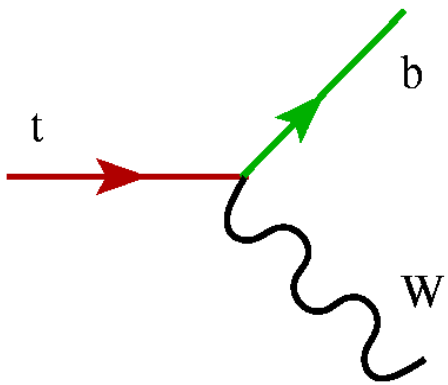
Observation of single top quark production at the Tevatron



top quark decay

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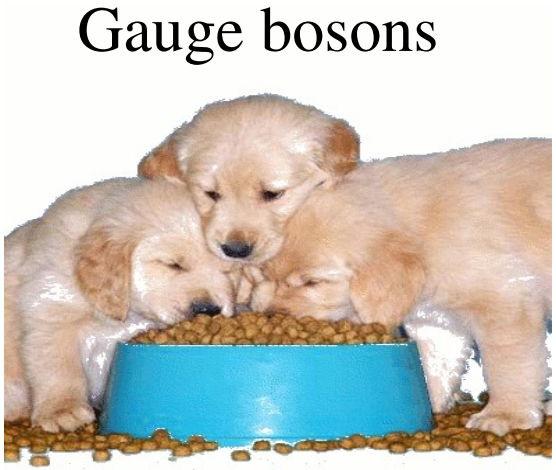
MICHIGAN STATE UNIVERSITY

High Energy-Astrophysics Seminar, December 7 2009

Outline

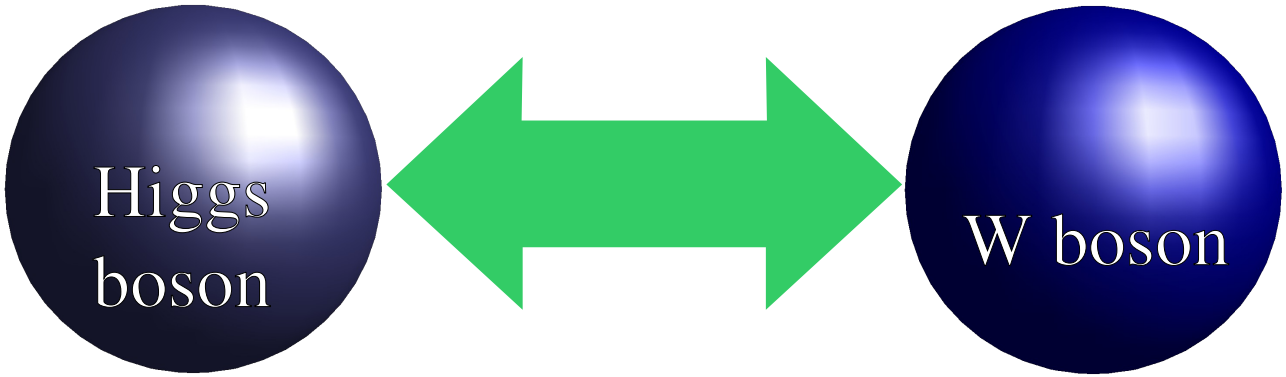
- Introduction
- Single top quark production
- Observation of single top quark production at DØ and CDF
- Tevatron combination
- New physics searches
- LHC outlook
- Conclusions

Electroweak symmetry breaking



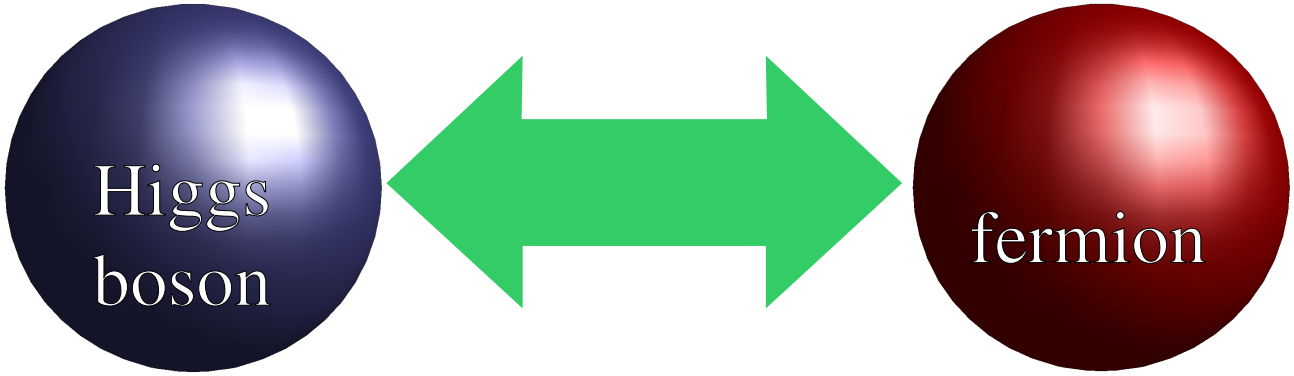
Electroweak symmetry breaking

Gauge boson coupling to Higgs field



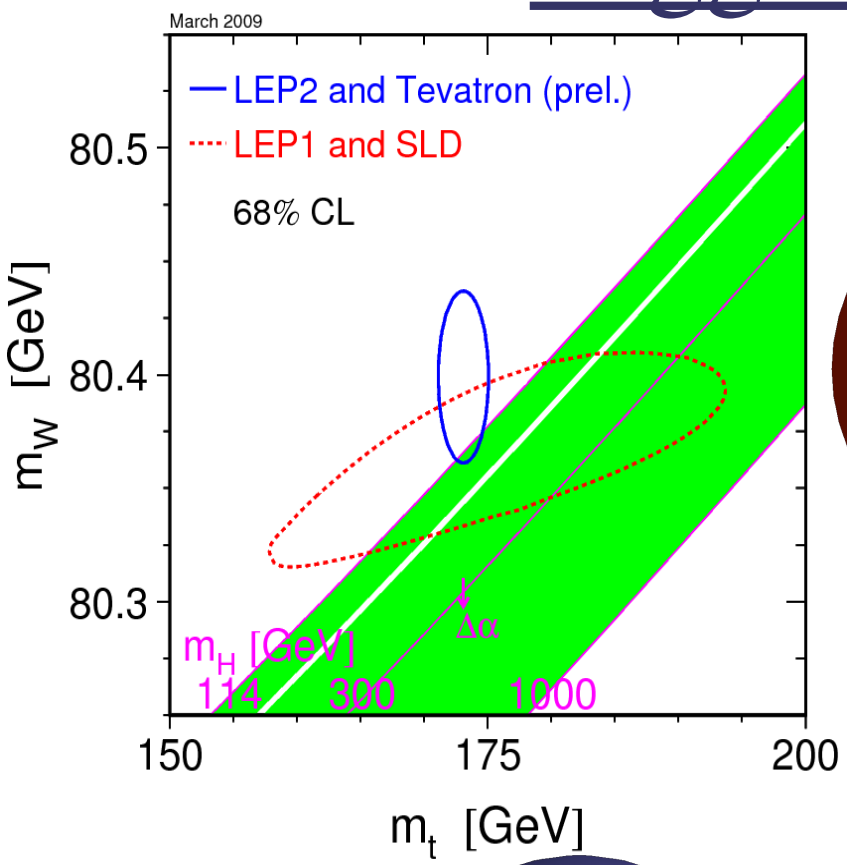
Fermion masses

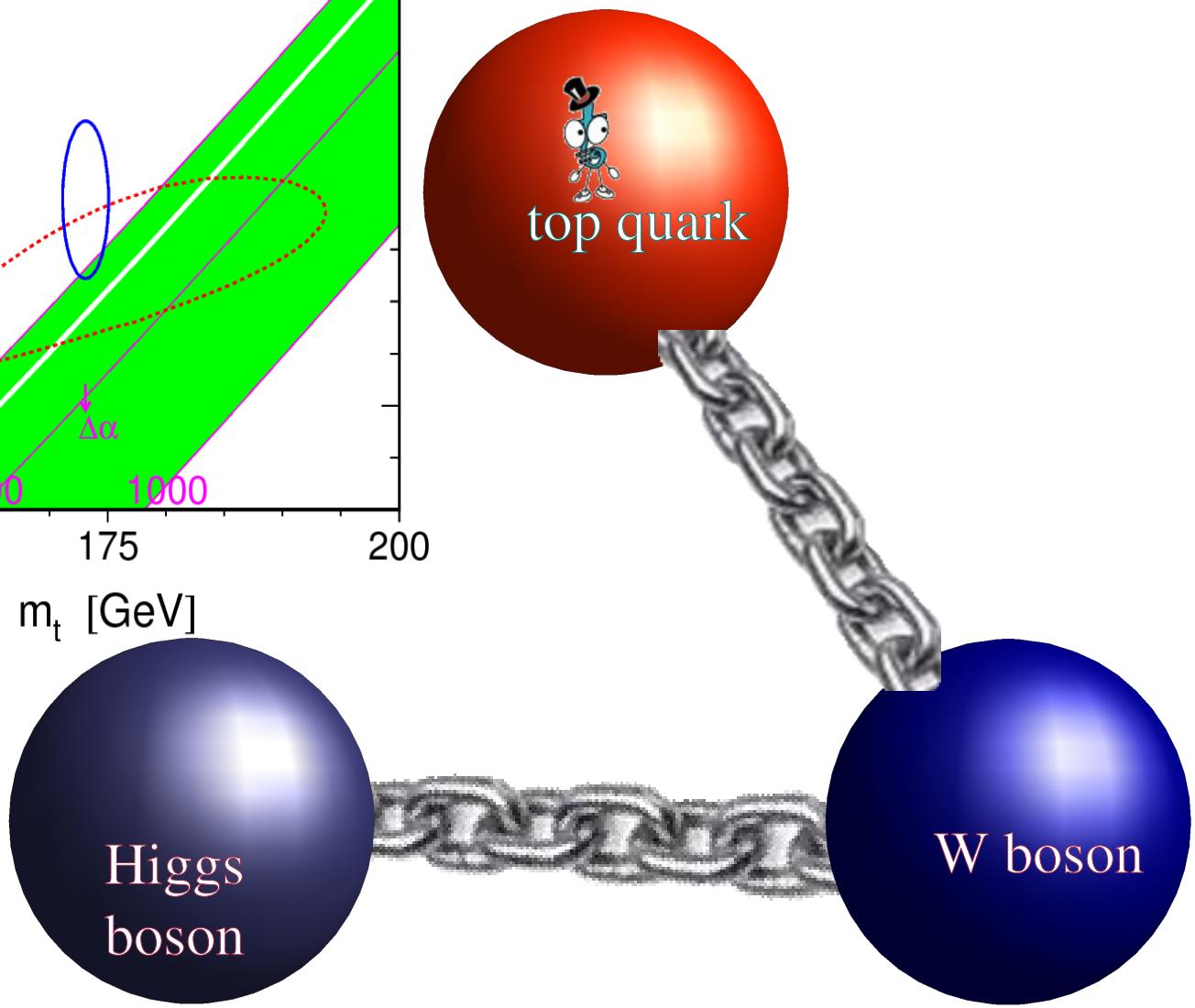
Fermions acquire mass through Higgs coupling



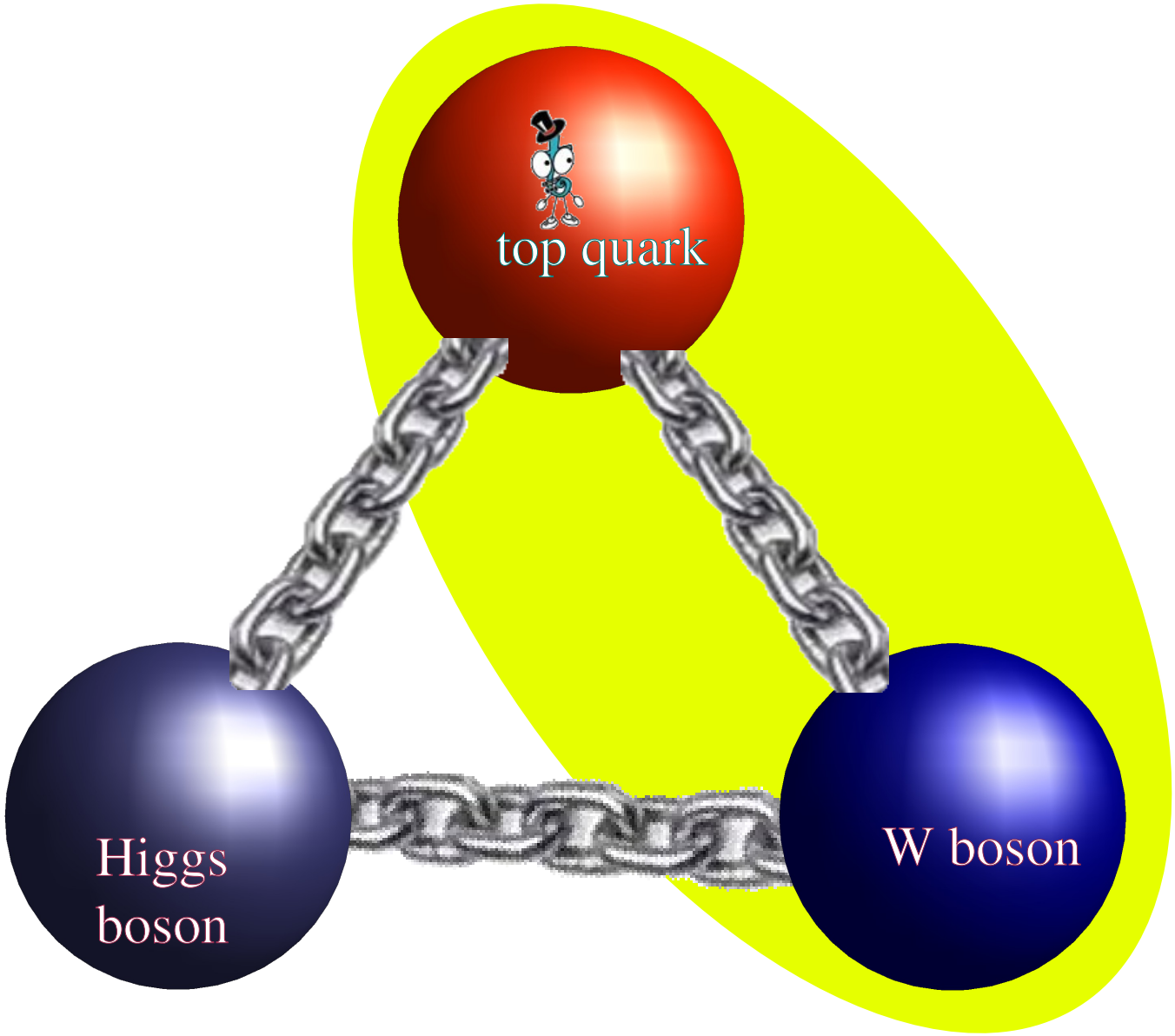
Coupling strength
~1

Higgs mass estimate

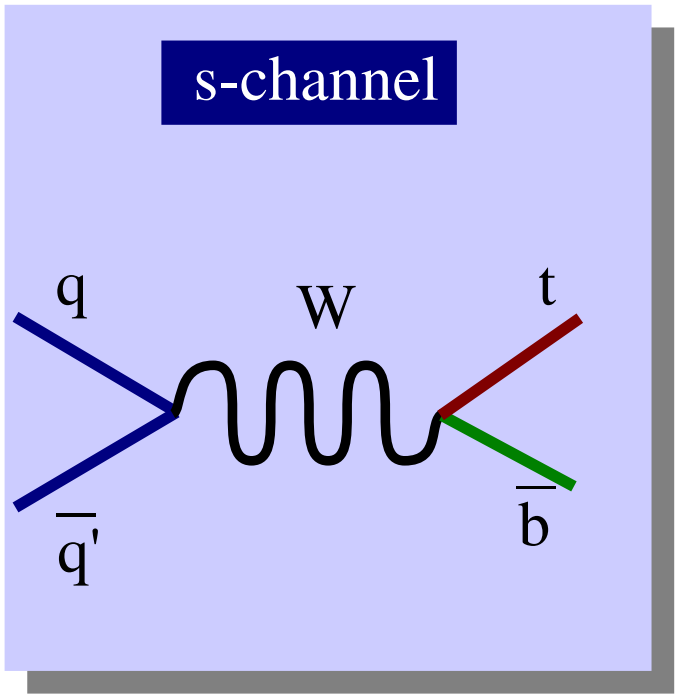


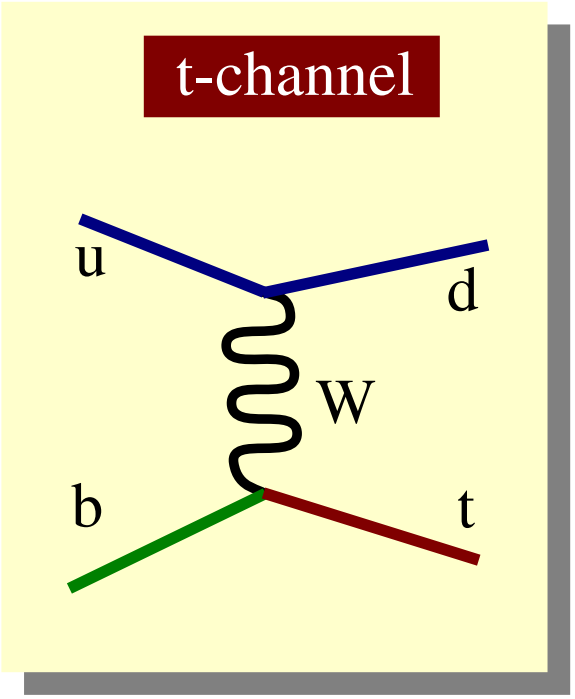


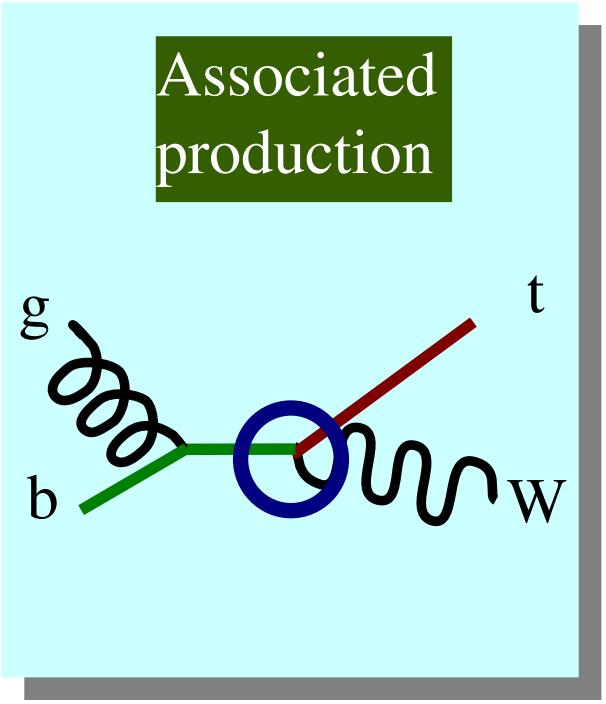
Key to electroweak symmetry breaking



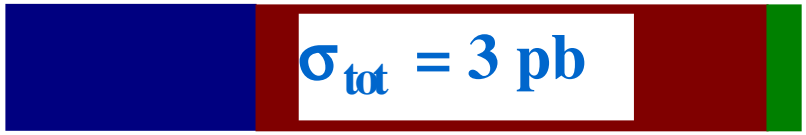
SM single top quark production







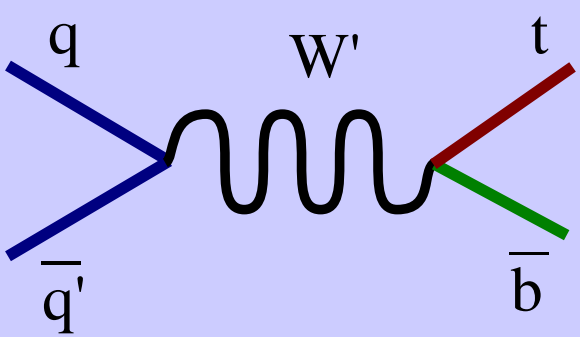
Tevatron:



LHC:
(14TeV)

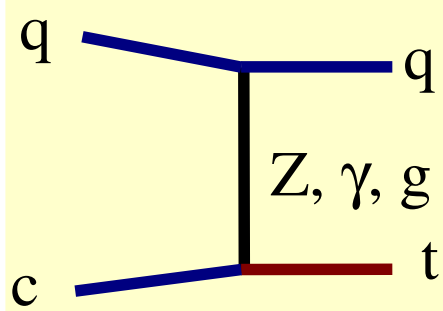
New physics

s-channel



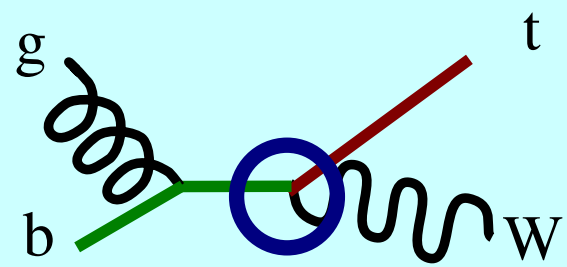
New heavy boson
Or charged Higgs

t-channel



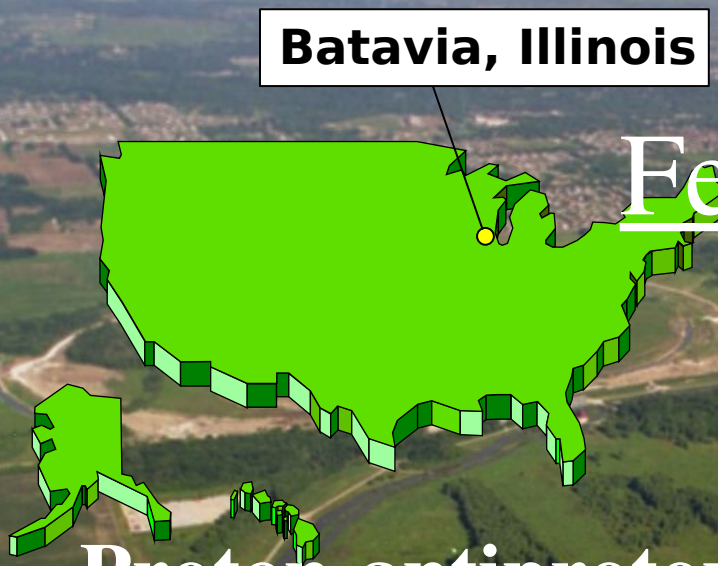
Flavor
Changing
Neutral
Current

Associated production



Modified
Wtb coupling

Experimental setup: Fermilab Tevatron in Run II



Proton-antiproton collider

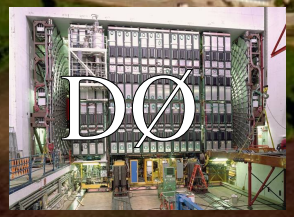
CM energy 1.96TeV

→ ***Energy frontier (until 8 days ago)***

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

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

→ ***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

Run I

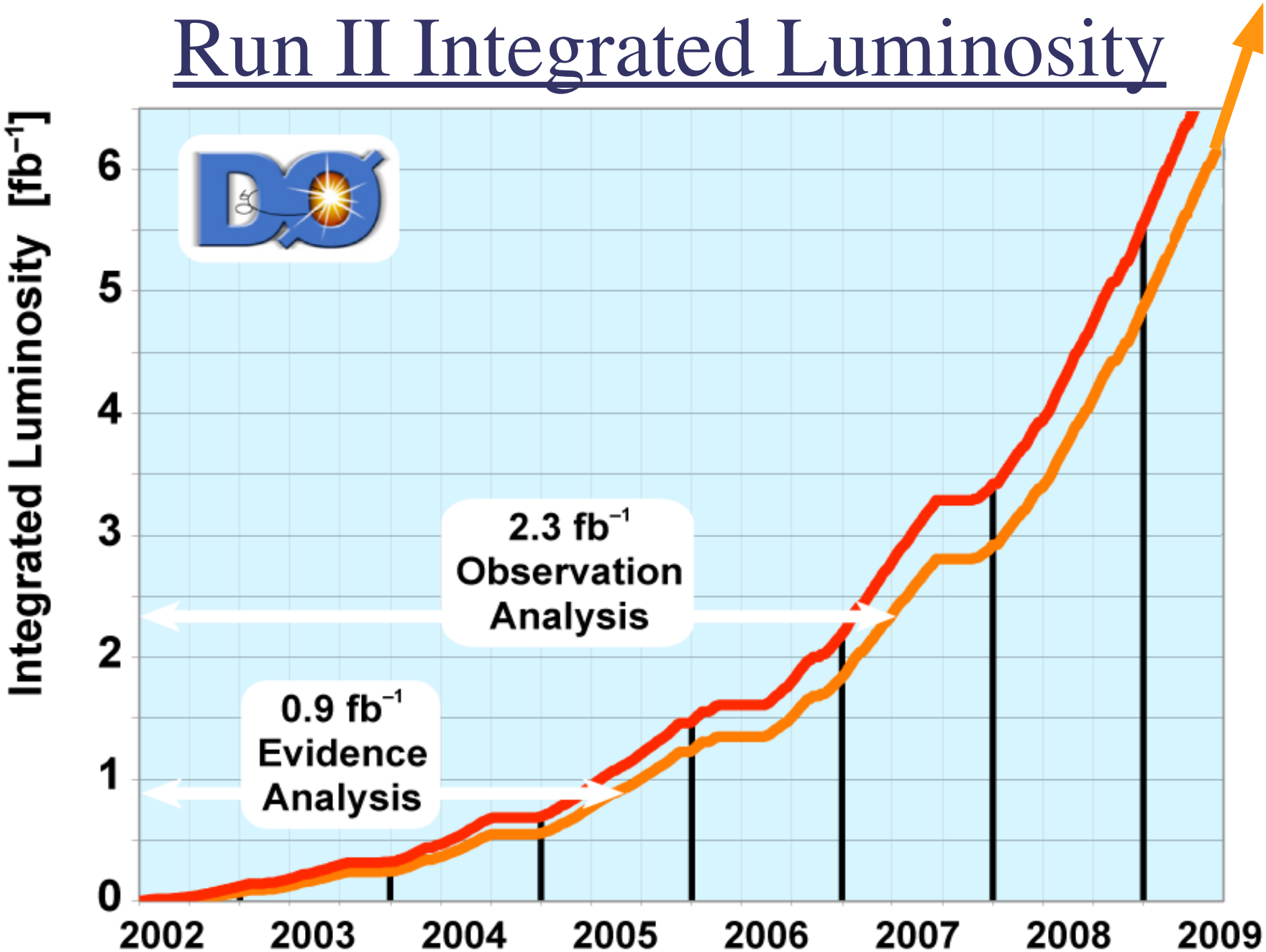
Run II

· 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

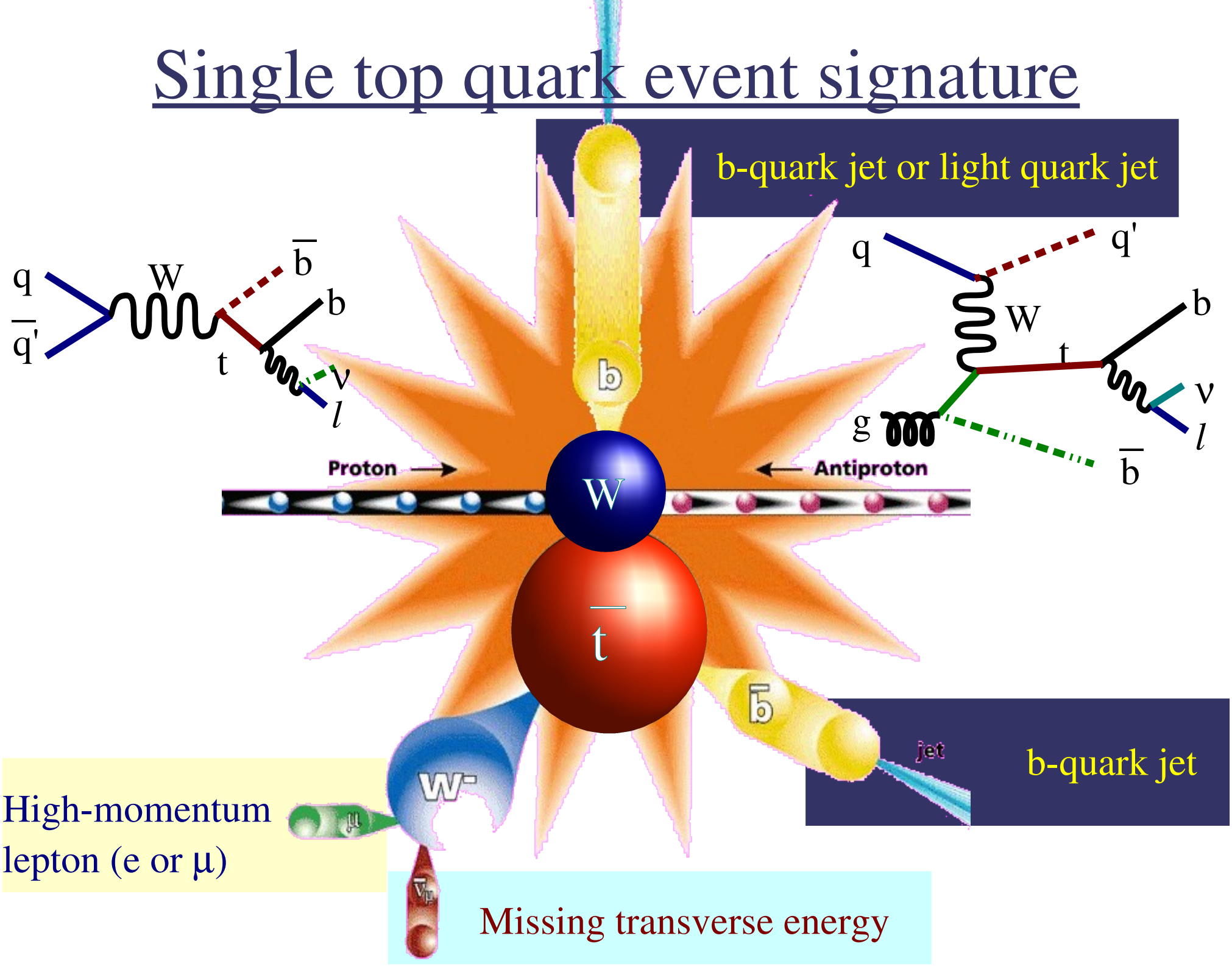
Measurement history

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

Fermilab Tevatron
Run II Integrated Luminosity

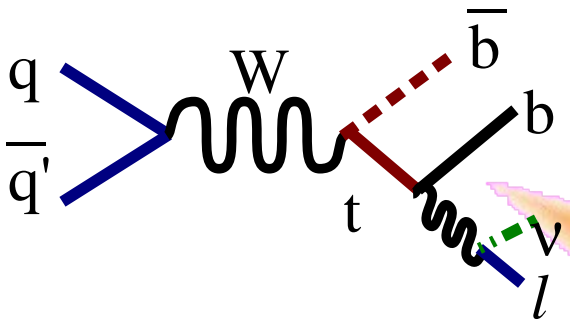


Single top quark event signature

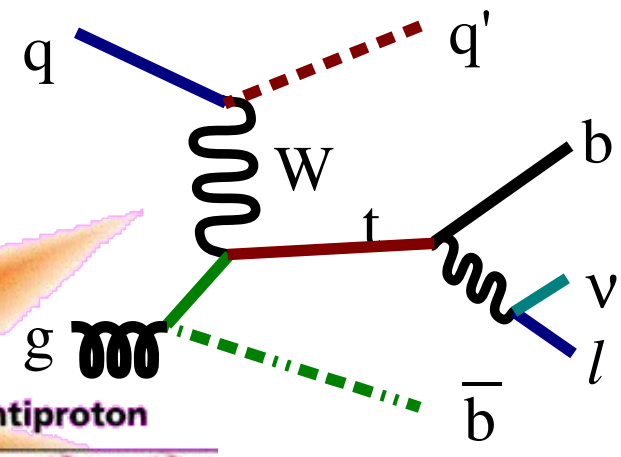


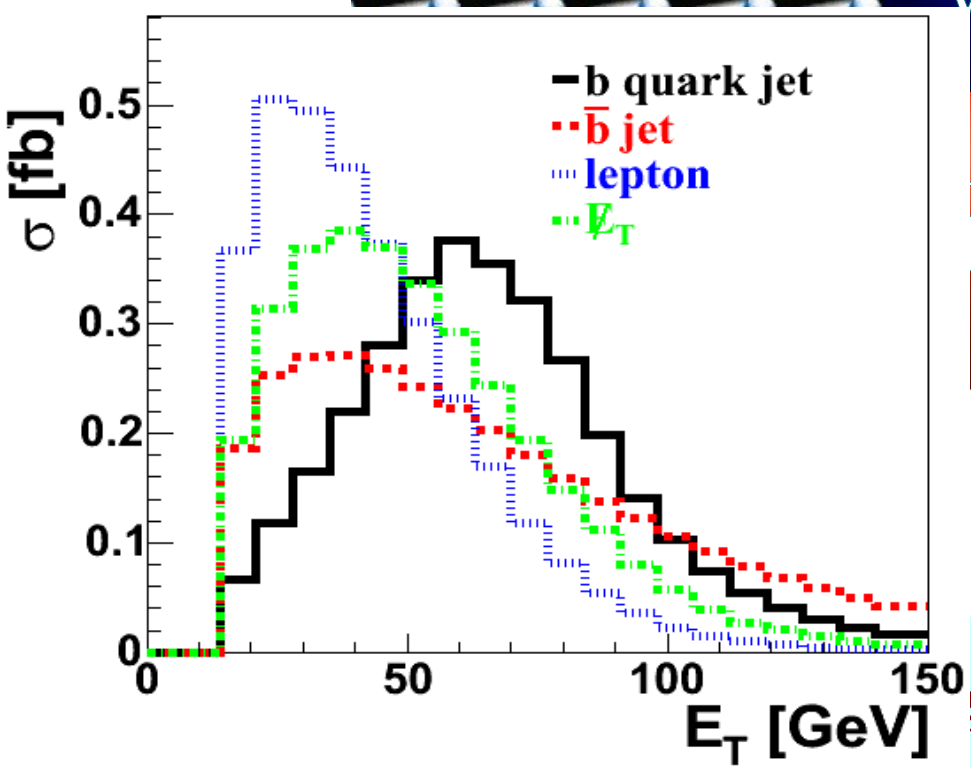
Single top quark event signature

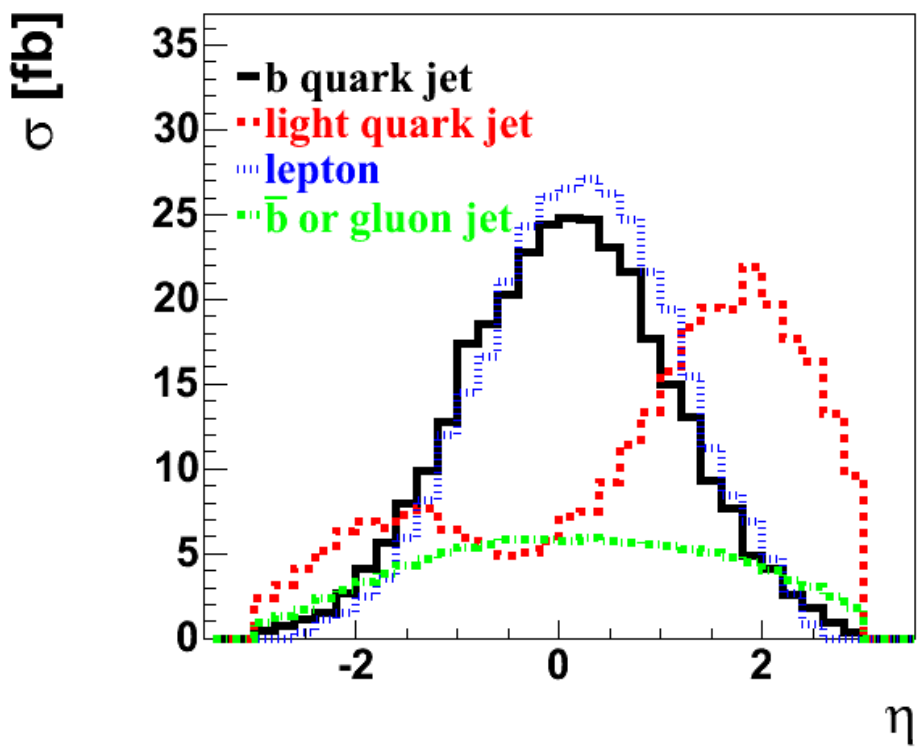
s-channel



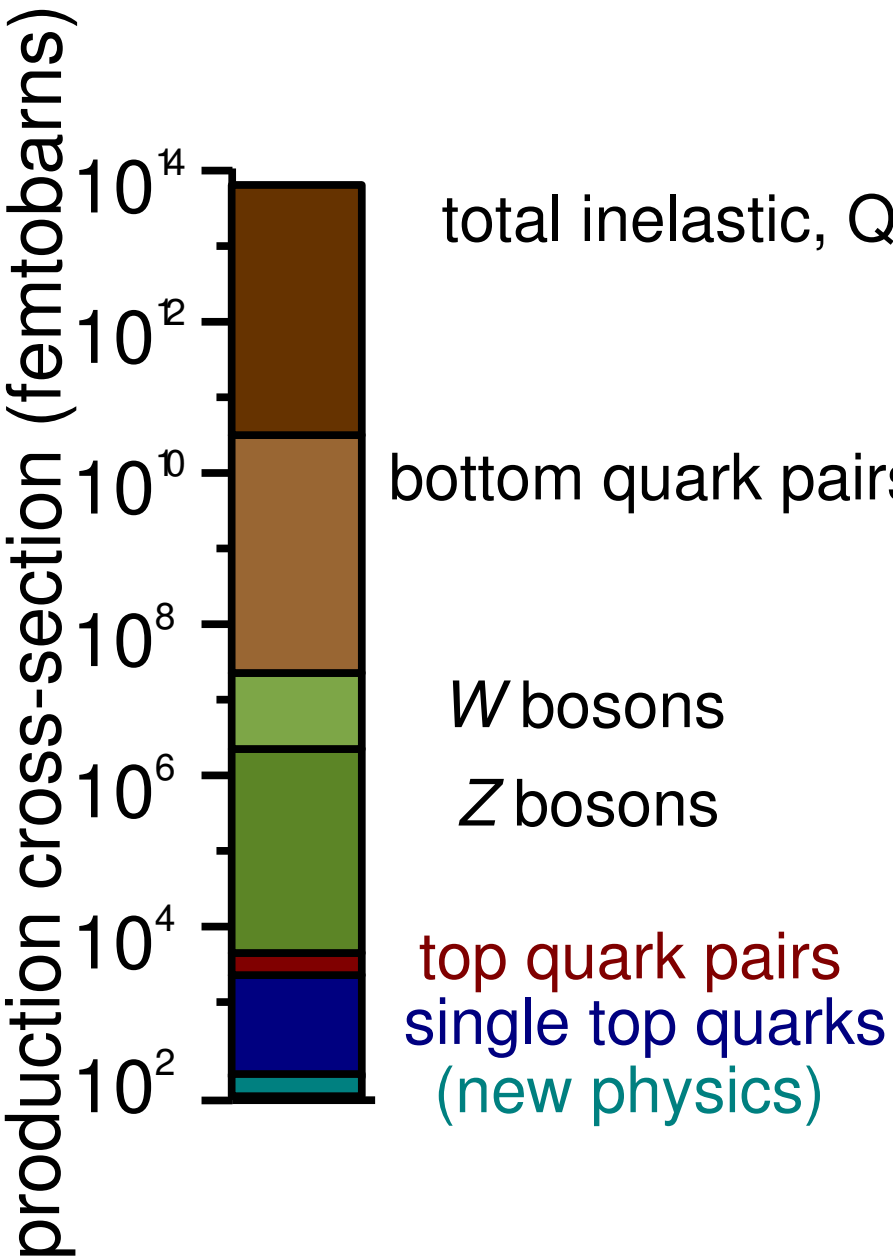
t-channel

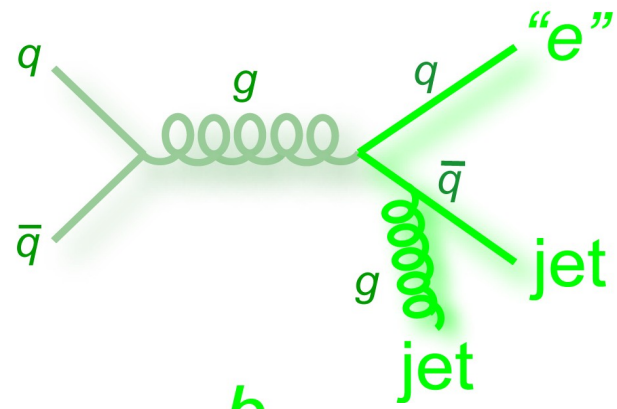


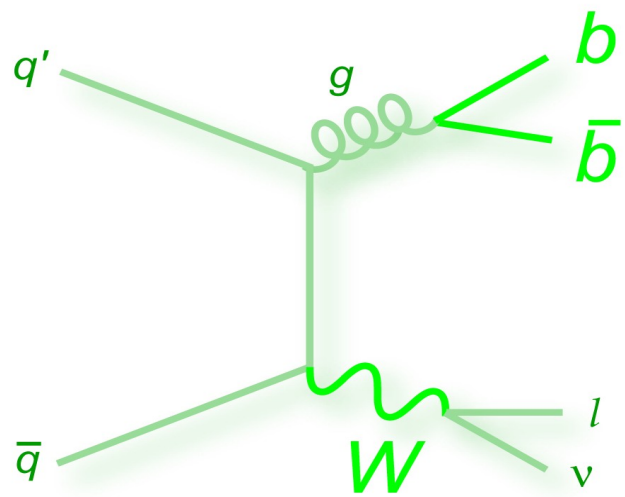


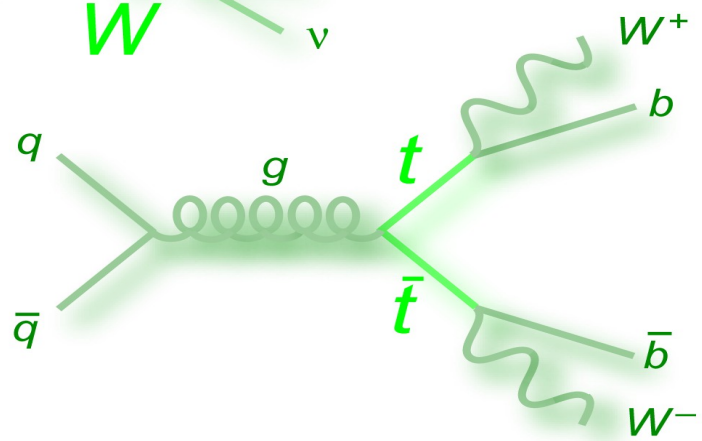


Background processes



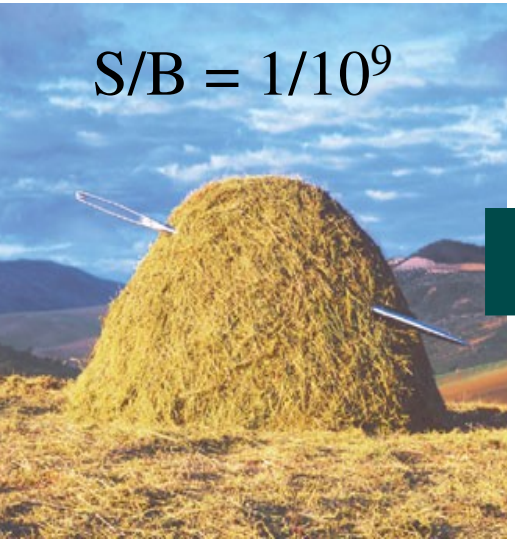




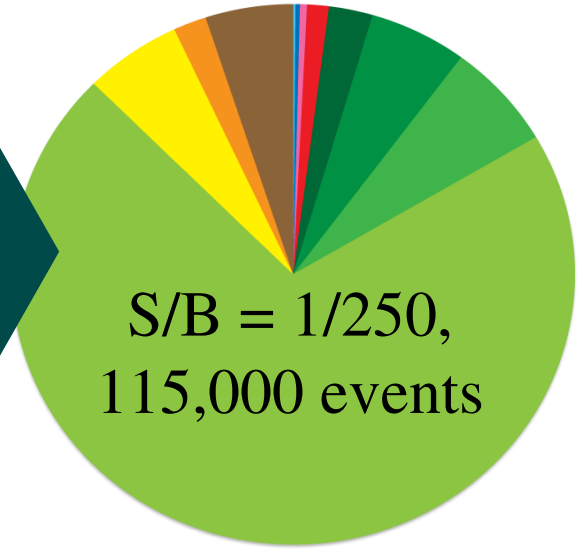


Analysis outline

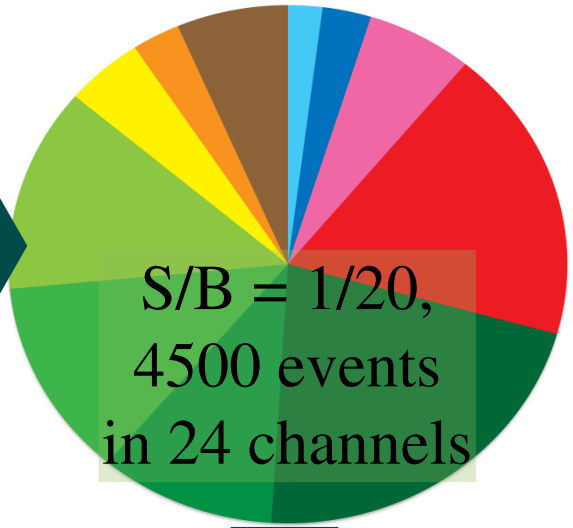
Trigger selection

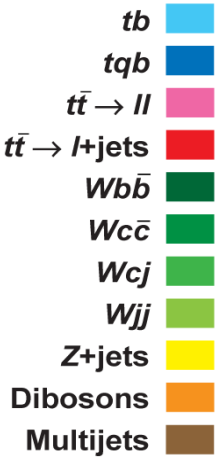


Single top event kinematics



b-quark tagging

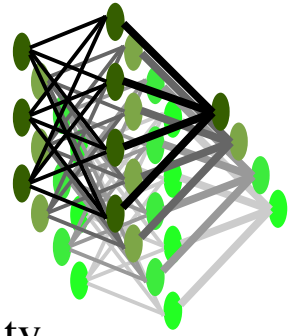




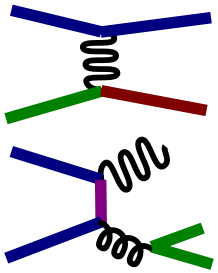
Multivariate techniques

BDT

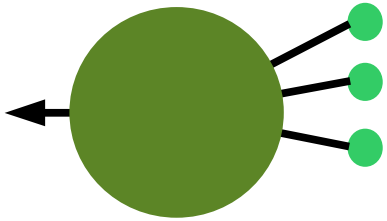
BNN



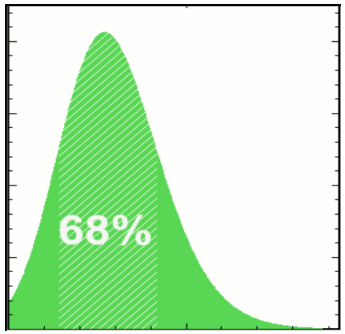
ME



Combination

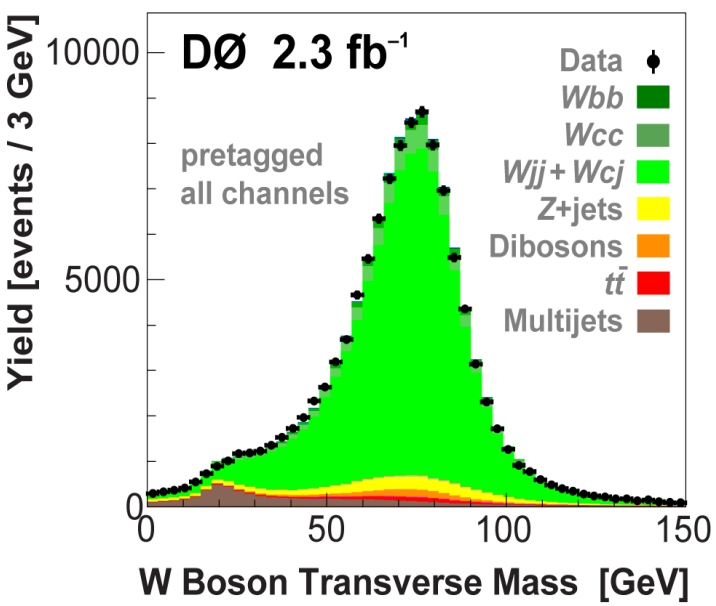


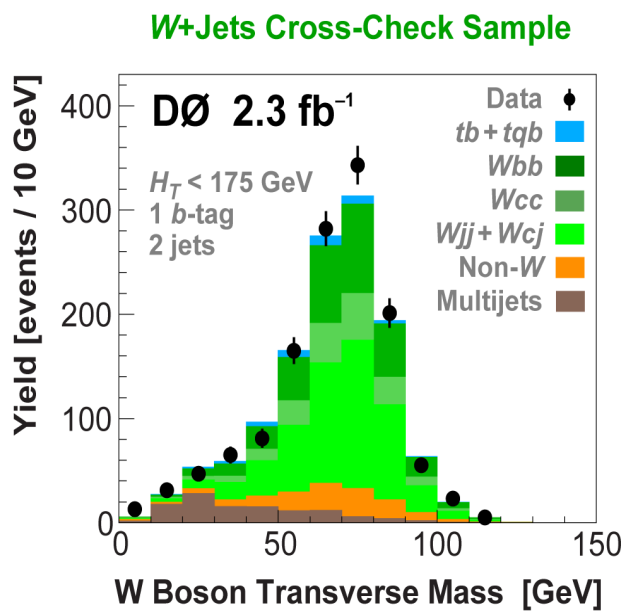
Statistical analysis

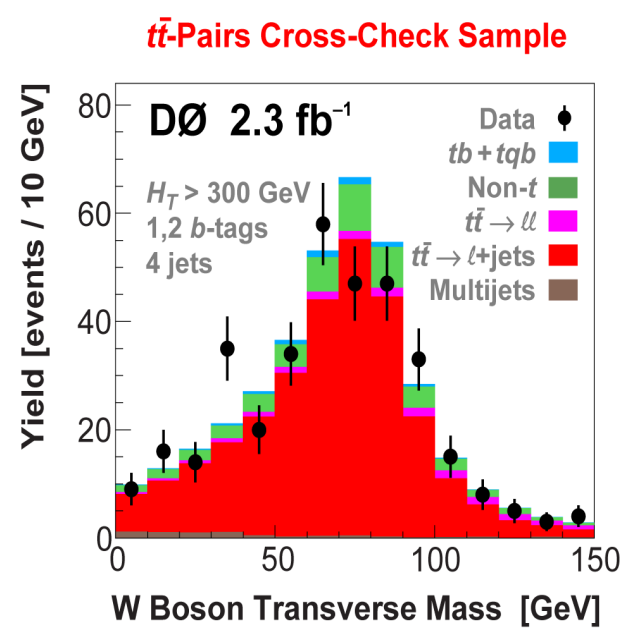


Analysis samples

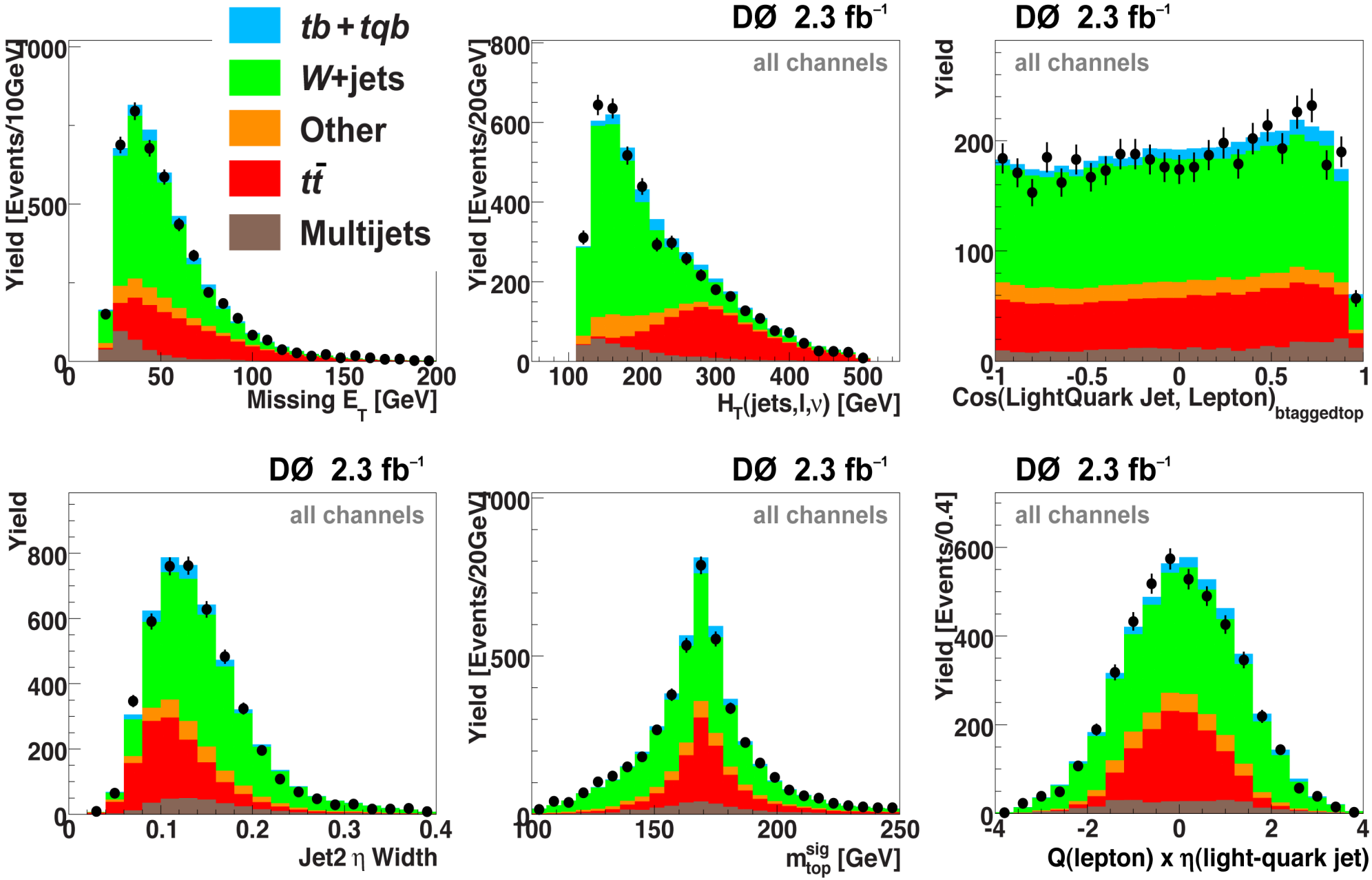
- Divide into 24 analysis channels
  - By b-tag multiplicity (1, 2), jet multiplicity (2, 3, 4), data taking period (before/after upgrade), lepton (e, μ)
- Cross-check samples
  - Enriched in W+jet events
  - Enriched in top pair events
- Check data/background agreement for all variables and multivariate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



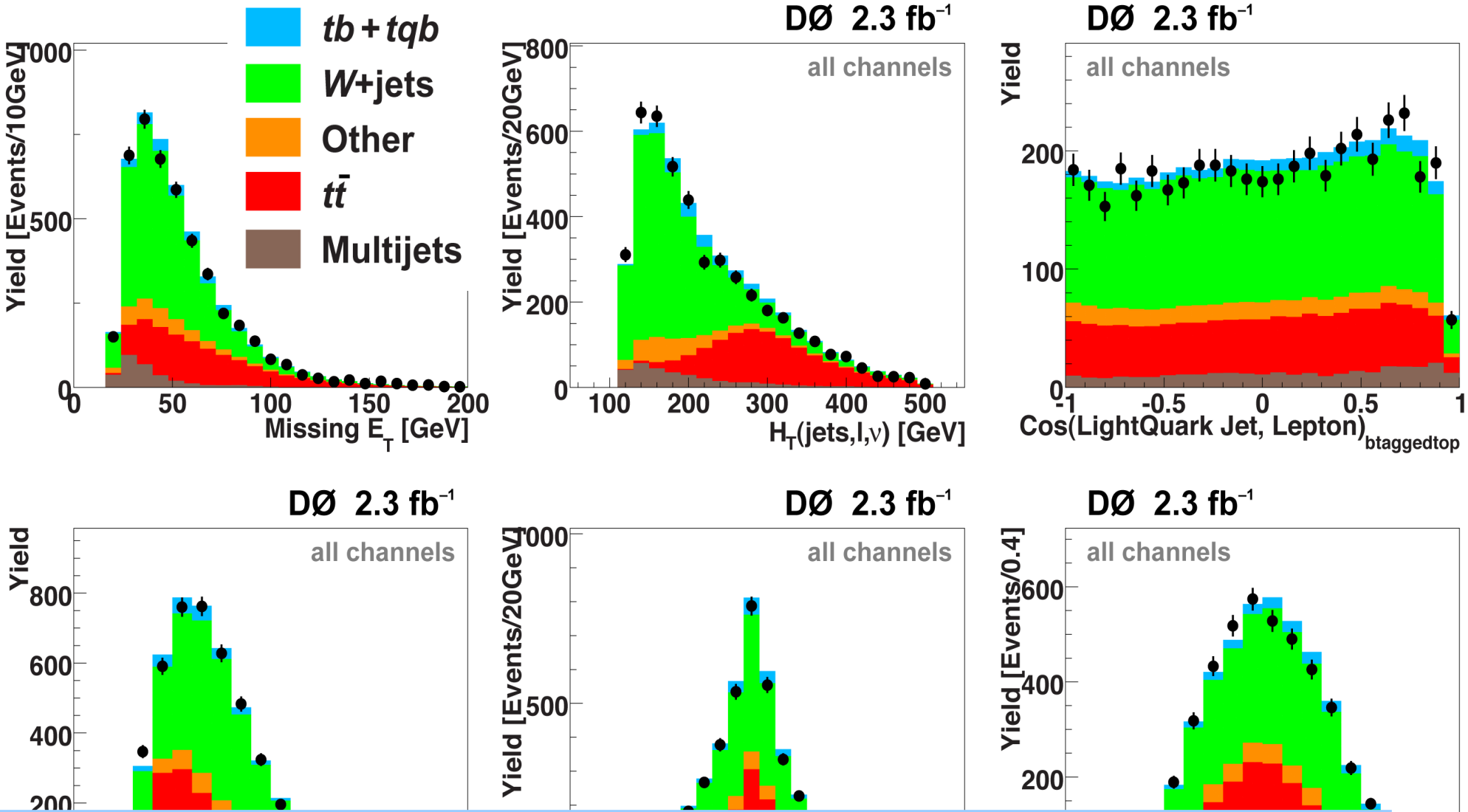




Important discriminating variables



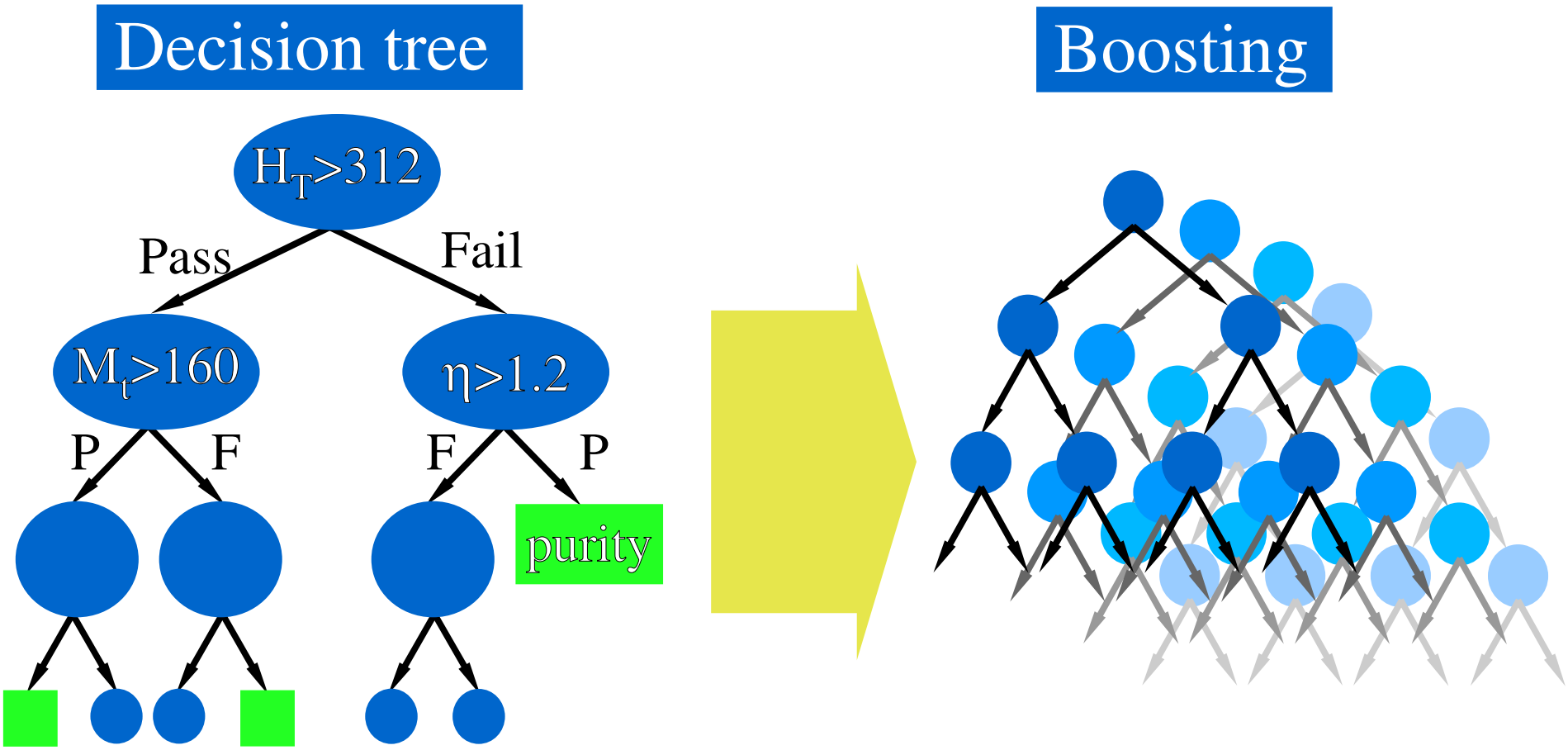
Important discriminating variables



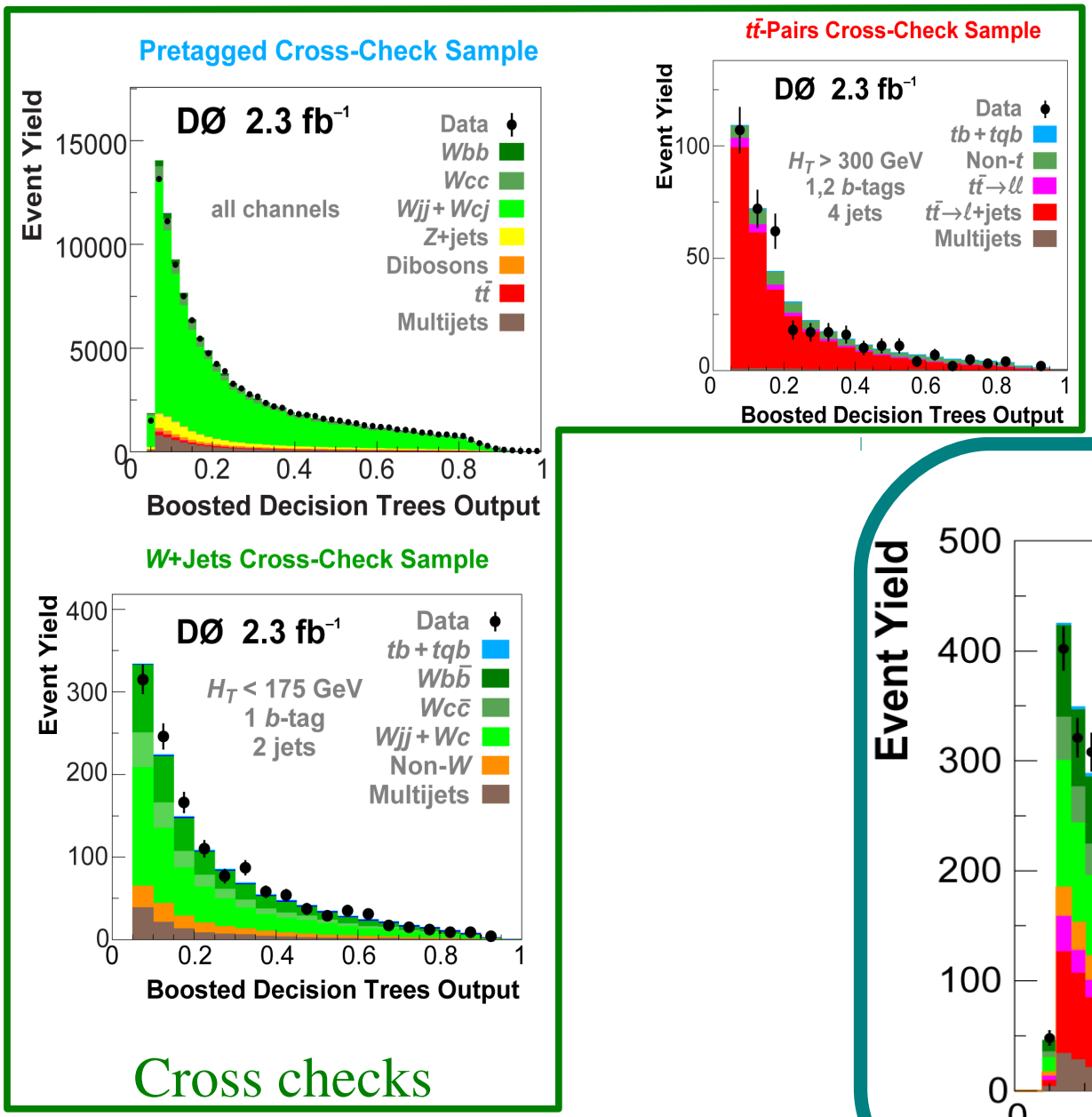
- Considered ~200 variables total for multivariate filters
- Chose 18-64 variables for each filter, depending on method and channel

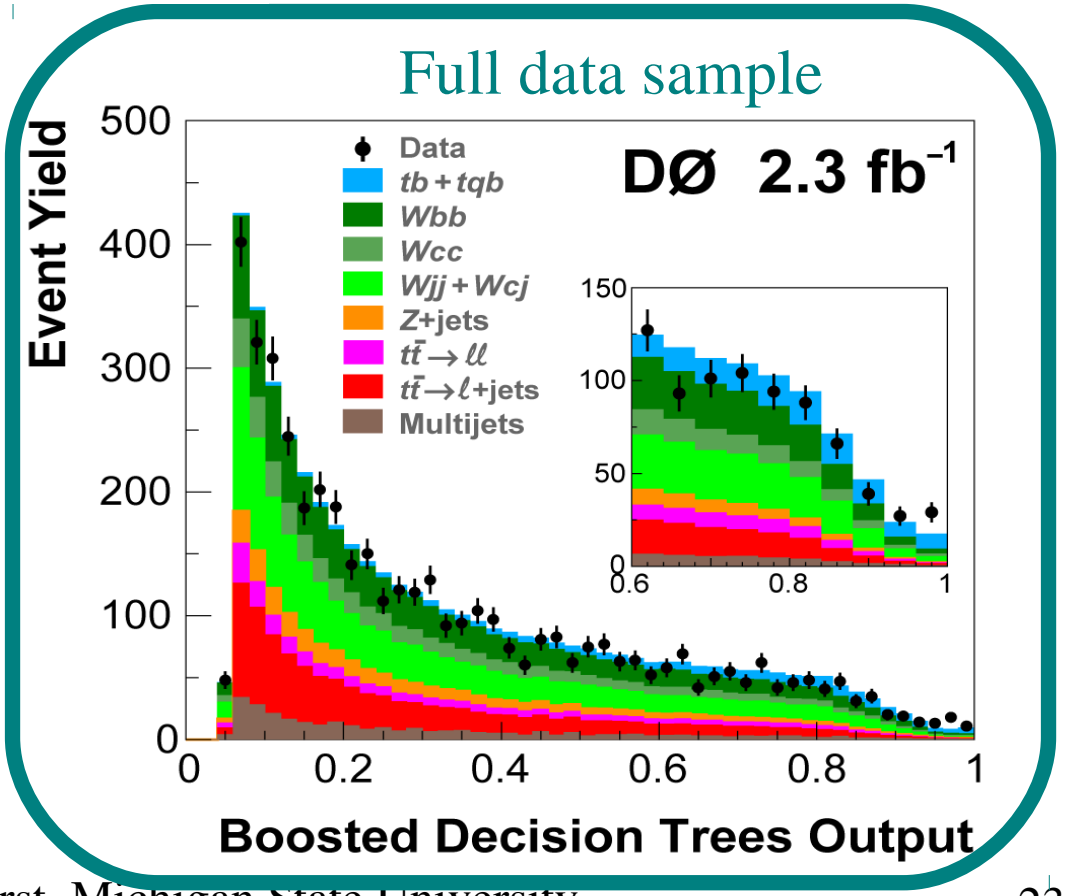
Multivariate Analysis

Boosted decision trees

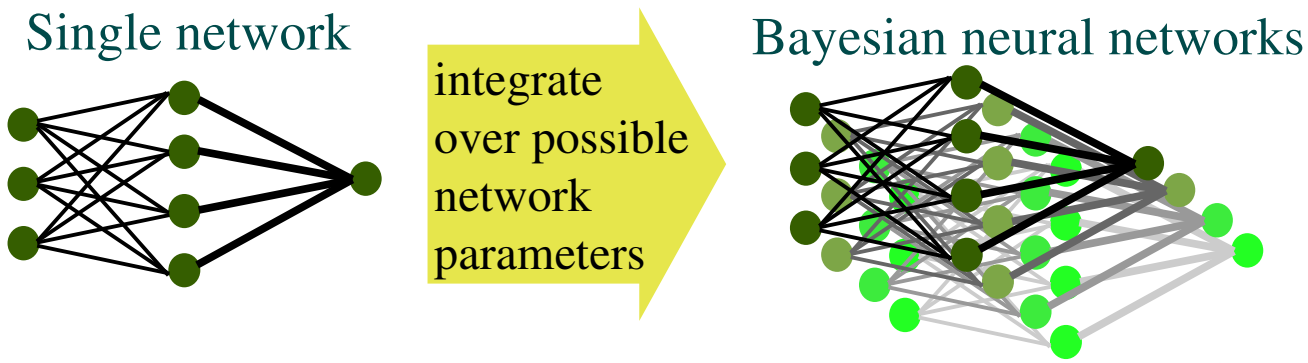


Boosted decision tree distributions

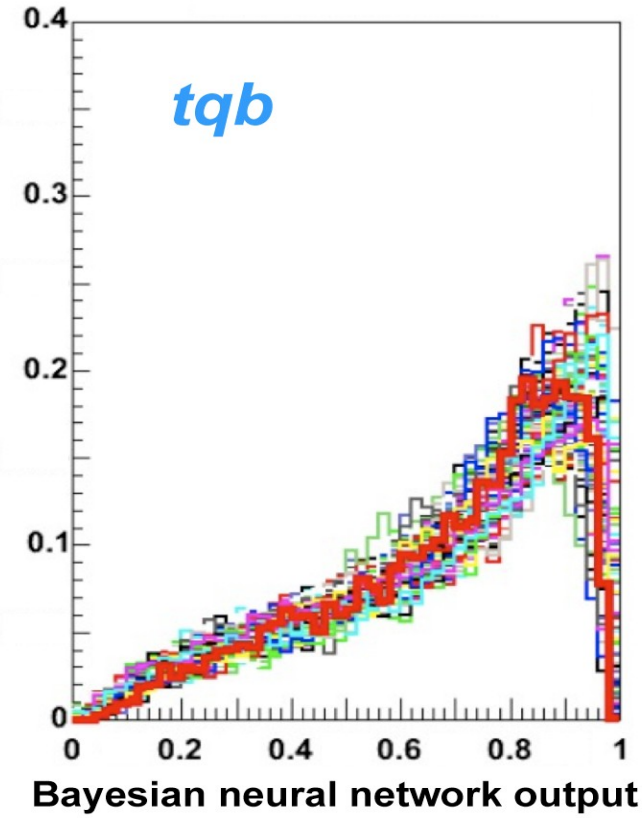




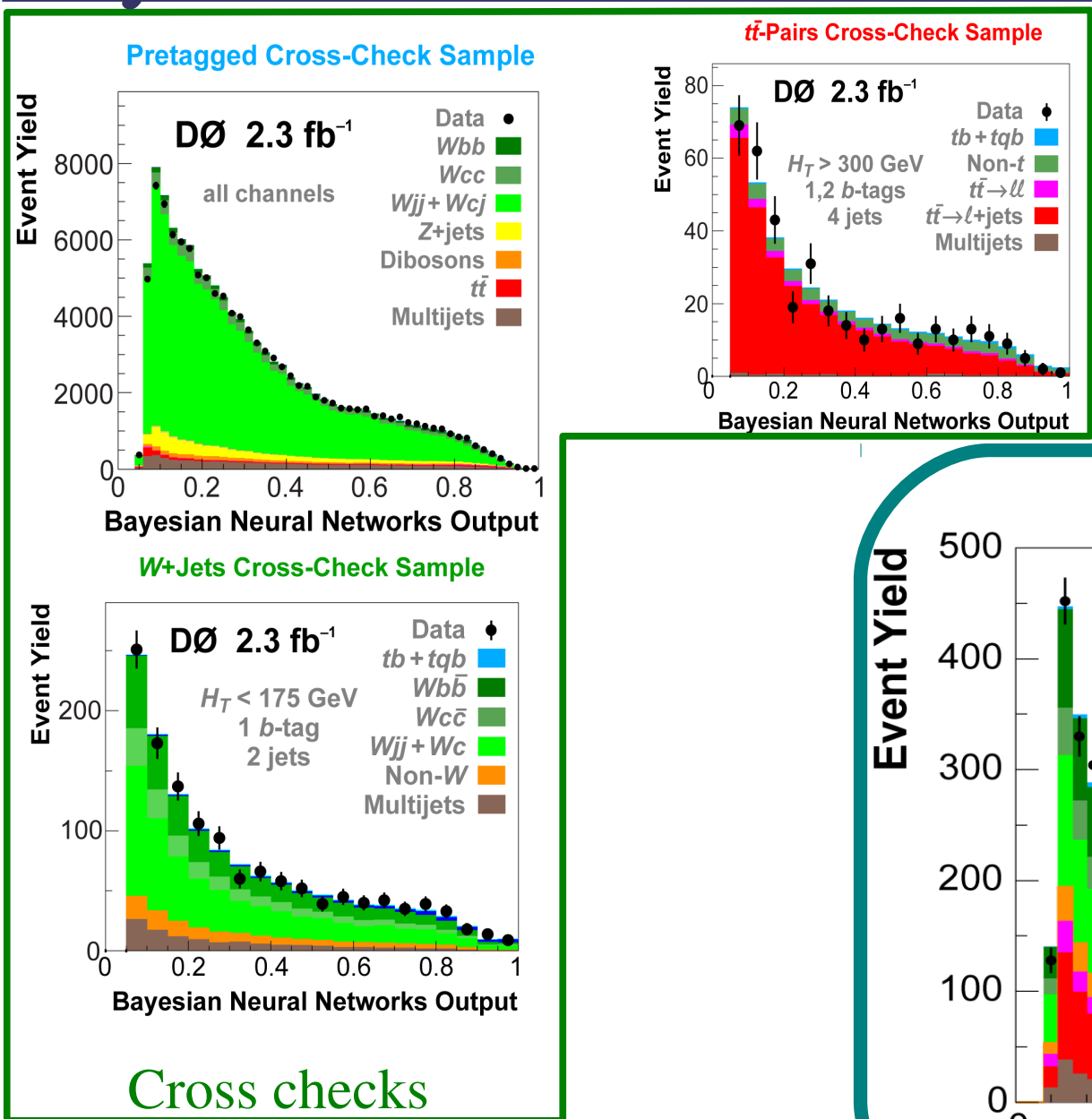
Bayesian neural networks

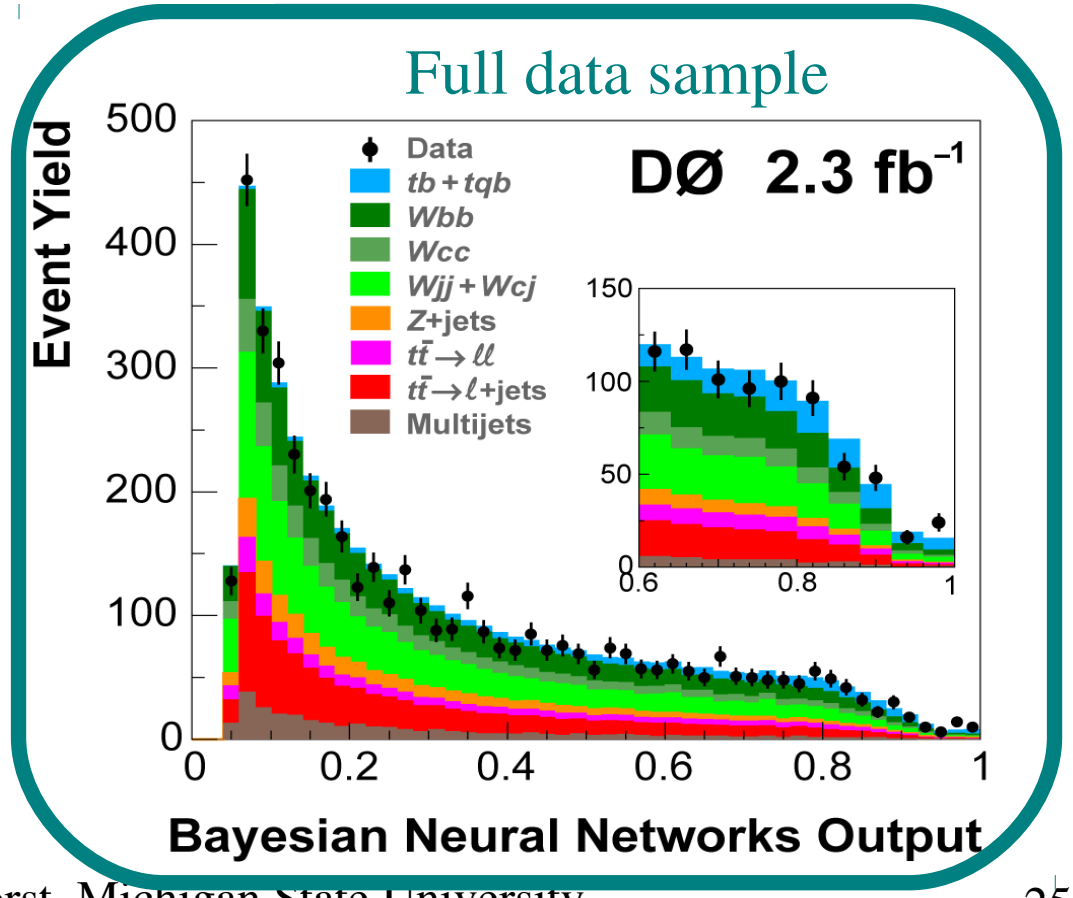


- NN with three layers, 24 input nodes, 40 hidden nodes
- Bayesian Idea:
  - Determine the posterior probability for each weight at each node
  - Sample from this posterior
  - Here: Average over 100 networks



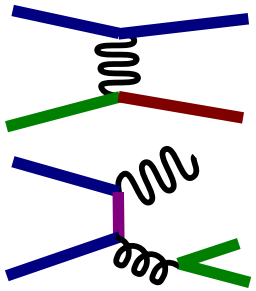
Bayesian neural network distributions





Matrix element analysis

Parton level matrix elements



integrate over measurement uncertainties

Signal discriminant

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

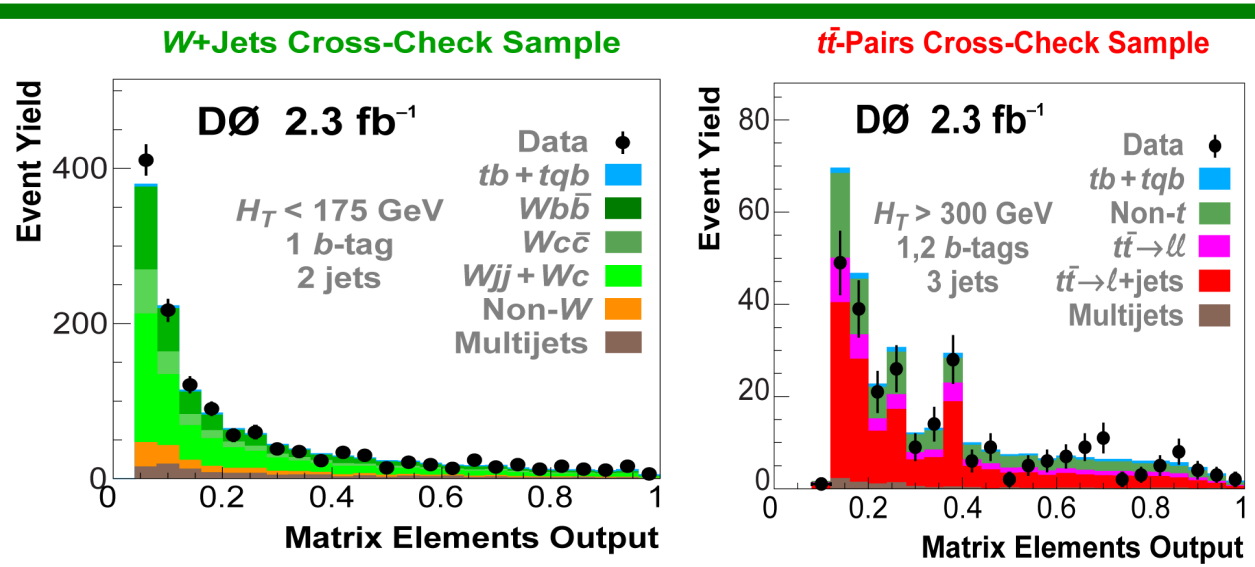
- Signal and background probability for each event is calculated from differential cross section

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

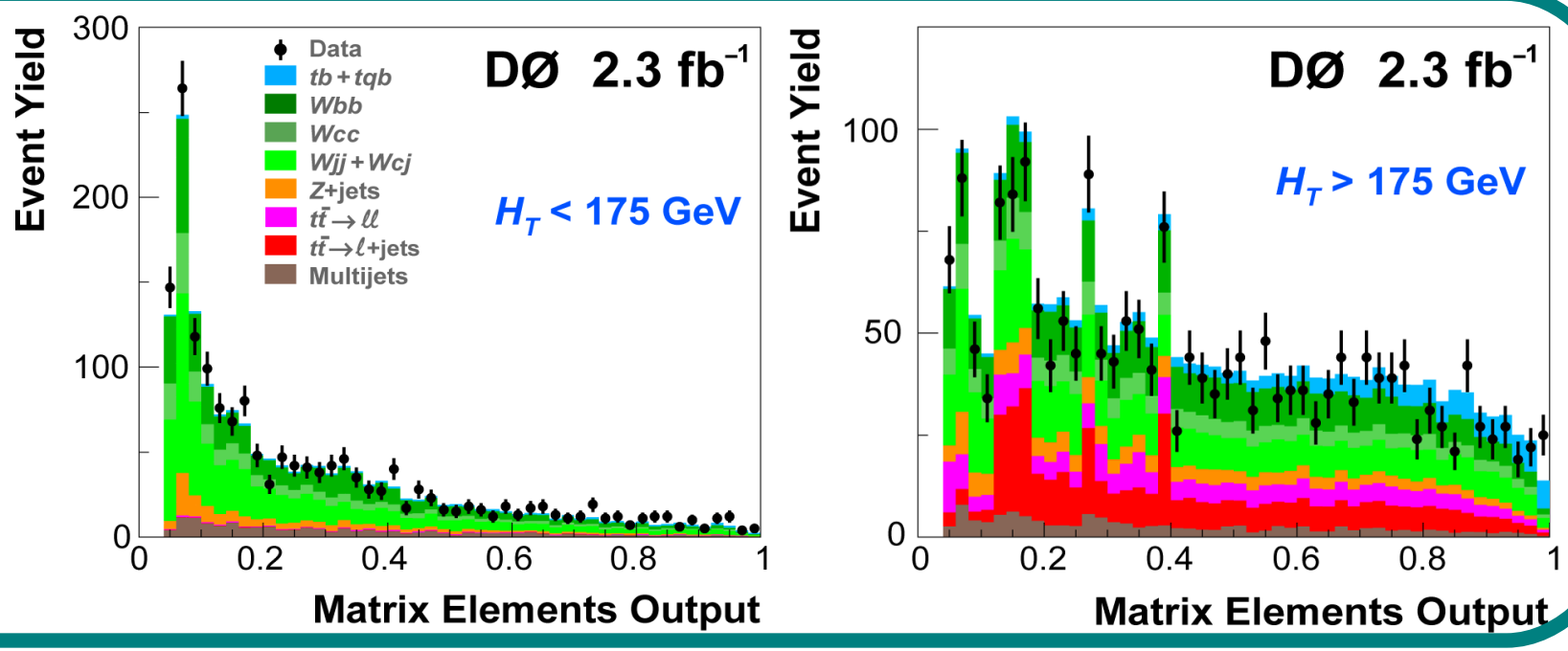
  - Integration over final state momenta
    - And over reconstructed momenta, transfer function
- Include ME for s-channel, t-channel, top pairs, diboson, W+jets (including gluons)
- Determine weights in two HT regions

Matrix element distributions

Cross checks

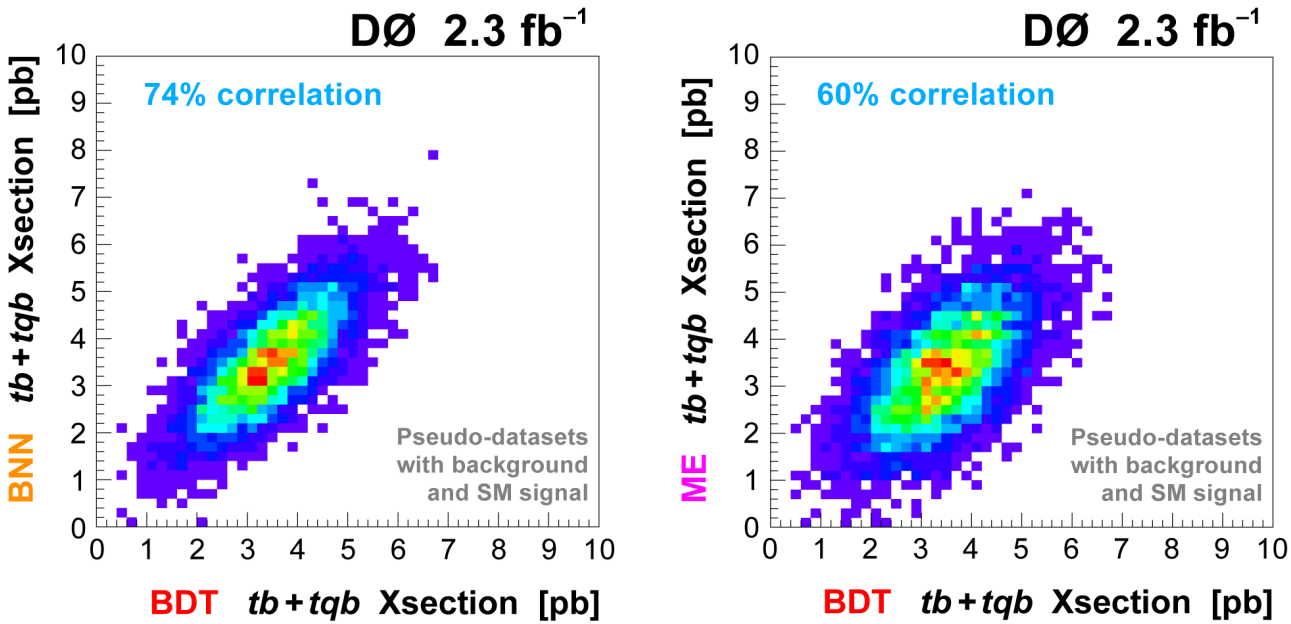


Full data sample

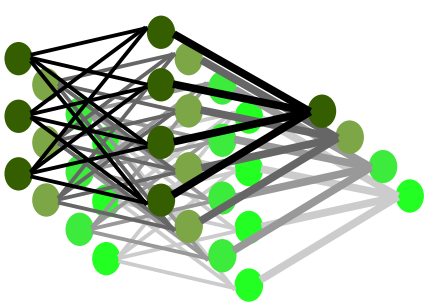


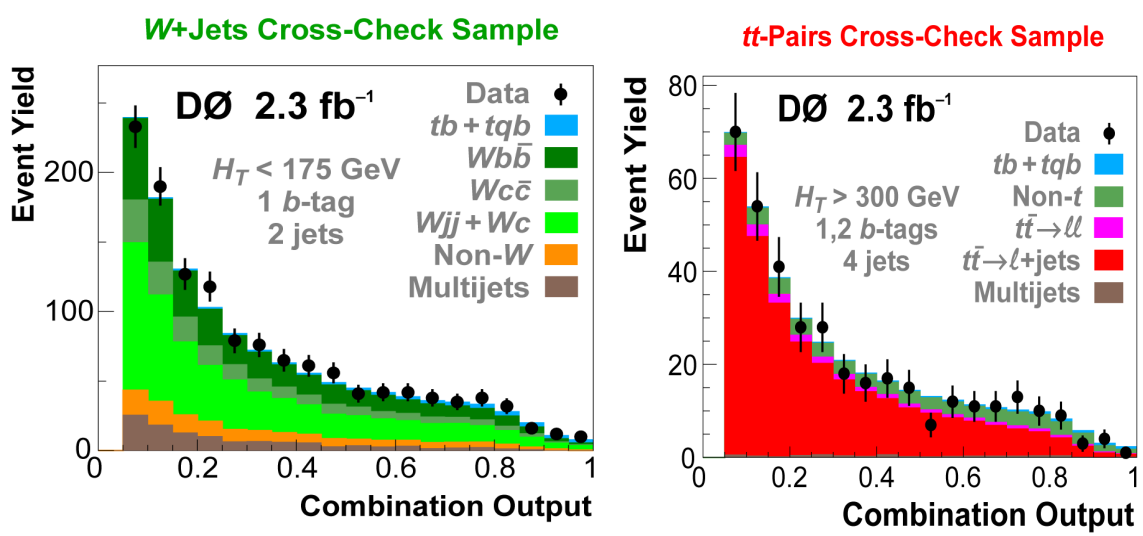
Combination: Another BNN

– Gain because each method provides unique separation



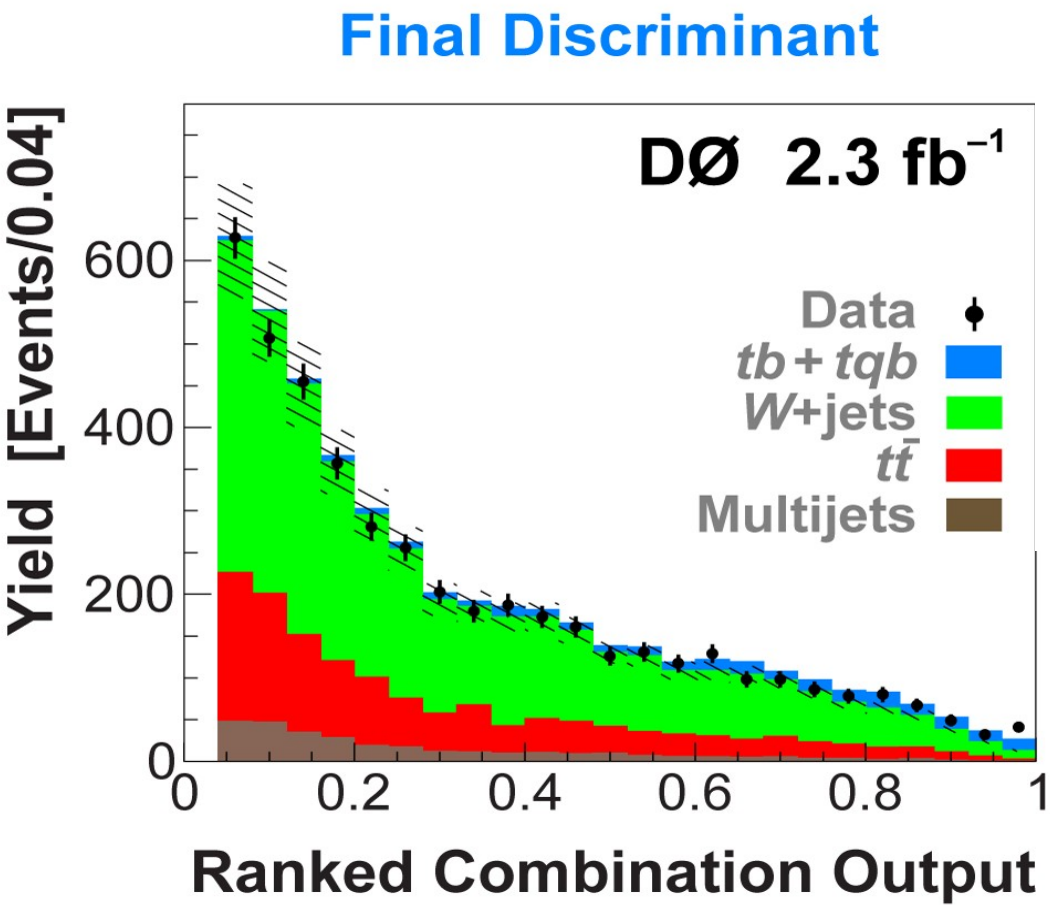
– Simple BNN, only 3 inputs: BDT, BNN, ME

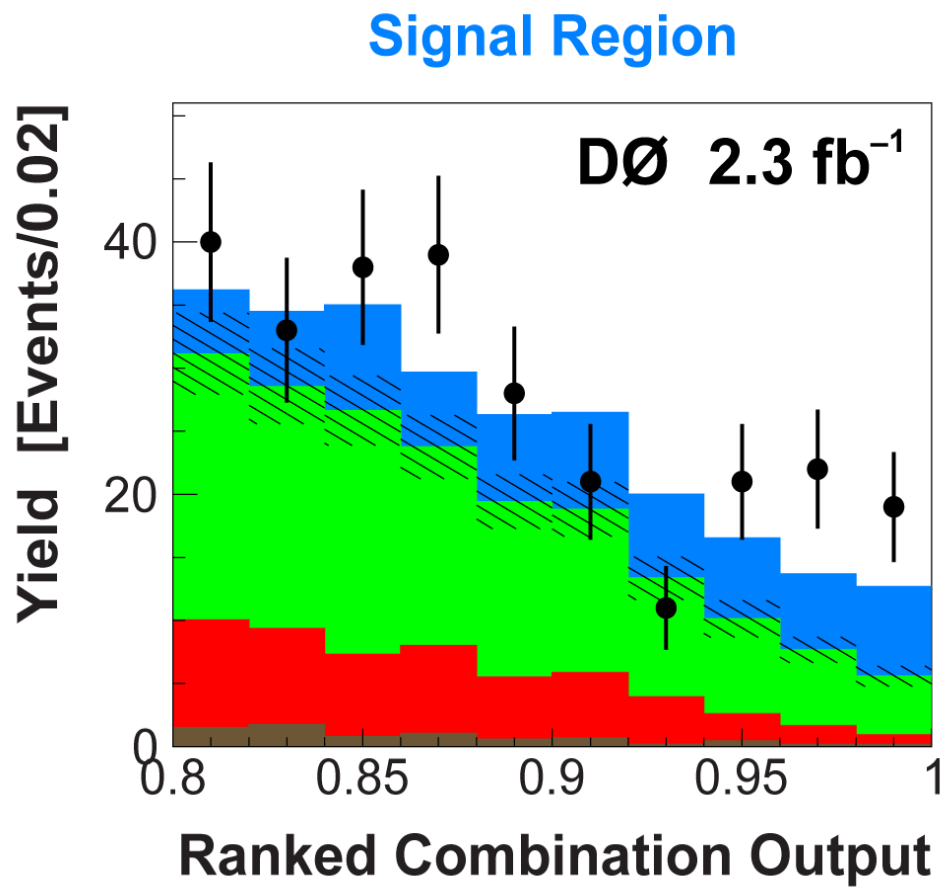




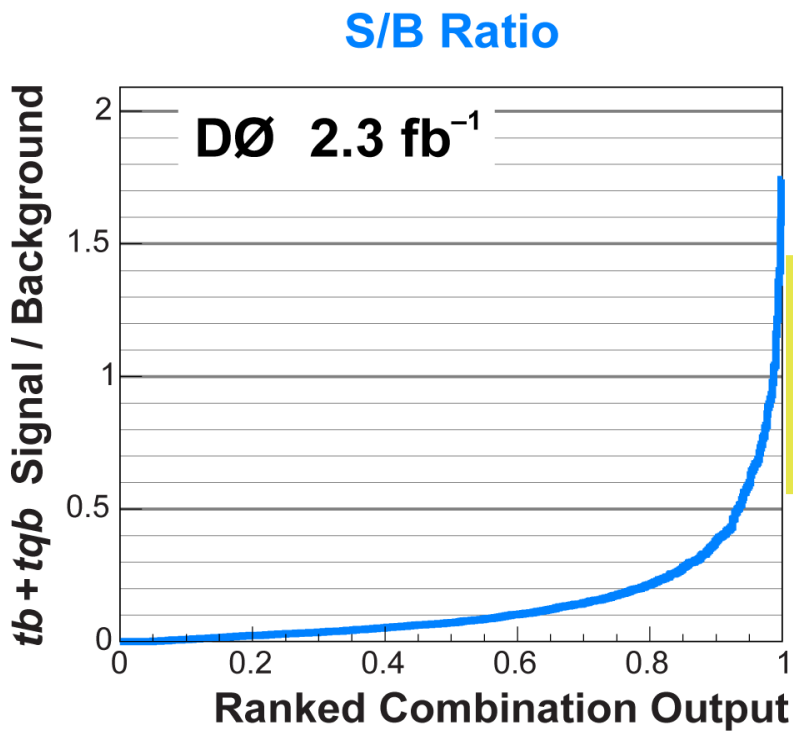
Combination distribution

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

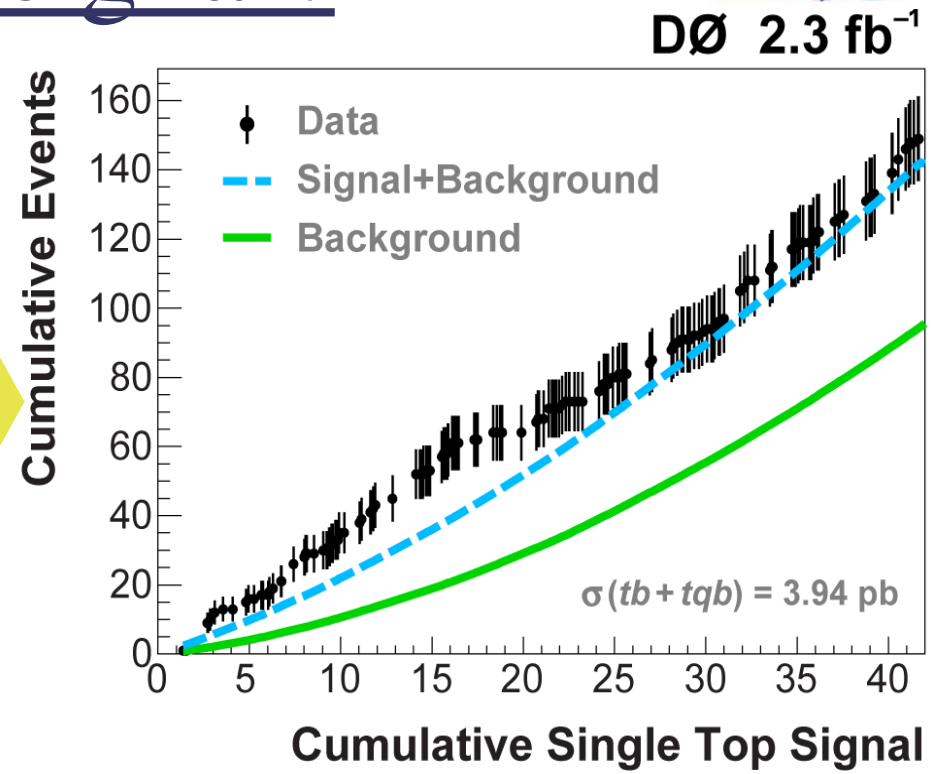


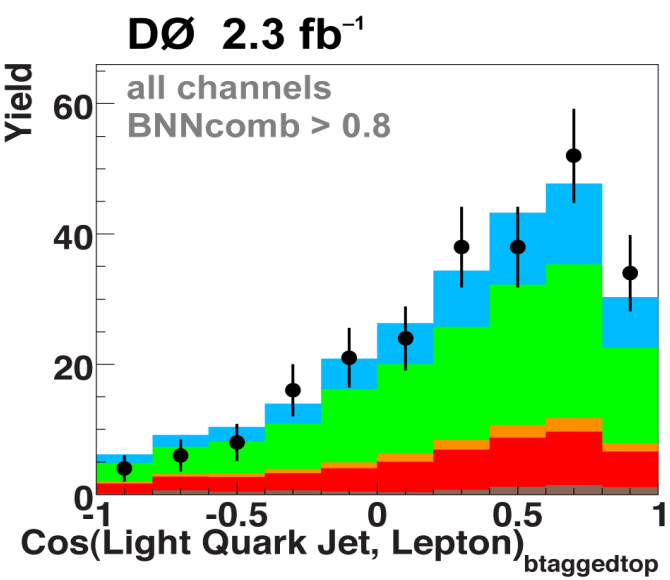


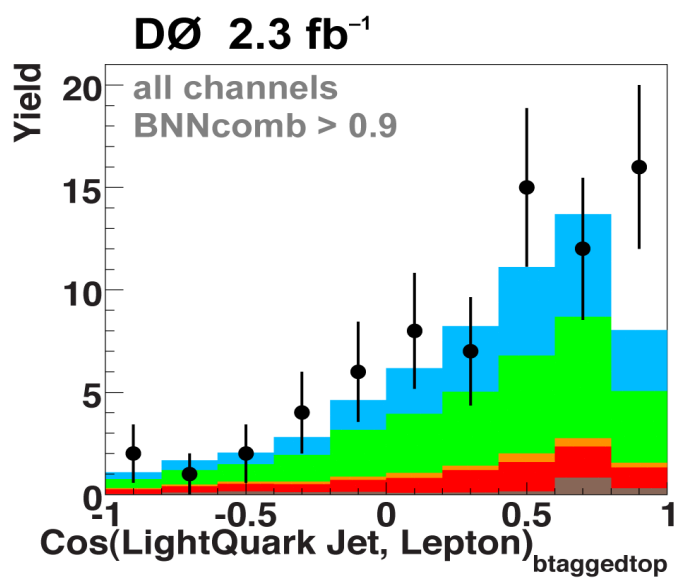
Is there a signal?

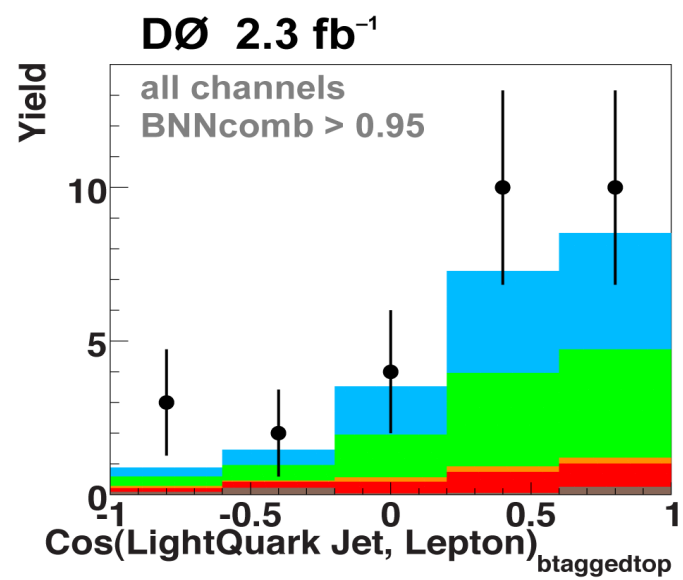


Sum bins right-to-left

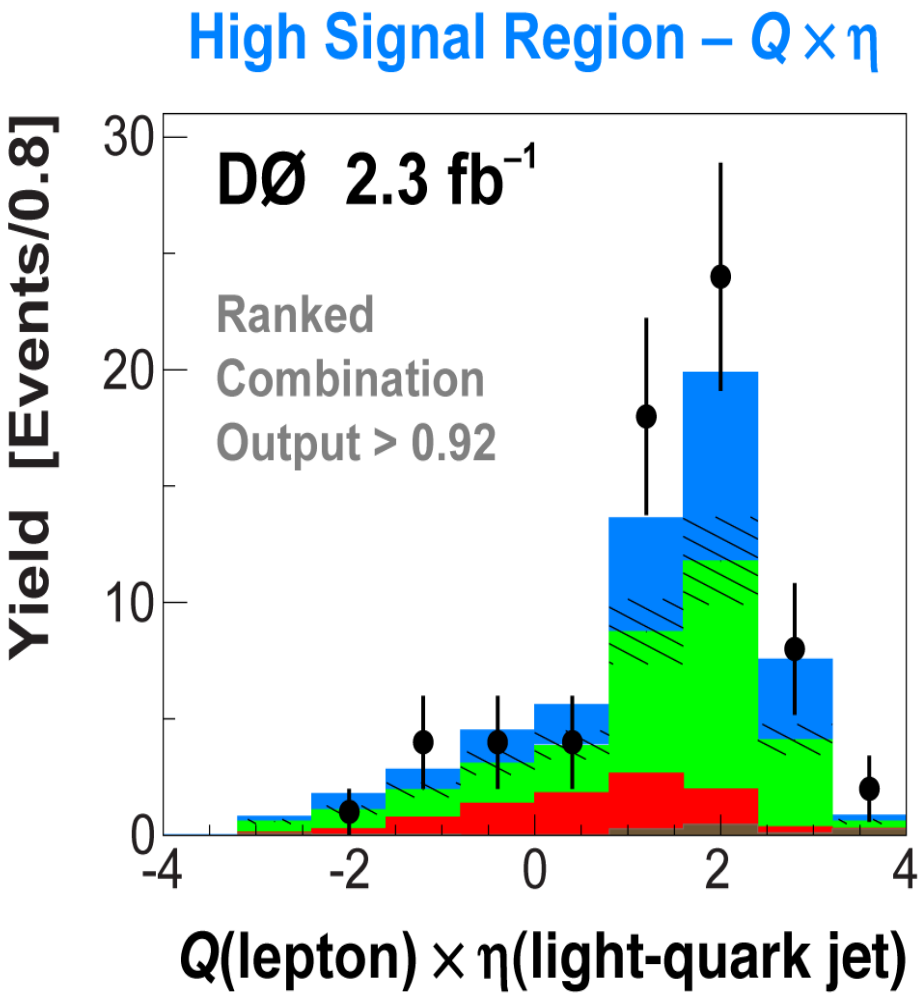


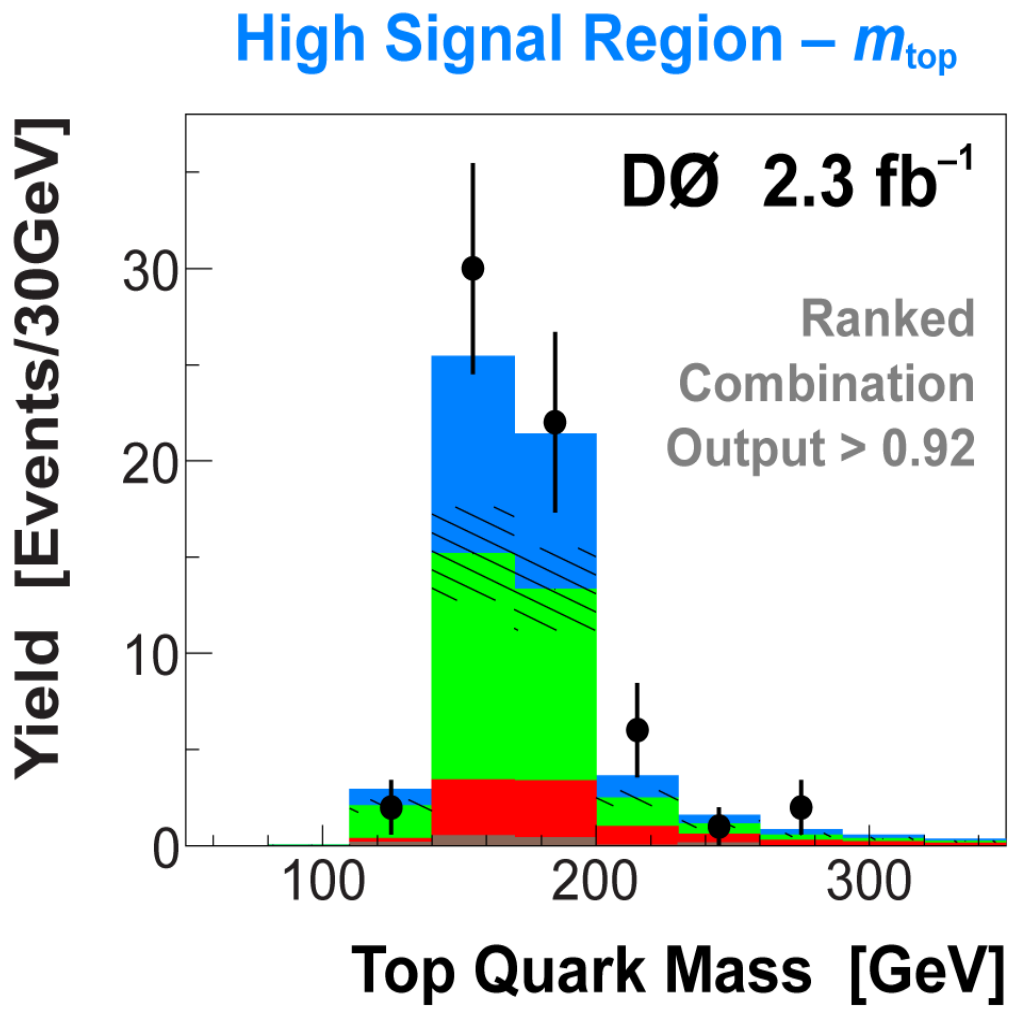






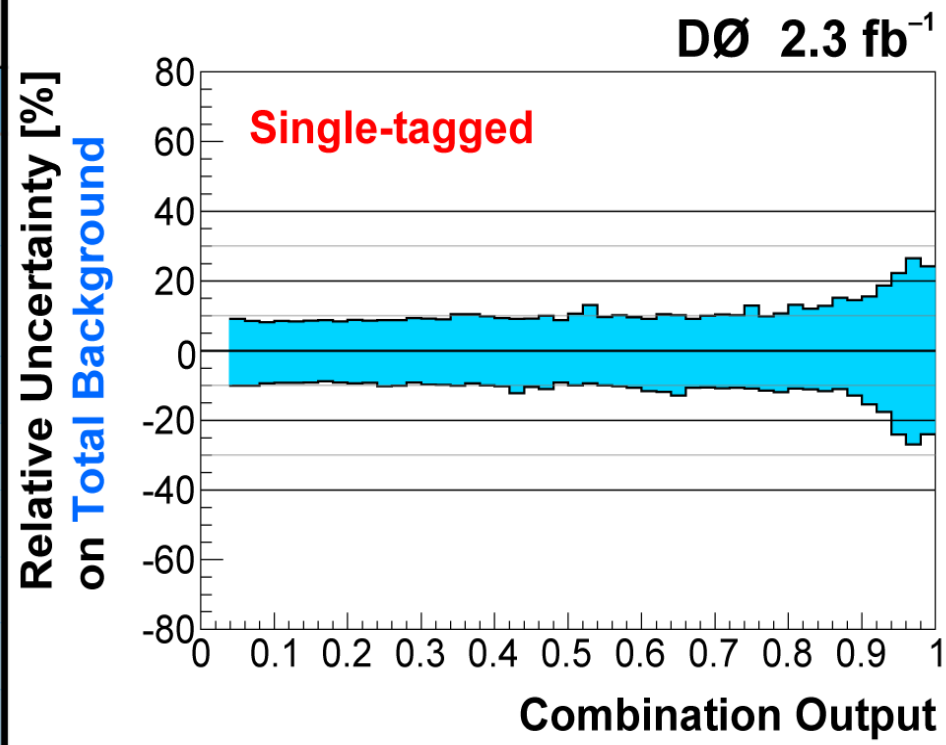
Kinematics in the signal region





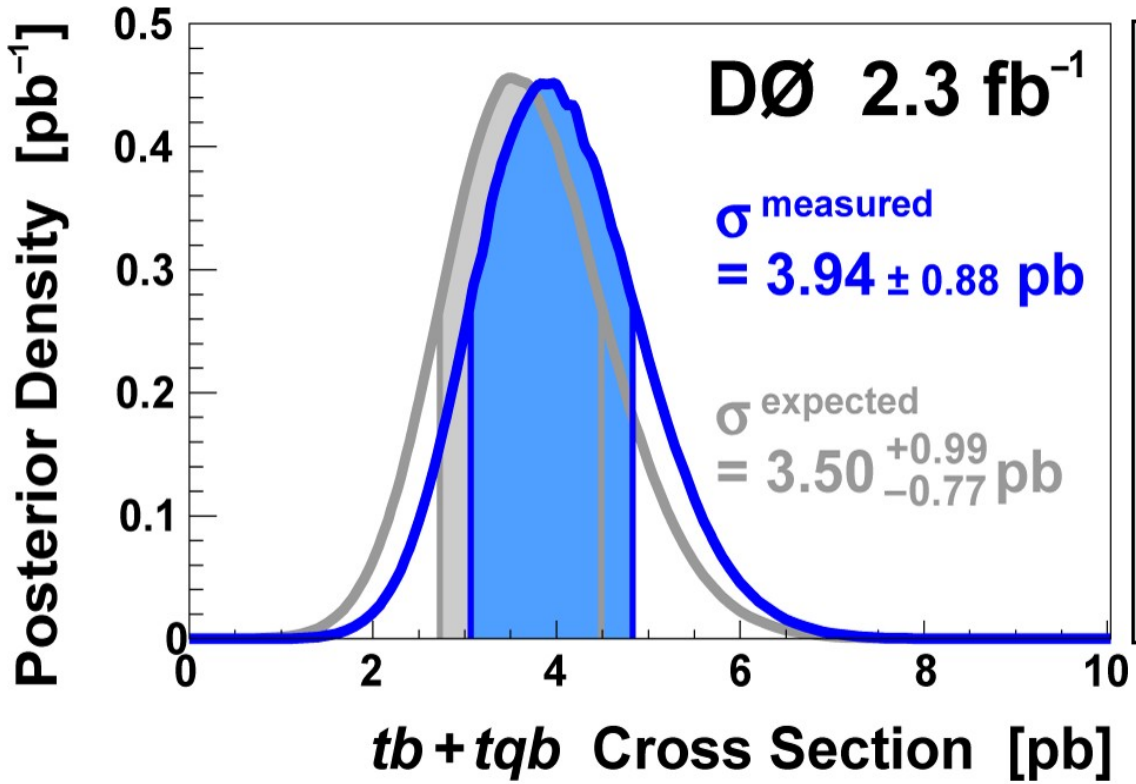
Systematic uncertainties

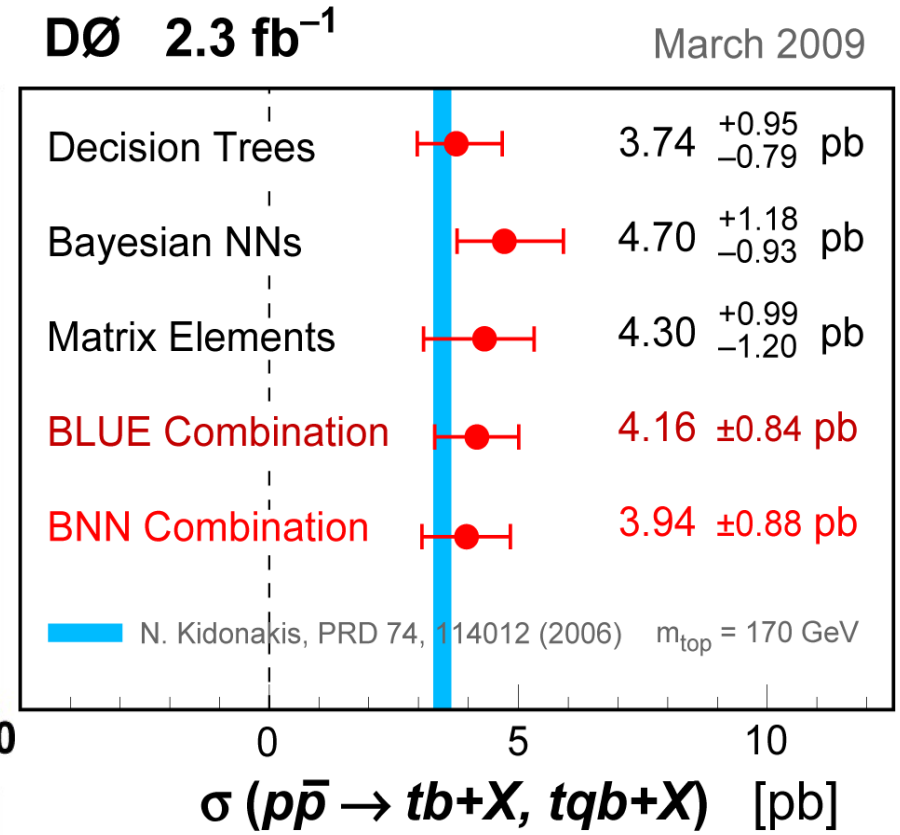
Systematic Uncertainties Ranked from Largest to Smallest Effect on Single Top Cross Section DØ 2.3 fb^{-1}	
Larger terms	
b-ID tag-rate functions (includes shape variations)	(2.1–7.0)% (1-tag) (9.0–11.4)% (2-tags)
Jet energy scale (includes shape variations)	(1.1–13.1)% (signal) (0.1–2.1)% (bkgd)
W+jets 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%



Statistical analysis

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

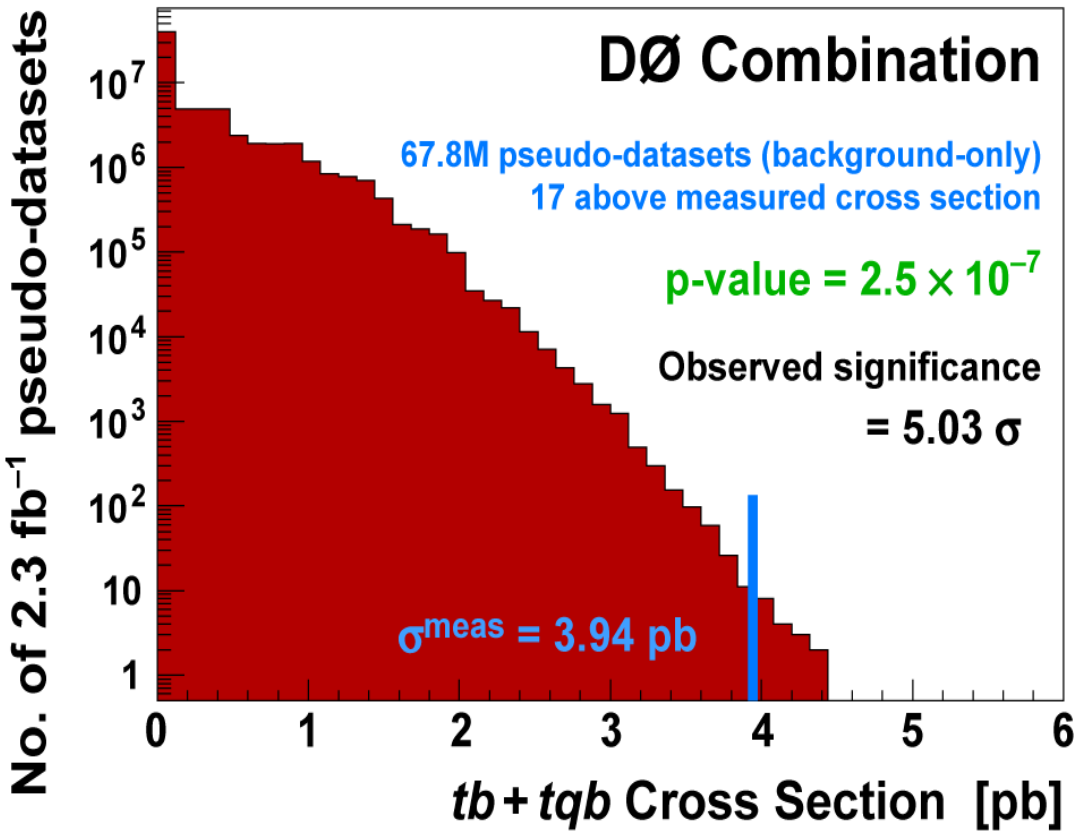




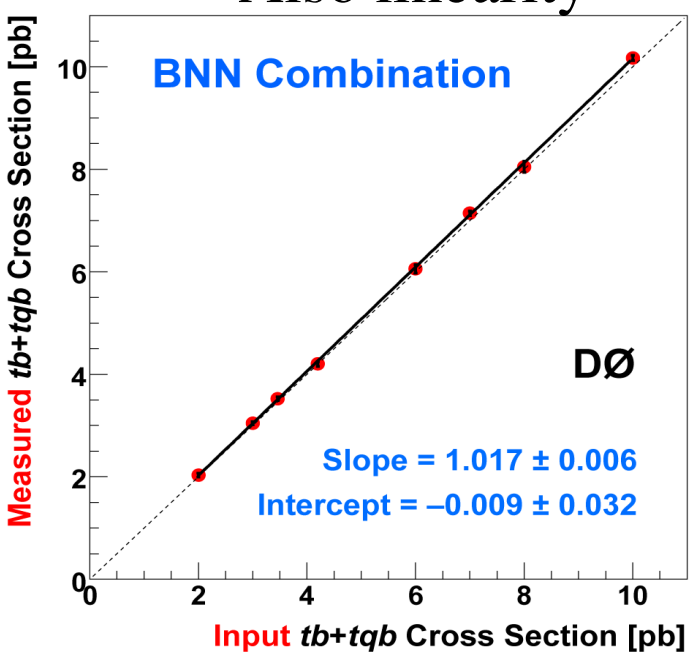
PRL 103, 092001 (2009)

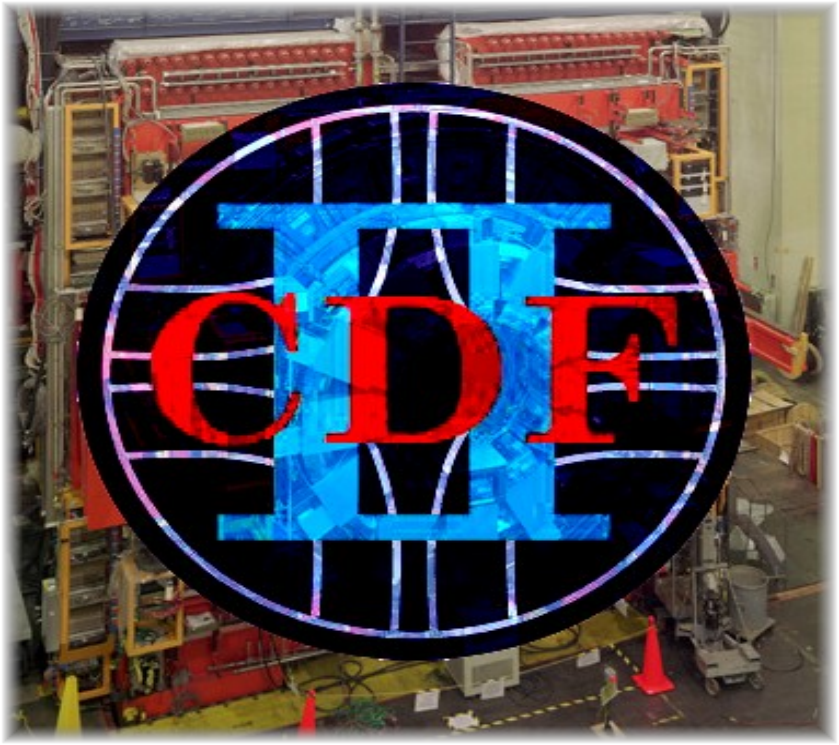
Significance

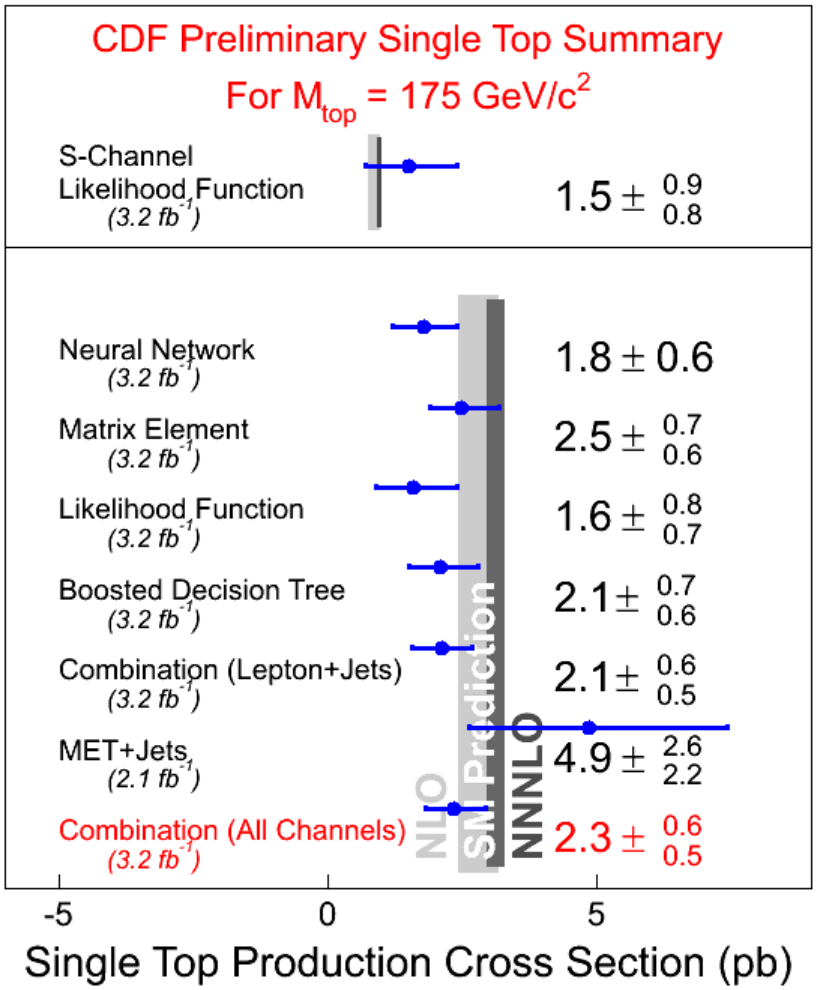
- Significance (p-value) and linearity and many tests through extensive ensemble testing
  - Ensembles of pseudo-data at various signal cross sections



Also linearity



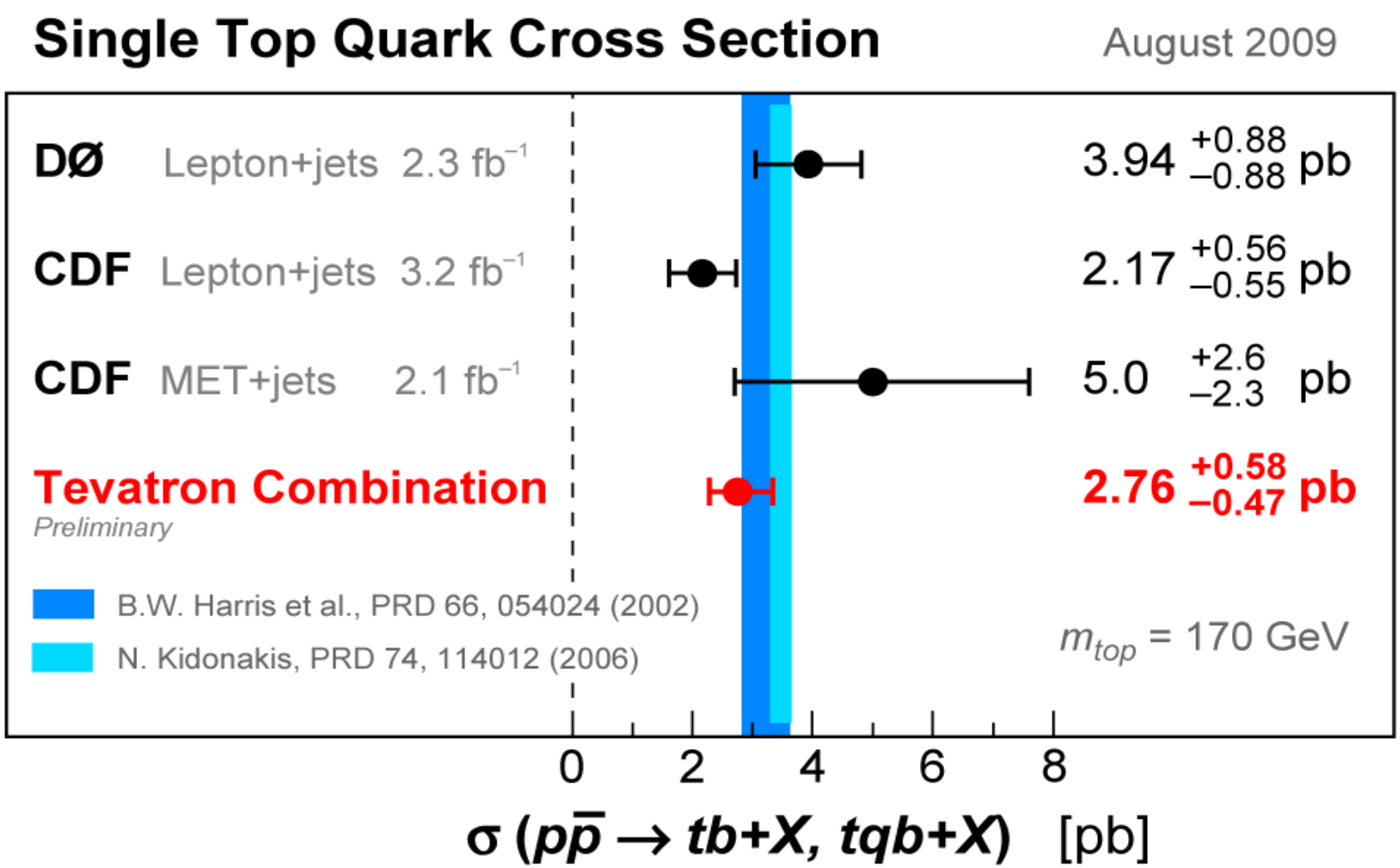




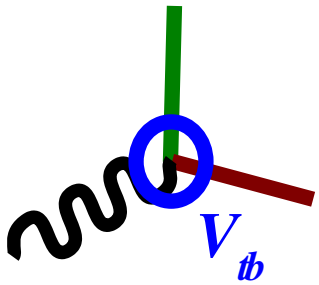
- Analyses based on 3.2 fb^{-1}
- Top mass 175GeV

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

Tevatron Combination



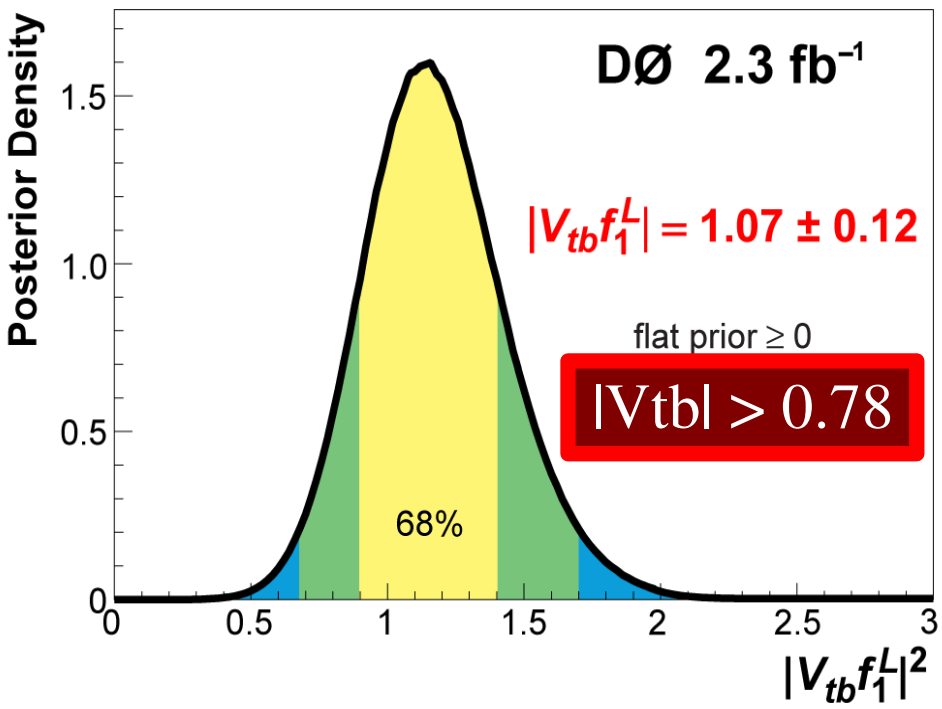
CKM matrix element $|V_{tb}|$

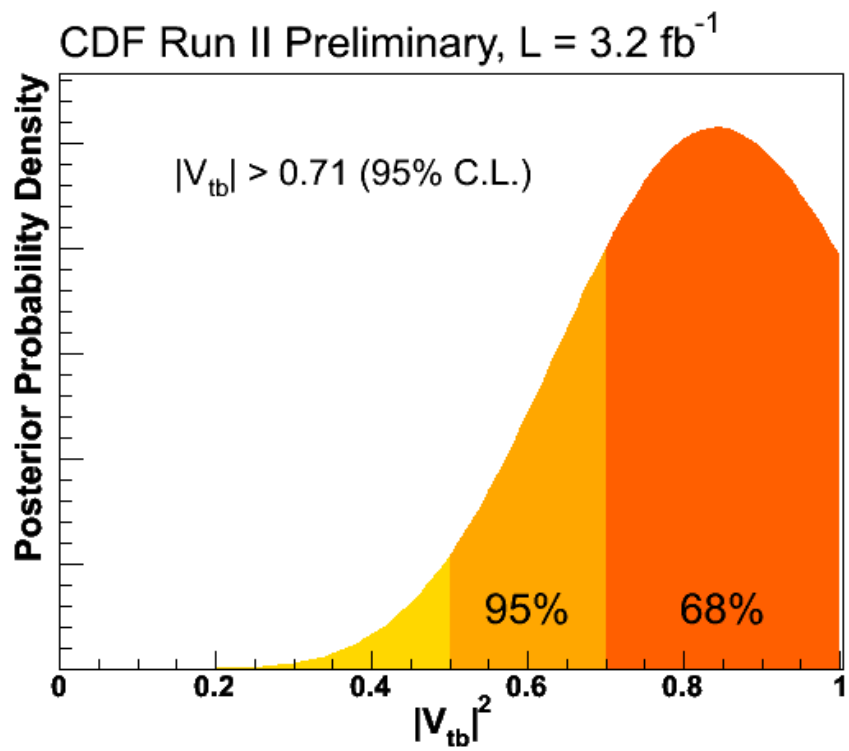


CKM Matrix

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

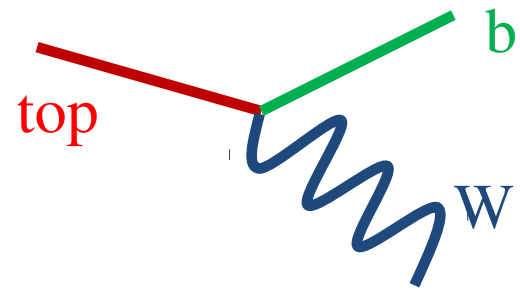
- Measurement: $|V_{tb} \times f_L{}^1|$
  - Assume top decays to b ($V_{tb} \gg V_{ts}, V_{td}$)
- No constraint on # of generations





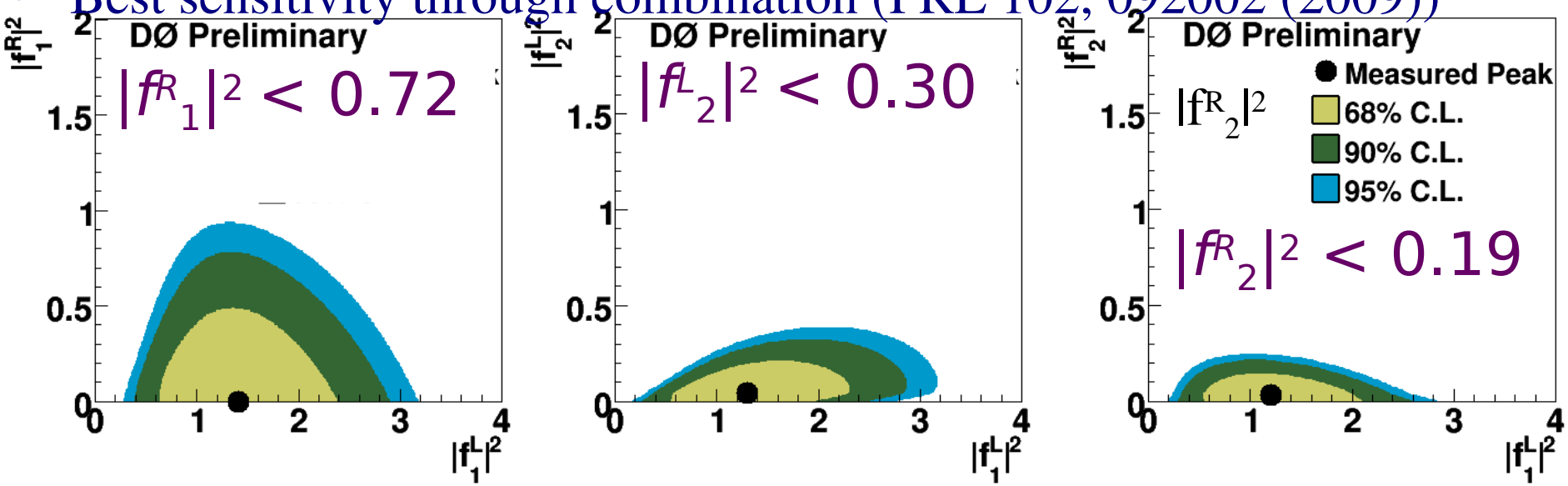
Single top polarization – anomalous coupling

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

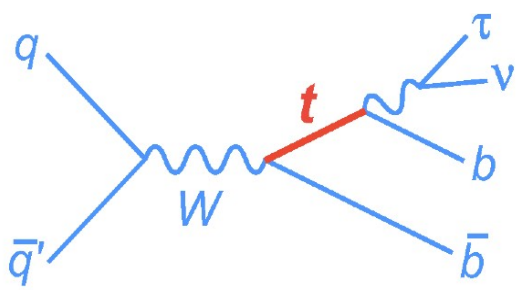


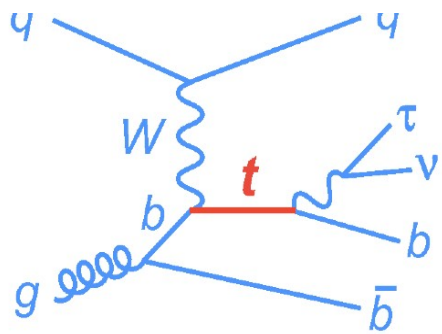
$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu V_{tb}(f_1^L P_L + f_1^R P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}(f_2^L P_L + f_2^R P_R)tW_\mu^- + h.c.$$

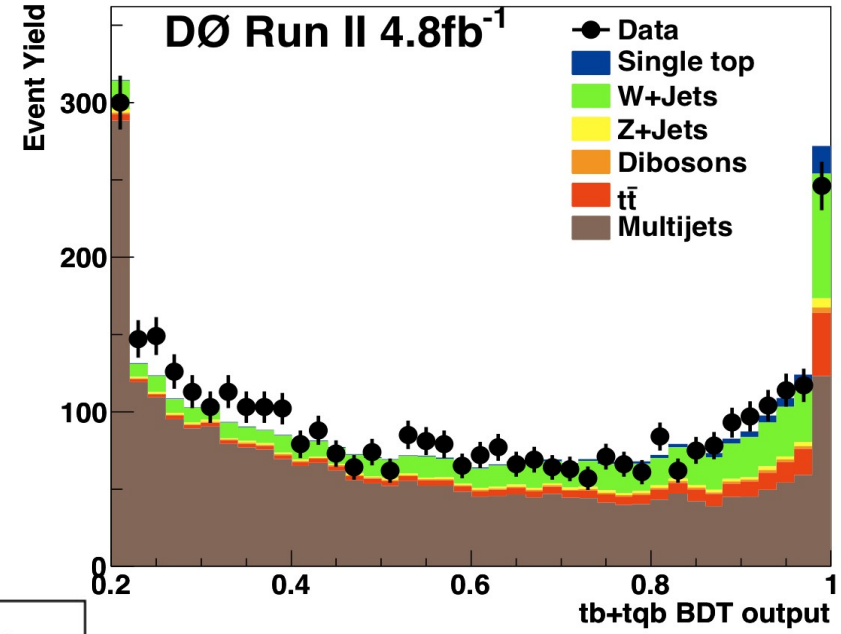
- Single top is sensitive to magnitude (PRL 101, 221801 (2008))
- ttbar to ratios of couplings (W helicity, PRL 100, 062004 (2008))
- Best sensitivity through combination (PRL 102, 092002 (2009))

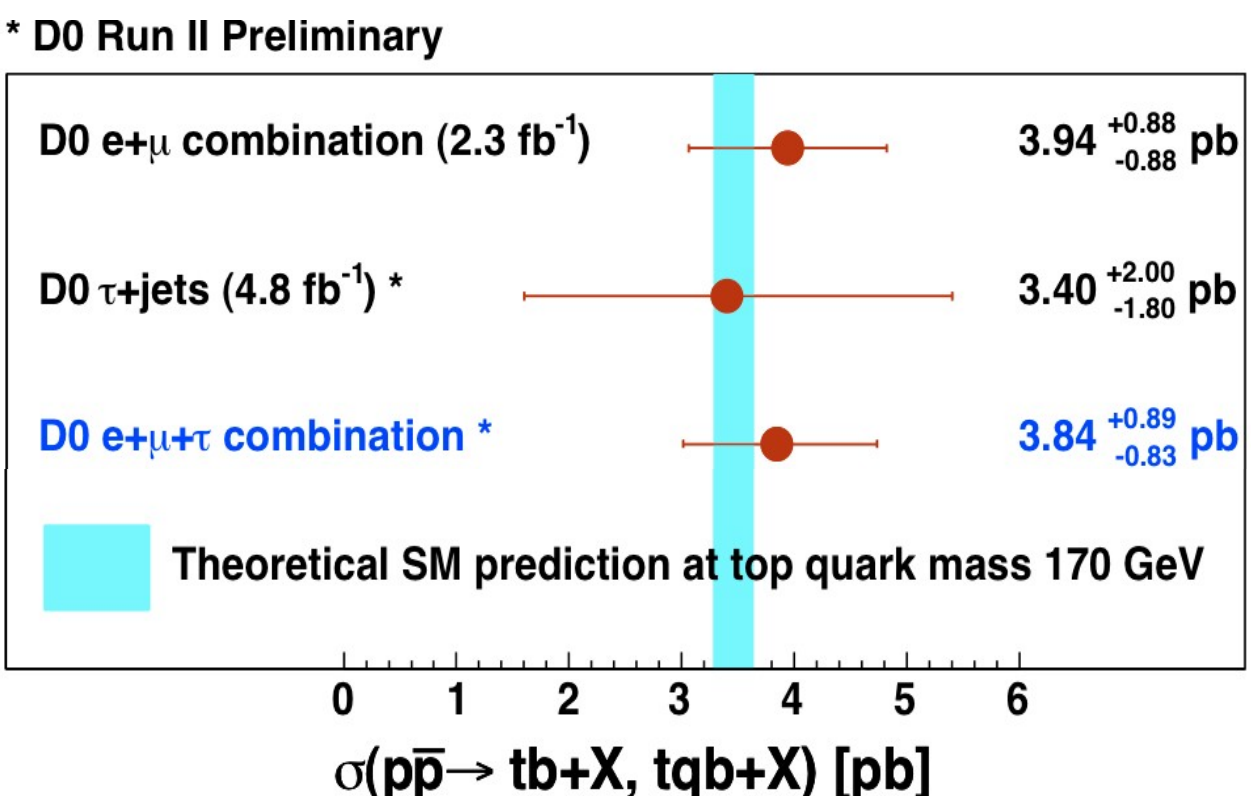


Single top in tau final state





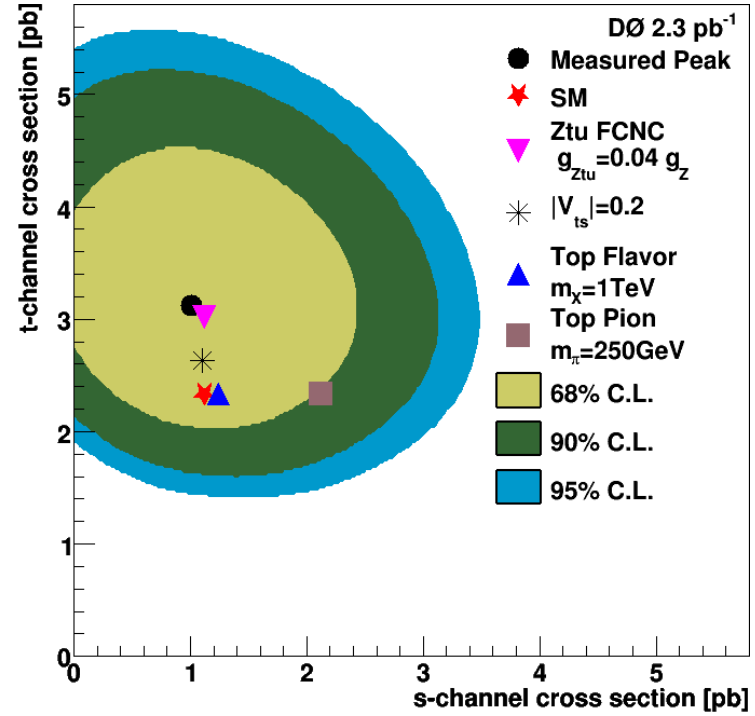


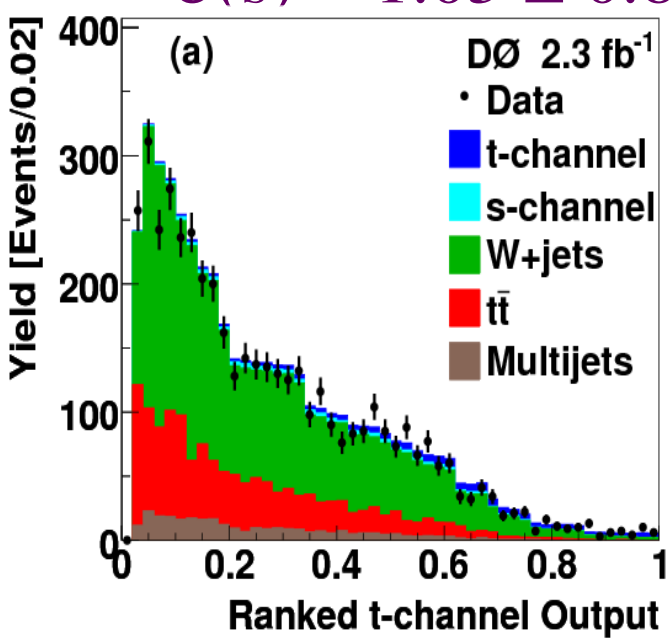


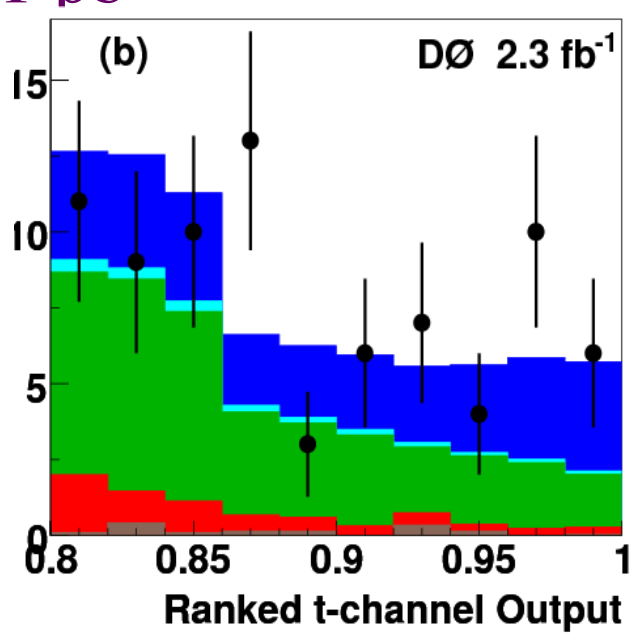
Submitted to PLB, arXiv.org:0912.1066

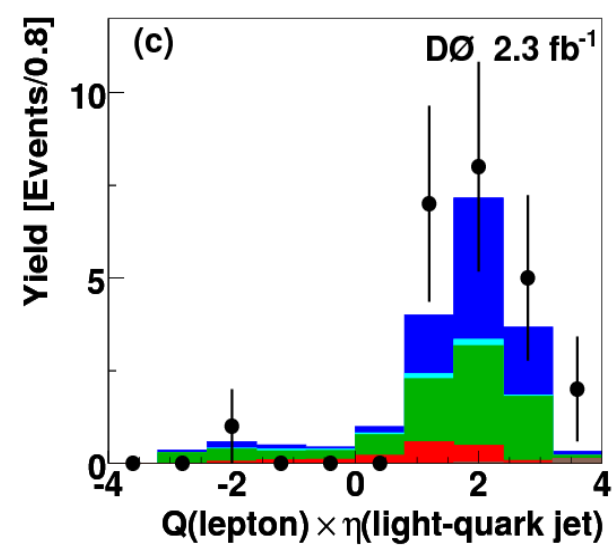
First evidence for t-channel production

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



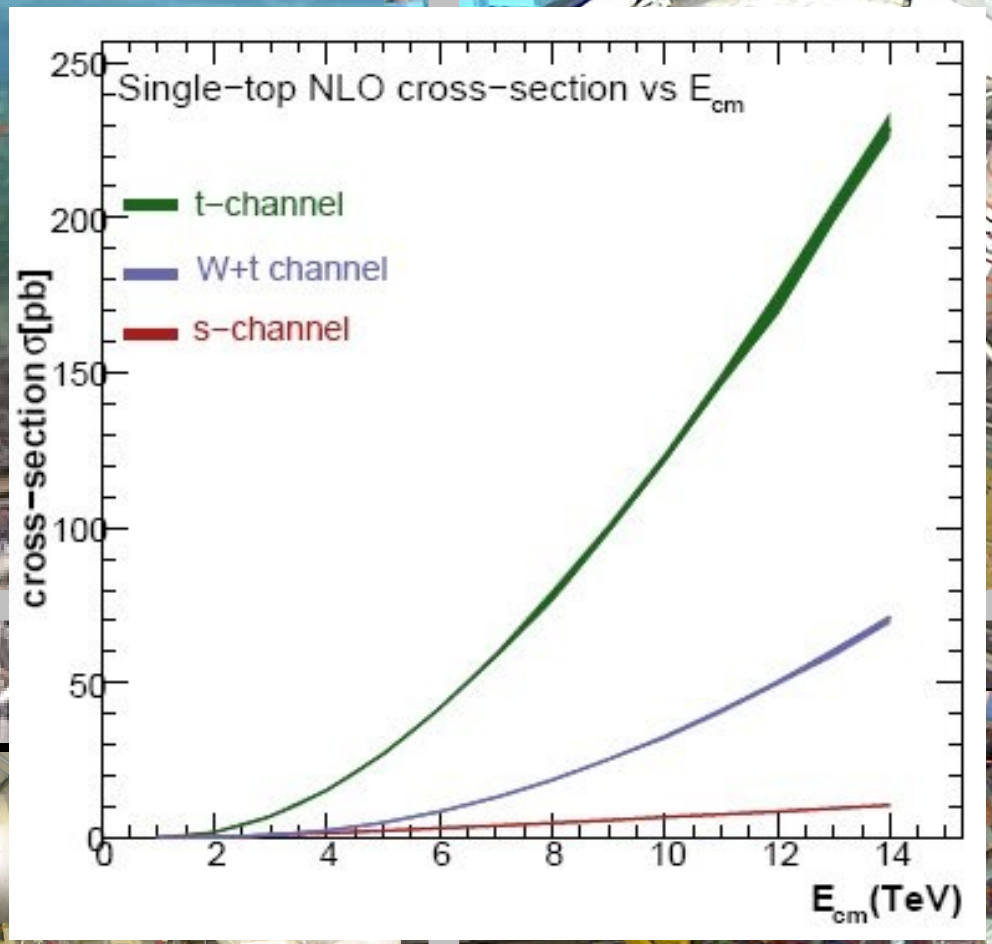






Submitted to PLB, arXiv.org:0907.4259

Single top at the LHC

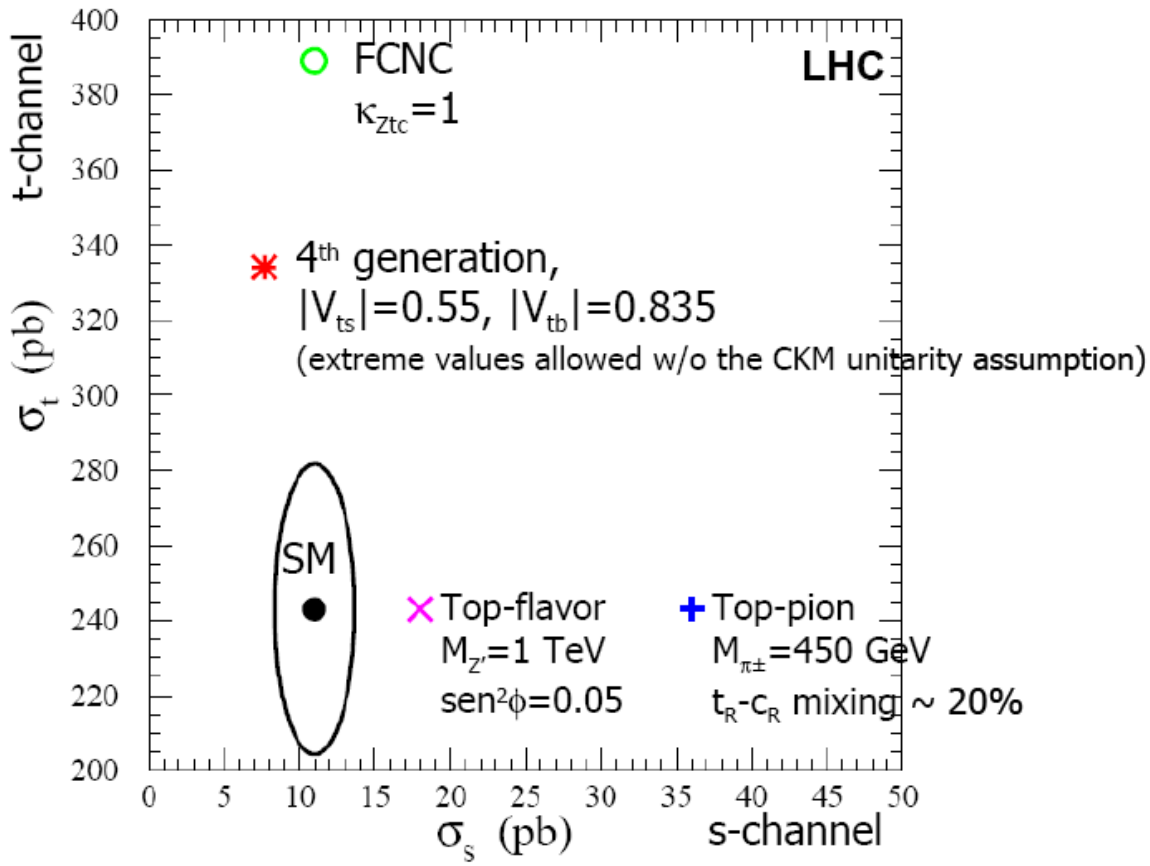


- Observe three single top production modes separately
  - t-channel: easy ☺ s-channel and assoc. prod: harder 😐
- Observe new physics *(if it can be seen)*
- Measure V_{tb} to few %

LHC: new physics in single top

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

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



Conclusions/Outlook

- Both Tevatron experiments have observed single top quark production at the 5 σ level
- Tevatron dataset continues to increase
  - Already over 5 fb^{-1} recorded
  - Separate s-channel from t-channel
  - Continue to look for new physics
- LHC:
  - Precision measurements in single top
  - Look for new physics in single top