

Single top quark physics at the Tevatron and the LHC



Reinhard Schwienhorst

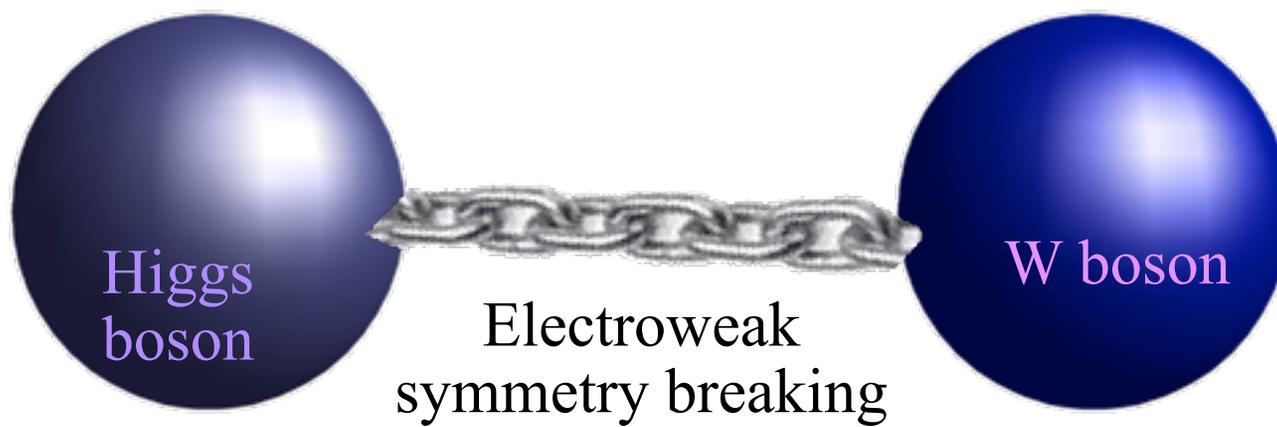


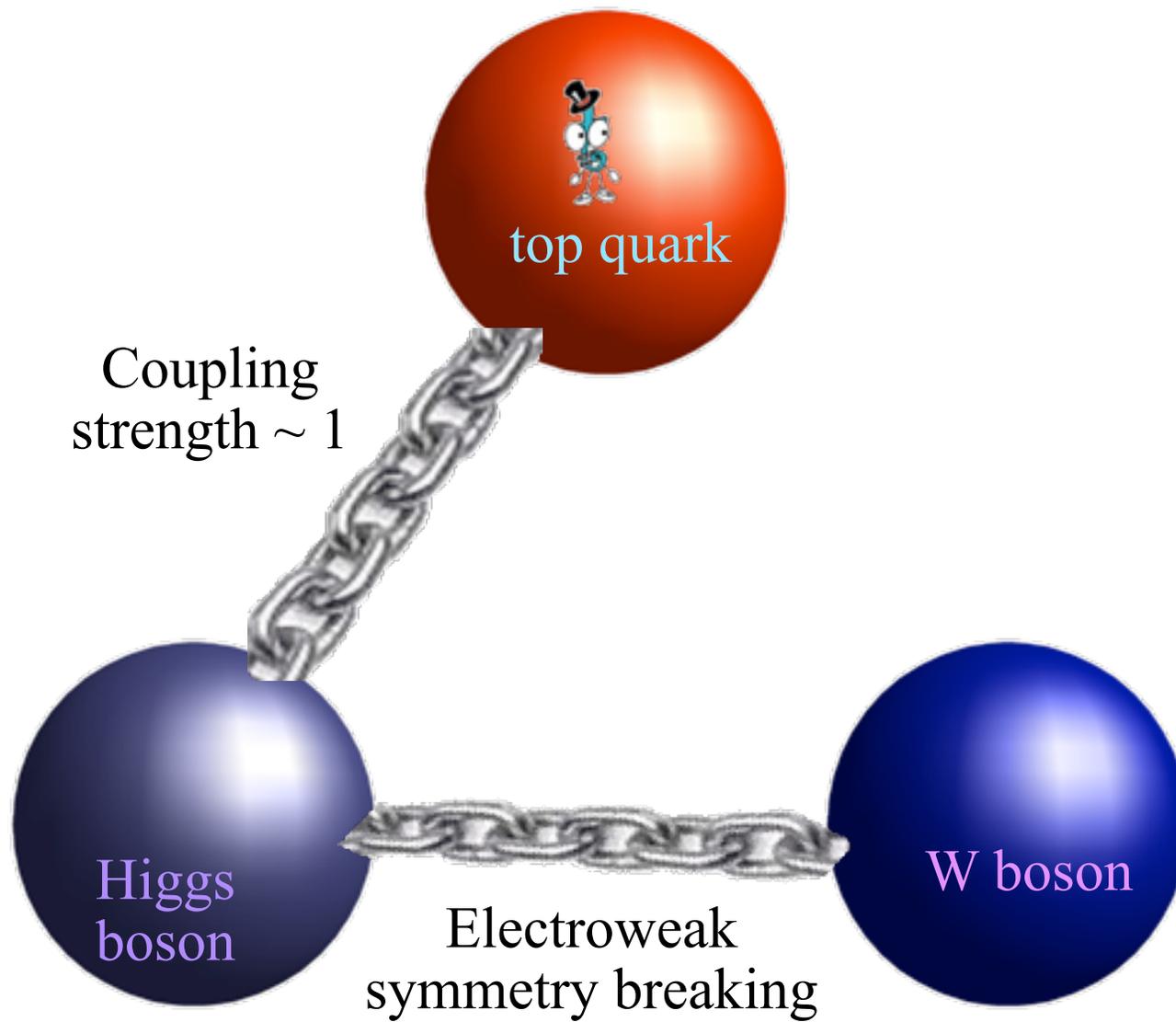
Dienstagsseminar, RWTH Aachen, July 5 2011

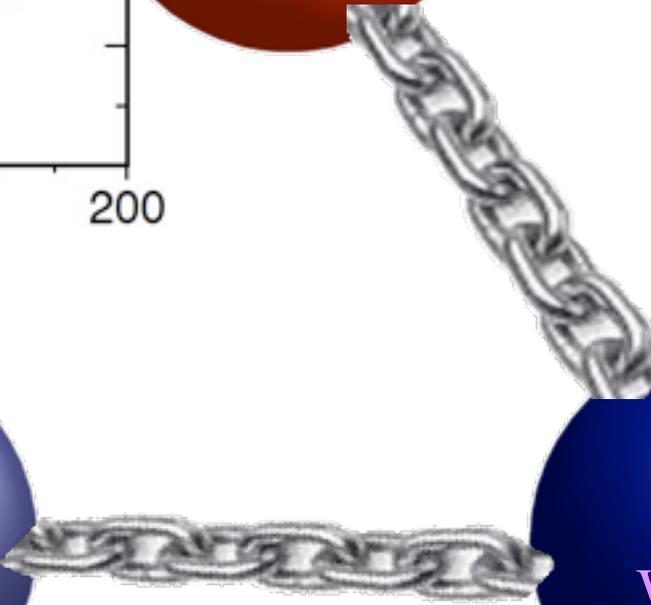
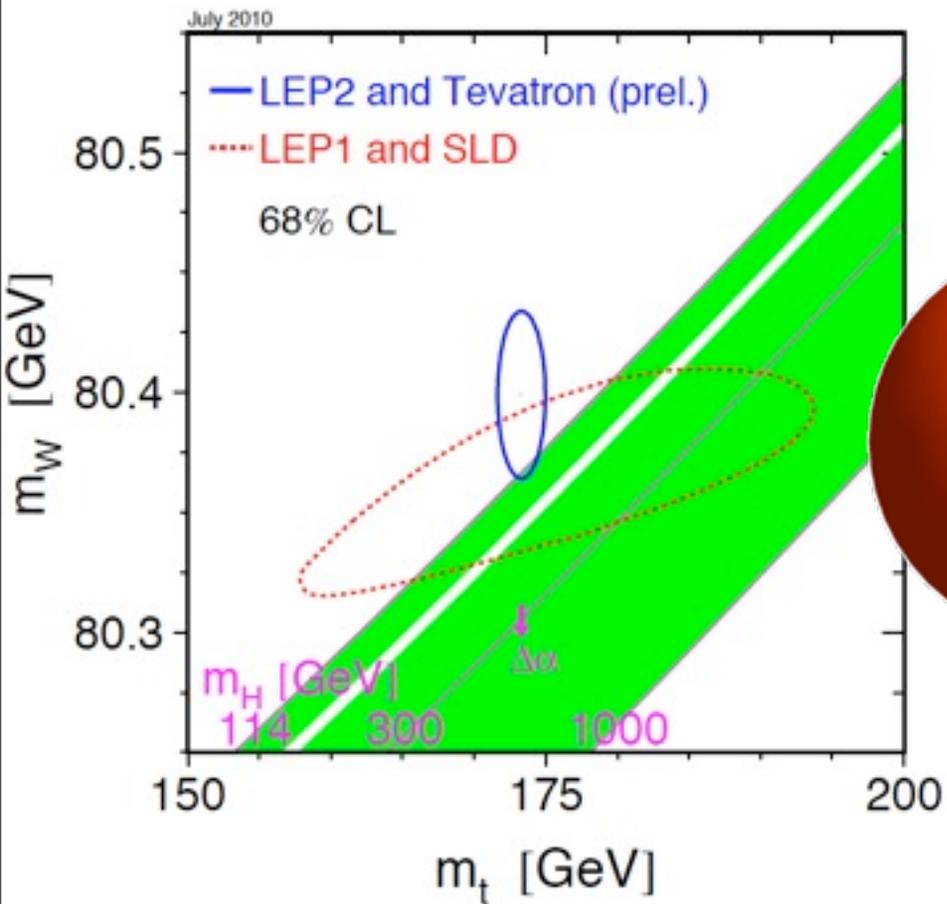


Outline

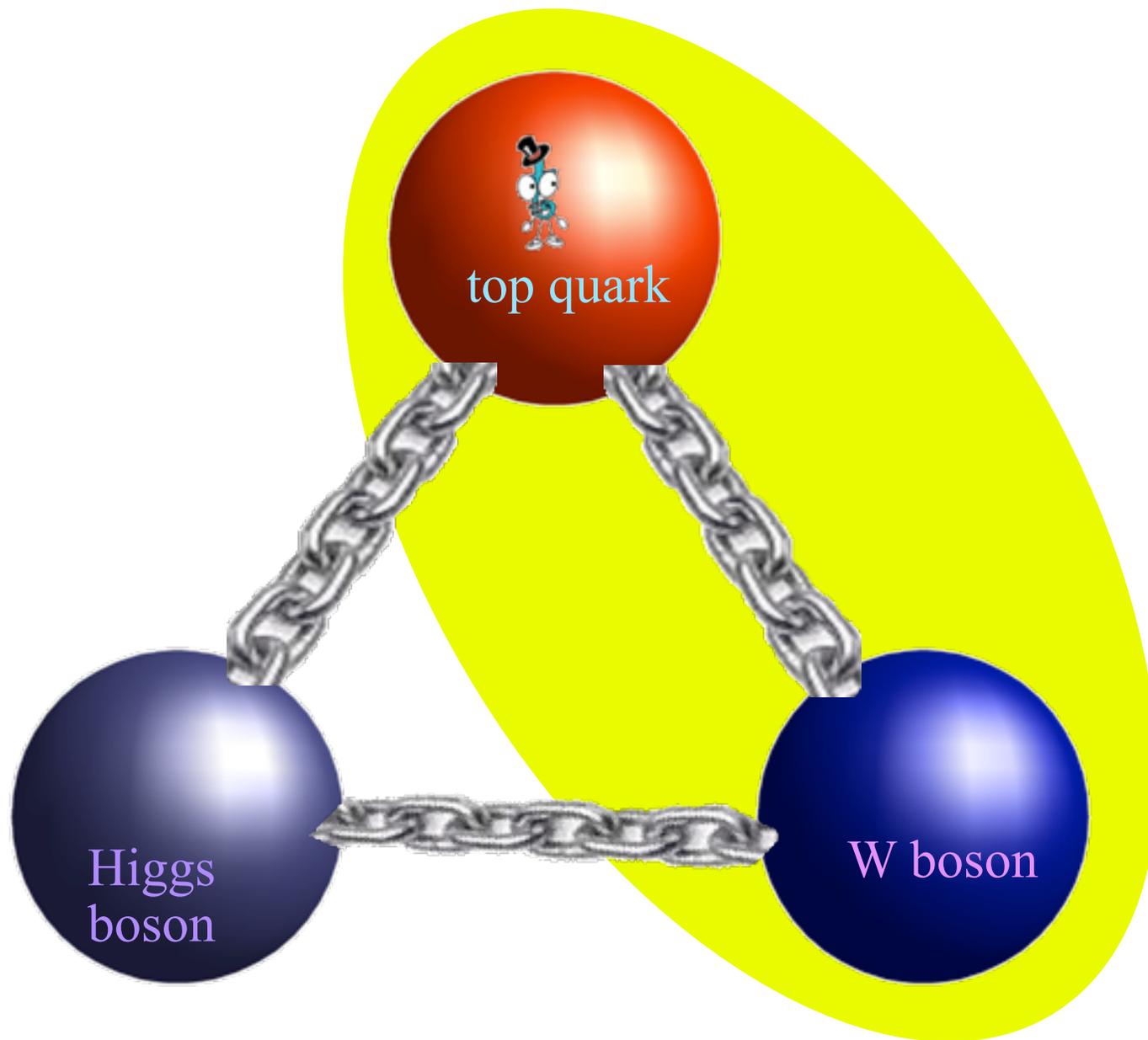
- Introduction
- Tevatron
 - SM
 - New physics
- LHC
- Conclusions



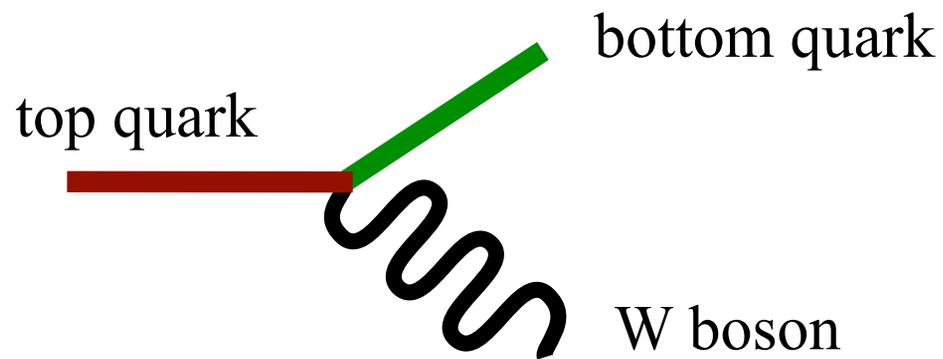




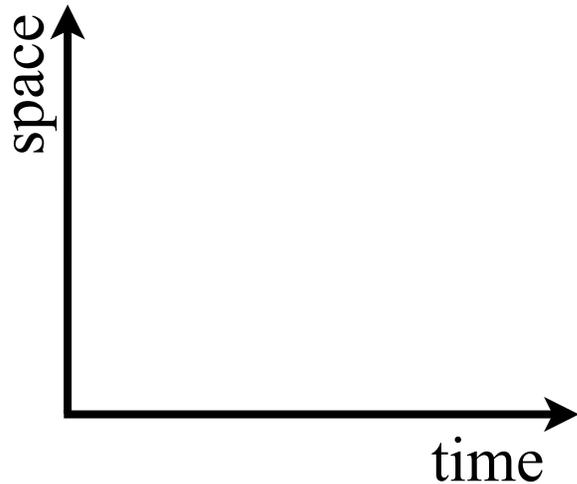
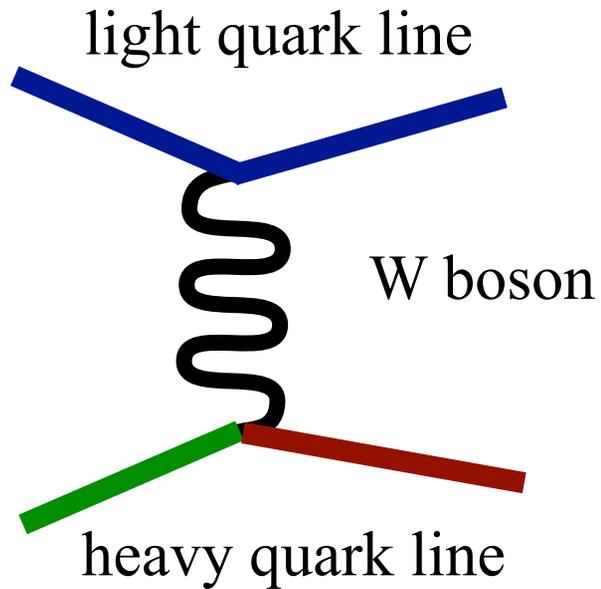
Key to electroweak symmetry breaking



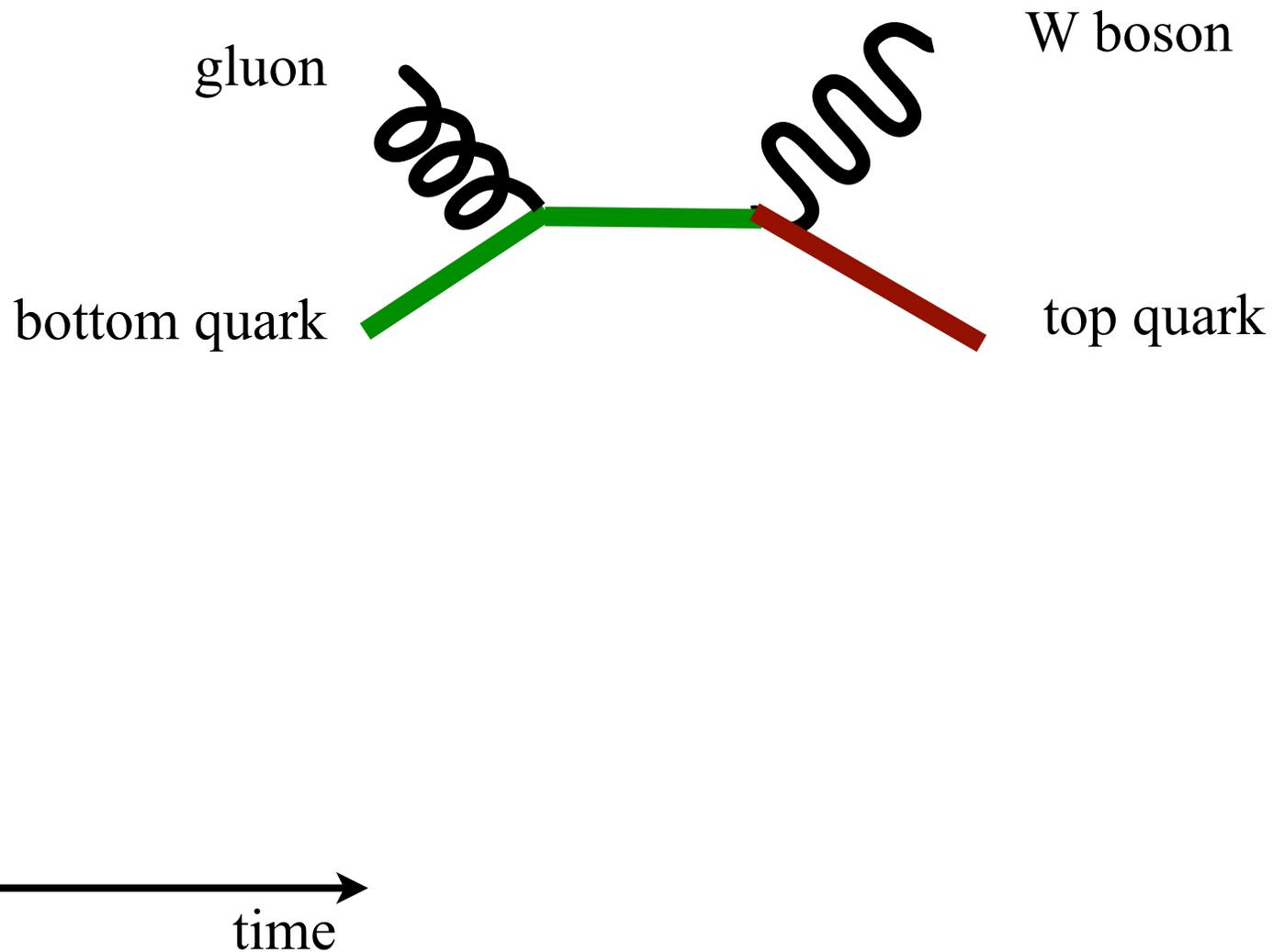
Top quark decay



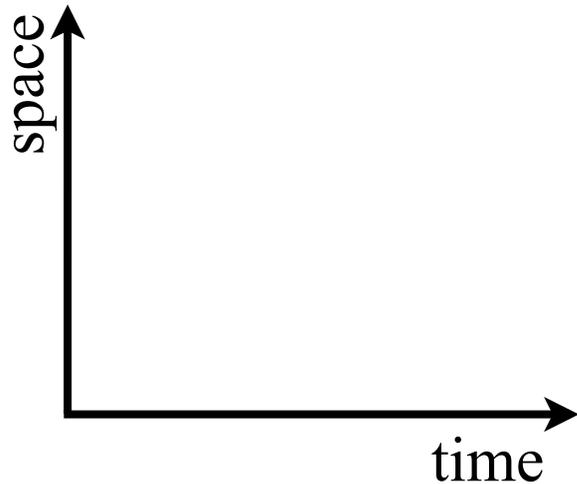
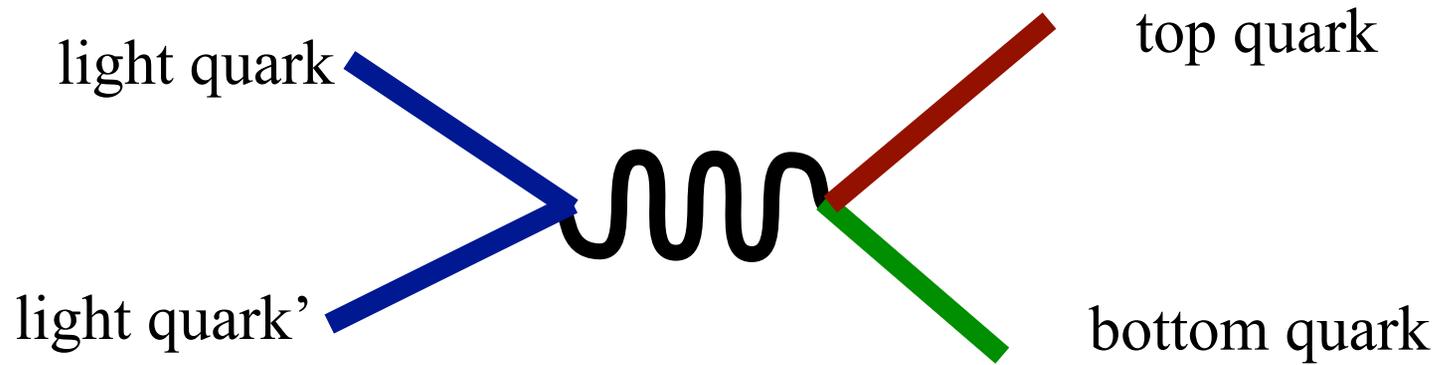
t-channel single top quark production



Wt associated production

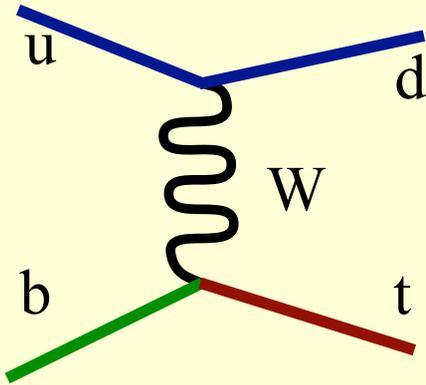


s-channel single top production

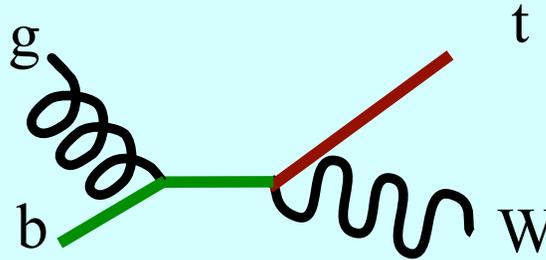


SM single top quark production

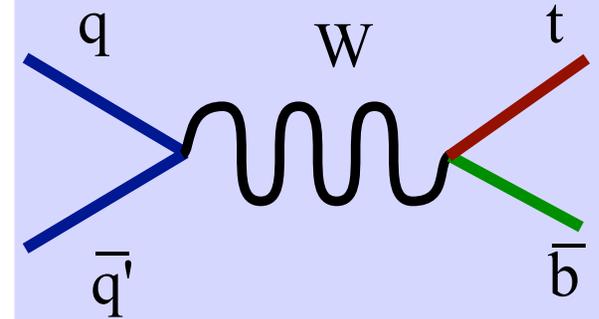
t-channel



Associated production



s-channel



Tevatron:

$$\sigma_{\text{tot}} = 3 \text{ pb}$$

LHC:
(7 TeV)

$$\sigma_{\text{tot}} = 76 \text{ pb}$$

LHC:
(14 TeV)

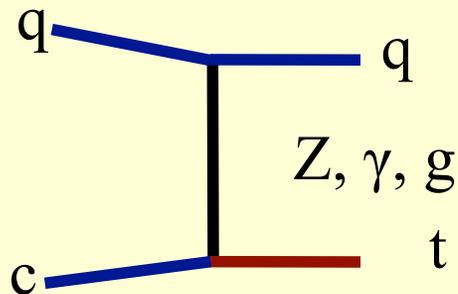
$$\sigma_{\text{tot}} = 326 \text{ pb}$$

SM tasks:

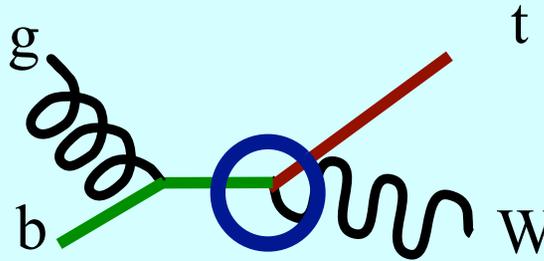
- Weak interaction of bare quarks
- Measure total cross section \rightarrow CKM matrix element $|V_{tb}|$
- Top polarization, PDFs

New physics in single top

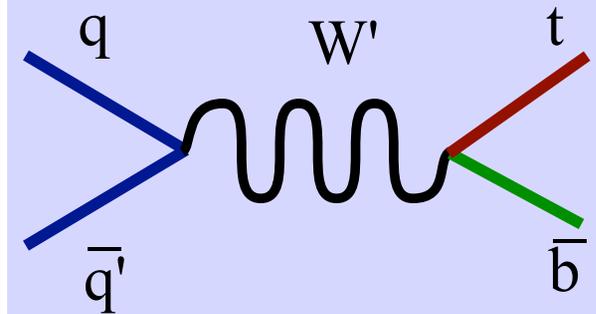
New interactions:
FCNC



New coupling:
modified Wtb
coupling
or anomalous
CKM matrix



New particles:
heavy boson
or charged Higgs
or T' or B'



New physics tasks:

- measure individual cross sections \rightarrow different modes sensitive to different new physics
- look for specific new physics scenarios
 - W' , fourth generation quarks, charged Higgs
 - gluon FCNC
 - anomalous Wtb couplings

Batavia, Illinois

Experimental setup: Fermilab Tevatron in Run II



Proton-antiproton collider
CM energy 1.96 TeV

→ *Energy frontier - until a year ago*

Instantaneous luminosity $>4E32 \text{ cm}^{-2}\text{s}^{-1}$

– >5 interactions per crossing, 1.7M crossing per second

→ *Proton-antiproton luminosity frontier*



Fermilab single top history



Publication history



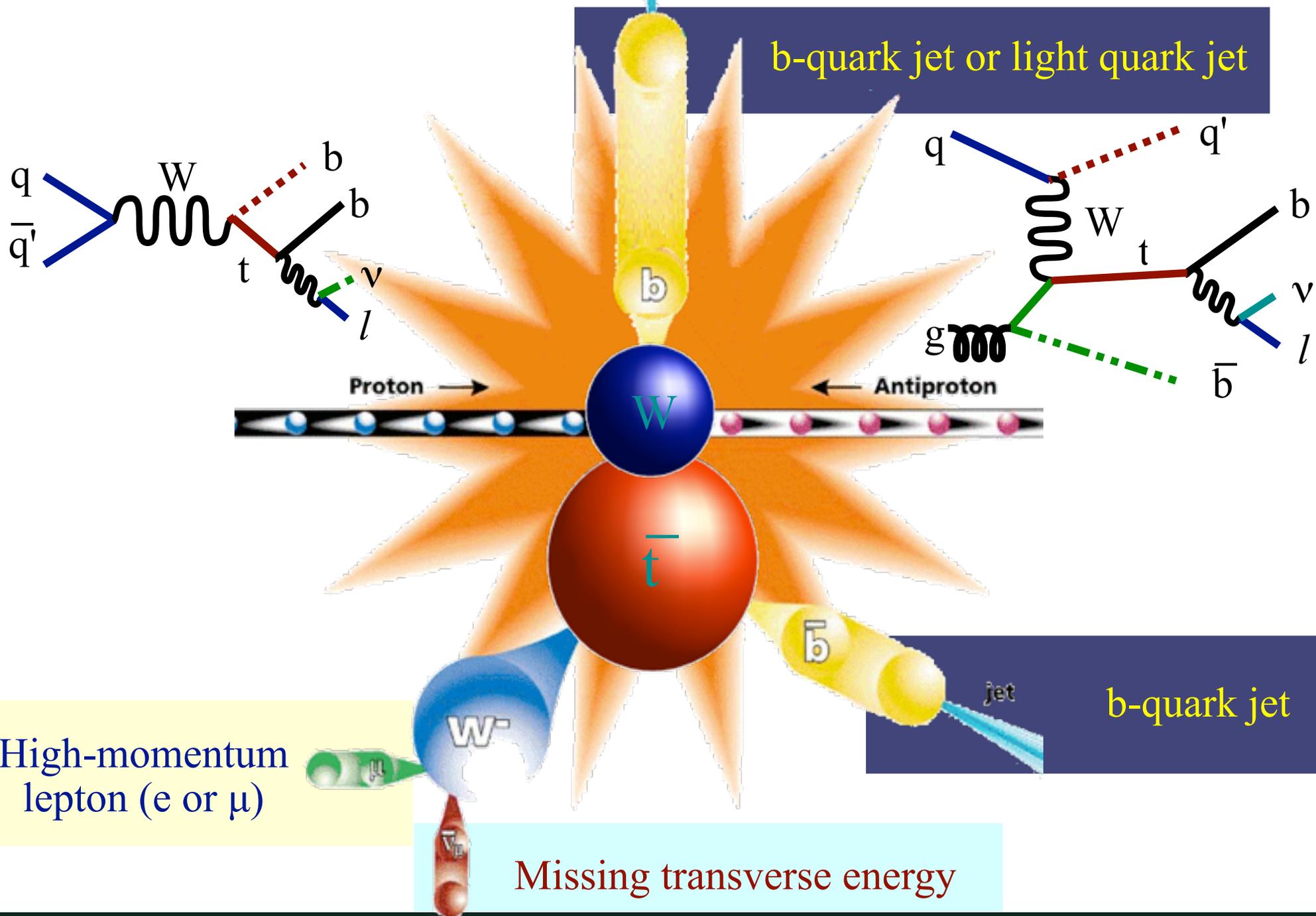
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- . Search: PLB 517, 282 (2001)
- . Search: PLB 622, 265 (2005)
- . W': PLB 641, 423 (2006)
- . Search: PRD 75, 092007 (2007)
- . Evidence: PRL 98, 181802 (2007)
- . FCNC: PRL 99, 191802 (2007)
- . W': PRL 100, 211802 (2007)
- . Evidence: PRD 78, 012005 (2008)
- . Wtb: PRL 101, 221801 (2008)
- . Wtb: PRL 102, 092002 (2009)
- . H⁺: (PRL) arXiv:0807.0859
- . **Observation: (PRL) arXiv:0903.0850**
- . tau search PLB 690, 5 (2010)
- . t-chan meas. PLB 682, 363 (2010)
- . FCNC PLB 693, 81 (2010)
- . top width PRL 106, 22001 (2011)
- . W' PLB 699, 145 (2011)
- . t-chan obs. (PLB) arXiv:1105.2788

Run I

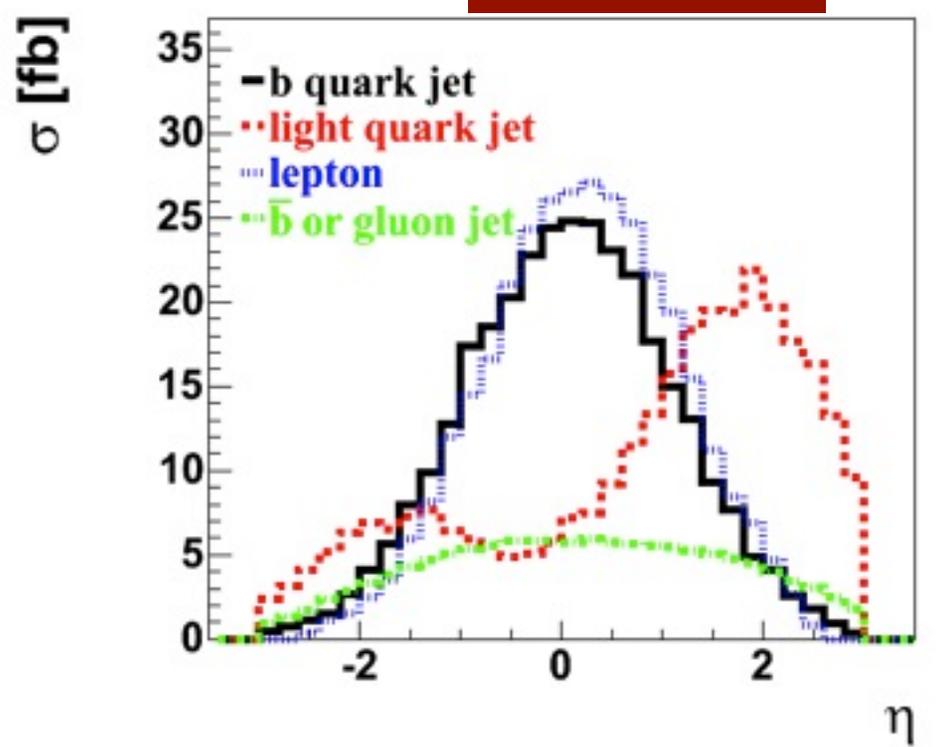
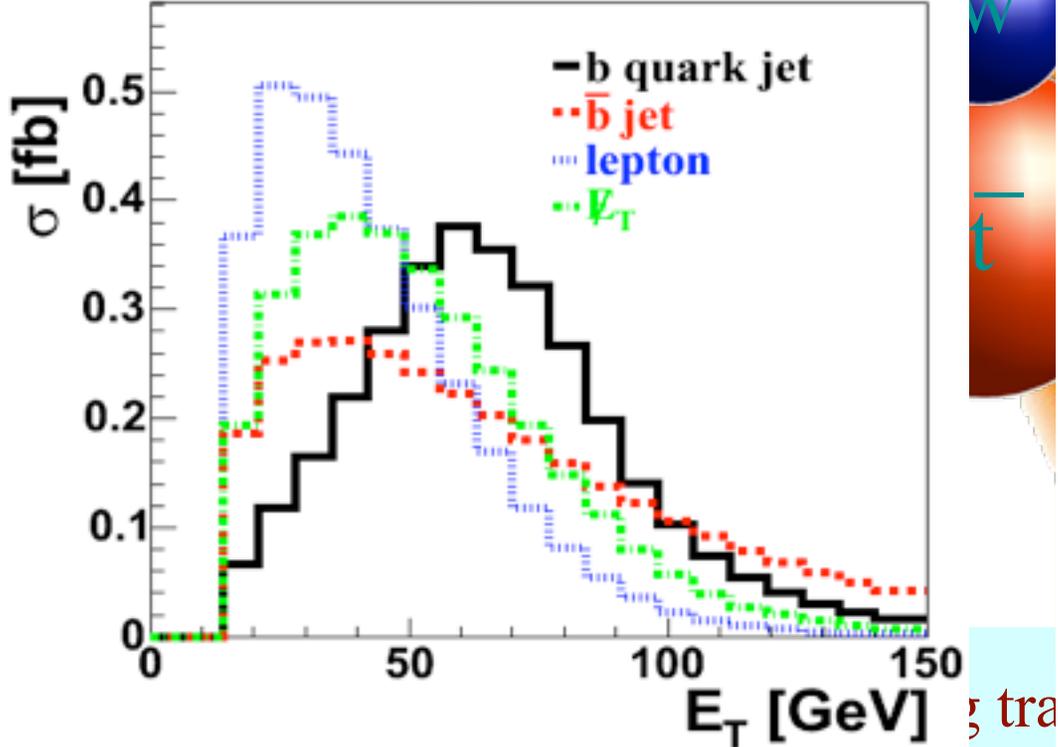
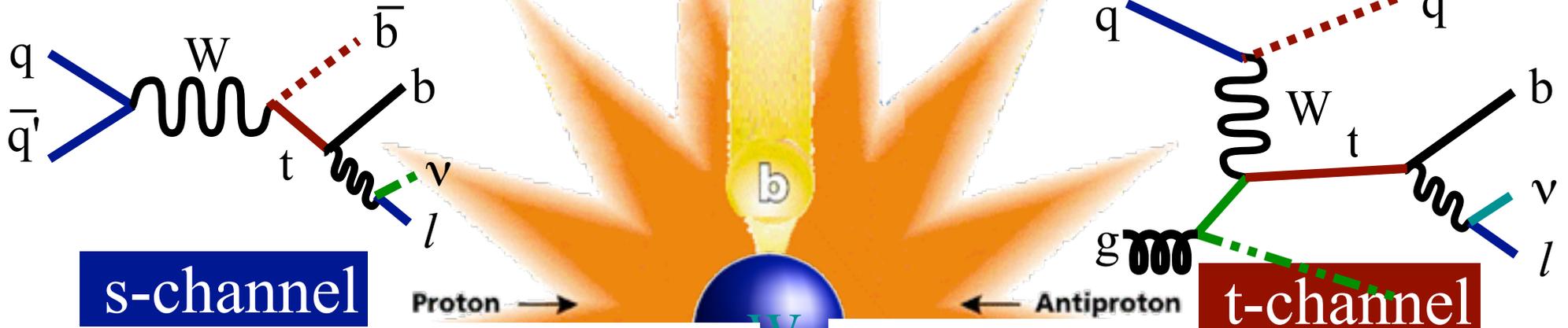
Run II

- . Search: PRD 65, 091102 (2002)
- . W' PRL 90, 081802 (2003)
- . Search: PRD 69, 052003 (2004)
- . Search: PRD 71, 012005 (2005)
- . Evidence: PRL 101, 252001 (2008)
- . FCNC: (PRL) arXiv:0812.3400
- . W': (PRL) arXiv:0902.3276
- . **Observation: (PRL) arXiv:0903.0885**
- . MET+jets PRD 81, 072003 (2010)
- . Observation PRD 82, 112005 (2010)

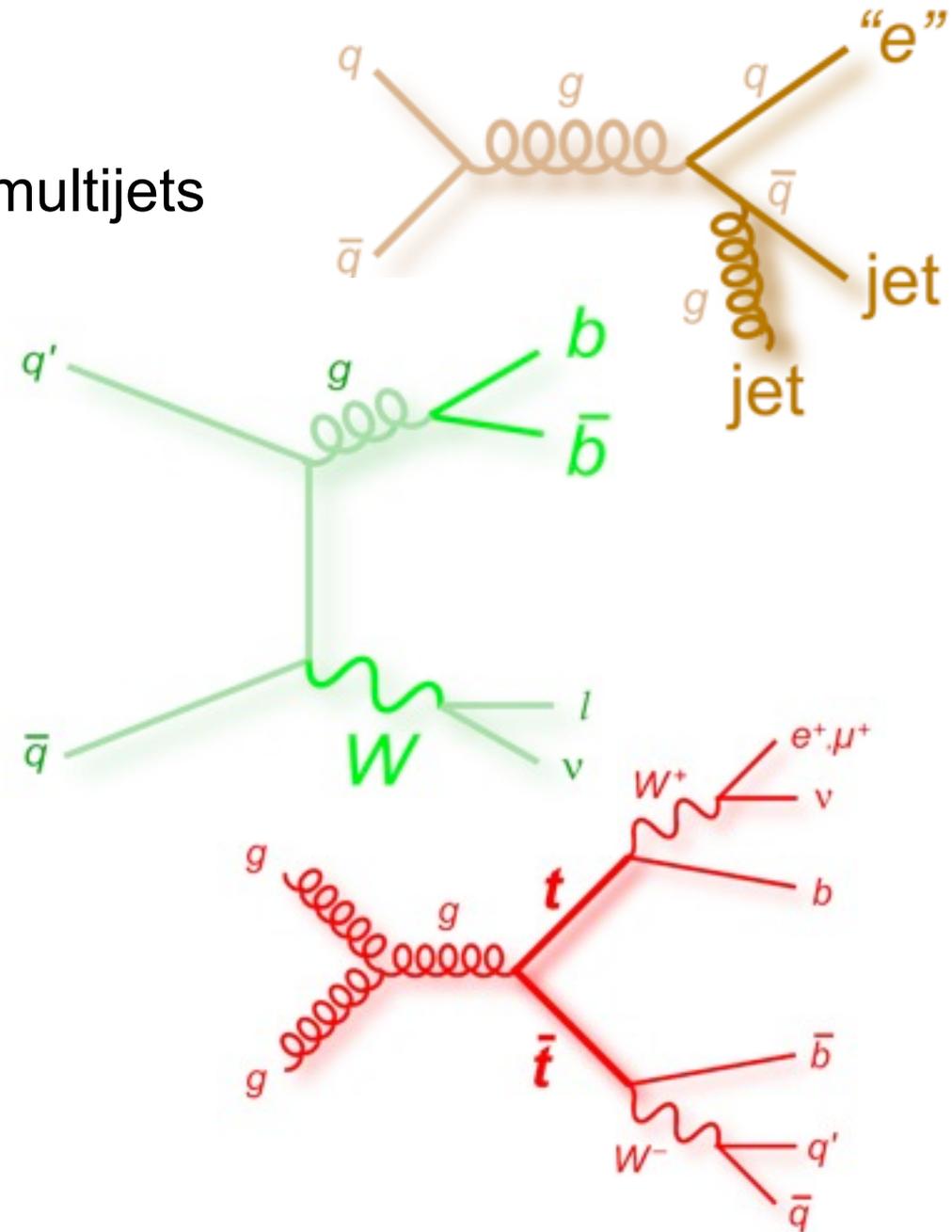
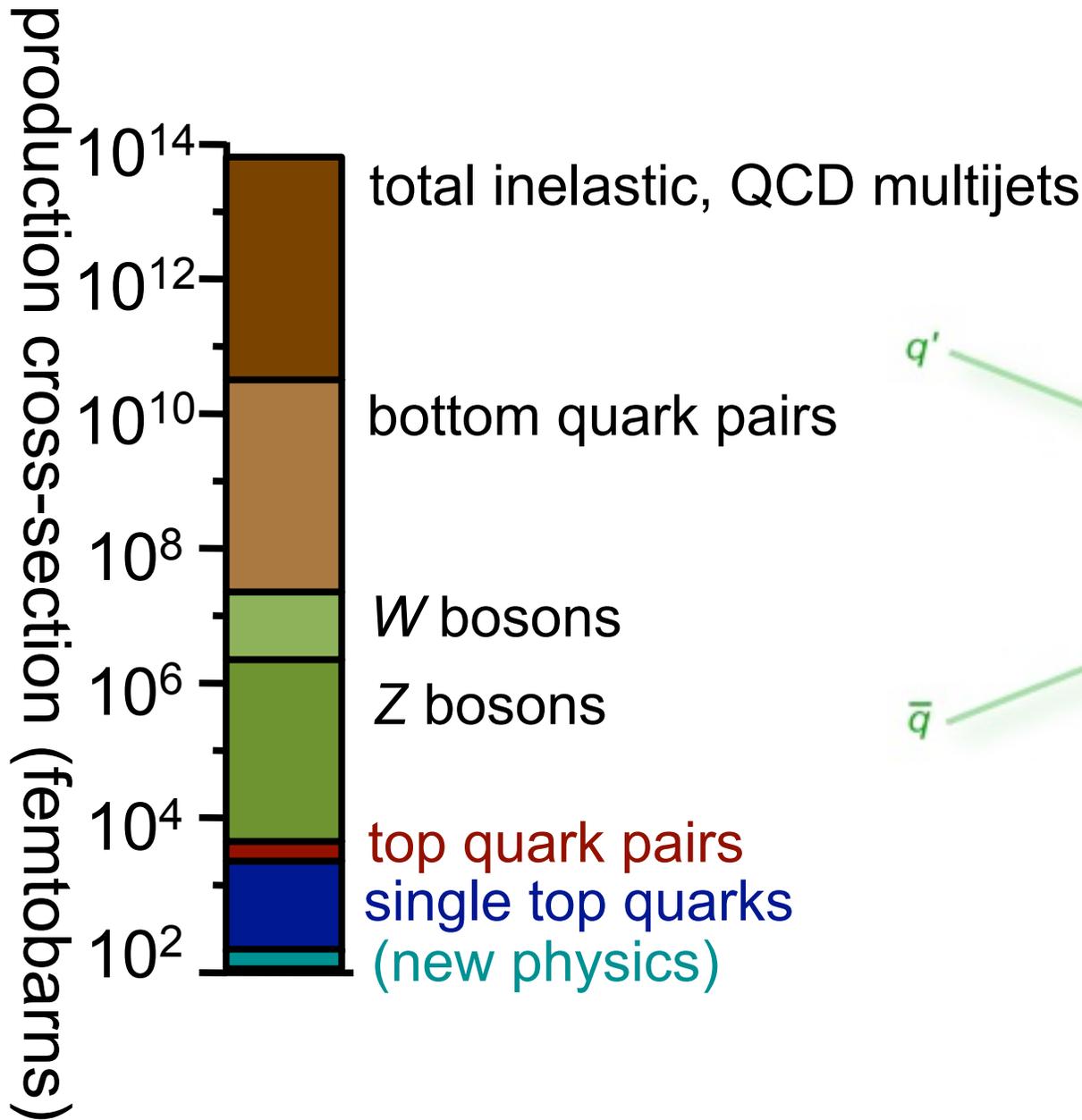
Single top quark event signature



Single top quark event signature

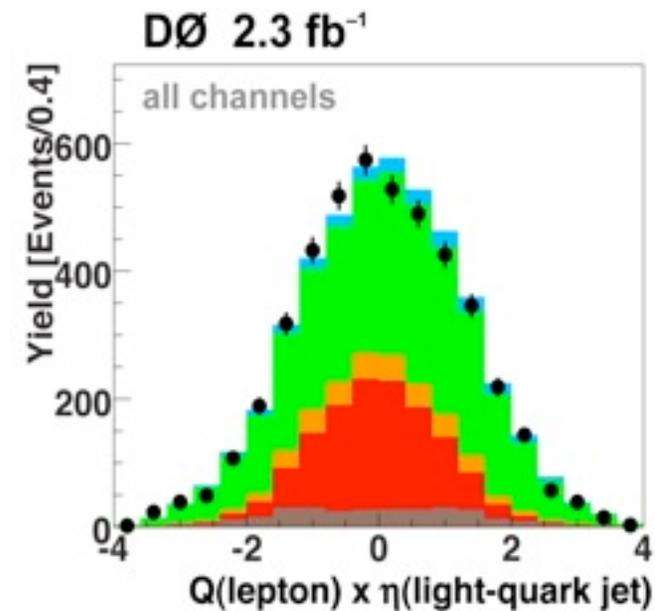
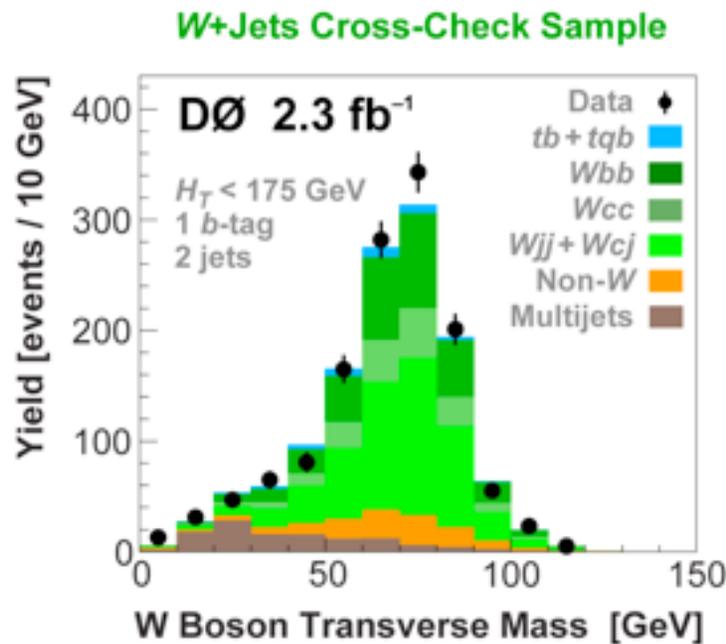
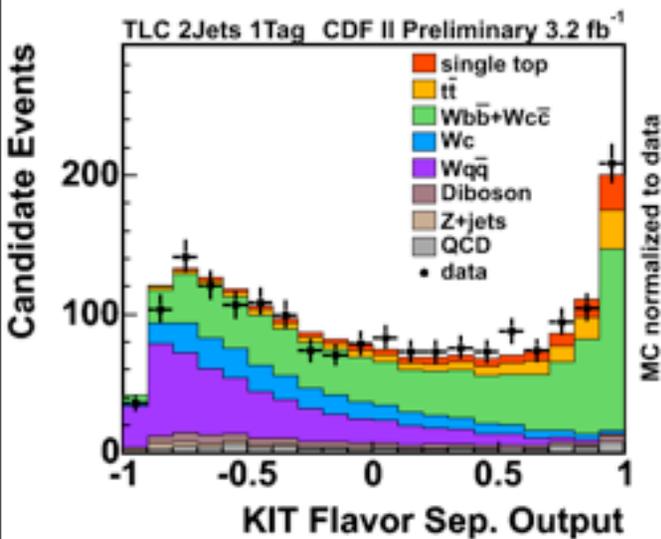
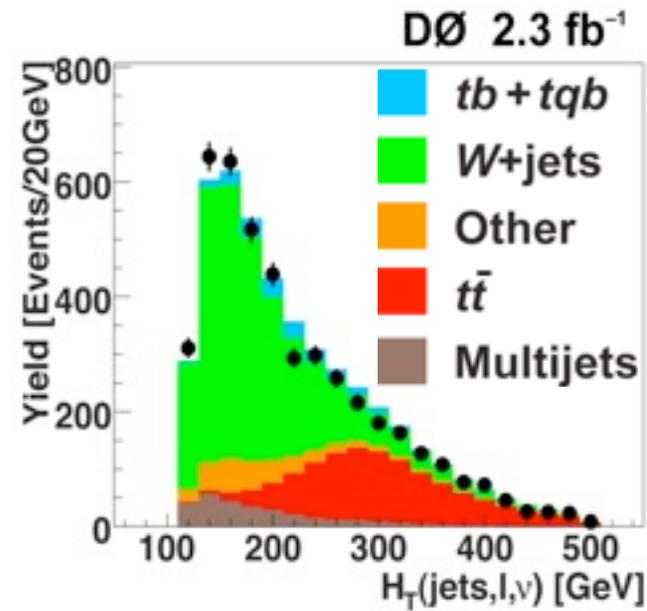
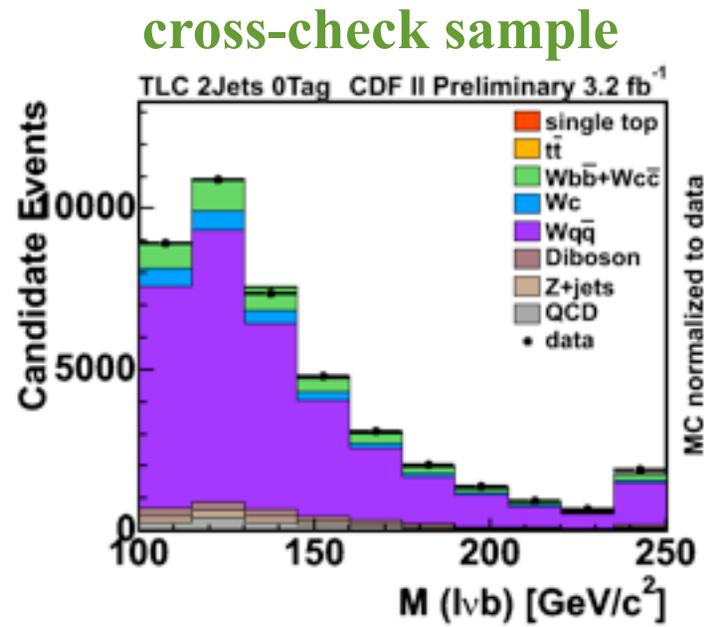
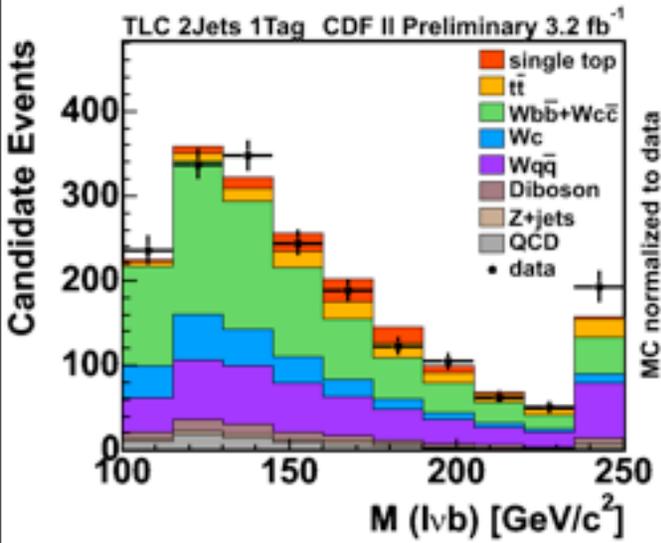


Background processes

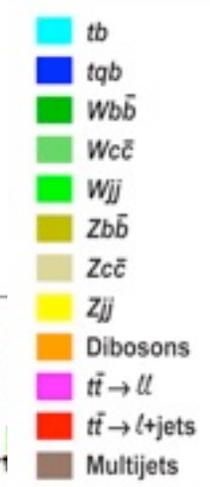
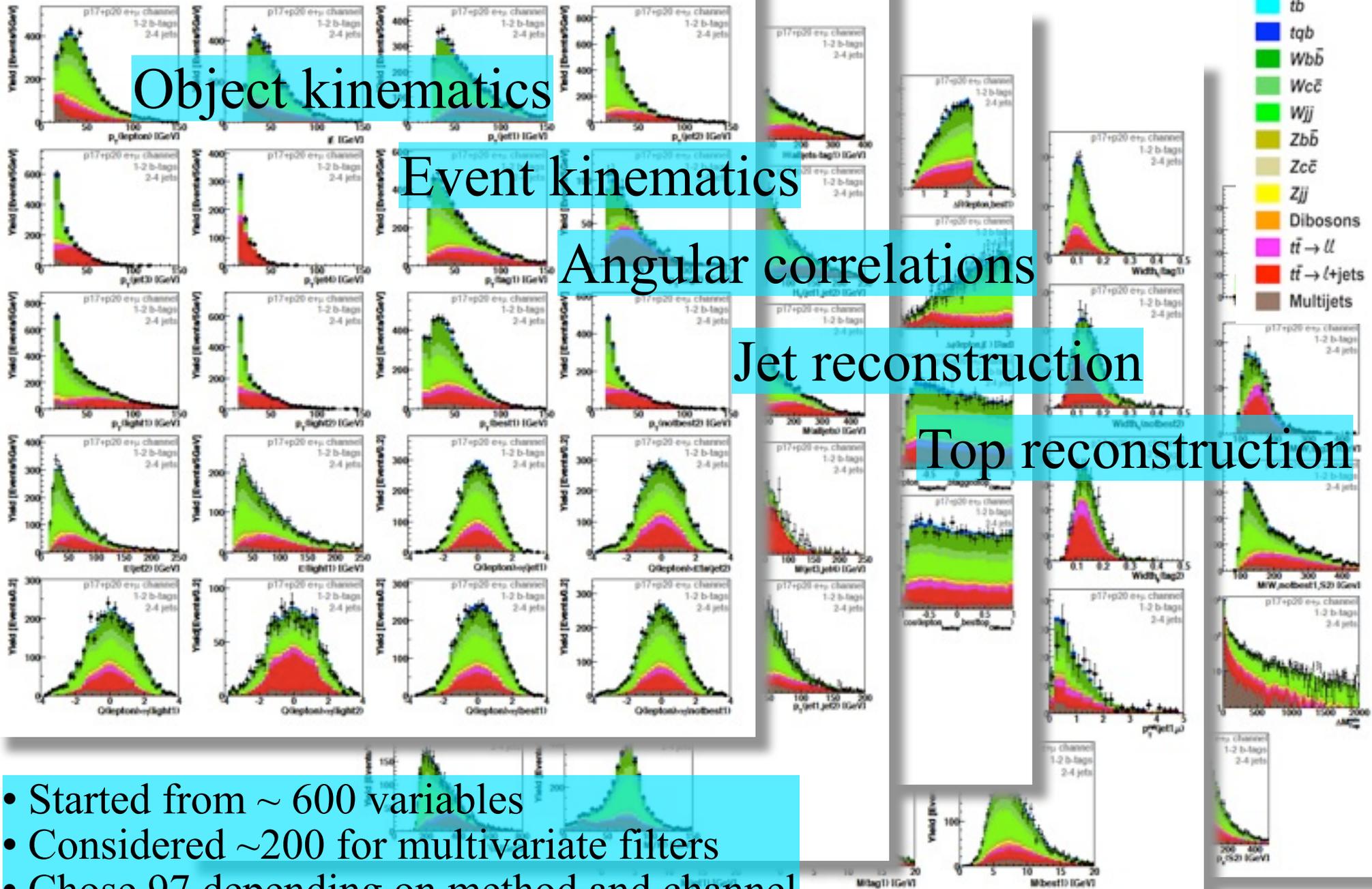




Discriminating variables



Discriminating variables

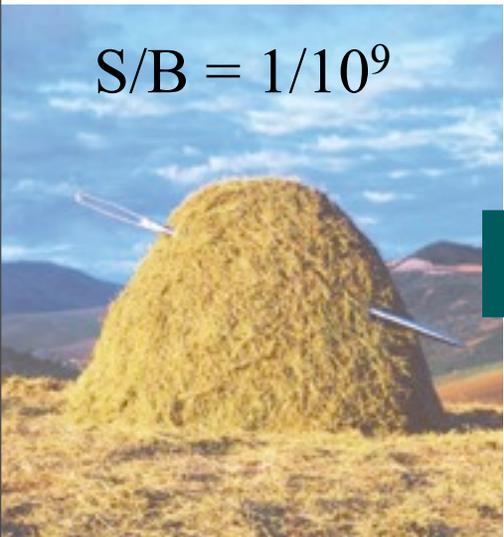


- Started from ~ 600 variables
- Considered ~200 for multivariate filters
- Chose 97 depending on method and channel

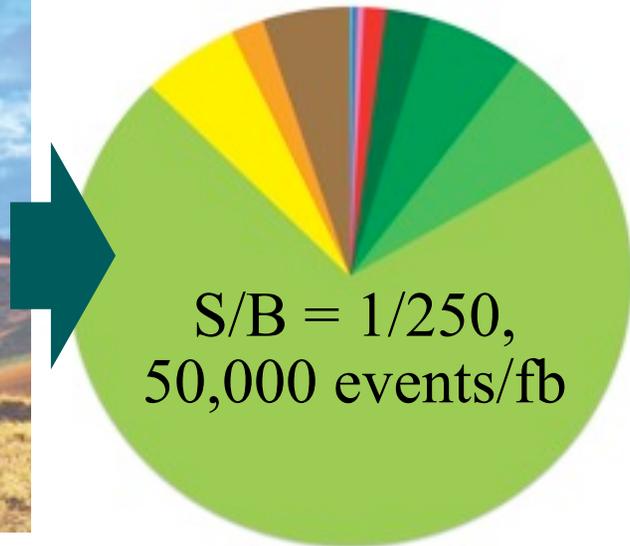
Reinhard Schwienhorst

Tevatron analysis outline

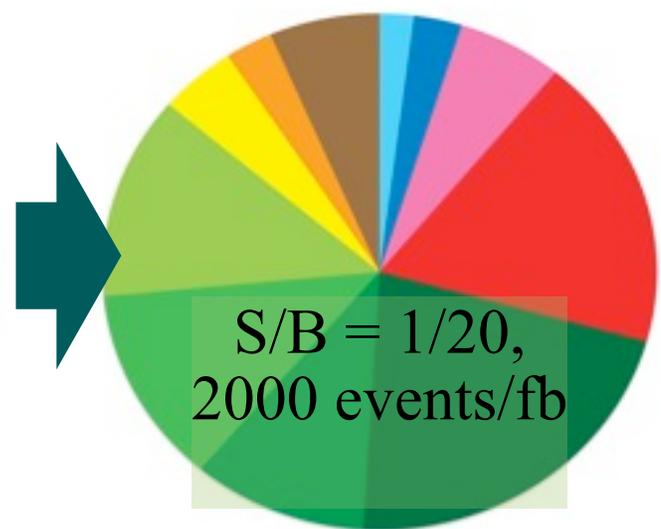
Trigger selection



Single top event kinematics

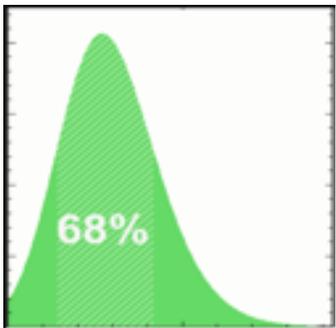


b-quark tagging

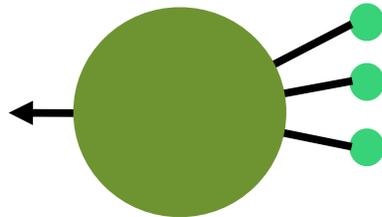


- tb
- tqb
- $t\bar{t} \rightarrow ll$
- $t\bar{t} \rightarrow l+jets$
- $Wb\bar{b}$
- $Wc\bar{c}$
- Wcj
- Wjj
- $Z+jets$
- Dibosons
- Multijets

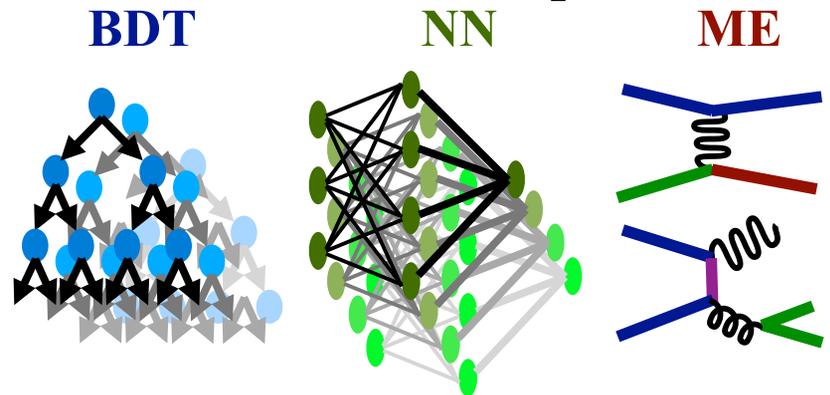
Statistical analysis



Combination



Multivariate techniques



Multivariate methods

Input:

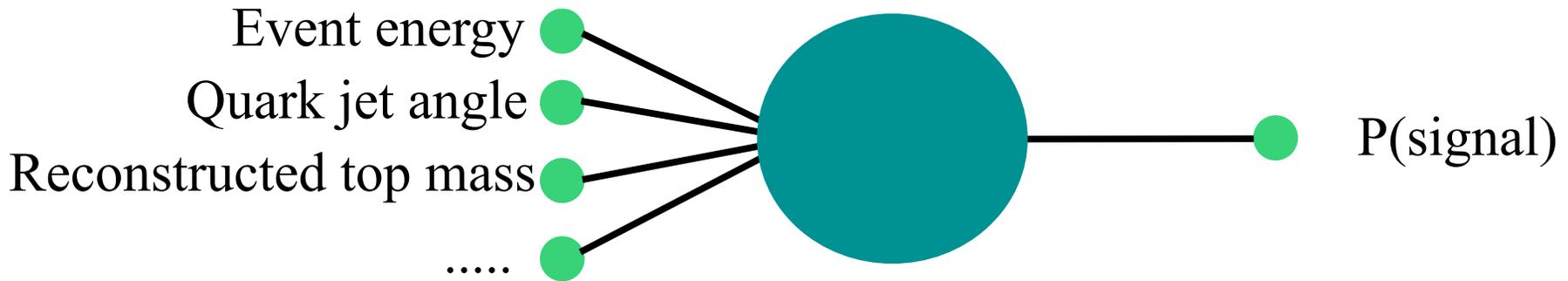
discriminating variables

Method:

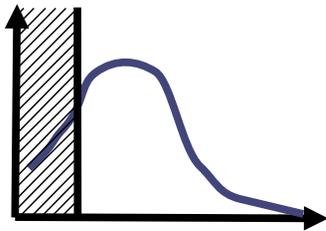
multivariate analysis

Output:

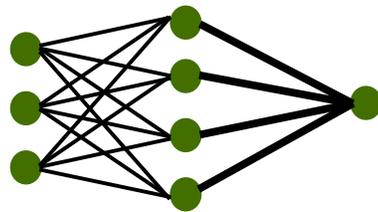
signal likelihood



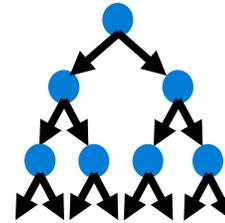
Cut-Based



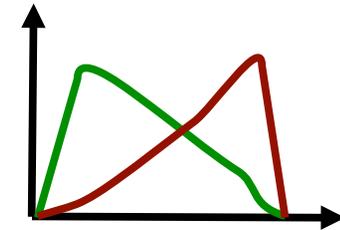
Neural networks



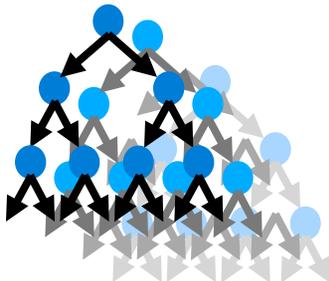
Decision trees



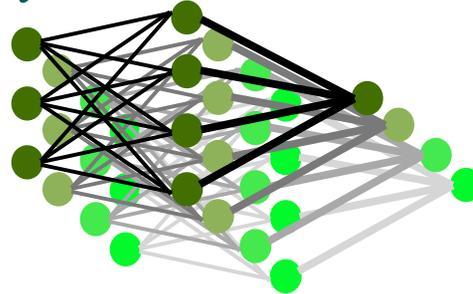
Likelihood



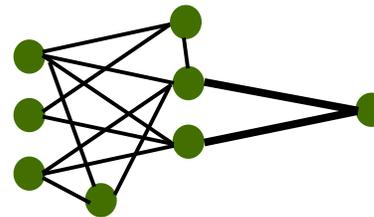
Boosted decision trees



Bayesian neural networks



Neuro evolution



Matrix Elements

$$d^n \sigma_{hs} \sim \frac{|\mathcal{M}|^2}{4 \sqrt{q_1^2 q_2^2 - m_2^2}} \times d\Phi_n$$



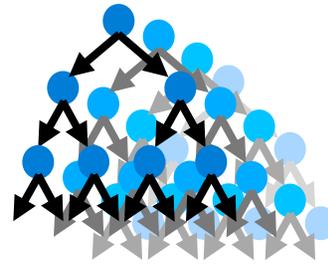
Single top production cross section



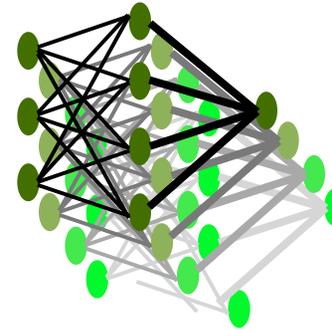
Several multivariate filters combined in one final discriminant

- BNN (DØ)
- NEAT (CDF)

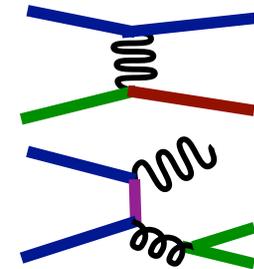
Boosted Decision Trees



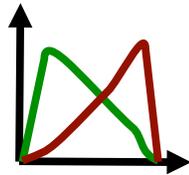
Neural Networks



Matrix Elements

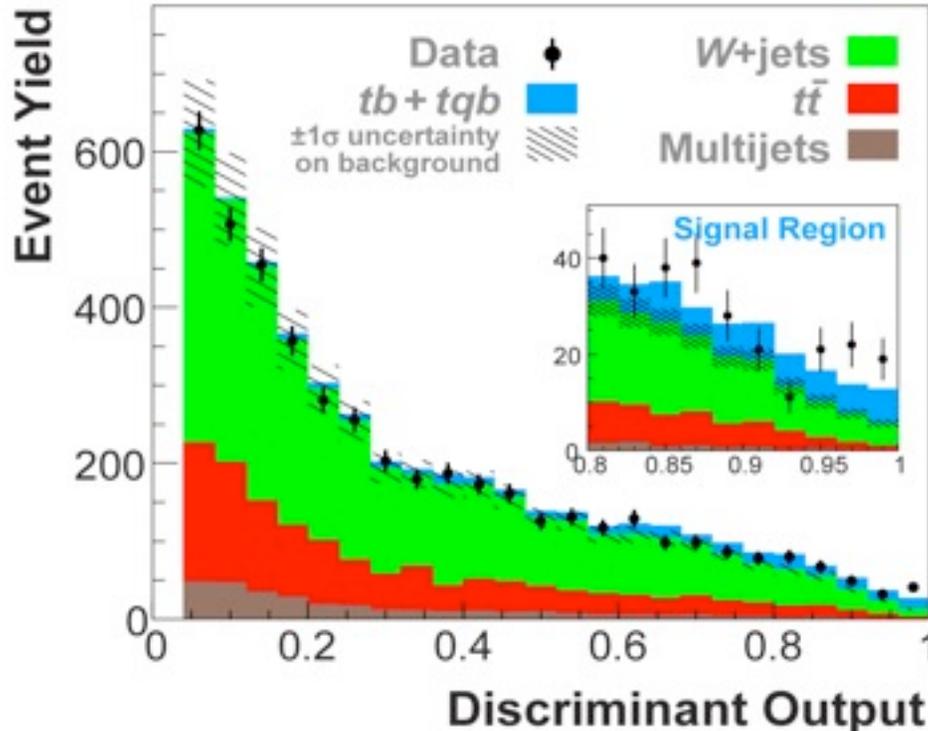


Likelihood

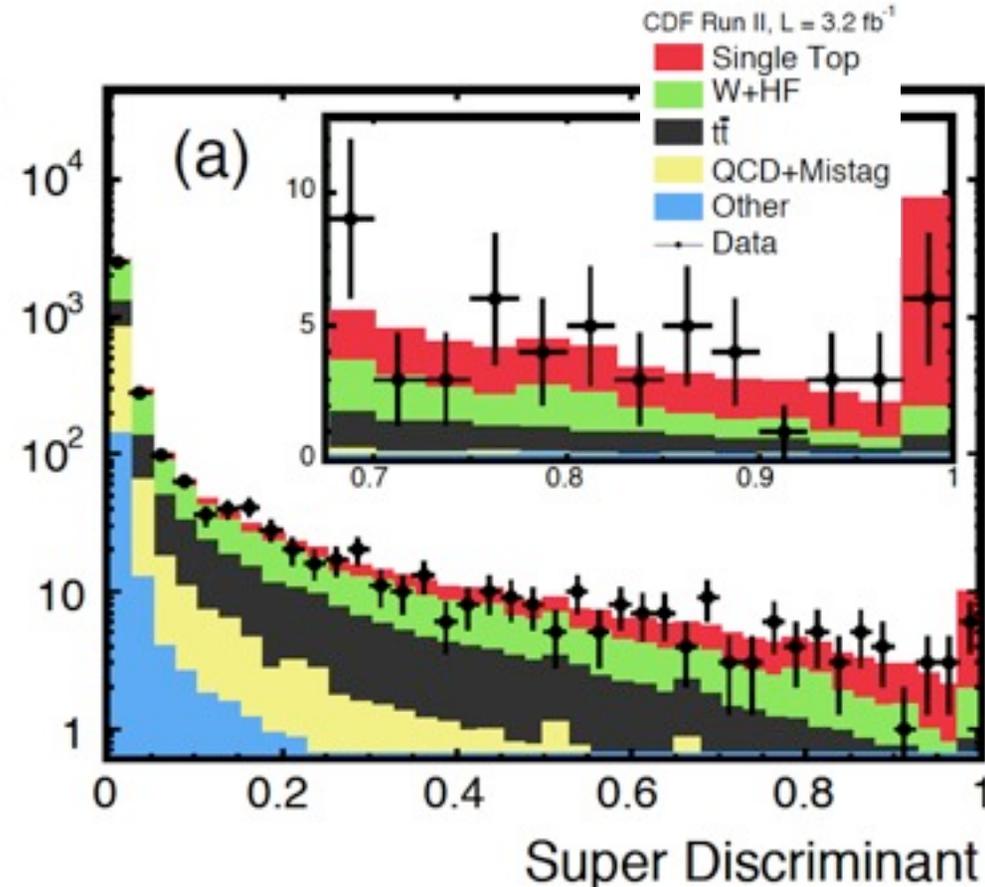


DØ Single Top

2.3 fb⁻¹



Events





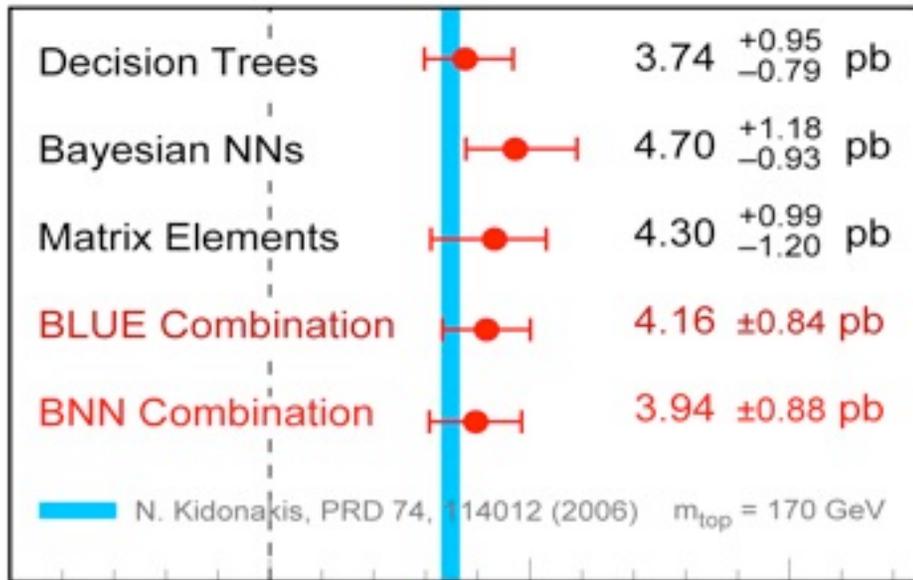
Cross sections

CDF Preliminary Single Top Summary

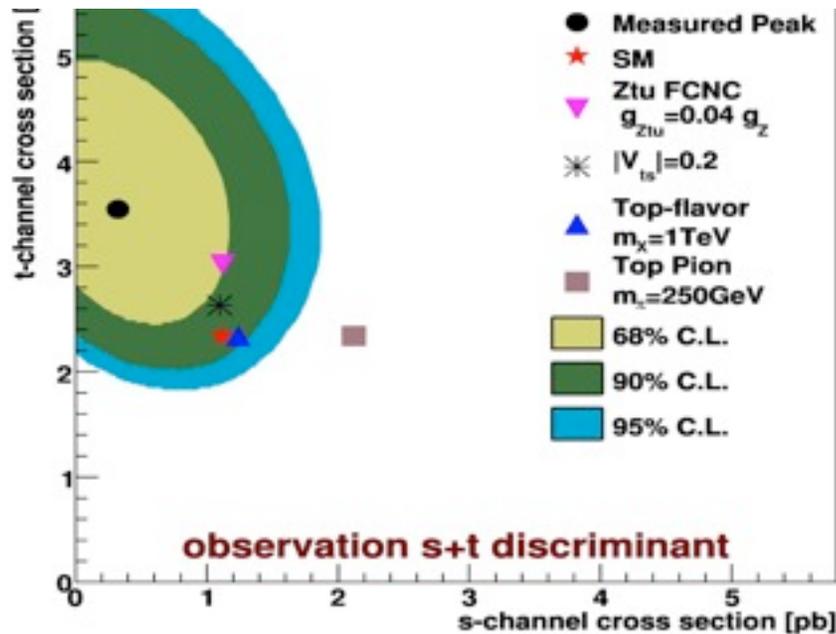


DØ 2.3 fb⁻¹

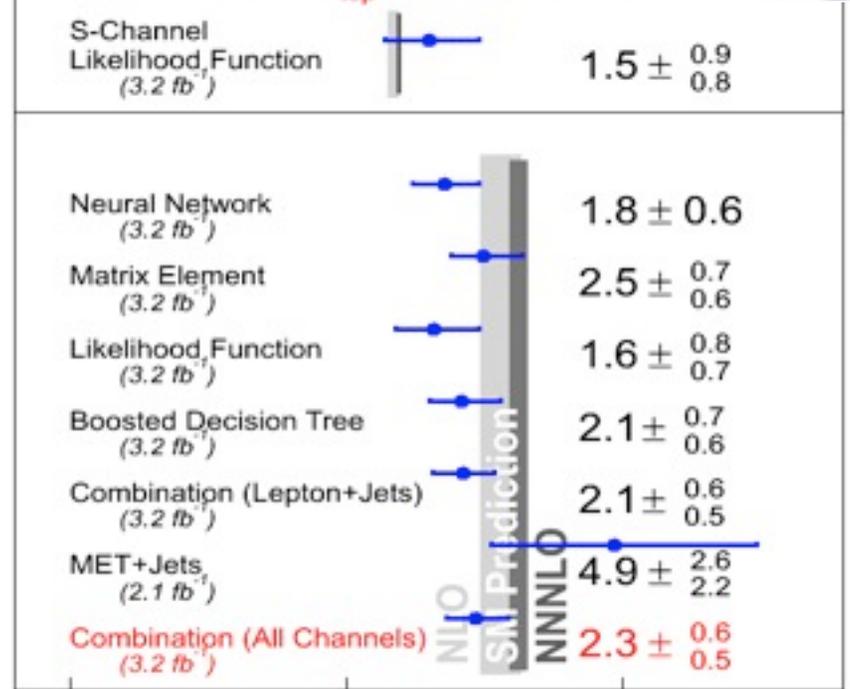
March 2009



$\sigma(p\bar{p} \rightarrow tb+X, tqb+X)$ [pb]

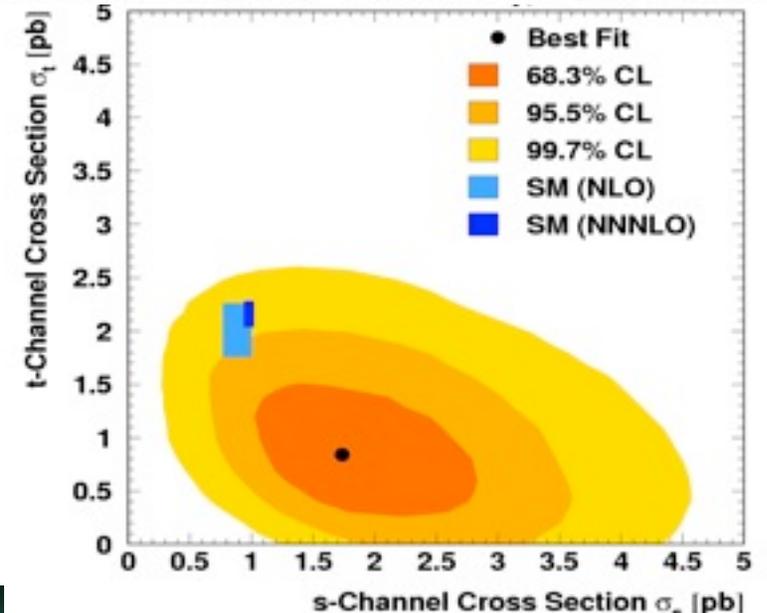


For M_{top} = 175 GeV/c²



Single Top Production Cross Section (pb)

NLO: Z.Sullivan, Phys.Rev.D70,114012 (2004) NNNLO: N.Kidonakis, Phys.Rev.D74,114012 (2006)



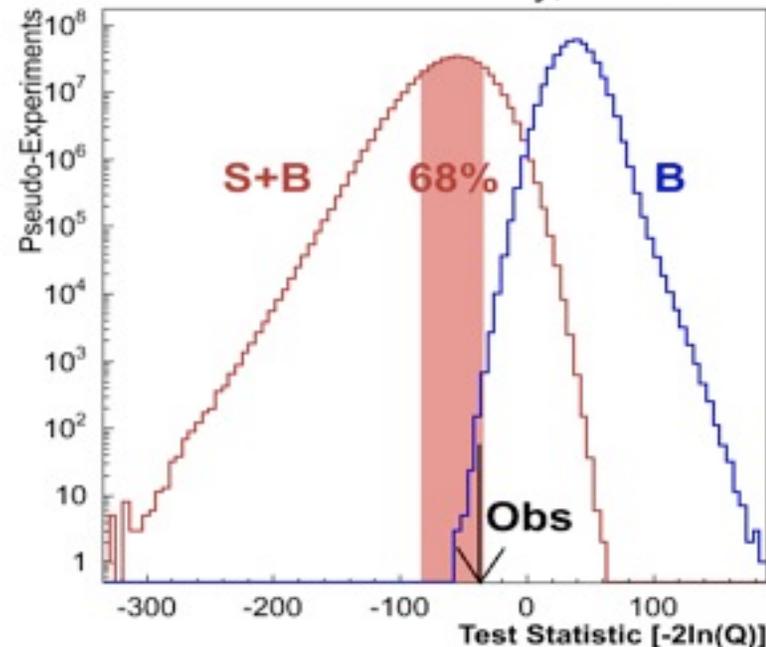


Tevatron combination



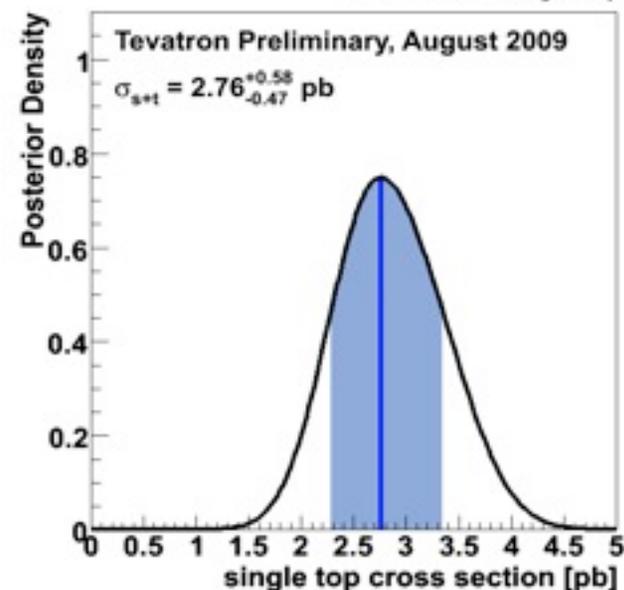
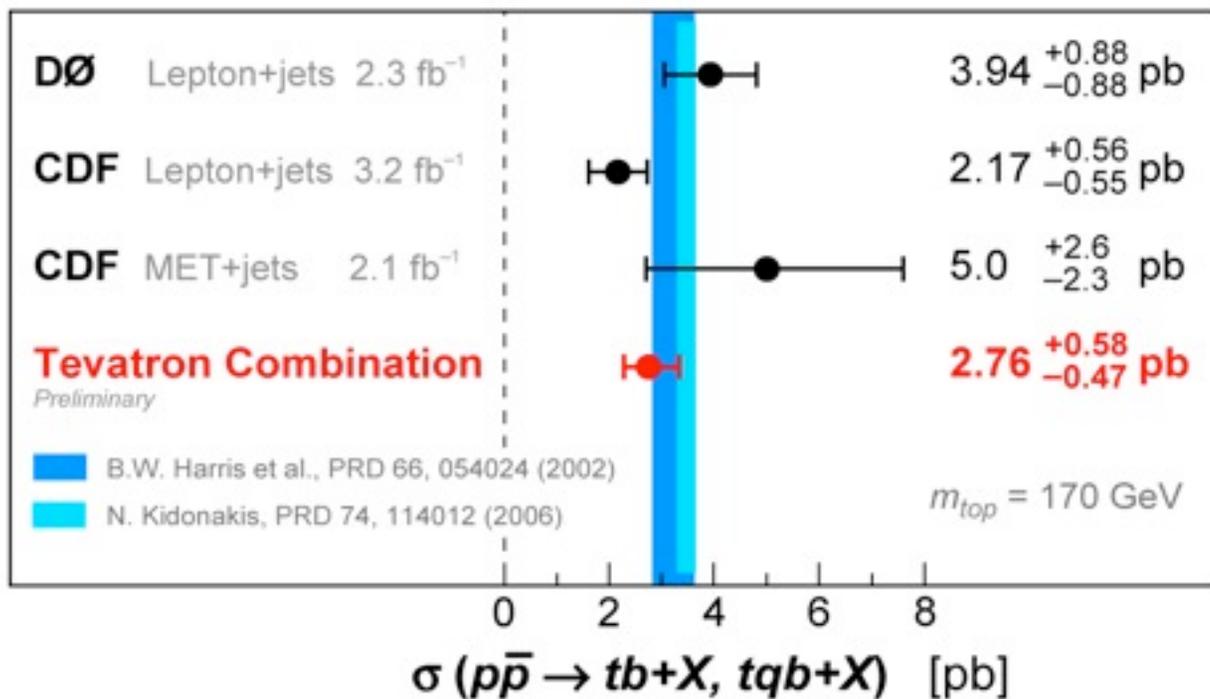
- Each experiment observes 5σ significance
- DØ and CDF measurements are consistent to 1.6σ
- Combination of MVA distributions
 - ⤴ Bayesian statistical analysis
 - ⤴ Taking all uncertainty correlations into account

CDF Run II Preliminary, L = 3.2 fb⁻¹



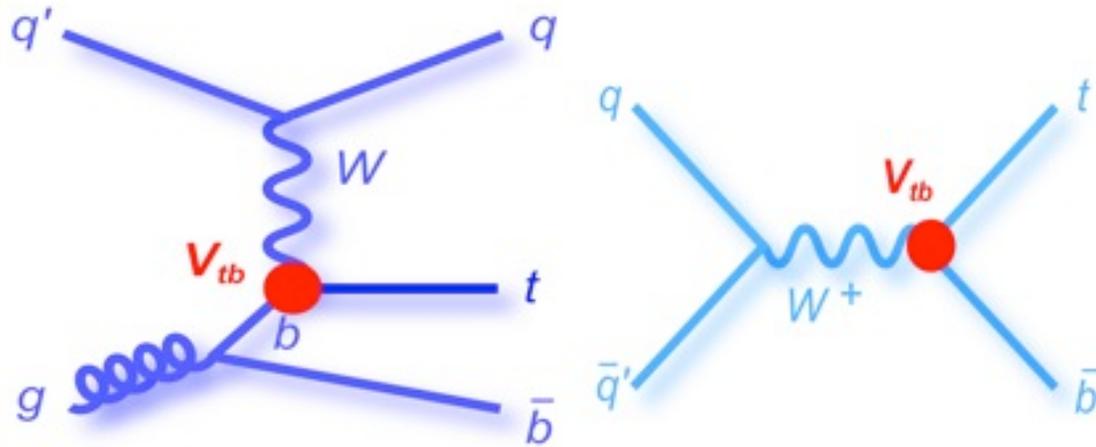
Single Top Quark Cross Section

August 2009





CKM matrix element V_{tb}



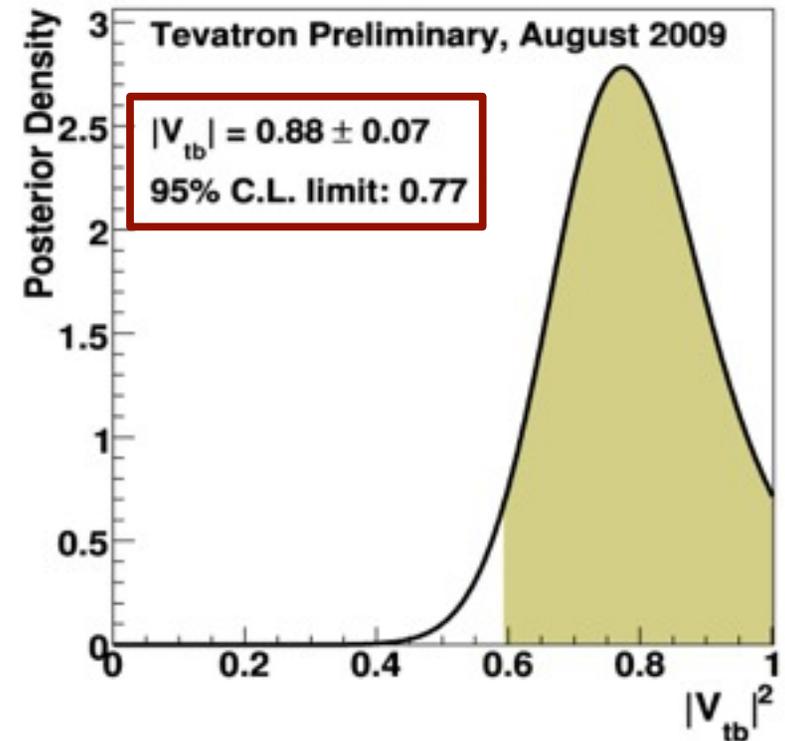
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

✦ Cross section $\propto |V_{tb}|^2$

– Assume SM top quark decay:
 $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$

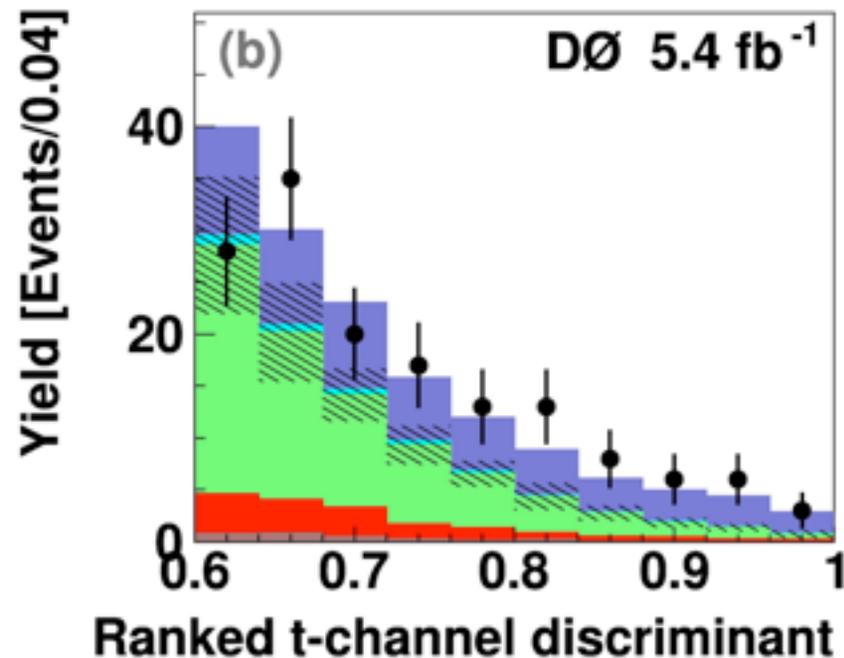
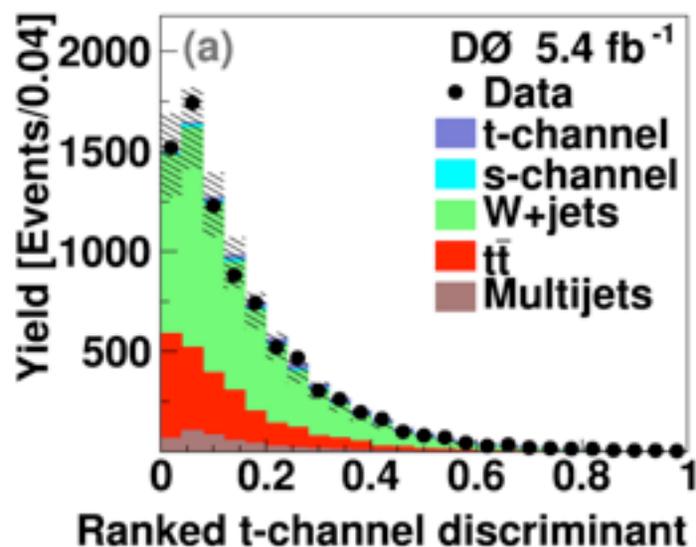
– Pure V-A and CP conserving W_{tb} vertex

✦ No assumption on number of families or unitarity

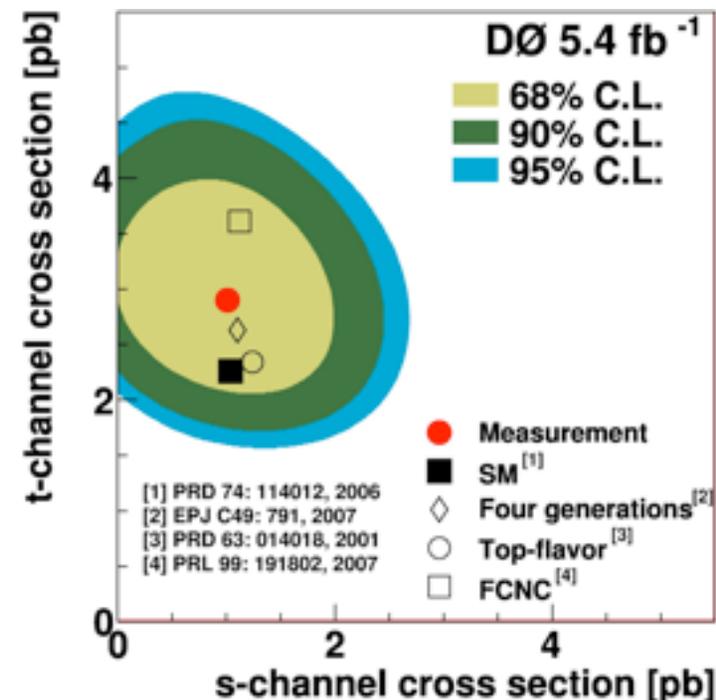
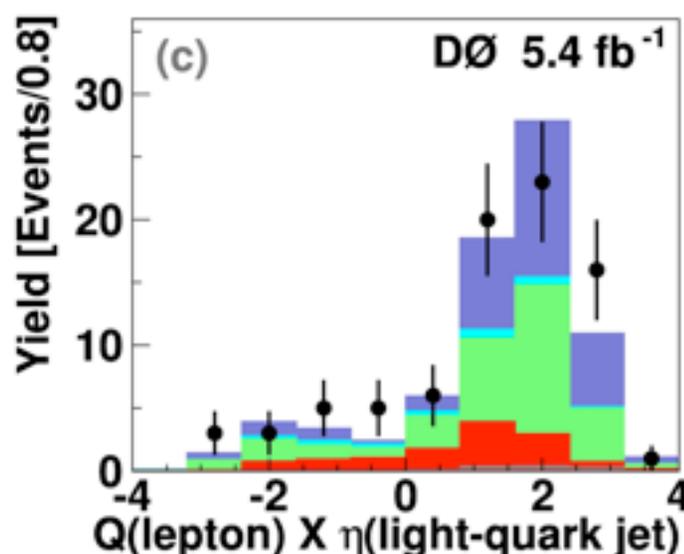
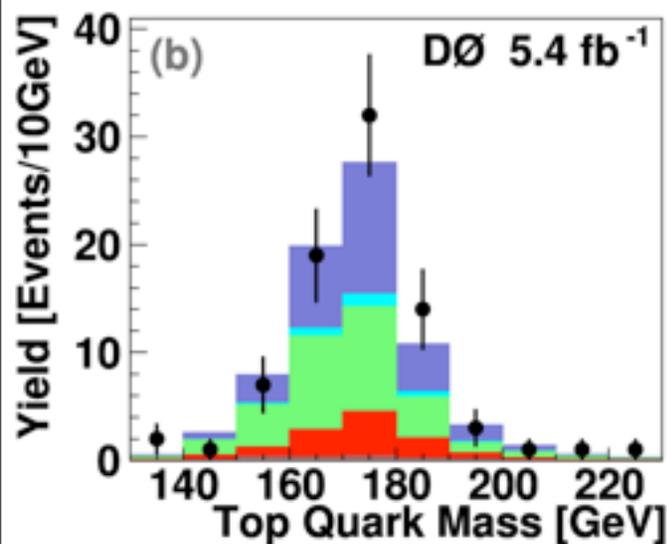


t-channel production

- New analysis with 5.4 fb^{-1}
- Dedicated t-channel filter
- No assumption about s-channel



- 5.5σ significance



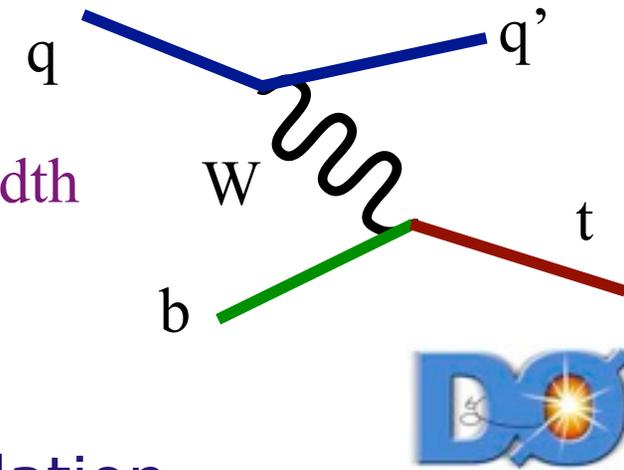
Top quark properties

- top quark width from t-channel cross section

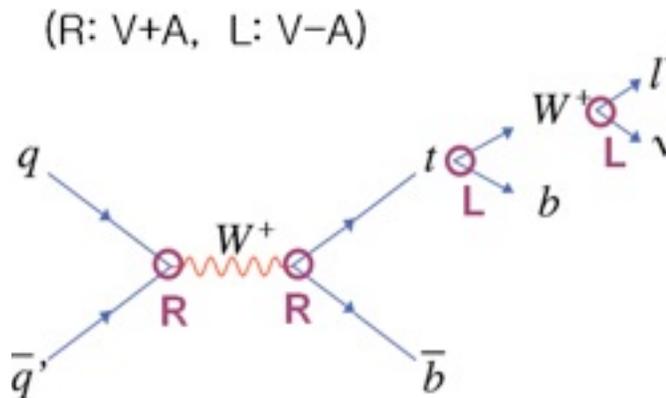
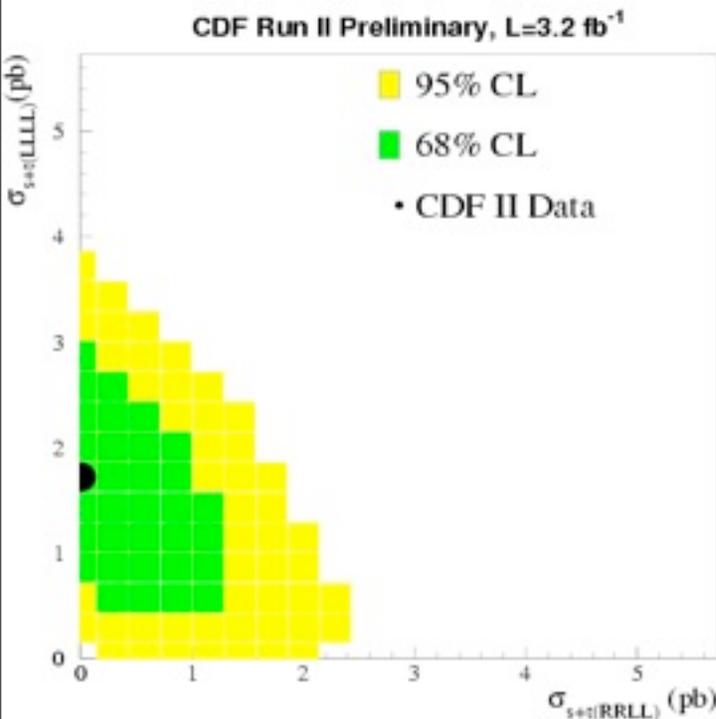
–use $R=B(t \rightarrow Wb)/B(t \rightarrow Wx)$ to obtain full width

$$\Gamma_t = 2.05^{+0.57}_{-0.52} \text{ GeV}$$

$$\tau_t = (3.2^{+1.1}_{-0.7}) \times 10^{-25} \text{ s}$$



- Top quark polarization from spin correlation



- Analysis using likelihood function
- Test for right-handed coupling in top production

$$polarization = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -1^{+1.5}_{-0}$$



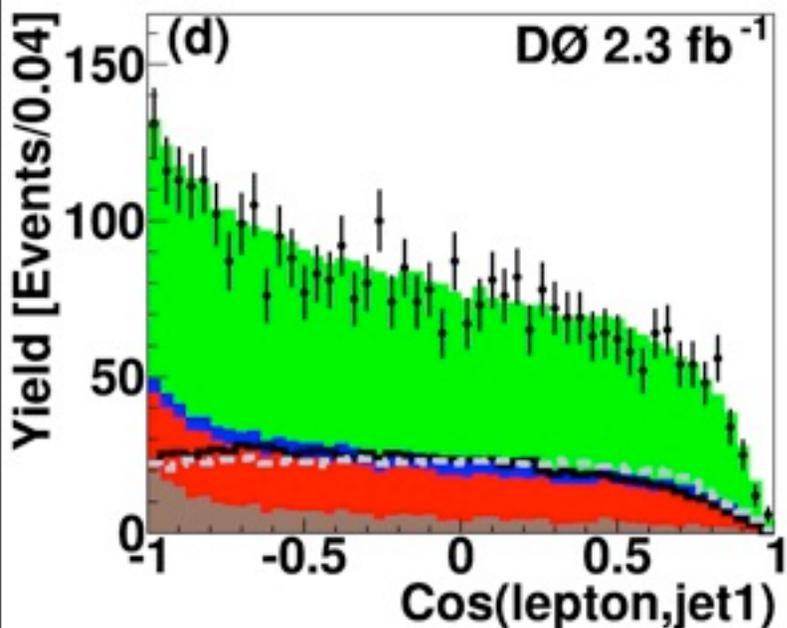
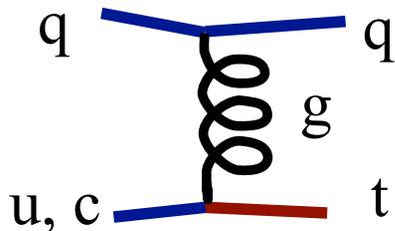
Tevatron new physics searches



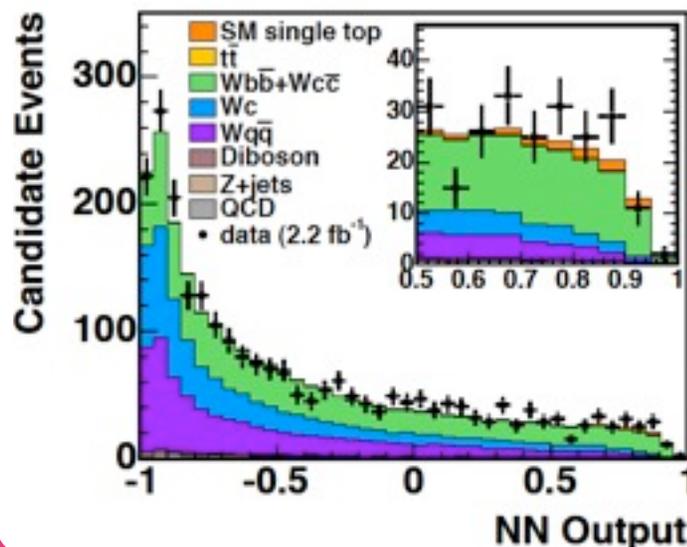
Gluon-FCNC in single top



- ✦ DØ: 2→2 process
- ★ Same final state as t-channel
- ★ multivariate analysis using BNN



- ✦ CDF: 2→1 process
- ★ multivariate analysis using NN



A Feynman diagram showing a quark (u, c) transitioning into a top quark (t) through a gluon loop (g).

$\frac{\kappa_{gtu}}{\Lambda} < 0.025 \text{ TeV}^{-1}$
 $\frac{\kappa_{gtc}}{\Lambda} < 0.105 \text{ TeV}^{-1}$

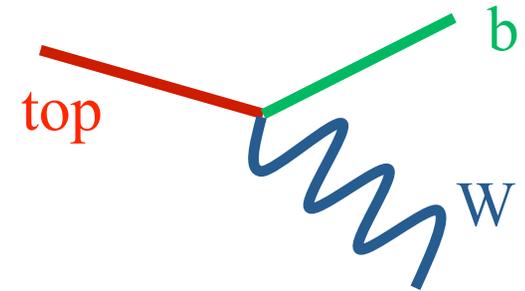
95% CL limits:

	tgu	tgc
Cross section	0.20 pb	0.27 pb
κ_{tgf}/Λ	0.013 TeV ⁻¹	0.057 TeV ⁻¹
$\mathcal{B}(t \rightarrow qg)$	2.0×10^{-4}	3.9×10^{-3}



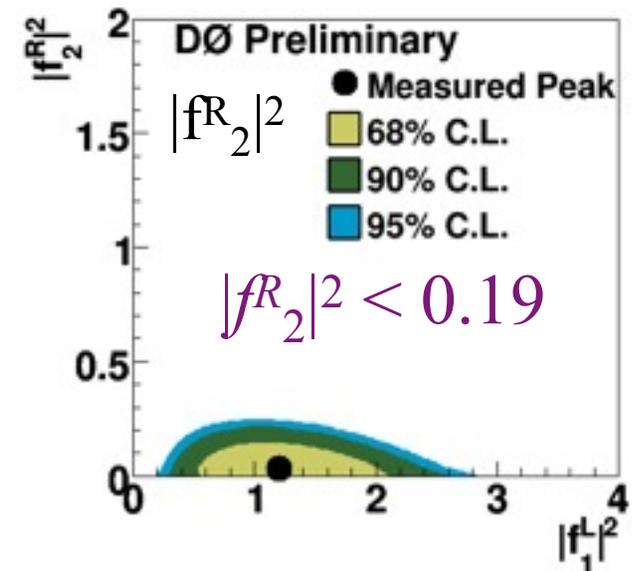
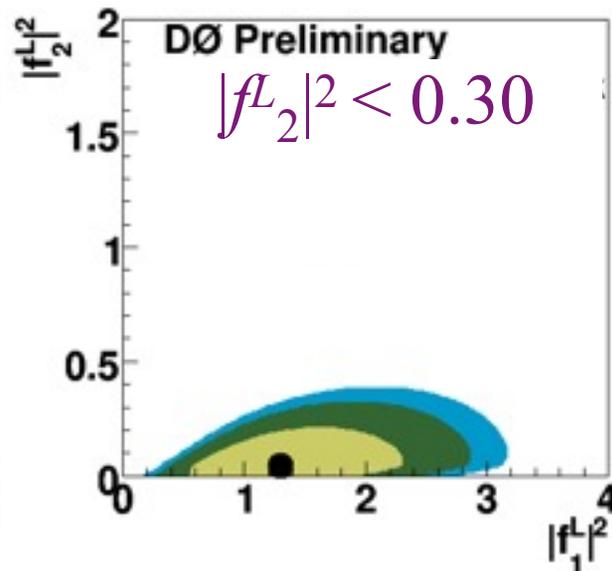
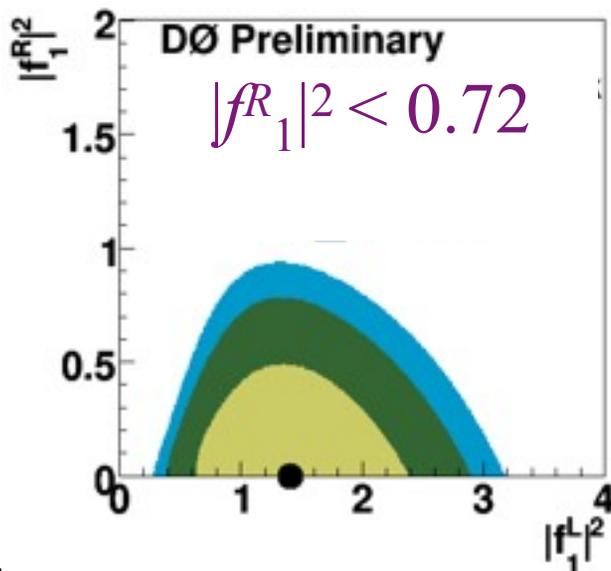
Single top anomalous coupling

- Left-vector (f_1^L , =1 in SM), right-vector (f_1^R), left-tensor (f_2^L), right-tensor (f_2^R)



$$\mathcal{L} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} (f_1^L P_L + f_1^R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (f_2^L P_L + f_2^R P_R) t W_\mu^- + h.c.$$

- Single top is sensitive to magnitude (PRL 101, 221801 (2008))
- ttbar to ratios of couplings (W helicity, PRL 100, 062004 (2008))
- Best sensitivity through combination (PRL 102, 092002 (2009))





Search for W' boson

- Explore simultaneously left-handed and right-handed couplings

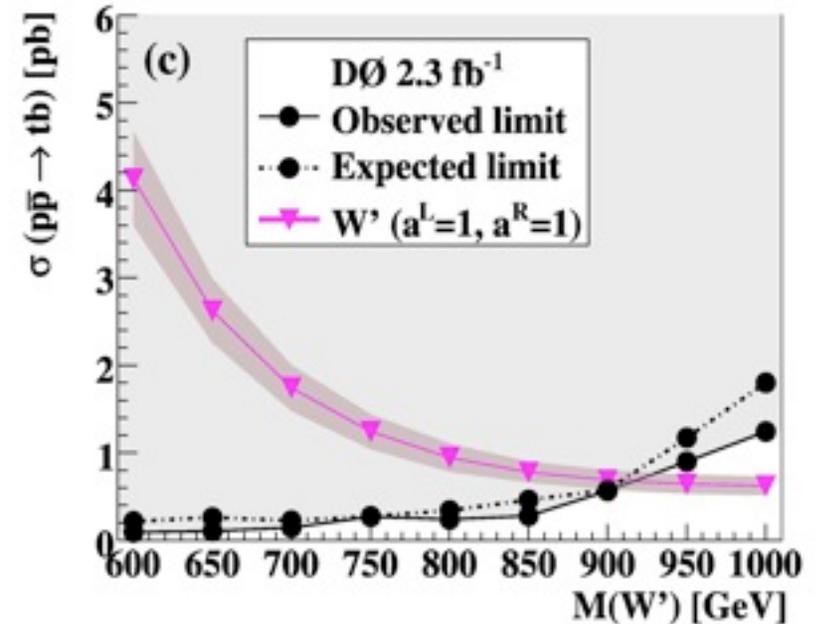
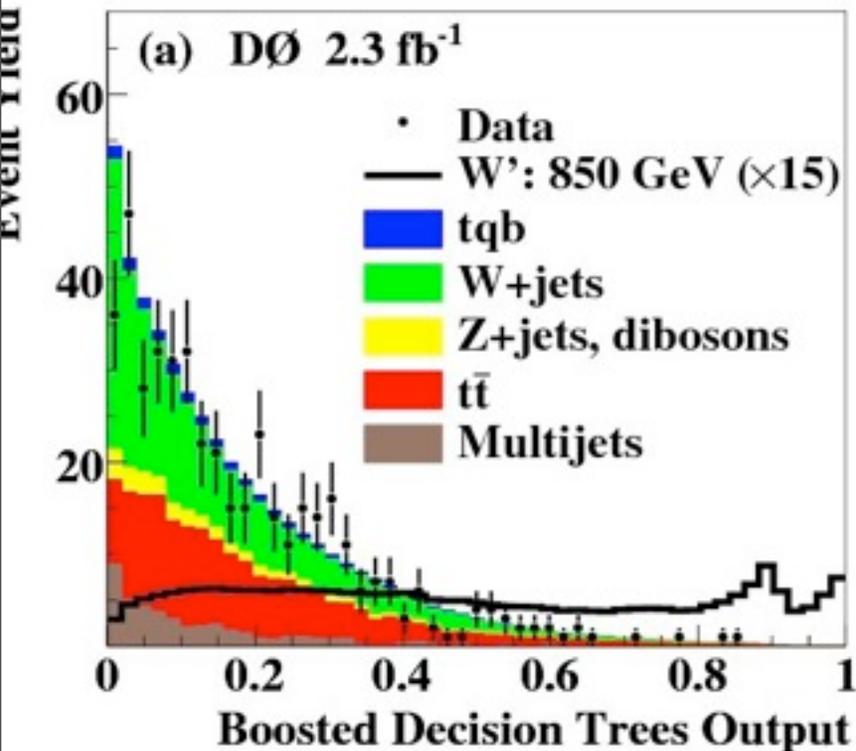
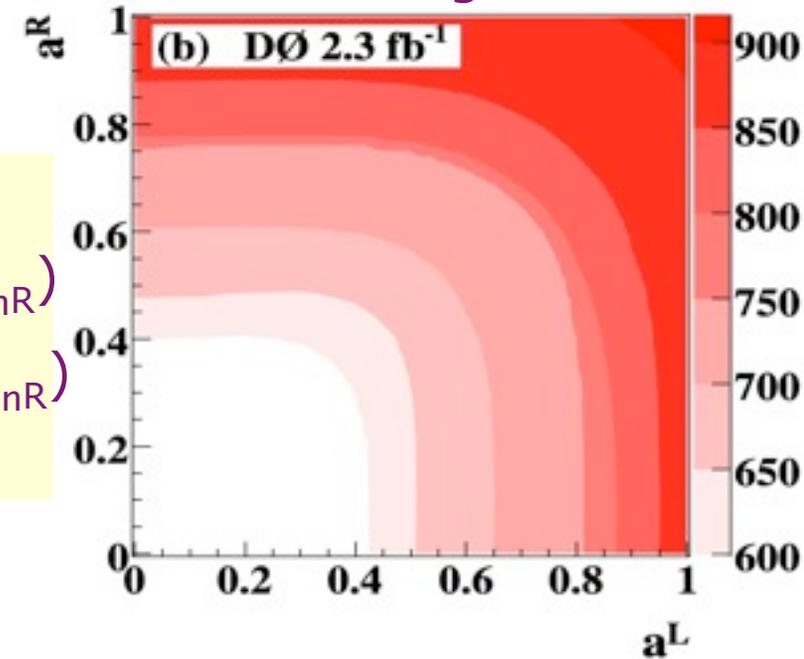
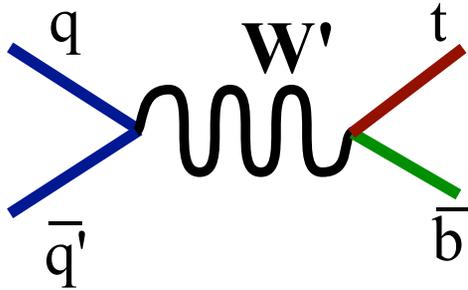
- 95% CL limits:

$M_{W'} > 863$ GeV (L only)

$M_{W'} > 885$ GeV (R, $M_{W'} < m_{nR}$)

$M_{W'} > 890$ GeV (R, $M_{W'} > m_{nR}$)

$M_{W'} > 916$ GeV (L+R)



Experimental setup: LHC at CERN

Proton-proton collider

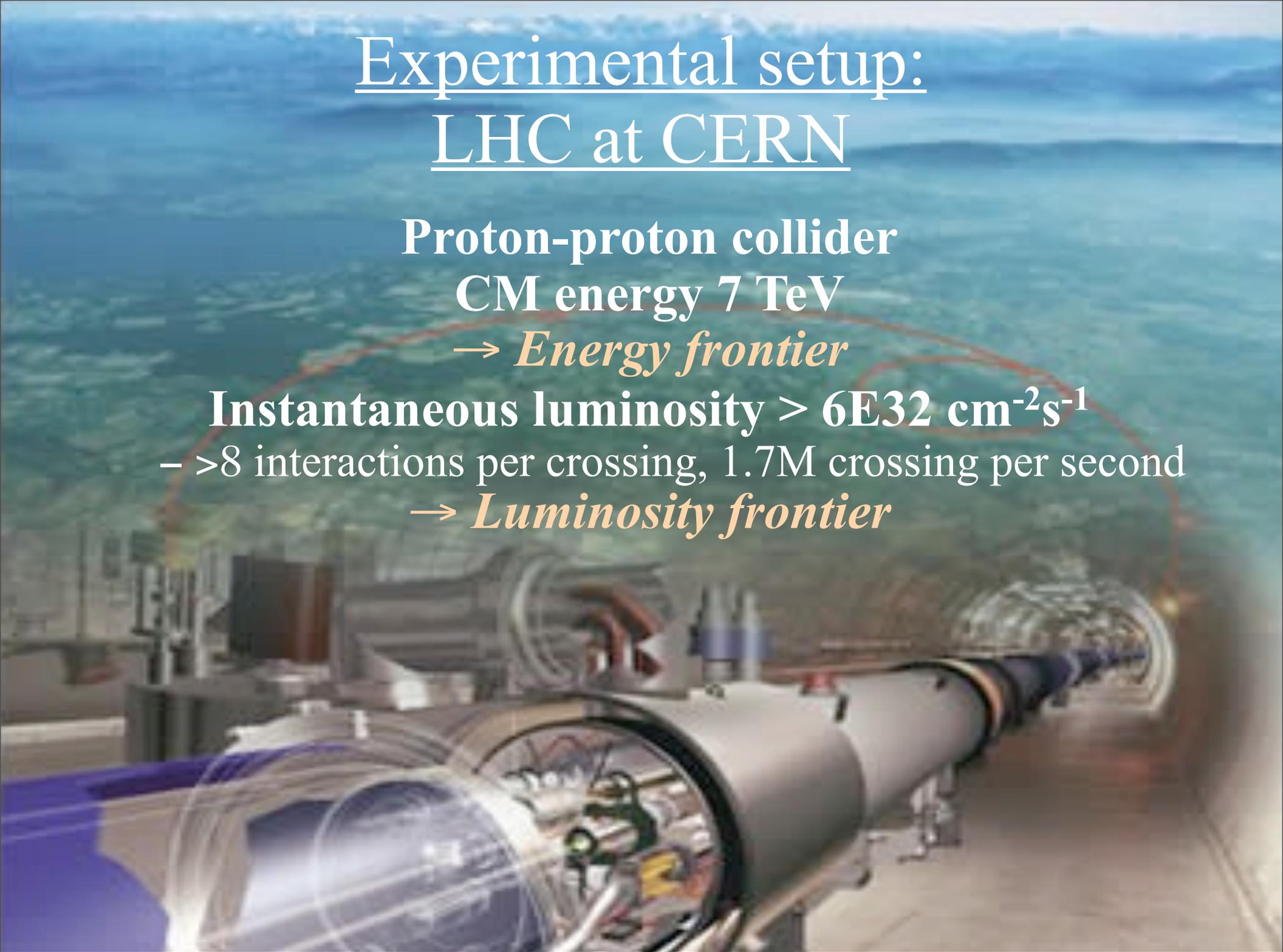
CM energy 7 TeV

→ *Energy frontier*

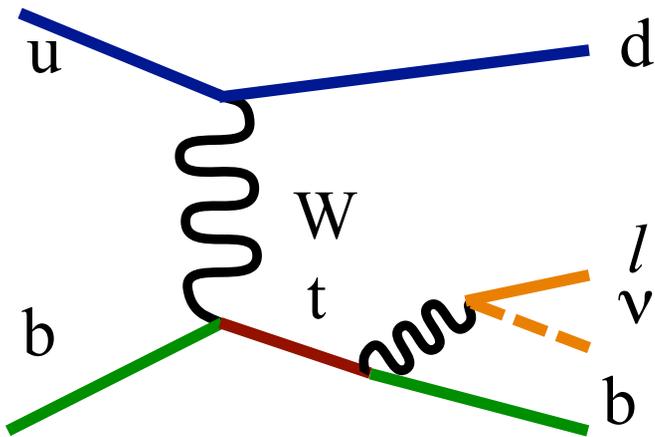
Instantaneous luminosity $> 6E32 \text{ cm}^{-2}\text{s}^{-1}$

– >8 interactions per crossing, 1.7M crossing per second

→ *Luminosity frontier*



Measurement of t-channel production



- 36 pb⁻¹ of 2010 data

Event selection:

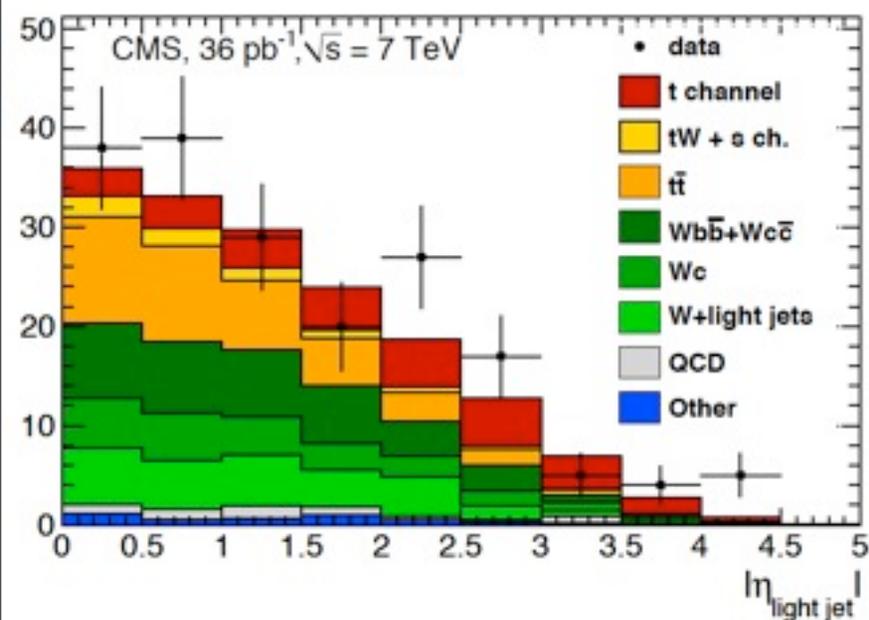
- 1 electron or muon
E_T (p_T) > 30/20 GeV
- M_T (W) > 50/40 GeV
- = 2 jets (p_T > 30 GeV), ≥1 b-tag
- fewer channels than Tevatron, tighter cuts

Background modeling:

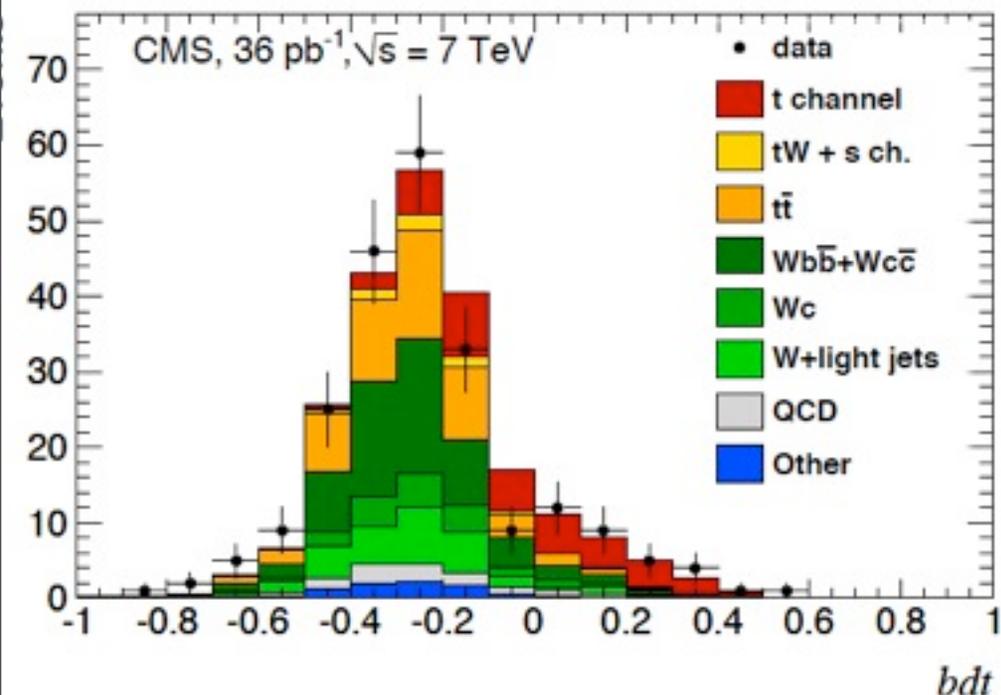
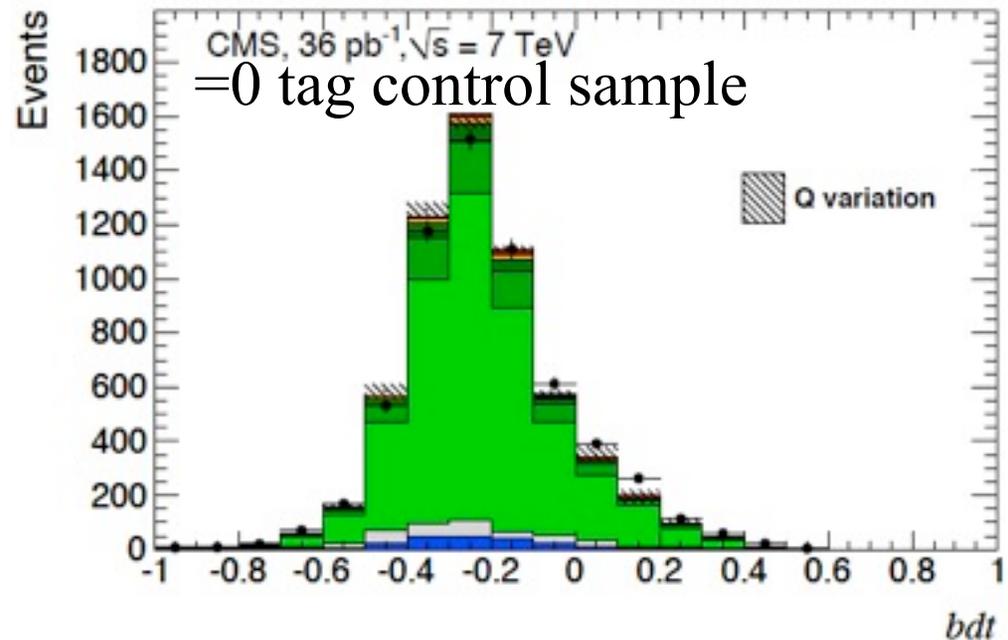
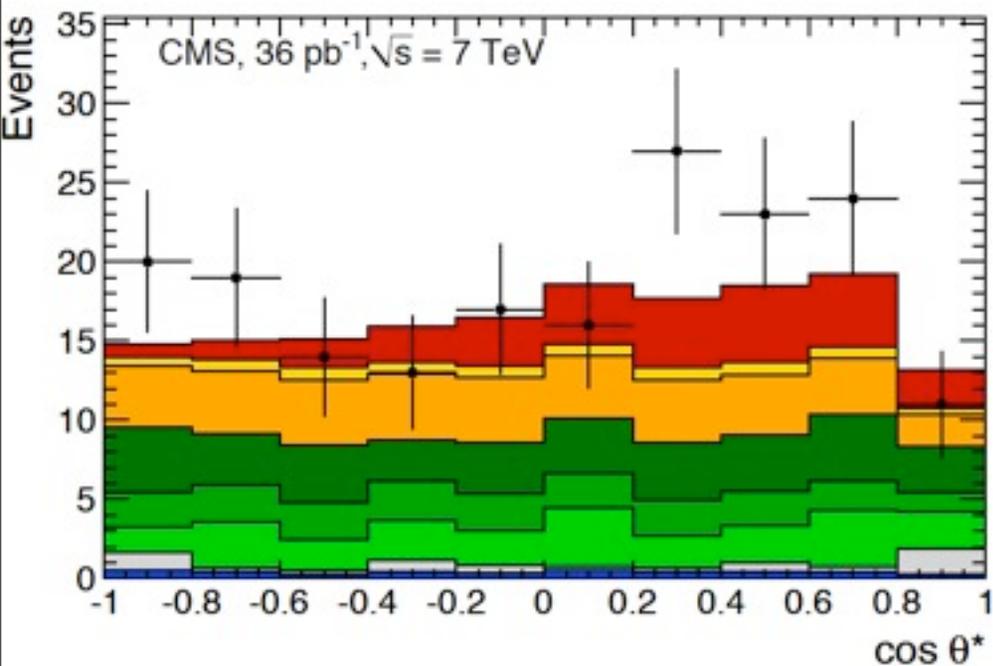
- normalize W+jets and QCD to data
- top background to theory

Analysis procedure:

- BDT with 37 variables
- 2-d fit to light jet η and spin correlation



t-channel result



• Combination using BLUE

combined: observed cross section:

$$\sigma_t = 83.6 \pm 29.8 \text{ pb}$$

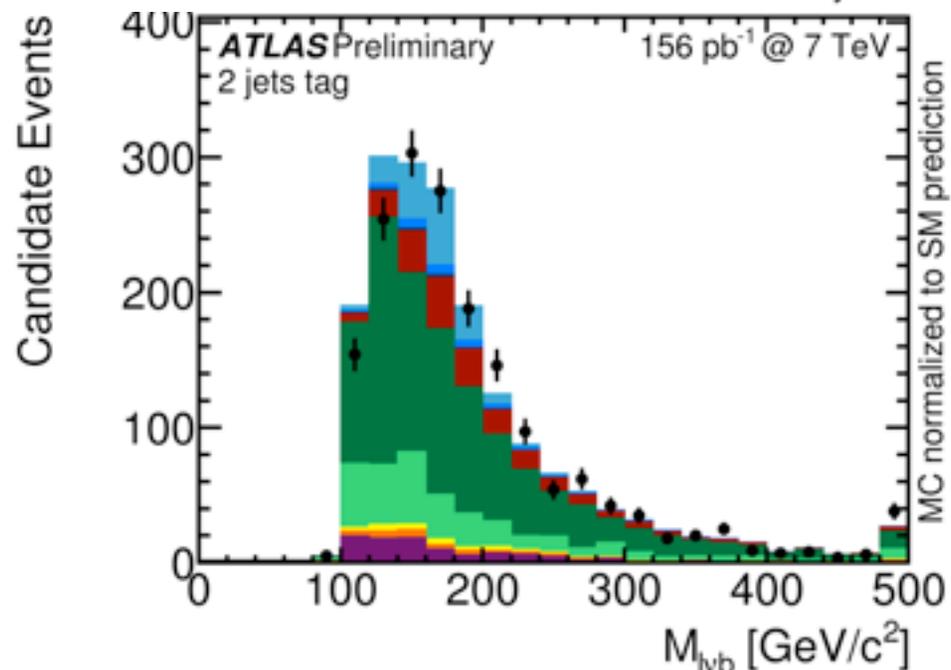
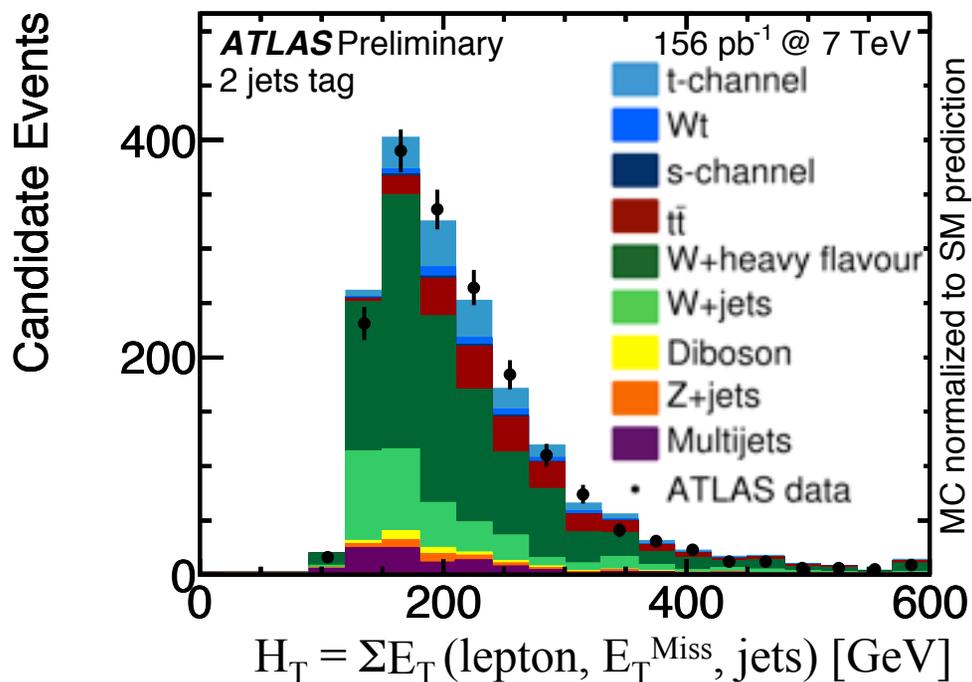
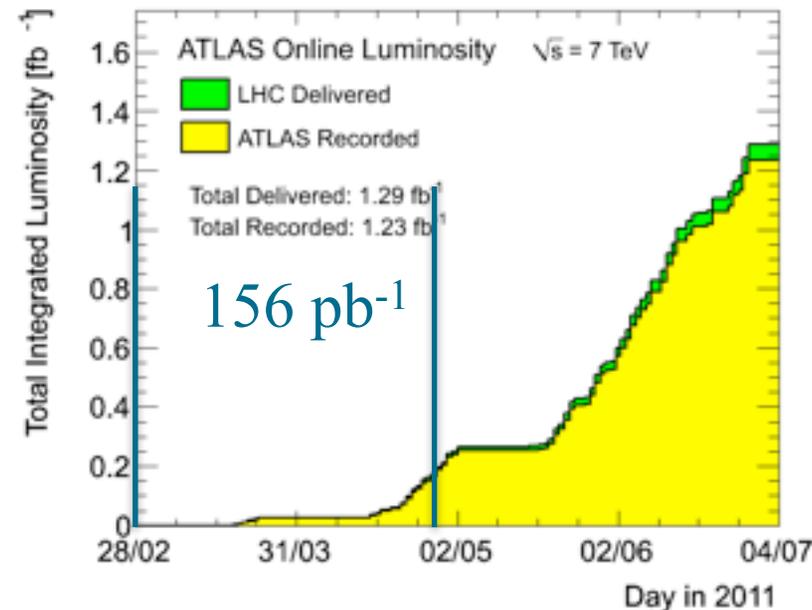
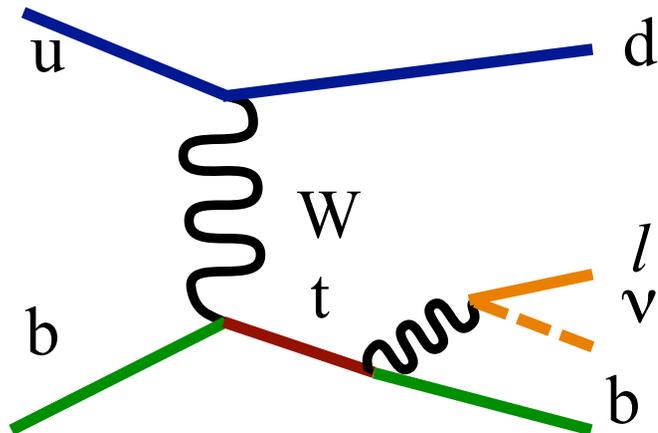
Observed significance: 3.5 σ

Observed $|V_{tb}| > 0.68$ at 95% CL

arXiv:1106.3052 [hep-ex]

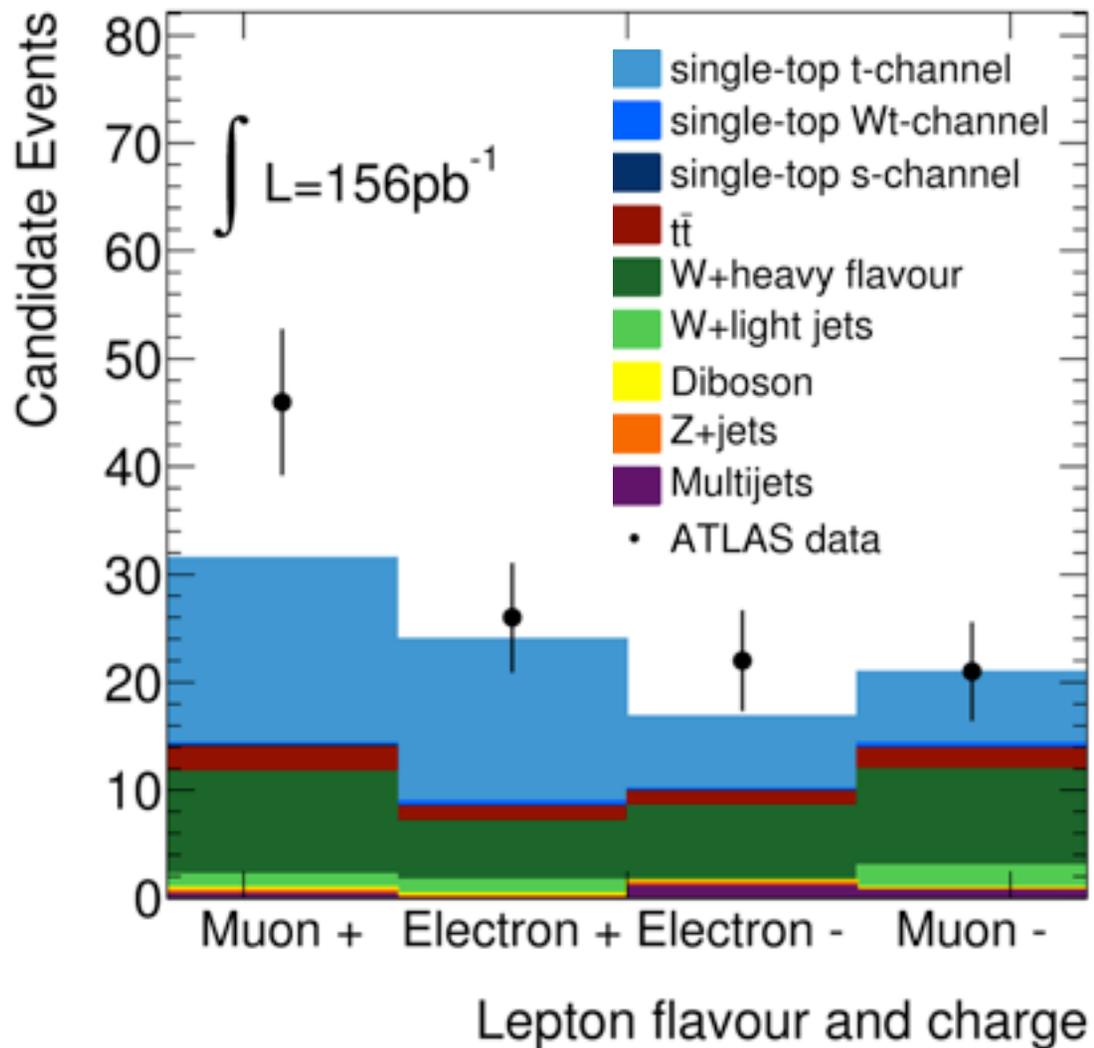
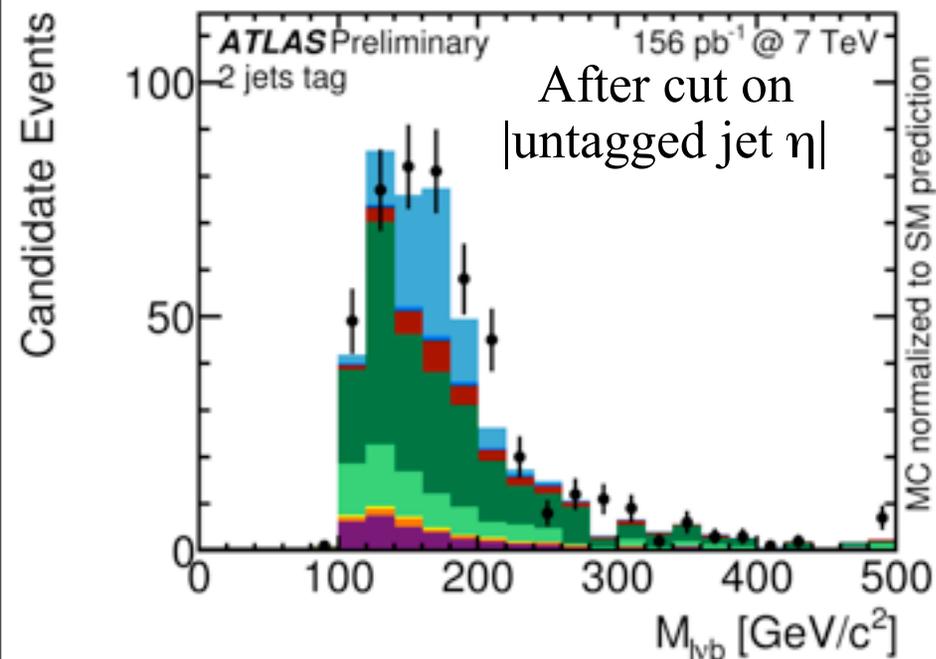
Measurement of t-channel production

- 156 pb⁻¹ of 2011 ATLAS data



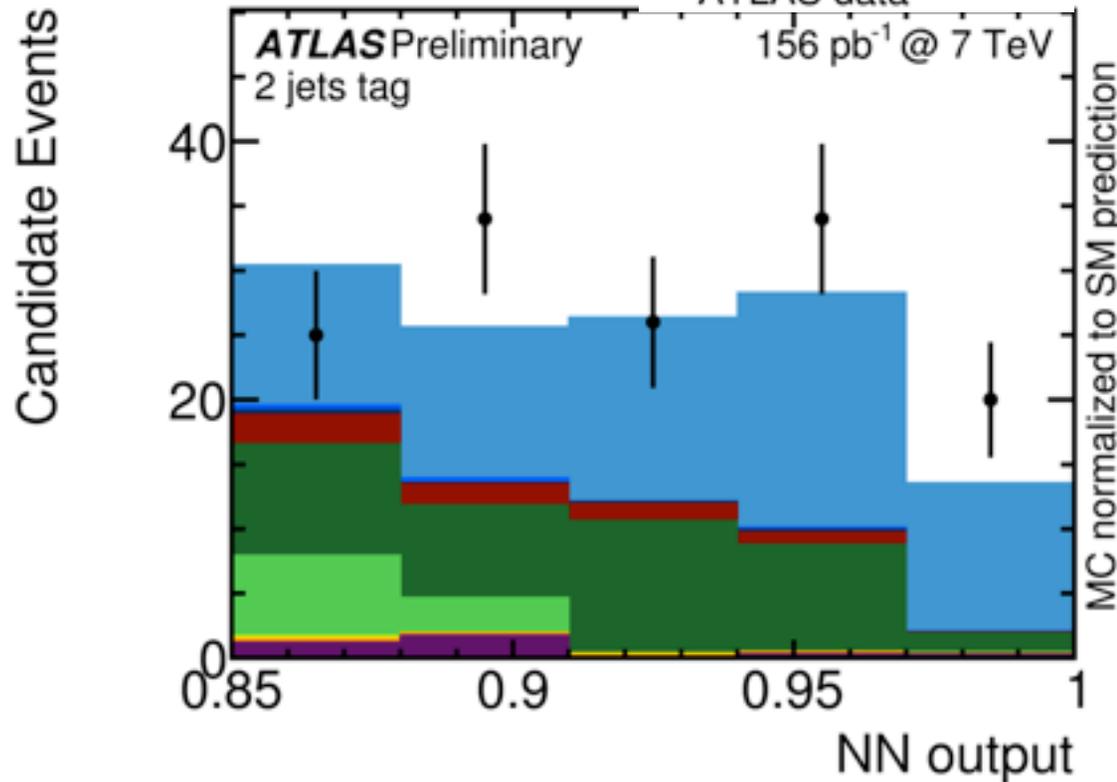
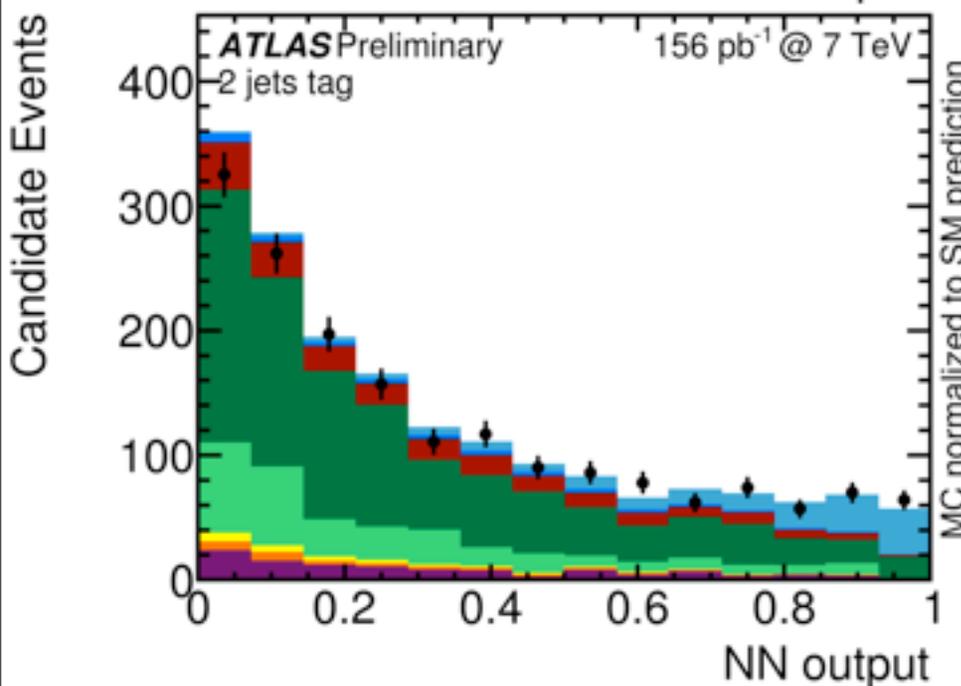
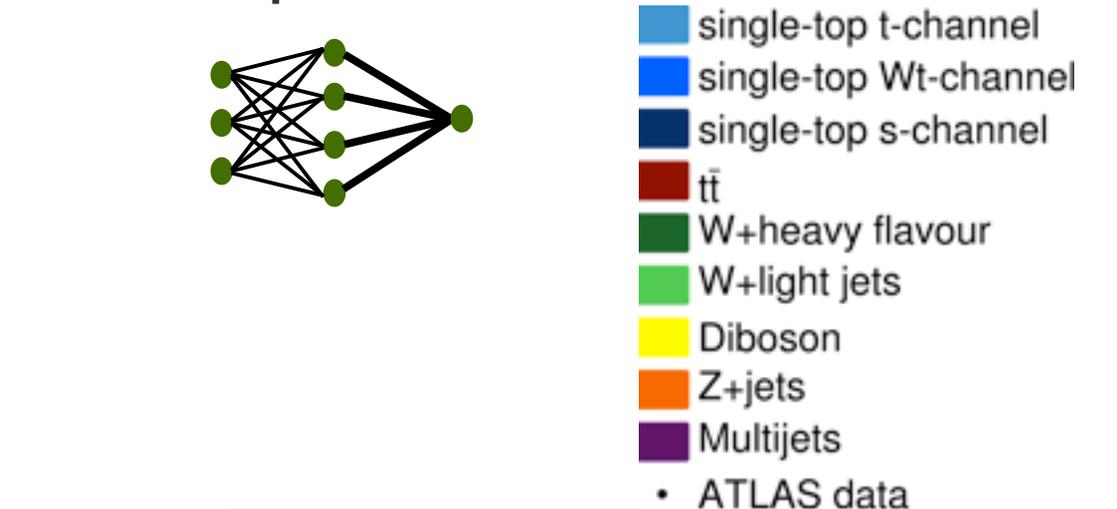
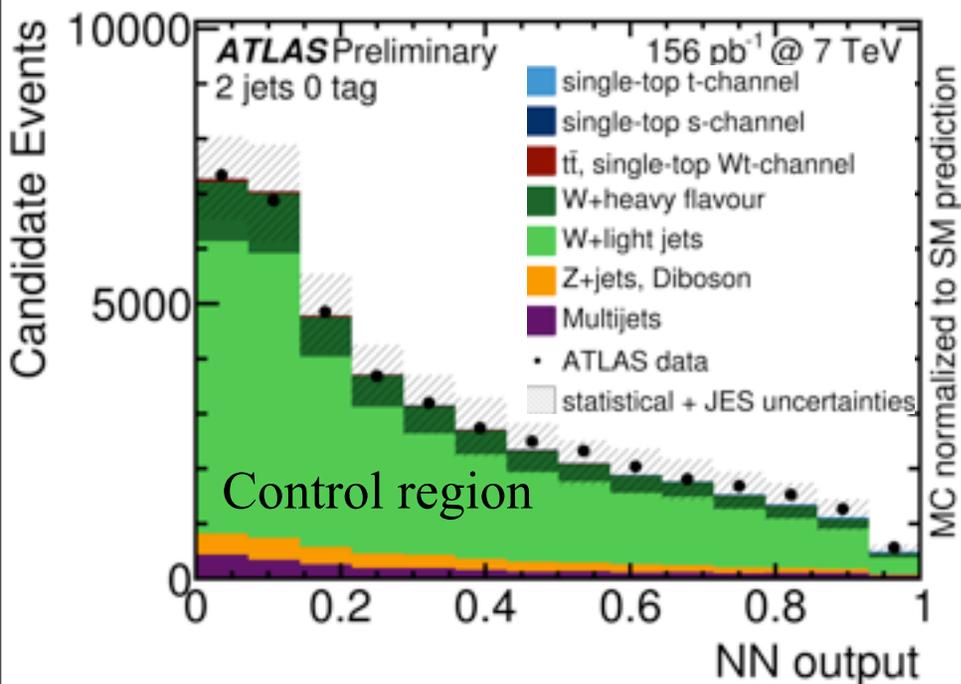
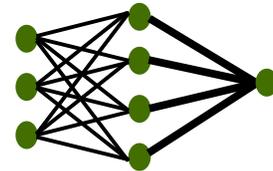
Cut-based t-channel analysis

- $|\text{untagged jet } \eta| > 2.0$
- $140 \text{ GeV} < \text{top quark mass} < 190 \text{ GeV}$
- $|\Delta\eta(\text{lepton, b-tagged jet})| < 1.5$
- $|\text{b-tagged jet } \eta| < 2.0$
- $H_T > 180 \text{ GeV}$
- separate by lepton flavor and top charge



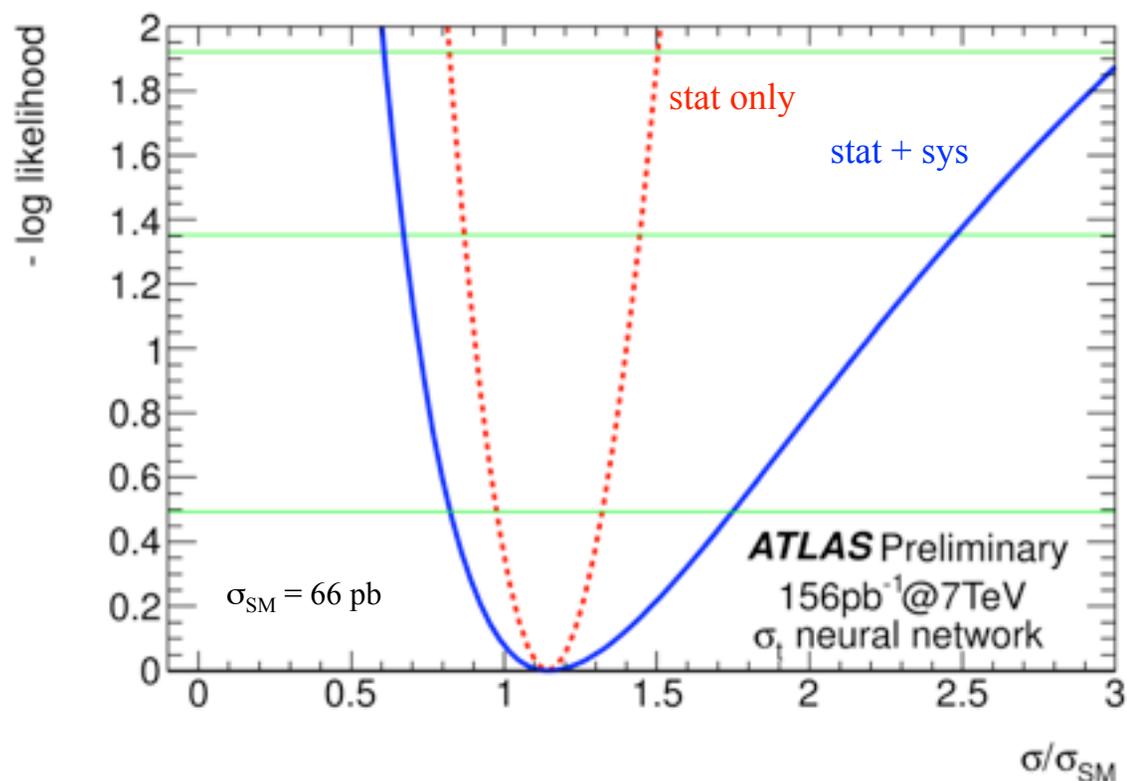
Neural network result

● 22 input variables



t-channel result

- Simple event-counting
- Expected cross section systematic uncertainties
 - B-tagging $\sim 12\%$
 - MC statistics $\sim 11\%$
 - ISR/FSR $\sim 6\%$
 - Signal modeling $+36_{-20}\%$
 - Total systematics $+55_{-29}\%$
- Statistical uncertainty 17%
 Cut-based: Observed cross section:
 $\sigma_t = 97^{+54}_{-30} \text{ pb}$
 Observed (expected) significance:
 $6.3 (4.5) \sigma$



NN: Observed cross section:

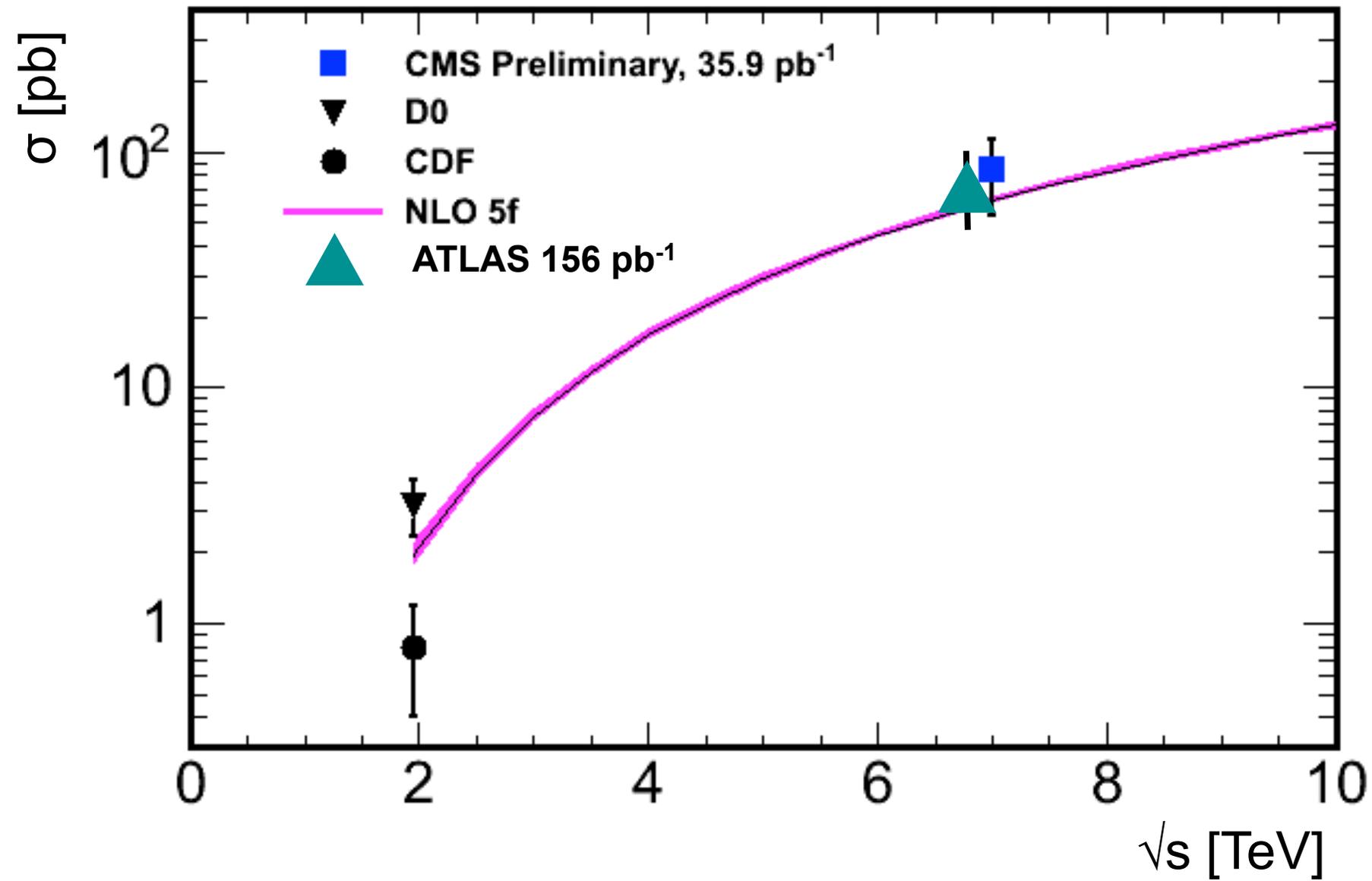
$$\sigma_t = 76^{+41}_{-21} \text{ pb}$$

Observed (expected) significance:

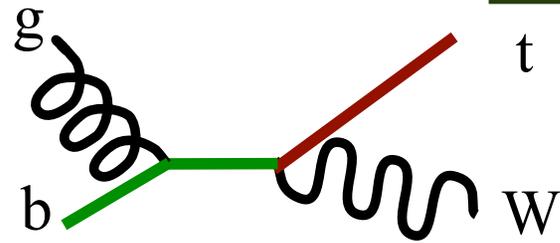
$$6.2 (5.7) \sigma$$



t-channel summary



Wt associated production

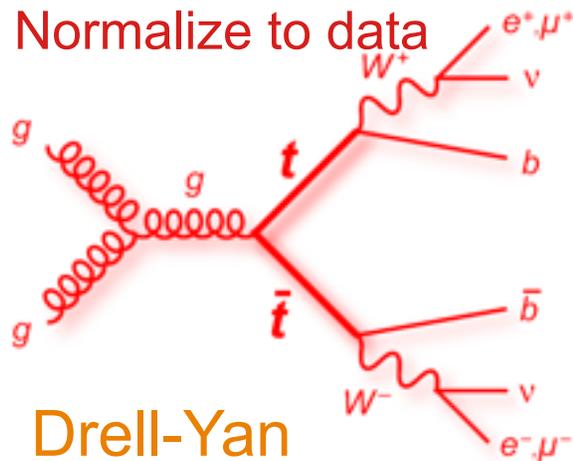


- Never before seen
- Search in lepton+jets and di-leptons

Dilepton backgrounds:

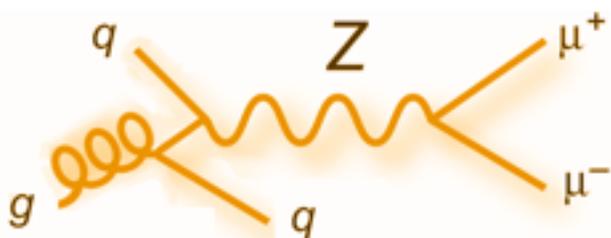
Top quark pairs

- Model using MC@NLO
- Normalize to data

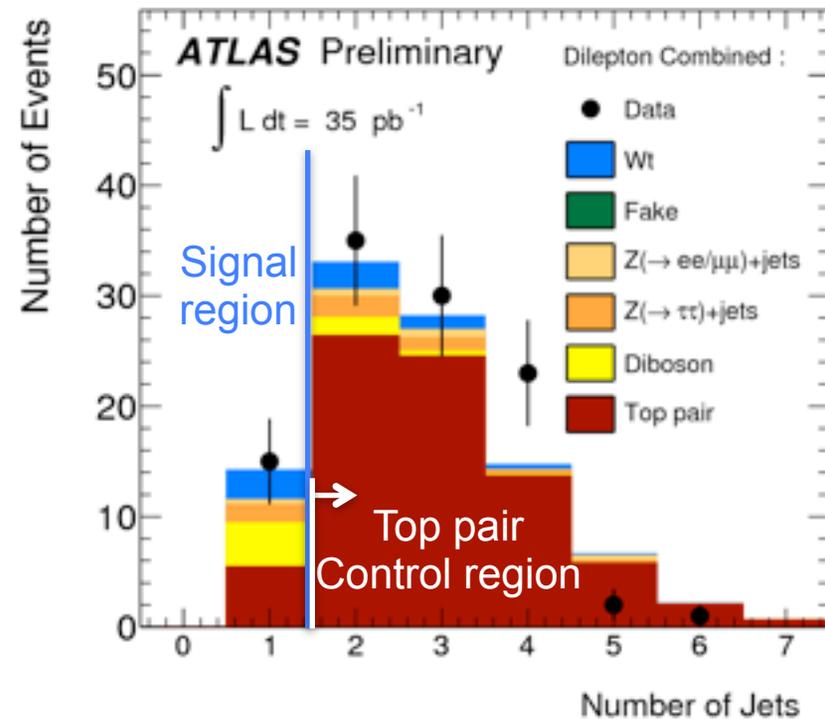


Drell-Yan

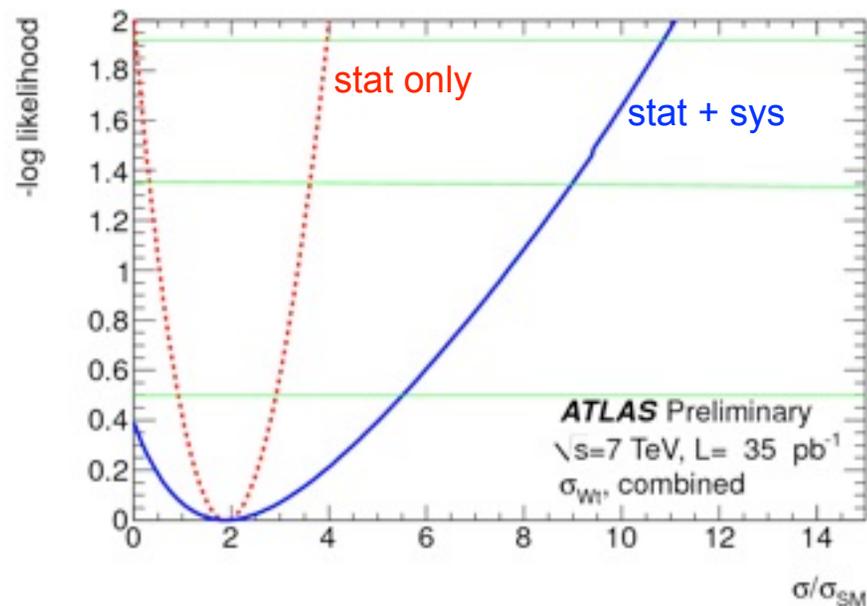
- Model using Alpgen
- Normalize to data



Smaller backgrounds from $Z \rightarrow \tau\tau$, dibosons, W +jets, multijets



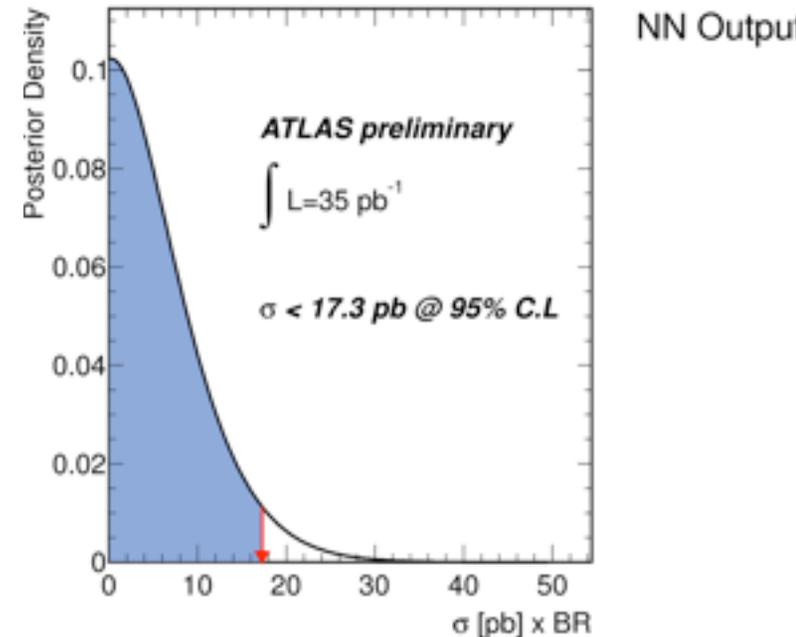
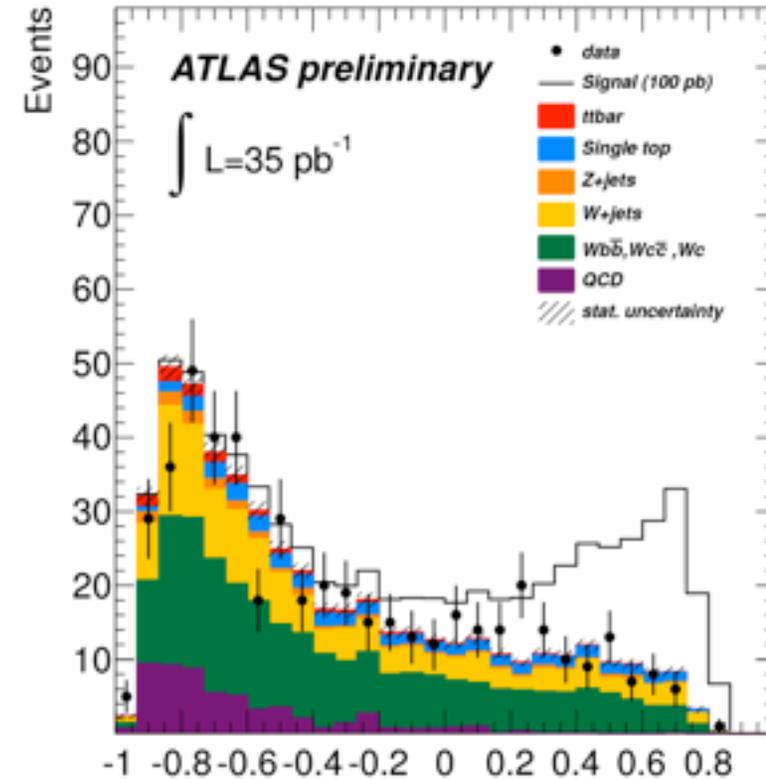
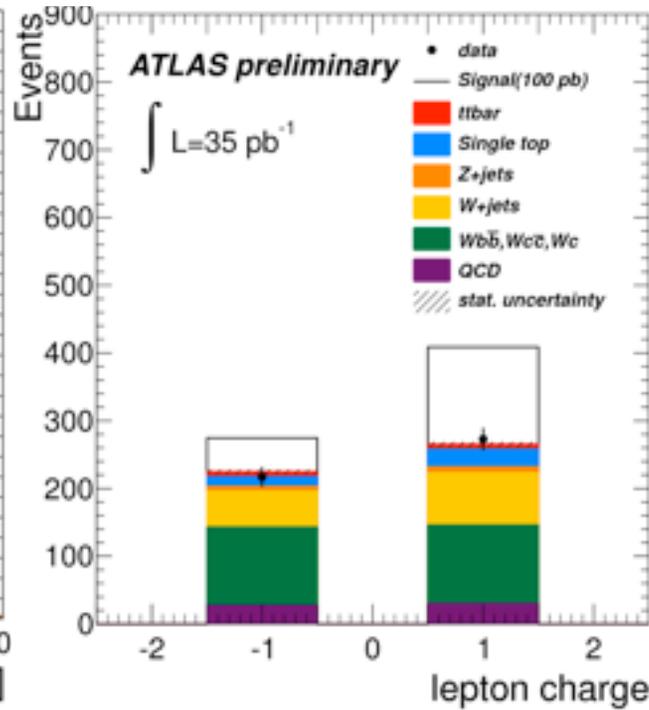
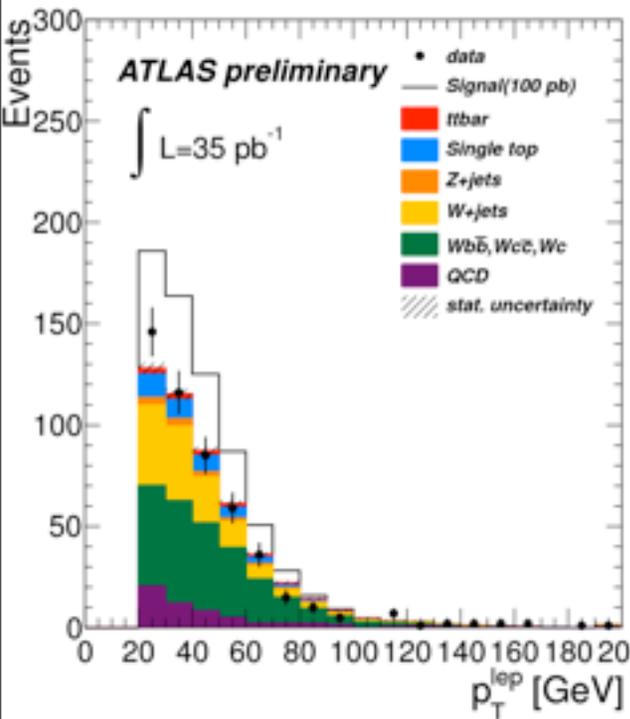
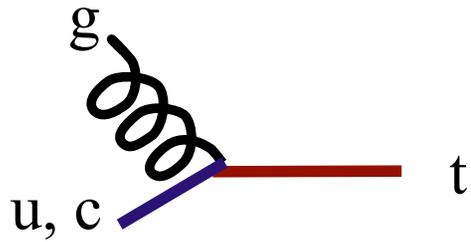
- Set limit of 158 pb ($10 \times \sigma_{Wt}^{SM}$)



LHC new physics searches

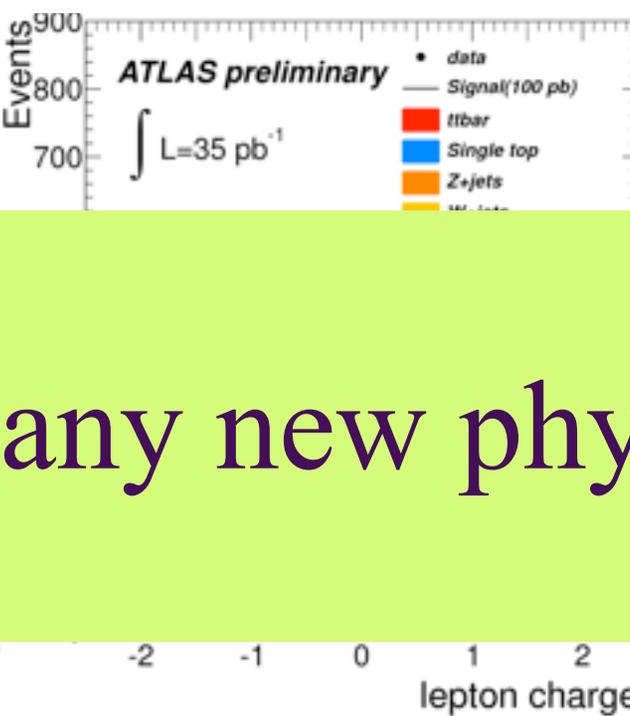
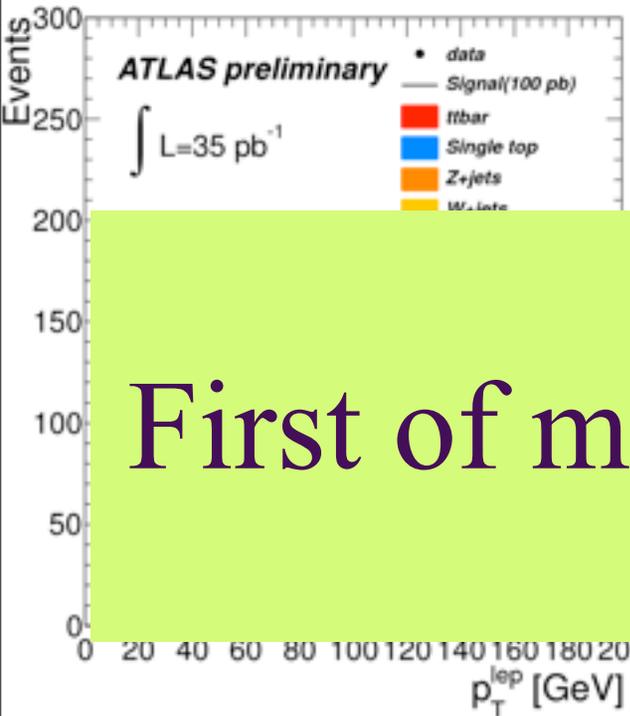
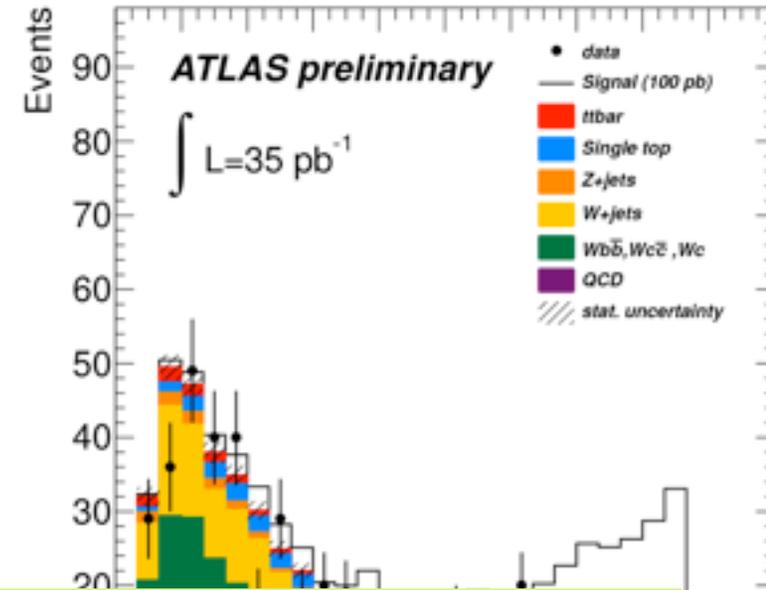
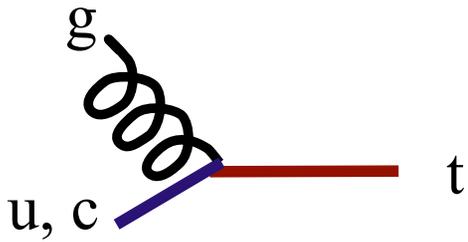
ATLAS FCNC search

- first single top new physics search
- single-top production

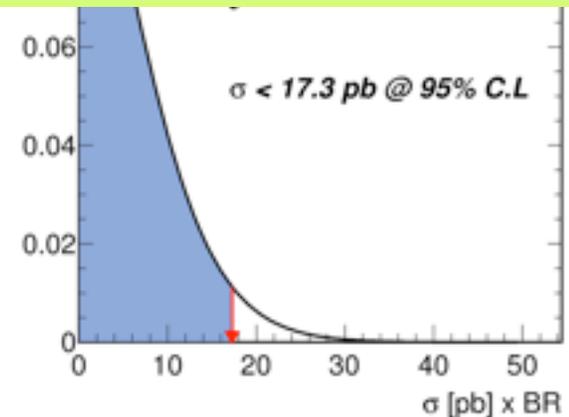


ATLAS FCNC search

- first single top new physics search
- single-top production



First of many new physics searches!



Many more new physics searches

- Anomalous couplings

$$\begin{aligned}\mathcal{L} = & -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu V_{tb}(f_1^L P_L + f_1^R P_R)tW_\mu^- \\ & - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}(f_2^L P_L + f_2^R P_R)tW_\mu^- + h.c.\end{aligned}$$

- In single top and in combination with ttbar

- Resonance searches

- New heavy boson W'

- ▶ With anomalous couplings?
 - ▶ With different CKM matrix - ttbar asymmetry?
 - ▶ Charged Higgs decaying to tb

- Fourth generation quarks

- ▶ B' or T' decaying to single top

- New particles produced together with single top

- Charged Higgs

- If discoveries are made elsewhere first?

- Measure coupling to top

Many more new physics searches

- Anomalous couplings - magnitude

$$\begin{aligned}\mathcal{L} = & -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu V_{tb}\left(f_1^L P_L + f_1^R P_R\right)tW_\mu^- \\ & -\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}\left(f_2^L P_L + f_2^R P_R\right)tW_\mu^- + h.c.\end{aligned}$$

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Many more new physics searches

- Anomalous couplings - magnitude, complex phase

$$\mathcal{L} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} (f_1^L P_L + f_1^R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (f_2^L P_L + f_2^R P_R) t W_\mu^- + h.c.$$

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- Anomalous couplings - magnitude, complex phase, CKM

$$\mathcal{L} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} (f_1^L P_L + f_1^R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (f_2^L P_L + f_2^R P_R) t W_\mu^- + h.c.$$

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Many more new physics searches

- Anomalous couplings - magnitude, complex phase, CKM

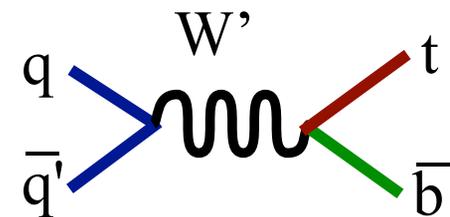
$$\mathcal{L} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} (f_1^L P_L + f_1^R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (f_2^L P_L + f_2^R P_R) t W_\mu^- + h.c.$$

-In single top and in combination with ttbar

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Many more new physics searches

- Anomalous couplings - magnitude, complex phase, CKM

$$\mathcal{L} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} (f_1^L P_L + f_1^R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (f_2^L P_L + f_2^R P_R) t W_\mu^- + h.c.$$

-In single top and in combination with ttbar

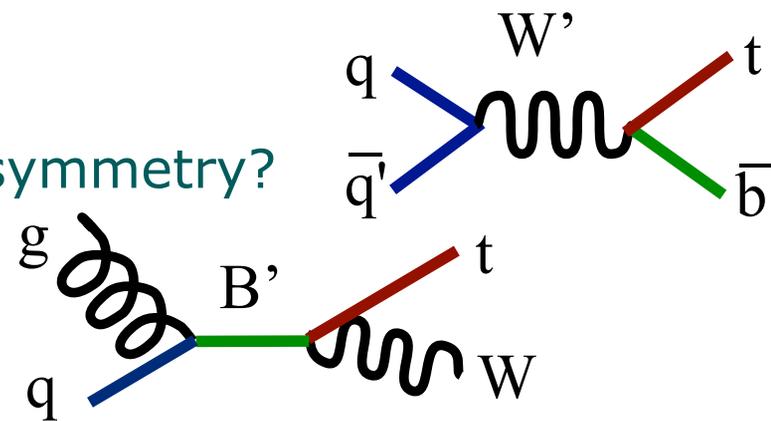
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Many more new physics searches

- Anomalous couplings - magnitude, complex phase, CKM

$$\mathcal{L} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} (f_1^L P_L + f_1^R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (f_2^L P_L + f_2^R P_R) t W_\mu^- + h.c.$$

-In single top and in combination with ttbar

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-New heavy boson W'

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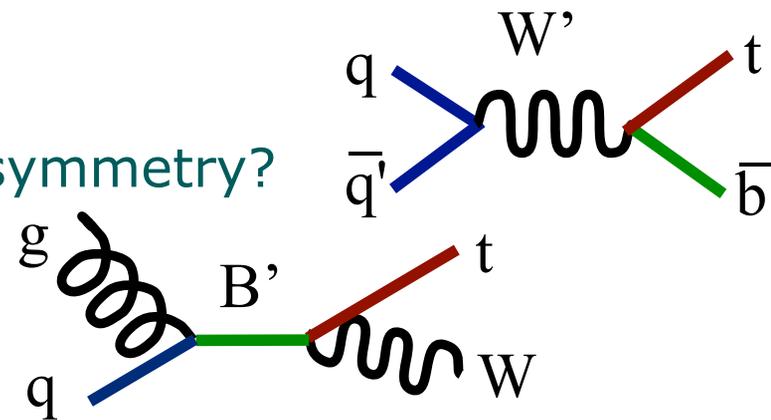
- ▶ B' or T' decaying to single top

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- If discoveries are made elsewhere first?

-Measure coupling to top



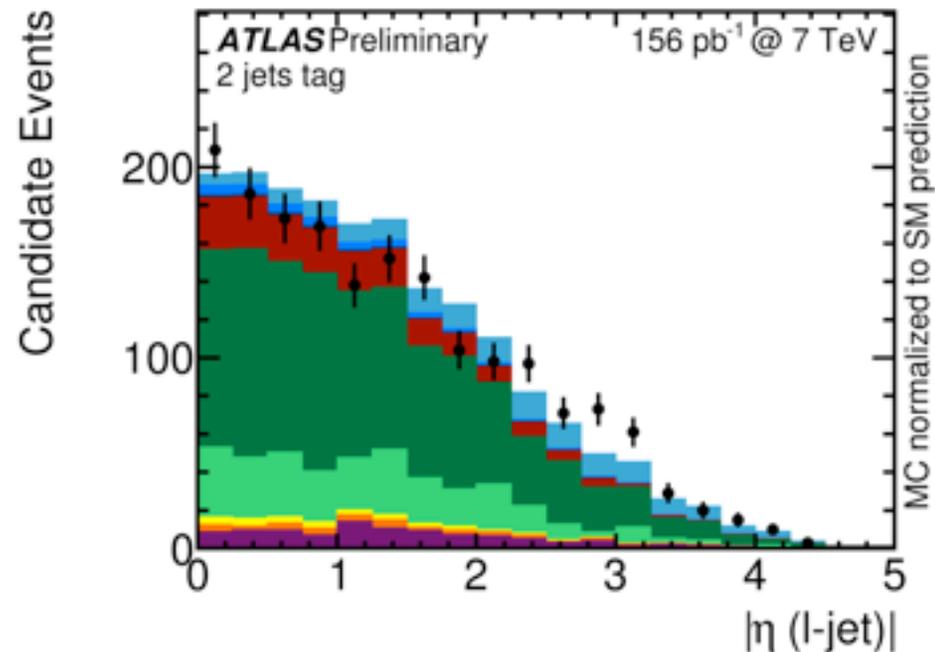
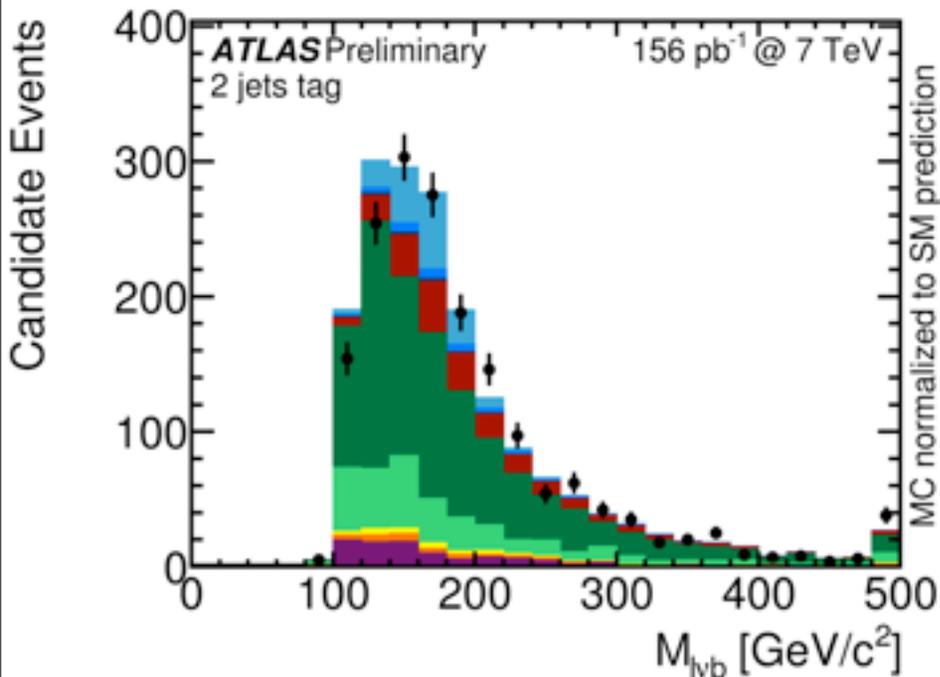
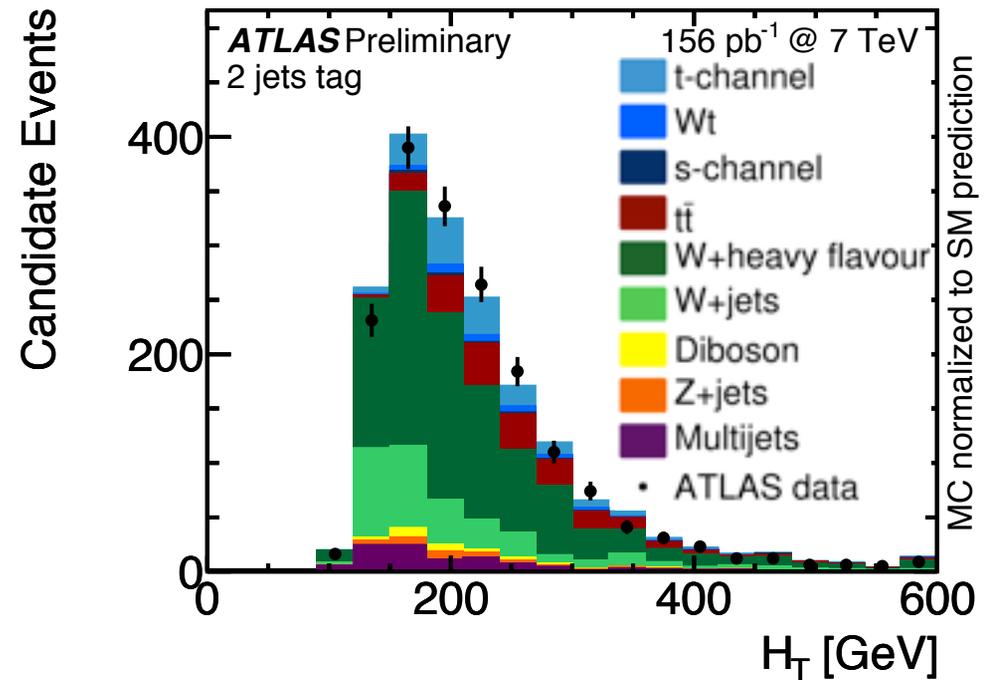
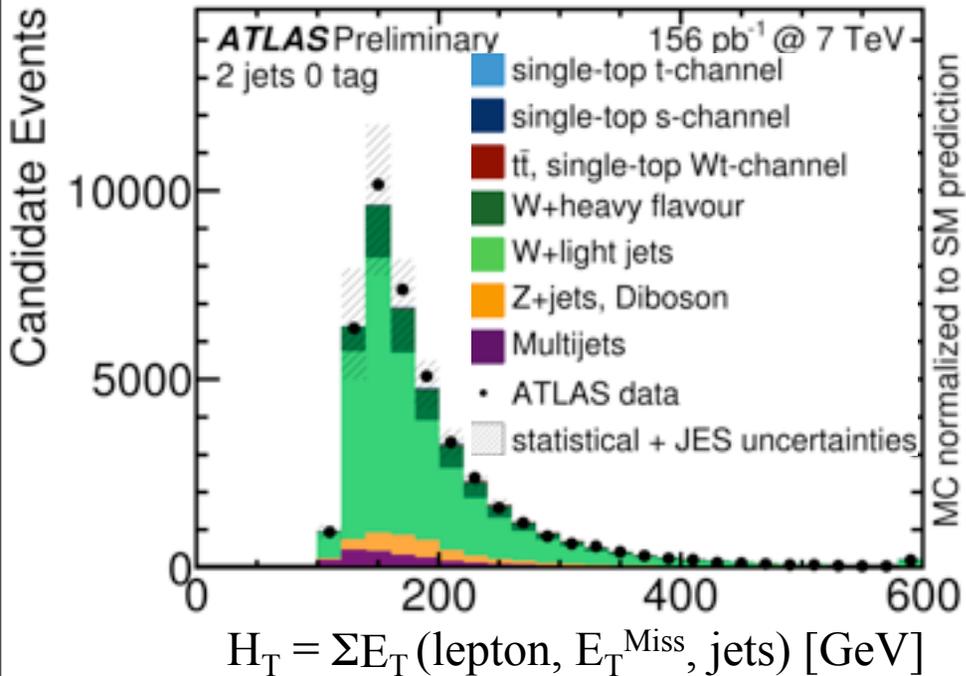
Summary/Outlook

- Single top production observed at Tevatron and LHC
 - Tevatron s-channel+t-channel observation in 2009
 - Tevatron t-channel isolation in 2011
 - LHC t-channel observation in 2011
 - LHC first limit on W_t
 - Next: W_t and s-channel observation
 - Single top as background to Higgs and other searches
- Single top as a tool to look for new physics
 - Tevatron: W' , FCNC, H^+ , anomalous couplings
 - LHC: FCNC
 - Next: many more LHC new physics searches

Larger LHC datasets will bring separate observation of all single top processes and many new physics searches

Additional Material

Background Modeling



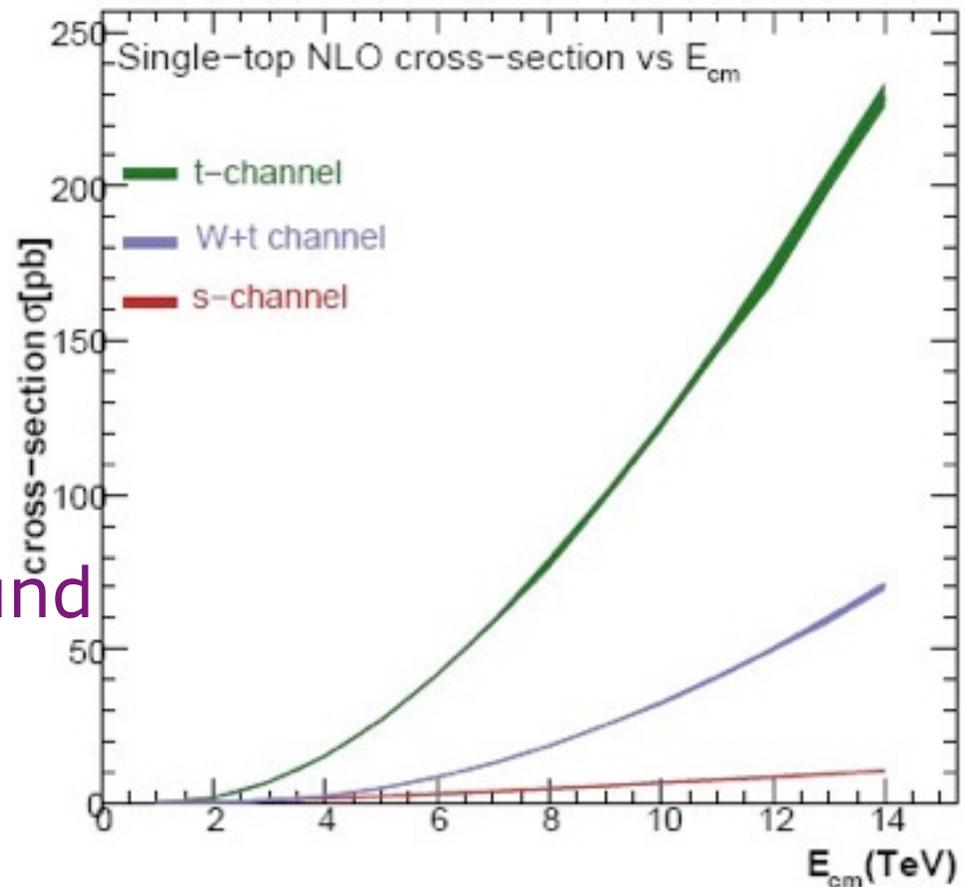
SM Single Top at the LHC

Single top signals larger than at Tevatron

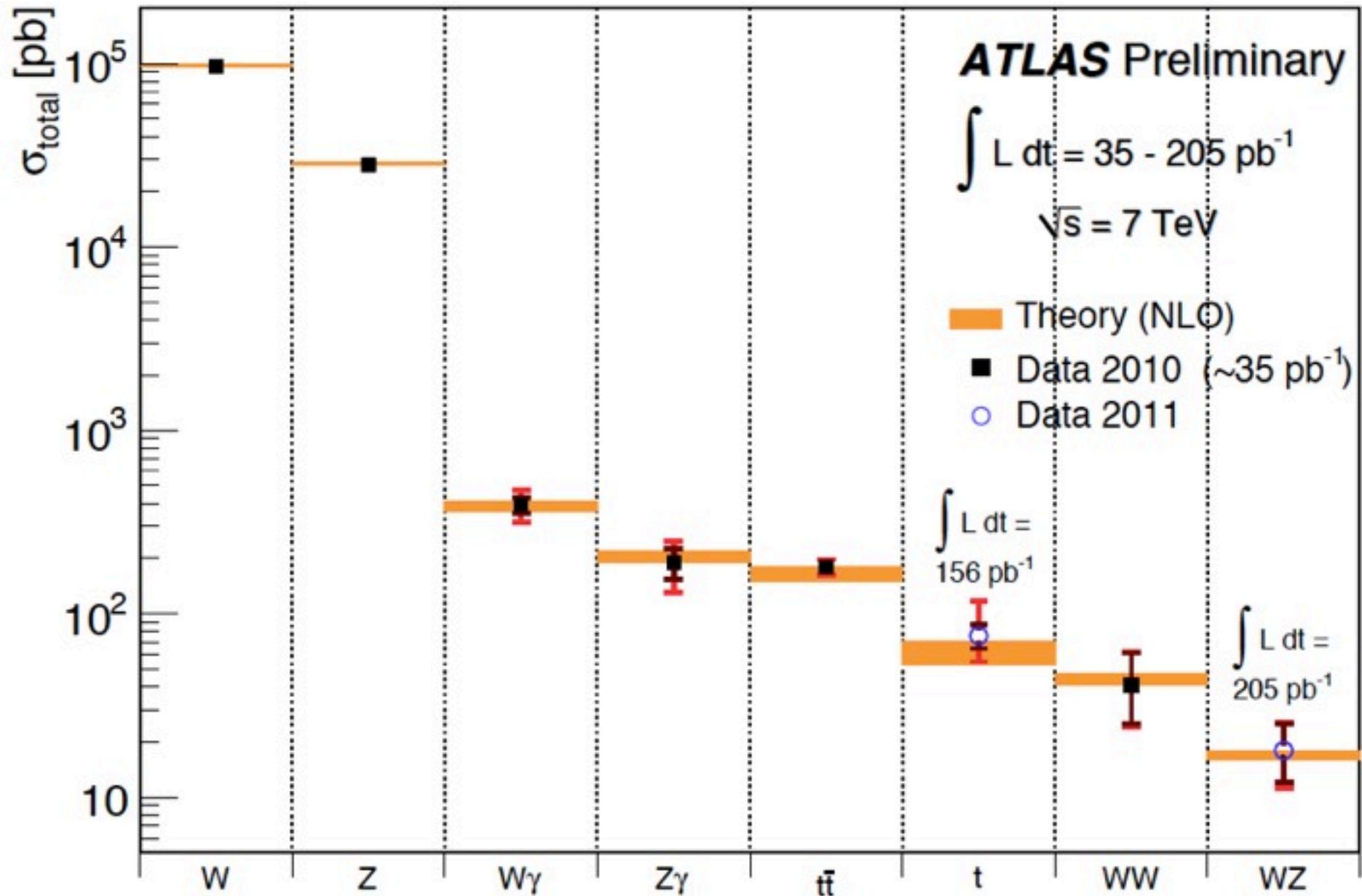
- Especially t-channel
- Even at 7 TeV

Backgrounds similar to Tevatron

- W+jets less important
- tt is dominant background

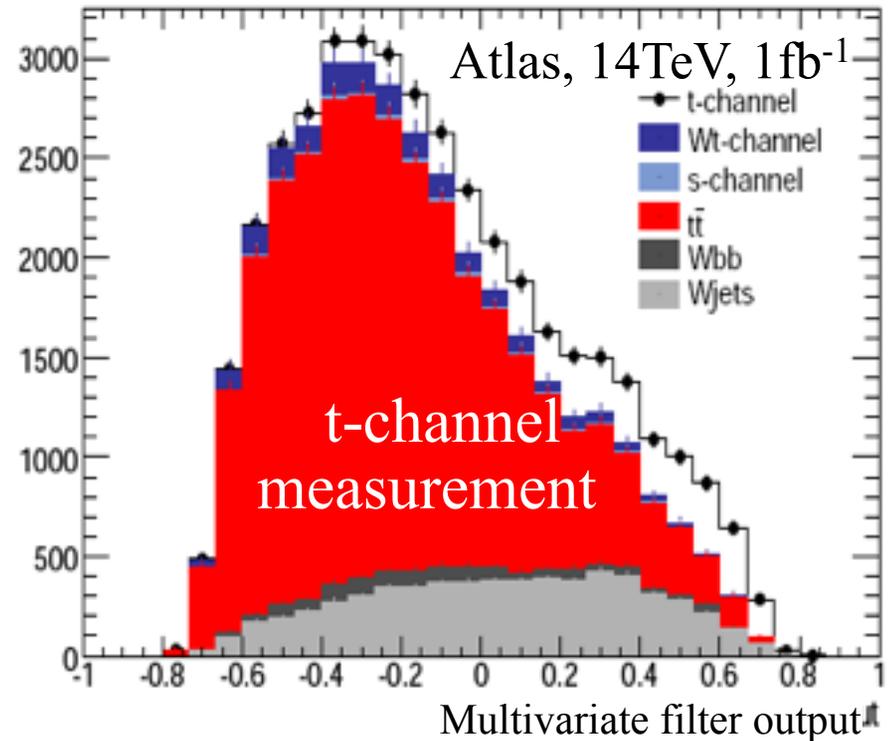
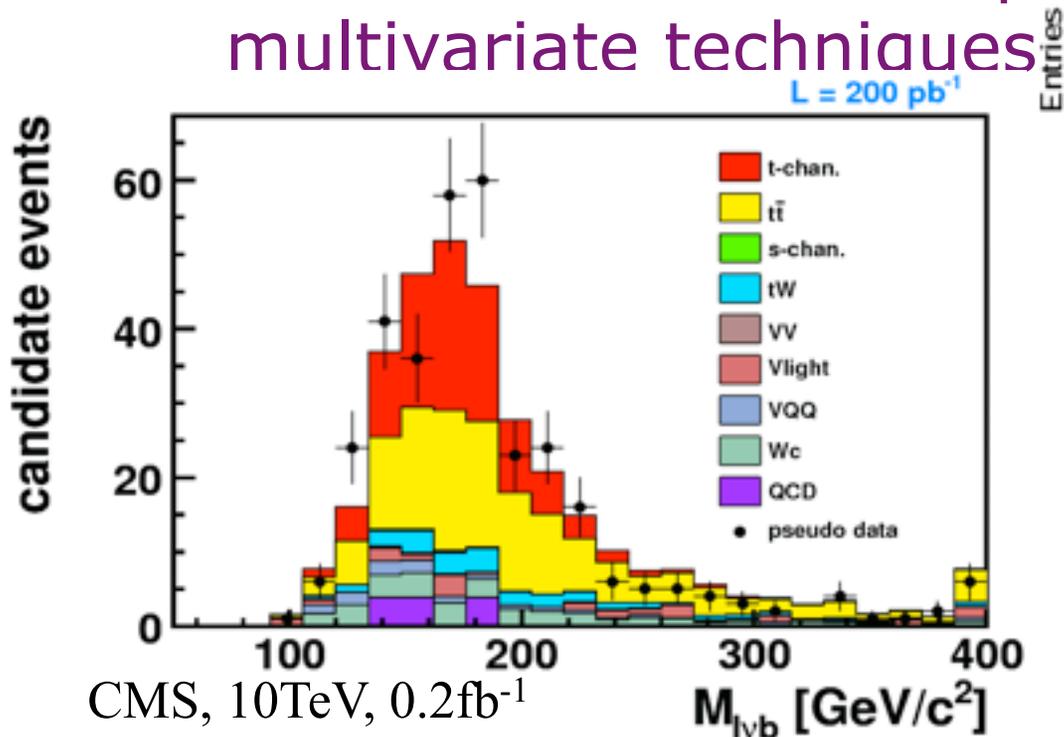


ATLAS Standard Model cross sections

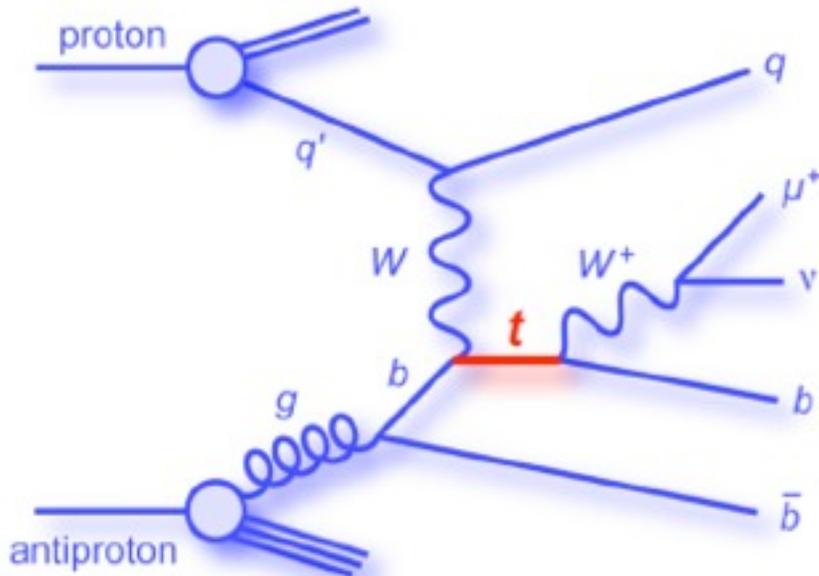


SM single top measurements

- ▶ **t-channel observation early**
 - In $\sim 200 \text{ pb}^{-1}$ at 10 TeV
 - Sufficient # of events for cut-based analysis
- ▶ **s-channel and Wt with $\sim 30 \text{ fb}^{-1}$**
 - Separate by b-tag and jet multiplicity
 - Earlier observation requires multivariate techniques



Single top event signature



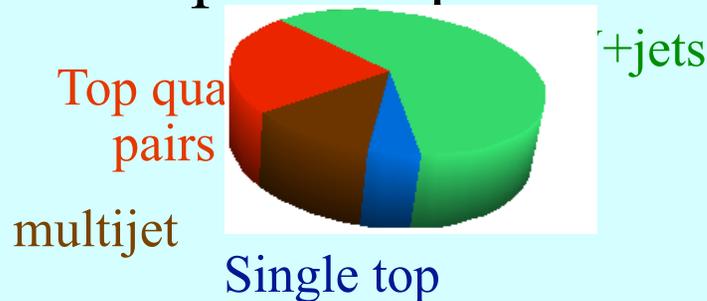
Basic event signature (e or m)

- Single lepton trigger or lepton+jets trigger
- One high- E_T leptons
 - ⤴ $E_T > 20$ GeV or 15 GeV
- Missing transverse energy
 - ⤴ Missing $E_T > 25$ GeV or 15 GeV
- 2-3 high- E_T jets (2-4 jets)
 - ⤴ $E_T > 15$ GeV

Expect at least one signal event per fb^{-1}

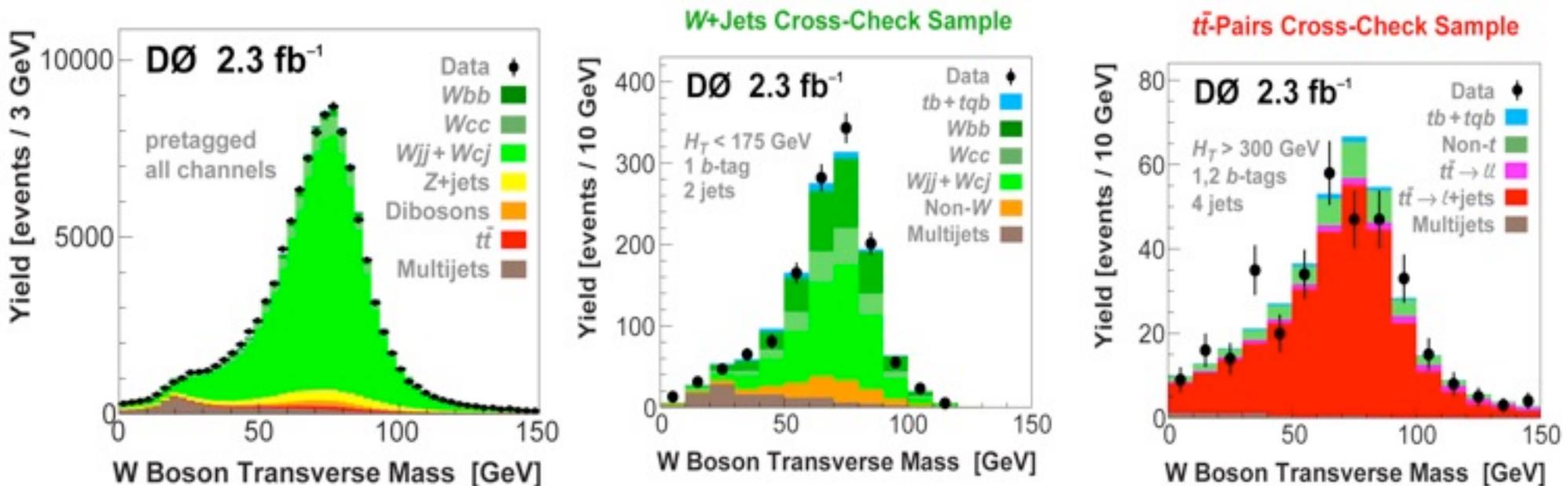
- After b-tagging
- S:B \sim 1:20

Event sample composition



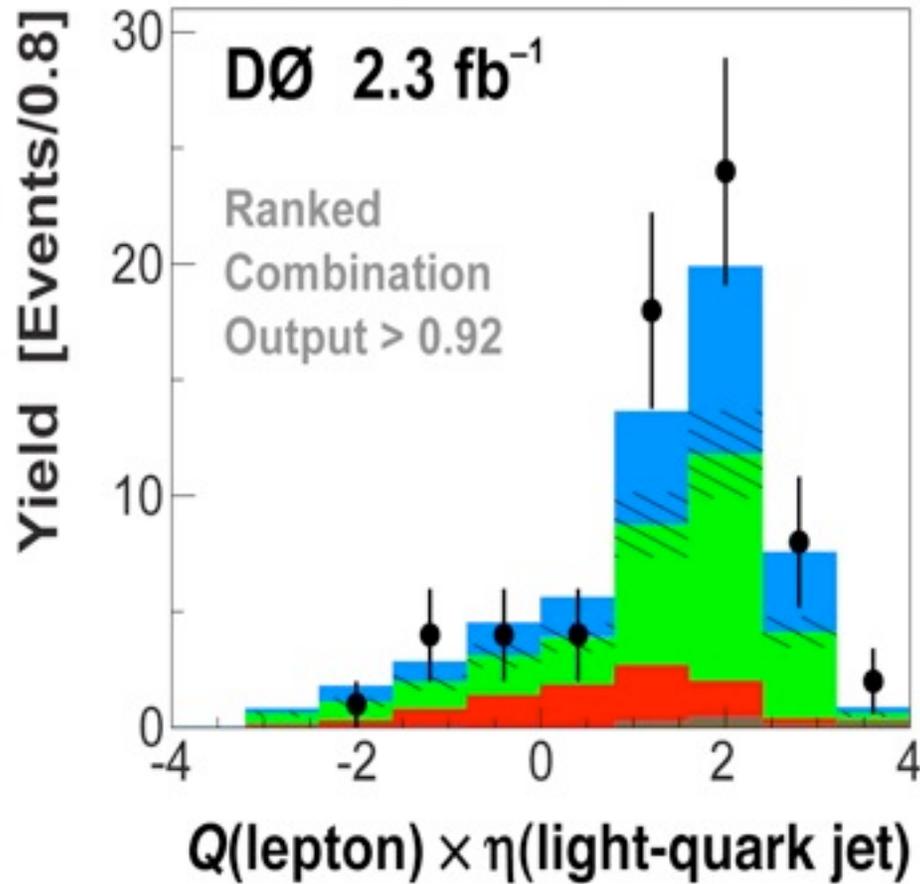
Analysis samples

- Divide into 24 analysis channels
 - ‡ By b-tag multiplicity (1, 2), jet multiplicity (2, 3, 4), data taking period (before/after upgrade), lepton (e, m)
- Cross-check samples
 - ‡ Enriched in W+jet events
 - ‡ Enriched in top pair events
- Check data/background agreement for all variables and multivariate filters in all samples

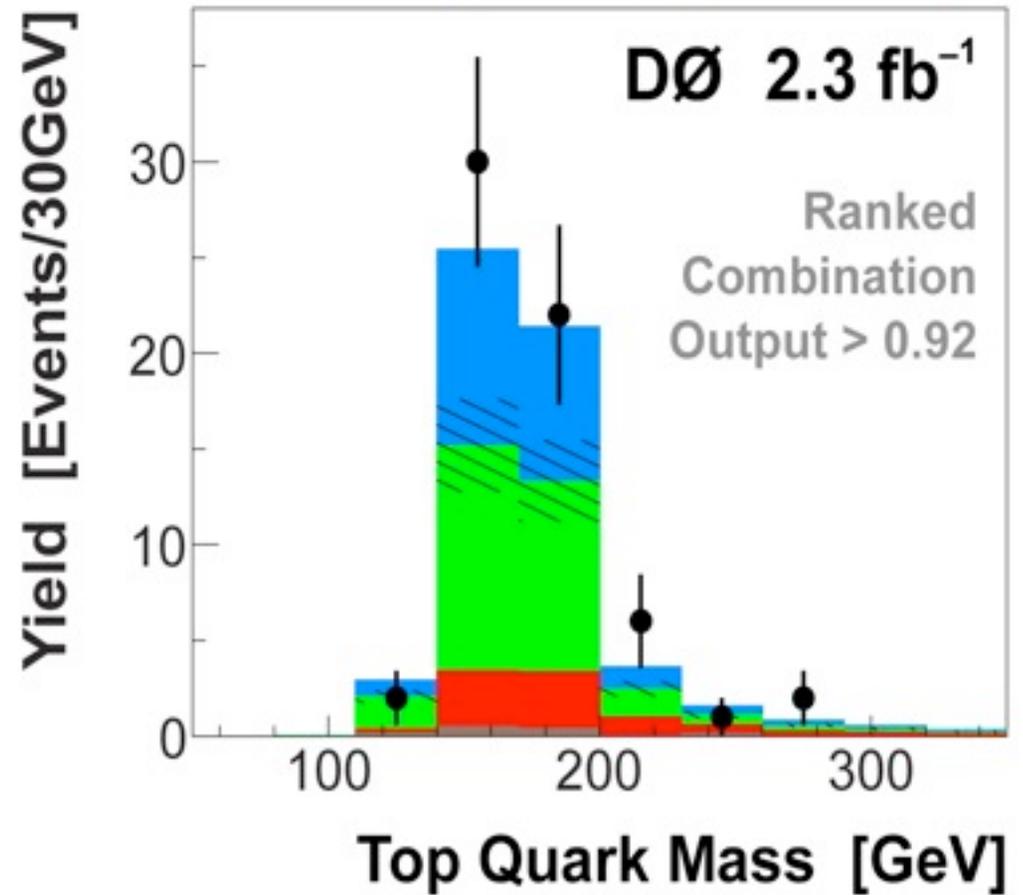


Kinematics in the signal region

High Signal Region – $Q \times \eta$



High Signal Region – m_{top}



Systematic uncertainties



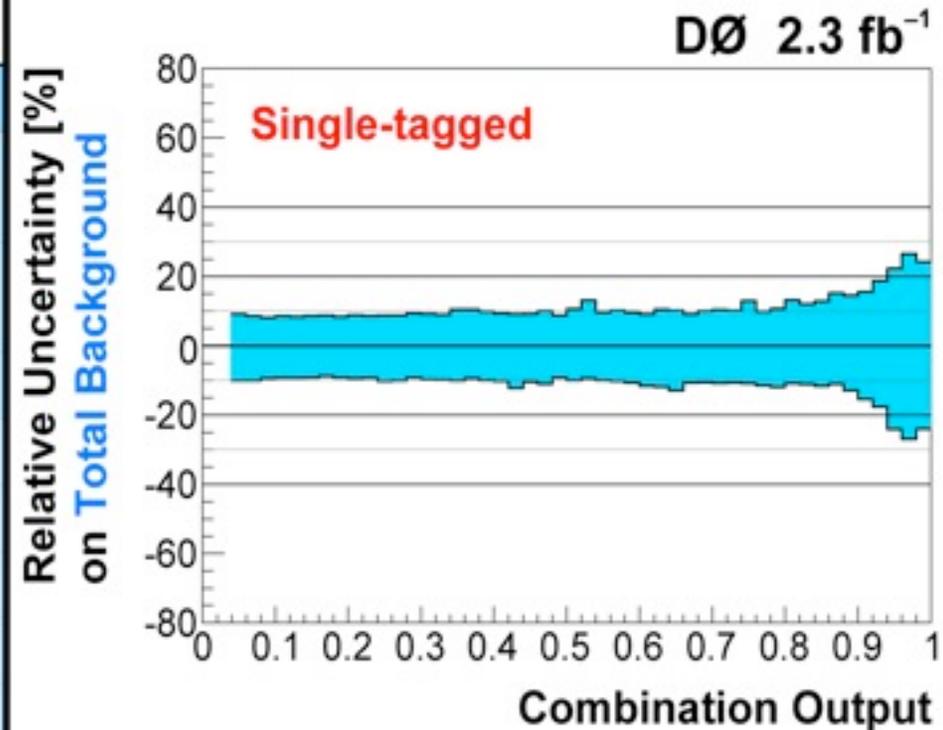
Systematic Uncertainties

Ranked from Largest to Smallest Effect
on Single Top Cross Section

DØ 2.3 fb⁻¹

Larger terms

<i>b</i> -ID tag-rate functions (includes shape variations)	(2.1–7.0)% (1-tag) (9.0–11.4)% (2-tags)
Jet energy scale (includes shape variations)	(1.1–13.1)% (signal) (0.1–2.1)% (bkgd)
<i>W</i> +jets heavy-flavor correction	13.7%
Integrated luminosity	6.1%
Jet energy resolution	4.0%
Initial- and final-state radiation	(0.6–12.6)%
<i>b</i> -jet fragmentation	2.0%
<i>t</i> \bar{t} pairs theory cross section	12.7%
Lepton identification	2.5%
<i>W</i> <i>b</i> <i>b</i> / <i>W</i> <i>c</i> <i>c</i> correction ratio	5%
Primary vertex selection	1.4%

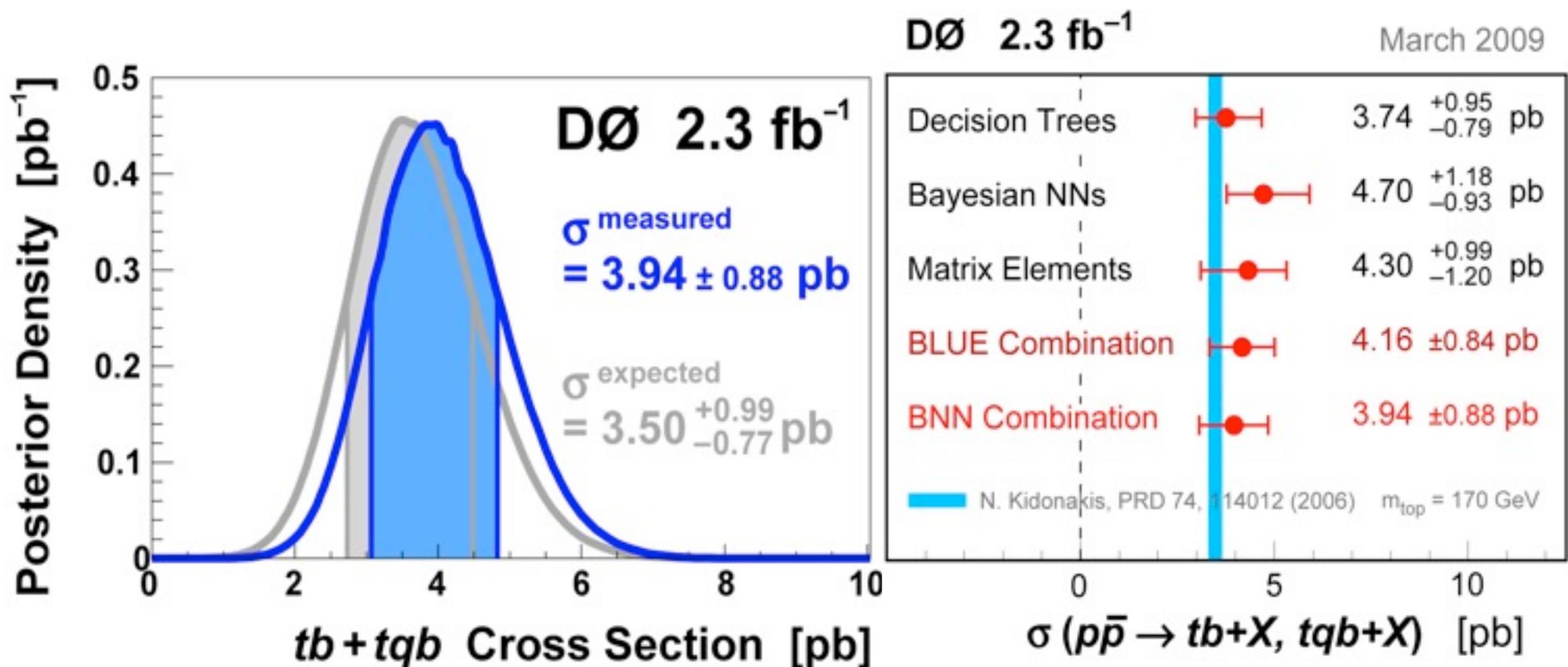


Statistical analysis

Bayesian statistical analysis

$$P(s|D) = P(D|s) * P(s)$$

- Posterior gives measured cross section and uncertainty

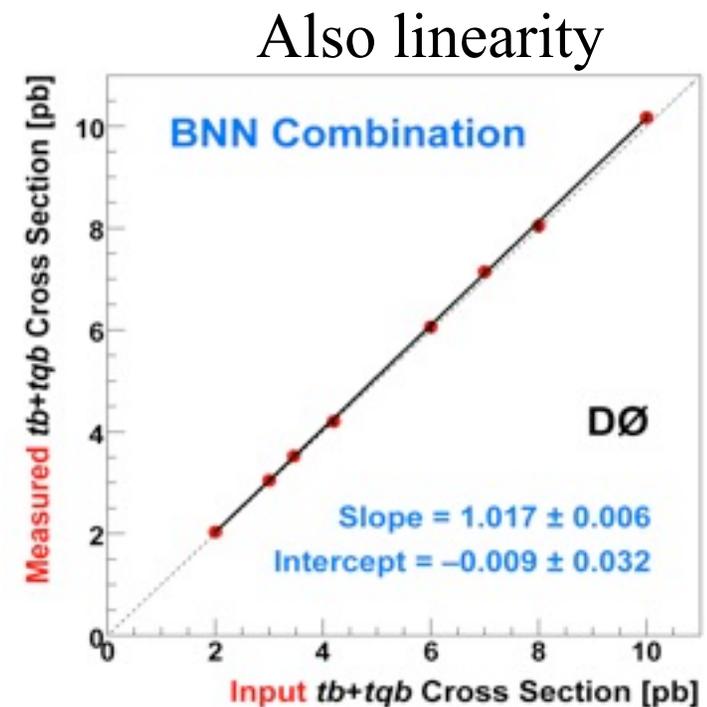
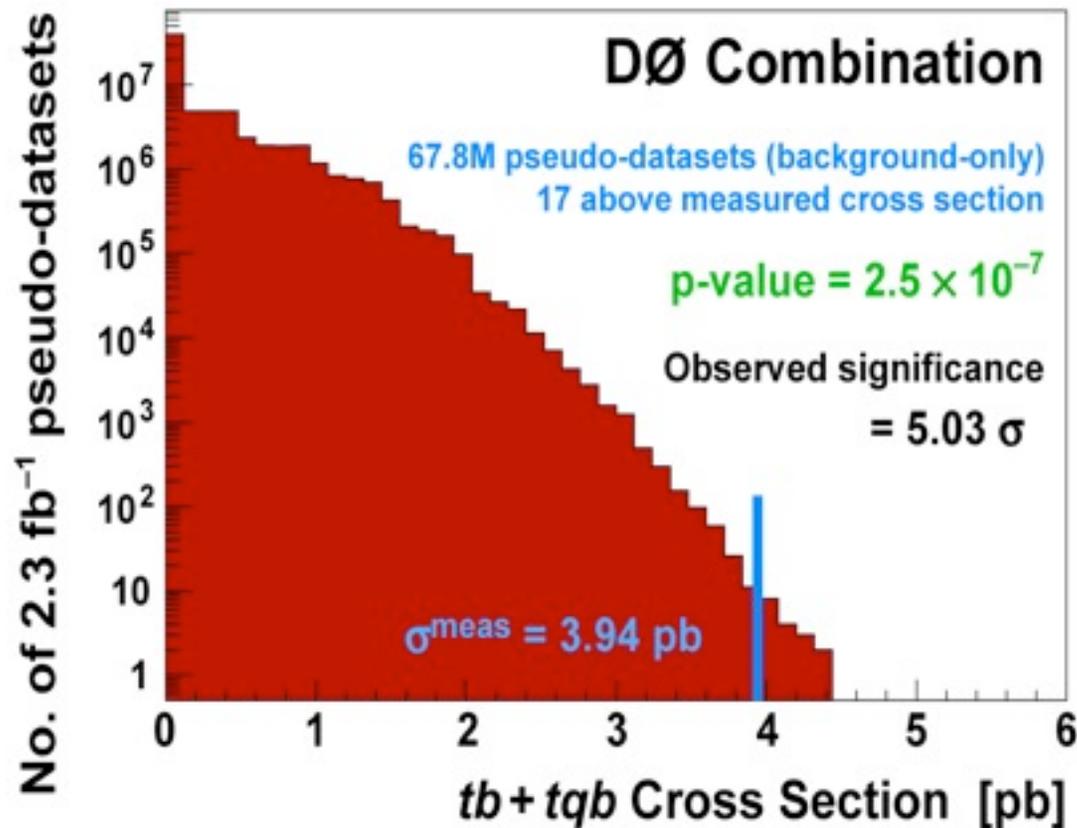


PRL 103, 092001 (2009)



Significance

- Significance (p-value) and linearity and many tests through extensive ensemble testing
 - Ensembles of pseudo-data at various signal cross sections



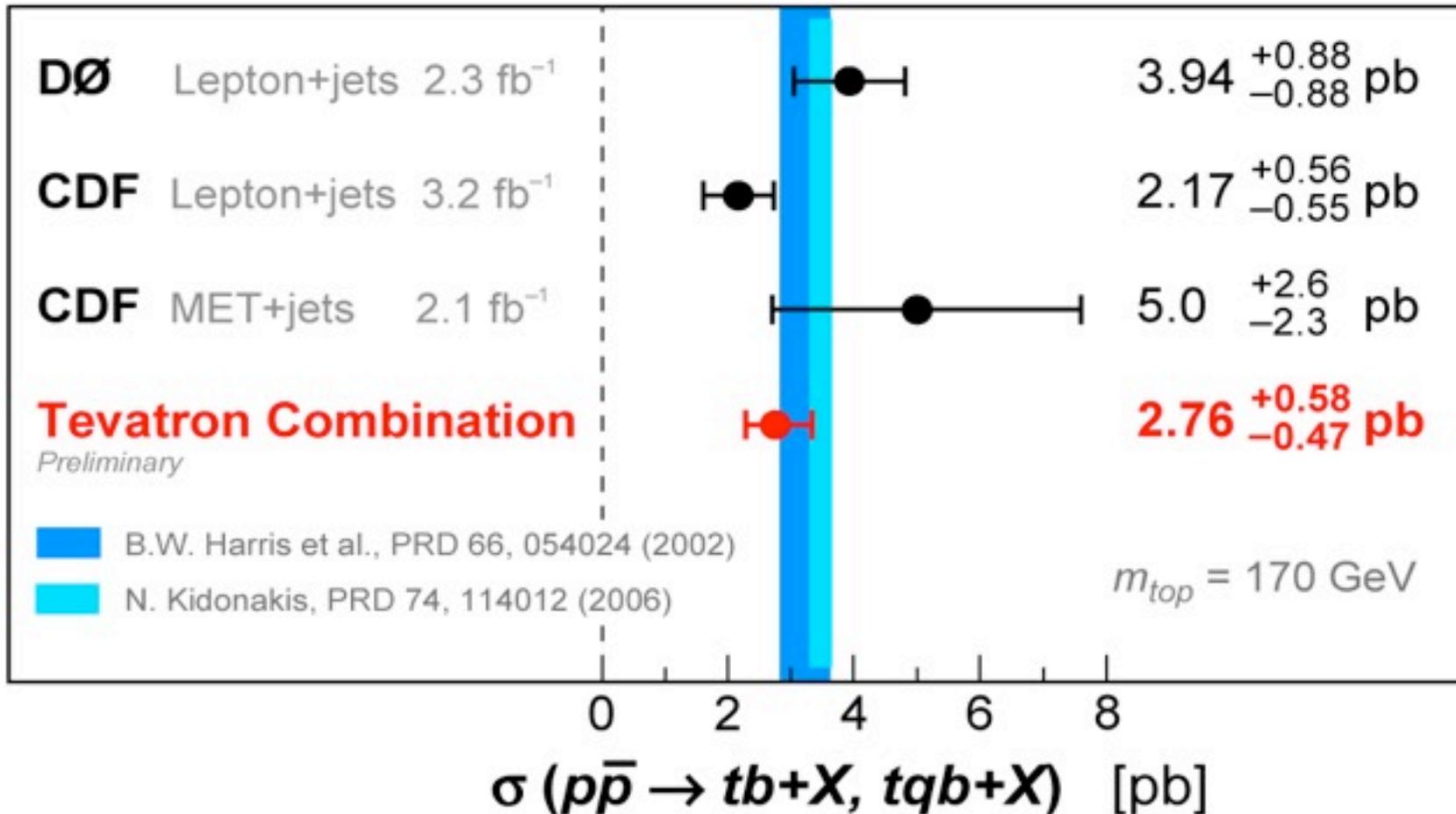


Tevatron Combination

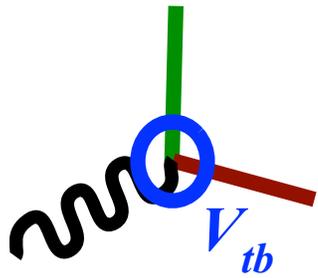


Single Top Quark Cross Section

August 2009



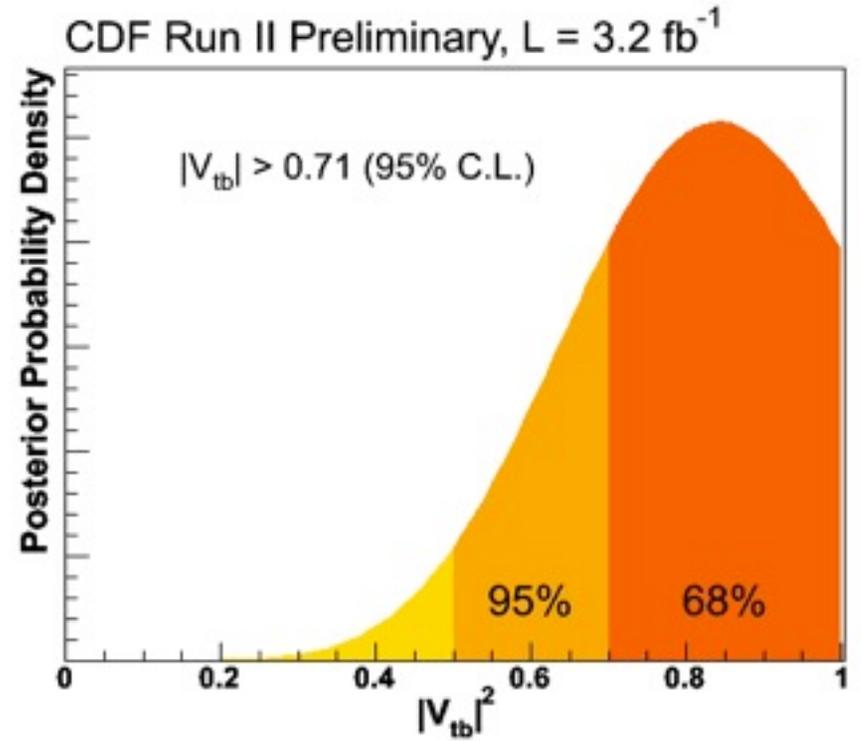
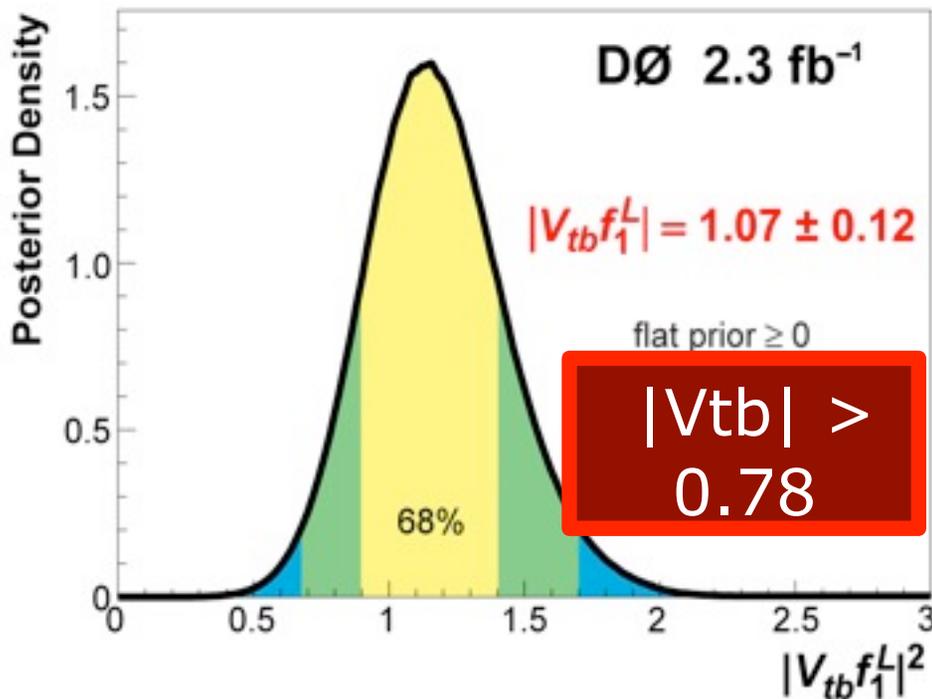
CKM matrix element $|V_{tb}|$



CKM Matrix

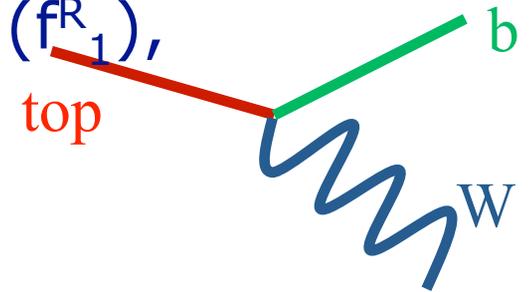
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \mathbf{V_{tb}} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Measurement: $|V_{tb}| \times f_L^1$
 - Assume top decays to b ($V_{tb} \gg V_{ts}, V_{td}$)
- No constraint on # of generations



Single top polarization – anomalous coupling

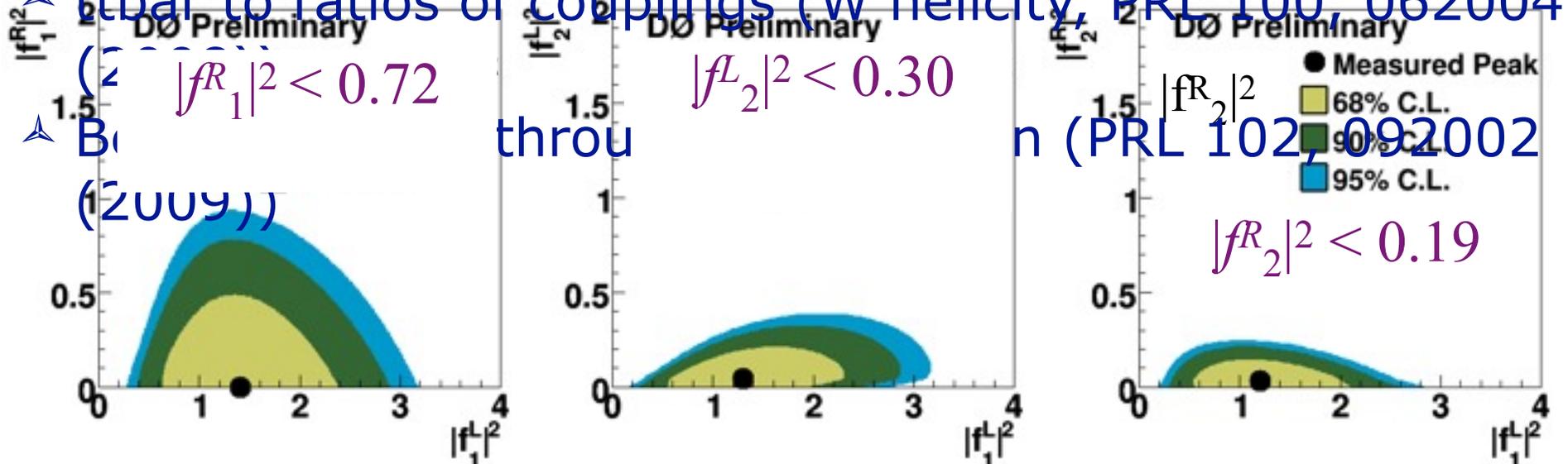
- Left-vector (f_1^L , =1 in SM), right-vector (f_1^R), left-tensor (f_2^L), right-tensor (f_2^R)



$$\mathcal{L} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} (f_1^L P_L + f_1^R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (f_2^L P_L + f_2^R P_R) t W_\mu^- + h.c.$$

- Single top is sensitive to magnitude (PRL 101, 221801 (2008))

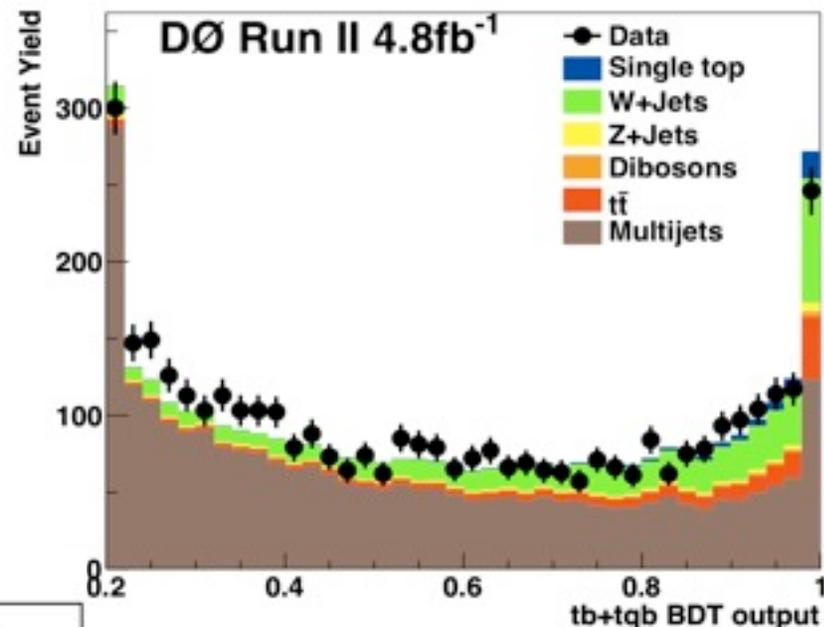
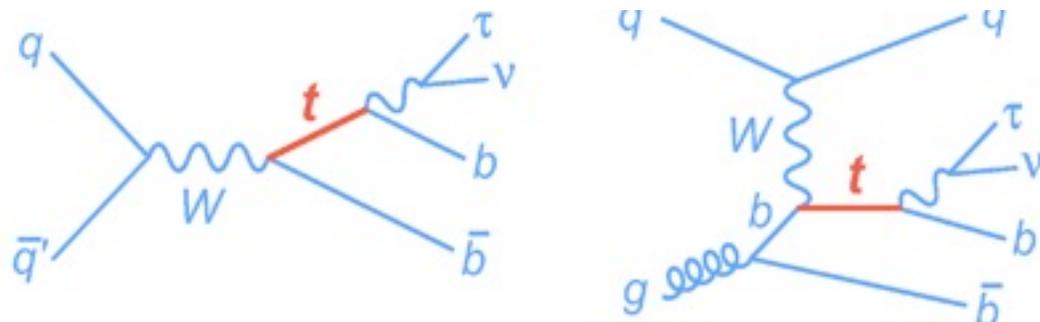
- $t\bar{t}$ to ratios of couplings (W helicity, PRL 100, 062004 (2000))



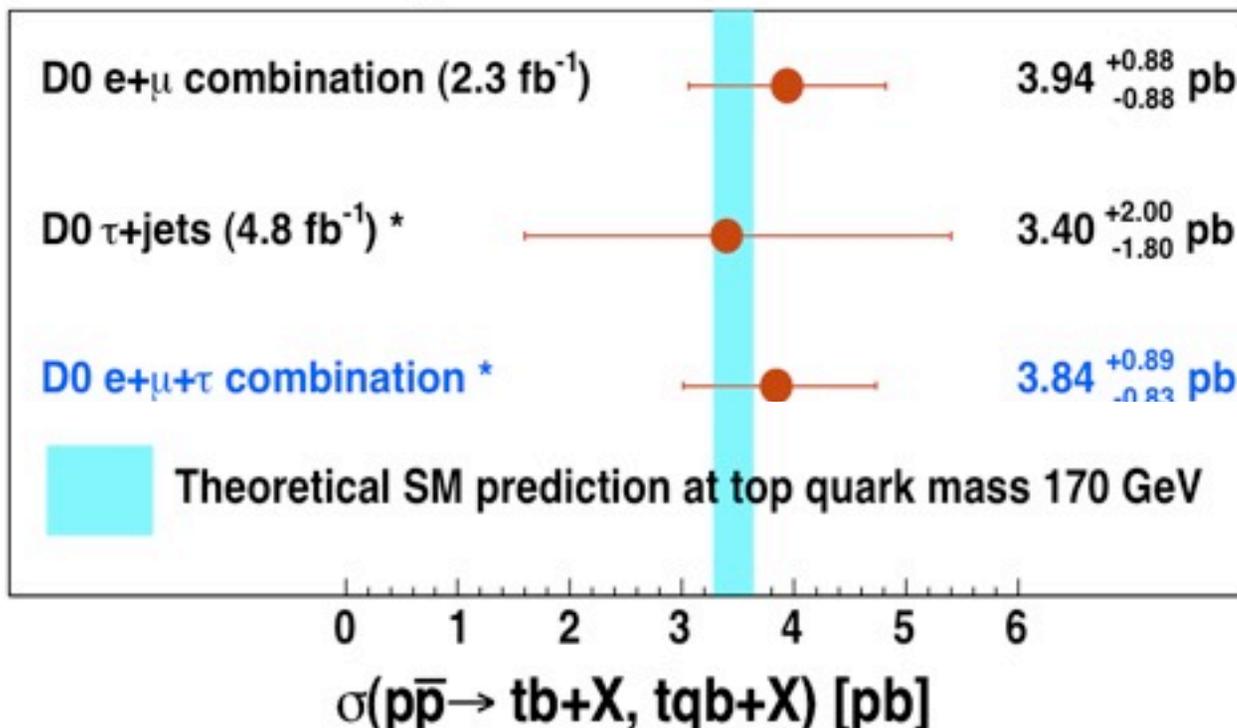
- Bound through $t\bar{t}$ (PRL 102, 092002 (2009))



Single top in tau final state



* DØ Run II Preliminary

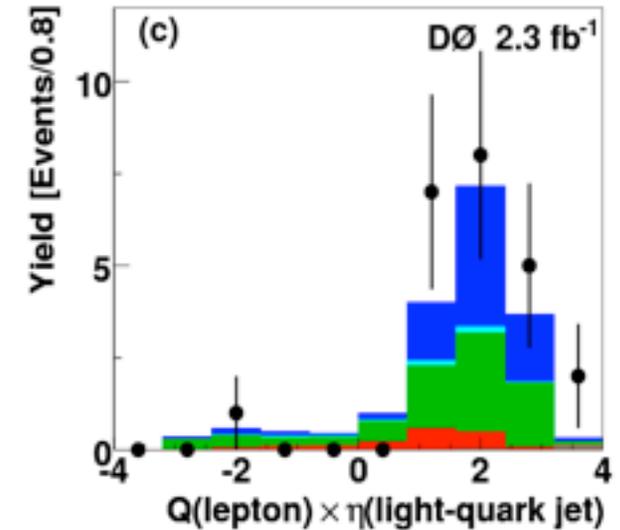
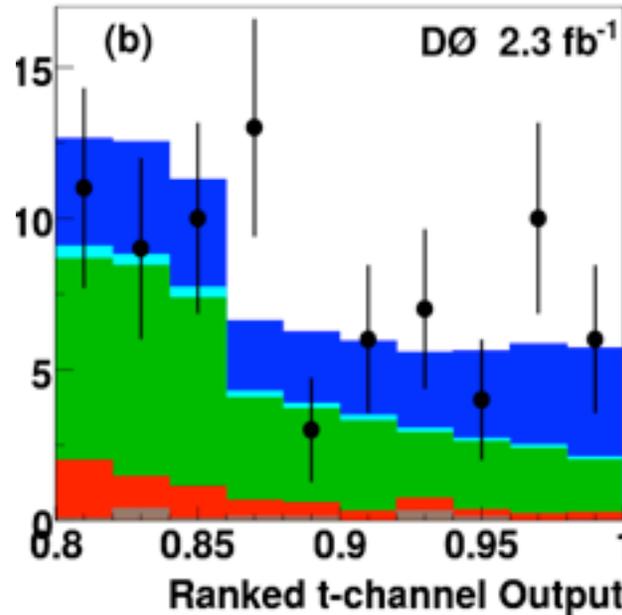
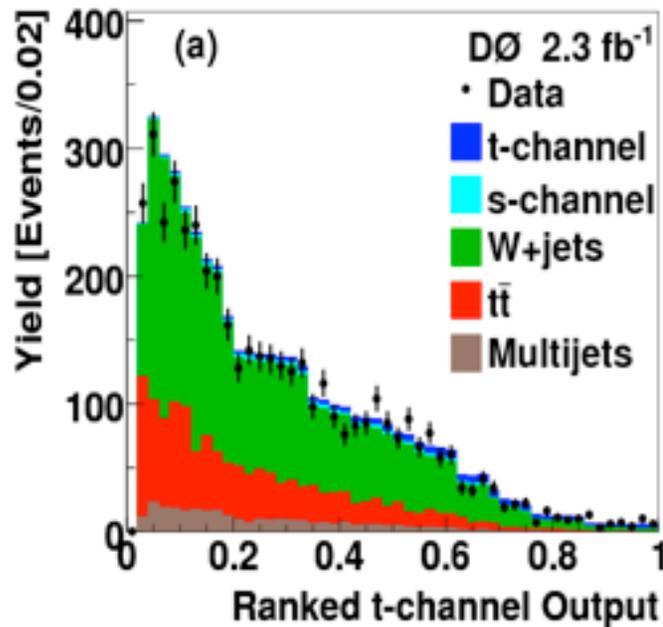
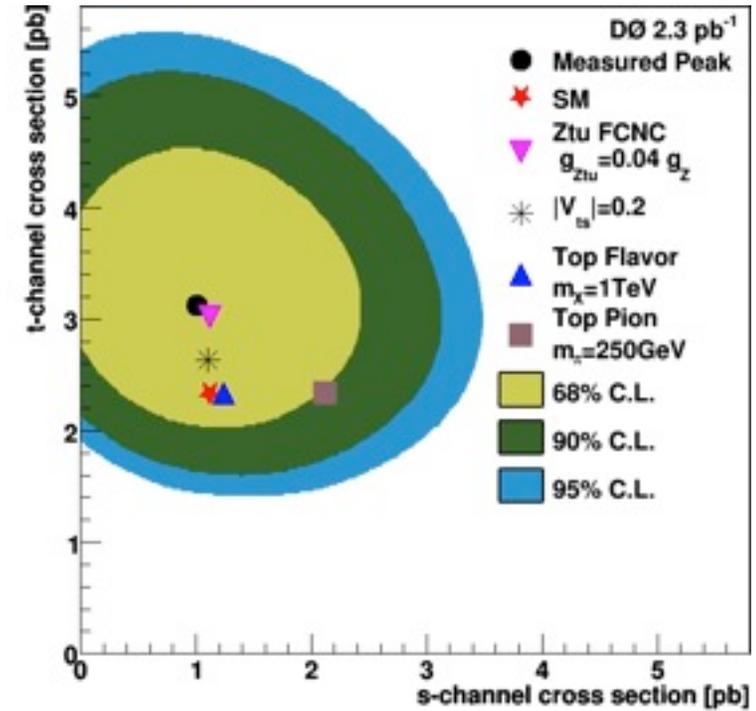


Submitted to PLB, arXiv.org:0912.1066



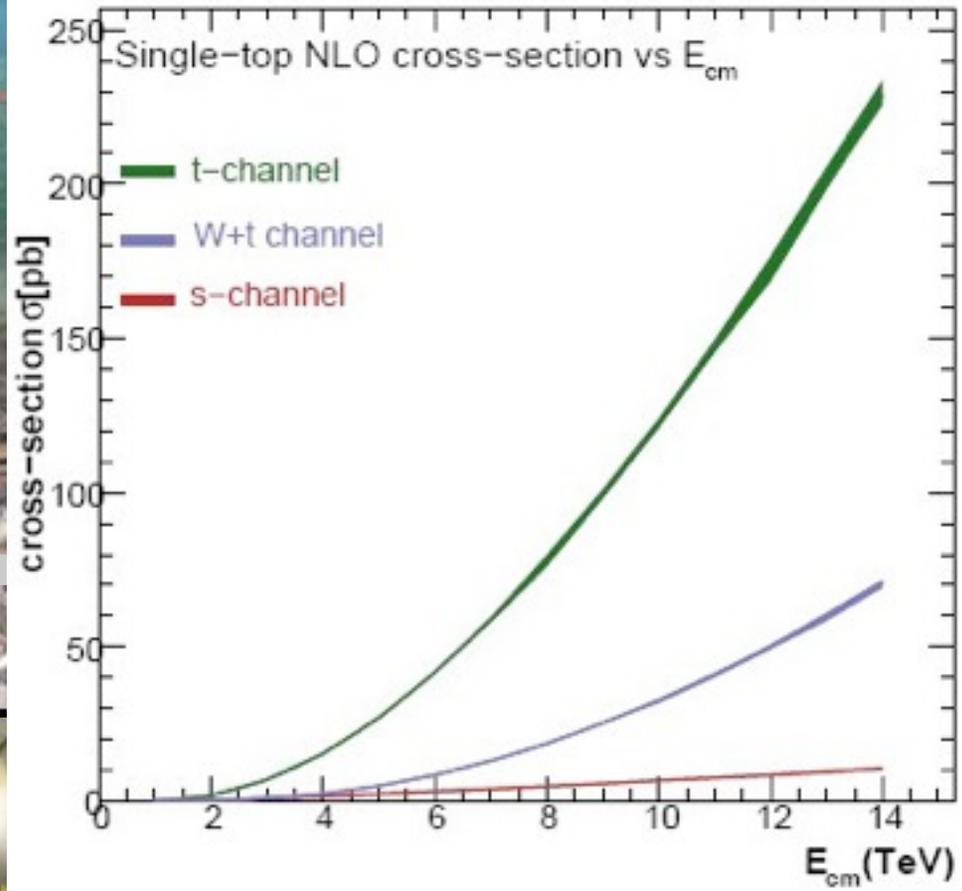
First evidence for t-channel production

- Train MVA filters for t-channel
- Measure t-channel and s-channel simultaneously
 - Remove s/t constraint
 - $s(t) = 3.14_{-0.81}^{+0.94}$ pb
 - Exp./obs. significance: 3.7/4.8 SD
 - $s(s) = 1.05 \pm 0.81$ pb



Submitted to PLB, arXiv.org:0907.4259

Single top at the LHC

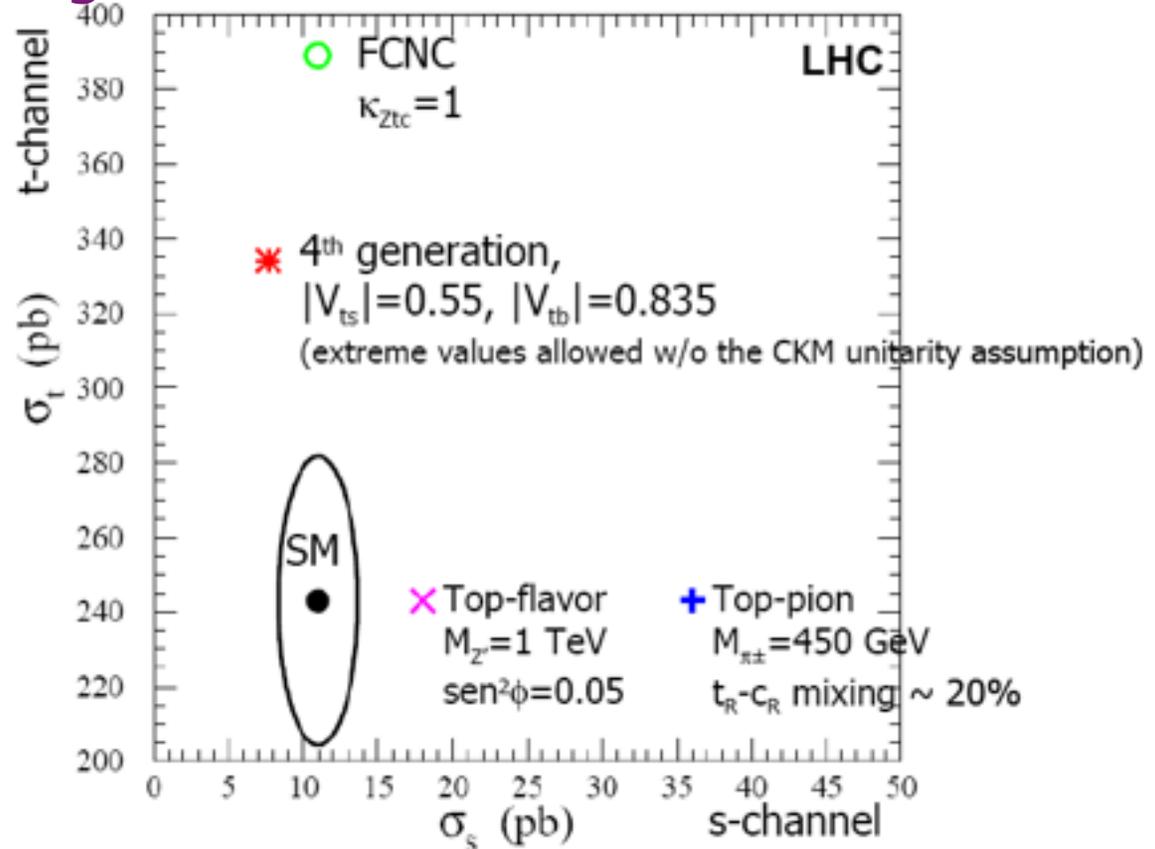


- Observe three single top production modes separately
 - △ t-channel: easy 😊
 - △ s-channel and assoc. prod: harder 😞
- Observe new physics (*if it can be seen*)
- Measure V_{tb} to few %

LHC: new physics in single top

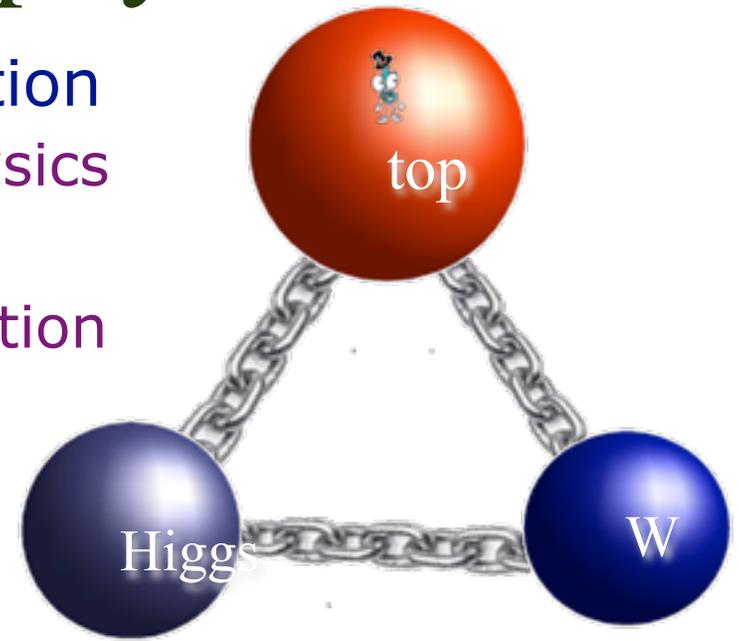
- ▶ Dedicated searches for specific signatures
 - Resonances: New heavy boson W' , heavy charged Higgs
 - FCNC interactions via gluon, photon, Z
 - Anomalous Wtb couplings
- ▶ Measure SM cross sections in detail
 - For 3 processes separately
 - Compare their ratios

T Tait, C.-P. Yuan, Phys.Rev. D63 (2001) 0140018



Single top quark physics

- ✦ Study top quark electroweak interaction
 - Sensitive to many models of new physics
- ✦ Important milestone towards Higgs
 - Background to associated WH production
 - Establish analysis techniques
- ✦ DØ: single top evidence in 2007, observation in 2009
 - Plus many searches for new physics
 - Now working on separating s-channel from t-channel
- ✦ LHC: single top in 7 TeV and in 14 TeV data
 - Initial measurement at 7 TeV
 - Separate different production modes at 14 TeV
 - Plus many direct searches for new physics
- ✦ Long-term: study interaction between top and new physics



Single top phenomenology

- ✦ $O(\alpha_s)$ QCD corrections to single top production and decay
 - Benitez, Heim, Brock, Schwienhorst
 - With MSU theorist C.P. Yuan and his former student Cao
- ✦ s-channel study at the Tevatron:
 - Cao, RS, Yuan,
PRD 71: 054023, 2005
- ✦ t-channel study at the Tevatron:
 - Cao, Benitez, RS, Brock, Yuan,
PRD 72: 094027, 2005
- ✦ s-channel at NLO at the LHC
 - Heim, RS, Cao, Yuan,
PRD 81: 034005, 2010
- ✦ Working on t-channel study at the LHC
- ✦ Also compared MCFM t-channel NLO with $D\emptyset$ simulation samples

