Truth and Beauty Together: Evidence for s-channel Single Top Production

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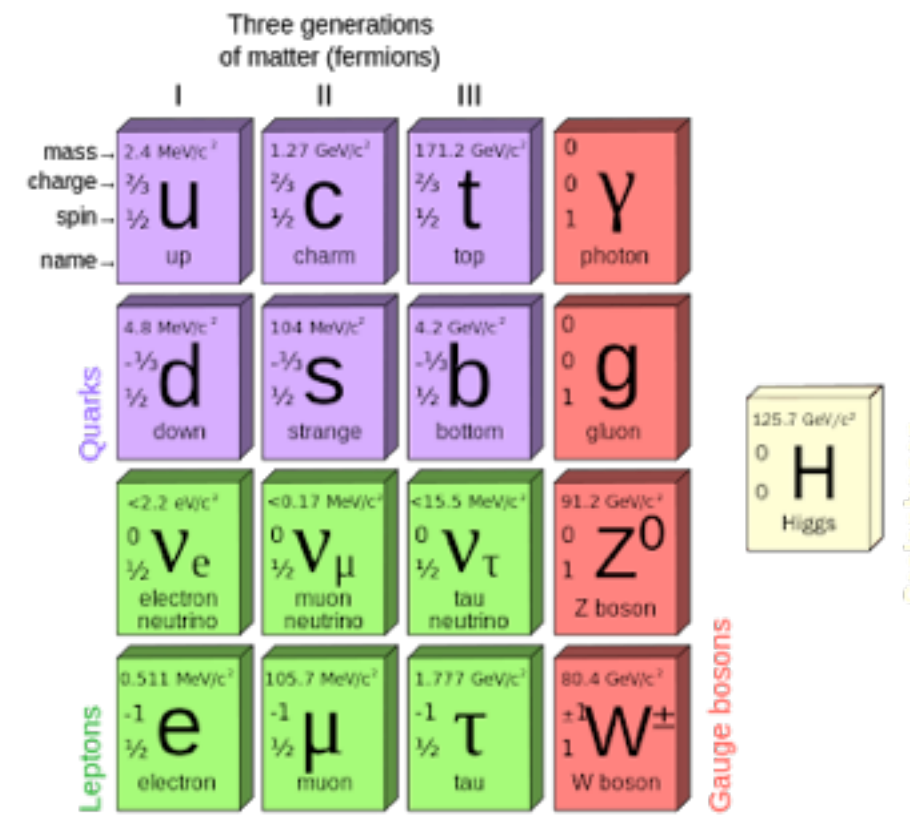
The Top (Truth) Quark

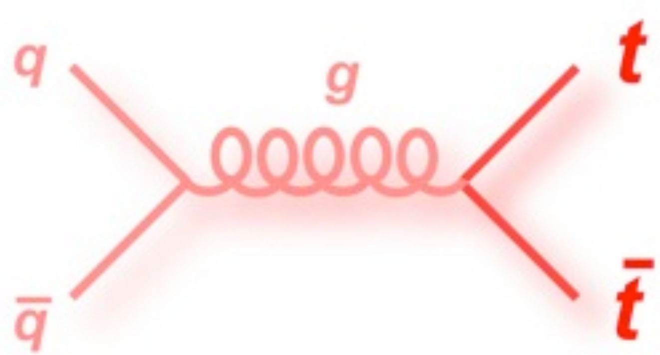
- Discovered by CDF and DØ at the Tevatron in 1995
- Heaviest known particle: 173.2±0.9 GeV (arXiv:1305.3929)
  - couples very strongly to the Higgs because of its mass
- Sensitive to new physics
- Decays as a free quark: short lifetime
  - width was measured in single top analysis PRD **85** 091194 (2012)



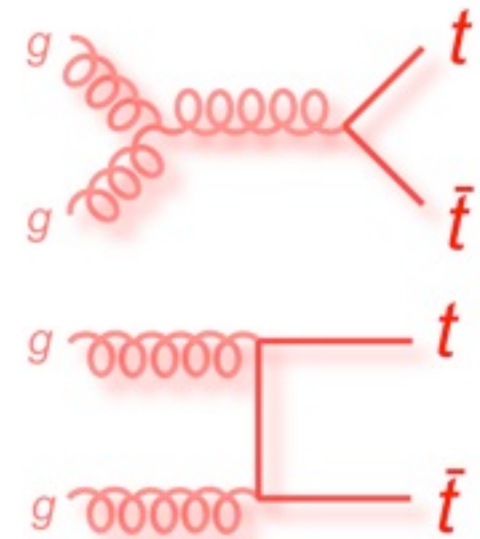
- Measurements:
  - production cross section
  - mass
  - angular properties of the decay products
  - width and lifetime
  - charge, m(t)-m($\bar{t}$)

Top Production at Hadron Colliders

- Strong interaction: top pair

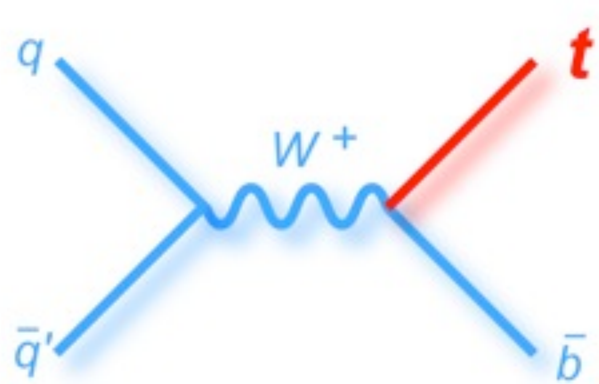


$q\bar{q}$ annihilation

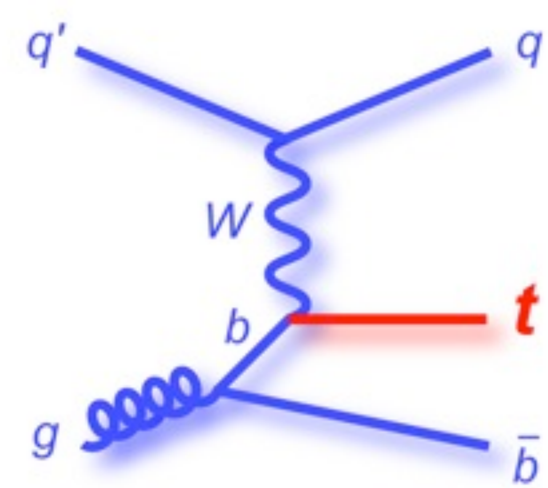


gg fusion

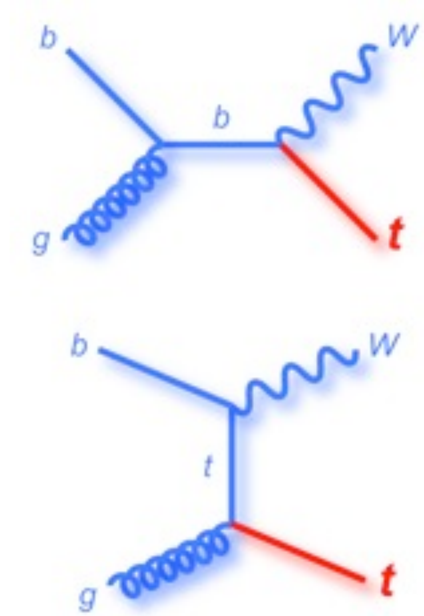
- Electroweak interaction: single top



s-channel (*tb*)



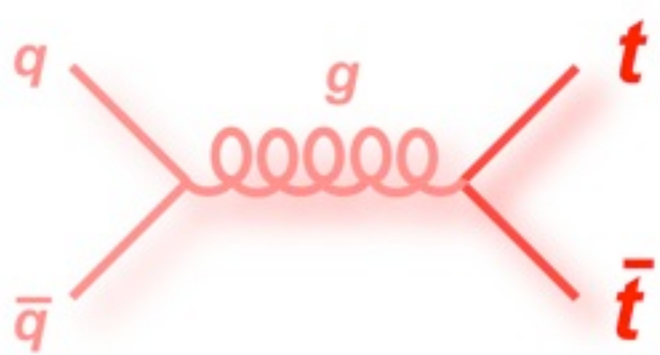
t-channel (*tqb*)



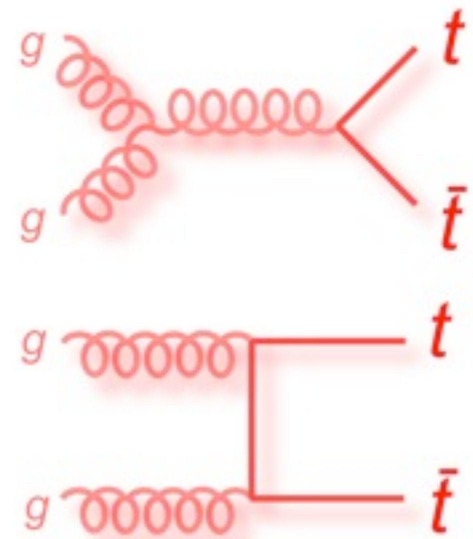
Associated (*tW*)

Top Production at Hadron Colliders

- Strong interaction: top pair



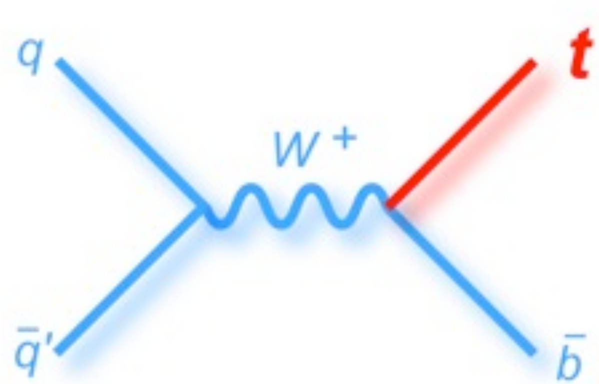
$q\bar{q}$ annihilation



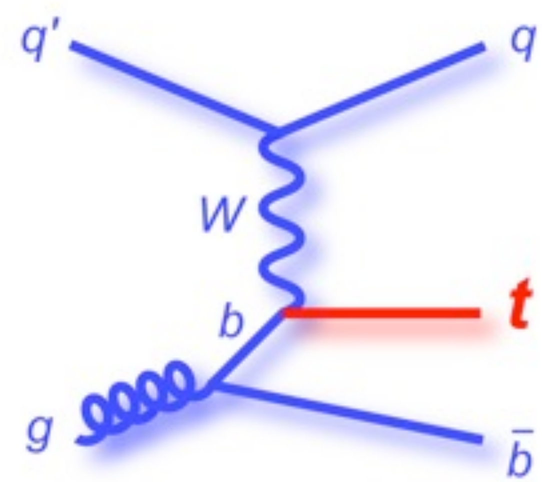
gg fusion

Main modes at Tevatron

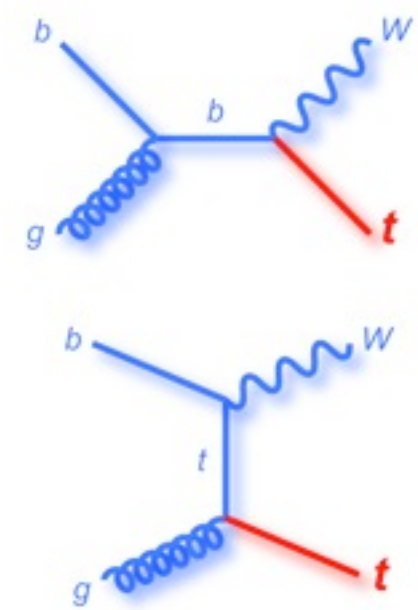
- Electroweak interaction: single top



s-channel (tb)



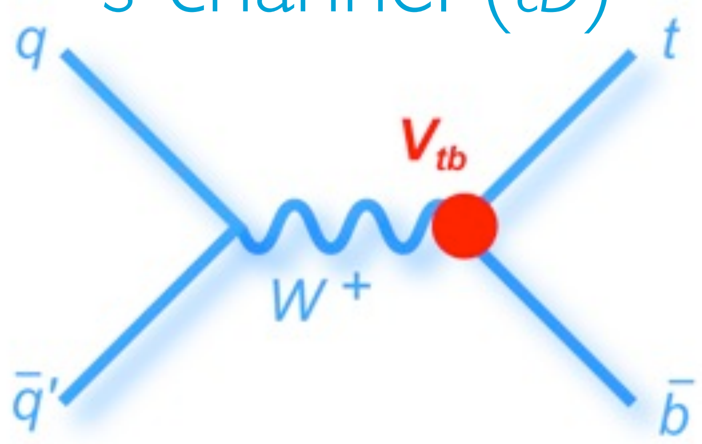
t-channel (tqb)



Associated (tW)

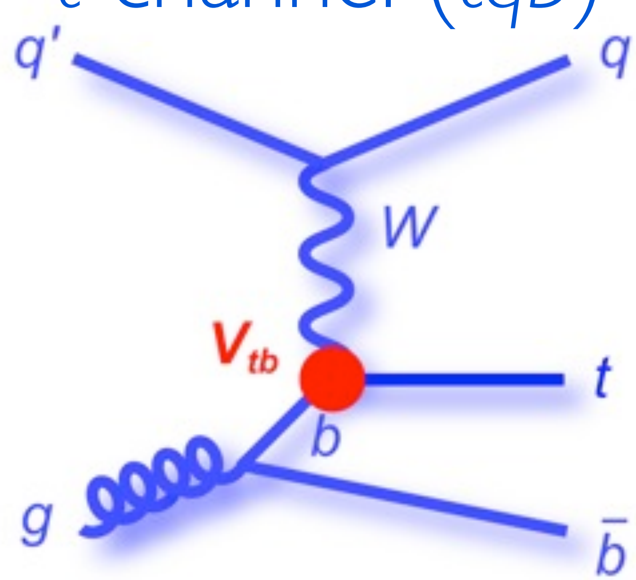
EW Top Quark Production

s-channel (tb)



$\sigma_{SM} = 1.04 \pm 0.08$ pb

t-channel (tqb)



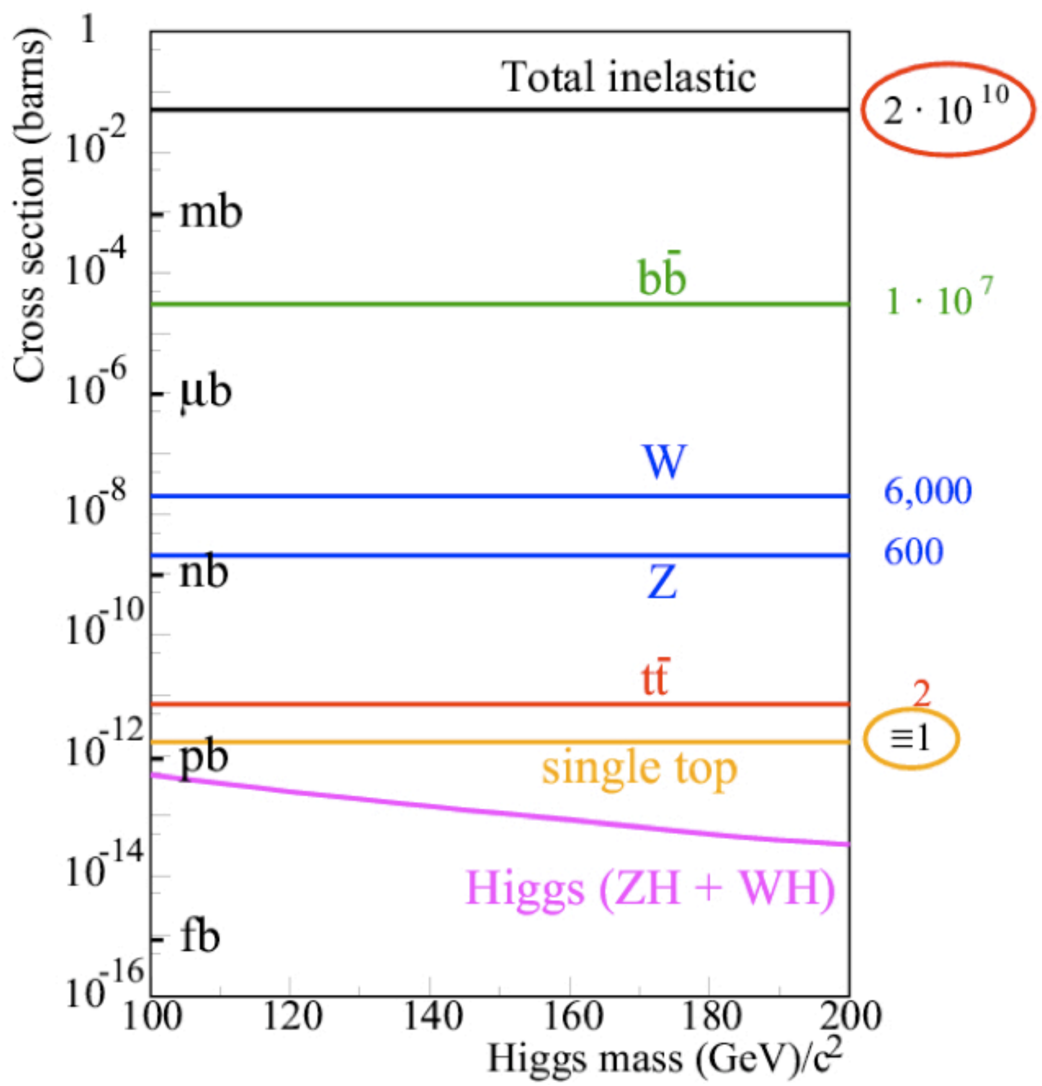
$\sigma_{SM} = 2.26 \pm 0.12$ pb

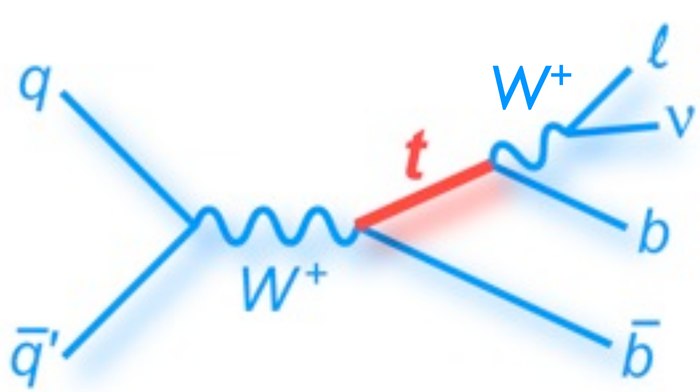
$M_{top} = 172.5$ GeV

N. Kidonakis, PRD 74.114012 (2006)

- Measure the two important single top-quark production modes at Tevatron: s and t channel
- Directly probe the CKM matrix element $|V_{tb}|$
- Measure the top decay width
- New physics can change σ_{tb} and σ_{tqb} differently:
  - σ_{tb}: New bosons
  - σ_{tqb}: FCNC, anomalous couplings
- σ_{tW} at the Tevatron is negligible

A Challenging Analysis





- Small cross section: ~3 pb
  - Tevatron produced 32k single top events
  - Analyze leptonic final state: 6.8k single top events
- Background dominated
  - Main background: W+jets
- To observe *tb*+*tqb*, needed 50 times more data than the top pair observation! (CDF, DØ)
  - PRL **103** 092001 (2009)

LHC: Limited *tb* Production

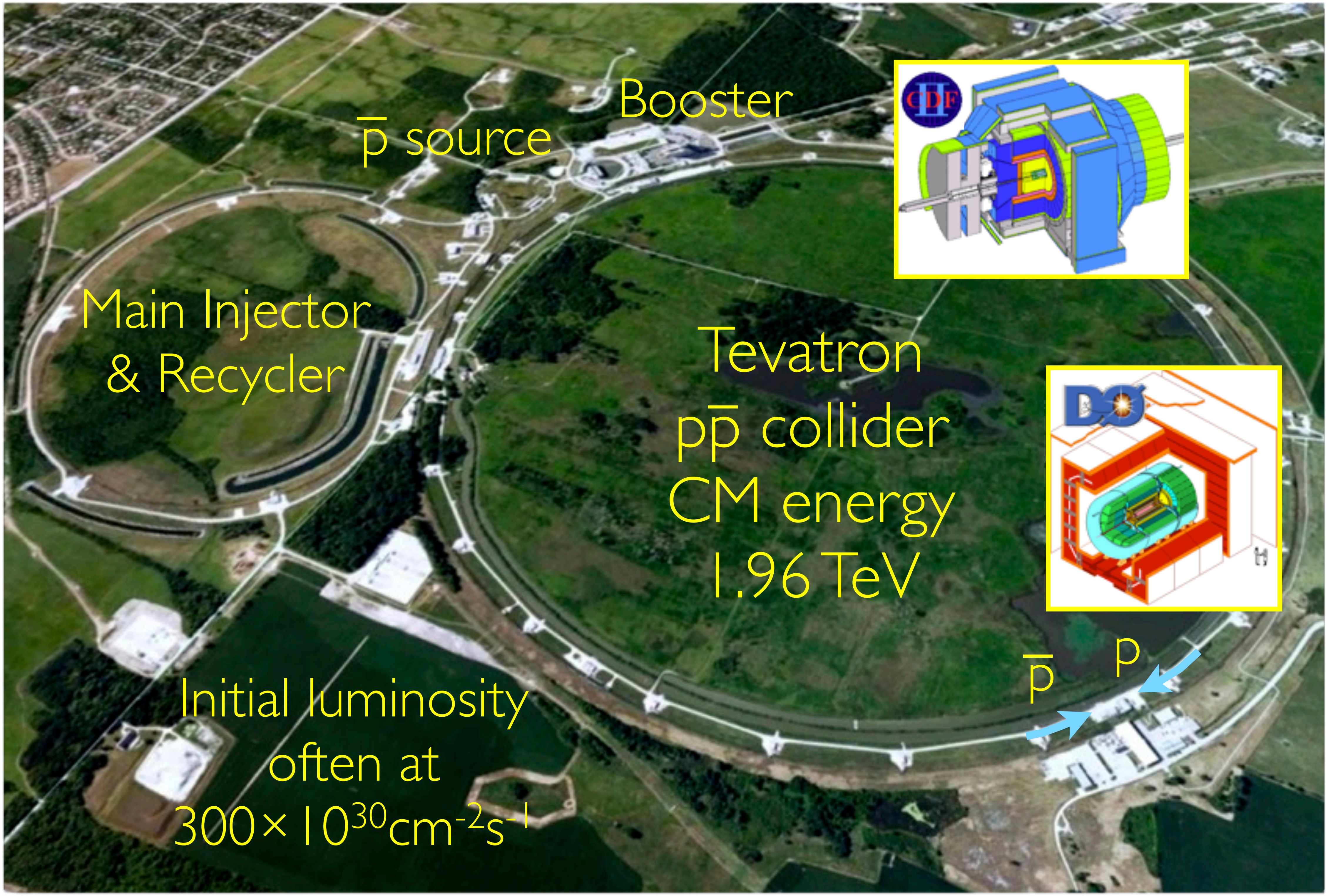
σ (pb) ~NNLO	*tb*	*tqb*	*tW*
Tevatron (1.96 TeV)	1.04	2.26	0.3
	×4 ↓	×30 ↓	×50 ↓
LHC (7 TeV)	4.56	65.9	15.6

Status up to June 2013

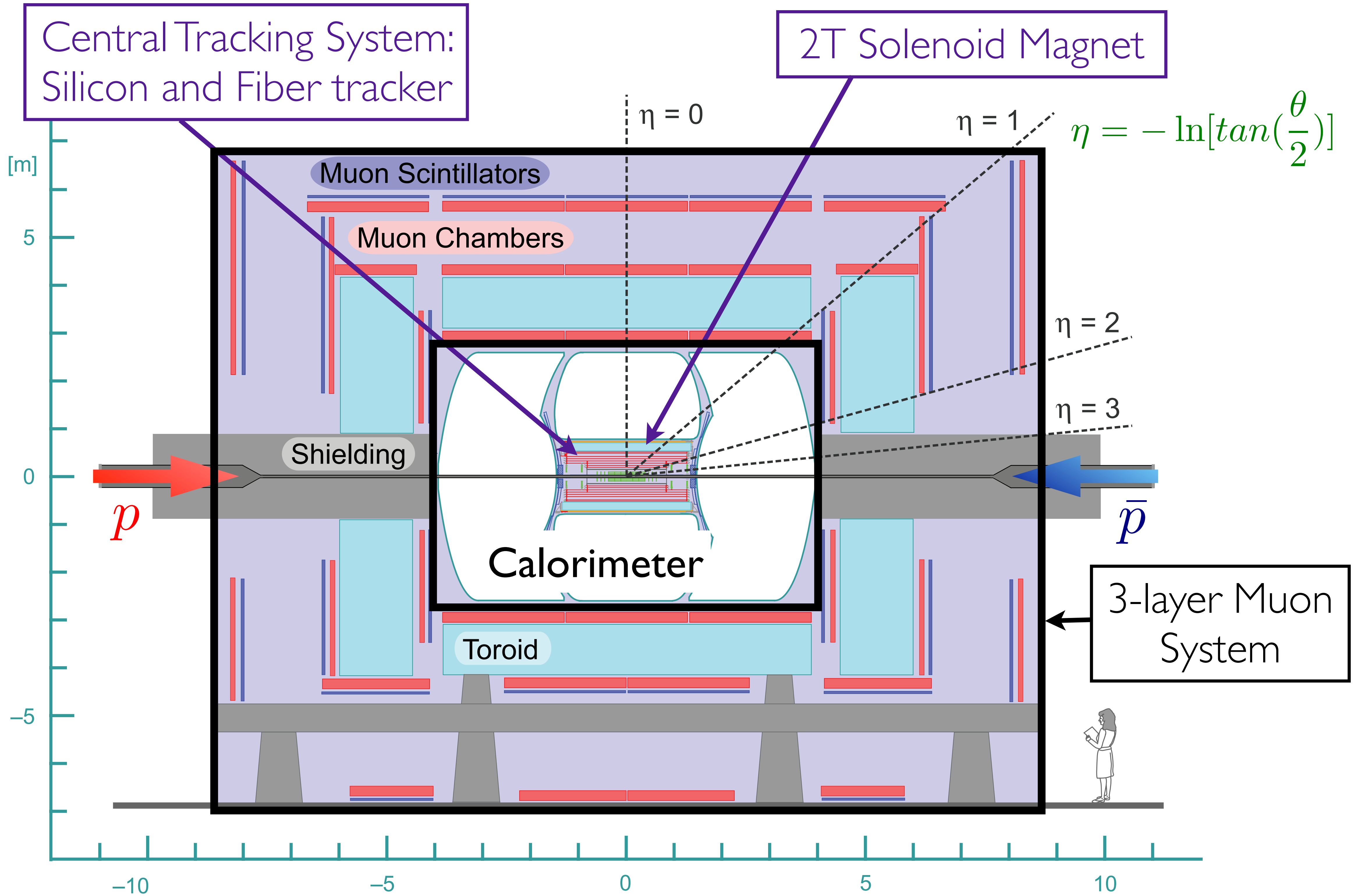
σ (pb) ~NNLO	*tb*	*tqb*	*tW*
Tevatron Prediction (1.96 TeV)	1.04	2.26	0.3
CDF (7.5 fb^{-1})	1.8±0.6	1.49±0.45	-
DØ (5.4 fb^{-1})	0.98±0.63	☑ **2.9±0.59**	-
LHC Prediction (7 TeV)	4.56	65.9	15.6
ATLAS (0.7-2.1 fb^{-1})	< 20.5 (95% C.L.)	☑ **83±20**	☐ 17±6
CMS (1.2-4.9 fb^{-1})	-	☑ **67±6**	☐ 16±5

☐ Evidence (3 SD) ☑ **Observation (5 SD)**

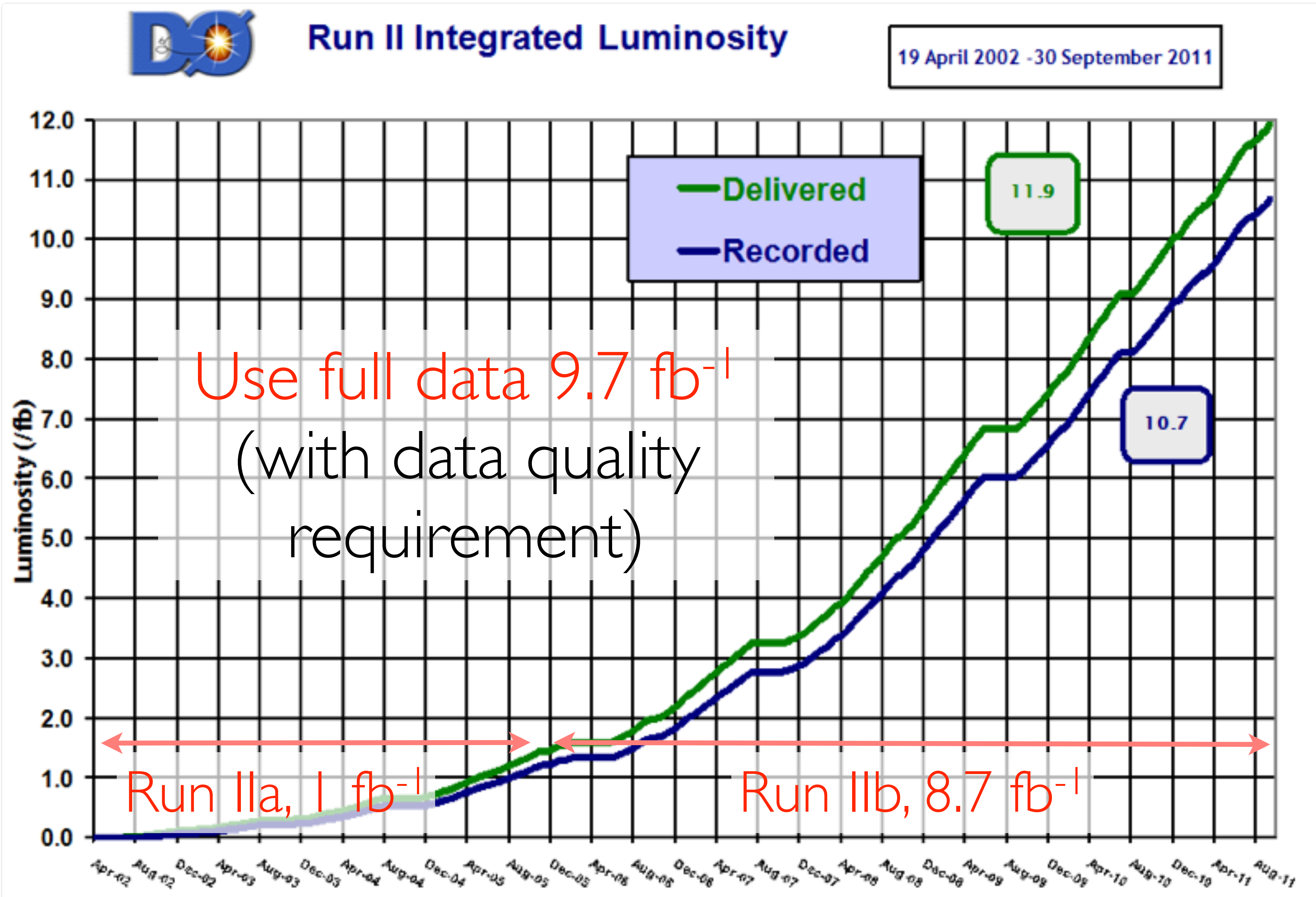
Fermilab Tevatron



DØ Detector

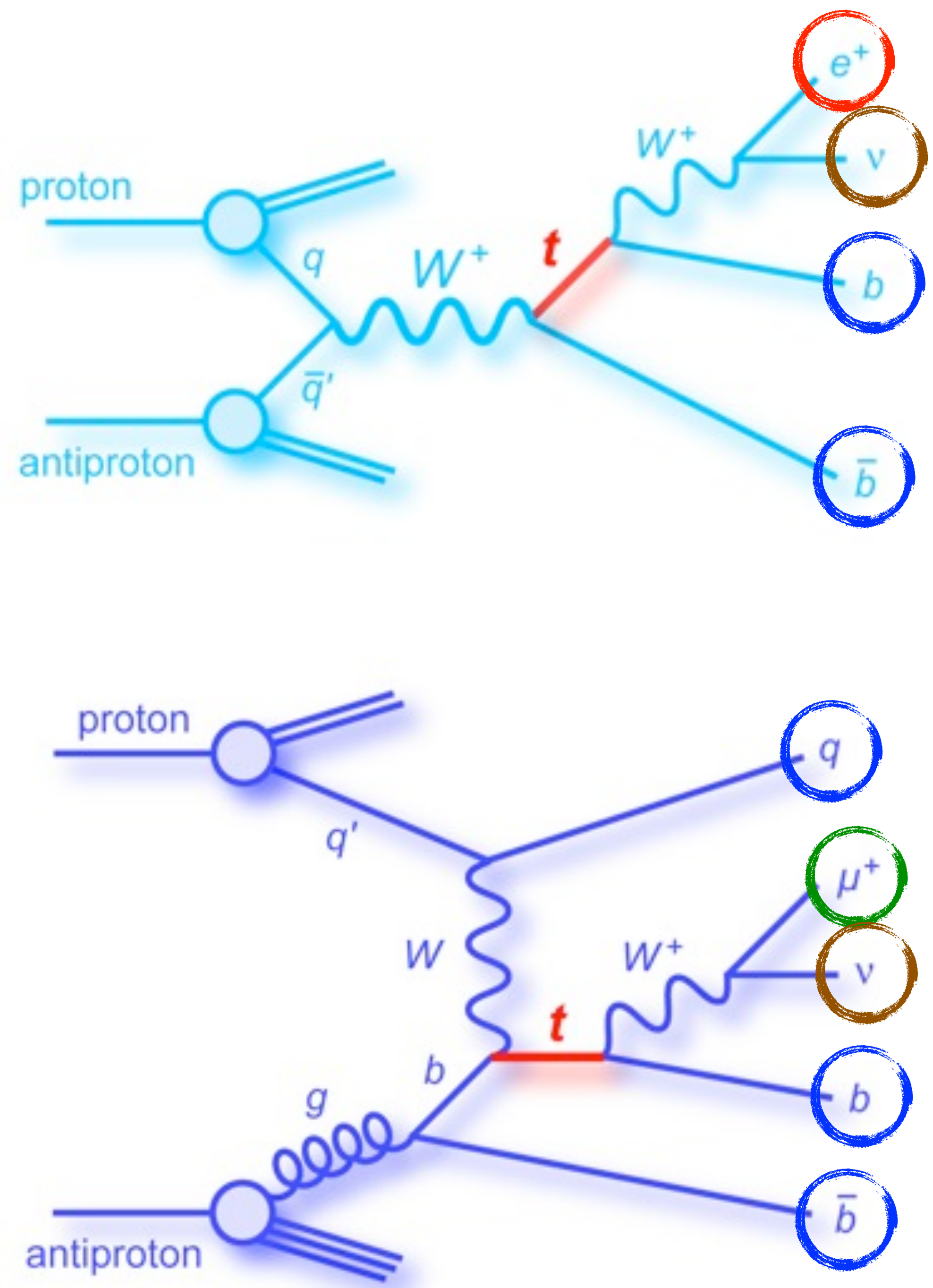

Central Tracking System:
Silicon and Fiber tracker
2T Solenoid Magnet
η = 0
η = 1
$\eta = -\ln[tan(\frac{\theta}{2})]$
[m]
Muon Scintillators
Muon Chambers
5
η = 2
η = 3
Shielding
0
p
$\bar{p}$
Calorimeter
3-layer Muon System
Toroid
–5
–10
–5
0
5
10

Data Taking



Run II Integrated Luminosity
19 April 2002 -30 September 2011
Delivered
Recorded
11.9
10.7
Luminosity (/fb)
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Use full data 9.7 fb-1
(with data quality requirement)
Run IIa, 1 fb-1
Run IIb, 8.7 fb-1

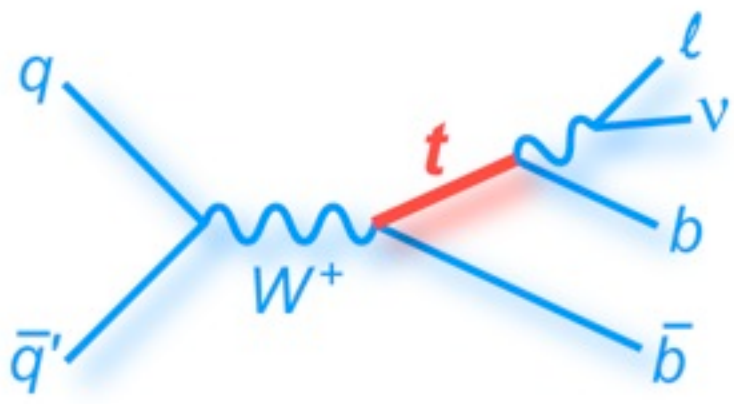
Event Selection



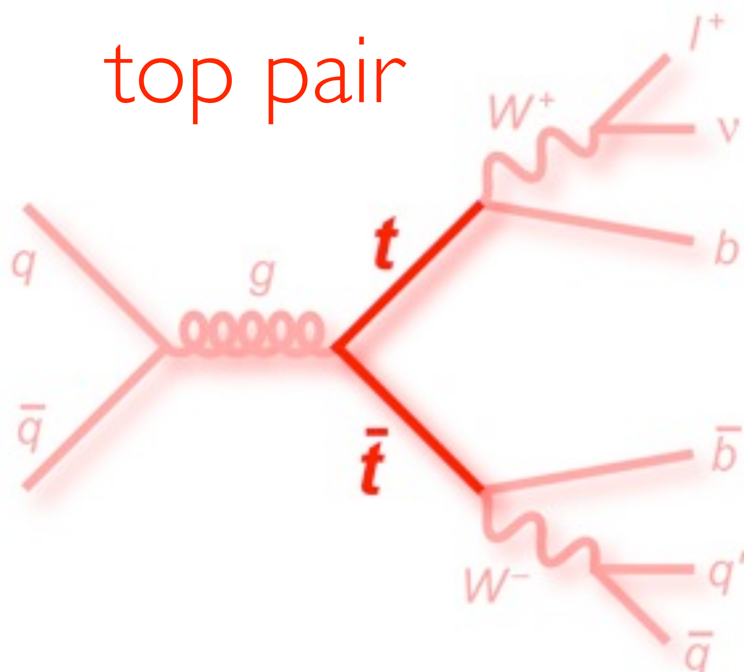
- Only one high p_T isolated electron or muon: $p_T > 20$ GeV
  - electron: $|\eta| < 1.1$
  - muon: $|\eta| < 2.0$
- Two or three jets
  - $p_T > 20$ GeV, $|\eta| < 2.5$
  - The leading jet $p_T > 25$ GeV
- Missing transverse energy > 20 GeV
- $H_T > 120$ GeV
  - H_T = all jet p_T + lepton p_T + missing transverse energy

Signal & Background Simulation

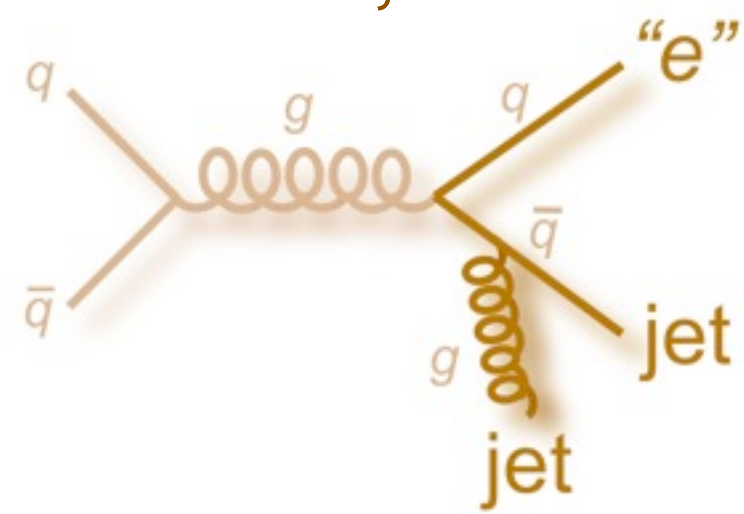
tb



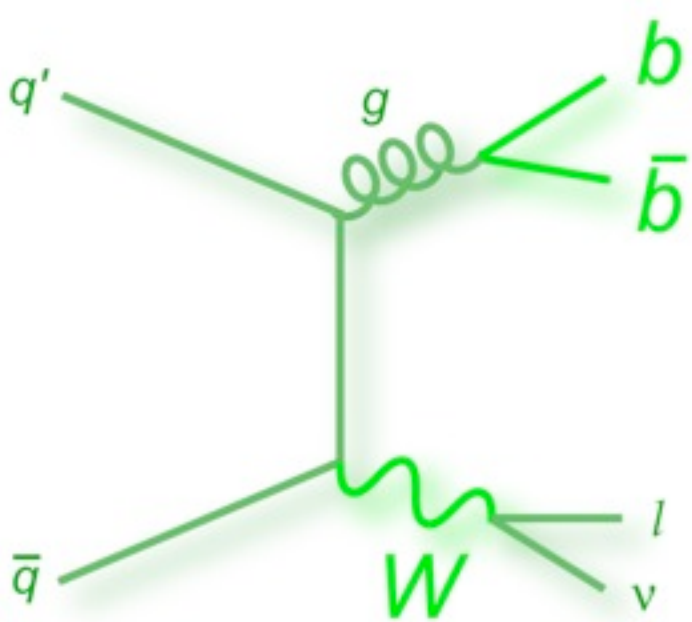
top pair



Multijet



W+jets



- Signals: CompHEP (NLO)+Pythia
- W+jets & top pair: Alpgen+Pythia
  - Correct Alpgen (LL) to NLO
    - e.g. a factor 1.9 for W+bb
- Multijet: Data with non-isolated lepton

W+jets & Multijet Normalization

- Determine the overall scales of multijet and W+jets background simultaneously

$$N_{\text{loose}} = N_{\text{loose}}^{\text{fake-}\ell} + N_{\text{loose}}^{\text{real-}\ell}$$

$$N_{\text{tight}} = \epsilon_{\text{fake-}\ell} N_{\text{loose}}^{\text{fake-}\ell} + \epsilon_{\text{real-}\ell} N_{\text{loose}}^{\text{real-}\ell}$$

W+jets & Multijet Normalization

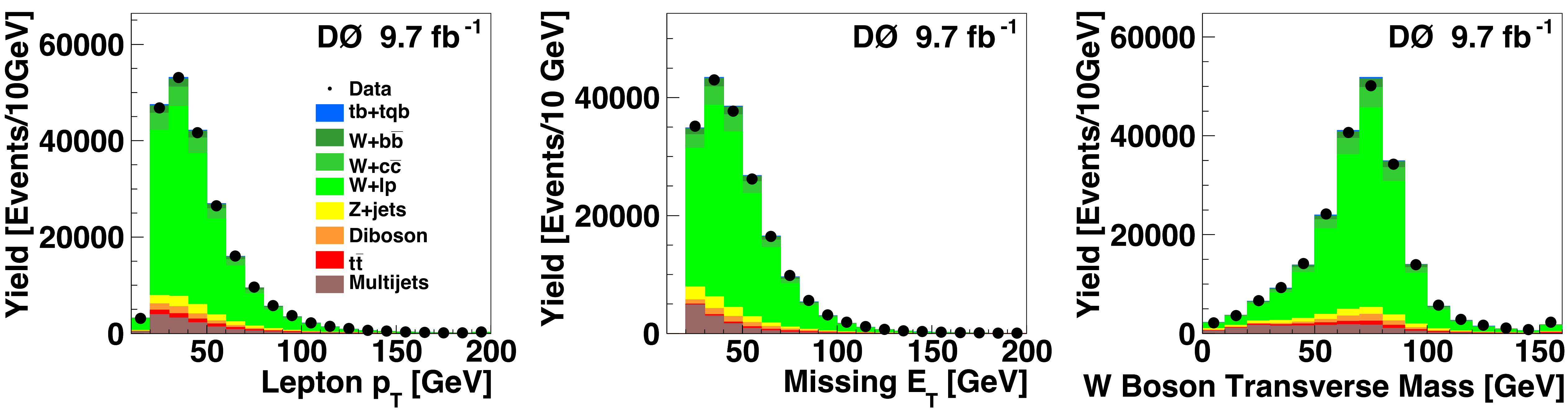
- Determine the overall scales of multijet and W+jets background simultaneously

Known from the selected data samples

$$N_{\mathrm{loose}} = N^{\mathrm{fake}\text{-}\ell}_{\mathrm{loose}} + N^{\mathrm{real}\text{-}\ell}_{\mathrm{loose}}$$

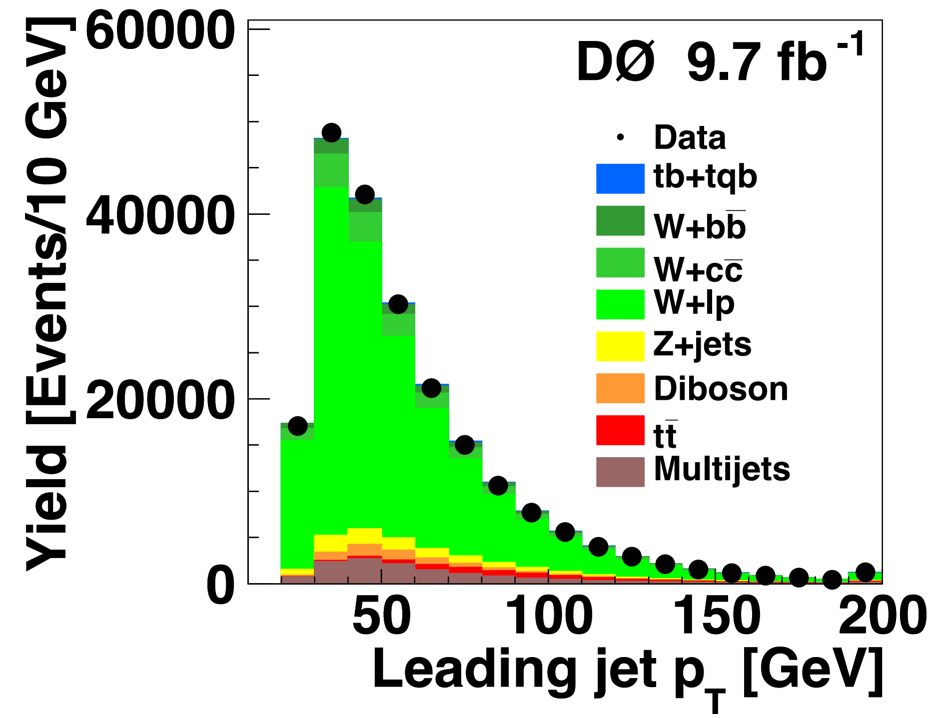
$$N_{\mathrm{tight}} = \epsilon_{\mathrm{fake}\text{-}\ell} N^{\mathrm{fake}\text{-}\ell}_{\mathrm{loose}} + \epsilon_{\mathrm{real}\text{-}\ell} N^{\mathrm{real}\text{-}\ell}_{\mathrm{loose}}$$

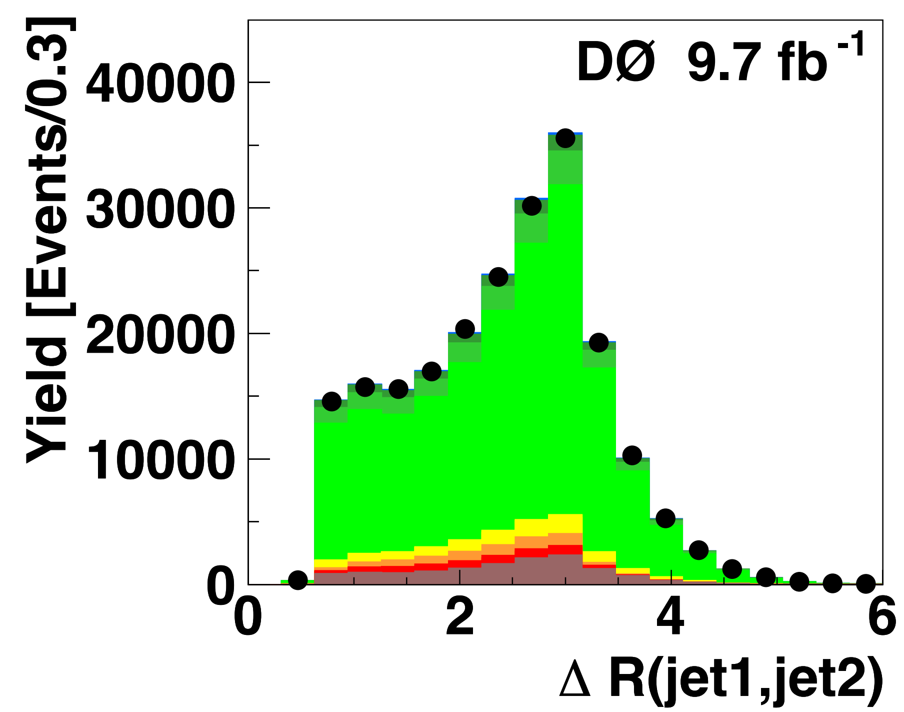
Determined from MC and data samples



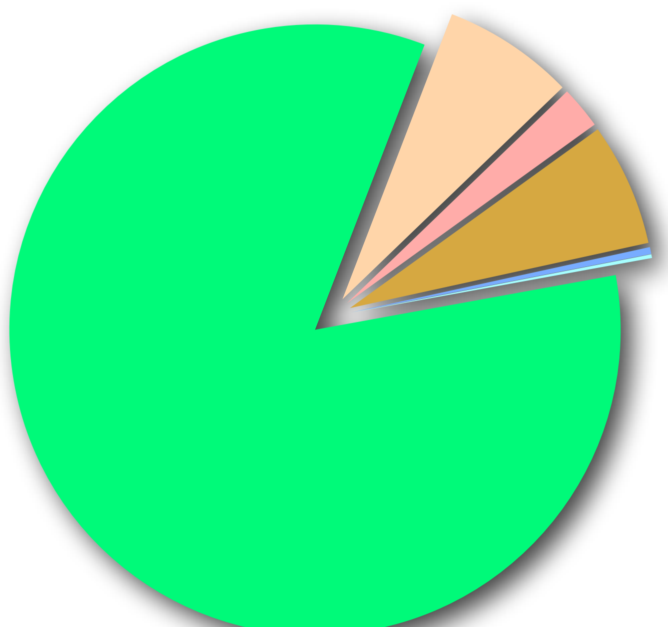
Background Modeling

- Dominated by backgrounds
- Correct the efficiency of the simulated samples to that of data
- Reweight the angular distributions of W+jets MC to data

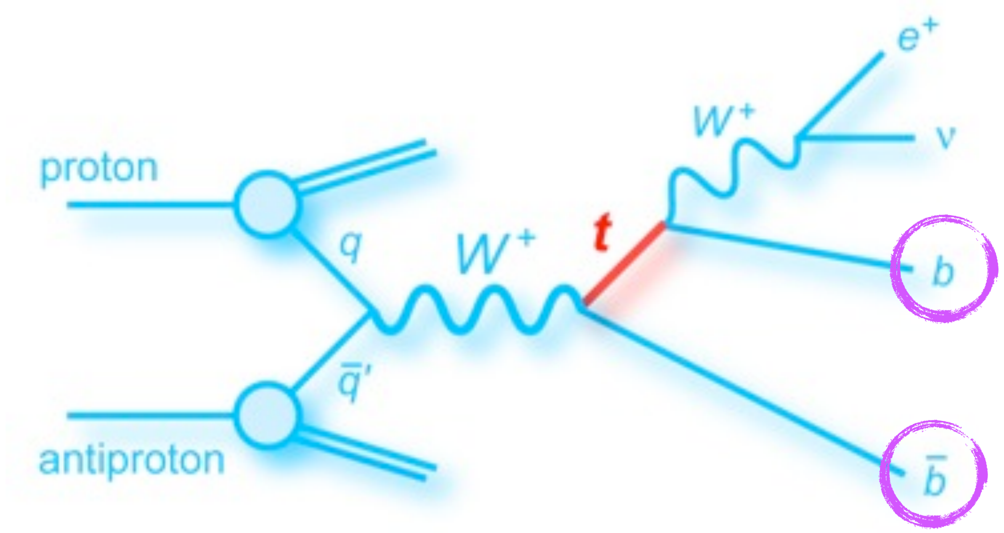


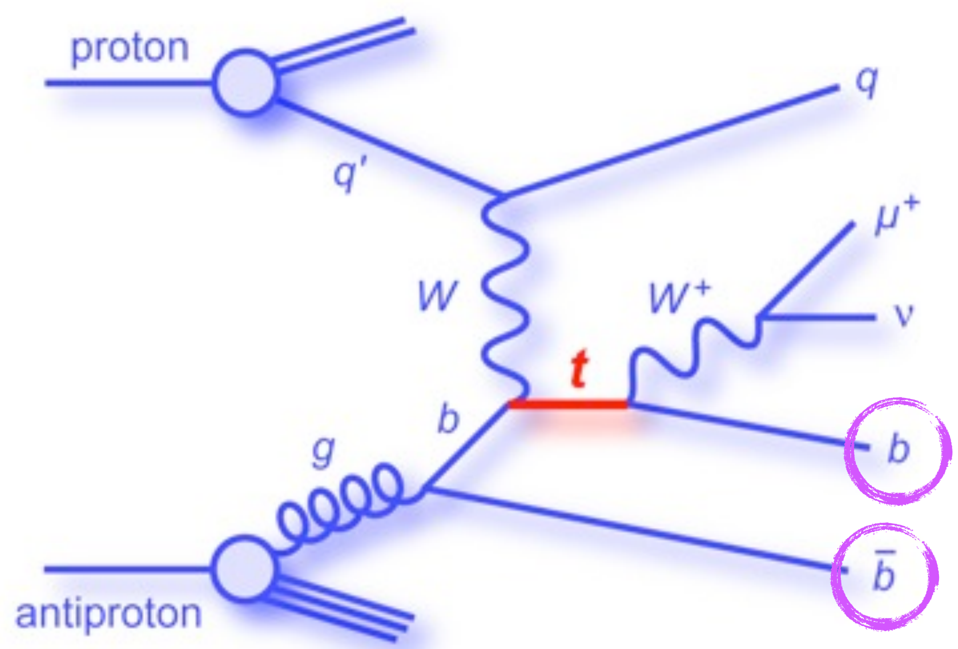


tb	423
tqb	793
W+jets	181721
Z+jets diboson	15115
top pair	4886
multijet	14164



Event Selection

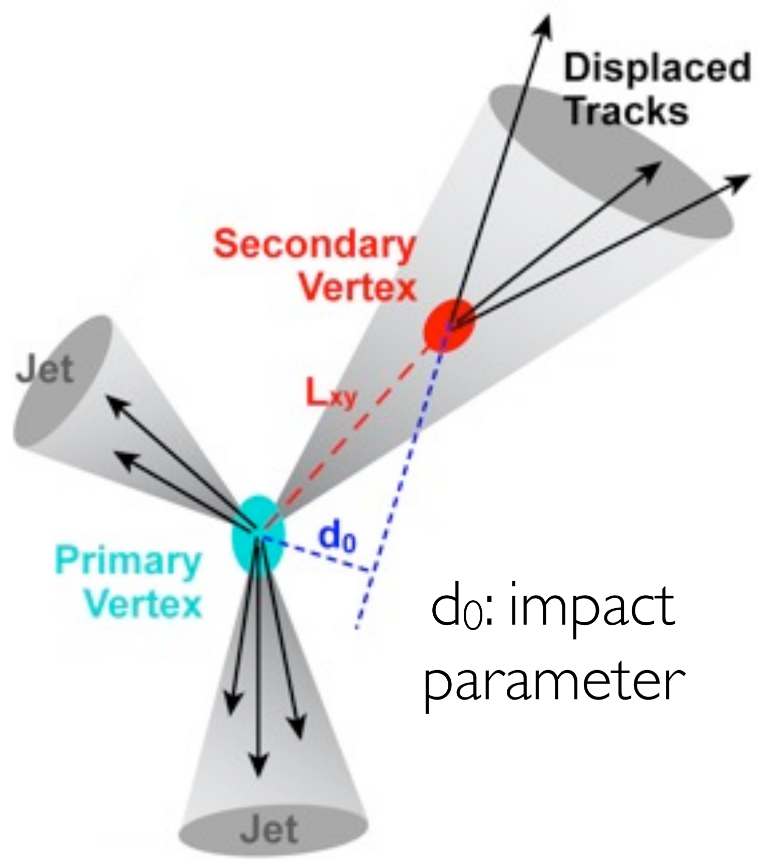




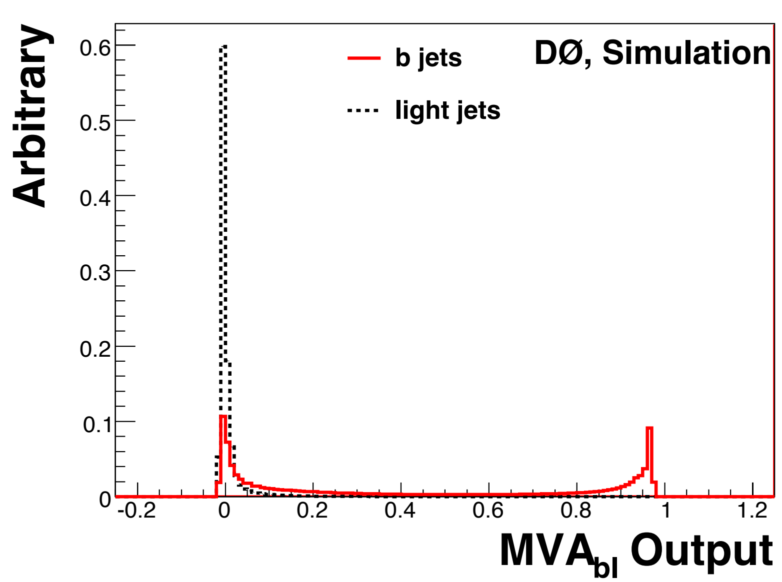
forward *b*-jet

- One high p_T isolated electron or muon: $p_T > 20$ GeV/c
  - electron: $|\eta| < 1.1$
  - muon: $|\eta| < 2.0$
- Two or three jets
  - $p_T > 20$ GeV/c, $|\eta| < 2.5$
  - The leading jet $p_T > 25$ GeV/c
- Missing transverse energy > 20 GeV/c
- Total transverse energy (H_T)
- Require one or two identified *b*-jets (*b*-tagging)

b-Jet Identification



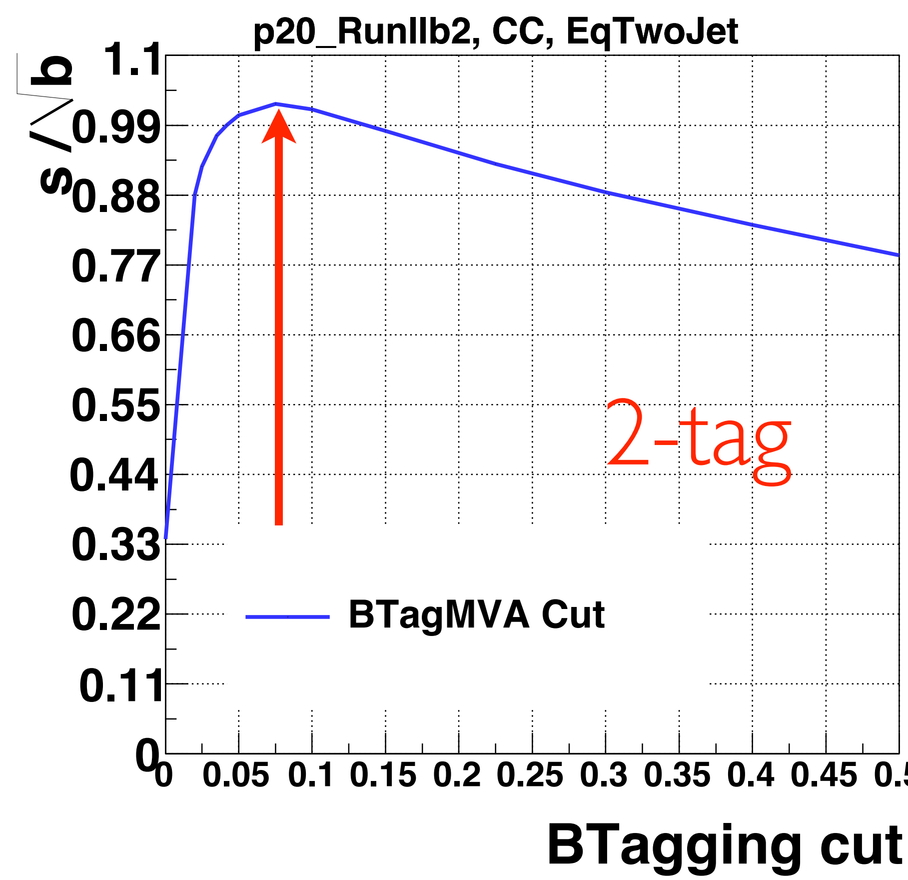
d_0: impact parameter



- Identify *b*-jet from *u*, *d*, *s*, *c*, and *g* jets
  - reduces a lot of backgrounds
- Features of *b*-hadron in *b*-jet
  - Long lifetime (~1 ps, L_{xy}~3 mm)
  - Large invariant mass
- Reconstruct a secondary vertex
- Make use of the displaced tracks (with large impact parameter)
- Use a multivariate technique to combine this information

b-ID Cut Optimization

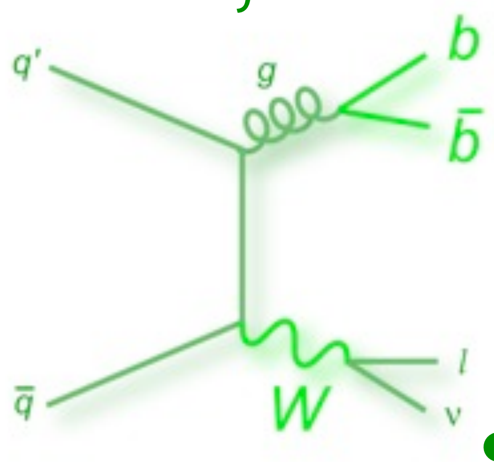
- Calculate $s/\sqrt{b}$ from the predicted signal and background events with each *b*-ID cut
- Maximize the *tb* signal rate
  - The *tb* events have two central *b*-jets
  - 2-tag channel: 2 jets with Loose *b*-ID
  - 1-tag channel: 1 jet with Tight *b*-ID, veto the 2nd jet with Loose *b*-ID
  - Non-overlapping categories



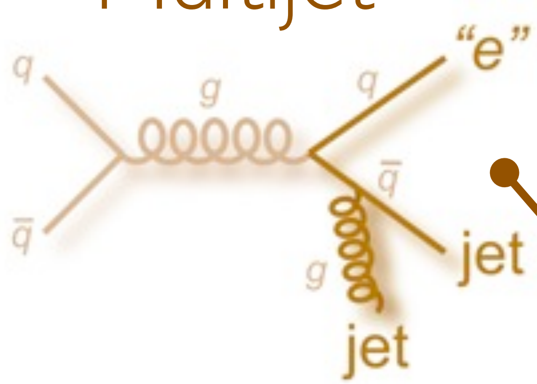
- Typical *b*-ID efficiency: 50% - 70%
- Fake rate: 2% - 7%

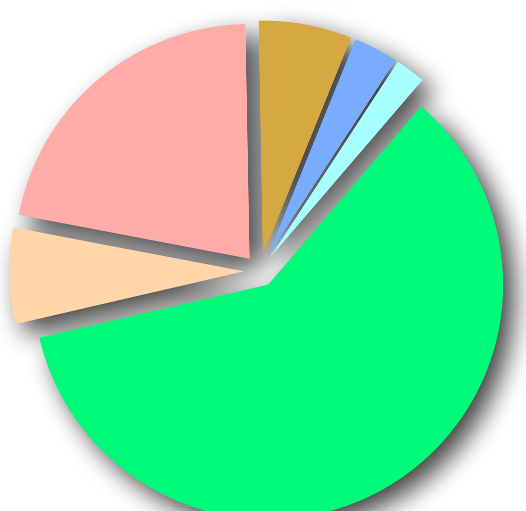
Event Yield

W+jets



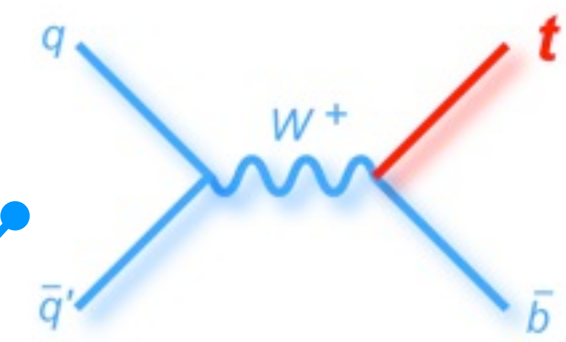
Multijet



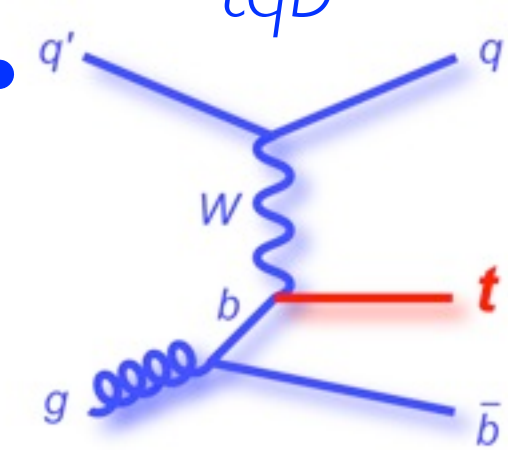


e, μ 2, 3-jets 1, 2 *b*-tags combined	
tb	257 ± 31
tqb	378 ± 53
W+jets	7394 ± 401
diboson, *Z*+jets	815 ± 71
top pair	2672 ± 284
multijet	789 ± 81
Total background	11669 ± 503
Data	12103

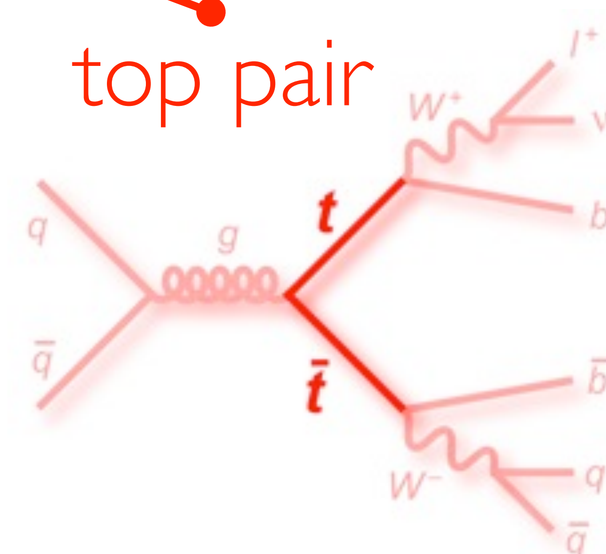
tb



tqb

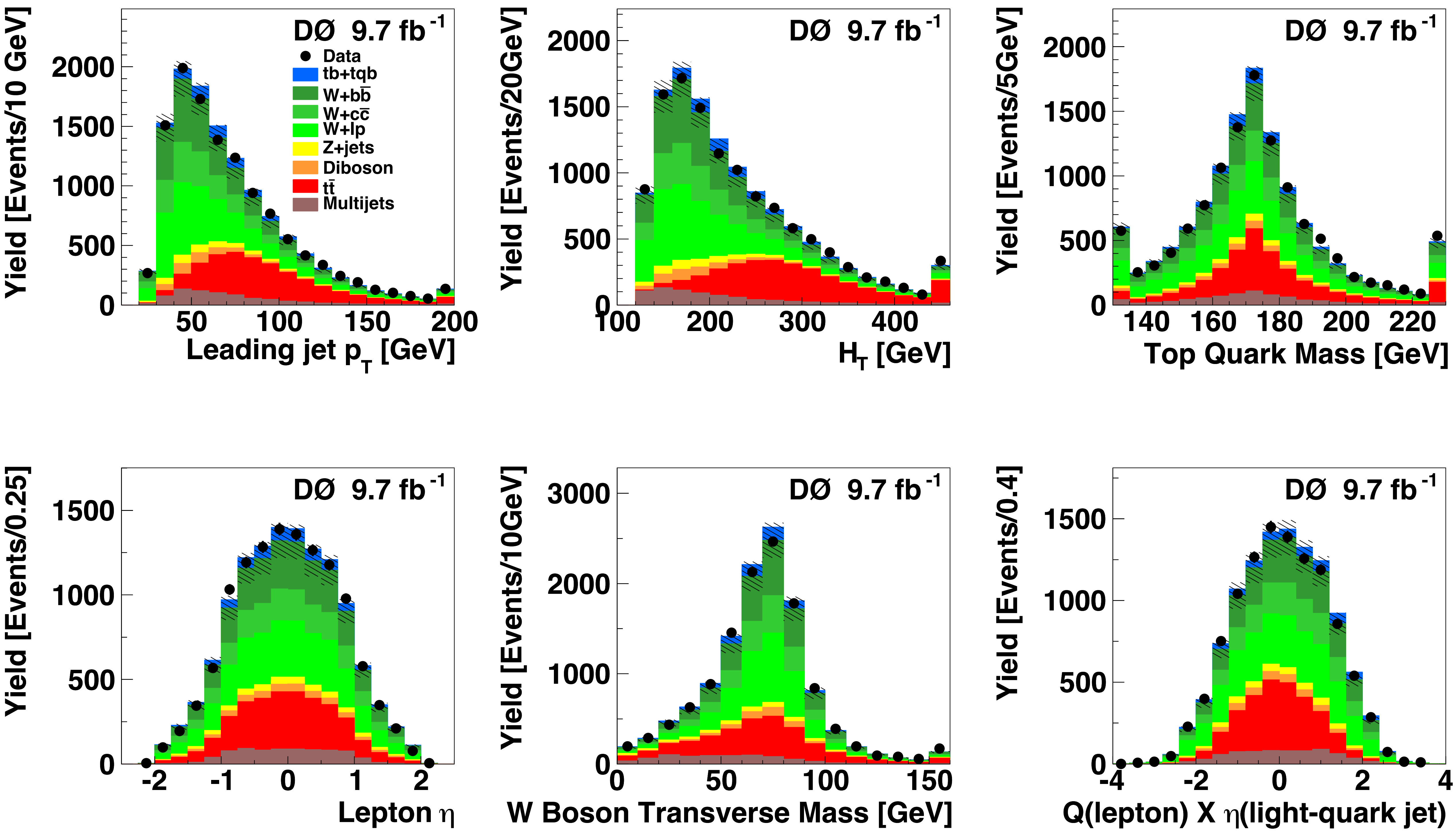


top pair



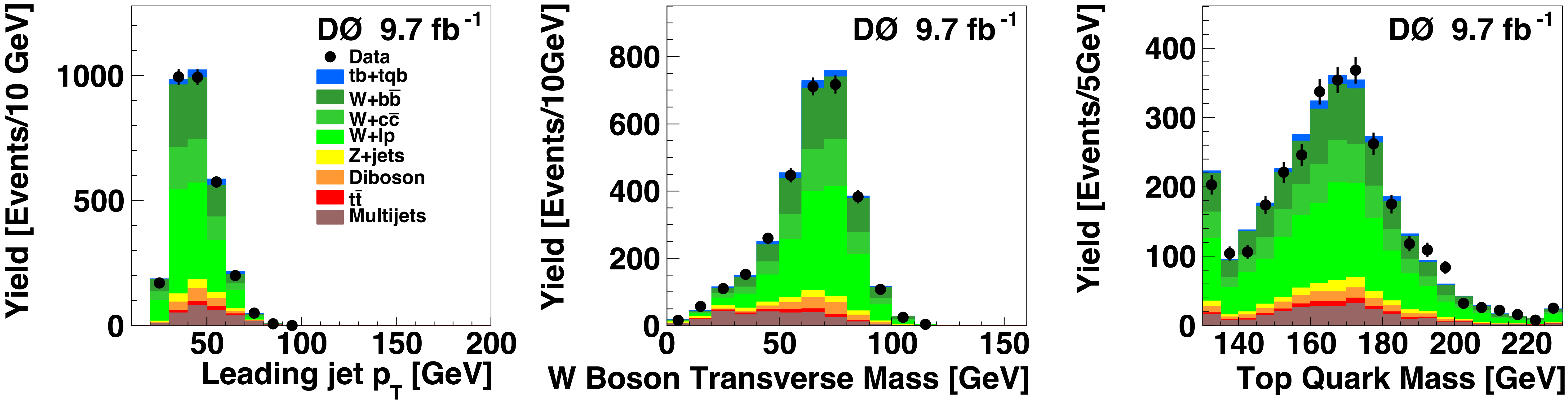
tb: *tqb*: B = 1: 1.5: 45

Data-Simulation Comparison

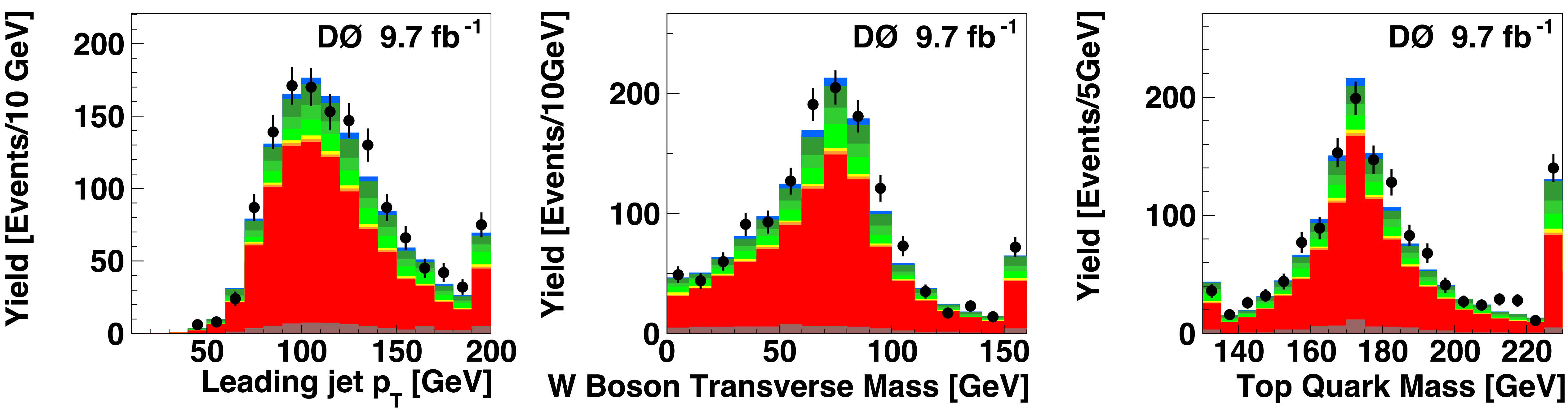


Cross-Check Samples

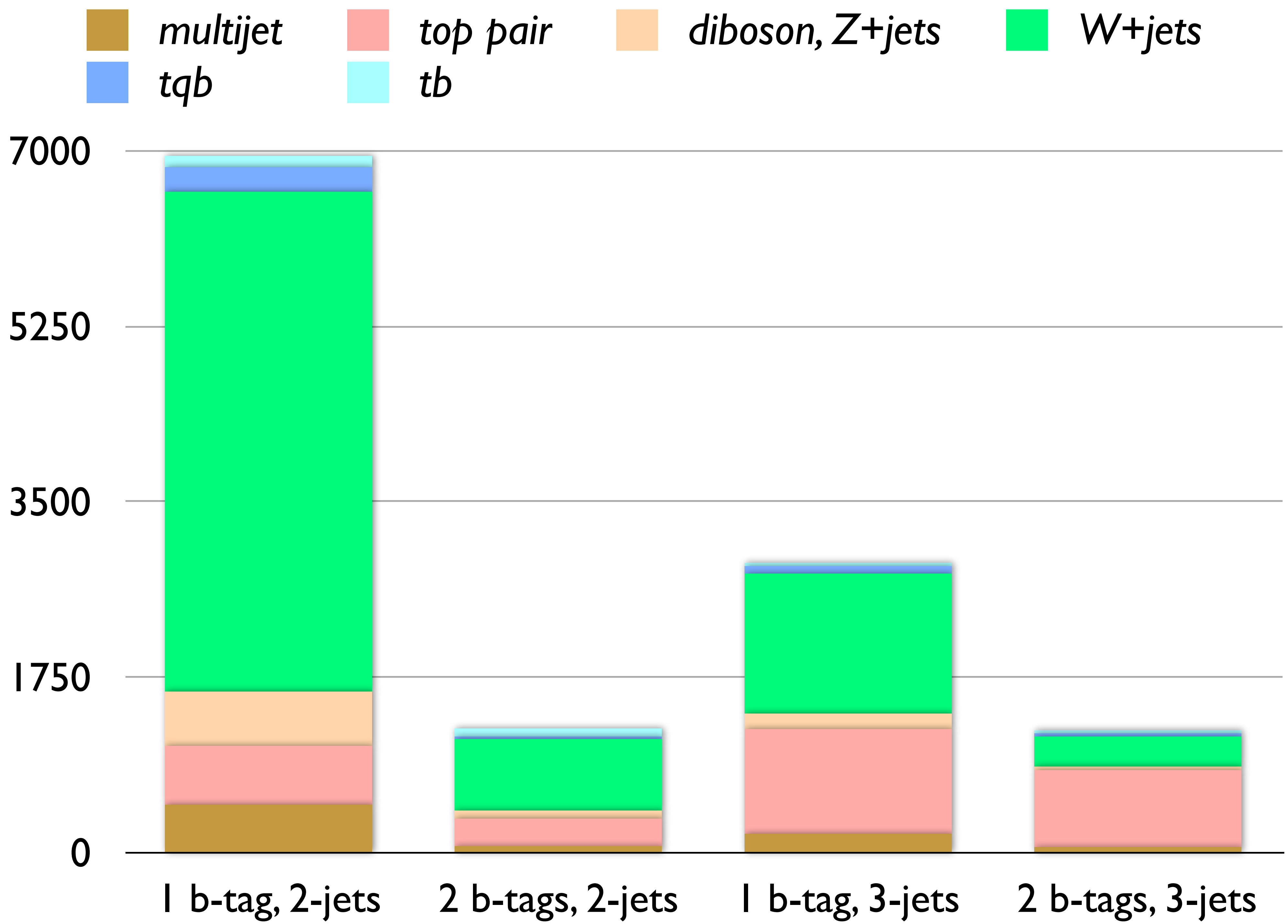
- W+jets enriched sample: 1 *b*-tag, 2 jets, H_T<175 GeV



- top pair enriched sample: at least 1 *b*-tag, 3 jets, H_T>300 GeV

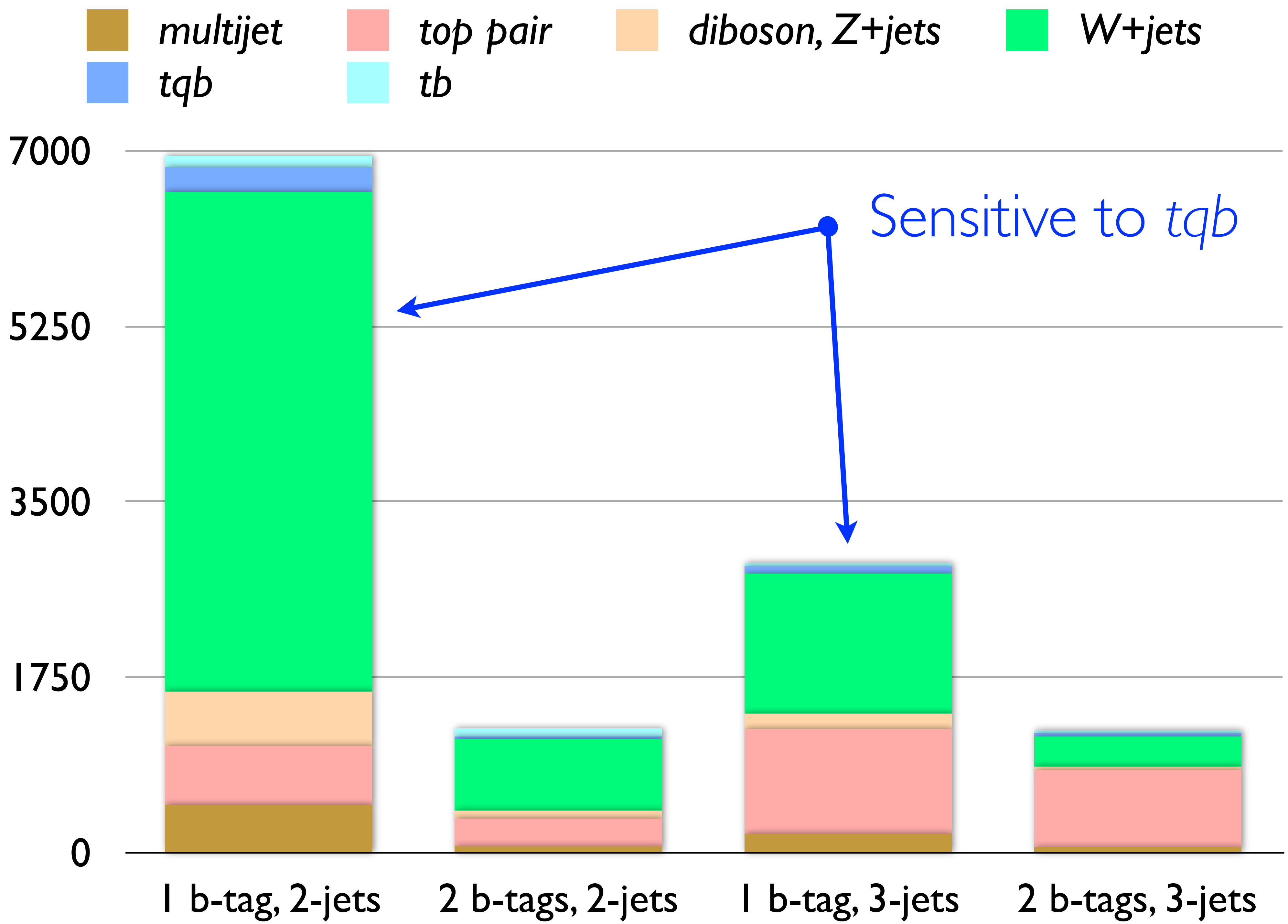


Background Contributions



tb: *tqb*: B 1: 2: 59 1: 0.3: 14 1: 2: 85 1: 1: 40

Background Contributions



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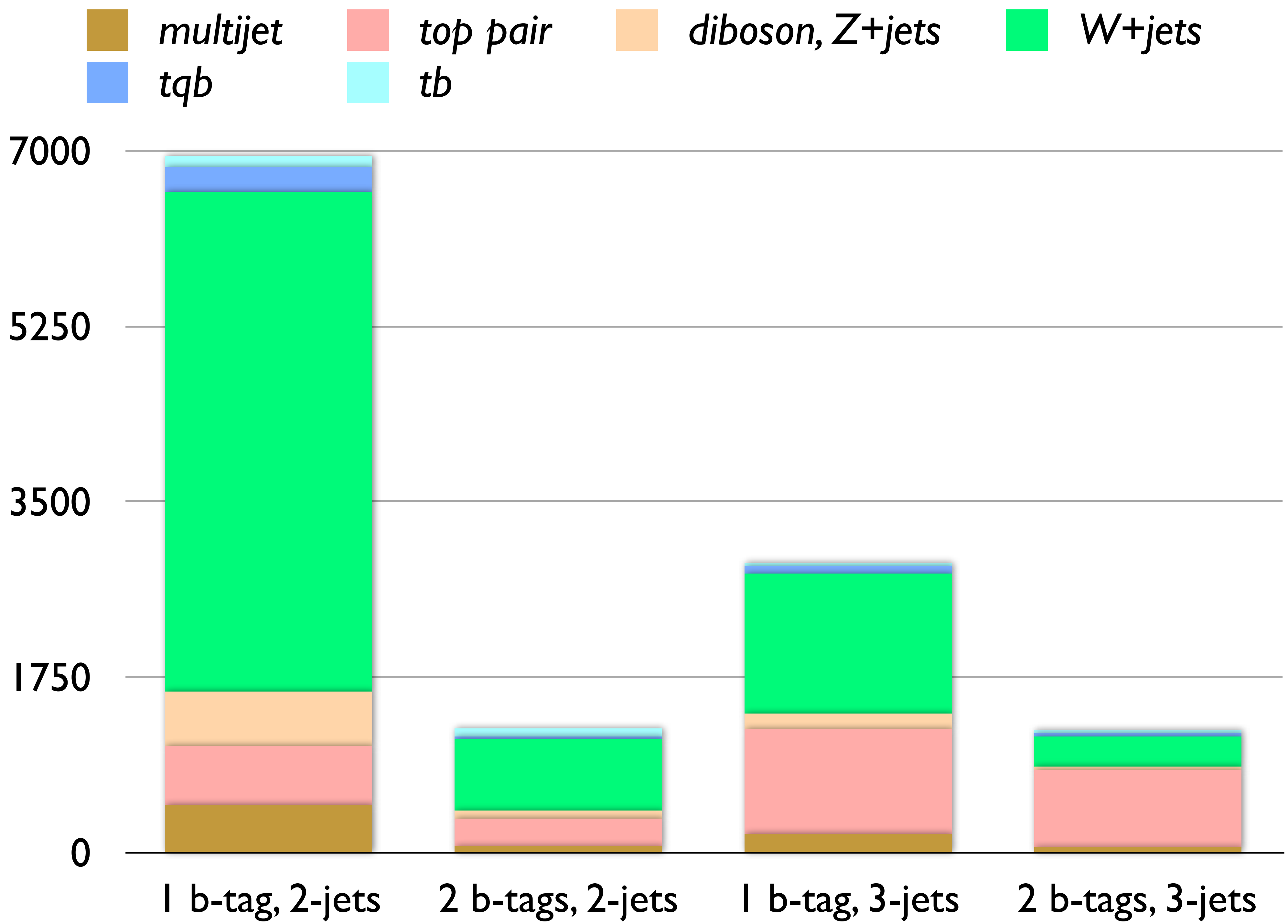
Background Contributions



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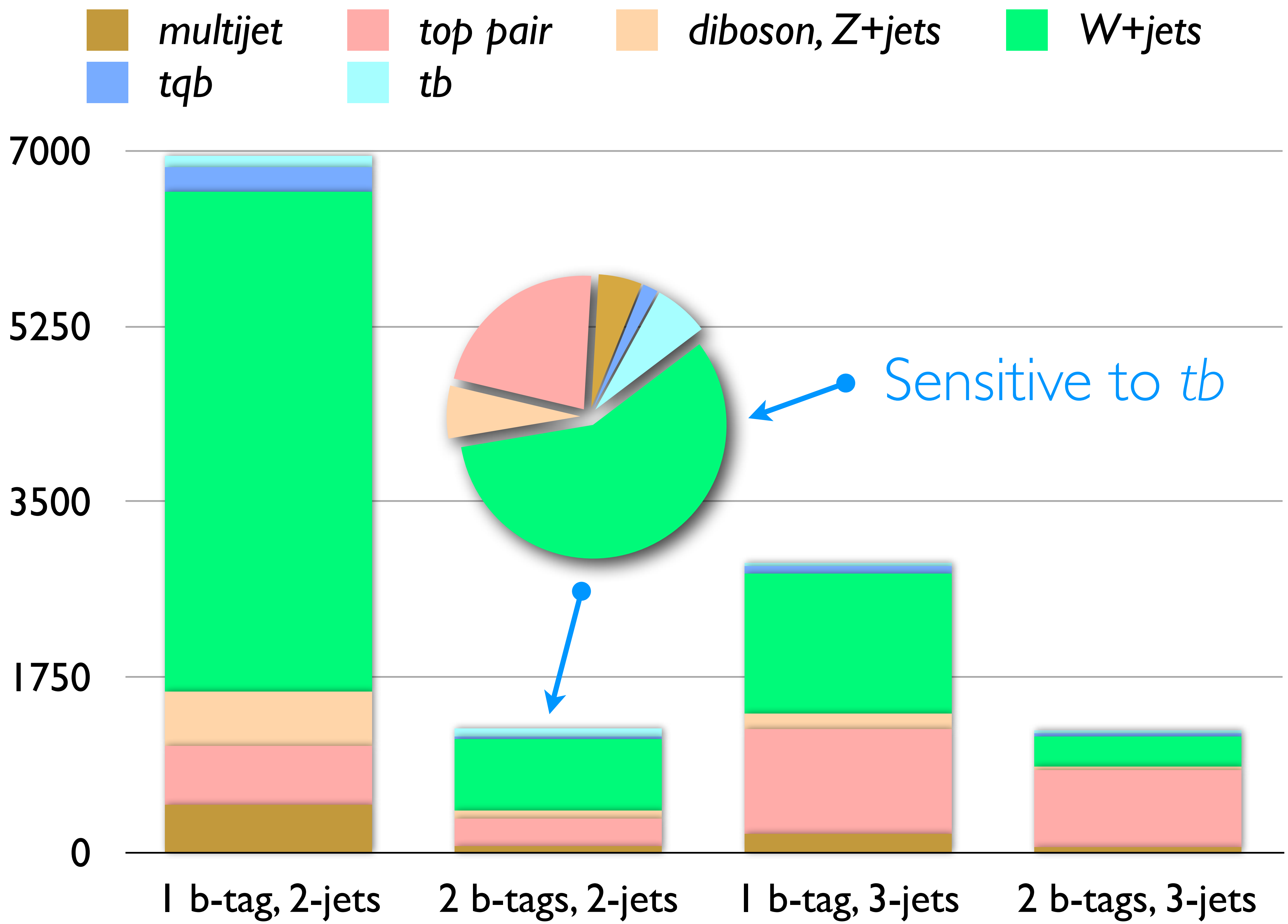
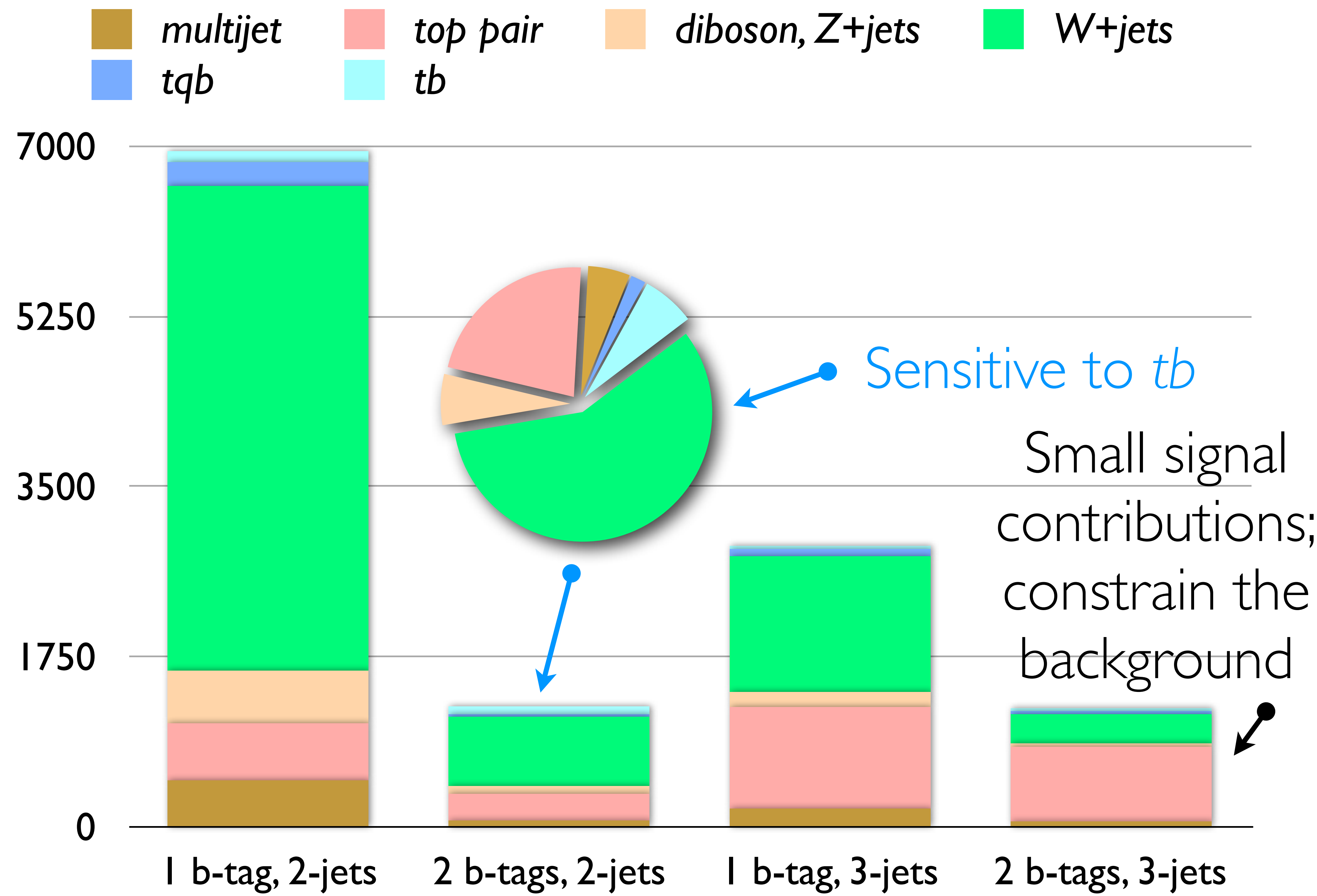
Background Contributions



tb: *tqb*: B	1 : 2 : 59	1 : 0.3 : 14	1 : 2 : 85	1 : 1 : 40

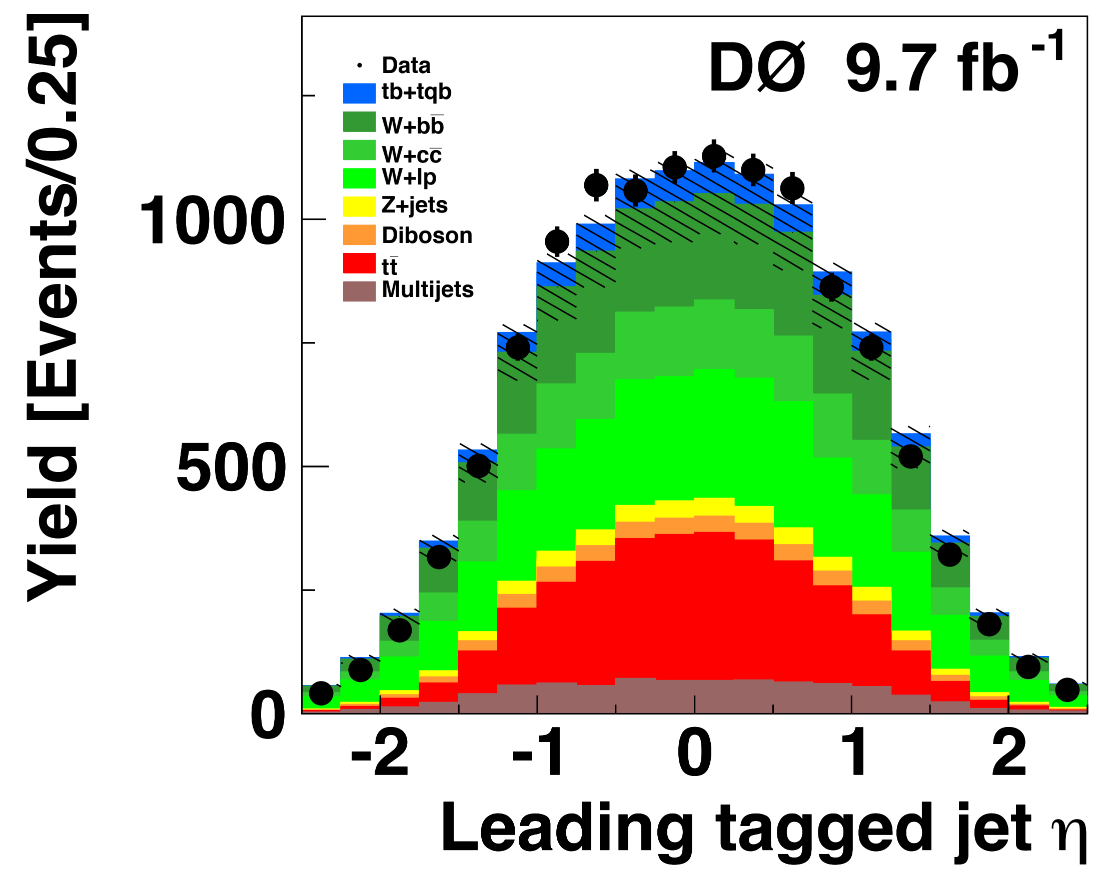
Background Contributions

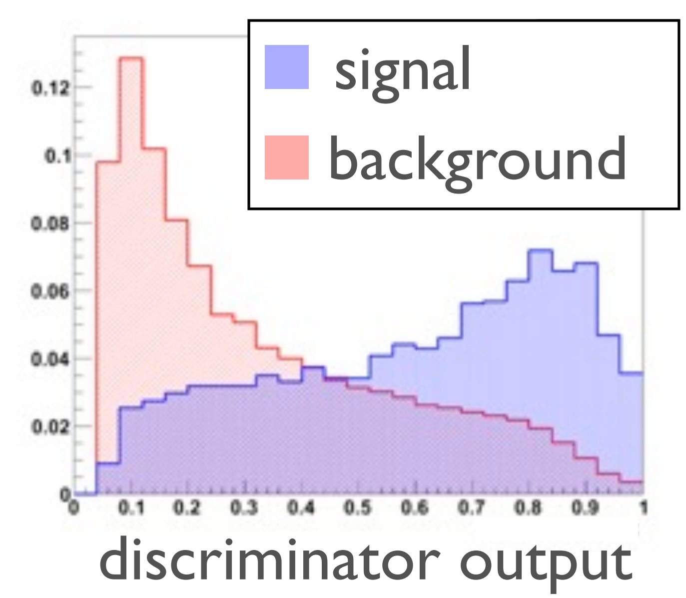


tb: *tqb*: B	1: 2: 59	1: 0.3: 14	1: 2: 85	1: 1: 40

Not A Counting Experiment

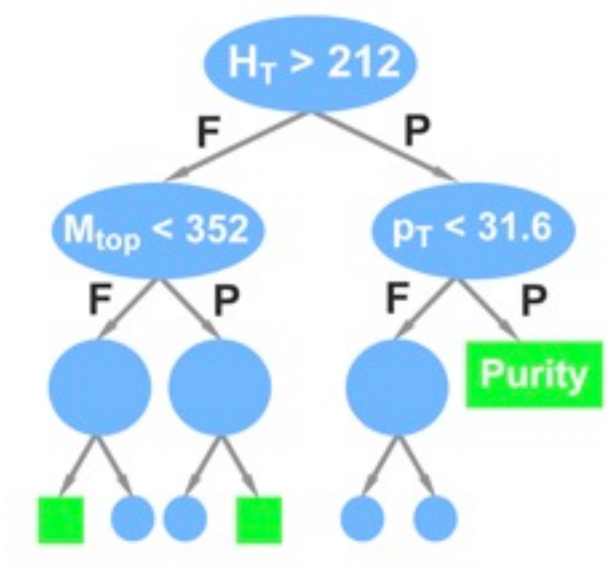
- The amount of signal is less than the uncertainty on the backgrounds
- Not feasible to perform a counting experiment
- Need a variable to separate the signals and backgrounds
- No single kinematic or topological variable is sufficient
- Need a multivariate method



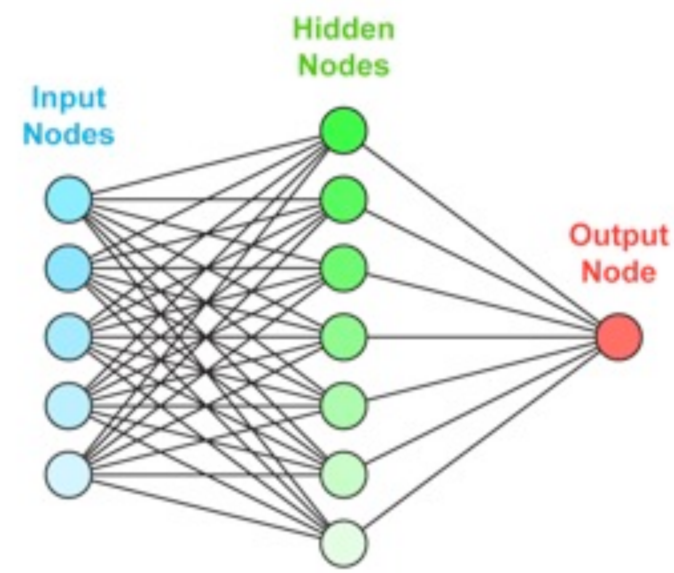


Multivariate Techniques

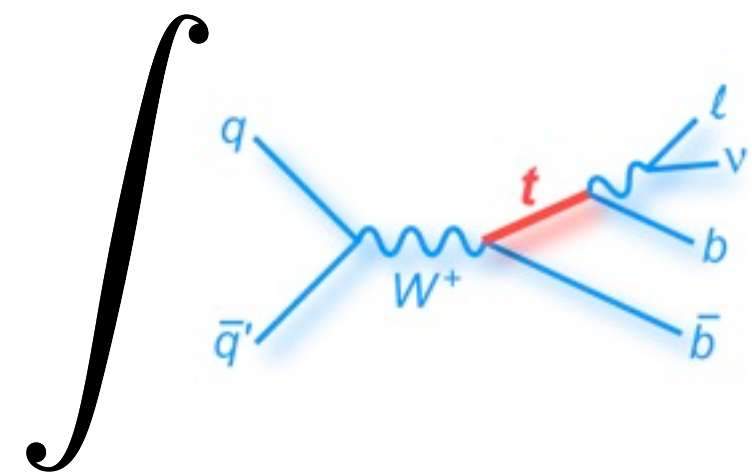
BDT



BNN

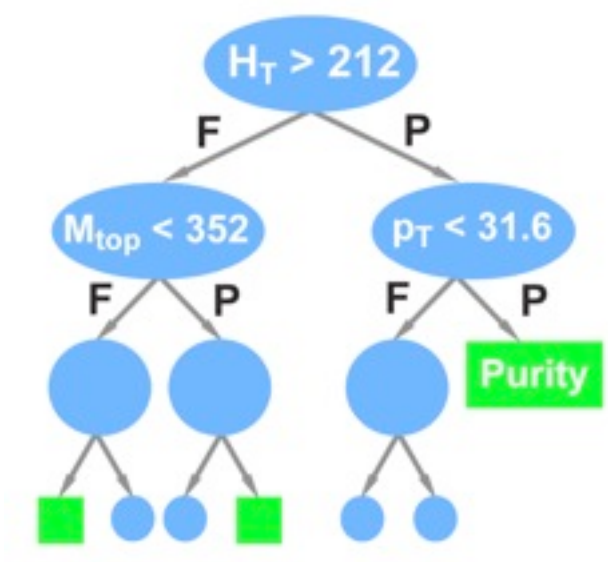


ME

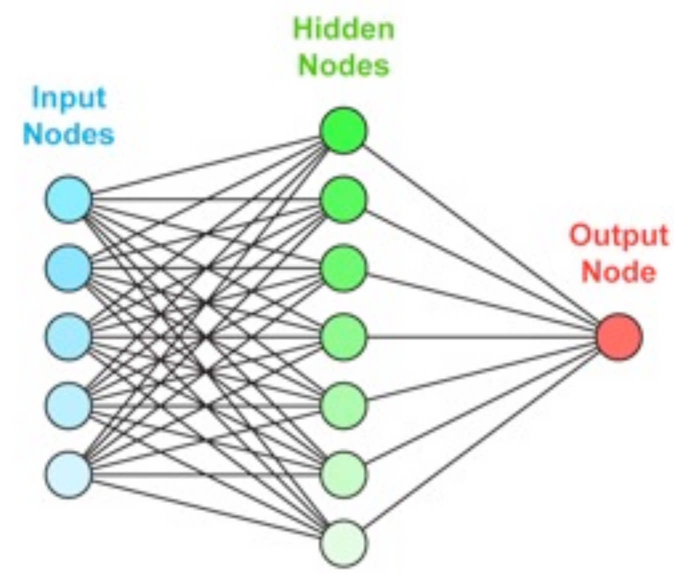


Multivariate Techniques

BDT

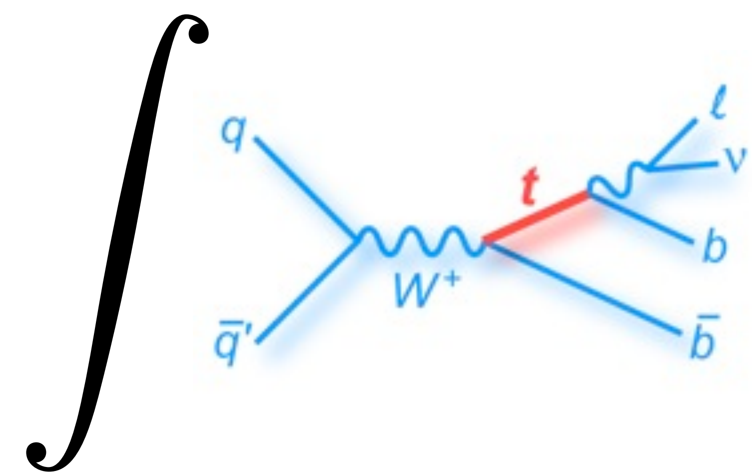


BNN



- Machine learning technique
- Use well-described variables (KS>0.25) as the input
- Train *tb* and *tqb* individually
  1/4 MC for training, 1/2 measurement
- Form *tb* and *tqb* discriminants

ME

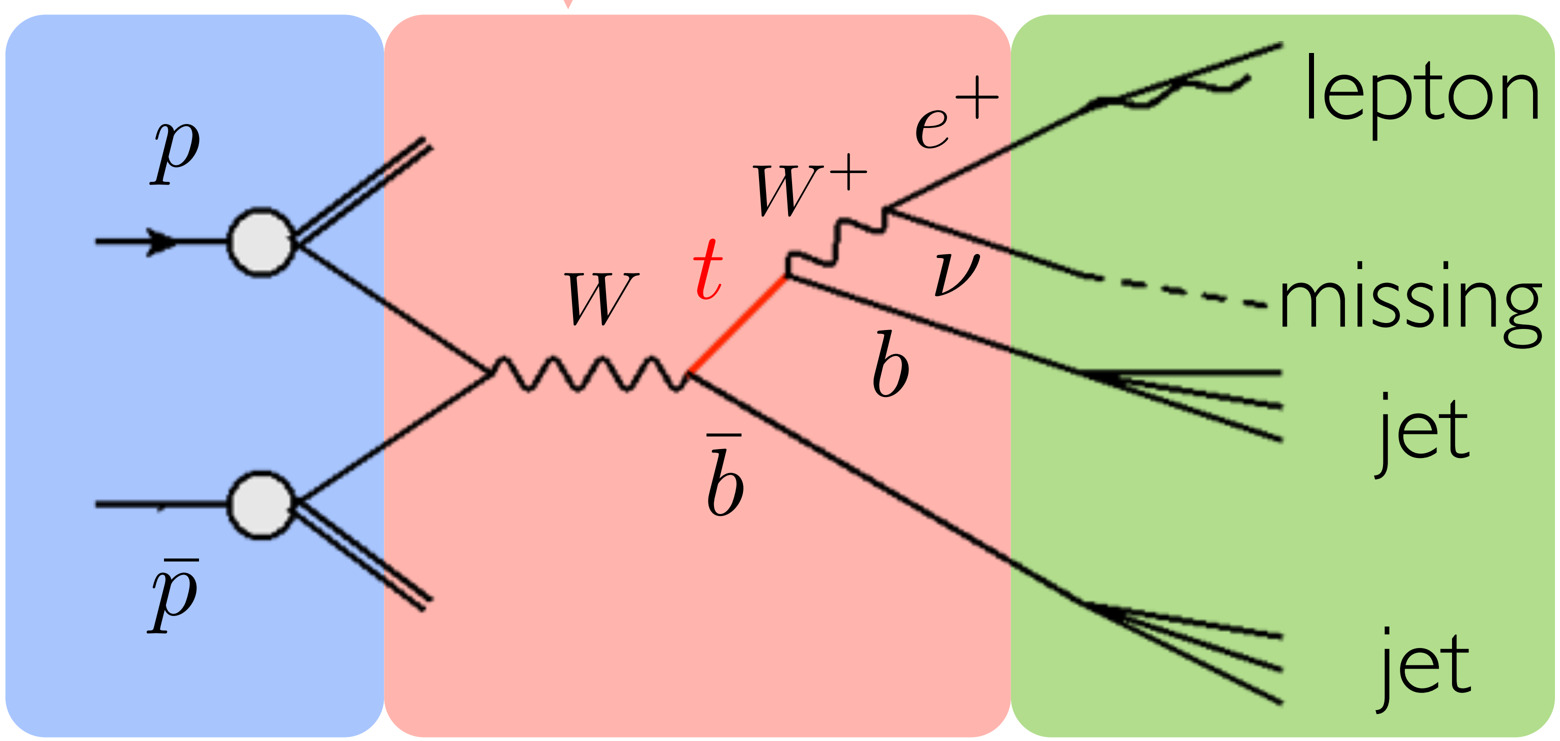


- Calculate probabilities
- Form *tb* and *tqb* likelihood ratios
- Less correlated with the others

Matrix Element Method

$$P(\vec{x}) = \frac{1}{\sigma^{obs}} \sum_{x,y} \sum_{i,j} \int f_i(q_1)dq_1 f_j(q_2)dq_2 \frac{\partial \sigma_{hs,ij}(\vec{y})}{\partial \vec{y}} W(\vec{x},\vec{y})d\vec{y}$$

LO Matrix Element



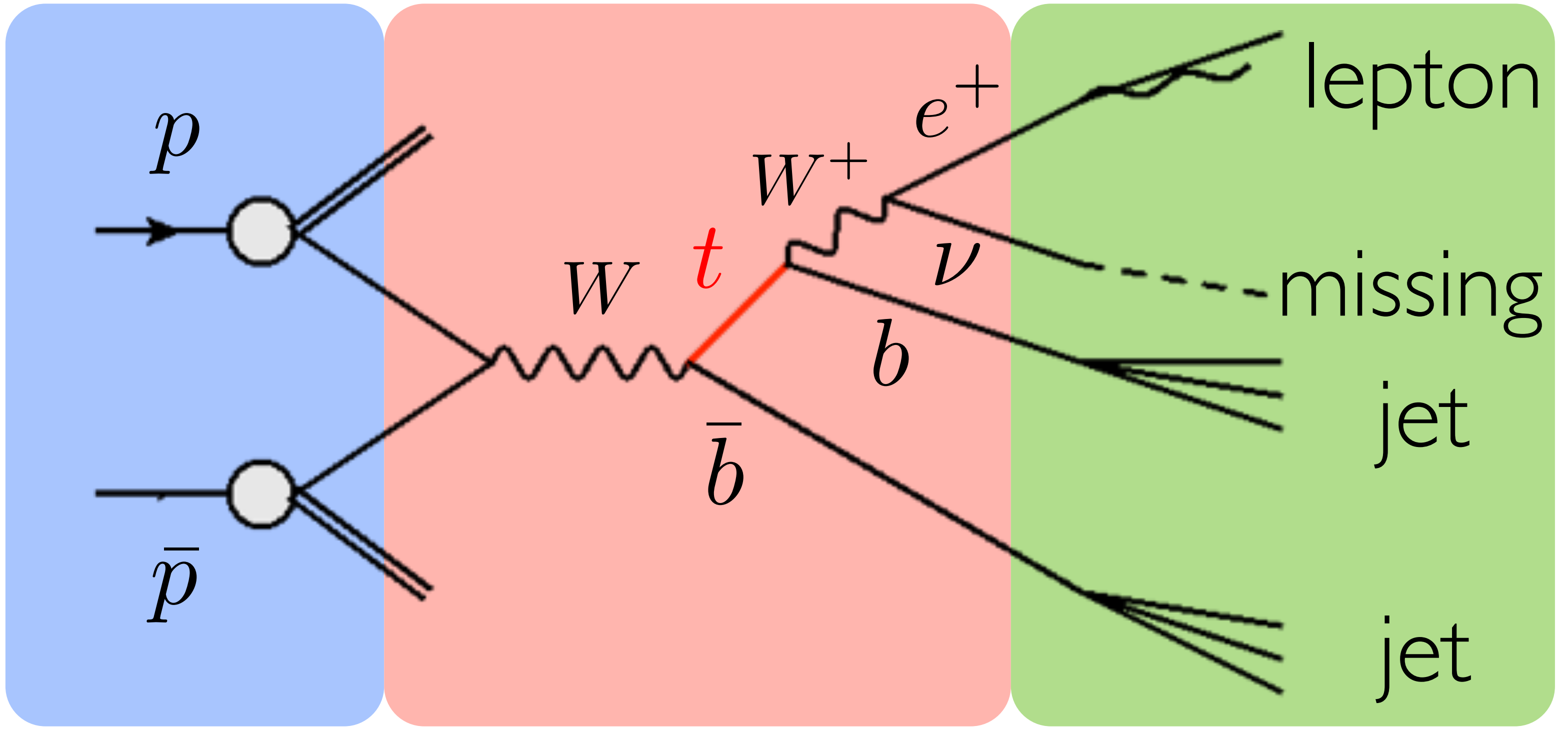
Matrix Element Method

$$P(\vec{x}) = \frac{1}{\sigma^{obs}} \sum_{x,y} \sum_{i,j} \int f_i(q_1)dq_1 f_j(q_2)dq_2 \frac{\partial \sigma_{hs,ij}(\vec{y})}{\partial \vec{y}} W(\vec{x},\vec{y})d\vec{y}$$

CTEQ6L PDF

LO Matrix Element

Detector Resolution: Transfer Functions for electrons, muons and jets



Matrix Element Method

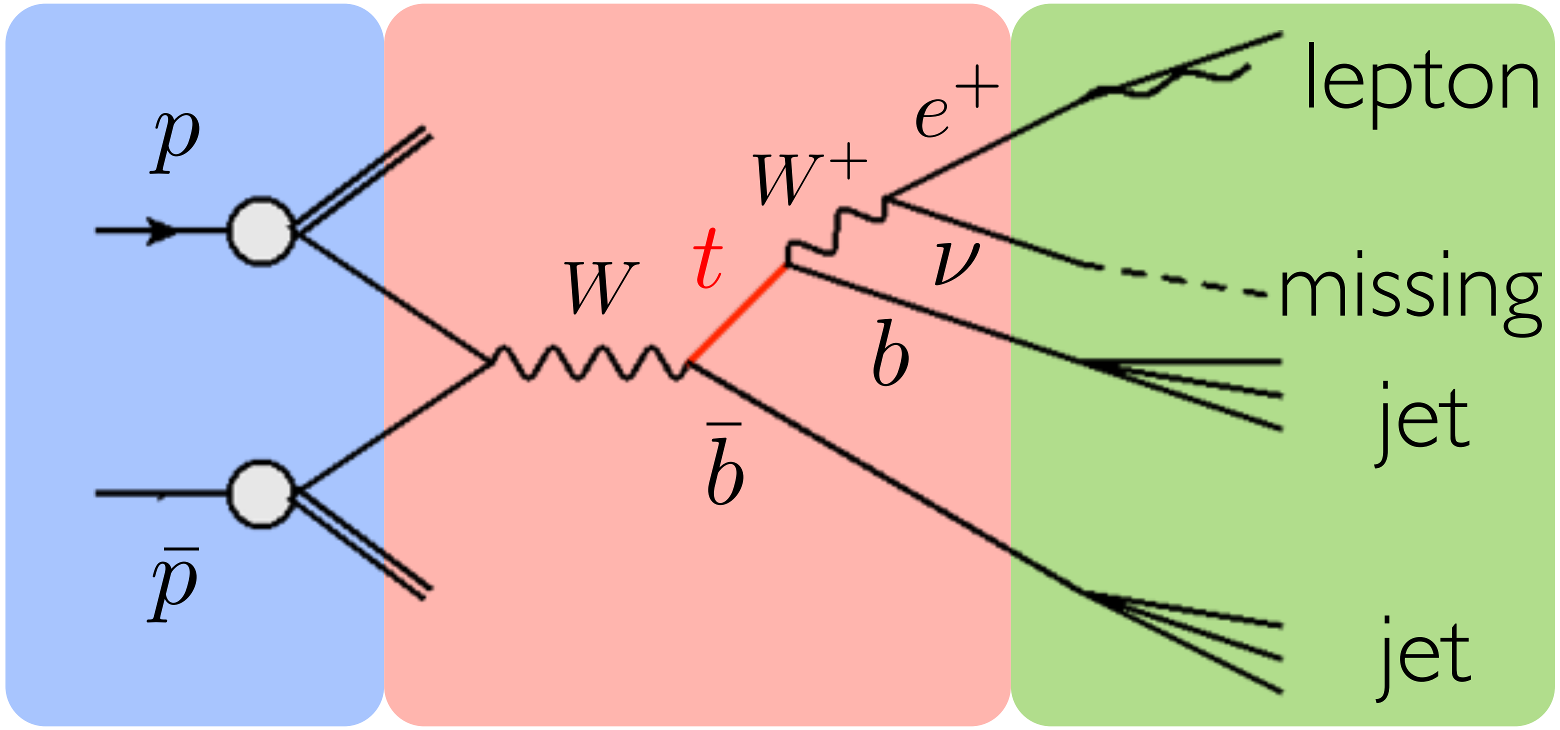
$$P(\vec{x}) = \frac{1}{\sigma^{obs}} \sum_{x,y} \sum_{i,j} \int f_i(q_1)dq_1 f_j(q_2)dq_2 \frac{\partial \sigma_{hs,ij}(\vec{y})}{\partial \vec{y}} W(\vec{x},\vec{y})d\vec{y}$$

Jet-Parton Assignment; Utilize *b*-ID

CTEQ6L PDF

LO Matrix Element

Detector Resolution: Transfer Functions for electrons, muons and jets



Matrix Element Method

$$P(\vec{x}) = \frac{1}{\sigma^{obs}} \sum_{x,y} \sum_{i,j} \int f_i(q_1)dq_1 f_j(q_2)dq_2 \frac{\partial \sigma_{hs,ij}(\vec{y})}{\partial \vec{y}} W(\vec{x},\vec{y})d\vec{y}$$

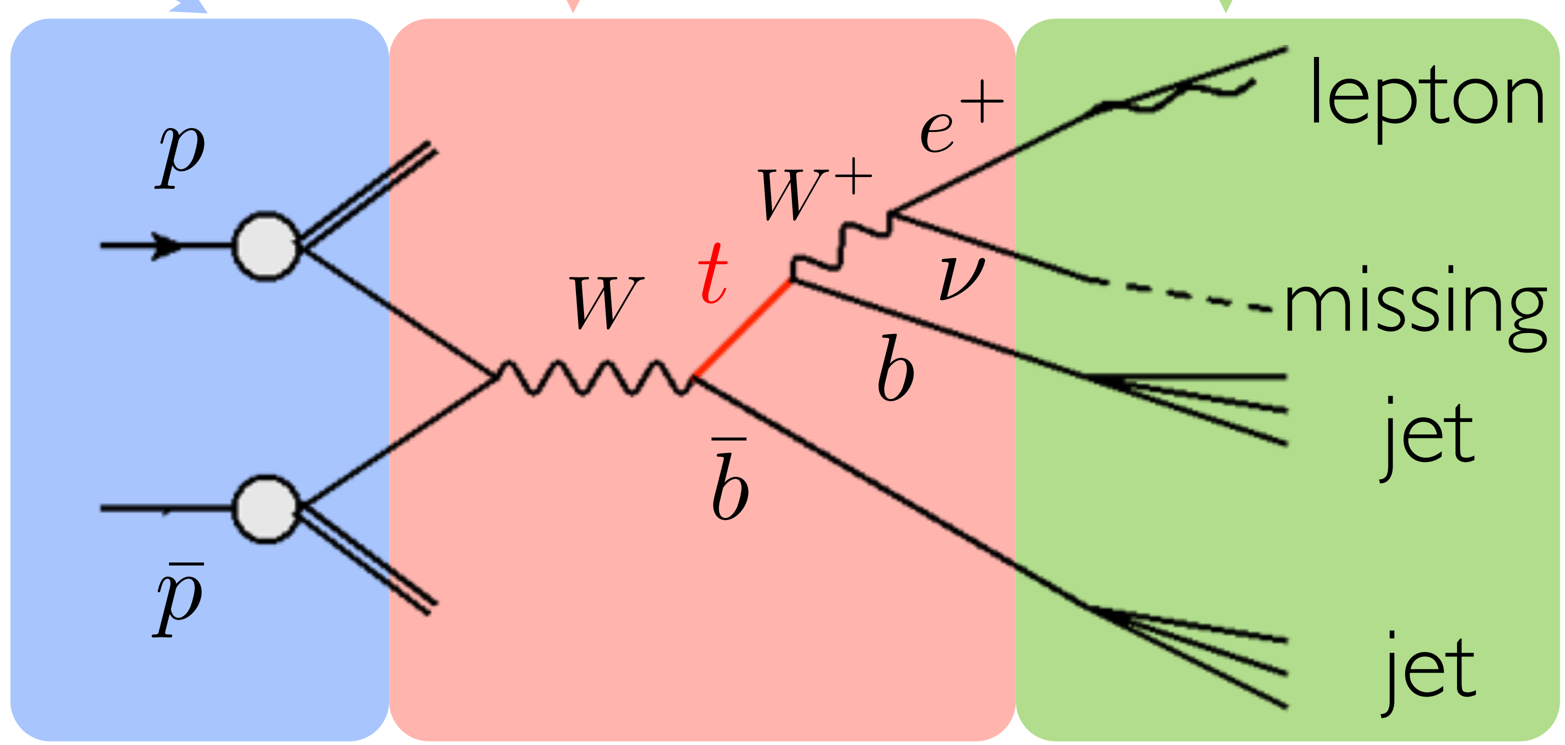
Jet-Parton Assignment; Utilize *b*-ID

CTEQ6L PDF

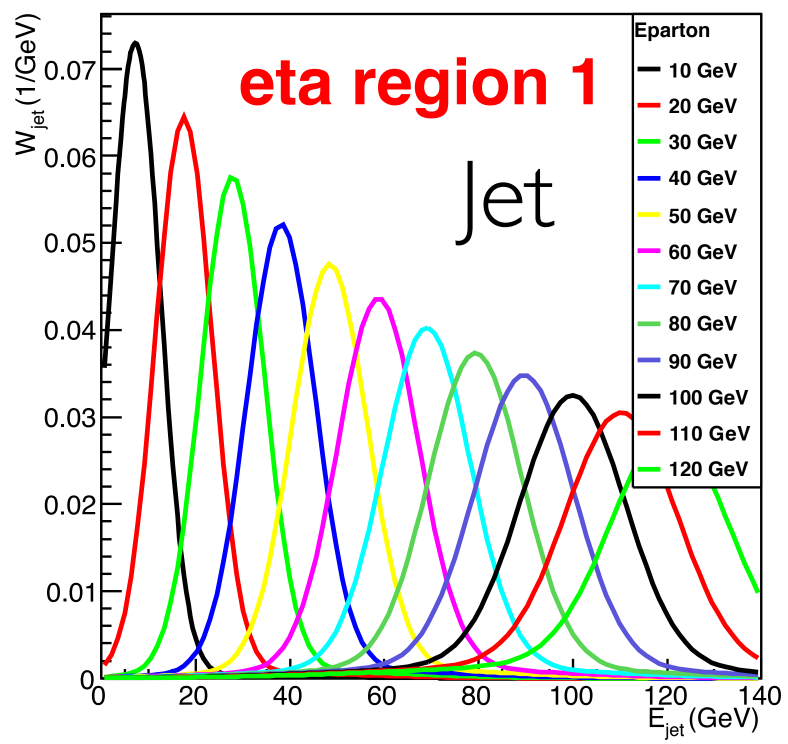
LO Matrix Element

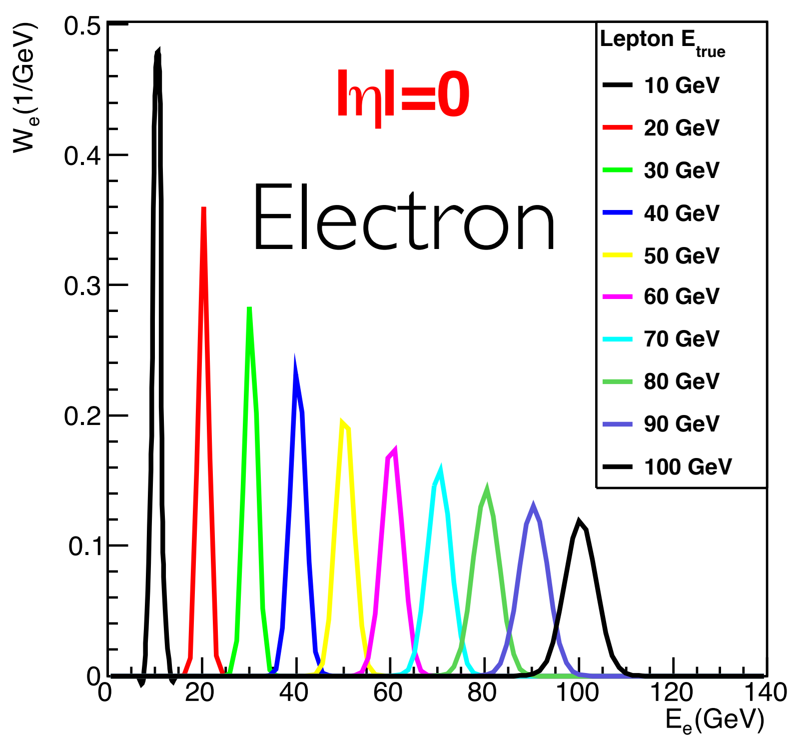
Detector Resolution: Transfer Functions for electrons, muons and jets

- Efficiently returns full event information
- Integration performed numerically



Transfer Functions: $W(\vec{x}, \vec{y})$





- Model the detector resolution effects
- For all final state objects: electrons, muons, jets, and jets mis-reconstructed as electrons
- Gaussian functions of difference between:
  - reconstructed and true energy (electrons, jets, fake electrons)
  - reconstructed and true transverse momentum (muons)
- Parameters determined from the simulated samples

Matrix Element Processes

Two Jets		Three Jets	
Name	Process	Name	Process
tb	$u\bar{d} \to t\bar{b}$	tbg	$u\bar{d} \to t\bar{b}g$
tq	$ub \to td$	tqb	$ug \to td\bar{b}$
	$\bar{d}b \to t\bar{u}$		$\bar{d}g \to t\bar{u}\bar{b}$
		tqg	$ub \to tdg$
			$\bar{d}b \to t\bar{u}g$
Wbb	$u\bar{d} \to Wb\bar{b}$	$Wbbg$	$u\bar{d} \to Wb\bar{b}g$
Wcg	$sg \to Wcg$	$Wugg$	$\bar{u}g \to W\bar{u}gg$
Wgg	$u\bar{d} \to Wgg$		
WW	$u\bar{u} \to WW$		
WZ	$u\bar{d} \to WZ$		
ggg	$gg \to ggg$		
$t\bar{t}$	$u\bar{u} \to t\bar{t}$	$t\bar{t}$	$u\bar{u} \to t\bar{t}$

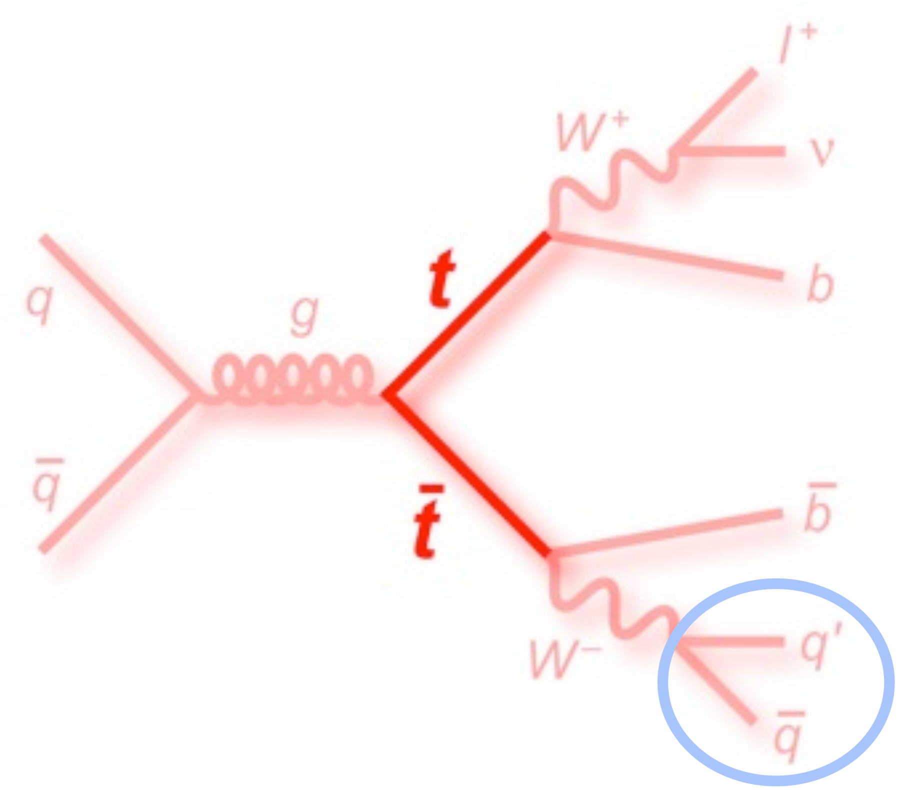
- the more background diagrams, the better discrimination

Dimensionality of Phase Space

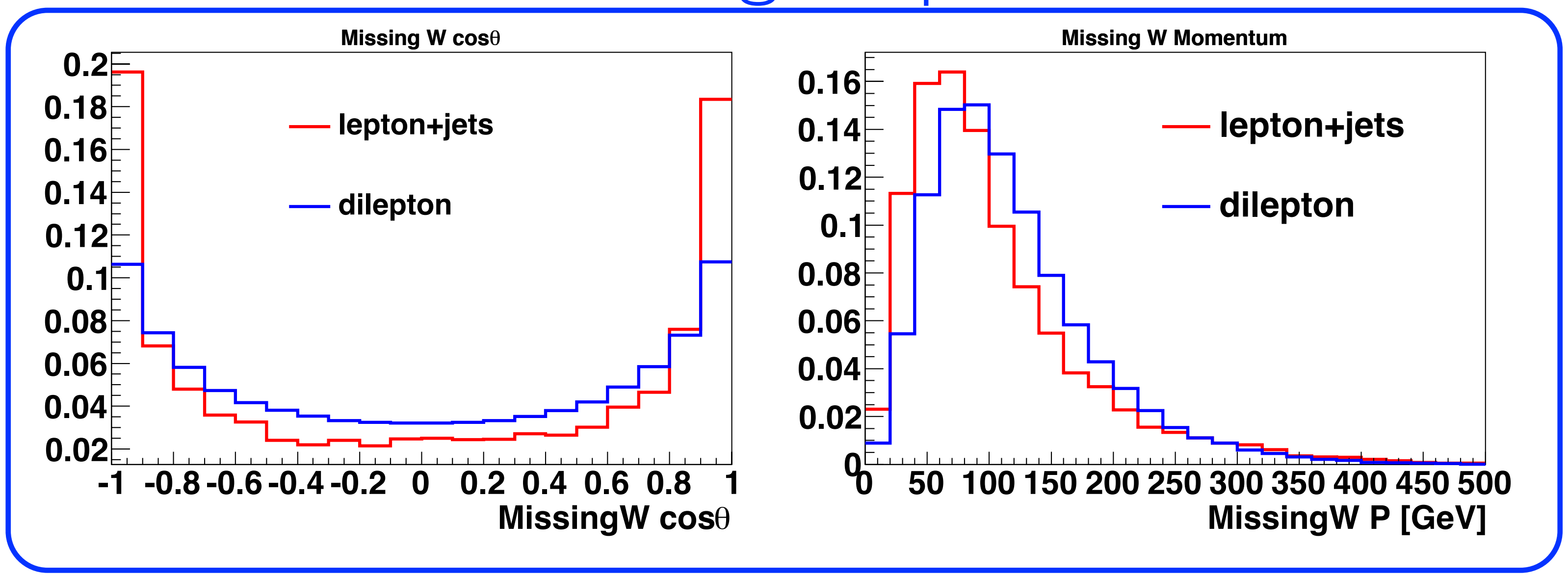
	D.O.F.	n=4 (2jets)	n=5 (3jets)
2 initial and n final state objects	$(2+n)\times 4$	24	28
Energy and momentum conservation	-4	-4	-4
All masses are known	$-(2+n)$	-6	-7
The initial partons are in z-axis	-2×2	-4	-4
The directions of the final objects are well measured, except neutrinos	$-2\times(n-1)$	-6	-8
Remaining dimensions	n	4	5
Final integration for signals		s_W, s_t, p_q, p^{tot}_z	s_W, s_t, p_q, $p_{q'}$, p^{tot}_z

Top Pair Modeling

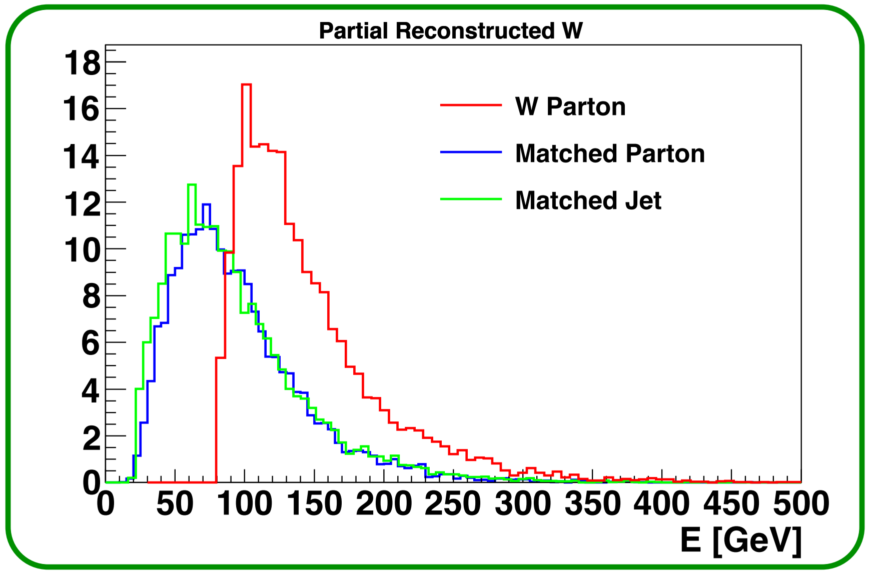
- Top pair→lνbqq'b (4 jets)
- Top pair yields in 2jet & 3jet channels are comparable to single top
- Light-jets are 1.6 times more likely to be lost than *b*-jets
- Use simulation to obtain a prior of missing jet (3jet) or missing *W* (2jet)



Missing W prior

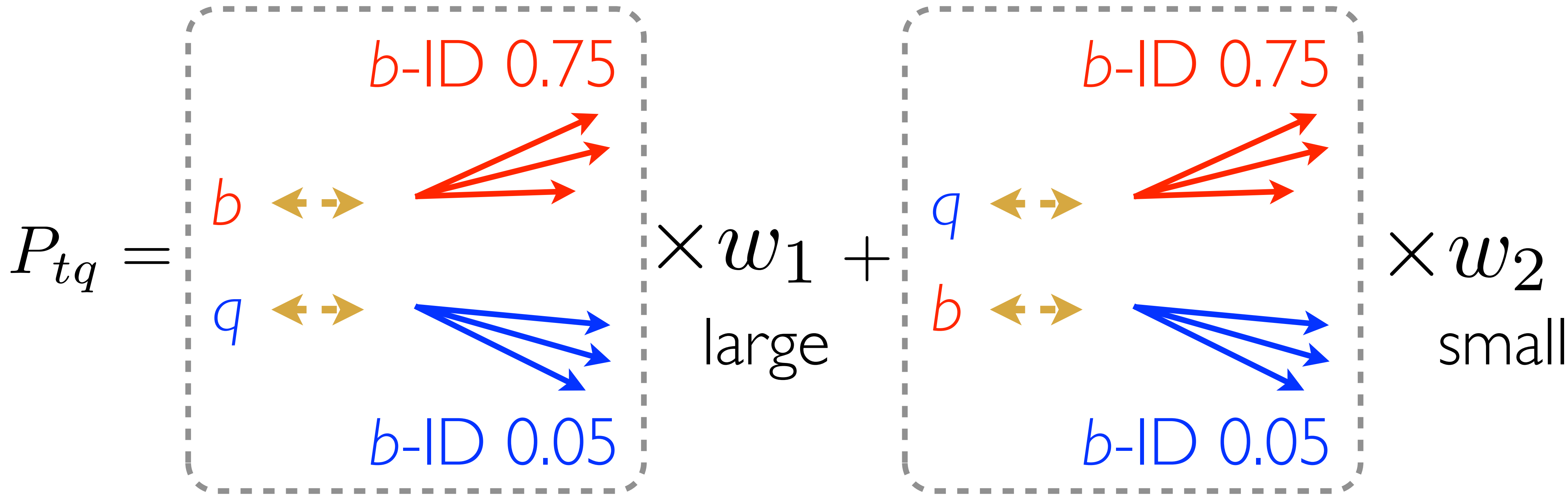


Missing Jet



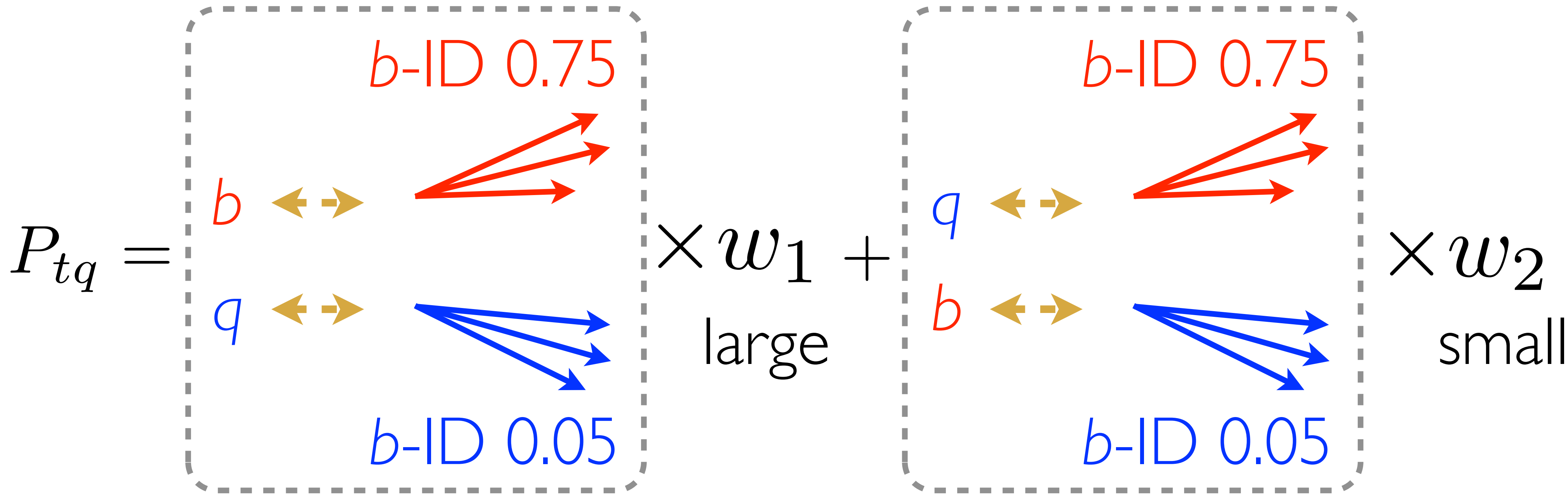
Discriminant

- *b*-ID output information included



Discriminant

- *b*-ID output information included

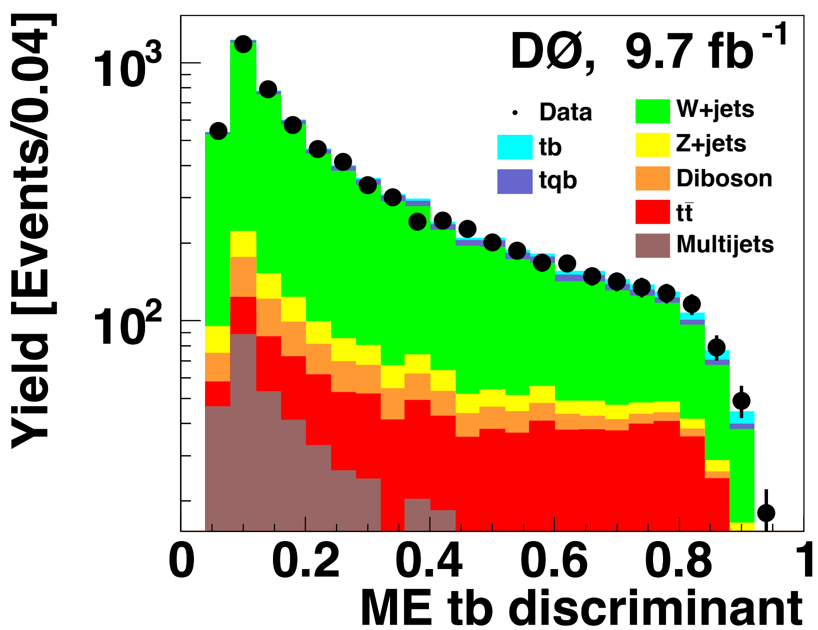


- Discriminant: Likelihood ratio

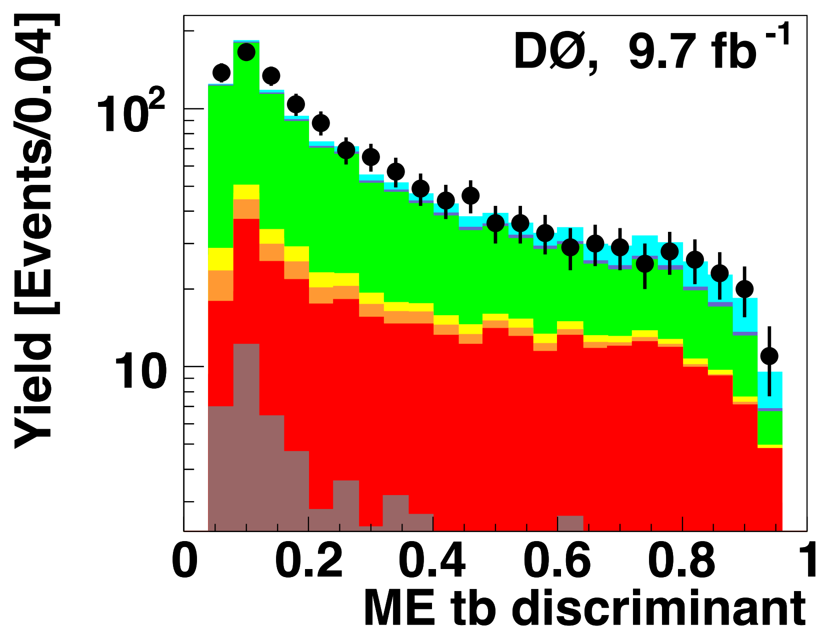
$$D(x) = \frac{P_{sig}(x)}{P_{sig}(x) + P_{bkgd}(x)}$$

ME Discriminant

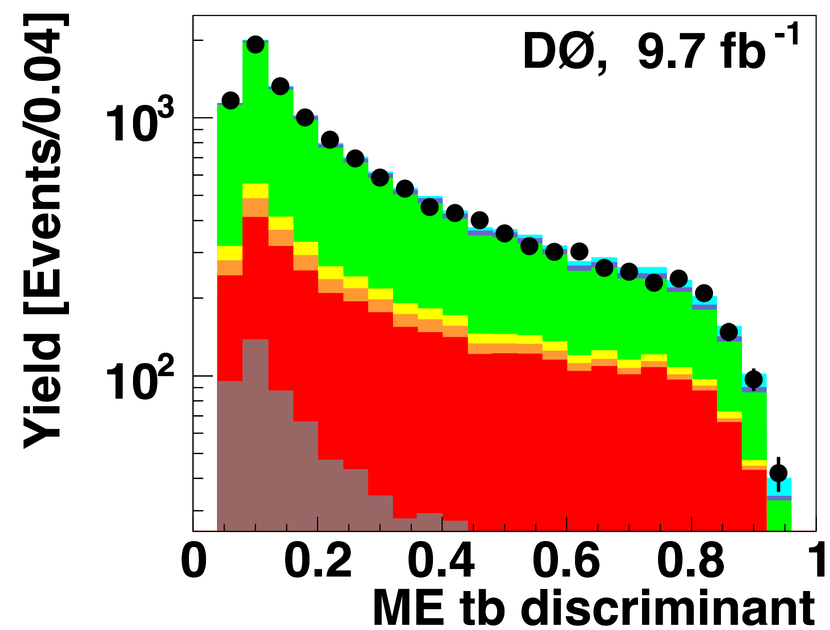
1 *b*-tag, 2 jets



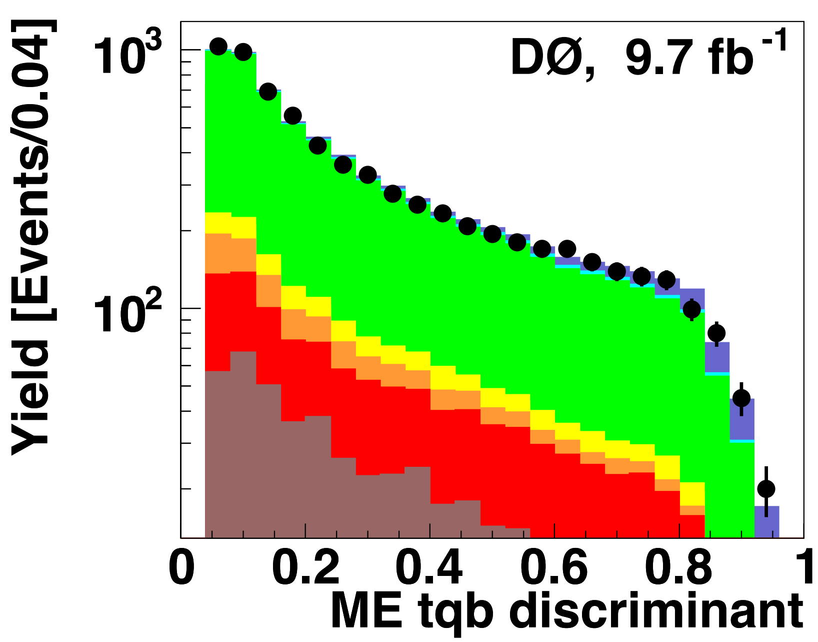
2 *b*-tags, 2 jets



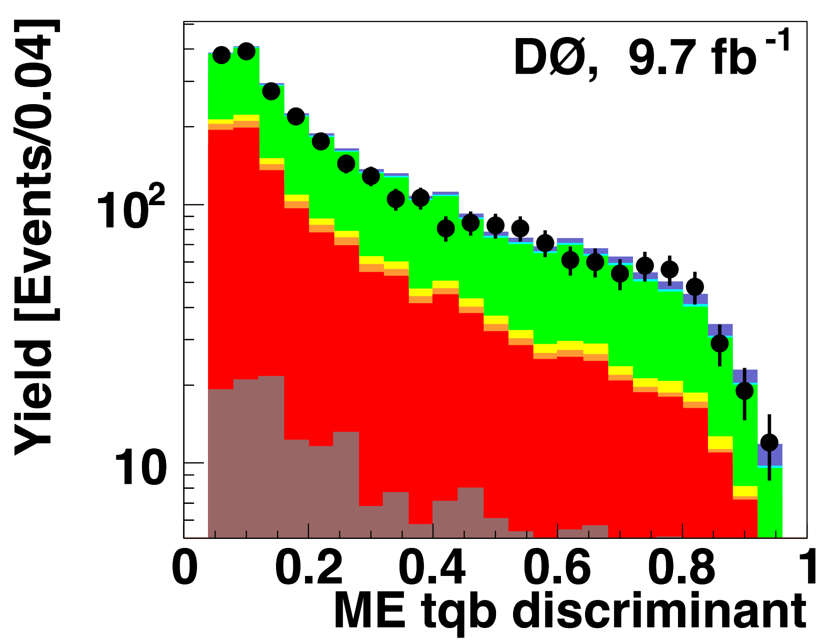
1-2 *b*-tags, 2-3 jets



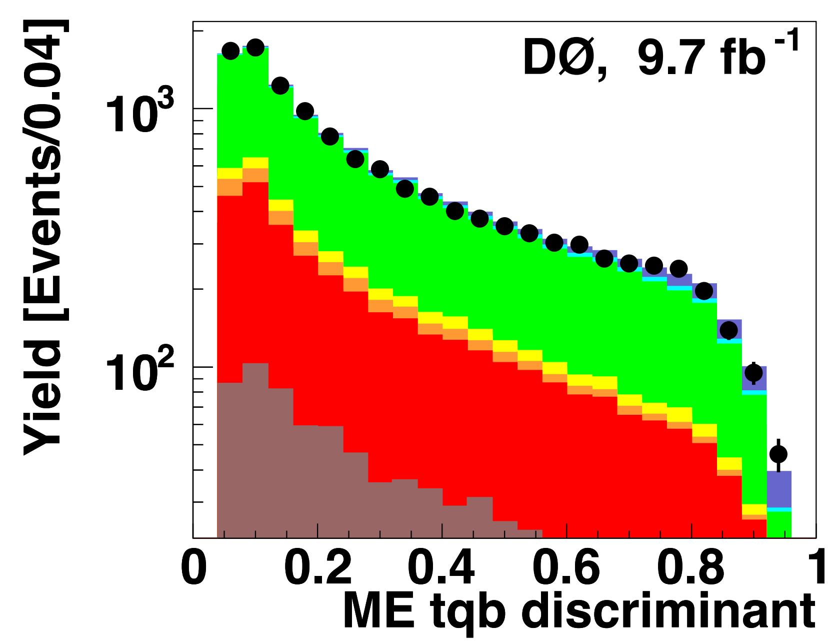
1 *b*-tag, 2 jets



1 *b*-tags, 3 jets

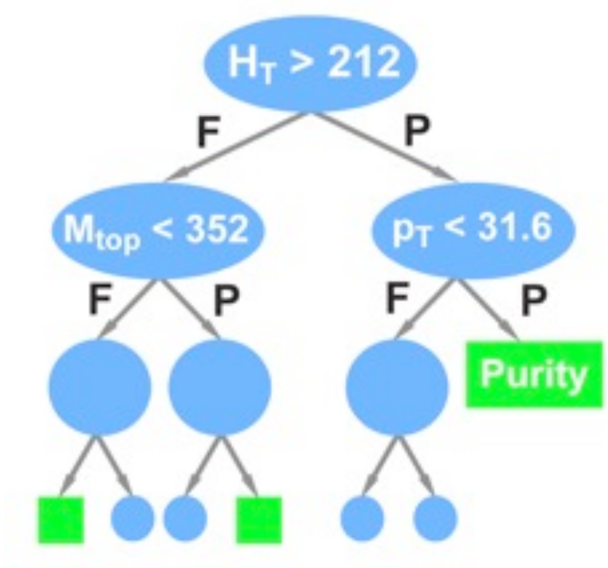


1-2 *b*-tags, 2-3 jets

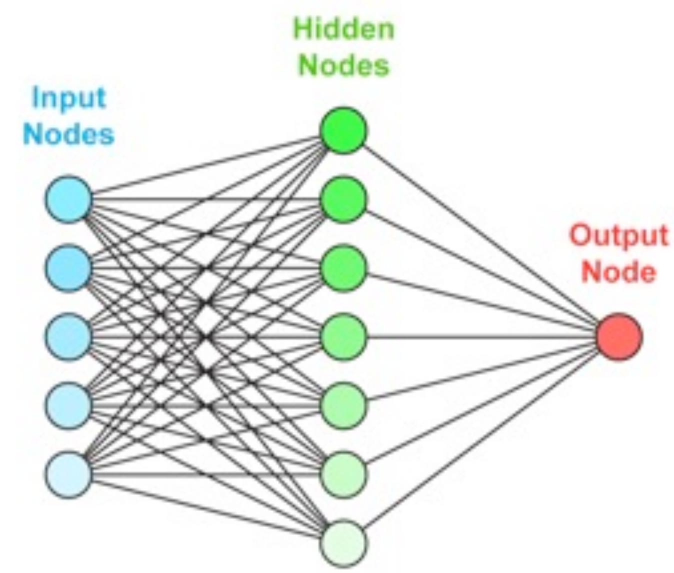


BNN Combination

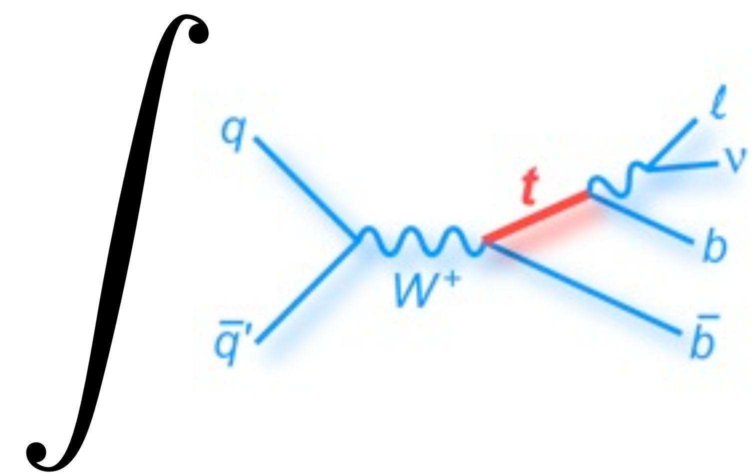
BDT



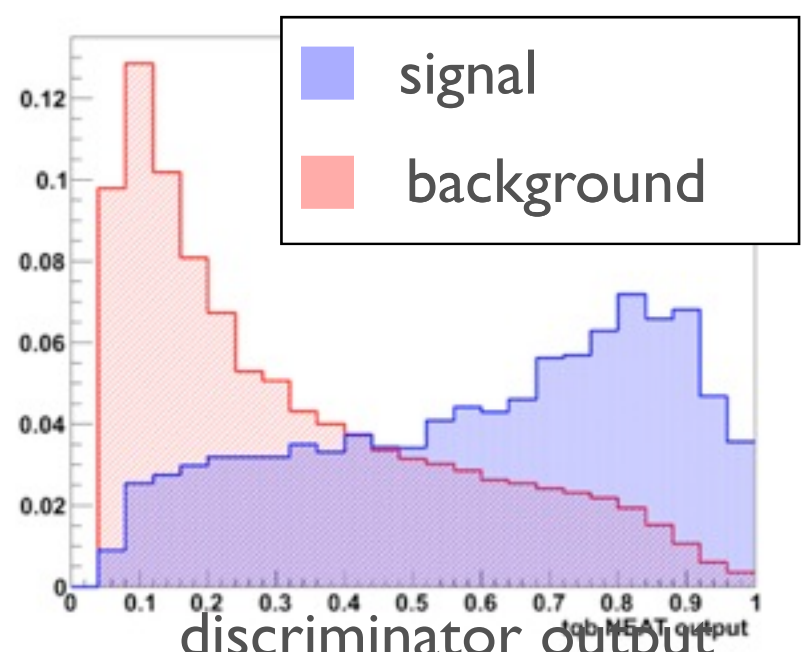
BNN



ME



Use BNN to combine the 3 methods



Correlations

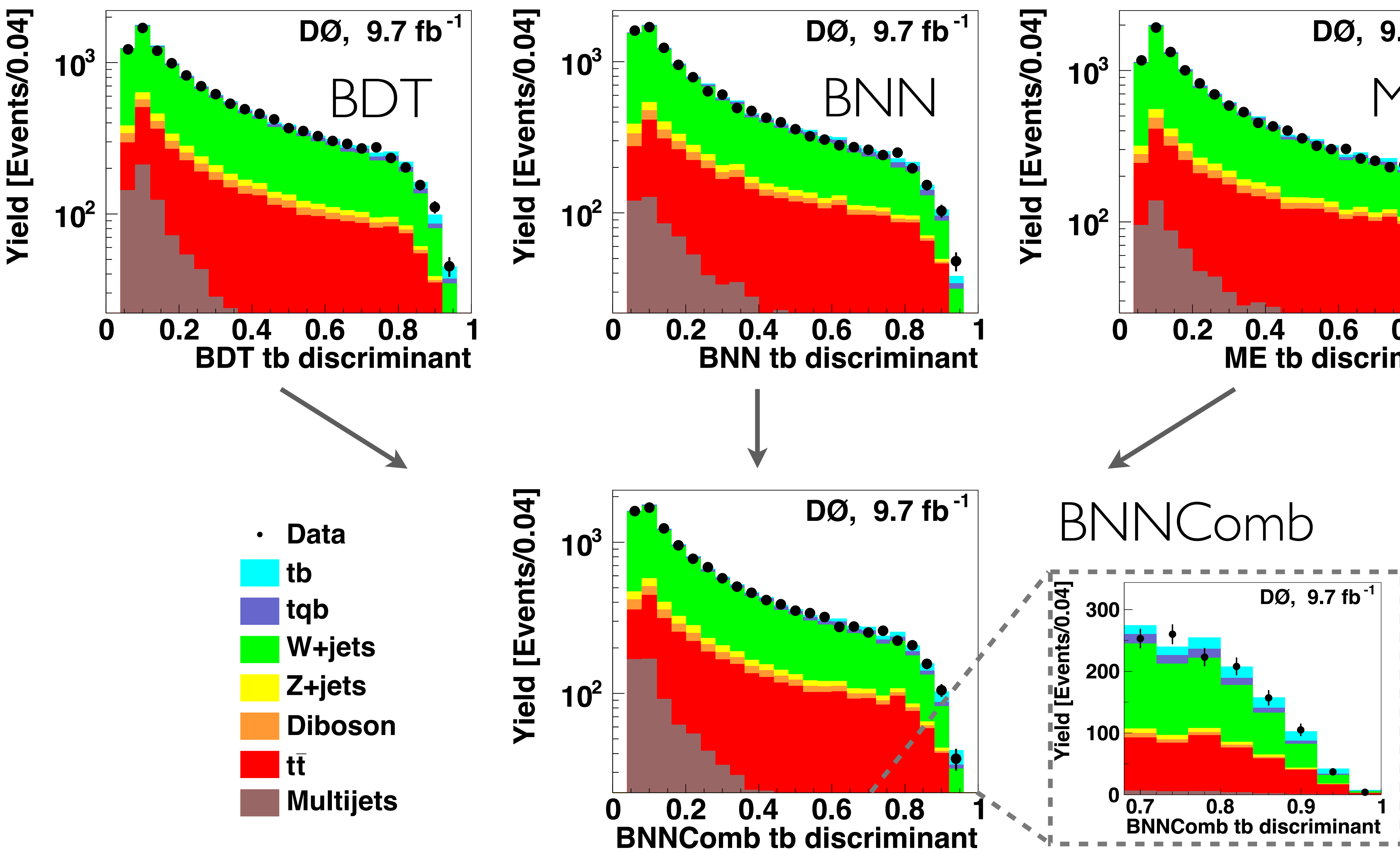
BDT

77% BDT ↔ BNN

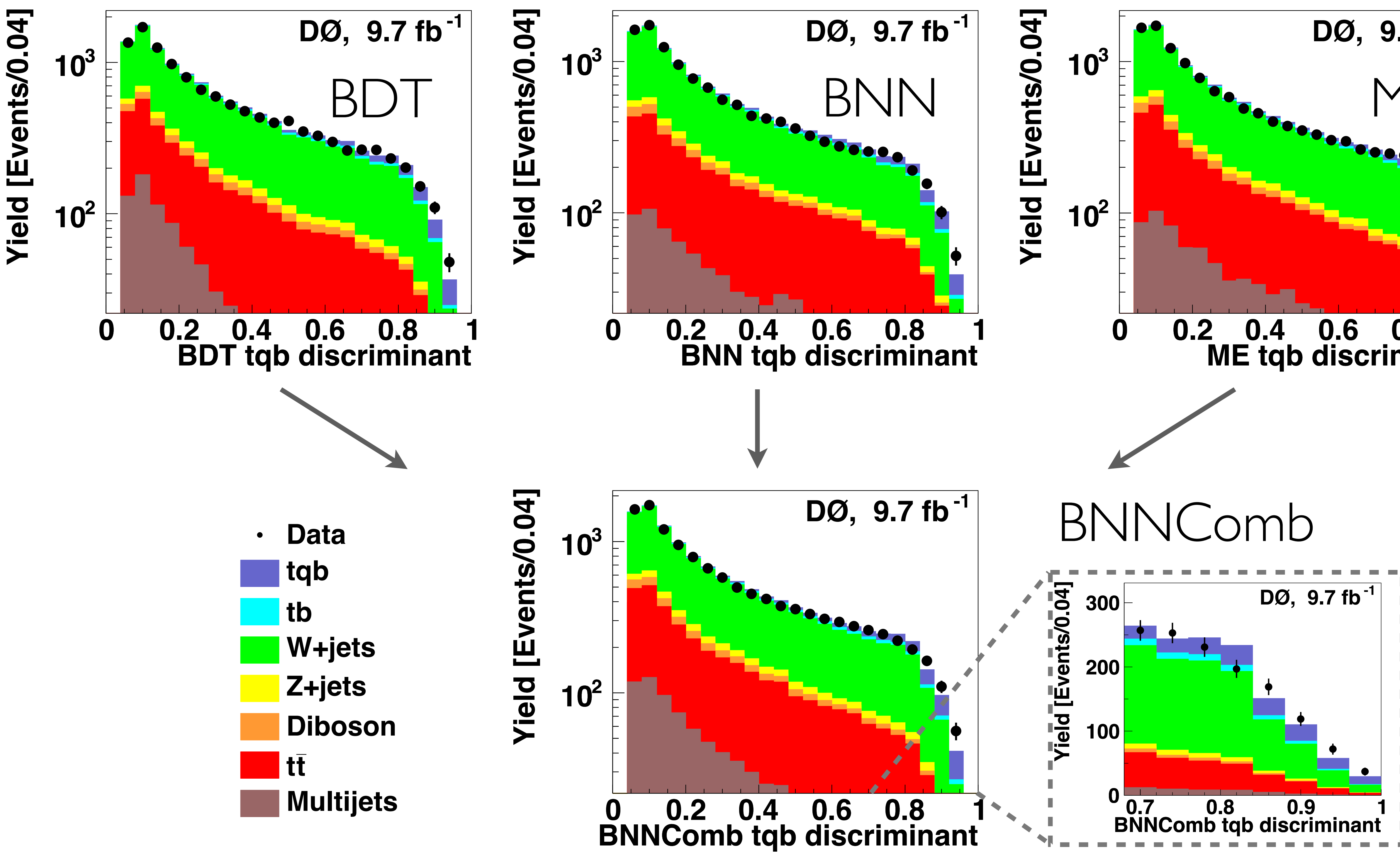
75% BDT ↔ ME

BNN ↔ ME 73%

BNN *tb* Combination

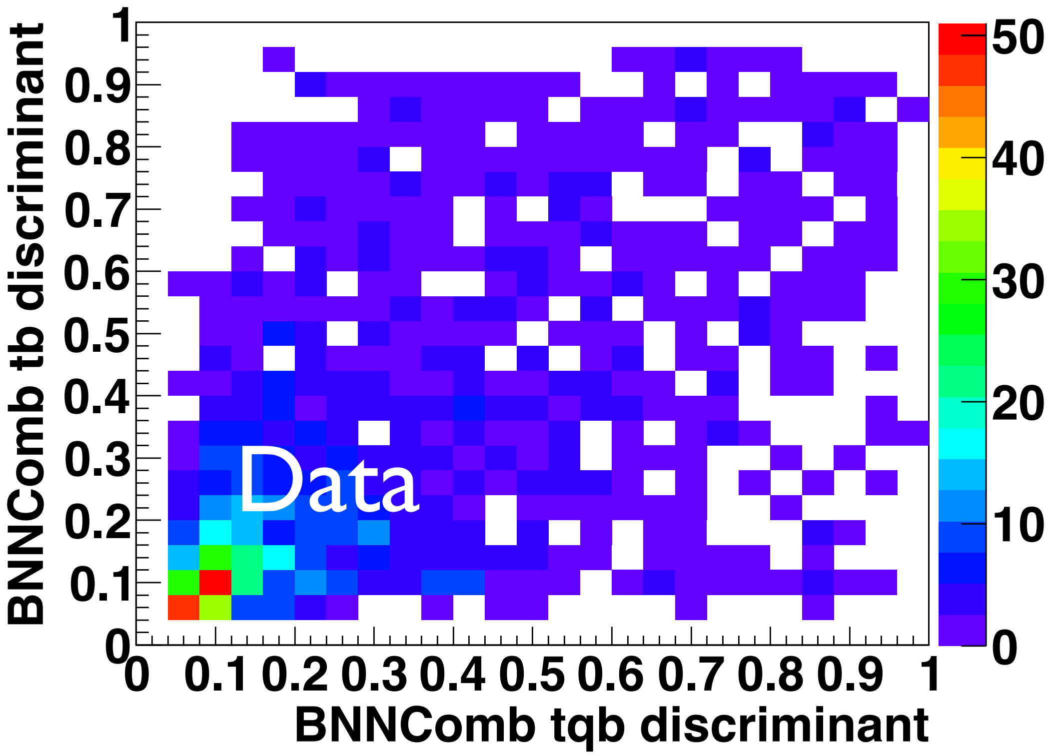


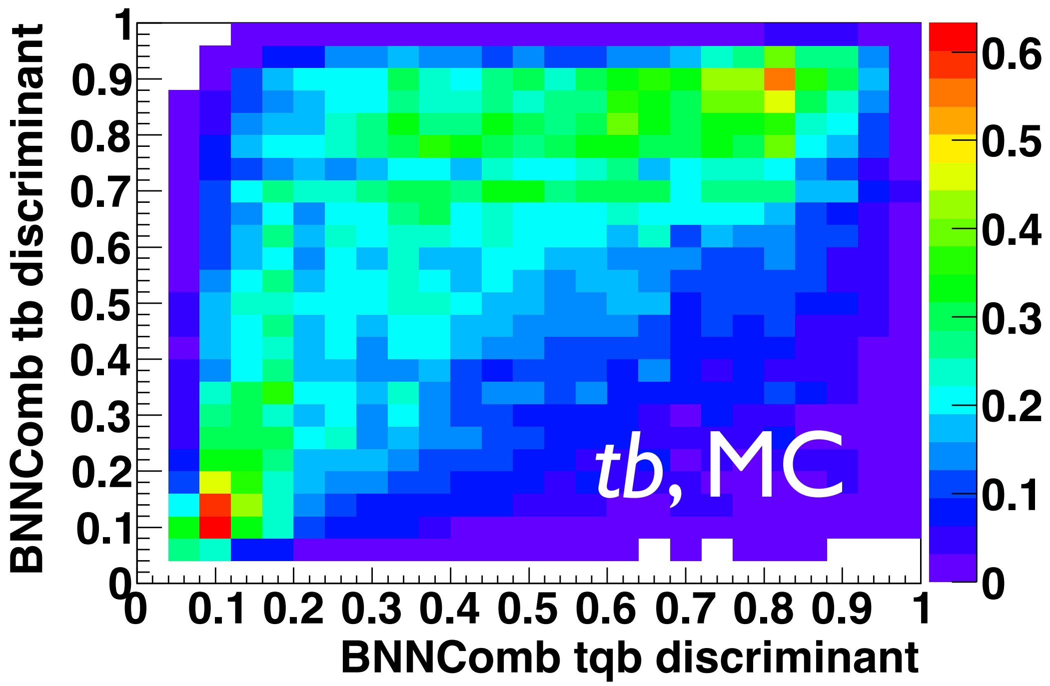
BNN *tqb* Combination



New Discriminant

- Aim to simultaneously measure *tb* and *tqb* signals without assuming the SM prediction for either
- At a first step, use a discriminant sensitive to both signals
- Ensure each bin containing enough statistics to have a stable measurement

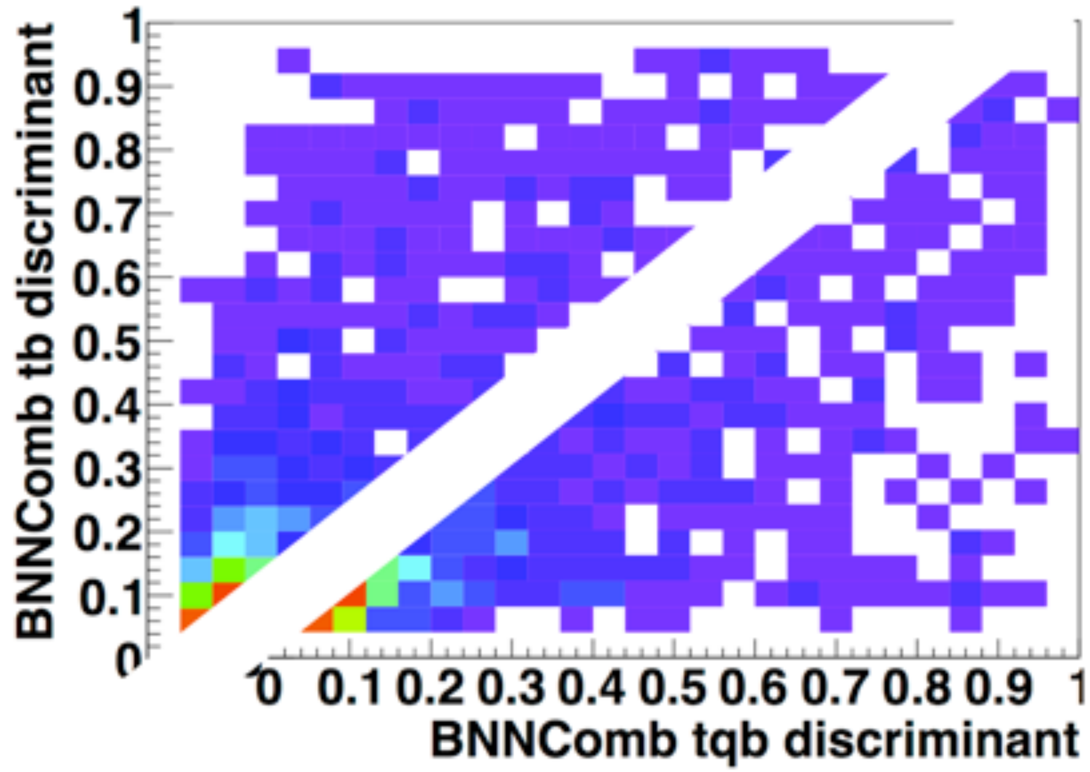




New Discriminant

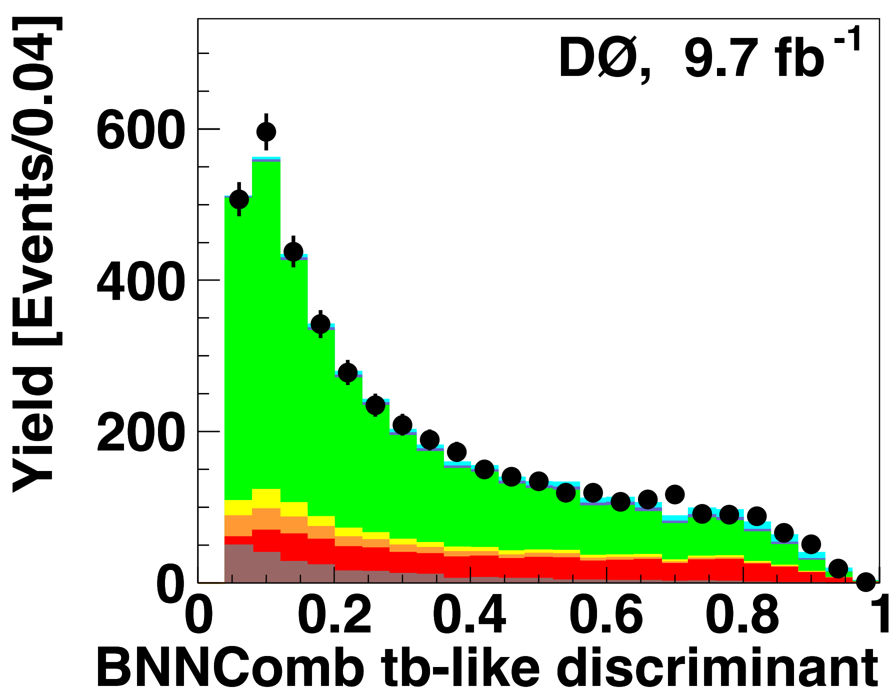
If $D_{tb} > D_{tqb}$:

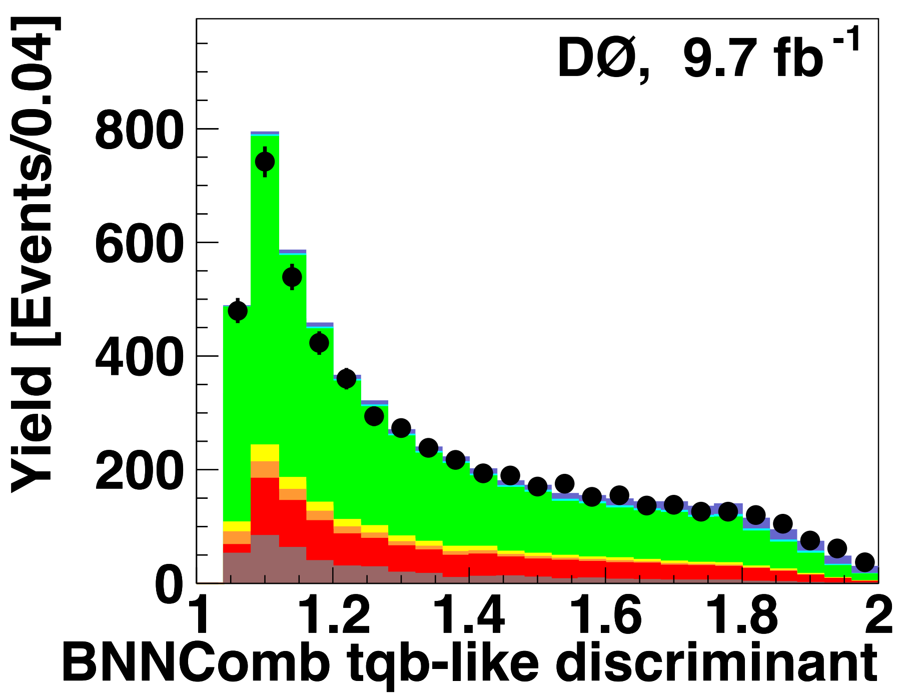
- *tb* category
- Use D_{tb}
- Plot in the range [0, 1]



If $D_{tqb} > D_{tb}$:

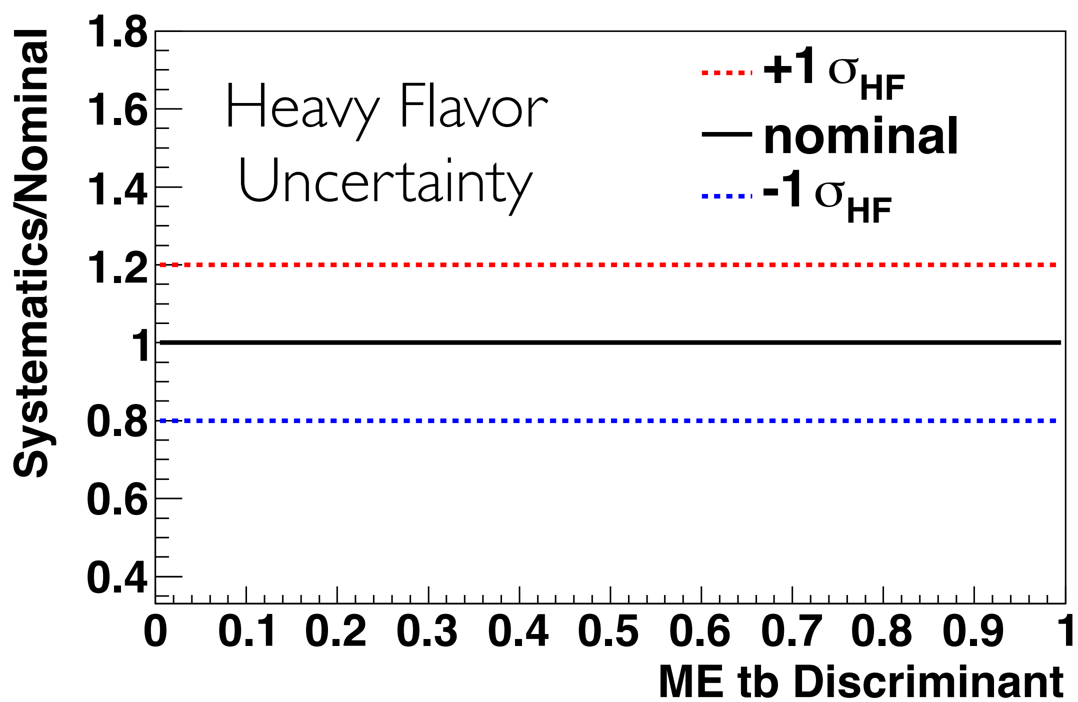
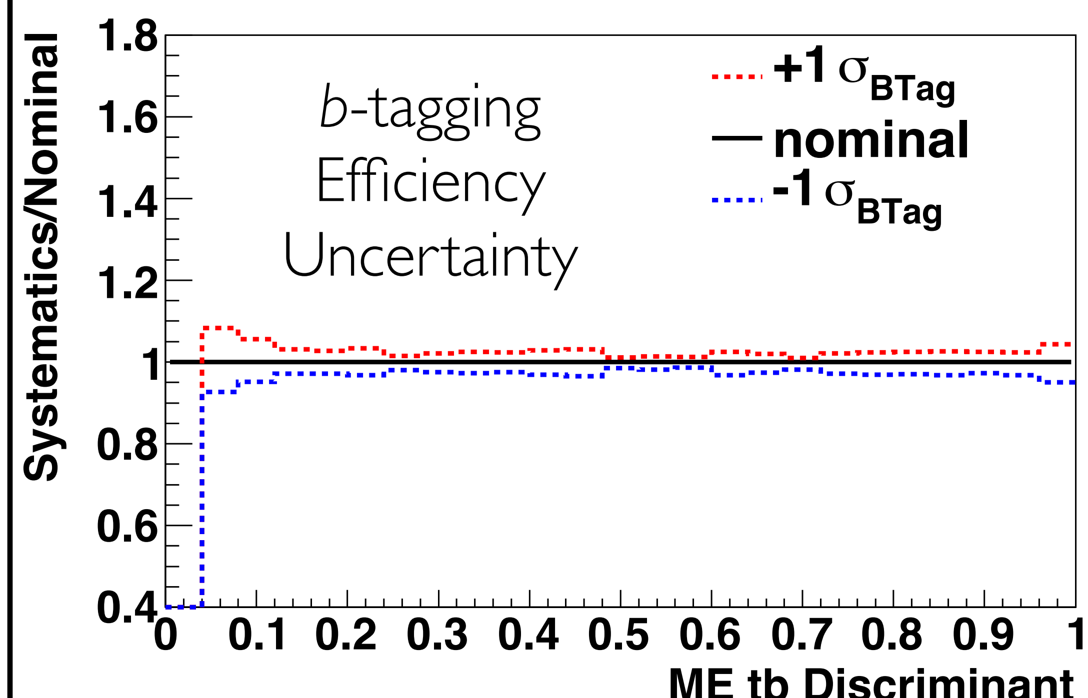
- *tqb* category
- Use D_{tqb}
- Plot in the range [1, 2]





Systematic Uncertainties

- Assign to each background and each analysis channel
- Some affect only the overall scale, and others affect also the discriminant outputs bin-by-bin (shape-changing)

Overall Scale	Overall Scale & Shape
	

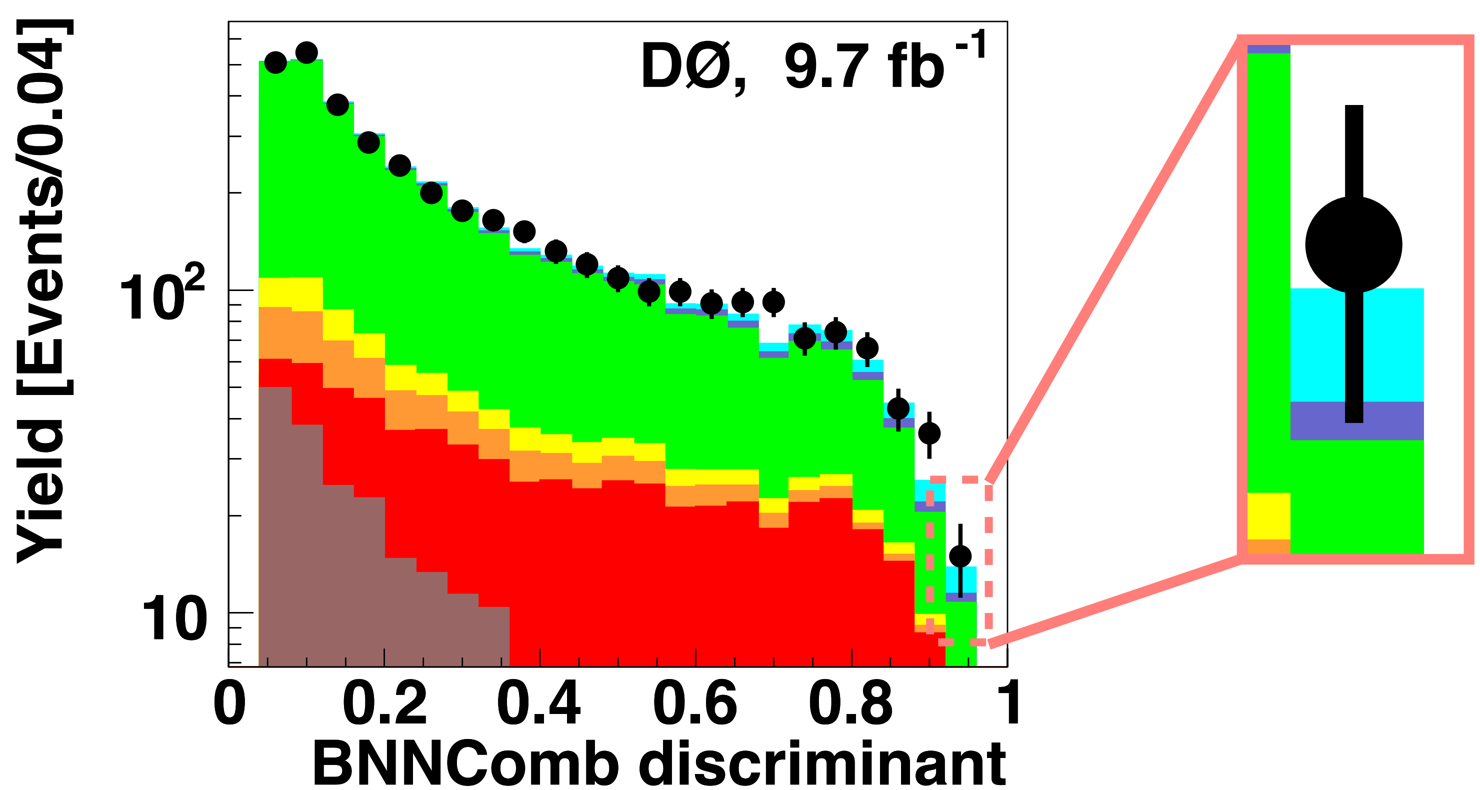
Systematic Uncertainties

- Assign to each background and each analysis channel
- Some affect only the overall scale, and others affect also the discriminant outputs bin-by-bin (shape-changing)
- Main uncertainties are listed here

Overall Scale		Overall Scale & Shape	
Integrated luminosity	6.1%	Jet reconstruction	up to 1.4%
Top pair cross section	9%	Jet energy resolution	up to 1.1%
Diboson cross section	7%	Jet energy scale	up to 1.2%
Trigger efficiencies	(3-5)%	Flavor-dependent JES	up to 1.3%
Jet fragmentation+higher order	(0.7-7.0)%	Jet vertex confirmation	up to 11%
Initial- and final-state radiation	(0.8-10.9)%	*b*-ID, 1 *b*-tagged channel	up to 6.6%
Heavy-flavor correction	20%	*b*-ID, 2 *b*-tagged channel	up to 8.8%
Multijet normalization	(9.2-42.1)%		

Cross Section Extraction

- Use the BNN combination discriminant in 25 bins
  - Use all bins (we don't cut on the discriminant)
- For each bin, the likelihood *L* to observe ***D* data events** with a known mean *h* is modeled by the Poisson distribution



To be measured: signal cross section

D

$$h = a_1 \sigma_1 + a_2 \sigma_2 + b$$

signal acceptance
tb: 2.6%
tqb: 1.8%

backgrounds (known)

Bayesian Approach

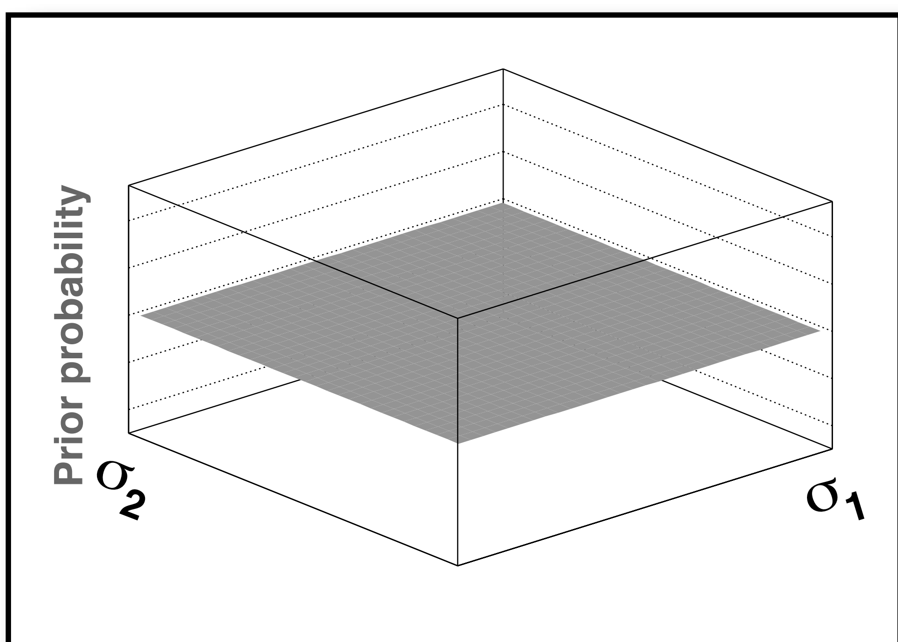
Poisson likelihood

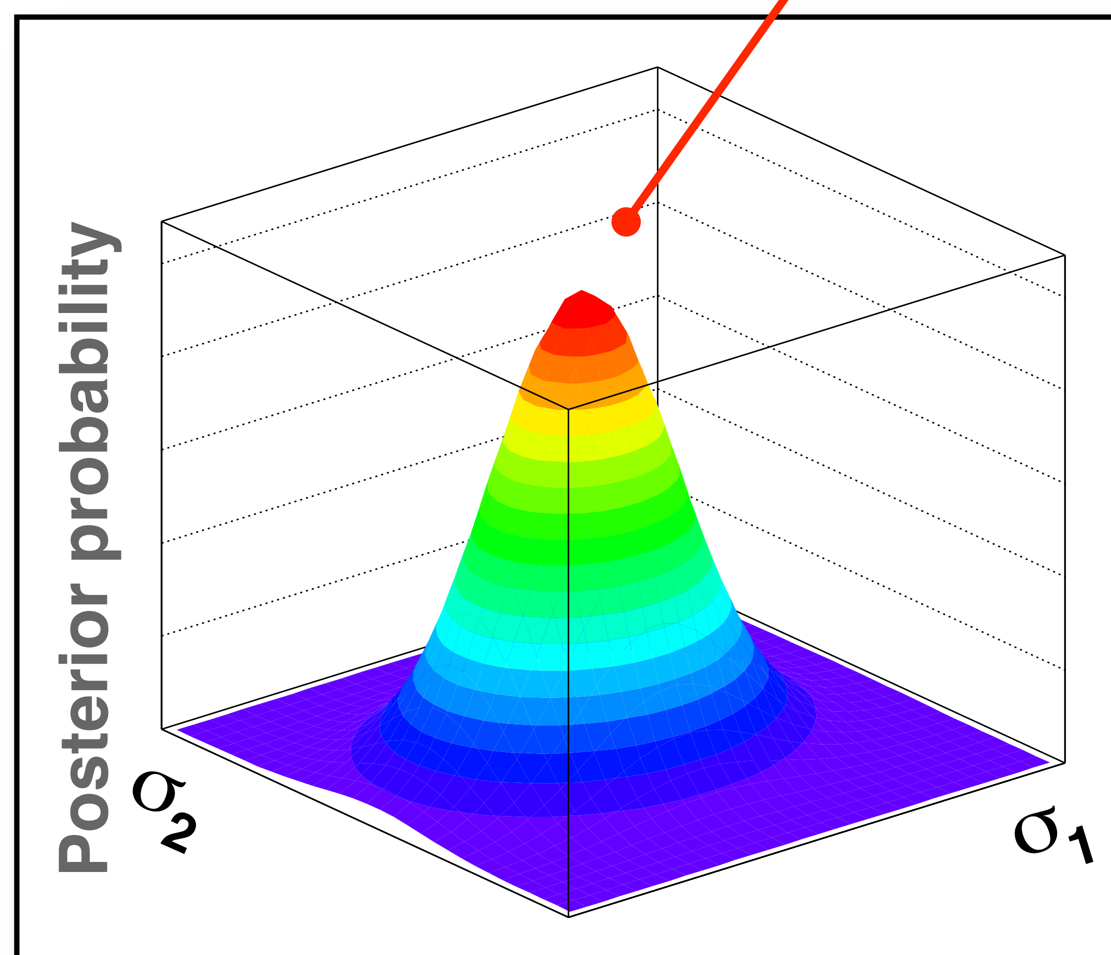
Our state of knowledge, *a*, *b* with systematic uncertainties

All systematics and their correlations taken into account

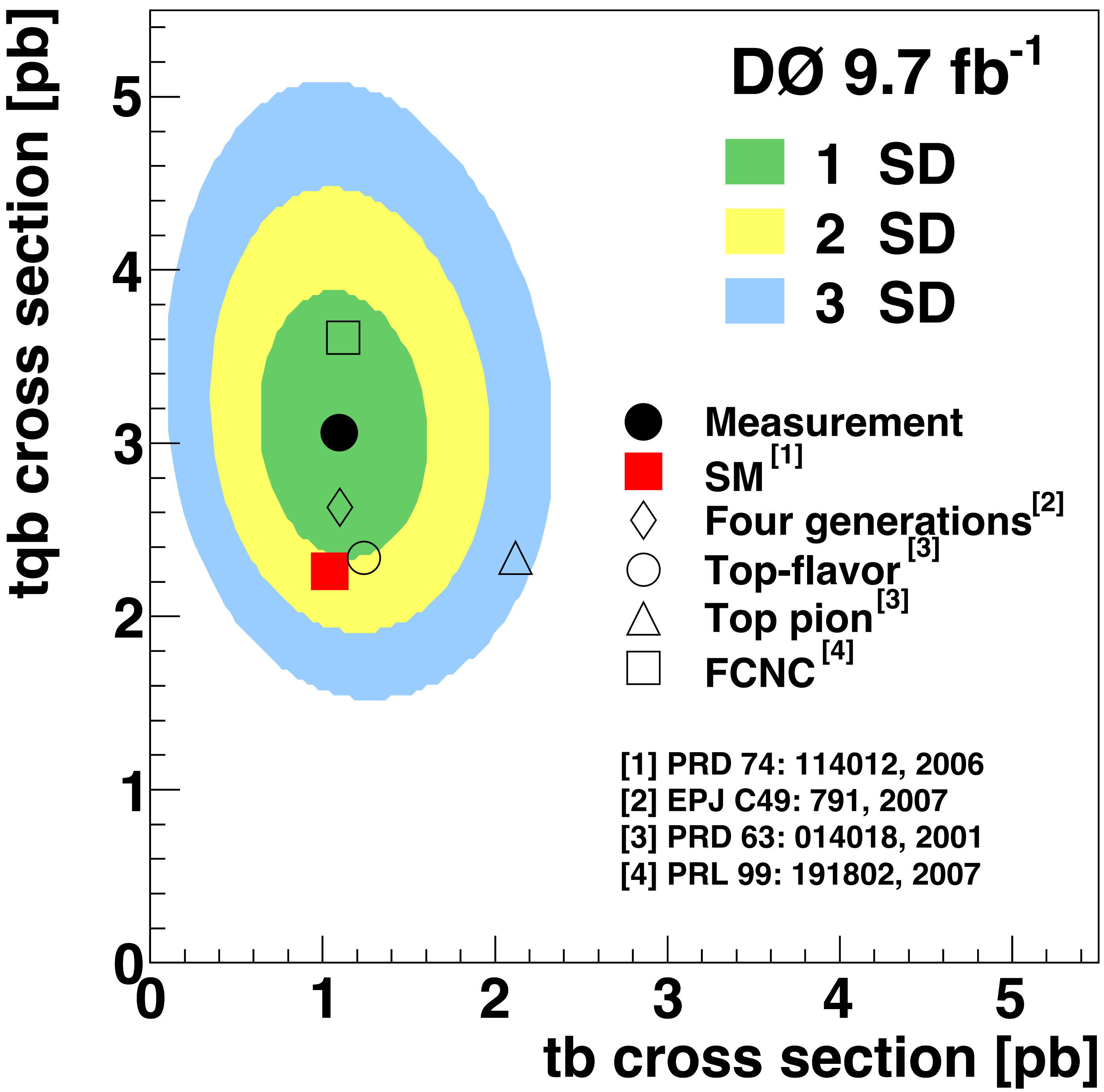
$$\int L(\mathbf{D}|\sigma_1, \sigma_2, \mathbf{a}_1, \mathbf{a}_2, \mathbf{b})\pi(\sigma_1, \sigma_2)\pi(\mathbf{a}_1, \mathbf{a}_2, b)d\mathbf{a}_1 d\mathbf{a}_2 db \propto p(\sigma_1, \sigma_2|D)$$

Uniform prior for the signal cross section

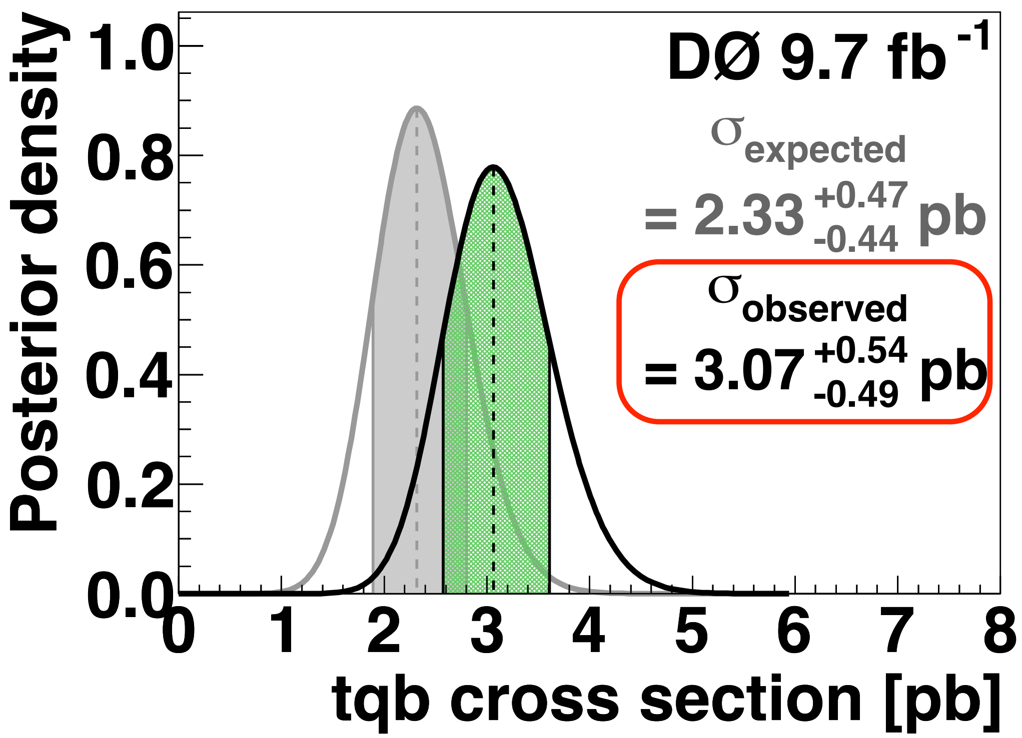




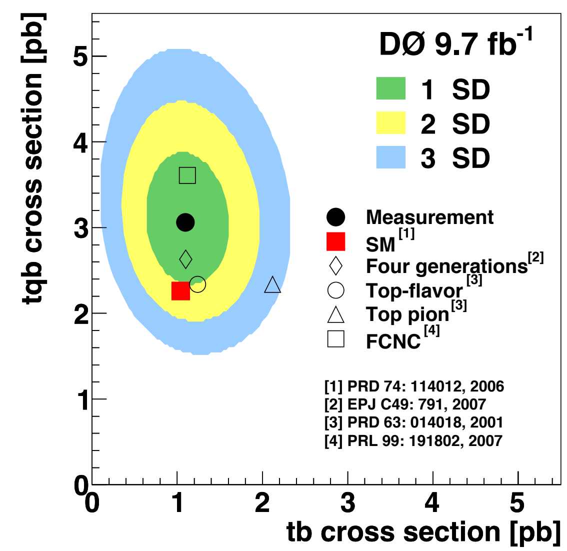
Two-dimensional Posterior



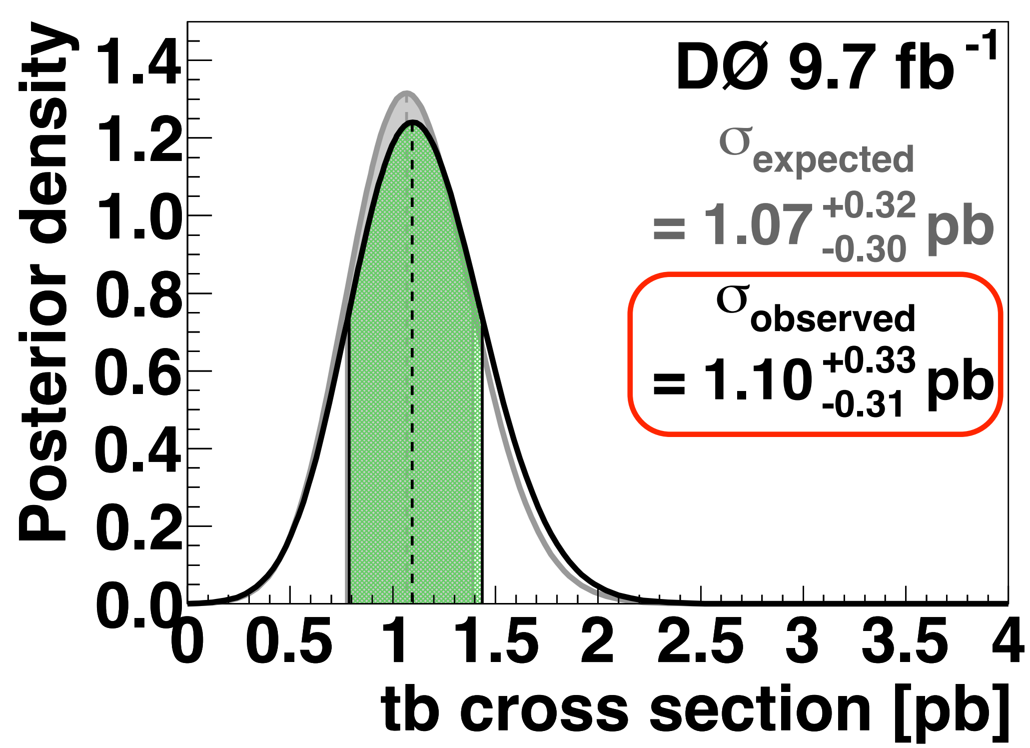
Measured Cross Section



(Integrate over σ_{tb})



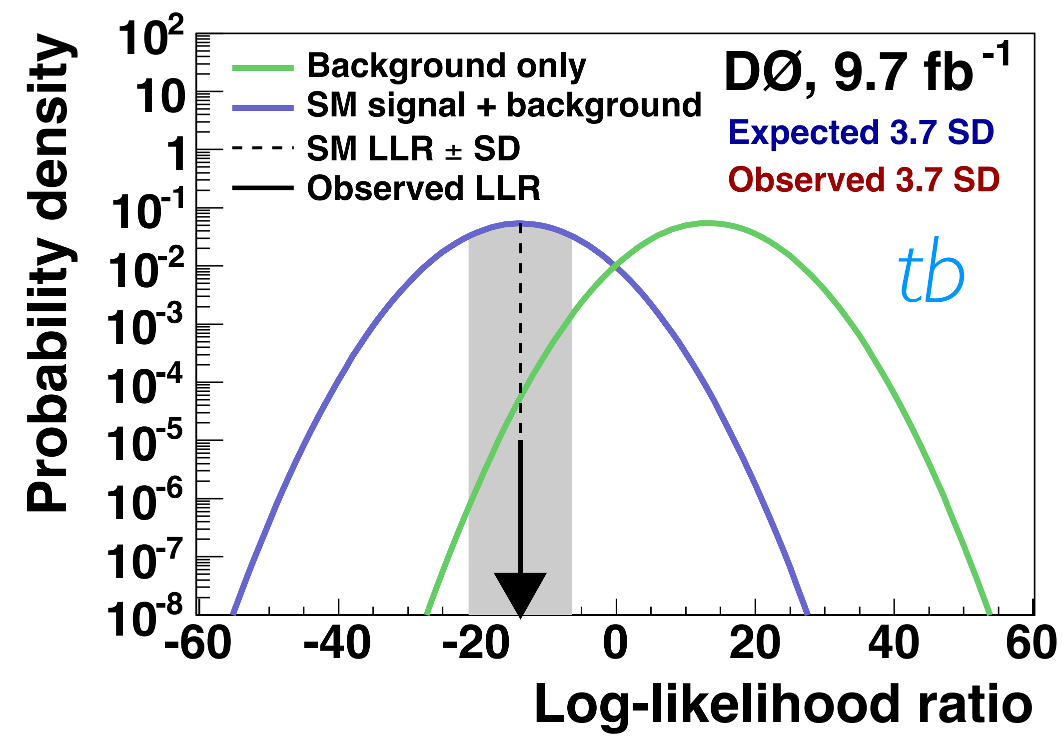
No assumption on SM σ_{tb}/σ_{tqb}!

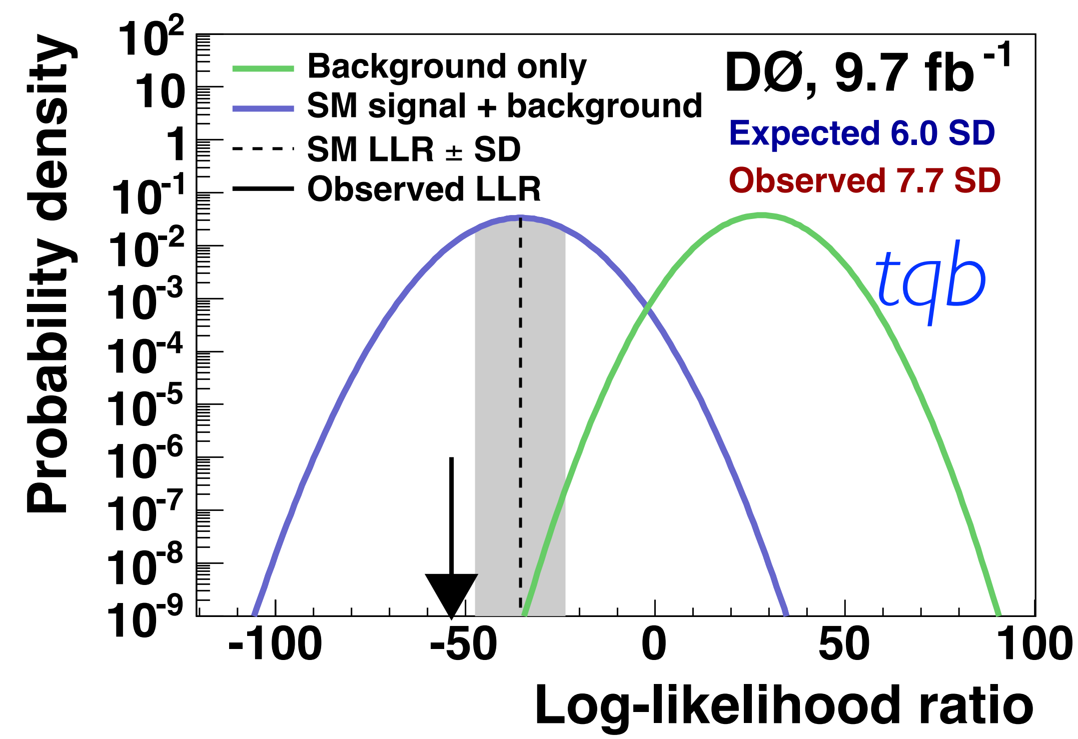


(Integrate over σ_{tqb})

Significance

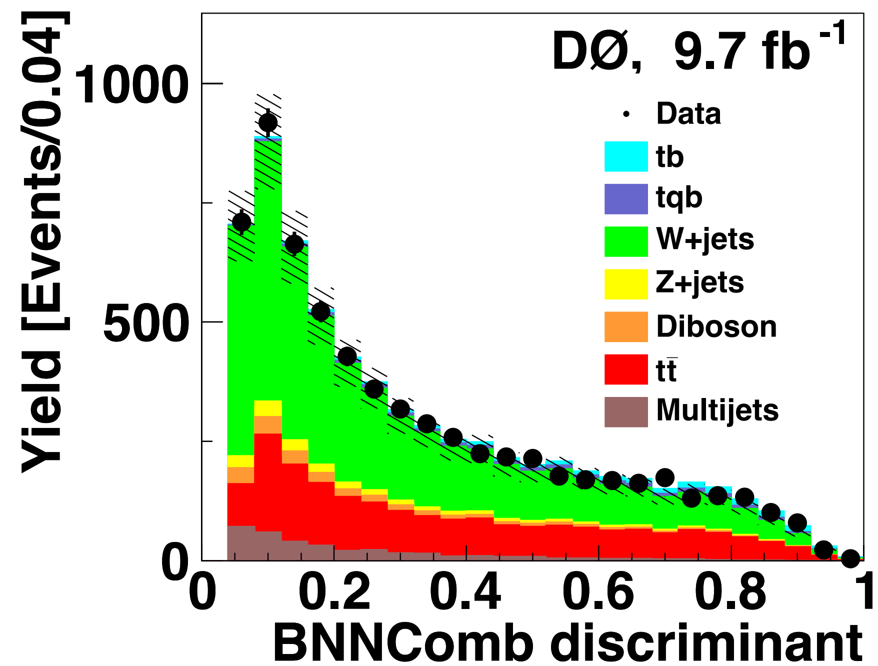
- Asymptotic approximation of the log-likelihood ratio
  - tests how likely the data is to fluctuate to the measured **σ** value, in the absence of the signals
- Expected p-values:
  - *tb*: 1.0×10^{-4} (3.7 SD)
  - *tqb*: 1.0×10^{-9} (6.0 SD)
- Observed p-values:
  - *tb*: 1.0×10^{-4} (3.7 SD)
  - *tqb*: 7.1×10^{-15} (7.7 SD)

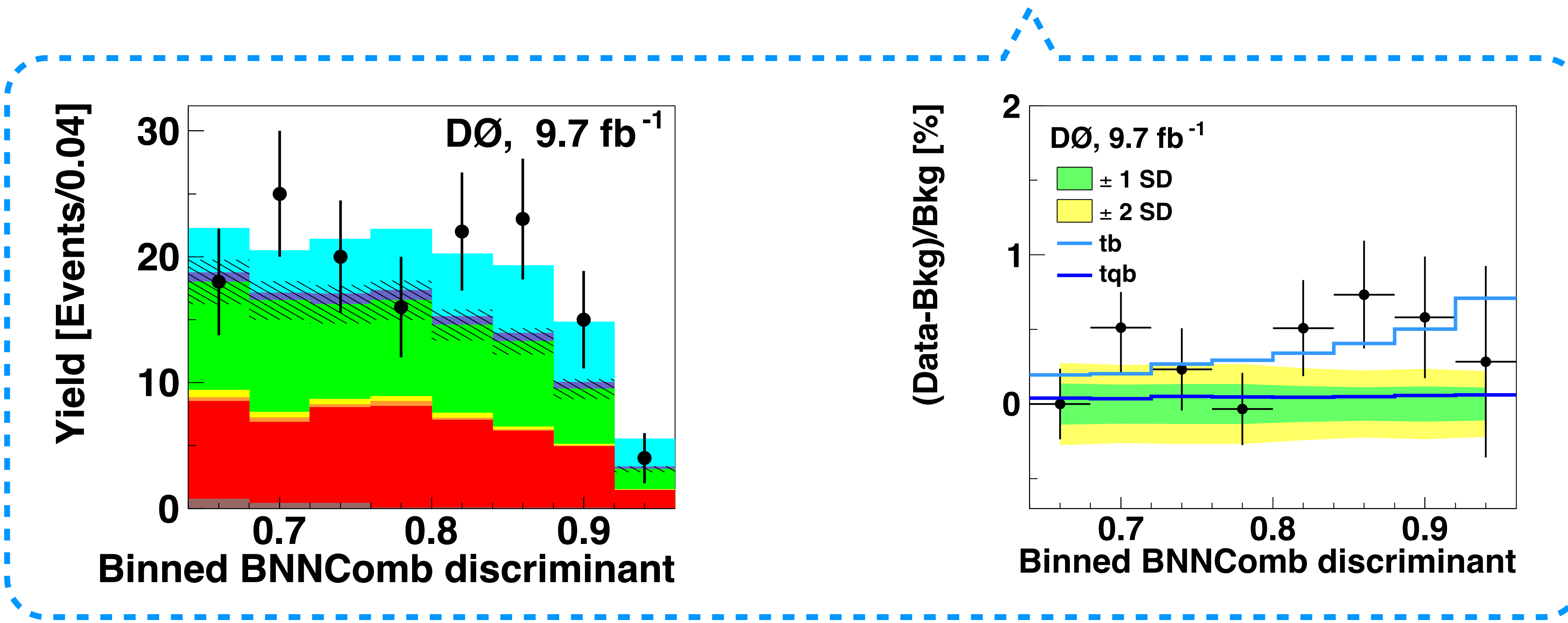




tb or Not *tb*?

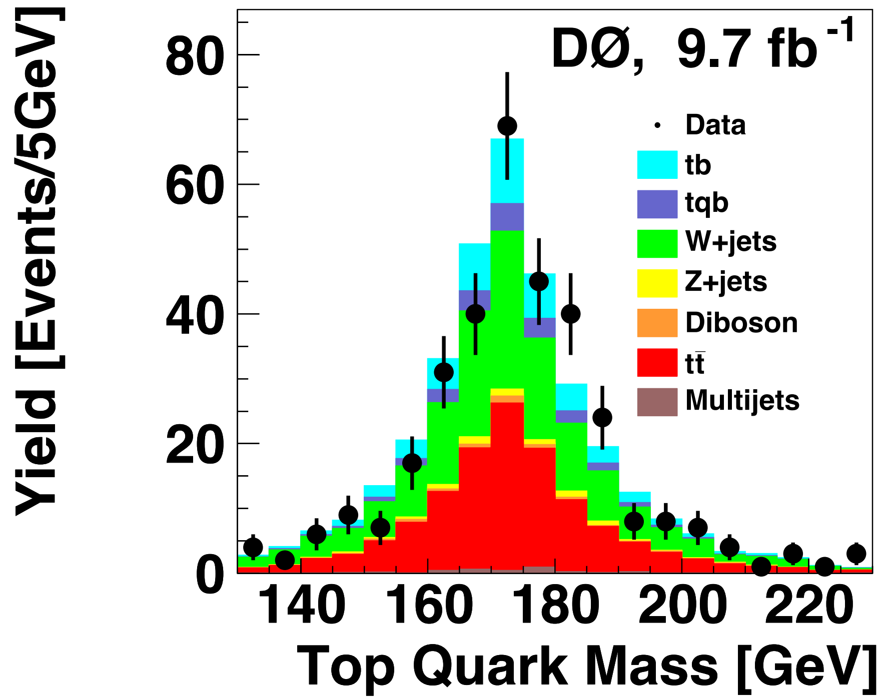
- BNNComb discriminant with the post-fit uncertainty
- Examine the most sensitive bins (largest S/B)
- Data favors the "truth and beauty"!

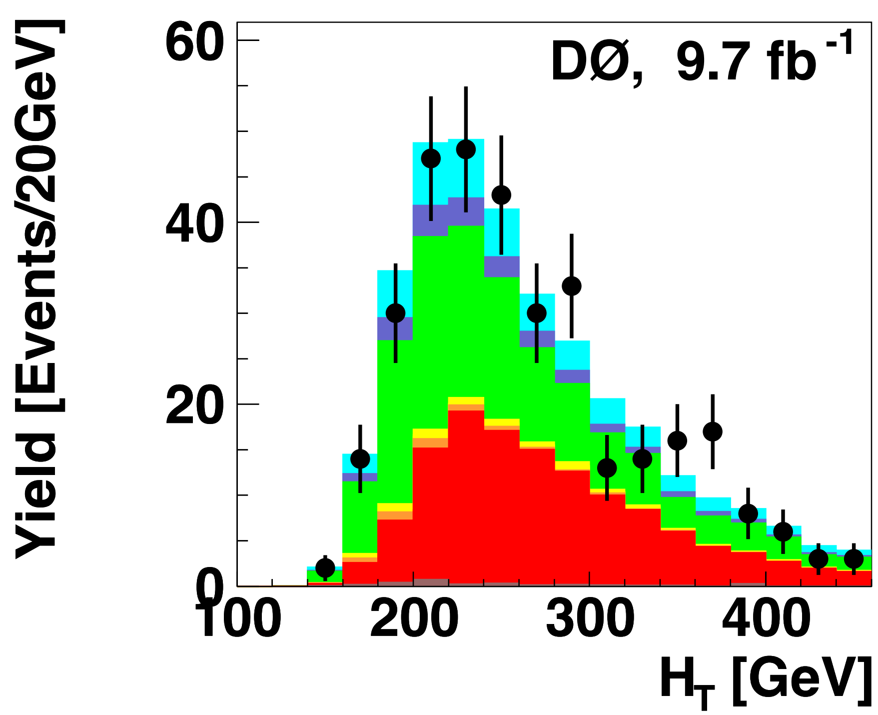




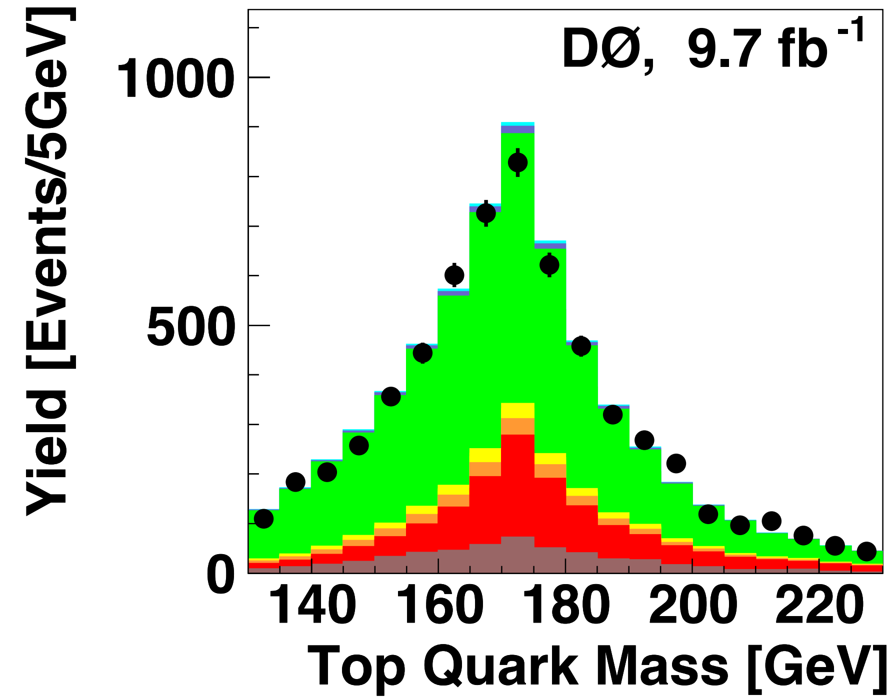
Event Characteristics

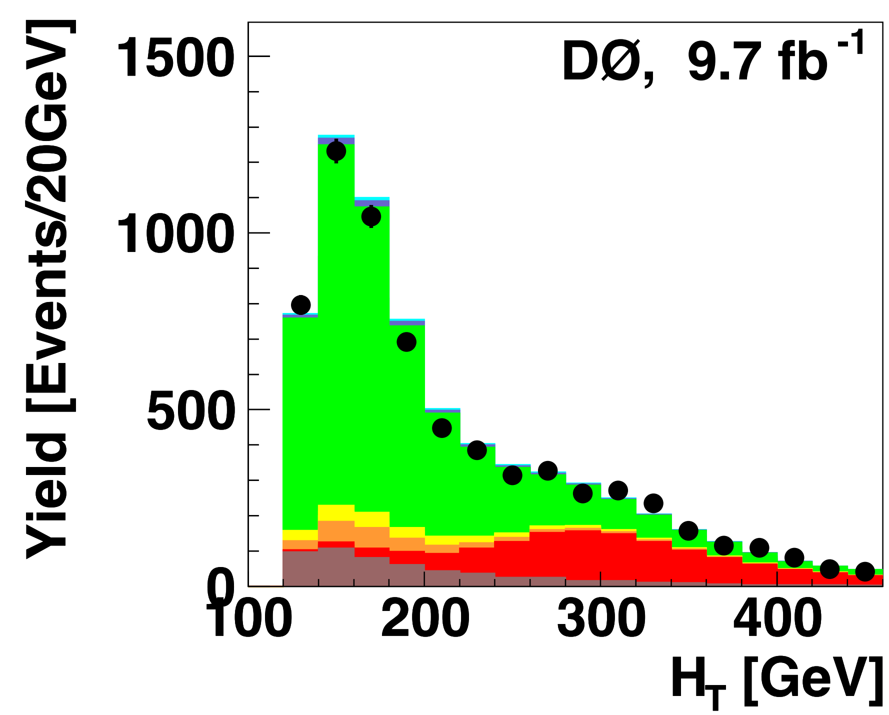
tb Category: $D_{tb} > 0.8$





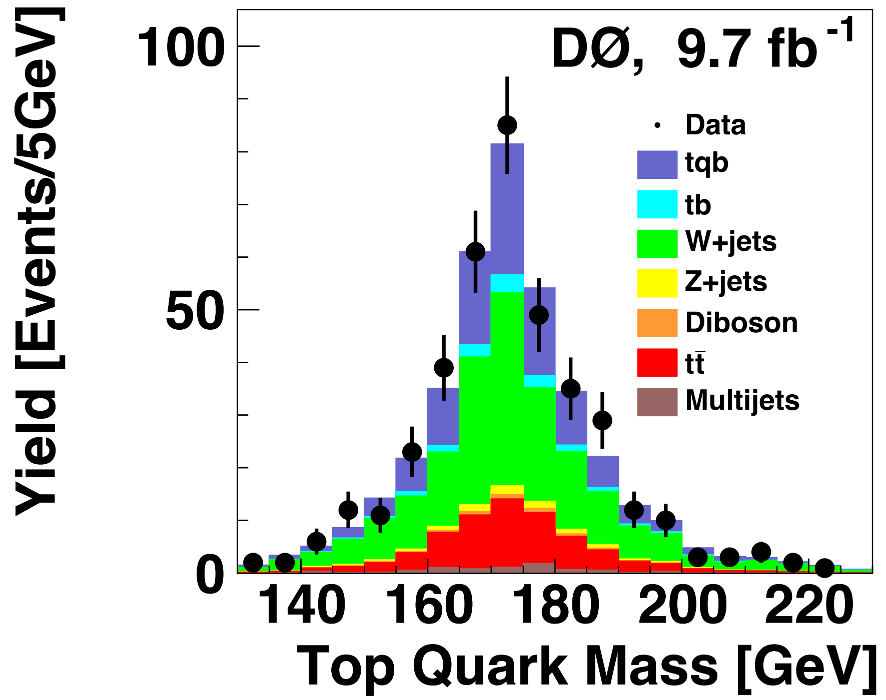
tb & *tqb* Depleted Region

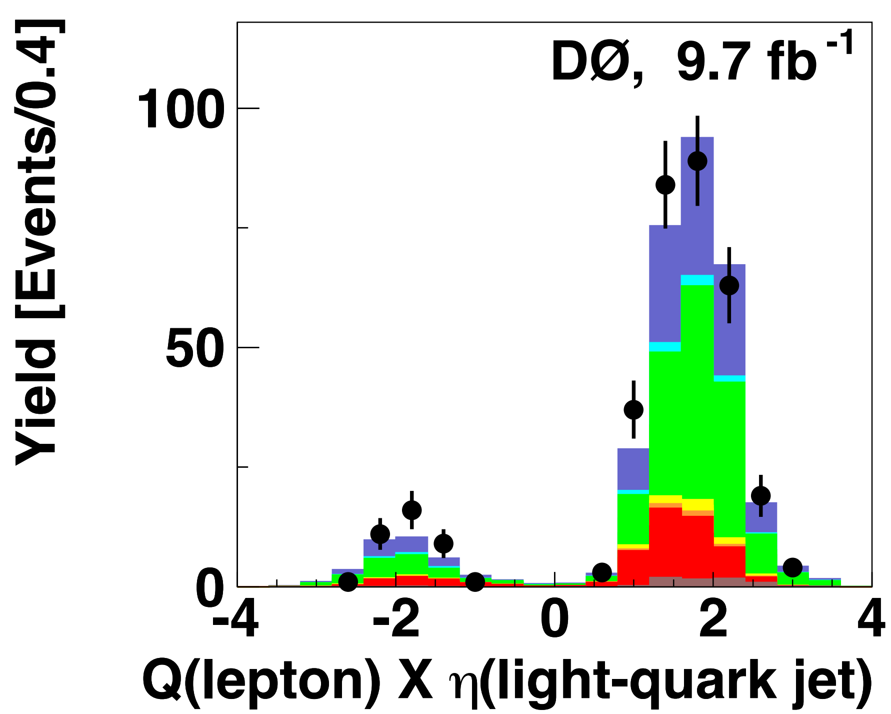




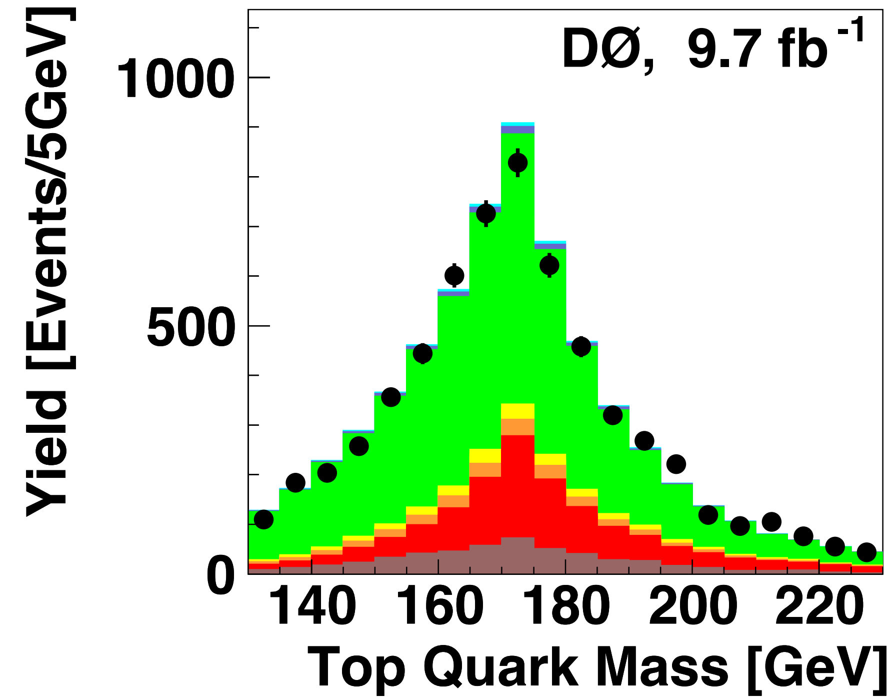
Event Characteristics

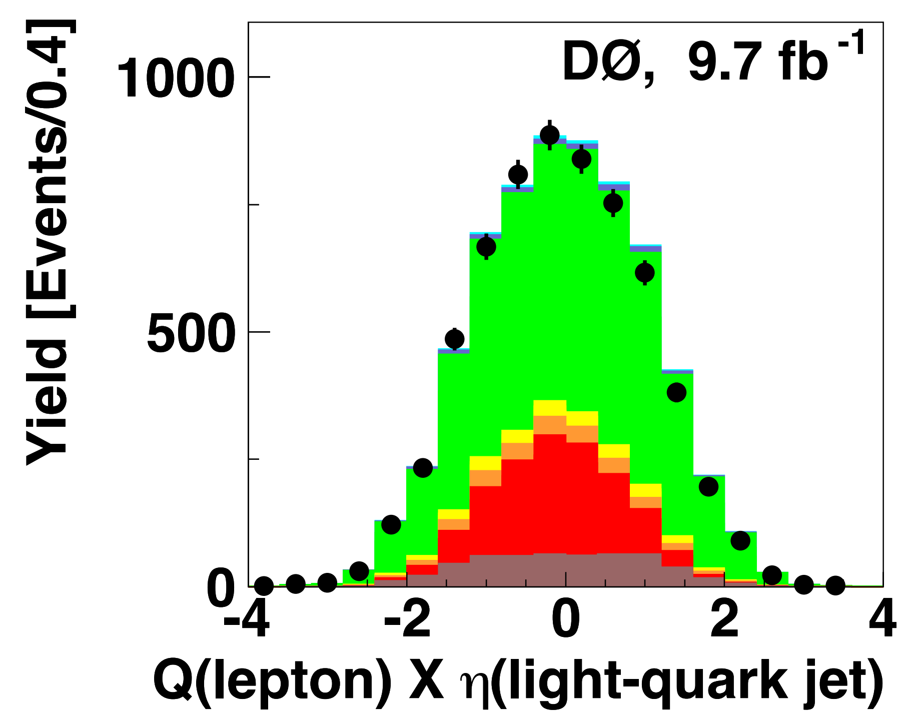
tqb Category: $D_{tqb} > 0.8$



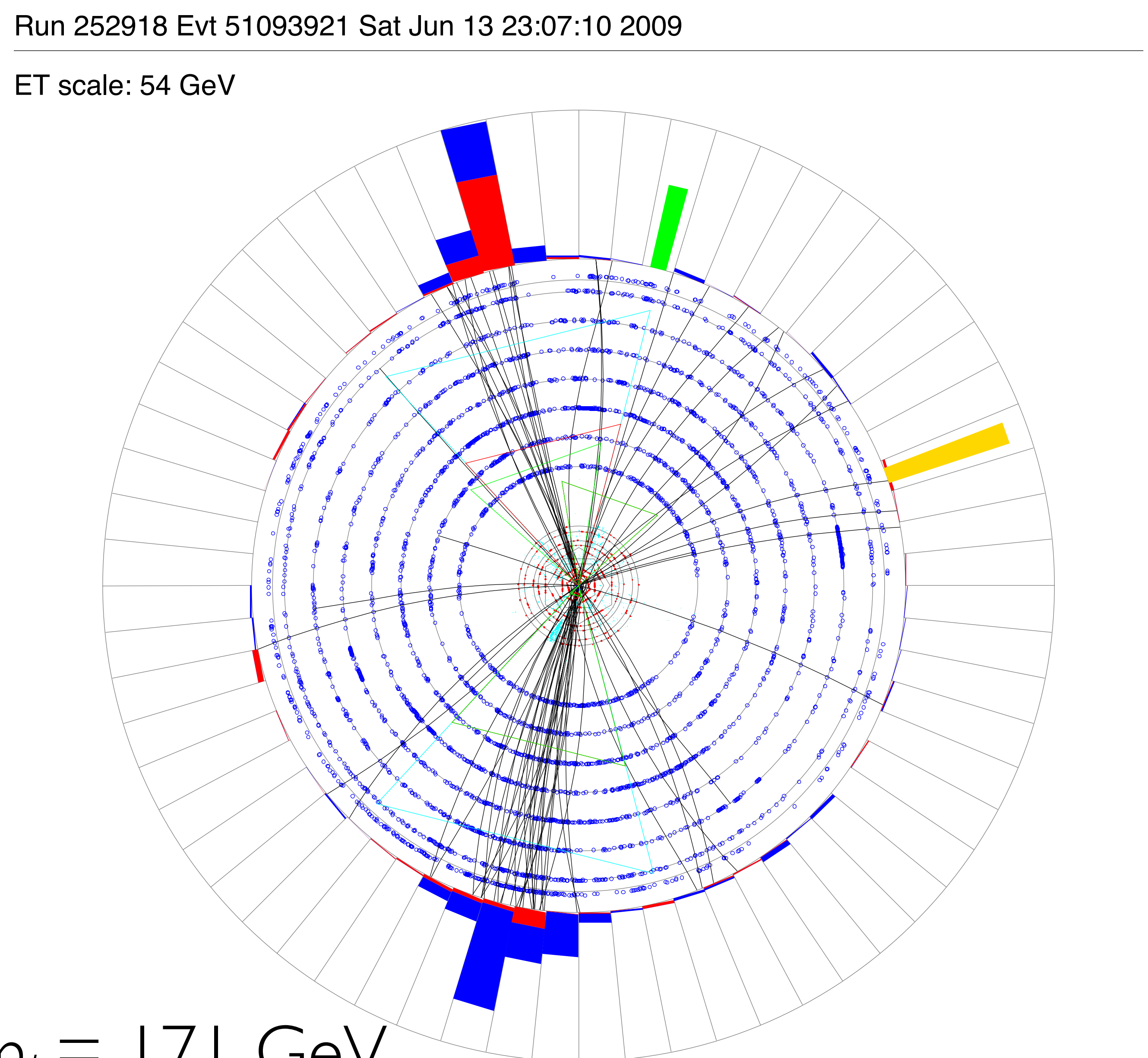


tb & *tqb* Depleted Region

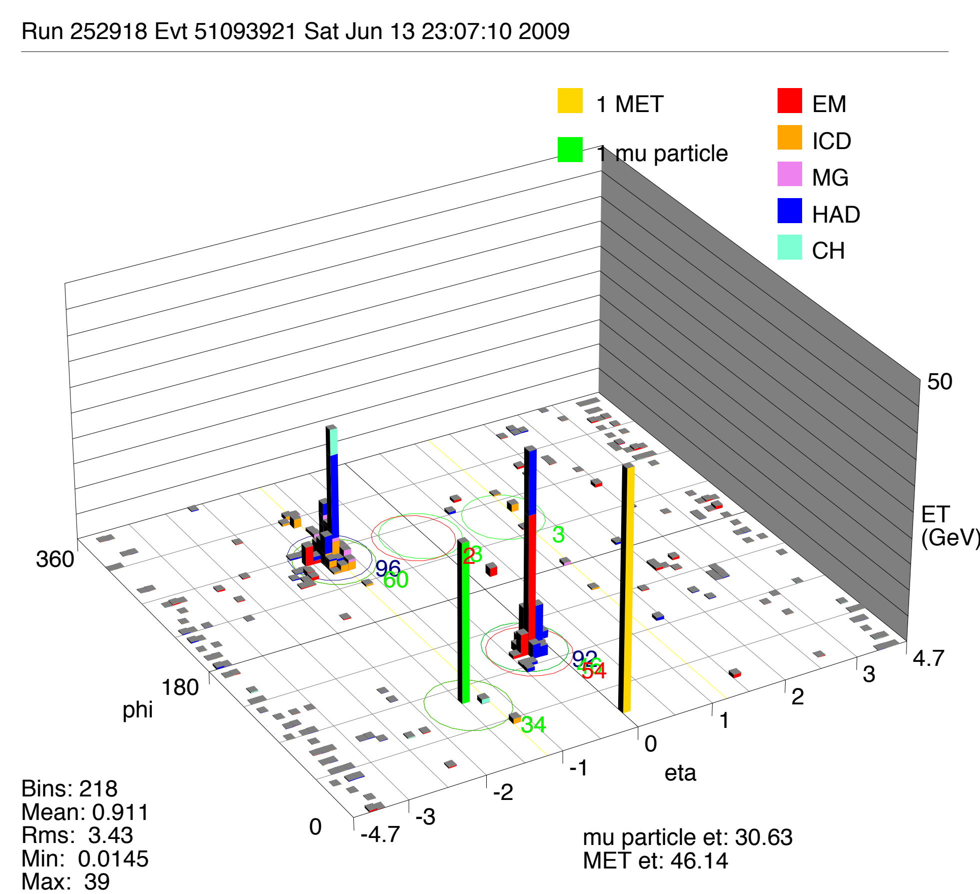




A *tb* Candidate



Run 252918
Event 51093921
Sat. June 13 23:07:10 2009



m_t = 171 GeV
Jet1 b-tag: 0.95
Jet2 b-tag: 0.84

Single Top in June 2013

σ (pb) ~NNLO	*tb*	*tqb*	*tW*
Tevatron Prediction (1.96 TeV)	1.04	2.26	0.3
CDF (7.5 fb^{-1})	1.81±0.6	1.49±0.45	-
DØ (9.7 fb^{-1})	☐ **1.10±0.33**	☑ **3.07±0.54**	-
LHC Prediction (7 TeV)	4.56	65.9	15.6
ATLAS (0.7-2.1 fb^{-1})	< 20.5 (95% C.L.)	☑ 83±20	☐ 17±6
CMS (1.2-4.9 fb^{-1})	-	☑ 67±6	☐ 16±5

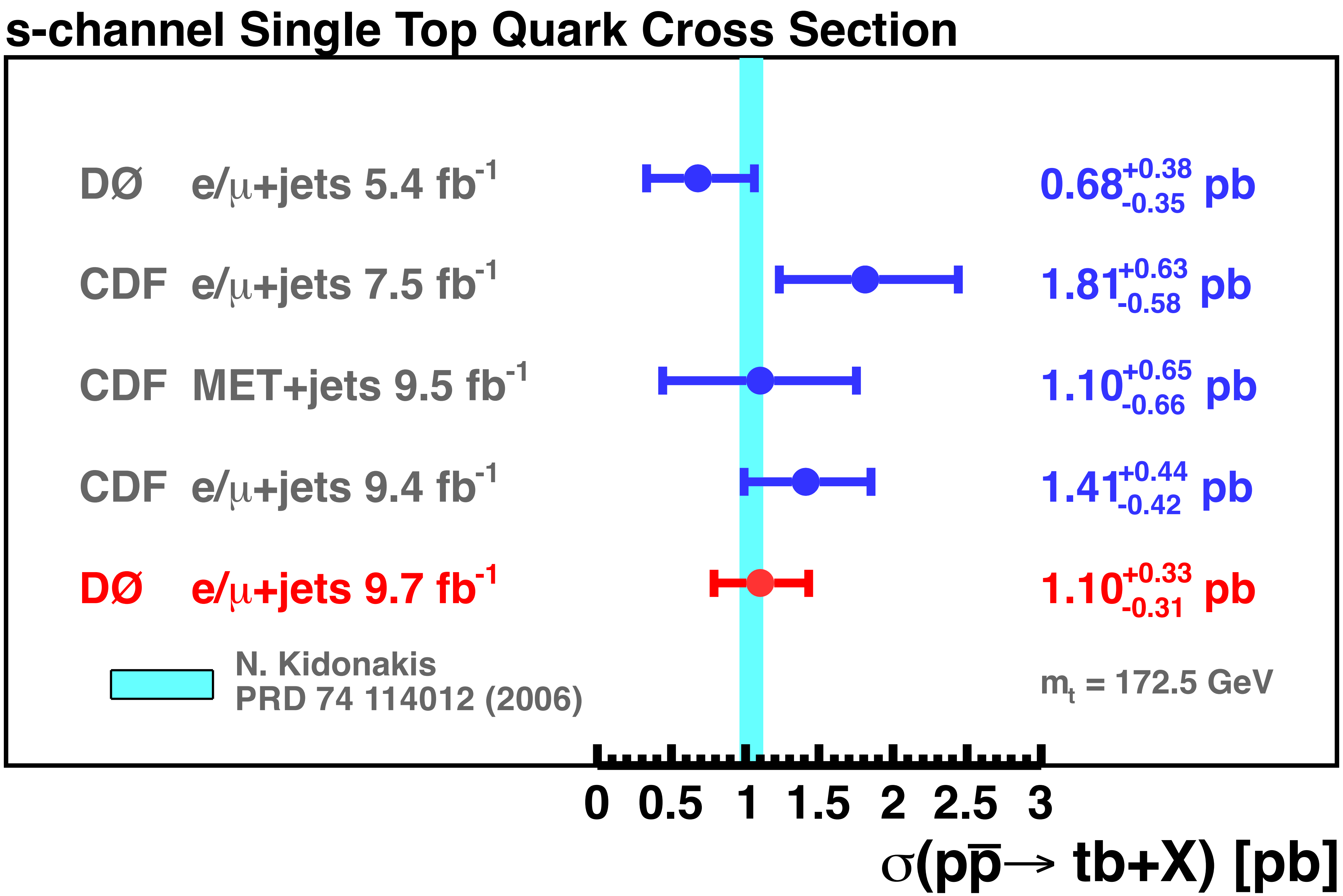
☐ Evidence (3 SD) ☑ Observation (5 SD)

Single Top Today

σ (pb) ~NNLO	*tb*	*tqb*	*tW*
Tevatron Prediction (1.96 TeV)	1.04	2.26	0.3
CDF (9.4 fb^{-1})	☐ 1.41±0.44 prelim.	Not ready	-
DØ (9.7 fb^{-1})	☐ **1.10±0.33**	☑ **3.07±0.54**	-
LHC Prediction (8 TeV)	5.55	87.2	22.2
ATLAS (0.7-20.3 fb^{-1})	< 26.5 (7 TeV)	☑ 95±18	☐ 27±5.8
CMS (1.2-12.2 fb^{-1})	-	☑ 80±13	☑ 23±5.5

☐ Evidence (3 SD) ☑ Observation (5 SD)

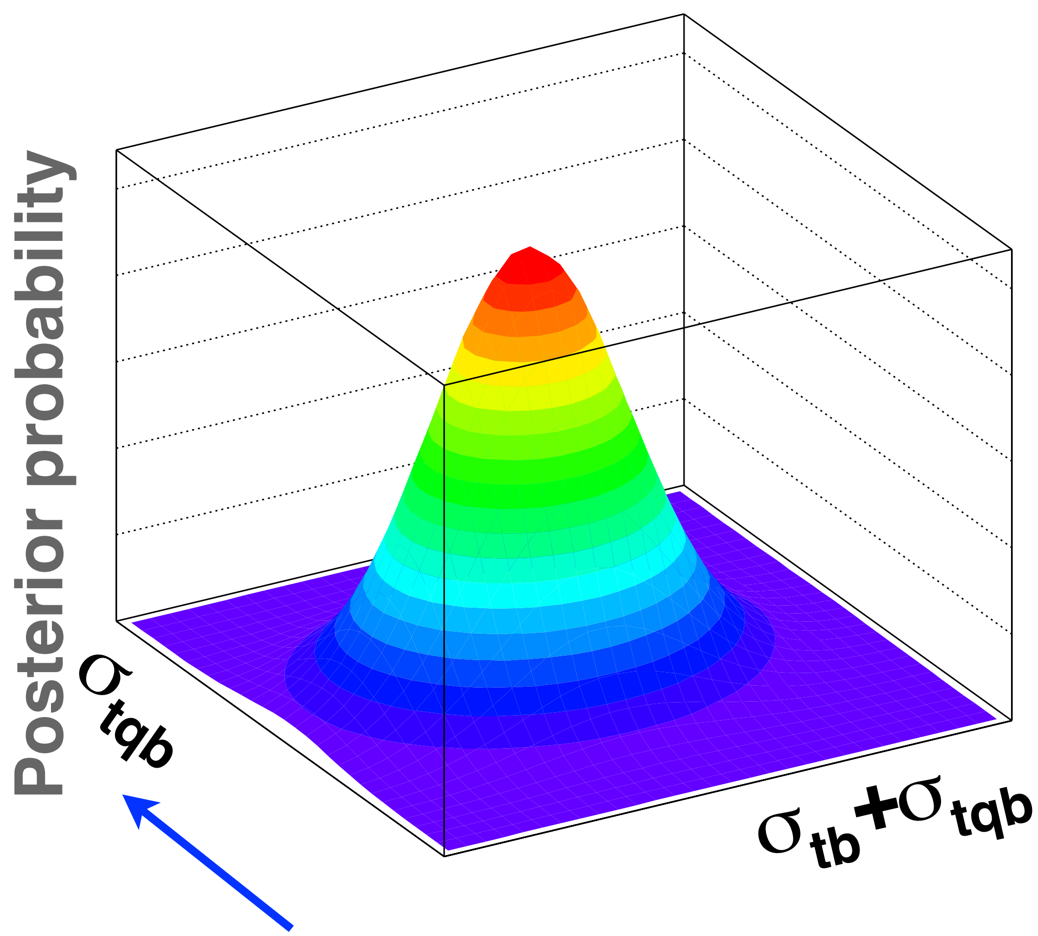
σ_{tb} Measurement History



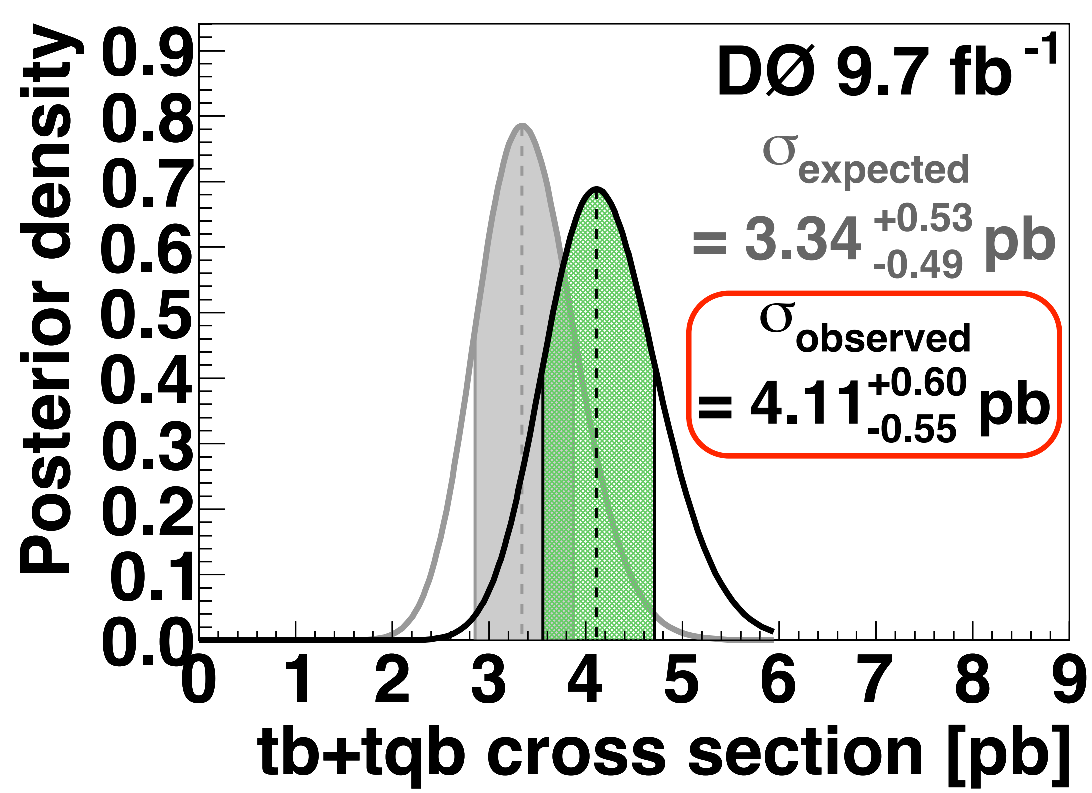
Each single method in the DØ 9.7 fb^{-1} analysis measures σ_{tb} with > 3 SD

Measured $\boldsymbol{\sigma}_{tb+tqb}$

- Measure $\boldsymbol{\sigma}_{tb+tqb}$ without assuming the SM $\boldsymbol{\sigma}_{tb}/\boldsymbol{\sigma}_{tqb}$
- Use 2D posterior p.d.f.

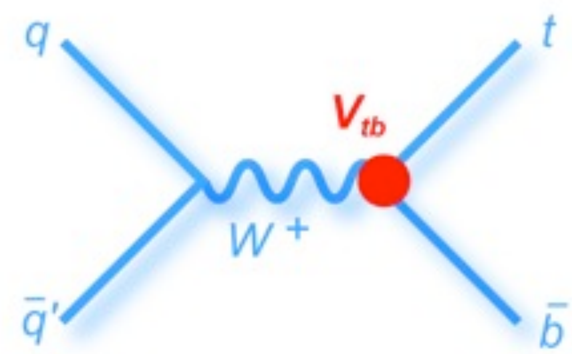


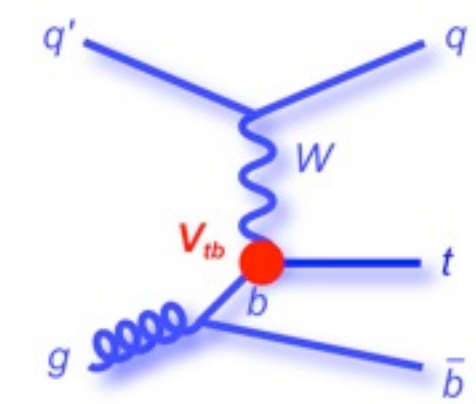
Integrate over $\boldsymbol{\sigma}_{tqb}$ and obtain a 1D posterior p.d.f. of $\boldsymbol{\sigma}_{tb+tqb}$



CKM Matrix Element $|V_{tb}|$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

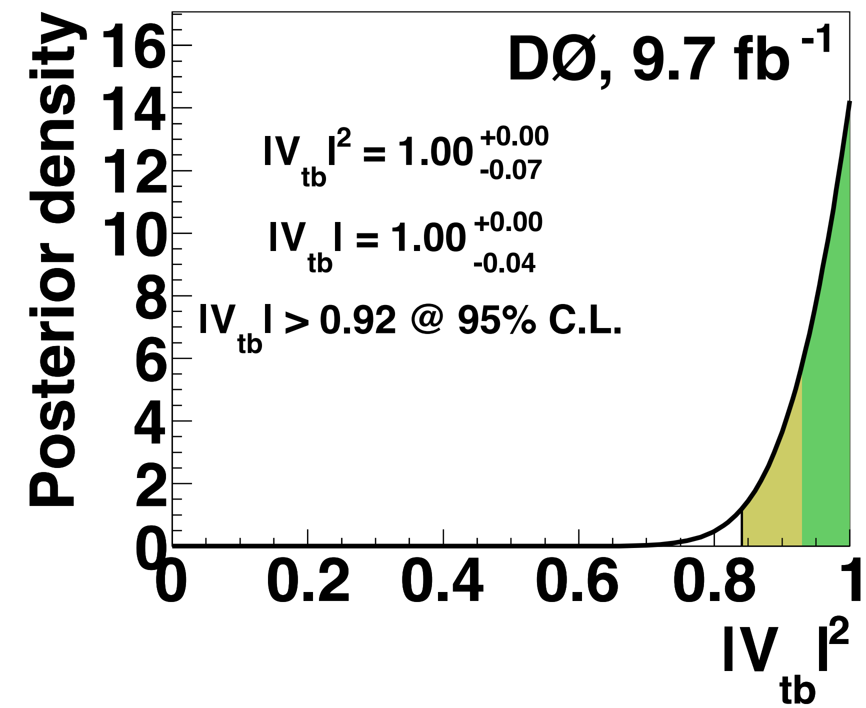


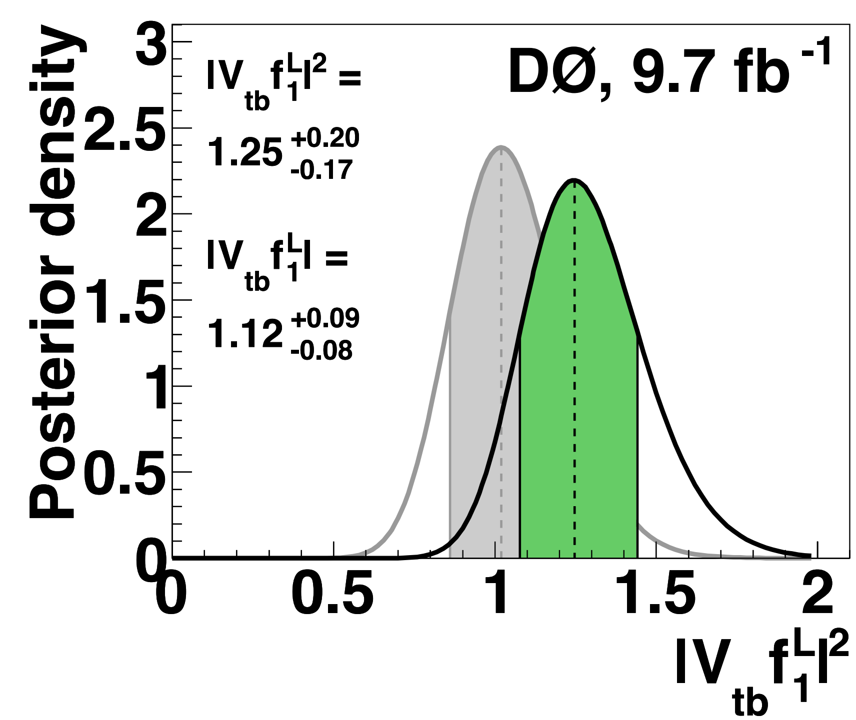


- σ_{tb+tqb} proportional to $|V_{tb}|^2$
- Lagrangian: $\mathcal{L} = -\frac{g}{\sqrt{2}} V_{tb}\, \bar{b}\gamma^{\mu}(f_1^L P_L)t\, W_{\mu}^{-}$ SM: $f_I^L = 1$
- Assume:
  - SM top decay: $|V_{td}|^2+|V_{ts}|^2 << |V_{tb}|^2$
  - Pure V-A interaction
  - CP conservation
- DO NOT assume
  - 3 generations
  - unitarity of the CKM matrix; allow $|V_{tb} f_I^L|^2 > 1$
  - σ_{tb}/σ_{tqb} (NEW)

CKM Matrix Element $|V_{tb}|$

- Assume $0 \leq |V_{tb}|^2 \leq 1$
  - $|V_{tb}| > 0.92$ @ 95% C.L.
- Allow $|V_{tb} f_l^L|^2 > 1$
  - $|V_{tb} f_l^L| = 1.12^{+0.09}_{-0.08}$
- Additional systematic uncertainties
  - theoretical uncertainty on single top cross sections
- Complementary to $R_{Wb/Wq}$ measurement in top decays
PRD **85**, 091104 (2012)



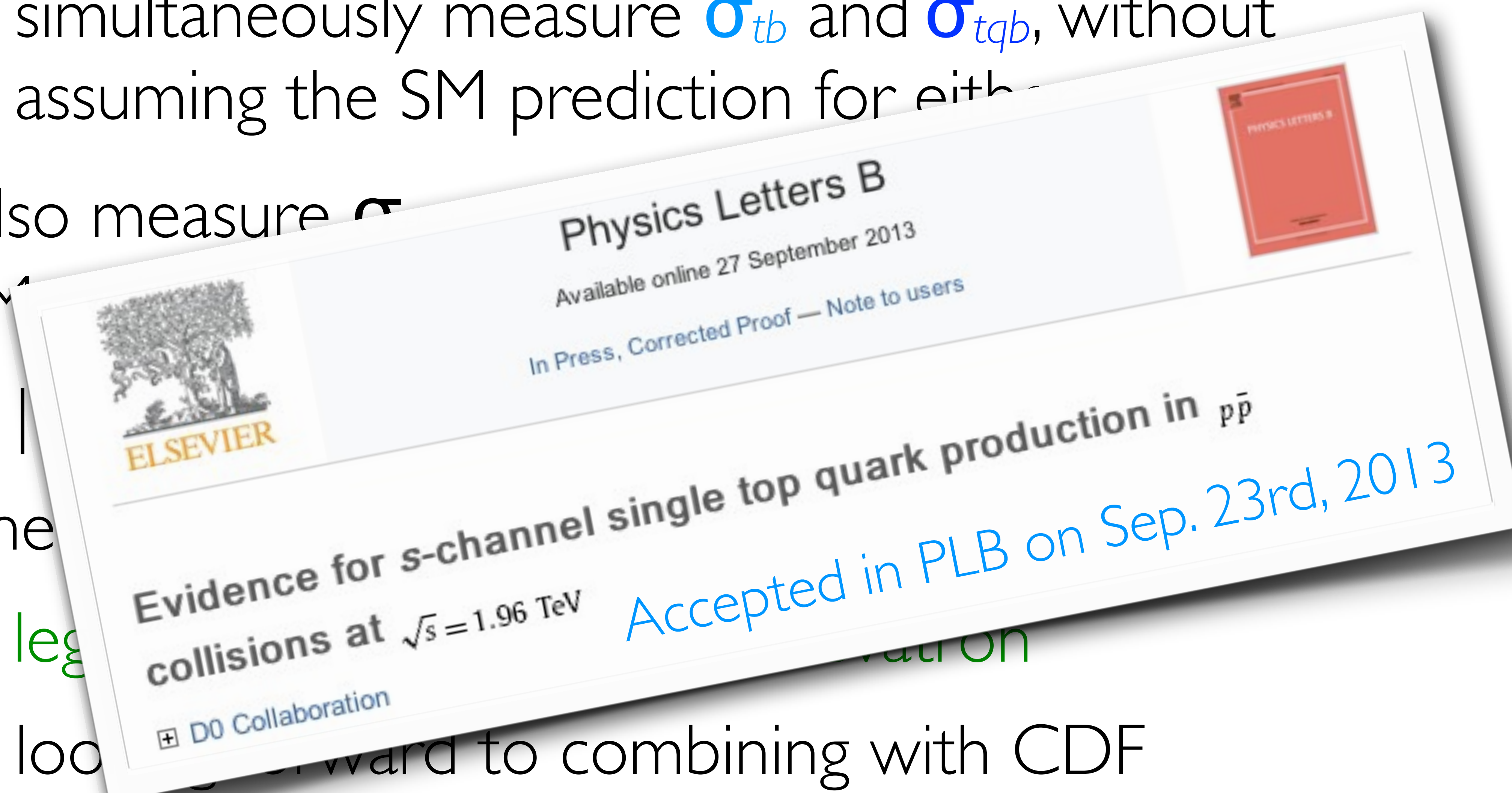


Conclusion

- First evidence of s-channel single top quark production
  - σ_{tb} = 1.10 ± 0.33 pb
  - simultaneously measure σ_{tb} and σ_{tqb}, without assuming the SM prediction for either
- Also measure σ_{tb+tqb} and $|V_{tb}|$ without assuming the SM ratio of σ_{tb}/σ_{tqb}
  - $|Vtb| > 0.92$ @ 95% C.L.
- The results are consistent with the SM predictions
- A legacy measurement at the Tevatron
  - looking forward to combining with CDF

Conclusion

- First evidence of s-channel single top quark production
  - σ_{tb} = 1.10 ± 0.33 pb
  - simultaneously measure σ_{tb} and σ_{tqb}, without assuming the SM prediction for eith
- Also measure σ
  SM
  - |
- The
- A leg ... atron
  - loo ... ward to combining with CDF

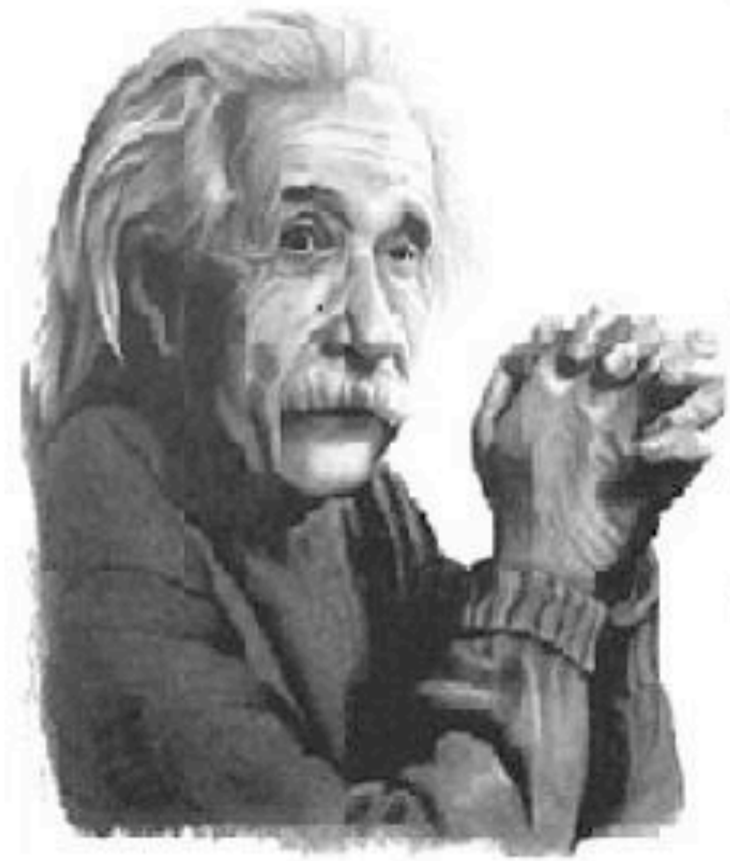

Physics Letters B

Available online 27 September 2013

In Press, Corrected Proof — Note to users

Evidence for s-channel single top quark production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

D0 Collaboration



The pursuit of truth and beauty is a sphere of activity in which we are permitted to remain children all our lives.

quotespedia.info

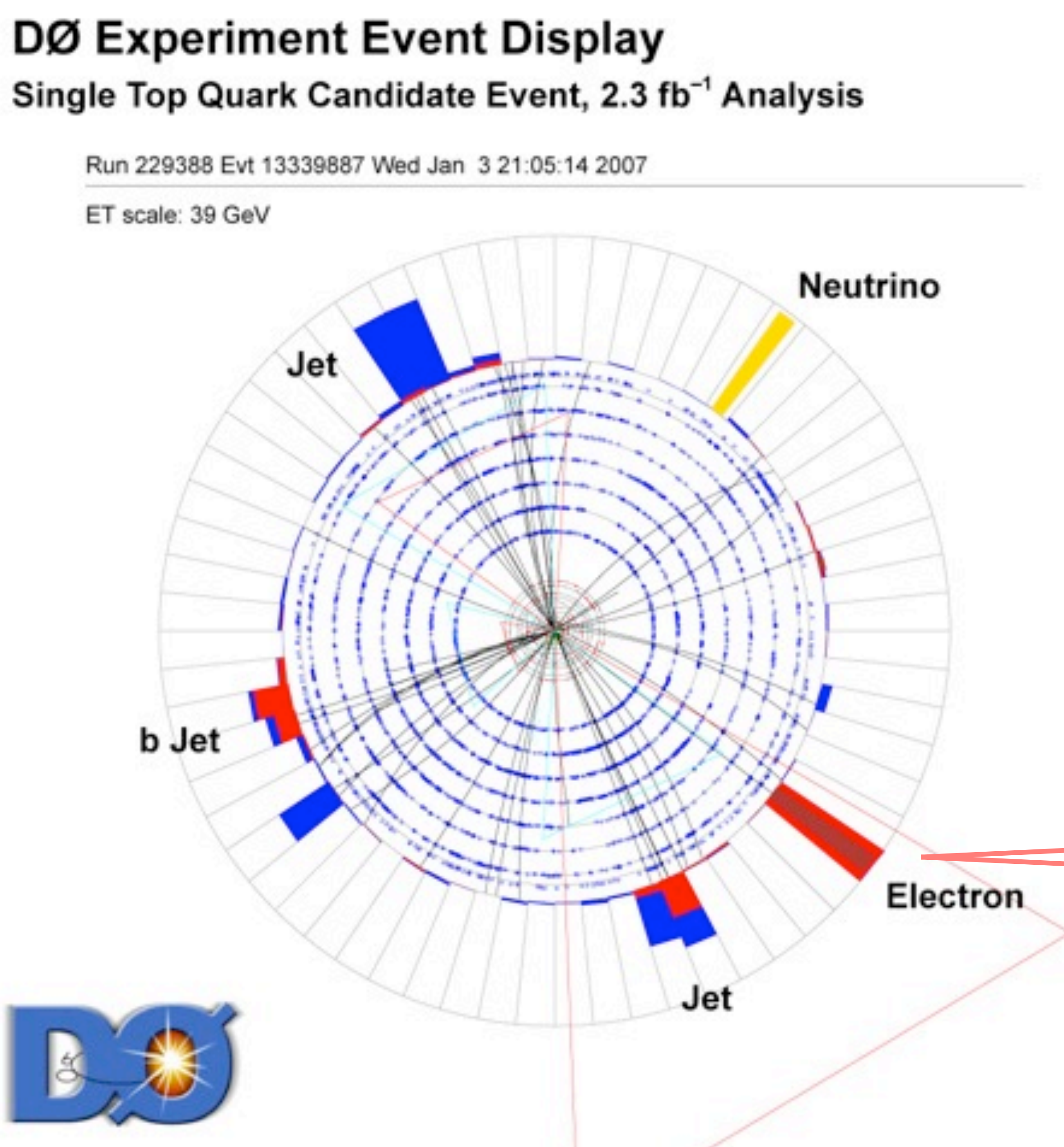
Albert Einstein

Thank you for your attention!

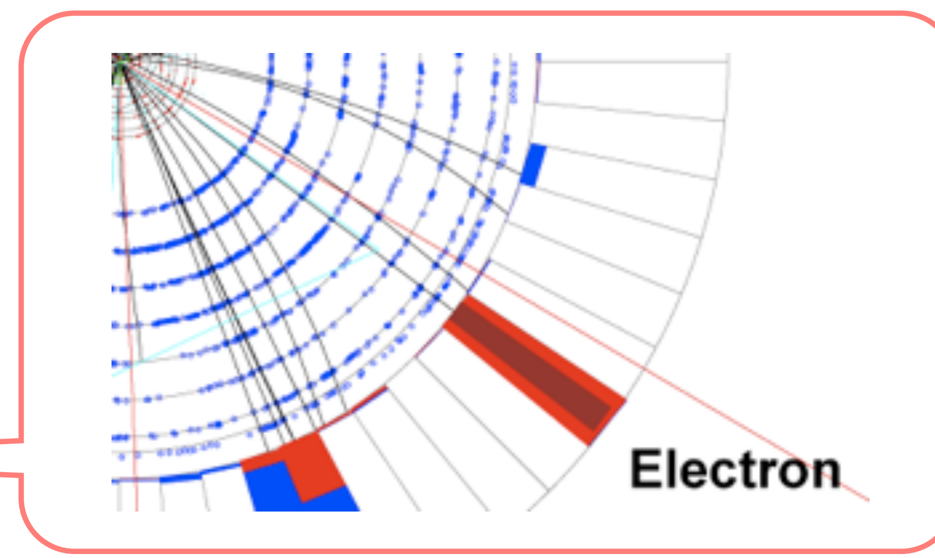
Backup Slides

Electron Reconstruction

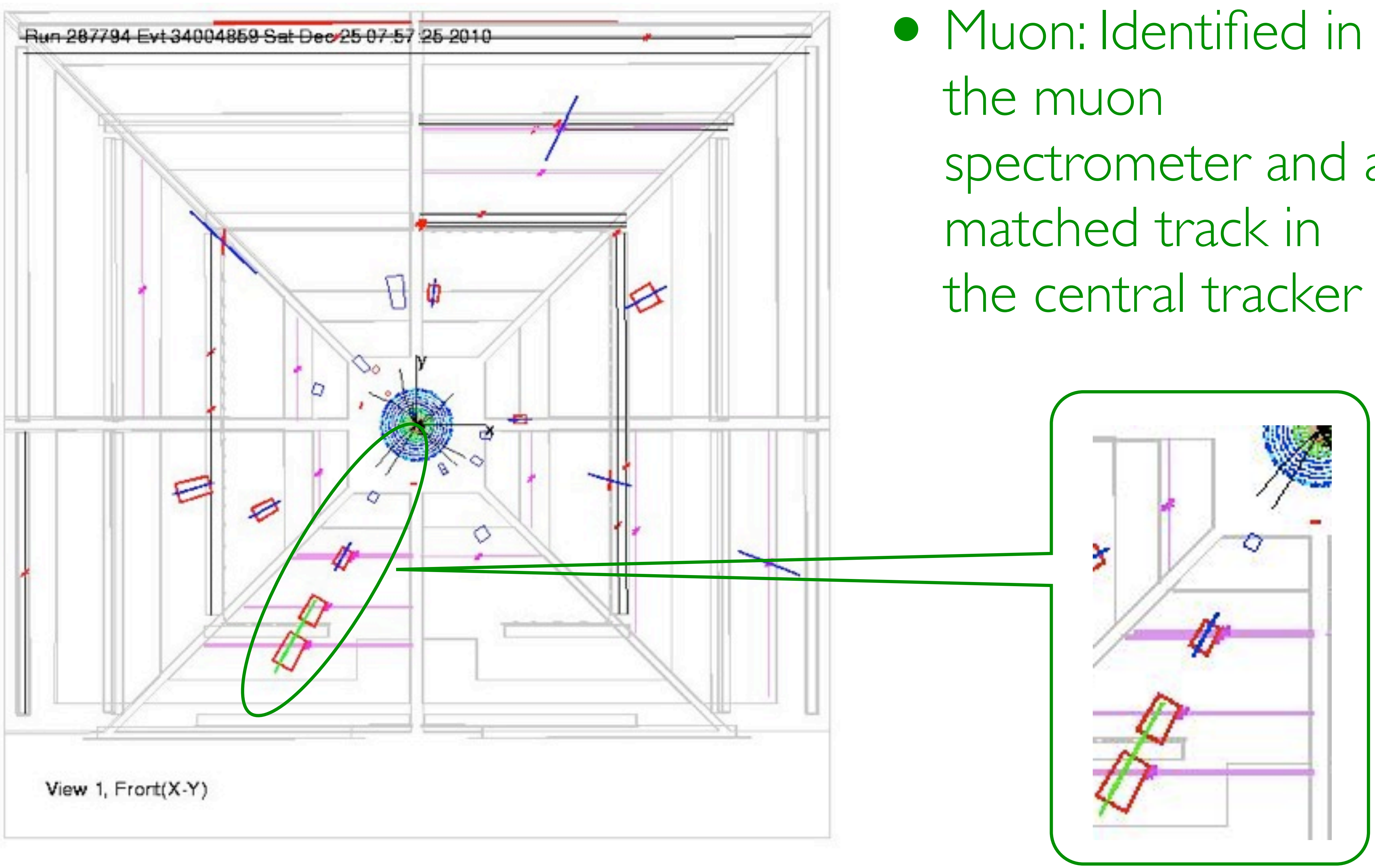
Transverse plane: Perpendicular to the proton beam



- Electron: Narrow cone of isolated EM calorimeter cluster



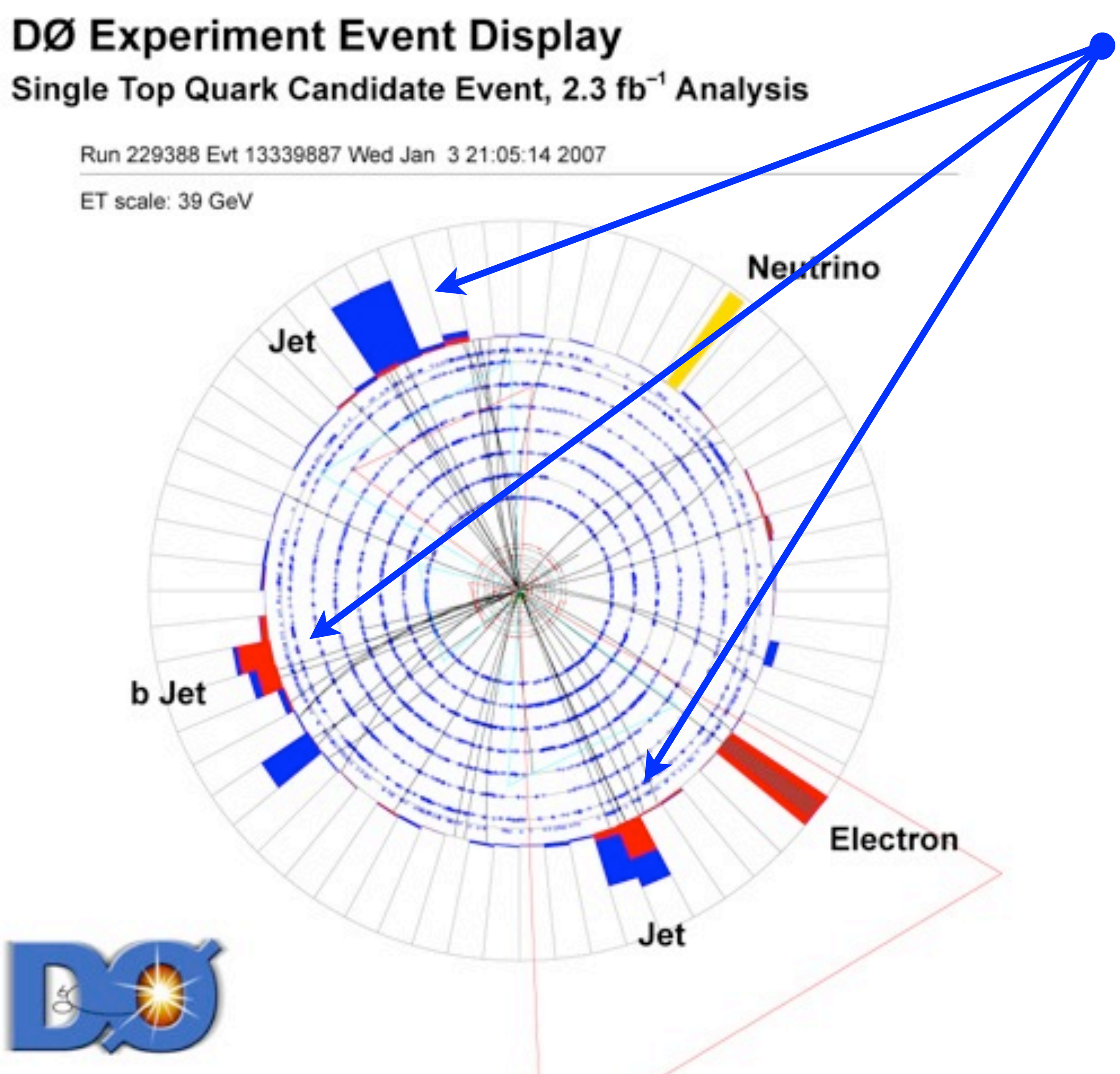
Muon Reconstruction



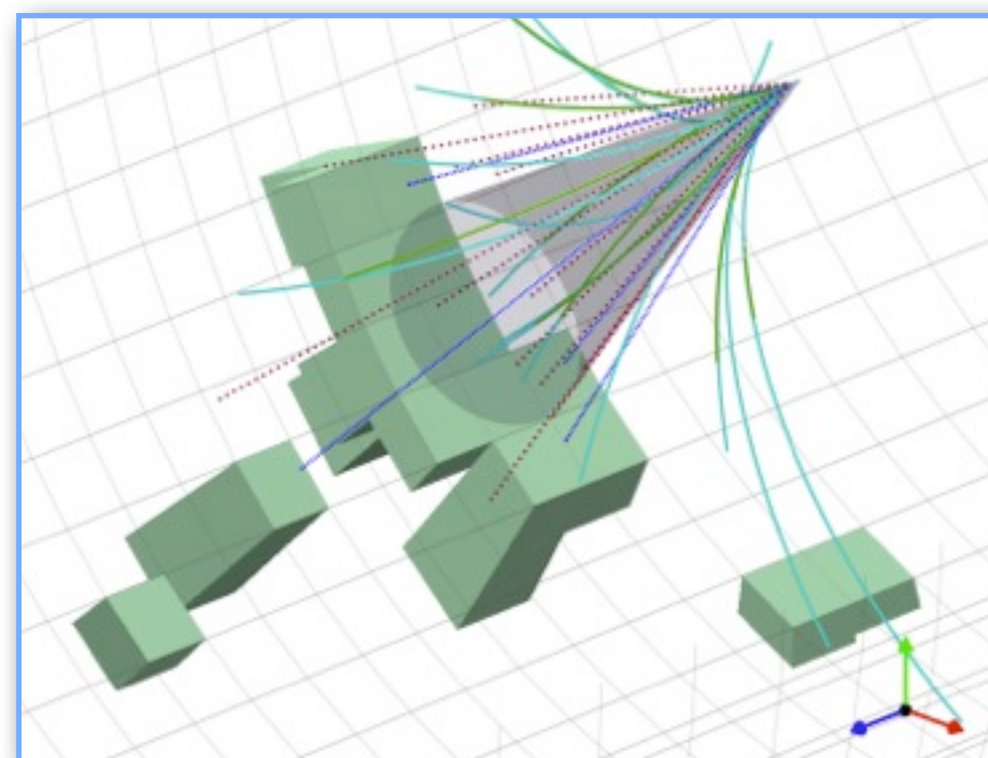
- Muon: Identified in the muon spectrometer and a matched track in the central tracker

Jet Reconstruction

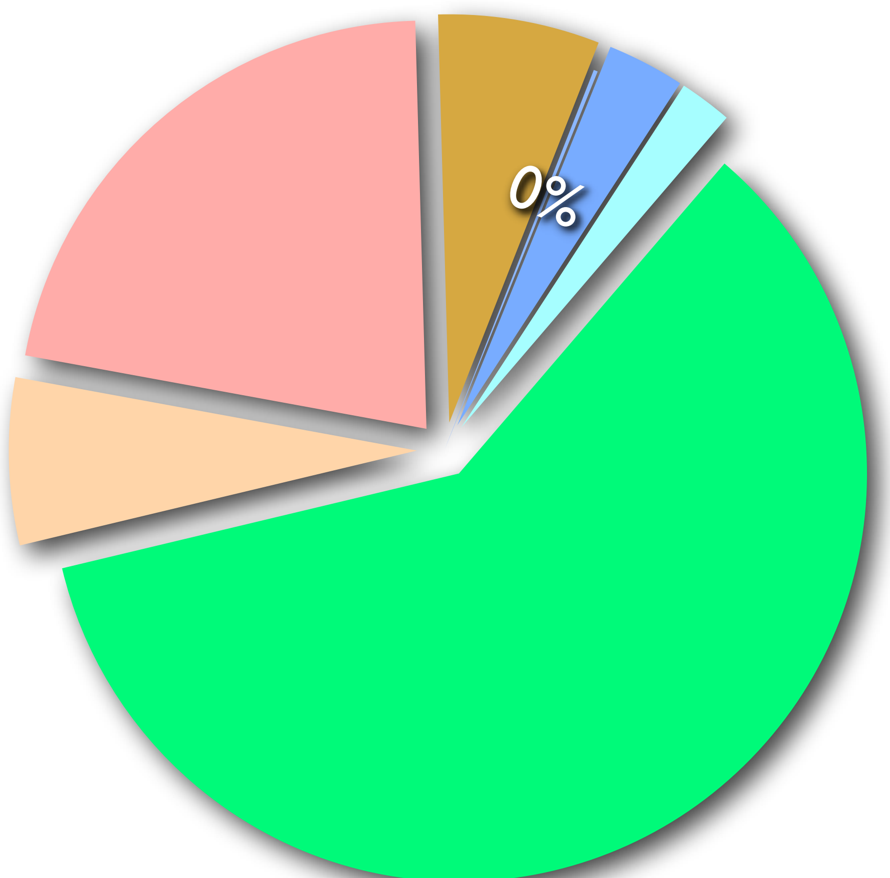
Transverse plane: Perpendicular to the proton beam



- Quark and gluon fragments → jet: Wide cone of hadron calorimeter energy clusters



tW Contribution at DØ

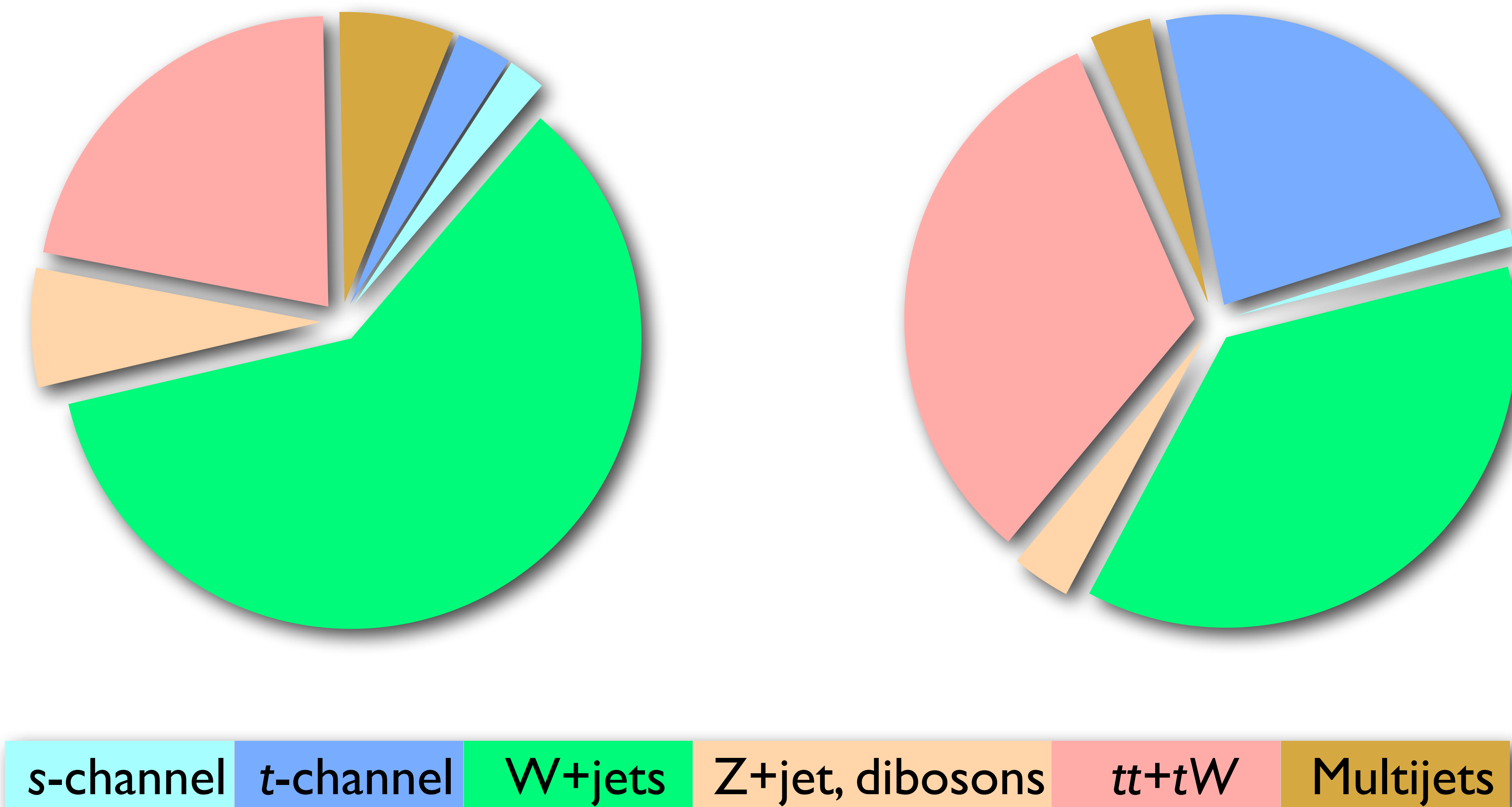


e, μ 2, 3-jets 1, 2 *b*-tags combined	
s-channel	257
t-channel	378
tW	20
W+jets	7394
diboson, *Z*+jets	815
top pair	2672
multijet	789
Total background	11669
Data	12103

Background Contribution

DØ

CMS
(arXiv:1209.4533v1)

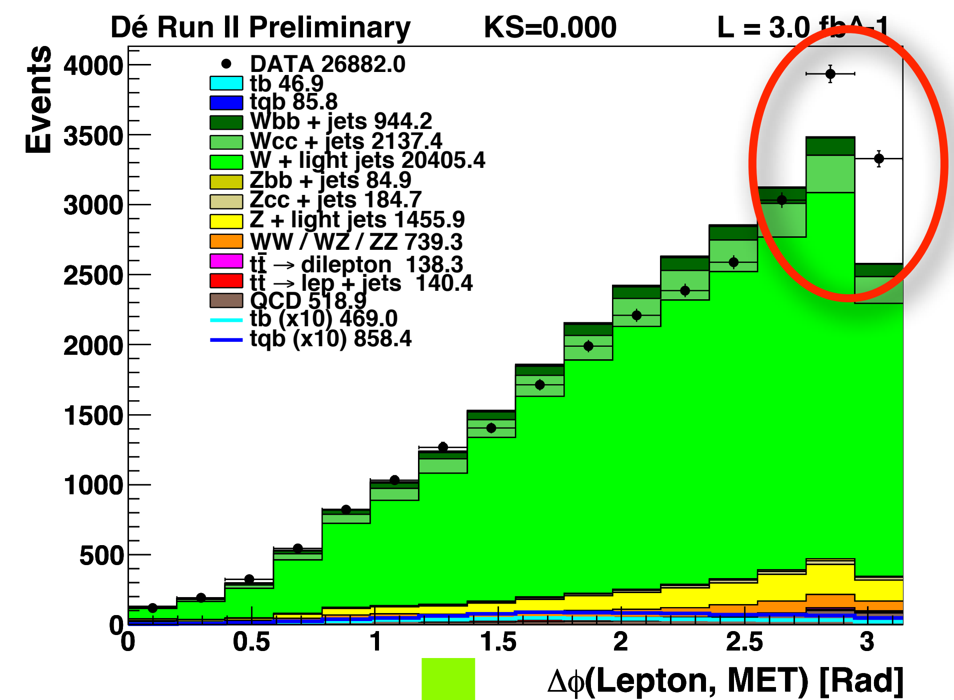


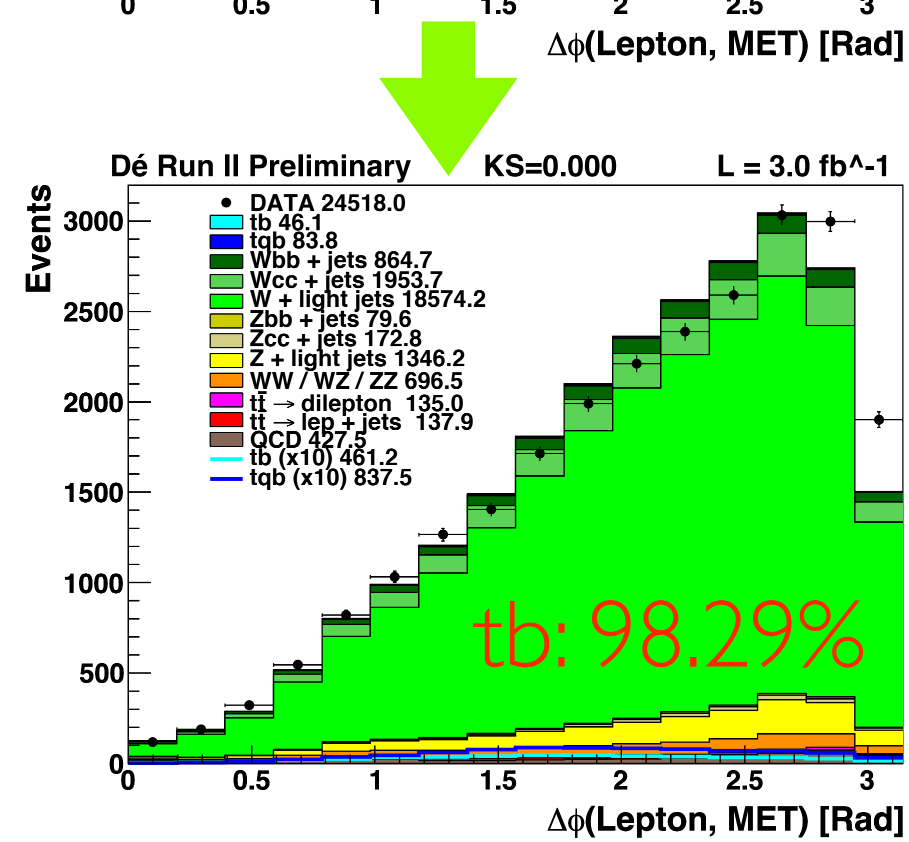
Additional Cuts

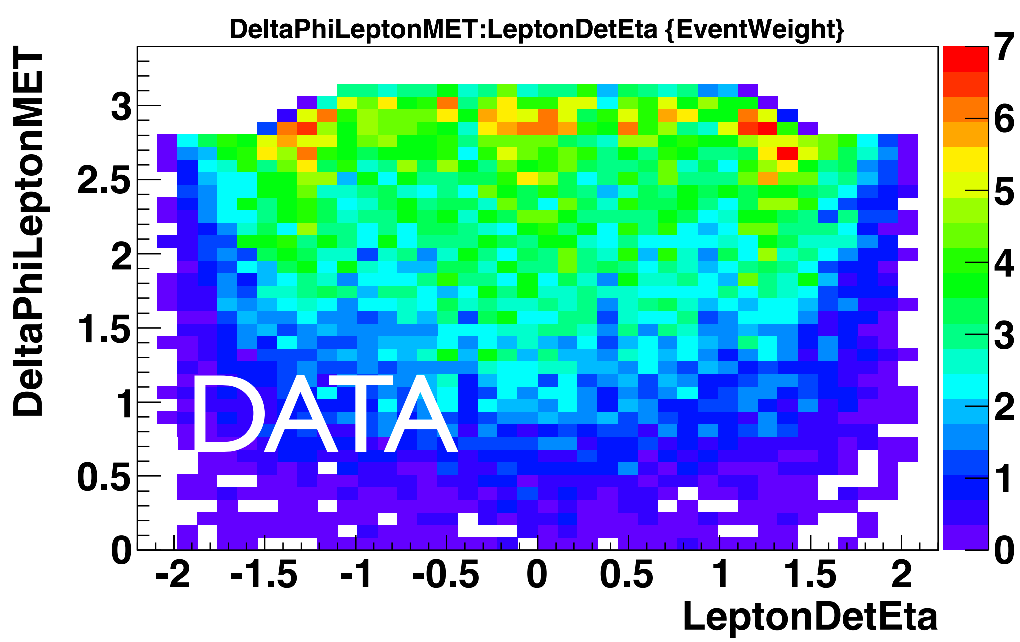
- H_T > 120/140/160 GeV (2/3/4 jet)
- MET > 25 GeV (3 and 4 jet)
- $\Delta\varphi$(MET, Jet1) < 1.5 + 0.0469MET
- Electron channel
  - $\Delta\varphi$(MET, Lep) > 2.0 - 0.05MET
  - $\Delta\varphi$(MET, Lep) > 1.5 - 0.03MET
  - $\Delta\varphi$(MET, Lep) < 2.0 + 0.0476MET
- Muon channel
  - $\Delta\varphi$(MET, Lep) > 1.4 - 0.0141MET
  - $\Delta\varphi$(MET, Lep) < 2.5 + 0.0214MET
  - $-ab/(\pi-a)+b\,\Delta\varphi(\text{MET, Lep})/(\pi-a)<|\text{mutrkcursig}|$
    (a, b) = (2.9, 10) (modified)
  - Trapezoid cut (new)

Δφ(Muon, MET) Issue

- Data-MC disagreement in the last bin of **Δφ**(Muon, MET) for mu+jets channel
- Re-derive muon TrackCurvSig cut
- Derive a "trapezoid" cut, and apply it after LeptonDetEta reweighting



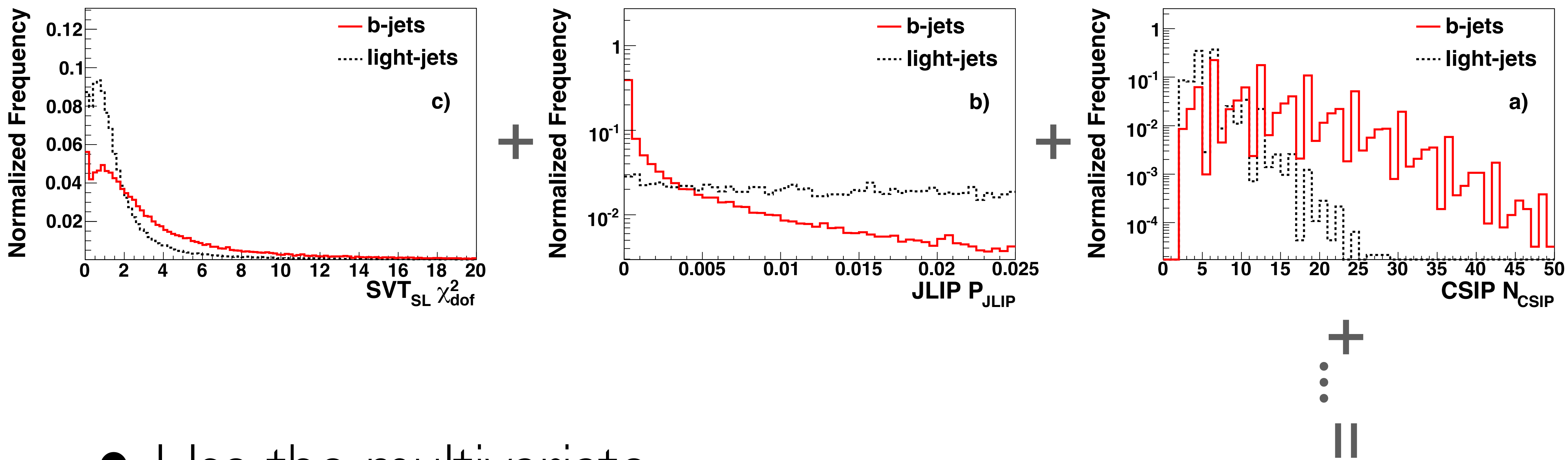




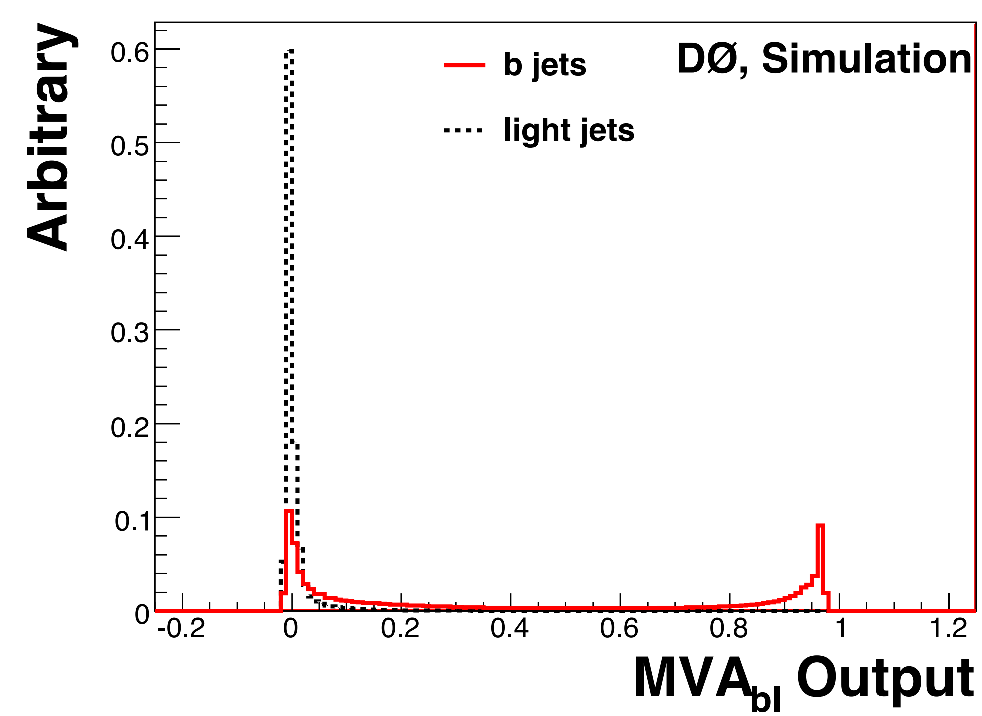
Reweightings

- The same reweightings as used in previous single top analysis
- e+jets:
  - InstLumi, Angular corrections
- μ+jets:
  - InstLumi, Lepton Detector η, Angular corrections
- InstLumi and Lepton Detector η reweightings
  - bin by bin, applied on all MCs
- Angular corrections
  - Jet1 η, Jet2 η, ΔR(Jet1, Jet2), Jet3 η, Jet4 η
  - Originally from Higgs group, with our ICD methods

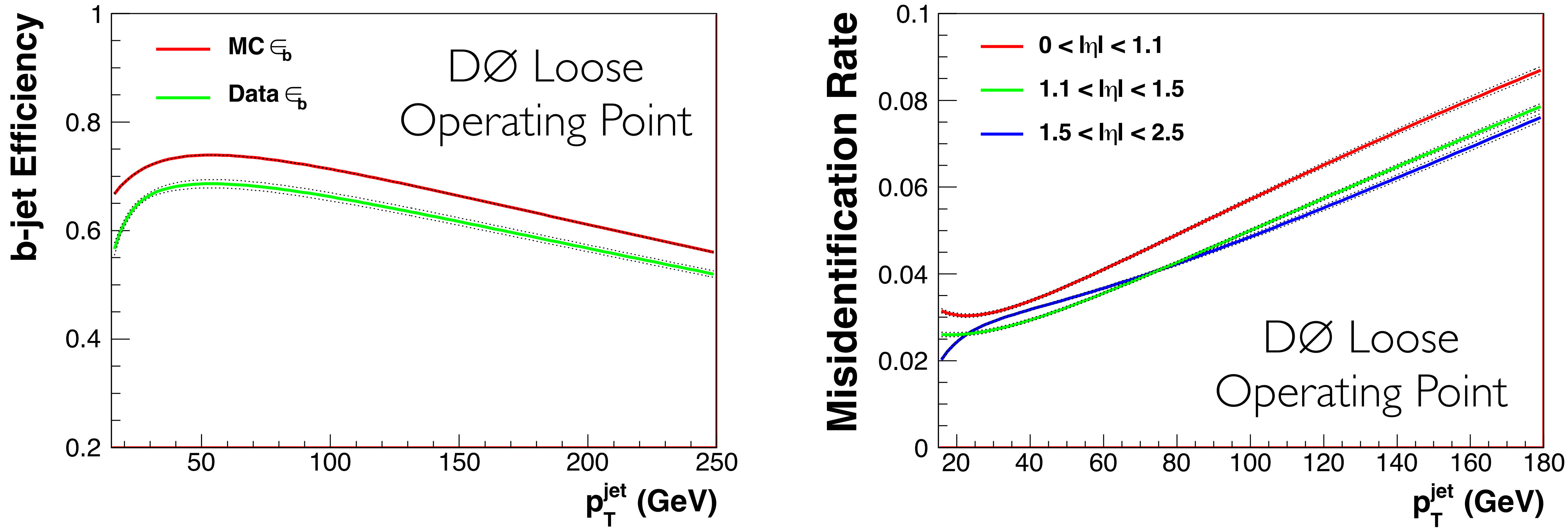
b-Jet Identification



- Use the multivariate technique (MVA) to combine these variables
- Optimize the cut on (the MVA output) to this analysis



b-ID Efficiency



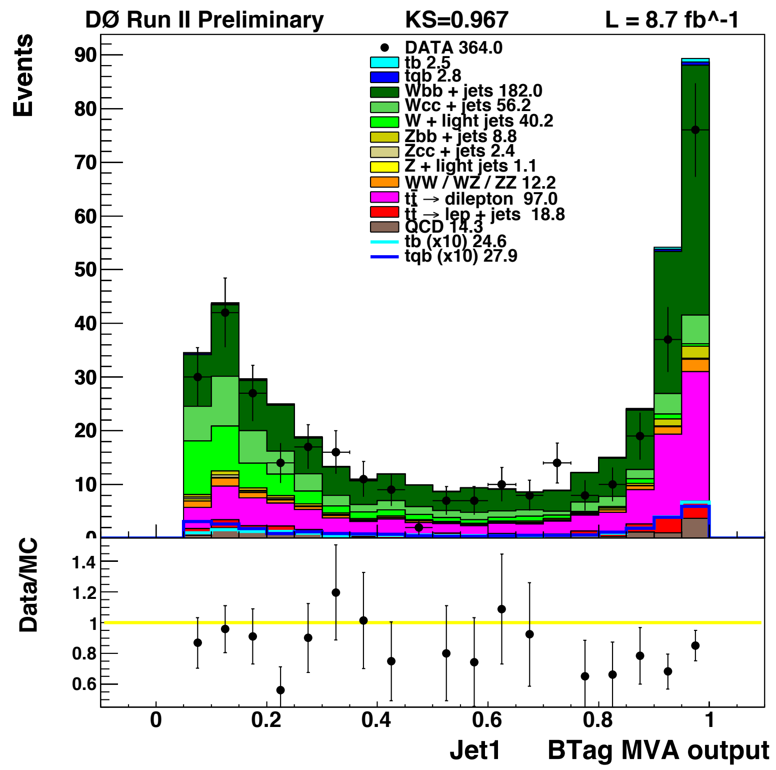
- *b*-identification efficiency: (50-70)%
- Misidentification rate: (3-8)%
- Obtain scale factors to correct the MC samples

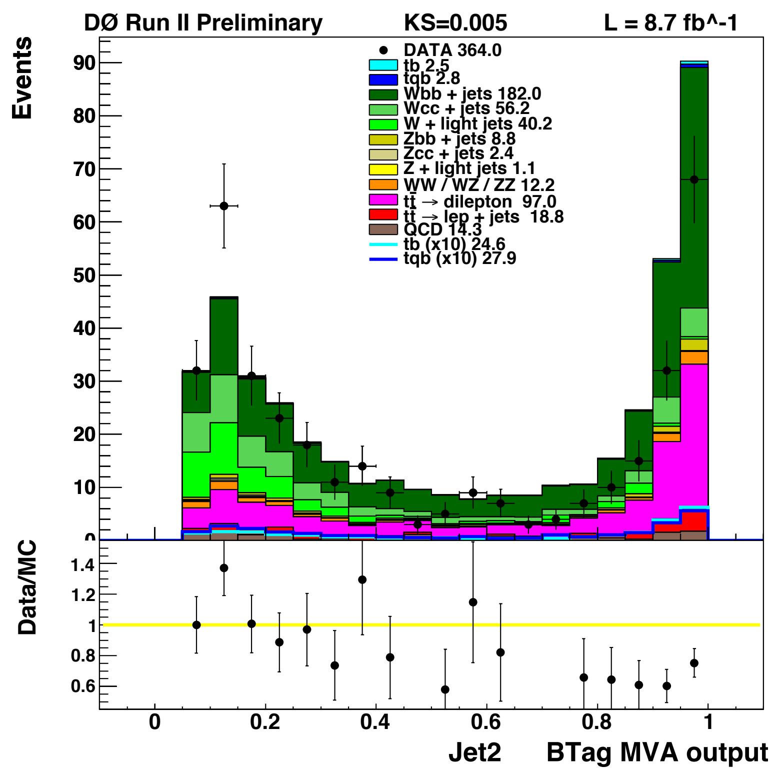
W Transverse Mass

$$M_T^2(W) = [\not{E}_T + p_T(\ell)]^2 - [\not{E}_{T\,x} + p_x(\ell)]^2 - [\not{E}_{T\,y} + p_y(\ell)]^2$$

Heavy-Flavor Modeling

- Observed mis-modeling in high *b*-ID output regions
  - particularly in 2-jet 2-tag channel
- Possible sources:
  - Alpgen distributions of the *W+bb/cc* samples
  - mis-modeling of the *b*-ID efficiency
- Could not identify the source owing to low data statistics in the mis-modeled regions
- Need an ad hoc correction

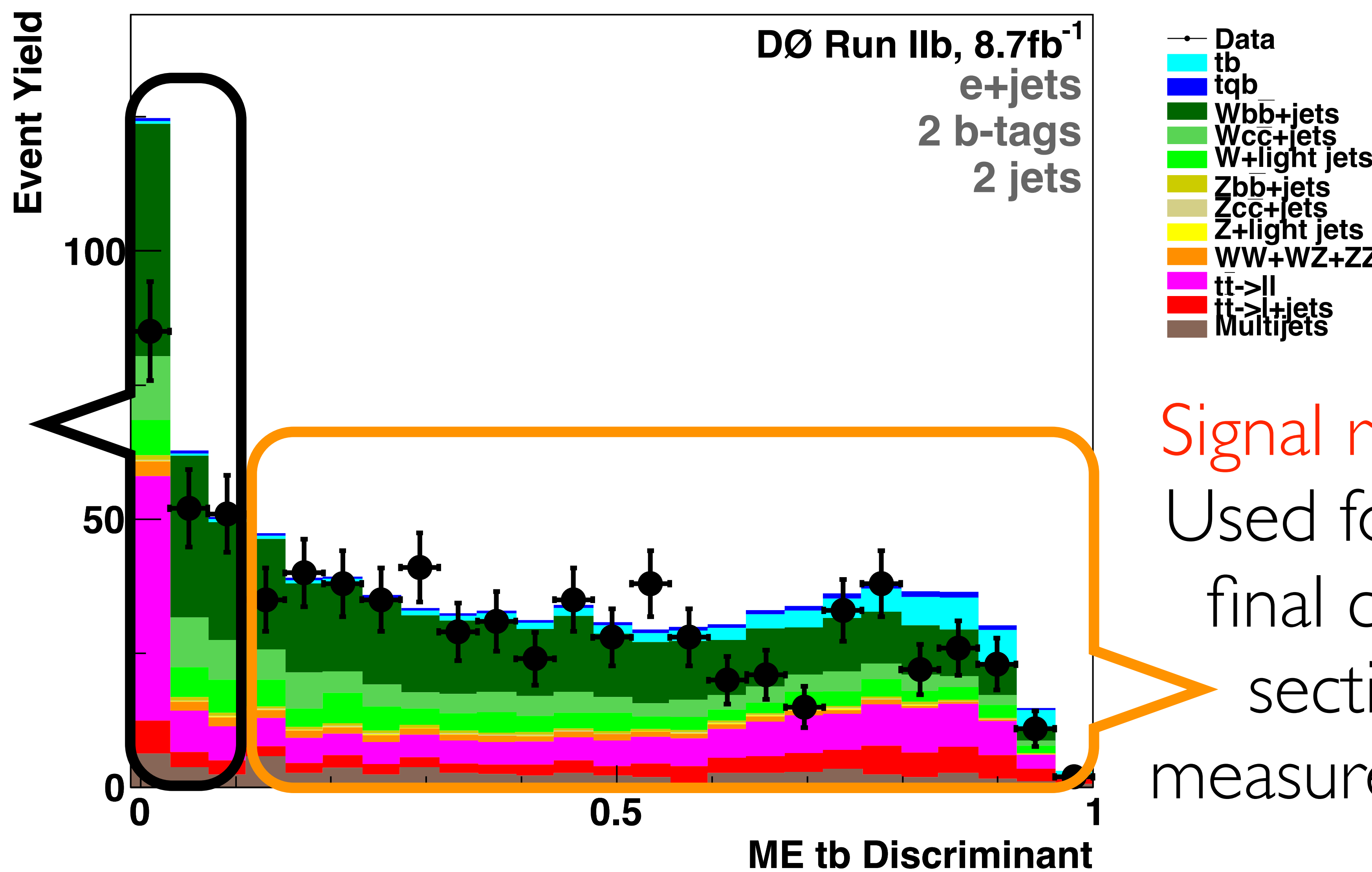




Heavy-Flavor Correction

- Use a part of data to derive the correction
- The Matrix Element discriminant is unbiased by the DØ simulation

Control region: Signal<1%; orthogonal; used to derive additional b-ID scale factor



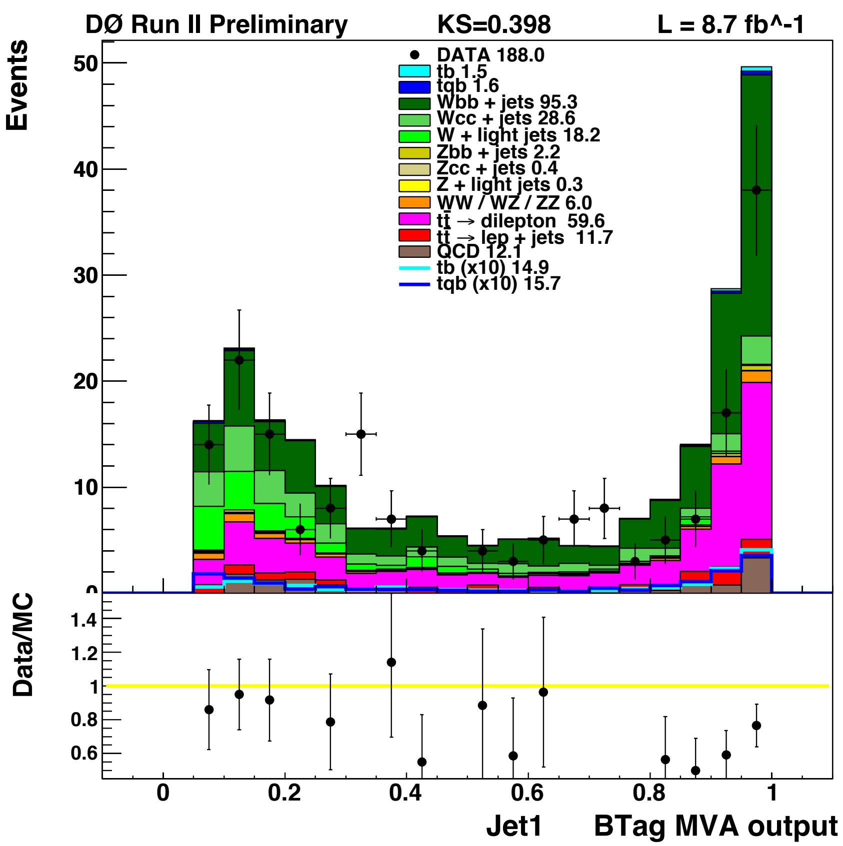
Signal region: Used for the final cross section measurement

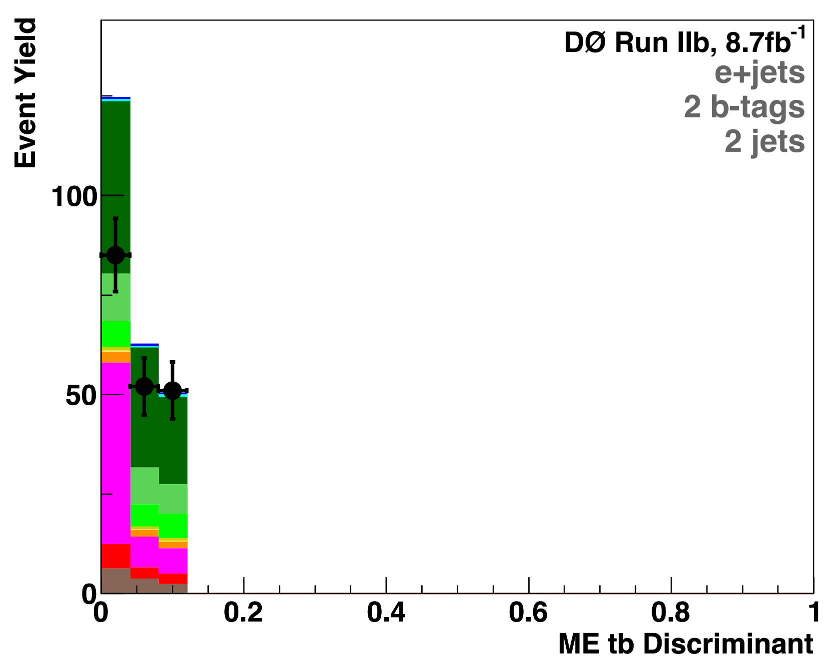
Heavy-Flavor Correction

- Without the constant heavy flavor scale factor 0.8
- Use the events with MED < 0.12, orthogonal to the events used for the cross section measurement
- Use the two JetBTagMVA (BL) bins, (0.9, 0.95), (0.95,1), to derive a jet-based correction
- The corrections are found to be channel-dependent
  - Derive from 1tag and 2tag, 2jet and 3jet channels individually
  - Combine the electron and muon channels
- Apply on the jet with JetBTagMVA (BL) > 0.9, for all heavy flavor jets in all the MC samples
  - The Data-MC agreement in JetBTagMVA (BL) < 0.9 is good

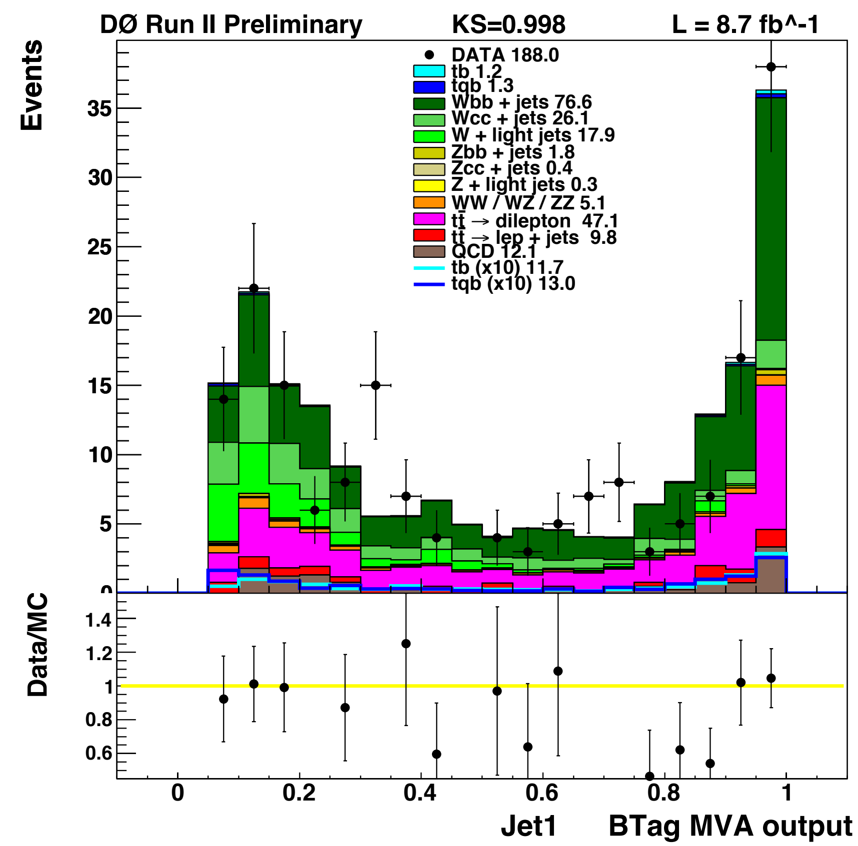
Control Region: e+2jets 2tag

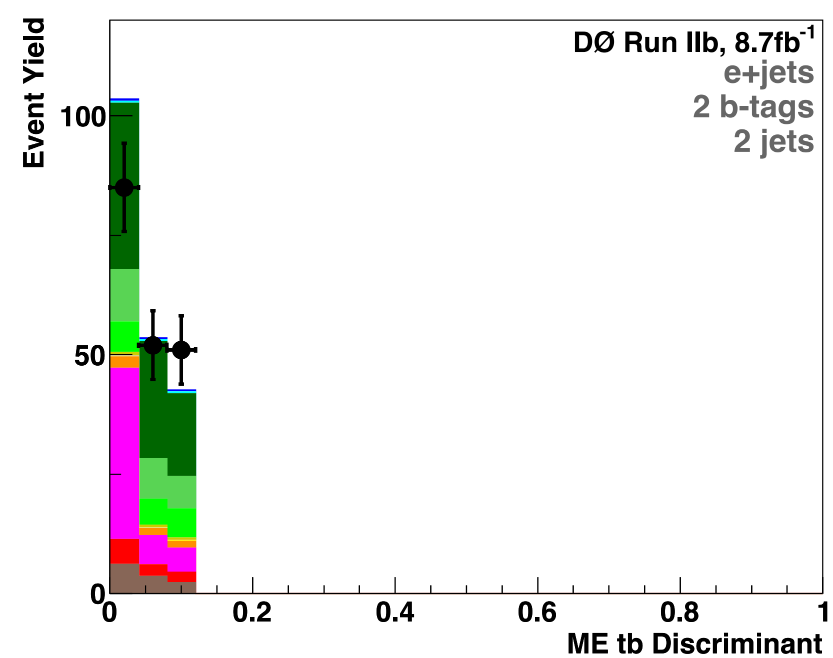
before corrections





after corrections





3 Methods for HF Scales

- Method 1: Use zero tagged samples

$$N^{(0)} = N^{(0)}_{wlp} + \lambda_{HF} N^{(0)}_{whp}$$

- Method 2: Normalize to Data in the orthogonal(0) and tagged(1) samples

$$N^{(0)} = \lambda(N^{(0)}_{wlp} + \lambda_{HF} N^{(0)}_{whp})$$

$$N^{(1)} = \lambda(N^{(1)}_{wlp} + \lambda_{HF} N^{(1)}_{whp})$$

- Method 3: Minimize χ^2 for b-ID outputs

$$\chi^2(\lambda_{HF}) = \sum_i \frac{[N_i - \lambda(\lambda_{HF})(N_{wlp,i} + \lambda_{HF} N_{whp,i})]^2}{E_i^2 + E^2_{wlp.i} + E^2_{whp,i}}$$

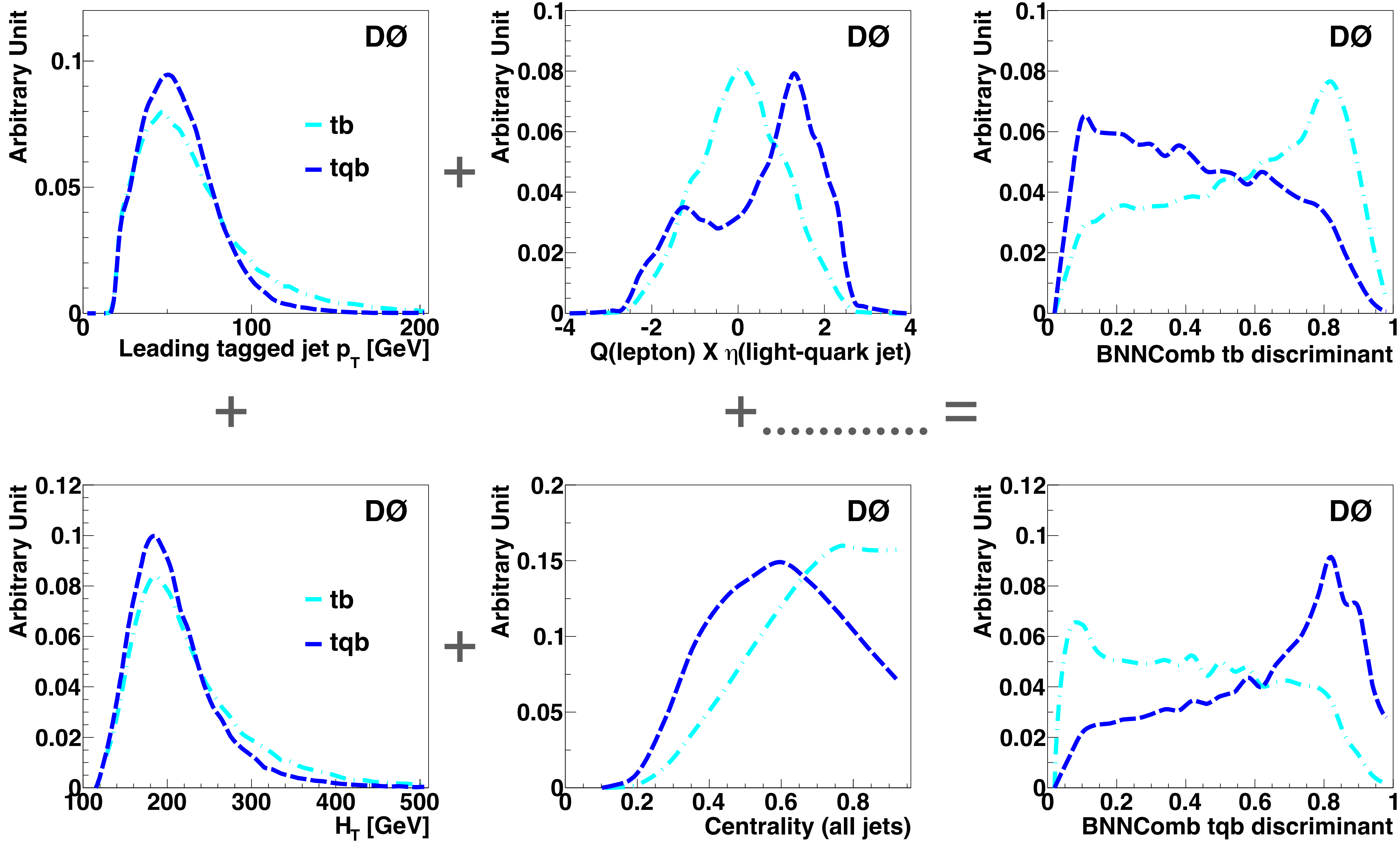
Heavy Flavor Scale Factor

- Derived the heavy flavor scale factor with the new HF corrected samples

	λ	λ_{HF}
Method 1	1	1.01± 0.03
Method 2	1.00	0.98± 0.03
Method 3	1.00	1.04± 0.05

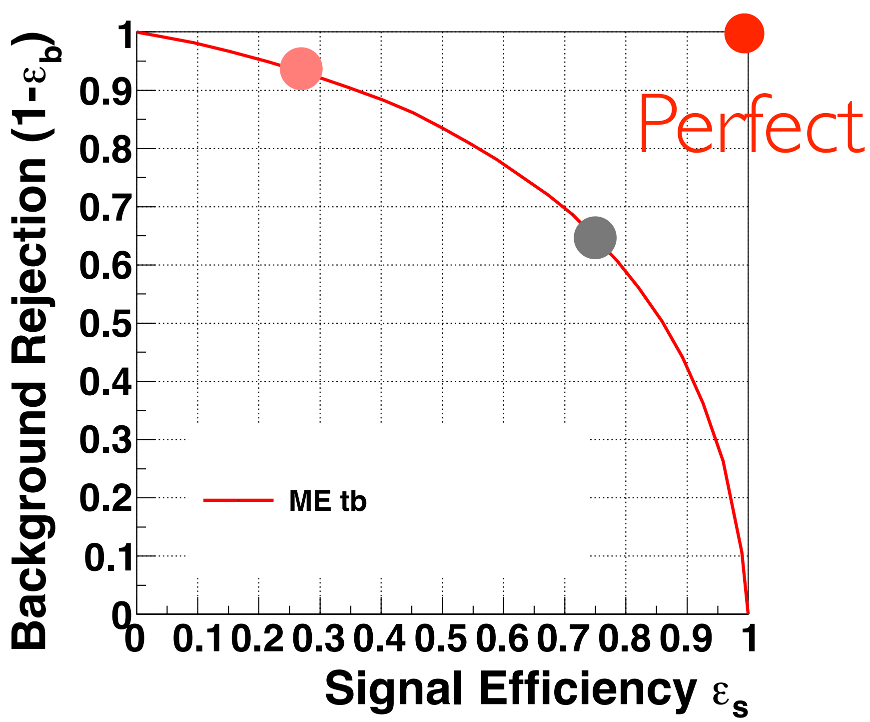
- The heavy flavor scale factors derived from all the three method are consistent with one
- λ_{HF} was 1.0 from M1 but 0.8 from M2 and M3

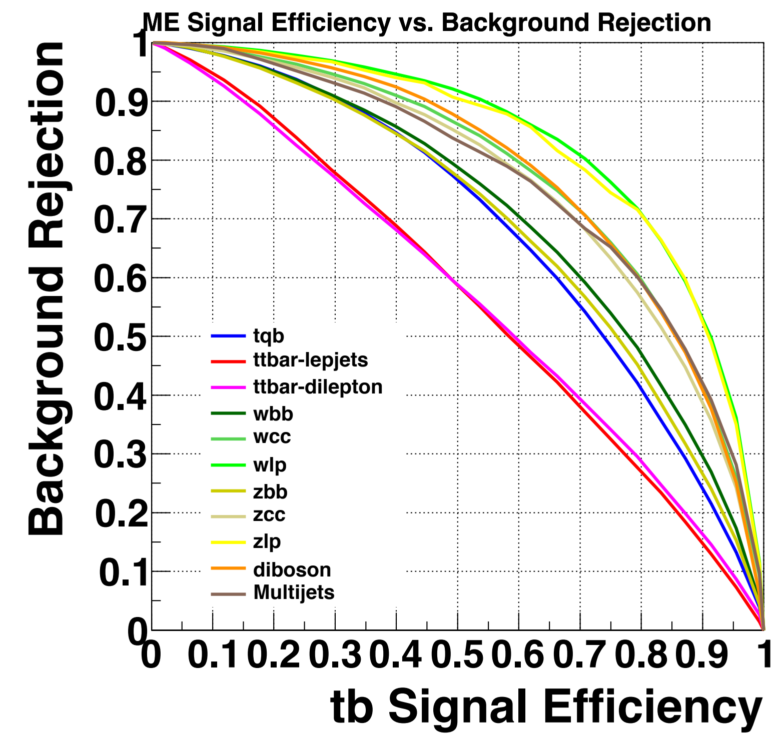
tb versus *tqb*

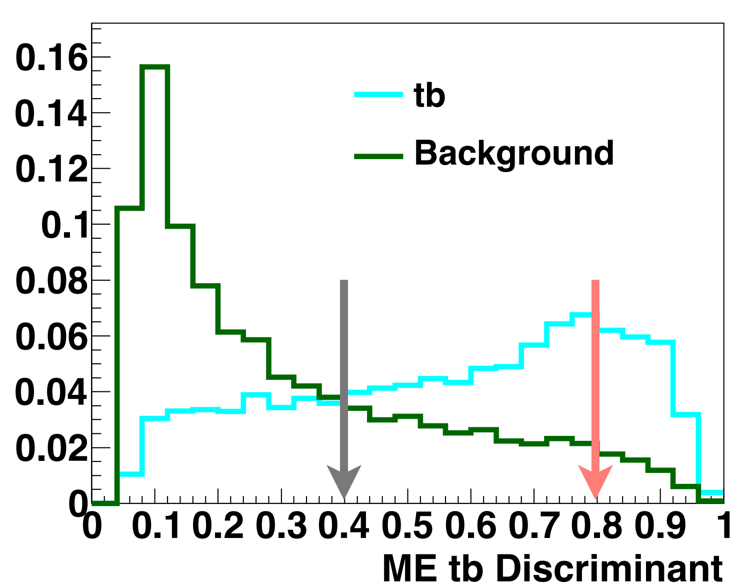


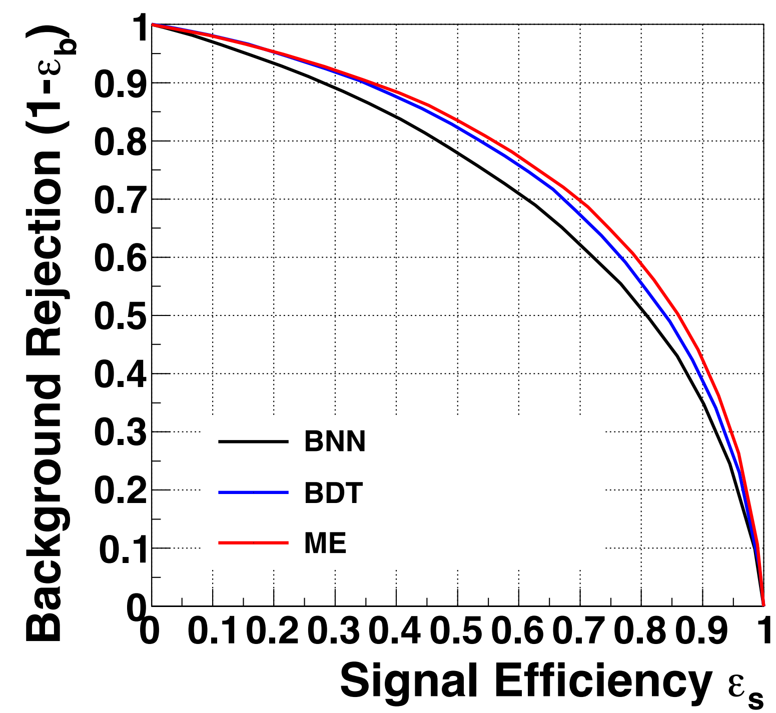
s-channel Performance

2 *b*-tags, 2 jets



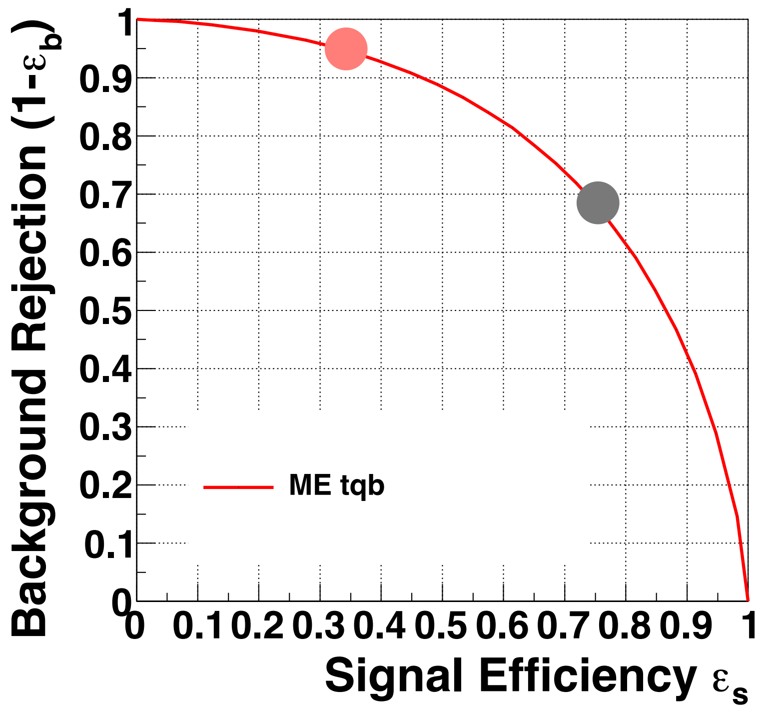


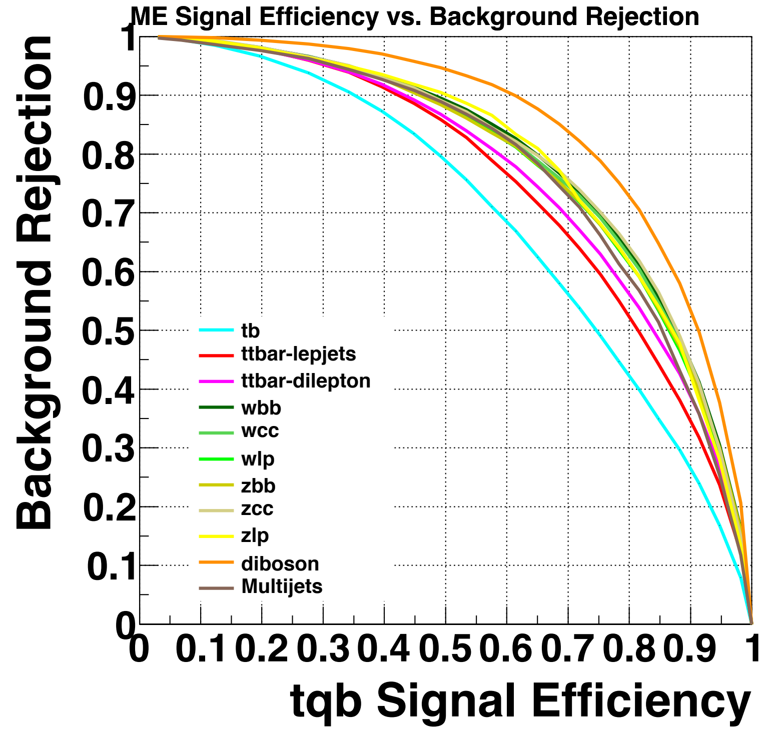


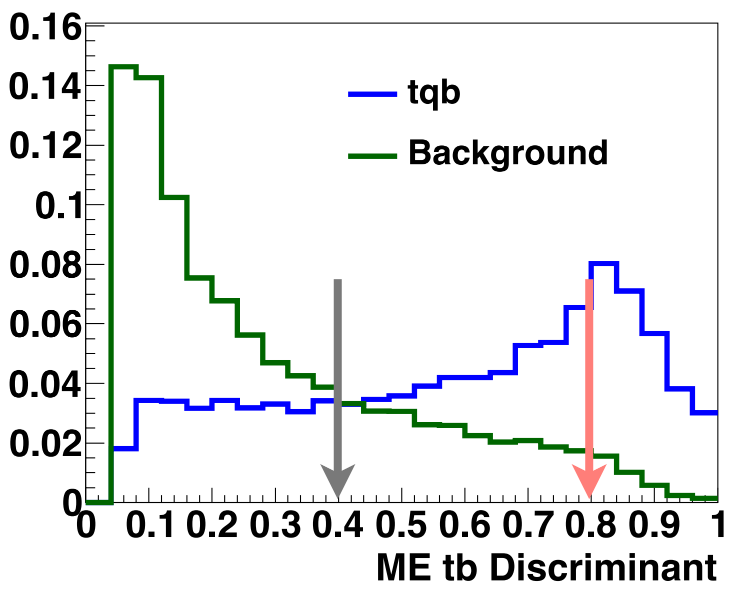


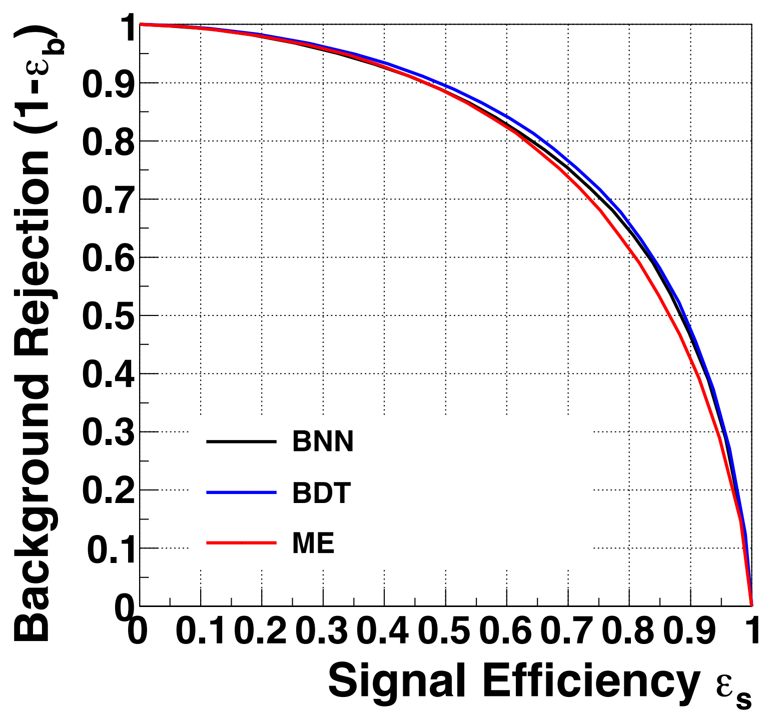
t-channel Performance

1 *b*-tag, 2 jets









Final tqb Discriminant

- ME discriminant: likelihood ratio

$$D(x) = \frac{P_{sig}(x)}{P_{sig}(x) + P_{bkgd}(x)}$$

- Include *b*-ID outputs in the probability: P→P^{bl}

	b	l	weight
Assignment 1	jet1	jet2	btag1×(1-btag2)
Assignment 2	jet2	jet1	(1-btag1)×btag2

$$P^{bl} = \frac{w_1 d\sigma_1 + w_2 d\sigma_2}{(w_1 + w_2)\sigma}$$

Final tb Discriminant

- b-ID outputs washed out by symmetric final states in 2 jet (sensitive to the *s*-channel)
- Use the probability without the *b*-ID outputs

$$P = \frac{d\sigma_1 + d\sigma_2}{\sigma}$$

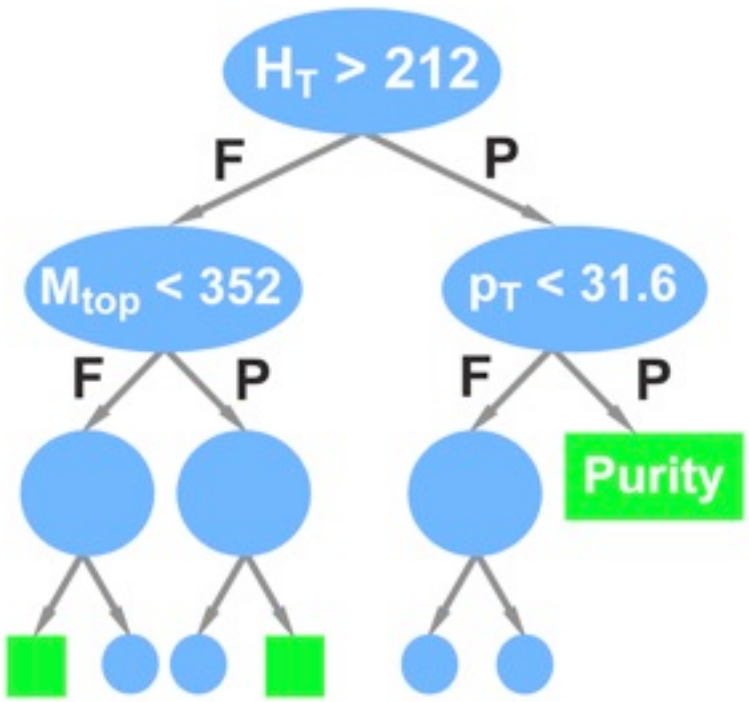
- Include the *b*-ID outputs according to each process

$$D(\vec{x}) = \frac{b \cdot P_S(\vec{x})}{b \cdot P_S(\vec{x}) + b \cdot P_{B:b-fs}(\vec{x}) + (1-b) \cdot P_{B:light-fs}(\vec{x})}$$

$$b = \mathrm{btag1} \cdot \mathrm{btag2};\ 1 - b = (1 - \mathrm{btag1})(1 - \mathrm{btag2})$$

Boosted Decision Tree

- Apply sequential cuts but keep the failing events
- Train another tree produced by enhancing misclassified events (boosting)
- Average multiple trees and boost the performance

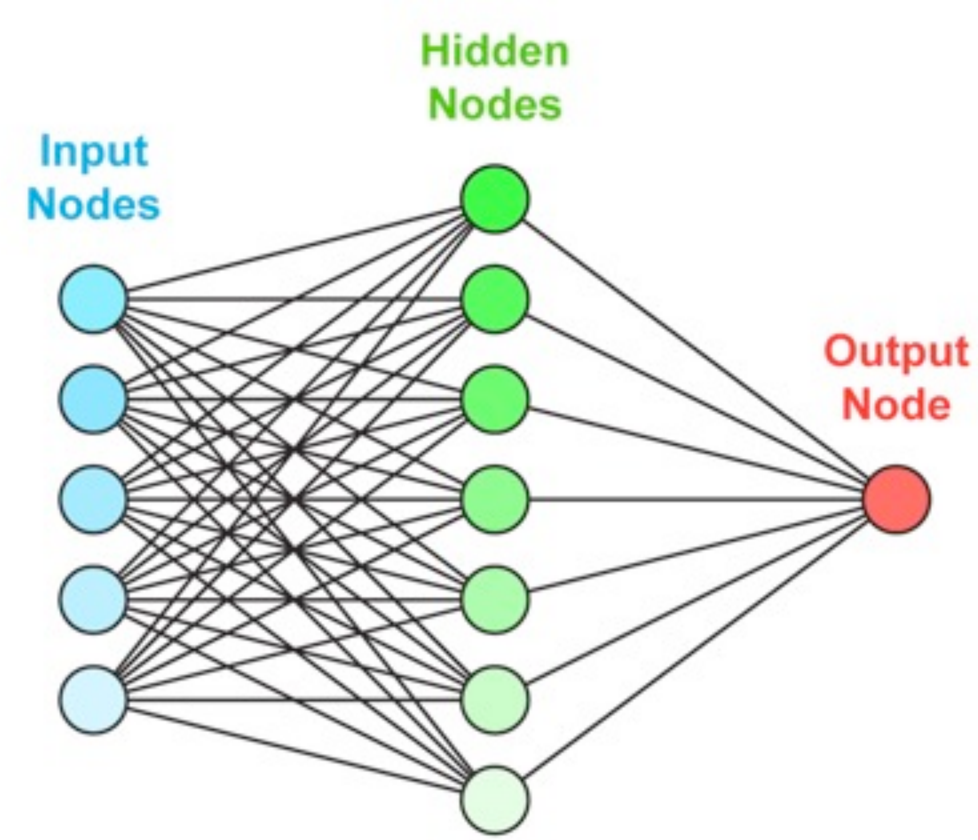


- Up to 30 variables

#	BDT input variables
1	$\not{E}_T$
2	$p_T(\ell)$
3	$\eta(\ell)$
4	$M(\text{jet1})$
5	$p_T(\text{untag1})$
6	$E(untag1)$
7	$M(untag1)$
8	$b_{\text{ID}}(\text{untag1})$
9	$p_T(\text{jet2})$
10	$b_{\text{ID}}(\text{tag1})$
11	$\Delta R(\text{jet1}, \text{jet2})$
12	$\Delta R_{\text{min}}(\ell, \text{jet})$
13	$\Delta\Phi(\ell, \not{E}_T)$
14	$\Delta\Phi(\text{jet2}, \not{E}_T)$
15	$\Delta\Phi(\text{jet1}, \not{E}_T)$
16	$Q(\ell) \times \eta(\text{untag1})$
17	$Q(\ell) \times \eta(\text{jet2})$
18	$Q(\ell) \times \eta(\ell)$
19	$Q(\ell) \times \eta(\text{tag1})$
20	$Q(\ell) \times \eta(\text{jet1})$
21	$\cos(\ell, \text{jet2})_{\text{lab}}$
22	$\cos(\ell, \text{jet1})_{\text{lab}}$
23	$H_T(\text{alljets})$
24	$H_T(\ell, \not{E}_T, \text{alljets})$
25	$H_T(\ell, \not{E}_T)$
26	$\text{Centrality}(\text{alljets})$
27	$M\text{jet1}, \text{jet2})$
28	$p_T(\text{jet1}, \text{jet2})$
29	$M_T(W)$
30	$p_T(W)$

Bayesian Neural Network

- NN produces a probability of an event to be produced by signal processes
- Average over many networks and improve the performance

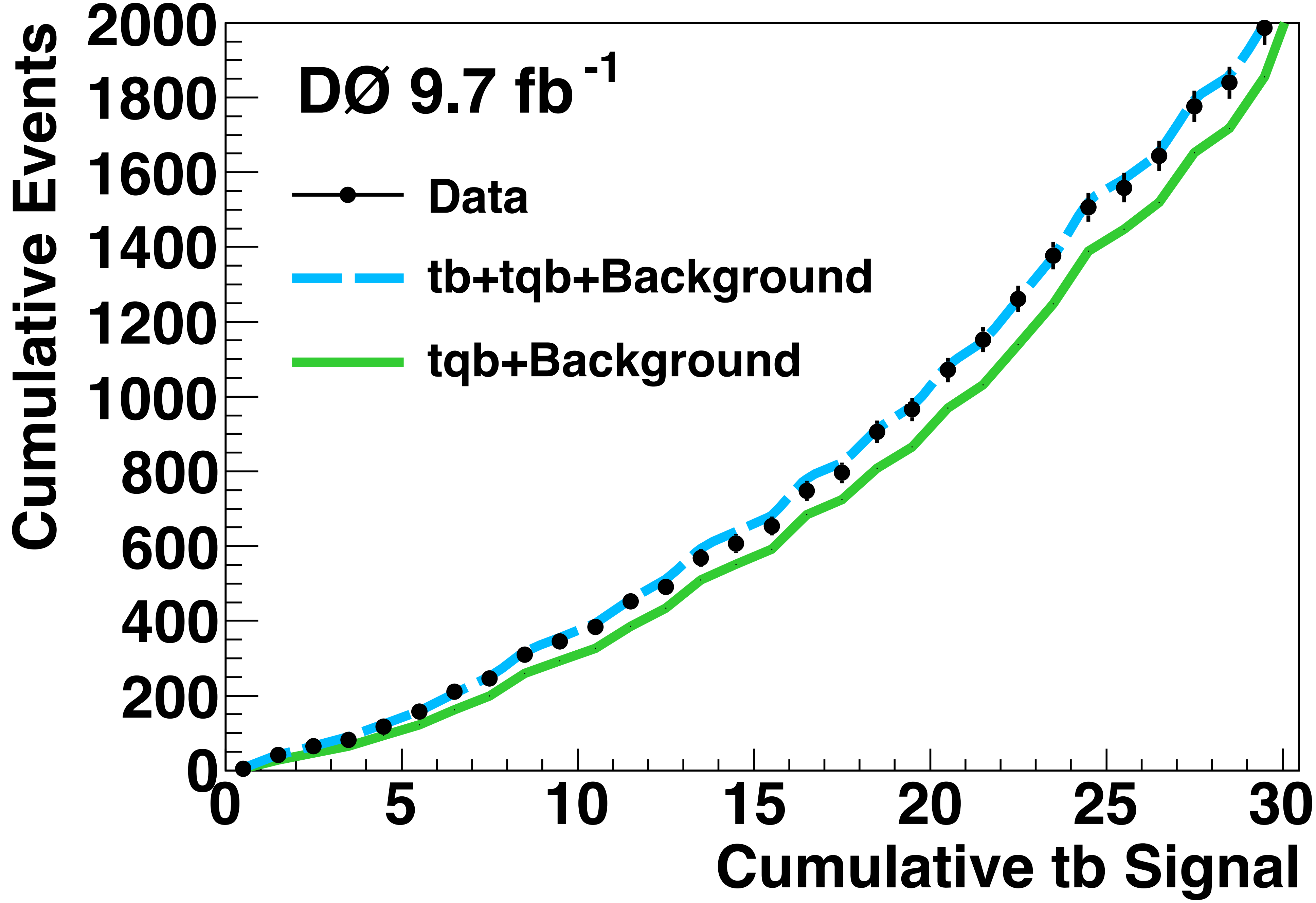


- Up to 21 variables

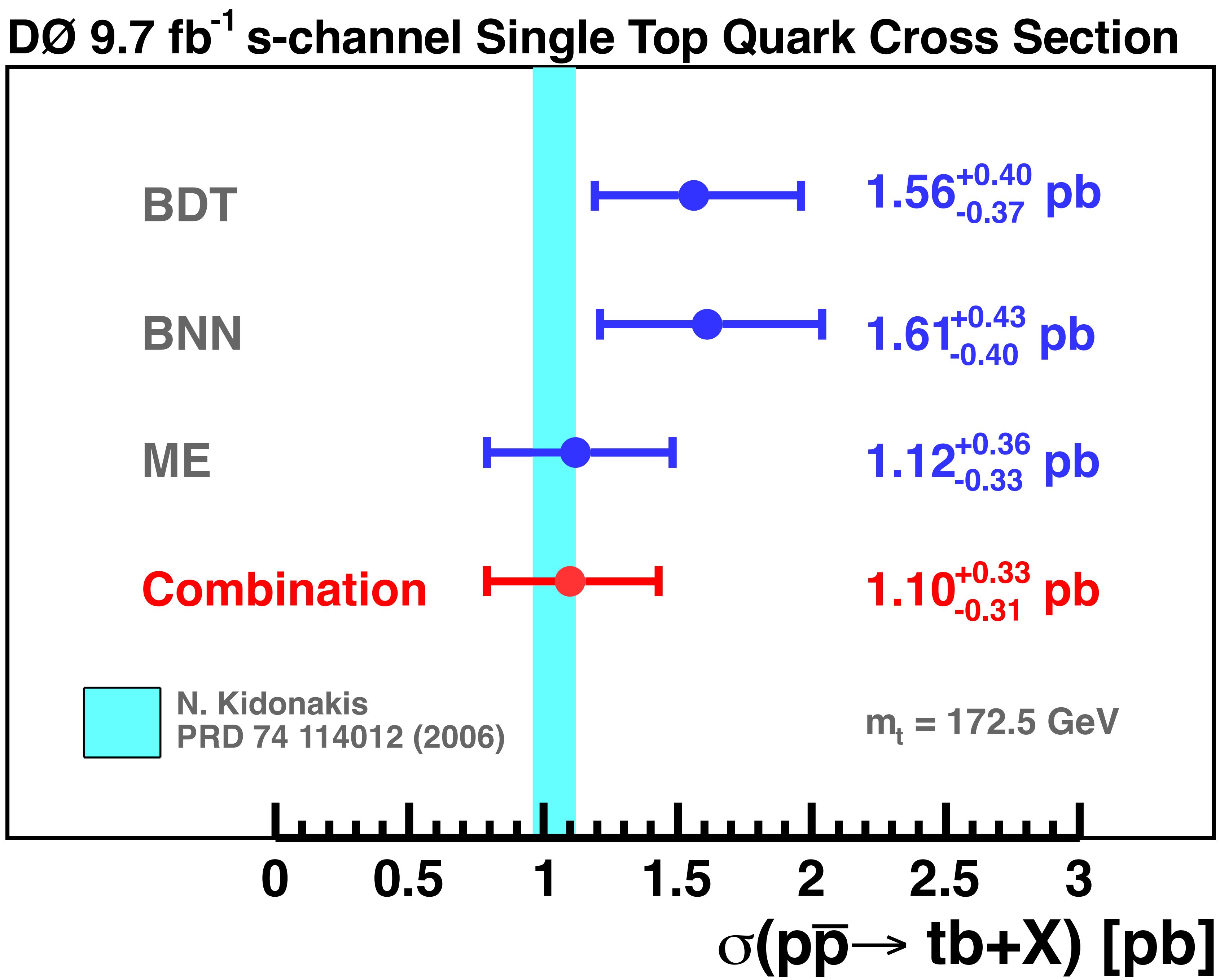
#	BNN input variables
1	$p_T(\mathrm{tag1})$
2	$\eta(\mathrm{tag1})$
3	$\Delta\Phi(\ell, \mathrm{tag1})$
4	$b_{\mathrm{ID}}(\mathrm{tag1})$
5	$p_T(\mathrm{untag1})$
6	$\eta(\mathrm{untag1})$
7	$\Delta\Phi(\ell, \mathrm{untag1})$
8	$b_{\mathrm{ID}}(\mathrm{untag1})$
9	$p_T(\ell)$
10	$\eta(\ell)$
11	$\not{E}_T$
12	$\Delta\Phi(\ell, \not{E}_T)$
13	$p_T(\mathrm{tag2})$
14	$\eta(\mathrm{tag2})$
15	$\Delta\Phi(\ell, \mathrm{tag2})$
16	$b_{\mathrm{ID}}(\mathrm{tag2})$
17	$p_T(\mathrm{untag2})$
18	$\eta(\mathrm{untag2})$
19	$b_{\mathrm{ID}}(\mathrm{untag2})$
20	$M_T(W)$
21	$Q(\ell) \times \eta(\mathrm{untag1})$

Cumulative *tb*-Signal Plot

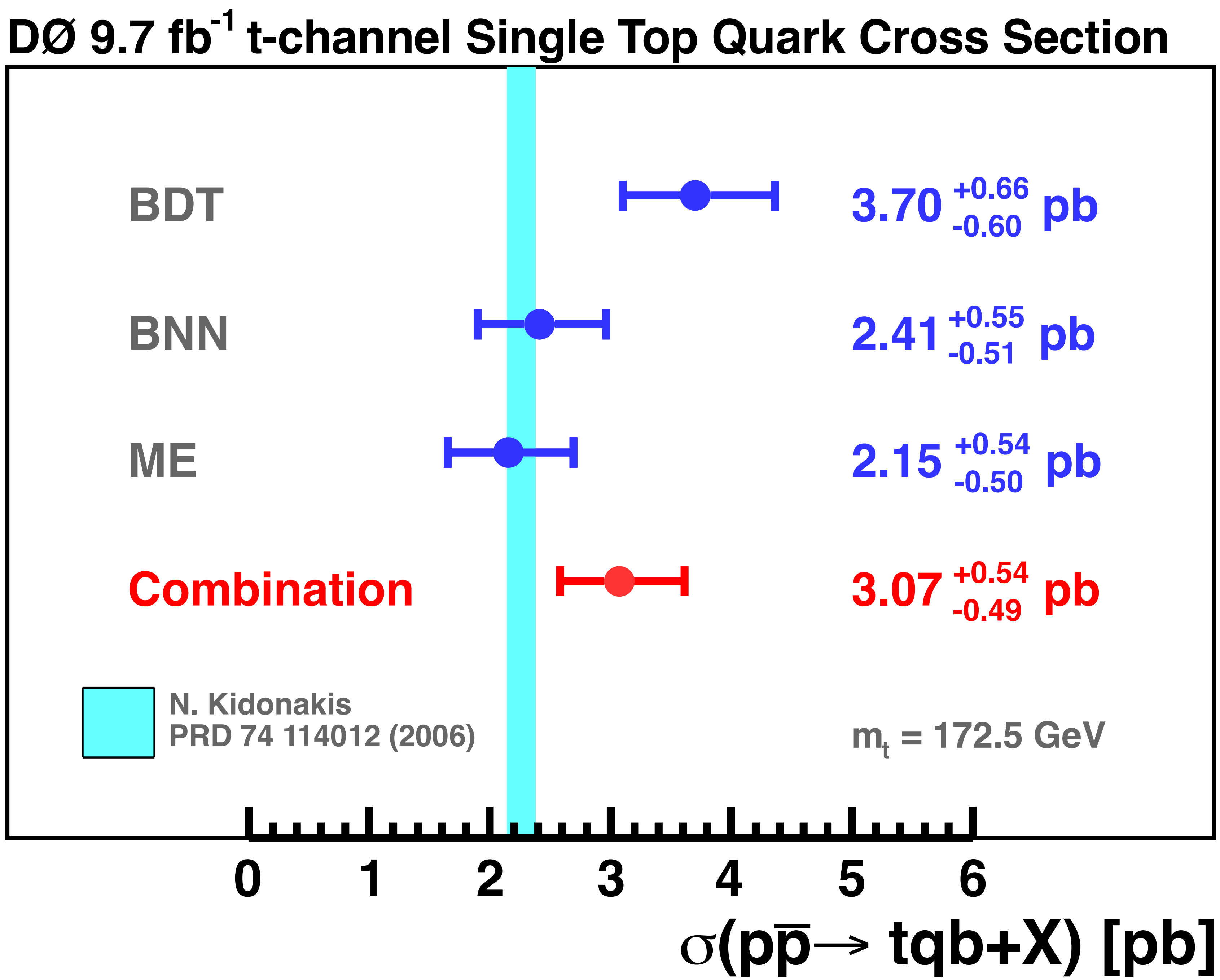
Integrating from the high significance bins backward



Summary of *tb* Results



Summary of *tqb* Results



Bayesian Approach

- Bayes' theorem

$$p(\sigma|D) = \frac{p(D|\sigma)p(\sigma)}{p(D)}$$

- Posterior p.d.f.

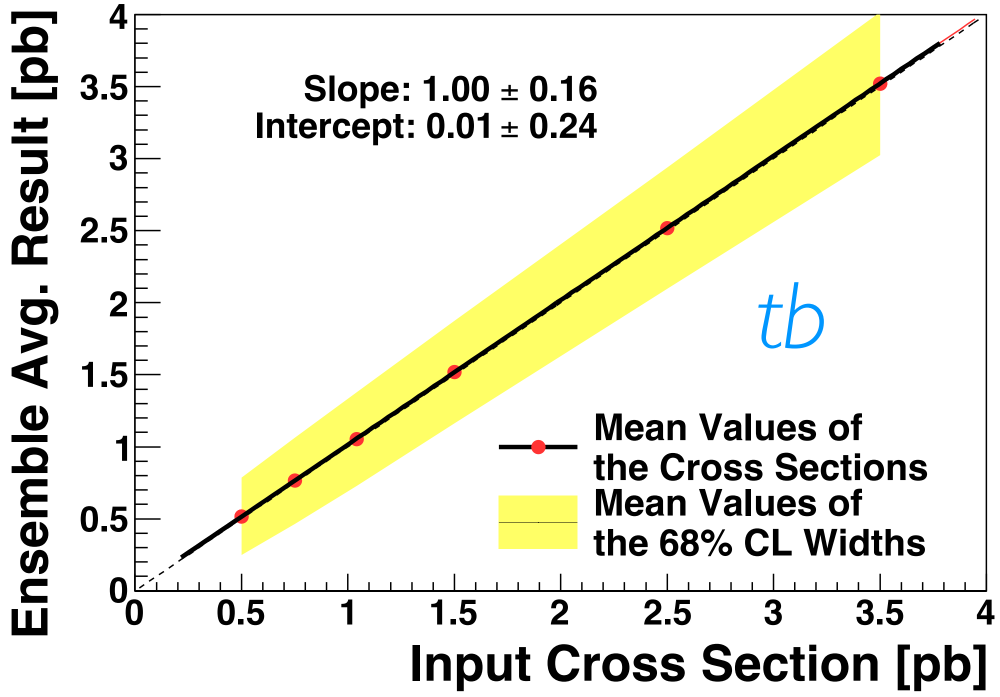
$$p(\sigma|D) = \frac{L(D|\sigma)\pi(\sigma)}{\int L(D|\sigma')\pi(\sigma')d\sigma'}$$

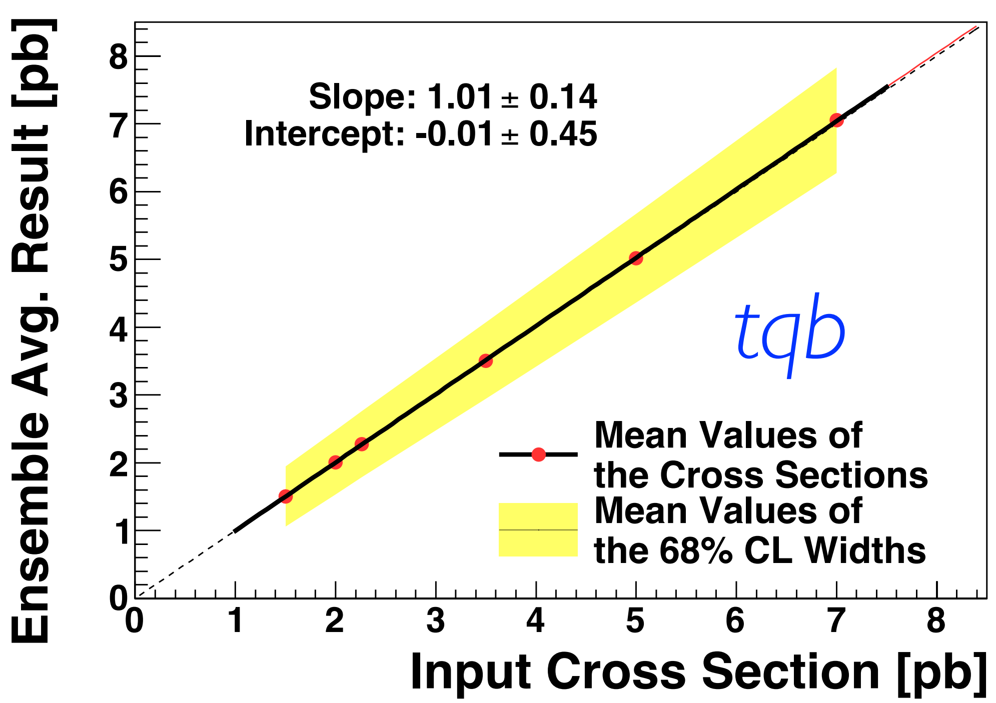
- Poisson distribution

$$L(D|d) = \frac{e^{-d}d^{D}}{\Gamma(D+1)}$$

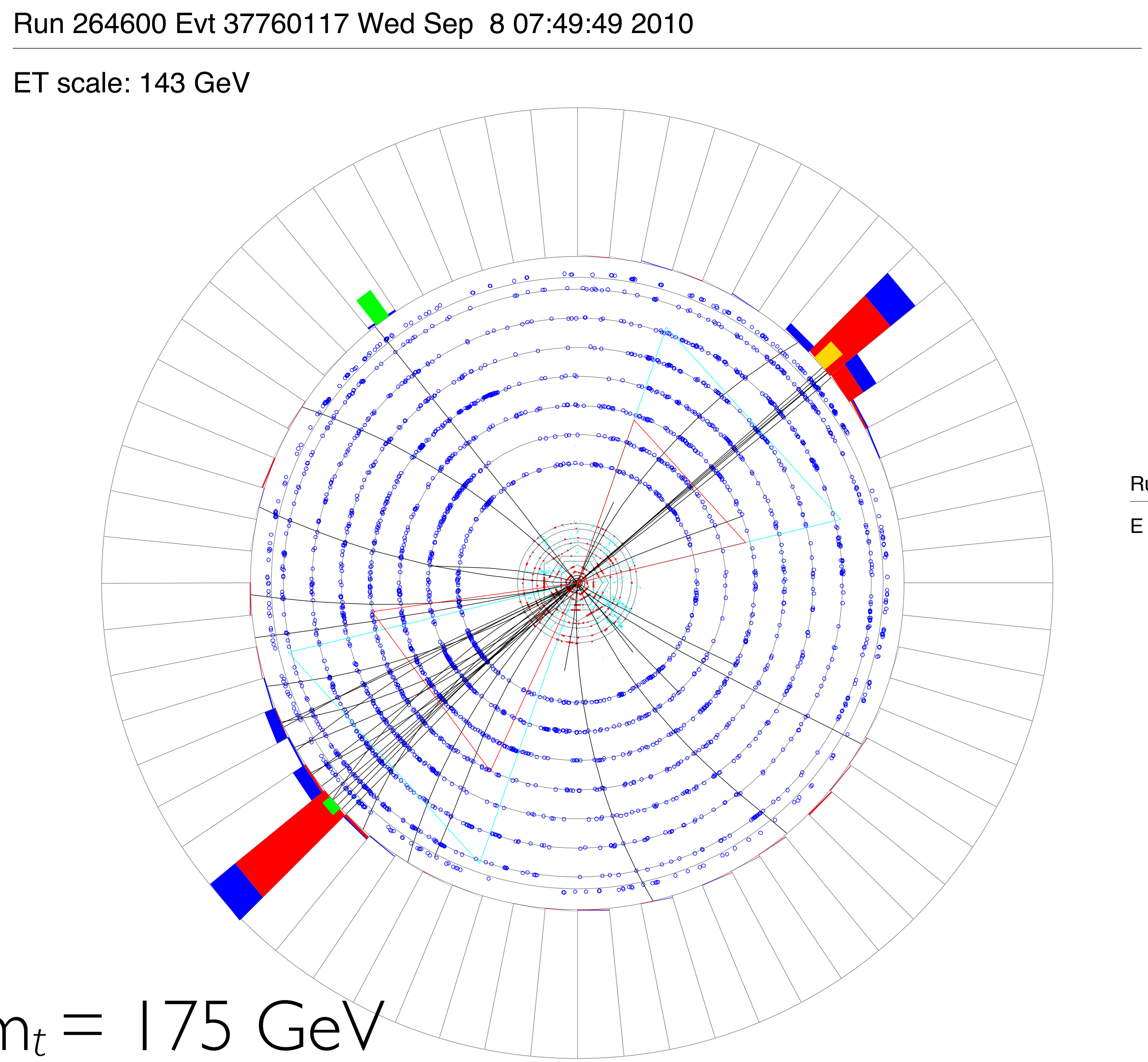
Ensemble Test

- Generate ensembles of pseudo-data samples
  - Each ensemble has a different input signal **σ**
  - All systematics included
- Extract the signal cross section from each pseudo-data sample
- No calibration needed

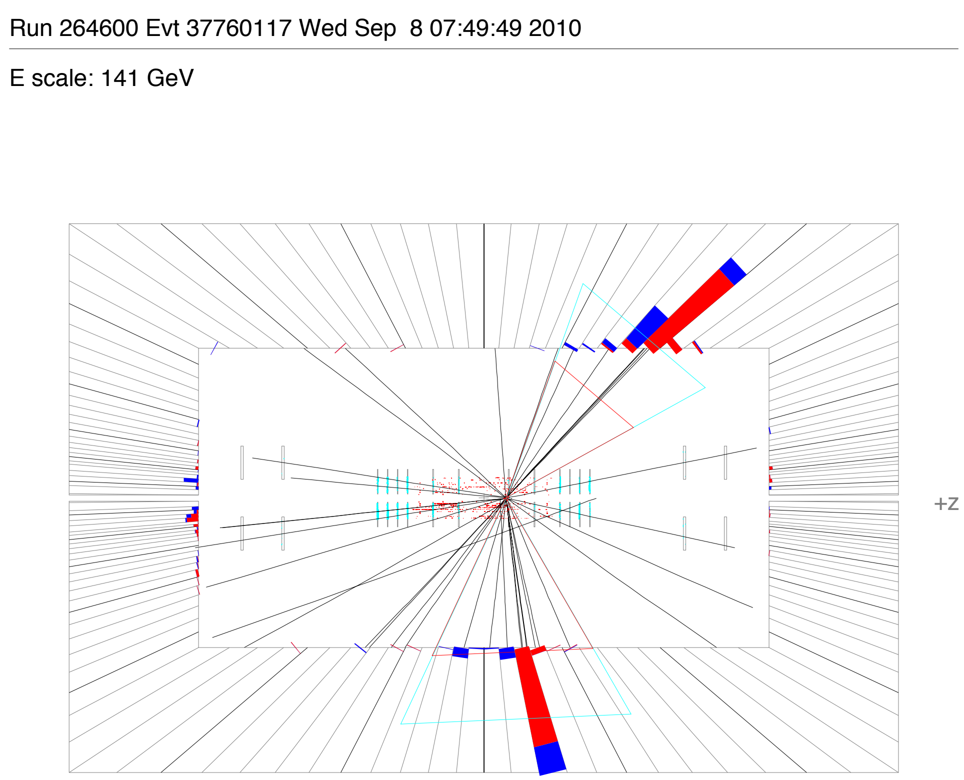




Another *tb* Candidate

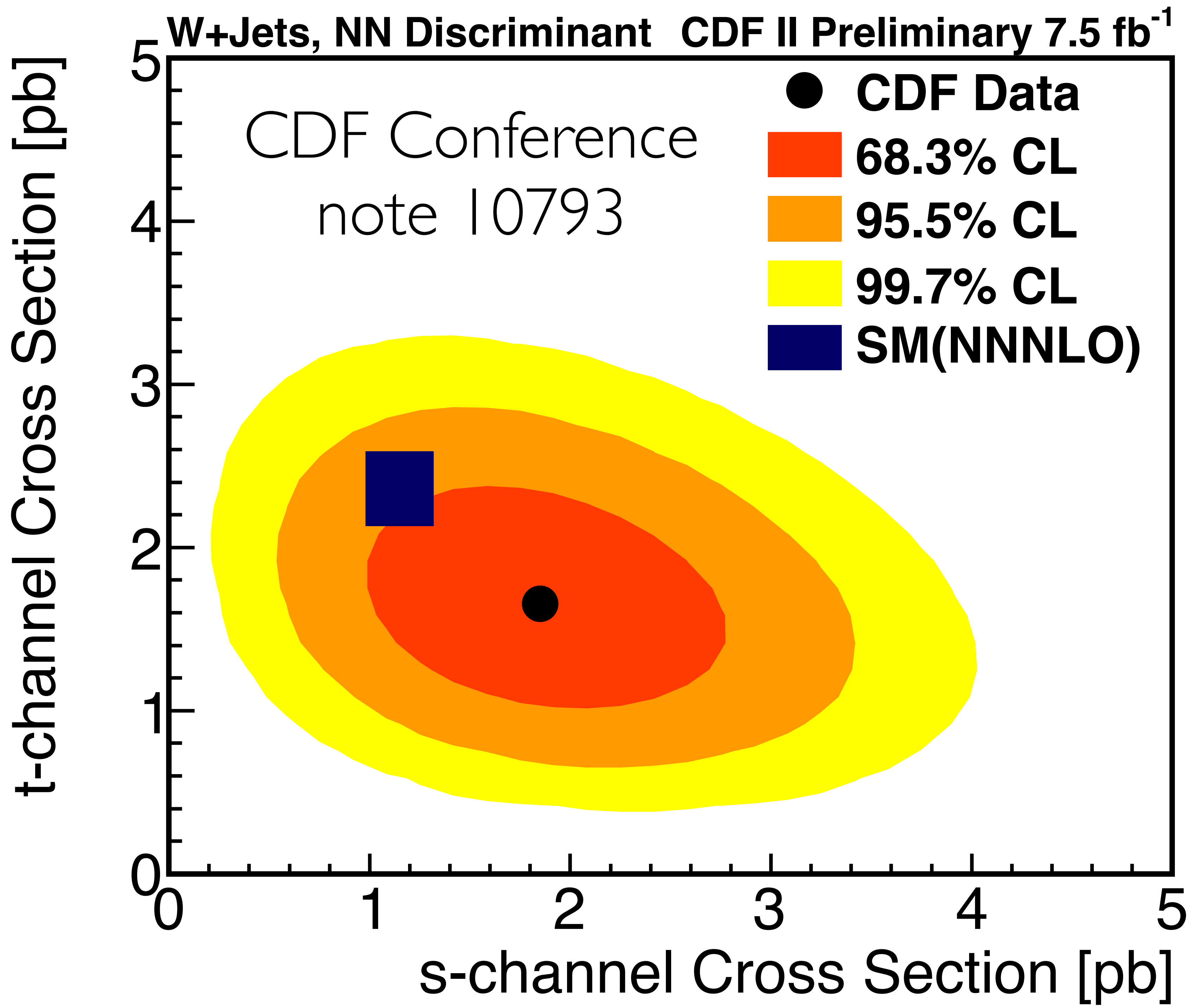


Run 264600
Event 37760117
Wed. Sep. 8 07:49:49 2010



m_t = 175 GeV
Jet1 b-tag: 0.32
Jet2 b-tag: 0.39

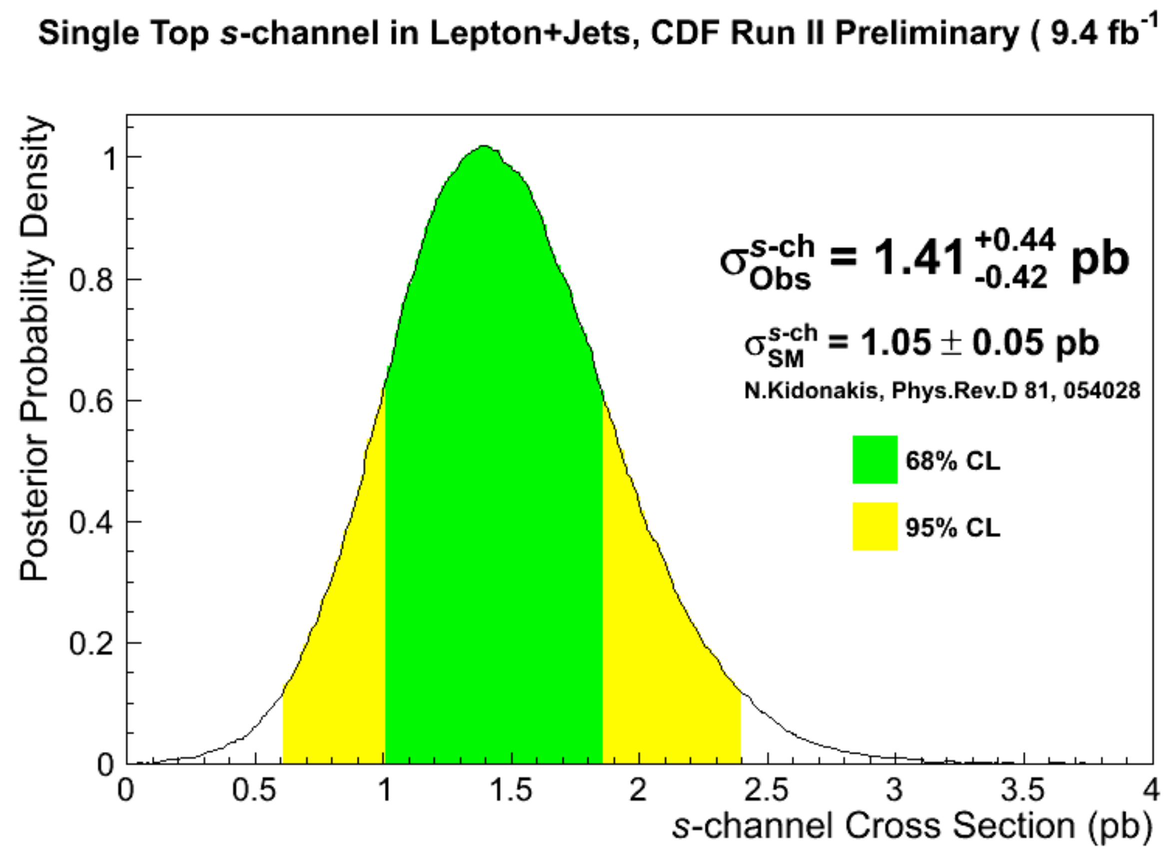
CDF Result 7.5 fb^{-1}



CDF Confirms Our Result

- In August, CDF also has the *tb* single top cross section measurement with 9.4 fb^{-1} (preliminary)
  - assumes the SM *tqb* production
  - has evidence of the *tb* production
    - σ_{tb} = 1.41± 0.44 pb
    - Significance: 3.8 SD (expected 2.9 SD)
  - confirms our result!

CDF presentation at DPF



CDF 9.4 fb^{-1}: Event Yield

Category	TT	TL	T	LL
WW	1.7±0.4	13.2±2.7	184±23	24.8±3.9
WZ	17.8±2.2	21.2±2.0	52.7±5.4	9.9±0.9
ZZ	2.4±0.3	2.4±0.2	7.1±0.7	0.96±0.08
Z + jets	10.9±1.2	20.7±2.3	163±18	27.1±3.1
$t\bar{t}$	163±21	194±19	502±50	58.1±6.6
Higgs	6.1±0.6	6.4±0.4	10.3±0.7	1.7±0.2
Wbb	246±99	327±130	1166±468	109±44
Wcc	19.0±7.8	120±49	1158±467	164±67
W + Mistag	4.3±1.3	62±13	978±141	242±34
Multijet	29±12	47±19	281±112	45±18
t and Wt-channel	18.1±2.5	35.3±4.2	251±28	13.6±1.5
s-channel	54.5±6.7	61.2±5.6	109±10	17.8±2.1
Total Prediction	573±155	911±248	4860±1320	714±181
Observed	466	765	4620	718
Significance	2.52	2.21	1.60	0.66

CDF 9.4 fb^{-1}: Systematics

Source of uncertainty	Rate	Shape	Affected samples
b tagging scale factor uncertainty	4%-18%		$t\bar{t}$, single top, WZ, ZZ, Higgs
Charm mistag rate	7%-37%		WW
W+jets mistag rate	4%-37%		W + Mistag jets
Luminosity uncertainty	6%		$t\bar{t}$, single top, diboson, Higgs
Lepton acceptance uncertainty	2%-4%		$t\bar{t}$, single top, diboson, Higgs
Cross section uncertainty	6%-10%		$t\bar{t}$, single top, diboson, Higgs
Initial/Final state radiation	0%-10%	√	$t\bar{t}$, single top
Multijet normalization	40%		Multijet
Z+jets normalization	45%		Z+jets
Wbb and Wcc normalization	30%		Wbb, Wcc
Wc normalization	30%		Wc
Jet energy scale	0%-10%	√	All
Normalization and factorization scale		√	W+jets
Electron multijet background		√	Electron multijet