Single top quark physics at the Tevatron and the LHC

Reinhard Schwienhorst

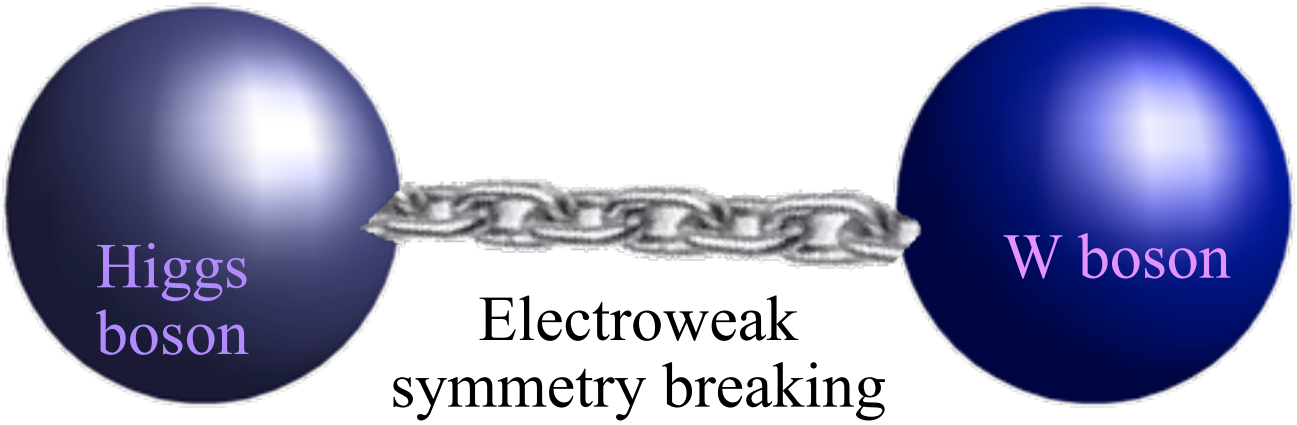
MICHIGAN STATE UNIVERSITY

Elementary Particle Physics Seminar, Shandong University, November 2011

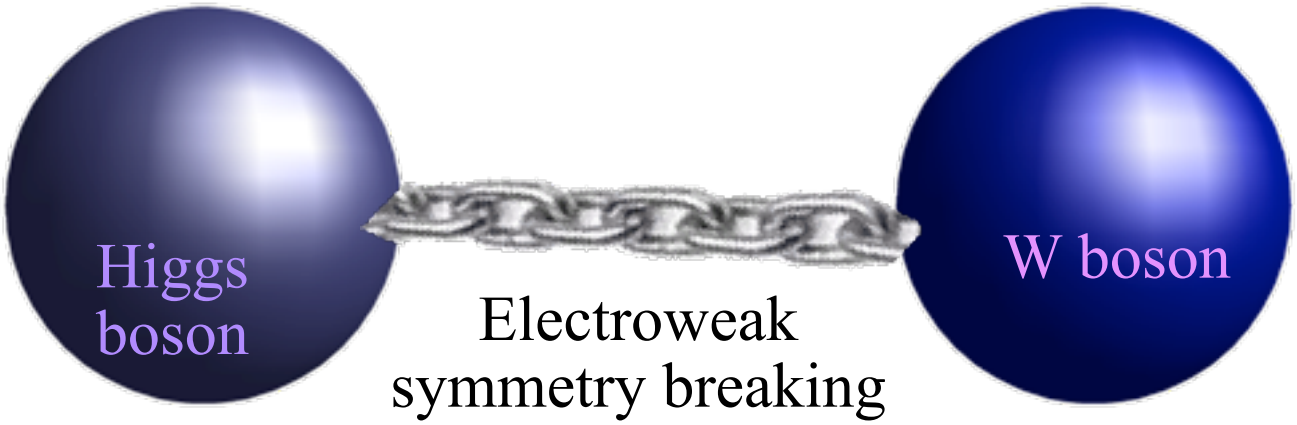
Outline

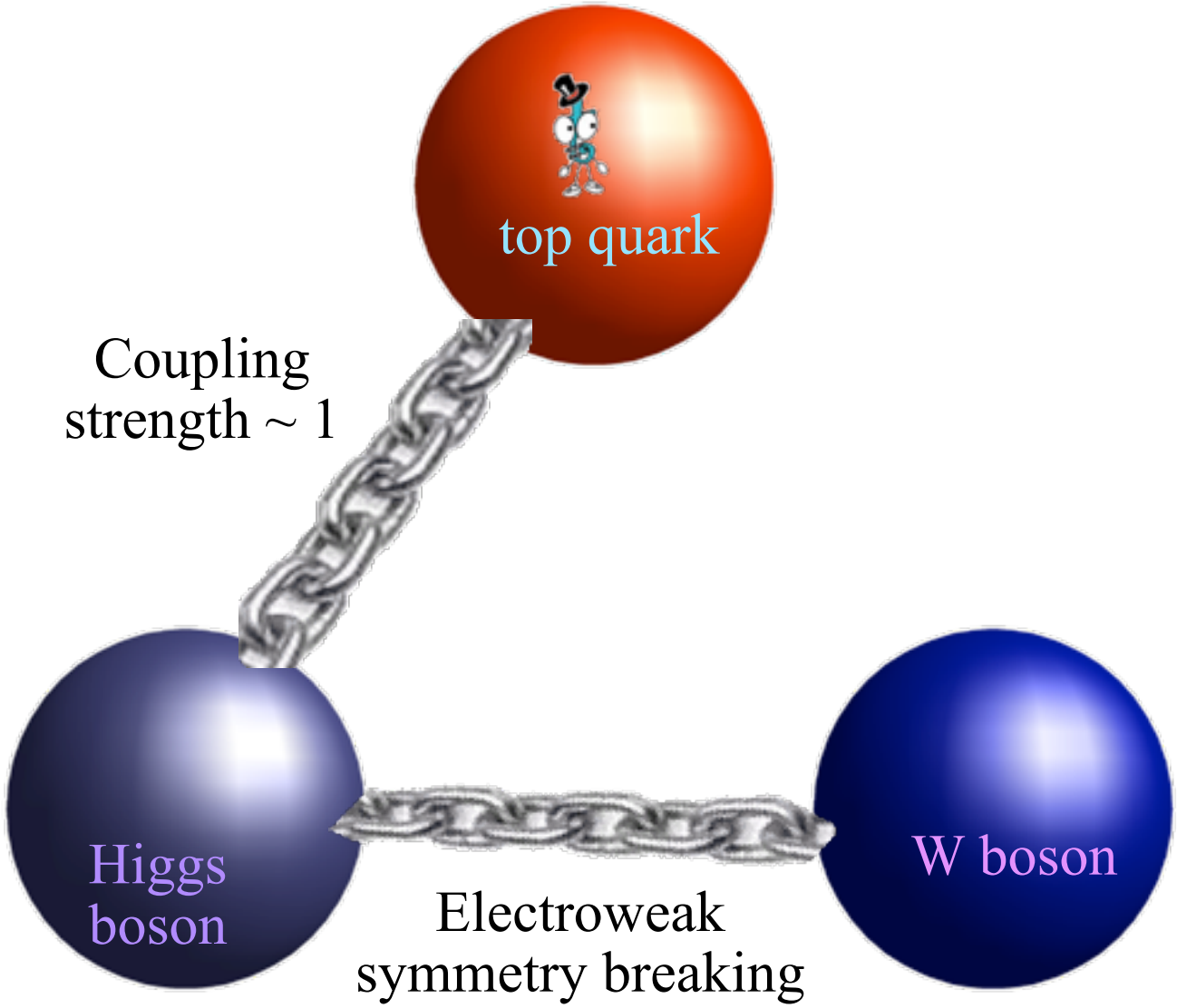
- Introduction
- Tevatron
  - SM
  - New physics
- LHC
  - SM
  - New physics
- Conclusions

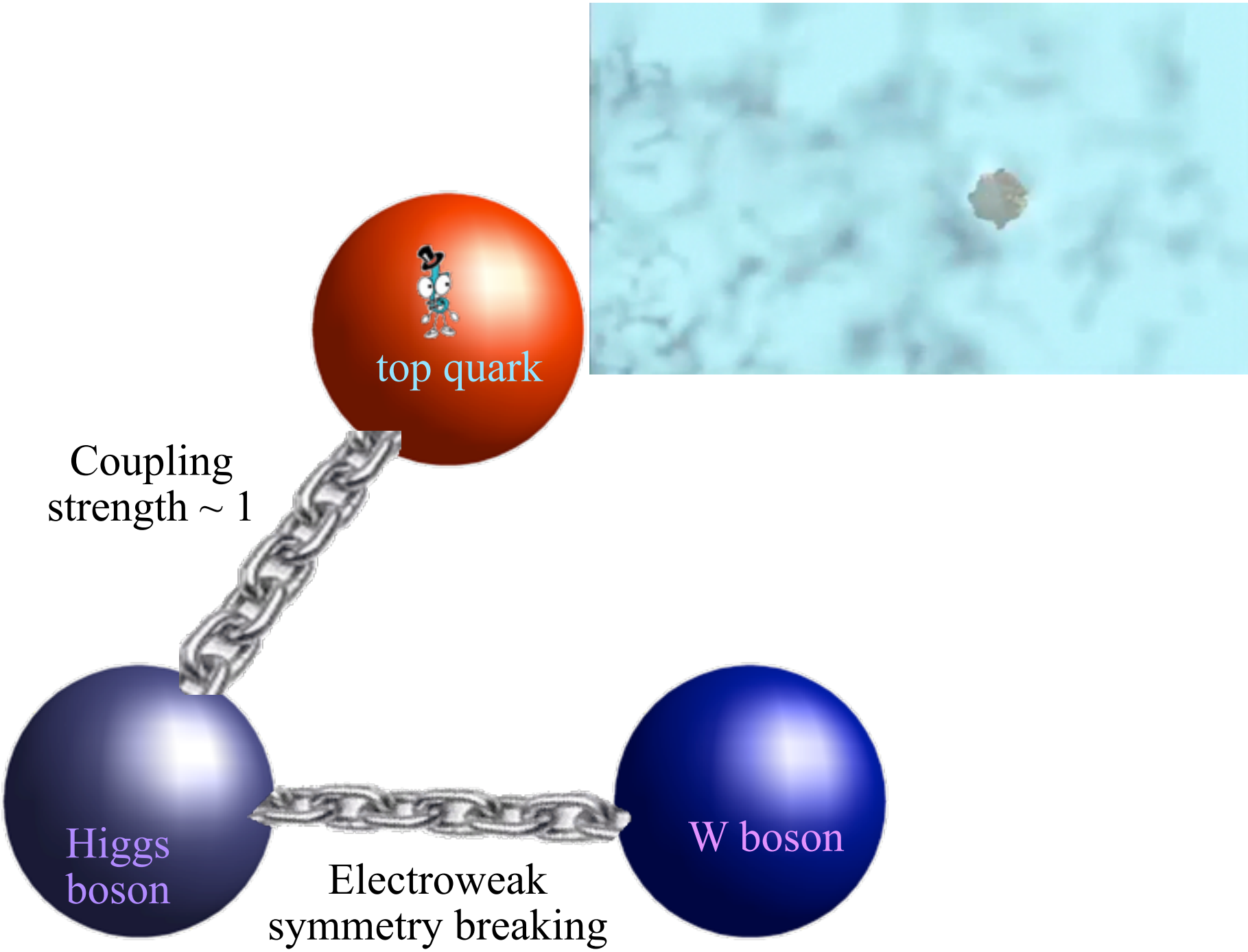
Higgs field

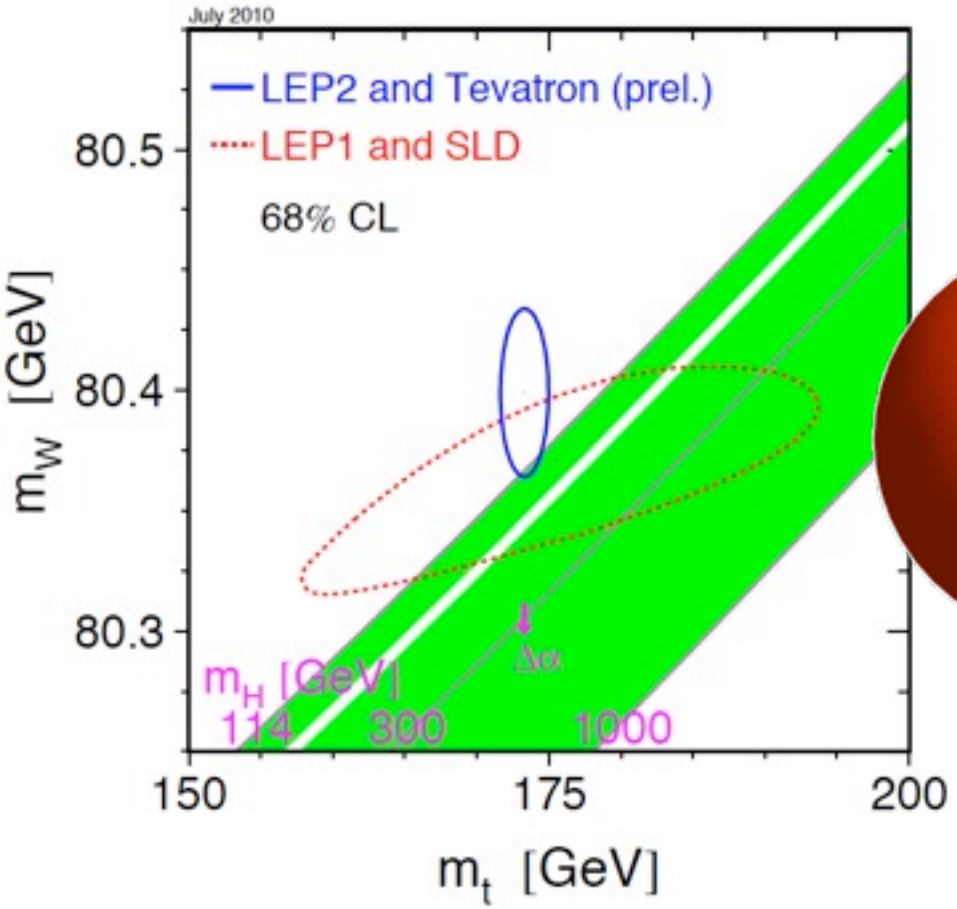


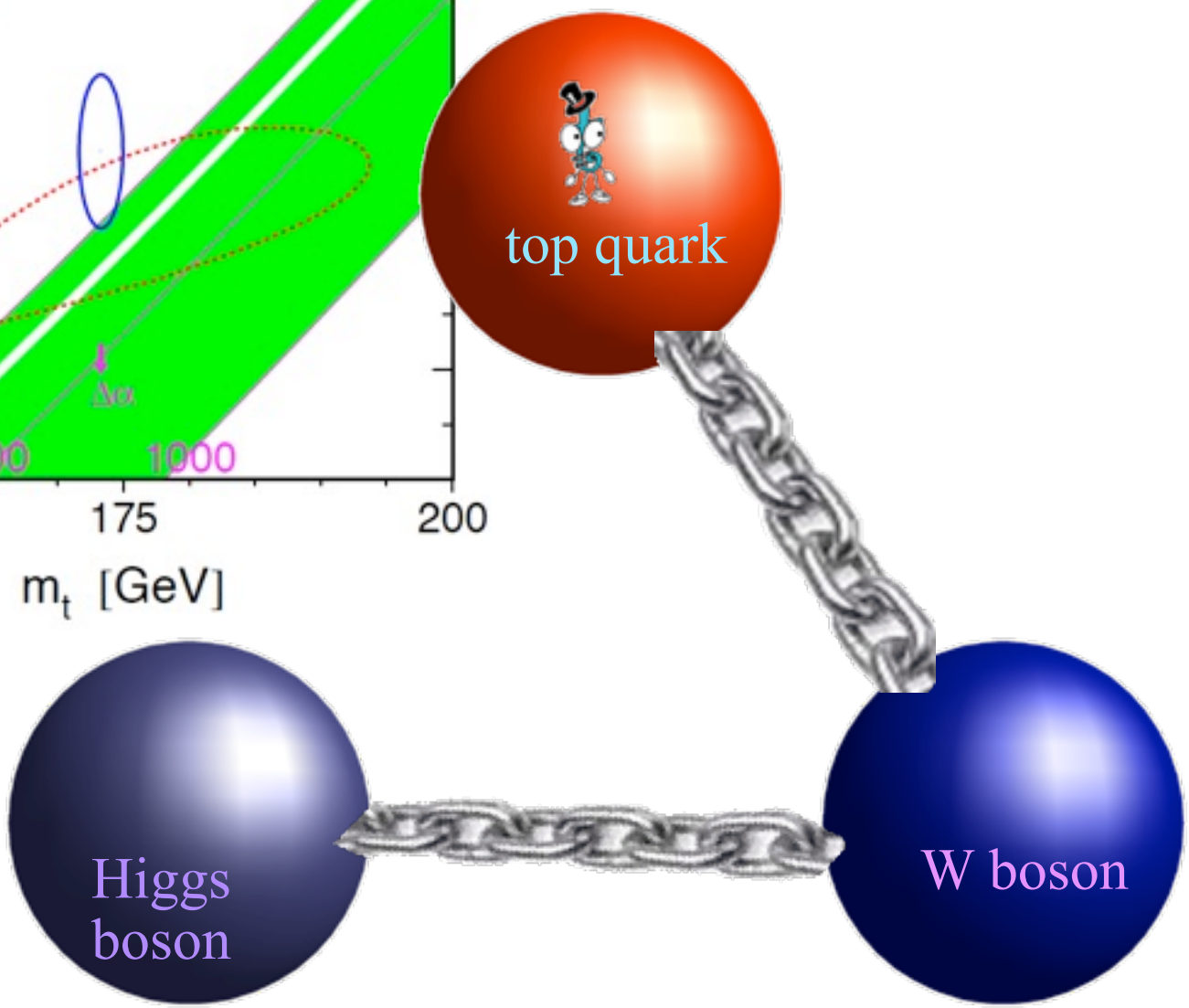
Higgs field



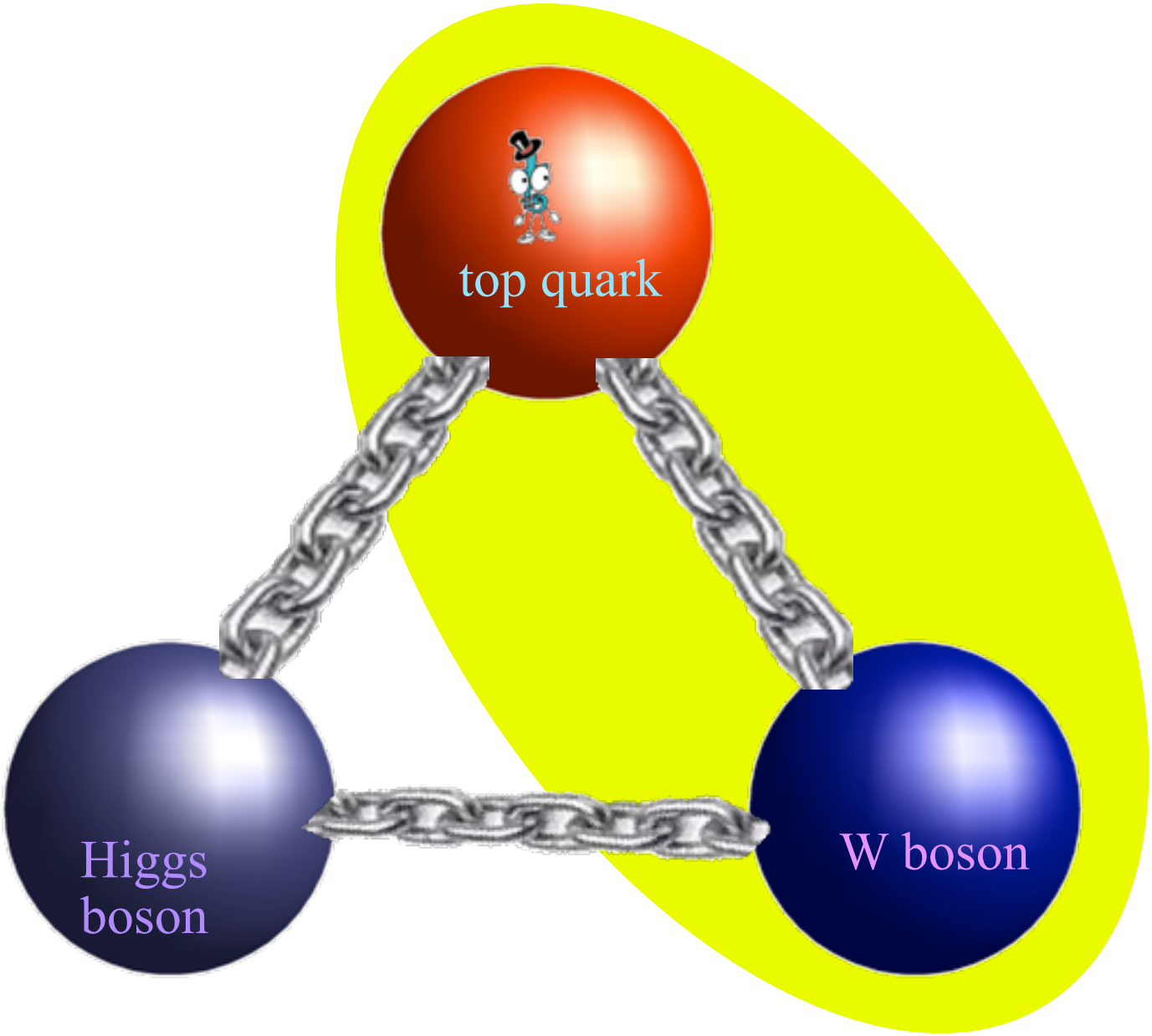

top quark
Coupling
strength ~ 1
Higgs
boson
Electroweak
symmetry breaking
W boson


top quark
Coupling
strength ~ 1
Higgs
boson
Electroweak
symmetry breaking
W boson

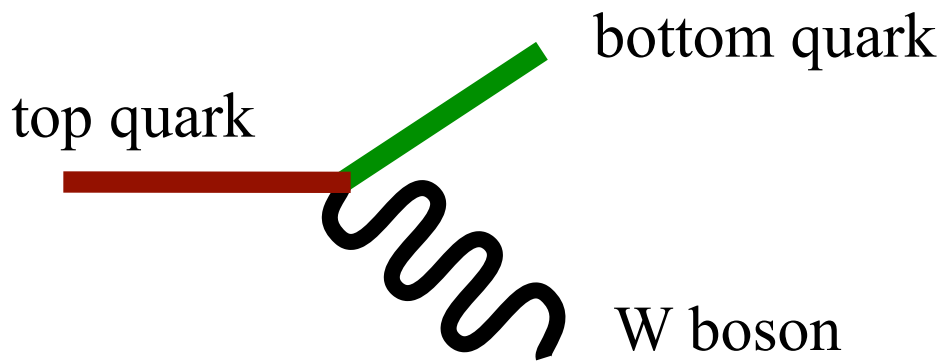

July 2010
LEP2 and Tevatron (prel.)
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
m_H [GeV]
114
300
1000
$\Delta\alpha$
150
175
200
m_t [GeV]

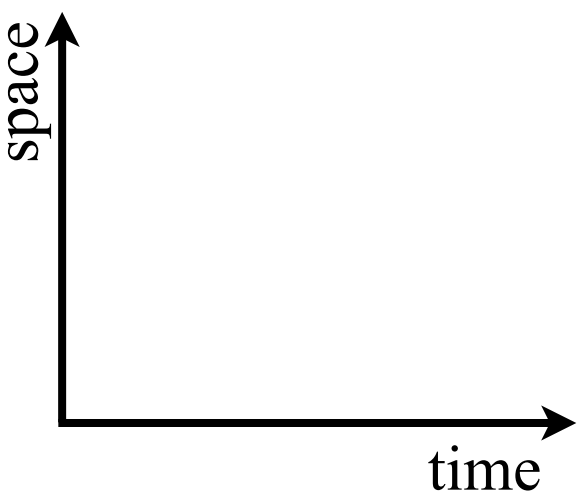

top quark
Higgs boson
W boson

Key to electroweak symmetry breaking

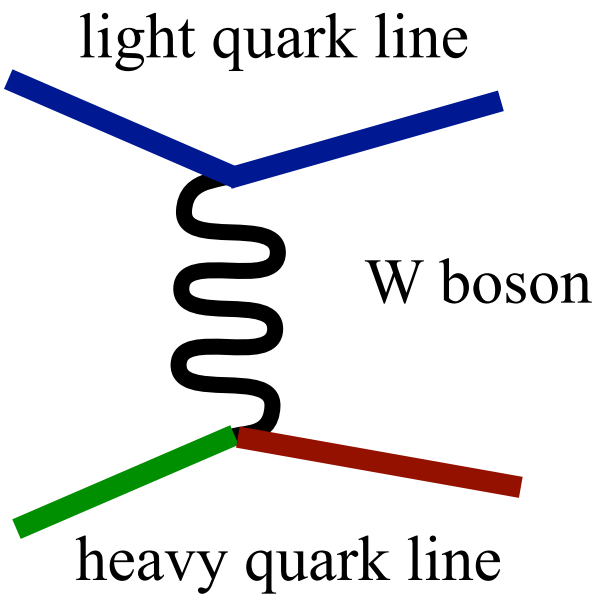


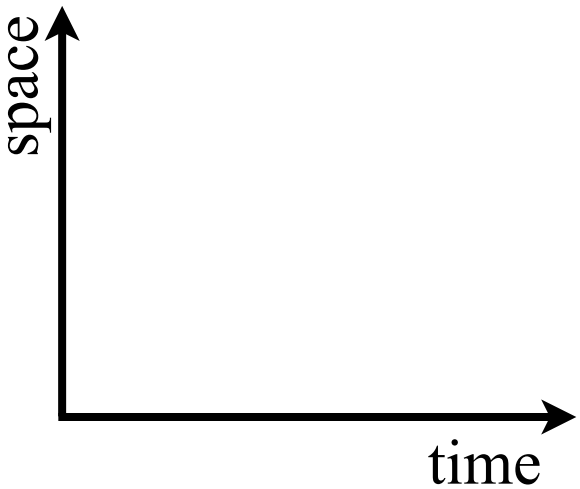
Top quark decay



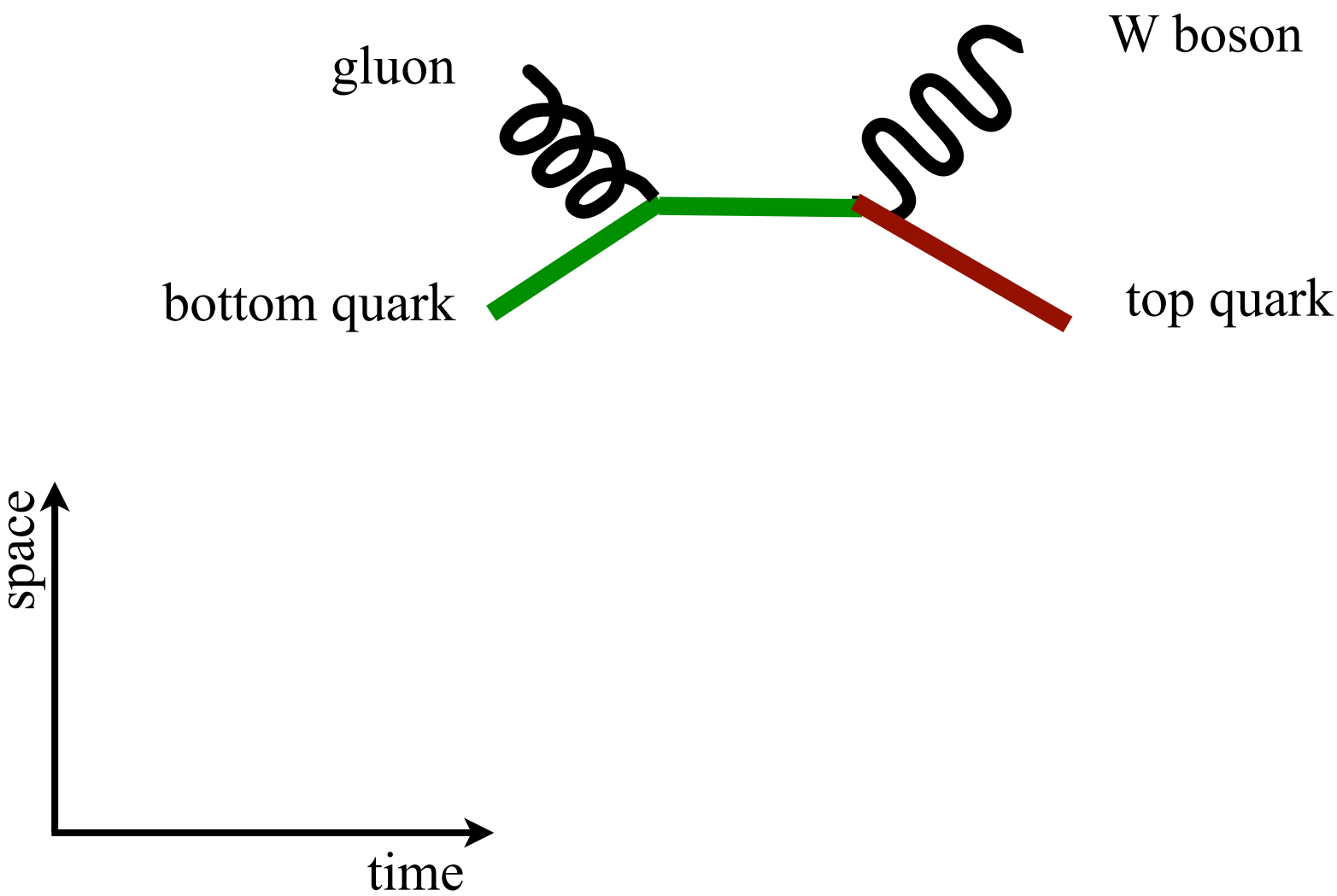


t-channel single top quark production

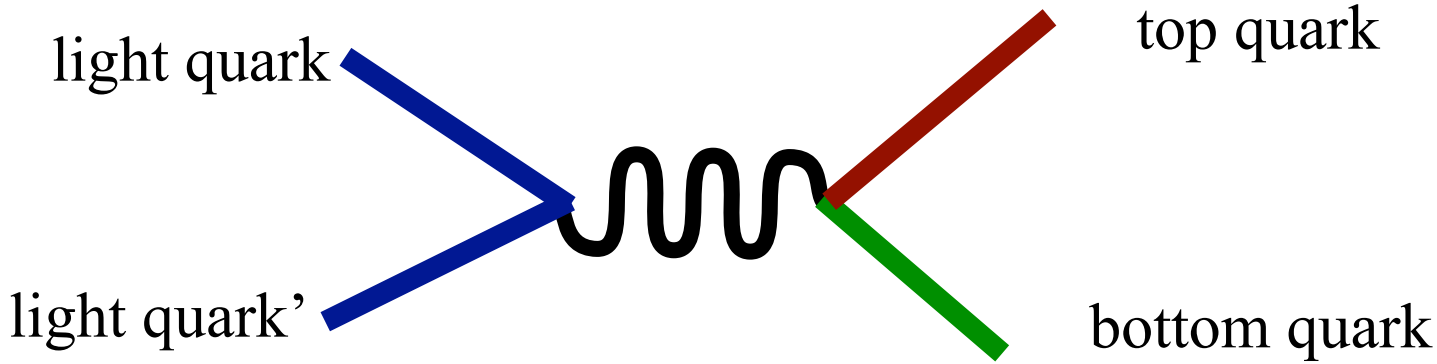


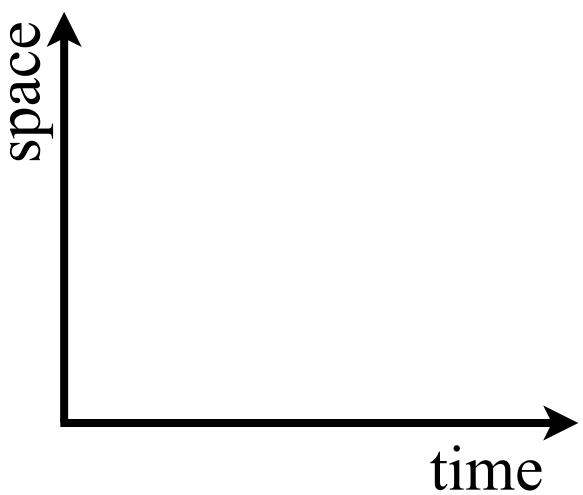


Wt associated production

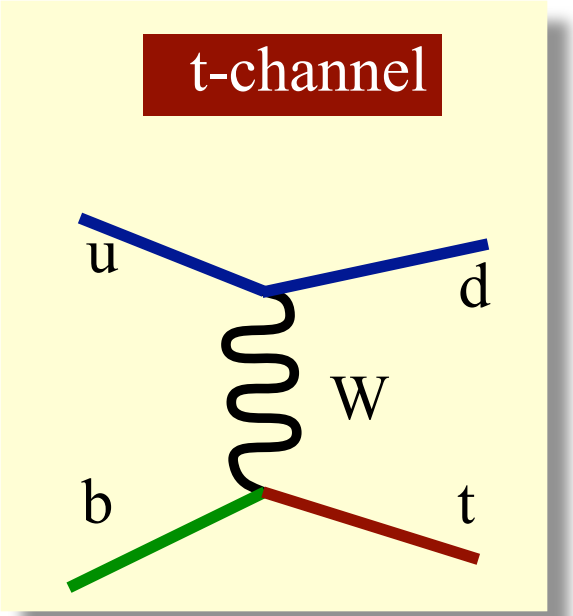


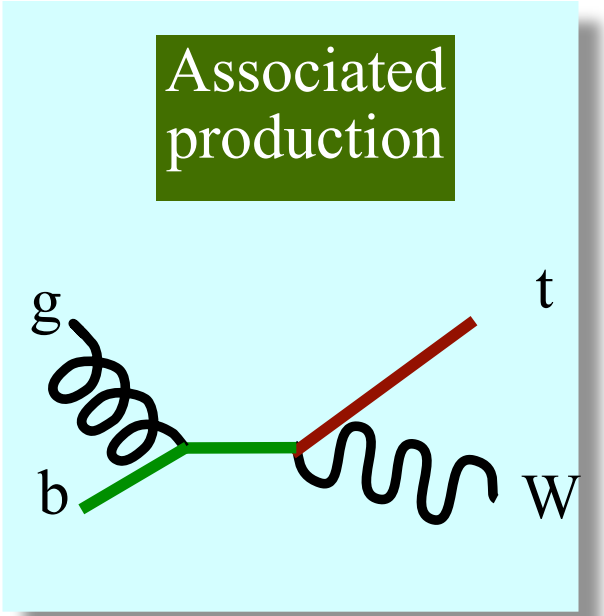
s-channel single top production

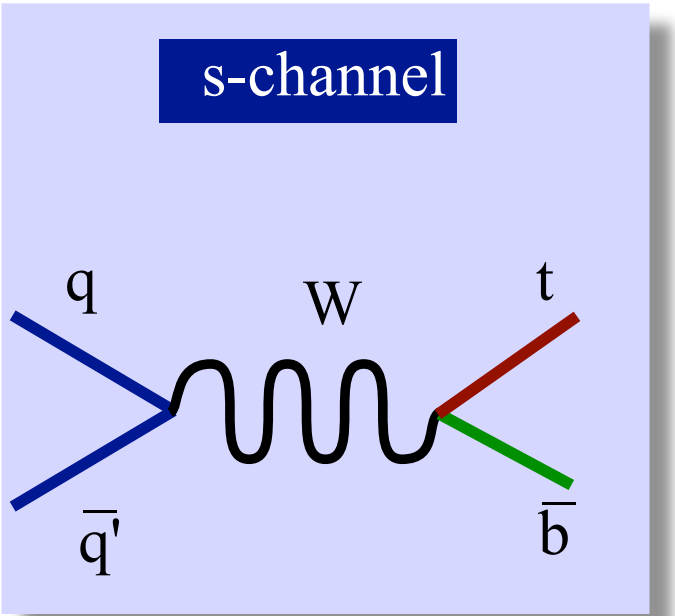


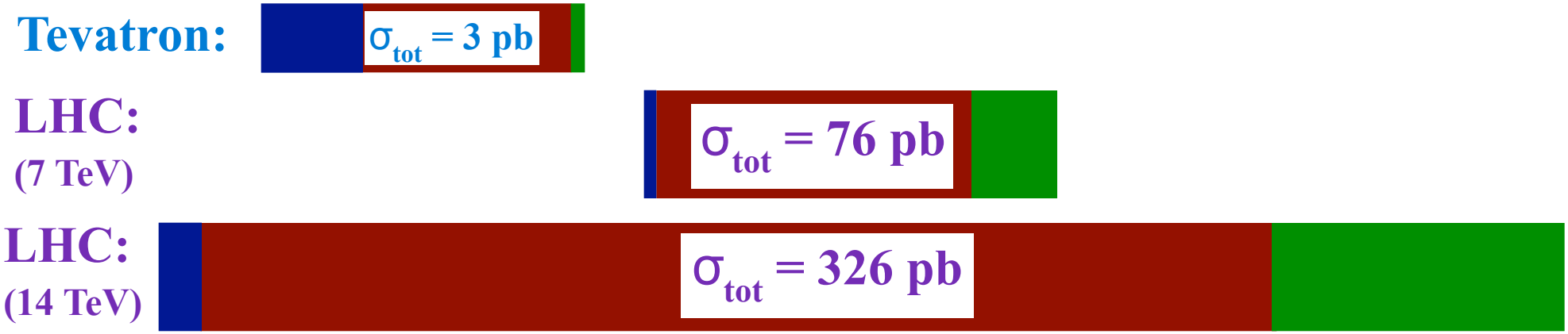


SM single top quark production







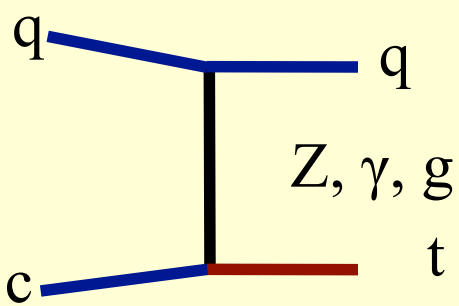


SM tasks:

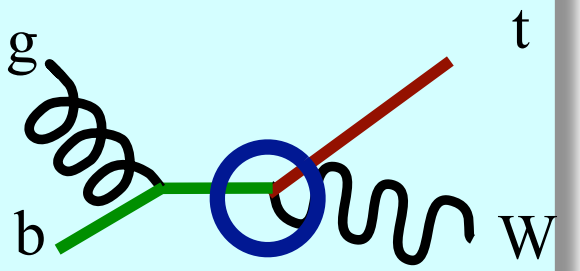
- Weak interaction of bare quarks
- Measure total cross section → CKM matrix element $|V_{tb}|$
- Top polarization, PDFs

New physics in single top

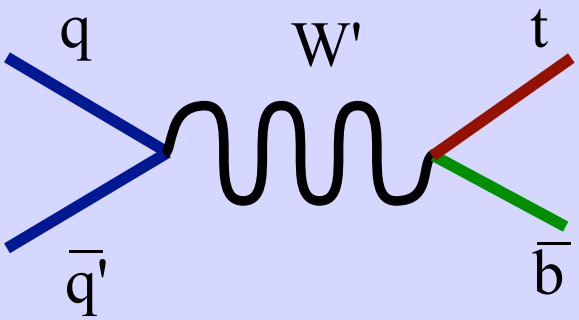
New interactions: FCNC



New coupling: modified Wtb coupling or anomalous CKM matrix



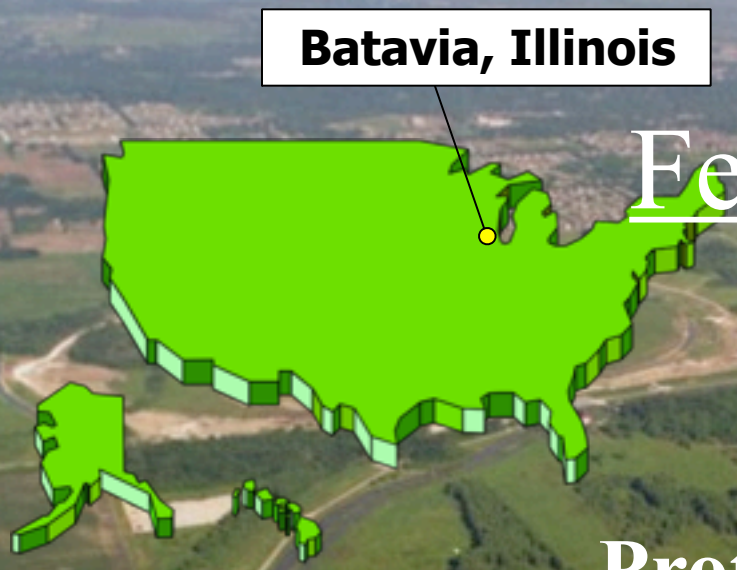
New particles: heavy boson or charged Higgs or T′ or B′



New physics tasks:

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

Experimental setup: Fermilab Tevatron in Run II



Proton-antiproton collider

CM energy 1.96 TeV

→ Energy frontier - until a year ago

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

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

→ Proton-antiproton luminosity frontier

Fermilab single top history

Publication history

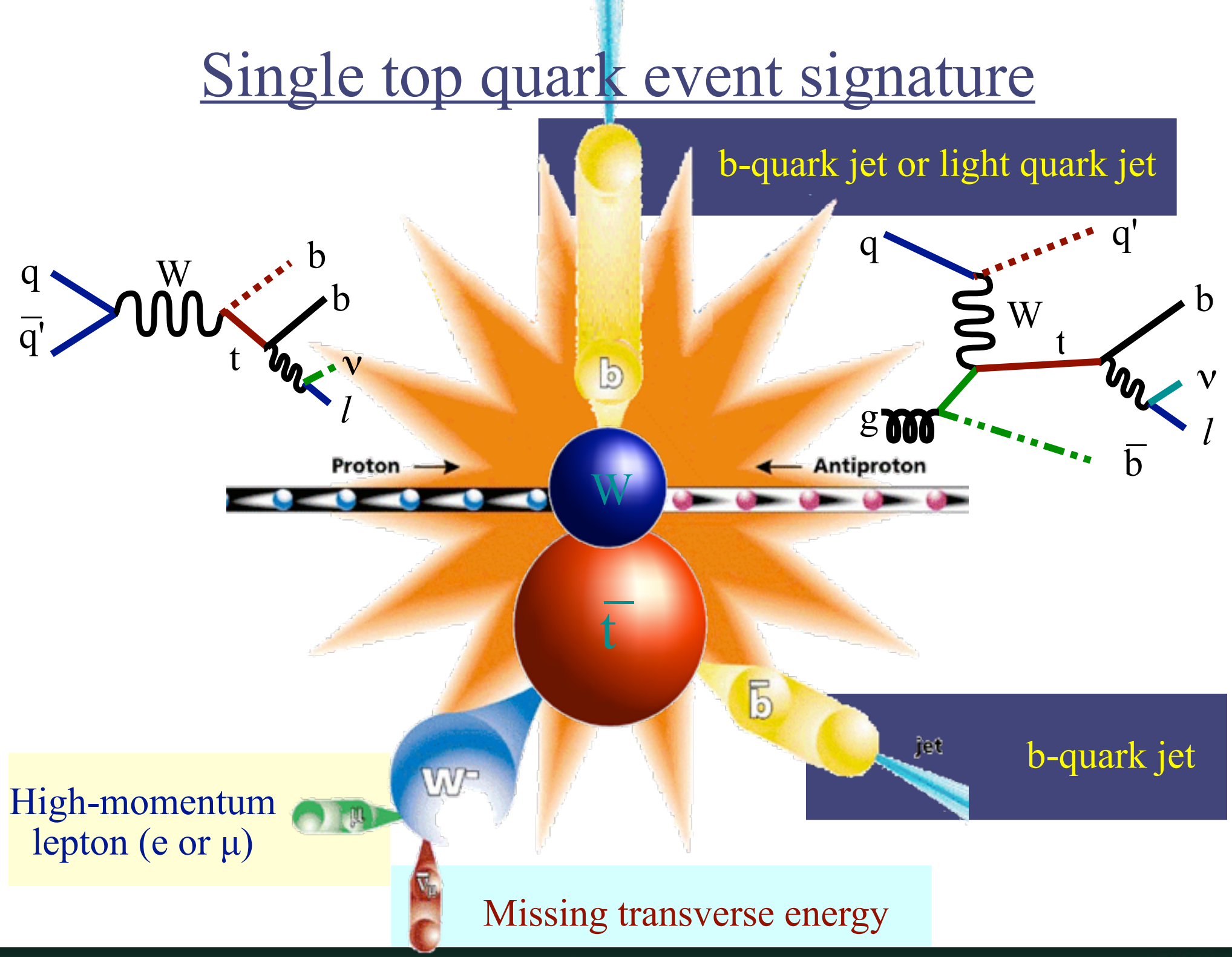
· Search:	PRD 63, 031101 (2000)
· Search:	PLB 517, 282 (2001)
· Search:	PLB 622, 265 (2005)
· W':	PLB 641, 423 (2006)
· Search:	PRD 75, 092007 (2007)
· Evidence:	PRL 98, 181802 (2007)
· FCNC:	PRL 99, 191802 (2007)
· W':	PRL 100, 211802 (2007)
· Evidence:	PRD 78, 012005 (2008)
· Wtb:	PRL 101, 221801 (2008)
· 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

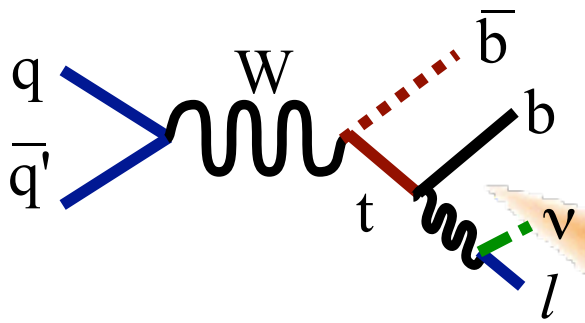
Run II

· 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)

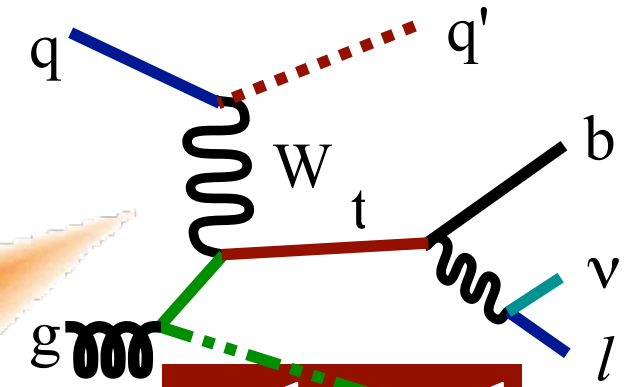
Single top quark event signature



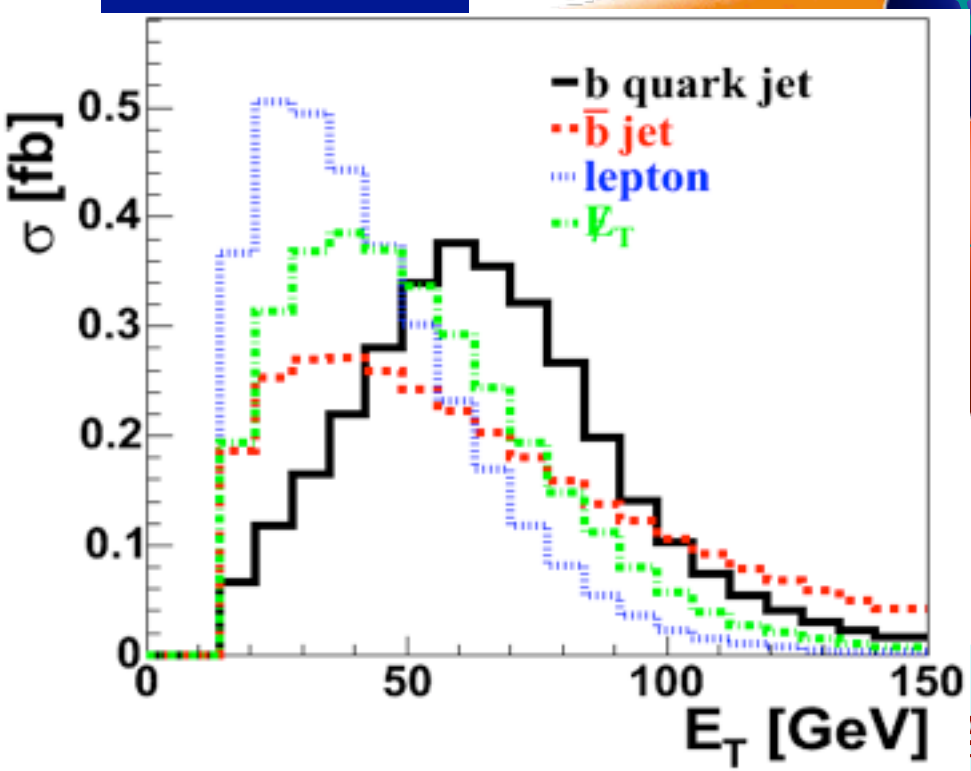
Single top quark event signature

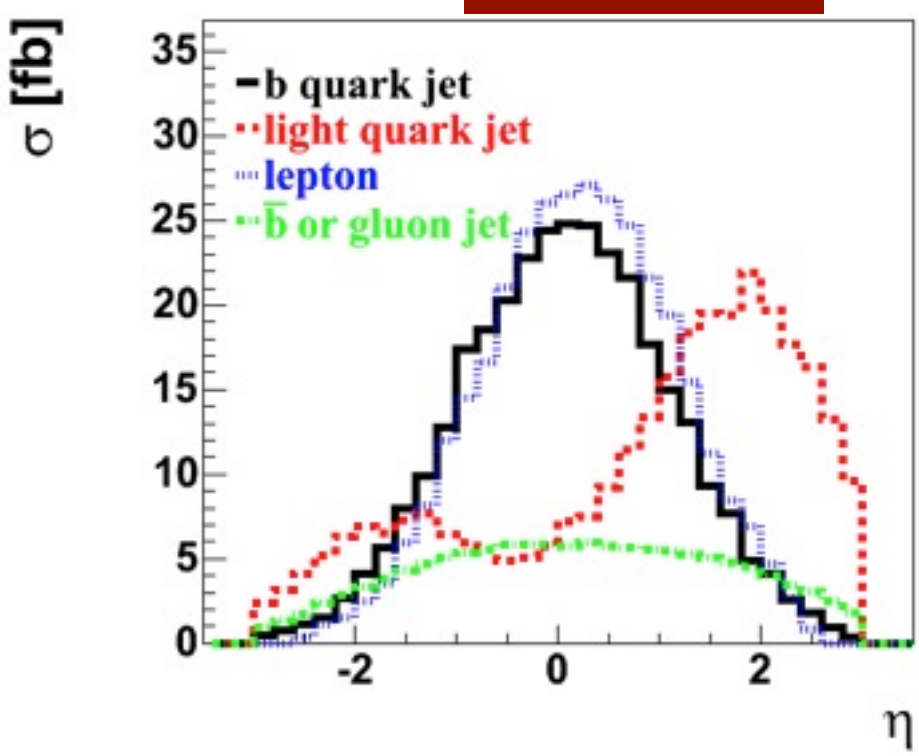


s-channel

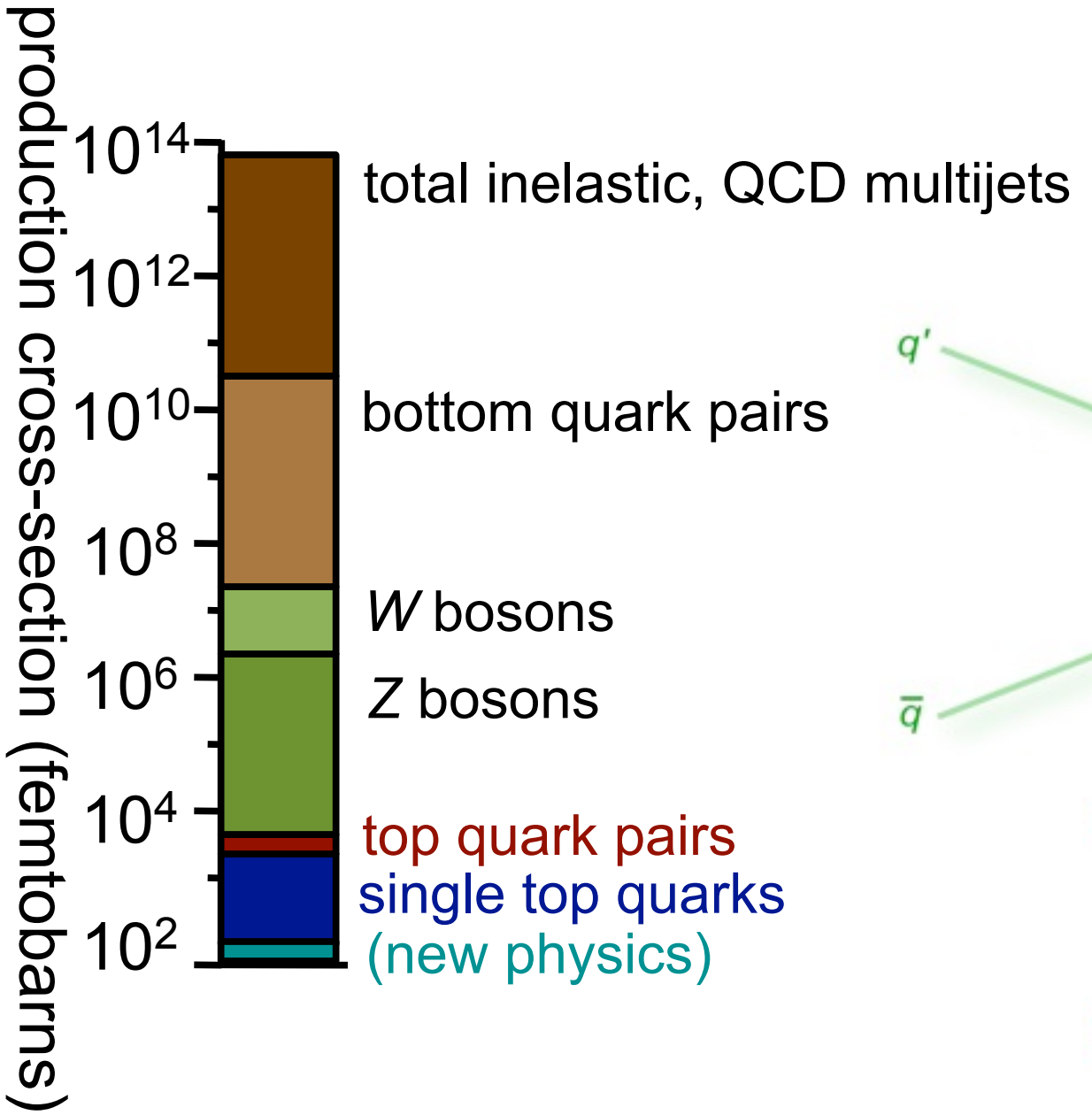


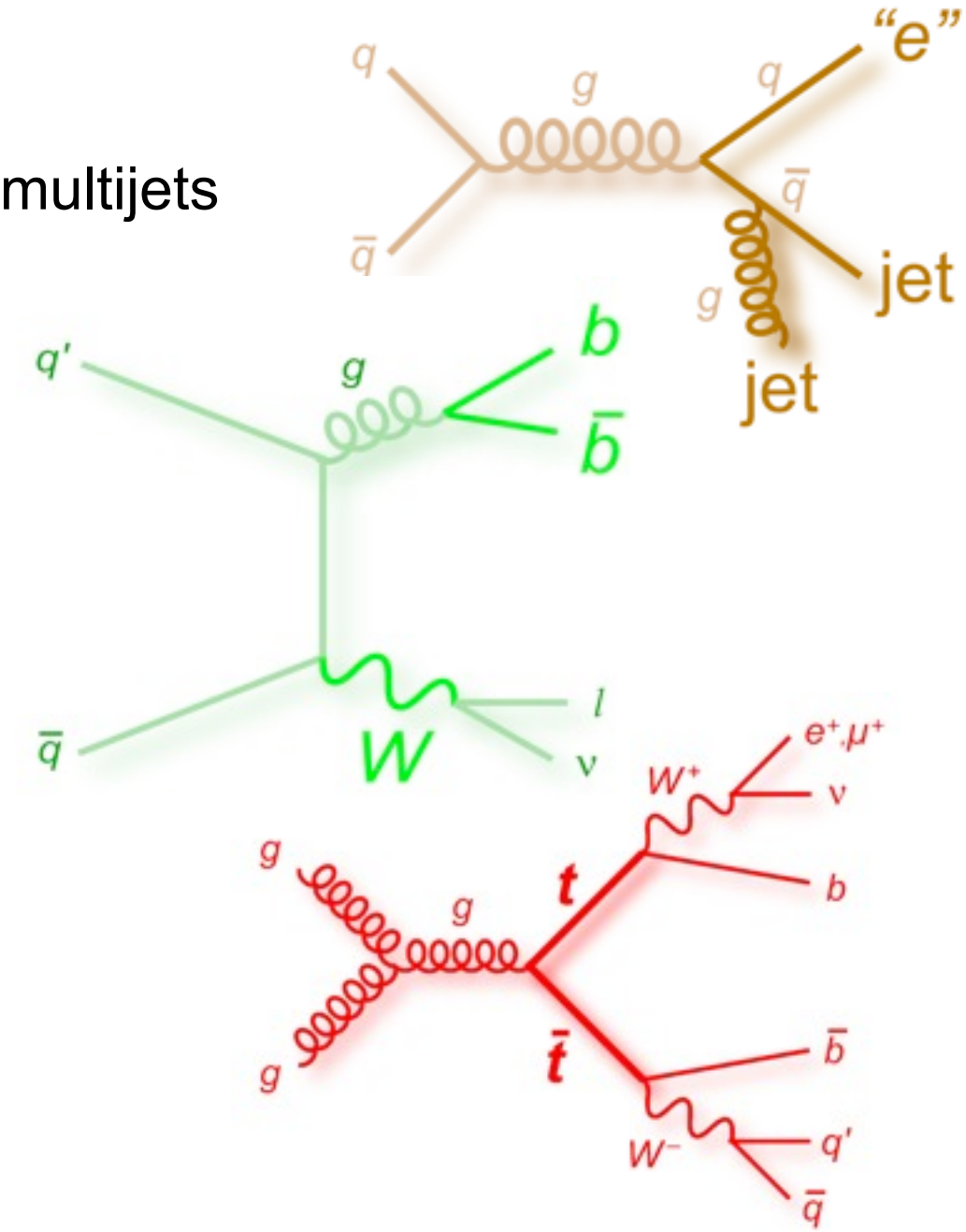
t-channel



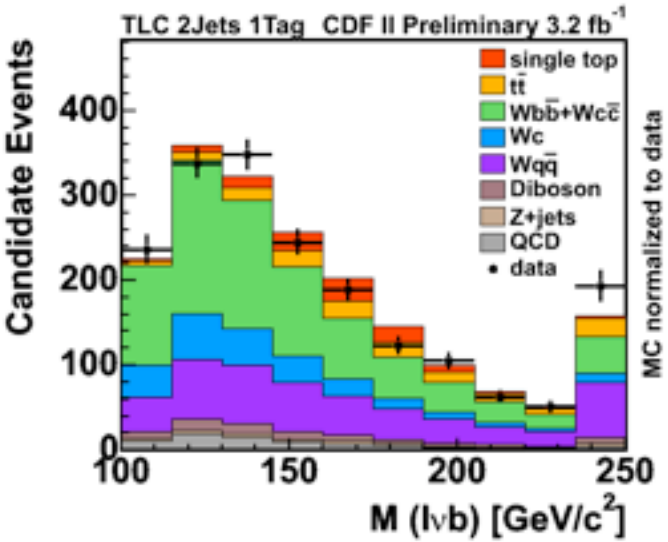


Background processes

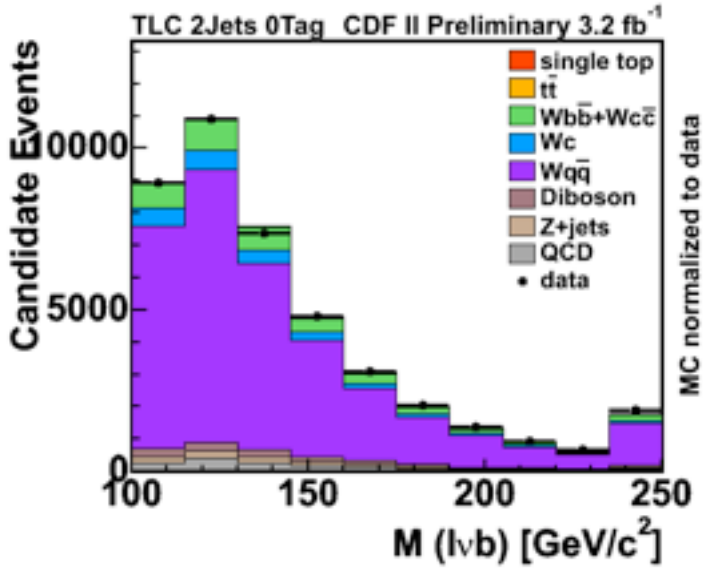


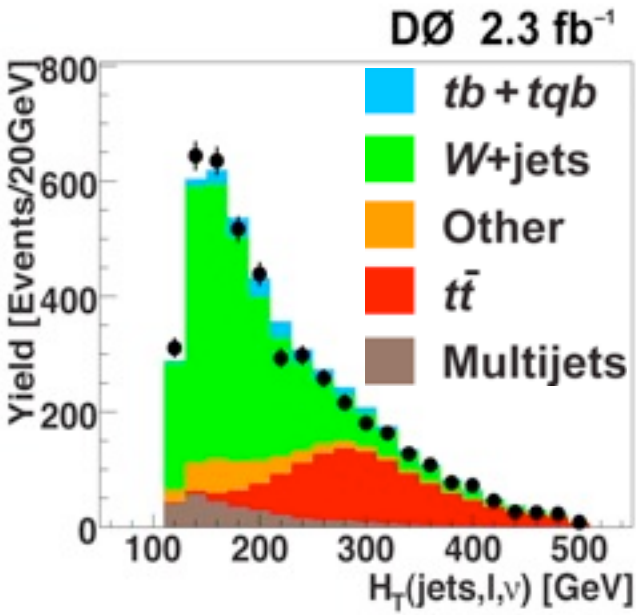


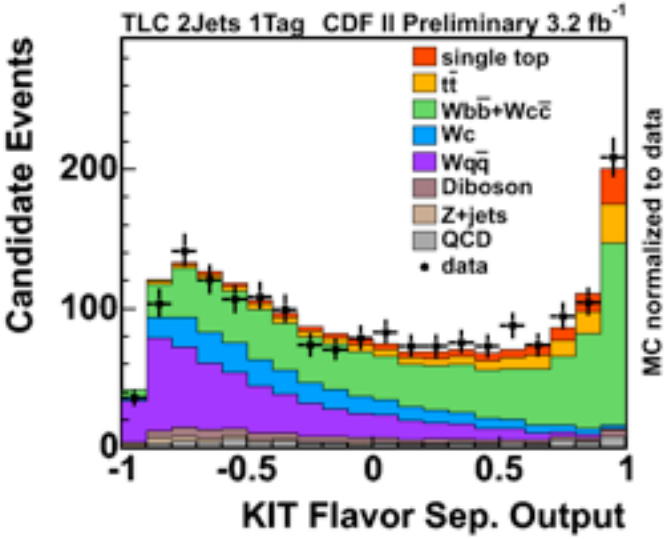
Discriminating variables



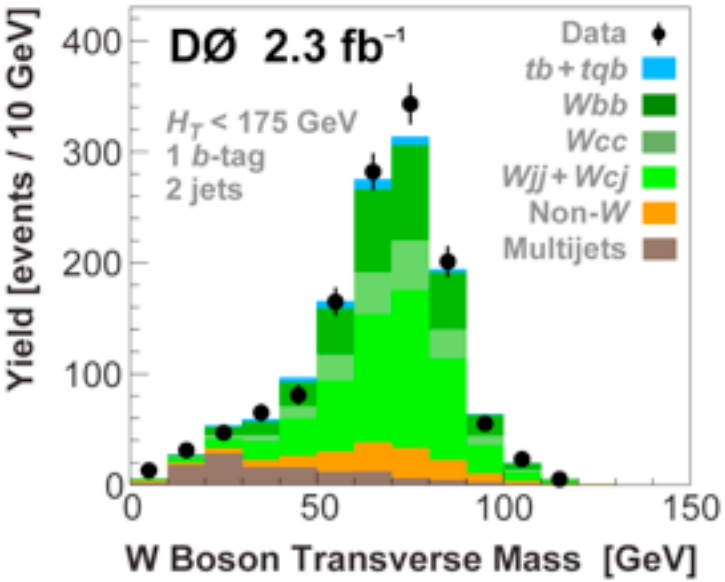
cross-check sample

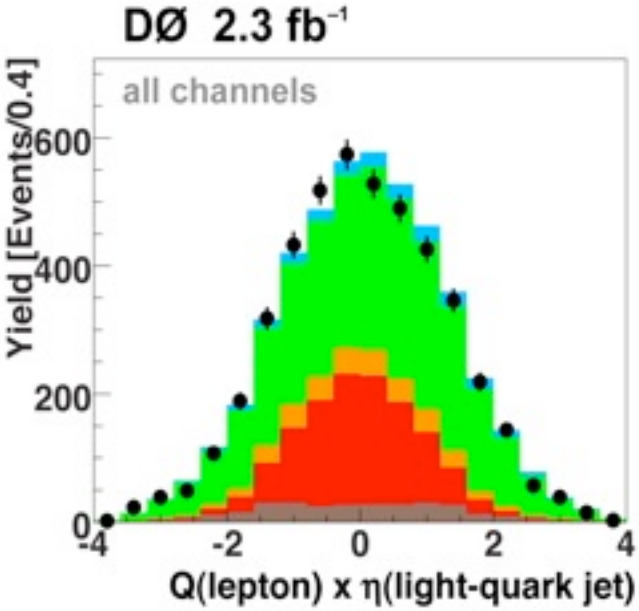




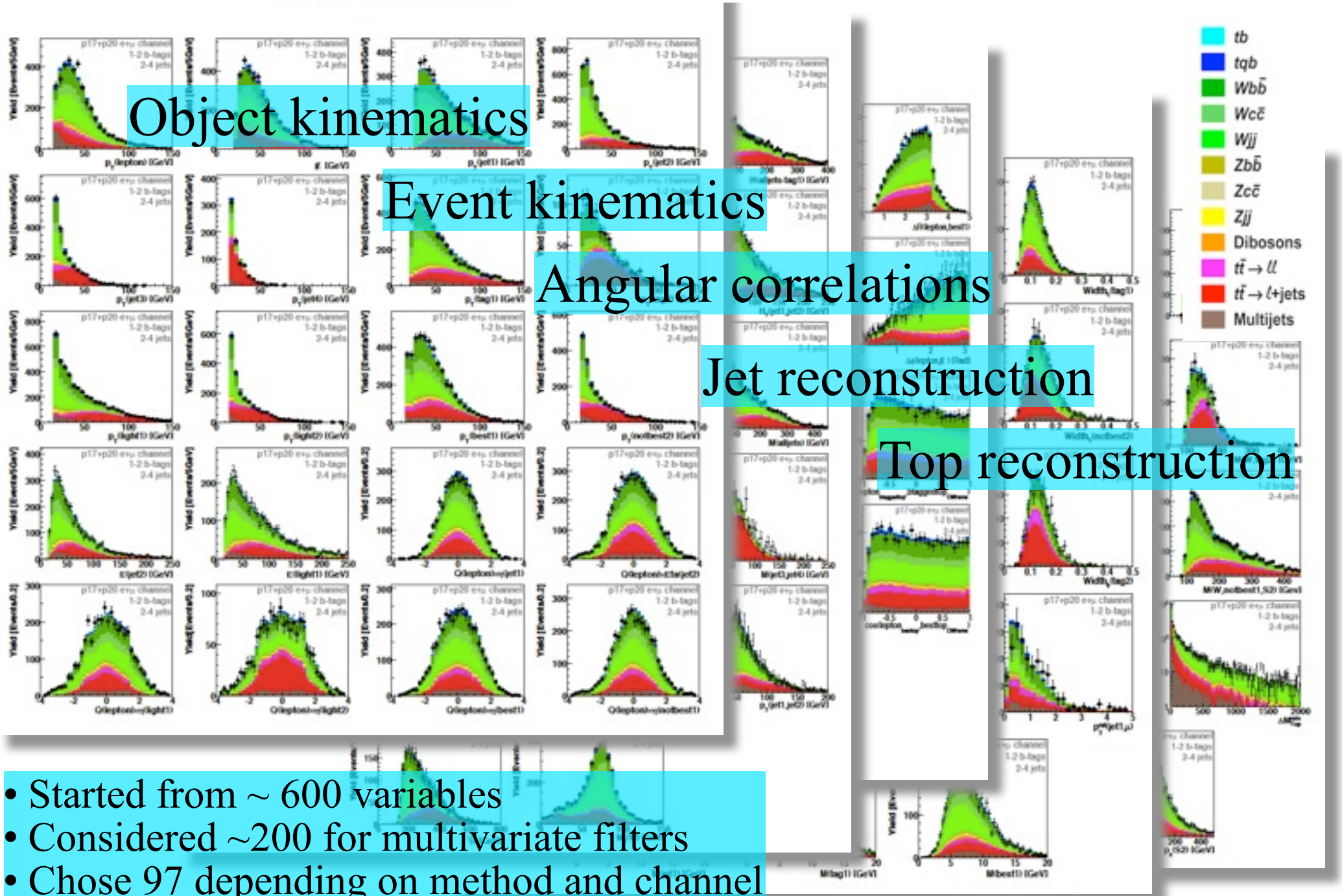


W+Jets Cross-Check Sample





Discriminating variables

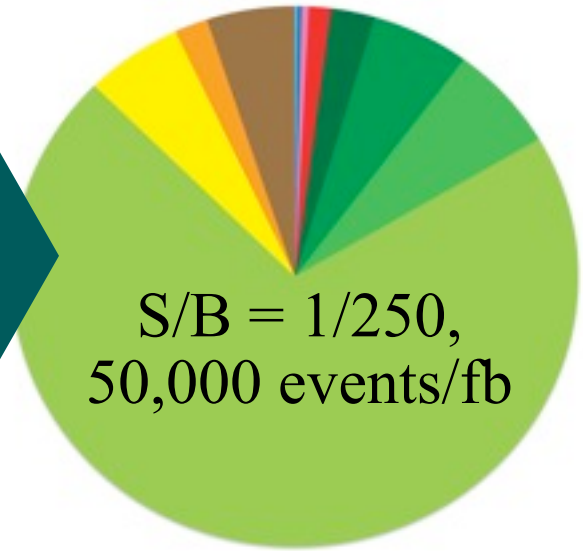


- Started from ~ 600 variables
- Considered ~200 for multivariate filters
- Chose 97 depending on method and channel

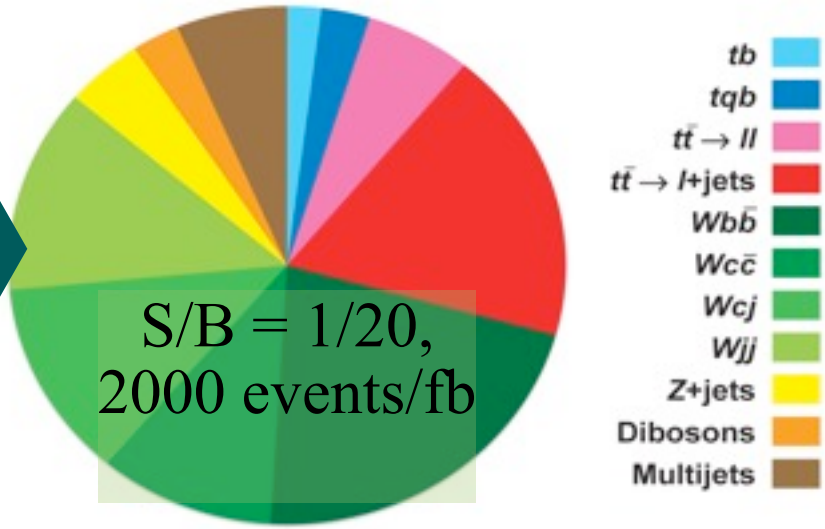
Tevatron analysis outline

Trigger selection

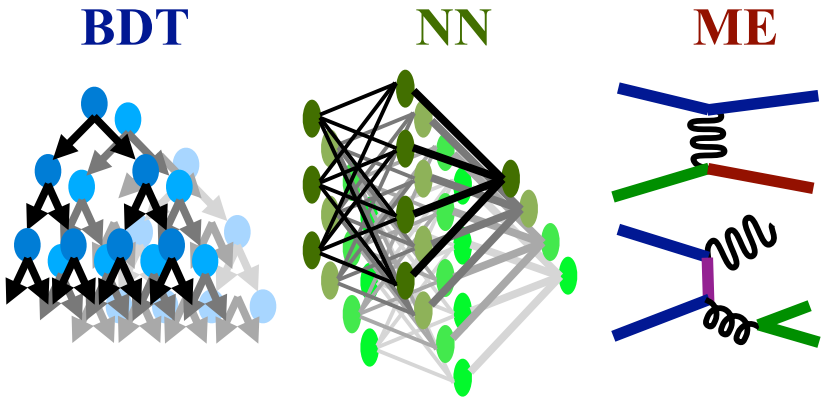
Single top event kinematics



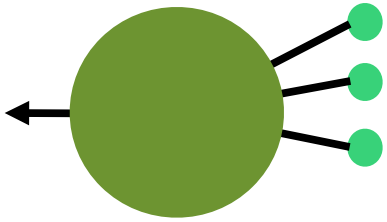
b-quark tagging



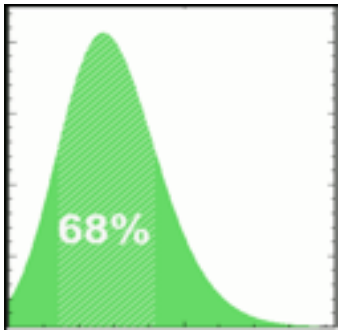
Multivariate techniques



Combination



Statistical analysis

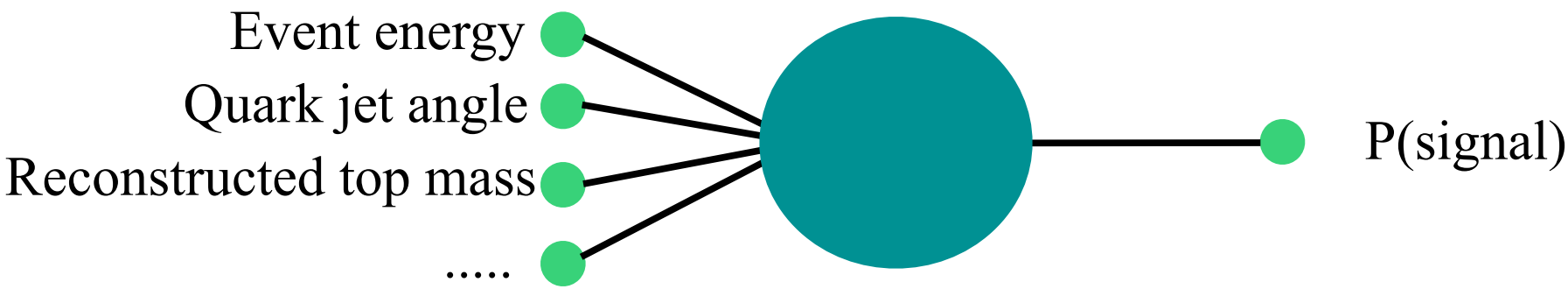


Multivariate methods

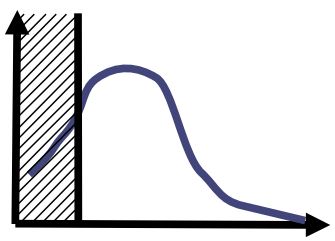
Input:
discriminating variables

Method:
multivariate analysis

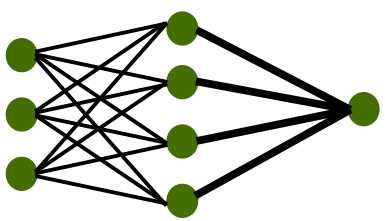
Output:
signal likelihood



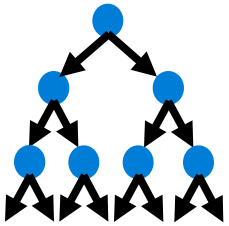
Cut-Based



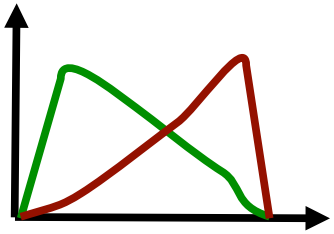
Neural networks



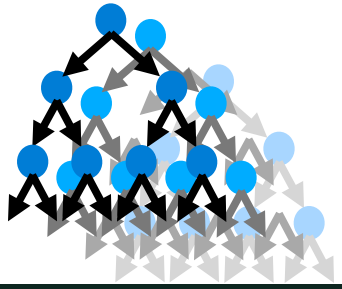
Decision trees



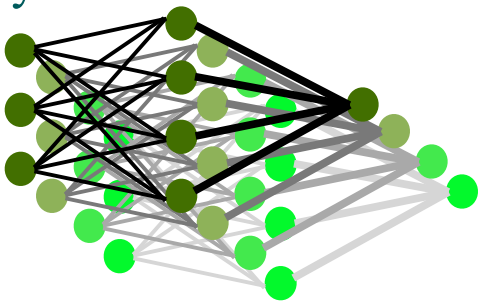
Likelihood



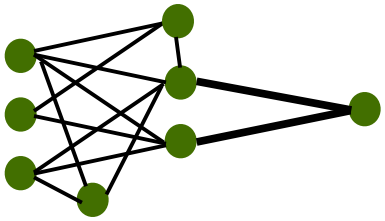
Boosted decision trees



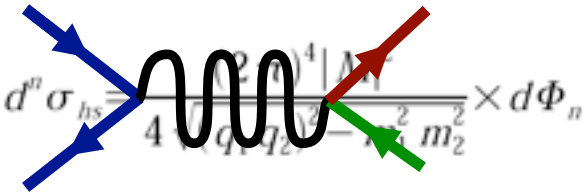
Bayesian neural networks



Neuro evolution



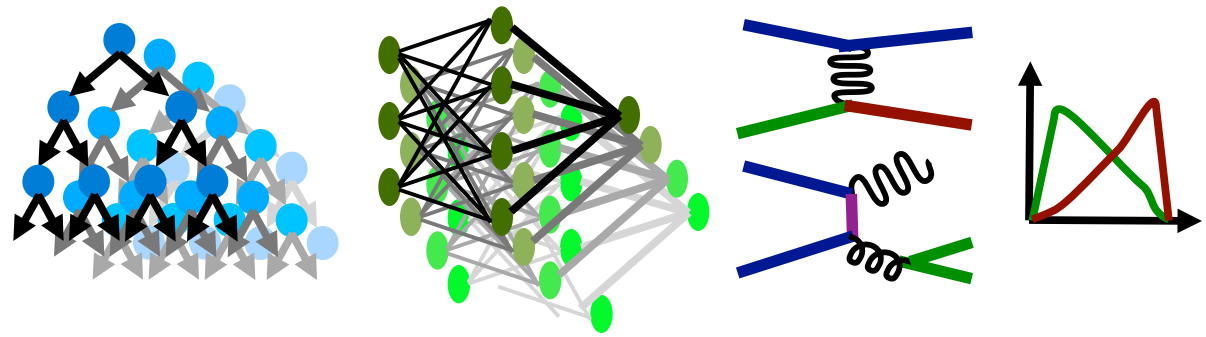
Matrix Elements

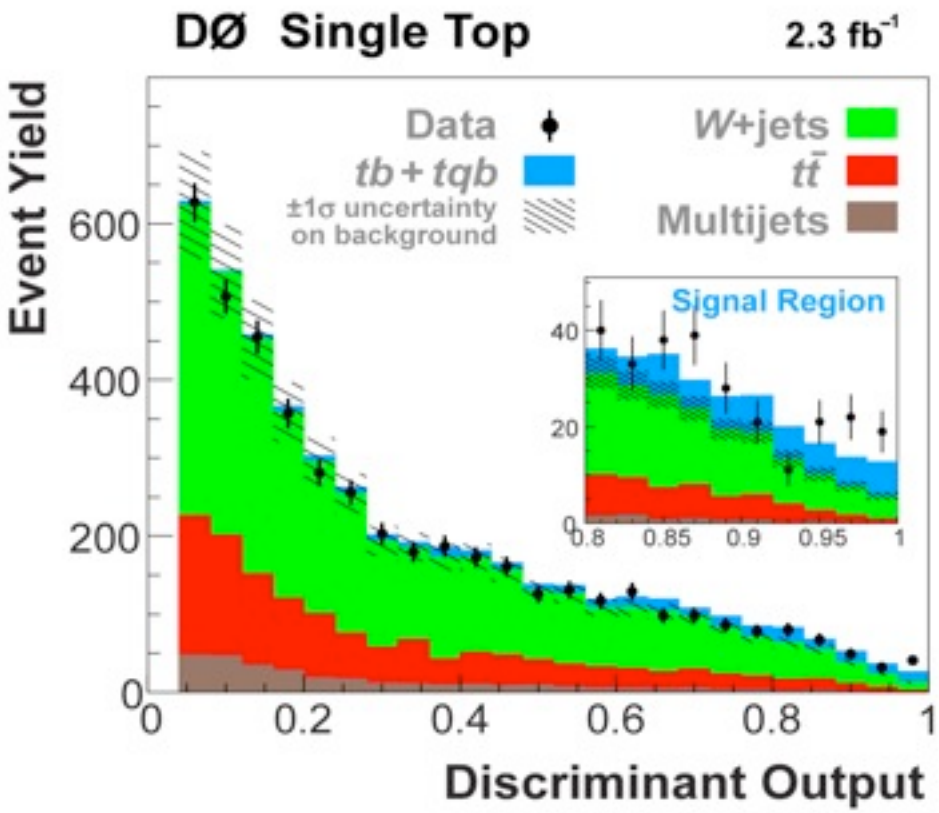


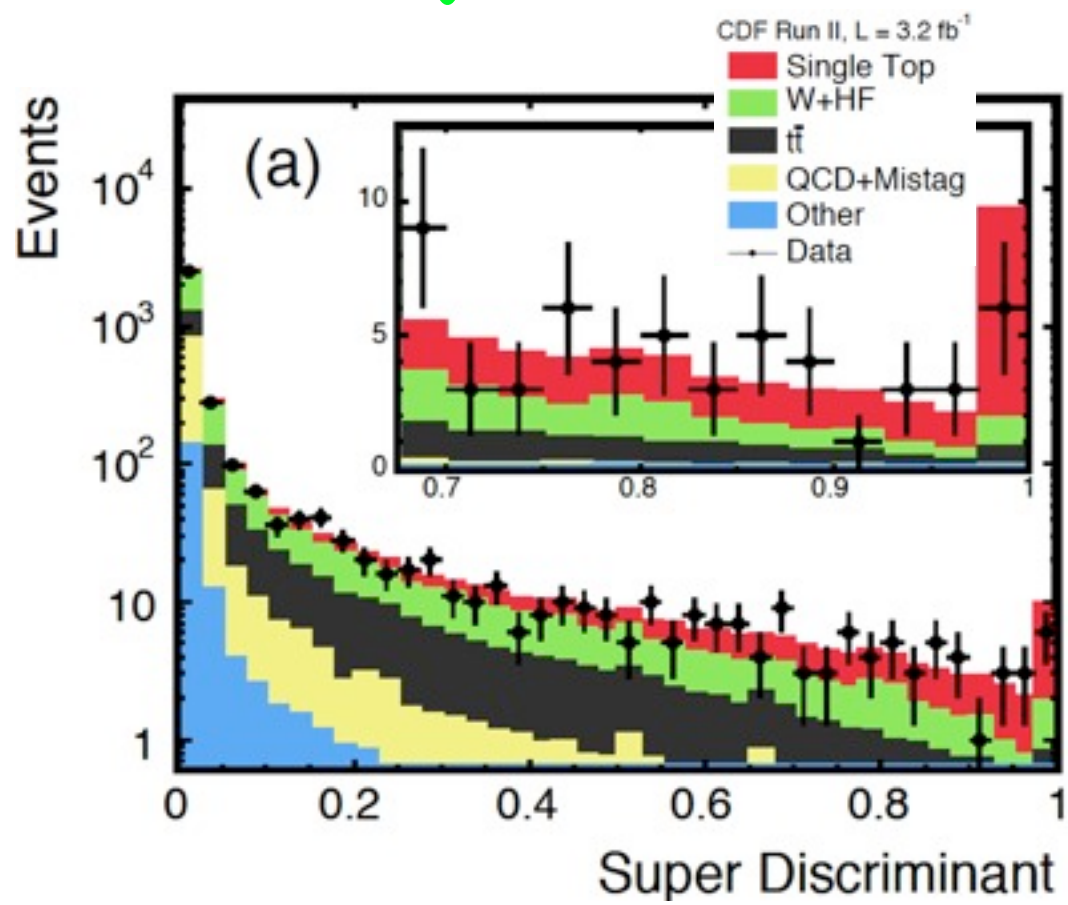
Single top production cross section

- Several multivariate filters combined in one final discriminant
  - BNN (DØ)
  - NEAT (CDF)

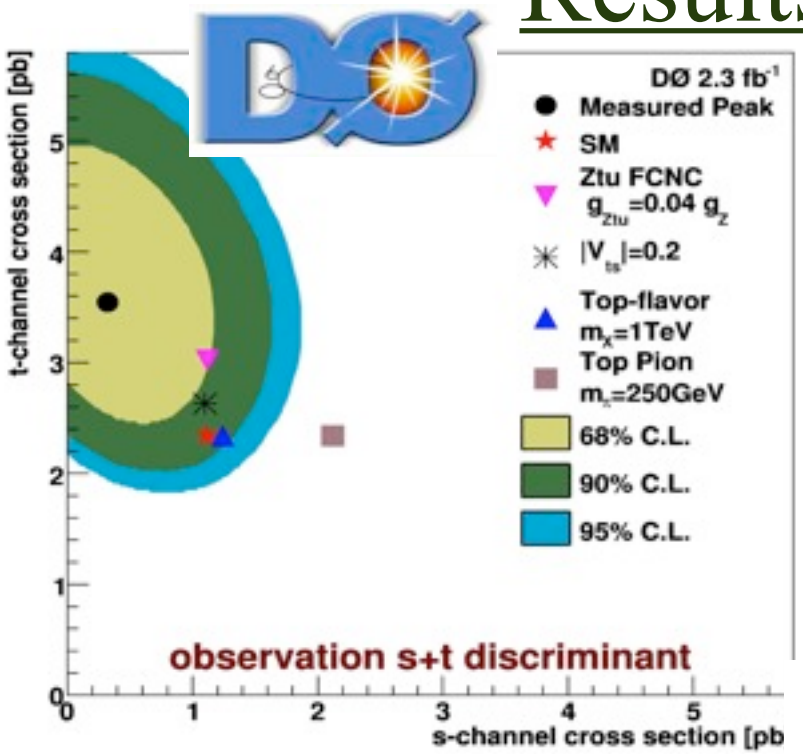
Boosted Decision Trees | **Neural Networks** | **Matrix Elements** | **Likelihood**



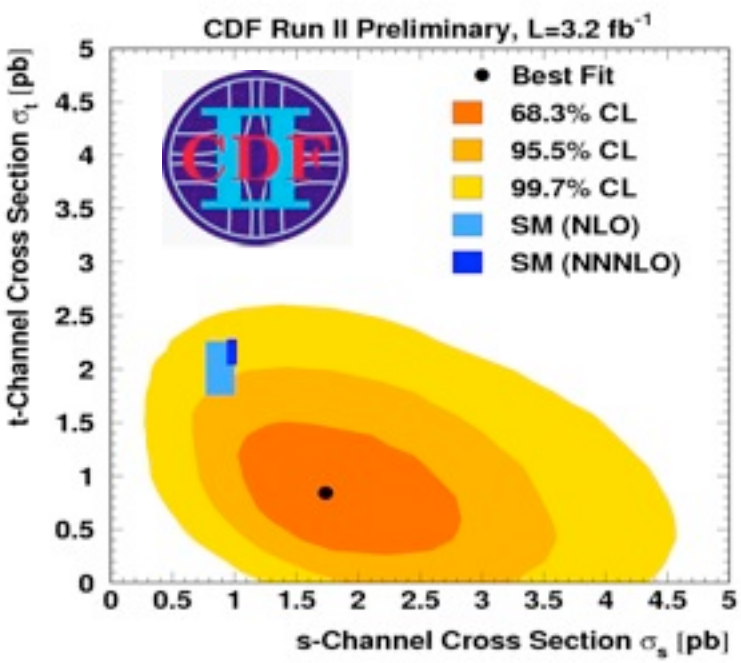


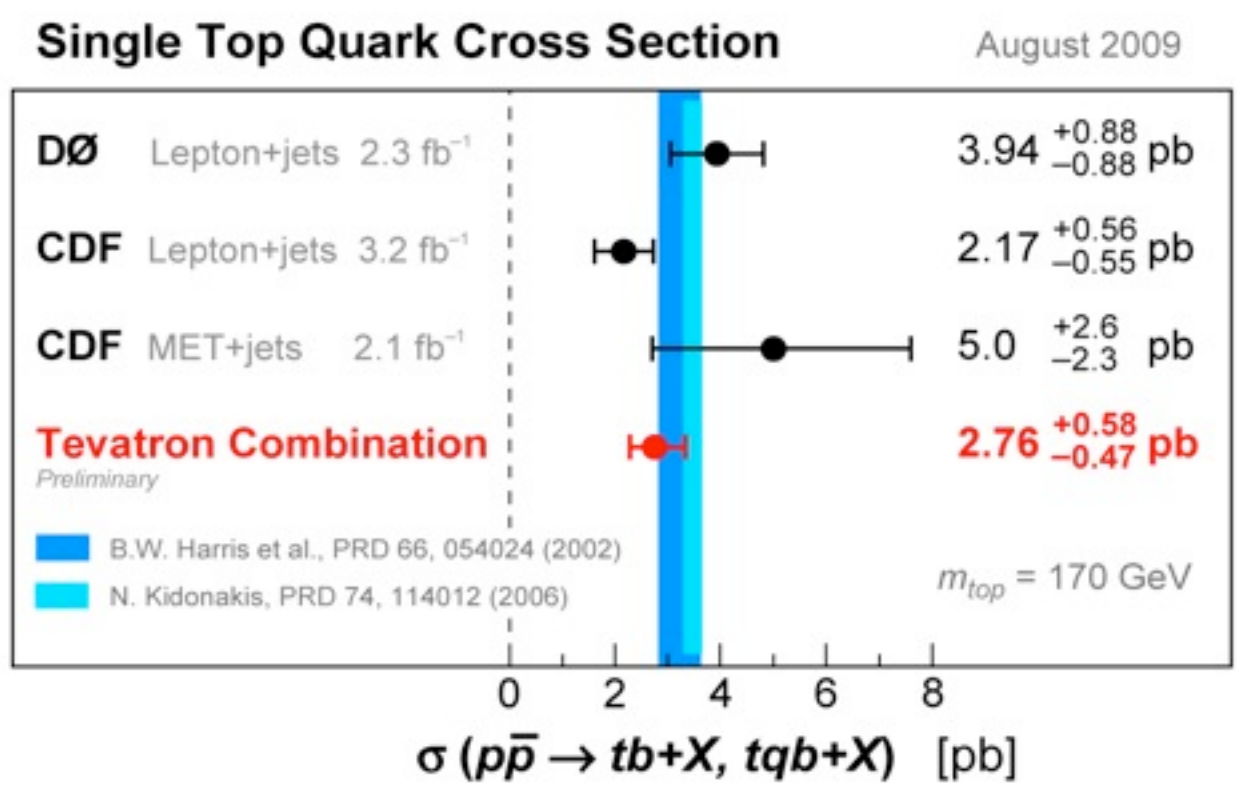


Results and combination

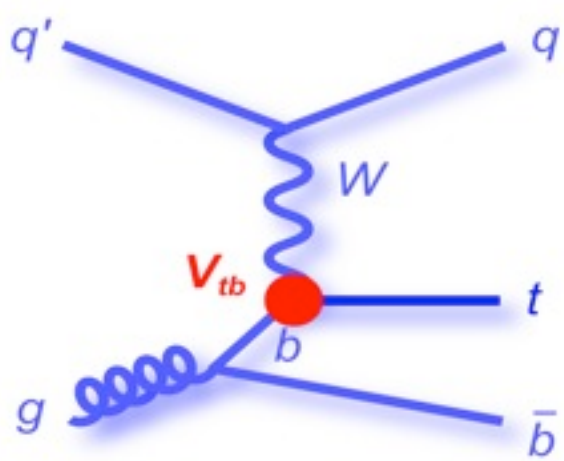


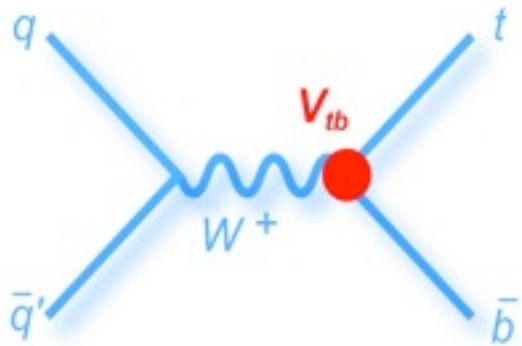
- Each experiment observes 5 σ significance
- DØ and CDF measurements are consistent to 1.6 σ
- Combination of MVA distributions
  - Bayesian statistical analysis
  - Taking all uncertainty correlations into account





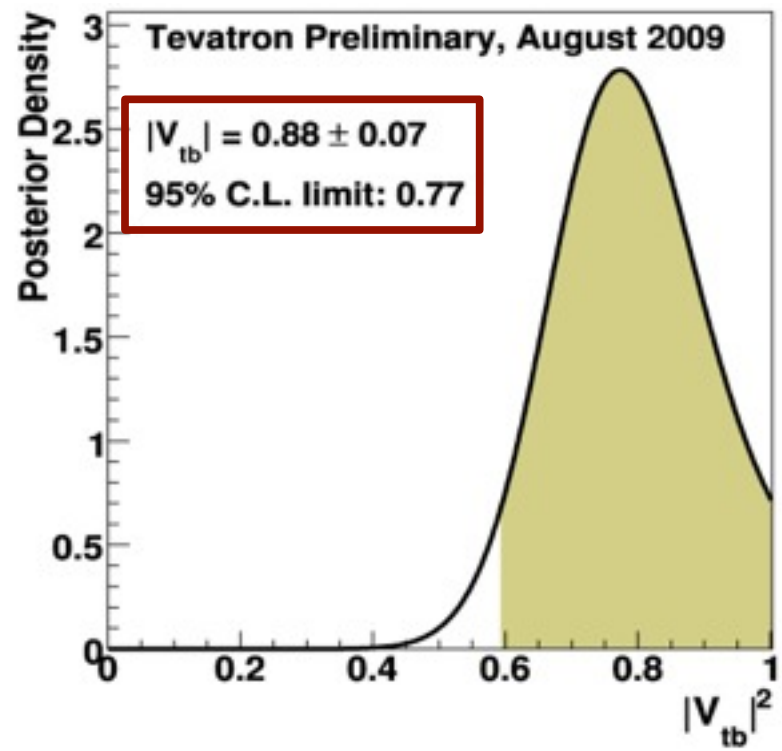
CKM matrix element Vtb





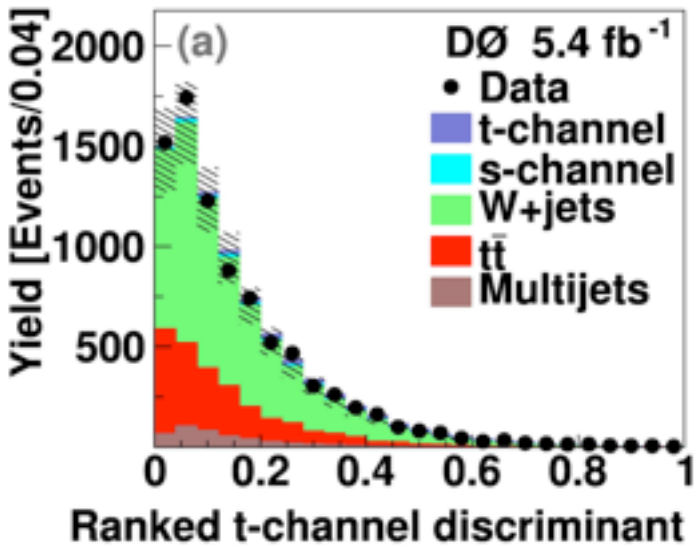
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

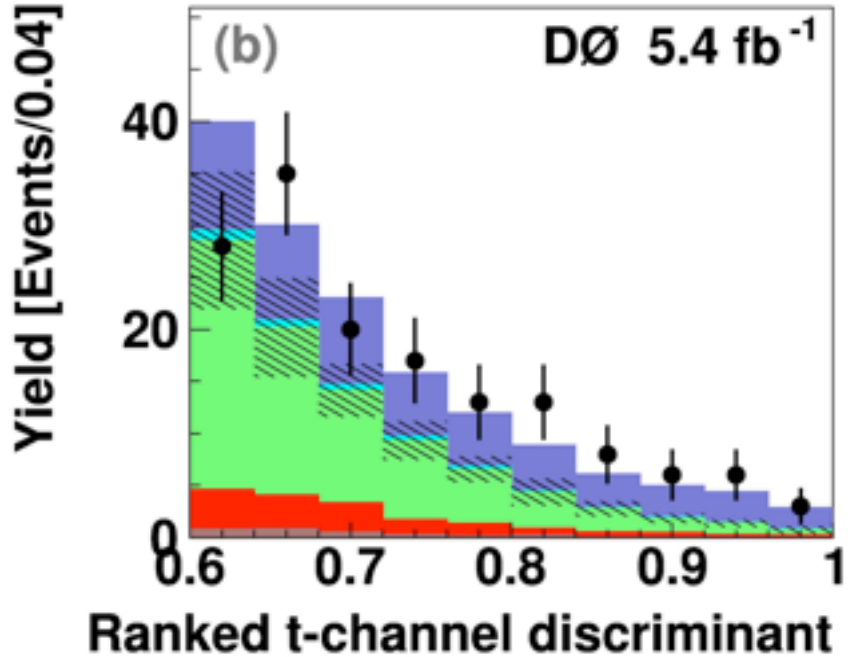
- Cross section ∝ $|V_{tb}|^2$
  - Assume SM top quark decay: $|V_{td}|^2+|V_{ts}|^2 \ll |V_{tb}|^2$
  - Pure V-A and CP conserving Wtb vertex
- No assumption on number of families or unitarity

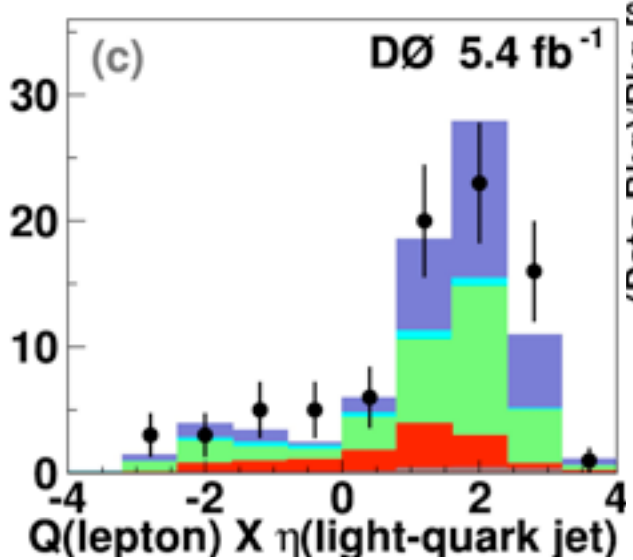


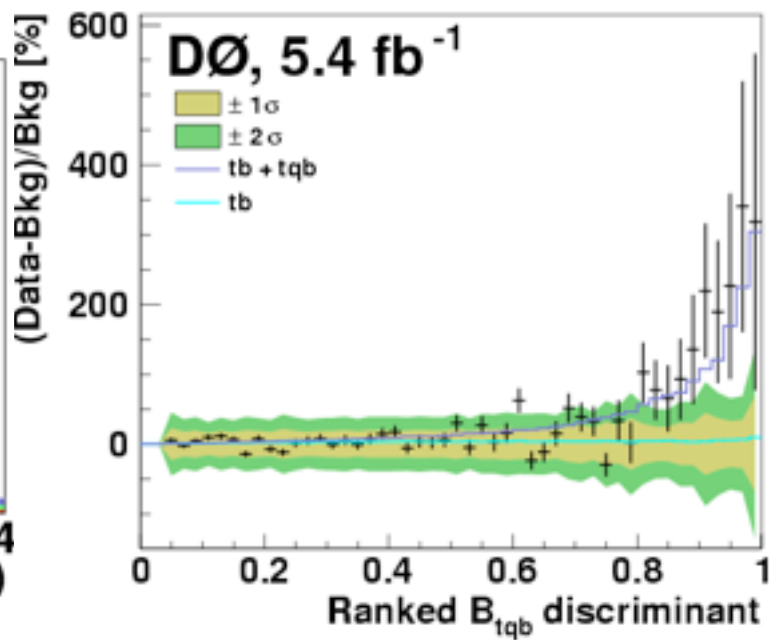
t-channel production

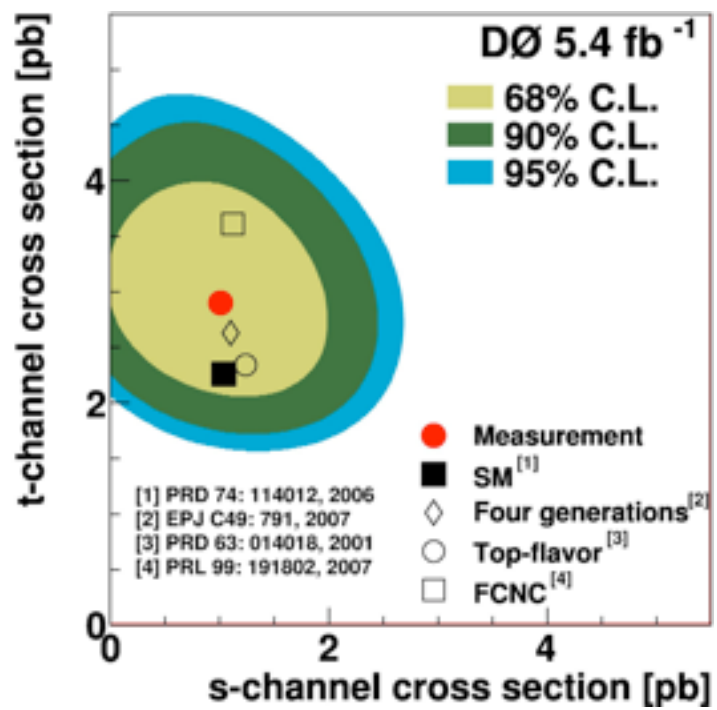
- New analysis with 5.4 fb^{-1}
- Dedicated t-channel filter
- No assumption about s-channel
- 5.5 σ significance





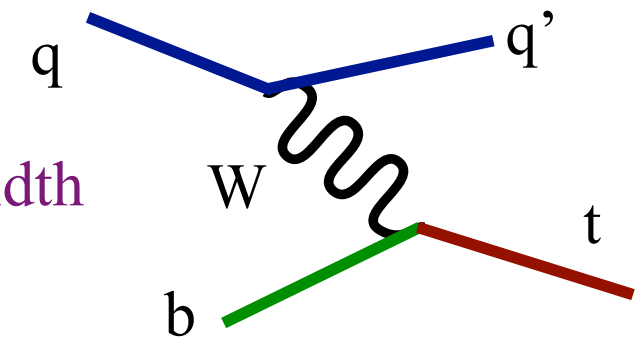






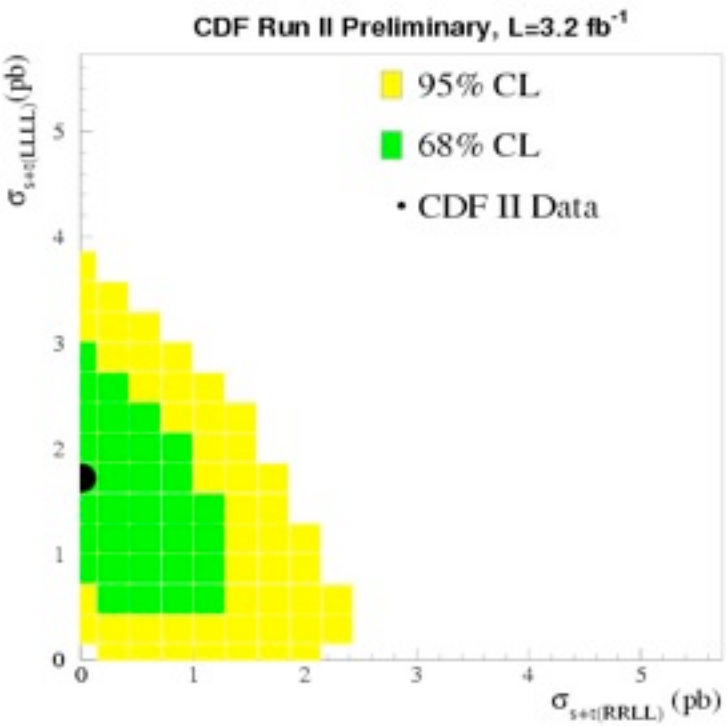
Top quark properties

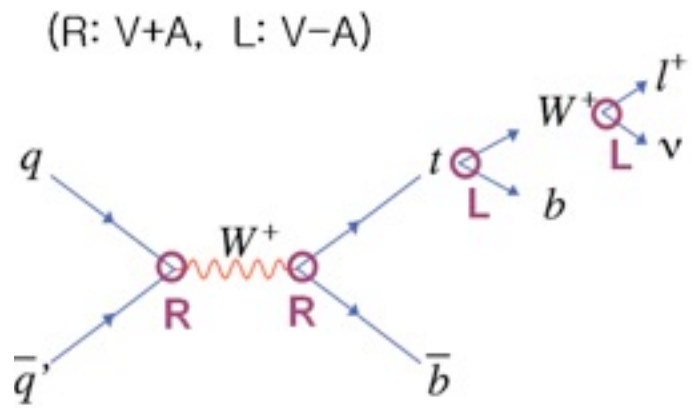
- top quark width from t-channel cross section
  - use R=B(t→Wb)/B(t→Wx) to obtain full width



$\Gamma_t = 2.05^{+0.57}_{-0.52}$ GeV $\tau_t = (3.2^{+1.1}_{-0.7}) \times 10^{-25}$ s

- Top quark polarization from spin correlation





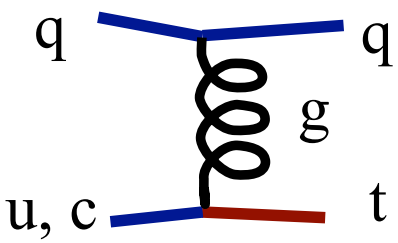
- Analysis using likelihood function
- Test for right-handed coupling in top production

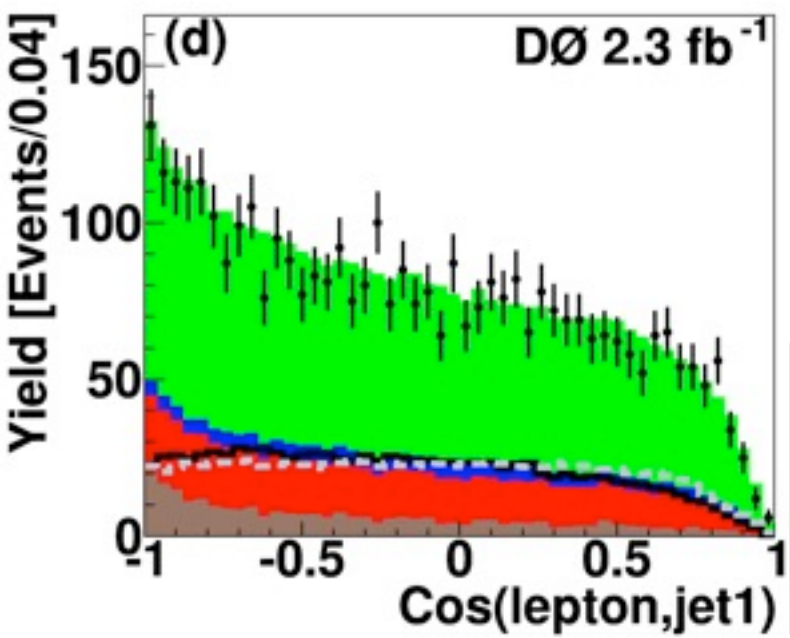
$$polarization = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -1^{+1.5}_{-0}$$

Tevatron new physics searches

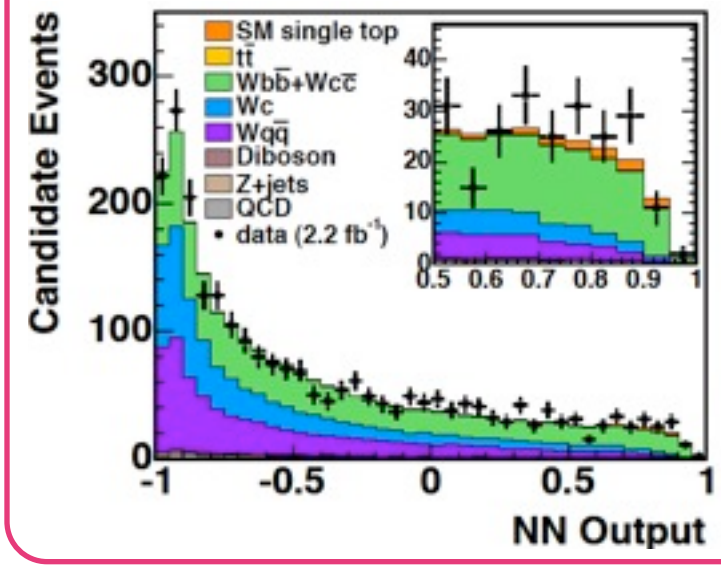
Gluon-FCNC in single top

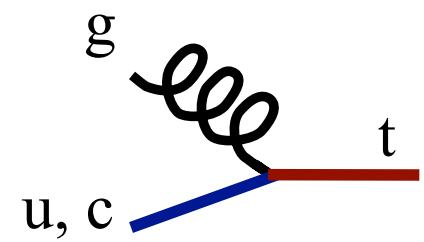
- D0: 2→2 process
  - ★Same final state as t-channel
  - ★multivariate analysis using BNN





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





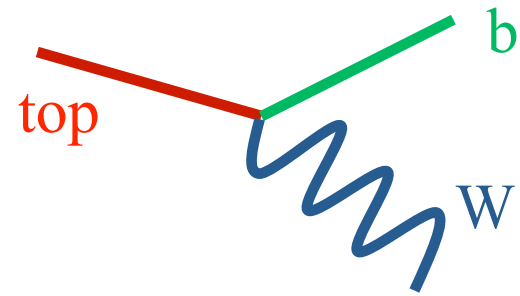
$$\frac{\kappa_{gtu}}{\Lambda} < 0.025\ \mathrm{TeV}^{-1}$$

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

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

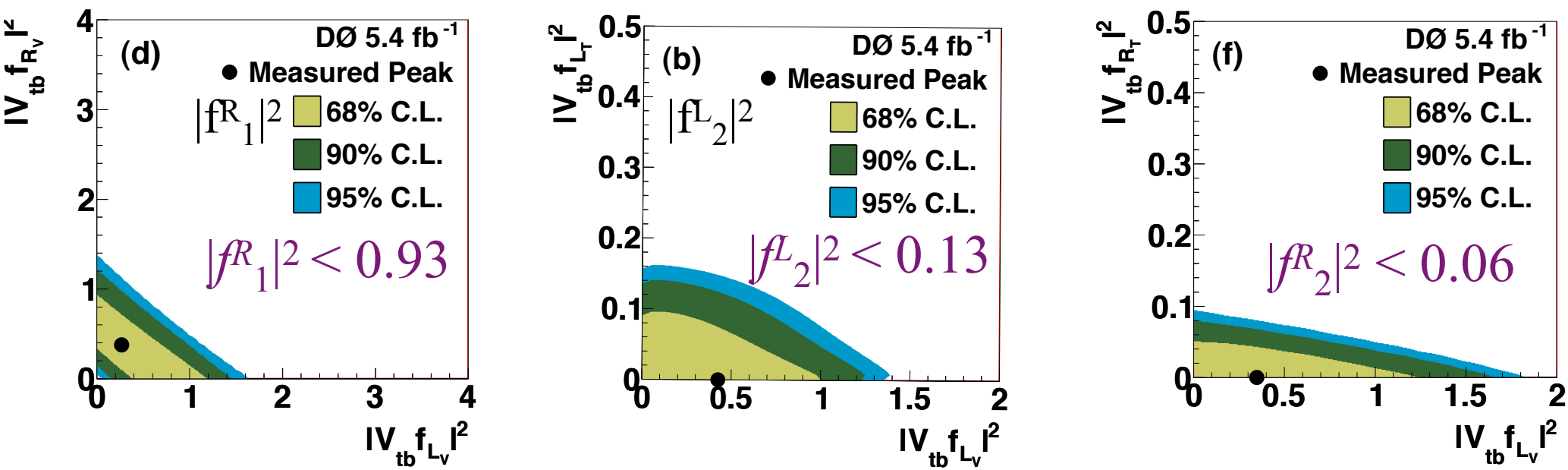
Single top anomalous coupling

- Left-vector (f^L_1, =1 in SM), right-vector (f^R_1), left-tensor (f^L_2), right-tensor (f^R_2)

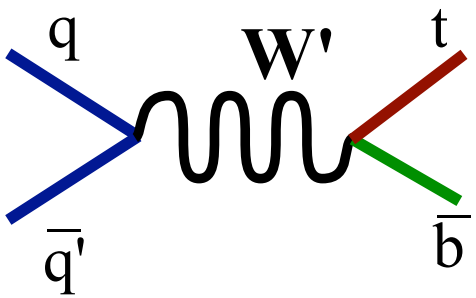


$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu V_{tb}(f_1^L P_L + f_1^R P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}(f_2^L P_L + f_2^R P_R)tW_\mu^- + h.c.$$

- 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



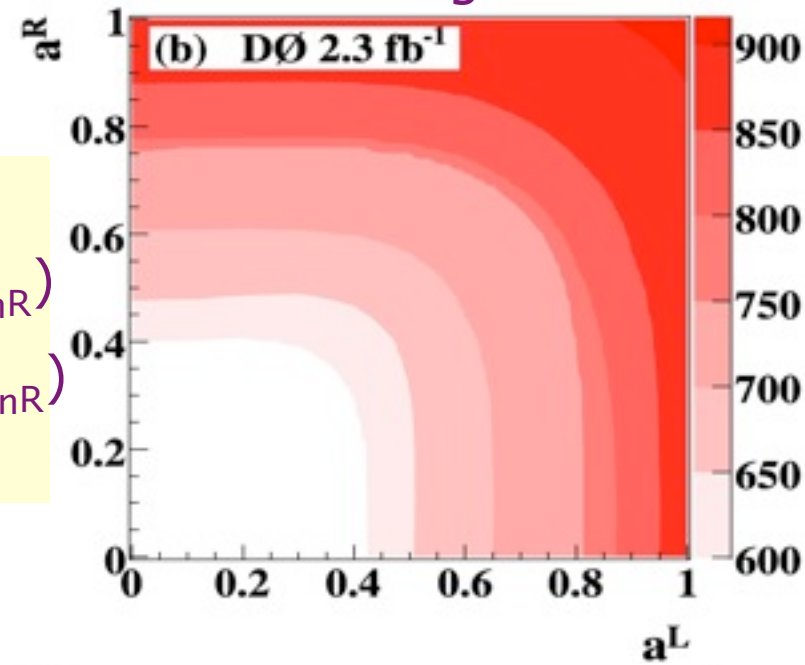
- Explore simultaneously left-handed and right-handed couplings
- 95% CL limits:

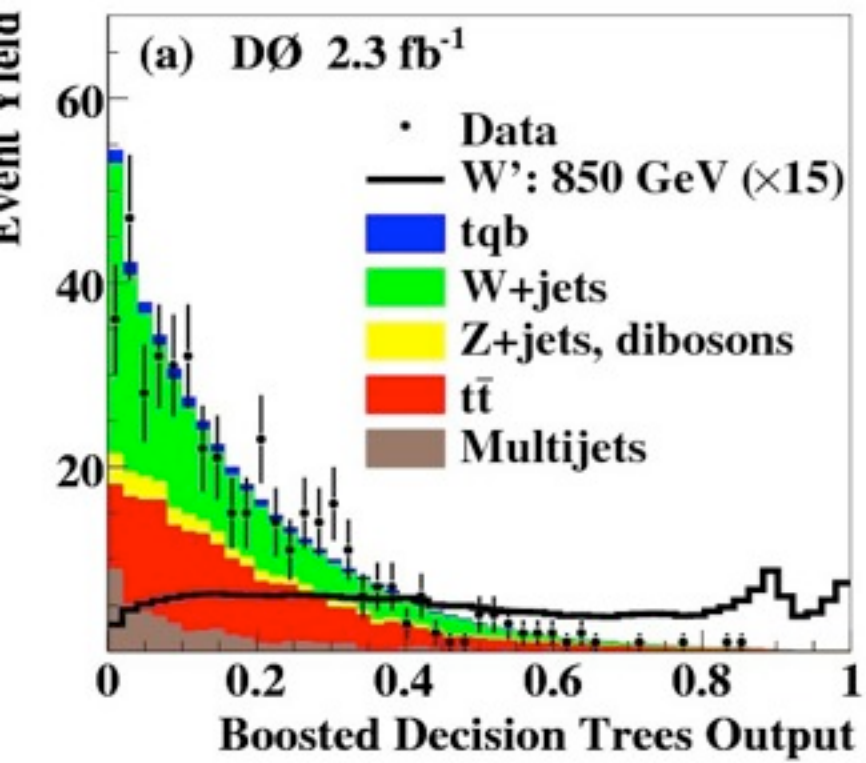
$M_{W'} > 863$ GeV (SM-like)

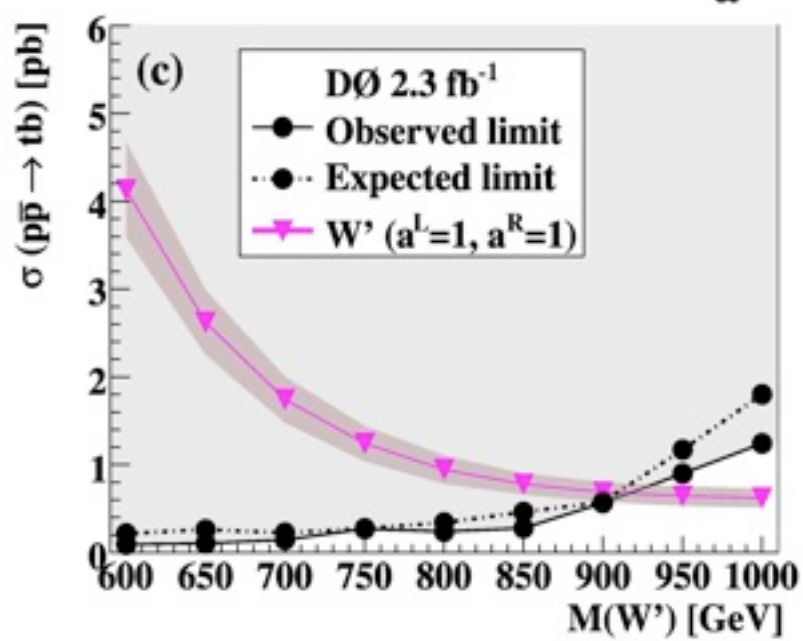
$M_{W'} > 885$ GeV (R, $M_{W'} < m_{nR}$)

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

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



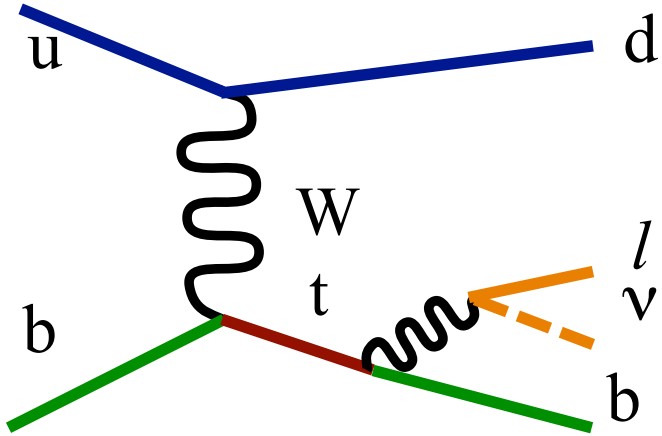




Large Hadron Collider

Large Hadron Collider

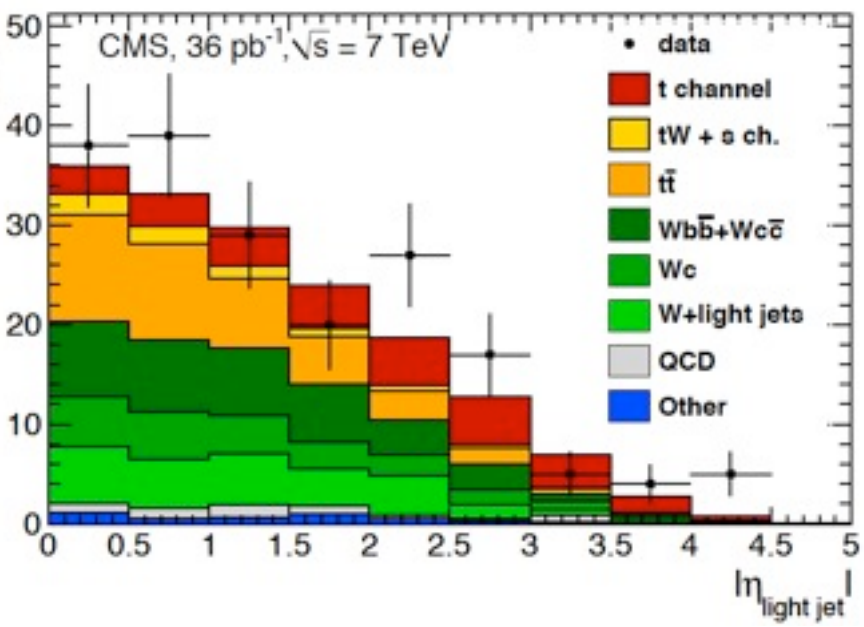
Measurement of t-channel production



- 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



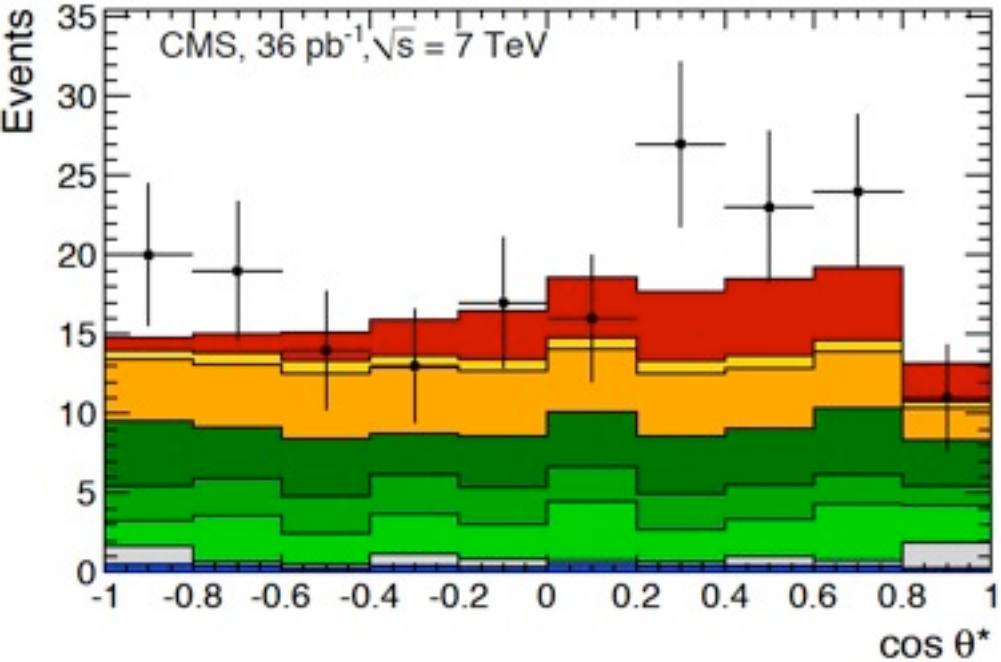
Background modeling:

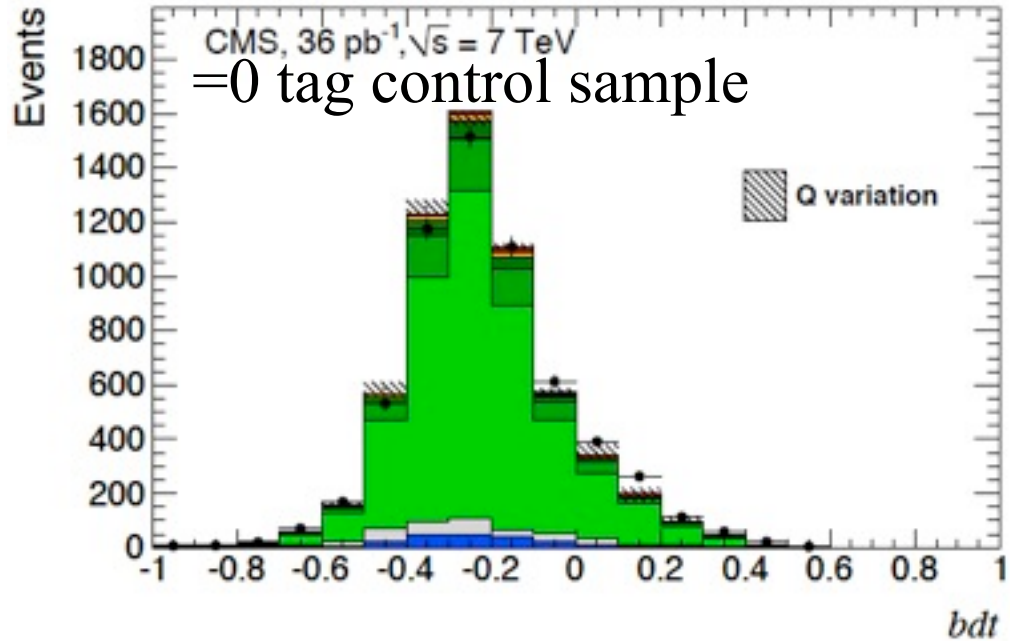
- normalize W+jets and QCD to data
- top background to theory

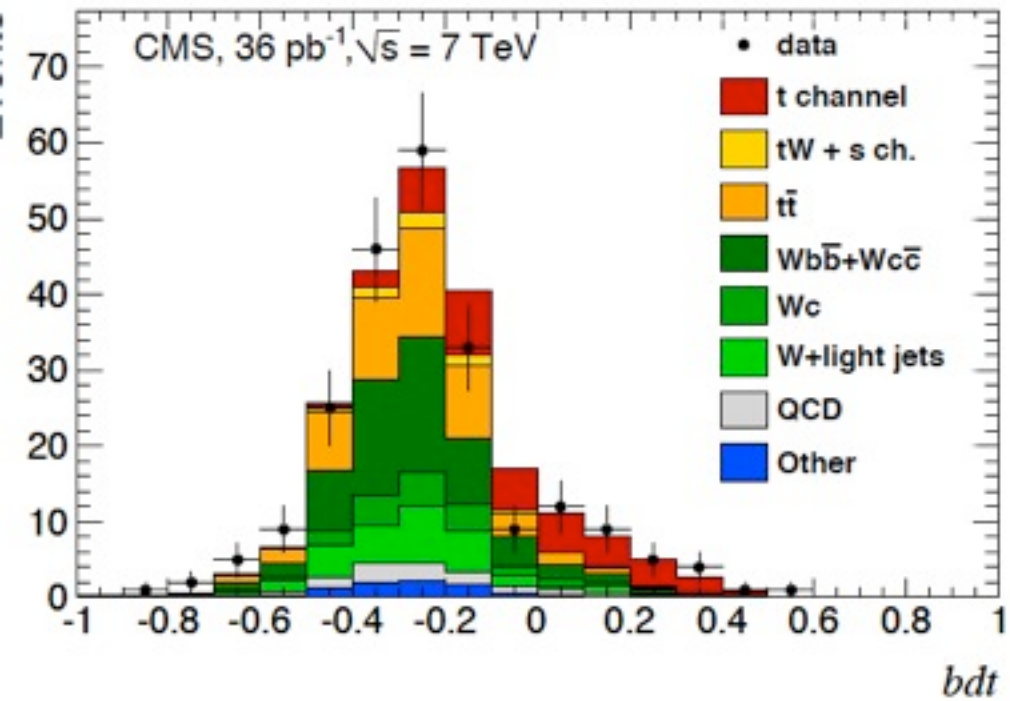
Analysis procedure:

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

t-channel result







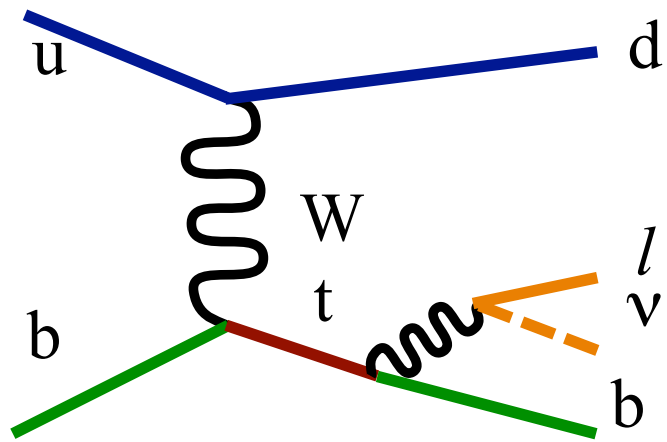
- Combination using BLUE

combined: observed cross section:
$\sigma_t = 83.6 \pm 29.8$ pb

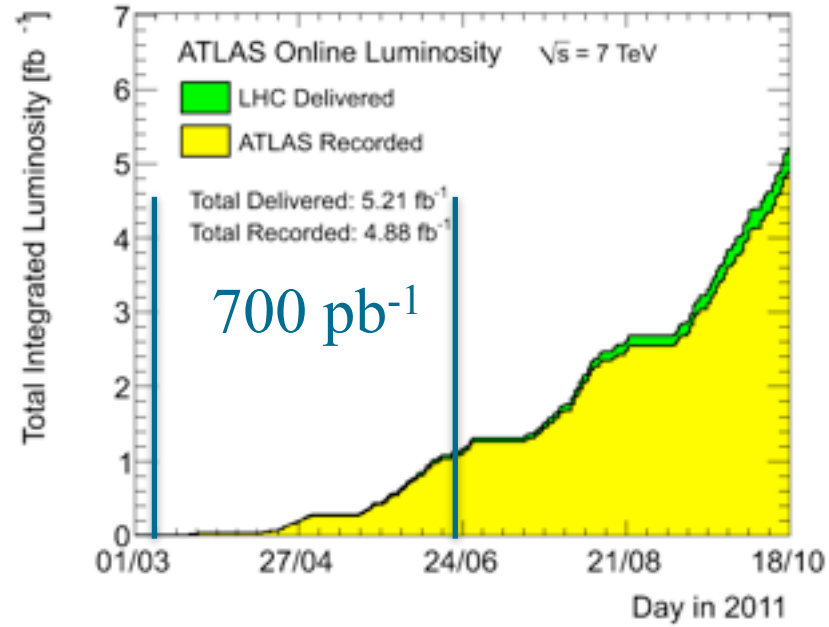
Observed significance: 3.5 σ
Observed |Vtb| > 0.68 at 95% CL

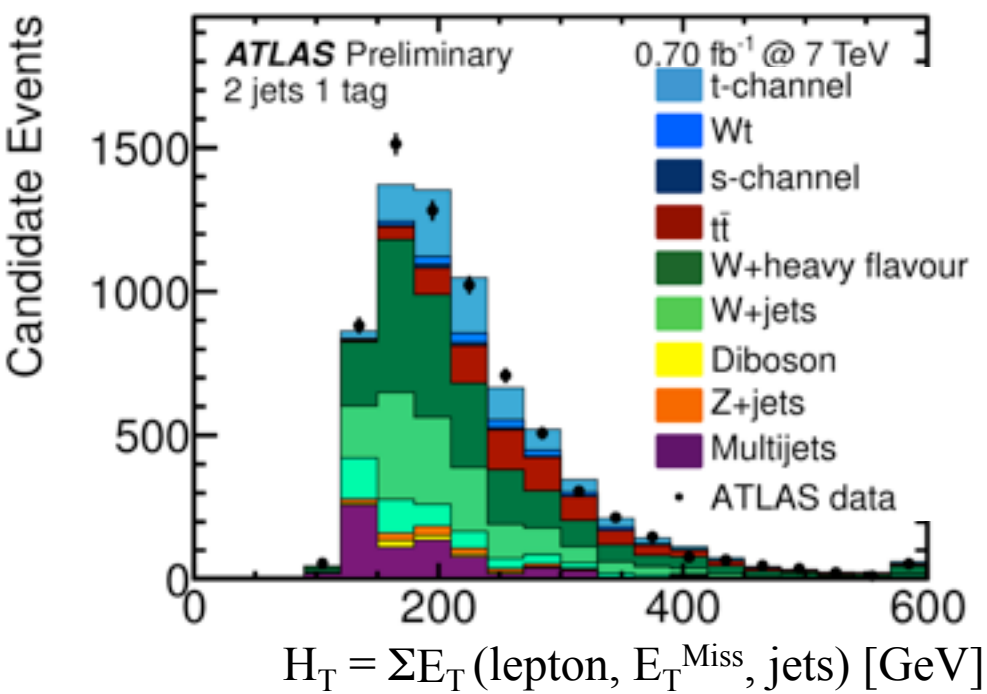
arXiv:1106.3052 [hep-ex]

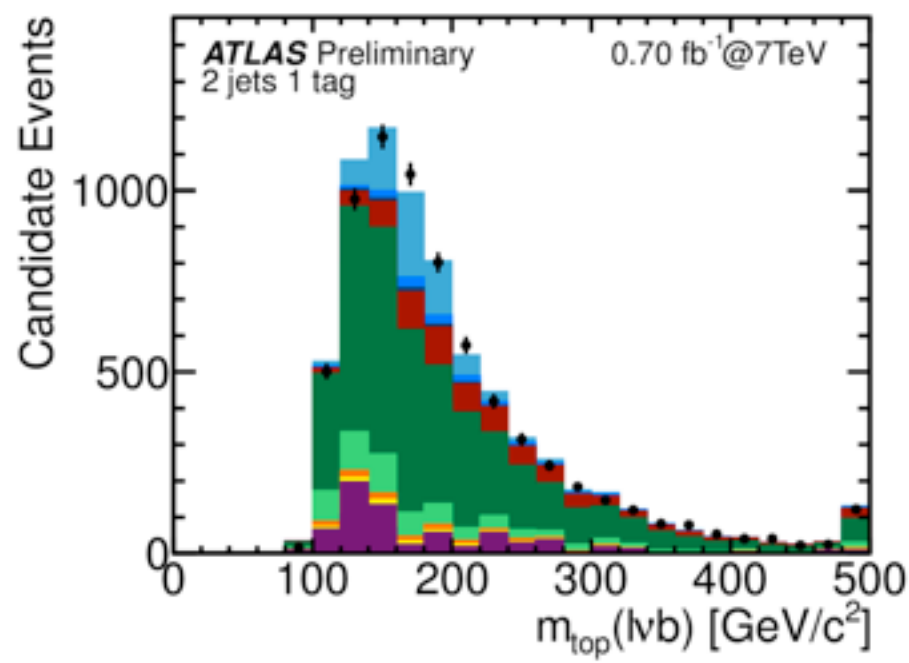
Measurement of t-channel production



- 700 pb^{-1} of 2011 ATLAS data

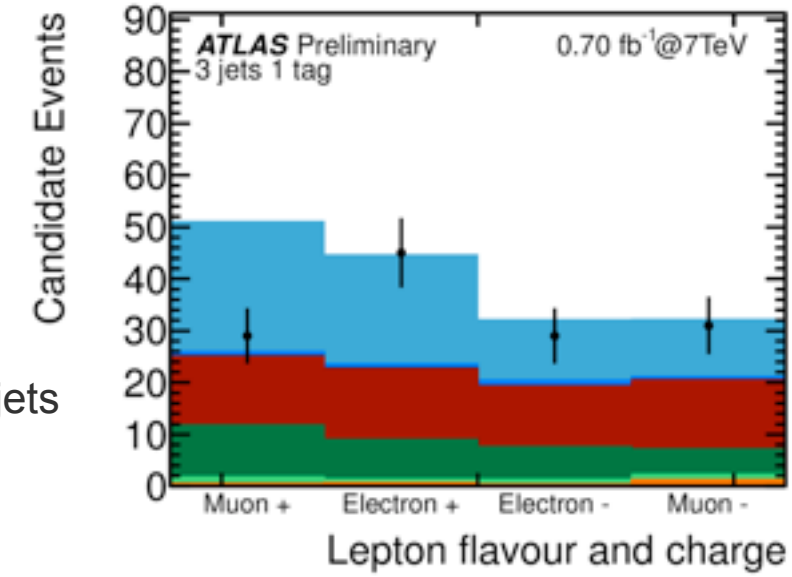




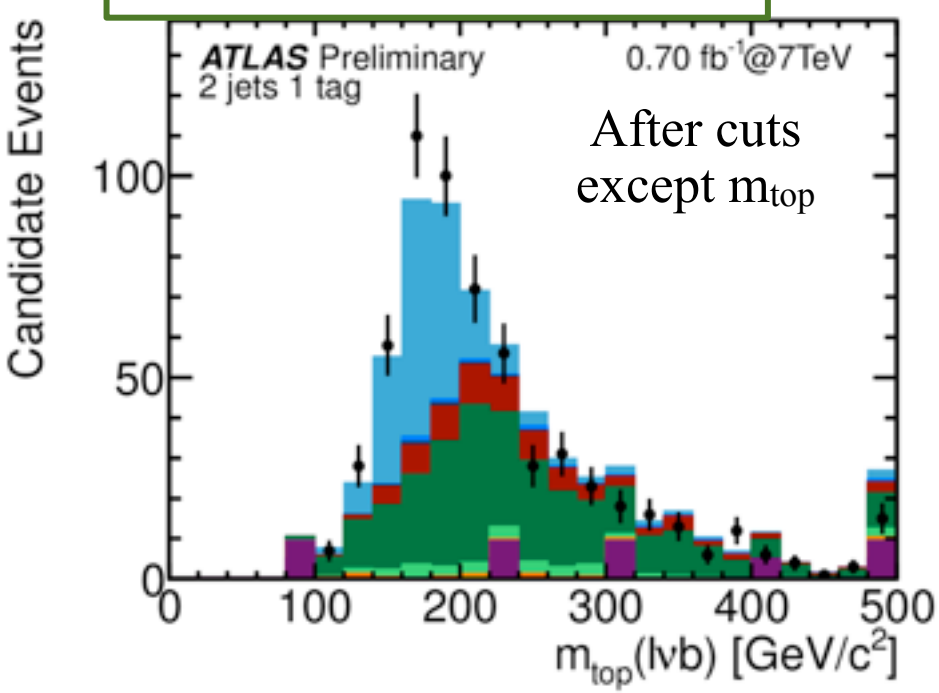


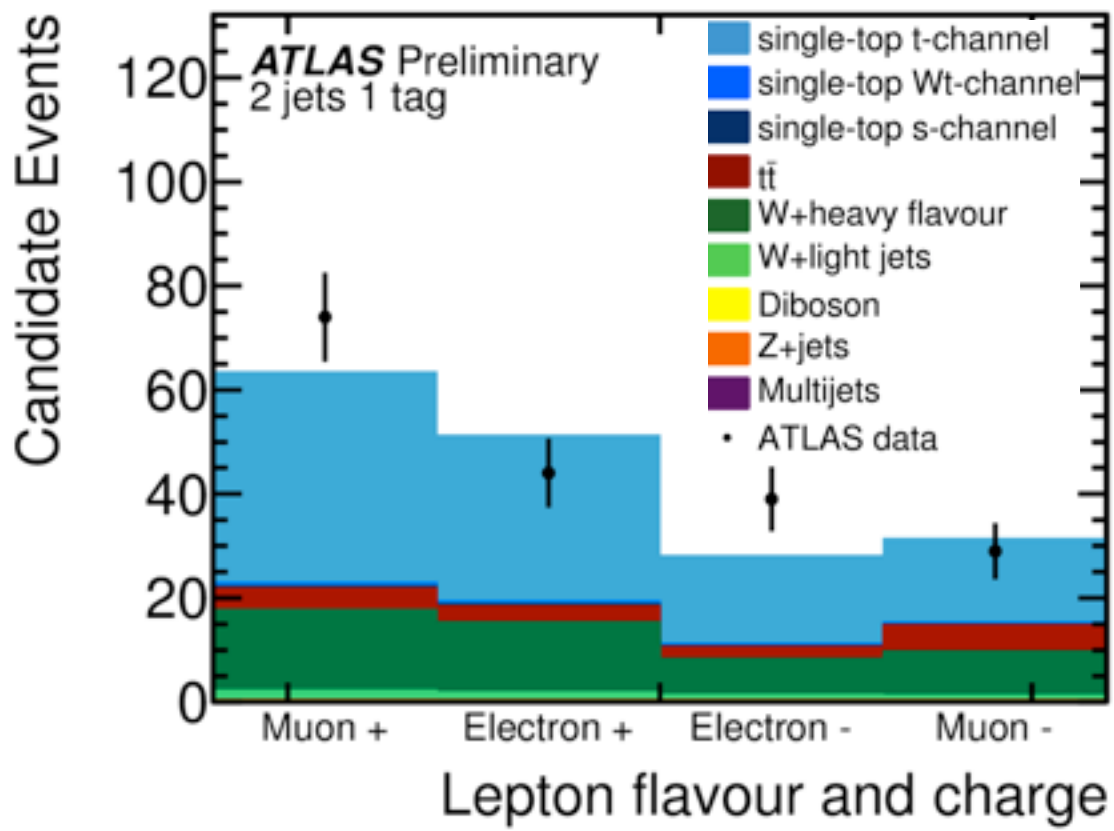
Cut-based t-channel analysis

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

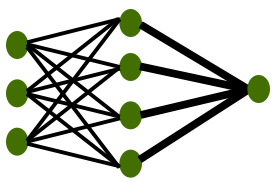


Observed cross section:
$\sigma_t = 90\ ^{+32}_{-22}$ pb
Observed significance:
7.6 σ



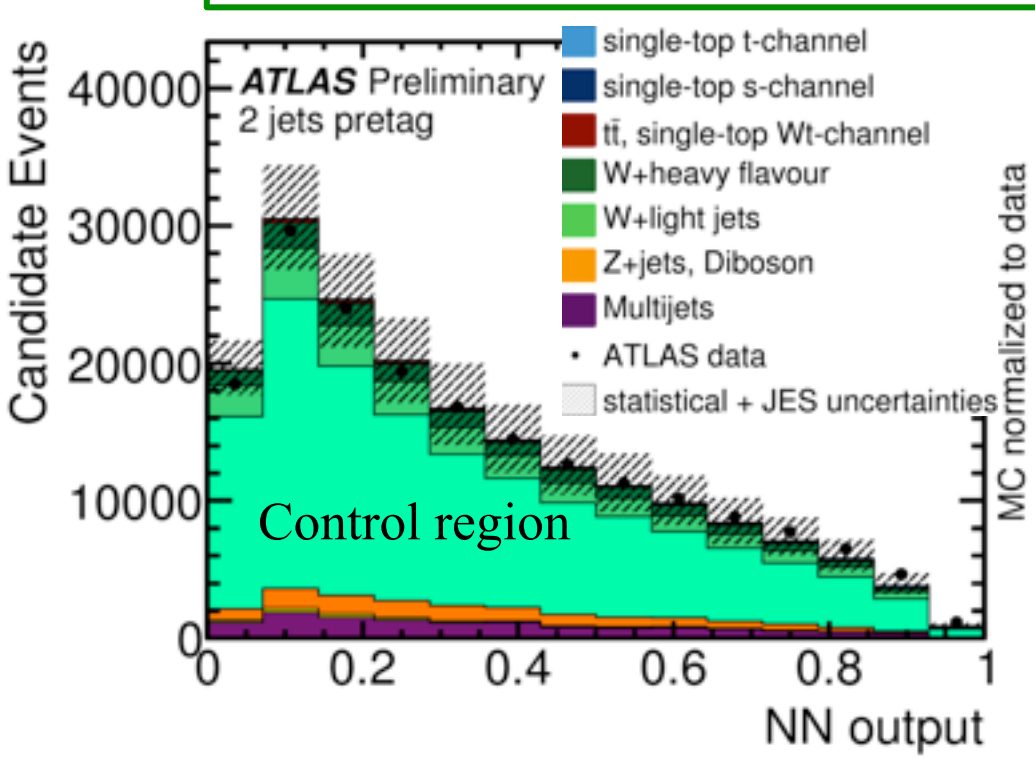


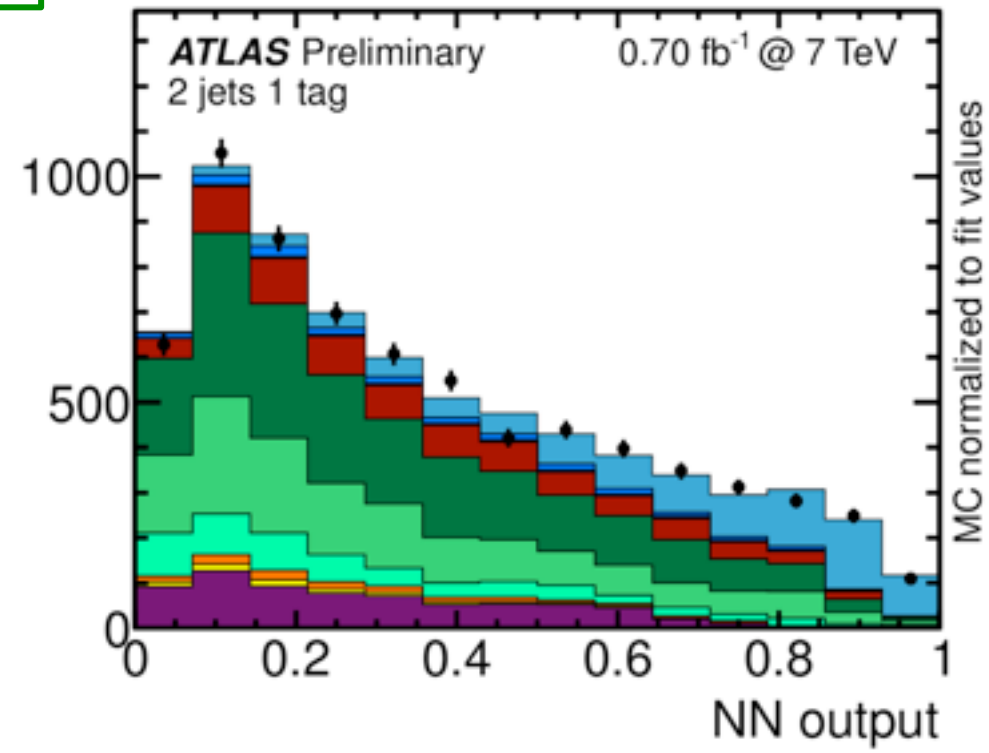
Neural network result



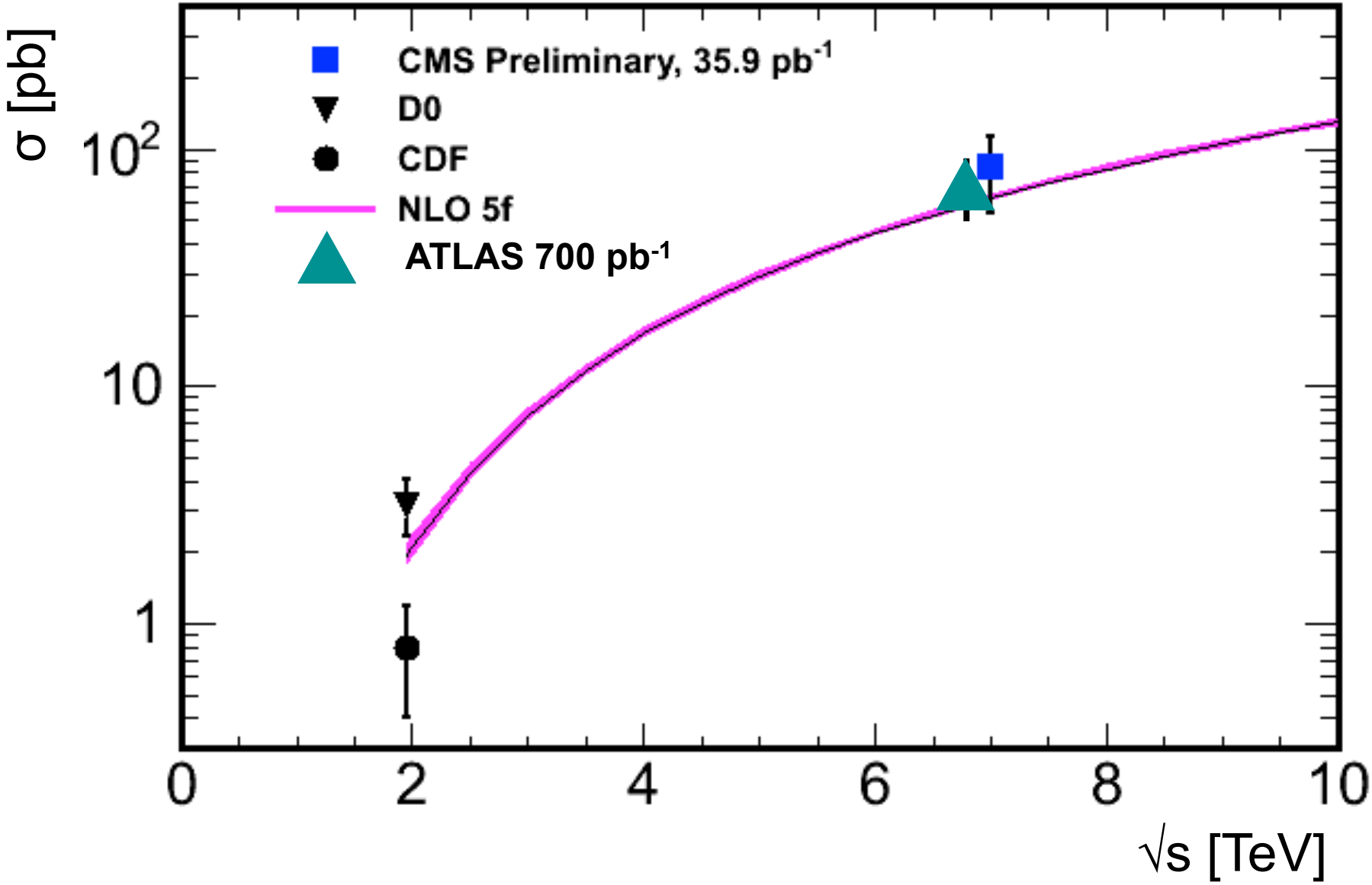
- 22 input variables
- fit shape to signal and W+jets background
- Systematic uncertainties:
  - jet energy scale, b-tagging

NN: Observed cross section:
$\sigma_t = 105\ ^{+37}_{-31}$ pb



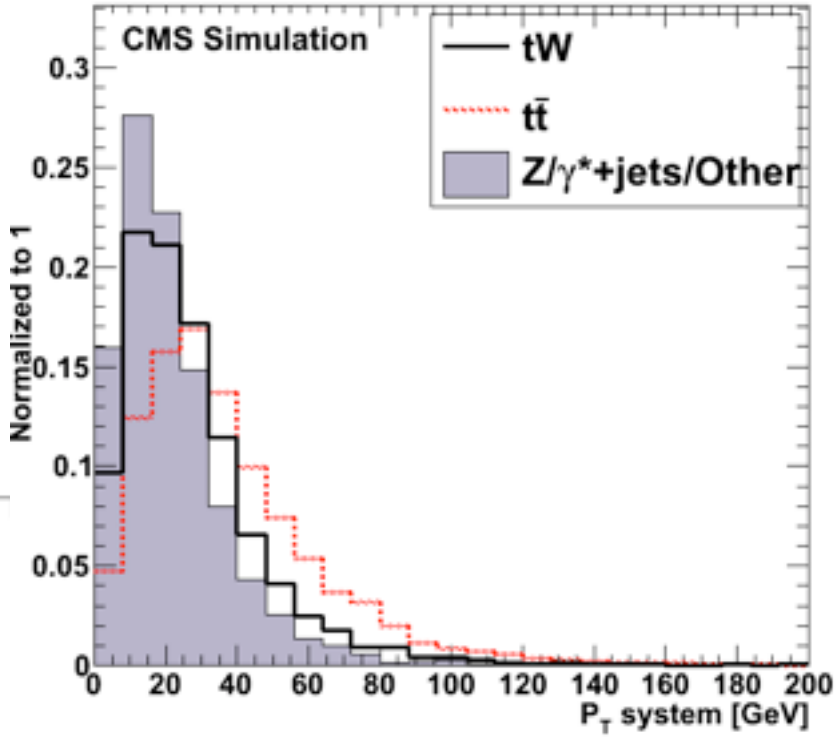


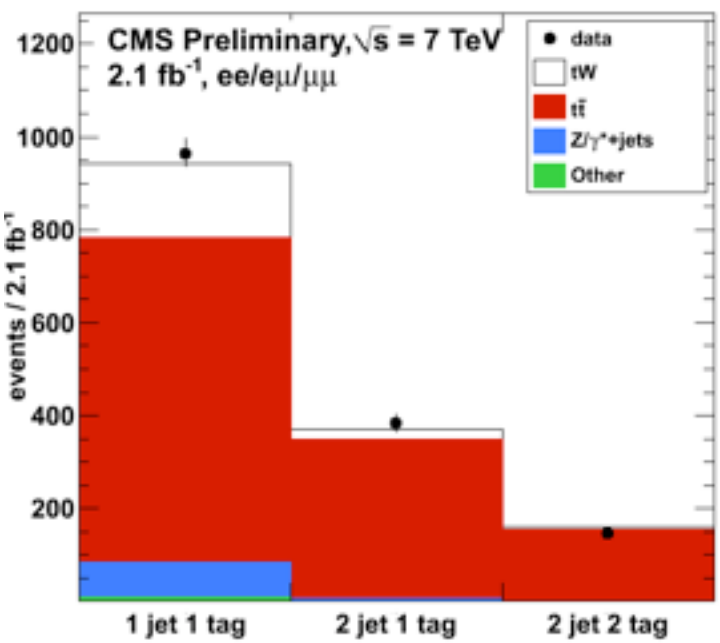
t-channel summary

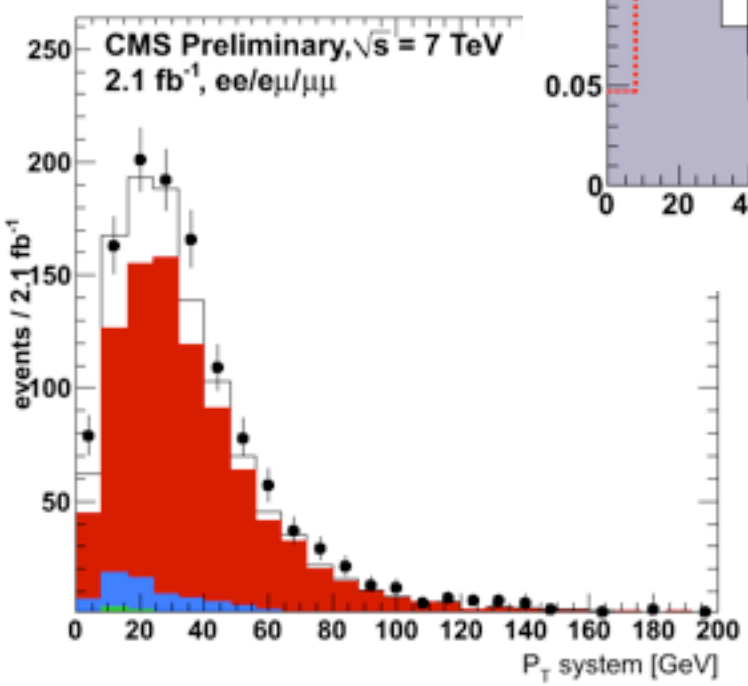


CMS Wt measurement

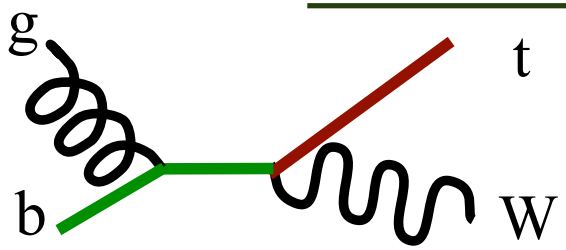
- Never before seen!
- Cut-based analysis using 2.1fb^{-1} of 2011 data
  - Important variable: p_T system
- Cross section from simultaneous fit to Wt and top pairs
- Observed significance 2.7σ



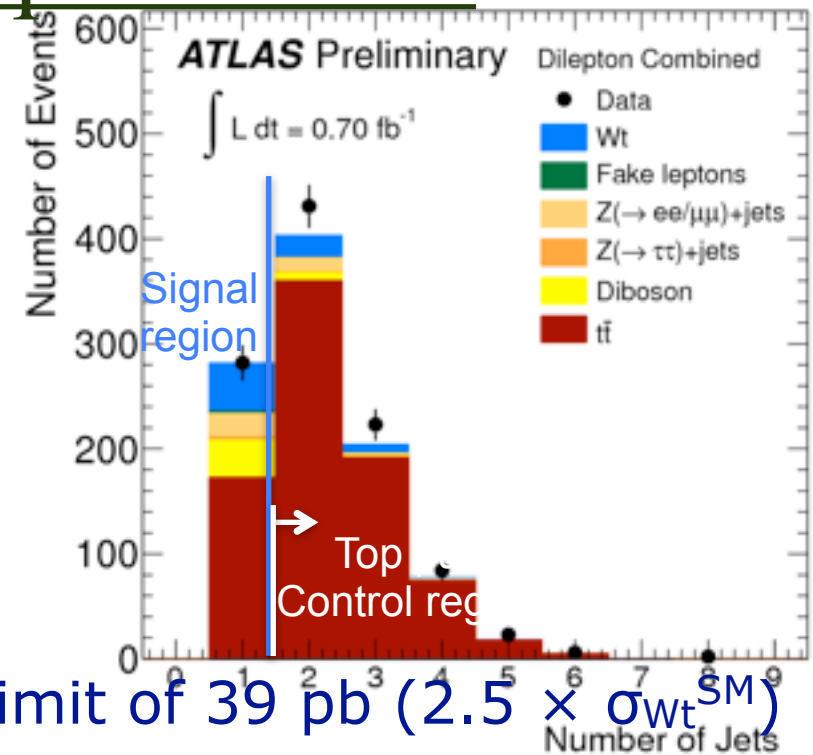




ATLAS Wt associated production



- Search in lepton+jets and di-leptons

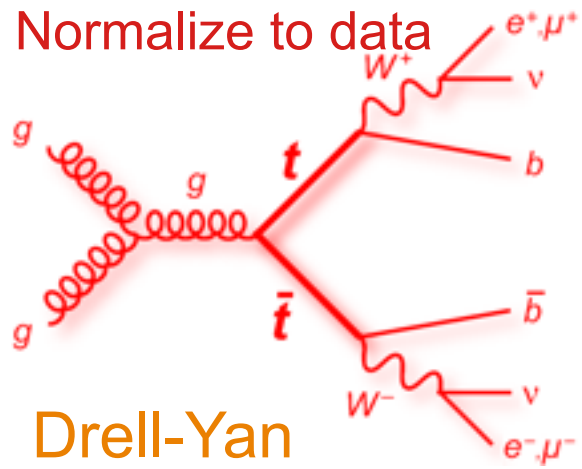


- Set limit of 39 pb ($2.5 \times \sigma_{Wt}^{SM}$)

Dilepton backgrounds:

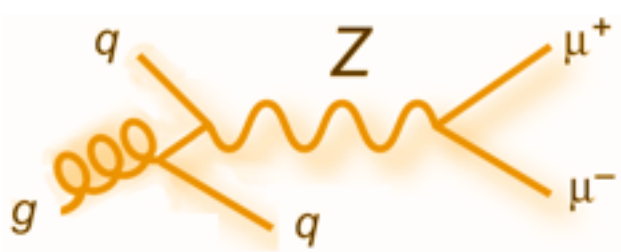
Top quark pairs

- Model using MC@NLO
- Normalize to data

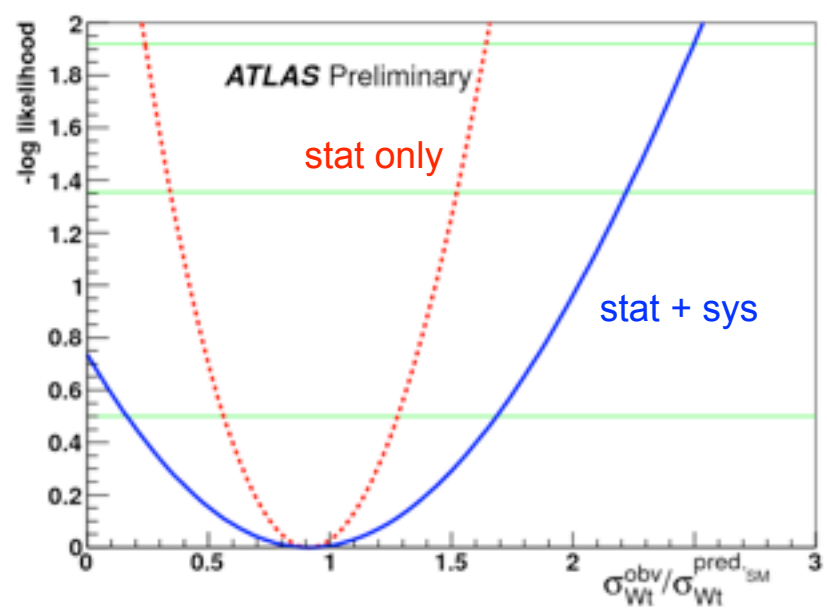


Drell-Yan

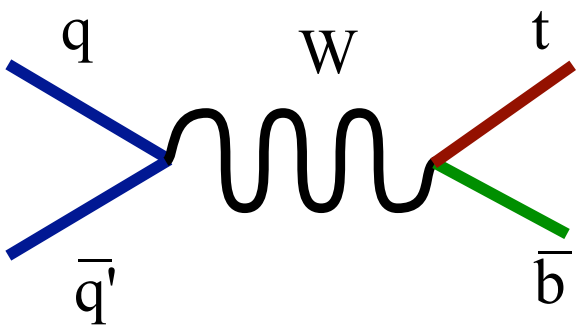
- Model using Alpgen
- Normalize to data

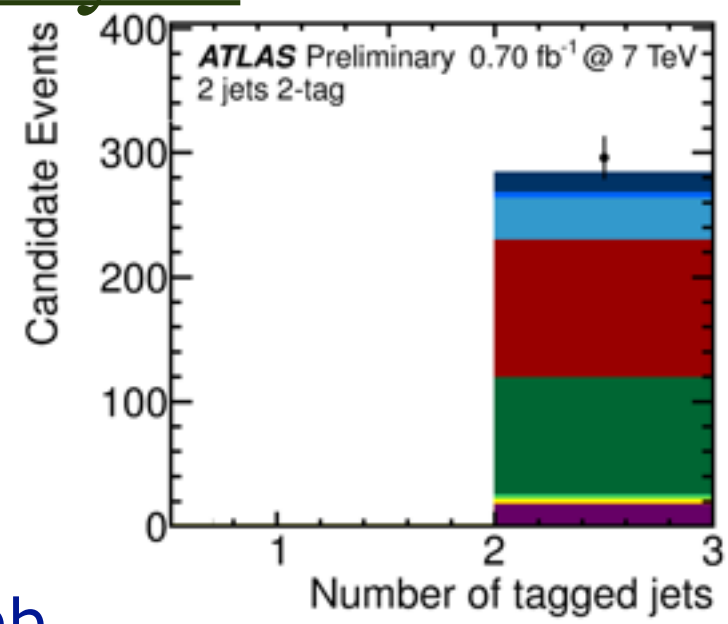


Smaller backgrounds from $Z \rightarrow \tau\tau$, dibosons, W+jets, multijets

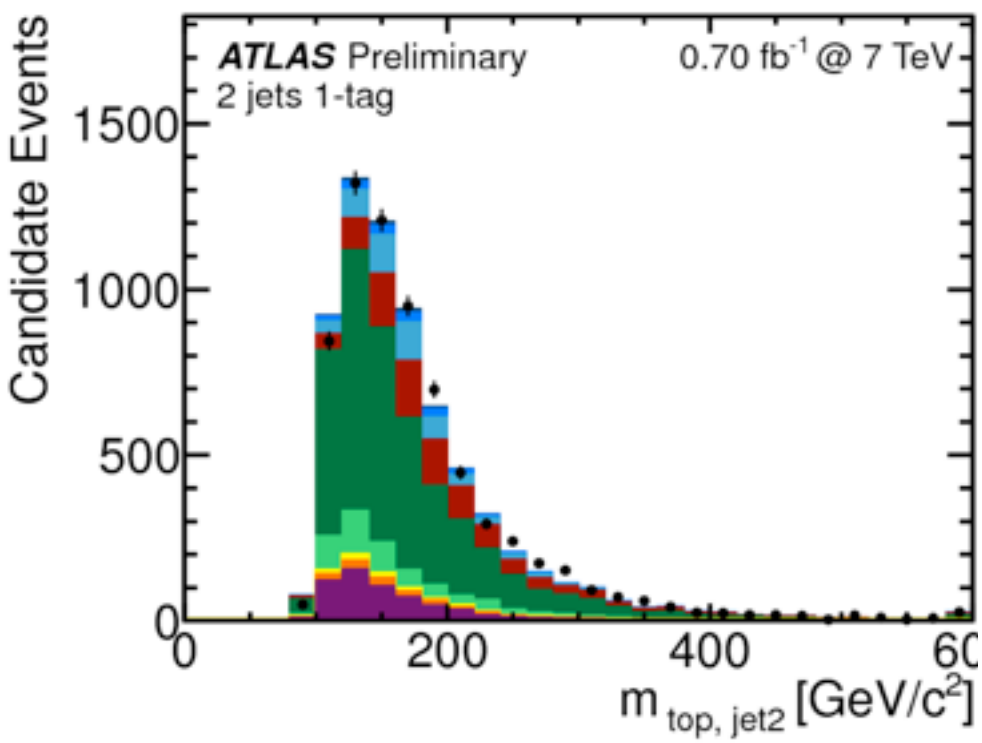


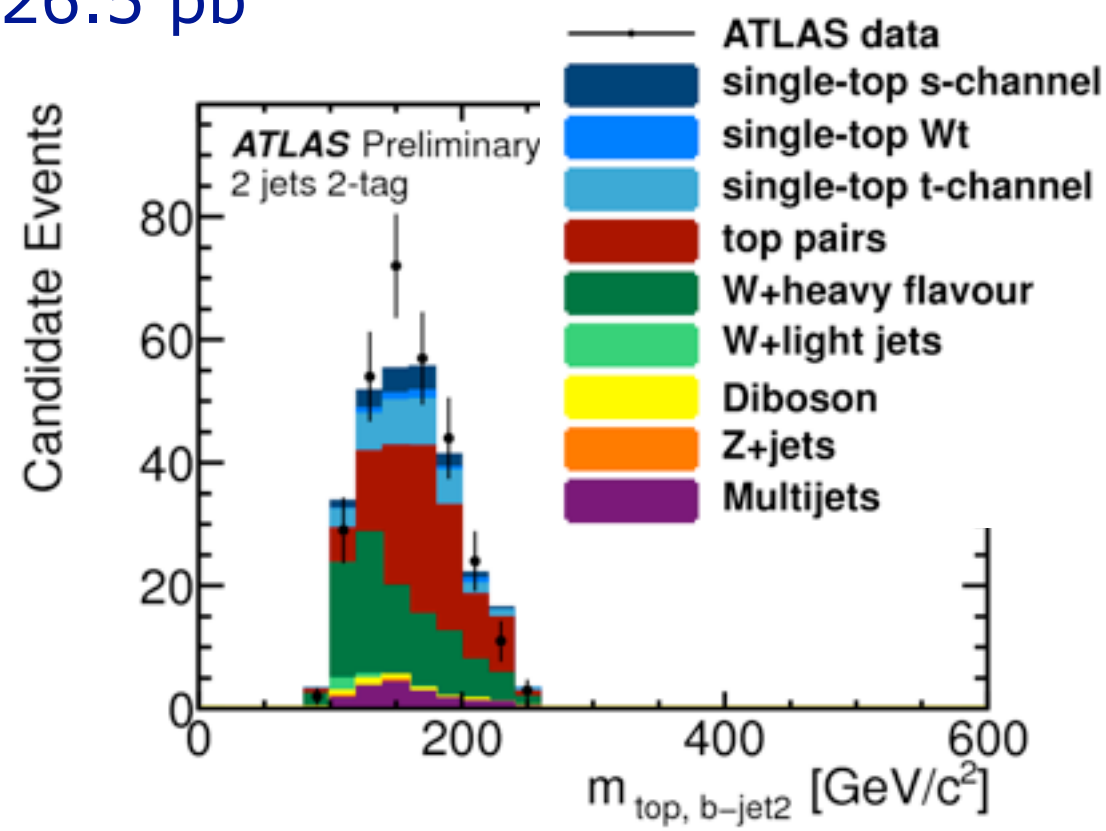
s-channel analysis





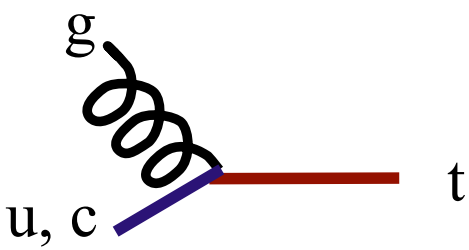
- Search in 700 pb^{-1}
- cut-based selection
- s-channel limit at 95% CL: 26.5 pb



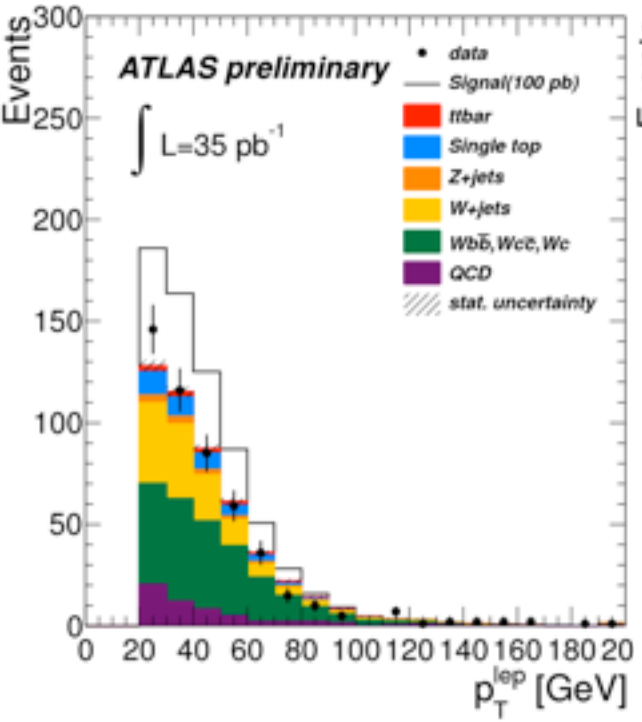


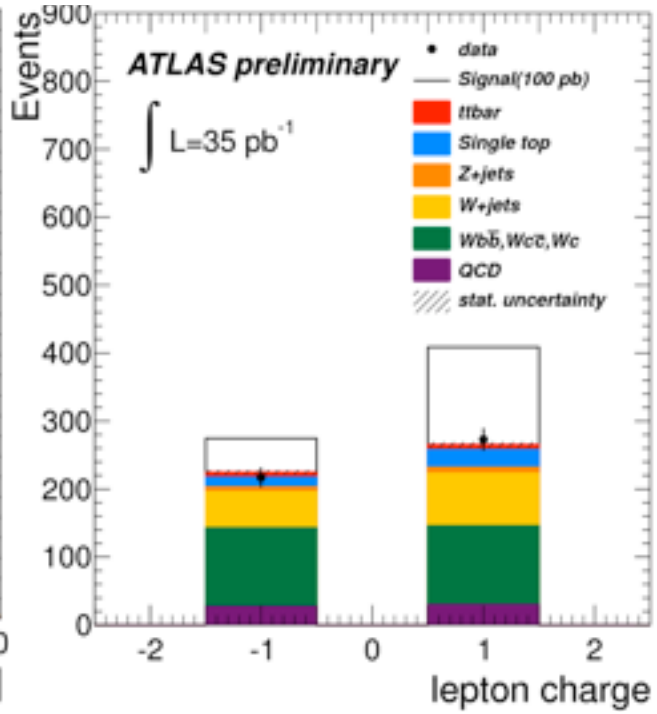
LHC new physics searches

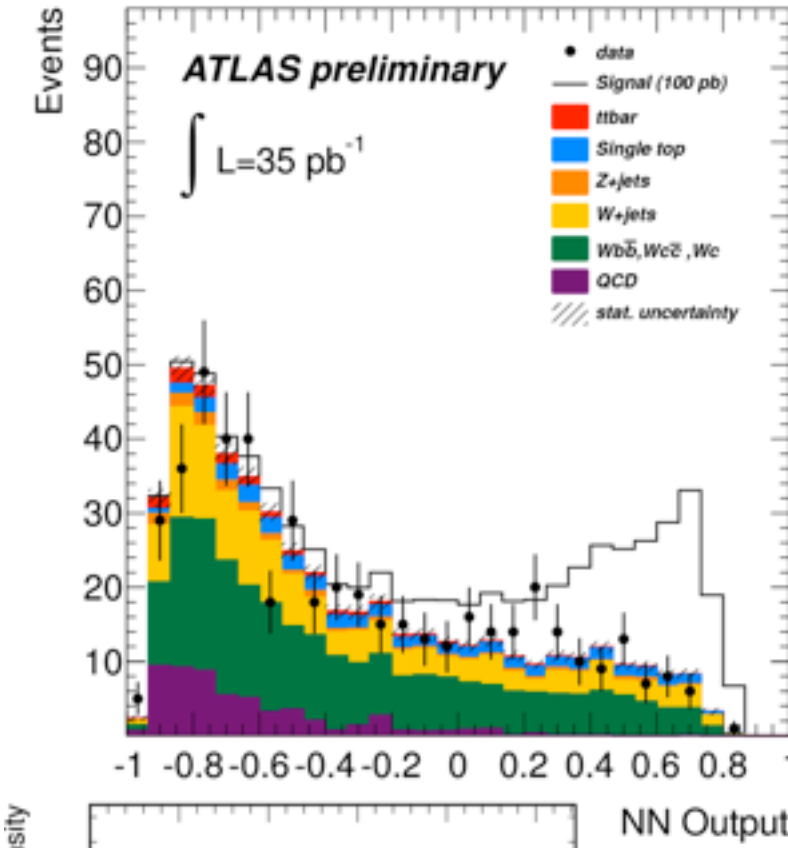
ATLAS FCNC search

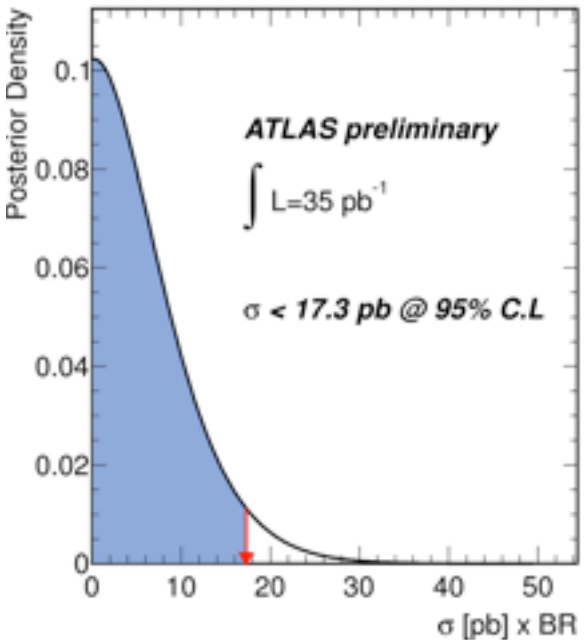


- first single top new physics search
- single-top production

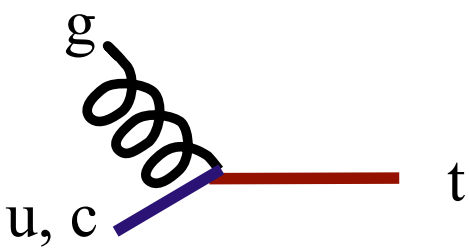




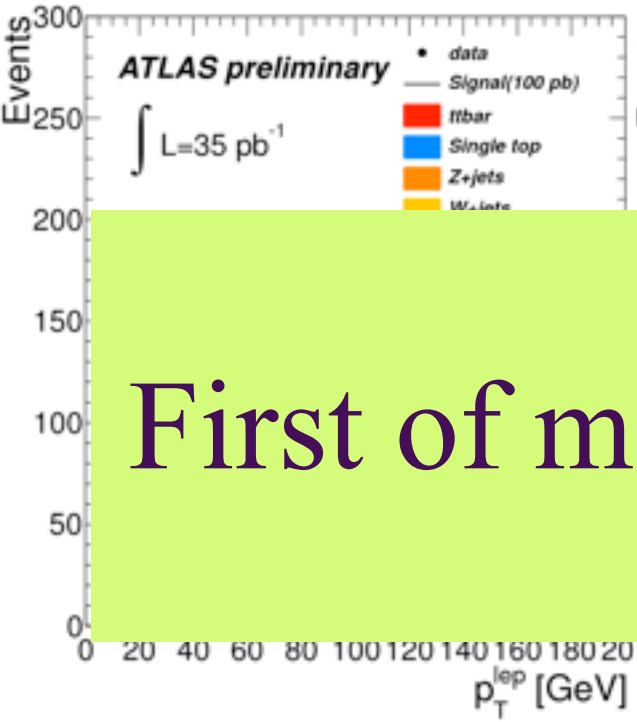


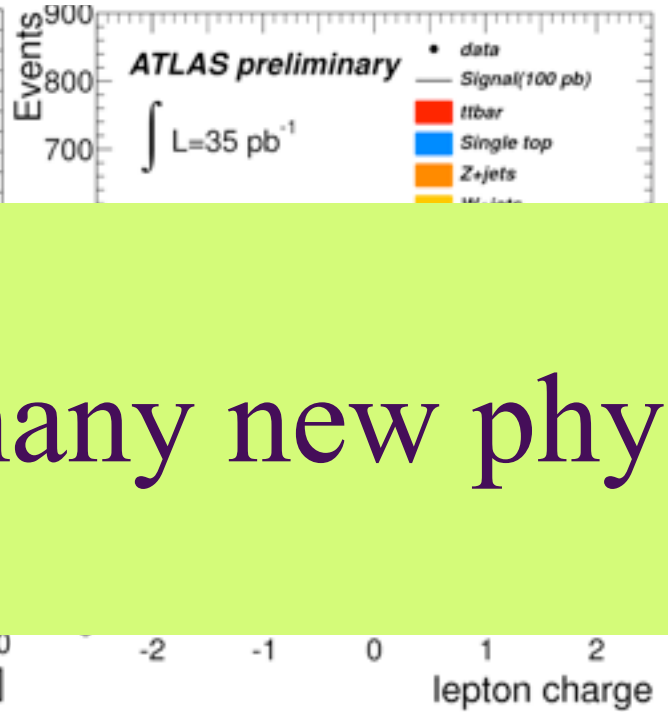


ATLAS FCNC search



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





First of many new physics searches!

Many more new physics searches

- Anomalous couplings

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

  - 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

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

  - 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

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

  - 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, CKM

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

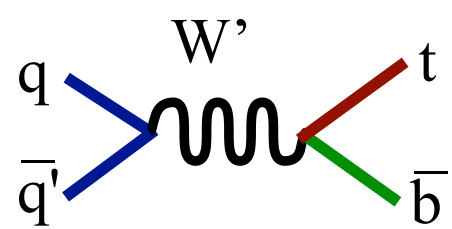
  - In single top and in combination with ttbar
- Resonance searches
  - New heavy boson W'
    - With anomalous couplings?
    - With different CKM matrix - ttbar asymmetry?
    - Charged Higgs decaying to tb
  - Fourth generation quarks
    - B' or T' decaying to single top
- New particles produced together 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, CKM

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

  - 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

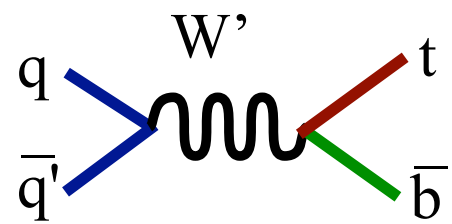


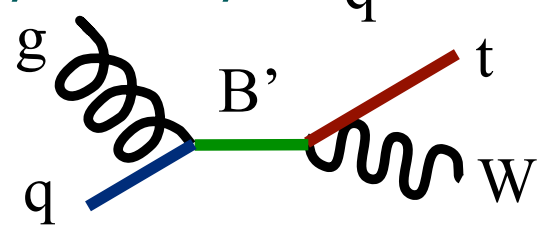
Many more new physics searches

- Anomalous couplings - magnitude, complex phase, CKM

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

  - 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



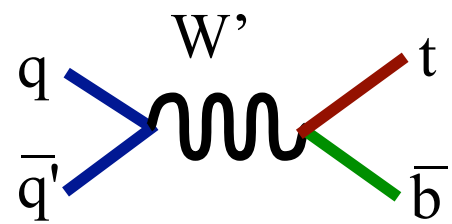


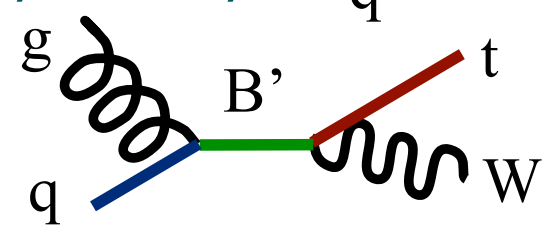
Many more new physics searches

- Anomalous couplings - magnitude, complex phase, CKM

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

  - 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

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