Top Quark Physics

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Outline

- Introduction (Why top is interesting?)
- Basic top production processes and rates
- Latest FNAL RUN2 results. Single top observation
- LHC perspectives
- "New Physics" via top quark
- Conclusions

Top Quark in SM

$Q^t_{em} = +\frac{2}{3} \mid e \mid$

Weak isospin partner of b quark: $T^t_3 = \frac{1}{2}$

Color triplet

spin-$\frac{1}{2}$

$$Q^i_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} c_L \\ s_L \end{pmatrix} \quad \begin{pmatrix} t_L \\ b_L \end{pmatrix}$$

$$u^i_R = u_R \quad c_R \quad t_R$$

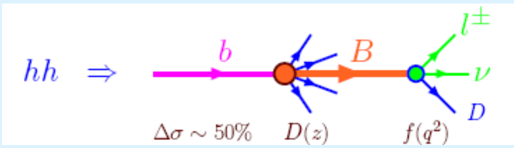
$$d^i_R = d_R \quad s_R \quad b_R$$

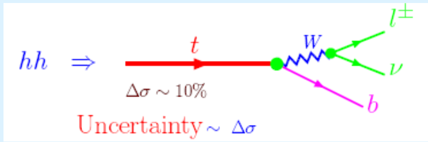
$SU(3)$	$SU(2)$	$U(1)_Y$
3	2	$\frac{1}{6}$
3	1	$\frac{2}{3}$
3	1	$-\frac{1}{3}$

In the Standard Model top quark couplings are uniquely fixed by the principle of gauge invariance, the structure of the quark generations, and a requirement of including the lowest dimension interaction operators.

Top quark is the heaviest elementary particle found so far with a mass slightly less than the mass of the gold nucleus

• Top decays ($\tau_t \sim 5 \times 10^{-25}\ sec$) much faster than a typical time-scale for a formation of the strong bound states ($\tau_{QCD} \sim 3 \times 10^{-24}\ sec$). So, top provides, in principle, a very clean source for a fundamental information.





• Top is so heavy and point like at the same time. One might expect a possible deviations from the SM predictions more likely in the top sector.

• Top Yukawa coupling ($\lambda_t = 2^{3/4} G_F^{1/2} m_t$) is very close to unit. Studies of top may shed a light on an origin of the mechanism of the EW symmetry breaking.

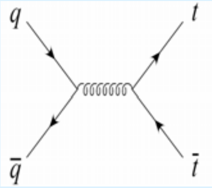
What is a role of the Top quark in nature?

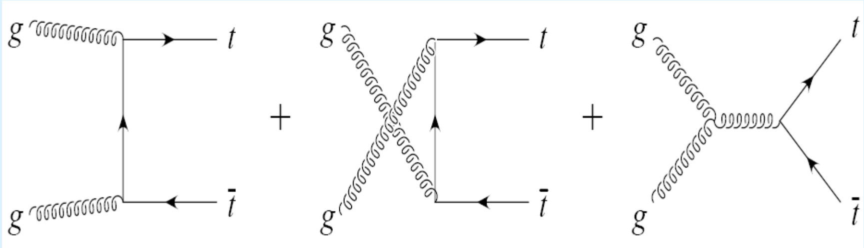
- No top hadrons
- Chiral anomaly cancellation in SM
- MSSM is alive because of heavy Top (light Higgs mass < 135-140 GeV)

$$M_h^{\max} = \sqrt{M_Z^2 + \epsilon} \qquad \epsilon = \frac{3 G_F \overline{m}_t^4}{\sqrt{2}\pi^2 \sin^2\beta}\left[f(t)\right] \qquad t = \log\left(\frac{M_S^2}{m_t^2}\right)$$

At hadron colliders top quarks may be produced either in pairs or singly

Two mechanisms of top pair production:

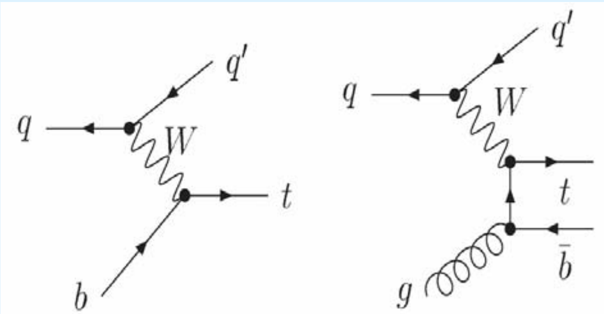




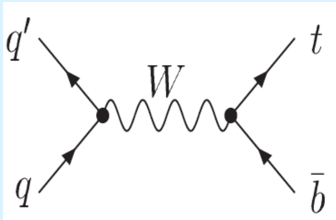
Top pair — strong top–gluon coupling in production and top-W-b coupling in decay

Single top — electroweak top-W-b coupling in production

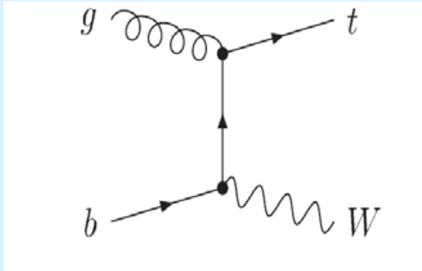
Three mechanisms of single top production:



t-channel



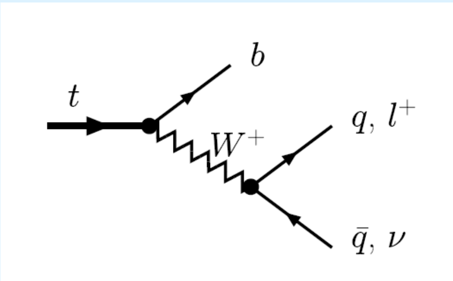
s-channel



Wt associated production

t-channel $(Q_W^2 < 0)$ s-channel $(Q_W^2 > 0)$ associated tW $(Q_W^2 = M_W^2)$

Q_W^2 - W-boson virtuality



In SM top decays to W-boson and b-quark practically with 100% probability

$$\Gamma(t \to bW)_{LO} \simeq 1.53 \text{ GeV}, \quad \Gamma(t \to bW)_{correc} = 1.42 \text{ GeV}$$

Basic top pair production cross sections

	σ_{NLO} (pb)	$q\bar{q} \to t\bar{t}$	$gg \to t\bar{t}$
Tevatron ($\sqrt{s} = 1.8$ TeV $p\bar{p}$)	$4.87 \pm 10\%$	90%	10%
Tevatron ($\sqrt{s} = 2.0$ TeV $p\bar{p}$)	$6.70 \pm 10\%$	85%	15%
LHC ($\sqrt{s} = 14$ TeV pp)	$833 \pm 15\%$	10%	90%

Basic single top production cross sections

	s channel	t channel	Wt	
Tevatron ($\sqrt{s} = 2.0$ TeV $p\bar{p}$)	$0.90 \pm 5\%$	$2.0 \pm 5\%$	$0.1 \pm 10\%$	3 pb
LHC ($\sqrt{s} = 14$ TeV pp)	$10.6 \pm 5\%$	$250 \pm 5\%$	$75 \pm 10\%$	335 pb

The single top rate is about 40% of the top pair rate

Cross sections at $\sqrt{s} = 1.96 TeV$

s-channel (tb)

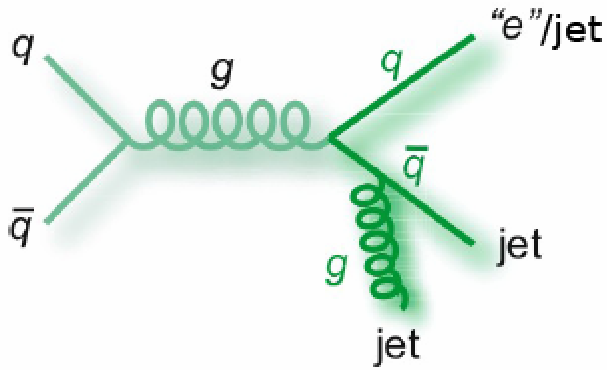
σ_{NLO} = 0.88 ± 0.11 pb

t-channel (tqb)

σ_{NLO} = 1.98 ± 0.25 pb

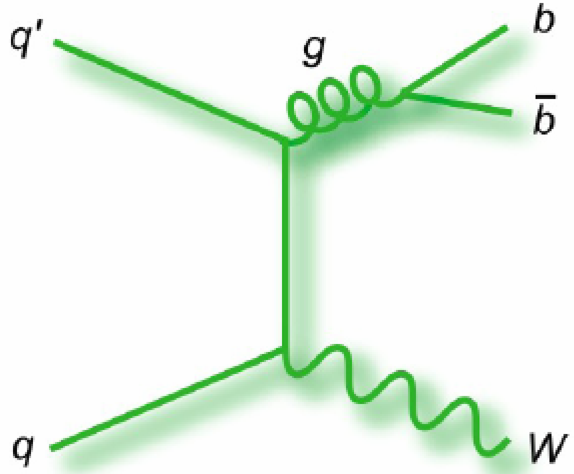
Serious problem (specially for single top) - Backgrounds

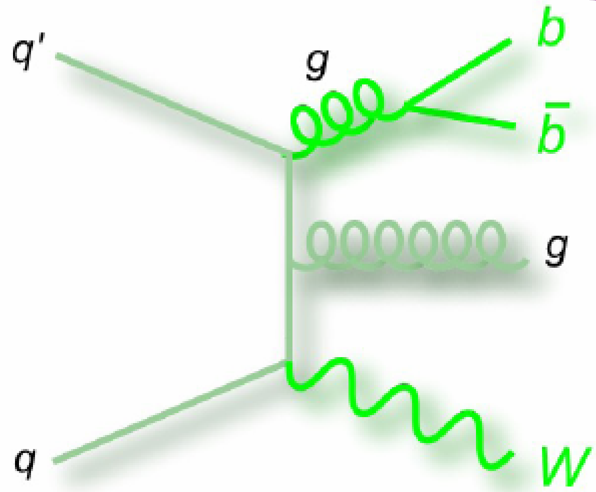
- Multi-jet



From data:
- Orthogonal sample with looser lepton ID
- B-tag jets randomly

- W+jets



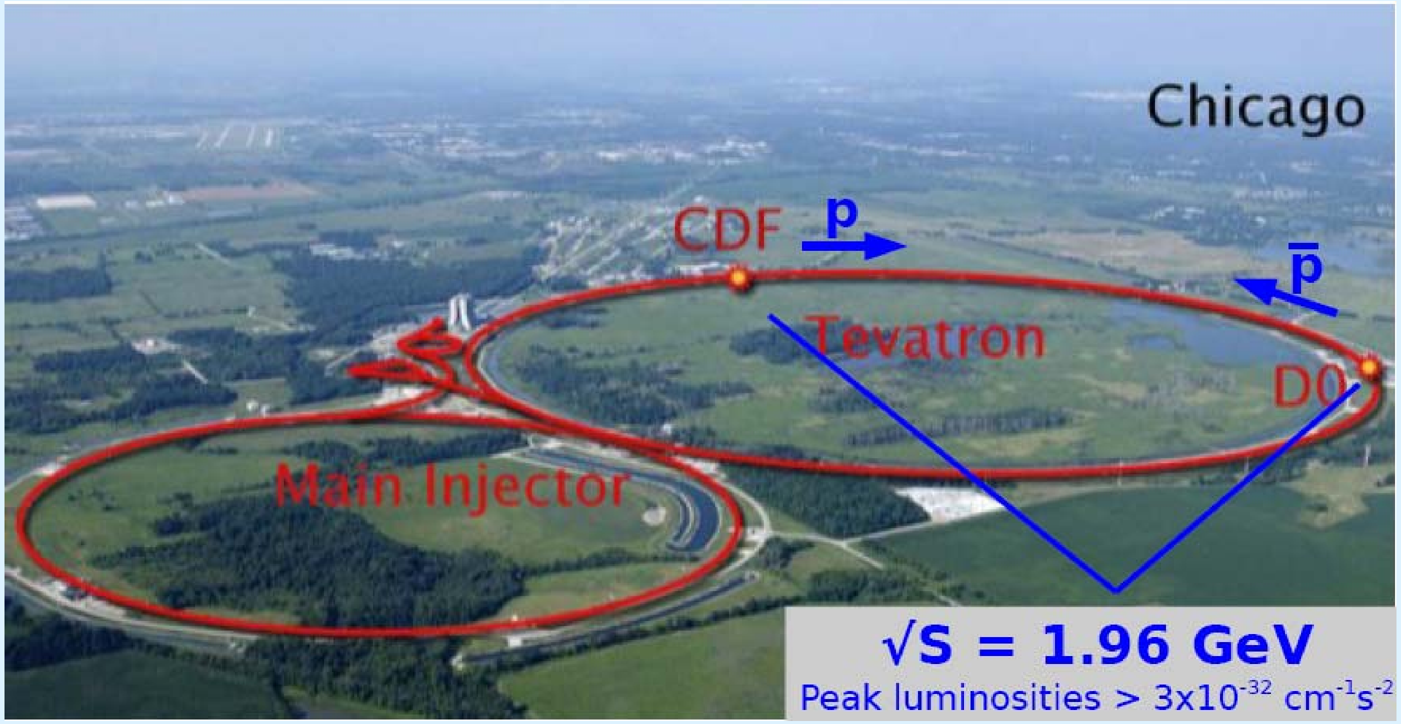


- Z+jets, diboson (WW,ZZ,WZ)
- Top pair is a background to single top!

MC

Top quark discovery in top pair production – 1995

Single top observation (5 sigma effect) – March 2009



Main tasks - studies of Top properties and BSM physics via Top

Single top

- Independent electroweak channel of the top quark production

- Direct |Vtb| CKM matrix element measurement

- Significant background to Higgs and many "new physics" (MSSM) processes

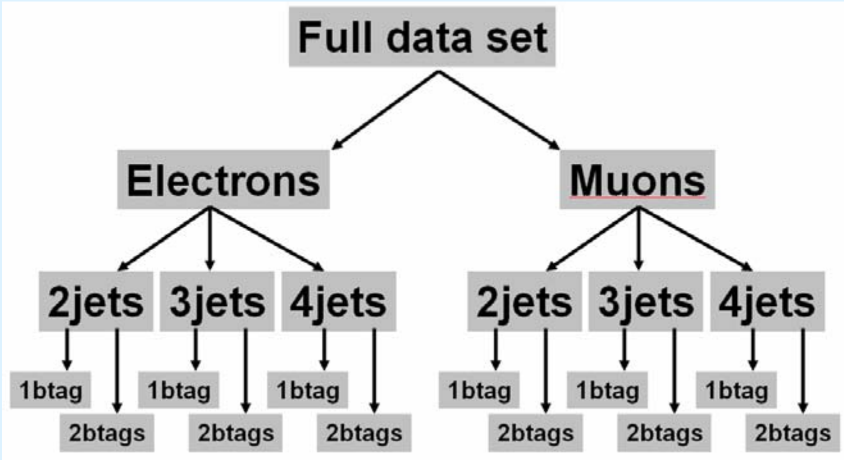
- Unique spin correlation properties

- Process of interest for "New physics"
  - Wtb anomalous couplings
  - FCNC
  - Searches for W' (e.g. Kaluza-Klein excitation of W-boson)
  - Searches for new strong dynamics (π_T, ρ_T)
  - …
- New delicate analysis techniques to extract small signals

Single top phenomenology:

Willenbrock, Dicus; Yuan; Cortese, Petronzio; Jikia, Slabospitsky; Ellis, Parke; Kane, Ladinsky, Yuan; Heinson, Belyaev,Boos; Stelzer, Willenbrock; Tait, Yuan; Belyaev, Boos, Dudko; Stelzer, Sullivan, Willenbrock; Boos, Dudko, Ohl; Tait, Yuan; Beccaria, Macorini, Renard, Verzegnassi; Cao, Wudka, Yuan.....

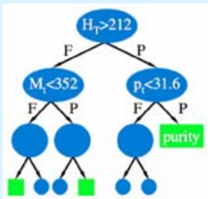
Multivariate Analysis Strategy



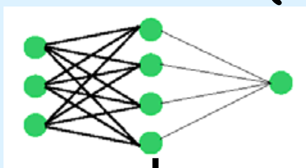
12 channels

Discriminating signal/background variables

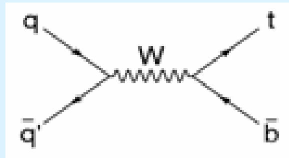
Boosted Decision Trees



Nueral Network (Bayes)



Matrix Element



single discriminant

Binned likelihood: Cross Section

Pseudo-data ("ensembles"): Signficance

Method of Optimal Variables

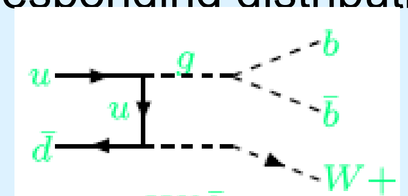
Boos, Dudko; Boos, Dudko, Ohl

- *Provides a general receipt how to choose most effective variables to separate Signal/Backgrounds*
- *Based on analysis of Feynman diagrams which contribute to the Signal and Backgrounds*

Three Classes of Variables

-**"Singular" Variables** (denominators of Feynman diagrams)

Most of the rates of signal and background processes come from the integration over the phase space region close to the singularities. If some of the singular variables are different or the positions of the singularities are different the corresponding distributions will differ most strongly



M_{bb} , P_{bb}

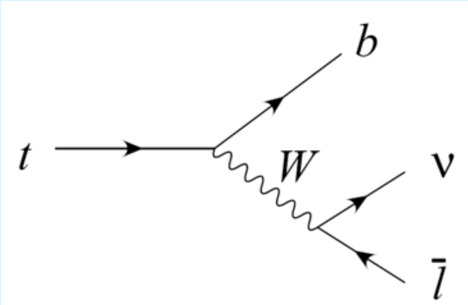
- **"Angular" Variables** (numerators of Feynman diagrar $\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_{ql}} = \frac{1+P\cos\theta^*_{ql}}{2}$

- "Threshold" Variables

s-hat and Ht variables relate to the fact that various signal and background processes may have very different energy thresholds

Spin correlations in single top

V-A vertex structure in SM



$$d\Gamma \sim |\mathcal{M}|^2 \sim (t + ms) \cdot \ell b \cdot \nu$$

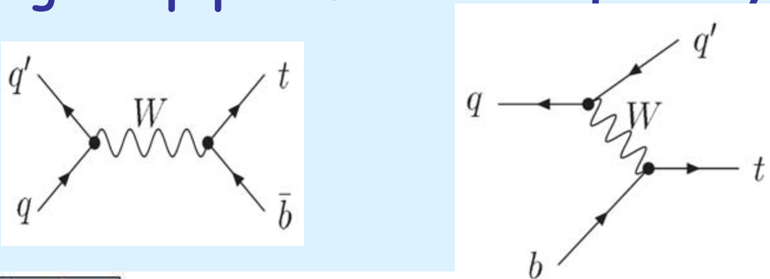
where in the top-quark rest frame, the spin four-vector $s = (0, \hat{s})$ is a unity $\hat{s}$ vector that defines the spin quantization axis of the top quark. In the top quark rest frame:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{1}{2}(1 + \cos\theta_\ell)$$

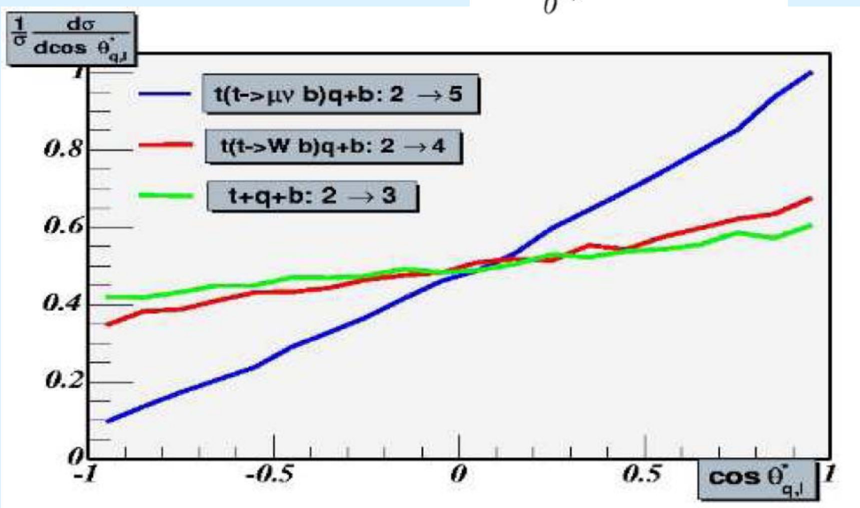
Hence the charged lepton tends to point along the direction of top spin

Single top production as top decay back in time

Mahlon, Parke; Boos, Sherstnev



Down-type component of weak isospin doublet - d-quark In production plays a role of lepton In decay



t-channel production

Best spin correlation variable – the angle between the lepton from W-decay and momentum of outgoing light jet in the top-quark rest frame. Polarization

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_{ql}} = \frac{1 + P\cos\theta^*_{ql}}{2}$$

$$P_{top} \approx 90\ \%$$

Problems and requirements for a generator for the single top signal:

- Double counting and negative weights
- Matching of various contributions at the generator level. One should have the correct NLO rate and correct shapes of the NLO distributions
- Matching to showering programs
- Correct spin correlations
- Finite top and W widths
- Separation Top and antiTop since the rates are different (for the LHC)
- Anomalous Wtb and FCNC couplings

Generators: MADGRAPH, TopRex, MC@NLO, ONETOP

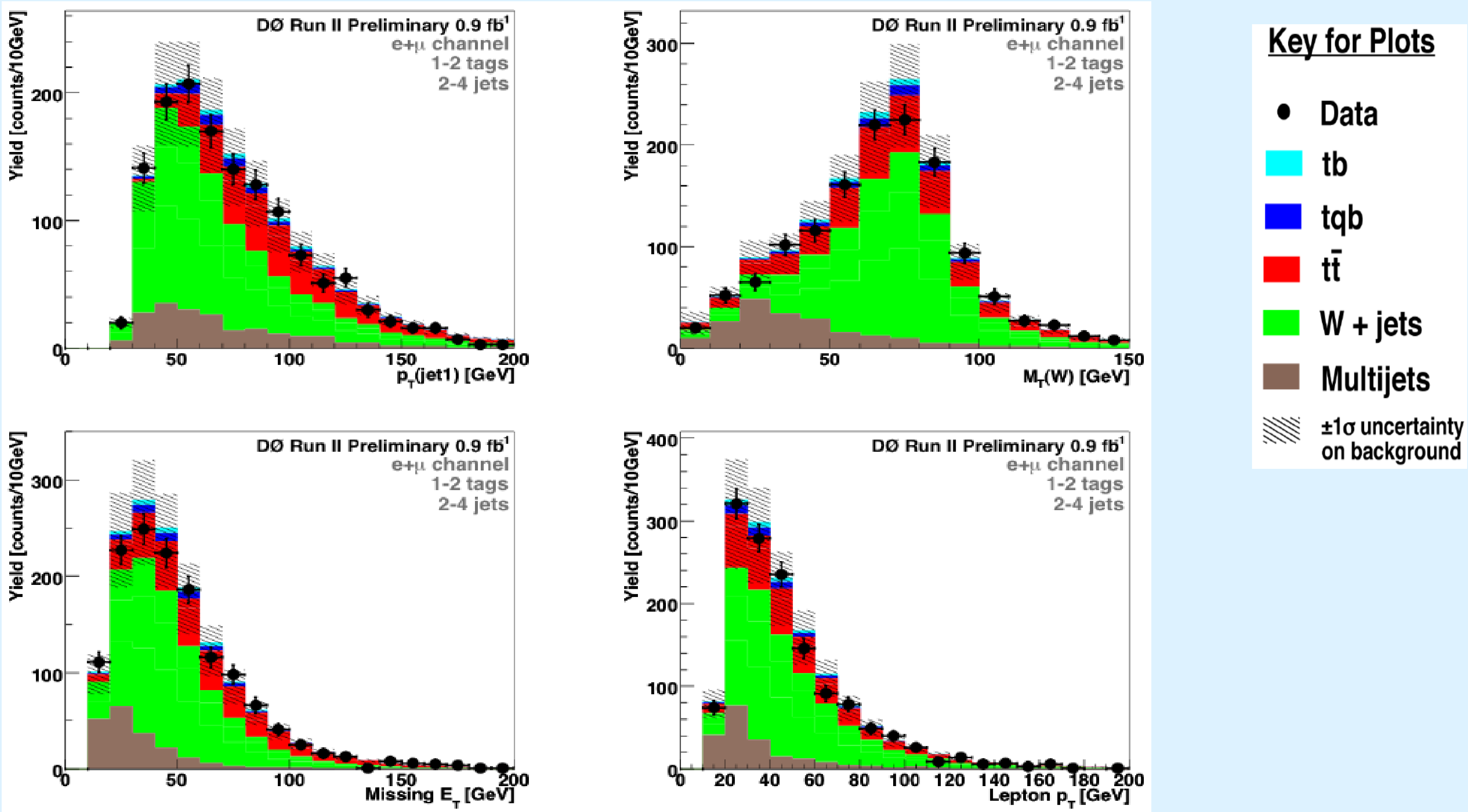
Stelzer, Maltoni (MADGRAPH); Slabospitsky (TopRex); Frixione, Webber (MC@NLO); C.-P.Yuan (ONETOP)

In D0 analysis:

SingleTop – NLO generator based on CompHEP

Boos, Bunichev, Dudko, Savrin, Sherstnev

Kinematic distributions of D0 data and MC events after preliminary selection



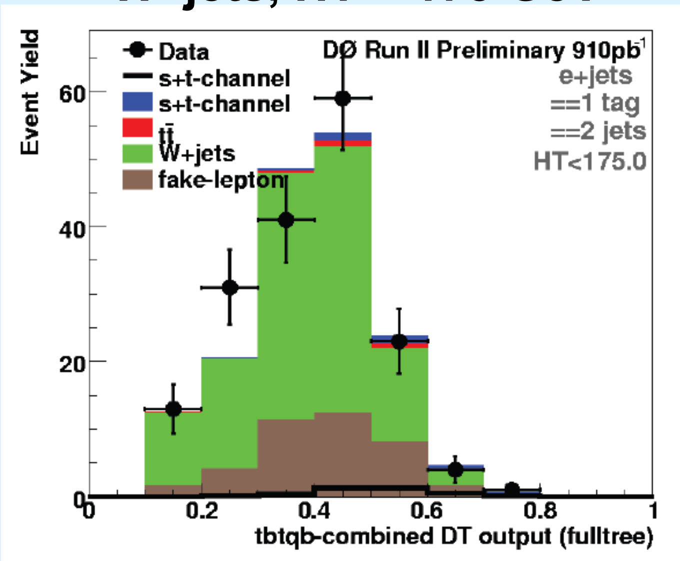
MC model of data works well

Single top signal smaller than total background uncertainty

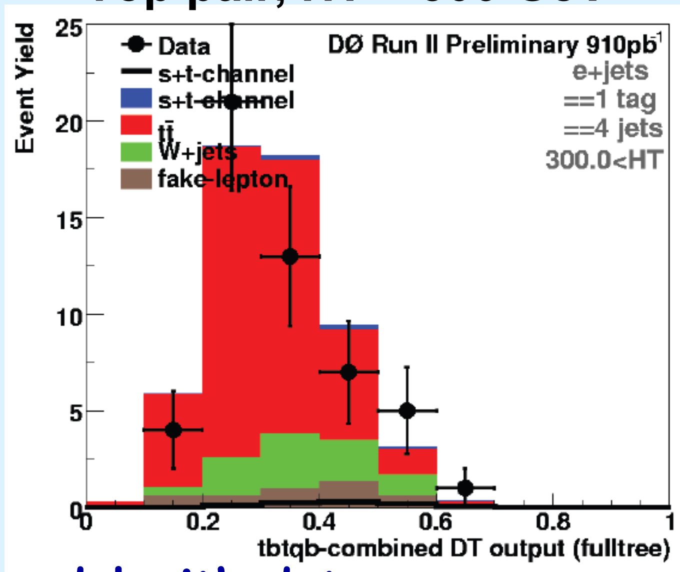
Counting experiment hopeless!!

Cross check examples

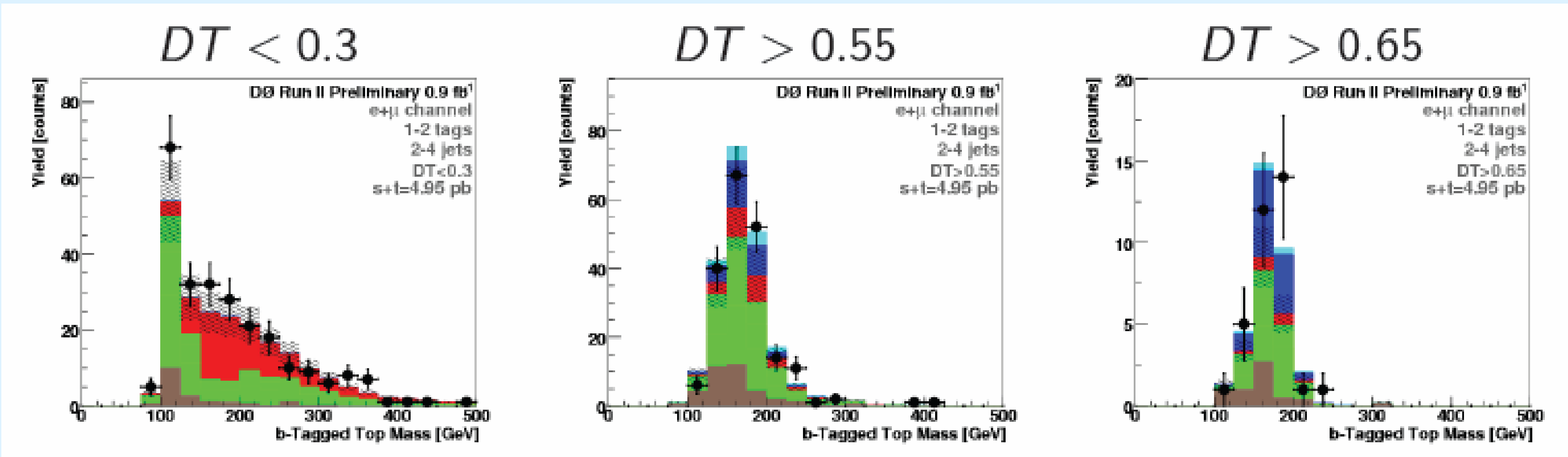
W+jets, HT < 175 GeV



Top pair, HT > 300 GeV

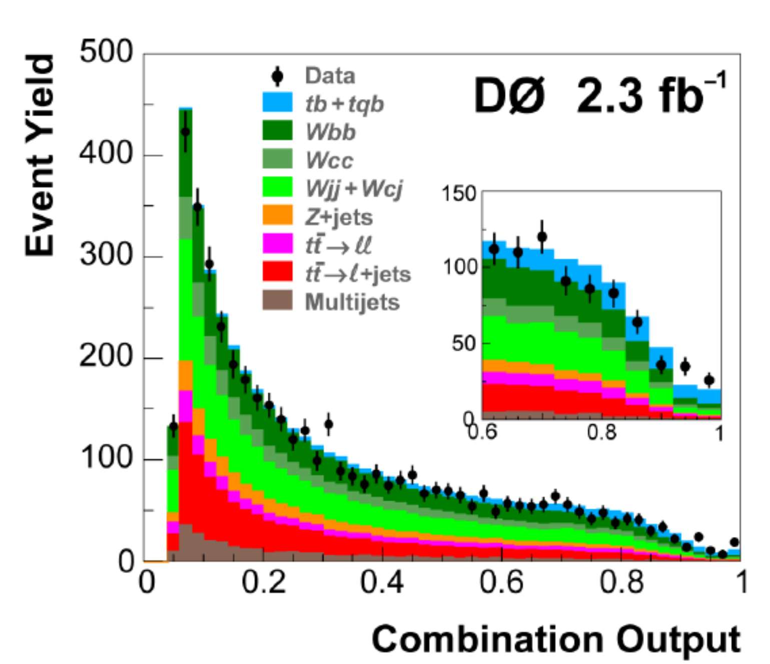


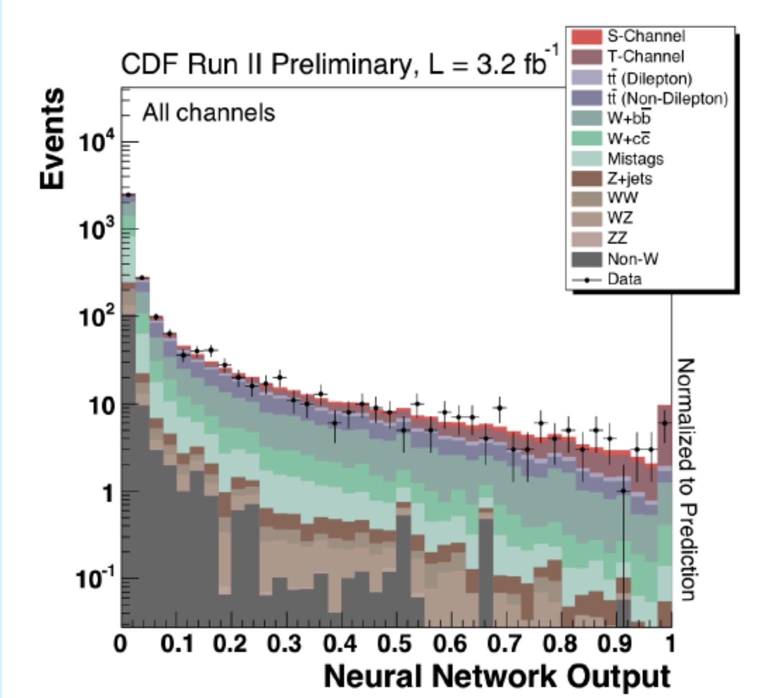
Good agreement of MC model with data



Excess in high DT output region

Tevatron observation





Combined Results

	$\mathcal{L}$ [fb^{-1}]	Significance Exp.	Obs.	σ_{s+t} [pb]
DØ	2.3	4.5σ	5.0σ	$3.9^{+0.9}_{-0.9}$
CDF	3.2	5.9σ	5.0σ	$2.3^{+0.6}_{-0.5}$

First direct measurement of $|V_{tb}|$

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

$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$

If CKM unitarity and 3 generations are assumed: $V_{tb} = 0.999100^{+0.000034}_{-0.000004}$

Without the 3-generation unitarity constrain $|V_{tb}|$ is left practically unconstrained:

$|V_{tb}| = 0.07 \div 0.9993$

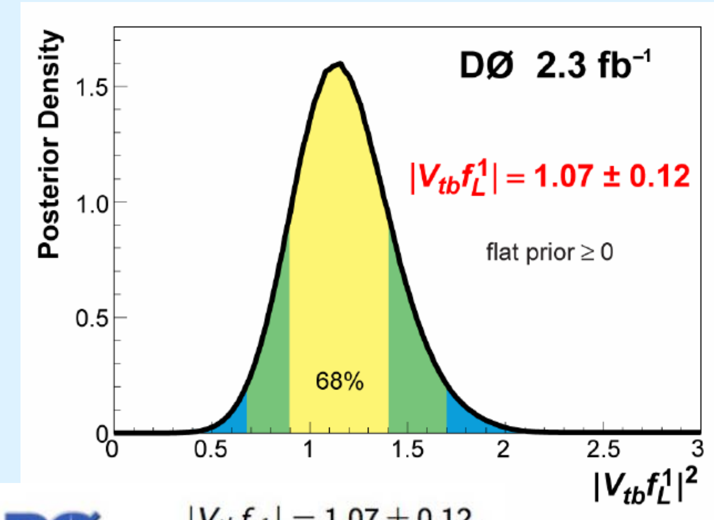
$$\sigma \sim |V_{tb} f_1^L|^2 \quad \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2 + (Exotics)}$$

→

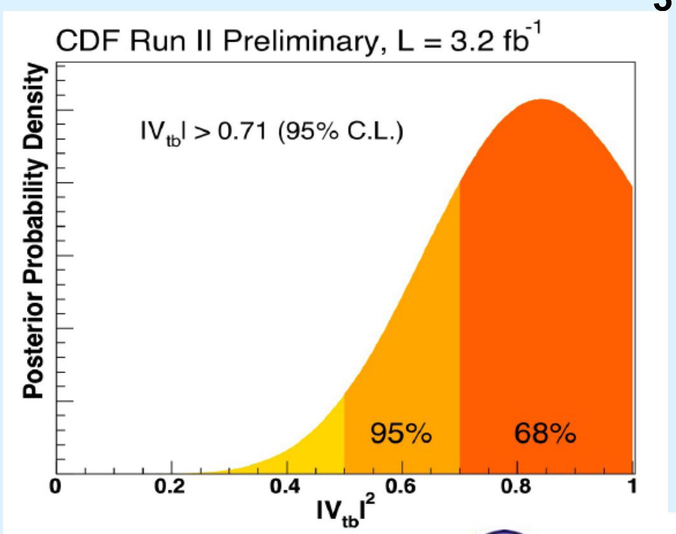
Assumptions:

* V-A interaction
* $|V_{tb}|^2 >> |V_{ts}|^2 + |V_{td}|^2 + (Exotics)$

No assumptions on: **CKM unitarity and 3 generations**



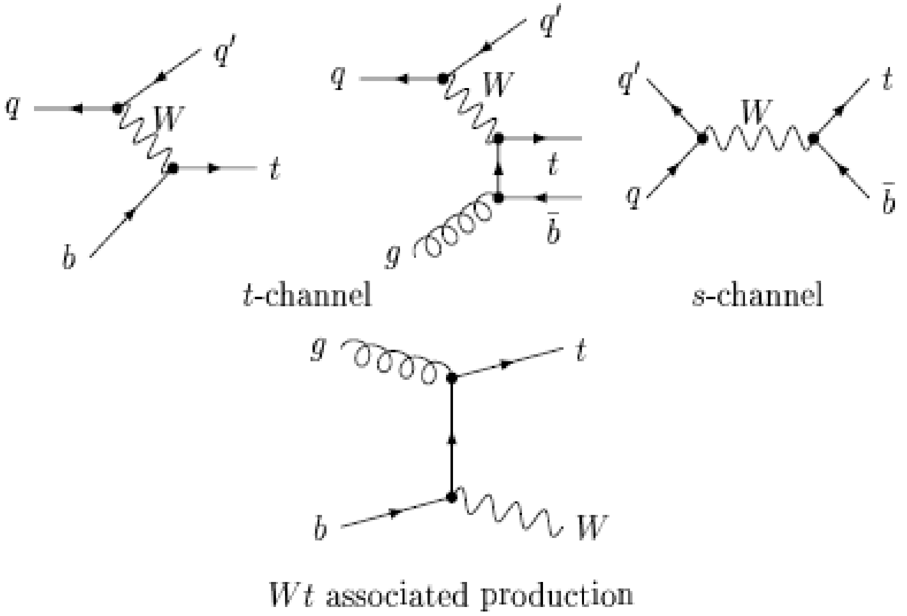
$|V_{tb} f_{L1}| = 1.07 \pm 0.12$,
$|V_{tb}| > 0.78$ at 95% CL



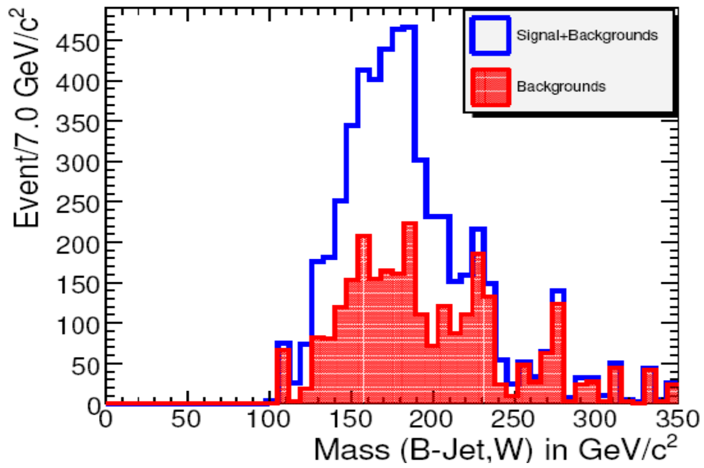
$|V_{tb}| = 0.91 \pm 0.11$,
$|V_{tb}| > 0.71$ at 95% CL

$|V_{tb}|$ measurements

At LHC and Tevatron Run2 via single top



Reconstracted single top at CMS

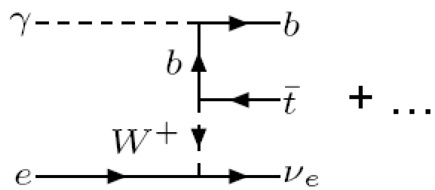


V_{tb}^2 could be measured with an accuracy of 10% dominated by systematics

(10% - Tevatron, 7-8% - LHC)

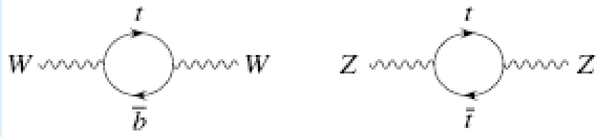
At ILC (1 TeV, 500 fb^{-1}) in $e\gamma$ collisions -

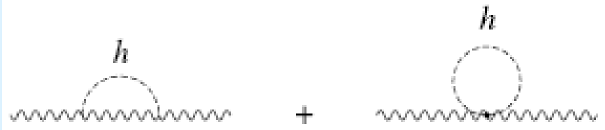
2-3 % accuracy dominated by statistics



Why do we need precise measurement of the Top mass?

In SM W-boson, Top quark and H boson masses are connected to each other via loop contributions to W and Z propagators





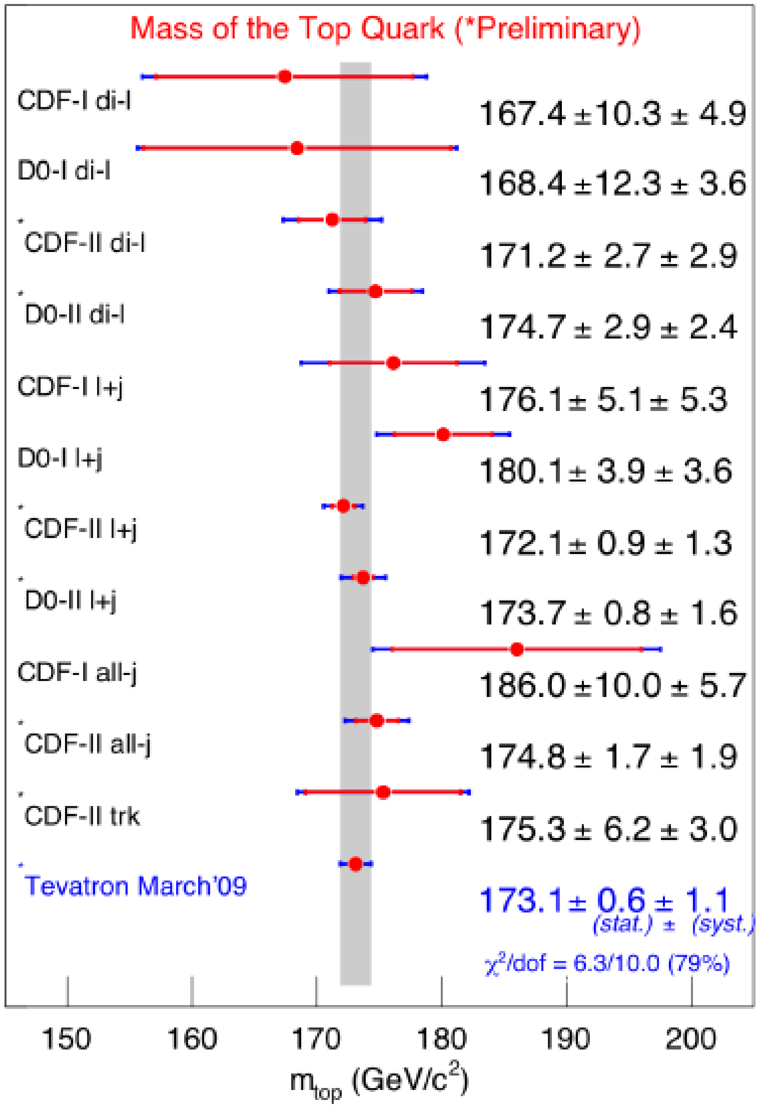
$M_W^2 = \frac{\frac{\pi\alpha}{\sqrt{2}G_F}}{s_W^2(1-\Delta r)}$ where Δr contains the one-loop corrections.

$(\Delta r)_{\rm top} \approx -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2}\frac{1}{t_W^2}$ where $t_W^2 \equiv \tan^2\theta_W$.

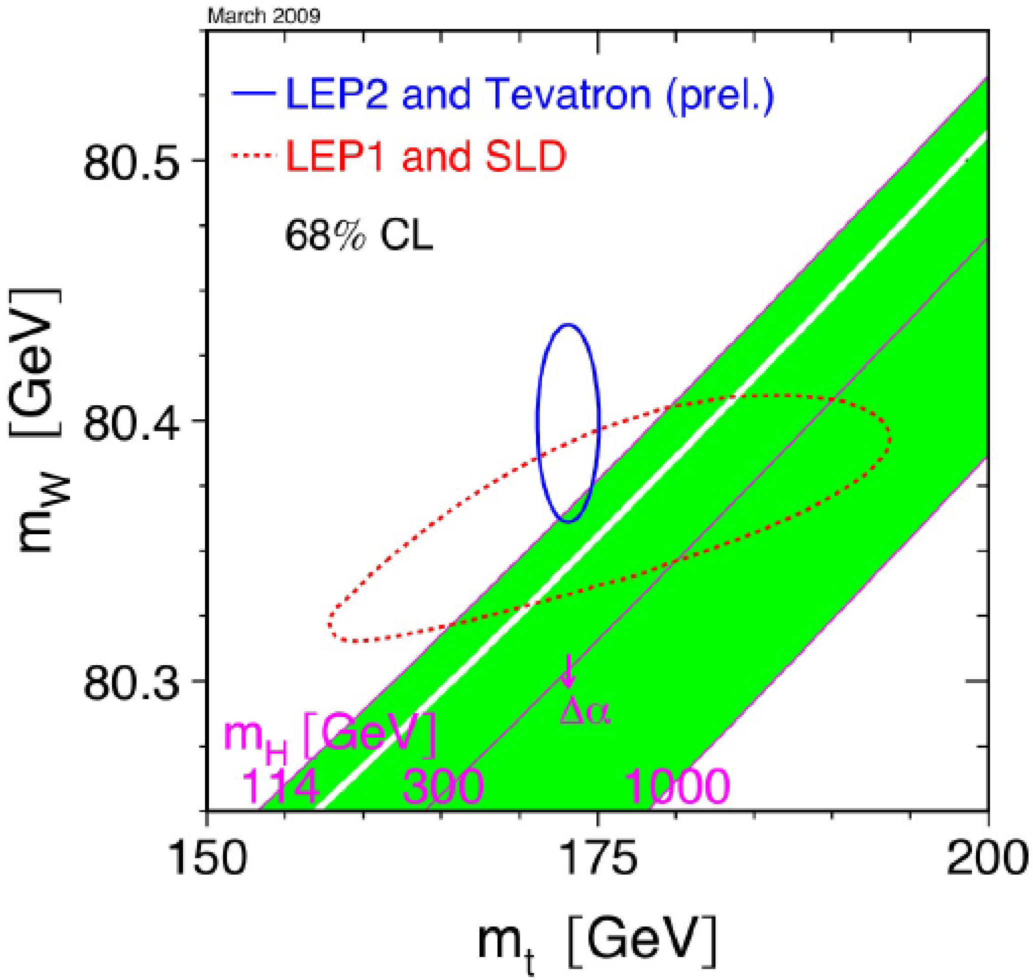
This one-loop correction depends quadratically on the top-quark mass.

$(\Delta r)_{\rm Higgs} \approx \frac{11 G_F M_Z^2 c_W^2}{24\sqrt{2}\pi^2} \ln\frac{m_h^2}{M_Z^2}$

This one-loop correction depends only logarithmically on the Higgs-boson mass, so Δr is not as sensitive to m_h as it is to m_t.

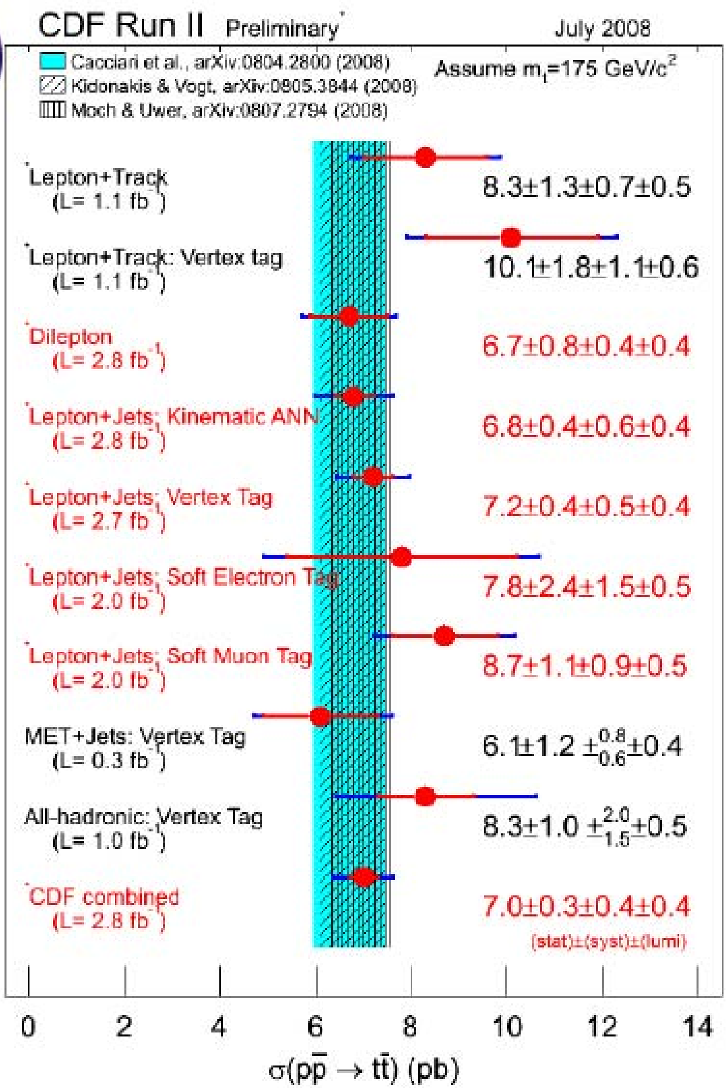


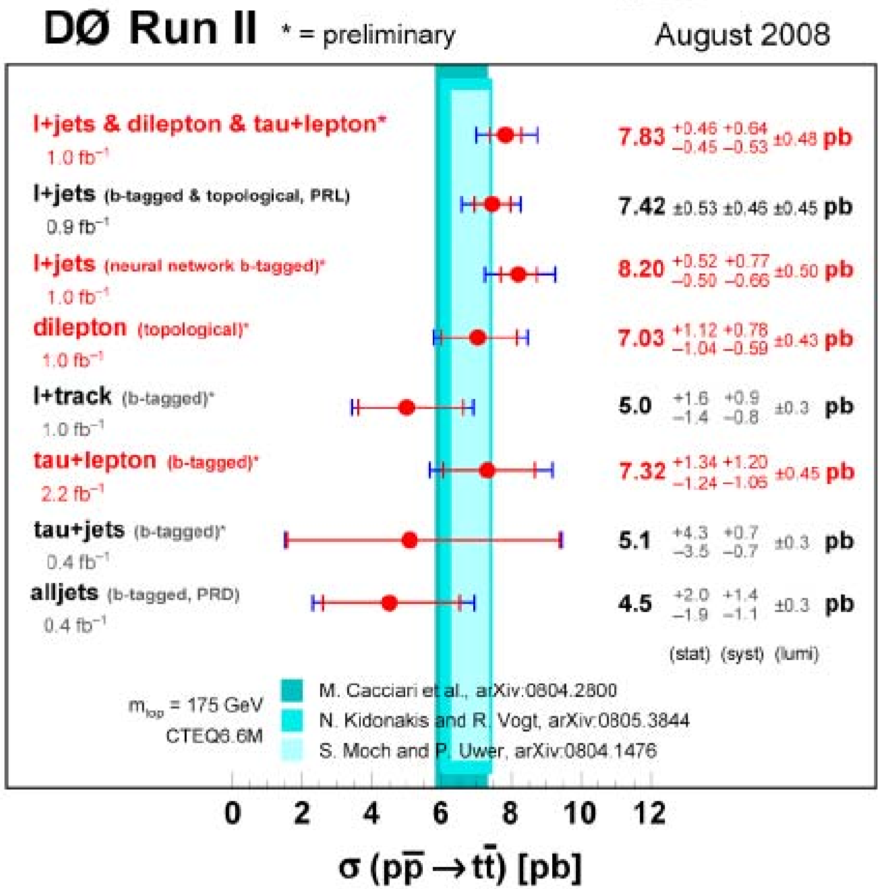
Mass of the Top Quark (*Preliminary)
CDF-I di-l
167.4 ±10.3 ± 4.9
D0-I di-l
168.4 ±12.3 ± 3.6
CDF-II di-l
171.2 ± 2.7 ± 2.9
D0-II di-l
174.7 ± 2.9 ± 2.4
CDF-I l+j
176.1± 5.1± 5.3
D0-I l+j
180.1± 3.9 ± 3.6
CDF-II l+j
172.1± 0.9 ± 1.3
D0-II l+j
173.7 ± 0.8 ± 1.6
CDF-I all-j
186.0 ±10.0 ± 5.7
CDF-II all-j
174.8 ± 1.7 ± 1.9
CDF-II trk
175.3 ± 6.2 ± 3.0
Tevatron March'09
173.1± 0.6 ± 1.1
(stat.) ± (syst.)
χ²/dof = 6.3/10.0 (79%)
150 160 170 180 190 200
m_top (GeV/c²)



March 2009
LEP2 and Tevatron (prel.)
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
Δα
m_H [GeV]
114 300 1000
150 175 200
m_t [GeV]

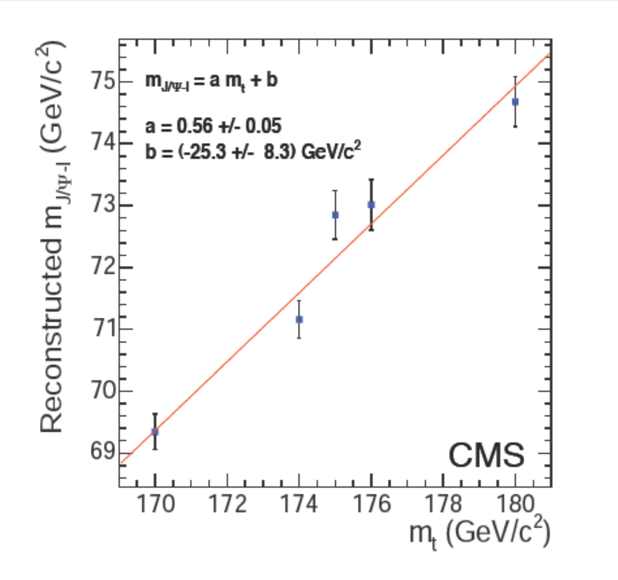
Top pair cross section measurement to be compare to precise computations



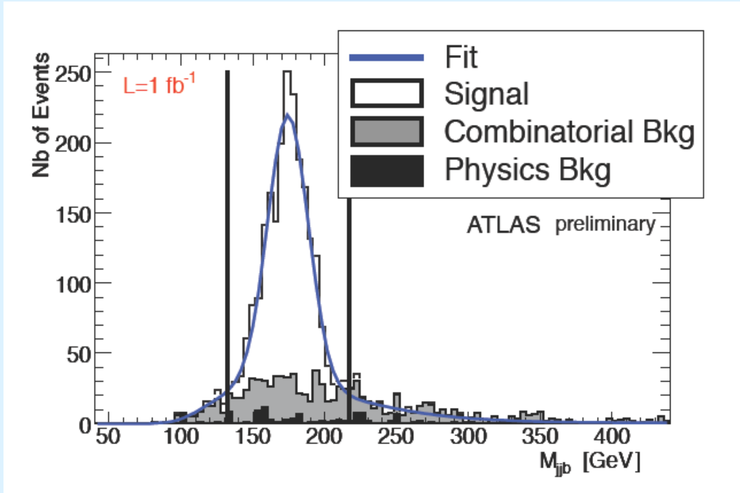


LHC is a real Top factory

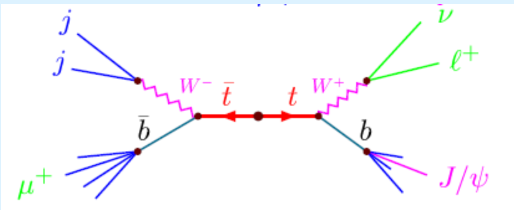
for $\mathcal{L} = 1\ \mathrm{fb}^{-1}$ we will have 8×10^5 $t\bar{t}$-pairs and 2.5×10^5 single tops



Correlation in J/Ψ + lepton mode



Reconstructed top mass in semileptonic mode



CMS analysis for the top mass (ATLAS similar)

$\mathcal{L} = 1\ \mathrm{fb}^{-1}$

$$\Delta M_t(\text{di-leptonic}) = \pm 1.5(\text{stat}) \pm 2.9(\text{syst})\ \text{GeV}$$
$$\Delta M_t(\text{semi-leptonic}) = \pm 0.7(\text{stat}) \pm 1.9(\text{syst})\ \text{GeV}$$
$$\Delta M_t(\text{fully hadronic}) = \pm 0.6(\text{stat}) \pm 4.2(\text{syst})\ \text{GeV}$$

$\mathcal{L} = 10\ \mathrm{fb}^{-1}$

$$\Delta M_t(\text{di-leptonic}) = \pm 0.5(\text{stat}) \pm 1.1(\text{syst})\ \text{GeV}$$
$$\Delta M_t(\text{semi-leptonic}) = \pm 0.2(\text{stat}) \pm 1.1(\text{syst})\ \text{GeV}$$

$\mathcal{L} = 20\ \mathrm{fb}^{-1}$

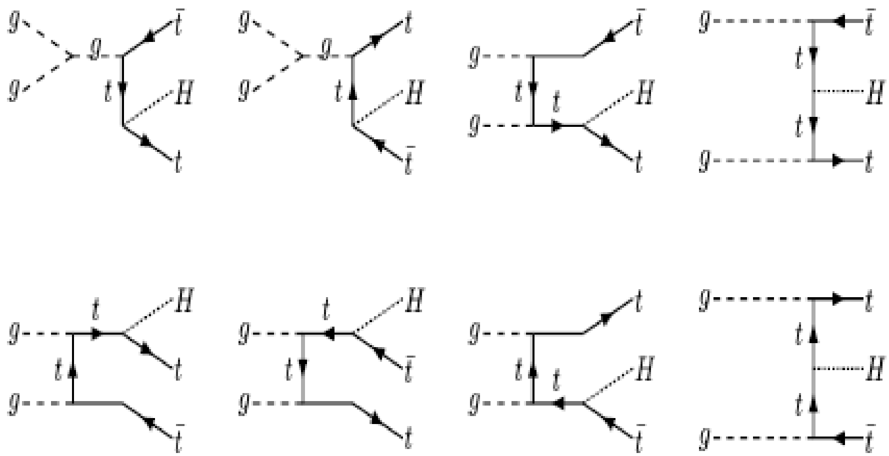
$$\Delta M_t(J/\Psi) = \pm 1.2(\text{stat}) \pm 1.5(\text{syst})\ \text{GeV}$$

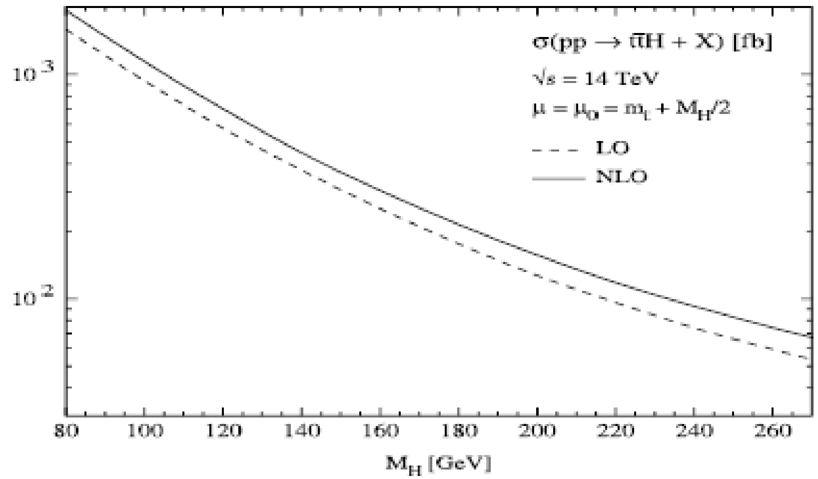
Top Yukawa coupling $t\bar{t}H$ measurements

For the LHC complete NLO computations have been performed

(LO diagrams are shown)

W. Beenakker et al. S.Dawson et al.





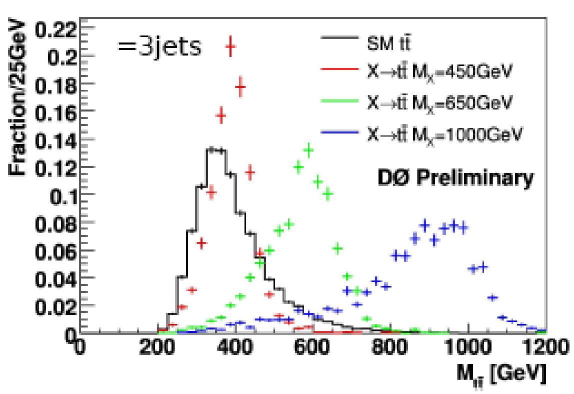
Top Yukawa could be measured with an accuracy from 16% at low Lumi to 11% at high Lumi regime

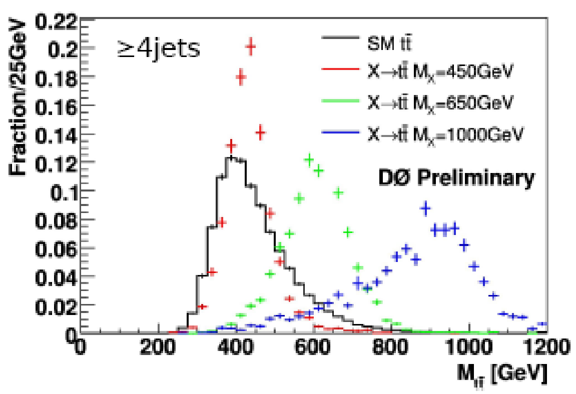
New Physics via Top

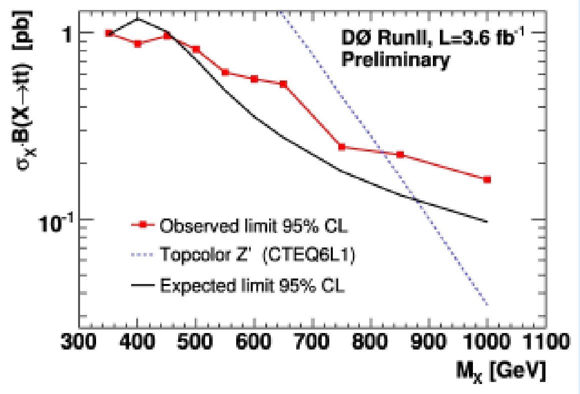
- New Particles
  - new resonances (KK states, W',Z', π_T, $\rho_{T\ ...}$)
  - charged Higgs
  - stop, sbottom, heavy T or B decaying to top

- New/anomalous interactions
  - Wtb anomalous couplings
  - FCNC
  - SUSY contributions

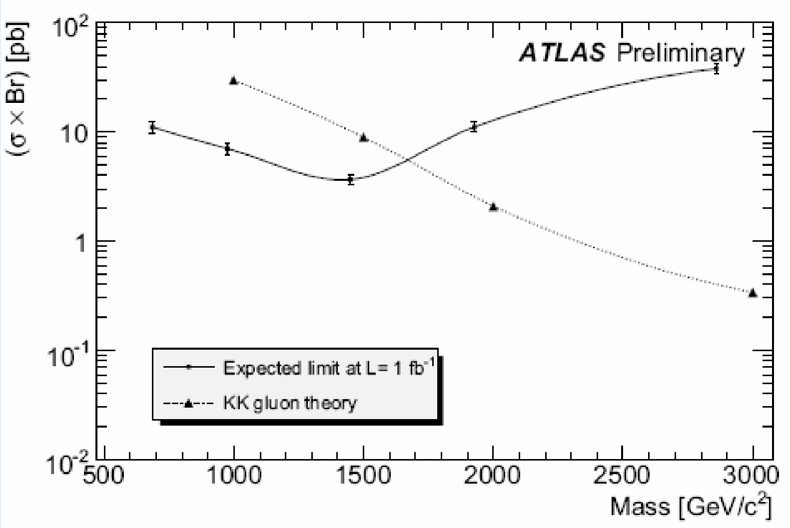
Resonances in top pair production





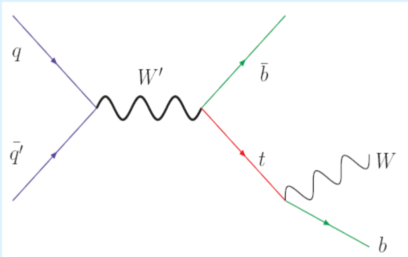


D0 limits based on 3.6 fb^{-1}: $M_{Z'}$ > 760 GeV at 95 % CL

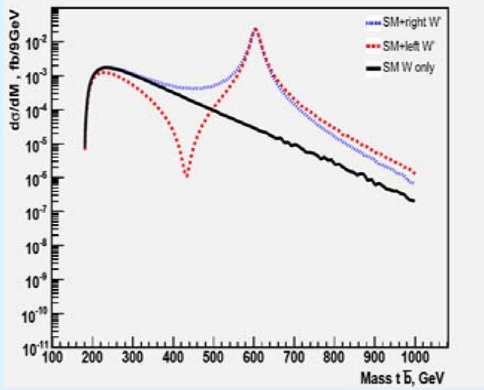


Kaluza-Klein gluon resonances can be excluded up to 1.5 TeV with 1 fb^{-1}

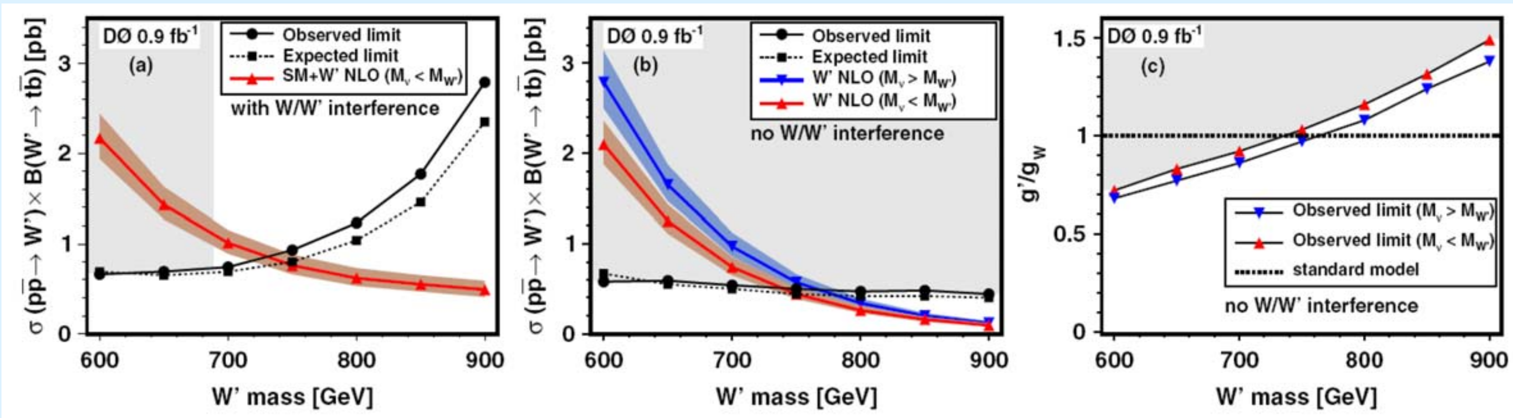
D0 searches for W’ resonance in single top



Boos, Bunichev, Dudko, Perfilov



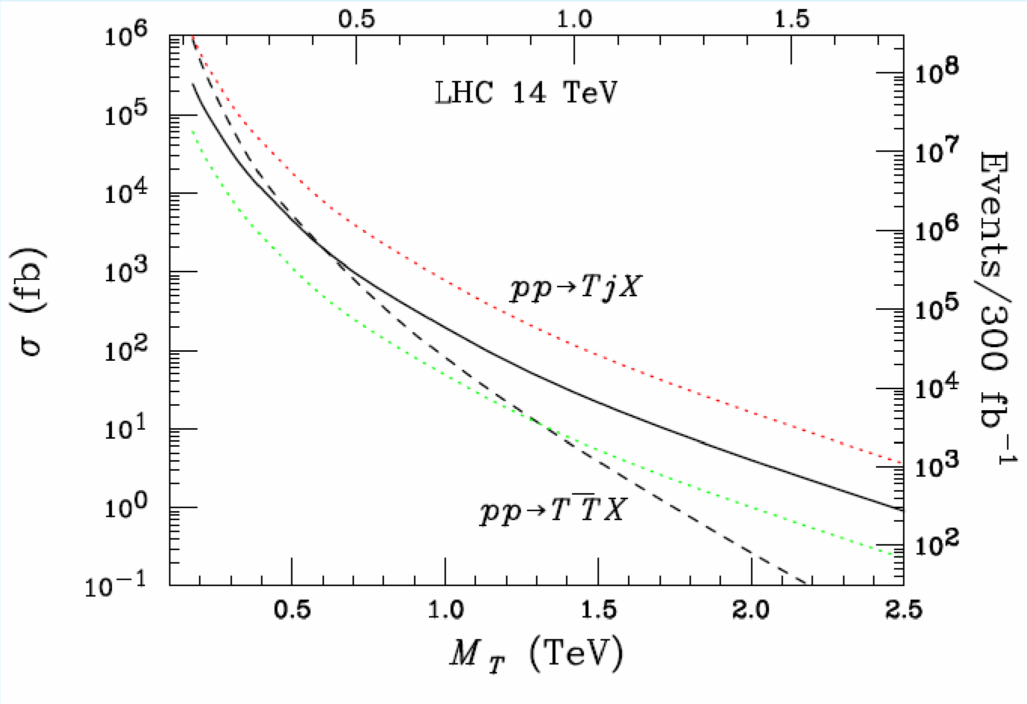
Negative interference



Tevatron Limits on W' boson mass (900 pb^{-1}): MW’ > 710 (730-770) GeV L(R)

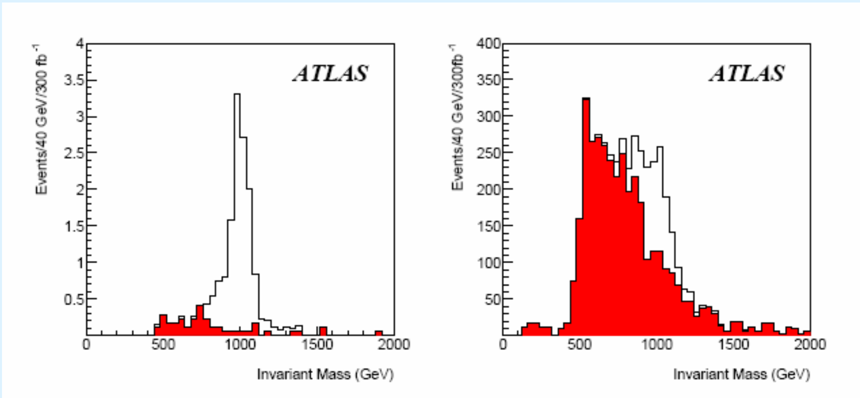
Expected LHC limits: 2-3 TeV (Detail CMS study in progress)

Production of top quark partner T predicted in many BSM in accord with “naturalness” argument to cancel quadratic scale dependence in loops (stop, Little Higgs Top, KK top mode…)

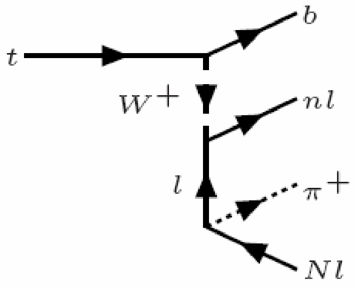


Single fermion T for various couplings (dominates for heavy T) and TT pair

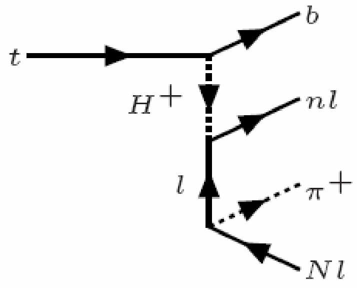
ATLAS simulation for T->tZ and T->Wb decay modes



Charged Higgs in Top Decay (impact of tau polarization)



diagr.1



diagr.2

In the rest frame of top $t \to bR \to b\tau\nu_\tau \to b\nu_\tau\bar{\nu}_\tau\pi$

where a resonance R is W boson or charged H

$$\frac{1}{\Gamma}\frac{d\Gamma}{dy_\pi} = \frac{1}{x_{max}-x_{min}}$$

$$\begin{cases} (1-P_\tau)log\frac{x_{max}}{x_{min}} + 2P_\tau y_\pi(\frac{1}{x_{min}} - \frac{1}{x_{max}}), & 0 < y_\pi < x_{min} \\ (1-P_\tau)log\frac{x_{max}}{y_\pi} + 2P_\tau(1-\frac{y_\pi}{x_{max}}), & x_{min} < y_\pi \end{cases}$$

where $y_\pi = \frac{E_\pi^{top}}{M_{top}}$, $\quad x_{min} = \frac{E_\tau^{min}}{M_{top}}$, $\quad x_{max} = \frac{E_\tau^{max}}{M_{top}}$, $\quad E_\tau^{min} = \frac{M_R^2}{2M_{top}}$, $\quad E_\tau^{max} = \frac{M_{top}}{2}$

$P_\tau = -1$ for W boson and $P_\tau = 1$ for charged Higgs

(M.Nojiri; E.B.,G.Moortgat-Pick, M.Sachwitz, A.Sherstnev, P.Zerwas;
E.B., S.Bunichev, M.Carena, C.Wagner)

$e^+e^- \rightarrow t\bar{t} \rightarrow \tau\nu_\tau b\bar{b} + 2jets$

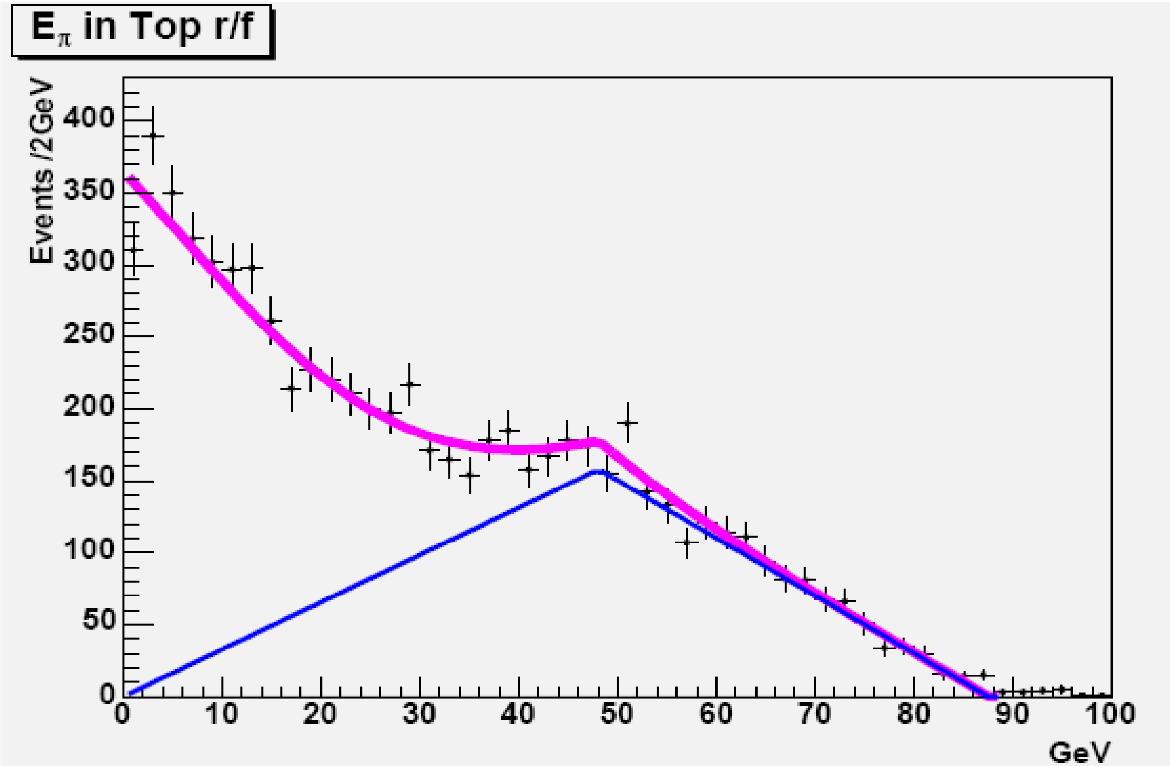
Simulations are performed for e^+e^- collisions at 500 GeV cms and for 500 fb^{-1} integrated luminosity

π-meson energy spectrum for the MSSM point
$\tan\beta = 50$, $\mu = 500$, $M_{H^\pm} = 130\ GeV$ with $Br(t \rightarrow H^+b) = 9.1\%$

E.B., S.Bunichev, M.Carena, C.Wagner

One of the most precise way to measure charged Higgs mass:

$M_{H^\pm}$ = 129.4 +/- 0.9 GeV



Anomalous Top Couplings

The top quark interactions of dimension 4:

$$\mathcal{L}_4 = -g_s \bar{t}\gamma^\mu T^a t G^a_\mu - \frac{g}{\sqrt{2}} \sum_{q=d,s,b} \bar{t}\gamma^\mu (v^W_{tq} - a^W_{tq}\gamma_5) q W^+_\mu$$
$$-\frac{2}{3} e \bar{t}\gamma^\mu t A_\mu - \frac{g}{2\cos\theta_W} \sum_{q=u,c,t} \bar{t}\gamma^\mu (v^Z_{tq} - a^Z_{tq}\gamma_5) q Z_\mu$$

The dimension 5 couplings have the generic form:

$$\mathcal{L}_5 = -g_s \sum_{q=u,c,t} \frac{\kappa^g_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} T^a (f^g_{tq} + i h^g_{tq}\gamma_5) q G^a_{\mu\nu} - \frac{g}{\sqrt{2}} \sum_{q=d,s,b} \frac{\kappa^W_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} (f^W_{tq} + i h^W_{tq}\gamma_5) q W^+_{\mu\nu}$$
$$-e \sum_{q=u,c,t} \frac{\kappa^\gamma_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} (f^\gamma_{tq} + i h^\gamma_{tq}\gamma_5) q A_{\mu\nu} - \frac{g}{2\cos\theta_W} \sum_{q=u,c,t} \frac{\kappa^Z_{tq}}{\Lambda} \bar{t}\sigma^{\mu\nu} (f^Z_{tq} + i h^Z_{tq}\gamma_5) q Z_{\mu\nu}$$

Present constrains come from

- Low energy data via loop contributions
  $K_L \to \mu^+\mu^-$, $K_L - K_S$ mass difference, $b \to l^+ l^- X$, $b \to s\gamma$
- LEP2
- Tevatron Run1,2
- HERA
- Unitarity violation bounds

Anomalous Wtb Couplings

- Lagrangian

$$\mathcal{L} = \frac{g}{\sqrt{2}} V_{tb} \left[W_\nu^- \bar{b} \gamma_\mu P_- t - \frac{1}{2M_W} W_{\mu\nu}^- \bar{b} \sigma^{\mu\nu} (F_2^L P_- + F_2^R P_+) t \right] + h.c.$$

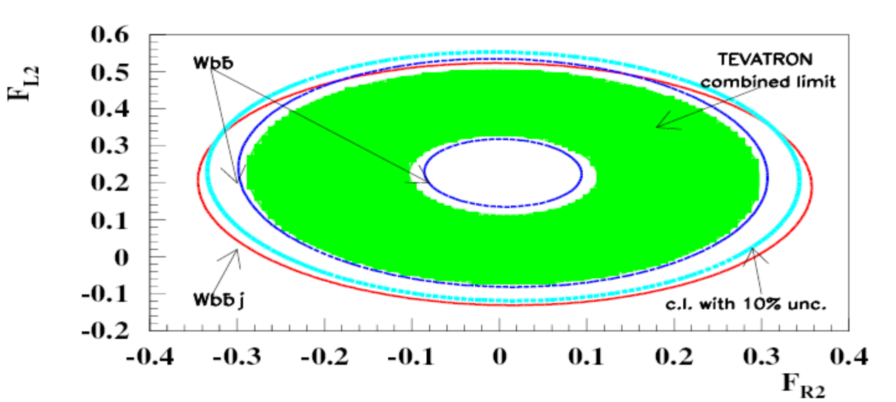
  with $W_{\mu\nu}^\pm = D_\mu W_\nu^\pm - D_\nu W_\mu^\pm$, $D_\mu = \partial_\mu - ieA_\mu$, $\sigma^{\mu\nu} = i/2[\gamma_\mu, \gamma_\nu]$ and $P_\pm = (1 \pm \gamma_5)/2$. The couplings F_2^L and F_2^R are proportional to the coefficients of the effective Lagrangian
  $F_{L2} = \frac{2M_W}{\Lambda} \kappa_{tb}^W (-f_{tb}^W - ih_{tb}^W)$,
  $F_{R2} = \frac{2M_W}{\Lambda} \kappa_{tb}^W (-f_{tb}^W + ih_{tb}^W)$, $|F_{L2,R2}| < 0.6$ from unitary bounds

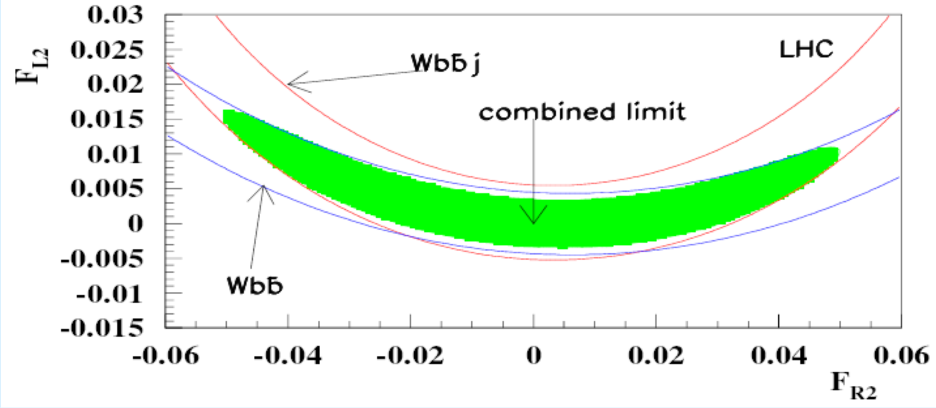
- $|V_{tb}|$ is very close to 1 in SM with 3 generations. ($|V_{tb}|$ is very weakly constrained in case of 4 generations, e.g.)

- A possible $V + A$ form factor is severely constrained by the CLEO $b \to s\gamma$ data to 3×10^{-3} level

Expectations for Wtb anomalous couplings for the Tevatron and LHC

E.B., L.Dudko, T.Ohl





D0 limits based on 900 pb[-1] data

Scenario	Cross Section	Coupling
(L_1, L_2)	$4.4^{+2.3}_{-2.5}$ pb	$\|V_{tb} f_1^L\|^2 = 1.4^{+0.6}_{-0.5}$
		$\|V_{tb} f_2^L\|^2 < 0.5$ at 95% C.L.
(L_1, R_1)	$5.2^{+2.6}_{-3.5}$ pb	$\|V_{tb} f_1^L\|^2 = 1.8^{+1.0}_{-1.3}$
		$\|V_{tb} f_1^R\|^2 < 2.5$ at 95% C.L.
(L_1, R_2)	$4.5^{+2.2}_{-2.2}$ pb	$\|V_{tb} f_1^L\|^2 = 1.4^{+0.9}_{-0.8}$
		$\|V_{tb} f_2^R\|^2 < 0.3$ at 95% C.L.

FCNC couplings

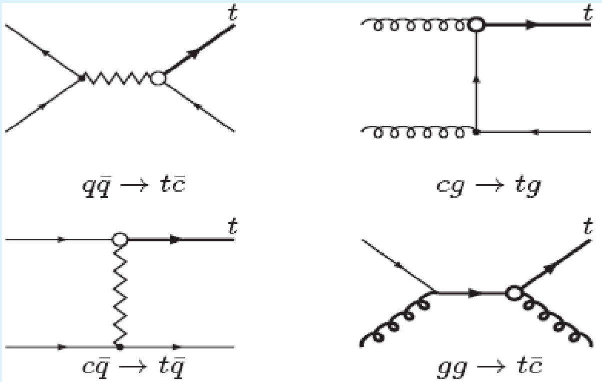
- Couplings: $tqg,\ tq\gamma,\ tqZ$, where $q = u, c$

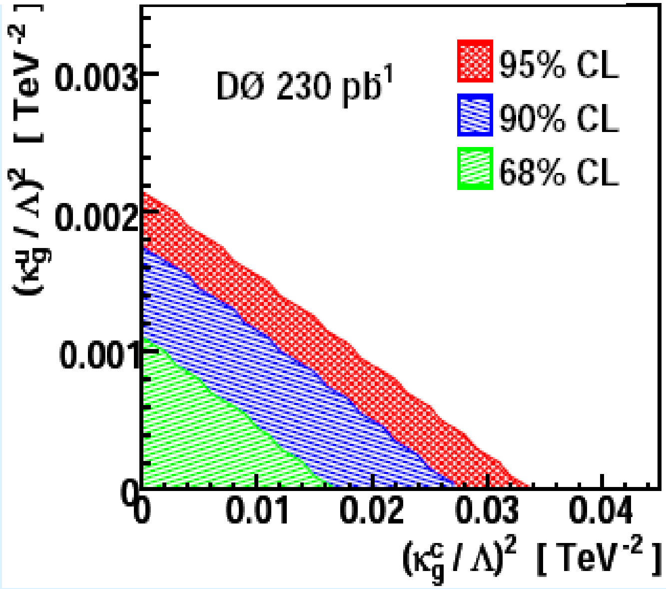
$$\Delta\mathcal{L}^{eff} = \frac{1}{\Lambda}\,[\kappa_{tq}^{\gamma,Z}\, e\bar{t}\sigma_{\mu\nu}qF_{\gamma,Z}^{\mu\nu} + \kappa_{tq}^{g} g_s\bar{t}\sigma_{\mu\nu}\frac{\lambda^i}{2}qG^{i\mu\nu}] + h.c.$$

D0 Limits on FCNC couplings 230 pb^{-1}:

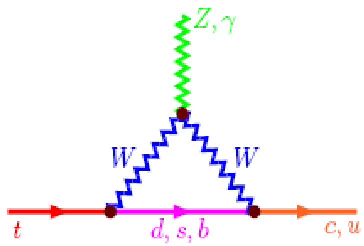
$\kappa_g^u/\Lambda < 0.037\ \mathrm{TeV}^{-1}$

$\kappa_g^c/\Lambda < 0.15\ \mathrm{TeV}^{-1}$





W' boson and FCNC MC event samples from SingleTop (CompHEP) generator



	SM	two-Higgs	SUSY
$BR(t \to cg)$	$5 \cdot 10^{-11}$	10^{-6}	10^{-3}
$BR(t \to c\gamma)$	$5 \cdot 10^{-13}$	10^{-6}	10^{-5}
$BR(t \to cZ)$	$\sim 10^{-13}$	10^{-9}	10^{-4}

FCNC decays are highly suppressed in SM $t \to qg,\quad t \to q\gamma,\quad t \to qZ$

To compare FCNC limits from top decays and top production one can express limits on FCNC couplings in term of Br fractions

$$\Gamma(t \to qg) = \left(\frac{\kappa^g_{tq}}{\Lambda}\right)^2 \frac{8}{3}\alpha_s m_t^3 \quad , \quad \Gamma(t \to q\gamma) = \left(\frac{\kappa^\gamma_{tq}}{\Lambda}\right)^2 2\alpha m_t^3,$$

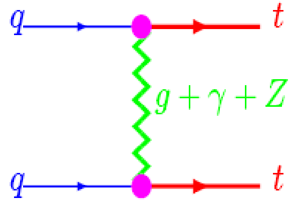
$$\Gamma(t \to qZ)_\gamma = \left(|v^Z_{tq}|^2 + |a^Z_{tq}|^2\right) \alpha\, m_t^3 \frac{1}{4M_Z^2 \sin^2 2\theta_W} \left(1 - \frac{M_Z^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_Z^2}{m_t^2}\right),$$

$$\Gamma(t \to qZ)_\sigma = \left(\frac{\kappa^Z_{tq}}{\Lambda}\right)^2 \alpha\, m_t^3 \frac{1}{\sin^2 2\theta_W} \left(1 - \frac{M_Z^2}{m_t^2}\right)^2 \left(2 + \frac{M_Z^2}{m_t^2}\right)$$

$t \to$	Tevatron Run II	LHC decay	LHC production	TESLA
$g\,q$	0.06%	1.6×10^{-3}	1×10^{-5}	–
$\gamma\,q$	0.28%	2.5×10^{-5}	3×10^{-6}	4×10^{-6}
$Z\,q$	1.3%	1.6×10^{-4}	1×10^{-4}	2×10^{-4}

Interesting process to be studied:

like top (tt or $\bar{t}\,\bar{t}$) pair production: $pp \to t\,t\,X \quad pp \to \bar{t}\,\bar{t}\,X$



$\sigma(tt) \propto (\kappa_g)^4$

no background from $t\bar{t}$ or from single-top

Conclusions

1. Single top observation at 5 sigma level

Combined Results

	$\mathcal{L}$ [fb^{-1}]	Significance Exp.	Significance Obs.	σ_{s+t} [pb]
DØ	2.3	4.5σ	5.0σ	$3.9^{+0.9}_{-0.9}$
CDF	3.2	5.9σ	5.0σ	$2.3^{+0.6}_{-0.5}$

Theory (NLO) : σ = 2.9 ± 0.3 pb

2. First direct V_{tb} measurement

DØ: $|V_{tb} f_{L1}| = 1.07 \pm 0.12$, $|V_{tb}| > 0.78$ at 95% CL

CDF: $|V_{tb}| = 0.91 \pm 0.11$, $|V_{tb}| > 0.71$ at 95% CL

3. Pair production cross section measurement

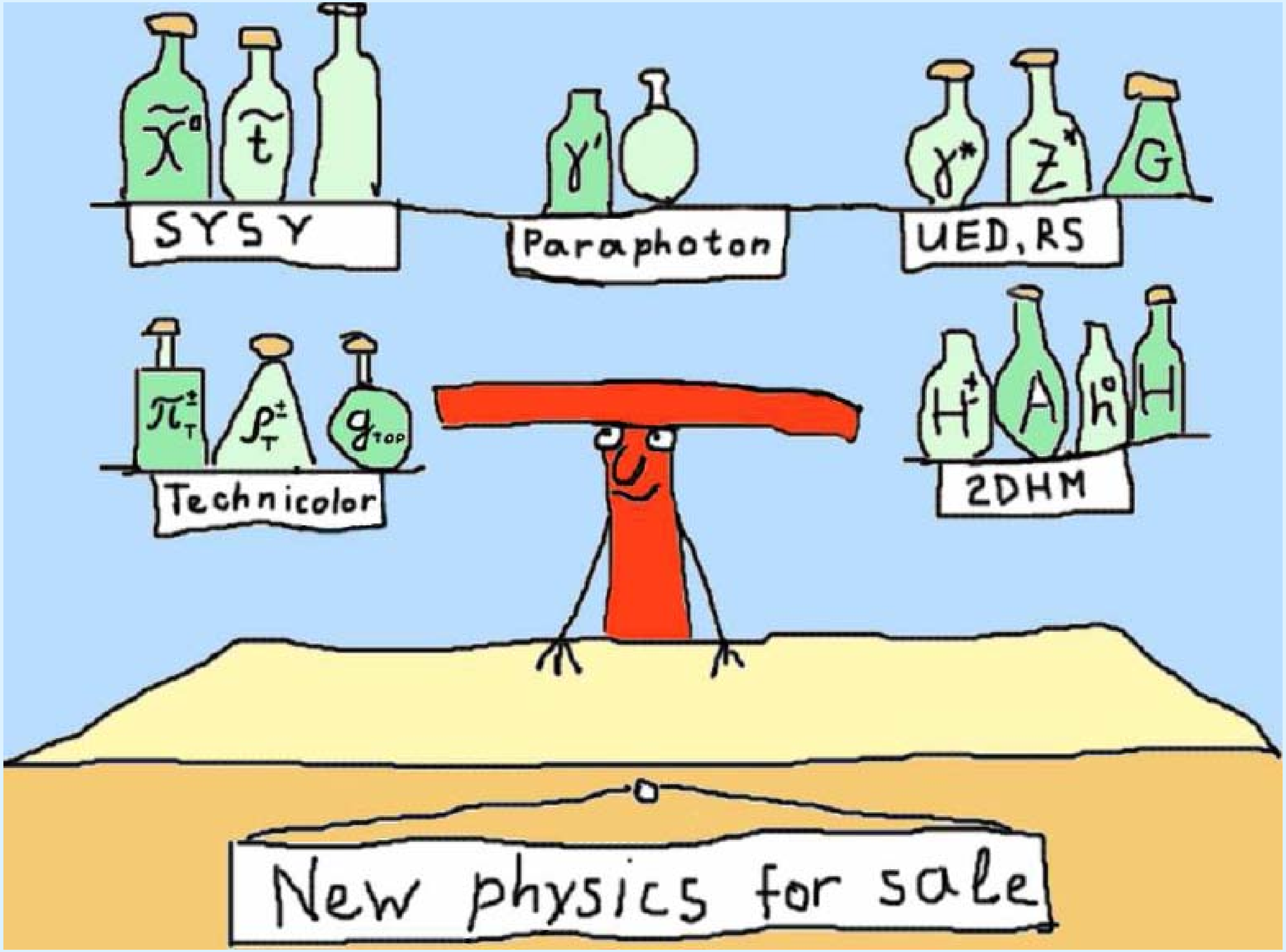
D0: 6.6 ± 0.9 (stat.+syst.) ± 0.4 (lumi)
CDF: 7.0 ± 0.3 (stat.) ± 0.4 (syst.) ± 0.4 (lumi)
Theory (NLO + NLL) : σ = 6.7 + 0.7 – 0.9 pb

4. Top mass (March 2009) M_{top} = 173.1±0.6 (stat.)± 1.1(syst.)

5. LHC as a top factory has great prospects to perform accurate measurements and to search for BSM via top improving Tevatron limits

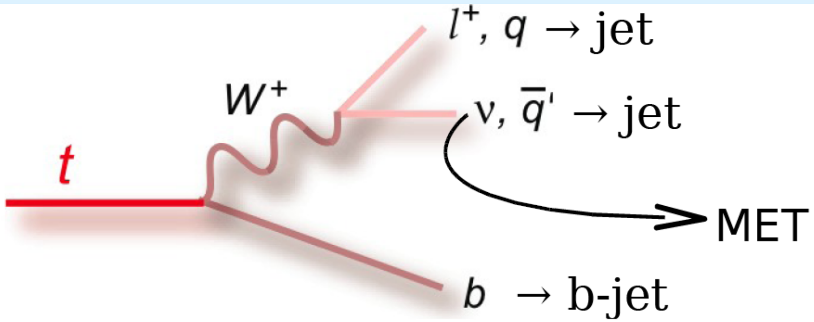
6. ILC/CLIC being complementary to the LHC allow to get significant improvements in accuracy (top mass, V_{tb}, anomalous couplings…) and observe new objects like paraphoton, if exist, which would be impossible at the LHC

(ILC: ΔM_{top} ~ 0.1 GeV from the threshold scan)

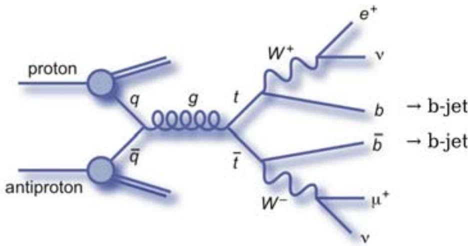

SYSY
Paraphoton
UED, RS
Technicolor
2DHM
New physics for sale

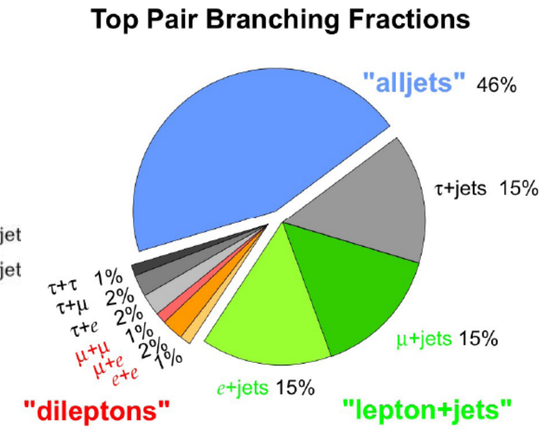
Back up slides

- Top decays:

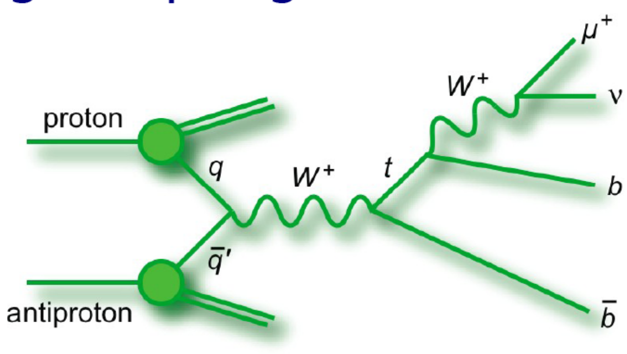


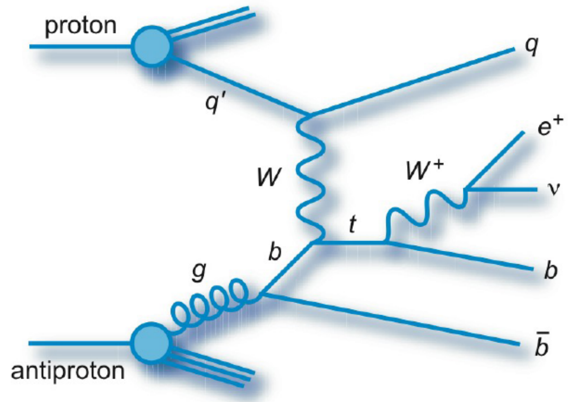
- Top pair signatures:
  - lepton + jets
  - dilepton
  - all jets





- Single Top Signatures:



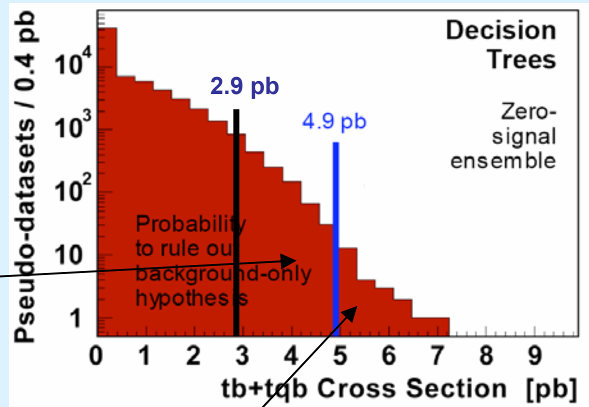


Significance

sets of pseudo-data ("ensembles")

Wonderful tool to test the analyses! Like running DØ many 1,000's of times

Each pseudo-dataset is like one DØ experiment
up to 68,000 pseudo-datasets per ensemble



Zero-signal ensemble, $\sigma_{(tb+tqb)}$ = 0 pb

Fraction of the ensemble of zero-signal pseudo-datasets give a cross section at least as large as the SM value, the "expected p-value"

For a Gaussian distribution, convert p-value to give "expected signficance"

Fraction of the ensemble of zero-signal pseudo-datasets give a cross section at least as large as the measured value, the "measured p-value"

For a Gaussian distribution, convert p-value to give "measured signficance"

$$p - value = \int_{\sigma^{obs}_{tb+tqb}}^{\infty} d\sigma_{tb+tqb} P_b(\sigma_{tb+tqb})$$

SM ensemble, $\sigma_{(tb+tqb)}$ = 2.9 pb

How consistent is the measured cross section with the SM value?

Fraction of the ensemble of SM-signal pseudo-datasets give a cross section at least as large as the measured value to get "consistency with SM"

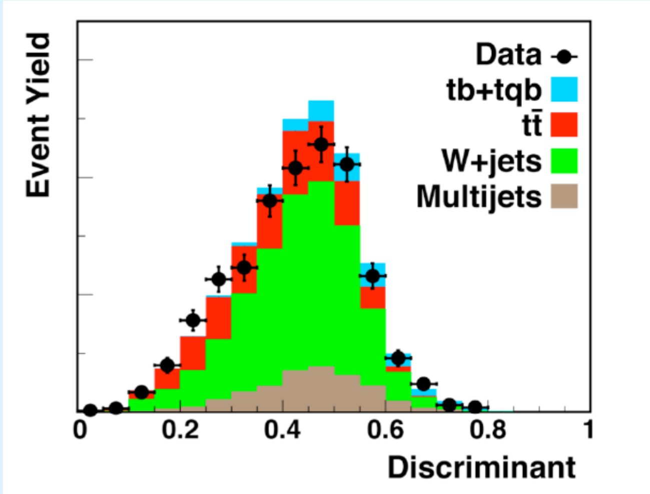
Cross section measurement

$$d = \sigma \cdot A \cdot L + \sum_i^{N_b} b_i$$

d – predicted number of events

b_i – predicted number of i-component background events

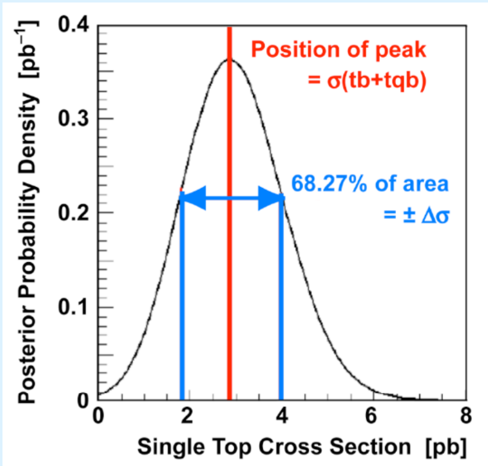
A – signal acceptance, L – integrated luminosity,
a= AL – effective luminosity



Binned likelihood from discriminant distribution using Poisson statistics:

$$\mathrm{Prob}(D|d) \equiv \mathrm{Prob}(D|\sigma, a, \mathbf{b}) = \prod_{i=1}^{\mathrm{Nbins}} \mathrm{Prob}(D_i|d_i)$$

$$\text{Posterior Probability Density}(\sigma|D) \propto \int_a \int_{\mathbf{b}} \mathrm{Prob}(D|\sigma, a, \mathbf{b})\ \mathrm{Prior}(a, \mathbf{b})\ \mathrm{Prior}(\sigma)\ da\ d\mathbf{b}$$



Posterior probability density using Bayes theorem.

Flat positive-defined prior for σ_{tb+tqb} : Θ(tb+tqb)

Systematic uncertainties in b_i are treated as Gaussian nuisance parameters.

Cross section and uncertainty from peak position of Bayesian posterior probability density