$t\bar{t}$ Cross Section Measurements At the Tevatron

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on behalf of CDF and D0 Collaborations

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TOP 2010

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Why Do We Study theTop Quark ?

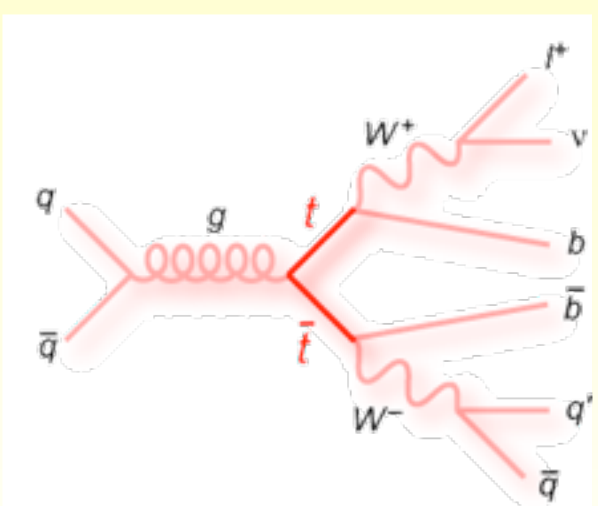
$$\mathcal{L}_{\text{Yukawa}} = -\lambda_t \overline{\psi_{Lt}} \Phi \psi_{Rt}$$

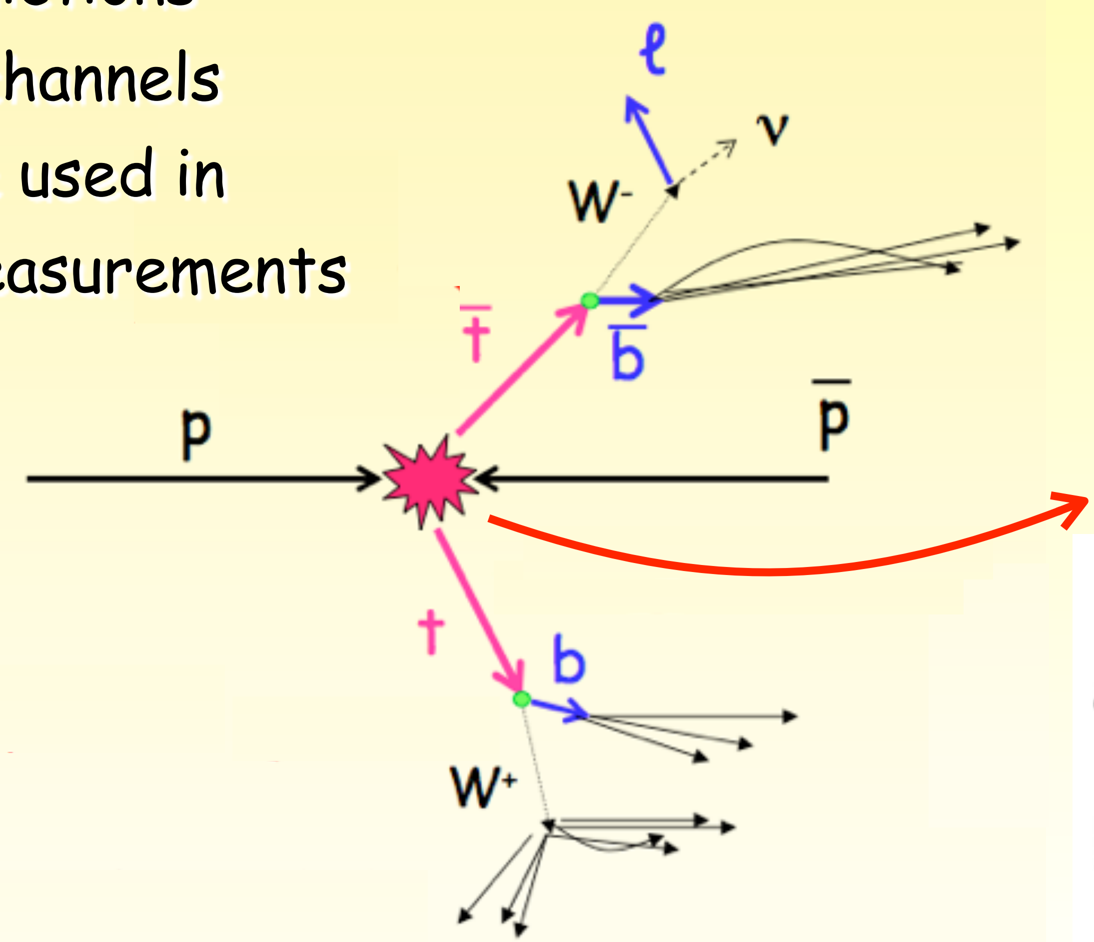
$$\lambda_t \approx 1??$$

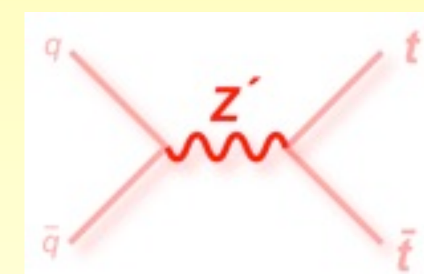
$$m_t >> m_b$$
$$\Gamma_t >> \Lambda_{QCD}$$

- The top quark is a special quark !
- What kind of role does it play in EW symmetry breaking ?

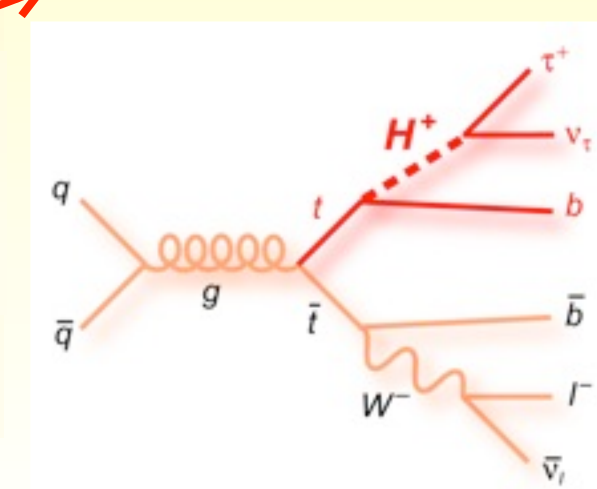
- Measure its strong production mechanism: $t\bar{t}$ cross section
  - compare with QCD predictions
  - measure in all possible channels
  - check $t\bar{t}$ selection to be used in the other properties measurements





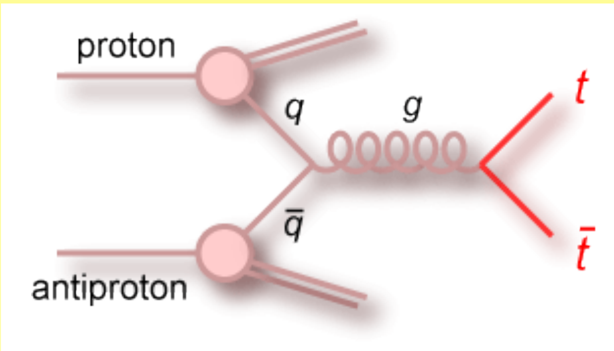


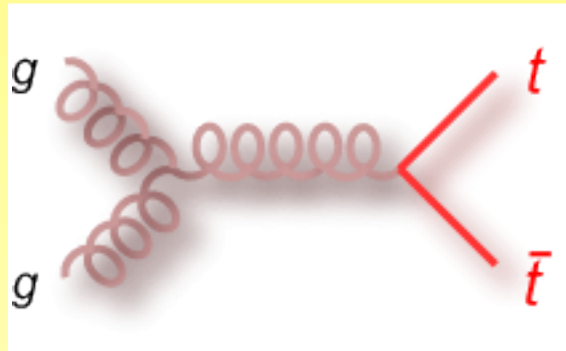
new physics ?



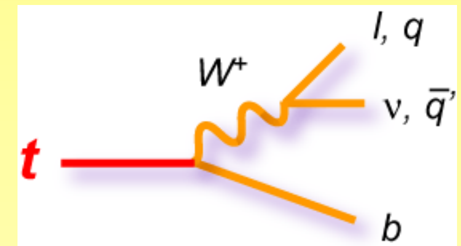
Top Strong Production and Decay At the Tevatron

- pair production and decay:





~ 85 %   ~ 15 %



B(t→Wb) ~ 100 %

- theoretical computations:

Mt = 172.5 GeV, $\sigma(t\bar{t}) \approx 7.5$ pb (~ NNLO)

S. Moch and P. Uwer	Phys. Rev. **D78** 034003 (2008)	$\sigma_{t\bar{t}} = 7.46^{+0.48}_{-0.67}$ pb
Kidonakis *et al.*	Phys. Rev. **D78** 074005 (2008)	$\sigma_{t\bar{t}} = 7.27^{+0.76}_{-0.85}$ pb
Cacciari *et al.*	JHEP **09** 127 (2008)	$\sigma_{t\bar{t}} = 7.14^{+0.76}_{-0.87}$ pb

$\Delta\sigma/\sigma \sim 8$ %

- comparison with LHC:

Mt = 172.5 GeV, $\sigma(t\bar{t}) \approx 161$ pb (@ 7 TeV)

with same ℓjets selection efficiency (4 jets): ~ 10 %

$$n_{t\bar{t}}(1fb^{-1} \text{ in one LHC exp.}) \approx 2n_{t\bar{t}}(10fb^{-1} \text{ in one Tevatron exp.})$$

We have large samples of $t\bar{t}$ events
A lot of our $t\bar{t}$ cross section measurements are already systematic limited

How Do We Measure the $t\bar{t}$ Cross Section ?

- Analysis strategy:

$$\sigma_{t\bar{t}} = \frac{N_{data} - N_{bkg}}{\epsilon_{t\bar{t}}(M_t)\int \mathcal{L}dt}$$

$\epsilon_{t\bar{t}}(M_t)$: from MC (Alpgen+Pythia or Pythia)

$\int \mathcal{L}dt$: analyzed integrated luminosity:
- removing poor quality data
- for the particular set of triggers used
- uncertainty: ~ 6 %

$$N_{data} - N_{bkg}$$

N_{bkg}:

$$(\epsilon_{bkg1}\sigma_{bkg1} + \epsilon_{bkg2}\sigma_{bkg2} + ...)\int \mathcal{L}dt$$

estimated by:
- event counting after selection cuts
- signal/background fit of a discriminant variable

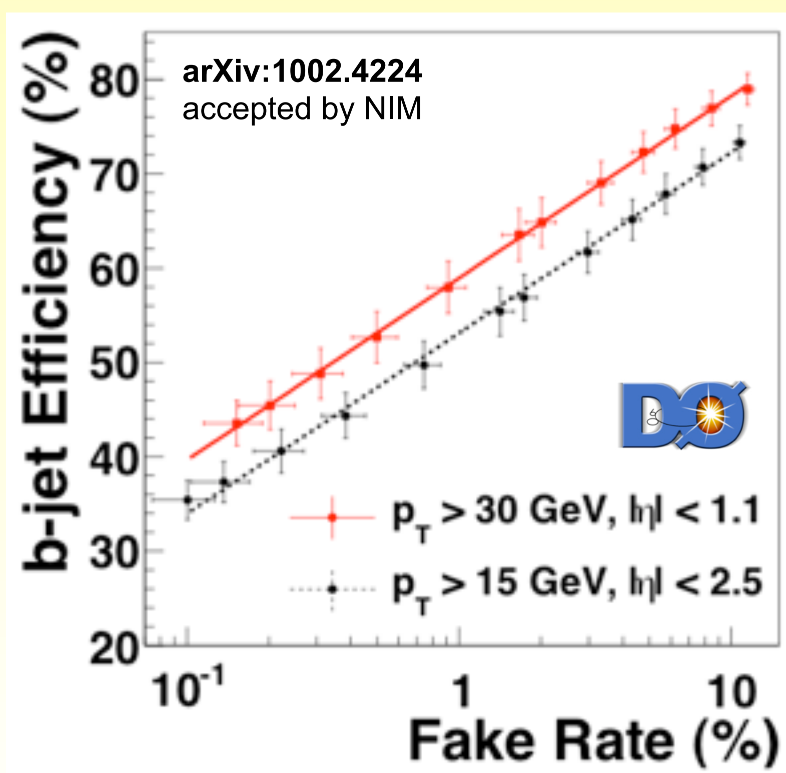
Channel	topological		b-tagging	
	counting	fit	counting	fit
ℓ jets		X	X	
$\ell\ell$	X		X	
$\ell\tau$			X	
all had				X

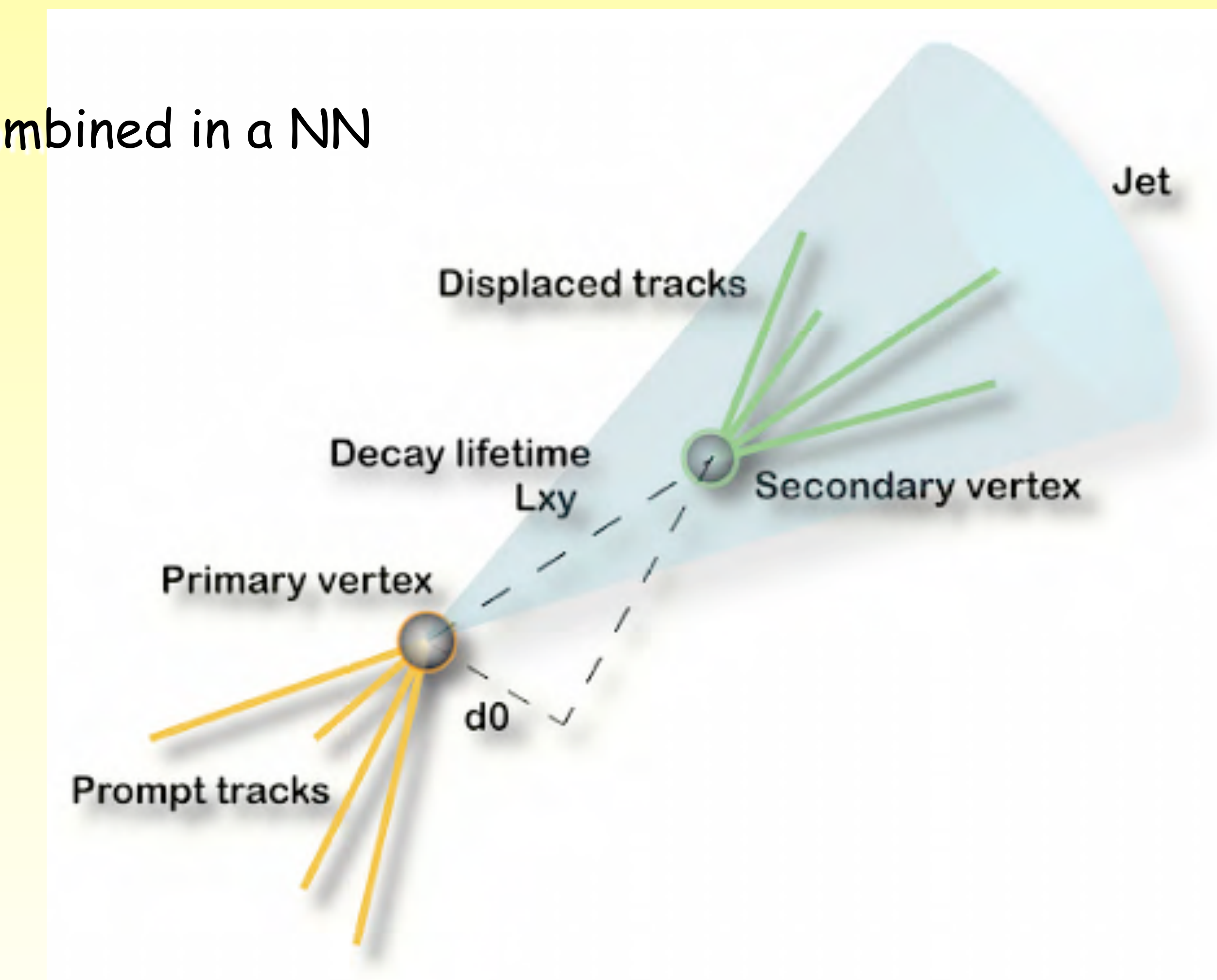
b Jet Tagging

- utilize b-jets special properties to separate them from light/gluon jets:
  - long b-hadrons decay length
  - b-hadrons semileptonic decay

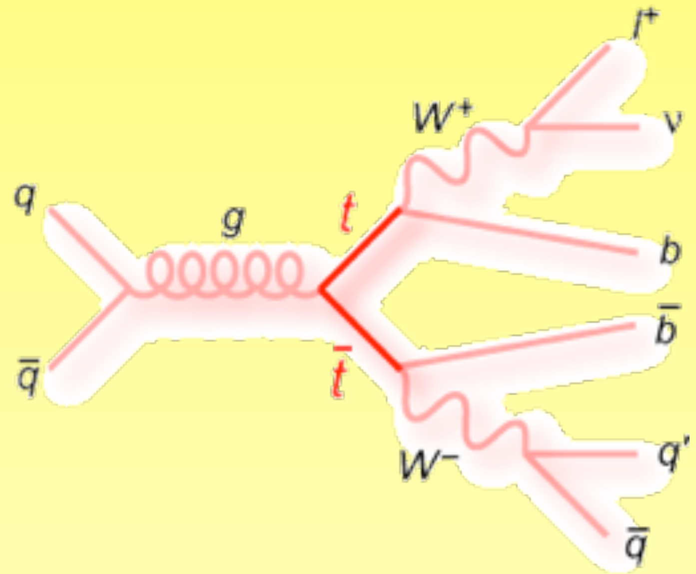
- 3 main b-tagging algorithms:
  - impact parameter based
  - secondary vertex reconstruction
  - soft lepton tag

  } combined in a NN

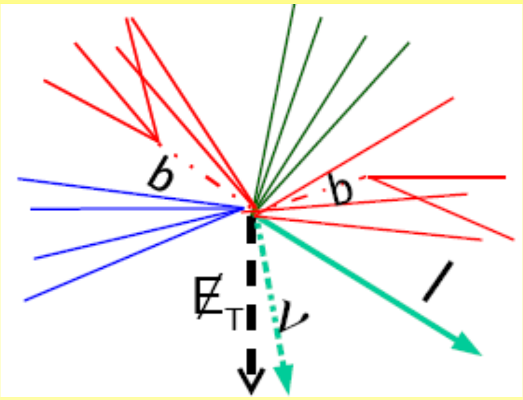




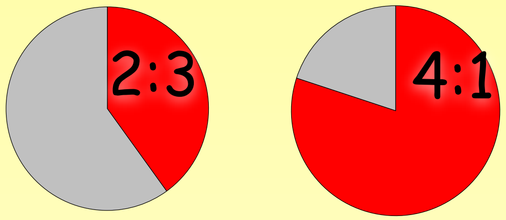
Lepton + Jets Channel



- signature:
  - high pt isolated lepton
  - large Missing Et (MET)
  - 4 jets (2 b-jets)



S/B (4 jets):



topological 1 b-tag

- main backgrounds:
  - W+jets (W+light, W+HF)
  - multijets
  - electroweak (Z+jets, diboson, single top)

W+jets → shape from MC (Alpgen), total among fitted to Data

multijets → no reliable estimation from MC
D0: data matrix method
CDF: fit the low part of the MET distribution

electroweak → using MC (Alpgen or Pythia, single top: CompHep or Madgraph)
normalized to the NLO cross sections

Multijet Background Estimation

- the matrix method:

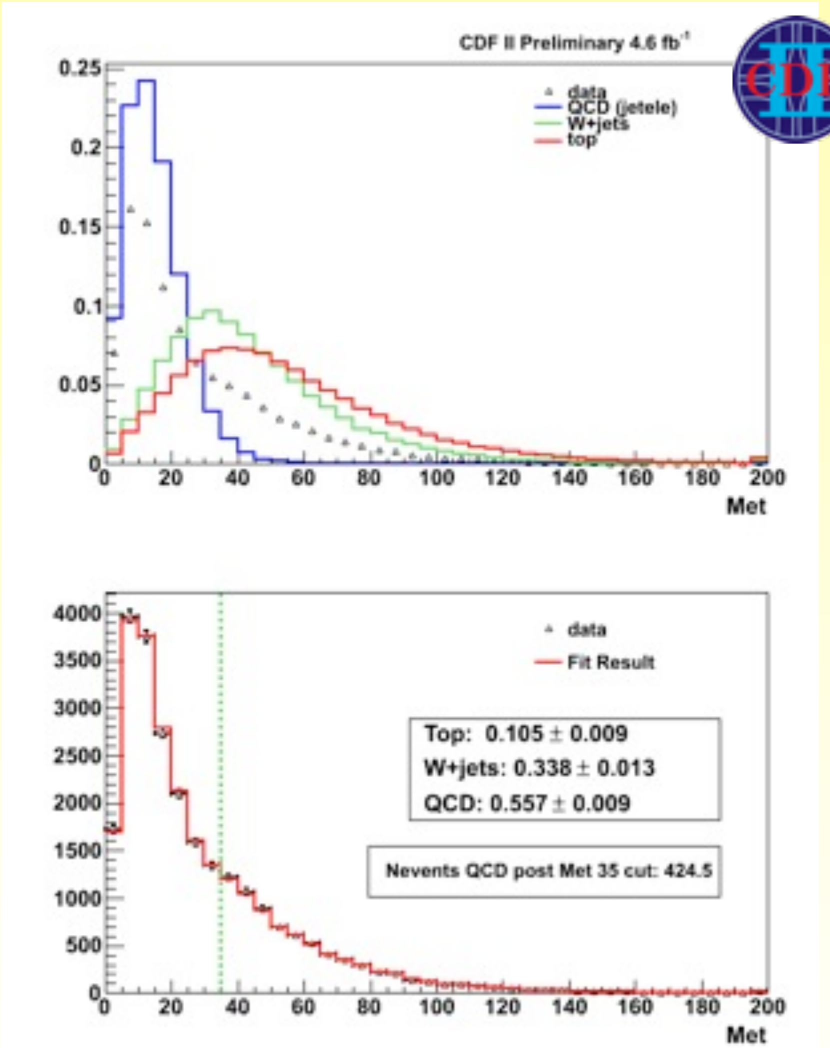
sample with loose isolated lepton: $N_{loose} = N_{QCD} + N_{signal}$ → W+jets, $t\bar{t}$, ...

subsample with tight isolated lepton: $N_{tight} = \epsilon_{QCD} N_{QCD} + \epsilon_{signal} N_{signal}$

(ϵ_{QCD}: low MET sample; ϵ_{signal}: from W MC)

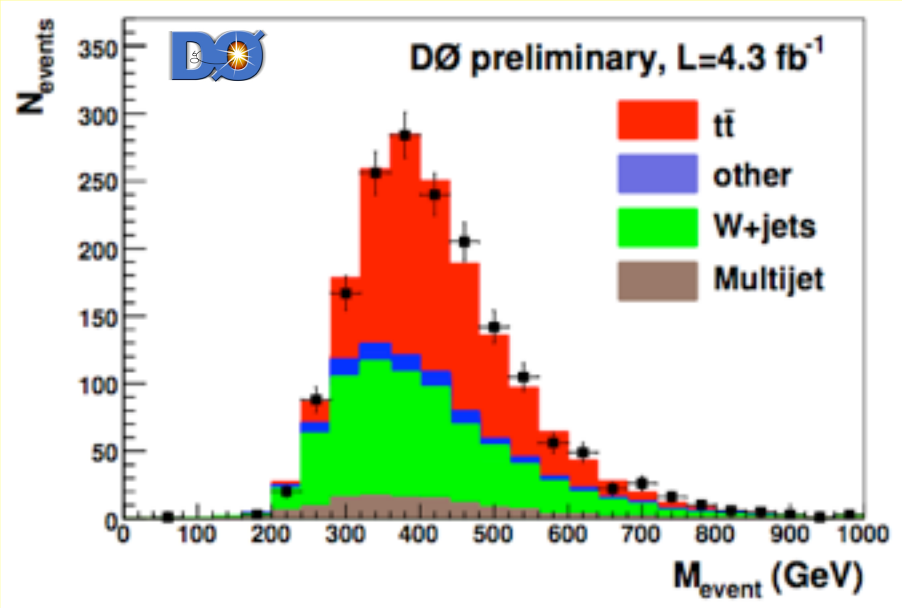
$$N_{QCD} = \frac{\epsilon_{signal} N_{loose} - N_{tight}}{\epsilon_{signal} - \epsilon_{QCD}}$$

- fit the low part of the MET distribution:
  - templates: multijets (data that fails lepton ID criteria), W+jets (Alpgen) and $t\bar{t}$ (Pythia)
  - fit the low MET part
  - extract fraction of multijets in the high MET part

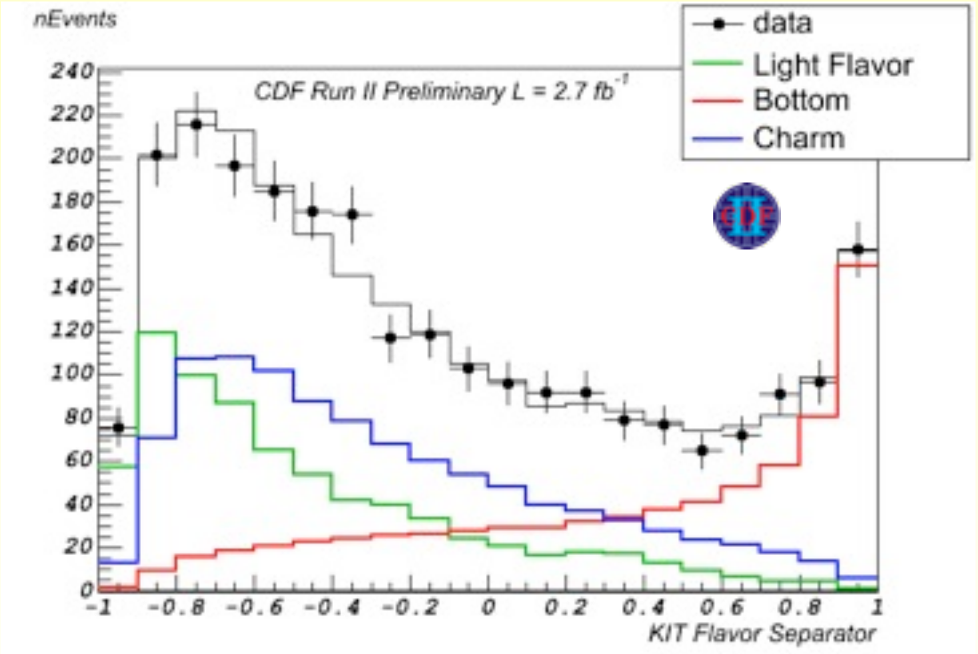


W+jets Normalization

- normalize to data before b-tagging:
  - shape from Algpen
  - $N_{W+jets} = N_{data} - N_{t\bar{t}} - N_{QCD} - N_{EW}$
  - in each jet multiplicity



- normalization of the W+heavy flavor fraction in W+jets:
  - W+HF cross section underestimated in the MC
  - W+HF content measured in data in the 1 or 1-2 jet event sample
    - NN trained to separate W+light from W+HF
    - scale the W+HF fraction to match the data (normalization extrapolated to higher jet multiplicities)



Lepton + Jets Topological Cross Section

- signal/background discrimination:
  - $t\bar{t}$ more energetic, central and isotropic than W+jets and multijets
  - NN (CDF) or BDT (D0) input variables: Ht, aplanarity, sphericity, ...
- cross section measurement:
  - template fit of $t\bar{t}$ and W+jets to the discriminant output

$\Delta\sigma / \sigma$ in %

Systematic	$t\bar{t}_{ANN}$
Luminosity	5.8
b-tag modeling	-
W+HF correction	-
Jet energy scale	2.9
Monte Carlo generator	2.6
Initial/final state radiation	0.4
PDF	0.9
Background shape model	1.9
Lepton ID/trigger	1.3
Total	7.5

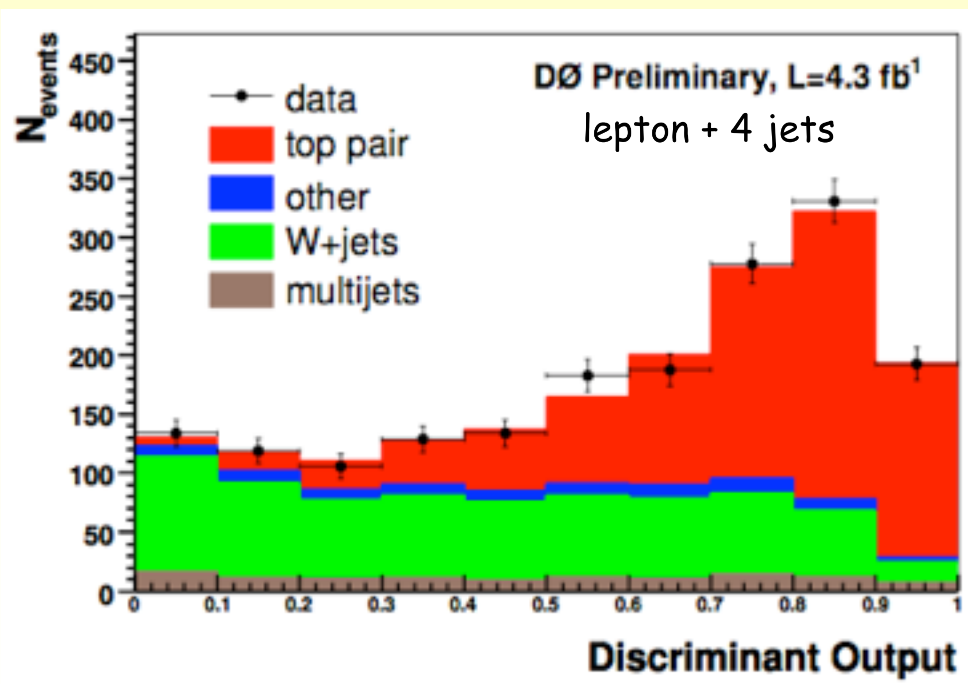
channel	$\sigma_{t\bar{t}}$[pb]
e+jets	$6.53^{+0.79}_{-0.69}$ (stat+syst)
μ+jets	$8.37^{+1.08}_{-0.93}$ (stat+syst)
ℓ+jets	$7.70^{+0.79}_{-0.70}$ (stat+syst)

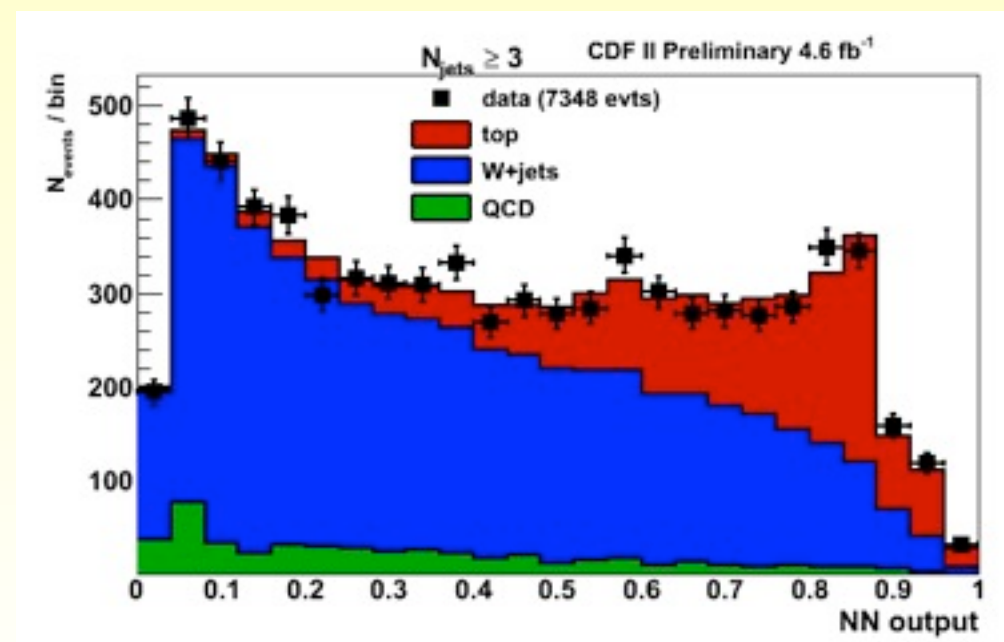
Mt = 172.5 GeV

$$\sigma_{t\bar{t}} = 7.71 \pm 0.37(\text{stat}) \pm 0.36(\text{sys}) \pm 0.45(\text{lumi})\text{pb}$$

Mt = 172.5 GeV

$\Delta\sigma / \sigma \sim 9$ %





Lepton + Jets Cross Section Using b-tagging

- counting by number of jets and b-tag jets:
  - b-tagging mistag rate measured in data, parametrization applied to W+jets

channel	sample	1 b-tag	≥ 2 b-tags
e+3 jets	W+jets	245 ± 25	20 ± 4
	Multijet	49 ± 8	4 ± 1
	Z+jets	20 ± 6	2 ± 1
	Other	29 ± 5	6 ± 1
	$t\bar{t}$	302 ± 25	120 ± 14
	Total	645 ± 33	153 ± 16
	Observed	648	154
e+4 jets	W+jets	41 ± 10	5 ± 1
	Multijet	15 ± 3	1 ± 0.2
	Z+jets	4 ± 2	0.4 ± 0.2
	Other	5 ± 1	1 ± 0.4
	$t\bar{t}$	229 ± 32	136 ± 19
	Total	294 ± 25	144 ± 19
	Observed	289	127

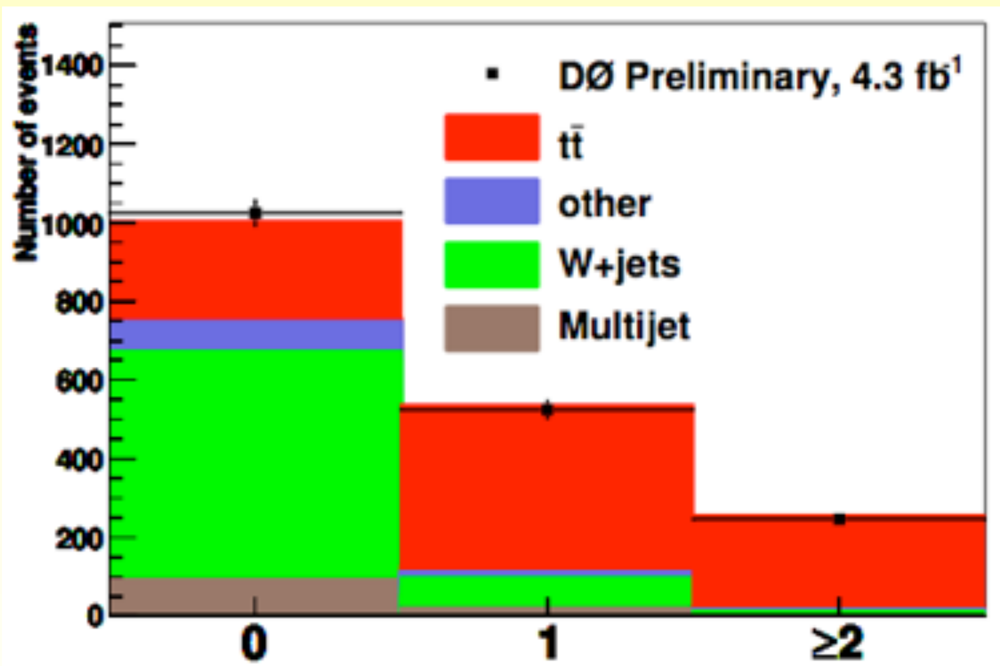
channel	$\sigma_{t\bar{t}}$[pb]
e+jets	$7.41^{+1.07}_{-0.96}$ (stat+syst)
μ+jets	$8.60^{+1.27}_{-1.06}$ (stat+syst)
ℓ+jets	$7.93^{+1.04}_{-0.91}$ (stat+syst)

Mt = 172.5 GeV

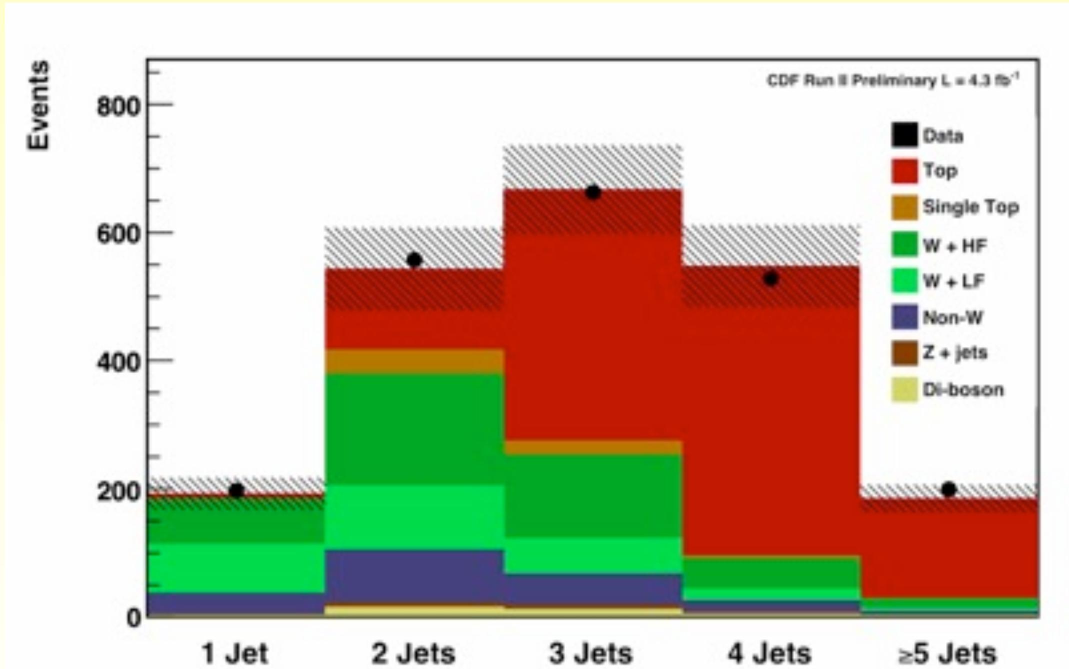
$$\sigma_{t\bar{t}} = 7.22 \pm 0.35(\text{stat}) \pm 0.56(\text{sys}) \pm 0.44(\text{lumi})\text{pb}$$

Mt = 172.5 GeV

$\Delta\sigma / \sigma \sim 11\,\%$



number of b-tagged jets



number of jets

$t\bar{t}$/Z Cross Section

submitted to PRL

- luminosity largest systematic uncertainty:
  - from luminosity detector acceptance and $p\bar{p}$ inelastic cross section
- remove luminosity uncertainty doing the ratio with the Z cross section:
  - $Z \rightarrow \ell\ell$ cross section measured with the same trigger
  - correlation of systematic uncertainties taken into account
  - multiply by the theoretical Z cross section:

$$\sigma_{t\bar{t}} = \left(\frac{\sigma_{t\bar{t}}}{\sigma_Z}\right)_{exp} (\sigma_Z)_{th}$$

$$(\sigma_{Z/\gamma^* \to \ell\ell})_{th} = 251.3 \pm 5.0 \text{ pb}$$

Eur. Phys. J. **C35**, 325 (2004)

- combination of the topological and b-tagging cross sections using BLUE

Systematic	$t\bar{t}_{tag}$	$t\bar{t}_{ANN}$	$Z/\gamma^* \to ll$
Luminosity	6.1	5.8	5.9
b-tag modeling	4.7	-	-
W+HF correction	4.0	-	-
Jet energy scale	4.1	2.9	-
Monte Carlo generator	2.7	2.6	-
Initial/final state radiation	0.6	0.4	-
PDF	0.6	0.9	1.4
Background shape model	0.2	1.9	0.3
Lepton ID/trigger	1.3	1.3	1.1
Total	10.0	7.5	6.2
Total $\sigma_{t\bar{t}}/\sigma_{Z/\gamma^* \to ll}$	8.2	4.7	

$$\text{topo}: \sigma_{t\bar{t}} = 7.82 \pm 0.38(\text{stat}) \pm 0.37(\text{sys}) \pm 0.15(\text{theory}) \text{ pb}$$

$$\text{b}-\text{tag}: \sigma_{t\bar{t}} = 7.32 \pm 0.36(\text{stat}) \pm 0.56(\text{sys}) \pm 0.14(\text{theory}) \text{ pb}$$

Mt = 172.5 GeV

combined:

$$\sigma_{t\bar{t}} = 7.70 \pm 0.52 \text{ pb}$$

$\Delta\sigma/\sigma \sim 6.8$ %

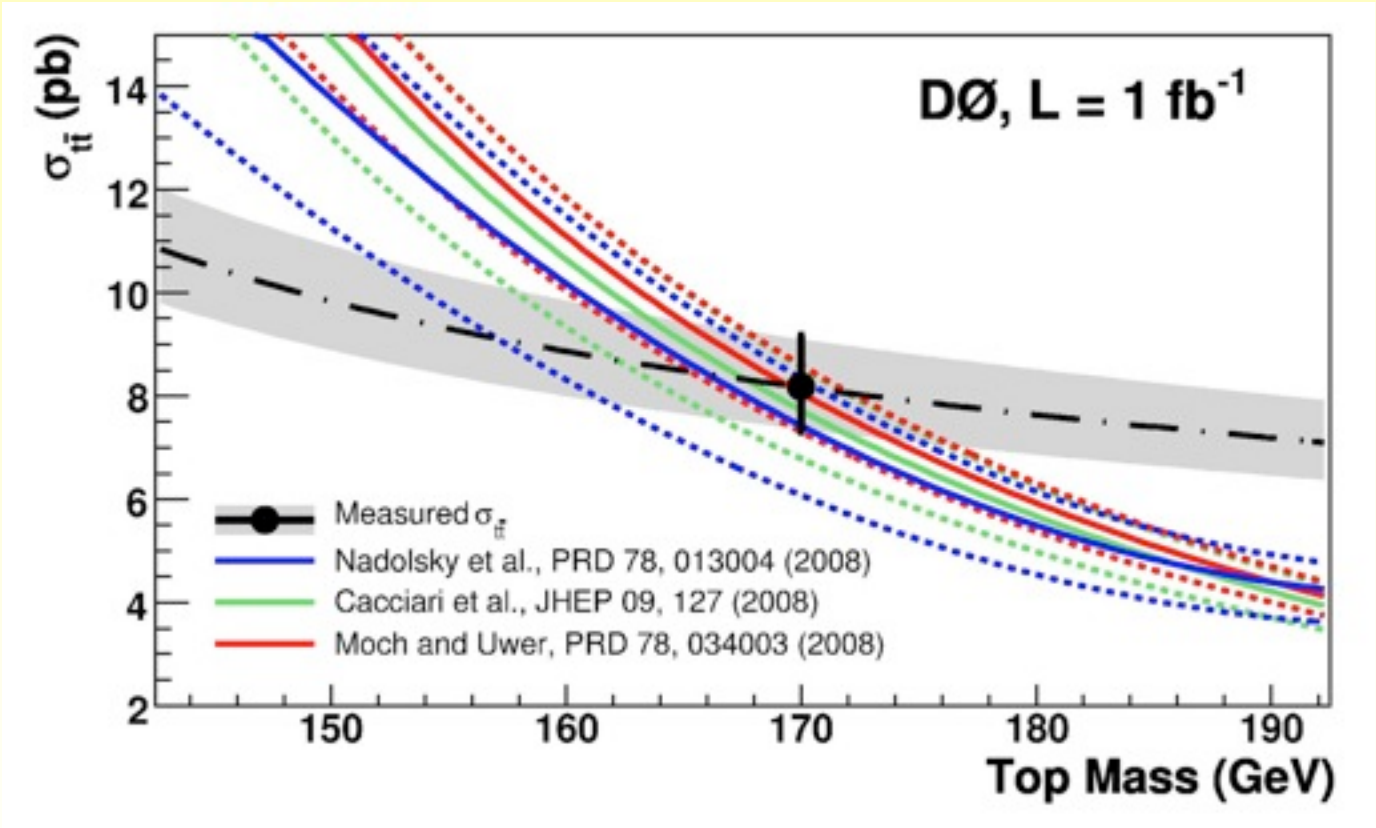
Mass Extraction From the Cross Section

PRD80 071102 (2009)

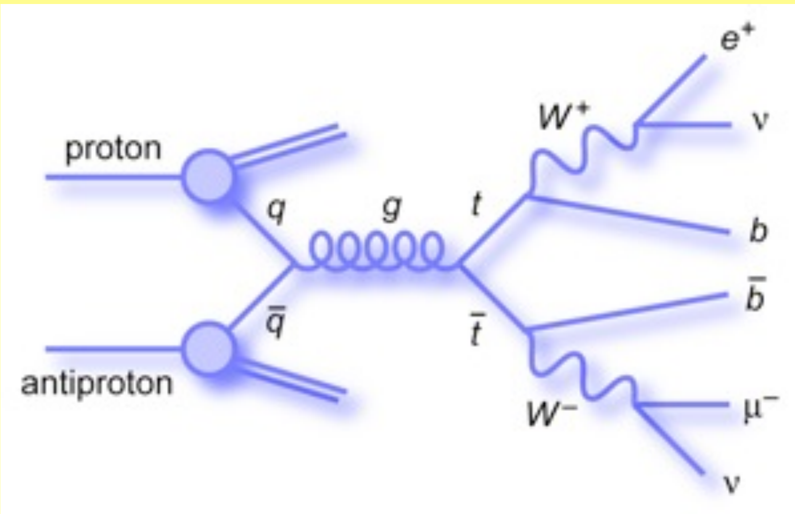
- indirect mass measurement less sensitive to any difference between pole mass and the mass used in the MC simulation used for direct measurements
- combine experimental and theoretical $t\bar{t}$ cross section vs top mass:
  - experimental dependency due to kinematics cut (selection efficiency)
  - theoretical: use the most accurate QCD computations (~NNLO)
- joint normalized likelihood function based on the theoretical and the total experimental uncertainty

Theoritical prediction	M_t (GeV)
NLO	$165.5^{+6.1}_{-5.9}$
Cacciari *et al.*	$167.5^{+5.8}_{-5.6}$
Moch and Uwer *et al.*	$169.1^{+5.9}_{-5.2}$
Kidonakis *et al.*	$168.2^{+5.9}_{-5.4}$

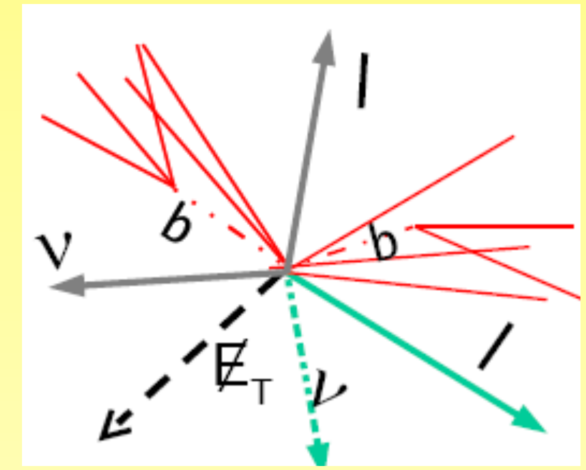
compatible with world average:
Mt = 173.1 ± 1.3 GeV



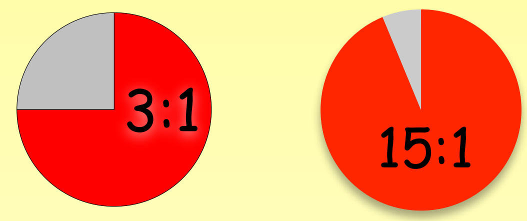
Dilepton Channel



- signature:
  - 2 high pt isolated leptons
  - large Missing Et (MET)
  - 2 b-jets



S/B:



topological 1 b-tag

- main backgrounds:
  - Drell-Yan, diboson → using MC (Alpgen or Pythia) normalized to the NLO cross sections. CDF: Z+jets contamination from high MET events in the Z mass range
  - Multijets (fake lepton) → estimated from data: fake rate using samples with one failing lepton criteria

Dilepton Cross Section

- signal/background discrimination
  - CDF: Ht and MET significance: MET divided by its error (ee/$\mu\mu$) cuts or b-tagging
  - D0: Ht cut and BDT trained against Z and diboson (ee/$\mu\mu$)

	ee	$e\mu$	$\mu\mu$
$Z \to \ell\ell$	$8.5^{+3.4}_{-3.4}$	$11.9^{+2.7}_{-2.5}$	$21.7^{+5.6}_{-6.2}$
Dibosons	$2.1^{+0.8}_{-0.8}$	$6.5^{+2.1}_{-2.0}$	$3.3^{+1.1}_{-1.2}$
Instrumental background	$0.1^{+0.2}_{-0.1}$	$10.7^{+4.1}_{-3.9}$	$3.2^{+0.8}_{-0.7}$
$t\bar{t} \to \ell\ell jj$ ($\sigma = 7.45$ pb)	$36.9^{+3.8}_{-3.8}$	143.4 ± 14.3	$45.1^{+4.4}_{-4.3}$
Total expected events	47.6 ± 6.2	$172.6^{+16.5}_{-16.4}$	$73.3^{+8.1}_{-8.8}$
Data	55	204	72

$t\bar{t}$ Signal Events with the tight SecVtx b-tag				
Source	ee	$\mu\mu$	$e\mu$	$\ell\ell$
WW	0.08±0.03	0.09±0.04	0.21±0.06	0.37±0.10
WZ	0.02±0.01	0.03±0.01	0.03±0.01	0.08±0.02
ZZ	0.08±0.06	0.07±0.06	0.02±0.02	0.17±0.14
DY+LF	0.51±0.05	0.60±0.05	0.28±0.03	1.39±0.12
DY+HF	0.51±0.04	1.41±0.11	0.37±0.03	2.28±0.18
Fakes	1.17±0.48	0.90±0.39	3.39±1.12	5.46±1.59
Total background	2.36±0.51	3.10±0.46	4.29±1.13	9.75±1.68
$t\bar{t}$ ($\sigma = 7.4$ pb)	30.22±1.91	29.63±1.87	70.10±4.38	129.96±8.10
Total SM expectation	32.59±2.32	32.73±2.25	74.39±5.42	139.71±9.66
Observed	22	44	71	137

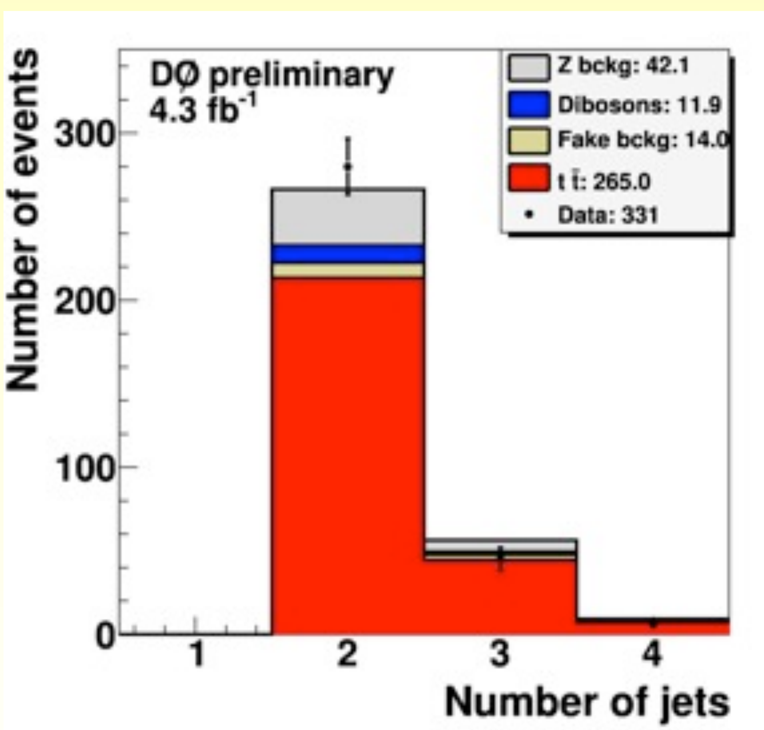
5.3 fb^{-1} DØ

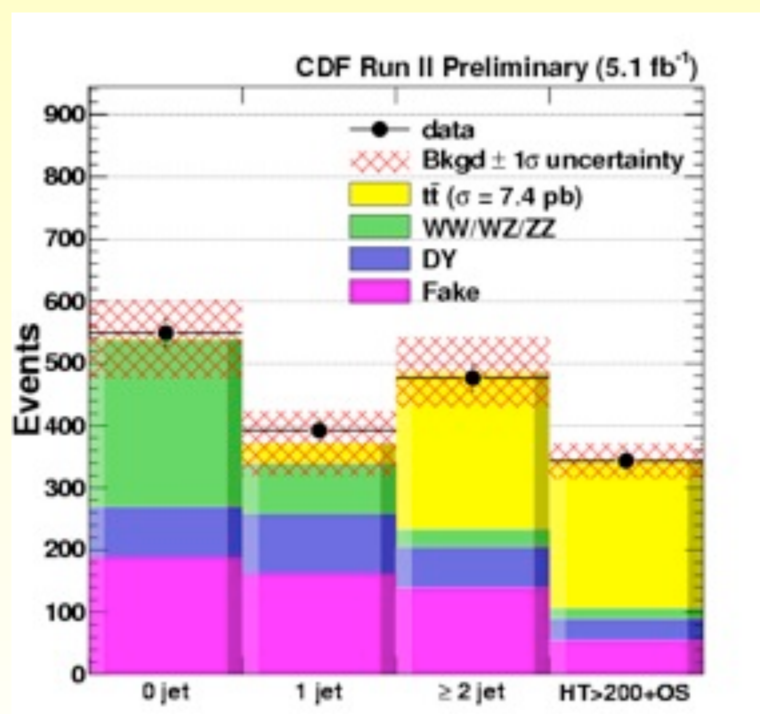
$$\sigma_{t\bar{t}} = 8.4 \pm 0.5\ (\text{stat})\ ^{+0.9}_{-0.8}\ (\text{syst})\ ^{+0.7}_{-0.6}\ (\text{lumi})\ \text{pb}.$$

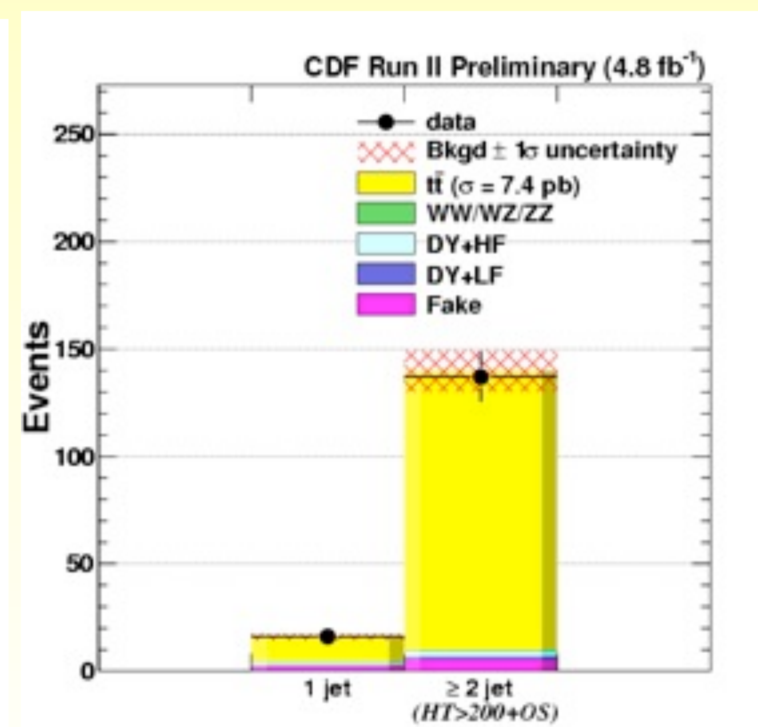
CDF

$$\text{topo} : \sigma_{t\bar{t}} = 7.40 \pm 0.58(\text{stat}) \pm 0.63(\text{sys}) \pm 0.45(\text{lumi})\ \text{pb}$$
$$\text{b-tag} : \sigma_{t\bar{t}} = 7.25 \pm 0.66(\text{stat}) \pm 0.47(\text{sys}) \pm 0.44(\text{lumi})\ \text{pb}$$

Mt = 172.5 GeV

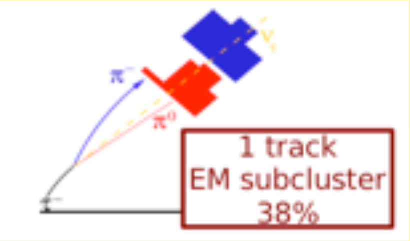


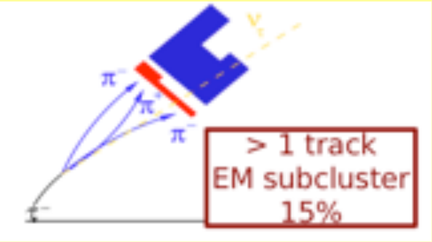




Lepton + τ Cross Section

- τ recontruction:
  - 3 NN depending of the τ decay types to separate from jets faking τ
  - 1 additional NN to separate τ type 2 from electron





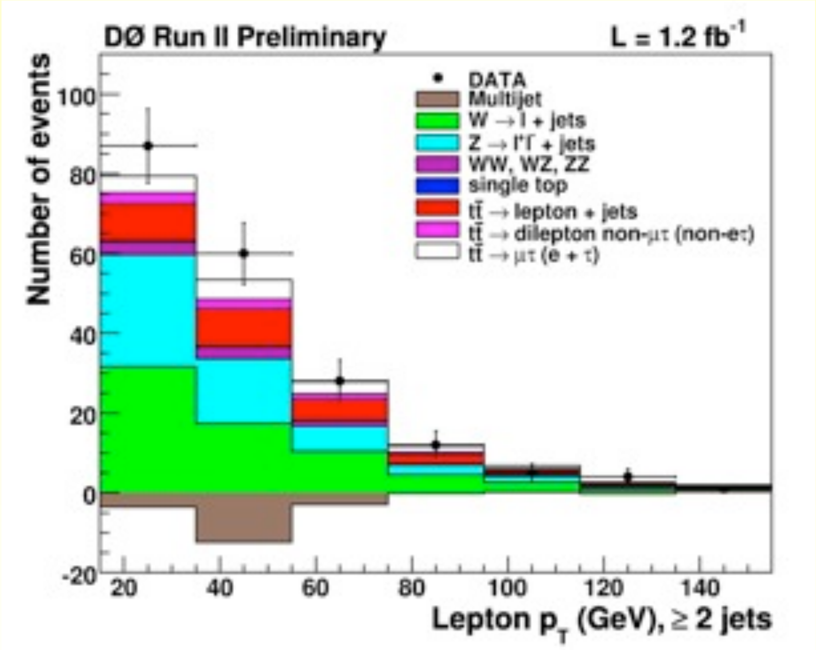
- main background after b-tagging:
  - W+jets (normalized to data), Z+jets, diboson from MC
  - Multijets from data (same sign events)

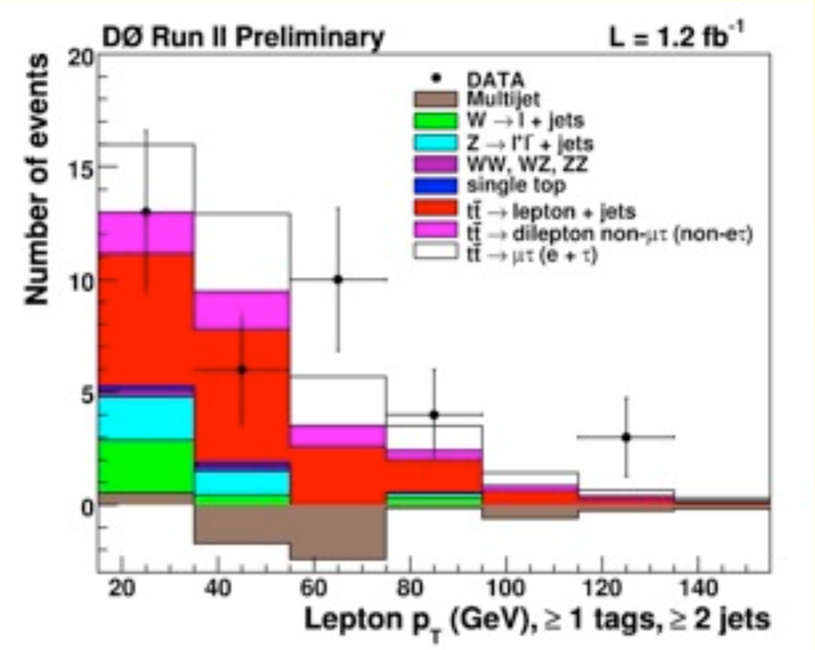
2.2 fb^{-1} DØ

$$\sigma(t\bar{t}) = 7.32^{+1.34}_{-1.24}(\text{stat})^{+1.20}_{-1.06}(\text{syst}) \pm 0.45(\text{lumi}) \text{ pb.}$$

Mt = 175 GeV

	$\mu\tau$ channel		$e\tau$ channel	
	before b-tagging	after b-tagging	before b-tagging	after b-tagging
Multijet	-16.38±6.25	-4.25±1.98	0.05±7.67	0.25±3.19
$W \to \ell\nu$ (+jets)	43.07±2.75	3.39±0.23	44.86±3.92	3.08±0.17
$Z \to \mu^-\mu^+(e^-e^+)$ (+jets)	19.69±0.73	1.52±0.05	7.51±0.51	0.47±0.03
$Z \to \tau^-\tau^+$ (+jets)	10.68±0.60	0.76±0.06	14.81±0.77	0.97±0.04
diboson	4.52±0.48	0.36±0.05	3.70±0.48	0.28±0.04
single top	0.49±0.01	0.25±0.01	0.49±0.01	0.26±0.01
$t\bar{t} \to \ell$+jets	11.97±0.18	7.46±0.13	15.61±0.22	9.95±0.16
$t\bar{t} \to \ell\ell$+jets non-$\mu\tau_h(e\tau_h)$	6.29±2.39	4.39±0.20	1.52±0.10	1.03±0.09
$t\bar{t} \to \mu\tau_h(e\tau_h)$+jets	7.45±0.07	5.24±0.05	7.82±0.07	5.52±0.06
total	87.79±6.91	19.12±2.00	96.28±8.68	21.32±3.20
data	103	19	94	17





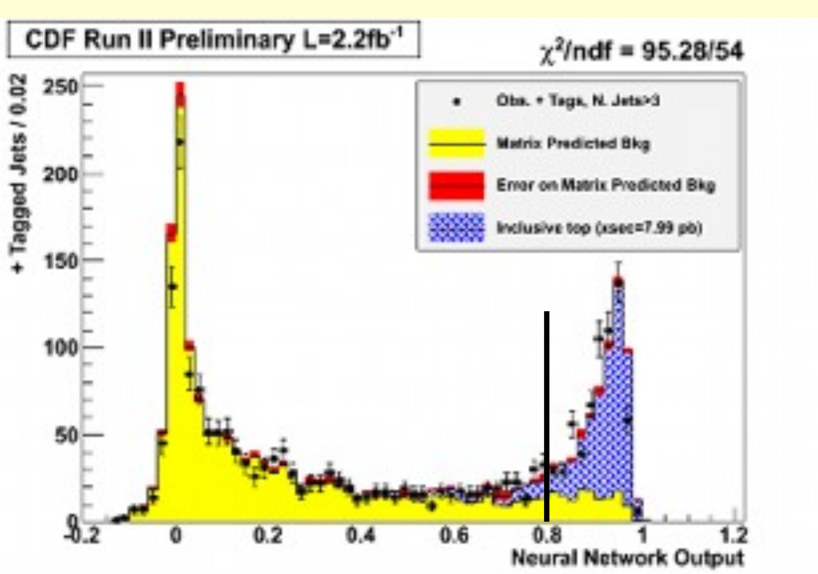
MET + Jets Cross Section

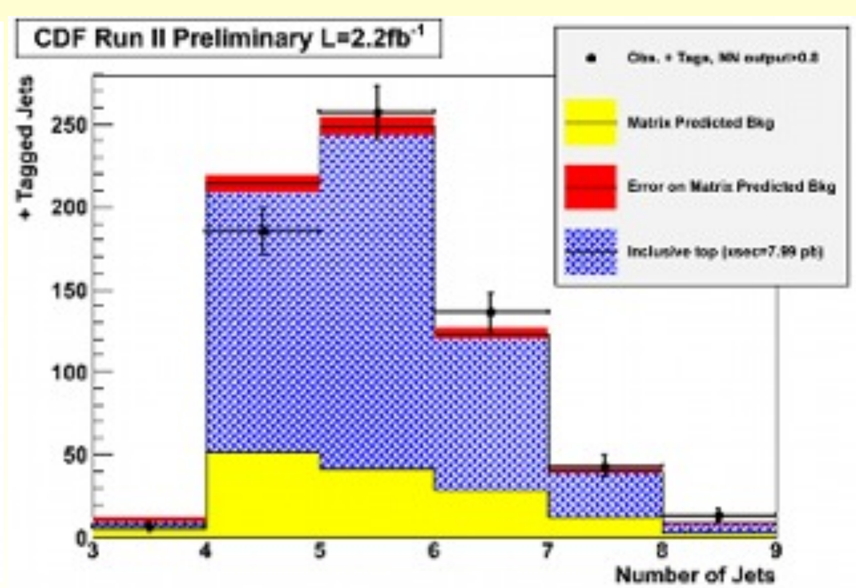
- MET + jets:
  - alternative way to select τ channels: large contribution from W ➔ τ ν
  - complementarity with channels with one identified lepton
- selection:
  - at least 3 strict identified jets
  - at least one b-tagged jet
  - NN trained against background, NN > 0.8
- background estimation:
  - b-tag rate/misrate evaluated from data in a 3 jet sample (small signal contamination)

sample composition	Tot.
all hadronic (%)	2.29
e +jets (%)	32.08
μ +jets (%)	22.71
dileptonic (%)	1.45
had. τ +jets (%)	27.73
lep. τ +jets (%)	10.76
$\tau\tau$ (%)	0.77
$e/\mu + \tau$ (%)	2.16

$$\sigma_{t\bar{t}} = 7.99 \pm 0.55 \text{ (stat)} \pm 0.76 \text{ (syst)} \pm 0.46 \text{ (lumi) } pb$$

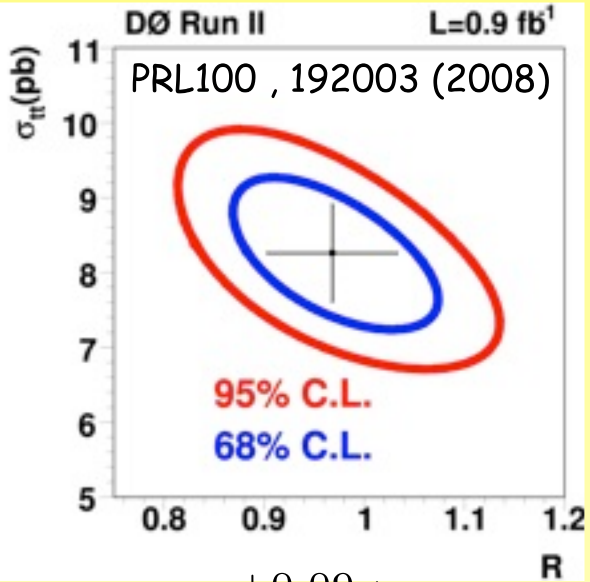
Mt = 172.5 GeV





Cross Section Ratio and Charged Higgs Searches

- cross section with different number of b-tag jets:
  - ℓjets with 0, 1 or 2 b-tag jets: $R = \dfrac{B(t \to Wb)}{B(t \to Wq)}$

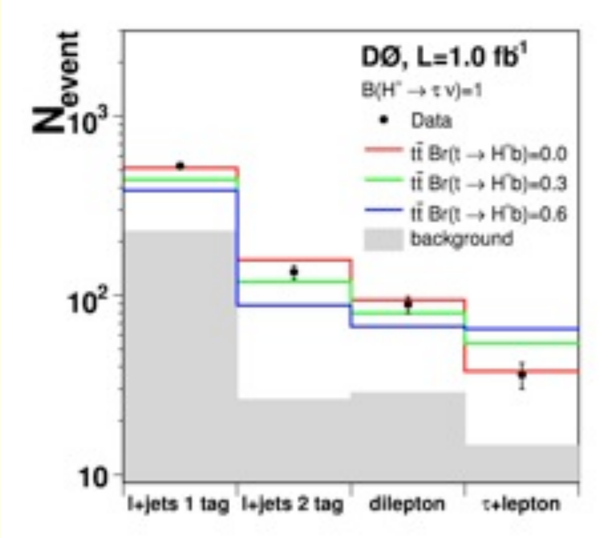


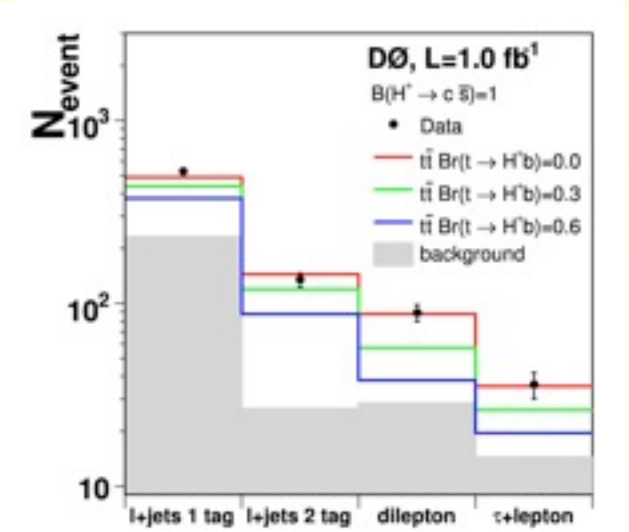
$R = 0.96^{+0.09}_{-0.08}(\mathrm{stat}+\mathrm{sys})$

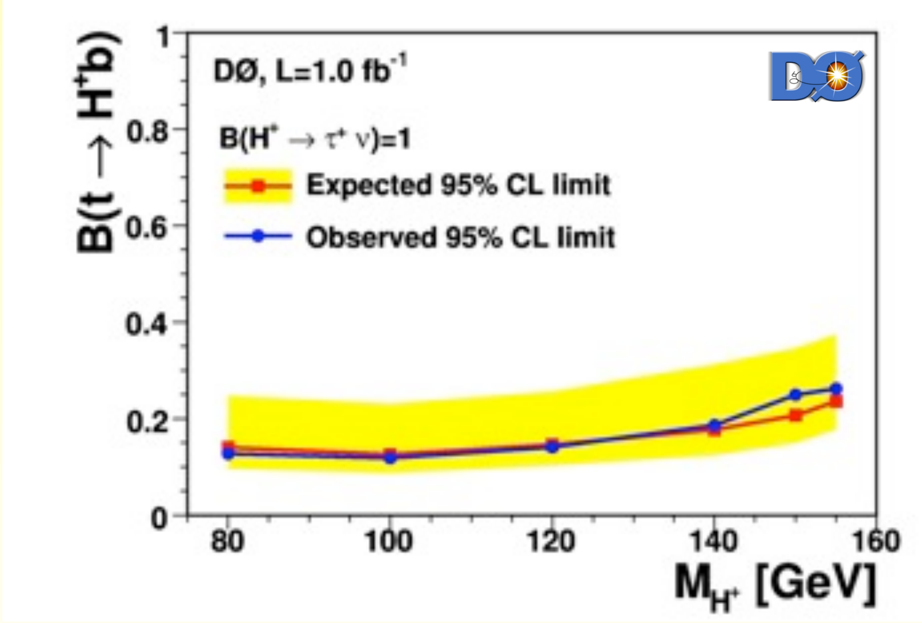
- cross section in different channels sensitive to new physics:
  - number of events in ℓjets, ℓℓ and ℓτ :

in SM extension with extended Higgs sector (like MSSM or HDM) t ➔ H^+b can compete with t ➔ Wb

Search here for H^+ ➔ $\tau\ \nu$ or $c\bar{s}$

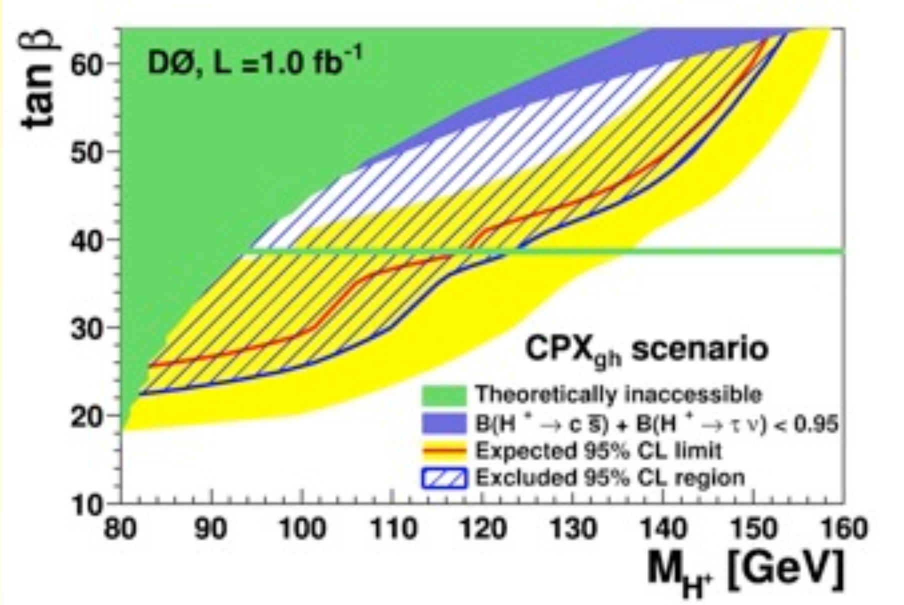






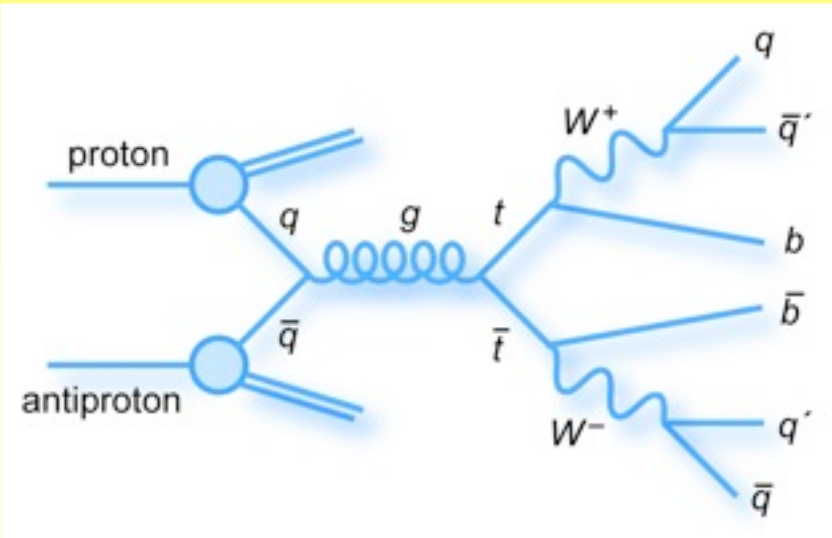
interpretation in the CPX scenario (strangephilic MSSM Higgs)

Eur.Phys.J **C66** 261-269,2010



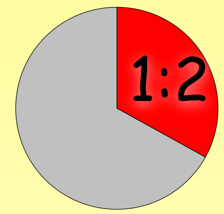
PLB 682, 278 (2009)

All Hadronic Channel

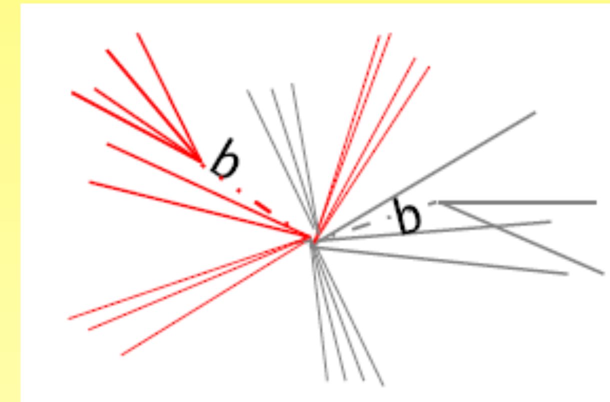


- signature:
  - 6 jets (2 b-jets)

S/B:



b-tagging



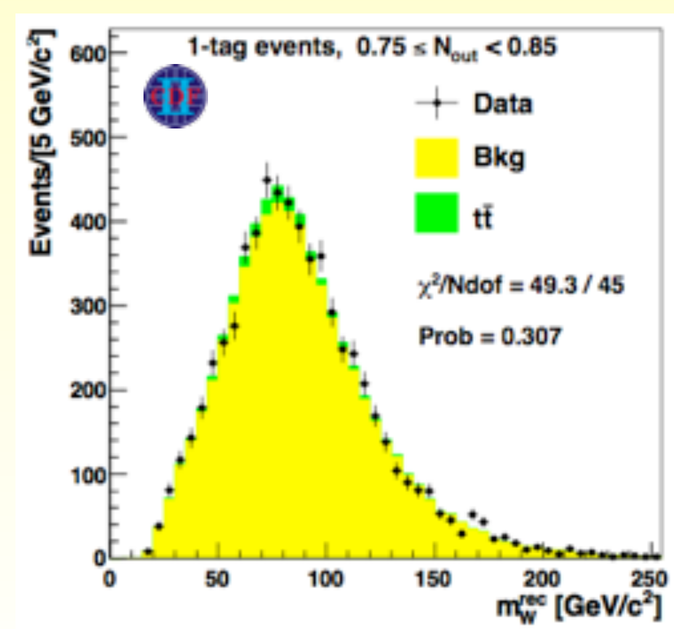
- main background:
  - Multijets: ~ cross section 3 orders of magnitude
    - estimated from data
    - b-tagging essential

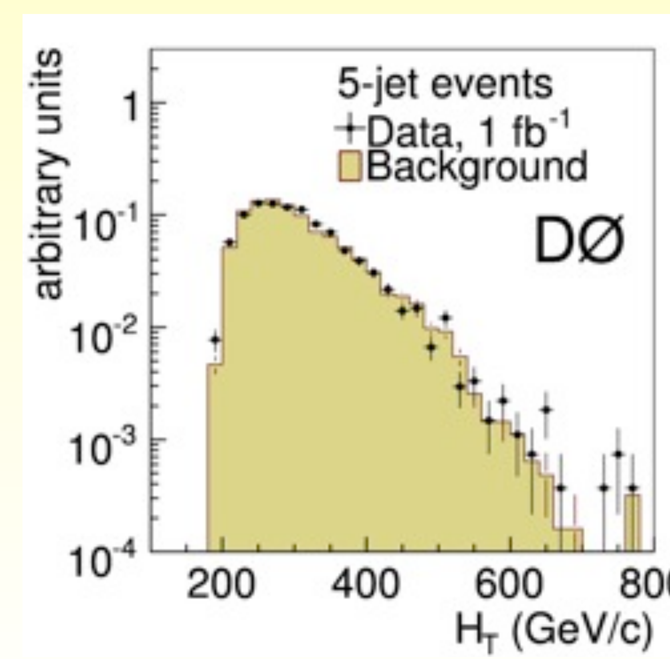
CDF: tag rate per jet evaluated using 4 jets events
D0: adding 1 jet to 5 jets events after 2 b-tags

signal sample:

CDF: $6 \leq N_{jets} \leq 8$

D0: $6 \leq N_{jets}$





All Hadronic Cross Section

- built a discriminant:
  - CDF: NN, D0: Likelihood
  - input variables: Ht, invariant masses, centrality, ...

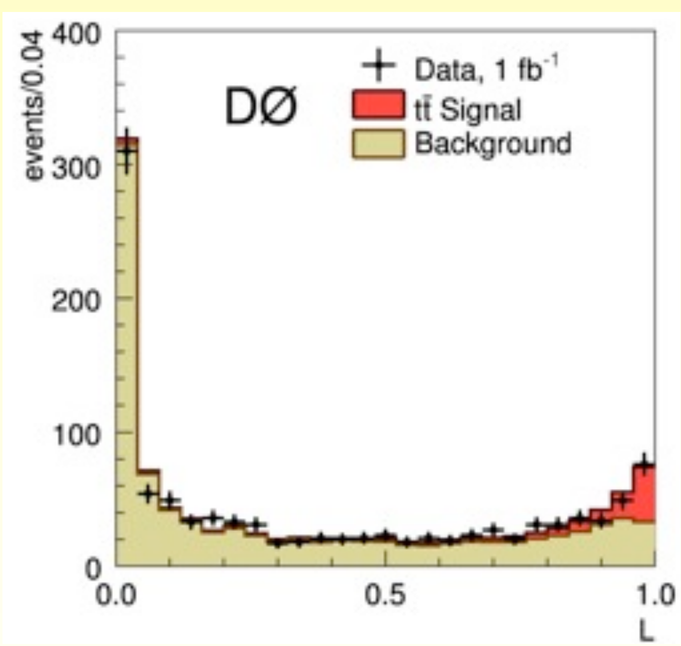
submitted to PRD

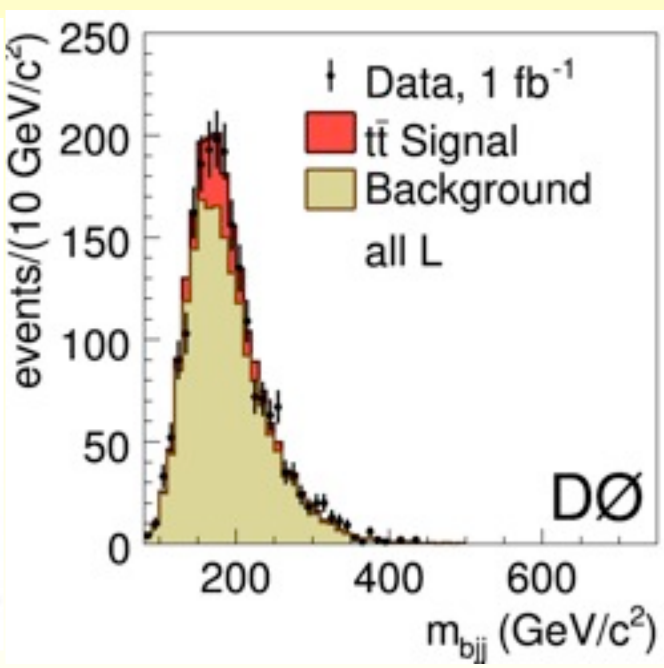
$$\sigma_{t\bar{t}}^{175\,\mathrm{GeV}/c^2} = 6.9 \pm 1.3\,(\mathrm{stat}) \pm 1.4\,(\mathrm{sys}) \pm 0.4\,(\mathrm{lum})\ \mathrm{pb}$$

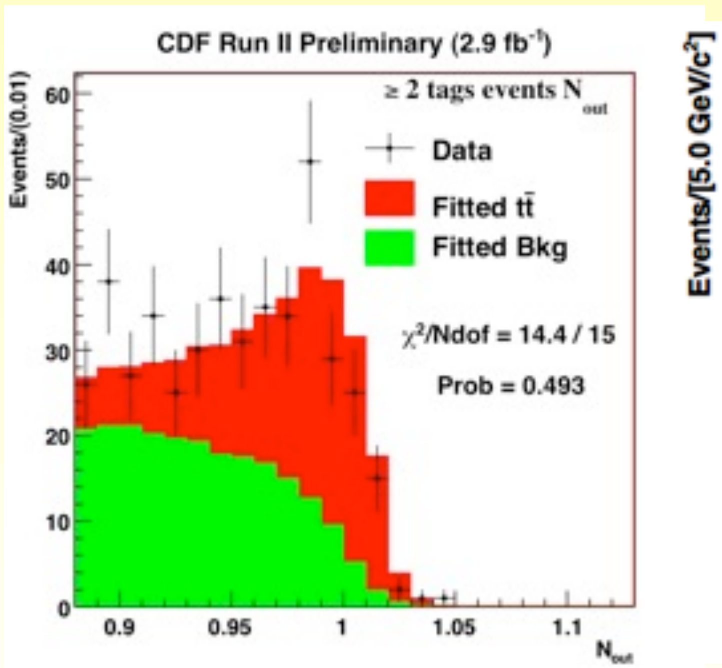
PRD 81, 052011 (2010)

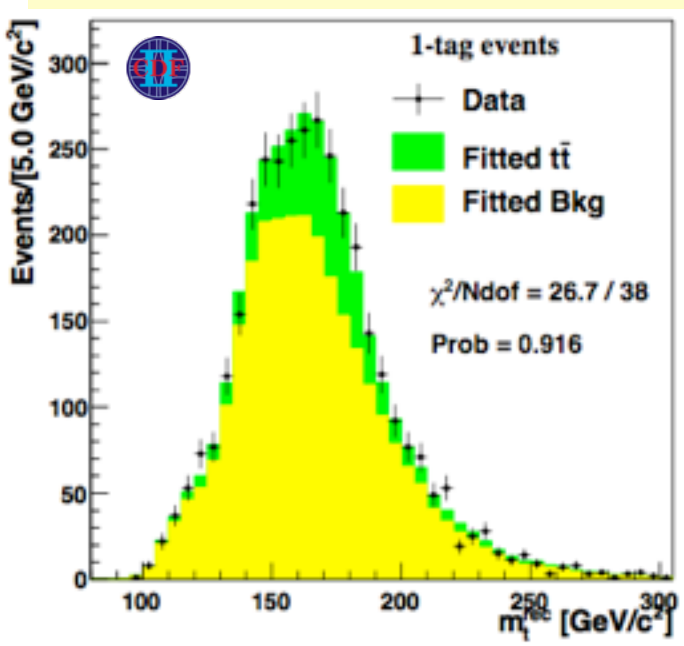
$$\sigma_{t\bar{t}} = 7.2 \pm 0.5(\mathrm{stat}) \pm 1.0(\mathrm{syst}) \pm 0.4(\mathrm{lum})\ \mathrm{pb}$$

Mt = 175 GeV

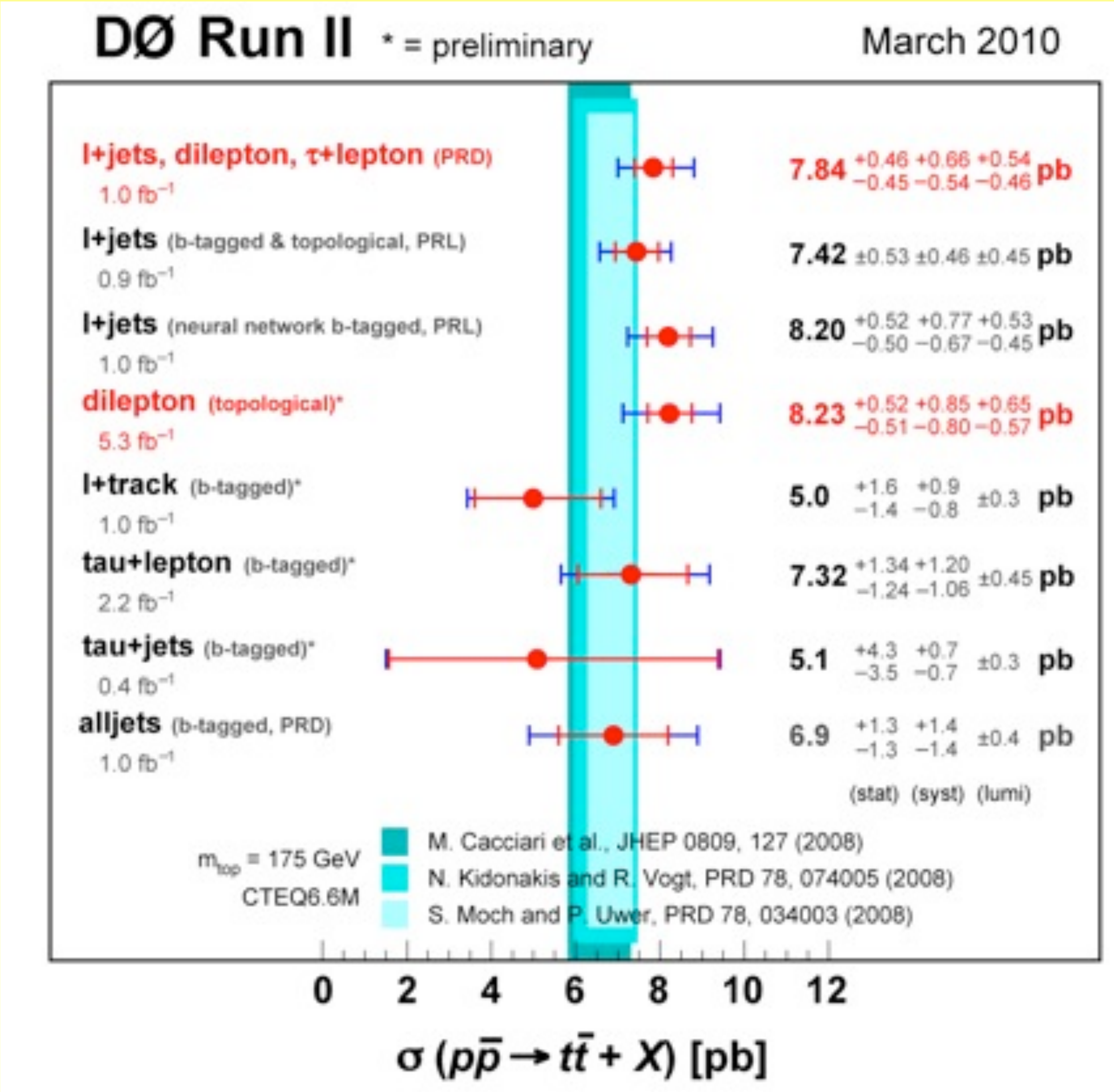


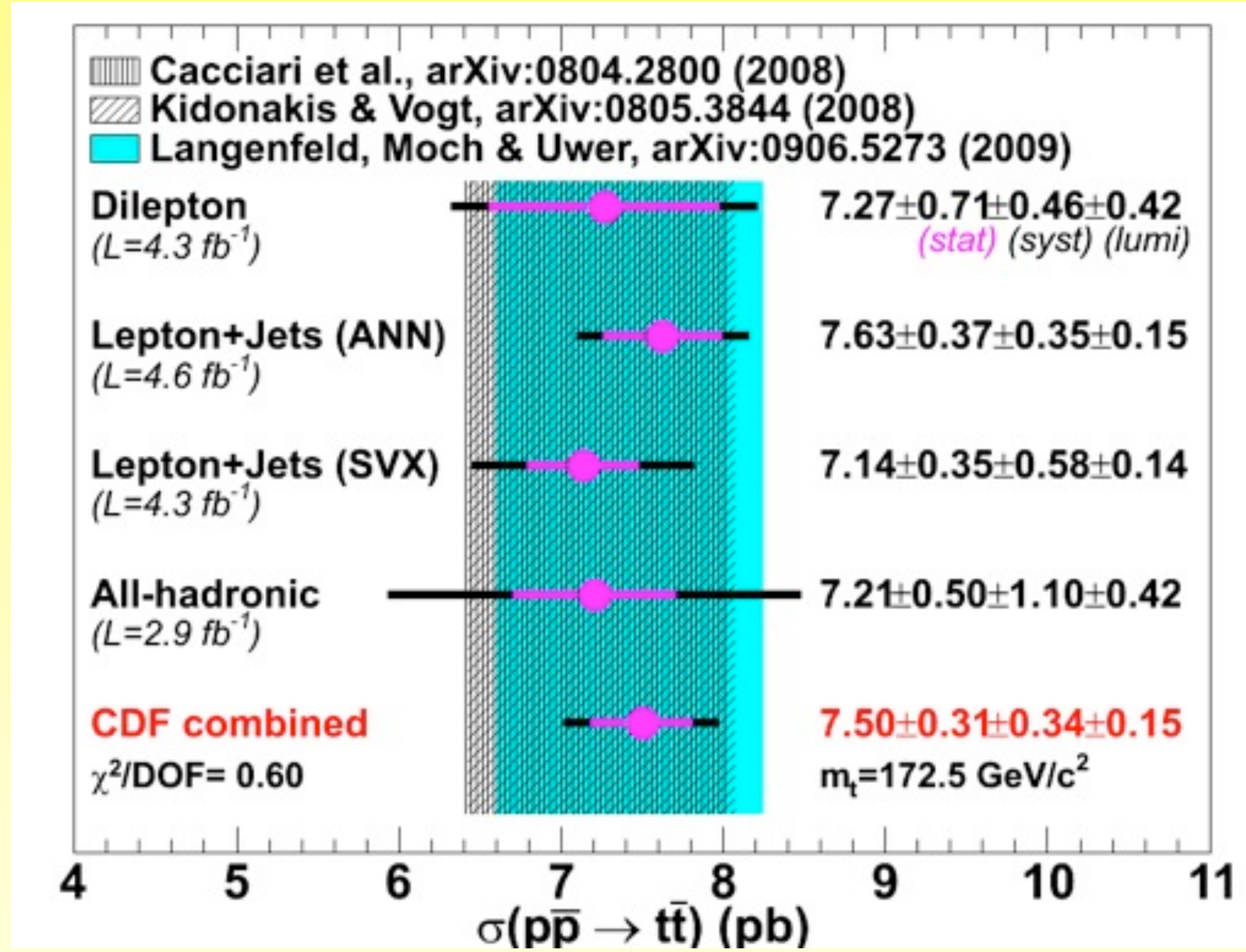






Summary of the Tevatron $t\bar{t}$ Cross Section





- *measurements in all the possible channels*
- *consistent with SM expectation*
- *CDF/D0 Combination:*

  - work in progress based on the example of the mass combination

$t\bar{t}$ + jets Cross Section

- test of QCD prediction, sensitive to NLO effects, different FB asymmetry than inclusive $t\bar{t}$
- lepton + jets selection:
  - W+jets: normalized to data before tagging
  - Multijets: estimated by a fit at the low MET
- simultaneous fit of $t\bar{t}$+0j and $t\bar{t}$+1j

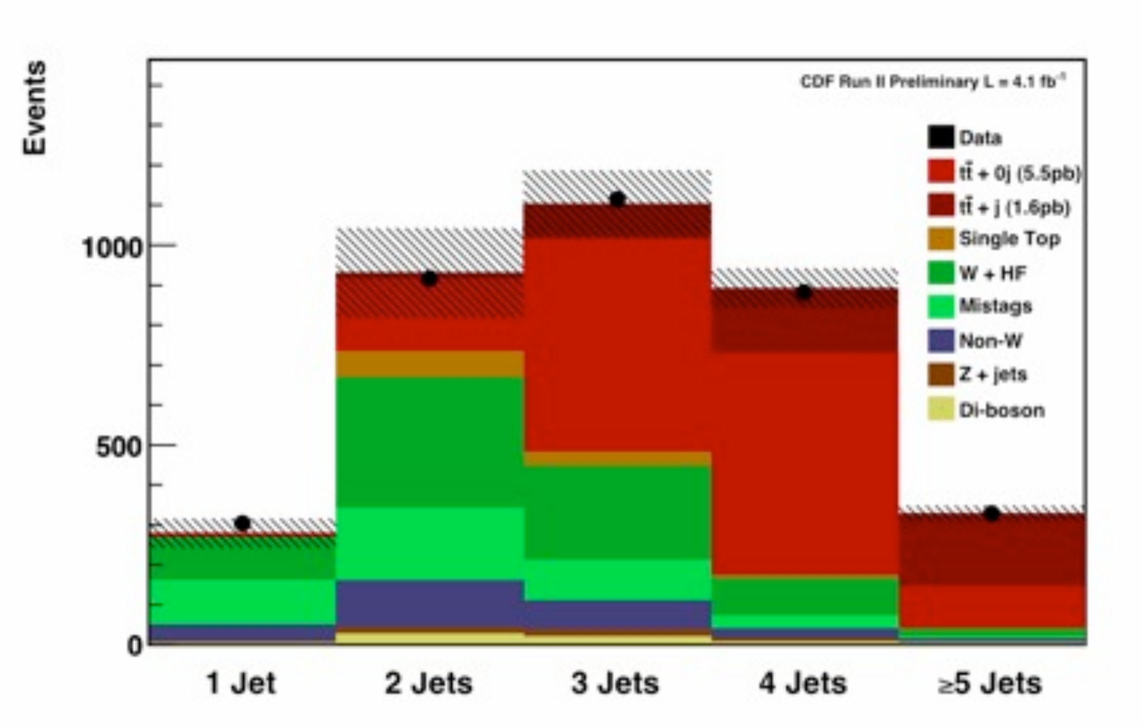
Systematic	$\Delta\sigma_{0j}$ pb	$\Delta\sigma_{0j}/\sigma_{0j}$ %	$\Delta\sigma_{+j}$	$\Delta\sigma_{+j}/\sigma_{+j}$ %
JES	0.27	4.9	0.48 pb	30.2
BTag SF	0.25	4.6	0.07	4.6
C Tag SF	0.01	0.2	0.01	0.4
Mistag Matrix	0.01	0.2	0.01	0.6
Heavy Flavor Correction	0.36	6.7	0.06	3.4
Luminosity	0.32	5.6	0.10	6.1
QCD Fraction	0.01	0.2	0.01	0.4
ISF/FSR	0.11	2.1	0.07	3.3
MC Generator	0.19	3.5	0.04	2.3
Trigger Eff	0.03	0.6	0.01	0.6
PDF	0.06	1.0	0.01	1.0
Total	0.65 pb	11.8 %	0.47 pb	36.5 %

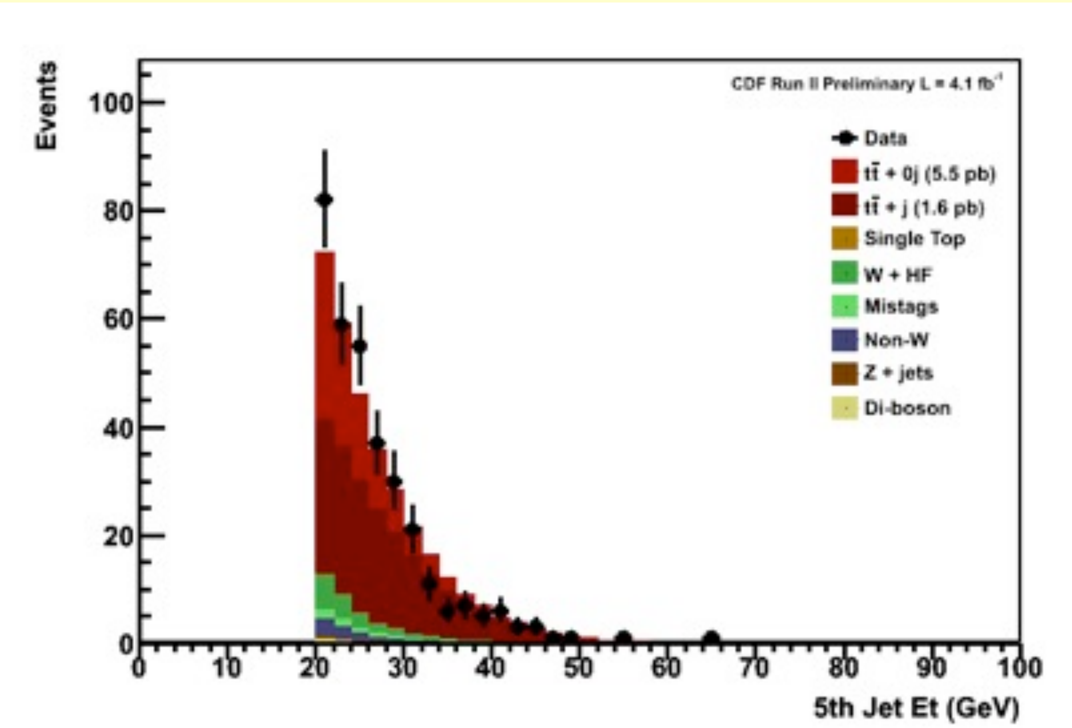
$$\sigma_{t\bar{t}jets} = 1.6 \pm 0.2(\text{stat}) \pm 0.5(\text{sys})\ \text{pb}$$

Mt = 175 GeV

$$\text{SM} : \sigma_{t\bar{t}jets} = 1.79^{+0.16}_{-0.31}\ \text{pb}$$

Mt = 174 GeV, EPJ C59 625 (2009)

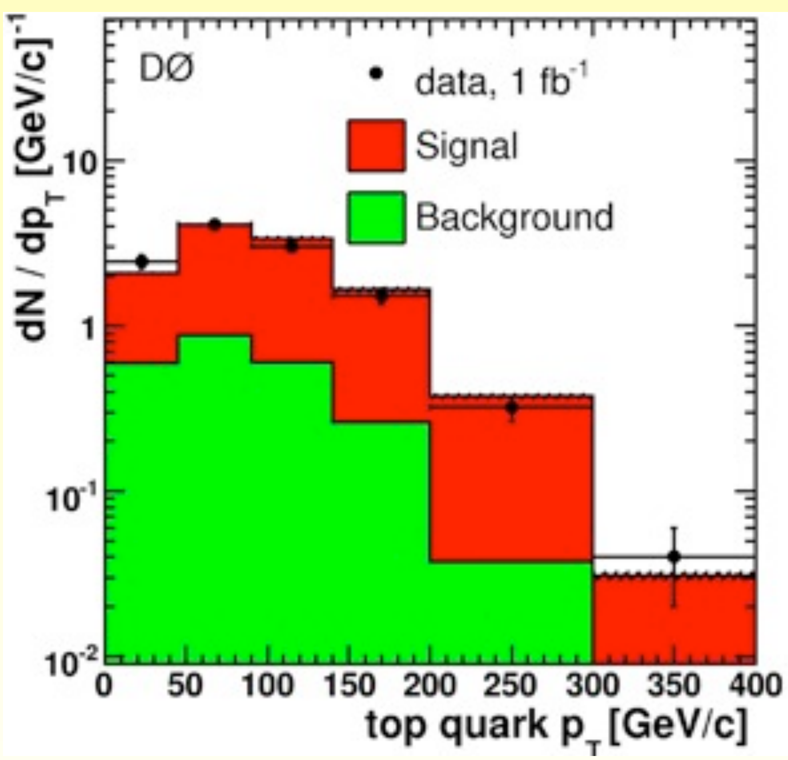


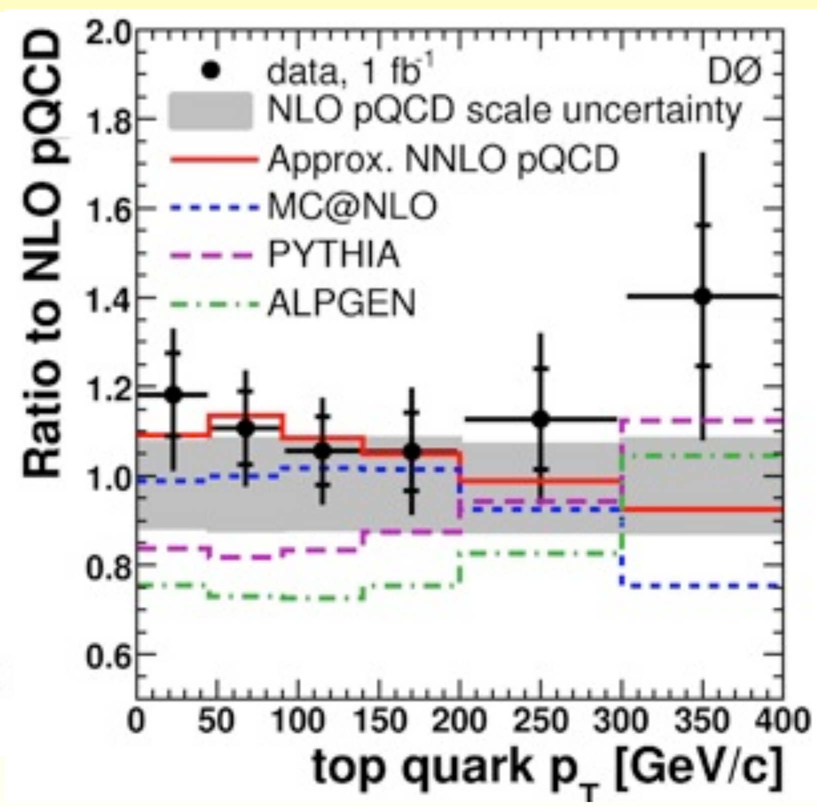


Differential Top Pt and $M_{t\bar{t}}$ Cross Sections

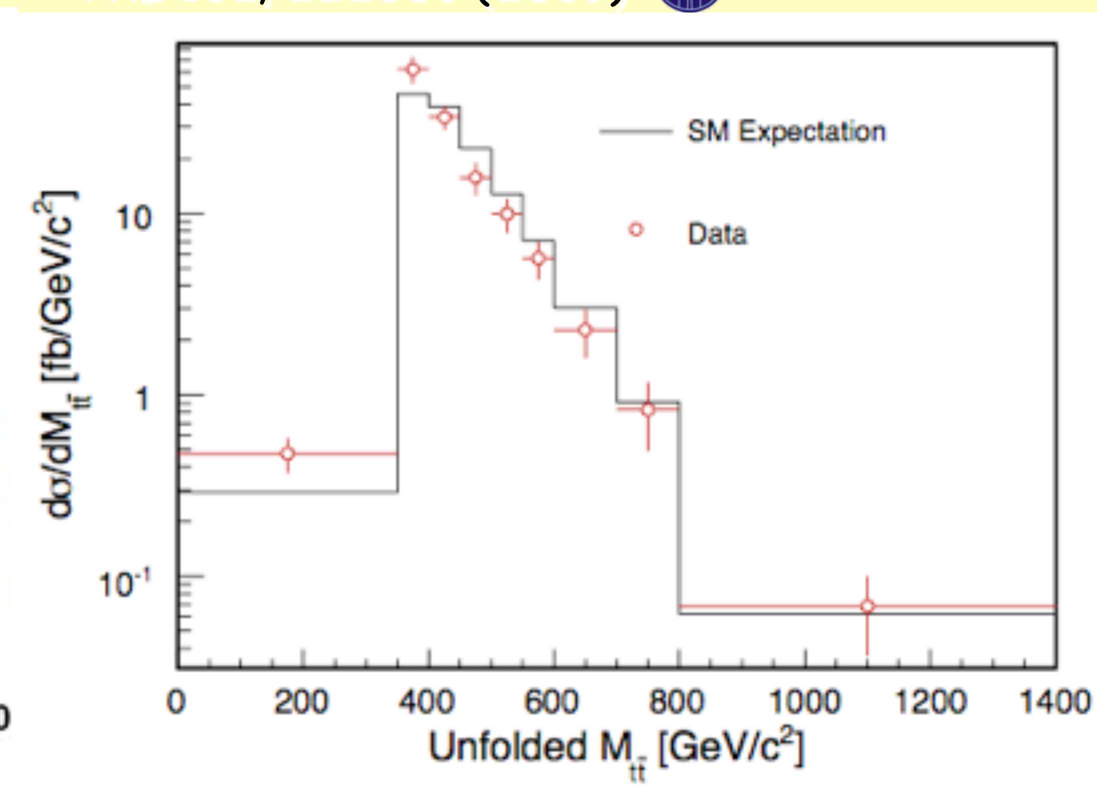
- New physics can distort differential top spectra:
  - deeper investigation than inclusive cross sections
- lepton + jets selection
  - full reconstruction of the $t\bar{t}$ events
  - subtract background contribution
  - unfold distributions from detector effects
- no deviation from SM expectation observed in data

submitted to PLB





PRL 102, 222003 (2009)



Conclusion

- the Tevatron experiments have measured the $t\bar{t}$ cross sections in all possible top decay channels
  - well understood $t\bar{t}$ samples
  - a lof of the measurements are now systematics limited
  - precision ~ 6.5 % using $t\bar{t}$/Z cross section ratio
  - allow to search for many deviations from SM expectations
- expect soon a Tevatron $t\bar{t}$ cross section combination
- will continue to scrutinize the top sector with more than 7 fb^{-1} on tape
  - decay channels with low statistics
  - cross section ratio, differential cross sections

See following talks for other Tevatron top properties results