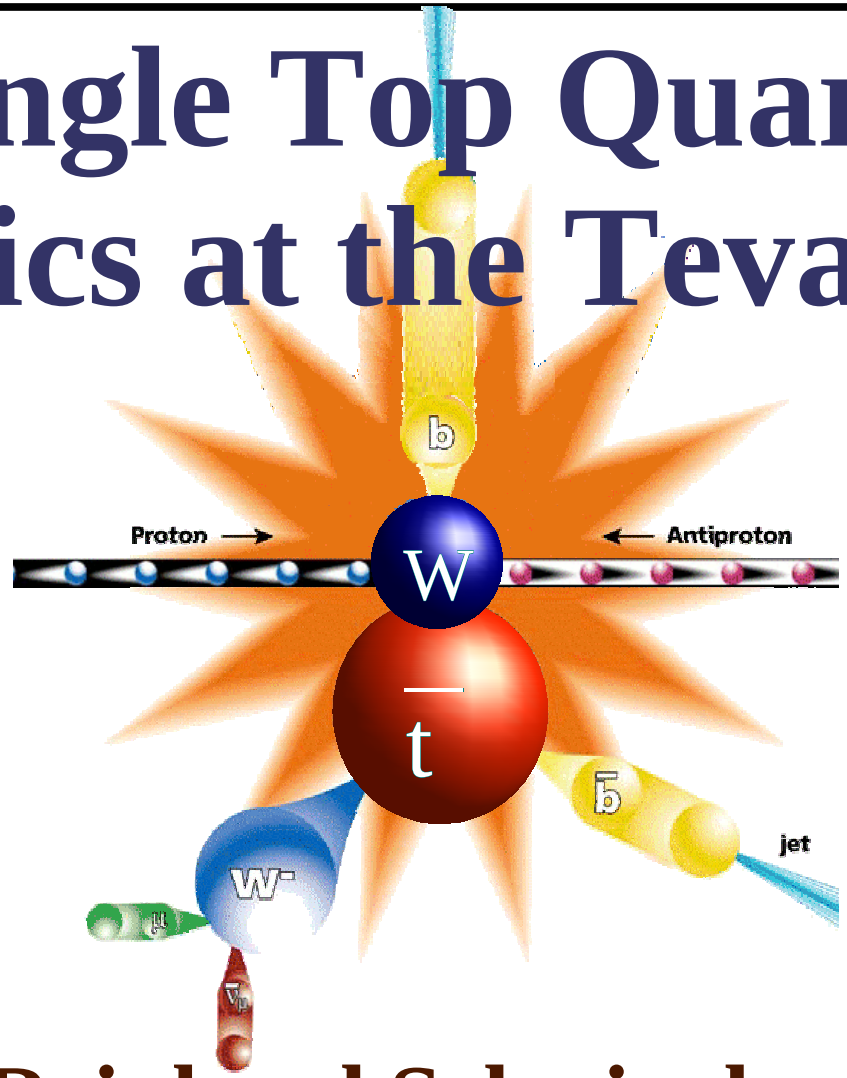
Single Top Quark Physics at the Tevatron



Reinhard Schwienhorst

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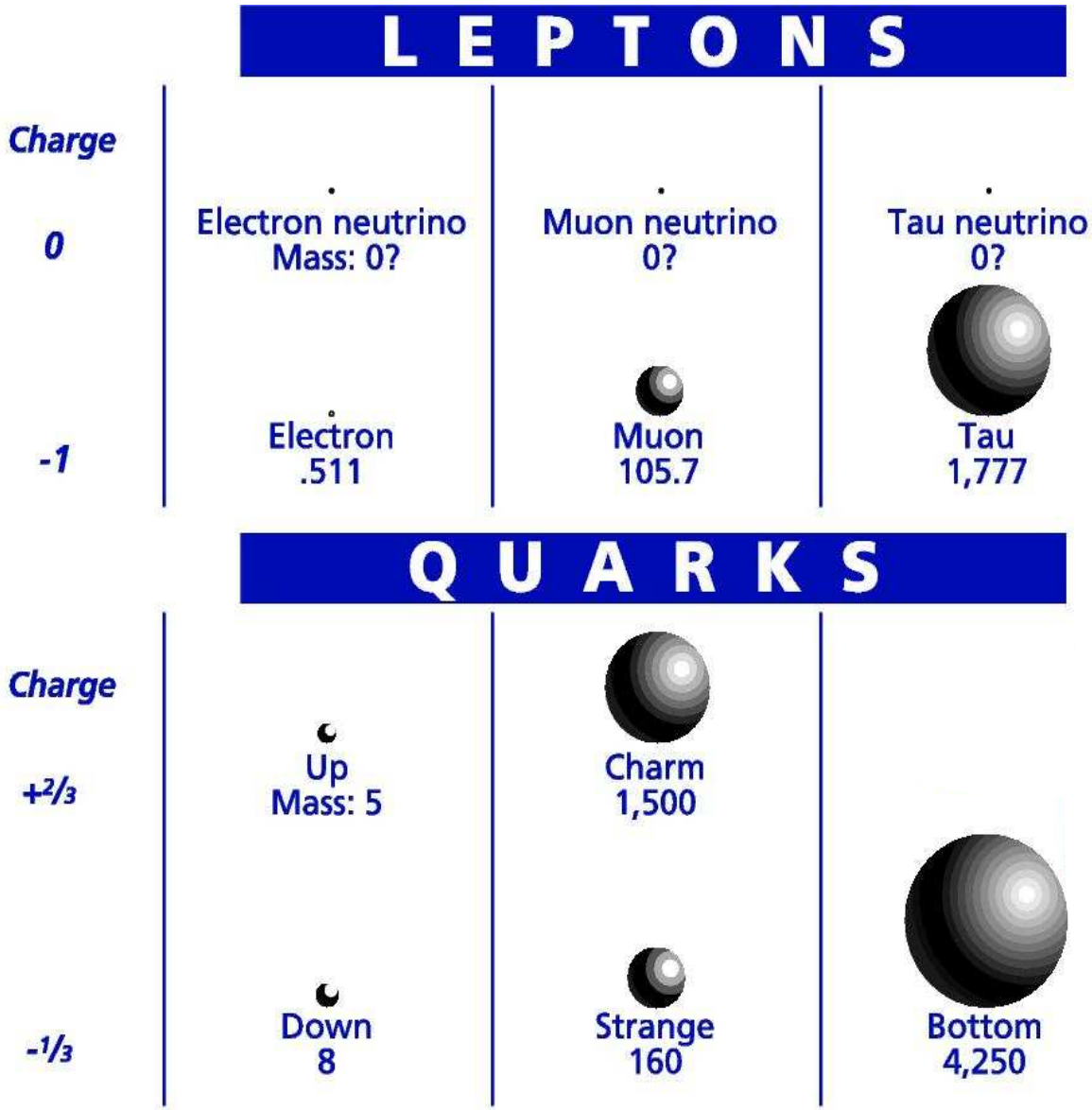
University of Chicago Lunch Seminar, 1/9/2006

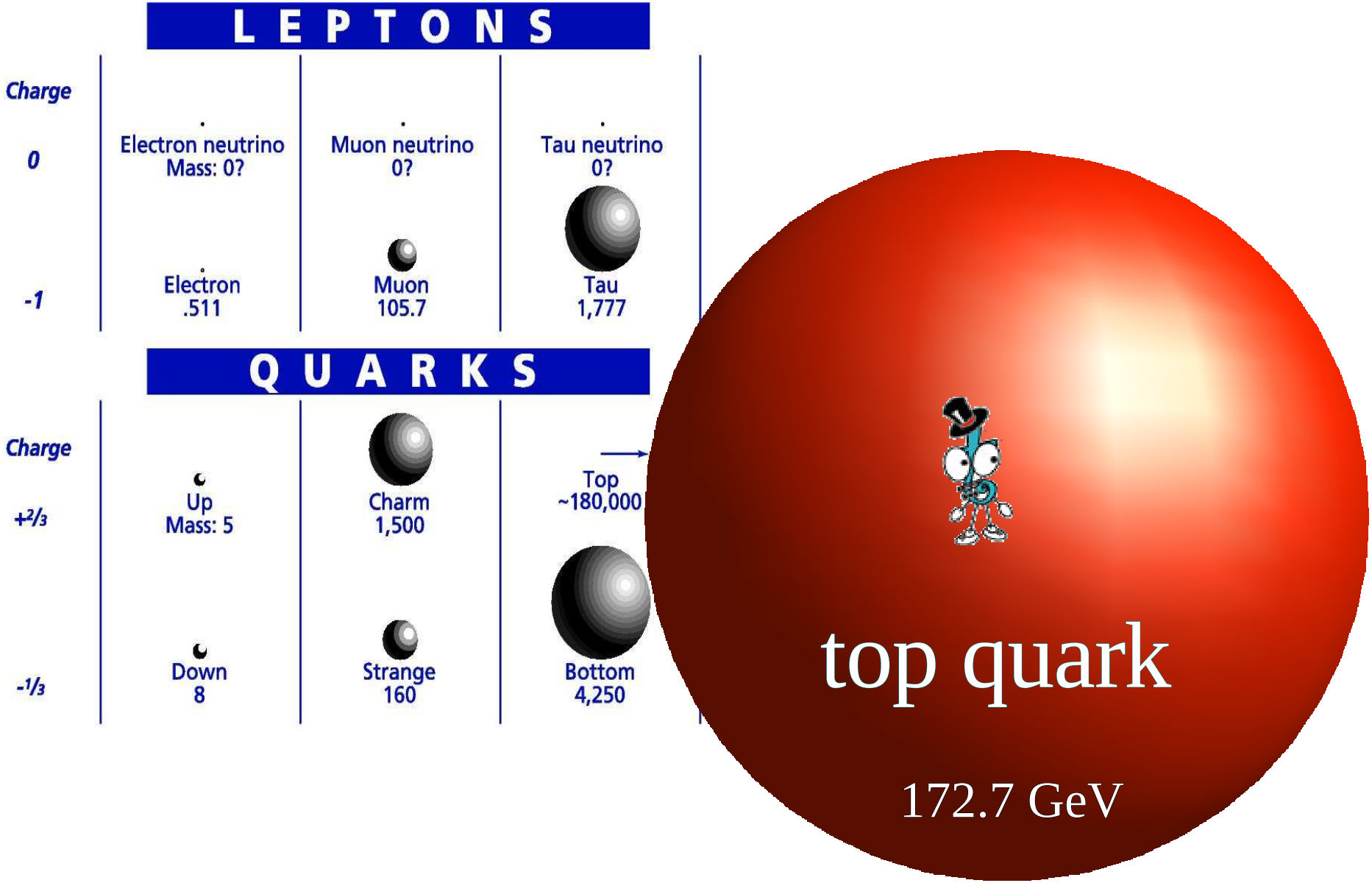
Outline

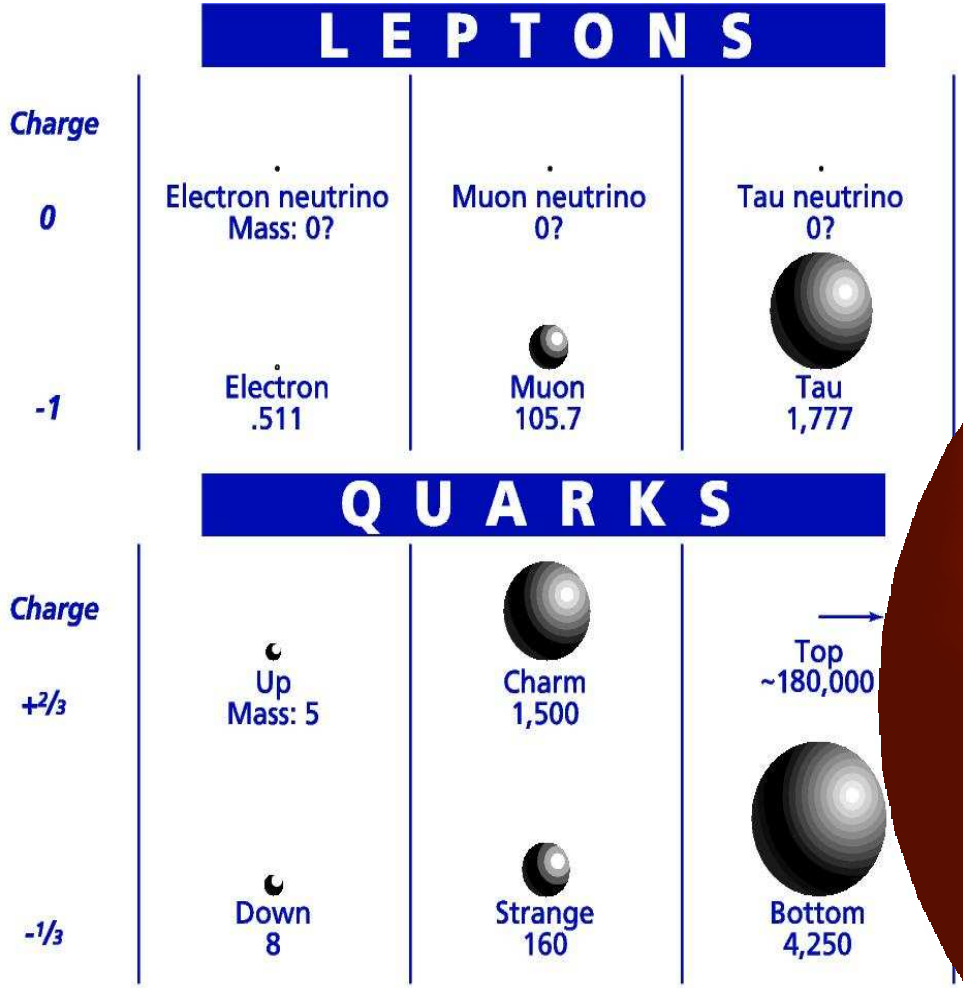
- Introduction
  - Electroweak top quark production
- Search for single top at the Tevatron
  - Detectors
  - Event selection
  - Event analysis
  - Results from CDF and DØ
- Outlook
  - Single top discovery?
  - Future studies of top quark couplings
- Conclusions

Fundamental Fermions

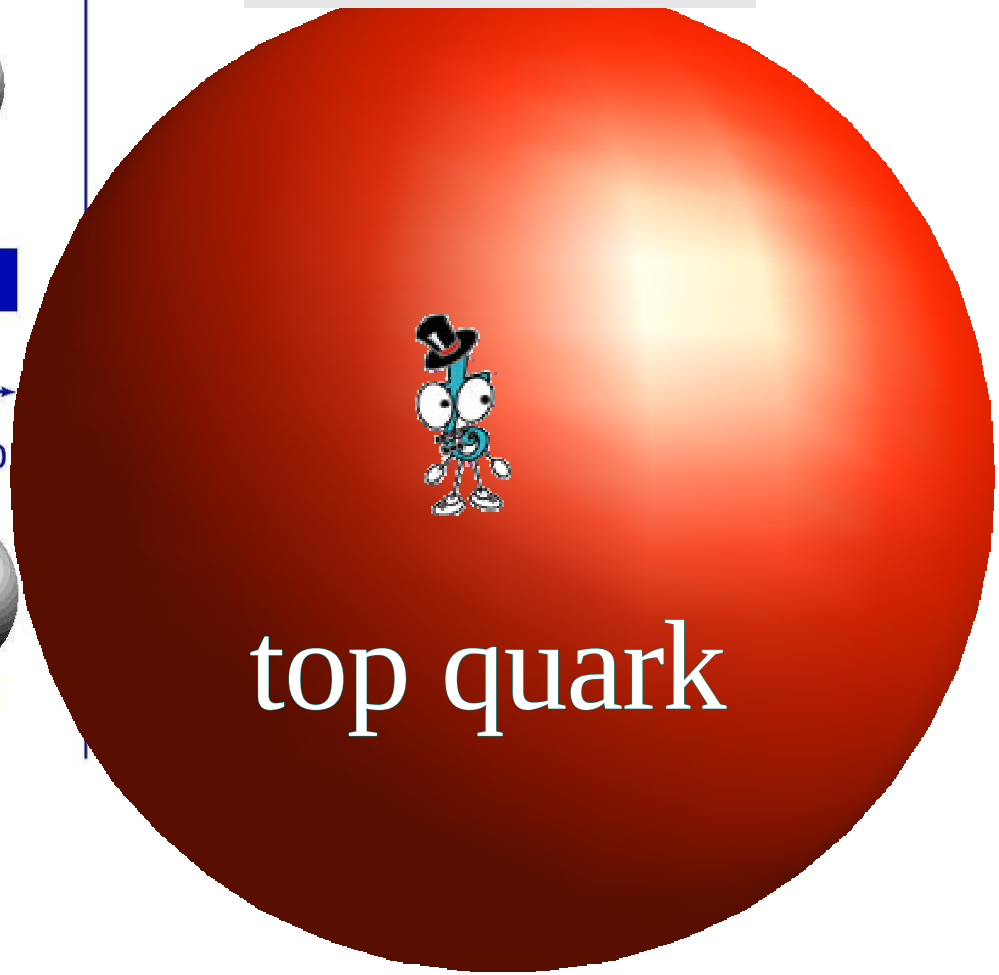


Fundamental Fermions



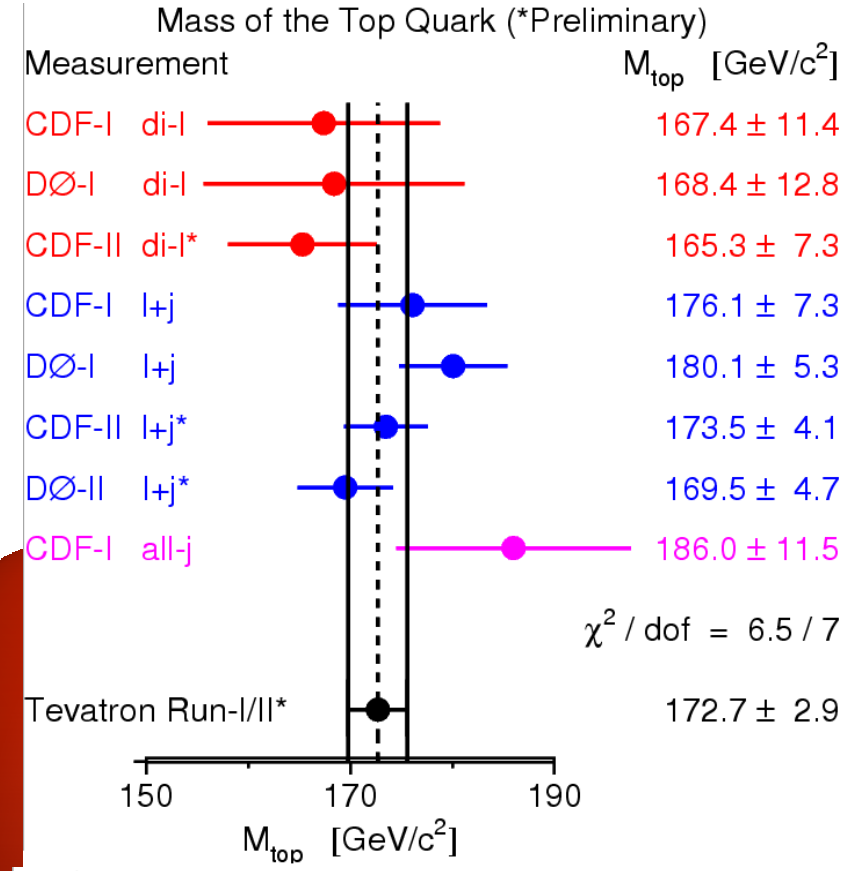


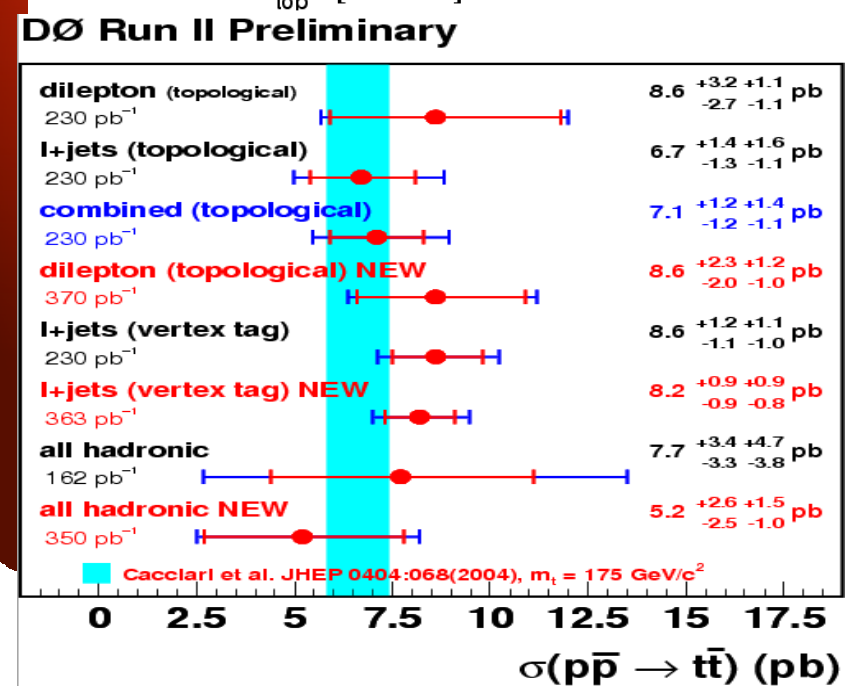
KING OF THE FERMIONS



We known experimentally:

- Top quark mass 172.7 ± 2.9 GeV
  - Yukawa coupling ~1
- SM strong interaction
- Top quark usually decays to *W* boson and *b* quark





We assume but don't actually know:

- Charge, Spin
- Electroweak interactions
  - Charged current
    - Total width
    - CKM matrix
  - Neutral current

Really don't know:

- Coupling to Higgs?
- Modified EW coupling?
- FCNC? Susy? New physics?

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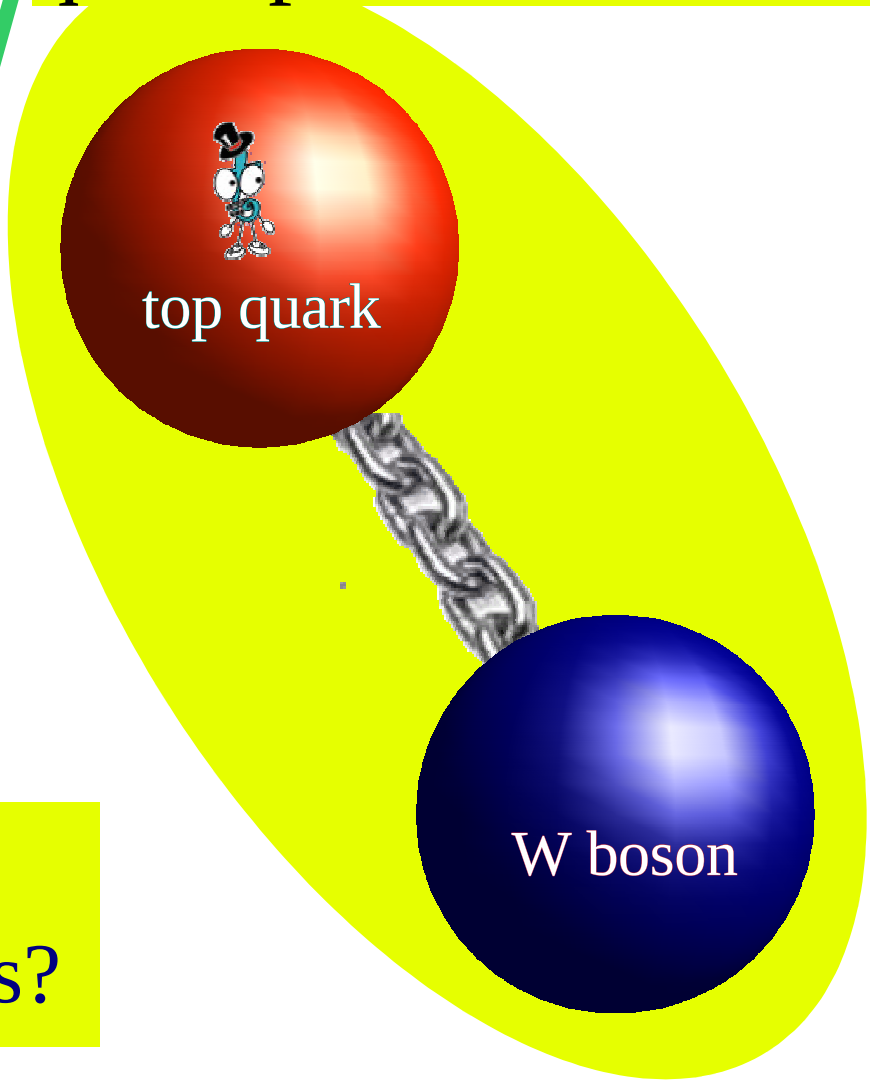
Study in single top quark production



Really don't know:

- Coupling to Higgs?
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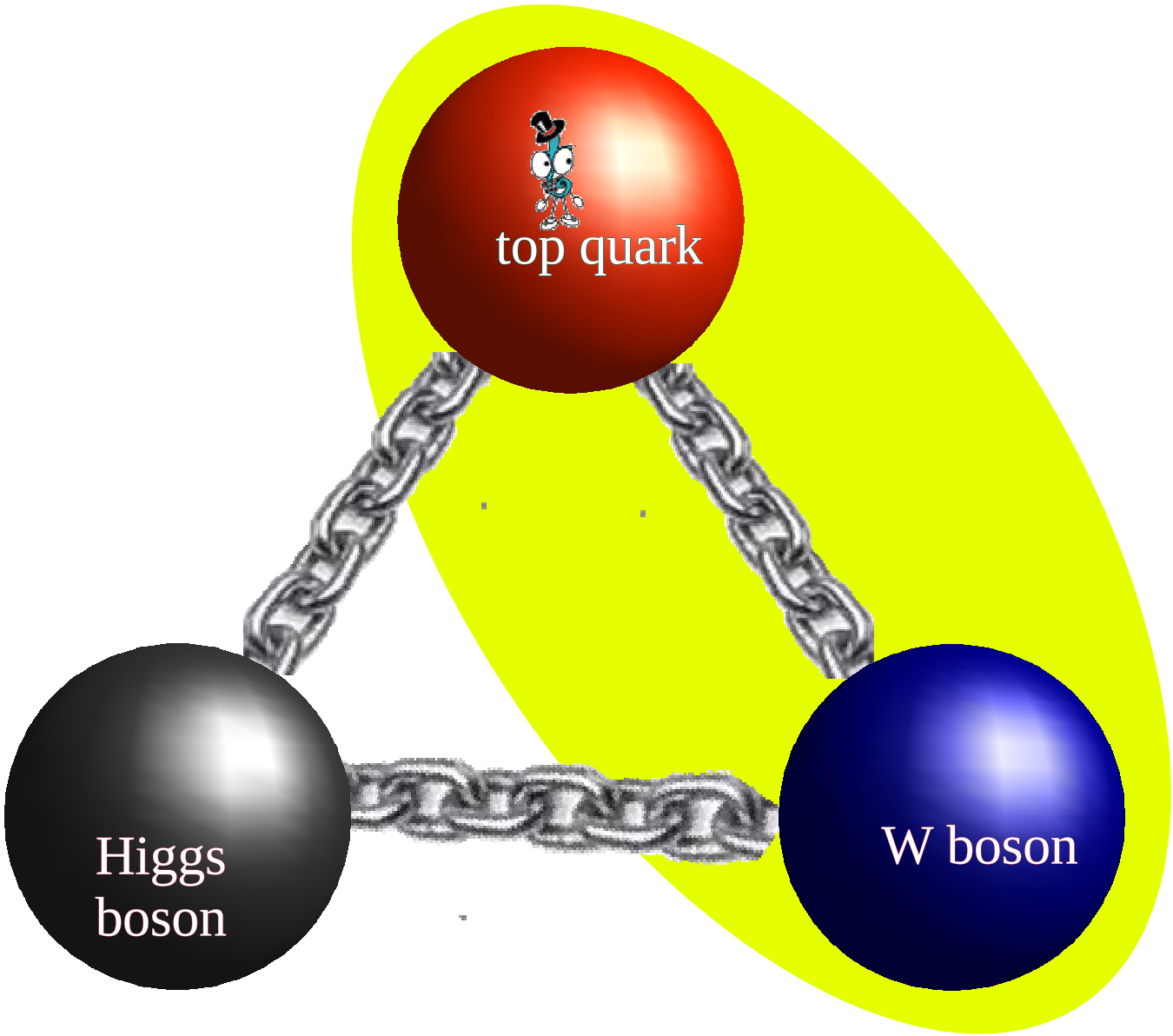
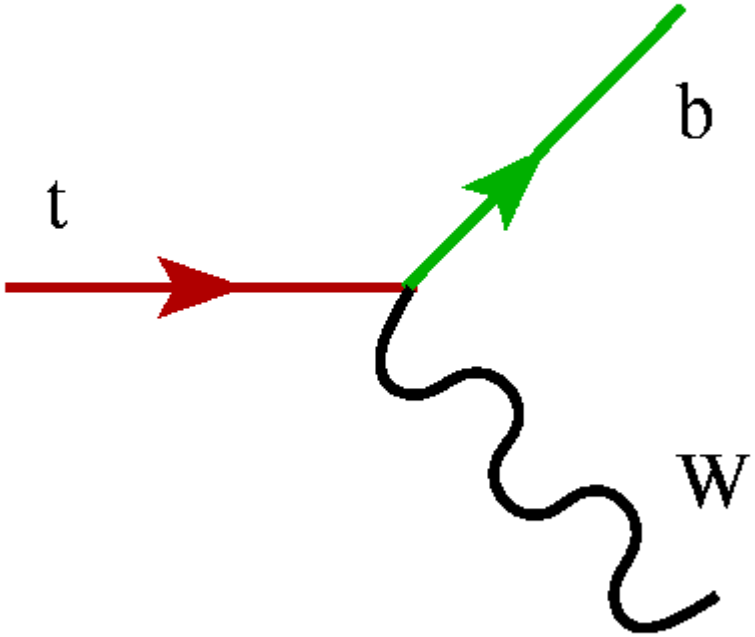
Key to electroweak symmetry breaking



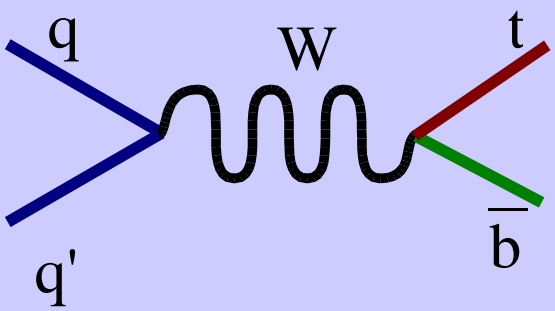
Top Quark Electroweak Charged Current Interaction



top quark decay

SM single top production

s-channel



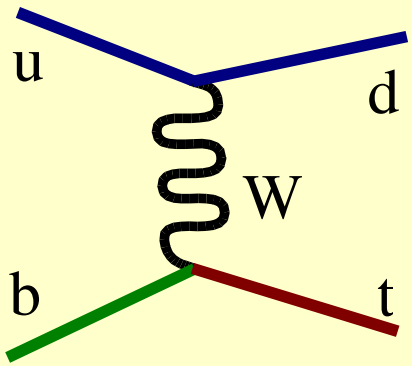
σ_{NLO}

TeV: 0.88 pb (±8%)

LHC, t: 6.6 pb (±10%)

LHC, $\bar{t}$: 4.1 pb (±10%)

t-channel



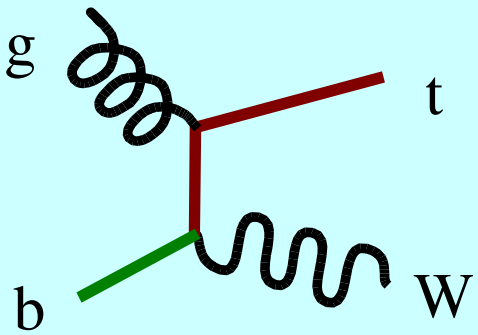
σ_{NLO}

1.98pb (±11%)

156 pb (±5%)

91 pb (±5%)

Associated production



σ_{NLO}

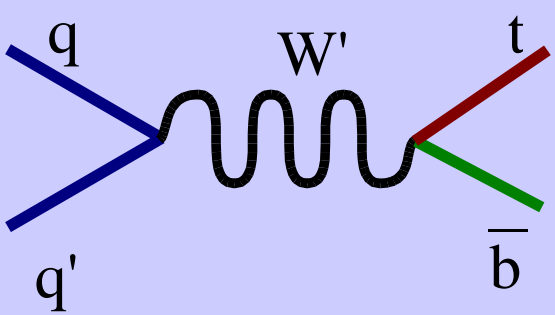
0.14 pb (±15%)

34 pb (±10%)

34 pb (±10%)

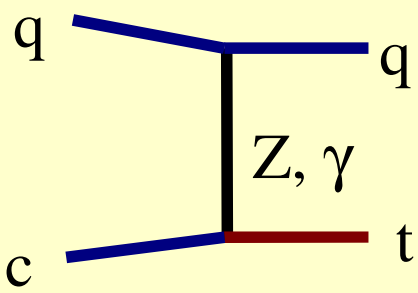
New Physics

s-channel



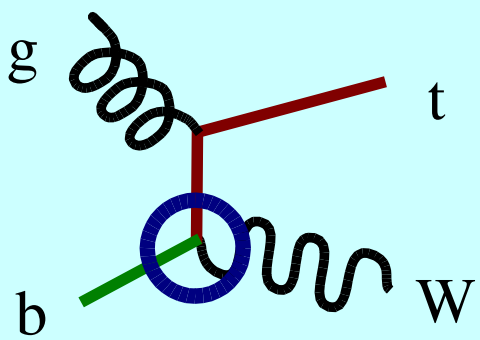
New heavy boson

t-channel



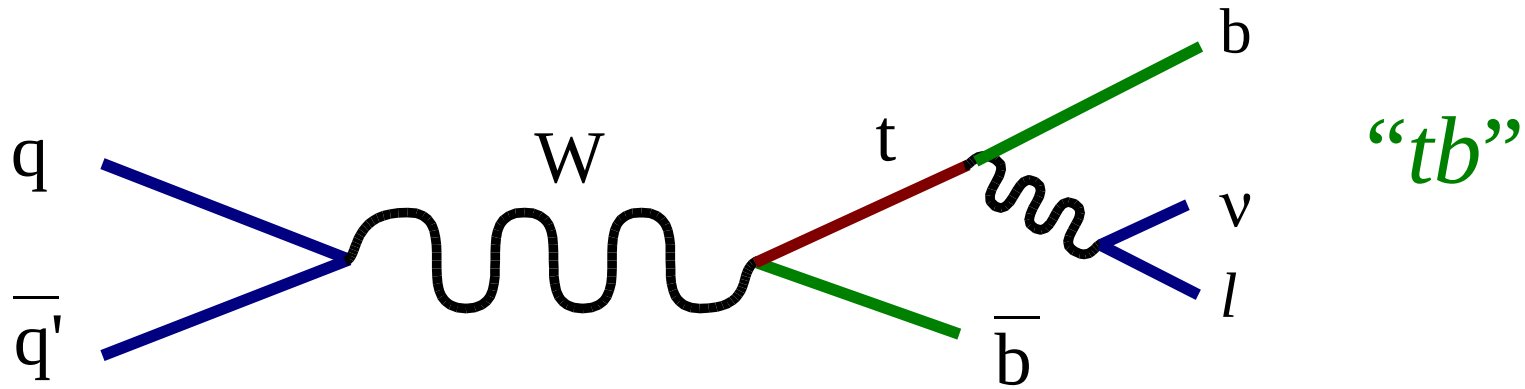
FCNC

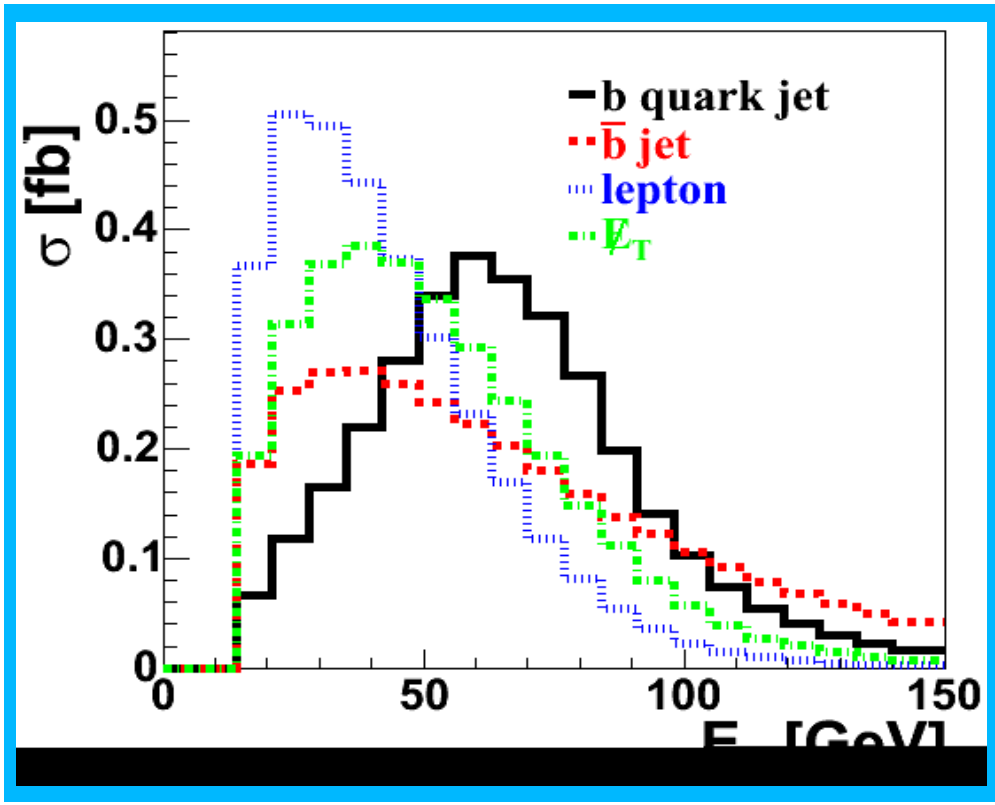
Associated production

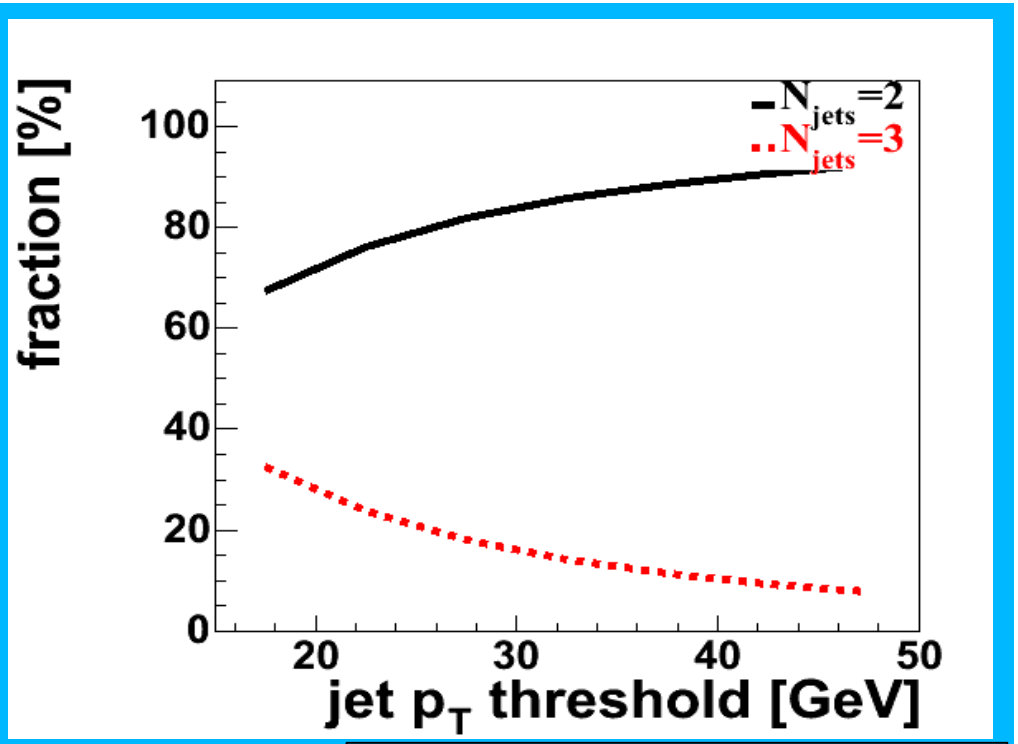


Modified Wtb coupling

Tevatron s-channel Signature

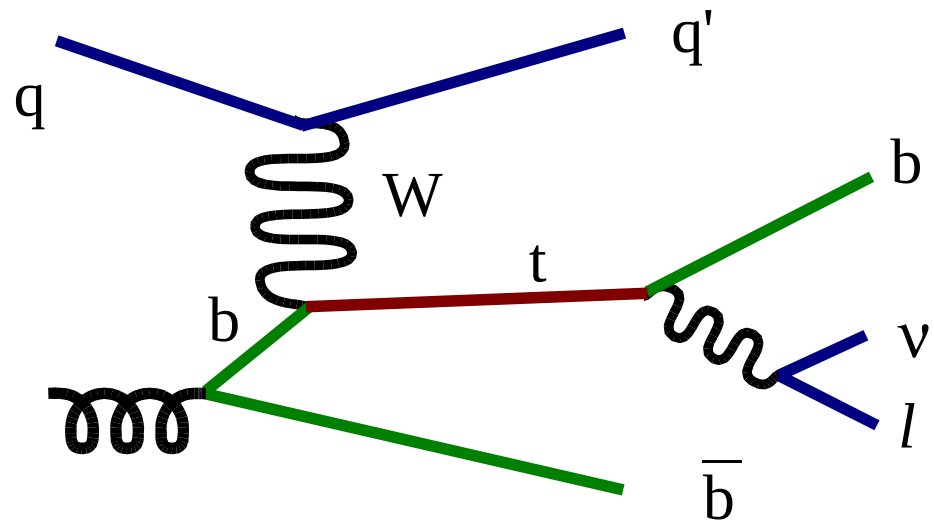




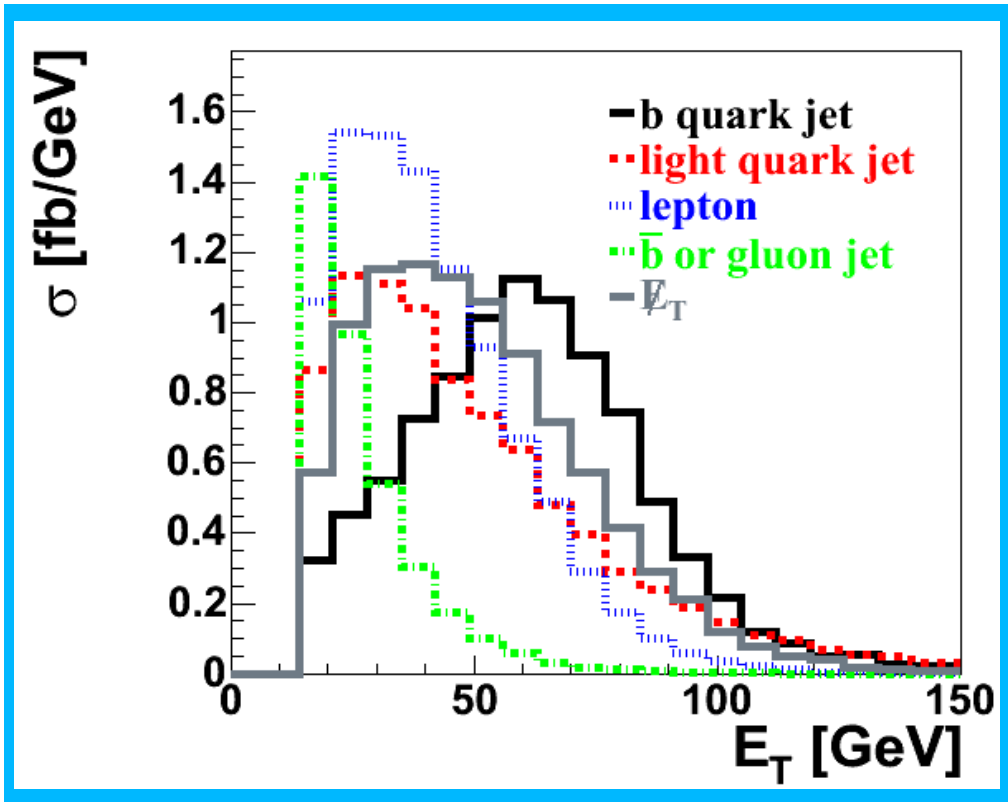


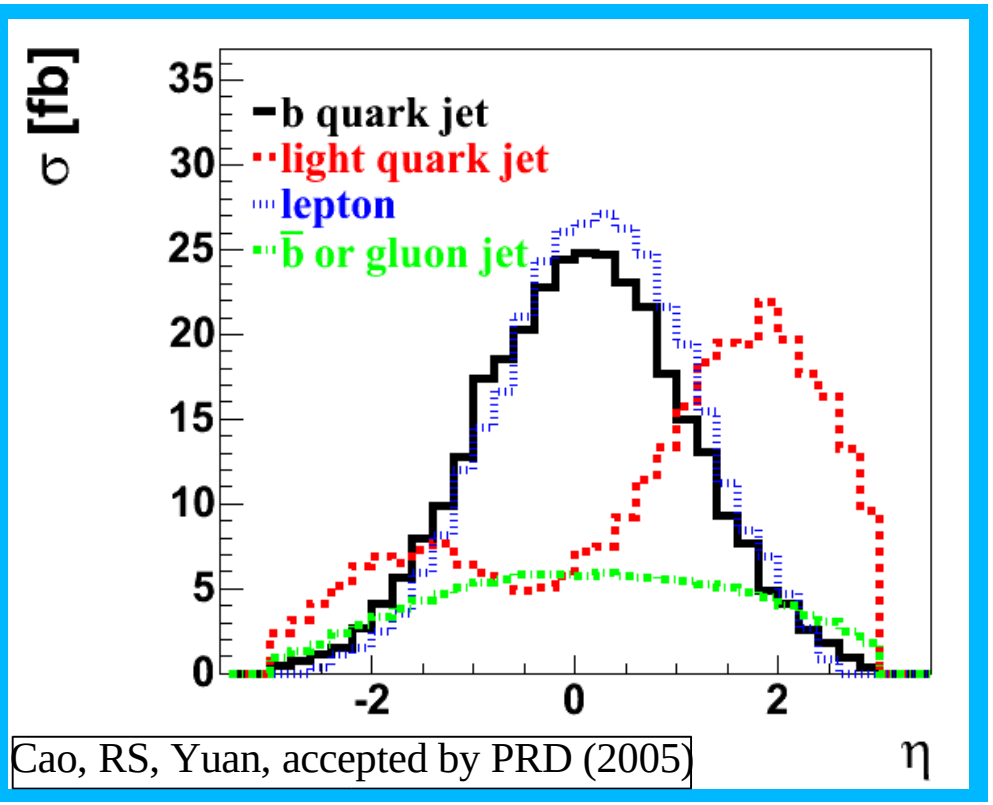
Cao, RS, Yuan PRD74, 054023 (2005)

Tevatron t-channel Signature



"tqb"





Cao, RS, Yuan, accepted by PRD (2005)

Tevatron Single Top Goals

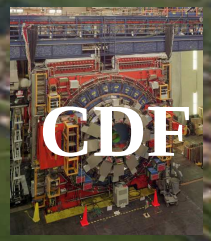
Production cross sections:	*s-channel*	*t-channel*	*s+t*
NLO calculation:	**0.88pb (±8%)**	**1.98pb (±11%)**	
Run I 95% CL limits, DØ:	< 17pb	< 22pb	
CDF:	< 18pb	< 13pb	< 14pb

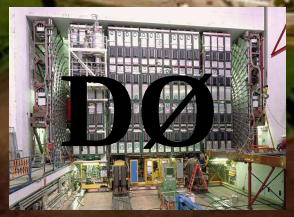
- Observe single top quark production
  - Tevatron discovery!
- Measure production cross sections $\rightarrow V_{tb}$
- Look for physics beyond the Standard Model
  - Coupled to the heavy top quark
- Study top quark spin correlations
- Understand as background
  - In searches for associated Higgs production

Experimental Detection of Single Top Events

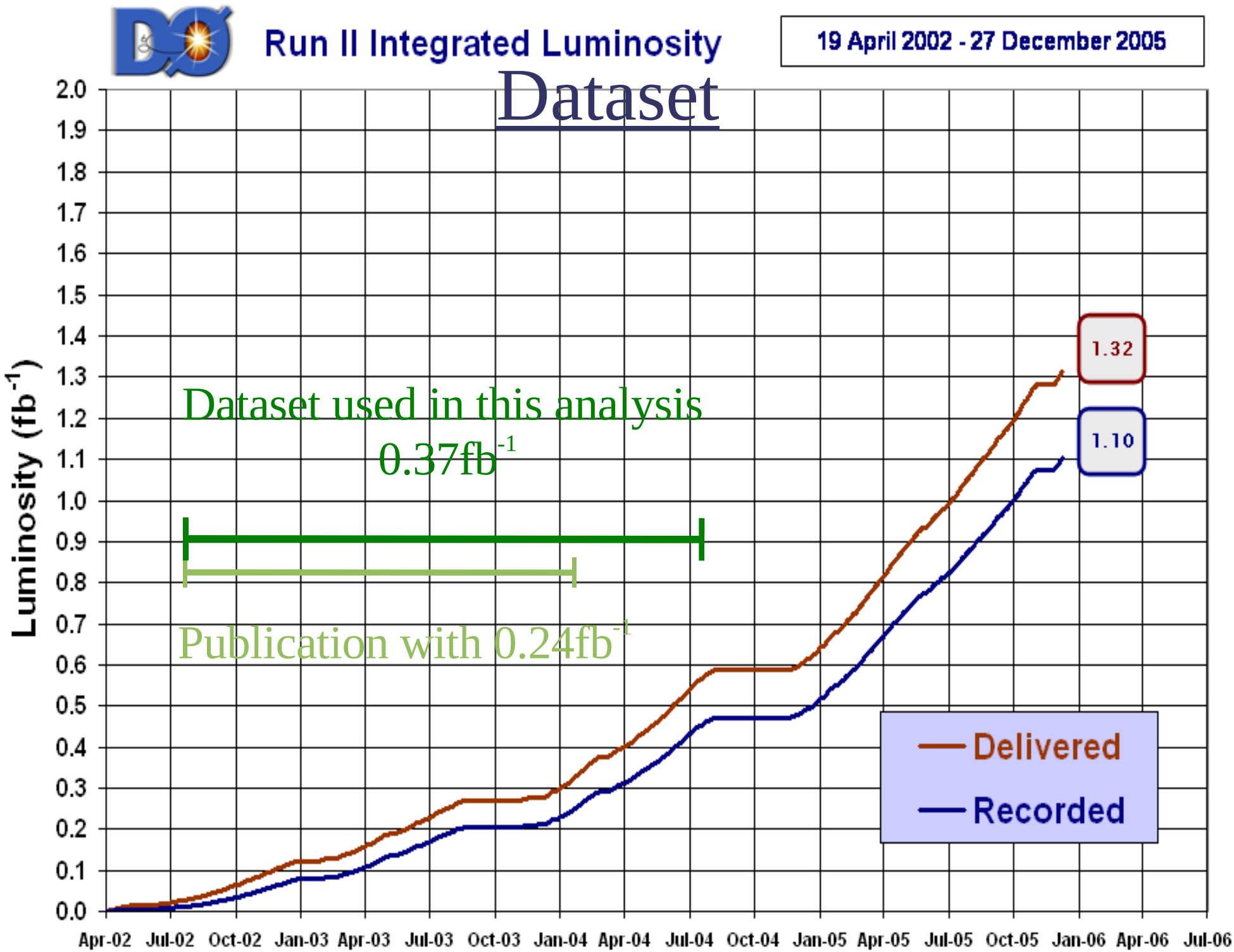
Experimental Setup: Fermilab Tevatron in Run II

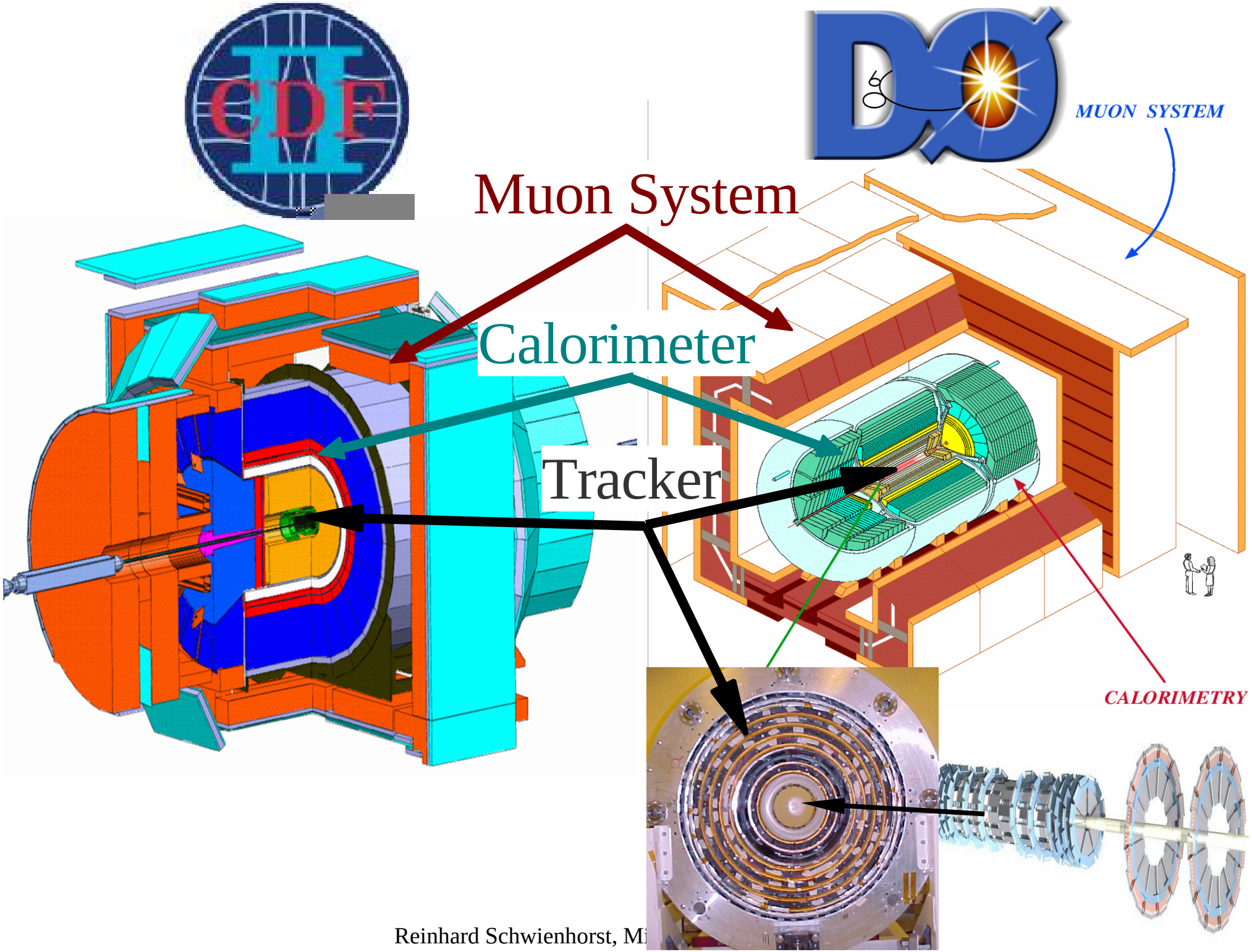
Proton-Antiproton Collider
CM Energy 1.96TeV
→ ***Energy Frontier***
Instantaneous luminosity
>160E30
→ ***Interaction Rate Frontier***





Dataset

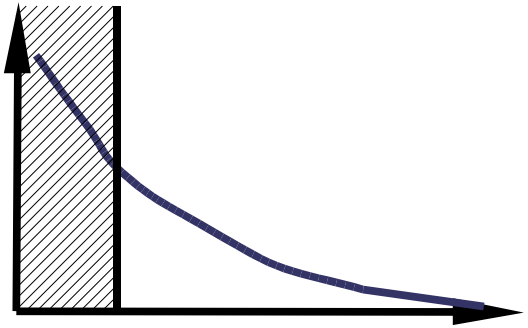

Run II Integrated Luminosity
19 April 2002 - 27 December 2005
Luminosity (fb^{-1})
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Apr-02
Jul-02
Oct-02
Jan-03
Apr-03
Jul-03
Oct-03
Jan-04
Apr-04
Jul-04
Oct-04
Jan-05
Apr-05
Jul-05
Oct-05
Jan-06
Apr-06
Jul-06
1.32
1.10
Dataset used in this analysis
0.37fb^{-1}
Publication with 0.24fb^{-1}
Delivered
Recorded

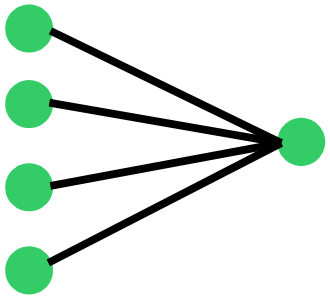

Muon System
Calorimeter
Tracker
MUON SYSTEM
CALORIMETRY

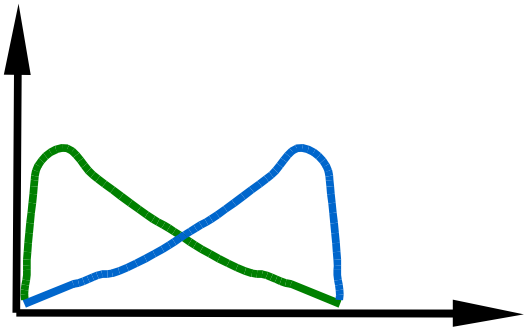
Analysis Outline

Goal:

Maximize Sensitivity



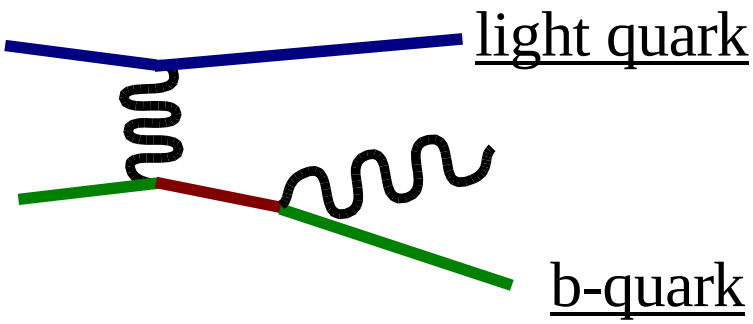


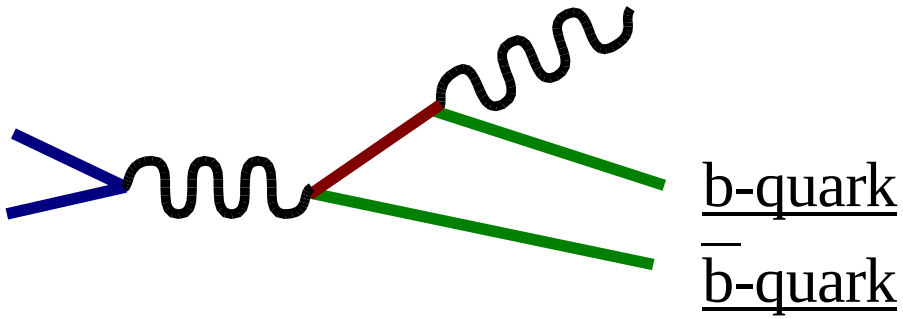


1. Event Selection
   - Select *W*-like events
   - Maximize acceptance
   - Model backgrounds
2. Event Analysis
   - Find discriminating variables
   - Cut/combine in multivariate analysis
3. Determine cross section
   - Event counting or binned likelihood
   - Separately for s-channel, t-channel, and combined

Event Selection

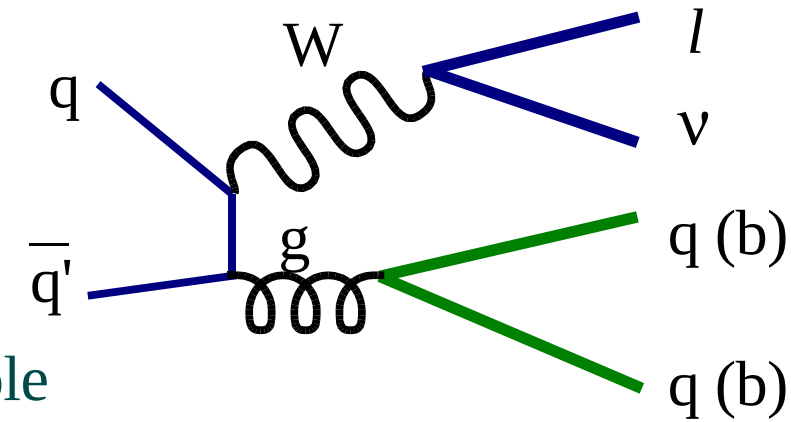
- Trigger:
  - Electron + ≥1 jets, muon + ≥1 jets
- Lepton:
  - 1 electron: $p_T > 15\text{GeV}$, $|\eta^{det}|<1.1$
  - 1 muon: $p_T > 15\text{GeV}$, $|\eta^{det}|<2.0$
- Neutrino: $\not{E}_T > 15\text{GeV}$
- Jets:
  - $p_T > 15\text{GeV}$, $|\eta^{det}|<3.4$, p_T (jet 1)> 25GeV
    $|\eta^{det}(\text{jet1})|<2.5$
  - $2 \leq n_{jets} \leq 4$
  - ≥ 1 b-tagged jet
- Reject mis-reconstructed events



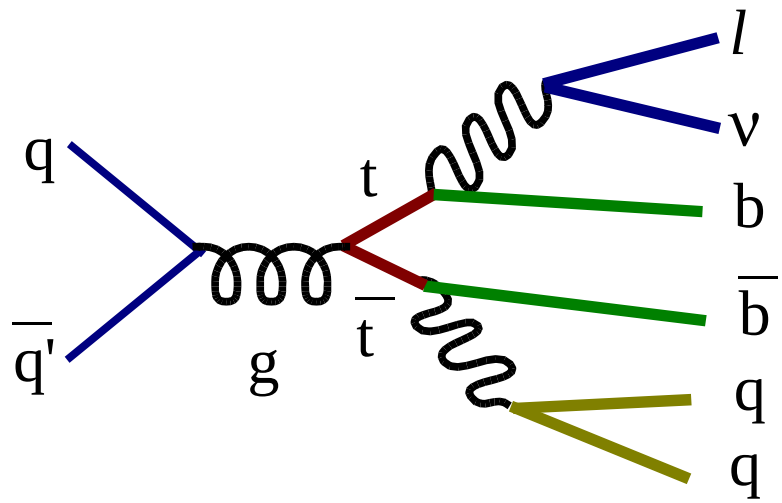


Background Modeling

- Based on data as much as possible
- W/Z+jets production
  - Estimated from MC/data
    - Distributions from MC
    - Normalization from pre-tagged sample
    - Flavor fractions from NLO

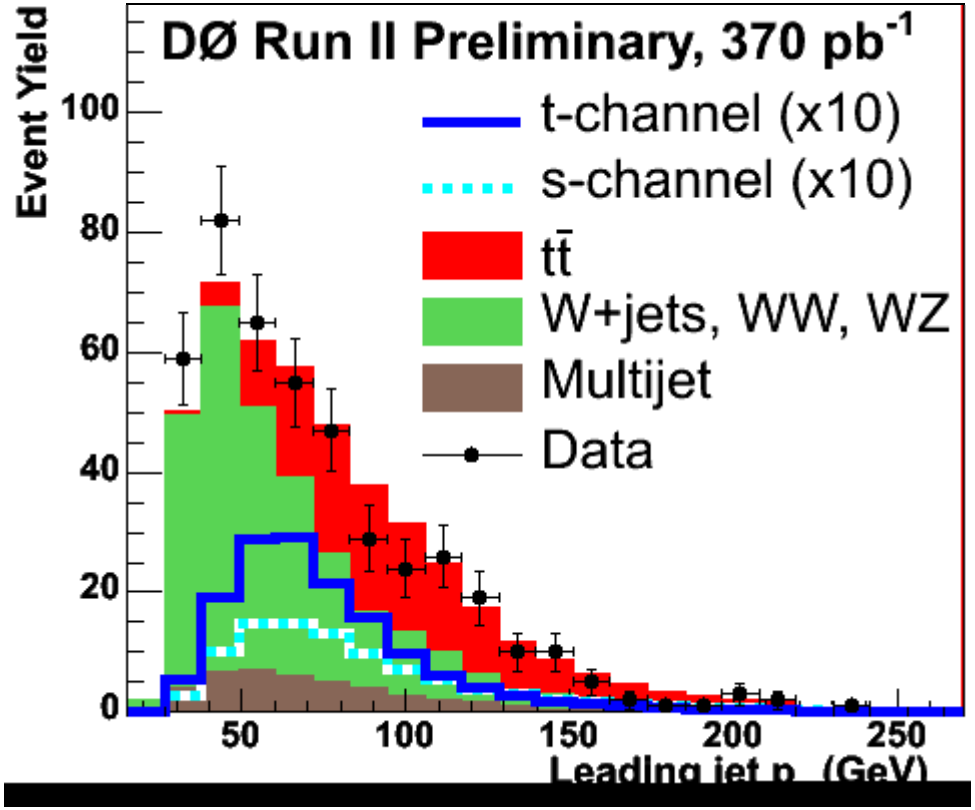


- Multijet events (misidentified lepton)
  - Estimated from data
- Top pair production
  - Estimated from MC
- Diboson (WZ, WW)
  - Estimated from MC

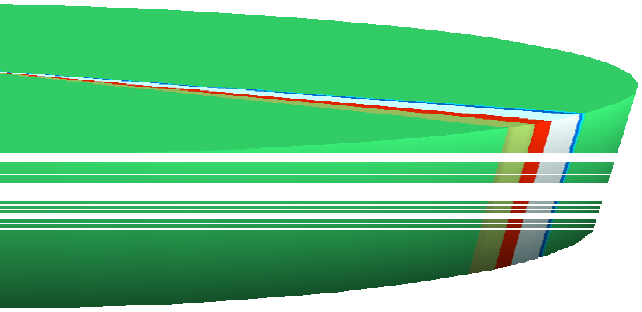


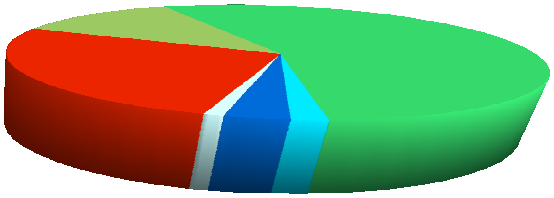
Event Yield in 370 pb^{-1}

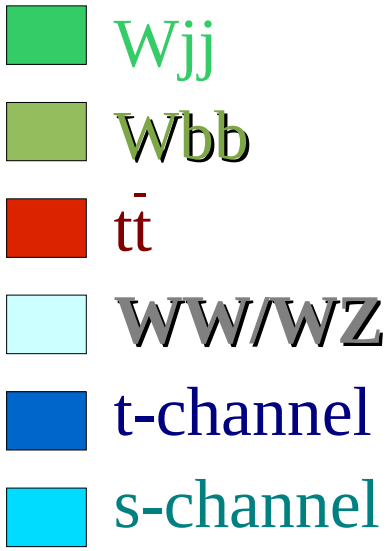
	s-channel	t-channel
Cut acceptance	23%	22%
b-tag efficiency	54%	38%
Signal yield	9.5	15.0
Bkgnd yield	452	
Data	443	
Signal/bkgnd	1:50	1:30



Pre-tagged	=1 b-tag	=2 b-tags
10,000 events	367 events	76 events



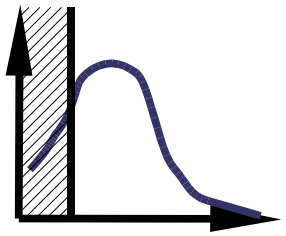




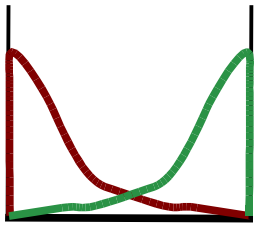
Event Analysis

- Advanced analysis techniques

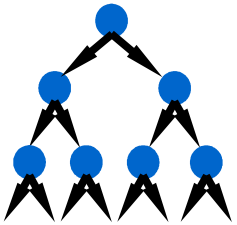
Cut-Based



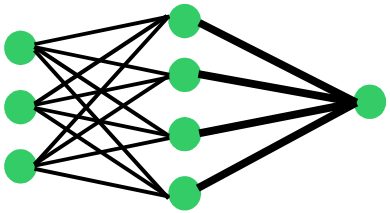
Likelihoods



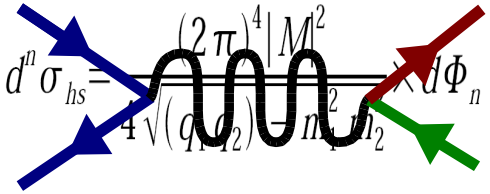
Decision Trees



Neural Networks



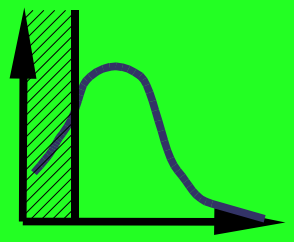
Matrix Elements



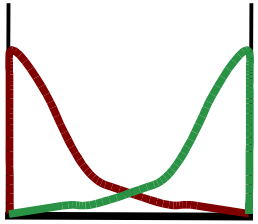
Event Analysis

- Advanced analysis techniques

Cut-Based



Likelihoods



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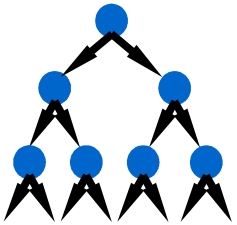

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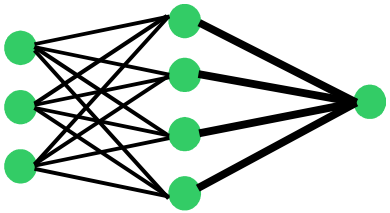

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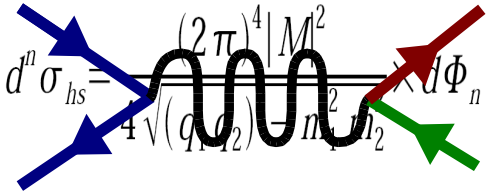
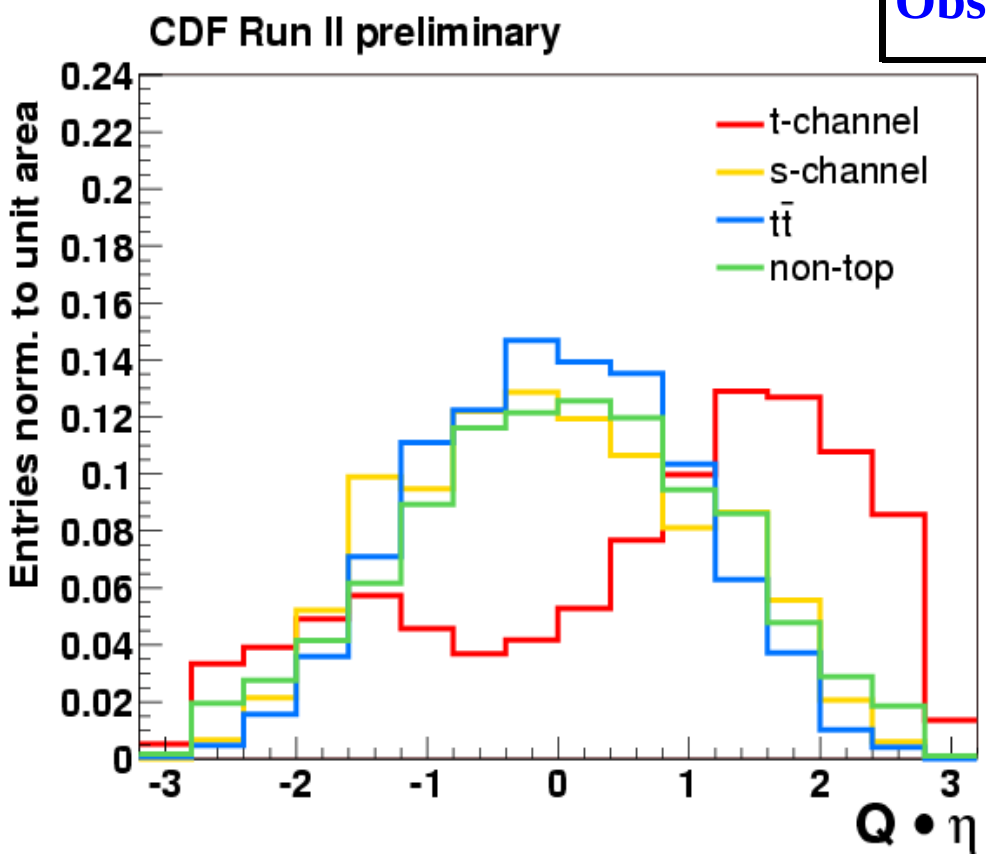


Cut-based analysis

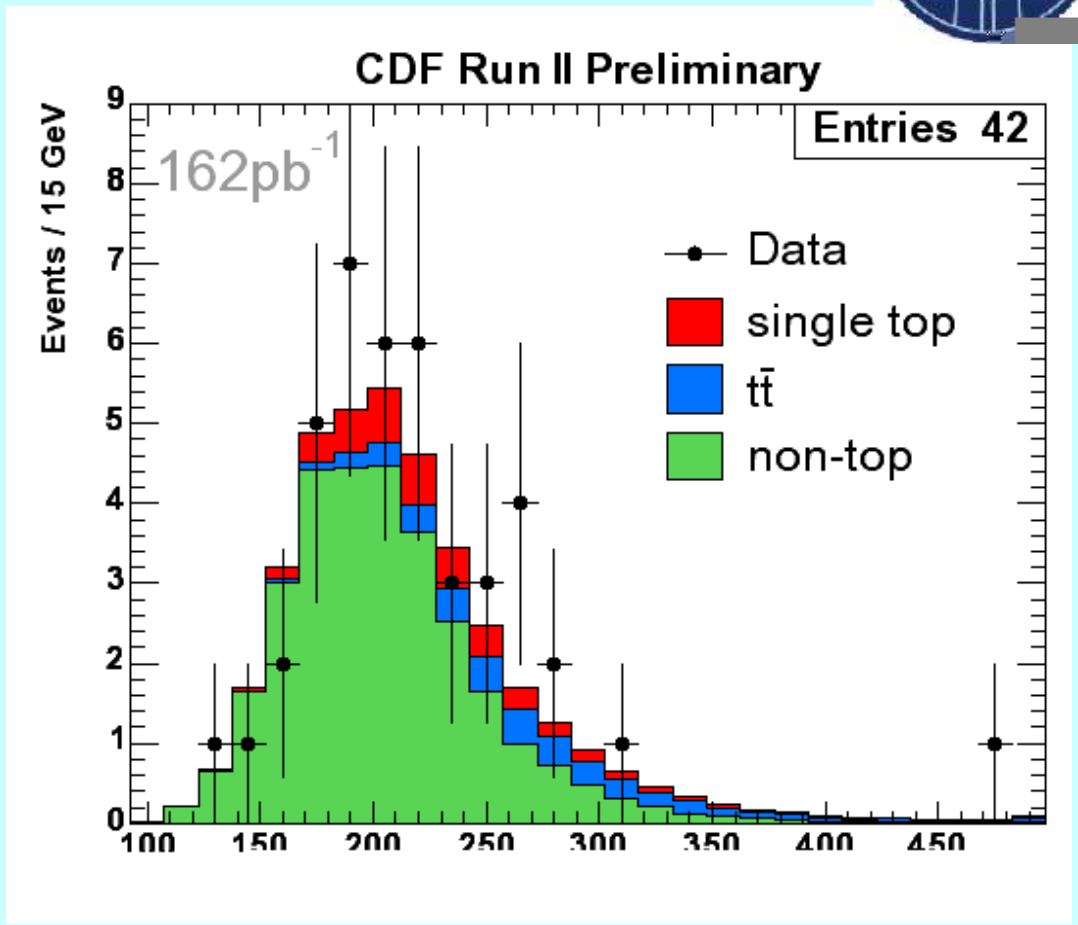
- Tight event selection
  - Exactly 2 jets
  - Include electrons and muons
  - Separate by b-tag: =1 tag and =2 tags
  - Cut on reconstructed top quark mass $140\ \text{GeV} \leq M_{l\nu b} \leq 210\ \text{GeV}$

	Events
Background sum	33.8 ± 5.9
t-channel	2.8 ± 0.5
s-channel	1.5 ± 0.2
Sum Single-Top	4.3 ± 0.5
Observed	**42**



Result

- Statistical analysis:
  - Likelihood fit
  - t-channel:
    - $Q \times \eta$ (untagged jet)
  - s-channel or s+t:
    - H_T (transverse event energy)



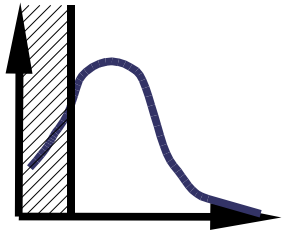
- Cross section limits:

	s-channel	*t-channel*	*s+t*
– CDF 95% CL limits: Phys.Rev.D71:012005 (2005)	< 14 pb	< 10 pb	< 17.8 pb

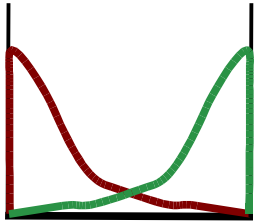
Event Analysis

- Advanced analysis techniques

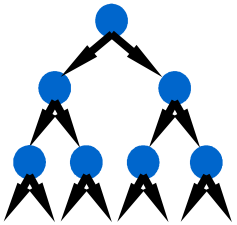
Cut-Based



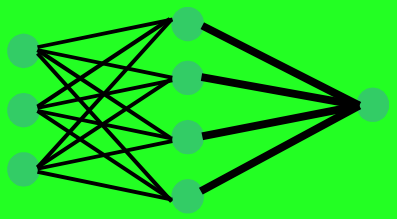
Likelihoods



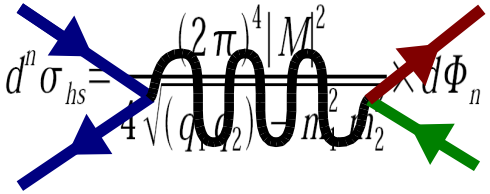
Decision Trees



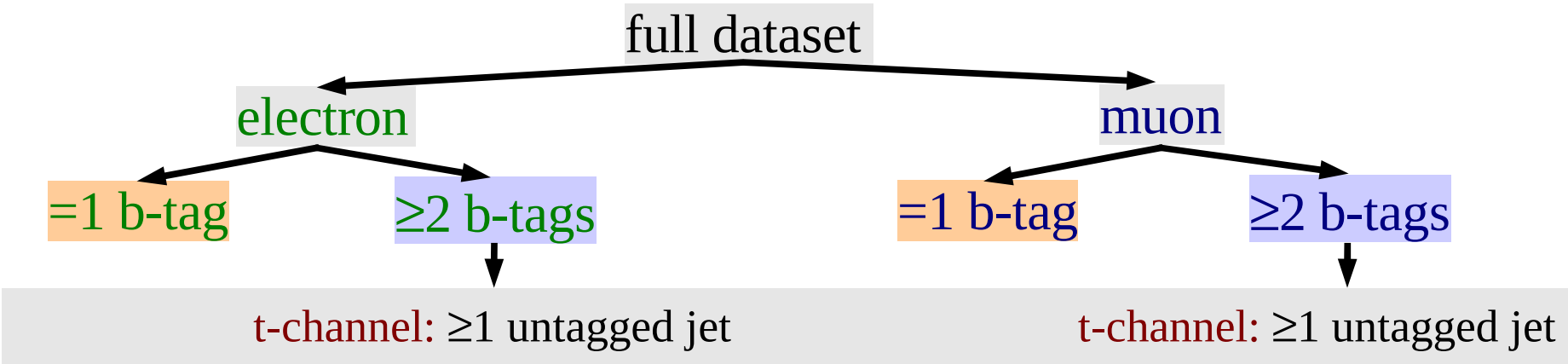
Neural Networks



Matrix Elements

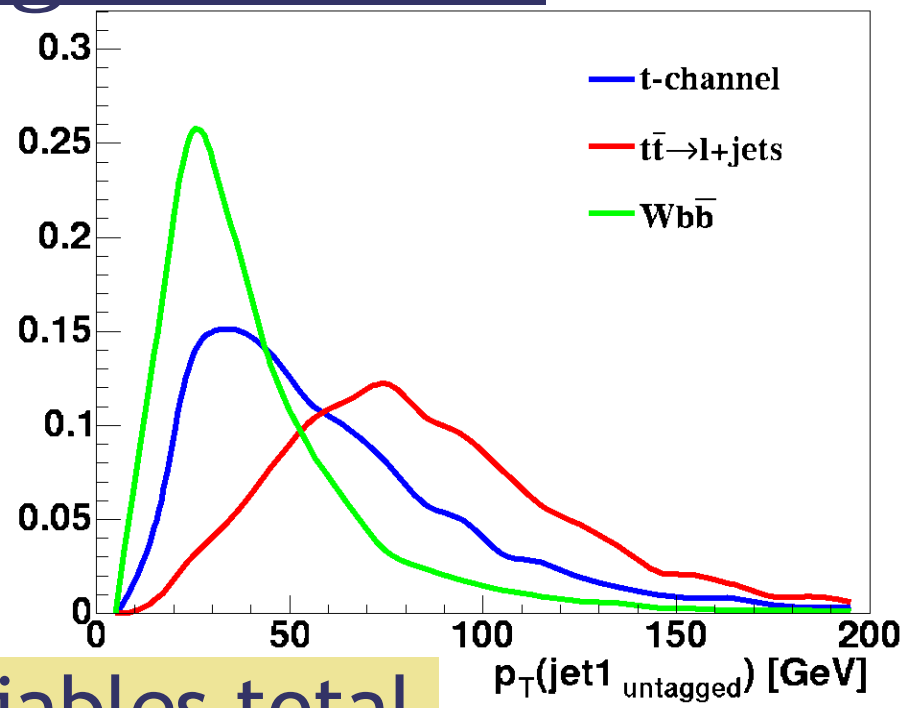


Analysis Strategy

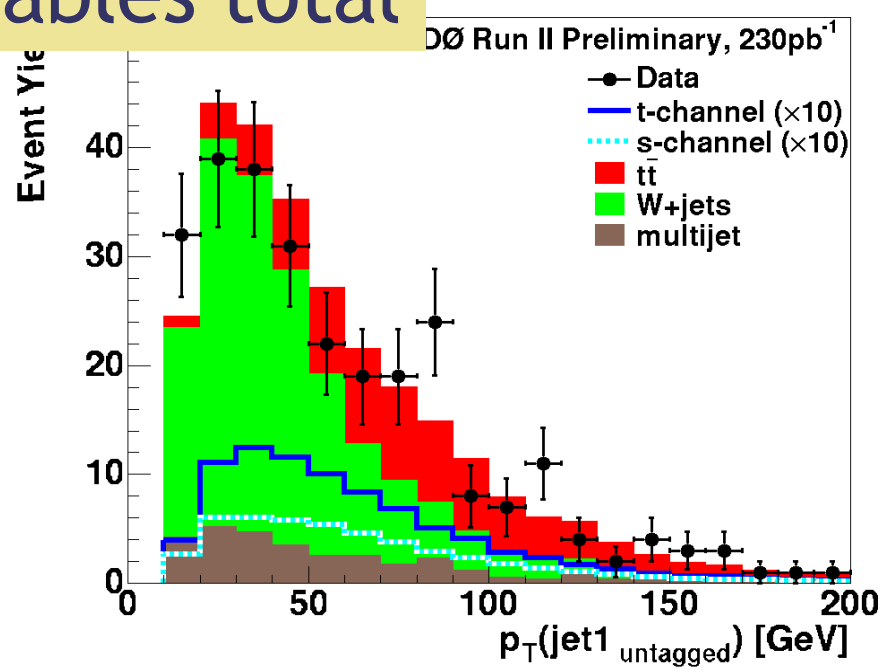


Discriminating Variables

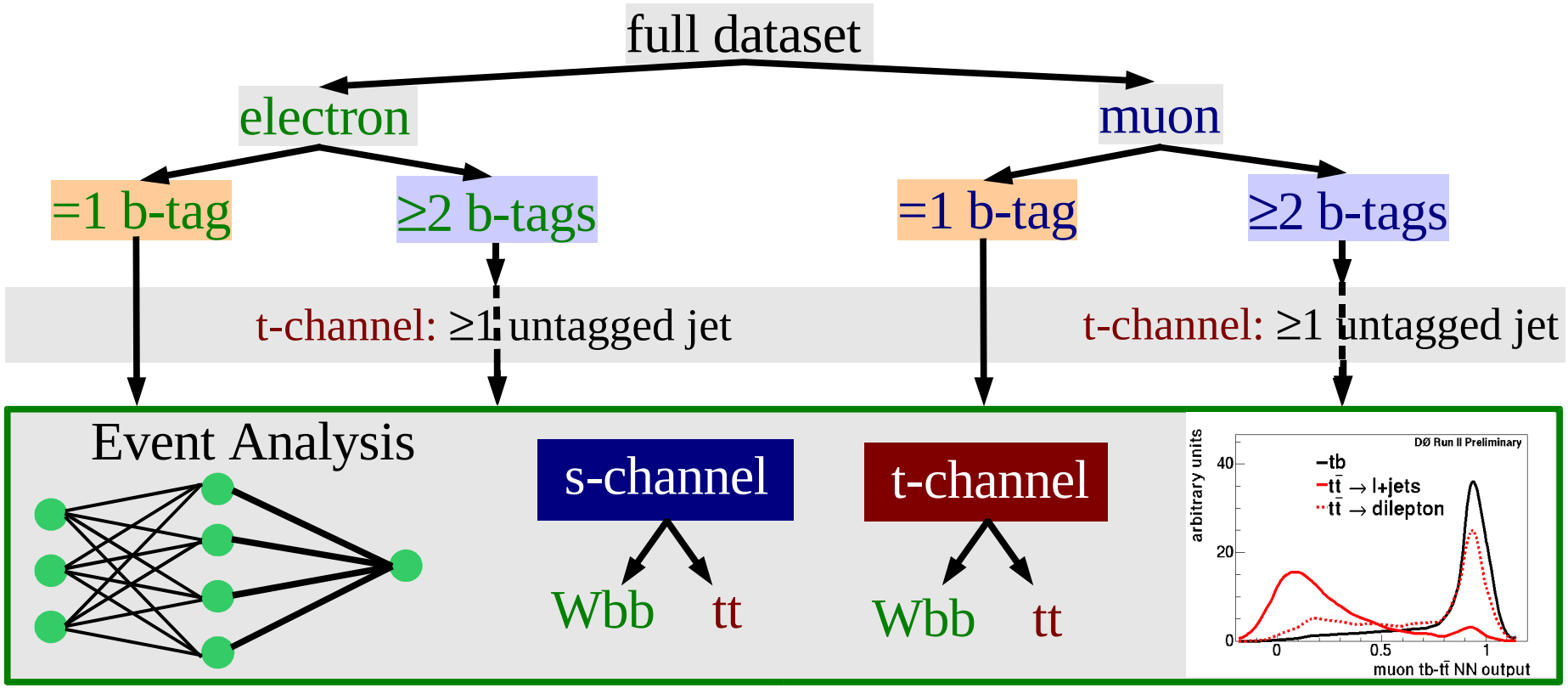
- Object kinematics
  - Jet p_T for different jets
    - Tagged, untagged,...
- Event kinematics
  - H (total energy)
  - H_T (transverse energy)
  - M (invariant mass)
  - M_T (transverse mass)
  - Summing over various objects in the event
- Angular variables
  - Jet-jet separation
  - Jet pseudorapidity (t-channel)
  - Top quark spin
  - Sphericity, aplanarity



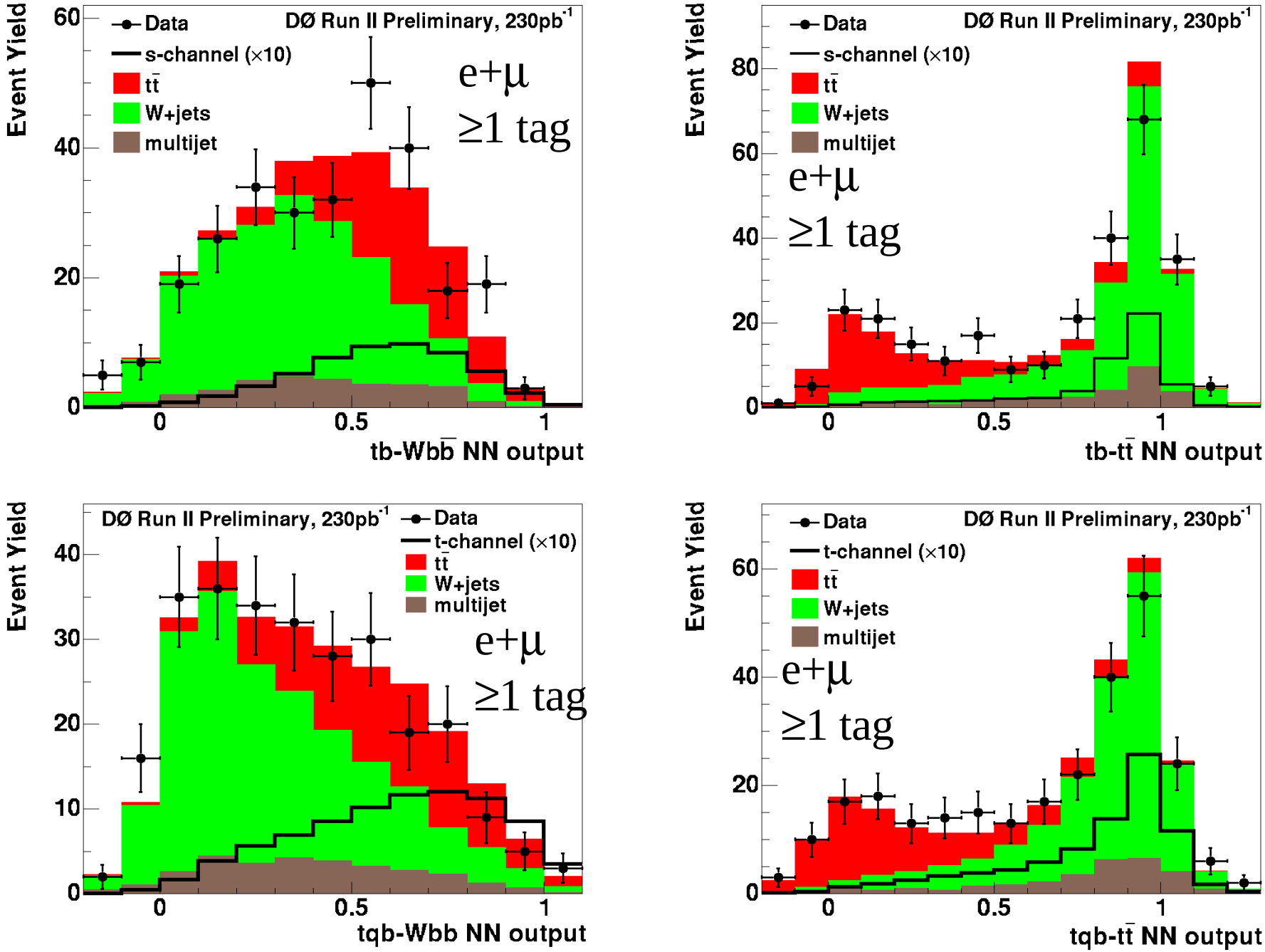
25 variables total



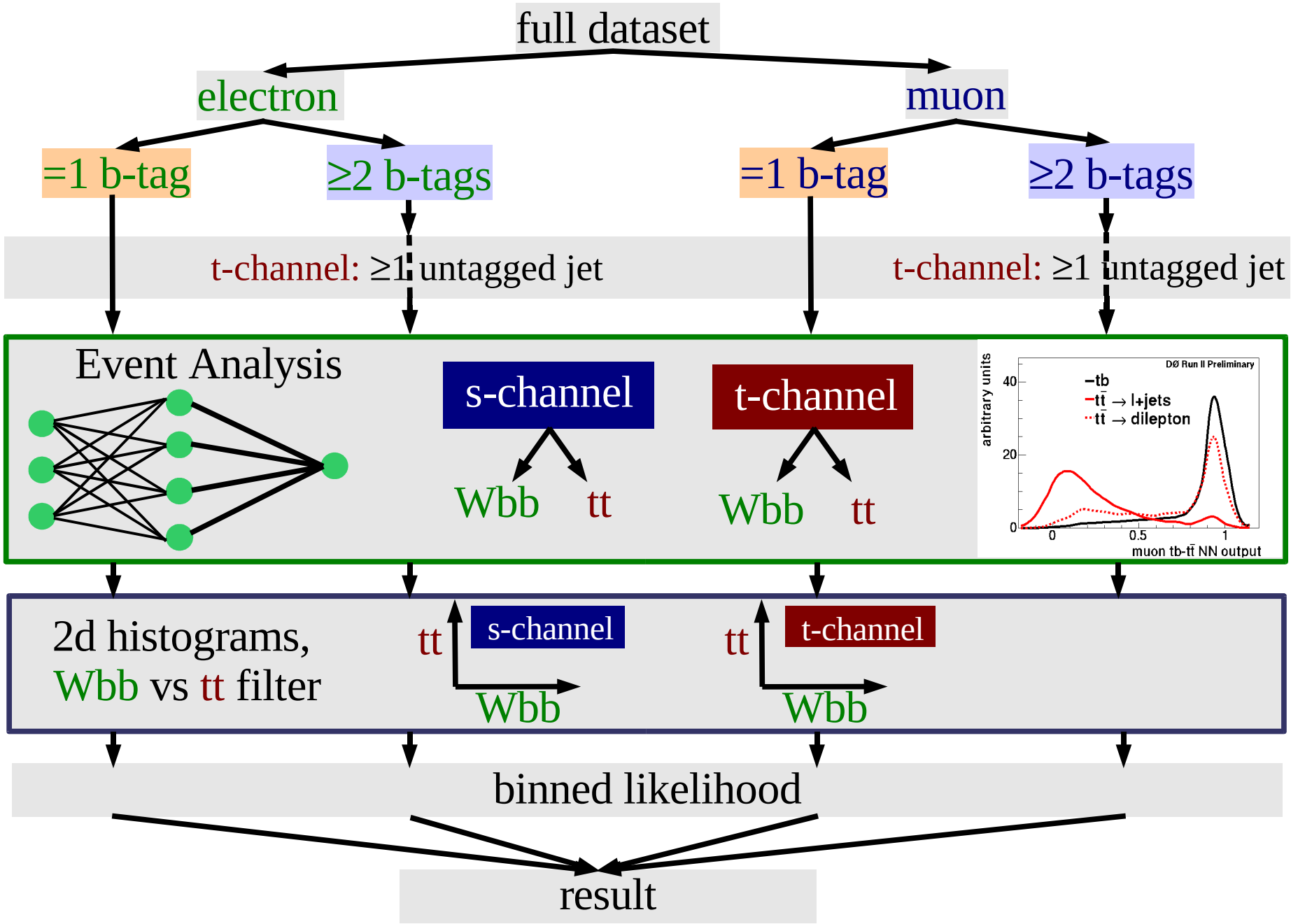
Analysis Strategy



Neural Network Output



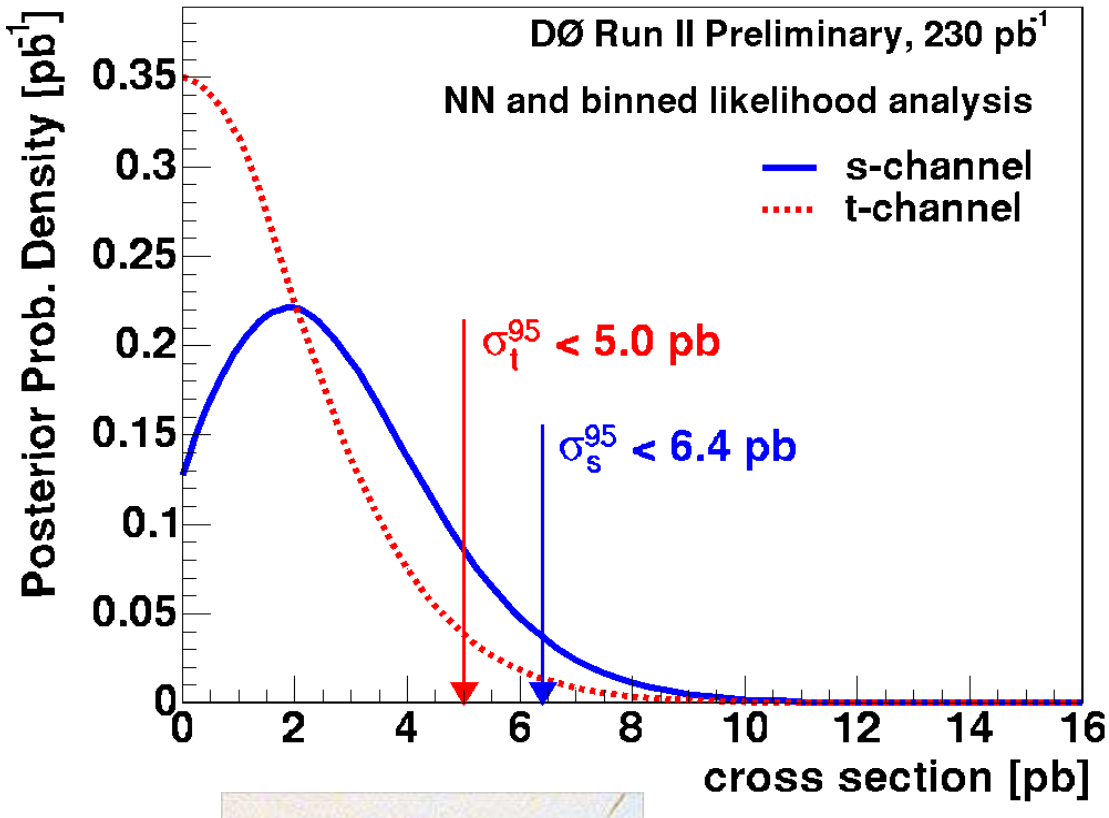
Analysis Strategy



Neural Network Result

- Dominant systematics
  - Jet energy scale, b-ID: 10%
  - Background norm: 15-20%
  - Object ID: 5%
- Total systematic

	=1 tag	≥2 tags
Signal acceptance	15%	25%
Background sum	10%	26%



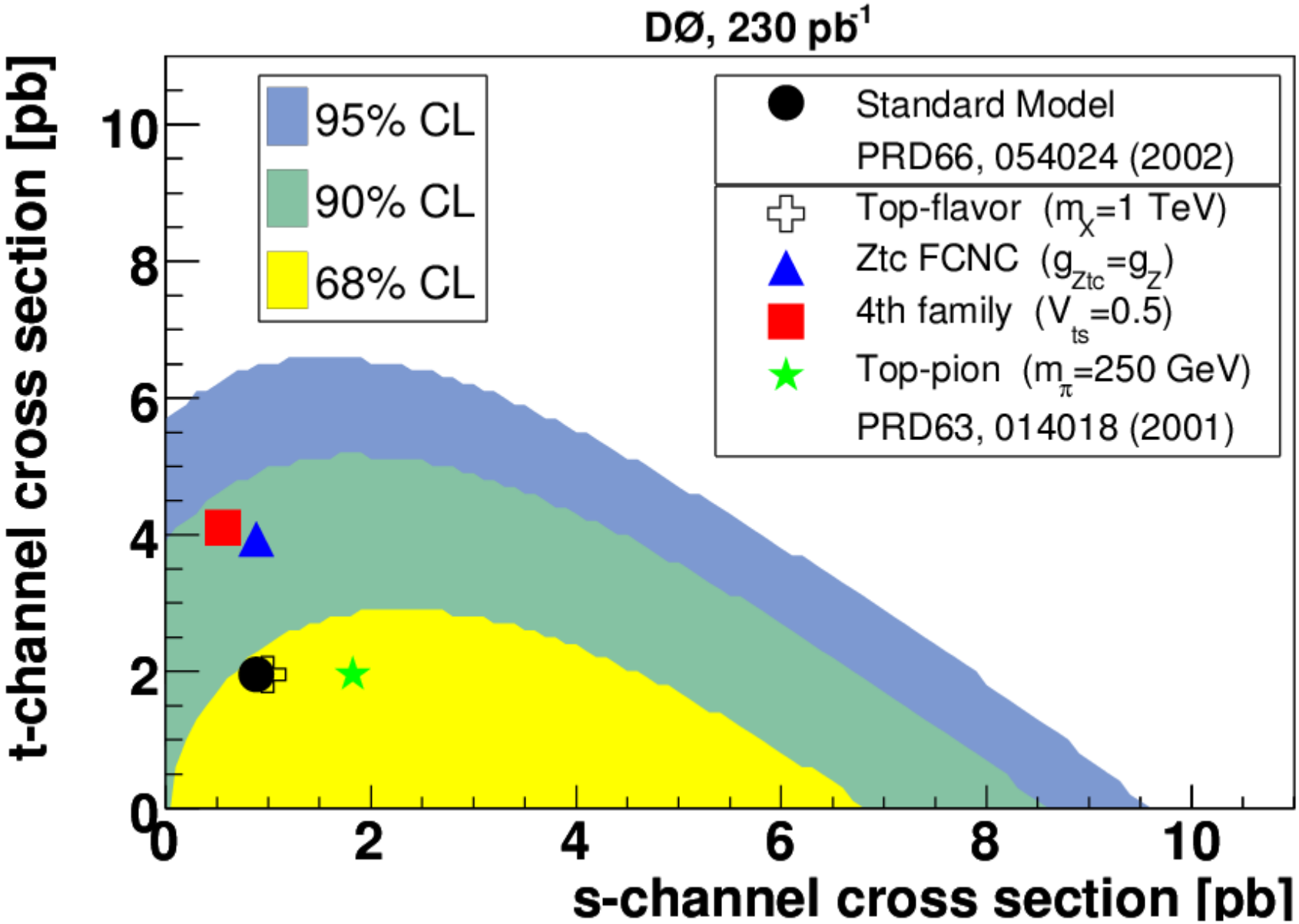
Expected/Observed limit:

σ_s < 4.5 / 6.4 pb

σ_t < 5.8 / 5.0 pb

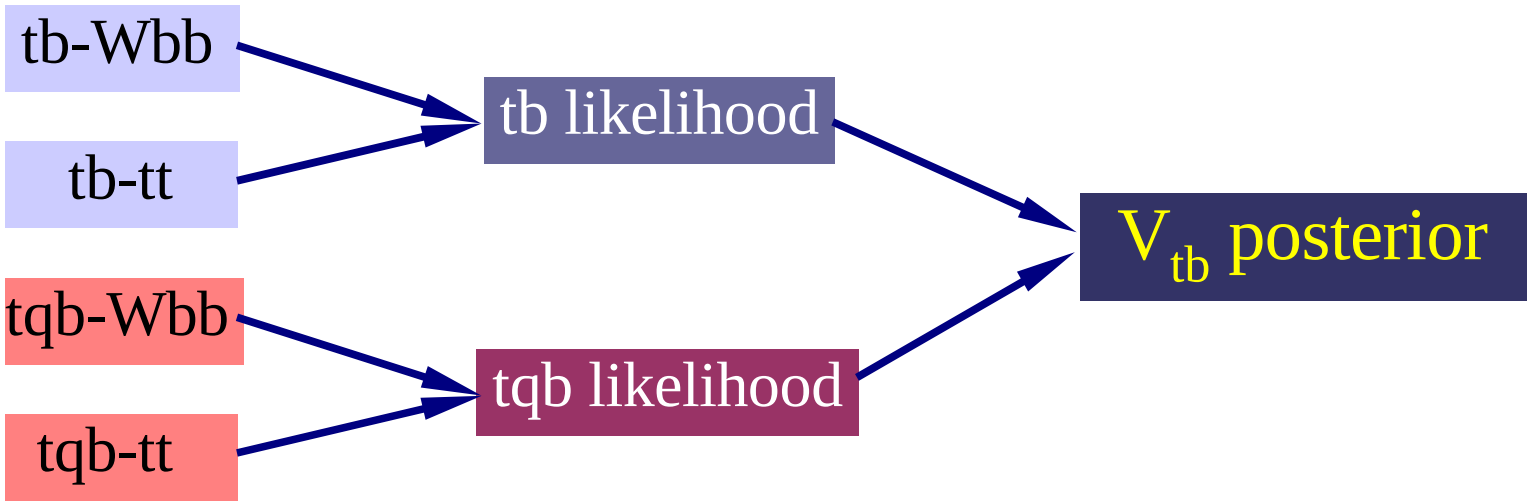
Published in PLB 622, 265 (2005)

Sensitivity to non-SM Single Top



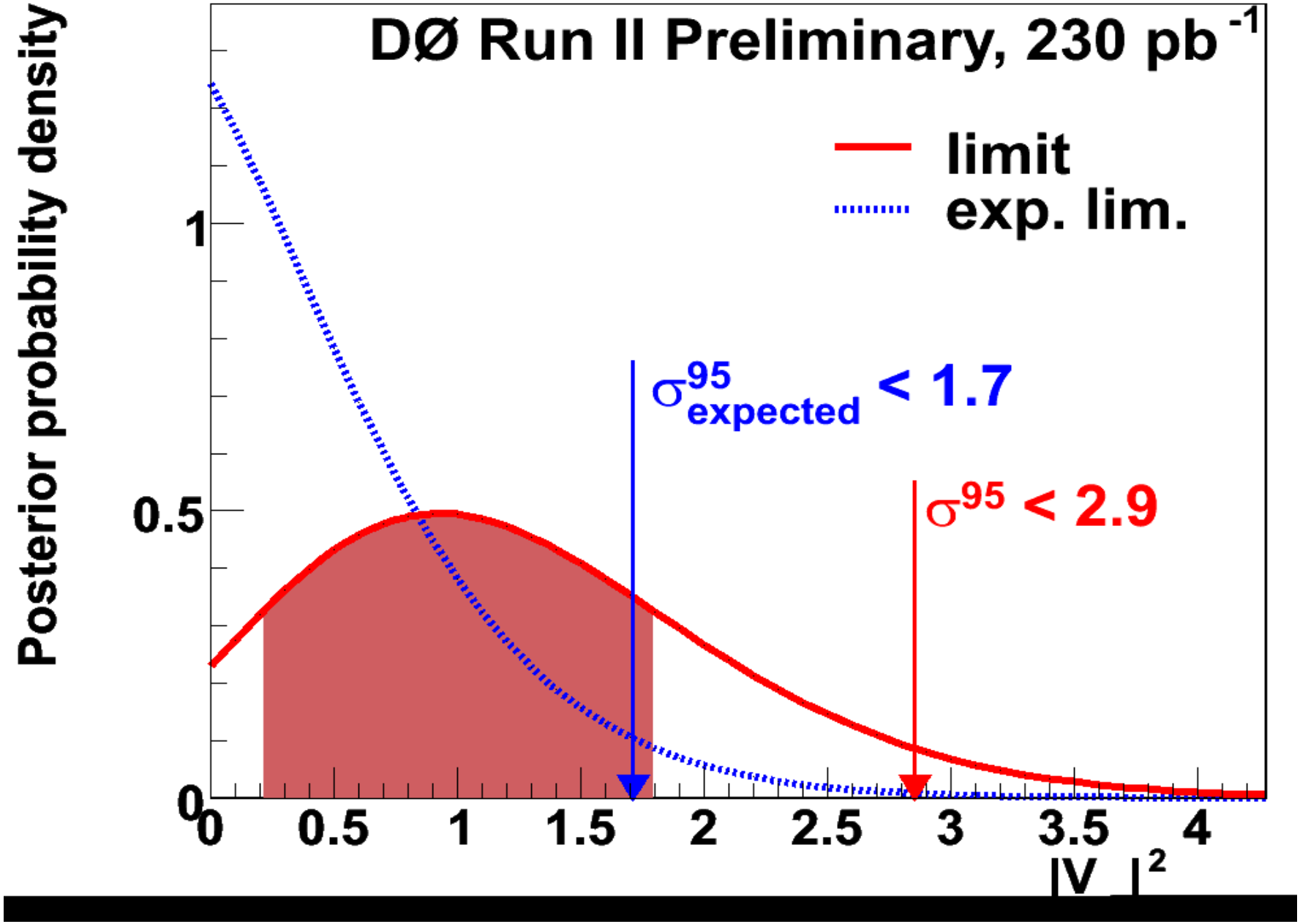
V_{tb} Coupling Limit

- Both the s-channel and t-channel cross sections are proportional to $|V_{tb}|^2$
  - Combine neural networks in a 2d likelihood function



  - Need to assume SM ratio of cross sections

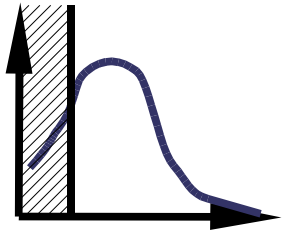
Probability density for $|V_{tb}|^2$



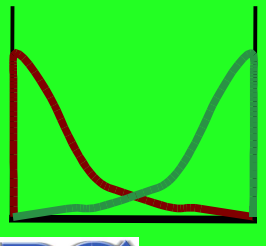
Event Analysis

- Advanced analysis techniques

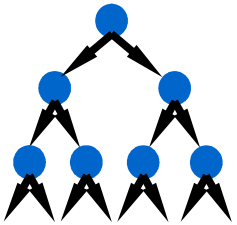
Cut-Based



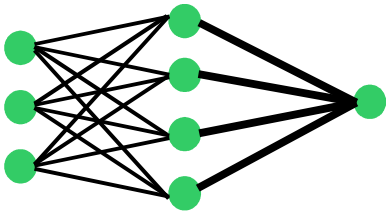
Likelihoods



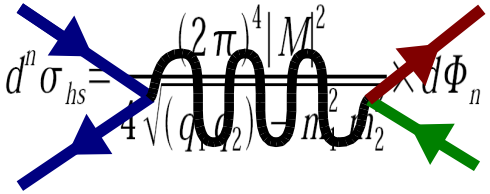
Decision Trees



Neural Networks

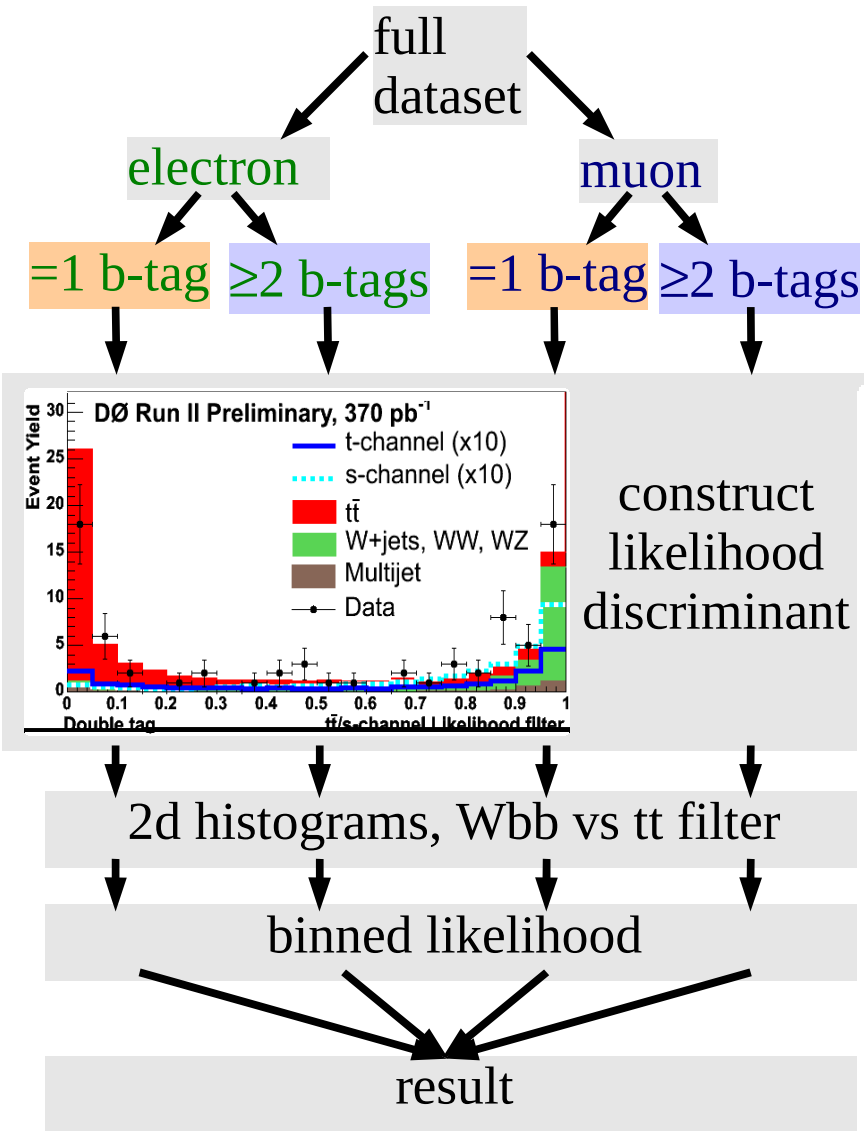


Matrix Elements

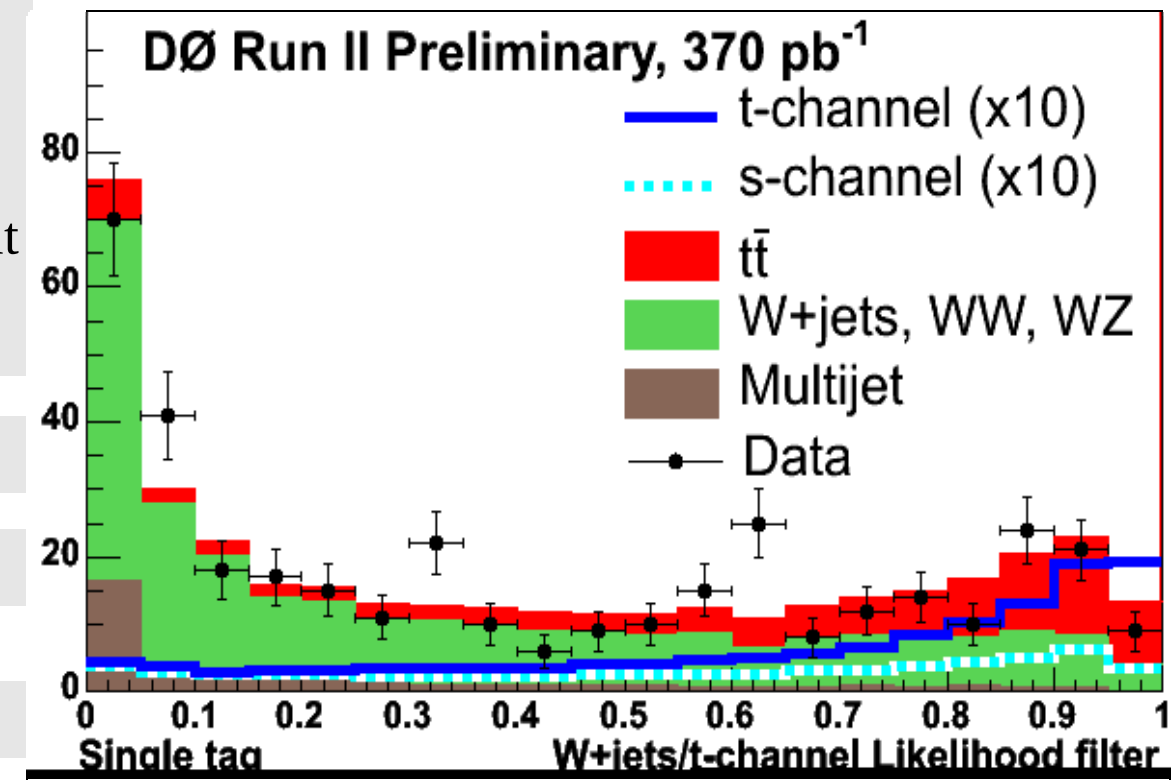


Likelihood Analysis (370 pb^{-1})

s-channel / t-channel

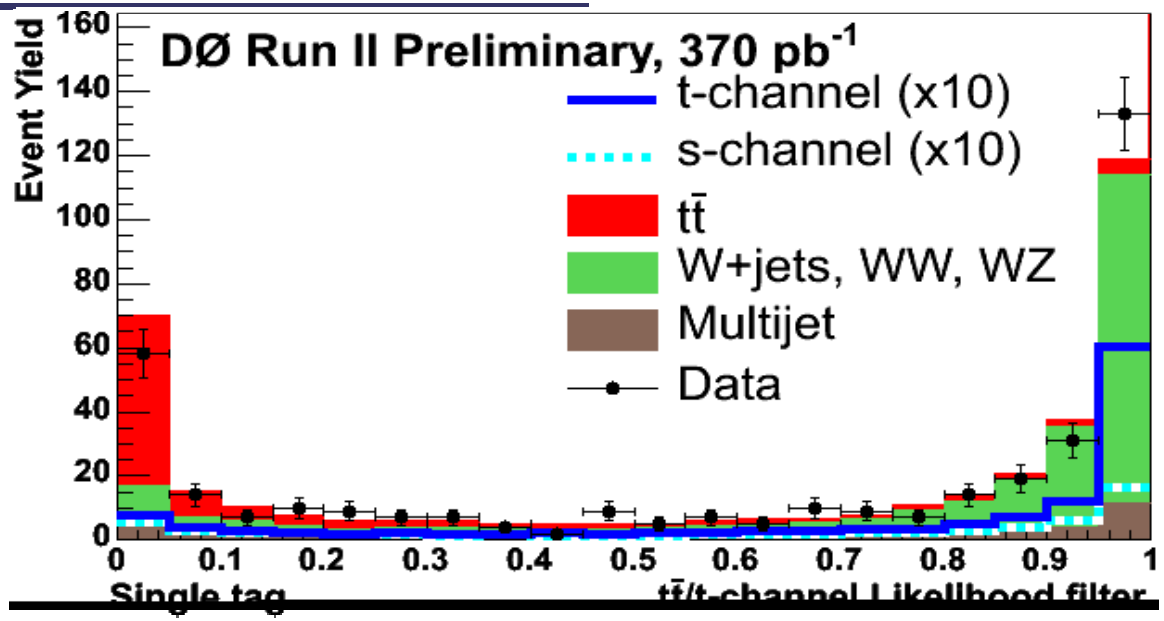


- Using jet lifetime tagger
  - Asymmetric tag requirements
    - At least one tight tag
    - Loose tagger cut for double tags



Likelihood Result

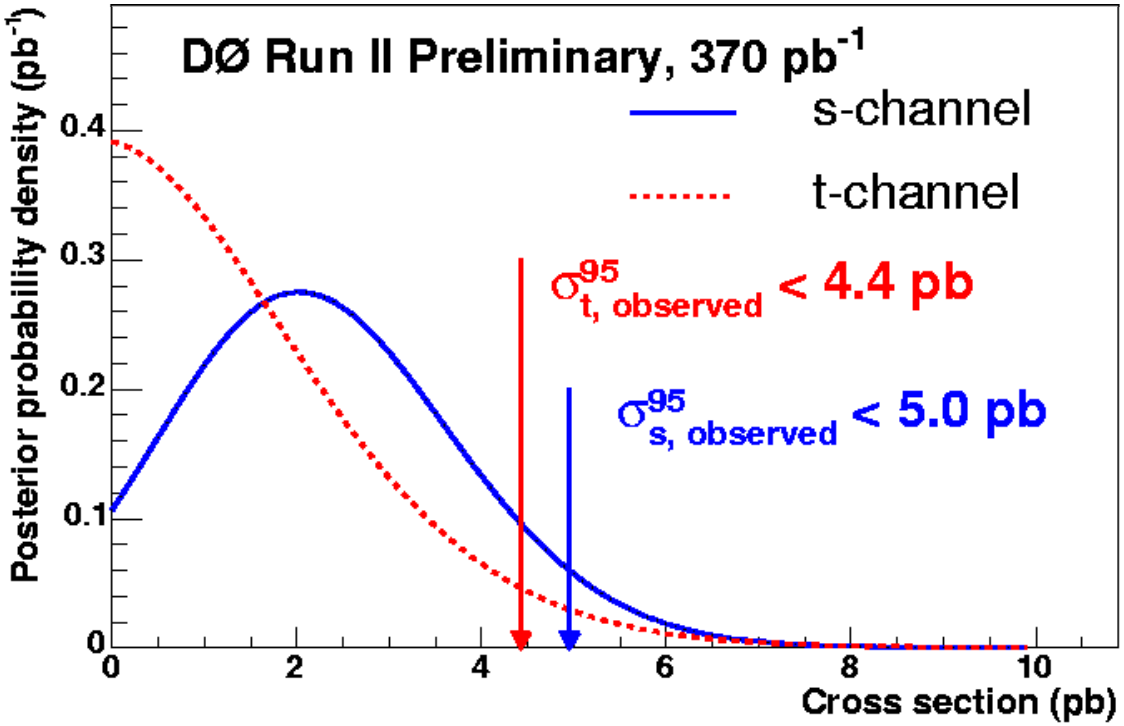
- Systematic uncertainties
  - b-tag modeling: 6-17%
  - Jet energy scale: 5%
  - Trigger modeling: 5%
  - Theory tt XS: 18%



Expected/Observed limit:

σ_s < 3.3 / 5.0 pb

σ_t < 4.3 / 4.4 pb



Summary

	s-channel	t-channel
NLO cross section	0.88 pb	1.98 pb

95% CL upper cross section limits [pb]

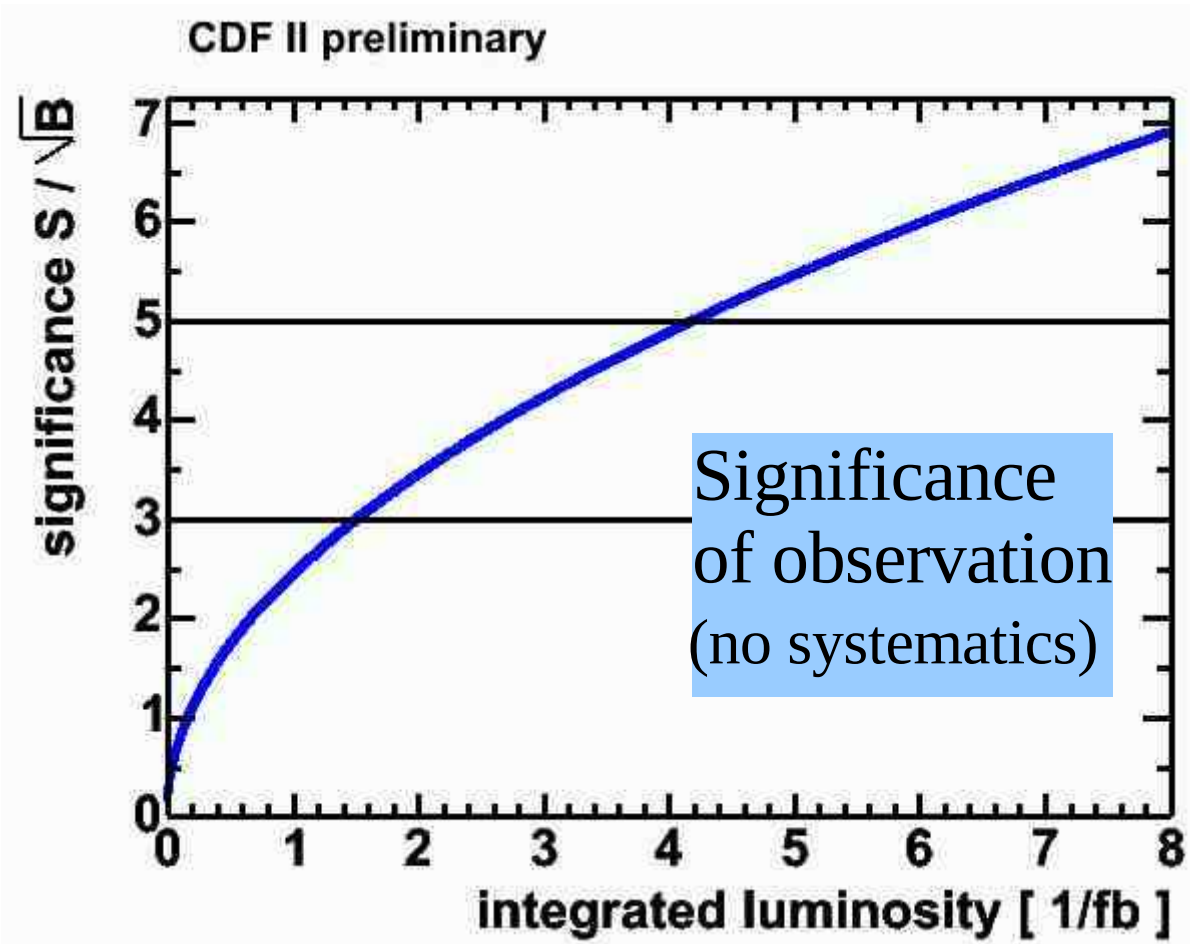
CDF ($160pb^{-1}$)	13.6	10.1
DØ NN ($230pb^{-1}$)	6.4	5.0
DØ Likelihood ($370pb^{-1}$)	5.0	4.4

Outlook

The future is here

Tevatron Single Top Future

- s+t combined
- NN search
- Cut on NN output (event counting)
- No systematics



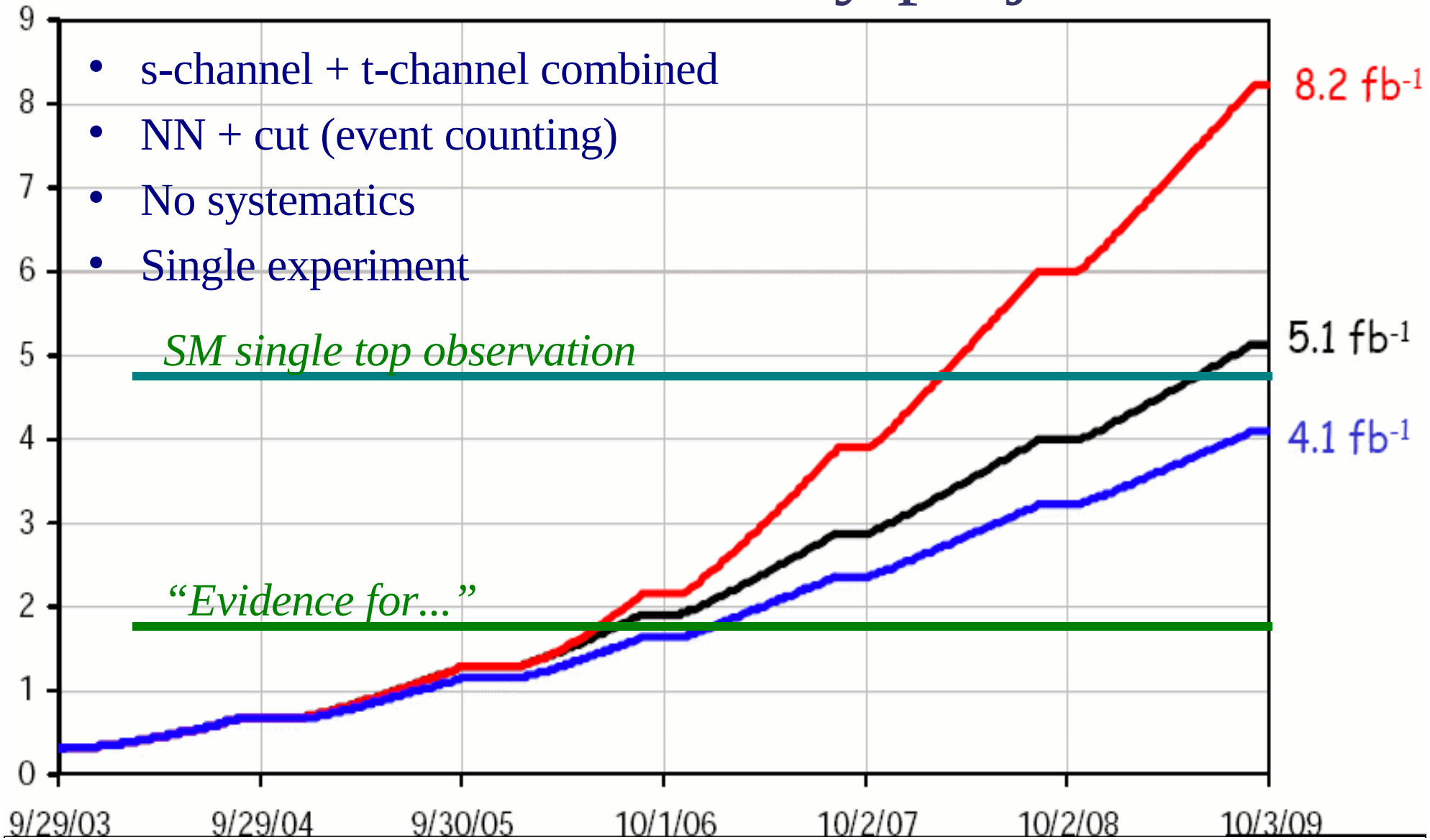
Improvements

- b-tagging
  - More signal
- Jet energy resolution
  - Better top mass reconstruction

Prospects

- Observe single top production in Run II
  - Discover new physics (if it's there)
- Measure $|V_{tb}|$ to ~10%

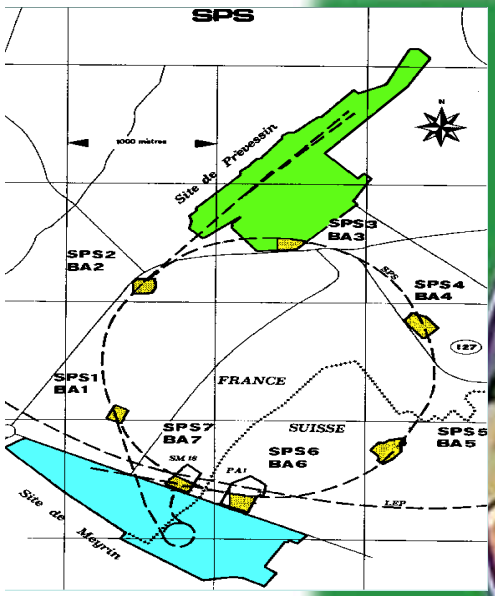
Tevatron luminosity projection



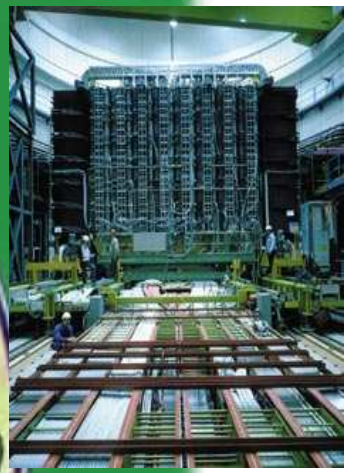
Conclusions

- Single top quark production is a key observation for the Tevatron
- Run II single top analysis going well
  - World's best limits are from DØ: $\sigma_s < 5.0$ pb, $\sigma_t < 4.4$ pb
  - Already reaching sensitivity to new physics
- Single Top is about to get really exciting in Run II
  - Both CDF and DØ will be close to discovery next year
- Top quark couplings are important to understand electroweak symmetry breaking
  - Study in detail at future colliders

Backup Slides


SPS
Site de Prevessin
SPS2
BA2
SPS3
BA3
SPS4
BA4
SPS1
BA1
FRANCE
SUISSE
SPS7
BA7
SPS6
BA6
SPS5
BA5
Site de Meyrin

WHERE IN THE
WORLD



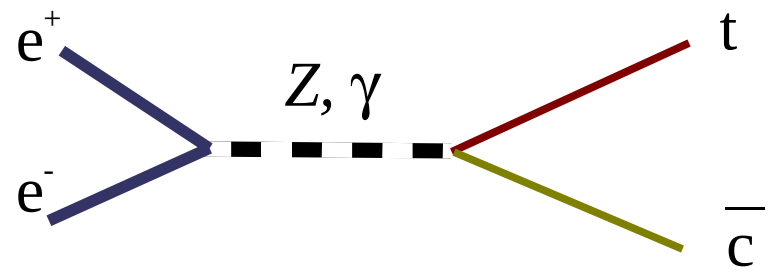
Single Top

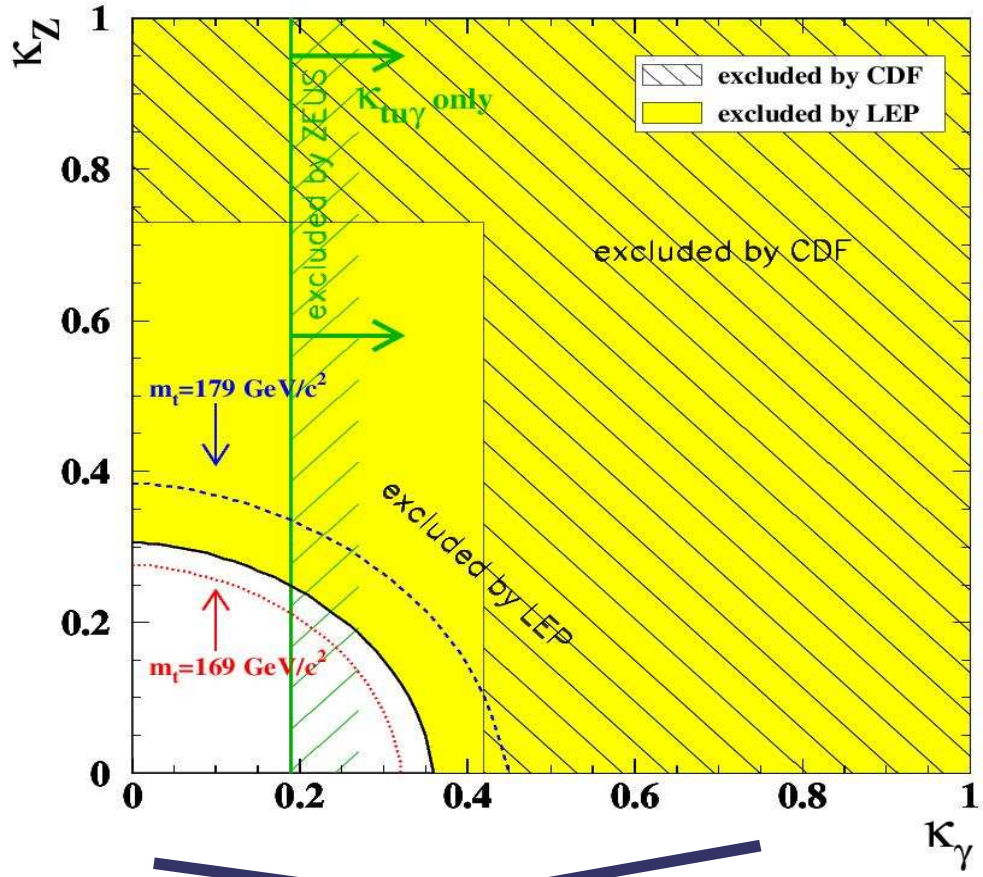
HERA
PETRA

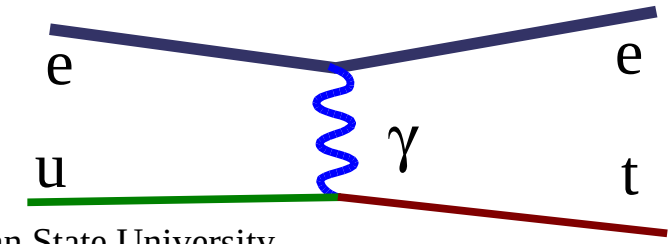
Single Top at LEP and Hera: FCNC

- LEP:
  - $e^+e^- \rightarrow tc$

- Hera:
  - $ep \rightarrow et$

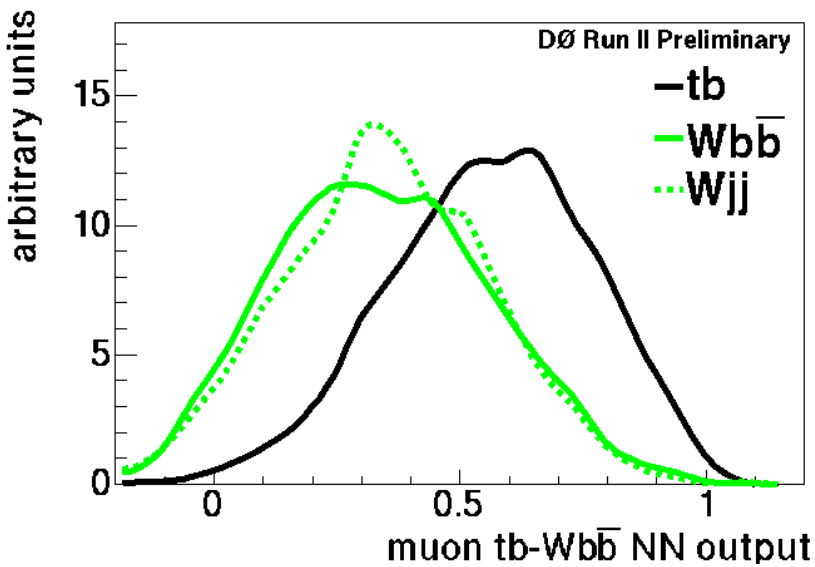


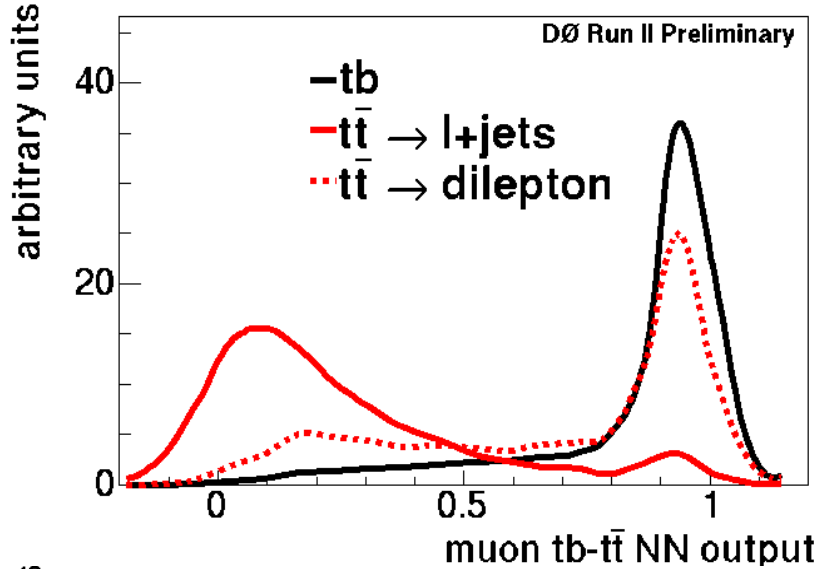


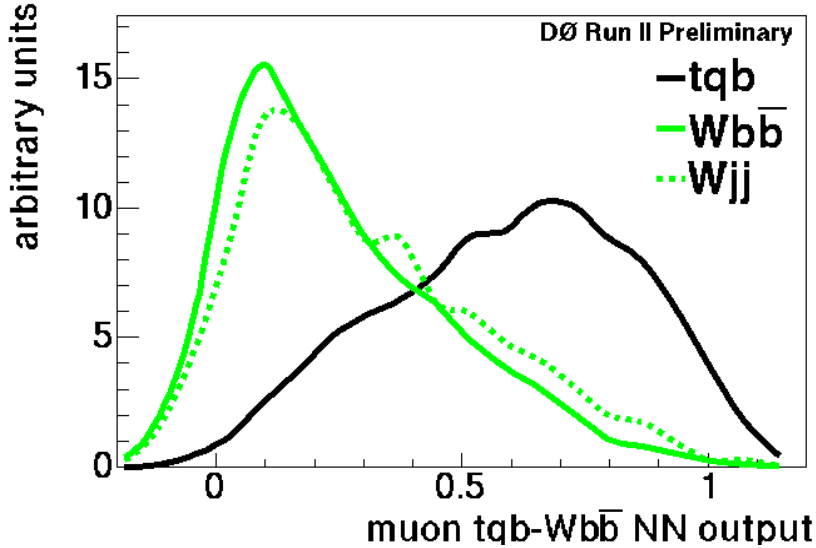


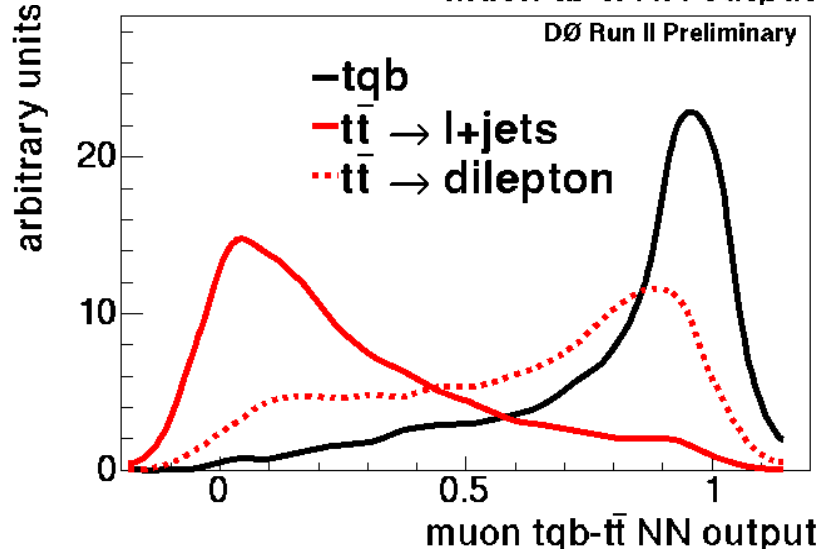
Neural Network Filters

- Focus on the largest backgrounds: Wbb and tt→*l*+jets
- Same variables for electron and muon channel
- Same filter for =1 tag and ≥2 tags





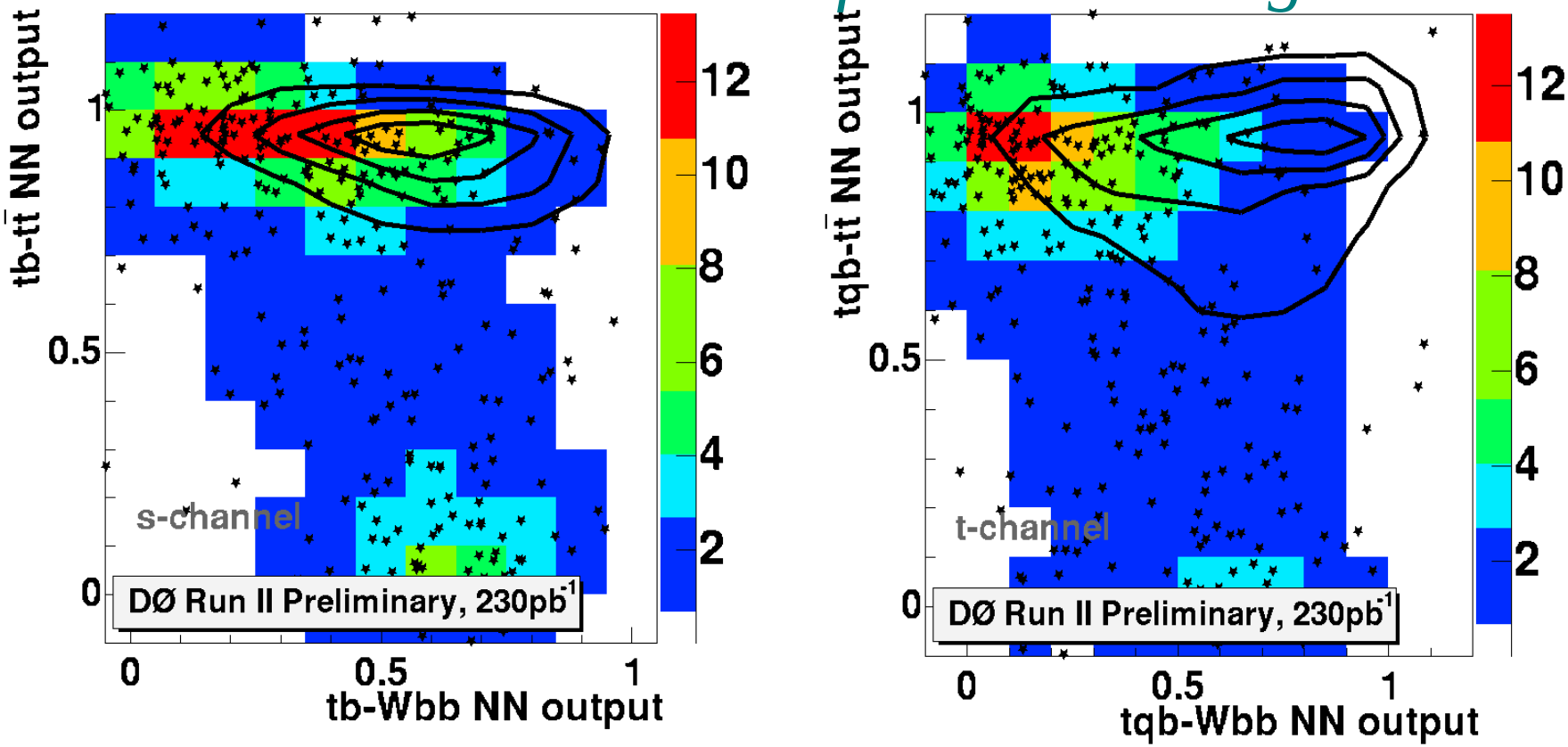




Result

- No evidence for single top signal
  - ➔ Set 95% CL upper cross section limit
  - – Using Bayesian approach and binned likelihood
  - – Including bin-by-bin systematics and correlations

Build binned likelihood from 2-d histograms

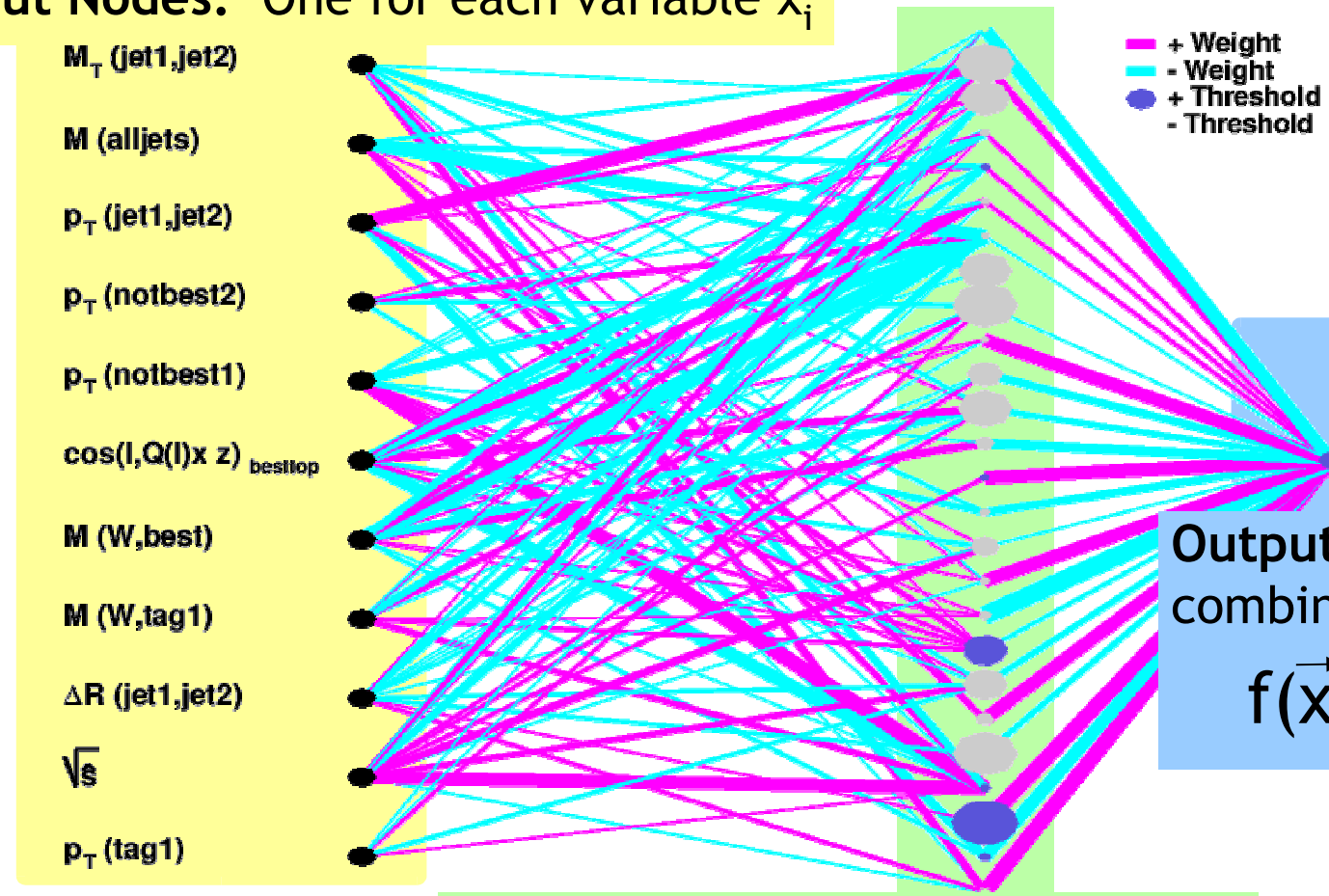


Variables:

	Signal-Background Pairs			
	tb		tqb	
	Wbb	$t\bar{t}$	Wbb	$t\bar{t}$
Individual object kinematics				
$p_T(\mathrm{jet1}_{\mathrm{tagged}})$	$\surd$	$\surd$	$\surd$	—
$p_T(\mathrm{jet1}_{\mathrm{untagged}})$	—	—	$\surd$	$\surd$
$p_T(\mathrm{jet2}_{\mathrm{untagged}})$	—	—	—	$\surd$
$p_T(\mathrm{jet1}_{\mathrm{nonbest}})$	$\surd$	$\surd$	—	—
$p_T(\mathrm{jet2}_{\mathrm{nonbest}})$	$\surd$	$\surd$	—	—
Global event kinematics				
$M_T(\mathrm{jet1},\mathrm{jet2})$	$\surd$	—	—	—
$p_T(\mathrm{jet1},\mathrm{jet2})$	$\surd$	—	$\surd$	—
$M(\mathrm{alljets})$	$\surd$	$\surd$	$\surd$	$\surd$
$H_T(\mathrm{alljets})$	—	—	$\surd$	—
$M(\mathrm{alljets}-\mathrm{jet1}_{\mathrm{tagged}})$	—	—	—	$\surd$
$H(\mathrm{alljets}-\mathrm{jet1}_{\mathrm{tagged}})$	—	$\surd$	—	$\surd$
$H_T(\mathrm{alljets}-\mathrm{jet1}_{\mathrm{tagged}})$	—	—	—	$\surd$
$p_T(\mathrm{alljets}-\mathrm{jet1}_{\mathrm{tagged}})$	—	$\surd$	—	$\surd$
$M(\mathrm{alljets}-\mathrm{jet}_{\mathrm{best}})$	—	$\surd$	—	—
$H(\mathrm{alljets}-\mathrm{jet}_{\mathrm{best}})$	—	$\surd$	—	—
$H_T(\mathrm{alljets}-\mathrm{jet}_{\mathrm{best}})$	—	$\surd$	—	—
$M(\mathrm{top}_{\mathrm{tagged}}) = M(W,\mathrm{jet1}_{\mathrm{tagged}})$	$\surd$	$\surd$	$\surd$	$\surd$
$M(\mathrm{top}_{\mathrm{best}}) = M(W,\mathrm{jet}_{\mathrm{best}})$	$\surd$	—	—	—
$\sqrt{\hat{s}}$	$\surd$	—	$\surd$	$\surd$
Angular variables				
$\Delta R(\mathrm{jet1},\mathrm{jet2})$	$\surd$	—	$\surd$	—
$Q(\mathrm{lepton}) \times \eta(\mathrm{jet1}_{\mathrm{untagged}})$	—	—	$\surd$	$\surd$
$\cos(\mathrm{lepton}, Q(\mathrm{lepton}) \times z)_{\mathrm{top}_{\mathrm{best}}}$	$\surd$	—	—	—
$\cos(\mathrm{lepton},\mathrm{jet1}_{\mathrm{untagged}})_{\mathrm{top}_{\mathrm{tagged}}}$	—	—	$\surd$	—
$\cos(\mathrm{alljets},\mathrm{jet1}_{\mathrm{tagged}})_{\mathrm{alljets}}$	—	—	$\surd$	$\surd$
$\cos(\mathrm{alljets},\mathrm{jet}_{\mathrm{nonbest}})_{\mathrm{all\ jets}}$	—	$\surd$	—	—

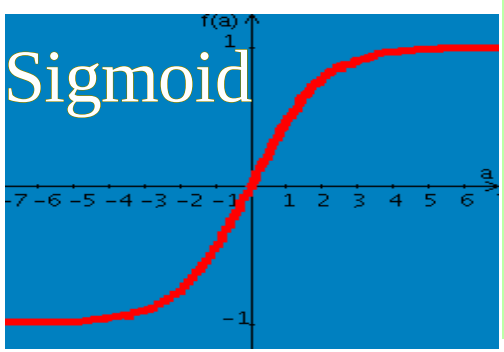
Neural Networks

Input Nodes: One for each variable x_i



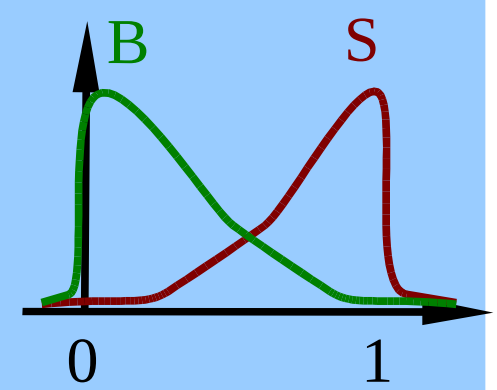
Output Node: linear combination of hidden nodes

$$f(\vec{x}) = \Sigma\, w'_k\, n_k(\vec{x},\vec{w}_k)$$



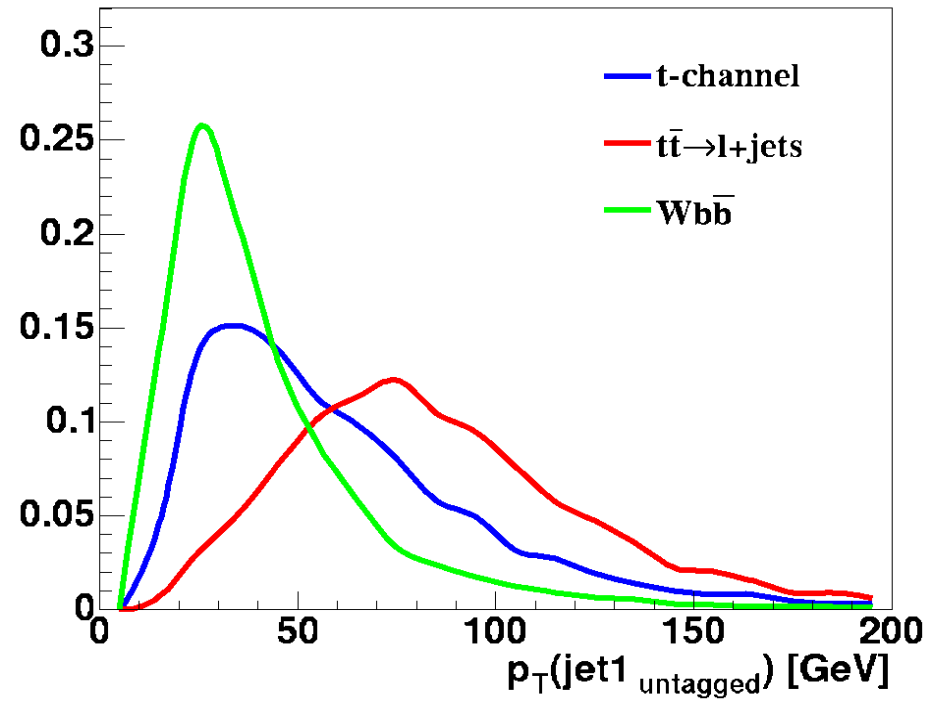
Hidden Nodes: Each is a sigmoid dependent on the input variables

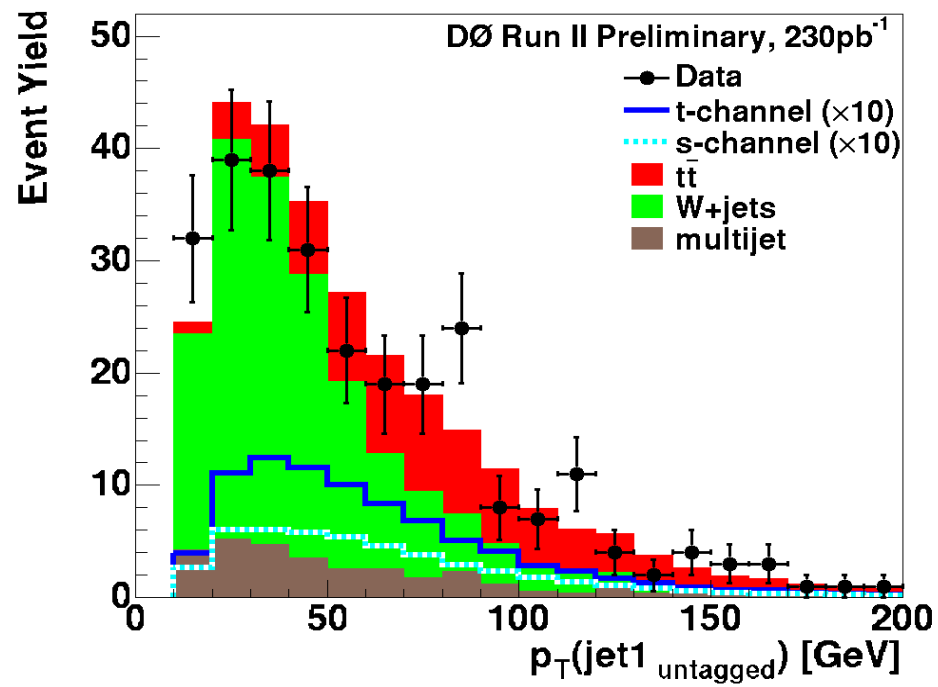
$$n_k(\vec{x},\vec{w}_k) = \frac{1}{1 + e^{-\Sigma\, w_{ik}\, x_i}}$$



Object p_T

- p_T of jets:
  - Both s-channel and t-channel:
    - $\text{Jet1}_{\text{tagged}}$
  - Only t-channel:
    - $\text{Jet 1}_{\text{untagged}}$
    - $\text{Jet 2}_{\text{untagged}}$
  - Only s-channel:
    - $\text{Jet 1}_{\text{non-best}}$
    - $\text{Jet 2}_{\text{non-best}}$

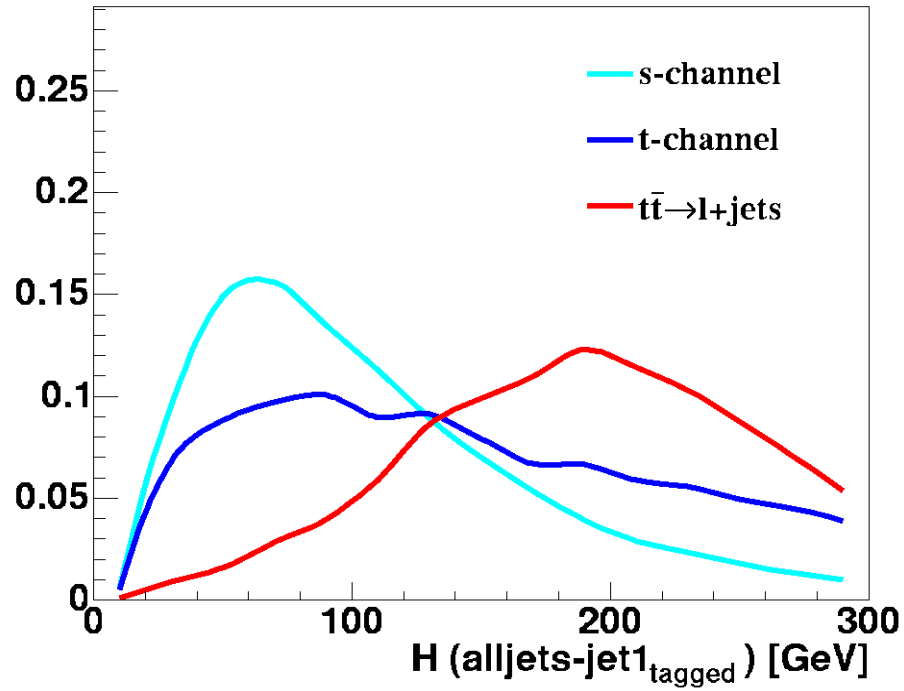


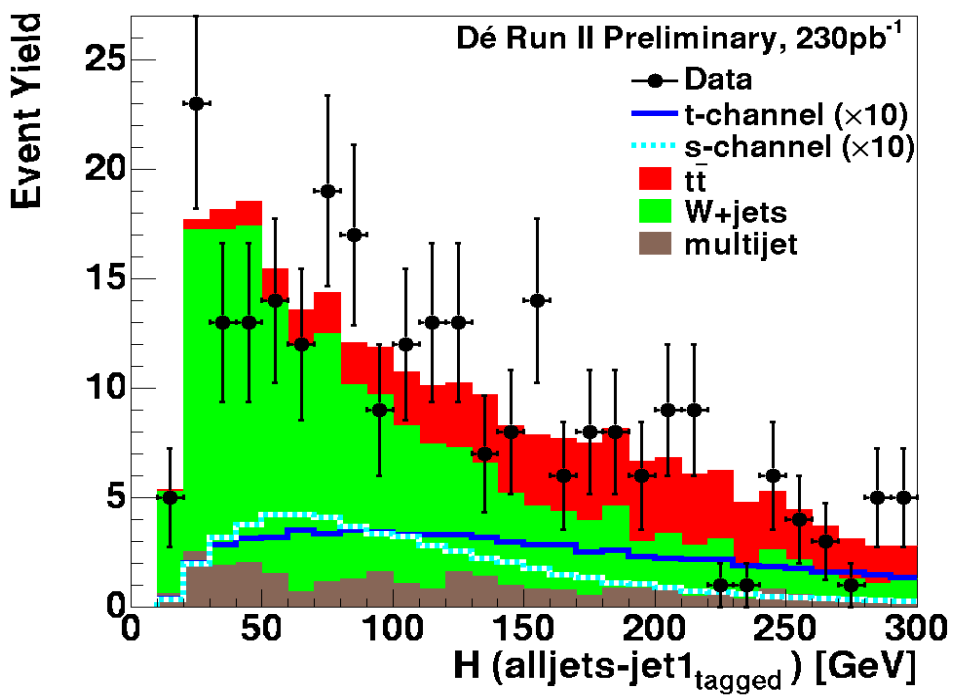


Event Energy

- Total energy $H = \Sigma_i E^i$

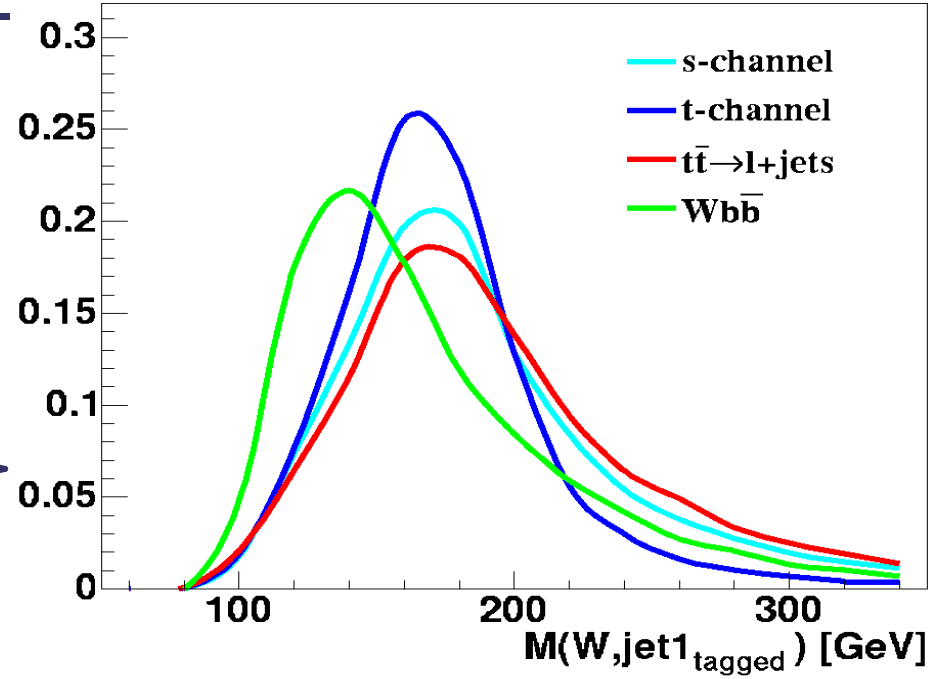
  transverse energy $H_T = \Sigma_i E^i_T$
  - Both s-channel and t-channel:
    - H(all jets – Jet1$_{tagged}$)
  - Only t-channel:
    - H_T(all jets)
    - H_T(all jets – Jet1$_{tagged}$)
  - Only s-channel:
    - H(all jets – Jet$_{best}$)
    - H_T(all jets – Jet$_{best}$)

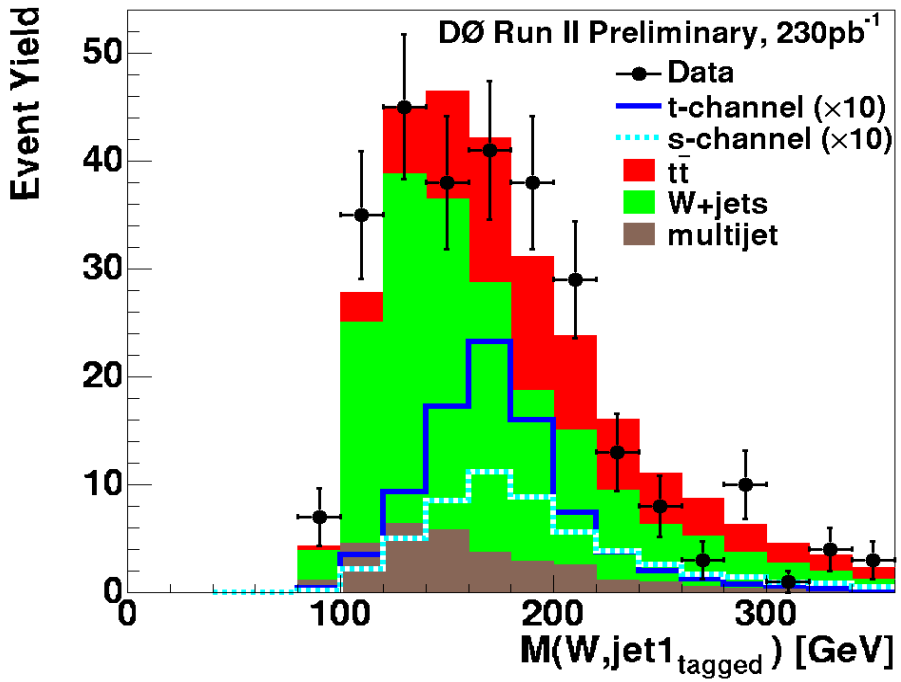




Reconstructed Objects

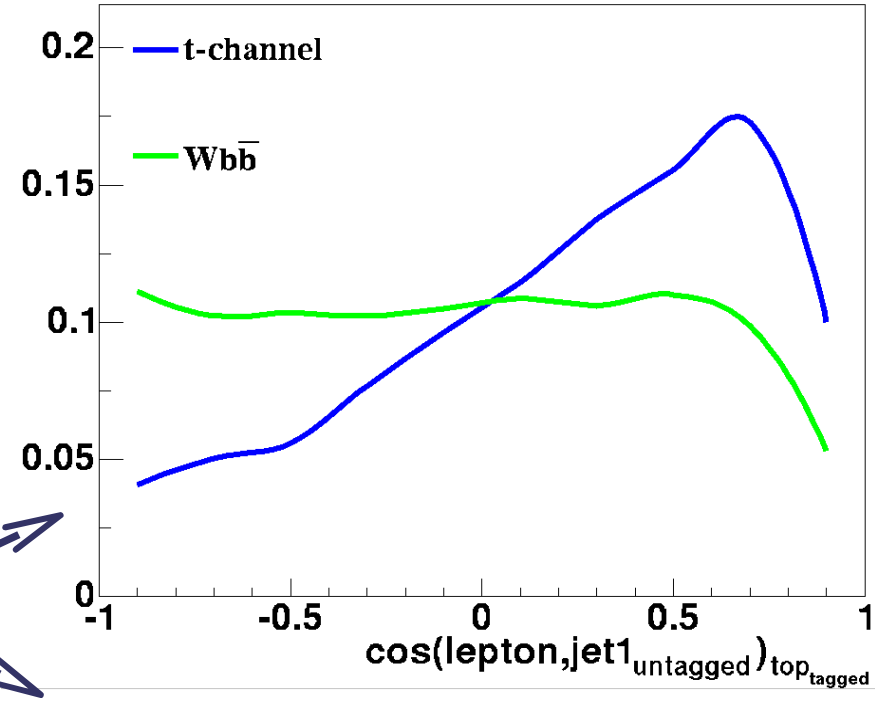
- Both s-channel and t-channel:
  - M(all jets)
  - p_T(all jets – Jet1$_{\text{tagged}}$)
  - M(top$_{\text{tagged}}$)
  - $\sqrt{\hat{s}}$
- Only t-channel:
  - M(all jets – Jet1$_{\text{tagged}}$)
- Only s-channel:
  - M_T(Jet1, Jet2)
  - p_T(Jet1, Jet2)
  - M(all jets – Jet1$_{\text{best}}$)
  - M(top$_{\text{best}}$)

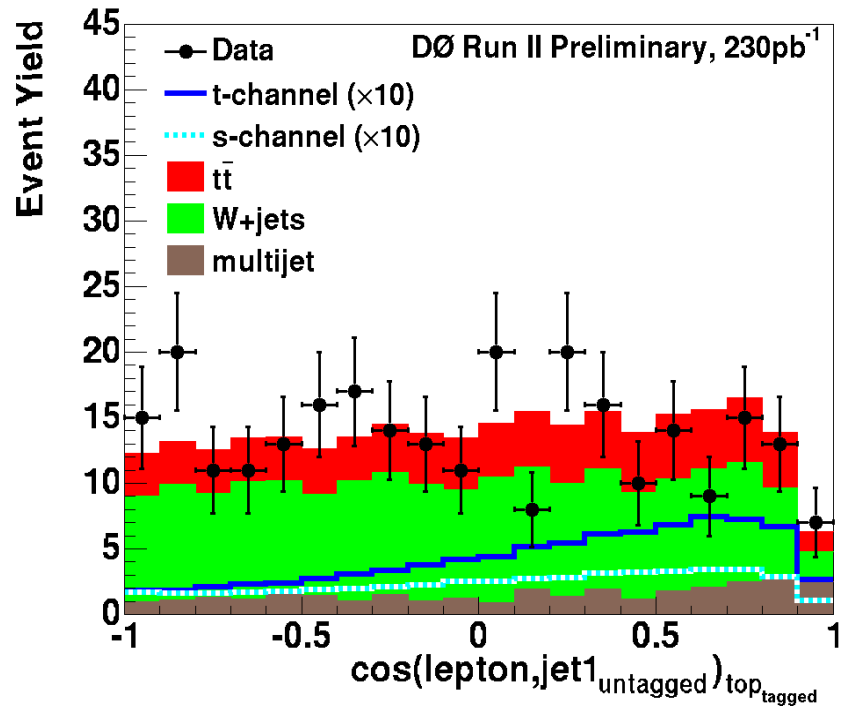




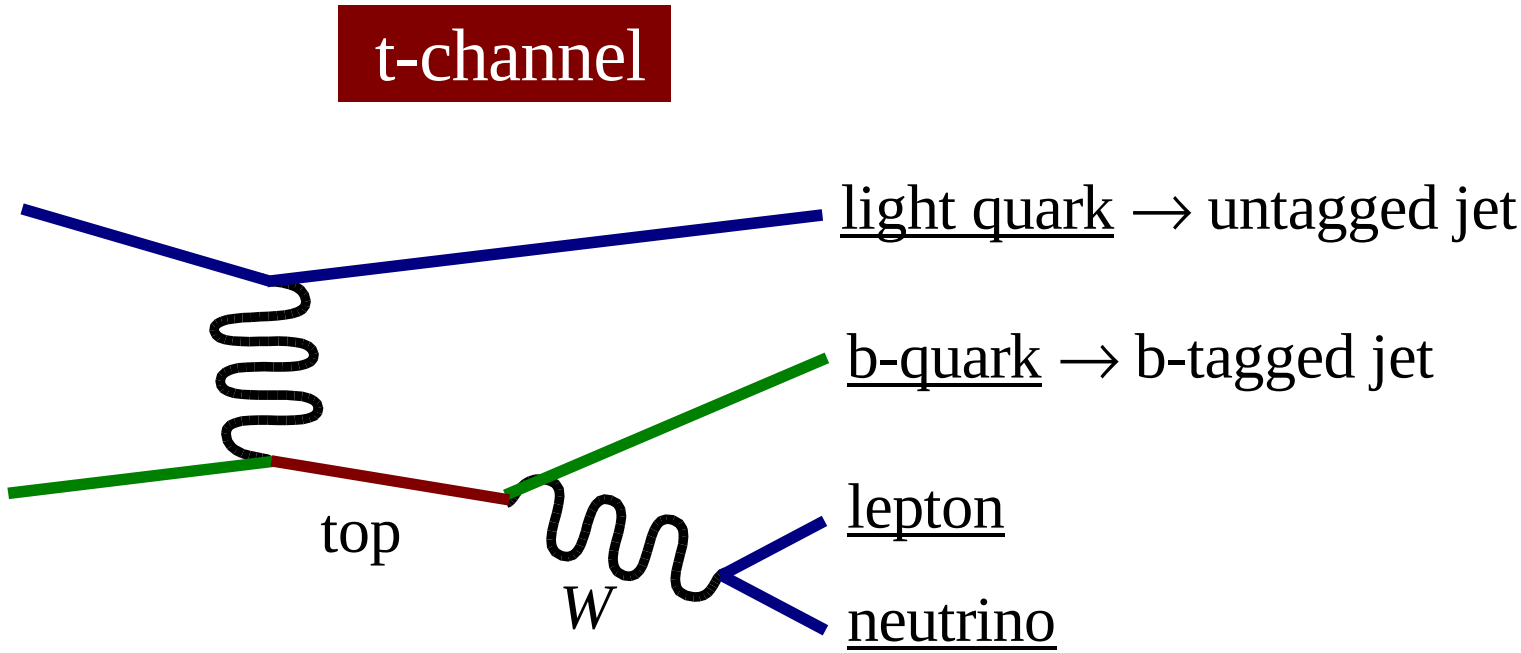
Angular Correlations

- Both s-channel and t-channel:
  - $\Delta R(\text{Jet1, Jet2})$
- Only t-channel:
  - $\eta(\text{Jet1}_{\text{untagged}}) \times Q(\text{lepton})$
  - $\cos(\text{lepton, Jet1}_{\text{untagged}})_{\text{top}_{\text{tagged}}}$
    - Spin correlation in optimal basis
  - $\cos(\text{all jets, Jet1}_{\text{tagged}})_{\text{all jets}}$
- Only s-channel:
  - $\cos(\text{lepton, } Q(\text{lepton}) \times z)_{\text{top}_{\text{best}}}$
    - Spin correlation in optimal basis
  - $\cos(\text{all jets, Jet1}_{\text{non-best}})_{\text{all jets}}$



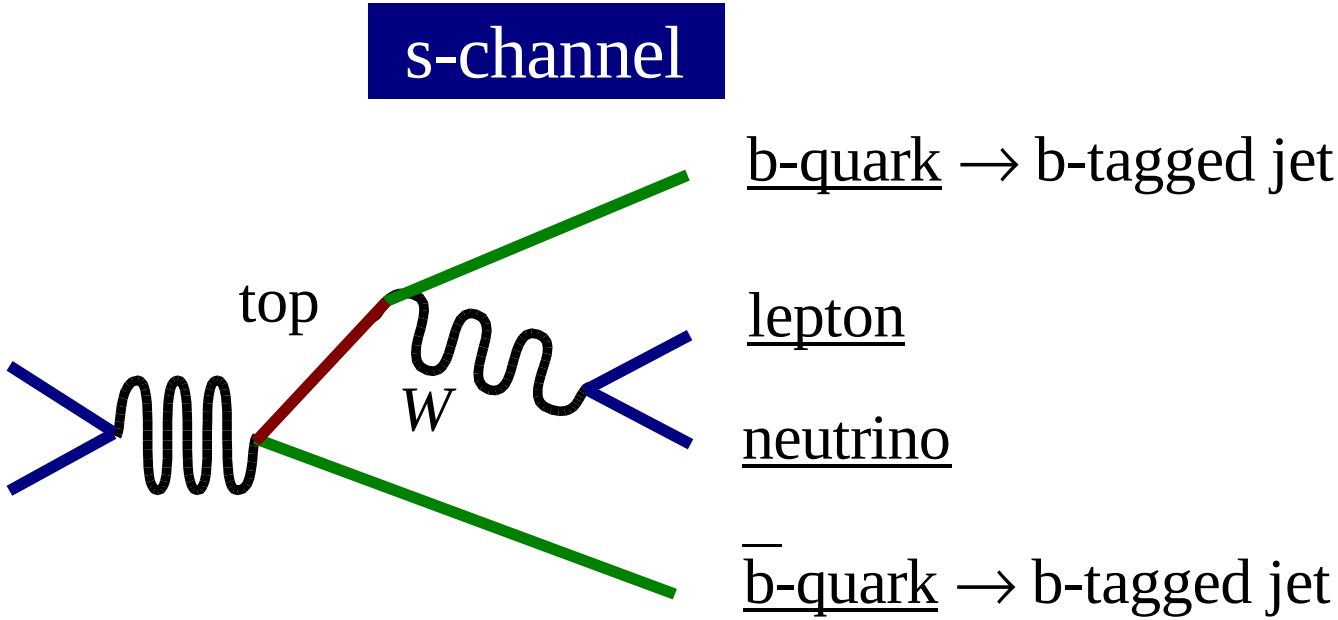


Final State Reconstruction



- Reconstruct W from lepton and $\not{E}_T$
- Reconstruct top quark from W and leading b-tagged jet
- Reconstruct light quark as leading untagged jet

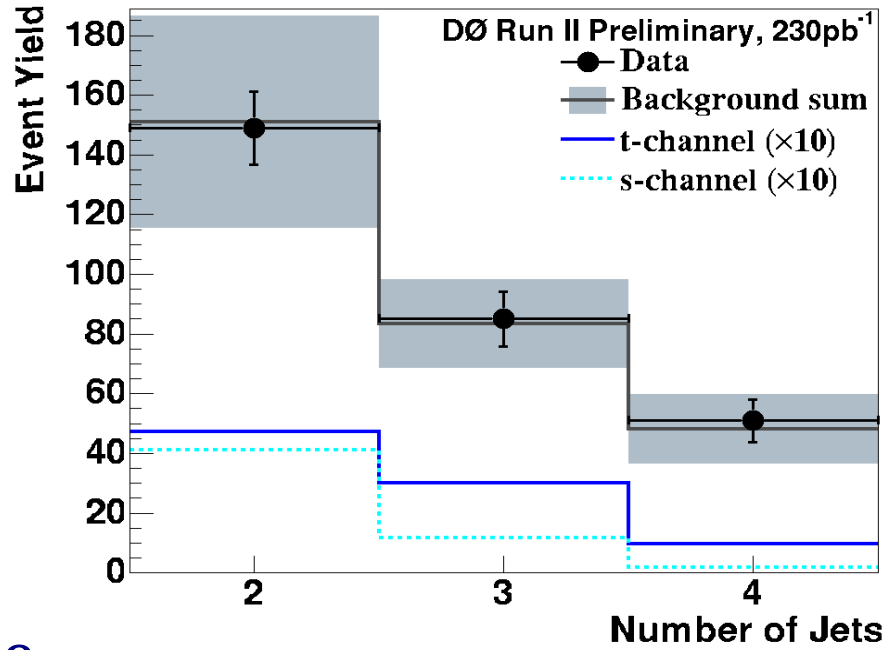
Final State Reconstruction



- Reconstruct W from lepton and $\not{E}_T$
- Reconstruct top quark from W and one of the jets using Best Jet Algorithm:
  - Pick jet for which $M(W,\text{jet})$ is closest to true top mass (175GeV)
- Reconstruct $\bar{b}$-quark as leading non-best jet

Systematic Uncertainties

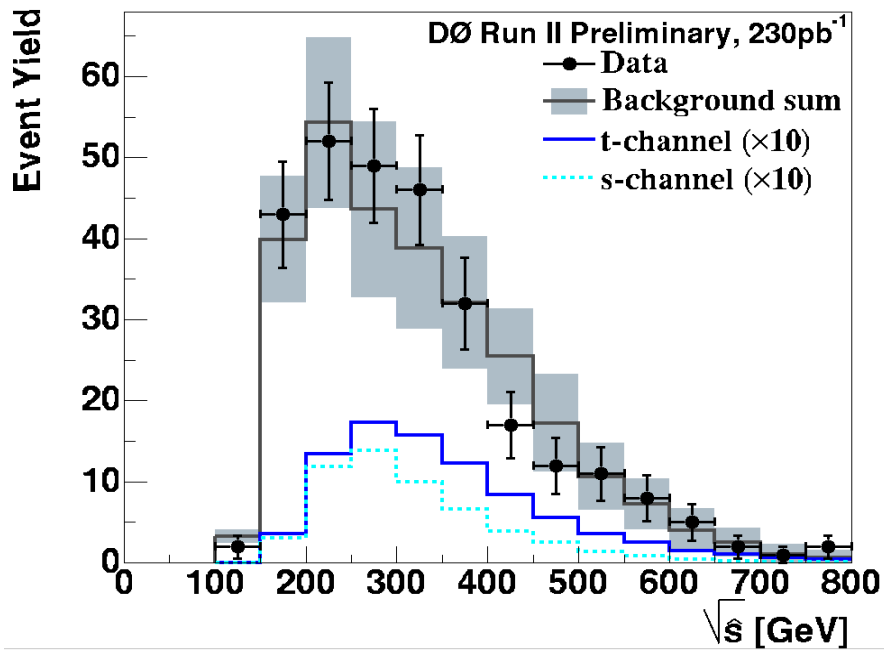
Monte Carlo Systematic Uncertainties	
Theory cross sections	15 %
SVT modeling, single (double) tag	10 %(20 %)
Jet Energy Scale	10 %
Trigger Modeling	6 %
Jet Fragmentation	6 %
Jet ID	5 %
ℓ ID	5 %



- Some uncertainties also affect shape
  - JES, b-tag and trigger modeling
- Total Uncertainty

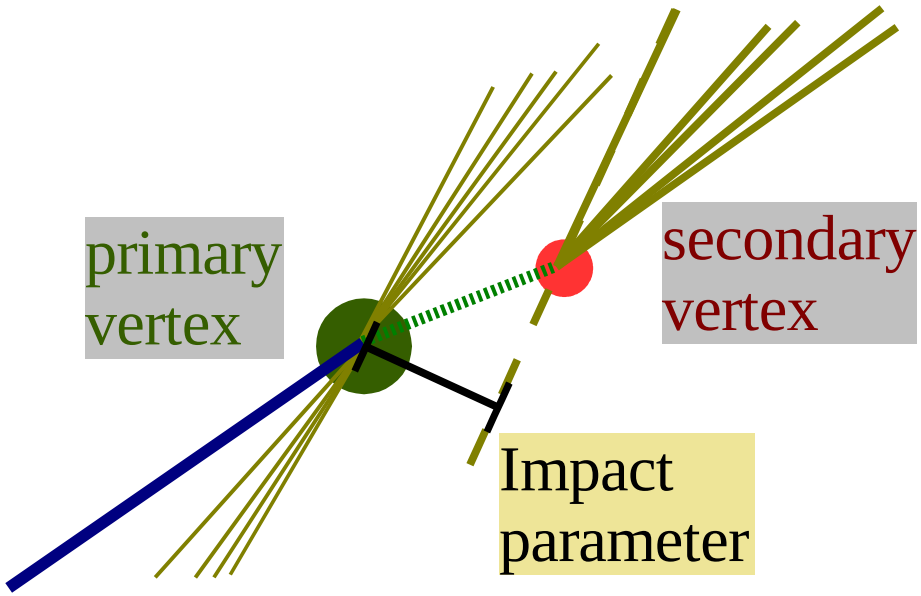
	=1 tag	≥2 tags
Signal acceptance	15%	25%
Background sum	10%	26%

Result is statistics limited



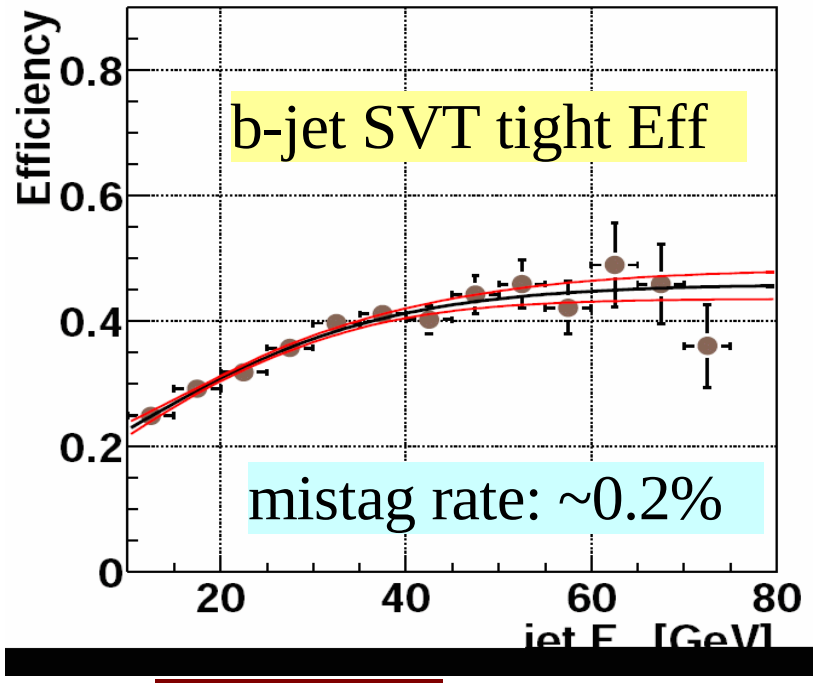
Event Selection: b-tagging

Algorithms:
- Secondary vertex tag
- Impact parameter (jet lifetime) tag



s-channel

- Final state:
  - 2 high-p_T b-jets
- ➔ Require ≥1 b-tagged jet

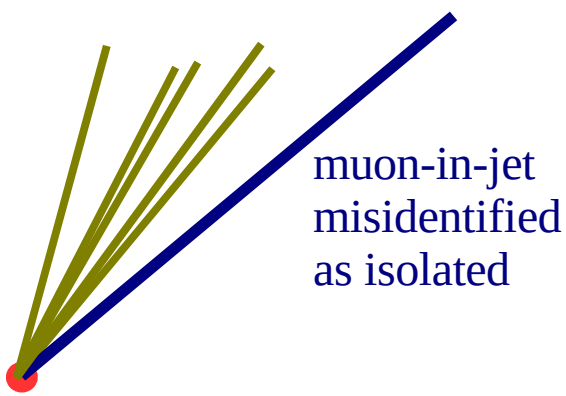


t-channel

- Final state:
  - 1 high-p_T b-jet
  - 1 high-p_T light quark jet
- ➔ Require ≥1 b-tagged jet
- ➔ Require ≥1 untagged jet

Mis-reconstructed Events?

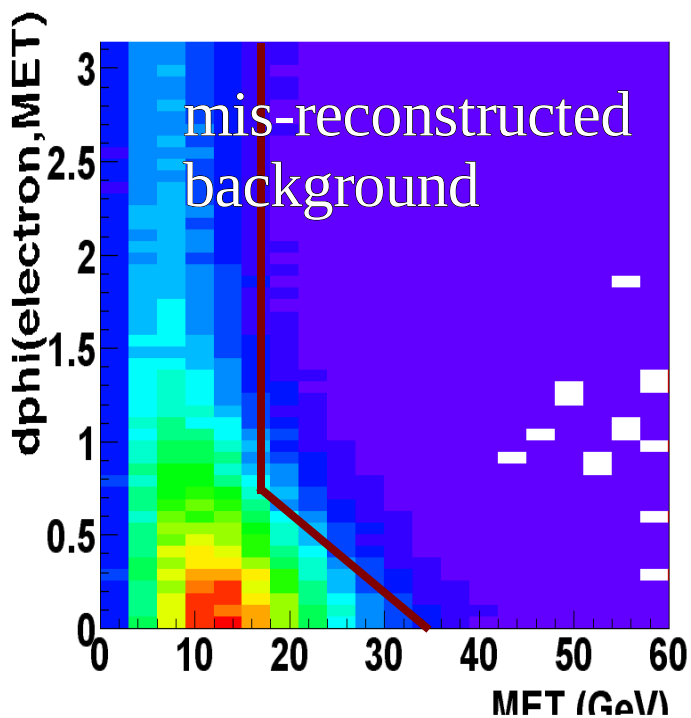
- Cosmic rays (muons)
- Mis-reconstructed vertex
  - Affects missing transverse energy
- Mis-reconstructed jets
  - fake electron
  - fake isolated muon

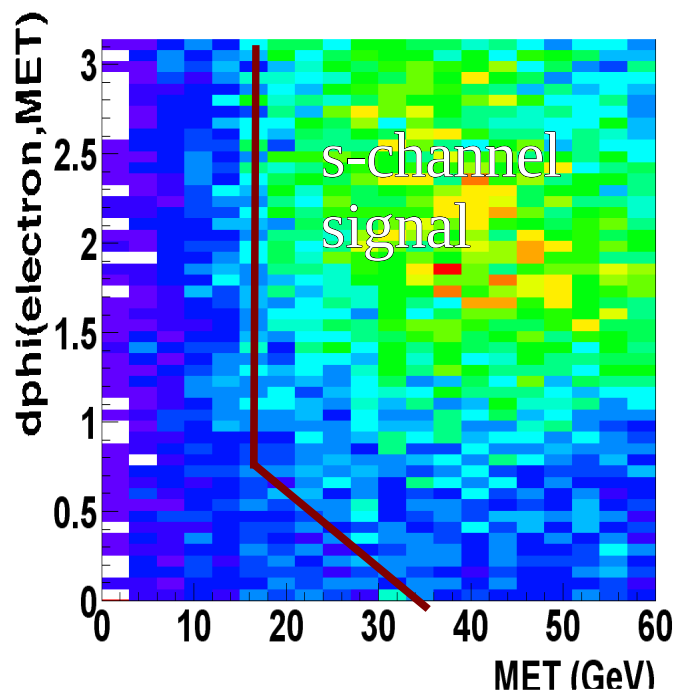


➔ Primary vertex constraints

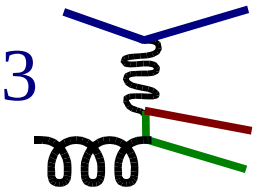
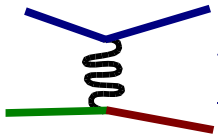
- Primary vertex with ≥3 tracks
- Lepton is required to originate from primary vertex

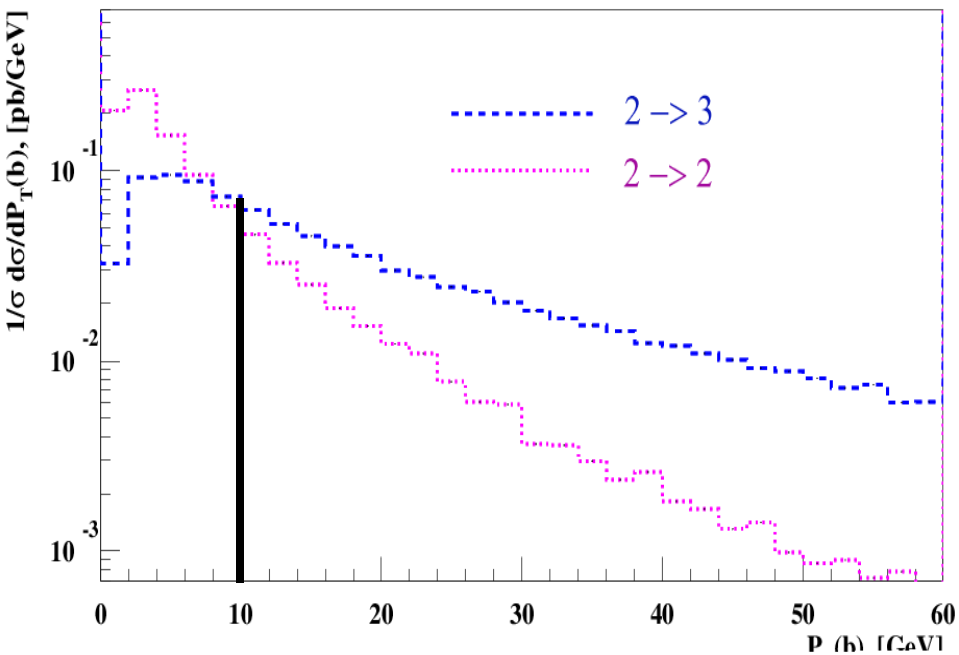
➔ Triangle Cuts

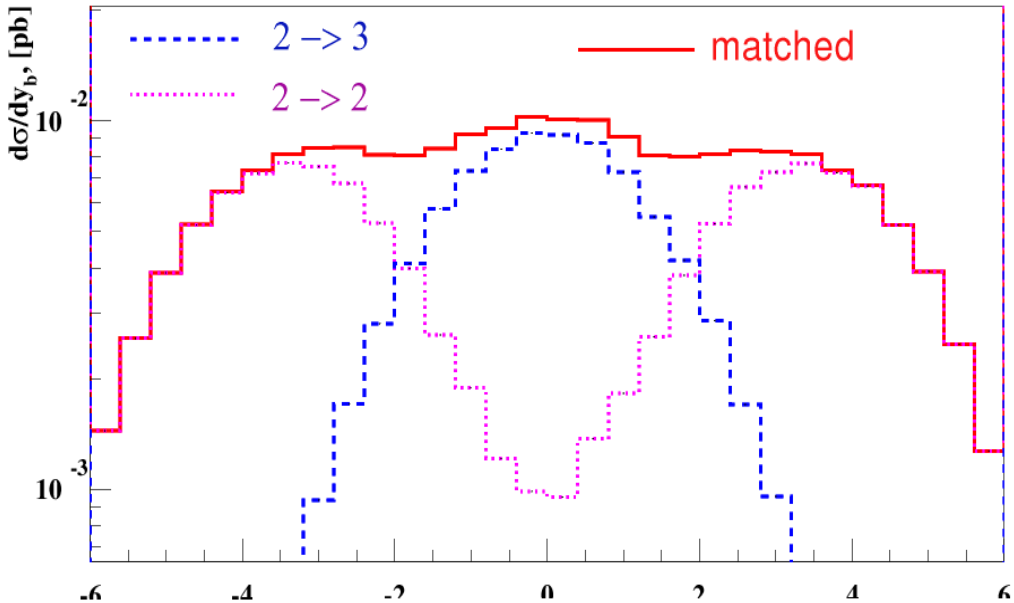




Signal Modeling

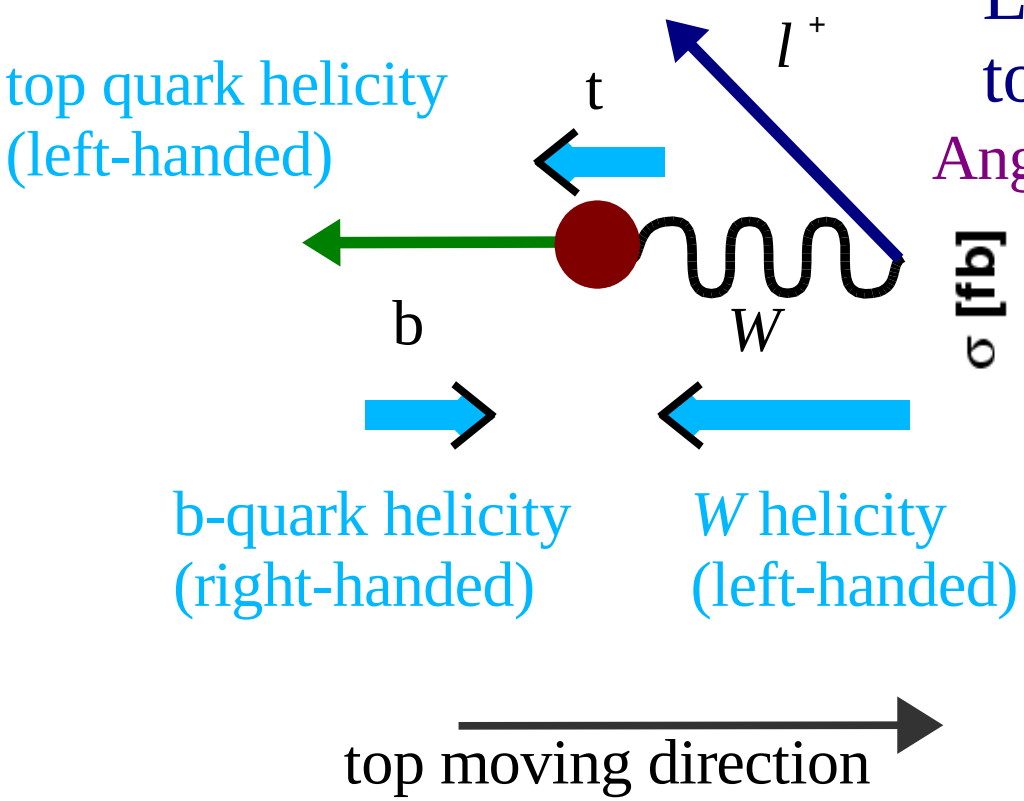
- CompHEP-based generator
  - Includes $O(\alpha_s)$ diagrams → reproduces NLO distributions
  - Including top quark spin correlations
- Normalize to NLO cross sections
- t-channel: match 2→3  and 2→2  processes





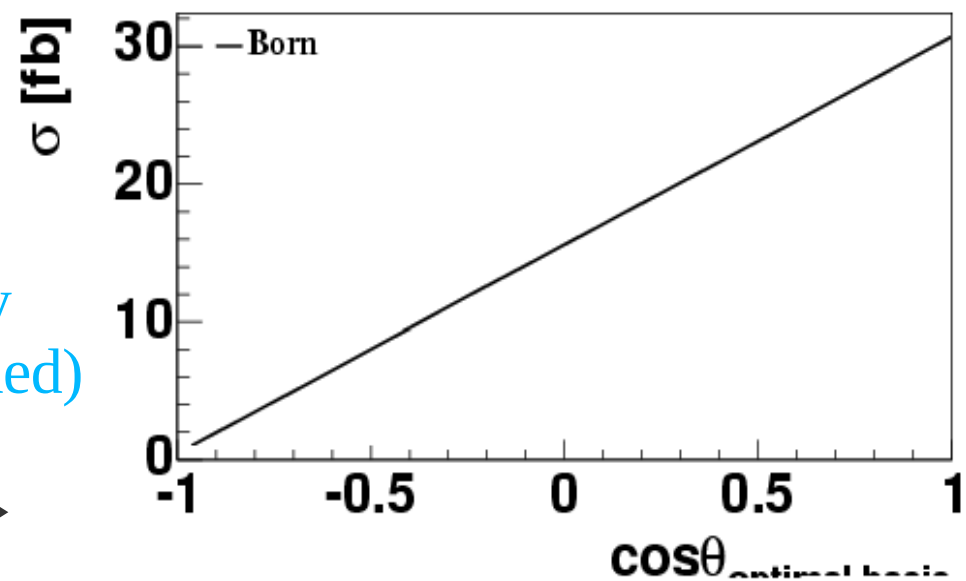
Top Quark Spin

- Top Quark decays before it hadronizes
  - Full spin information is preserved in the decay products
  - Electroweak charged current interaction is left-handed
- Top polarization in the top rest frame:

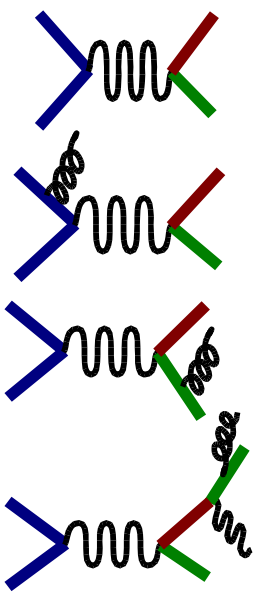


Lepton moves along
top spin direction

Angle between light quark and lepton:

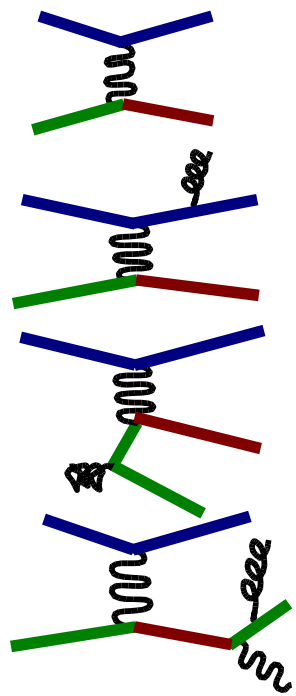


Relative Contributions to NLO rate including Top Production and Decay



s-channel	
NLO rate	0.86pb
Born level	65%
Initial state	22%
Final state	11.5%
Decay	1.2%

Cao, RS, Yuan hep-ph/0409040

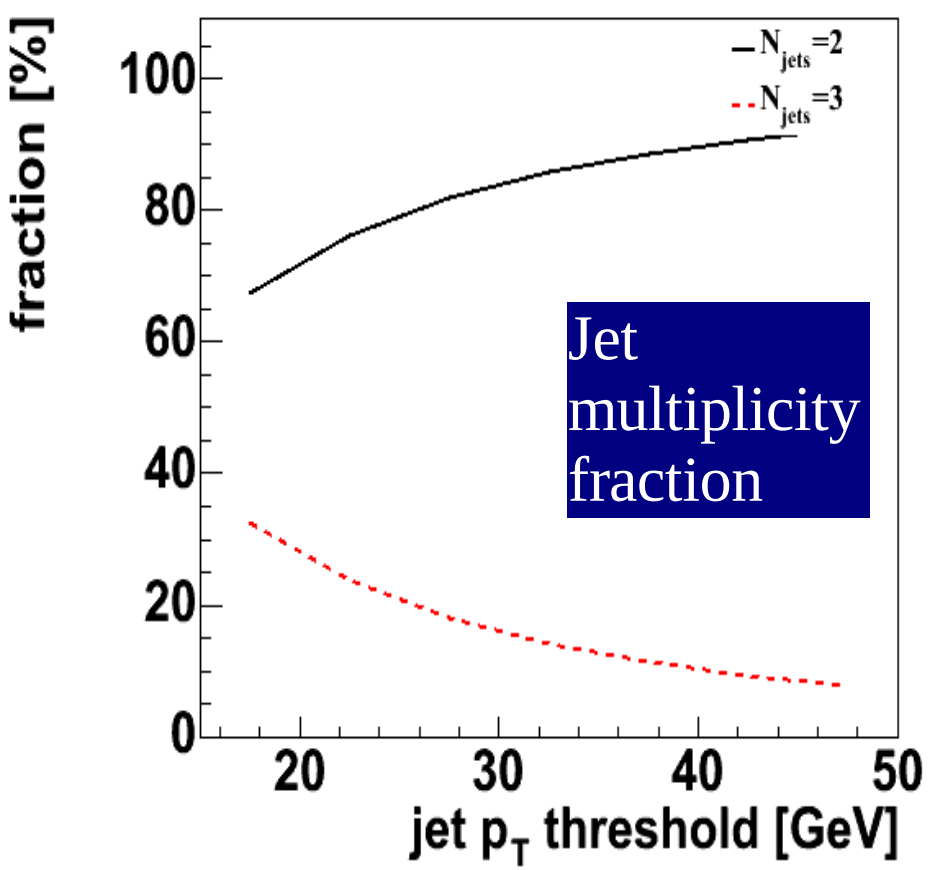


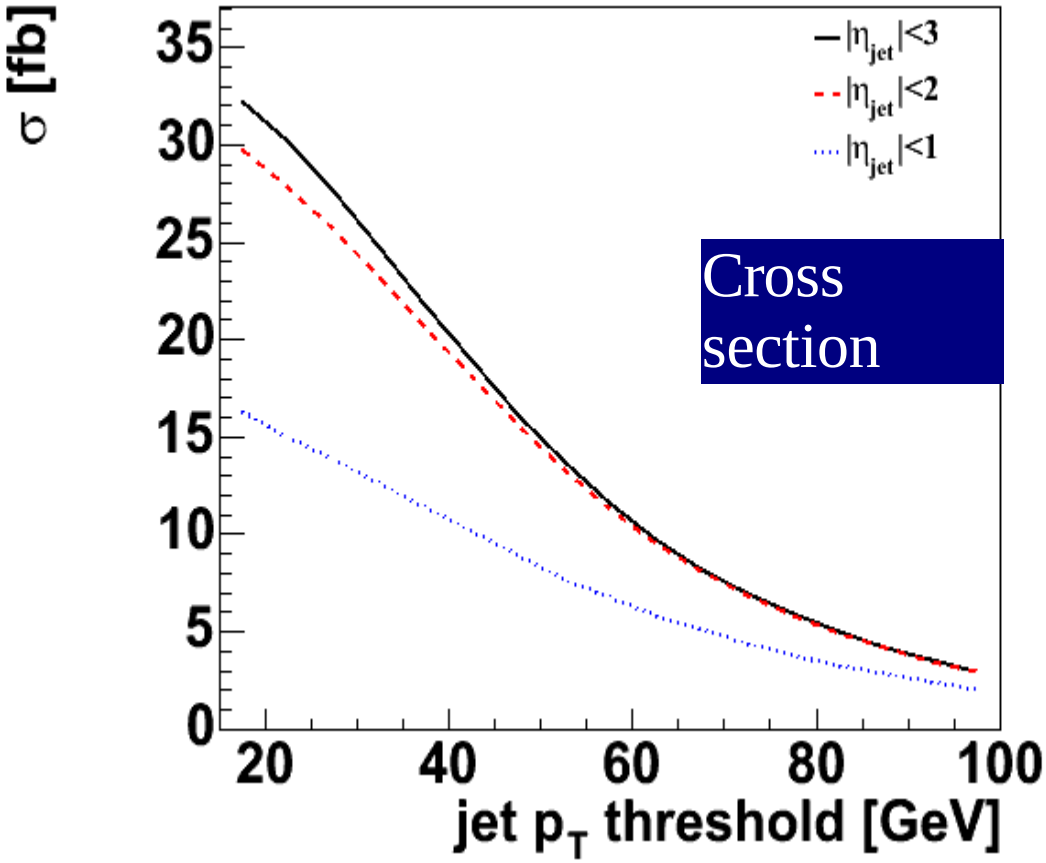
t-channel	
NLO rate	1.9pb
Born level	105%
Light quark	13%
Heavy quark	-11%
Decay	-7%

- O(as) corrections large for the s-channel
  - Only small rate correction for the t-channel
    - Decay correction is 2nd order effect, top mass and top width

Kinematic effect of $O(\alpha_s)$ Corrections

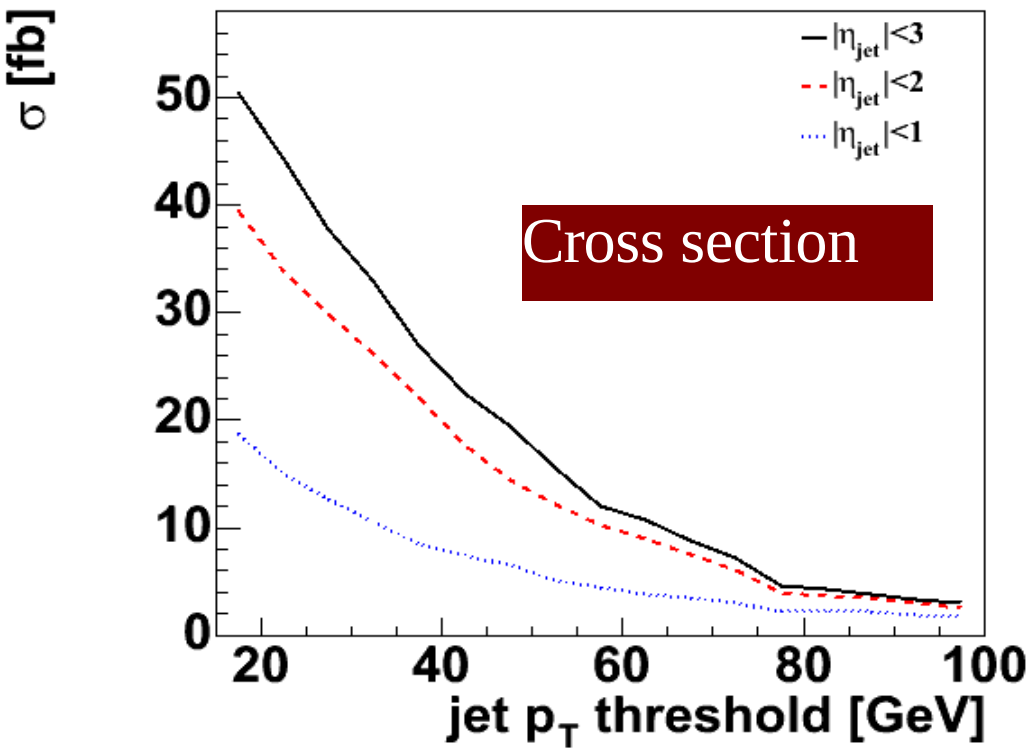
- After simple parton level selection cuts:
  - 1 lepton, p_T>15GeV, $|\eta|$<2, missing E_T>15GeV
  - ≥2 jets, p_T>15GeV, $|\eta|$<3
- Example: s-channel jet multiplicity

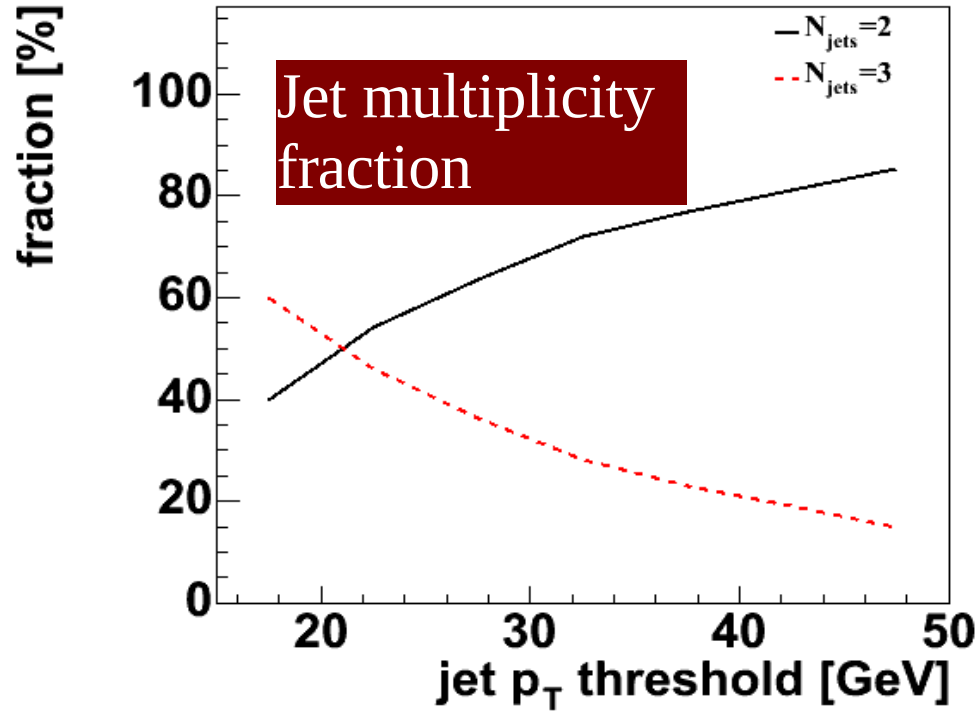


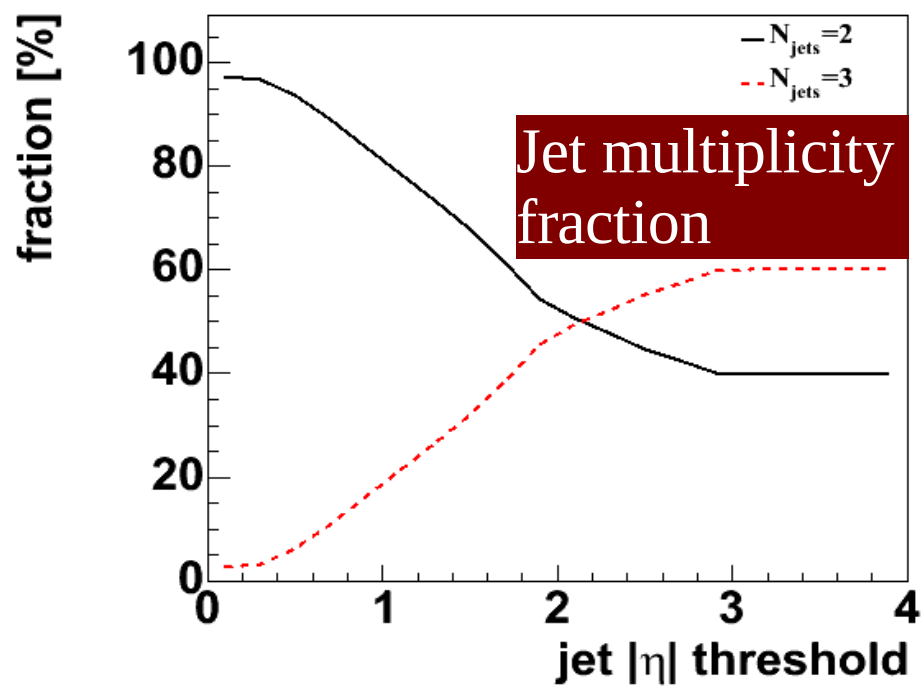


Cao, RS, Yuan hep-ph/0409040

Single Top t-channel at NLO







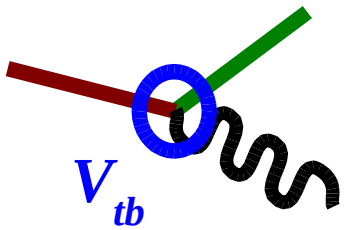
- After simple cuts
  - Large number of 3-jet events
    - Depends strongly on jet p_T and η cuts

Tevatron Single Top Goals

- Observe single top quark production

Tevatron Single Top Goals

- Observe single top quark production
- Measure production cross sections $\rightarrow V_{tb}$



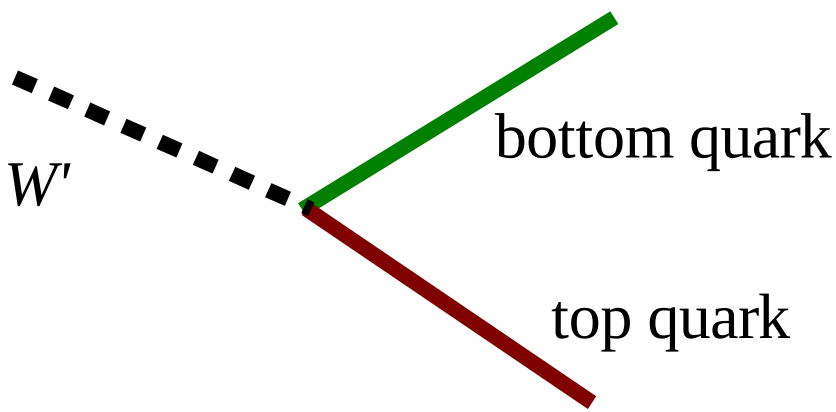
CKM Matrix

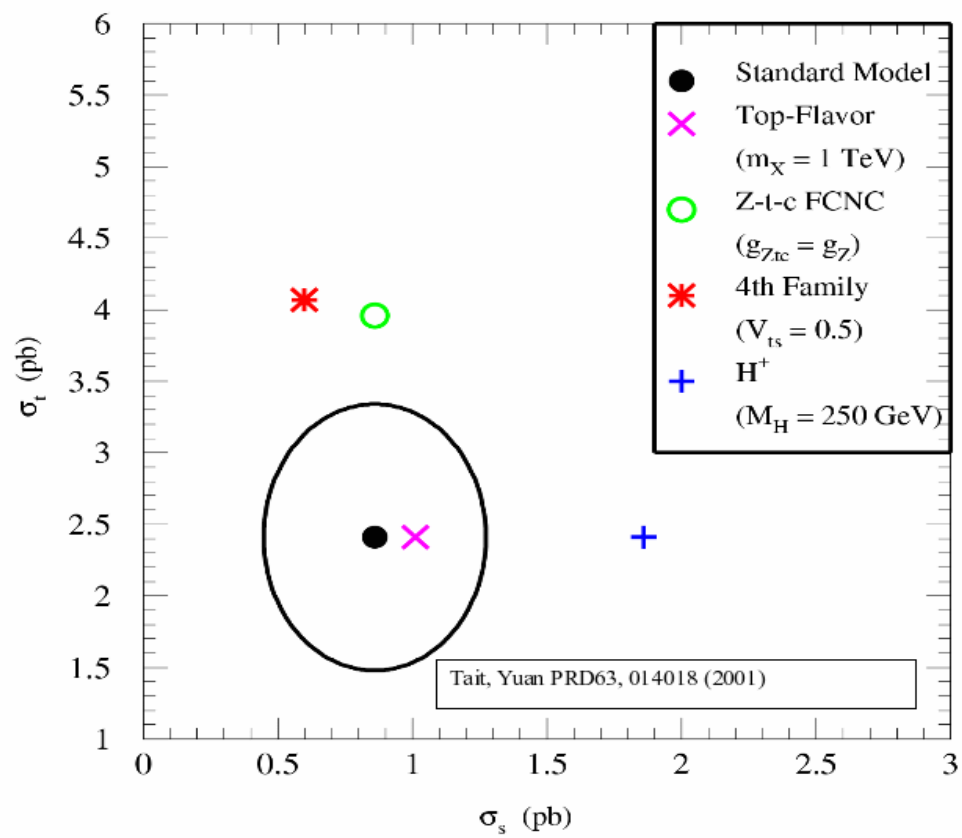
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Tevatron Single Top Goals

- Observe single top quark production
- Measure production cross sections $\rightarrow V_{tb}$
- Look for physics beyond the Standard Model
  - Different sensitivity for s-channel and t-channel

Example:Top-Flavor



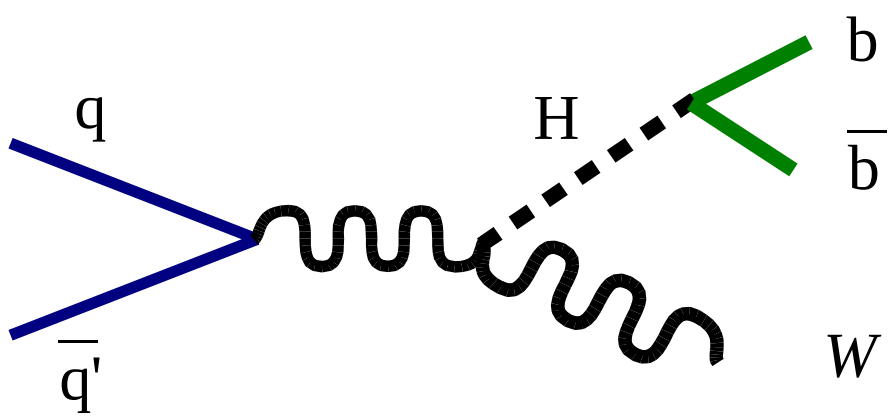


Tevatron Single Top Goals

- Observe single top quark production
- Measure production cross sections $\rightarrow V_{tb}$
- Look for physics beyond the Standard Model
- Study top quark spin correlations – probe V-A
  - Physics with ~100% polarized top quarks

Tevatron Single Top Goals

- Observe single top quark production
- Measure production cross sections $\rightarrow V_{tb}$
- Look for physics beyond the Standard Model
- Study top quark spin correlations – probe V-A
- Irreducible background in searches for associated Higgs production



Gateway to the Higgs