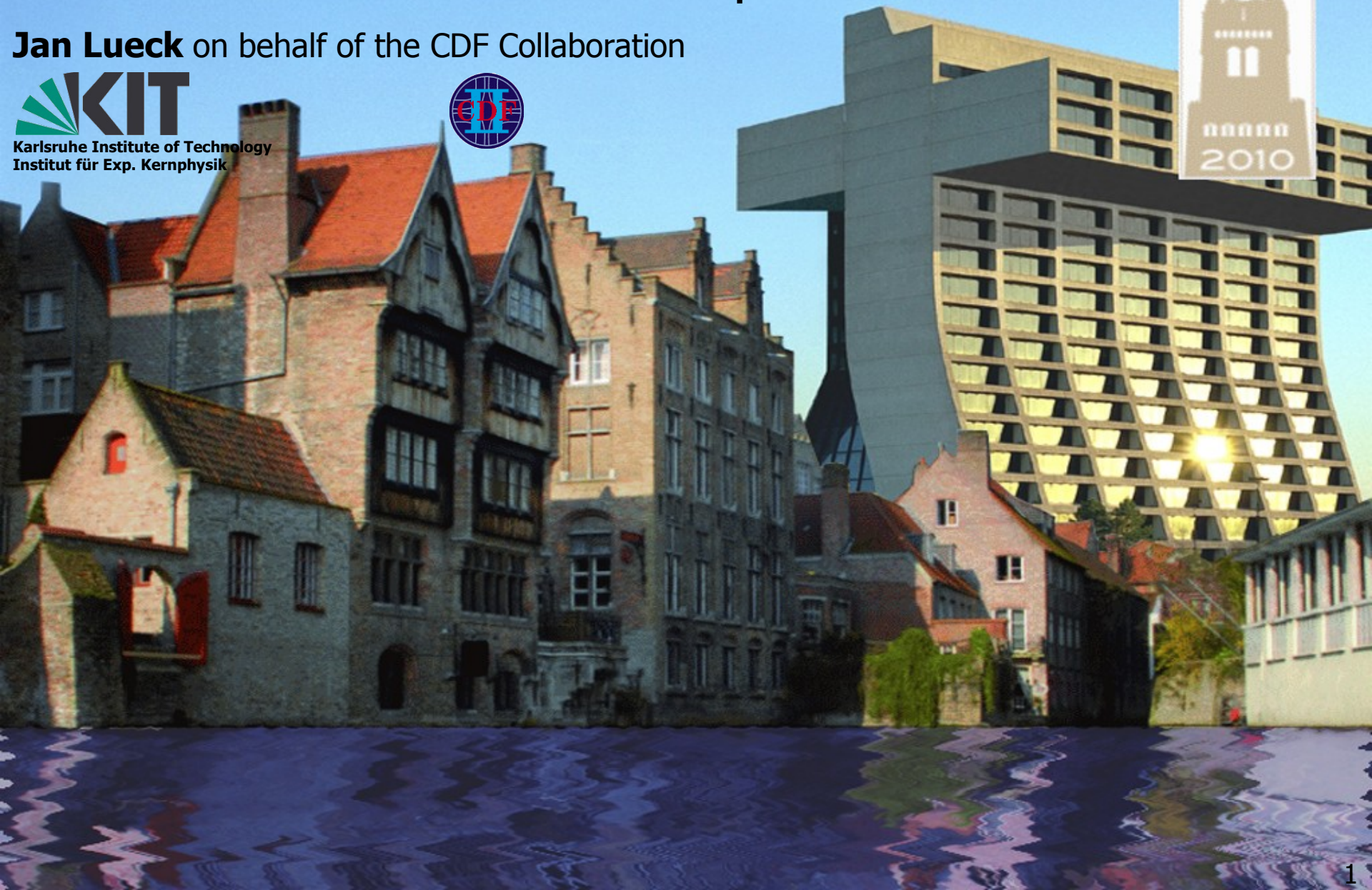
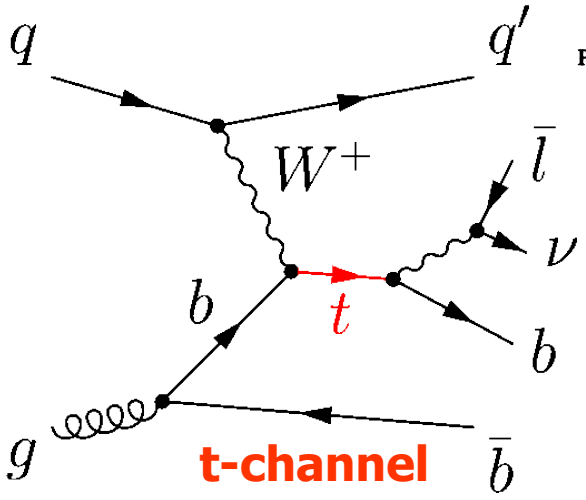
Observation of Single Top Quark Production with the CDF II Experiment

Jan Lueck on behalf of the CDF Collaboration

Karlsruhe Institute of Technology
Institut für Exp. Kernphysik



Motivation



PHYSICAL REVIEW D VOLUME 34, NUMBER 1 1 JULY 1986

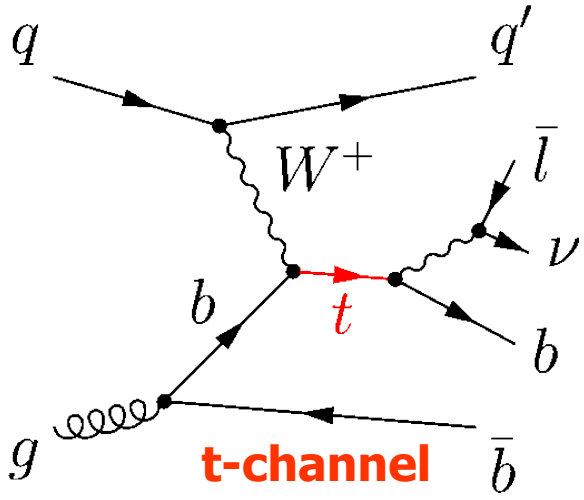
Production of heavy quarks from *W*-gluon fusion

Scott S. D. Willenbrock and Duane A. Dicus
Theory Group and Center for Particle Theory, University of Texas, Austin, Texas 78712
(Received 3 February 1986)

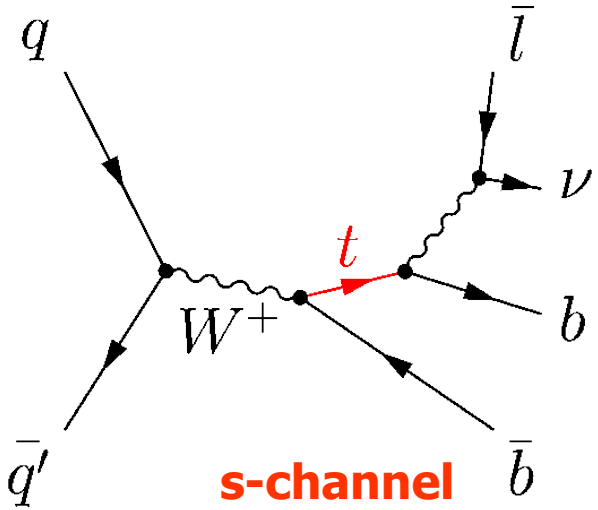
We show that heavy-quark production via *W*-gluon fusion in high-energy pp and $\bar{p}p$ collisions is an important source of the heavier member of an $SU(2)_L$ doublet of quarks if the mass splitting within the doublet is large. *W*-gluon fusion exceeds the strong production of heavy quarks for mass splittings greater than 300–350 GeV at $\sqrt{s}=10$ TeV and 400–450 GeV at $\sqrt{s}=40$ TeV. An al-

Scott Willenbrock, Duane Dicus, Phys. Rev. **D34**, 155 (1986).

Motivation

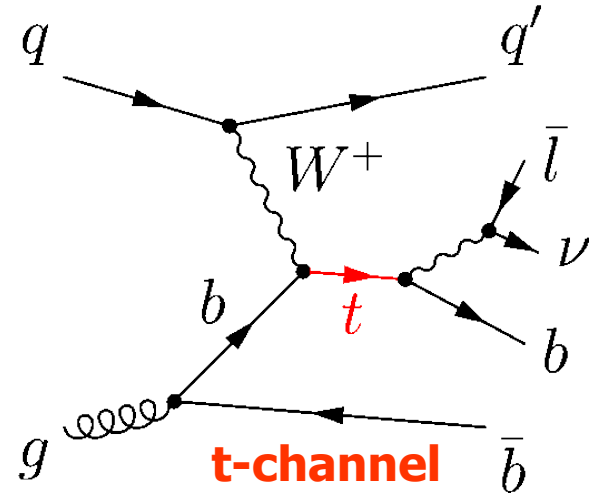


t-channel

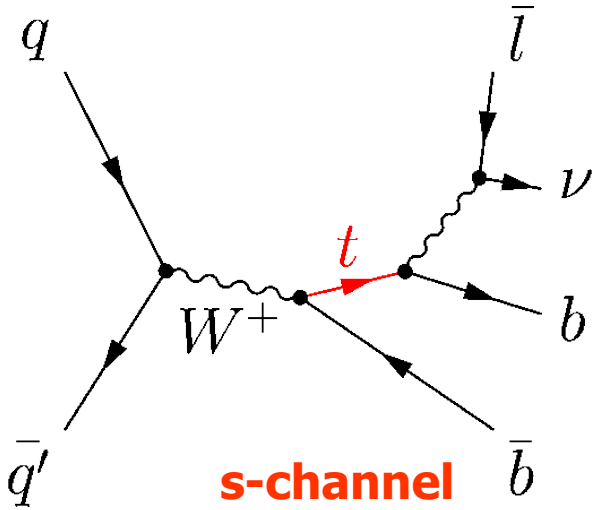


s-channel

Motivation



t-channel



s-channel

SM-Expectations:

$\sigma_{\text{t-channel NLO}} = 2.0 \pm 0.3$ pb

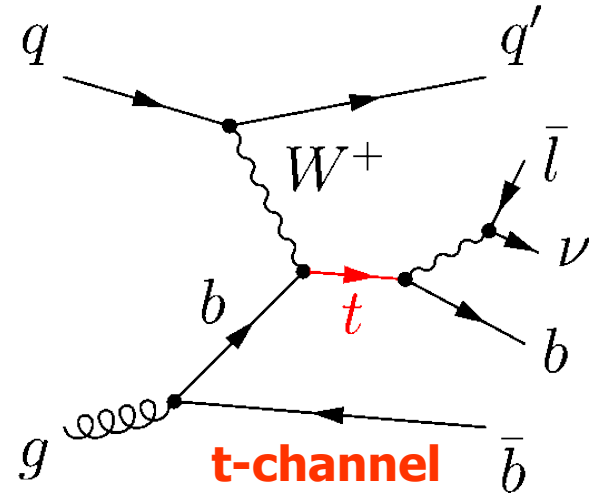
$\sigma_{\text{s-channel NLO}} = 0.9 \pm 0.1$ pb

$\sigma_{\text{single top NLO}} = 2.9 \pm 0.4$ pb

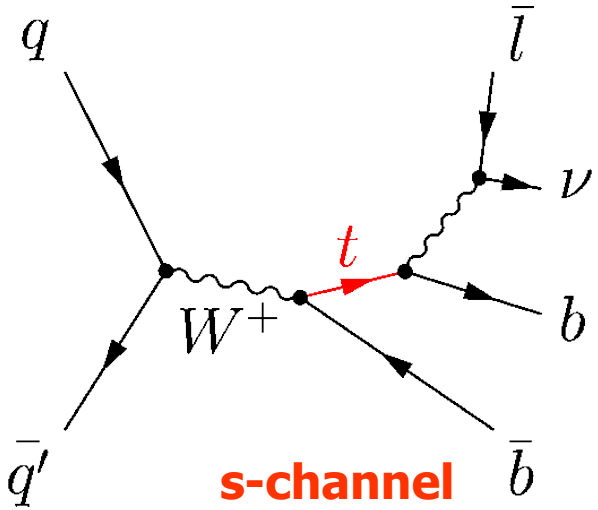
for $M_{Top} = 175$ GeV/c^2

Harris et al., Phys. Rev. D 66, 054024 (2002)
Sullivan, Phys. Rev. D 70, 114012 (2004)
Kidonakis, Phys. Rev. D 74, 114012 (2006)

Motivation



t-channel



s-channel

- Test of SM, sensitive to BSM
- Direct Measurement of $|V_{tb}|^2$
- Test of b-Quark PDF
- Milestone for WH Searches at the Tevatron
- Analogue to WH Searches

SM-Expectations:

$\sigma_{\text{t-channel NLO}} = 2.0 \pm 0.3$ pb

$\sigma_{\text{s-channel NLO}} = 0.9 \pm 0.1$ pb

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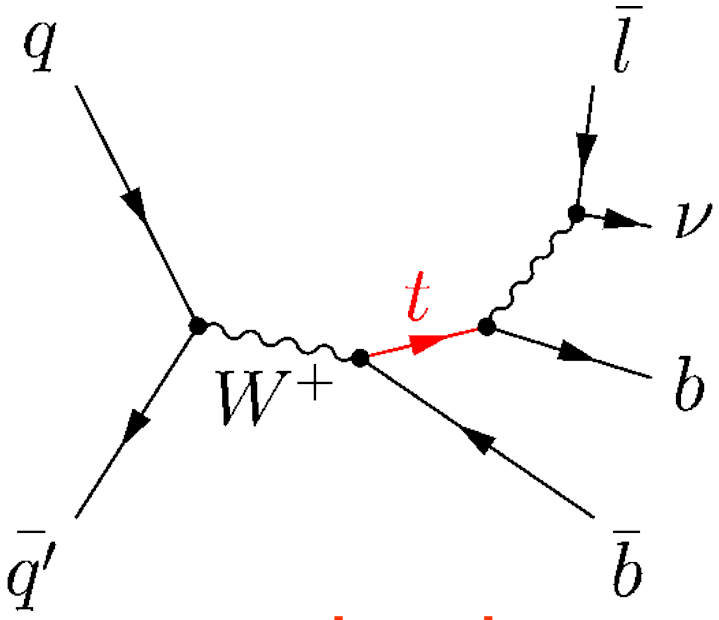
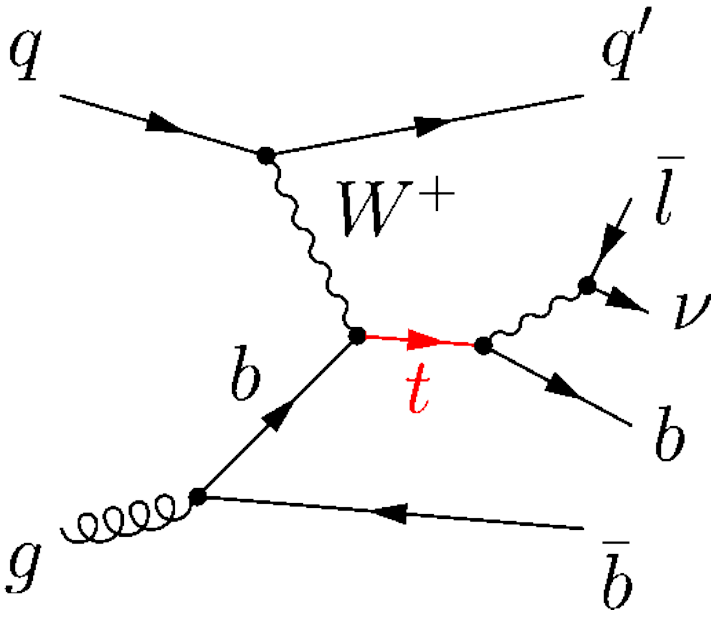
Sullivan, Phys. Rev. D 70, 114012 (2004)
Kidonakis, Phys. Rev. D 74, 114012 (2006)

Event Signature

Signature: Top-Quark Decay ~100% into W-Boson and b-Quark with $W \rightarrow l + \nu$



s-channel



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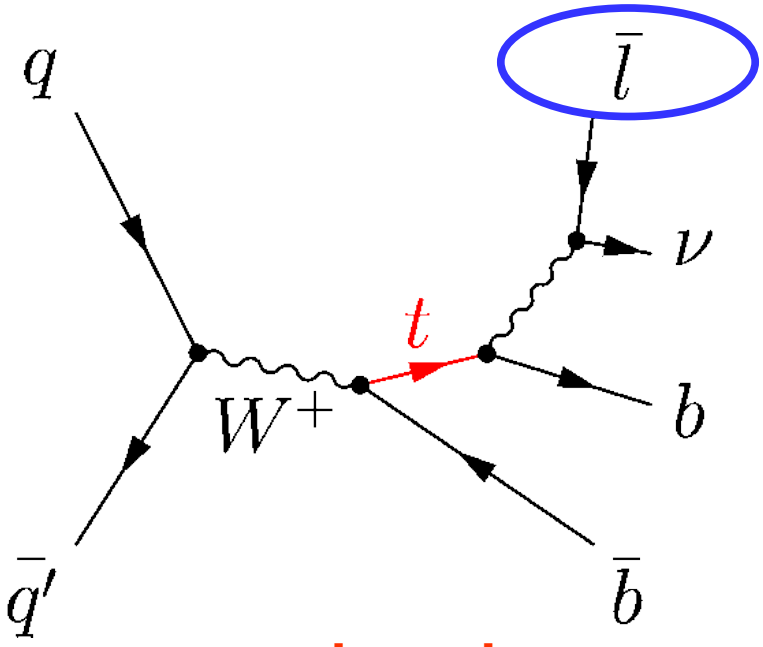
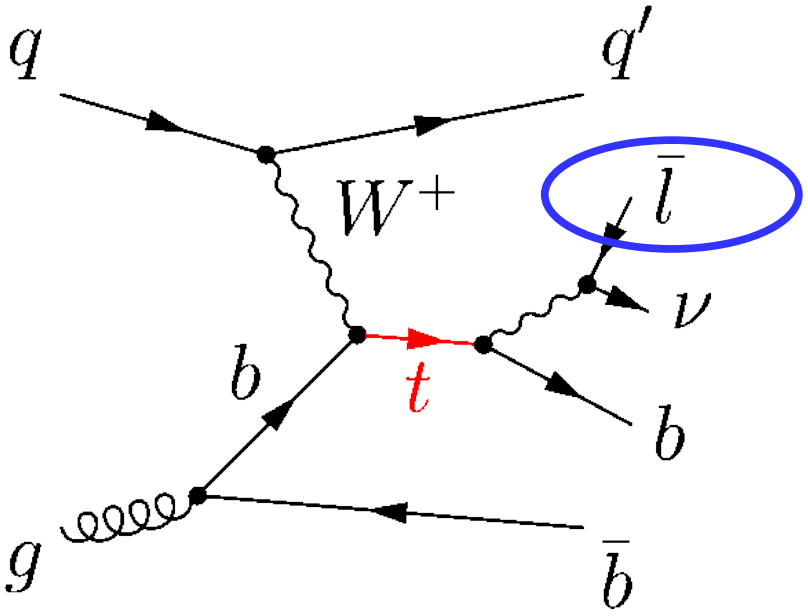
with W → l + ν



s-channel



t-channel

- **exactly 1 isolated charged Lepton** (e/μ) **(Lepton+Jets)**
or **Veto on identified Lepton** (e/μ), sensitive to τ **(MET+Jets)**

Event Signature

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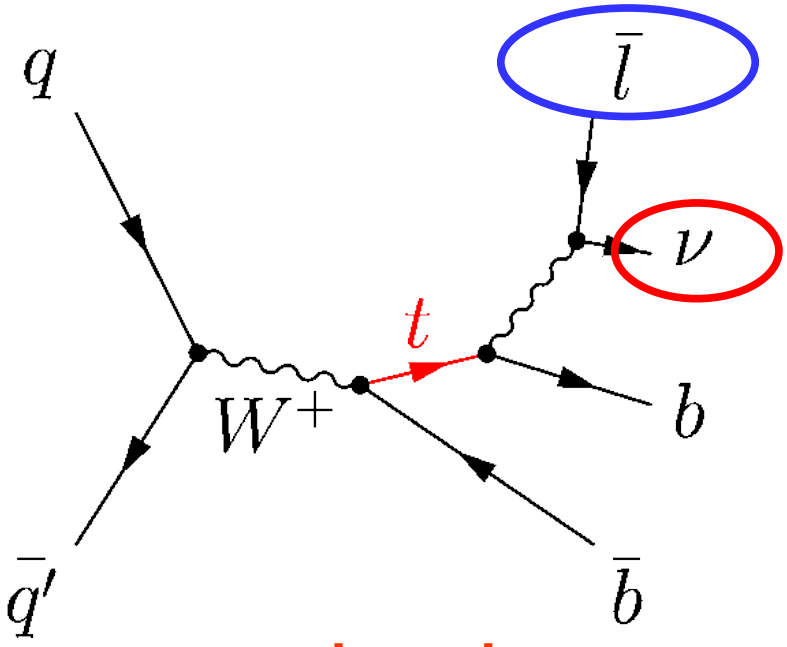
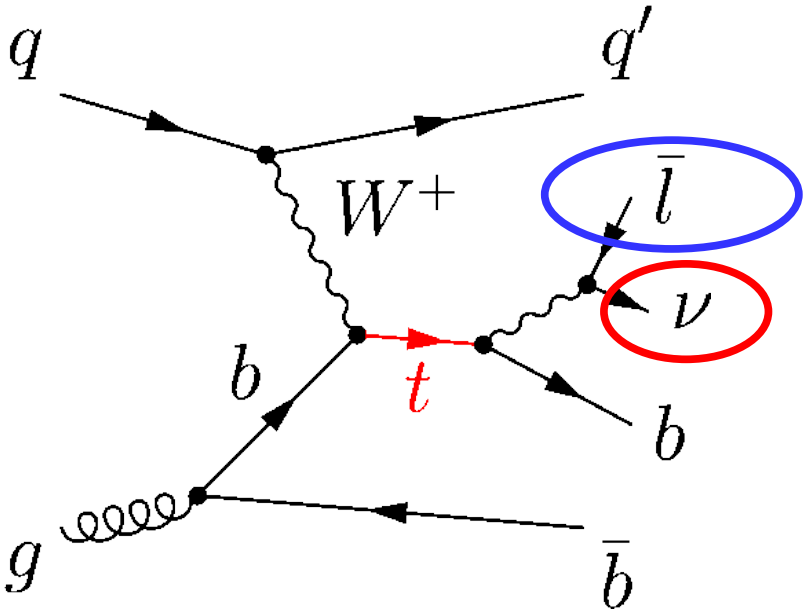
with W → l + ν



s-channel



t-channel

- **exactly 1 isolated charged Lepton** (e/μ) **(Lepton+Jets)**
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- **Missing Transverse Energy**

Event Signature

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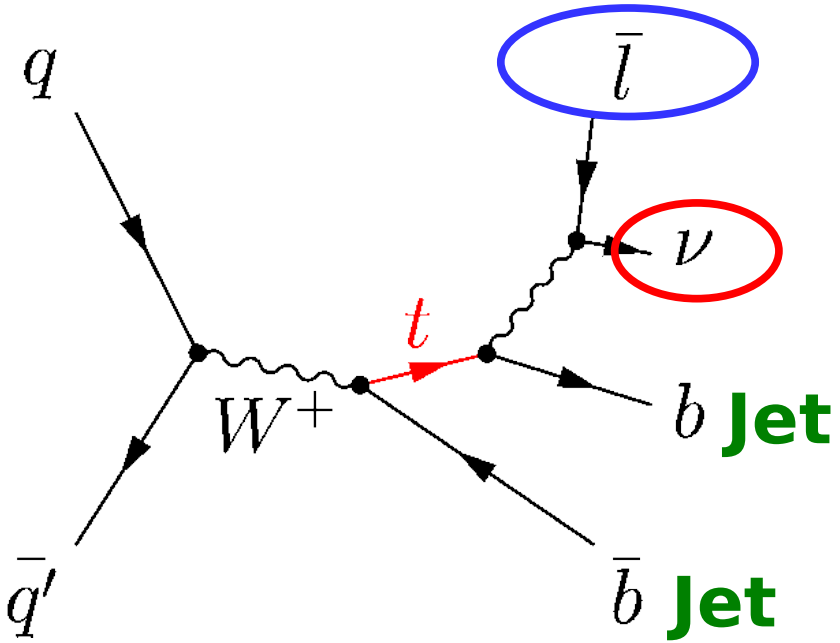
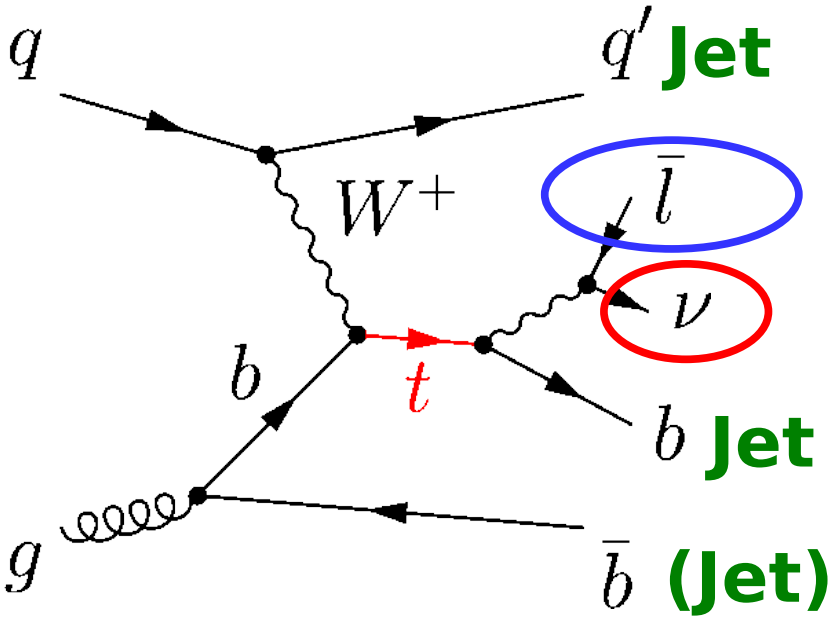
with W → l + ν



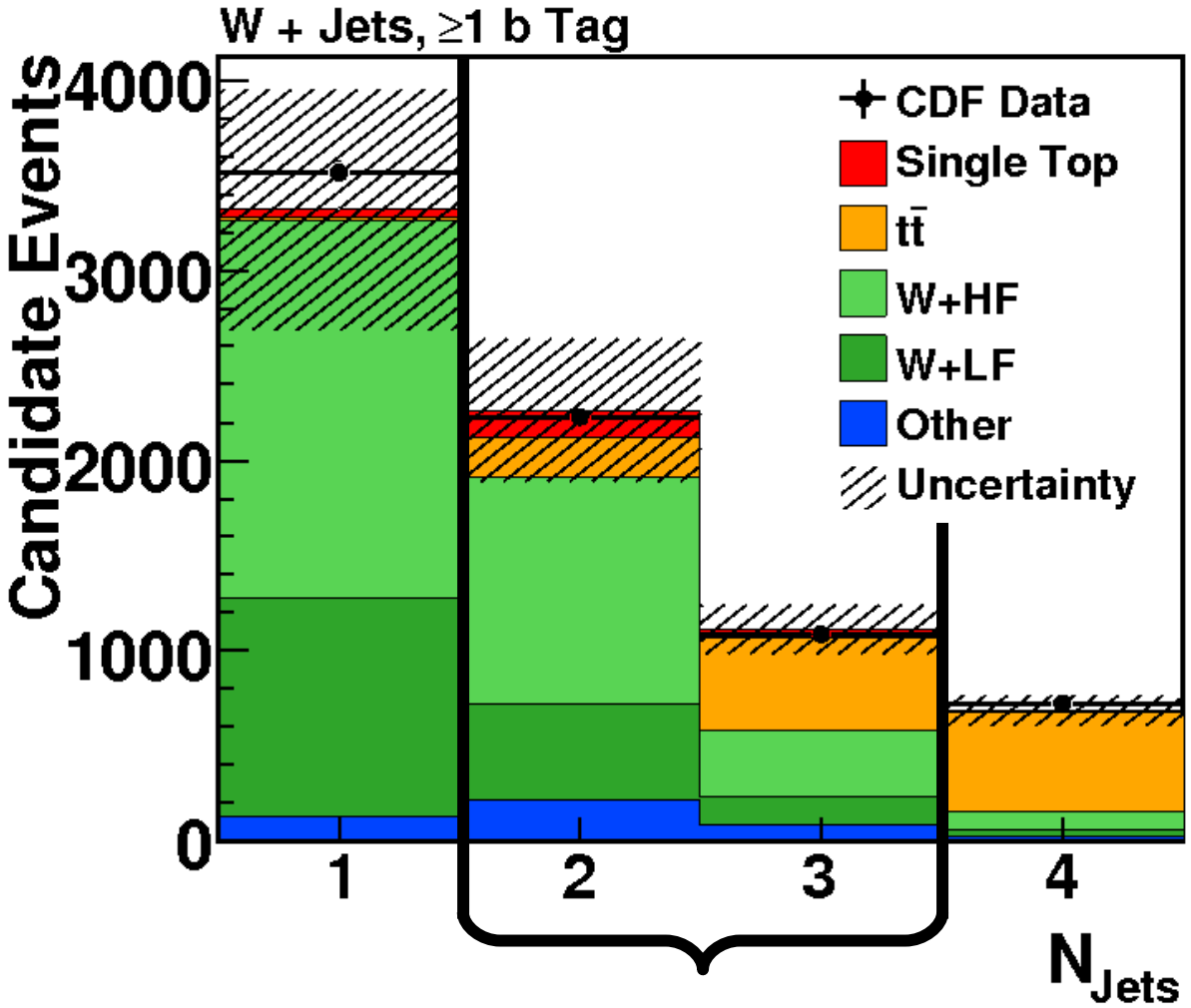
s-channel



t-channel

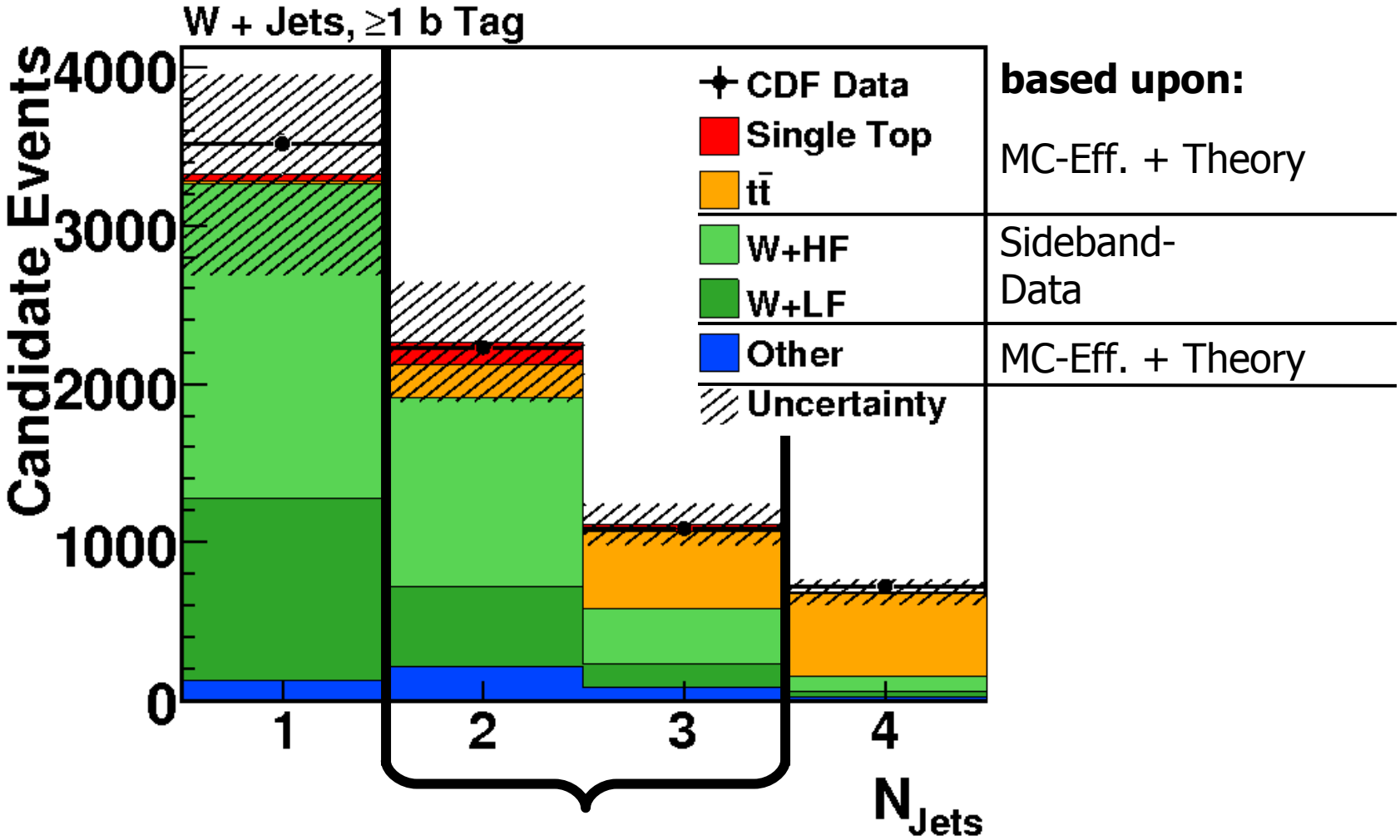
- **exactly 1 isolated charged Lepton** (e/μ) **(Lepton+Jets)**
  or **Veto on identified Lepton** (e/μ), sensitive to τ **(MET+Jets)**
- **Missing Transverse Energy**
- **2 or 3 Jets** with at least 1 b Tag
- QCD-Veto, Z-Veto, Cosmic-Veto,…

L+J Background Estimate 3.2 fb^{-1}



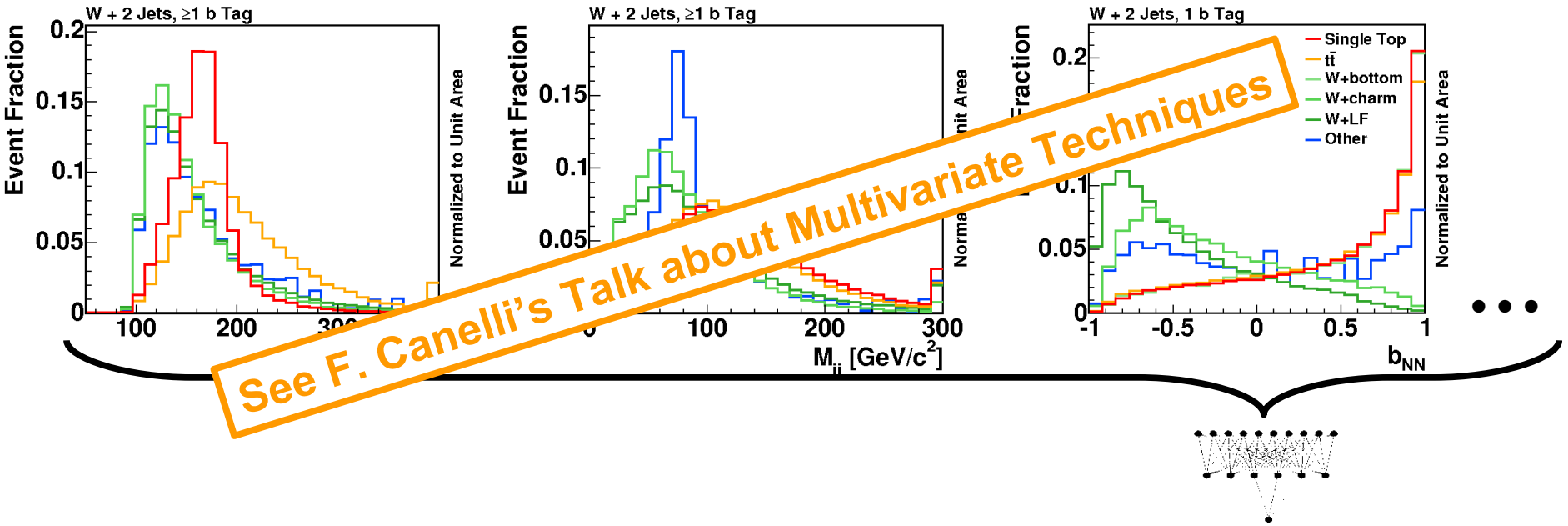
Signal region divided into Jets (2 or 3), b-Tags (1 or 2) and Trigger (Lepton or MET+Jets), i.e. 8 independent Channels

L+J Background Estimate 3.2 fb^{-1}



Signal region divided into Jets (2 or 3), b-Tags (1 or 2) and Trigger (Lepton or MET+Jets), i.e. 8 independent Channels

Multivariate Methods

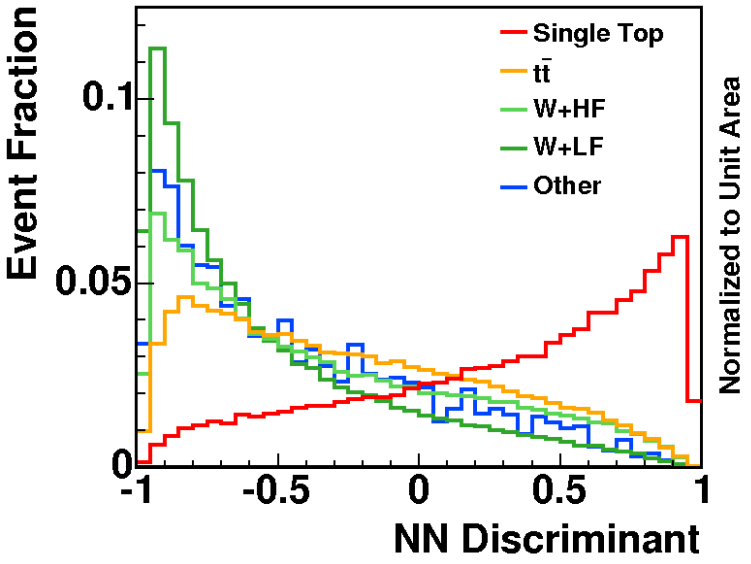


NeuroBayes® Neural Network **(NN)**

Likelihood-Function **(LF)**

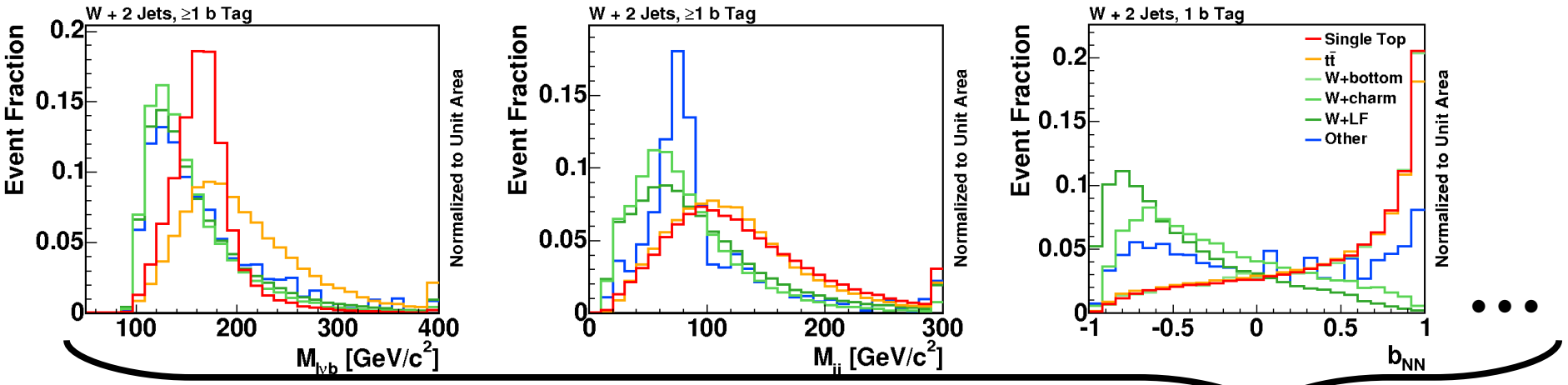
Boosted-Decision-Tree-Method **(BDT)**

Matrix-Element-Method **(ME)**



expected Sensitivity: 5.2σ

Multivariate Methods



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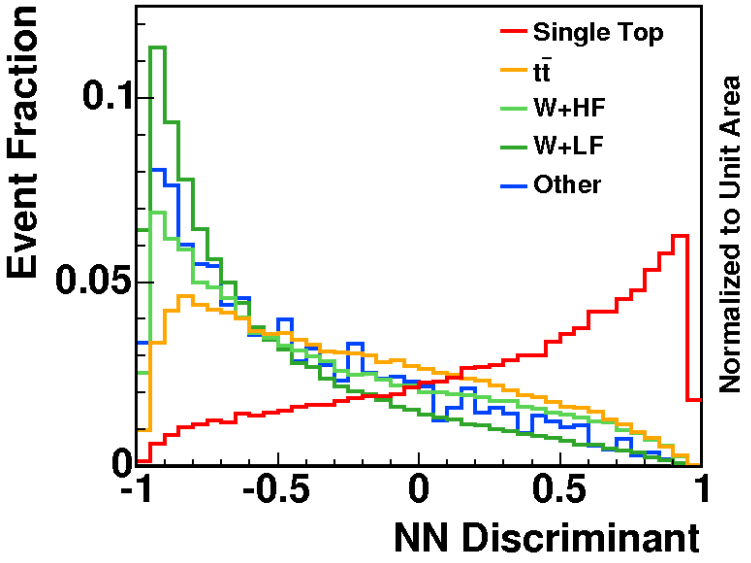
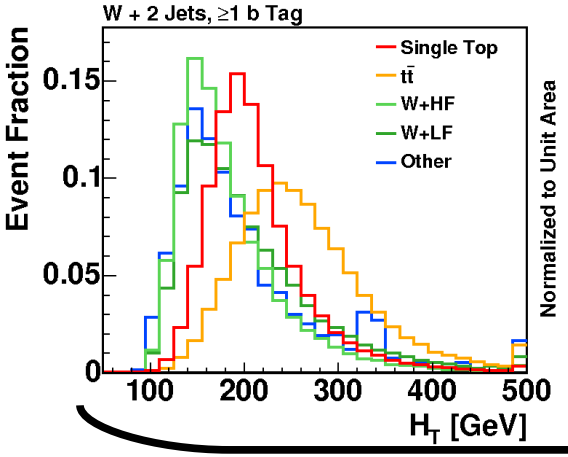
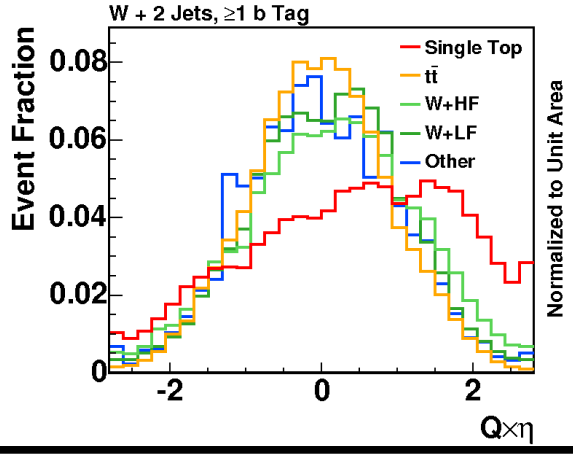
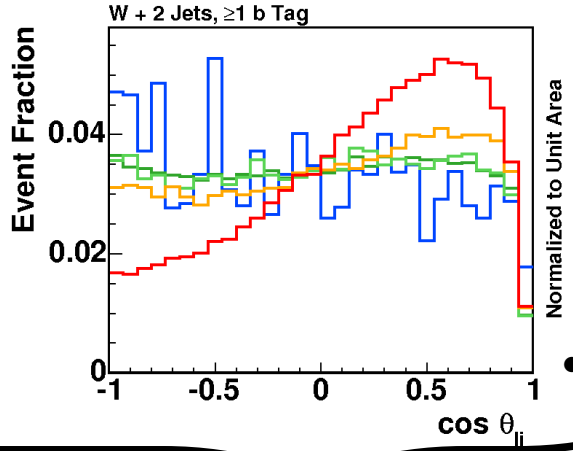


expected Sensitivity: 5.2σ

Multivariate Methods







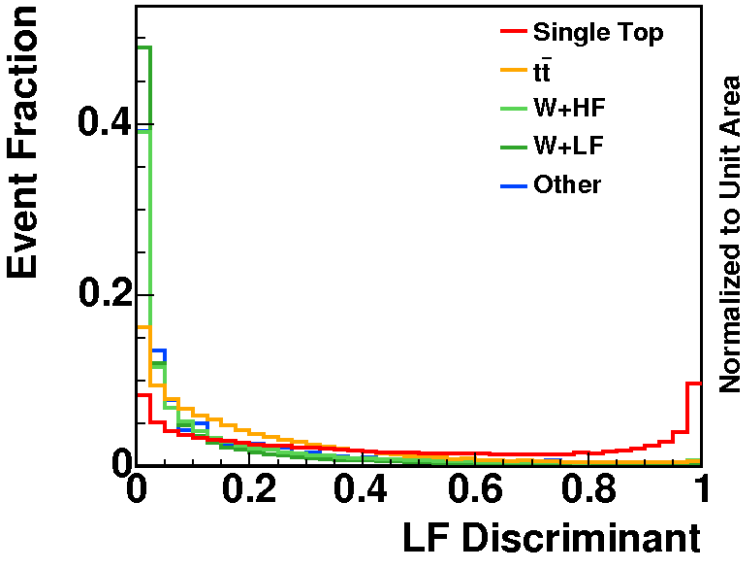
$$\mathcal{L}^{signal} = \frac{\prod_{i=1}^{n_{val}} P_i^{\text{signal}}}{\prod_{i=1}^{n_{val}} P_i^{\text{signal}} + \sum_{m=1}^{n_{bkg}} \prod_{i=1}^{n_{val}} P_i^{m} \times \alpha^m}$$

NeuroBayes® Neural Network **(NN)**

Likelihood-Function **(LF)**

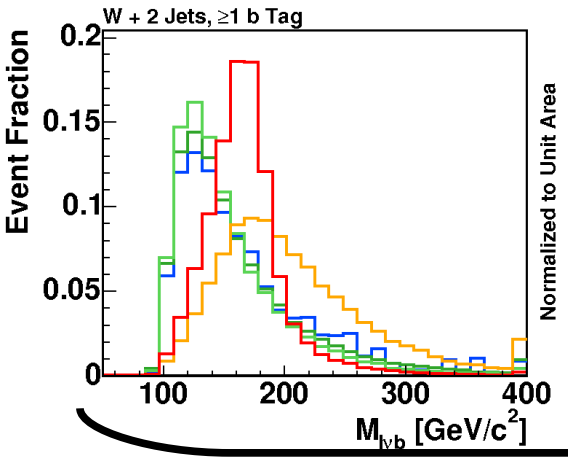
Boosted-Decision-Tree-Method **(BDT)**

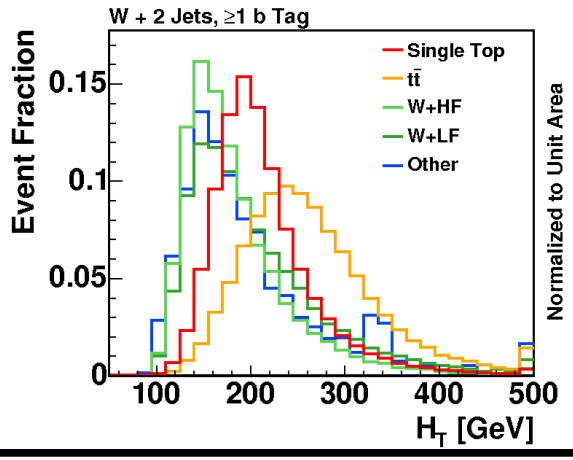
Matrix-Element-Method **(ME)**

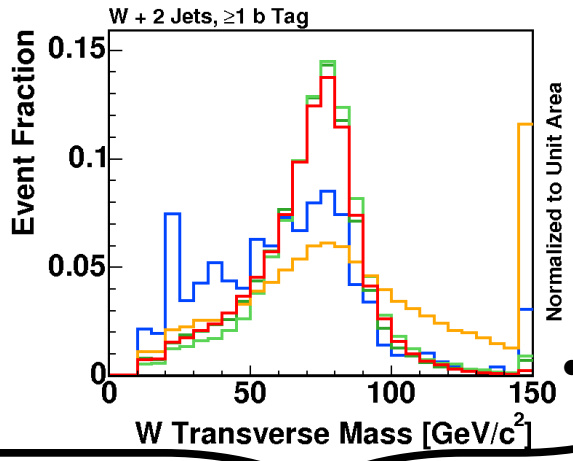


expected Sensitivity: 4.0σ

Multivariate Methods





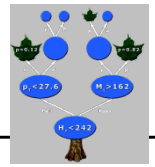


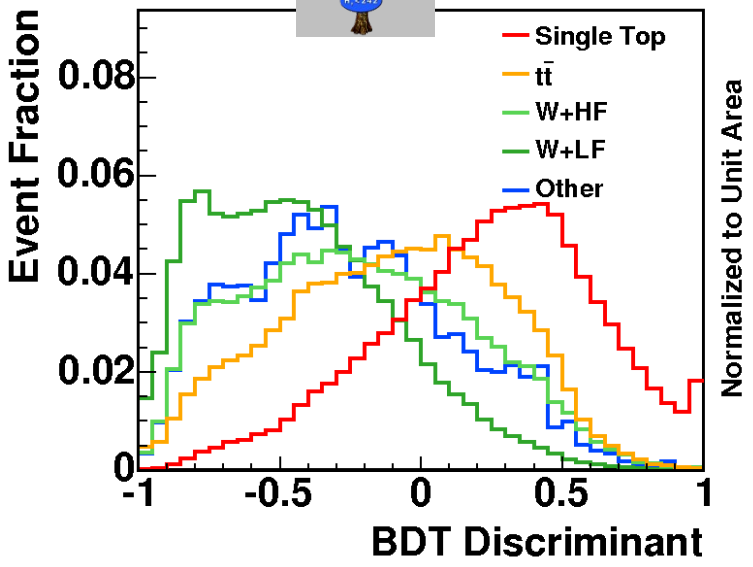
NeuroBayes® Neural Network (NN)

Likelihood-Function (LF)

Boosted-Decision-Tree-Method (BDT)

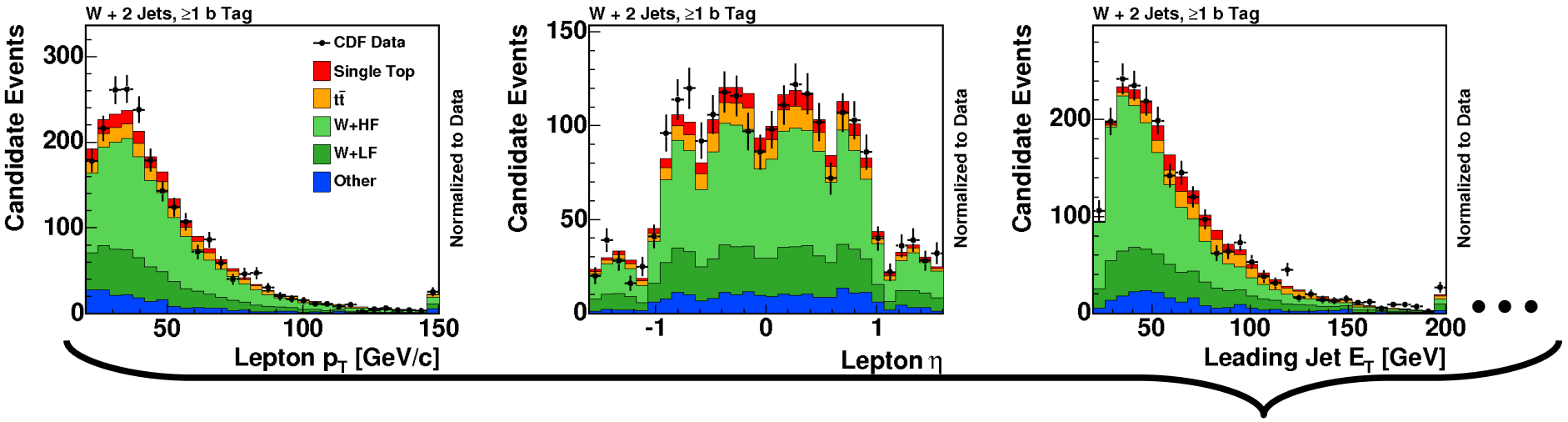
Matrix-Element-Method (ME)





expected Sensitivity: 5.2σ

Multivariate Methods



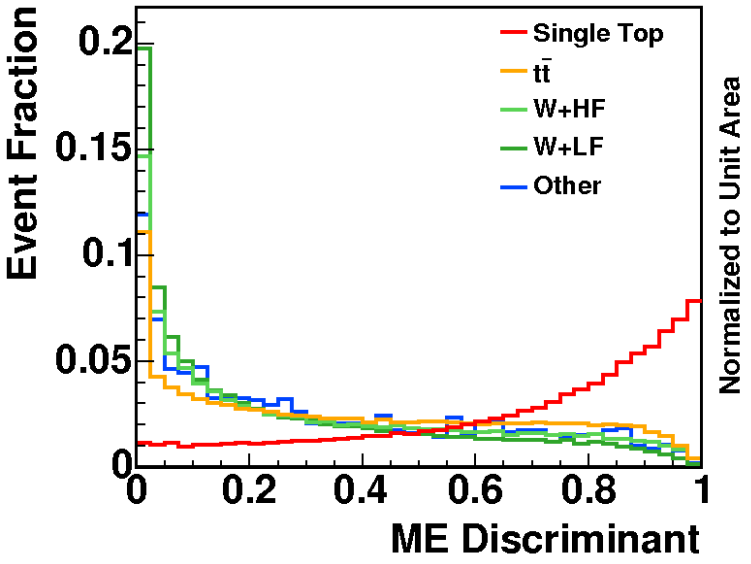
$$EPD = \frac{b \cdot P_{\sin gletop}}{b \cdot P_{\sin gletop} + b \cdot (P_{Wb\bar{b}} + P_{t\bar{t}}) + (1-b) \cdot (P_{Wc\bar{c}} + P_{Wcj} + P_{Wgg})}$$

NeuroBayes® Neural Network (NN)

Likelihood-Function (LF)

Boosted-Decision-Tree-Method (BDT)

Matrix-Element-Method (ME)



expected Sensitivity: 4.9σ

Systematic Uncertainties

Source	Rate	Shape
JES	0...16%	X
ISR/FSR	0...15%	X
PDF	2...3%	X
Monte Carlo generator	1...5%	
Event detection efficiency	0...9%	
Luminosity	6.0%	
KIT Flavor Separator		X
Mistag model		X
QCD model		X
Q^2 scale in Alpgen MC		X
Input variable mismodeling		X
W+bottom normalization	**30%**	
W+charm normalization	**30%**	
W+light normalization	**17...29%**	
tt-bar normalization	23%	

Systematic Uncertainties

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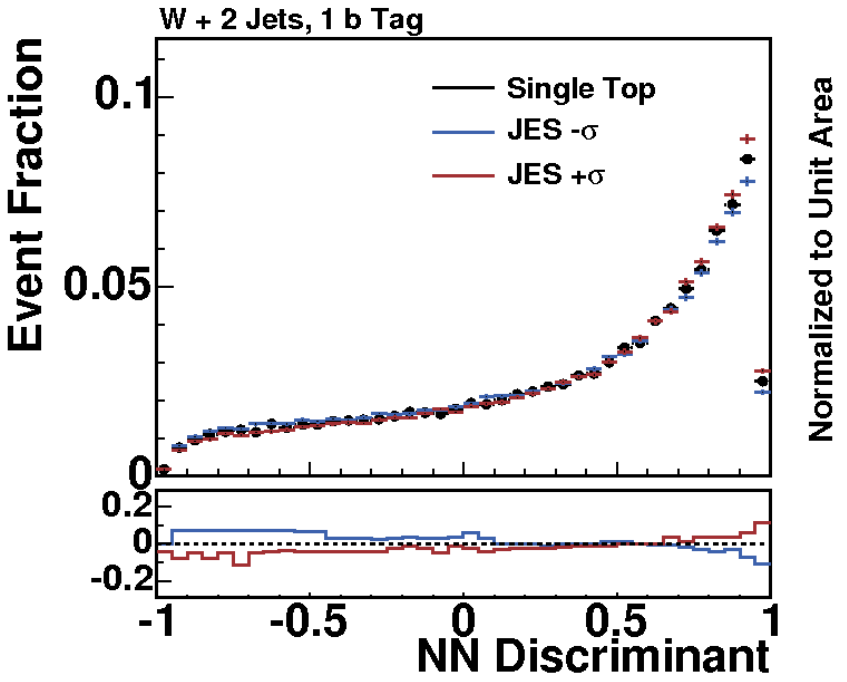
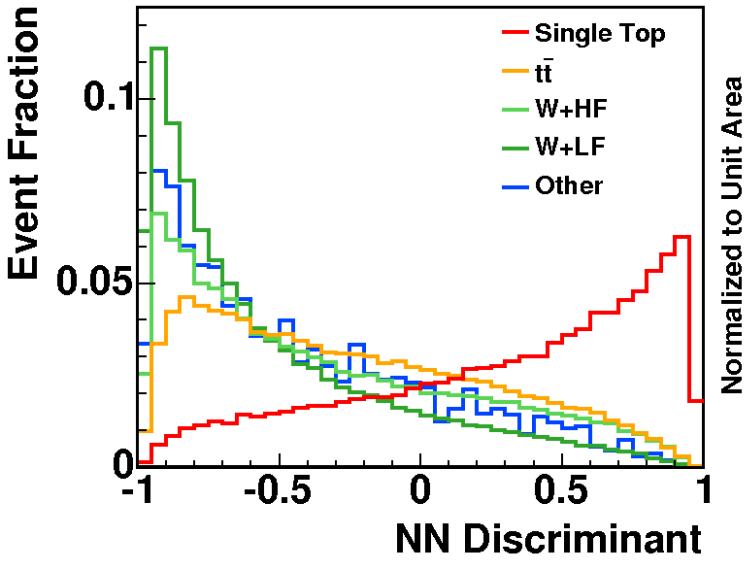
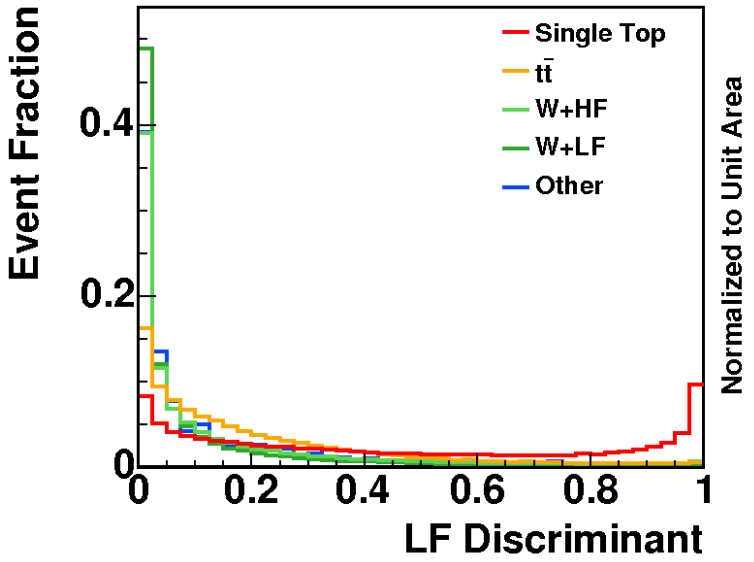
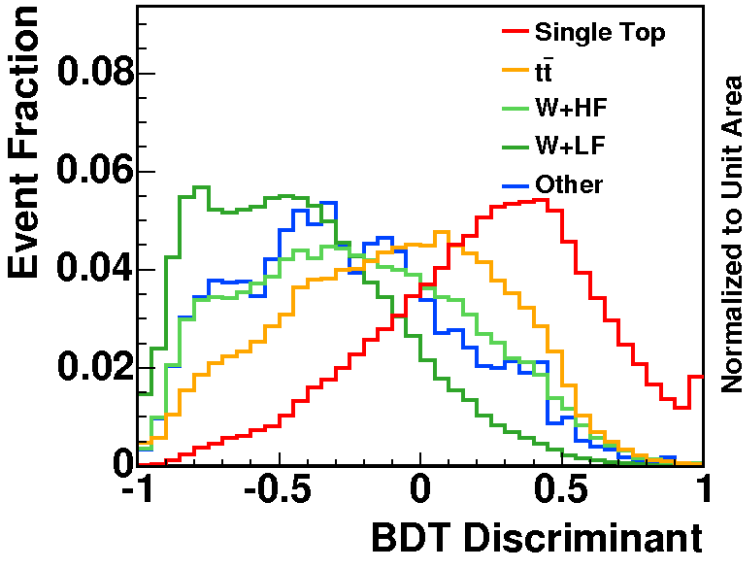
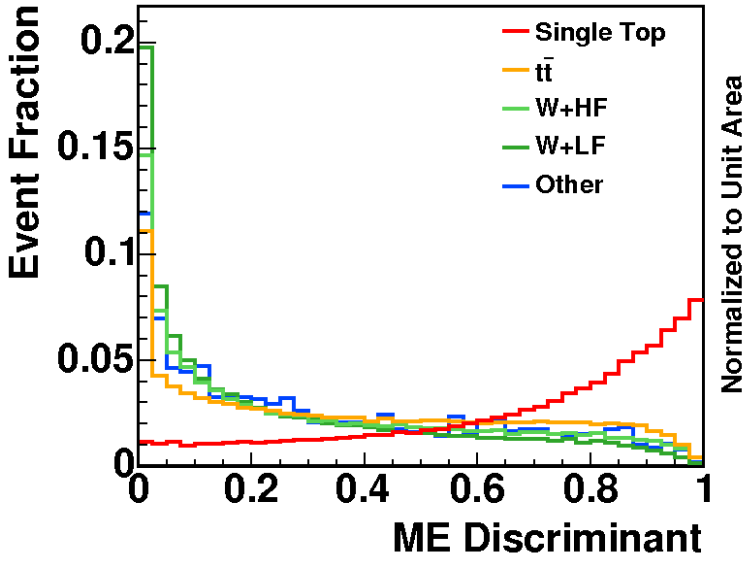


Lepton+Jets Combination









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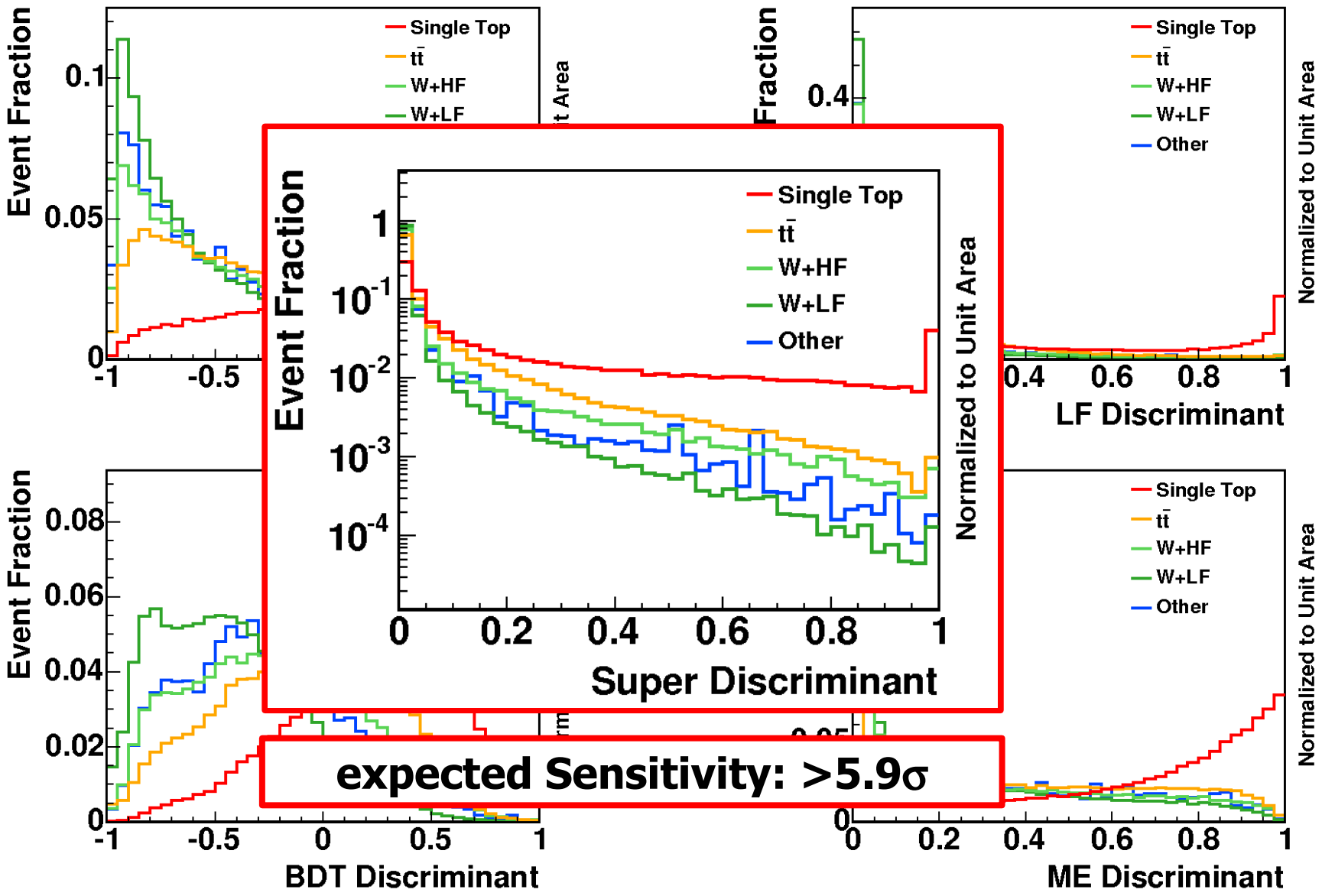


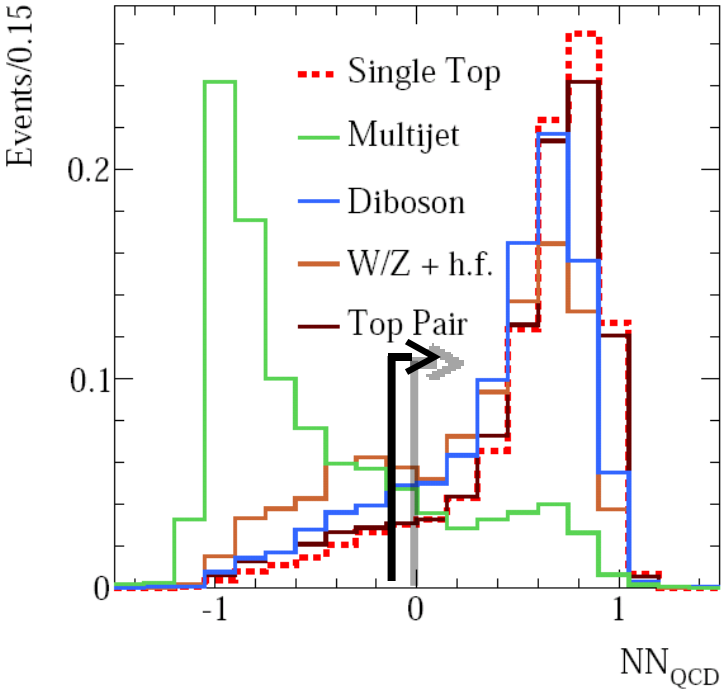
MET+Jets Analysis (MJ) 2.1 fb^{-1}

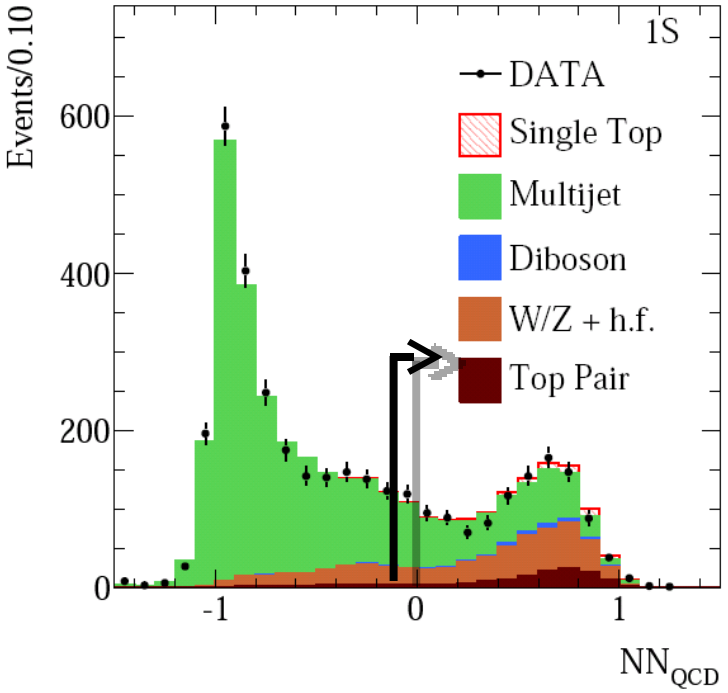
Orthogonal Selection to Lepton+Jets:

- **Veto on reconstructed Electrons und Muons**
- **MET > 50 GeV**
- **2 or 3 Jets (at least with 1 reconstructed secondary Vertex or 1 Jet-Probability Tag)**

NN-Selection against QCD Multijets

~33% absolute Gain in Signal Acceptance wrt. L+J Selection





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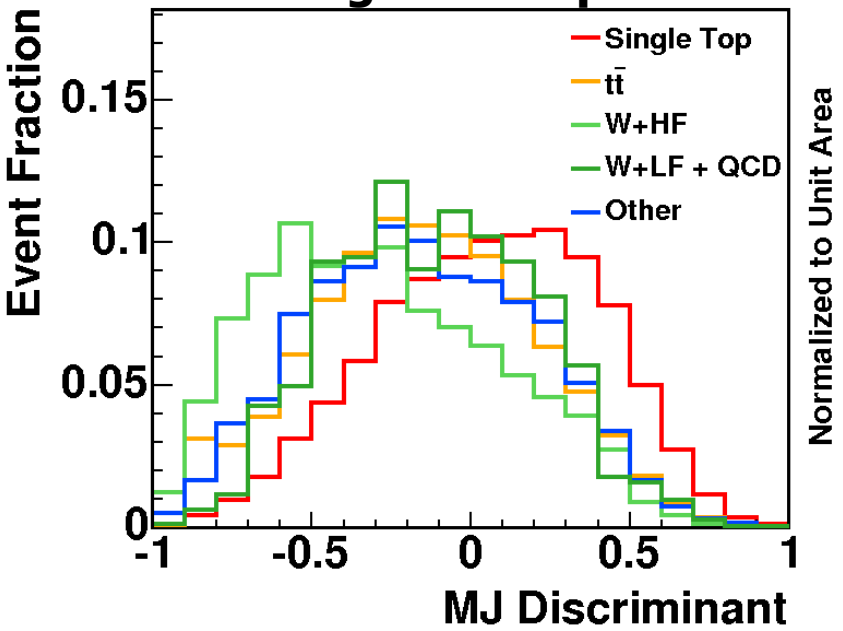
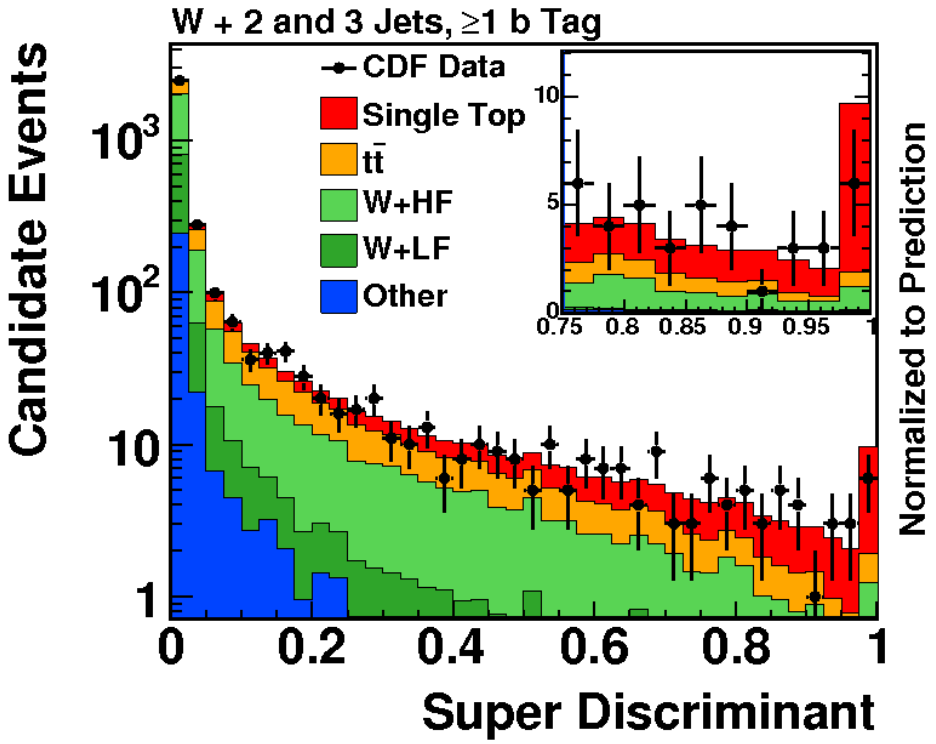
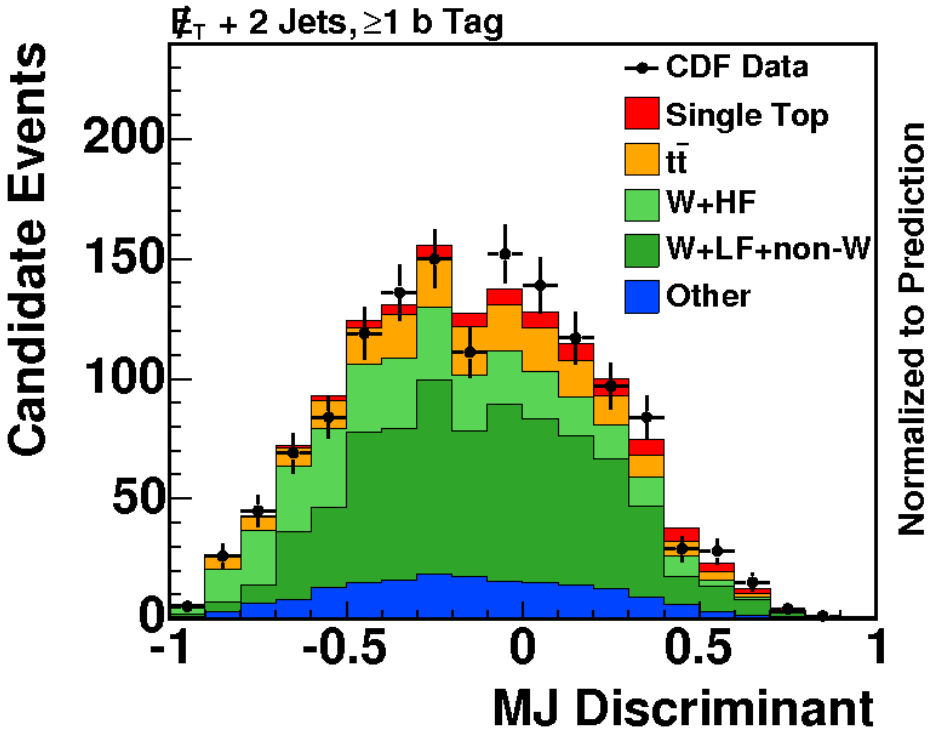


expected Sensitivity: 1.4σ

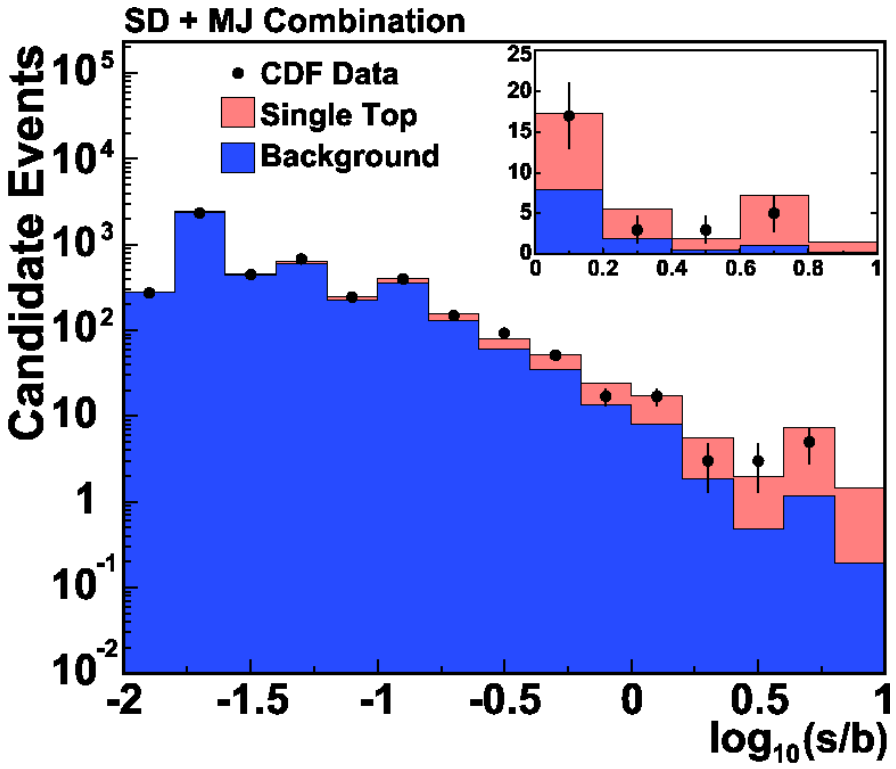
SD+MJ Combination





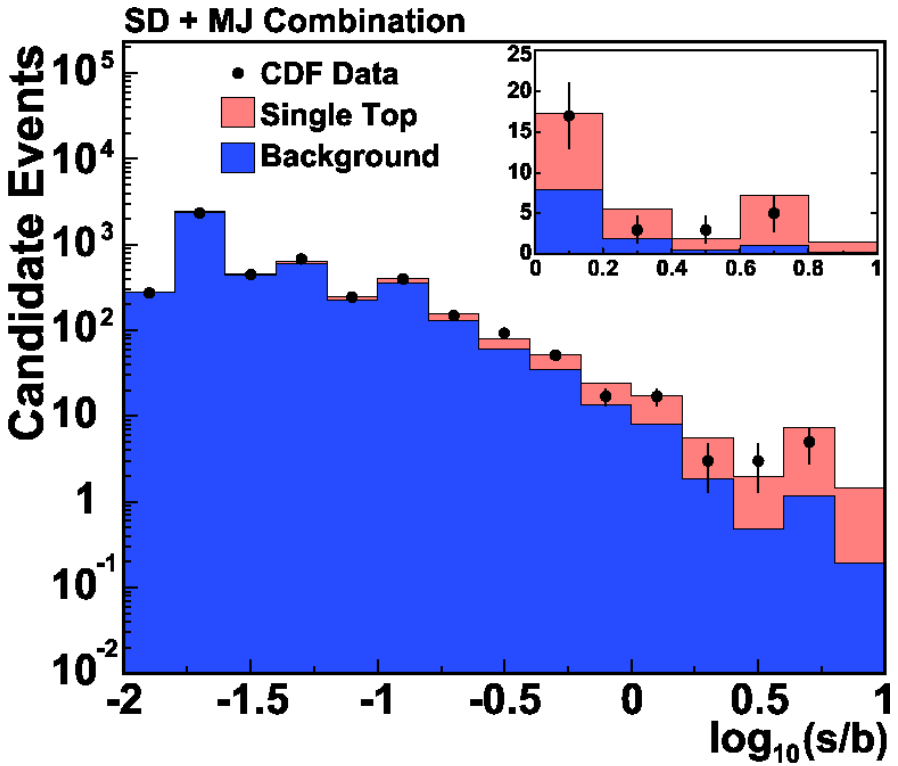
Simultaneous Extraction of the Signal Fraction from the Super Discriminant and the orthogonal MJ Discriminant
Marginalization of a Likelihood with incorporated systematic Rate, Shape and Bin-by-Bin MC statistical Uncertainties

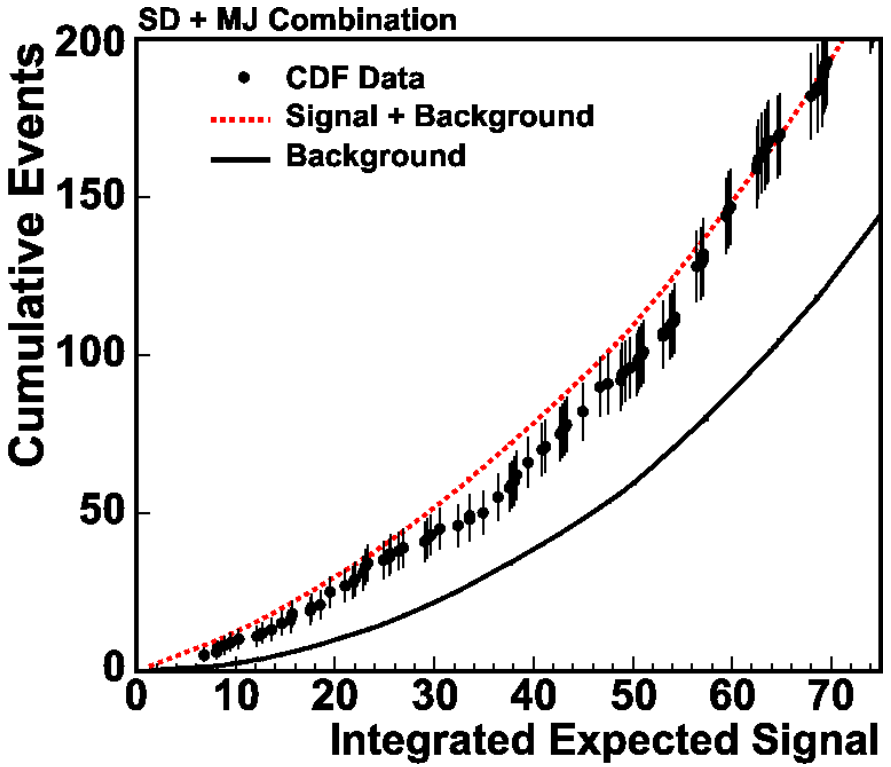
SD+MJ Combination



Distribution of both orthogonal Samples ordered by similar s/b compared to the SM Prediction

SD+MJ Combination

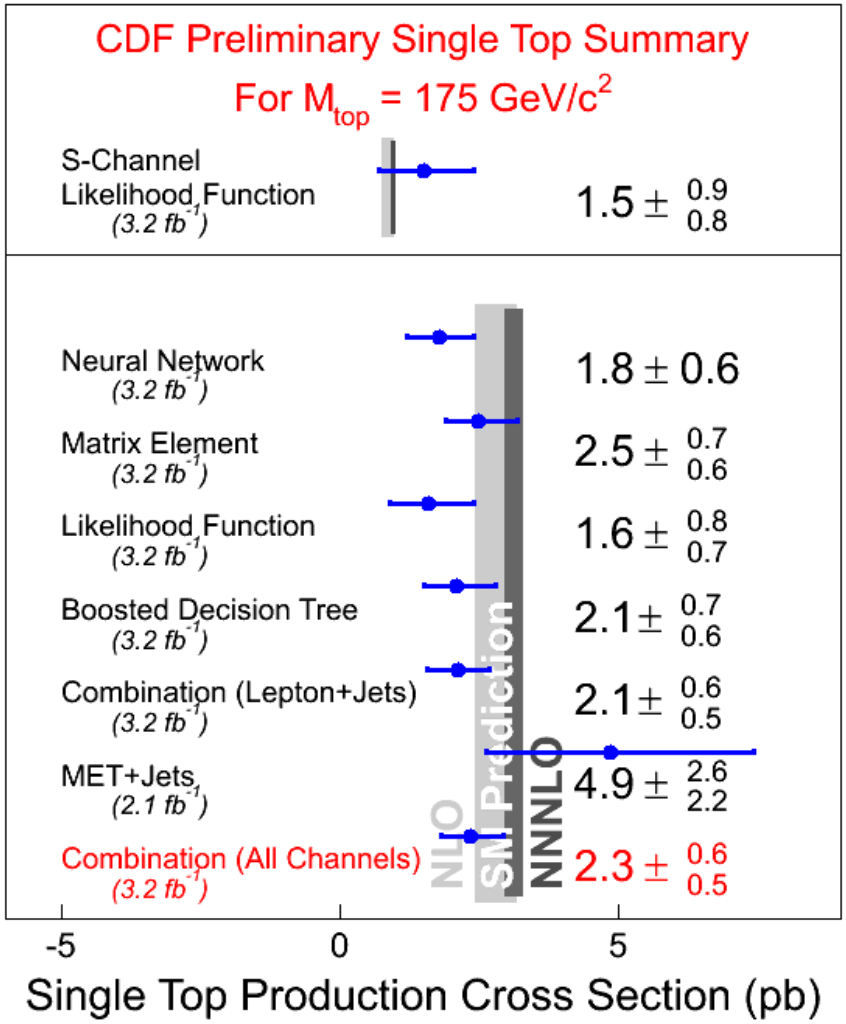




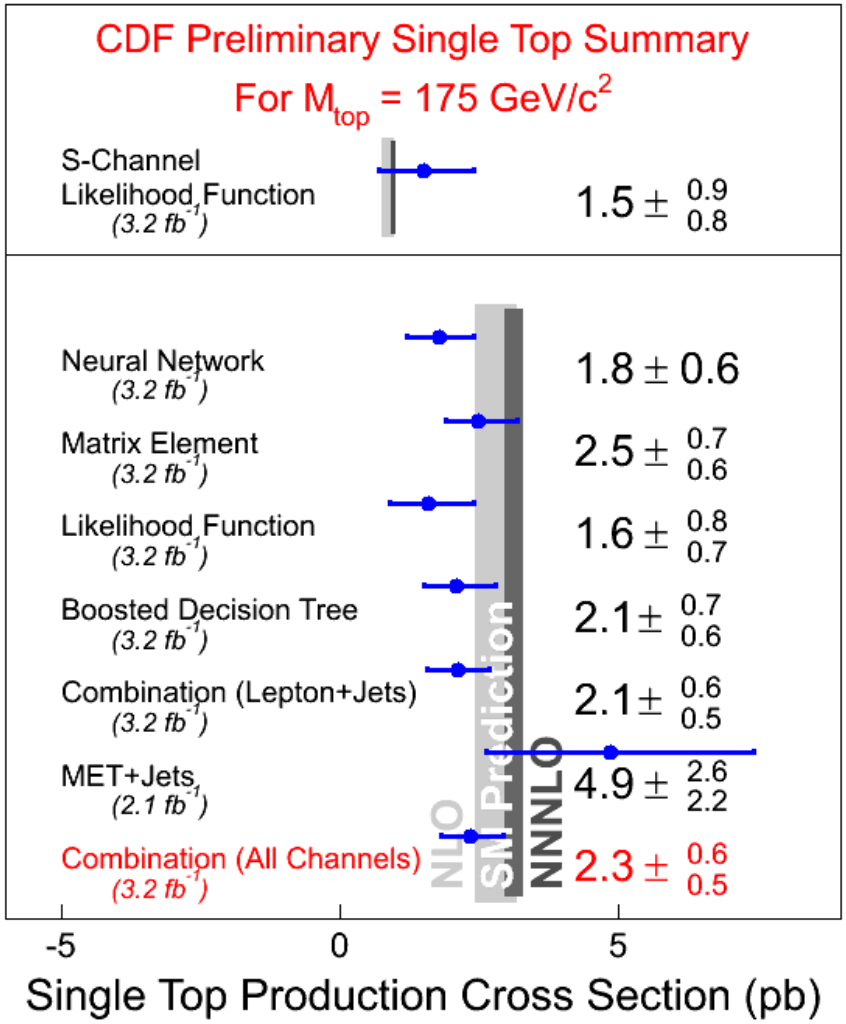
Distribution of both orthogonal Samples ordered by similar s/b compared to the SM Prediction

Accumulated Distribution (integrated starting on the high-s/b Side) shows clear Excess of Data over Background Prediction

Results

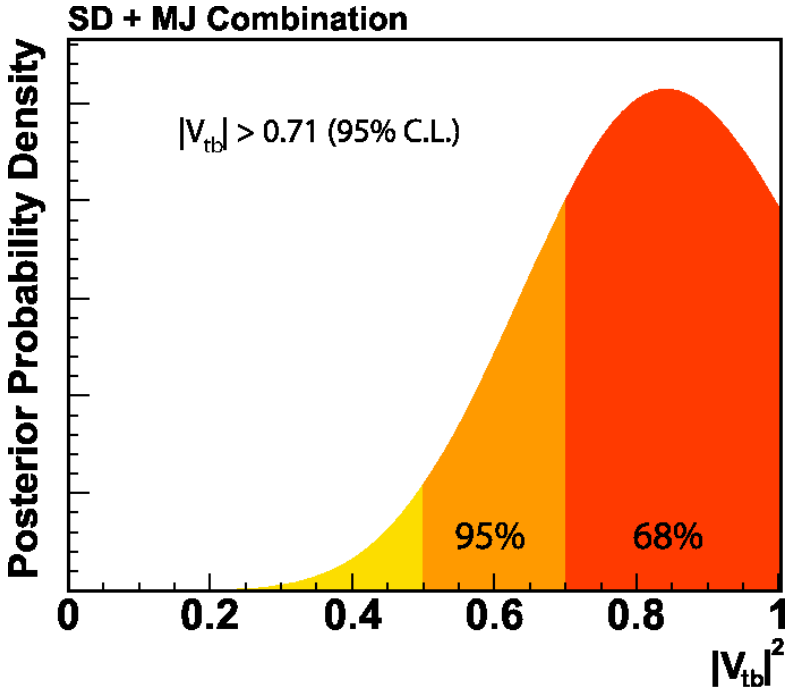

CDF Preliminary Single Top Summary
For M_{top} = 175 GeV/c^2
S-Channel Likelihood Function (3.2 fb^{-1})
$1.5 \pm {}^{0.9}_{0.8}$
Neural Network (3.2 fb^{-1})
1.8 ± 0.6
Matrix Element (3.2 fb^{-1})
$2.5 \pm {}^{0.7}_{0.6}$
Likelihood Function (3.2 fb^{-1})
$1.6 \pm {}^{0.8}_{0.7}$
Boosted Decision Tree (3.2 fb^{-1})
$2.1 \pm {}^{0.7}_{0.6}$
Combination (Lepton+Jets) (3.2 fb^{-1})
$2.1 \pm {}^{0.6}_{0.5}$
MET+Jets (2.1 fb^{-1})
$4.9 \pm {}^{2.6}_{2.2}$
Combination (All Channels) (3.2 fb^{-1})
$2.3 \pm {}^{0.6}_{0.5}$
NLO
SM Prediction
NNNLO
-5
0
5
Single Top Production Cross Section (pb)

Results

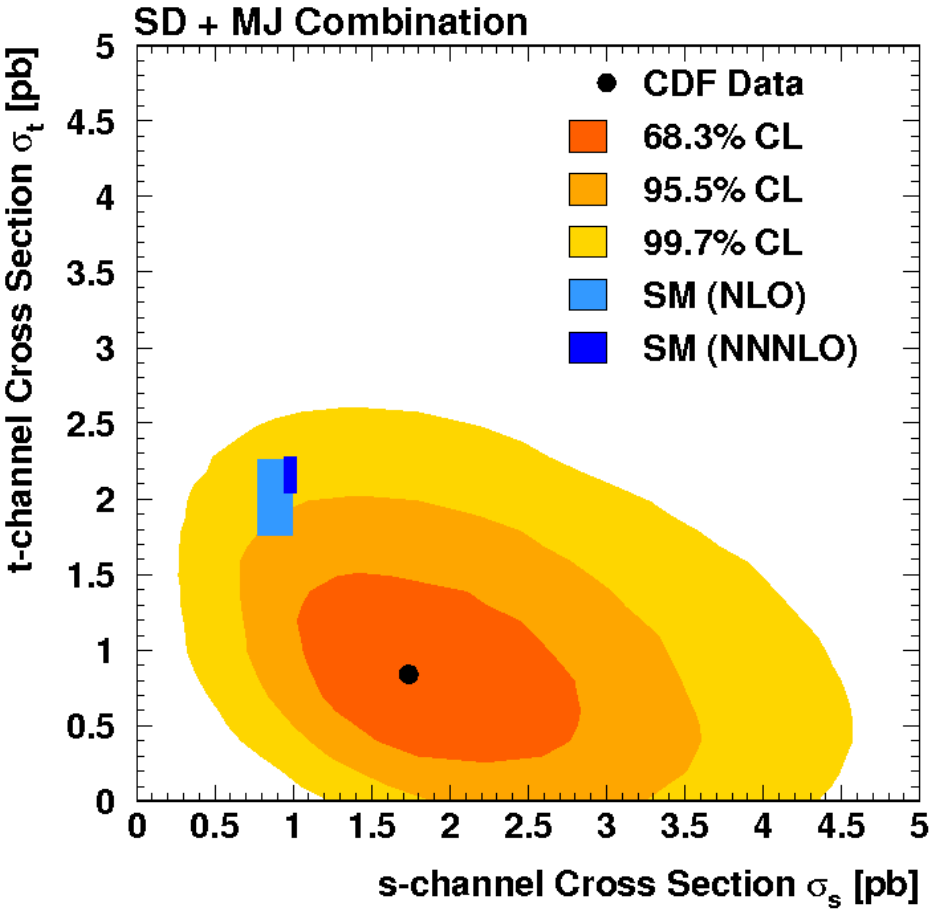


Assumption: $|V_{tb}|^2 >> |V_{ts}|^2 + |V_{td}|^2$

$|V_{tb}| = 0.91 \pm 0.11$ (exp.) ± 0.07 (theory)



2D-Result

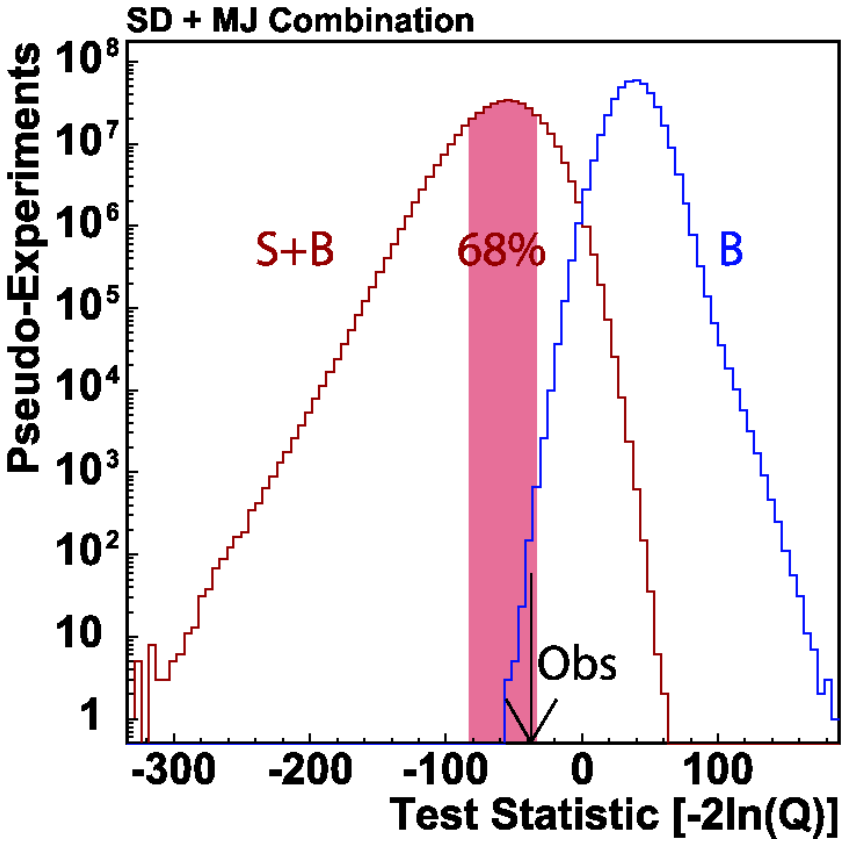


$\sigma_{\text{t-channel}} = 0.8\ ^{+0.7}_{-0.5}$ pb

$\sigma_{\text{s-channel}} = 1.8 \pm 0.1$ pb

Simultaneous Extraction of both the t- and s-channel Signal Fractions from the Super Discriminant and the orthogonal MJ Discriminant

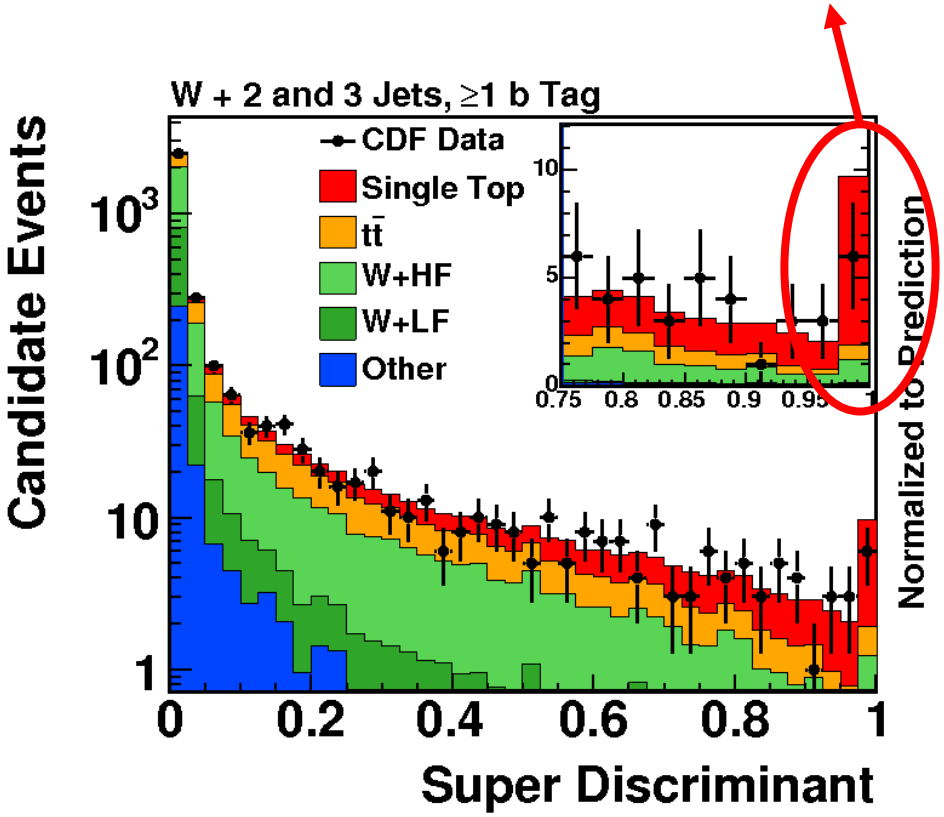
Signal Significance



expected Sensitivity:	>5.9 σ
observed Significance:	5.0 σ

Golden Lepton+Jets Events

Run	Event	Lepton	KIT NN	BDT	LF	ME	NN	SD	H_T	$M_{l\nu b}$	$Q \times \eta$
148916	792764	CEM	0.94	0.76	0.94	0.97	0.94	0.99	219.0	189.7	-2.15
206282	3294678	CMUP	0.99	0.76	0.80	0.98	0.94	1.0	307.3	178.0	1.31
229936	4412760	CMX	1.00	0.95	1.00	0.99	0.97	1.0	221.0	171.1	2.03
242557	1564229	CEM	0.54	0.85	1.00	0.99	0.93	1.0	189.8	164.5	2.84
262776	4920497	CEM	0.86	0.95	1.00	1.00	0.92	1.0	191.8	160.8	2.67



Golden Lepton+Jets Events

Run	Event	Lepton	KIT NN	BDT	LF	ME	NN	SD	H_T	$M_{l\nu b}$	$Q \times \eta$
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206282	3294678	CMUP	0.99	0.76	0.80	0.98	0.94	1.0	307.3	178.0	1.31
229936	4412760	CMX	1.00	0.95	1.00	0.99	0.97	1.0	221.0	171.1	2.03
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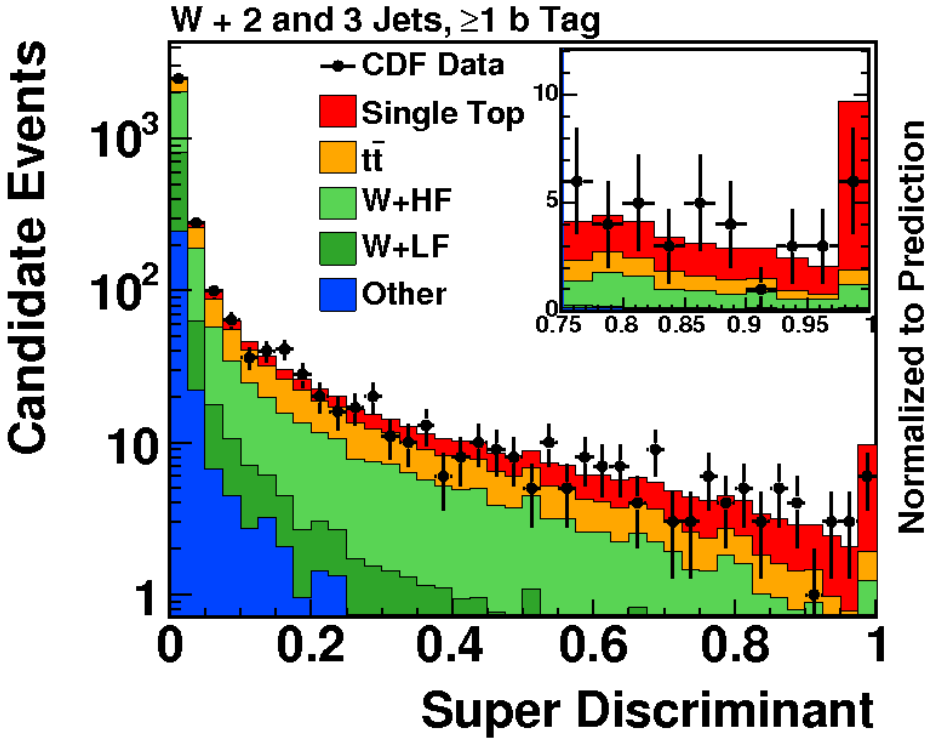
ø 172.8



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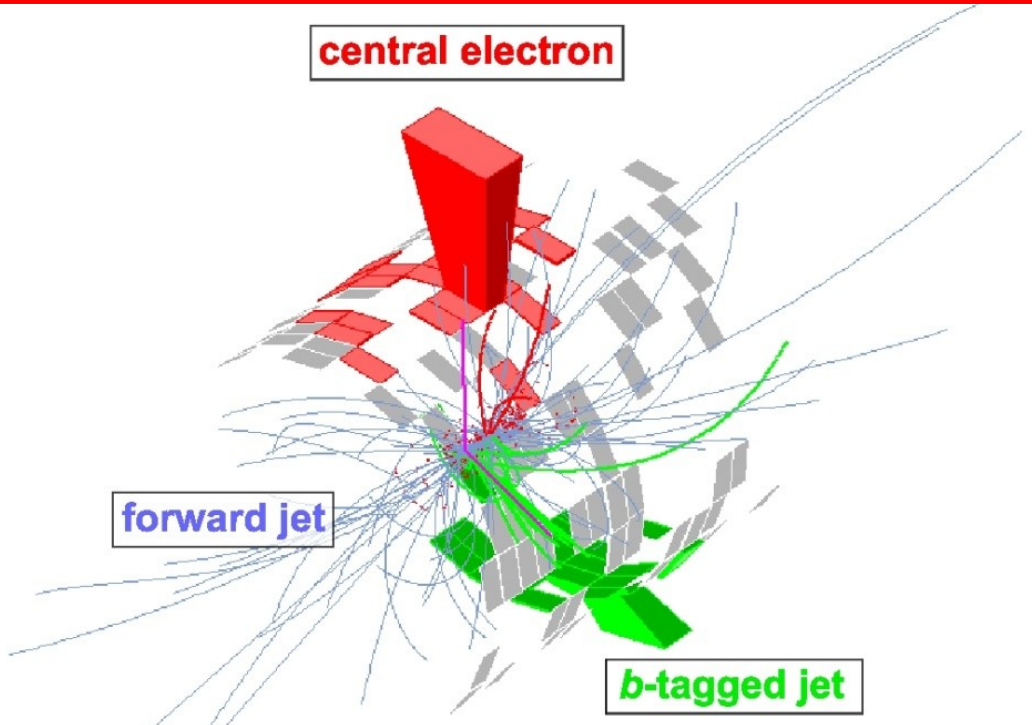
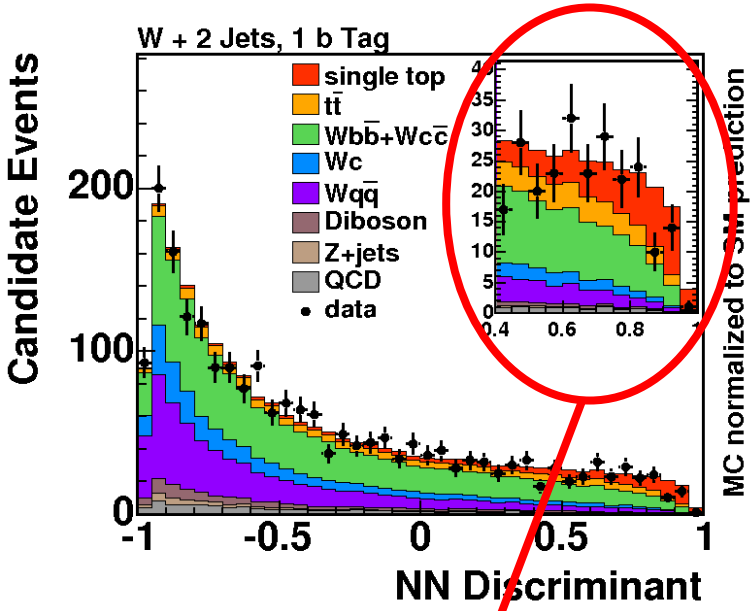
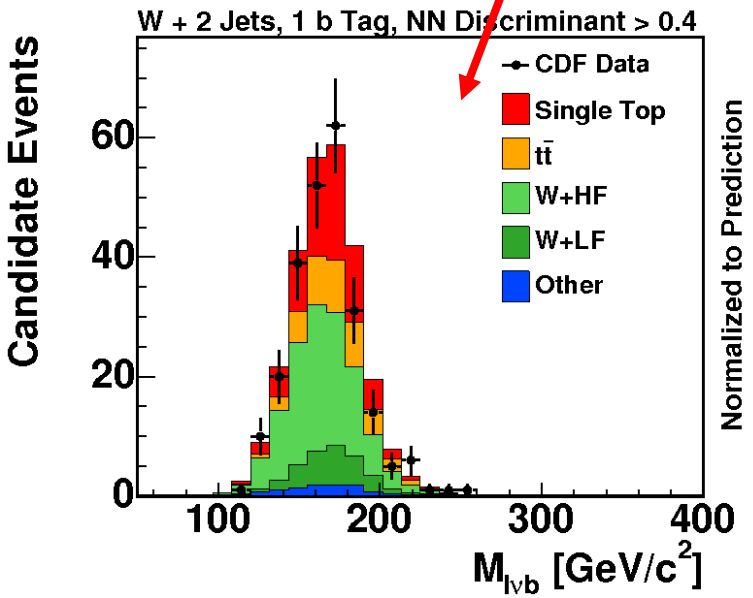


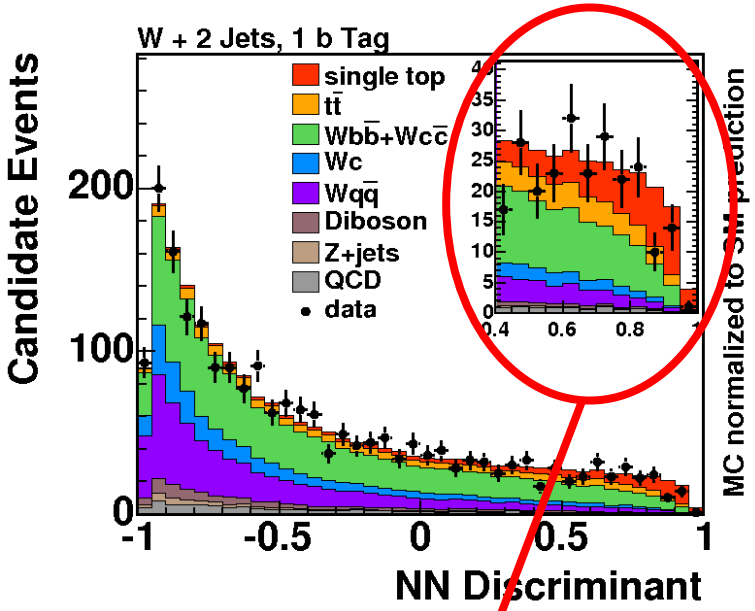
t-channel Candidate
recorded on March 29th 2008

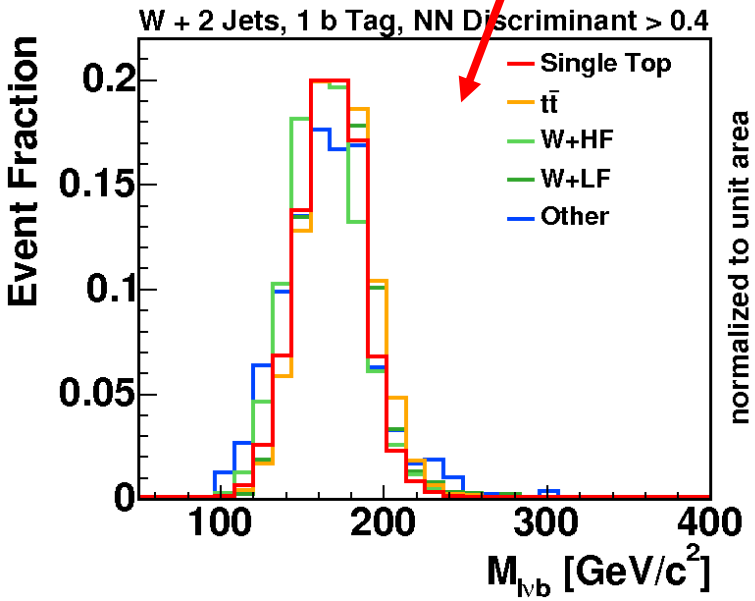
Top Quark Mass Peak



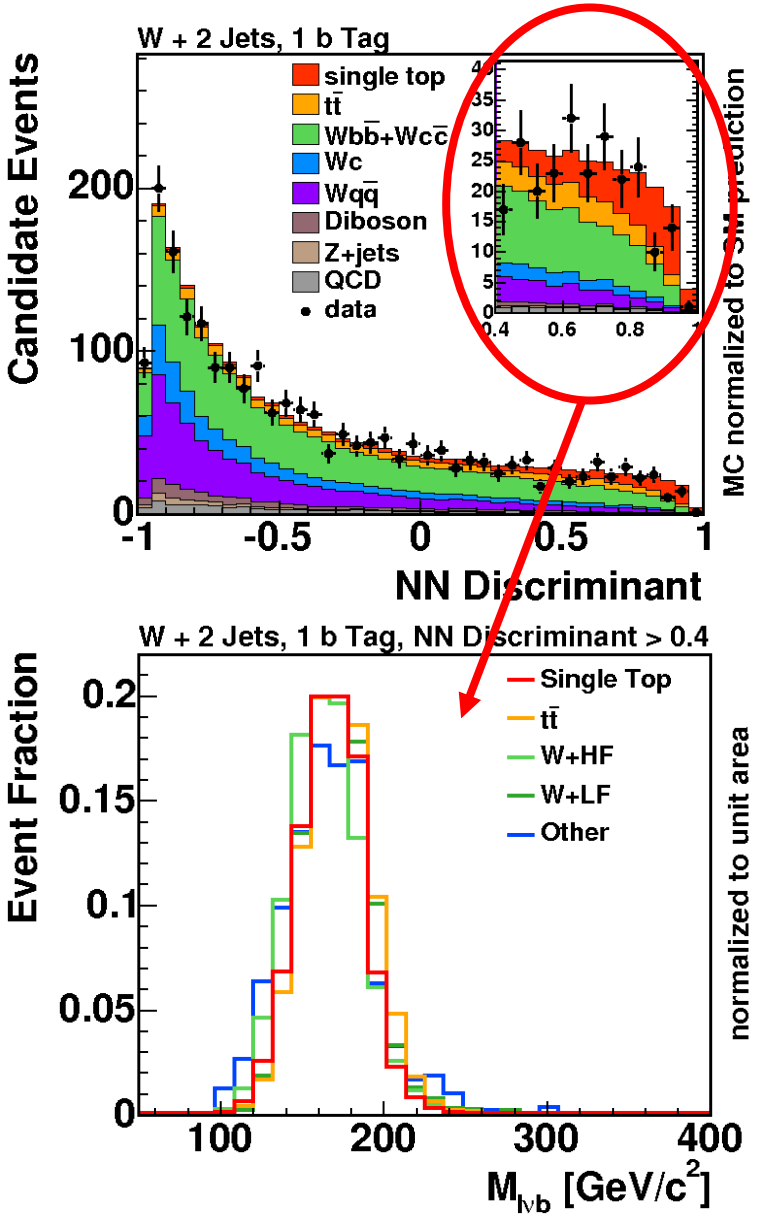


Top Quark Mass Peak





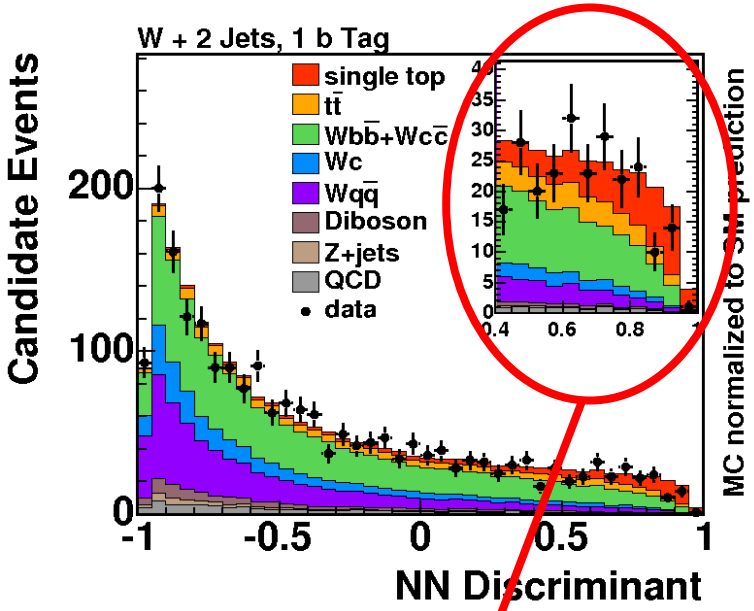
Top Quark Mass Peak

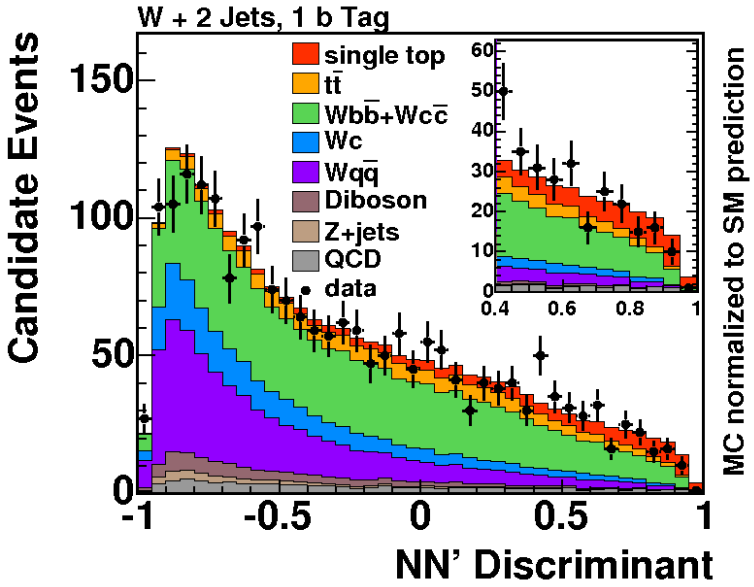


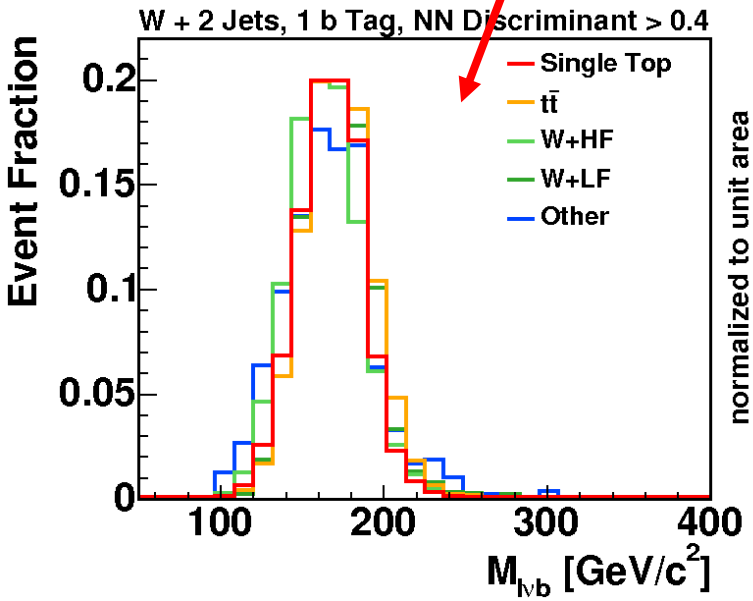
Train NN' Discriminant without M_{lvb} and highly (>20%) correlated Input Variables:

- Transverse Top Quark Mass: 65%
- H_T: 45%
- Dijet mass: 24%

Top Quark Mass Peak







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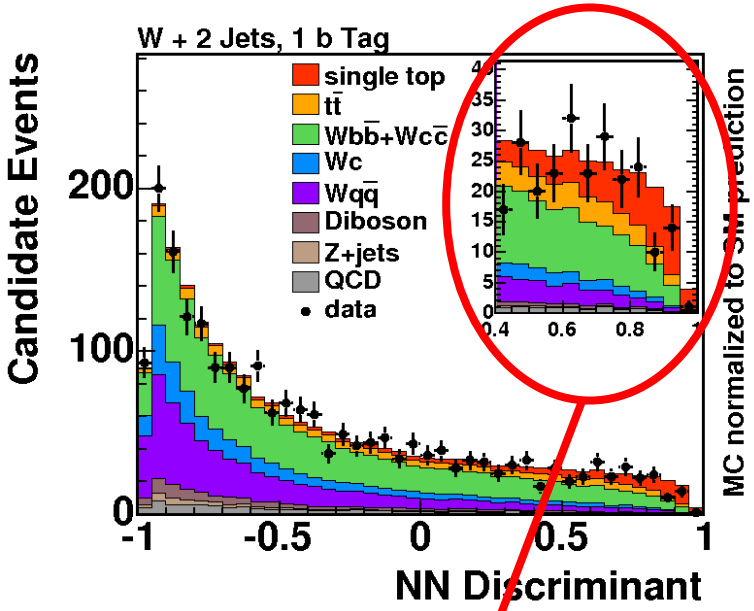
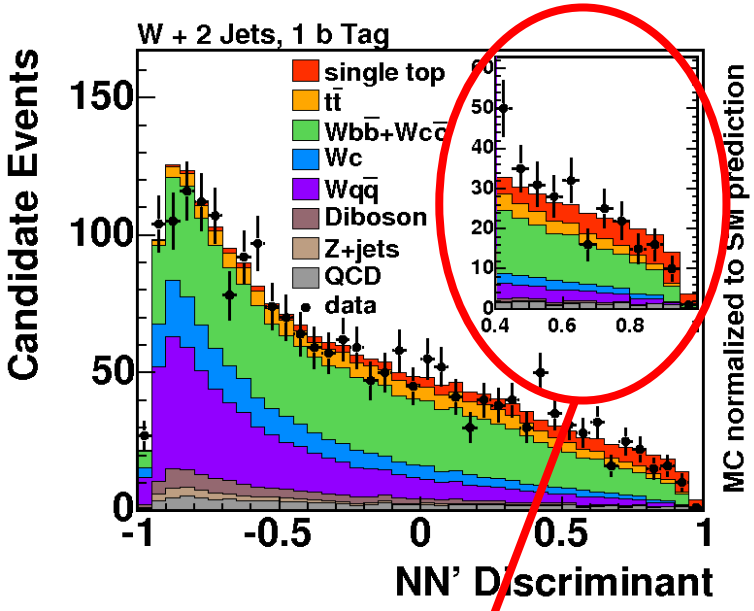
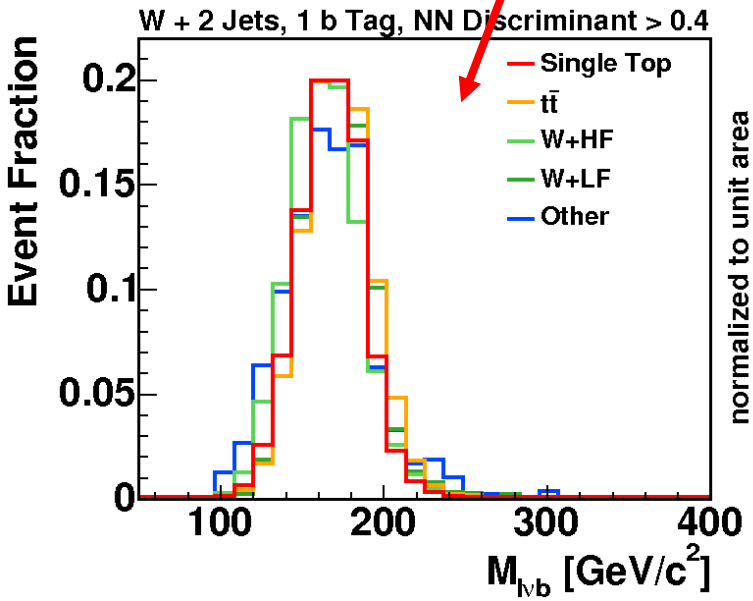
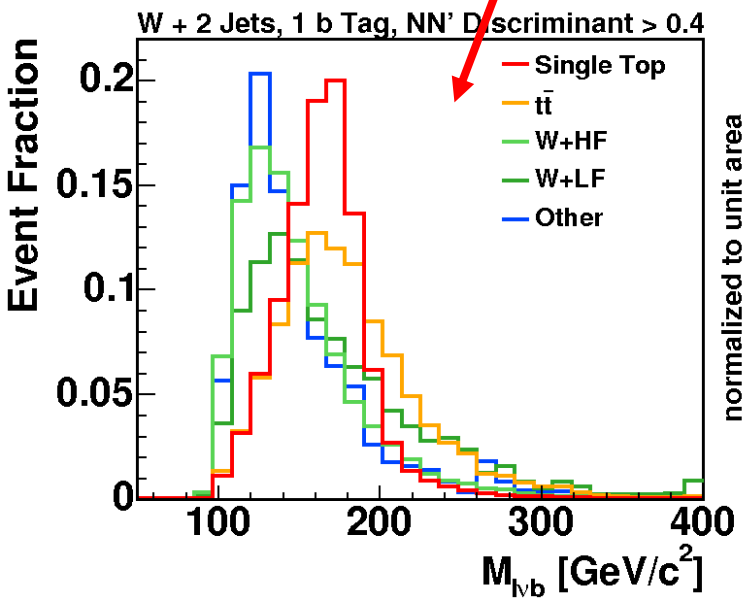
Top Quark Mass Peak

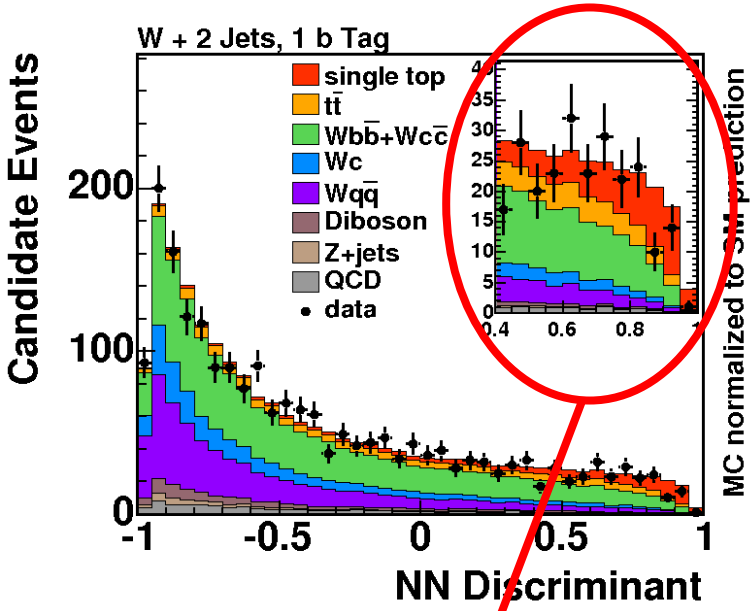


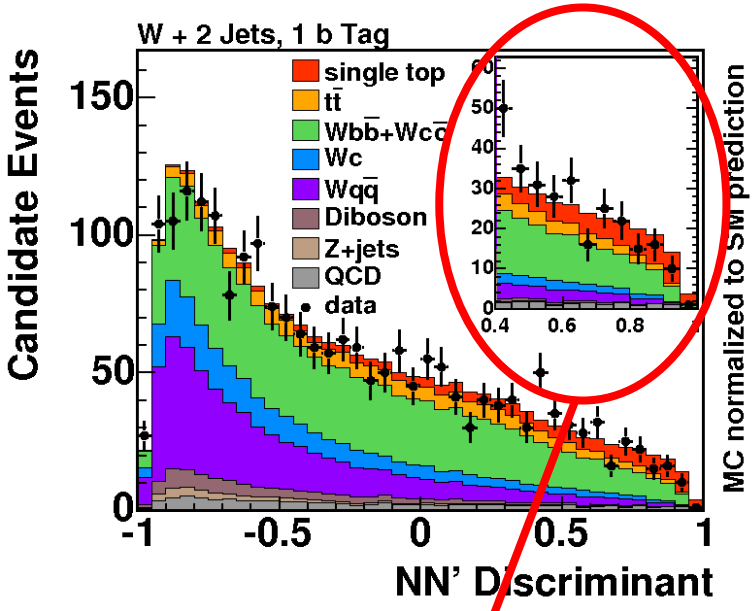


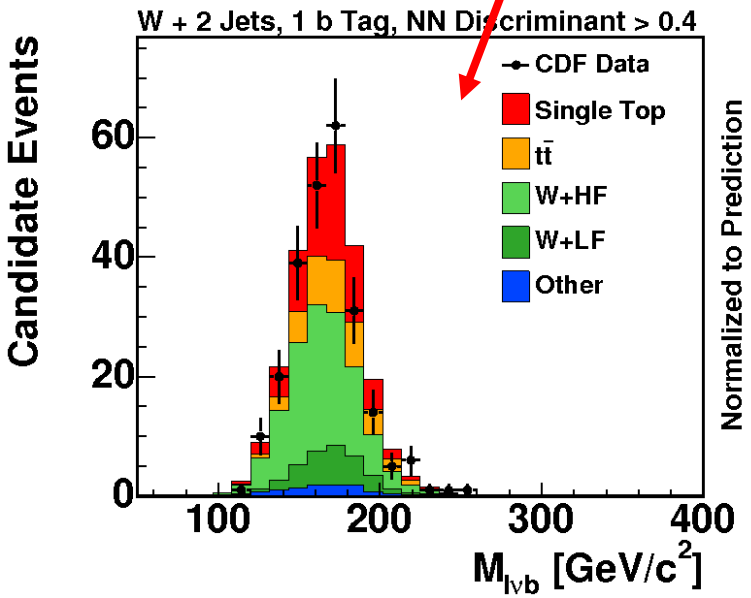


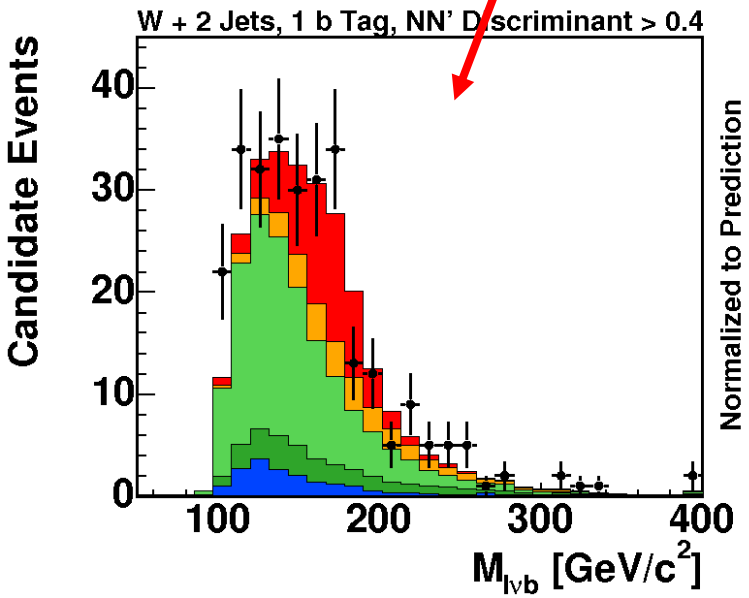


Top Quark Mass Peak









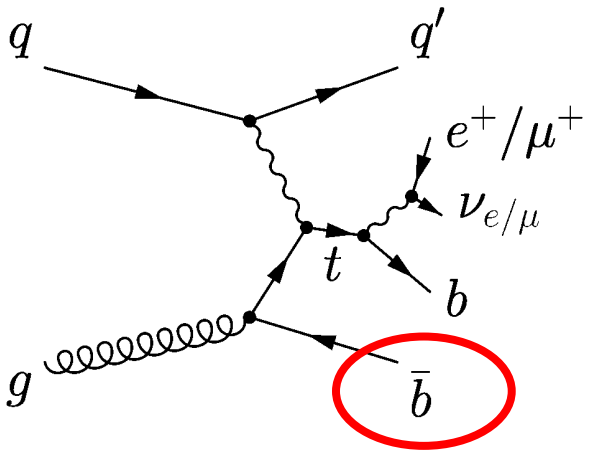
Single Top MC Theory

Next-to-leading-order predictions for t-channel single-top production at hadron colliders

J. M. Campbell[a], R. Frederix[b,c], F. Maltoni[c], F. Tramontano[d]
[a] *Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom*
[b] *PH Department, Theory group, CERN 1211-CH Geneva, Switzerland*
[c] *Center for Particle Physics and Phenomenology (CP3), Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*
[d] *Università di Napoli Federico II, Dipartimento di Scienze Fisiche, and INFN, Sezione di Napoli, I-80126 Napoli, Italy*

We present the predictions at next-to-leading order (NLO) in the strong coupling for the single-top cross section in the t channel at the Tevatron and the LHC. Our calculation starts from the $2 \to 3$ Born amplitude $gq \to tb\bar{q}'$, keeping the b-quark mass non-zero. A comparison is performed with a traditional NLO calculation of this channel based on the $2 \to 2$ Born process with a bottom quark in the initial state. In particular, the effect of using kinematic approximations and resumming logarithms of the form $\log(Q^2/m_b^2)$ in the $2 \to 2$ process is assessed. Our results show that the $2 \to 3$ calculation is very well behaved and in substantial agreement with the predictions based on the $2 \to 2$ process.

PACS numbers: 12.38.Bx, 14.65.Ha



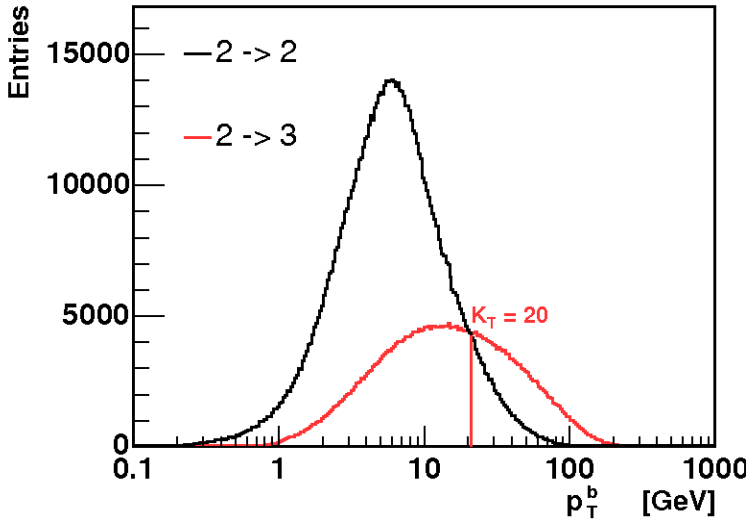
New 4-Flavor Calculation treats Spectator b as NLO Observable

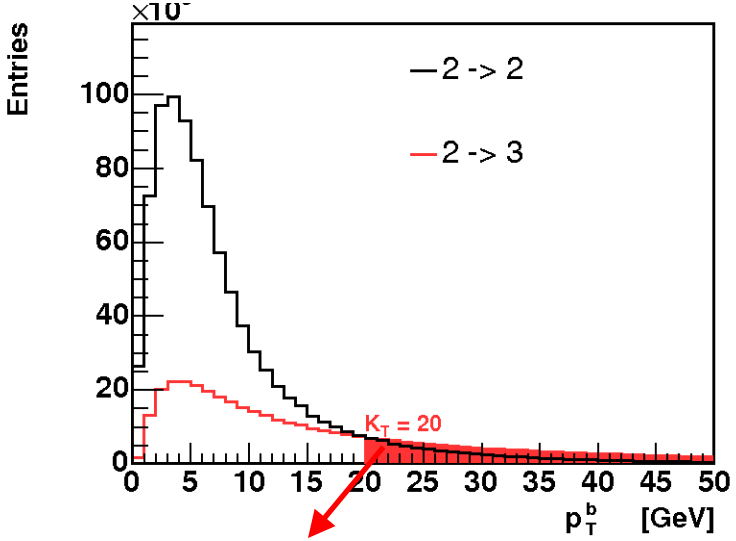
J. Campbell et al.,Phys.Rev.Lett.102, 182003 (2009)

In contrast, ZTOP is a 5-Flavor Calculation with Spectator b as LO Observable

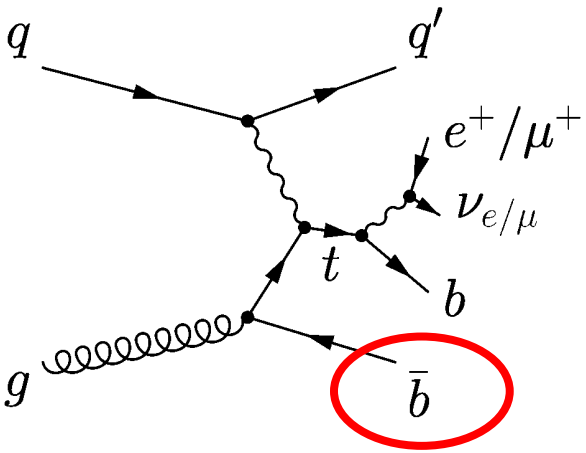
Z. Sullivan, Phys. Rev. D 70, 114012 (2004)

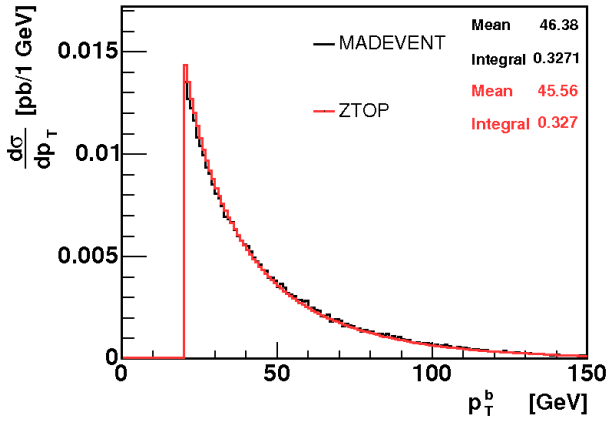
Single Top MC Matching

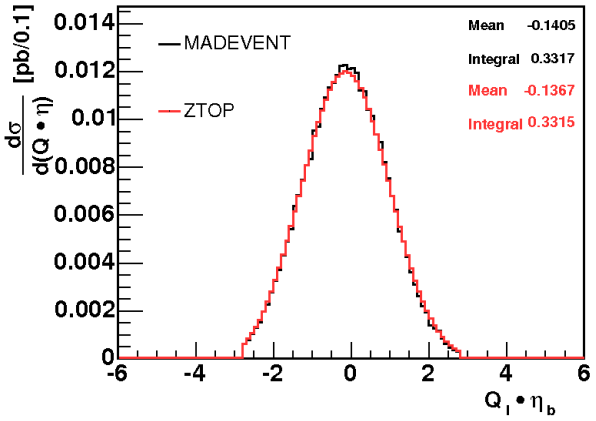




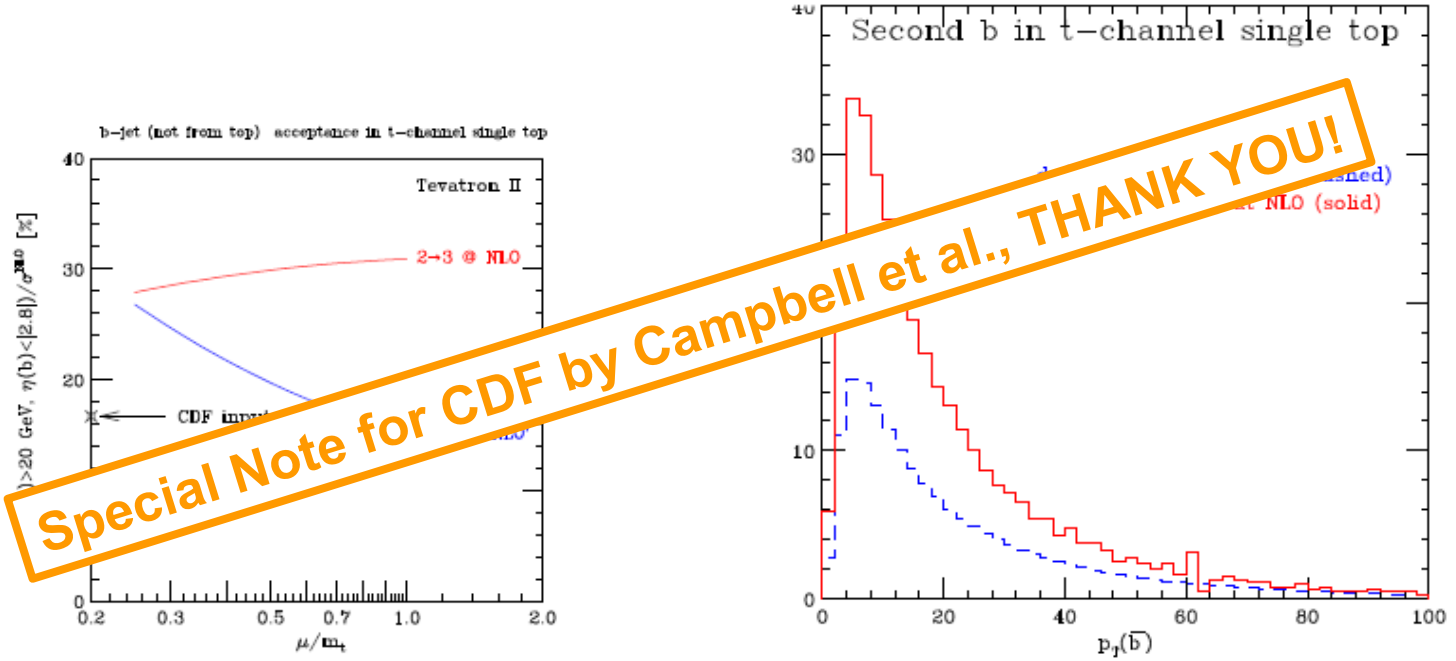
ZTOP Prediction:
Rate within CDF's Acceptance







Single Top MC

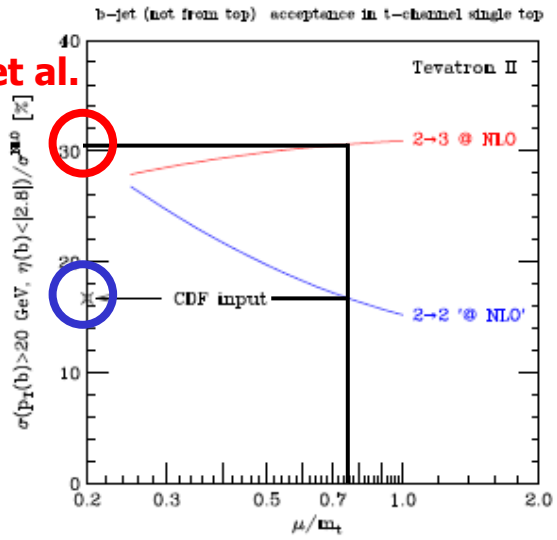


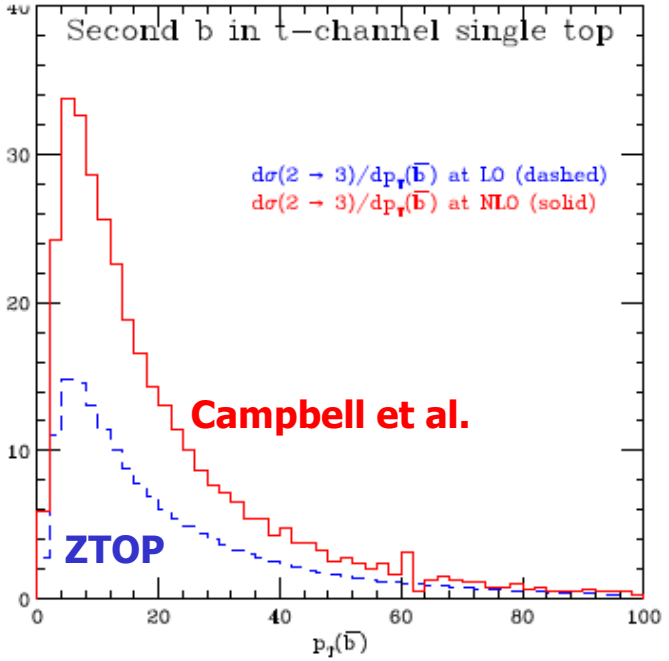
Special Note for CDF by Campbell et al., THANK YOU!

Single Top MC

Campbell et al.
30.5%

16.7%
from ZTOP



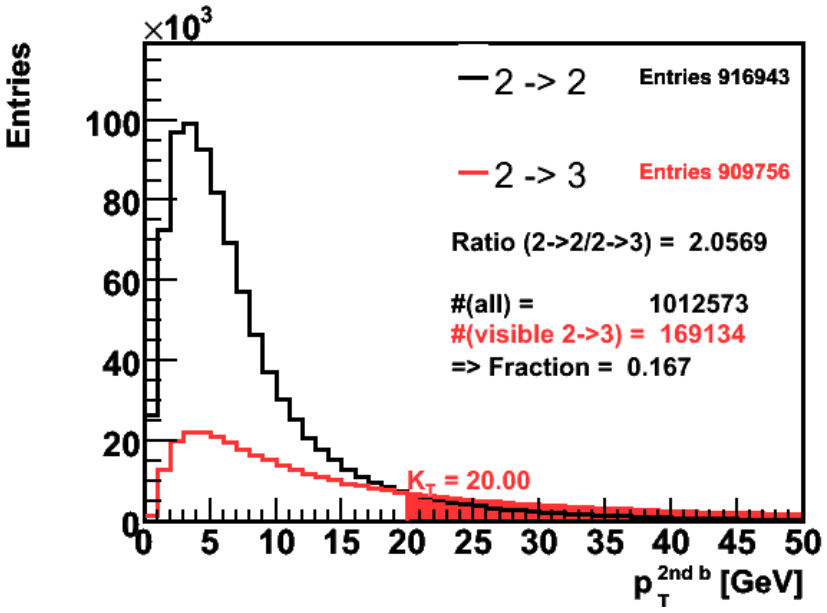


New Campbell et al. 4-Flavor NLO Calculations predict nearly twice the Rate

Could this explain CDF's low t-channel and high s-channel measurement?

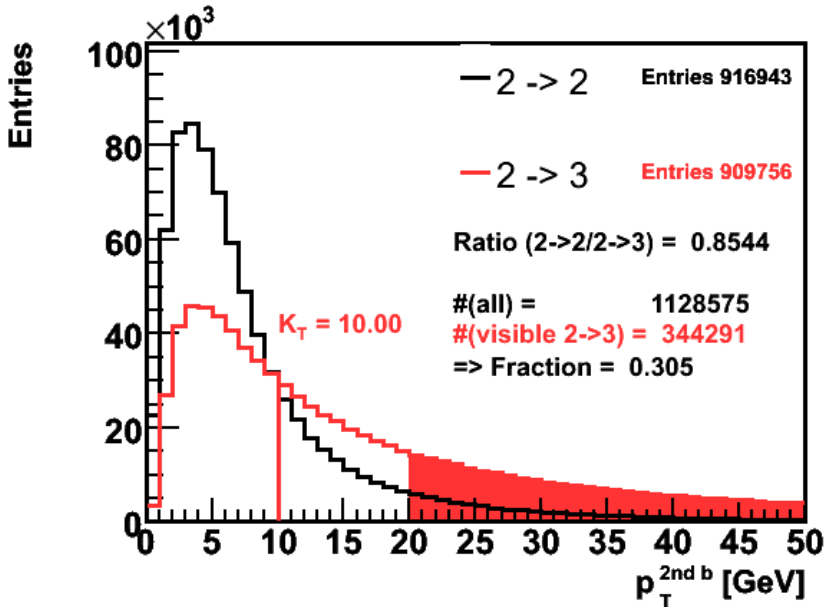
New Single Top MC Matching

CDF Standard



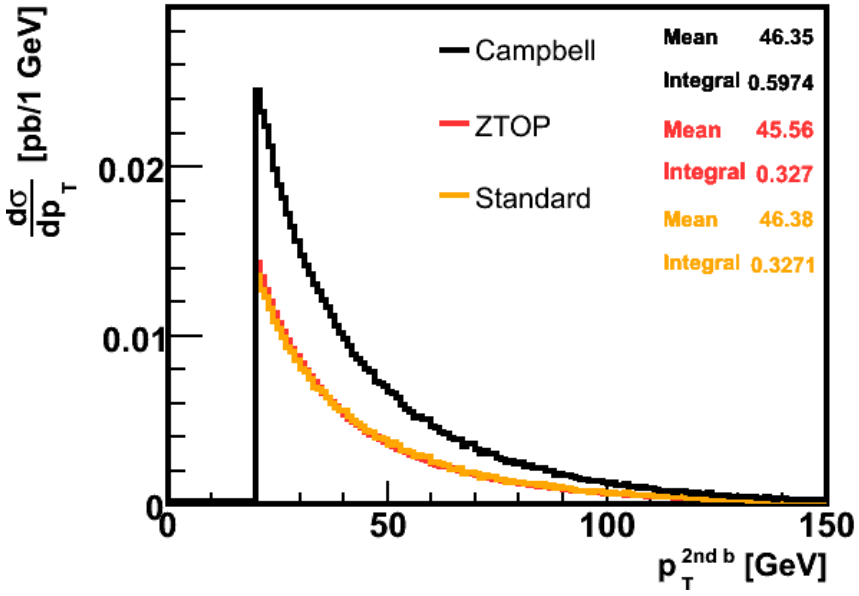
67% 2->2
33% 2->3

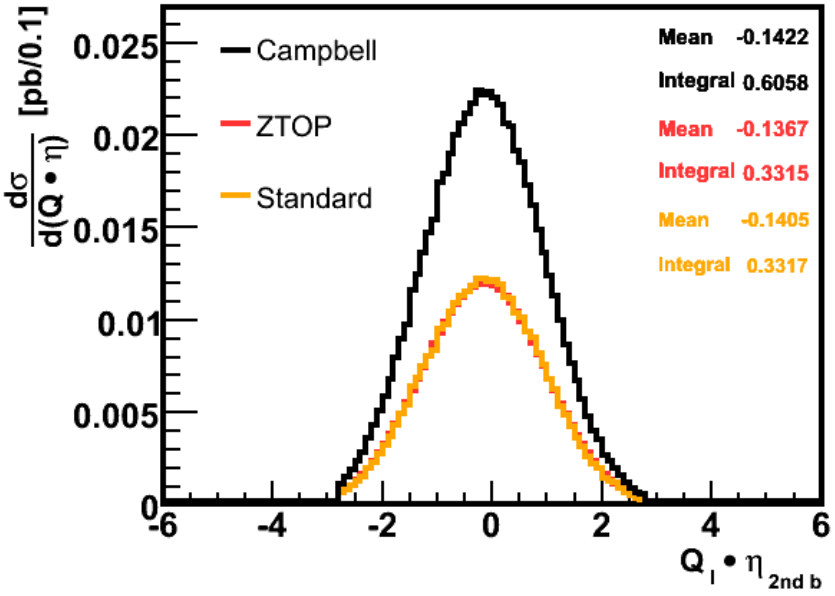
Campbell et al.



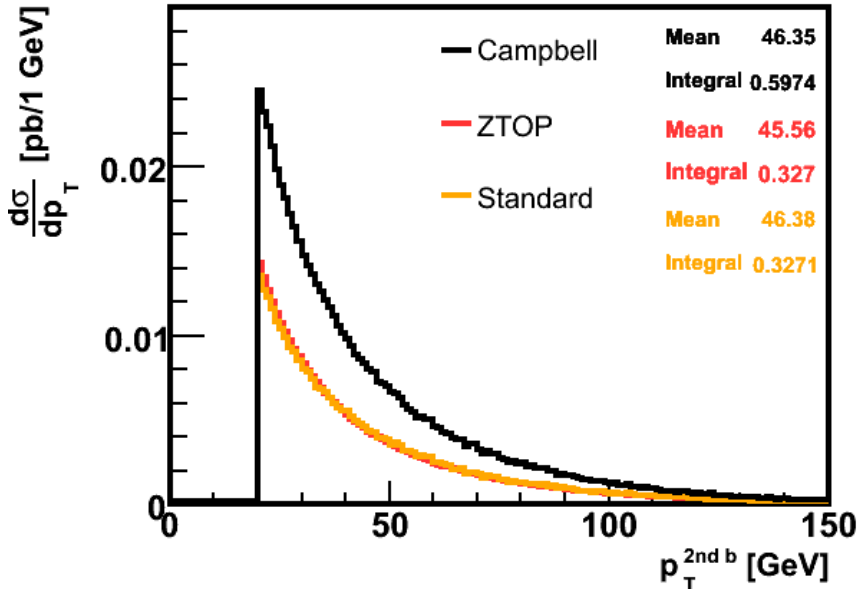
46% 2->2
54% 2->3

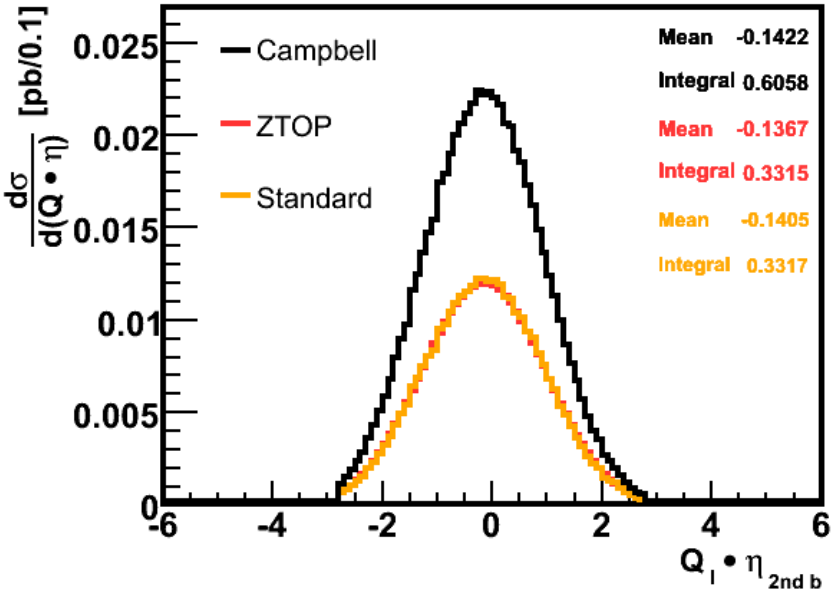
New Single Top MC Matching

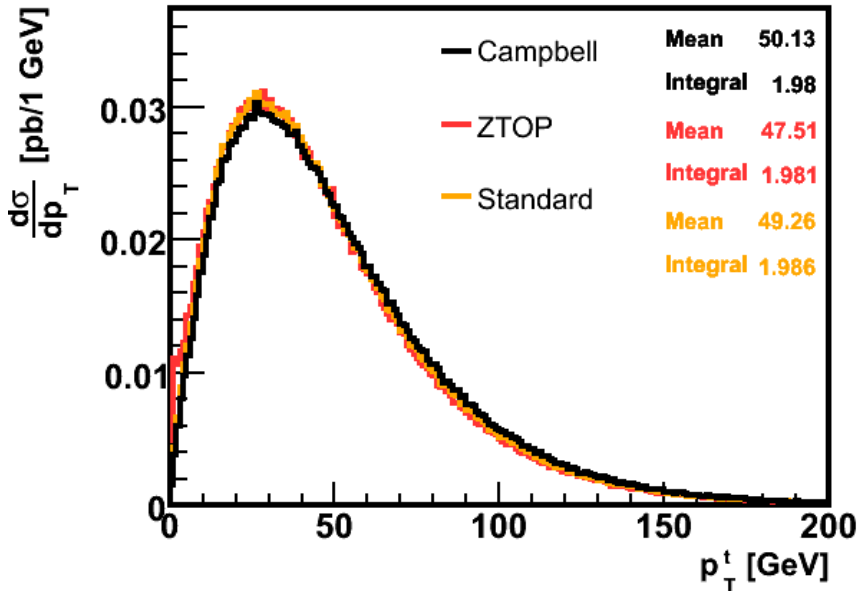


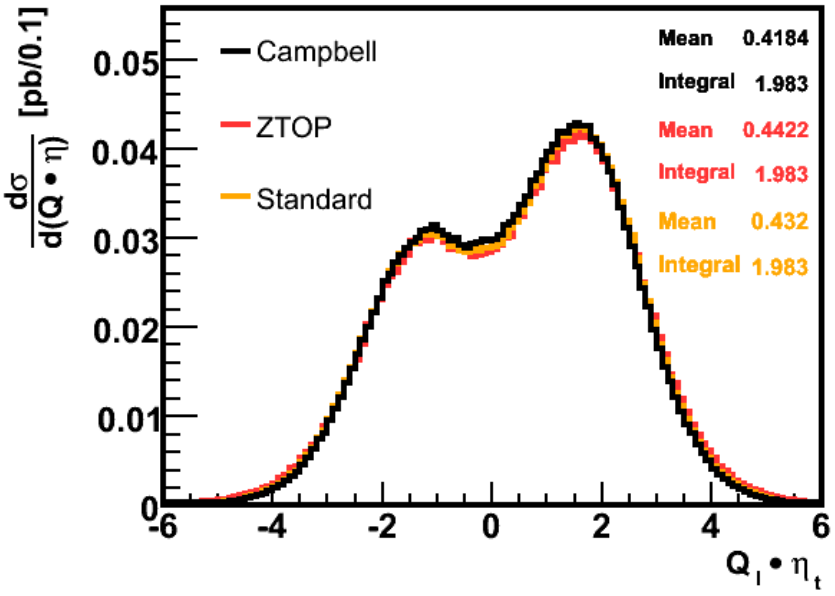


New Single Top MC Matching

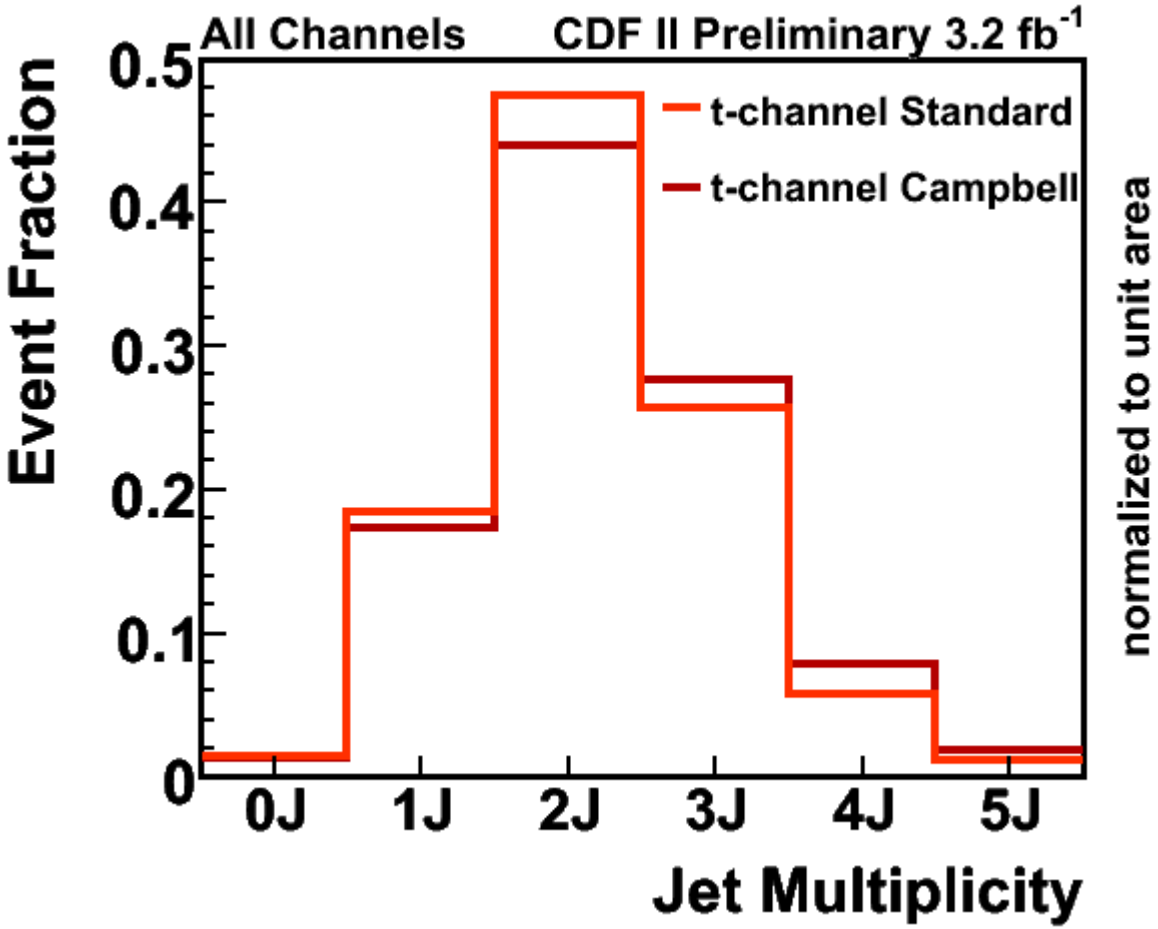




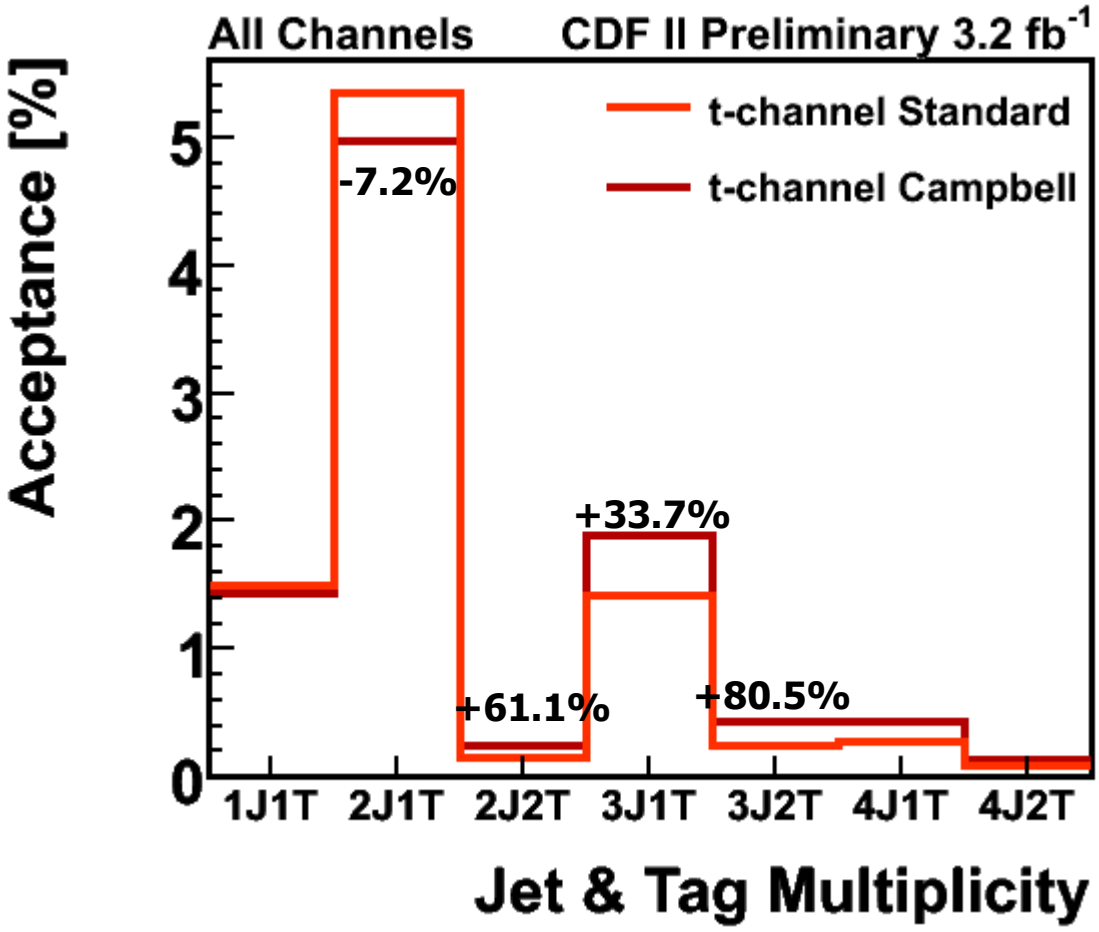




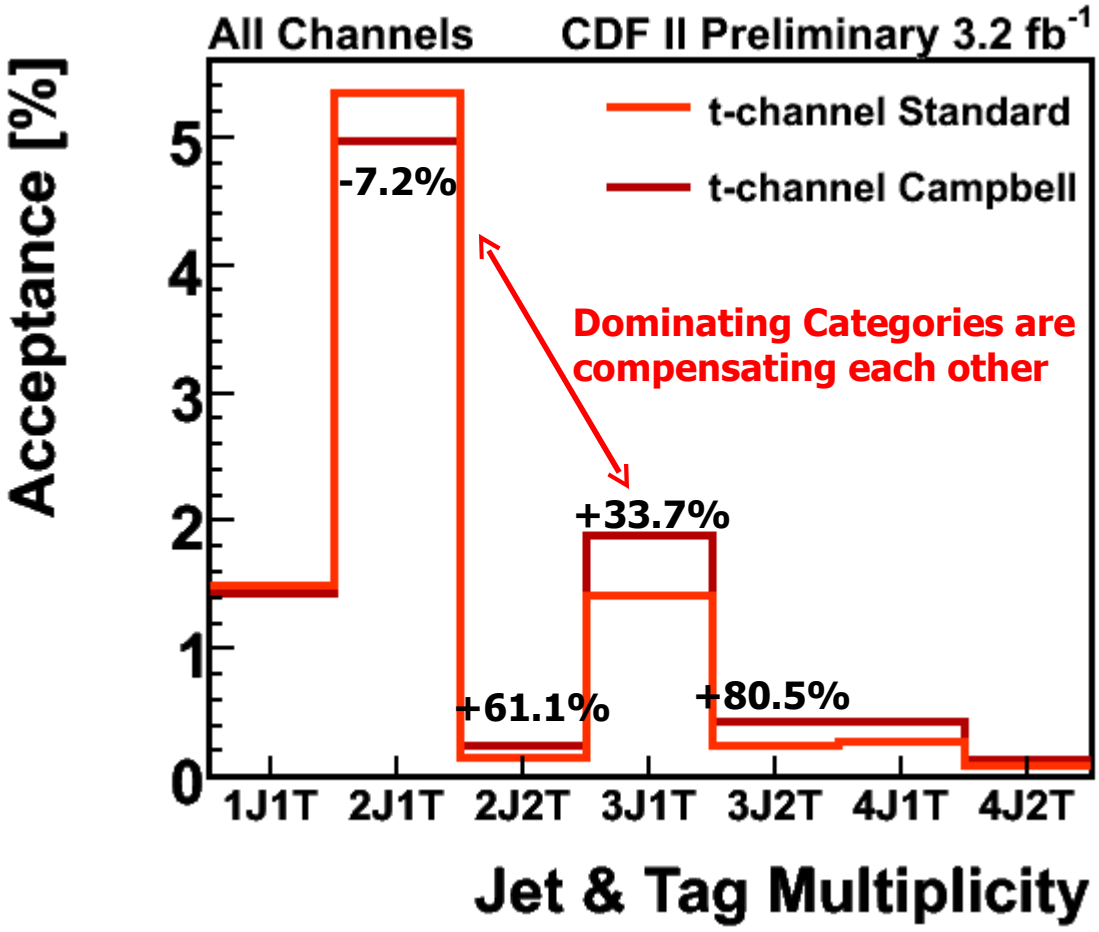
New Single Top MC Matching



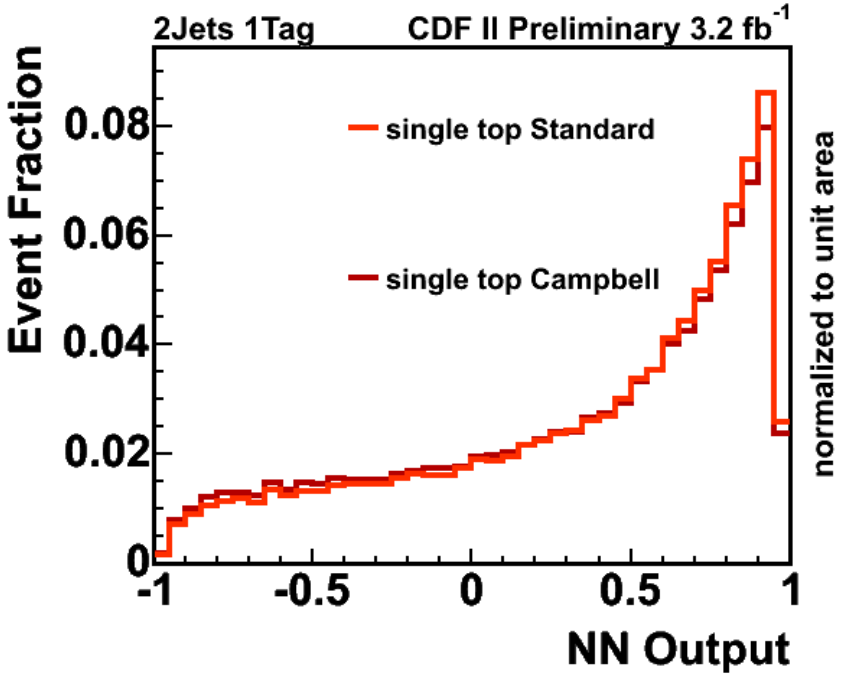
New Single Top MC Matching

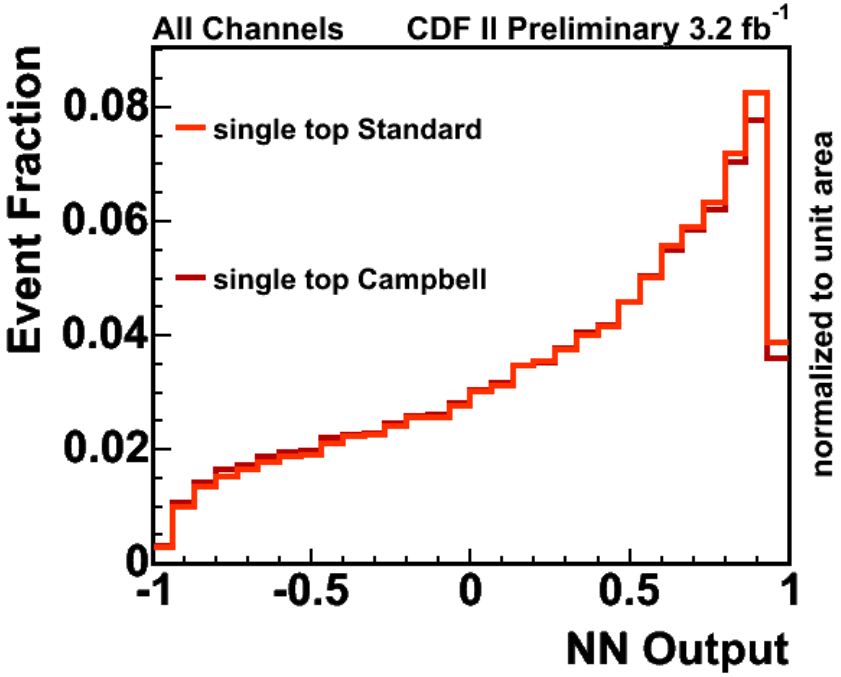


New Single Top MC Matching



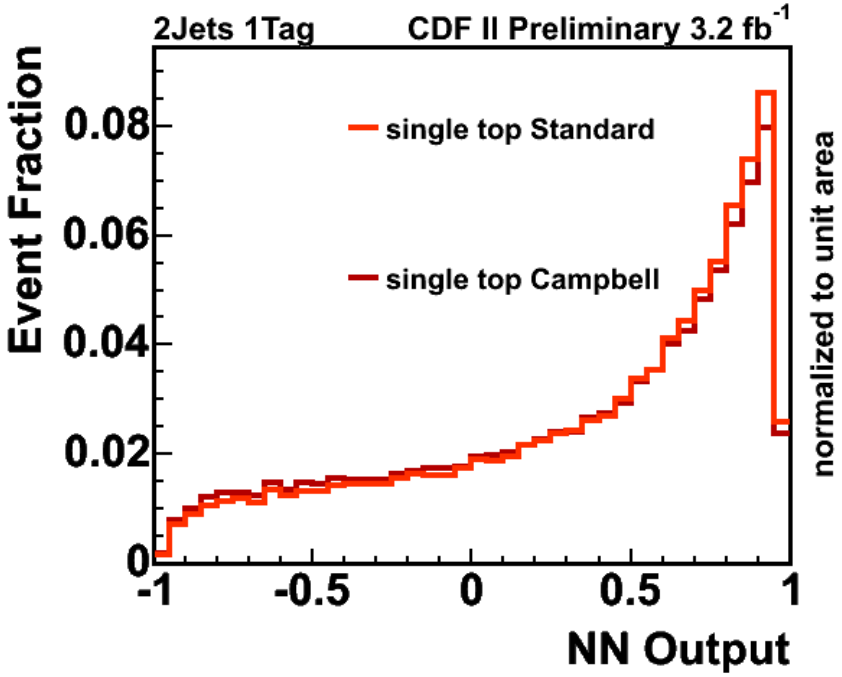
New Single Top MC Matching

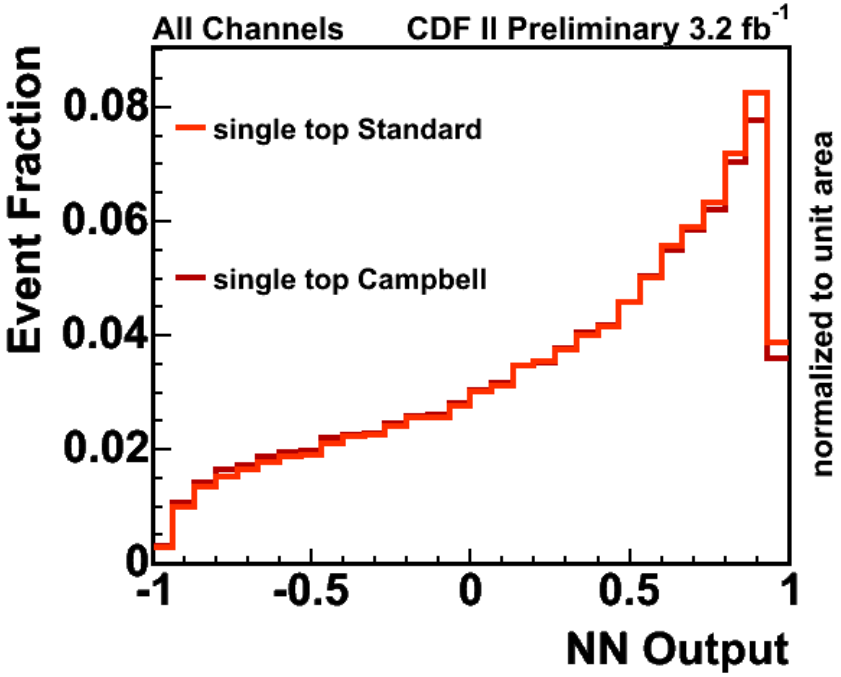




Discriminants don't seem to change significantly

New Single Top MC Matching





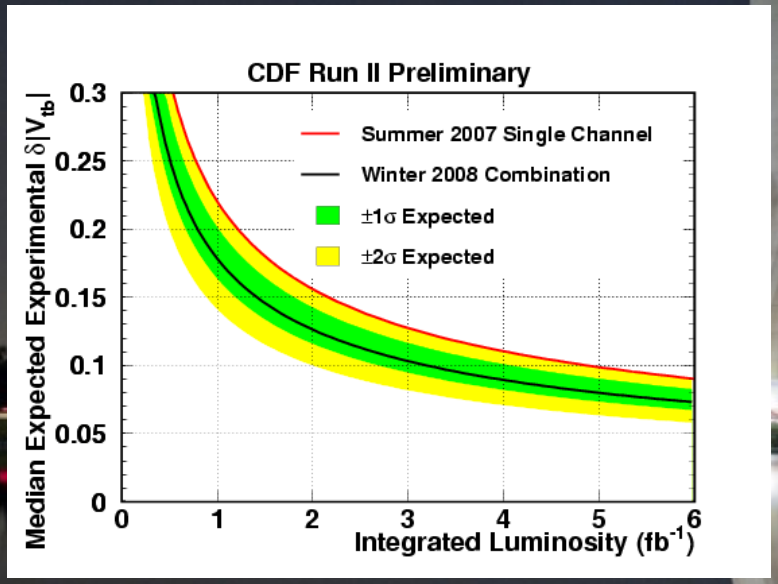
Discriminants don't seem to change significantly

We changed the acceptances (assuming that the discriminant shapes don't change) to the new matching according to Campbell et al., and at the end we got the very same numbers within one decimal for the 1D combined fit as well as for the 2D separate fit.

Summary

Past: **CDF developed advanced Methods to establish a small Signal against a highly uncertain Background**

Present: **CDF already has a Single-Top Polarization Analysis**
CDF will look at a doubled Data Set in 1D and 2D



Future: **Given the actual LHC Status, our Results will last some more years…**

photo: Reidar Hahn; artwork: Jan Lueck

Phys. Rev. Lett. 101, 252001 (2008)
Phys. Rev. Lett. 103, 092002 (2009)
Phys. Rev. D 81, 07203 (2010)
arXiv:1004.1181 (submitted to PRD)

Backup I – Event Yield

	W + 1 jet	W + 2 jets	W + 3 jets	W + 4 jets
$Wb\bar{b}$	823.7 ± 249.6	581.1 ± 175.1	173.9 ± 52.5	44.8 ± 13.7
$Wc\bar{c}$	454.7 ± 141.7	288.5 ± 89.0	95.7 ± 29.4	27.2 ± 8.5
Wcj	709.6 ± 221.1	247.3 ± 76.2	50.8 ± 15.6	10.2 ± 3.2
Mistags	1147.8 ± 166.0	499.1 ± 69.1	150.3 ± 21.0	39.3 ± 6.2
Non-W	62.9 ± 25.2	88.4 ± 35.4	35.4 ± 14.1	7.6 ± 3.0
$t\bar{t}$ production	17.9 ± 2.6	167.6 ± 24.0	377.3 ± 54.8	387.4 ± 54.8
Diboson	29.0 ± 3.0	83.3 ± 8.5	28.1 ± 2.9	7.1 ± 0.7
Z+jets	38.6 ± 6.3	34.8 ± 5.3	14.6 ± 2.2	4.0 ± 0.6
Total Background	3284.1 ± 633.8	1990.1 ± 349.6	926.1 ± 113.4	527.7 ± 60.3
s-channel	10.7 ± 1.6	45.3 ± 6.4	14.7 ± 2.1	3.3 ± 0.5
t-channel	24.9 ± 3.7	85.3 ± 12.6	22.7 ± 3.3	4.4 ± 0.6
Total Prediction	3319.7 ± 633.8	2120.5 ± 350.1	963.4 ± 113.5	535.4 ± 60.3
Observation	3516	2090	920	567

Large Fraction of non-b Processes

Backup II – KIT Flavor Separator