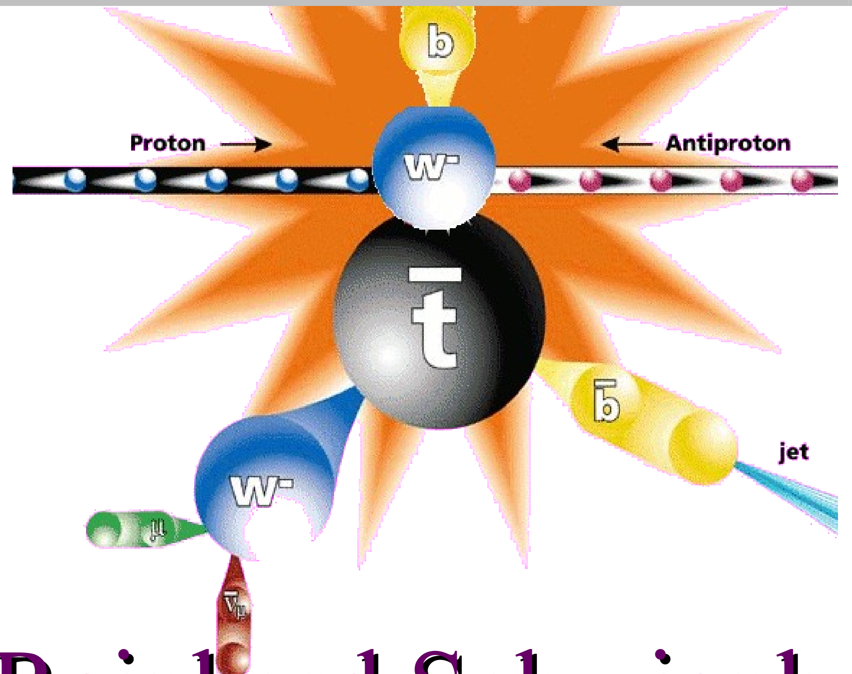
Observation of single top quark production at DØ



Reinhard Schwienhorst

MICHIGAN STATE UNIVERSITY

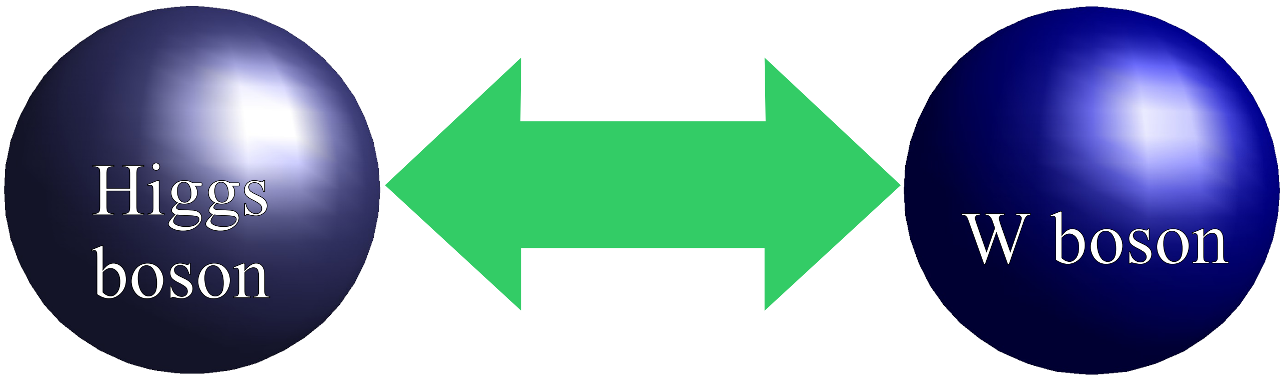
LPHE Seminar, Mai 2009

Outline

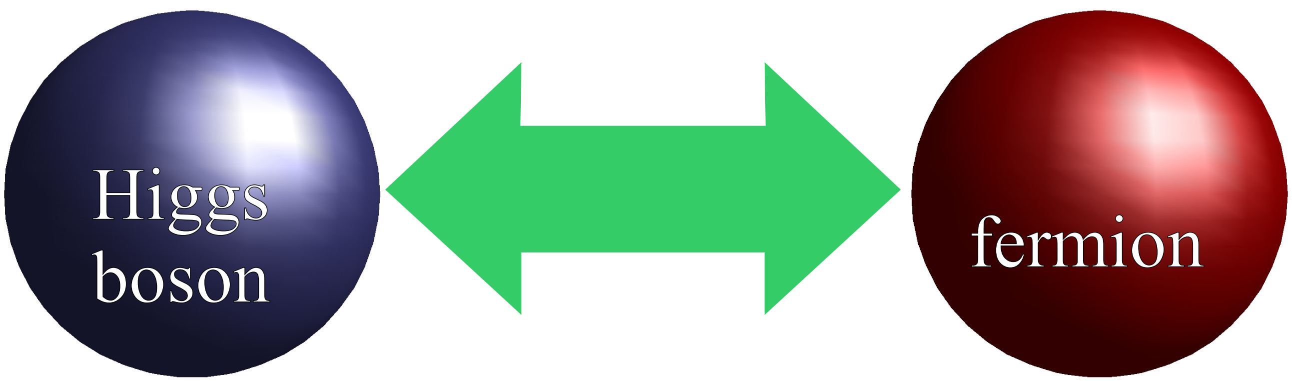
- Introduction
- Single top quark production
- Observation of single top quark production at DØ
- New physics searches
- Other experiments (CDF, LHC)
- Conclusions

Electroweak symmetry breaking

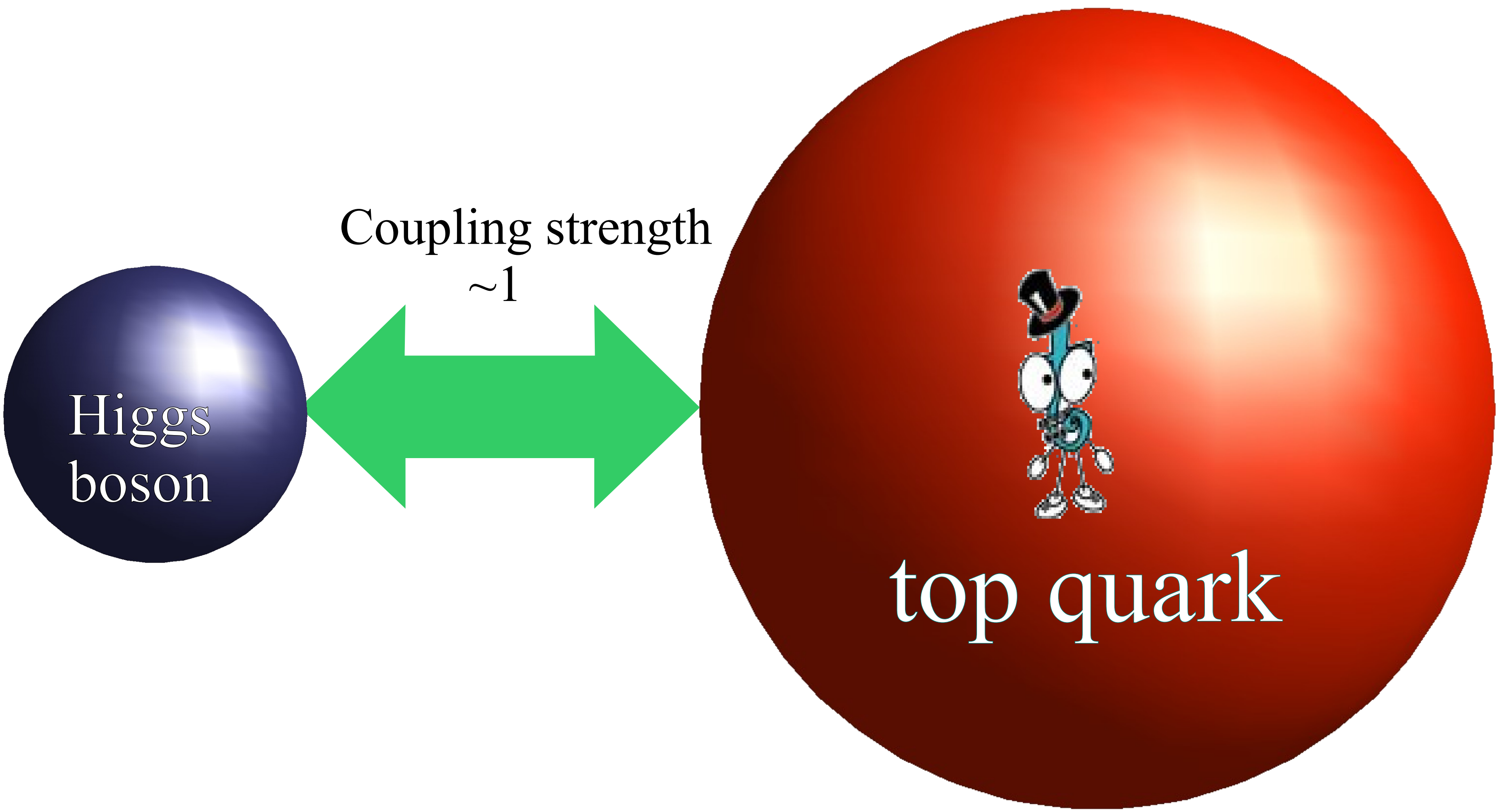
Gauge boson coupling to Higgs field



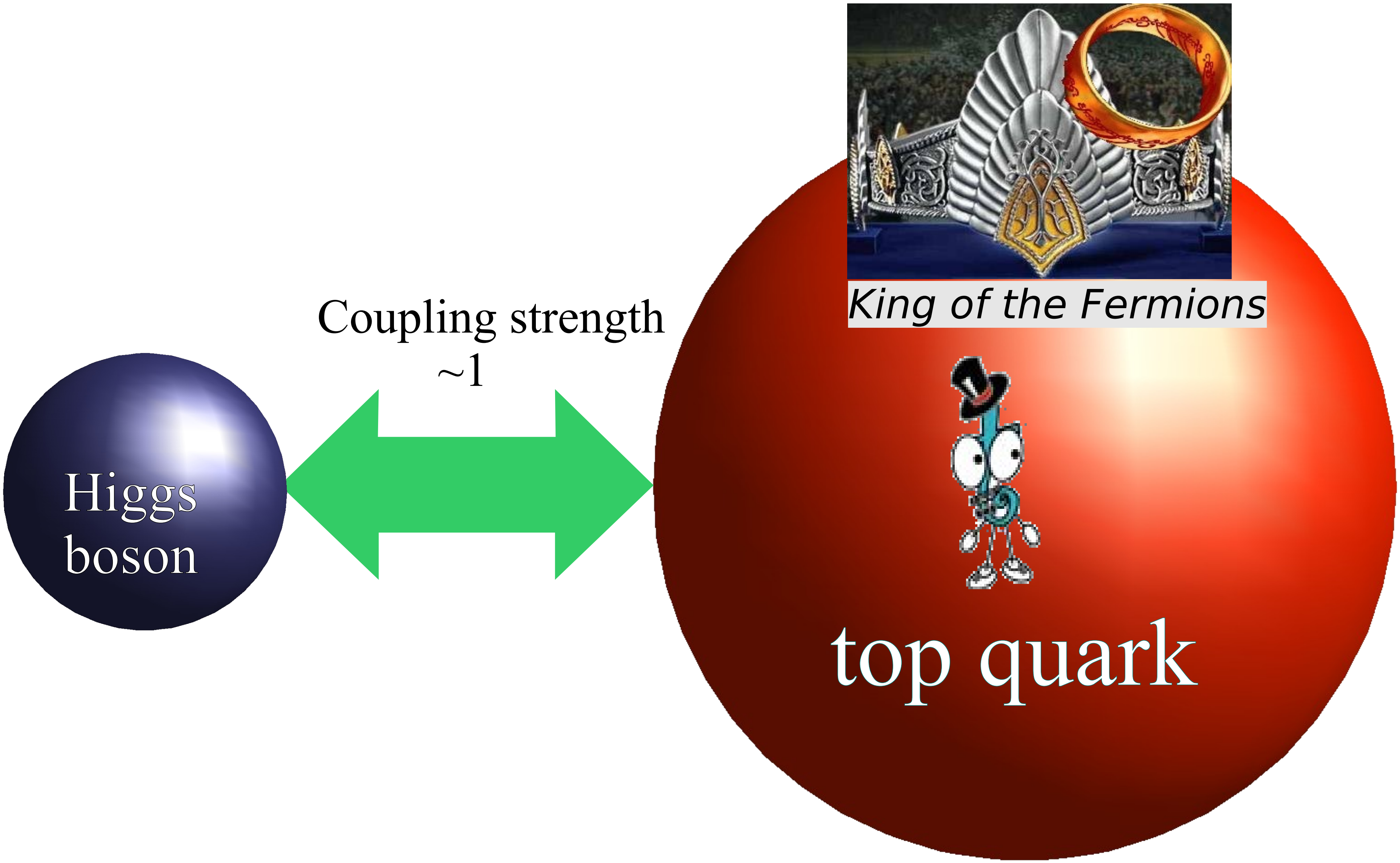
Fermions acquire mass through Higgs coupling



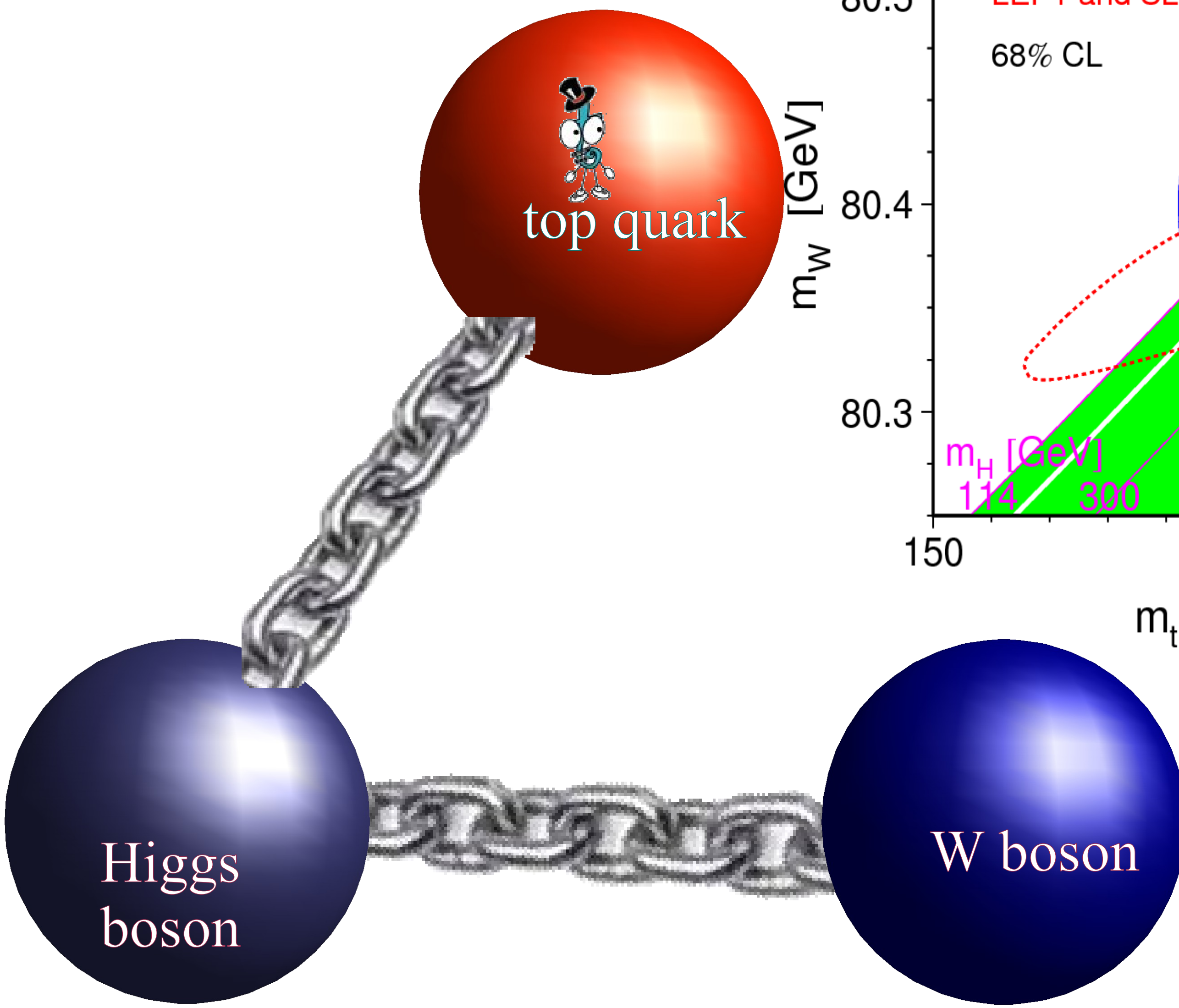
Top quark

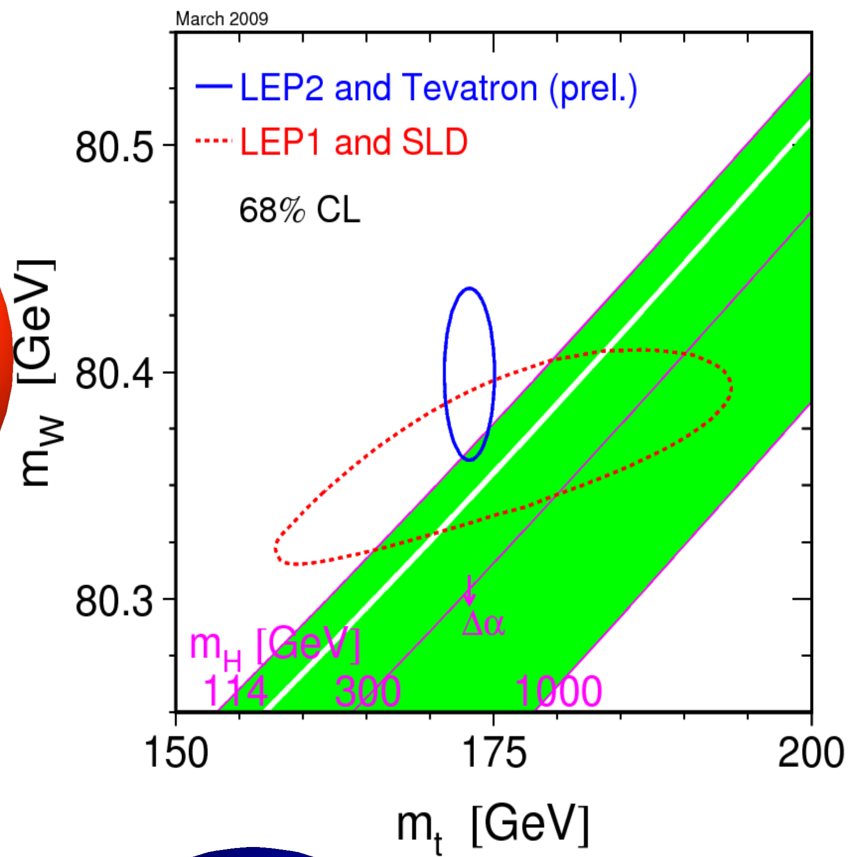


Top quark

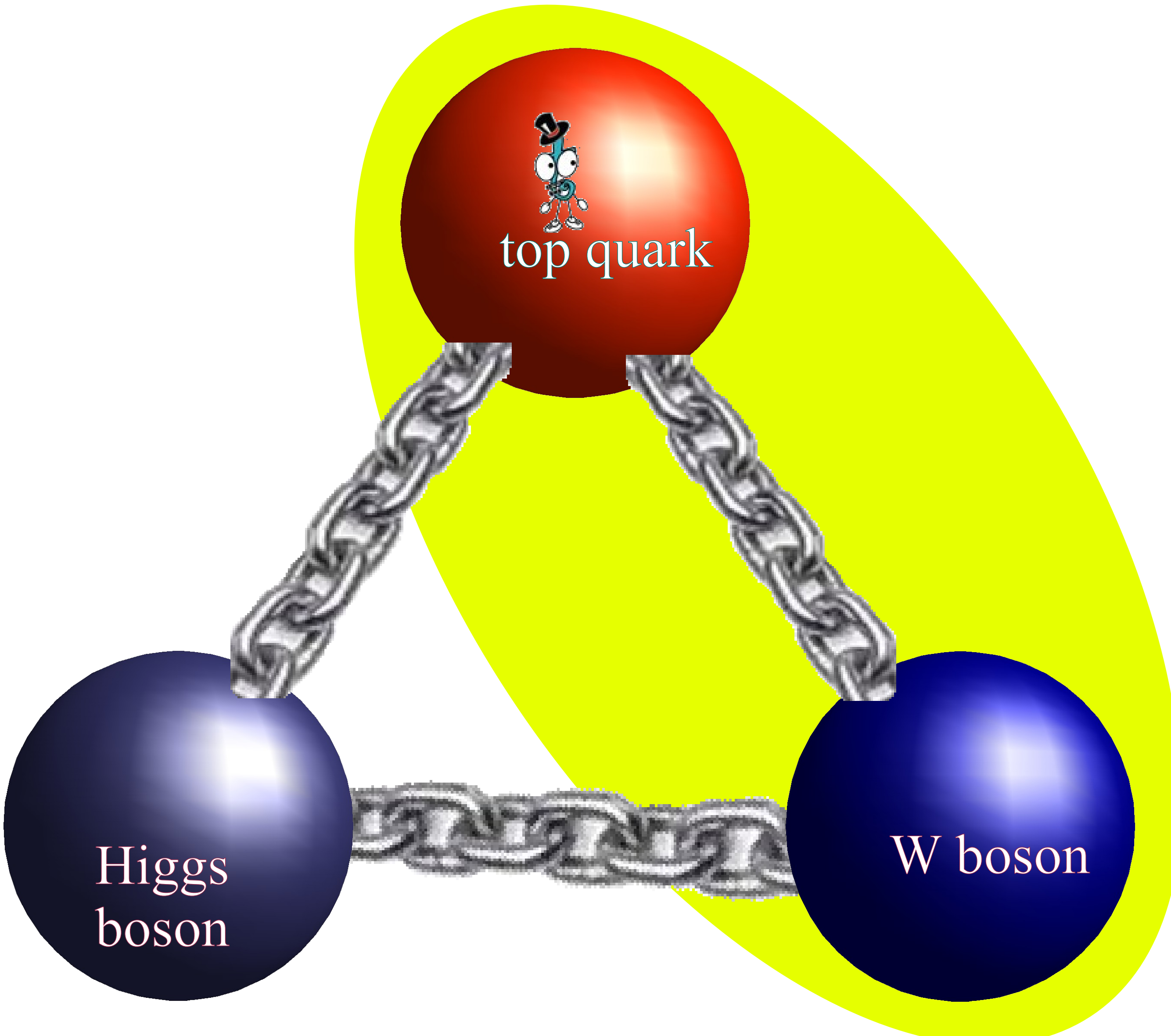

King of the Fermions
Coupling strength
~1
Higgs
boson
top quark

Higgs mass estimate

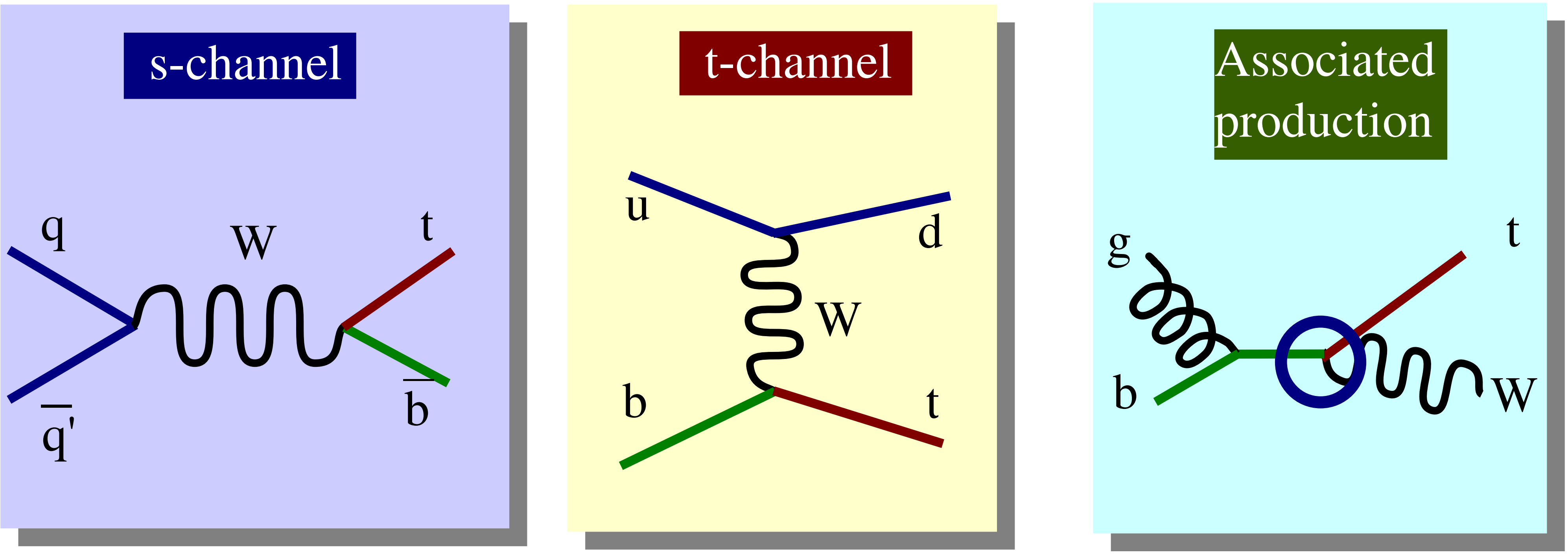


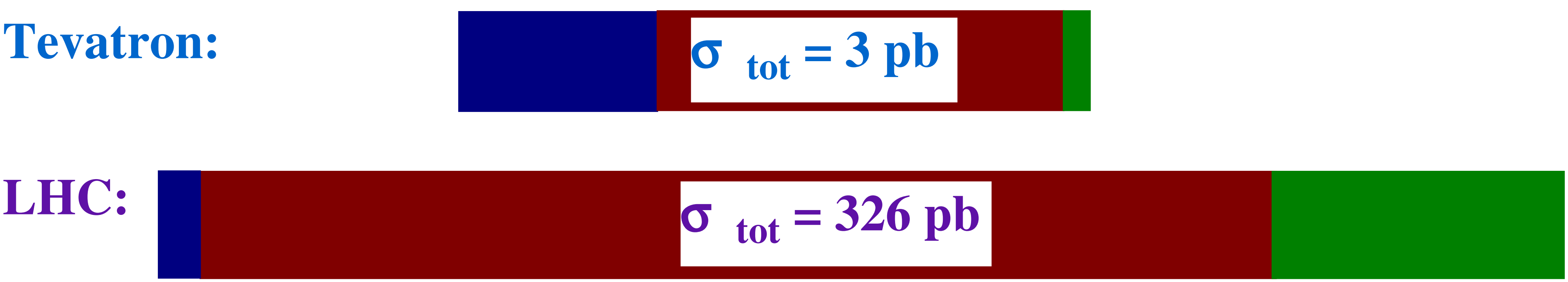


Key to electroweak symmetry breaking



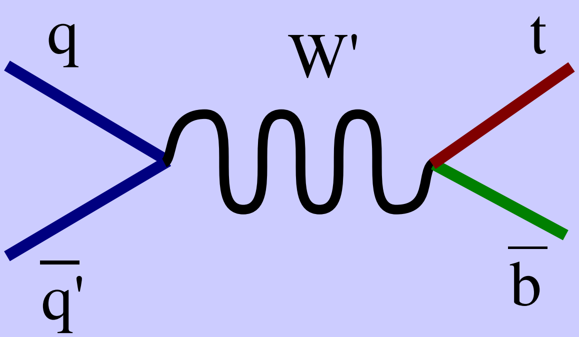
SM single top quark production





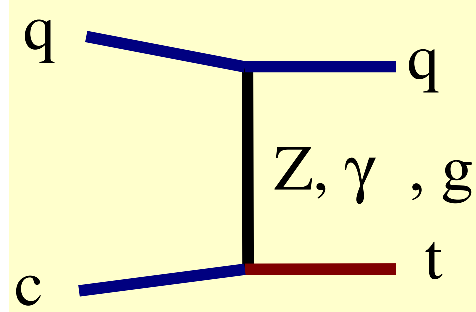
New physics

s-channel



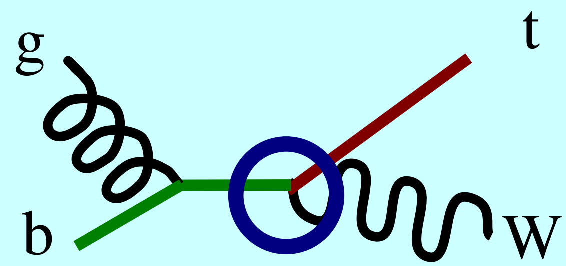
New heavy boson

t-channel



Flavor Changing Neutral Current

Associated production



Modified Wtb coupling

Production cross sections: *s-channel* *t-channel*

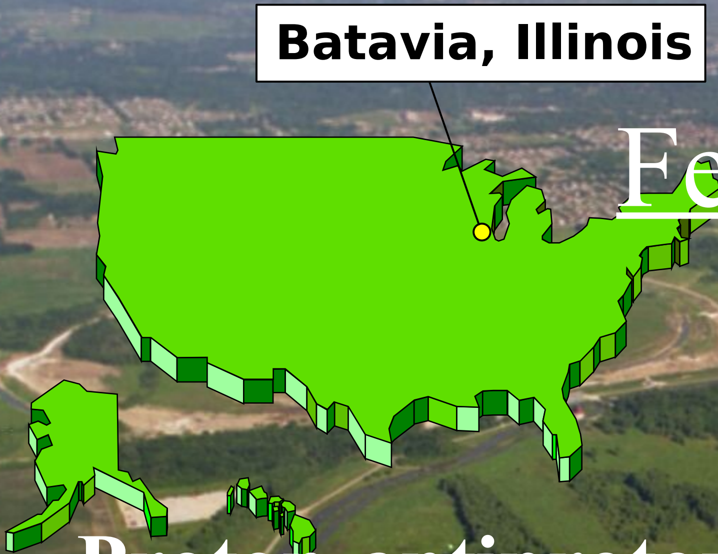
(N)NLO calculation: **1.12 pb (±5%)** **2.34 pb (±6%)**

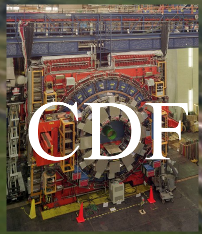
(m_{top} = 170 GeV)

Tevatron single top goals

- Discover single top quark production!
- Measure production cross sections
  $\rightarrow$ CKM quark mixing matrix element V_{tb}
- Look for physics beyond the standard model
  - Coupled to the heavy top quark
- Study top quark spin correlations
- Understand as background to many other searches
- Explore analysis techniques that will also be used elsewhere

Experimental setup: Fermilab Tevatron in Run II





Proton-antiproton collider

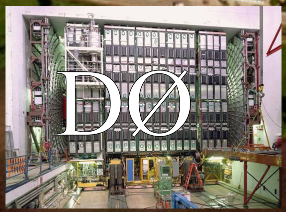
CM energy 1.96TeV

→ ***Energy frontier***

Instantaneous luminosity >400E30cm^{-2}s^{-1}

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

→ ***Luminosity frontier***



Fermilab single top history

Publication history

DØ

· 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

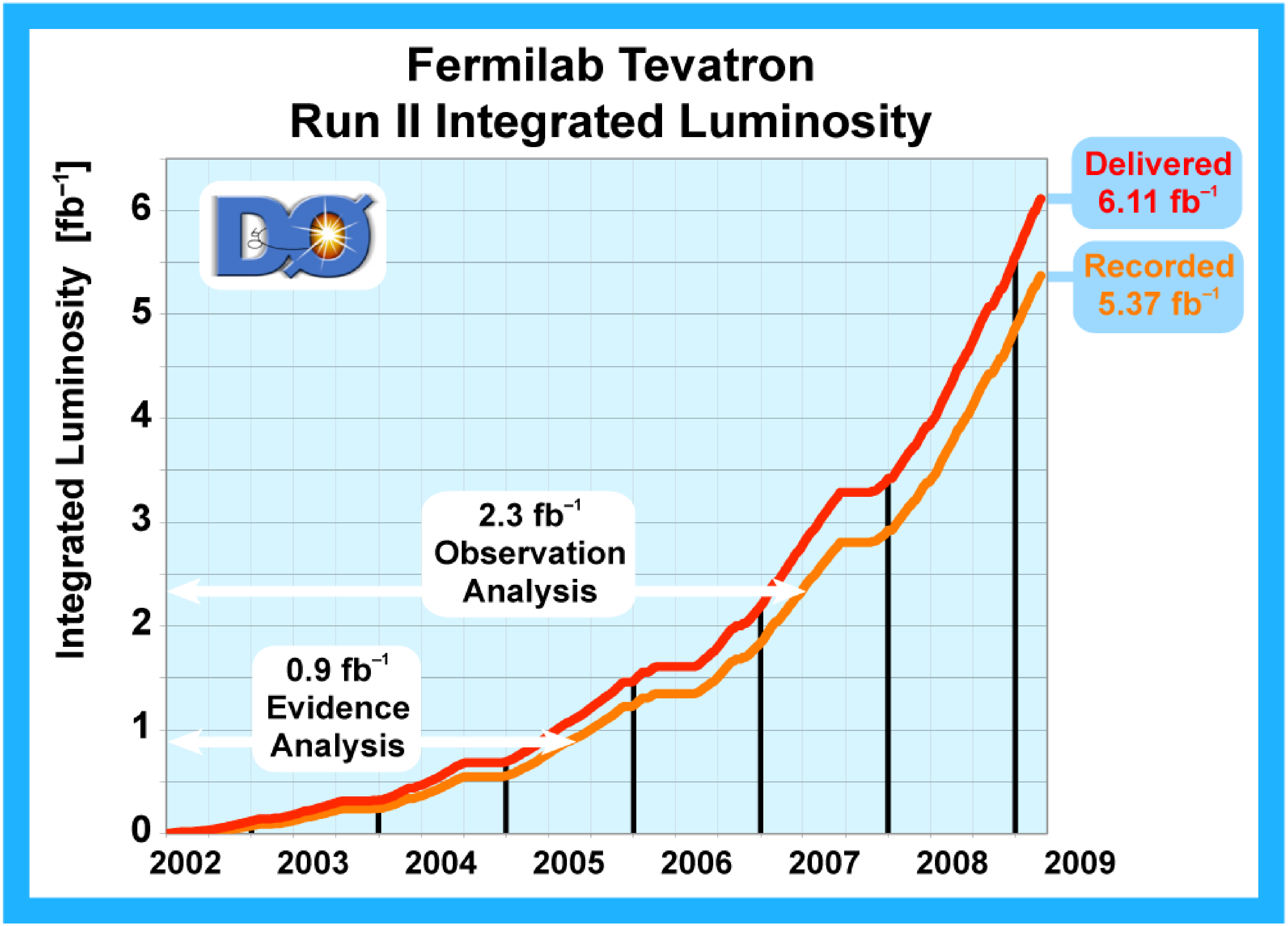
Run II

CDF

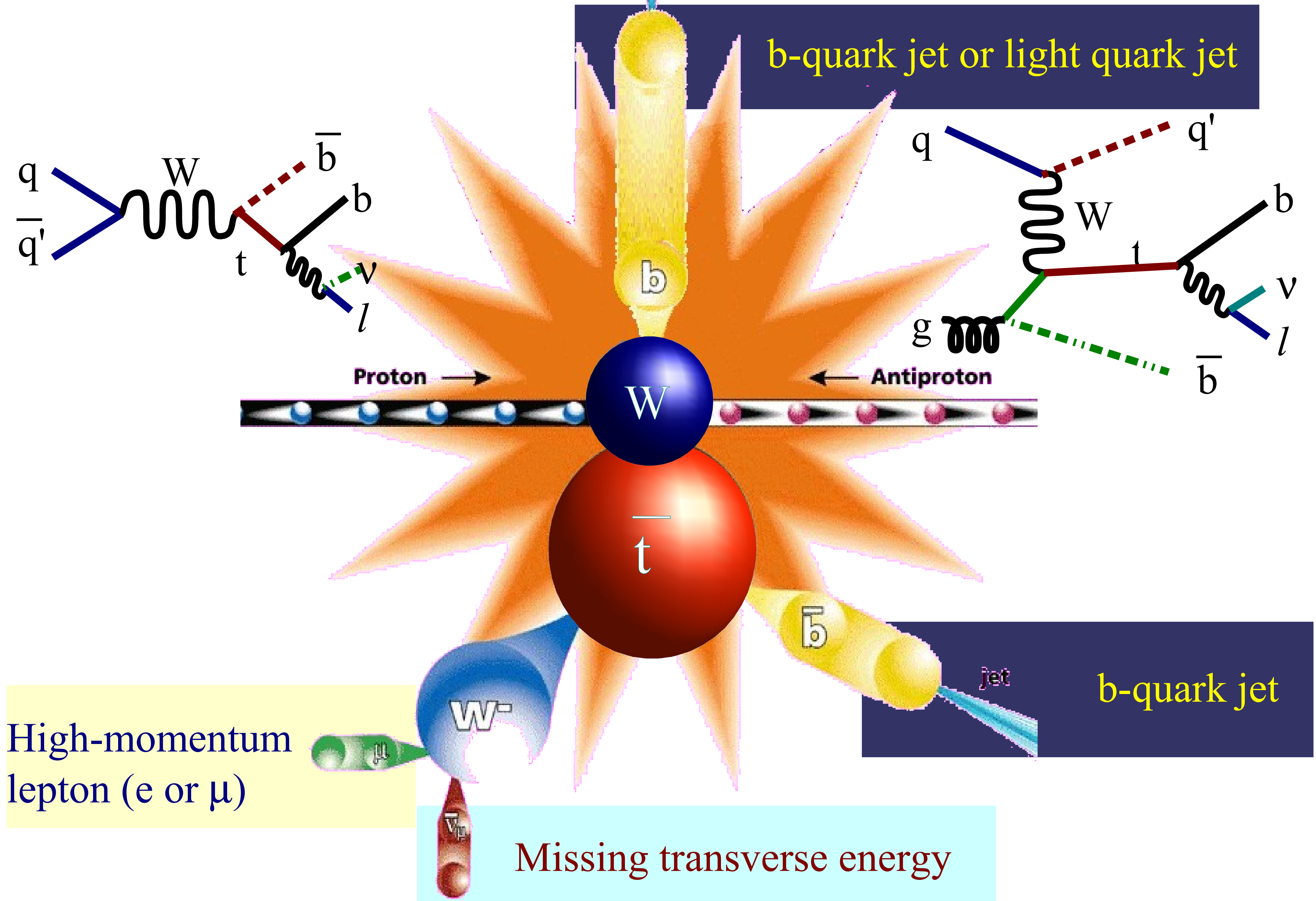
· Search:	PRD 65, 091102 (2002)
· W'	PRL 90, 081802 (2003)
· Search:	PRD 69, 052003 (2004)
· Search:	PRD 71, 012005 (2005)
· Evidence:	PRL 101, 252001 (2008)
· FCNC:	(PRL) arXiv:0812.3400
· W':	(PRL) arXiv:0902.3276
· Observation:	(PRL) arXiv:0903.0885

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

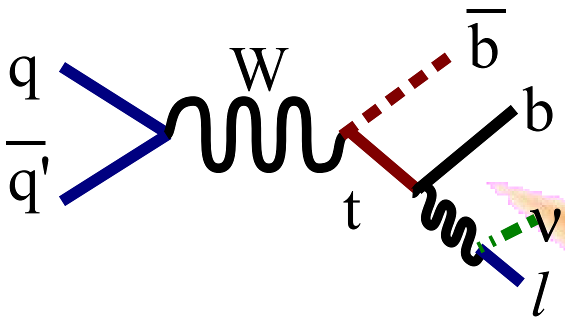

Fermilab Tevatron
Run II Integrated Luminosity
Integrated Luminosity [fb⁻¹]
Delivered
6.11 fb⁻¹
Recorded
5.37 fb⁻¹
2.3 fb⁻¹
Observation
Analysis
0.9 fb⁻¹
Evidence
Analysis
0
1
2
3
4
5
6
2002
2003
2004
2005
2006
2007
2008
2009

Single top quark event signature

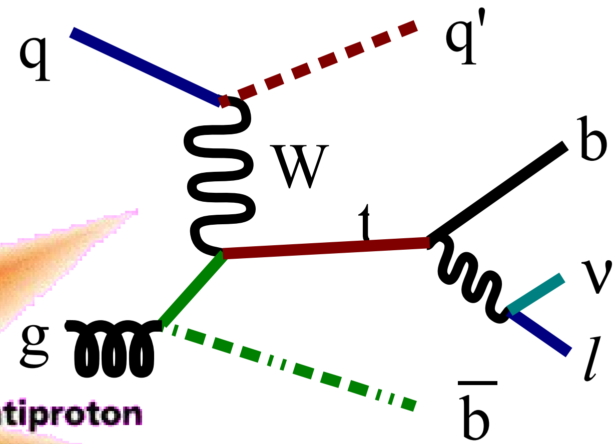


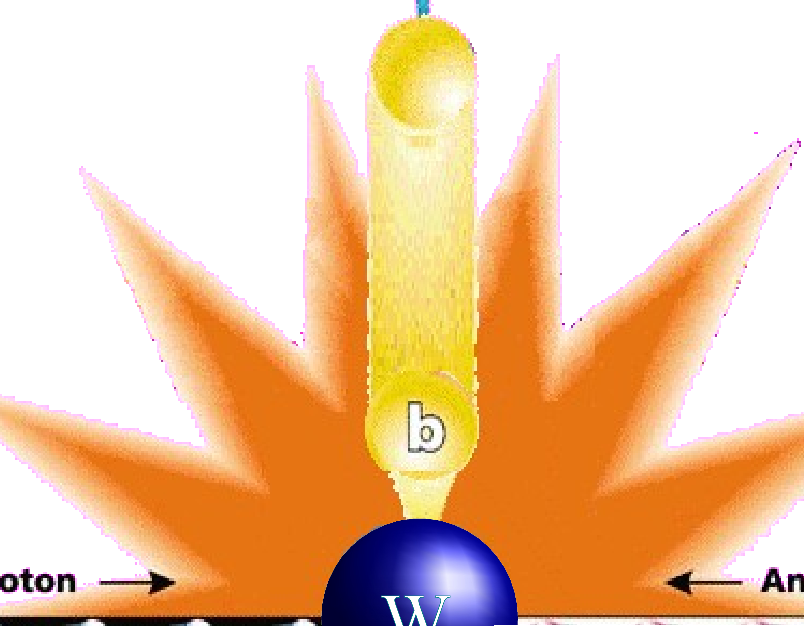
Single top quark event signature

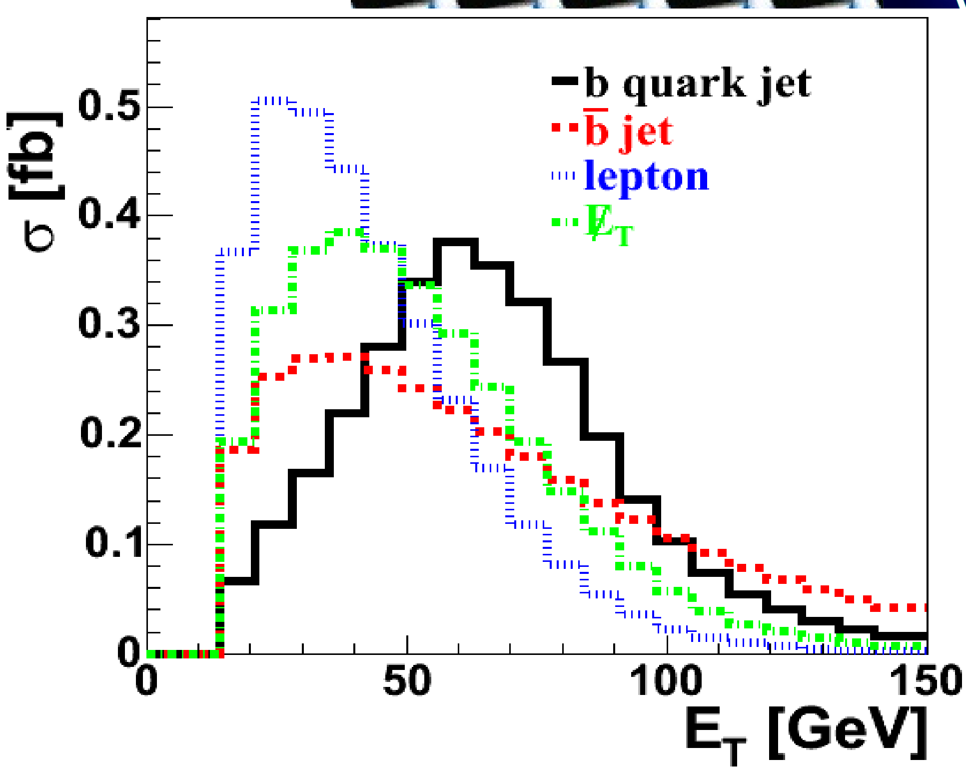
s-channel

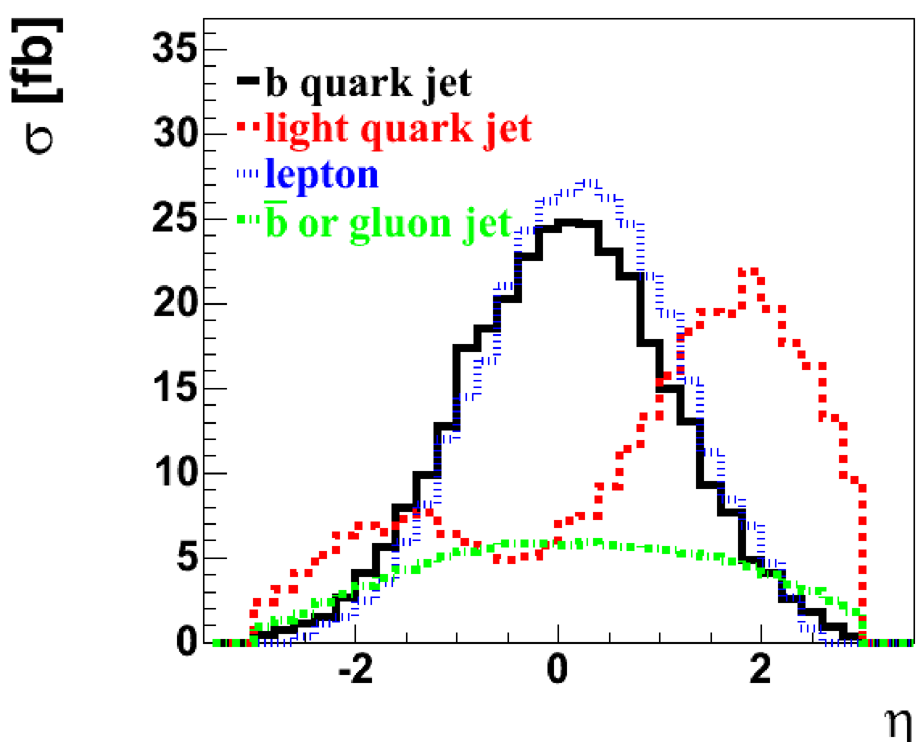


t-channel

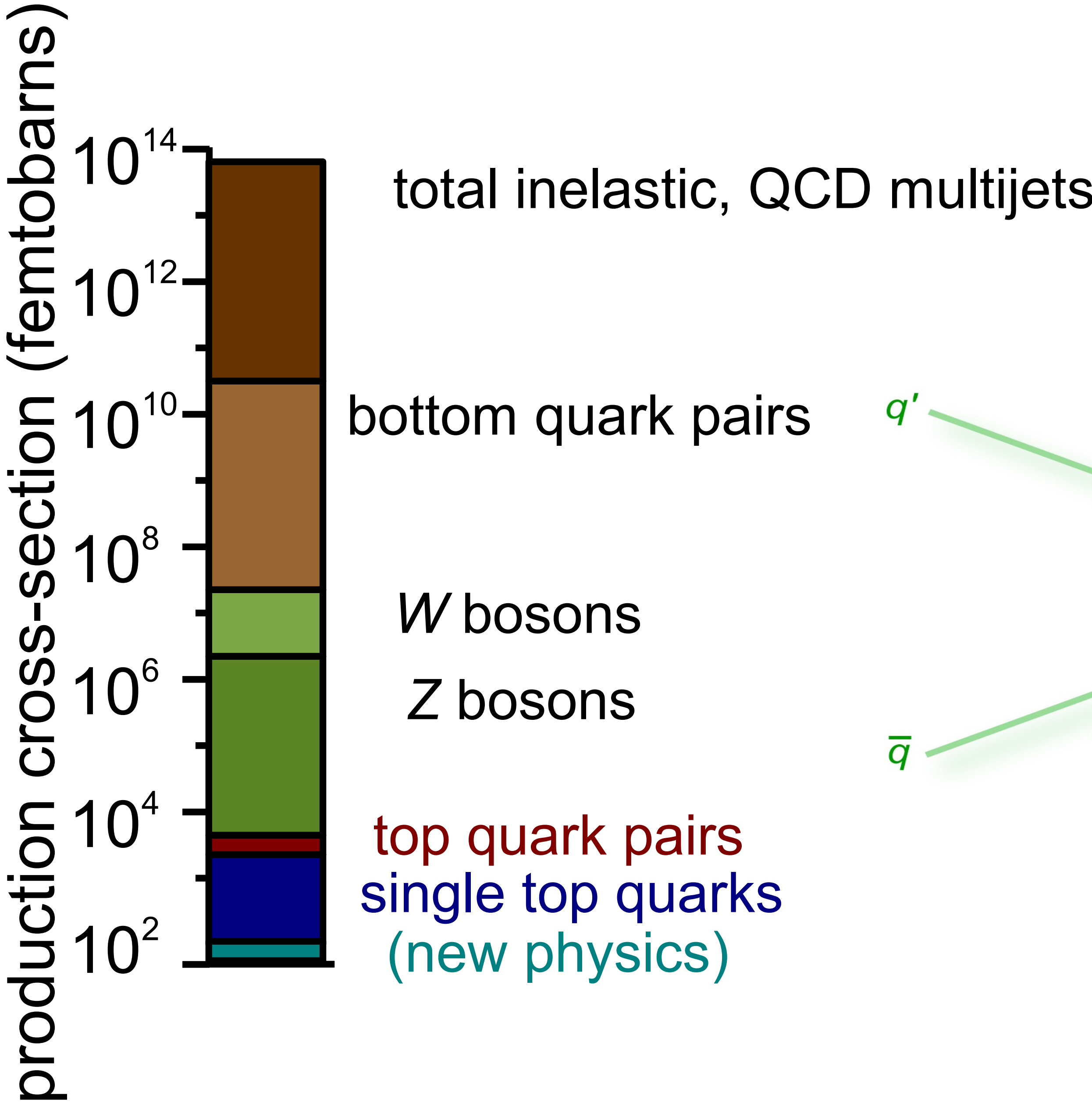


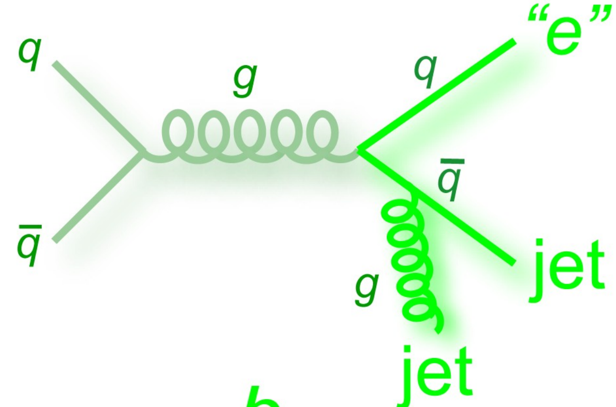


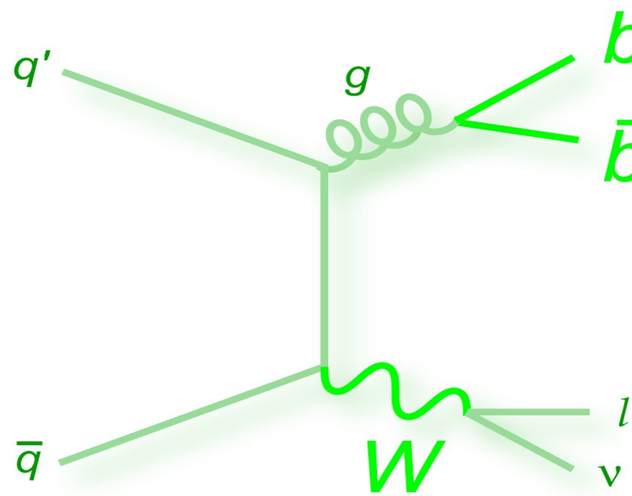


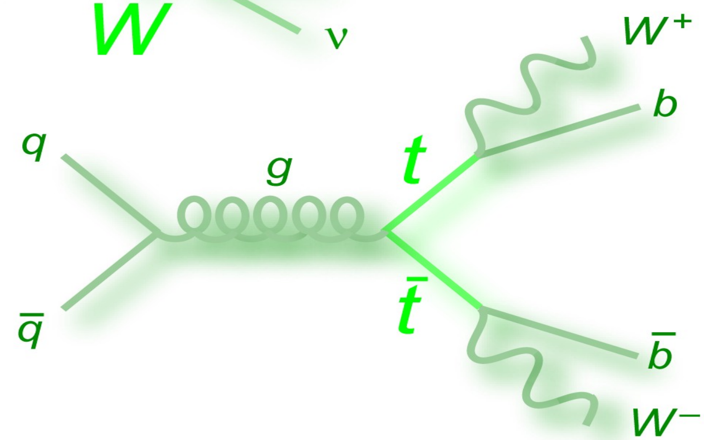


Background processes





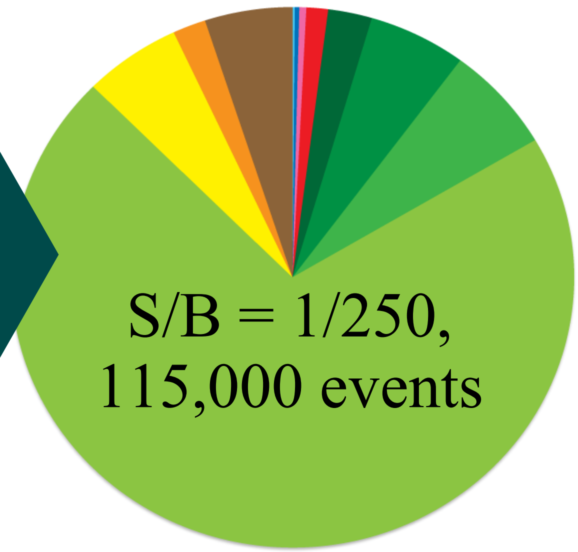




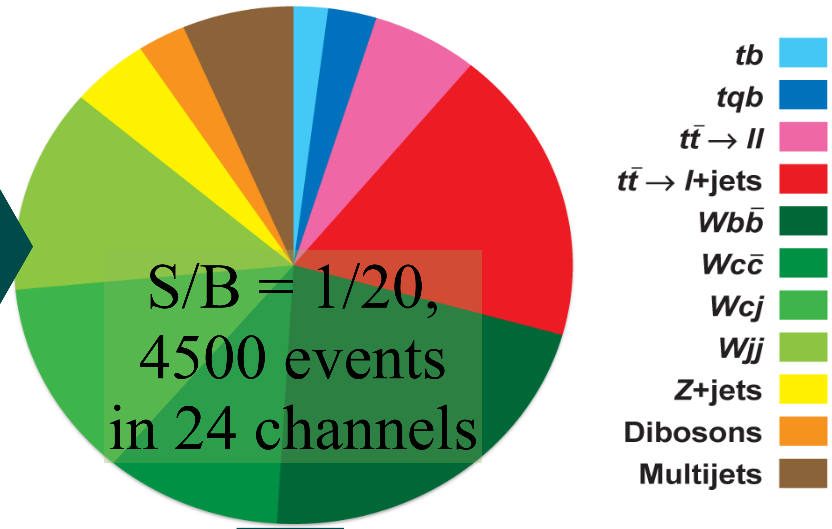
Analysis outline

Trigger selection

Single top event kinematics

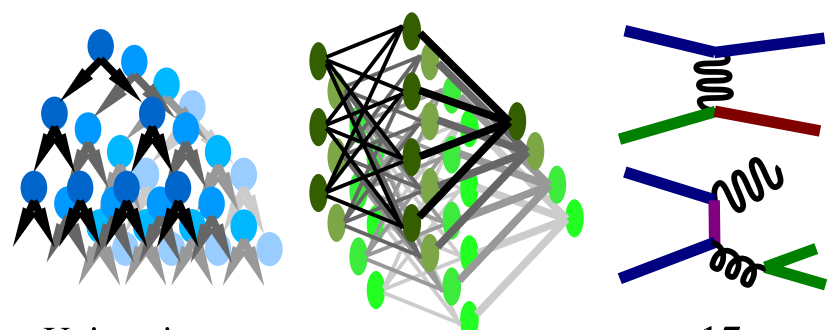


b-quark tagging

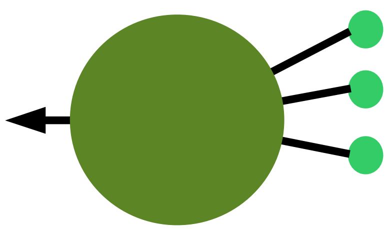


Multivariate techniques

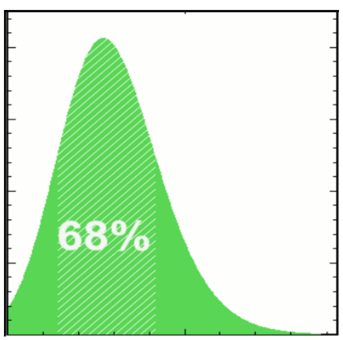
BDT **BNN** **ME**



Combination



Statistical analysis

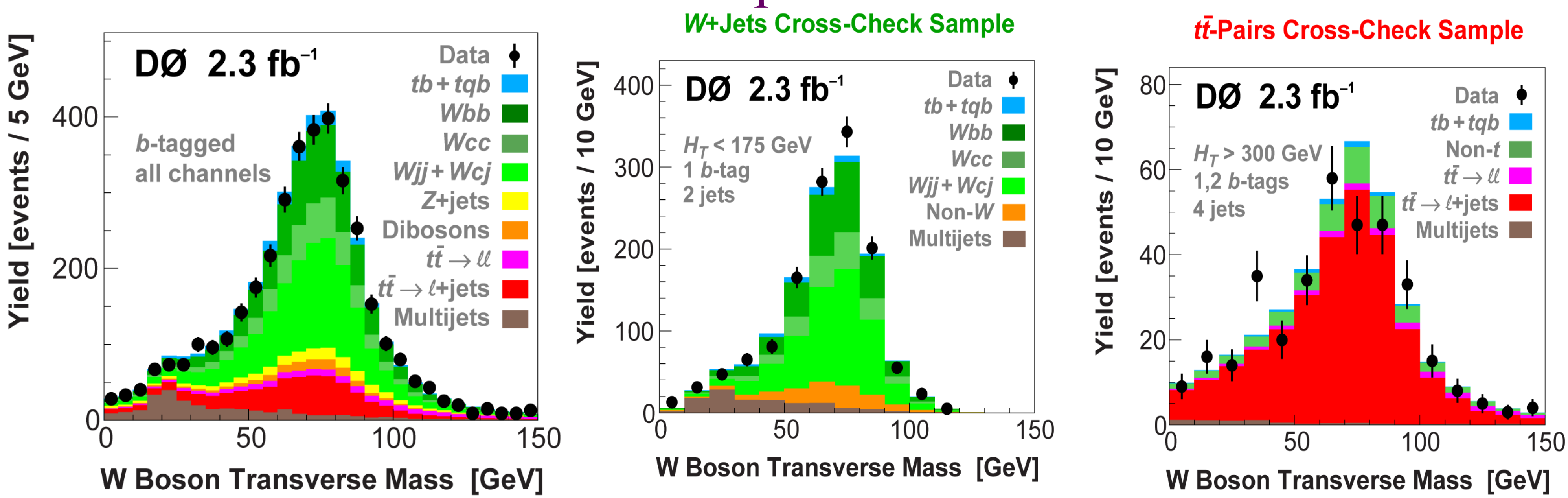


Analysis samples

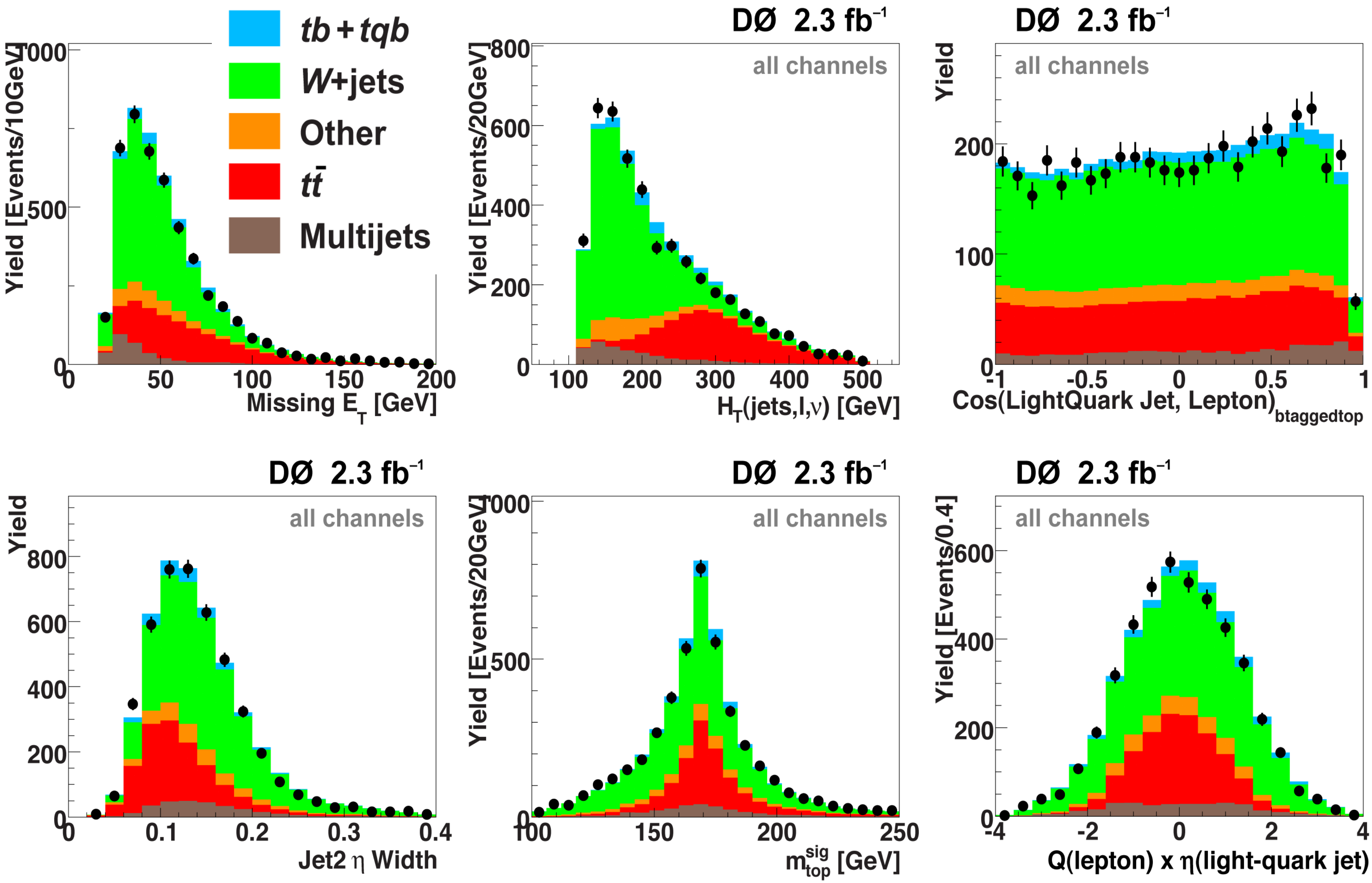
– Divide into 24 analysis channels
  - By b-tag multiplicity (1, 2), jet multiplicity (2, 3, 4), data taking period (before/after upgrade), lepton (e, μ)

– Cross-check samples
  - Enriched in W+jet events
  - Enriched in top pair events

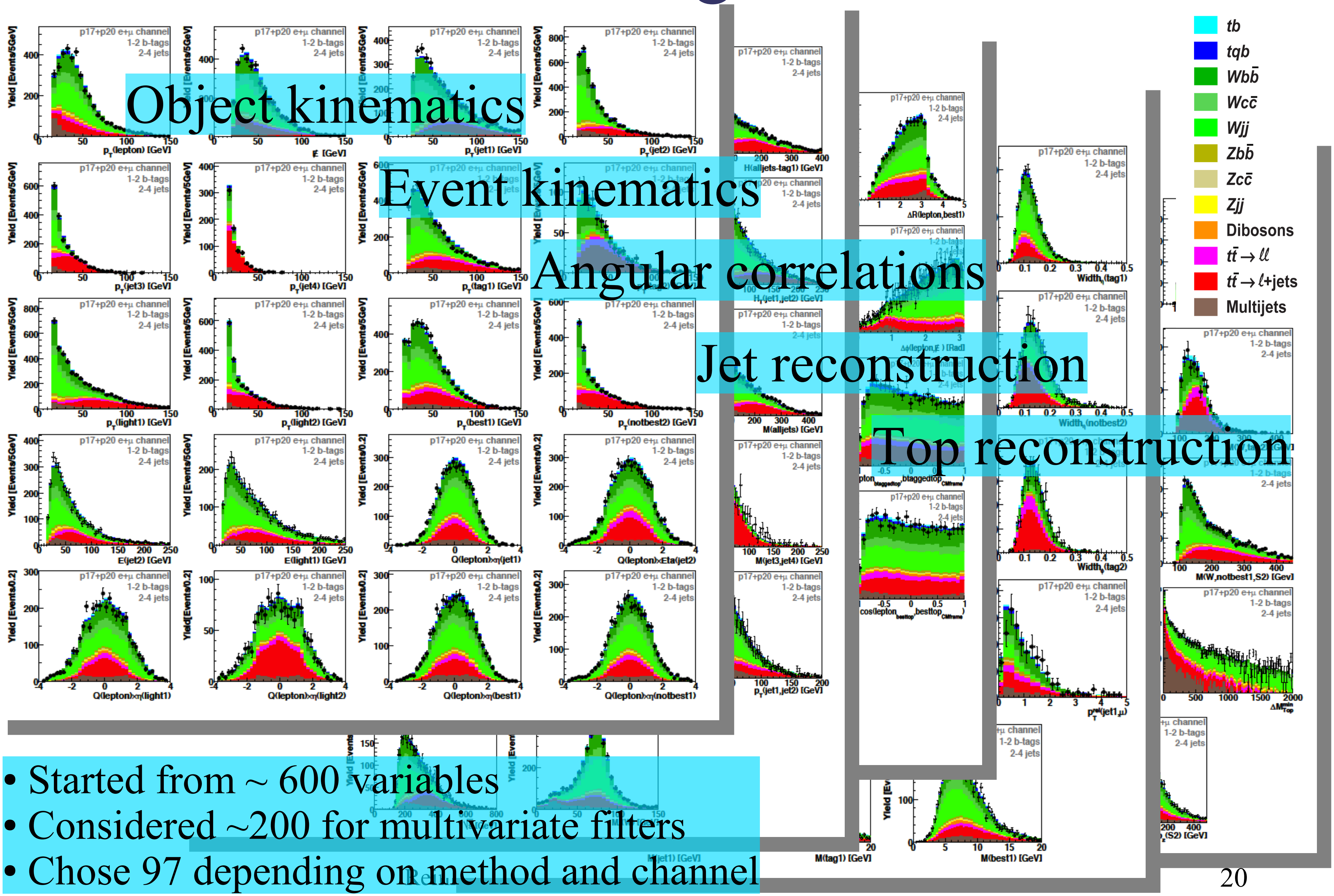
– Check data/background agreement for all variables and multivariate filters in all samples



Important discriminating variables

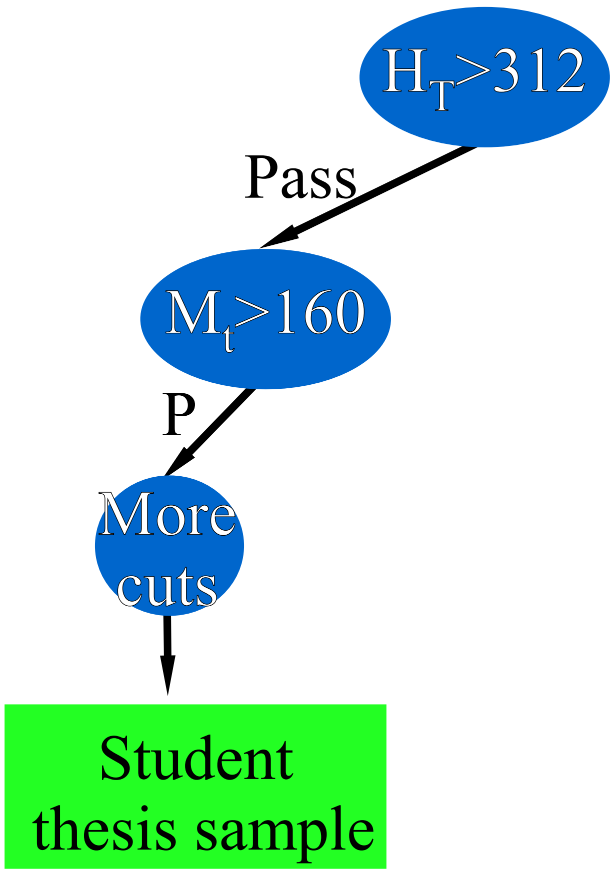


Discriminating variables

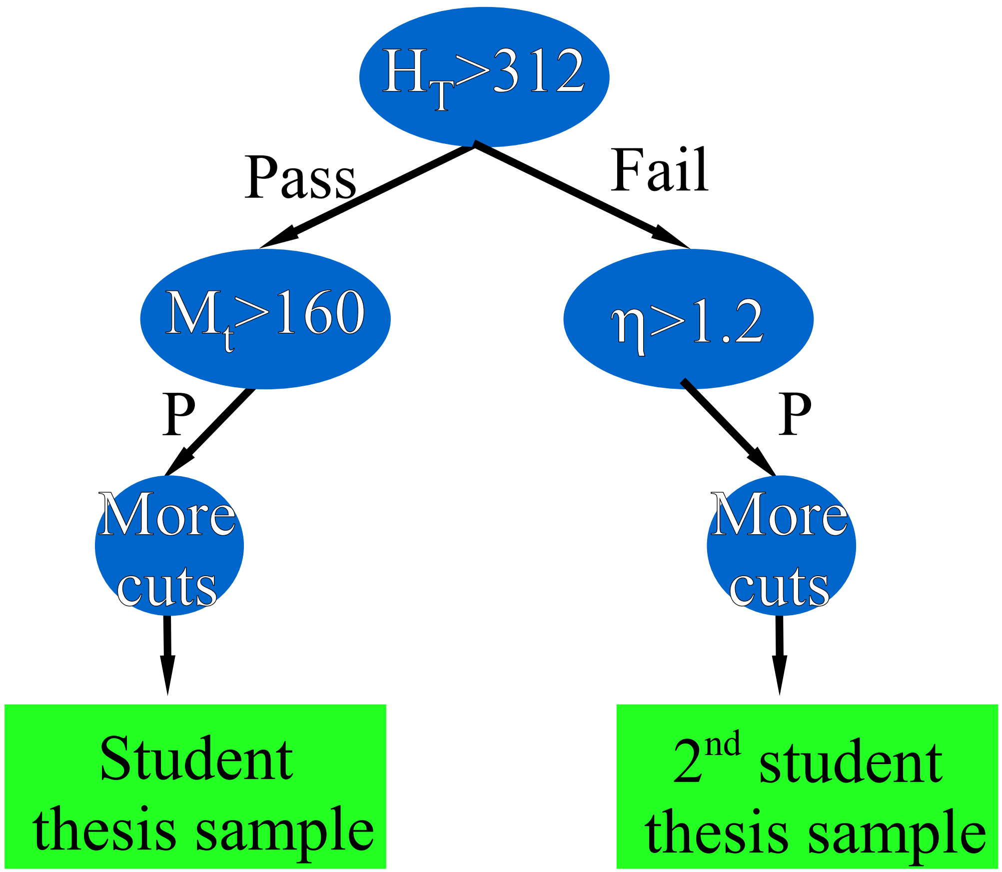


- Started from ~ 600 variables
- Considered ~200 for multivariate filters
- Chose 97 depending on method and channel

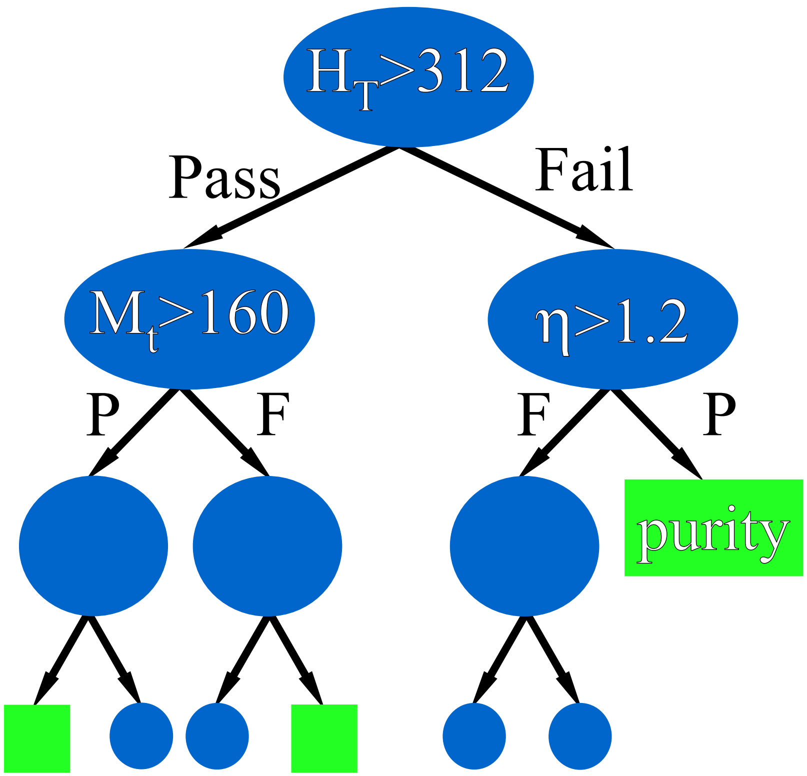
How to build a decision tree: cut-based analysis



How to build a decision tree: orthogonal data samples

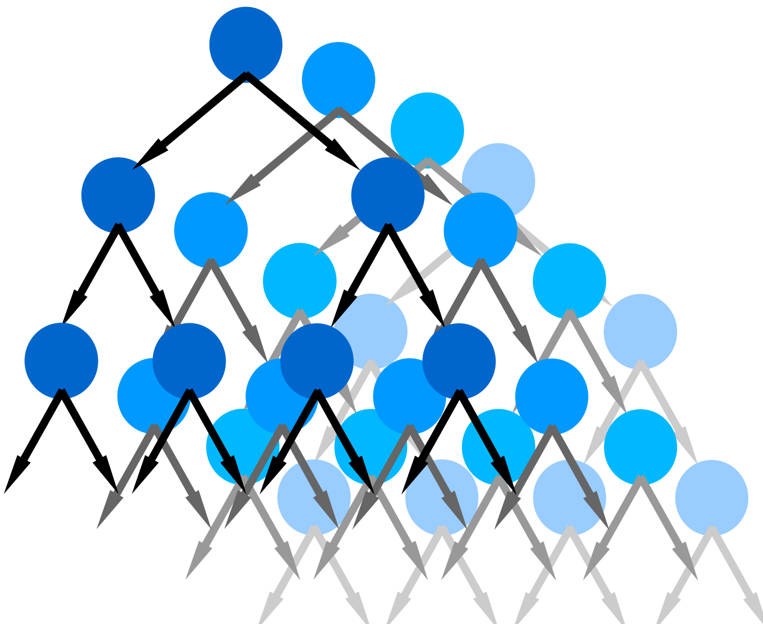


Decision tree



- 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

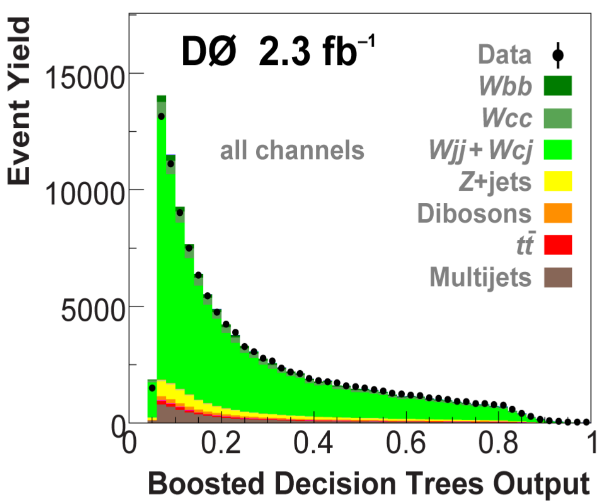
Boosted decision tree



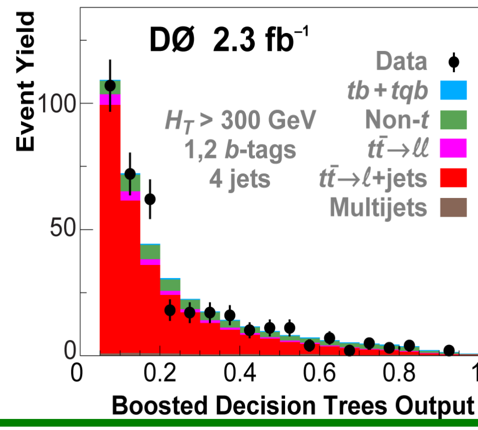
- Cuts produce branches
- Terminal leaf: calculate purity = $N_S/(N_S+N_B)$ from MC signals and backgrounds
- Each data event is assigned the purity value of the leaf it falls into
- Typical trees: hundreds of leafs
- Boosting: Average over many trees, each built by iteratively increasing weight of mis-classified events
- Typically 20-100 boosting cycles

Boosted decision tree distributions

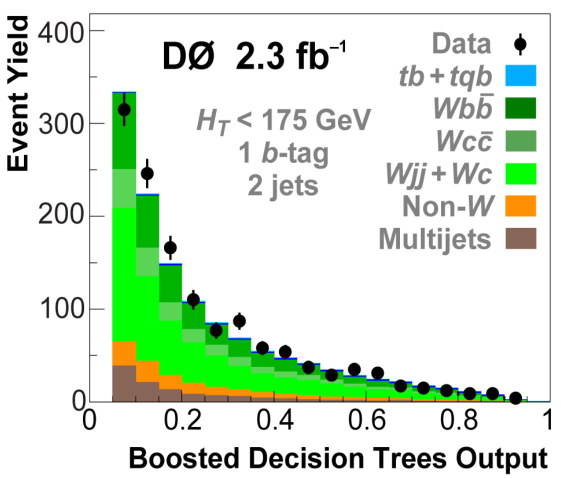
Pretagged Cross-Check Sample



$t\bar{t}$-Pairs Cross-Check Sample

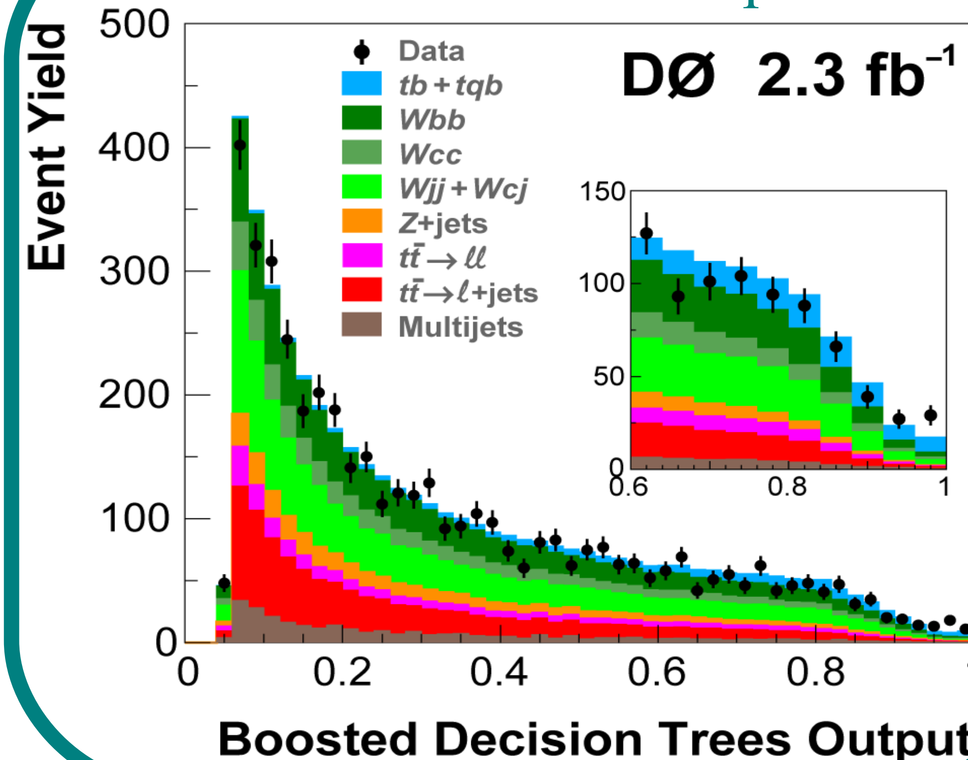


W+Jets Cross-Check Sample

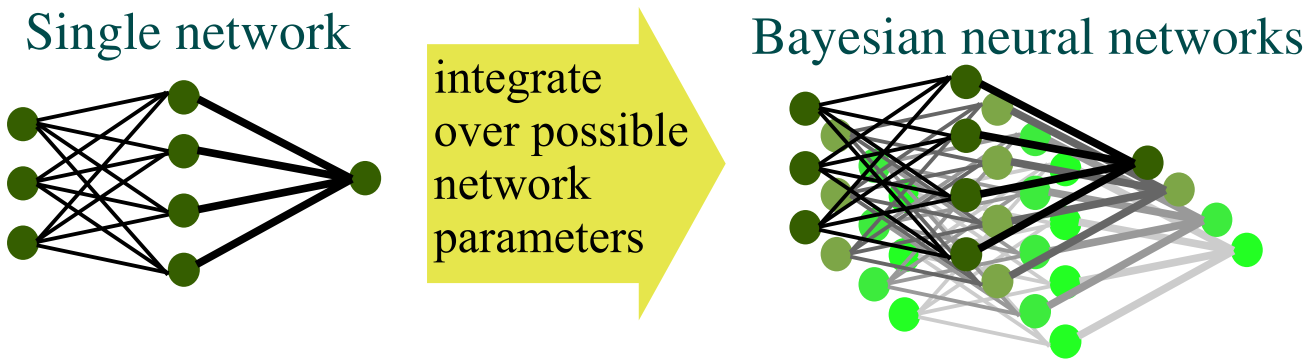


Cross checks

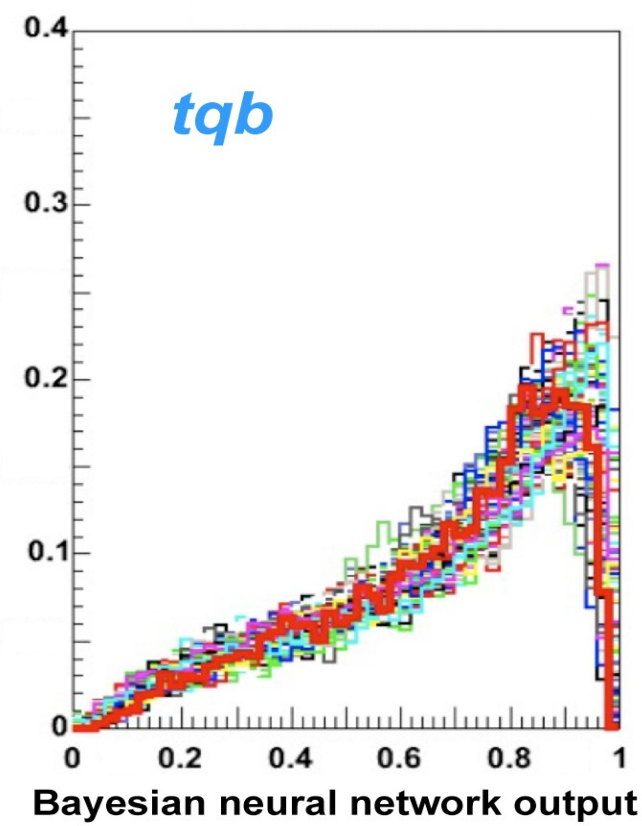
Full data sample



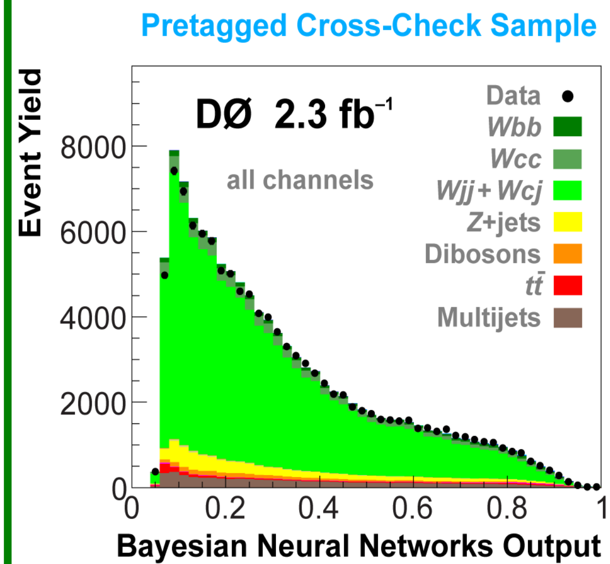
Bayesian neural networks

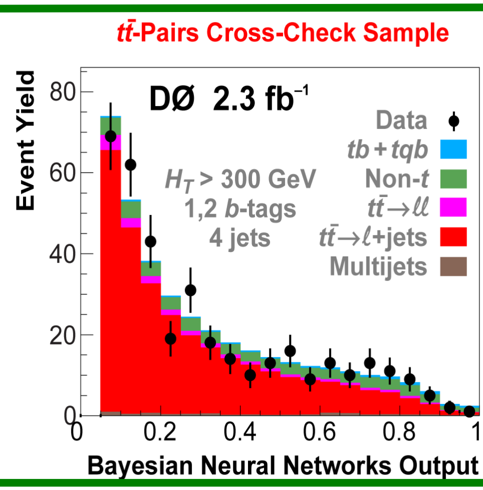


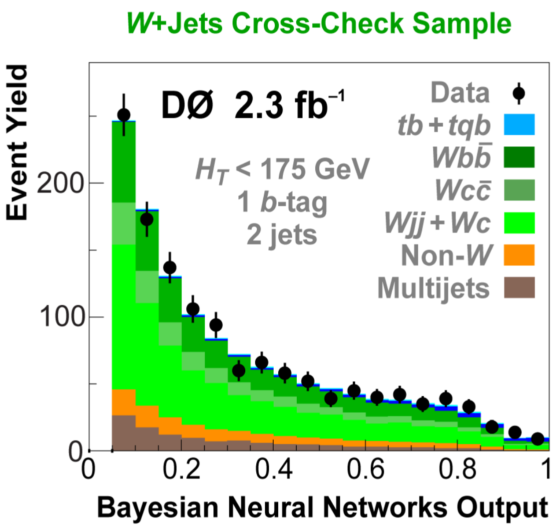
- NN with three layers, 24 input nodes, 40 hidden nodes
- Bayesian Idea:
  - Determine the posterior probability for each weight at each node
  - Sample from this posterior
  - Here: Average over 100 networks



Bayesian neural network distributions

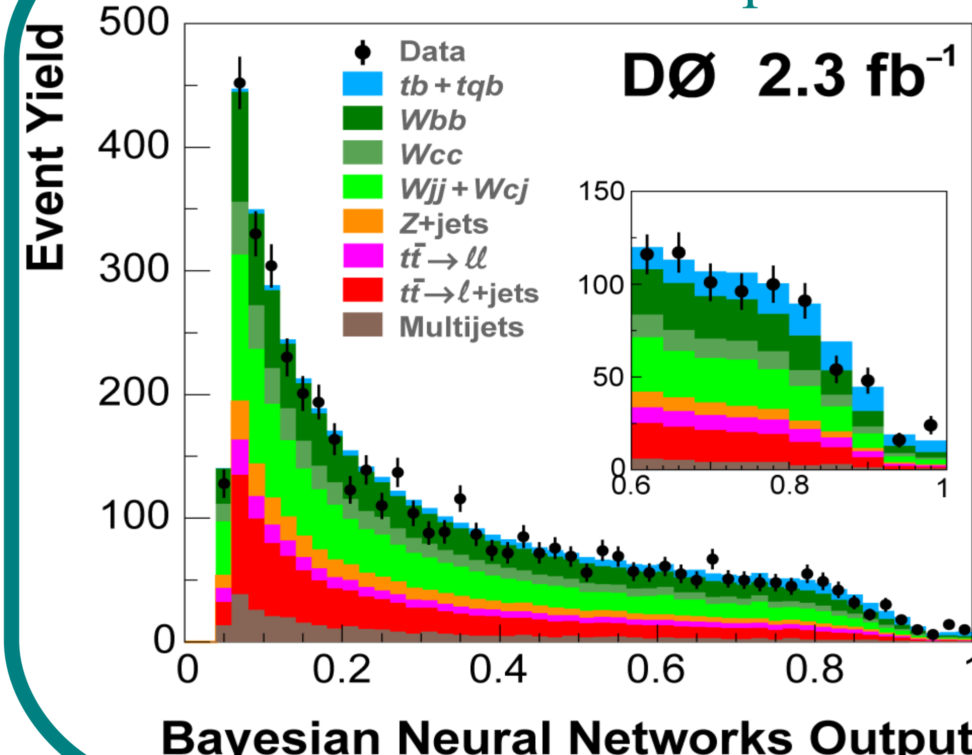






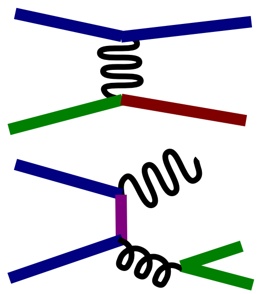
Cross checks

Full data sample



Matrix element analysis

Parton level
matrix elements



integrate
over
measurement
uncertainties

Signal discriminant

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

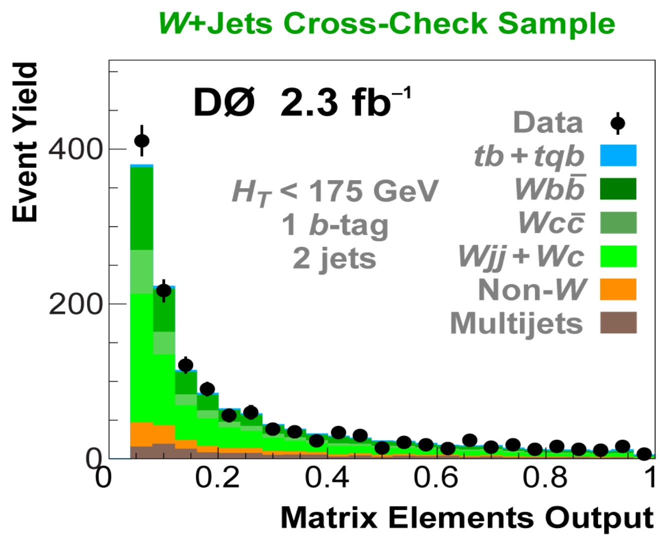
- Signal and background probability for each event is calculated from differential cross section

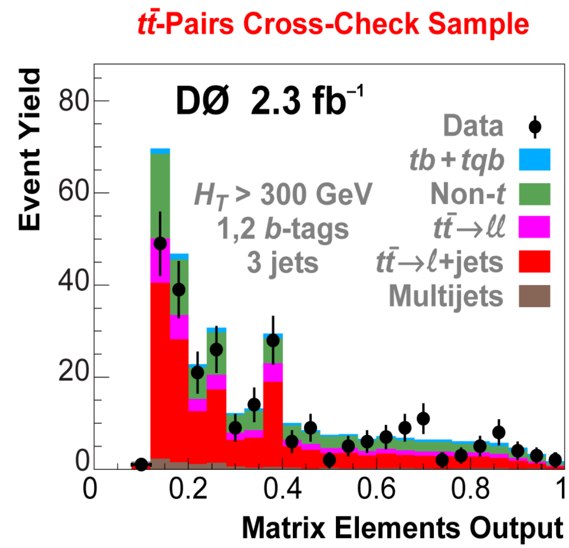
$$P_{Signal}(\vec{x}) = \frac{1}{\sigma_S} d\sigma_S(\vec{x}) \quad \sigma_S = \int d\sigma_S(\vec{x})$$

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

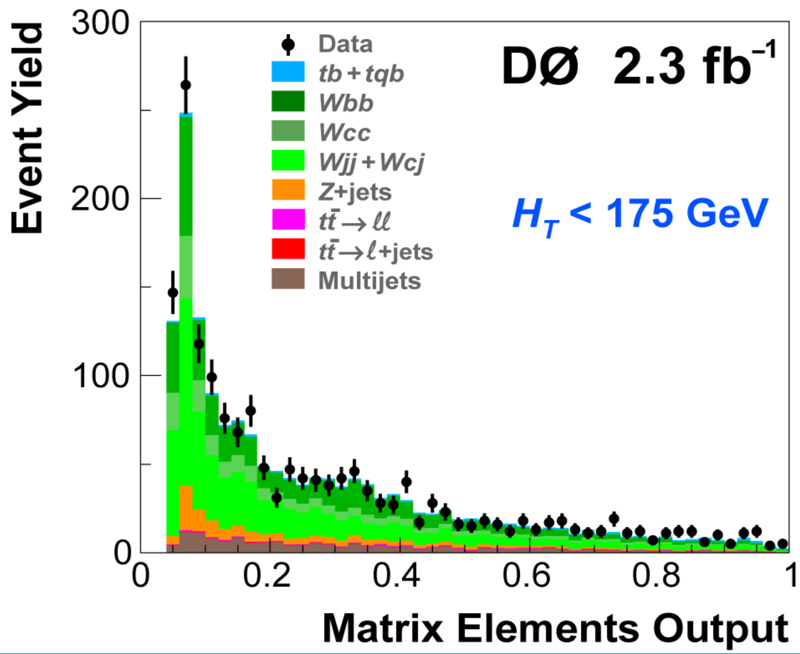
Matrix element distributions

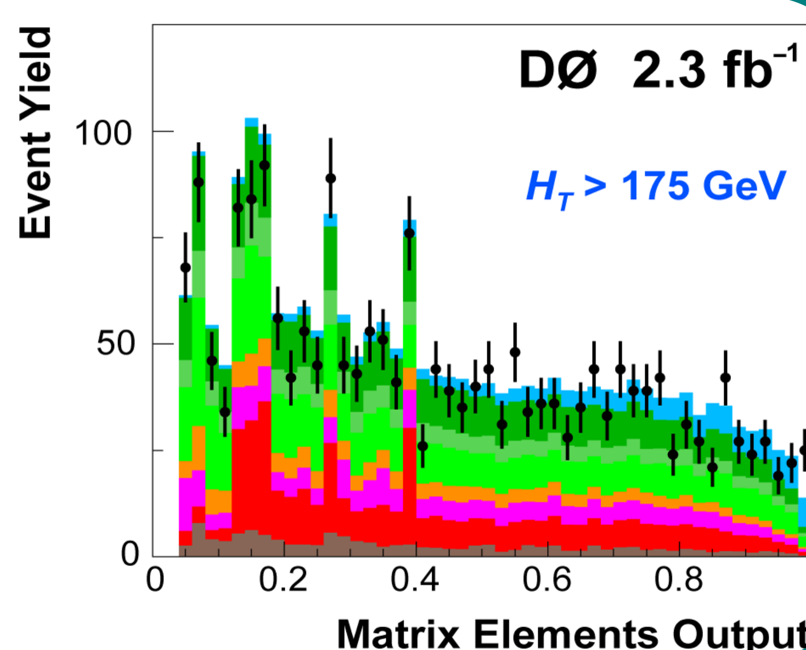
Cross checks





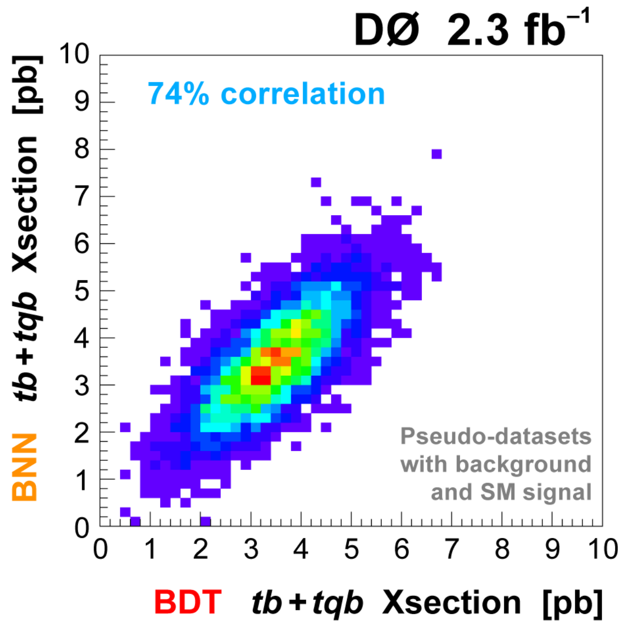
Full data sample

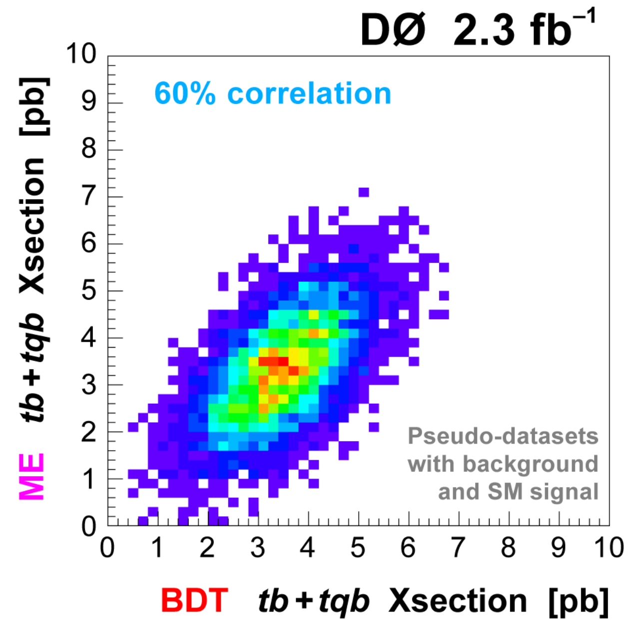




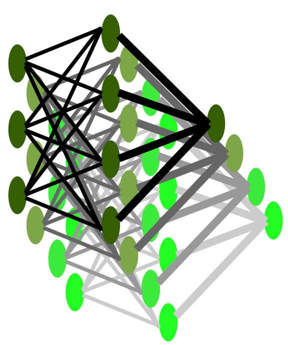
Combination: Another BNN

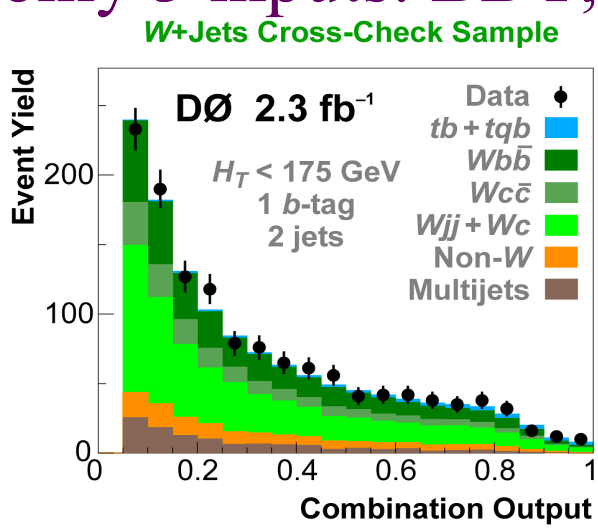
– Gain because each method provides unique separation

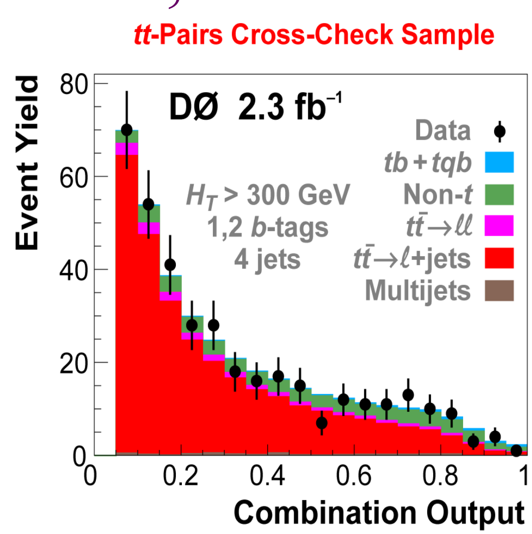




– Simple BNN, only 3 inputs: BDT, BNN, ME

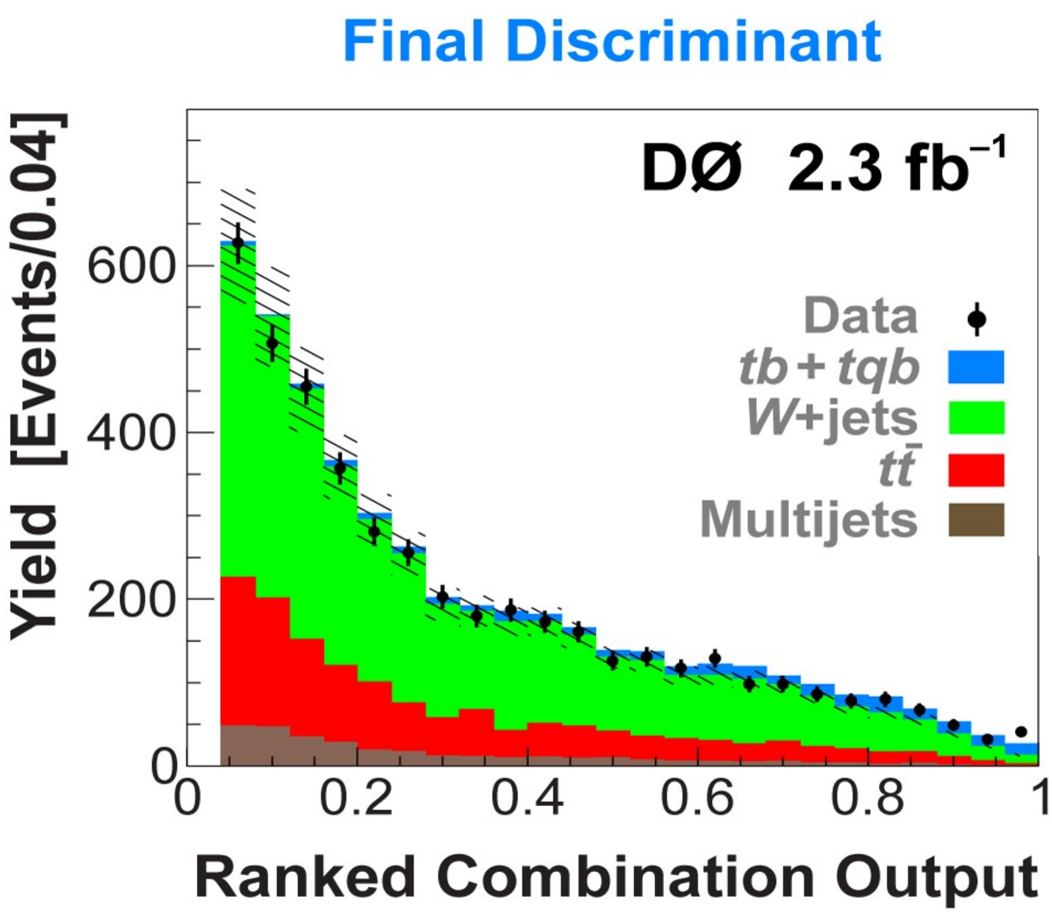


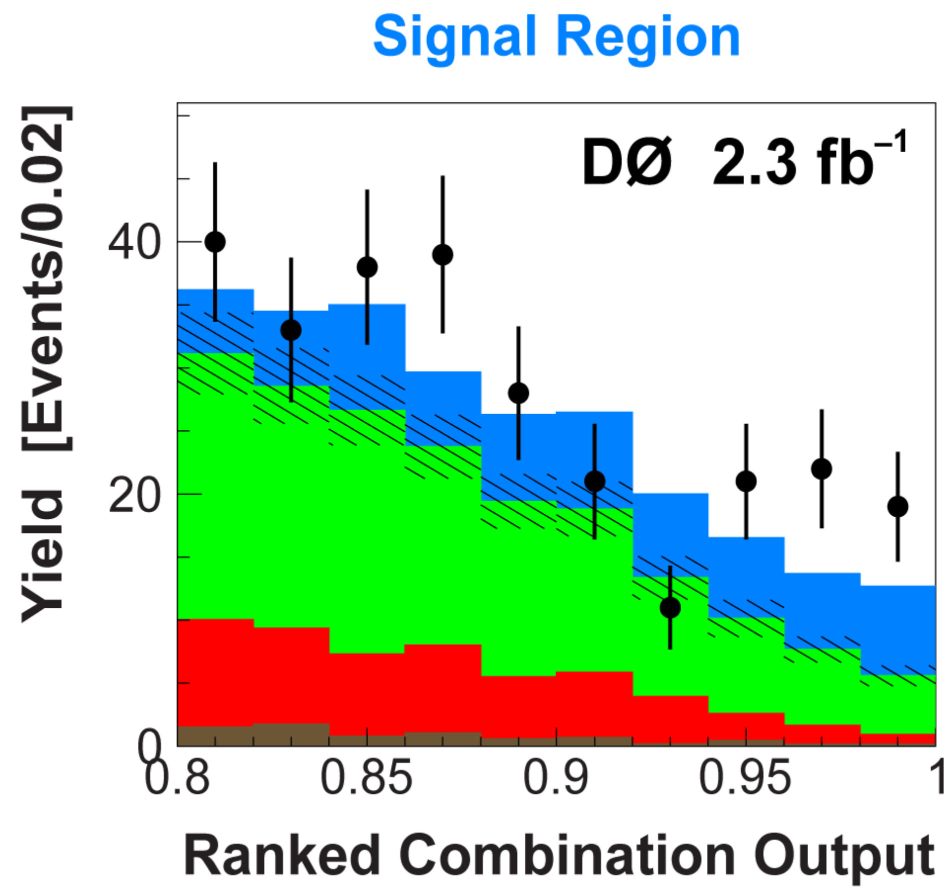




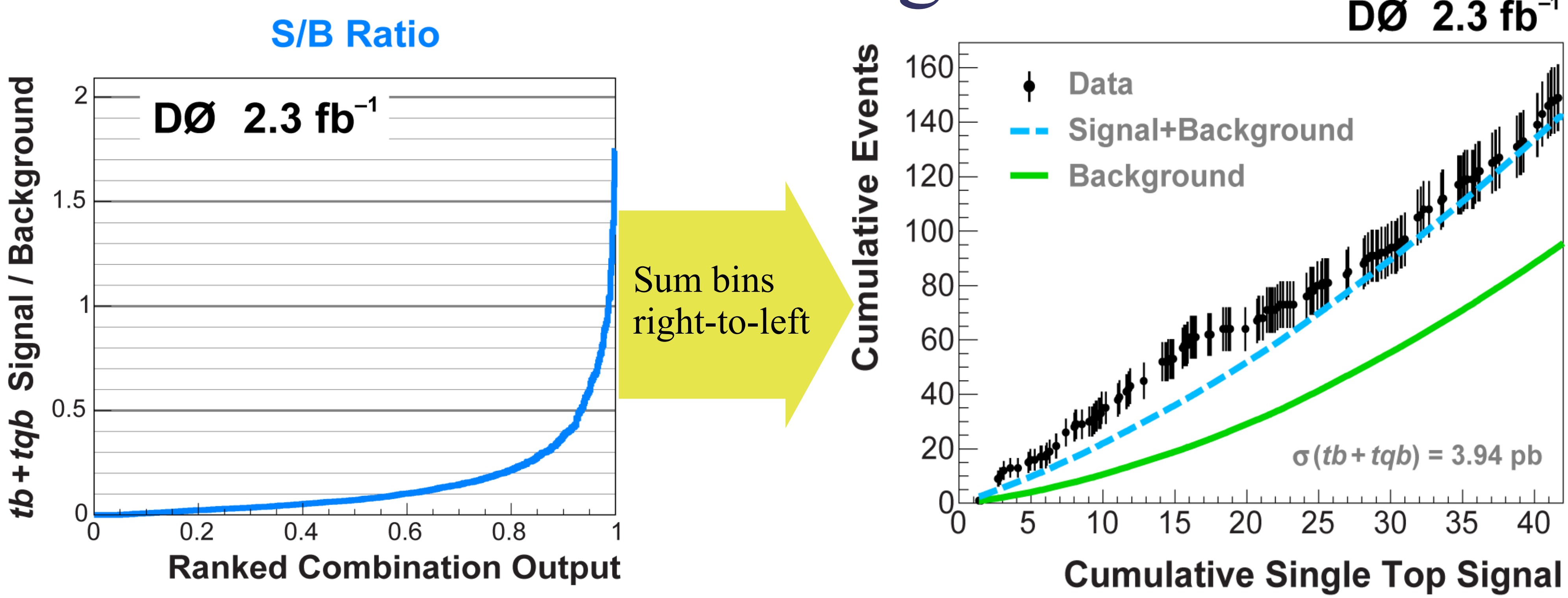
Combination distribution

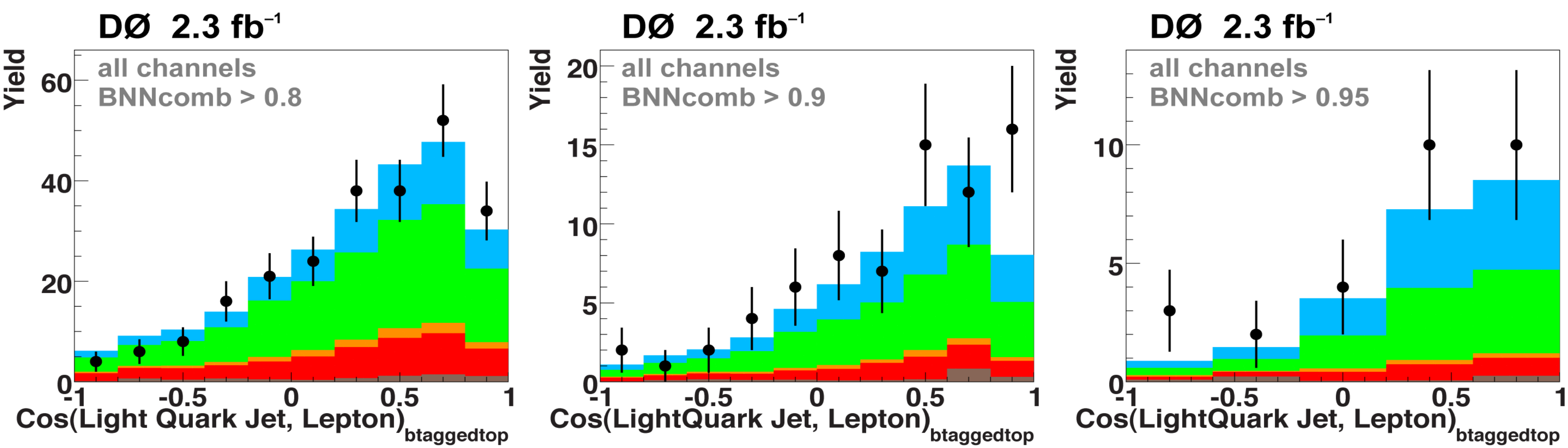
- Combine 24 channels,
  50 bins per channel,
  sort bins by s/b



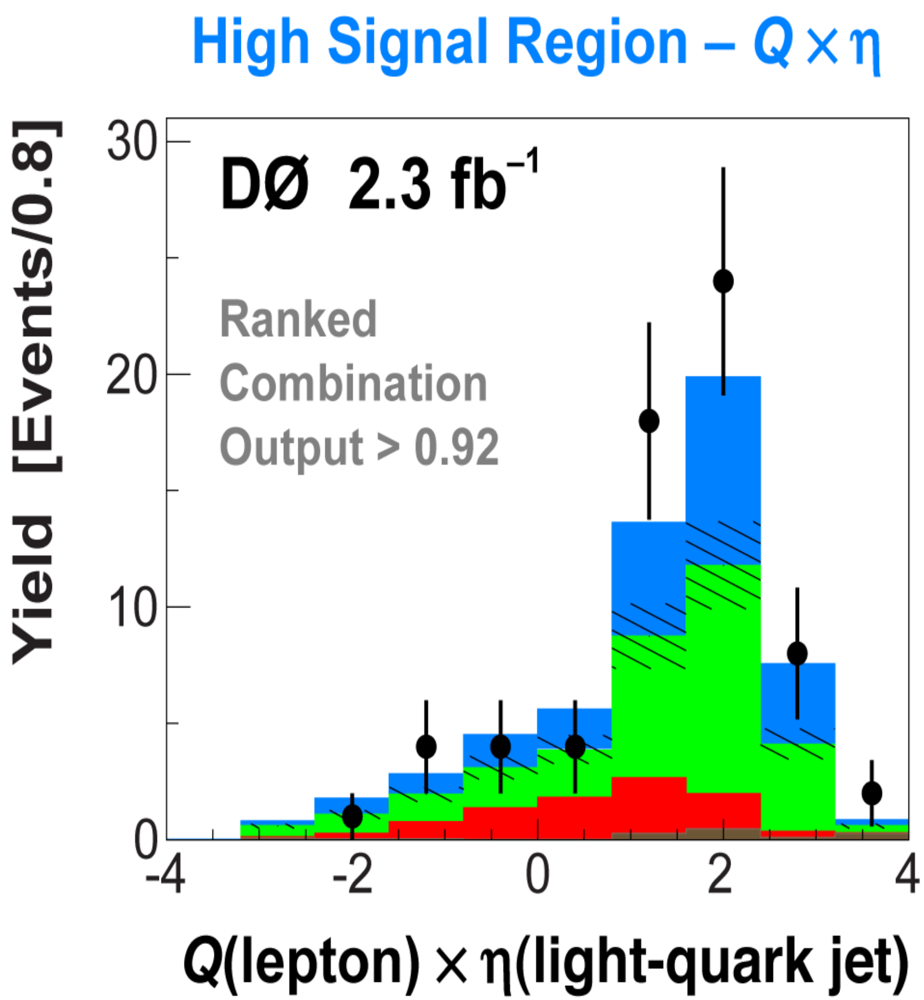


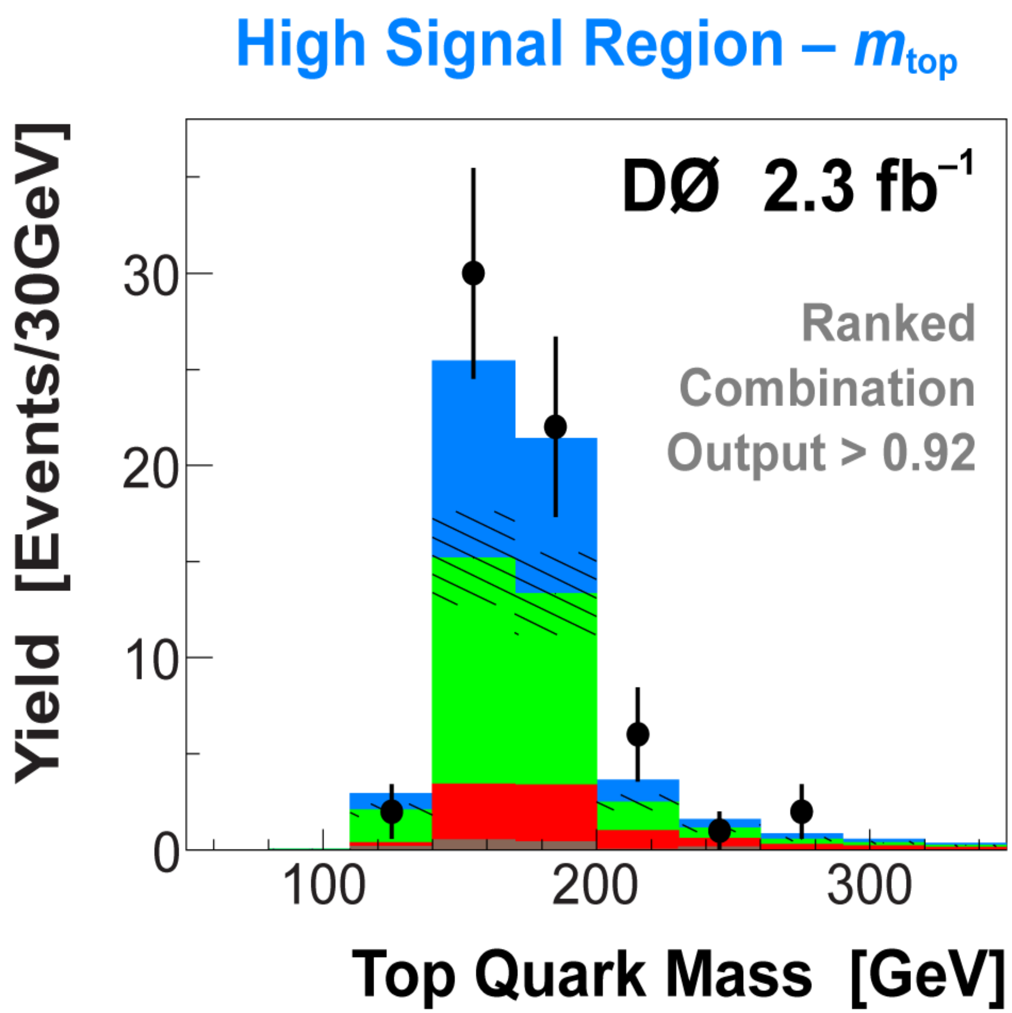
Is there a signal?





Kinematics in the signal region





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%

Systematic Uncertainties

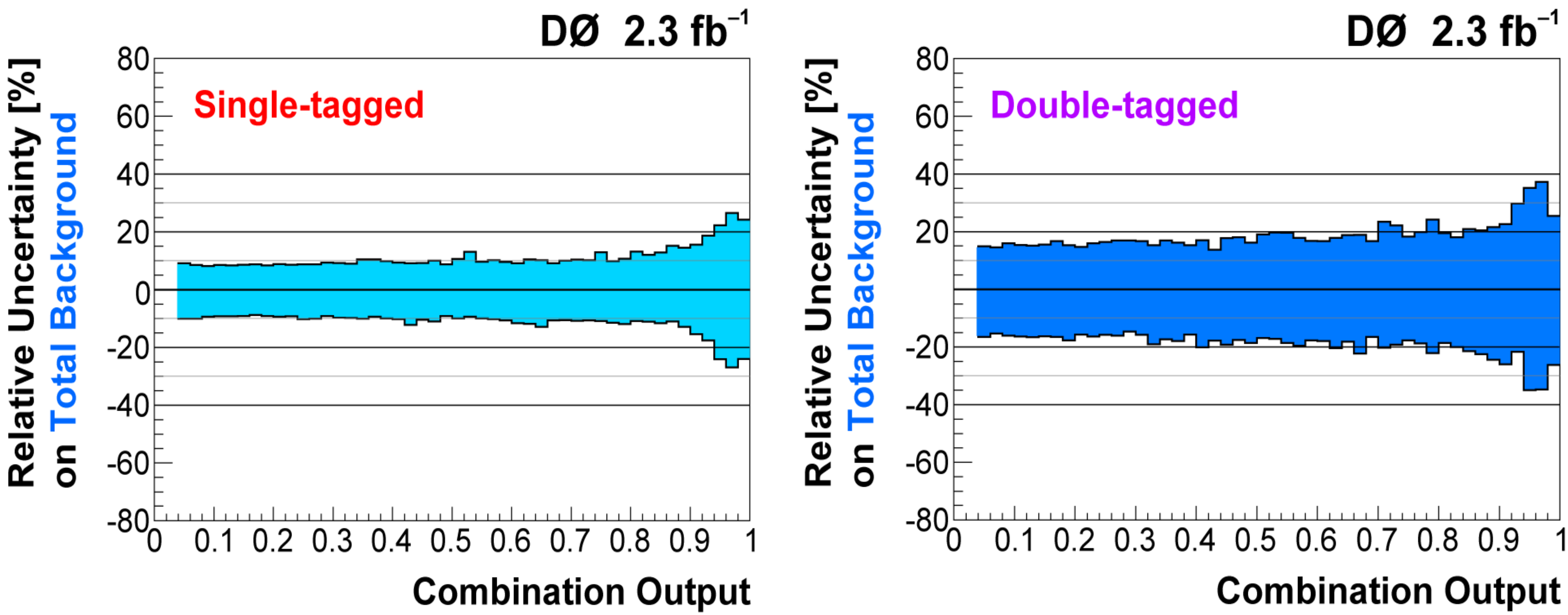
Ranked from Largest to Smallest Effect on Single Top Cross Section

DØ 2.3 fb^{-1}

Smaller terms	
Monte Carlo statistics	(0.5–16.0)%
Jet fragmentation	(0.7–4.0)%
Branching fractions	1.5%
Z+jets heavy-flavor correction	13.7%
Jet reconstruction and identification	1.0%
Instantaneous luminosity correction	1.0%
Parton distribution functions (signal)	3.0%
Z+jets theory cross sections	5.8%
W+jets and multijets normalization to data	(1.8–3.9)% (*W*+jets) (30–54)% (multijets)
Diboson theory cross sections	5.8%
Alpgen *W*+jets shape corrections	shape only
Trigger	5%

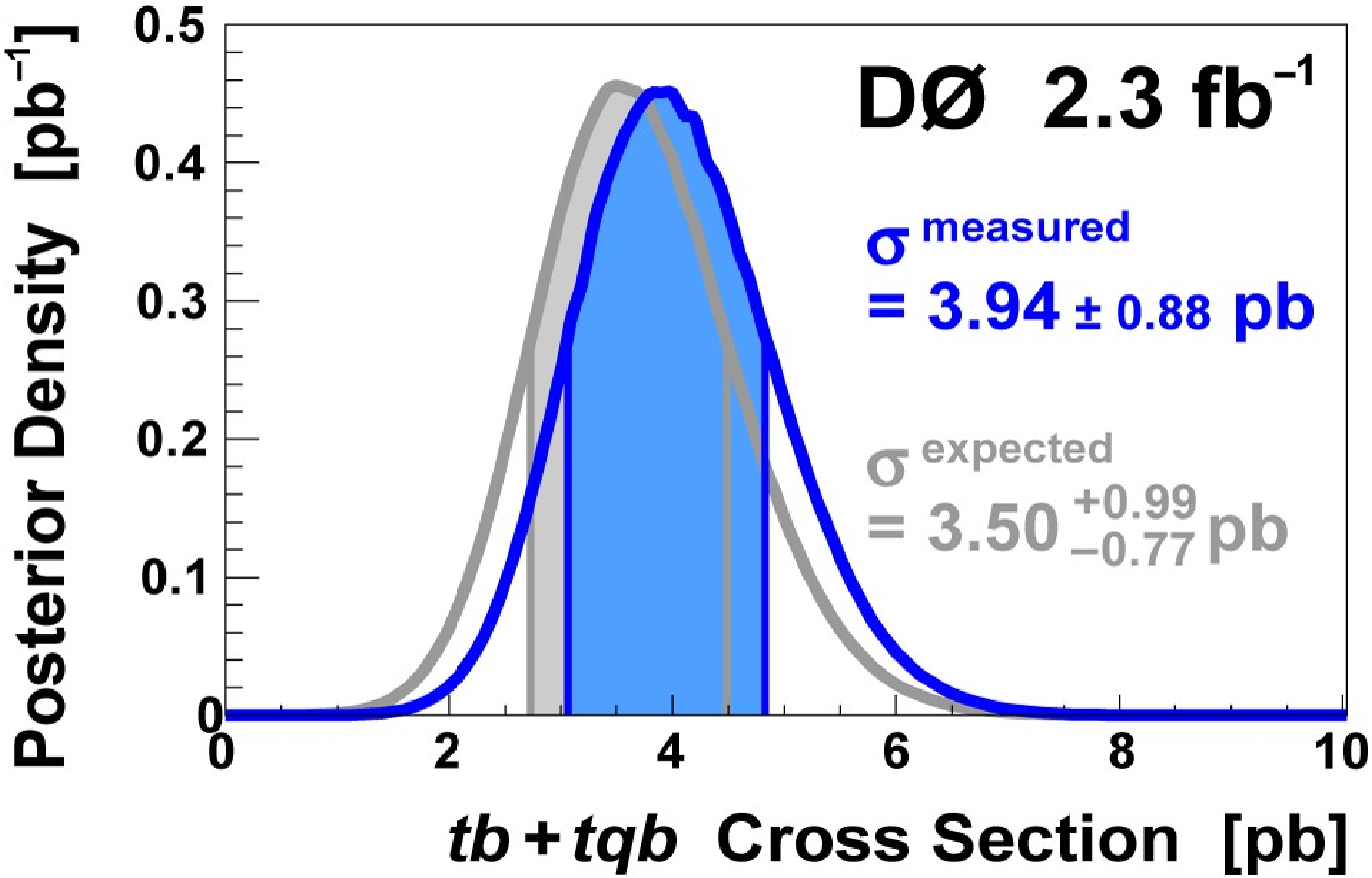
Shape systematics

– Mainly jet energy scale and b-tag modeling



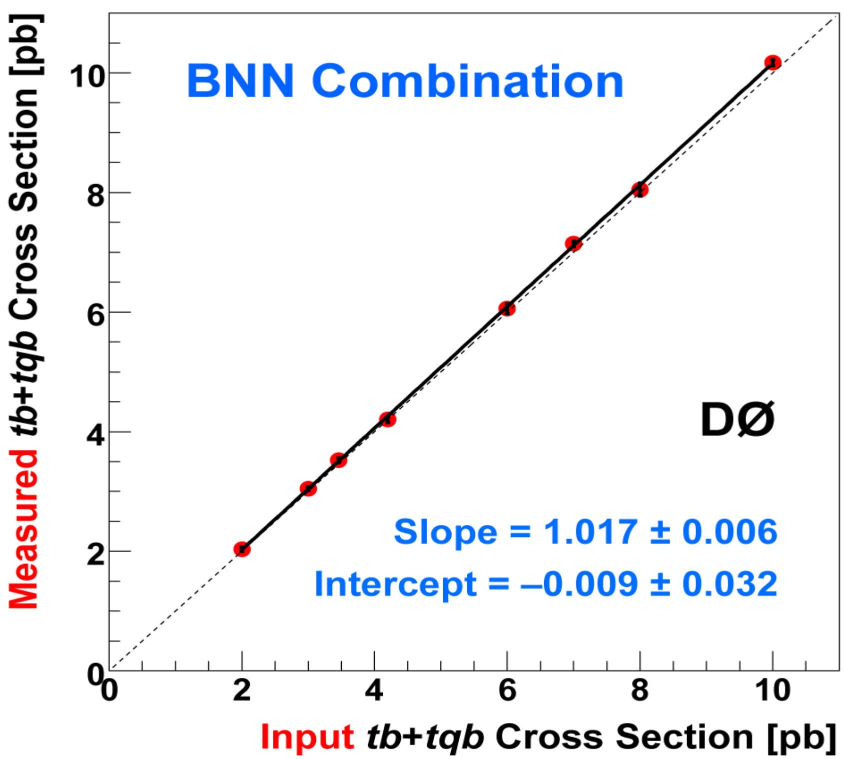
Statistical analysis

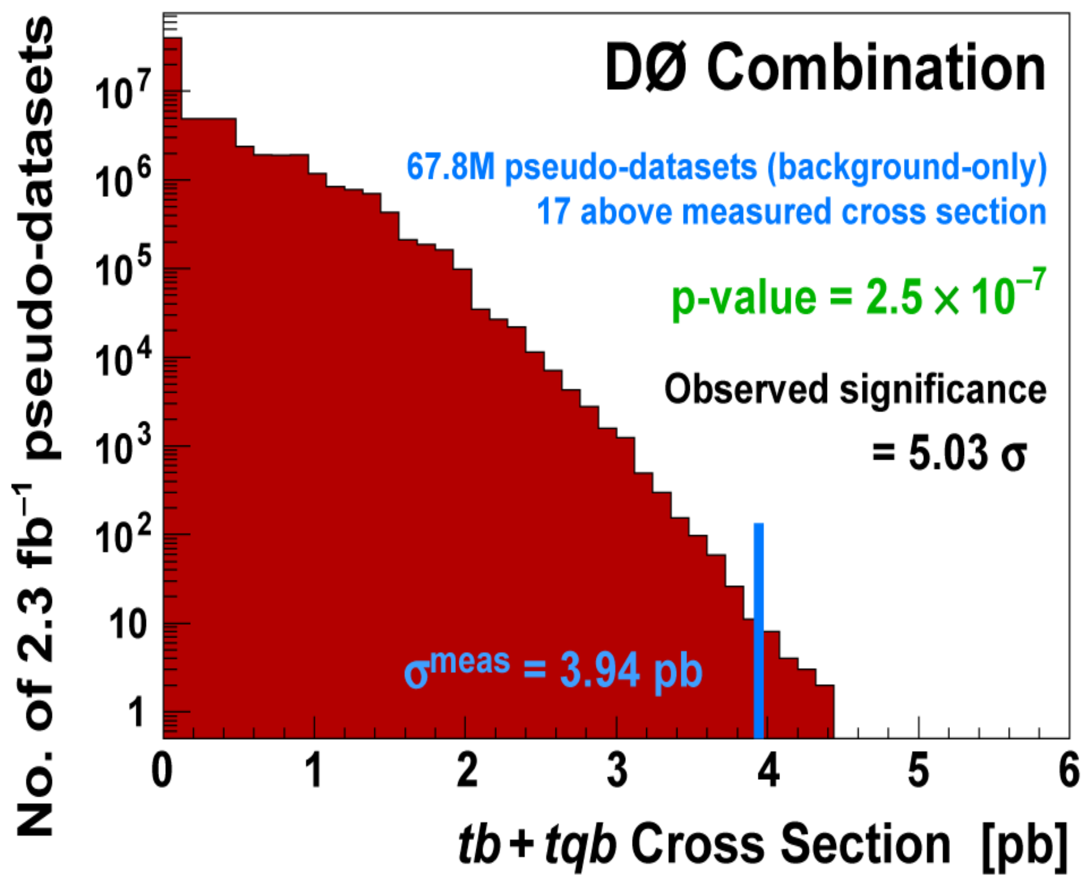
- Bayesian statistical analysis
  P(s|D) = P(D|s)*P(s)
  - Posterior gives measured cross section and uncertainty



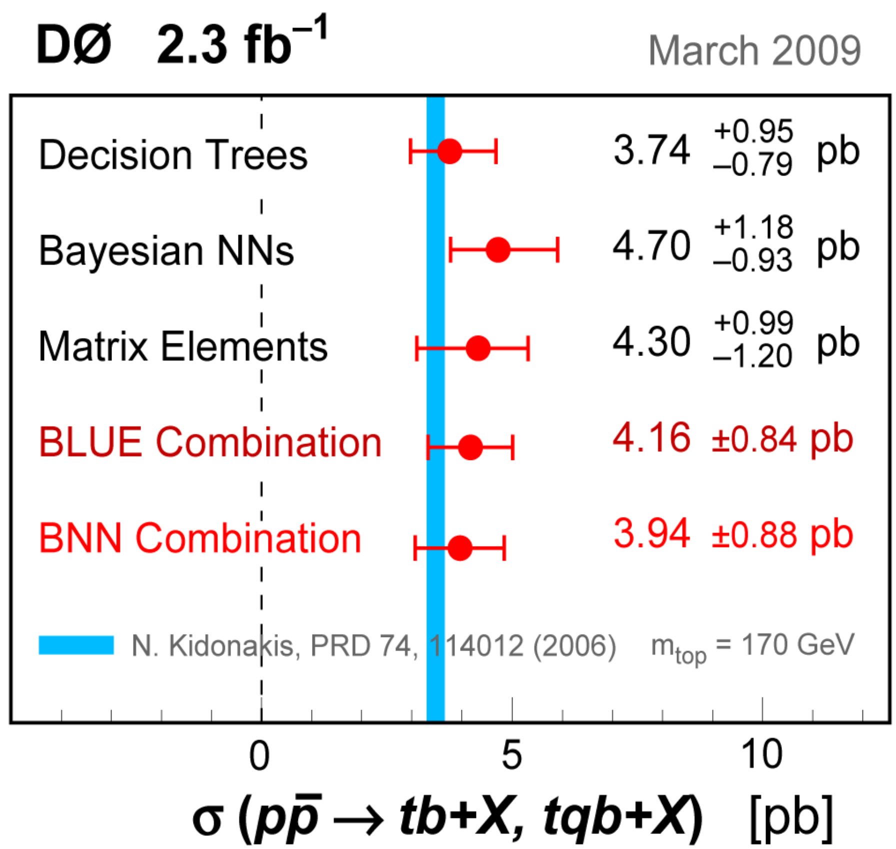
Significance

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



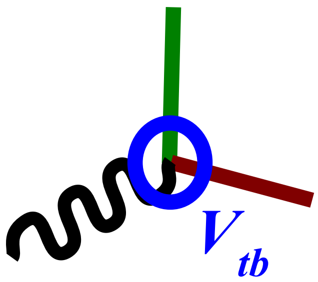


DØ 2.3 fb^{-1} Single Top Results			
Analysis Method	Single Top Cross Section	Significance	
		Expected	Measured
Boosted Decision Trees	$3.74^{+0.95}_{-0.79}$ pb	4.3 σ	4.6 σ
Bayesian Neural Networks	$4.70^{+1.18}_{-0.93}$ pb	4.1 σ	5.4 σ
Matrix Elements	$4.30^{+0.99}_{-1.20}$ pb	4.1 σ	4.9 σ
Combination	3.94 ± 0.88 pb	4.5 σ	5.0 σ



ArXiv:0903.0850,
Submitted to PRL

CKM matrix element $|V_{tb}|$

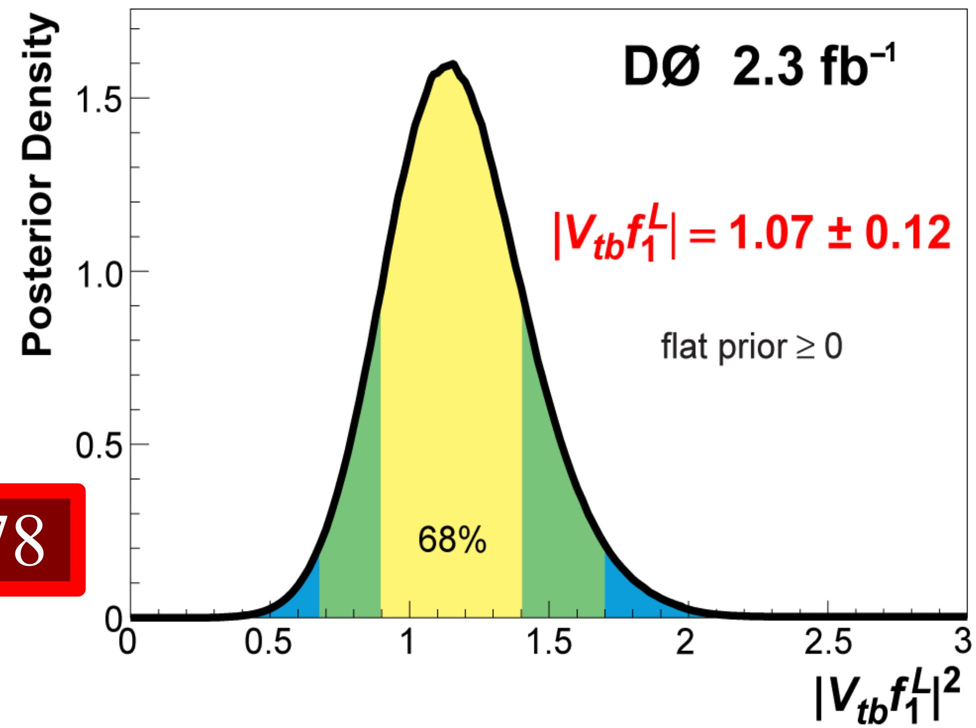


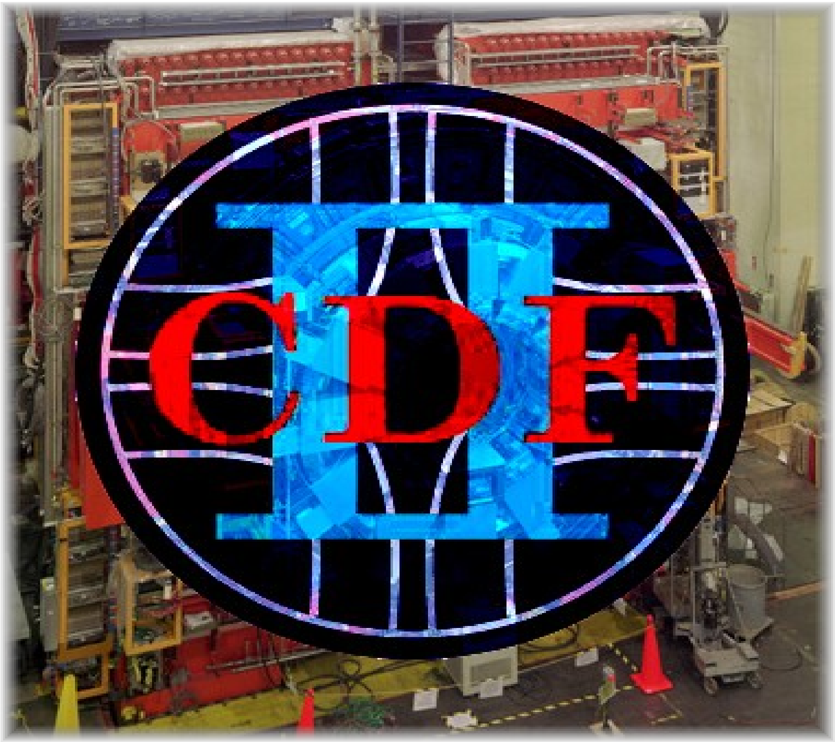
CKM Matrix

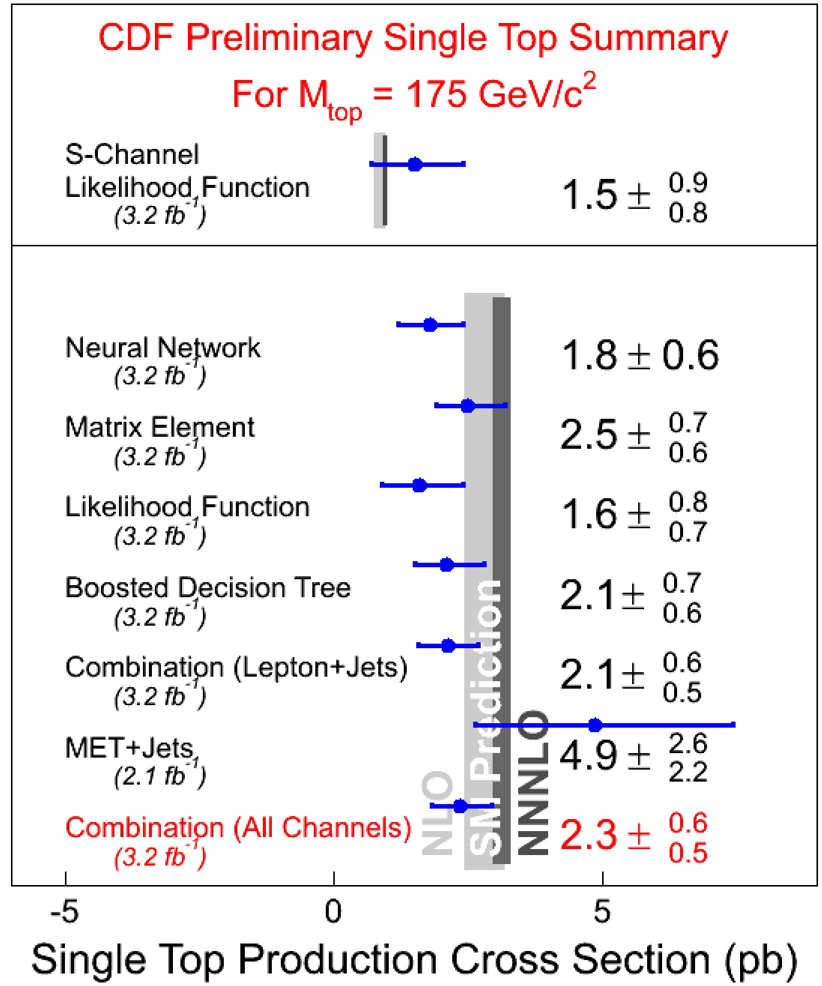
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- 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.: $|Vtb| > 0.78$







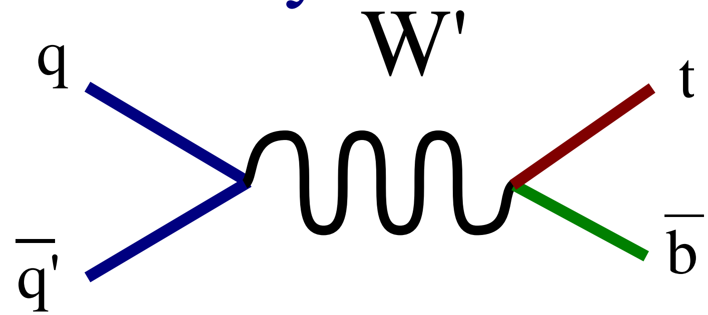
- Analyses based on 3.2 fb^{-1}
- Top mass 175GeV, NLO cross sections
- Increased acceptance
- Added MET+Jets channel
- 5 multivariate methods, even more search channels

Tevatron summary

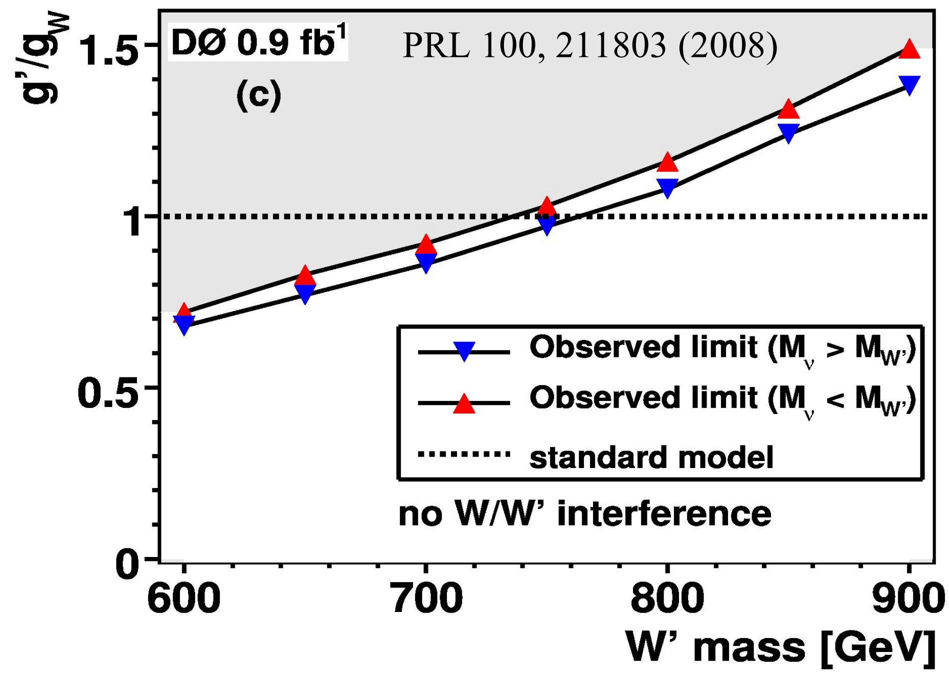
Single Top Cross Section	Signal Significance Expected	Signal Significance Observed	CKM Matrix Element V_{tb}
March 2009	**DØ (2.3 fb^{-1})**	arXiv:0903.0850	(m_{top} = 170 GeV)
3.94 ± 0.88 pb	4.5 σ	5.0 σ	$\lvert V_{tb} f_1^L \rvert = 1.07 \pm 0.12$ $\lvert V_{tb} \rvert > 0.78$ at 95% CL
March 2009	**CDF (3.2 fb^{-1})**	arXiv:0903.0885	(m_{top} = 175 GeV)
$2.3\,^{+0.6}_{-0.5}$ pb	>5.9 σ	5.0 σ	$\lvert V_{tb} f_1^L \rvert = 0.91 \pm 0.13$ $\lvert V_{tb} \rvert > 0.71$ at 95% CL

Searches for new physics in single top

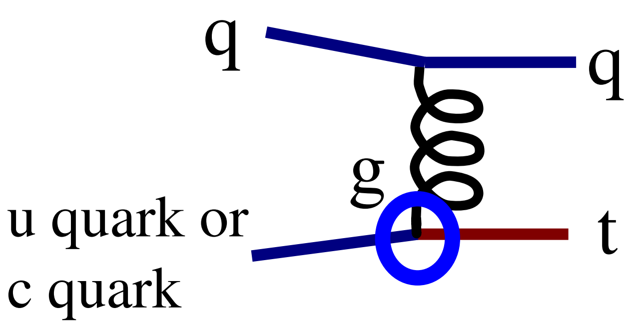
- Searches for new heavy boson W':

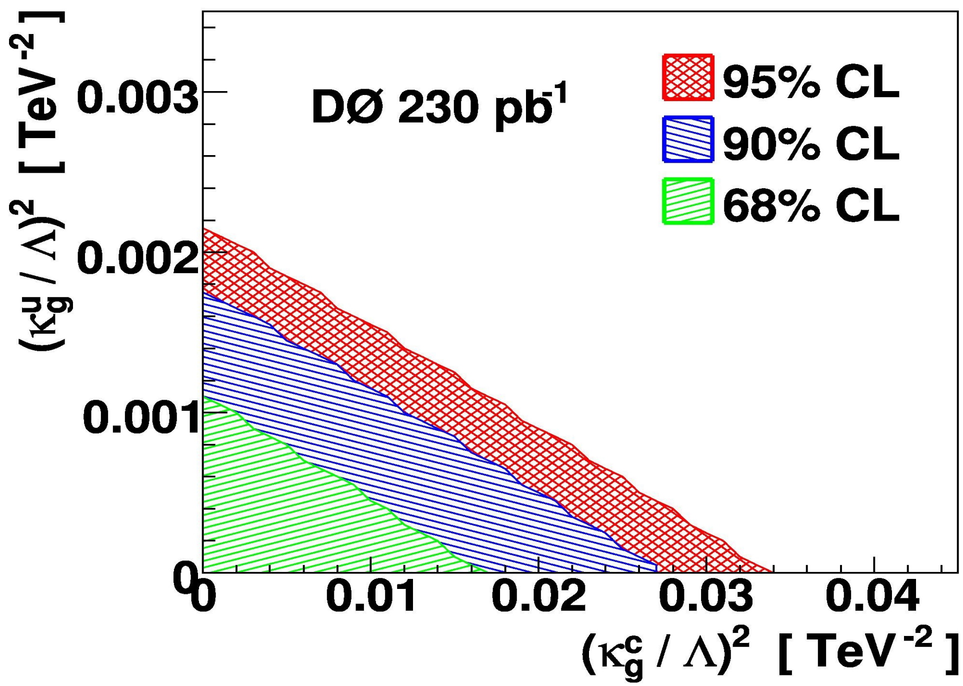


  - CDF prelim result, 1.9fb^{-1}: M > 800 GeV and M > 825 GeV

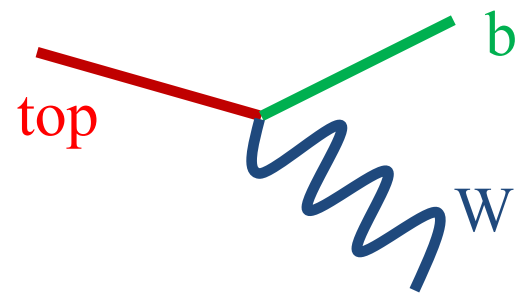


- Similar: DØ Susy H$^+$ search
- Flavor-changing neutral currents:





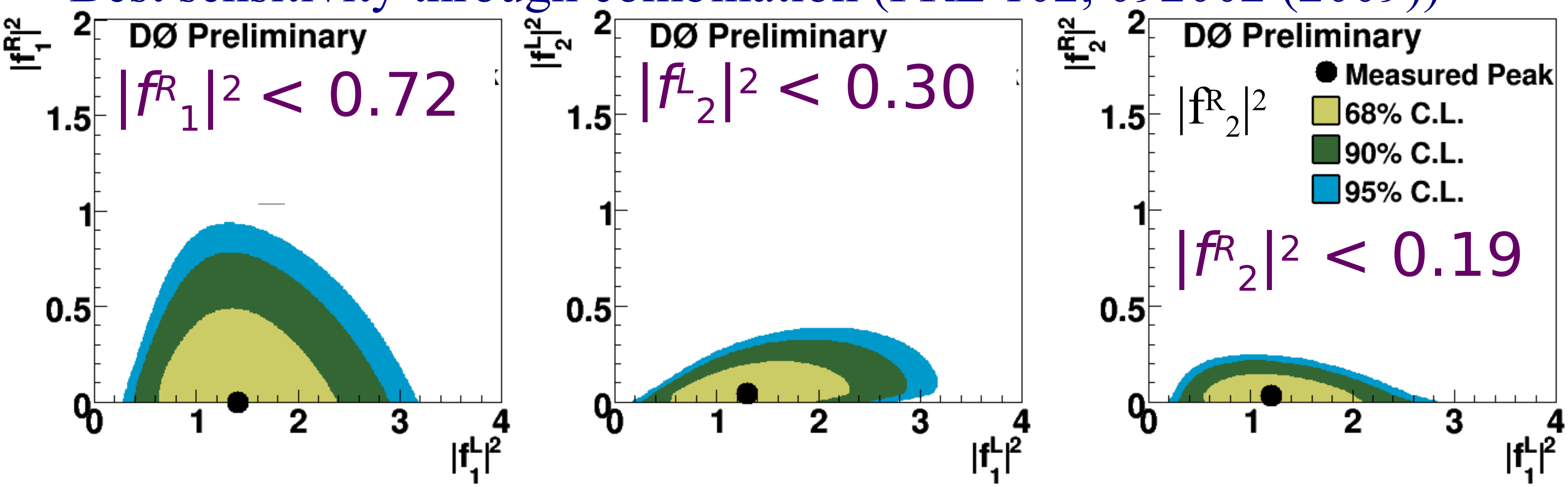
Single top polarization – anomalous coupling



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

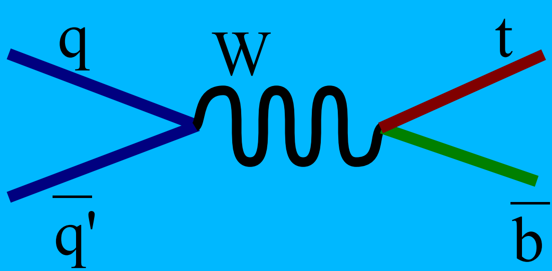
$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}(f_1^L P_L + f_1^R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(f_2^L P_L + f_2^R P_R)tW_{\mu}^{-} + h.c.$$

- 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))

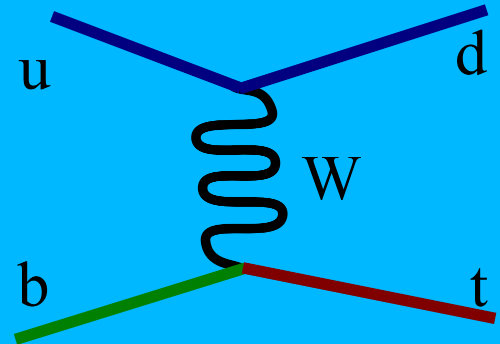


Single top at the LHC

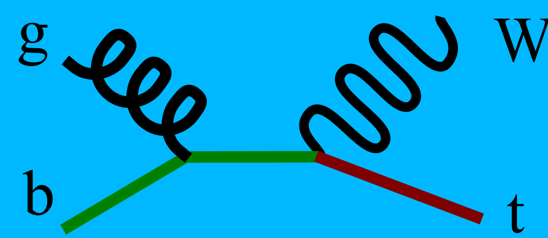
s-channel: 10.7 pb



t-channel: 247 pb



associated production: 68 pb

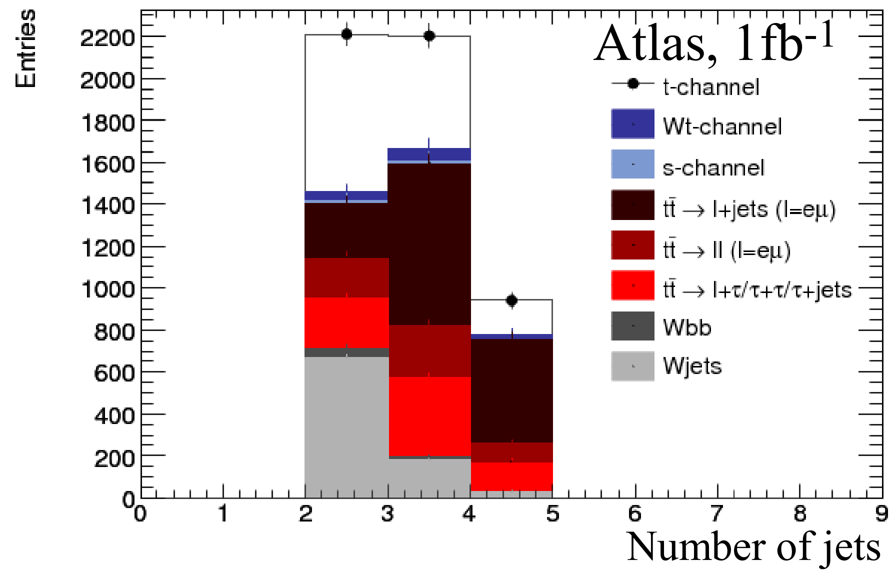


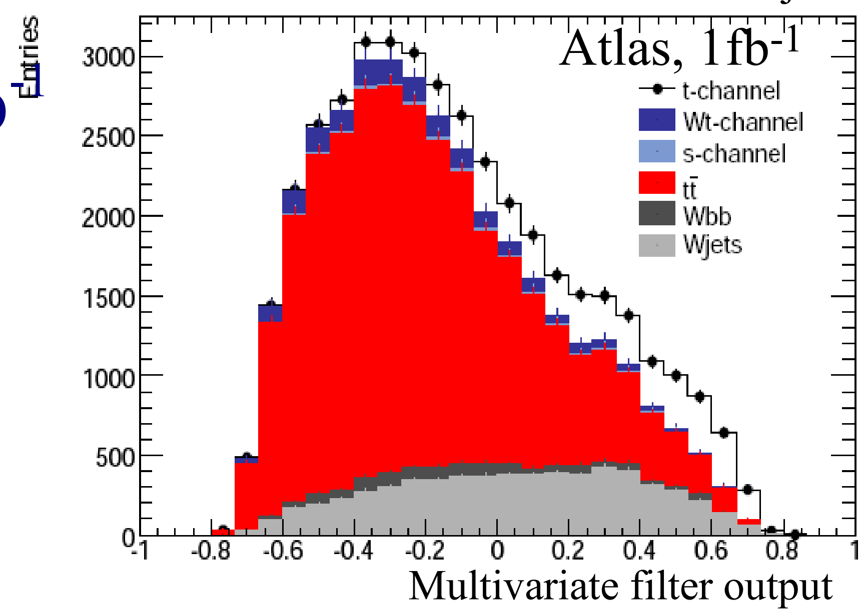
- Observe three single top production modes separately
  - t-channel: easy 🙂 s-channel and assoc. prod: harder
- Observe new physics *(if it can be seen)*
- Measure V_{tb} to few %
- Study spin correlations

SM Single Top at the LHC

t-channel

- Backgrounds are similar to Tevatron, yet different
  - W+jets less important
  - $t\bar{t}$ is dominant background
- t-channel observation early
  - Large cross section
  - Could be seen with simple cuts
- s-channel and Wt with ~30 fb^{-1}
  - Separate by b-tag and jet multiplicity
  - Earlier observation requires multivariate techniques

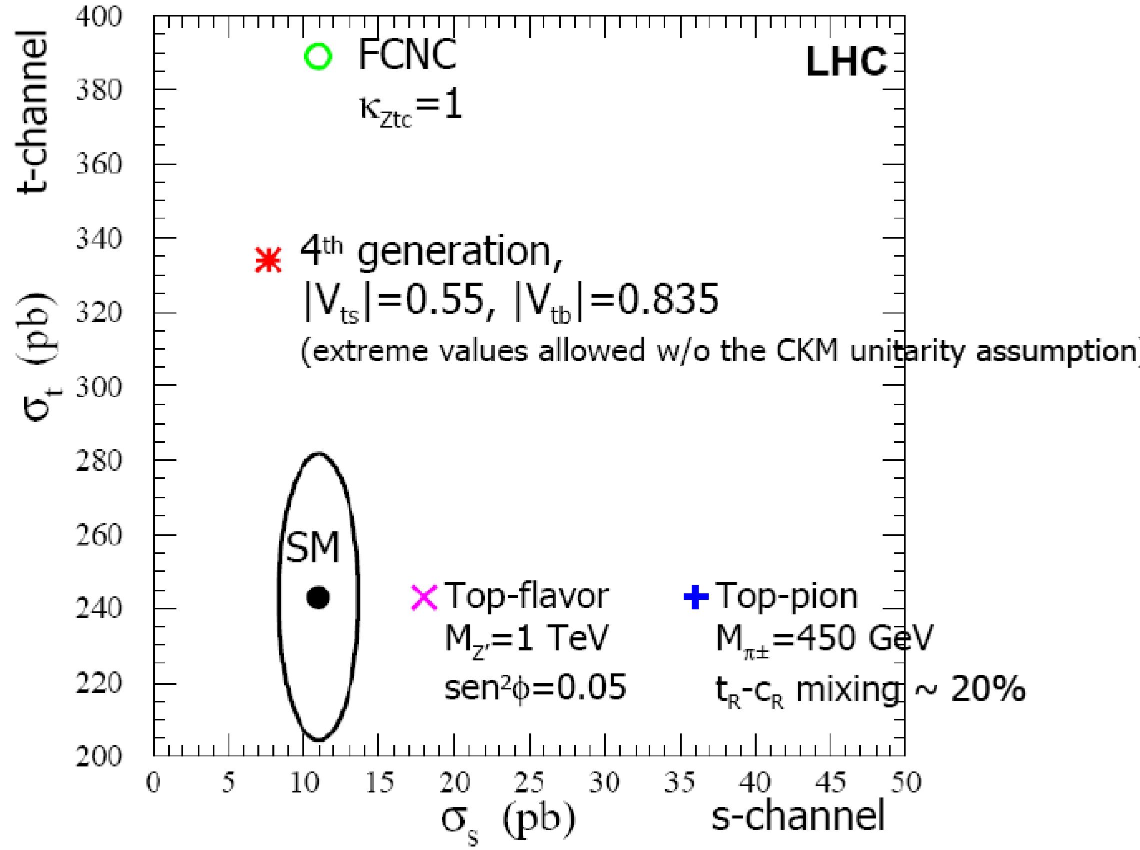




LHC: new physics in single top

- Dedicated searches for specific signatures
  - New heavy boson W'
  - FCNC interactions via gluon, photon, Z
  - Anomalous couplings
- Measure SM cross sections in detail
  - And 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 will increase to 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