Observation of Single Top Quark Production at the Tevatron

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BERGISCHE UNIVERSITÄT WUPPERTAL

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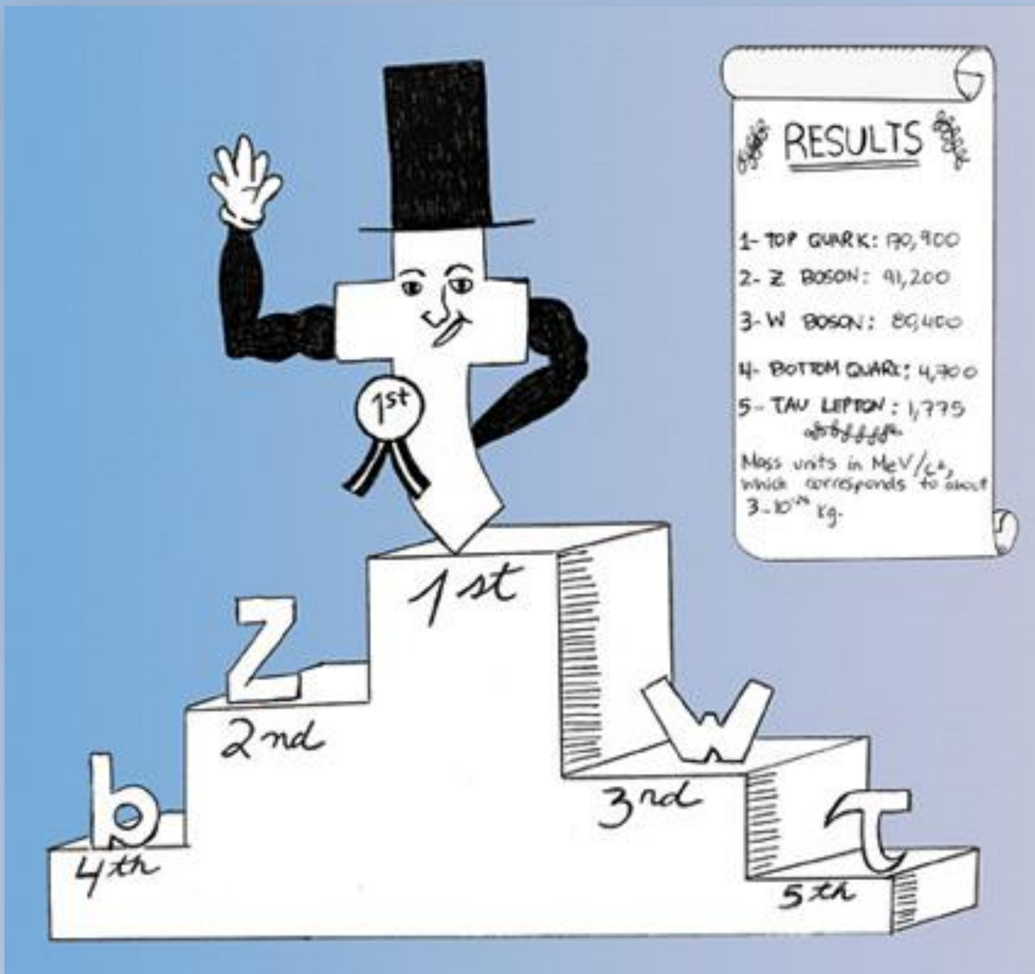
Why Studying Top Quarks ?



By far the heaviest know elementary particle.

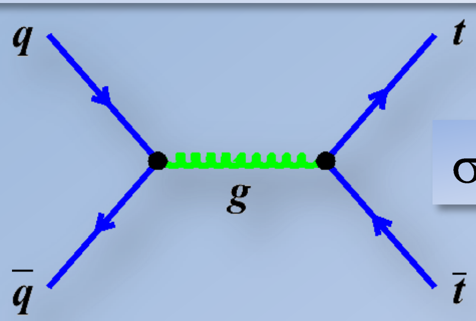
Tight connection to the Higgs-Boson and Electroweak Symmetry Breaking

It decays before it hadronizes.

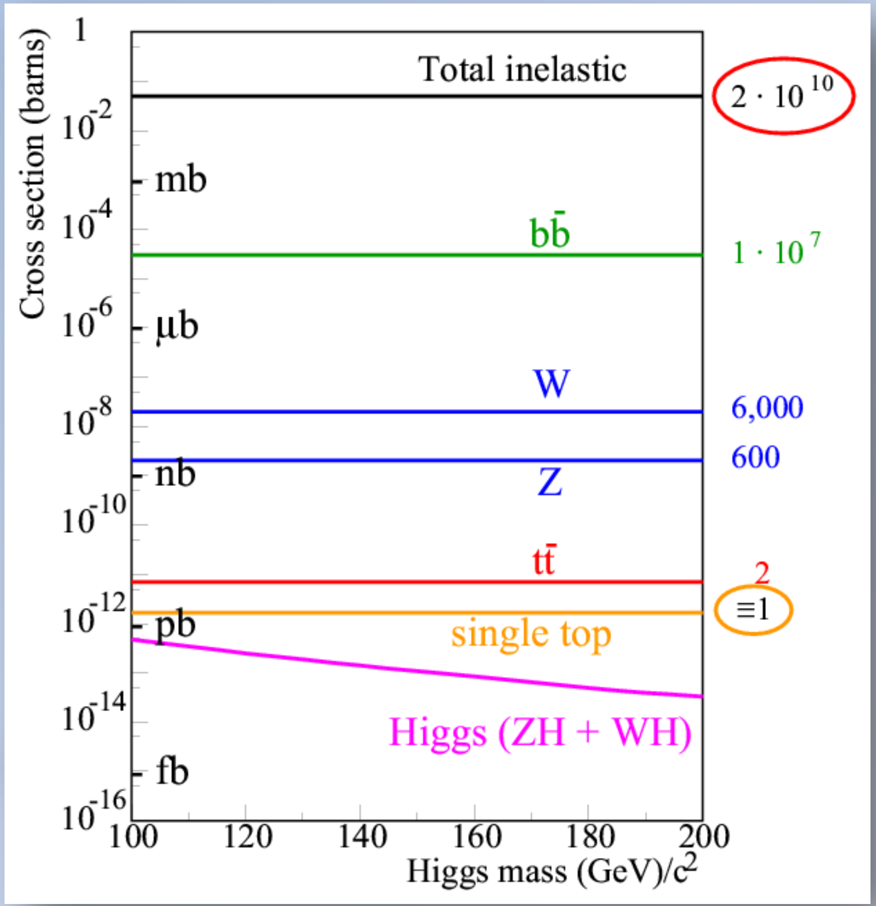
It is still a teenager, discovered in 1995, and still not many have been seen!

Top Quark Production

Production via the strong interaction

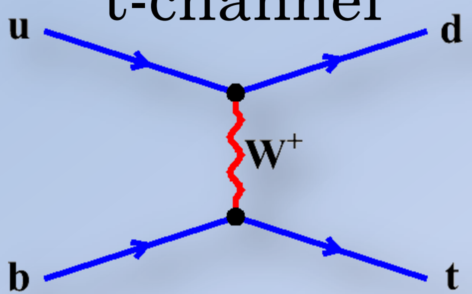


$\sigma_{tt} = 6.7 \pm 0.8$ pb

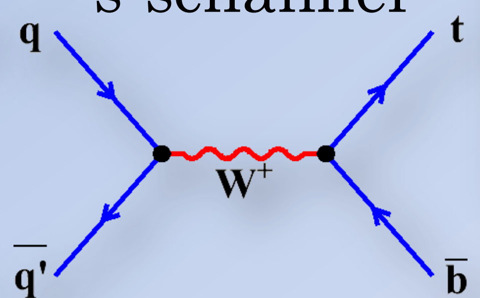


Produktion via the weak interaction

t-channel



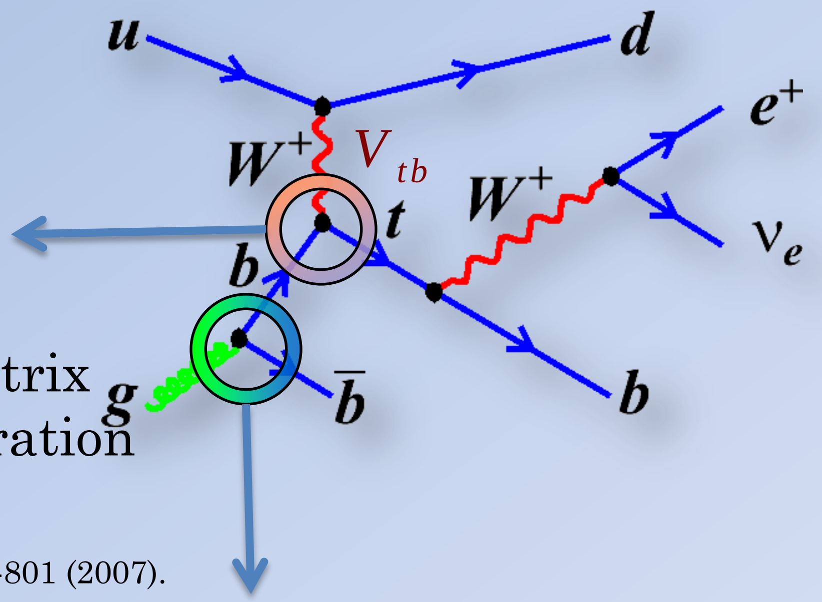
s-schannel



$\sigma_t = 2.0 \pm 0.3$ pb $\sigma_s = 0.9 \pm 0.1$ pb

B.W. Harris et al. Phys. Rev. D 66, 054024 (2002), Z. Sullivan, Phys. Rev. D 70, 114012 (2004)
compatible results: Campbell/Ellis/Tramontano, Phys. Rev. D 70, 094012 (2004)
N. Kidonakis, Phys.Rev. D 74, 114012 (2006)

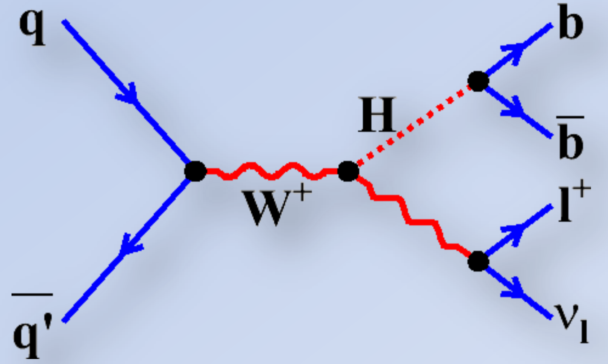
Why measure single top ?



- Test of standard model predictions
  - Does this process exist?
  - Cross section $\propto |V_{tb}|^2$
  - Test of the unitarity of the CKM Matrix
    - Hints for existance of a 4th generation
    - A vector t' is also possible?

    J. Alwall et. al., "Is $|V_{tb}| \sim 1$?", Eur. Phys. J. C49 791-801 (2007).

  - Test of the b-quark structure function: DGLAP evolution
- Preparation of Higgs seraches
  - same signature $\rightarrow$ same tools can be used



Why measure single top?

Reason #4 : More work for theorists

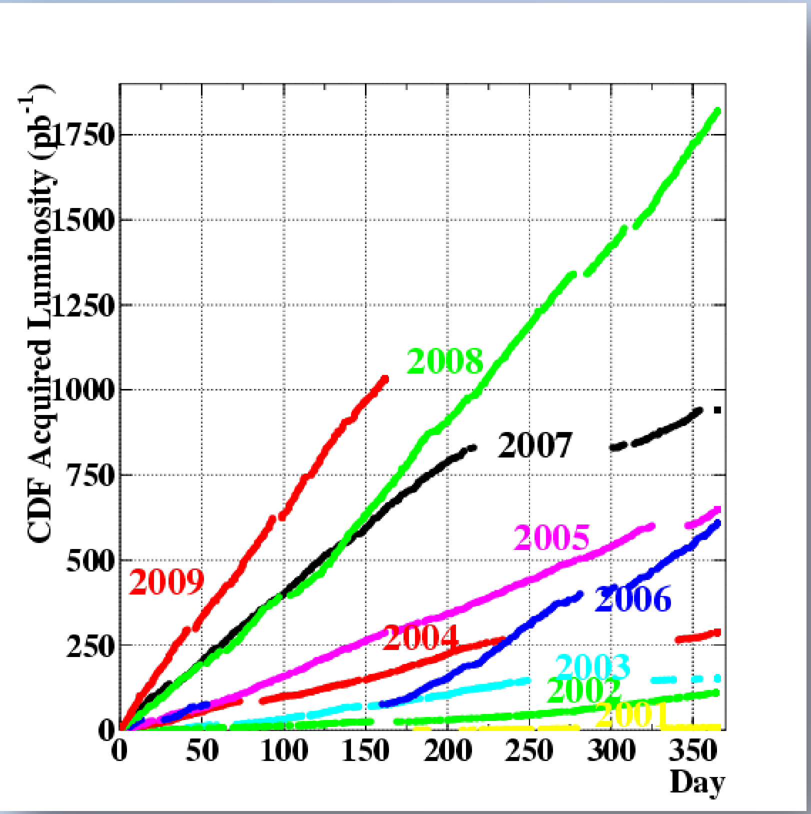
- Extraction of V_{tb}/anomalous coupling very sensitive to theory input.
- Not so much of an issue now, but something for the precision future.
- Top mass important, e.g. 10% change in cross-section for 170→175 GeV.
- Other uncertainties: PDF (beware the bottom quark!), scale, α_s, m_b.

↖ e.g. down by ~10% from 2004 to now

Calculation	Reference	PDF	cross- section	uncert.
s- NLO	e.g. Sullivan, PRD 70 (2004) 114012	CTEQ6.6M	0.42	(+0.4, -0.4)
s- resNLO*	Kidonakis, PRD 74:114012,2006.	MRST2004NNLO	0.52	(+0.03, -0.03)
t- 2→3 NLO	JC et al., arXiv:0903.0005	CTEQ6.6M	0.93	(+0.16, -0.18)
t- 2→2 NLO	e.g. Sullivan, PRD 70 (2004) 114012	CTEQ6.6M	0.99	(+0.12, -0.10)
t- 2→2 resNLO*	Kidonakis, PRD 74:114012,2006.	MRST2004NNLO	1.12	(+0.06, -0.06)

Stolen from Fabio Maltoni

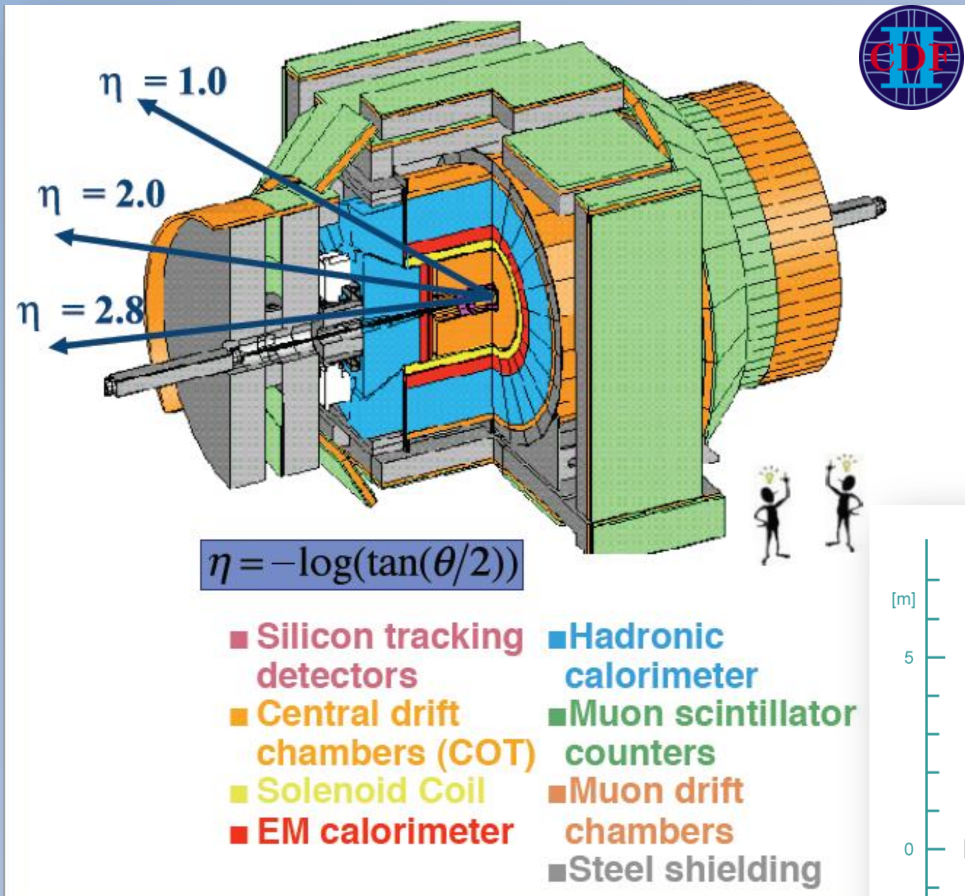
Tevatron



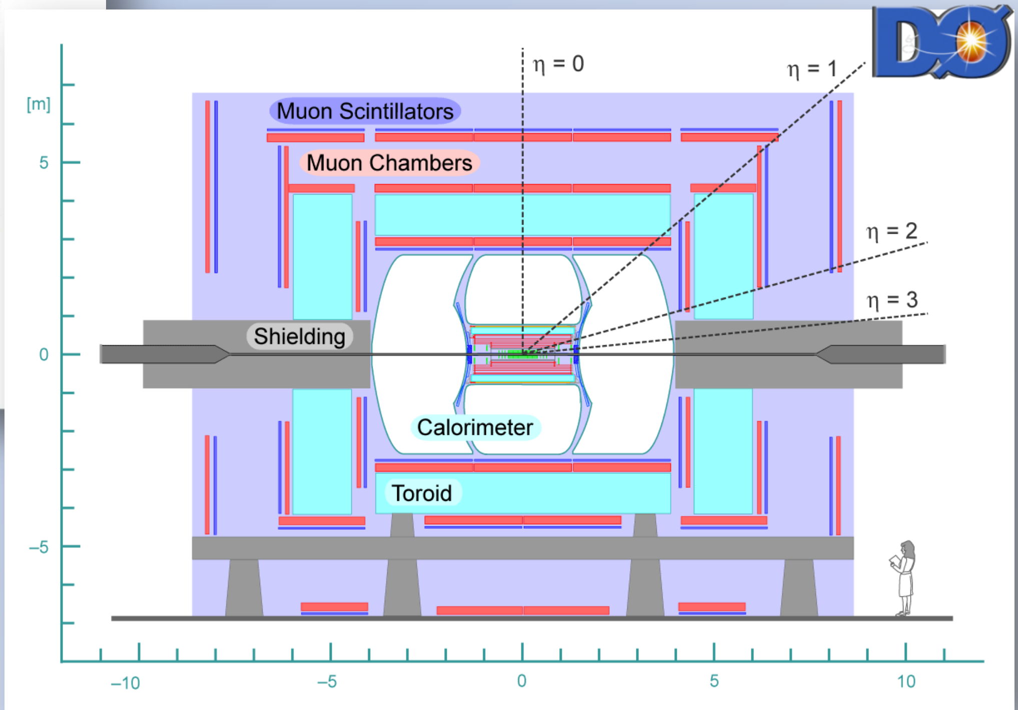
Proton-Antiproton collisions with a rate of 1.7 MHz
Center-of-mass energy: $\sqrt{\hat{s}} = 1.96\,\mathrm{TeV}$

Record Luminosity: $\mathcal{L} = 3.53 \cdot 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
World Record for hadron colliders!

The experiments

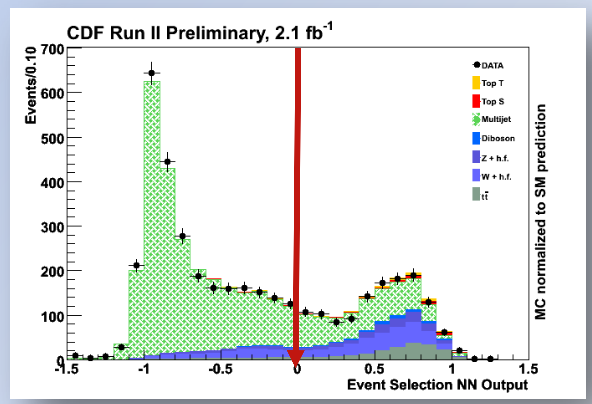


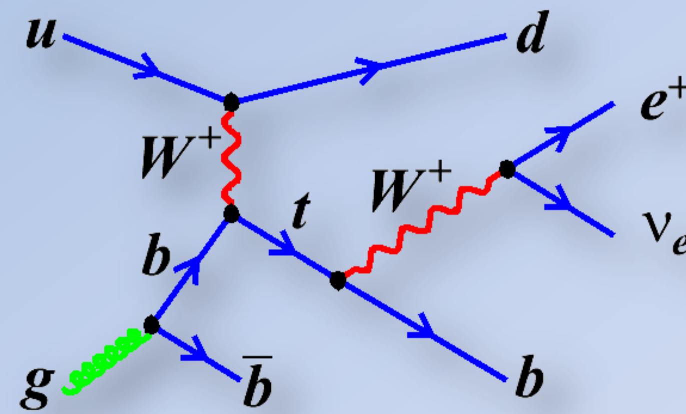
For single top analyses:
The whole detector has to be used!

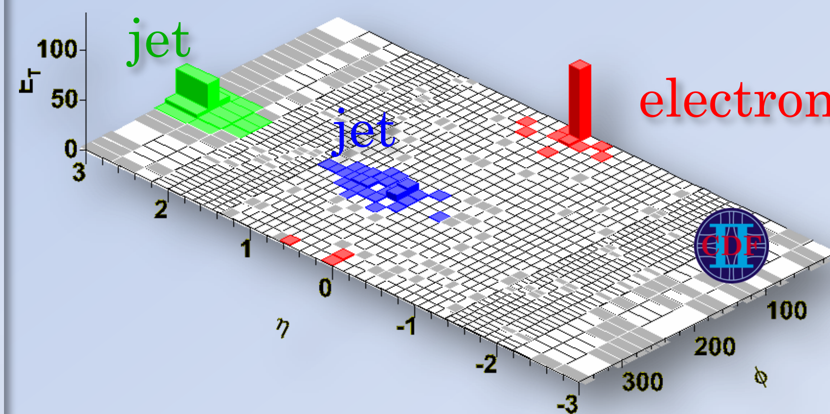


Event selection / signature

- High p_T lepton + MET + jets Selection:
  - Exact 1 lepton (electron / muon)
  - Missing transverse energy
  - 2 - 4 jets
  - At least one identified b jet
  - Veto against cosmic muons / Z bosons
  - Cuts to reduce QCD background
- MET + jets Selection:
  - Missing transverse energy
  - Veto against leptons
  - 2 or 3 jets
  - Cut on NN output to suppress QCD

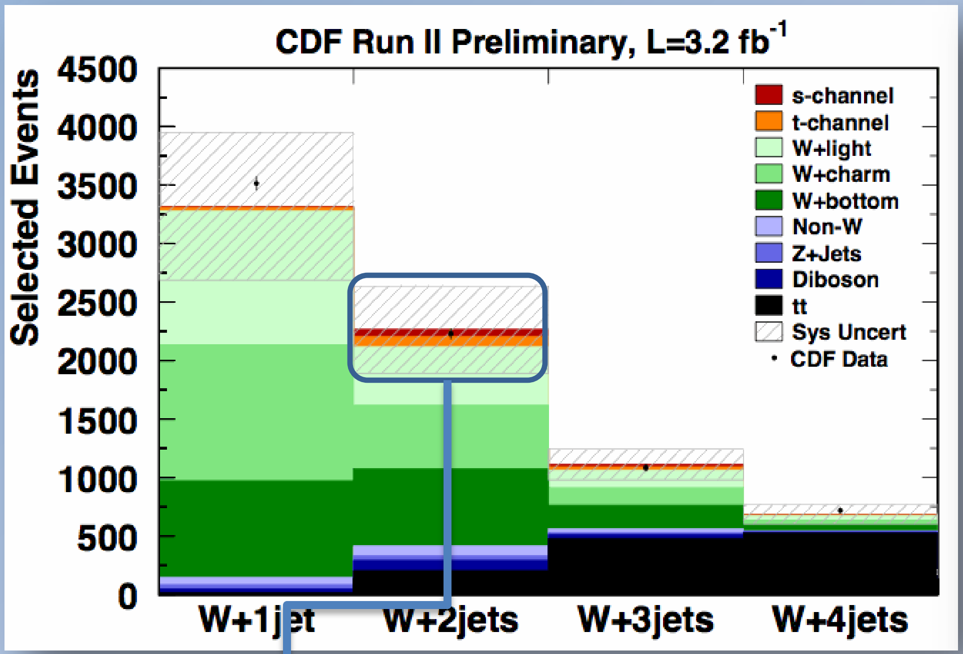






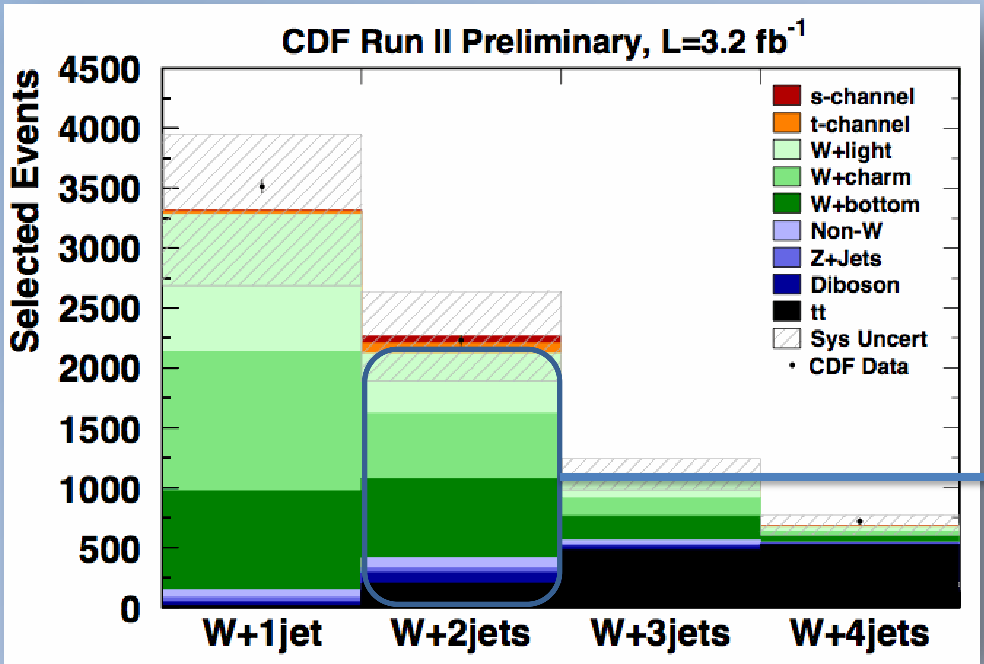
Both experiments have increased their acceptance !

Why is it such difficult?

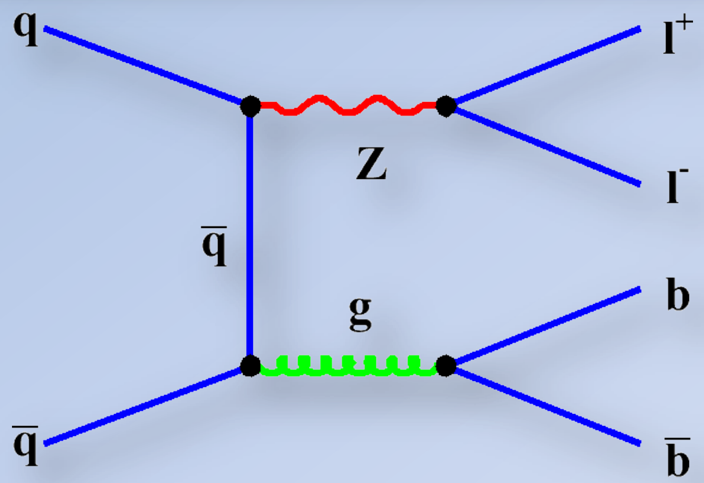


Single top signal is hidden behind a huge background
→ precise estimation of the background rates
→ good model for the backgrounds

Background composition

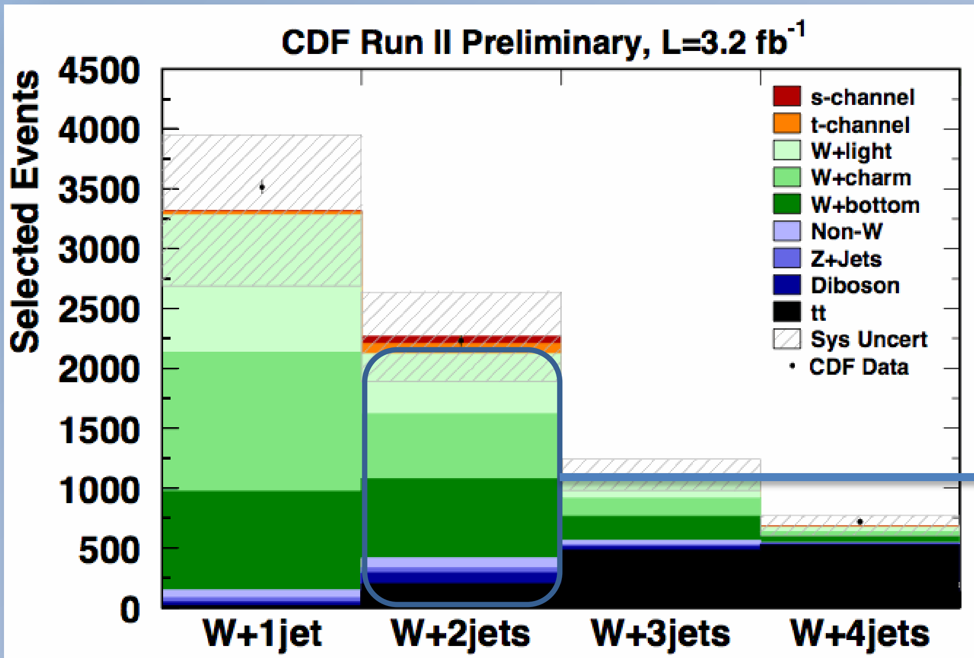


Most sensitiv channel:
Events with 2 Jets and
one W boson



Z+bb

Background compostion



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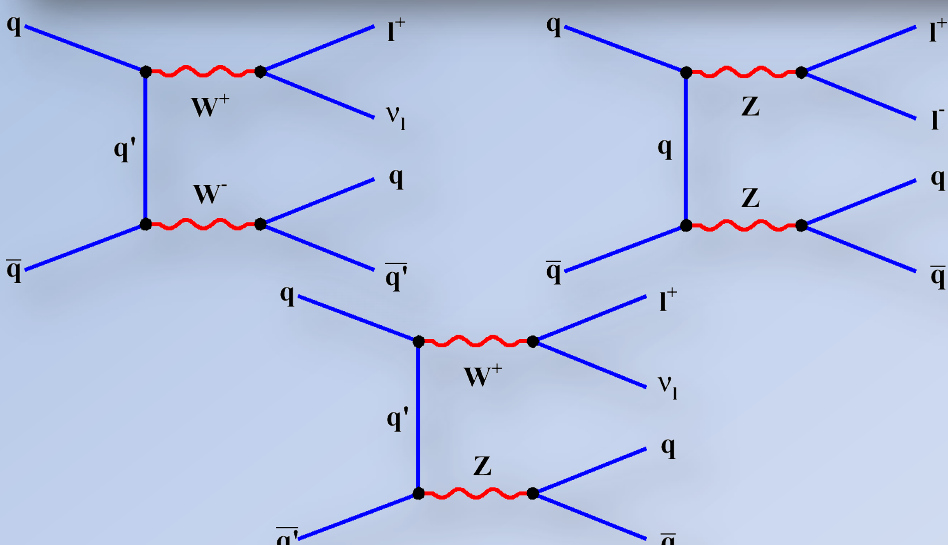

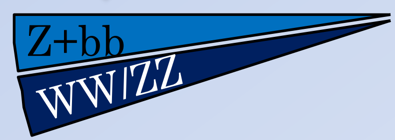

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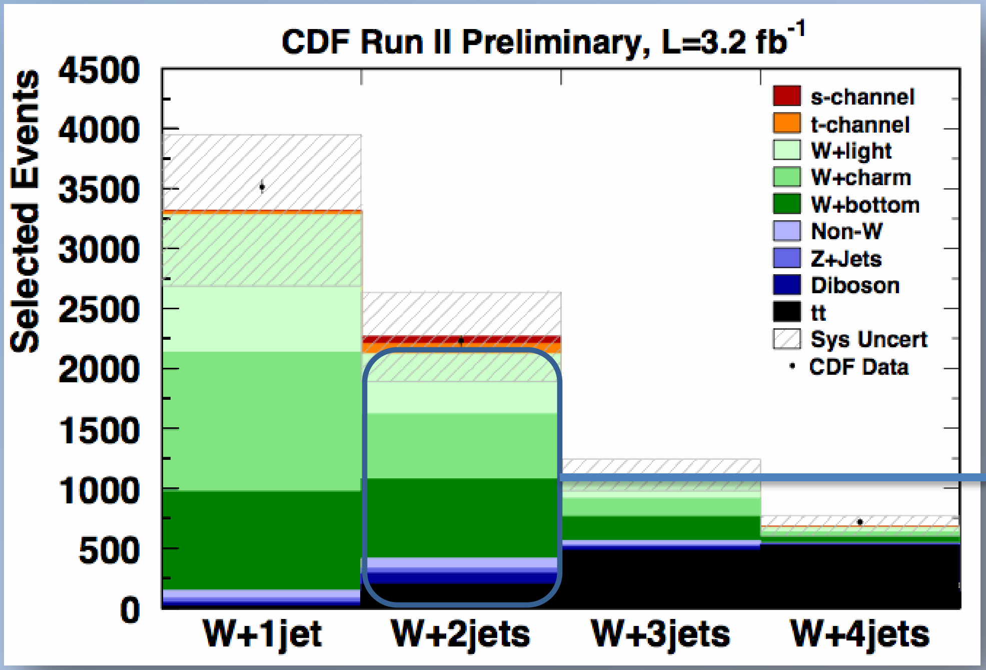

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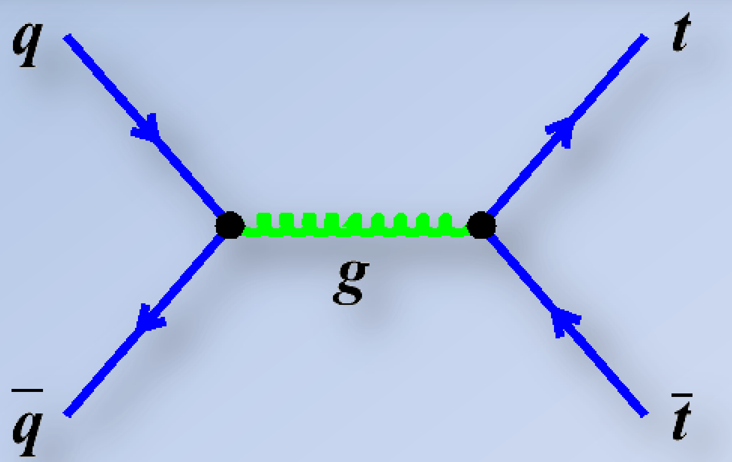

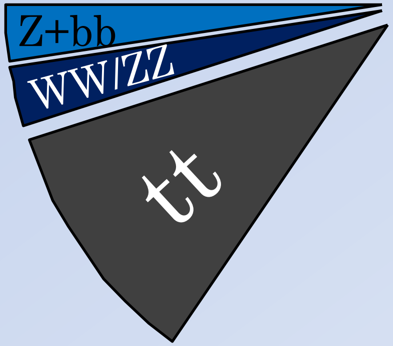

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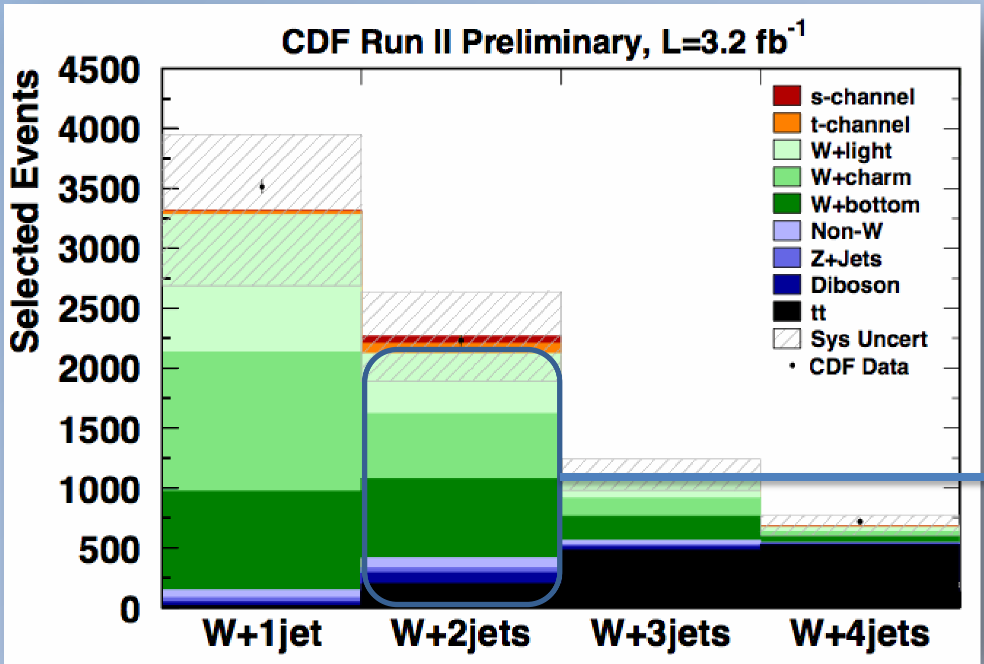

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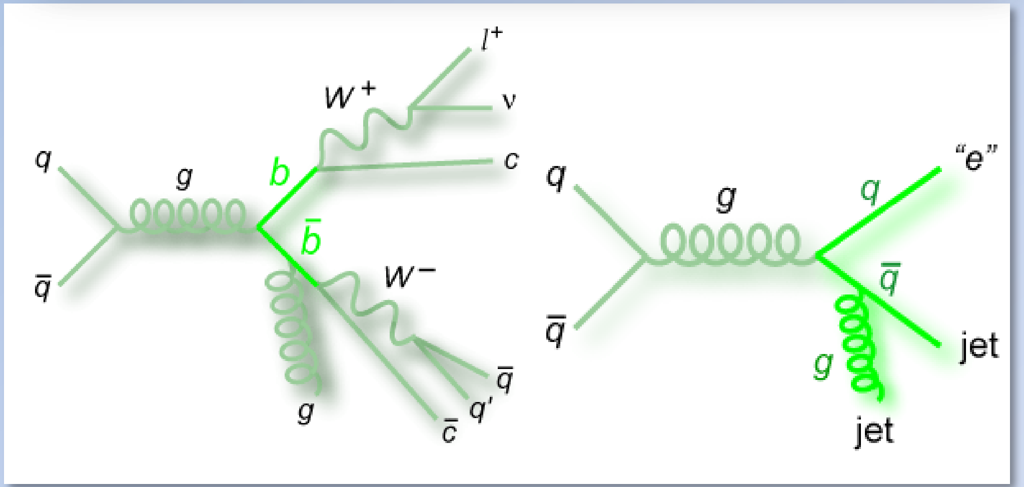
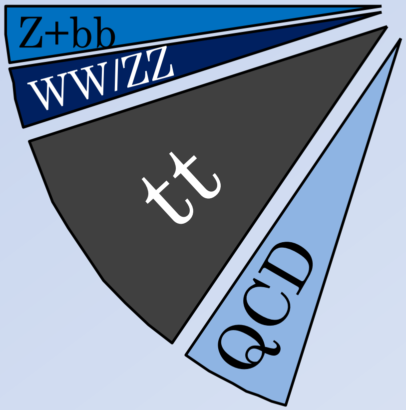
Events with 2 Jets and one W boson





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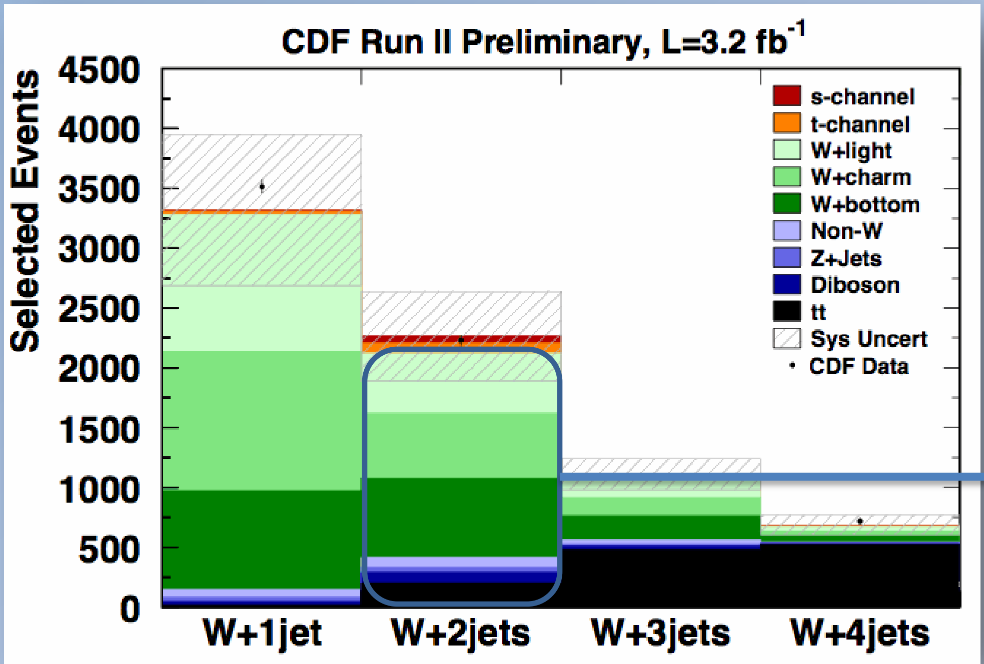

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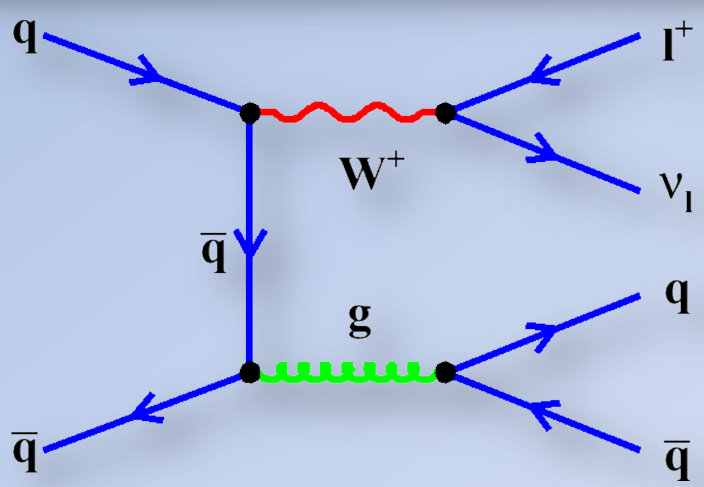

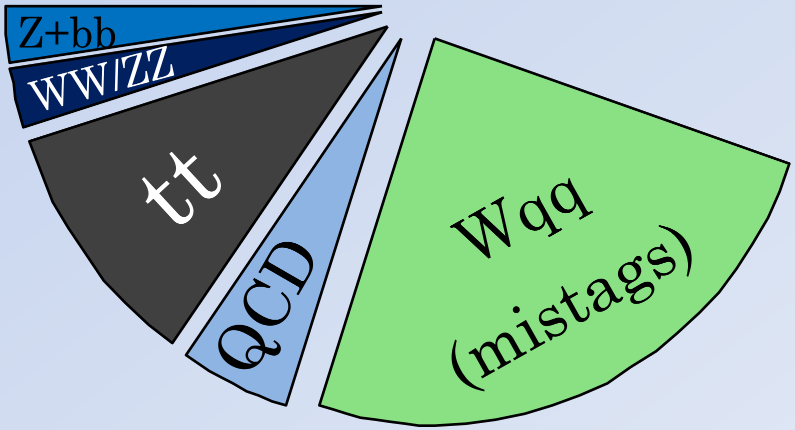

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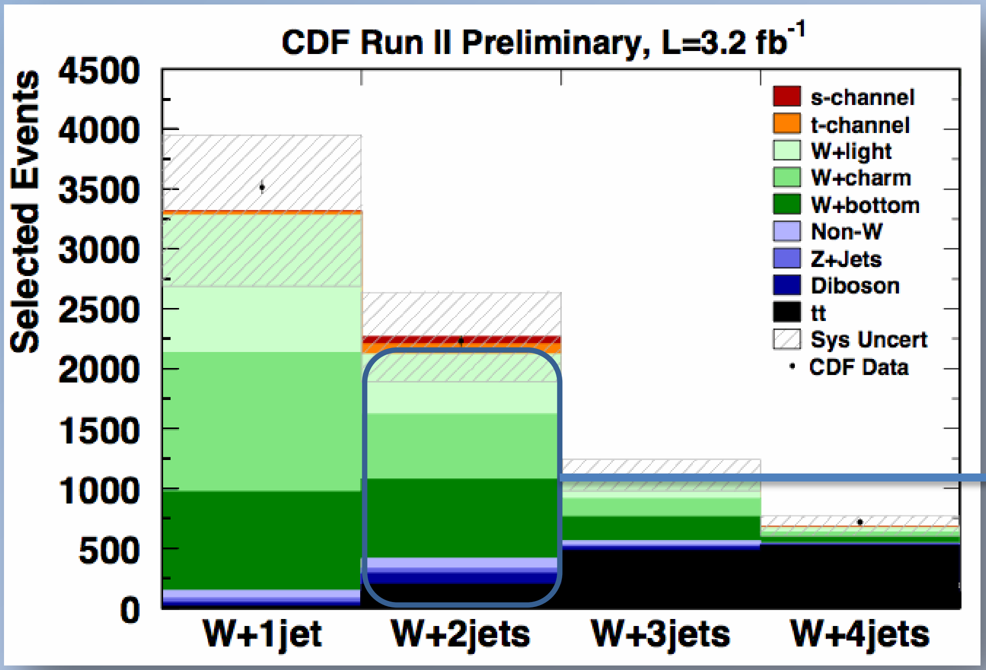

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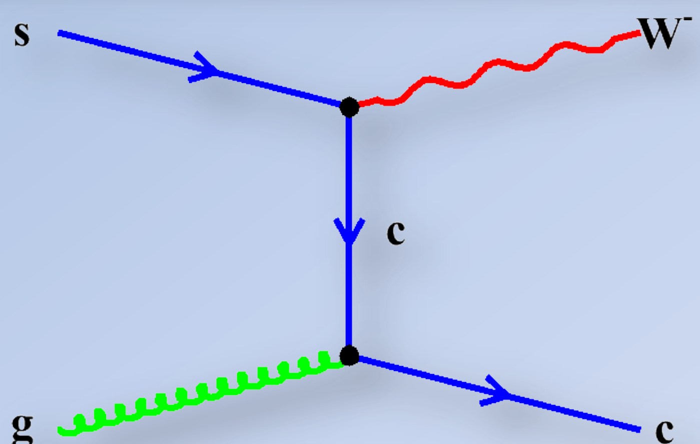

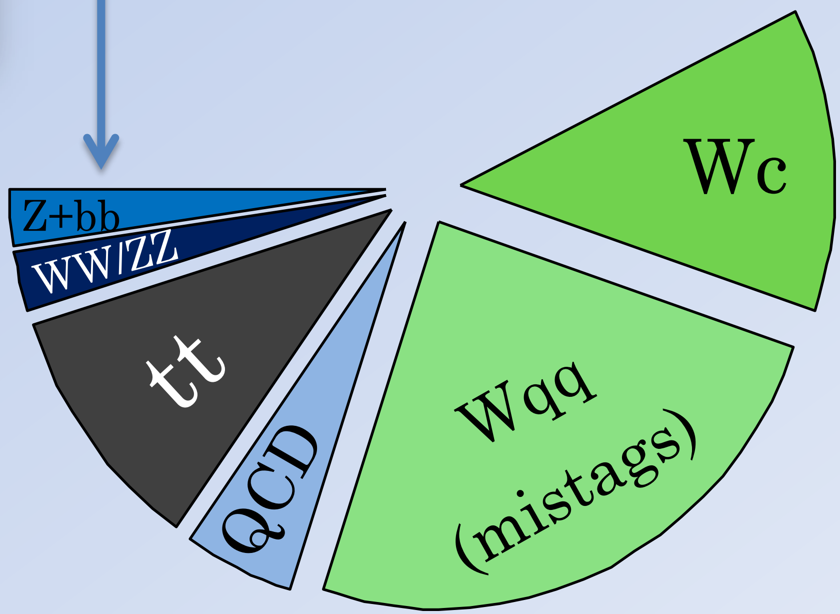

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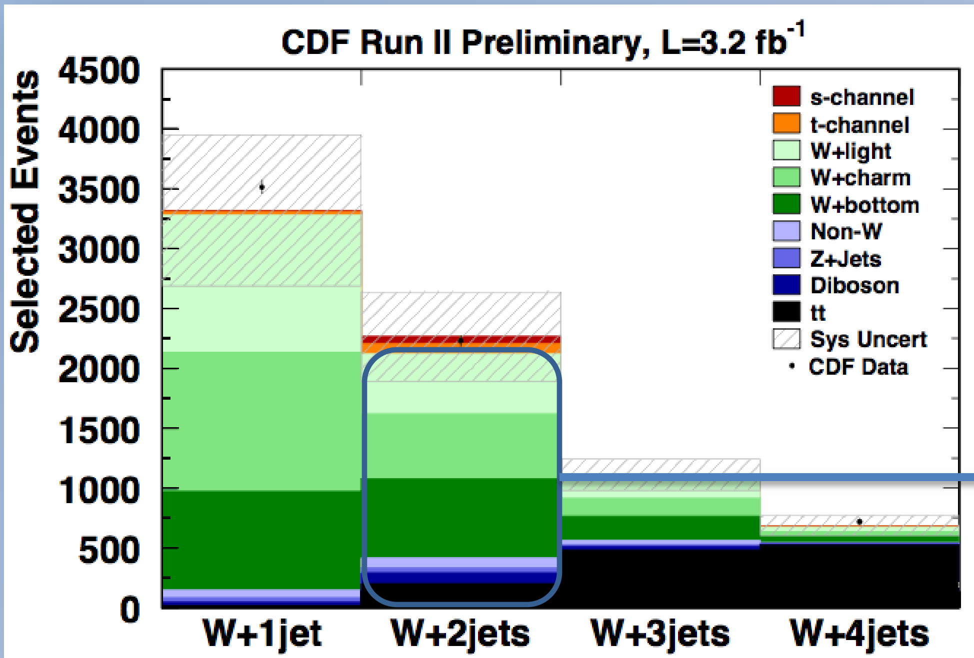

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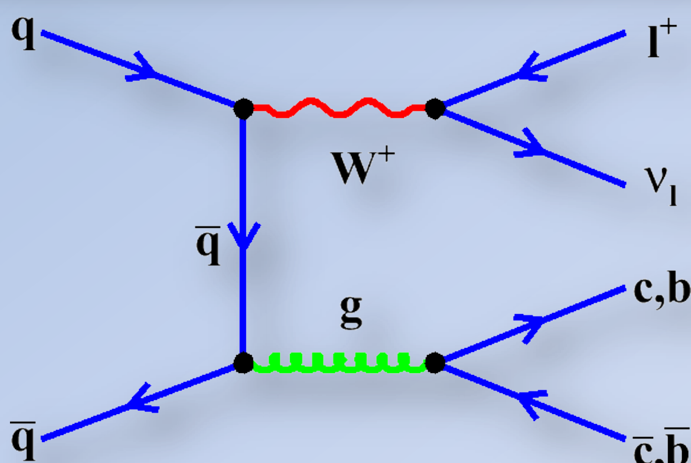
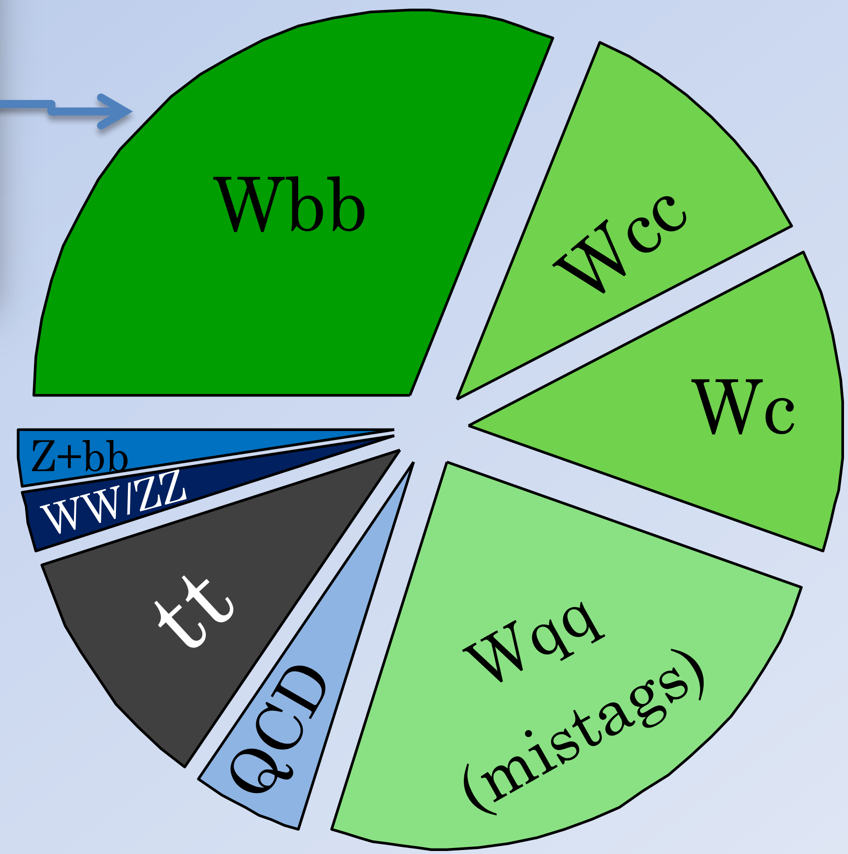
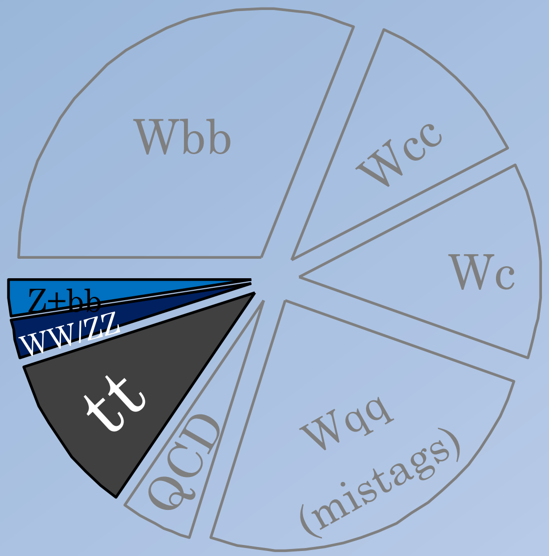




Theoretically simple processes



Top pair production
Electroweak processes
(WW / WZ / ZZ, Z→bb)

Rate:
Theoretical cross section,
Efficiencies from Monte Carlo events

$$N = \sigma \cdot \varepsilon \cdot \mathcal{L}$$

Model:
Pythia Monte Carlo
Alpgen+Pythia (DØ for top pair production)

The only backgrounds which can be completely described by Monte Carlo simulations.

QCD Multijet / Instrumental background

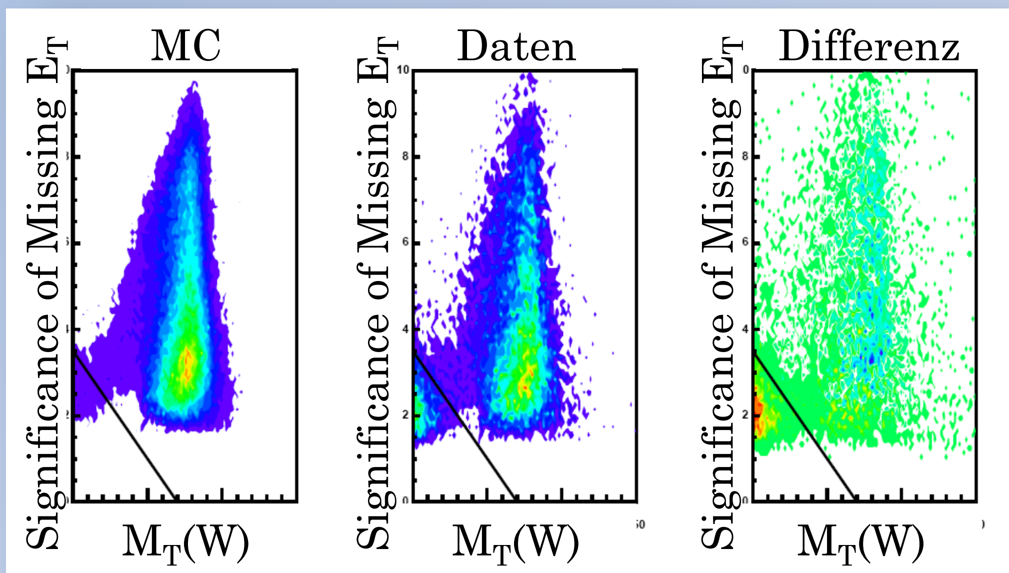
Rate:

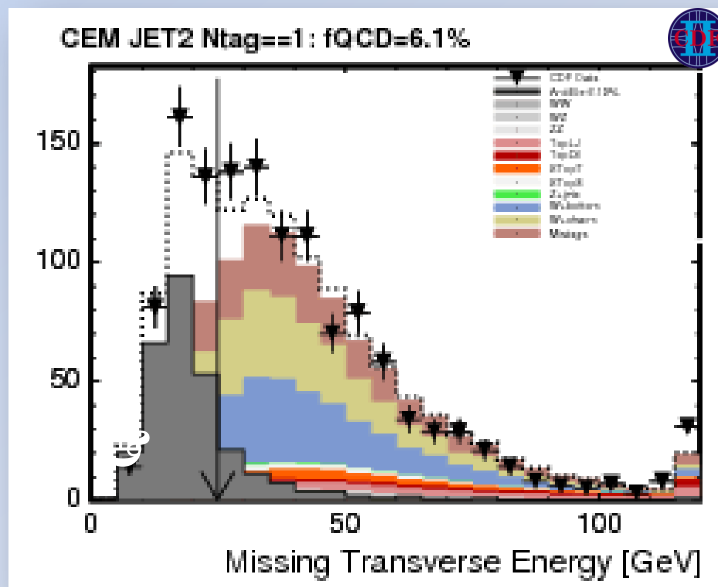
Fit to the distribution of missing transverse energy

Model:

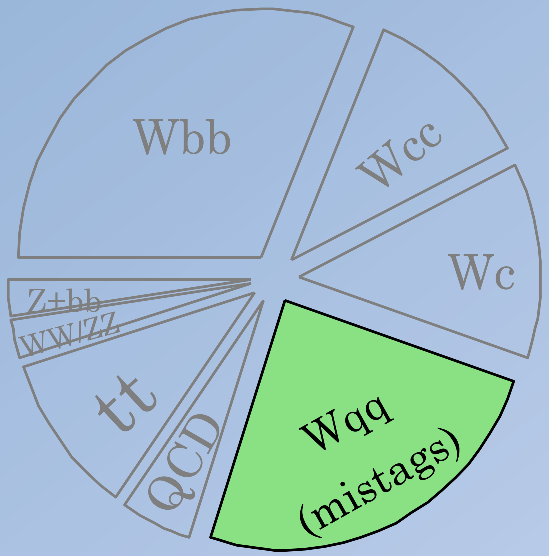
„Jetele“ : jet trigger data,
electromagnetic jet → electron

„AntiEle“: lepton trigger data
EM objects, which doesn’t pass all ID cuts



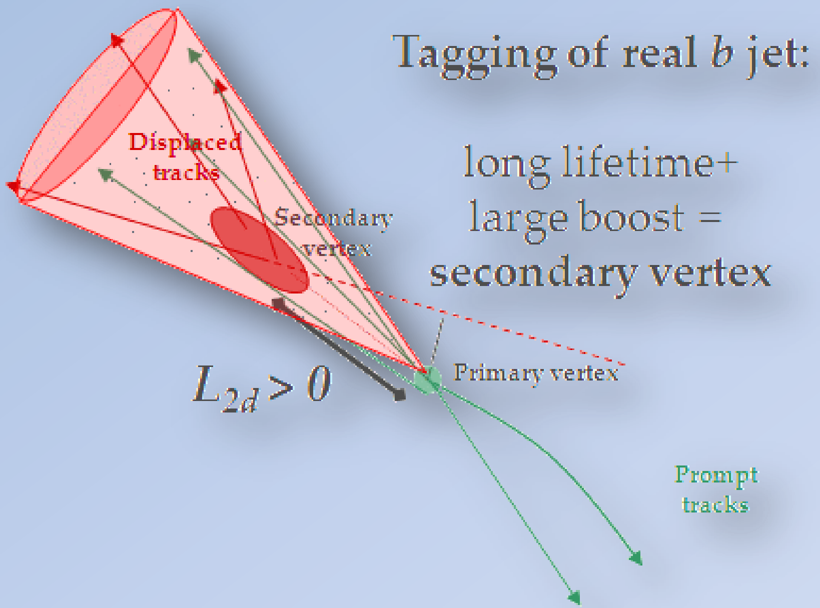


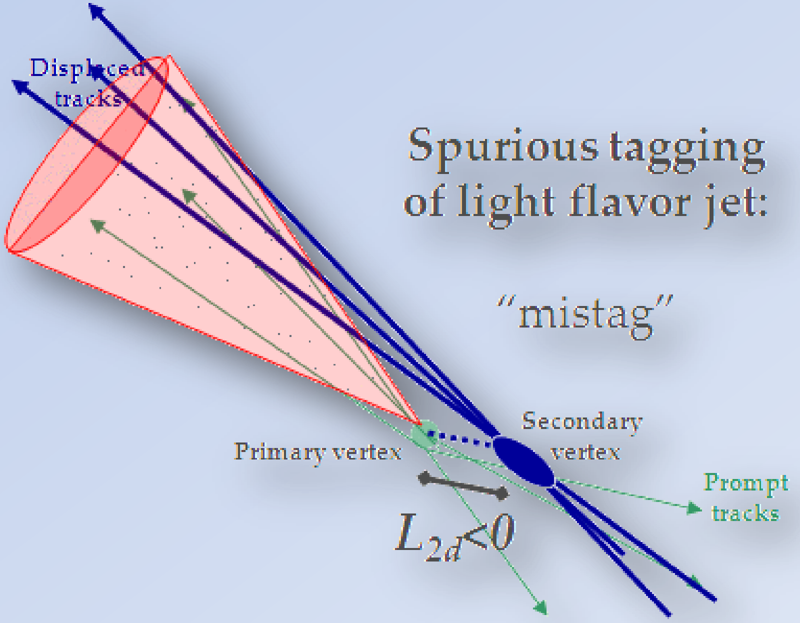
W + light flavor jets / Mistags



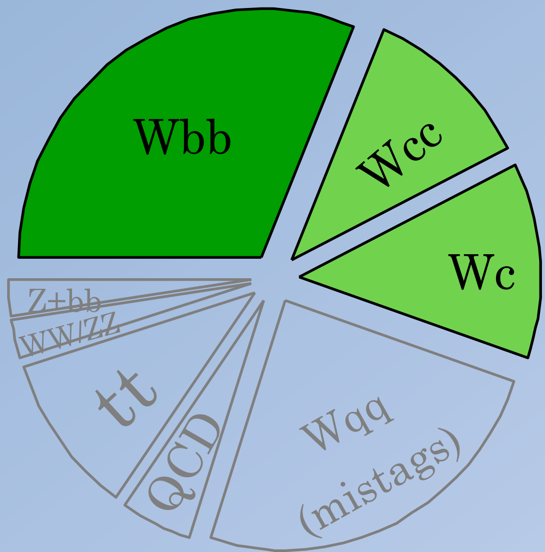
Rate:
Mistag matrix,
taken from jet trigger data
Mistags can't be simulated with MC

Model:
Alpgen + Pythia Monte Carlo without btag
btag → thrown according to mistag matrix





W + heavy flavor jets



Rate:

Normalizing on „pretag data“

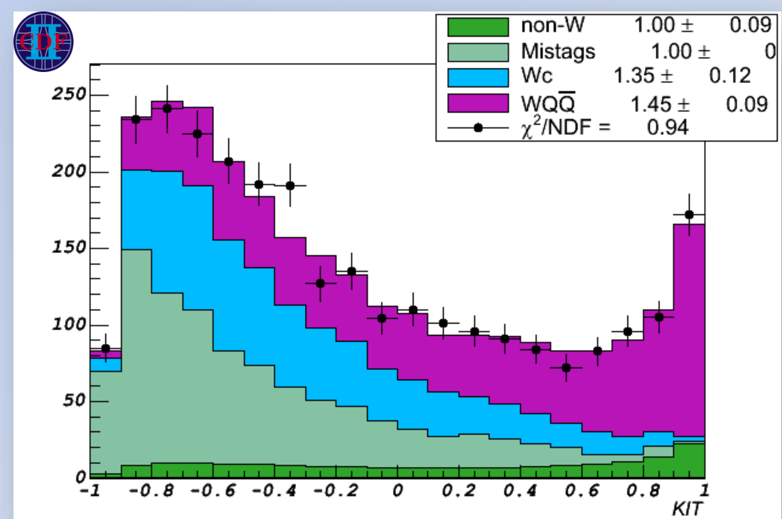
→ LO – NLO - factor

Determiniation of the heavy flavor fractions in W+1jet events → heavy flavor K-factor

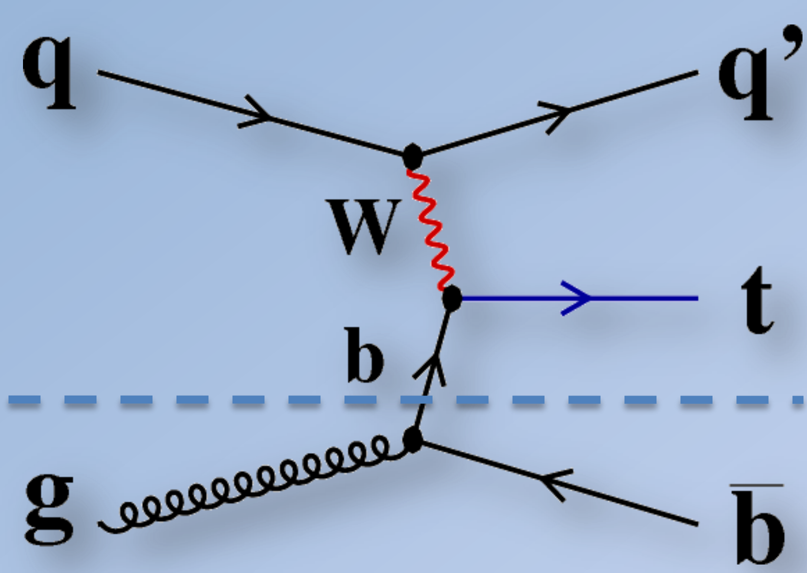
Normalizing to theory (MCFM-NLO)

Model:

Alpgen + Pythia Monte Carlo



Signal Model



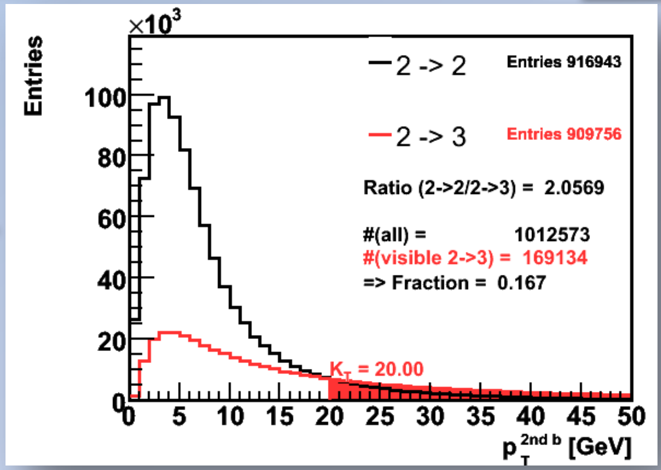
2→2 and 2 →3
processes have to be matched

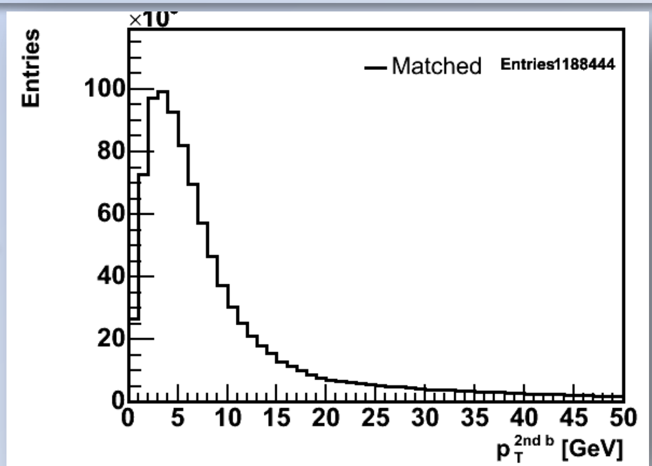
Rate (for a-priori sensitivity):
Theoretical cross section,
Efficiencies from Monte Carlo events

$$N = \sigma \cdot \varepsilon \cdot \mathcal{L}$$

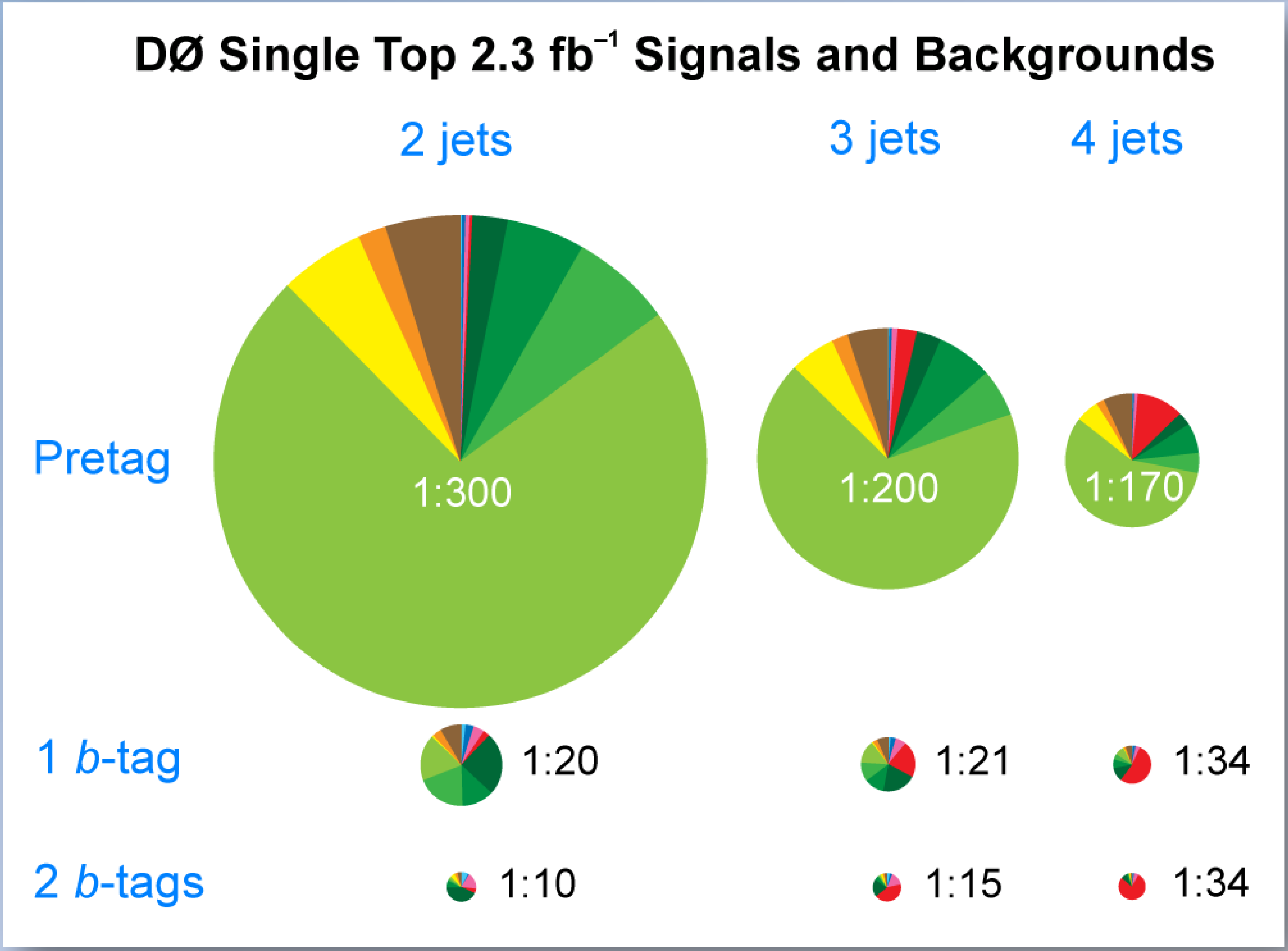
Model:
- MadEvent + Pythia (CDF)
- CompHEP + Pythia (DØ)

→ both methods try to reproduce the NLO kinematics





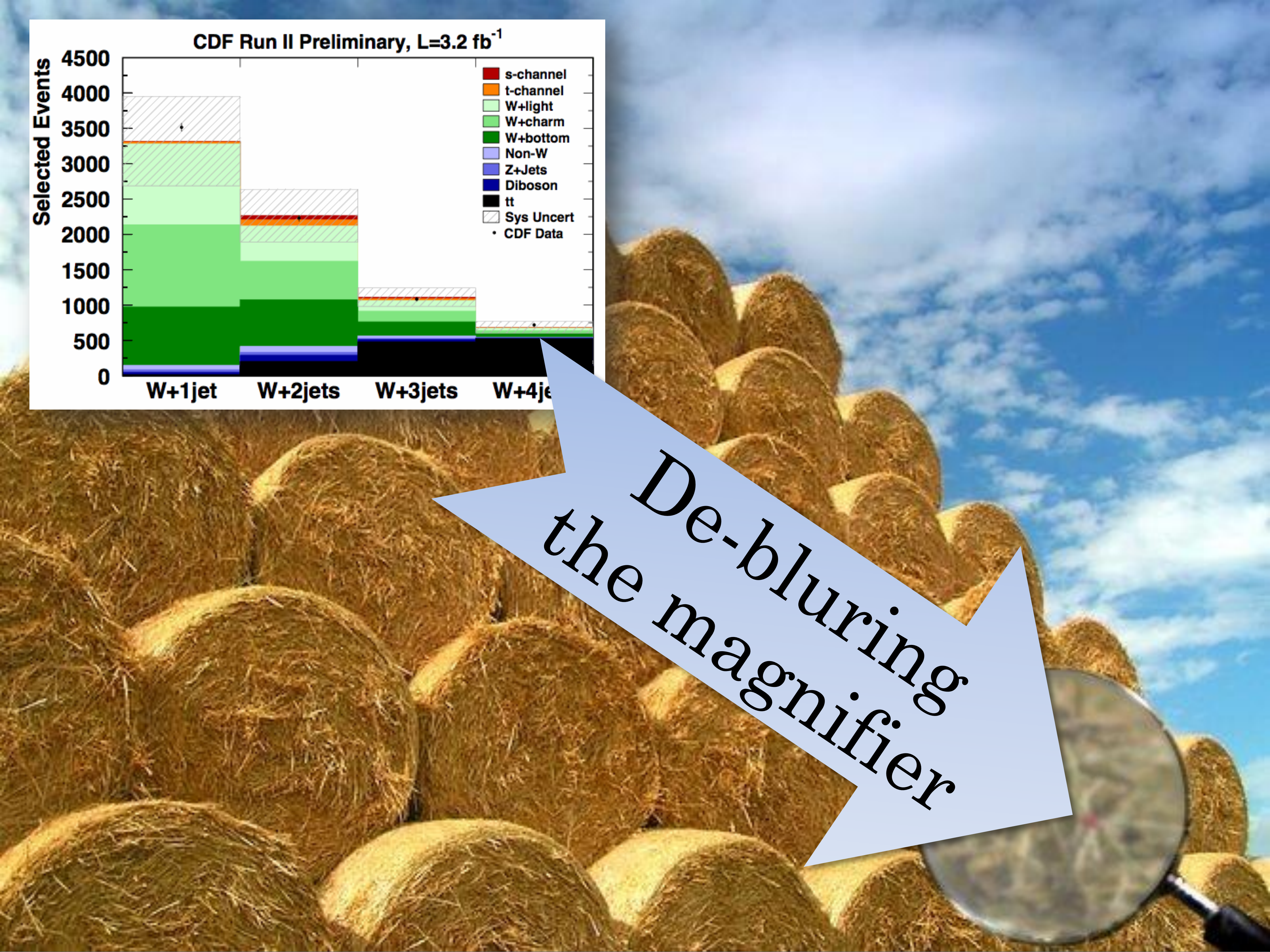
Summary of different channels



Expected number of events

Single Top Observation – Event Yields			
	DØ 2.3 fb^{-1}	CDF 3.2 fb^{-1}	CDF 2.1 fb^{-1}
	Lepton+$\not{E}_T$+jets / *b*-tagged		$\not{E}_T$+jets / *b*-tagged
tb + *tqb* signal *1,*2	223 ± 30	191 ± 28	64 ± 10
W+jets	2,647 ± 241	2,204 ± 542	304 ± 116 *4
Z+jets, dibosons	340 ± 61	171 ± 15	171 ± 54
$t\bar{t}$ pairs *1,*2, *3	1,142 ± 168	686 ± 99	185 ± 30
Multijets	300 ± 52	125 ± 50	679 ± 28 *5
Total prediction	4,652 ± 352	3,377 ± 505	1,403
Data	4,519	3,315	1,411

*1 DØ's *tb*+*tqb* signal and $t\bar{t}$ background use m_{top} = 170 GeV (and signal $\sigma_{(N)NLO}$)
*2 CDF's *tb*+*tqb* signal and $t\bar{t}$ background use m_{top} = 175 GeV (and signal σ_{NLO})
*3 DØ's analysis includes 4-jet events, so the $t\bar{t}$ yield is higher
*4 CDF's $\not{E}_T$+jets channel *W*+jets yield does not include *Wjj* where *j* = light jet
*5 CDF's $\not{E}_T$+jets channel Multijets yield includes *Wjj* events


CDF Run II Preliminary, L=3.2 fb^{-1}
Selected Events
4500
4000
3500
3000
2500
2000
1500
1000
500
0
s-channel
t-channel
W+light
W+charm
W+bottom
Non-W
Z+Jets
Diboson
tt
Sys Uncert
CDF Data
W+1jet
W+2jets
W+3jets
W+4je
De-bluring
the magnifier

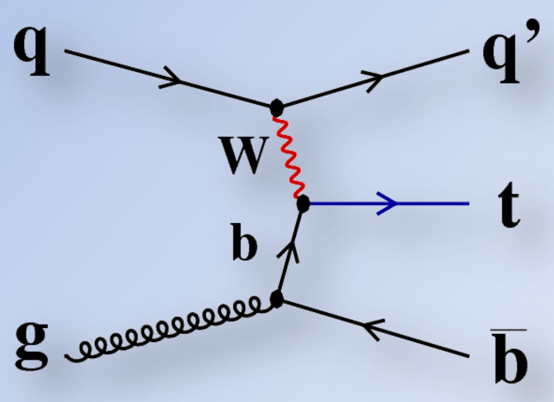
Shape Fit

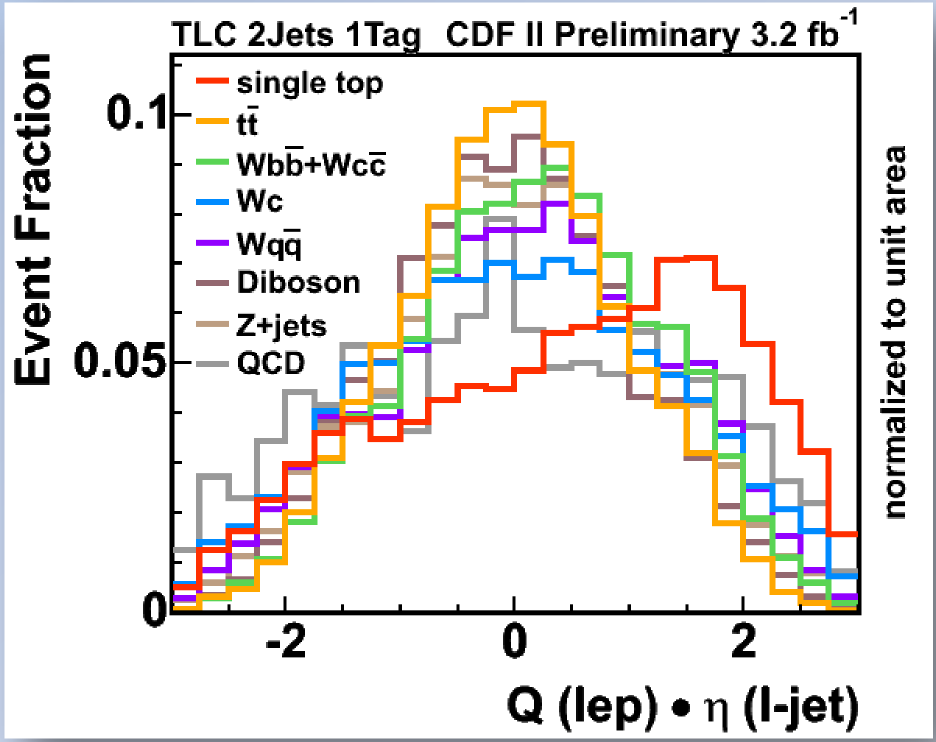
$$L(signal, bkg1..bkg4) = \prod_{k=1}^{B} \frac{e^{-\mu_k} \mu_k^{n_k}}{n_k!} \prod_{j=1}^{4} G(bkg_j \mid 1, \Delta_j)$$

Use shape fit to gain sensitivity also for the background calibration

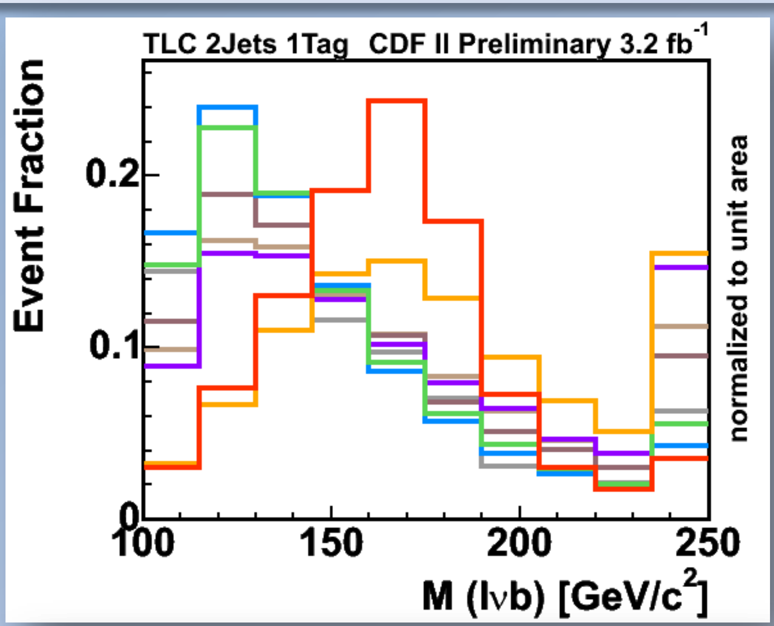
Parts of distribution can have much better purity

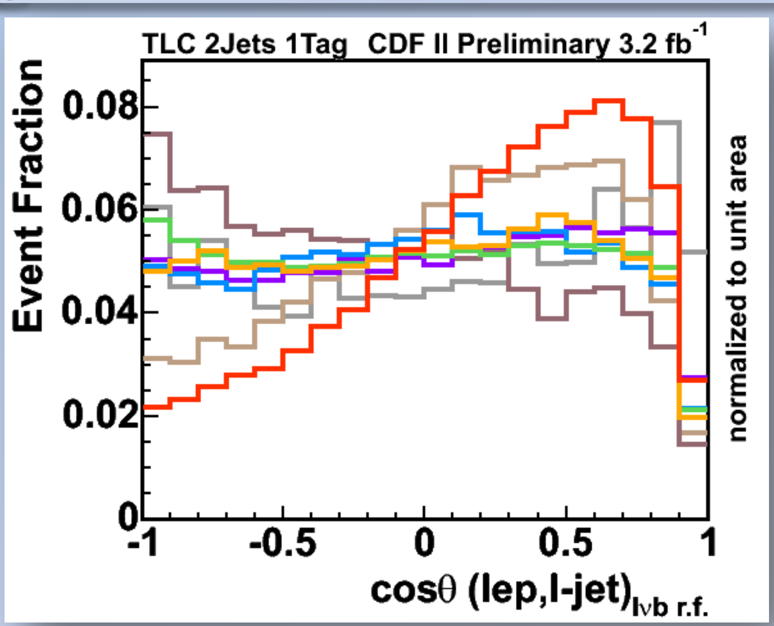
Which variable is the best one?

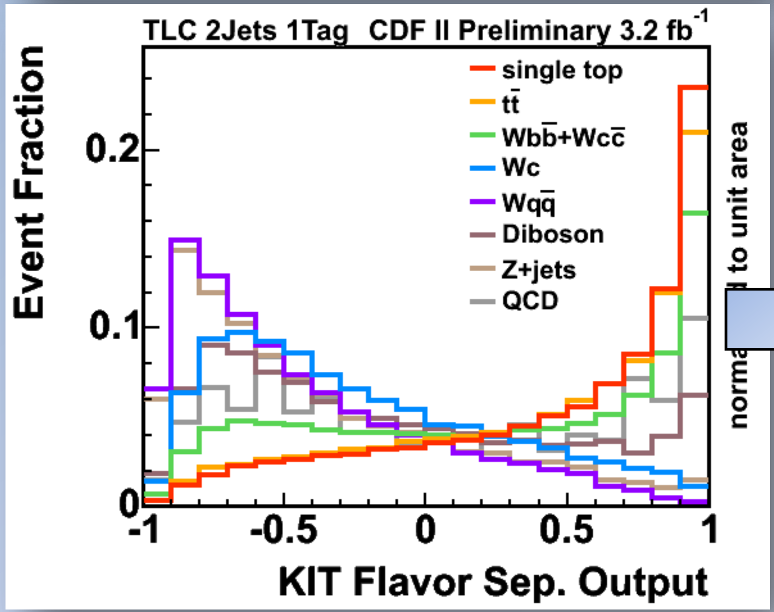




Discriminating variables

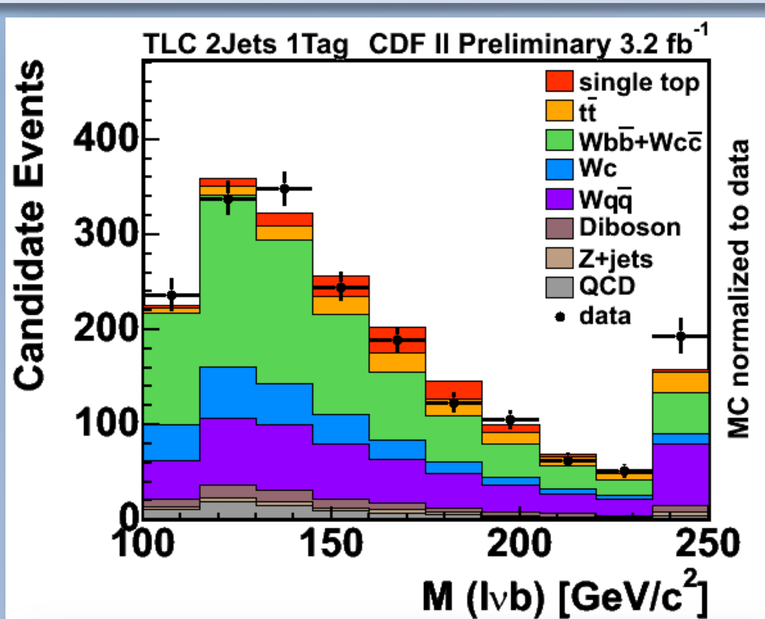


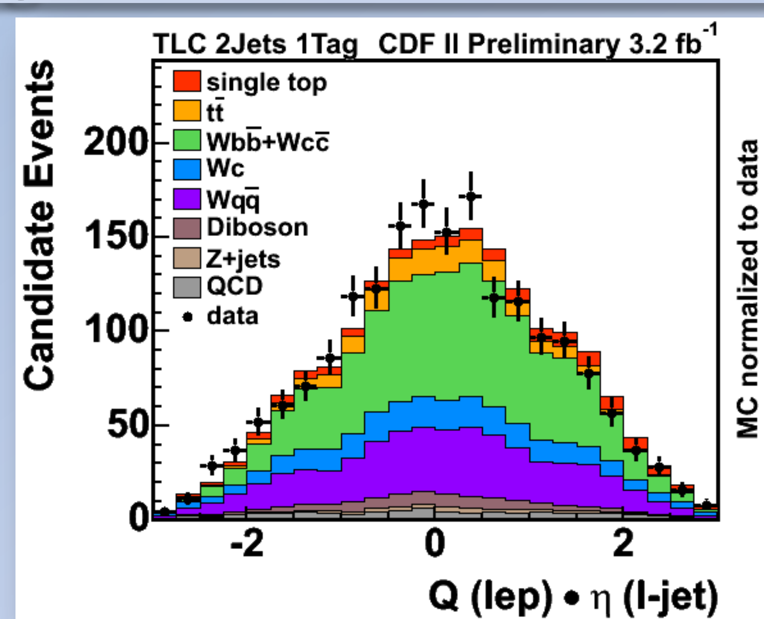


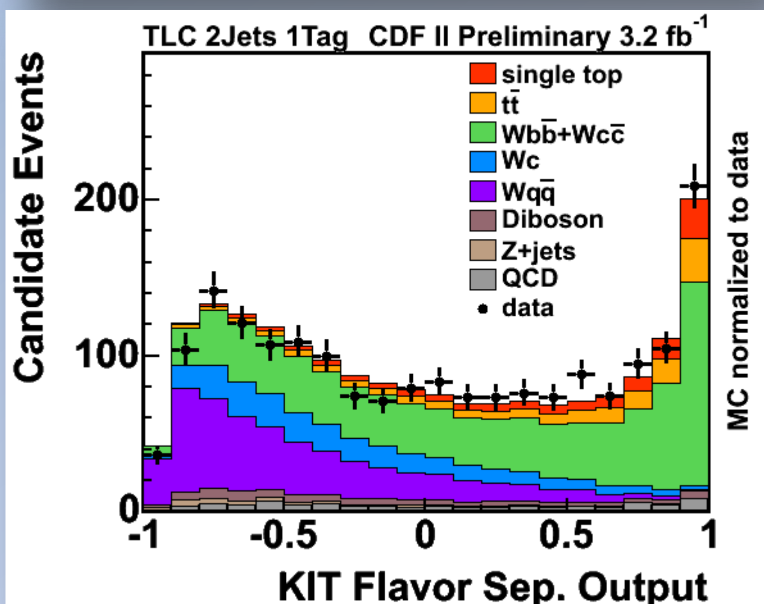


Flavor separator:
All events contain a b-tagged jet
Only 50% contain a real btag
→ Neural network using:
L_{xy}, vertex mass, track multiplicity, impact parameter, semi-leptonic decay information, etc ….

Discriminating variables







No single variable powerful enough.

Each variable contains useful information.

Need to combine information from many variables.

→ Multivariate Analyses

Search strategy

Signal Model

Background Model

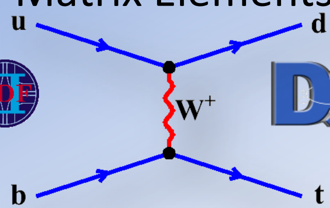
Measured Events

Event Selection

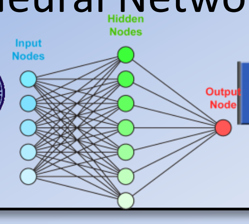
Check of input variables

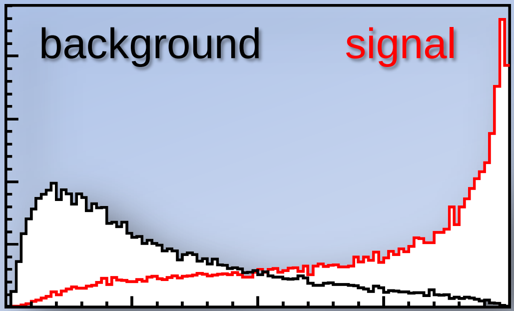
Mulitvariate Analyses

Matrix Elements



Neural Networks



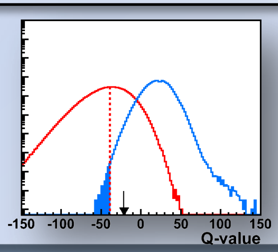


Boosted Decision Trees

Likelihood Discriminate

$$\mathcal{L}_k(\{x_i\}) = \frac{\prod_{i=1}^{n_{var}} p_{ik}}{\sum_{m=1}^{5}\prod_{i=1}^{n_{var}} p_{im}}$$

Ensemble tests



Blind analysis !

Search strategy

Signal Model

Background Model

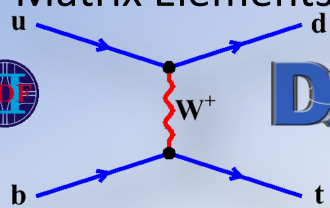
Measured Events

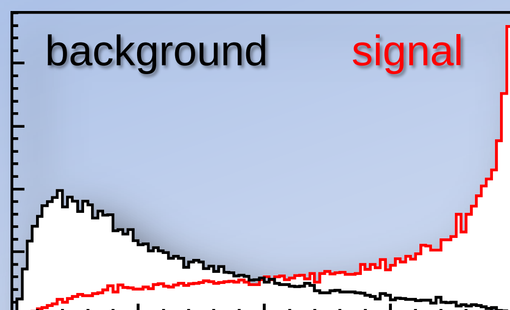
Event Selection

Check of input variables

Mulitvariate Analyses

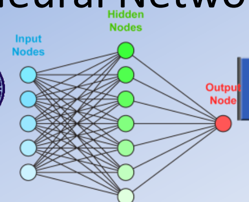
Matrix Elements





Boosted Decision Trees

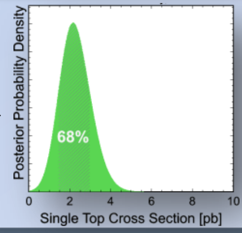
Neural Networks

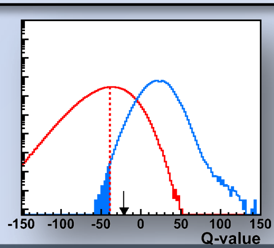


Likelihood Discriminate

$$\mathcal{L}_k(\{x_i\}) = \frac{\prod_{i=1}^{n_{var}} p_{ik}}{\sum_{m=1}^{5} \prod_{i=1}^{n_{var}} p_{im}}$$

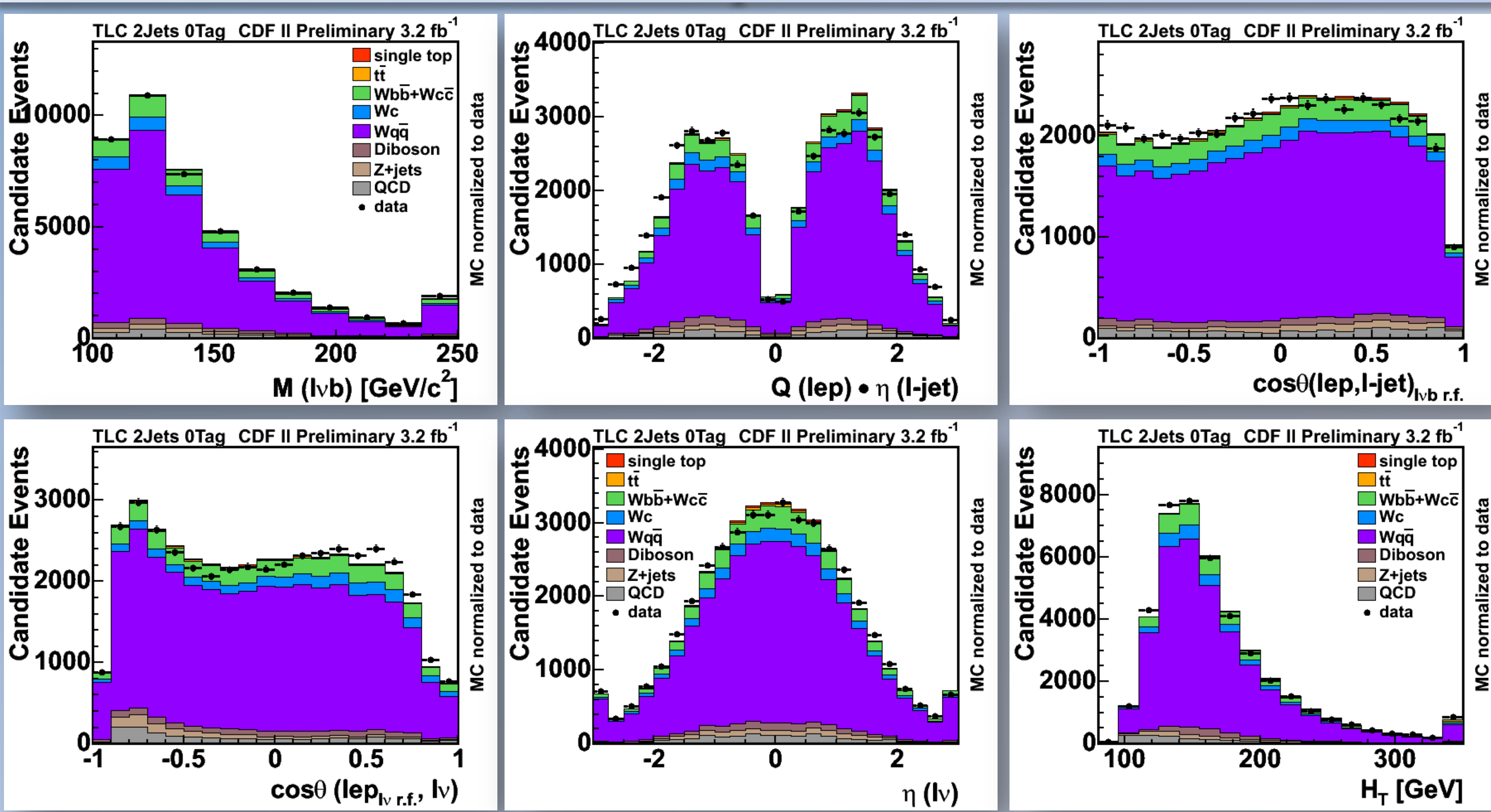
Extraction of cross section





Ensemble tests

Check of input variables



Each variable in each channel has to checked in different side bands

Overview about Multivariate Analyses

CDF

High p_T lepton + MET + jets:
- single & double tagged
- W+2jet & W+3jet
- 2 lepton categories

MET + jets:
- W+2 jet & W+3jet

Neural Networks → NEAT
Matrix Elements → NEAT
Bosted Decision Trees → NEAT
Likelihood Function → NEAT

MET+jets Neural Networks

DØ

High p_T lepton + MET + jets:
- single & double tagged
- W+2jet & W+3jet & W+4jets
- 2 lepton categories
- 2 data taking periods

Bayesian Neural Networks → BNN
Matrix Elements → BNN
Bosted Decision Trees → BNN

Matrix Element Method

Idea: Compute an event probability P for signal and background hypothese

Integration over part of the phase space Φ_4

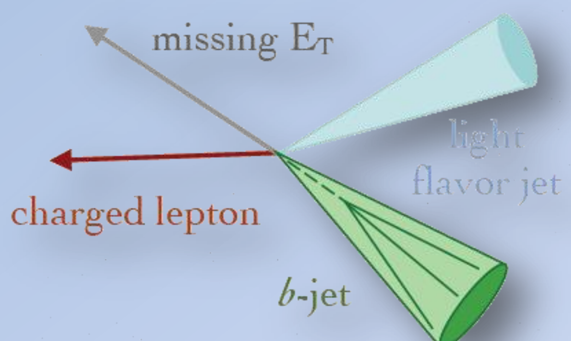
Parton distribution functions (CTEQ6)

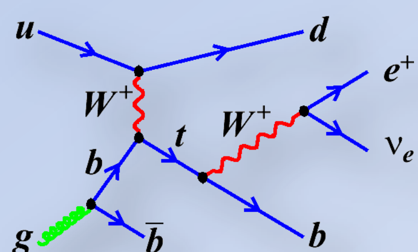
$$P(p_l^\mu, p_{j1}^\mu, p_{j2}^\mu) = \frac{1}{\sigma}\int d\rho_{j1}\, d\rho_{j2}\, dp_\nu^z \sum_{comb} \phi_4\, |M(p_i^\mu)|^2 \frac{f(q_1) f(q_2)}{|q_1||q_2|} W_{jet}(E_{jet}, E_{part})$$

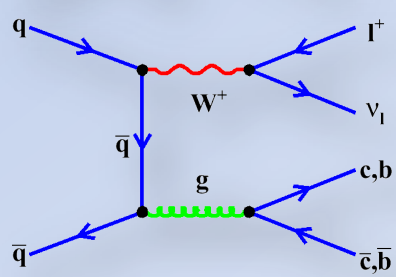
Input: lepton and jet-vectors

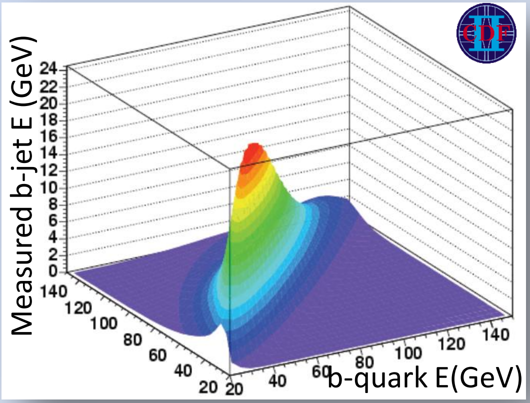
Leading order matrix elements

Probability of measuring a jet energy E_j if E_p was produced.









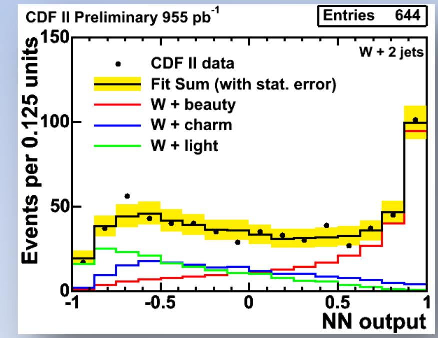
Calculation of the discriminate:

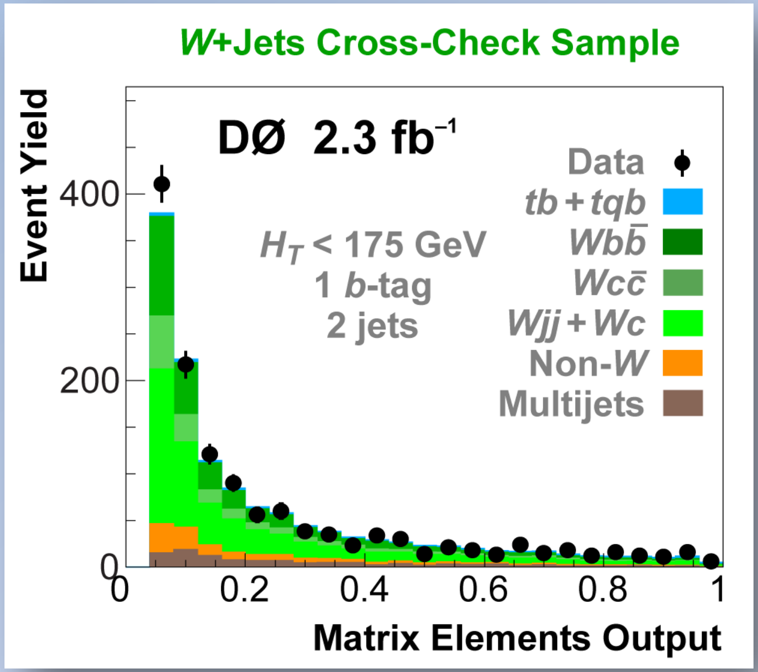
DØ:

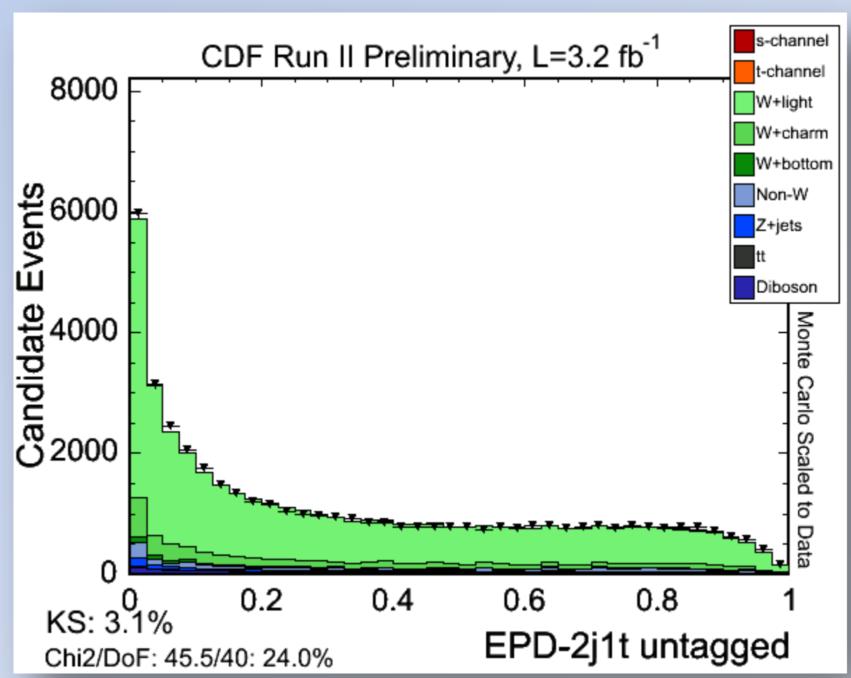
$$L = \frac{P_{signal}(x)}{P_{signal}(x) + P_{bkg}(x)}$$

CDF:

$$EPD = \frac{b \cdot P_{signal}(x)}{b \cdot P_{signal}(x) + b \cdot P_{b-bkg}(x) + (1-b) P_{nonb-bkg}(x)}$$

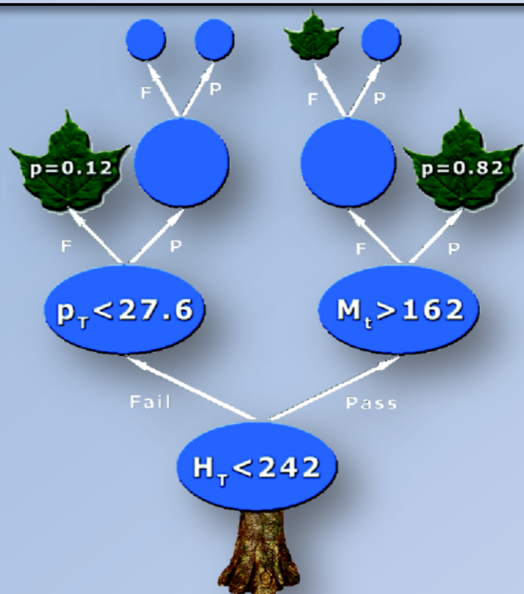






Boosted Decision Trees

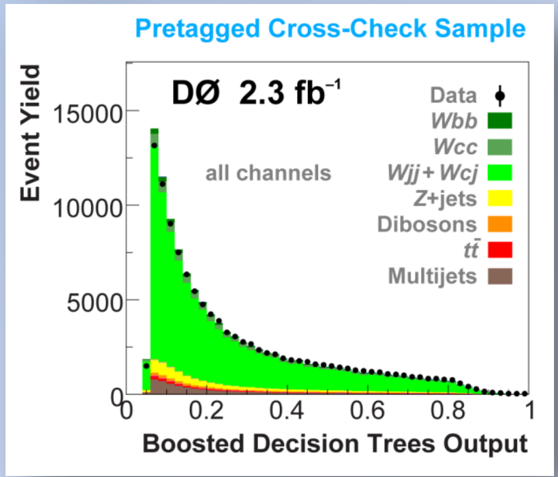
Idea: Advance application of a cut based analysis using a boost algorithm

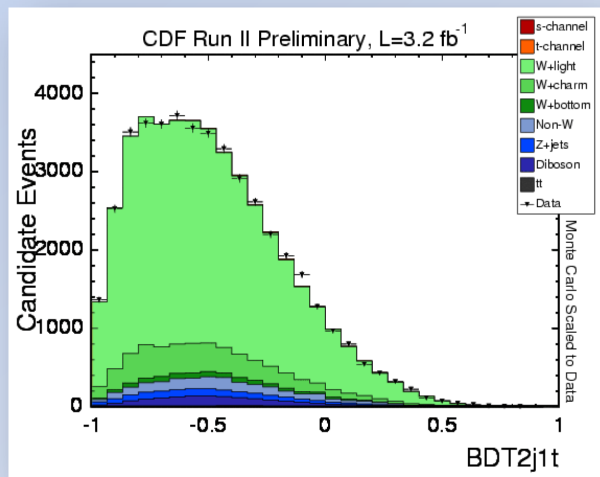


- Large number of input variables
- Cuts produces branches
- Terminal leaf calculate:

$$\text{purity} = N_S/N_S + N_B$$

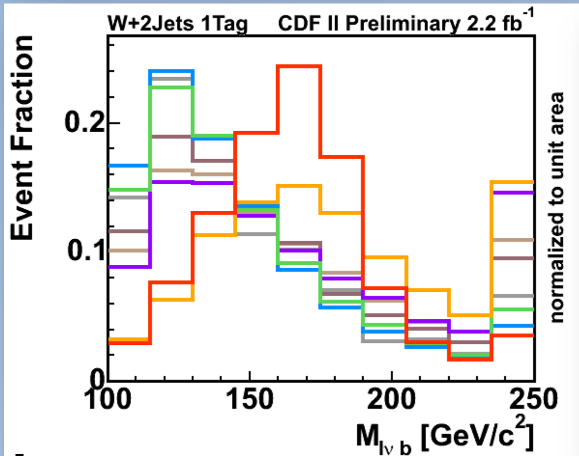
- Each data event is assigned the purity value of the leaf it falls into
- Boosting: Create series of many trees by reweighting based on value of misclassification

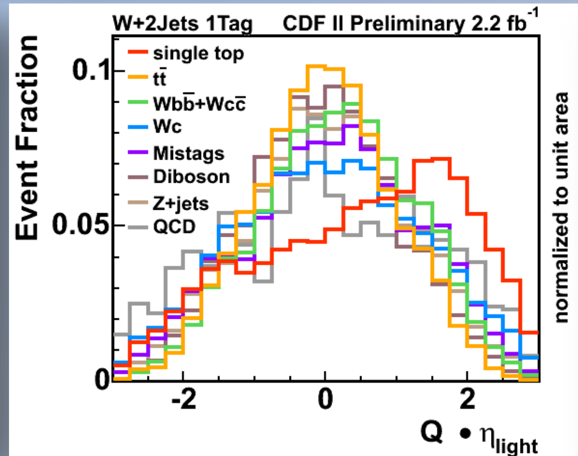


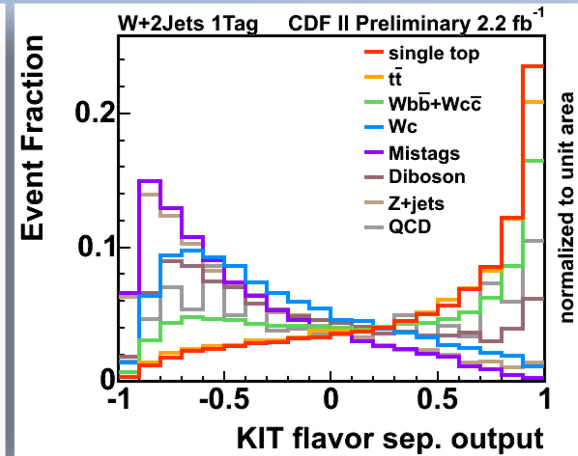


Neural Networks

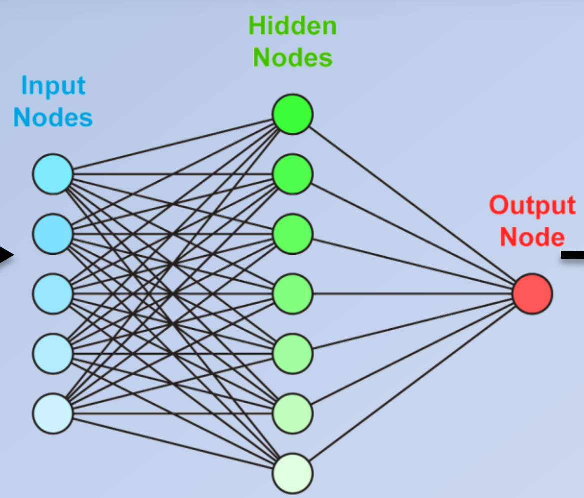
Idea: Combine many variables including correlations in one discriminate

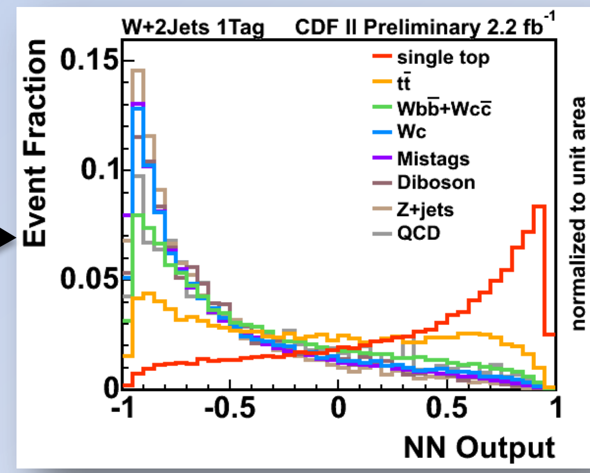






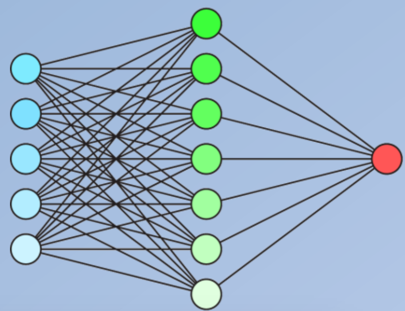
…



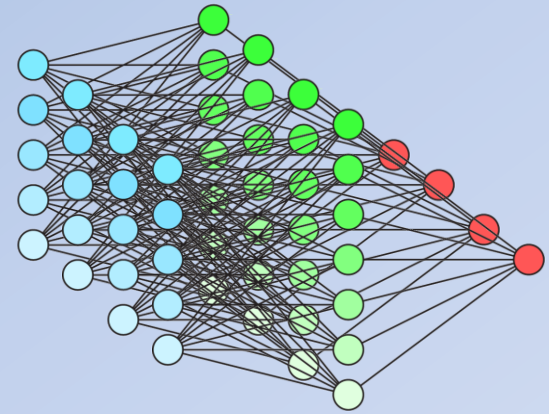


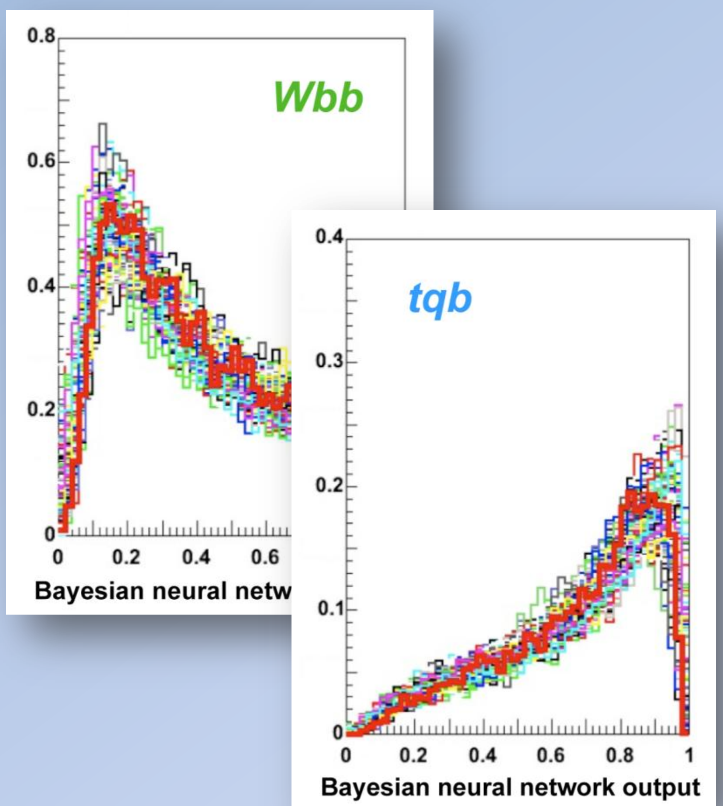
Used in lepton trigger (NeuroBayes) and MET+jets analysis (TMVA)

Bayesian Neural Networks

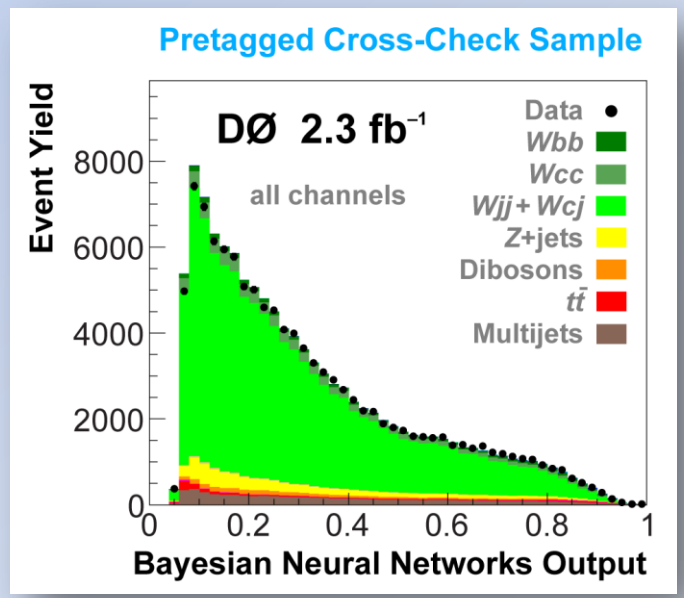


Train several networks with different parameters

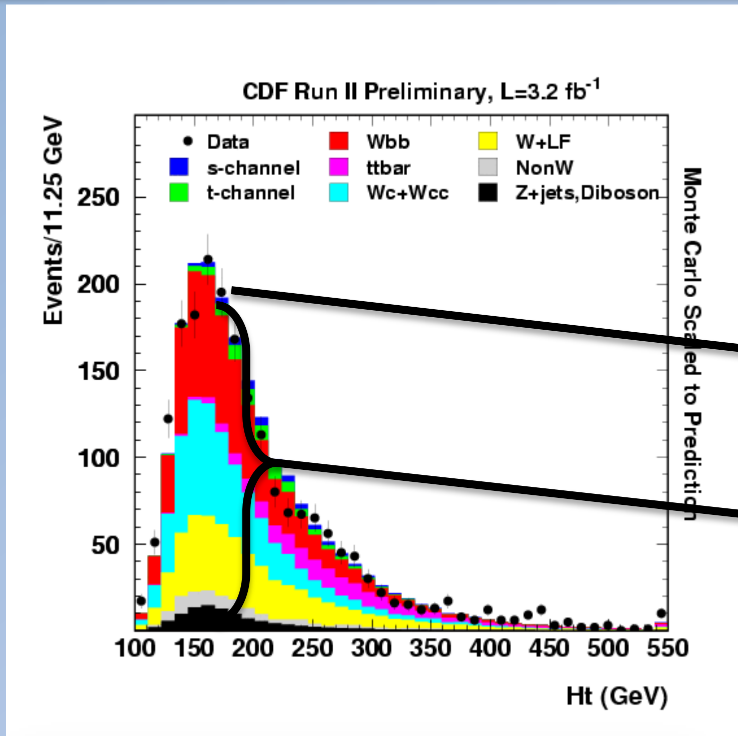


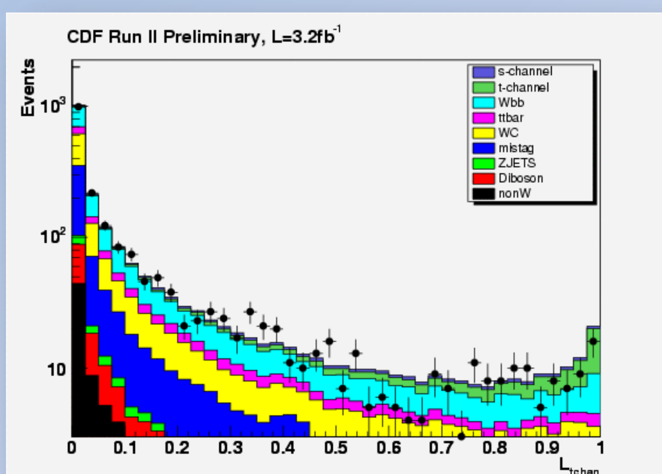


Average of 100 networks



Multivariate Likelihood Methode





- Combines several sensitive variables into a single variale
- Pioneered at LEP

$$N_i^{sig}, \quad N_i^{bkg}$$

$$p_i^{sig} = \frac{N_i^{sig}}{N_i^{sig} + N_i^{bkg}}$$

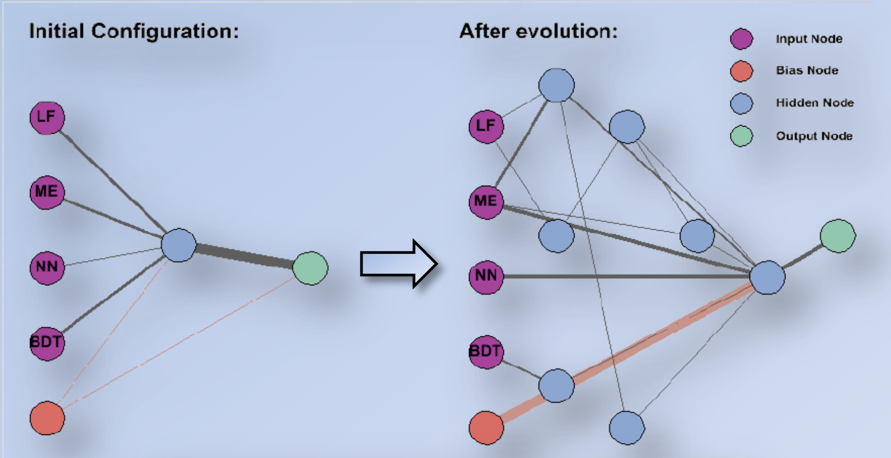
$$L(x) = \frac{\prod p_i^{sig}(x_i)}{\prod p_i^{sig}(x_i) + \prod p_i^{bkg}(x_i)}$$

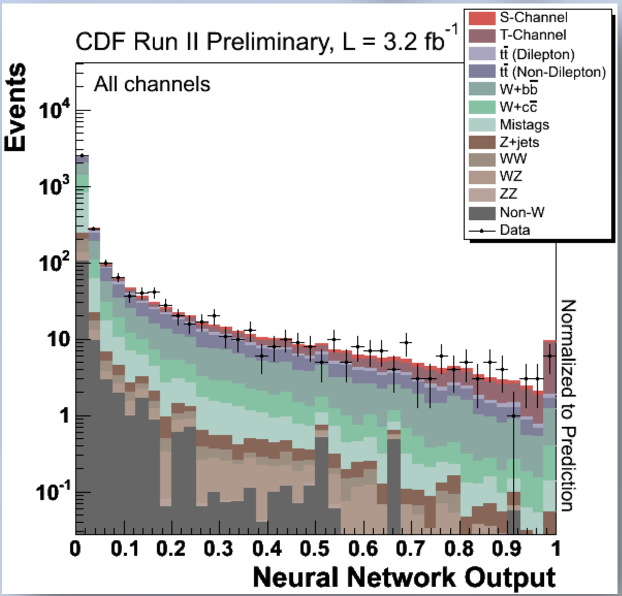
Combination

Idea: Building a super-discriminate using the individual discriminates as inputs

- Using NEAT neural network
  ("Neuro-Evolution of Augmenting Topologies")
  K.O. Stanley and R.Miikulainen,
  Evolutionary Computation **10 (2)** 99-127(2002)
  - candidate networks compete against each other
  - Automatically optimizes
    - network topology, weights
    - output histogram binning
    - includes systematic errors in optimization procedure

- Inputs:
  - Matrix elements
  - Boosted decision tree
  - Neural network
  - Likelihood

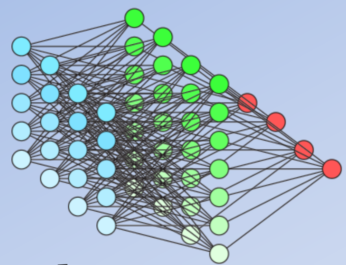




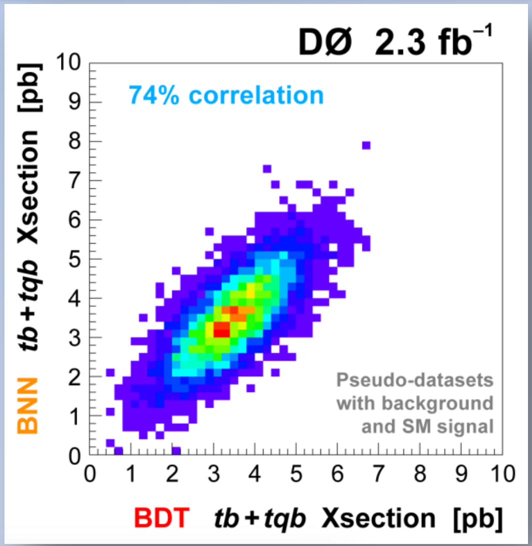
Combination

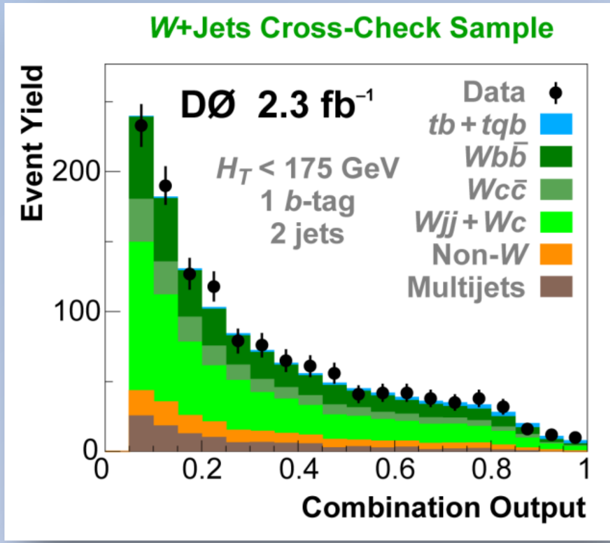
Idea: Building a super-discriminate using the individual discriminates as inputs

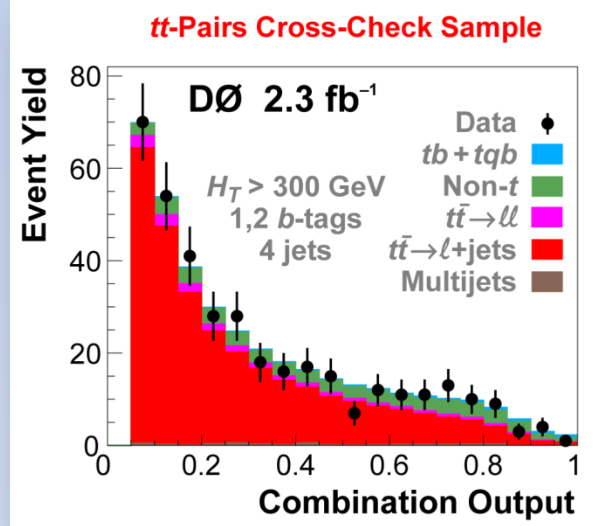
- Using a simple BNN



- Inputs:
  - Matrix elements
  - Boosted decision tree
  - Bayesian Neural network

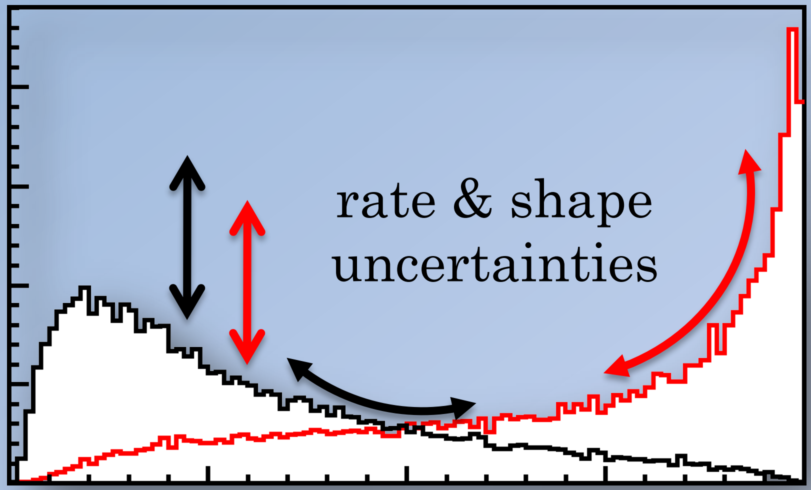


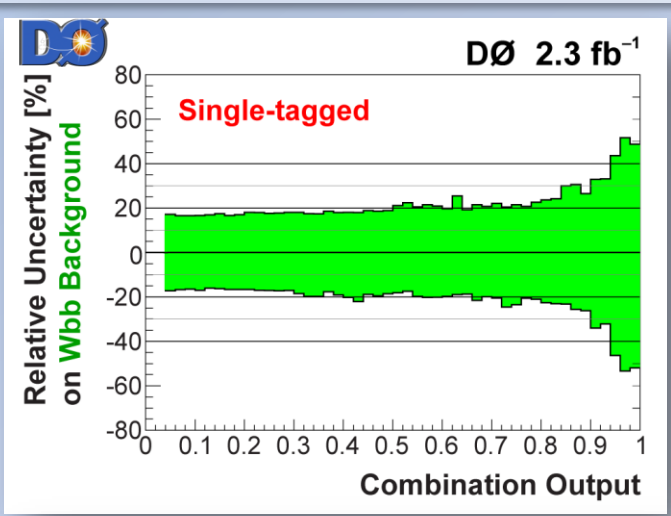


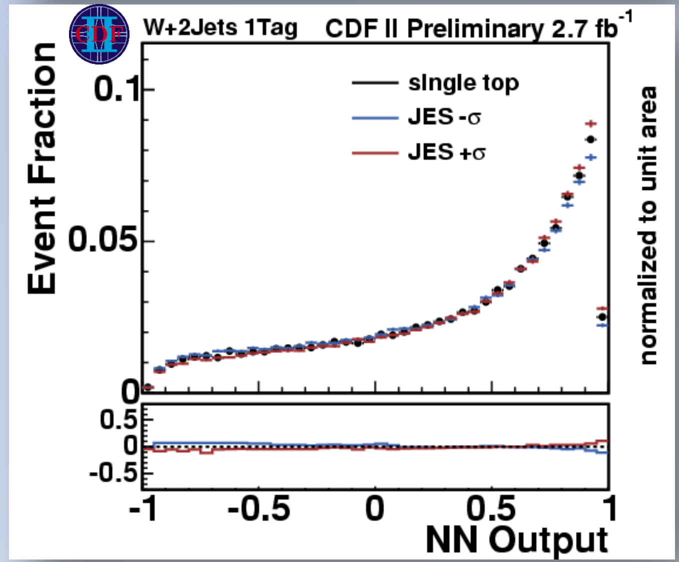


Systematic uncertainties

Even after a good agreement between simulation and observation one has to carefully asses systematics.







Consider sources that affect rate, discriminant shape, or both.

MC statistics treated as a source of systematic uncertainty in each bin independently

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%

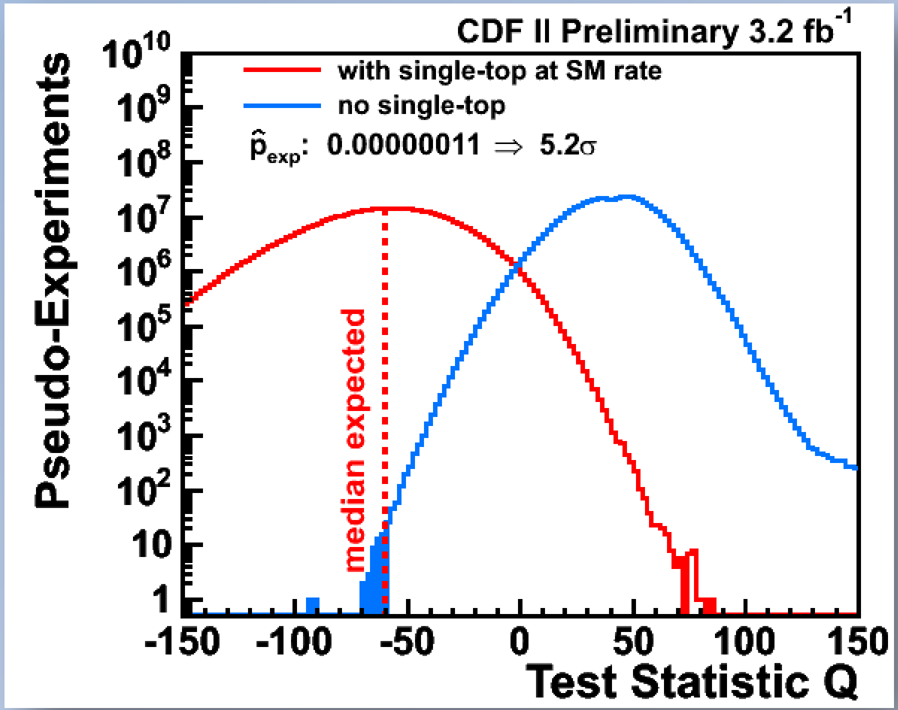
Systematic Uncertainty	Rate	Shape
Jet Energy Scale	0...10%	✓
Initial + Final State Radiation	0...15%	✓
Parton Distribution Functions	2...3%	✓
Monte Carlo Generator	1...5%	
Event Detection Efficiency	0...9%	
Luminosity	6%	
Neural Net B-tagger		✓
Mistag Model		✓
Q^2 scale in ALPGEN MC		✓
Input variable mismodeling		✓
Wbb+Wcc normalization	30%	
Wc normalization	30%	
Mistag normalization	17...29%	
ttbar normalization & m_{top}	23%	✓

Hypothesis testing : p-value

p-value = probability of upward fluctuation of background to the data or something even more "signal-like"

Signal-Like Outcomes

Background-Like Outcomes



$$Q = \frac{P(\text{data} \mid s+b, \hat{\theta})}{P(\text{data} \mid b, \hat{\hat{\theta}})}$$

θ = nuisance parameters

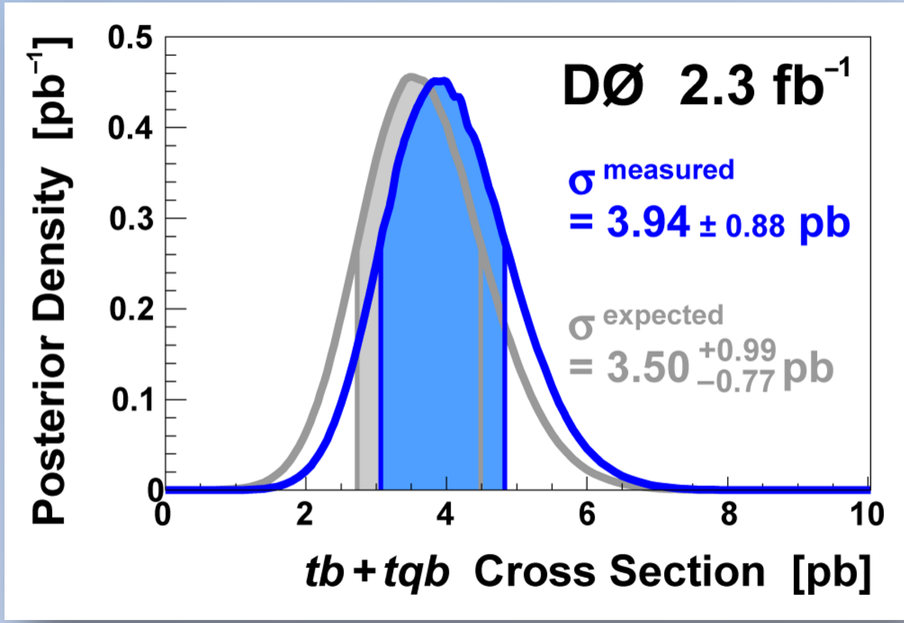
Fit for W+jets scale factors. Fluctuate all nuisance parameters in pseudo-experiments

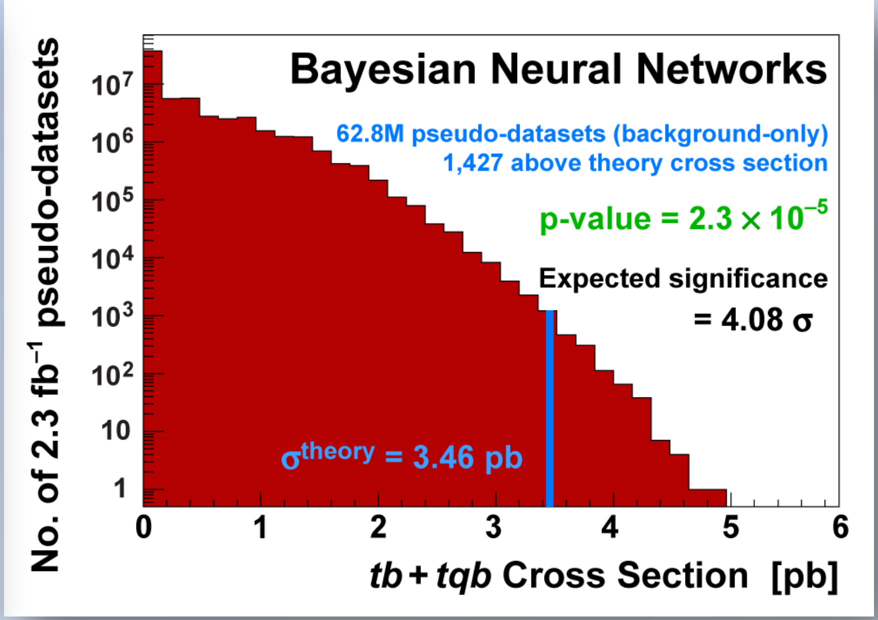
Statistical analysis

Bayesian statistical analysis:
P(s | D) = P(D | s) * P(s)

Posterior gives the measured cross section and uncertainty.

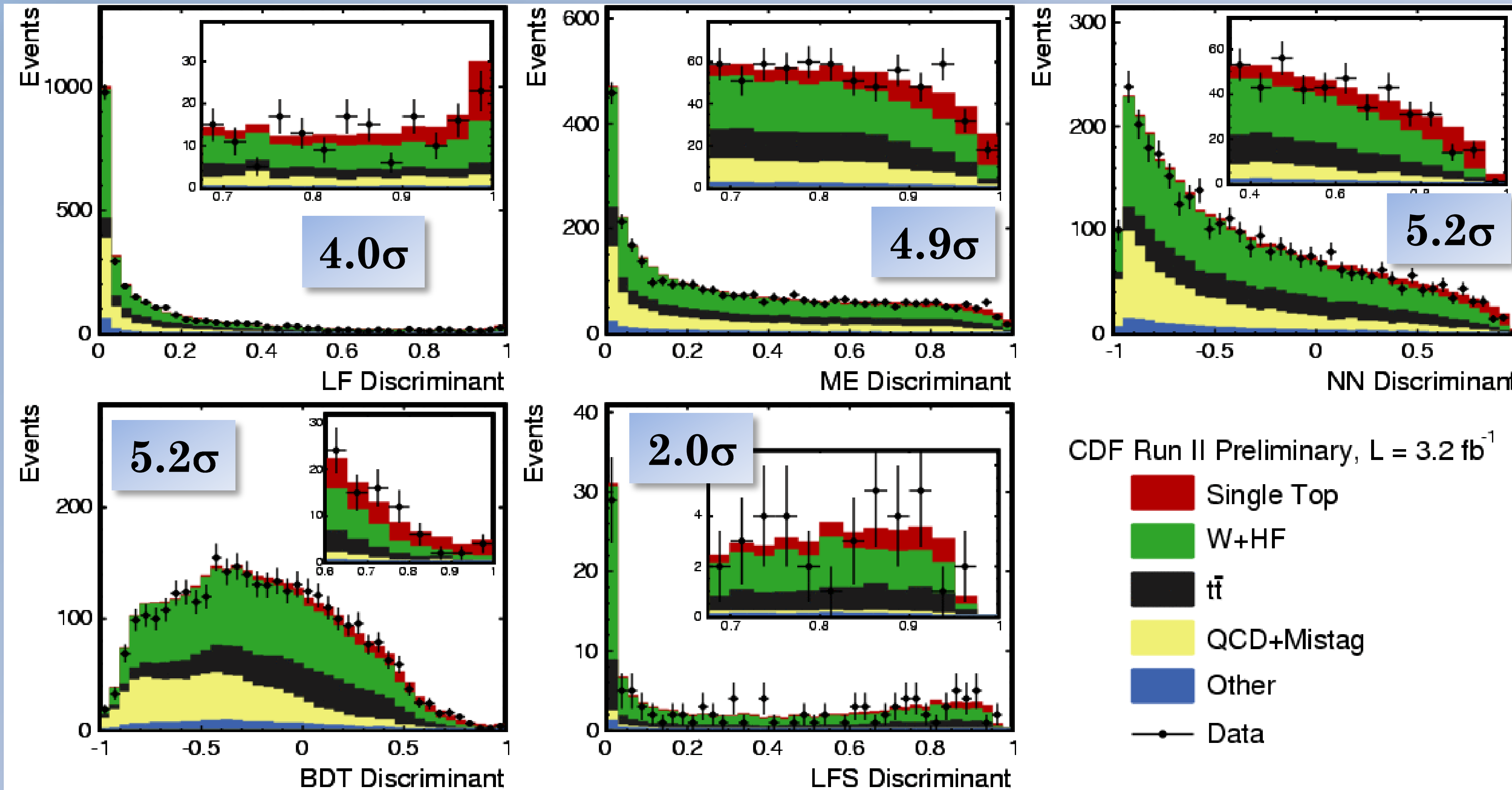
Throwing background only events
→ determination of sensitivity





Results from

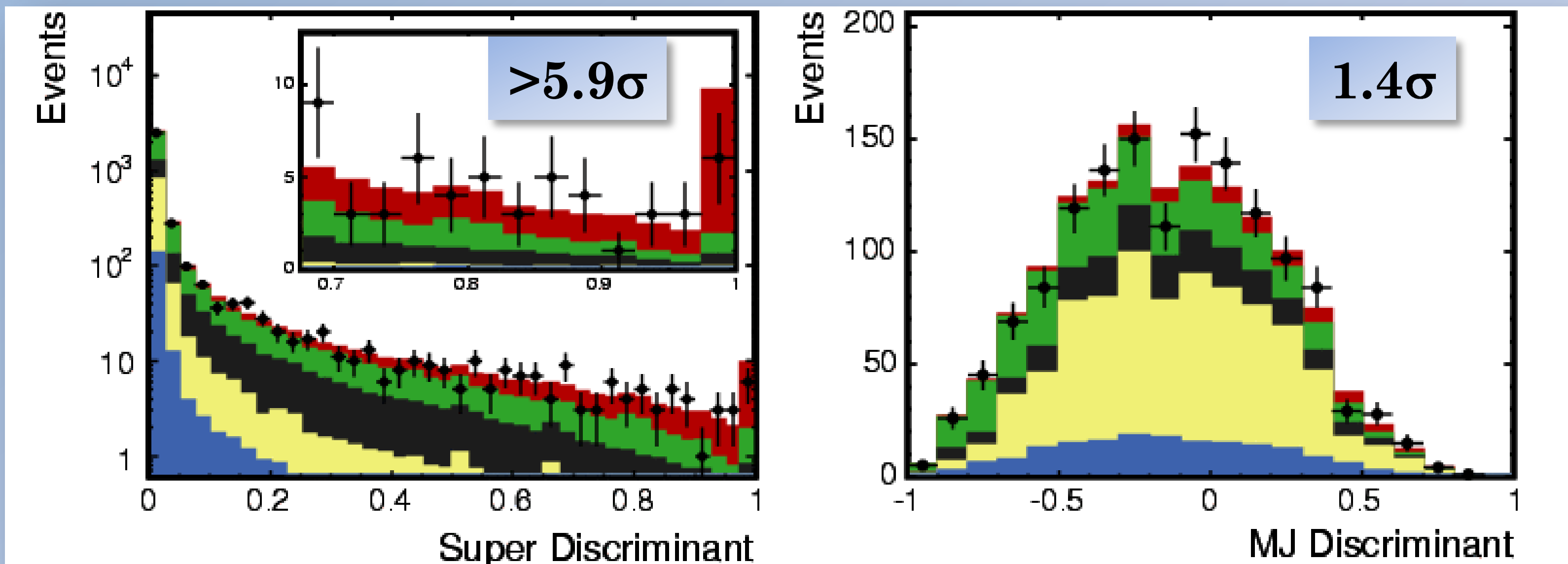
Expected sensitivity

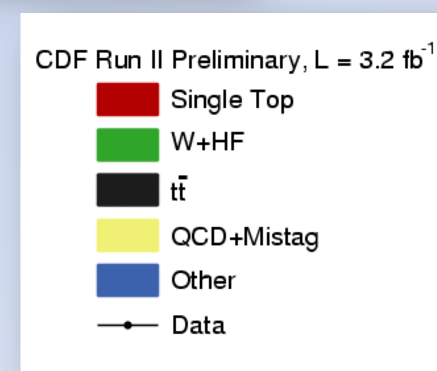


Discriminants normalized to prediction

High p_T lepton + MET + jets

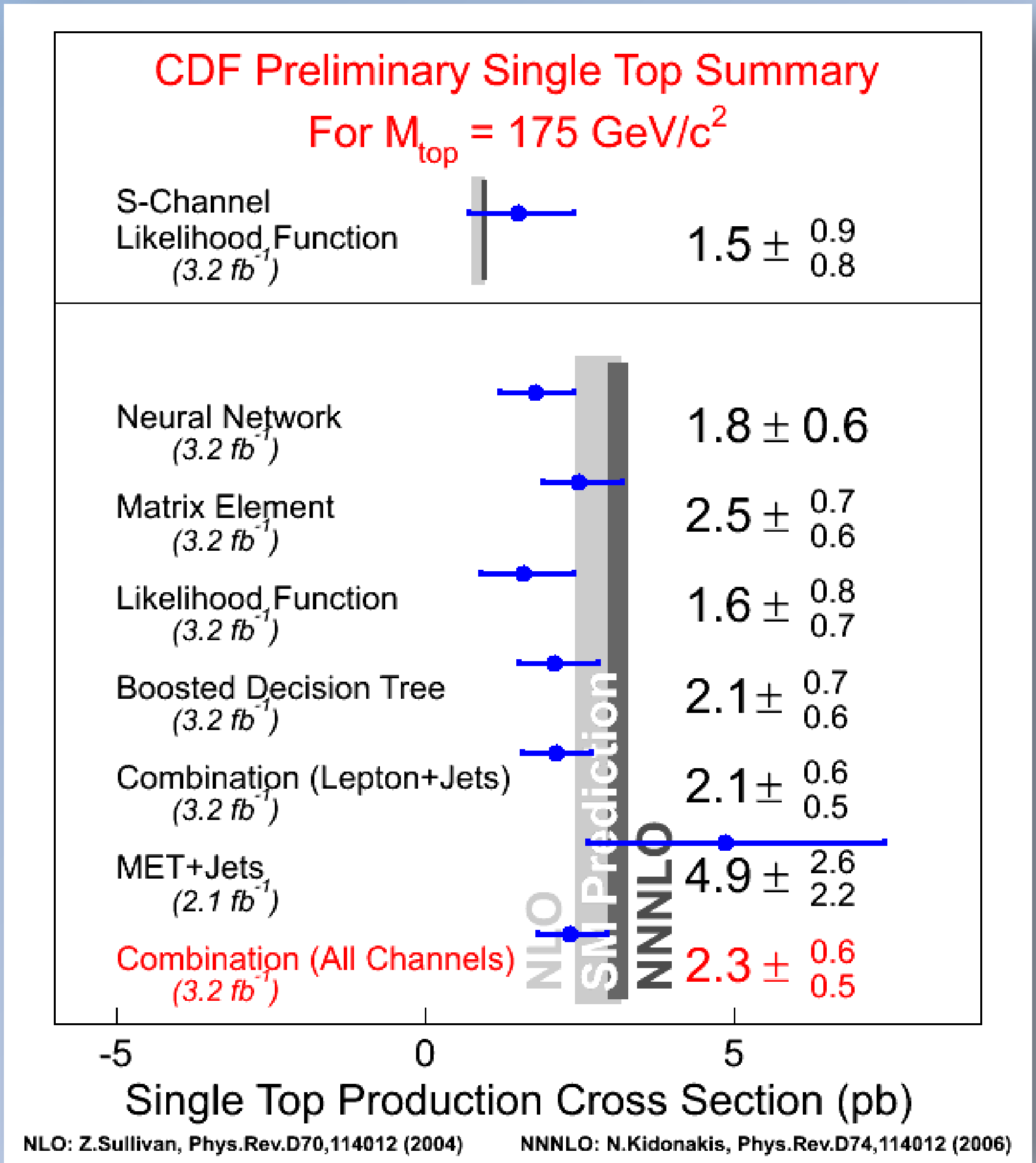
MET + jets





Perform combined cross section fit over the two orthogonal analyses

Summary of individual measurements



Top mass

$M_{top} = 175\ \mathrm{GeV/c^2}$

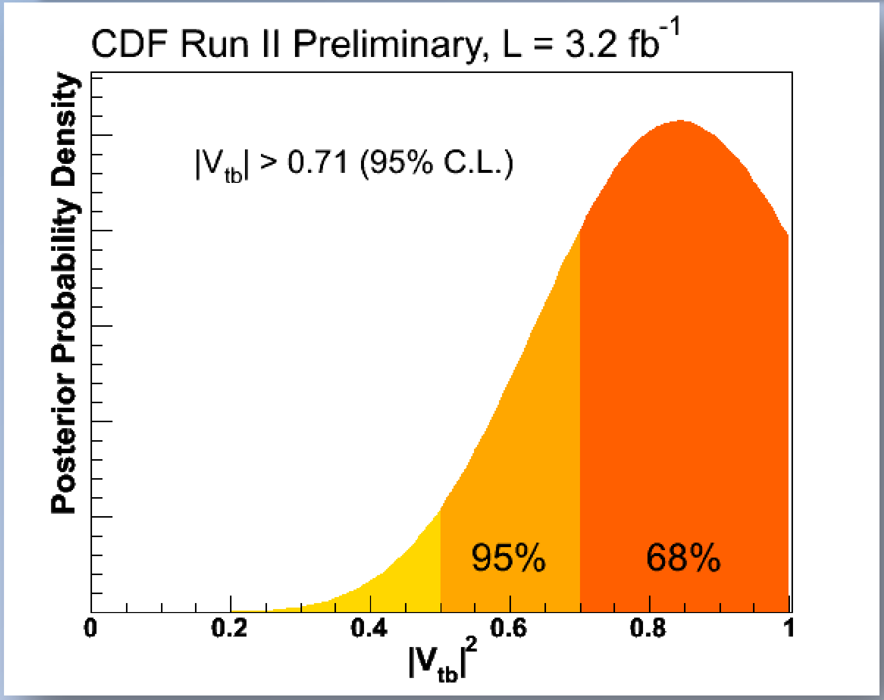
Theory cross section

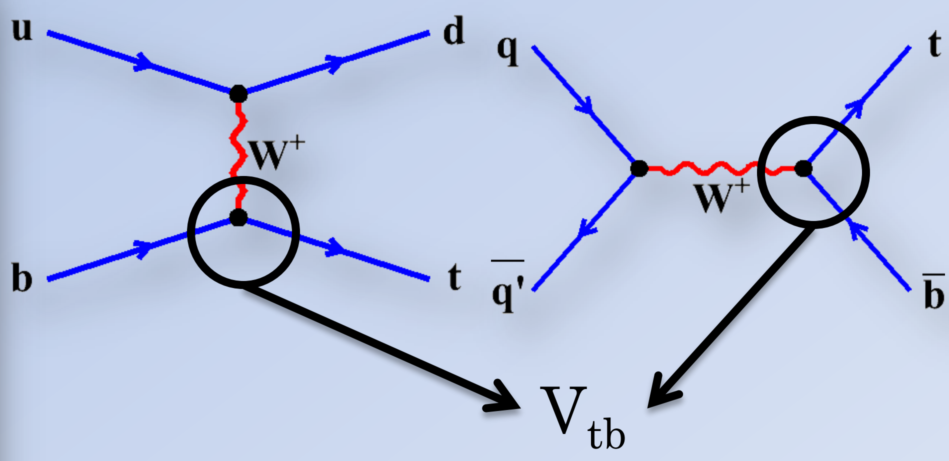
$\sigma = 2.9 \pm 0.3$ pb

Measurement of $|V_{tb}|$

Using cross section result measure $|V_{tb}|$
Assume Standard Model (V-A) coupling
and $|V_{tb}| >> |V_{ts}|, |V_{td}|$
(from BR(t →Wb) measurements)

$$|V_{tb,meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} \cdot |V_{tb,SM}|^2$$





$|V_{tb}| = 0.91 \pm 0.11$ (stat+syst) $\pm$ 0.07 (theory)

CDF combined fit:
$|V_{tb}| > 0.71$ at 95% C.L.

Z. Sullivan, Phys.Rev. D70 (2004) 114012

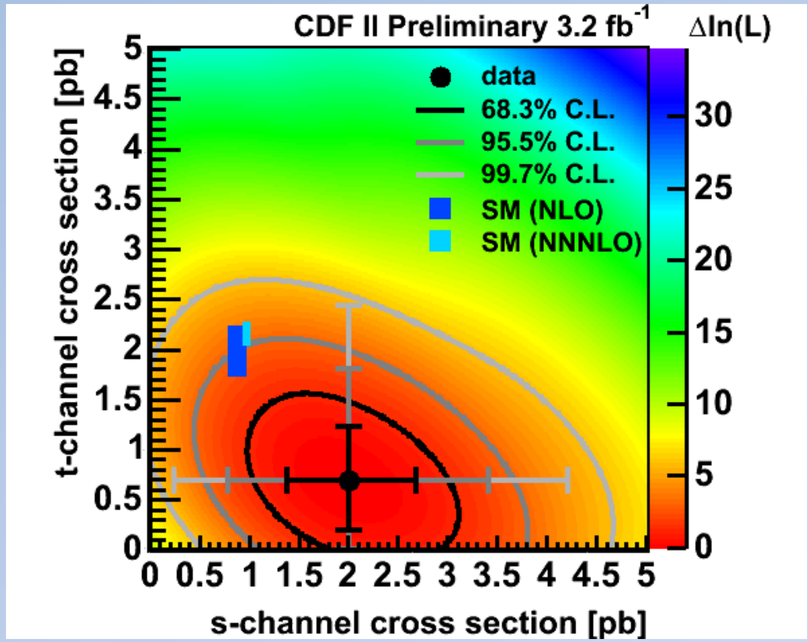
Separate measurement

Measure σ_s and σ_t separately

Interesting because s- and t-channels have different sensitivity to BSM models

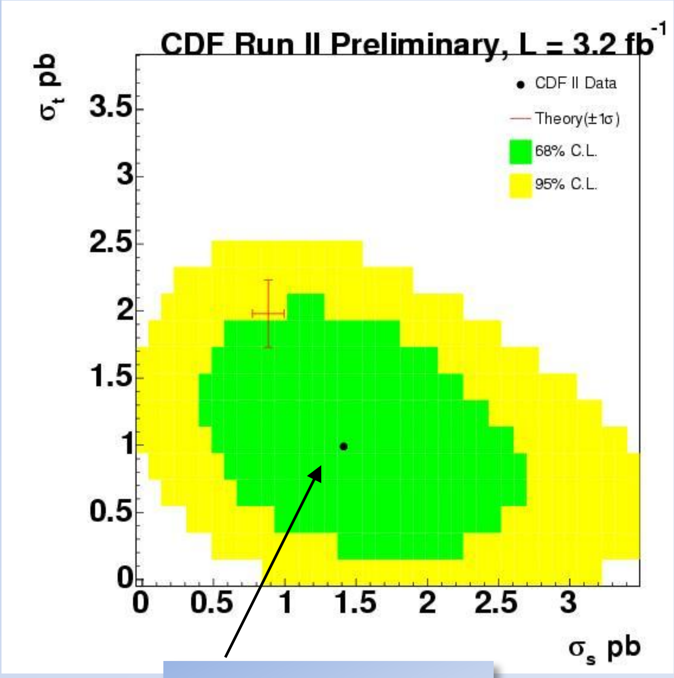
Train dedicated s-channel and t-channel discriminants and fit 2D

Neural network



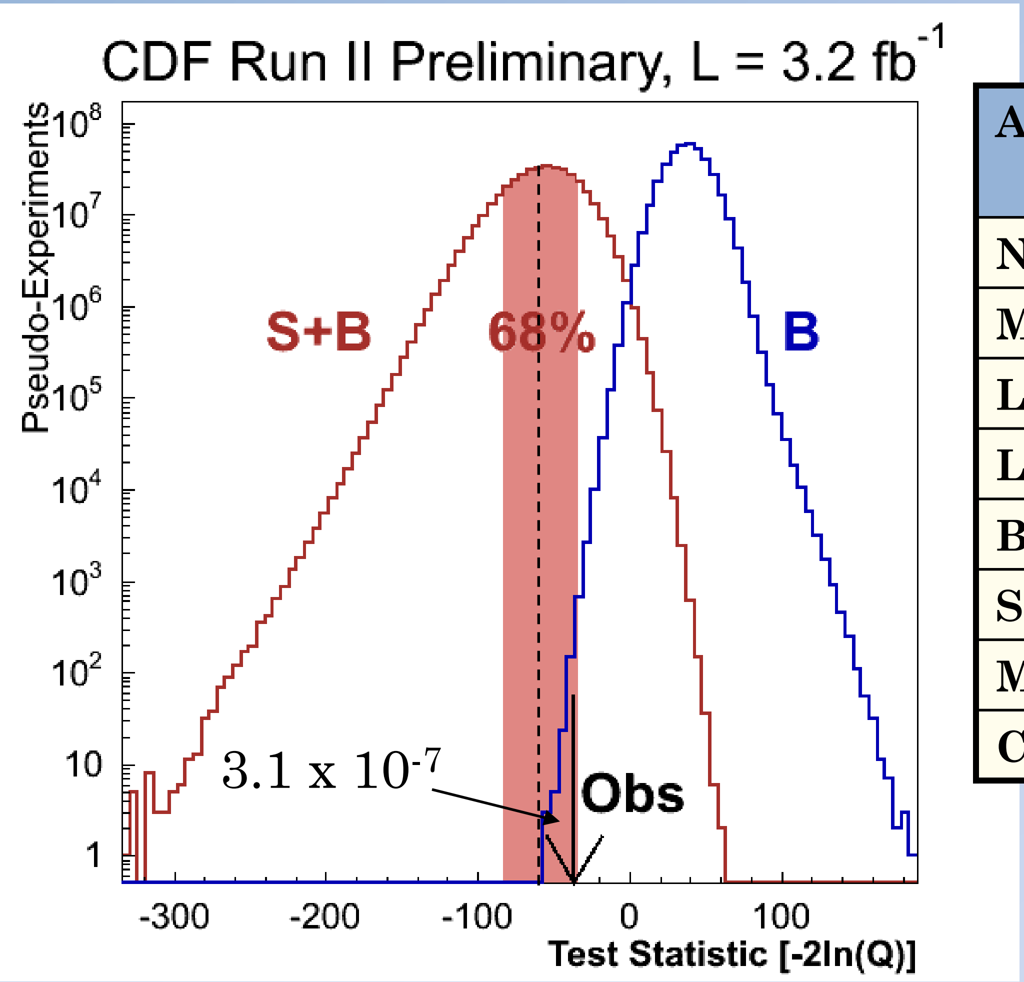
$\sigma_s = 2.0$ pb
$\sigma_t = 0.7$ pb

Likelihood function



$\sigma_s = 1.4$ pb
$\sigma_t = 1.0$ pb

Observation @ CDF



Analysis	Significance Std.Dev. (σ)	Sensitivity Std.Dev. (σ)
NN	3.5	5.2
ME	4.3	4.9
LF	2.4	4.0
LFS	2.0	1.1
BDT	3.5	5.2
SD	4.8	>5.9
MJ	2.1	1.4
Combined	5.0	>5.9

Observation !

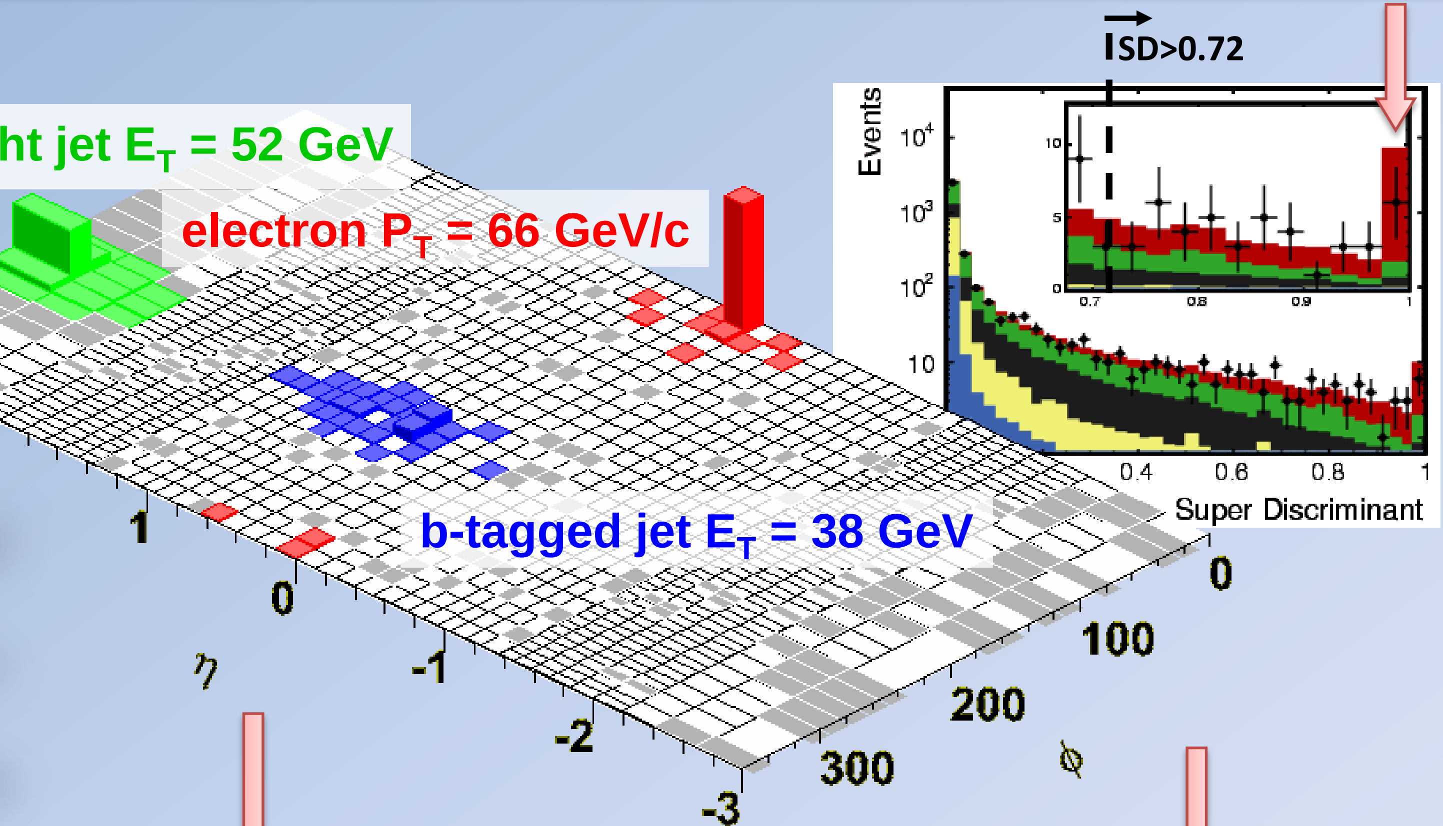
Expected p-value : xxx x10 $^{-10}$: > 5.9σ

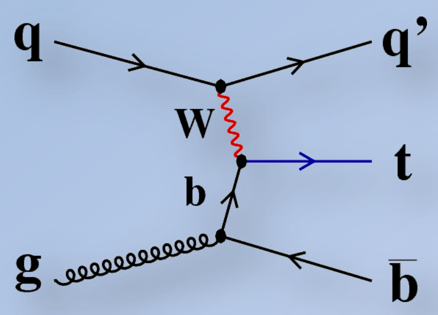
Observed p-value: 3.1 x10^{-7} : 5.0σ

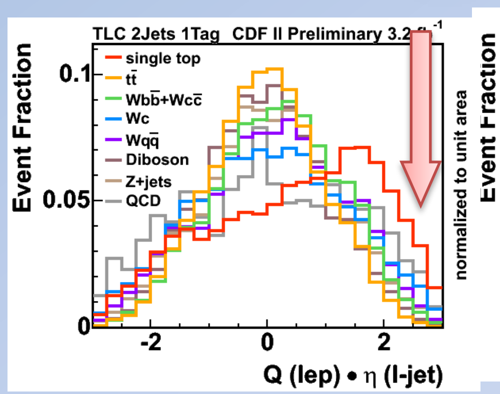
400 Mio pseudo-experiments! (130,000 CPU hrs)

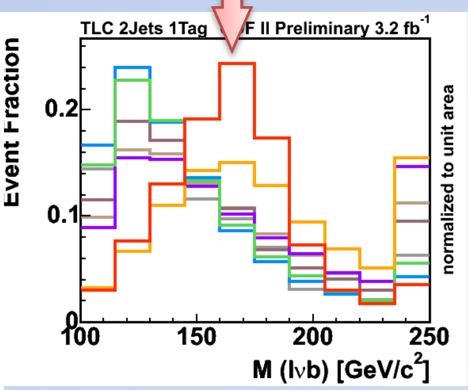
A golden event

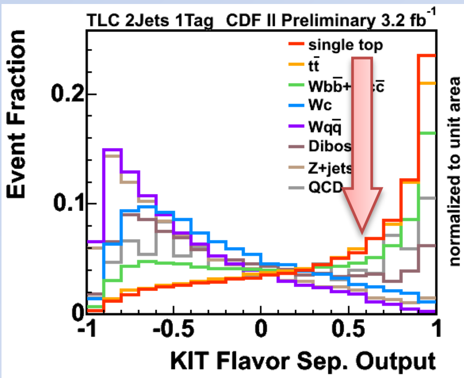
Event taken 2007/05/27

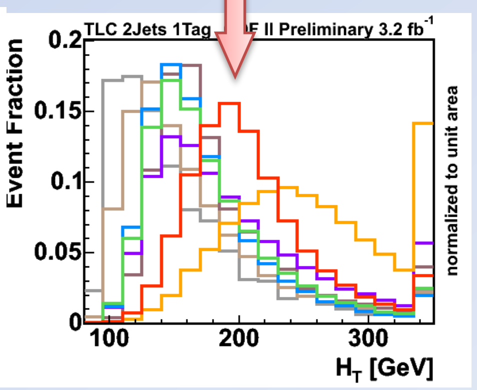






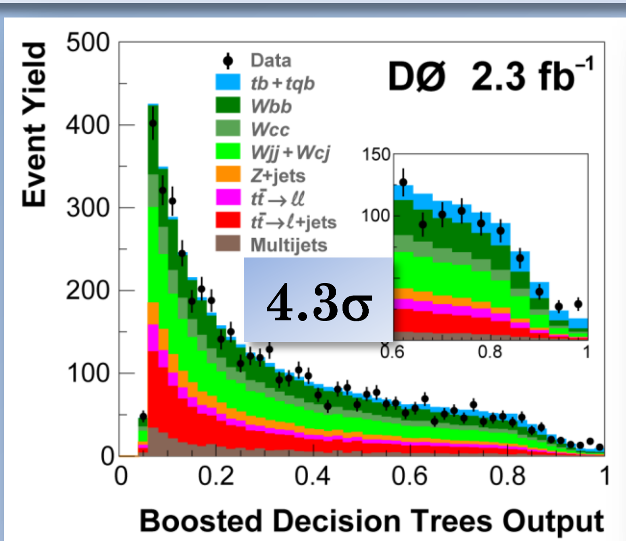


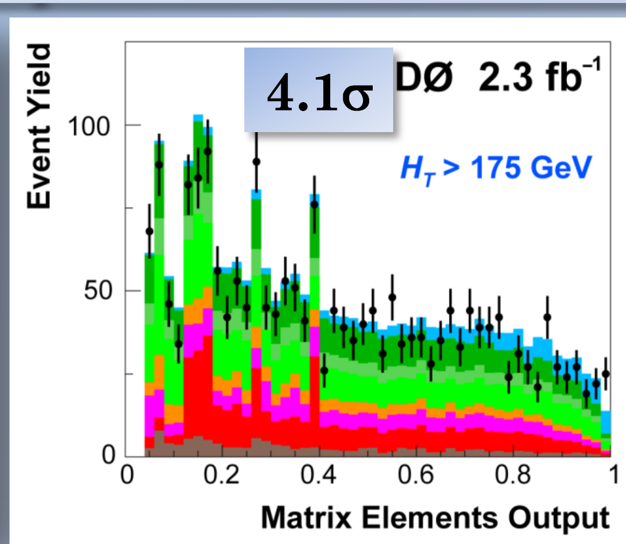


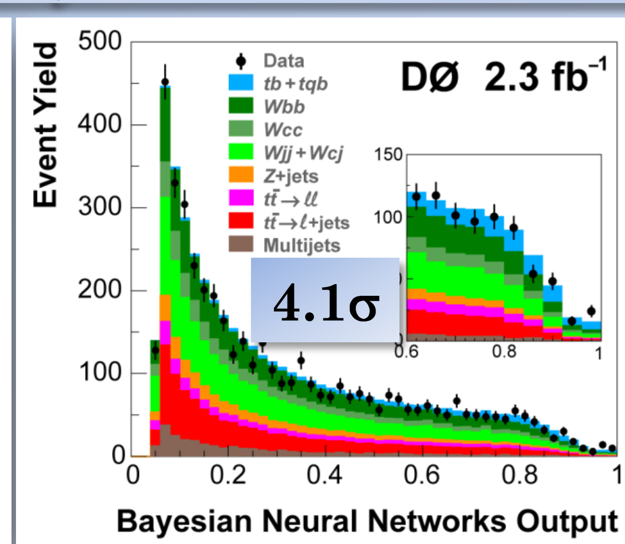


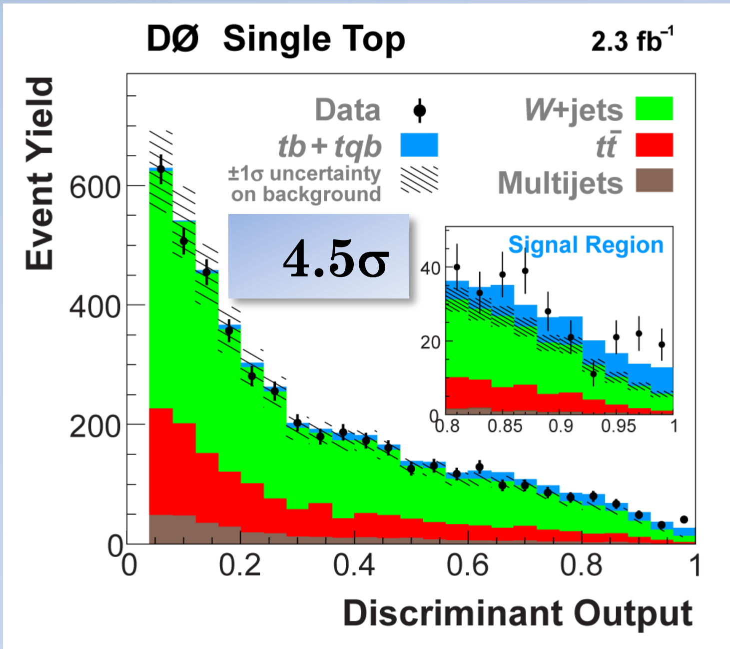
Results from DØ

Expected sensitivity

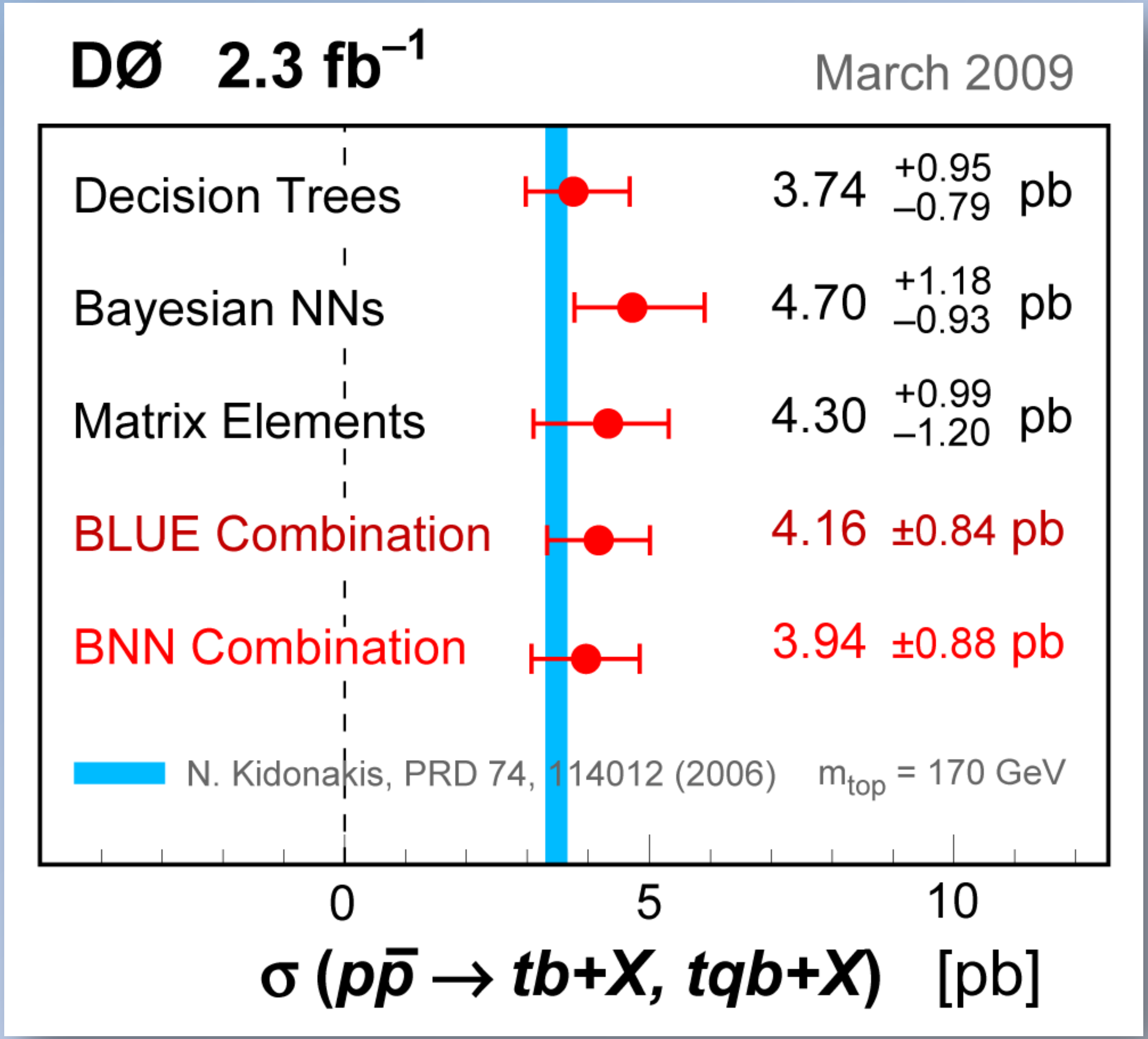








Summary of individual measurements



Top mass

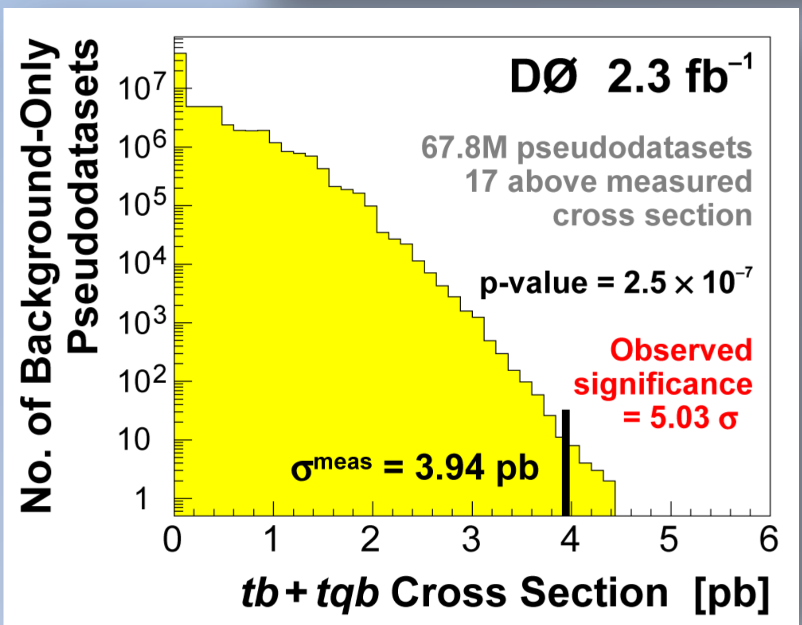
M_{top} = 170 GeV/c²

Theory cross section

σ = 3.5 ± 0.2 pb

Observation @ DØ

DØ 2.3 fb^{-1} Single Top Results			
Analysis Method	Single Top Cross Section	Significance Expected	Significance 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



Observation !

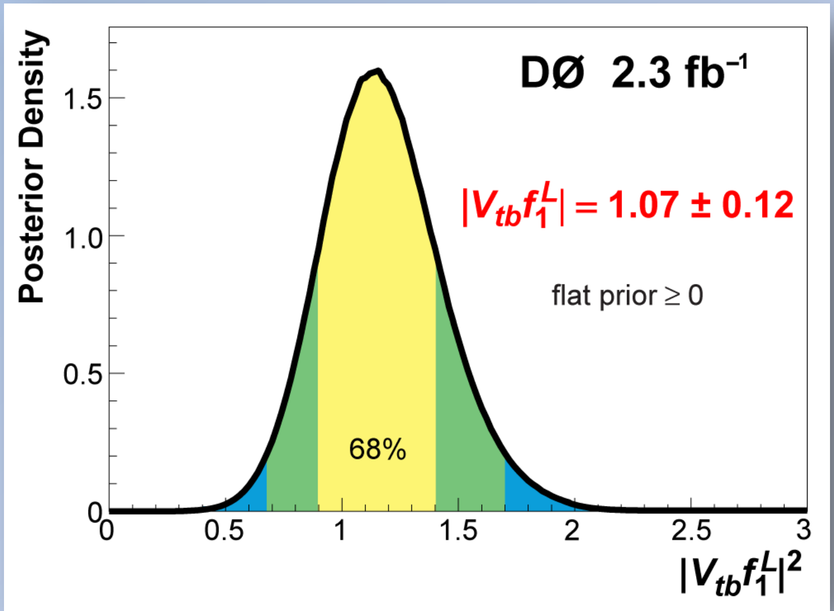
Measurement of $|V_{tb}|$

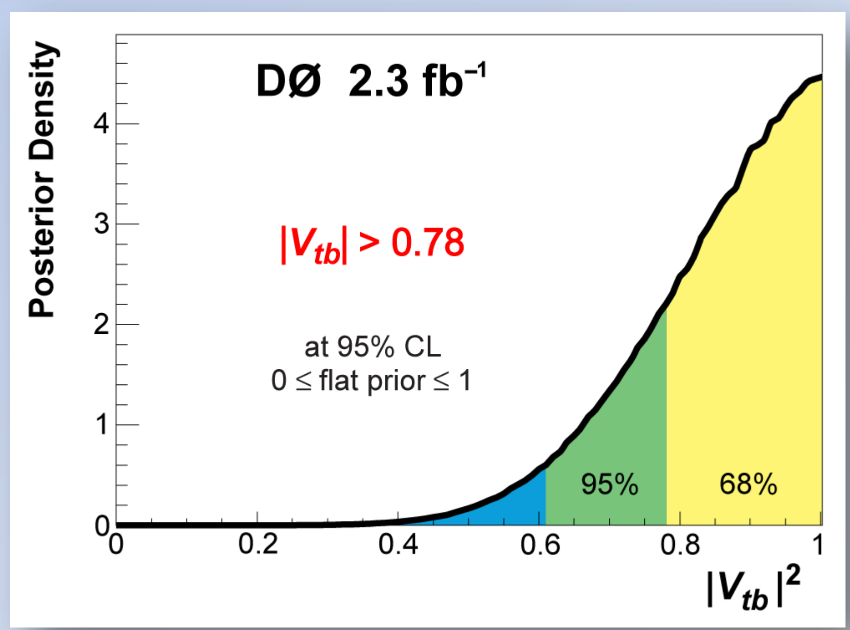
Using cross section result measure $|V_{tb}|$

Assume Standard Model (V-A) coupling $f_1^R = f_2^L = f_2^R = 0$

and $|V_{tb}| >> |V_{ts}|, |V_{td}|$

$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$

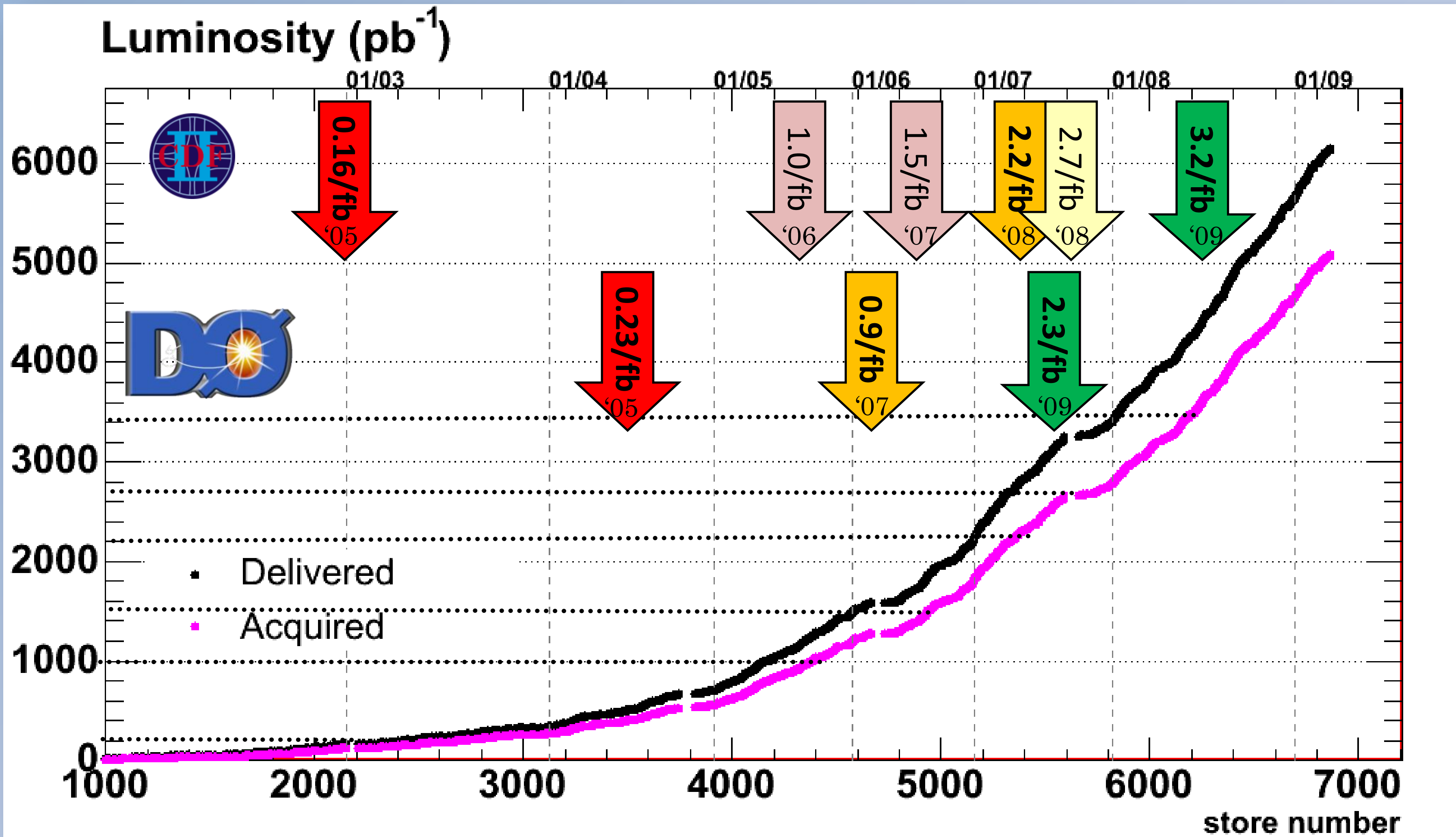




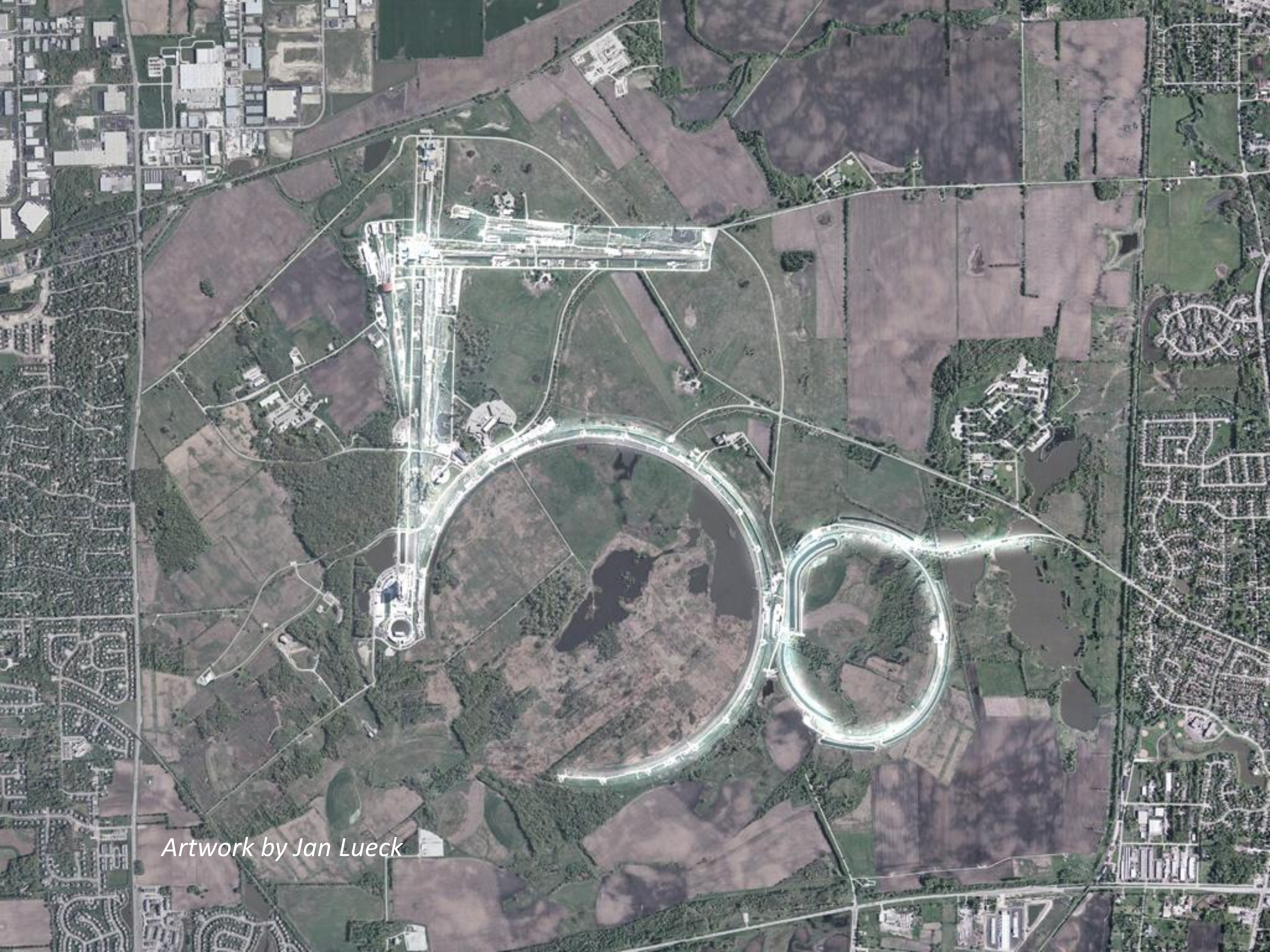
Tevatron summary

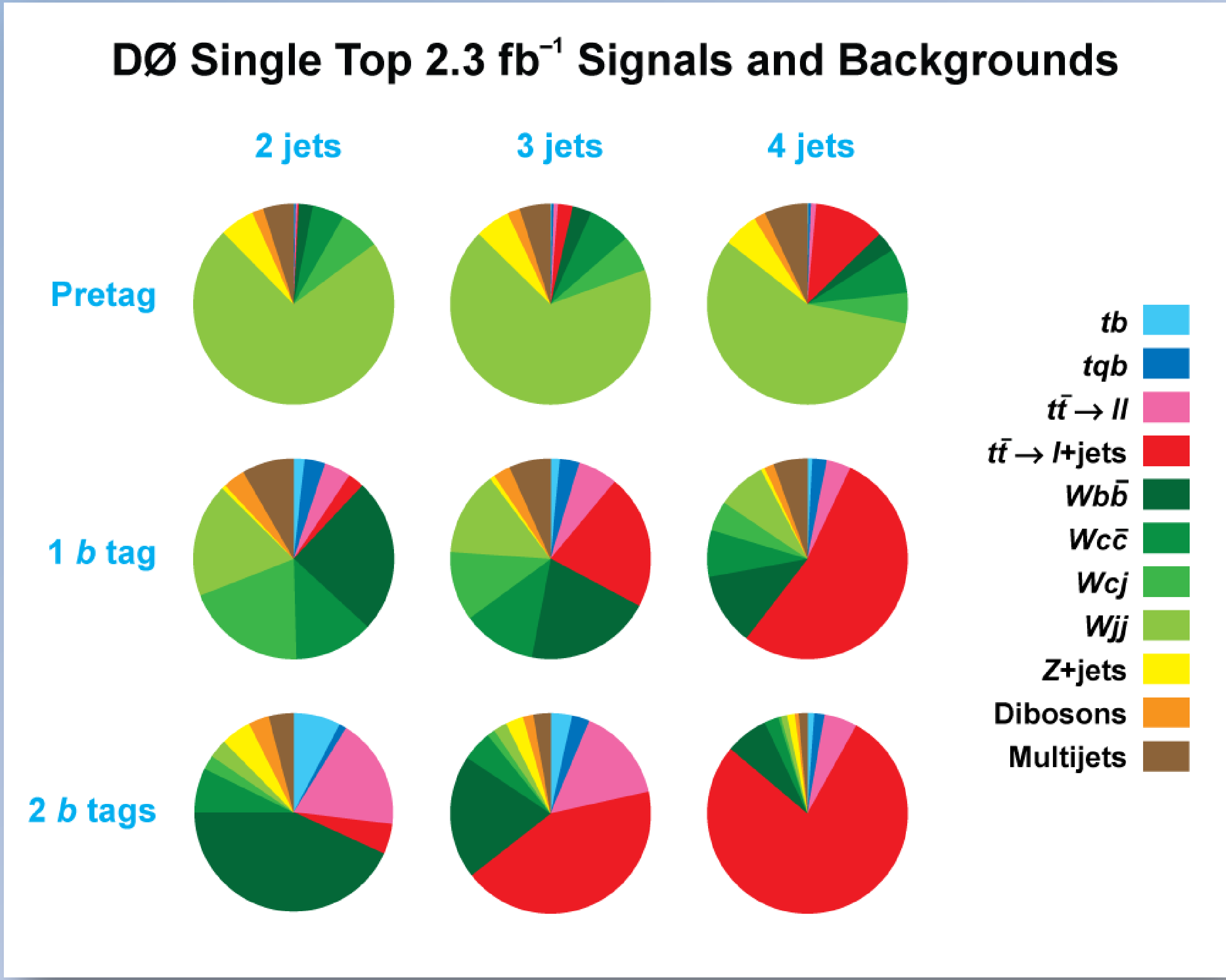
Single Top Cross Section	Signal Significance Expected	Signal Significance Observed	CKM Matrix Element V_{tb}
March 2009 DØ (2.3 fb^{-1}) arXiv:0903.0850 (m_{top} = 170 GeV)			
3.94 ± 0.88 pb	4.5 σ	5.0 σ	$\lvert V_{tb} f_1^L \rvert = 1.07 \pm 0.12$ $\lvert V_{tb} \rvert > 0.78$ at 95% CL
March 2009 CDF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

After long journey …




CELEBRATE!
photo: Reidar Hahn; artwork: Jan Lueck


Artwork by Jan Lueck


DØ Single Top 2.3 fb^{-1} Signals and Backgrounds
2 jets
3 jets
4 jets
Pretag
1 b tag
2 b tags
tb
tqb
$t\bar{t} \rightarrow ll$
$t\bar{t} \rightarrow l$+jets
$Wb\bar{b}$
$Wc\bar{c}$
Wcj
Wjj
Z+jets
Dibosons
Multijets

Expected events for 3.2 / 2.1 fb^{-1}

MET + high p_T lepton + 2 jets 3.2 fb^{-1}
(single + double SECVTX tag)

s-channel	58.1	8.4
t-channel	87.6	13.0
Single top	145.7	21.4
tt	204.1	29.6
Dibosons	88.3	9.1
Z + jets	36.5	5.6
W + bb	656.9	198.0
W + cc	292.2	90.1
W + cj	250.4	77.2
W + light flavor	501.3	69.6
Non-*W*	89.6	35.8
Total background	2119.3	350.9
Total prediction	2265.0	375.4
Observed	**2229**	

} ~30% (W + bb, W + cc, W + cj)

MET+ ≥2 jets 2.1 fb^{-1}
(single + double SECVTX tag, SECVTX + JetProb.)

s-channel	29.6	2.7
t-channel	34.5	6.1
Single top	64.1	8.8
tt	184.5	30.2
Diboson	42.1	6.7
W + HF	304.4	115.5
QCD multijet	679.4	27.9
Total background	1339.9	170
Total prediction	1404	172
Observed	**1411**	

Event selection for 2.3 fb^{-1}

Event Yields in 2.3 fb^{-1} of DØ Data Electron + muon, 1 tag + 2 tags combined			
Source	**2 jets**	**3 jets**	**4 jets**
s-channel *tb*	62 ± 9	24 ± 4	7 ± 2
t-channel *tqb*	77 ± 10	39 ± 6	14 ± 3
$W+b\bar{b}$	678 ± 104	254 ± 39	73 ± 11
$W+c\bar{c}$	303 ± 48	130 ± 21	42 ± 7
$W+cj$	435 ± 27	113 ± 7	24 ± 2
$W+jj$	413 ± 26	140 ± 9	41 ± 3
$Z+$jets	141 ± 33	54 ± 14	17 ± 5
Dibosons	89 ± 11	32 ± 5	9 ± 2
$t\bar{t} \rightarrow \ell\ell$	149 ± 23	105 ± 16	32 ± 6
$t\bar{t} \rightarrow \ell+$jets	72 ± 13	331 ± 51	452 ± 66
Multijets	196 ± 50	73 ± 17	30 ± 6
Total prediction	2,615 ± 192	1,294 ± 107	742 ± 80
Data	2,579	1,216	724

$$\mathcal{L}(\beta_1, \ldots, \beta_5; \delta_1, \ldots, \delta_{10}) = \underbrace{\prod_{k=1}^{B} \frac{e^{-\mu_k} \cdot \mu_k^{n_k}}{n_k!}}_{Poisson\ term} \cdot \underbrace{\prod_{j=2}^{5} G(\beta_j | 1, \Delta_j)}_{Gauss\ constraints} \cdot \underbrace{\prod_{i=1}^{10} G(\delta_i, 0, 1)}_{Systematics}$$

$$\mu_k = \sum_{j=1}^{5} \beta_j \cdot \underbrace{\left\{ \prod_{i=1}^{10} [1 + |\delta_i| \cdot (\epsilon_{ji+} H(\delta_i) + \epsilon_{ji-} H(-\delta_i))] \right\}}_{Normalization\ Uncertainty}$$

$$\underbrace{\cdot\ \alpha_{jk}}_{Shape\ P.} \cdot \underbrace{\left\{ \prod_{i=1}^{10} (1 + |\delta_i| \cdot (\kappa_{jik+} H(\delta_i) + \kappa_{jik-} H(-\delta_i))) \right\}}_{Shape\ Uncertainty}$$