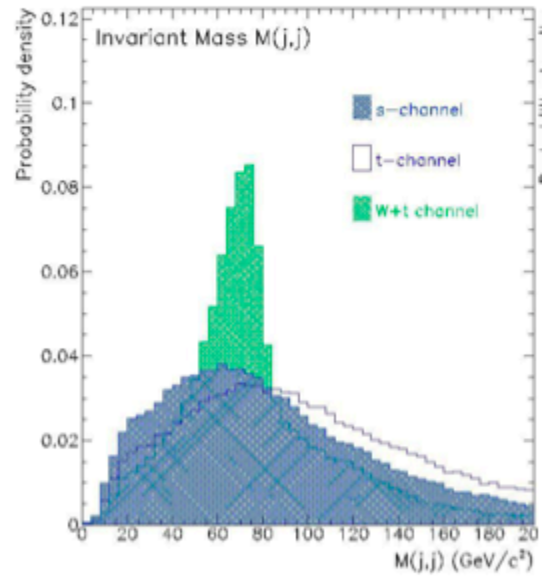
- N(jet) = 2 → reduces tt by a factor ~ 20 vs W*
- 2 high-p_T b-jets → reduces WQQ by ~2 and Wg by ~8
- $M_{l\nu b}$ and H_T → reduce non-top by ~2

Wt channel



Selection of a specific topology

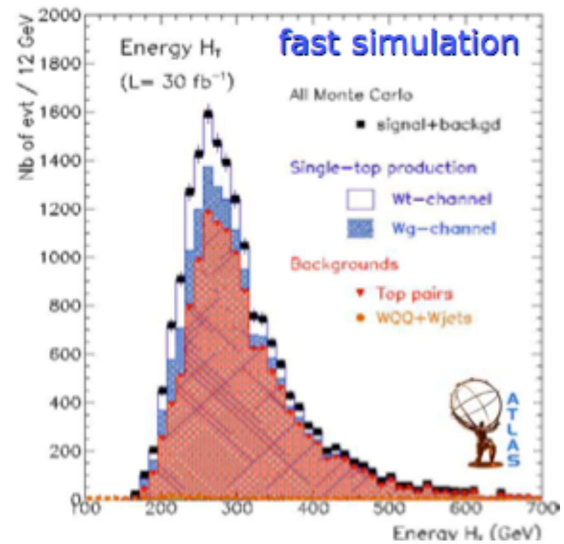
- Number of high-p_T jets Njet) = 3
- Presence of a high-p_T b-tagged jets
  → Only **one** b-jet in W+t events
- Presence of a W-boson mass peak
  → requires $60 < M(j,j) < 90$ GeV/c²
- Reconstruct $M_{l\nu b}$ within ±25 GeV/c²
- Window in H_T or Invariant Mass



	W*	Wg	W+t	tt	WQQ	W+jets
Pre-Selection ε(%)	26.2	23.7	22.4	38.3	1.46	0.05
Selection ε(%)	0.16	0.25	0.88	0.35	0.004	0.0003
N^{event}(30 fb⁻¹) ± MC stat.	105 ± 5	4,050 ± 80	4,720 ± 80	26,300 ± 400	90 ± 20	xxx ± 85

- N(jet) = 3 → reduces Wjj & WQQ ~3.5 wrt W+t
- M(jj) ~ M_W → reduces WQQ/jets by ~3 wrt W+t

→ Good knowledge of tt background is mandatory



V_{tb} Measurement

- Indirect measurement
  - based on CKM unitarity constraint (3 generations)

$$\frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = \frac{BR(t \to Wb)}{BR(t \to Wq)}$$

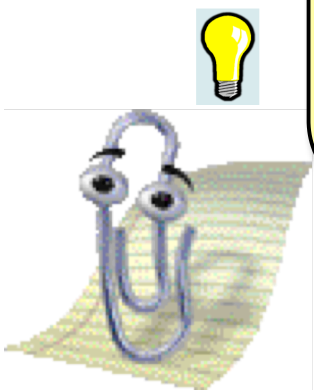
- Direct measurement
  - based on electroweak single top production ($\sigma \propto |V_{tb}|^2$)
    - measure yield of single top production
    - combine with $BR(t \rightarrow Wb)$ and M_t (from tt channel)
  - unbiased test of 3-generation structure of SM
  - penalized by poor knowledge of W+jets, WQQ background
  - no systematic effects taken into account

channel	S/B	uncertainties on σ		$\Delta V_{tb}/V_{tb}$
		stat ($30 fb^{-1}$)	theoretical	
s-channel	0.55	5.6%	7.5%	4.7%
t-channel	2.3	0.54%	11%	5.5%

Top quark pair production as calibration tool

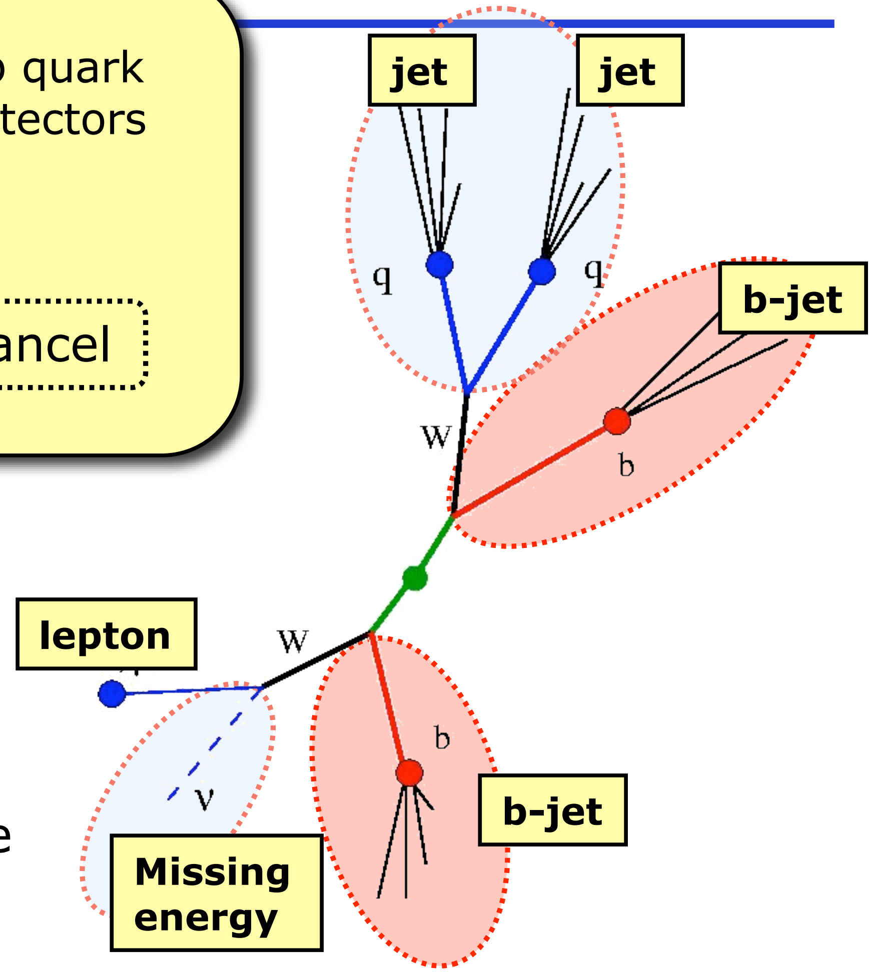
You can use production of top quark pairs to help calibrate LHC detectors in complex event-topologies

Yes No Cancel



→ A candle for complex topologies:

- Calibrate light jet energy scale
- Calibrate missing E_T
- Obtain enriched b-jet sample
- Leptons and trigger

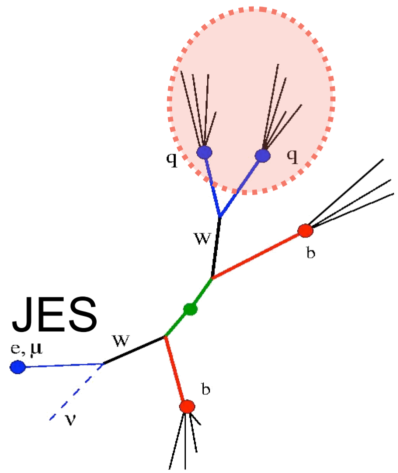


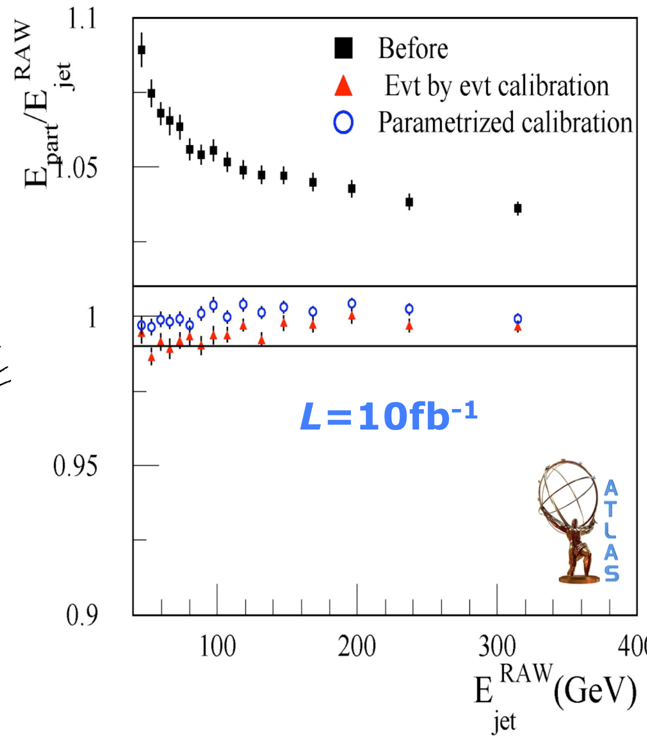
Note candles: 2 W-bosons
2 top quarks

Calibrating jet energy scale

One of the most relevant systematic effects on M_t

- jet energy: measurement of parton energy
- 1% uncertainty on absolute JES induces δM_t~1GeV/c^2
- sizeable effects also from
  - b-jet energy scale
  - QCD radiation, underlying event, cone algorithm
- at start-up, 5÷10% uncertainty
  - test-beam data
- <u>in-situ correction with Z/γ+jet</u>
  - p_T(jet) correction
  - residual mass shift (2% on M_t)
- $M_{jj}=M_W$ additional constraint on JES
- clean W→jj sample needed
  - 80% purity within tt→lν+jets

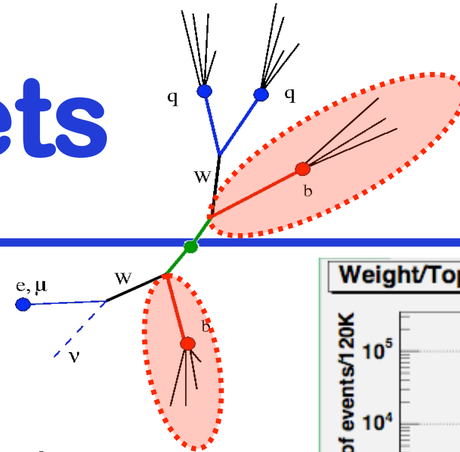




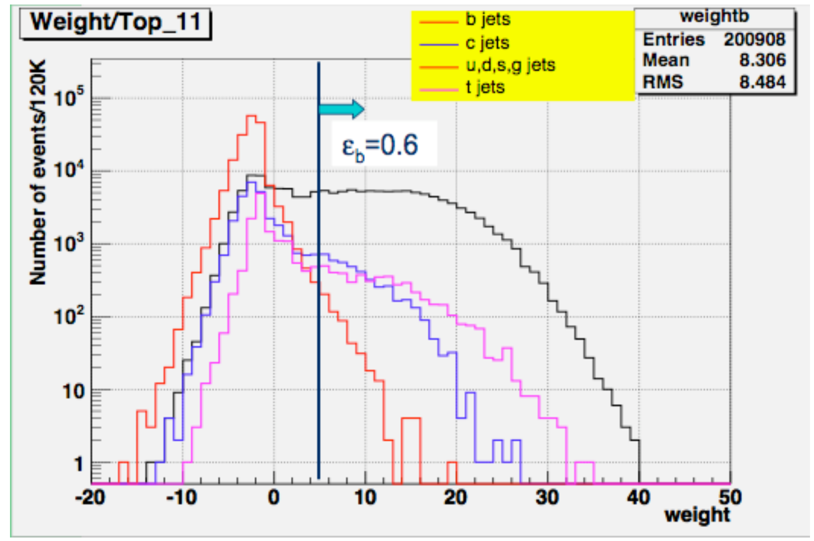
- goal: 2÷3% uncertainty in 1 year (target 1%)
- Alternative method: P_T balance in Z/γ + jet events

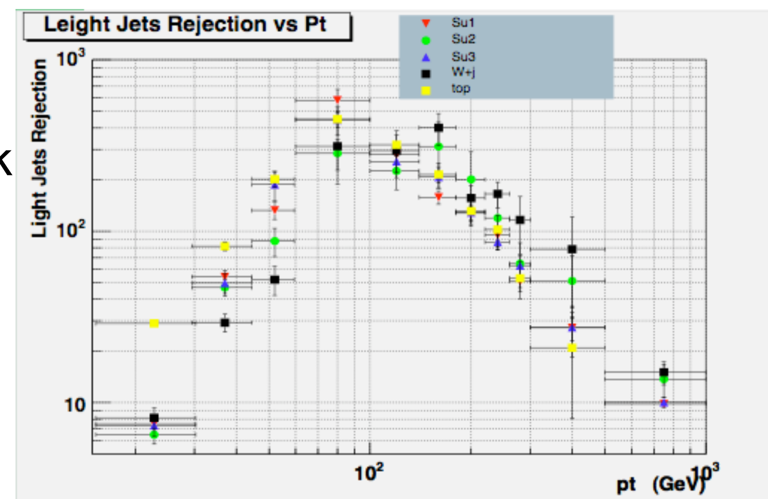
full simulation
tt MC@NLO

Calibrating b-jets



- b-tagging techniques rely on
  - impact parameter of decay tracks
  - primary/secondary vertex separation
  - soft leptons
    - targeting b and c semileptonic decays
- Typical performances
  - efficiency ~60% on p_T>40GeV/c jets
  - light flavour rejection $1/\varepsilon_u$~200
- Jets from b-quarks need specific corrections
  - semileptonic decays of heavy-flavoured quark
    - neutrino induces a large shift on the jet energy
    - effect enhanced if lepton is muon (MIP)
    - jet direction affected as well as jet energy



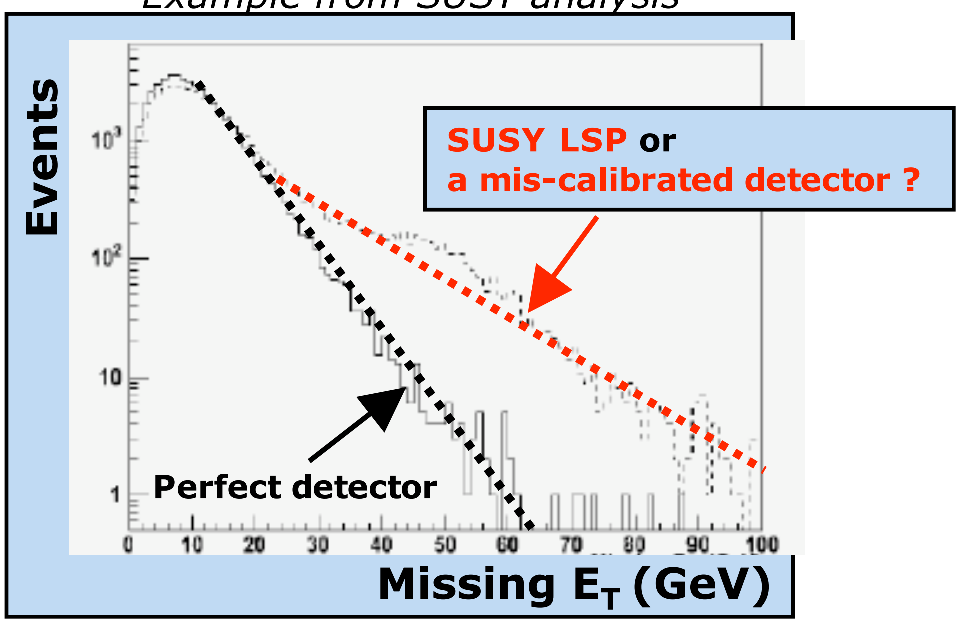


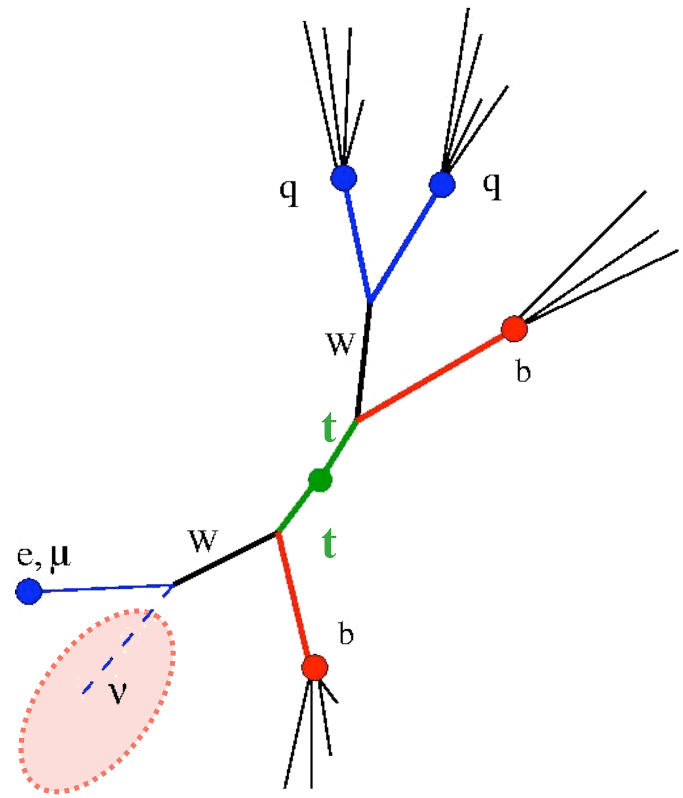
Calibrating the missing energy

- P_μ(neutrino) constrained from kinematics: M_W
  → known amount of missing energy per event

- Calibration of missing energy **vital** for **all** (R-parity conserving) SUSY and most exotics!

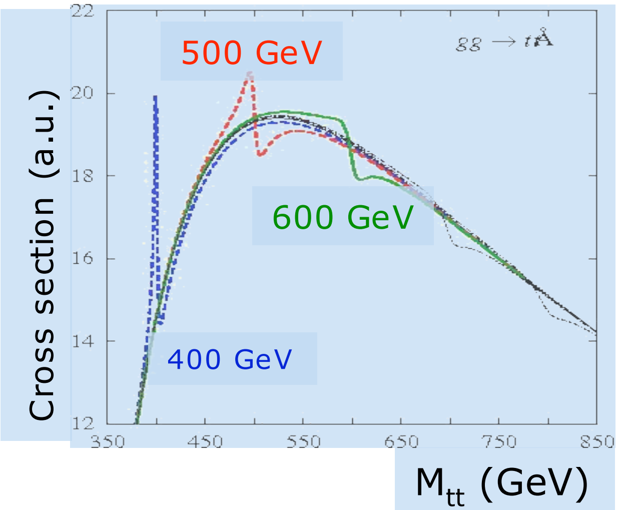
Example from SUSY analysis





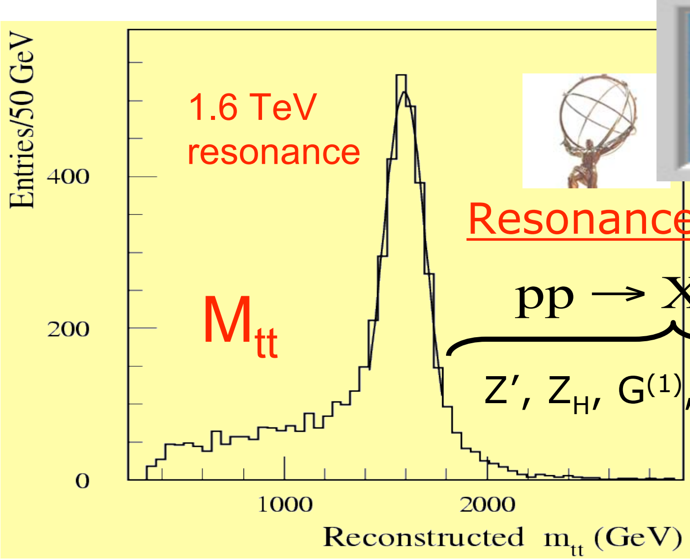
Range: $50 < P_T < 200$ GeV

A window to new physics ?



Structure in M_{tt}

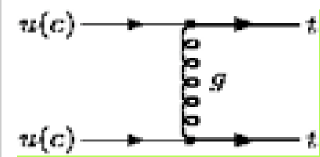
Interference from MSSM Higgses
H,A→ tt (can be up to 6-7% effect)



Resonances in M_{tt}

$$pp \to X \to t\bar{t}$$

Z′, Z_H, $G^{(1)}$, SUSY, ?



Like-sign tt ?

FCNC decays: GIM suppressed in SM, can be enhanced in SM extensions

q=u,c	t→Zq	t→γq	t→gq
BR(*L*=10fb^{-1})	$3.4\cdot10^{-4}$	$6.6\cdot10^{-5}$	$1.4\cdot10^{-3}$
BR(*L*=100fb^{-1})	$6.5\cdot10^{-5}$	$1.8\cdot10^{-5}$	$4.3\cdot10^{-4}$

Conclusions

1) Top quarks are produced by the millions at the LHC:
→ Almost no background:
to measure top quark properties will be easy

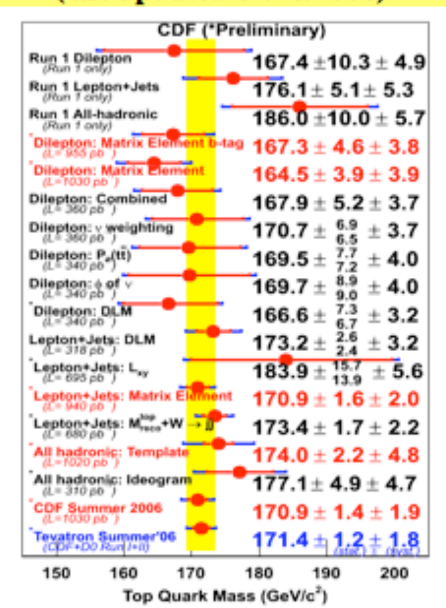
2) Top quarks are THE calibration signal for complex topologies:
→ Most complex SM candle at the LHC
→ Vital input for detector commissioning/calibration

3) Top quarks pair-like and singly produced……
as a window to new physics:
→ FCNC, SUSY, MSSM Higgs,
Resonances, anomalous couplings
Also important SUSY background

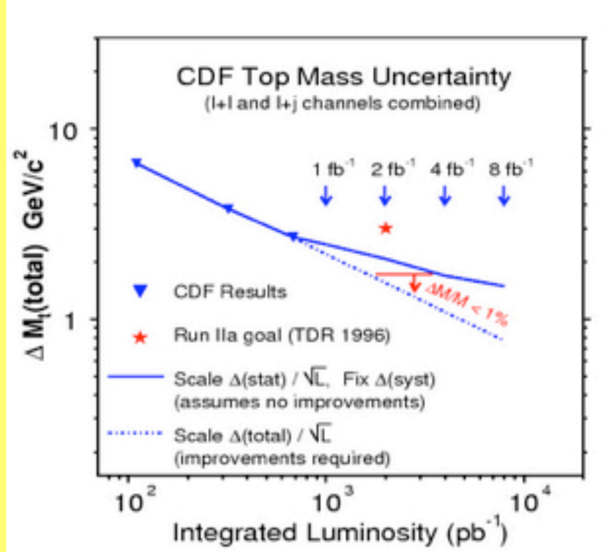
Backup Slides

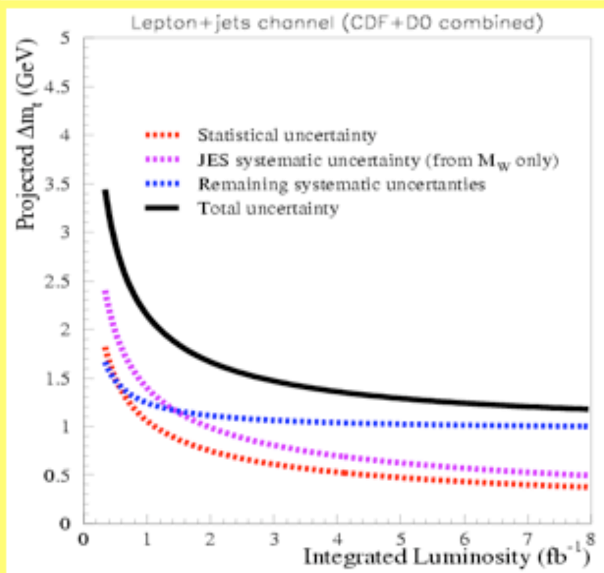
Top Mass Now

All CDF measurements (last updated 07/26/2006)

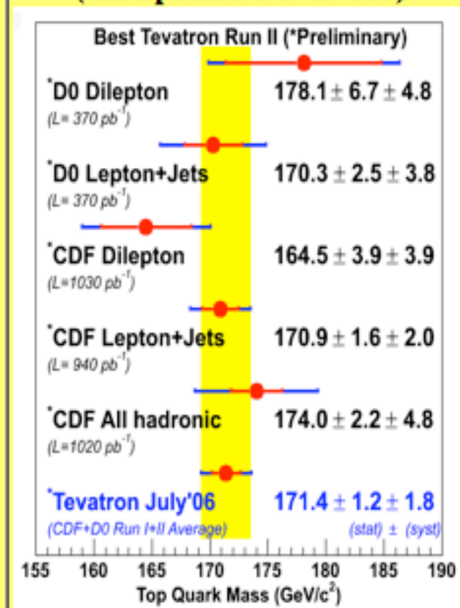


gif and eps



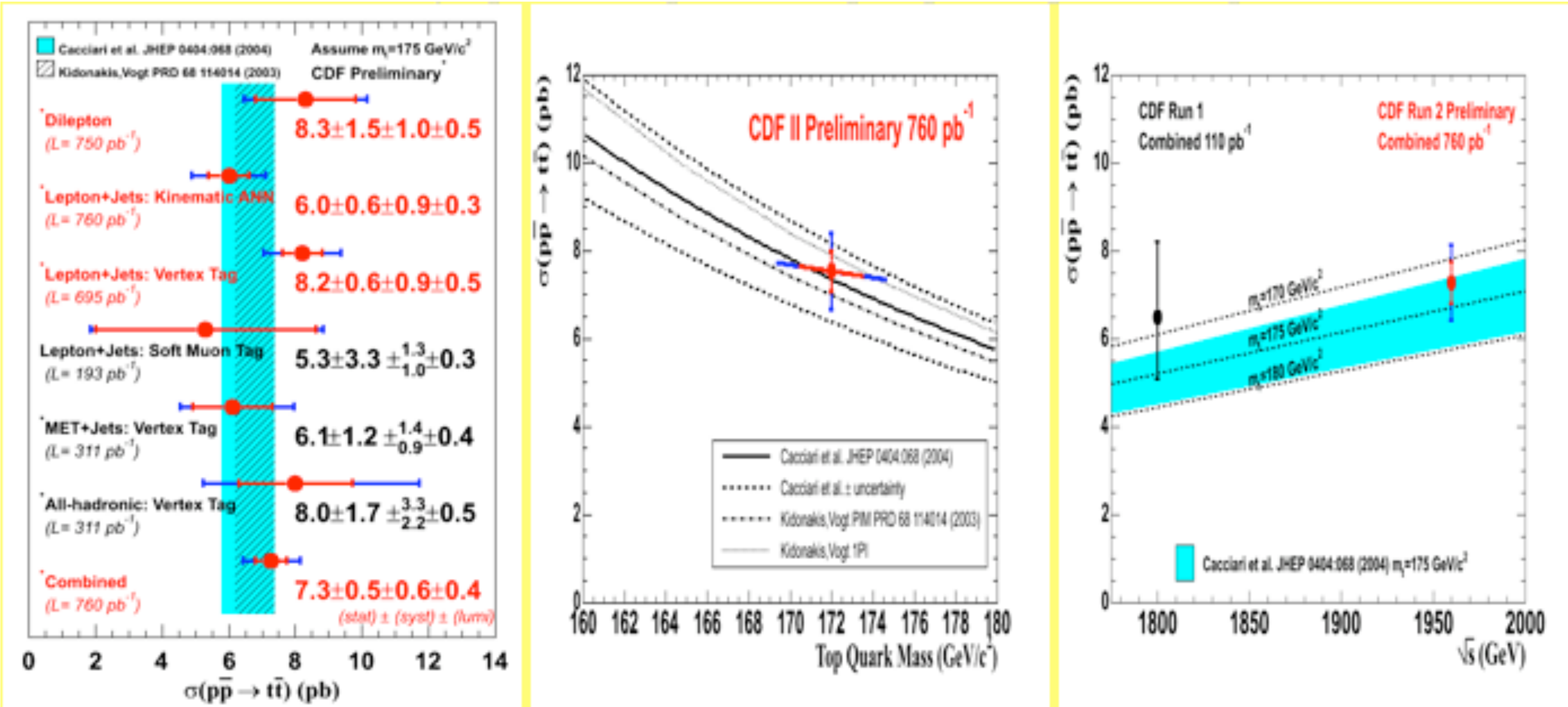


CDF and D0 best (last updated 07/26/2006)



gif and eps

Top Cross Section Now



Top Properties Now

Top quark production and decay properties			
lepton+jets	Search for resonances in ttbar mass spectrum	95% C.L. on $\sigma \times$BR(X->ttbar)	680
lepton+jets	Search for a Massive Fourth Generation t' Quark	t' mass > 258 GeV at 95% CL	760
lepton+jets	Top Quark Lifetime	$c\tau_{top} < 52.5$ μm @ 95% C.L.	318
dilepton	Search for Anomalous Kinematics	1.0-4.5%	194
lepton+tau	t->τ νq	5 obs vs 2.7+-0.4 bkg p-value 15%, or 1sigma excess	350
dilepton, lepton+jets, single and double Vertex b-tags	BR(t->Wb)/BR(t->Wq)	1.12 + 0.21 - 0.19 (stat) + 0.17 -0.13 (syst) > 0.61 @ 95% C.L.	162
dilepton, lepton+tau, lepton+jets single and double Vertex b-tags	Search for Charged Higgs in top decays	Limits on BR(t->H^+b)	194,162
lepton+jets	Top Production Mechanism	0.25+-0.24(stat)+-0.10(syst) for xs(gg->ttbar)/xs(ppbar->ttbar)	330

W helicity Now

W Helicity Plain English explanation			
lepton+jets	cosθ *	F_0= 0.61 +-0.12(stat) +-0.04 (syst) $F_+ < 0.11$ @ 95% C.L.	955
dilepton, lepton+jets (Run II)	M_{lb}^2	$F_+ < 0.09$ @ 95% C.L.	750
lepton+jets	cosθ *	F_0= 0.59 +-0.12(stat) +0.07-0.06(syst) $F_+ < 0.10$ @ 95% C.L.	955
lepton+jets	Combined cosθ * and Lepton Pt spectrum	F_0= 0.74 +0.22 -0.34 (stat+syst) $F_+ < 0.27$ @ 95% C.L.	162
dilepton, lepton+jets Run I	M_{lb}^2	$F_+ < 0.18$ @ 95% C.L.	109