

Single top quark physics at the Tevatron and the LHC



Reinhard Schwienhorst

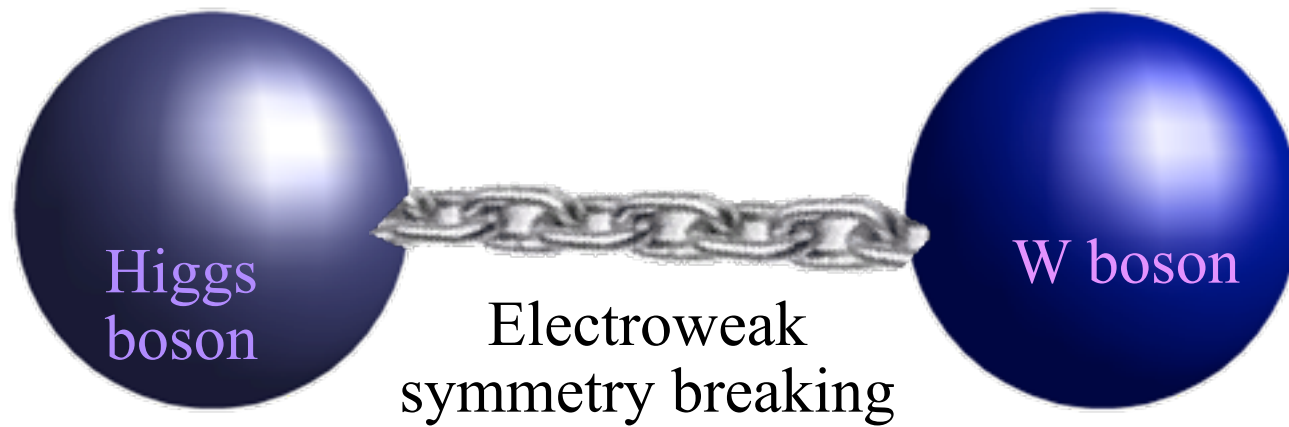


PKU HEP Seminar, November 2011

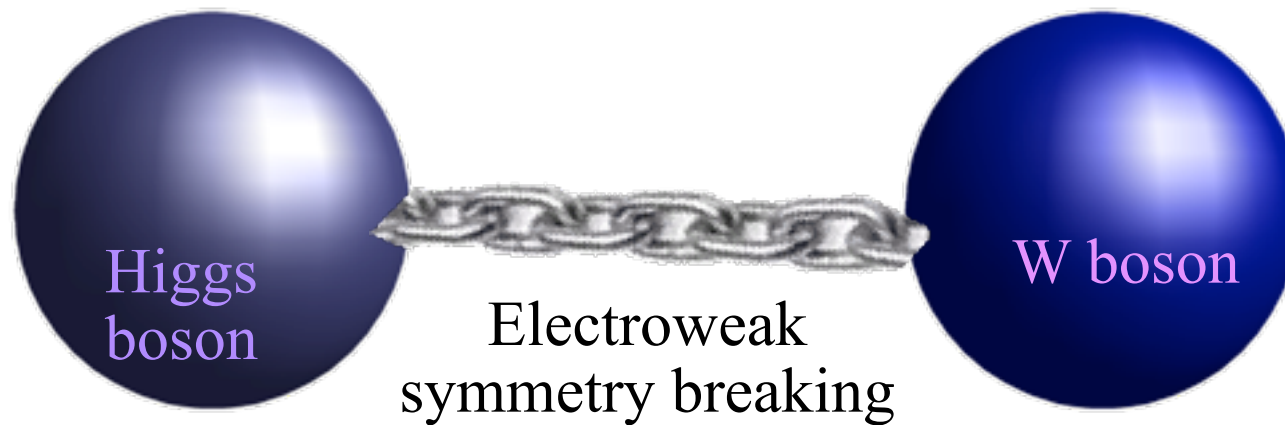
Outline

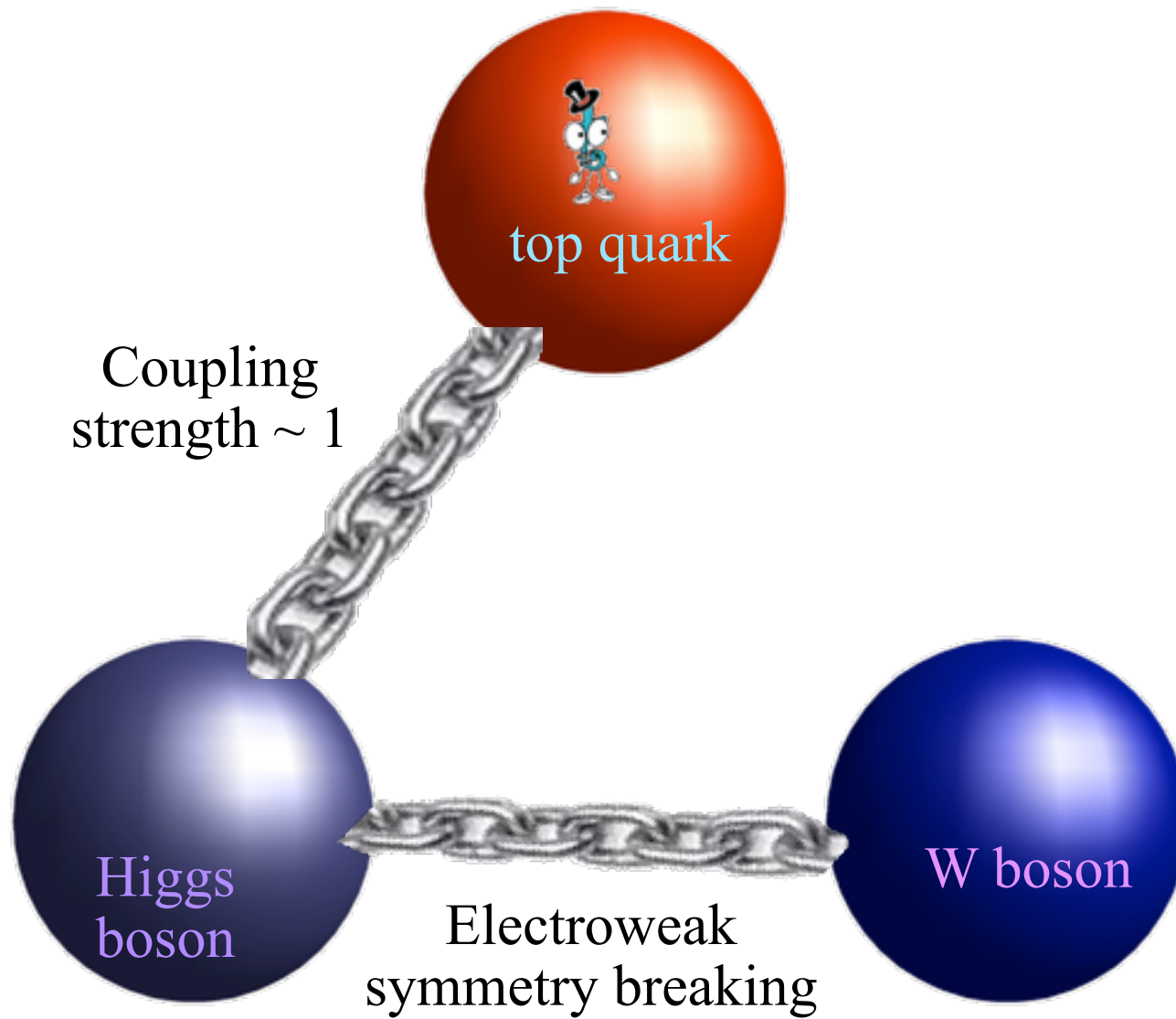
- Introduction
- Tevatron
 - SM
 - New physics
- LHC
 - SM
 - New physics
- Conclusions

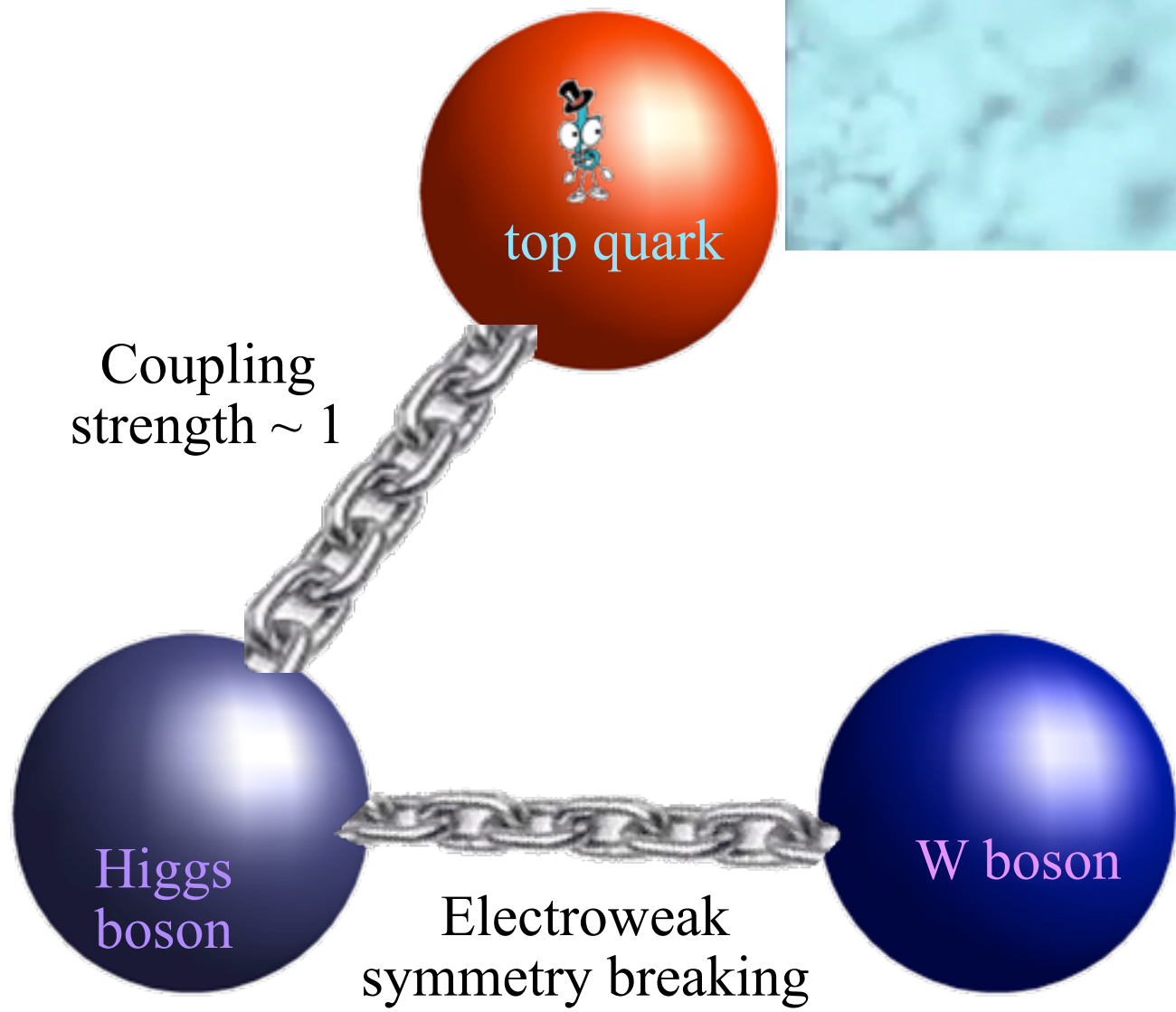
Higgs field

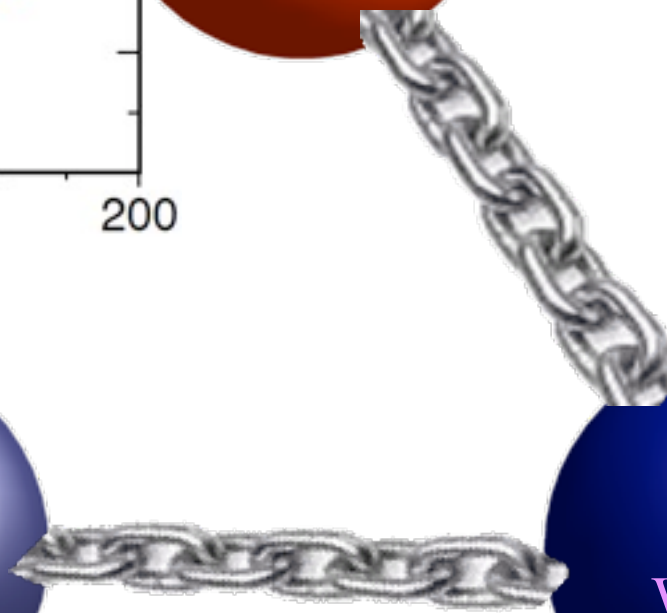
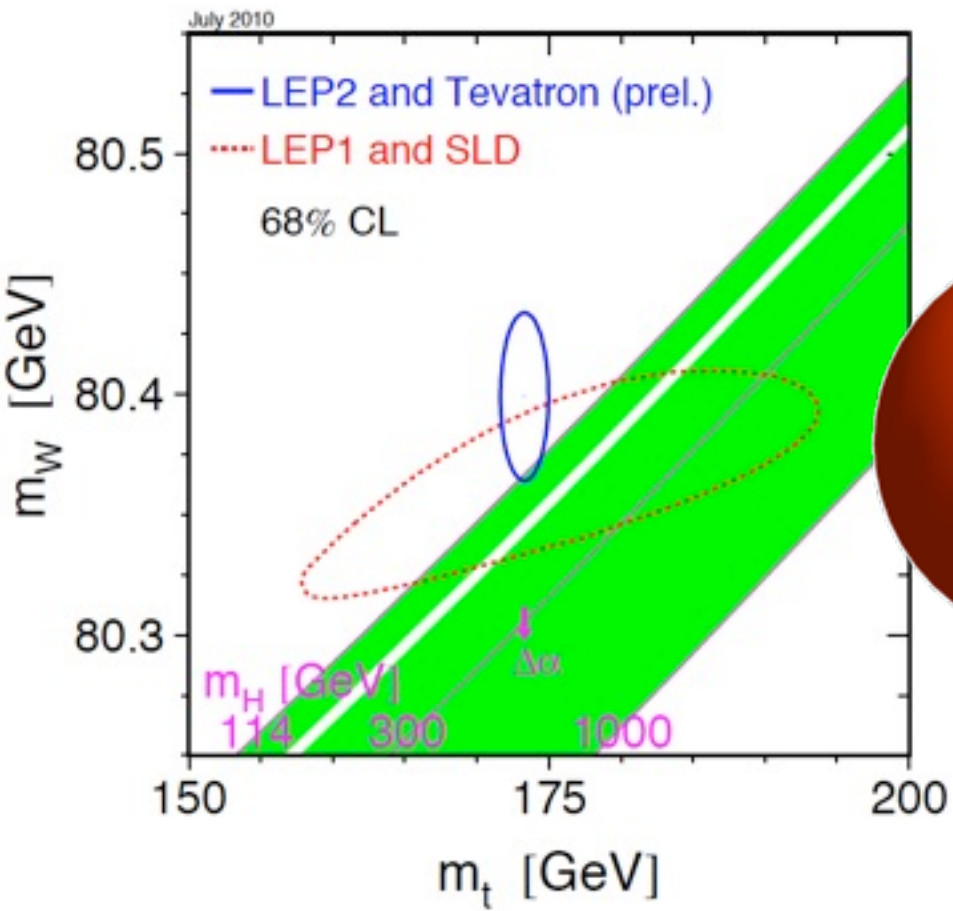


Higgs field

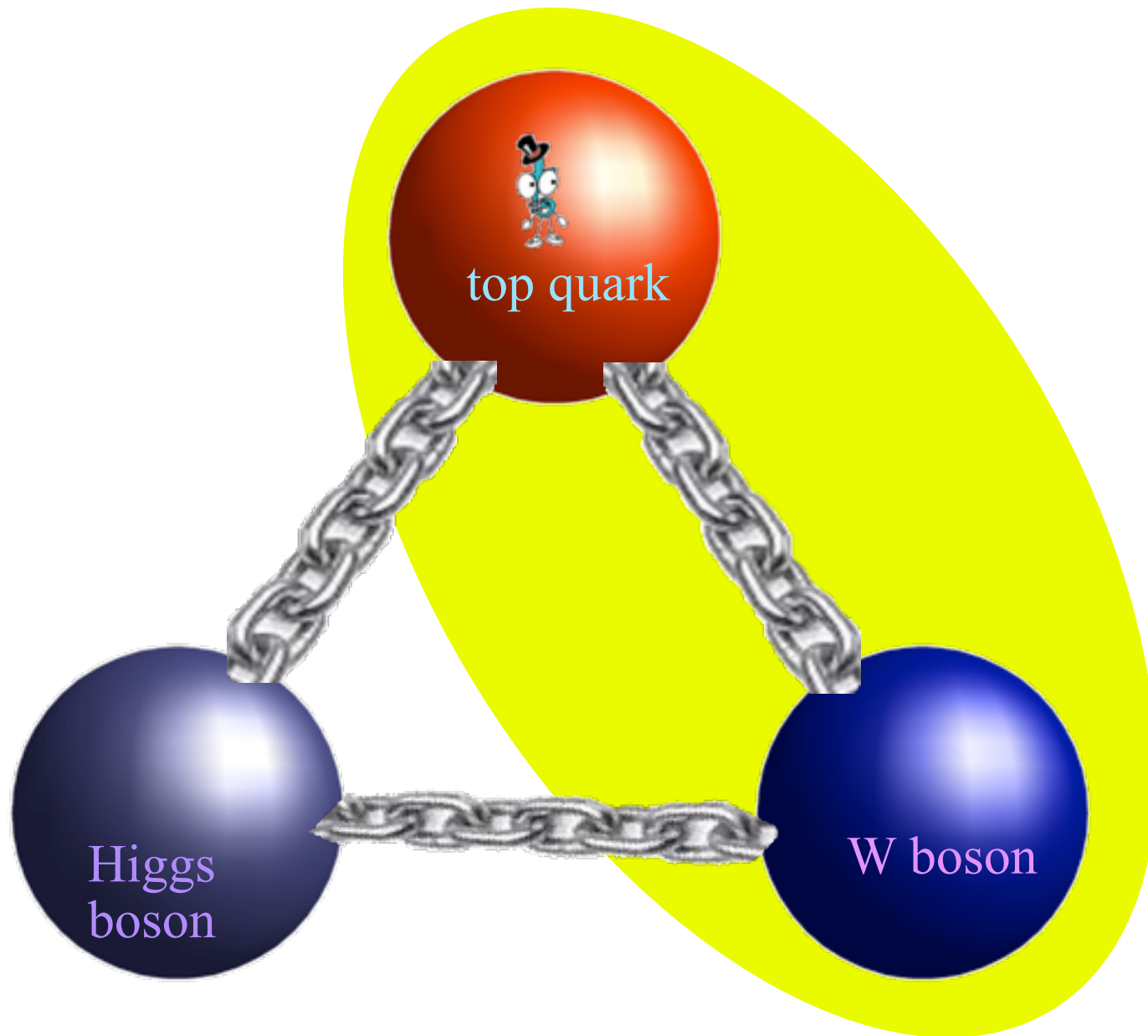




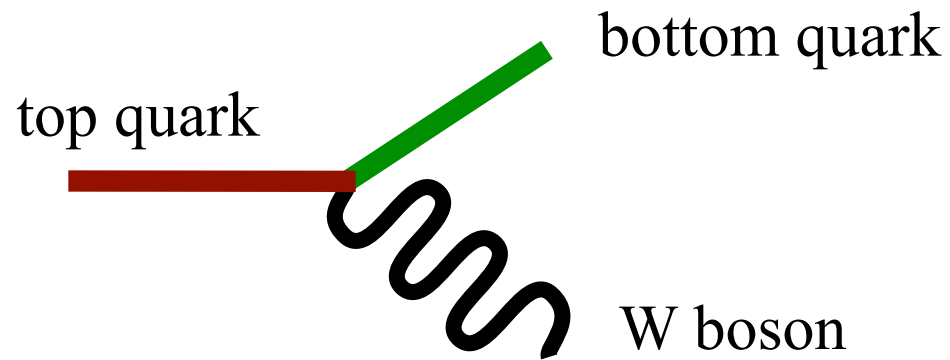




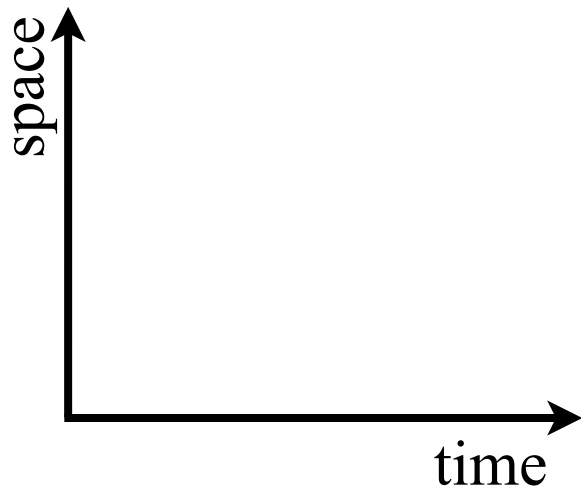
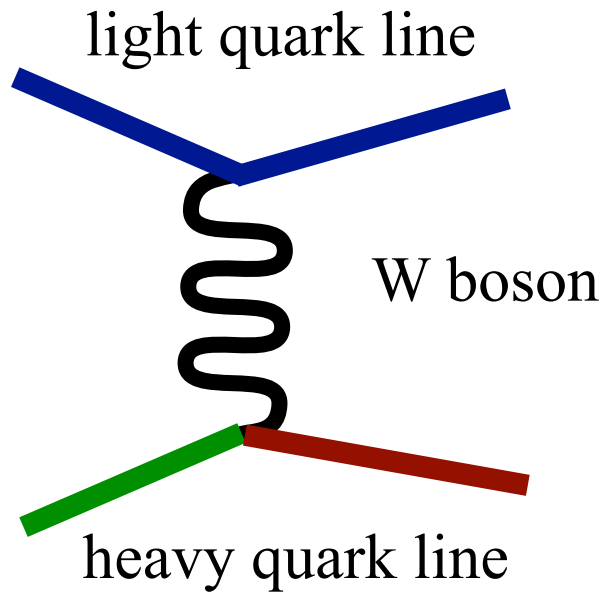
Key to electroweak symmetry breaking



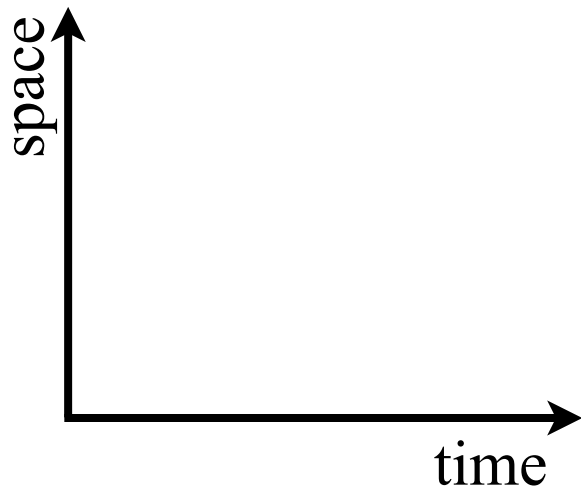
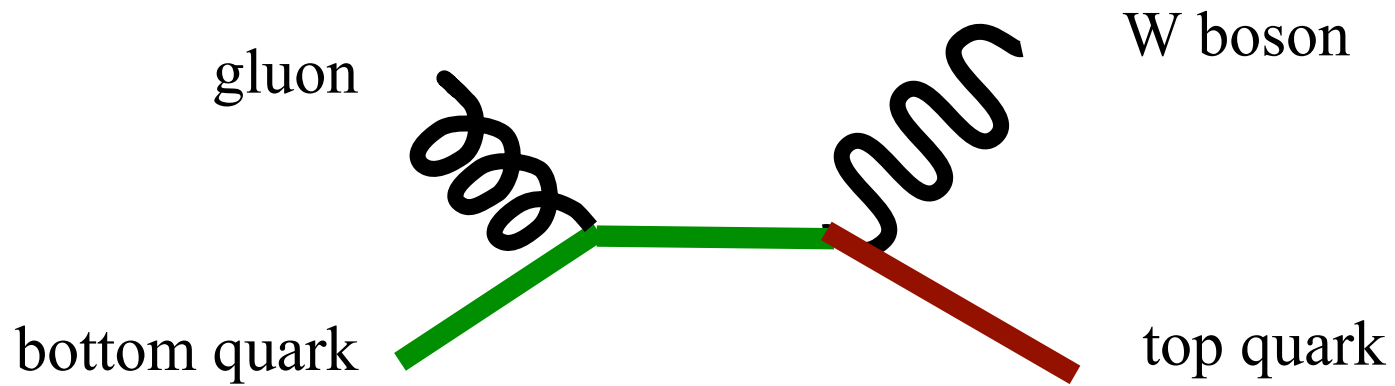
Top quark decay



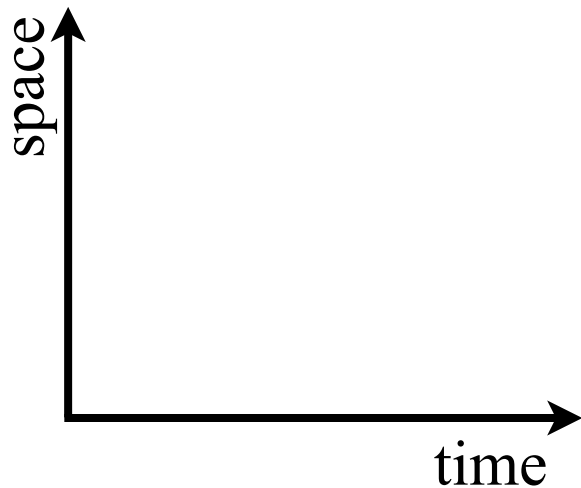
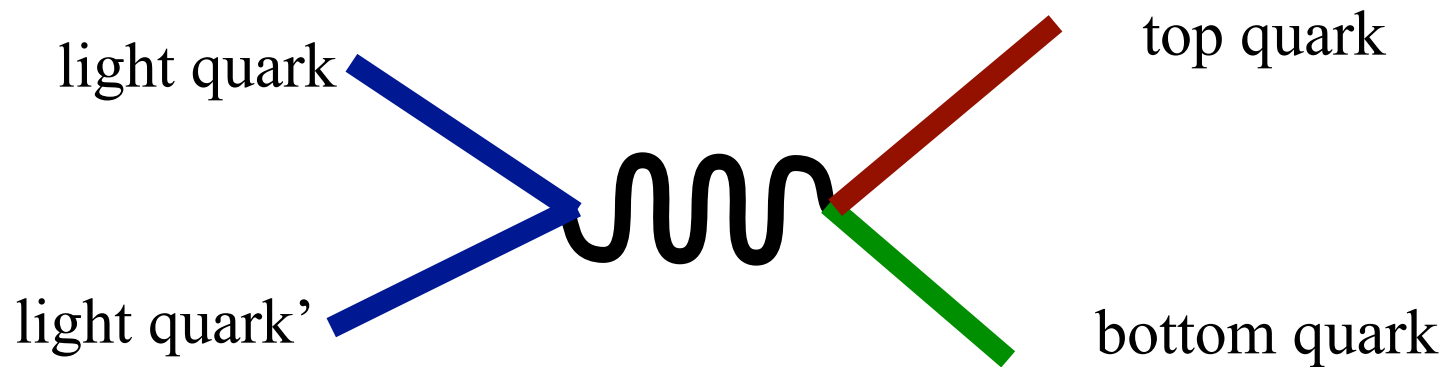
t-channel single top quark production



Wt associated production

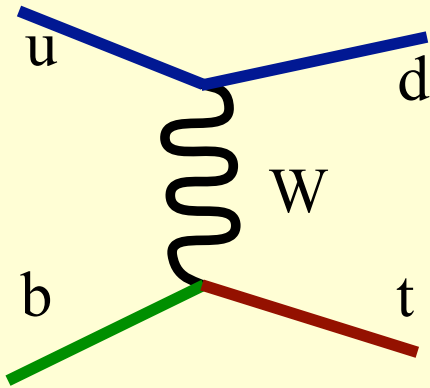


s-channel single top production

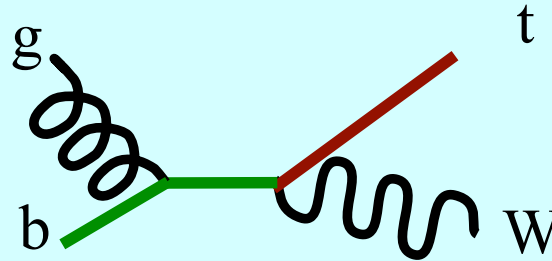


SM single top quark production

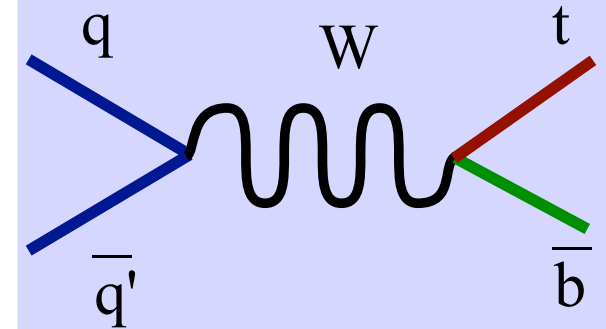
t-channel



Associated production



s-channel



Tevatron:

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

LHC:

(7 TeV)

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

LHC:

(14 TeV)

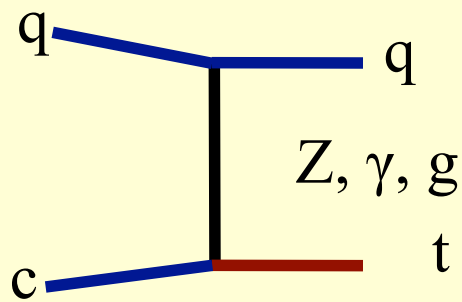
$$\sigma_{\text{tot}} = 326 \text{ pb}$$

SM tasks:

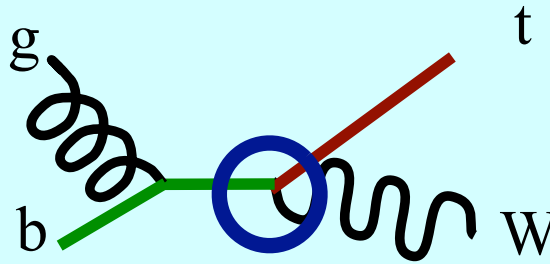
- Weak interaction of bare quarks
- Measure total cross section \rightarrow CKM matrix element $|V_{tb}|$
- Top polarization, PDFs

New physics in single top

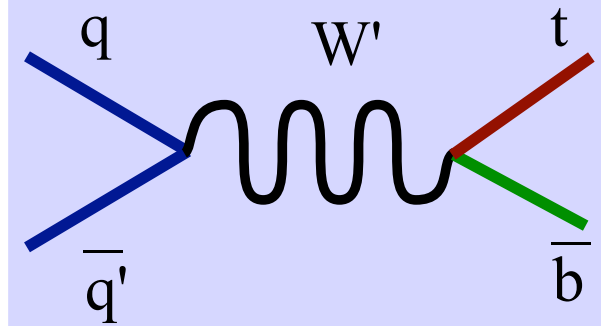
New interactions:
FCNC



New coupling:
modified Wtb
coupling
or anomalous
CKM matrix



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

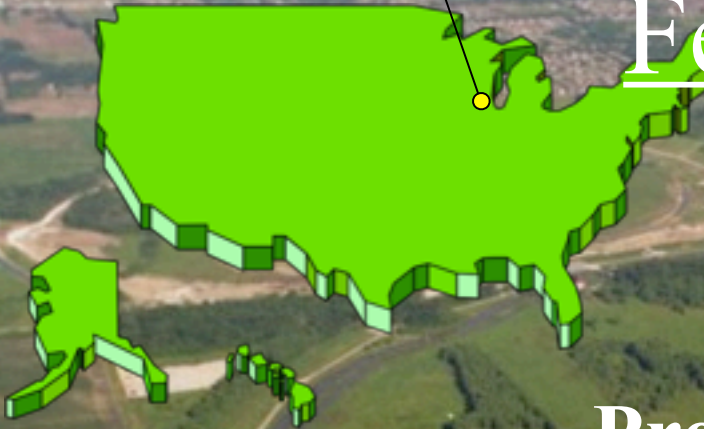


New physics tasks:

- 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



- . Search: PRD 63, 031101 (2000)
- . 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
- . s+t meas (PRD) arXiv:1108.3091
- . Wtb coupl. (PLB) arXiv

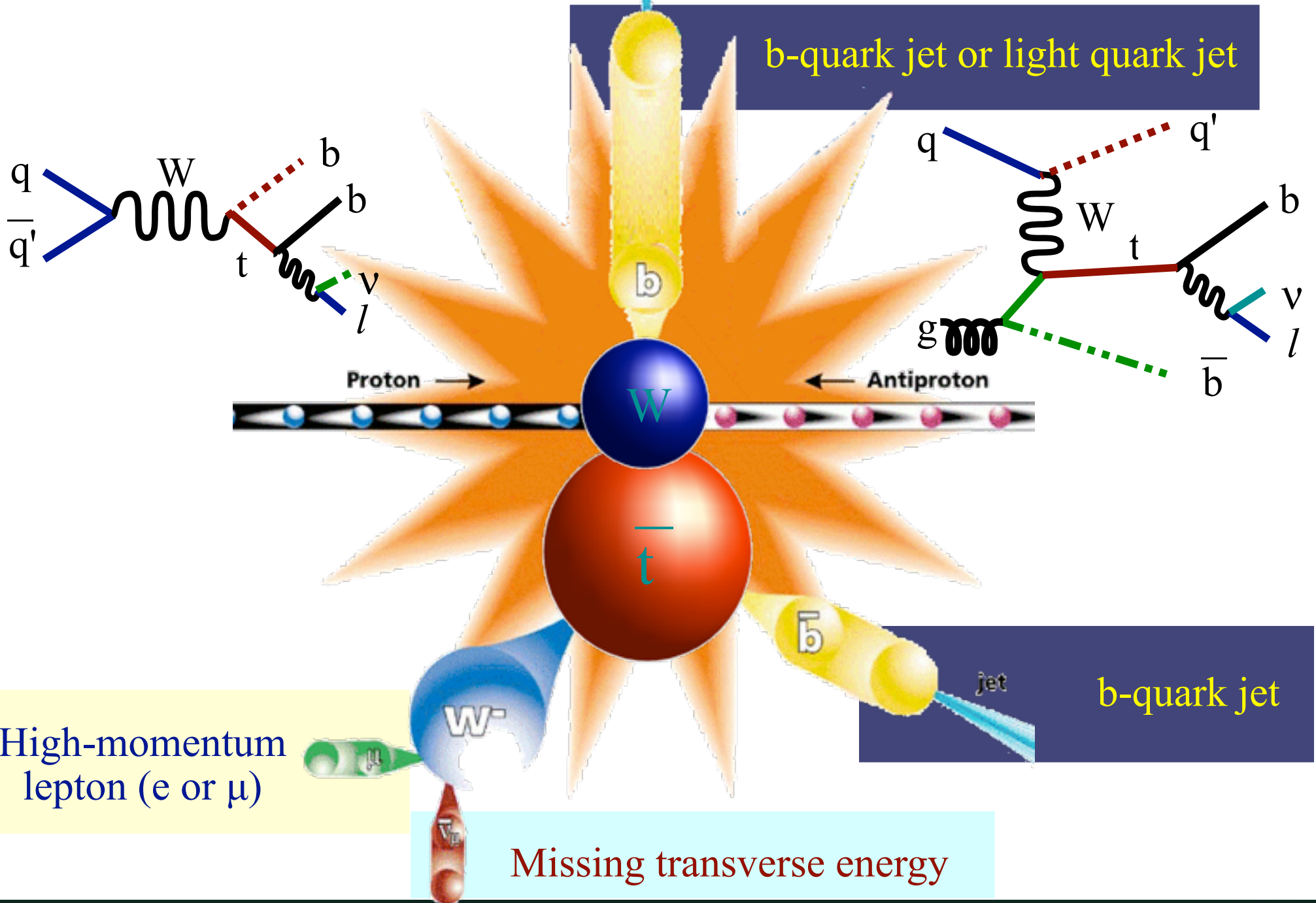
Run I

Run II

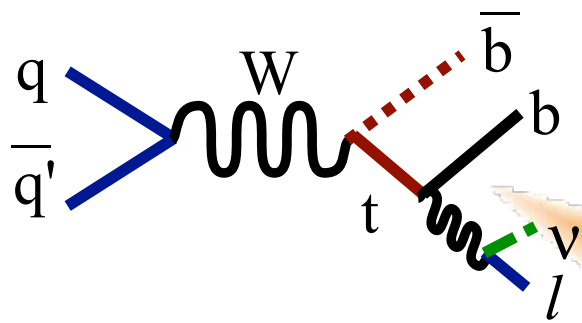
- . Search: PRD 65, 091102 (2002)
- . W' PRL 90, 081802 (2003)

- . 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)

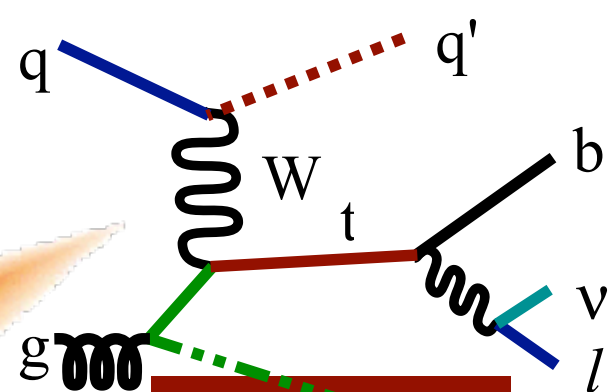
Single top quark event signature



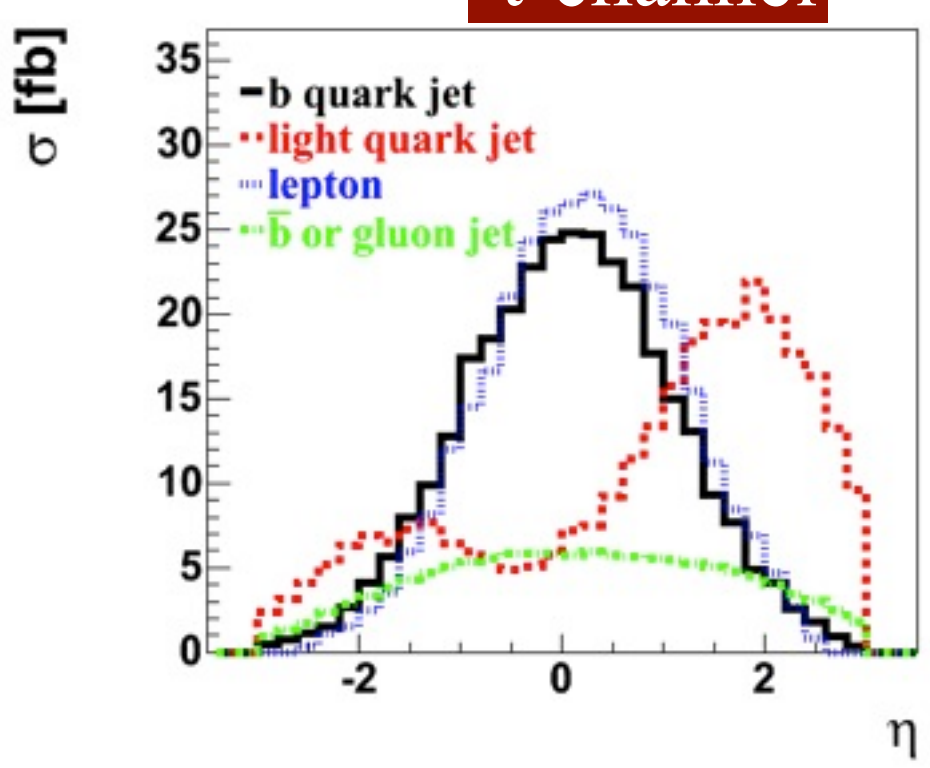
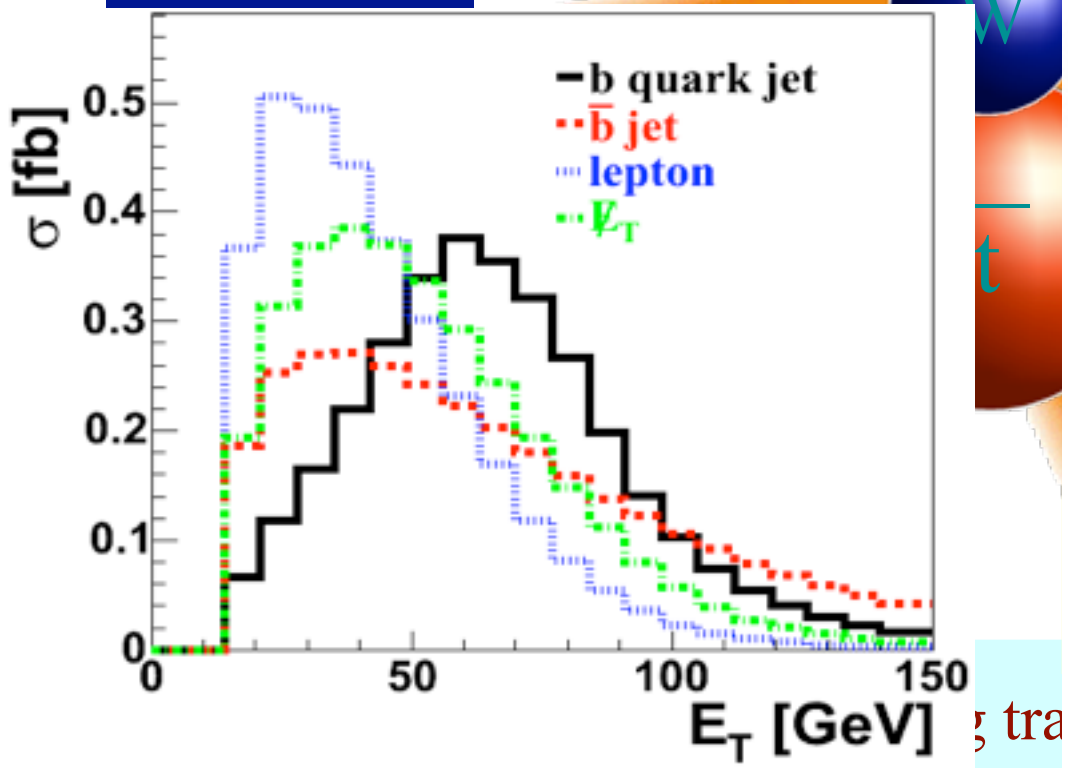
Single top quark event signature



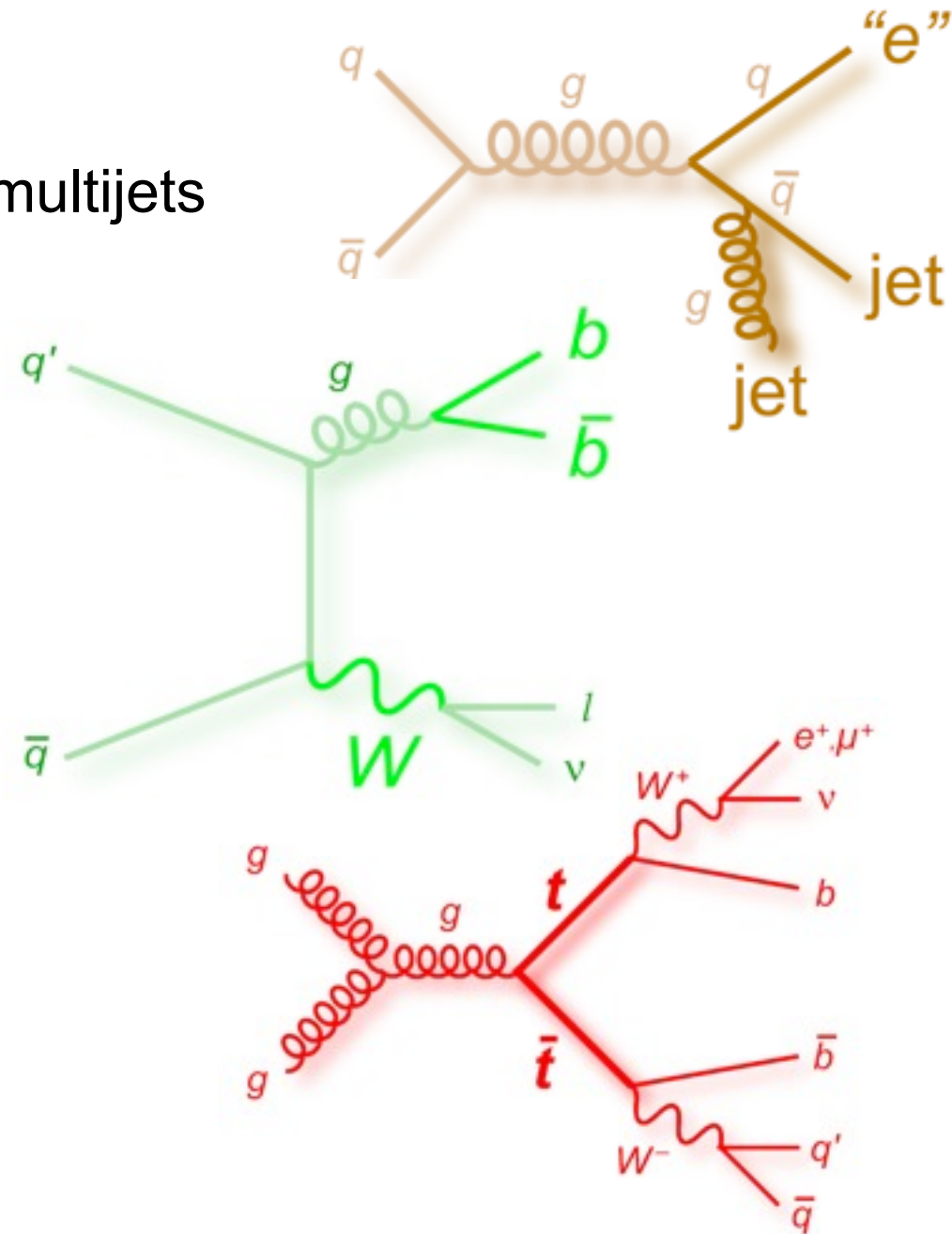
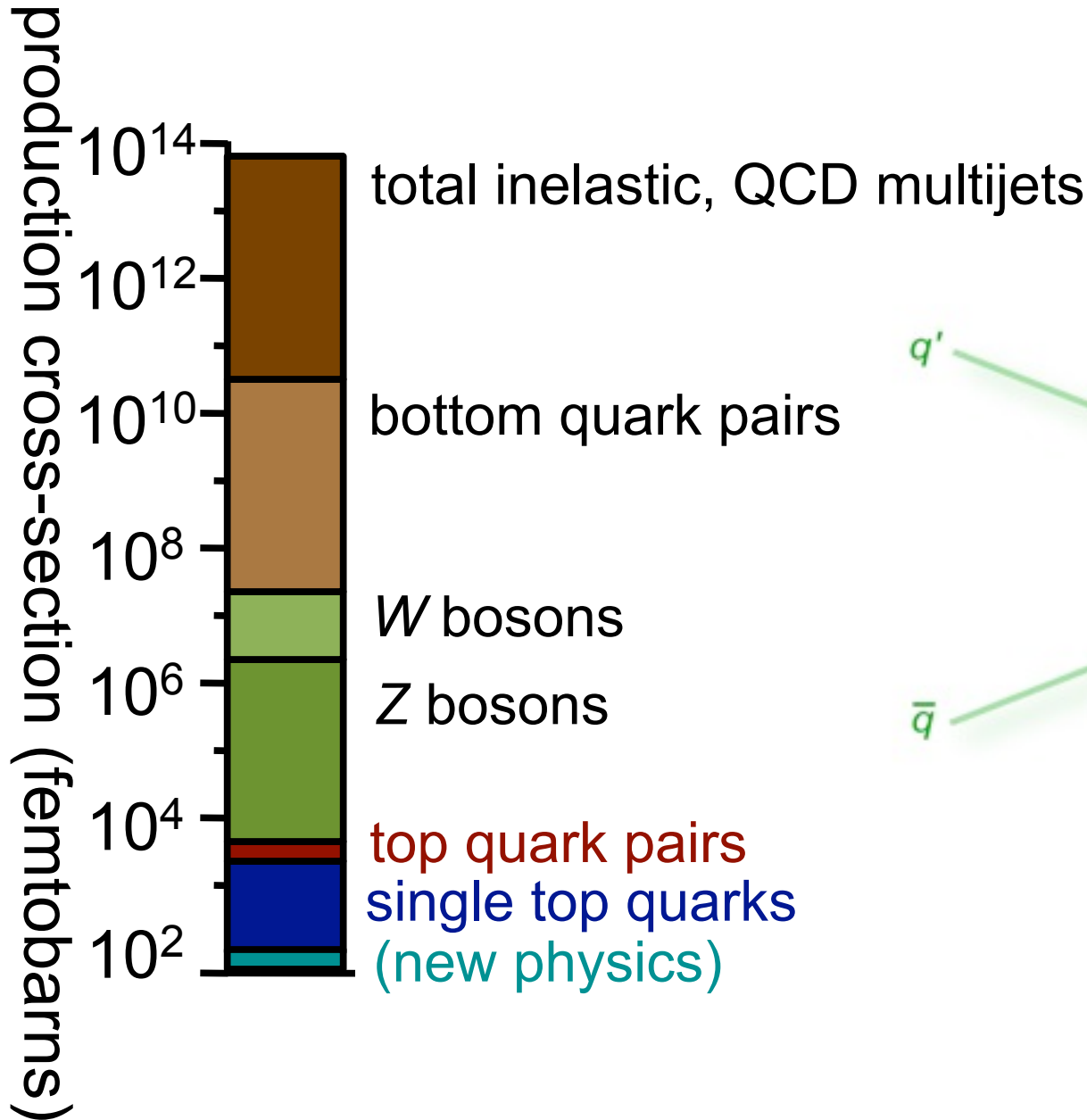
s-channel



t-channel

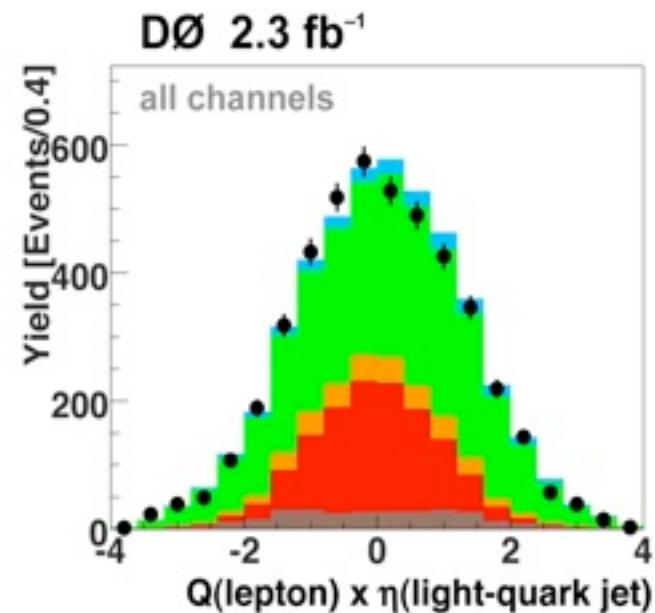
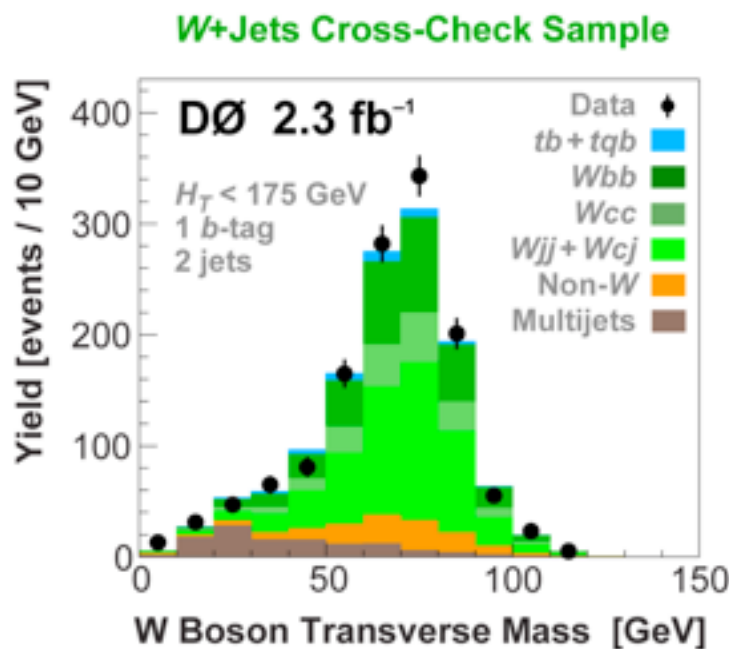
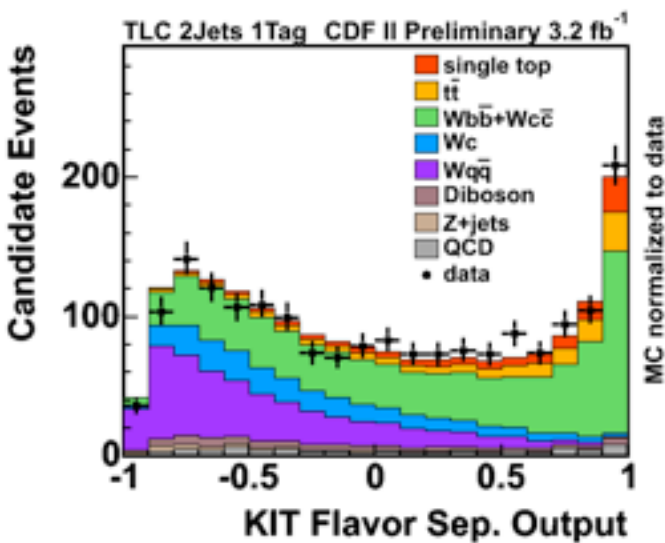
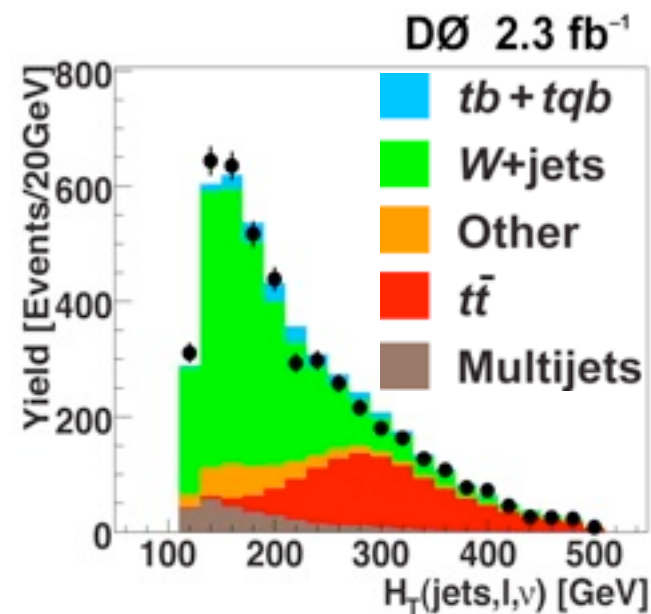
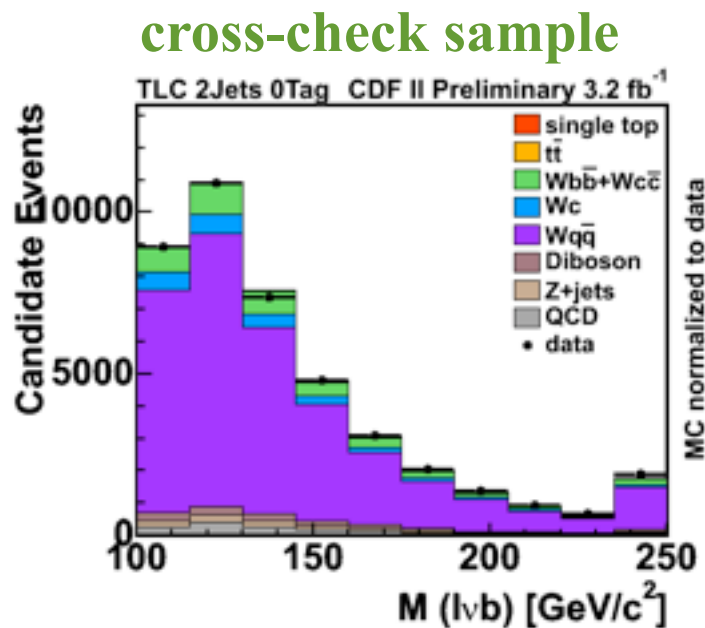
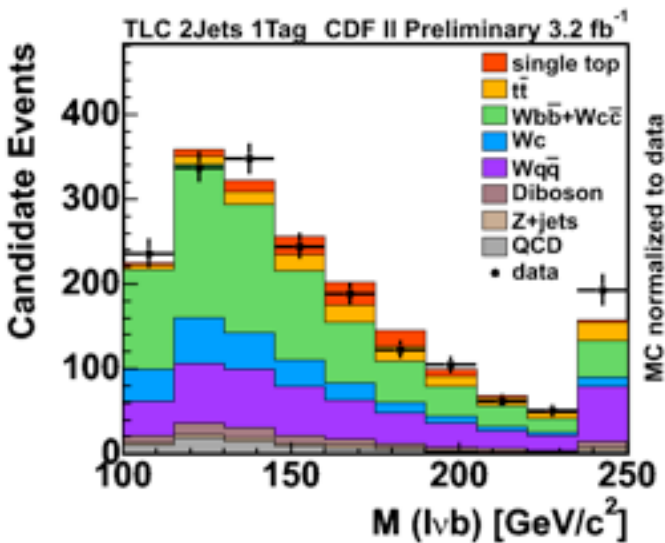


Background processes

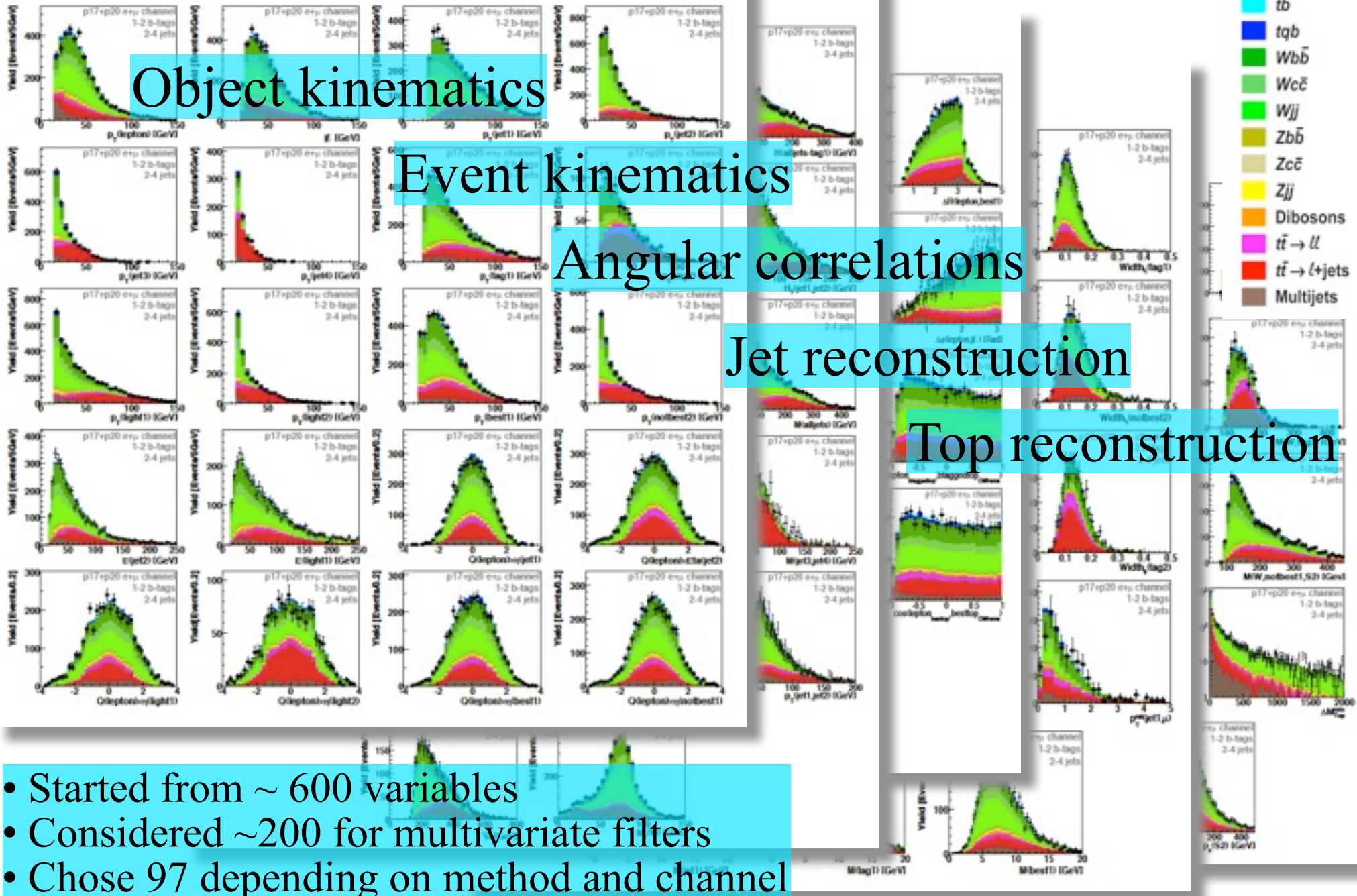




Discriminating variables



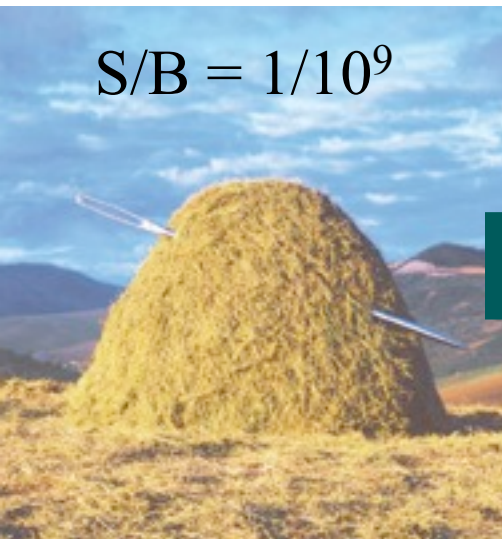
Discriminating variables



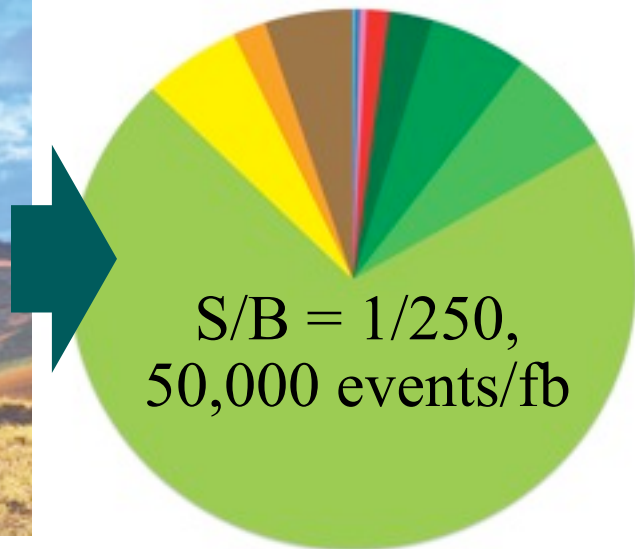
- Started from ~ 600 variables
- Considered ~ 200 for multivariate filters
- Chose 97 depending on method and channel

Tevatron analysis outline

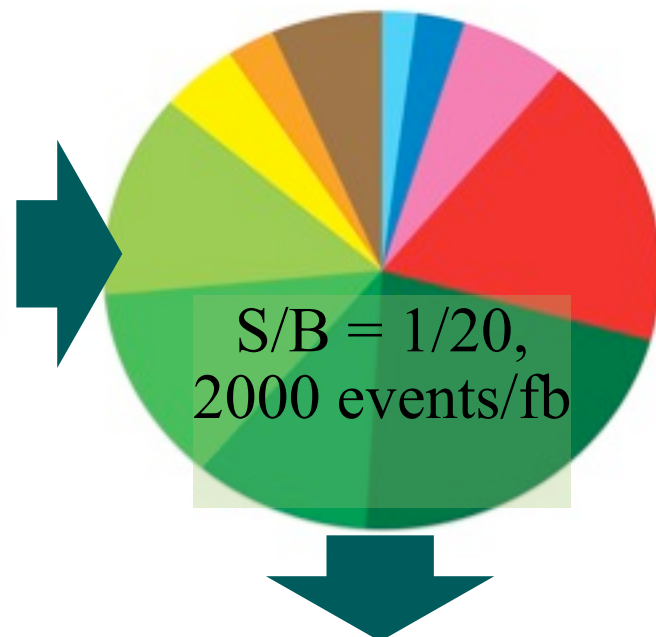
Trigger selection



Single top event kinematics

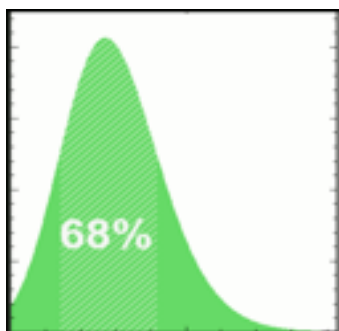


b-quark tagging

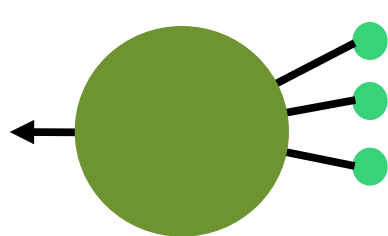


- tb
- tqb
- $t\bar{t} \rightarrow ll$
- $t\bar{t} \rightarrow l+jets$
- $Wb\bar{b}$
- $Wc\bar{c}$
- Wcj
- Wjj
- $Z+jets$
- Dibosons
- Multijets

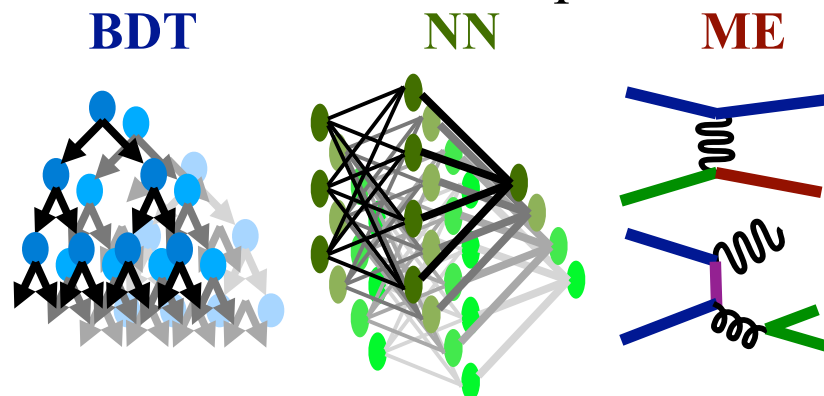
Statistical analysis



Combination



Multivariate techniques



Multivariate methods

Input:

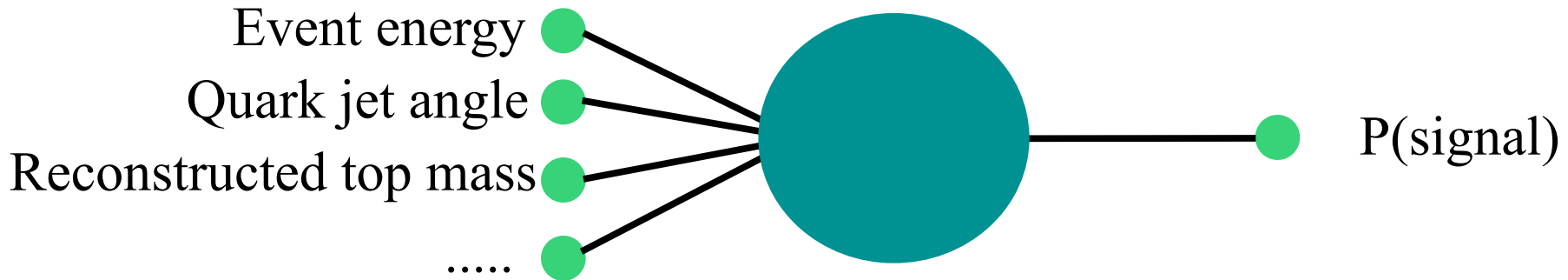
discriminating variables

Method:

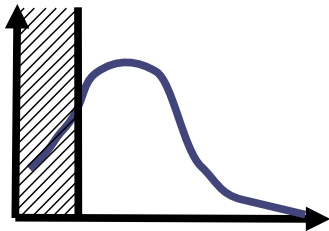
multivariate analysis

Output:

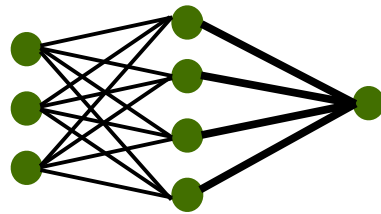
signal likelihood



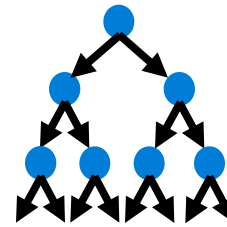
Cut-Based



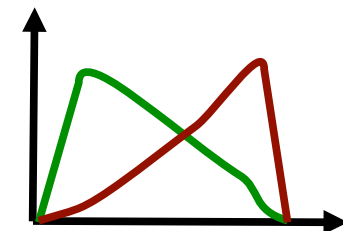
Neural networks



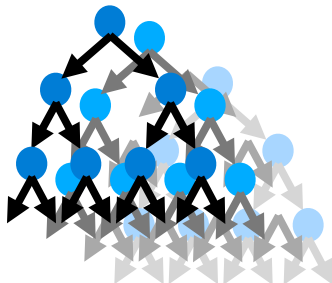
Decision trees



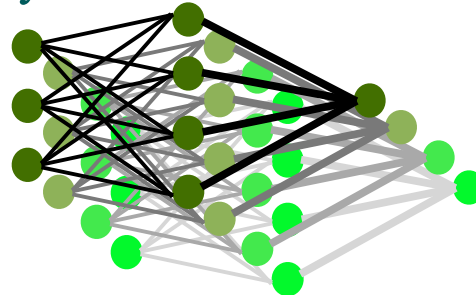
Likelihood



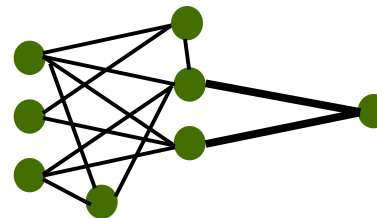
Boosted decision trees



Bayesian neural networks



Neuro evolution



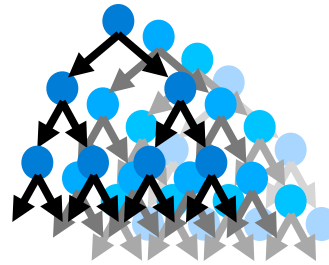
Matrix Elements

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

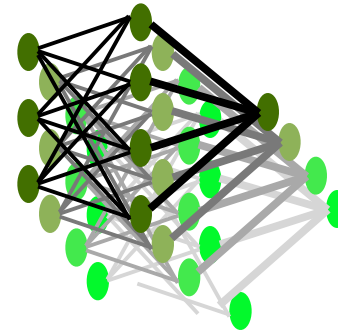
Several multivariate filters combined in one final discriminant

- BNN (DØ)
- NEAT (CDF)

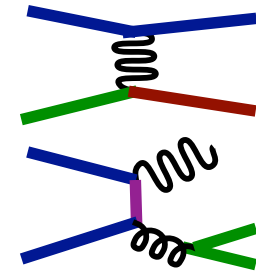
Boosted Decision Trees



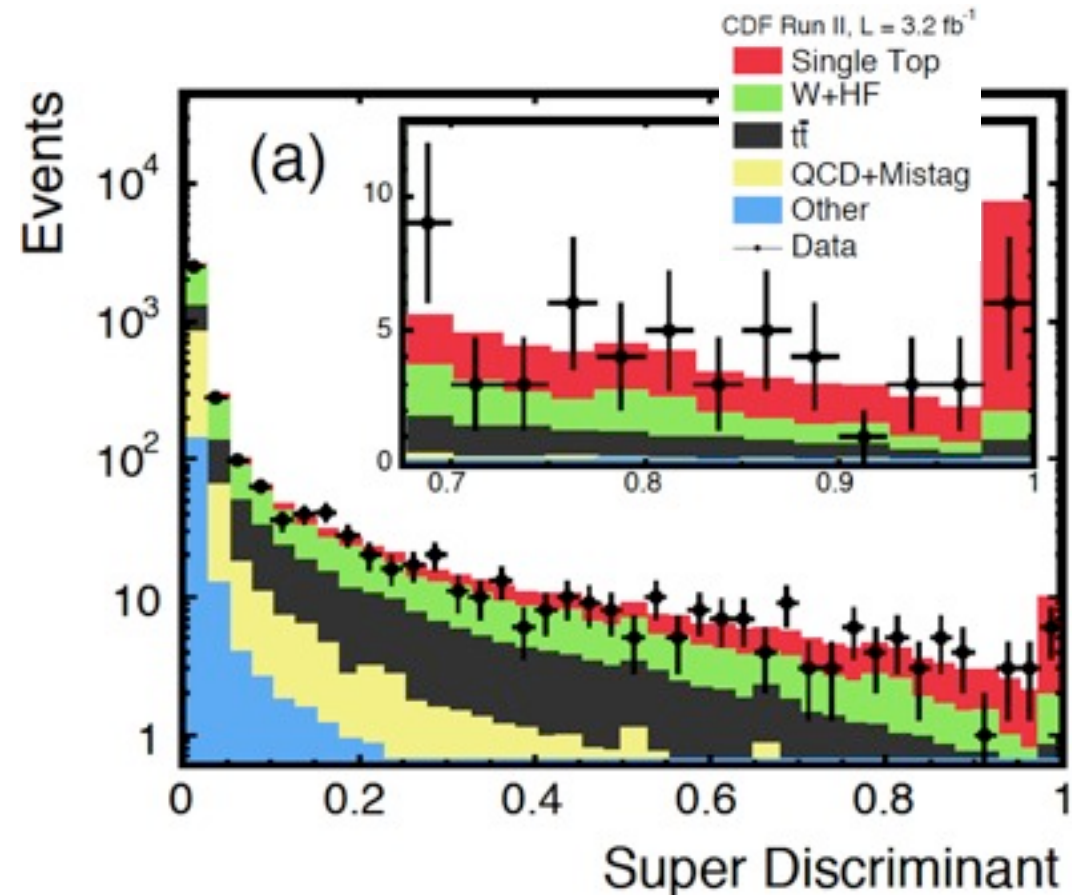
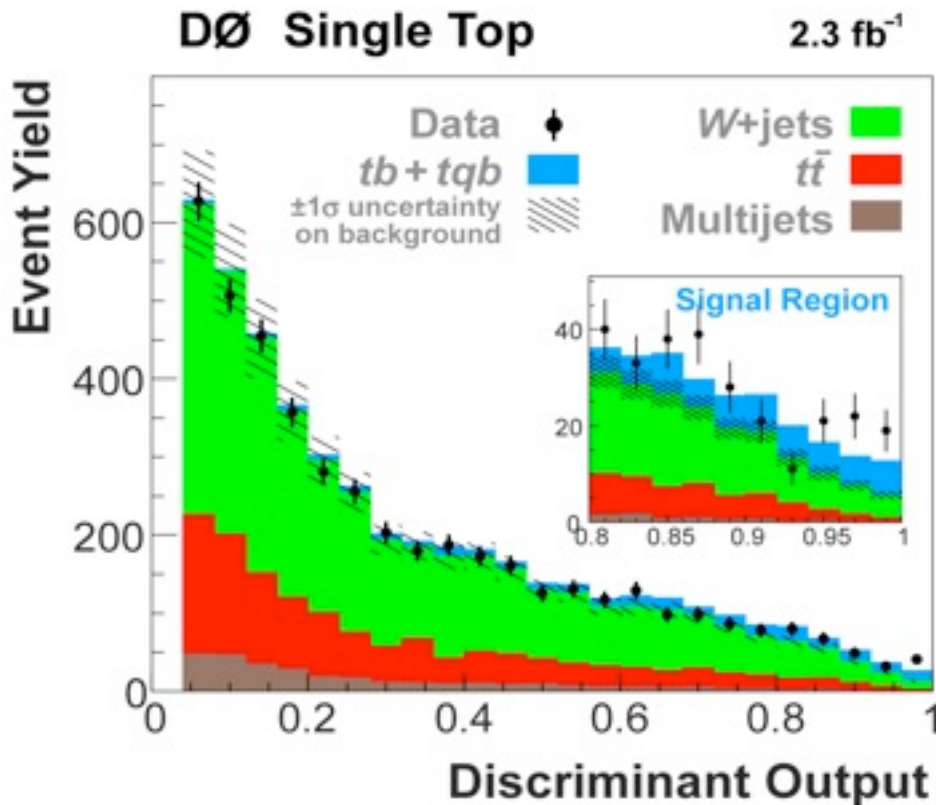
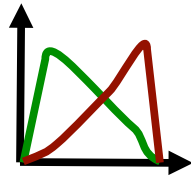
Neural Networks



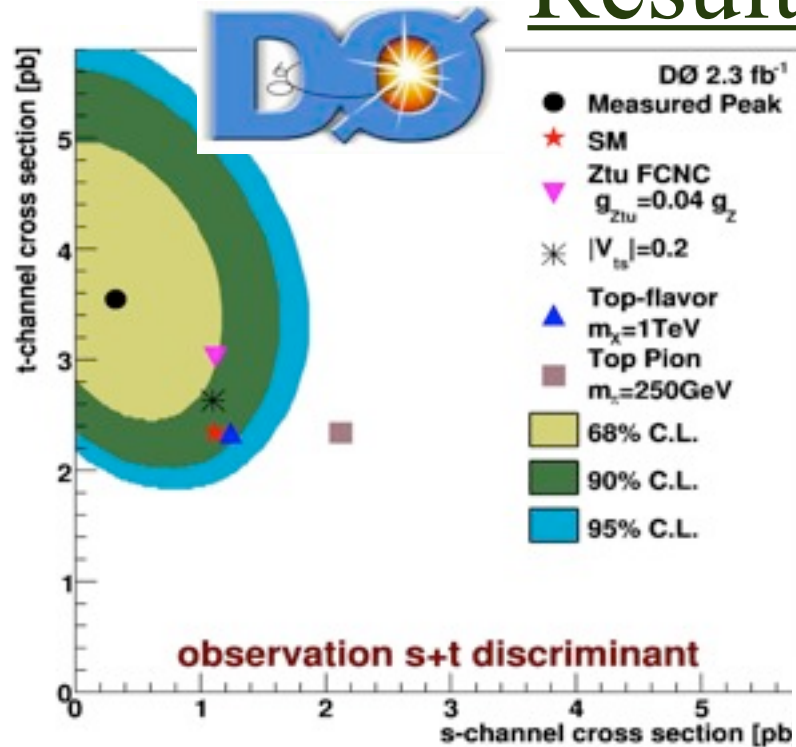
Matrix Elements



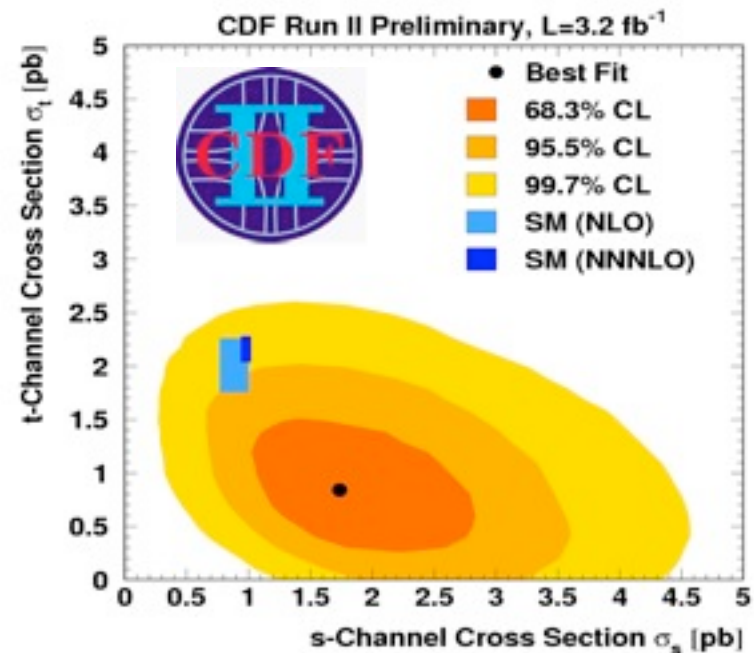
Likelihood



Results and combination

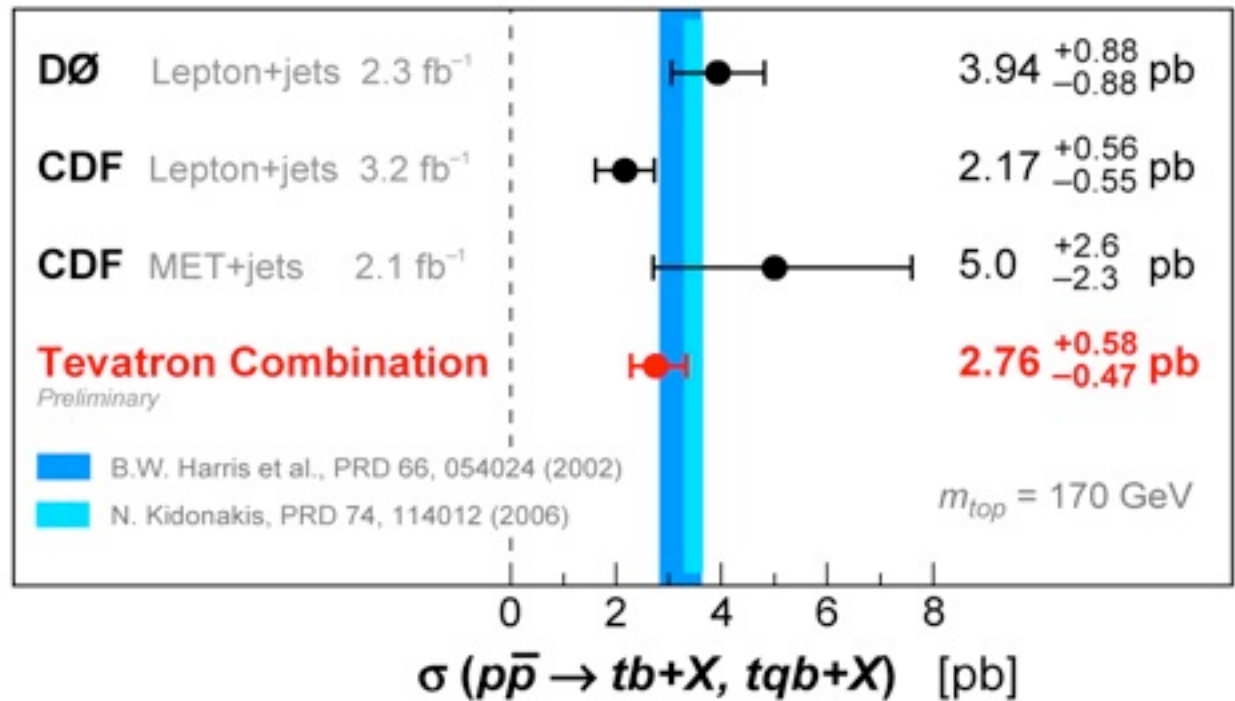


- Each experiment observes 5 σ significance
- DØ and CDF measurements are consistent to 1.6 σ
- Combination of MVA distributions
 - ▲ Bayesian statistical analysis
 - ▲ Taking all uncertainty correlations into account



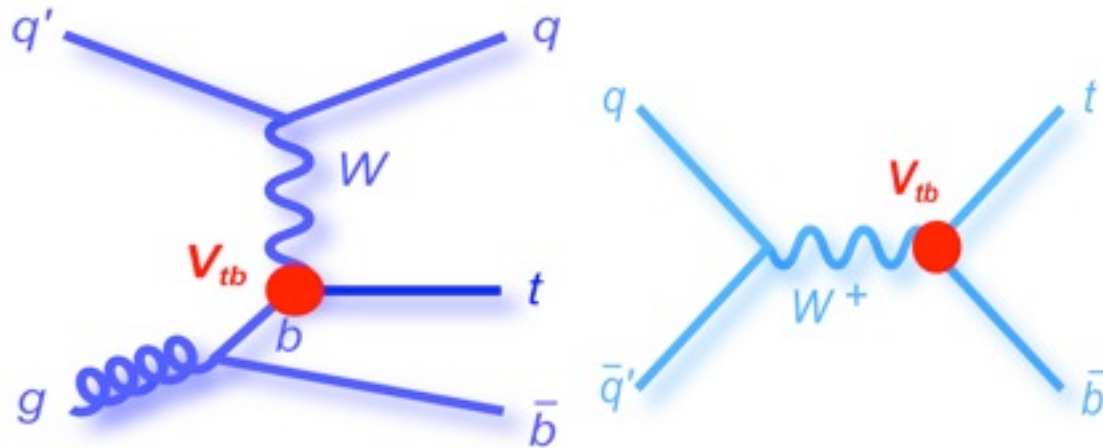
Single Top Quark Cross Section

August 2009



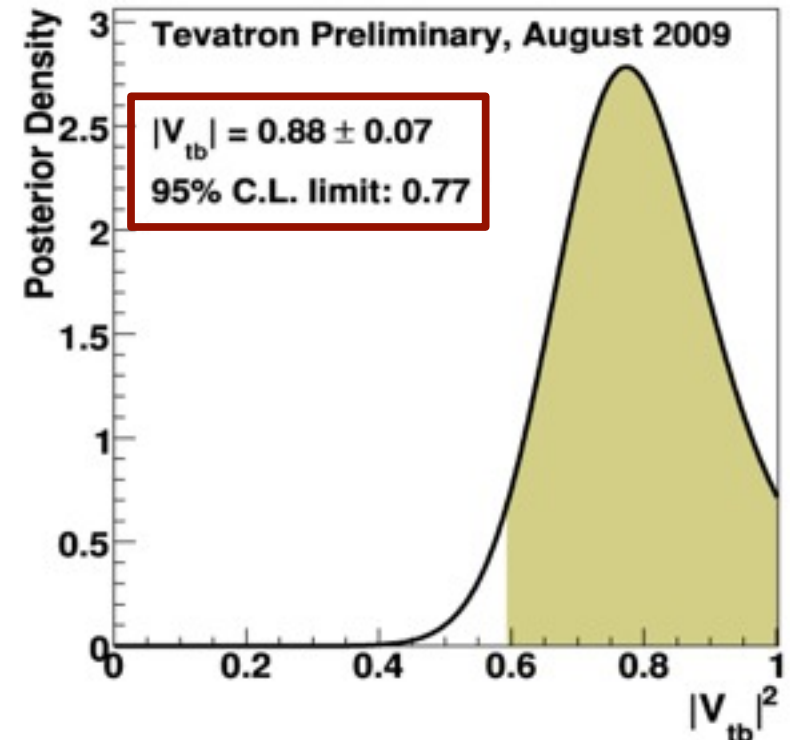


CKM matrix element V_{tb}



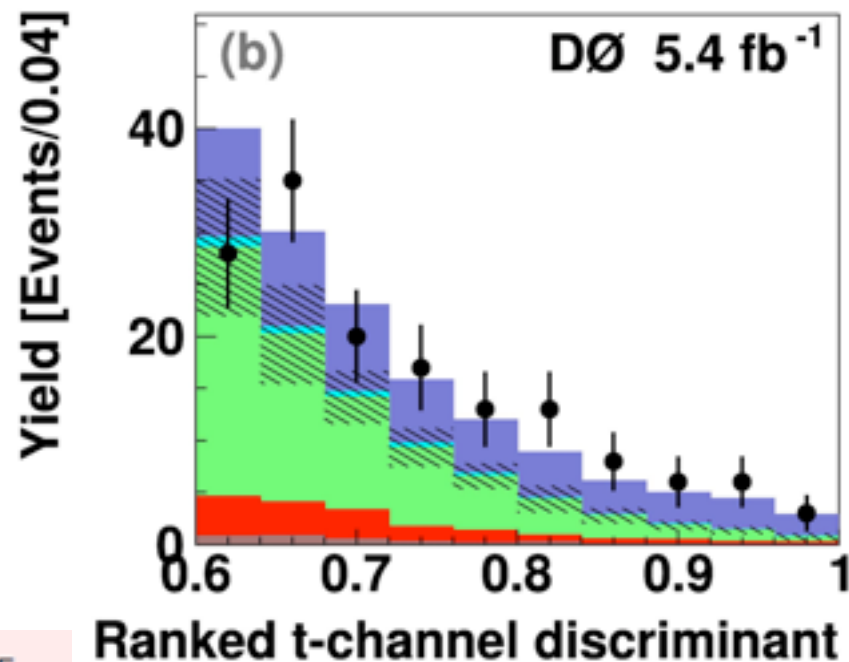
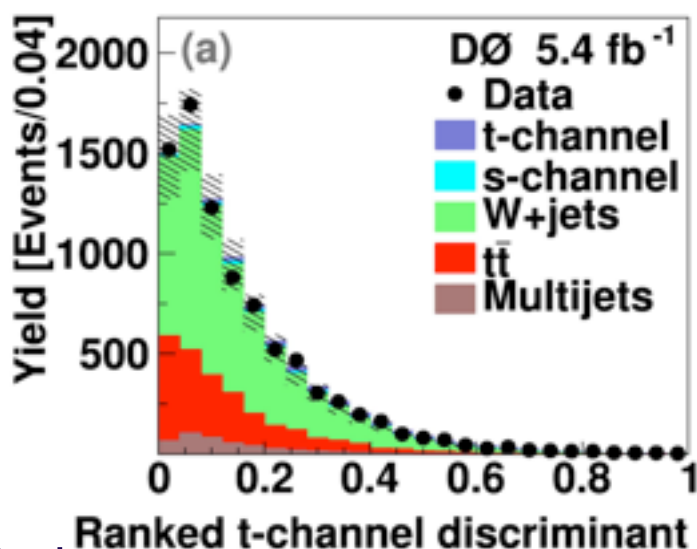
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \mathbf{V_{tb}} \end{pmatrix}$$

- ✦ 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

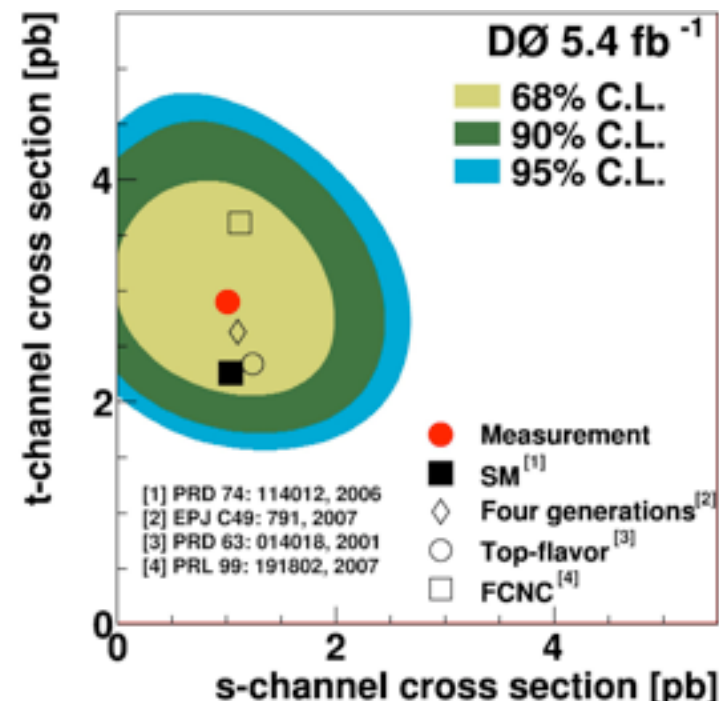
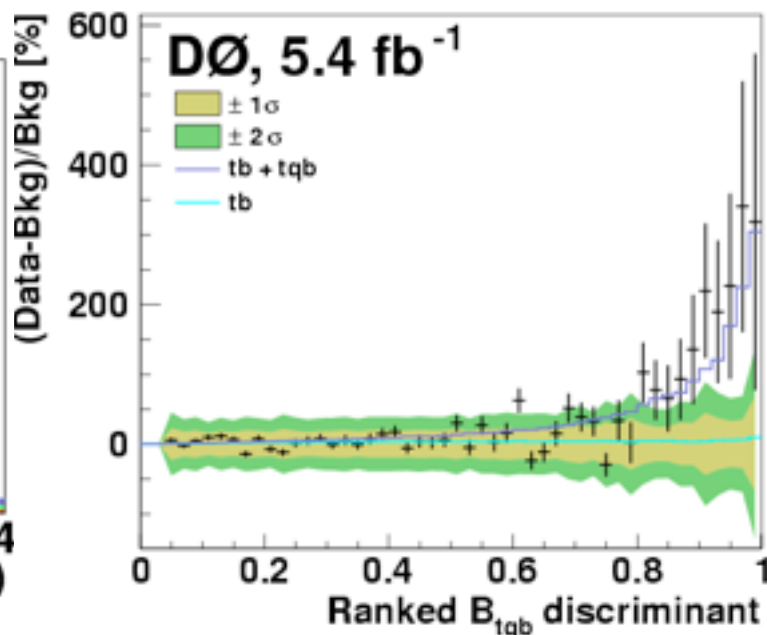
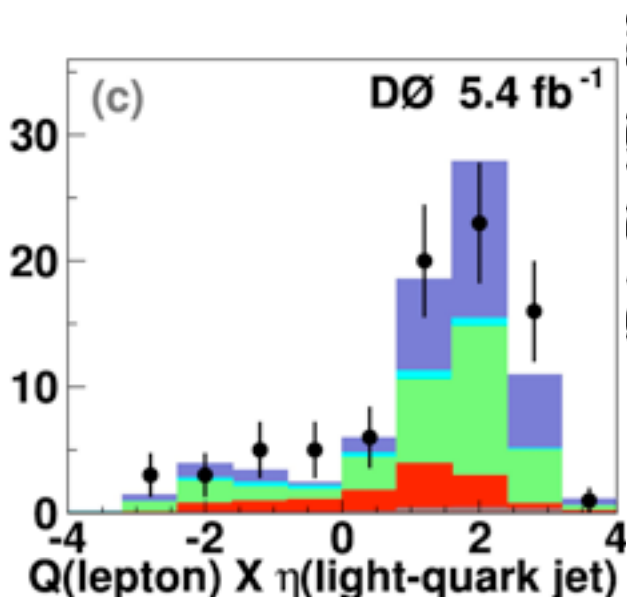


t-channel production

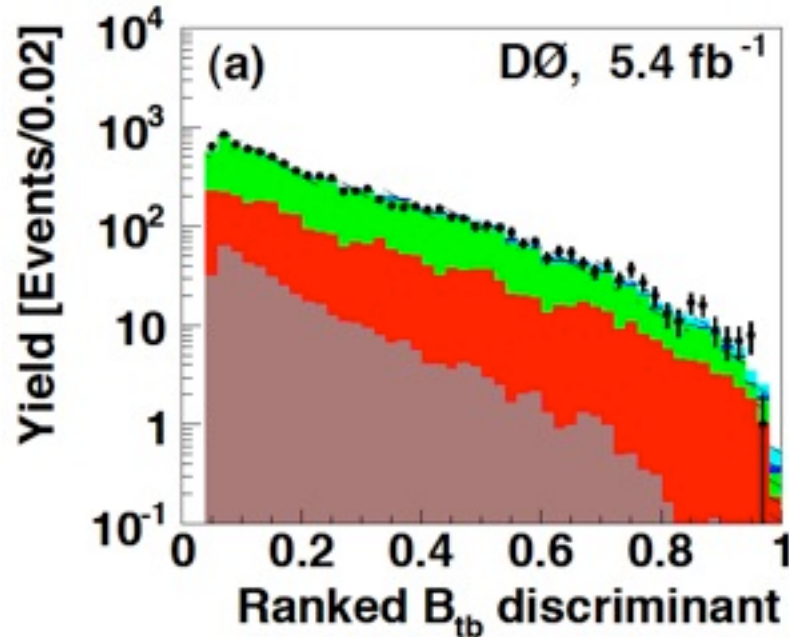
- New analysis with 5.4 fb⁻¹
- Dedicated t-channel filter
- No assumption about s-channel
- $\sigma_{t\text{-channel}} = 2.90 \pm 0.59$ pb
- 5.5 σ significance
- Also measure top width



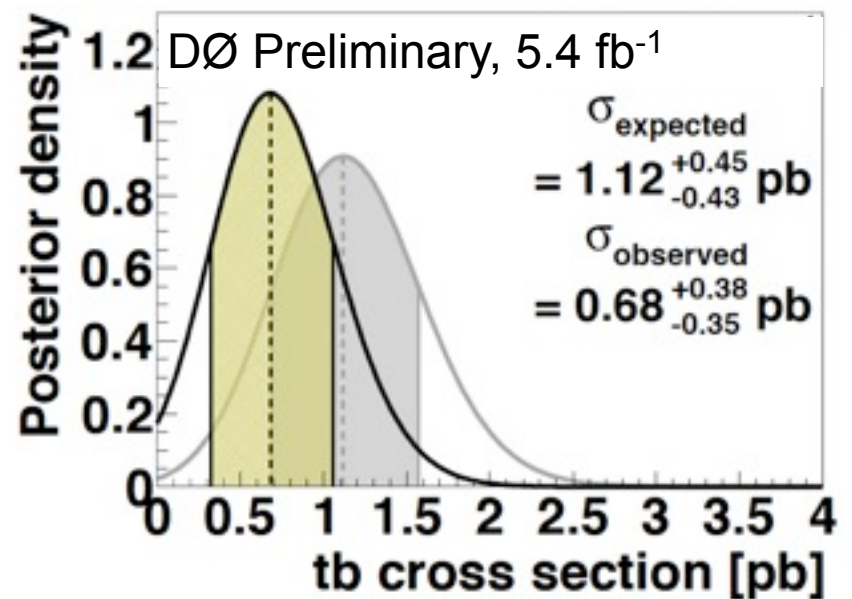
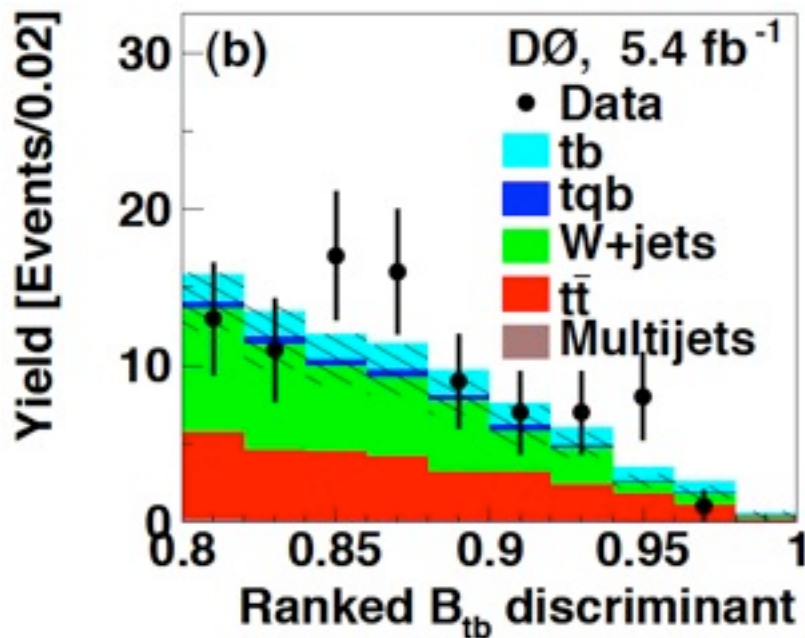
$$\tau_t = (3.2^{+1.1}_{-0.7}) \times 10^{-25} \text{ s}$$



s-channel analysis



- Train MVA filters for s-channel signal
 - Include t-channel as background
- No evidence for s-channel yet
 - Significance ~ 2 SD



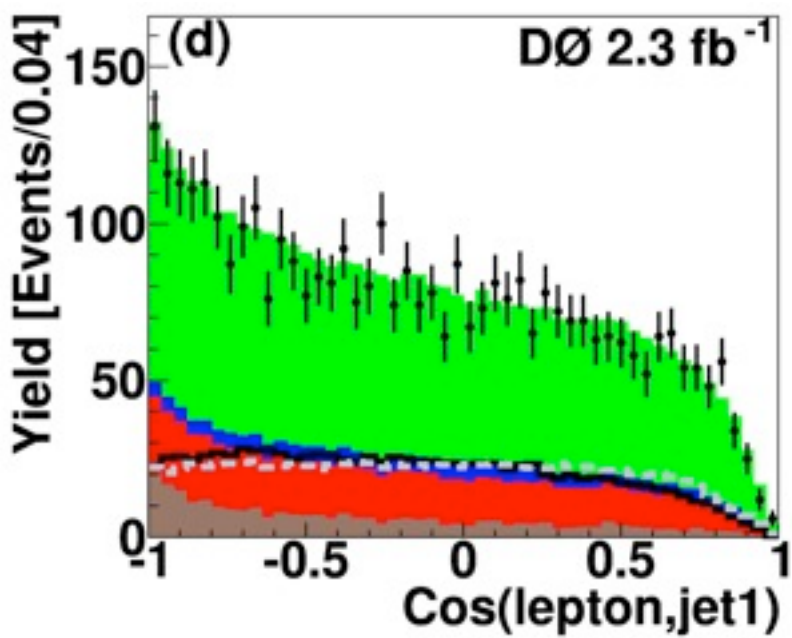
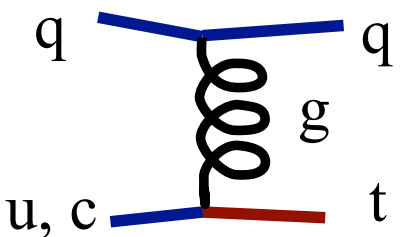
Tevatron new physics searches



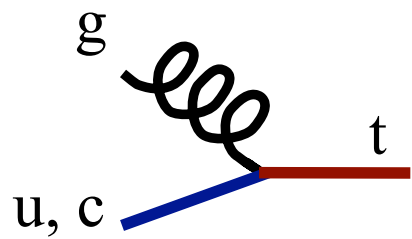
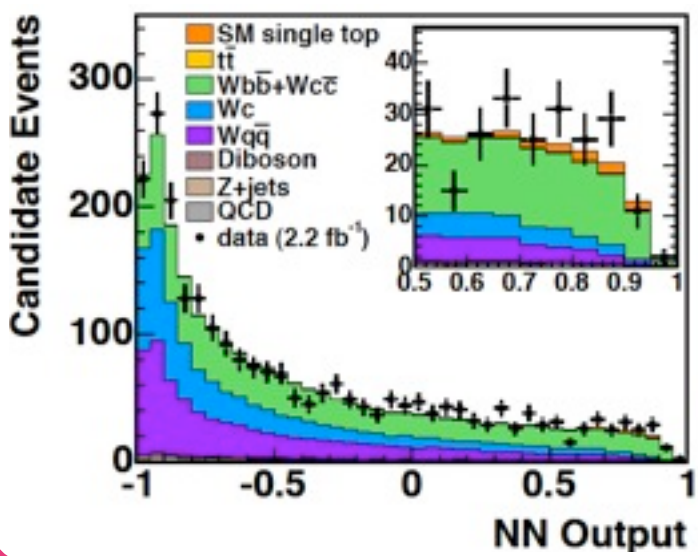
Gluon-FCNC in single top



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



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



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

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

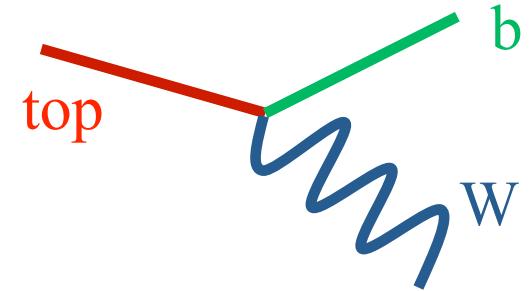
95% CL limits:	tgu	tgc
Cross section	0.20 pb	0.27 pb
κ_{tgf}/Λ	0.013 TeV^{-1}	0.057 TeV^{-1}
$\mathcal{B}(t \rightarrow qg)$	2.0×10^{-4}	3.9×10^{-3}



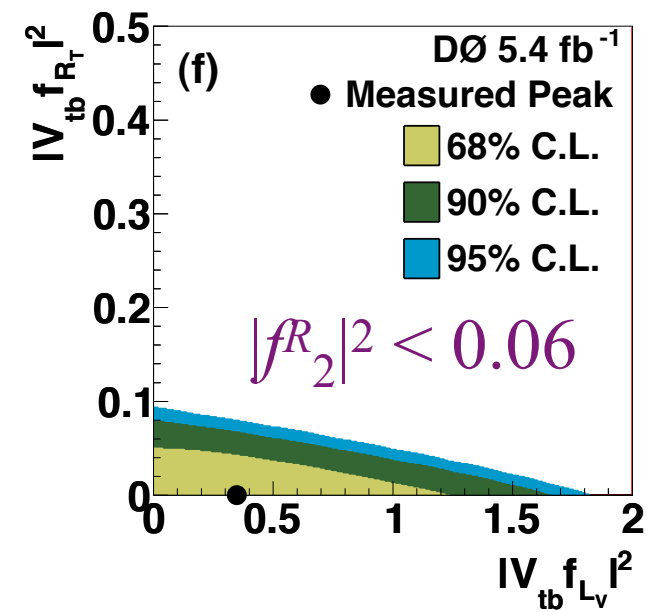
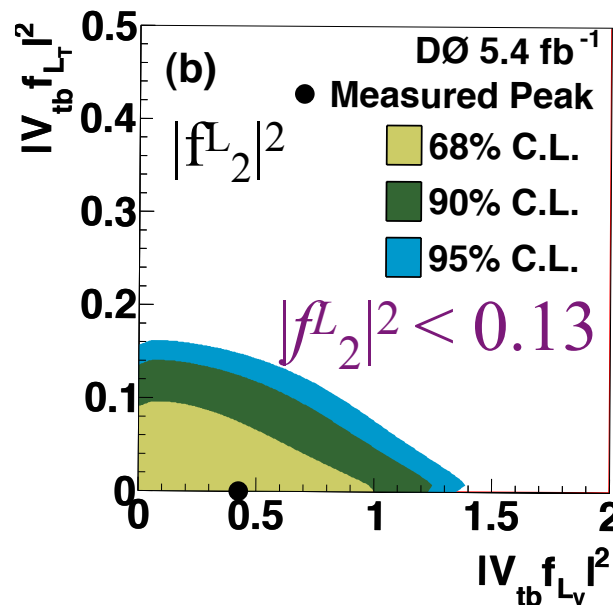
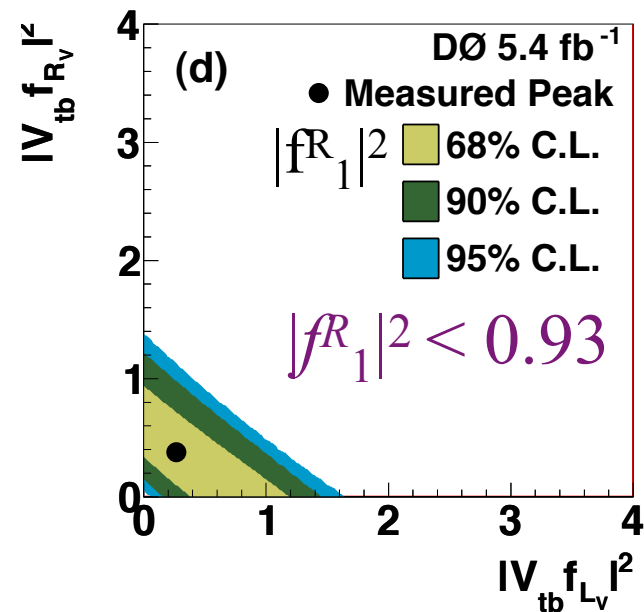
Single top anomalous coupling

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

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



- W helicity measurement and single top anomalous couplings searches are both sensitive: combine (PRL 102, 092002 (2009))
- Updated measurement with 5.4 fb^{-1}





Search for W' boson

– Explore simultaneously left-handed and right-handed couplings

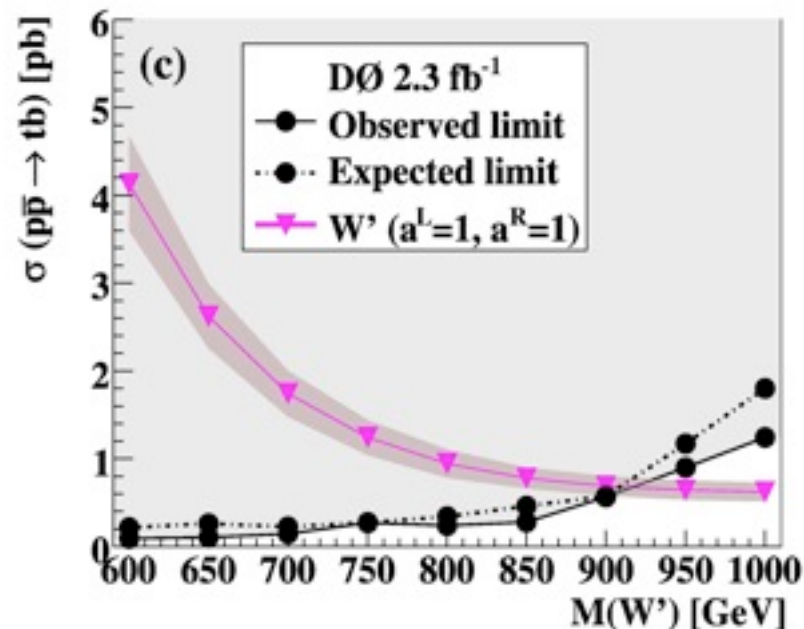
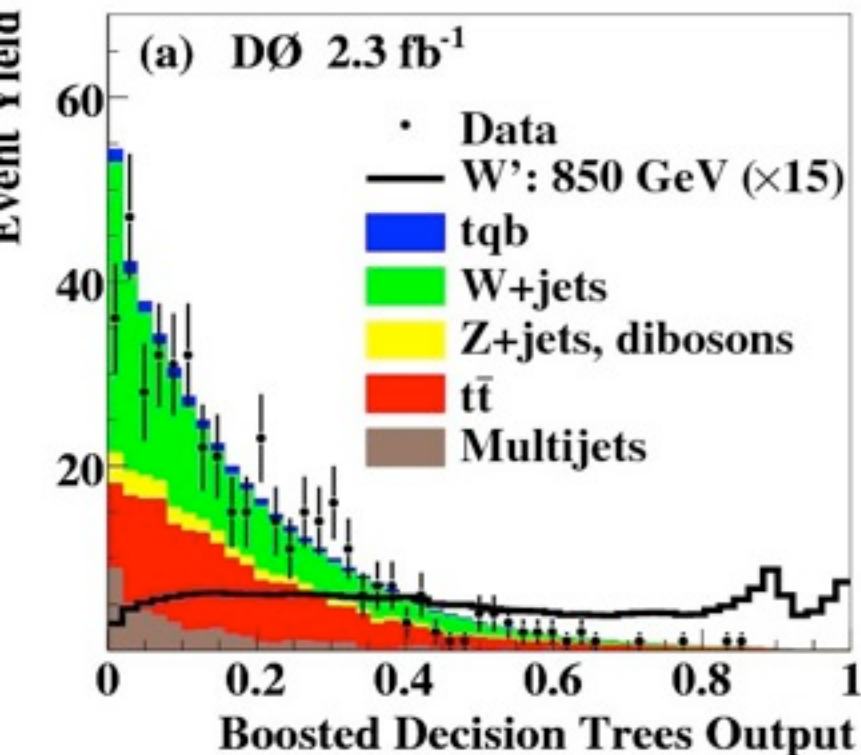
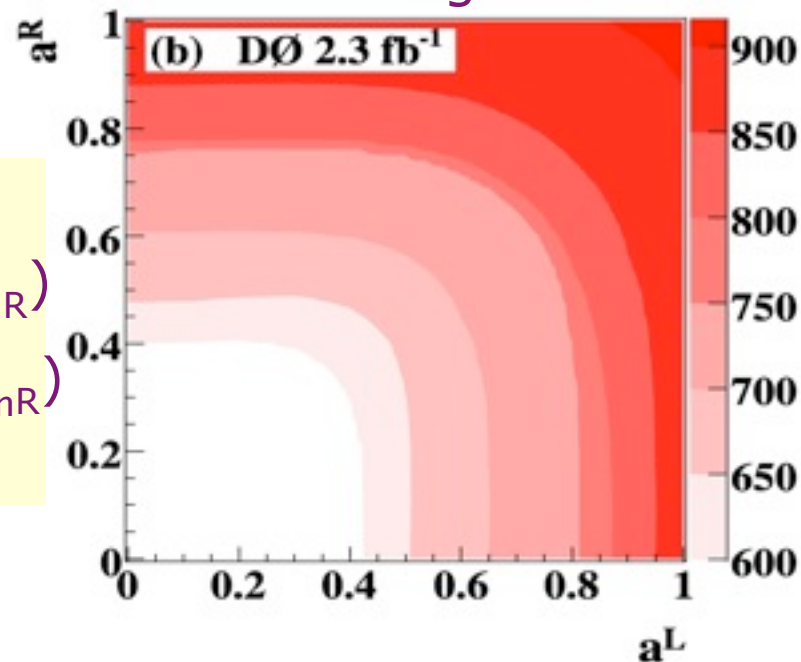
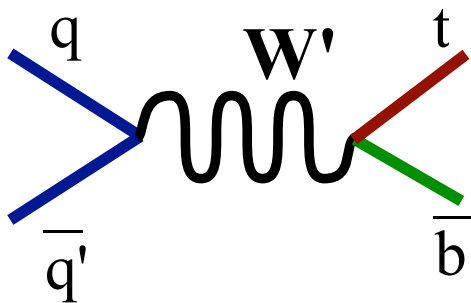
– 95% CL limits:

$M_{W'} > 863$ GeV (SM-like)

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

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

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



LHC at CERN

Proton-proton collider
CM energy 7 TeV so far

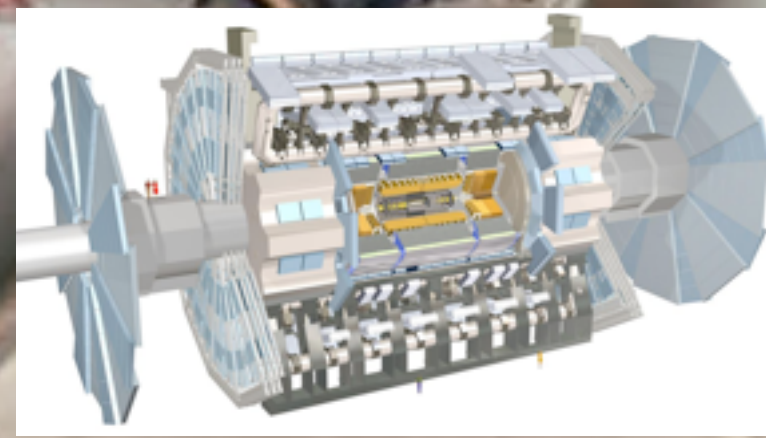
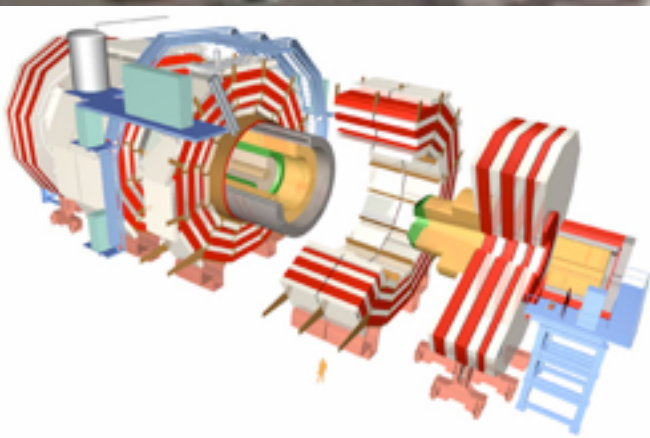
→ *Energy frontier*

Integrated luminosity $\sim 5 \text{ fb}^{-1}$

Instantaneous luminosity $> 6 \text{E}32 \text{ cm}^{-2}\text{s}^{-1}$

→ 8 interactions per crossing, 1.7M crossing per second

→ *Luminosity frontier*

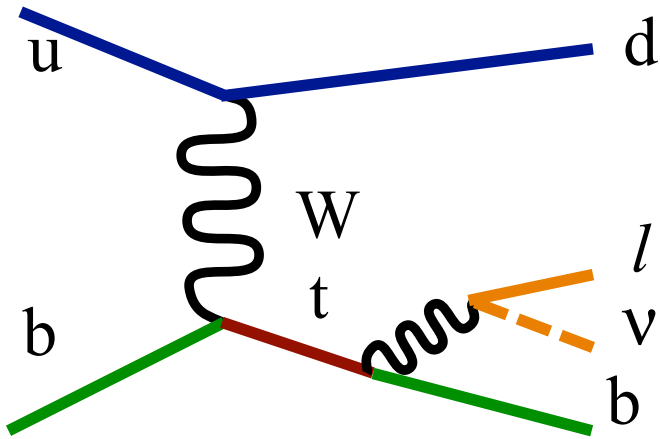


Large Hadron Collider

Large Hadron Collider



Measurement of t-channel production



- 36 pb⁻¹ of 2010 data

Event selection:

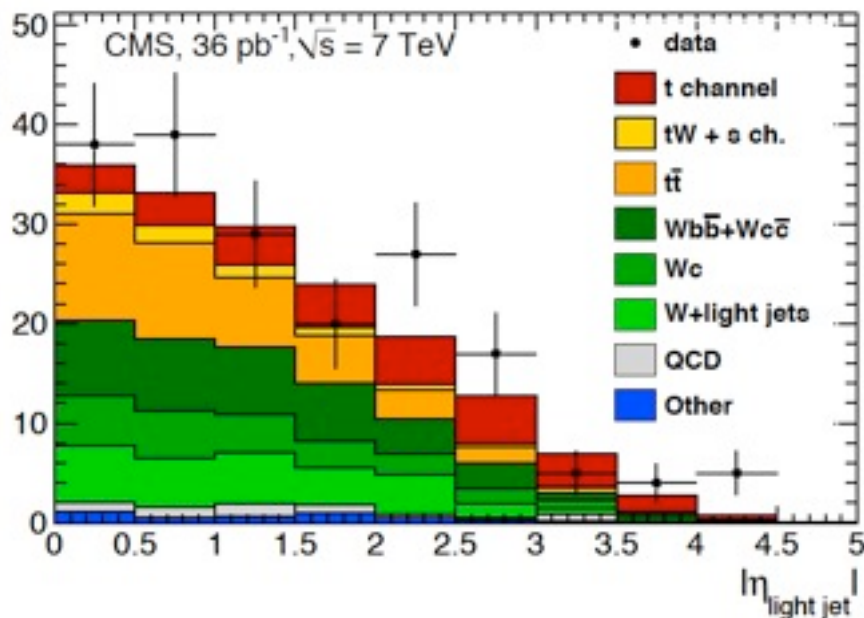
- 1 electron or muon
E_T (p_T) > 30/20 GeV
- M_T (W) > 50/40 GeV
- = 2 jets (p_T > 30 GeV), ≥1 b-tag
- fewer channels than Tevatron, tighter cuts

Background modeling:

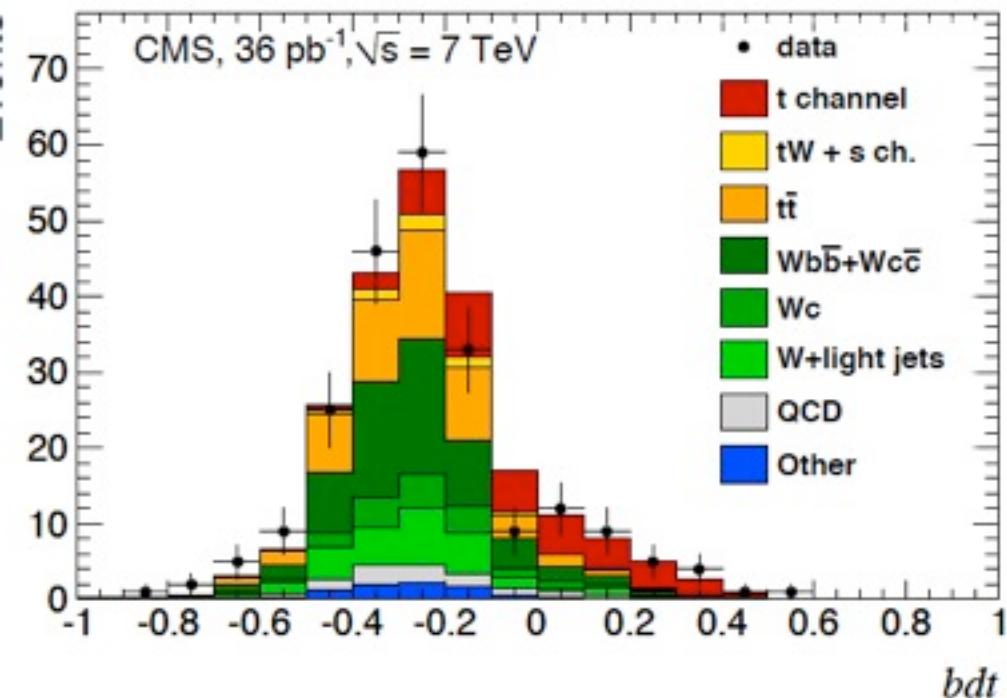
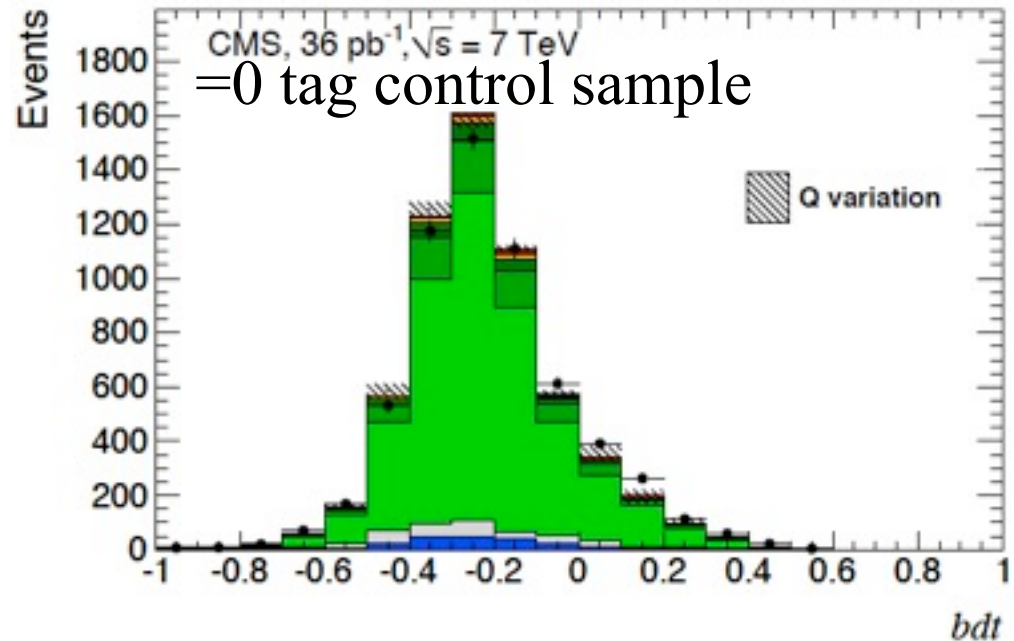
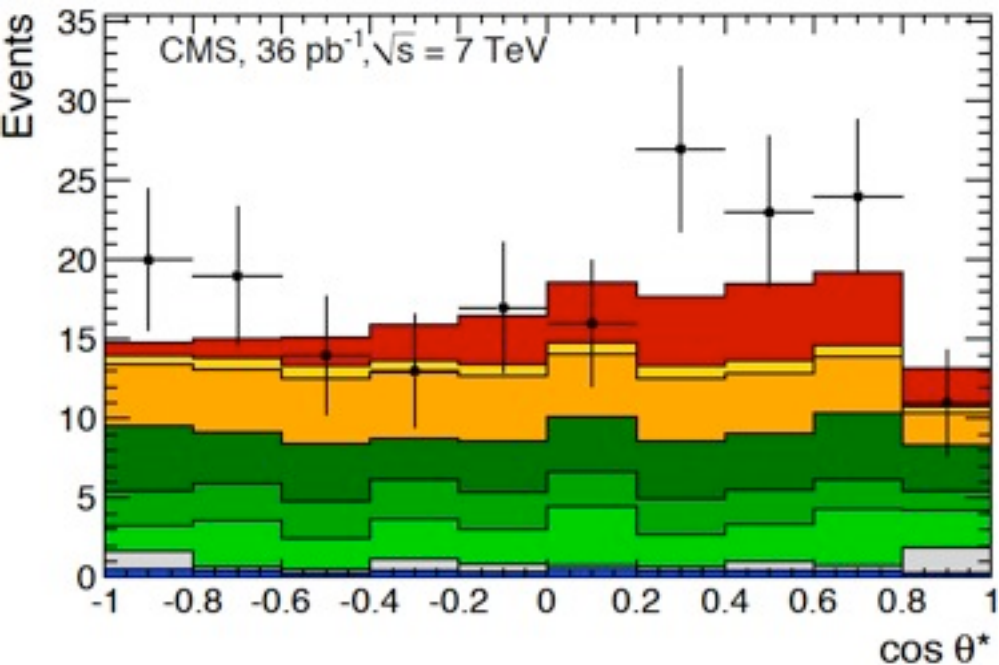
- normalize W+jets and QCD to data
- top background to theory

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:

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

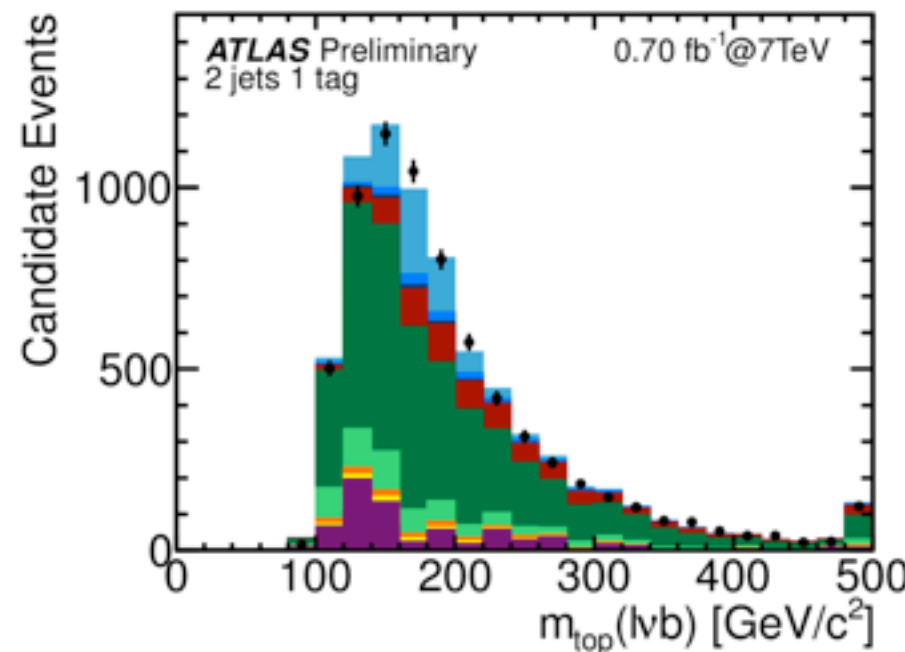
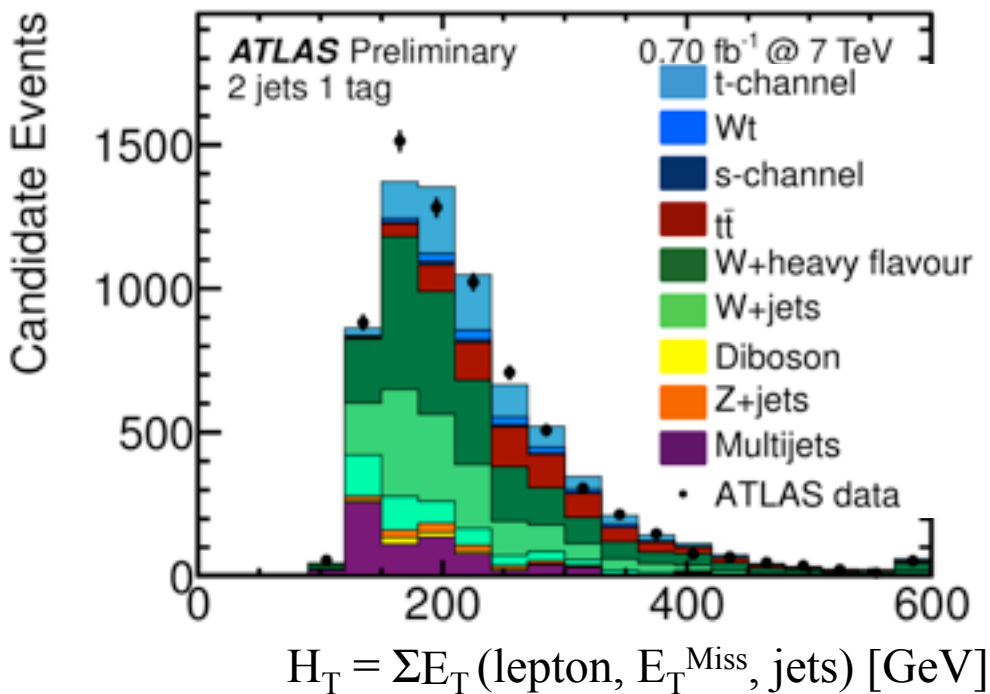
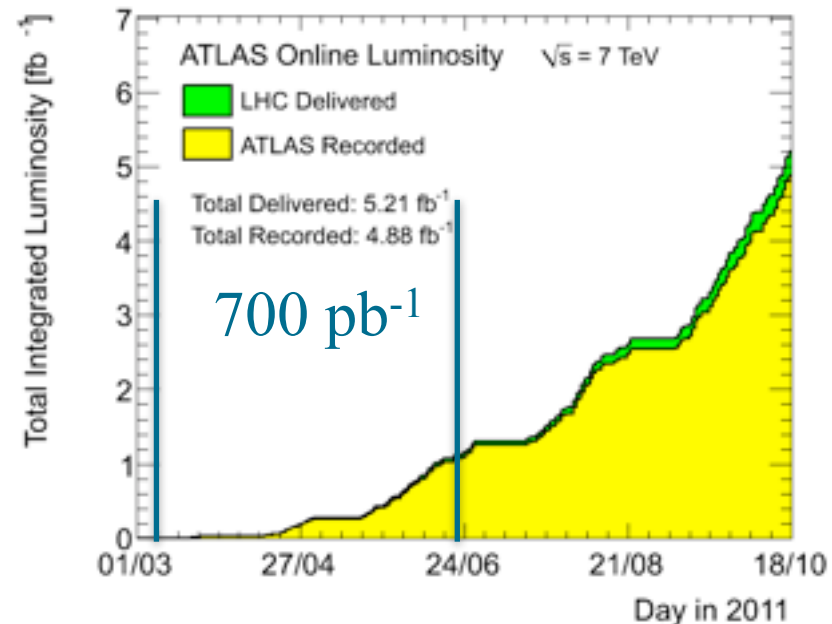
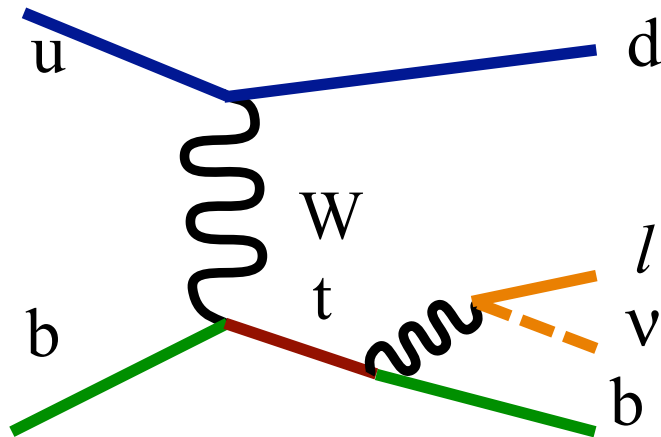
Observed significance: 3.5 σ

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

arXiv:1106.3052 [hep-ex]

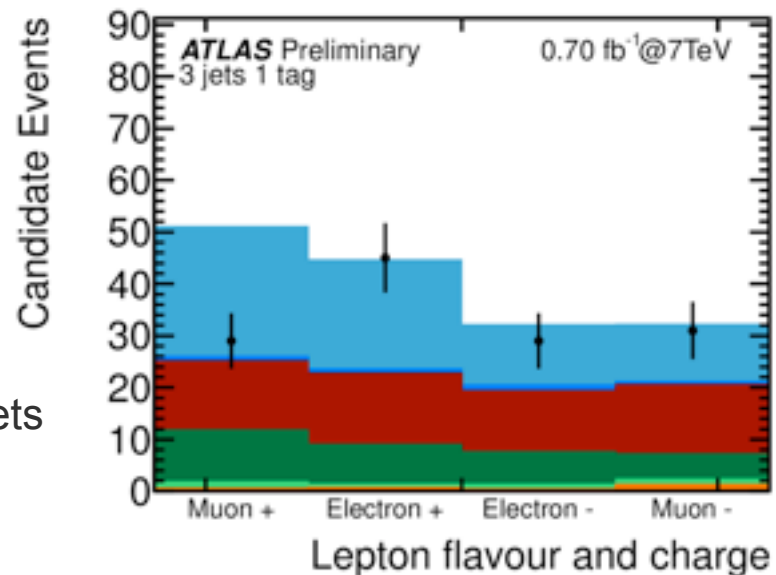
Measurement of t-channel production

- 700 pb⁻¹ of 2011 ATLAS data



Cut-based t-channel analysis

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

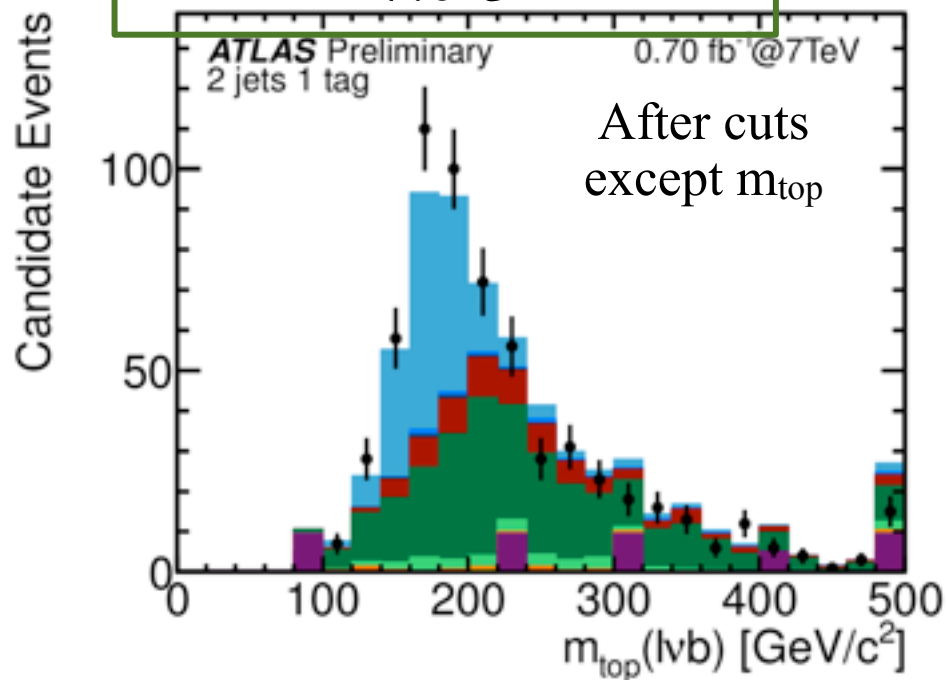
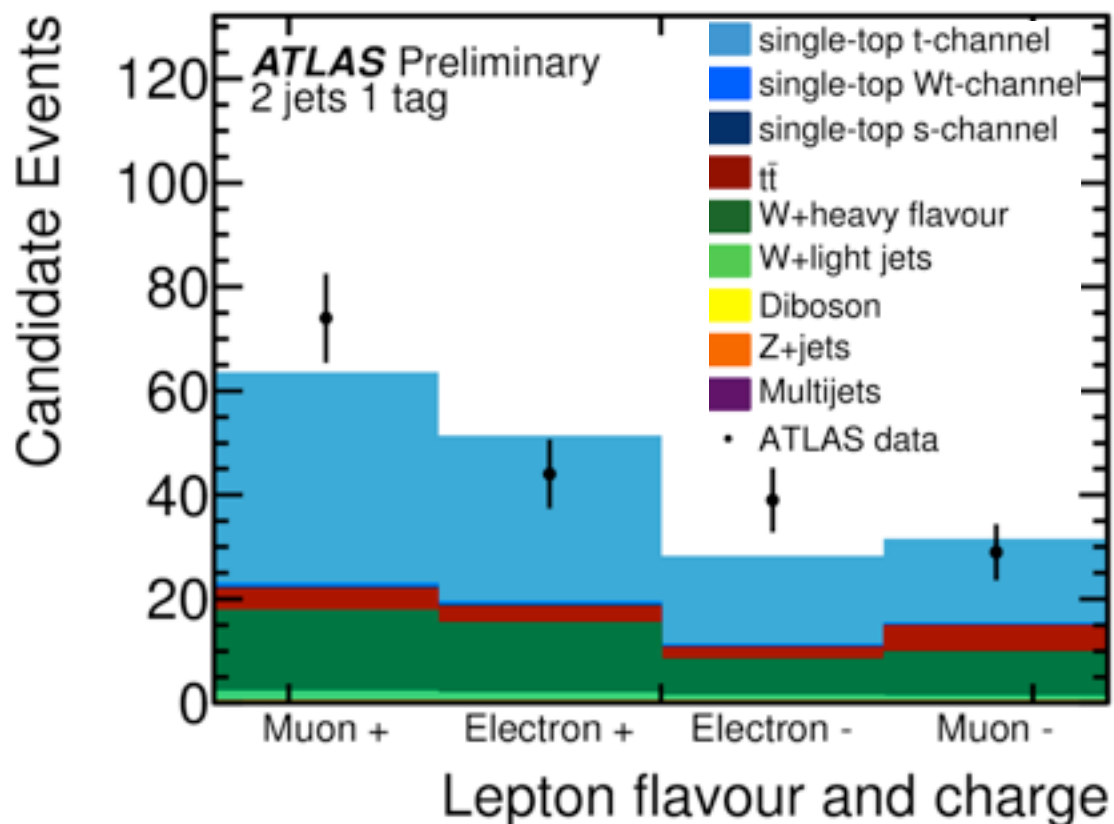


Observed cross section:

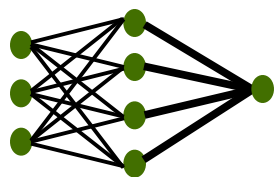
$$\sigma_t = 90^{+32}_{-22} \text{ pb}$$

Observed significance:

$$7.6 \sigma$$



Neural network result

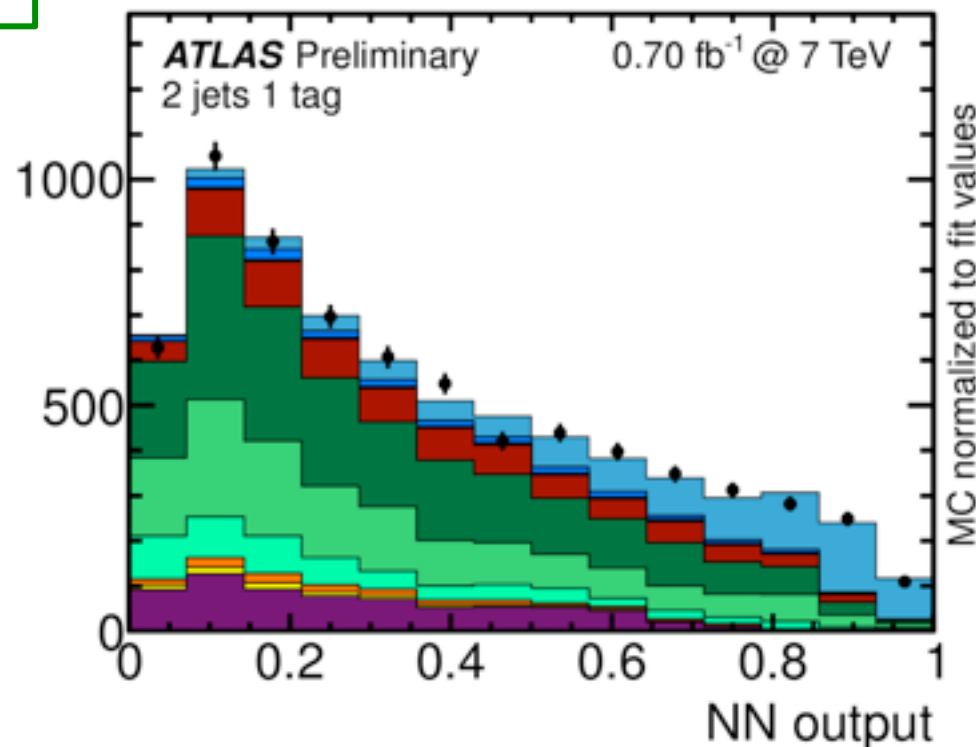
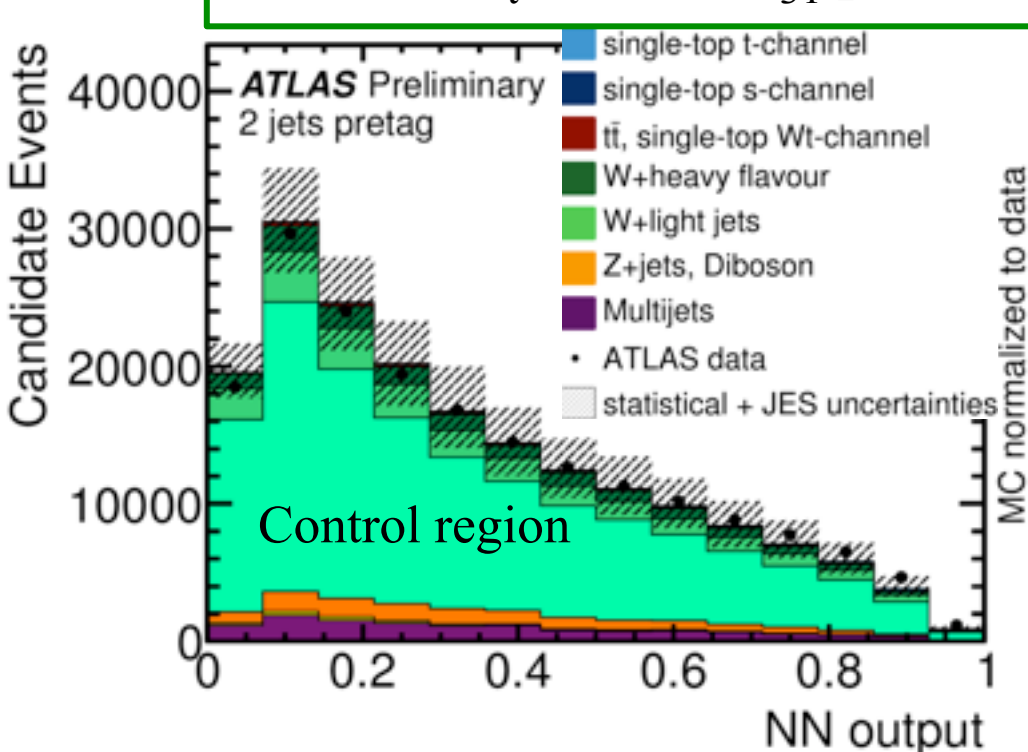


- 22 input variables
- fit shape to signal and W+jets background
- Systematic uncertainties:
 - jet energy scale, b-tagging

- single-top t-channel
- single-top Wt-channel
- single-top s-channel
- $t\bar{t}$
- W+heavy flavour
- W+light jets
- Diboson
- Z+jets
- Multijets
- ATLAS data

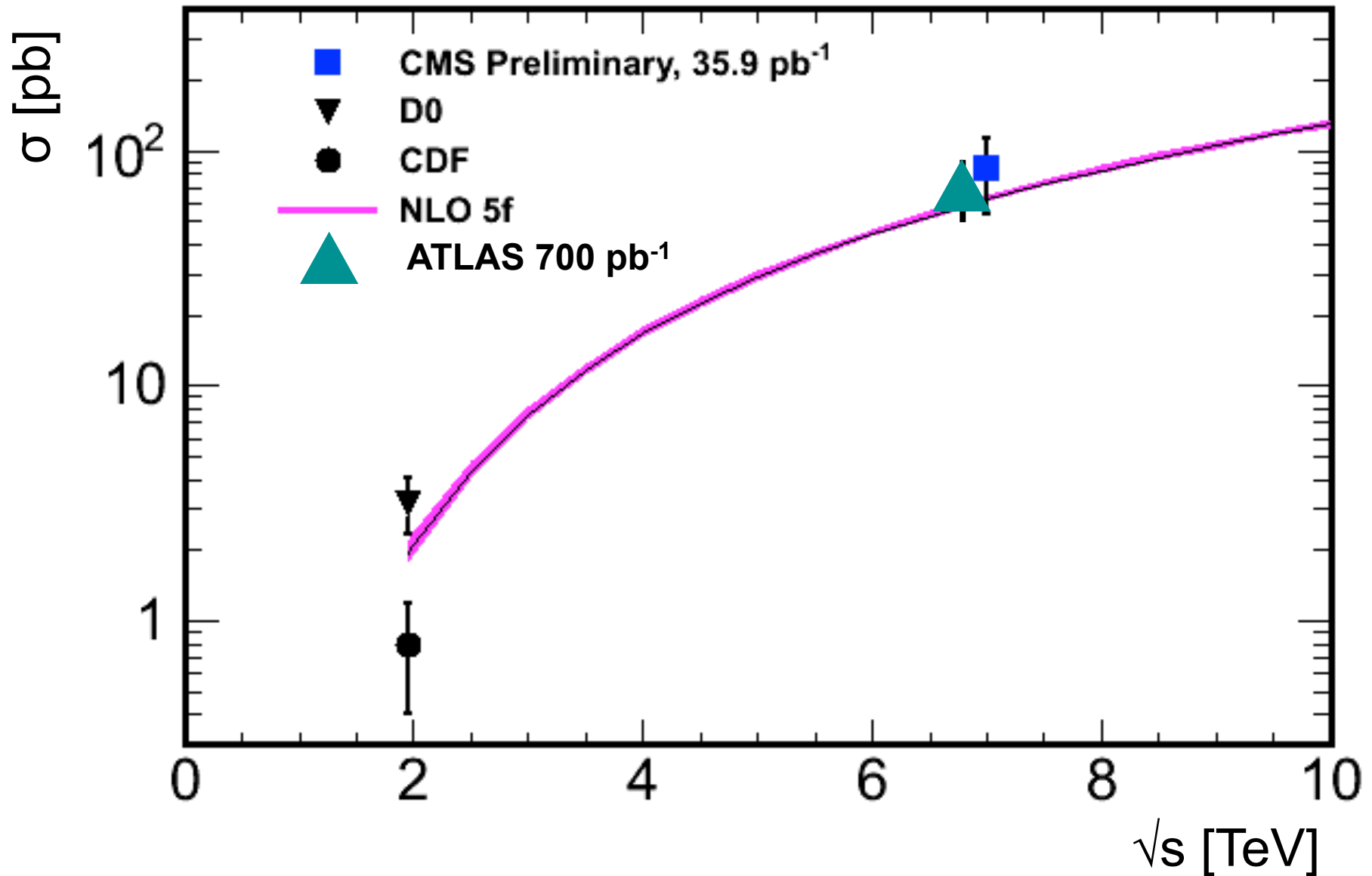
NN: Observed cross section:

$$\sigma_t = 105^{+37}_{-31} \text{ pb}$$





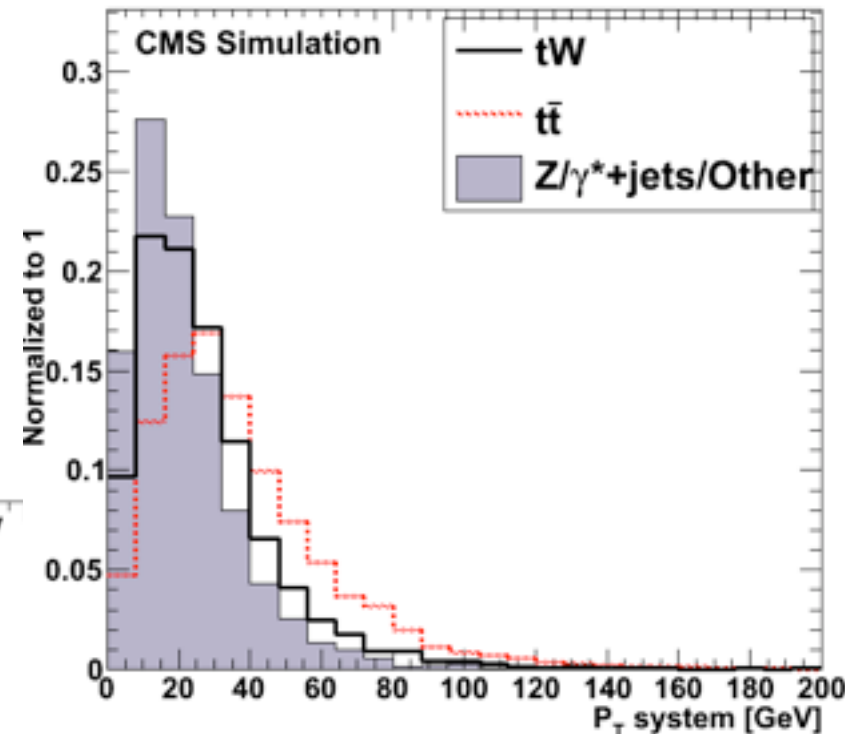
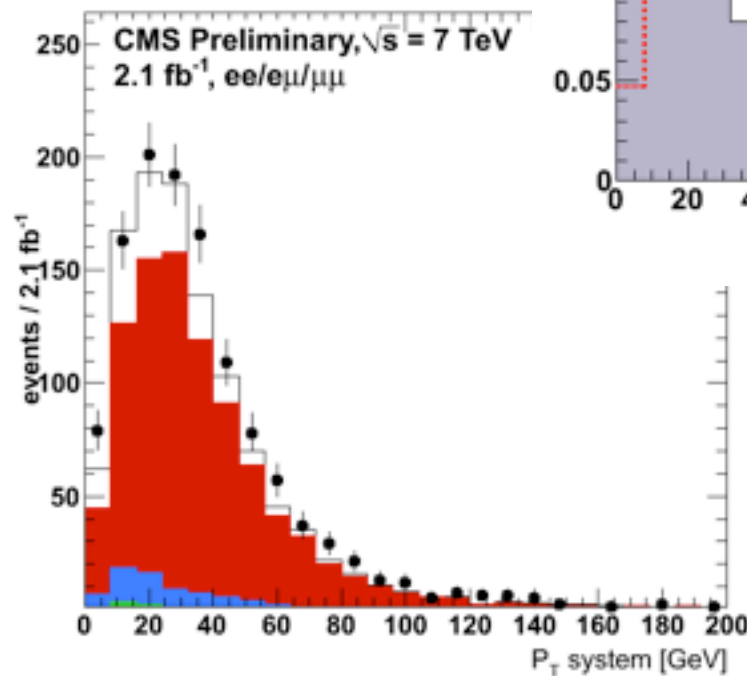
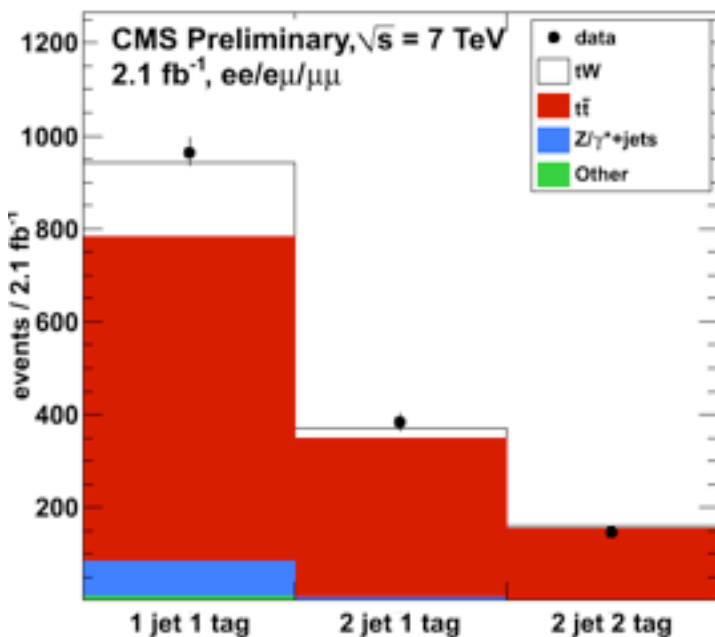
t-channel summary



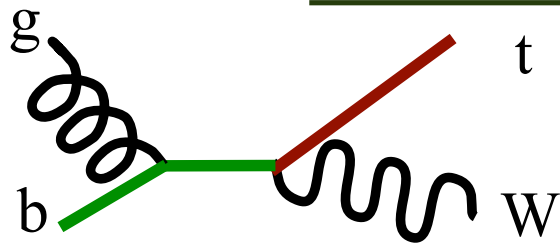
CMS Wt measurement



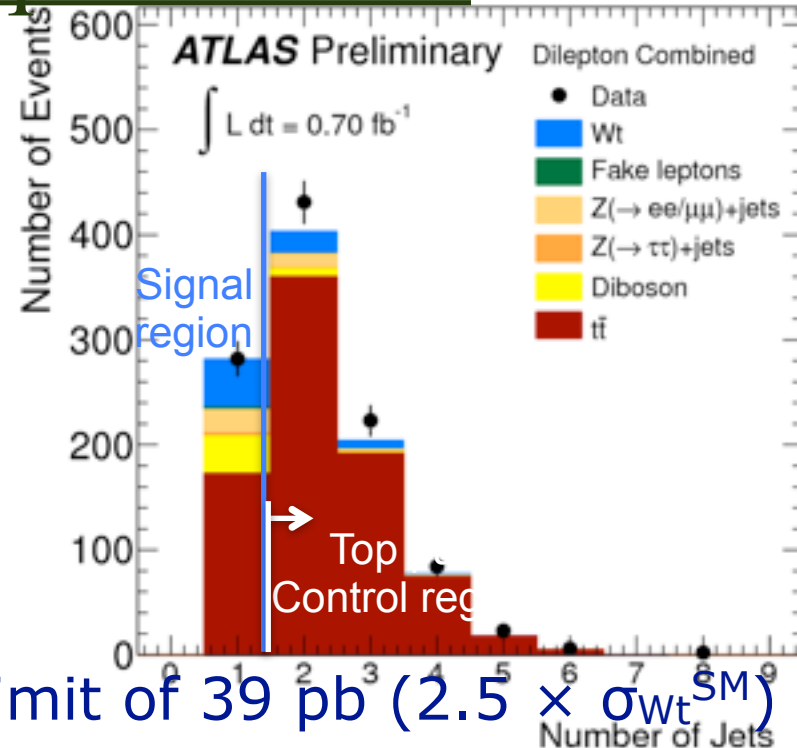
- Never before seen!
- Cut-based analysis using 2.1fb^{-1} of 2011 data
 - Important variable: p_T system
- Cross section from simultaneous fit to Wt and top pairs
- Observed significance 2.7σ



ATLAS Wt associated production



- Search in lepton+jets and di-leptons

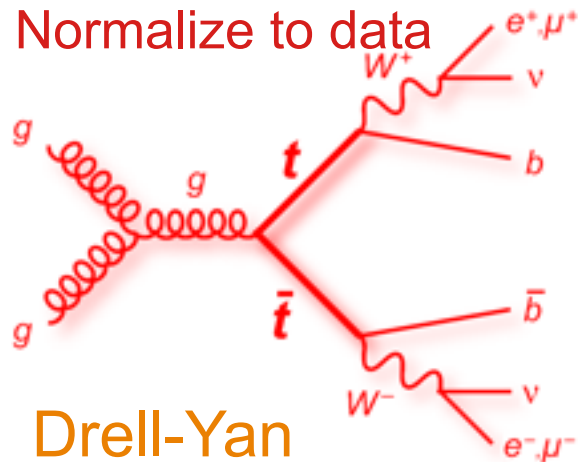


- Set limit of 39 pb ($2.5 \times \sigma_{Wt}^{SM}$)

Dilepton backgrounds:

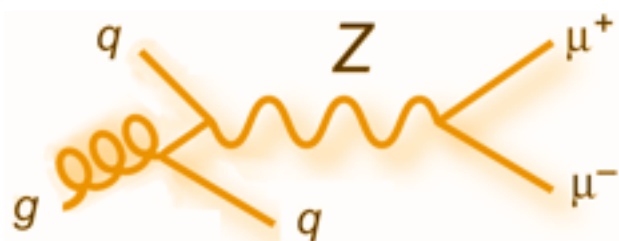
Top quark pairs

- Model using MC@NLO
- Normalize to data

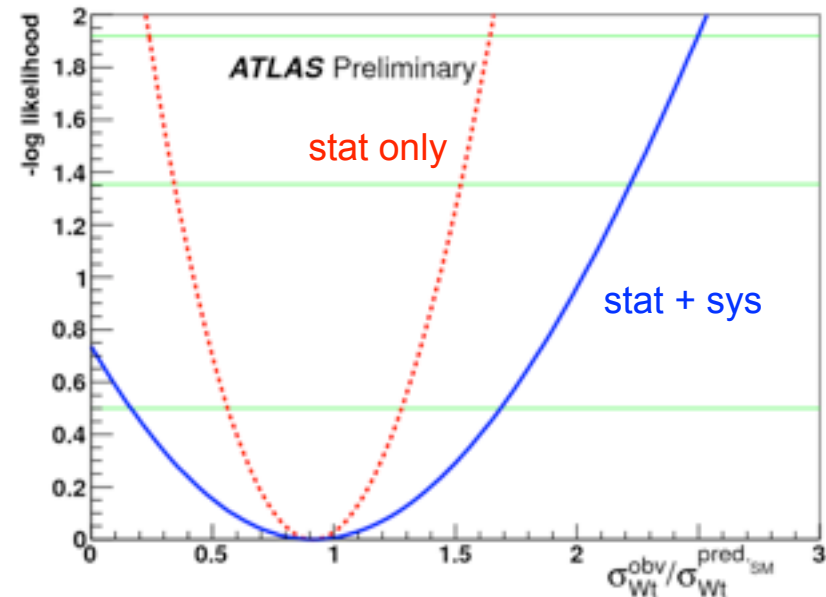


Drell-Yan

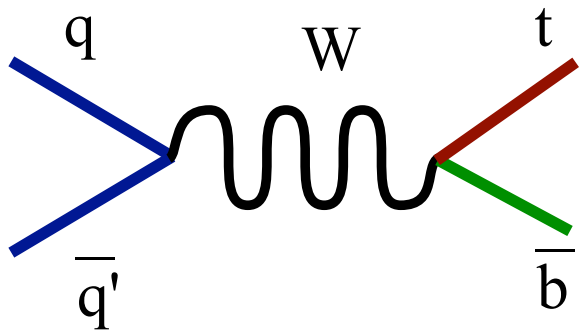
- Model using Alpgen
- Normalize to data



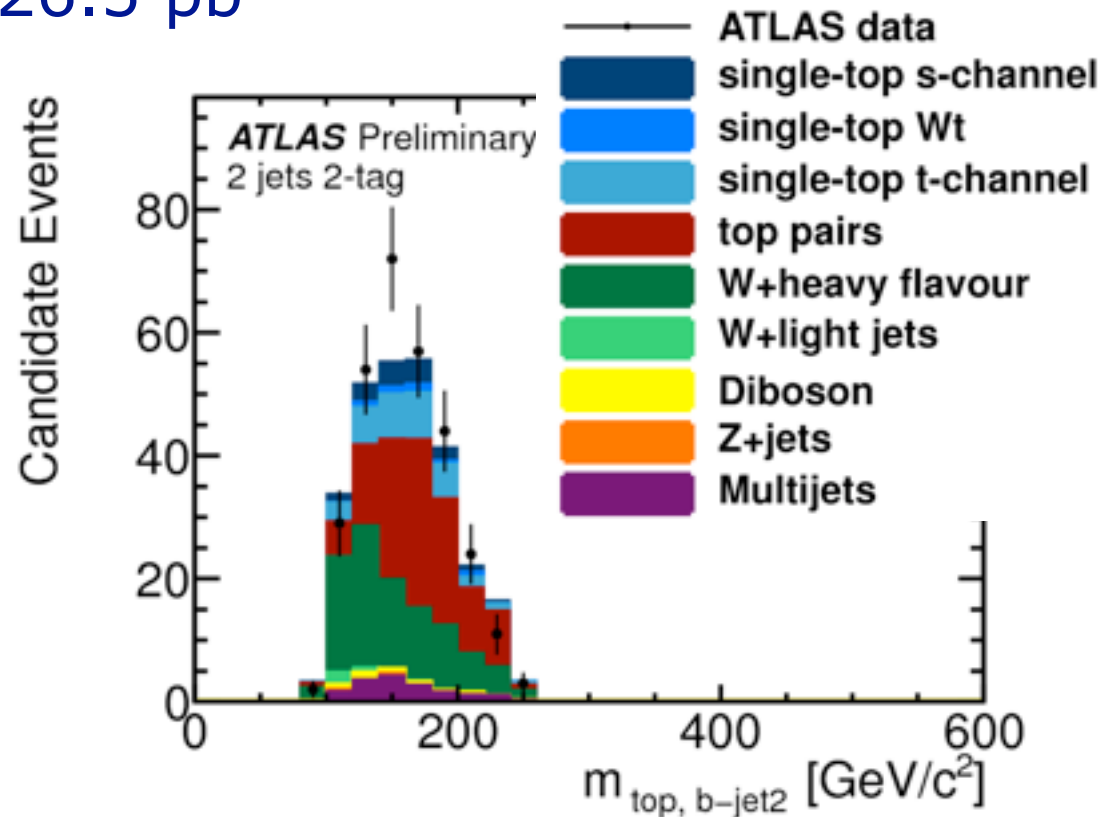
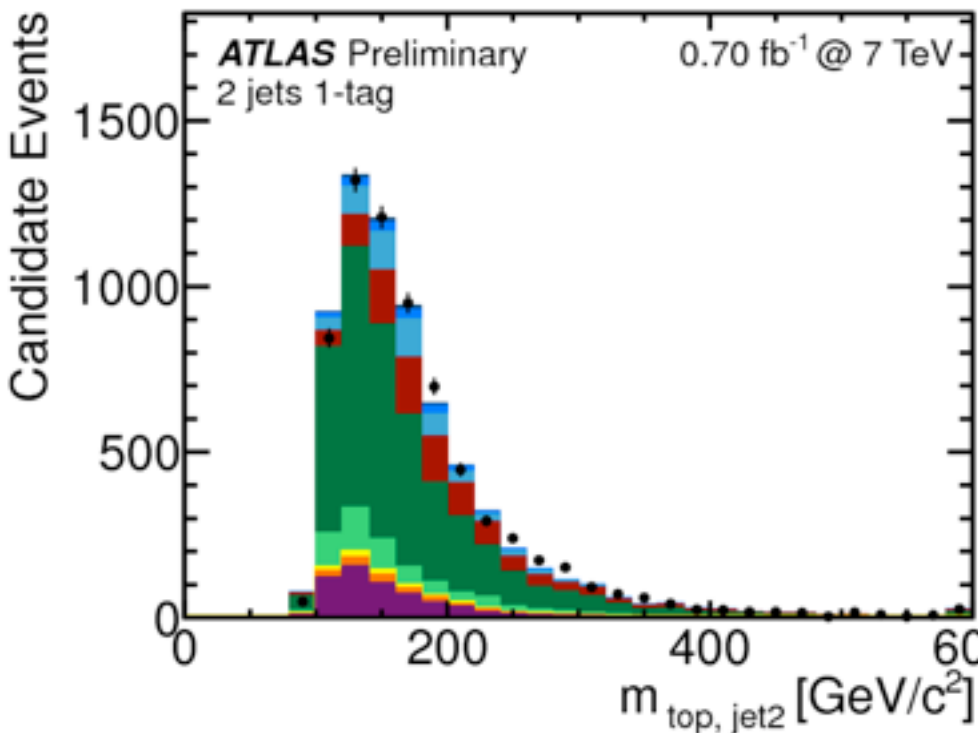
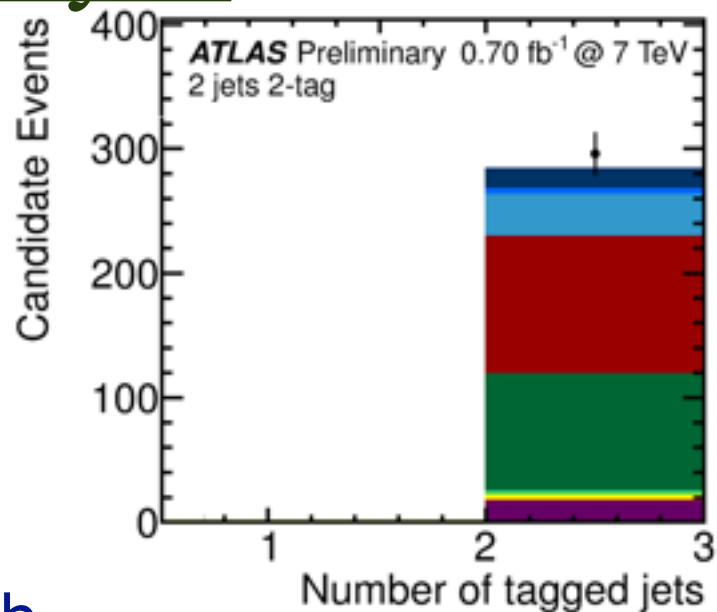
Smaller backgrounds from $Z \rightarrow \tau\tau$, dibosons, W +jets, multijets



s-channel analysis



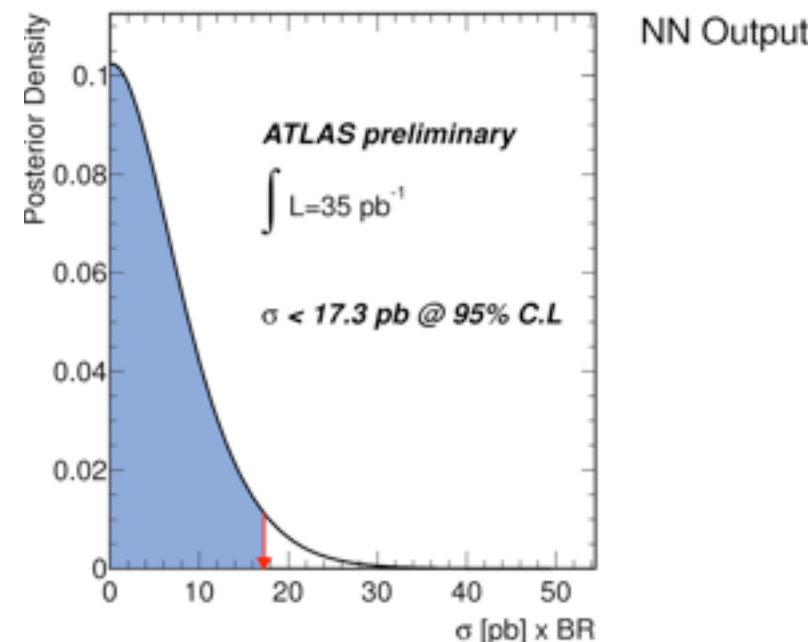
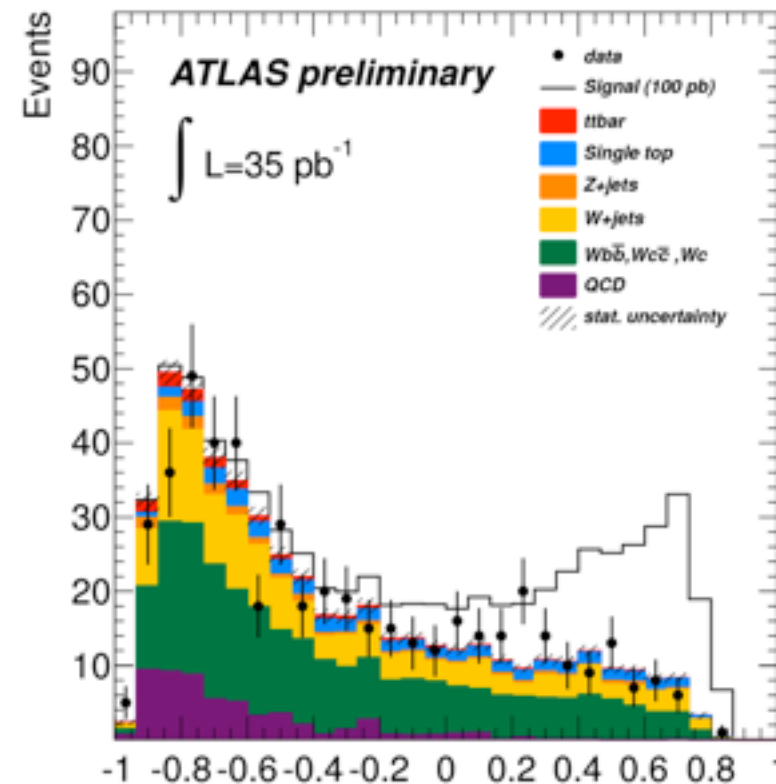
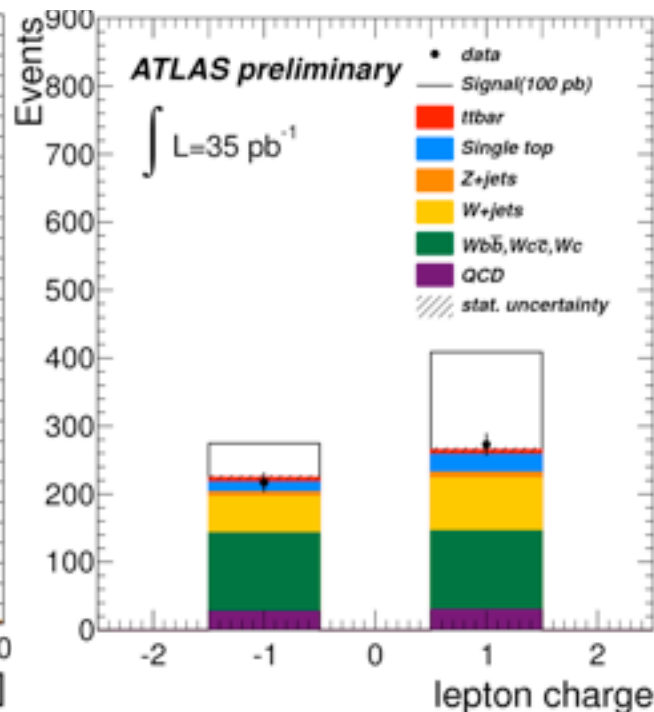
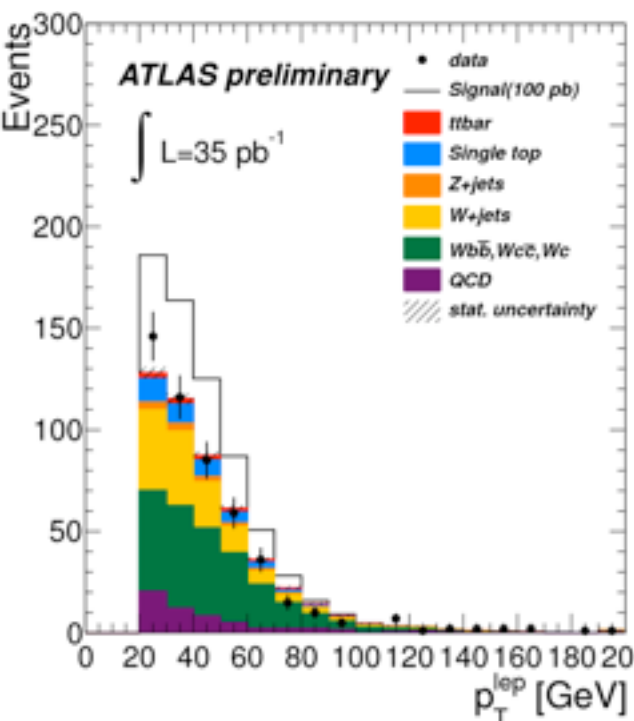
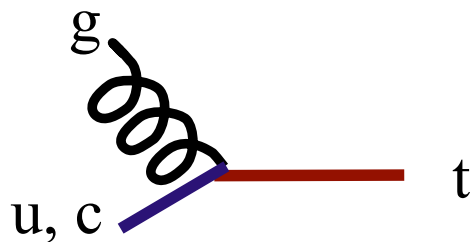
- Search in 700 pb^{-1}
- cut-based selection
- s-channel limit at 95% CL: 26.5 pb



LHC new physics searches

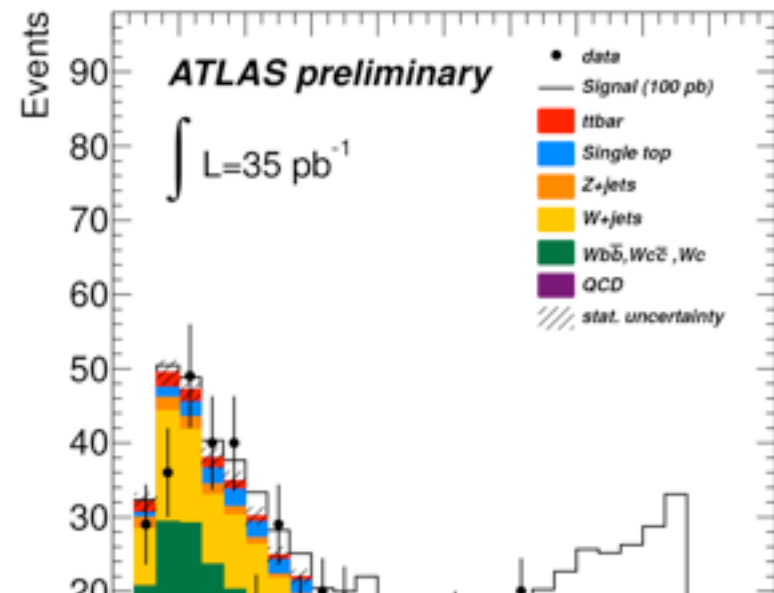
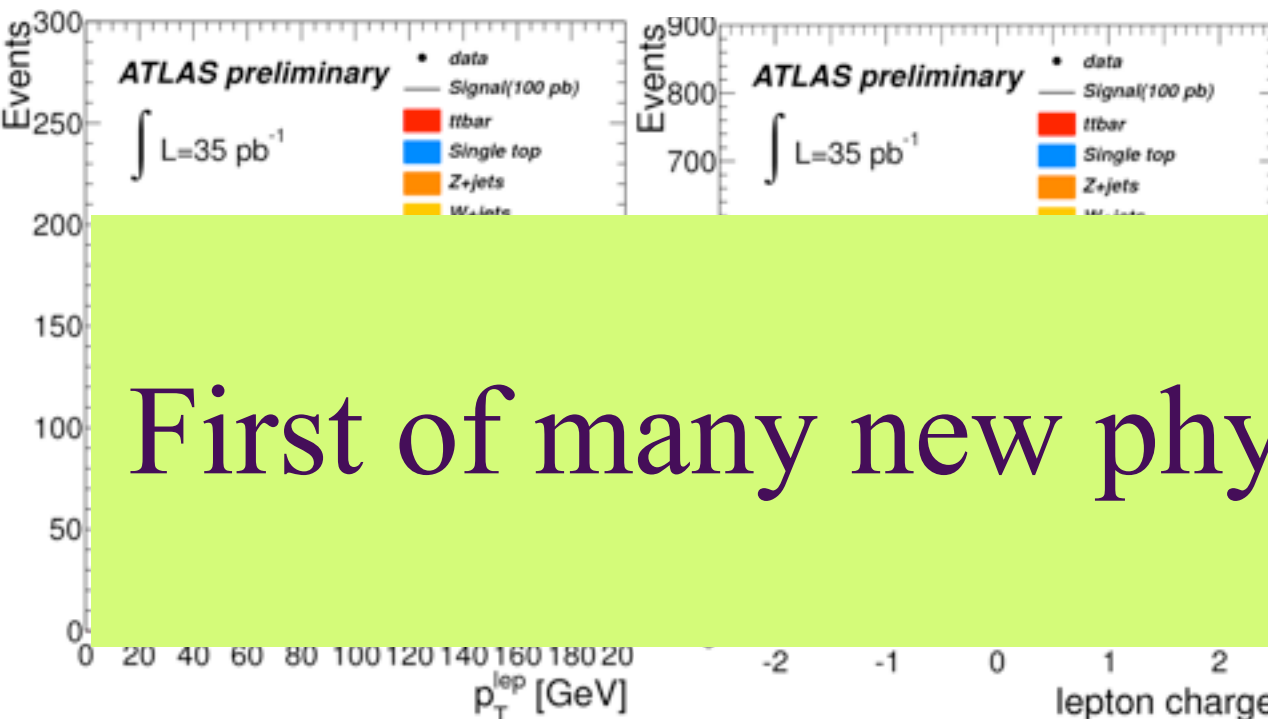
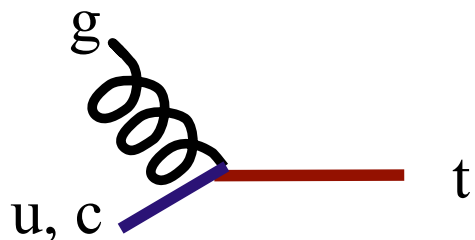
ATLAS FCNC search

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

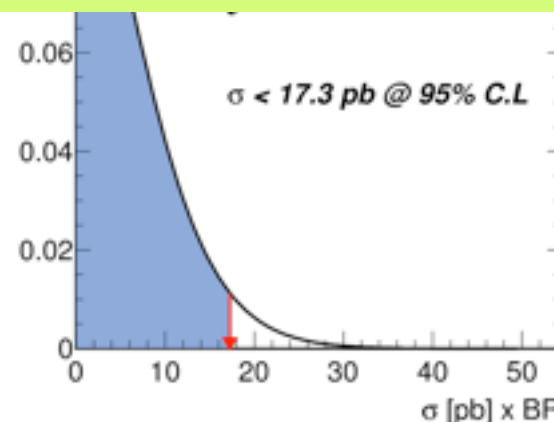


ATLAS FCNC search

- 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

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

- 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, complex phase

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

-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, 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

- 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, complex phase, CKM

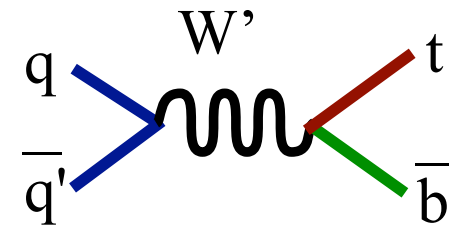
$$\mathcal{L} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} (f_1^L P_L + f_1^R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (f_2^L P_L + f_2^R P_R) t W_\mu^- + h.c.$$

-In single top and in combination with ttbar

- Resonance searches

-New heavy boson W'

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



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

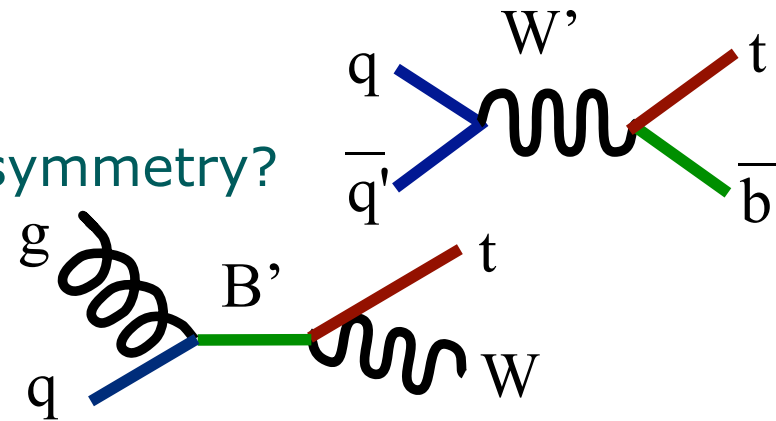
- Resonance searches

-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



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

- Resonance searches

-New heavy boson W'

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

-Fourth generation quarks

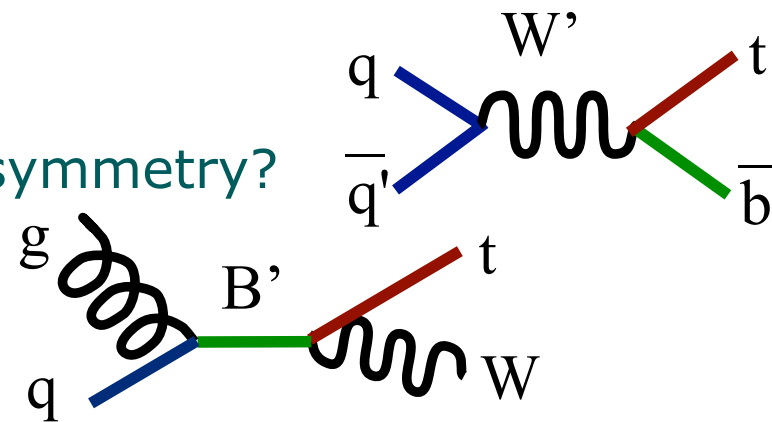
- ▶ B' or T' decaying to single top

- New particles produced together with single top

-Charged Higgs

- If discoveries are made elsewhere first?

-Measure coupling to top



China in ATLAS single top

- Shandong University
 - Cunfeng Feng with Jin Wang, Xiaohu Sun, Peng Ge

- Also at other institutions

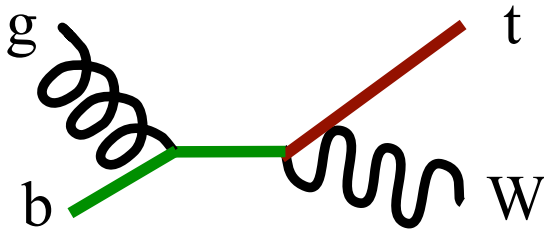
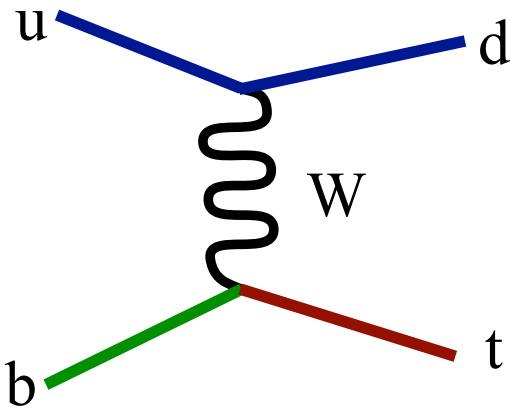
- Jin Wang and Xiaohu Sun also at Grenoble

- ▶t-channel and FCNC

- Peng Ge also at MSU

- ▶Wt and B' search

- Huaqiao Zhang at MSU



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 Wt and s-channel
 - Next: Wt 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