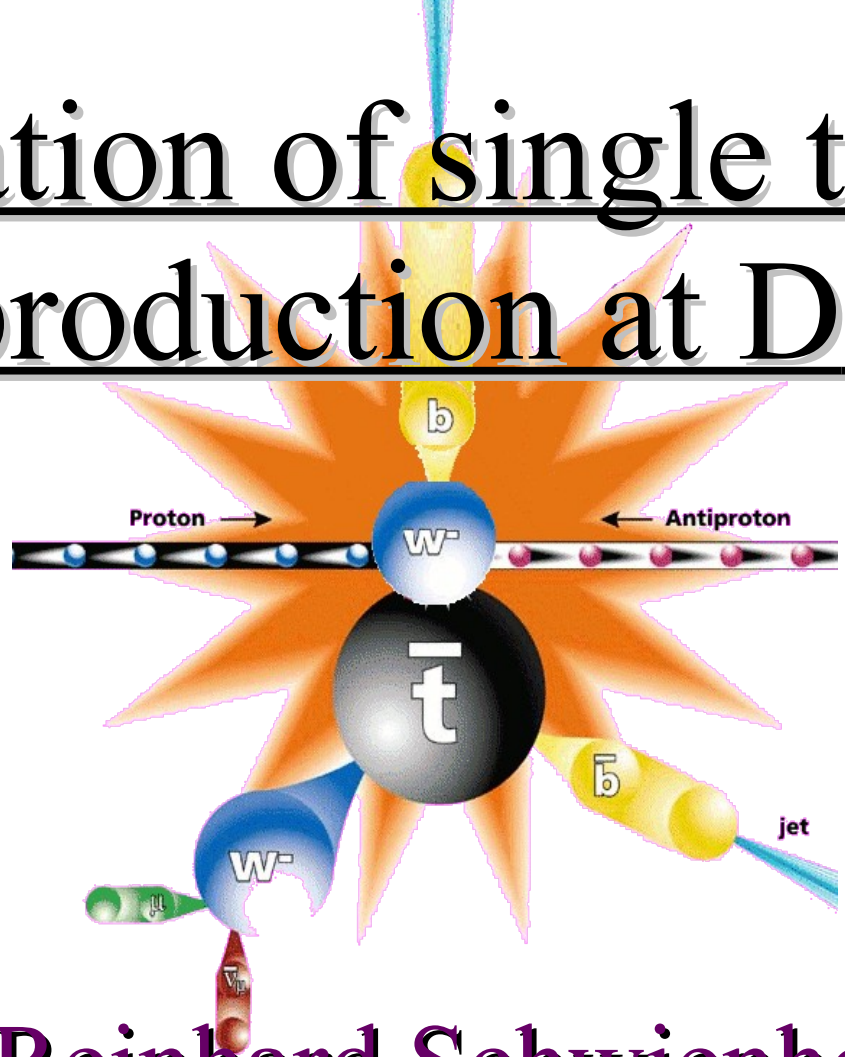
Observation of single top quark production at DØ



Reinhard Schwienhorst

MICHIGAN STATE UNIVERSITY

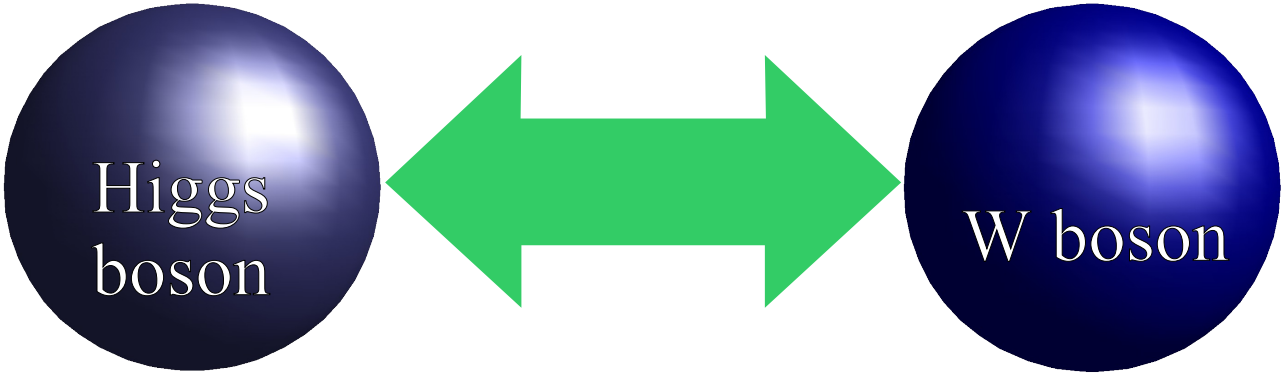
II. Physikalisches Institut Seminar, Universität Göttingen, 23. Oktober 2009

Outline

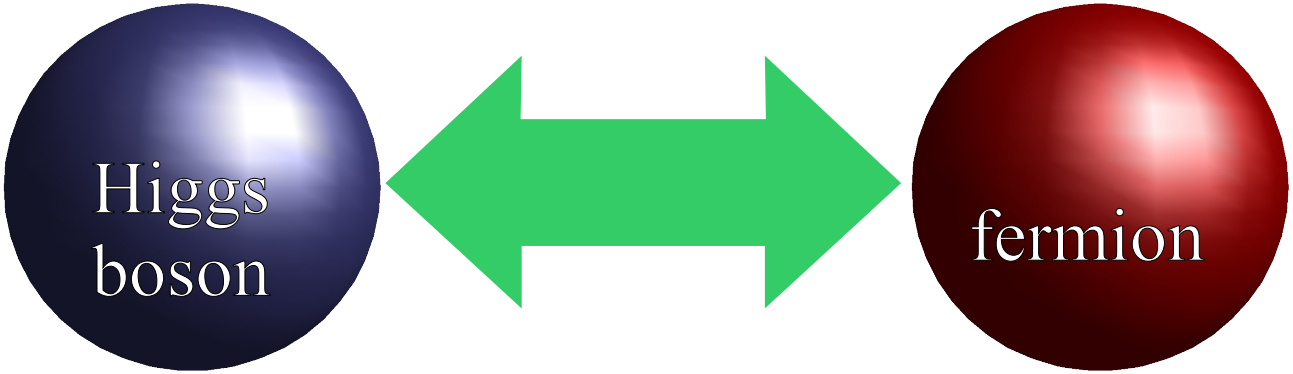
- Introduction
- Single top quark production
- Observation of single top quark production at DØ
- CDF and Tevatron combination
- New physics searches
- LHC outlook
- Conclusions

Electroweak symmetry breaking

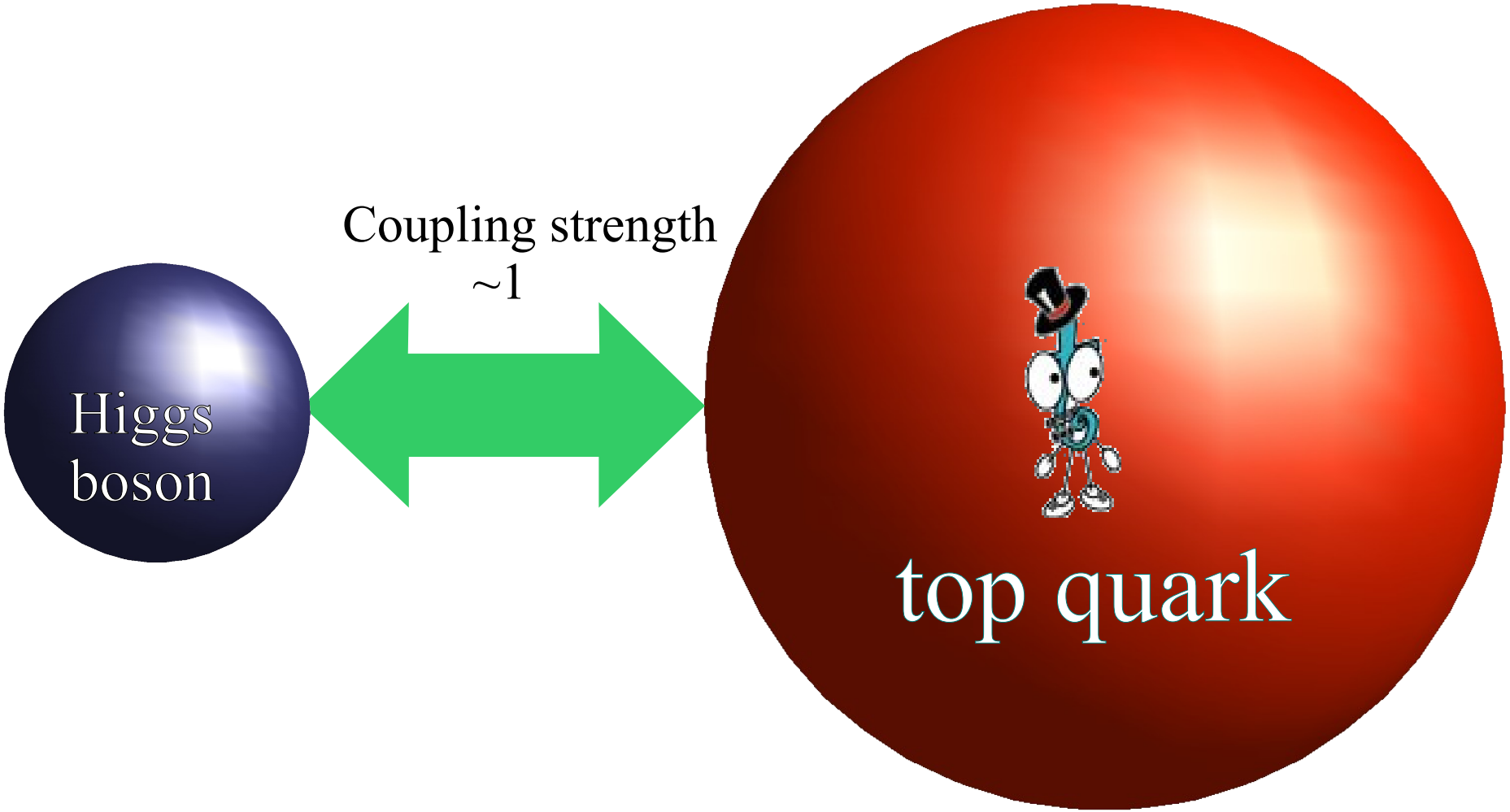
Gauge boson coupling to Higgs field



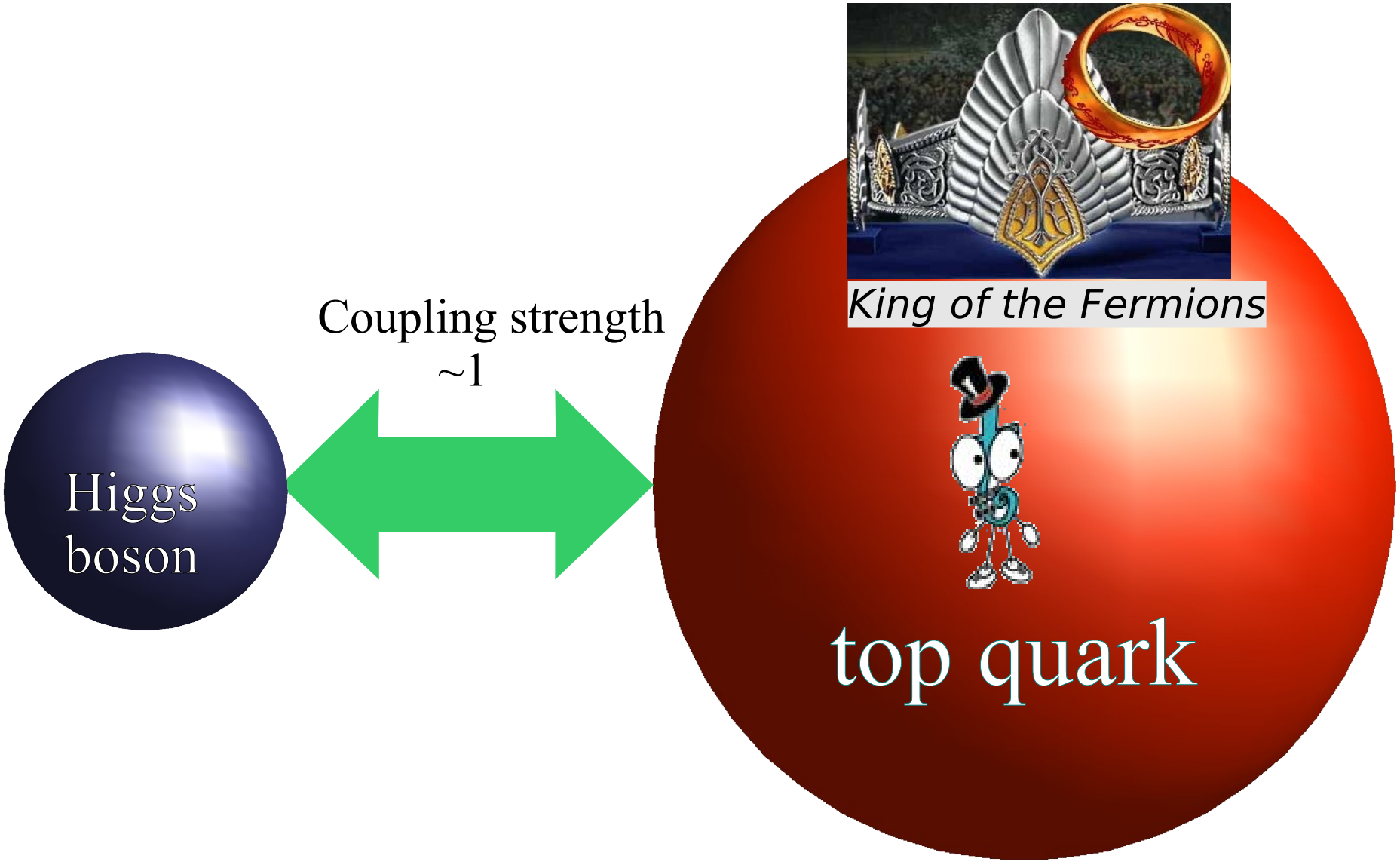
Fermions acquire mass through Higgs coupling



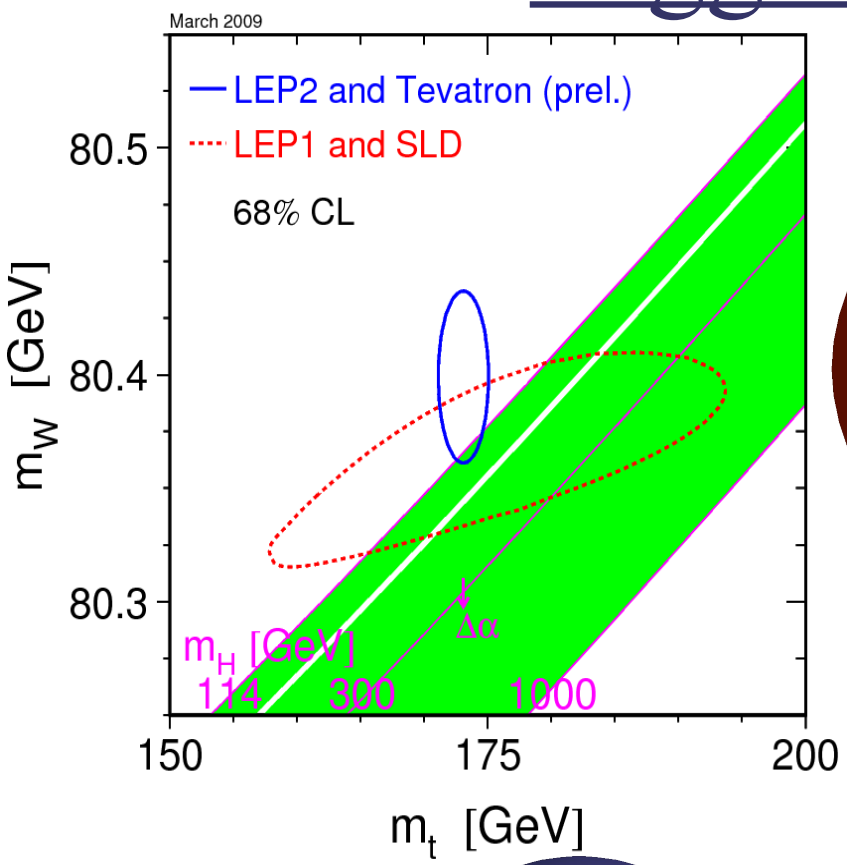
Top quark

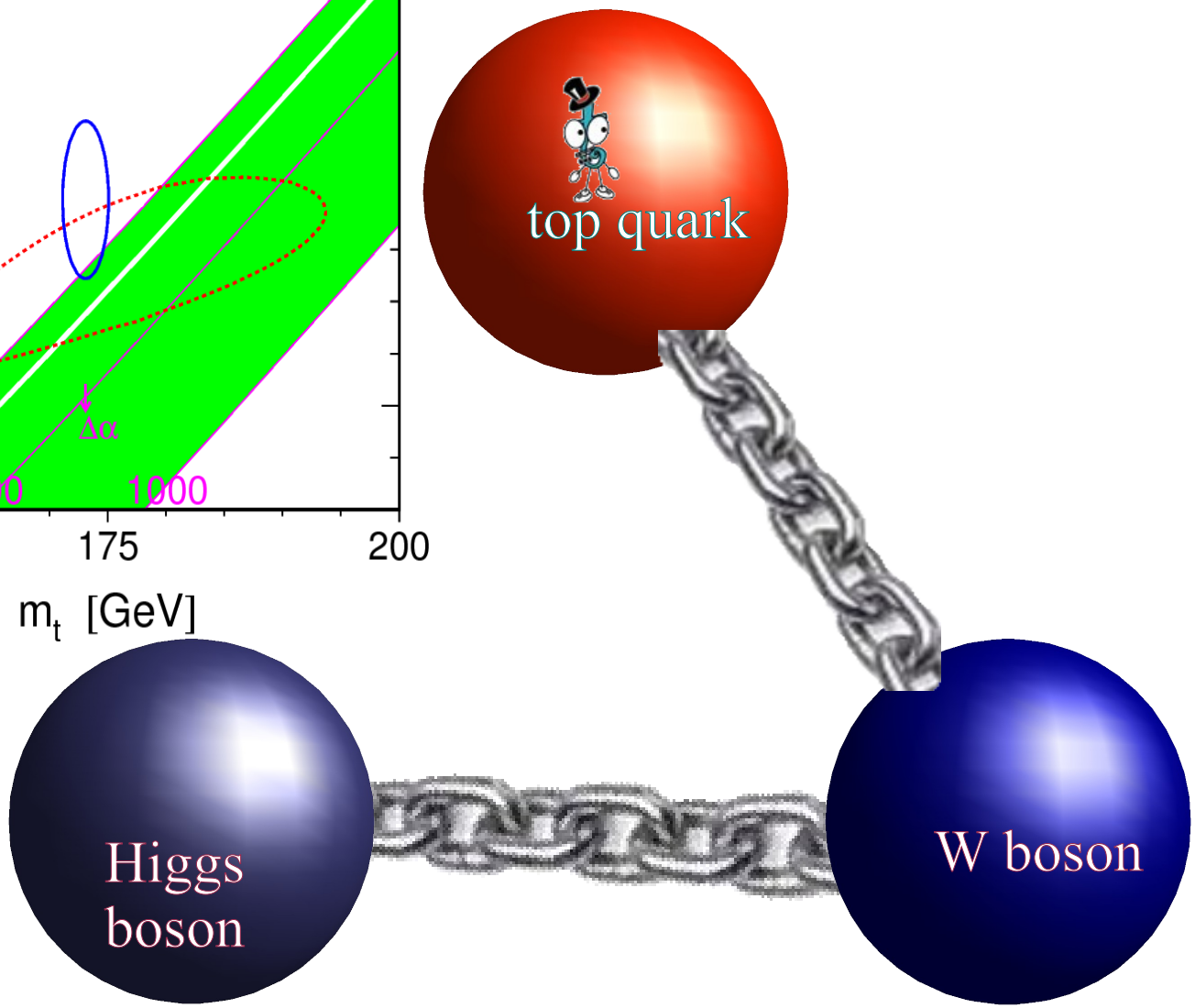


Top quark

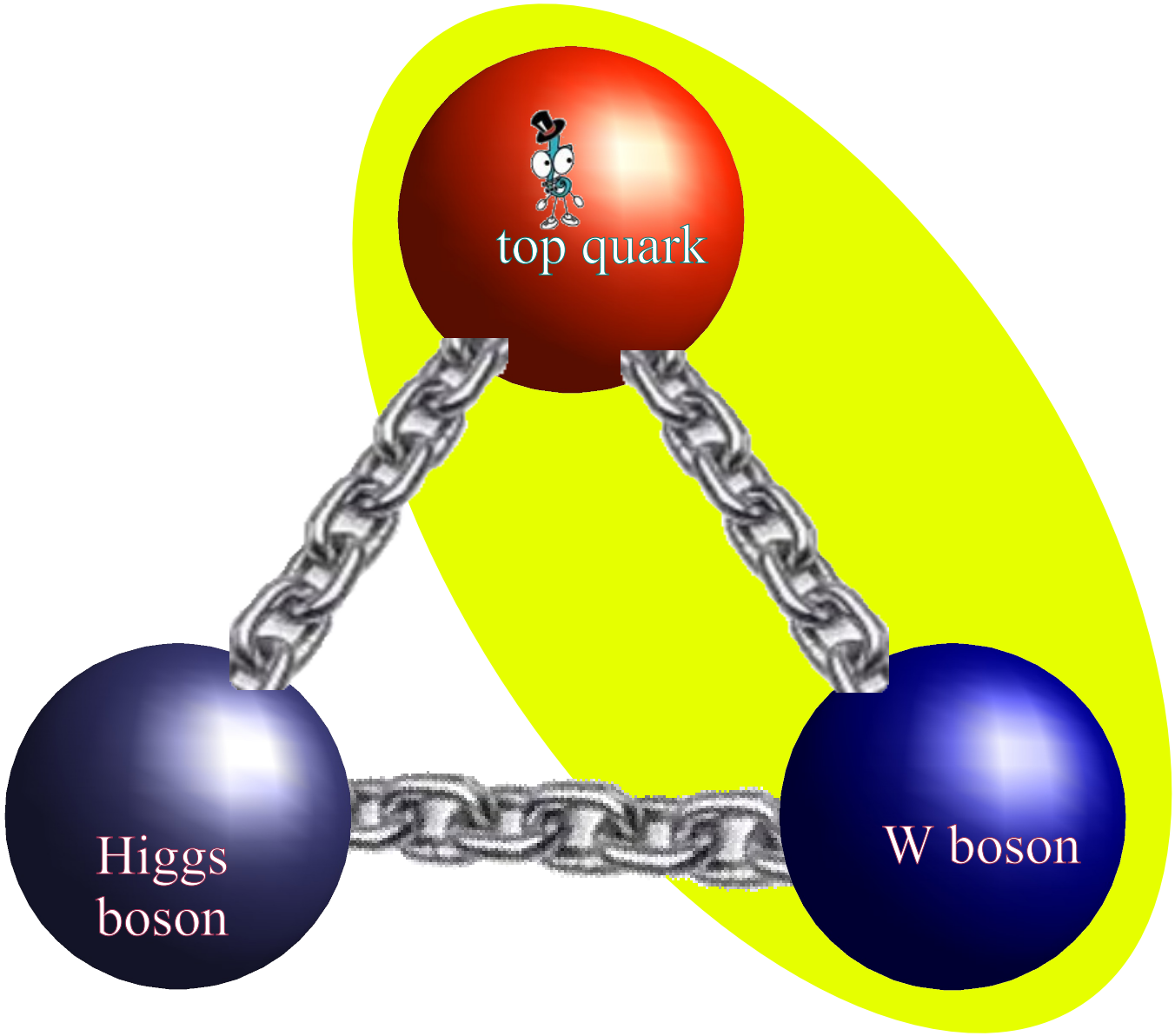

King of the Fermions
Coupling strength
~1
Higgs
boson
top quark

Higgs mass estimate

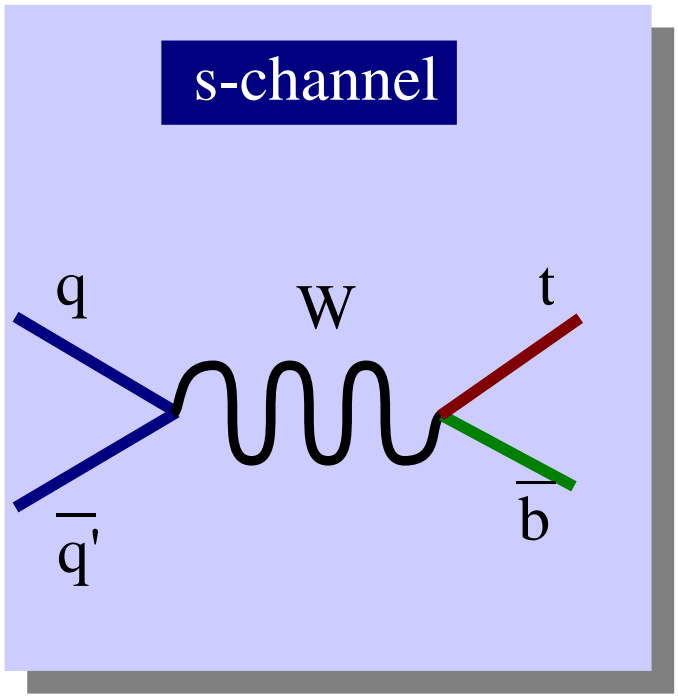


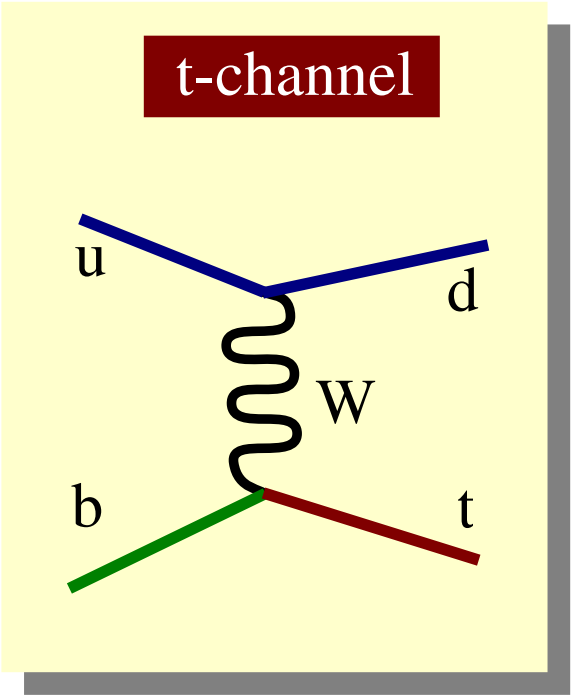


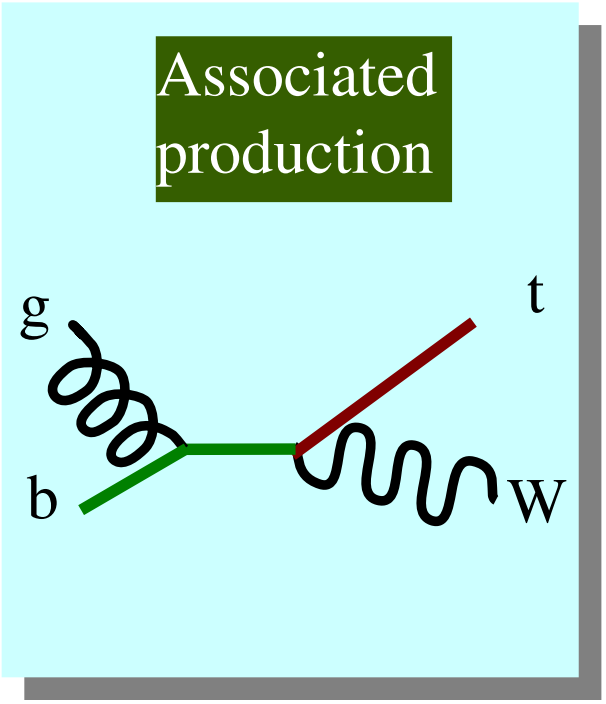
Key to electroweak symmetry breaking



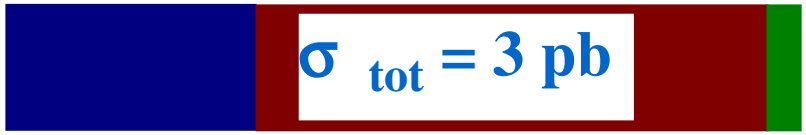
SM single top quark production



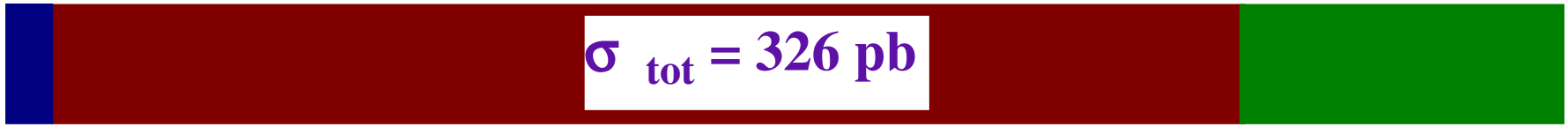




Tevatron:

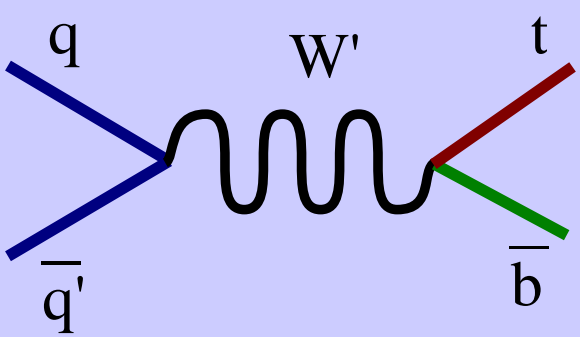


LHC:



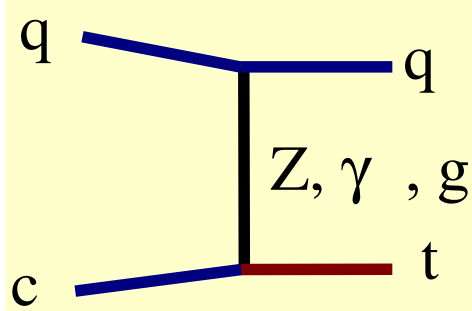
New physics

s-channel



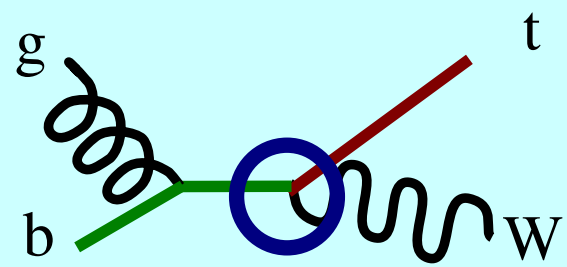
New heavy boson
Or charged Higgs

t-channel



Flavor
Changing
Neutral
Current

Associated production



Modified
Wtb coupling

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

Run I

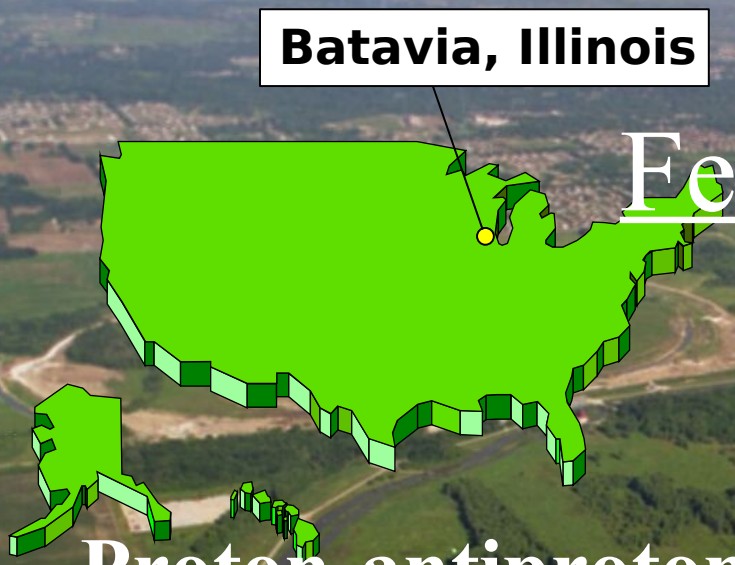
Run II

· 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

Measurement history

Single Top Cross Section	Signal Significance Expected	Signal Significance Observed	CKM Matrix Element V_{tb}
December 2006 DØ (0.9 fb^{-1})			PRL 98, 181802 (2007)
4.7 ± 1.3 pb	2.3 σ	3.6 σ	$\lvert V_{tb} f_1^L \rvert = 1.31^{+0.25}_{-0.21}$ $\lvert V_{tb} \rvert > 0.68$ at 95% CL
September 2008 CDF (2.2 fb^{-1})			PRL 101, 252001 (2008)
2.2 ± 0.7 pb	4.9 σ	3.7 σ	$\lvert V_{tb} f_1^L \rvert = 0.88^{+0.13}_{-0.12}$ $\lvert V_{tb} \rvert > 0.66$ at 95% CL

Experimental setup: Fermilab Tevatron in Run II



Proton-antiproton collider

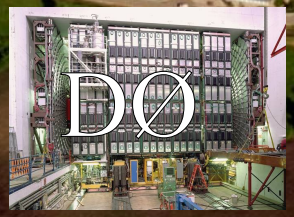
CM energy 1.96TeV

→ ***Energy frontier***

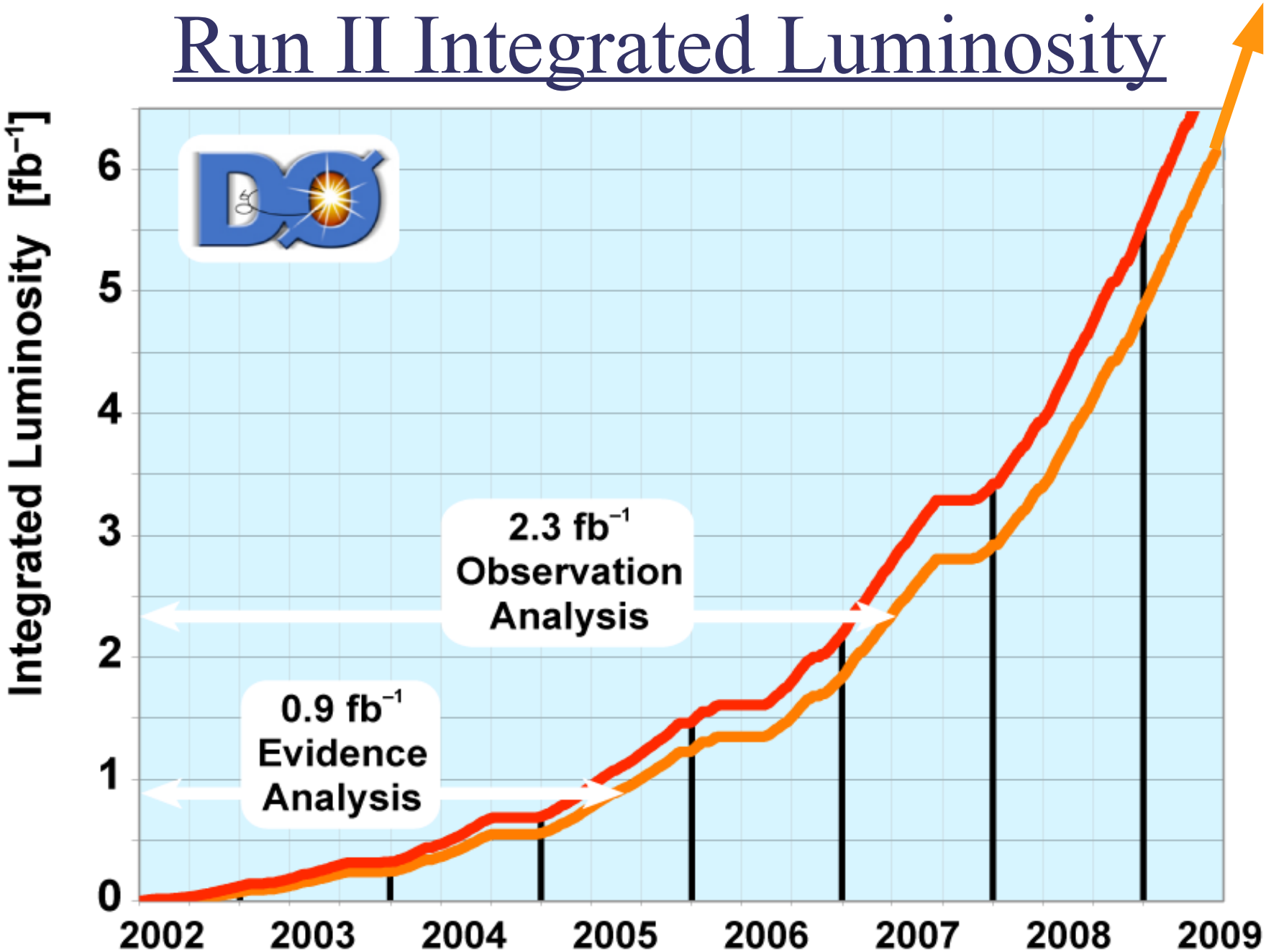
Instantaneous luminosity >350E30cm^{-2}s^{-1}

– >4 interactions per crossing, 1.7M crossing per second

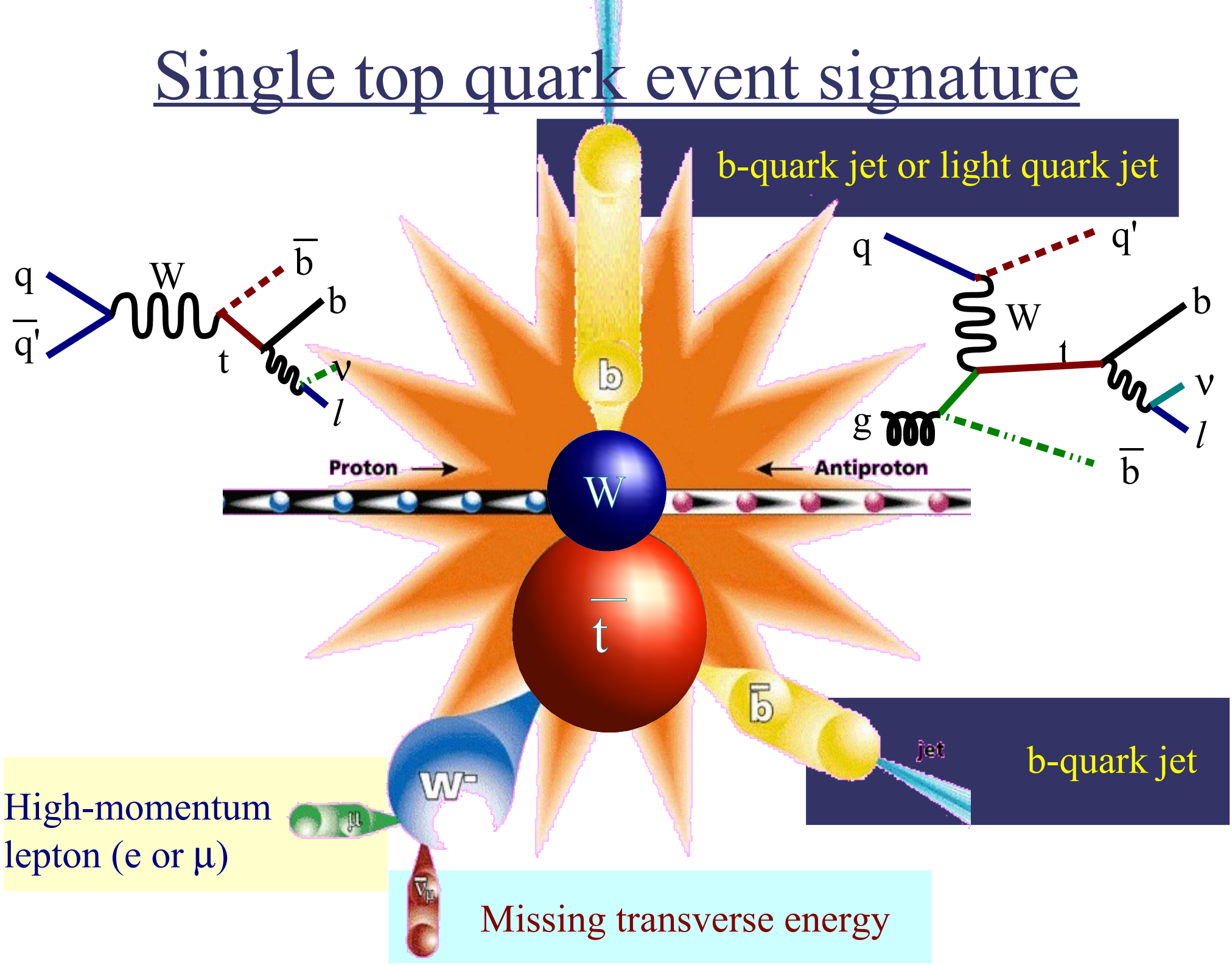
→ ***Luminosity frontier***



Fermilab Tevatron Run II Integrated Luminosity

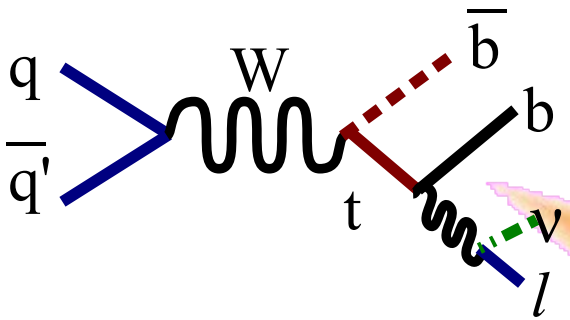


Single top quark event signature

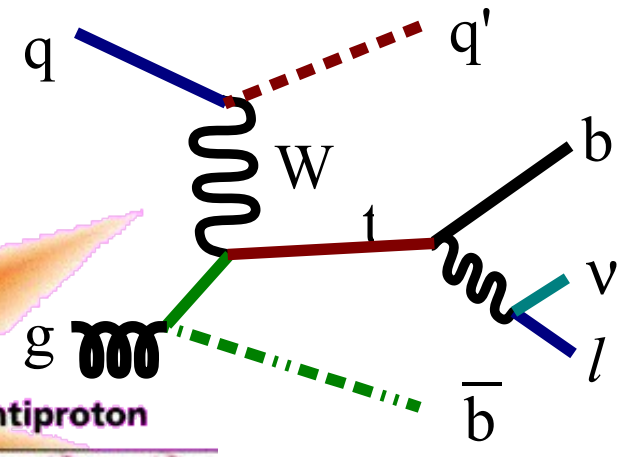


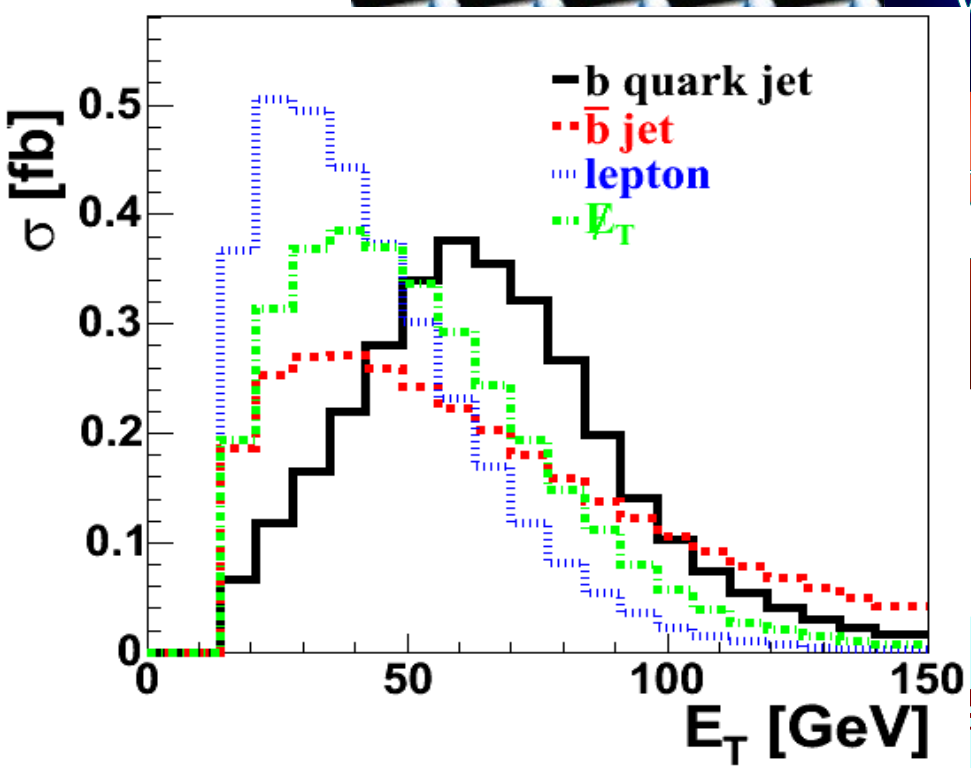
Single top quark event signature

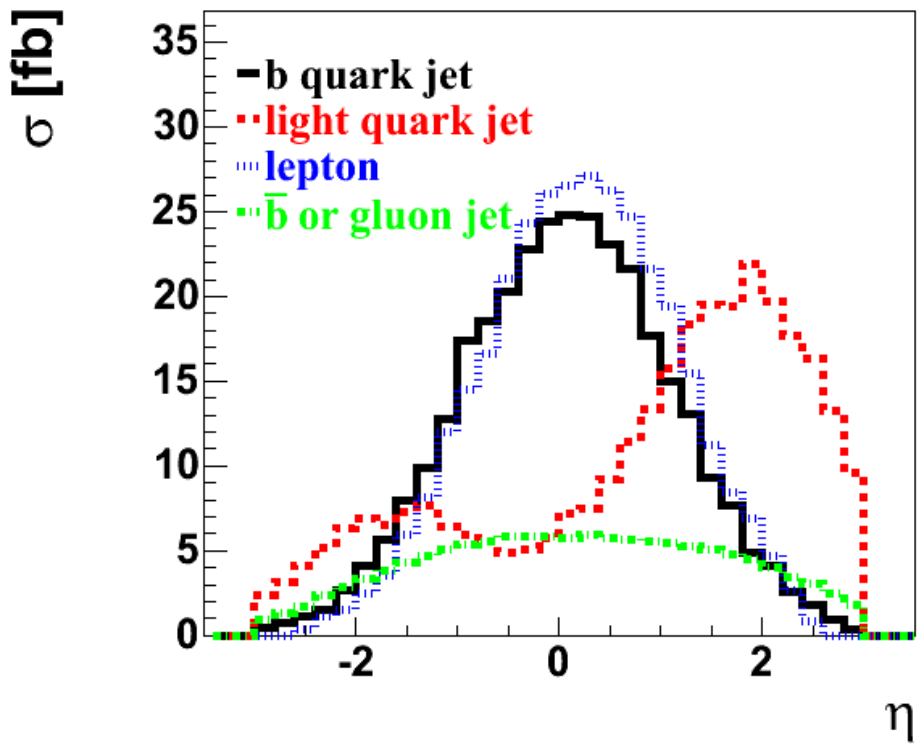
s-channel



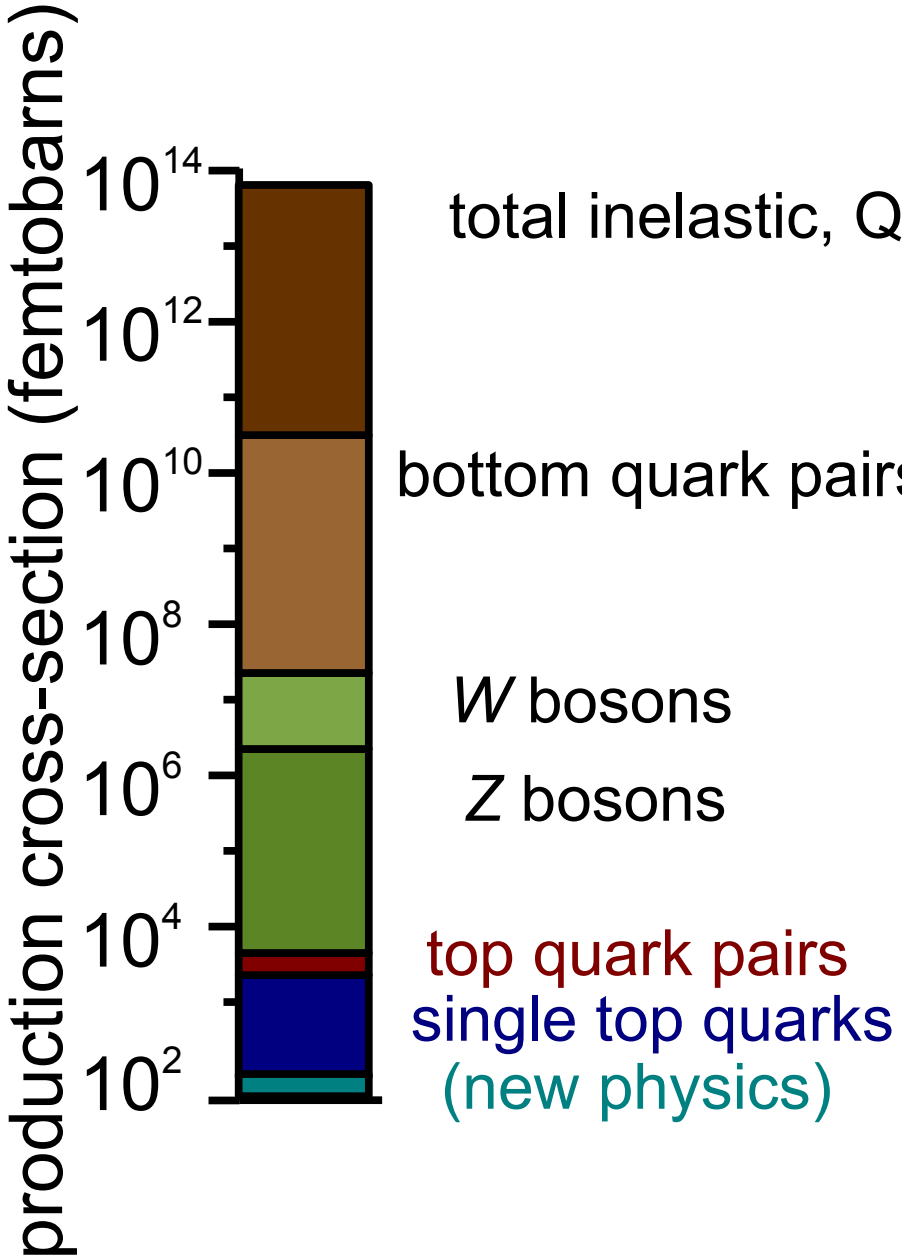
t-channel

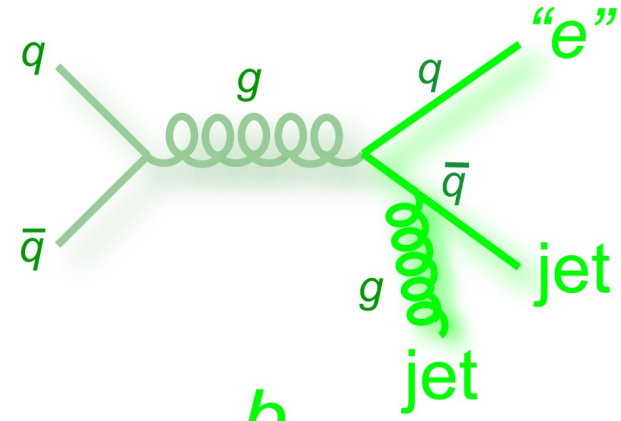


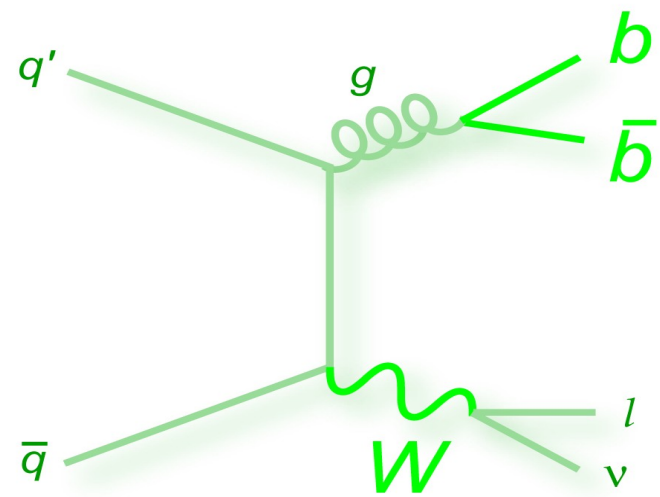


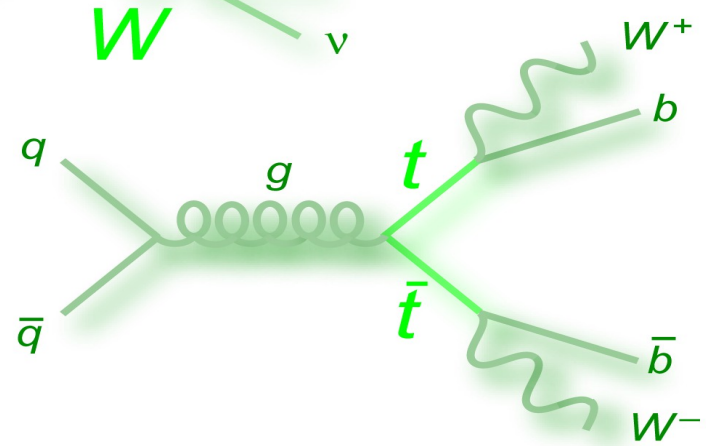


Background processes



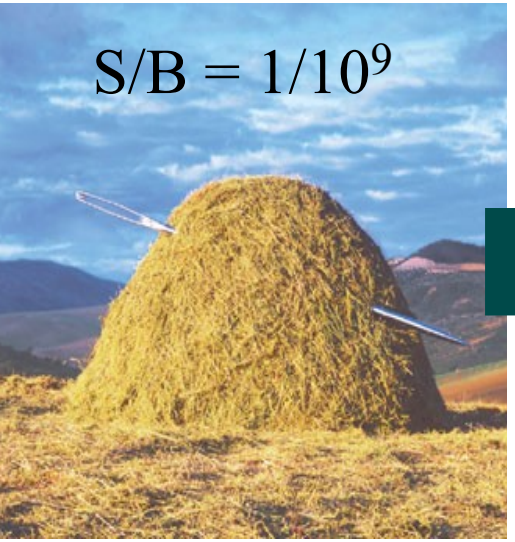




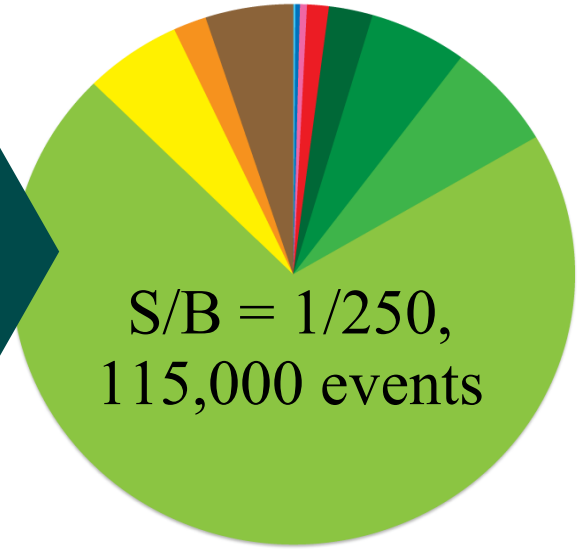


Analysis outline

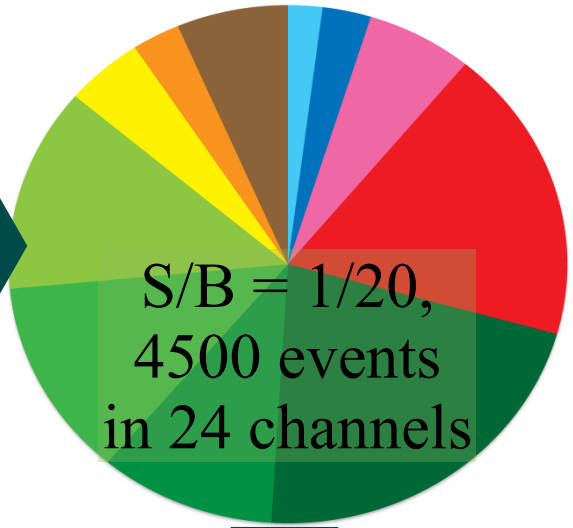
Trigger selection



Single top event kinematics

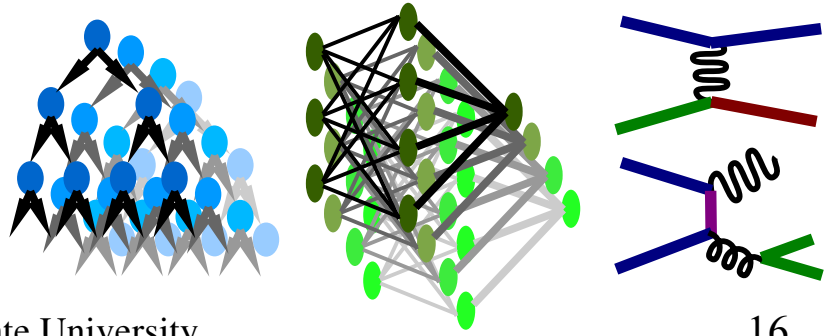


b-quark tagging

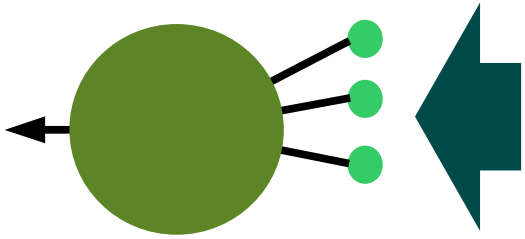


Multivariate techniques

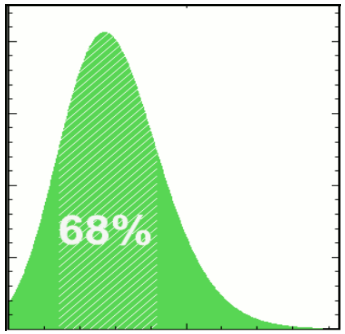
BDT **BNN** **ME**



Combination

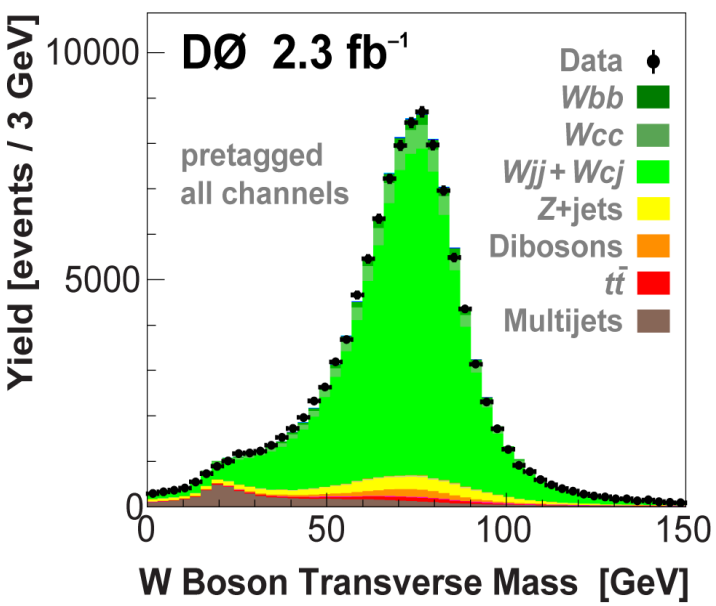


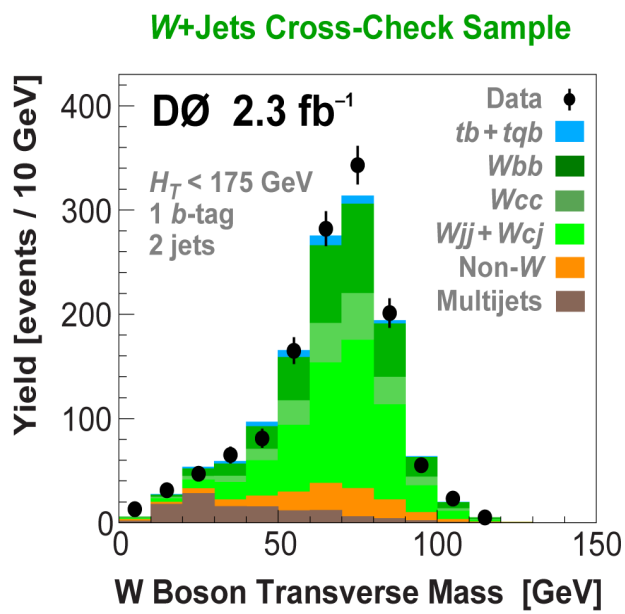
Statistical analysis

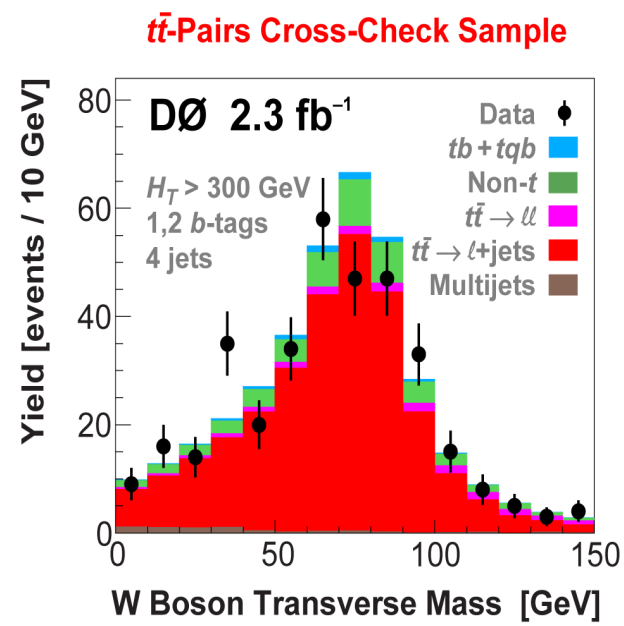


Analysis samples

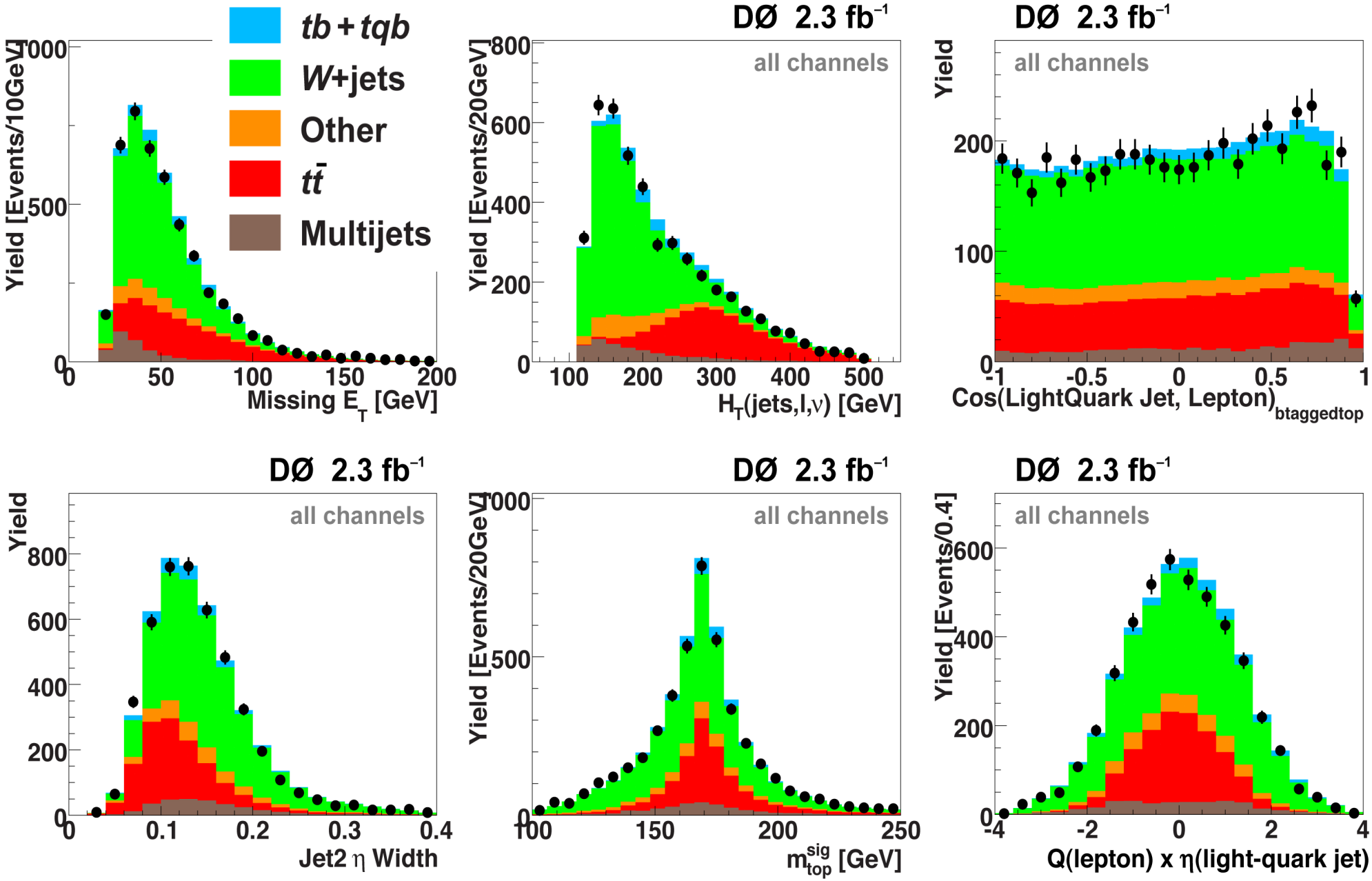
- Divide into 24 analysis channels plus cross-check samples
  - By b-tag multiplicity (1, 2), jet multiplicity (2, 3, 4), data taking period (before/after upgrade), lepton (e, μ)
  - Pre-tag sample for W+light quark jets and QCD
  - Cross-check sample enriched in W+jet events
  - Cross-check sample enriched in top pair events
- Check data/background agreement for all variables and multivariate filters in all samples



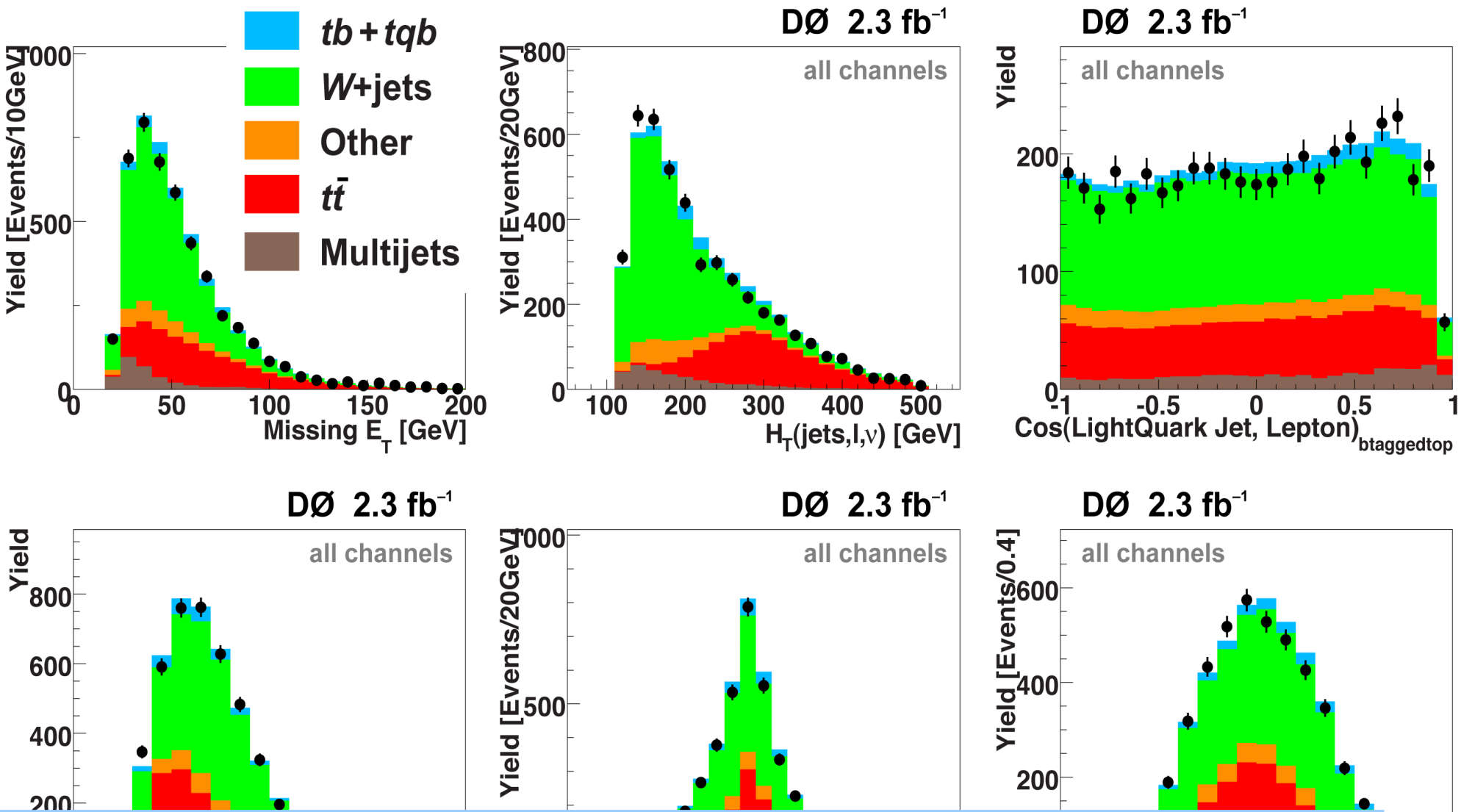




Important discriminating variables

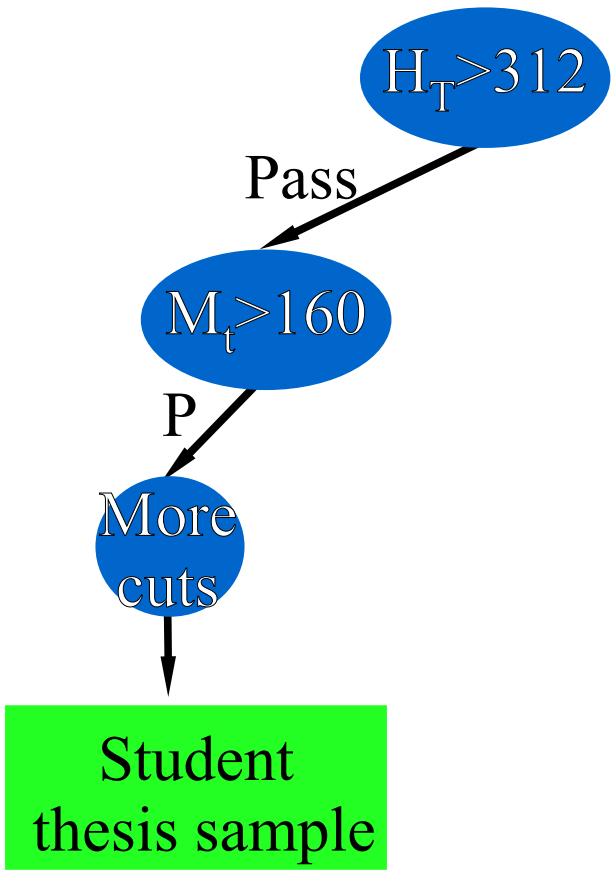


Important discriminating variables

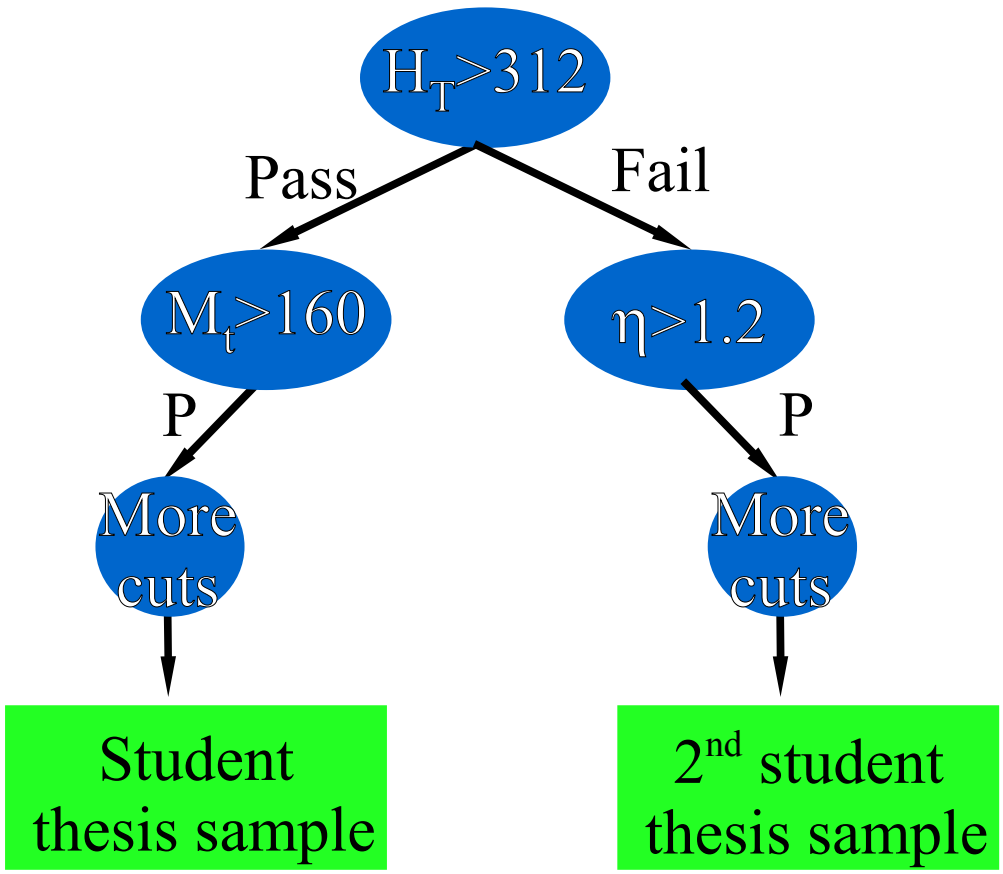


- Considered ~200 variables total for multivariate filters
- Chose 18-64 variables for each filter, depending on method and channel

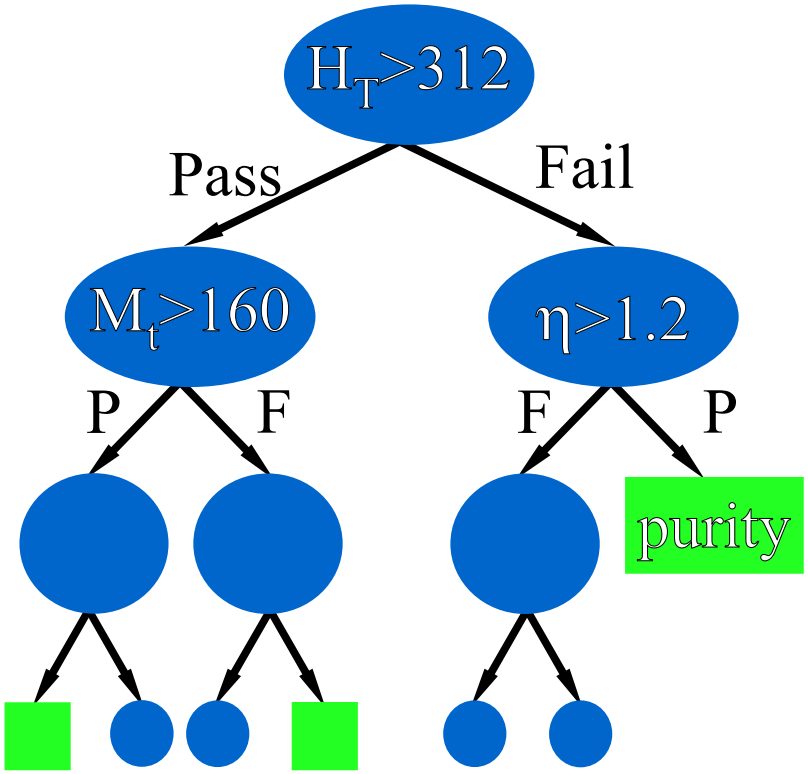
From cut-based analysis to decision tree



From cut-based analysis to decision tree

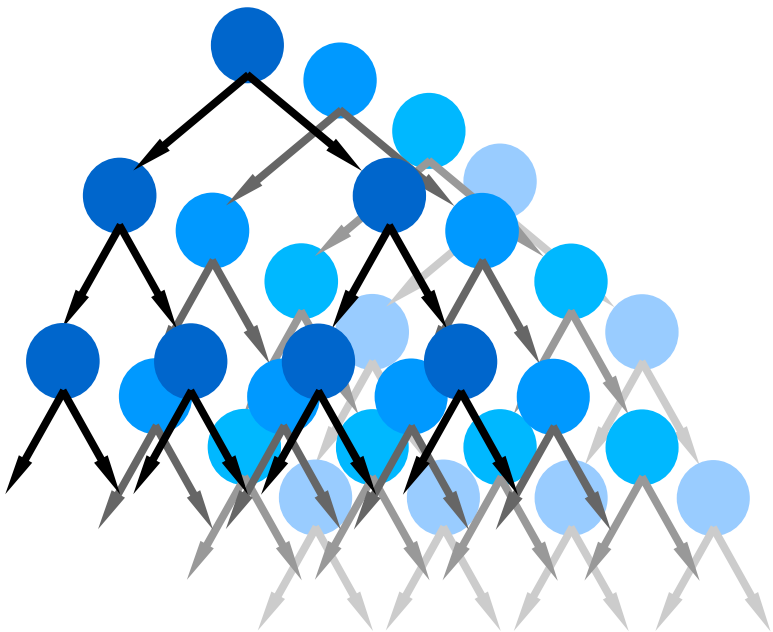


From cut-based analysis to decision tree



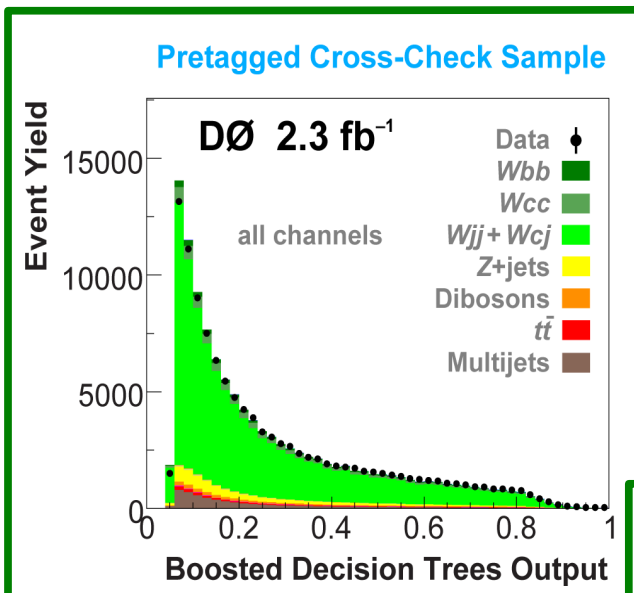
- Cuts produce branches
- Terminal leaf: calculate purity = $N_S/(N_S+N_B)$ from MC signals and backgrounds
- Each data event is assigned the purity value of the leaf it falls into
- Typical trees: hundreds of leafs

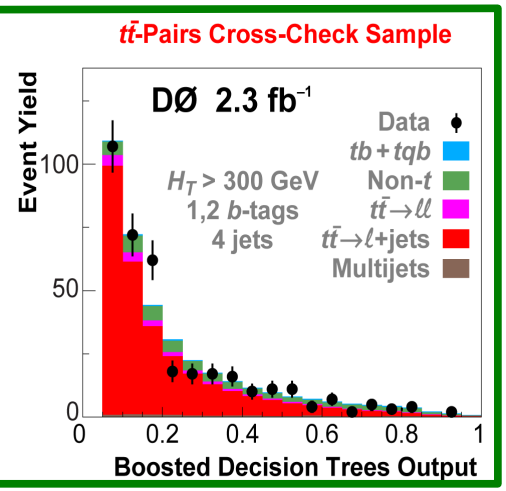
Boosted decision tree

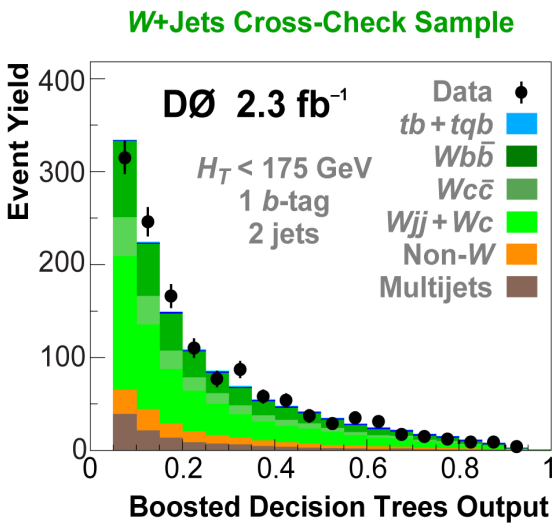


- Boosting:
  Average over many trees, each built by iteratively increasing weight of mis-classified events
- Typically 20-100 boosting cycles

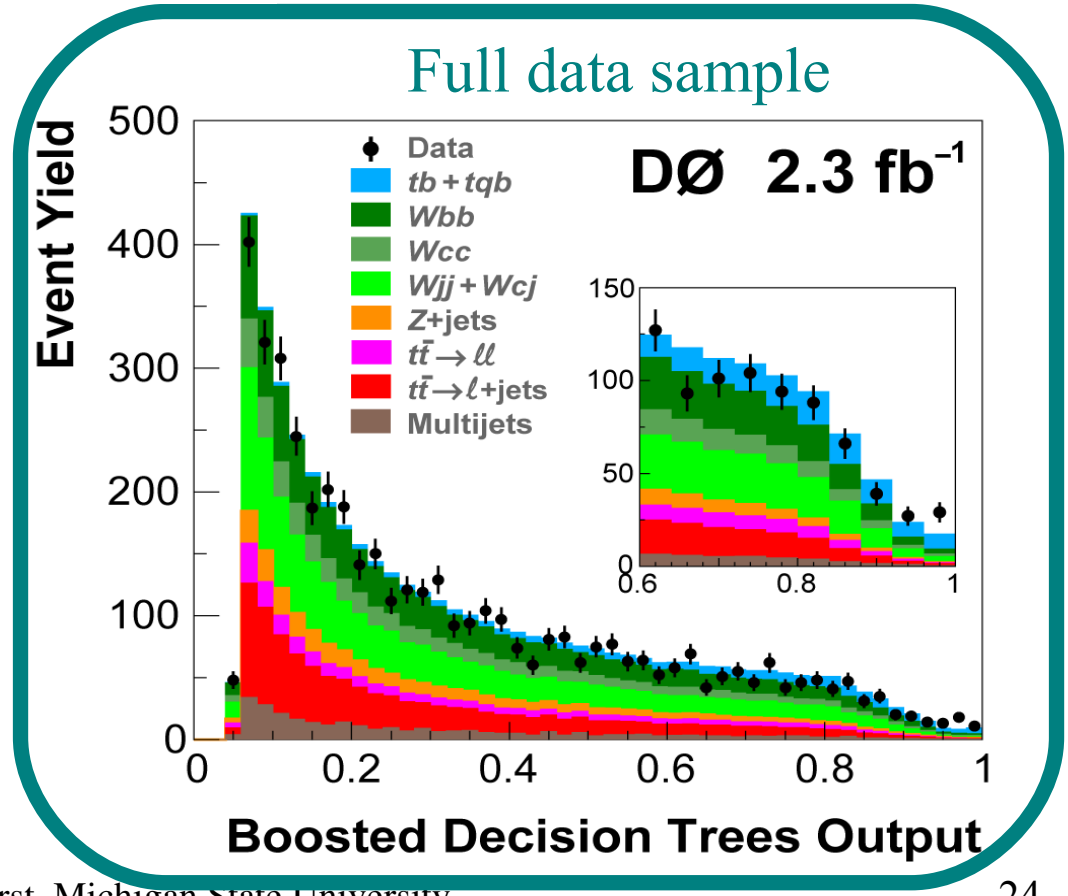
Boosted decision tree distributions



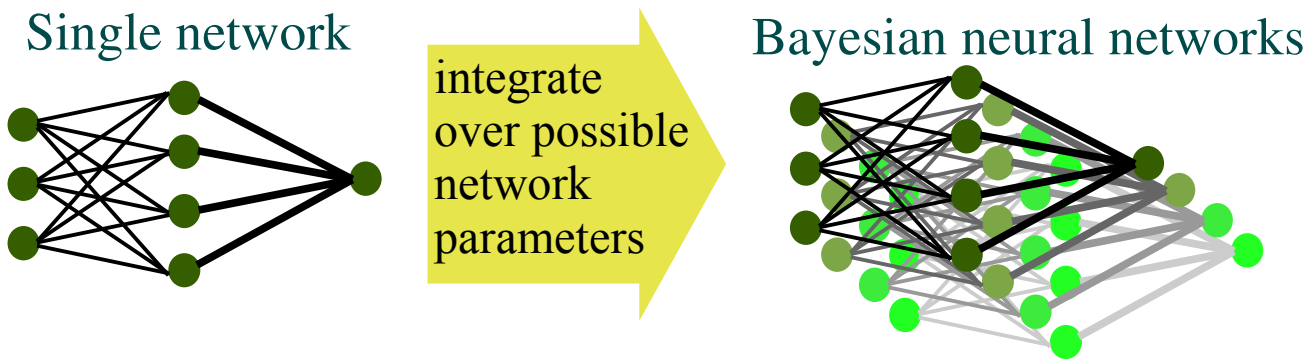




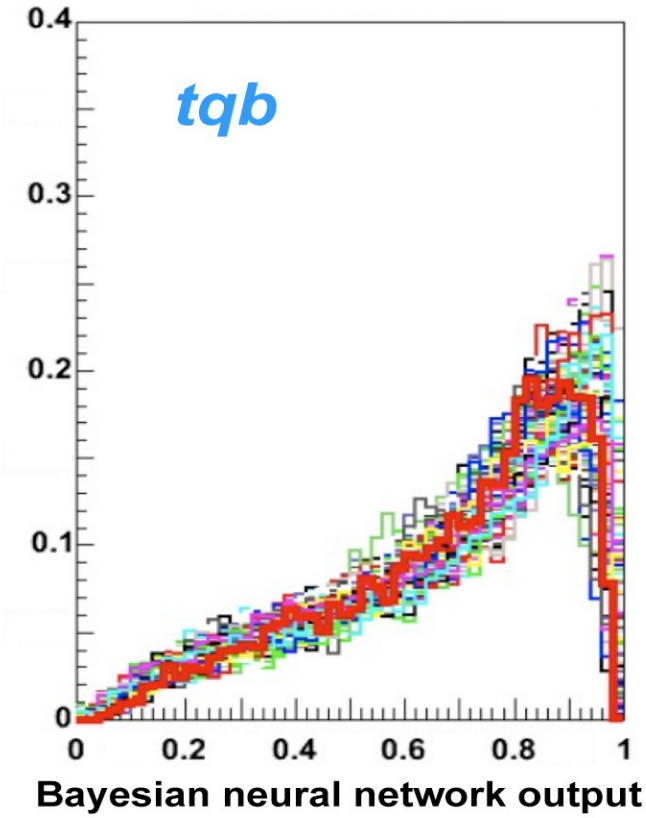
Cross checks



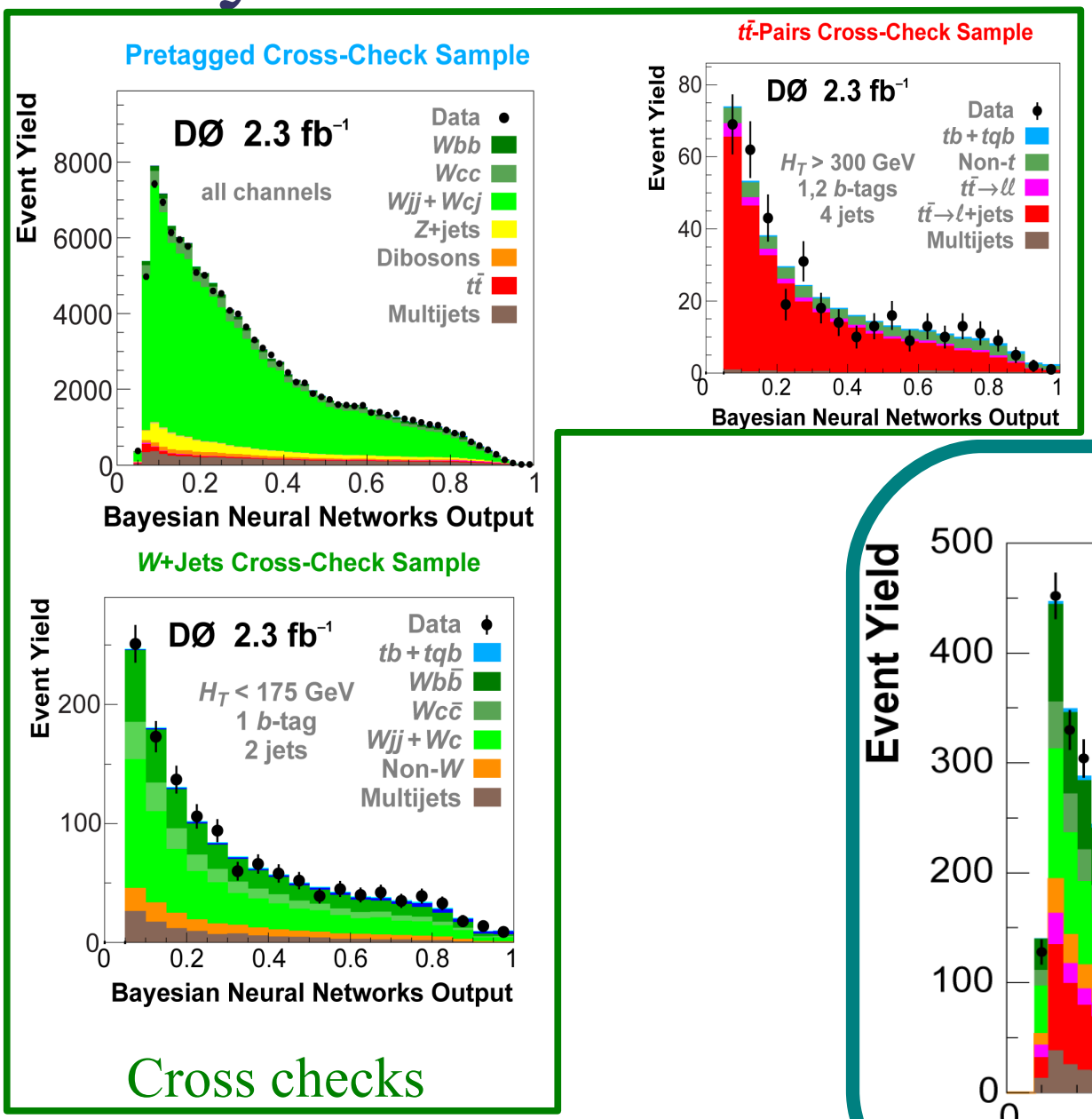
Bayesian neural networks

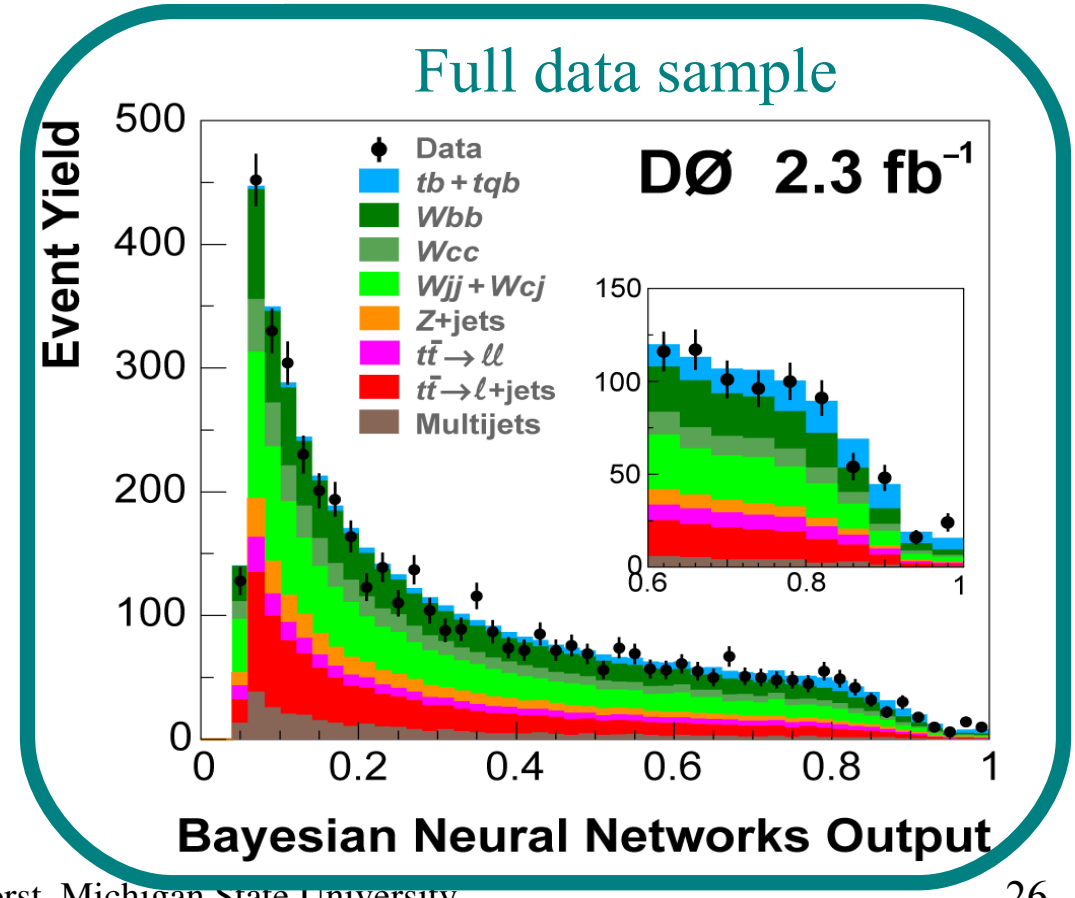


- NN with three layers, 24 input nodes, 40 hidden nodes
- Bayesian Idea:
  - Determine the posterior probability for each weight at each node
  - Sample from this posterior
  - Here: Average over 100 networks



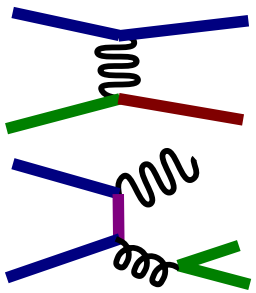
Bayesian neural network distributions





Matrix element analysis

Parton level matrix elements



integrate over measurement uncertainties

Signal discriminant

$$L = \frac{P(sig)}{P(sig) + P(bkg)}$$

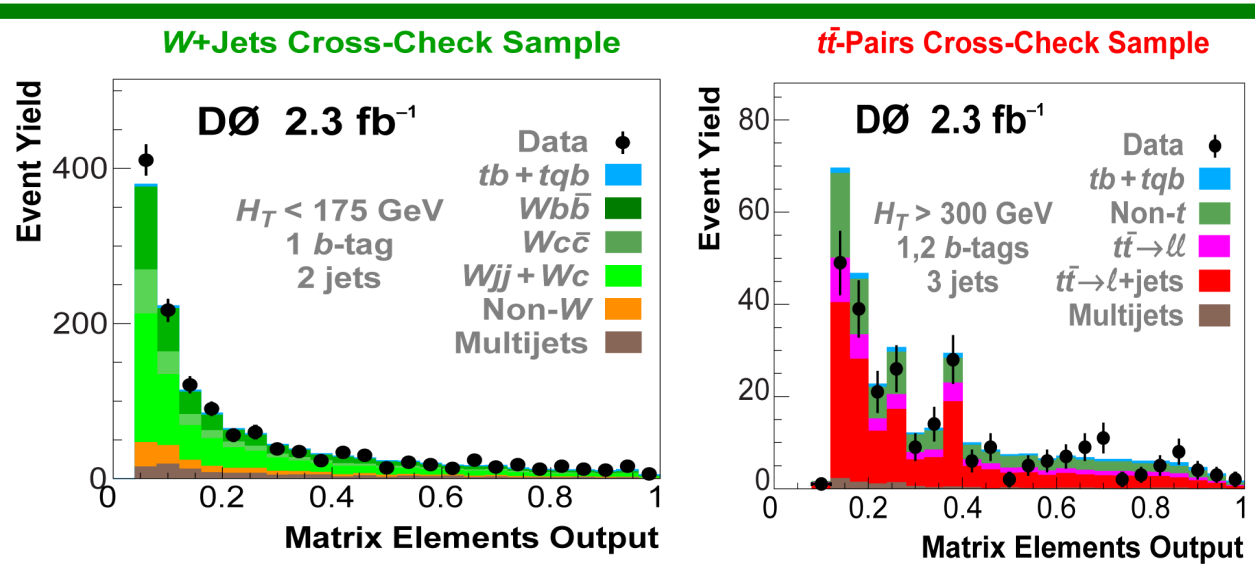
- Signal and background probability for each event is calculated from differential cross section

$$P_{Signal}(\vec{x}) = \frac{1}{\sigma_S} d\sigma_S(\vec{x}) \quad \sigma_S = \int d\sigma_S(\vec{x})$$

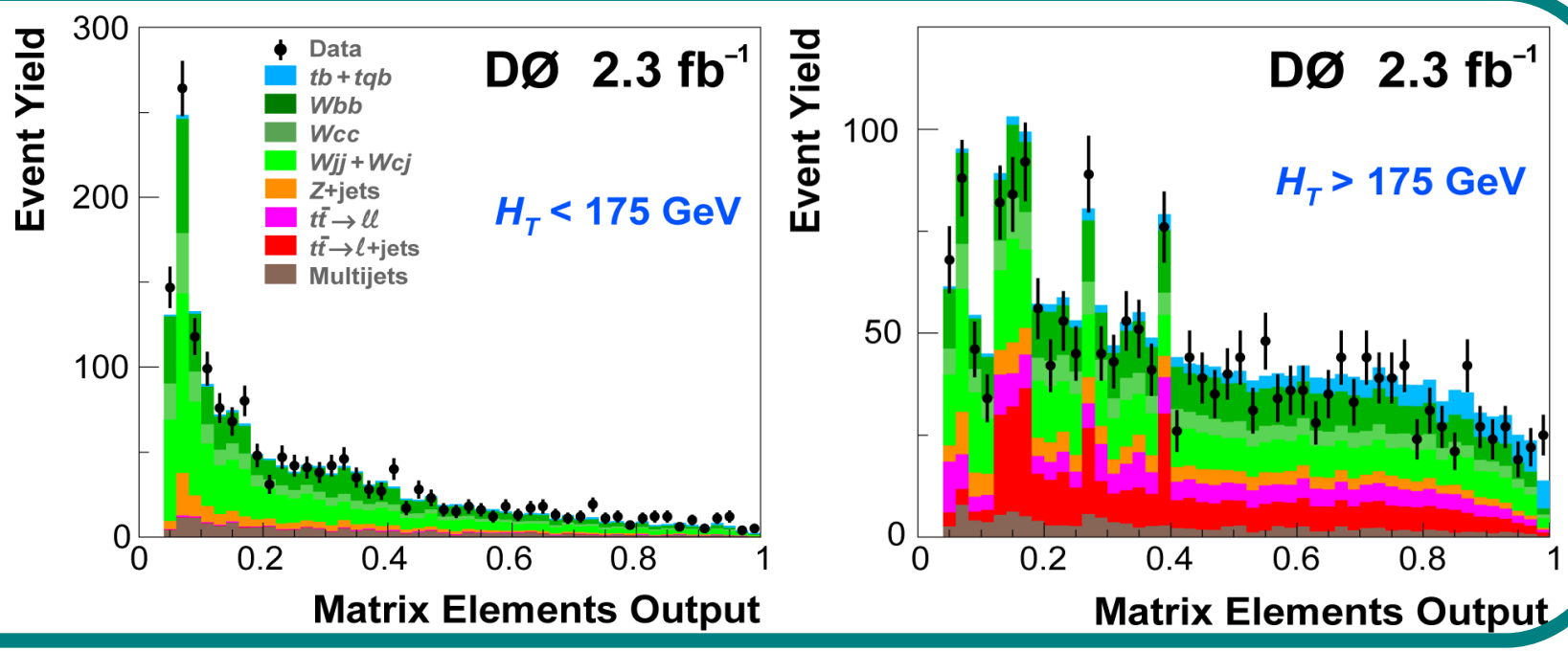
  - Integration over final state momenta
    - And over reconstructed momenta, transfer function
- Include ME for s-channel, t-channel, top pairs, diboson, W+2jets, W+3jets (including gluons)
- Determine weights in two HT regions

Matrix element distributions

Cross checks

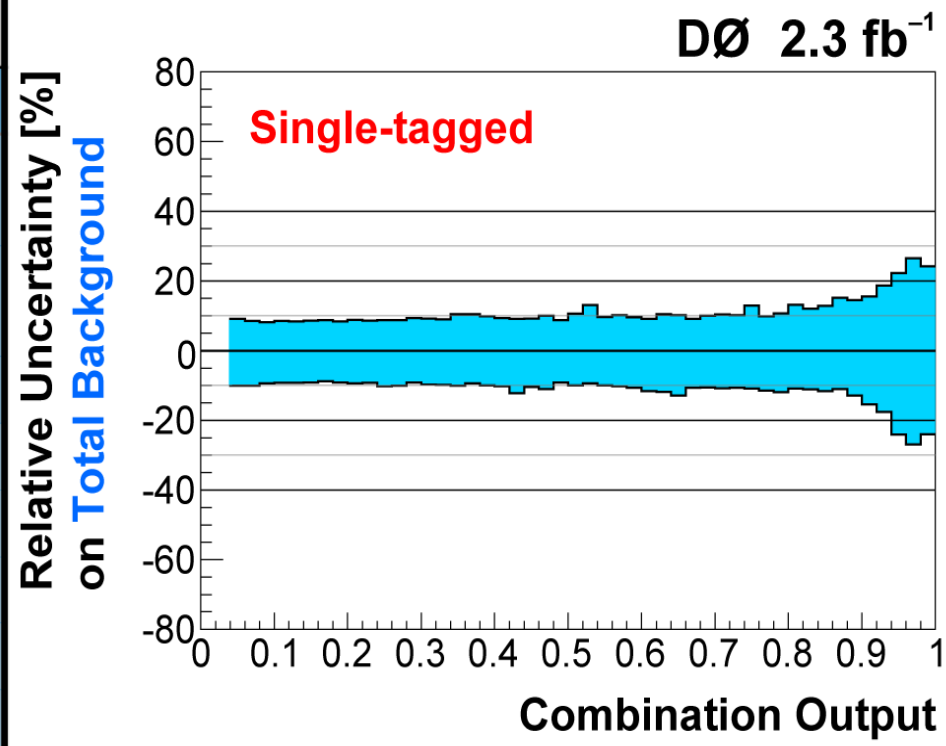


Full data sample



Systematic uncertainties

Systematic Uncertainties Ranked from Largest to Smallest Effect on Single Top Cross Section DØ 2.3 fb^{-1}	
Larger terms	
b-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)
W+jets heavy-flavor correction	13.7%
Integrated luminosity	6.1%
Jet energy resolution	4.0%
Initial- and final-state radiation	(0.6–12.6)%
b-jet fragmentation	2.0%
$t\bar{t}$ pairs theory cross section	12.7%
Lepton identification	2.5%
Wbb/Wcc correction ratio	5%
Primary vertex selection	1.4%

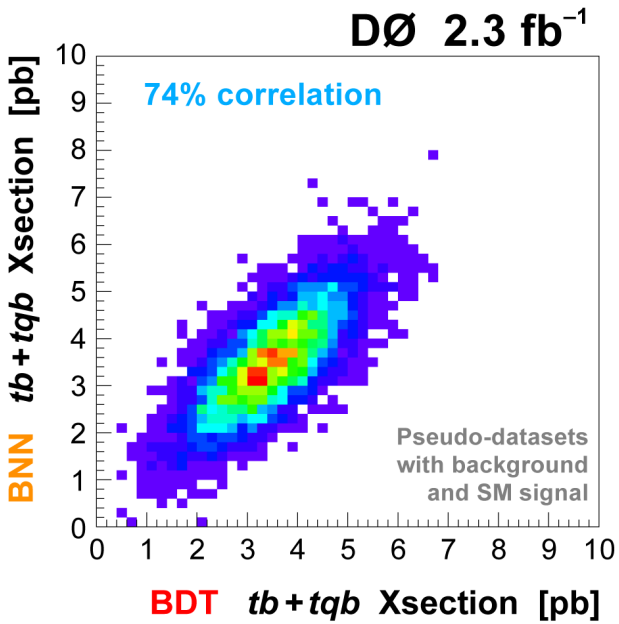


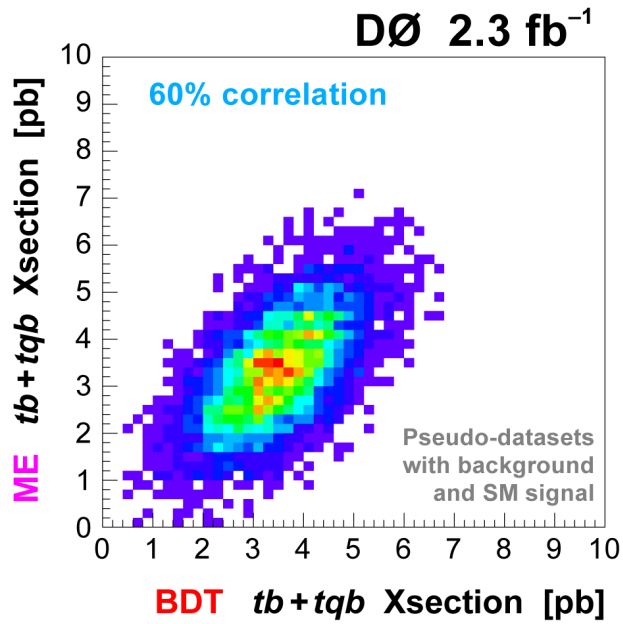
Multivariate Analyses

DØ 2.3 fb^{-1} Single Top Results			
Analysis Method	Single Top Cross Section	Significance	
		Expected	Measured
Boosted Decision Trees	$3.74^{+0.95}_{-0.79}$ pb	4.3 σ	4.6 σ
Bayesian Neural Networks	$4.70^{+1.18}_{-0.93}$ pb	4.1 σ	5.4 σ
Matrix Elements	$4.30^{+0.99}_{-1.20}$ pb	4.1 σ	4.9 σ

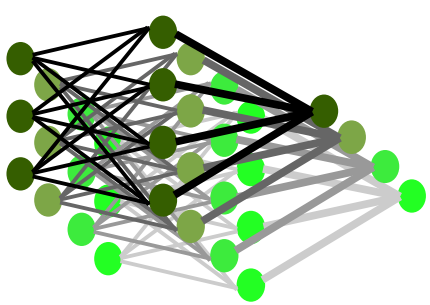
Combination: Another BNN

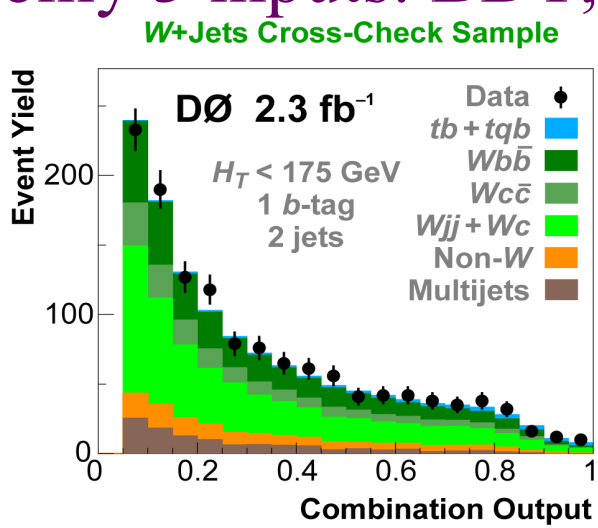
– Gain because each method provides unique separation

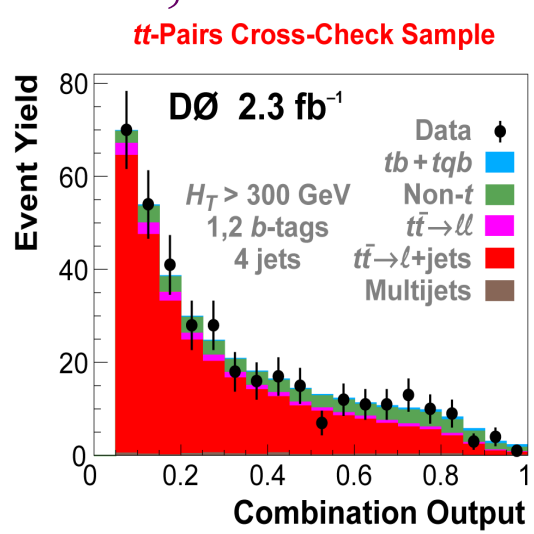




– Simple BNN, only 3 inputs: BDT, BNN, ME

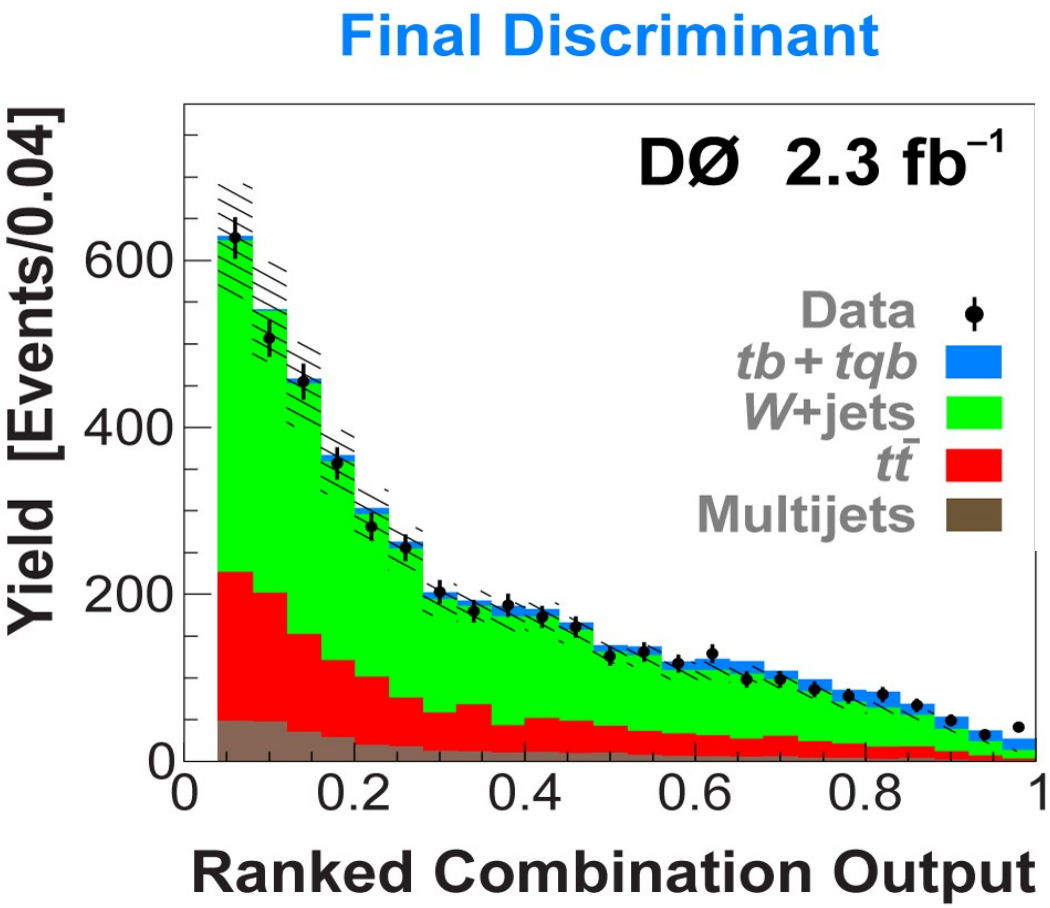


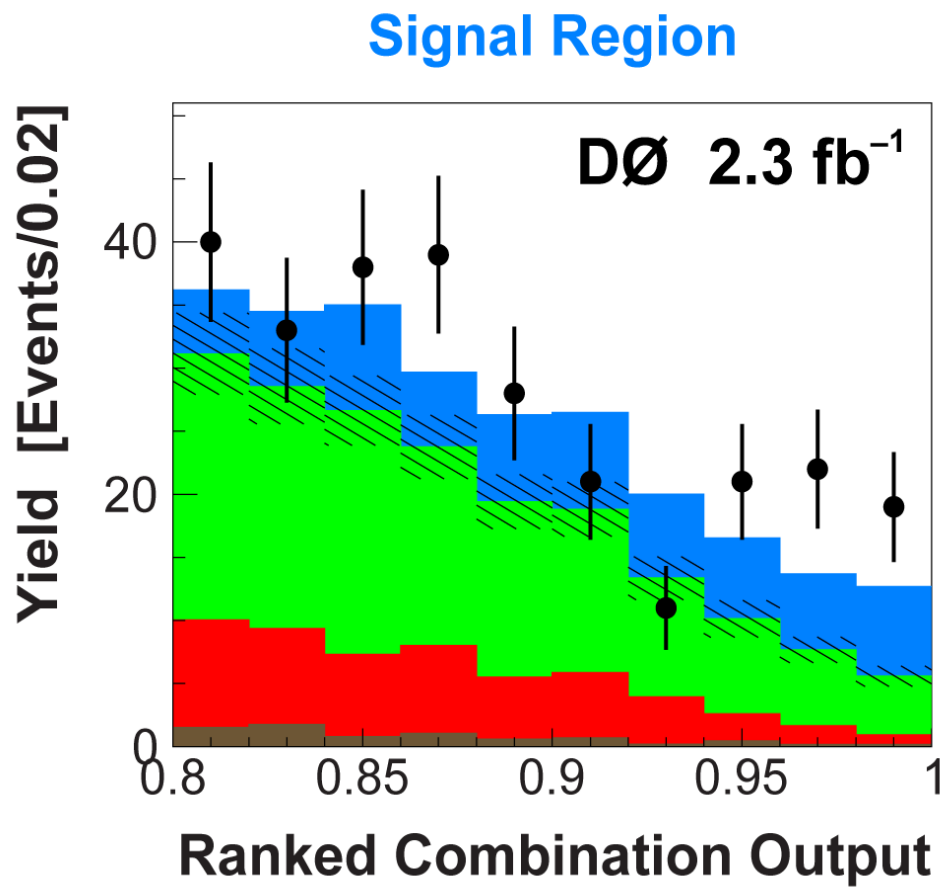




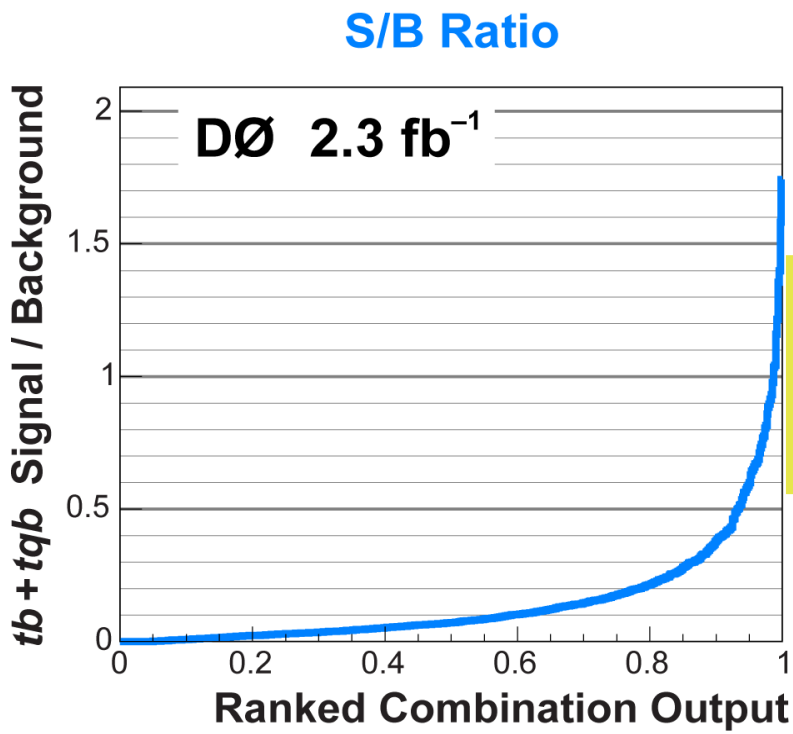
Combination distribution

- Combine 24 channels,
  50 bins per channel,
  sort bins by s/b

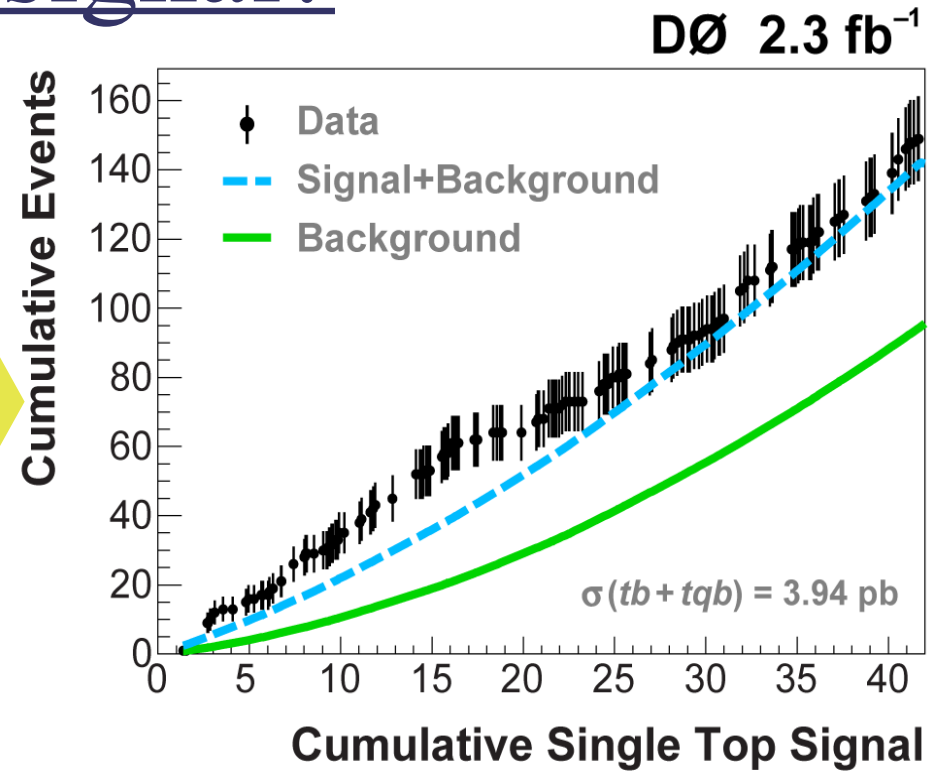


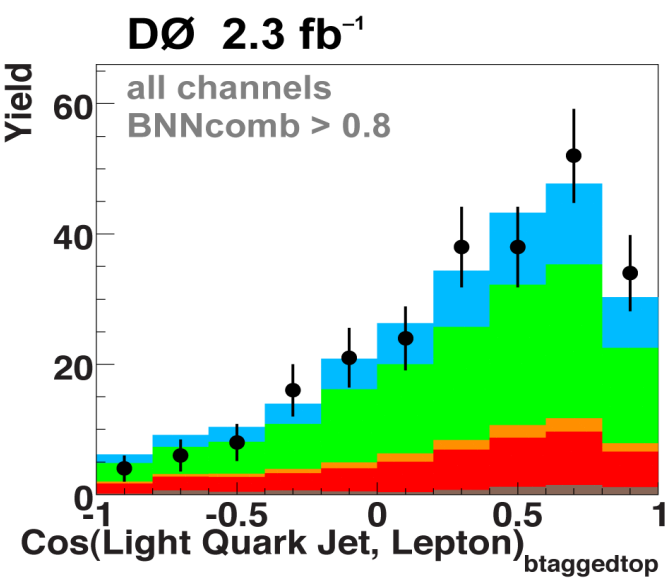


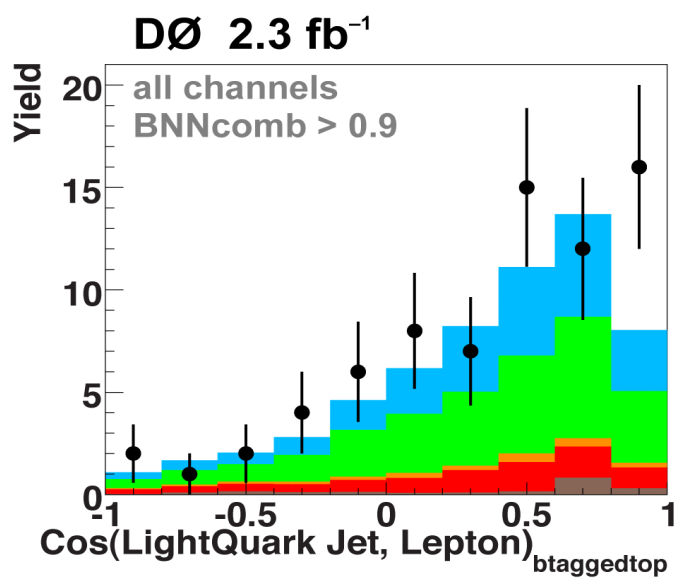
Is there a signal?

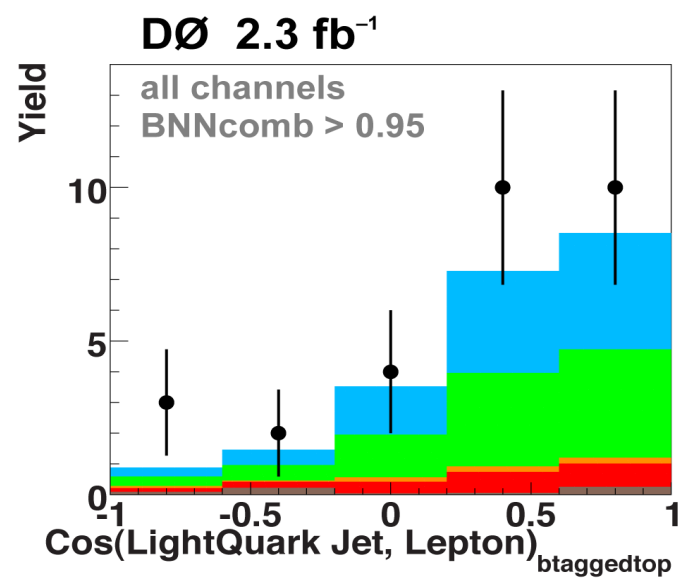


Sum bins right-to-left

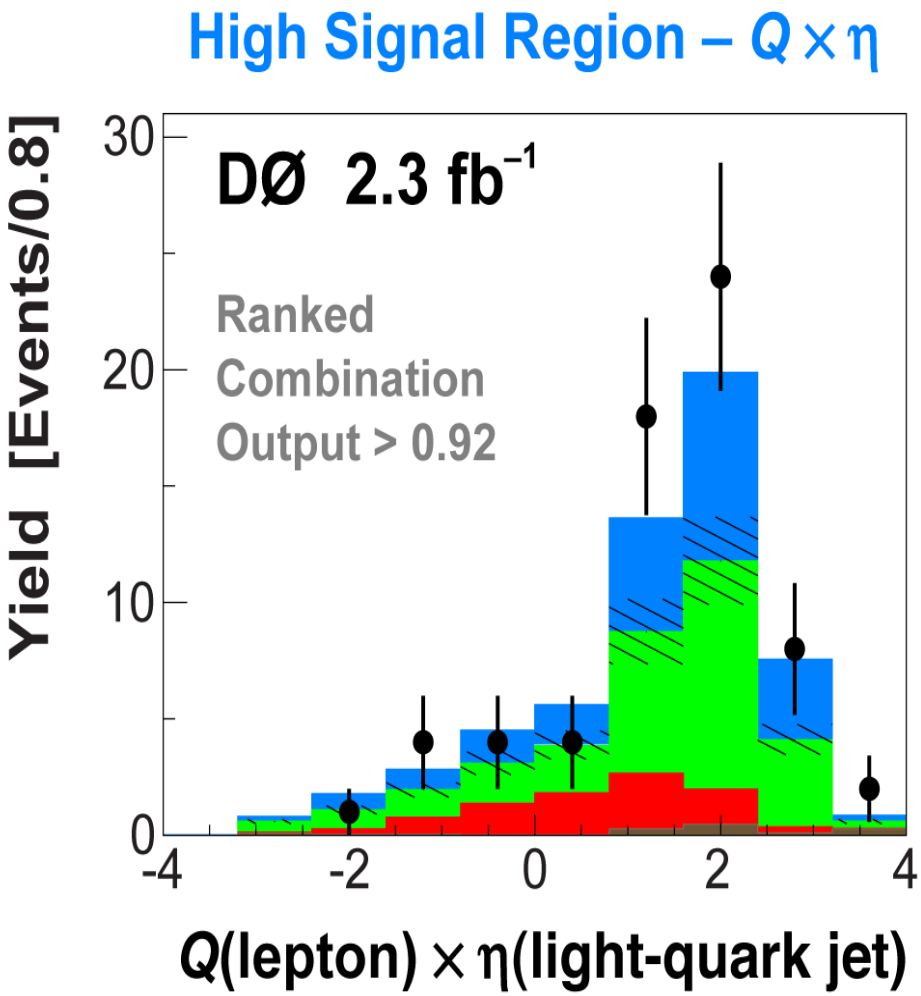


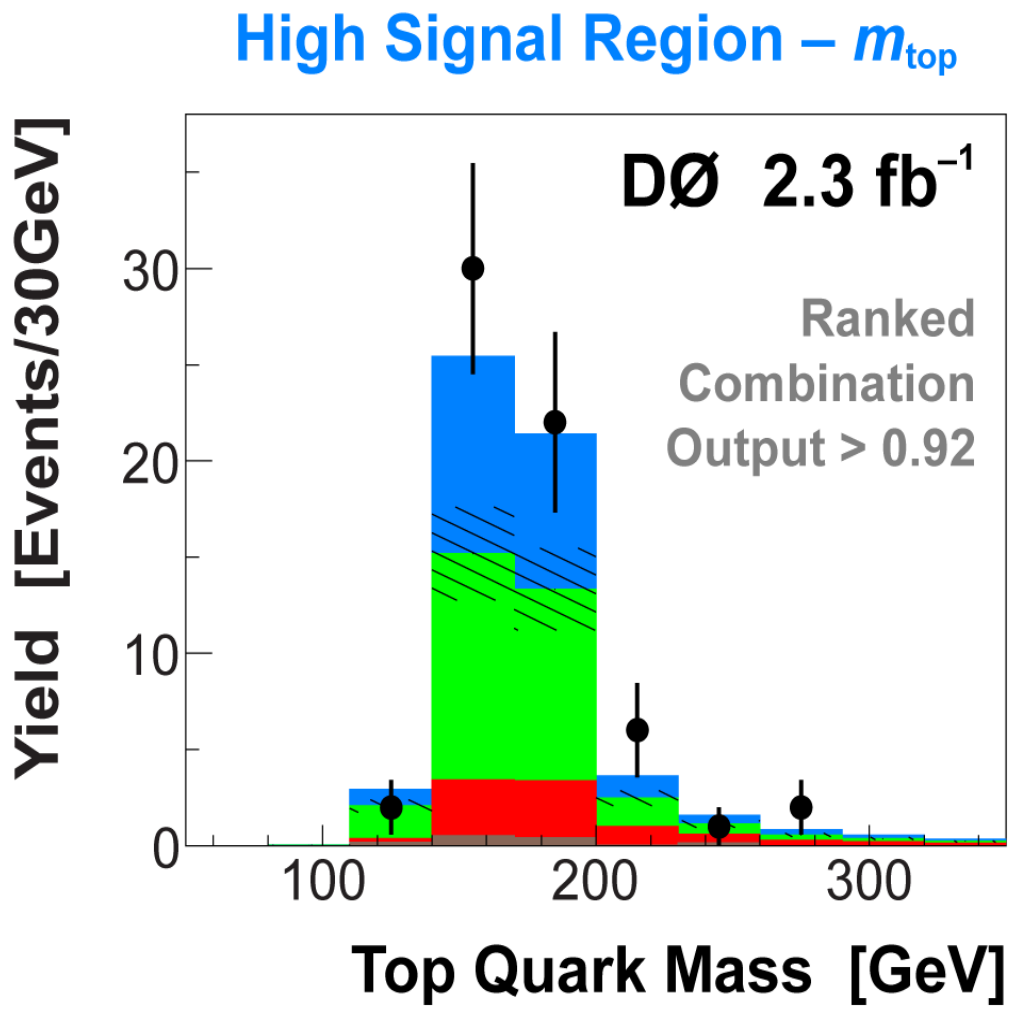






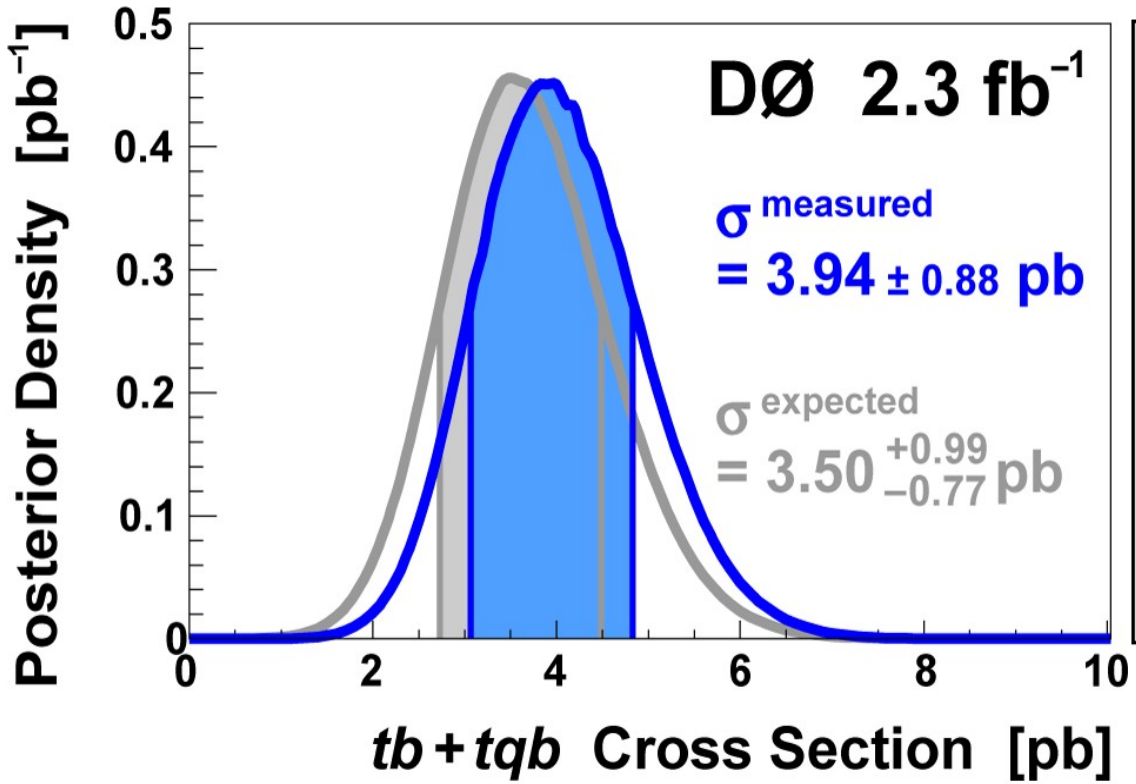
Kinematics in the signal region

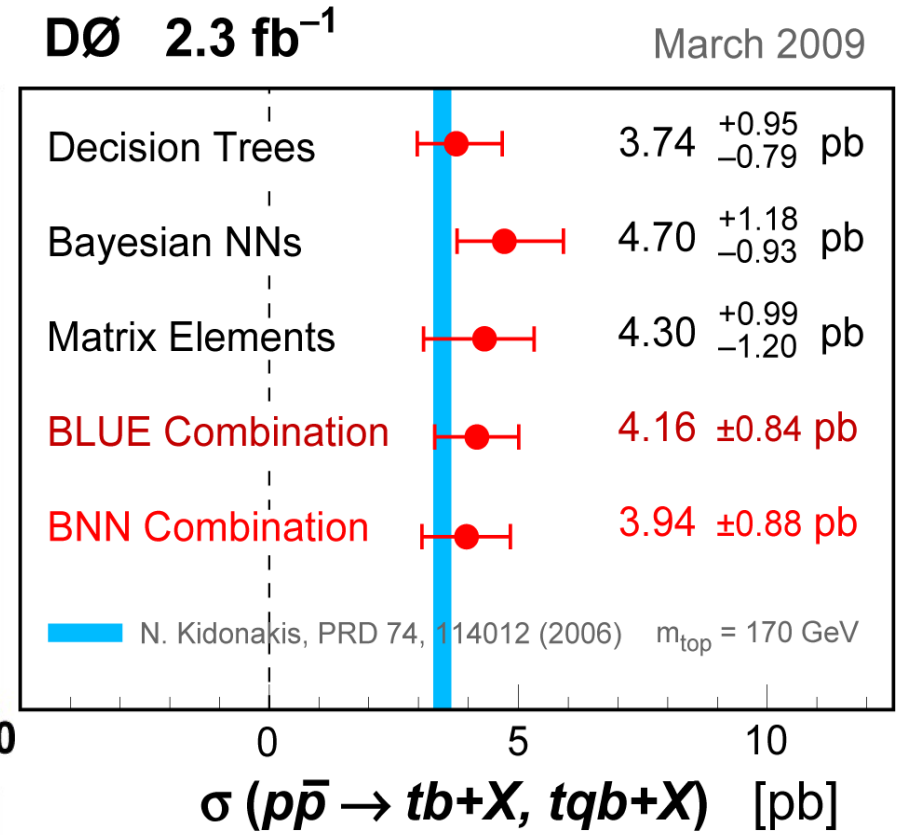




Statistical analysis

- Bayesian statistical analysis
  $P(s|D) = P(D|s)*P(s)$
  - Posterior gives measured cross section and uncertainty

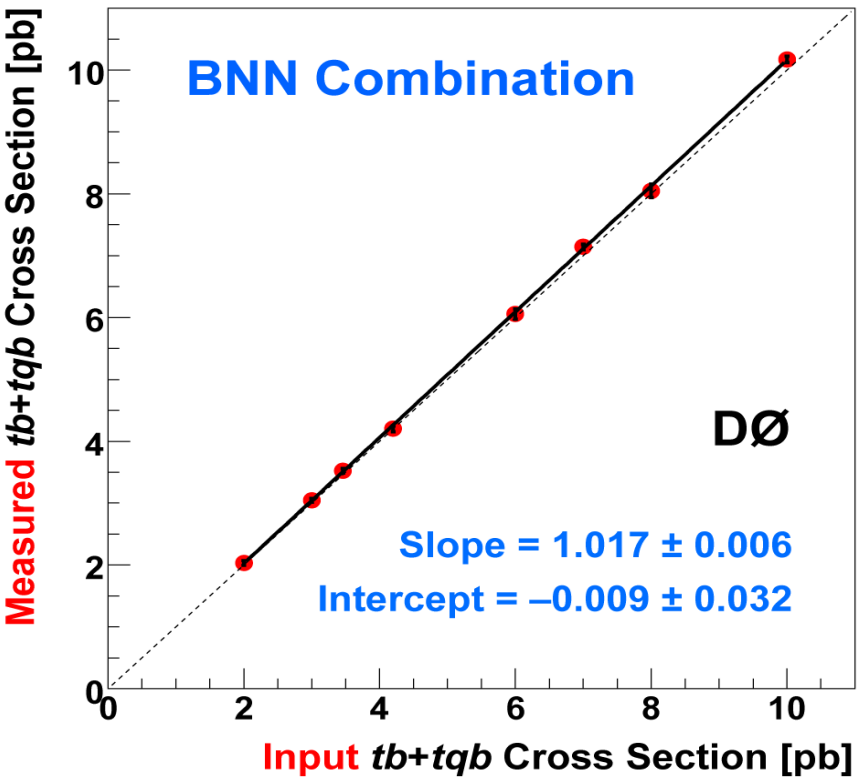


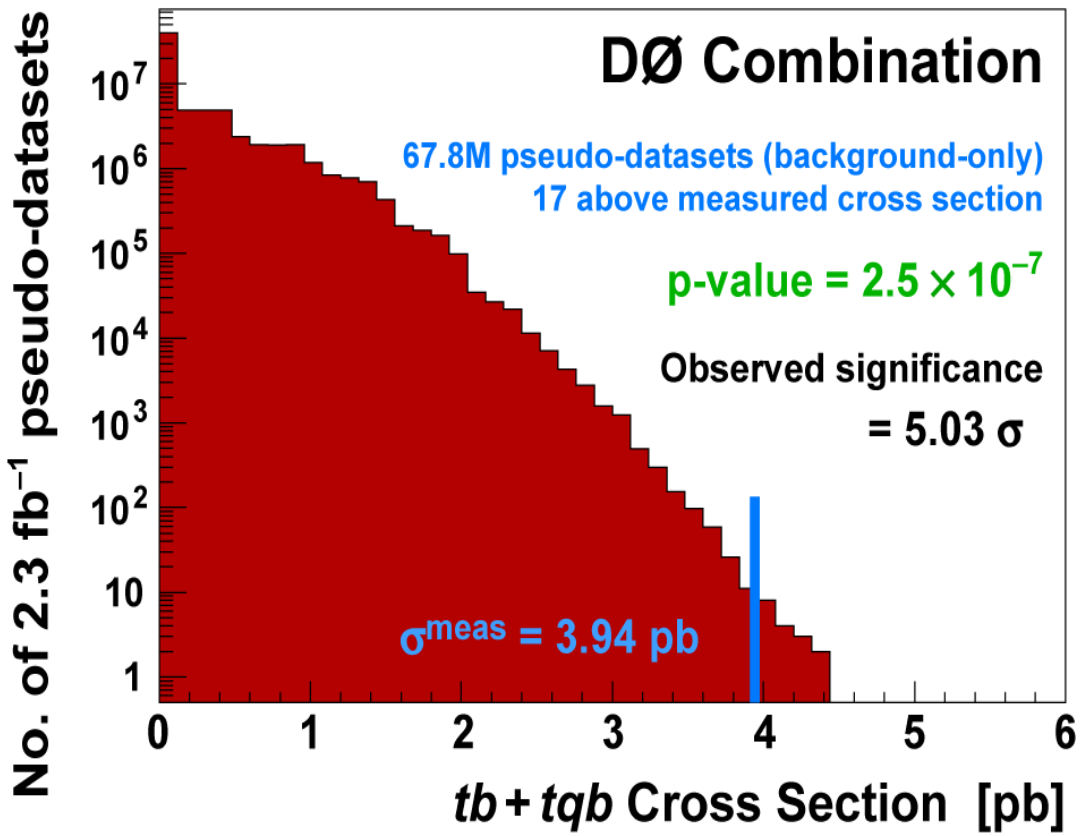


PRL 103, 092001 (2009)

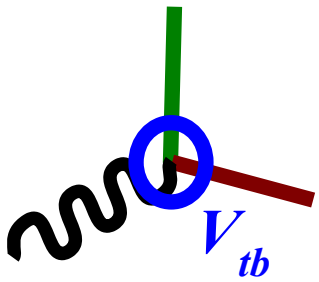
Significance

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





CKM matrix element $|V_{tb}|$

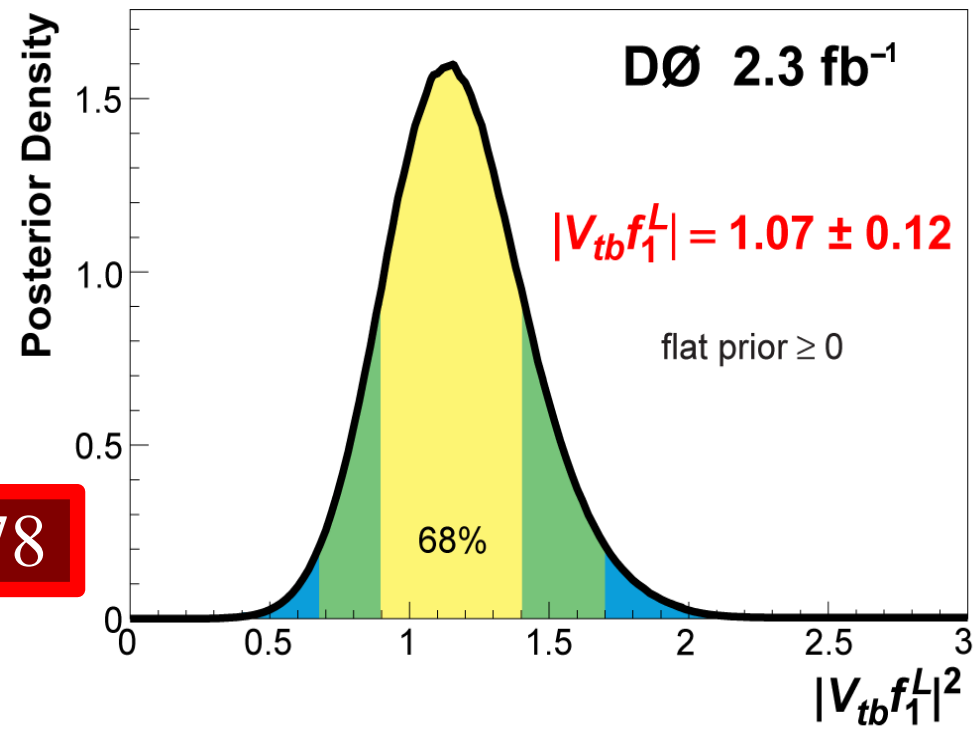


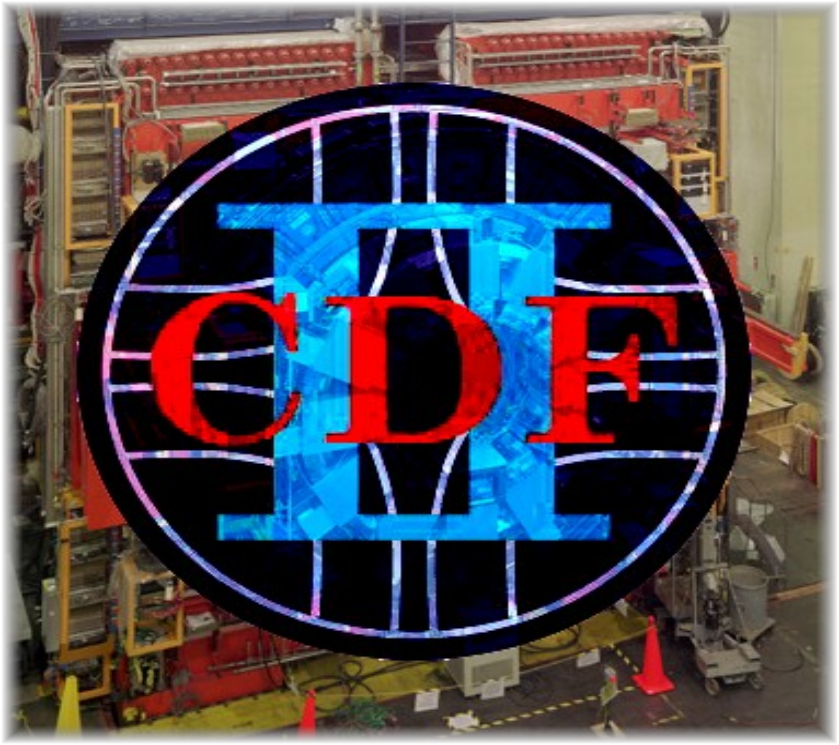
CKM Matrix

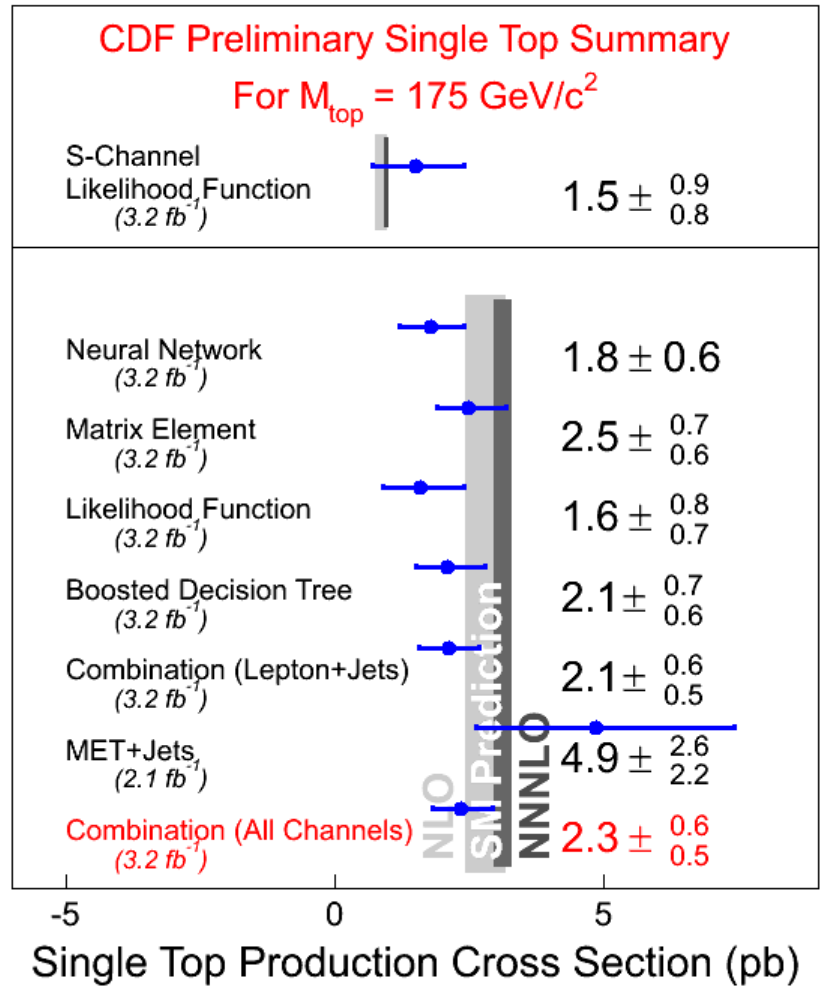
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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

  $\rightarrow$ lower limit on V_{tb}
  - At the 95% C.L.: $|Vtb| > 0.78$



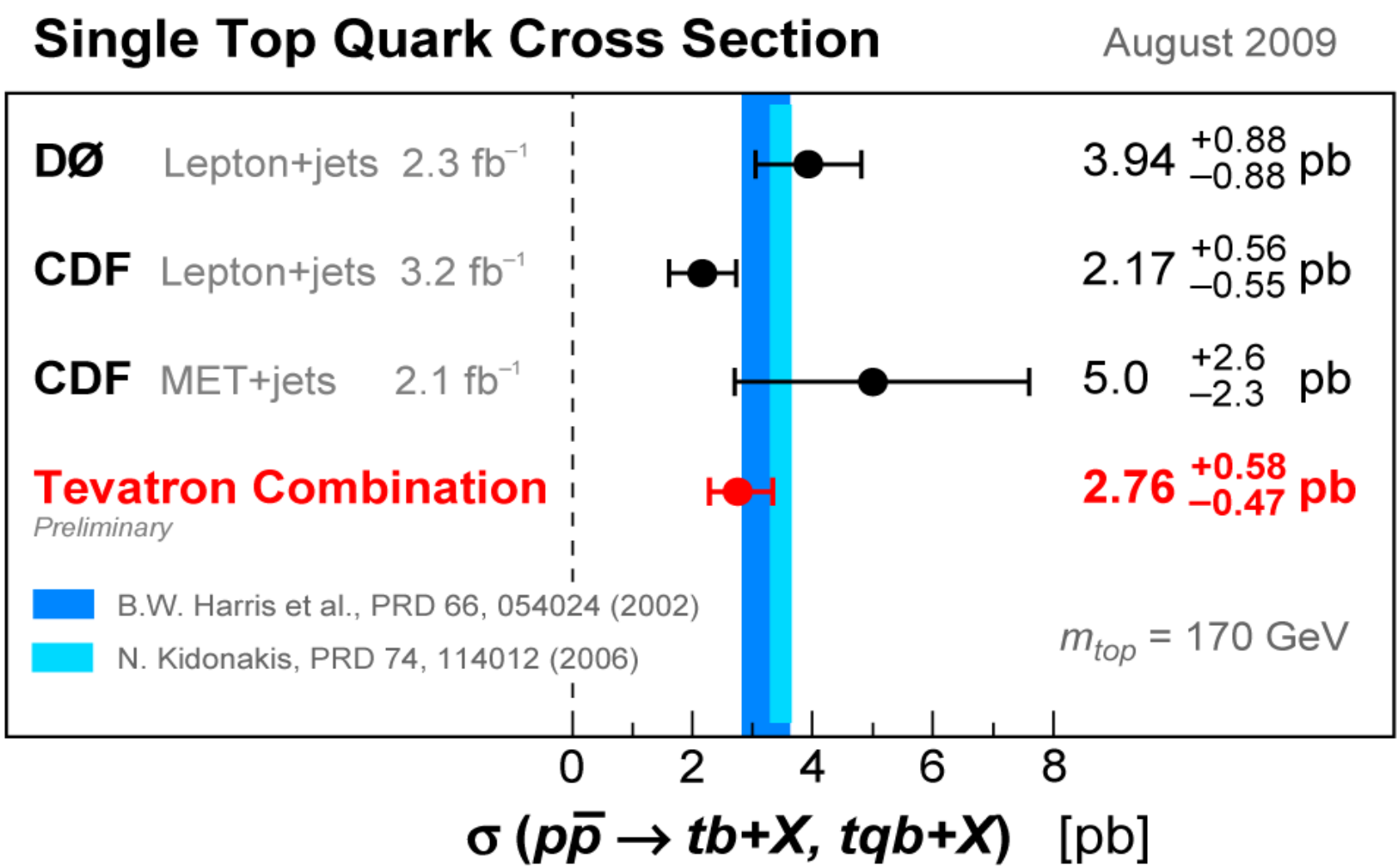




- Analyses based on 3.2 fb^{-1}
- Top mass 175GeV

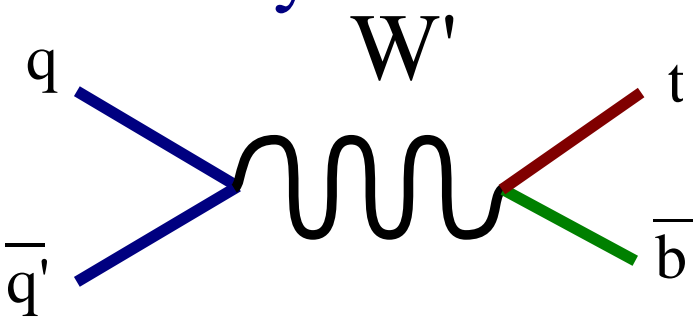
- Include MET+Jets channel
- 5 multivariate methods, separate s-channel search

Tevatron Combination

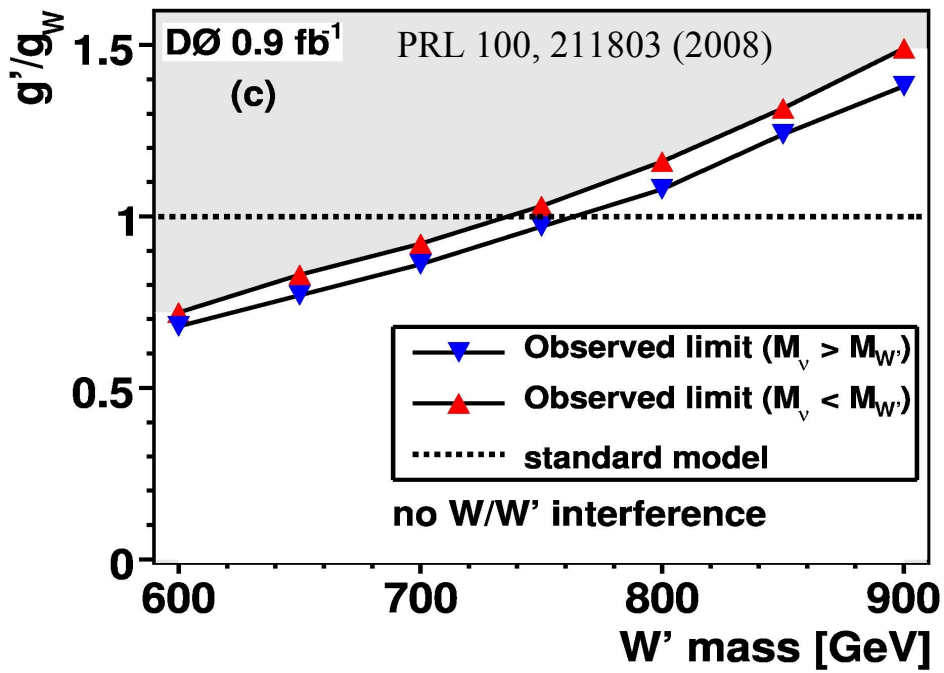


Searches for new physics in single top

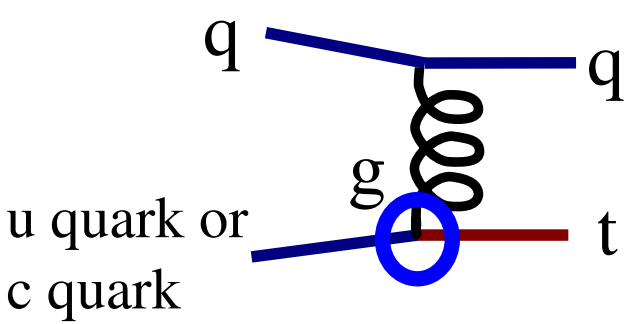
- Searches for new heavy boson W':

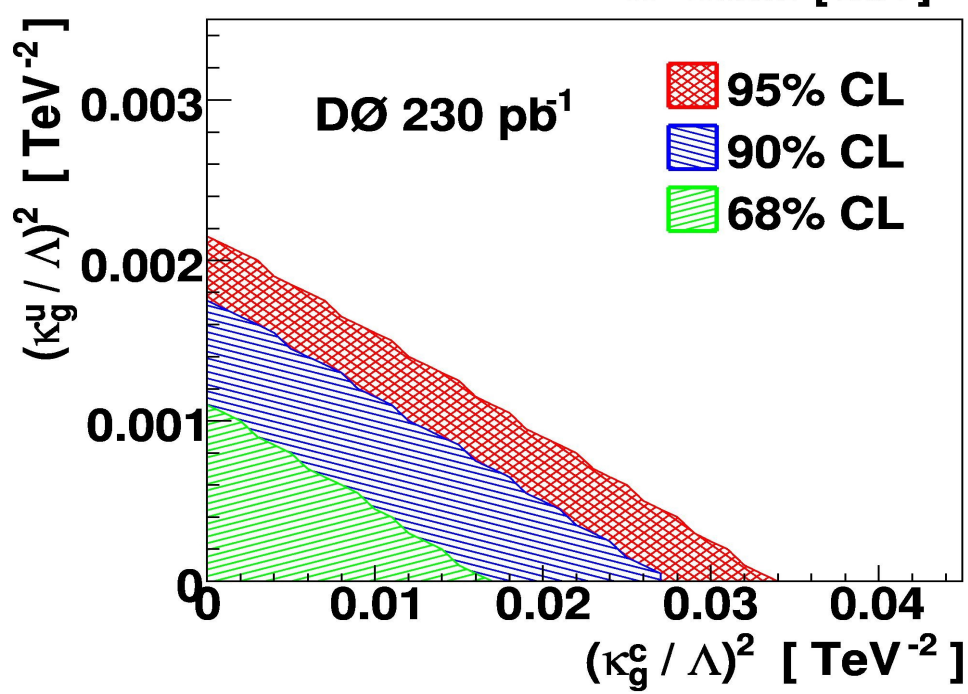


  – CDF prelim result, 1.9fb^{-1}: M > 800 GeV and M > 825 GeV



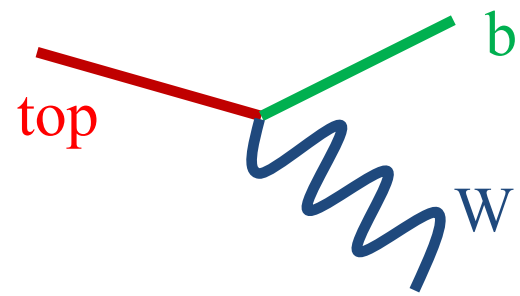
- Similar: DØ Susy H^+ search
- Flavor-changing neutral currents:





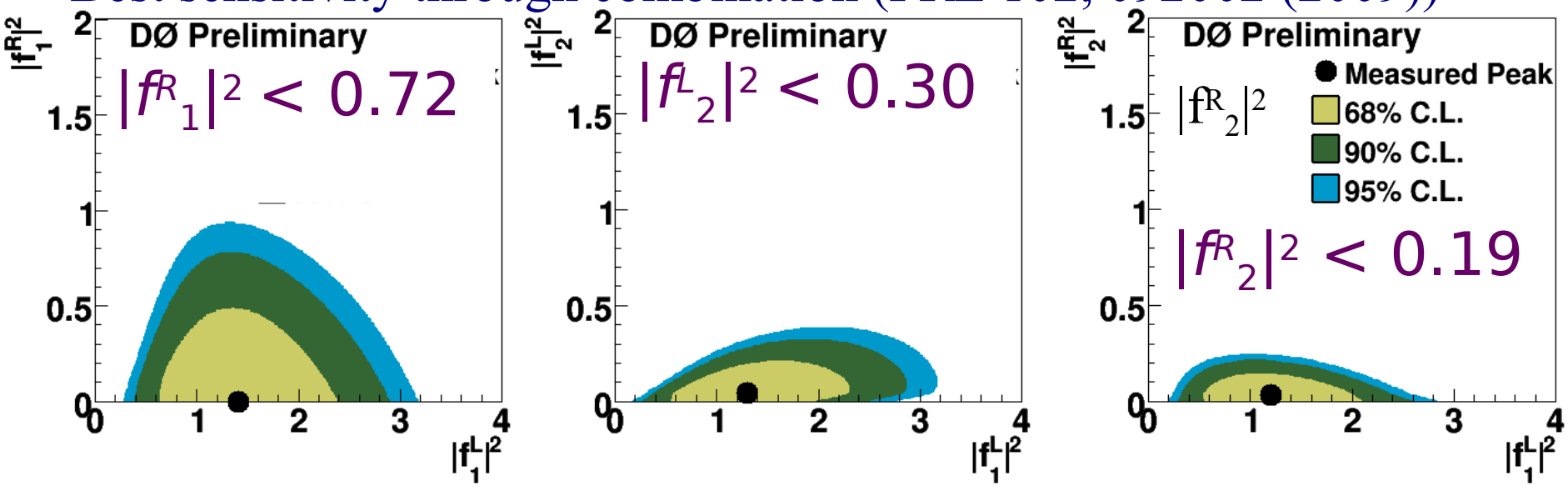
Single top polarization – anomalous coupling

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



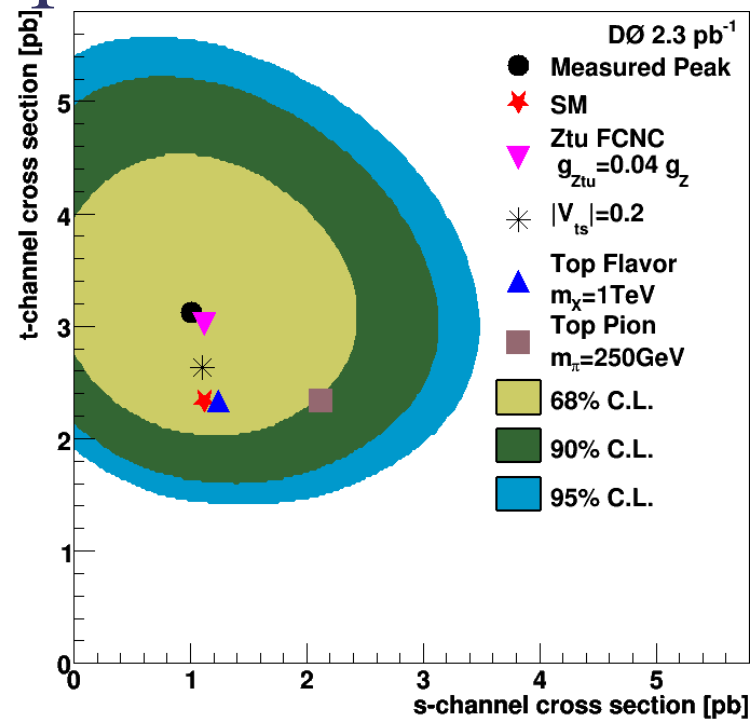
$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu V_{tb}(f_1^L P_L + f_1^R P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}(f_2^L P_L + f_2^R P_R)tW_\mu^- + h.c.$$

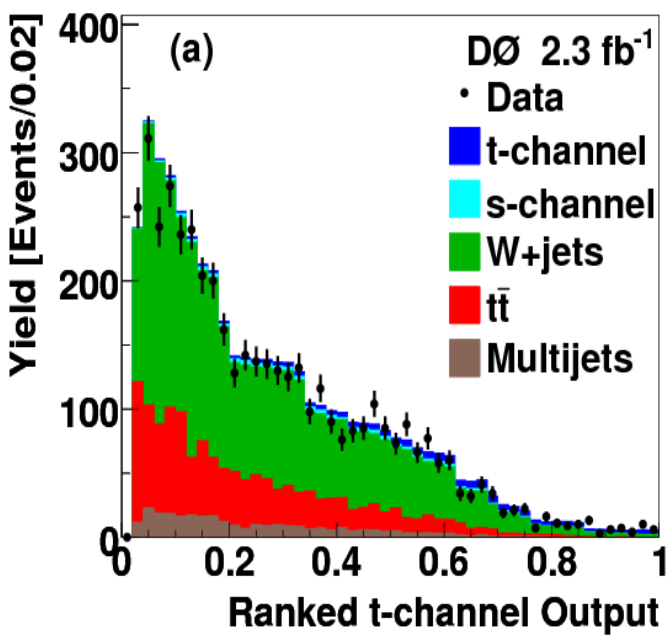
- Single top is sensitive to magnitude (PRL 101, 221801 (2008))
- ttbar to ratios of couplings (W helicity, PRL 100, 062004 (2008))
- Best sensitivity through combination (PRL 102, 092002 (2009))

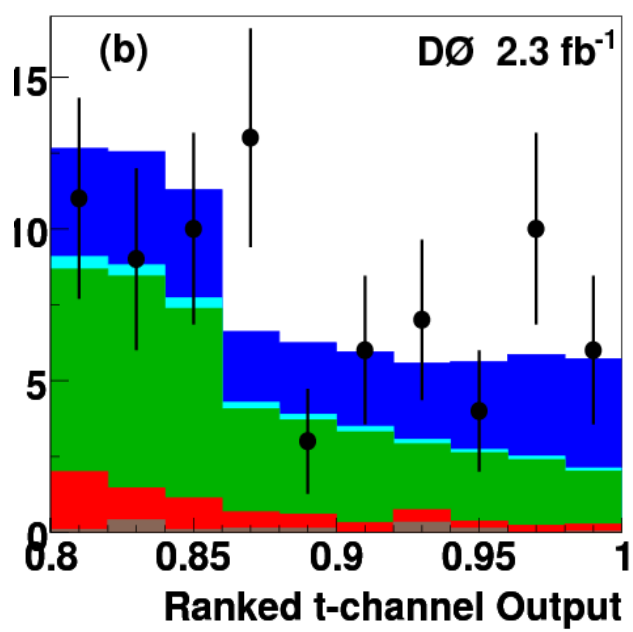


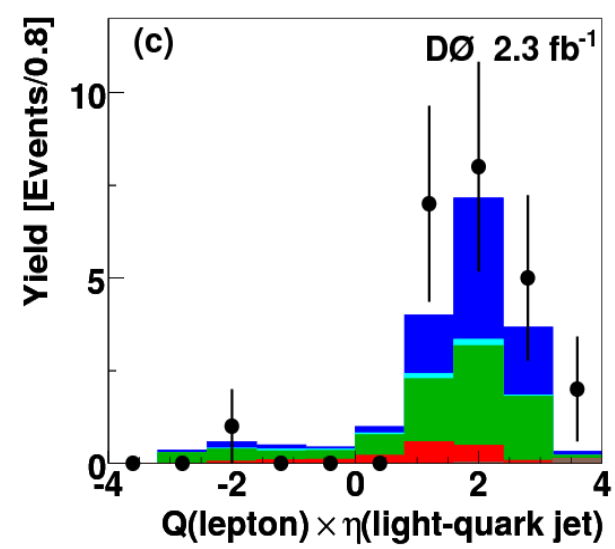
First evidence for t-channel production

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





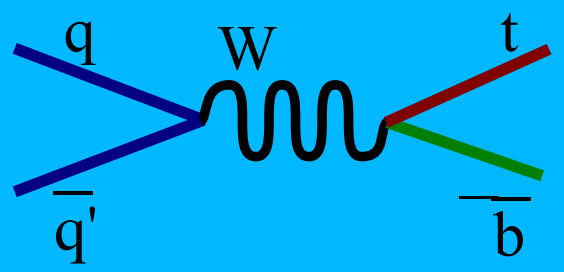




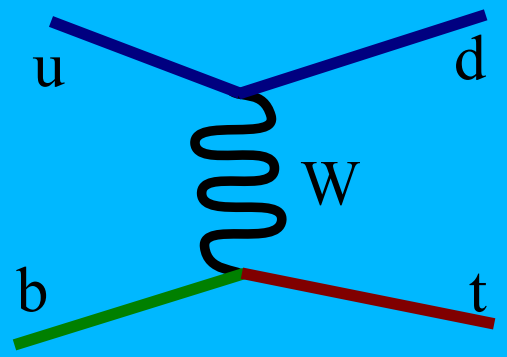
Submitted to PLB, arXiv.org:0907.4259

Single top at the LHC

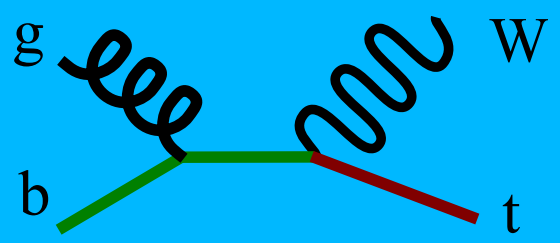
s-channel: 10.7 pb



t-channel: 247 pb



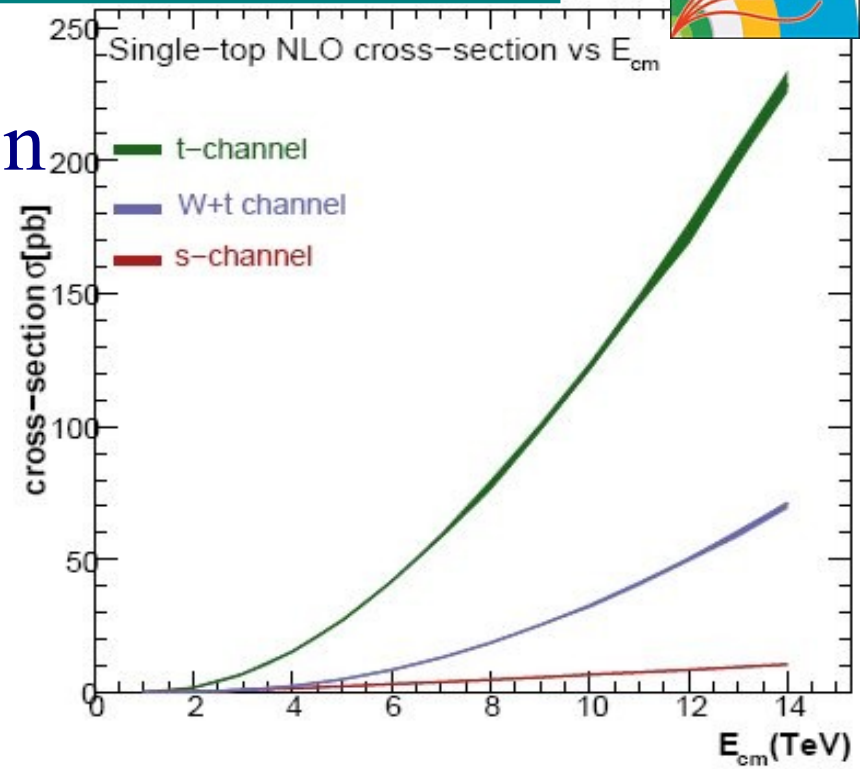
associated production: 68 pb

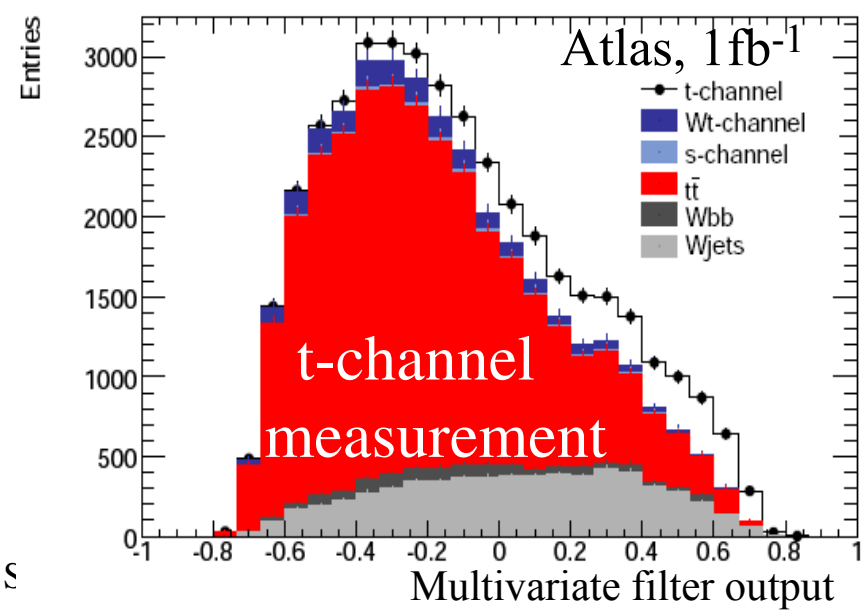


- Observe three single top production modes separately
  - t-channel: easy ☺ s-channel and assoc. prod: harder 😐
- Observe new physics *(if it can be seen)*
- Measure V_{tb} to few %
- Study spin correlations

SM Single Top at the LHC

- Backgrounds similar to Tevatron
  - W+jets less important
  - $t\bar{t}$ is dominant background
- t-channel observation early
  - In ~200 pb^{-1} at 10 TeV
  - Sufficient # of events for cut-based analysis
- s-channel and Wt with ~30 fb^{-1}
  - Separate by b-tag and jet multiplicity
  - Earlier observation requires multivariate techniques

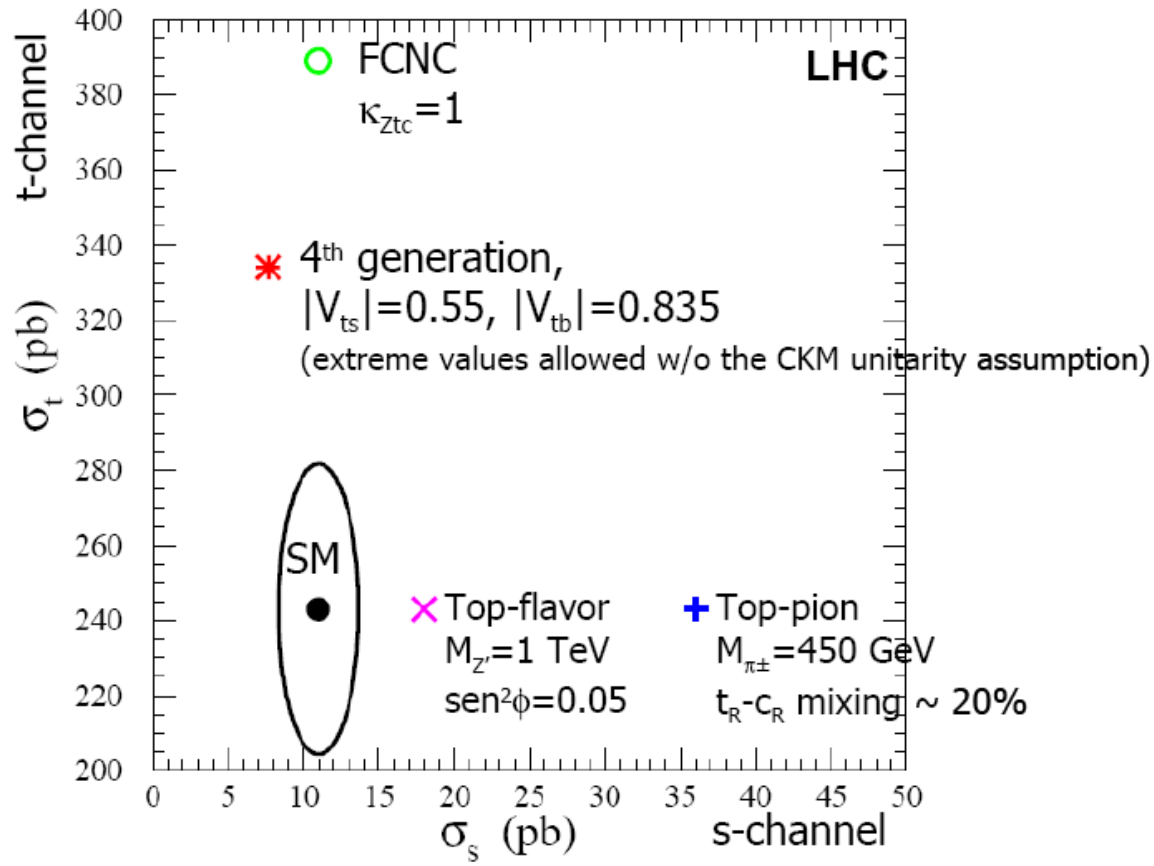




LHC: new physics in single top

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

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



Conclusions/Outlook

- The Tevatron experiments are getting to know the top quark very well
- Both experiments have observed single top quark production
- Tevatron dataset now over 5 fb^{-1}
  - Separate s-channel from t-channel
  - Look for new physics
- LHC:
  - Precision measurements in single top
  - Look for new physics connected to heavy top quark