Single top
from Standard Model to New Physics

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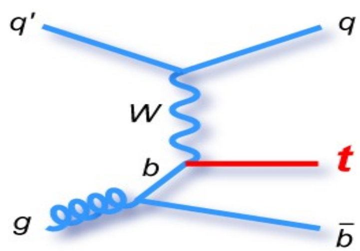
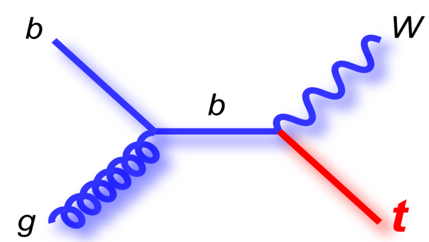
- Single top in Standard Model
- Single top as a background to searches
- Single top as a window on new physics
- Status at Tevatron
- What about CMS
  - Physics TDR results
  - What's going on

Single Top in the Standard Model

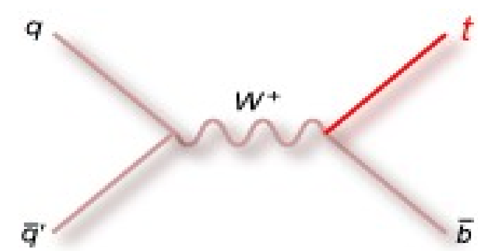
Three production modes mediated by the ElectroWeak force:



t-channel
σ_{Tev} ~ 2 pb
σ_{LHC} ~ 240pb



Wt production
σ_{Tev} ~ 0.1 pb
σ_{LHC} ~ 60pb

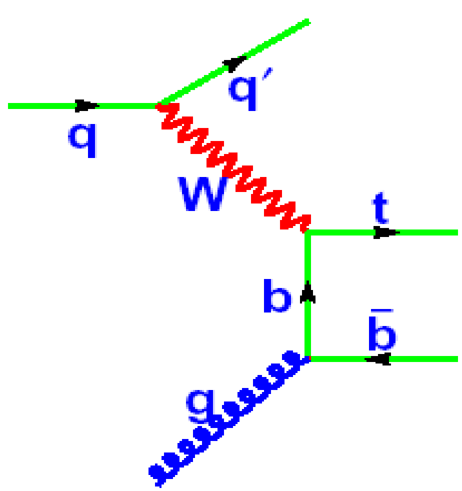


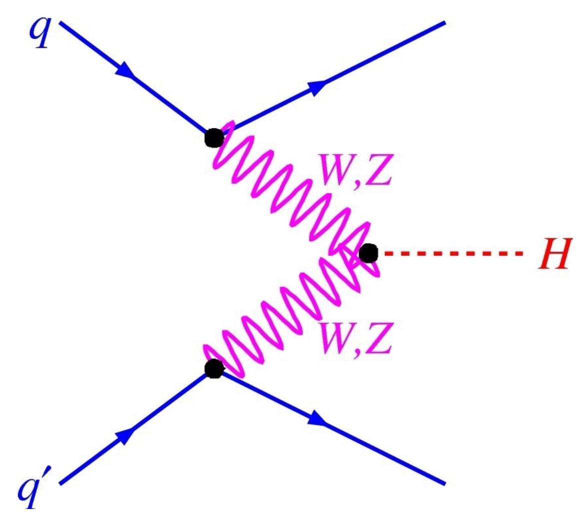
s-channel
σ_{Tev} ~ 0.9 pb
σ_{LHC} ~ 10pb

- Directly related to $|V_{tb}|$, not a ratio
- Possibility to study top properties (mass, polarization, charge) with less reconstruction ambiguities than in ttbar
- Wt is out of Tevatron reach, but it will be accessible to LHC
- Together the 3 channels provide complementary informations on Wtb coupling, since they probe it for $q^2<0$, $q^2>0$, $q^2=0$

Single Top as a benchmark

- The most abundant production mode, t-channel, is characterized by its forward energetic jet
- Precious signature for isolating it from background, but also quite complicated η region, for both detector (HF) and phenomenology (UE, PU, ...)
- But it's mandatory to understand this region as soon as possible: forward jets are also the signature of VBF





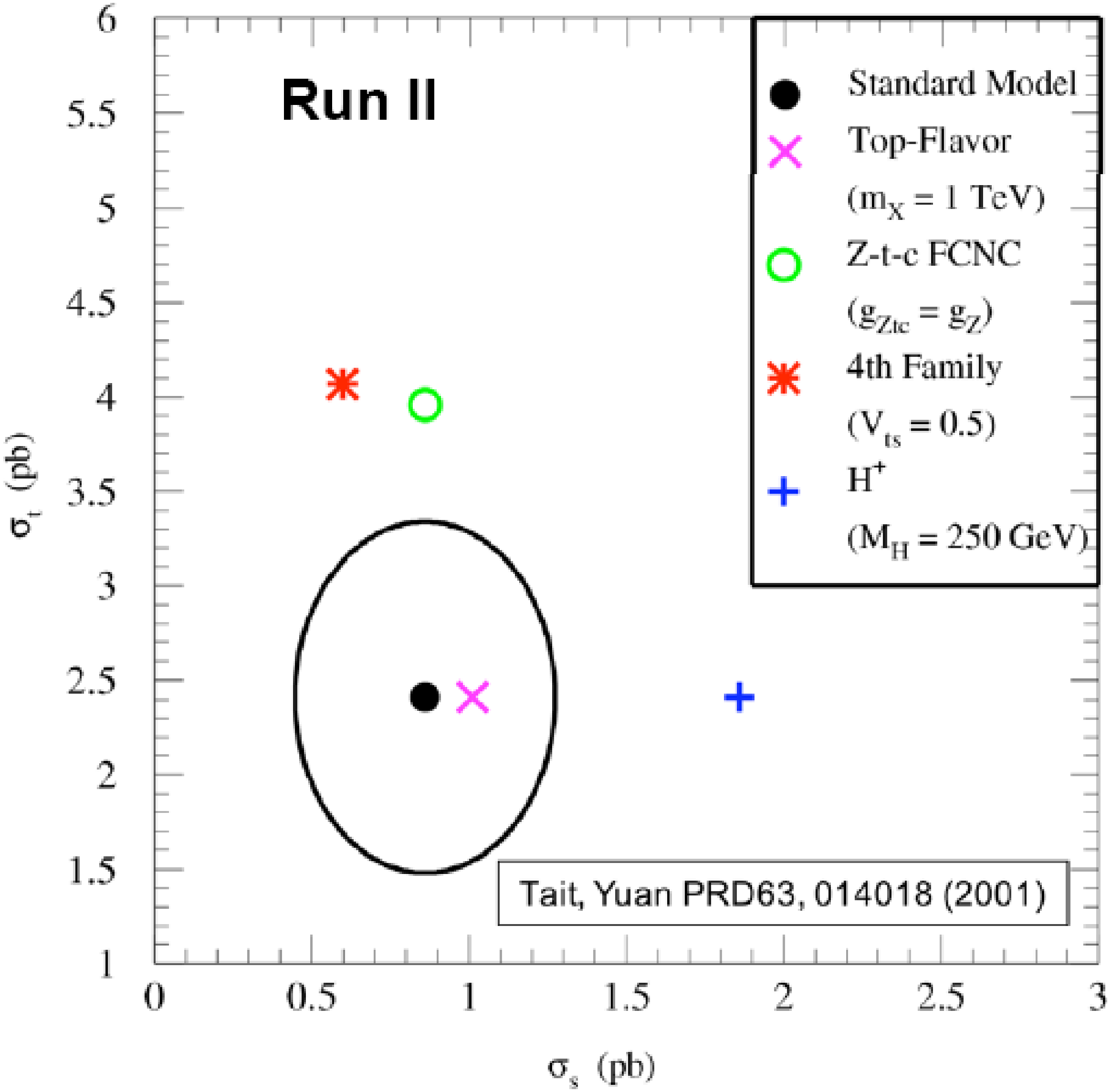
Single Top as noise

- In the $H \rightarrow WW \rightarrow l\nu l\nu$ search, after jet veto the Wt/tt ratio increases
  - Wt becomes a significant contamination
  - Difficult to extract it from dedicated control samples, we currently rely on NLO estimates to disentangle it from the “tt control sample”
    - Campbell et al., Les Houches 2005 report: hep-ph/0604120
- In the $gb \rightarrow H^{\pm}t$ search ($H \rightarrow \tau\nu$), $gb \rightarrow Wt$ ($W \rightarrow \tau\nu$) can only be reduced by exploiting the spin difference (tau spectrum and/or angular distribution)
- In general, whatever has ttbar as background (eg SUSY) has also a single top contamination

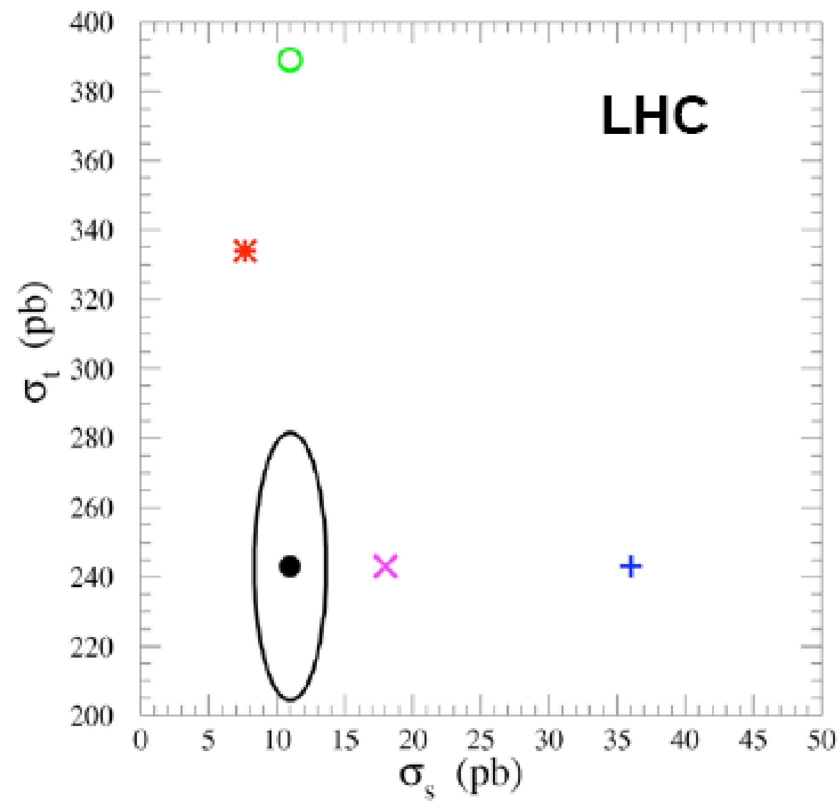
Single Top as signal of new physics

- The same final states of the SM single top (i.e. tq, tb, Wt) can come from non-SM fundamental processes
- t': if $M_{b'} > M_{t'}$, main decay is Wb
  - And for $M_{t'}$>270 GeV, the t'q production mode is favored over $t'\bar{t}'$: enhancement of t-channel at high mass/HT
- W' (including W*, W_{KK}, ...) would enhance the s-channel
  - If their coupling is SM (e.g. W_{KK}), they will be observed in leptonic decays much earlier than in single top
  - But the b.r.'s are model dependent; in some models the coupling to $l\nu$ is suppressed / tb is enhanced (e.g. W_R / W*)
- Any model with FCNC (e.g. SUSY) enhances t-channel: while SM needs a **b** in the initial state, FCNC can have a **u**

The σ_s/σ_t plane



Theory + statistical (2/100 fb^{-1})
3σ deviation curves



Caveat: obsolete plots, for illustration only

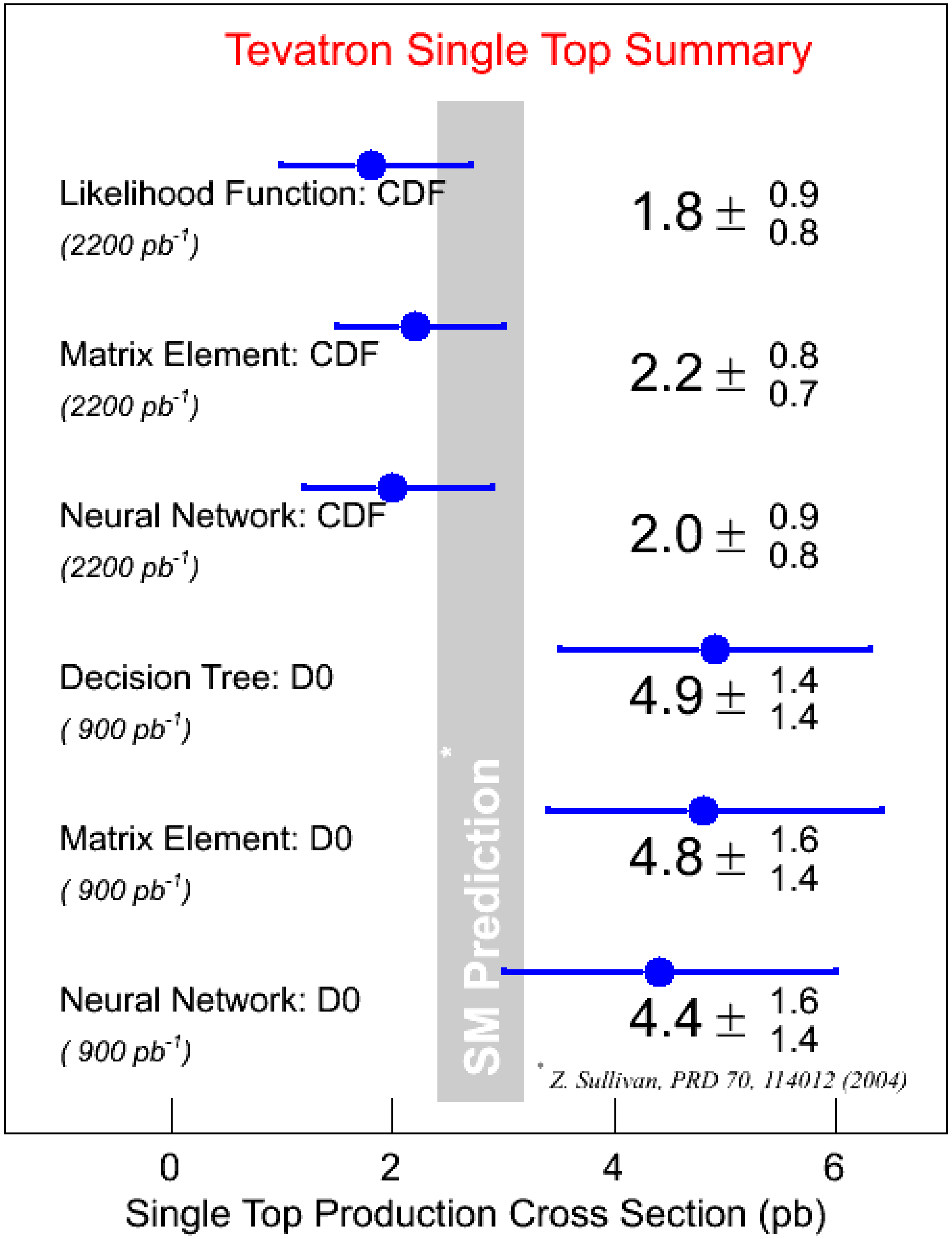
V_{tb} in a 4x4 or 4x3 matrix

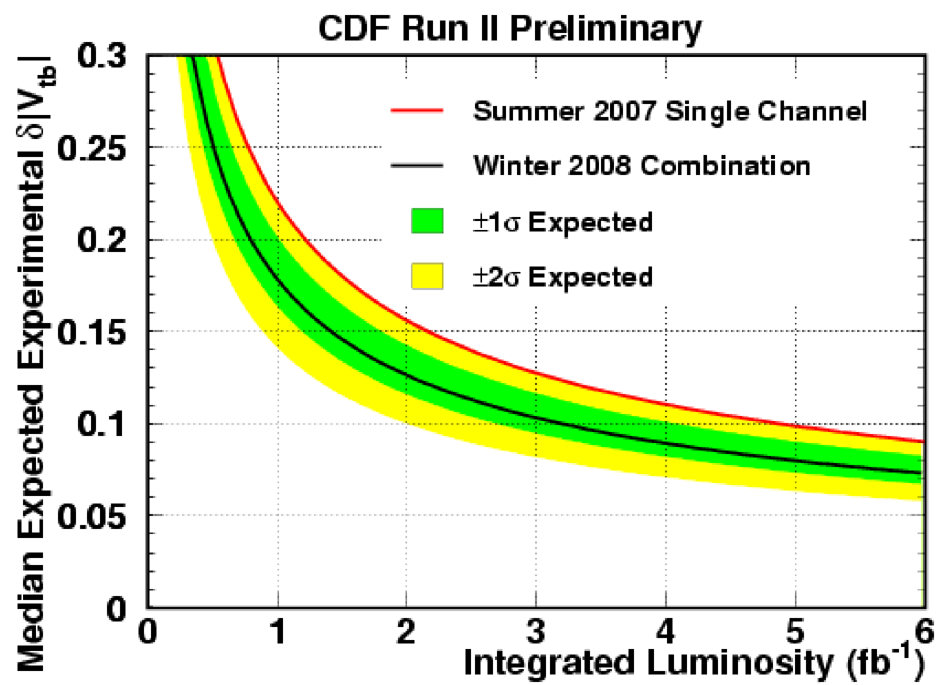
- SM, 3x3: $0.9990<|V_{tb}|<0.9992$ @90%CL
- Alwall et al. (EPJ C49 p791, hep-ph/0607115) reexamined the direct and indirect experimental constraints when CKM is minimally extended to a 4th family, or to a single pseudo-vector quark (b'/t')
- $V_{tb} \sim V_{tb}^{CKM}\cos\theta$; θ: t-t' mixing angle (u-t' and c-t' mixings are very tightly constrained by experiments); limits depend on $M_{t'}$ (Tevatron limit: $M_{t'}/M_t>1.5$)
- With 4th family: $V_{tb}>0.93$
- With pseudo-vector t': $V_{tb}>0.91$

This sets a clear goal for the precision that we want to achieve on Vtb. Nota: 10% on x-sect = 5% on Vtb

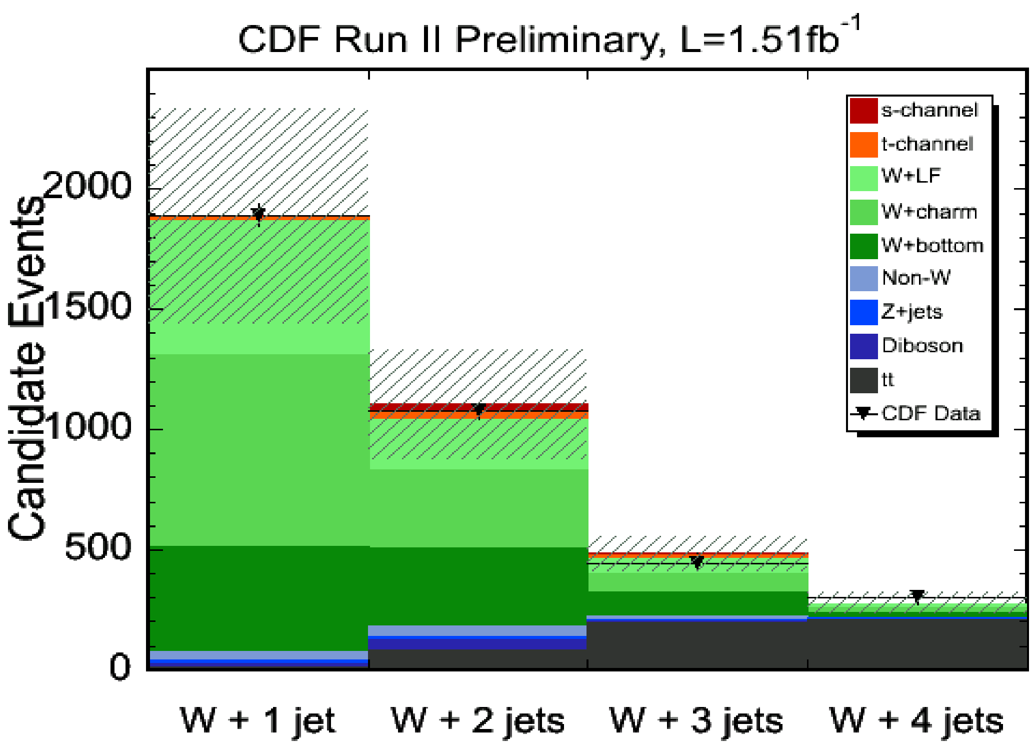
- Nota bene: here is assumed that no other particles exist; a more rich zoology at low energy can further relax the limits

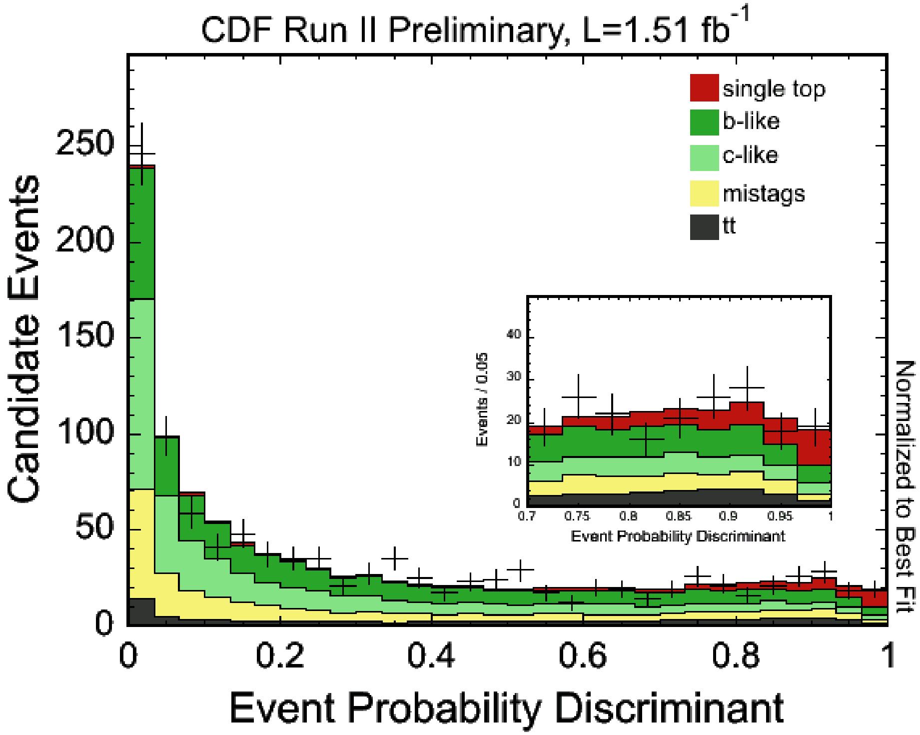
Status at Tevatron

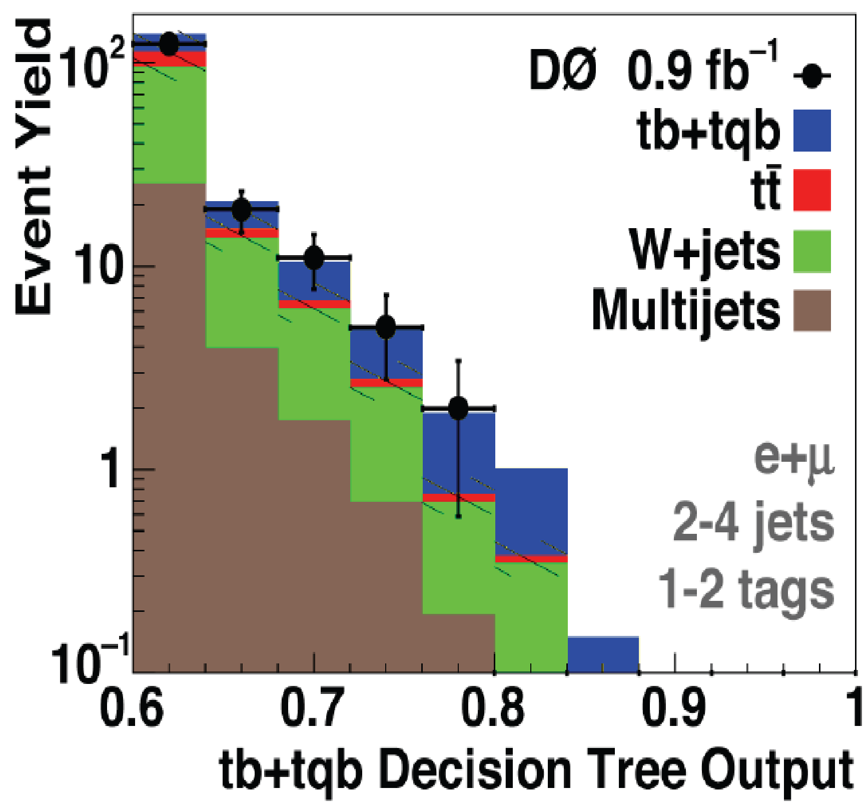




Needles in a barn







D0 also separates s- and t-channel according to b-tag and angular asymmetry:

σ_s=1.0±0.9 pb

$\sigma_t=4.2^{+1.8}_{-1.4}$ pb

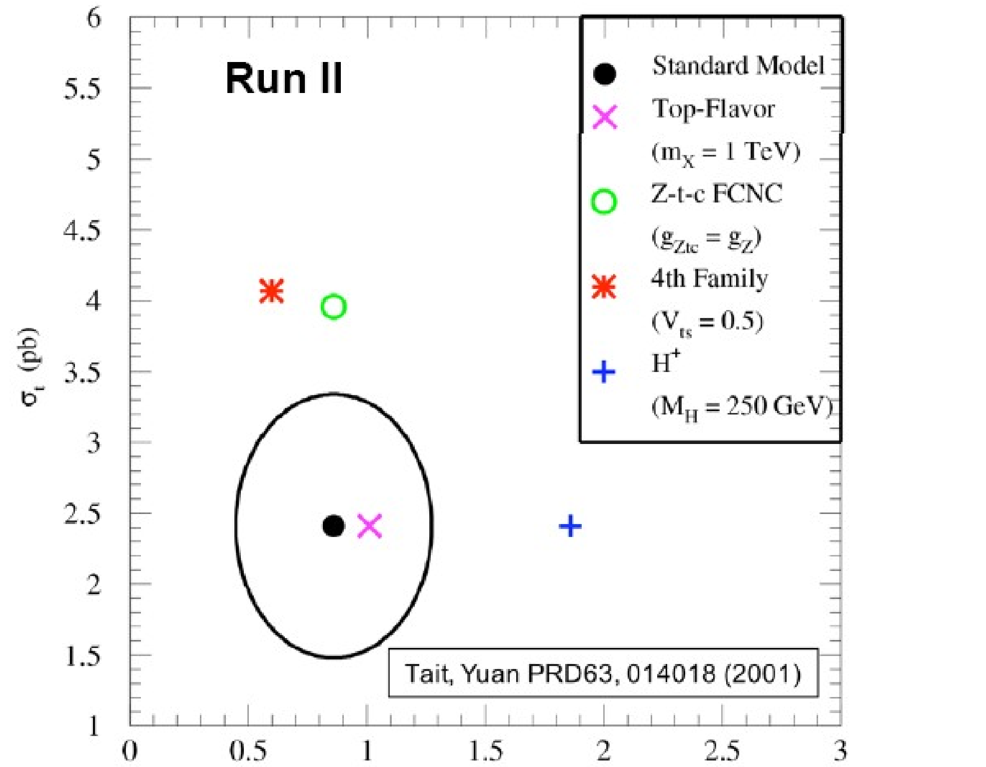
CDF recently "blessed" an analysis for s-channel only, with 1.9 fb-1, giving $\sigma_s=0.6^{+0.9}_{-0.6}$ pb

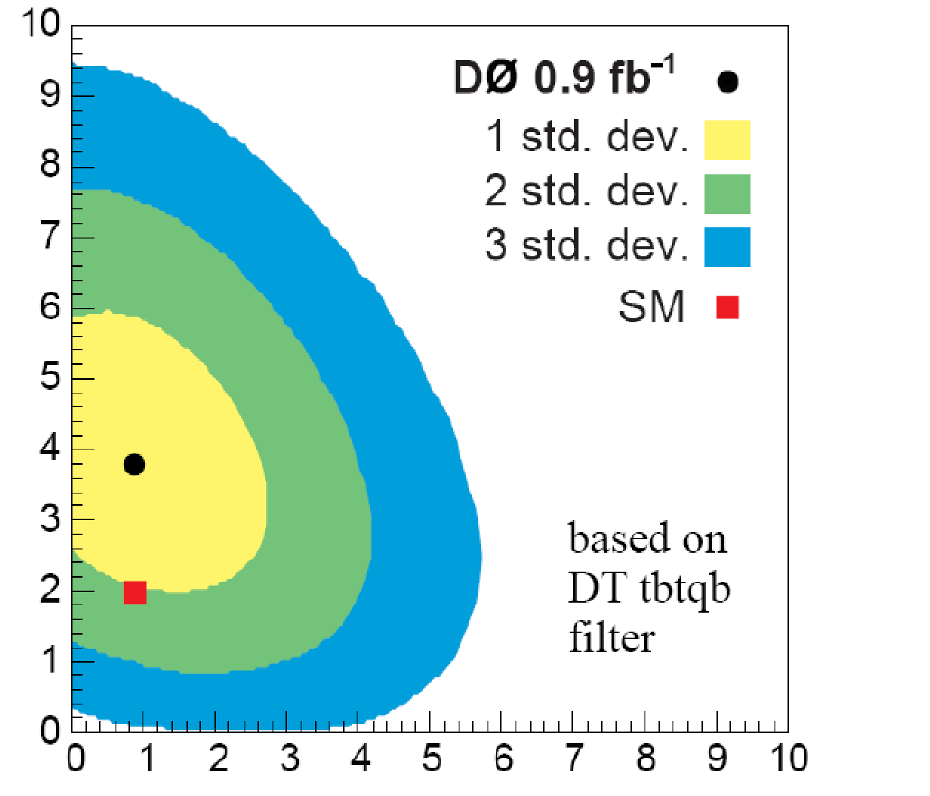
(ie σ_s<2.77 pb @95%CL)

Direct search for W'→tb (CDF):

$M_{W'}$>800 GeV ($M_{W'}>M_{\nu R}$)

$M_{W'}$>825 GeV ($M_{W'}<M_{\nu R}$)





From Tevatron to LHC

	1.96 TeV	14 TeV	
ttbar pairs	6.7±0.7 pb	833^{+52}_{-39} pb	(x170)
Single top (s-channel)	0.88±0.06 pb	10.7±0.7 pb	**(x10)**
Single top (t-channel)	1.98±0.14 pb	247±10 pb	(x120)
Single top (Wt channel)	0.15±0.04 pb	66±2 pb will be discovered at LHC	(x400)
Wjj (*)	~1200 pb	~7500 pb	(x6)
bb+other jets (*)	$\sim 2.4 \times 10^5$ pb	$\sim 5 \times 10^5$ pb	(x2)

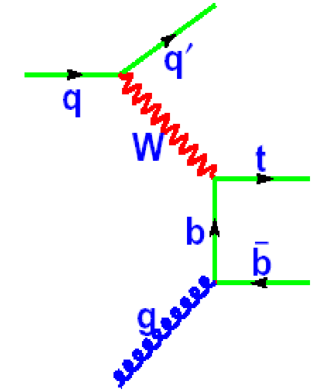
(*) with kinematic cuts in order to better mimic signal
Belyaev, Boos, and Dudko [hep-ph/9806332]

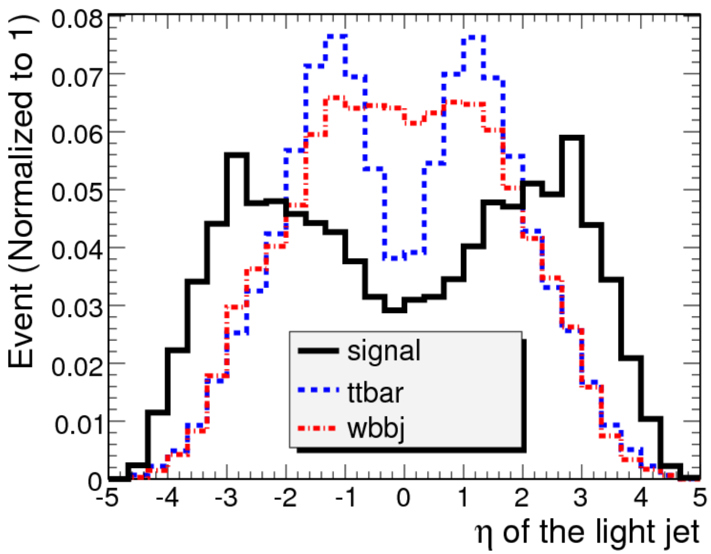
Analyses will be quite different from Tevatron

Single Top studies in CMS

- TDR analyses, also described in CMS NOTE 2006/084 (t- and s-channel) and 2006/086 (Wt)
  - Described in the next slides
  - These analyses assumed a **10 fb^{-1}** scenario
- Some improvements since then (in ORCA/FAMOS, never presented for public approval):
  - First look at polarization by H.Mermekaya et al.
  - NN analysis for t-channel (L.Dudko, A.Markina et al., CMS-IN 2007/045)
  - Several analysis improvements in all 3 channels in G.Petrucciani's thesis (see later + backup slides)

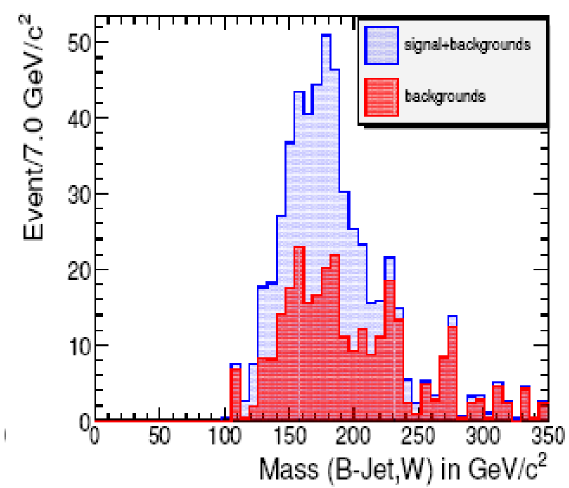
TDR results: t-channel





Selection:

- 1 muon (isolated), MET (type I), 2 jets
- 1 jet b-tagged and central, 1 jet forward
- Σ_T is defined as vectorial sum of transverse momenta (including MET)
- Cuts on Σ_T, M_T^W and M_{top}
- **S/B=1.3**

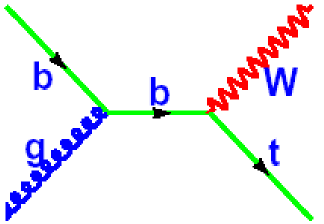


sample	selected	ΔN_{th}	ΔN_{Lum}	$\Delta N_{\mathrm{b-tag}}$	JES	tot.	ΔN_{stat}
t-channel	2330	93.2	116	93.2	26	177.5	48.3
$t\bar{t}$	1147	80.3	57.3	45.9	84	137.5	33.9
$Wb\bar{b}j$	188	32	9.4	7.5	4.5	34.5	13.7
Wjj	402	20	20	16.1	0	32.6	20

$\Delta\sigma/\sigma$ = 2.7% (stat) + 8.1% (syst) + 5% (lumi) = 9.9% @10fb^{-1}

CMS NOTE 2006/086

TDR results: W-associated



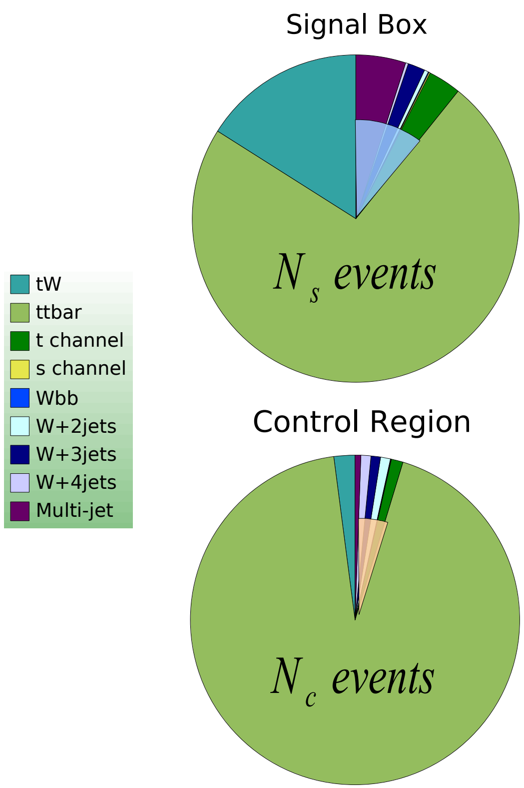
Selection (dileptonic):

- 1e+1μ (isolated), MET
- 1 jet, b-tagged
- **S/B=1/3**

In both cases, almost all the surviving background is ttbar; normalization over data (control samples with one more jet, in both channels) cancels out most of the systematics.

Selection (single lepton):

- 1 e/μ (isolated), MET
- 3 jets, 1 b-tagged
- Cuts on M_T^W, M(jj), M_{top} and other topological variables
- **S/B=1/5**

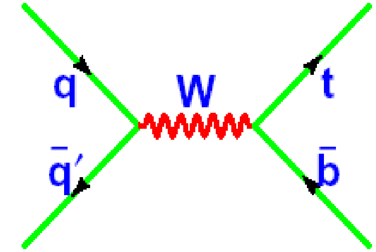


Δσ/σ (2l)=8.8%(stat)+23.9%(syst)+5%(lumi)

Δσ/σ (1l)=7.5%(stat)+16.8%(syst)+5%(lumi)

CMS NOTE 2006/084

TDR results: s-channel



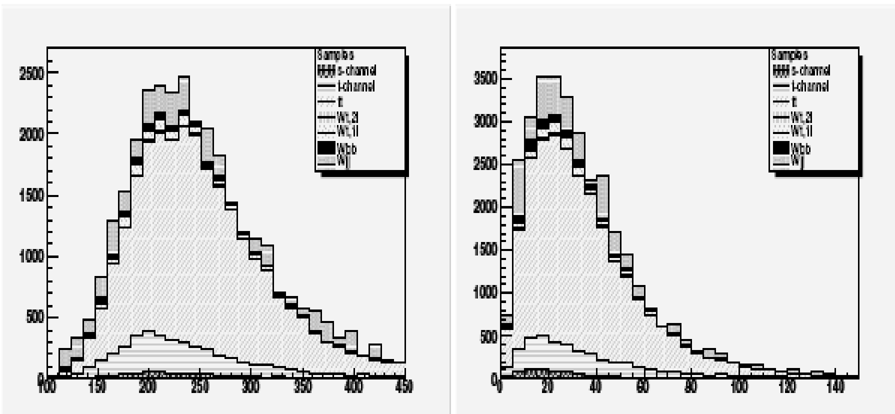


Figure 13: Distribution of the scalar (left) and of the vectorial (right) sum in the transverse plane of the momenta of the lepton, of the $\not{E}_T$ and of the two b-jets.

Selection:

- 1 e/μ (isolated), MET)
- 2 jets, both b-tagged
- Cuts on Σ_T, M_T^W, M_{top} and other topological variables
- **S/B=1/7**

- s-channel: 273±3(JES)±11(btag)±1.5(M_{top})±2(PDF)±1.5(ISR/FSR)
- t-channel: 629±25(theo)±8(JES)±25(btag)
- ttbar: 1258±63(theo)±75(JES)±50(btag)
- Wbb: 155±8(theo)±7(JES)±6(btag)

A normalization over data had to be developed (two control samples: one for tt->1l, one for tt->2l) in order to keep under control the tt background and normalize most of the systematics. What remains is mostly due to the JES systematic alone.

$\Delta\sigma/\sigma$ = 18% (stat) + 31% (syst) + 5% (lumi) = 36% @10fb^{-1}

Where can we improve?

- In Summer 2006, AG and G.Petrucciani (Pisa) refined all 3 analyses, in particular:
  - Jet collection cleaning, e.g. use of tracks from prim.vtx
  - More control samples for bkg normalization
  - **More systematics and backgrounds**
  - Improvements: t-channel 10%→8%, Wt(SL) 19%→14%, Wt(DL) 25%→18%, s-channel 36%→24%
  - http://indico.cern.ch/conferenceDisplay.py?confId=4945

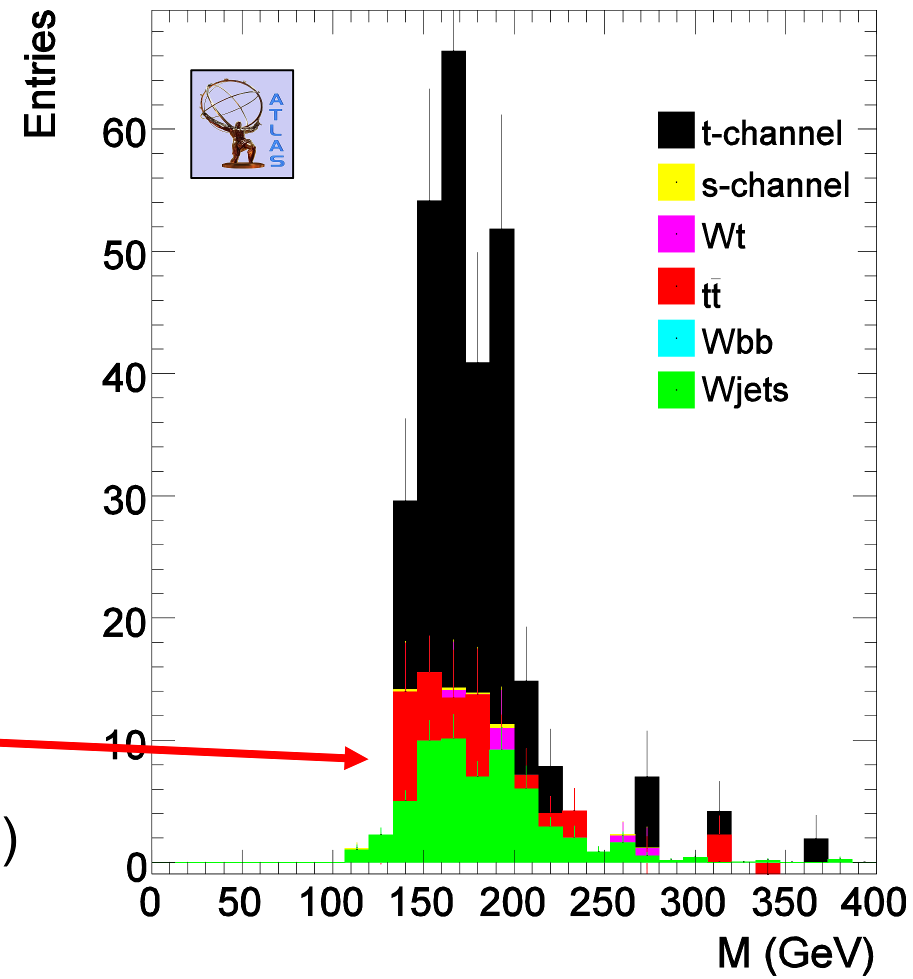
On the other side of Bdg.40

- ATLAS has always paid much attention to single top
  - With one notable exception: they never studied Wt→2l
- Difficult to compare prospects: their most detailed studies, in a 30 fb^{-1} scenario, assumed very well known systematics (e.g. JES = ±1%) while our TDR (10 fb^{-1}) assumes JES from ±5% to ±2.5% (E_T-dependent)
  - Substituting "by hand" common systematics in the final results would be unfair: with a significantly different JES uncertainty, strategies would have been radically different
- ATLAS has just completed a public paper (CSC) with all 3 channels + polarization, in a 1 fb^{-1} scenario with a look at 100 pb^{-1} and 20 pb^{-1}(!!!); **16 people involved**

Single top: t-channel (ATLAS)

courtesy by Marina Cobal

- Cut analysis: low multiplicity jet events, 1 light jet forward, 1 b-jet with P_T > 50 GeV
  - ε_{signal} = 1.81%
  - S/B ~ 37%
  - Few % stat. accuracy with few fb-1
  - Systematics = 45.2%
- Adding a BDT based on 6 kin. variables, better ttbar rejection:
  - $\Delta\sigma/\sigma$=±8.7%(stat)±9.8(sys)=±13.1%(tot)



Note: they assume JES uncertainty 1%
CMS will not certainly have this level of understanding after 1/fb. The only hope to have something similar is to rely very little on HCAL.
(PFlow is clearly the first option that comes to my mind.)

Ongoing activities in CMS

16:00->*17:00* **Kick-off meeting for Single-top physics**

Description:

Short presentations overviewing the current efforts on single-top physics, including plans for the near future.

16:00	Introduction (05') (Slides)	Andrea Giammanco (*UCL Louvain-la-Neuve*)
16:05	Single top activities in Karlsruhe (20') (Slides)	Julia Weinelt (*Inst. fuer Experimentelle Kernphys.-Universitaet Karlsruhe*)
16:25	Single top activities in Moscow (20') (Slides)	Lev Dudko (*SINP MSU, Moscow*) , Anastasia Markina (*SINP MSU, Moscow*)
16:45	Single top activities in Louvain (15') (Slides)	Andrea Giammanco (*UCL Louvain-la-Neuve*)

- Only t-channel
- Groups doing something since 2007:
  - Louvain (AG): trigger studies, see next slides
  - Karlsruhe: mostly generator-level studies (matching “à la Boos” for MadGraph, cross-validation of generators, ...)
  - Moscow: trying to reproduce the TDR
  - Teheran: just starting now

Trigger performances in single top

- Code adapted from Loic's code, CMSSW_1_6_x
  - cvs: */UserCode/giammanco/Trigger/TriggerPathEfficiency*
- Input: MC@NLO + full simulation
- Trigger table: 10E32 (see next slide)
- Here I will give numbers for two definitions of trigger efficiency:
  - Ntrig/Ntot
  - Ntrig/Noff: restricted to a “signal region” defined by:
    - 1 e/μ with p_T^{reco}>20 GeV and $|\eta|$<2.0
    - 2j with $p_T^{uncalib}$>20 GeV, one $|\eta|$<2.4, the other $|\eta|$>2.4
    - EM fraction of jet energy < 0.8

HLT table 10E32 (partial)

Trigger path name	**HLT threshold (GeV)**
HLT1MuonNonIso	**16**
HLT1MuonIso	**11**
HLT1ElectronRelaxed	**17**
HLT1Electron	**15**
HLT2MuonNonIso	**3,3**
HLT2ElectronRelaxed	**12,12**
HLTXElectronMuonRelaxed	**10,10**
HLTXElectronMuon	**8,7**
HLT1jet	**200**

$N_{trigger}/N_{tot}$

Electron channel, L1:

L1_SingleIsoEG10	82.3%
L1_SingleEG15	83.2% (+5.8%)
L1_ETM40	65.9% (+5.9%)
L1_DoubleJet70	30.4% (+0.3%)
L1_IsoEG10_Jet30	69.8% (+0.0%)

Electron channel, HLT:

HLT1Electron	53.5%
HLT1ElectronRelaxed	53.2% (+2.5%)
HLTXElectron1Jet	49.1% (+4.3%)
HLTXElectron2Jet	7.7% (+0.0%)
HLT1MET	26.6% (+10.1%)
HLTXElectronTau	24.5% (+0.0%)
HLT1Tau1MET	40.9% (+3.5%)
HLT1Tau	9.6% (+0.0%)

Gain with respect to previous entries in list

Muon channel, L1:

L1_SingleMu7	73.5%
L1_ETM40	43.4% (+11.0%)
L1_Mu5_Jet20	67.6% (+0.3%)

Muon channel, HLT:

HLT1MuonIso	65.2%
HLT1MuonNonIso	64.0% (+3.2%)
HLTXMuonJets	47.3% (+1.4%)
HLT1MET	22.5% (+6.2%)

Only the main bits are listed here, but all were checked.
L1 is pre-requisite for HLT (HLT is actually L1*HLT).
MET behaves differently between e/mu because it is uncorrected (see backup slides).

$N_{trigger}/N_{offline}$

Electron channel, L1:

L1_SingleIsoEG10	92.0%
L1_SingleEG15	98.8% (+7.0%)
L1_ETM40	76.1% (+0.8%)
L1_DoubleJet70	73.3% (+0.1%)
L1_IsoEG10_Jet30	92.0% (+0.0%)

Electron channel, HLT:

HLT1Electron	72.3%
HLT1ElectronRelaxed	76.1% (+4.1%)
HLTXElectron1Jet	77.3% (+5.0%)
HLTXElectron2Jet	28.1% (+0.0%)
HLT1MET	41.6% (+7.7%)
HLTXElectronTau	52.2% (+0.0%)
HLT1Tau1MET	58.6% (+2.2%)
HLT1Tau	20.8% (+0.0%)

Muon channel, L1:

L1_SingleMu7	93.1%
L1_ETM40	65.1% (+4.7%)
L1_Mu5_Jet20	93.7% (+0.2%)

Muon channel, HLT:

HLT1MuonIso	84.3%
HLT1MuonNonIso	88.9% (+5.3%)
HLTXMuonJets	84.7% (+0.6%)
HLT1MET	40.5% (+4.4%)

General conclusions: we can live with the 1l triggers alone, but 1e+1j and MET bits can help significantly in the signal region.

HLT efficiency ~ 90%(e)/95%(μ) achieved with only the red entries.

Negligible dependence on MET offline cut (tried 0, 20, 40 GeV)

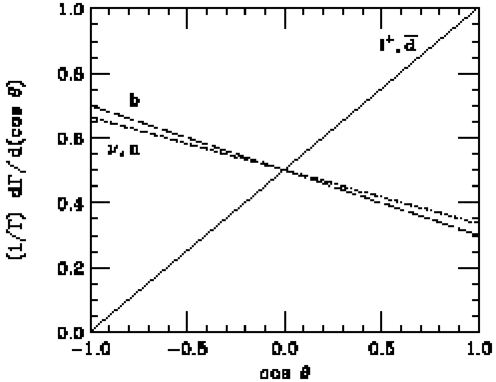
Conclusions

- EWK top production will be abundant at LHC, single top studies easier than at Tevatron (but not easy!)
- Precious window on some new physics
- Painful background to some other new physics
  - Also a bkg to bkg-enriched control samples (e.g. W+2j)
- Direct measurement of Vtb. Well defined goal: $\Delta\sigma/\sigma \sim 10\%$ (even in t-channel only) is enough to start setting constraints on new up-type quarks
- After the burst of single top activities in 2005-2006, little has been done in CMS
- Large room for improvements

Backup slides

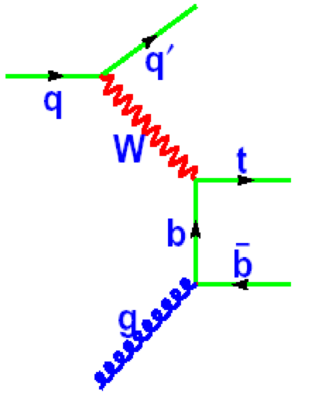
Not only x-section: new physics in Polarization

- Top's chirality is 100% left-handed in EWK production
  - $\tau_{decoherence} > \tau_{decay}$: decay products are probes of polarization
  - $(d\Gamma/\Gamma)/d(\cos\theta) = ½(1 + A\cos\theta)$
  - $A(l) = +1$, $A(b) = -0.40$, $A(\nu) = -0.33$



- Problem: at the top mass, helicity ≠ chirality
  - Solution: in the top frame, spin axis ∥ d-type quark direction
  - Which d-type quark?
    - Tevatron, s-channel: take the anti-proton direction (correct in 98% of cases); not applicable at LHC
    - LHC: take the recoil quark's direction in t-channel
    - How-to: boost into reco top frame, plot angle between lepton and untagged jet, correct for acceptance/bkg, extract slope

Update: t-channel



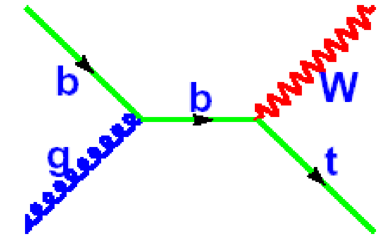
- This "exploratory" study was performed with TopReX+FAMOS
- The electron channel was also considered
- Neutrino reconstruction: real part of complex solutions
- Jet definition: use of α parameter
- γ-jet calibration instead of MC (some difference below 50 GeV)
- Significant improvement: S/B=2.7 with the TDR cuts! (Was 1.3)
- Analysis has been re-optimized with a genetic algorithm
- Much tighter cuts, thanks to the possibility (due to the use of tracks to define jets) of lowering the threshold for vetoing the 3rd jet (the main ttbar killer): S/B=4.7

Process	Yield $[10\,\mathrm{fb}^{-1}]$	
t channel	550	± 23
$\mathrm{W}+2\mathrm{j}$	26	± 18
$\mathrm{W}+3\mathrm{j}$	15	± 15
$\mathrm{tW}\ (1\ell)$	12	± 4
$\mathrm{Wb\bar{b}}$	8	± 4
$\mathrm{t\bar{t}}$	1	$\pm 8^{\dagger}$
$\mathrm{W}+4\mathrm{j}$	0	$\pm 48^{\dagger}$

	$\Delta\sigma/\sigma$	
Statistics	-4.5%	$+4.5\%$
$\sigma(tW)$ $[\pm 15\%]$	-0.3%	$+0.3\%$
$\sigma(W+nj)$ $[\pm 10\%]$	-1.1%	$+1.1\%$
luminosity $[5\%]$	-5.6%	$+5.6\%$
jet energy scale	-2.8%	$+3.1\%$
b tagging	-1.2%	$+0.6\%$
Total uncertainty	-7.9%	$+7.9\%$
Simulated statistics	-2.9%	$+2.9\%$

was 10%

Update: W-associated



- Jet cleaning: N(tracks)>1; α>0.1 for single-leptonic and α>0.2 for di-leptonic (where only the b-jet has to be present)
- Top reconstruction (W-b pairing) in single-leptonic: minimum $\Delta R(W,b)$ is found to be sufficient
- Di-leptonic: added cut on Σ_T (defined as in t-ch. & s-ch. analyses)
- Single-leptonic: a control sample has been selected also for W+jets, reverting the cuts on b-tagging and M(jj)
- Single-leptonic: S/B=0.55 (was 0.19), mostly thanks to α cut!

Statistics	−5.2%	+5.2%
$\sigma(Wb\bar{b})$ [±10.0%]	−0.3%	+0.3%
σ(t ch.) [±4.0%]	−0.8%	+0.8%
luminosity [5%]	−6.1%	+6.1%
jet energy scale	−2.9%	+7.1%
b tagging	−3.9%	+0.0%
PDF†	−1.6%	+1.6%
Pile-up†	−10.3%	+10.3%
Total uncertainty	**−14.0%**	**+14.9%**
Simulated statistics	−13.4%	+13.4%

Single-leptonic

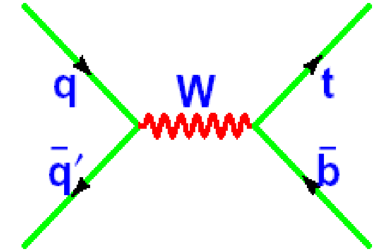
was 19%

Statistics	−10.9%	+10.9%
$\sigma(W+jets)$ [±10%]	−0.7%	+0.7%
luminosity [5%]	−5.5%	+5.5%
jet energy scale	−10.3%	+7.8%
b tagging	−4.5%	+2.3%
PDF†	−6.6%	+4.4%
Pile-up†	+6.1%	6.1%
Total uncertainty	**−18.6%**	**+16.4%**
Simulated statistics	−11.5%	+11.5%

Di-leptonic

was 25%

Update: s-channel



- Top reconstruction (W-b pairing): minimum $\Delta R(W,b)$ instead of jet charge (just for practical reasons; performance is similar)
- Analysis re-optimized (better S/B: 0.2 vs 0.13, but lower efficiency), main difference: higher thresholds for jets
- Control sample also for t-channel bkg
- Re-calibration of jets (assuming a shift of 2.7% on the m(jj) peak) has a significant impact on systematics

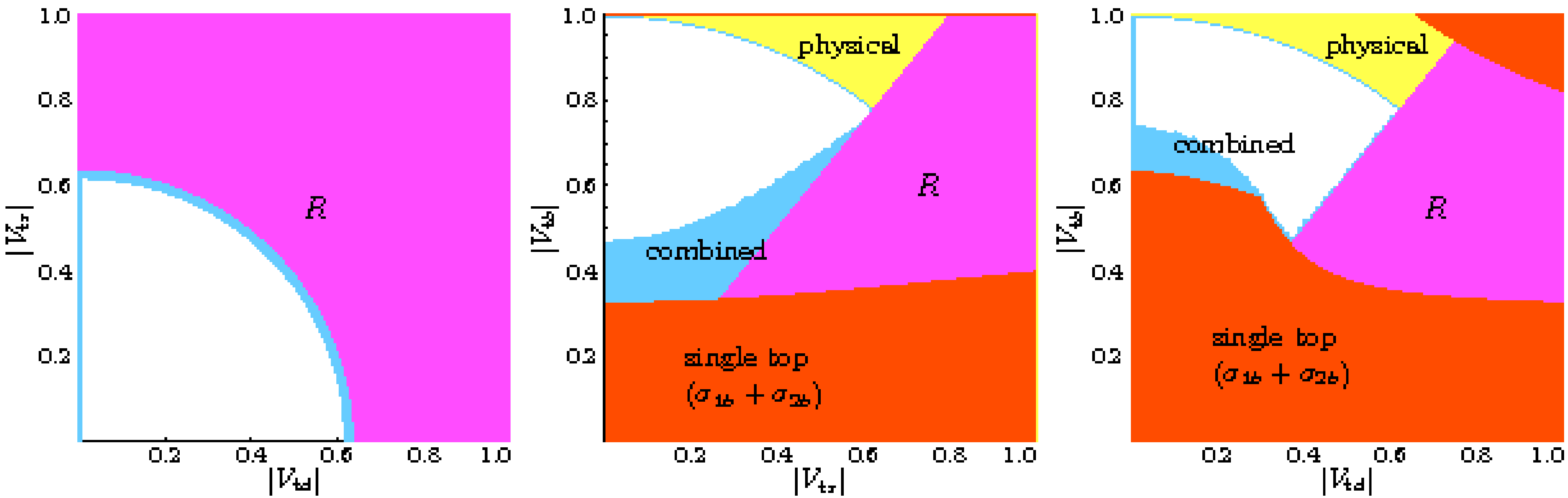
Statistics	-20.2%	$+20.2\%$
$\sigma(W + jets)$ [$\pm10\%$]	-7.6%	$+7.6\%$
$\sigma(Wb\bar{b})$ [$\pm10\%$]	-7.1%	$+7.1\%$
$\sigma(tW)$ [$\pm10\%$]	-2.5%	$+2.57\%$
luminosity [5%]	-6.0%	$+6.0\%$
jet energy scale†	-3.2%	$+1.1\%$
b tagging	-6.1%	$+0.4\%$
Total uncertainty	**-24.6%**	**$+23.6\%$**
Simulated statistics	-31.5%	$+31.5\%$

was 36%

Limits on V_{ti} from R and single top

R = BR(t→Wb) / BR(t→W + any quark)

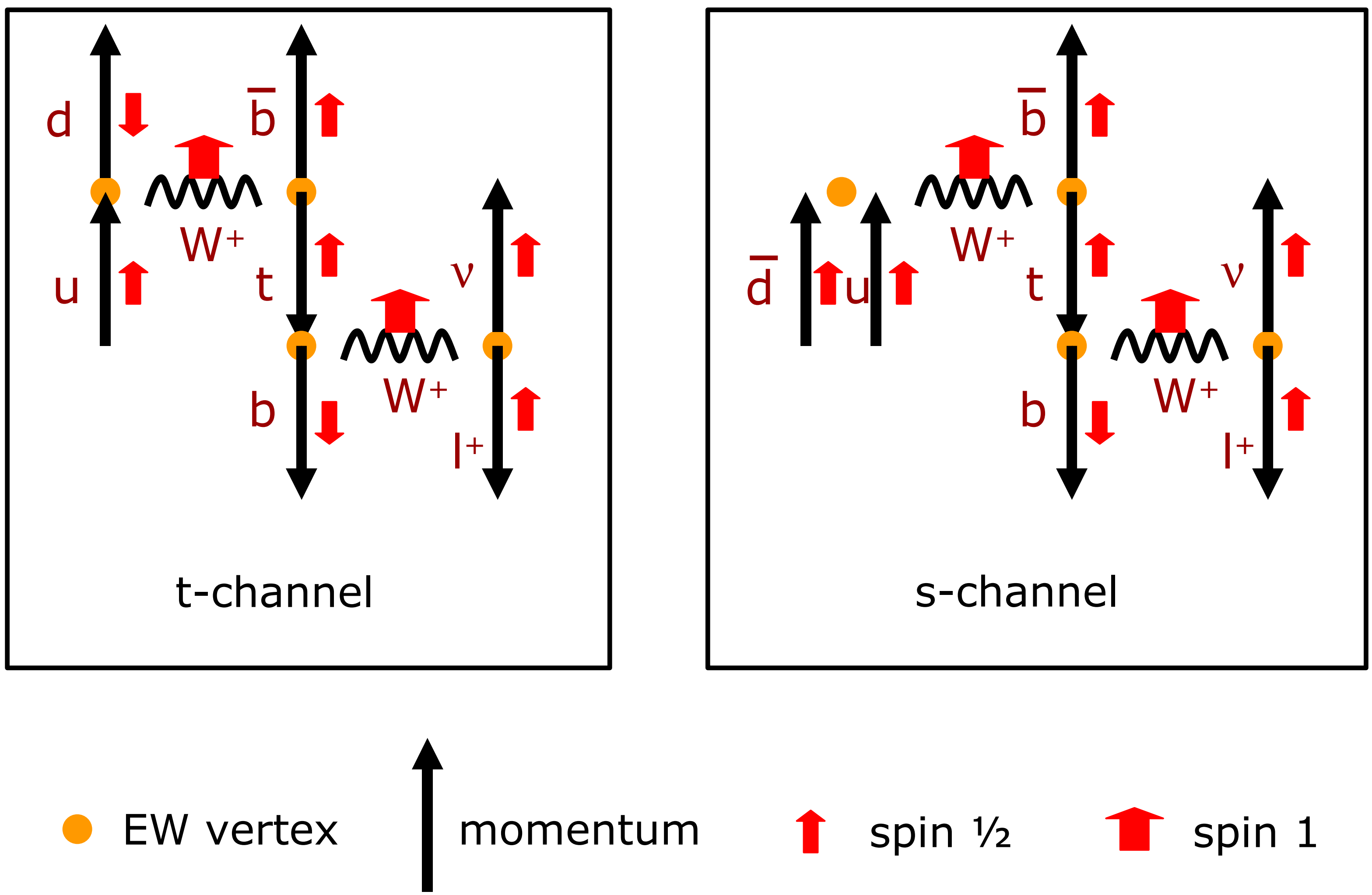
$$R = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{td}|^2 + |V_{ts}|^2}$$



from hep-ph/0607115 (EPJ C 2007) updated in arXiv:0801.1800 [hep-ph],
"Collider aspects of flavour physics at high Q"
using Tevatron data on single top and R, and no unitarity constraint

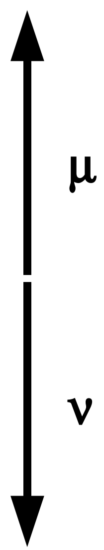
...but EW-/B-physics tightly constrain "minimal" extensions of CKM!

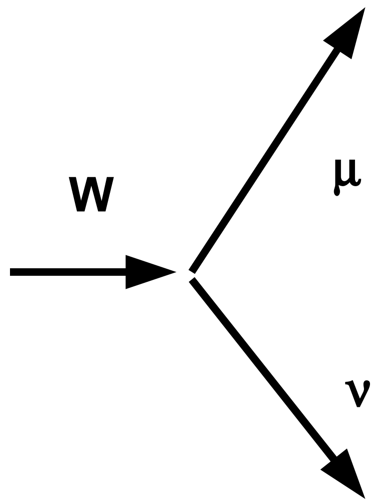
Spin flow

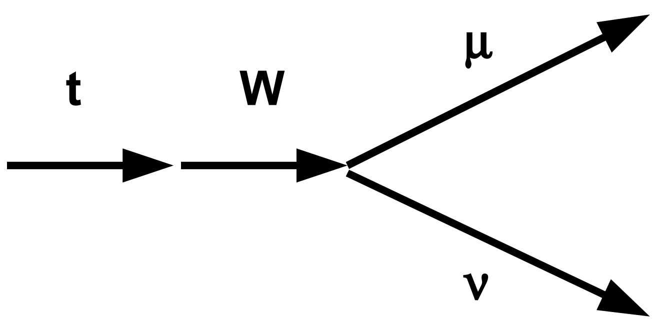


d
b̄
W+
u
t
ν
W+
b
l+
t-channel
b̄
W+
d̄
u
t
ν
W+
b
l+
s-channel
EW vertex
momentum
spin ½
spin 1

(back-of-the-envelope calculation)



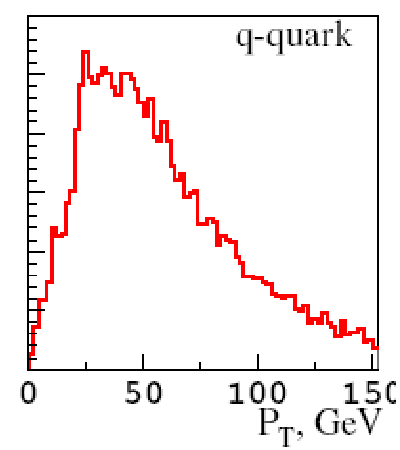




In the W rest frame, lepton and neutrino are back-to-back (**Δϕ=180°**).

In the top rest frame, if lepton and neutrino are orthogonal to the W direction, **Δϕ=98°**

In the laboratory rest frame, if the W flies in the top direction and the top has P=50 GeV, **Δϕ=76°**



The muon momentum is mostly lost. The electron, on the contrary, gives over-accounted momentum, due to e/h>1. In high-boost events MET(mu)>MET(e), in soft events it's the contrary. Compare L1 vs HLT.