Top Quark Physics (part 1)

S. Tokár, Comenius Univ., Bratislava

HASCO Summer School , Goettingen 2012

Topics in This Talk

- Motivation for top physics
- Top production cross section
- Top quark mass (constraint on Higgs mass)
- Single top production (top partial width, V_{tb}, spin effects…)
- Forward-backward/charge asymmetry in tt-bar
- Top spin effects (Top-antitop spin correlations)
- FCNC in tt-bar production

Top quark –heaviest SM elem. particle

- ❑ Top quark: discovered at Fermilab (CDF + D0) in 1995
- ❑ Completed the 3rd generation of SM fermions

leptons	Q	T_3	quarks	Q	T_3
ν_e ν_μ ν_τ	0	1/2	u c **t**	2/3	1/2
e μ τ	-1	-1/2	d s b	-1/3	-1/2

SM fundamental fermions, Q≡ electric charge,
T3≡ 3rd comp. of weak isospin

- ❑ Top quark mass (m_{top}): 173.5 ±0.6± 0.8 GeV ($35\times m_b$)
- ❑ Main object of study at Fermilab
  - ✓ final sample 10fb^{-1} ⇒ 70 000 $t\bar{t}$-pair produced
- ❑ A very important object of study for LHC –
  - ✓ Top factory: ≈ 1.5 M, ≈10M tt-bar per 10 fb^{-1} for 7 and 14 TeV, resp.

Top quark physics: Motivation

- Very high mass: near EWSB scale η

  Top Youkawa coupling $\lambda_t = \sqrt{2} m_{top}/\eta \approx 1$

- tt-bar production X-sections: test of QCD

  $\rightarrow$ to is produced at very small distances $1/m_t \Rightarrow$ $\alpha_s(m_{top}) \approx 0.1$: pert. expansion converges rapidly

- Top decays before hadronization

$1/m_t$	$<$	$1/\Gamma_t$	$<$	$1/\Lambda$	$<$	m_t/Λ^2
Production time	$<$	Lifetime	$<$	Hadronization time	$<$	Spin decorrelation time

$\rightarrow$ study of spin characteristics (test of V-A)

- Cross sections sensitive to new physics

  $\rightarrow$ resonat production of $t\bar{t}$, decay: $t \rightarrow Hb$

- Important background for Higgs studies

Top is special!

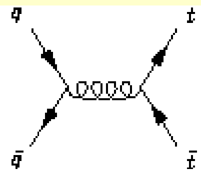
Stringent tests of SM
+
Search for New physics

$\eta = 246$ GeV
$\Lambda \approx 250$ MeV

Top Quark Production

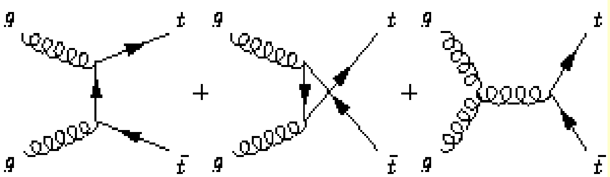
LHC √s = 7-14 TeV vs Tevatron √s = 1.96 TeV

Strong $t\bar{t}$ pair production | **EW single top quark production**



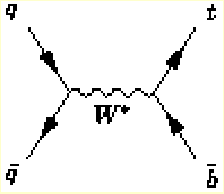
$q\bar{q} \to t\bar{t}$

(13%, 85%)



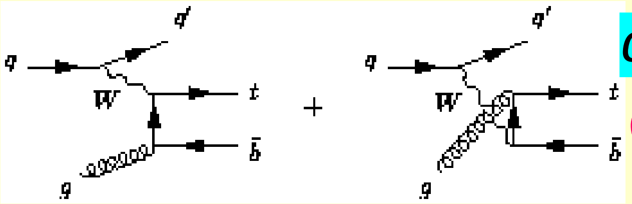
$gg \to t\bar{t}$

(87%,15%)



$q\bar{q} \to t\bar{b}$

(Drell-Yan)



$qg \to q' t\bar{b}$

(W-g fusion)

Tevatron: X-sec ≈ 7 pb (5%) X-sec ≈ 3 pb (t + t-bar)

LHC /7TeV: ≈ 165 pb ≈ 85 pb

/8TeV: ≈ 230 pb ε≤5%

/14TeV: ≈ 870 pb ≈ 320 pb

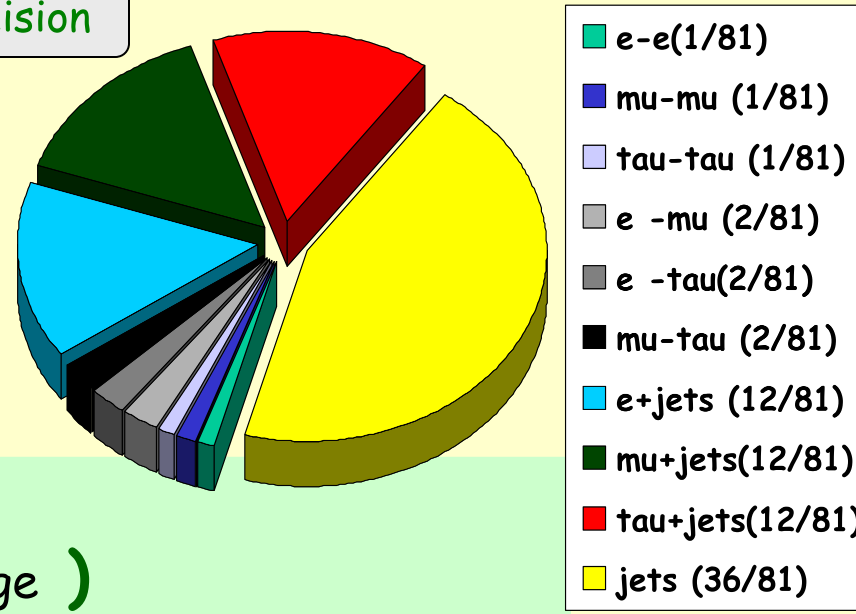
Top Quark Decay

SM: by far dominant ***t→bW***

α_s^2 precision

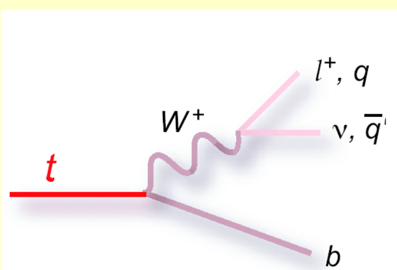
$$\frac{\Gamma(t \to bW)}{|V_{tb}|^2} \approx 0.807 \times \frac{G_F m_t^3}{8\pi\sqrt{2}} = 1.42\,GeV$$

$\tau_{top} \approx 5\times10^{-25}$sec << τ_{hadr} (10^{-23}sec)

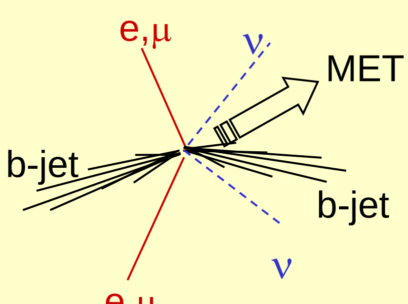


Top decays before hadronization !!!

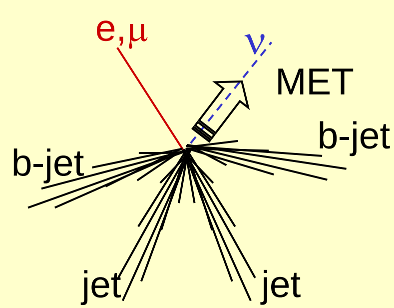
- **No tt-bar bound states** (gluon exchange)
- ***t,W helicity from SM V-A*** (no depolarization via hadronization)



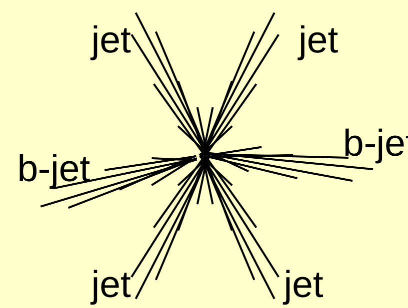
tt-bar samples via W decays



Dilepton
(BR~5%, low bckg)



Lepton+jets
(BR~30%, moderate bckg)



All-hadronic
(BR~46%, huge bckg)

Cross Section of Top Quark production

$t\,\bar{t}$ Production Cross Section

Top quark X-section: Experiment vs Theory

Factorization theorem:

theory

$$\sigma = \sum_{i,j} \int dx_1 dx_2\, F_i^{(1)}(x_1,\mu_F) F_j^{(2)}(x_2,\mu_F)\, \hat{\sigma}_{ij}(s;\mu_F,\mu_R)$$

experiment

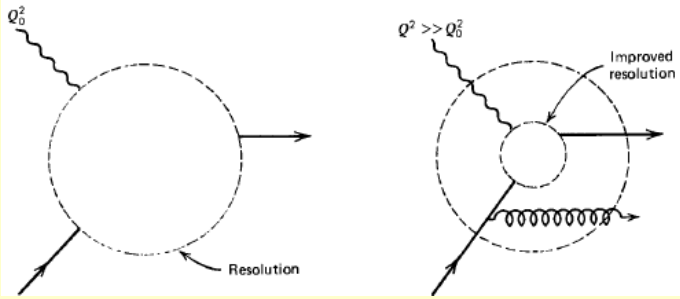
Parton Distribution Functions (PDFs)

$F_i^{(\lambda)}(x_\lambda,\mu_F)$ ≡ probability density to observe a parton ***i*** with longitudinal momentum fraction x_λ in incoming hadron λ, when probed at a scale μ_F

μ_F ≡ factorization scale (a free parameter) - it determines the proton structure if probed (by virtual photon or gluon) with $q^2 = -\mu_F^2$

μ_R ≡ renormalization scale – defines size of strong coupling constant

Usual choice: $\mu_F = \mu_R = \mu \in (m_t/2,\ 2m_t)$

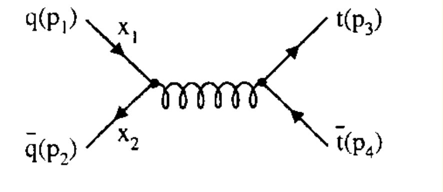


$t\ \bar{t}$ Production Cross Section

The LO top quark pairs cross section (Born term):

$$d\hat{\sigma} = \frac{1}{2(p_1+p_2)^2}\frac{d^3p_3}{(2\pi)^3 2E_3}\frac{d^3p_4}{(2\pi)^3 2E_4}\delta(p_1+p_2-p_3-p_4)\overline{|M|^2}$$

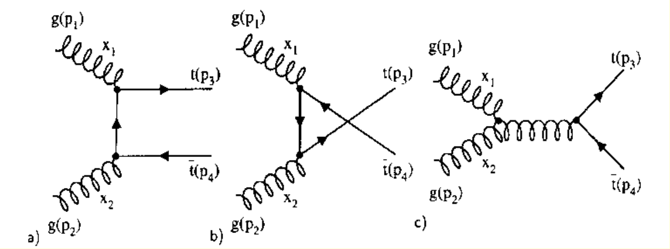
Quark –antiquark annihilation



$$\overline{|M|^2}(q\bar{q}\to t\bar{t}) = (4\pi\alpha_s)^2\frac{8}{9}\left(2\frac{(p_1\cdot p_3)^2+(p_2\cdot p_3)^2}{(p_1\cdot p_2)^2}+\frac{m_t^2}{(p_1+p_2)^2}\right)$$

Averaged over initial and summed over final color and spin state

Gluon fusion



$$\overline{|M|^2}(gg\to t\bar{t}) = (4\pi\alpha_s)^2\left(\frac{(p_1+p_2)^4}{24(p_1\cdot p_3)(p_2\cdot p_3)}-\frac{8}{9}\right)$$

$$\times\left(4\frac{(p_1\cdot p_3)^2+(p_2\cdot p_3)^2}{(p_1\cdot p_2)^4}+\frac{4m_t^2}{(p_1+p_2)^2}-\frac{m_t^4(p_1+p_2)^4}{(p_1\cdot p_3)^2(p_2\cdot p_3)^2}\right)$$

Experiment:

LO tt-bar Xsec is not sufficient!

Higher orders are needed

$t\,\bar{t}$ Production Cross Section

Theory for top X-section is at NNLO:

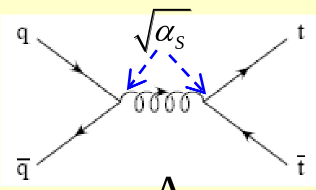
Xsec is expanded into series of strong coupling constant:

$$\sigma_{ij}\left(\beta,\frac{\mu^2}{m^2}\right)=\frac{\alpha_S^2}{m^2}\left\{\sigma_{ij}^{(0)}+\alpha_S\left[\sigma_{ij}^{(1)}+L\sigma_{ij}^{(1,1)}\right]+\alpha_S^2\left[\sigma_{ij}^{(2)}+L\sigma_{ij}^{(2,1)}+L^2\sigma_{ij}^{(2,2)}\right]+O\left(\alpha_S^3\right)\right\}$$

$LO\sim\alpha_S^2$, $NLO\sim\alpha_S^3$, $NNLO\sim\alpha_S^4\ \cdots$ $\beta=\sqrt{1-4m^2/s}$ $L\equiv$ big log term

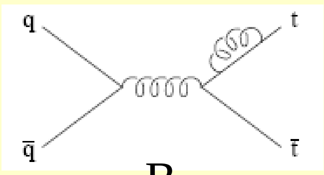
NLO: virtual and real corrections are added to LO

Virtual corrections:



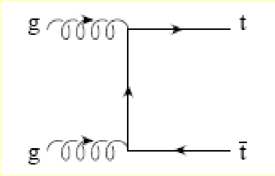
A

+

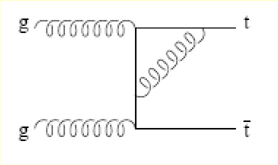


B

+ ...

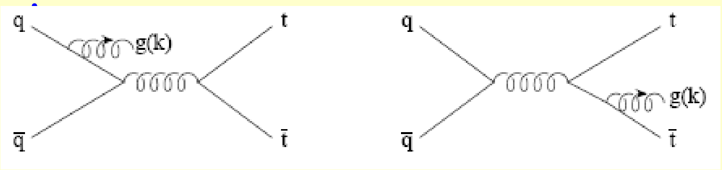


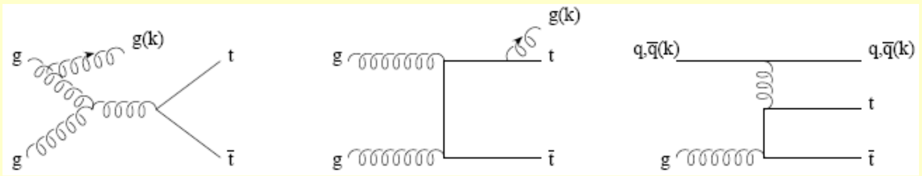
+



Taking $|A+B|^2=\ldots+AB^*+\ldots$, $AB^*\sim\alpha_S^3$

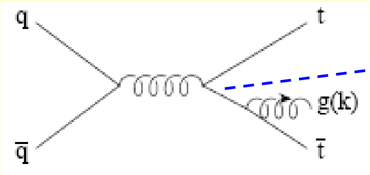
Real corrections – with real gluons ($\sim\alpha_S^3$):





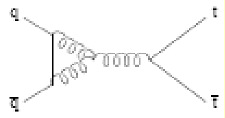
A few top Cross Section issues

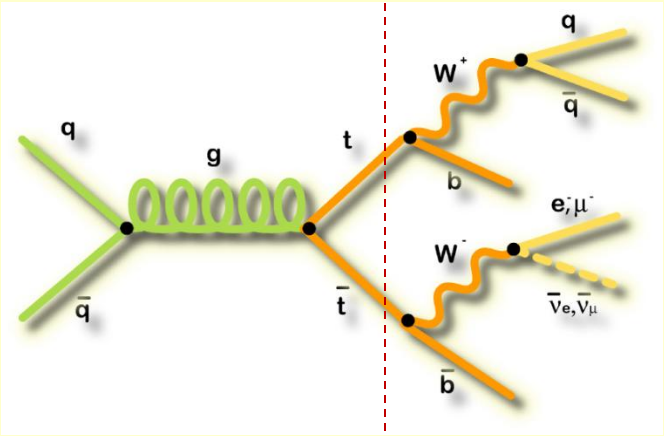
Higher order real and virtual corrections exhibit IR and UV divergences:

Example: 

$$\text{propagator} = \frac{1}{(p+k)^2} = \frac{1}{2E_pE_k}\cdot\frac{1}{1-\beta_p\cos\theta}, \quad \beta_p = \sqrt{1-m^2/E_p^2}$$

✓ IR singularity: $E_k \to 0$ and $1-\beta_p\cos\theta \to 0 \Rightarrow$ cancelled when Xsec of virtual and real emission are summed also mass singularities are cancelled $\Rightarrow$ Cancelation is not full $\Rightarrow$ presence of big logs (L) in Xsec terms !

✓ UV singularities in loops () are handled by renormalization.



In real we observe $t\bar{t}$ decay products not $t\bar{t}$

Factorization is used based on the narrow width approximation:

- ✓ polarized top quarks are produced on mass shell
- ✓ polarized on-shell top quarks decay

Narrow width app. vs direct pp→WWbb:

For LHC 7TeV/DIL: Xsec(fb) 837 vs 841 also done for 14 and 1.96TeV

Top cross section - measurement

Selection criteria: trigger + offline selection ⇒ candidate events

- Depend on the analysed channel: $t\bar{t}$ production
  - lepton+jets (LJ), dilepton (DL) and all hadronic mode (AH)
  - ***lν2b2j*** ***2(lν)2b*** ***2b4j*** all: ***+1j, 2j…***
  - LJ: single lepton high-p_T (E_T) trigger applied + Reconstructed level:
    - ✓ 1 high-p_T lepton + ≥4high-p_T jets (1-2b-tagged) + high $\not{E}_T$
    - ✓ Restricted on pseudo-rapidity, $p_T\,(E_T) > 20$ GeV $\not{E}_T > 20$ GeV
  - What are selection criteria for DL and AH?

- Background processes – non $t\bar{t}$ events also pass Selection criteria:
  - Bascic bkgd processes for LJ channel:
    - ✓ W+jets, Z+jets, diboson, single top quark, QCD multijets
  - Bkgd processes: studied using MC + data driven techniques

$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bkg}}{A \cdot \varepsilon \int L dt}$$

N_{obs}(N_{bkg}) ≡ observed (expected bkgd) events
A ≡ acceptance, ε ≡ trigger efficiency, L≡ luminosity

Theory (NNLO) vs Experiment

	Tevatron	LHC 8GeV
TOPIXS 1.0	$7.00^{+0.21\,+0.29}_{-0.31\,-0.25}$	$229.8^{+16.5\,+9.7}_{-16.7\,-9.0}$
top++ 1.3	$7.00^{+0.20\,+0.29}_{-0.31\,-0.24}$	$230.2^{+15.3\,+9.8}_{-15.2\,-9.0}$
HATHOR	$7.07^{+0.31\,+0.29}_{-0.40\,-0.24}$	$246.8^{+13.4\,+10.8}_{-17.7\,-9.9}$
TopNNLO	$6.59^{+0.07\,+0.63}_{-0.41\,-0.47}$	$220.0^{+11.7\,+19.0}_{-11.8\,-18.5}$
Kidonakis 2010	$7.08^{+0.00\,+0.36}_{-0.24\,-0.27}$	
D0 2011	$7.56^{+0.63}_{-0.56}$	
CDF 2009	$7.50^{+0.48}_{-0.48}$	
CMS 2012		227^{+15}_{-15}

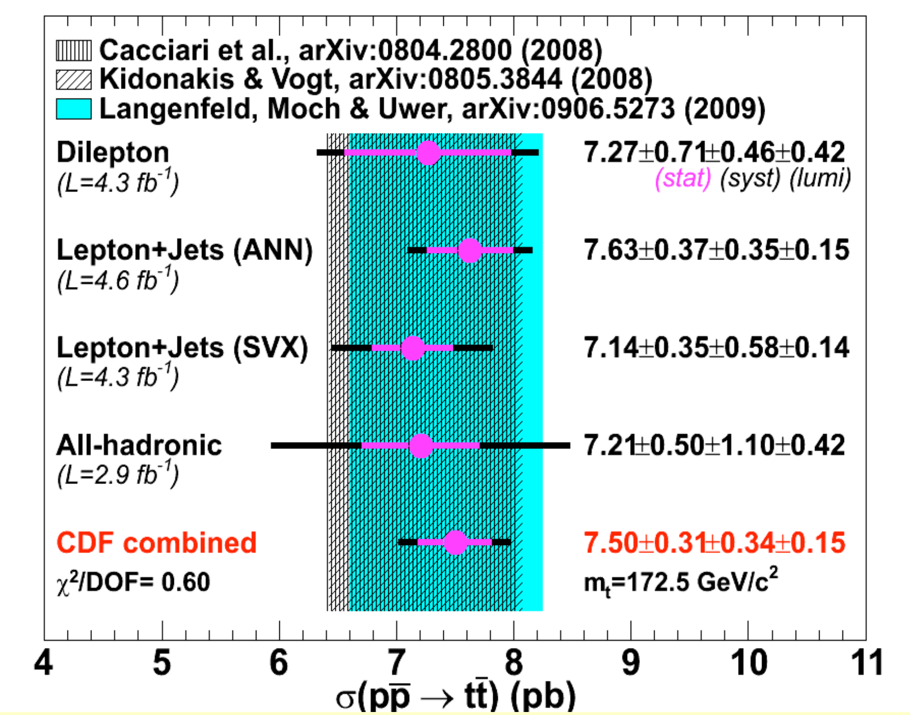
theory (TOPIXS 1.0 – Kidonakis 2010)

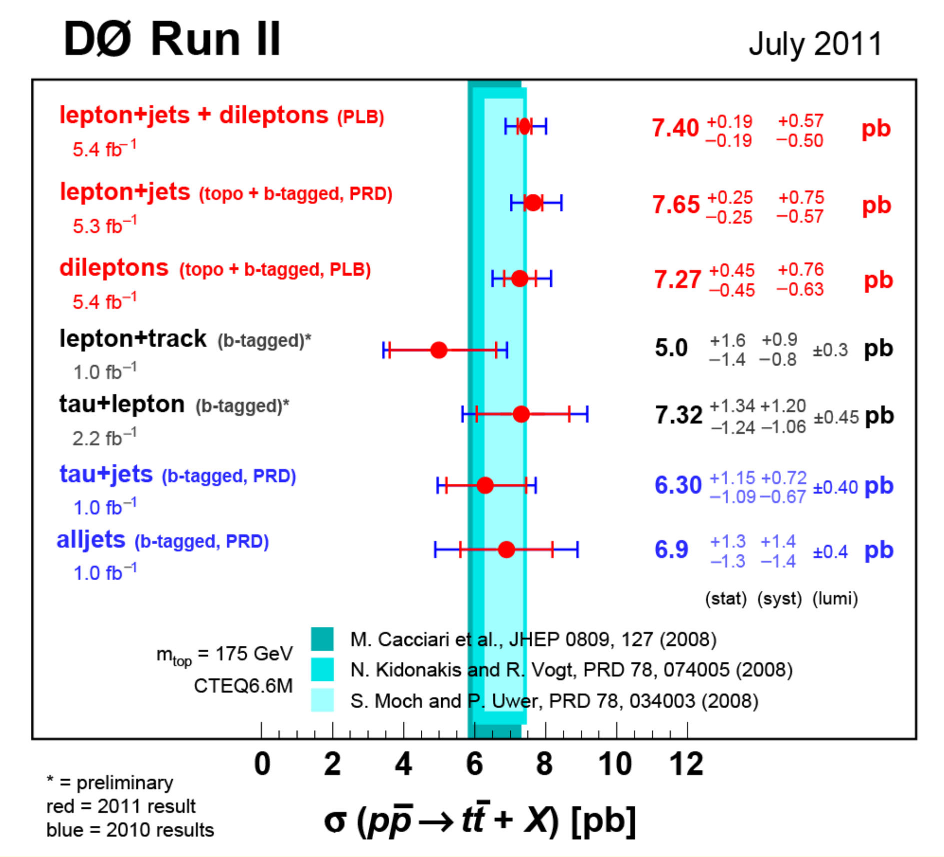
experiment (D0 2011 – CMS 2012)

Theory: Tevatron ≈ 5%, experiment: CDF ≈ 6.4%, CDF+D0 ≈ 5.5%
LHC ≈ 4% CMS ≈ 6.3%
Events: CDF: 1 200 vs CMS: 7 000

Tevatron (2TeV): Top pair cross sections

CDF combination





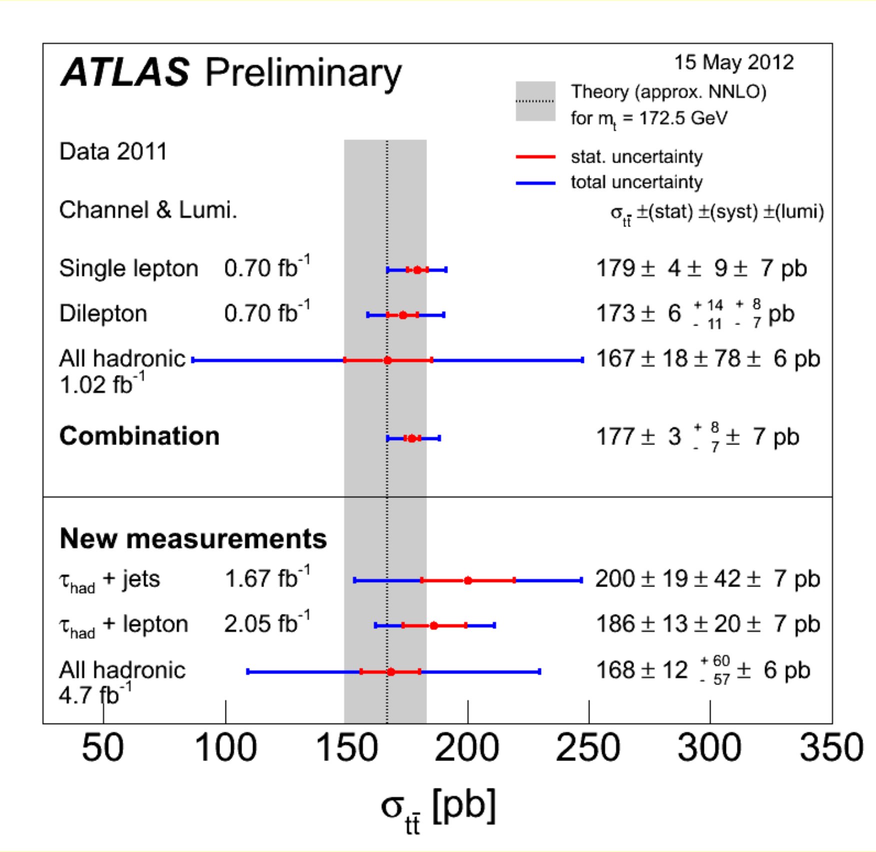
Main uncertainties

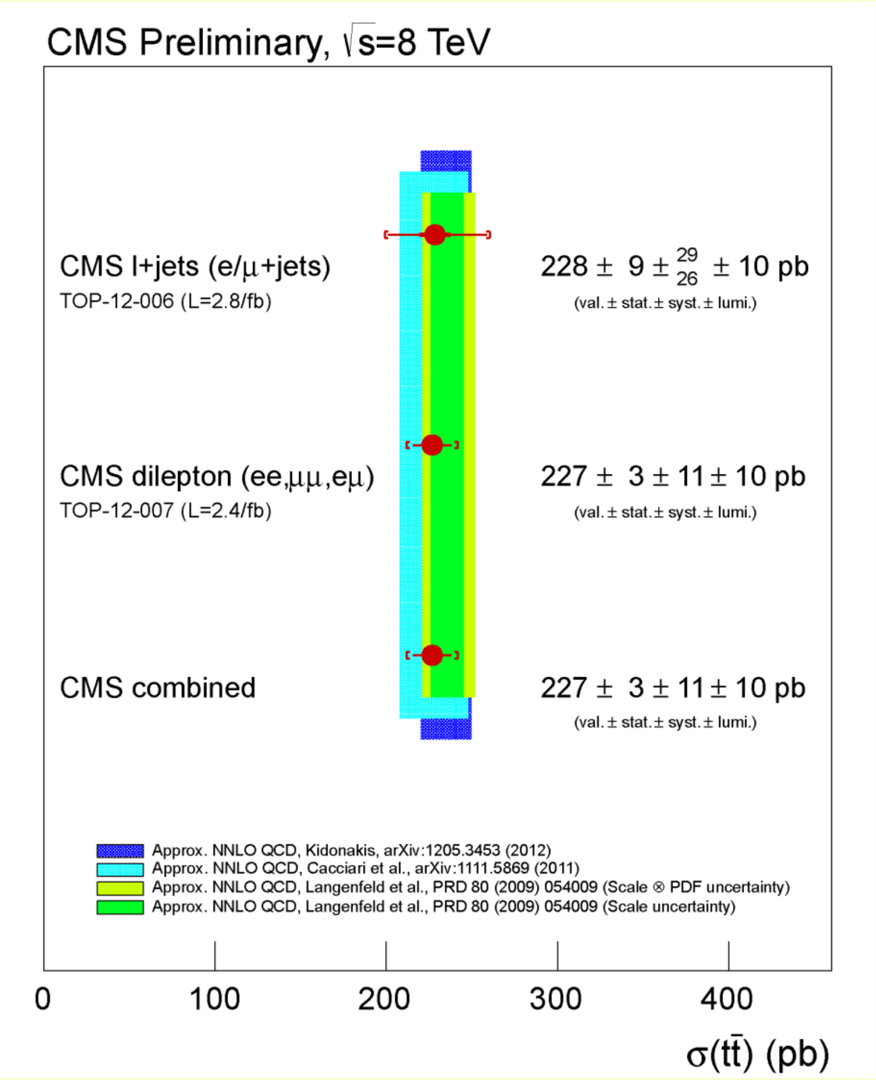
- ✓ JES for all
- ✓ b-tagging for SVX analysis
- ✓ Generator for all

- ❖ All channels are compatible
- ❖ Exper. error ≈ theo. Error
- ❖ Full NNLO needed!

LHC ttbar cross section measurement

Atlas, √s=7 TeV





- ✓ A good agreement with theory
- ✓ Statistical error plays no role ...

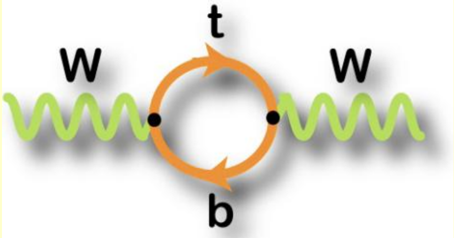
Top Quark Mass Reconstruction

Top mass and EW precision physics

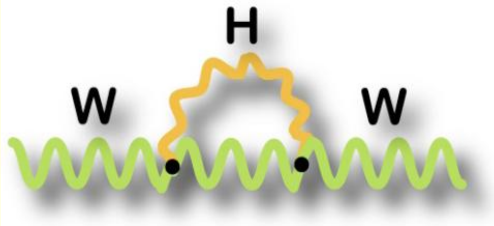
Masses of top, W and Higgs are bounded by

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r),\qquad \Delta r=\Delta\alpha+\frac{s_W}{c_W}\Delta\rho+(\Delta r)_{nl}$$

From rad. Corrections to W-boson propagator
(any process, e.g. $\mu^- \to \nu_\mu W^- \to \nu_\mu e^- \bar{\nu}_e$) :



$\Delta\rho \sim m_t^2$

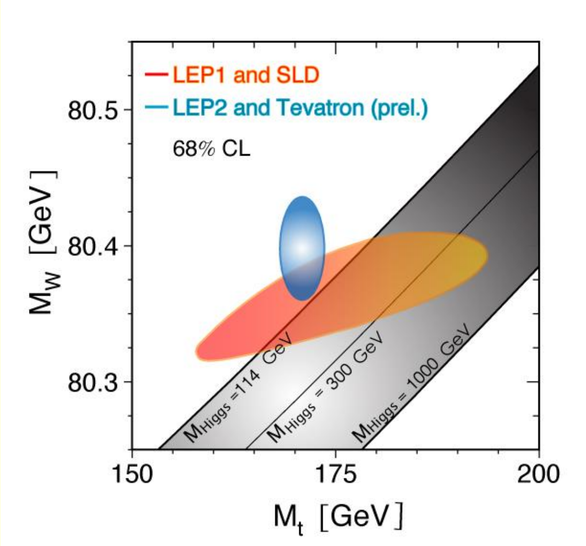


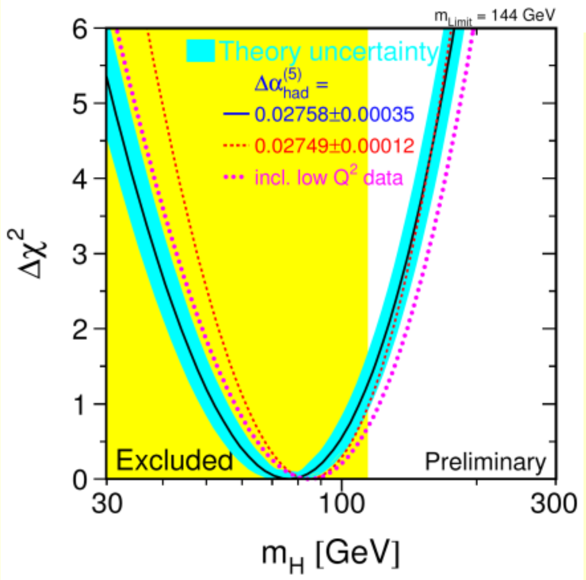
$(\Delta r)_{nl} \propto \ln M_H$

Precise M_W and m_t ⇒ constraint on M_H!

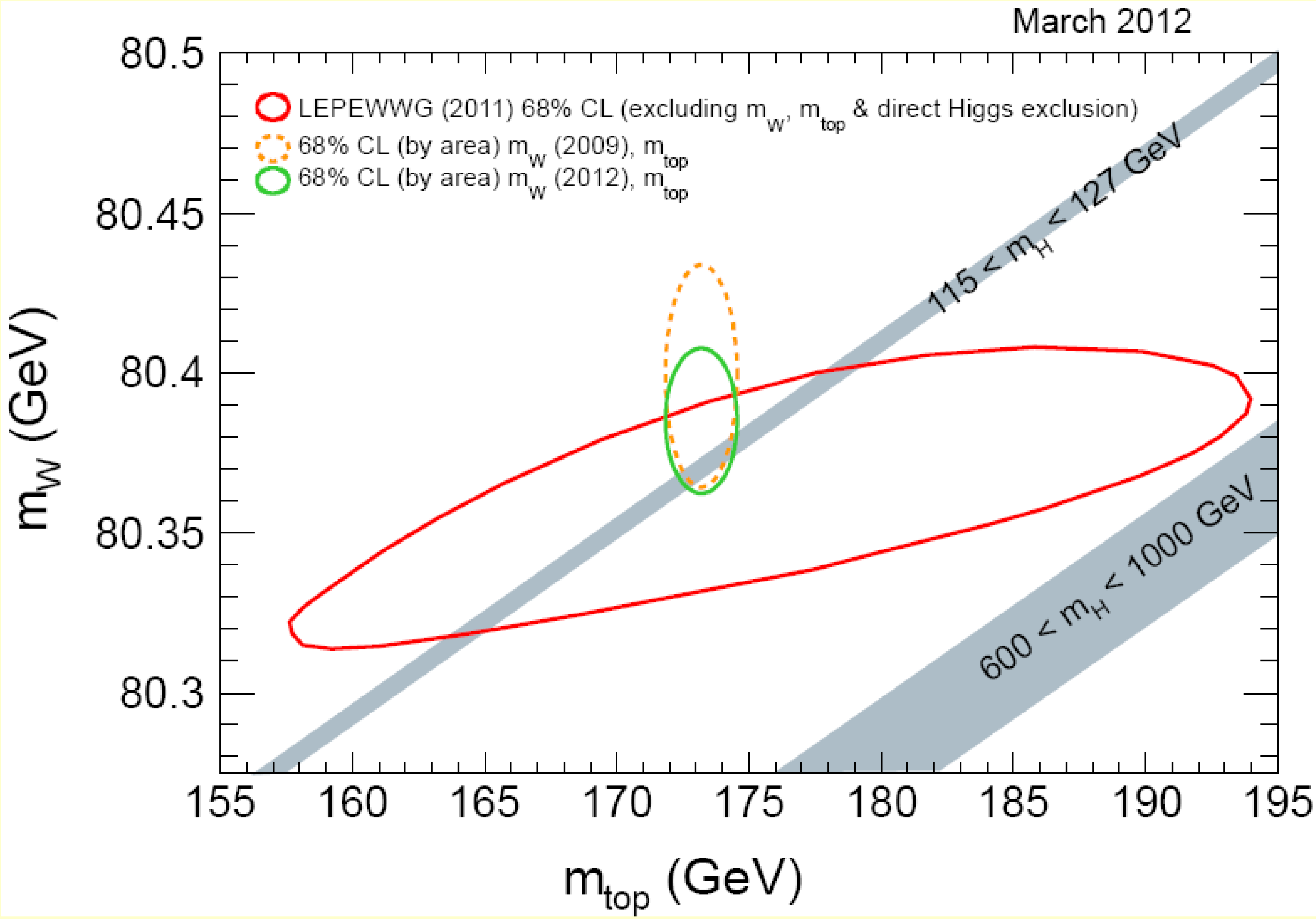
✓ LHC can improve: Δm_t and ΔM_W

✓ **Stringent consistency test of SM**





…an another Higgs restriction plot



What will be happen with the green ellipse after 20-30 fb^{-1}?…

How to measure top mass?

Top quark mass can be reconstructed in all $t\bar{t}$ topologies (LJ, DL AH)

Best results usually in lepton + jets topology

- Different approaches are used - usually:
  - ✓ Template methods – different variants
  - ✓ Matrix element methods – use dependence of top pair production Xsec on top quark mass.
  - ✓ Any variable correlated with top quark mass can be used for determination of top mass – e.g. mean lepton p_T (LJ, DL)
- To retrieve top mass usully event kinematic should be reconstructed

Top quark mass template method

Basic idea of template method - L+jets topology :

- ✓ to find invariant mass of top decay products: $t \to bq\bar{q}, \bar{t} \to \bar{b}l\nu, \ t \leftrightarrow \bar{t}$
- ✓ Using reconstructed objects of candidate events a kinematic fitter is used to find 4-momenta of top decays products .
- ✓ Kinematic fitter minimizes χ^2 function, e.g.:

$$\chi^2 = \sum_{i=l,4\,jets} \frac{\left(p_T^{i,fit} - p_T^{i,meas}\right)^2}{\sigma_i^2} + \sum_{j=1.2} \frac{\left(U_j^{fit} - U_j^{meas}\right)^2}{\sigma_j^2} + \frac{\left(M_{jj} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(M_{l\nu} - M_W\right)^2}{\Gamma_W^2} + \frac{\left(M_{bjj} - m_t^{rec}\right)^2}{\Gamma_t^2} + \frac{\left(M_{bl\nu} - m_t^{rec}\right)^2}{\Gamma_t^2}$$

Problem: for candidate event we can have several event configurations – connected with different assignments of jets to quarks - without b-tagging: 12 configurations per a LJ event (and for 1 or 2-btags?)

- ✓ The χ^2 fit is applied to all the event configurations
- ✓ KF gives for each event comb. m_t^{rec} and χ^2 - correct $m_t^{rec} \Leftrightarrow$ minimal χ^2

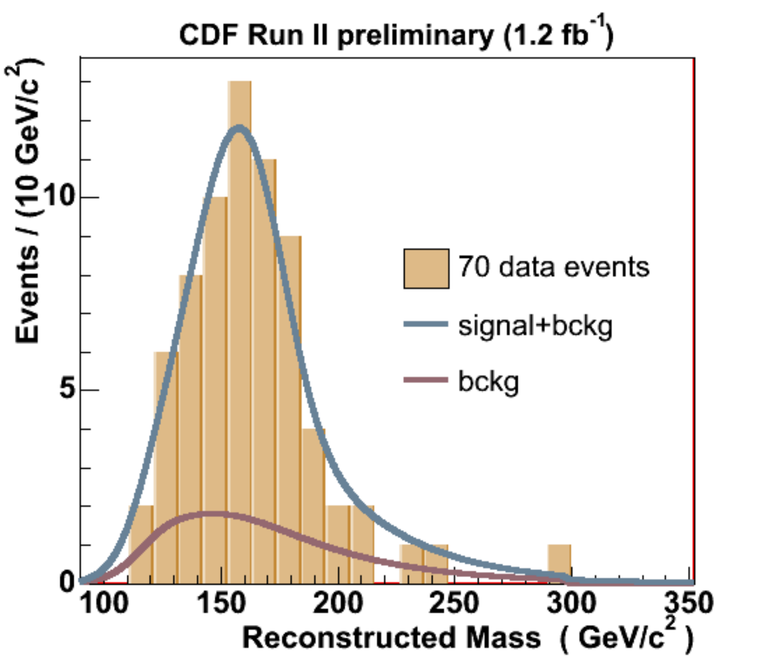
Using MC for a given input top mass - expected rec. mass distribution (template) can be found – data mass distr. is compared with mass templates

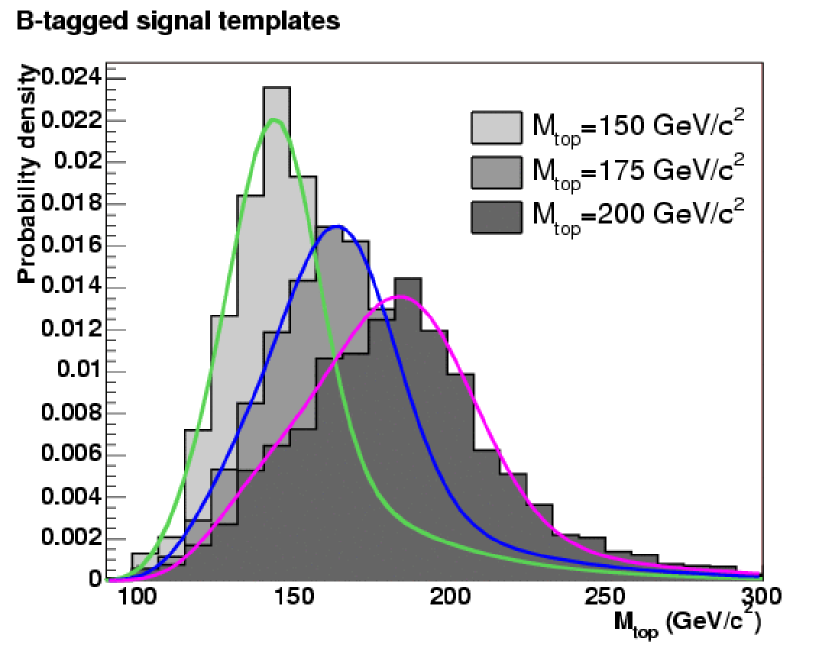
Top mass in DIL chanel: templates

✓ Top quark mass measured in dilepton channel using a template method.

✓ Due to 2 neutrinos M_{top} reconstruction from dilepton events is underconstrained $\Rightarrow$ $p_z^{t\bar{t}}$ fixed to solve event kinematics

✓The sample is separated into b-tagged and non-tagged samples.





For each event M_{top}^r reconstructed assum.:

$$M_{W^\pm} = 80.4\,\mathrm{GeV/c^2},\ M_t = M_{\bar{t}} \text{ and } p_z^t + p_z^{\bar{t}} = 0$$

$$M_{top} = 169.7^{+5.2}_{-4.9}\ (\text{stat.})\ \pm 3.1\ (\text{syst.})\ \mathrm{GeV/c^2}$$

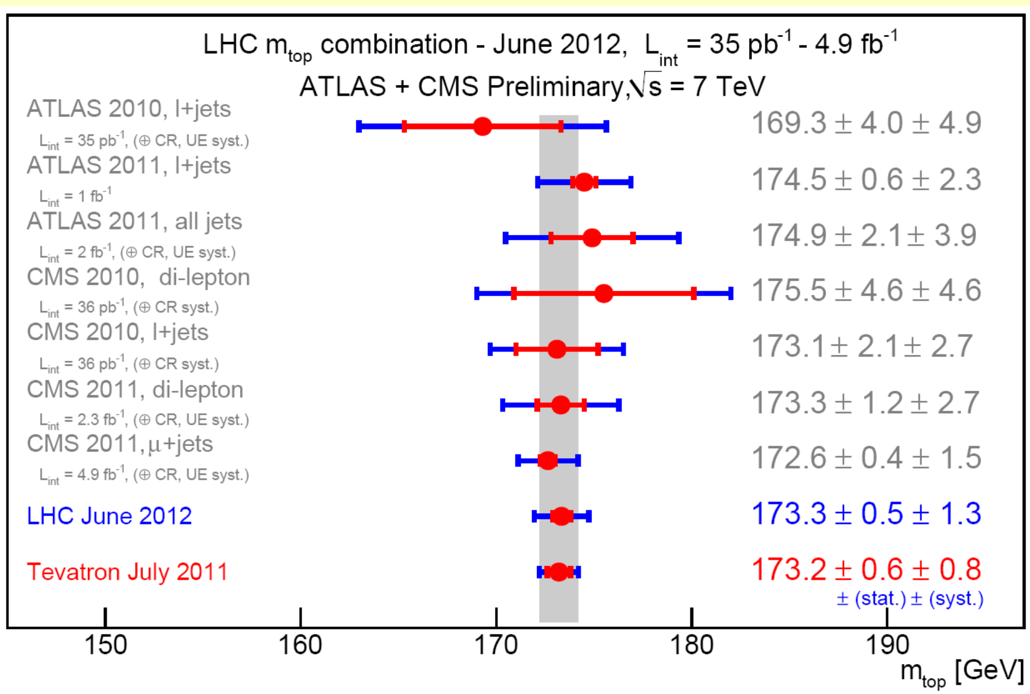
using a cross-section constraint

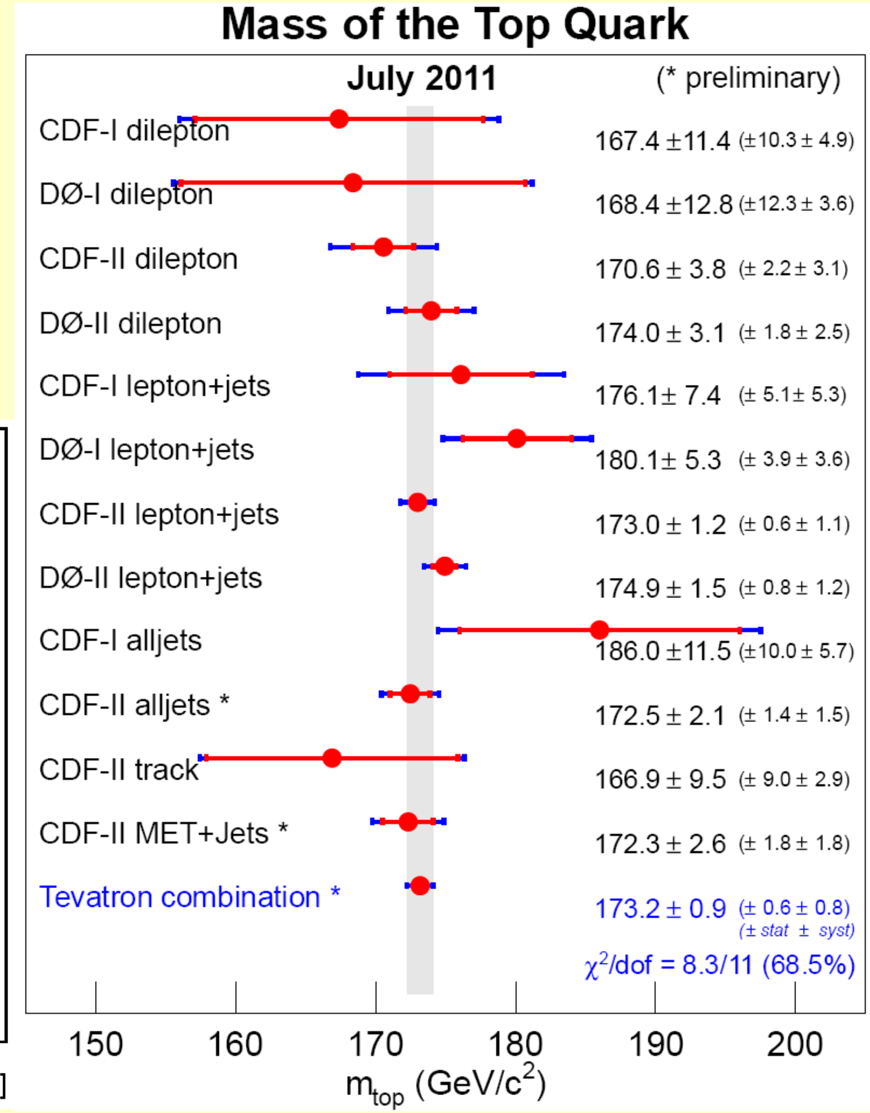
$$M_{top} = 170.7^{+4.2}_{-3.9}\ (\text{stat.})\ \pm 2.6\ (\text{syst.})\ \pm 2.4(\text{th.})\ \mathrm{GeV/c^2}$$

Top quark mass

Tevatron (CDF, D0) →

LHC: ATLAS, CMS



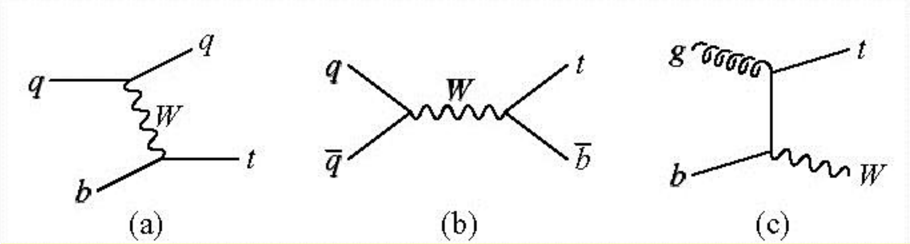


Single Top Quark production

Single top quark production

Production via weak forces

- Xsection~$|V_{tb}|^2$
  (direct measurement of V_{tb})
- Significant bckgd to Higgs signal
- Single top –100% polarization
  (test of V-A structure of EW)
- Possible new physics



t-channel s-channel assoc. prod.

	Tevatron	7 TeV LHC	14 TeV LHC
t ($\bar{t}$) "t"-ch	1.2	40 (20)	150 (100)
t ($\bar{t}$) "s"-ch	0.55	2.5 (1.4)	7 (4)
tW^-	0.15	8	45

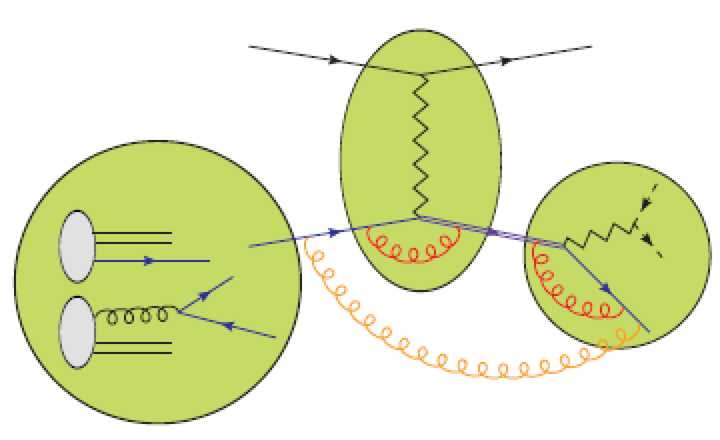
Signature of Single Top Event

- ✓ Only 1 isolated high p_T lepton (e or μ): p_T > 20 GeV
- ✓ High miss-p_T (E_T) > 25 GeV
- ✓ 2 or 3 high p_T jets: p_T > 20 GeV
- ✓ $\geq$ 1 b-tagged jet

Single top quark cross section

Present status:

- ✓ Production and decay are factorized
- ✓ NLO corrections in production
- ✓ resummation of soft logs
- ✓ top decay, at LO/NLO, spin correlations
- ✓ off-shell effects / non-factorizable corrections
- ✓ ***b*** quark issues (m_b mass) ...



Variety of theoretical approches:
Go to NNLO taking big logs

Single top: s-channel

Kidonakis m_t = 173 GeV

$$\sigma_{TeV} = 0.523^{+0.001\,+0.030}_{-0.005\,-0.028}\ \text{pb}$$

$$\sigma_{LHC} = 3.170\ ^{+0.06}_{-0.06}\ ^{+0.13}_{-0.10}\ \text{pb}$$

Zhu et al. m_t = 173.2 GeV

$$\sigma_{TeV} = 0.467^{+0.010}_{-0.010}\ \text{pb}$$

$$\sigma_{LHC} = 2.81\ ^{+0.16}_{-0.10}\ \text{pb}$$

Single top: t-channel and assoc.prod

Single top: t-channel, calculated at m_t = 173 GeV

Kidonakis[1103.2792]

$$\sigma_{TeV} = 1.04^{+0.00}_{-0.02} \pm 0.06 \text{ pb}$$

$$\sigma_{LHC7} = 41.7\,^{+1.6}_{-0.2} \pm 0.8 \text{pb}$$

$$\sigma_{LHC14} = 151\,^{+4}_{-1} \pm 3 \text{pb}$$

Zhu et al. [1010.4509]

$$\sigma_{TeV} = 0.982 \text{ pb}$$

$$\sigma_{LHC7} = 40.9\,^{+0.1}_{-0.1} \text{ pb}$$

$$\sigma_{LHC14} = 152.4\,^{+0.4}_{-1.0} \text{ pb}$$

An excellent compatibility of the theoretical calculations

W t production : Kidonakis [1005.4451], at m_t = 173 GeV

$$\sigma\left(tW^{-}\right) = 7.8 \pm 0.2\,^{+0.00}_{-0.02} \text{ pb}$$

- ✓ NLO → 'N'NLO: 8% increase at 7 TeV LHC
- ✓ At LHC assoc. production gives a noticeable contribution

Single top: experimental analysis

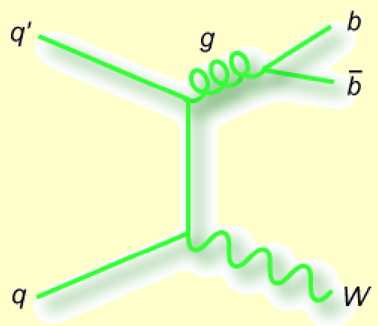
Single top quark production first observed by D0 and CDF in 2009

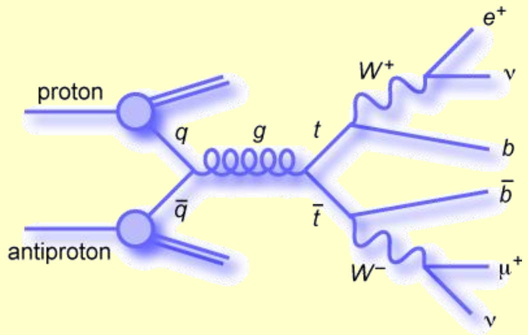
Main problem in experiment:
huge background – an example from
CDF andlysis at $L=3.2\ fb^{-1}$

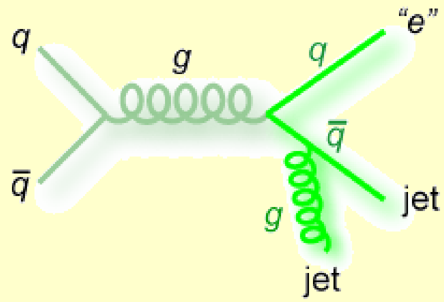
Single top	145.7 ±	21.4
Total background	2119.3 ±	350.9
Total prediction	2265.0 ±	375.4
Observed	2229	

Main Backgrounds

W + jets | top-antitop pairs | QCD multijet production







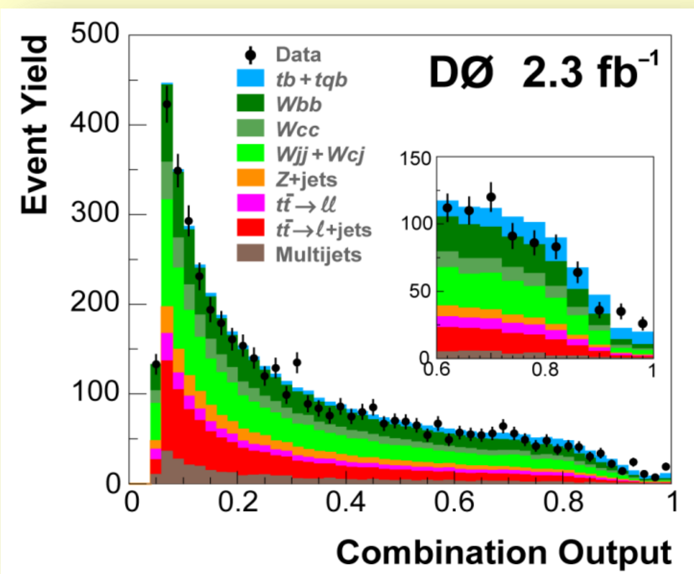
Multivariate techniques

To cope with background Multivariate techniques (MVT) are used:

- ✓ Neural Networks (NN)
- ✓ Boosted Decision Tree (BDT)
- ✓ Matrix Element (ME)
- ✓ Likelihood Discriminants (LD)

Basic idea: a set of different kinematic variables ($M_{l\nu b}$, H_T, M_{jj}, M_T...) is used as input for MVT which employ them to optimize Signal vs Background.

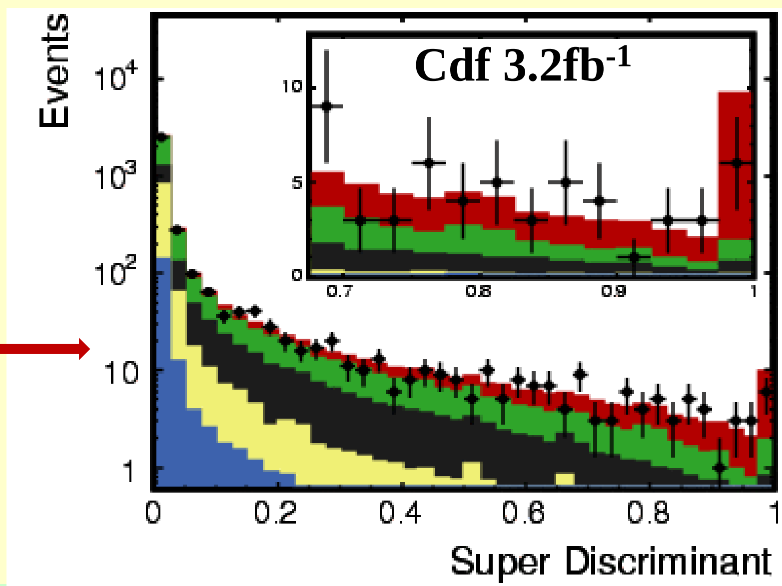
Output of MVT: output discriminat – a variable in (0,1) or (-1, 1)



p-value:

2.5×10^{-7}

3.1×10^{-7}



ATLAS: single top quark

Xsec of single top quark production in the t-channel, L=1.04 fb^{-1}, pp collision data at $\sqrt{s} = 7$ TeV

SM expectation: $\sigma_t = 64^{+2.7}_{-2.0}$ pb, $\sigma_{Wt} = 15.7 \pm 1.1$pb, $\sigma_s = 4.6 \pm 0.2$pb

Event selection: exactly one charged lepton (e or μ), two or three jets, and $\not{E}_T > 25\,\mathrm{GeV}$, $m_T(W) > \left(60\,\mathrm{GeV} - \not{E}_T\right)$

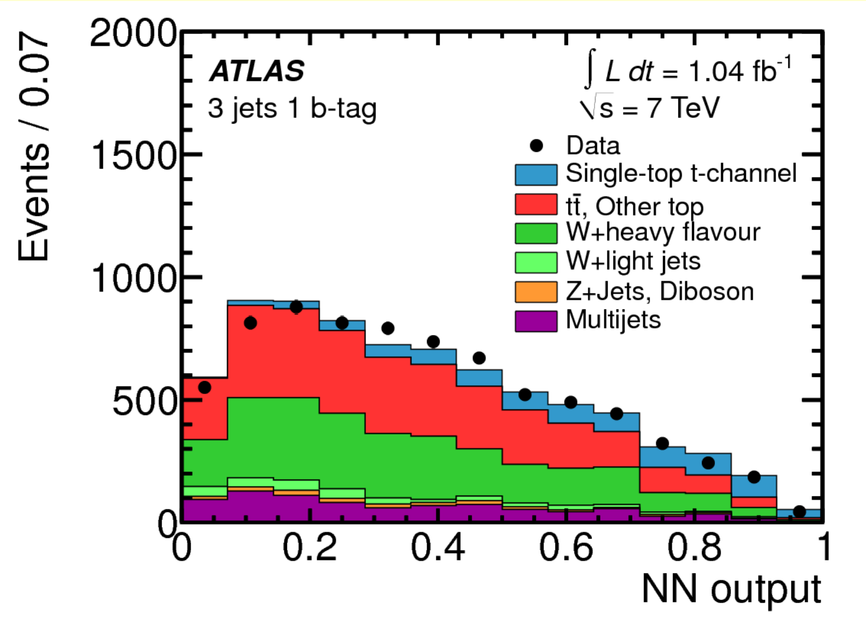
	Electron		Muon	
	2-jet	3-jet	2-jet	3-jet
single-top *t*-channel	447 ± 11	297 ± 7	492 ± 12	323 ± 8
$t\bar{t}$, other top	785 ± 52	1700 ± 120	801 ± 53	1740 ± 130
W+light jets	350 ± 100	128 ± 56	510 ± 150	209 ± 91
W+heavy flavour jets	2600 ± 740	1100 ± 400	3130 ± 880	1270 ± 480
Z+jets, diboson	158 ± 63	96 ± 44	166 ± 61	80 ± 31
Multijet	710 ± 350	580 ± 290	440 ± 220	270 ± 140
Total expected	5050 ± 830	3900 ± 520	5530 ± 930	3900 ± 520
Data	5021	3592	5592	3915

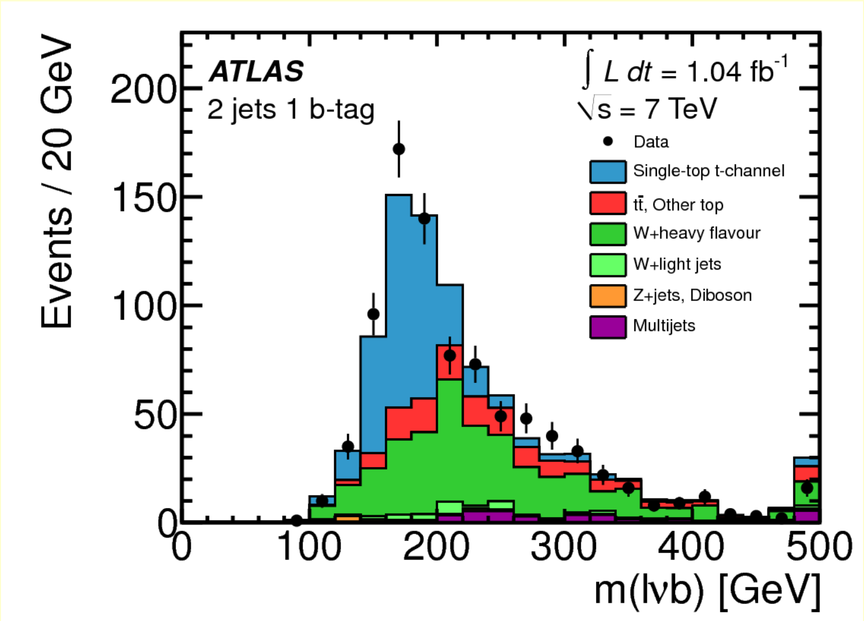
Higher # events than in CDF: 18300 vs 2200

Higher signal % : 8.5% vs 6.5%

NN discriminant: 12 input variables in the jet data set: $m(\ell\nu b)$, the highest p_T untagged jet $|\eta(j_u)|$ and $E_T(j_u)$ - most important

ATLAS: single top quark





Measured Xsec in the t-channel, simultaneous measurement in the 2-jet and 3-jet channels:

$$\sigma_t = 83 \pm 4(\text{stat})^{+20}_{-19}(\text{syst})\,\text{pb} = 83 \pm 20\,\text{pb}$$

Significance: *7.2σ*

$|V_{tb}|^2$ is extracted: ratio of the observed σ_t and SM expectation:

$|V_{tb}| = 1.13^{+20}_{-19}$ + the 95% C.L. lower limit $|V_{tb}|$ is 0.75.

(see arXiv.1205.3130, sub. Phys. Lett.B)

Thank you!