Single Top Quark Physics at the Tevatron

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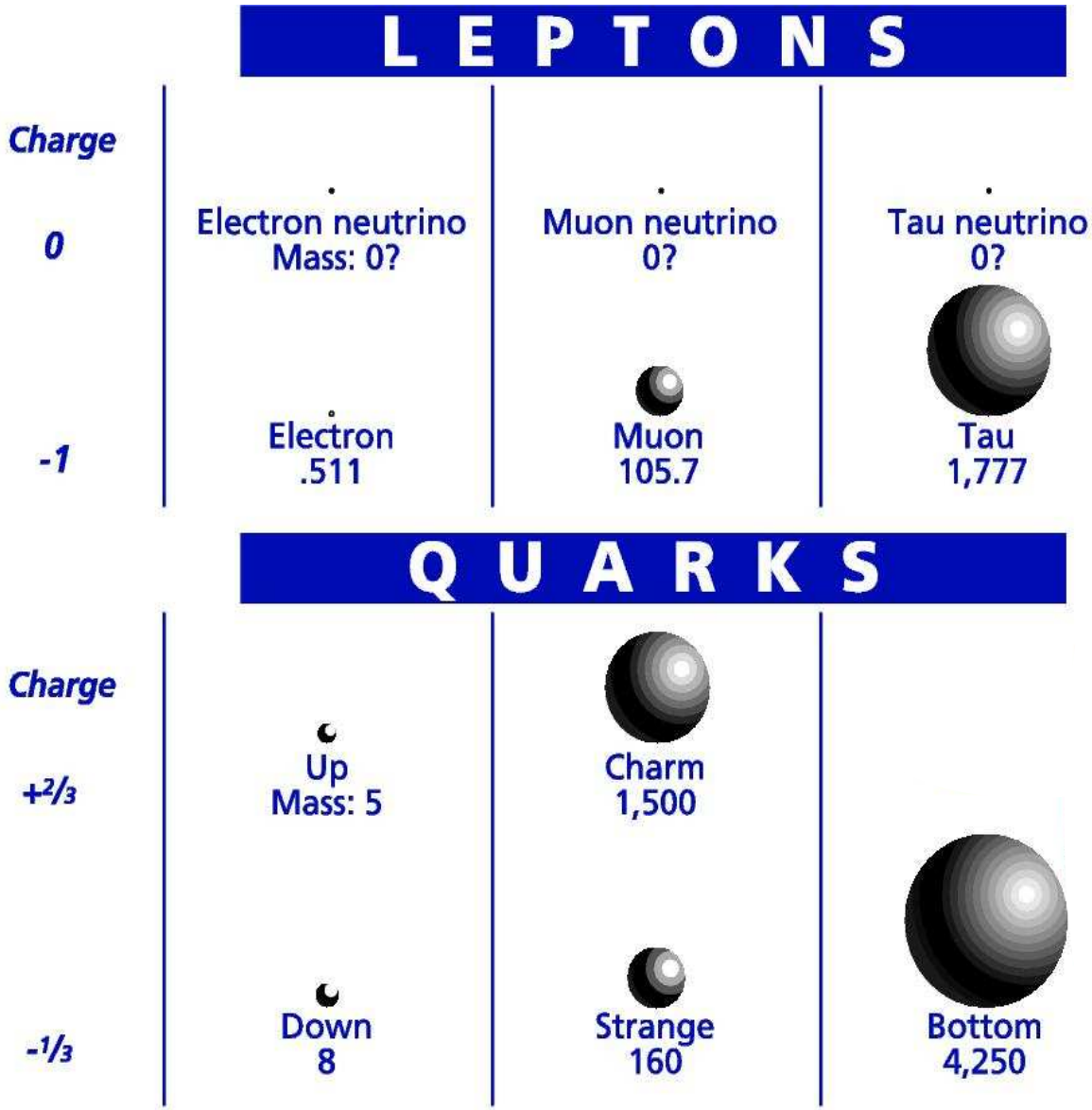
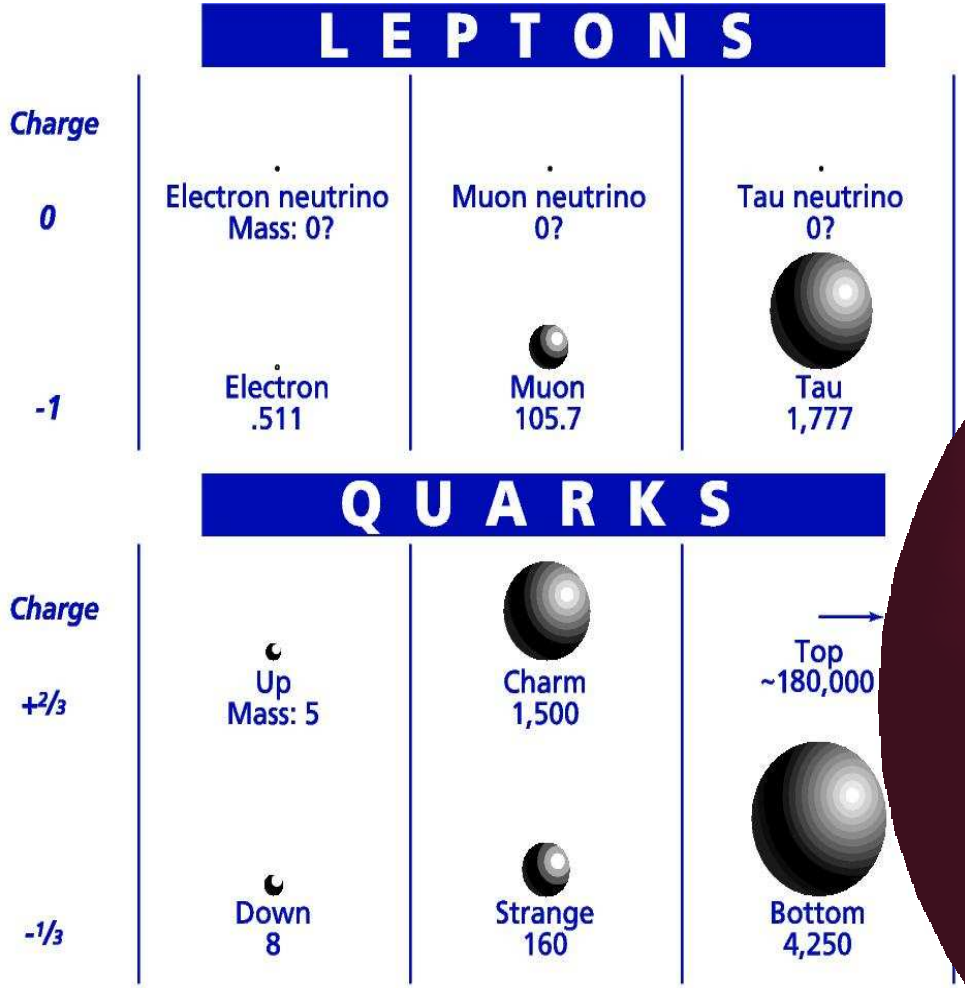
Outline

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

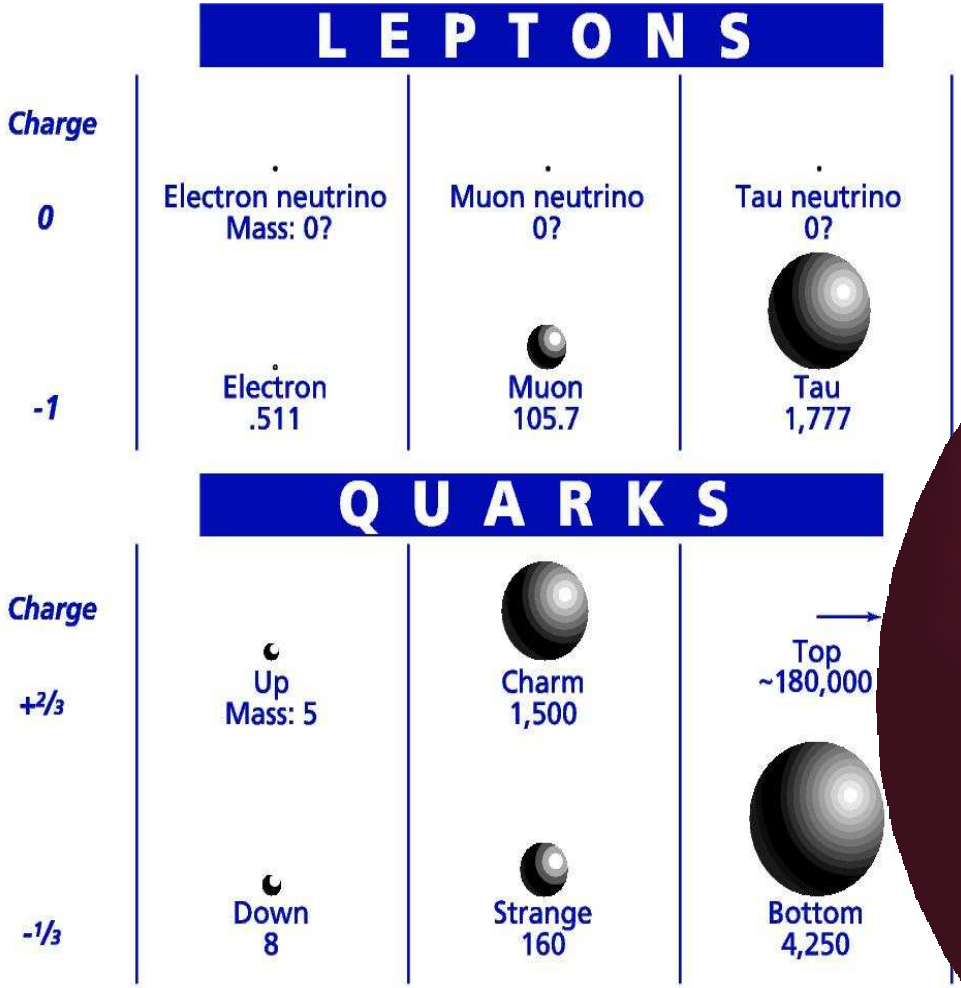
Fundamental Fermions

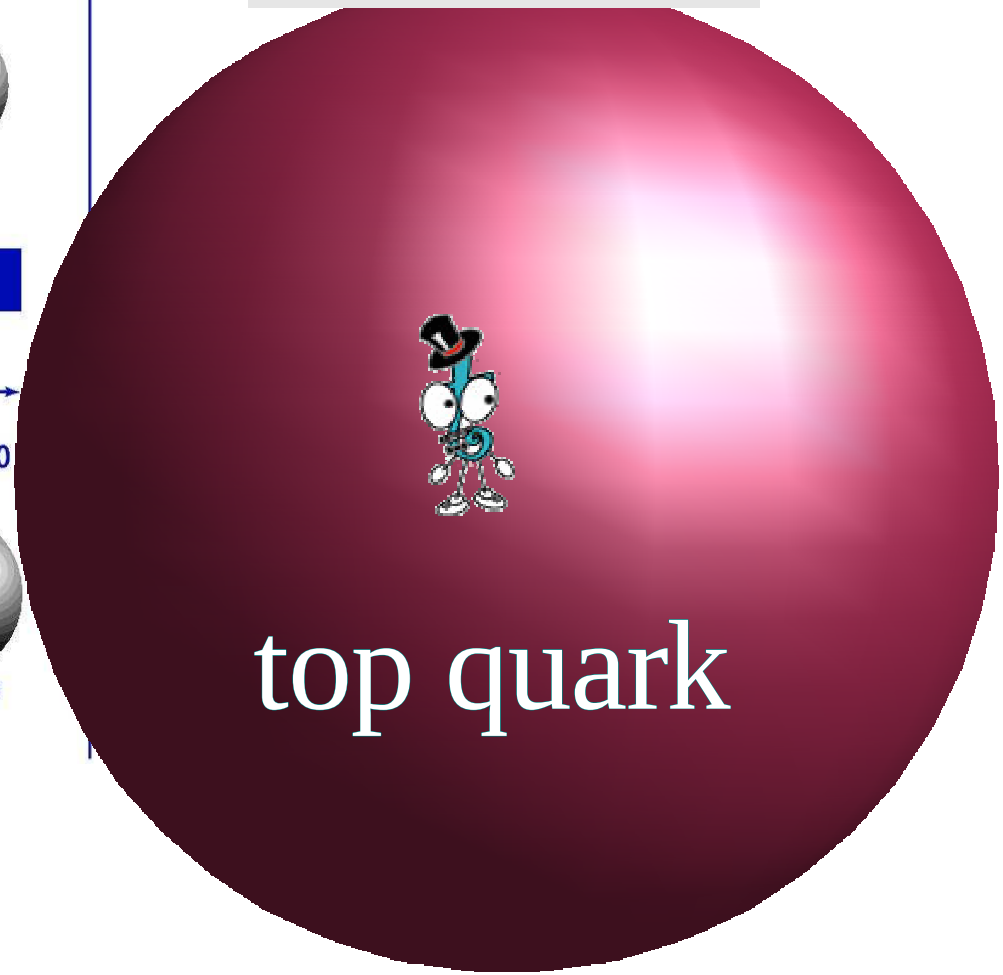


Fundamental Fermions



King of the Fermions

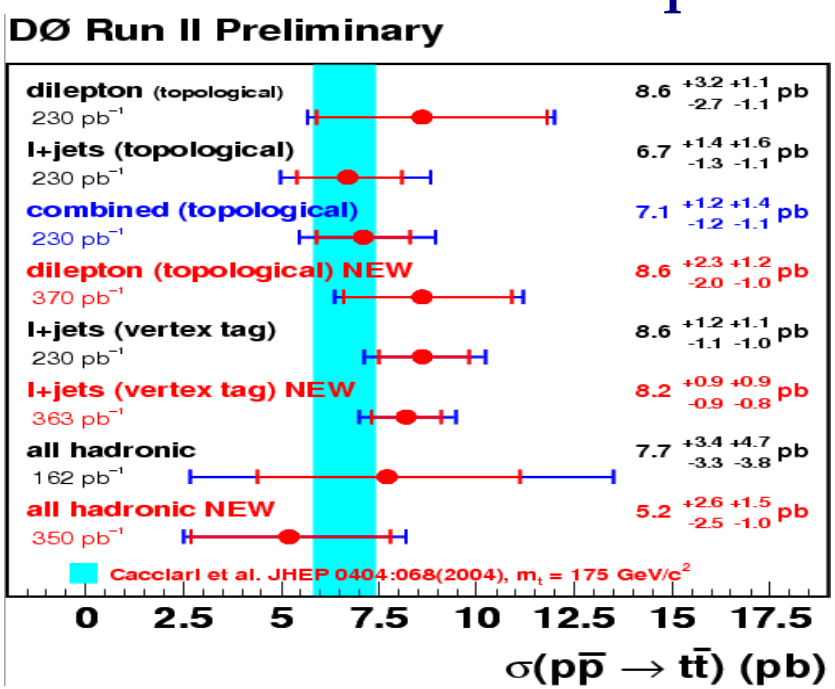


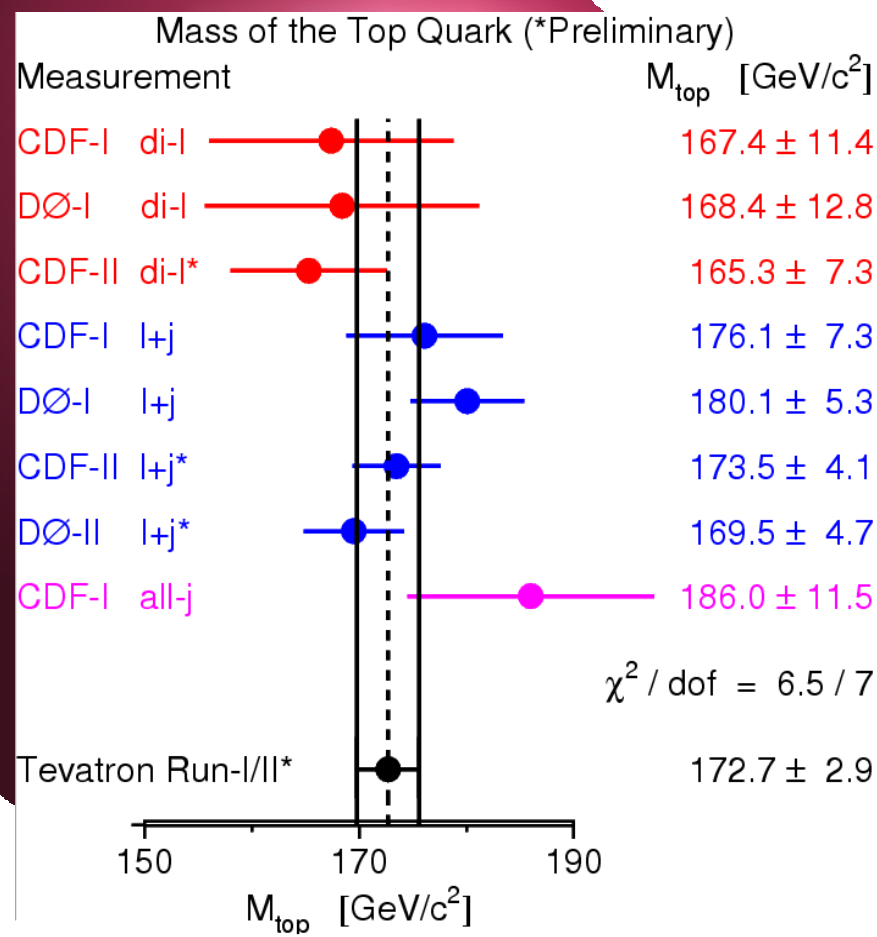


We known experimentally:

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

KING OF THE FERMIONS

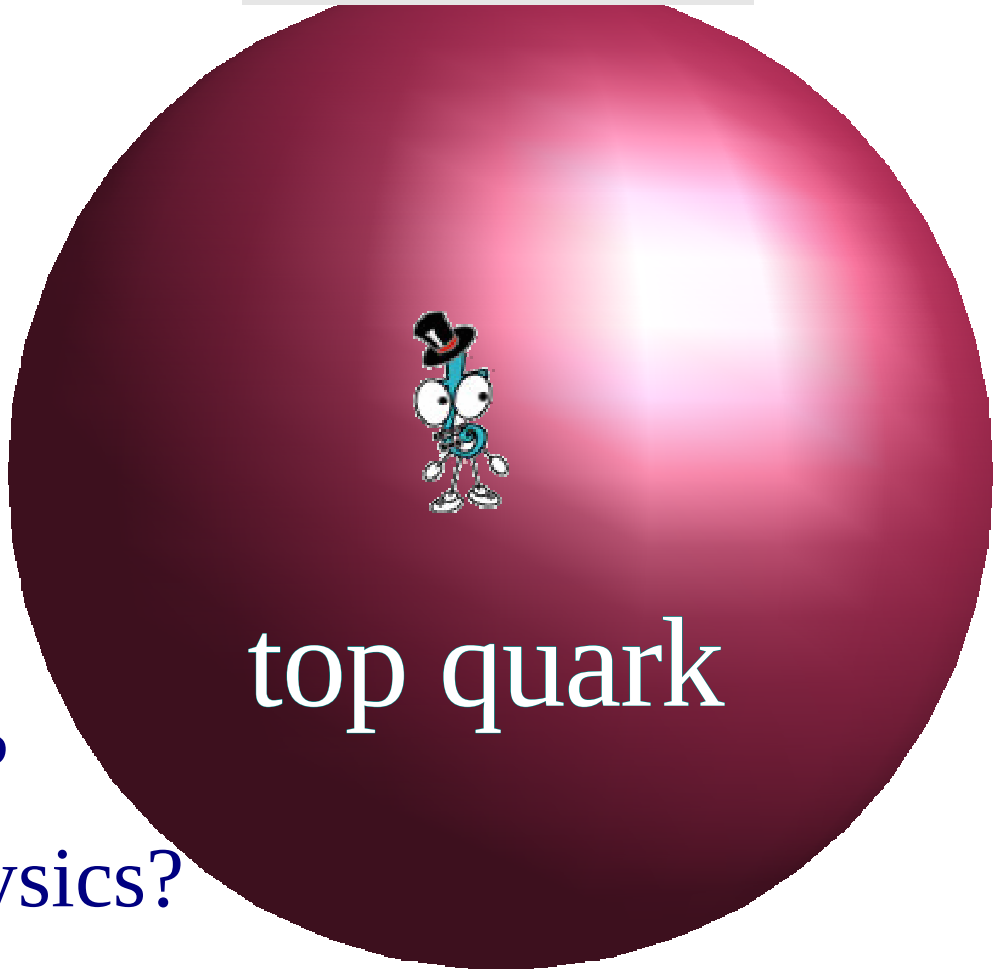




We assume but don't actually know:

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

KING OF THE FERMIONS



Really don't know:

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

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    - Total width
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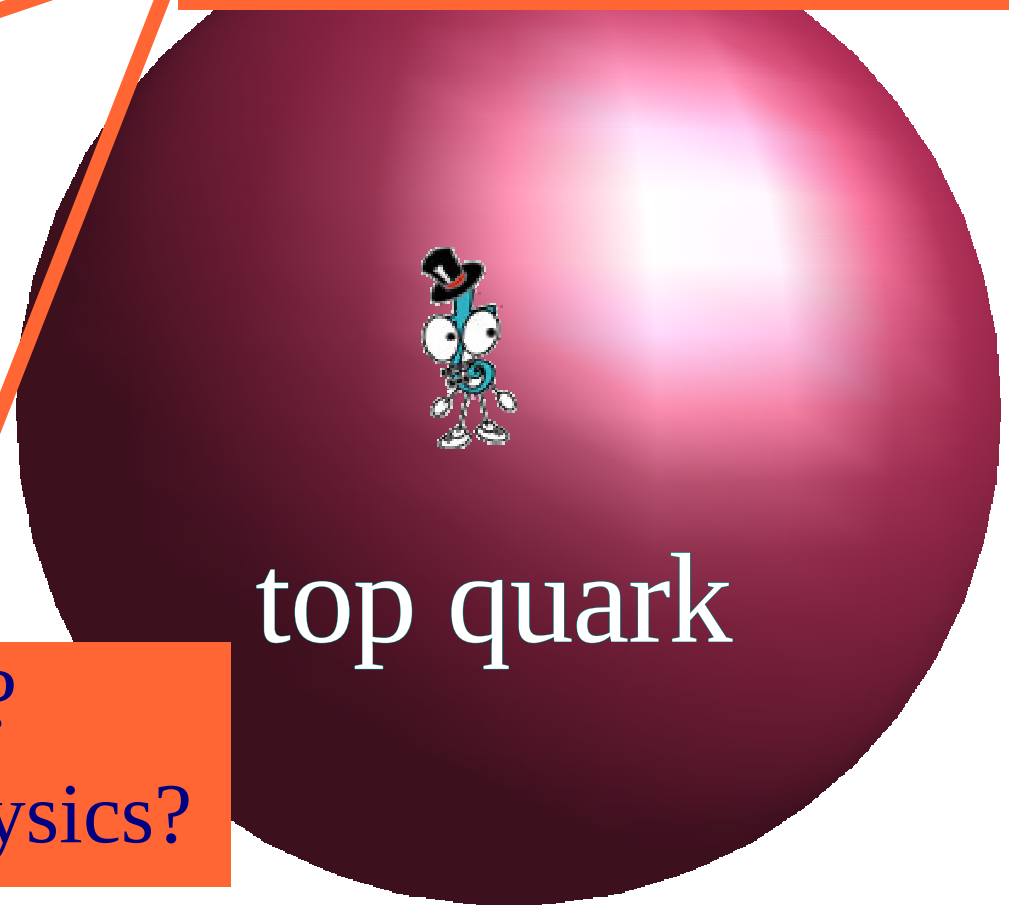
Address at the Tevatron



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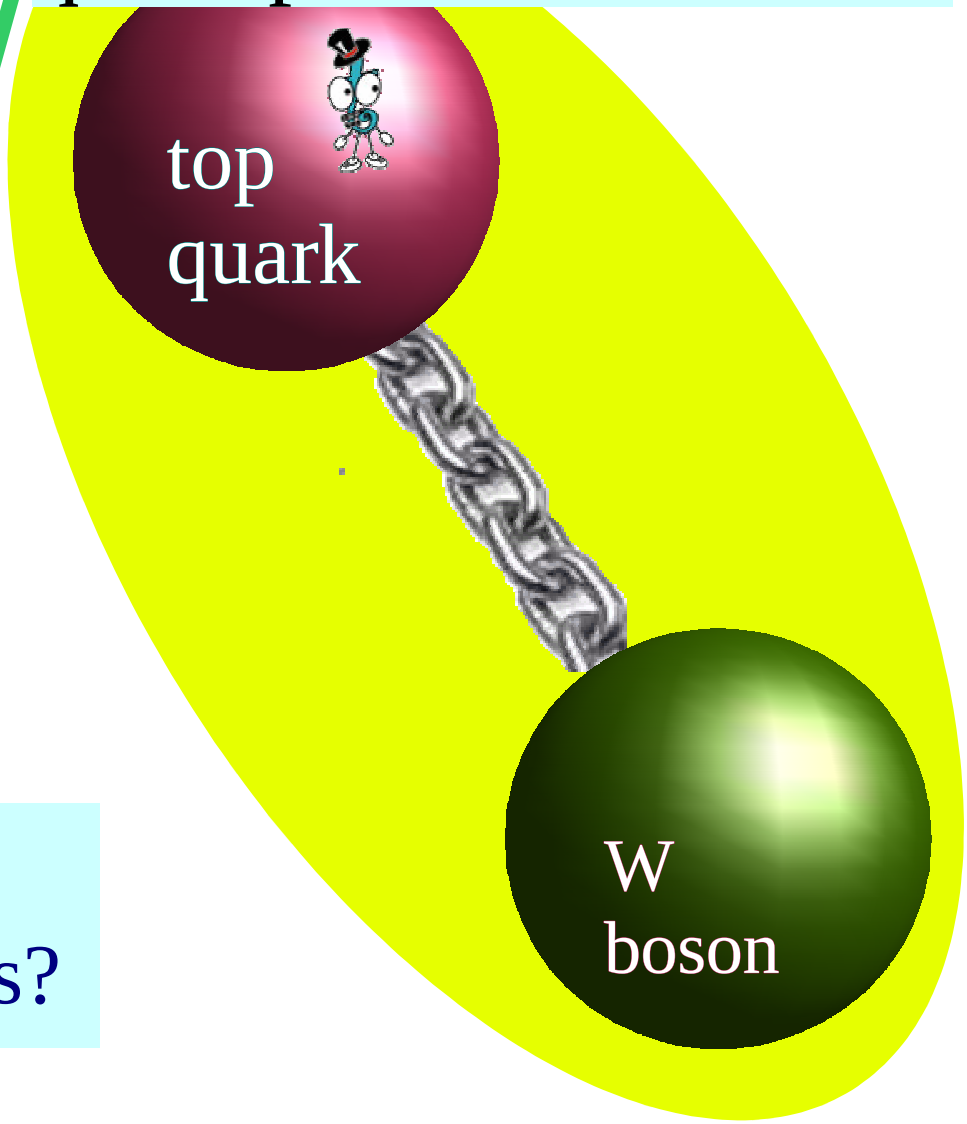
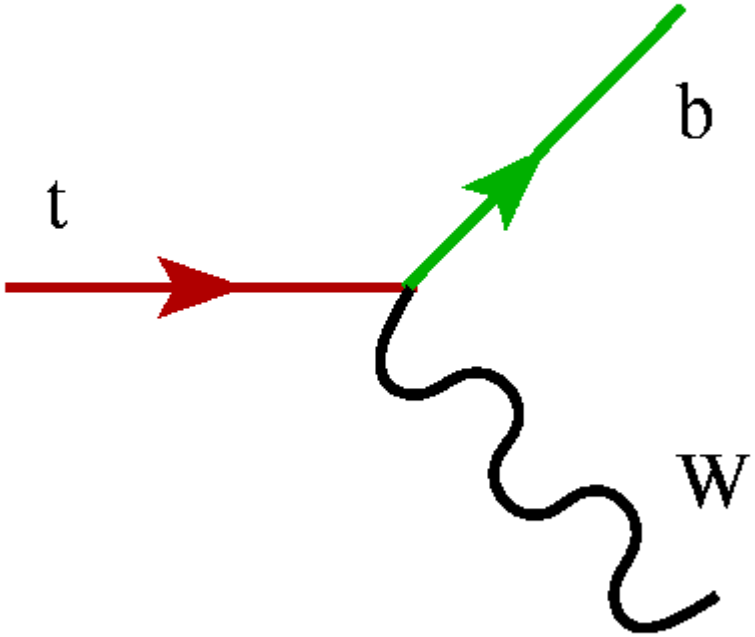
Study in single top quark production

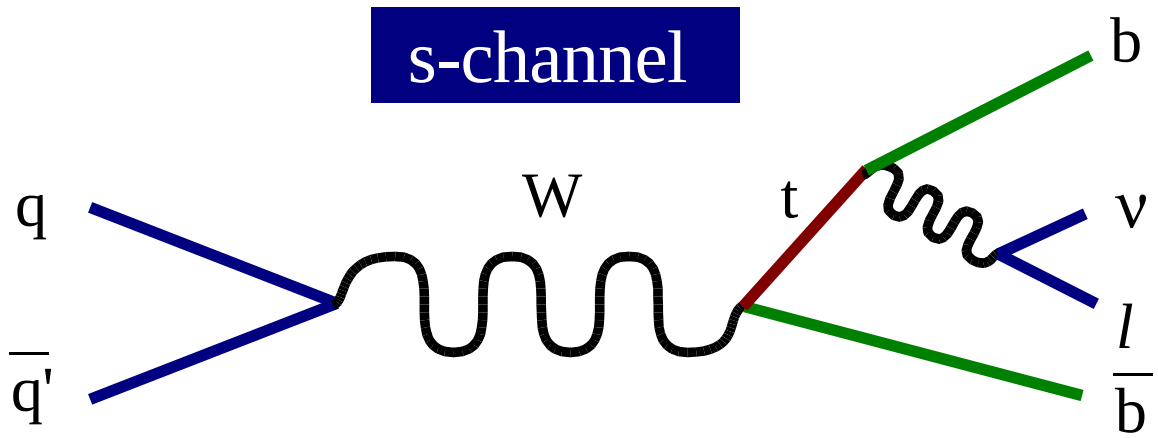


Top Quark Electroweak Charged Current Interaction



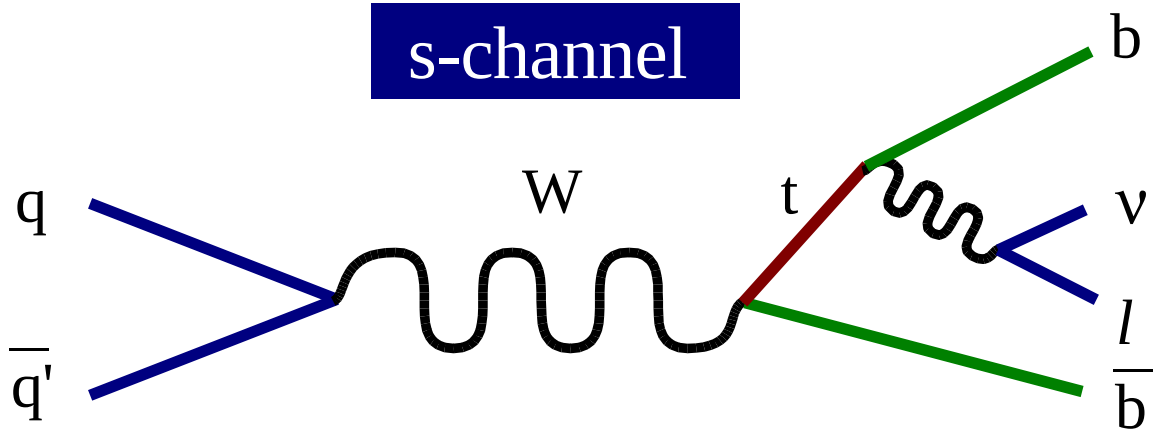
top quark decay

Electroweak Production of Top at the Tevatron

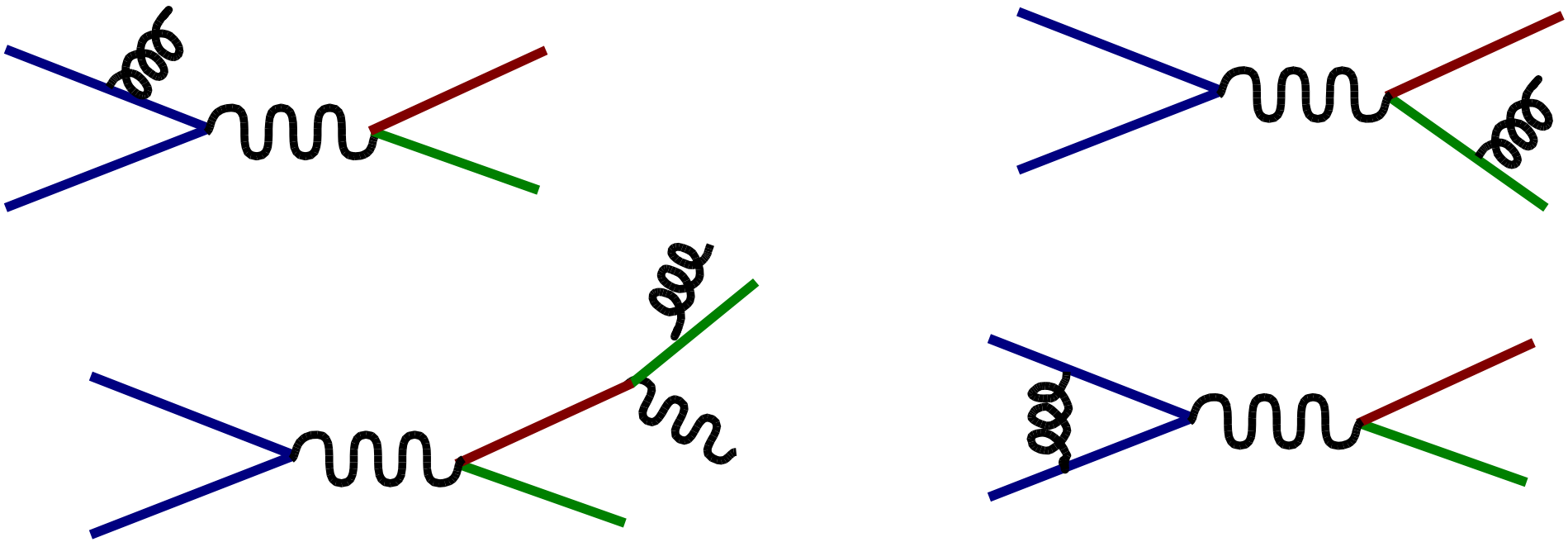


Electroweak Production of Top at the Tevatron

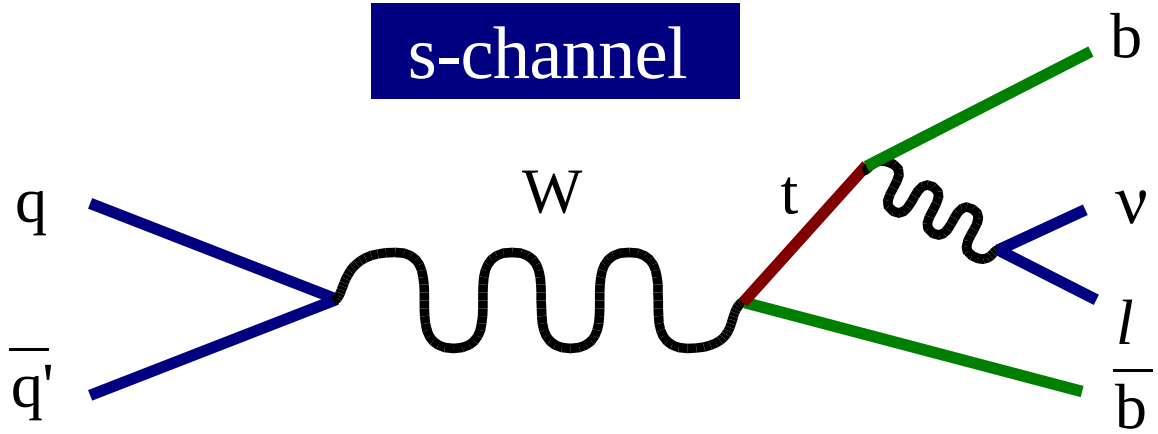
s-channel

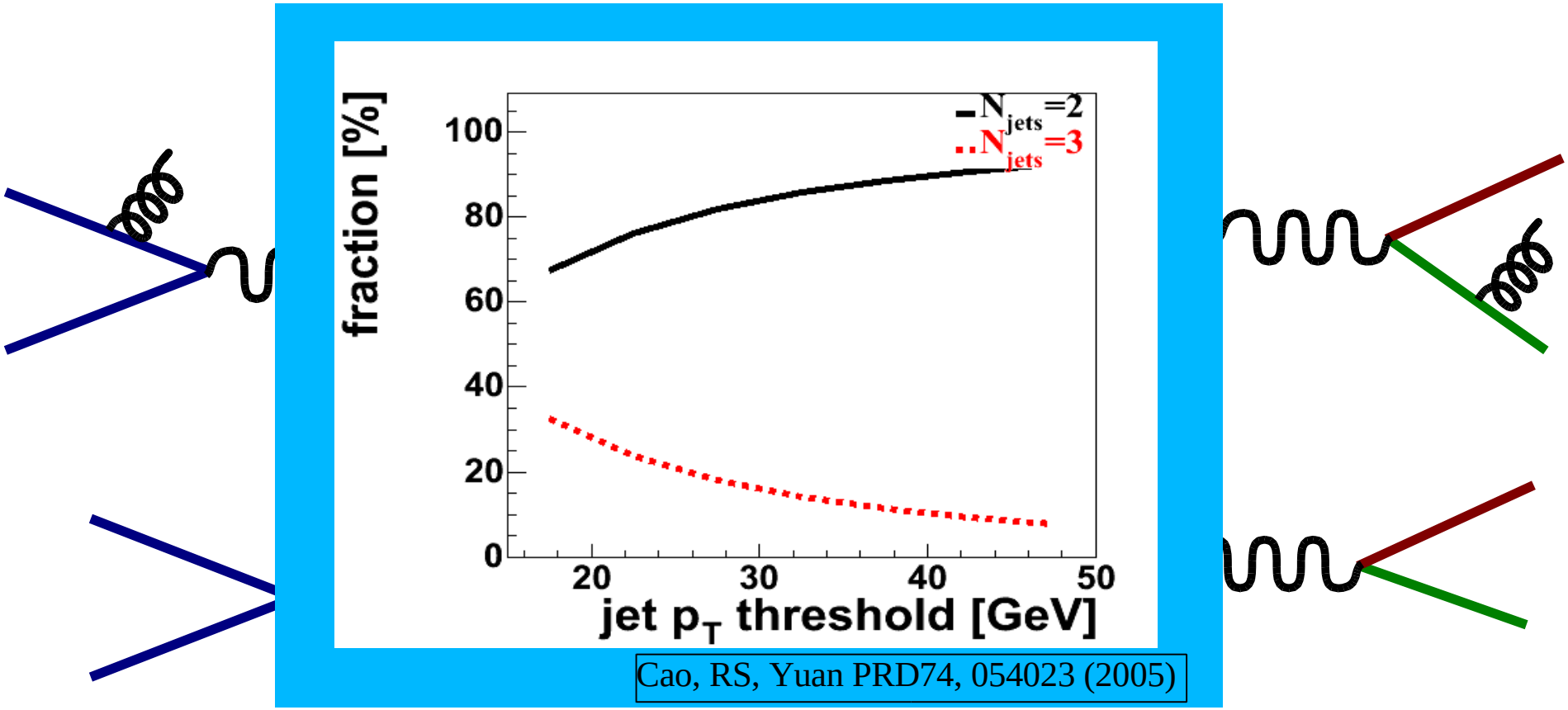


$O(\alpha_s)$ QCD corrections:



Electroweak Production of Top at the Tevatron

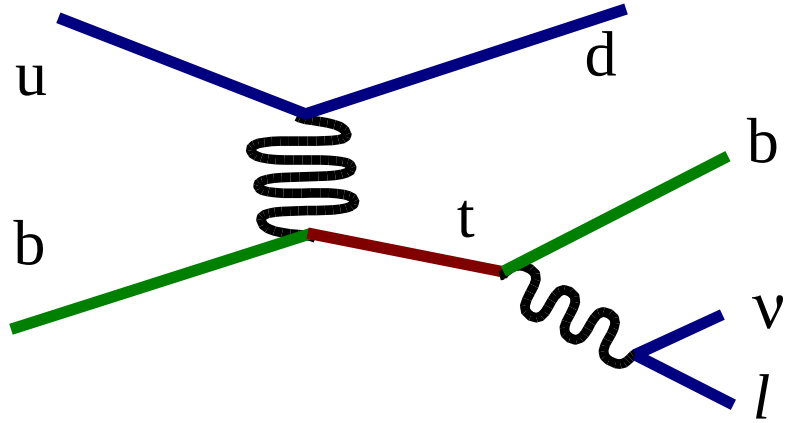




Cao, RS, Yuan PRD74, 054023 (2005)

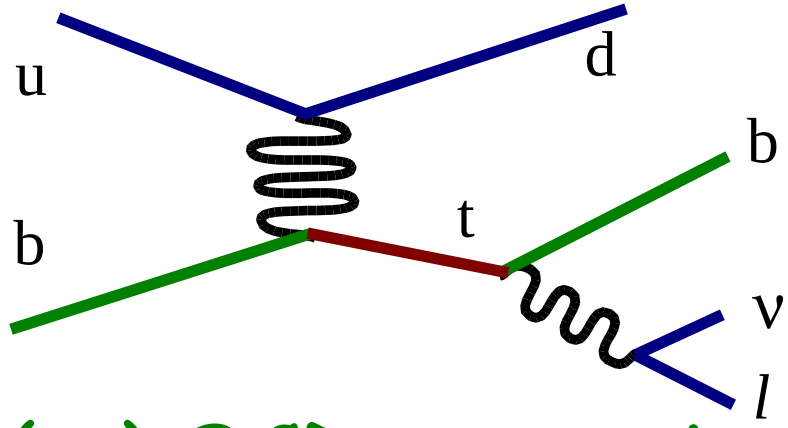
Electroweak Production of Top at the Tevatron

t-channel



Electroweak Production of Top at the Tevatron

t-channel



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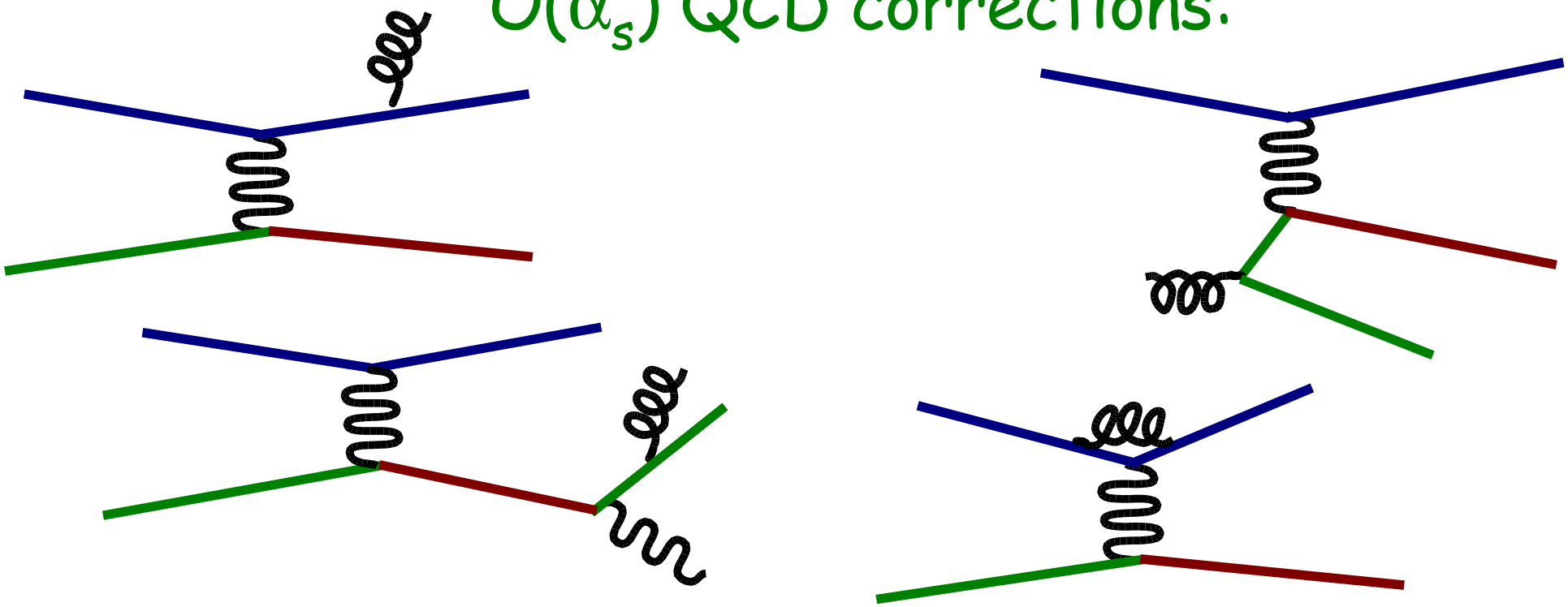
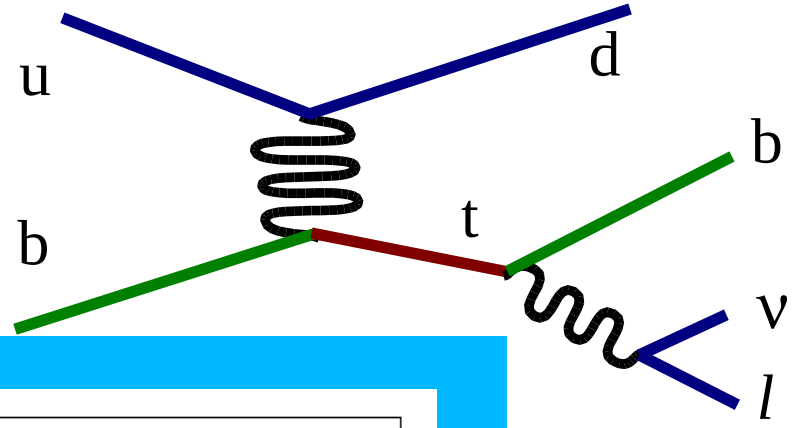
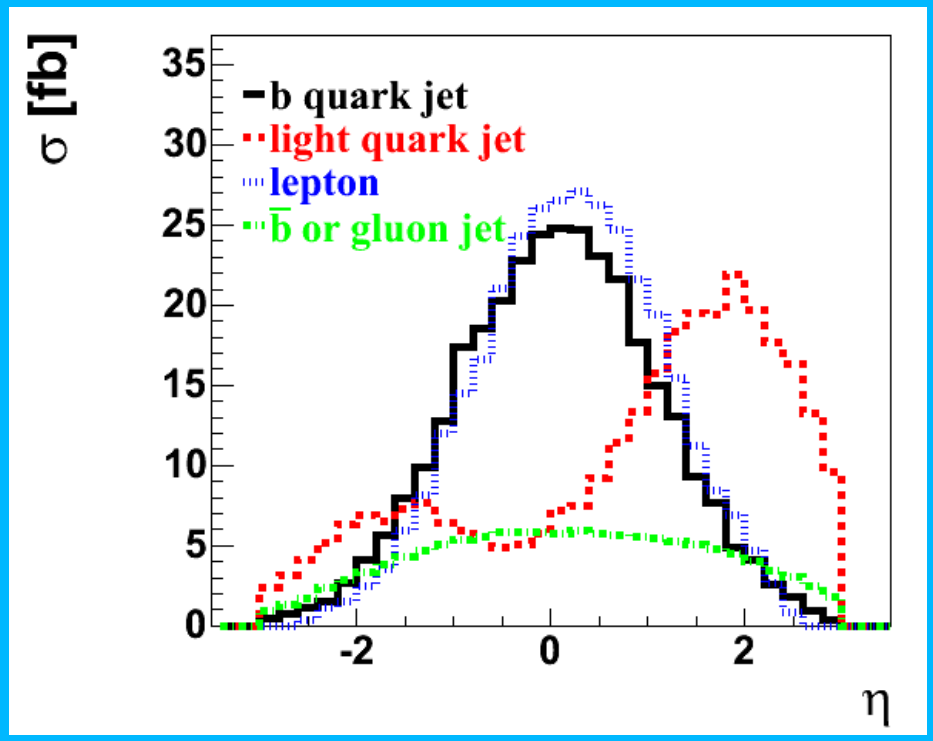


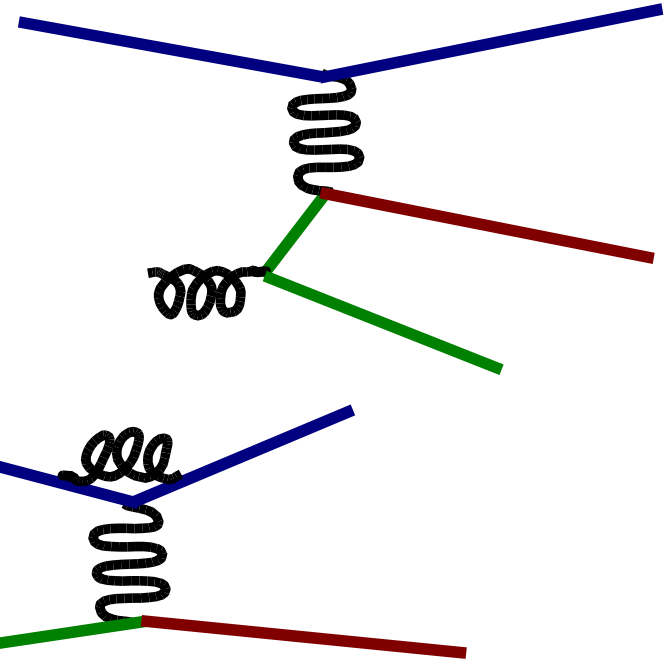
Electroweak Production of Top at the Tevatron

t-channel





Cao, RS, Benitez, Brock, Yuan hep-ph/0504230

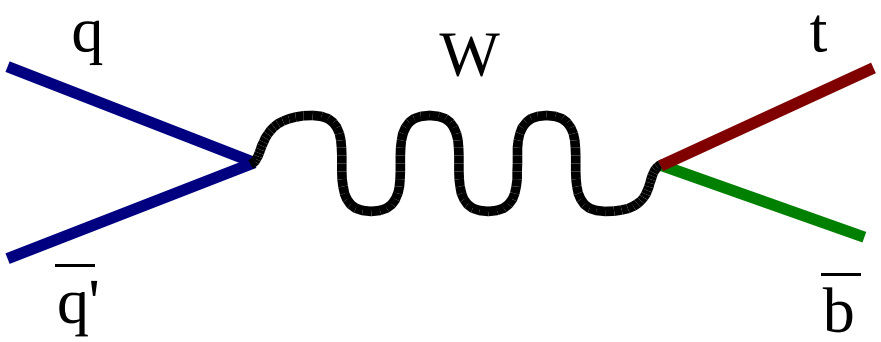


Tevatron Single Top Goals

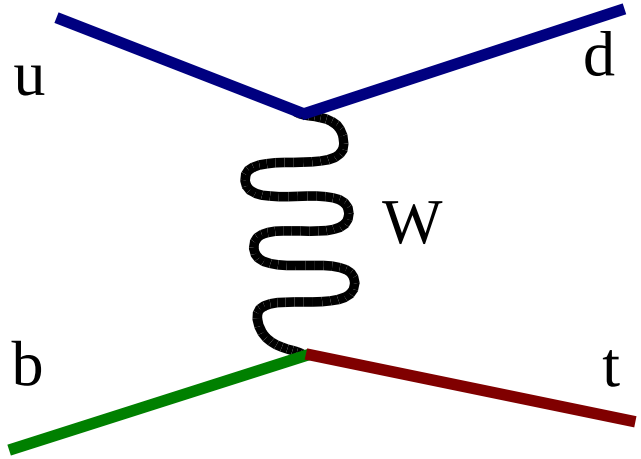
- Observe single top quark production
  - Tevatron discovery!
- Measure production cross sections $\rightarrow V_{tb}$
- Look for physics beyond the Standard Model
  - Coupled to the heavy top quark
- Study top quark spin correlations
  - probe V-A
- Understand as background
  - irreducible background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

Tevatron Single Top after Run I

s-channel



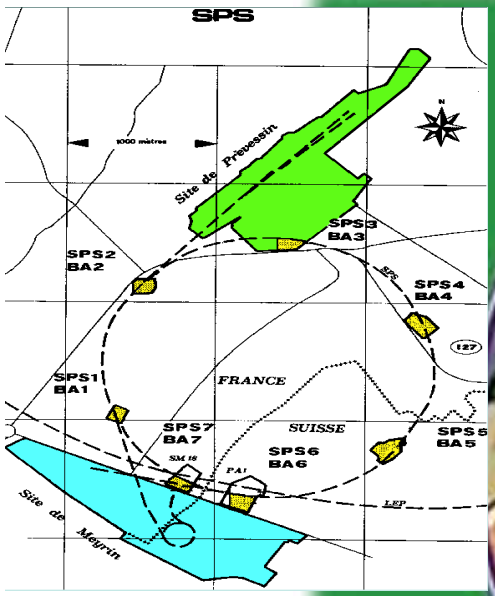
t-channel



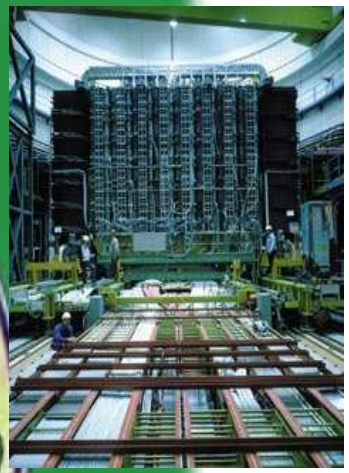
- Production cross section:

	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

- Other Standard Model production mode (*Wt*) negligible


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



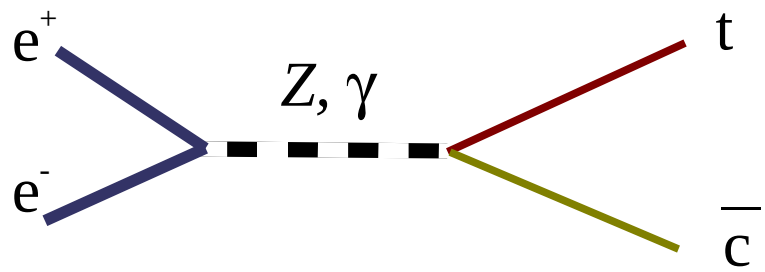
Single Top

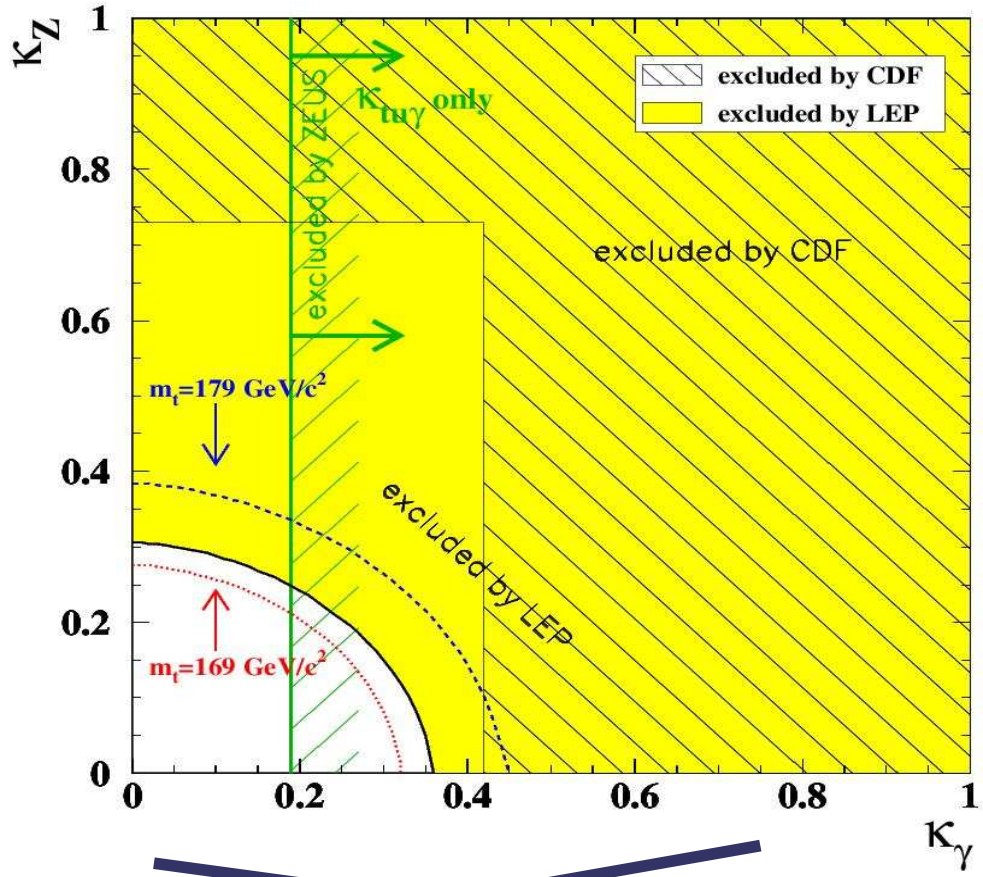
HERA
PETRA

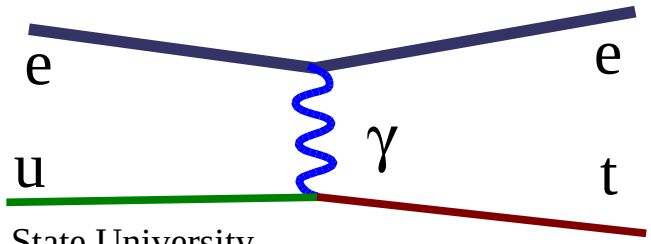
Single Top at LEP and Hera: FCNC

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

- Hera:
  - $ep \rightarrow et$



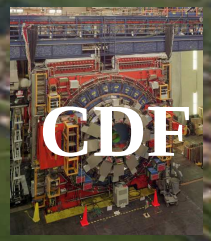


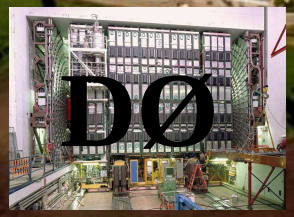


Experimental Detection of Single Top Events

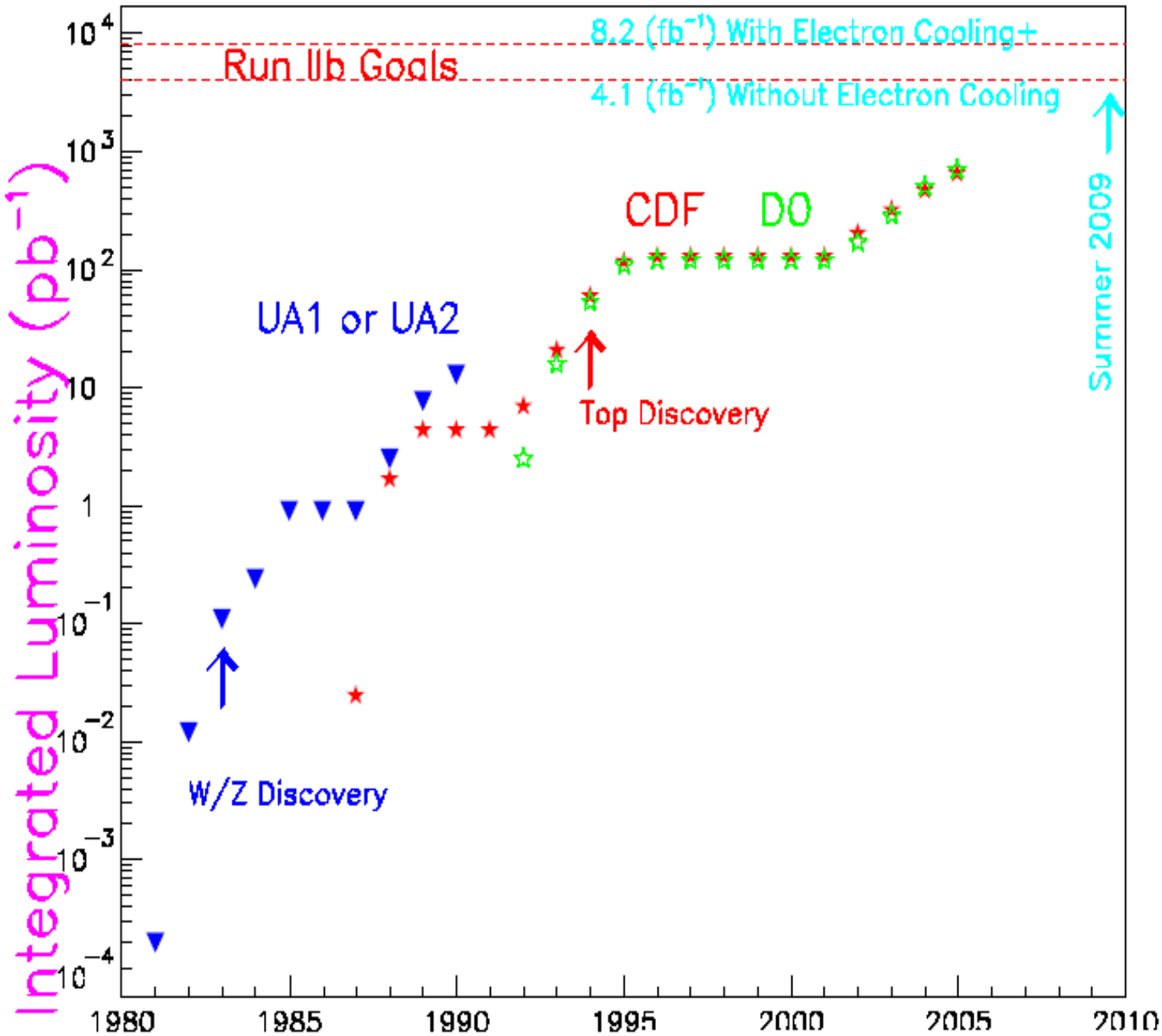
Experimental Setup: Fermilab Tevatron in Run II

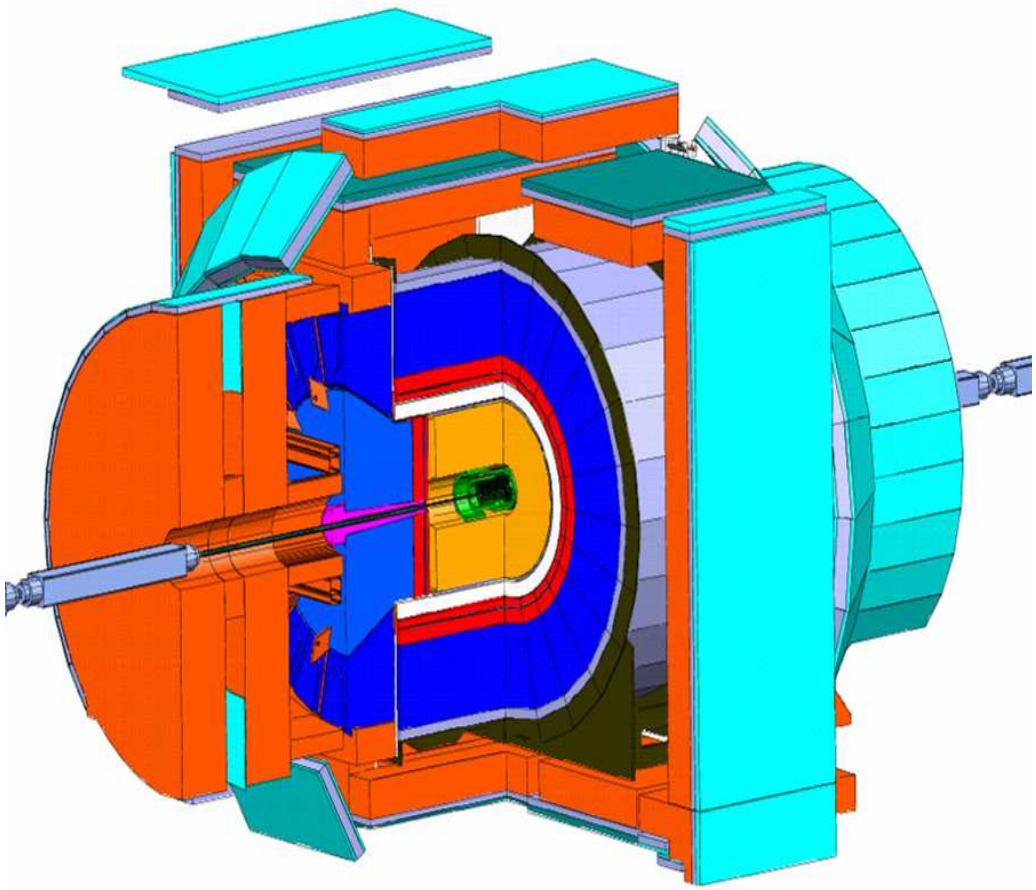
Proton-Antiproton Collider
CM Energy 1.96TeV
→ ***Energy Frontier***
Instantaneous luminosity
>160E30
→ ***Luminosity Frontier***

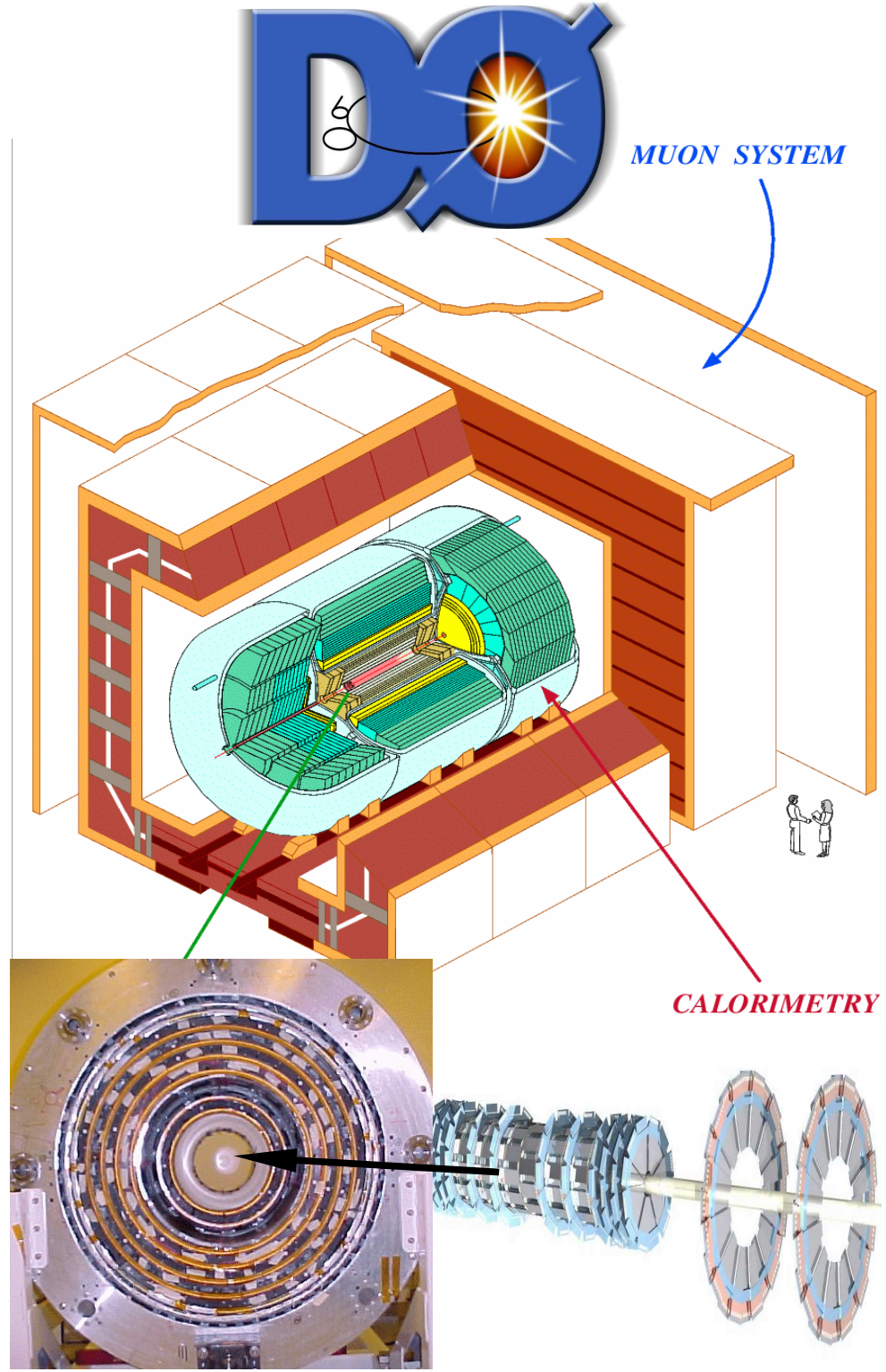




Hadron Collider Integrated Luminosity



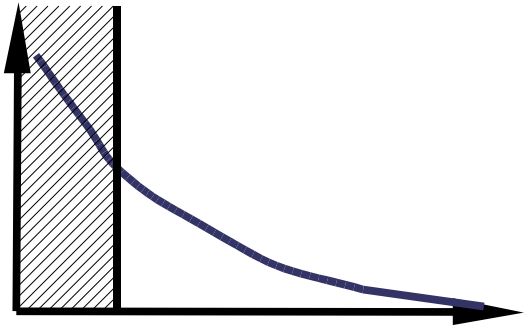


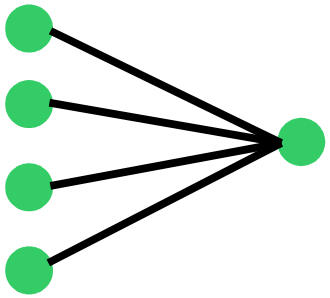

MUON SYSTEM
CALORIMETRY

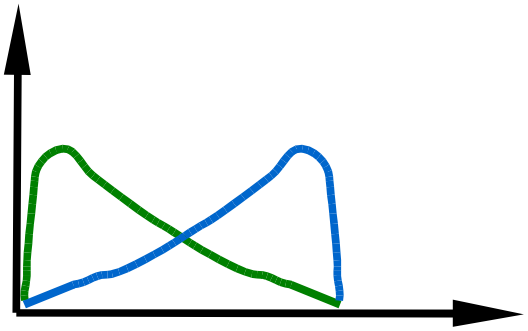
Analysis Outline

Goal:

Maximize Sensitivity



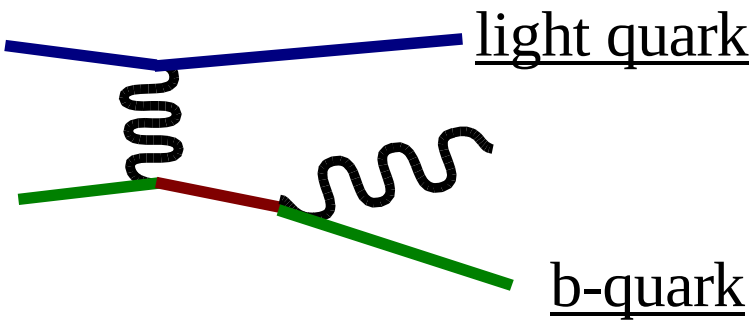


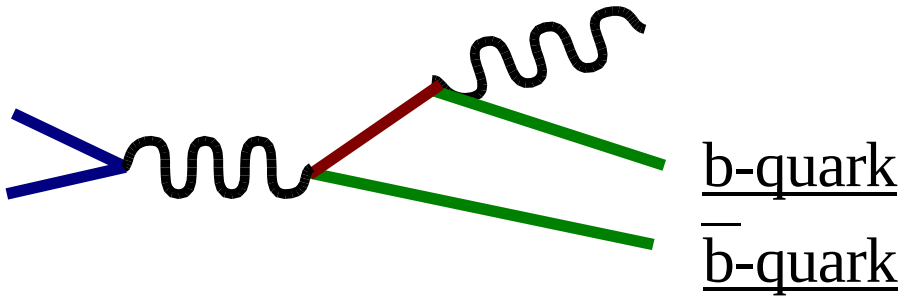


1. Event Selection
   - Select *W*-like events
   - Maximize acceptance
   - Model backgrounds
2. Event Analysis
   - Find discriminating variables
   - Cut/combine in multivariate analysis
3. Determine cross section
   - Event counting or Binned likelihood
   - Separately for s-channel, t-channel, and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

Event Selection

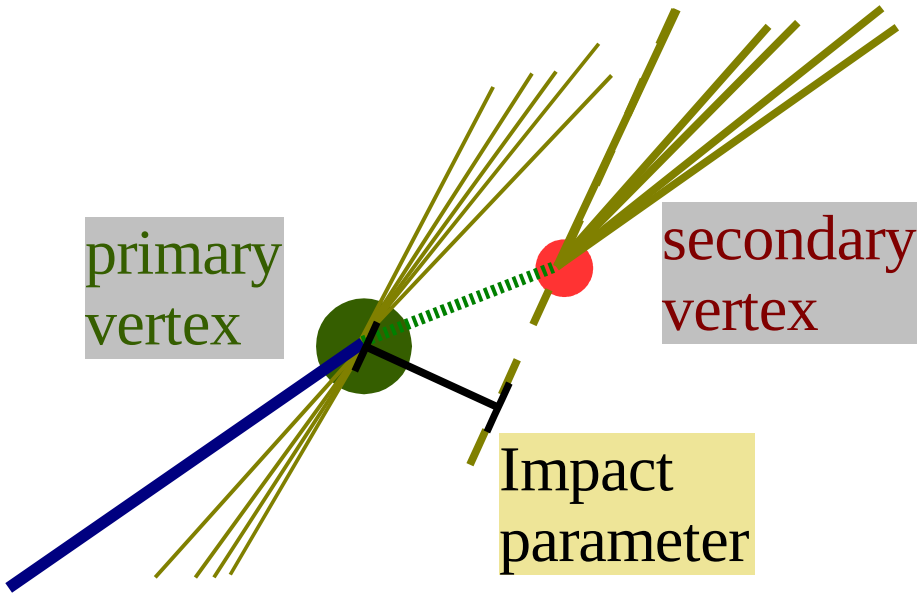
- Trigger:
  - Electron + ≥1 jets, muon + ≥1 jets
- Lepton:
  - 1 electron: $p_T > 15\text{GeV}$, $|\eta^{det}|<1.1$
  - 1 muon: $p_T > 15\text{GeV}$, $|\eta^{det}|<2.0$
- Neutrino: $\not{E}_T > 15\text{GeV}$
- Jets:
  - $p_T > 15\text{GeV}$, $|\eta^{det}|<3.4$, p_T (jet 1)> 25GeV, $|\eta^{det}(\text{jet1})|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





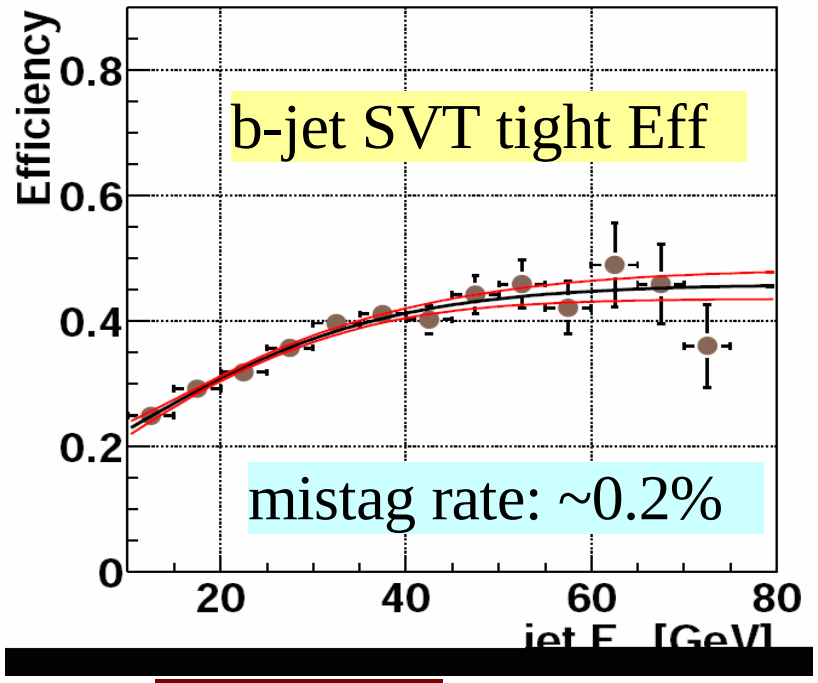
Event Selection: b-tagging

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



s-channel

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

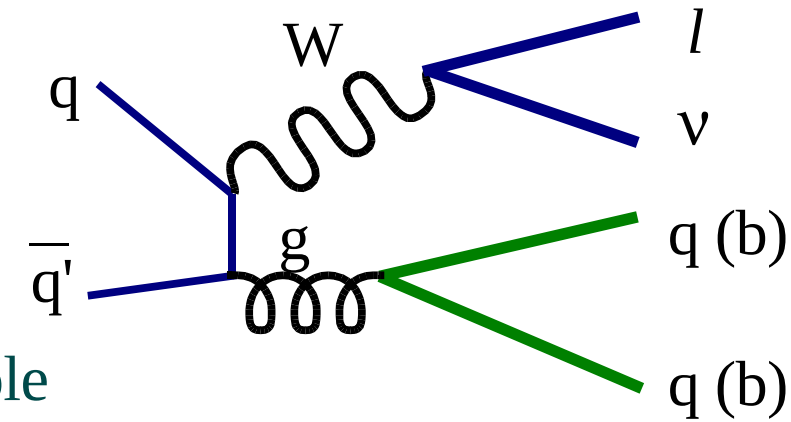


t-channel

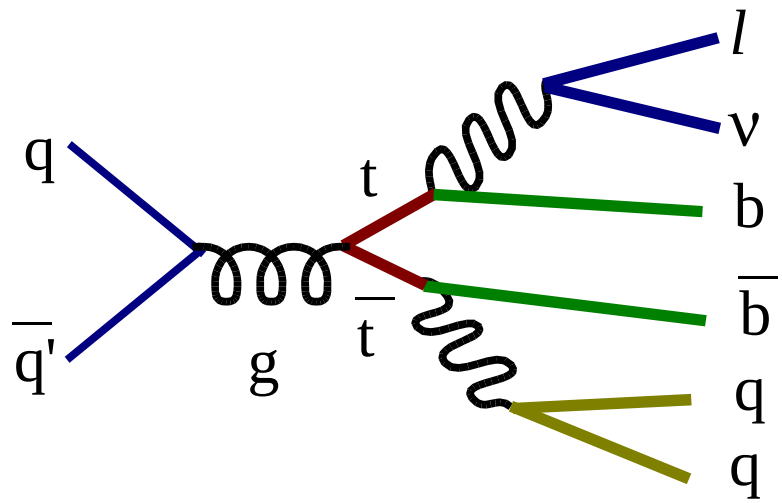
- Final state:
  - 1 high-p_T b-jet
  - 1 high-p_T light quark jet
- ➔ Require ≥1 b-tagged jet
- ➔ Require ≥1 untagged jet

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

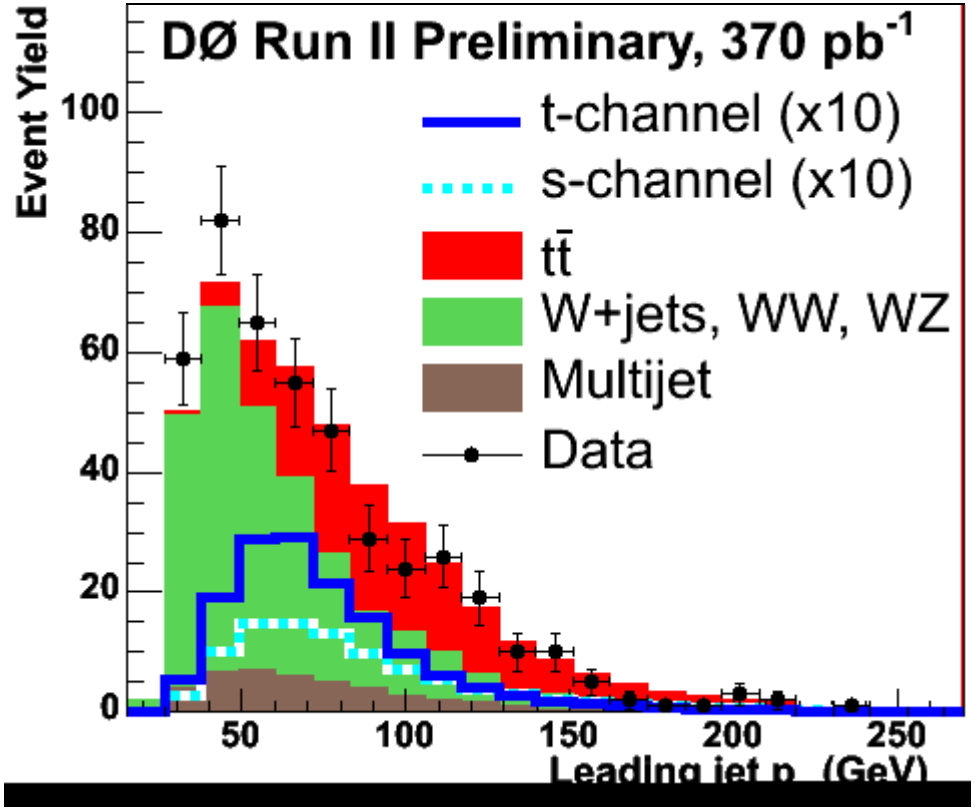


- Multijet events (misidentified lepton)
  - Estimated from data
- Top pair production
  - Estimated from MC
- Diboson (WZ, WW)
  - Estimated from MC

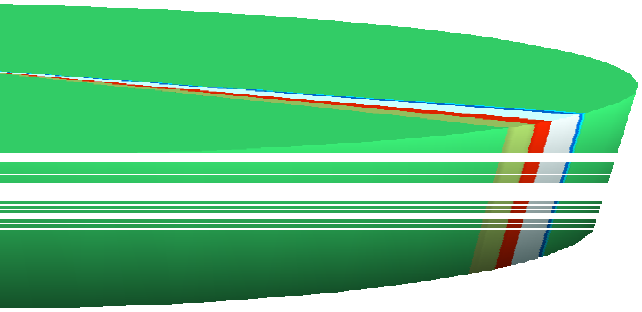


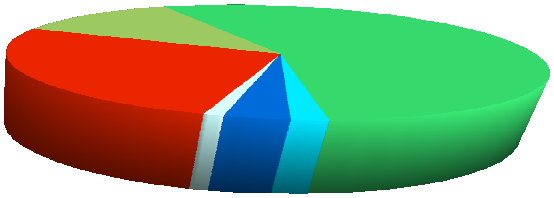
Event Yield in 370 pb^{-1}

	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



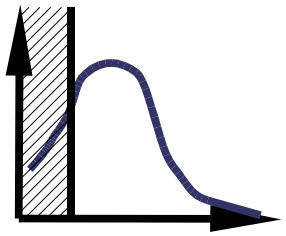


- Wjj
- Wbb
- $t\bar{t}$
- WW/WZ
- t-channel
- s-channel

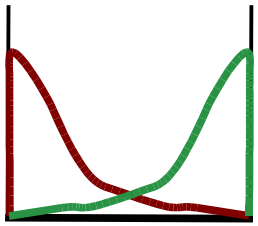
Event Analysis

- Advanced analysis techniques

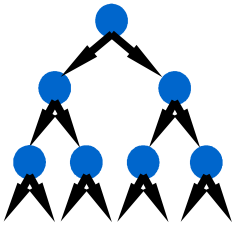
Cut-Based



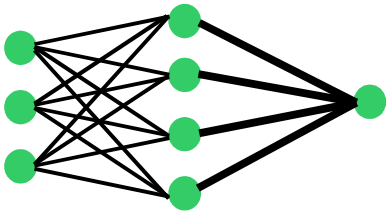
Likelihoods



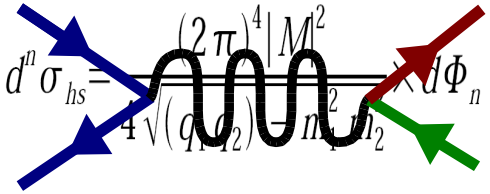
Decision Trees



Neural Networks



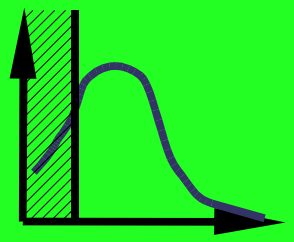
Matrix Elements



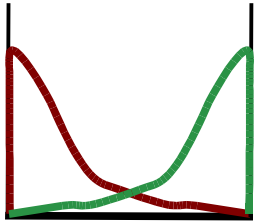
Event Analysis

- Advanced analysis techniques

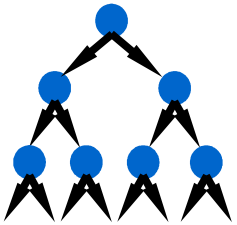
Cut-Based



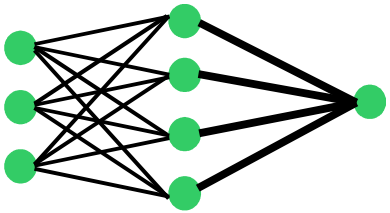
Likelihoods



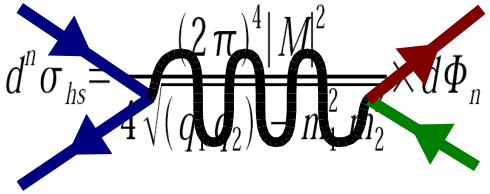
Decision Trees



Neural Networks



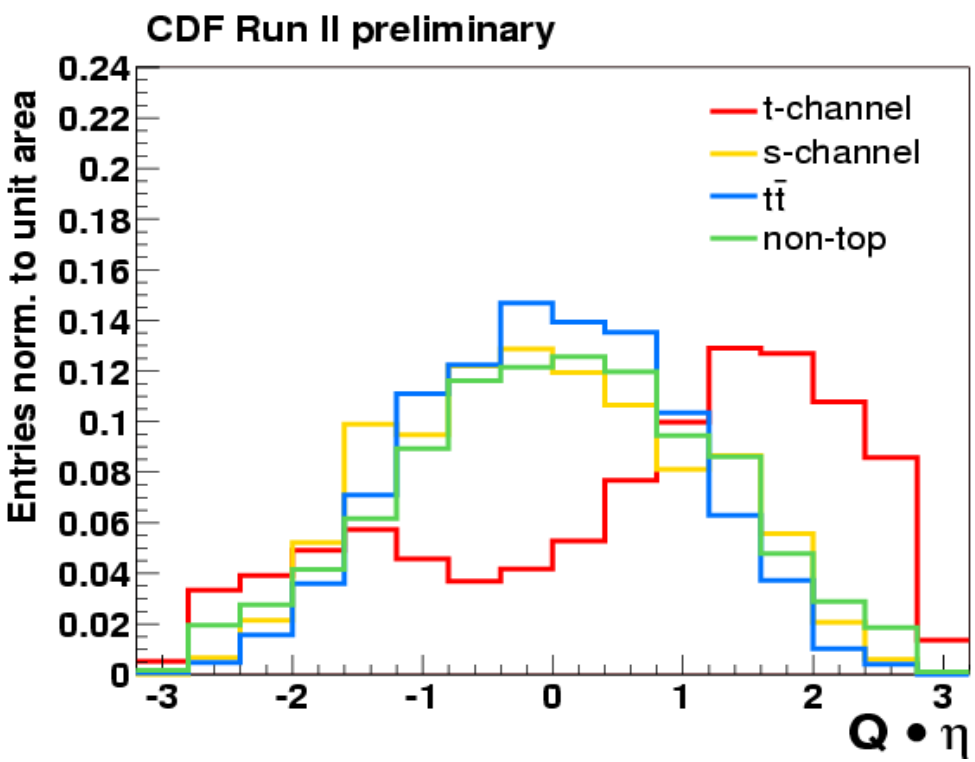
Matrix Elements

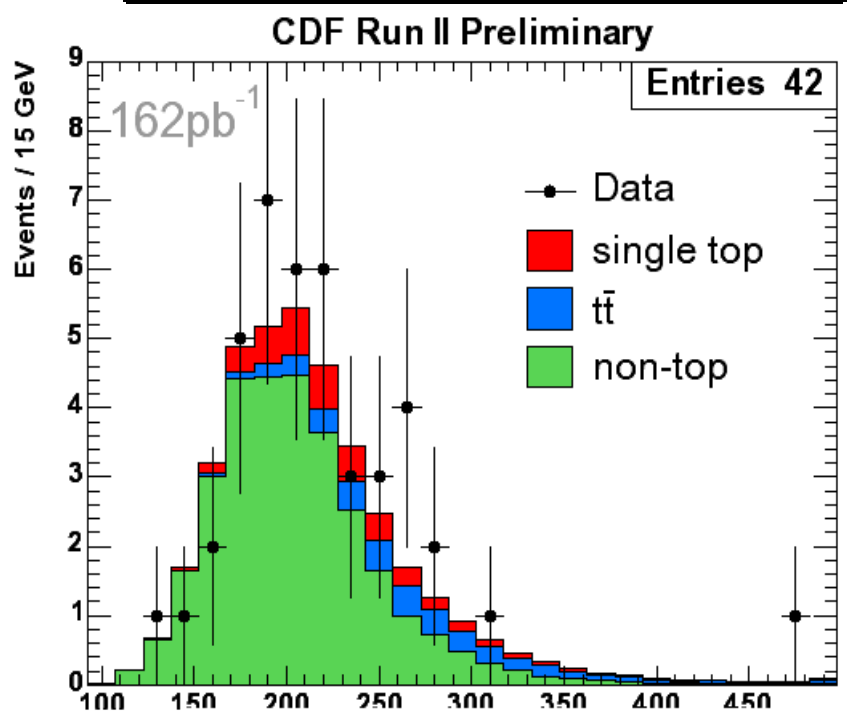


Cut-based analysis

- Tight event selection
  - Exactly 2 jets
- Cut on separating variables
  - Top quark mass
- Likelihood fit to discriminating distribution
  - $Q \times \eta$, H_T

	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**

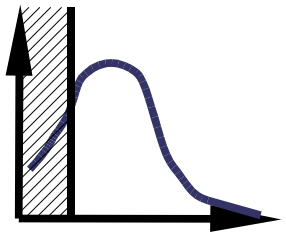




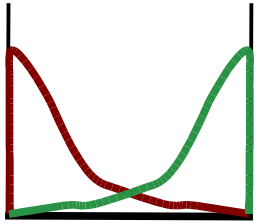
Event Analysis

- Advanced analysis techniques

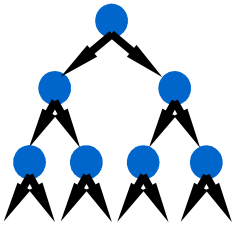
Cut-Based



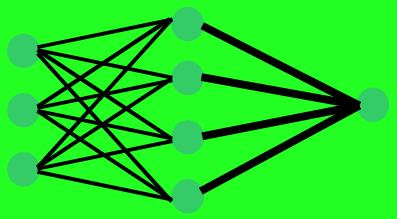
Likelihoods



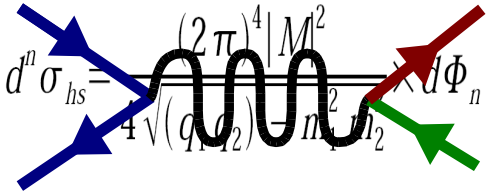
Decision Trees



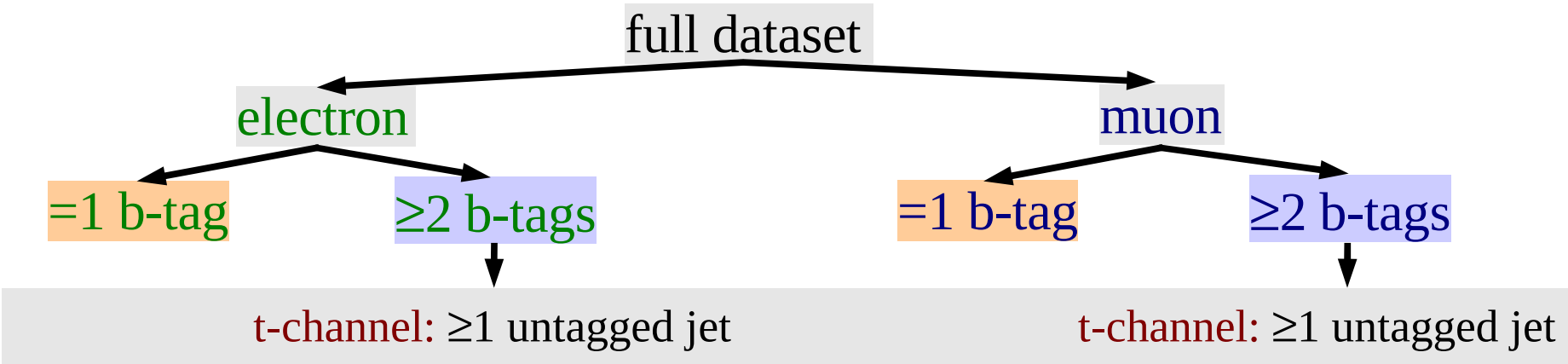
Neural Networks



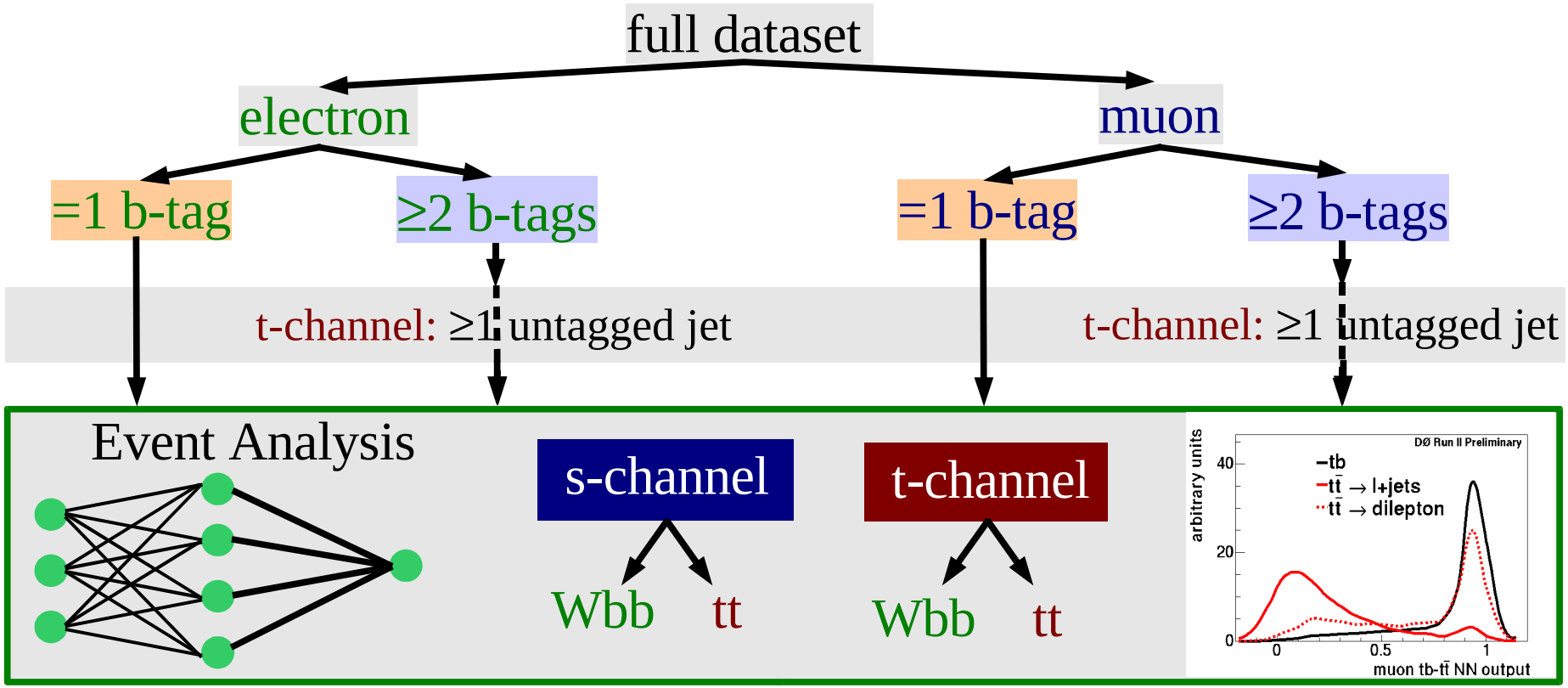
Matrix Elements



Analysis Strategy

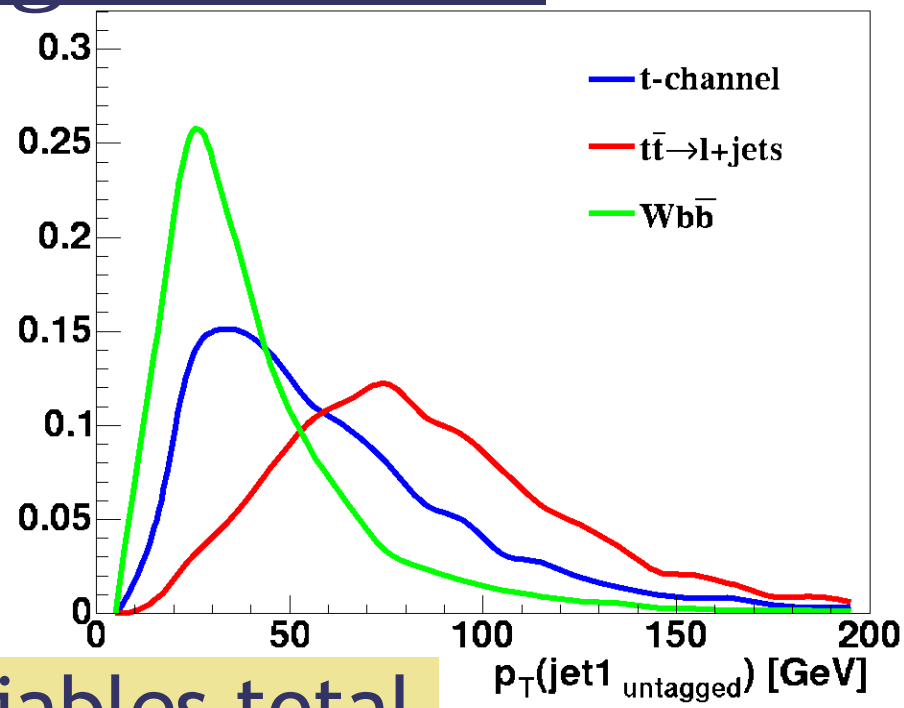


Analysis Strategy

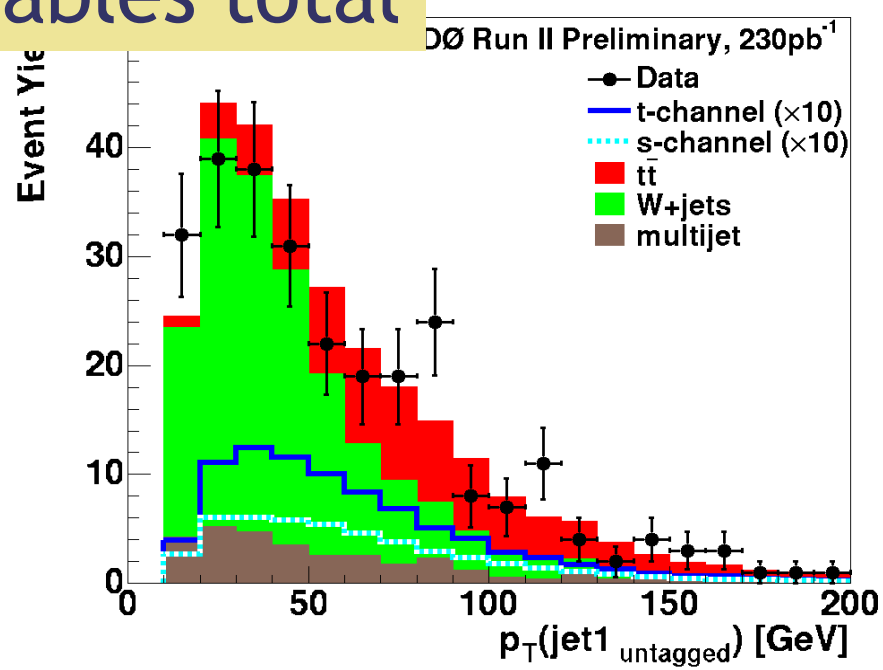


Discriminating Variables

- 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

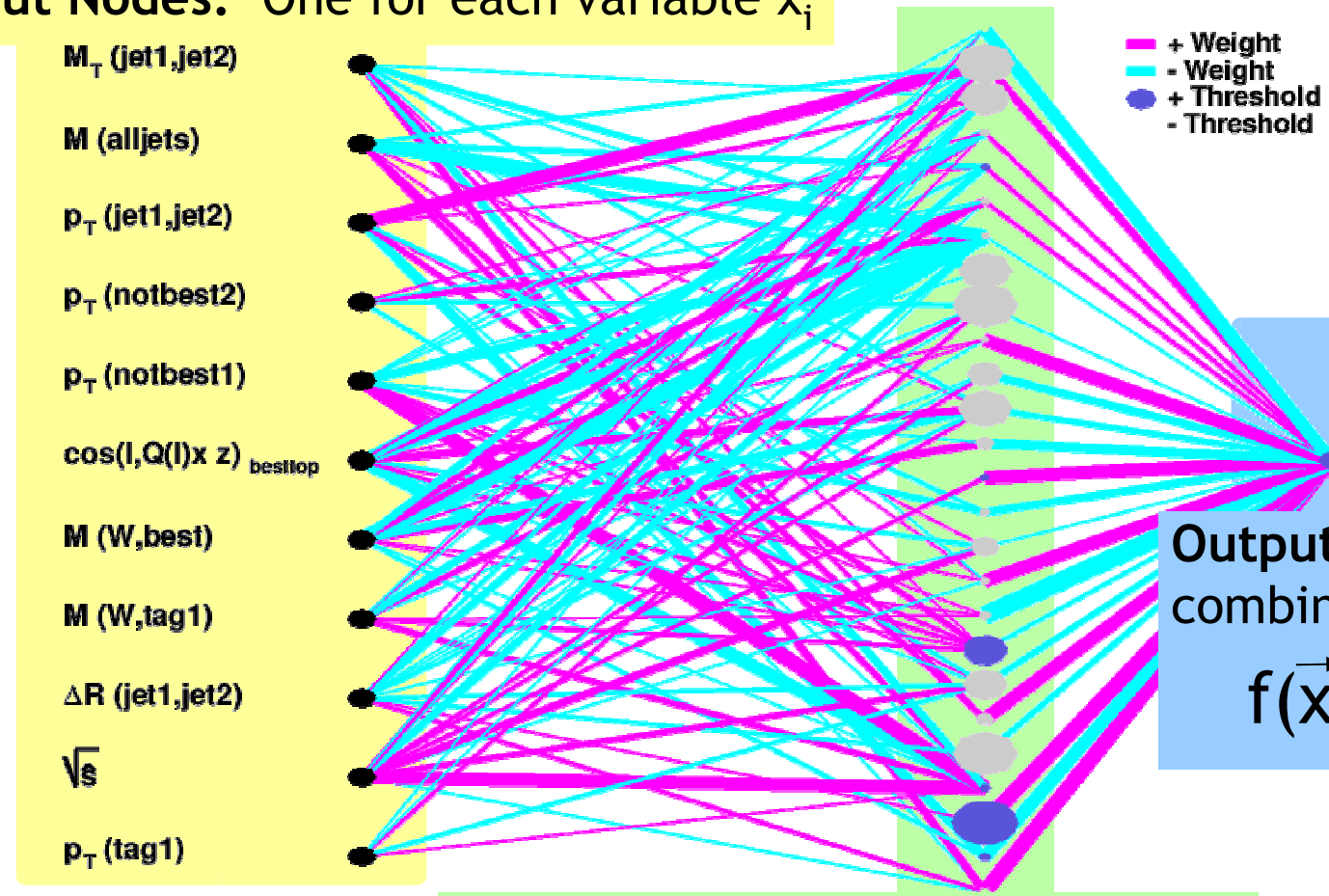


25 variables total



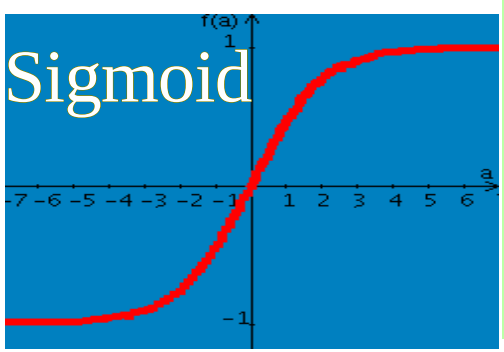
Neural Networks

Input Nodes: One for each variable x_i



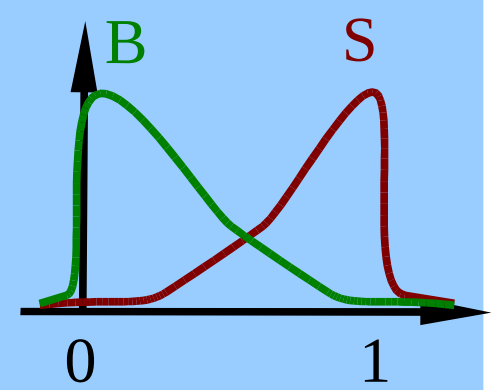
Output Node: linear combination of hidden nodes

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

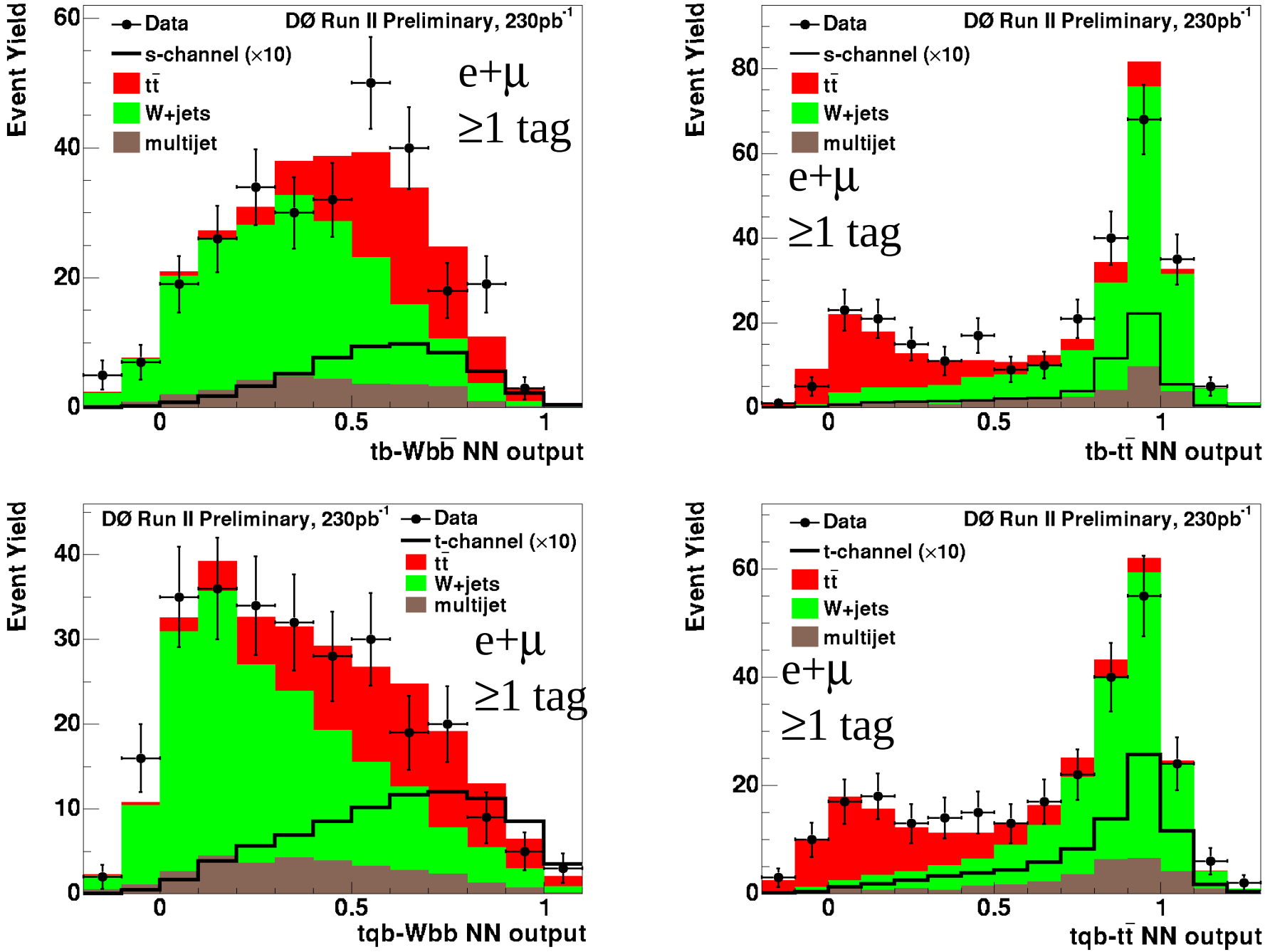


Hidden Nodes: Each is a sigmoid dependent on the input variables

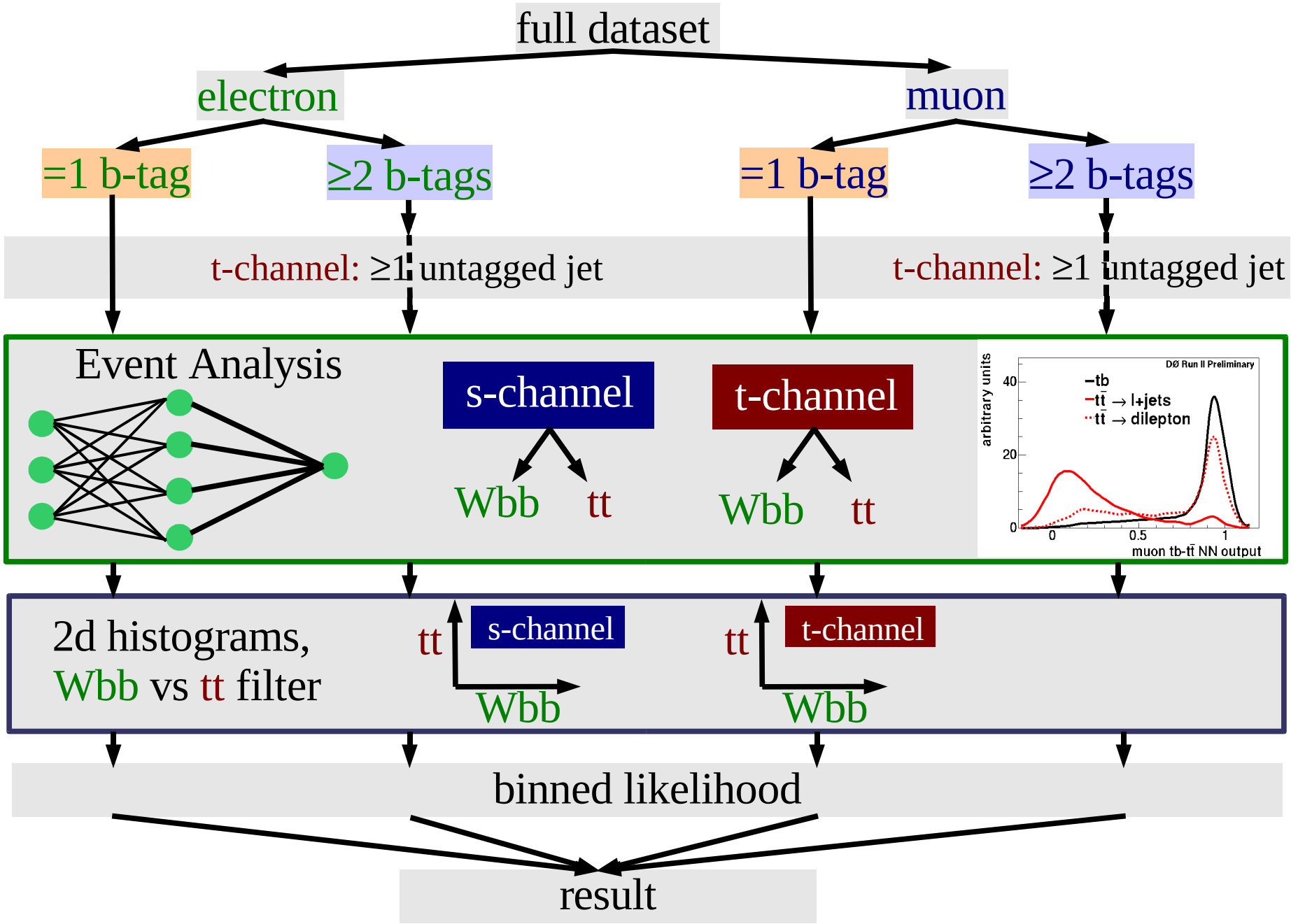
$$n_k(\vec{x},\vec{w}_k) = \frac{1}{1 + e^{-\Sigma\, w_{ik}\, x_i}}$$



Neural Network Output



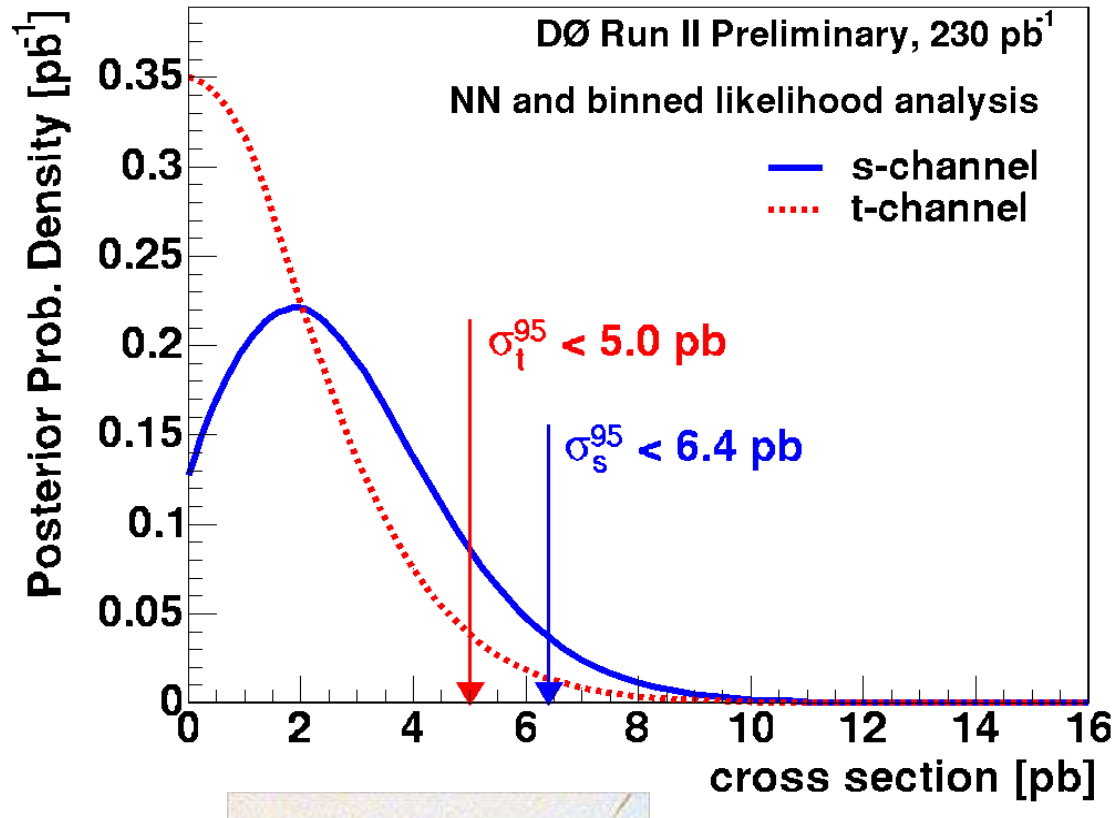
Analysis Strategy



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%



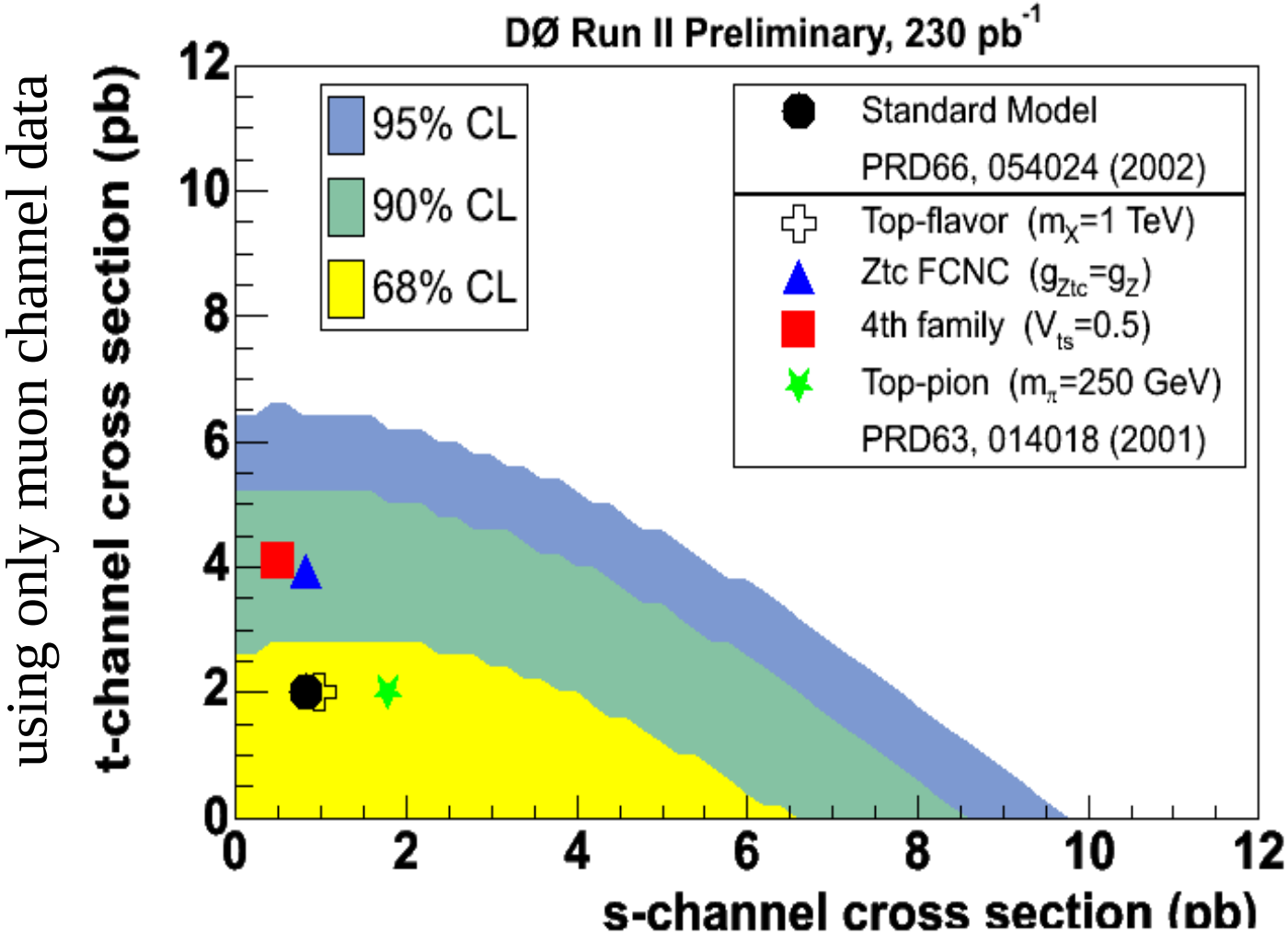
Expected/Observed limit:

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

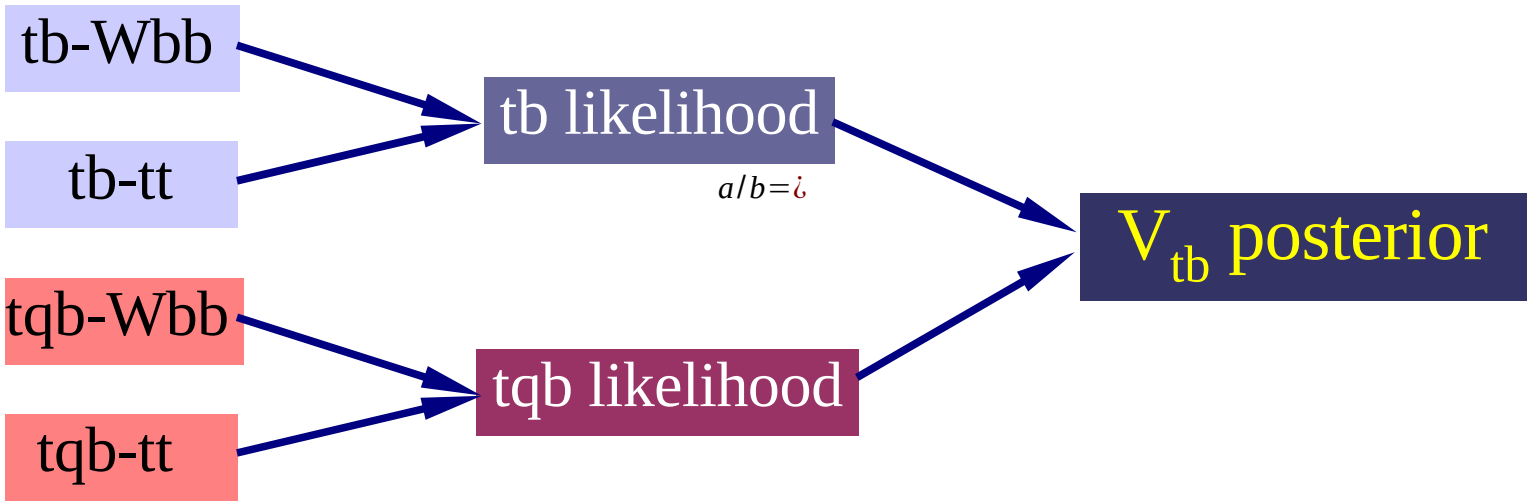


using only muon channel data

using only electron channel data

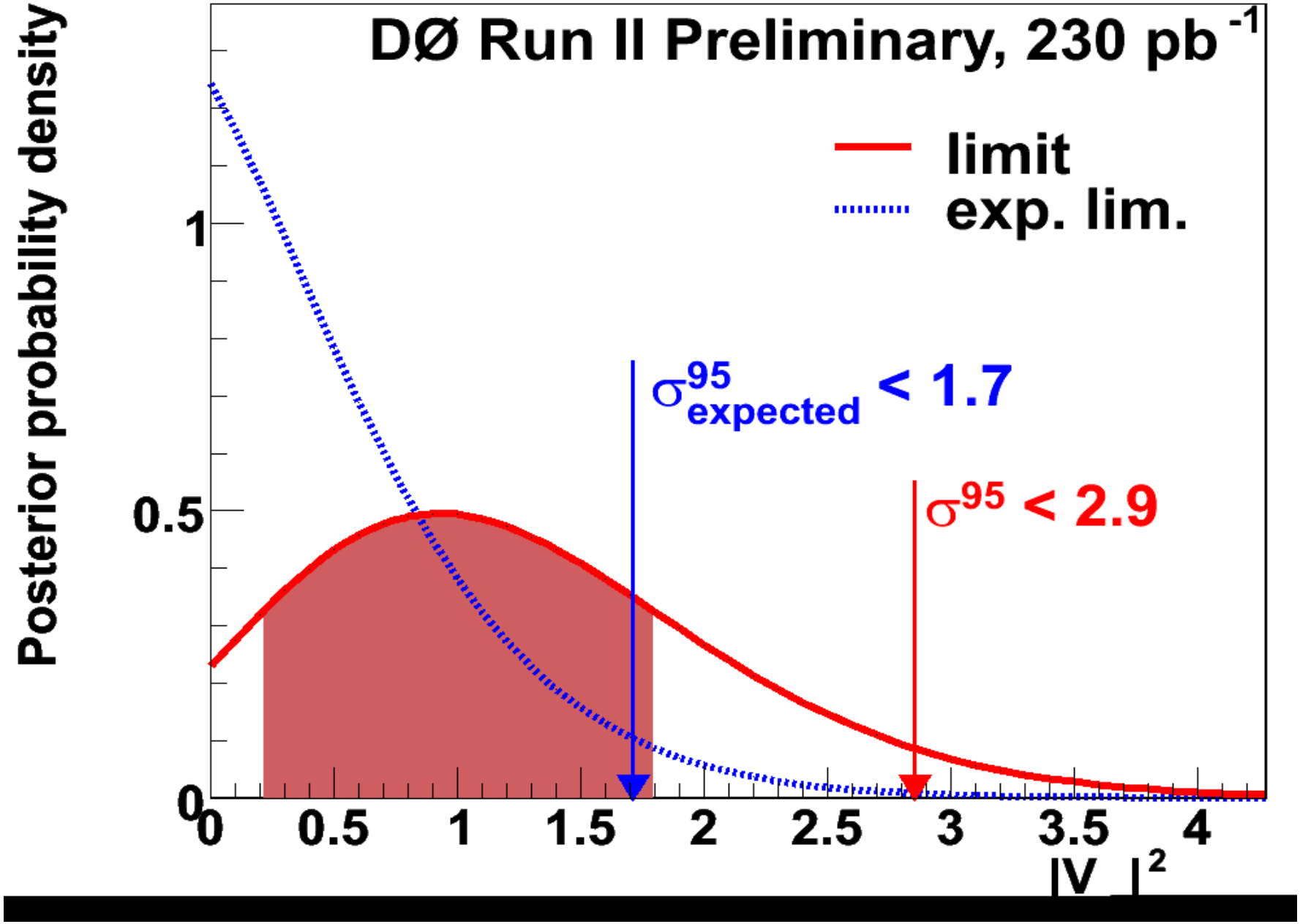
V_{tb} Coupling Limit

- 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

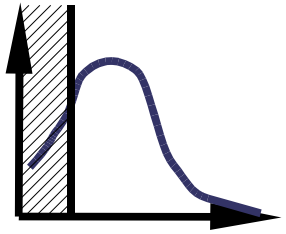
Bayesian Posterior density for $|V_{tb}|^2$



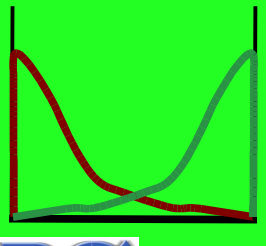
Event Analysis

- Advanced analysis techniques

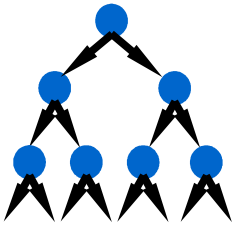
Cut-Based



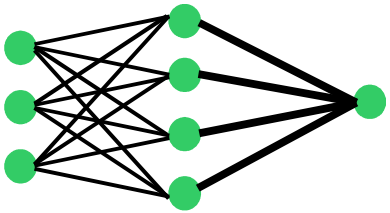
Likelihoods



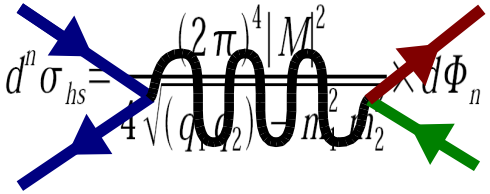
Decision Trees



Neural Networks

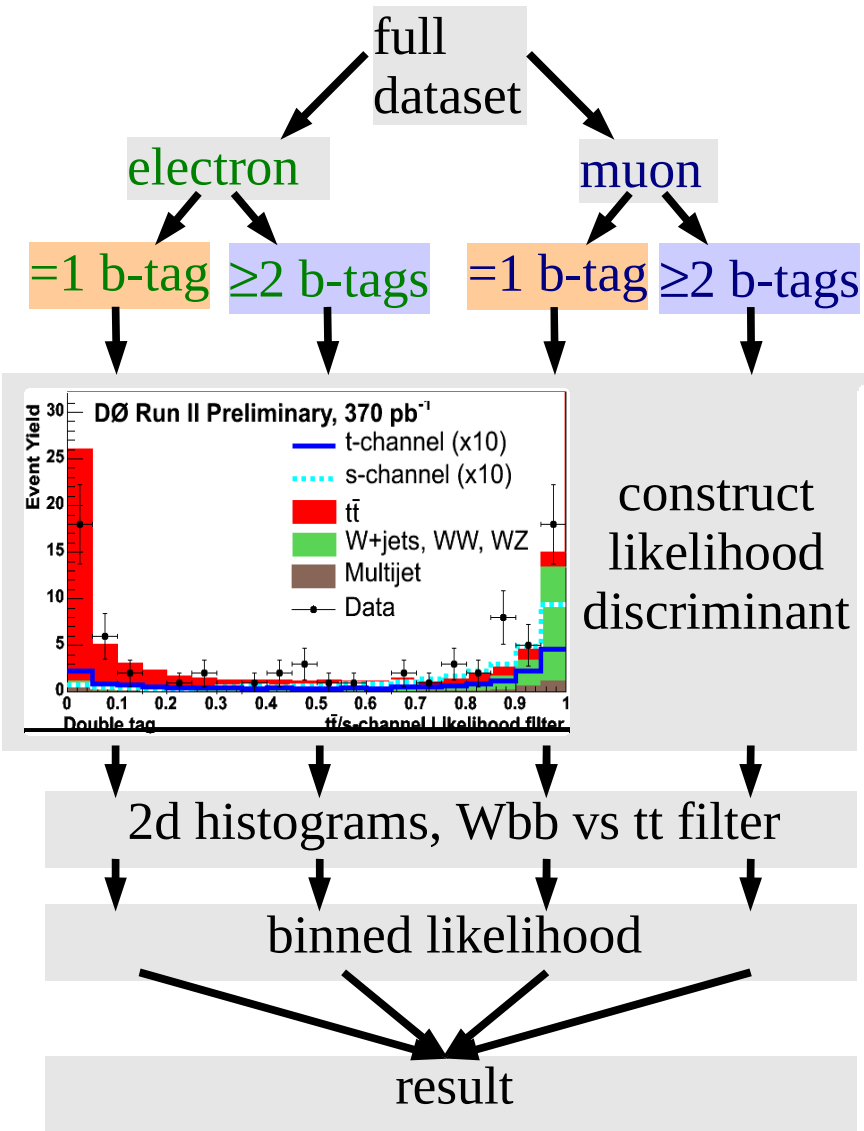


Matrix Elements

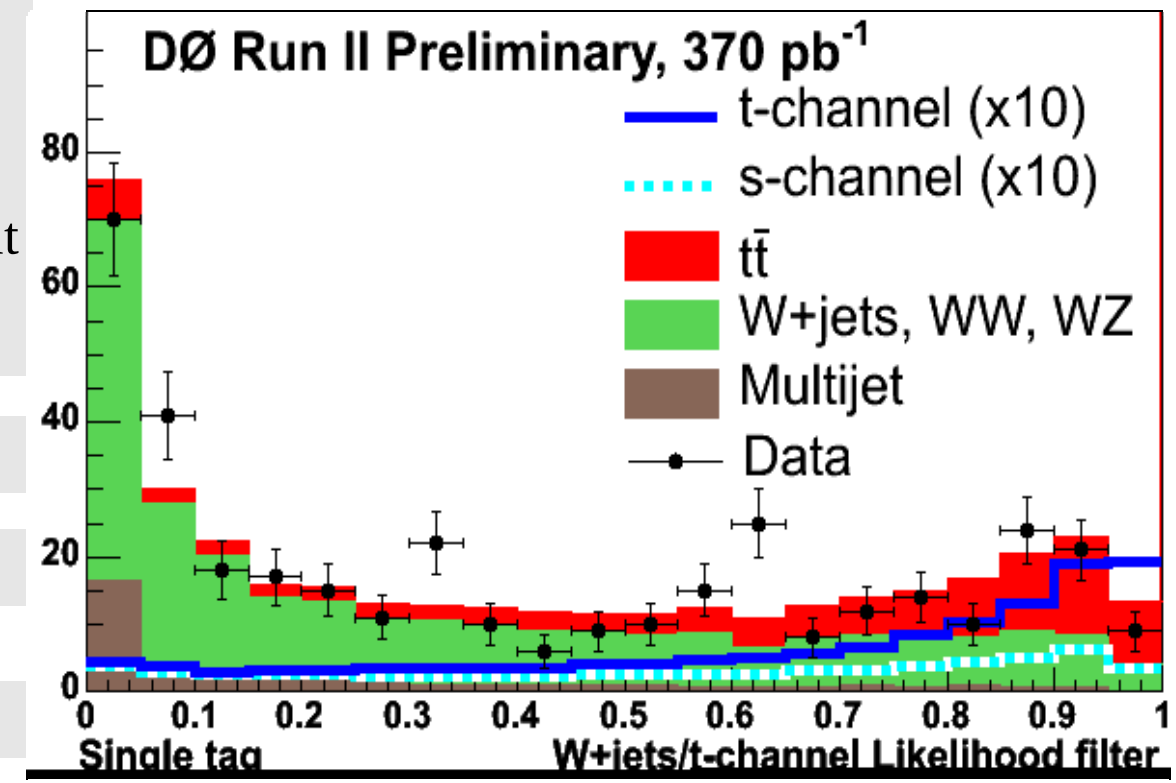


Likelihood Analysis (370 pb^{-1})

s-channel / t-channel

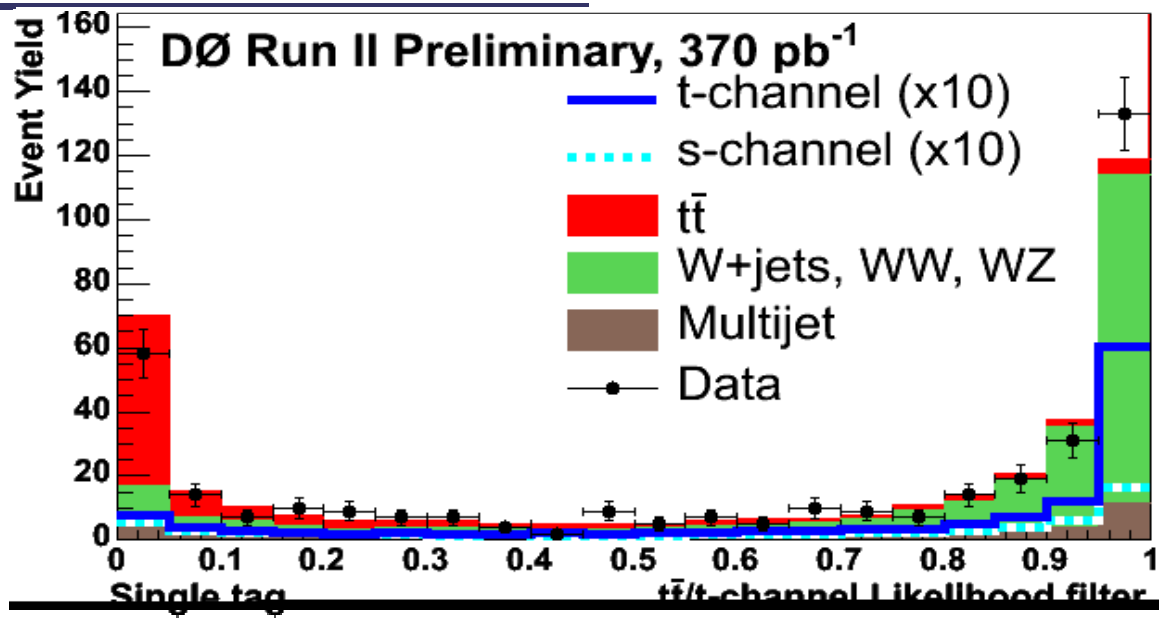


- Using jet lifetime tagger
  - Asymmetric tag requirements
    - At least one tight tag
    - Loose tagger cut for double tags



Likelihood Result

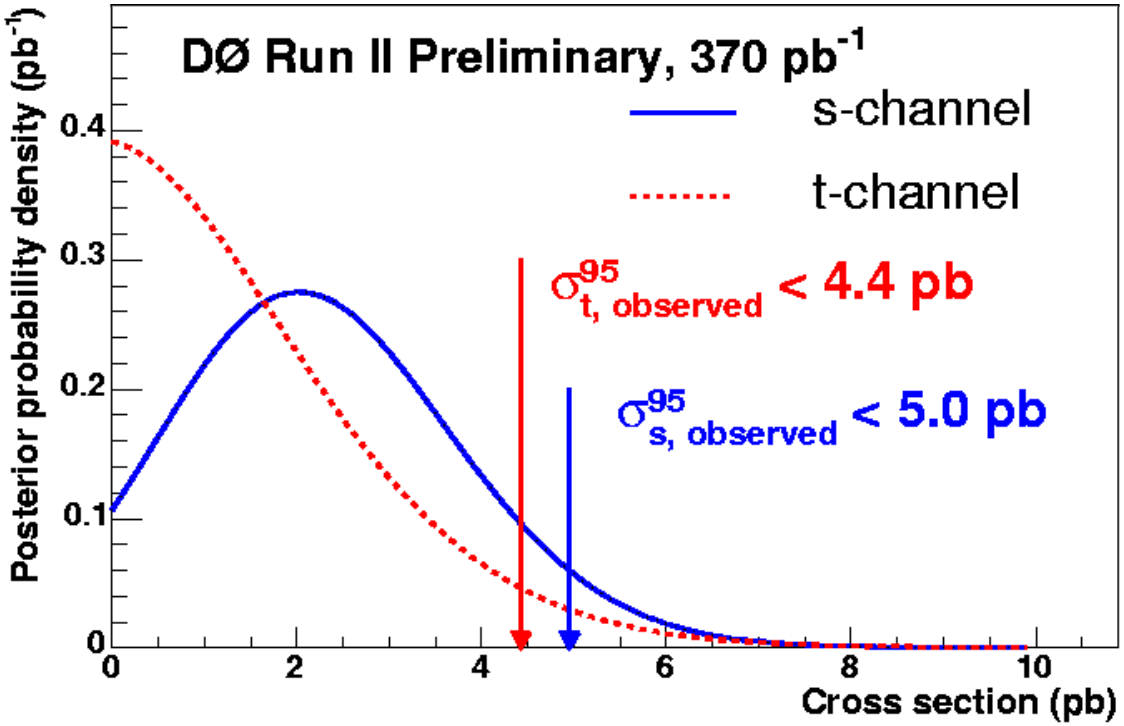
- Systematic uncertainties
  - b-tag modeling: 6-17%
  - Jet energy scale: 5%
  - Trigger modeling: 5%
  - Theory tt XS: 18%
  -



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]

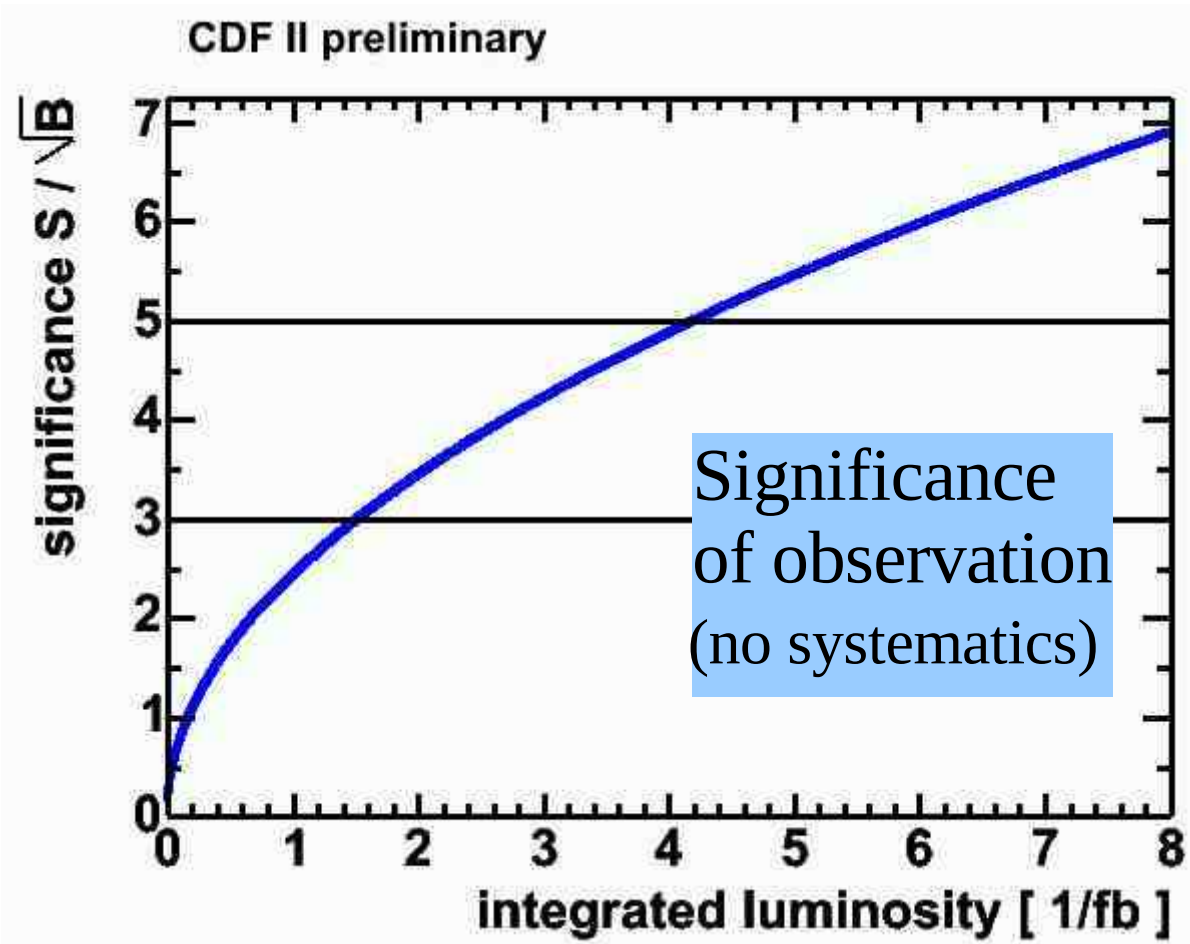
CDF ($160pb^{-1}$)	13.6	10.1
DØ NN ($230pb^{-1}$)	6.4	5.0
DØ Likelihood ($370pb^{-1}$)	5.0	4.4

Outlook

The future is here

Tevatron Single Top Future

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



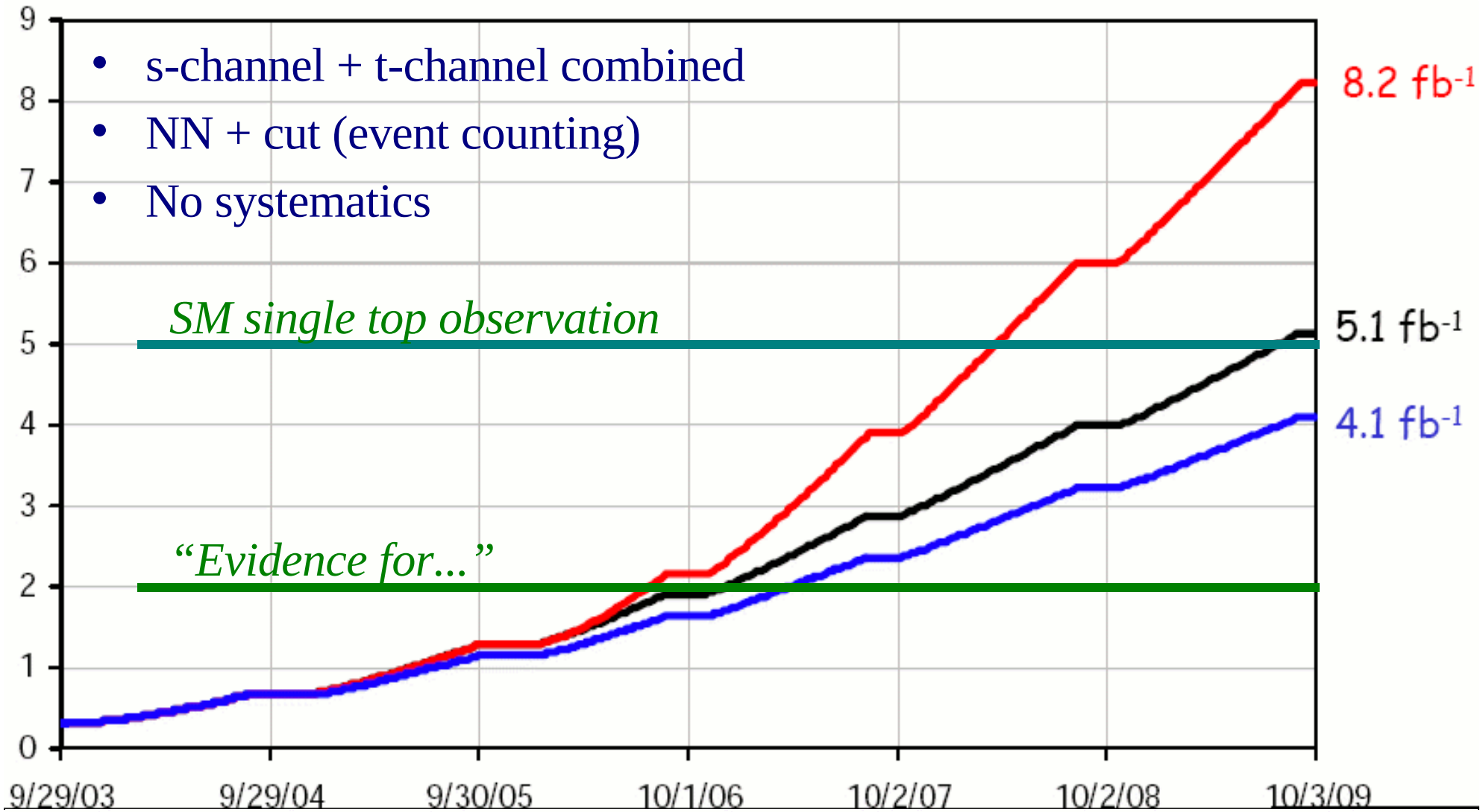
Improvements

- 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%

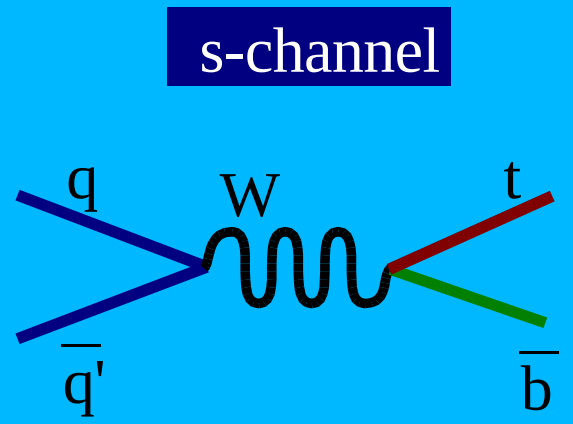
Tevatron luminosity projection

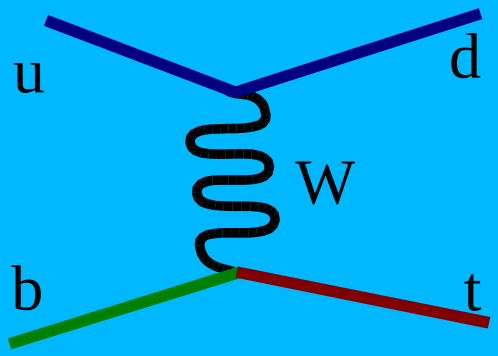


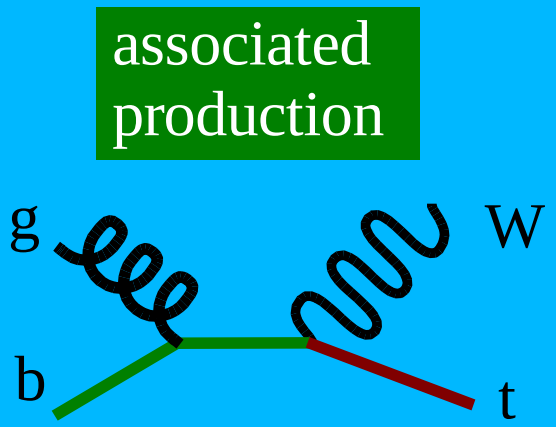
Outlook

Top is the gateway quark

SM Single Top Production at the LHC





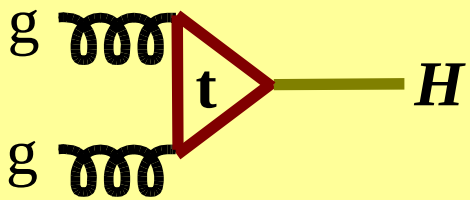


- Observe three single top production modes separately
- Measure V_{tb} to few %
- Study spin correlations

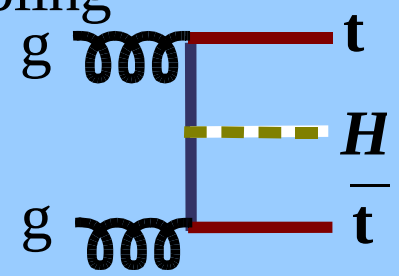
LHC as a Higgs Discovery Machine

Neutral Higgs

Dominant Higgs production mechanism at the LHC:



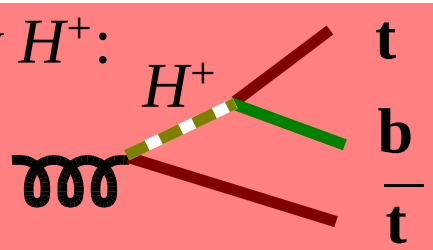
Top-Higgs Yukawa coupling



Discover with ~30fb^{-1}

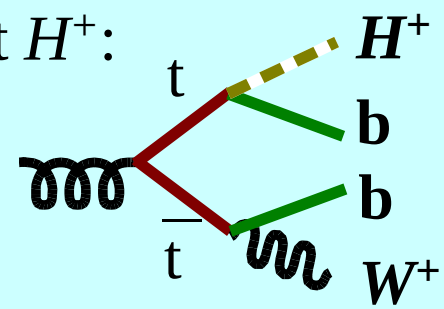
Supersymmetry: Charged Higgs

Heavy H^+:



Discovery possible with ~30fb^{-1}

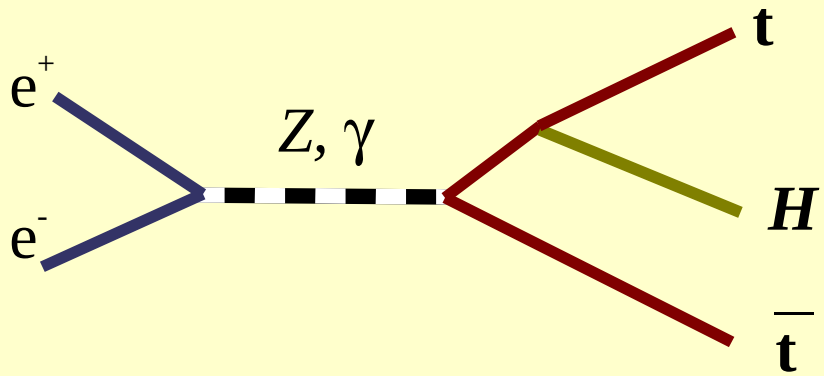
Light H^+:



Discover with ~30fb^{-1}

Top quark Yukawa coupling

Precision coupling measurement at a future e^+e^- collider



International Linear Collider

Conclusions

- Single top quark production is a key observation for the Tevatron
- DØ Run II single top analysis going well
  - World's best limits: $\sigma_s < 5.0$ pb, $\sigma_t < 4.4$ pb
  - Already reaching sensitivity to new physics
- Single Top is about to get really exciting in Run II
  - Will be close to discovery in ~ 1 year
- Top quark couplings will be studied in detail at future colliders