Measuring Single Top Quark Production at DØ With The Matrix Element Method

- The Tevatron and The DØ Experiment
- The Top Quark and Single Top Production
- Single Top Event Signature At DØ
- Tevatron Run IIa Dataset
  - Analysis Strategy and Background Estimation
- Matrix Element Method
- Single Top Results with ~1 fb^{-1}

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Ph. D. Thesis Defense
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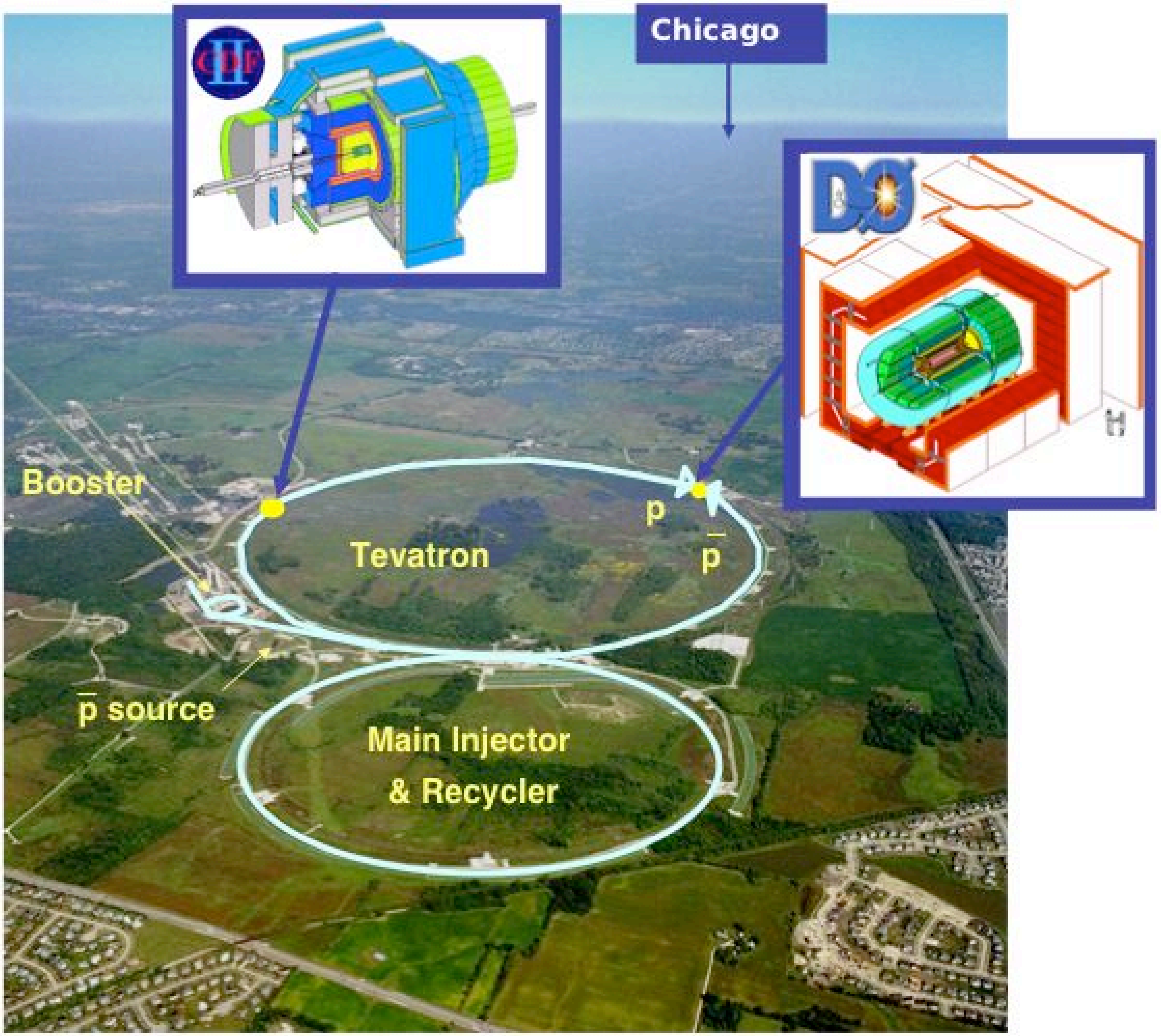
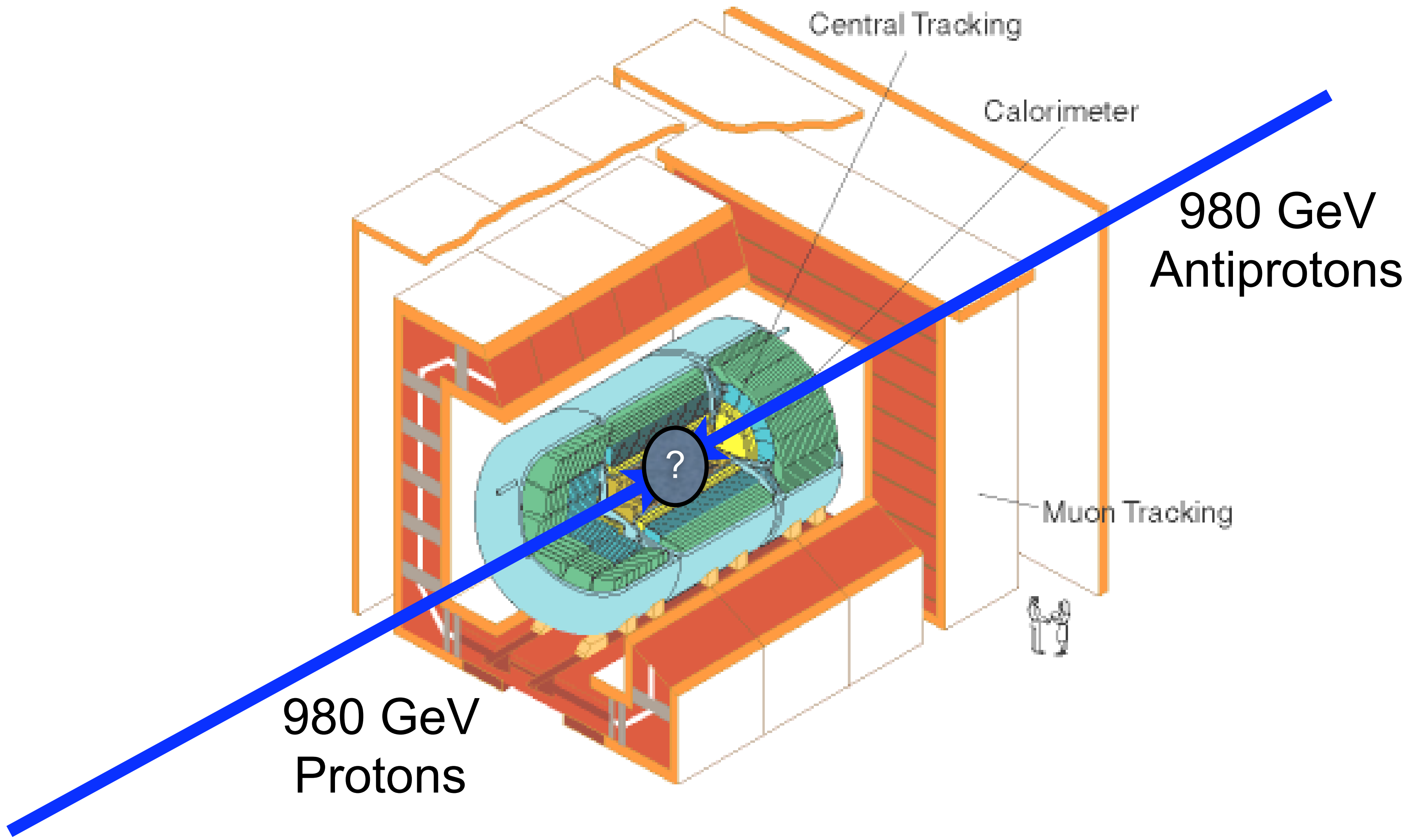
The Tevatron at Fermilab

- Tevatron is a proton-antiproton collider
- World's highest energy particle accelerator
  - $\sqrt{s}$ = 1.96 TeV
- Run I: 1992-1996
  - Top discovery in 1995!
- Run II: 2001 - Present
  - B_s Mixing in 2006
  - Limits on SUSY and Higgs production
- Currently, the only place in the world to study the top quark

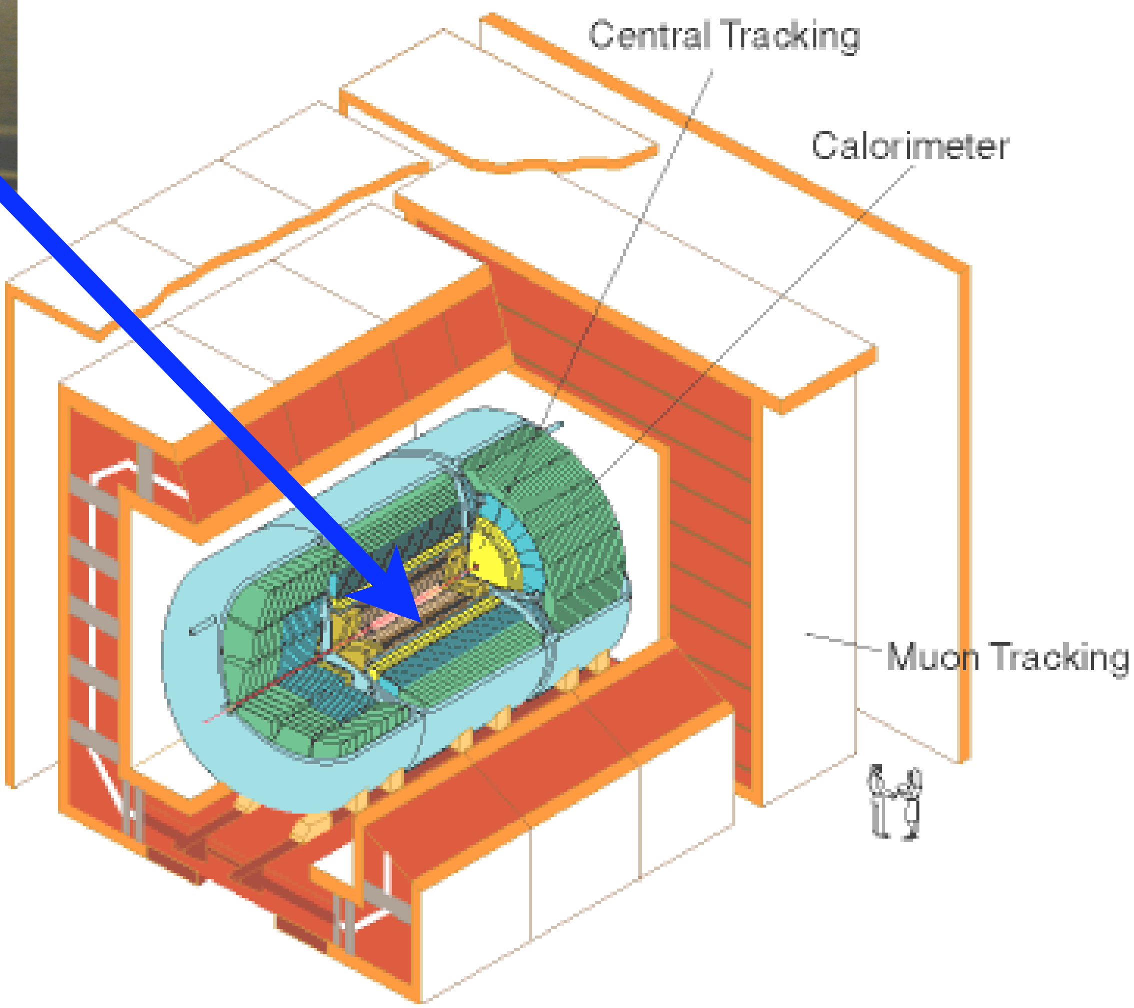


The Run II DØ Experiment



The Run II DØ Experiment

<u>Silicon Detector</u>
Vertex measurement
and tracking close to PV



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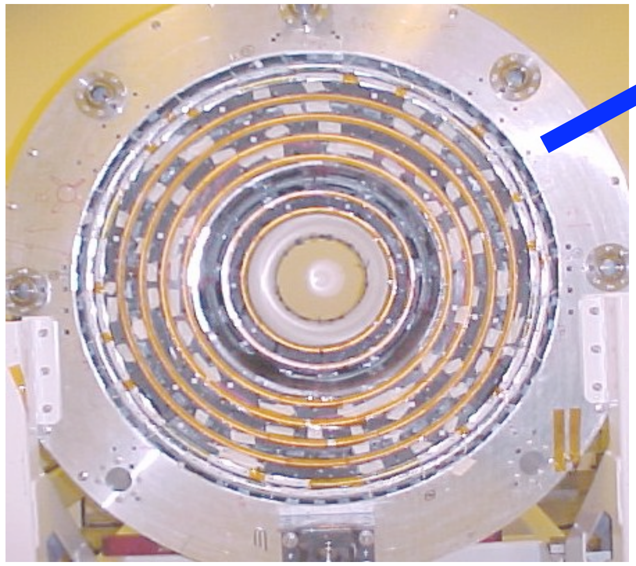
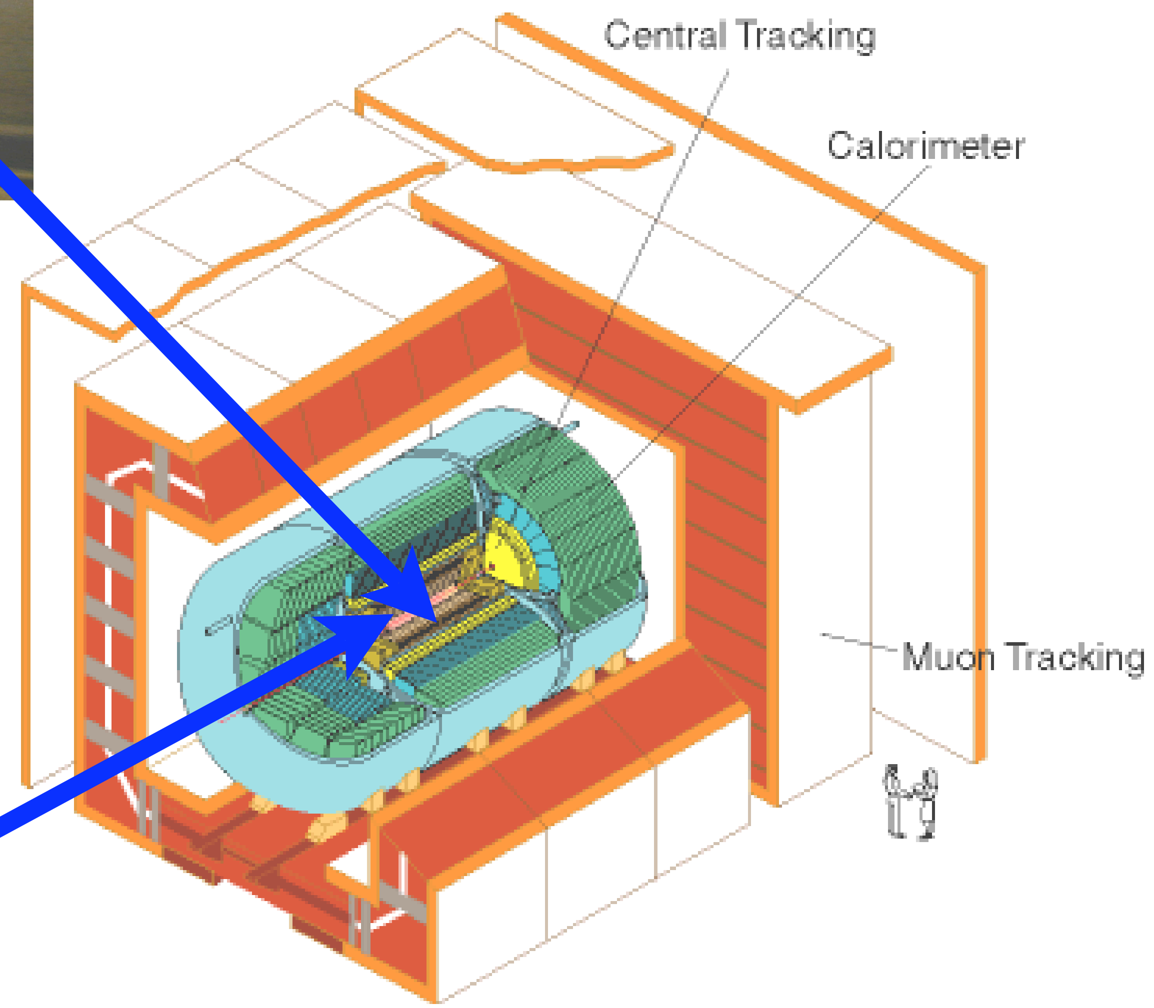
<u>Fiber Tracker</u>
Charged particle tracking
momentum + charge





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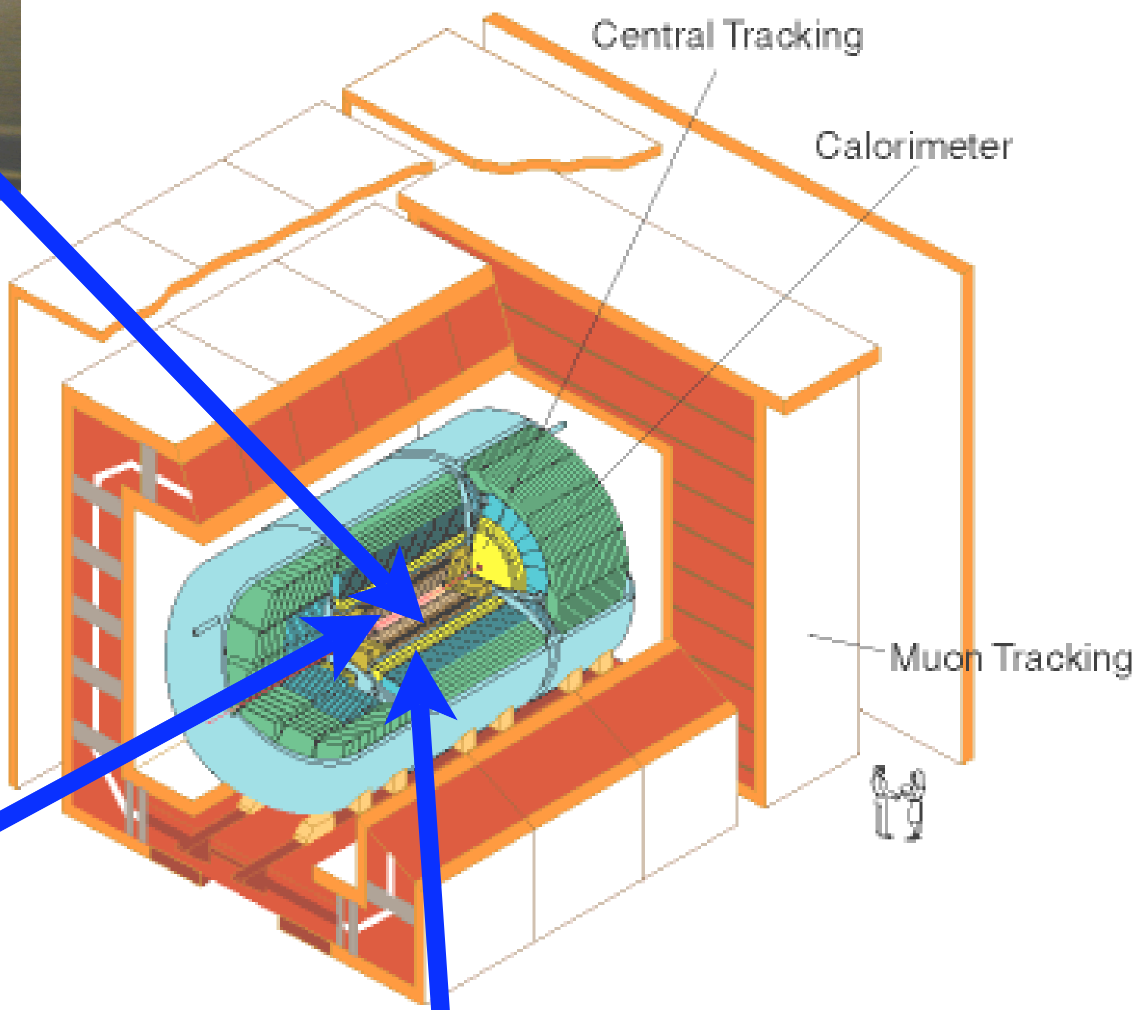

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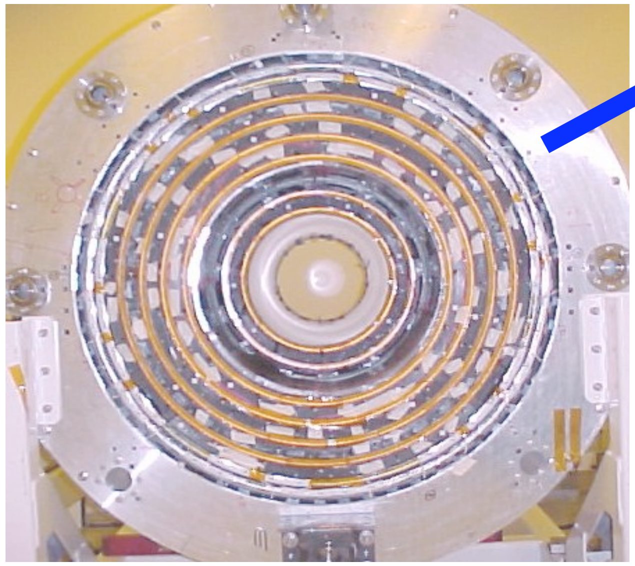
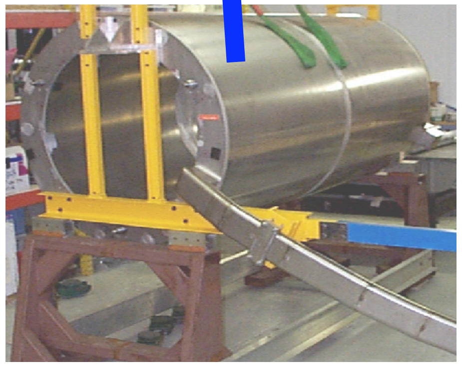


<u>Solenoid</u>
Trackers in
2 Telsa



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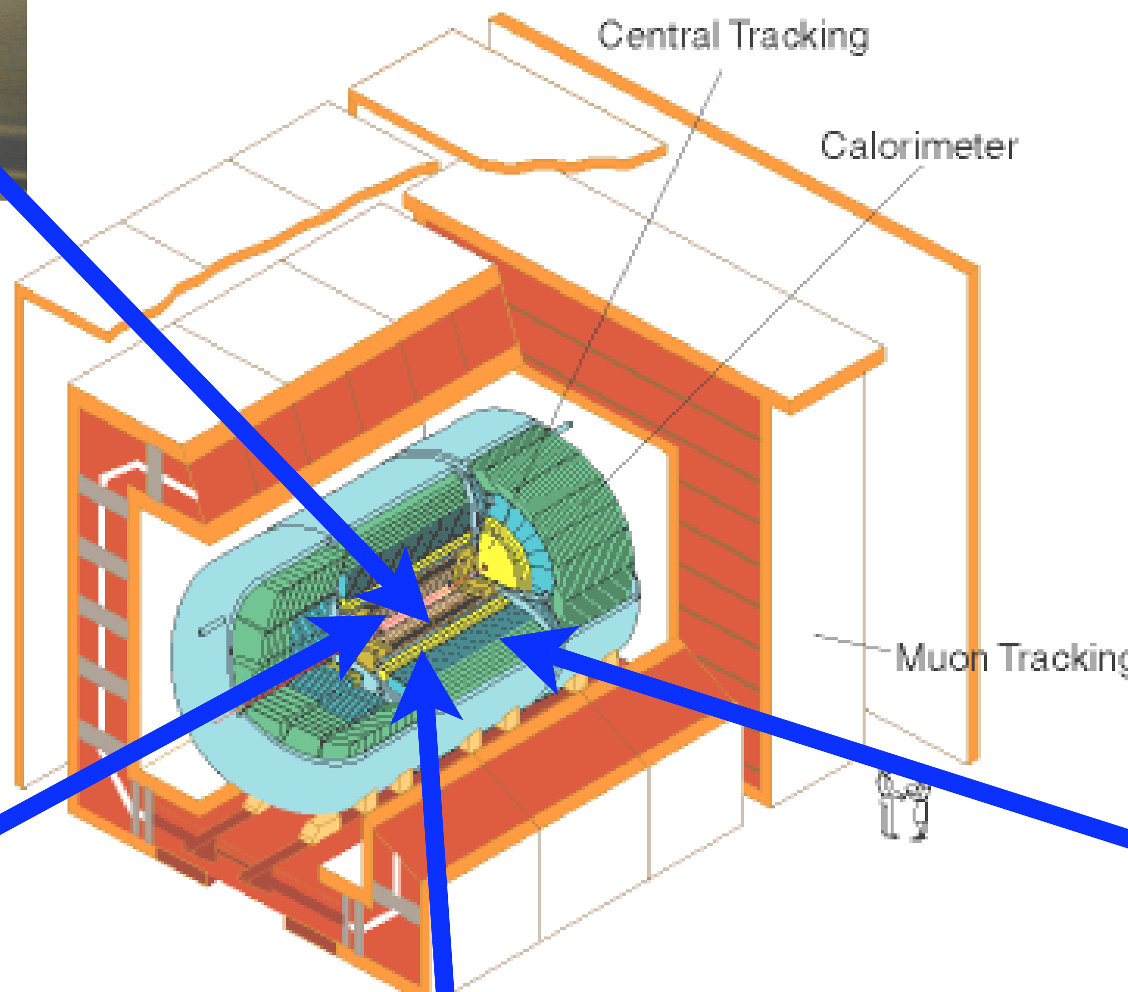

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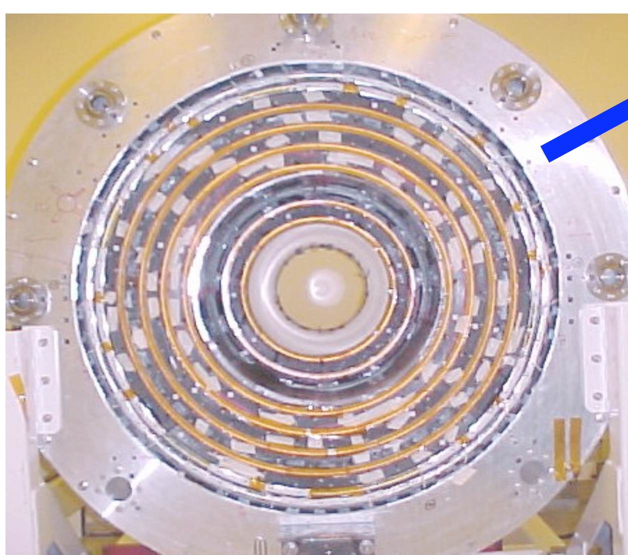

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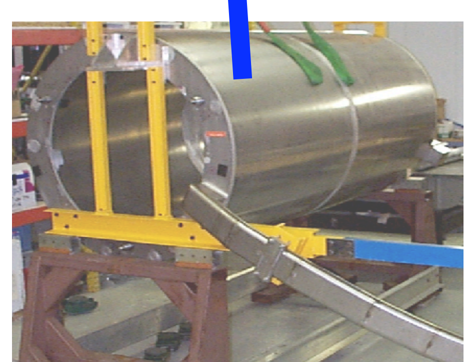
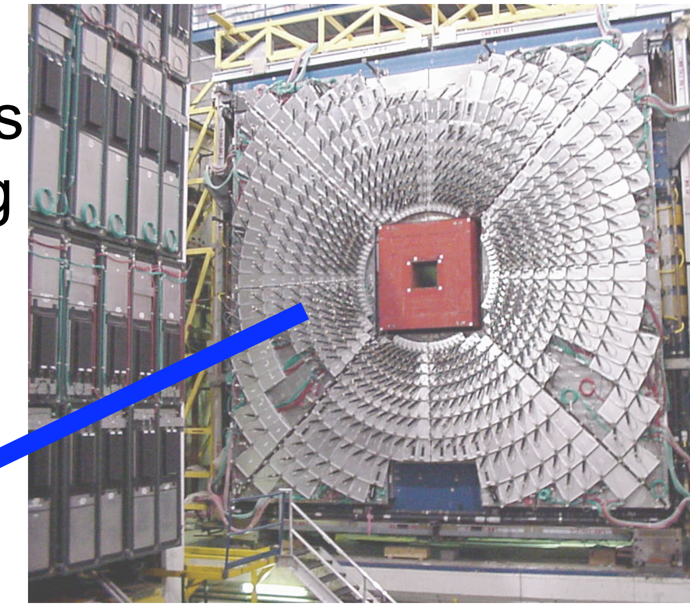


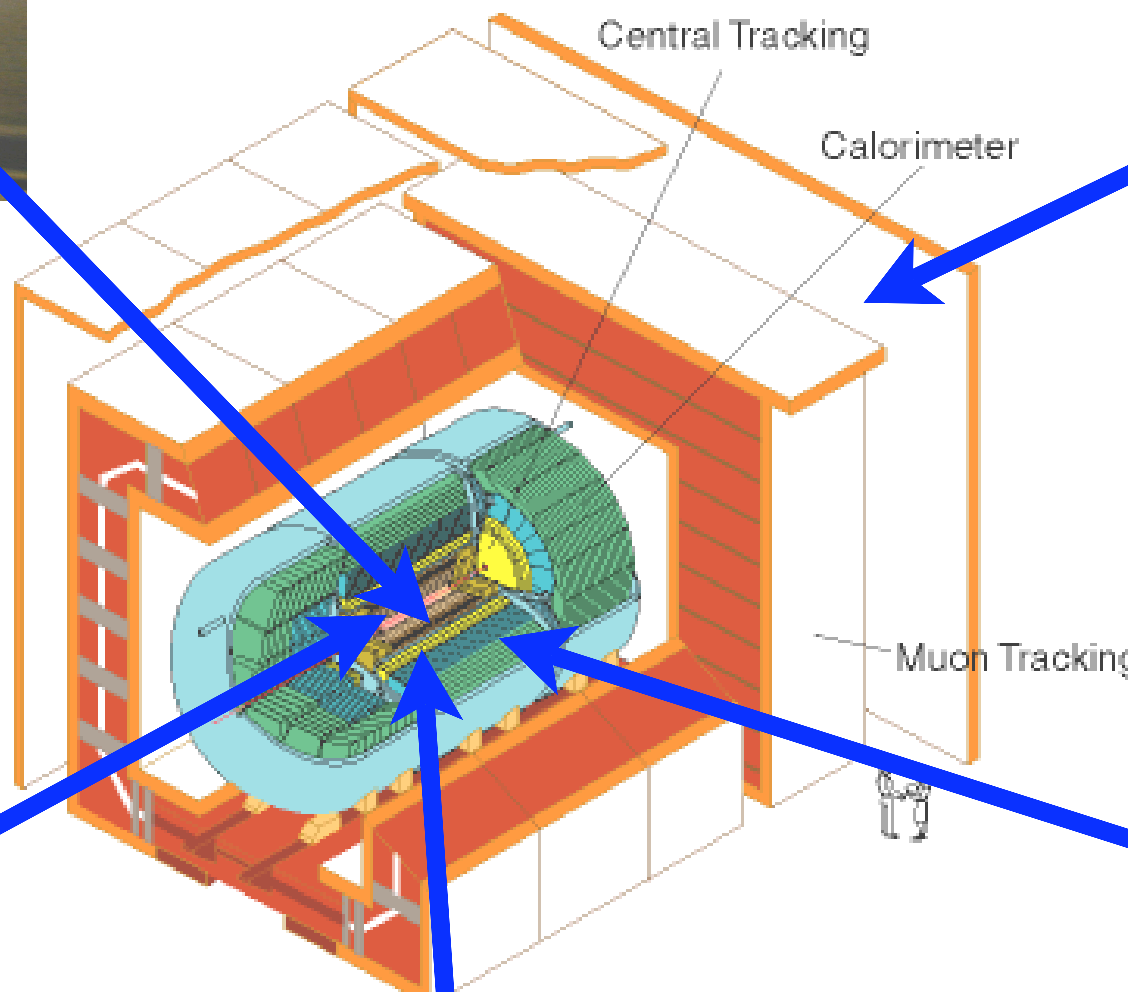
<u>EM & Hadronic Calorimeter</u>
Energy
measurement

The Run II DØ Experiment

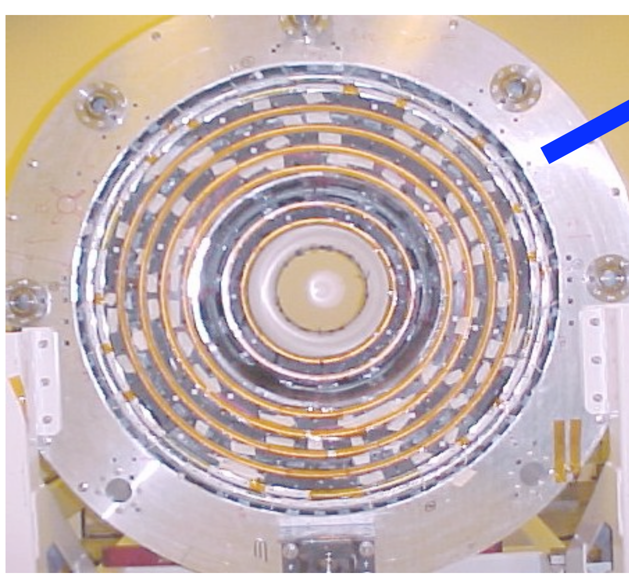
Silicon Detector
Vertex measurement
and tracking close to PV

Muon System
Drift chambers / scintillators
Muon position and tracking





Fiber Tracker
Charged particle tracking
momentum + charge



Solenoid
Trackers in
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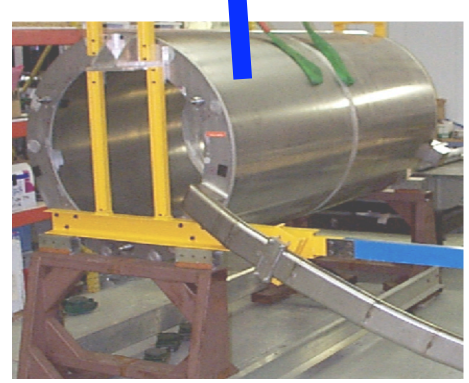

EM & Hadronic Calorimeter
Energy
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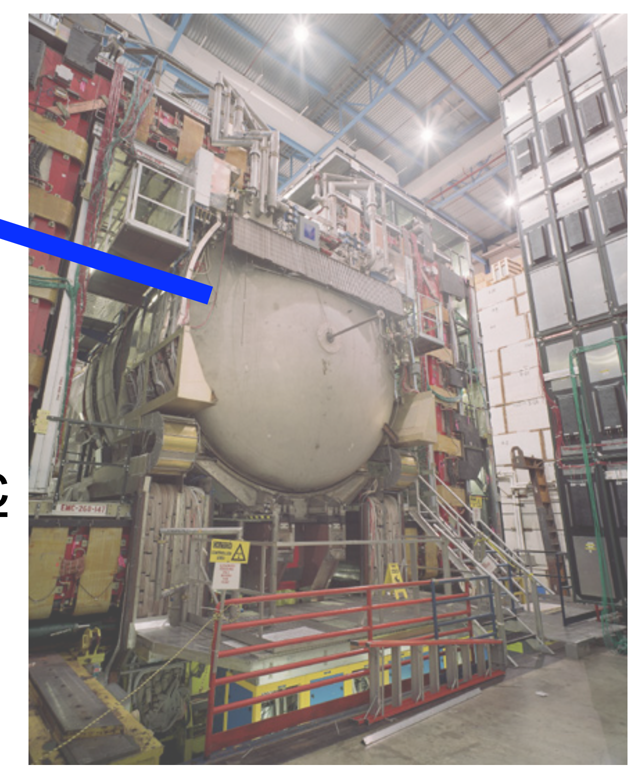
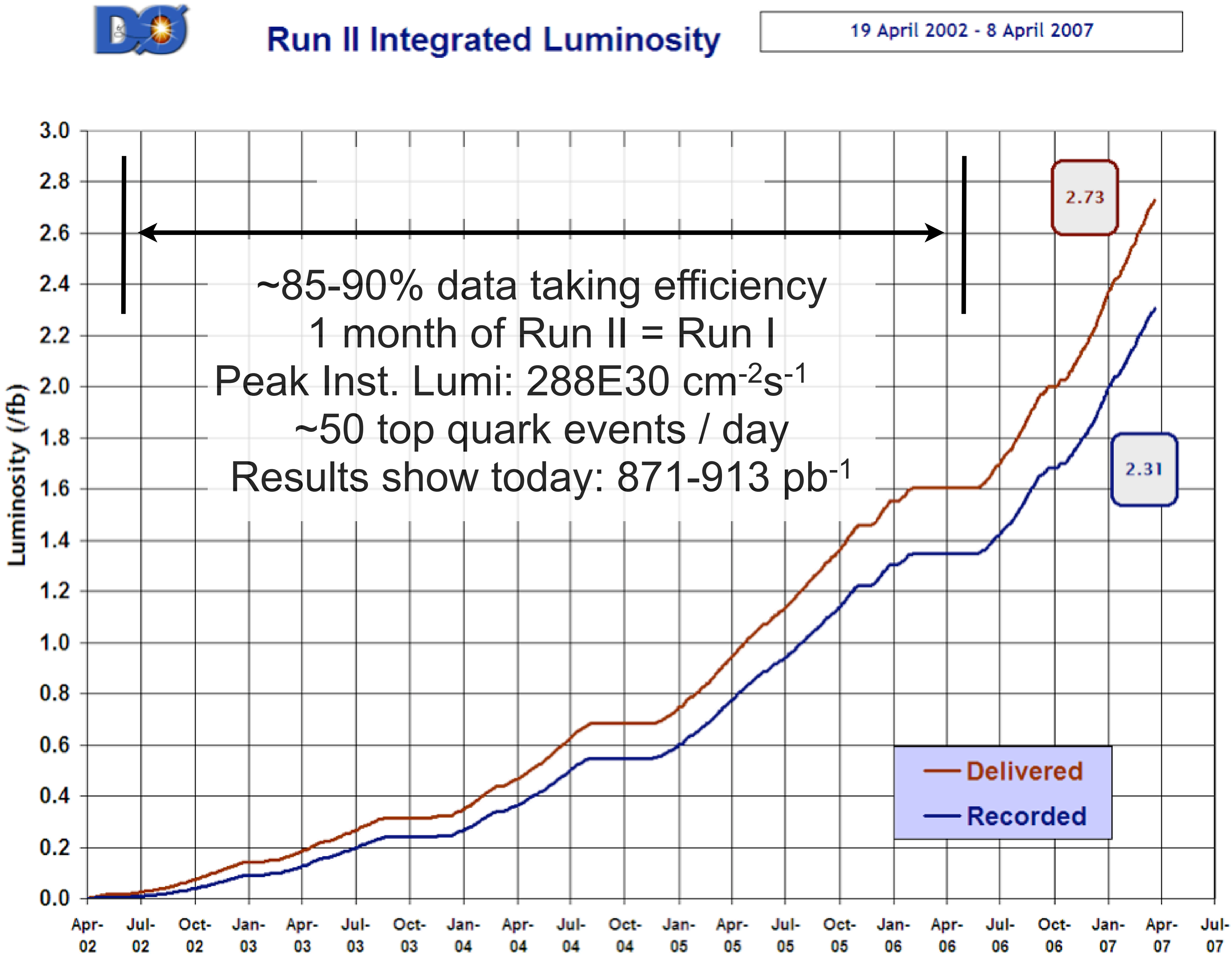


Run II Data Taking



The Top Quark

- Top quark was discovered in 1995 by the CDF and DØ collaborations
- Interesting properties:
  - Very massive

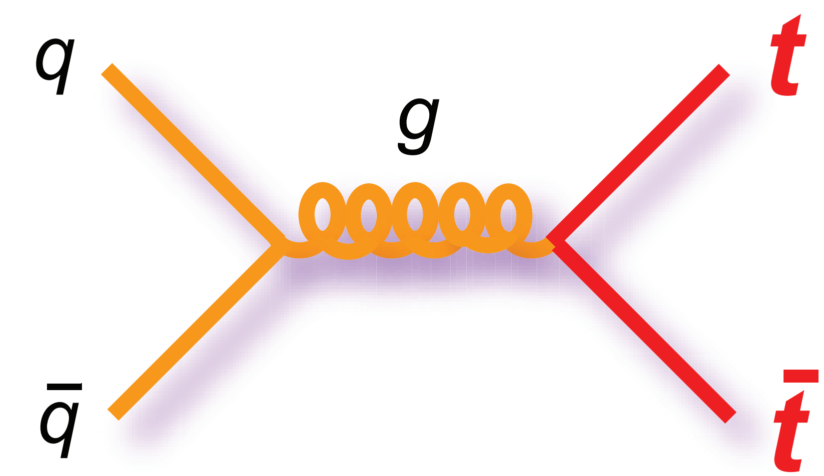
$$m_t = 170.9 \pm 1.8 \text{ GeV}/c^2$$

Tevatron EWWG (hep-ex/0703034)

  - Short lifetime - No QCD bound states

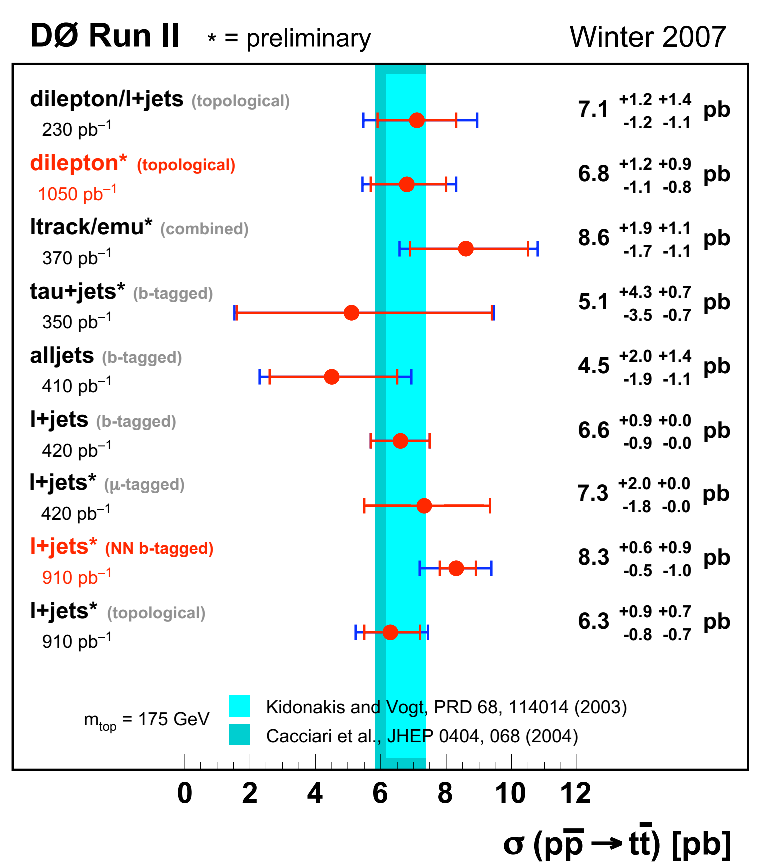
$$\tau_t \approx 3 \times 10^{-25}\text{s} << 1/\Lambda_{\text{QCD}}$$

  - Decays as free quark; BR($t \to Wb$)≈1



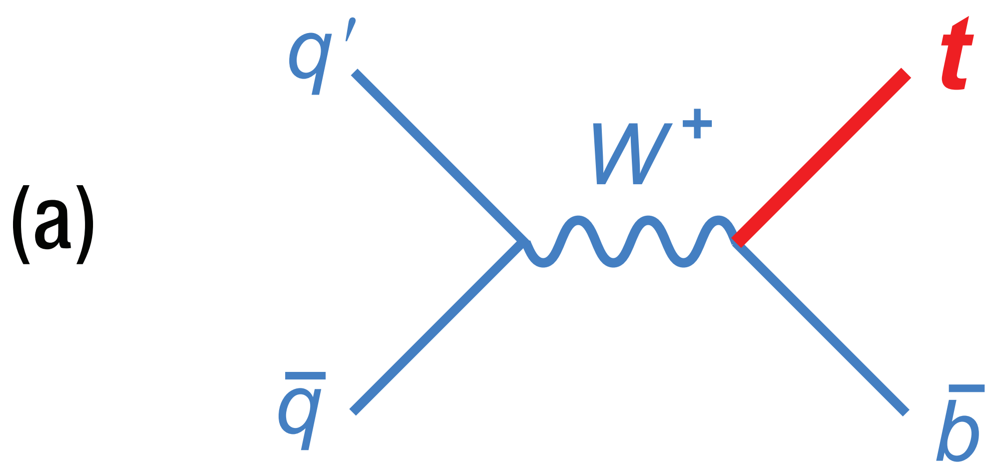
- Studied in QCD pair production
  - For m_t = 175 GeV → σ(tt) = 6.8 pb
  - Occurs in ~1:10 billion collisions!
  - Rate well measured at Run II

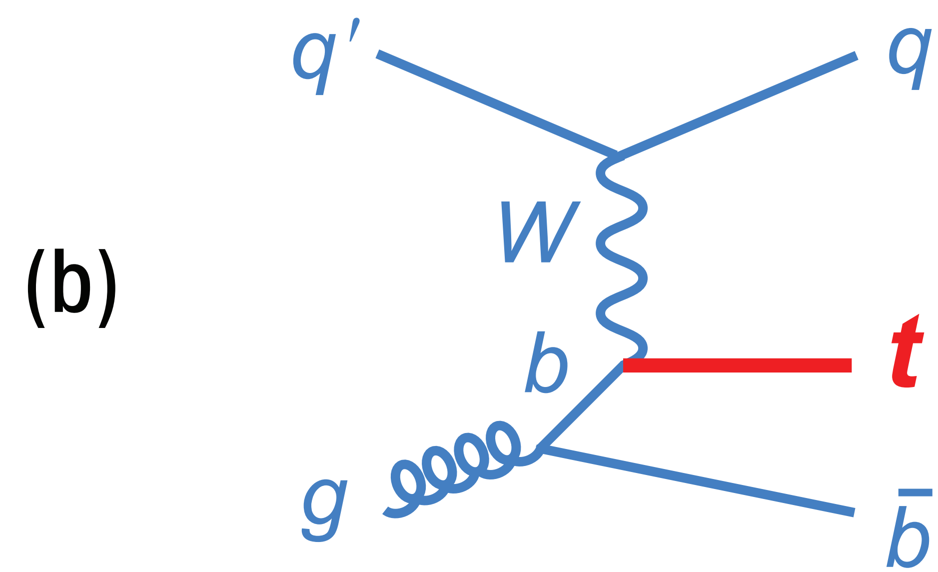
Results From DØ



Single Top Quark Production

- Top quarks can also be production through an electroweak interaction
- Two production modes at the Tevatron





$$\sigma_s^{\mathrm{NLO}} = 0.88 \pm 0.11\mathrm{pb} \qquad \sigma_t^{\mathrm{NLO}} = 1.98 \pm 0.25\mathrm{pb}$$

B.W. Harris et. al (hep-ph/0207055)
Z. Sullivan (hep-ph/0408049)

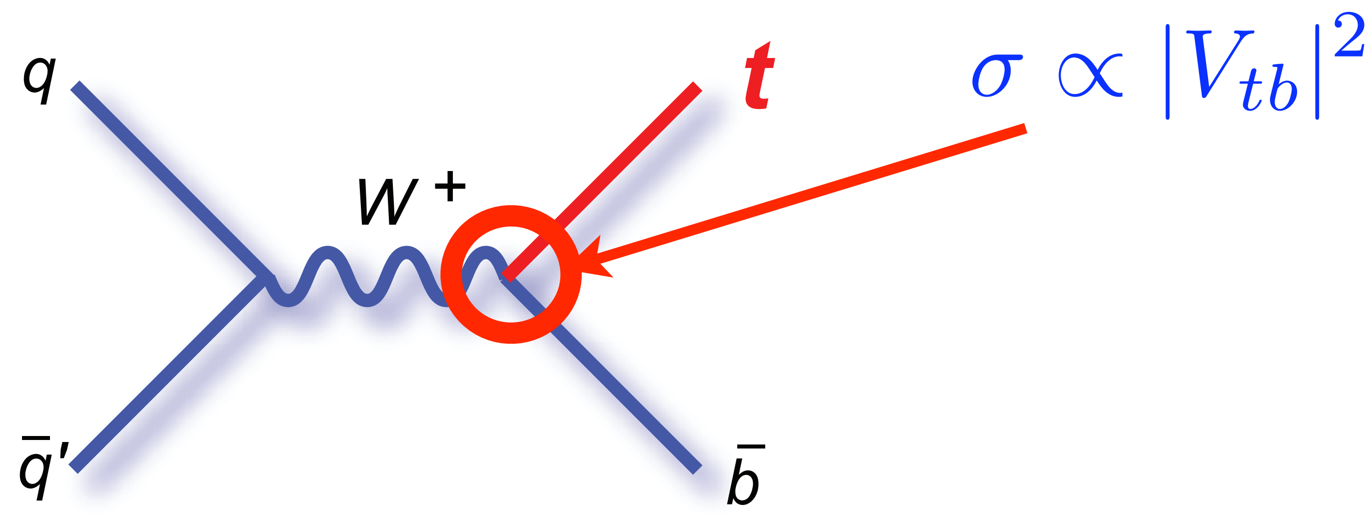
- Current 95% CL limits

DØ with 370 pb^{-1} $\sigma_s^{D\O} < 5.0\mathrm{pb}$ $\sigma_t^{D\O} < 4.4\mathrm{pb}$

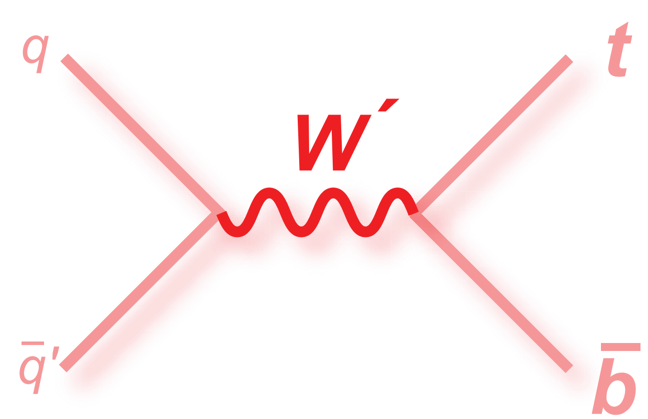
CDF with 700 pb^{-1} $\sigma_s^{CDF} < 3.1\mathrm{pb}$ $\sigma_t^{CDF} < 3.2\mathrm{pb}$

Motivation For Measuring Single Top

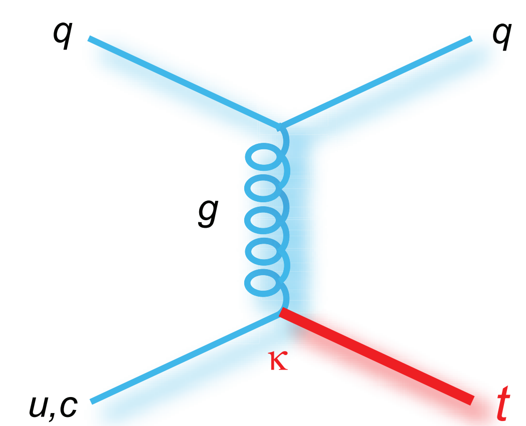
- Test of Standard Model
  - Sole method to determine **V**$_{tb}$ without assuming **VV**†=1 → Test unitarity



  - Source of ~100% polarized top quarks
- Sensitive to beyond the Standard Model processes



s-channel sensitive
to new resonances



t-channel sensitive to flavor
changing neutral currents

Not An Easy Search

- Low rate: σ(tb+tqb) ~ 1/2 σ(tt)
  - Single top quarks produced in 1:20 billion collisions
  - Produced ~ once per hour at Tevatron
- Large backgrounds
  - Pair production:

$$t\bar{t} \rightarrow \ell\nu + 2b + 2l$$

$$t\bar{t} \rightarrow \ell\nu\ell\nu + 2b$$

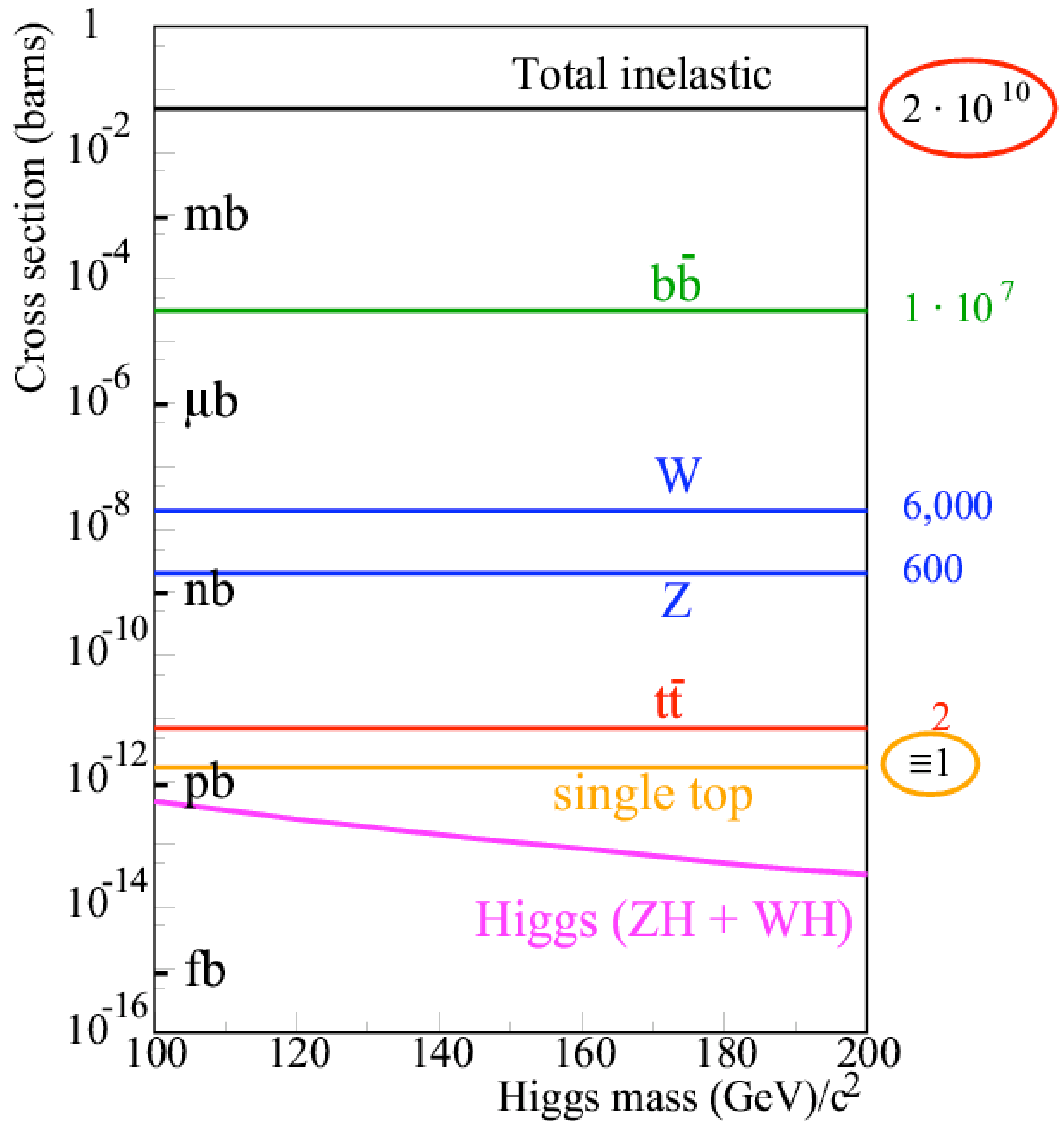
    - fairly unique = low background rate
  - Single top:

$$tb \rightarrow \ell\nu + 2b$$

$$tqb \rightarrow \ell\nu + 2b + 1l$$

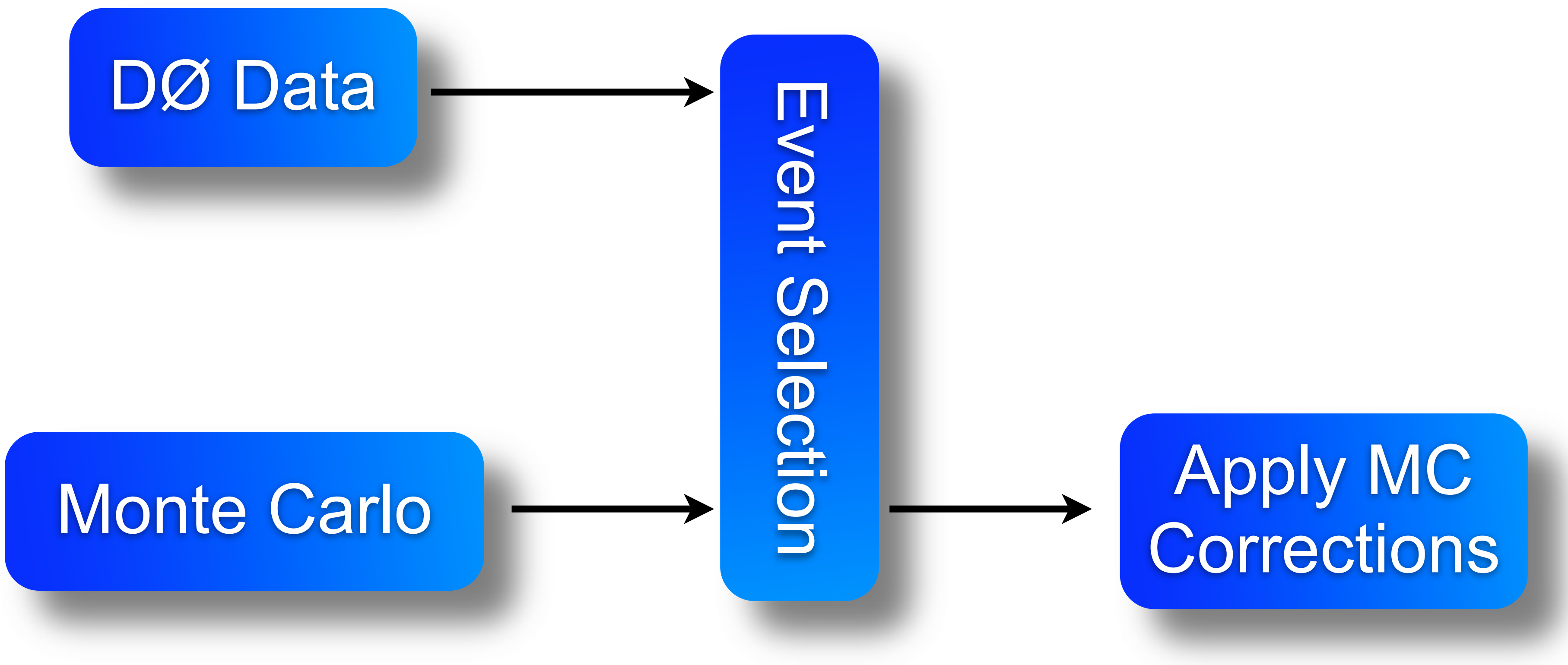
    - very common = high background rate

Cross Sections at √s = 1.96 TeV



Single Top Analysis Flow

Single Top Analysis Flow



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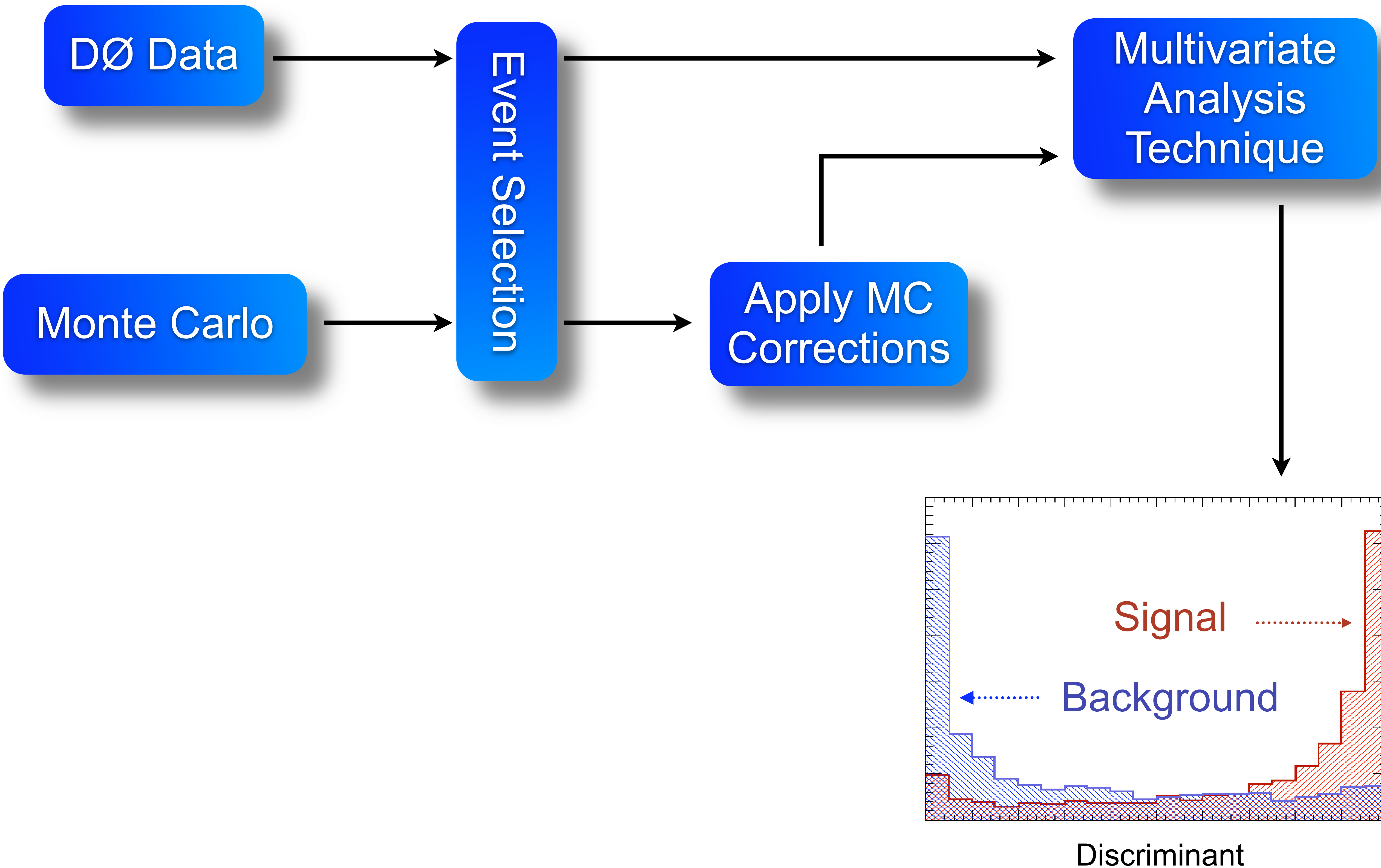

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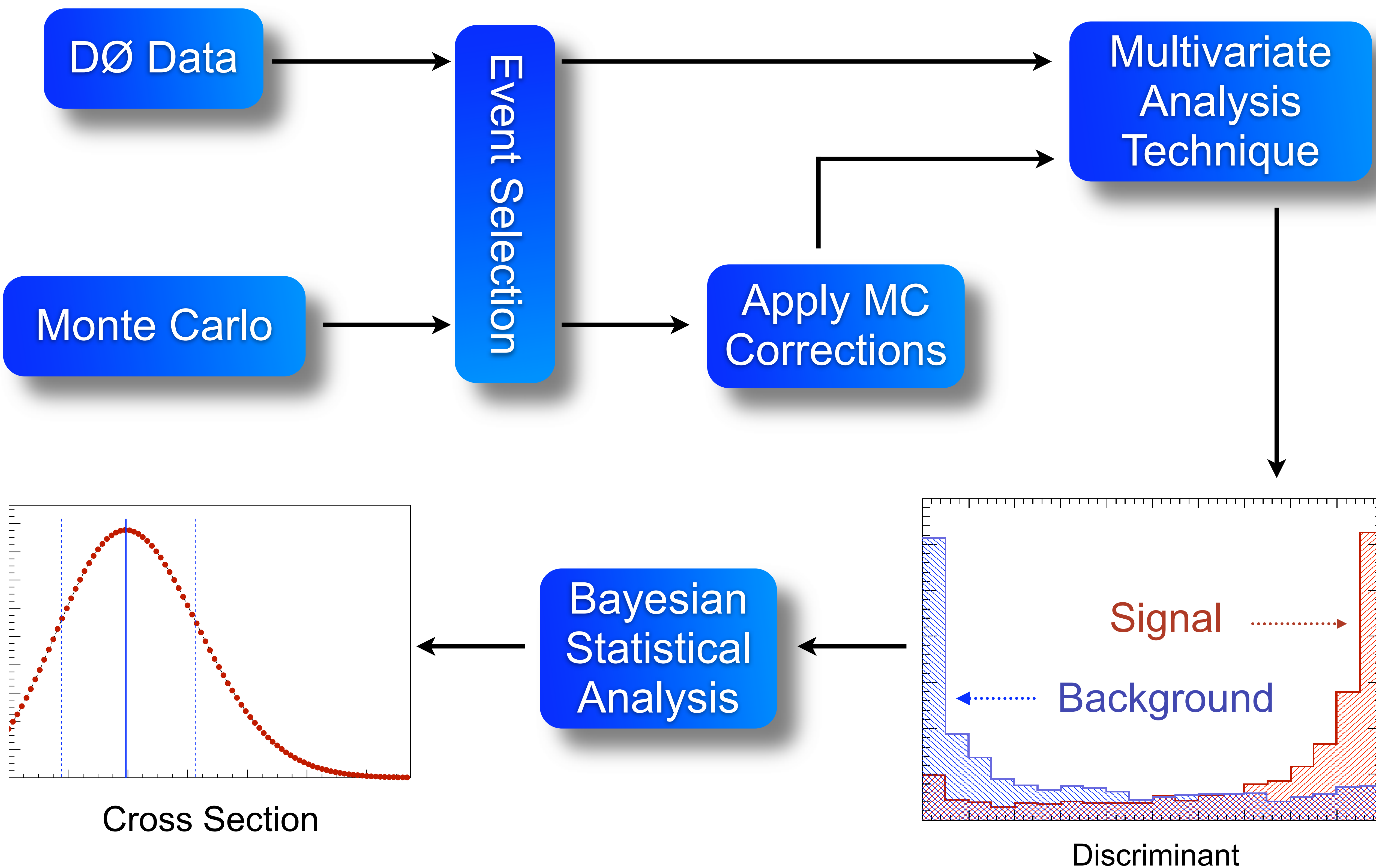
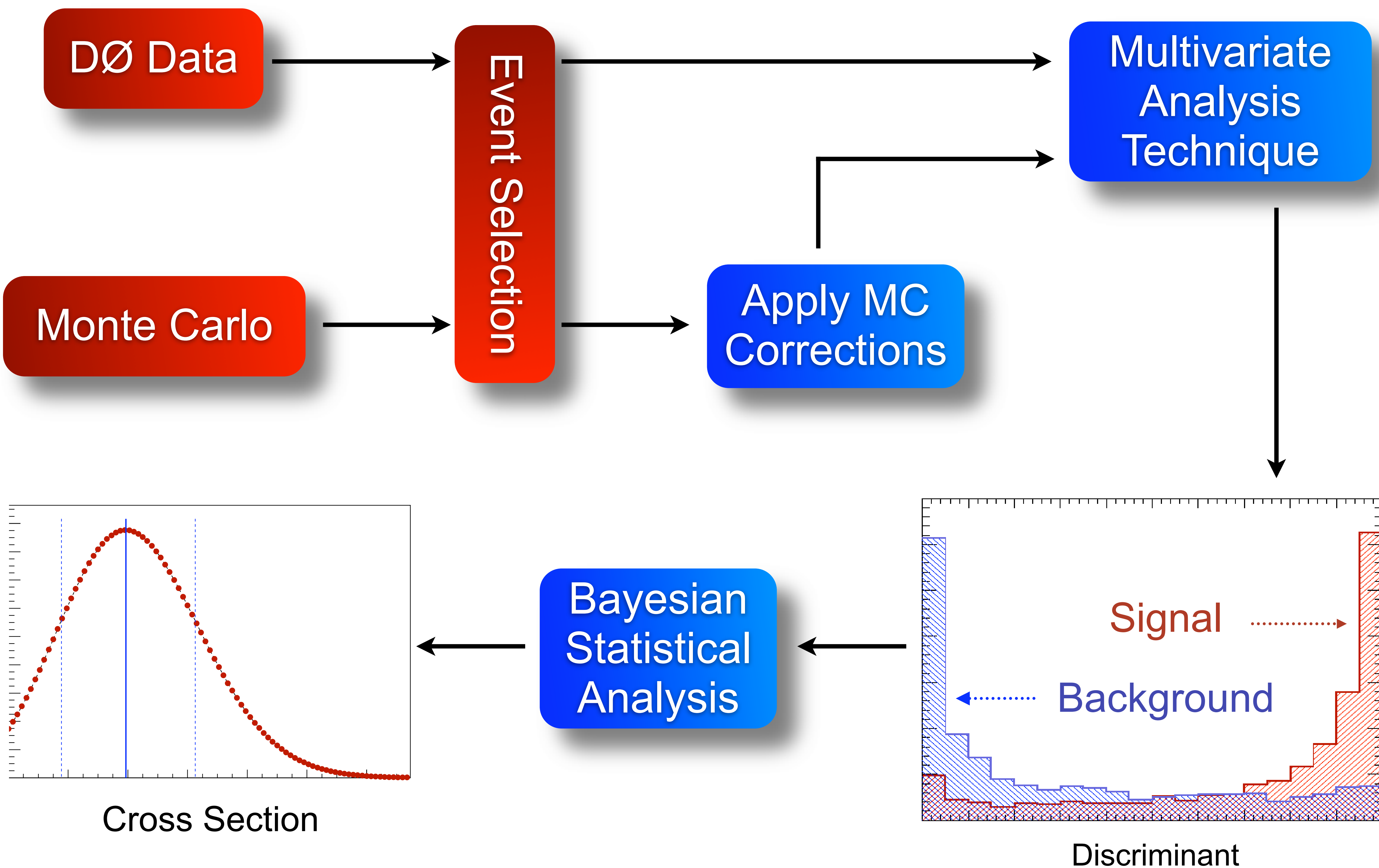
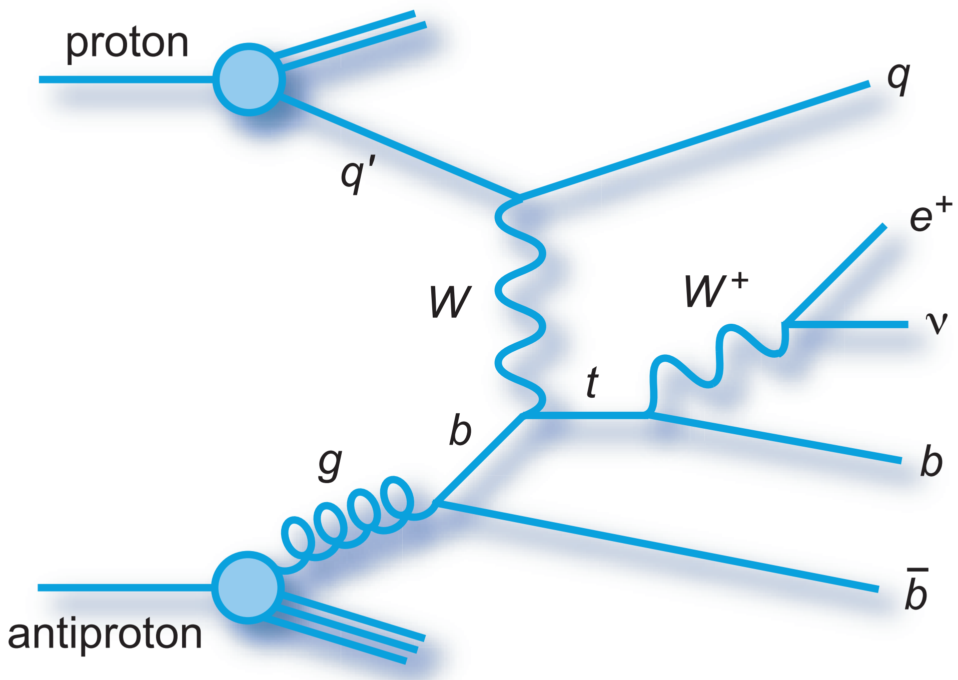


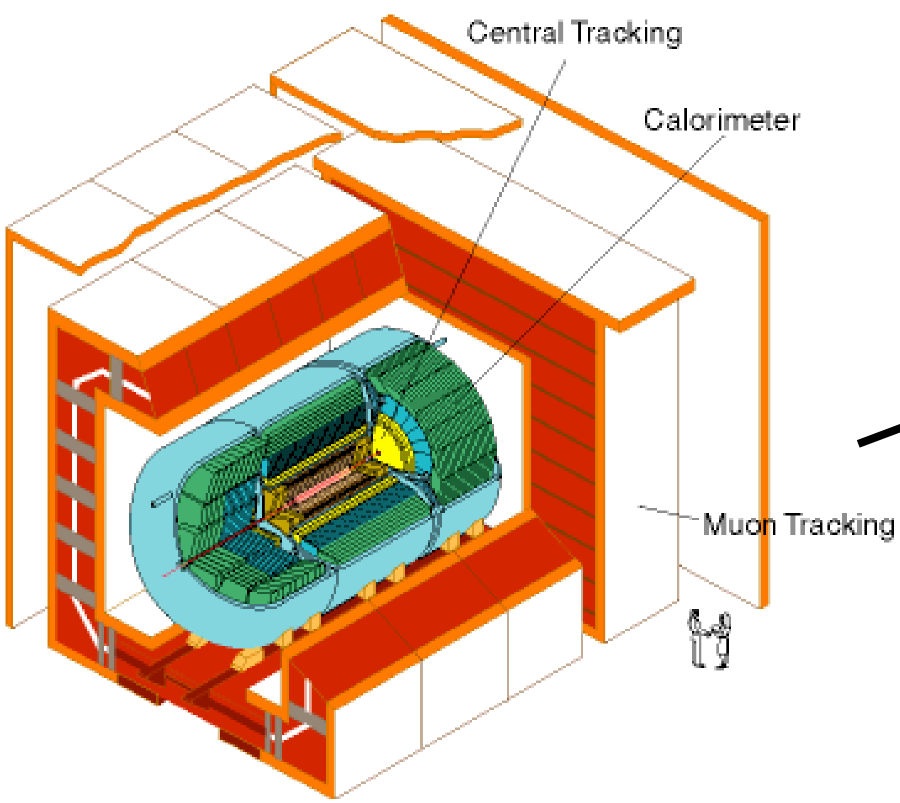
Single Top Analysis Flow

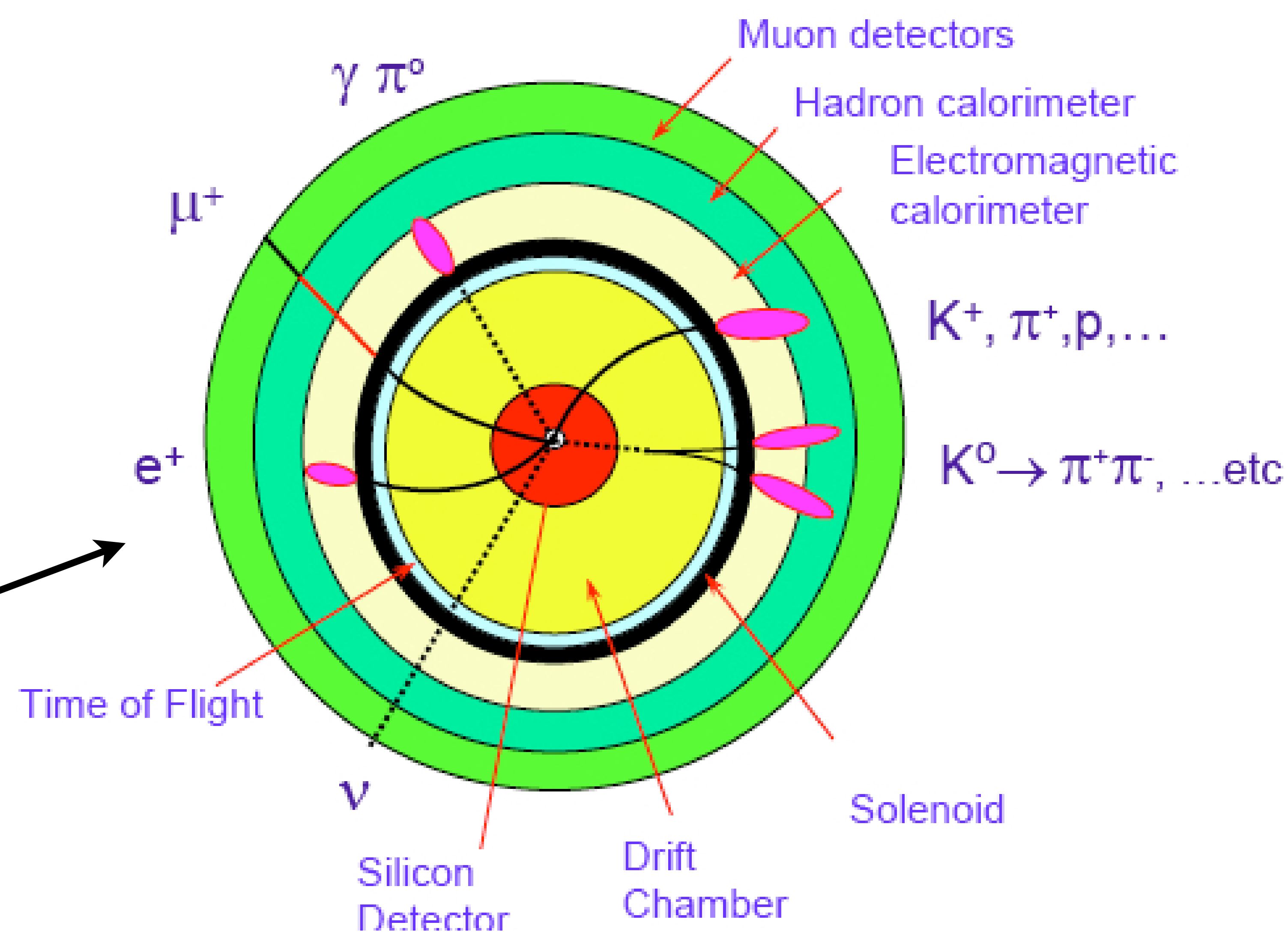


Event Reconstruction and Selection

We look for single top in the lepton+jets decay channel







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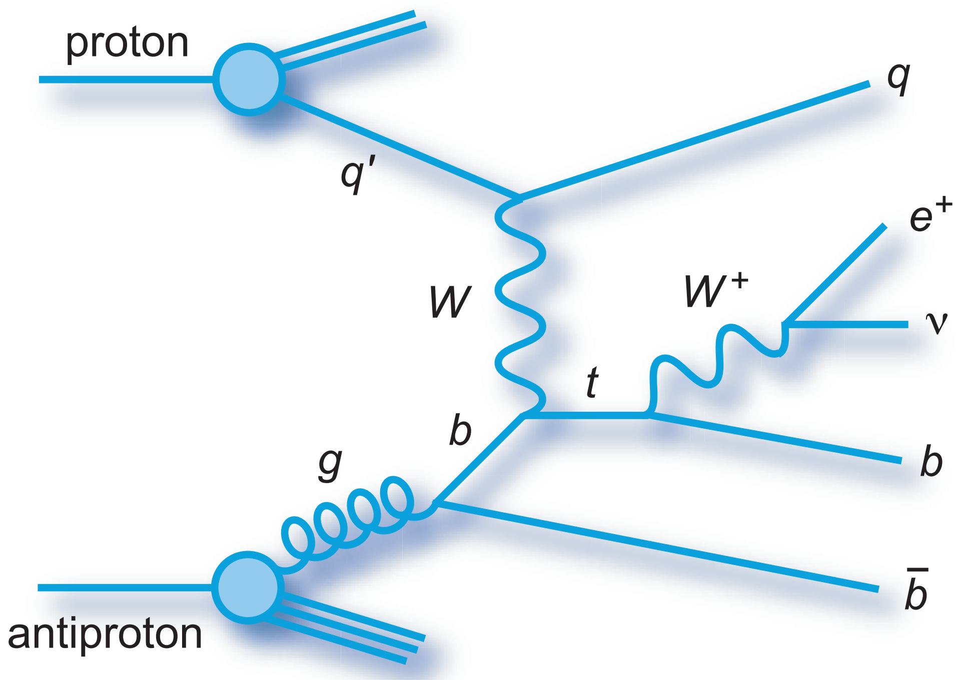
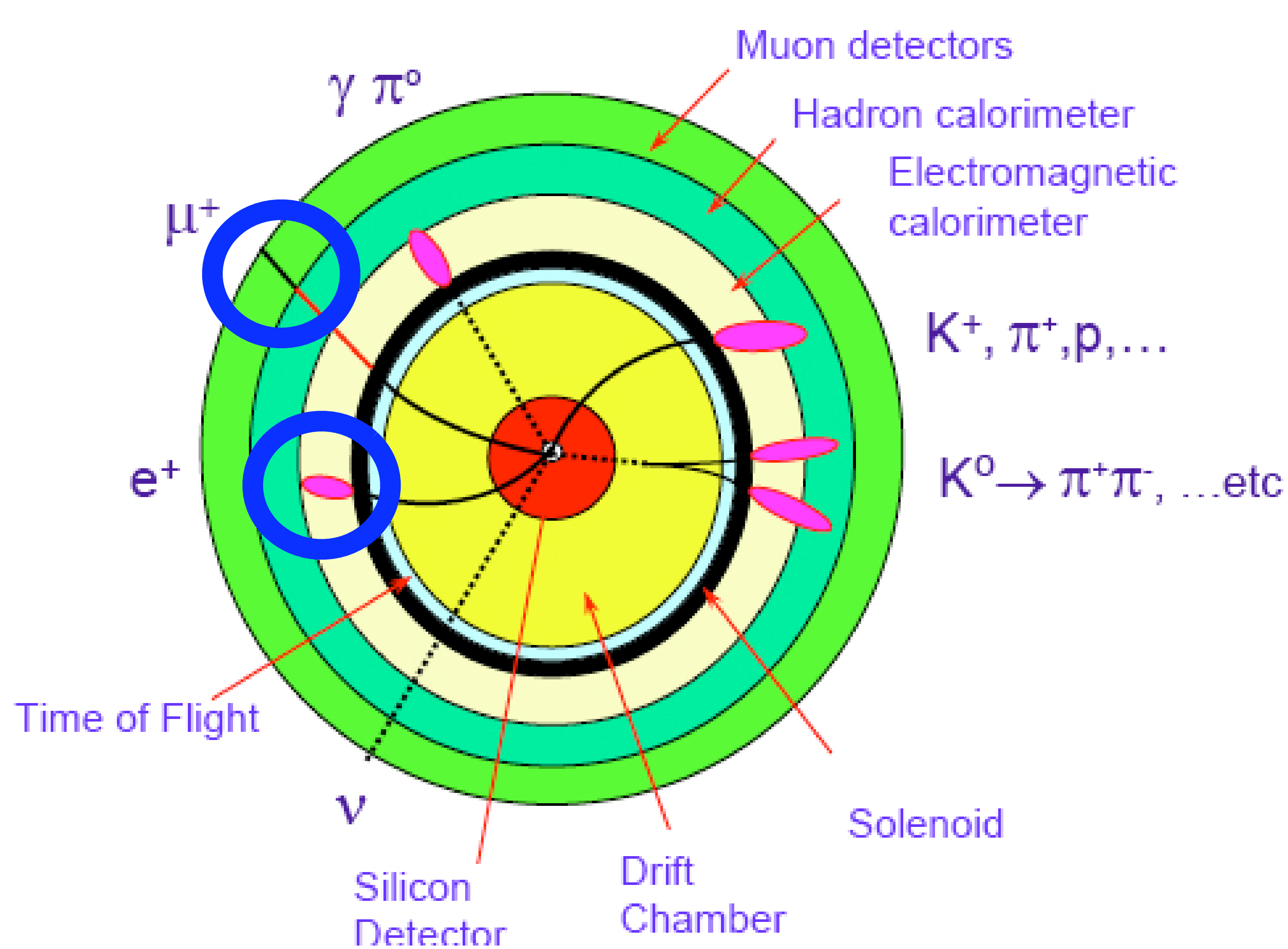


Electron: Narrow tower in EM Cal
Muon: Hits in the muon system
Select: 1 lepton w/ P_T > 15 GeV



Event Selection

- 1 Lepton w/ P_T > 15 GeV

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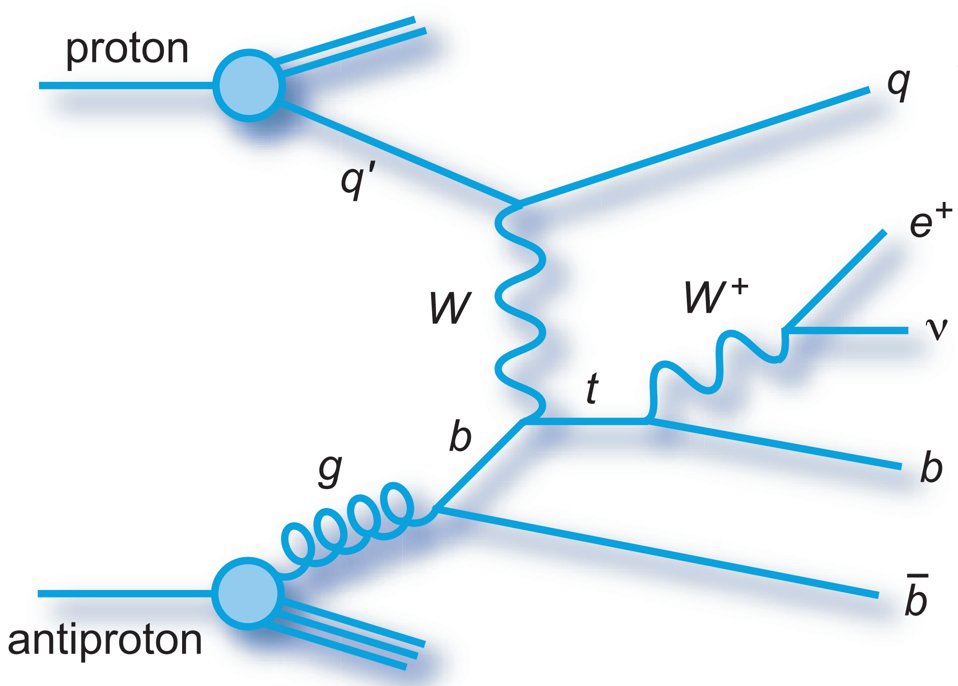
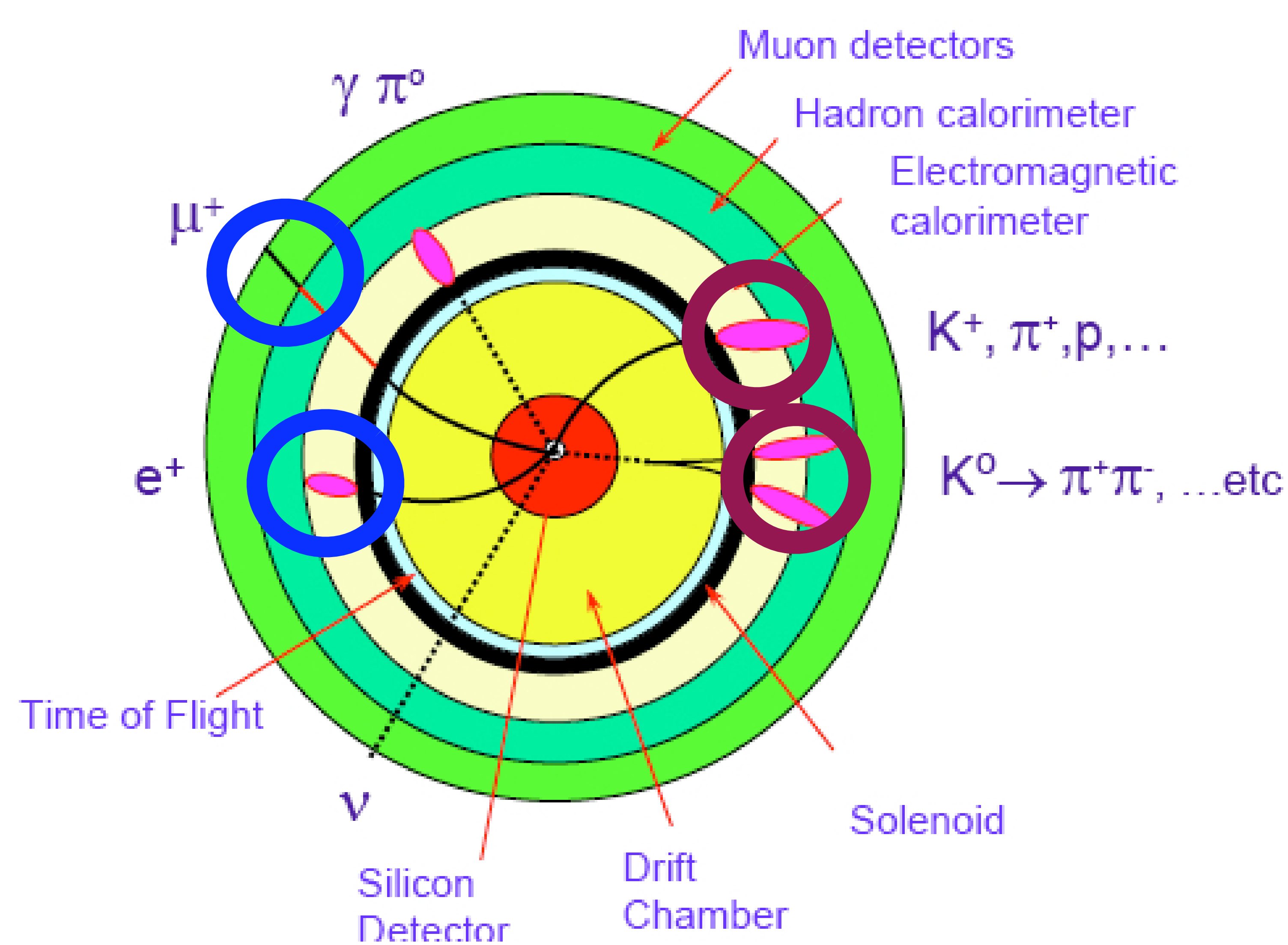


Narrow cone of particles detected in the calorimeter - “jet”
Select: 2-4 jets w/ P_T > 15 GeV

Electron: Narrow tower in EM Cal
Muon: Hits in the muon system
Select: 1 lepton w/ P_T > 15 GeV



Event Selection

- 1 Lepton w/ P_T > 15 GeV
- 2-4 Jets w/ P_T > 15 GeV

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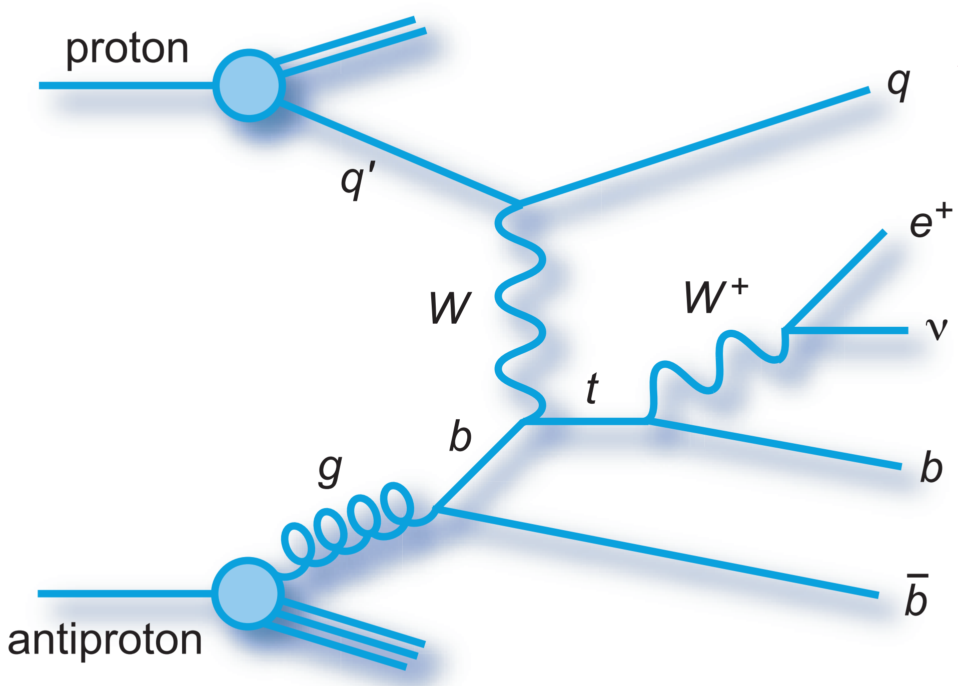

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Select: 2-4 jets w/ P_T > 15 GeV

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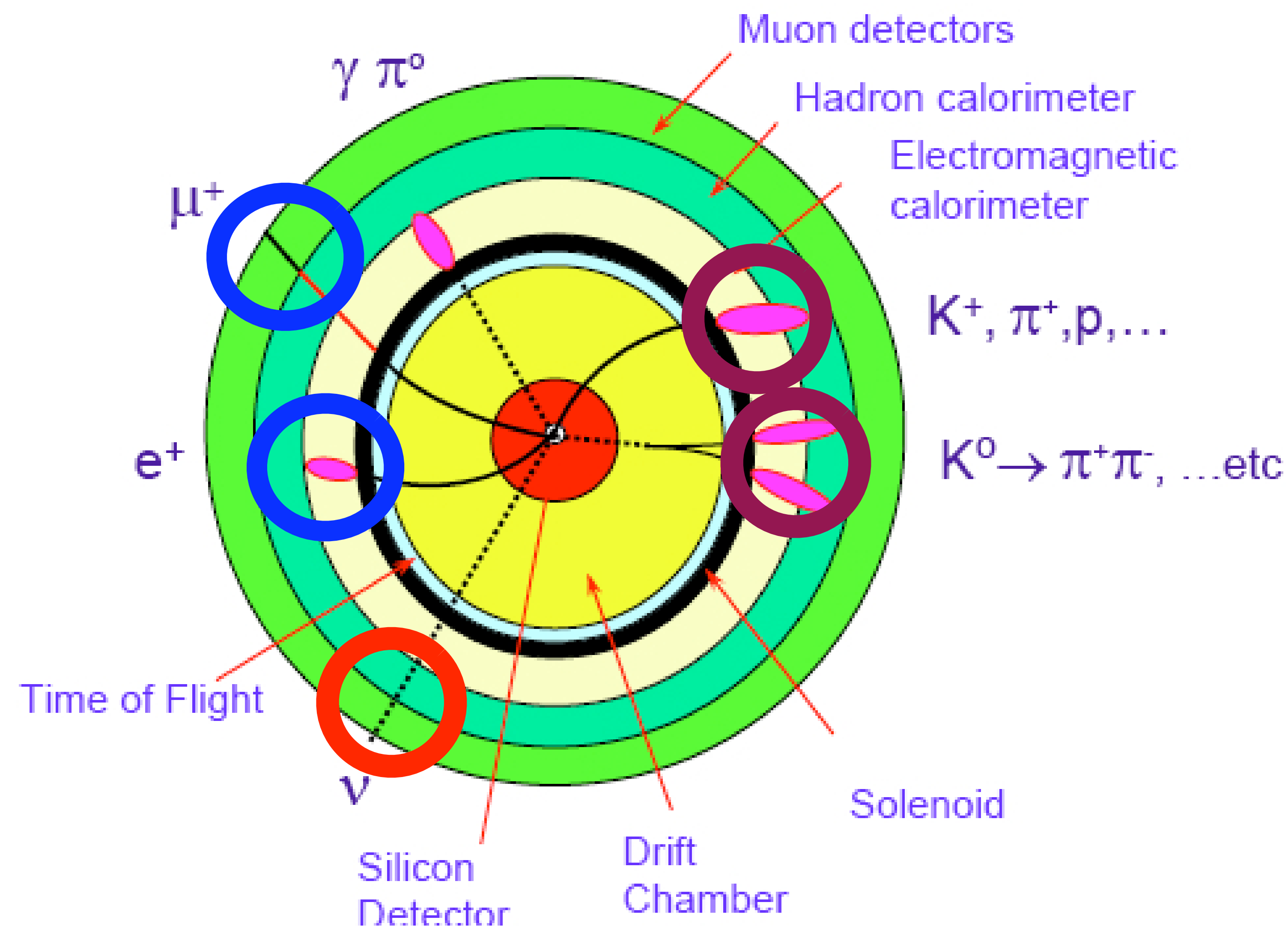
Muon: Hits in the muon system
Select: 1 lepton w/ P_T > 15 GeV

Missing Transverse momentum
Select: Missing E_T > 15 GeV

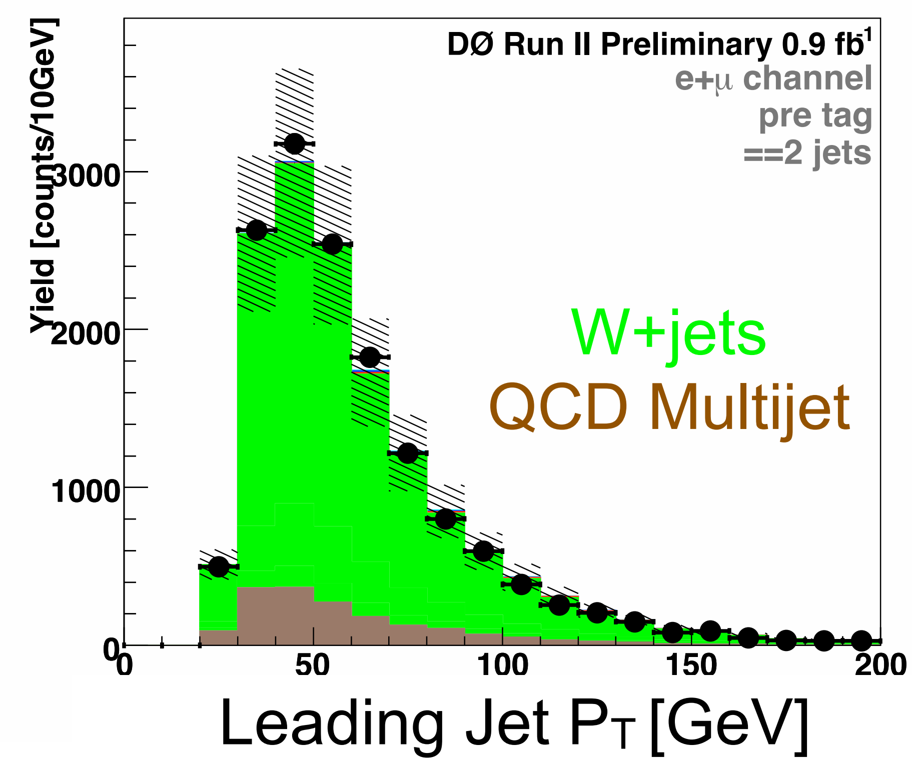


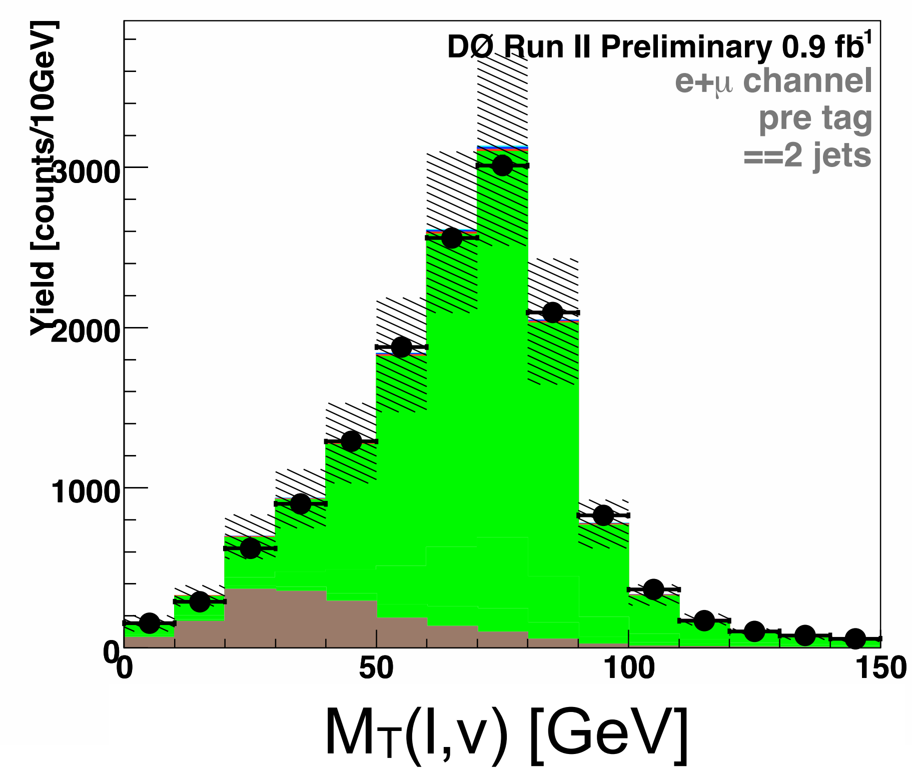
Event Selection

- 1 Lepton w/ P_T > 15 GeV
- 2-4 Jets w/ P_T > 15 GeV
- Missing E_T > 15 GeV

W+jets Background Normalization

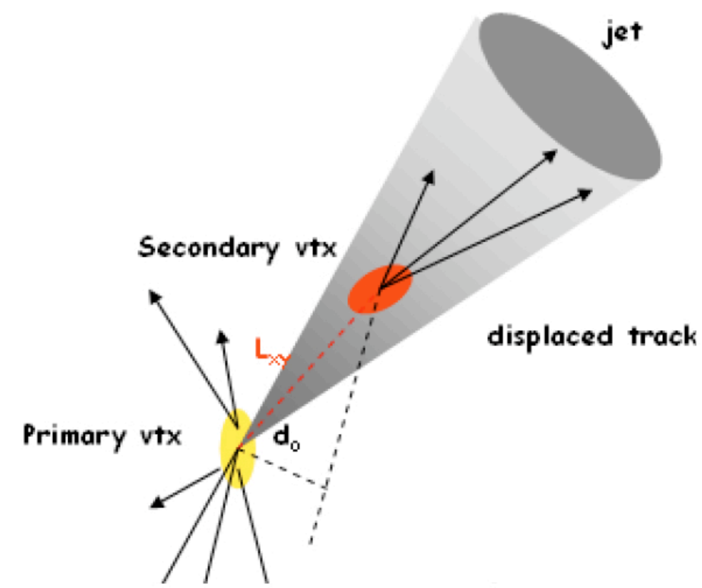
- Large W+jets sample after event selection
  - Signal to Background ~ 1:200
  - Backgrounds are W+jets and QCD Multijet
- Normalize W+jets to data in low signal region
  - Shape taken from Monte Carlo
  - W+jets - ALPGEN w/ MLM matching
  - Multijet - data events
  - $\sigma'(W+jets) \sim 1.5 \times \sigma_{LO}$
  - W+cc(bb) scaled by an additional 1.5 (effective k factor) - Measured in data



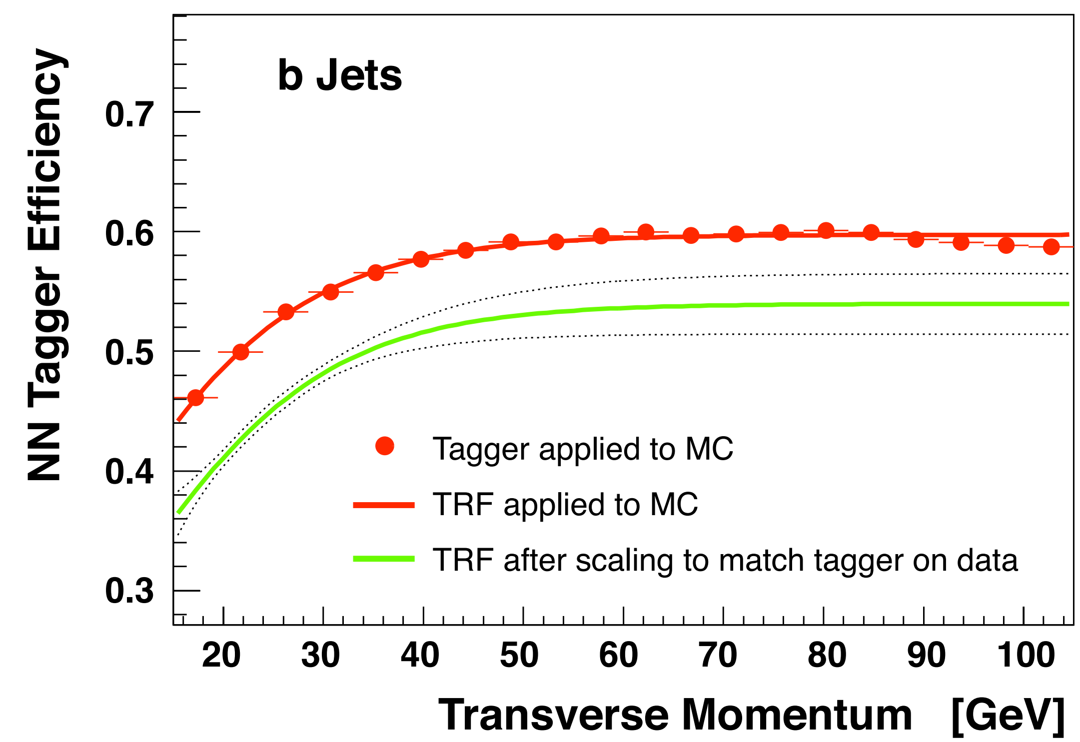


b-Tagging Algorithm

- Single top events have at least one *b* quark while largest background does not
  - Would like to select events with ≥1 *b* quark. Need to know jet flavor.
- Use neural network trained on B Hadron Characteristics
  - Relatively long lived (weak decay) → Displaced decay vertex (~mm)
  - Higher track multiplicity
  - Relatively large M(tracks)

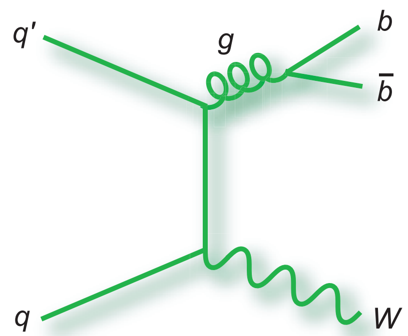


- Apply tagging probability to MC (TRF) parameterized in P_T and η
  - TRF(b quark) ~ 50%
  - TRF(c quark) ~ 10%
  - TRF(l quark) ~ 0.5%

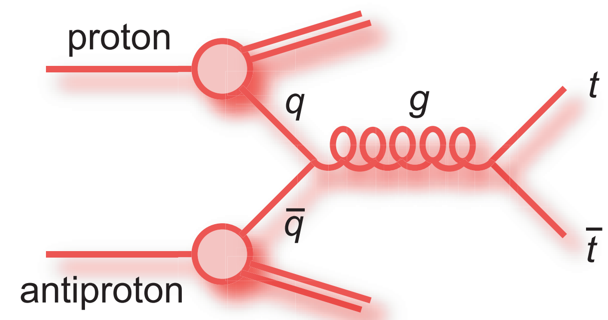


Backgrounds After *b*-Tagging

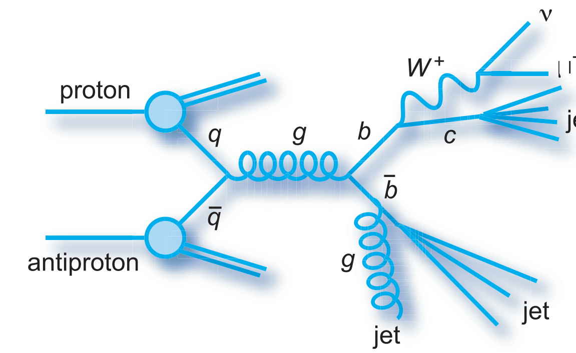
- Three main backgrounds after selecting events with ≥1 b-jet



W+jets



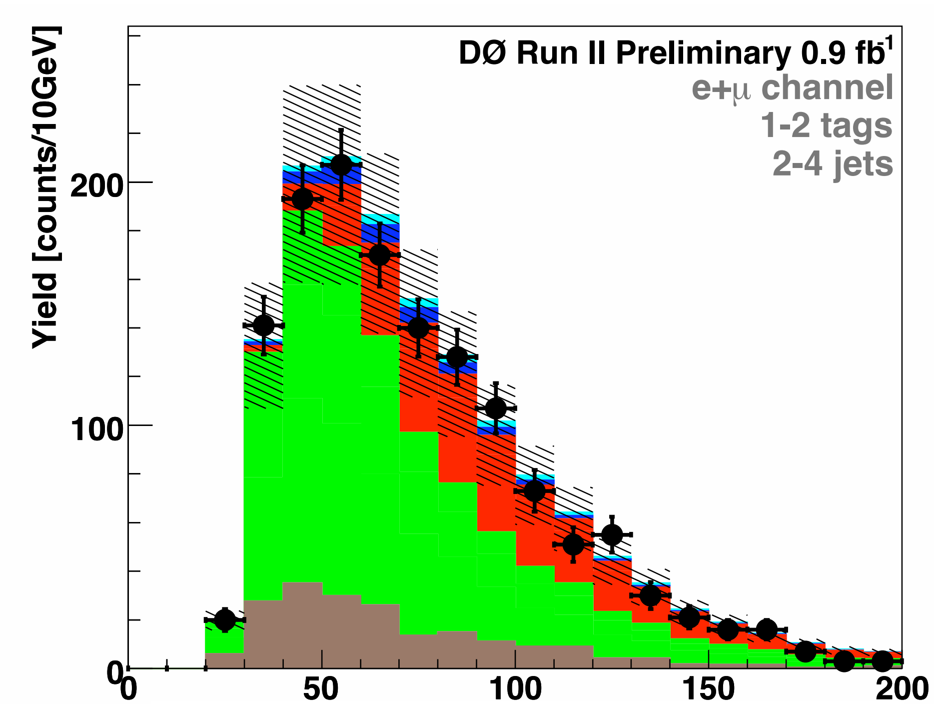
ttbar



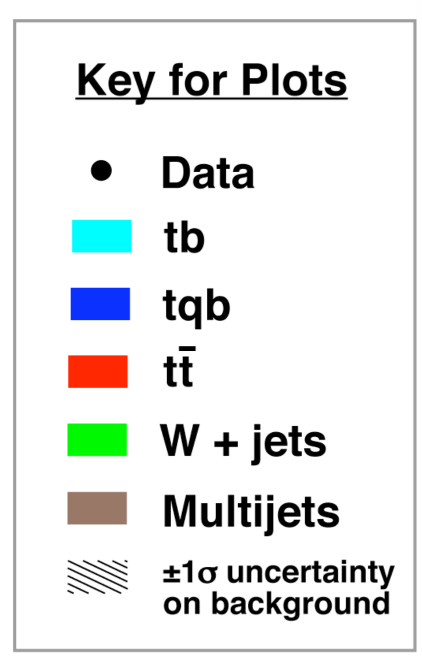
QCD Multijet

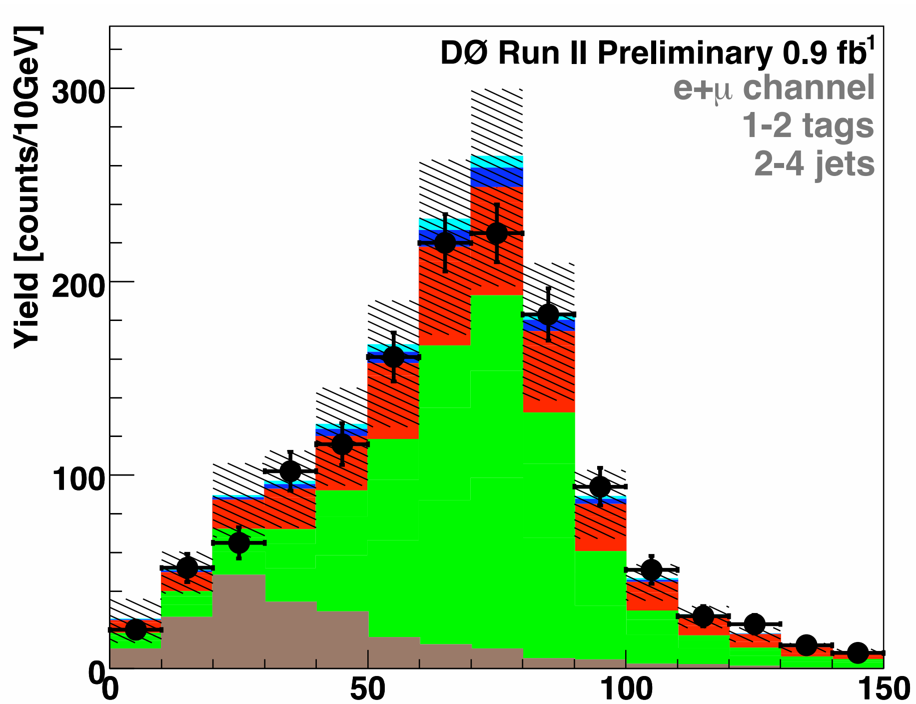
  - ttbar is modeled using ALPGEN and normalized to NLLO cross section (6.8 pb)

- Good agreement between data and expectation after *b*-tagging



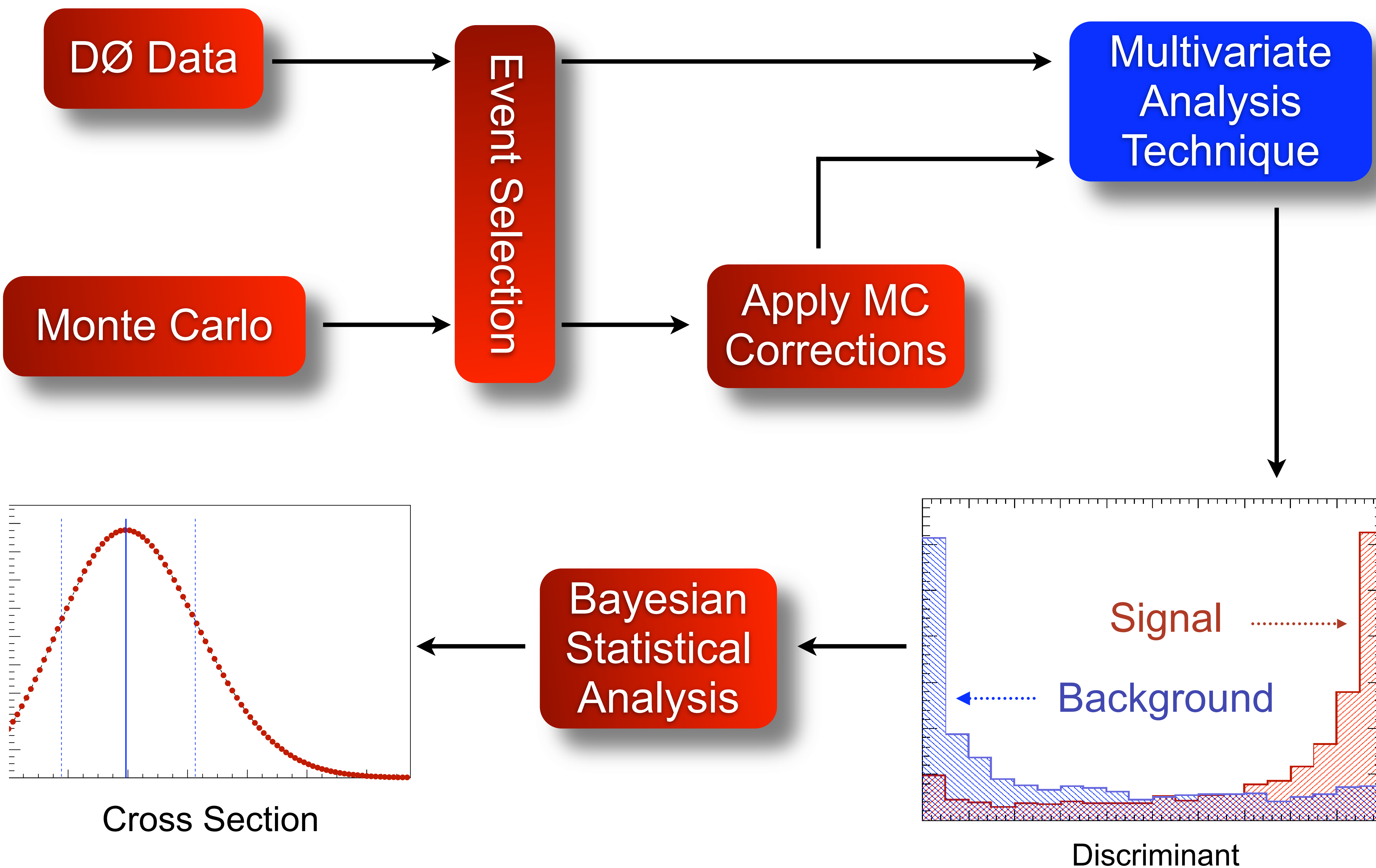
Leading Jet P_T





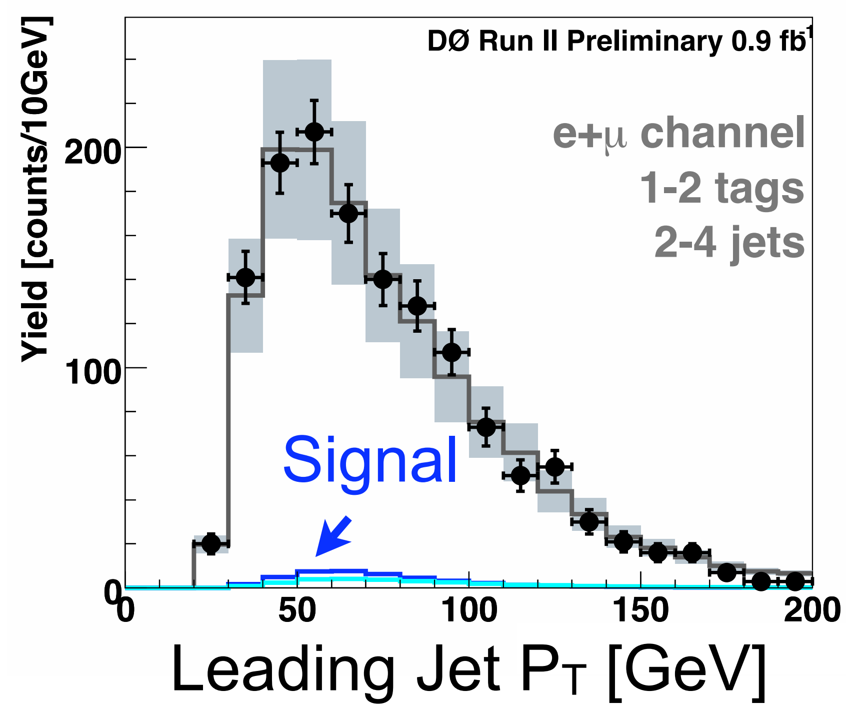
W Transverse Mass

Single Top Analysis Flow

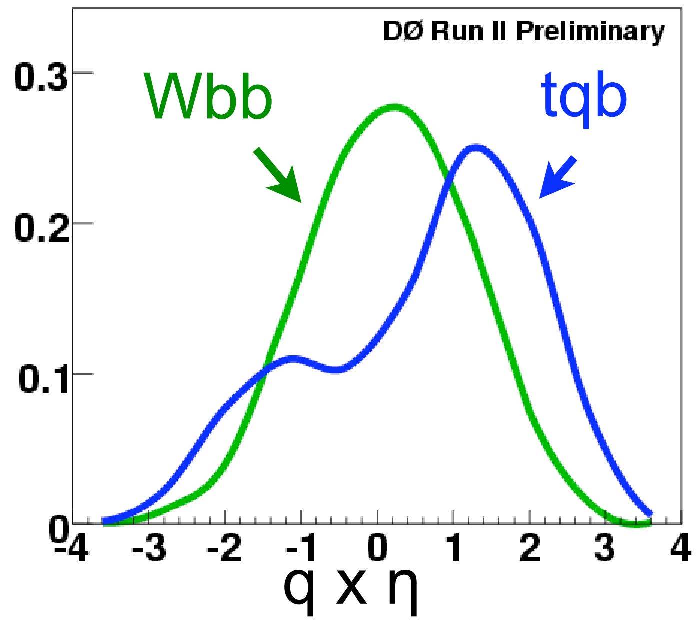


Motivation For Matrix Element Analysis

- Single top search suffers from large backgrounds after event selection
  - After tagging, S:B ~ 1:20 and systematic errors > signal ⇒ no counting experiment



- Common idea: Look at variables that separate signal and background
  - Ex. charge of lepton x η of un-tagged jet
- Can combine variables into event probability using neural network, decision tree, etc...



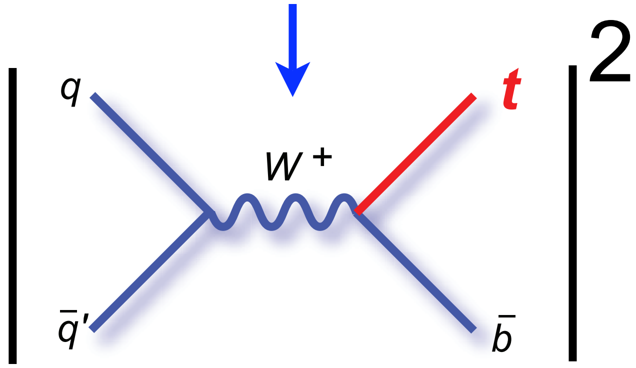
Matrix Element Analysis

- For each event, define a probability it originated from signal or background
  - Define as the normalized N-dimensional differential cross section for process *i*

$$P_i(\vec{y}) \equiv \frac{1}{\sigma_i}\frac{d\sigma_i}{dy} \quad ; \quad \frac{d\sigma_i}{dy} \propto |\mathcal{M}_i|^2 \quad ; \; i = S, B$$

  - **y** ≡ parton-level four-vectors

e.g.



- Account for detector by convoluting with detector resolution function
  - Map parton state (**y**) to detector state (**x**)

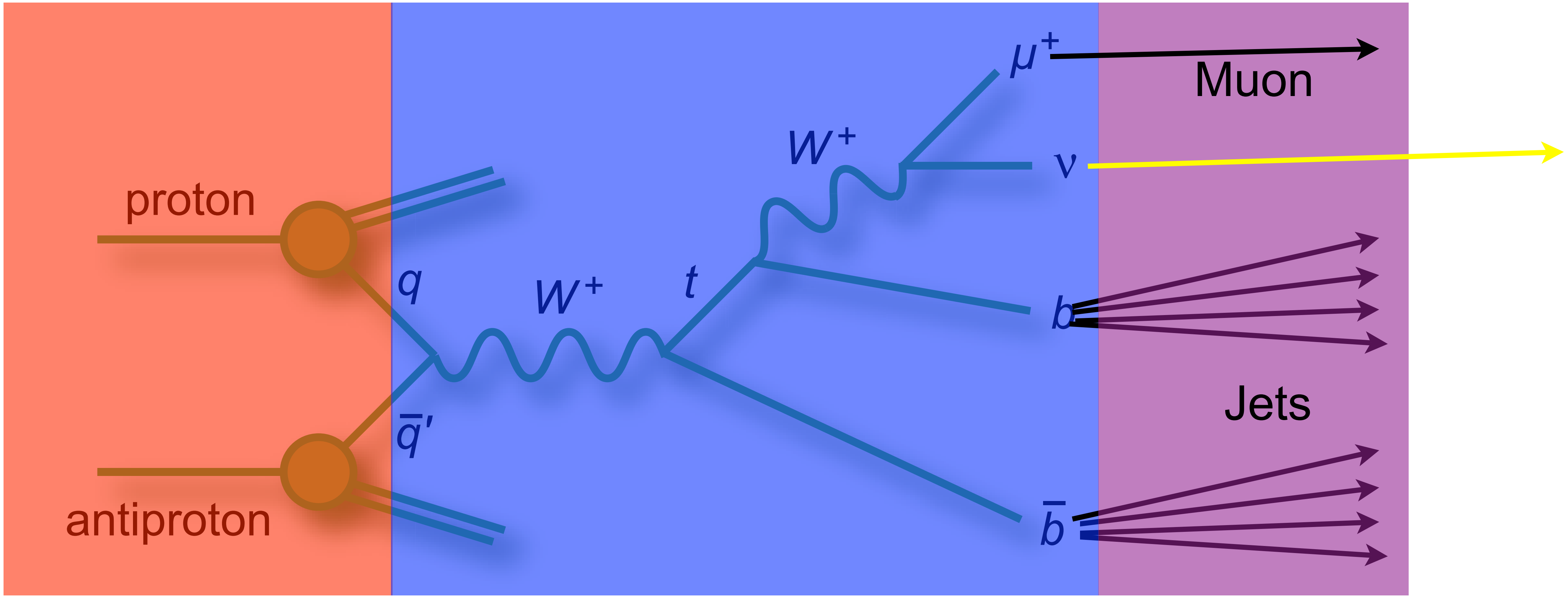
$$P_i(\vec{x}) \equiv \frac{1}{\sigma_i'} \int \frac{d\sigma_i}{dy} \times W(\vec{x}|\vec{y}) \; dy$$

  - W(**x**|**y**) is called the transfer function

Matrix Element Analysis

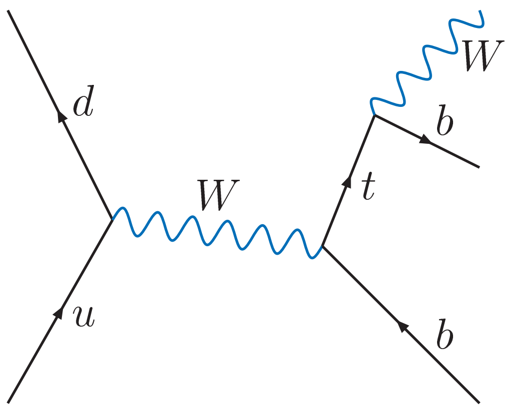
- For each event compute the following detector level differential cross section

$$\underbrace{\frac{d\sigma}{d\vec{x}}}_{\text{Detector level differential cross section}} \propto \underbrace{\int \frac{f(q_1)}{q_1}\frac{f(q_2)}{q_2}dq_1dq_2}_{\text{CTEQ6 Parton distribution functions}} \times \underbrace{|\mathcal{M}(\vec{y})|^2 d\Phi(\vec{y})}_{\text{LO matrix elements from Madgraph times PS factor}} \times \underbrace{W(\vec{y}|\vec{x})}_{\text{Map parton state } \mathbf{y} \text{ onto detector state } \mathbf{x}}$$

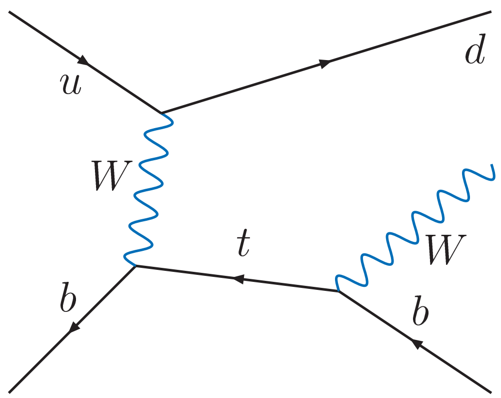


Signal & Background Processes

- Must match number of jets to number of generated partons
- Signal Processes

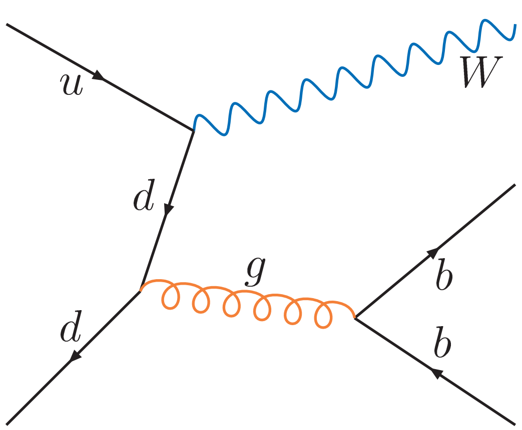


s-channel w/ 2 jets

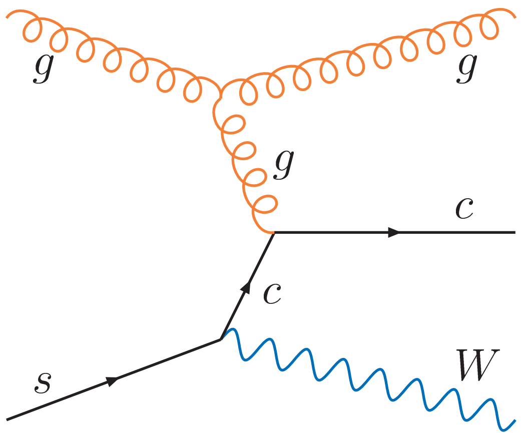


t-channel w/ 2 jets

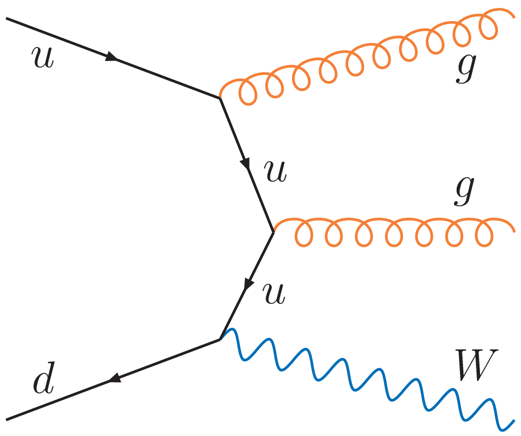
- Background Processes



Wbb w/ 2 jets



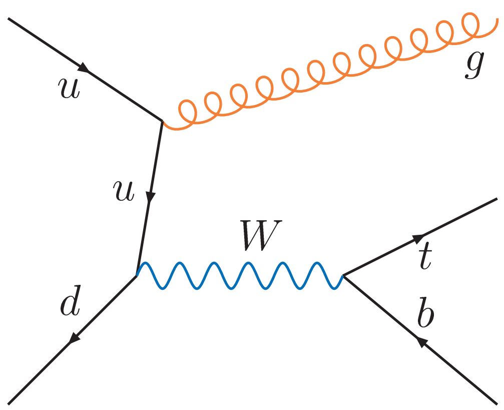
Wcg w/ 2 jets



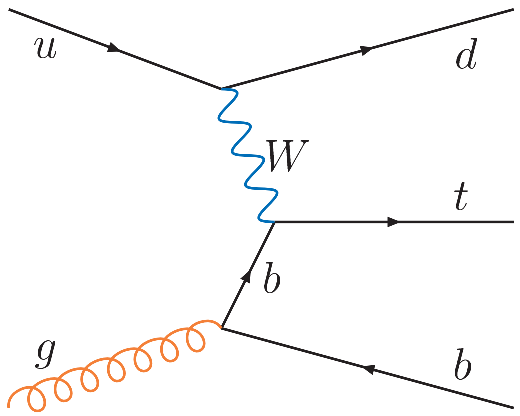
Wgg w/ 2 jets

Signal & Background Processes

- Must match number of jets to number of generated partons
- Signal Processes

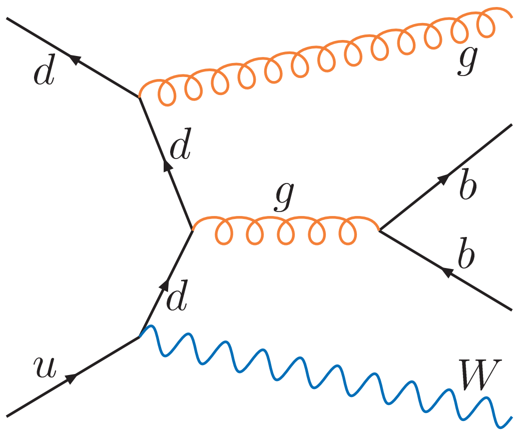


s-channel w/ 3 jets



t-channel w/ 3 jets

- Background Processes



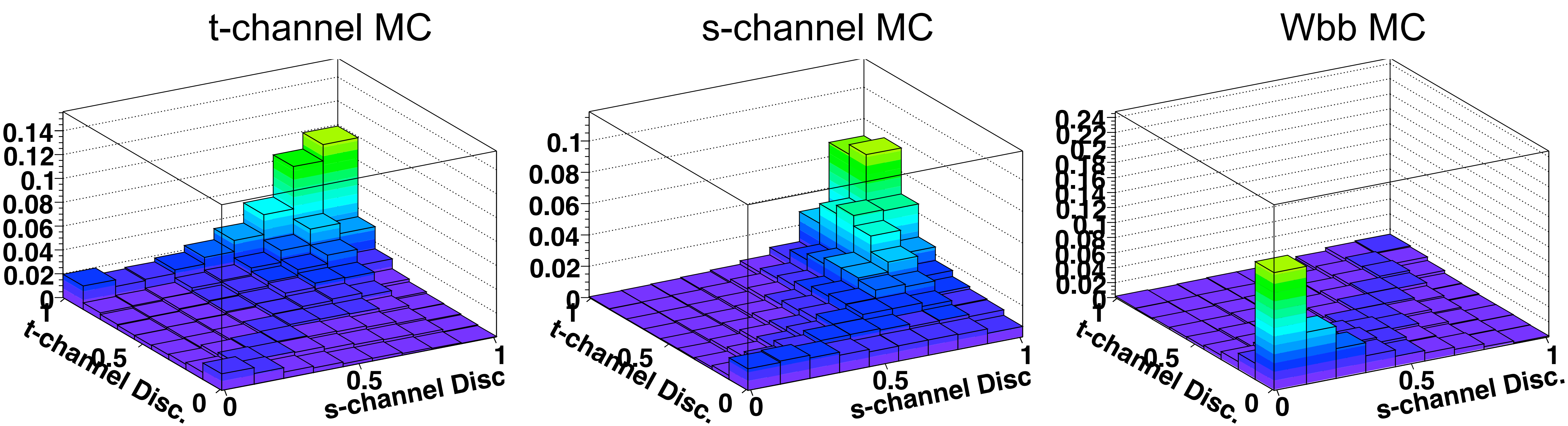
Wbbg w/ 3 jets

Matrix Element Discriminant

- Combine signal and background probability densities using the *a-posteriori* Bayesian probability density for signal given the event
  - Two discriminants: s-channel as signal and t-channel as signal

$$D_{tb|tqb}(\vec{x}) = \frac{P_{\mathrm{tb|tqb}}(\vec{x})}{P_{\mathrm{tb|tqb}}(\vec{x}) + P_{\mathrm{Background}}(\vec{x})}$$

- Result: Nice separation of signal and background

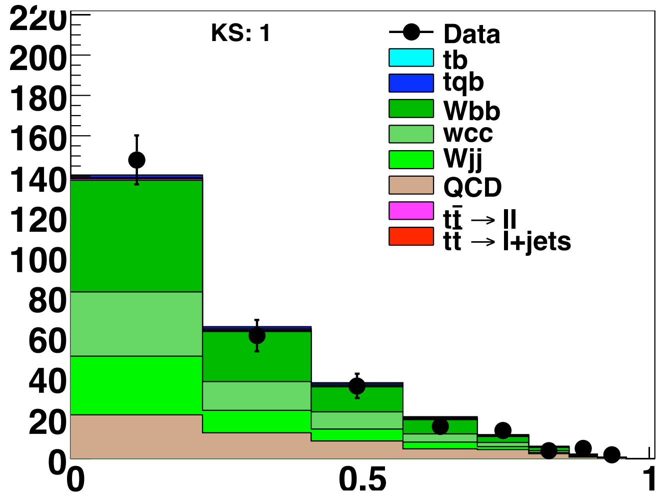


Cross Check W+jets Estimation

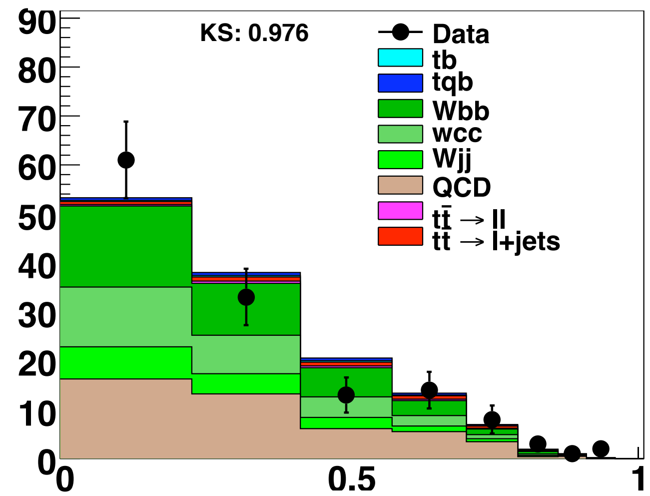
- Calculate discriminant in regions with little signal to cross check background
- Define: W+jets sample (H_T<175 GeV) $H_T = \sum_{\mathrm{jets}} \mathrm{P_T(jet)} + \mathrm{P_T}(\mathrm{e},\mu) + \not{E}_{\mathrm{T}}$

Events with 2 jets

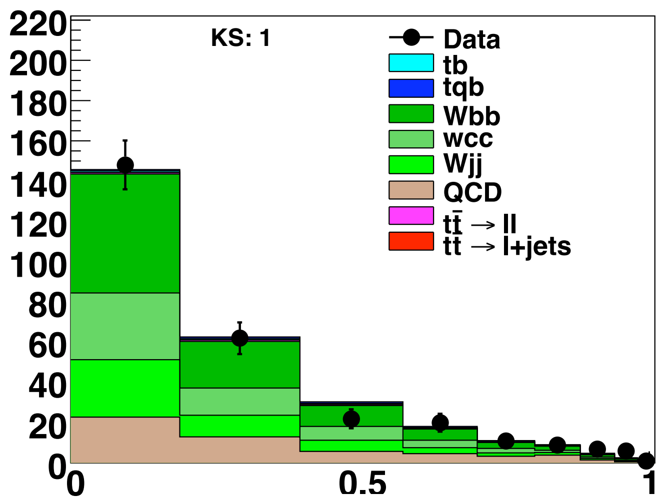
Events with 3 jets



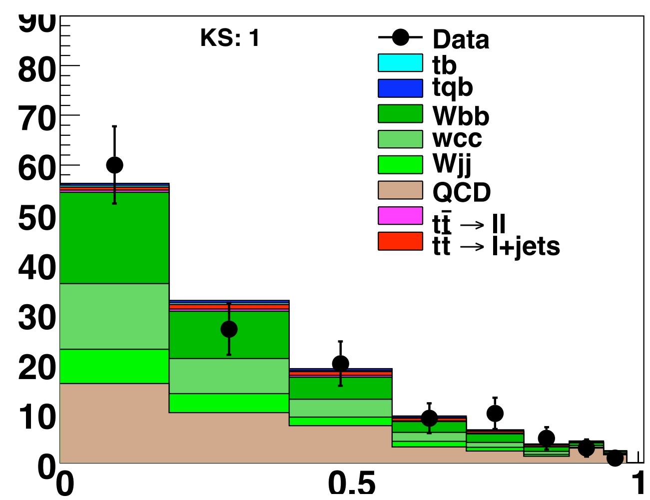
s-channel disc.



s-channel disc.

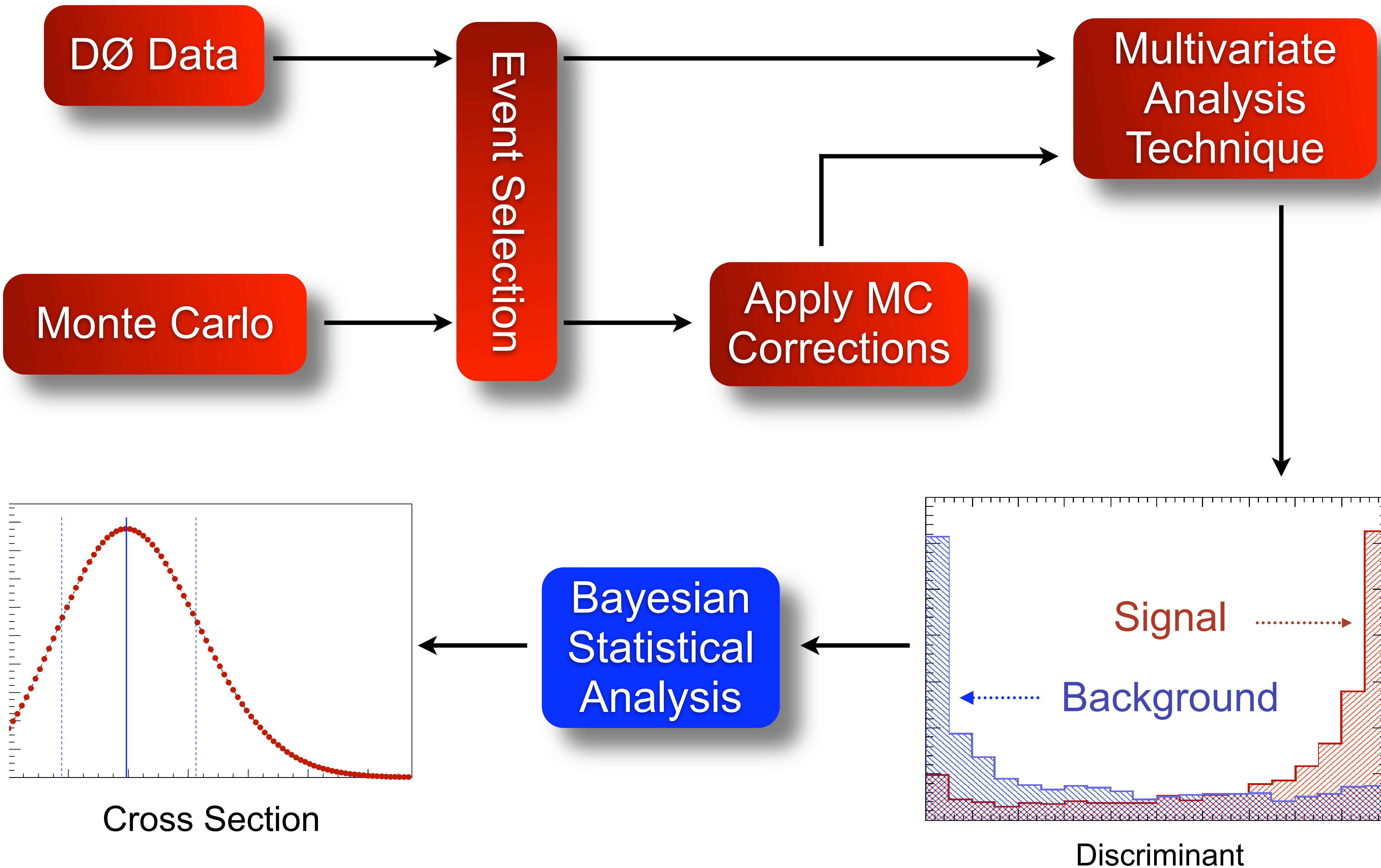


t-channel disc.



t-channel disc.

Single Top Analysis Flow

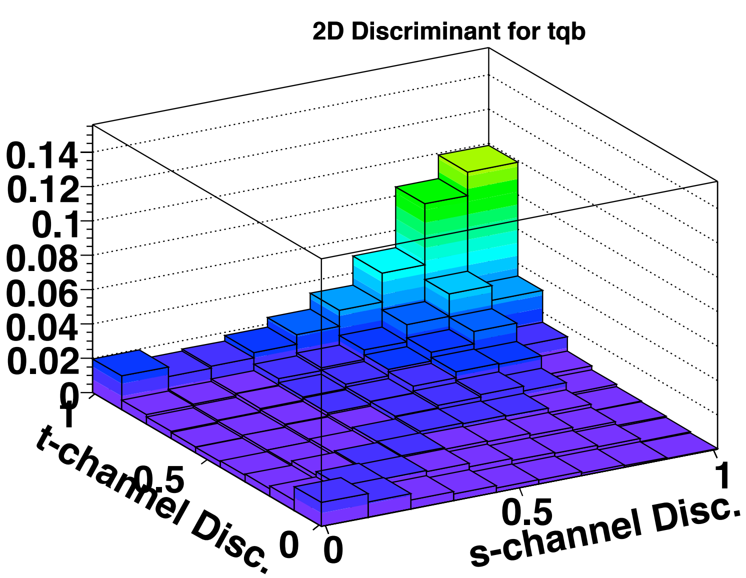


Cross Section Measurement Method

- Determine cross section by calculating the Bayesian posterior density function
  - Question: What is the probability density for the cross section given the data?

$$P(\sigma|N_{obs}) = \underbrace{\beta}_{\text{Normalization}} \times \int \underbrace{\mathcal{L}(N_{obs}|\alpha, n_B, \sigma)} \times \underbrace{\pi(\alpha, n_B)}\,\underbrace{\pi(\sigma)}\;\underbrace{d\alpha dn_B}_{\text{Integrate over “nuissance” parameters}}$$

$$\mathcal{L}(N_{obs}|n_{exp}) = \frac{n_{exp}^{N_{obs}} e^{-n_{exp}}}{N_{obs}!}$$



Acceptance and Background Prior

- Sample multivariate Gaussian with μ=[α,n] and σ=[δα,δn] (*next slide*)

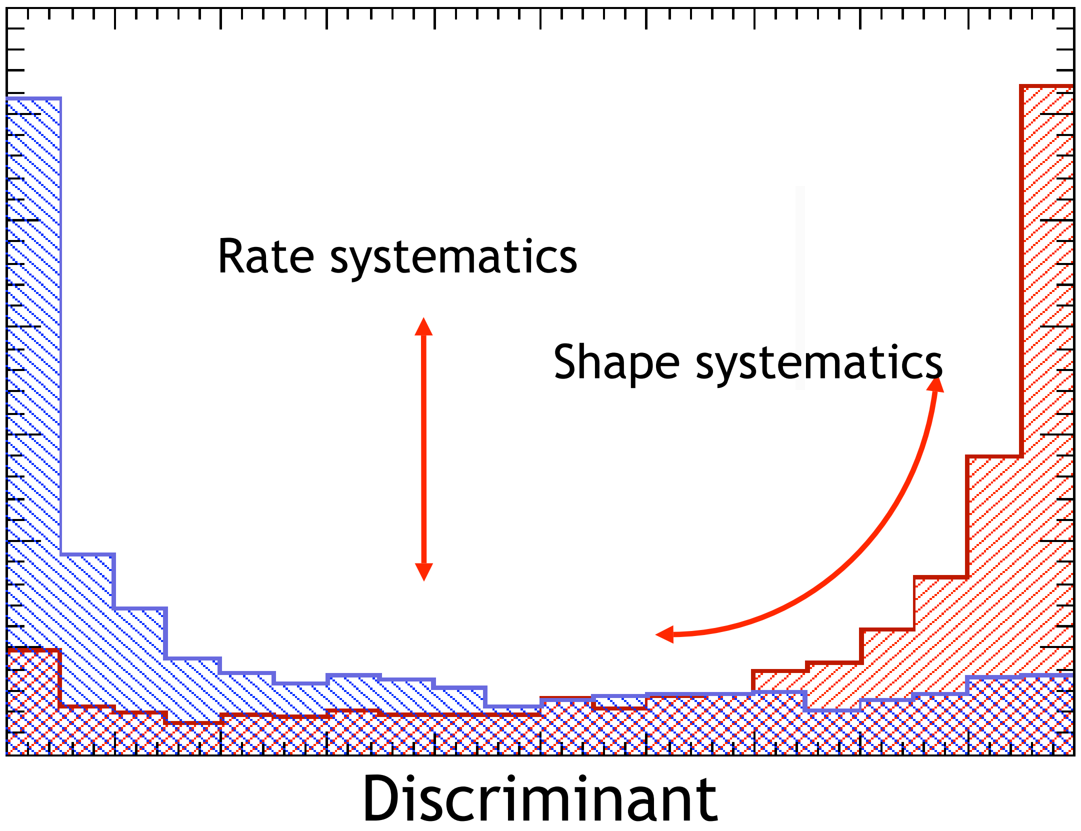
Cross Section Prior

$$\pi(\sigma) = \frac{1}{\sigma_{\max}}, 0 < \sigma < \sigma_{\max}$$

Systematic Errors

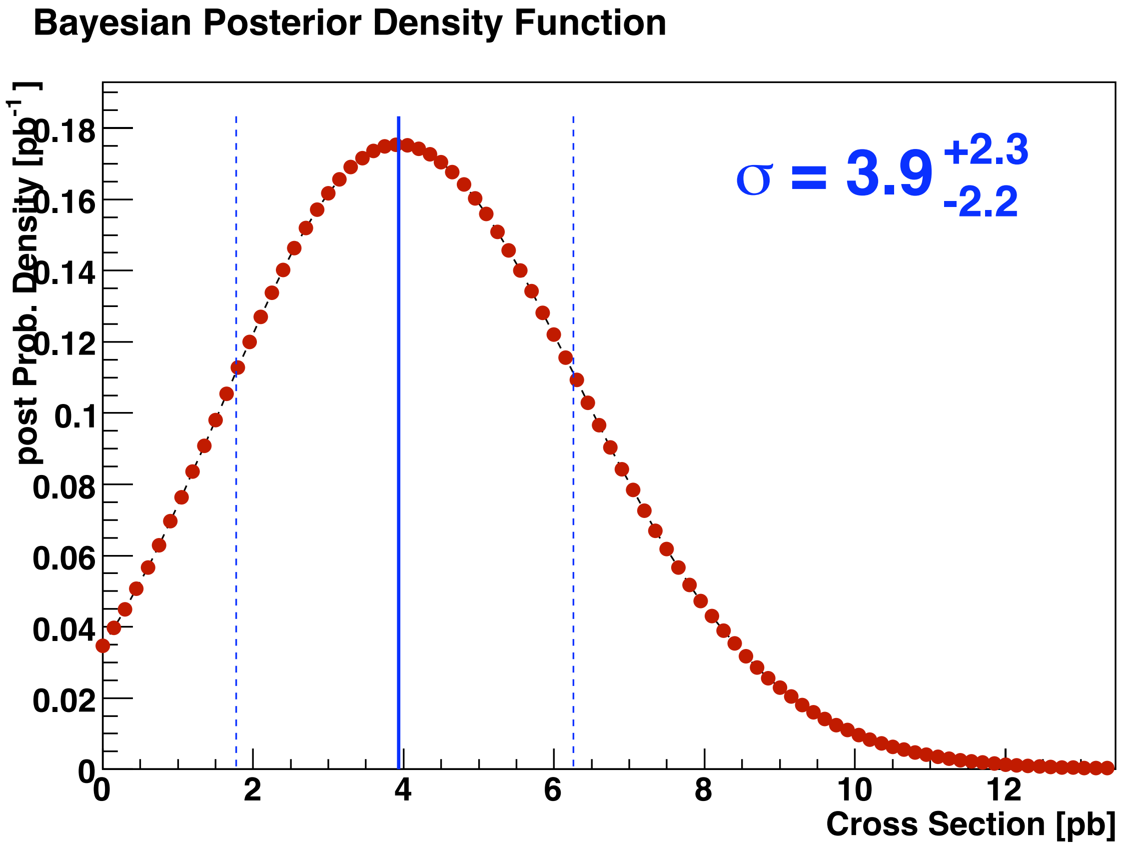
- Uncertainty in model, energy scale, or normalization affect signal and background yields → uncertainty on cross section
- Size of systematic determined by rerunning analysis with ±1 sigma errors
- Systematics in BLUE and GREEN affect rate and RED affects rate and shape

Source of Uncertainty	Size
Top pairs normalization	18%
W+jets & multijets normalization	18–28%
Integrated luminosity	6%
Trigger modeling	3–6%
Lepton ID corrections	2–7%
Jet modeling	2–7%
Other small components	Few %
Jet energy scale	1–20%
Tag rate functions	2–16%

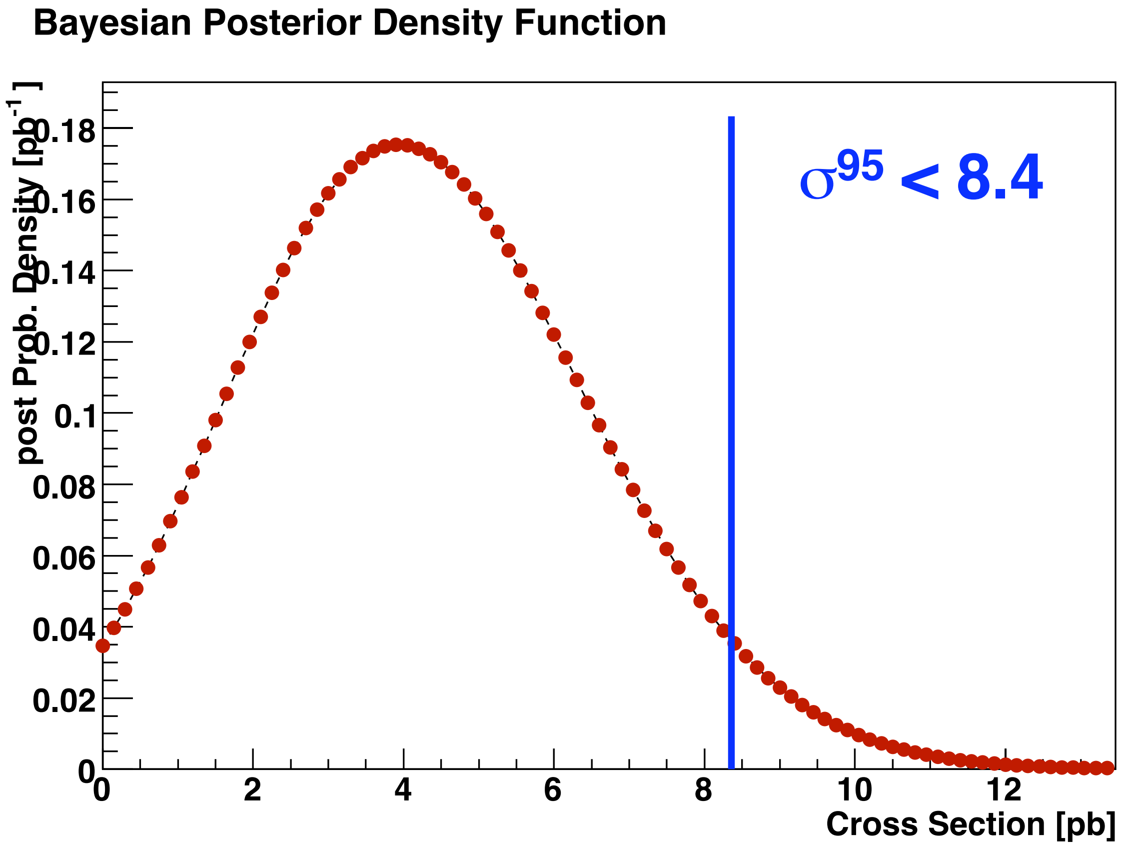


Cross Section Measurement Method

- Two possibilities: (1) excess of data over background and (2) no excess



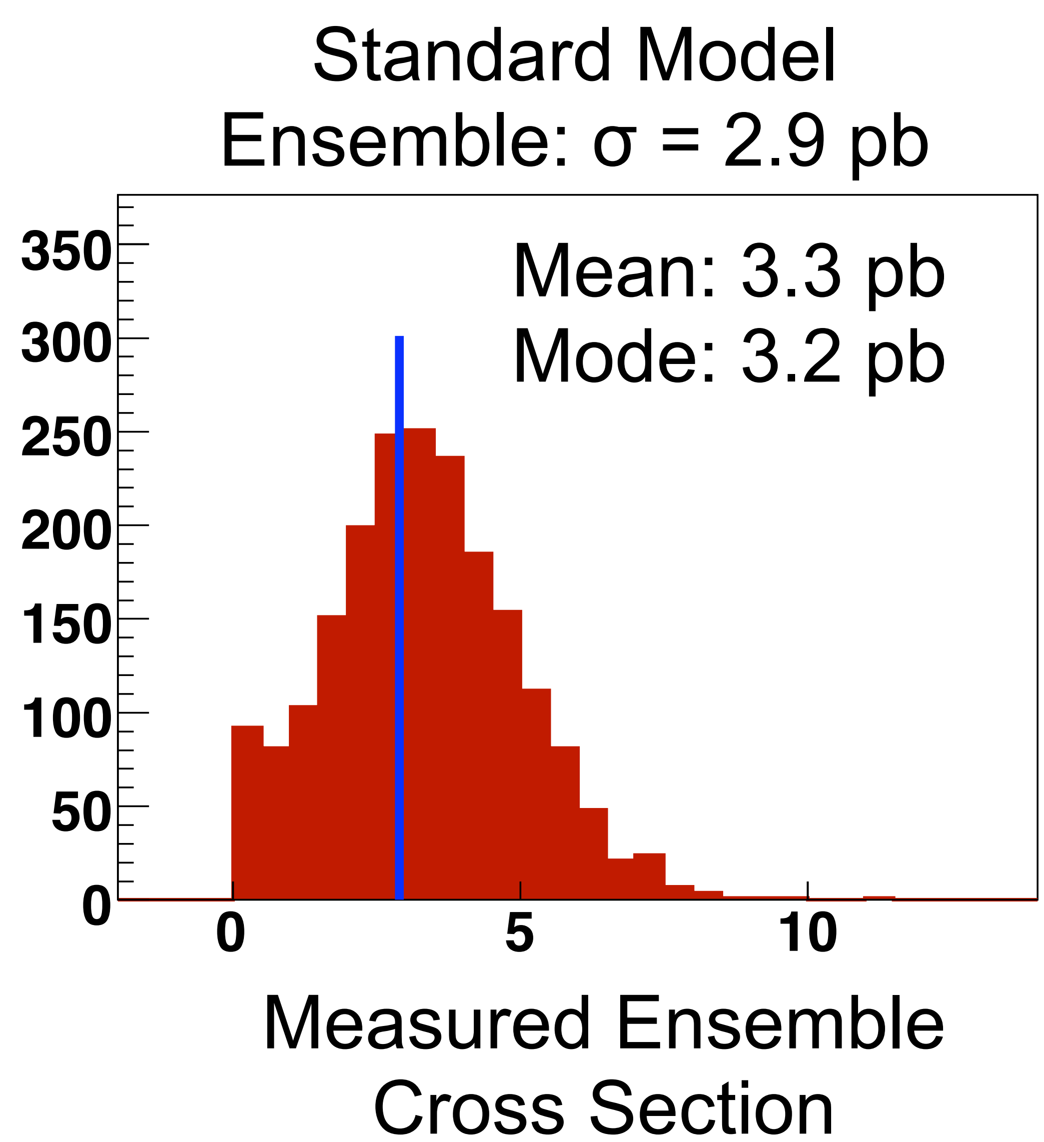
excess → cross section

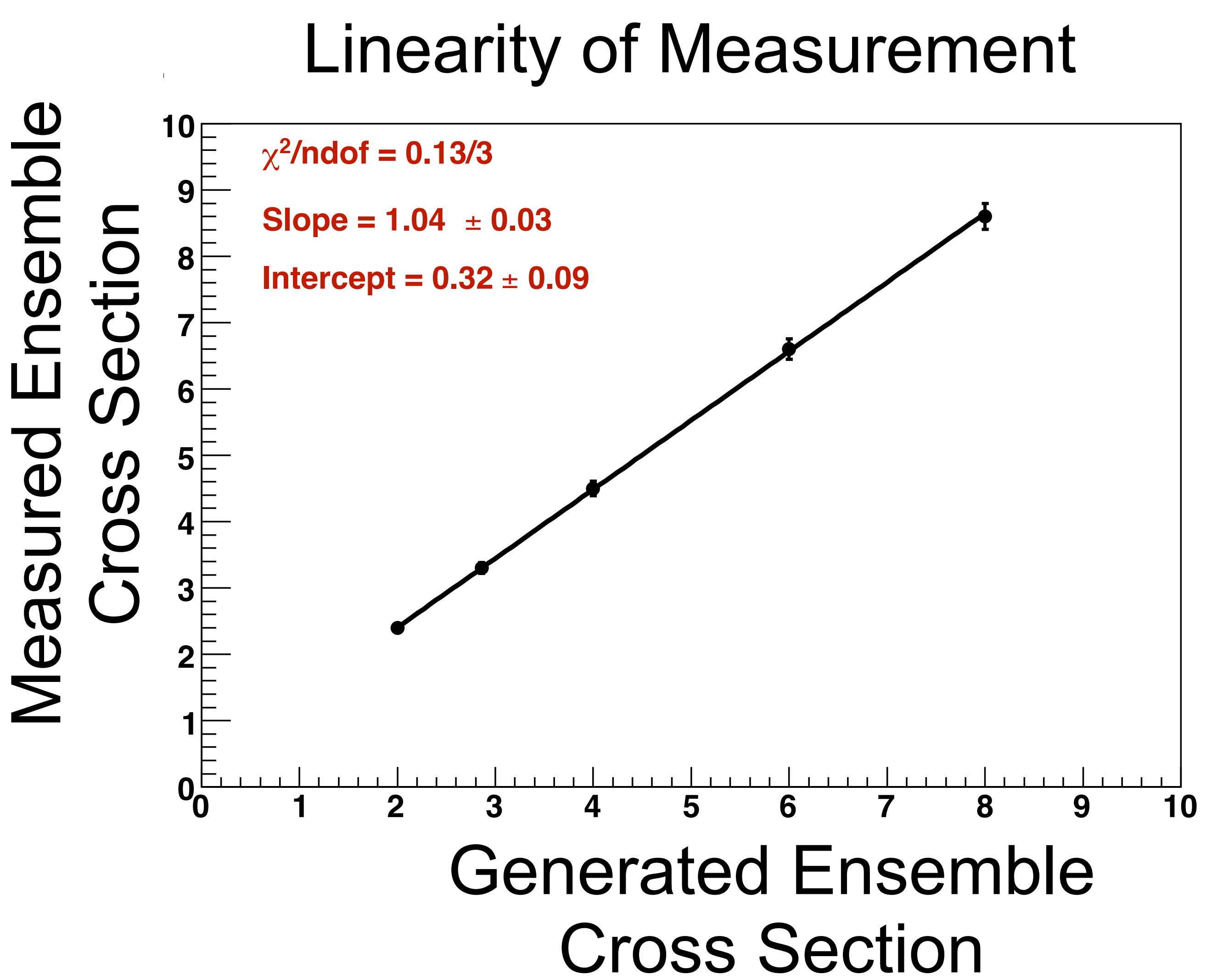


no excess → upper limit

Linearity of Cross Section Measurement

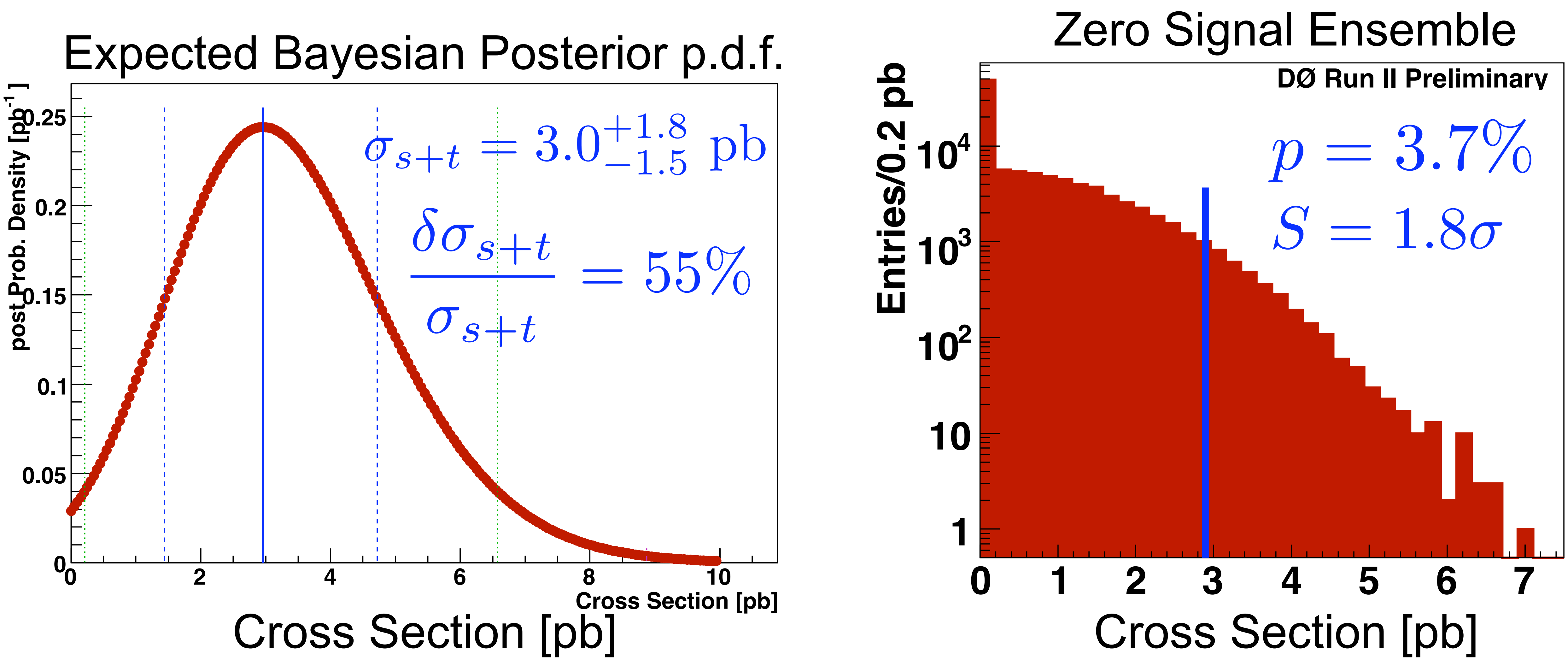
- Test procedure before running on data
- Create ensembles with known signal fraction and measure cross section
- Plot: input vs measured cross section





Expected Cross Section Resolution

- Check expected cross section resolution
  - Perform analysis with $N_{obs} = N_{signal} + N_{back}$
- Check sensitivity to background fluctuation
  - Create ensemble with zero signal fraction. Calculate *p*-value for SM single top



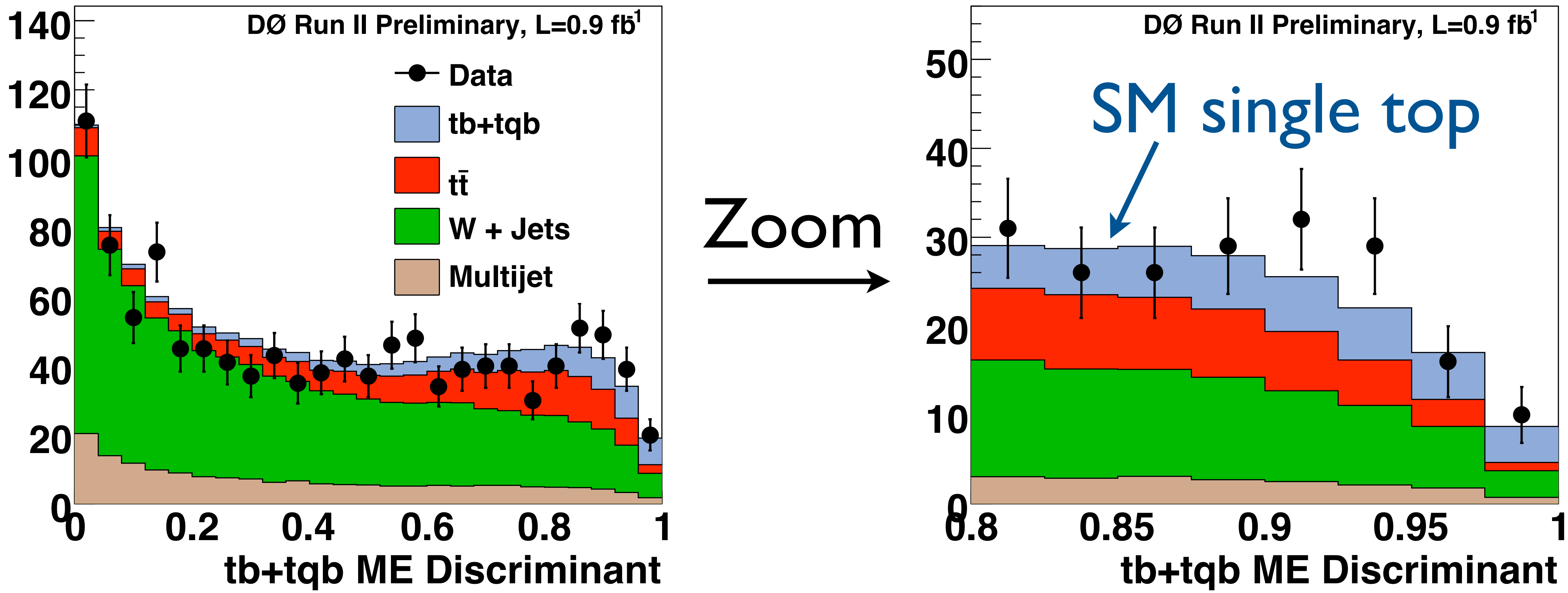
Results with ~ 1 fb^{-1}

Excess of Data Above Background

- Evaluating discriminant on data, single MC, and background MC, an excess of data over the background was observed!

$$\sigma_{tb+tqb} = 4.6^{+1.8}_{-1.5}\mathrm{pb}$$

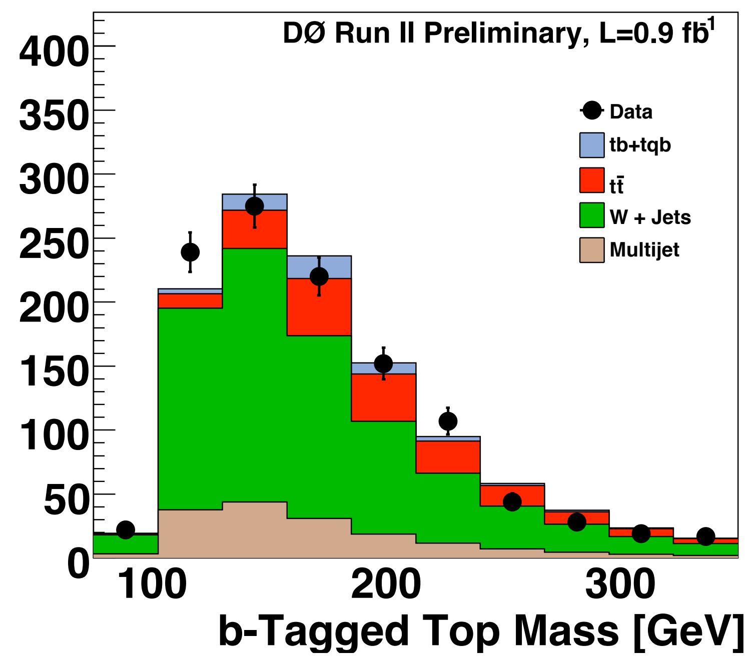
- Visually demonstrated using 1D discriminant

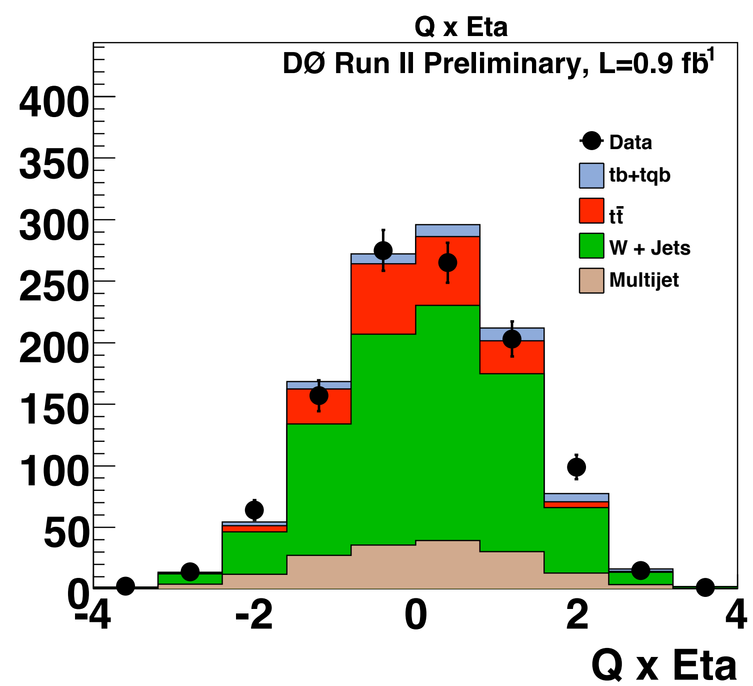


Consistent with Single Top?

- Look at M(l,v, *b*-tagged jet) and q x η. Expect M(l,v, *b*-tagged jet) ~ 175 (top mass) and q x η to be asymmetric w/ peak in forward direction (+η)

All Events



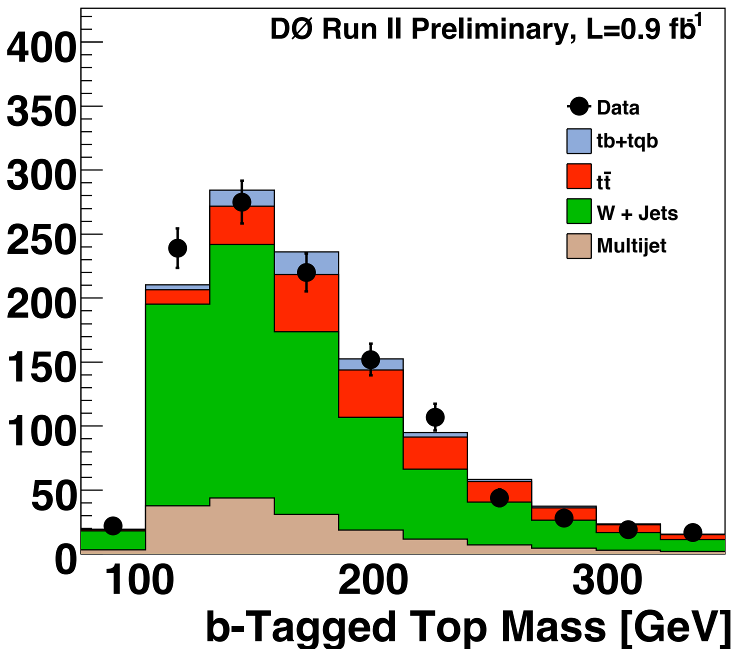


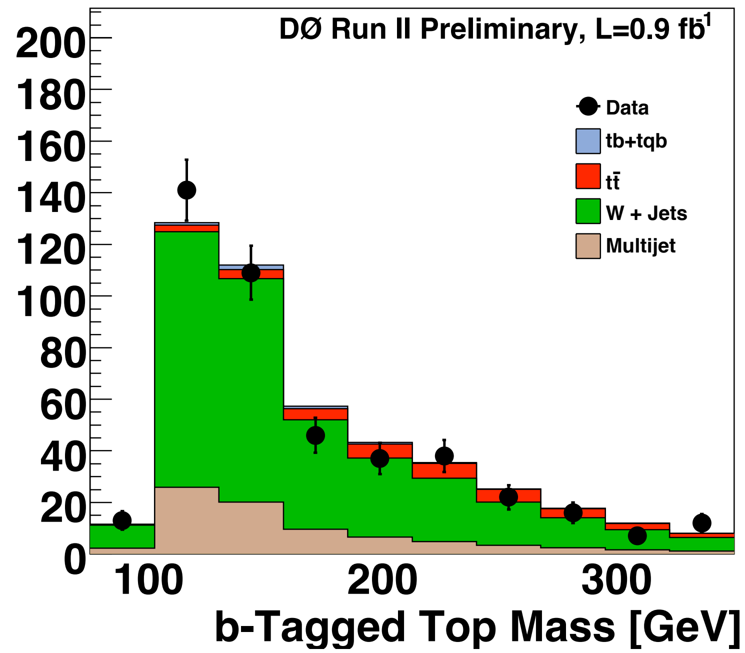
Consistent with Single Top?

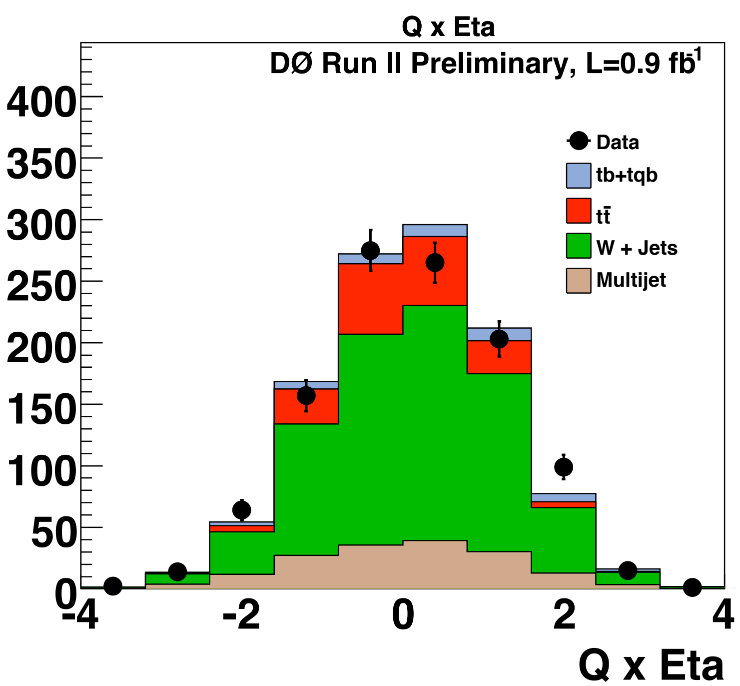
- Look at M(l,ν, *b*-tagged jet) and q x η. Expect M(l,ν, *b*-tagged jet) ~ 175 (top mass) and q x η to be asymmetric w/ peak in forward direction (+η)

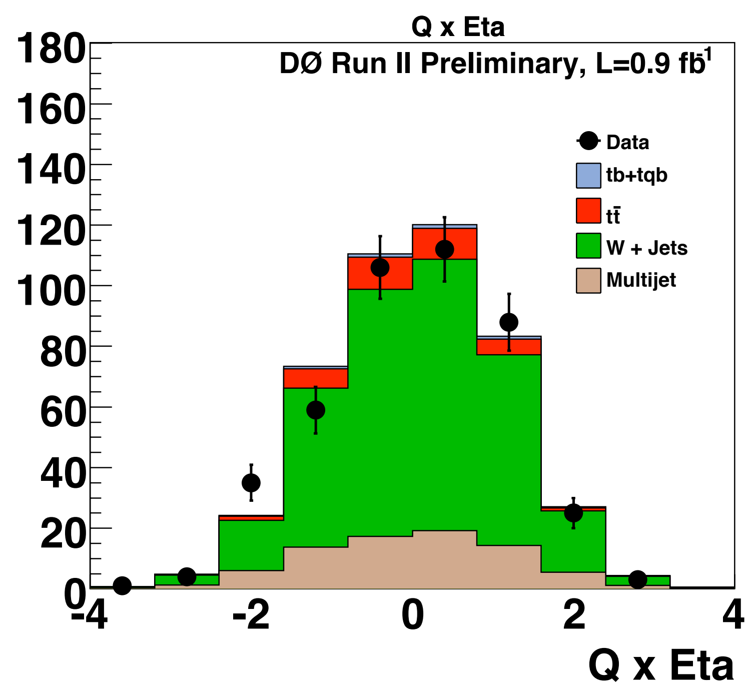
All Events

Background-like w/ D < 0.4





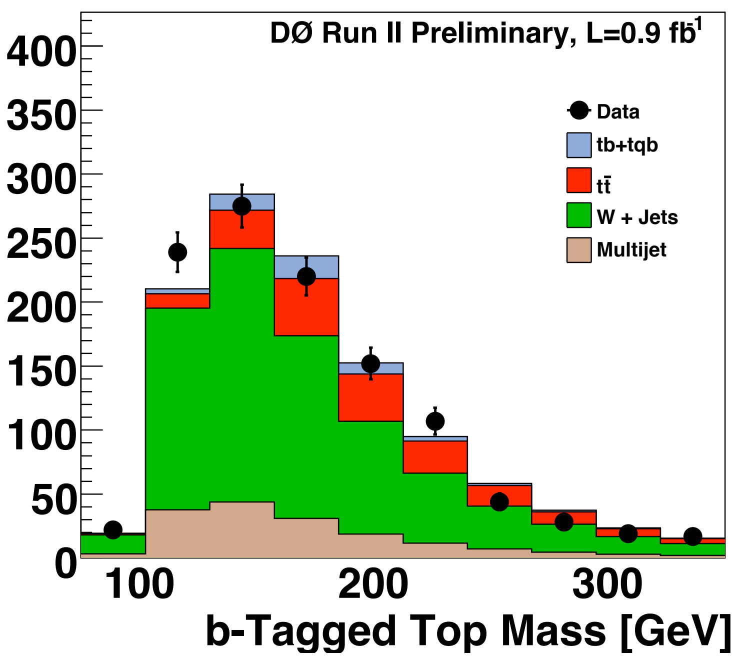


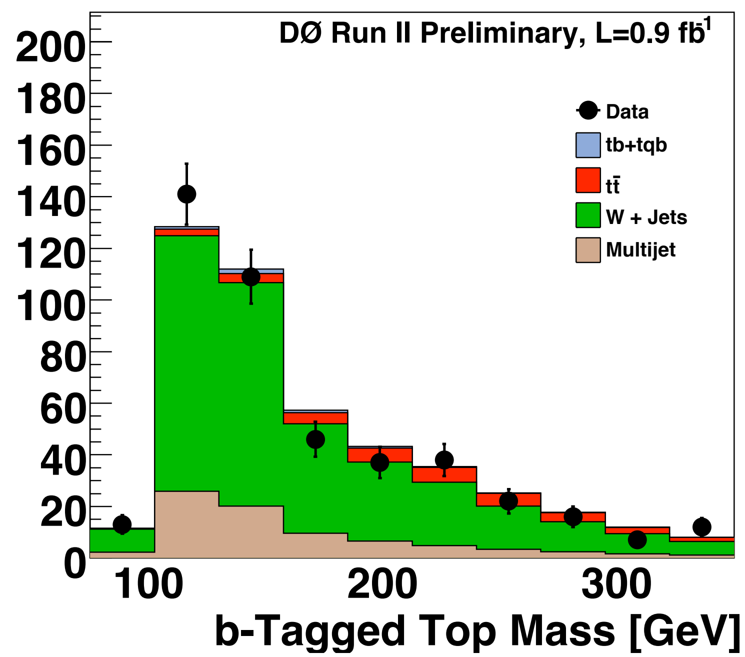


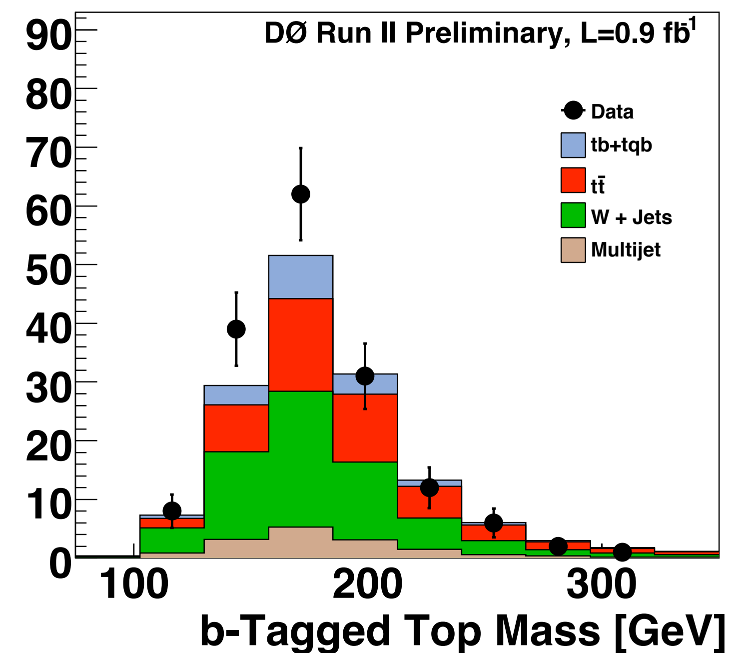
Consistent with Single Top?

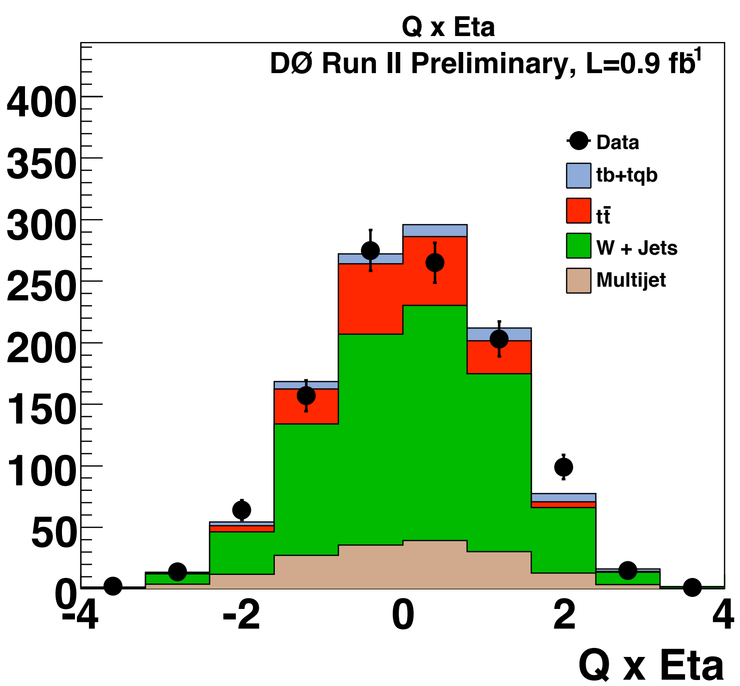
- Look at M(l,ν, *b*-tagged jet) and q x η. Expect M(l,ν, *b*-tagged jet) ~ 175 (top mass) and q x η to be asymmetric w/ peak in forward direction (+η)

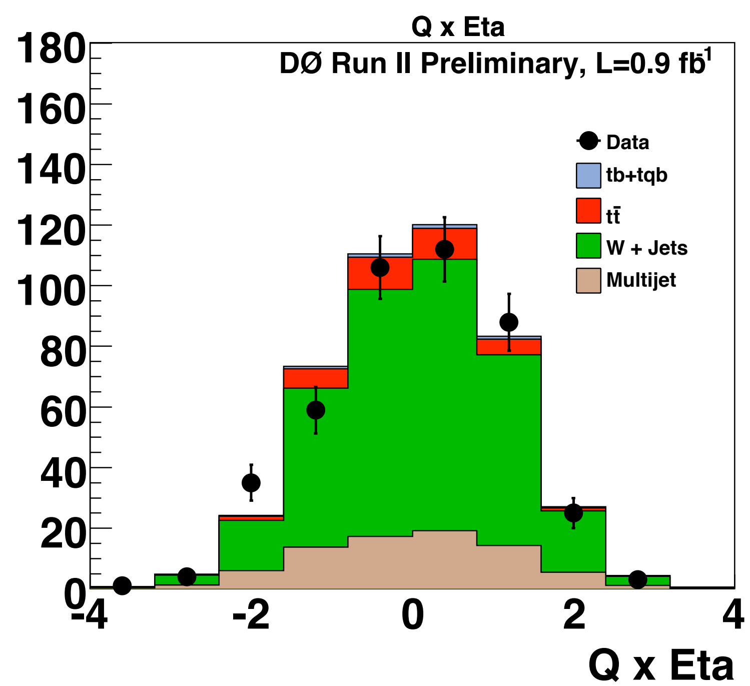
All Events | Background-like w/ D < 0.4 | Signal-like w/ D > 0.7

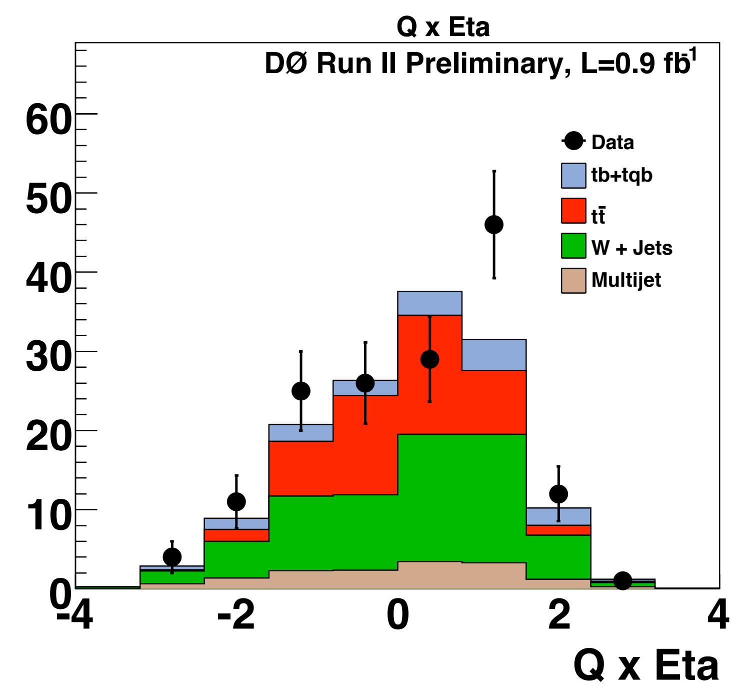








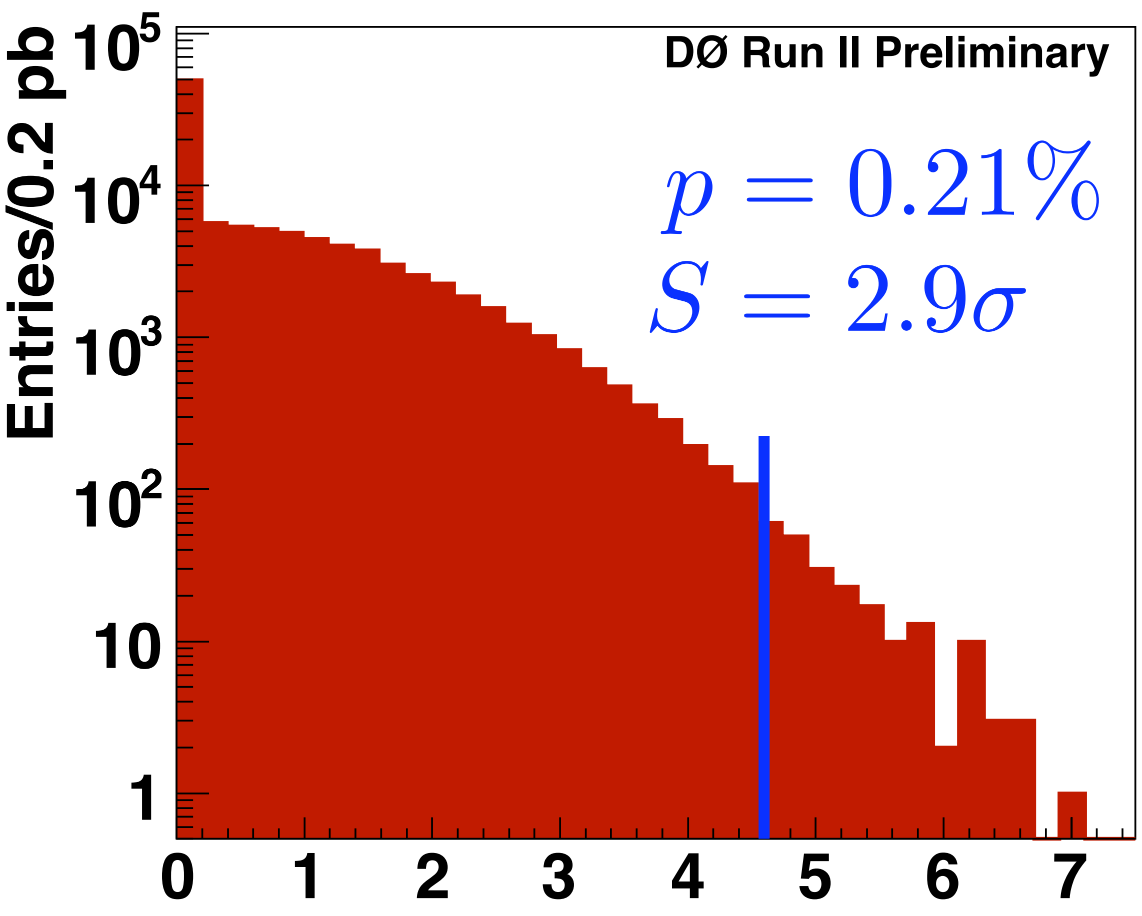




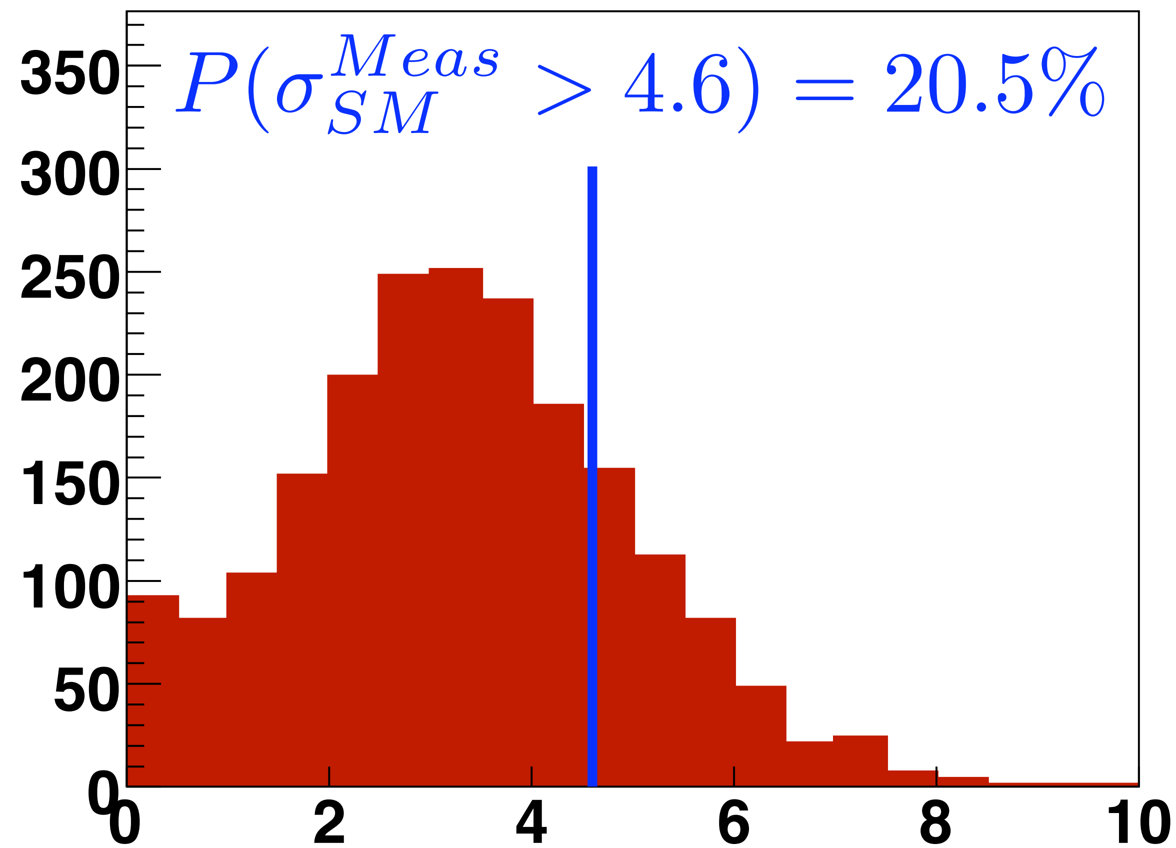
Significance and SM Compatibility

- Determine probability of upward fluctuation from background (*p*-value)
- Determine compatibility with SM prediction

Zero Signal Ensemble

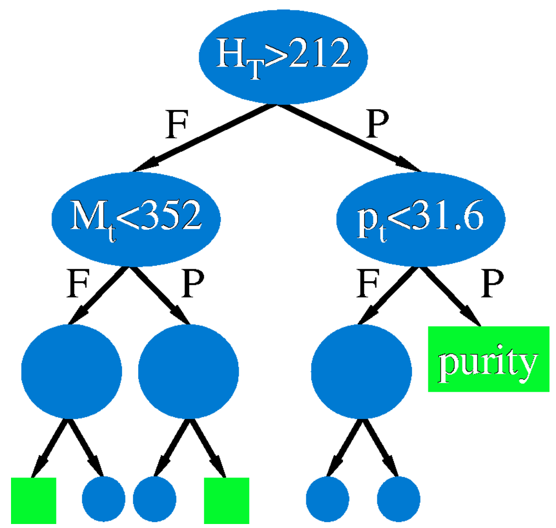


Standard Model Ensemble

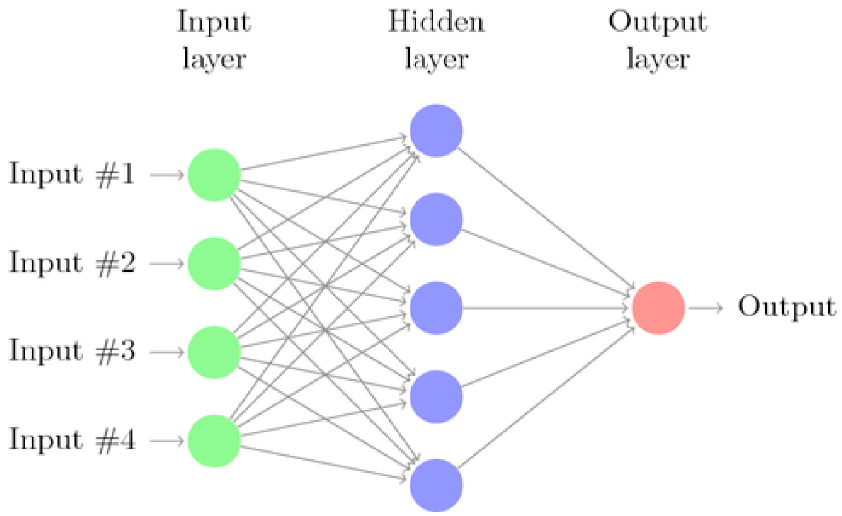


One of Three Single Top Analyses

- DØ performed three searches for single top production
  - Matrix Element (you just heard about this)
  - Boosted Decision Trees



  - Bayesian Neural Network



	Bayesian NN		Matrix Element		Decision Trees	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
σ(tb+tqb)[pb]	**$3.2^{+2.0}_{-1.8}$**	**5.0 ± 1.9**	**$3.0^{+1.8}_{-1.5}$**	**$4.6^{+1.8}_{-1.5}$**	**$2.7^{+1.6}_{-1.4}$**	**4.9 ± 1.4**
Significance	**1.3σ**	**2.4σ**	**1.8σ**	**2.9σ**	**2.1σ**	**3.4σ**

First evidence for single top quark production!

SM compatibility is 11%.

Single Top Announcement

- Announced at Fermilab Wine & Cheese seminar on December 8, 2006

SCIENTIFIC AMERICAN

PHYSICS

Alone at the Top

CLOSER TO GOD: FERMILAB MAKES SOLO TOP QUARKS BY ALEXANDER HELLEMANS

CERN COURIER

Scientists at the D0 experiment discover new path to the top

DZero finds evidence of rare single top quark; Observation marks a step closer to finding Higgs boson

Batavia, Ill.--Scientists o
Fermi National Accelera
December 8, 2006 the fi
subatomic process invol
predictions made by par
In the longer term, the te
search for an even more

HIGH-ENERGY PHYSICS

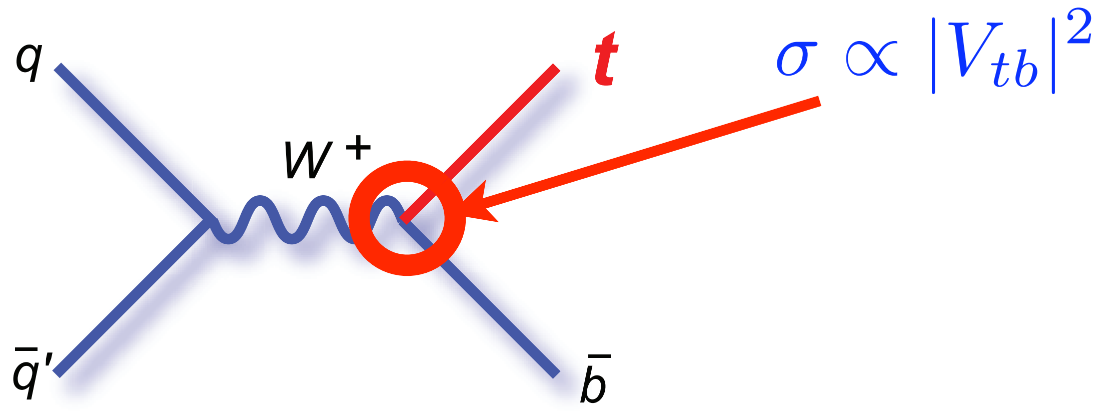
nature physics

Top quarks go it alone

The first, long-sought evidence for the production of single top quarks, by the weak interaction, has been reported from a sophisticated analysis of a large number of proton–antiproton collisions at the Tevatron.

Single Top Measurement → Vtb

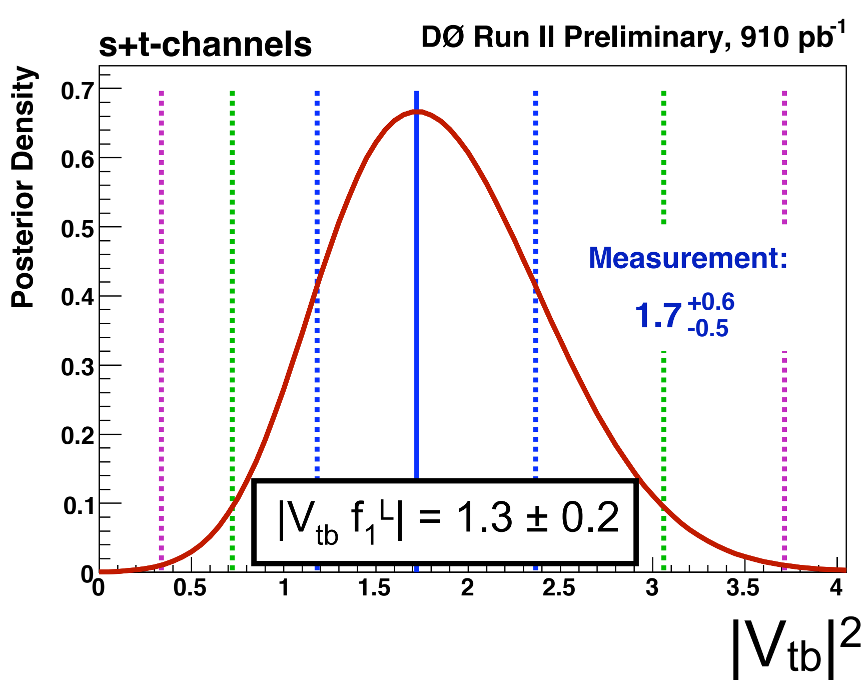
- After measuring single top cross section, we turn around and determine V_{tb}
- Use decision tree measurement for V_{tb}
- Assume:
  - $|V_{td}|^2 + |V_{ts}|^2 << |V_{tb}|^2$
  - Pure V-A and CP conserving vertex

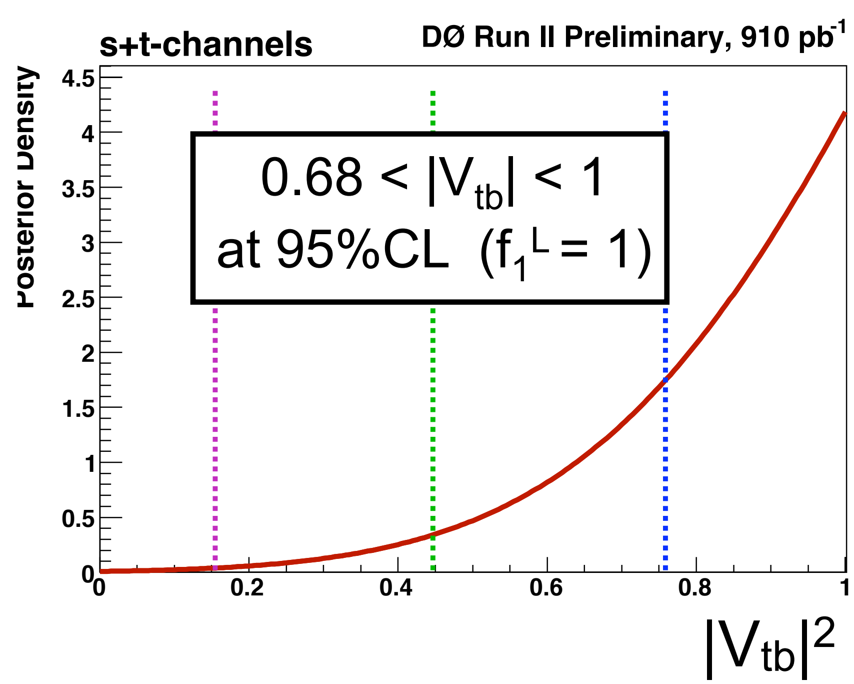


- Does not assume three quark generations
- Build posterior for $P(V_{tb}|N_{obs})$ integrating over additional theoretical errors

Additional theoretical uncertainties		
	tb	tqb
Top mass	13 %	8.5 %
Scale	5.4 %	4.0 %
PDF	4.3 %	10 %
α_s	1.4 %	0.01 %

hep-ph/0408049





Combined DØ Single Top Result

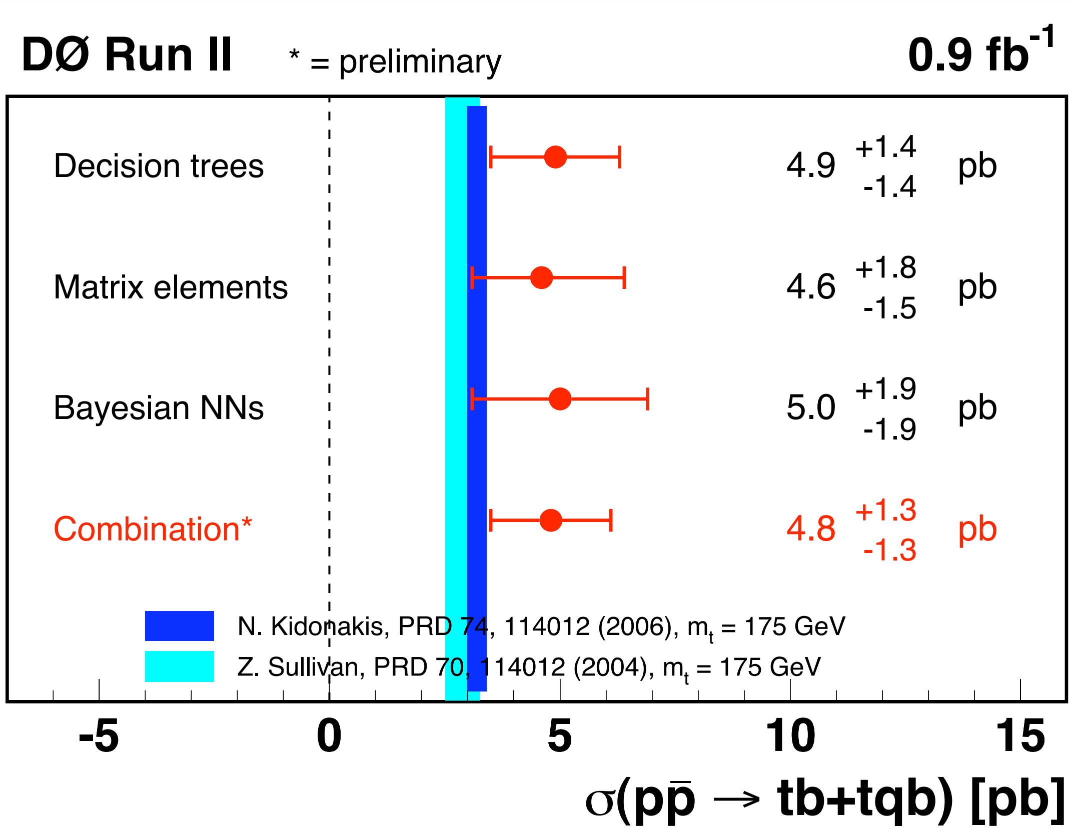
- The matrix element, Bayesian neural network, and decision tree analyses were combined using the BLUE (Best Linear Unbiased Estimator) method

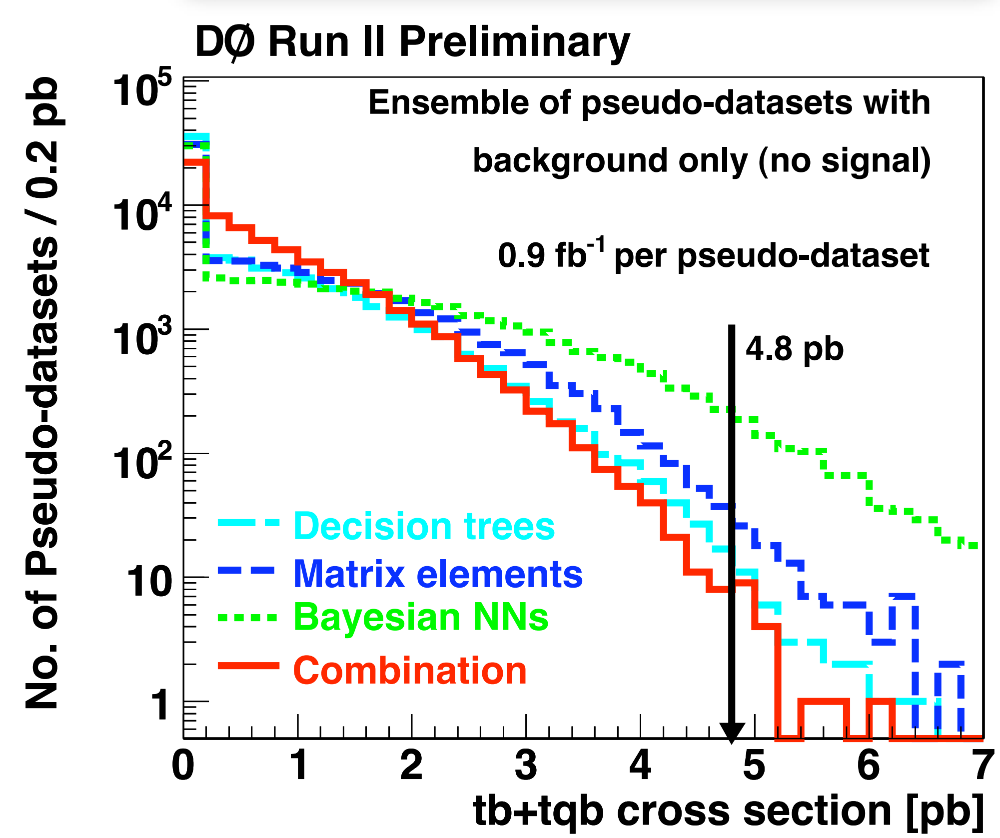
$$\sigma_{\text{comb}} = w_{BNN}\sigma_{BNN} + w_{DT}\sigma_{DT} + w_{ME}\sigma_{ME}$$

  - Need to know correlation between analyses to determine weights

$$\boxed{\sigma_{\text{comb}} = 4.8 \pm 1.3 \text{ pb}}$$

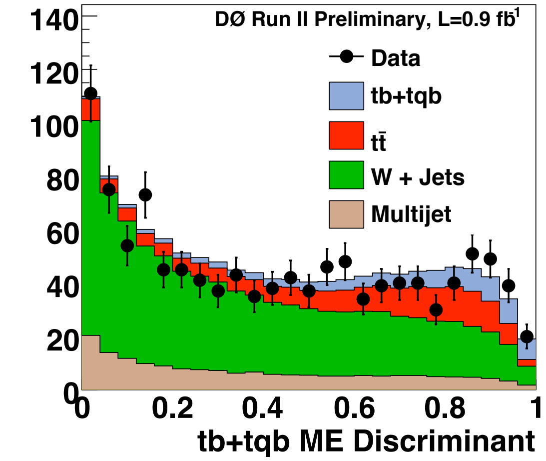
$$\boxed{\text{Sig} = 3.5\sigma}$$





Conclusion

- Using ~ 1 fb^{-1} of DØ Run IIa data, we measure the combined tb+tqb single top cross section with the matrix element method as



$$\boxed{\sigma_{tb+tqb} = 4.6^{+1.8}_{-1.5}\mathrm{pb}}$$

- Three DØ single top analyses are combined and measure a cross section of

$$\boxed{\sigma_{\mathrm{comb}} = 4.8 \pm 1.3 \ \mathrm{pb}}$$

$$\boxed{\mathrm{Sig} = 3.5\sigma}$$

- The three single top measurements were recently accepted for publication by PRL [hep-ex/0612052]

- PRD including combination is coming soon

- DØ has more than 2 fb^{-1} of data on tape: Push towards 5σ, measure σ_{tb} and σ_{tqb}, and of course, keep an eye out for new physics

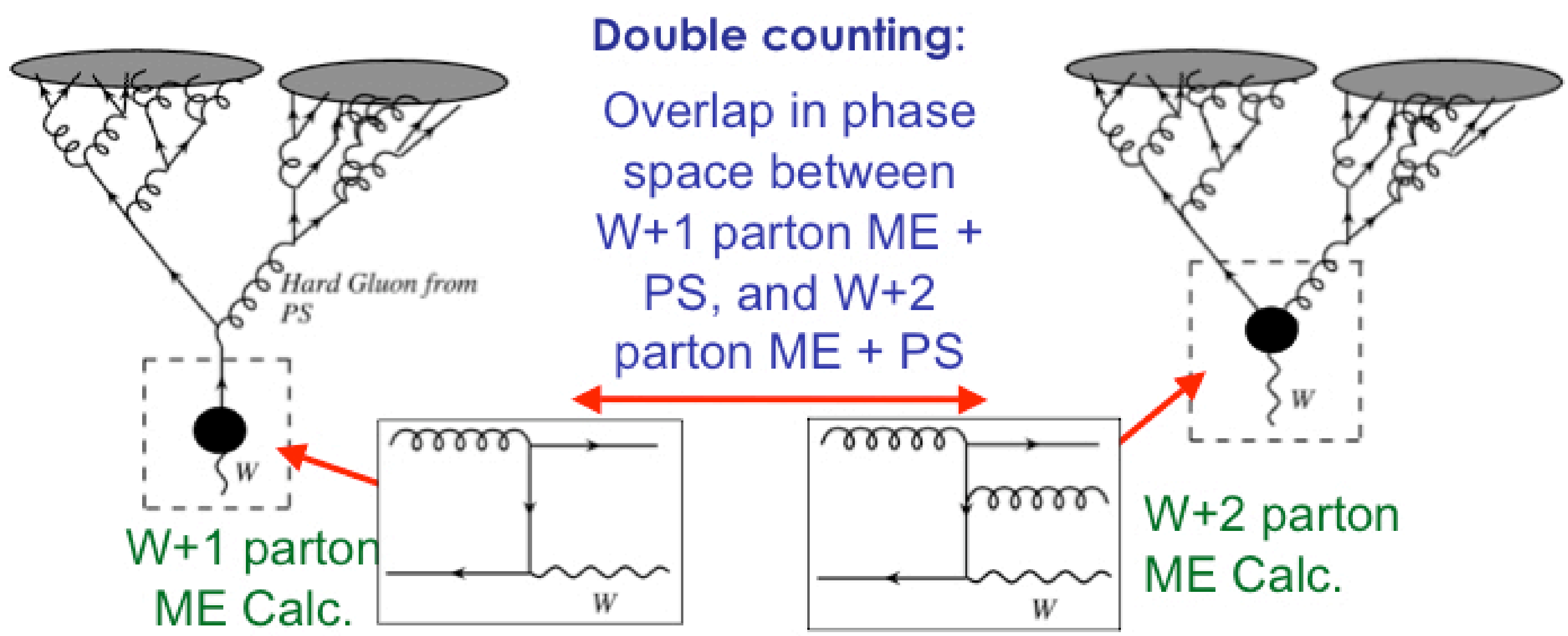
Thanks

- Gordon Thanks for taking me as a student and getting me into the game
- Aran Thanks for answering the 10 million questions I have and keeping me company at Fermilab
- My committee Thanks for listening and reading
- DØ Single top group + Matrix Element working group
  Special thanks to Aurelio Juste for getting me started with matrix elements
- Good friends Thanks for the Key West trip in January (20 degrees in Chicago and 80 degrees in Key West)
- Ruth I couldn't have done it without you

Backup Slides

MLM Matching

- Monte Carlo generators use 2→N matrix element calculation with parton shower to simulate “soft” QCD processes
- Problem: Double counting phase space when combining samples after parton shower has added jets
  - Example:



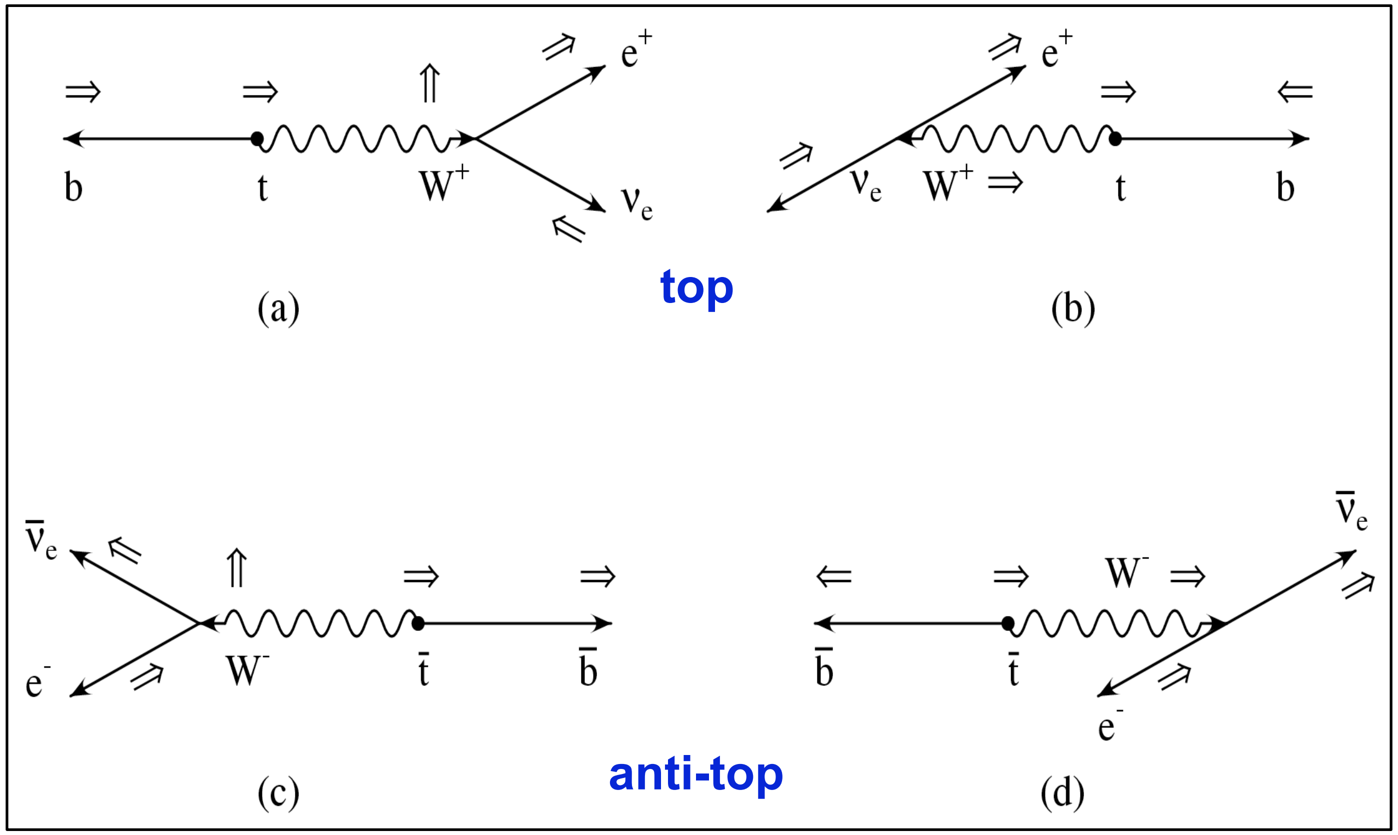
- Solution: ME+PS matching - DØ uses MLM matching scheme
- MLM scheme: (1) generate independent parton samples (e.g. W+0lp, W+1lp, etc..), (2) Run parton shower, (3) Run jet clustering algorithm, (4) Keep event if $N_{partons} = N_{jets}$

Top Polarization

- Top quark is 100% polarized along the direction of the d-type quark

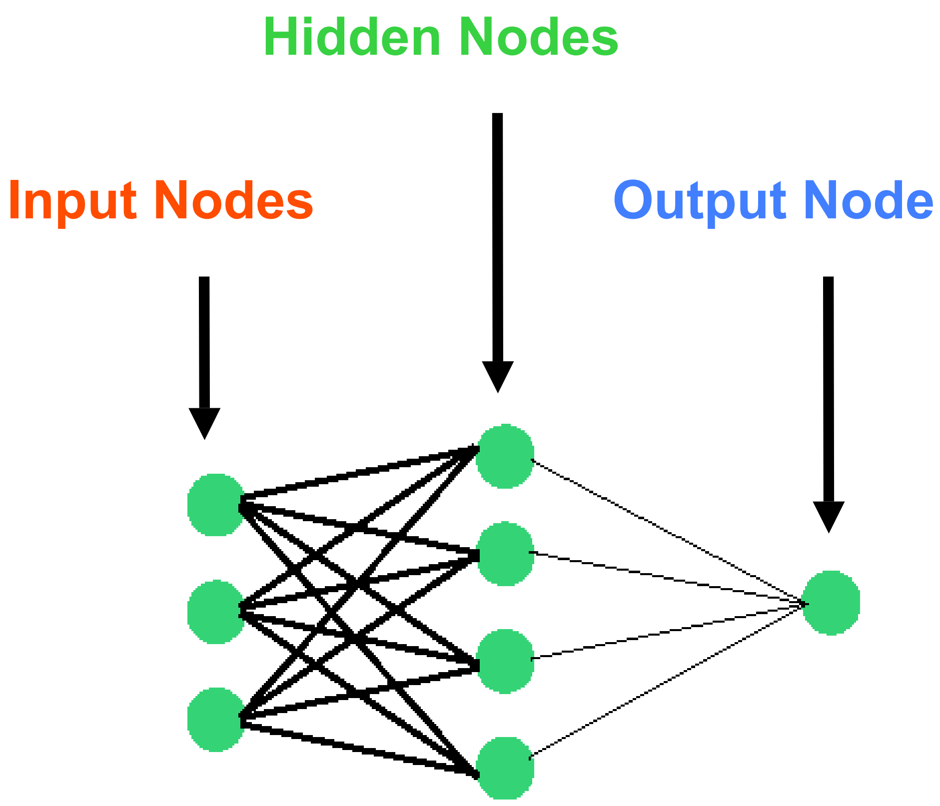
Mahlon and Parke [hep-ph/9611367]

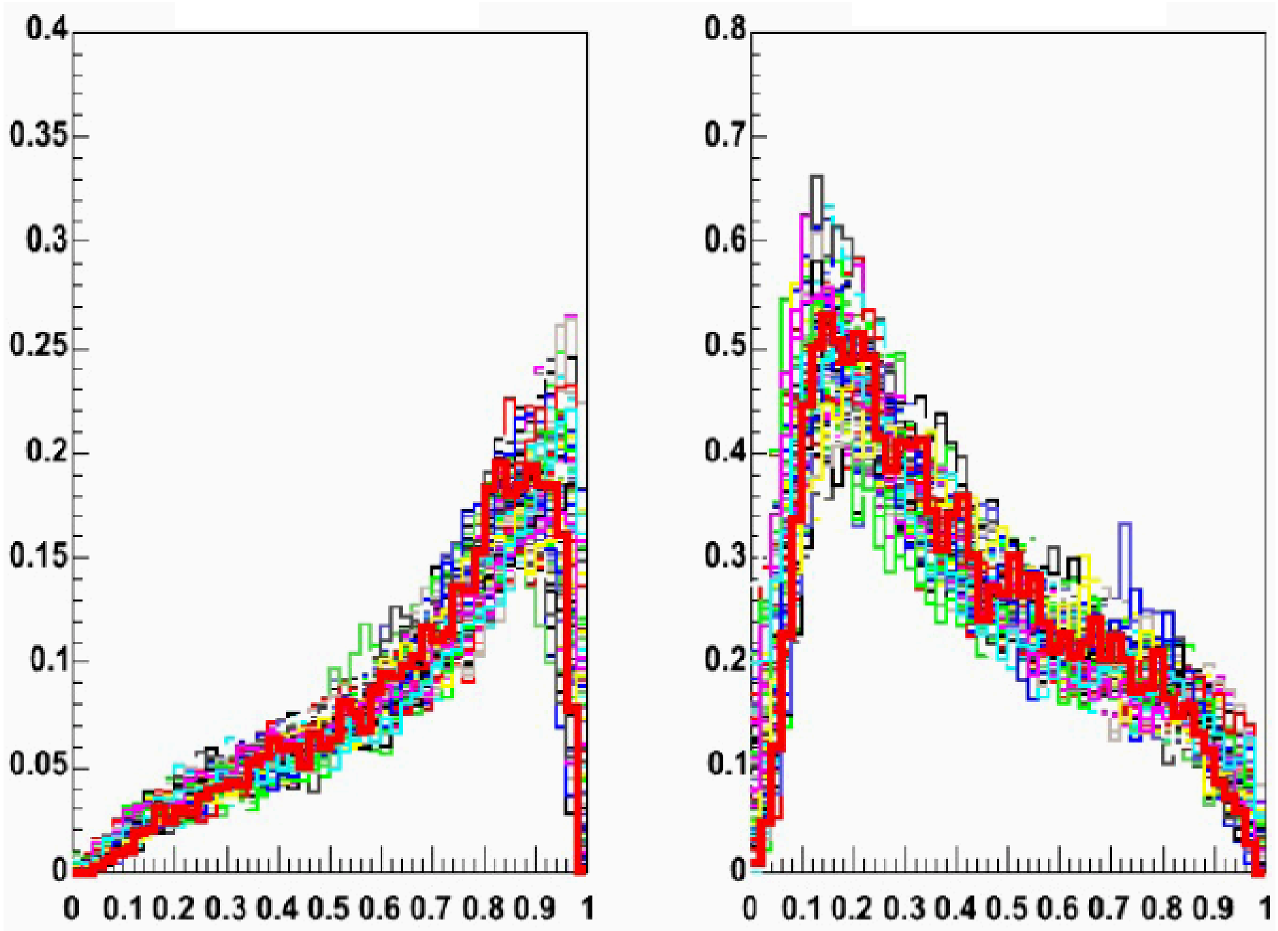
- Top quark polarization is also correlated to the momentum of the lepton from the W decay since both top and W decay electroweakly.
  - Boost into top quark rest frame
  - Choose top quark spin to be in the direction of d-type quark
  - $|M|^2 \propto 1 + \cos(\theta_{lep\text{-}d})$
- tb: 98% polarization if we choose the antiproton direction
- tqb: 96% polarization if we choose the spectator (d-type) quark direction



Bayesian Neural Networs

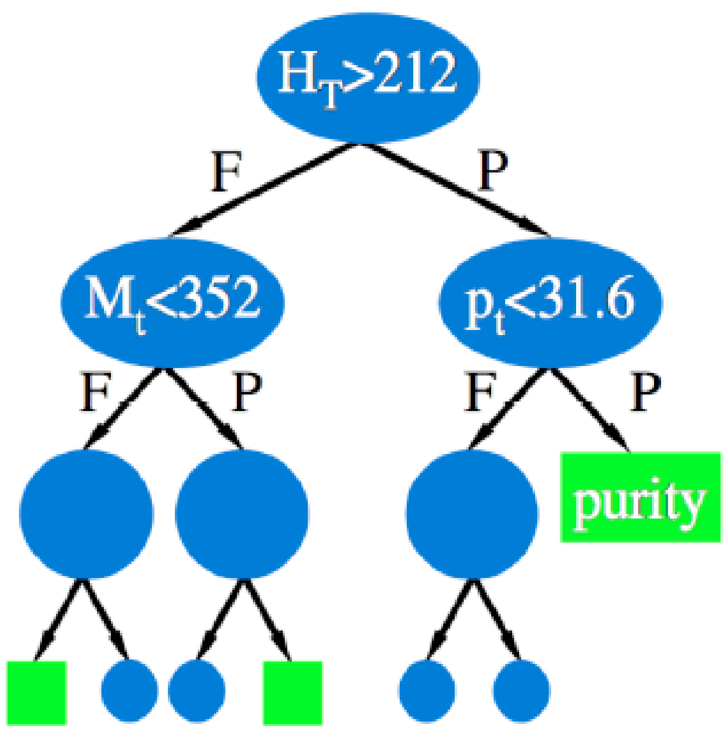
- Use 24 variables for training networks (input nodes).
- Train network on signal and background simulated events:
  - Signal tends to one and background tends towards zero (output node).
- Average many different networks for stability (hidden nodes).
- Less prone to over-training.



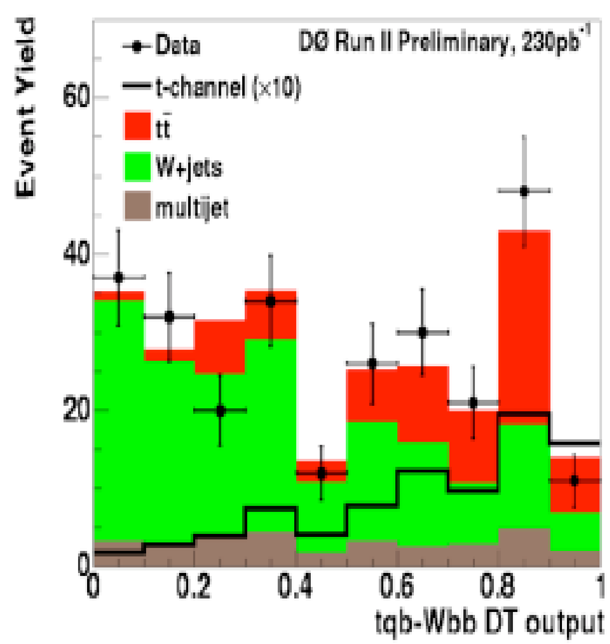


Decision Trees

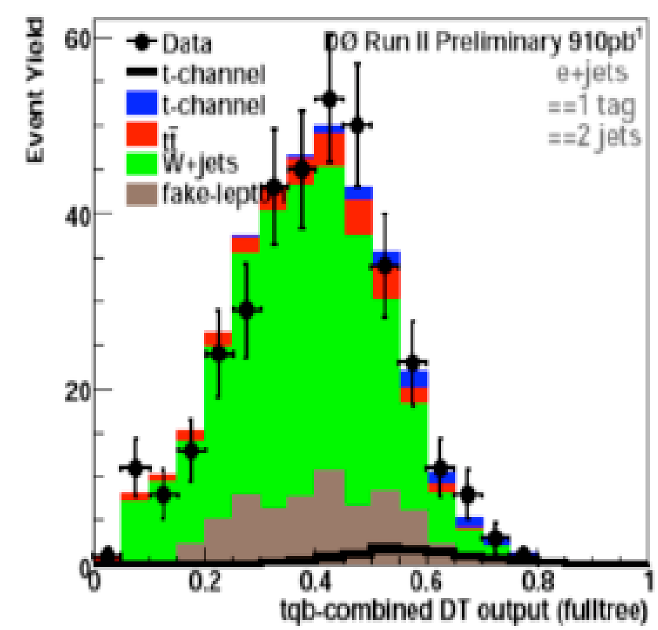
- Goal: recover events that fail a simple cut-based analysis
- Use 49 variables for training: most discriminating variables M(alljets), M(W,b-tag1), cos(b-tag1,lepton), Q(lepton)*η(untagged1)
- Decision tree output for each event = leaf purity: $N_S/(N_S+N_B)$
- Train network on signal and background simulated events:
  - Signal tends to one and background tends towards zero
- Boosting: retrain 20 times to improve "weak classifier"



Before boosting

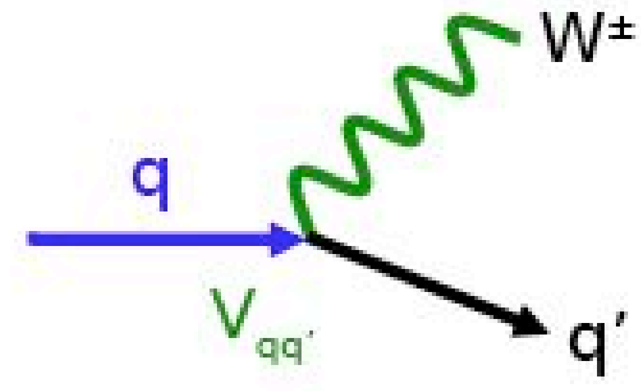


After boosting



$|V_{tb}|$

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



- Most general Wtb vertex:

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

- Assume:
  - **SM top decay**: $V_{td}^2 + V_{ts}^2 \ll V_{tb}^2$
  - Pure V-A interaction: $\mathbf{f_1^R = 0}$
  - CP conservation: $\mathbf{f_2^L = f_2^R = 0}$

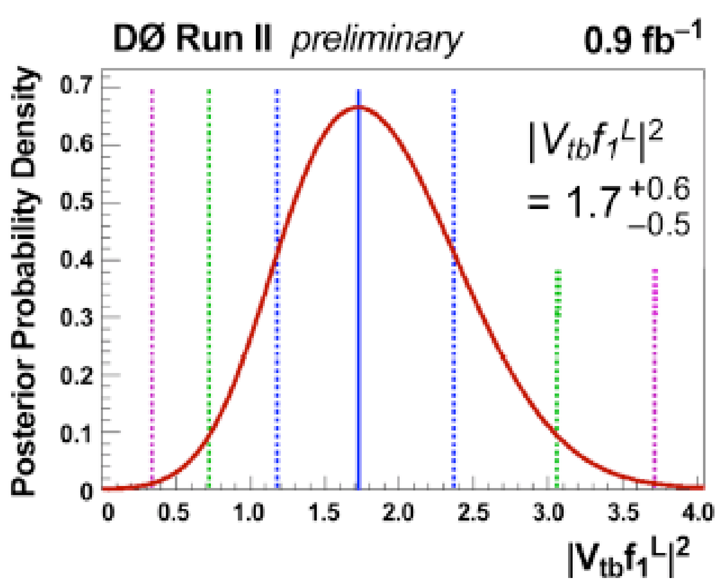
We are effectively measuring the **strength of the V-A coupling**: $|\mathbf{V_{tb} f_1^L}|$, which can be >1

Vtb

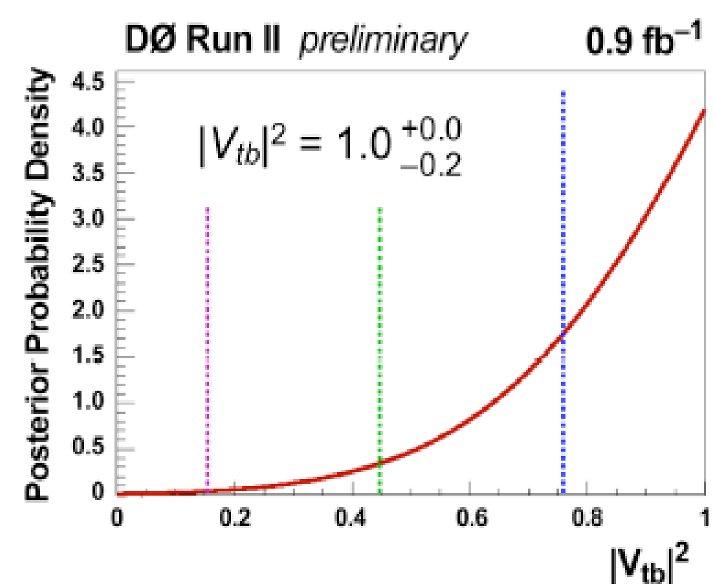
$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$

- Assuming standard model production:
  - Pure V-A and CP conserving interaction: $f_1^R = f_2^L = f_2^R = 0$.
  - $|V_{td}|^2 + |V_{ts}|^2 << |V_{tb}|^2$ or $B(t \rightarrow Wb) \sim 100\%$.

Additional theoretical uncertainties		
	tb	*tqb*
Top mass	13 %	8.5 %
Scale	5.4 %	4.0 %
PDF	4.3 %	10 %
α_s	1.4 %	0.01 %



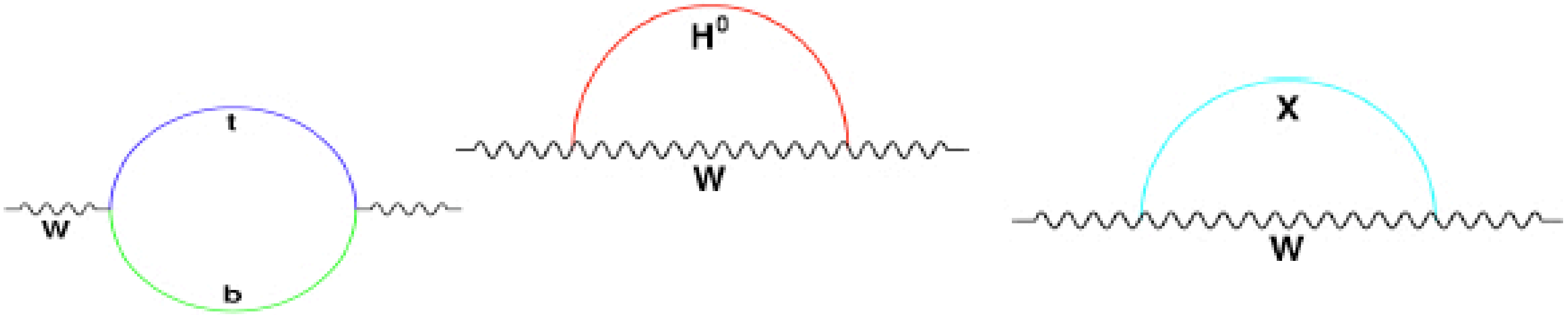
$|V_{tb}\ f_1^L| = 1.3 \pm 0.2$



$0.68 < |V_{tb}| < 1$
at 95%CL ($f_1^L = 1$)

Radiative Corrections To W Mass

- Radiative corrections due to heavy quark and Higgs loops and exotica

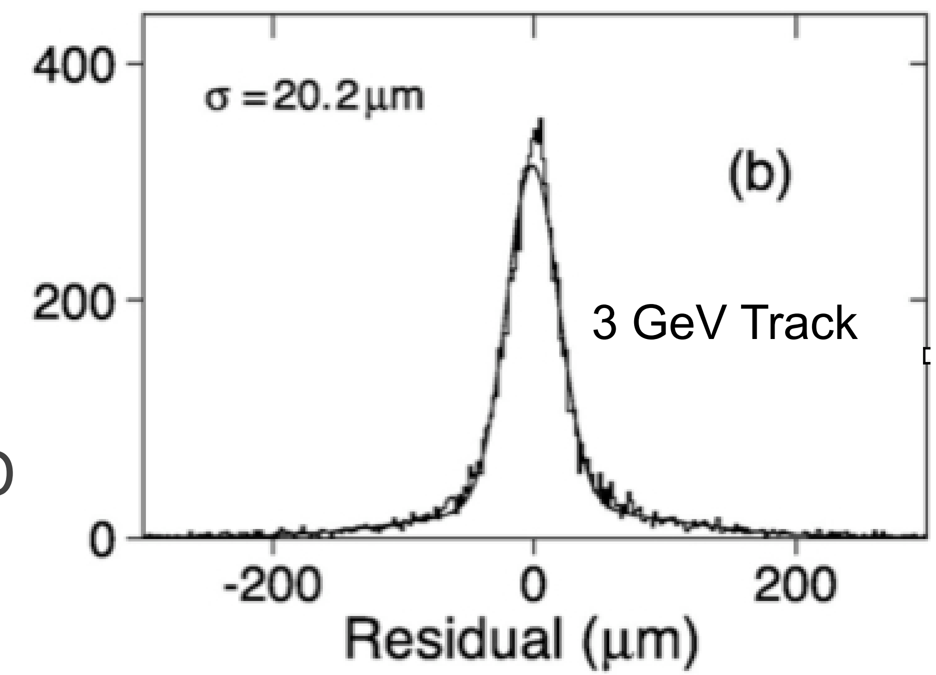


Motivate the introduction of the ρ parameter: $M_W{}^2 = \rho\, M_Z{}^2 \cos^2\theta_W$
with the predictions $(\rho-1) \sim M_{top}{}^2$ and $(\rho-1) \sim \ln M_H$

- In conjunction with M_{top}, the W boson mass constrains the mass of the Higgs boson, and possibly new particles beyond the standard model

Detector Alignment and Calibration

- Tracker
  - Optical survey determines position of the SMT and CFT elements.
  - Cosmic rays and tracks to inter-align tracker elements. CFT calibrated with 450 nm from LED

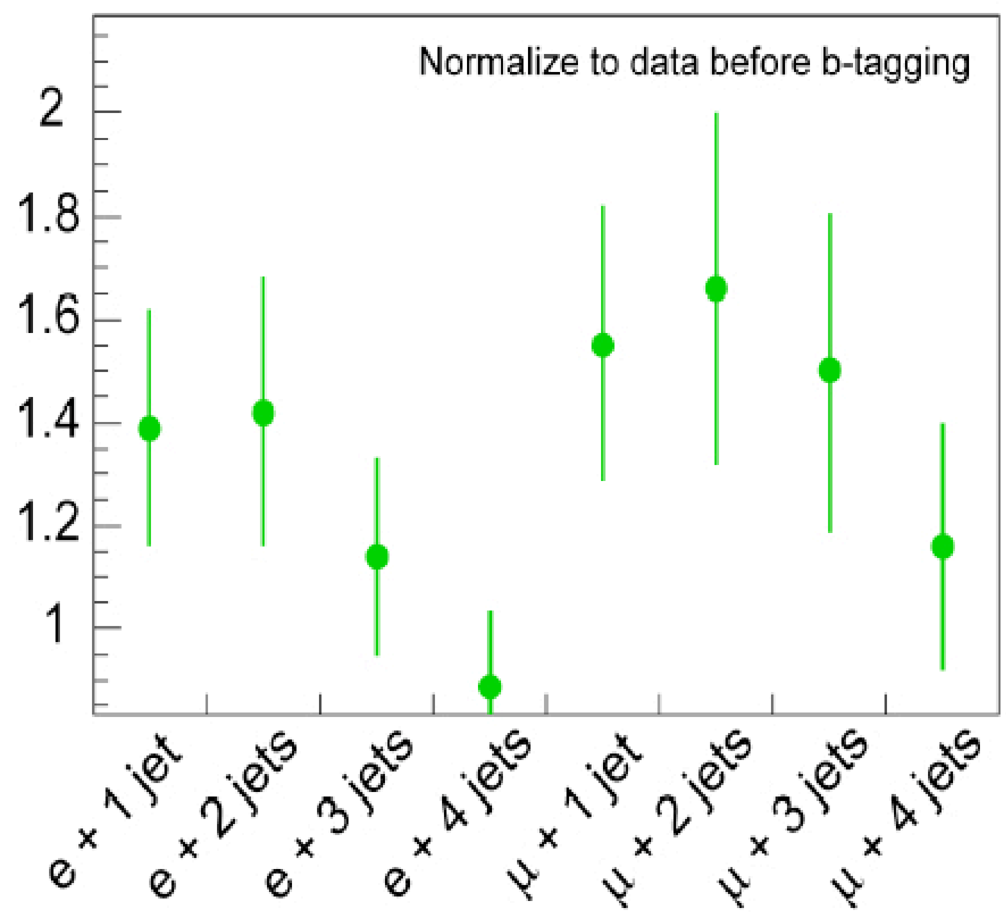


- Solenoidal Magnetic Field
  - Measured by Hall probes located the detector
- Calorimeter
  - Calibrated by pulser boards. Liquid Argon purity measured w/ ^{241}Am
  - Energy scale measured “offline” using dijet and photon+jet events
- Muon
  - Scintillators are monitored and calibrated using a LED source.
  - Muon momentum scale measured “offline” using $Z \rightarrow \mu\mu$ events

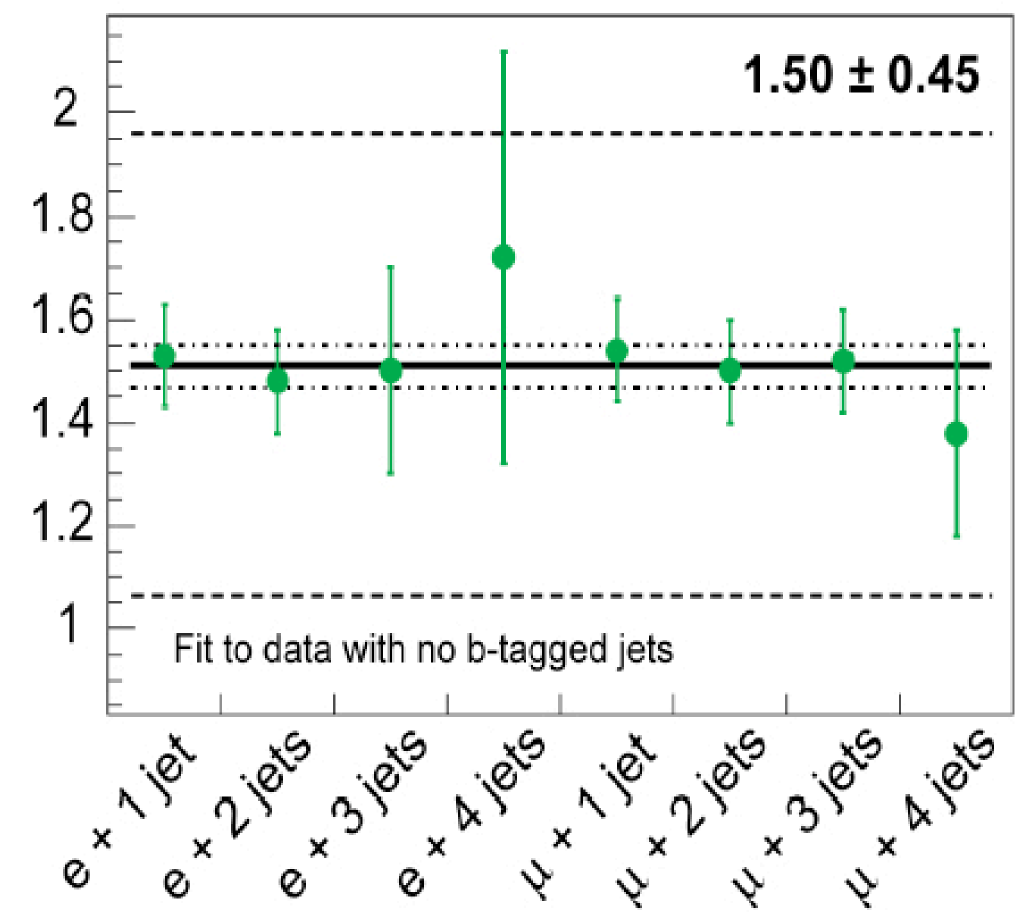
k-Factor

- Problem: Can not use MCFM (NLO calculation) for W+jets because of matching and MCFM does not include certain relative processes
- Solution: Measure effective k-factor in data
- Data = α(Wbb+Wcc) + Wjj + ttbar + QCD Multijet
- Measure in =0 *b*-tag sample to remove bias from signal dataset

W+jets normalization factors



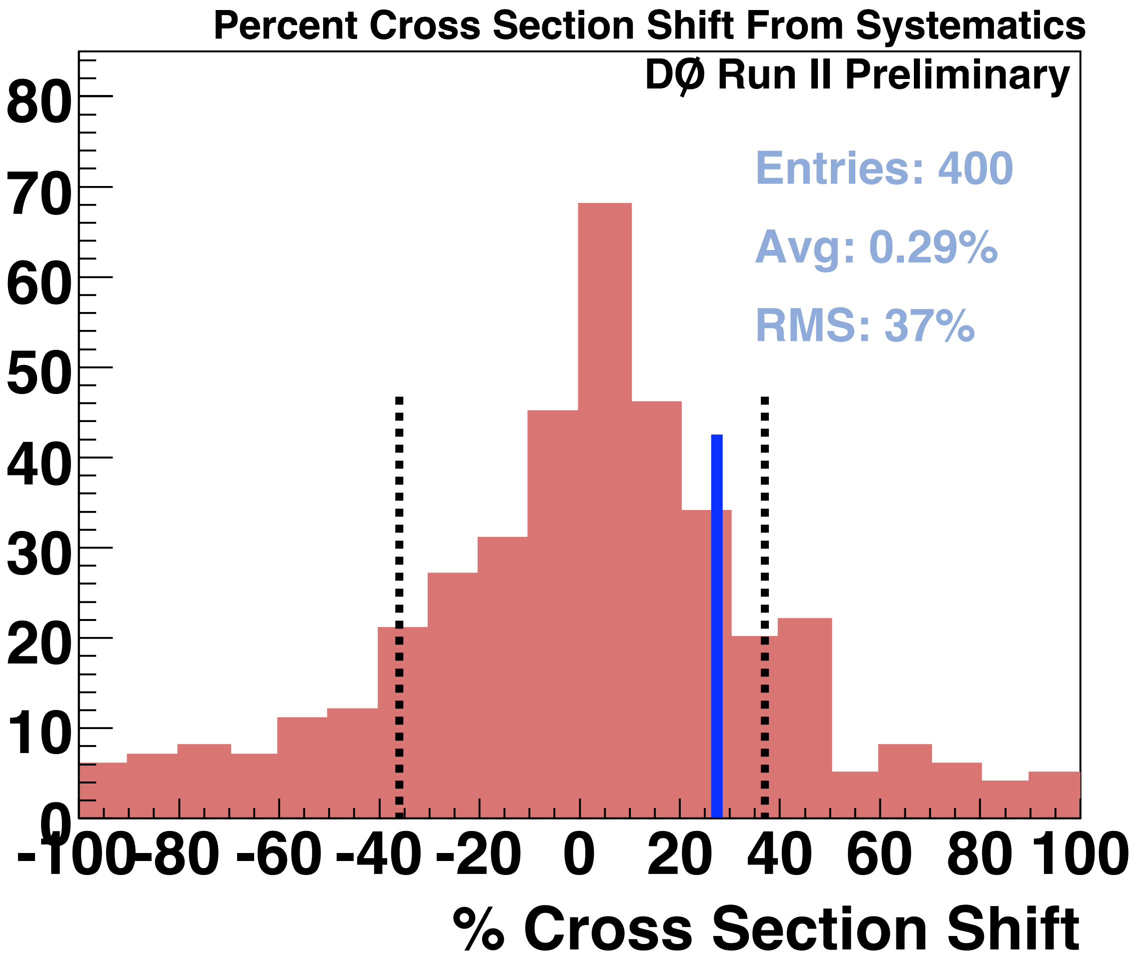
$Wb\bar{b}+Wc\bar{c}$ scale factor



Cross Section Shift When Adding Syst.

- When including systematics, we see a 27% increase in the cross section.
- Can test this with SM ensembles with and without systematics.

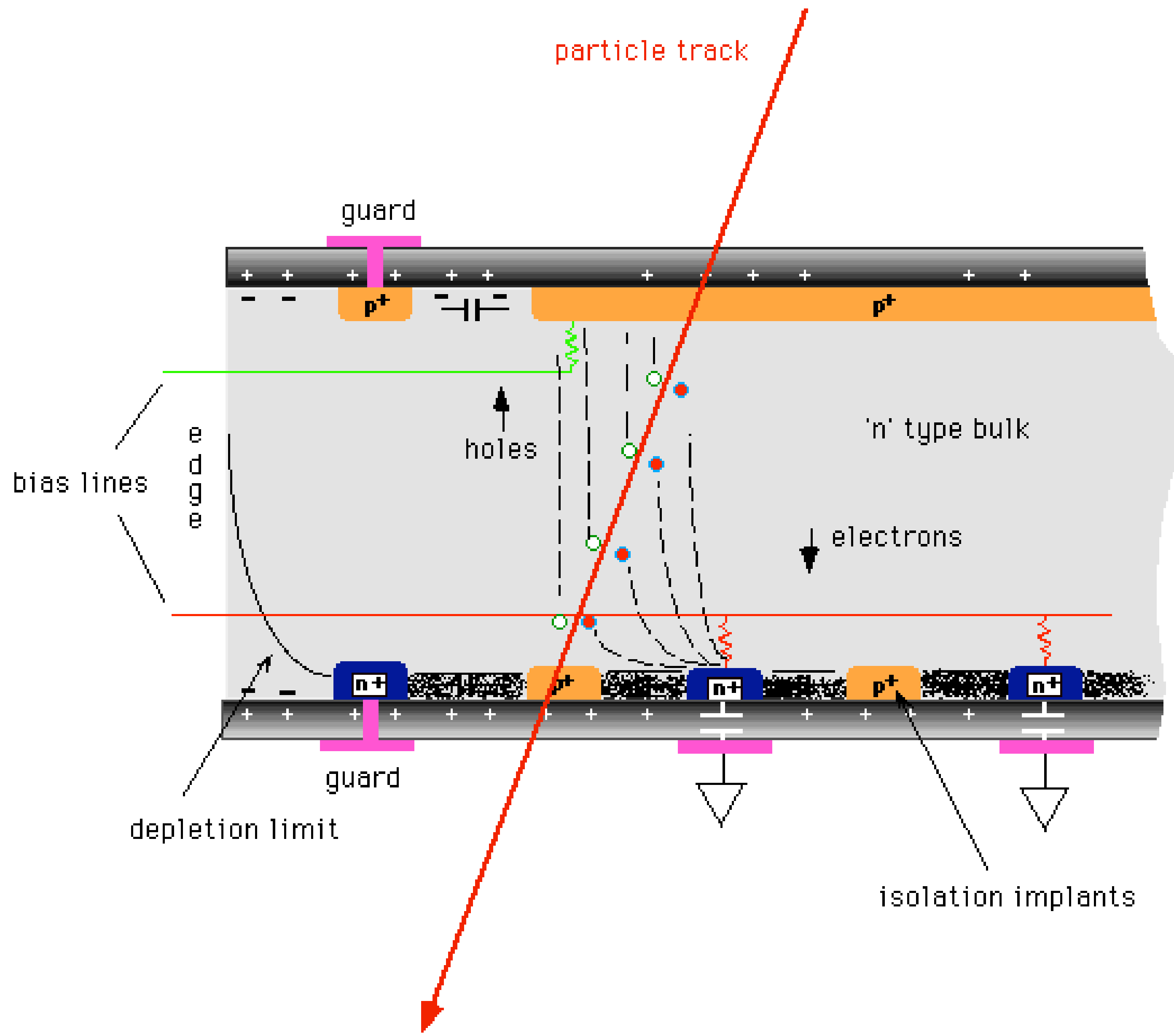
$$\%\text{Shift} = \frac{\sigma_{\text{sys}} - \sigma_{\text{nosys}}}{\sigma_{\text{nosys}}}$$



- Our measured % shift falls within the 1σ bands ⇒ Our shift is reasonable

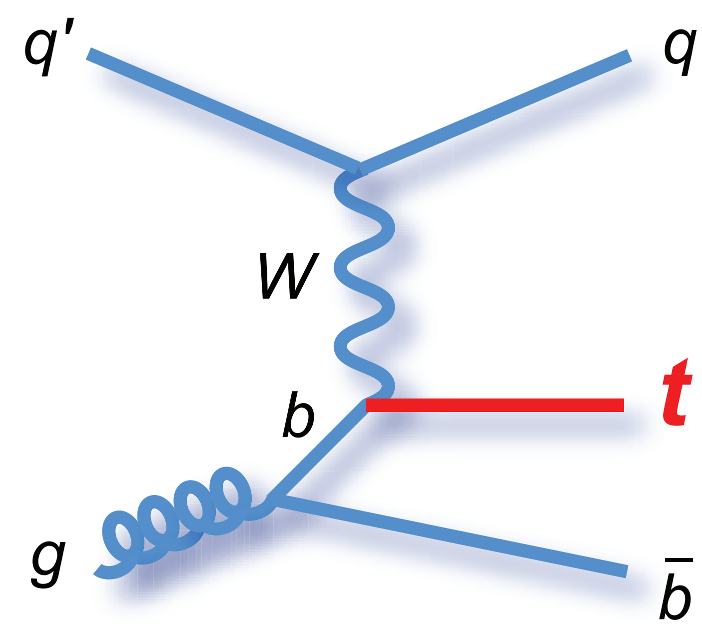
Silicon Detectors

- Charged particle interacts with the silicon to produce electron-hole pairs (electrons are moved from the valence to the conduction band)
- The application of a bias voltage produces an electric field, which causes the electrons and holes to move toward active sensors
  - E ∝ pulse height
- Silicon detectors are characterized by their dark current
  - current flowing from the detector when reversed biased

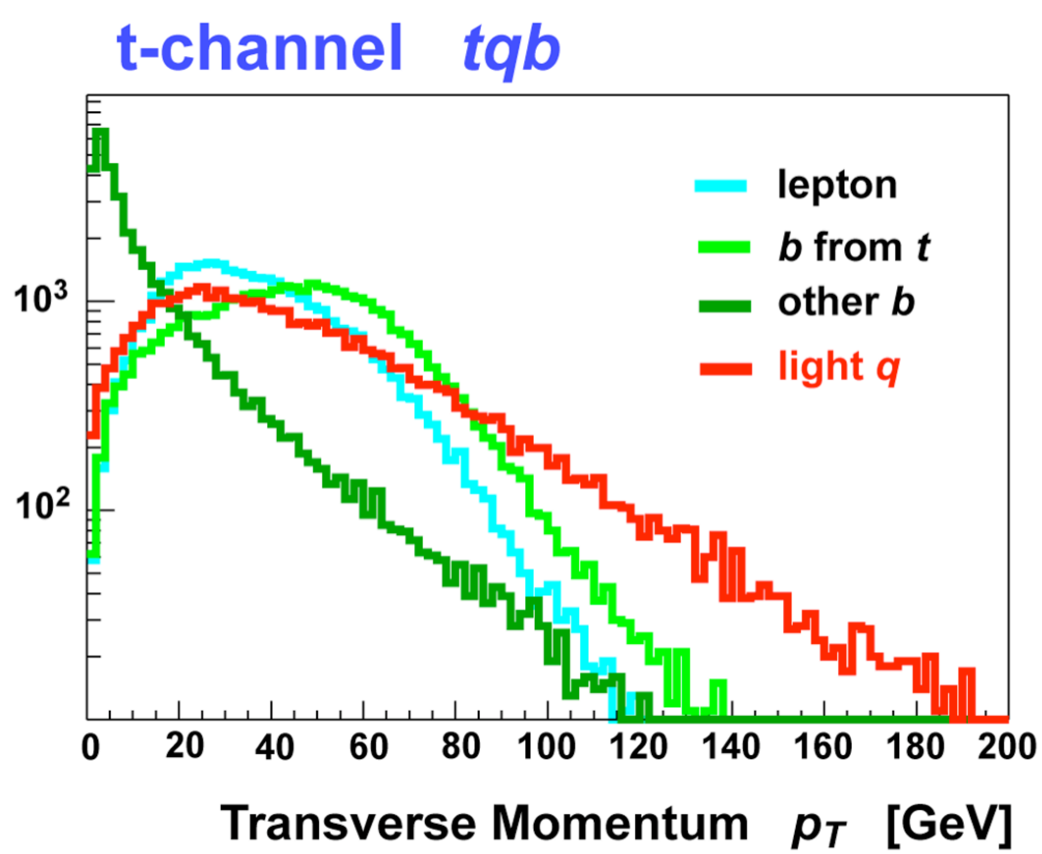


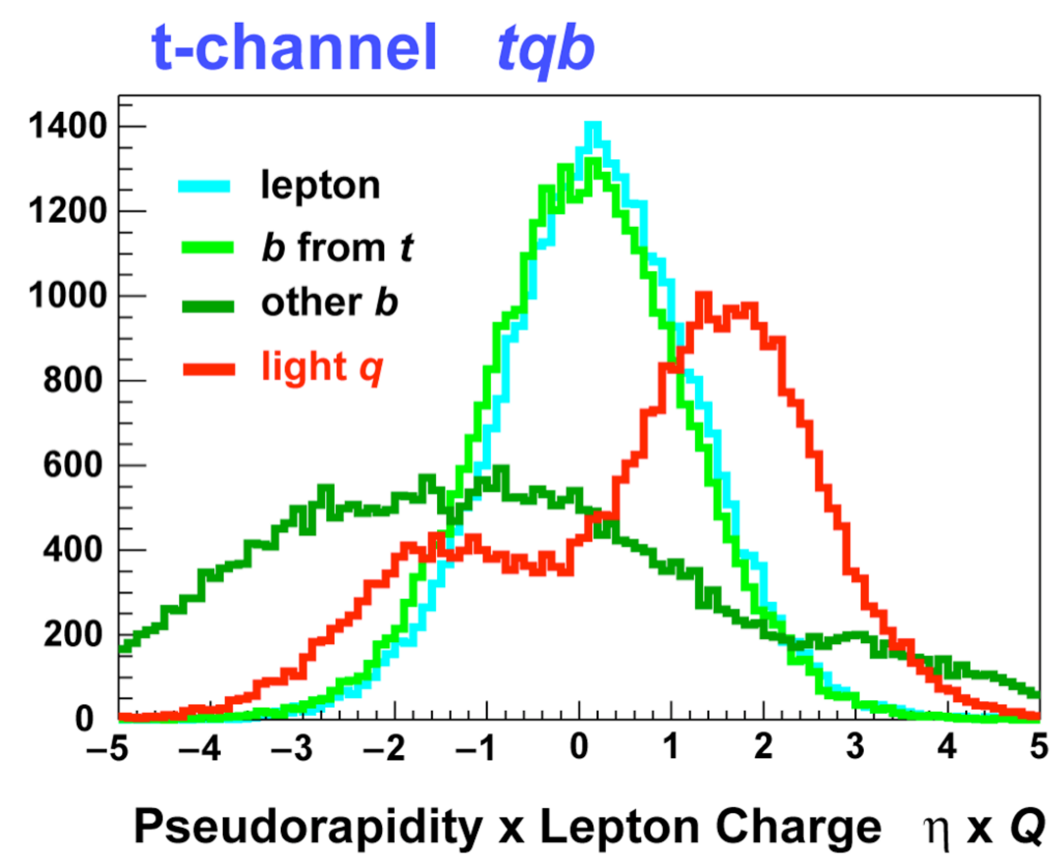
Single Top At The Parton Level

- We generate single top signal using CompHEP+Pythia
- Features:
  - Spin information is retained through decay chain (important for top)
  - Effective NLO generator. It reproduces NLO distributions from ZTOP and MCFM



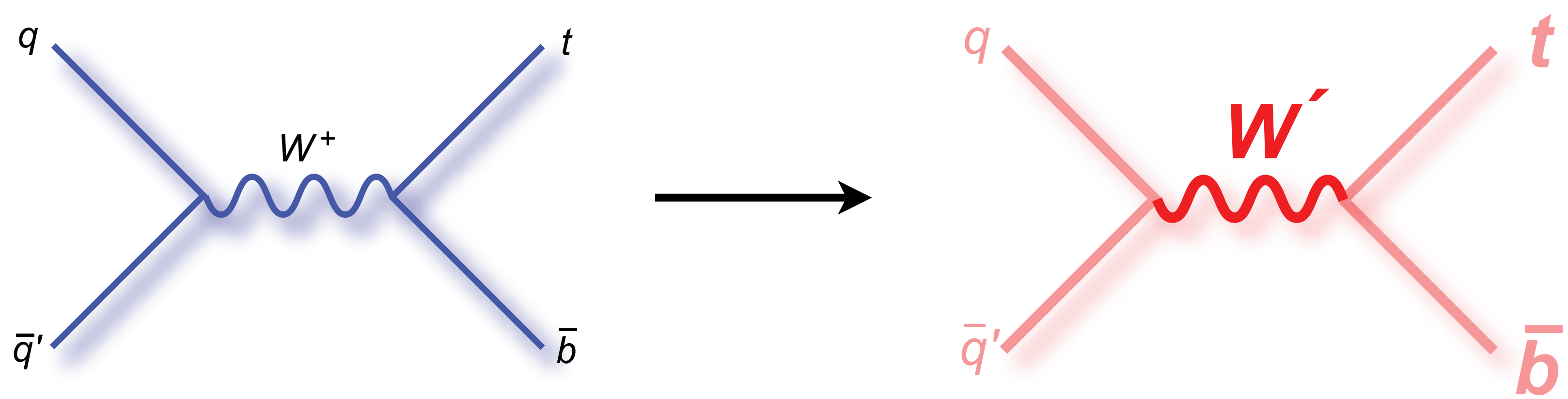
- Parton-level t-channel P_T and η dtributions



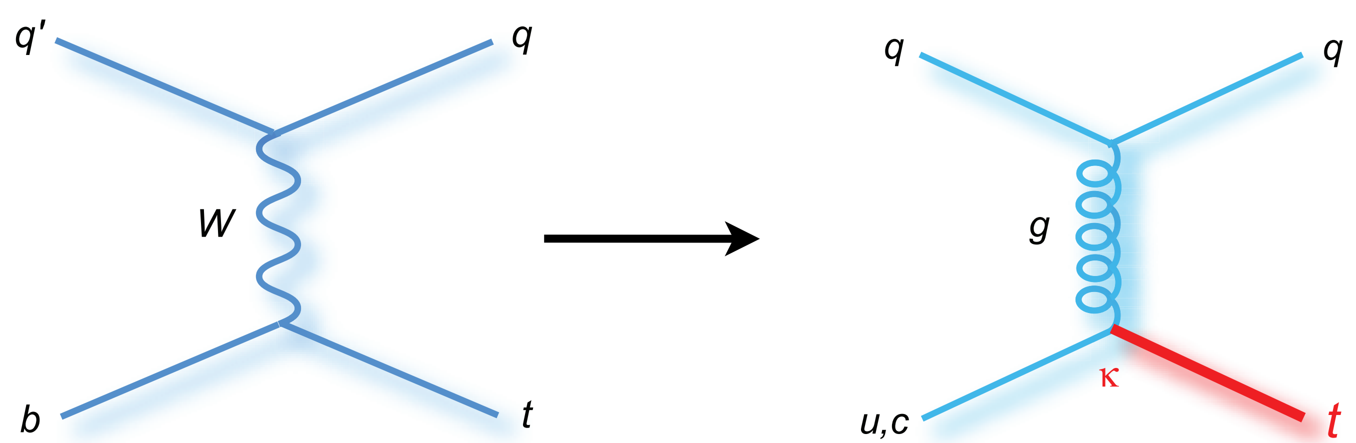


More Motivation For Measuring Single Top

- Single top is sensitive to physics BTSM
- s-channel is sensitive to charged bosons



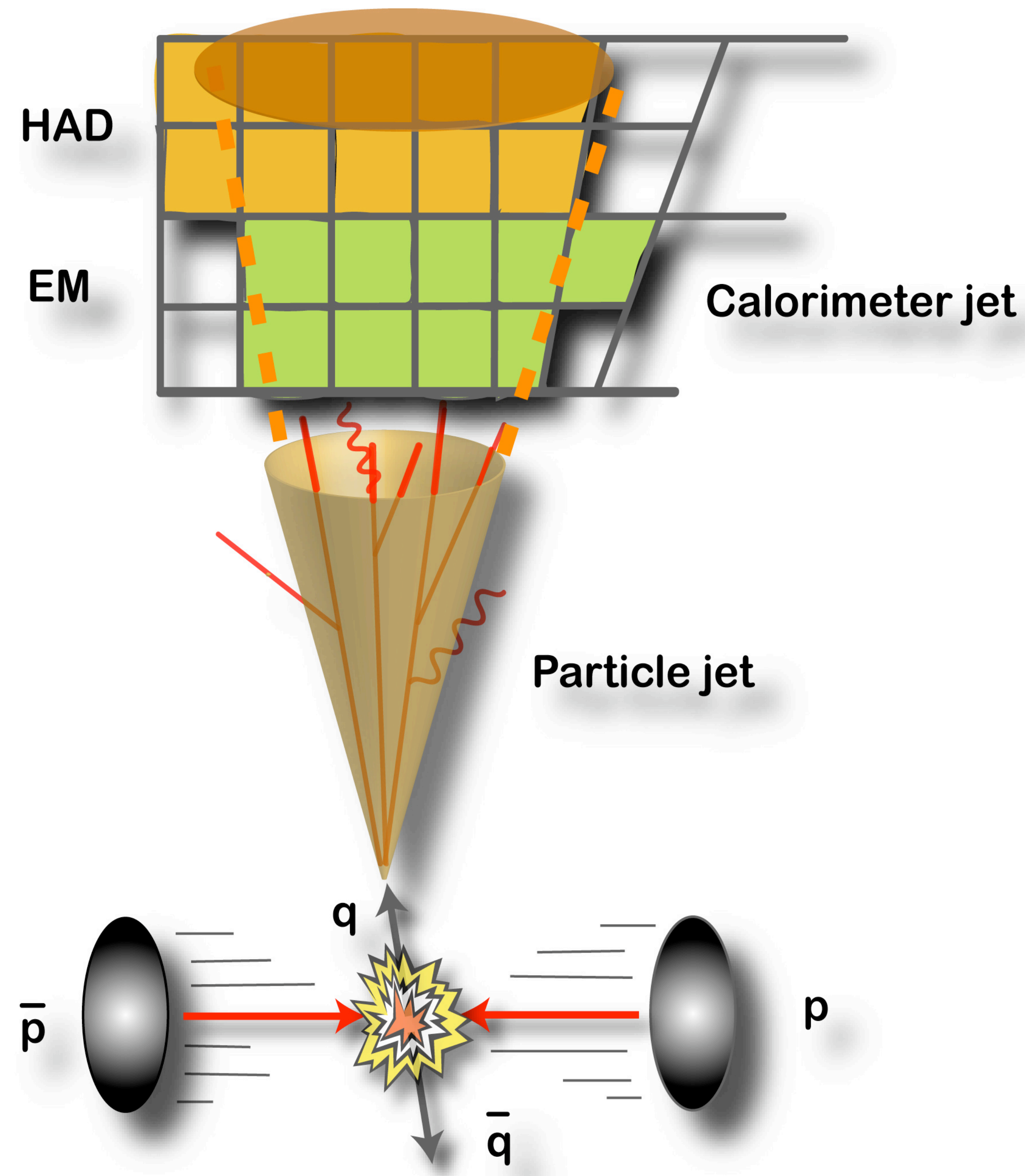
  - DØ w/ 230 pb^{-1} ; M(W'$_R \rightarrow$ qq',lν) > **630** GeV and M(W'$_R \rightarrow$ qq') > **670** GeV [hep-ex/0607102]
  - CDF w/ 955 pb^{-1} ; M(W'$_R \rightarrow$ qq') > **760** GeV (M(W'$_R$)> M(ν$_R$)) and M(W'$_R \rightarrow$ qq') > **790** GeV (M(W'$_R$) < M(ν$_R$))
- t-channel is sensitive to flavor changing neutral currents in the top section



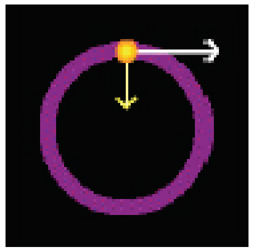
  - DØ w/ 230 pb^{-1} ; κ_{cg}/Λ < **0.15** TeV^{-1} and κ_{ug}/Λ < **0.037** TeV^{-1} [hep-ex/0702005]

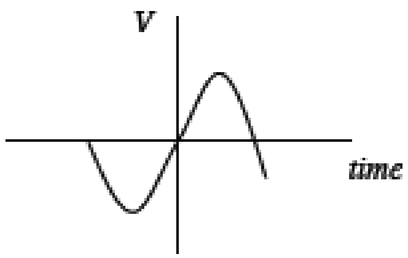
Transfer Functions: W(*x*|*y*)

- Map parton to detector object
- Account for detector resolution
- Electrons (Z → ee Monte Carlo)
  - Central only; $f(E_e, \theta)$
- Muons (Z → μμ Monte Carlo)
  - w/ and w/o SMT hits; $f(q/p_T)$
  - Central ($|\eta|<1.6$) and forward ($1.6<|\eta|<2$)
- Jets (ttbar Monte Carlo)
  - 3 jet types (light, b, b → μ); $f((E_j, E_p)$



Acceleration





$mv^2/R = evB$

$\Longrightarrow R = mv / eB$

$= p / eB$

What frequencies do we need?

Let's say v ~ c,

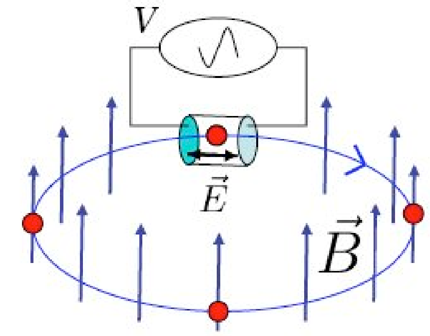
and say R = 1 m

then,

$f = v / 2\pi R$

$= (3 \times 10^8 \text{ m/s}) / (2\pi \text{ 1m})$

$= 5 \times 10^7 / \text{s} = 50 \text{ MHz}$



And as the particle speeds up, the frequency of the cavity must change in step ("in sync")

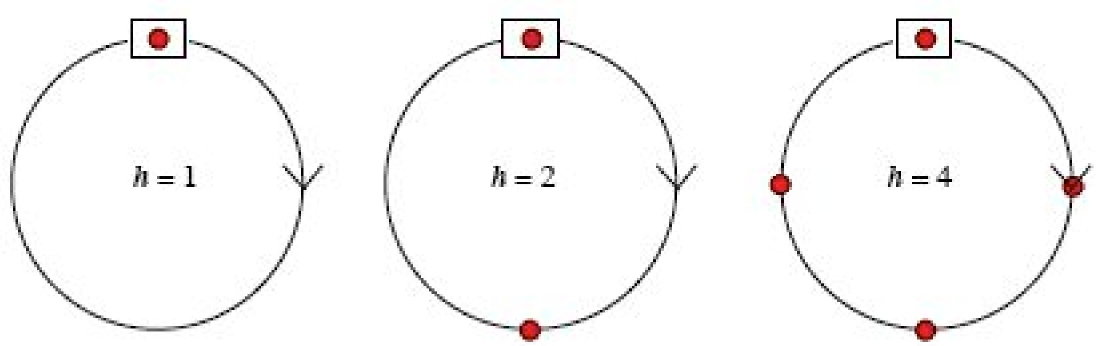
thus, we use RF cavities and power sources…
FM Radio Stations: 88 - 108 MHz!

Voltage = $V \sin(2\pi f t + \delta)$

$f = 1/T = v / 2\pi R$

Each revolution,
energy changes by amount
$\Delta E = e V \sin(\delta)$

– If the RF cavity frequency is twice the revolution frequency, then there can be two bunches sustained in the synchrotron. If $f_{rf} = h \times f_0$, then there can be h bunches.



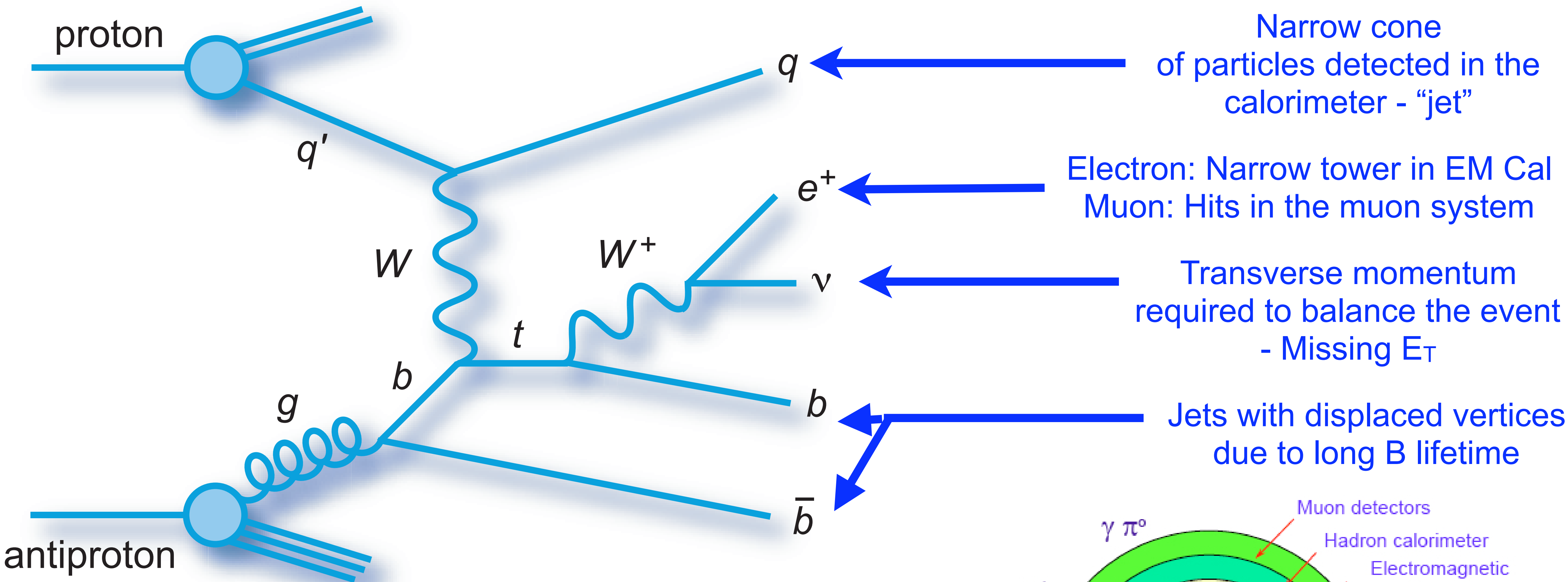
Tevatron

$R = 1000$ m
$h = 1113$

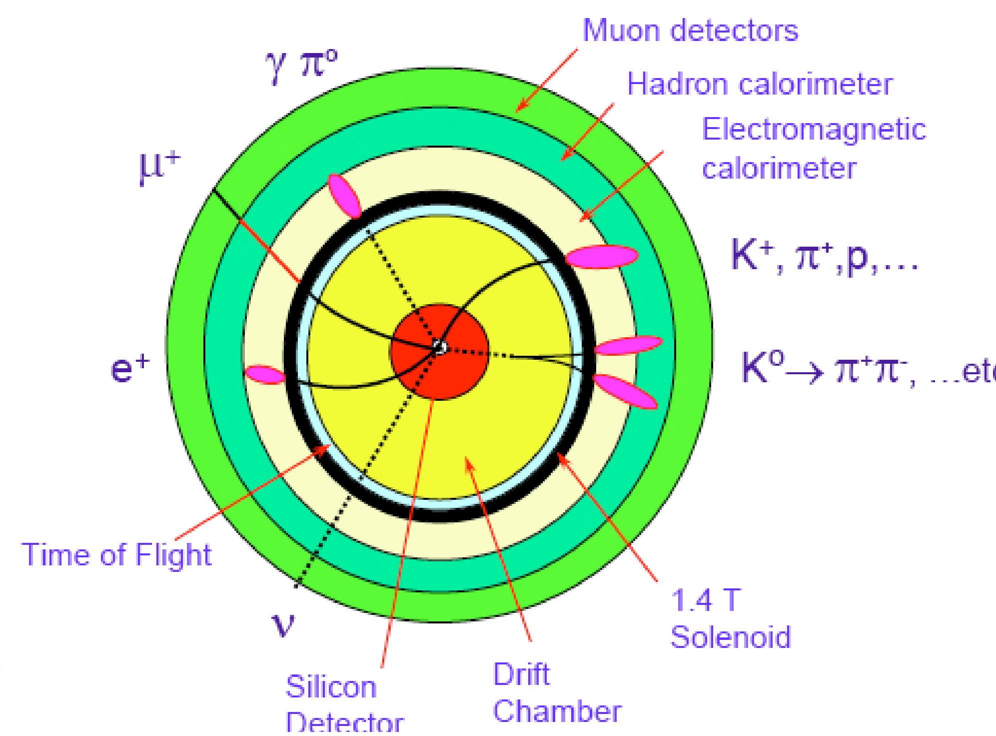
$R = 500$ m
$h = 588$

Single Top Search Strategy

- We look for single top in the “lepton+jets” decay channel

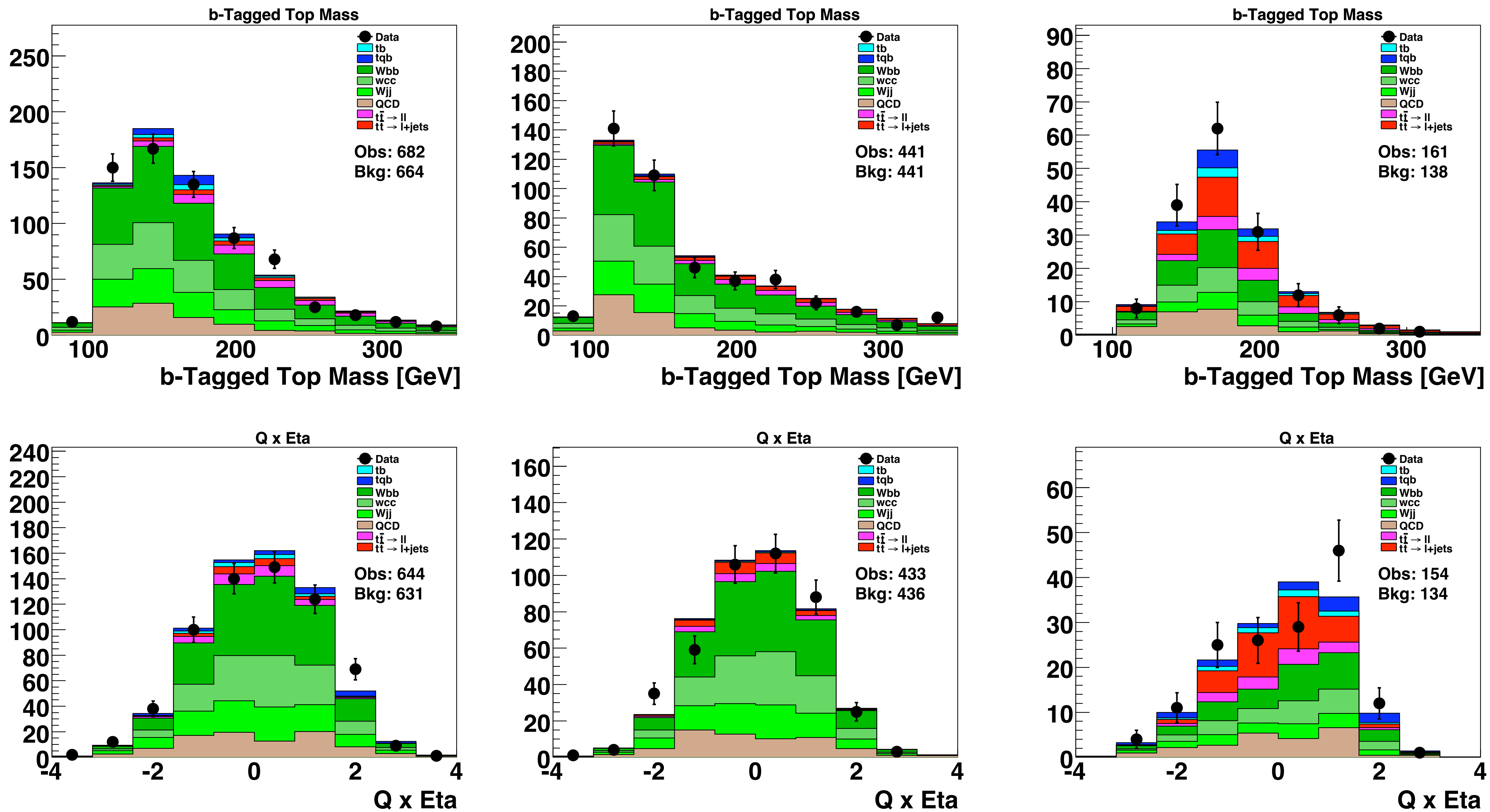


- Maximize signal acceptance
  - Electron of muon with P_T > 15 GeV
  - Missing E_T > 15 GeV
  - Between two and four jets with P_T > 15 GeV



Event Characteristics

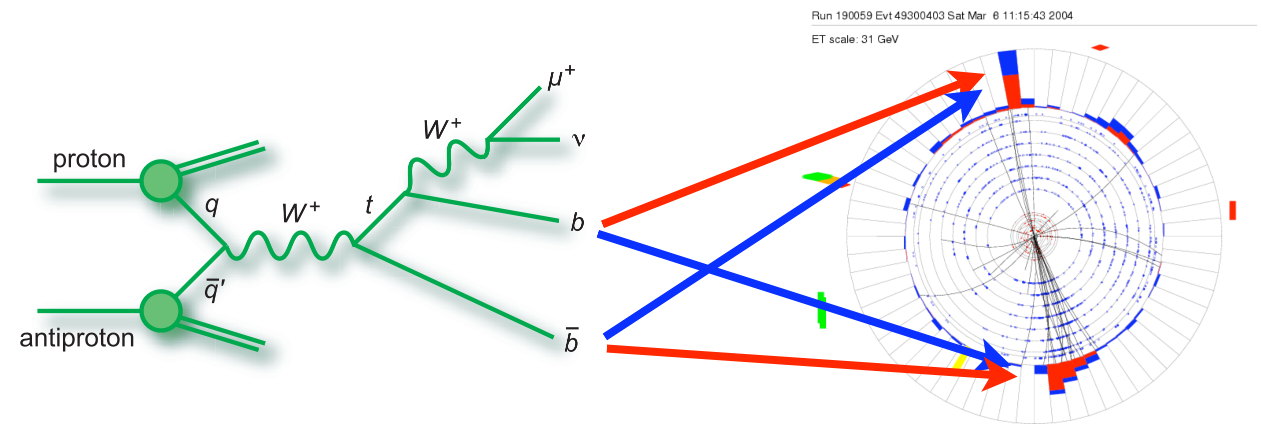
- Look at variables sensitive to single top before and after a cut on the discriminant.



- All Events D(x) < 0.4 D(x) > 0.7

Jet-Parton Assignment

- We must sum over all jet parton combinations to ensure we choose the correct assignment.



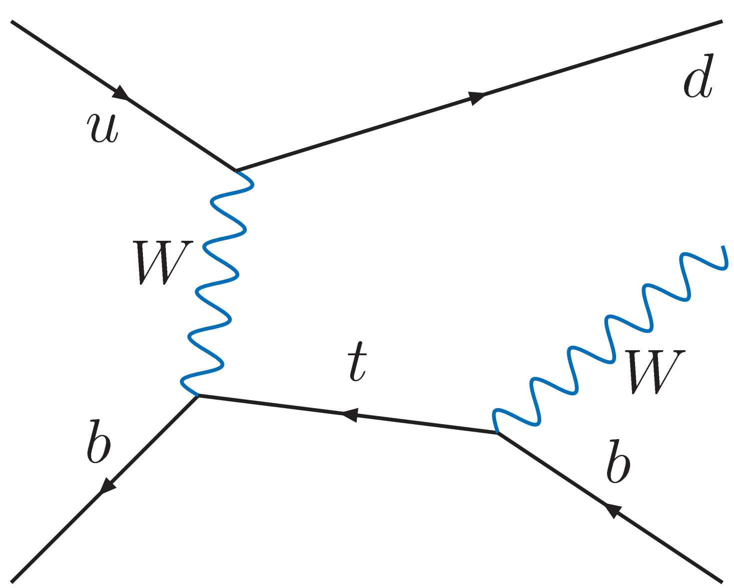
$$d\sigma(\vec{x}) = \sum_{\text{comb}} \varepsilon_{\text{comb}} \times d\sigma_{\text{comb}}(\vec{x})$$

  - If we no knowledge of the correct assignment, then $\varepsilon_{\text{comb}}$ = constant

- We can use b-tagging TRFs to help assign b jets to b quarks and untagged jet to light quarks.

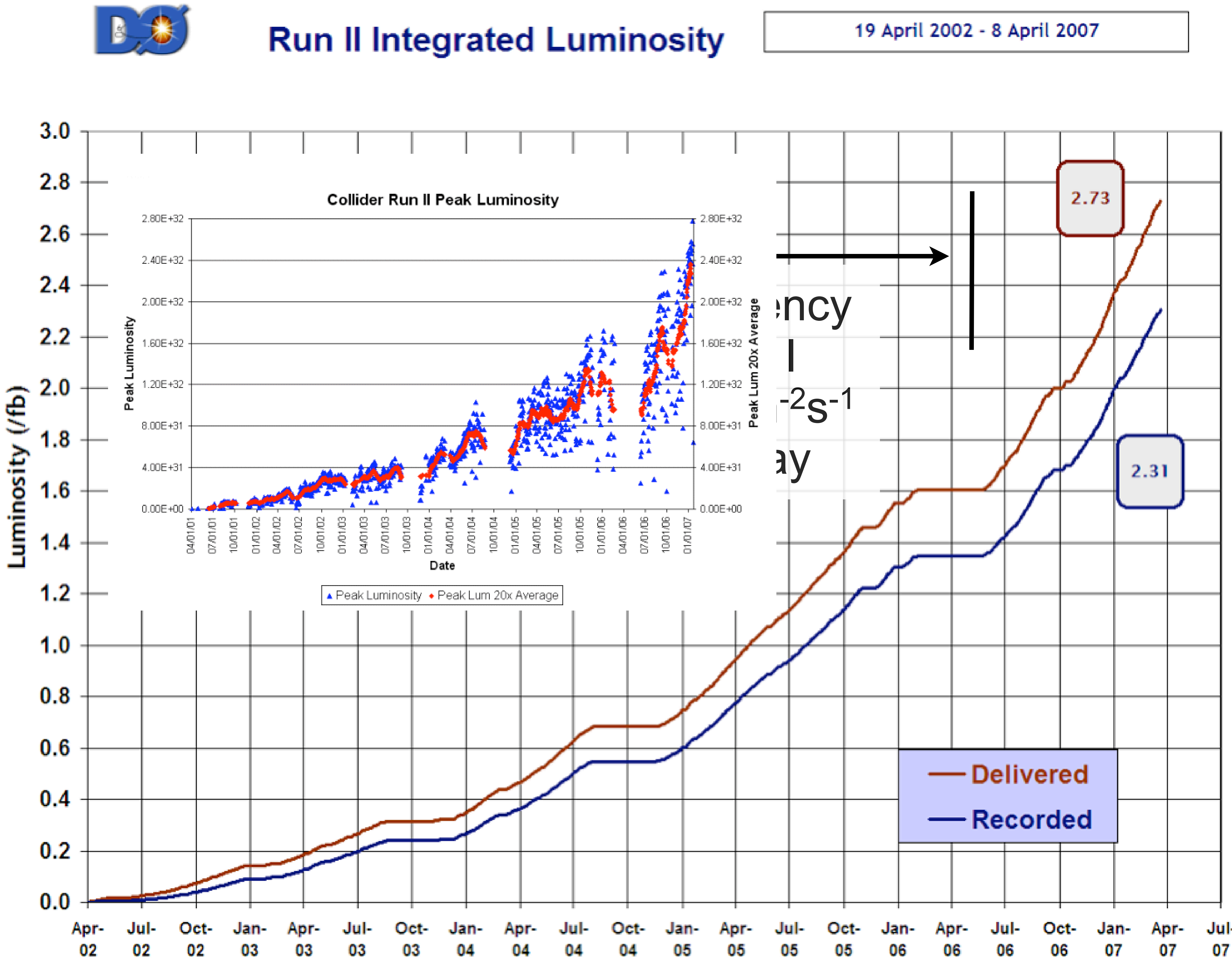
  - If jet is b-tagged and parton is b quark, then weight by b TRF.
    Same for charm and light quarks.

- Example: Single tagged t-channel event.
  Final state is b quark and light quark



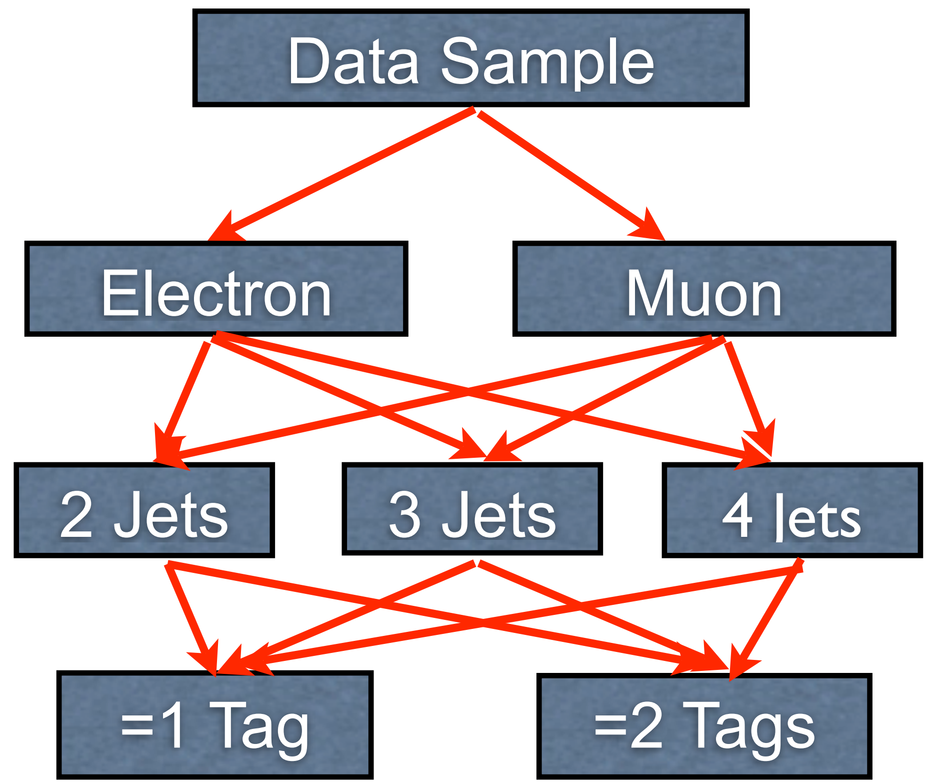
- $$d\sigma(\vec{x}) = \varepsilon_b(1-\varepsilon_l)d\sigma_{bl} + (1-\varepsilon_b)\varepsilon_l d\sigma_{lb}$$

Run II Data Taking

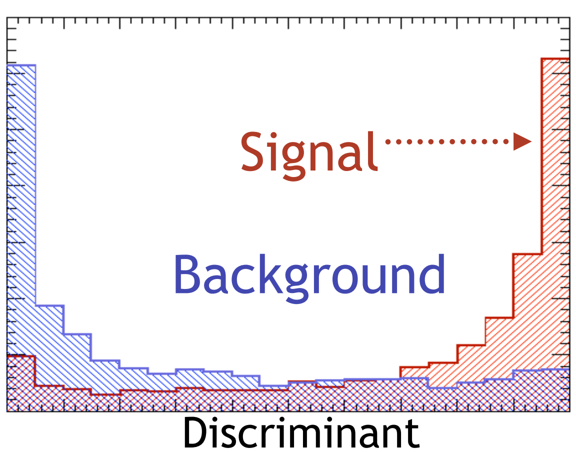


Single Top Measurement Strategy

- Select W+jet-like events
  - Maximize single acceptance while ensuring backgrounds are well-modeled
- Divide data sample by number of jets, W decay lepton, and number b-tags
  - Lepton: trigger separately on electron and muon. Backgrounds also different
  - Jets: s-channel and t-channel in two jet bin, while t-channel also in third
  - b-tags: s-channel and t-channel with one tag, while s-channel should have two



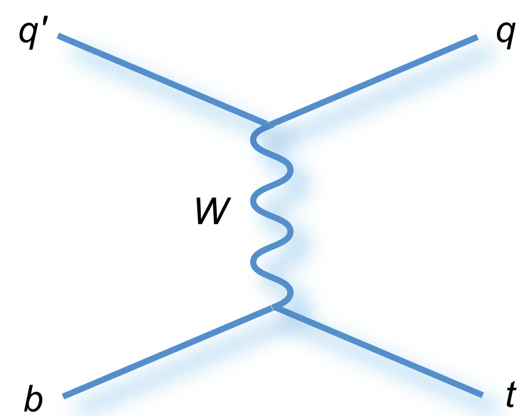
- Separate signal and background
  - **Matrix element method**, boosted decision trees, bayesian neural networks

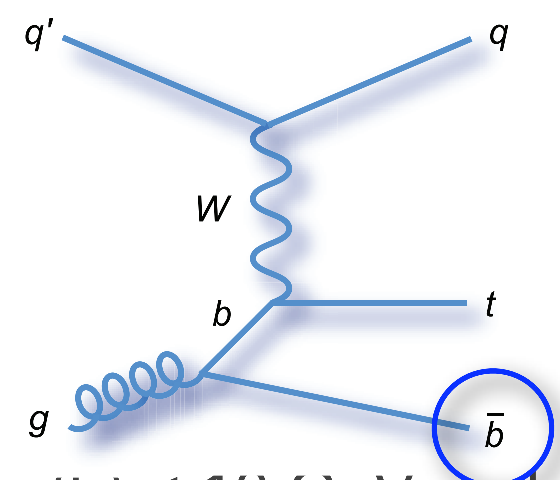


- Combine samples when determining cross section

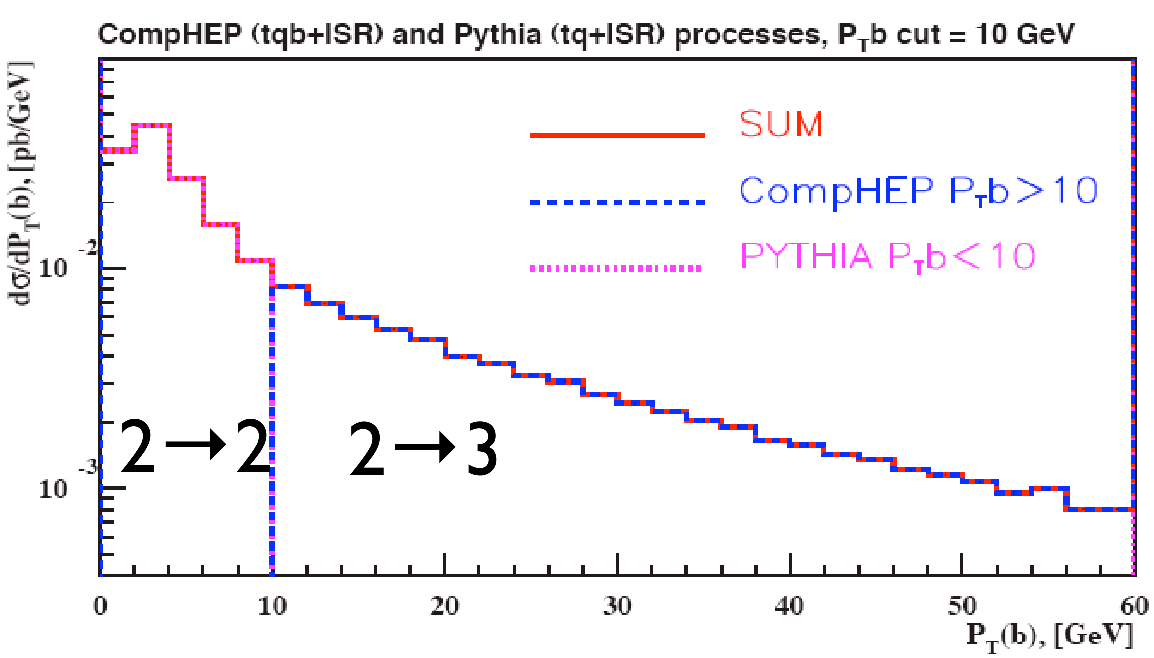
Single Top Event Generation

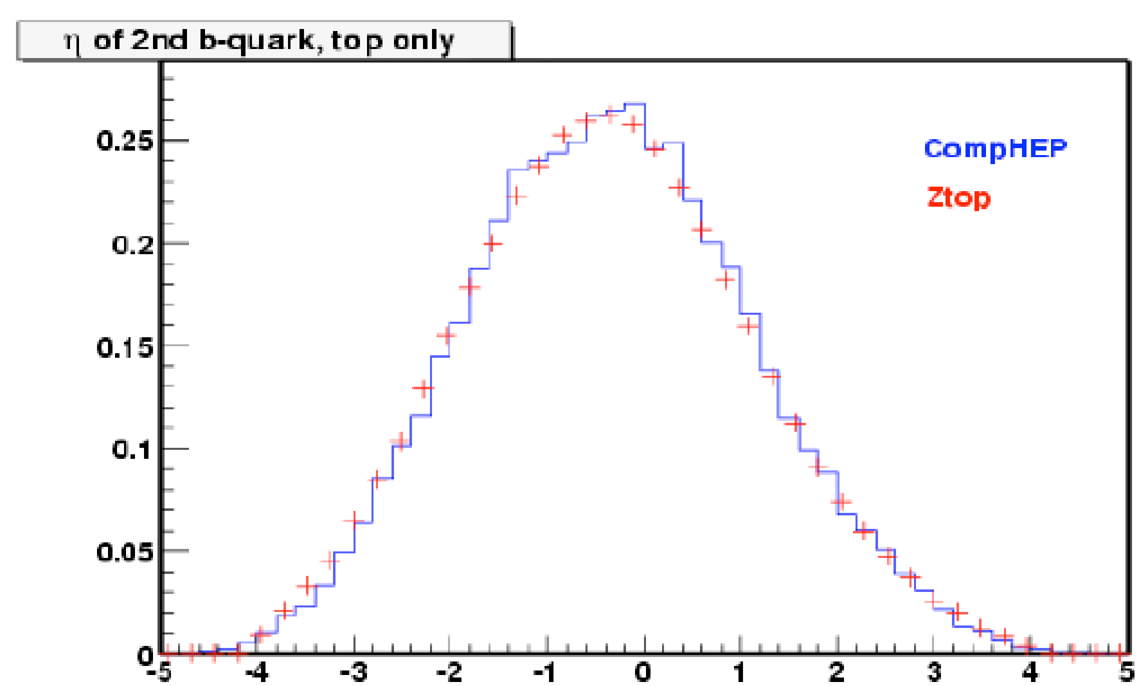
- Use CompHEP+Pythia parton shower to model signal
- Avoid double counting when





- Procedure:
  - Define two regions of phase space: (1) $p_T(b) < 10$ GeV and (2) $p_T(b) > 10$ GeV
  - (1) use 2→2 diagram with Pythia g→bb; (2) use 2→3 diagram from CompHEP





Combined Result

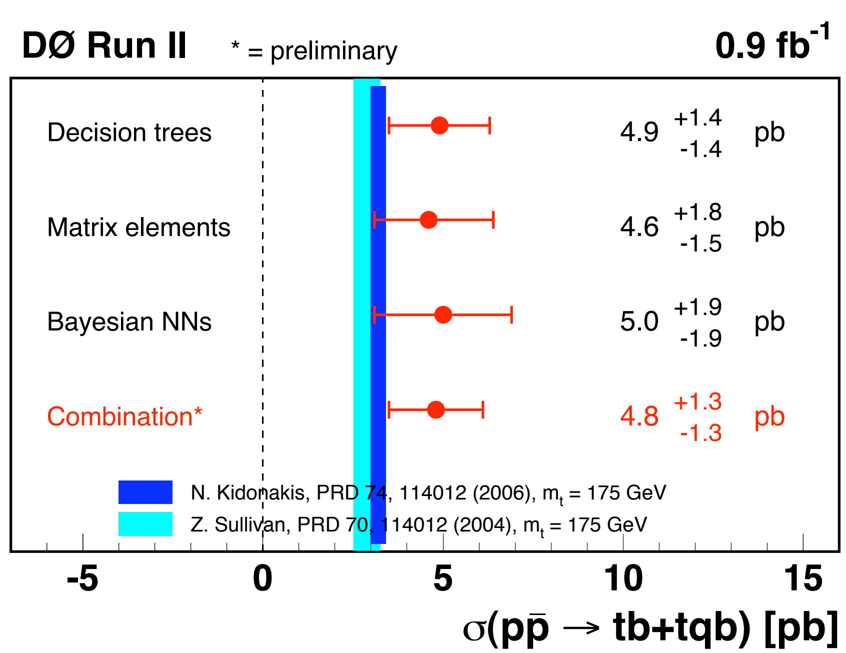
- The matrix element, Bayesian neural network, and decision tree analyses were combined using the BLUE (Best Linear Unbiased Estimator) method

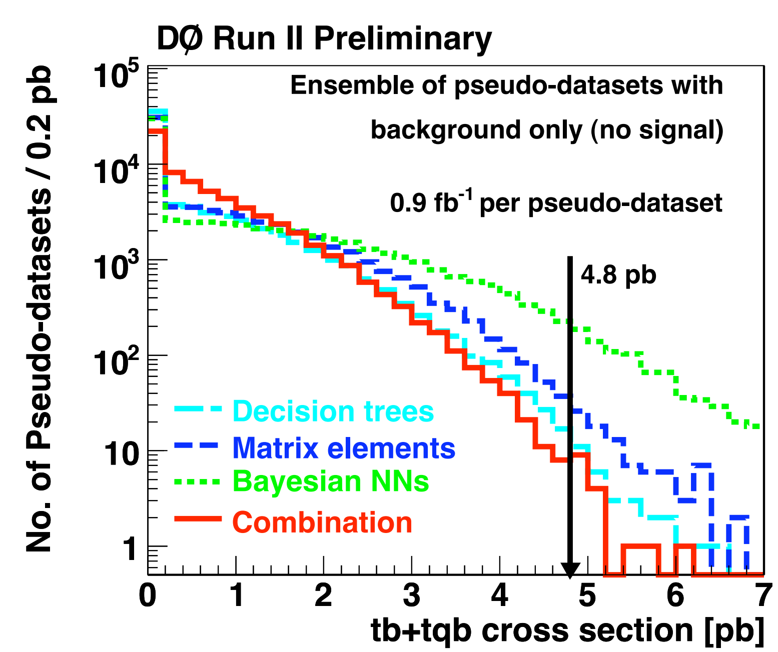
$$\sigma_{\rm comb} = w_{BNN}\sigma_{BNN} + w_{DT}\sigma_{DT} + w_{ME}\sigma_{ME}$$

- Need to know correlation between analyses to determine weights
- Use Standard Model ensemble set

$$w_i = \frac{\sum_j \mathrm{Cov}^{-1}(\sigma_{\rm i},\sigma_{\rm j})}{\sum_{i,j} \mathrm{Cov}^{-1}(\sigma_{\rm i},\sigma_{\rm j})}$$

$$\rho = \begin{array}{cccc} DT & ME & BNN & \\ \end{array}$$
$$\rho = \left(\begin{array}{ccc} 1 & 0.57 & 0.51 \\ 0.57 & 1 & 0.45 \\ 0.51 & 0.45 & 1 \end{array}\right)\begin{array}{c} DT \\ ME \\ BNN \end{array}$$

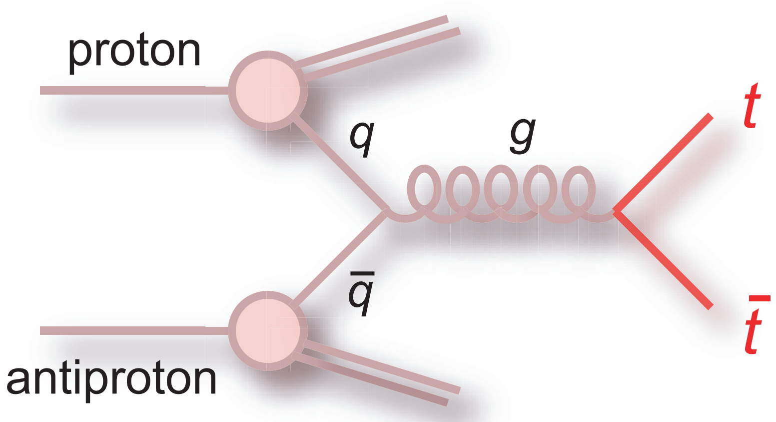




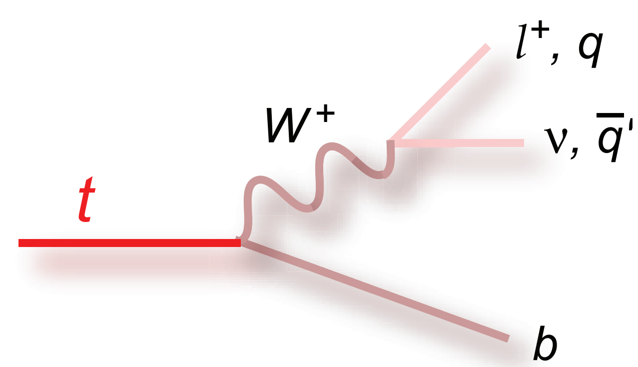
QCD Top Pair Production

- The top quark is studied at the Tevatron in QCD pair production
  - For m_t = 175 GeV → σ(tt) = 6.7 pb

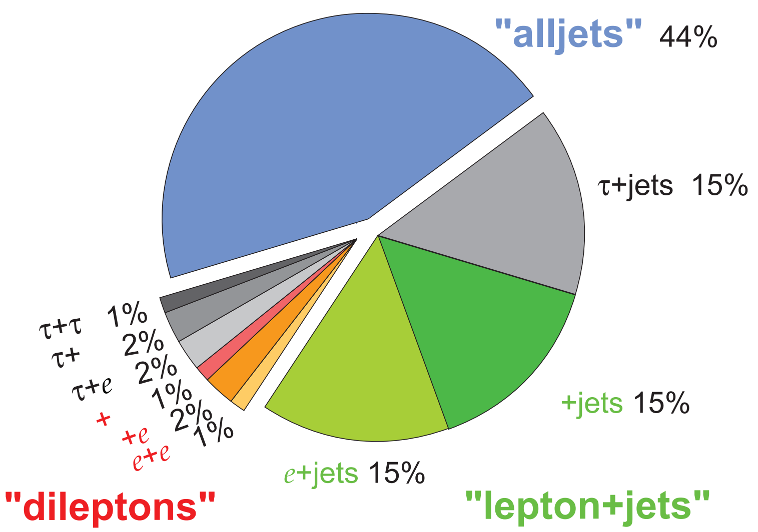
QCD Production



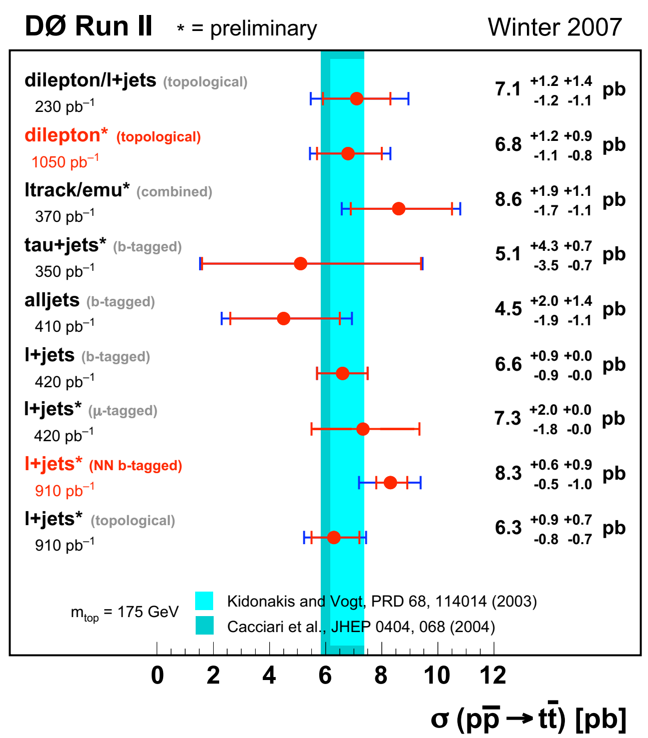
Top Decay



Channel Branching Fraction

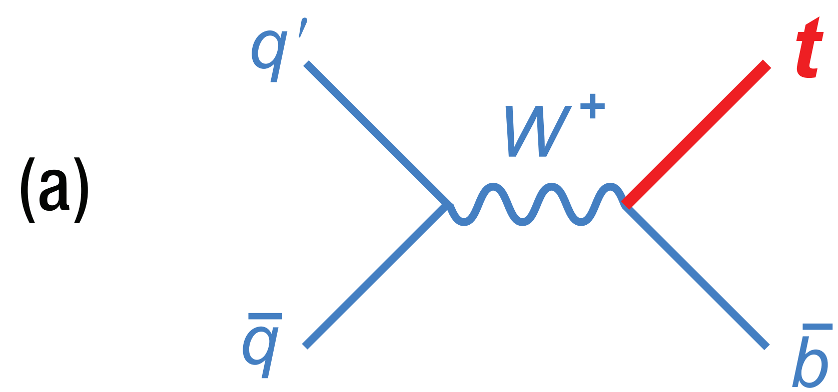


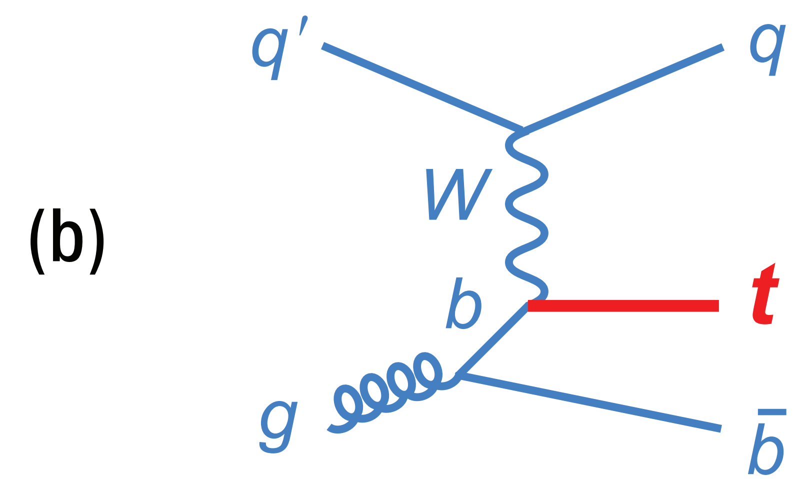
- Well measured at Run II by DØ and CDF



Single Top Quark Production

- Top quarks can also be production through an electroweak interaction
- Two production modes at the Tevatron





$$\sigma_s^{\mathrm{NLO}} = 0.88 \pm 0.11\mathrm{pb} \qquad \sigma_t^{\mathrm{NLO}} = 1.98 \pm 0.25\mathrm{pb}$$

B.W. Harris et. al (hep-ph/0207055)
Z. Sullivan (hep-ph/0408049)

- Motivation (1) : W-t-b electroweak vertex in production $\Rightarrow \sigma_{tb+tqb} \propto |V_{tb}|^2$
- If three quark generations → |Vtb| is highly constrained

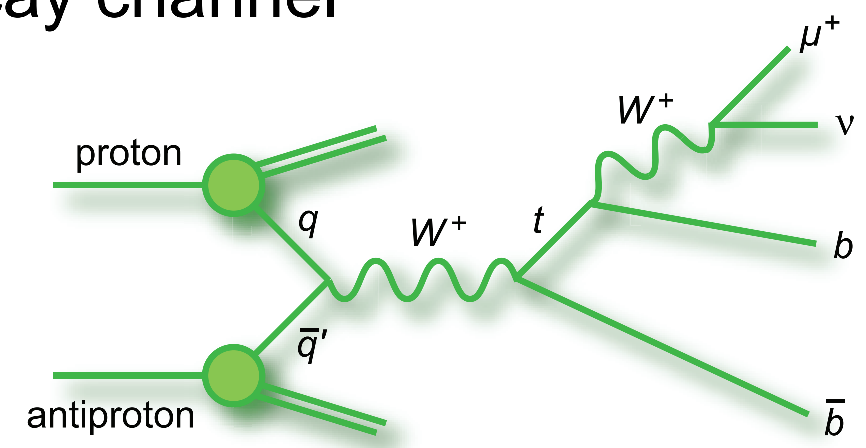
$$|V_{tb}| = 0.999100^{+0.000034}_{-0.000004}$$

- Measured lower limits assuming unitarity $|V_{tb}| > 0.78$

D. Acosta et. al (hep-ex/0505091)
V. M. Abazov et al. (hep-ex/0603002)

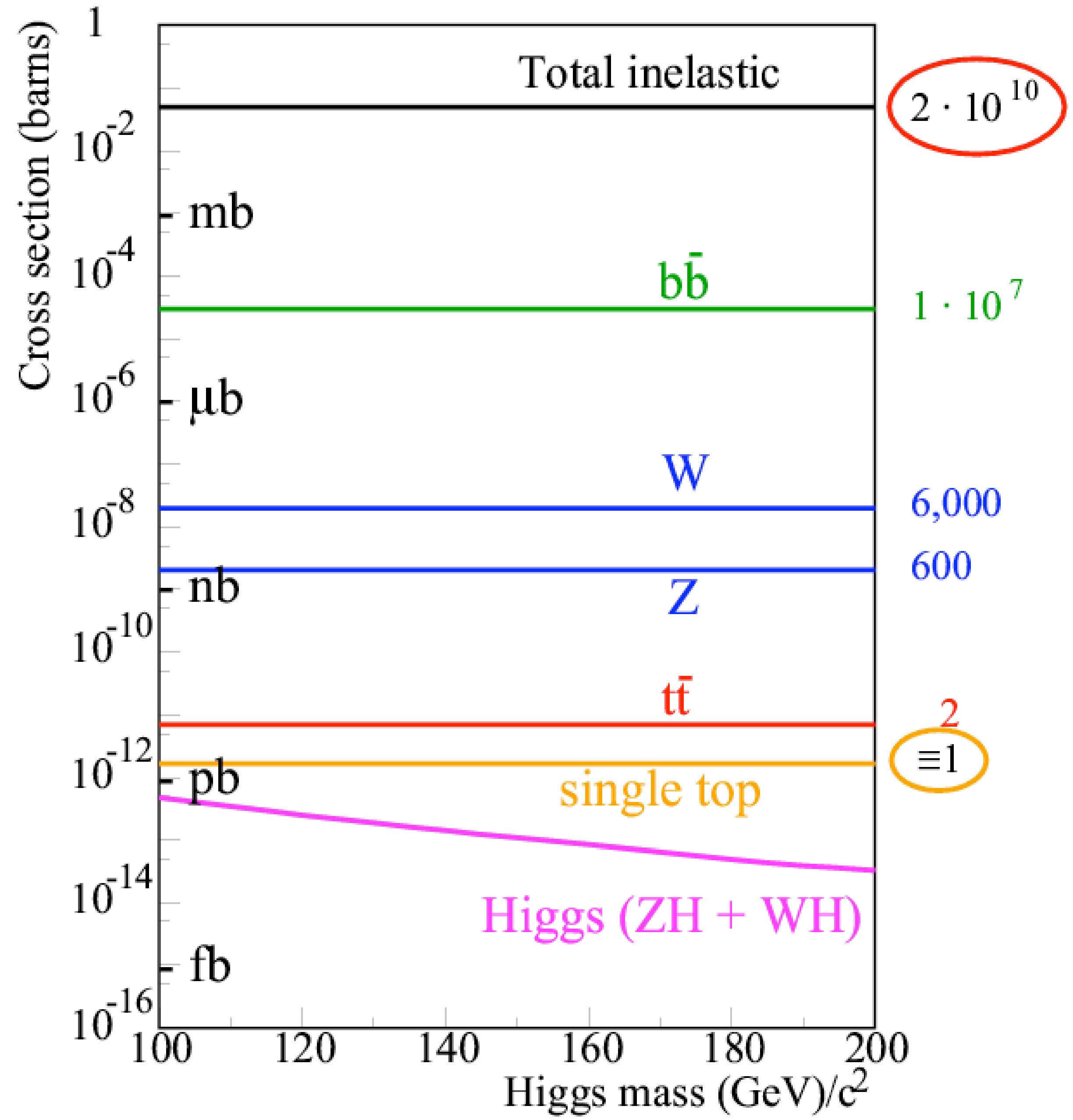
Single Top Search Strategy

- Tevatron produces one single top event for every 20 billion collisions
  - Still ~15-20 events per day
- Look for single top in lepton+jets decay channel



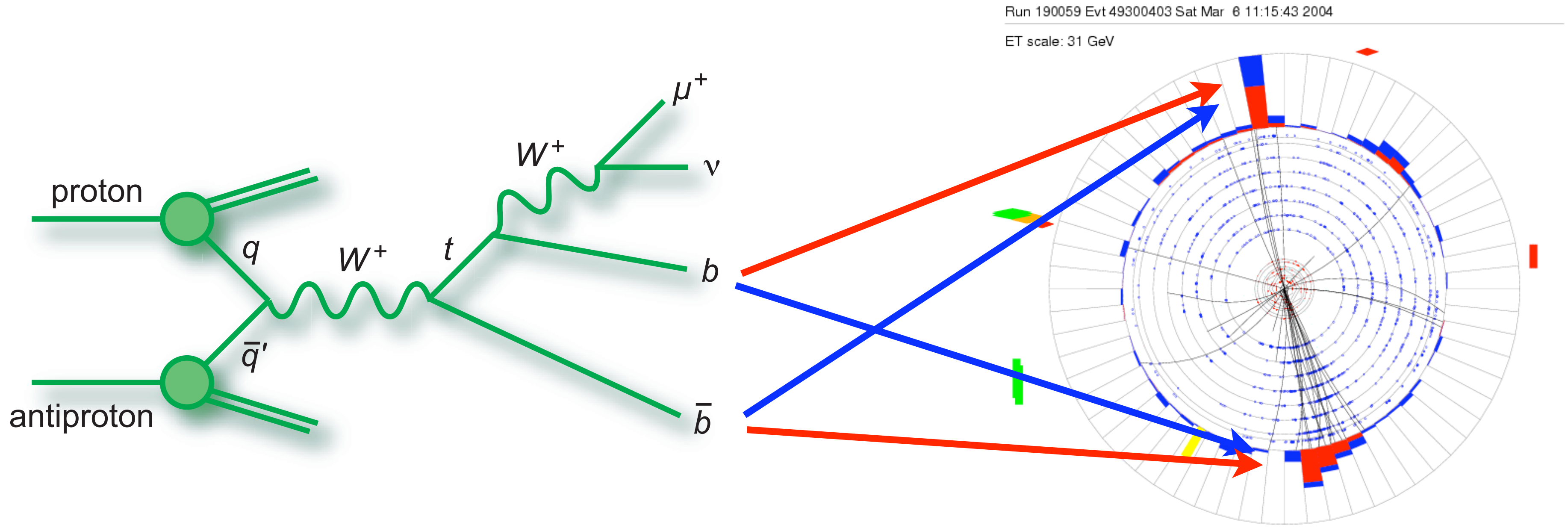
  - Trigger on one lepton + b from top decay
- Select W+jets-like events:
  - One high p_T lepton from W decay
  - large missing E_T (do not detect the neutrino from W decay)
  - Between two and four jets

Cross Sections at $\sqrt{s}$ = 1.96 TeV



Jet to Parton Assignment

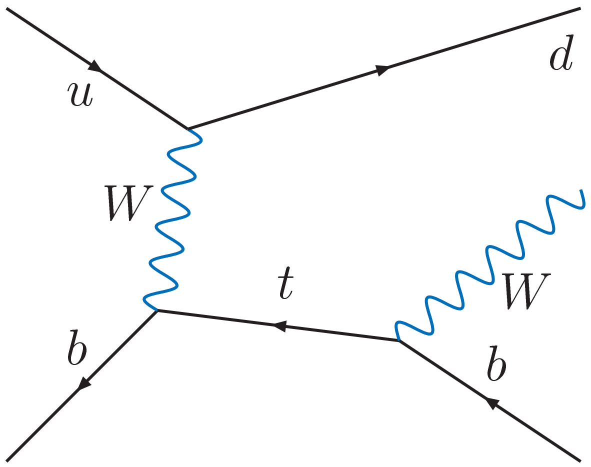
- Events with two jets have two possible jet-parton permutations



- Define event probability as weighted sum over all jet-parton permutations

$$P(\vec{x}) = \sum_i \varepsilon_i \times P_i$$

- Weight permutations by *b*-tagging probability depending on parton flavor
  - *b*-tagged jet matched to b quark
  - ! *b*-tagged jet matched to light quark



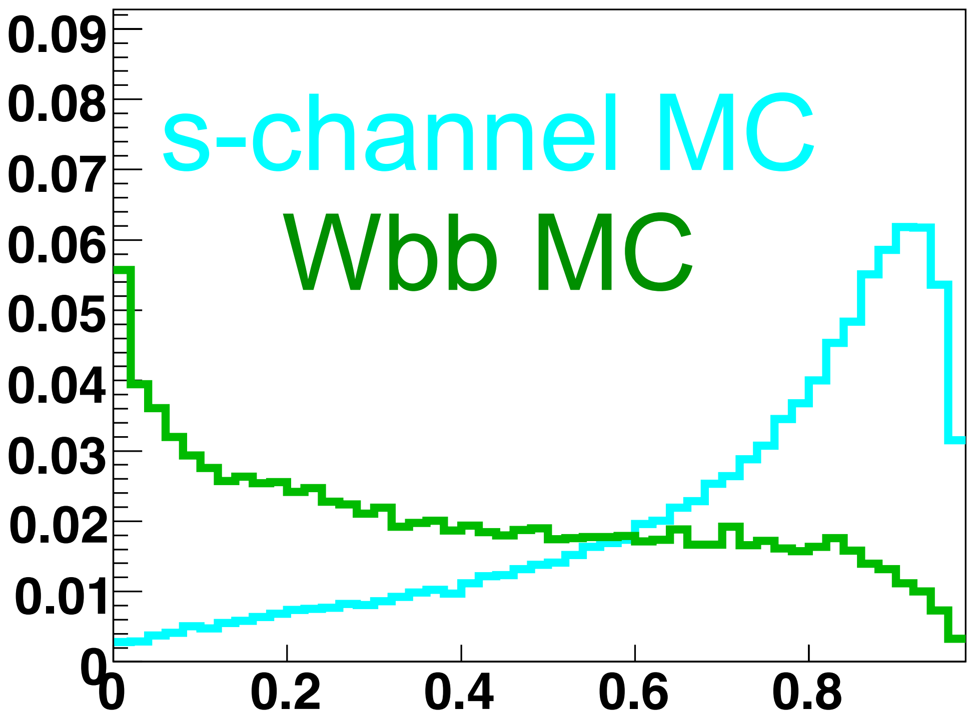
Matrix Element Discriminant

- Combine signal and background probability densities using the *a-posteriori* Bayesian probability density for signal given the event
  - Two discriminants: s-channel as signal and t-channel as signal

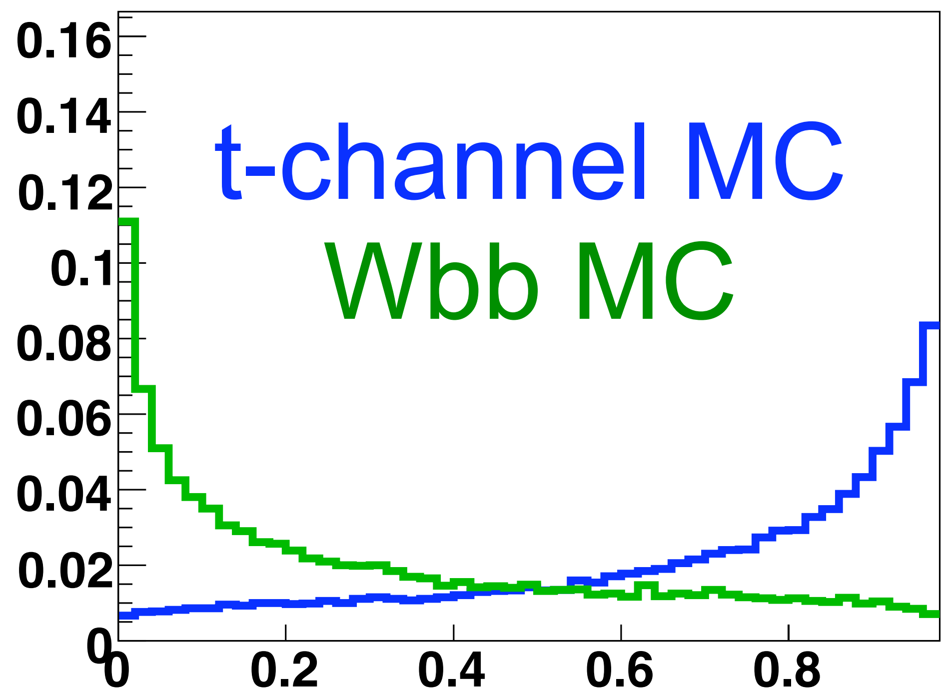
$$D_{tb|tqb}(\vec{x}) = \frac{P_{\mathrm{tb|tqb}}(\vec{x})}{P_{\mathrm{tb|tqb}}(\vec{x}) + P_{\mathrm{Background}}(\vec{x})}$$

- Performance on signal and background Monte Carlo events

s-channel Discriminant



t-channel Discriminant

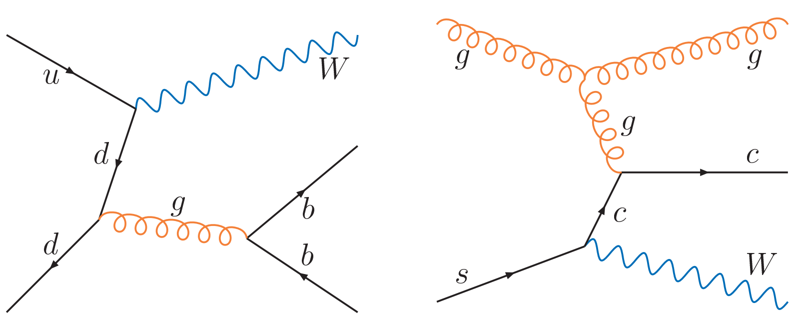


Matrix Element Discriminant

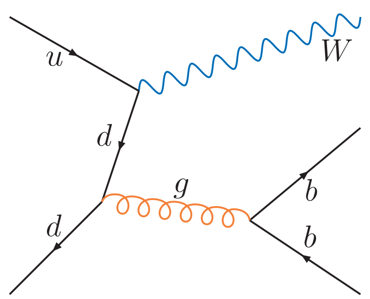
- Combine signal and background probability densities using the *a-posteriori* Bayesian probability density for signal given the event
  - Two discriminants: s-channel as signal and t-channel as signal

$$D_{tb|tqb}(\vec{x}) = \frac{P_{\mathrm{tb|tqb}}(\vec{x})}{P_{\mathrm{tb|tqb}}(\vec{x}) + P_{\mathrm{Background}}(\vec{x})}$$

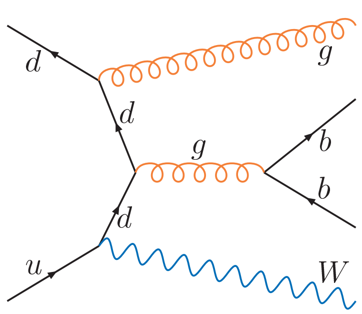
- $P_{\mathrm{Background}}$ depends on number of *b*-tags and number of jets



Events w/ 2 jets and one *b*-tag



Events w/ 2 jets and two *b*-tags

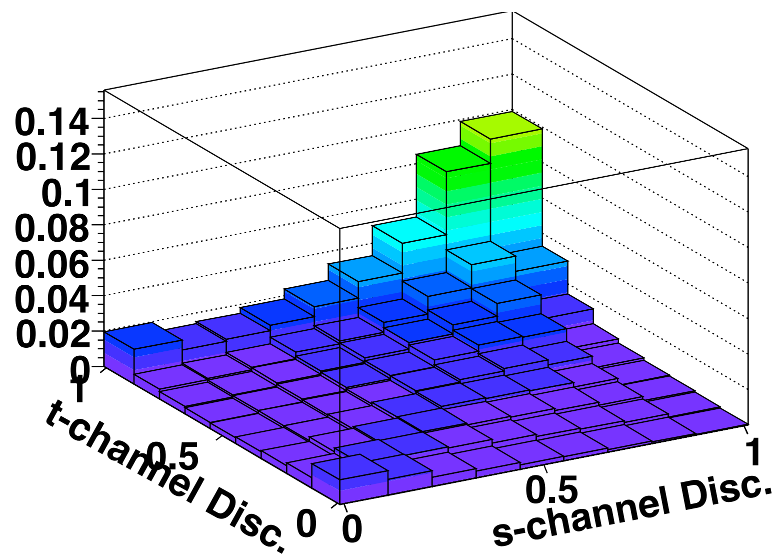


Events w/ 3 jets and one or two *b*-tags

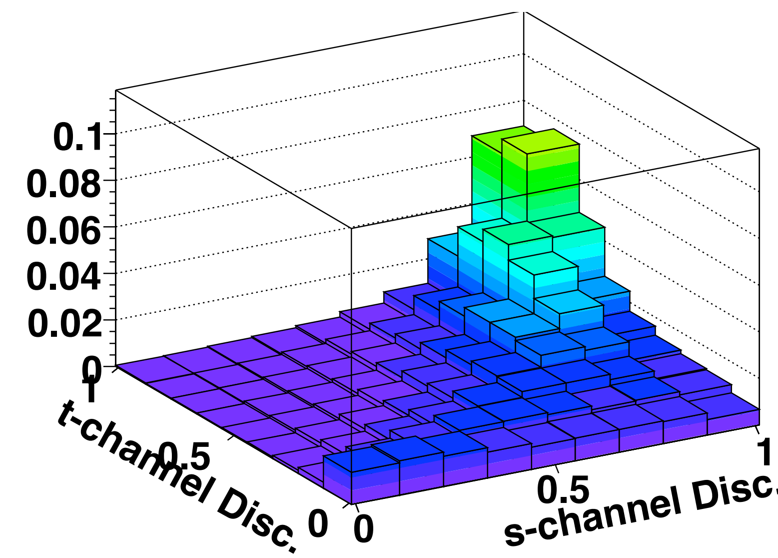
Discriminant Performance

- Calculate discriminant for signal and background Monte Carlo events

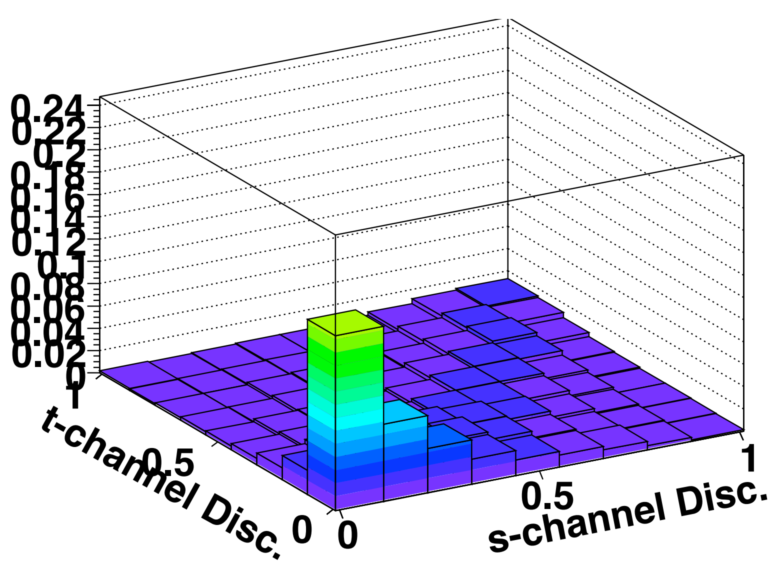
t-channel MC



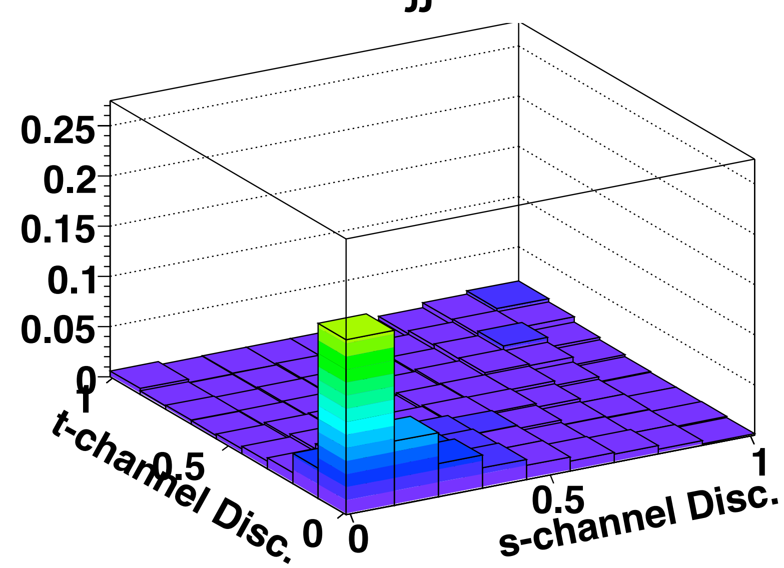
s-channel MC



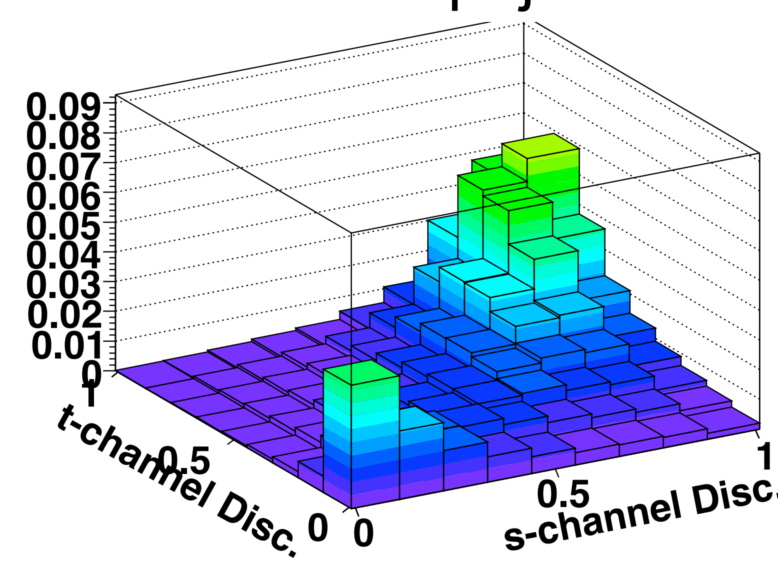
Wbb MC



Wjj MC



ttbar → lep+jets MC



Cross Section Measurement Method I

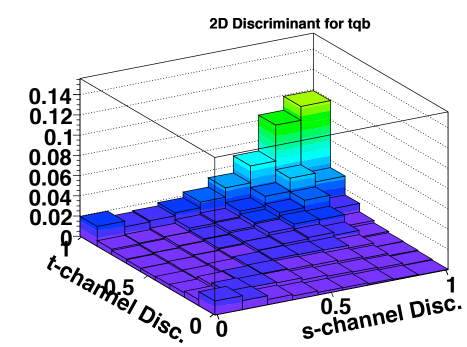
- Determine cross section by calculating the Bayesian posterior density function
- Bayes Theorem (general): $P(A|B) = \dfrac{P(B|A)P(A)}{P(B)}$
- Bayes Theorem (high energy physics)

$$P(n_{exp}|N_{obs}) = \frac{P(N_{obs}|n_{exp})P(n_{exp})}{P(N_{obs})}$$

$$n_{\rm exp} \rightarrow n_{\rm sig} + n_{\rm back} = a \times \sigma_{\rm sig} + \sum_i n_{\rm back,i}$$

- $P(N_{obs}|n_{exp})$: Likelihood of observing N events given *n* expected

$$P(N_{obs}|n_{exp}) \rightarrow \mathcal{L}(N_{obs}|n_{exp}) = \frac{n_{exp}^{N_{obs}} e^{-n_{exp}}}{N_{obs}!}$$



- $P(n_{exp})$: $P(n_{exp}) \rightarrow \pi(n_{exp}) \rightarrow \pi(a, \vec{n}_{back}, \sigma) = \pi(\sigma) \times \pi(a, \vec{n}_{back})$
- $P(N_{obs})$: Normalization

$$\pi(\sigma) = \frac{1}{\sigma_{\rm max}}, 0 < \sigma < \sigma_{\rm max}$$

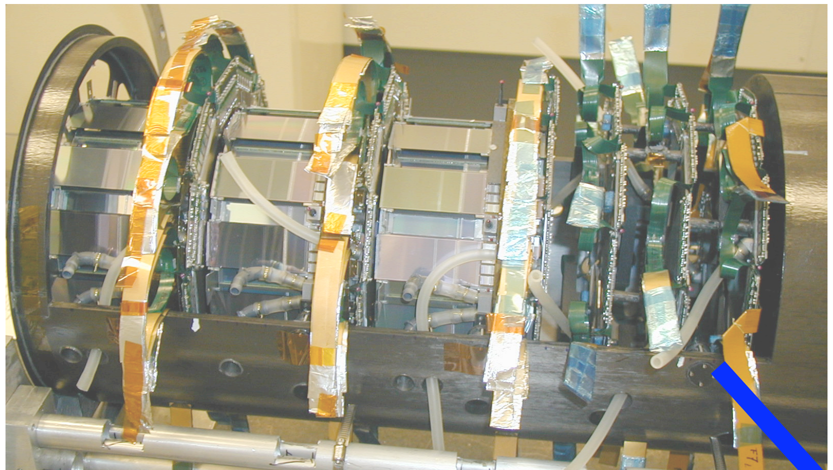
Cross Section Measurement Method II

- Acceptance ***a*** and background estimate $\boldsymbol{n_{back}}$ have errors due to systematic uncertainties of signal and background yields
  - $\pm\delta a$ = | Signal($\pm 1\sigma$ factor) - Signal(Nominal) | / Signal(Nominal)
  - $\pm\delta n_{back}$ = | Background($\pm 1\sigma$ factor) - Background(Nominal) | / Background(Nominal)
- Example:
  - Jet Energy Scale: factor applied to jets to correct measured jet energy back to the particle level.
  - Apply nominal JES to signal and background to get nominal yields
  - Apply $\pm 1\sigma$ JES to signal and background to get $\pm 1\sigma$ yields

Source of Uncertainty	Size
Top pairs normalization	18%
W+jets & multijets normalization	18–28%
Integrated luminosity	6%
Trigger modeling	3–6%
Lepton ID corrections	2–7%
Jet modeling	2–7%
Other small components	Few %
Jet energy scale	1–20%
Tag rate functions	2–16%

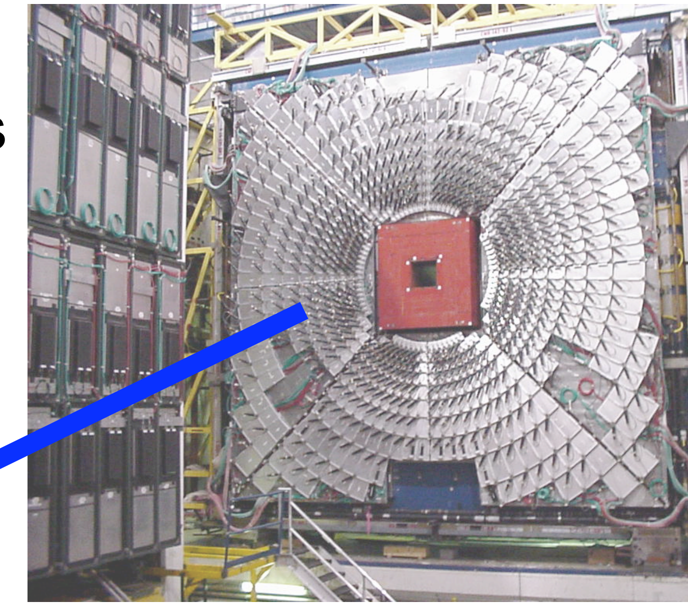
- $\pi\left(a, \vec{n}_{back}\right)$ is then sampled from multivariate Gaussian: G([$\pm\delta a$, $\pm\delta n_{back}$])

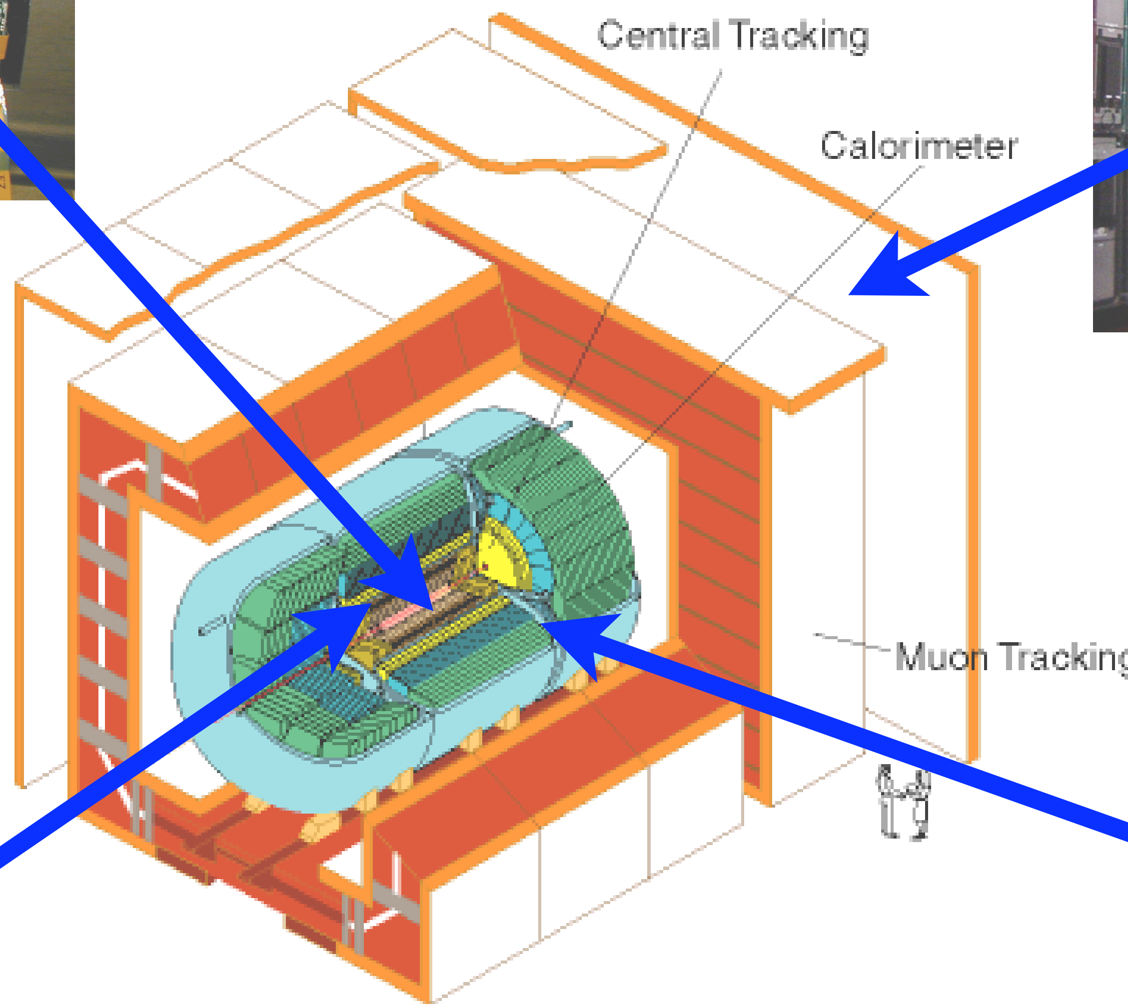
The Run II DØ Experiment



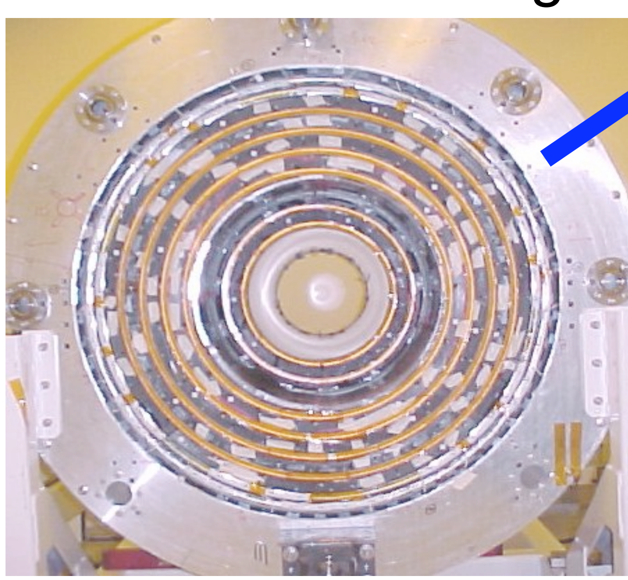
Silicon Detector
Vertex measurement
and tracking close to PV

Muon System
Drift chambers / scintillators
Muon position and tracking





Fiber Tracker
Charged particle tracking
momentum + charge



Liquid Ar/Ur Calorimeter
Energy measurement for
electrons, photons, and hadrons