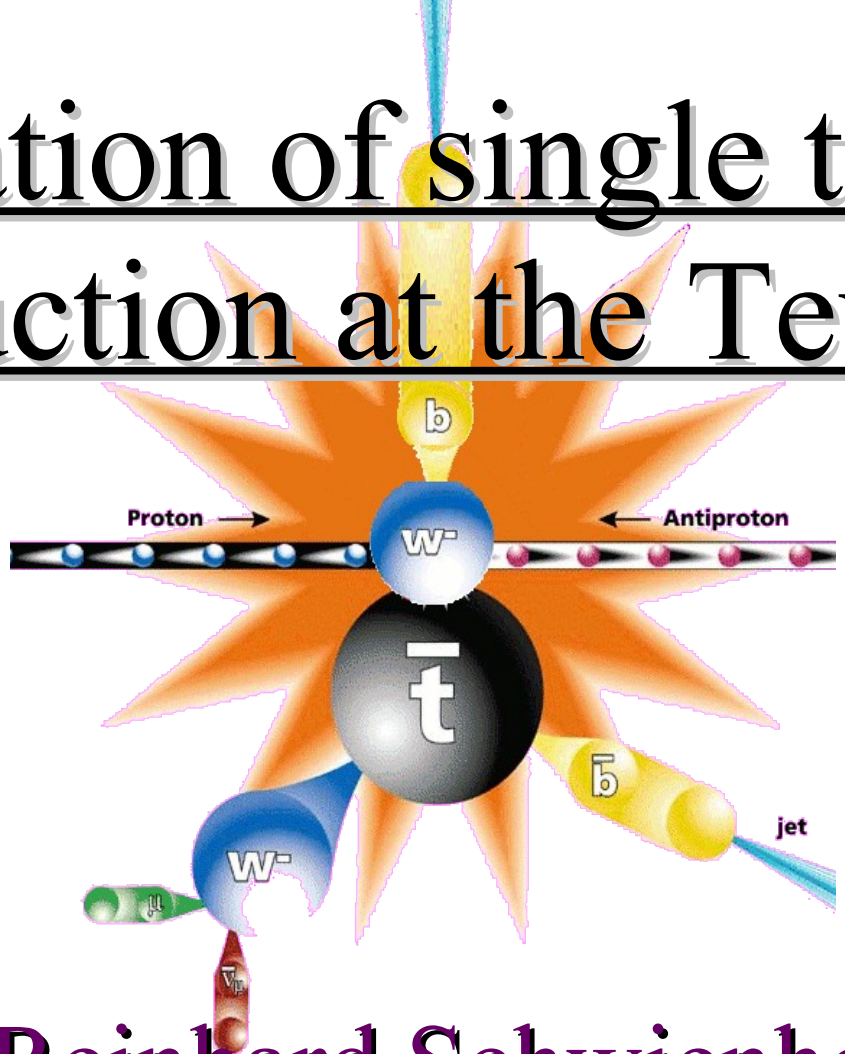
Observation of single top quark production at the Tevatron



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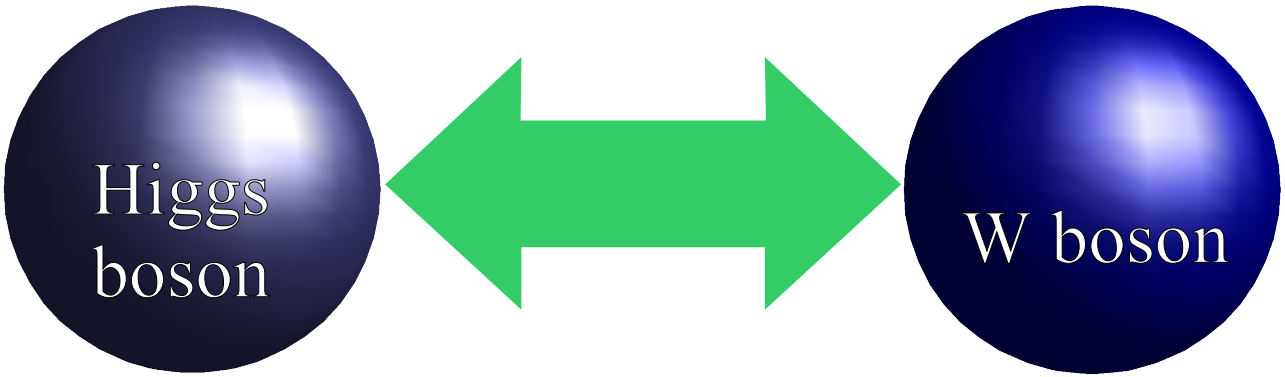
DESY Zeuthen Physik Seminar, 17 Juni, 2009

Outline

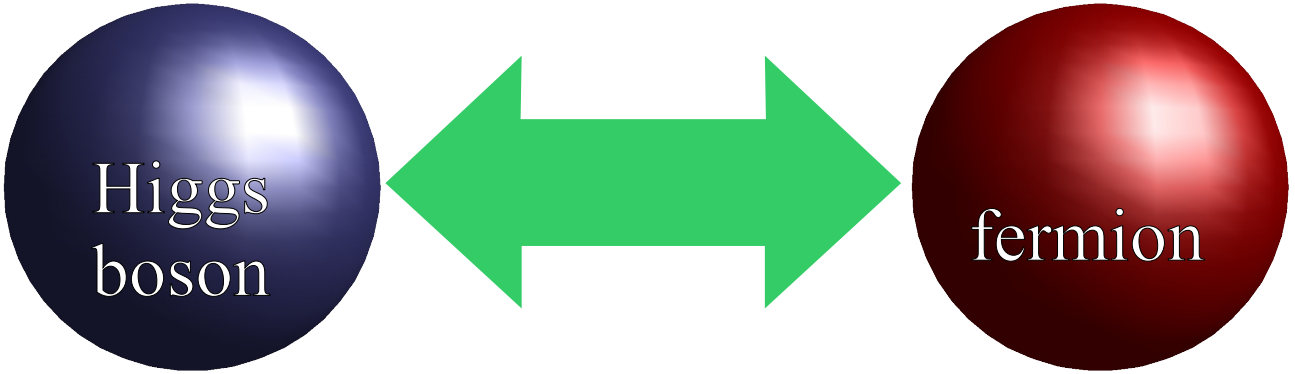
- Introduction
- Single top quark production
- Tevatron single top samples
- DØ result (m_{top}=170GeV, $xs_{(N)NLO}$=3.46pb)
- CDF result (m_{top}=175GeV, xs_{NLO}=2.88pb)
- Searches for new physics
- LHC outlook
- Conclusions

Electroweak symmetry breaking

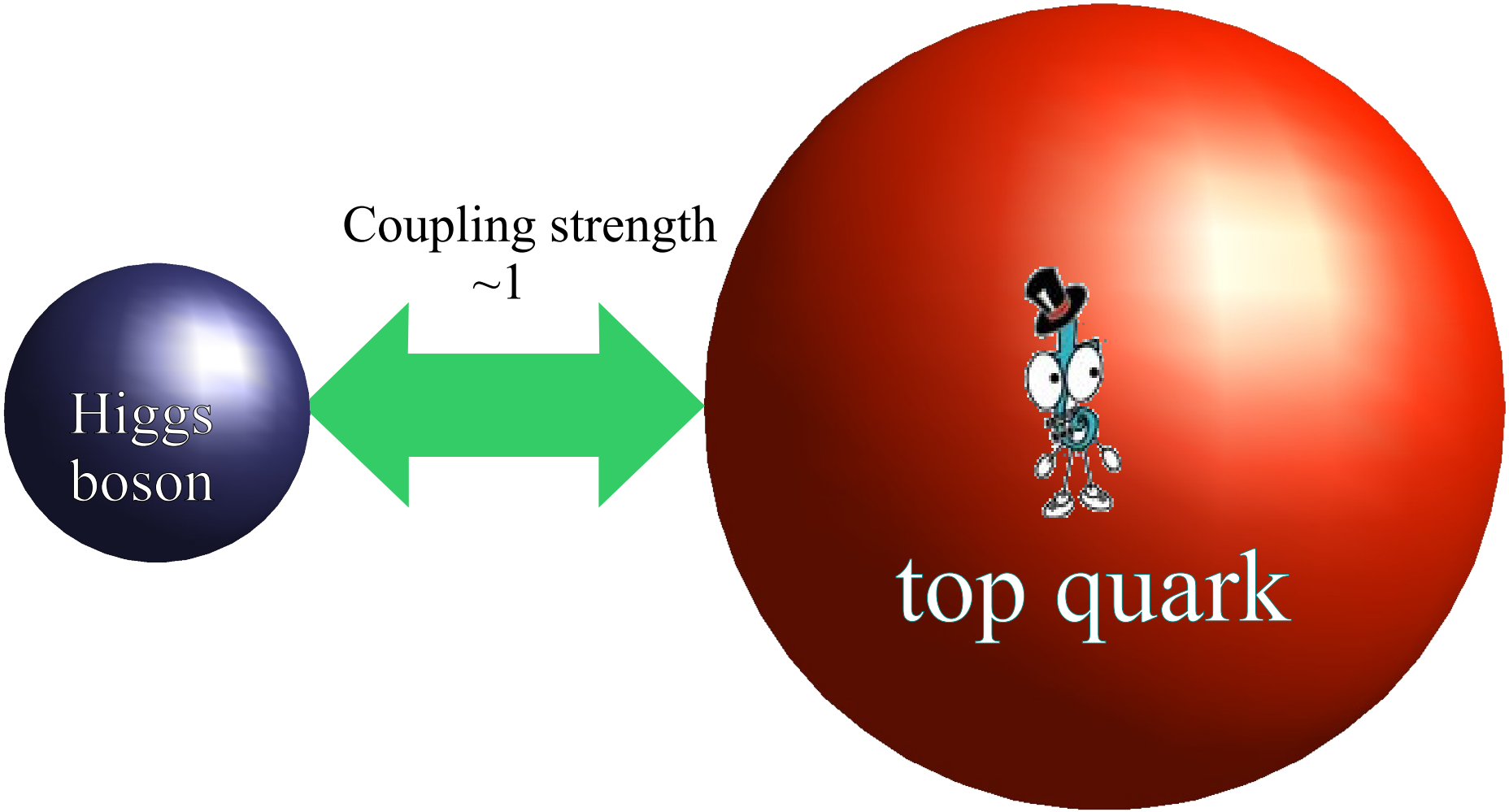
Gauge boson coupling to Higgs field



Fermions acquire mass through Higgs coupling



Top quark



Top quark

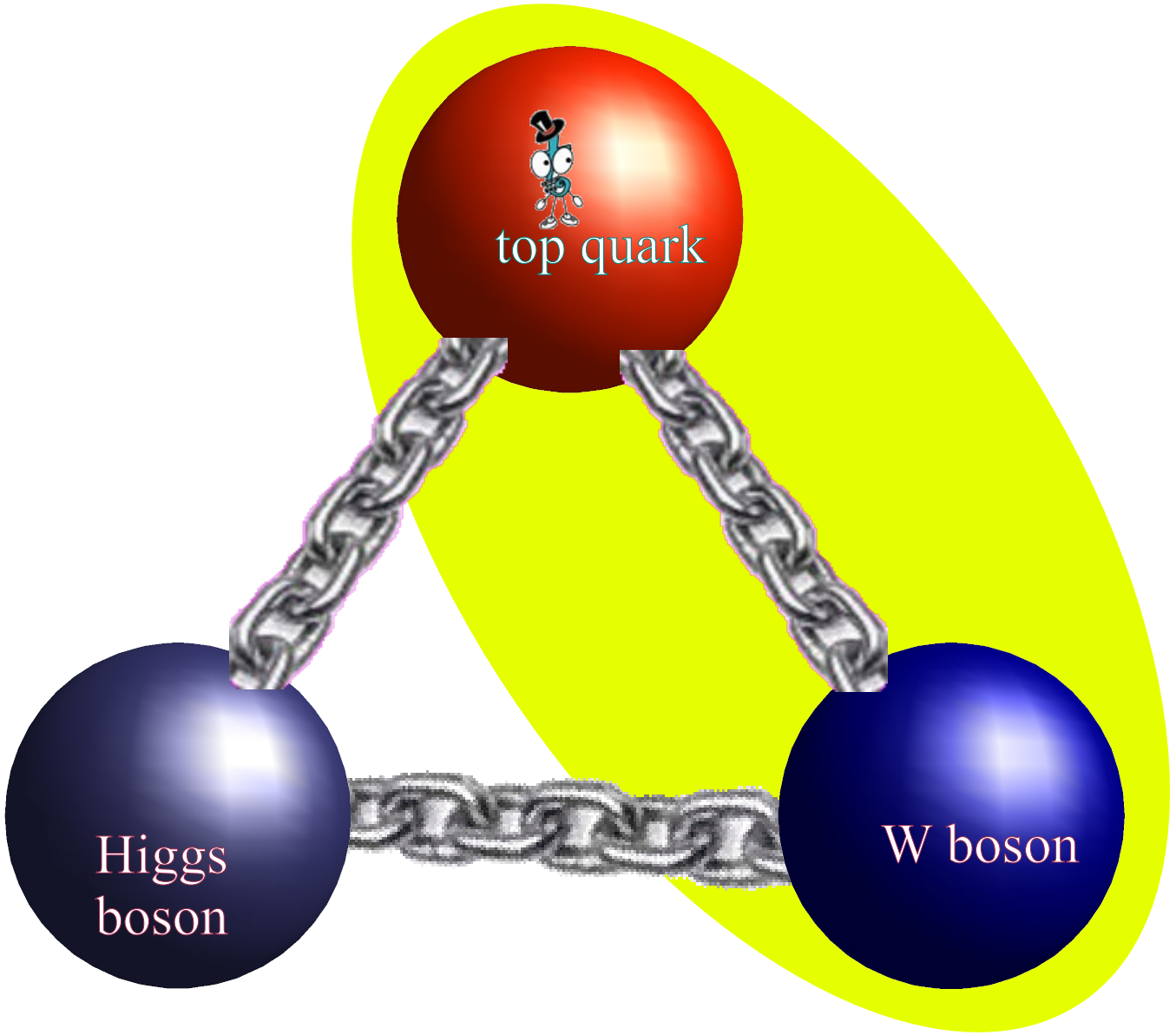
King of the Fermions

Coupling strength
~1

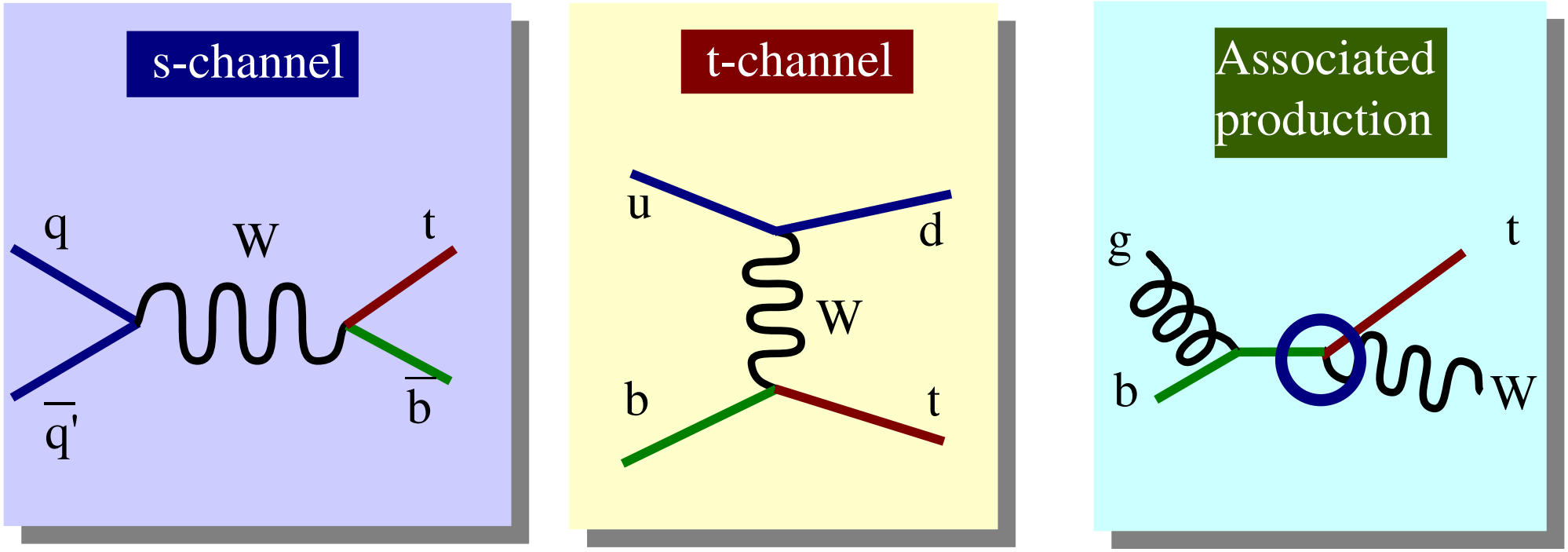
Higgs boson

top quark

Key to electroweak symmetry breaking



SM single top quark production

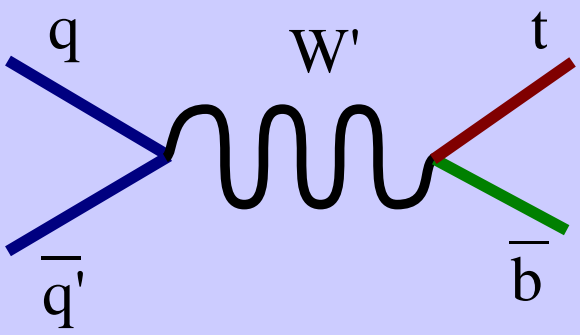


Tevatron: $\sigma_{tot} = 3$ pb

LHC: $\sigma_{tot} = 326$ pb

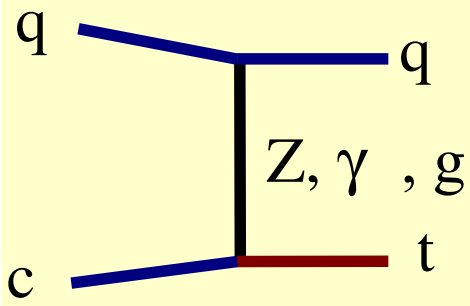
New physics

s-channel



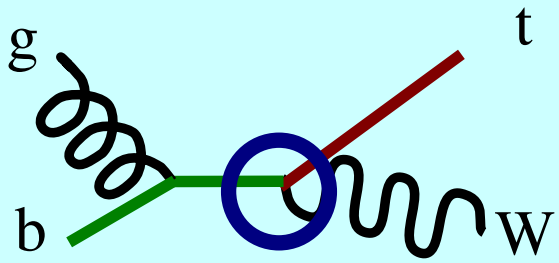
New heavy boson

t-channel



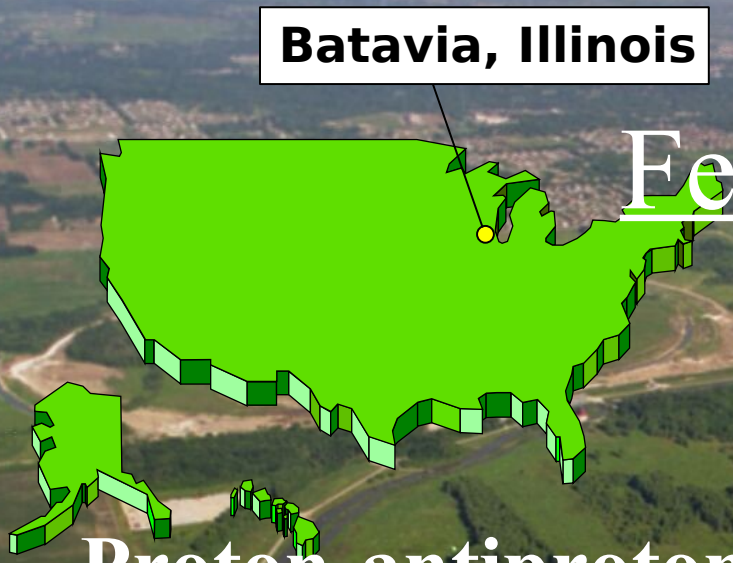
Flavor Changing Neutral Current

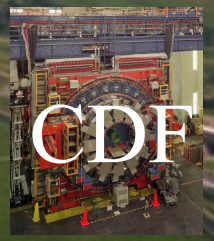
Associated production



Modified Wtb coupling

Experimental setup: Fermilab Tevatron in Run II





Proton-antiproton collider

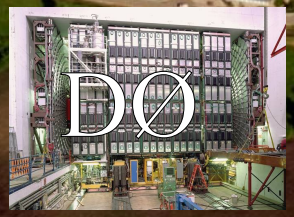
CM energy 1.96TeV

→ *Energy frontier*

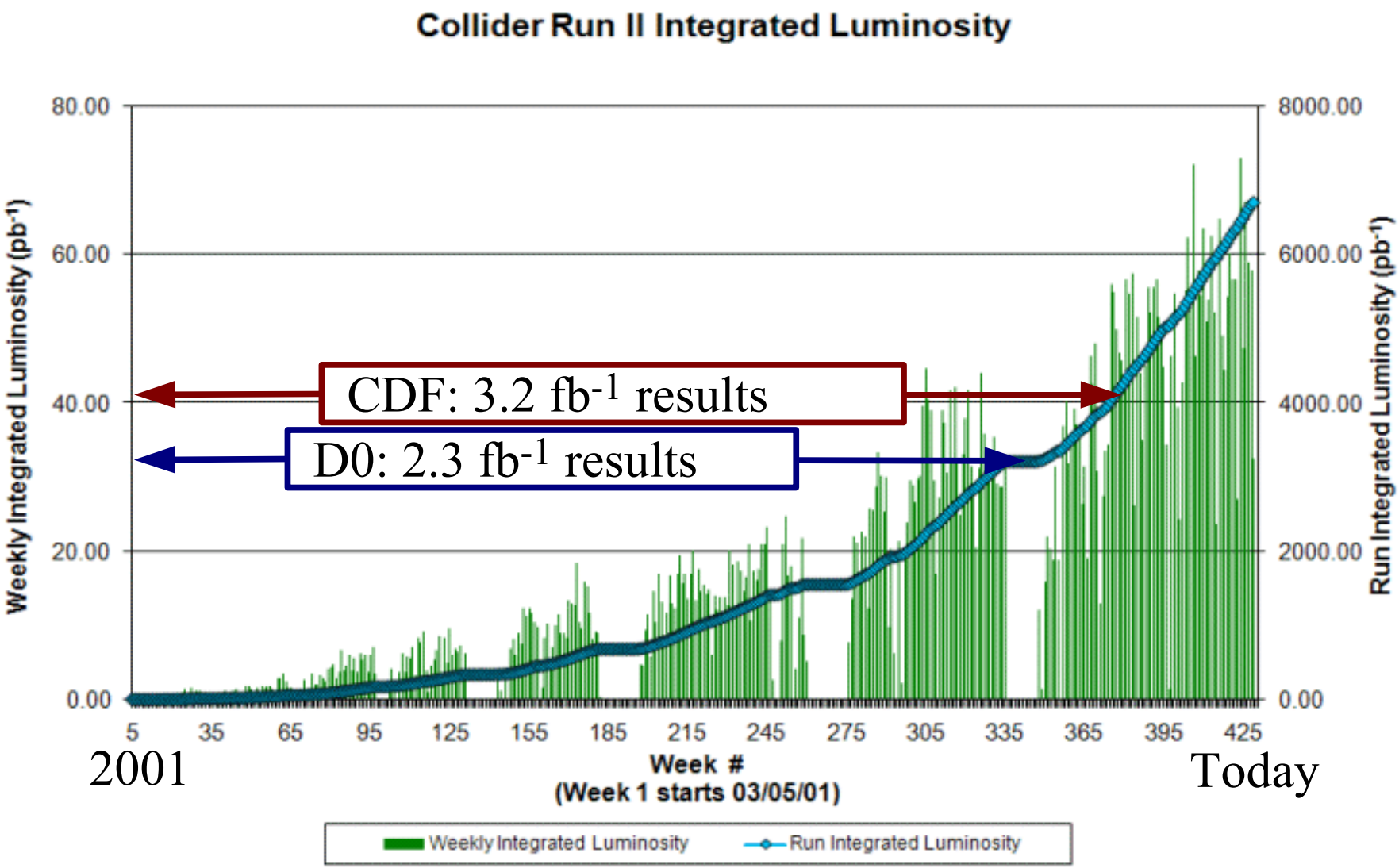
Instantaneous luminosity >250E30cm^{-2}s^{-1}

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

→ *Luminosity frontier*



Tevatron luminosity



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

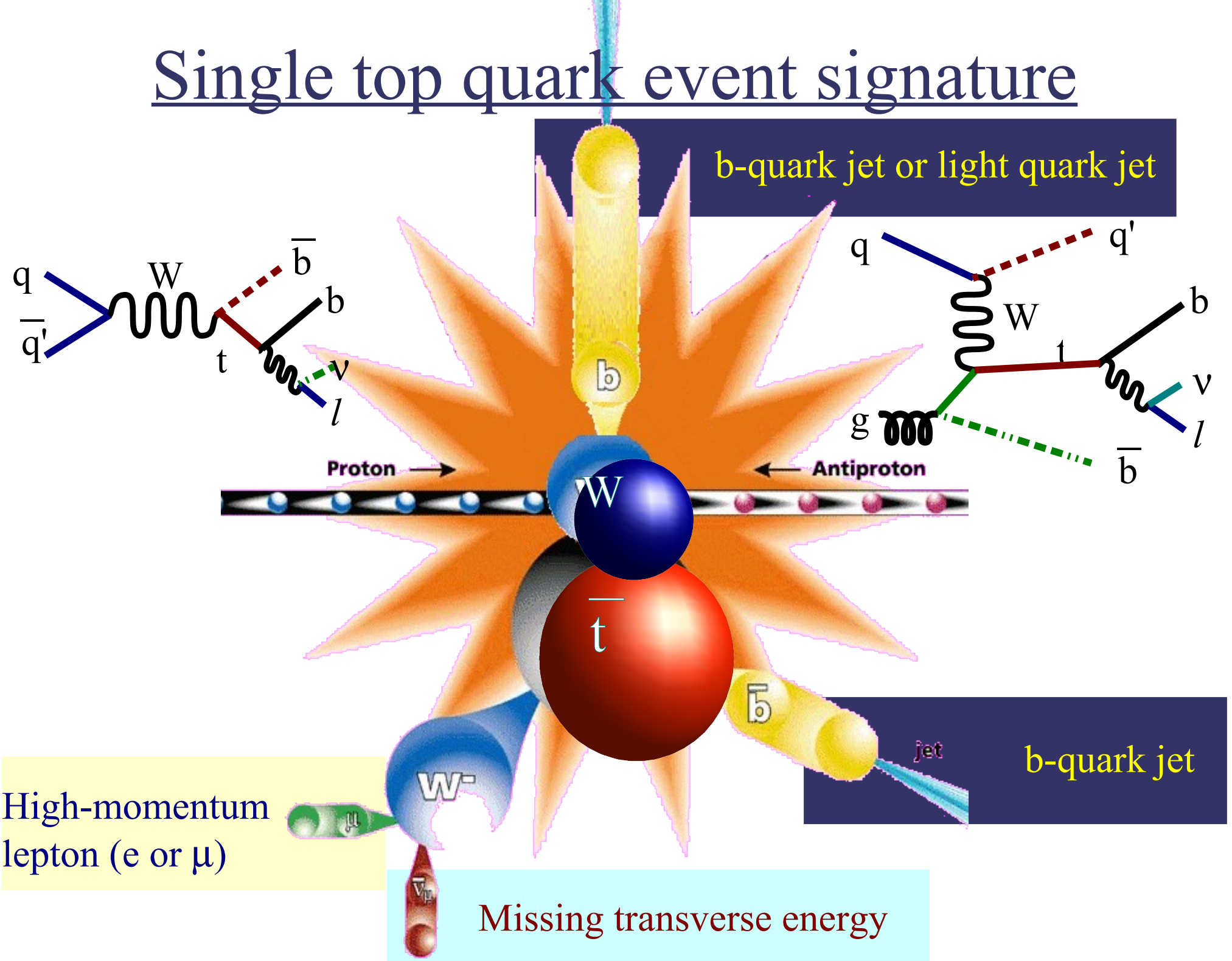
Production cross sections:

	s-channel	*t-channel*
(N)NLO calculation:	**1.12 pb (±5%)**	**2.34 pb (±6%)**
(m_{top} = 170 GeV)		

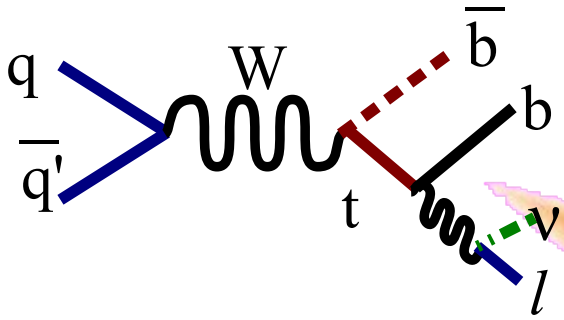
Tevatron single top goals

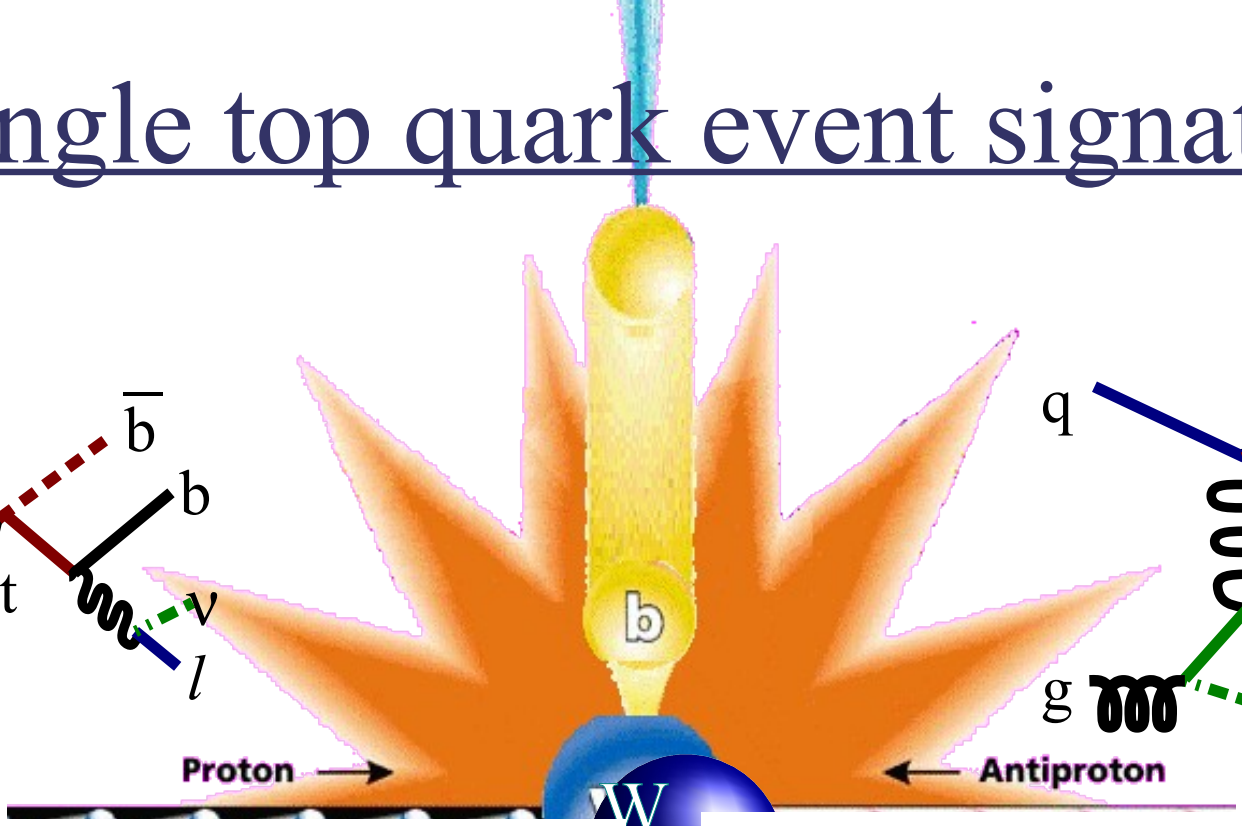
- Discover single top quark production!
- Measure production cross sections
  → CKM quark mixing matrix element V_{tb}
- Look for physics beyond the standard model
  - Coupled to the heavy top quark
- Study top quark spin correlations
- Understand as background to many other searches
- Explore analysis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

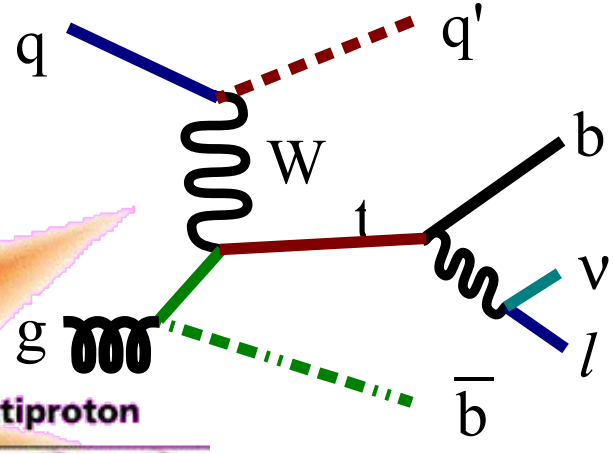
Single top quark event signature

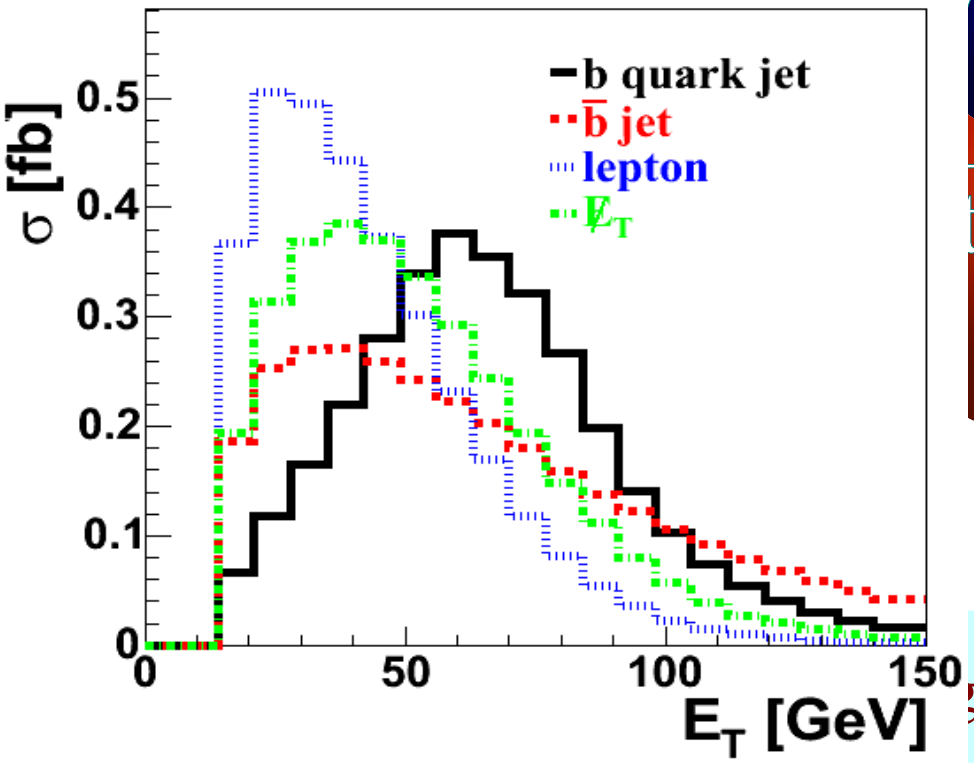


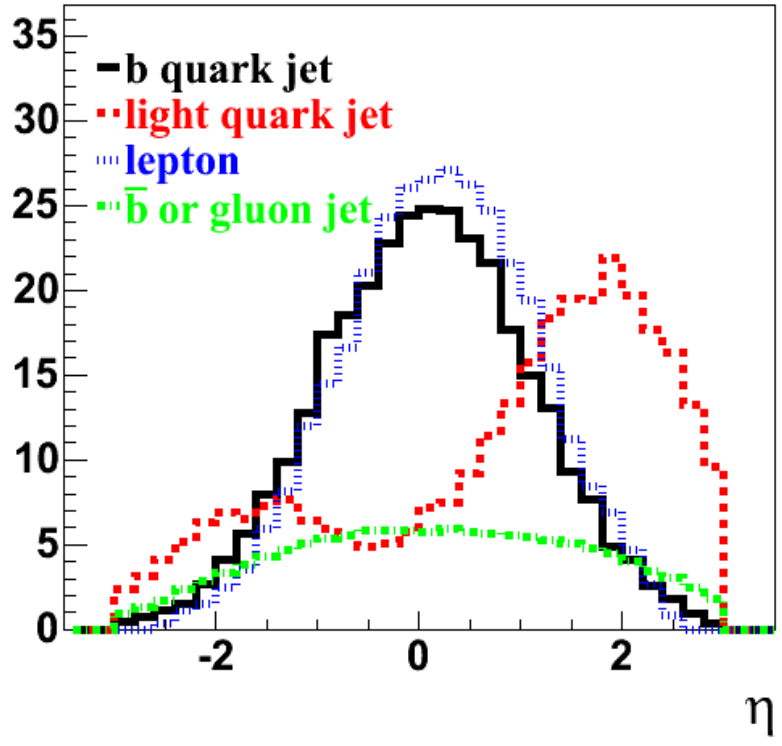
Single top quark event signature



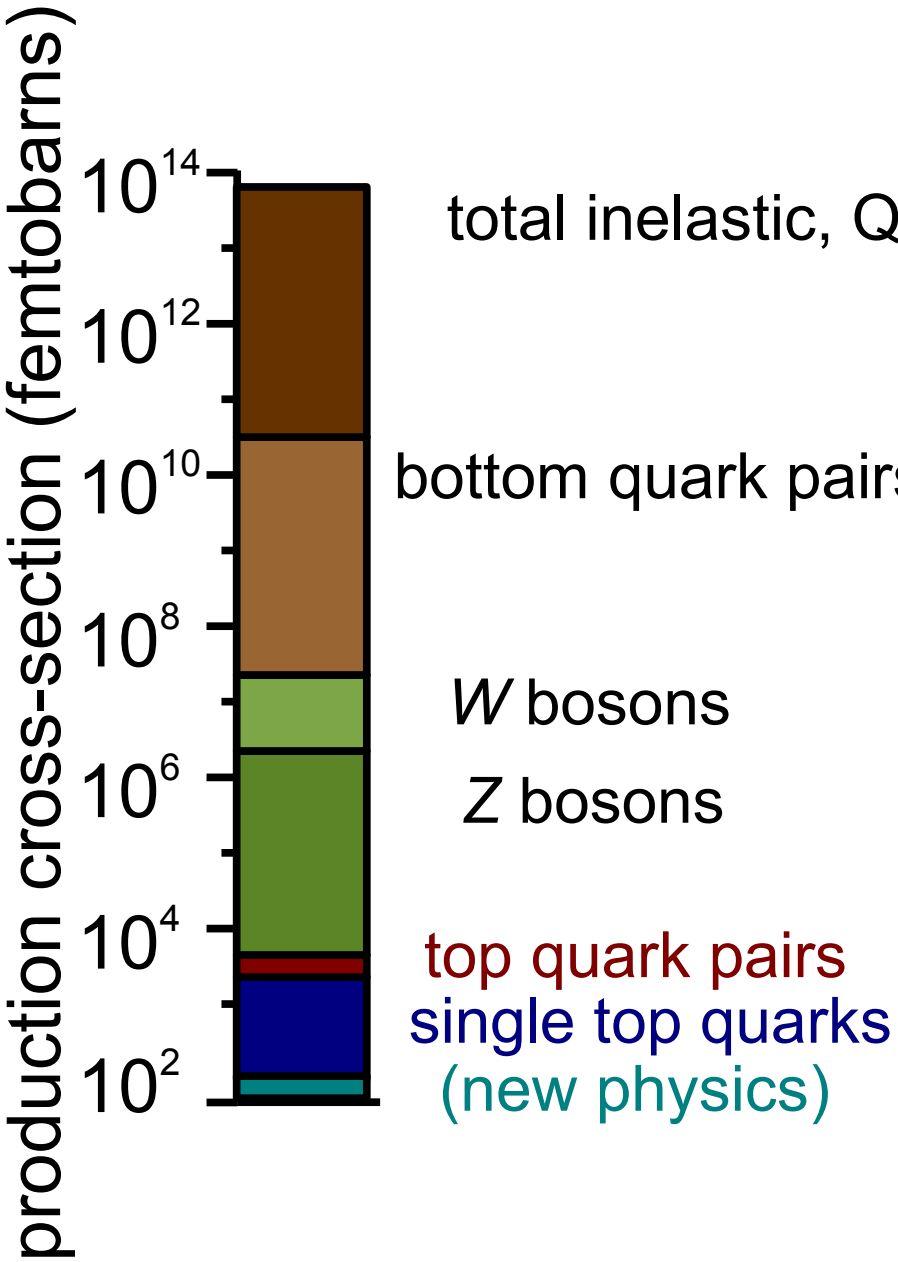








Background processes



total inelastic, QCD multijets

bottom quark pairs

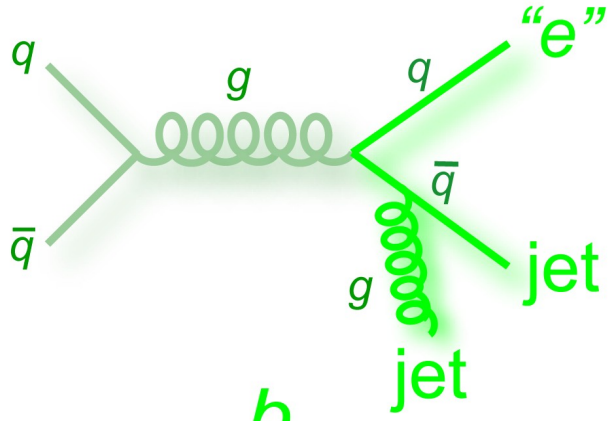
W bosons

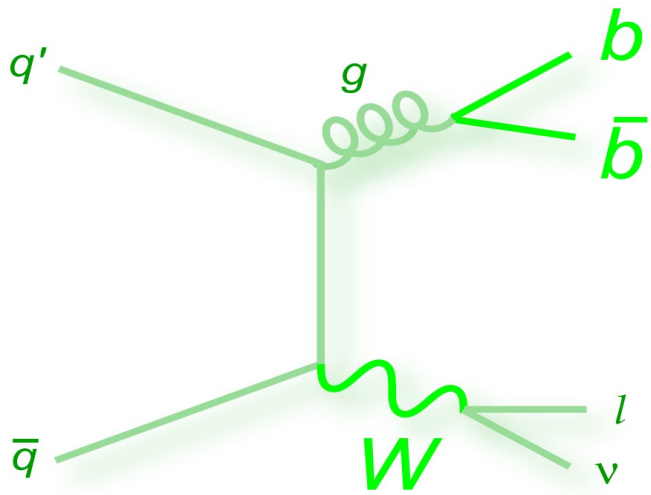
Z bosons

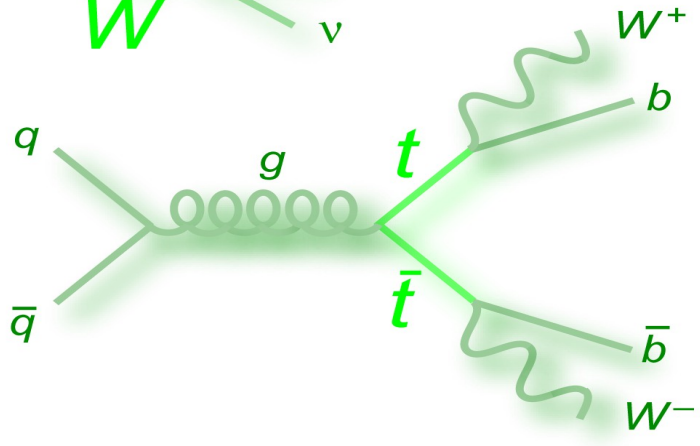
top quark pairs

single top quarks

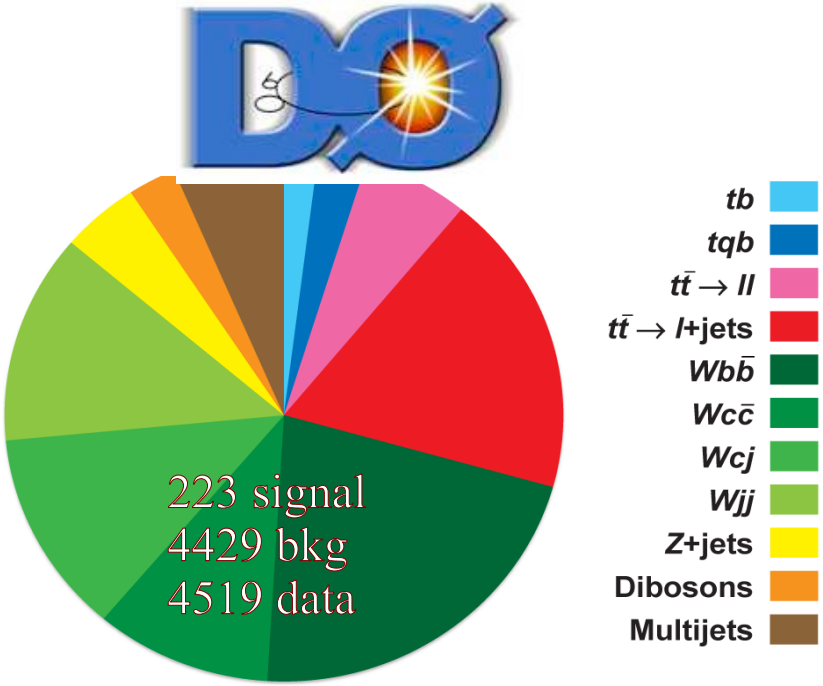
(new physics)

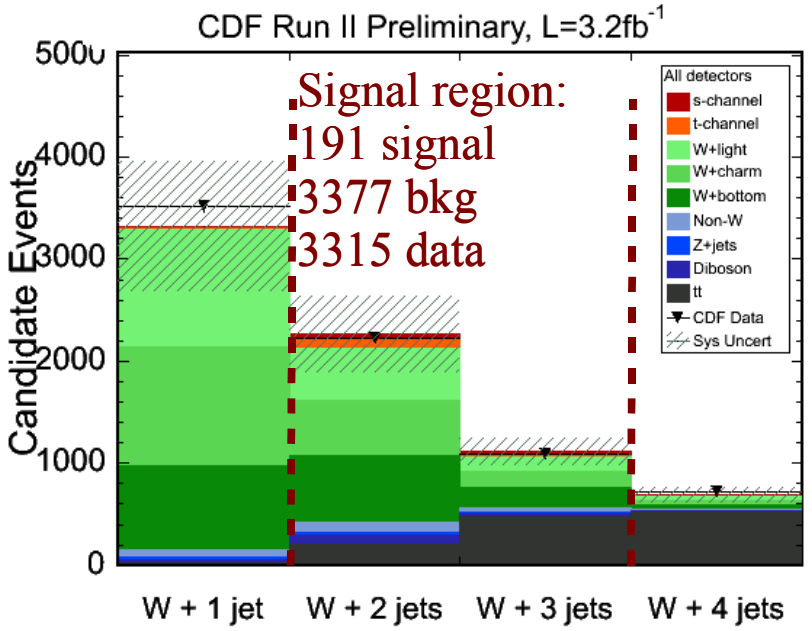




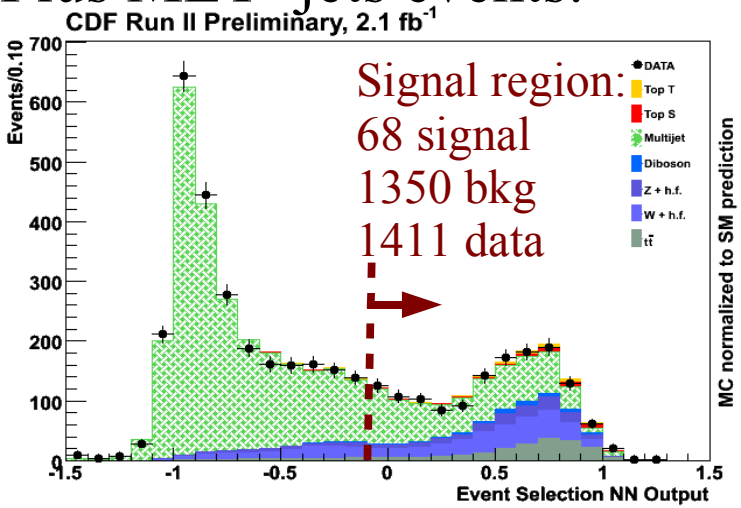


Sample Composition





Plus MET+jets events:

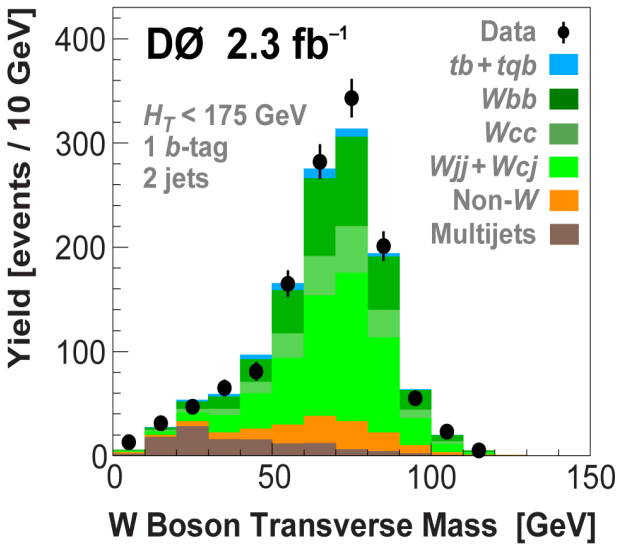


- Divided into 24 analysis channels
  - By b-tag multiplicity, lepton, jet multiplicity, data taking period

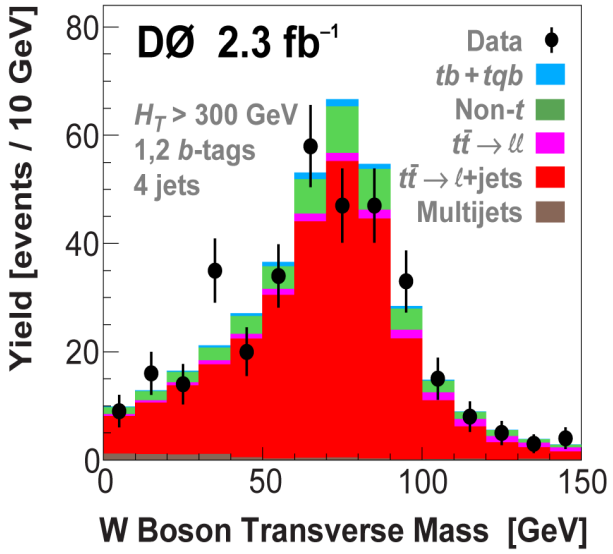
Cross-check samples

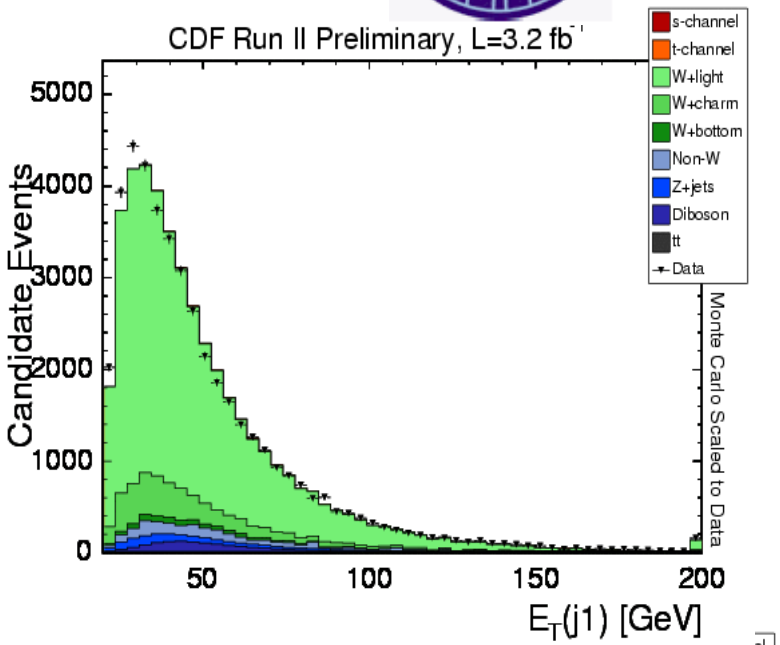
- Pretag
- Enriched in W+jets
- Enriched in top pairs

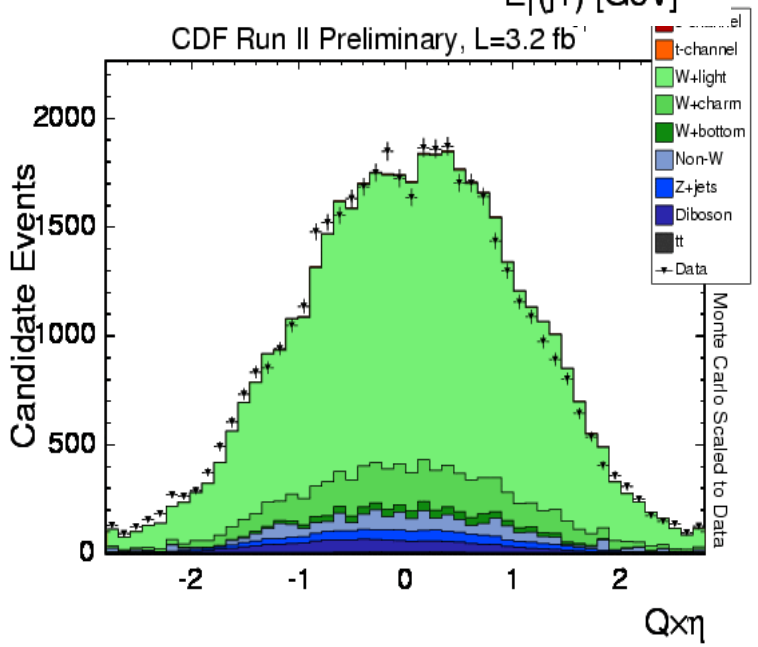
W+Jets Cross-Check Sample



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

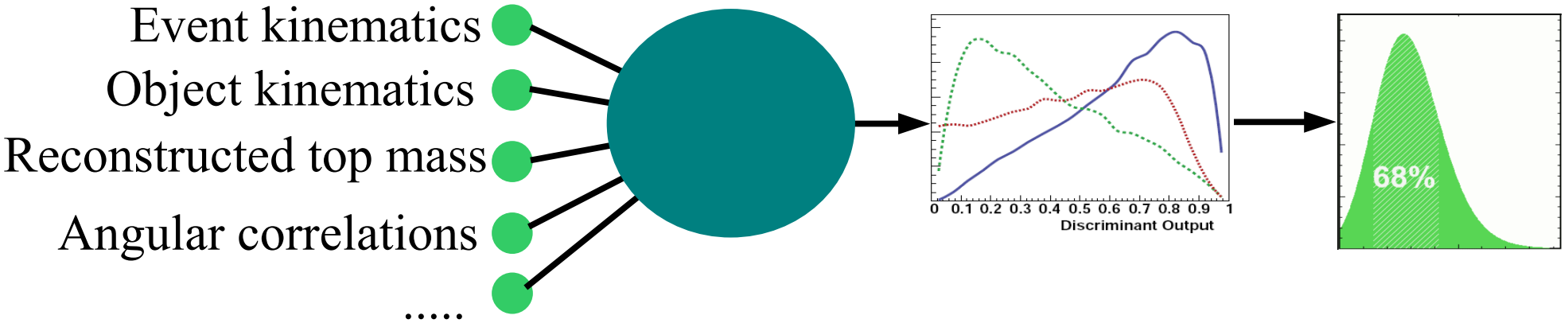






Single top analysis

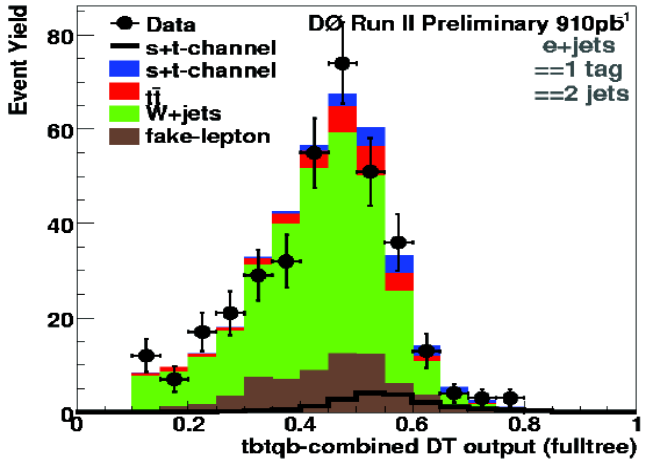
discriminating variables | multivariate classifier | signal likelihood | statistical analysis



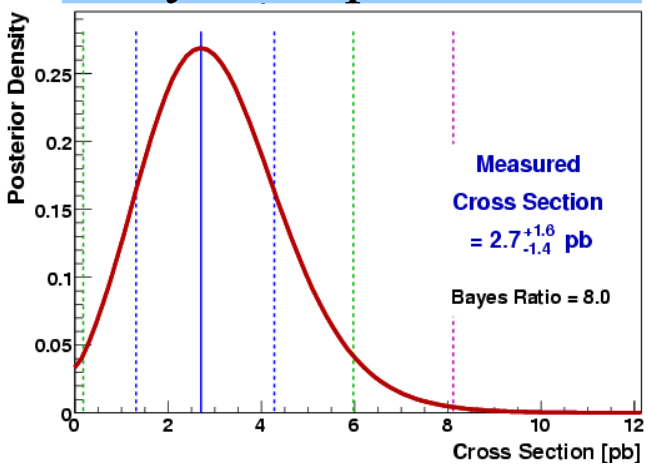
- Classifiers:
  - Likelihood function
  - Neural network
  - Bayesian neural networks
  - Matrix Element
  - Boosted decision trees

Measurement Procedure

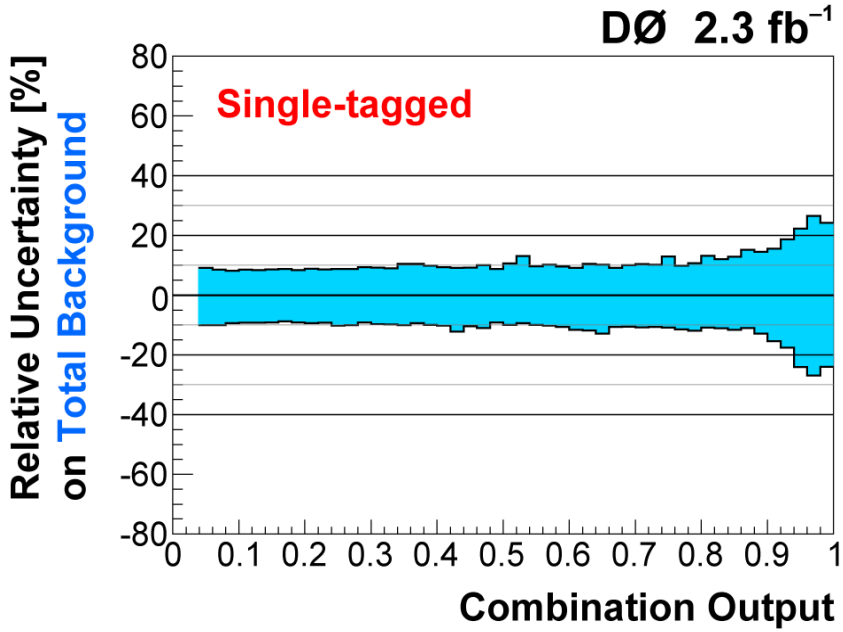
Multivariate Output



Bayesian posterior



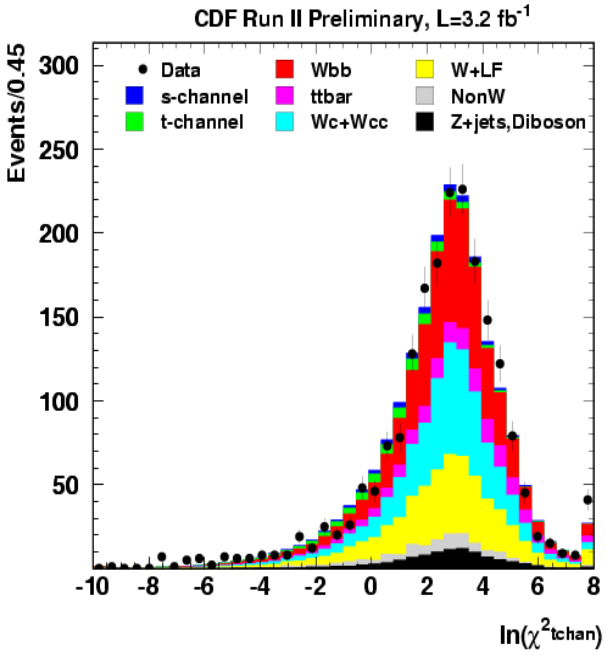
– Including many systematic uncertainties

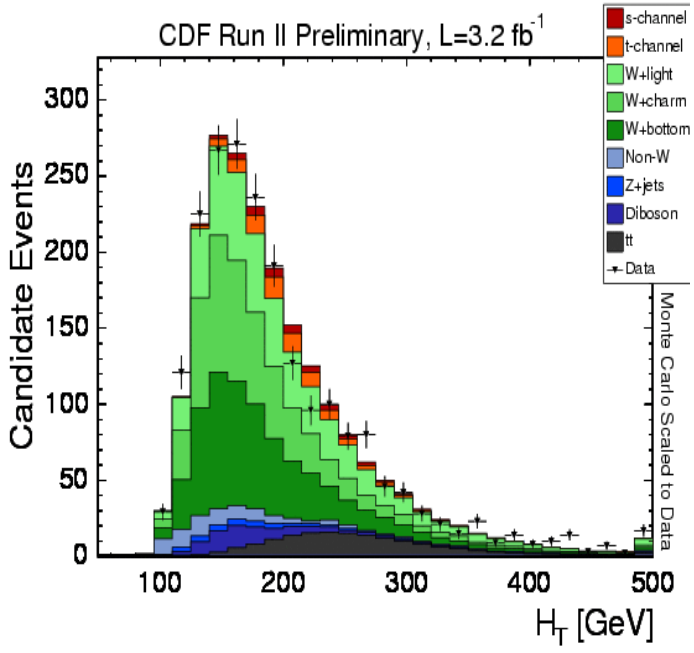


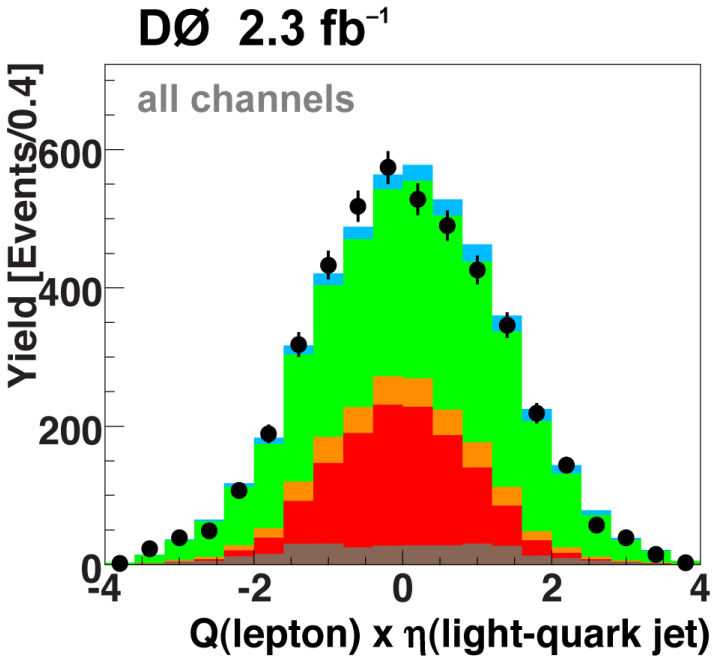
Systematic uncertainty	Rate	Shape
Jet energy scale	0…16%	X
Initial state radiation	0…11%	X
Final state radiation	0…15%	X
Parton distribution functions	2…3%	X
Monte Carlo generator	1…5%	
Event detection efficiency	0…9%	
Luminosity	6.0%	
Neural-net *b* tagger	N/A	X
Mistag model	N/A	X
Non-*W* model	N/A	X
Q^2 scale in Alpgen MC	N/A	X
Monte Carlo mismodeling	N/A	X
W+bottom normalization	30%	
W+charm normalization	30%	
Mistag normalization	17…29%	
tt-bar normalization	23%	

Discriminant Variables

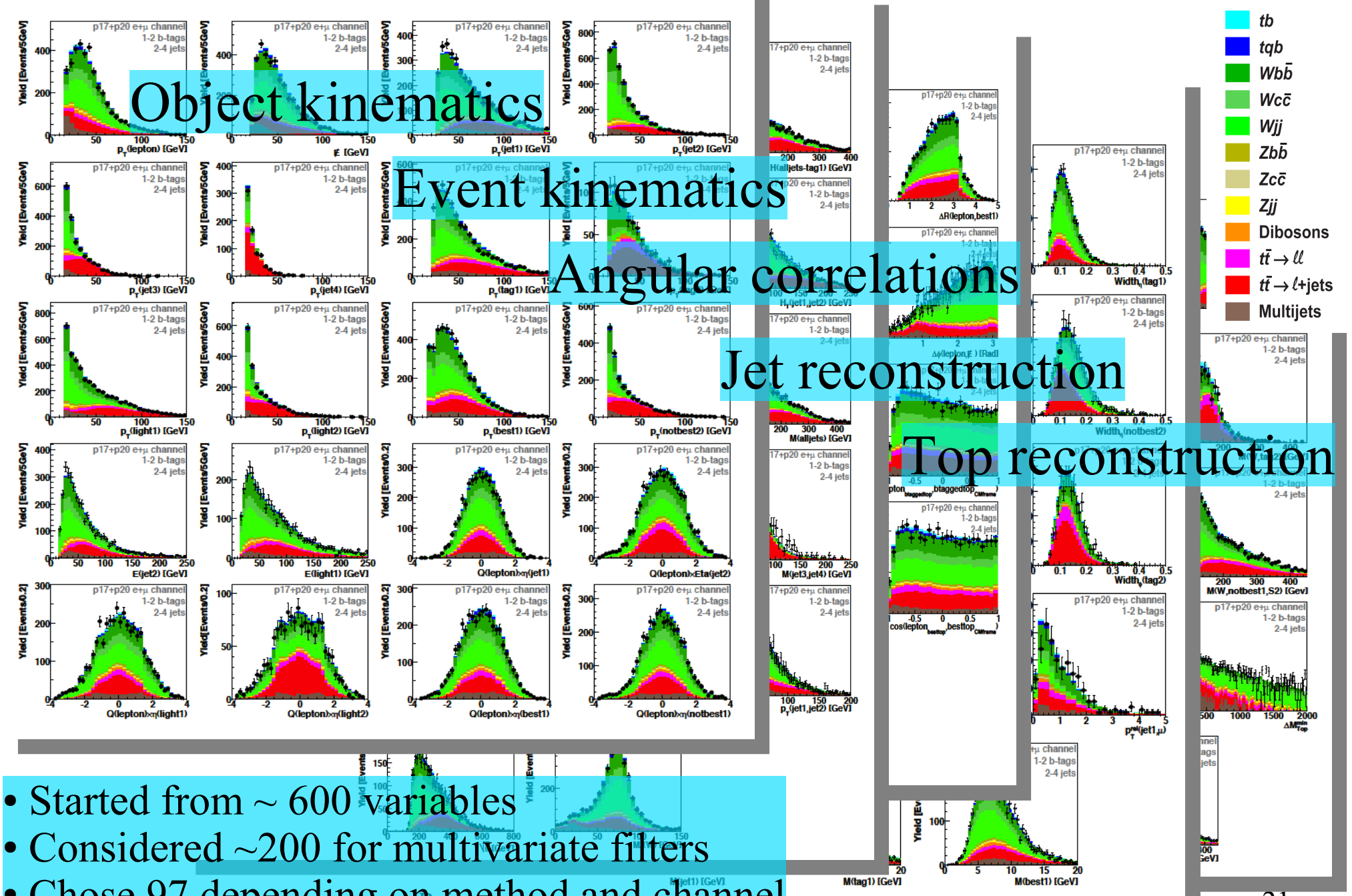
- Object and event kinematics, top reconstruction
  - D0 also jet reconstruction
    64, 24 variables used by BDT, BNN
  - CDF also b-tag probability
    22, 14, 13 variables used by BDT, NN, Lhood





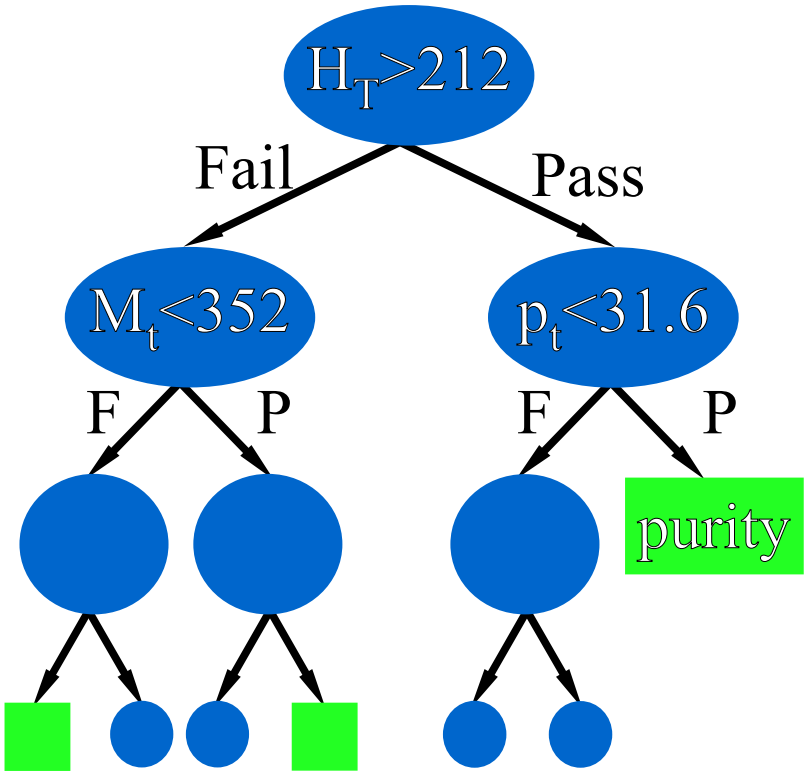


Discriminating variables

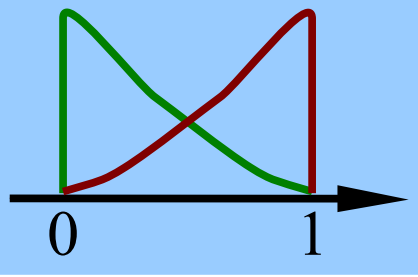


- Started from ~ 600 variables
- Considered ~200 for multivariate filters
- Chose 97 depending on method and channel

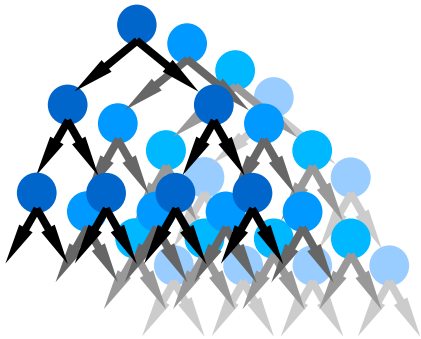
Boosted decision trees



- Send each event down the tree
- Each node ⬭ corresponds to a cut
  - Divide sample in two: Pass↔Fail
- A leaf ■ corresponds to a node without branches
  - Defines purity = $N_S/(N_S+N_B)$ from MC sample
- Training: optimize signal/background separation
- Output: purity for each event



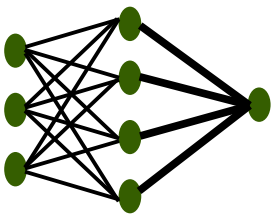
- Boosting: average over many trees (~100)
  - Iterative tree building: train each new tree focusing more and more on misclassified events



Neural networks

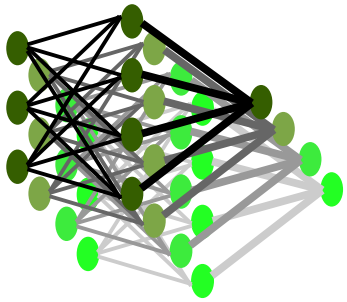
Bayesian neural networks

Single network

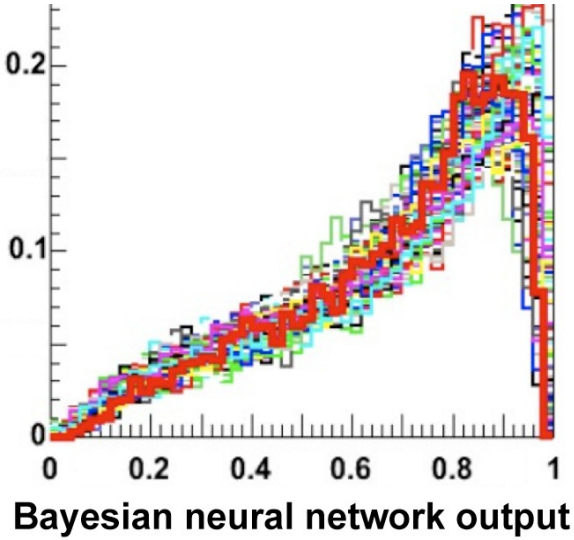


integrate over network weights

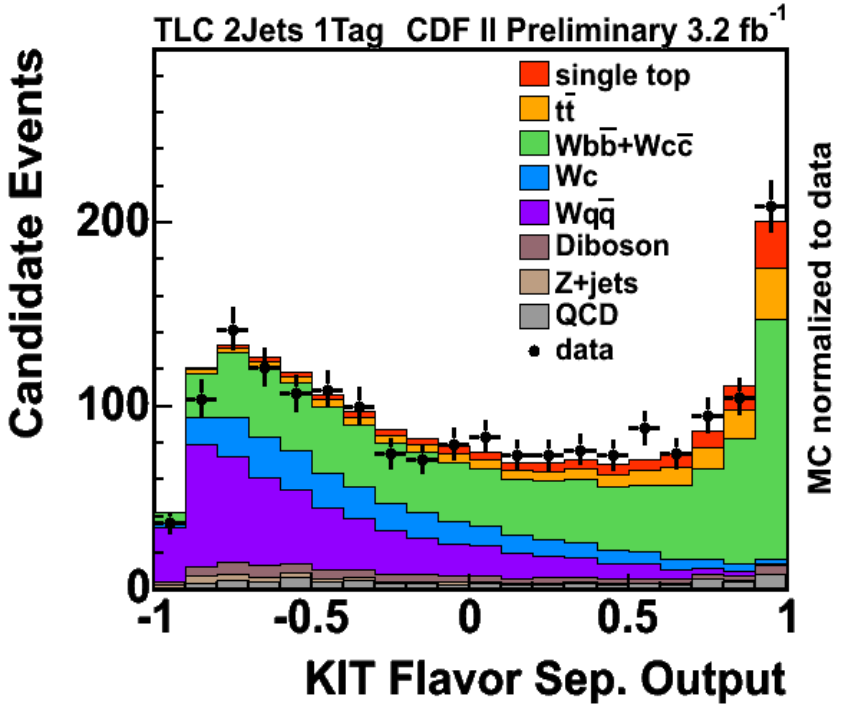
Bayesian NN



- Bayesian Idea:
  - Determine the posterior probability for each weight at each node
  - Sample from this posterior
  - Here: Average over 100 networks



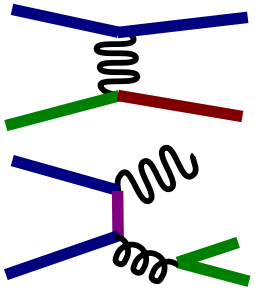
- Neural network jet flavor separator



- Analysis with 4 networks, divided into 2 channels according to trigger
- 14 variables

Matrix element analysis

Parton level matrix elements



integrate over measurement uncertainties

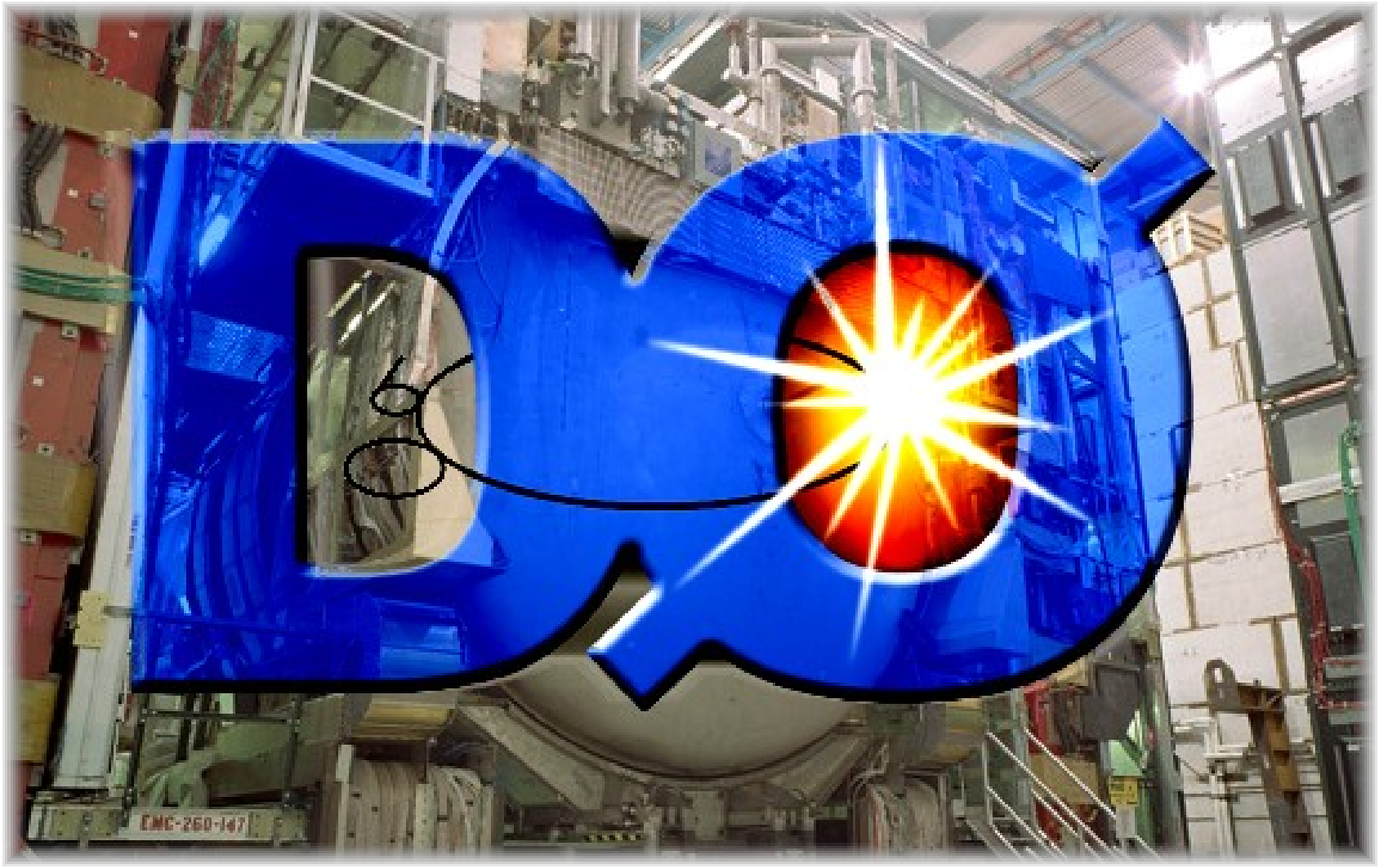
Signal discriminant

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

- Integration over final state momenta
  - And over reconstructed momenta, transfer function
- Include ME for s-channel, t-channel, W+jets (incl. gluons), top pairs, diboson

– Determine weights in two different HT regions
  - W+jets vs ttbar dominated

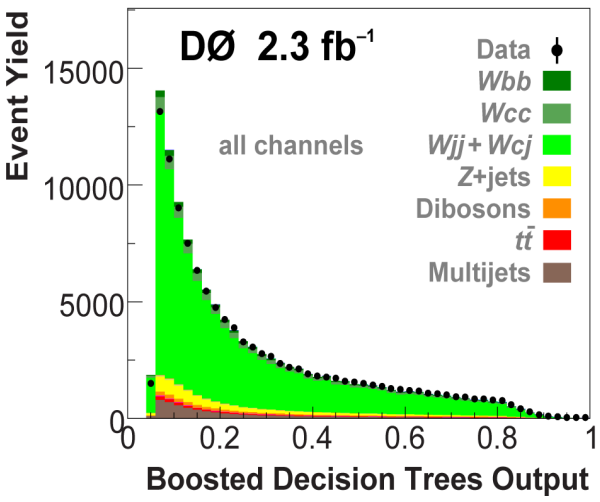
– Analyze 2-jet and 3-jet events
  - Include b-tag NN as weight in likelihood ratio



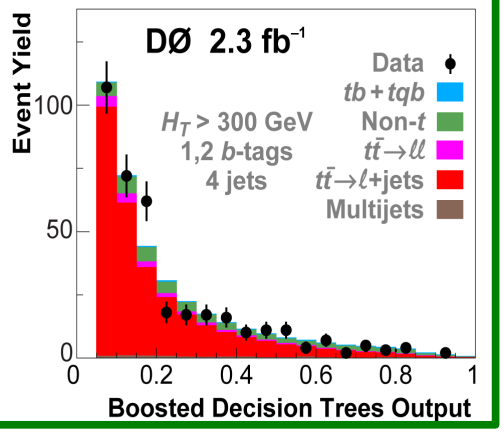
- 2.3 fb^{-1} analysis (arXiv:0903.0850)
  - Increased signal acceptance
  - Improved multivariate filter performance

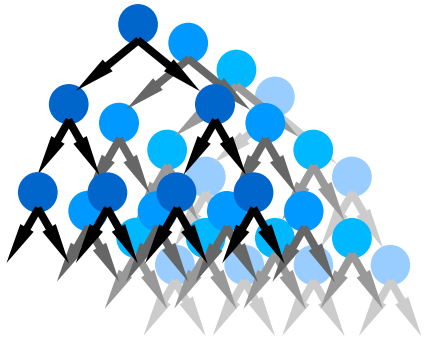
Boosted decision tree distributions

Pretagged Cross-Check Sample

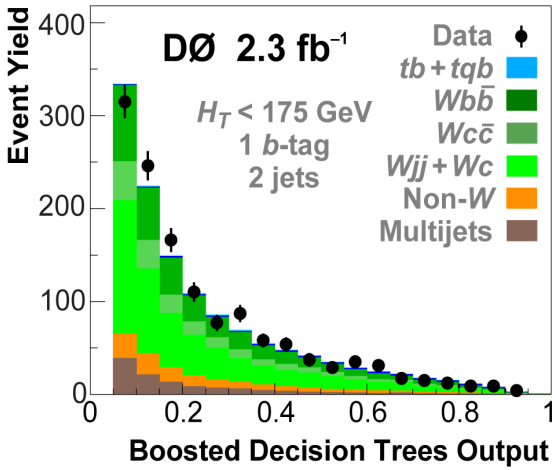


$t\bar{t}$-Pairs Cross-Check Sample



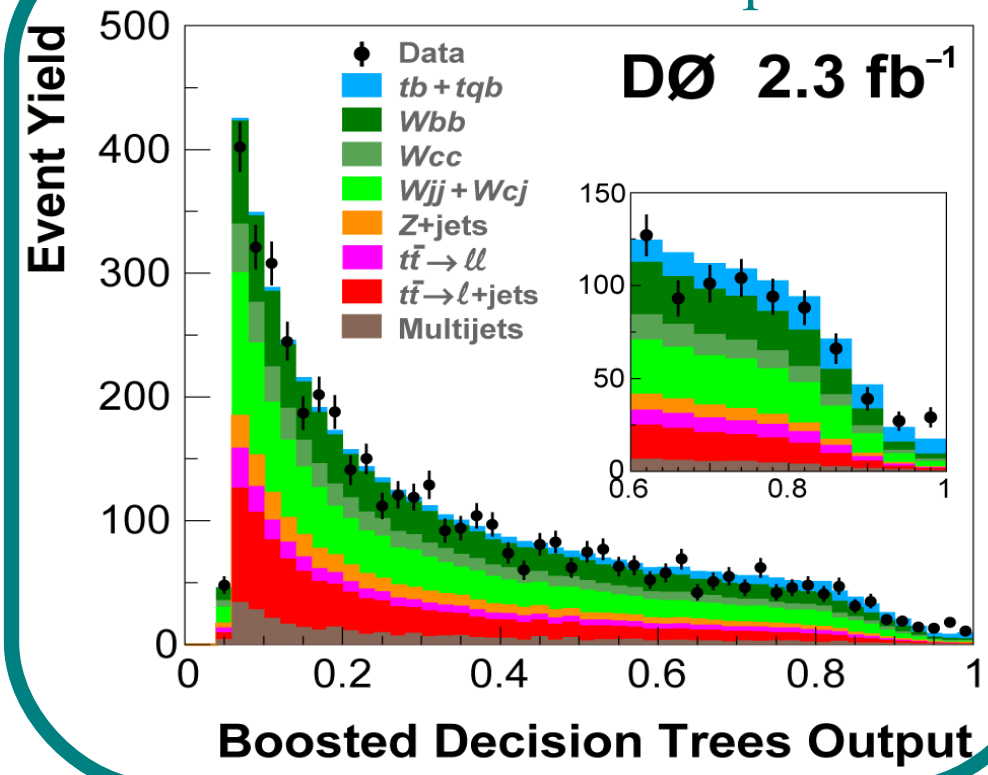


W+Jets Cross-Check Sample



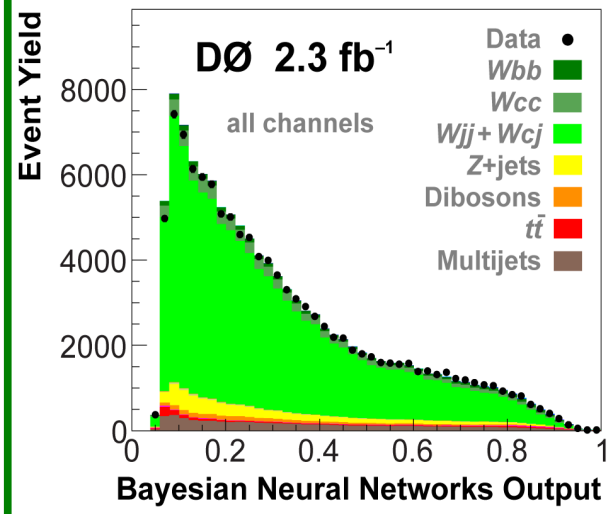
Cross checks

Full data sample

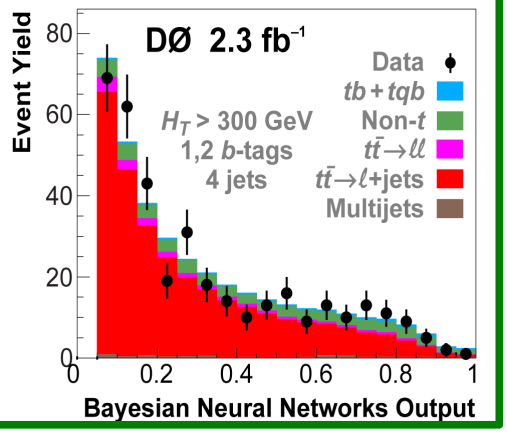


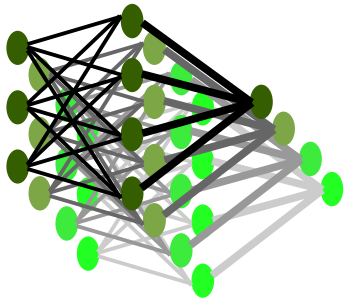
Bayesian neural network distributions

Pretagged Cross-Check Sample

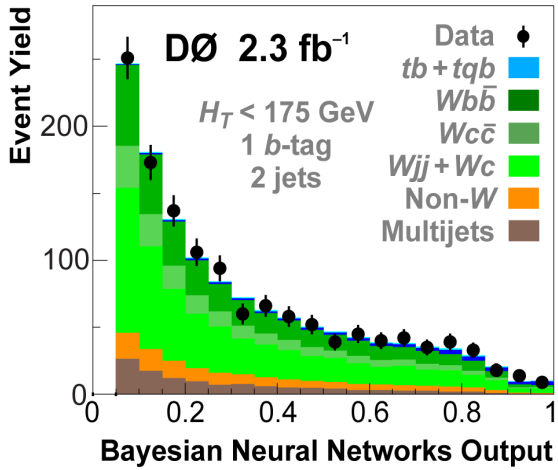


$t\bar{t}$-Pairs Cross-Check Sample



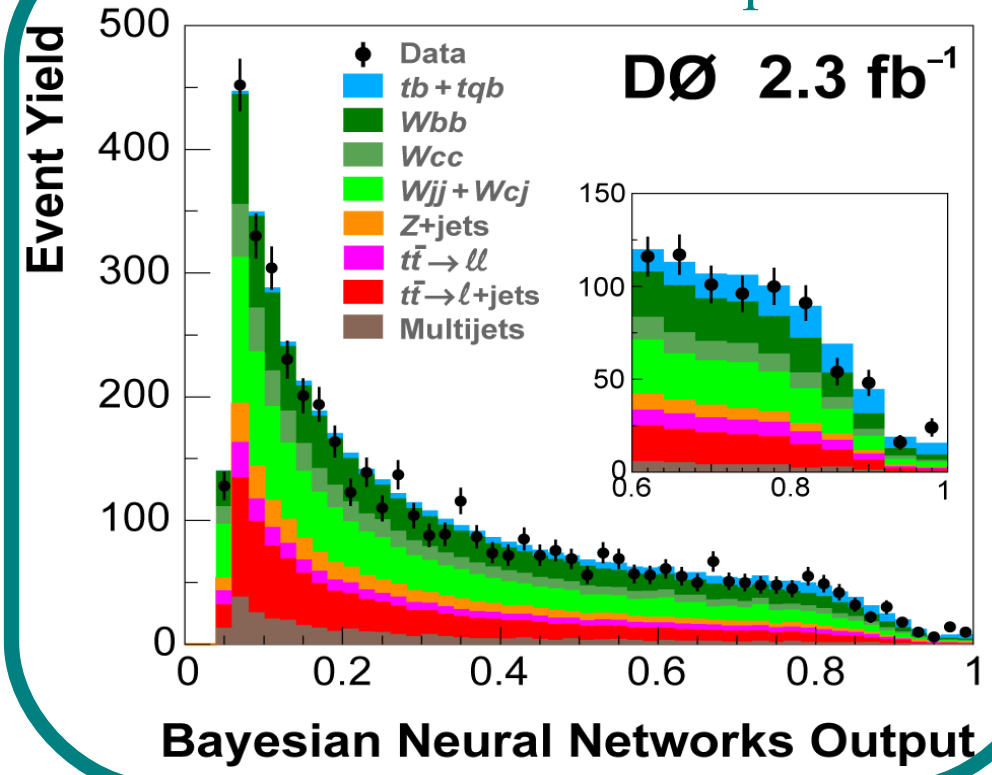


W+Jets Cross-Check Sample



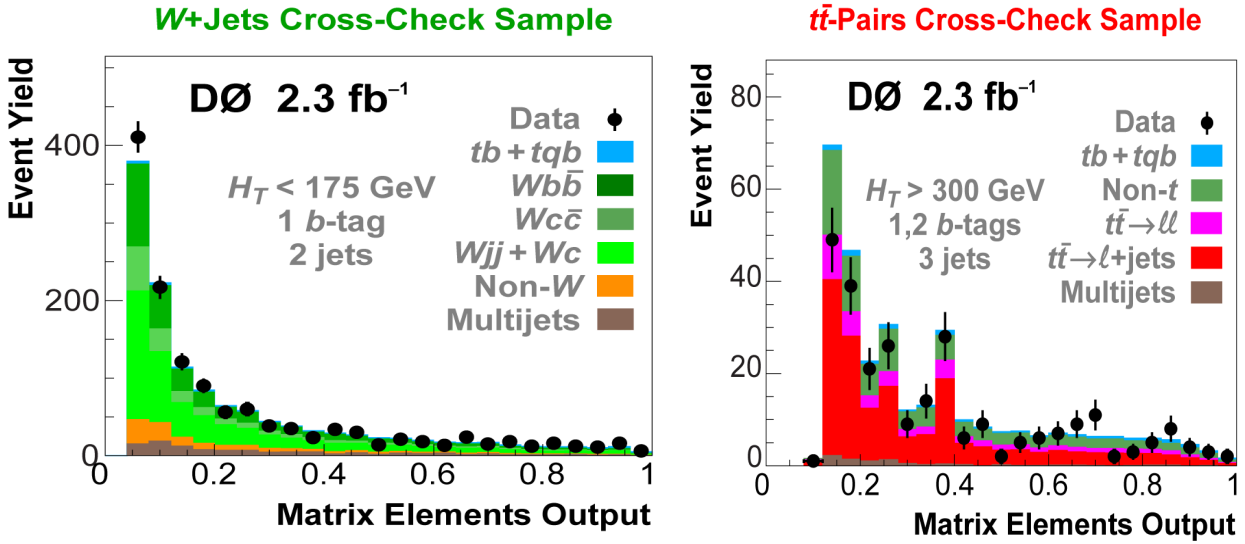
Cross checks

Full data sample

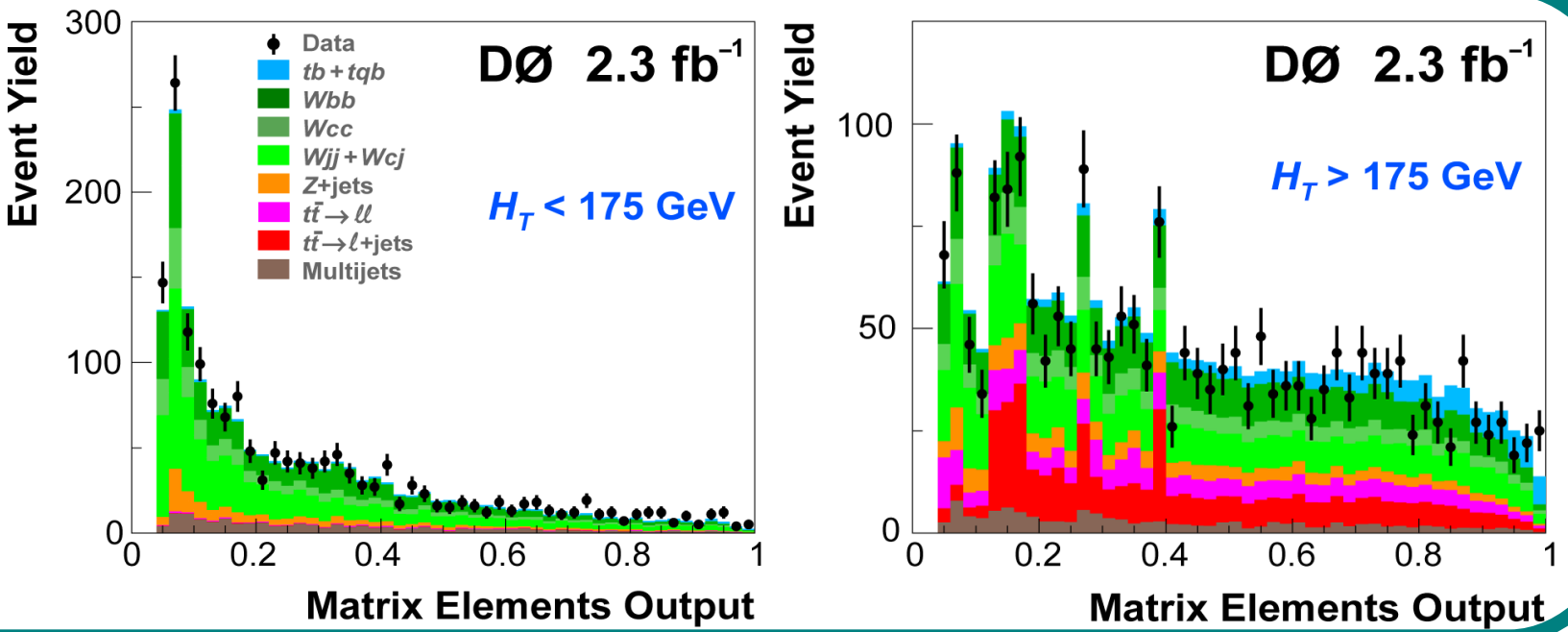


Matrix element distributions

Cross checks

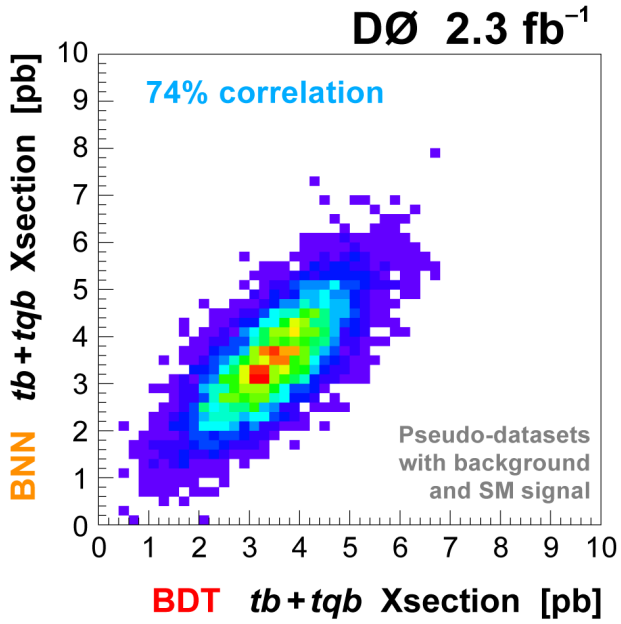


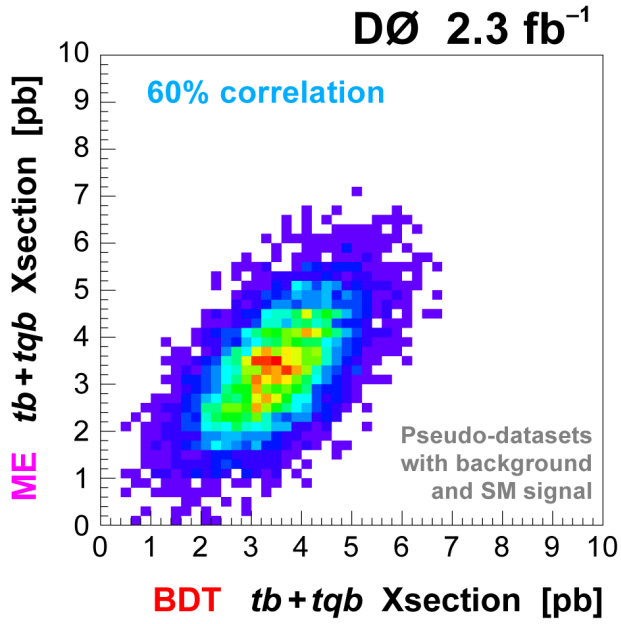
Full data sample



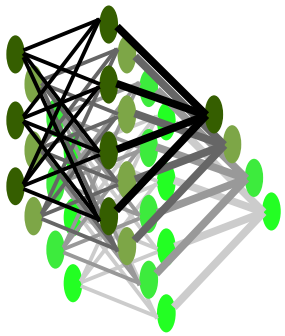
Combination: Another BNN

– Gain because each method provides unique separation

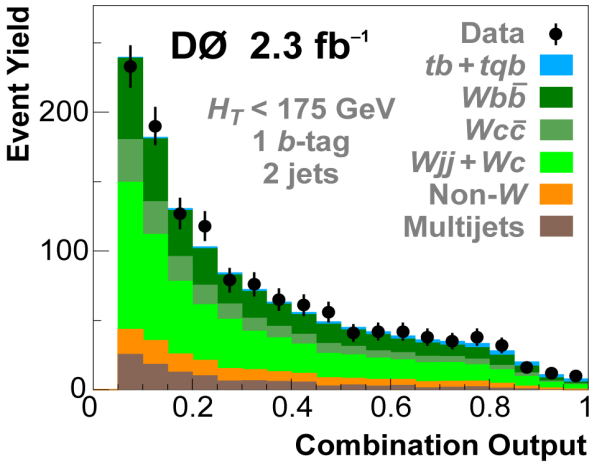




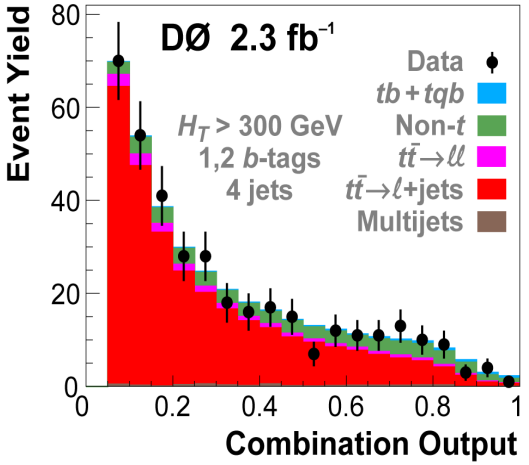
– Simple BNN, only 3 inputs: BDT, BNN, ME



W+Jets Cross-Check Sample

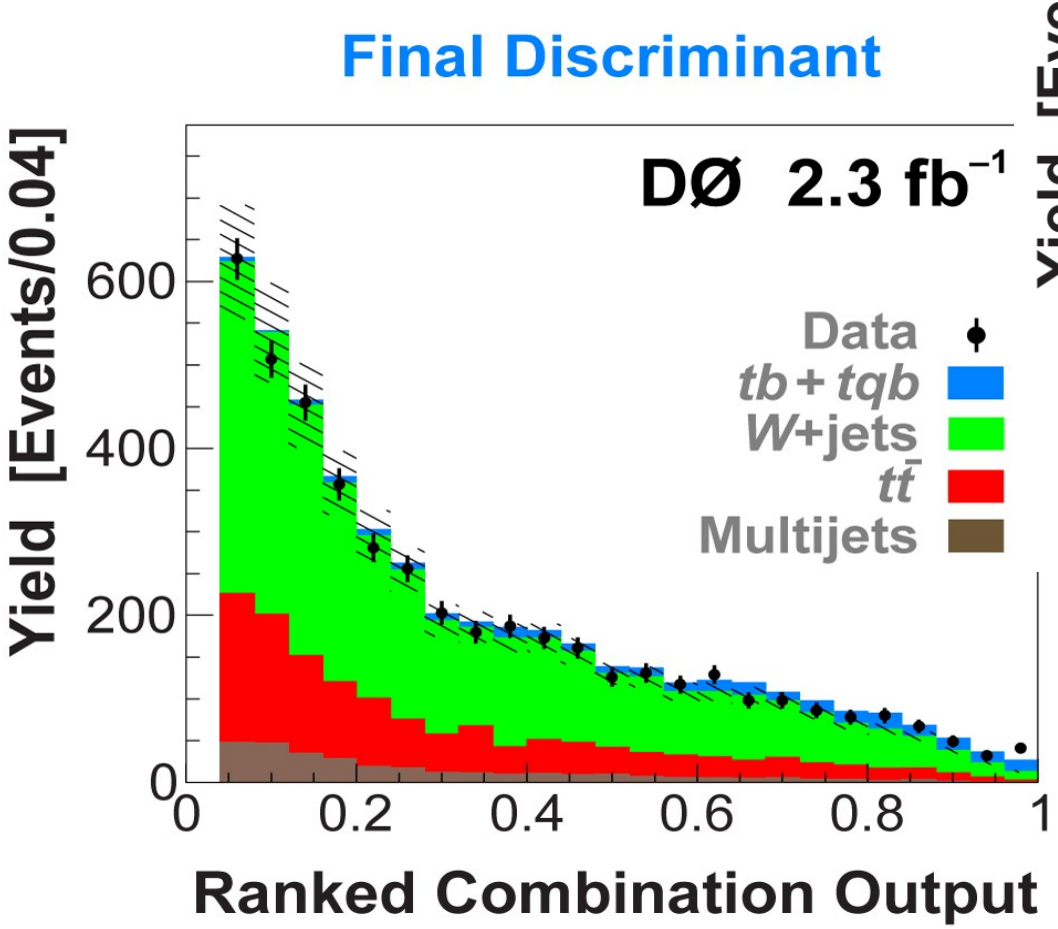


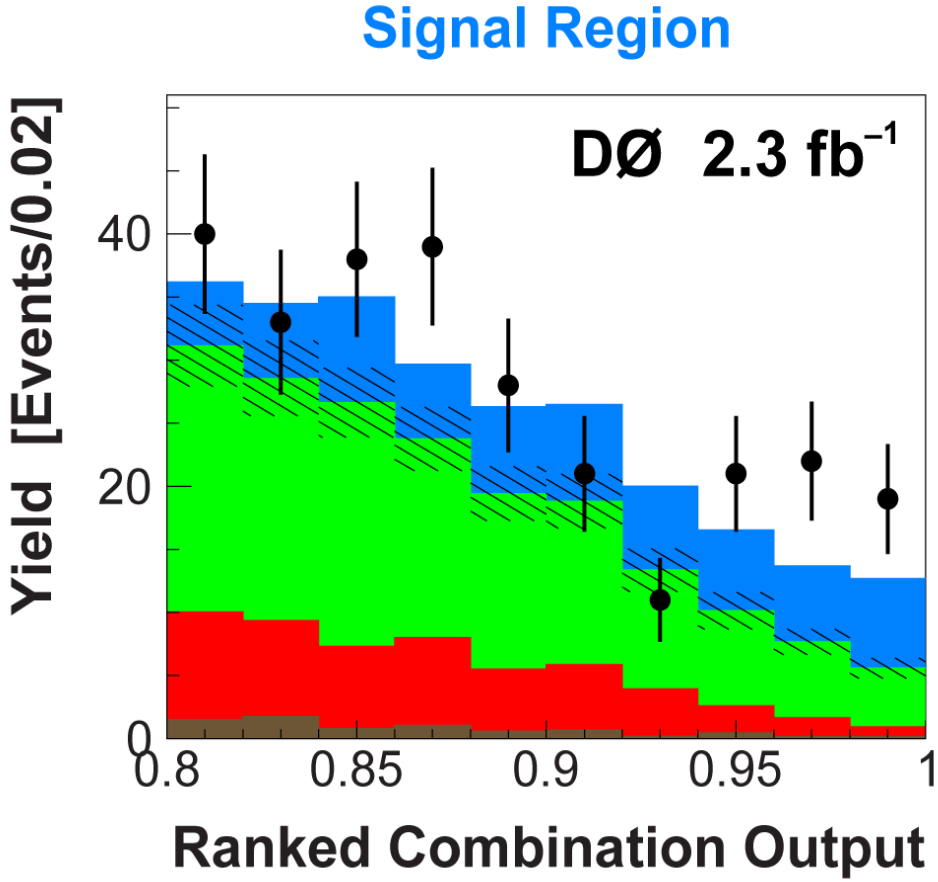
tt-Pairs Cross-Check Sample



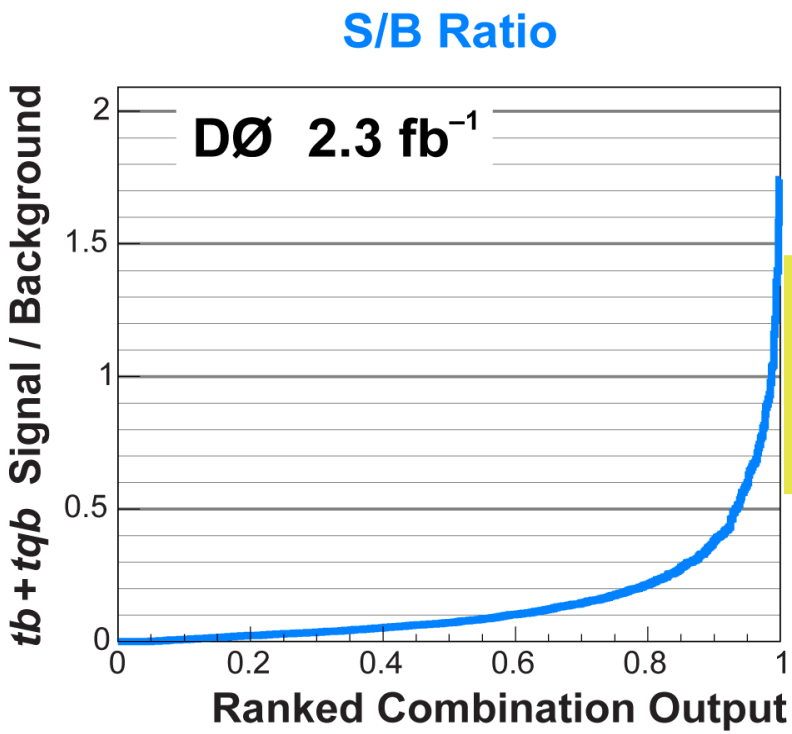
Combination distribution

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

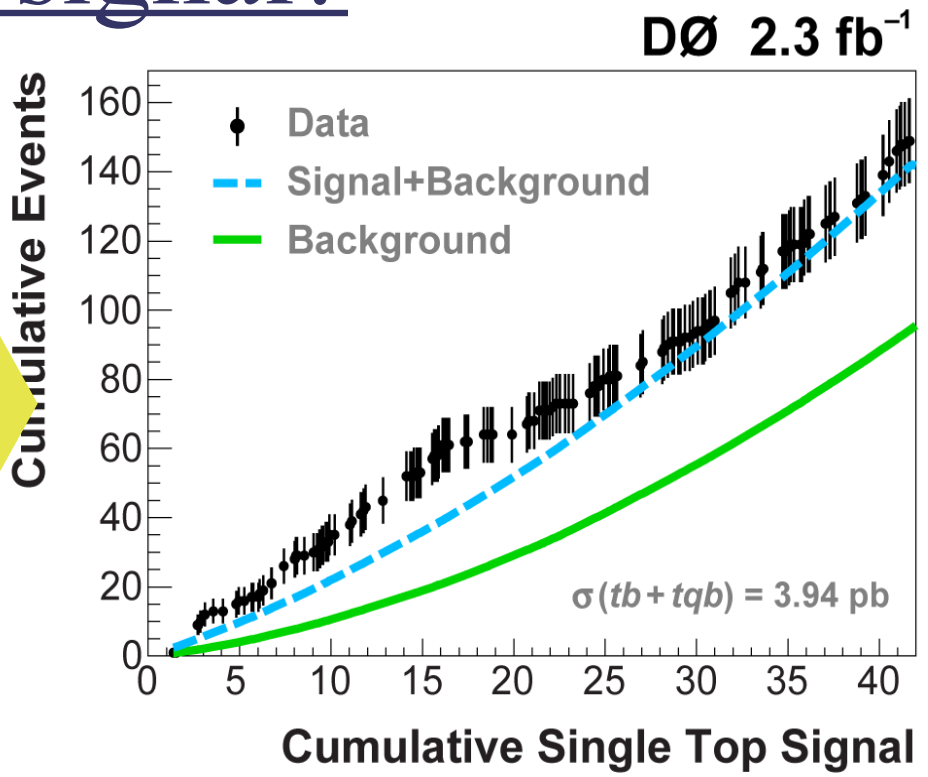


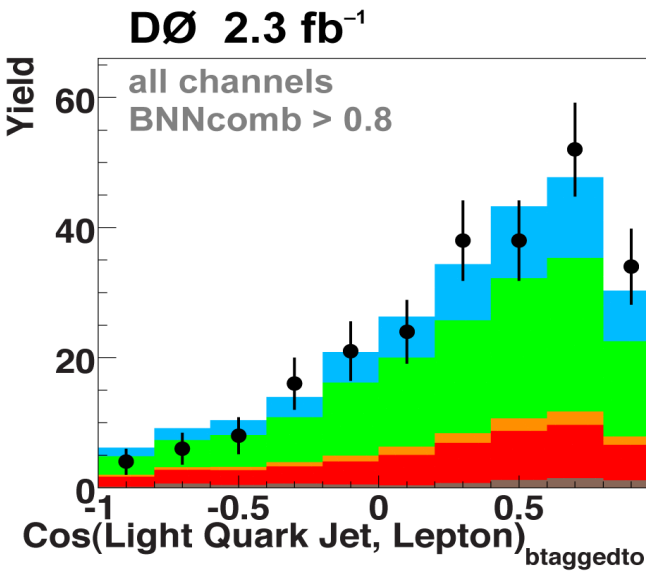


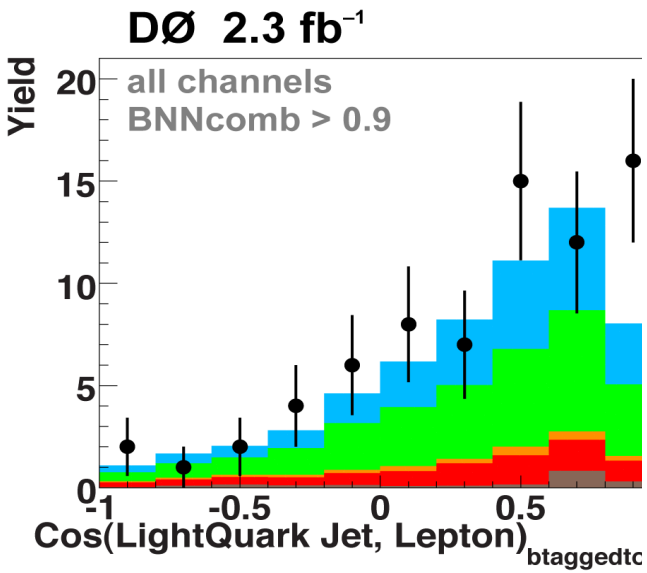
Is there a signal?

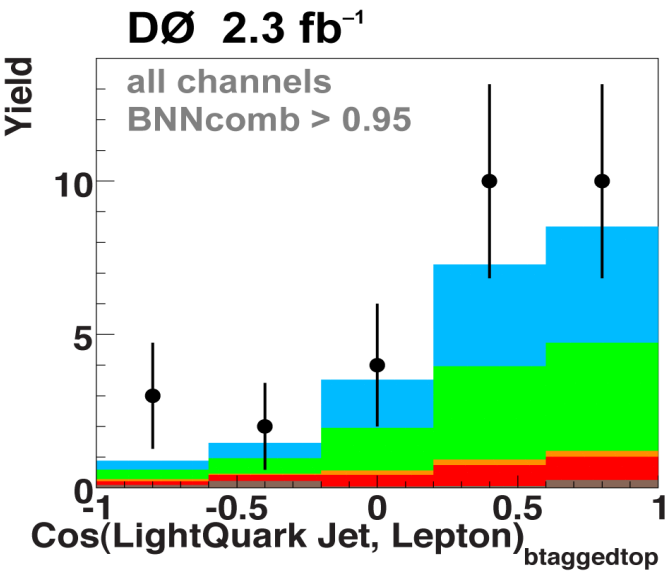


Sum bins right-to-left

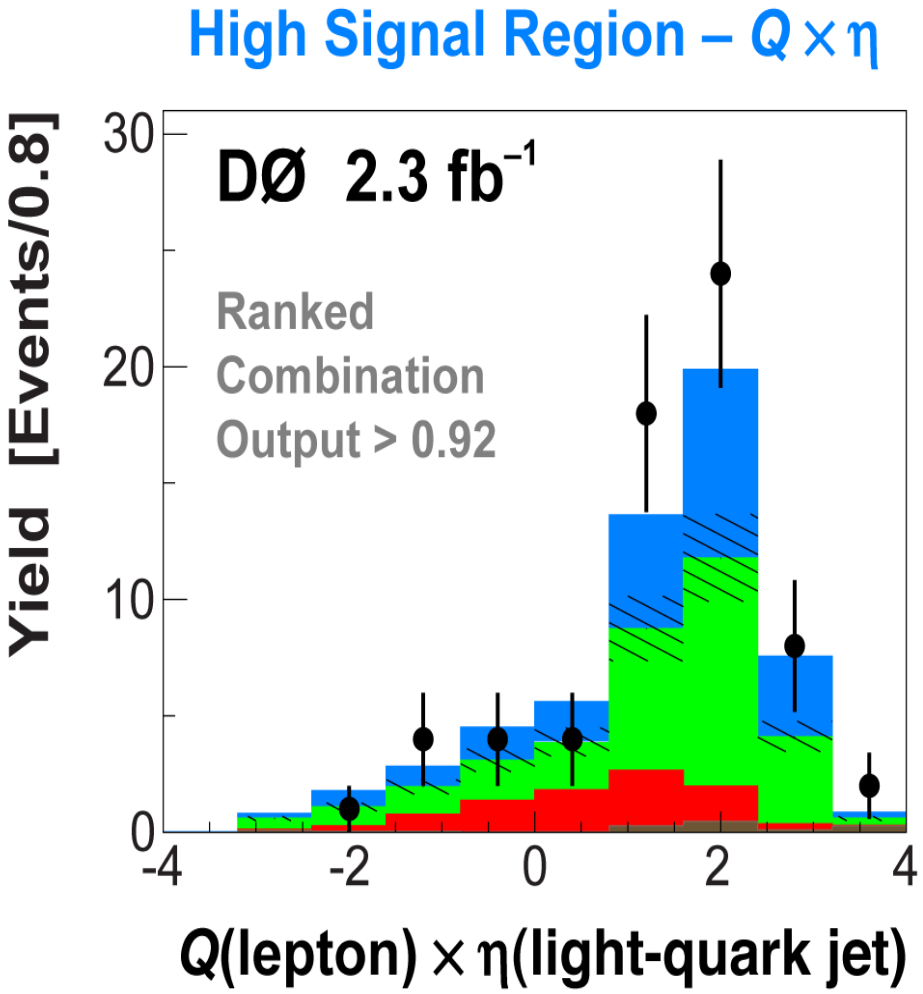


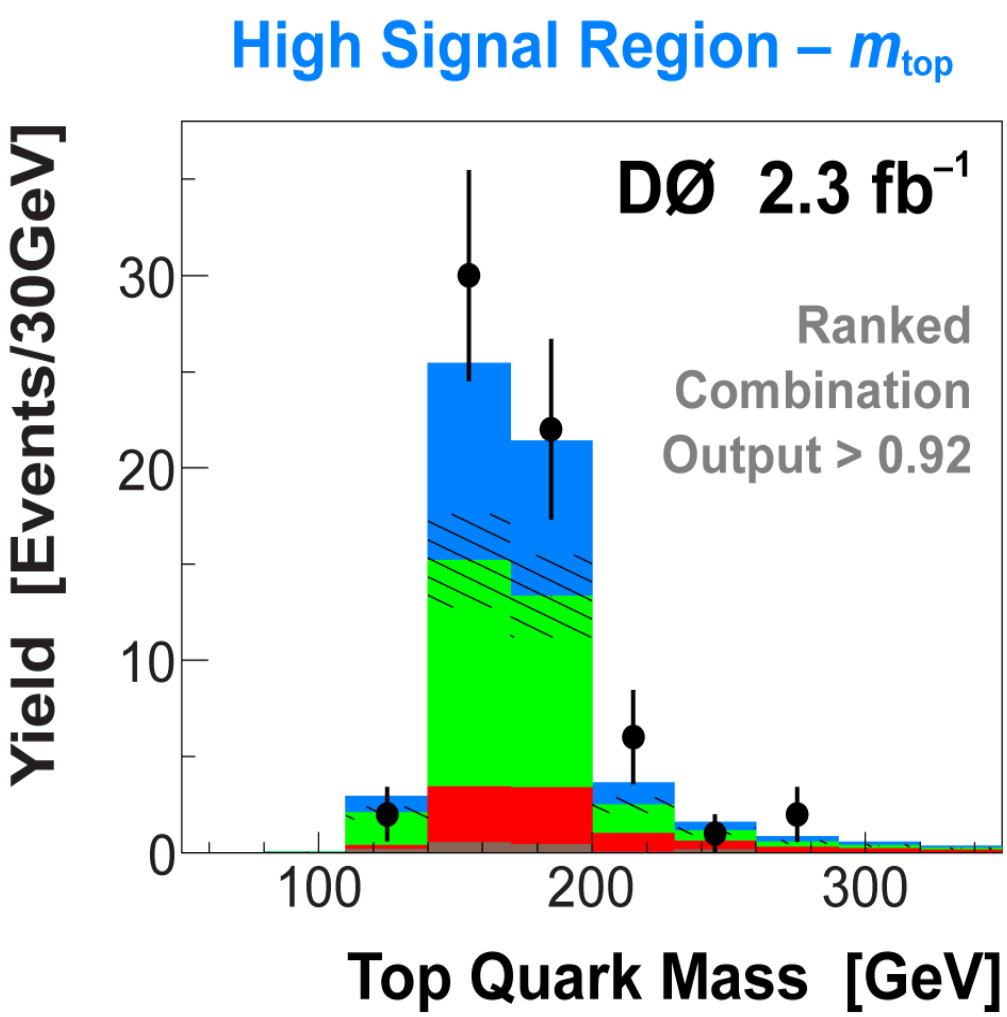


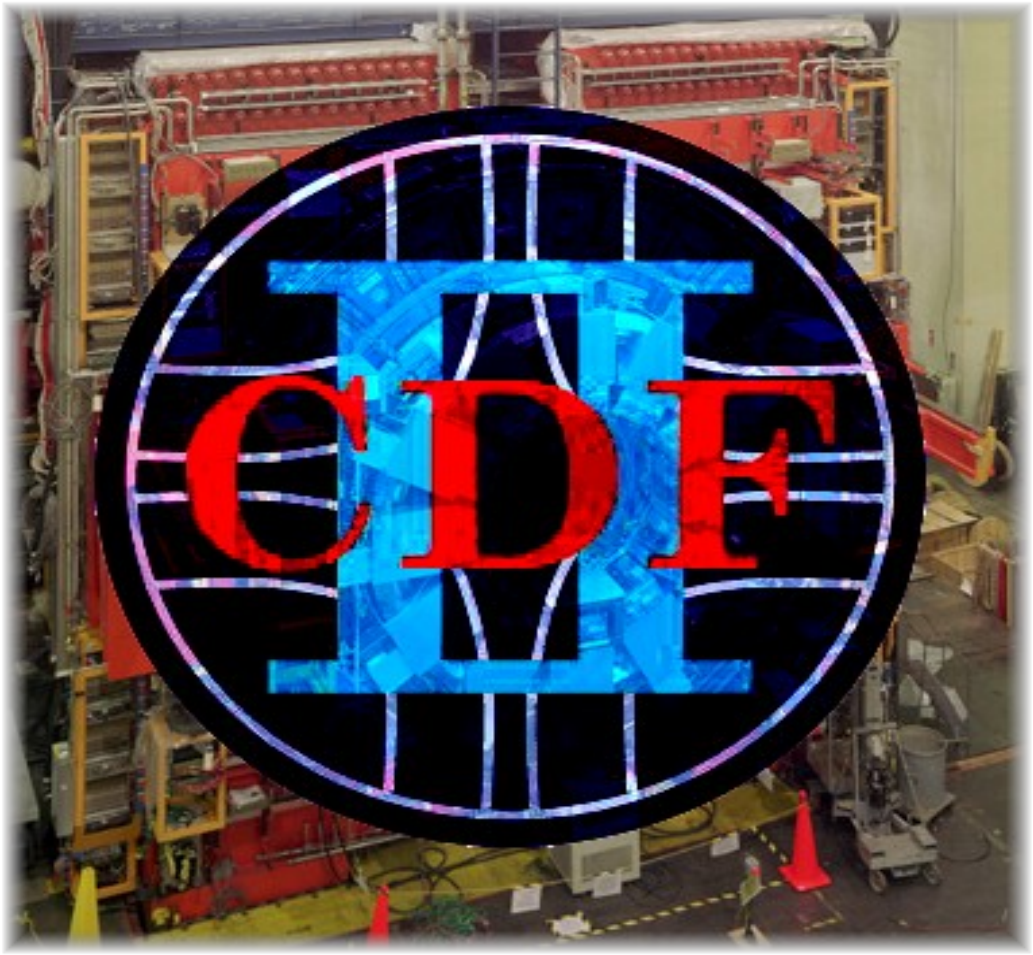




Kinematics in the signal region





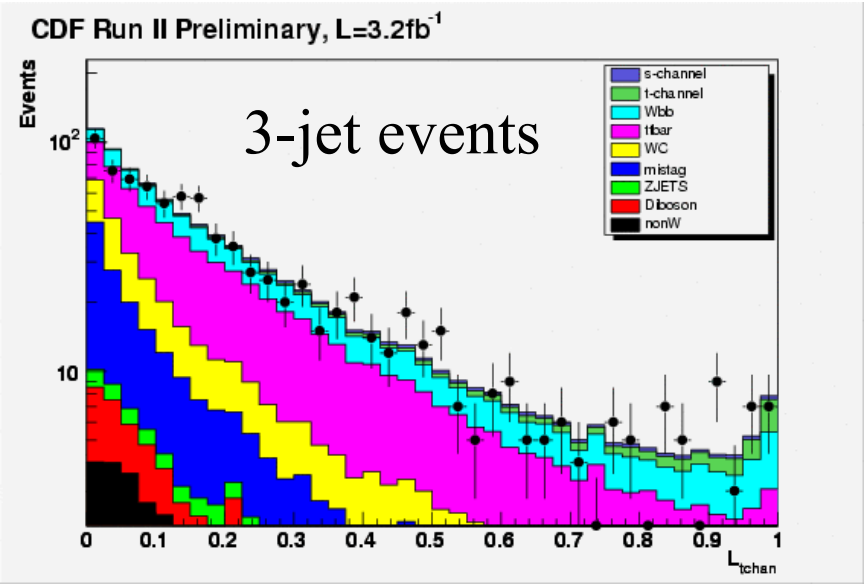


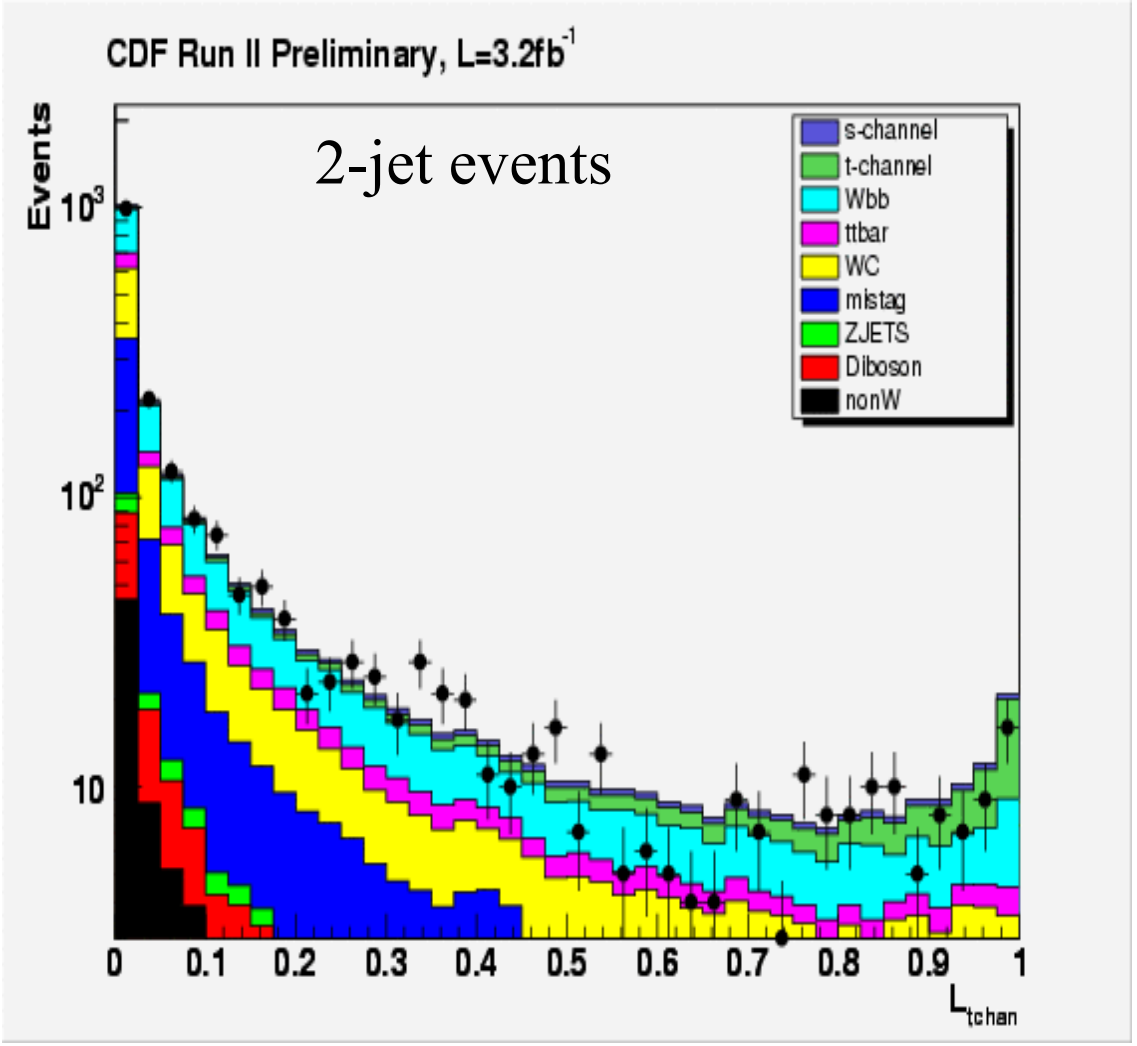
- 3.2 fb^{-1} analysis (arXiv:0903.0885)

- Combine 5 lepton+jets channels
- Include MET+jets channel

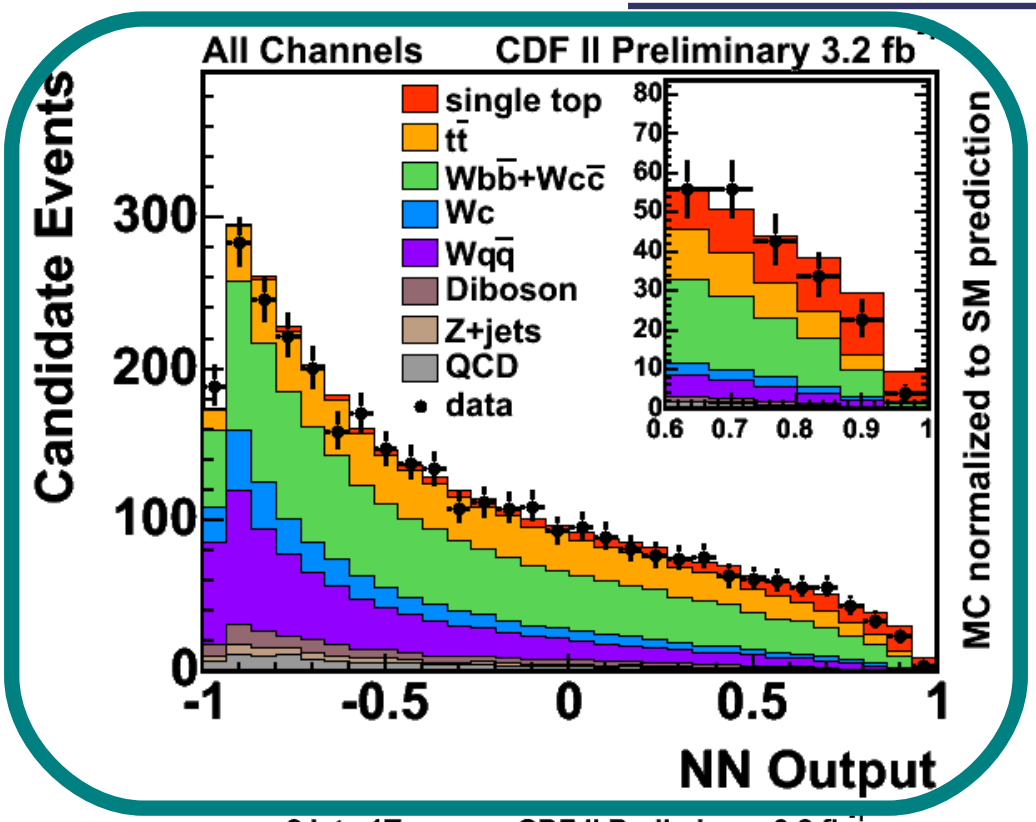
Multivariate likelihood function

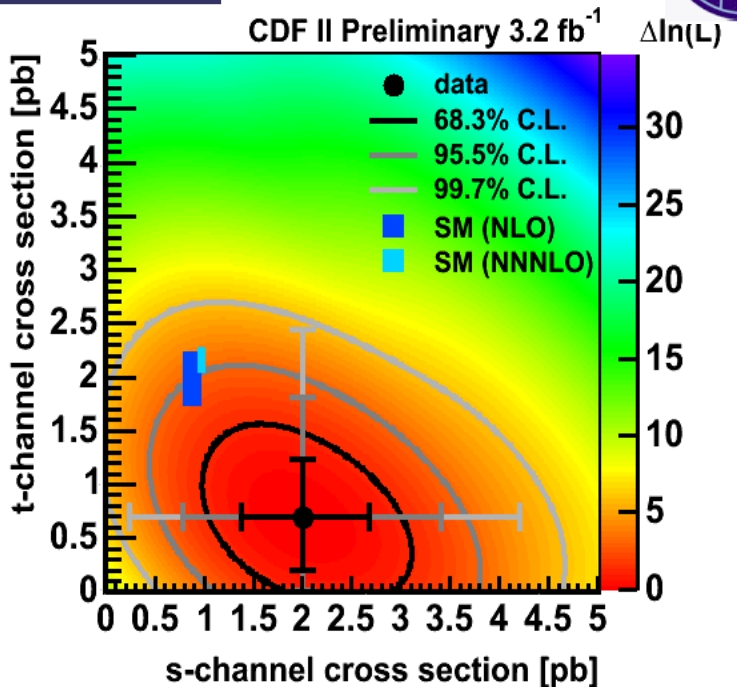
- Likelihood functions built from 7 variables (10 for 2-tags)
  - Kinematic variables
  - b-tag NN output
  - kinematic top decay solver
  - t-channel ME
    - No transfer functions, no integration

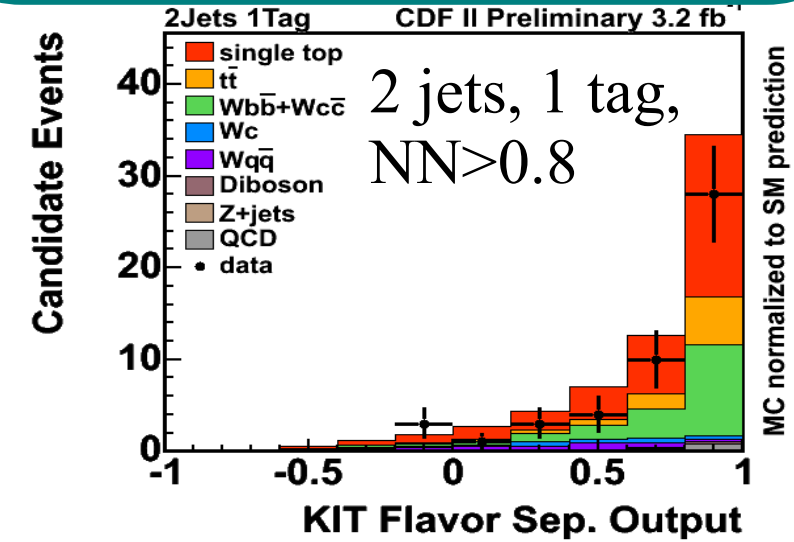


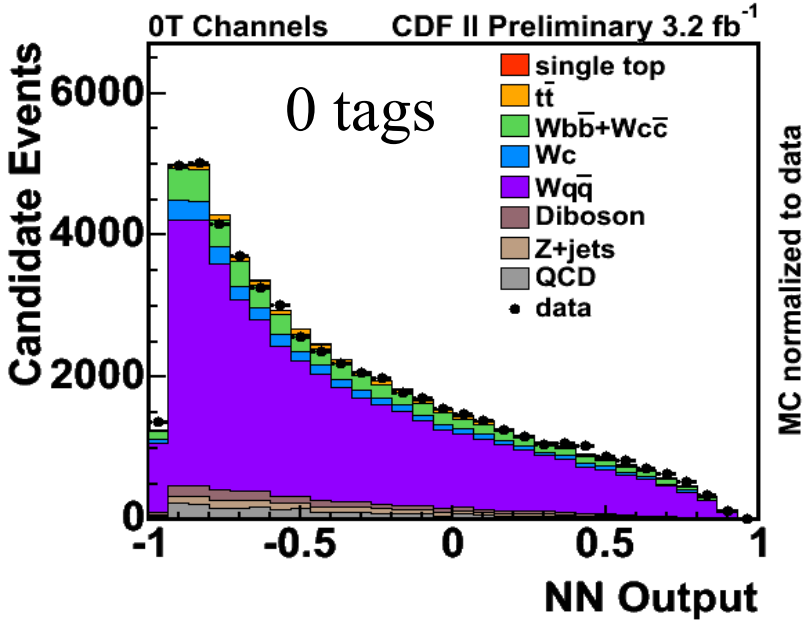


Neural Networks

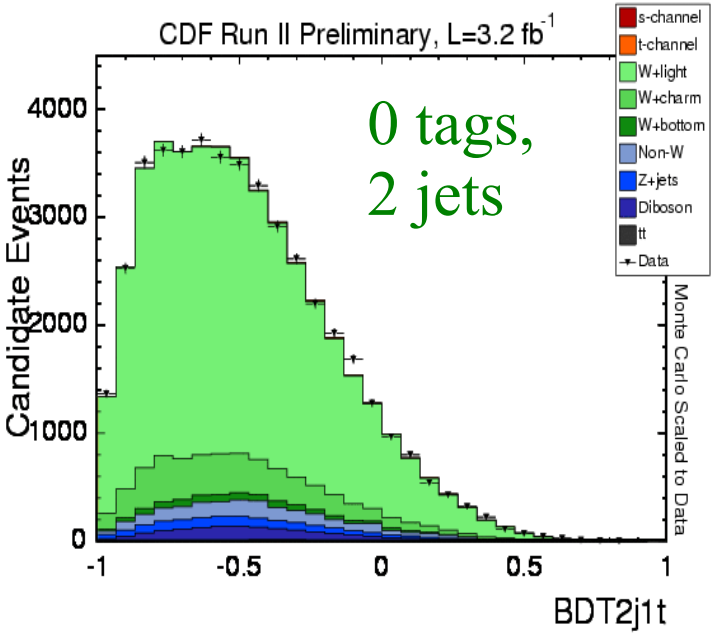


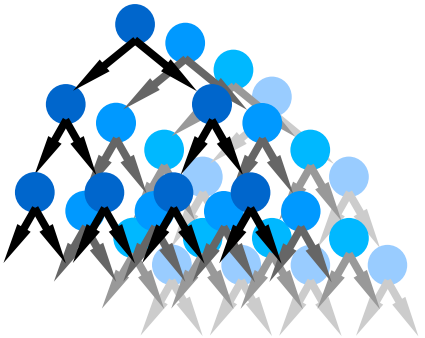


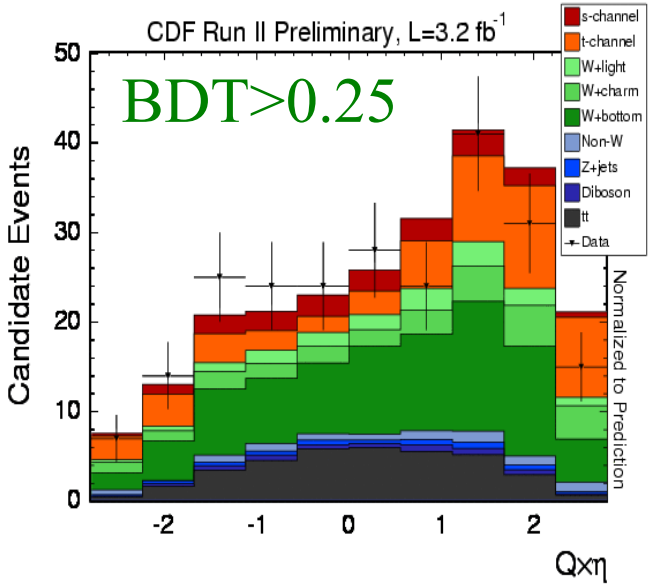


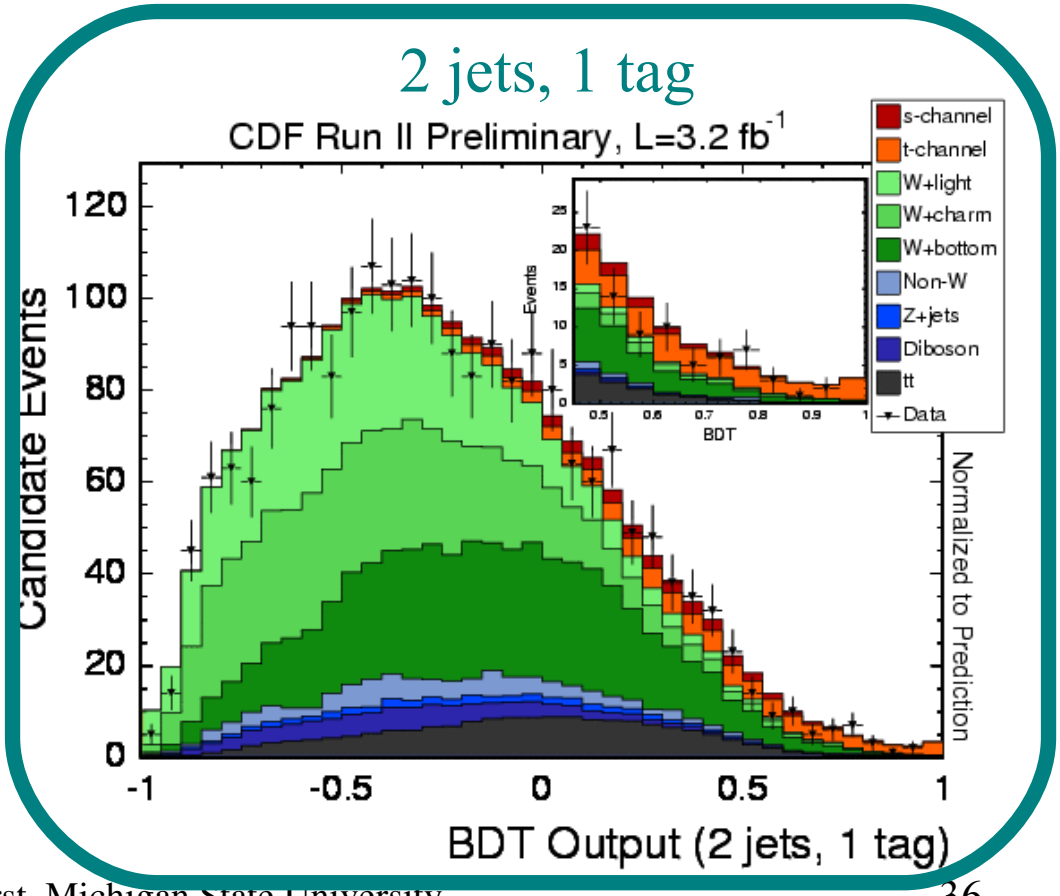


Boosted decision tree distributions

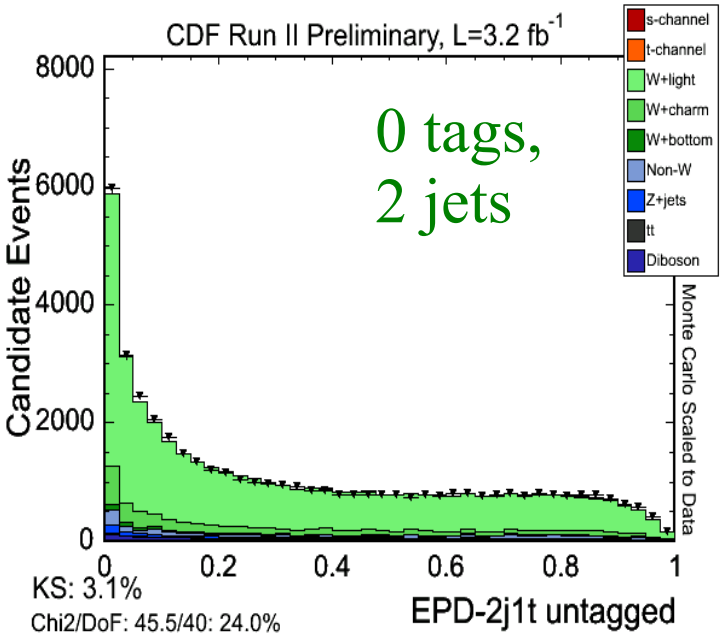


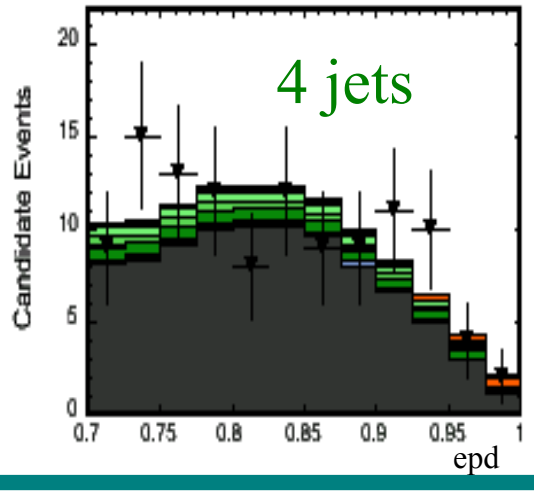


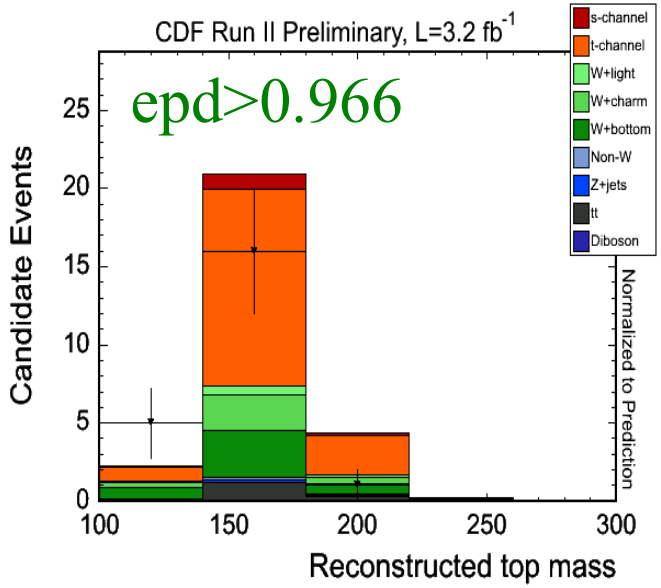


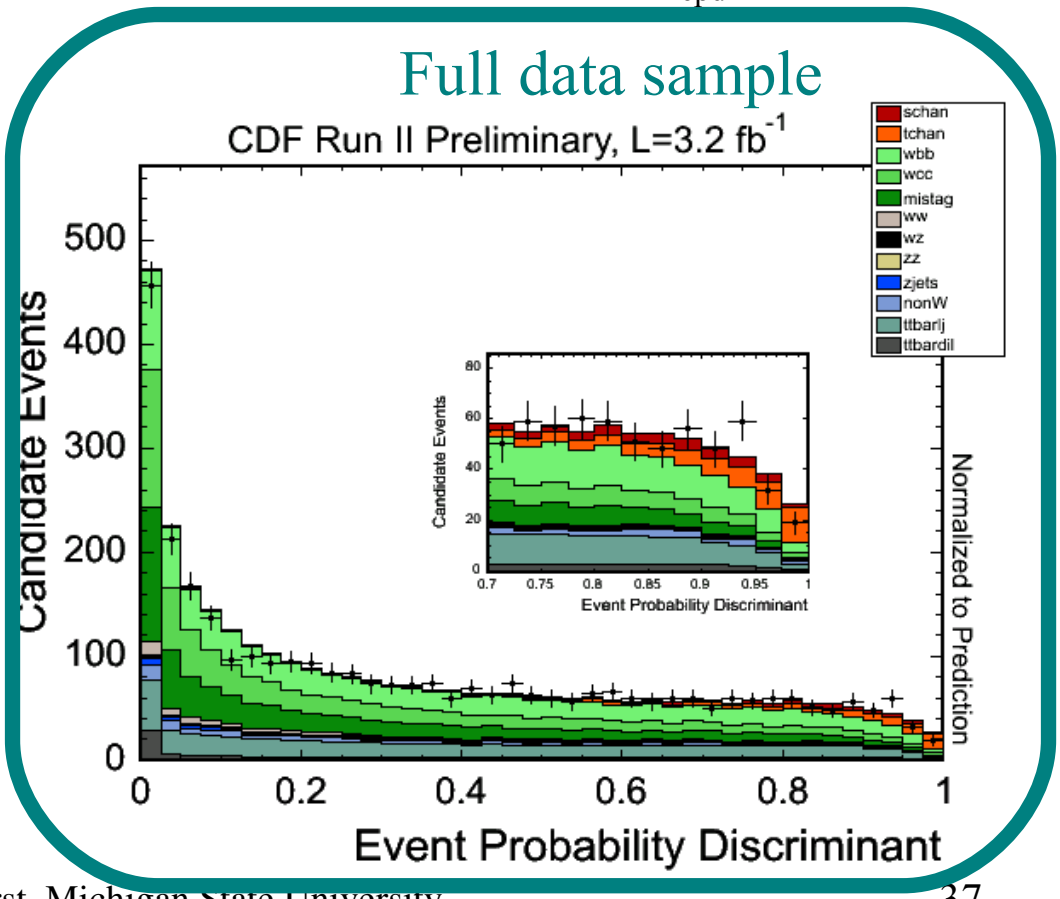


Matrix element analysis



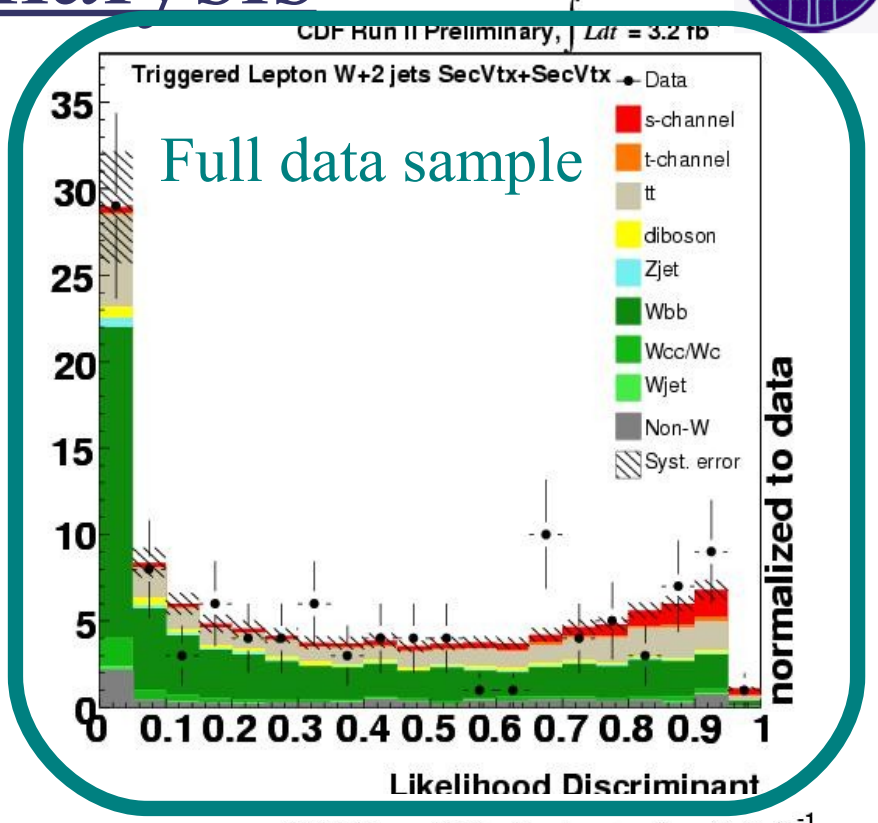


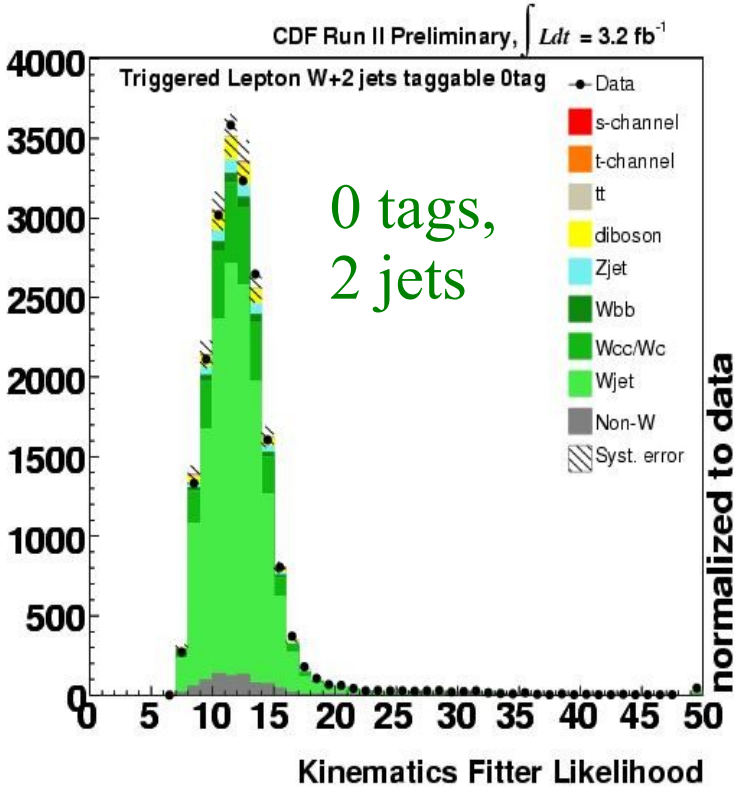


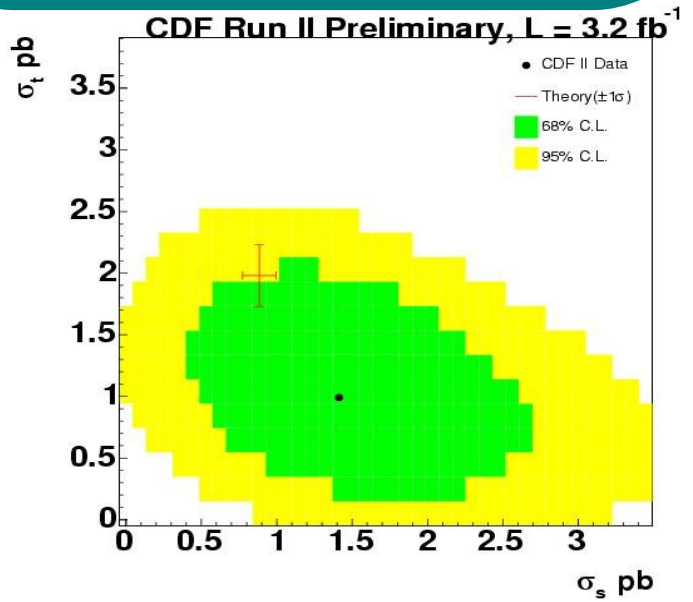


s-channel analysis

- 2 or 3 jets, 2 tags, using different taggers
- Likelihood to extract s-channel signal

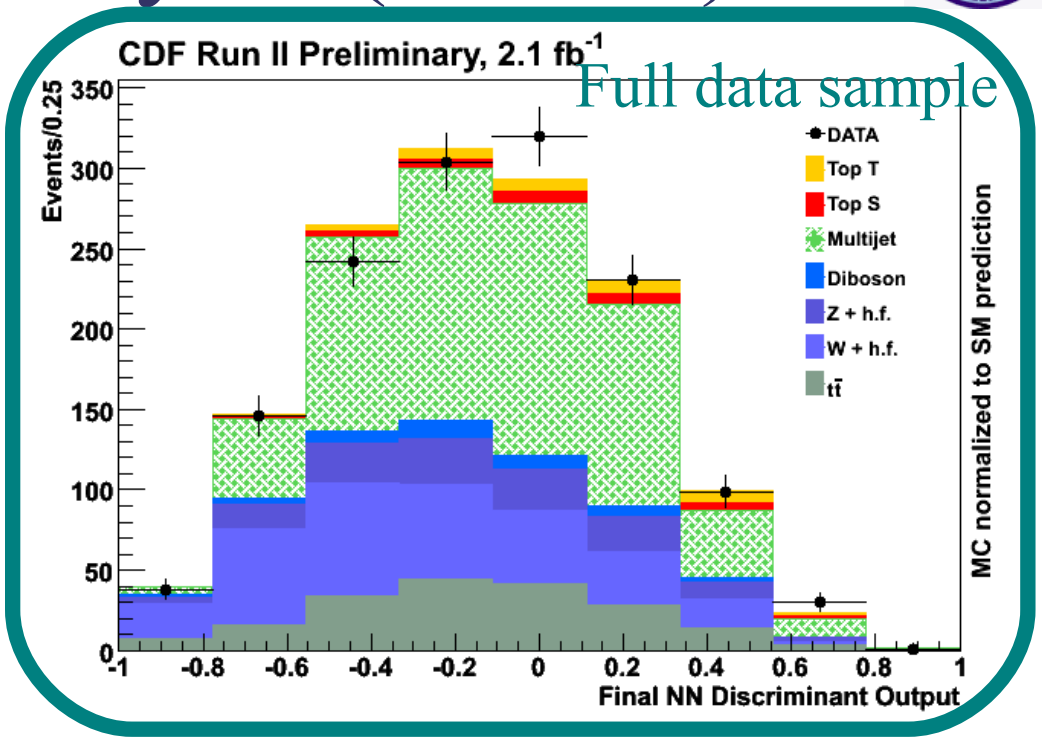


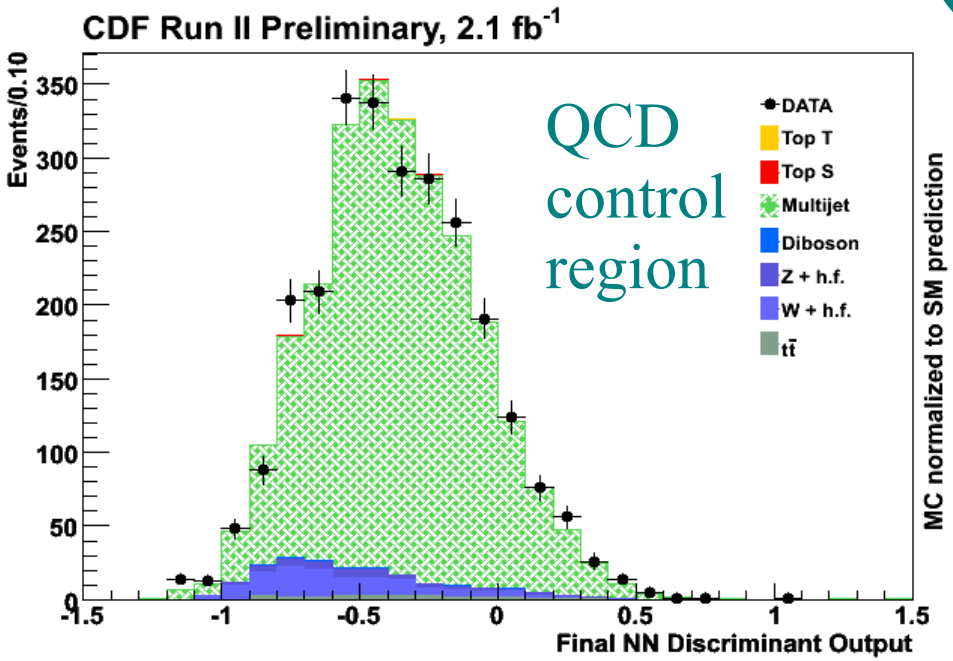


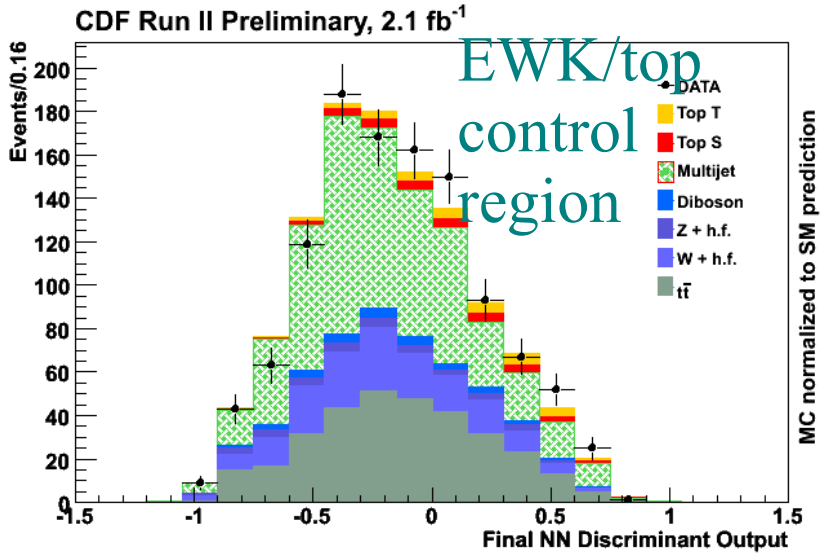


MET + jets analysis (2.1fb^{-1})

- Sample includes leptons that were missed plus tau decays
- Event selection neural network to reject QCD
- Final neural network with 11 inputs

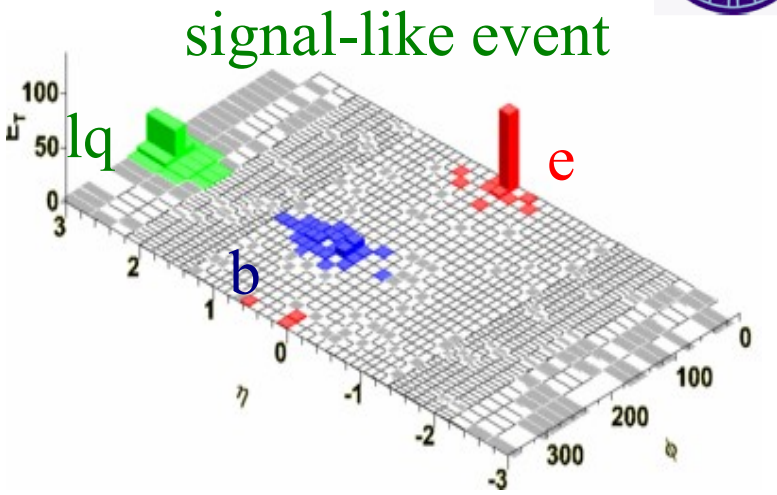


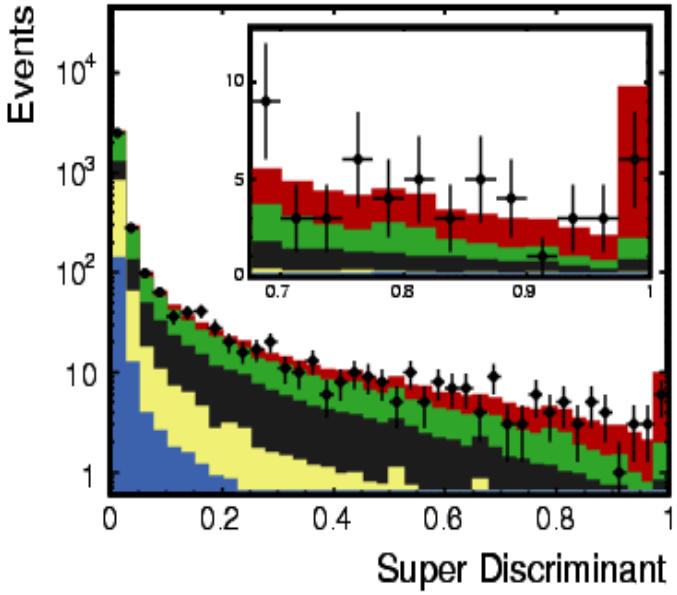


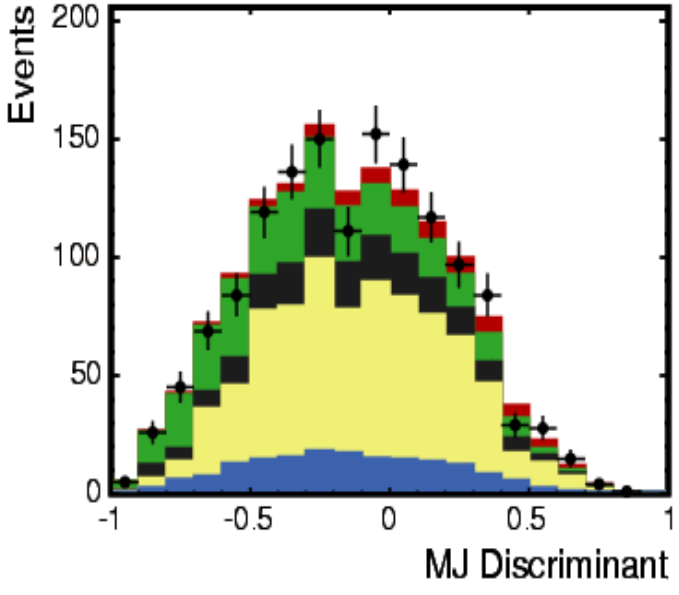


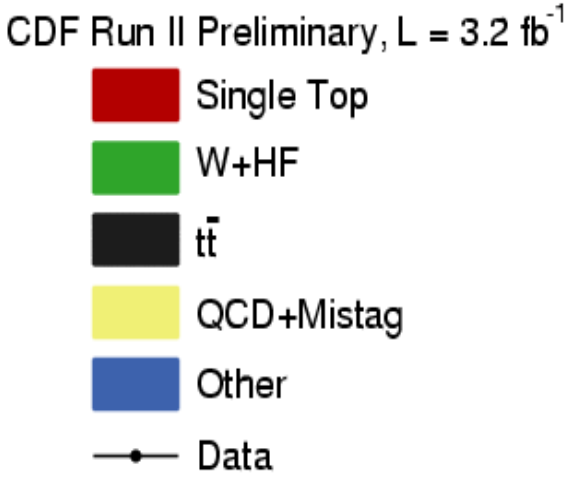
Combination

- NEAT – NeuroEvolution of Augmenting Technologies
  - Neural network combining lepton+jets analyzes
  - Also optimize binning
- Then simultaneous signal fit to NEAT and MET+jets NN

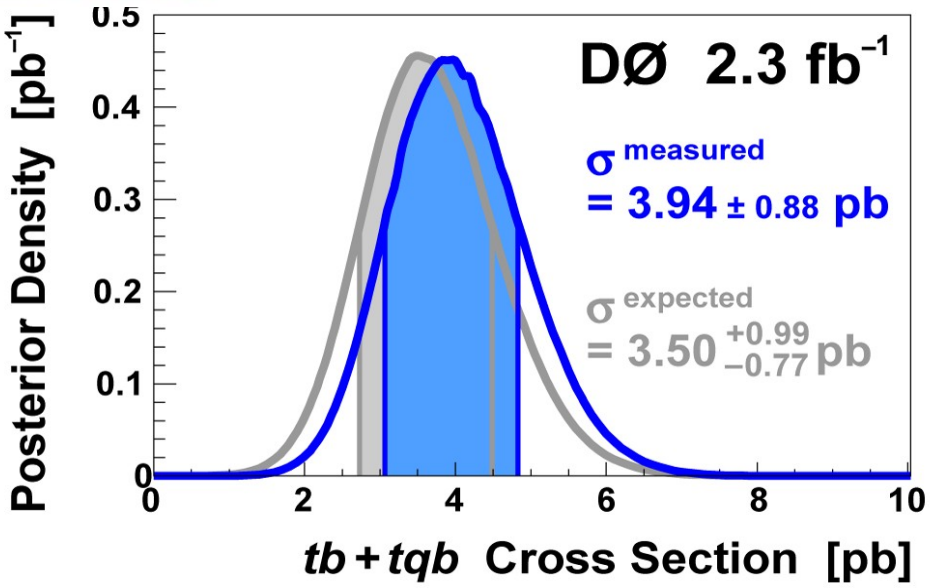


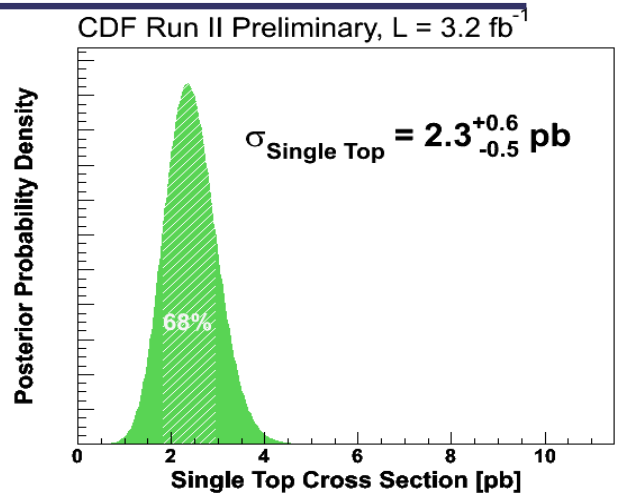


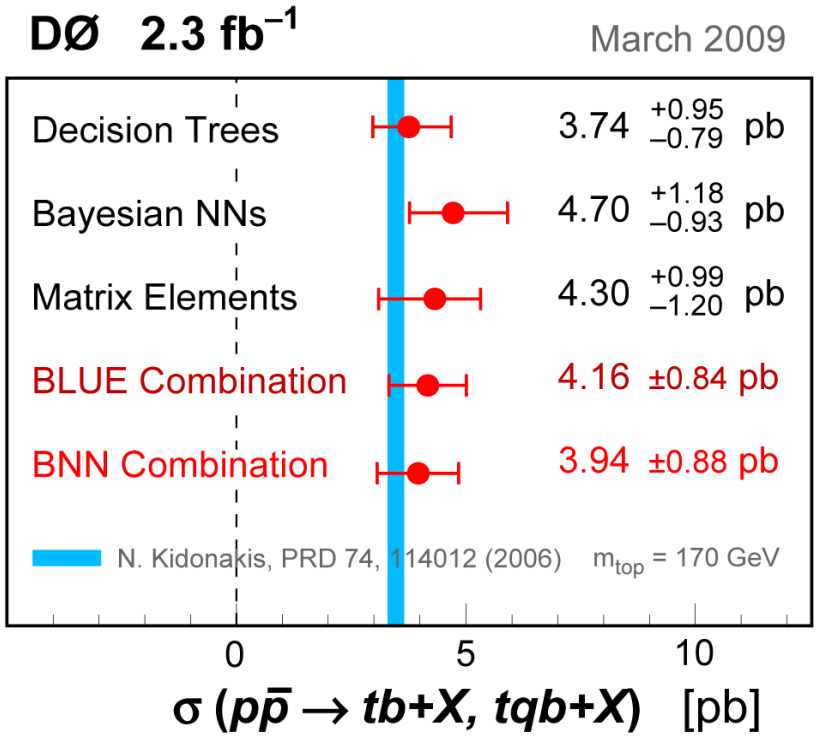


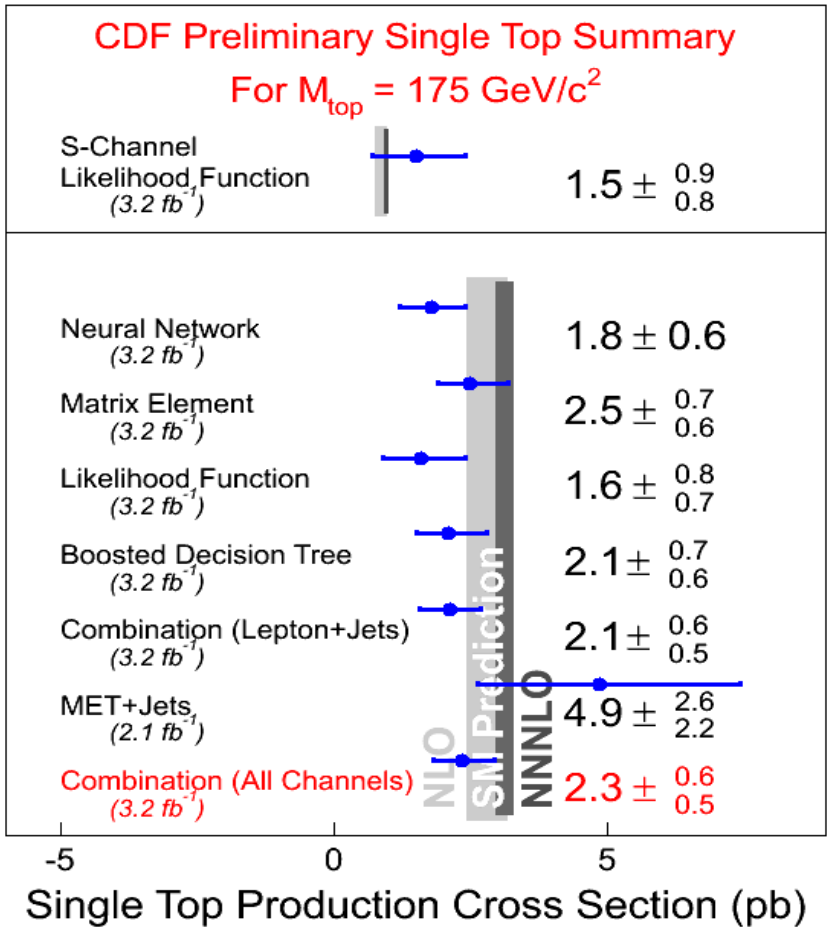


Cross section measurement









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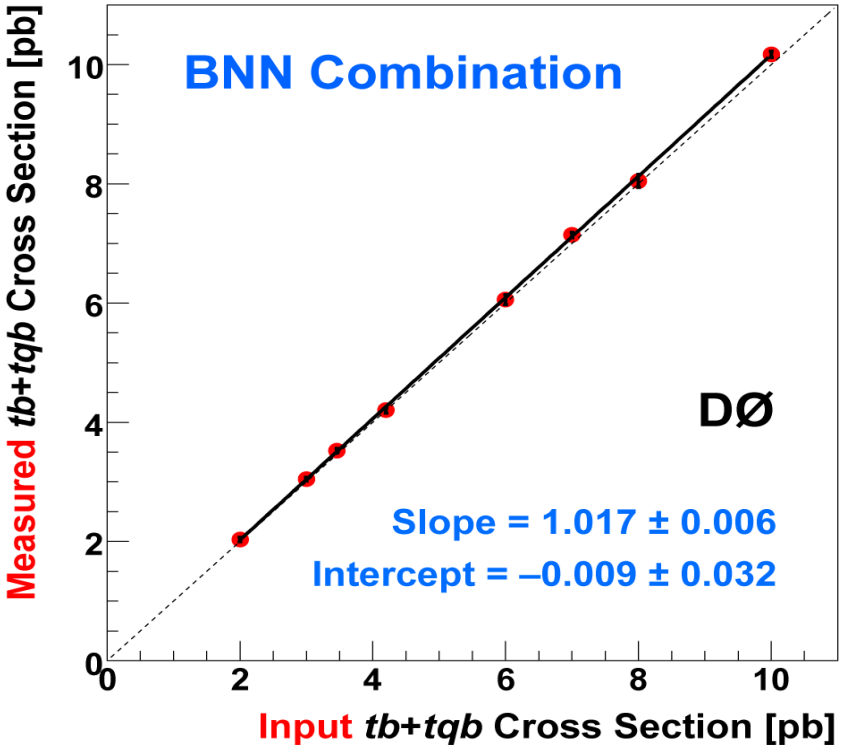
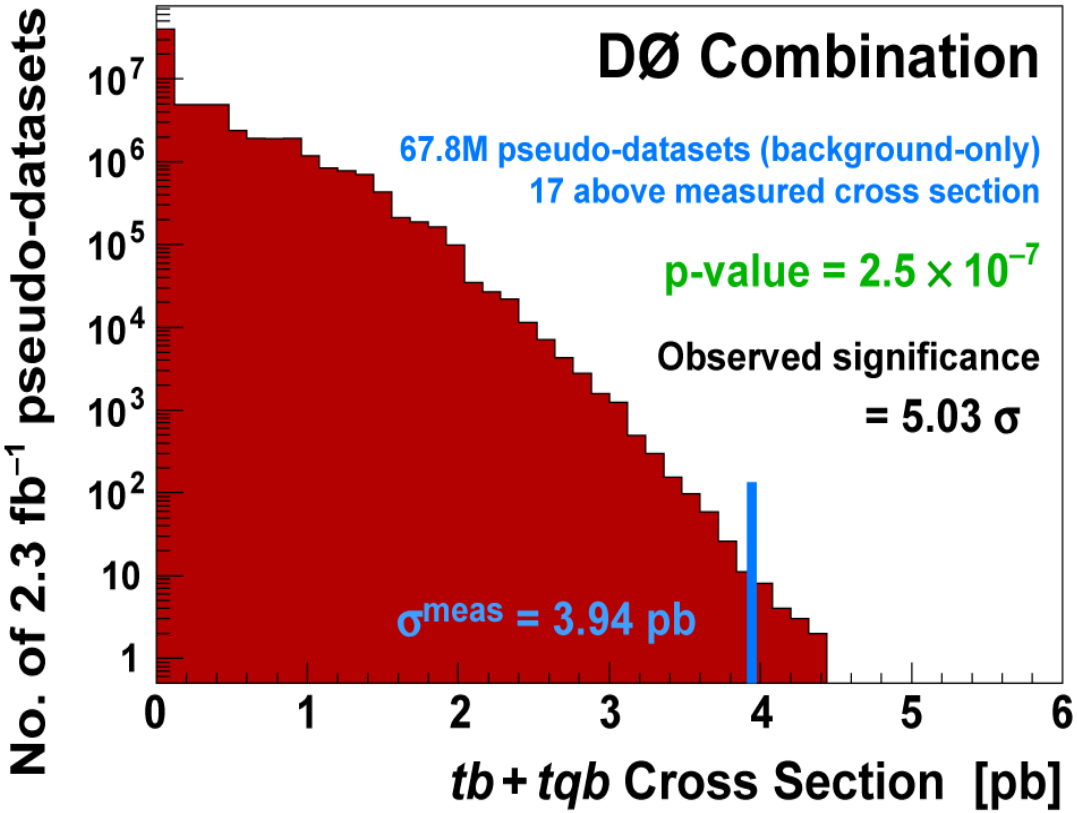
Significance

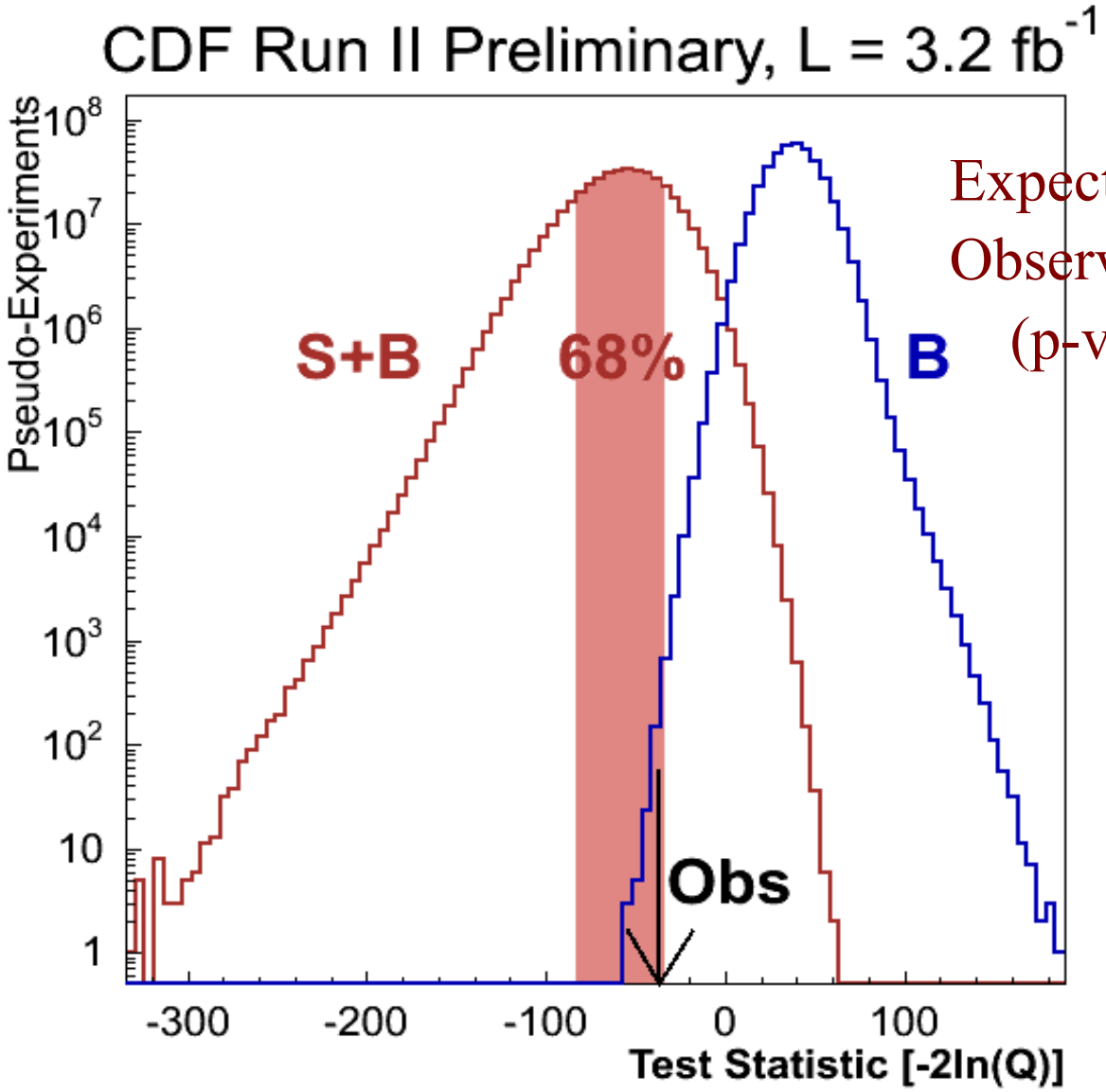
- Significance (p-value) and linearity and many checks through extensive ensemble testing
  - Ensembles of pseudo-data at various signal cross sections
  - Each passed through full Bayesian analysis





Significance

- Log-likelihood ratio calculation

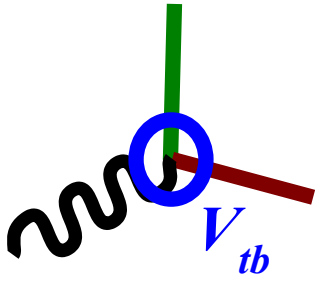


Expected significance > 5.9σ

Observed significance 5.0σ

(p-value 3.1×10^{-7})

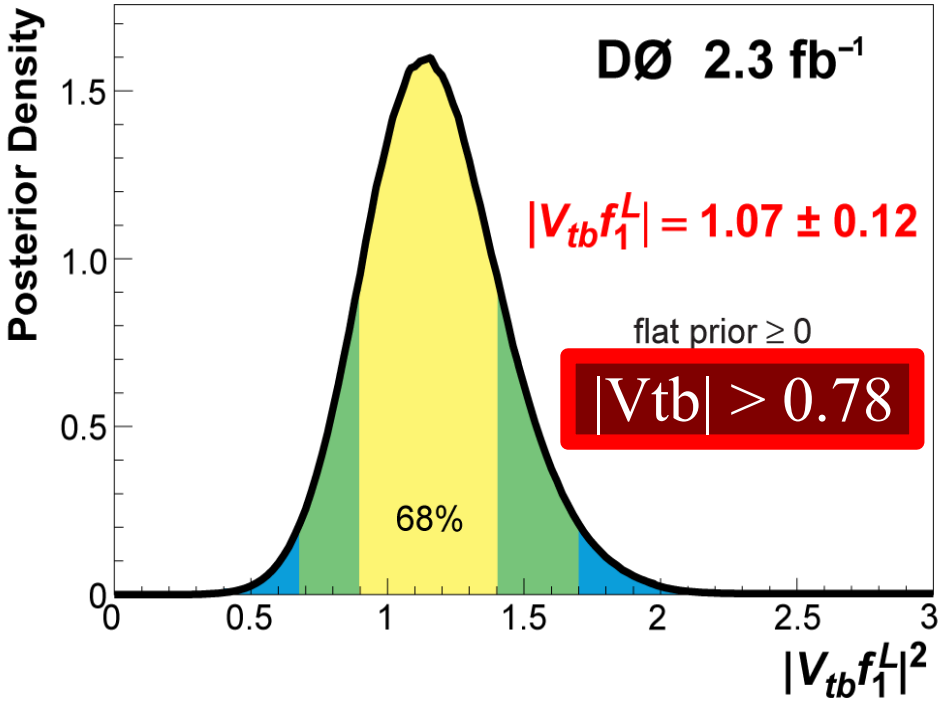
CKM matrix element $|V_{tb}|$

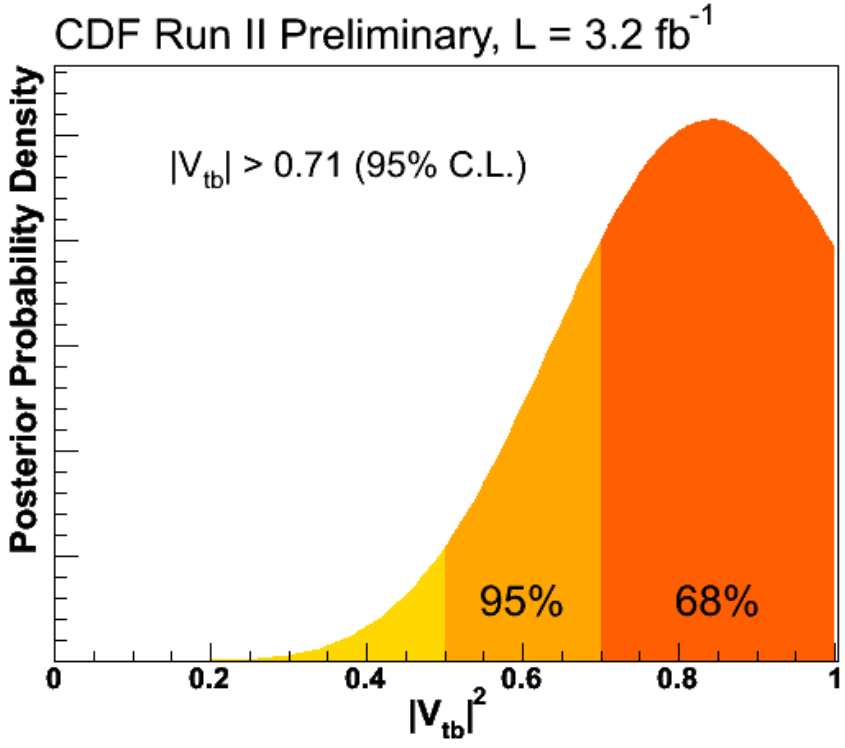


CKM Matrix

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

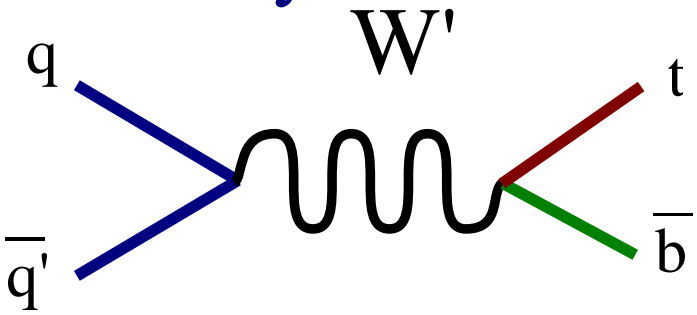
- Measurement: $|V_{tb} \times f_L{}^1|$
  - Assume top decays to b ($V_{tb} \gg V_{ts}, V_{td}$)
- No constraint on # of generations





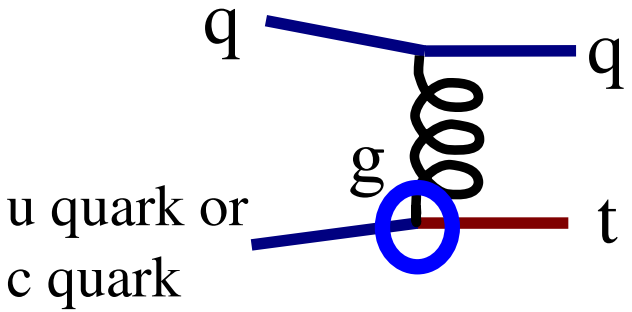
Searches for new physics in single top

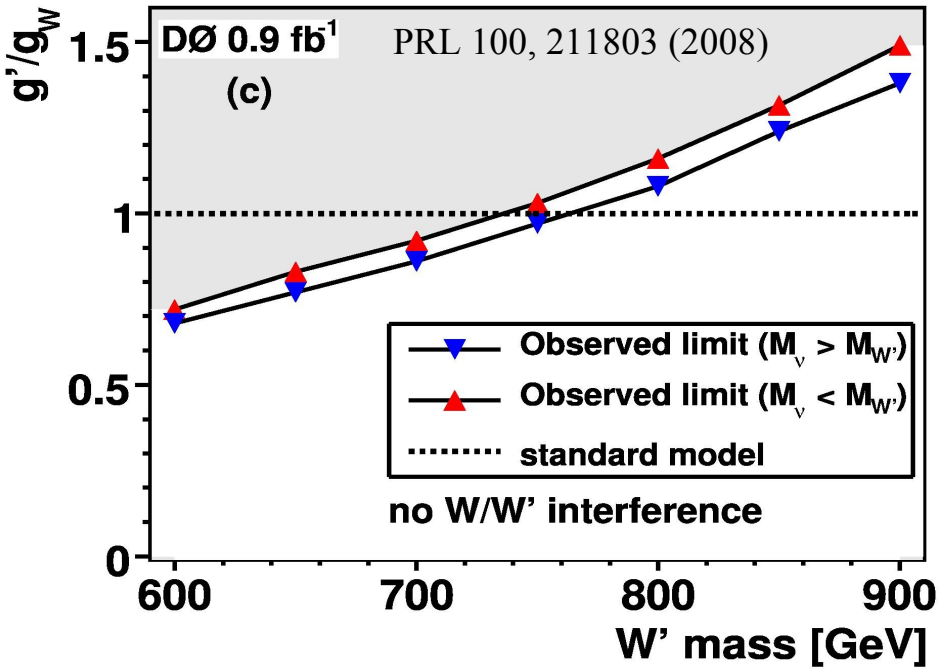
- Searches for new heavy boson W':

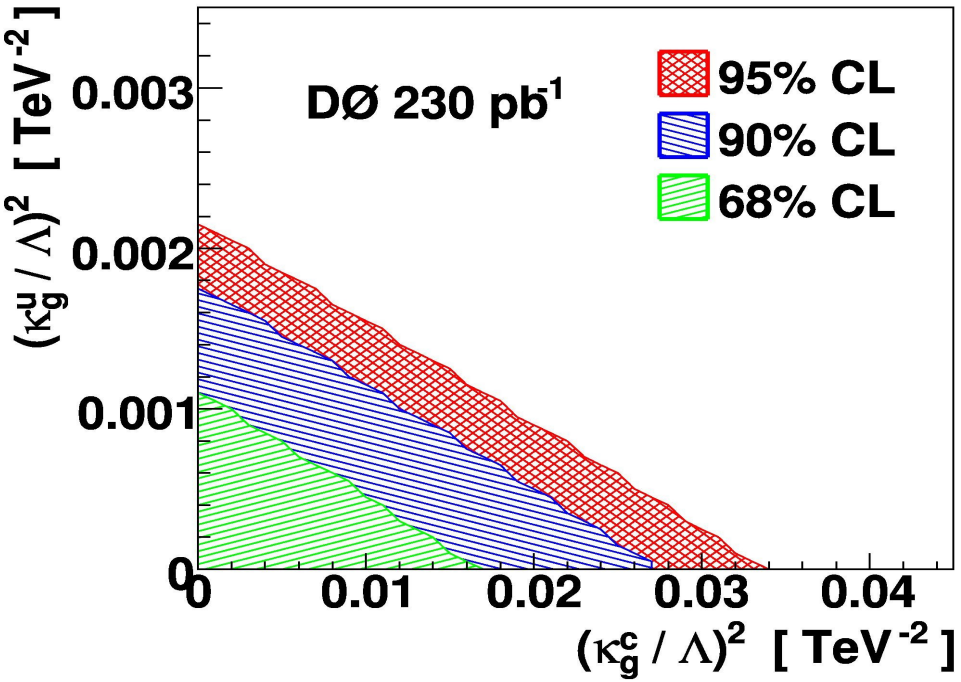


  - CDF prelim result, 1.9fb^{-1}: M > 800 GeV and M > 825 GeV

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

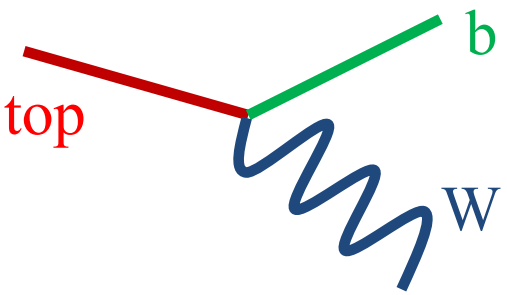






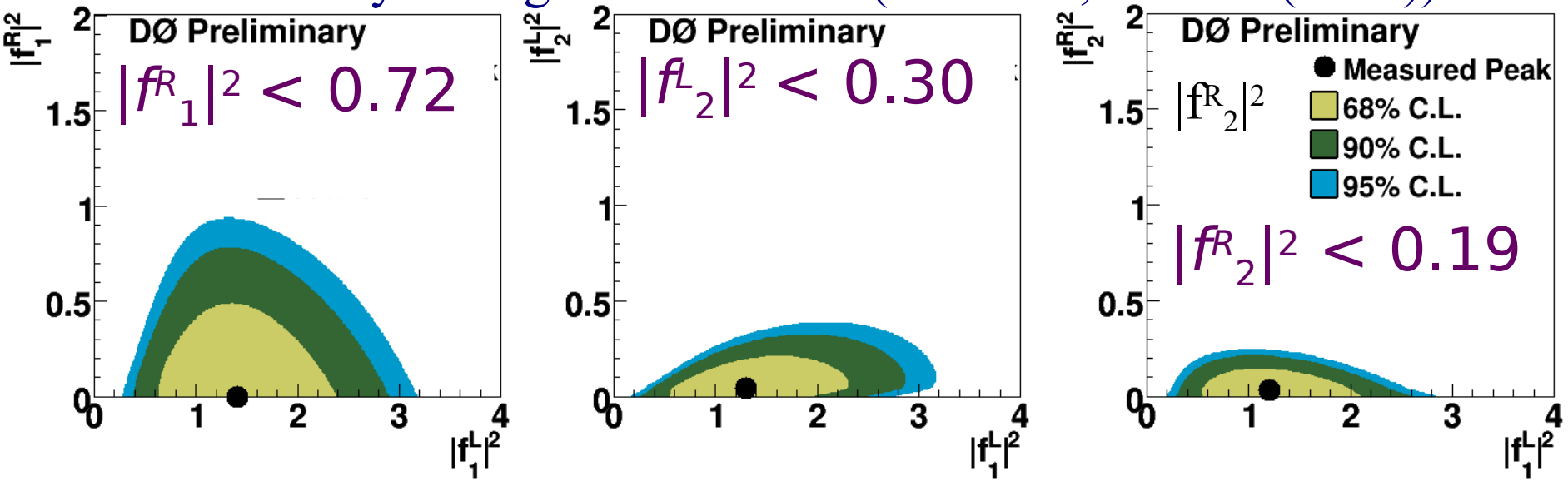
Single top anomalous coupling

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



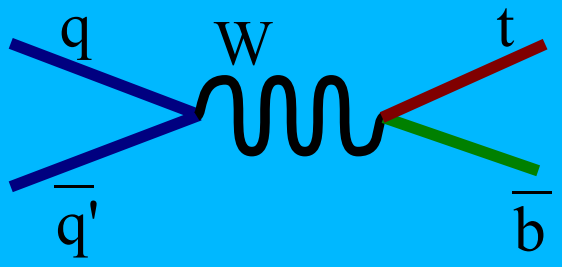
$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu V_{tb}(f_1^L P_L + f_1^R P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{M_W}(f_2^L P_L + f_2^R P_R)tW_\mu^- + h.c.$$

- 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))

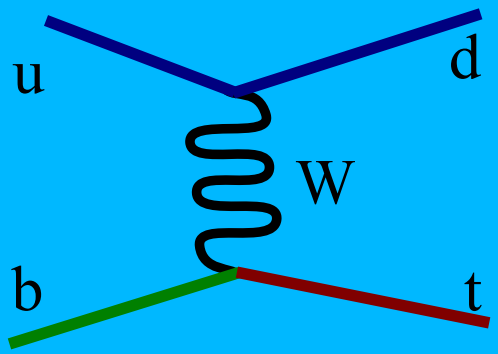


Single Top future: LHC

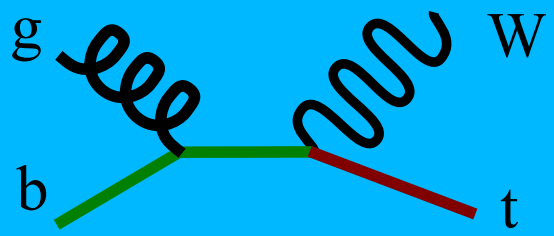
s-channel: 10.7 pb



t-channel: 247 pb



associated production: 68 pb

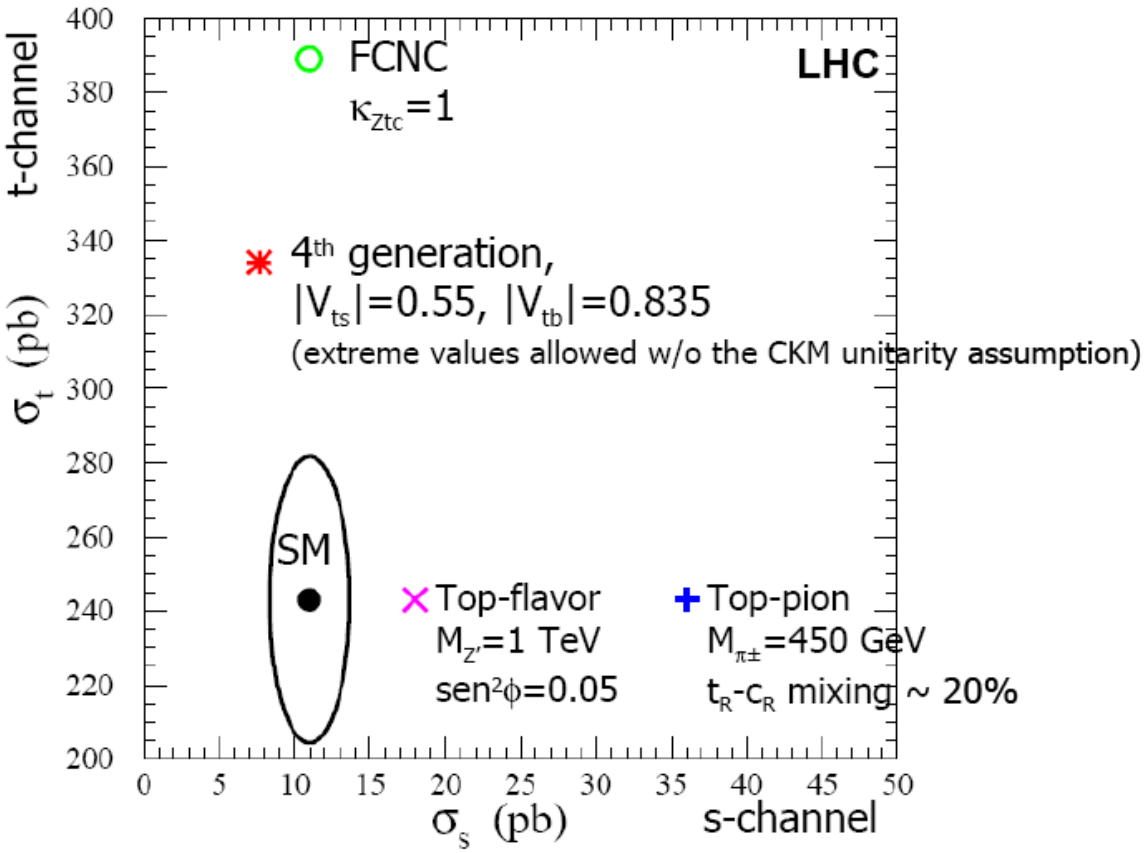


- Observe three single top production modes separately
  - t-channel: easy  s-channel and assoc. prod: harder
- Observe new physics *(if it can be seen)*
- Measure V_{tb} to few %
- Study spin correlations

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

- 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