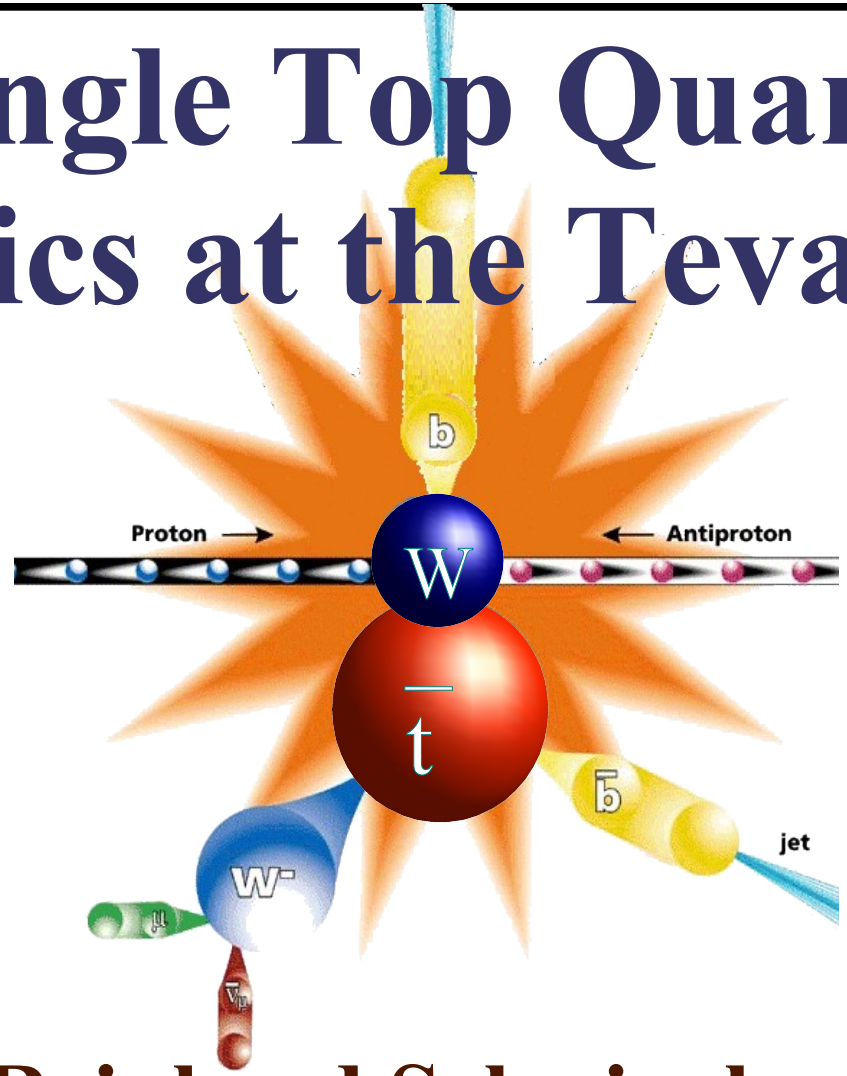
# Single Top Quark Physics at the Tevatron





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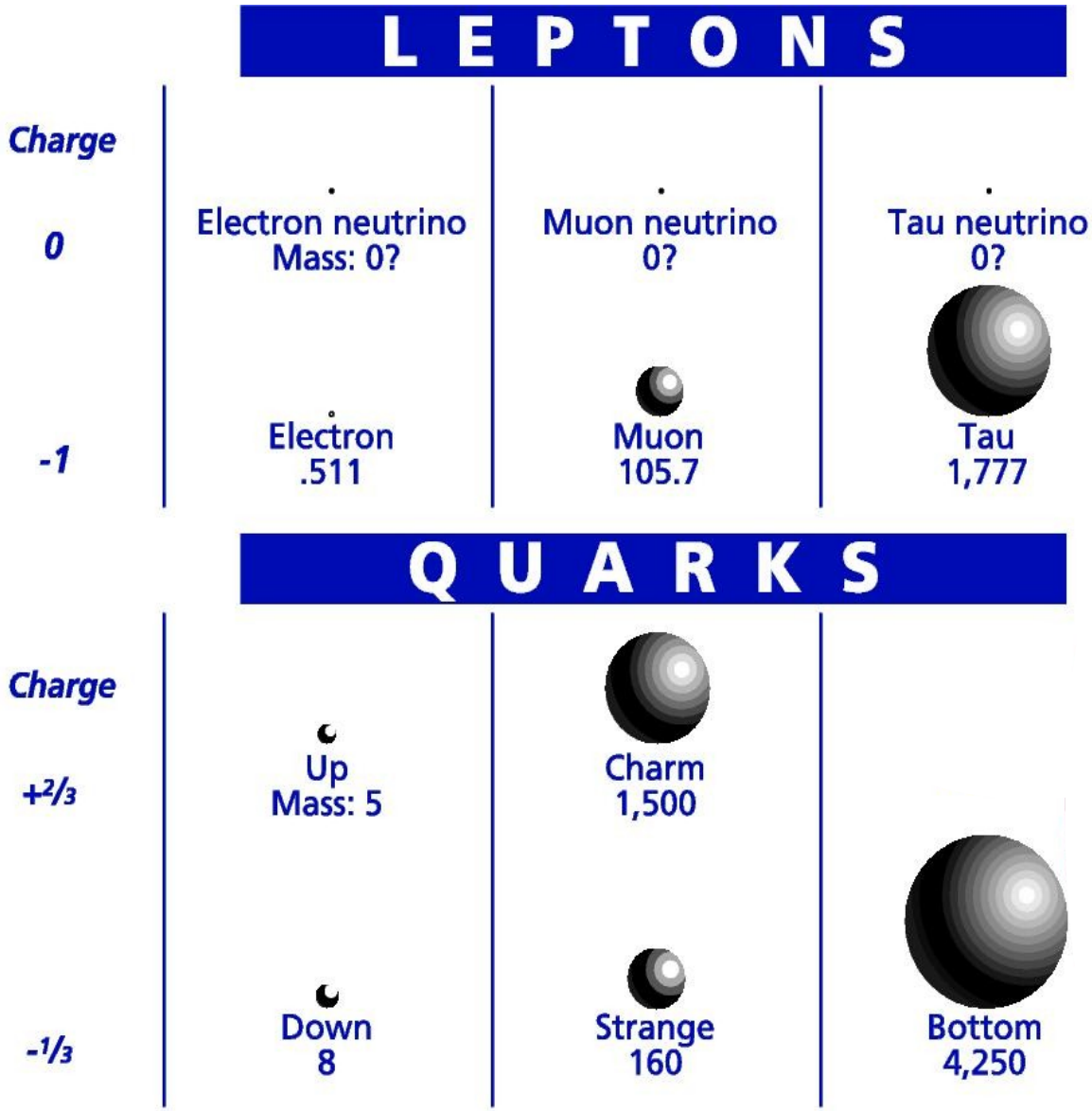
Harvard University LPPC Seminar, 12/6/2005

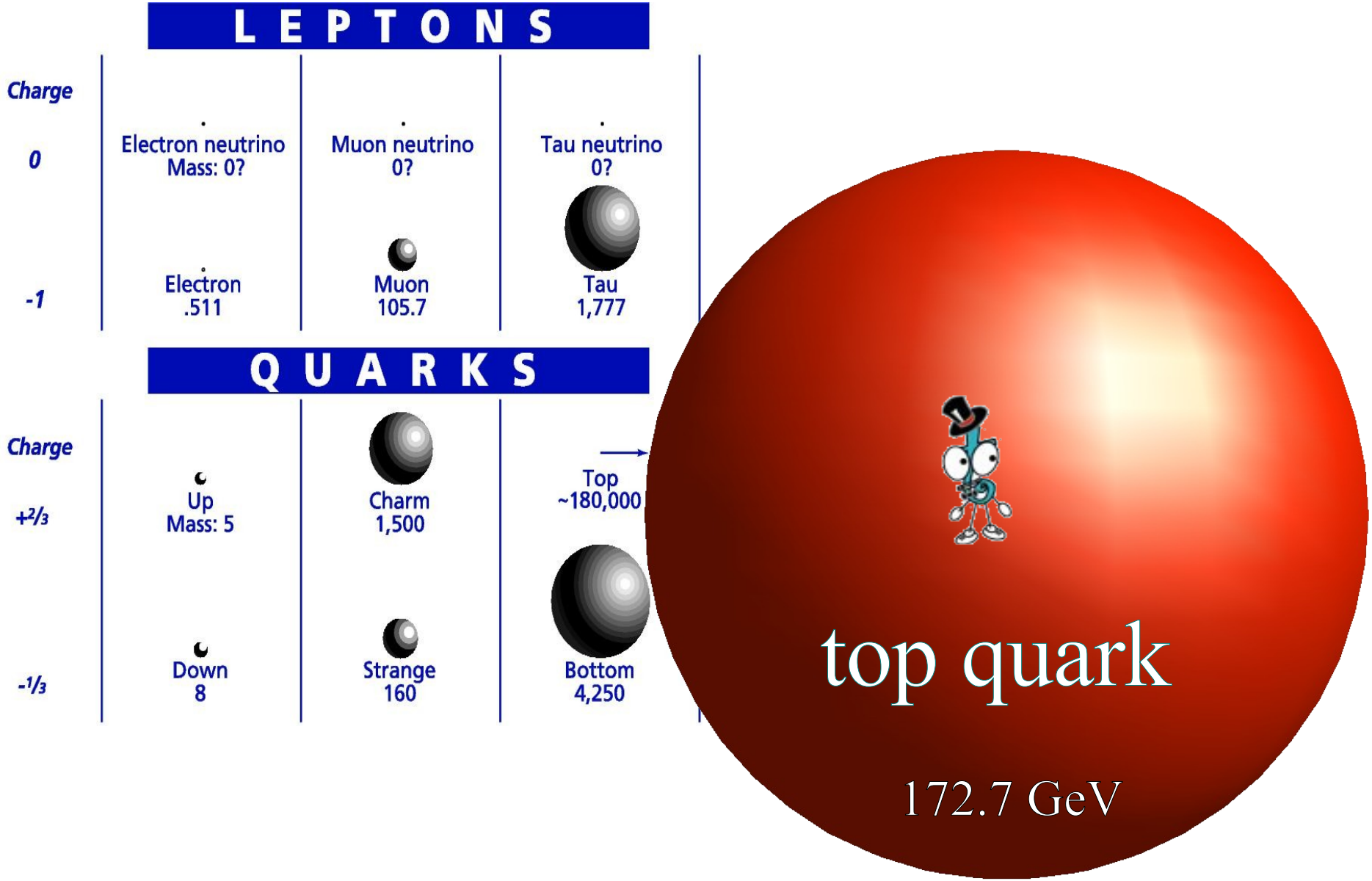
# Outline

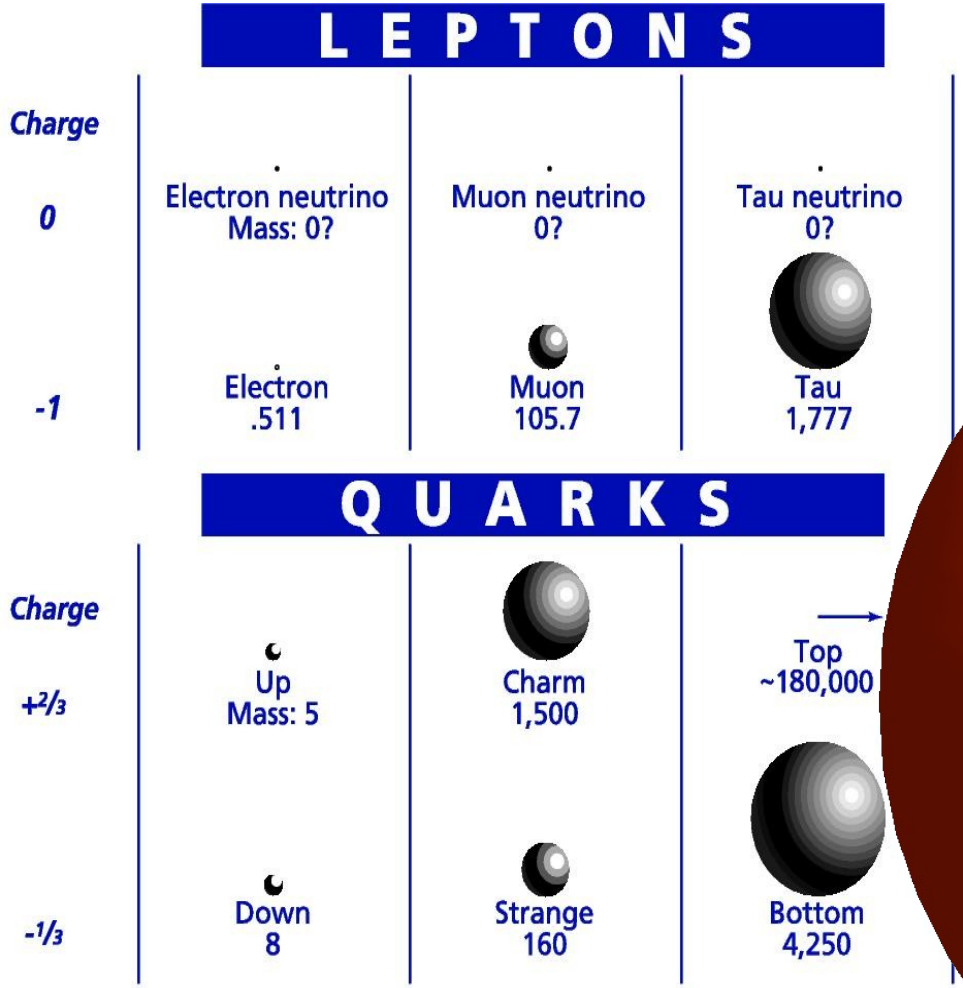
- Introduction
  - Electroweak top quark production
- Search for single top at the Tevatron
  - Detectors
  - Event selection
  - Event analysis
  - Results from CDF and DØ
- Outlook
  - Single top discovery?
  - Future studies of top quark couplings
- Conclusions

# Fundamental Fermions

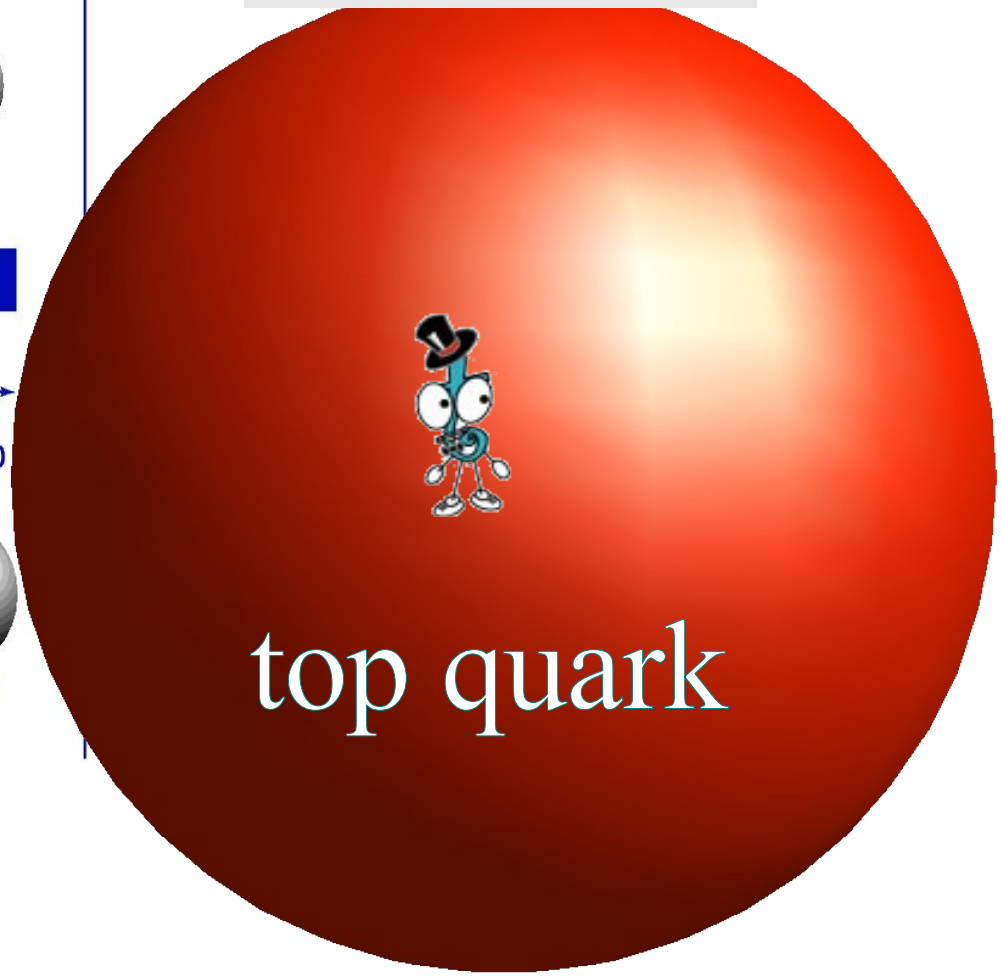


# Fundamental Fermions



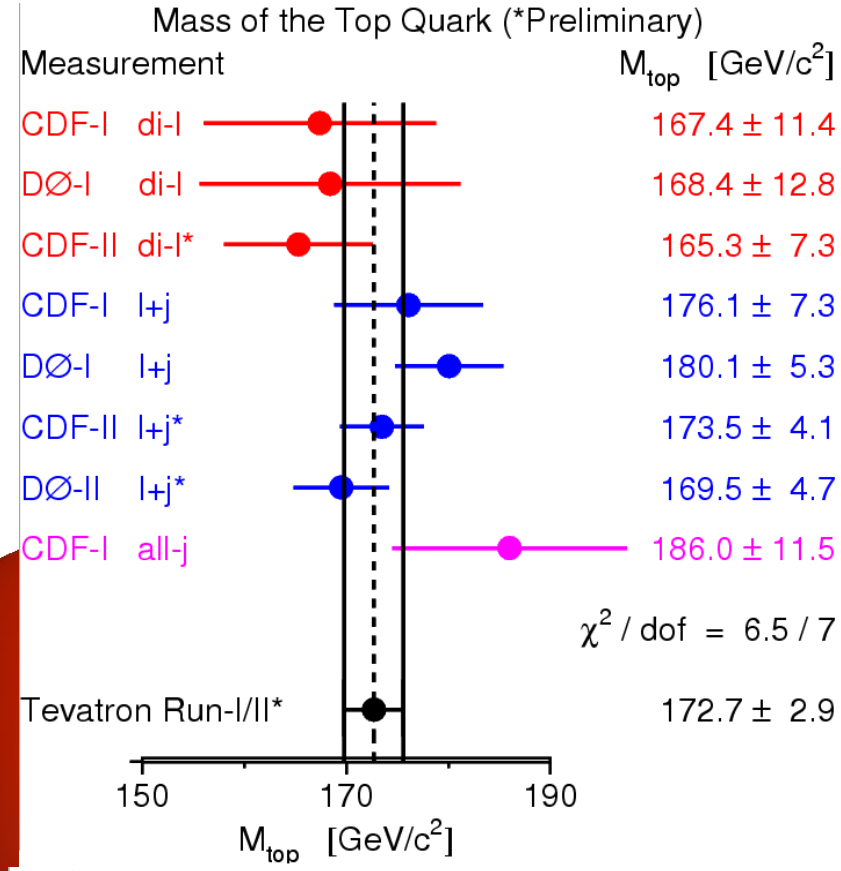


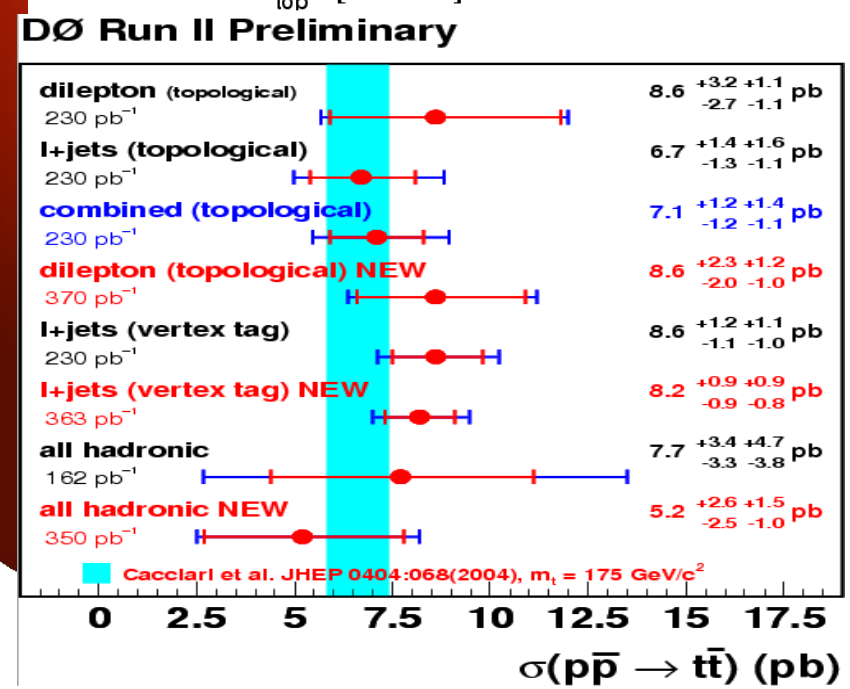
KING OF THE FERMIONS



# 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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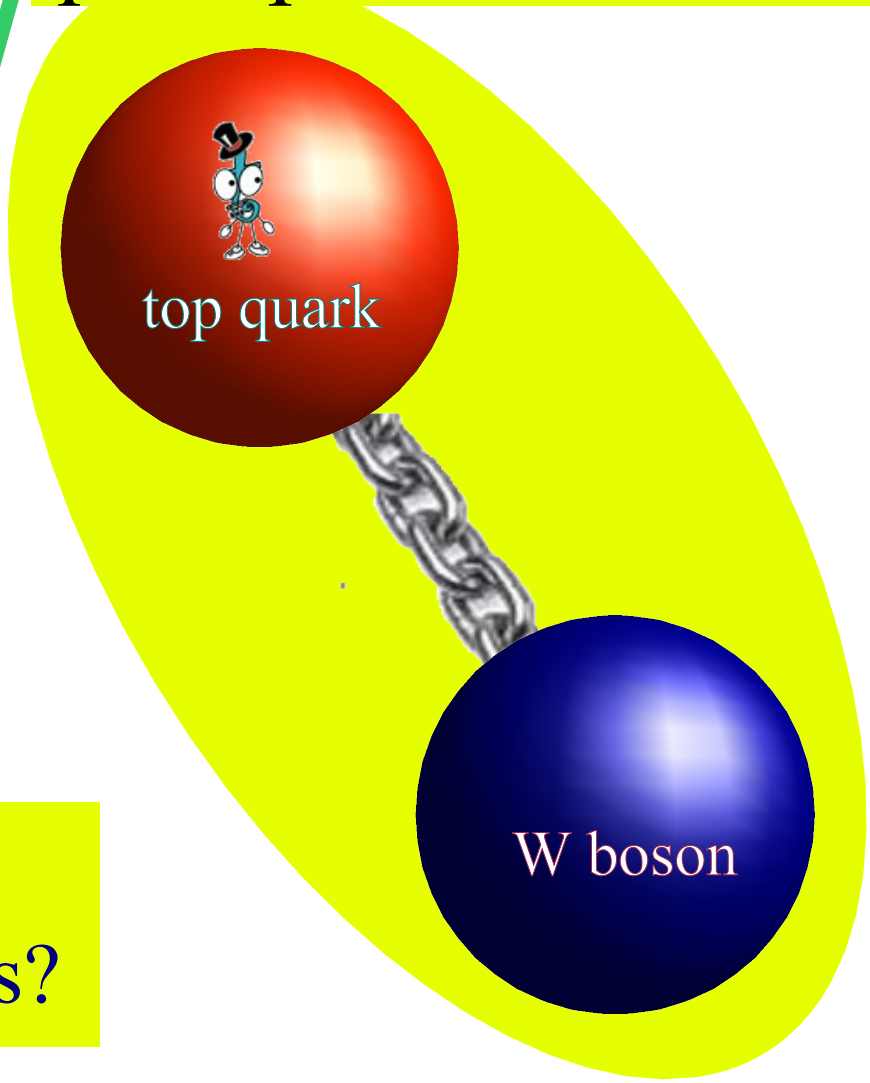
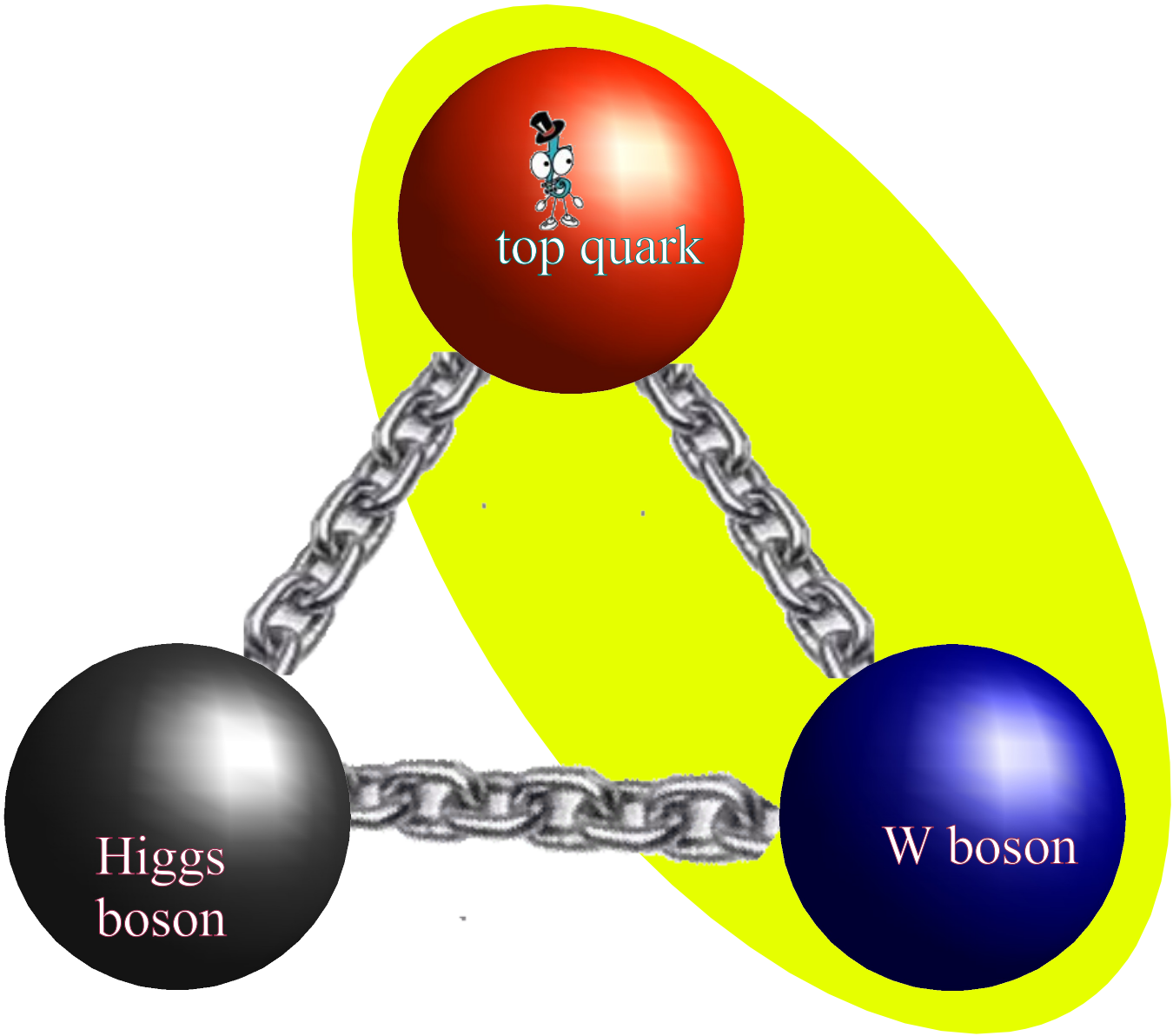
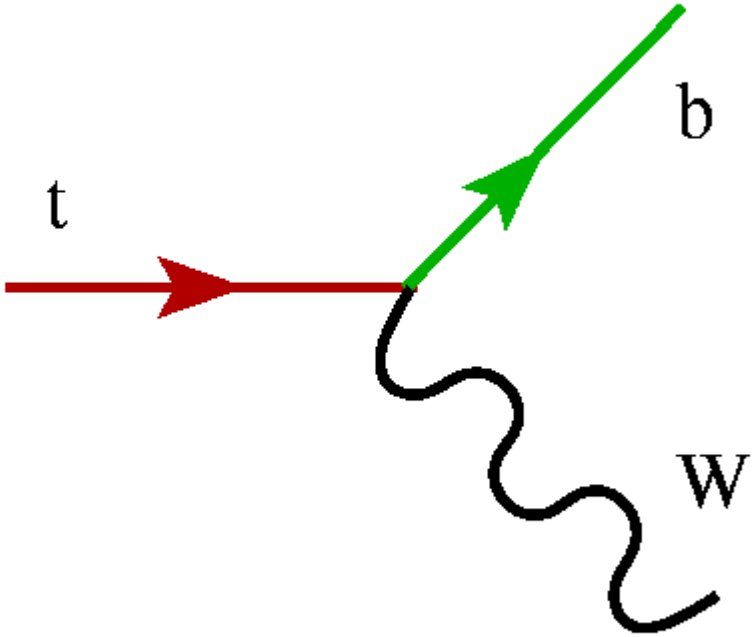
Study in single top quark production



# Key to electroweak symmetry breaking



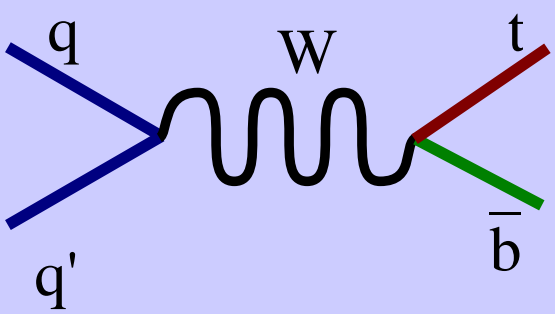
# Top Quark Electroweak Charged Current Interaction




top quark decay

# SM single top production

**s-channel**



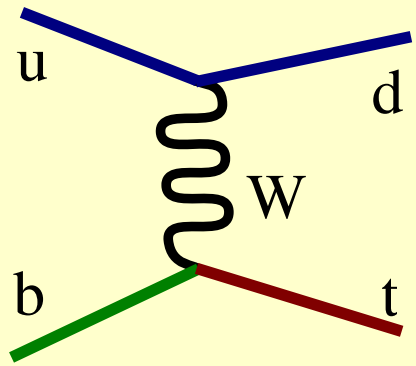

$\sigma_{NLO}$

**TeV: 0.88 pb (±8%)**

**LHC, t: 6.6 pb (±10%)**

**LHC, $\bar{t}$: 4.1 pb (±10%)**

**t-channel**



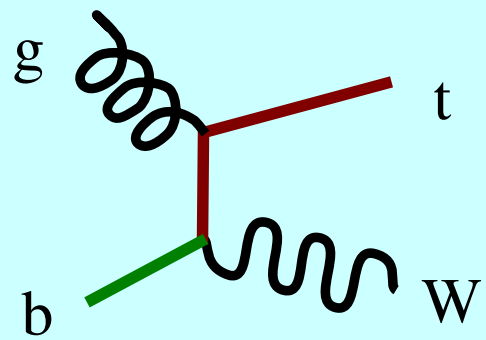

NLO

**1.98pb (±11%)**

**156 pb (±5%)**

**91 pb (±5%)**

**Associated production**




NLO

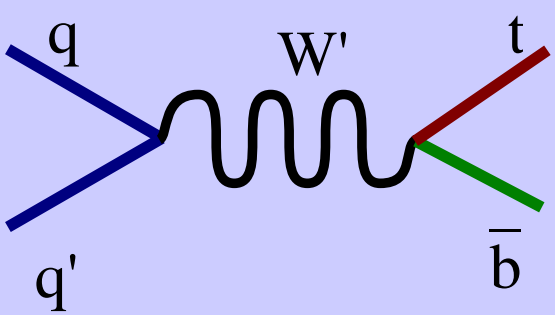
**0.14 pb (±15%)**

**34 pb (±10%)**

**34 pb (±10%)**

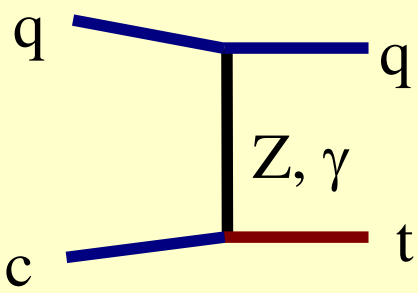
# New Physics

s-channel



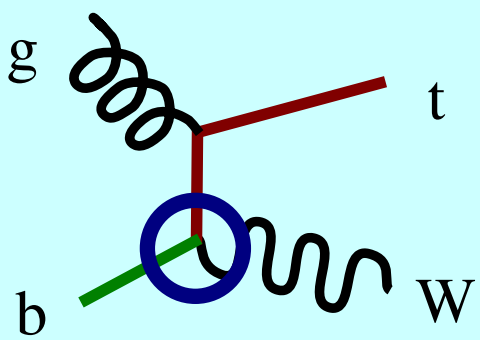

New heavy boson

t-channel

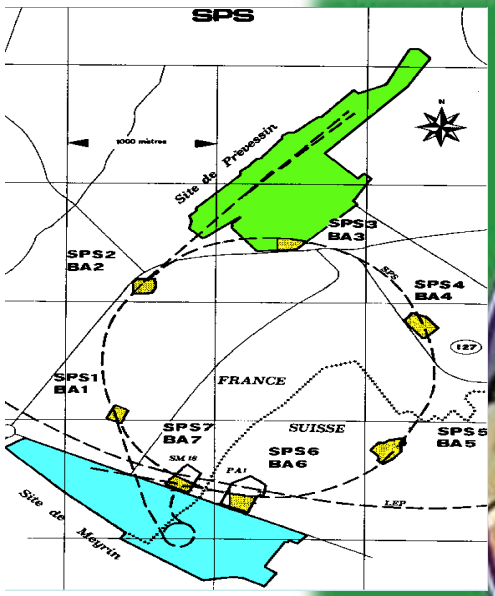



FCNC

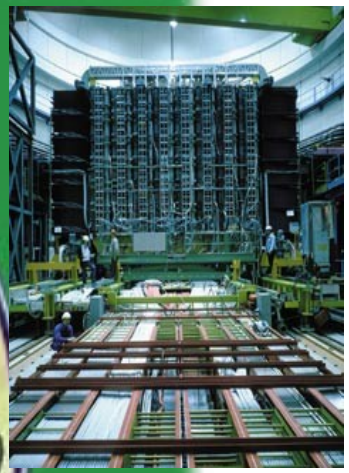
Associated production




Modified Wtb coupling


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

WHERE IN THE
WORLD

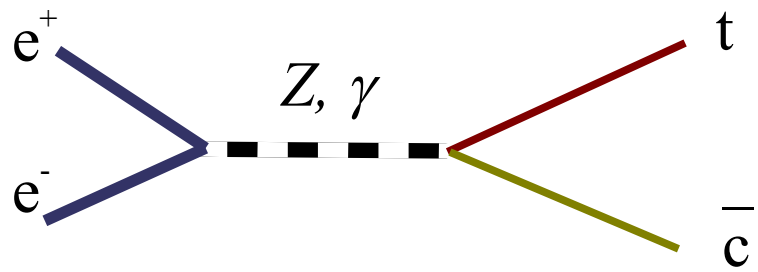


# Single Top

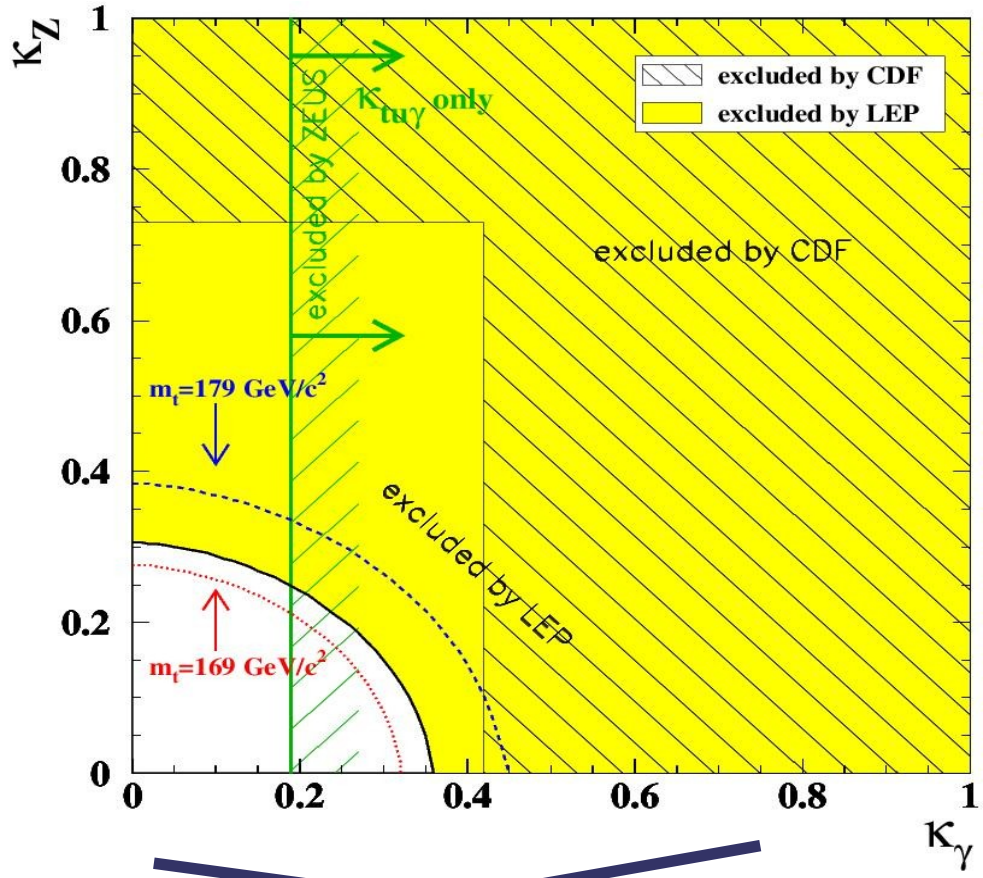
HERA
PETRA

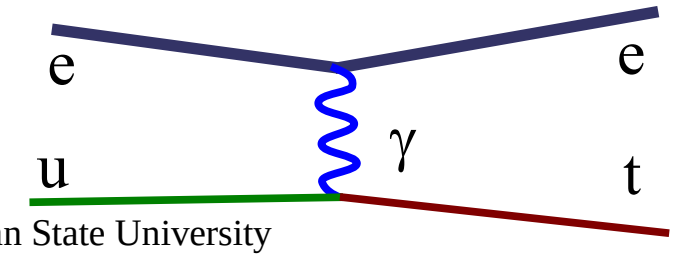
# Single Top at LEP and Hera: FCNC

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

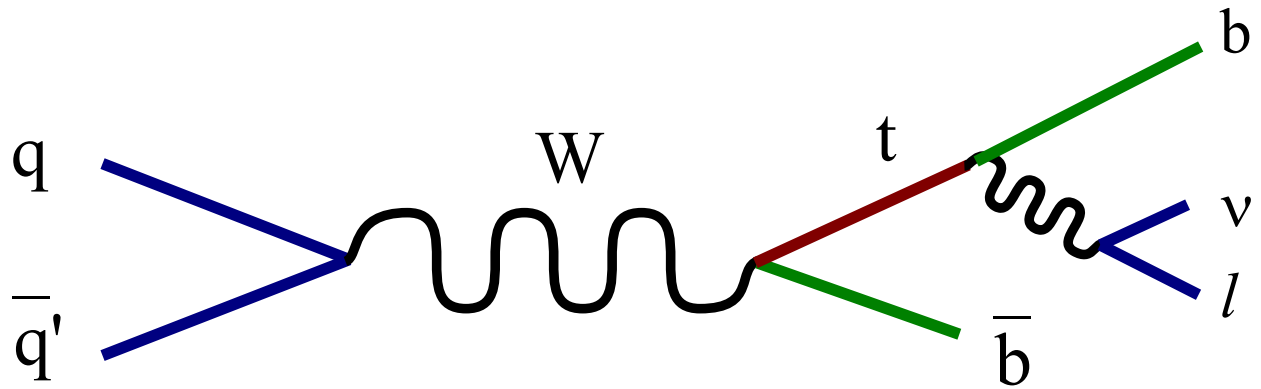



- Hera:
  - $ep \rightarrow et$

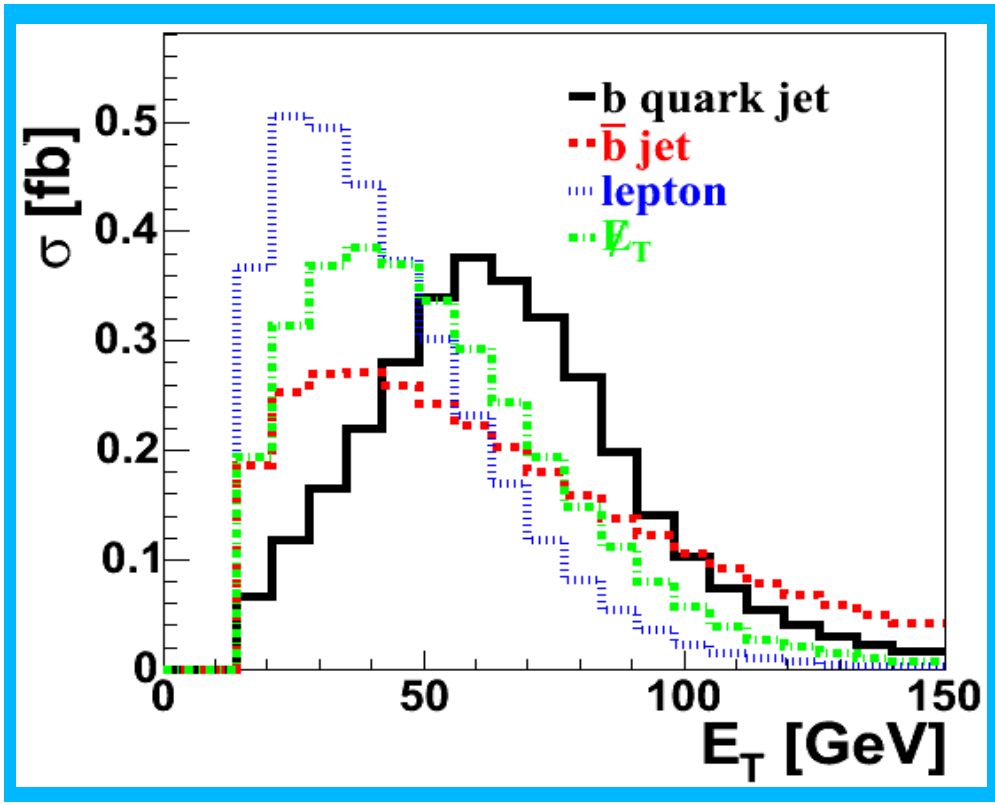


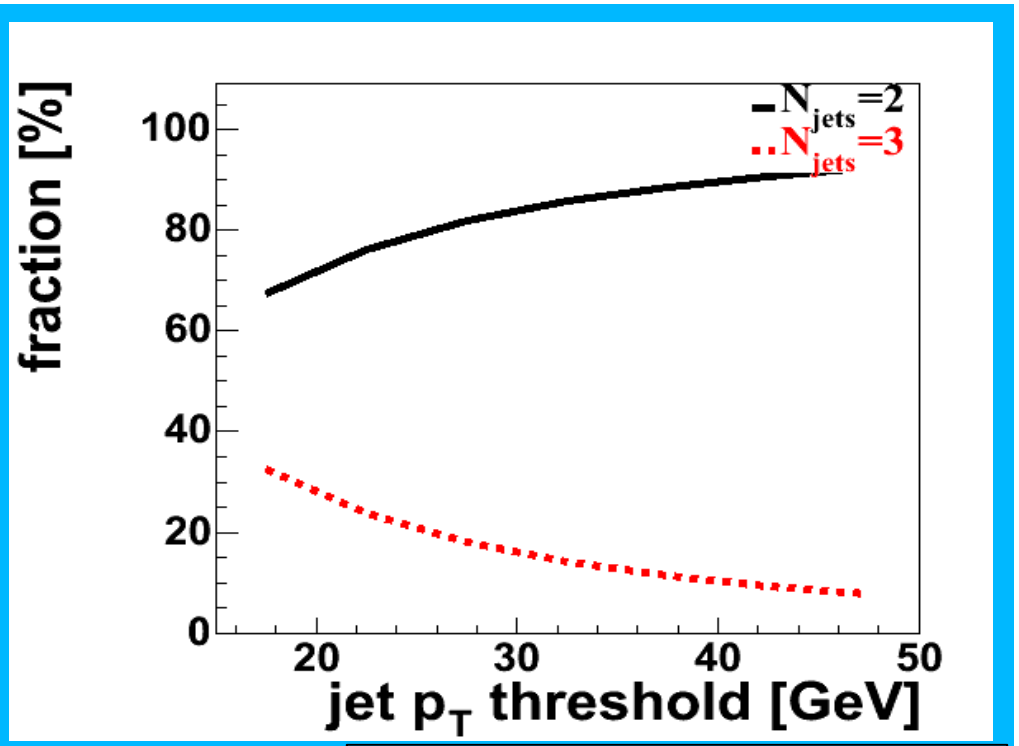



# Tevatron s-channel Signature



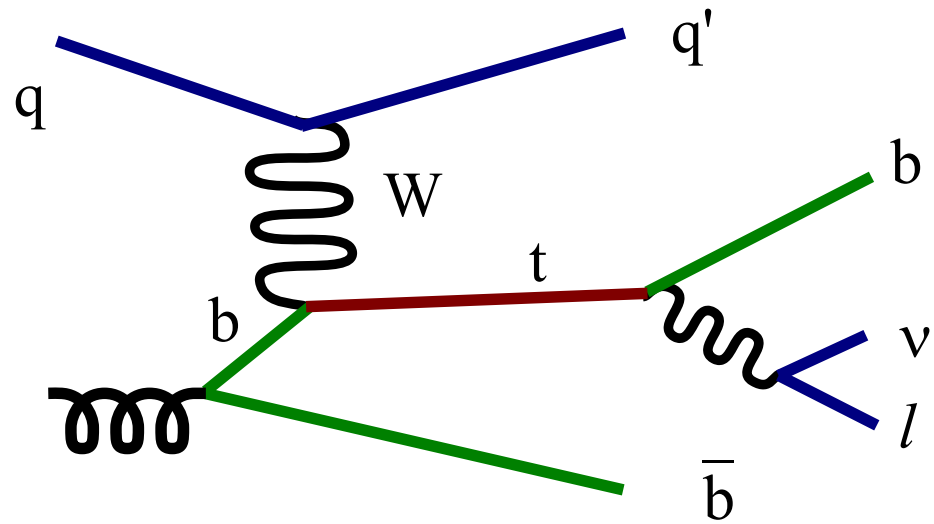

"*tb*"



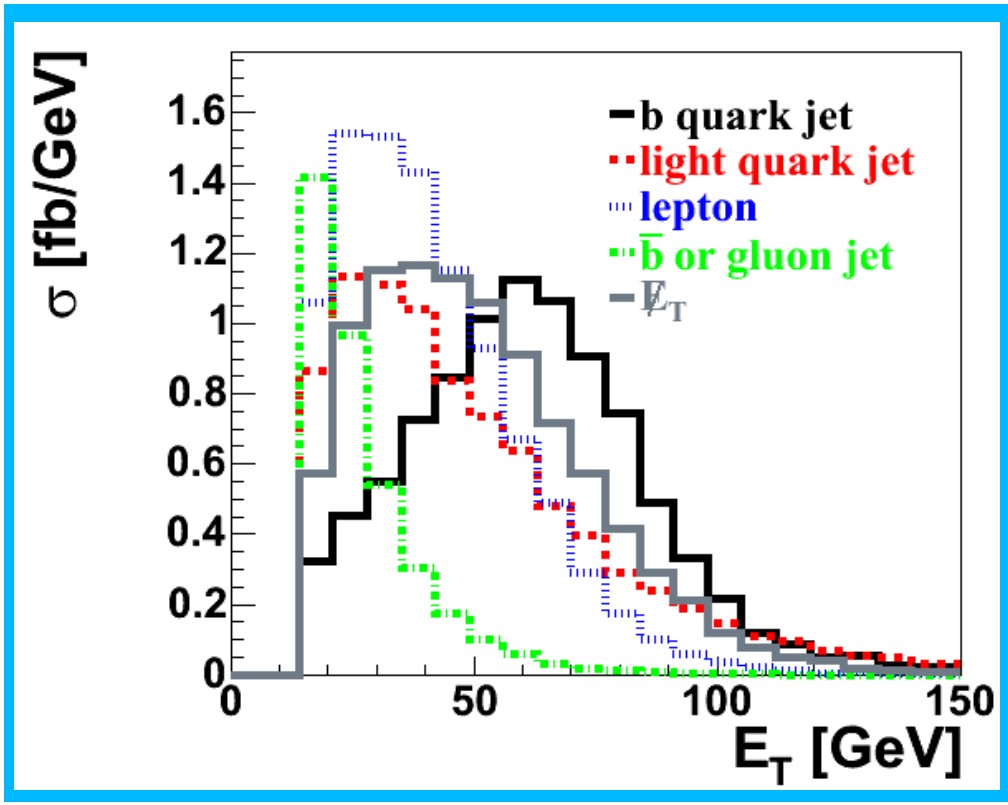



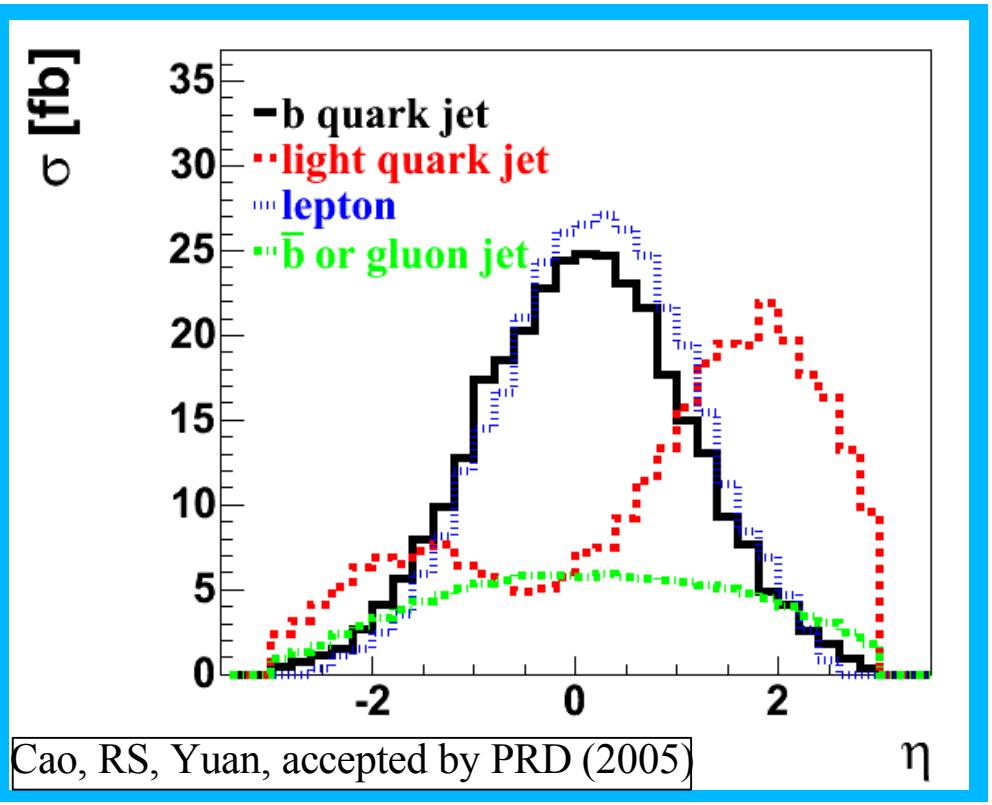

Cao, RS, Yuan PRD74, 054023 (2005)

# Tevatron t-channel Signature




*"tqb"*




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

# Tevatron Single Top Goals

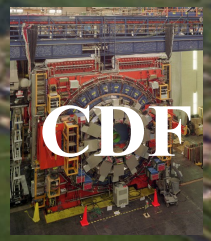
| Production cross sections: | *s-channel* | *t-channel* | *s+t* |
|---|---|---|---|
| NLO calculation: | **0.88pb (±8%)** | **1.98pb (±11%)** | |
| Run I 95% CL limits, DØ: | < 17pb | < 22pb | |
| CDF: | < 18pb | < 13pb | < 14pb |

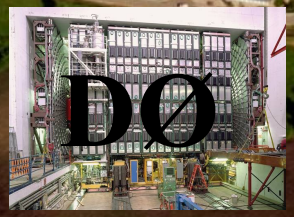
- Observe single top quark production
  - Tevatron discovery!
- Measure production cross sections → $V_{tb}$
- Look for physics beyond the Standard Model
  - Coupled to the heavy top quark
- Study top quark spin correlations
- Understand as background
  - In searches for associated Higgs production

# Experimental Detection of Single Top Events

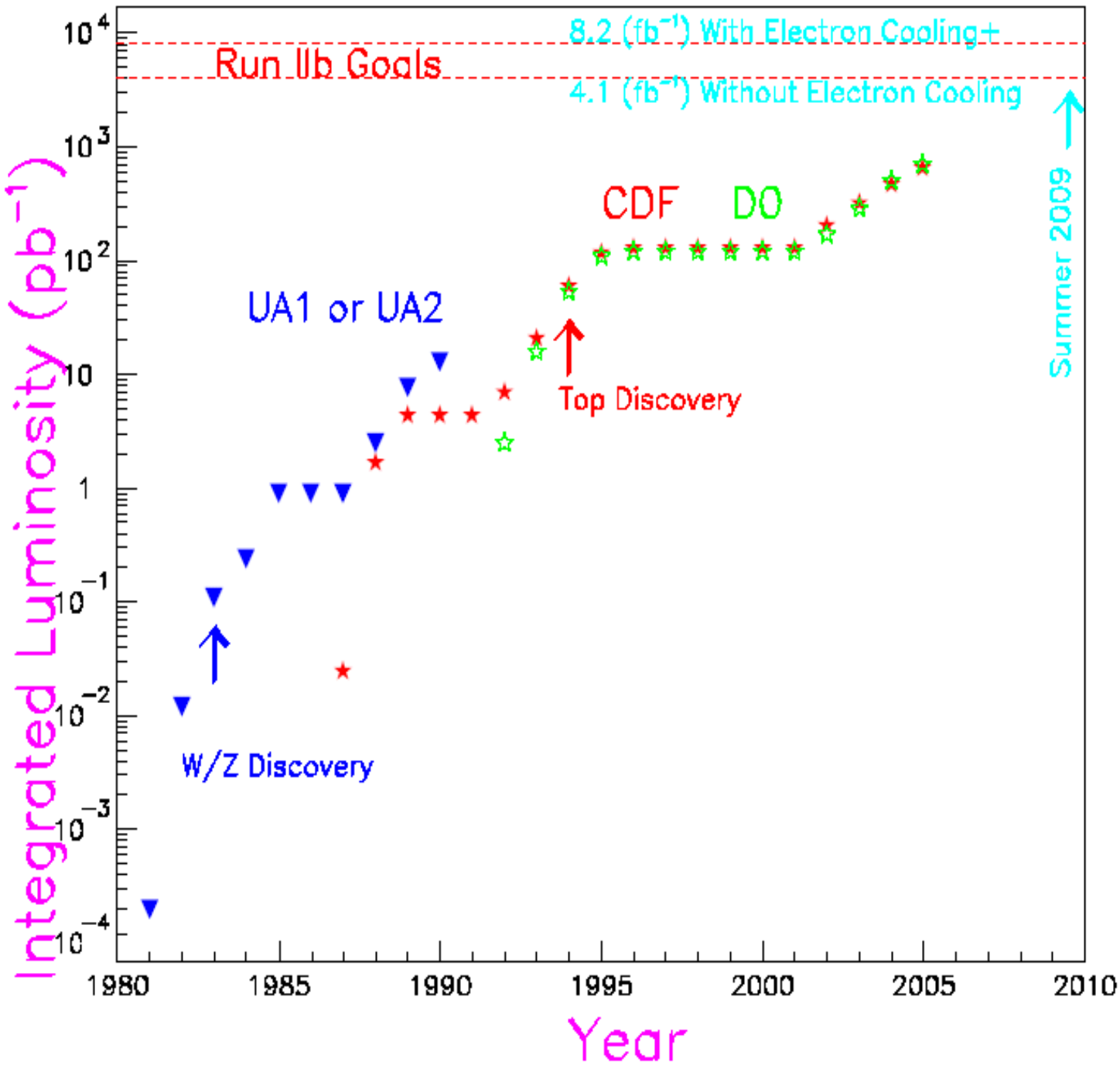
# Experimental Setup: Fermilab Tevatron in Run II

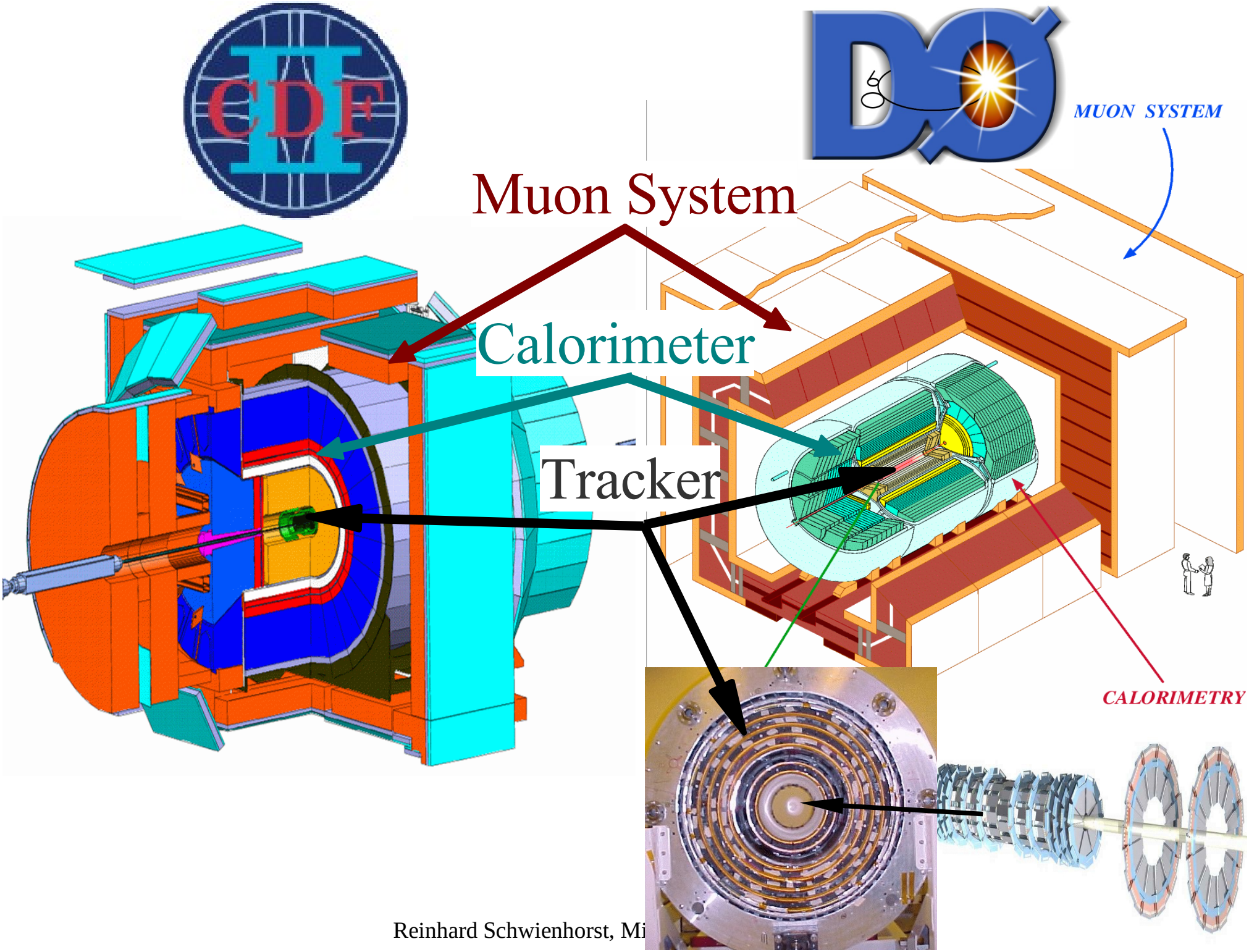
**Proton-Antiproton Collider**
**CM Energy 1.96TeV**
→ ***Energy Frontier***
**Instantaneous luminosity**
**>160E30**
→ ***Interaction Rate Frontier***



# Hadron Collider Integrated Luminosity

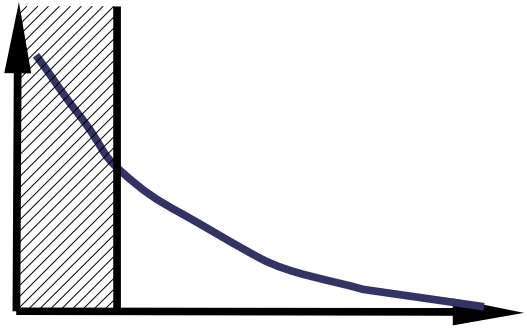


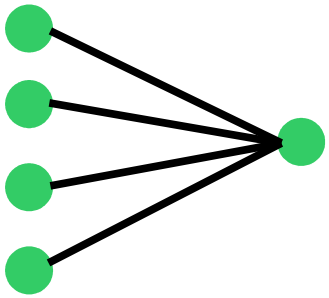

Muon System
Calorimeter
Tracker
MUON SYSTEM
CALORIMETRY

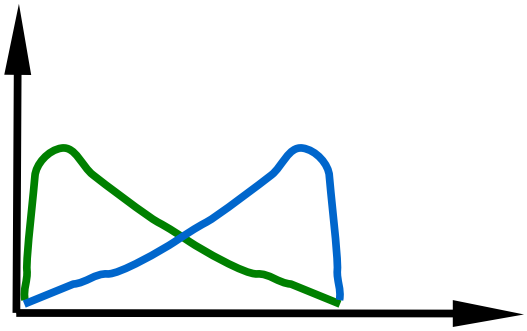
# Analysis Outline

Goal:

*Maximize Sensitivity*



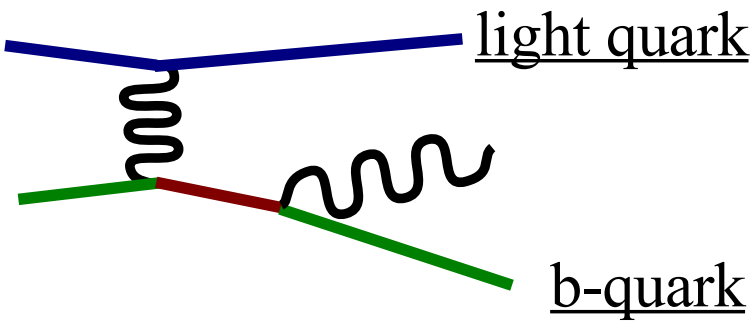


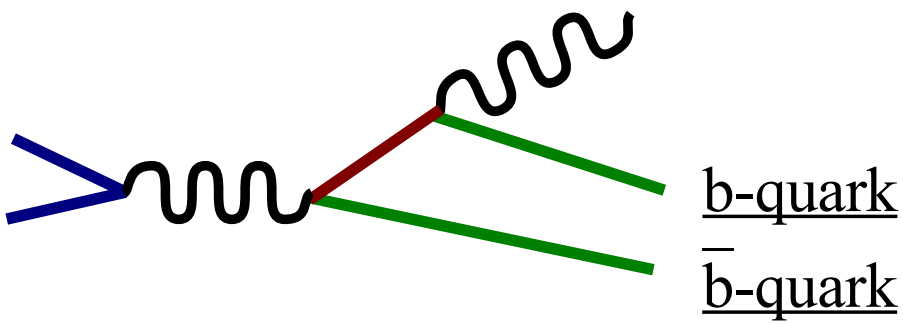


1. Event Selection
   - Select *W*-like events
   - Maximize acceptance
   - Model backgrounds
2. Event Analysis
   - Find discriminating variables
   - Cut/combine in multivariate analysis
3. Determine cross section
   - Event counting or binned likelihood
   - Separately for s-channel, t-channel, and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

# Event Selection

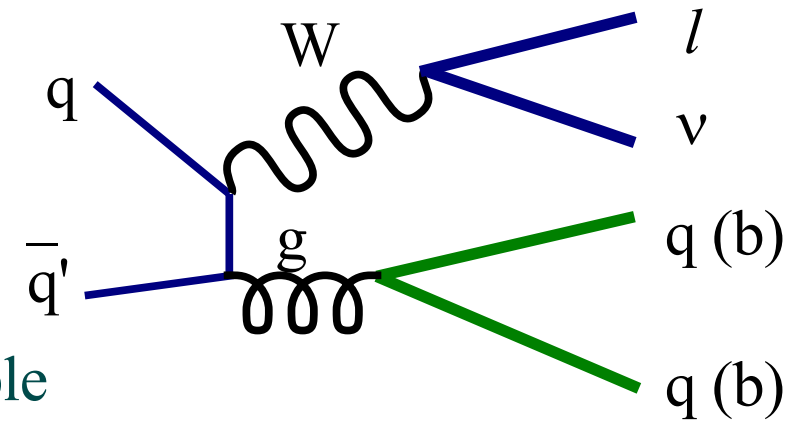
- Trigger:
  - Electron + ≥1 jets, muon + ≥1 jets
- Lepton:
  - 1 electron: $p_T > 15\text{GeV}$, $|\eta^{det}|<1.1$
  - 1 muon: $p_T > 15\text{GeV}$, $|\eta^{det}|<2.0$
- Neutrino: $\not{E}_T > 15\text{GeV}$
- Jets:
  - $p_T > 15\text{GeV}$, $|\eta^{det}|<3.4$, $p_T$ (jet 1)> 25GeV, $|\eta^{det}(\text{jet1})|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

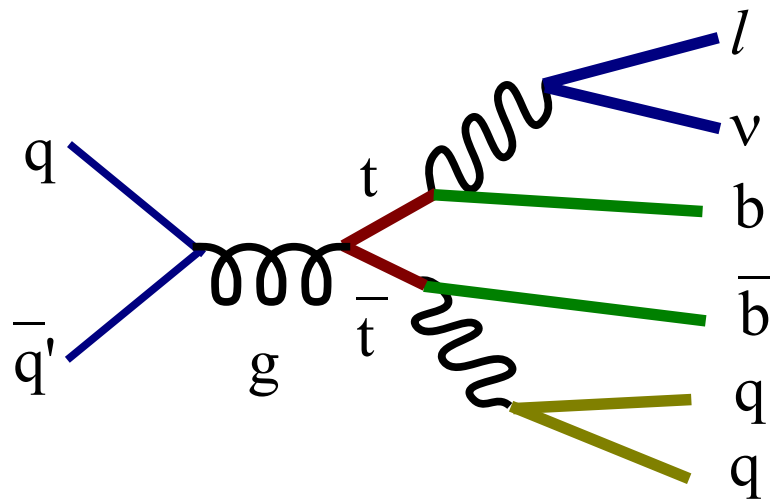


# Background Modeling

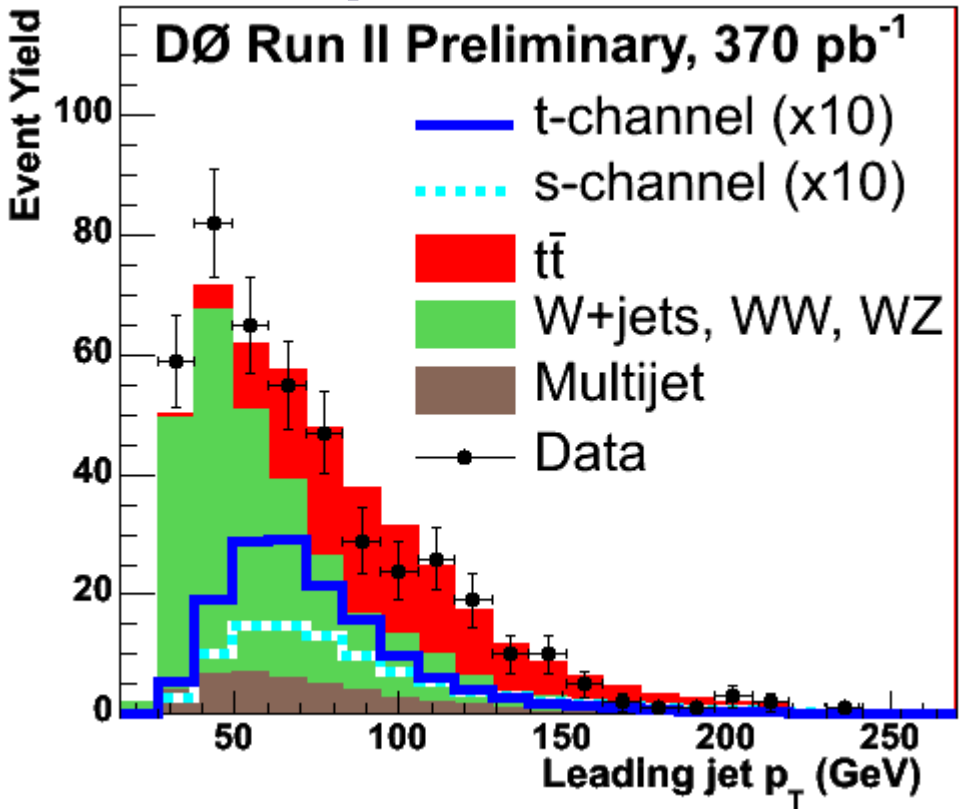
- Based on data as much as possible
- W/Z+jets production
  - Estimated from MC/data
    - Distributions from MC
    - Normalization from pre-tagged sample
    - Flavor fractions from NLO
- Multijet events (misidentified lepton)
  - Estimated from data
- Top pair production
  - Estimated from MC
- Diboson (WZ, WW)
  - Estimated from MC



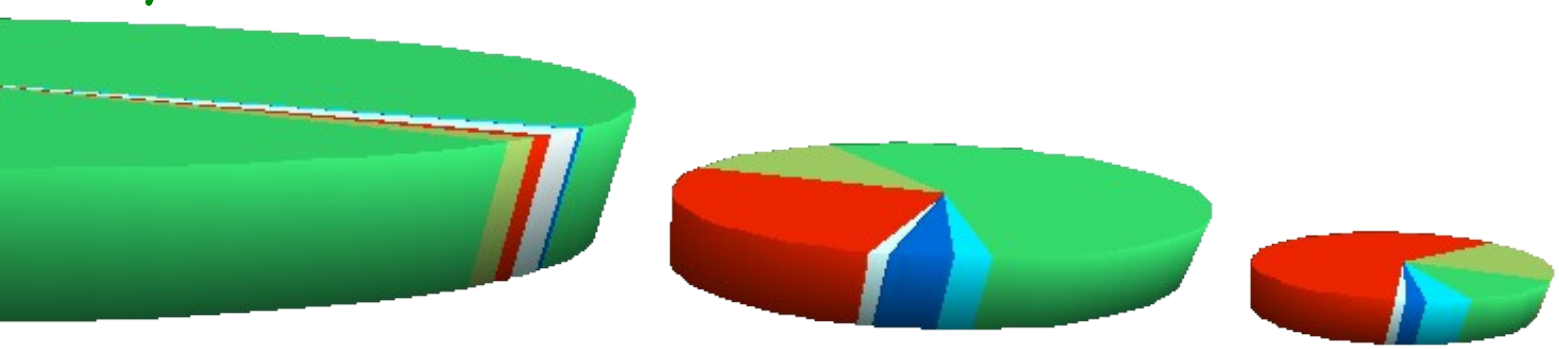



# Event Yield in 370 pb$^{-1}$

| | 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 |

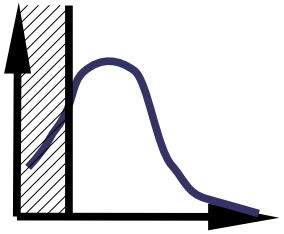


Wjj
Wbb
$t\bar{t}$
WW/WZ
t-channel
s-channel

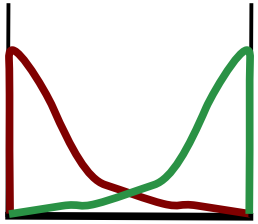
# Event Analysis

- Advanced analysis techniques

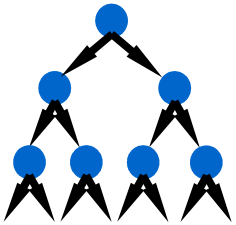
Cut-Based



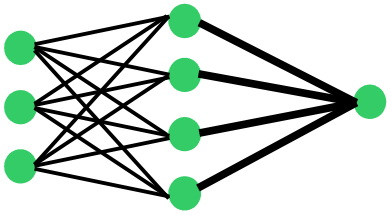
Likelihoods



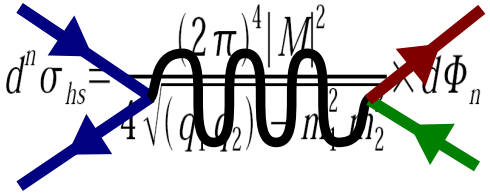
Decision Trees



Neural Networks



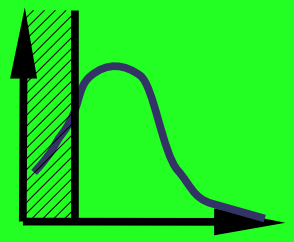
Matrix Elements



# Event Analysis

- Advanced analysis techniques

Cut-Based



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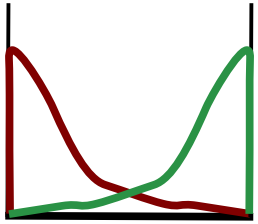

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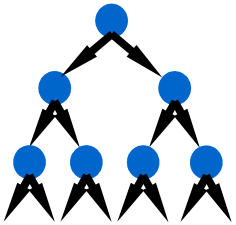

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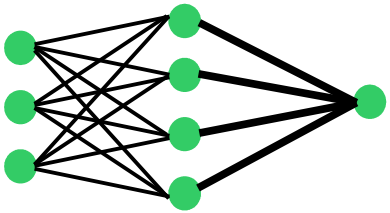
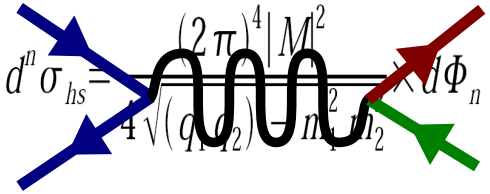


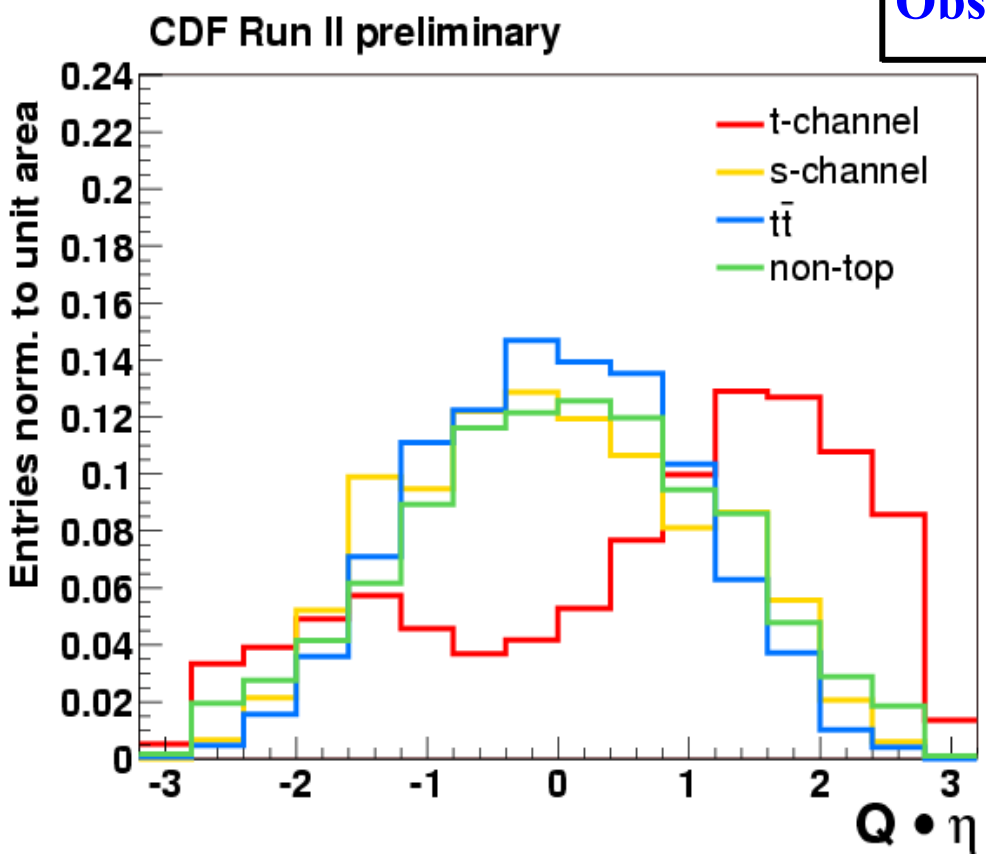
Matrix Elements



# Cut-based analysis

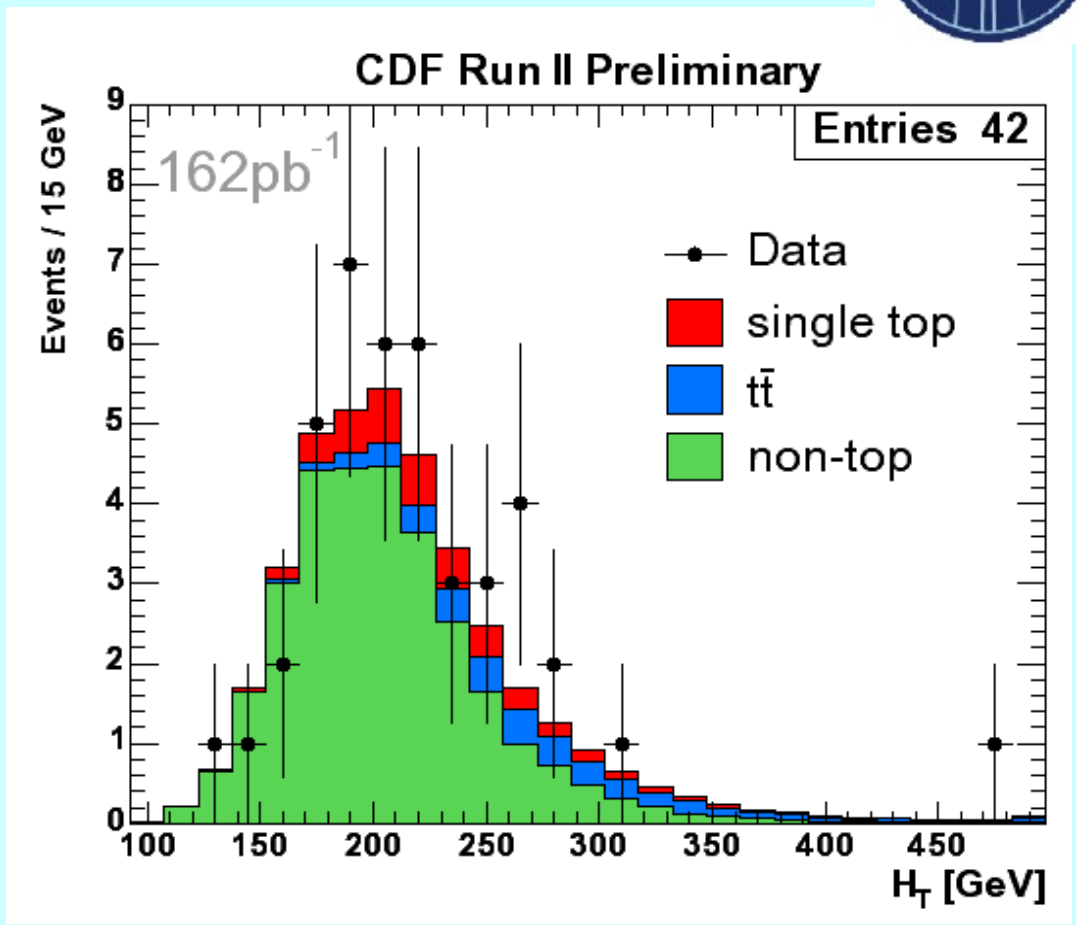
- Tight event selection
  - Exactly 2 jets
  - Include electrons and muons
  - Separate by b-tag: =1 tag and =2 tags
  - Cut on reconstructed top quark mass $140\ \text{GeV} \leq M_{l\nu b} \leq 210\ \text{GeV}$

| | 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)



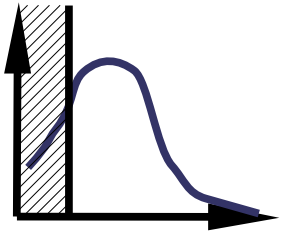

  - Cross section limits:

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

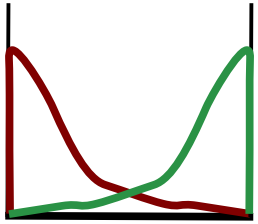
# Event Analysis

- Advanced analysis techniques

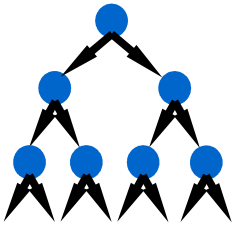
Cut-Based



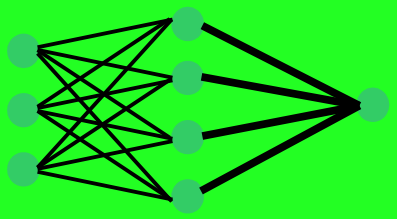
Likelihoods



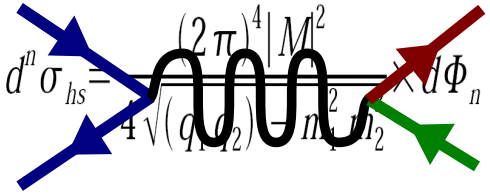
Decision Trees



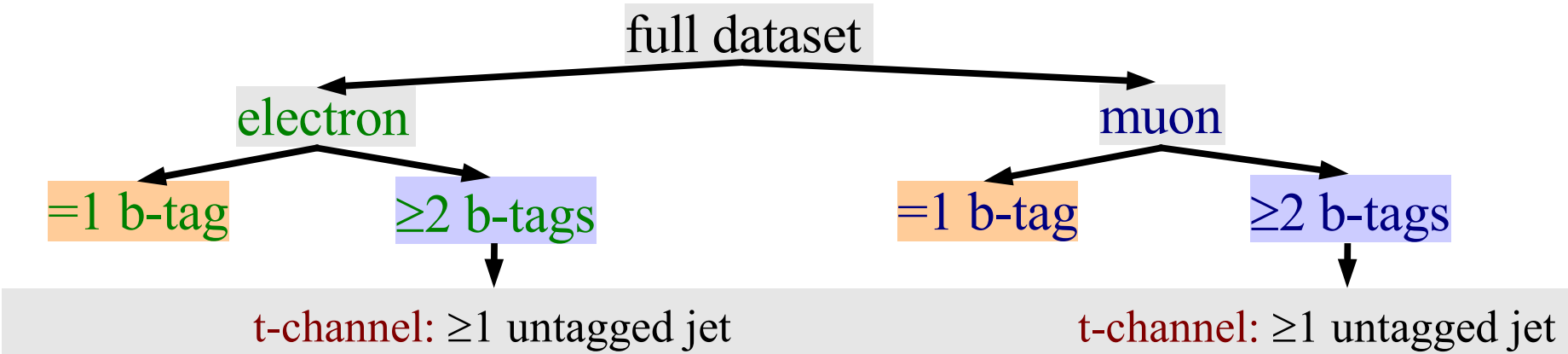
Neural Networks



Matrix Elements

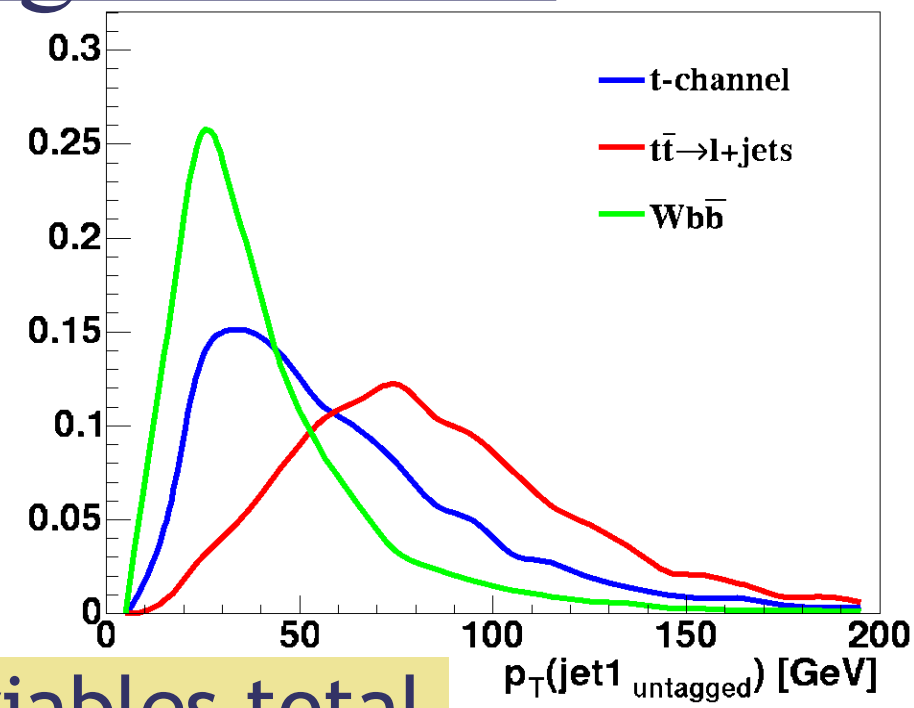


# Analysis Strategy

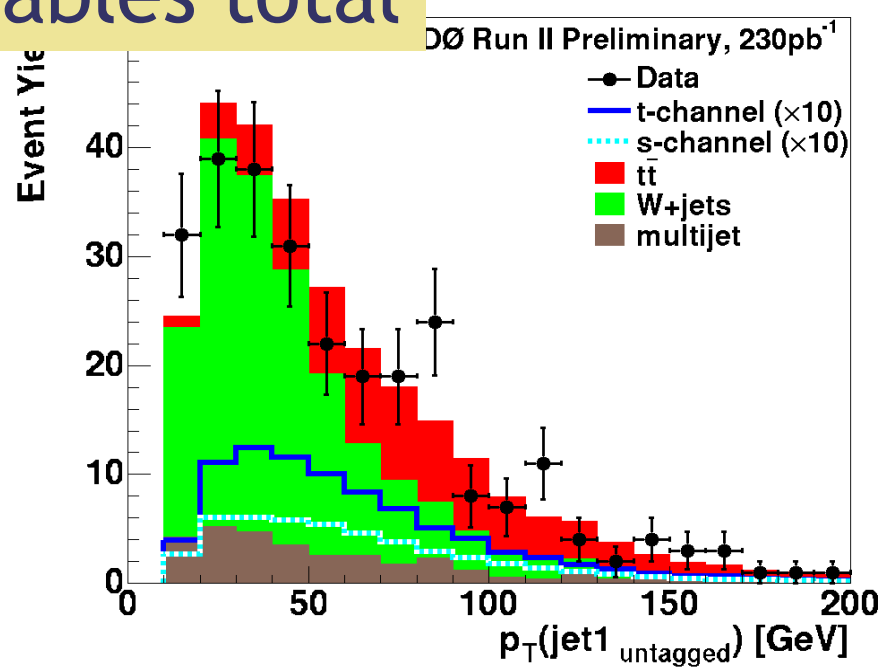


# Discriminating Variables

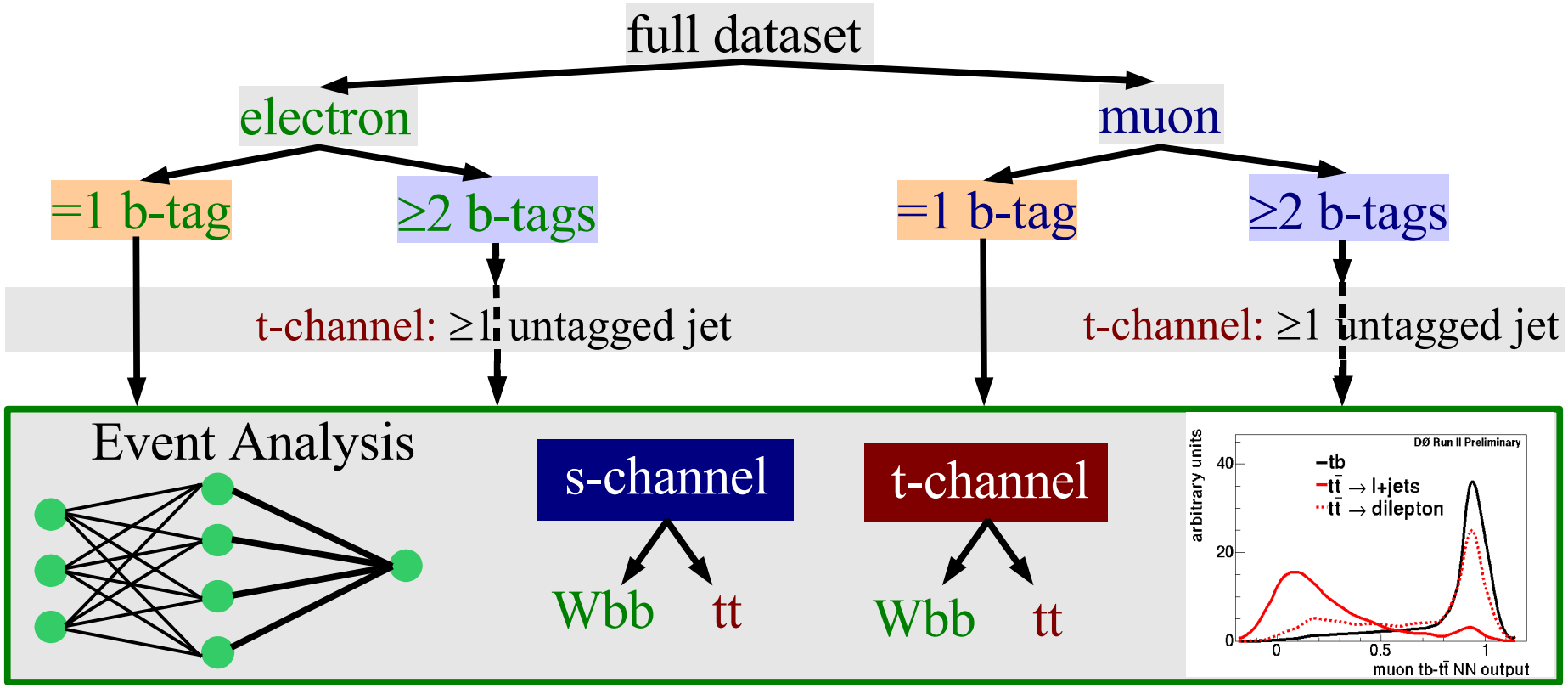
- Object kinematics
  - Jet $p_T$ for different jets
    - Tagged, untagged,...
- Event kinematics
  - $H$ (total energy)
  - $H_T$ (transverse energy)
  - $M$ (invariant mass)
  - $M_T$ (transverse mass)
  - Summing over various objects in the event
- Angular variables
  - Jet-jet separation
  - Jet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



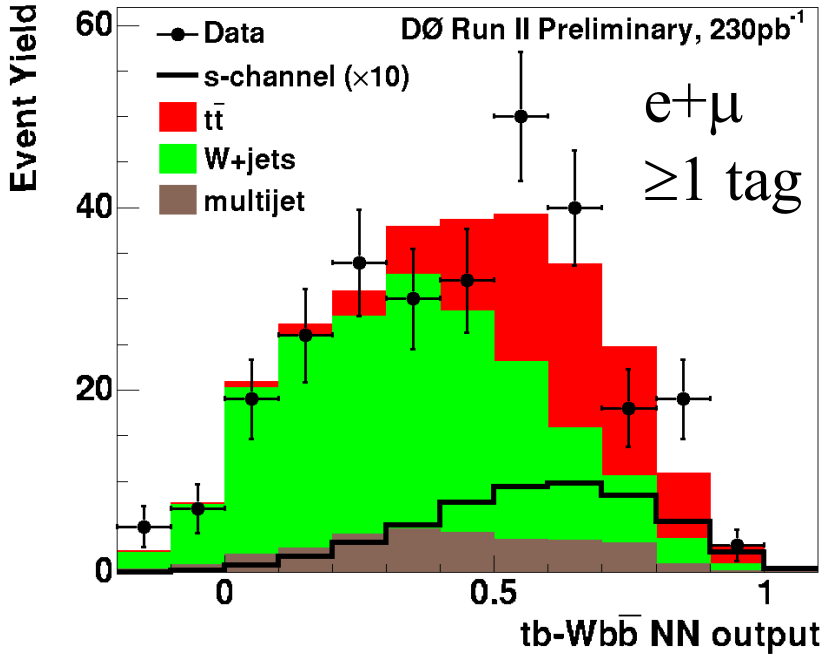

25 variables total

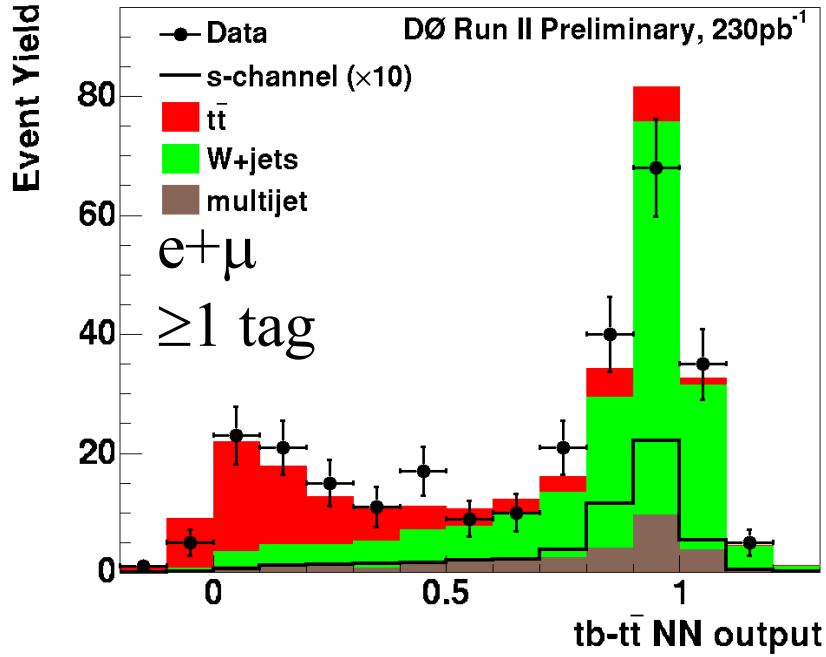


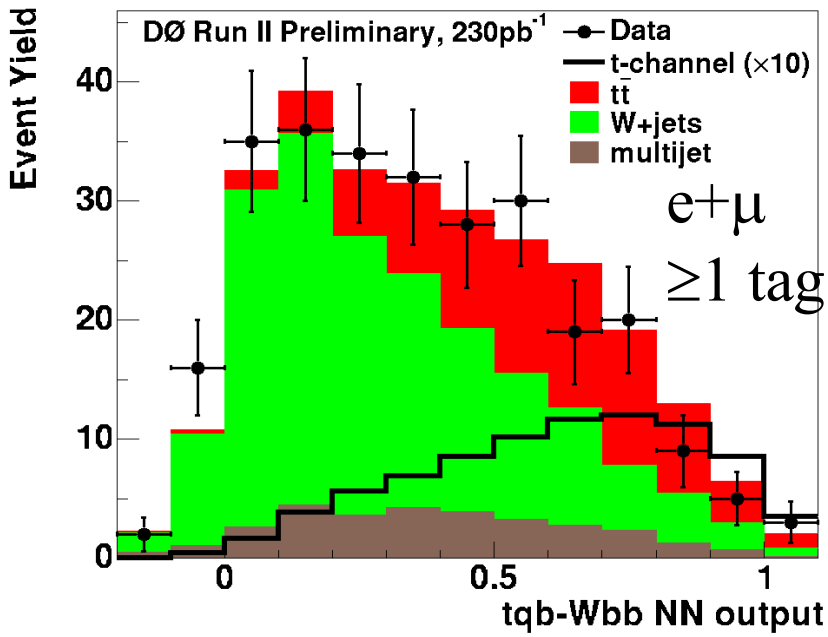
# Analysis Strategy

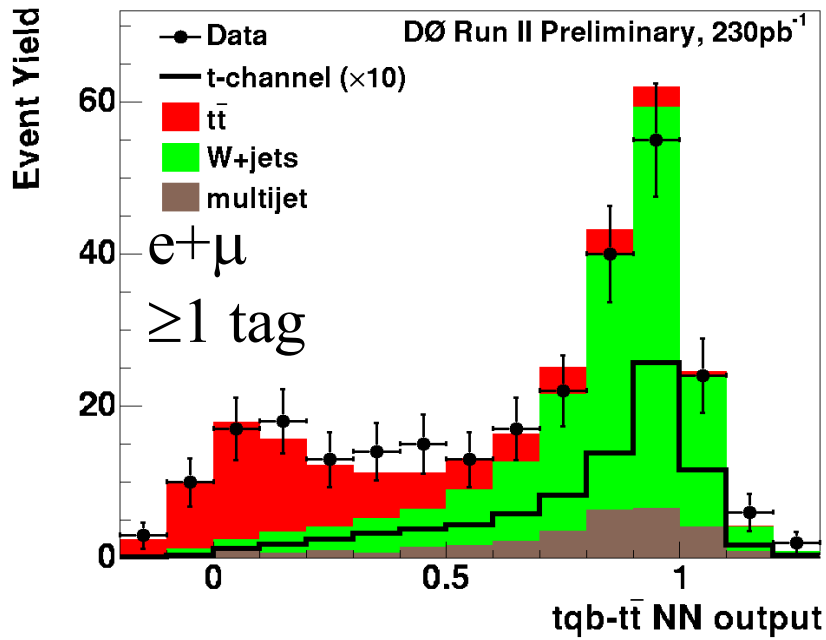


# Neural Network Output

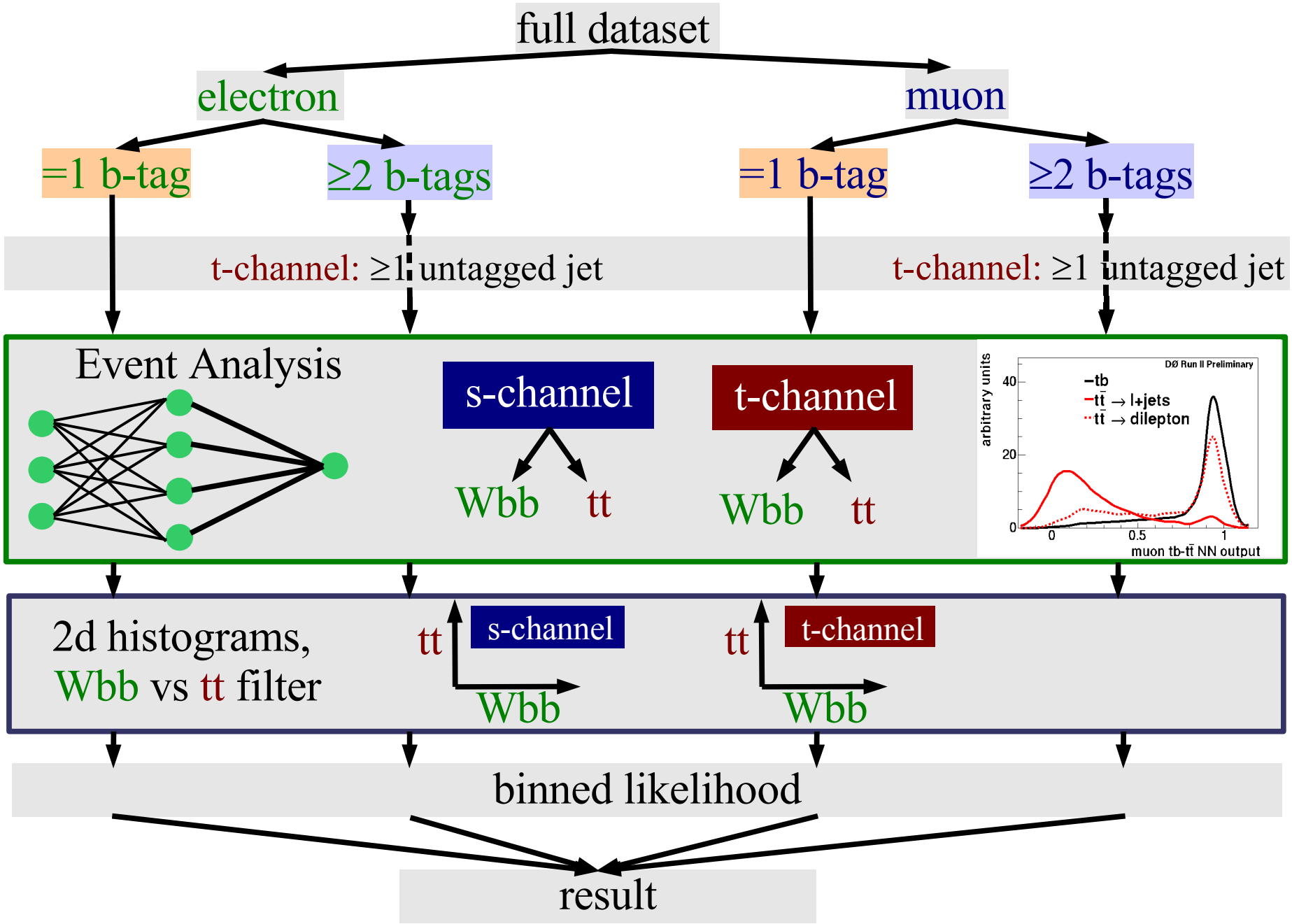


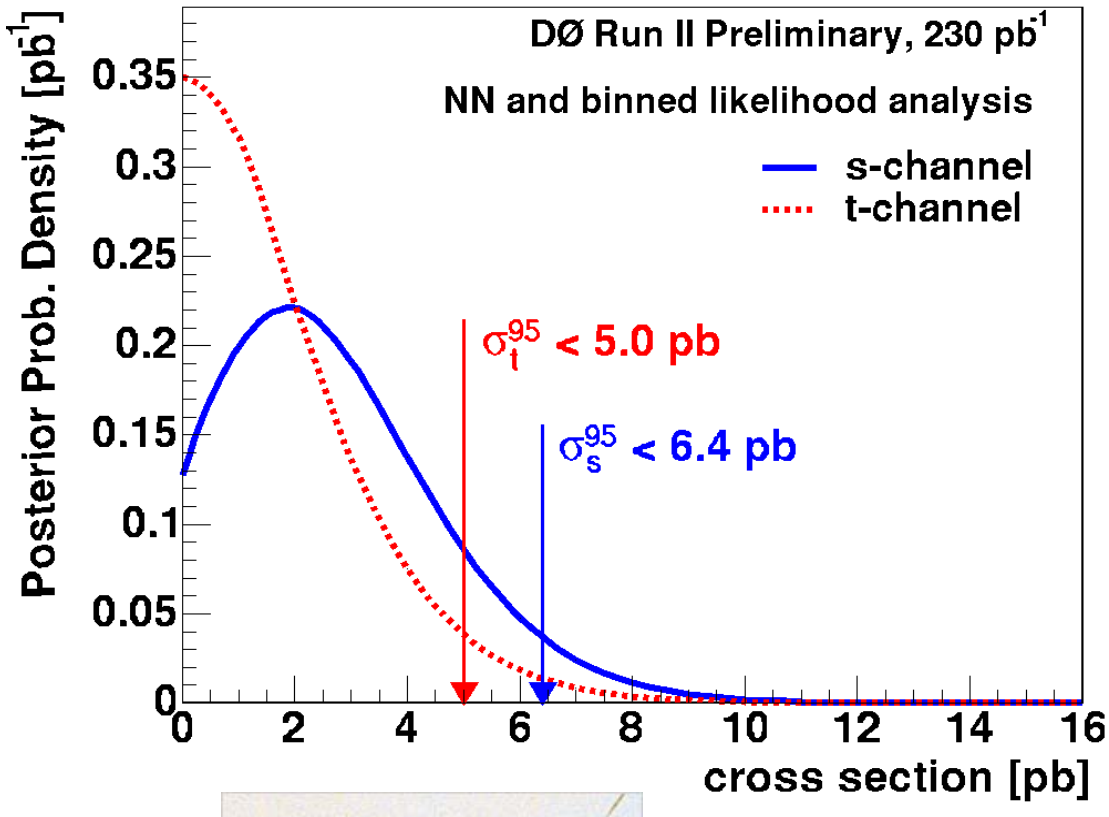
# Analysis Strategy



# 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% |



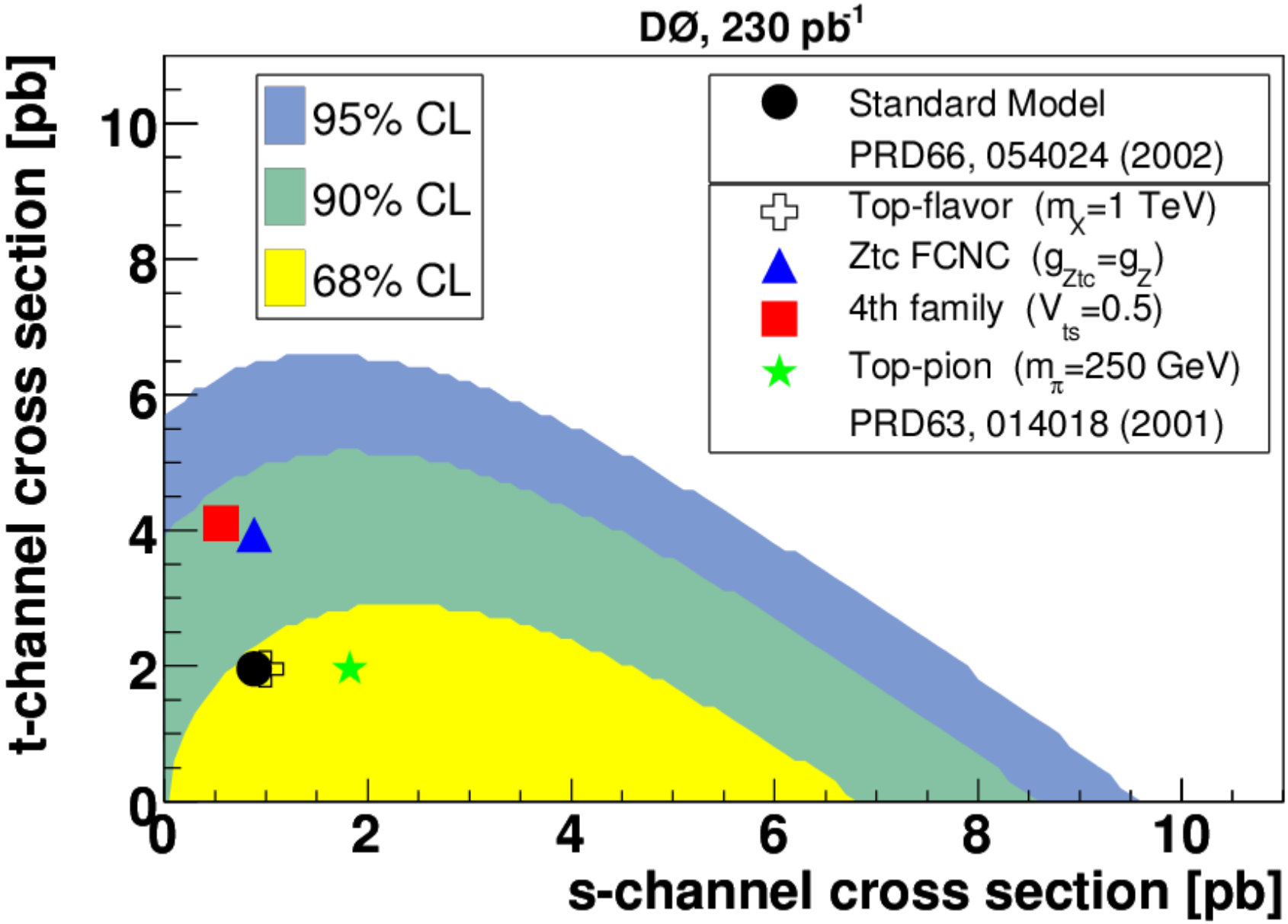

**Expected/Observed limit:**

$\sigma_s$ < 4.5 / 6.4 pb

$\sigma_t$ < 5.8 / 5.0 pb

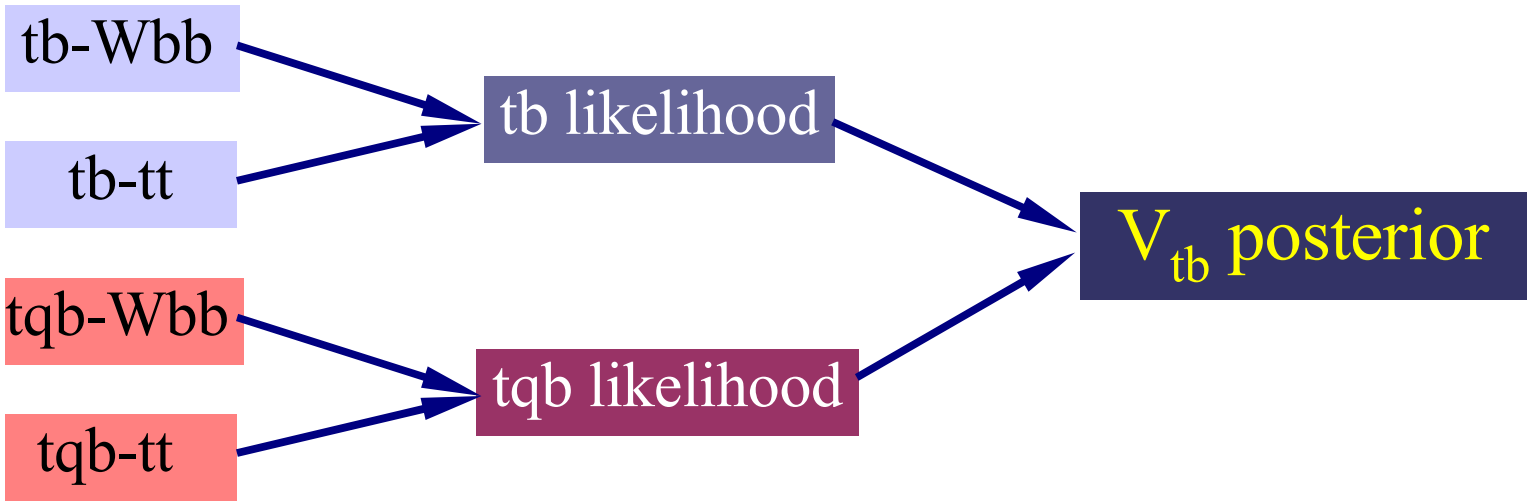
Published in PLB 622, 265 (2005)

# Sensitivity to non-SM Single Top



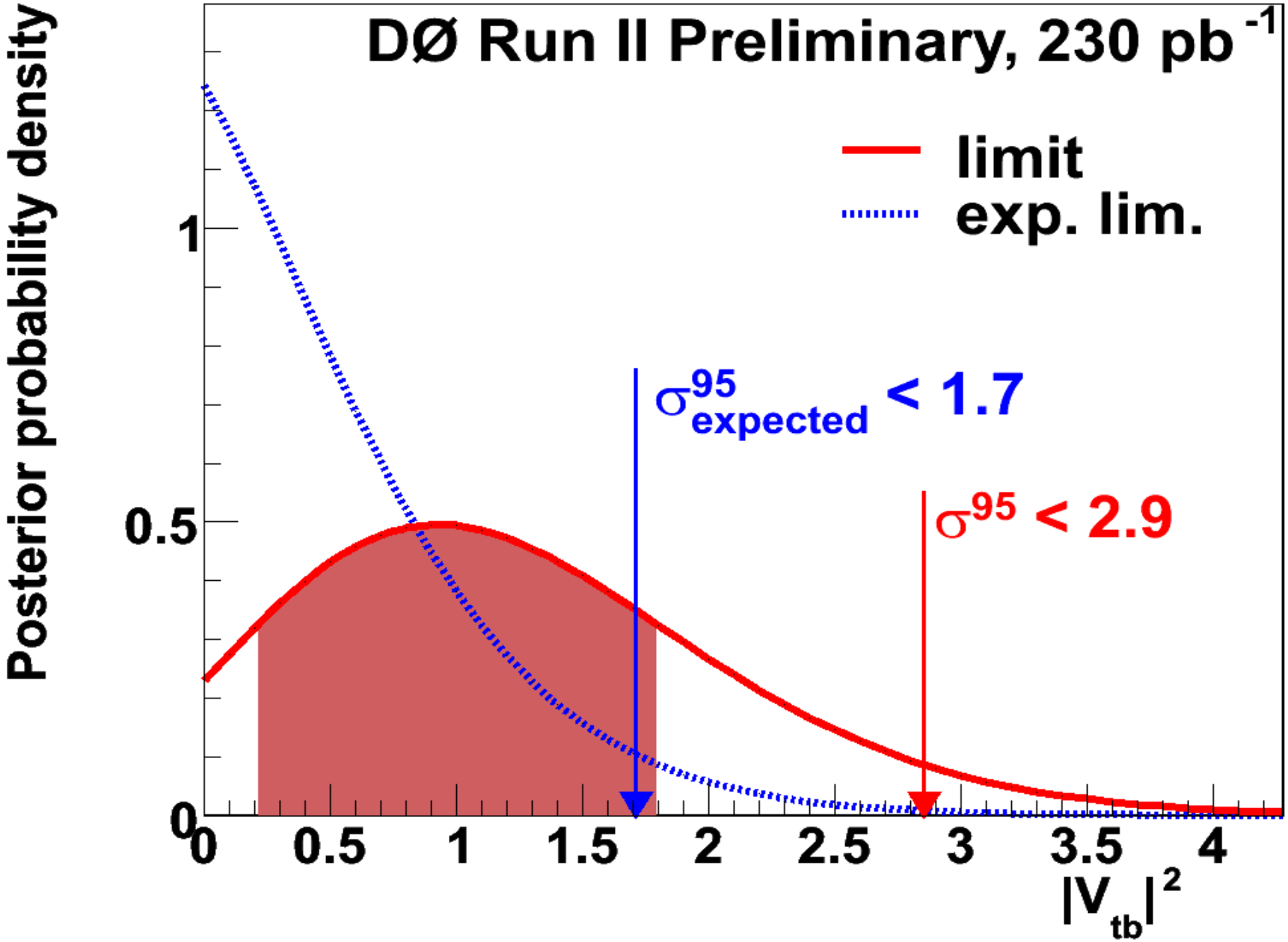
# $V_{tb}$ Coupling Limit

- 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

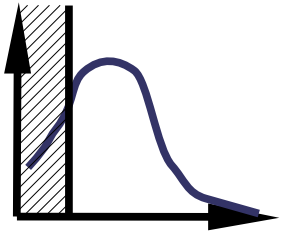
# Probability density for $|V_{tb}|^2$



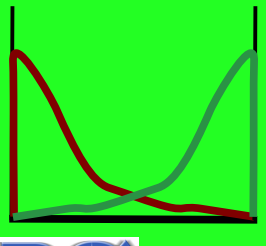
# Event Analysis

- Advanced analysis techniques

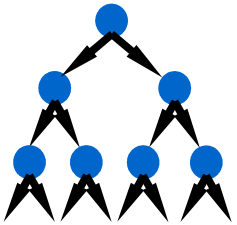
Cut-Based



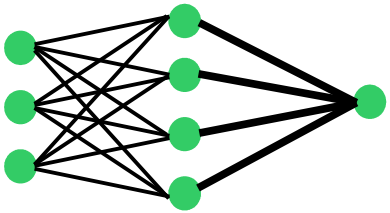
Likelihoods



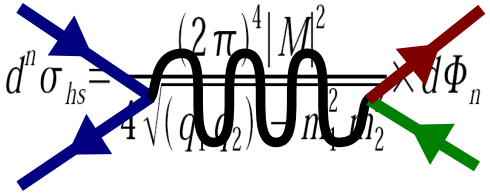
Decision Trees



Neural Networks

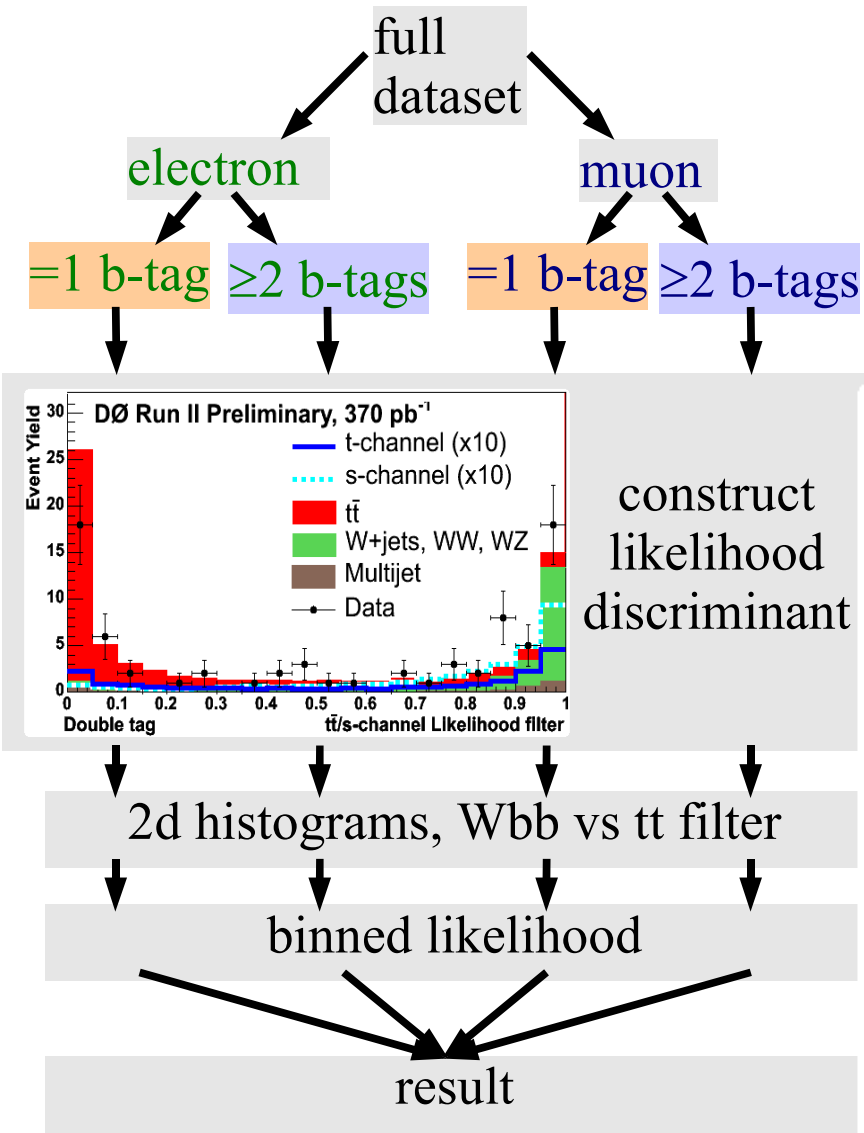


Matrix Elements

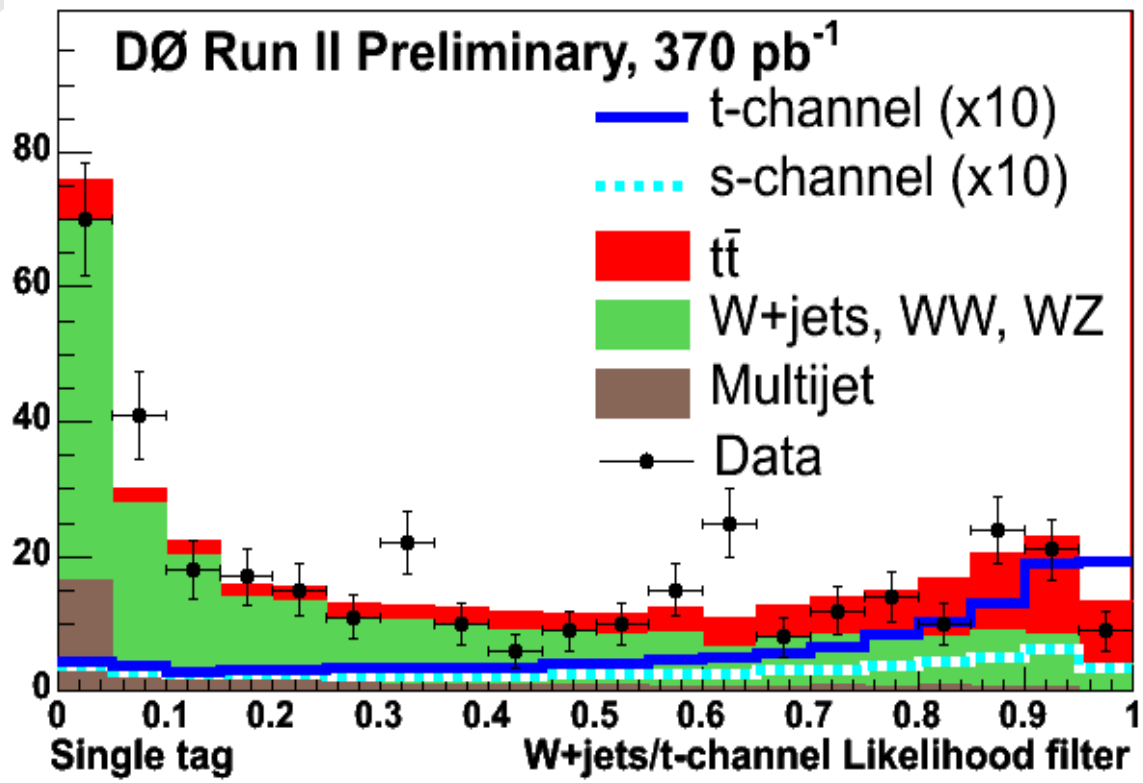


# Likelihood Analysis (370 pb$^{-1}$)

s-channel / t-channel

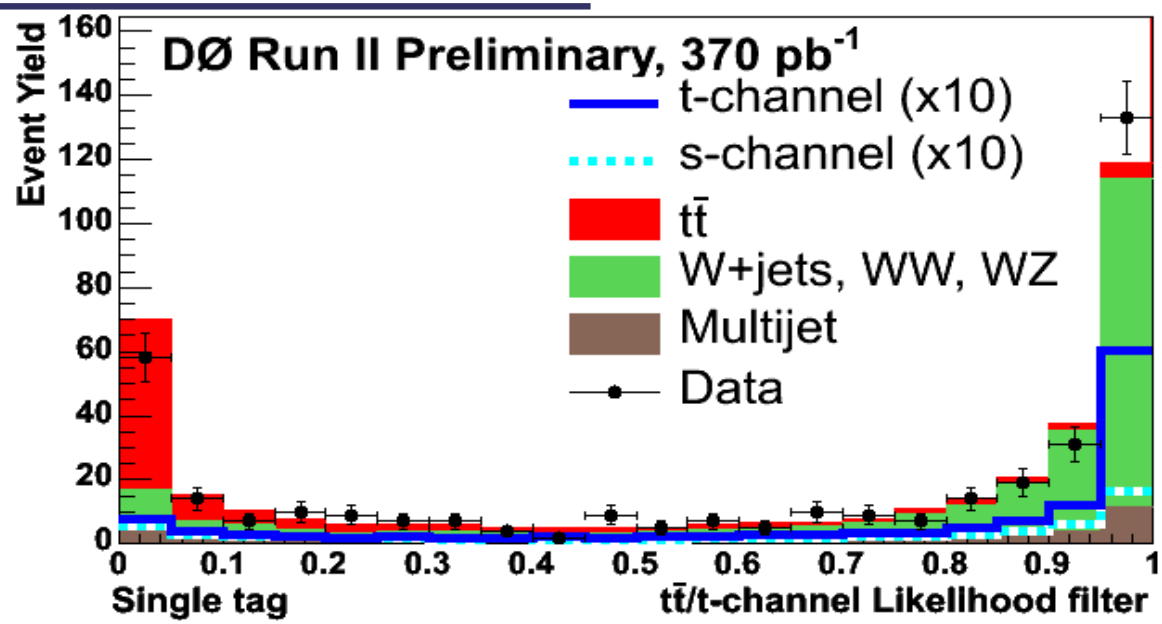



- Using jet lifetime tagger
  - Asymmetric tag requirements
    - At least one tight tag
    - Loose tagger cut for double tags



# Likelihood Result

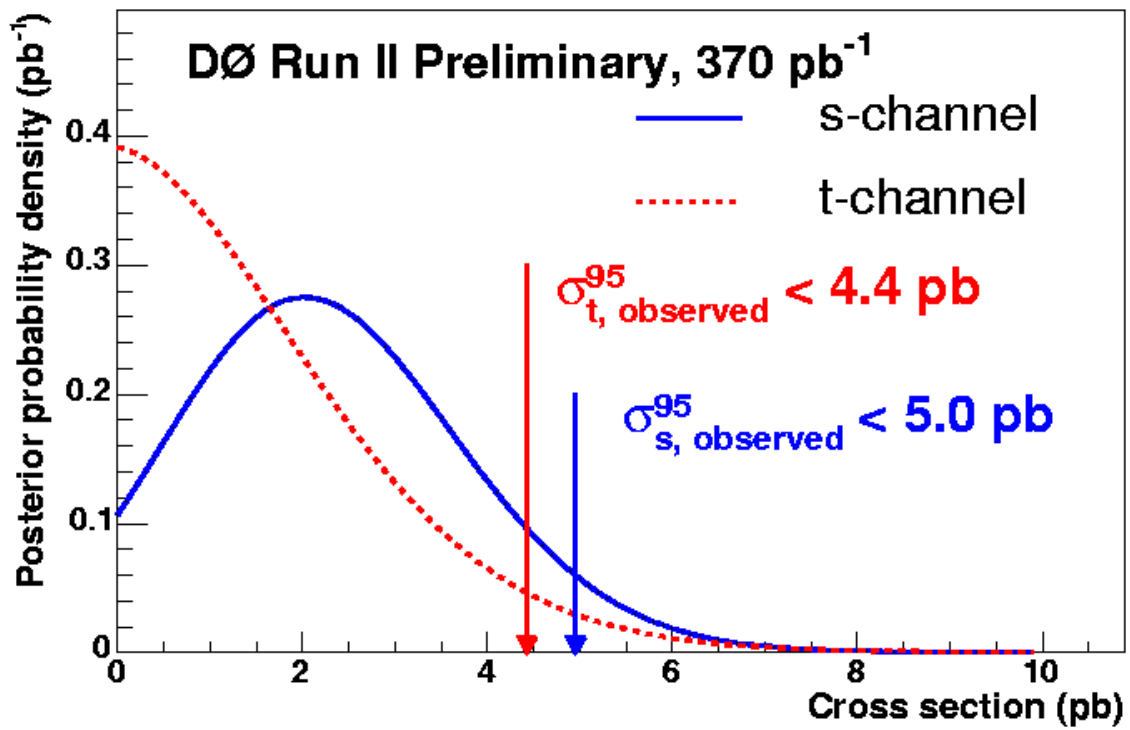
- Systematic uncertainties
  - b-tag modeling: 6-17%
  - Jet energy scale: 5%
  - Trigger modeling: 5%
  - Theory tt XS: 18%




**Expected/Observed limit:**

$\sigma_s < 3.3 / 5.0$ pb

$\sigma_t < 4.3 / 4.4$ pb



# Summary

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

95% CL upper cross section limits [pb]

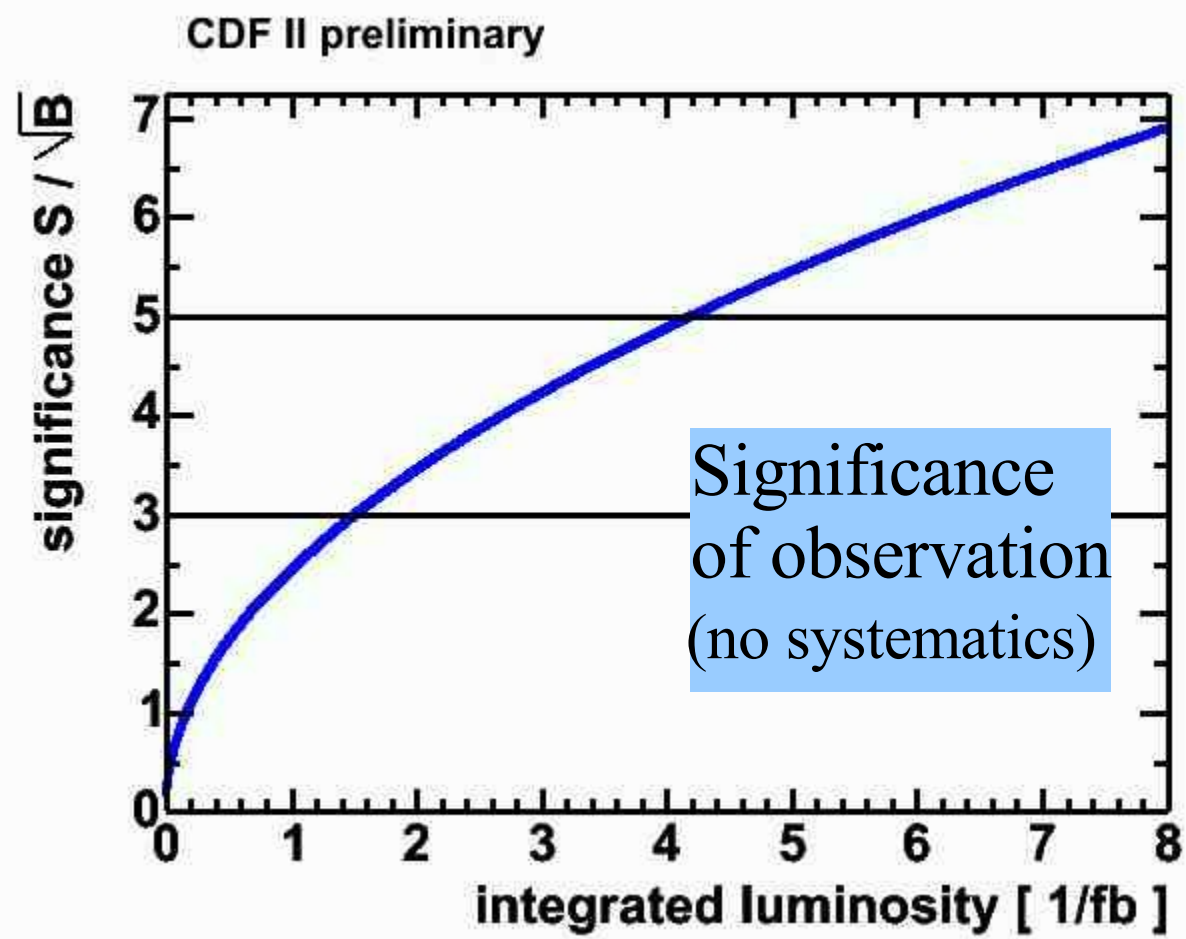
| | | |
|---|---|---|
| CDF ($160pb^{-1}$) | 13.6 | 10.1 |
| DØ NN ($230pb^{-1}$) | 6.4 | 5.0 |
| DØ Likelihood ($370pb^{-1}$) | 5.0 | 4.4 |

# Outlook

The future is here

# Tevatron Single Top Future

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



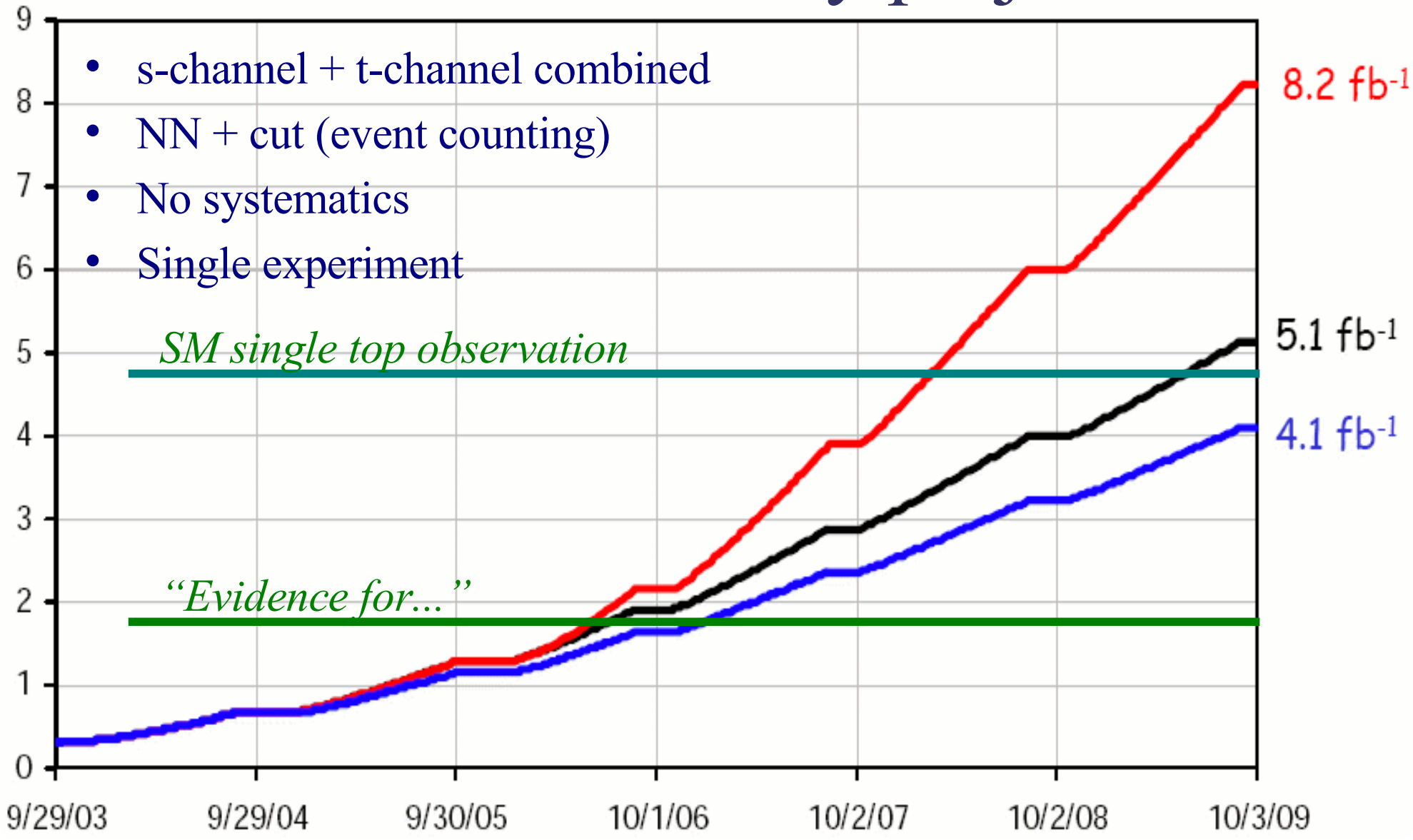

## Improvements

- 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%

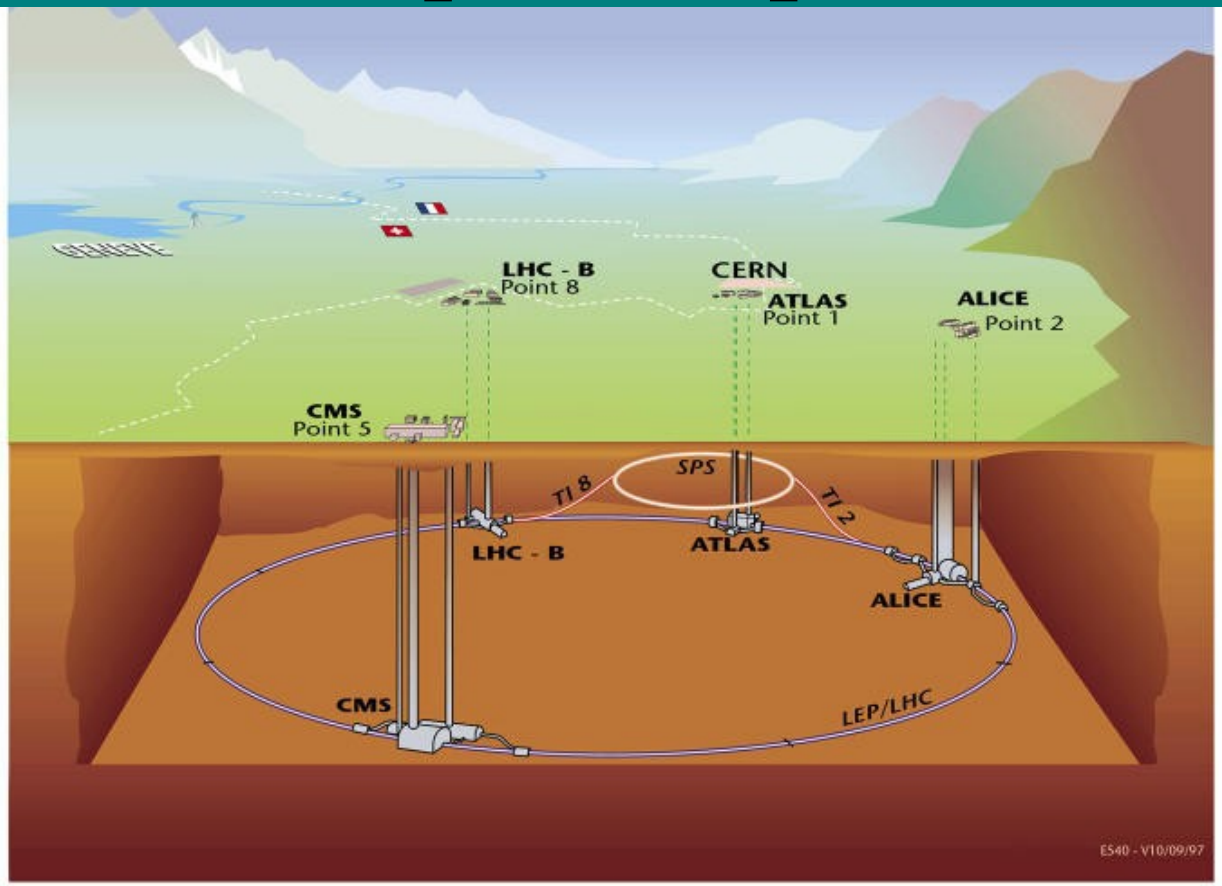
# Tevatron luminosity projection

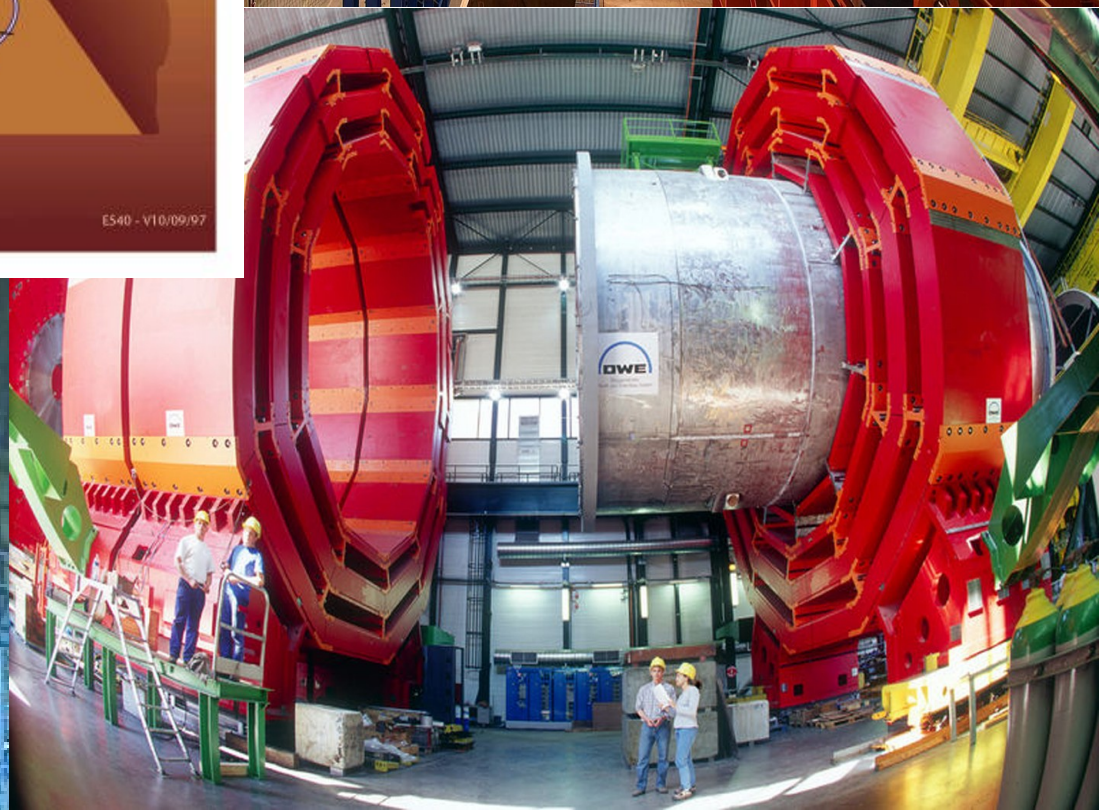


# Outlook

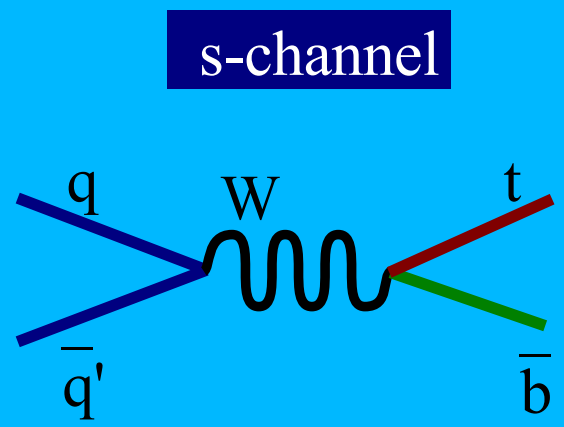
Top is the gateway quark

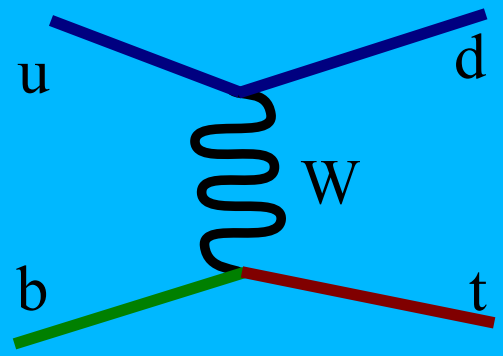
# LHC: proton-proton collider at 14 TeV

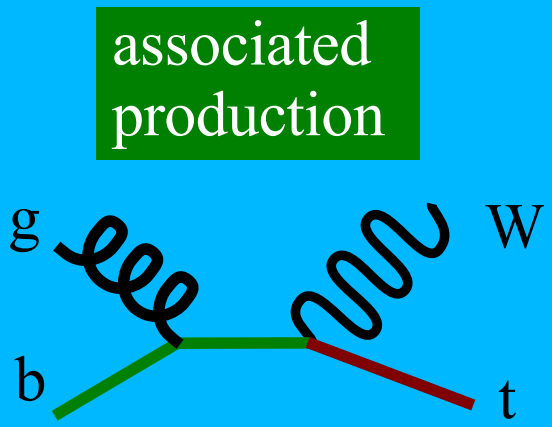




# SM Single Top Production at the LHC



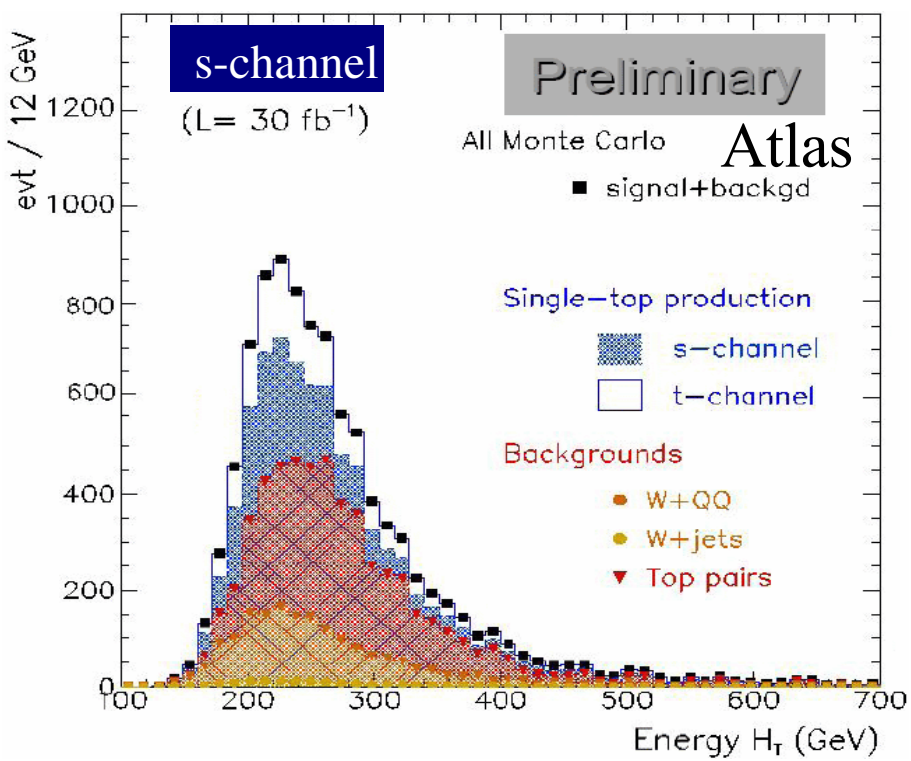



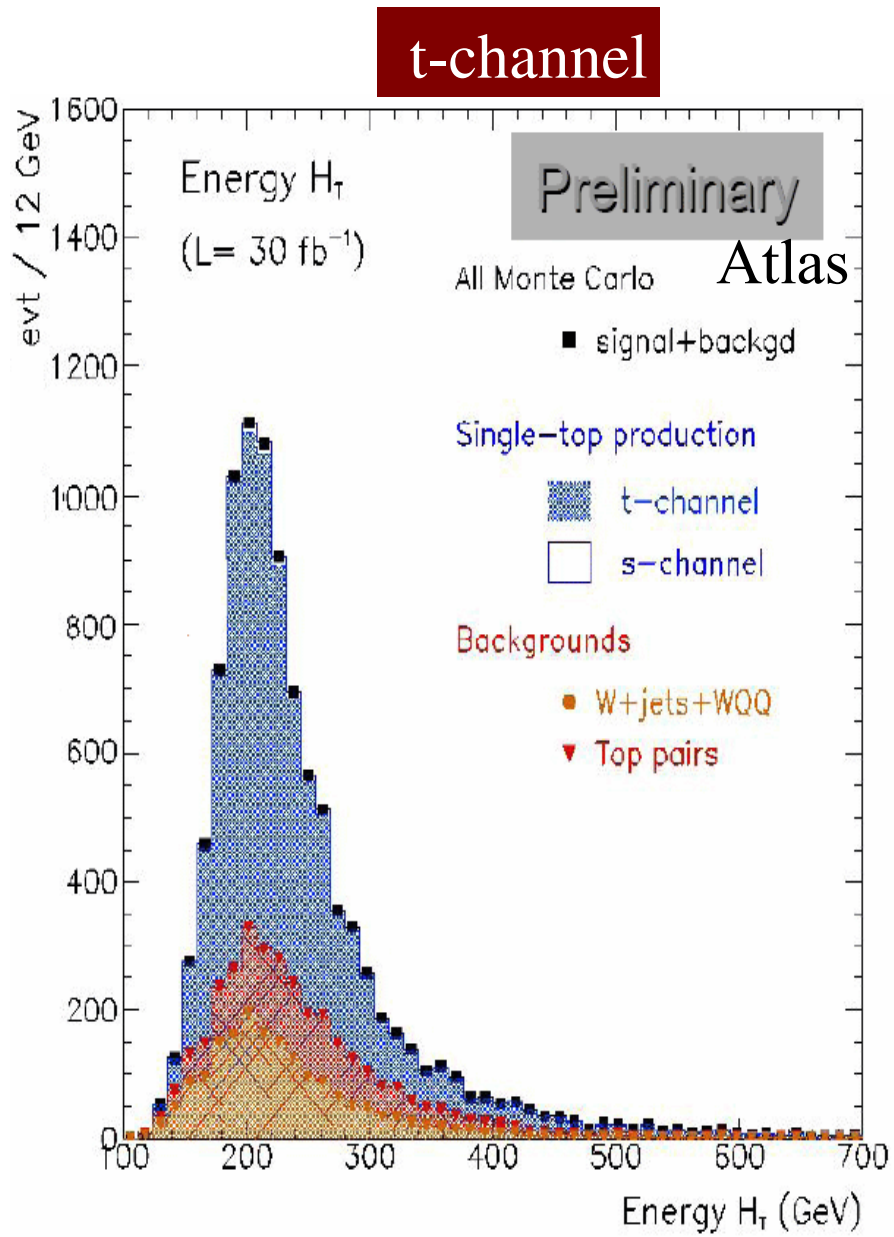




- Observe three single top production modes separately
- Measure $V_{tb}$ to few %
- Study spin correlations

# SM Single Top at the LHC

- Backgrounds are similar but different
  - W+jets is less, $t\bar{t}$ more important
- Signal extraction is similar
  - b-tagging is very important
  - single/double tags for t/s-channel
  - t/s-channel search is easier/harder than at the Tevatron

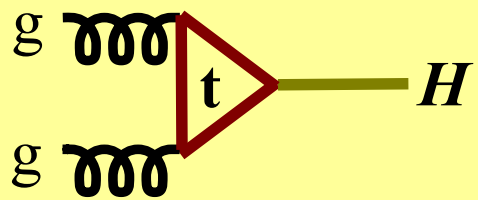


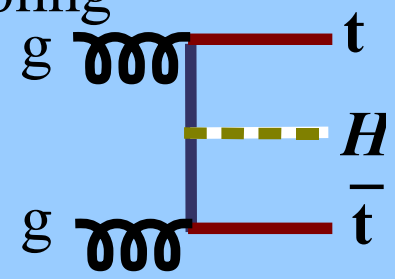
# LHC as a Discovery Machine

## Neutral Higgs

Dominant Higgs production mechanism at the LHC:



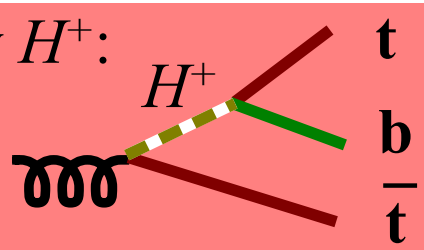

Top-Higgs Yukawa coupling




Discover with ~30fb$^{-1}$

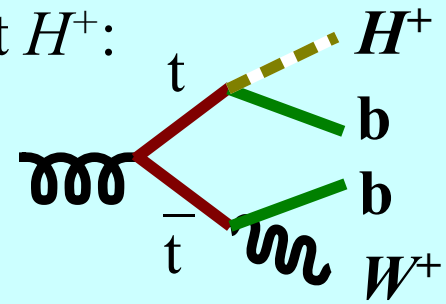
## Supersymmetry: Charged Higgs

Heavy $H^+$:




Discovery possible with ~30fb$^{-1}$

Light $H^+$:




Discover with ~30fb$^{-1}$

# 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