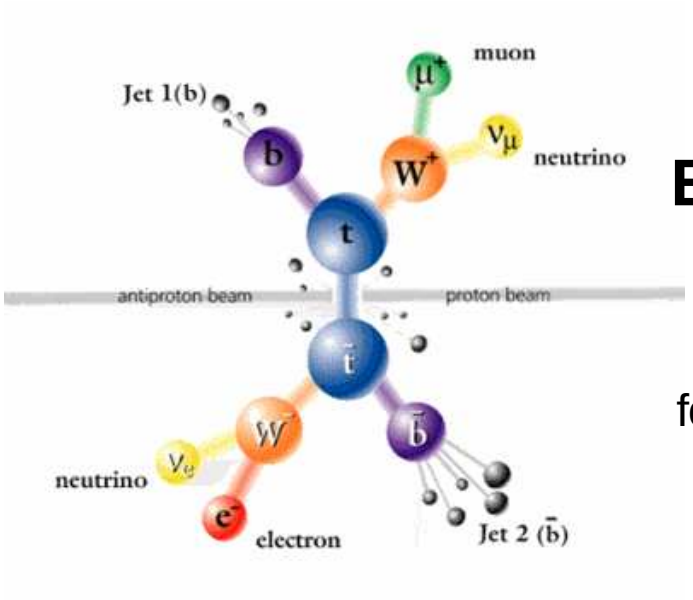
TOOLS FOR TOP AT CDF



Enrique Palencia

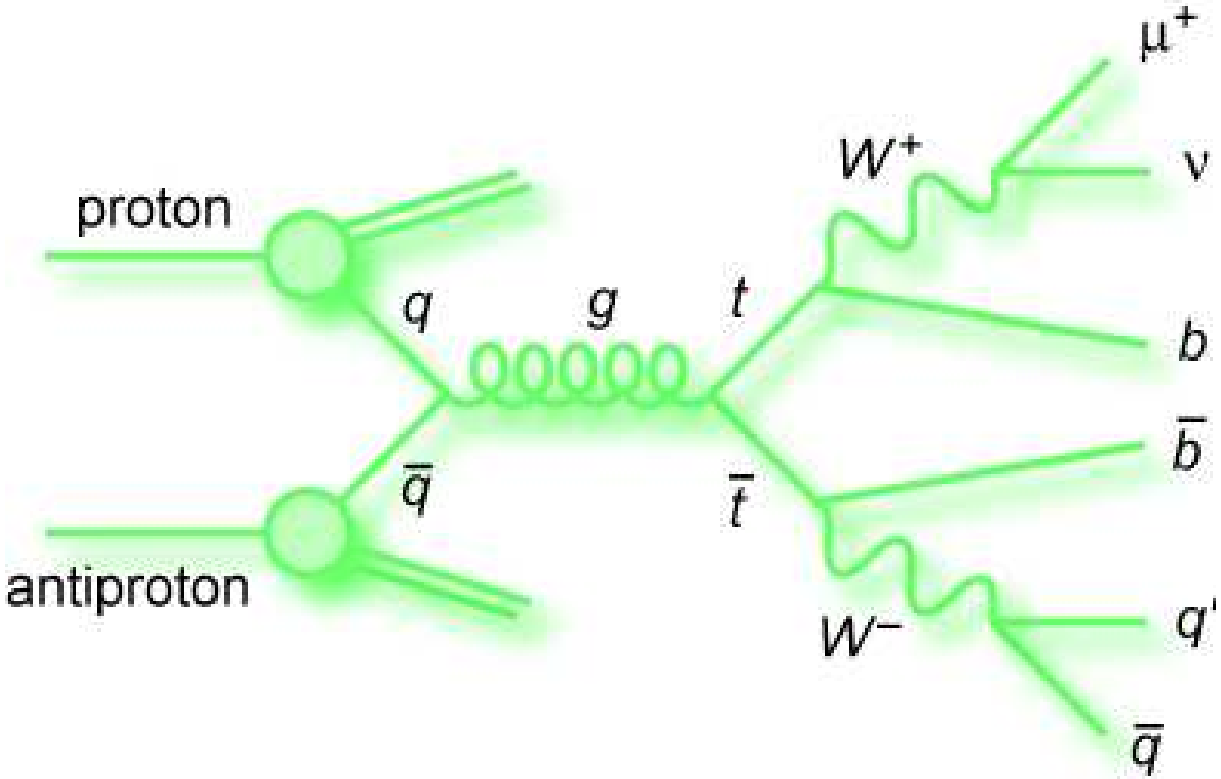
Fermilab

for the CDF Collaboration

Top 2008, Isola d'Elba (Italy), May 18-24, 2008

Outline

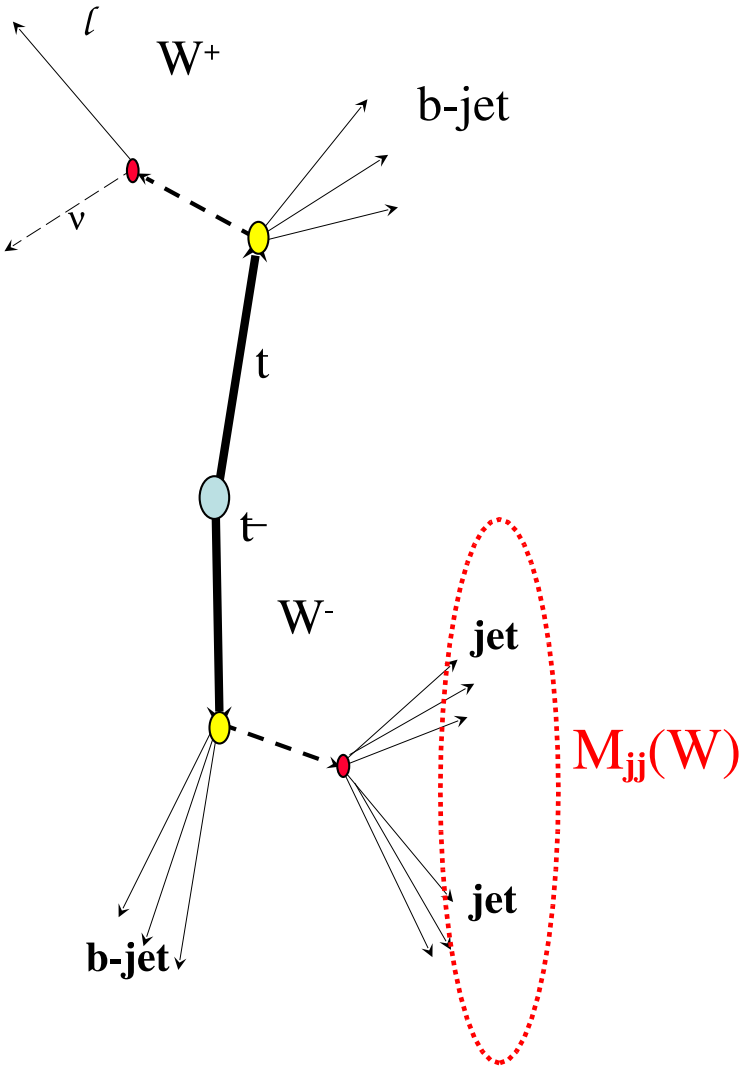
- Jet Energy Scale
- Lepton Identification
- B Tagging
- Neural Networks



JET ENERGY SCALE

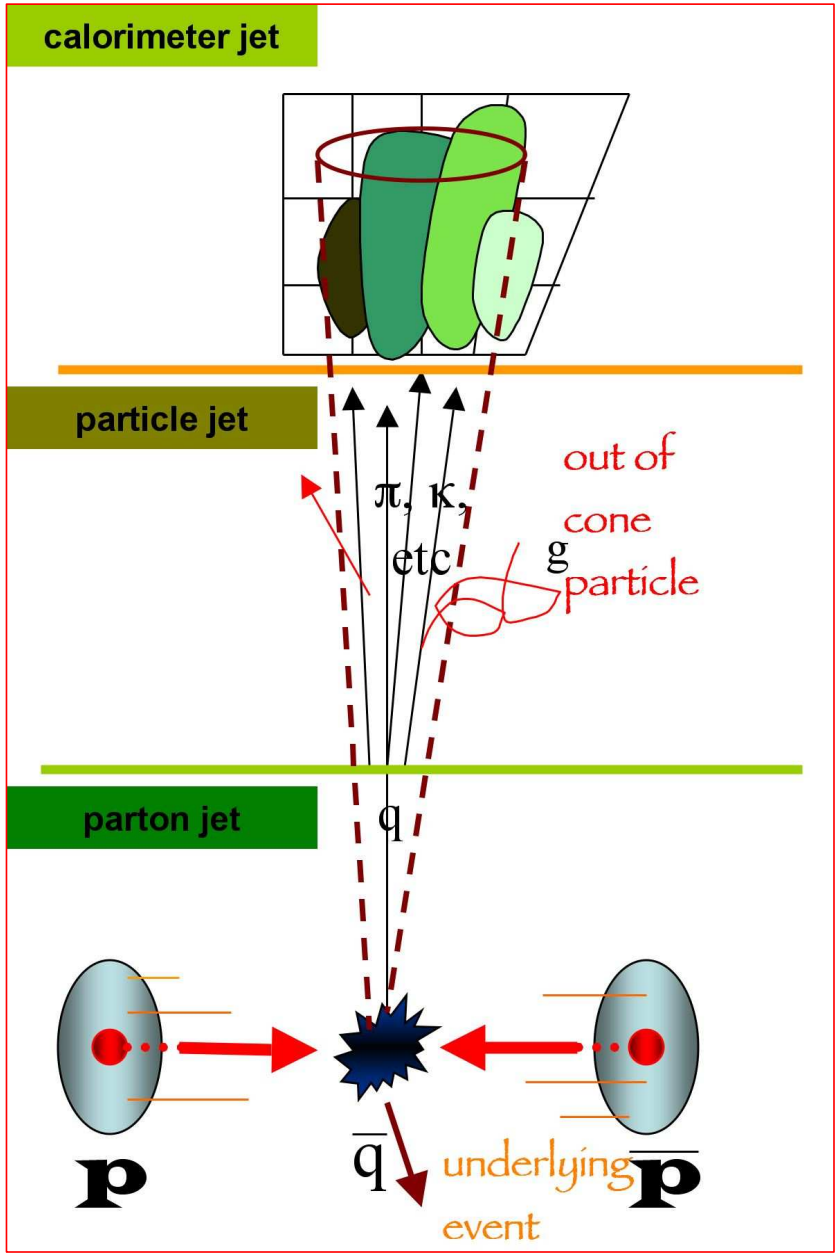
- Largest systematic uncertainty (from differences betwen data and MC)

- ... but we can exploit W⟶qq decays (when possible) to measure *in situ* the jet energy scale, JES



Why JES is so Challenging?

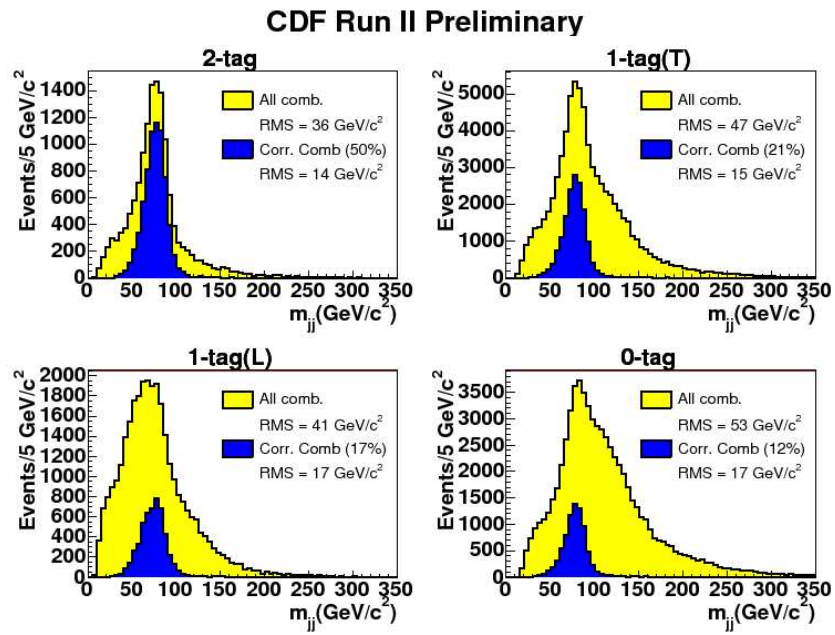
- Complex detector properties $\Rightarrow$ instrumental effects
  - ◊ Non-linear response to hadrons
  - ◊ Different response to electron and hadrons
  - ◊ Un-instrumented regions
  - ◊ Large fluctuations in deposited energy, especially for hadrons
- Algorithms with complex behaviour (cone, cone-midpoint, K_T)
- Complex underlaying physics
  - ◊ Fragmentation and hadronization
  - ◊ Initial and final state gluon radiation
  - ◊ Flavor of parent parton

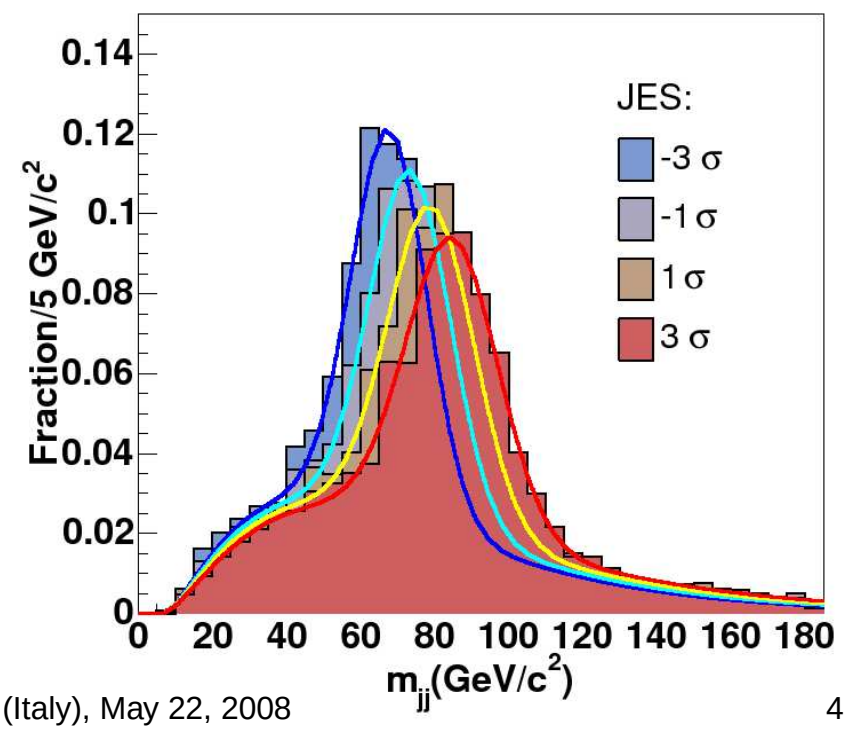


- Need to correct for all these effects to obtain the true energy of the jet

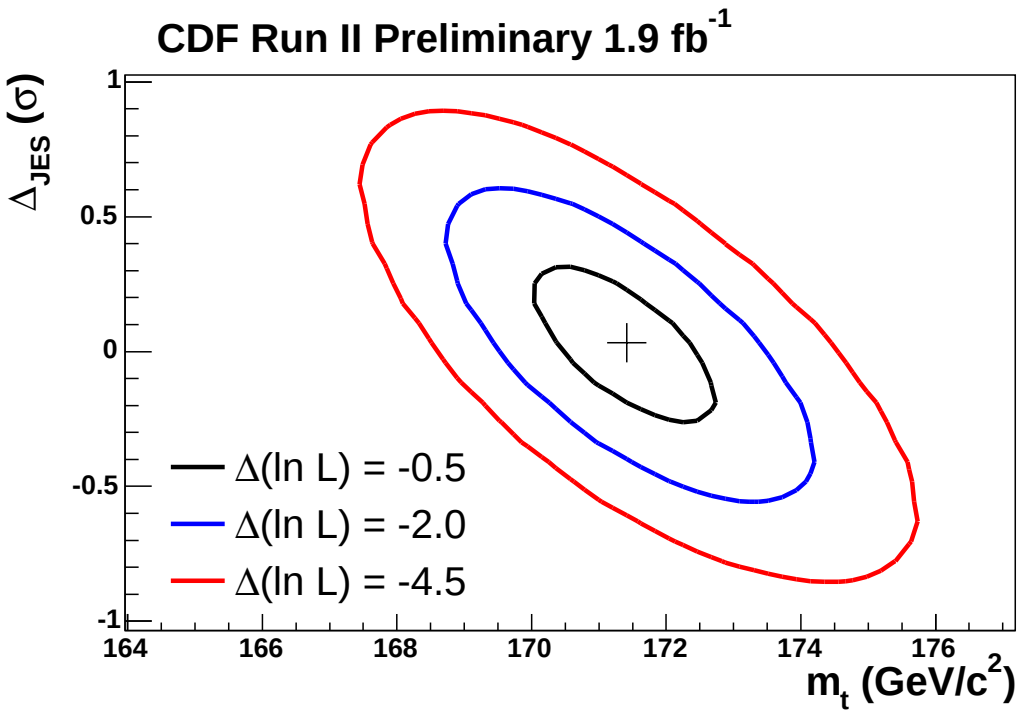
JES *in situ* Calibration

- Constrain the invariant mass of the non-b tagged jets to be the mass of W
- Build templates using the invariant mass, m_{jj}, of all non-tagged jet pairs
- Instead of assuming JES and measure M_W, assume M_W and measure JES
- Parameterize P(m_{jj}; JES) same as P(m_{top}^{reco}; m_{top})
- 40% improvement
- JES uncertainty scales directly with statistics, dominant systematic now scales as $1/\sqrt{N}$

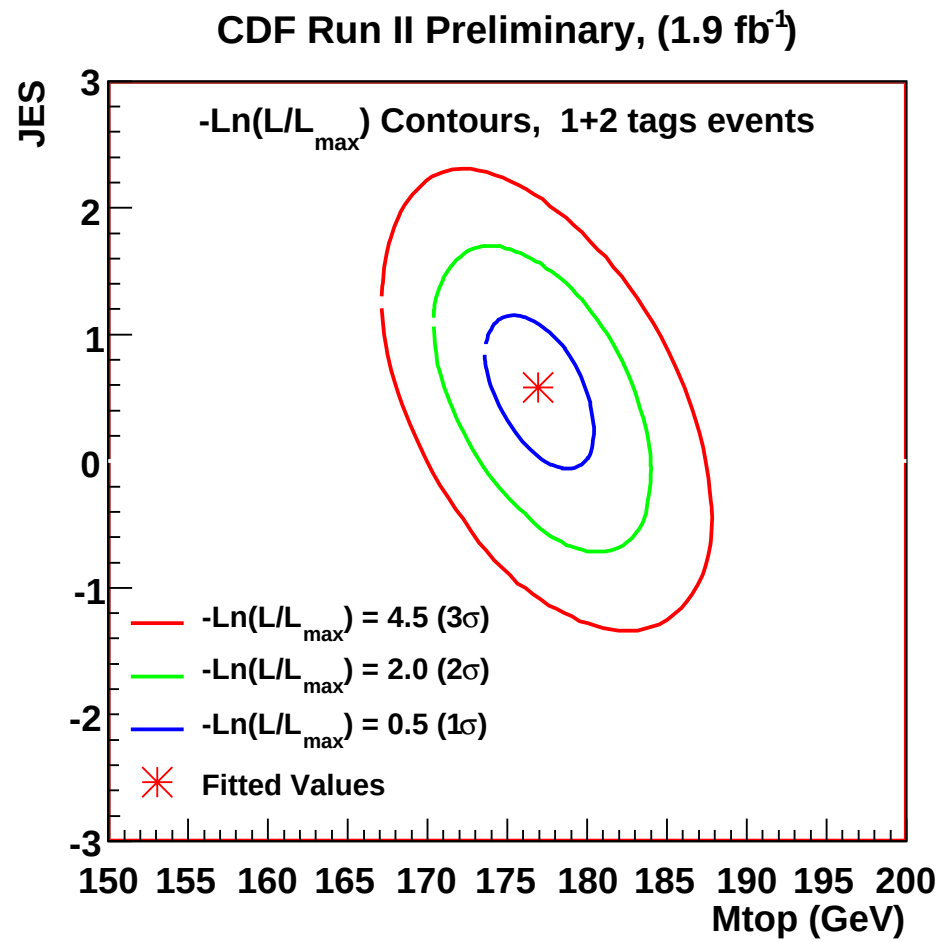




Top Results using JES *in situ* Calibration

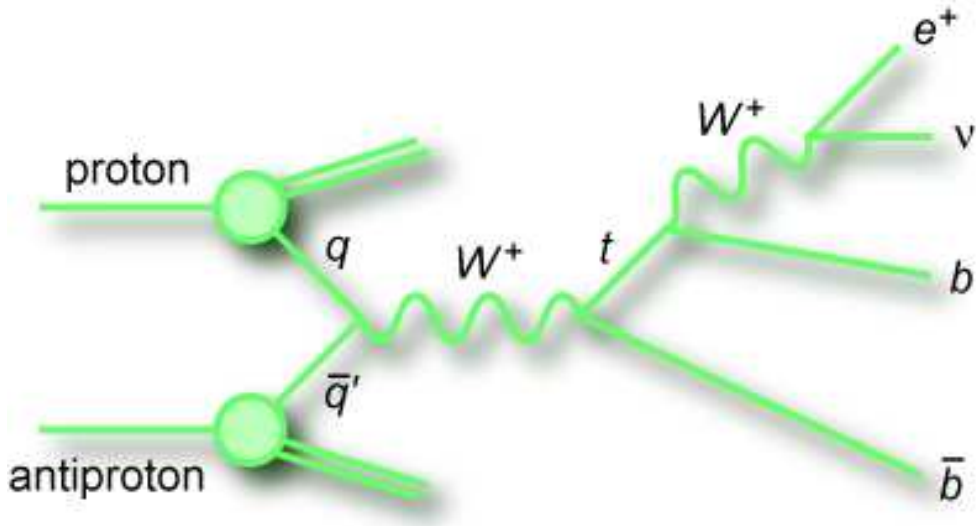


$$M_{top}(l+jets) = 171.4 \pm 1.5(stat + JES) \pm 1.0(syst)\ GeV$$



$$M_{top}(had) = 177.0 \pm 3.7(stat + JES) \pm 1.6(syst)\ GeV$$

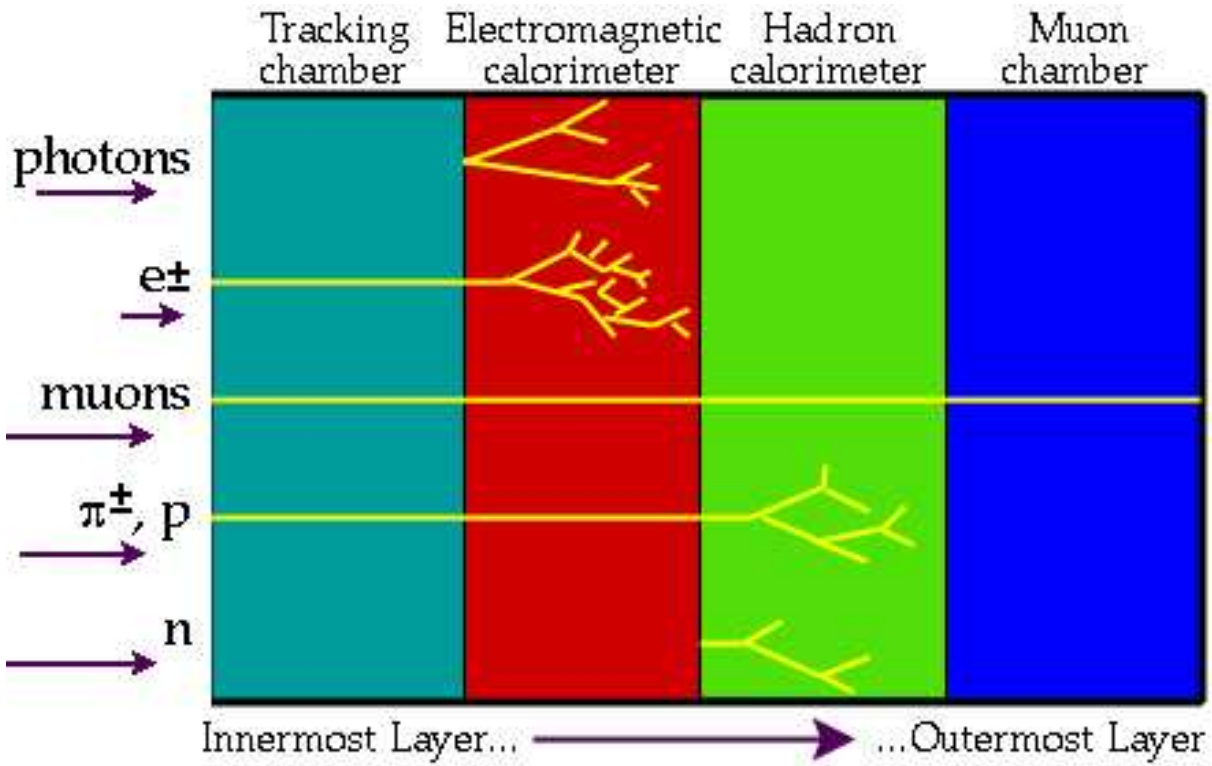
LEPTON ID



- The presence of a lepton from the leptonic decay of the W helps triggering the top sample

Electron and Muon Identification

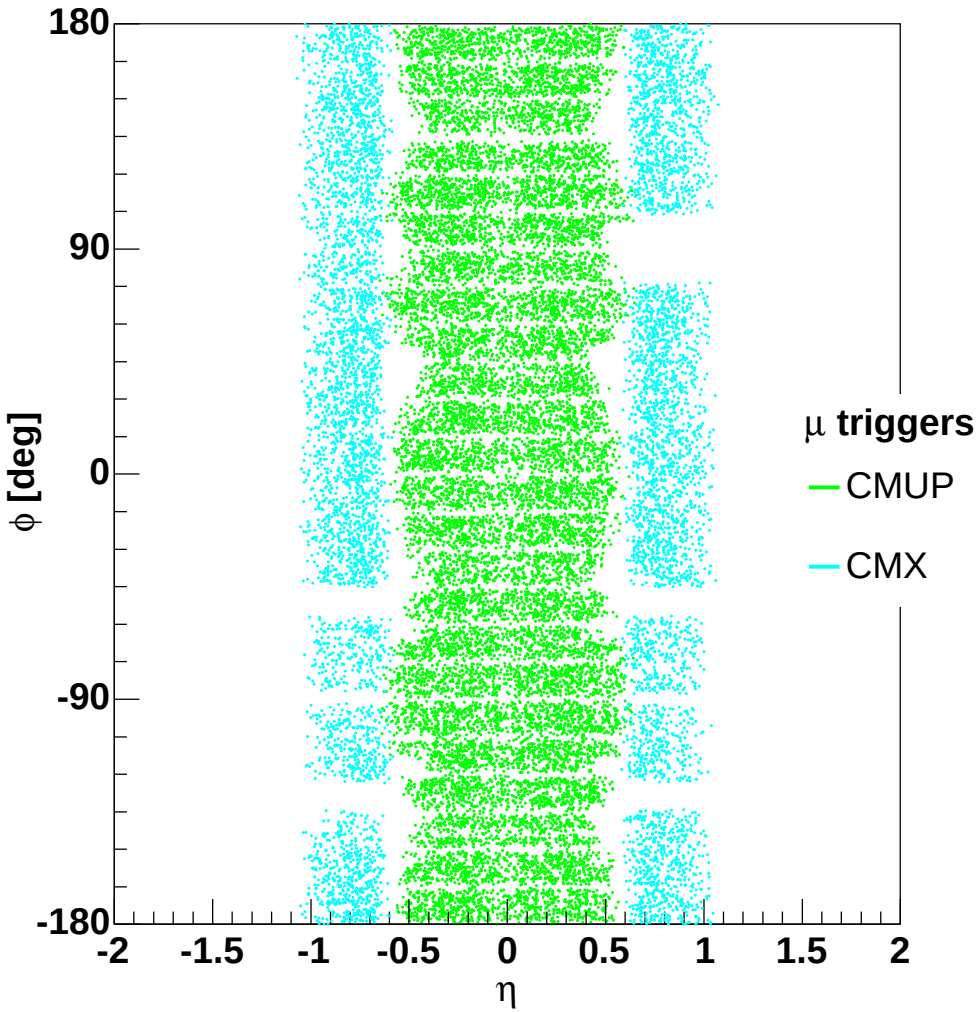
- Electrons
  - ◊ Have a charged particle track
  - ◊ Leave almost all of their energy in the electromagnetic calorimeter
  - ◊ Ask for no other nearby tracks (do not want leptons from heavy flavor jets)

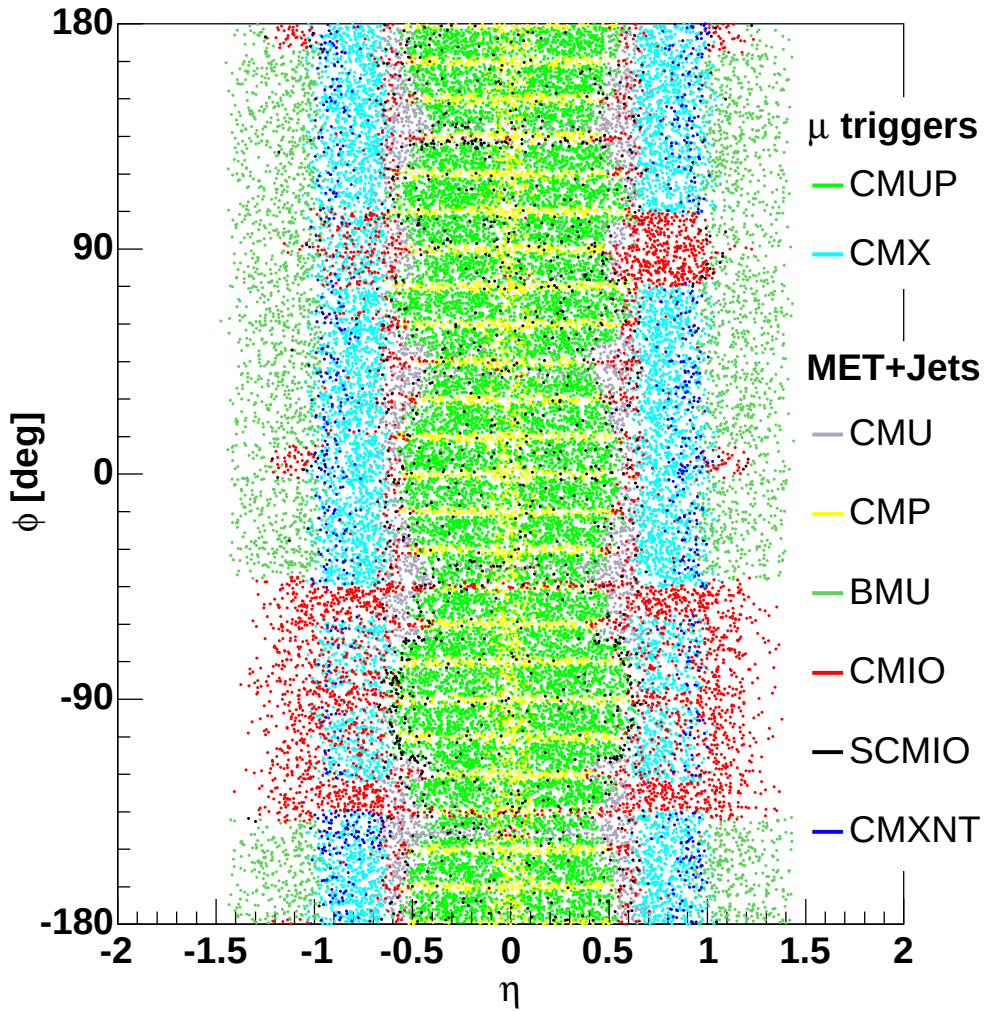


- Muons
  - ◊ Have a charged particle track
  - ◊ Minimum ionizing particles: leave very little energy in the calorimeter
  - ◊ Find a ”stub“ in the muon detectors
  - ◊ Ask for no other nearby tracks

Extended Muon Coverage

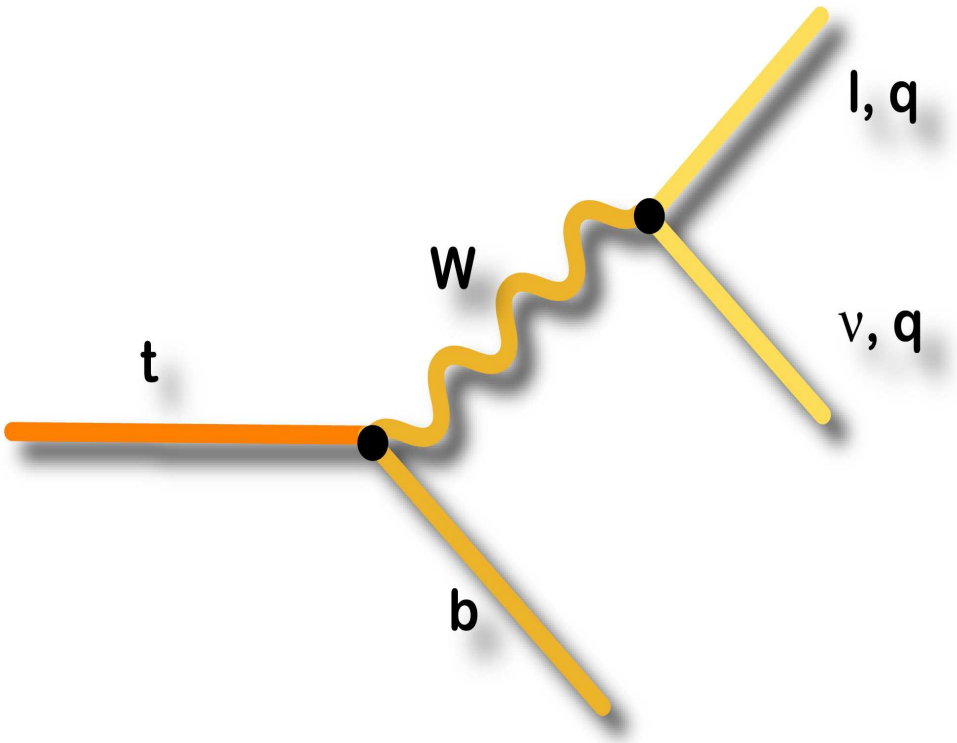
- Increase acceptance by taking muons from complementary triggers ($\not\!\!E_T$+ 2 jets)
- New muons fill the “cracks” left by triggered muons (∼30% gain in muon acceptance)





- Improve overall single top sensitivity by ∼7%

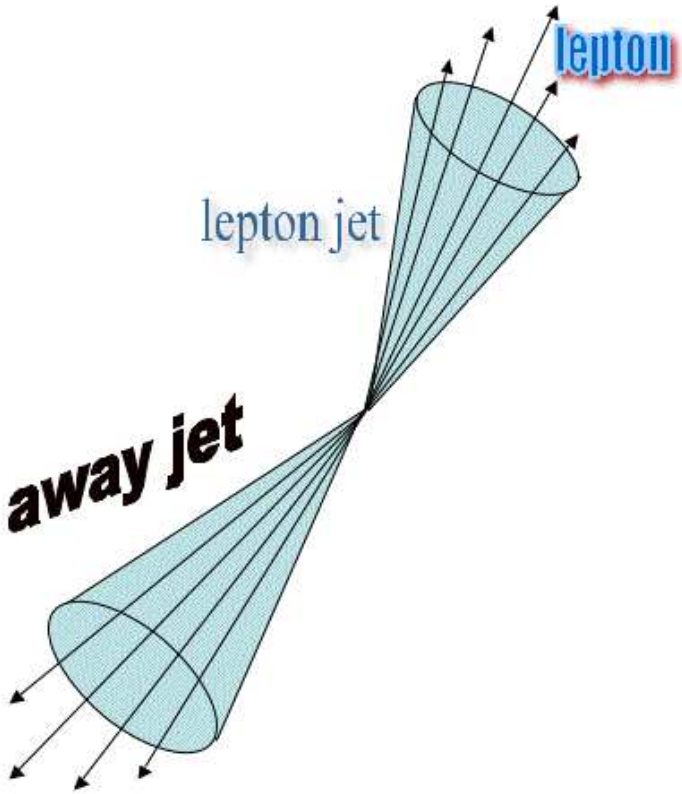
B-TAGGING



- We expect t $\longrightarrow$Wb most of the times
- Most backgrounds do not have bottom quark jets

Efficiency Measurement

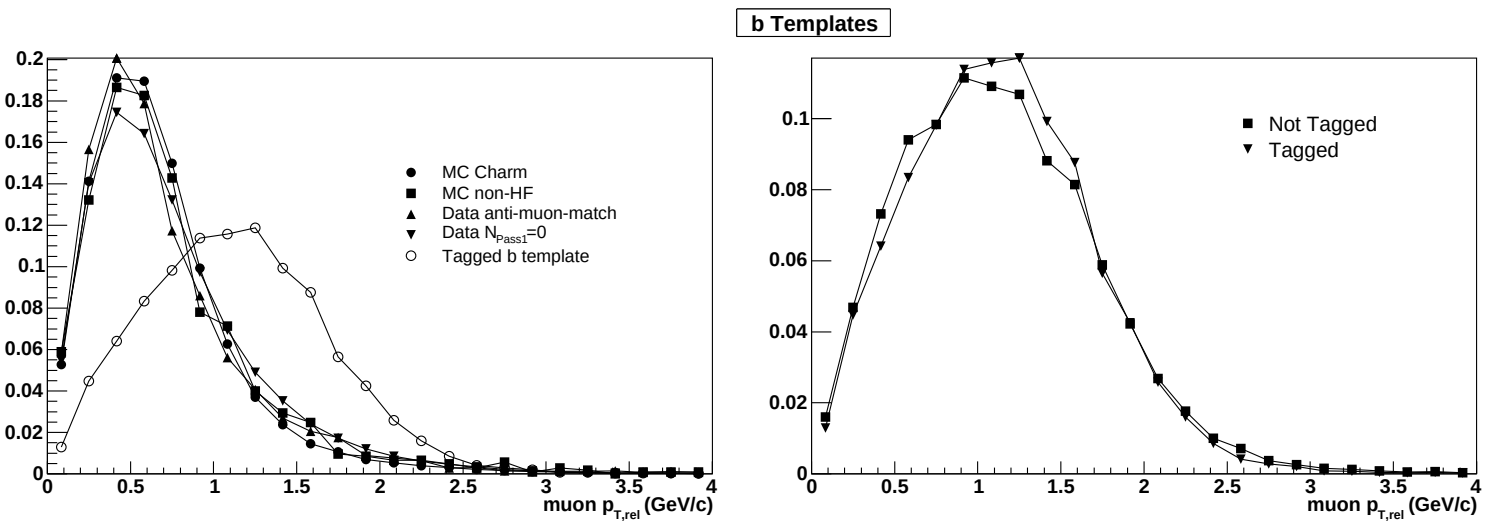
- Understanding tag efficiency in MC is easy
- What one really need is the efficiency of tagging b-jets in data
- Based on 8 GeV muon (and electron) data samples: enriched in real b-jets
- Require the presence of a jet (lepton jet) with a lepton inside (indicative of semileptonic b decay)

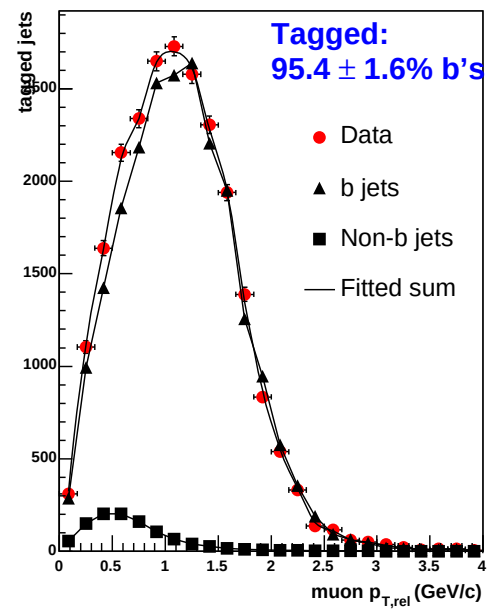


- Require the presence of another jet (away jet) with a tag (enhance b fraction)
- Two independent methods
  - ♢ One relies in muon jets and fits the b and non-b content using templates of the relative p_T of the muon with respect to the jet axis (next slide)
  - ♢ The other uses double tag events where the away jet is paired to an electron jet

Efficiency Measurement: Muon Method

- Use high relative transverse momentum (p_T^{rel}) of muons from b decays
- Divide muon jets into two subsamples: tagged and untagged
- Generate p_T^{rel} templates for b (from MC) and non-b (from MC or data) jets
  - ◇ the non-b templates are very similar
  - ◇ the b templates are similar for tagged and untagged b-jets

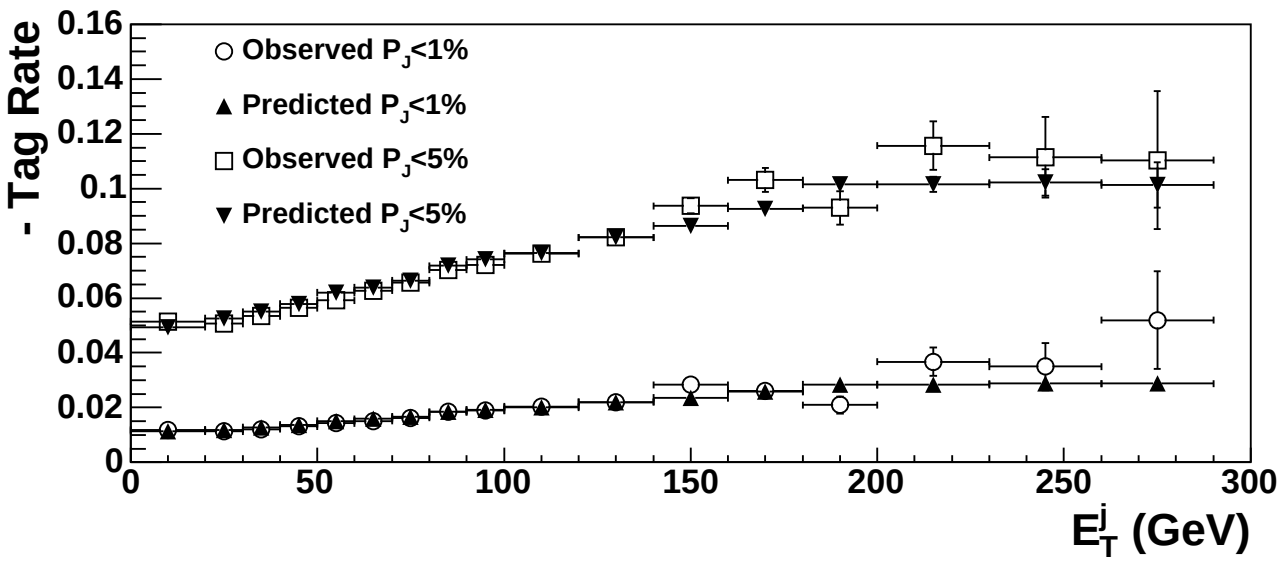




- Fit p_T^{rel} spectrum from data to find fraction of b and non-b jets in tagged and untagged samples

Mistag Rate

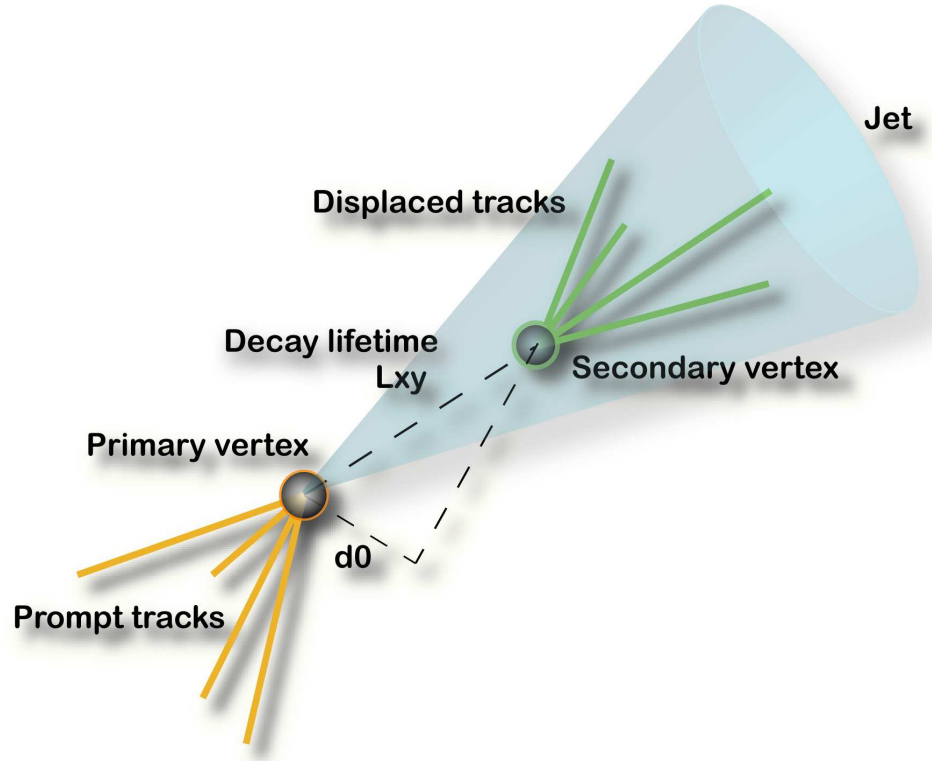
- Mistag rate: probability of tagging a light jet as a heavy flavor one
- Determined using inclusive jet data samples
- Parameterized as a 6 dimensional look-up table (mistag matrix): E_T, N_{trk}, $\sum E_T^j$, η, Z_{vtx}, ϕ
- Cross check using independent samples: observed (multijet trigger) vs prediction (inclusive jet data)



- Still need to correct for the negative tags of real heavy flavor, for K_s and Λs and interactions with detector material

Secondary Vertex Algorithm

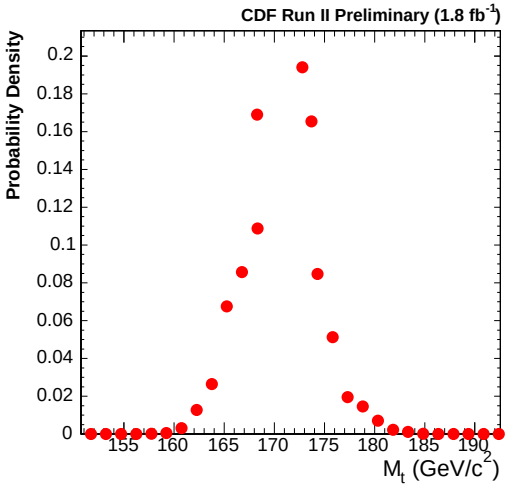
- B decay signature has a displaced vertex (long lifetime) $\Rightarrow$ travels L_{xy} $\sim$3 mm before decaying
- Attempt to construct a secondary vertex using large impact parameter (d_0) tracks with a 2-pass scheme
- Fit displaced tracks to a common vertex and cut on L_{XY} significance

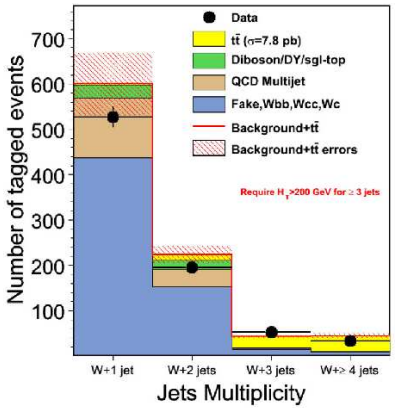


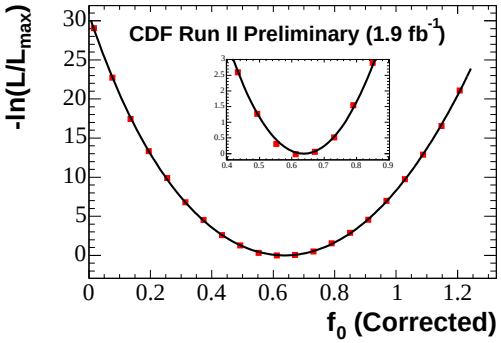
- Relies heavily on excellent performance and understanding of the silicon tracker

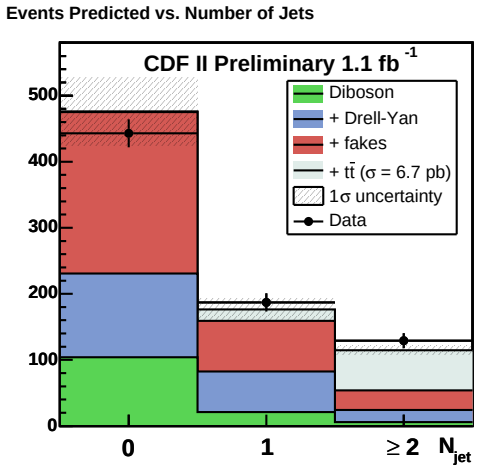
	Tight	Loose
b-tag eff. (per $t\bar{t}$ event) (%)	$\sim$60	$\sim$69
Overall mistag rate (%)	$\sim$0.5	$\sim$1.2

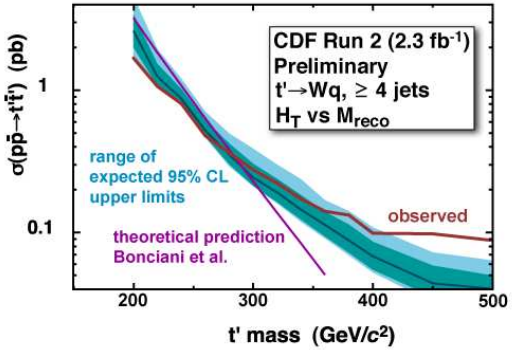
Top Results with SecVtx: A lot!!!

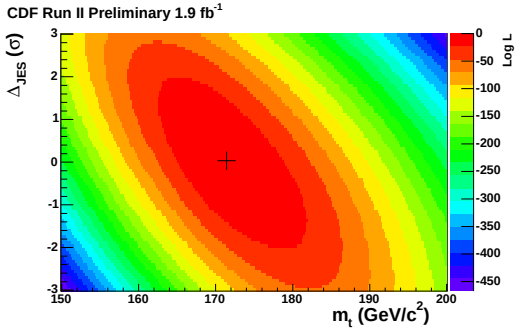


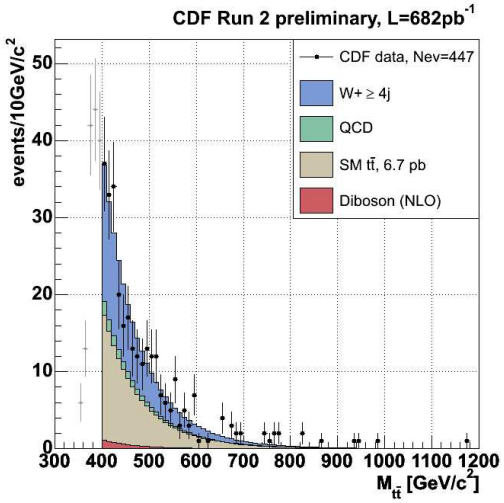


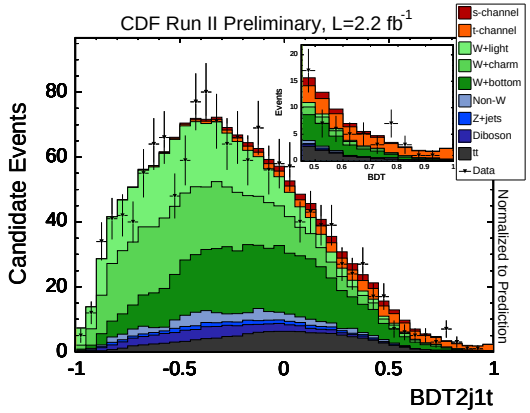


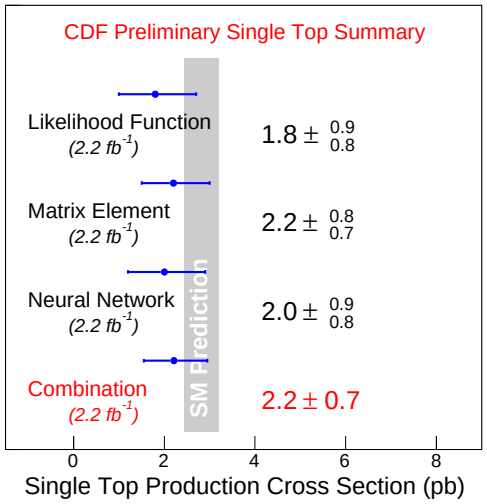


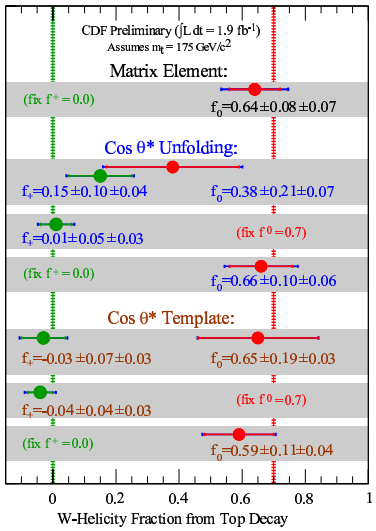


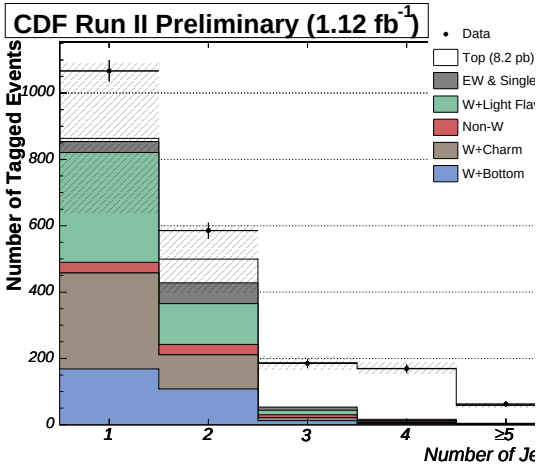


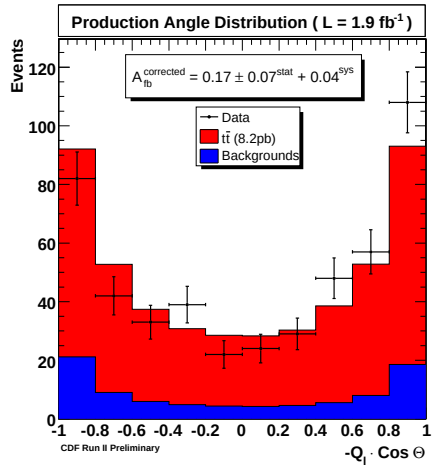






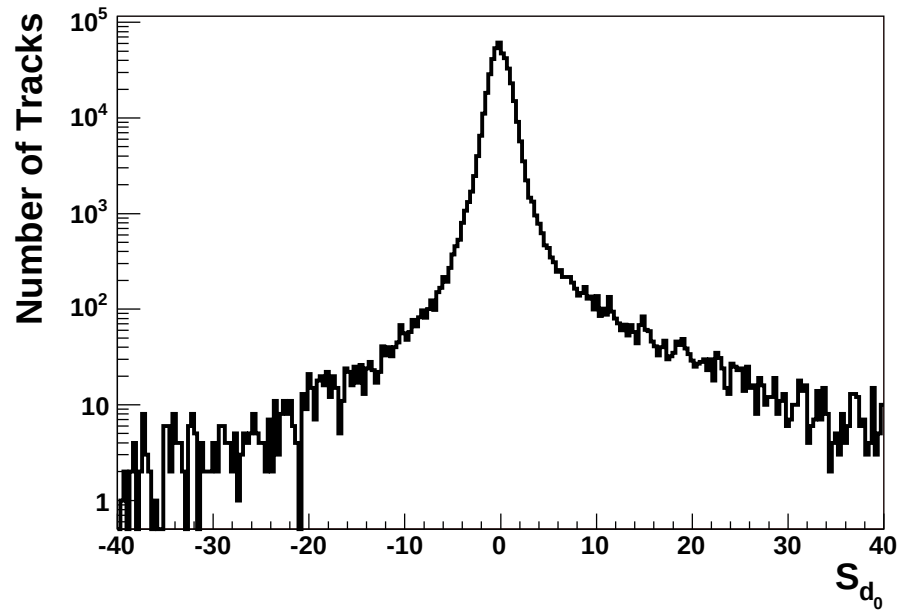


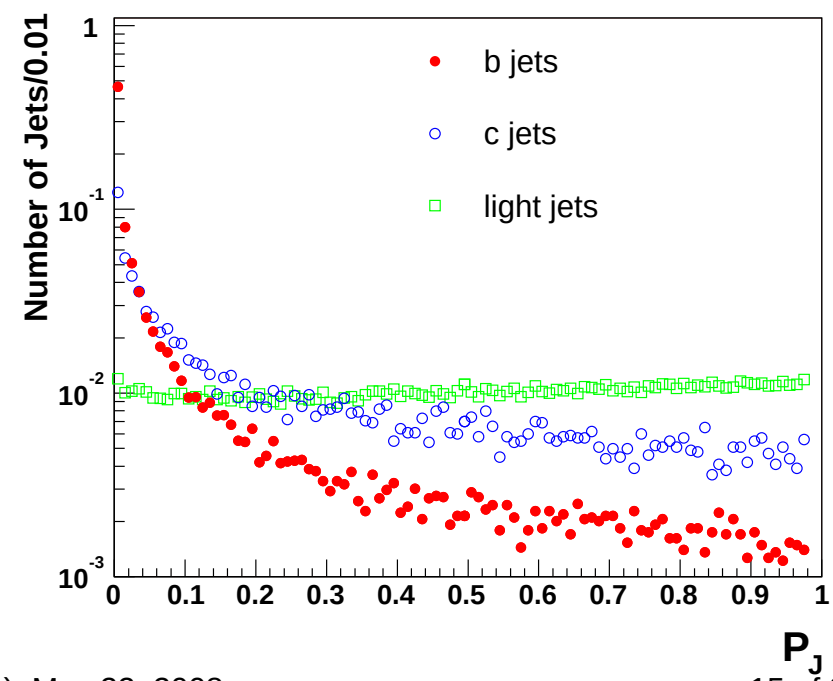




Jet Probability Tagger

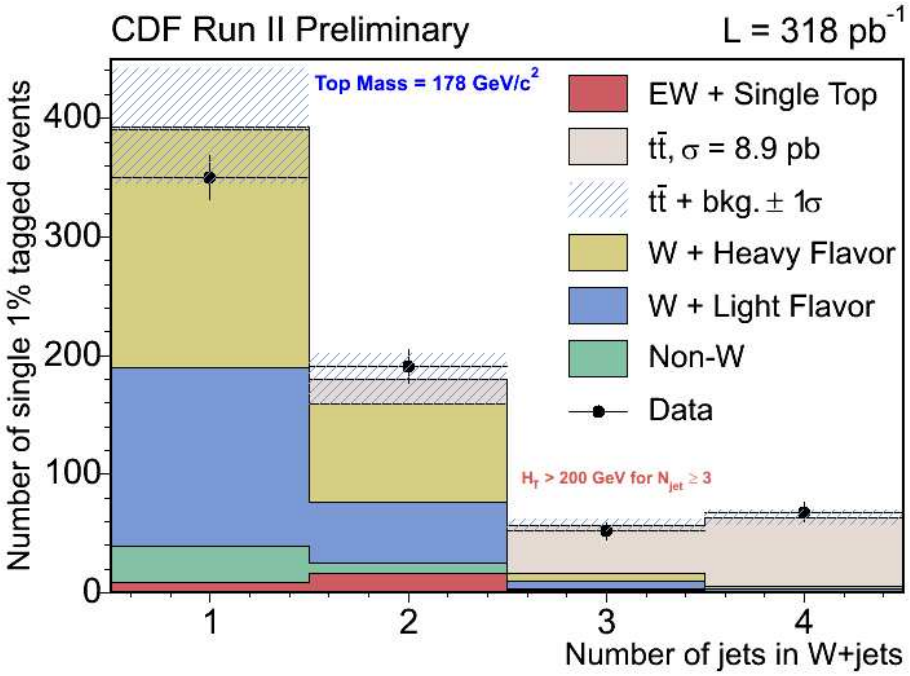
- Look for displaced tracks form the primary vertex (based on the impact parameter significance, S_{d_0})
- Build a probability (P_{tr}) for all tracks in a jet to come from a primary vertex
- $P_{tr} \longrightarrow P_J$ that, physically, is the probability for a jet to come from the primary vertex
- Provides a continous variable
- Uniform for light quark or gluon jets. Peaks at 0 for jets containing displaced tracks from HF decays

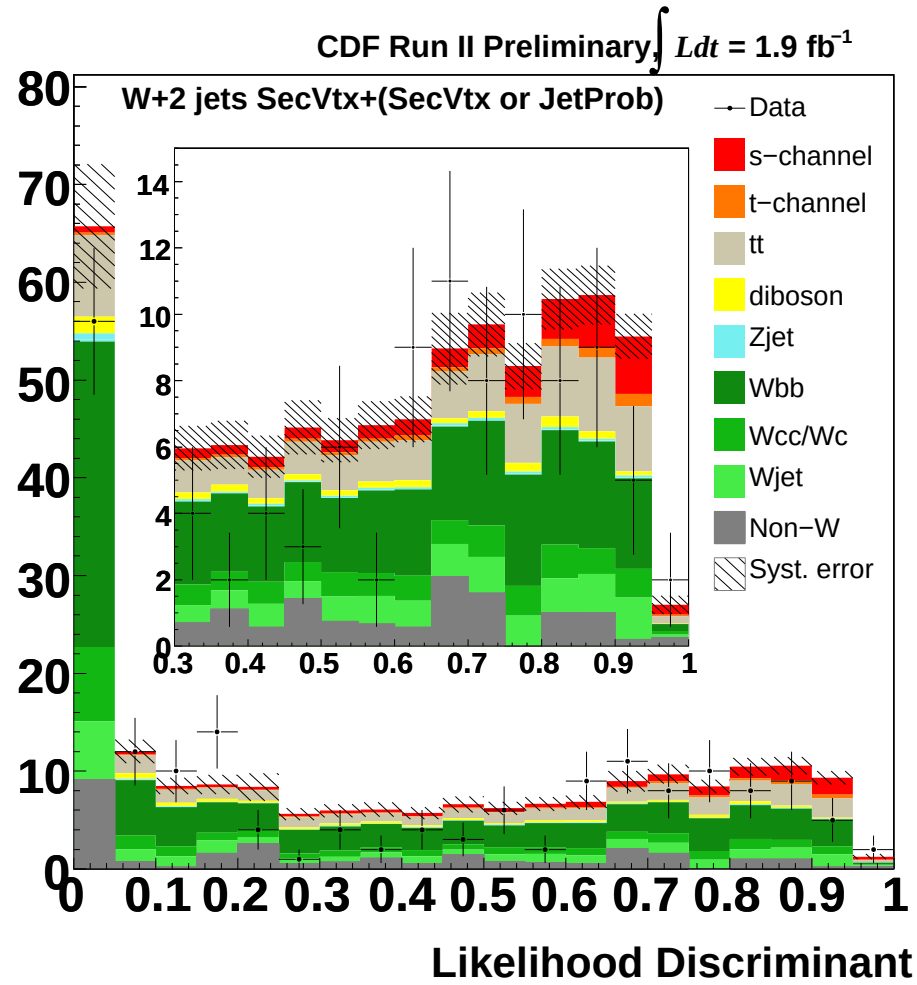




	$P_J < 1\%$	$P_J < 5\%$
b-tag eff. (per $t\bar{t}$ event)	∼55	∼69
Overall mistag rate (%)	∼1.22	∼5.30

Top Results with Jet Probability: $\sigma_{t\bar{t}}$, σ_{s-chan}





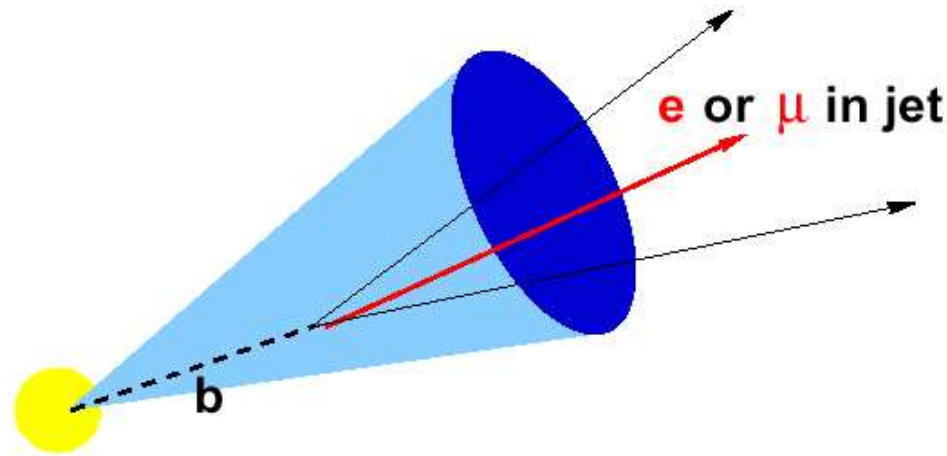
$$\sigma_{t\bar{t}} = 8.9 \pm 1.0(stat)^{+1.1}_{-1.0}(syst)\ pb$$

$$\sigma_{s-chann} < 2.77\ pb\ (95\%\ C.L.)$$

$$\sigma_{s-chann} = 0.6^{+0.9}_{-0.6}\ pb\ (\sigma_{SM} = 0.88\ pb)$$

Soft Muon Tagger

- Use different information than lifetime taggers
- B can decay semileptonically: $b \to l\nu c$
- Looks for an energetic lepton inside a jet
- Based on a "global χ^2", L, to identify muons



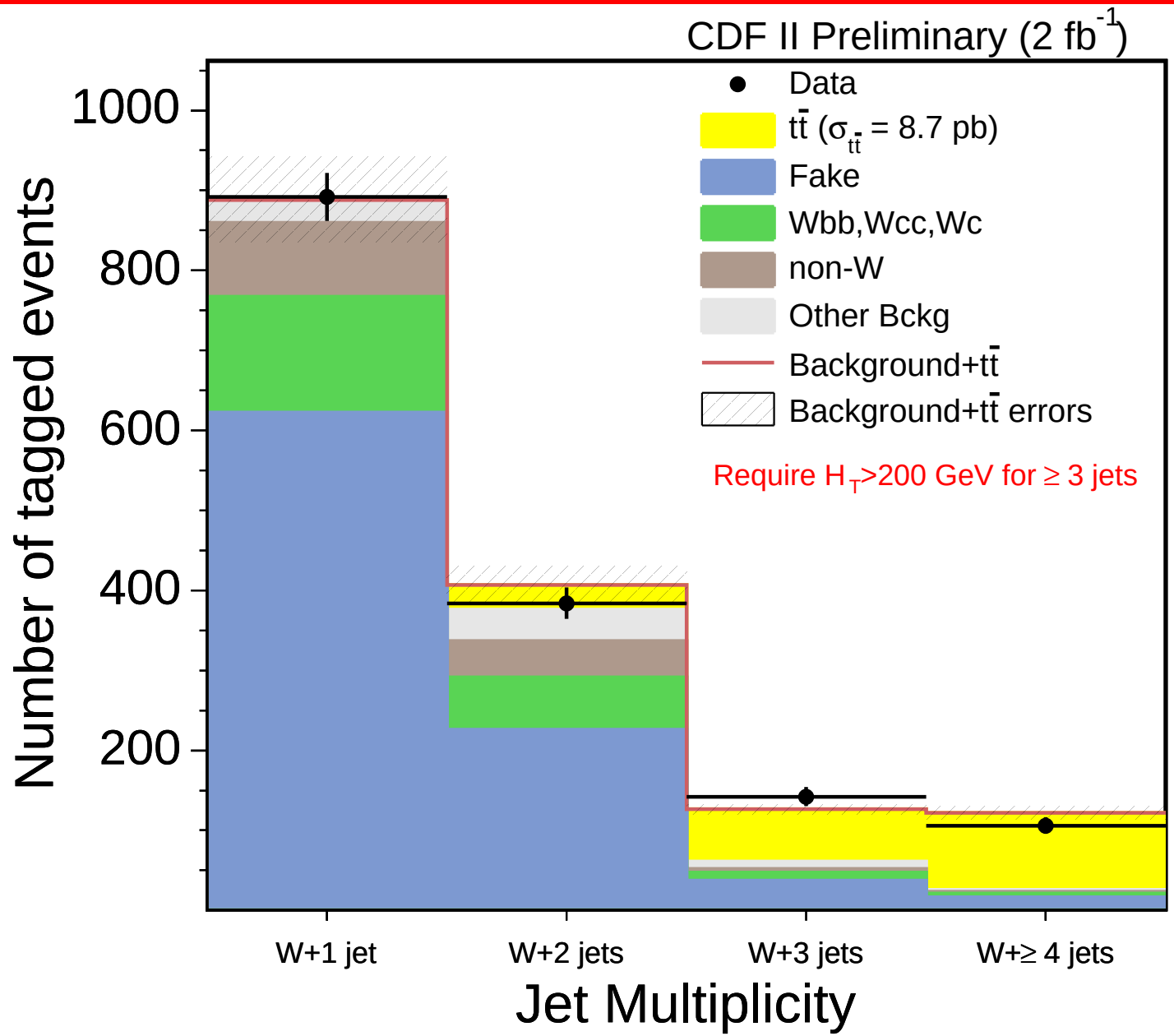
- $b \to \ell\nu c$ (BR $\sim$ 20%)
- $b \to c \to \ell\nu s$ (BR $\sim$ 20%)

  - ♢ L combines information from muon matching variables
  - ♢ There is no calorimetry or isolation requirements

- Considers tracks with $\Delta R_{slt-jet}$ <0.6, $|\Delta Z_{slt-Zvtx}|$ <5 and $p_T > 3$ GeV
- A jet is tagged if there is a SLTμ with L<3.5

	SLT μ
b-tag eff. (per jet) (%)	$\sim$10
Overall mistag rate (per track) (%)	$\sim$0.7

Top Results with Soft Muon Tagger: $\sigma_{t\bar{t}}$



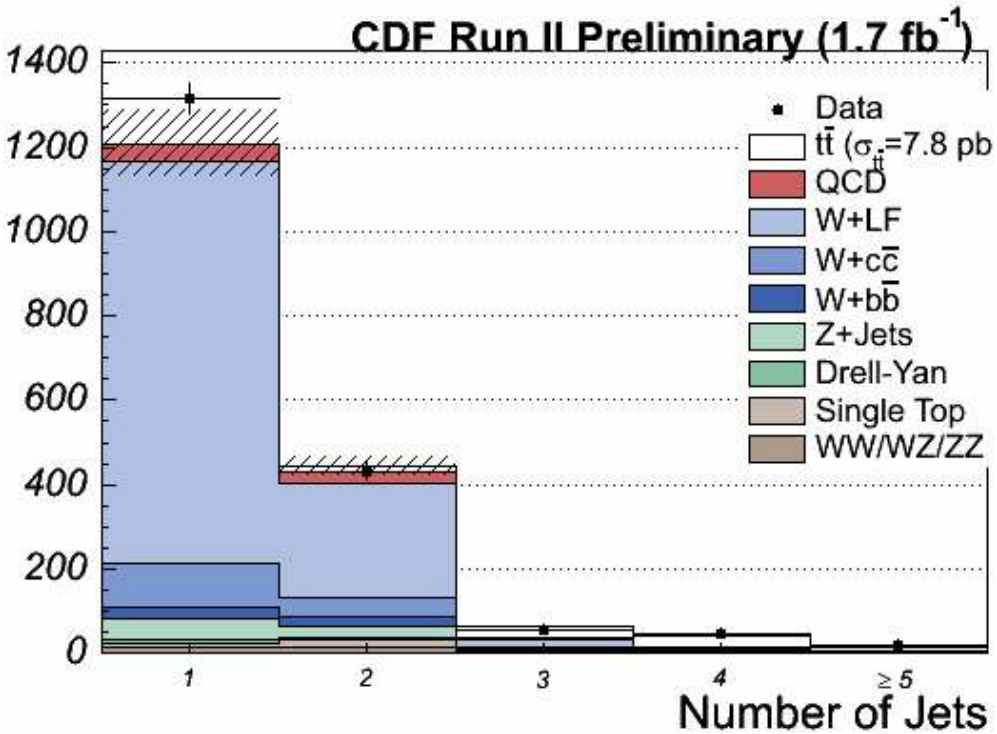
$$\sigma_{t\bar{t}} = 8.7 \pm 1.1(stat)^{+0.9}_{-0.8}(syst) \pm 0.6(lumi)\ pb$$

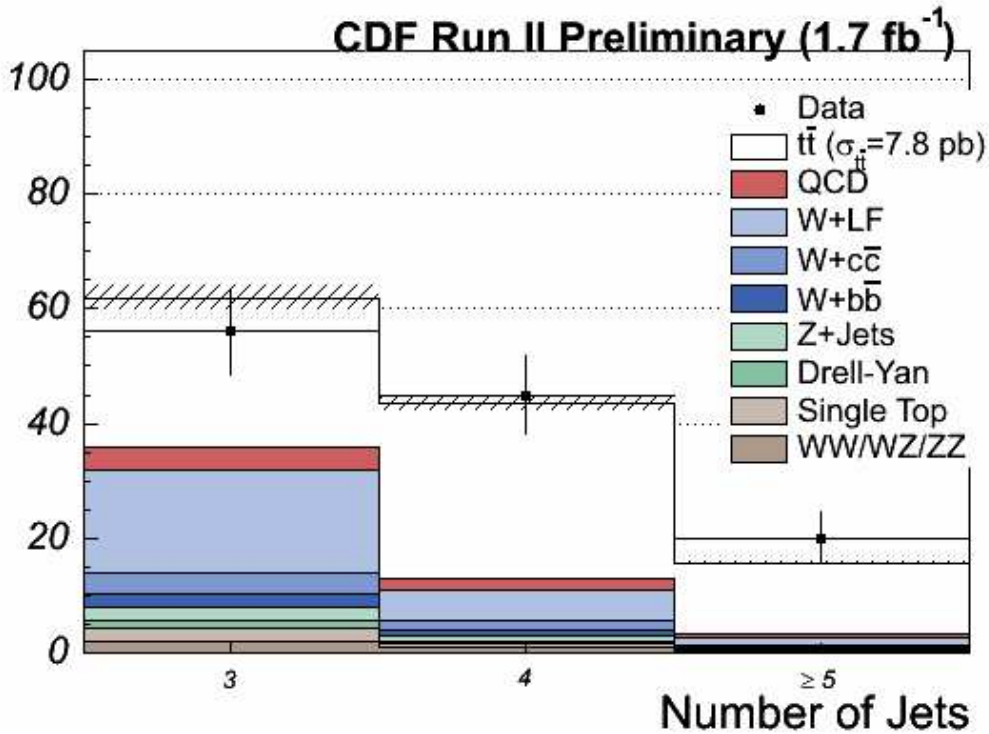
Soft Electron Tagger

- New in RunII (More difficult than muon tagger)
- Begins extrapolating well measured tracks (p_T >2 Gev) to the calorimeter
- Before consideration in a likelihood, electrons must pass some basic ID cuts
- Use data to parameterize the tagging rate for electrons and fake electrons in data in MC (as a function of p_T, η and isolation)
  - ♢ Conversion electrons for the electron tagging rate
  - ♢ Tracks in generic jets for the fake electron tagging rate
- Reject electrons from conversions by looking for the conversion partner or by finding missing silicon layers

	SLT e
b-tag eff. (per $t\bar{t}$ event) (%)	∼8
Overall mistag rate (per track) (%)	∼0.5

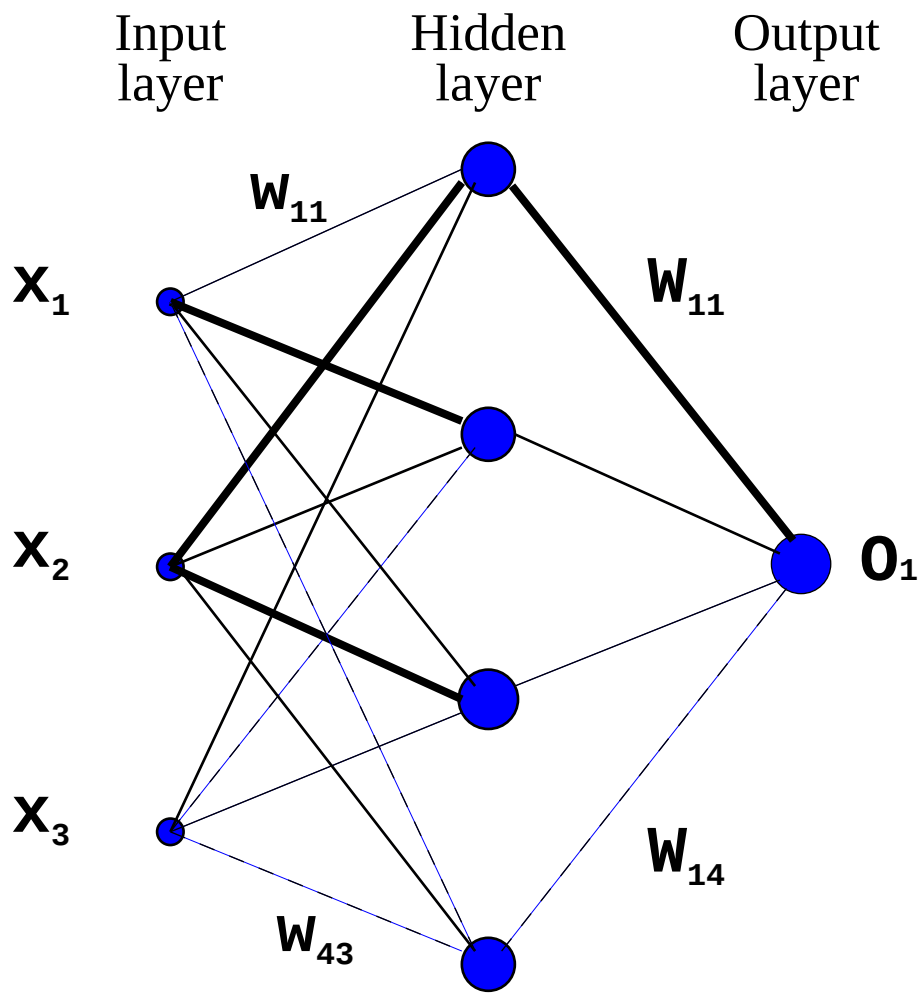
Top Results with Soft Electron Tagger: $\sigma_{t\bar{t}}$





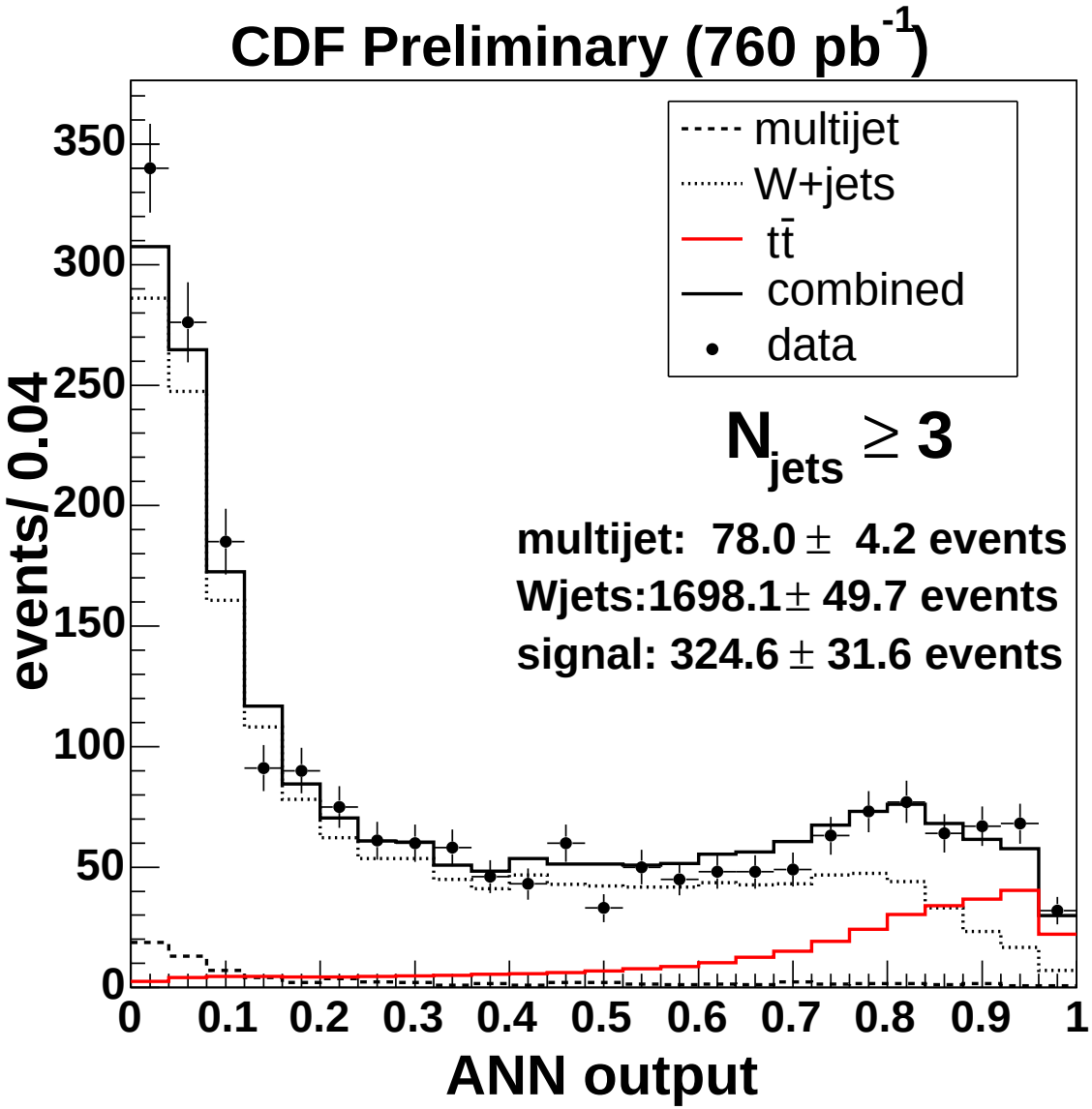
$$\sigma_{t\bar{t}} = 7.8 \pm 2.4(stat) \pm 1.5(syst) \pm 0.5(lumi)\ pb$$

NEURAL NETWORKS



NN for $\sigma_{t\bar{t}}$: Kinematical Analysis in Pretag Sample

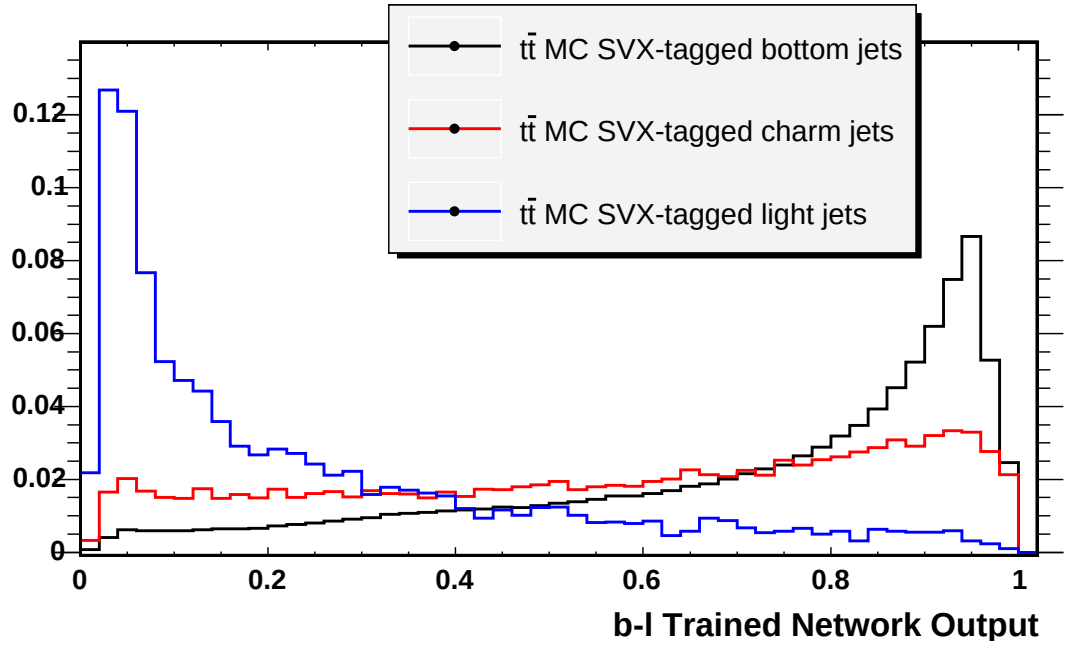
- Expected S/B$\sim$1:5 (1:1.5) in W + $\geq$3 (4) pretag jets samples
- Top pair events are central, spherical end energetic
- Exploits the discrimination available from kinematical and topological variables to distinguish top pairs from bkg
- Neural Network with 7 input variables: H_T, event aplanarity, η_{max}, $\sum p_z / \sum E_T$, min(M_{jj}), E_T(j1)+E_T(j2)+E_T(j3), min (ΔR_{jj})

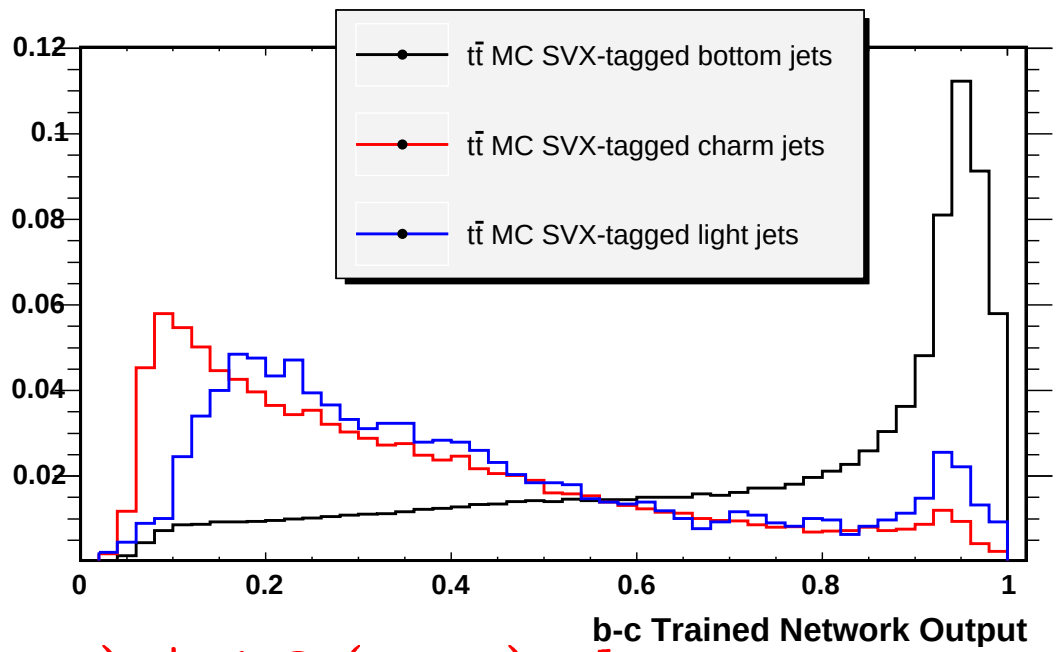


$$\sigma_{t\bar{t}} = 6.0 \pm 0.6\,(stat) \pm 0.9\,(syst)\,pb$$

NN for $\sigma_{t\bar{t}}$: purifying the SecVtx tagged sample

- Two NN trained with $t\bar{t}$ MC sample
  - ◇ one to distinguish bottom from light jets
  - ◇ another to distinguish bottom from charm
- 16 input variables (vertex mass, decay length, track multiplicity...)
- NNO(b-l)>0.182, NNO(b-c)>0.242
  - ◇ Keep 90% of SecVtx tagged b jets
  - ◇ Reject 65% of light jets and 51% of charm jets





$$\sigma_{t\bar{t}} = 8.2 \pm 0.6\ (stat) \pm 1.0\ (syst)\ pb$$

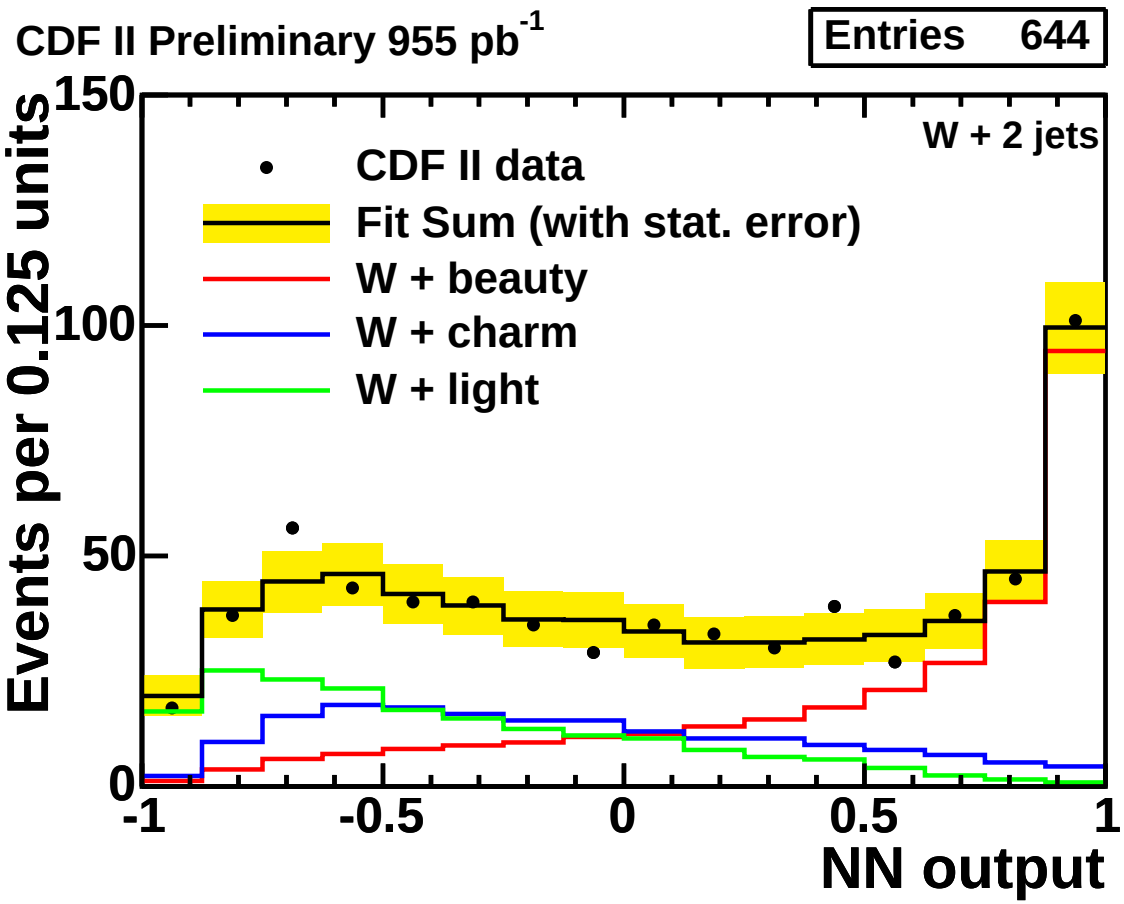
NN for Single Top search

- About 50% of the background in the W+2 jets sample do not contain b quarks (even though a secondary vertex is required)

- NN to separate jets from b-quark from c and light-quark jets

- Jet and track variables (vertex mass, decay length, track multiplicity...)

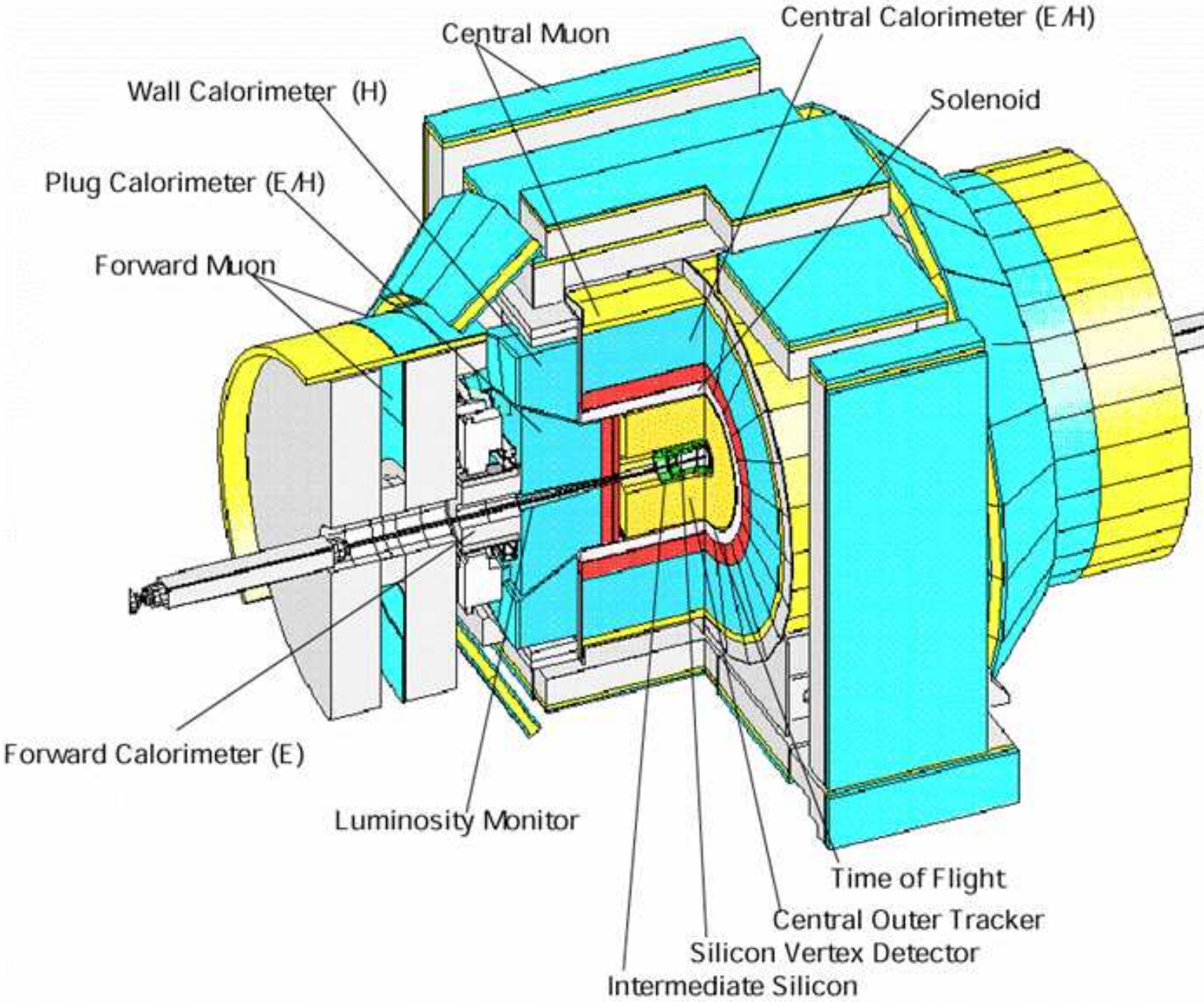
- Replace yes-no by a continous variable



- Improves single top sensitivity by 10-20%!!!

And, of course, the CDF detector!

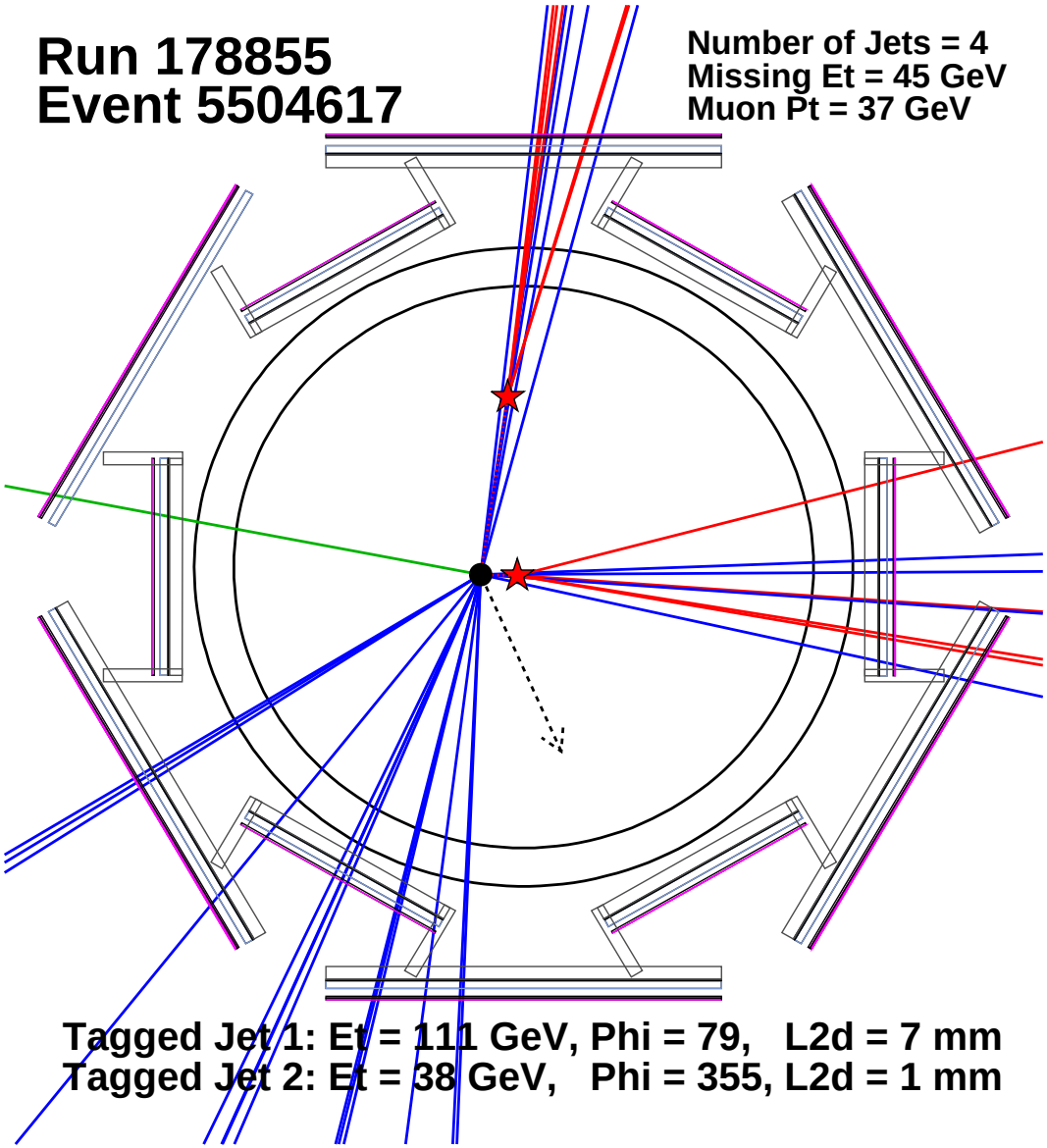
- Great performance!!!
- Tracking system for b-tagging and electron id
- Calorimetry for jet energy scale and electron id
- Muon system for muon id



BACK-UP SLIDES

Detecting the Top Quark

- Top events:
  - are energetic, central and spherical
  - have $\not\!\!E_T$ from neutrinos in leptonic modes
  - have jets with high E_T
  - have two high E_T b-jets
- Main backgrounds:
  - Dilepton: $Z \to l^- l^+$
  - L+jets: $W + jets$ (few % have b or c)
- Identifying b-jets improves S/B
  - Secondary Vertex Tagger
  - Jet Probability Tagger
  - Soft Lepton Tagger



Secondary Vertex Algorithm

- Attempt to construct a secondary vertex using large impact parameter (d_0) tracks with a 2-pass scheme:

- Pass 1:

  1. Construct 2-track ”seed” vertex
  2. Attach other tracks consistent with seed
  3. Iterate, prunning away attach tracks that spoil vertex fit
  4. Candidate vertex require to have $\geq$ 3 tracks

- Pass 2: tighter track d_0 significance requirement

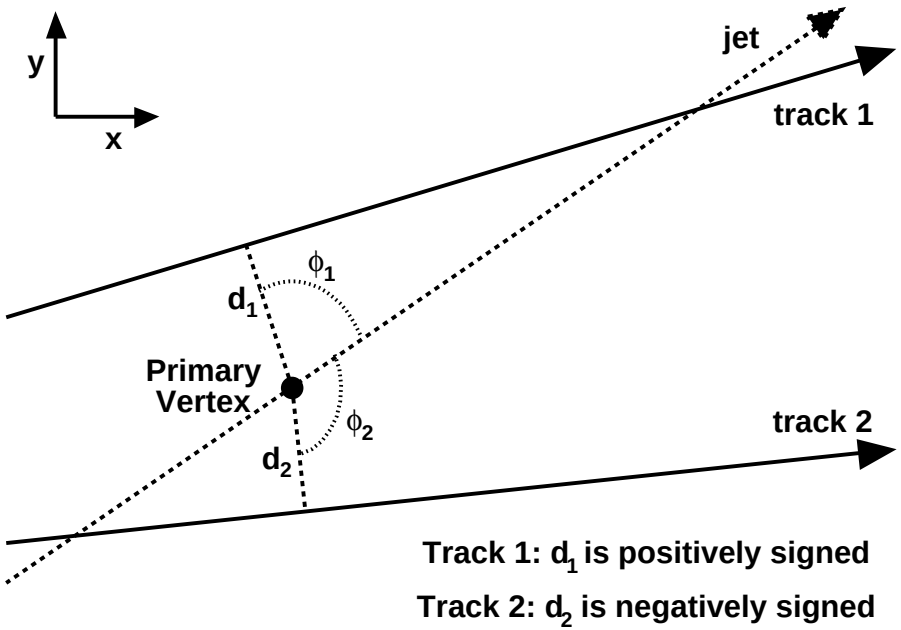
  1. Try to vertex all tracks to a single point
  2. Remove tracks that spoil the fit and revertex
  3. Candidate vertex require to have $\geq$ 2 tracks

- Apply vertex quality cuts

- If vertex survive, the jet is tagged

Jet Probability Algorithm (I)

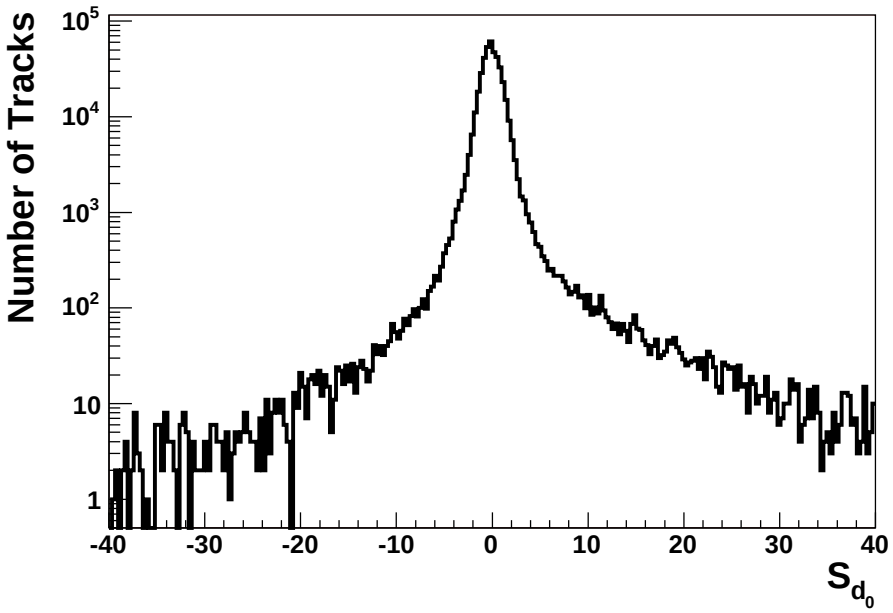
- Signed impact parameter: $d_0 > 0$ if point of closest approach to the primary vertex lies in the same direction as the jet direction (cos $\phi > 0$)



- + (-) Jet Probability: only tracks with positive (negative) impact parameter

  - ◇ + Jet Probability ⇒ positive tags
  - ◇ - Jet Probability ⇒ mistags

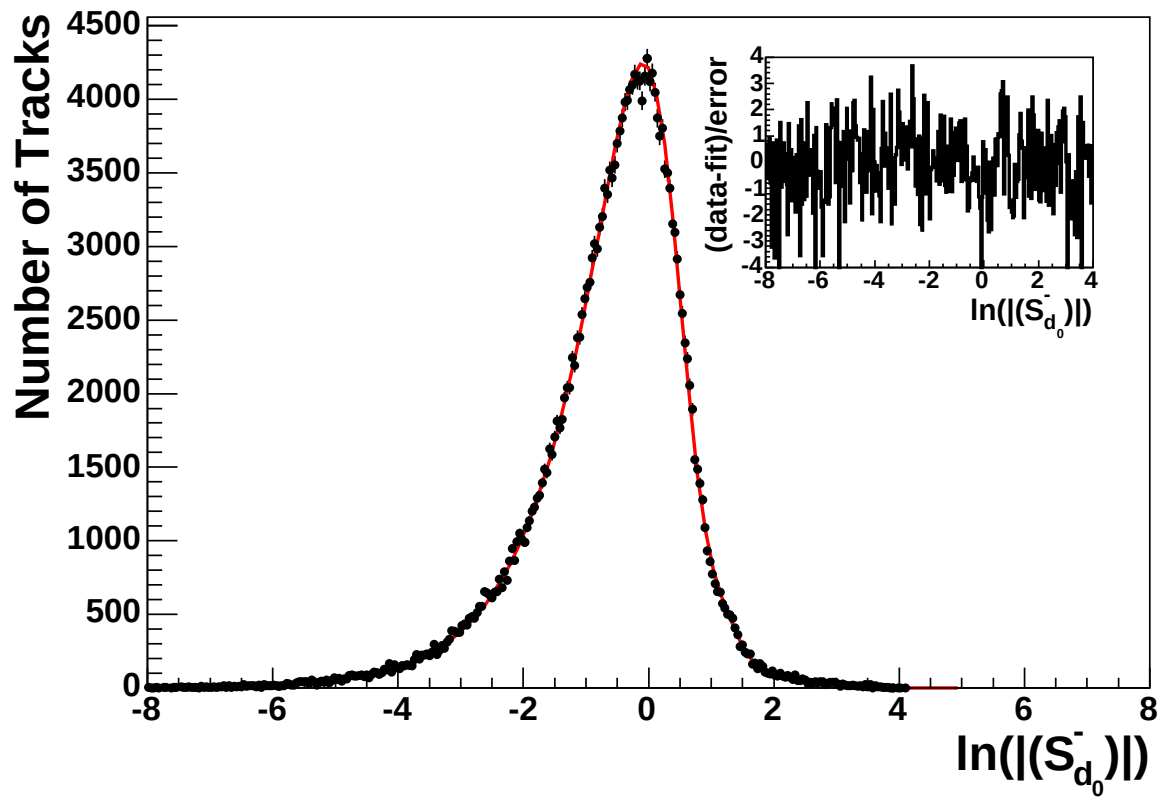
- Track impact parameter significance: $S_{d_0} = d_0/\sigma_{d_0}$



Jet Probability Algorithm (II)

- Fit the negative side of the track impact parameter significance distribution to obtain a resolution function $R(S)$ (different for data and MC)
- $R(S)$ used to determine the probability ($P_{tr}(S_{d_0})$) that the impact parameter significance of a given track is due to the detector resolution
- Probability that a jet is consistent with a zero lifetime hypothesis:

$$\prod_{l=1}^{N_{tr}} P_{tr} \times \sum_{k=0}^{N_{tr}-1} \frac{(-ln \prod_{l=1}^{N_{tr}} P_{tr})^k}{k!}$$



Deduction of the Jet Probability Formula

- If we have a jet with 2 tracks with positive impact parameter which probabilities are P_1 and P_2 and $K \equiv P_1 \cdot P_2$

$$0 \leq P_i \leq 1 \text{ i=1,2} \Longrightarrow 0 \leq K \leq 1$$

- The area below and in the left of the curve of constant probability K is the set of combinations, for the 2 tracks, of having a probability less or equal than K. And this area is defined as Jet Probability, P_J

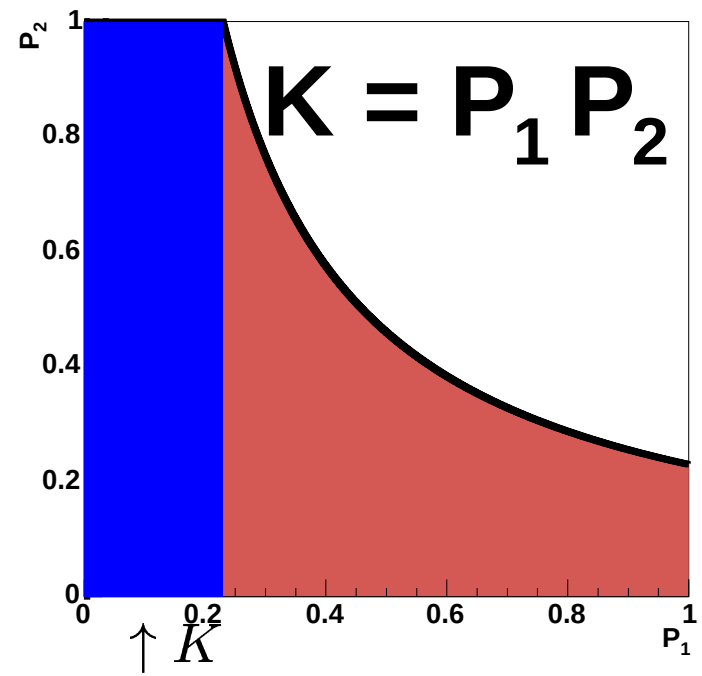
$\diamond$ $P_J = A + B,\ A = K \cdot 1$

$\diamond$ $B = \int_{x=K}^{x=1} f(x)dx = \int_{x=K}^{x=1} \frac{K}{x} dx = -K LnK$

$\Longrightarrow P_J = K(1 - LnK)$

- In general, it can be shown that

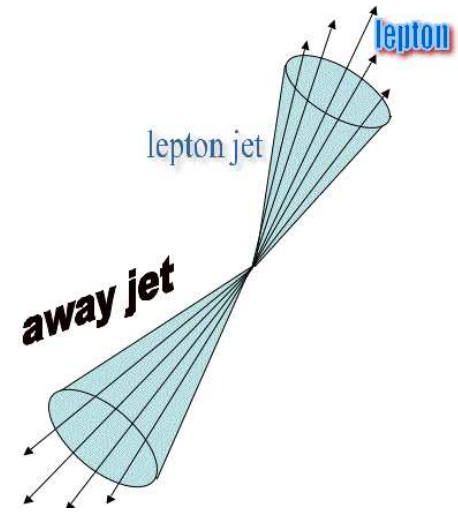
$$P_J = \prod_{l=1}^{N_{tr}} P_{tr} \times \sum_{r=0}^{N_{tr}-1} \frac{(-ln \prod_{l=1}^{N_{tr}} P_{tr})^r}{r!}$$

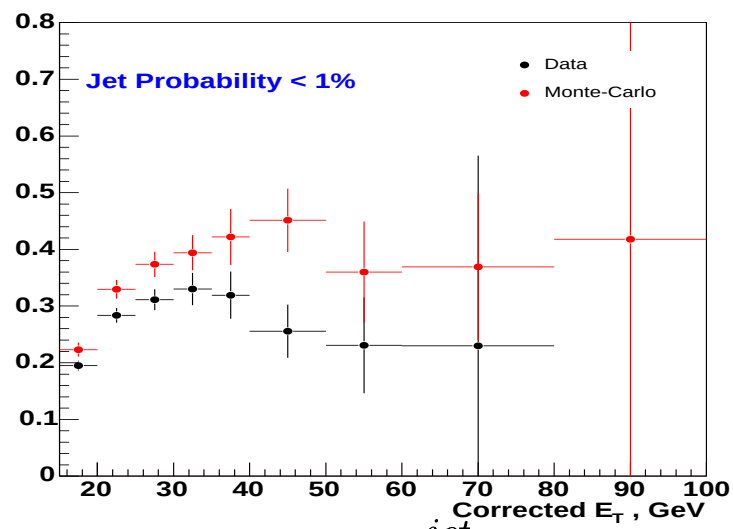


B-Tag Efficiency

- Measured using an 8 GeV inclusive electron data sample (it is enriched with HF due to the semileptonic B decays)
- Double tag method: as heavy flavor quarks are mostly produced in pairs, heavy flavor content in one jet is enhanced requiring that the "other" jet (away jet) is tagged
- Efficiencies to tag a heavy flavor jet with $E_T > 15$ GeV and 318 pb^{-1}

Jet Probability	$P_J < 1\%$	$P_J < 5\%$
ϵ^{data}	0.258 ± 0.018	0.334 ± 0.026
ϵ^{MC}	0.316 ± 0.021	0.392 ± 0.026
Scale Factor (SF)	0.817 ± 0.070	0.852 ± 0.072





Effi ciency vs E_T^{jet} (P_J <1%) in inclusive electron sample

B-Tag Efficiency: Methods

- Measured using an 8 GeV inclusive electron data sample and a generic 2→2 Herwig MonteCarlo sample
- Single tag method: $\epsilon = \frac{N_{ej}^{+} - N_{ej}^{-}}{N_{ej}} \cdot \frac{1}{F_B}$
  - ◇ Disadvantage: relays on the correct determination of the heavy flavor fraction in the sample
- Double tag method: sample of events with two jets

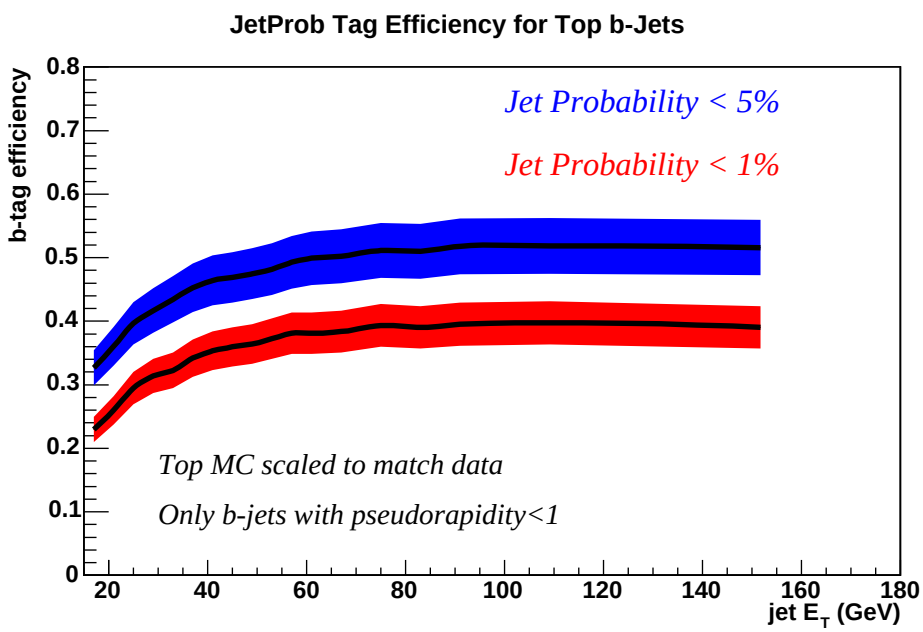
$$\epsilon = \frac{(N_{a+}^{e+} - N_{a+}^{e-}) - (N_{a-}^{e+} - N_{a-}^{e-})}{N_{a+} - N_{a-}} \cdot \frac{1}{F_B^a}$$

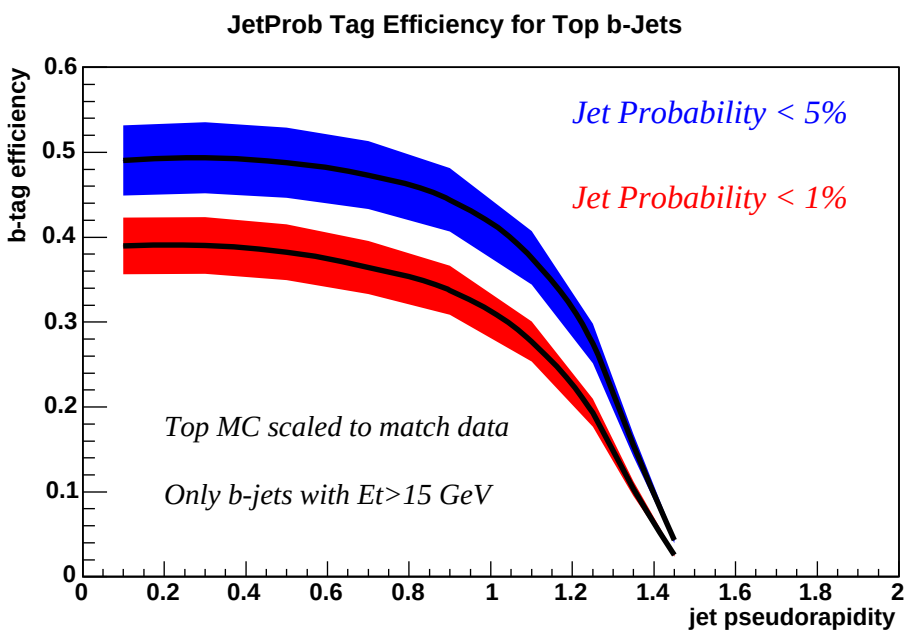
- Calculation of the heavy flavor content in the jet (F_B) has to be corrected for the contribution from charm (determined from MC): $F_B = F_b(1 + \lambda_{c/b})$
  - ◇ F_b from $D^0 \to K\pi$ decays: $F_b = \frac{N_{D^0}}{N_{ej}} \cdot \frac{1}{\epsilon_{D^0}}$
  - ◇ F_b from cascade muons: select b-hadrons with 2 semiletonic decays (b → c → X) emitting a pair e-μ with opposite charge:

$$F_b = \frac{1}{\epsilon_\mu} \frac{N_{ej}^{\mu}(OS) - N_{ej}^{\mu}(SS)}{N_{ej}}$$

Jet Probability Efficiency in $t\bar{t}$ Events

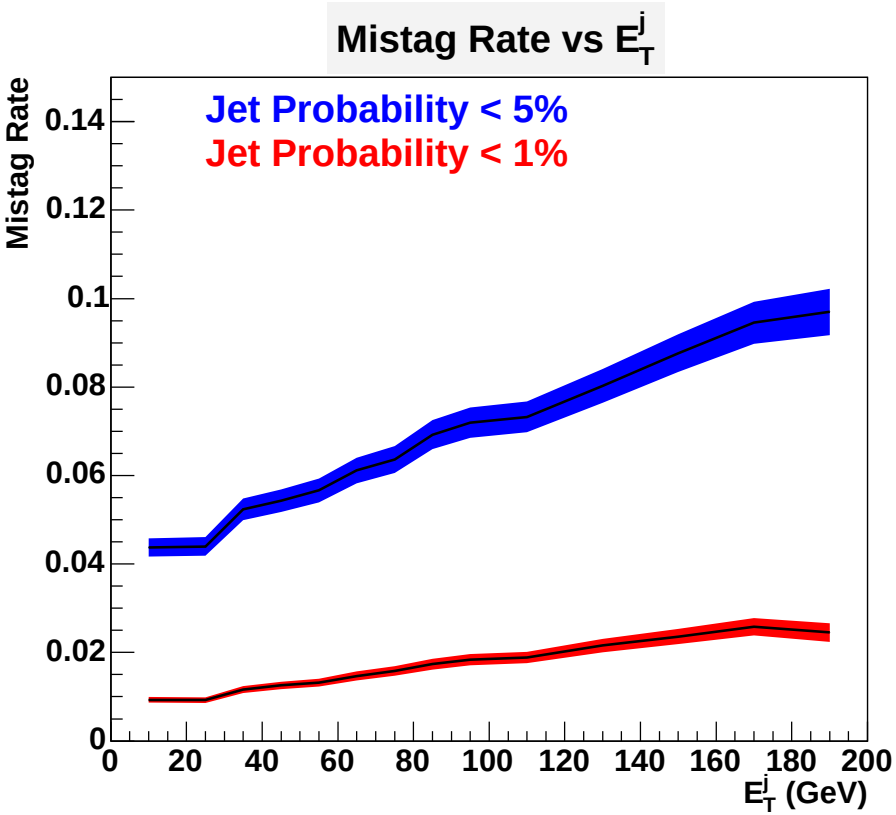
- b-tagging efficiency (tag rate $\times$ SF) per jet in a top Monte Carlo sample. Bands represent the systematic error due to the scale factor.

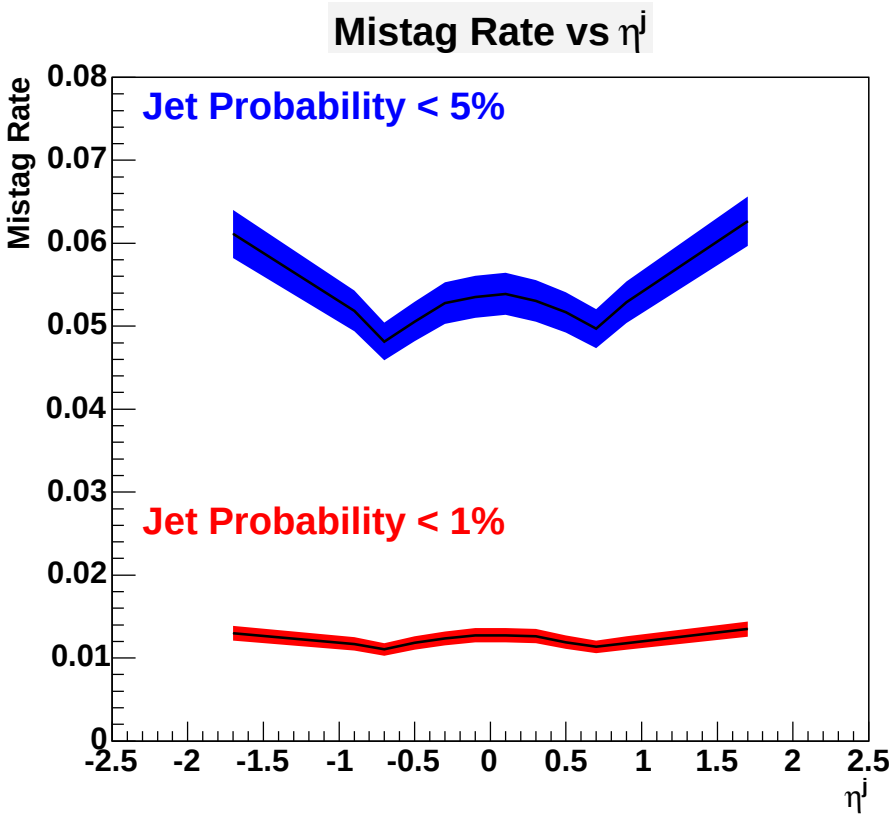




b-tagging efficiency (%)	$P_J < 1\%$	$P_J < 5\%$
per jet	35 ± 3	47 ± 4
per $t\bar{t}$ event	55 ± 4	69 ± 4

Jet Probability Mistag Rate vs E_T and η





- Bands represent the total uncertainty (statistical and systematic added in quadrature).

Scale Factor Dependence with the Jet E_T

- Used two different samples with high energy jets (jet20 and jet50)
- Cannot calculate the SF since we do not know the content of HF
- ... but variations on HF fractions are small for a large range of E_T $\Rightarrow$ we can estimate the E_T dependence of the SF from the E_T dependence of the ratio of positive tag excess between data and MC
- We combined the slope obtained with the 3 samples
- Slope is consistent with a flat dependence $\Rightarrow$ SF is valid at any E_T

Sample	$P_J < 1\%$	$P_J < 5\%$
Inclusive Electron	-0.0082 $\pm$ 0.0037	-0.0081 $\pm$ 0.0044
Jet 20	-0.0008 $\pm$ 0.0019	-0.0028 $\pm$ 0.0024
Jet 50	0.0005 $\pm$ 0.0008	0.0005 $\pm$ 0.0009
Weighted Average	-0.00002 $\pm$ 0.00070	-0.00020 $\pm$ 0.00072

Tag Rate Matrix Definition

Bin	E_T (GeV)	Trk. Mult.	$\sum E_T^{\text{jets}}$ (GeV)	$\lvert\eta\rvert$	$\lvert Z_{\text{vtx}}\rvert$ (cm)	ϕ
1	[0,20)	2	[0,80)	[0,1.0)	[0,10)	$[\frac{-\pi}{12}, \frac{\pi}{12})$
2	[20,35)	3	[80,140)	≥ 1.0	[10,20)	$[\frac{\pi}{12}, \frac{3\pi}{12})$
3	[35,50)	4,5	[140,220)		[20,40)	$[\frac{3\pi}{12}, \frac{5\pi}{12})$
4	[50,65)	6,7	≥ 220		[40,50)	$[\frac{5\pi}{12}, \frac{7\pi}{12})$
5	[65,80)	8,9			[50,60)	$[\frac{7\pi}{12}, \frac{9\pi}{12})$
6	[80,100)	10-13			≥ 60	$[\frac{9\pi}{12}, \frac{11\pi}{12})$
7	[100,120)	≥ 14				$[\frac{11\pi}{12}, \frac{13\pi}{12})$
8	[120,150)					$[\frac{13\pi}{12}, \frac{15\pi}{12})$
9	[150,180)					$[\frac{15\pi}{12}, \frac{17\pi}{12})$
10	≥ 180					$[\frac{17\pi}{12}, \frac{19\pi}{12})$
11						$[\frac{19\pi}{12}, \frac{21\pi}{12})$
12						$[\frac{21\pi}{12}, \frac{23\pi}{12})$

Mistag Asymmetry Correction

- "Raw" mistag rate gives (# of negative tags) / (all pretag jets)
- But the "true" mistag rates is (# of mistags) / (all pretag light jets)
- So, we need to correct for:
  - ♢ # of negative tags is NOT # of positive tagged light jets (mistags)
    $\Rightarrow \alpha = (\#\ of\ mistags)/(\#\ of\ negative\ tags)$
  - ♢ Get ride of HF jets in the denominator of the mistag rate
    $\Rightarrow \beta = (all\ pretag\ jets)/(all\ pretag\ light\ jets)$
- $\Rightarrow$ True = Raw $\times\ \alpha \times\ \beta$

Event Selection

- Two high E_T jets required
- Away jet, used to improve purity
  - ♢ Jet $E_T > 15$ GeV
  - ♢ $|\phi_{away} - \phi_\mu| > 2.0$ rad
  - ♢ $|\eta| < 1.5$
  - ♢ ≥ 2 good loose SecVtx tracks
  - ♢ Loose SecVtx tag
  - ♢ $M_{vtx} > 1.5$
- Muon jet, used in the analysis
  - ♢ μ-jet $E_T > 20$ GeV
  - ♢ μ $p_T > 9$ GeV/c
  - ♢ $|z_{0,\mu}| < 60.0$ cm
  - ♢ $|z_{0,\mu} - z_{0,prim}| < 5.0$ cm
  - ♢ $\text{CMU}_\mu |\delta x| < 3.0$ cm
  - ♢ $\text{CMP}_\mu |\delta x| < 5.0$ cm
  - ♢ $|\eta_\mu| < 0.6$
  - ♢ $\text{I}_{0.4} > 0.1$
  - ♢ μ through all SVX-II