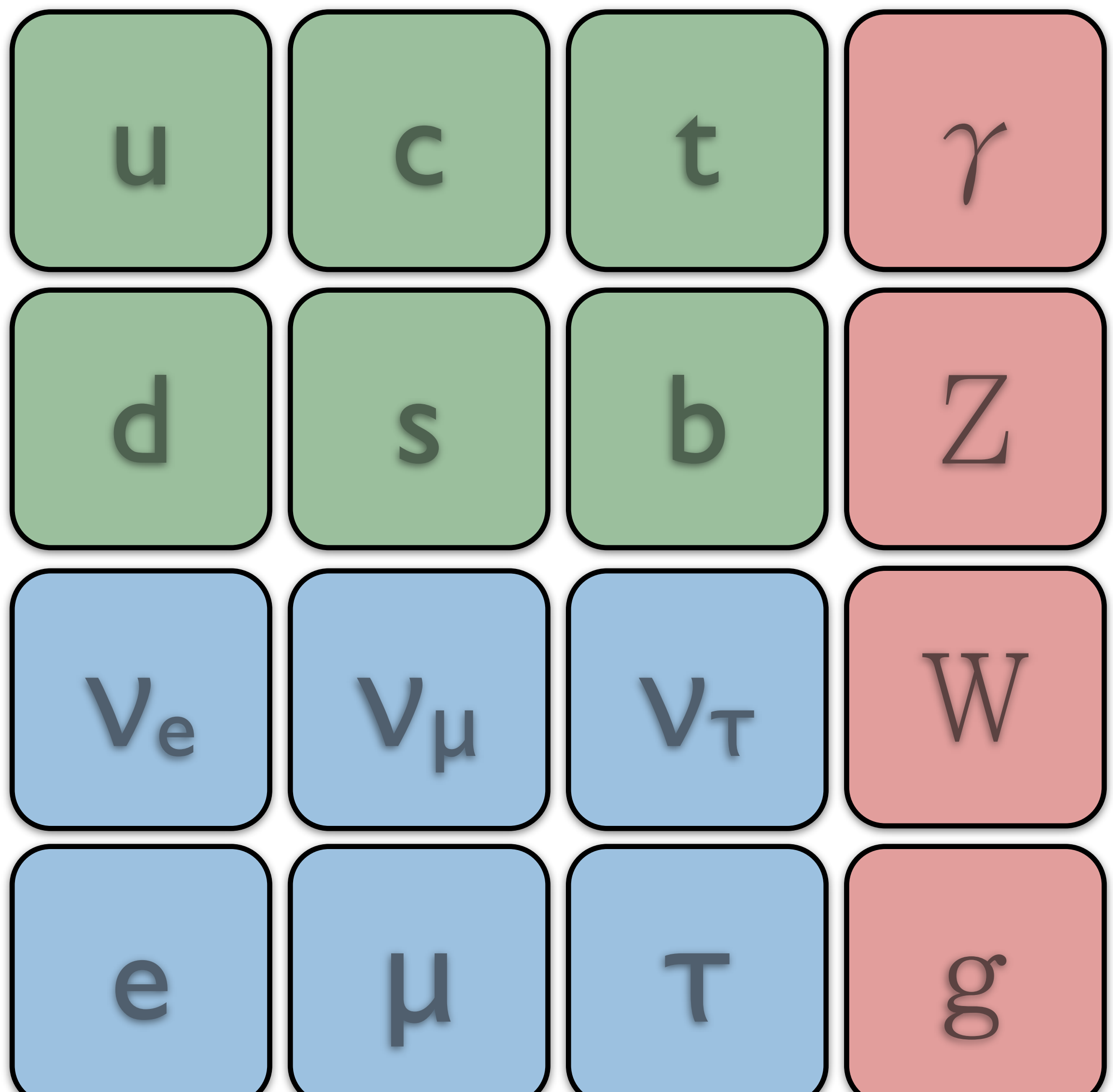
Top Production at the Tevatron

High Energy Seminar
University of Virginia, Nov 12th 2008

Tom Schwarz
University of California Davis

UCDAVIS
UNIVERSITY OF CALIFORNIA

The Standard Model
Top Quark



The Standard Model
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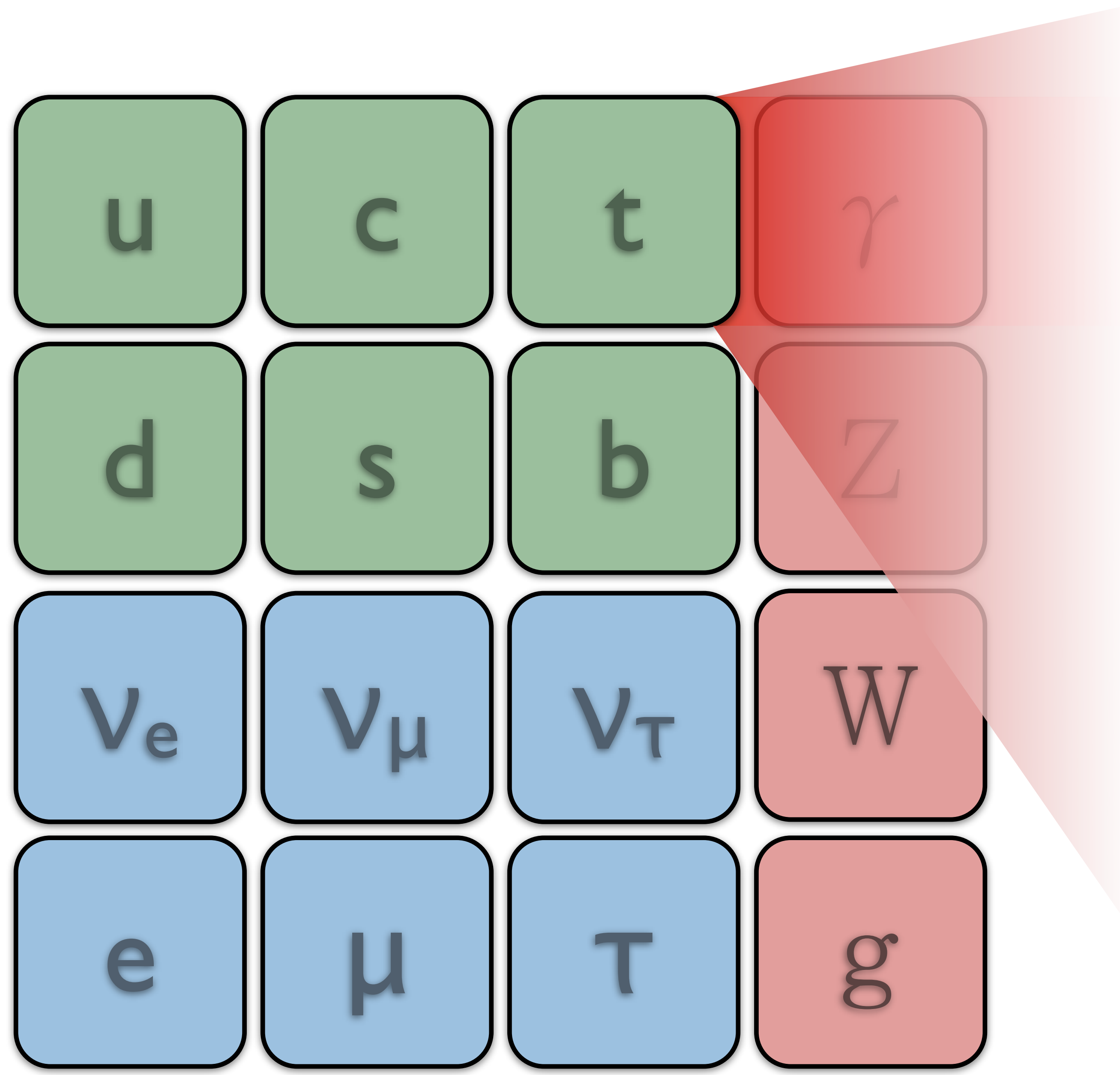
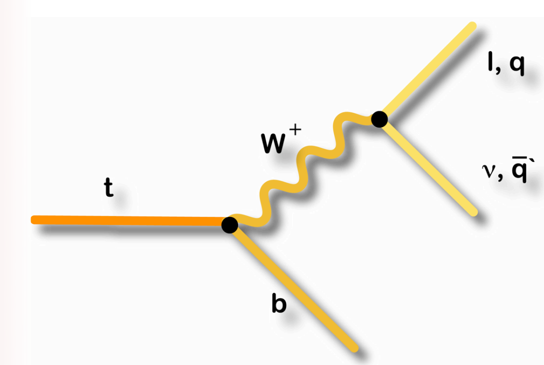


spin 1/2

charge +2/3

$$\begin{pmatrix} t \\ b \end{pmatrix}_L \quad t_R$$

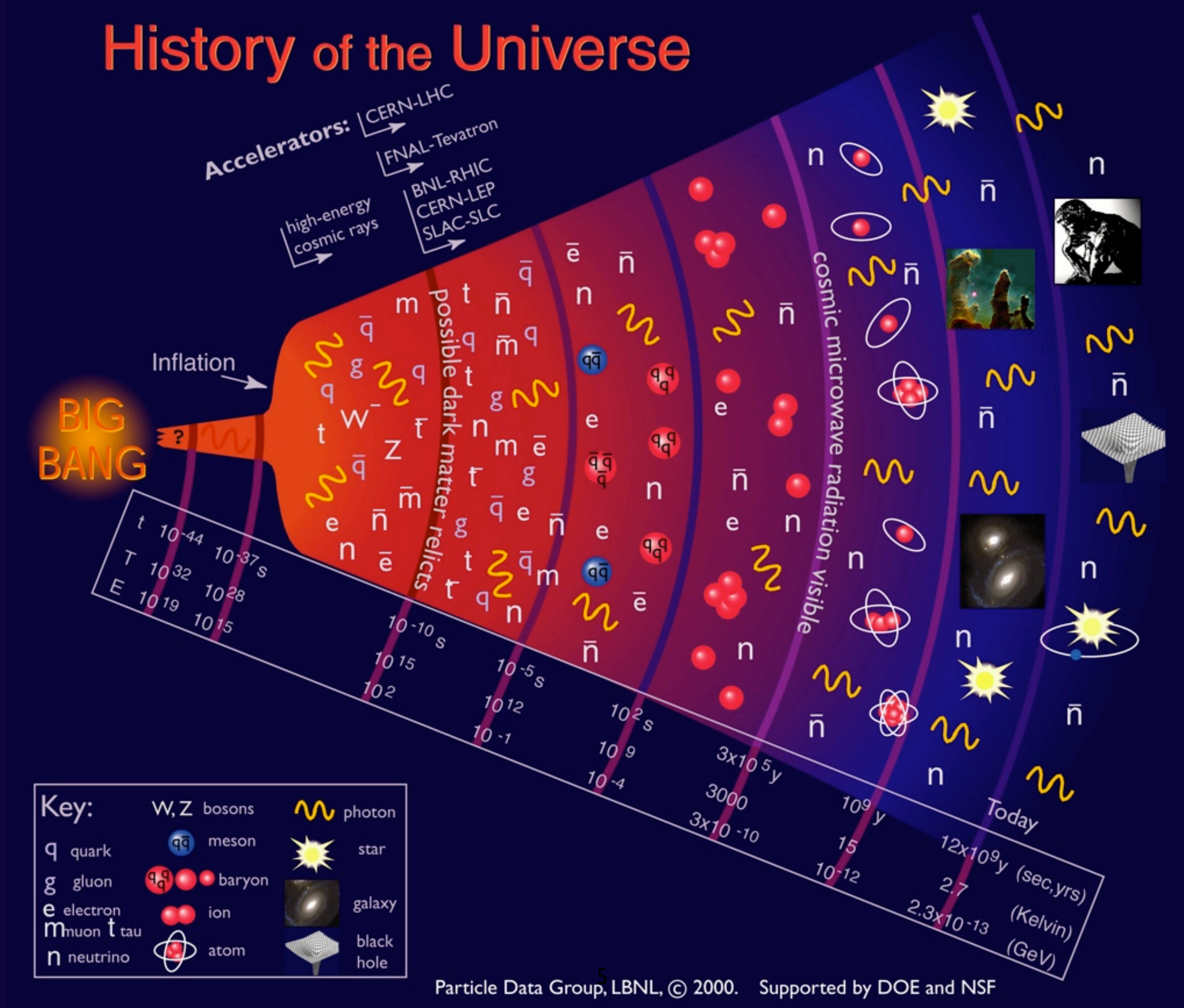


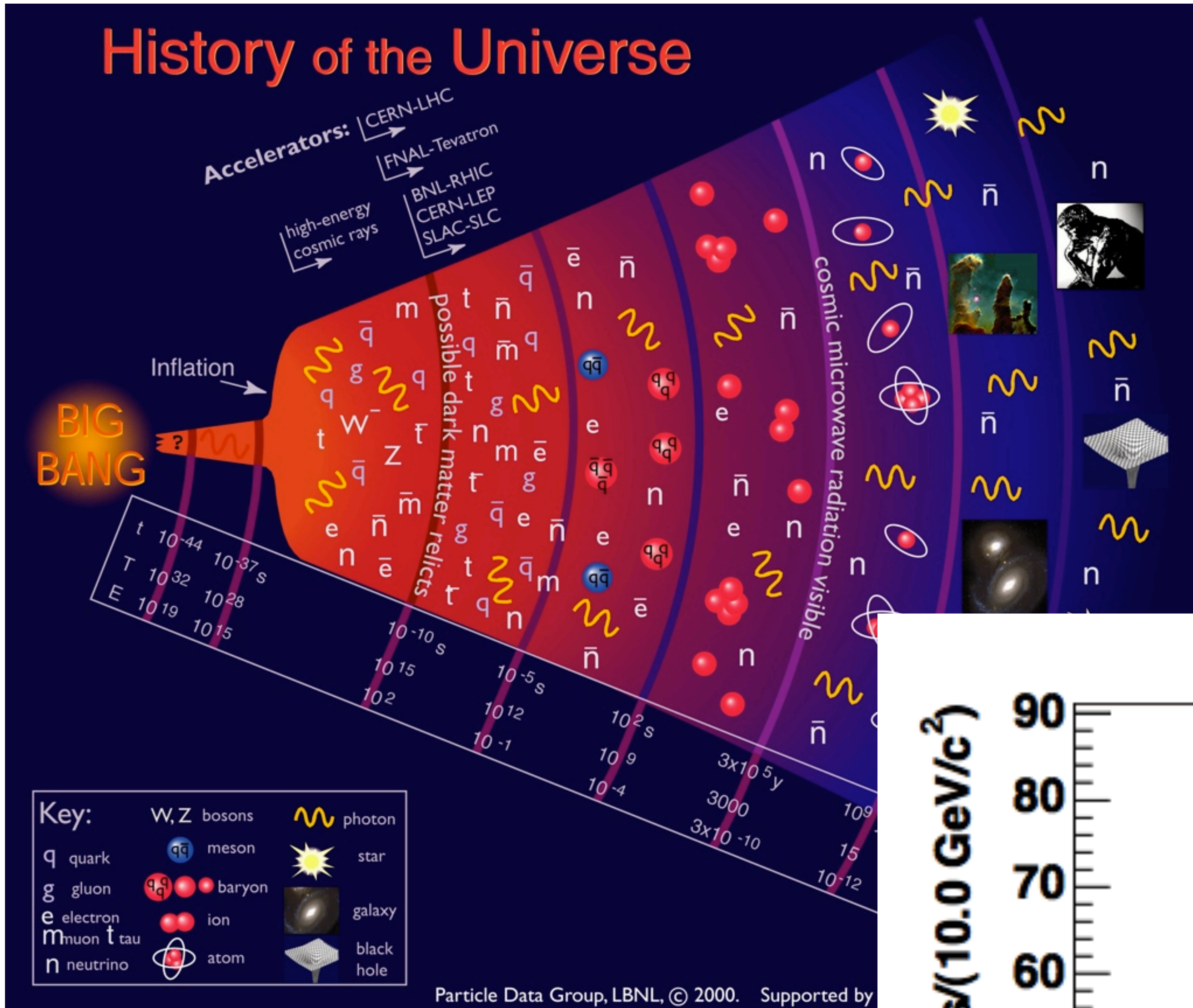
up

3 MeV

•

Area ∝ Mass


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF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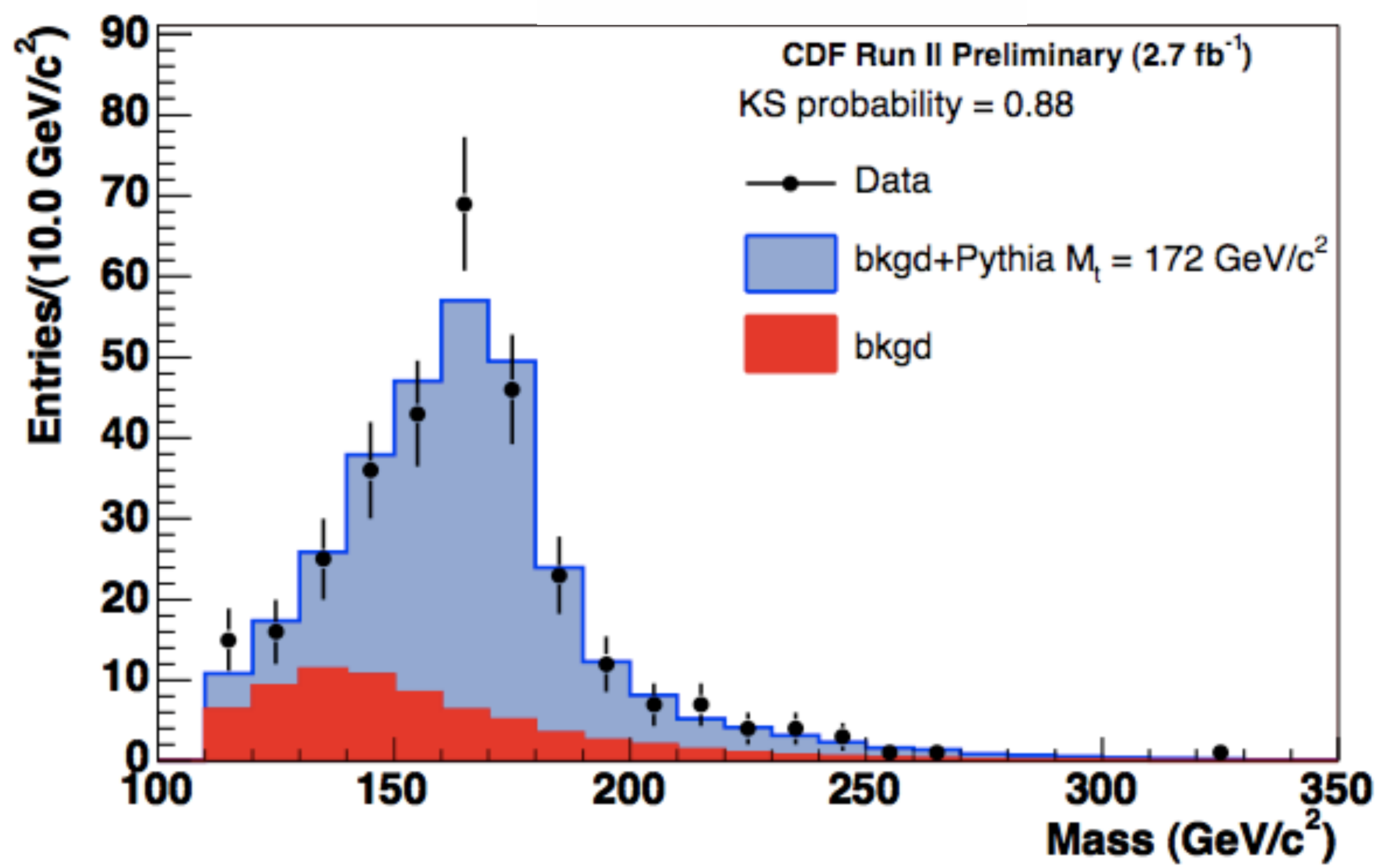
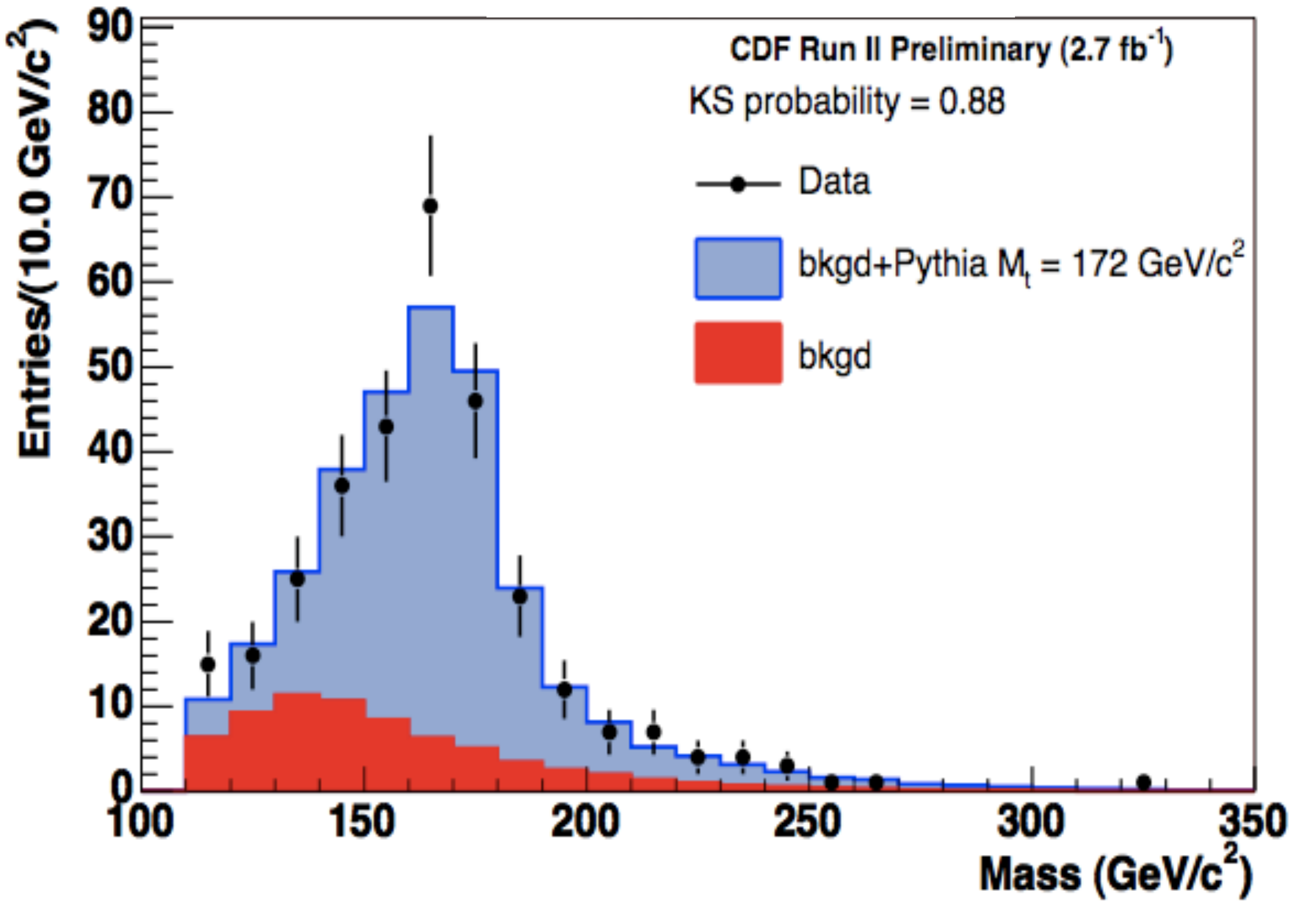

CDF Run II Preliminary (2.7 fb^{-1})
KS probability = 0.88
Data
bkgd+Pythia M_t = 172 GeV/c^2
bkgd
Entries/(10.0 GeV/c^2)
Mass (GeV/c^2)

CDF Run II

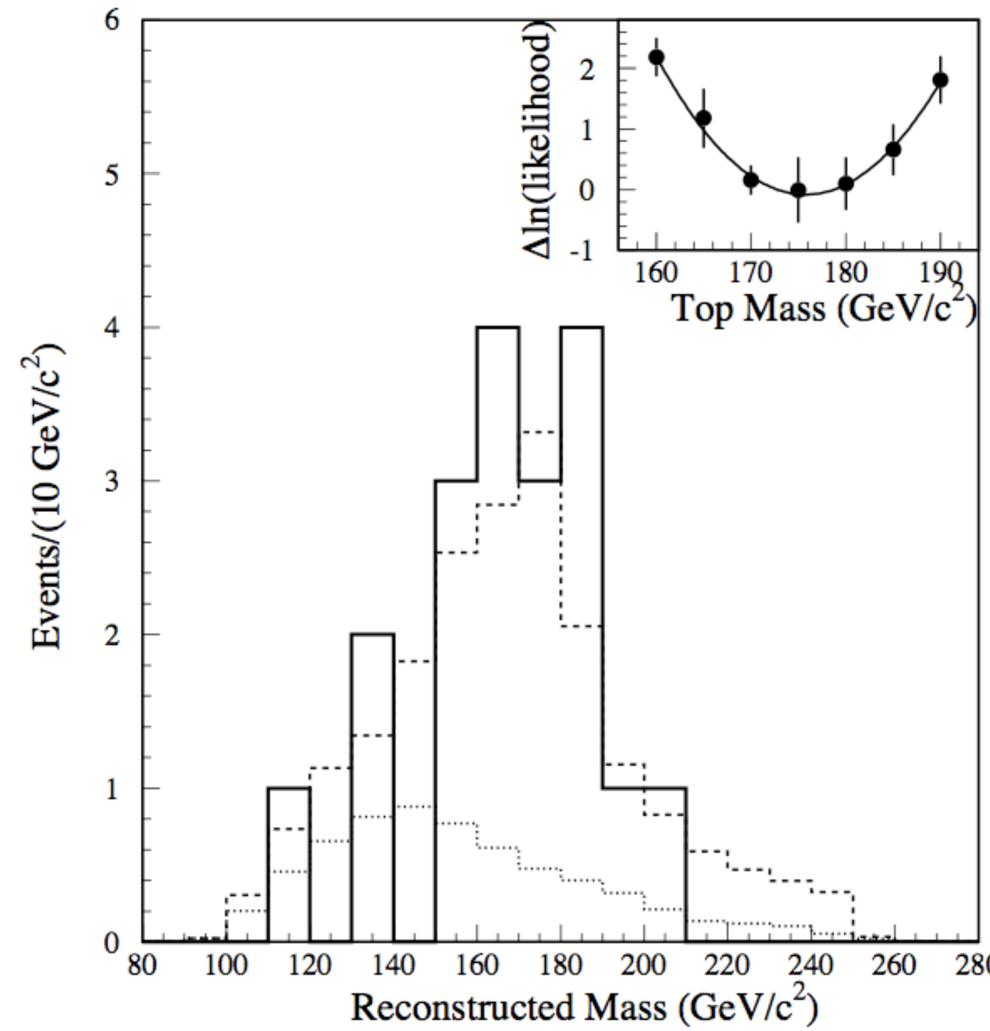
2.7 fb^{-1}



$$\mathbf{M_t = 172.3 \pm 1.9\ \ GeV/c^2}$$

Run I Observation

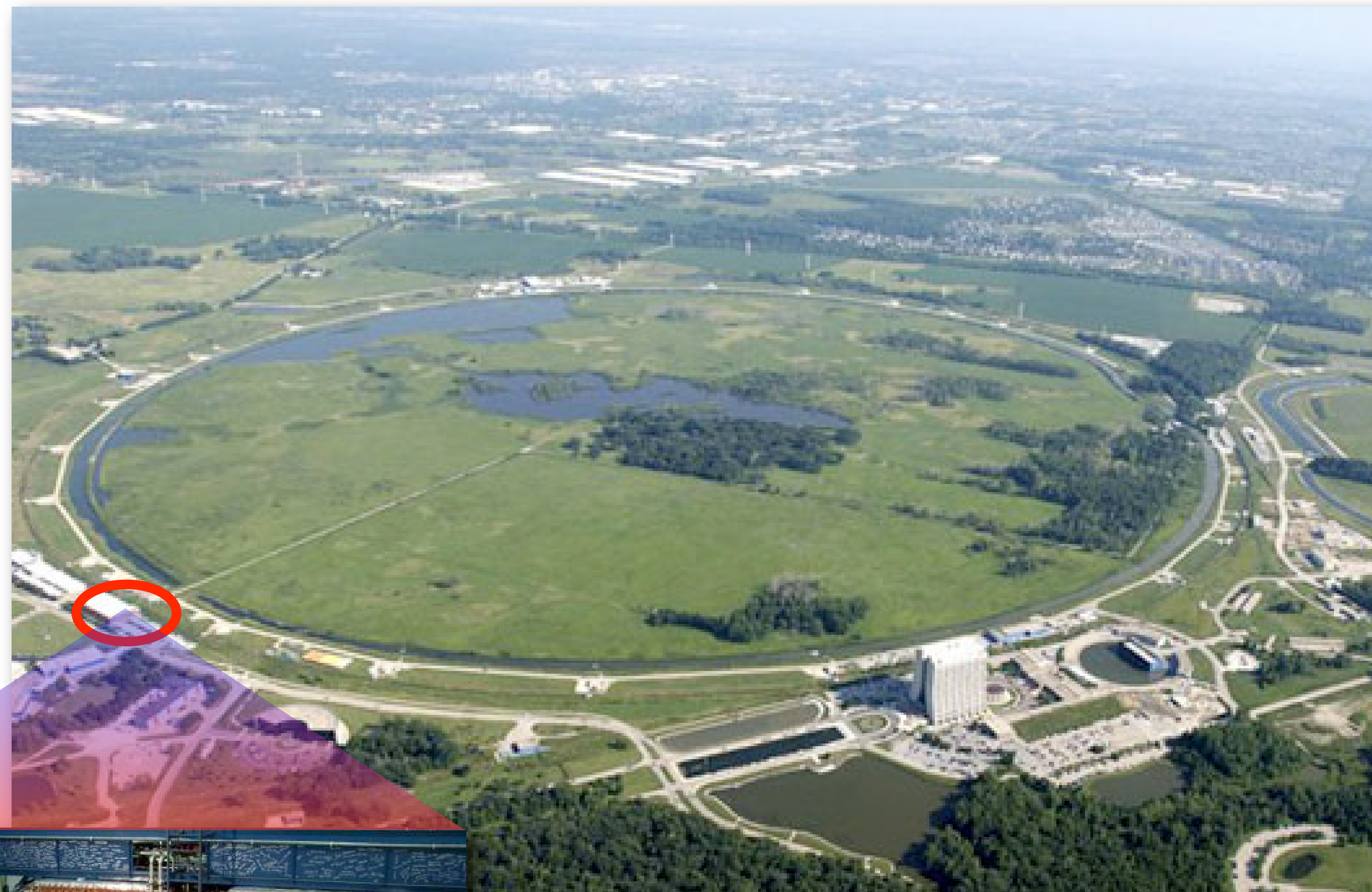
67 pb^{-1}



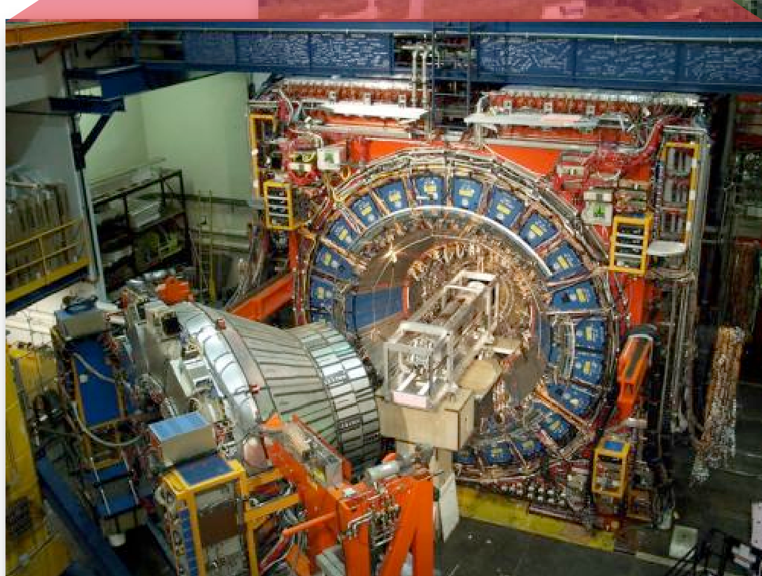
$$\mathbf{M_t = 176 \pm 12.8\ \ GeV/c^2}$$

The Tevatron

Colliding protons and anti-protons at 1.96 TeV



CDF



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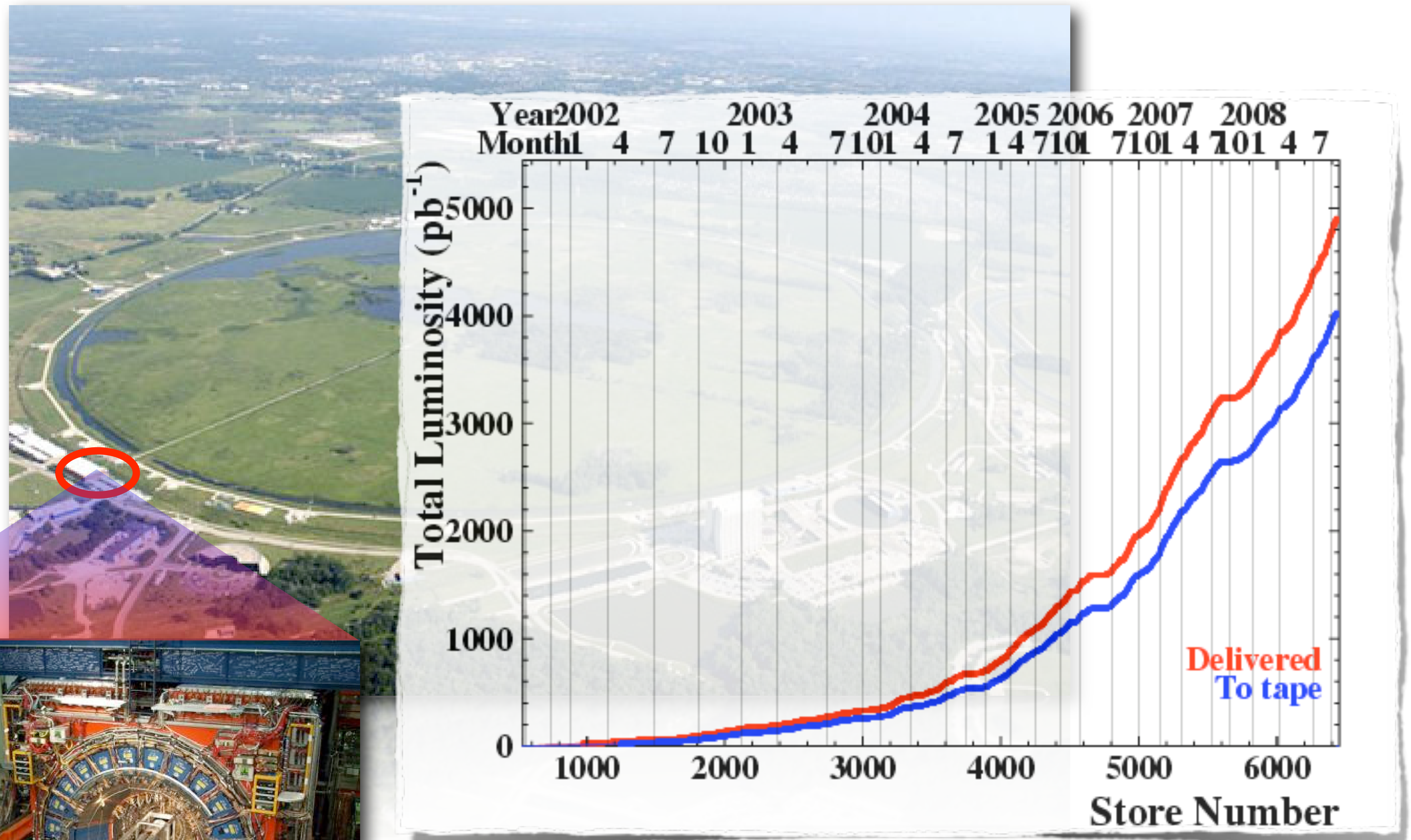

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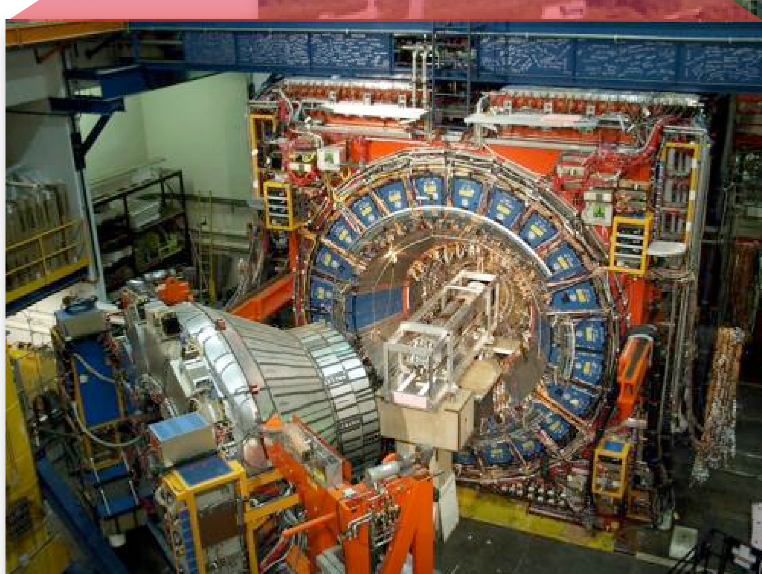
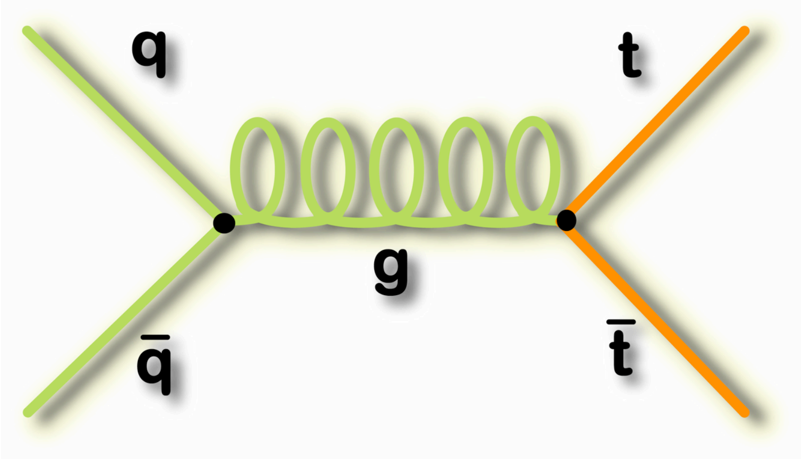


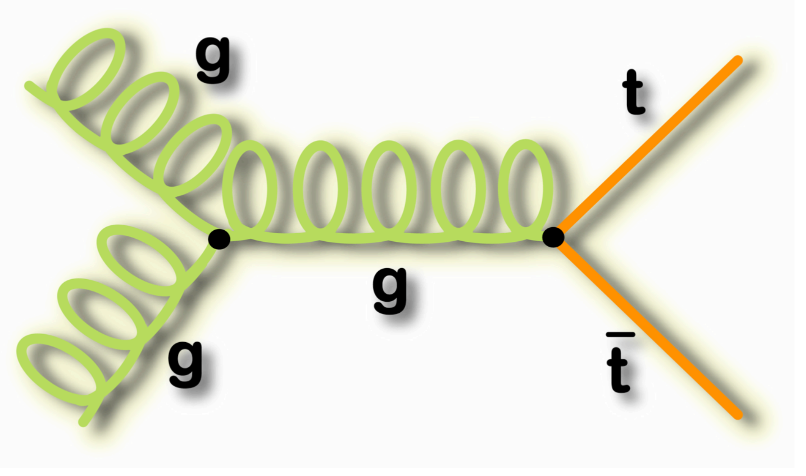
~ 5 fb^{-1} delivered

~ 3 fb^{-1} in current analysis

How is Top Produced?

Mostly through the Strong Force



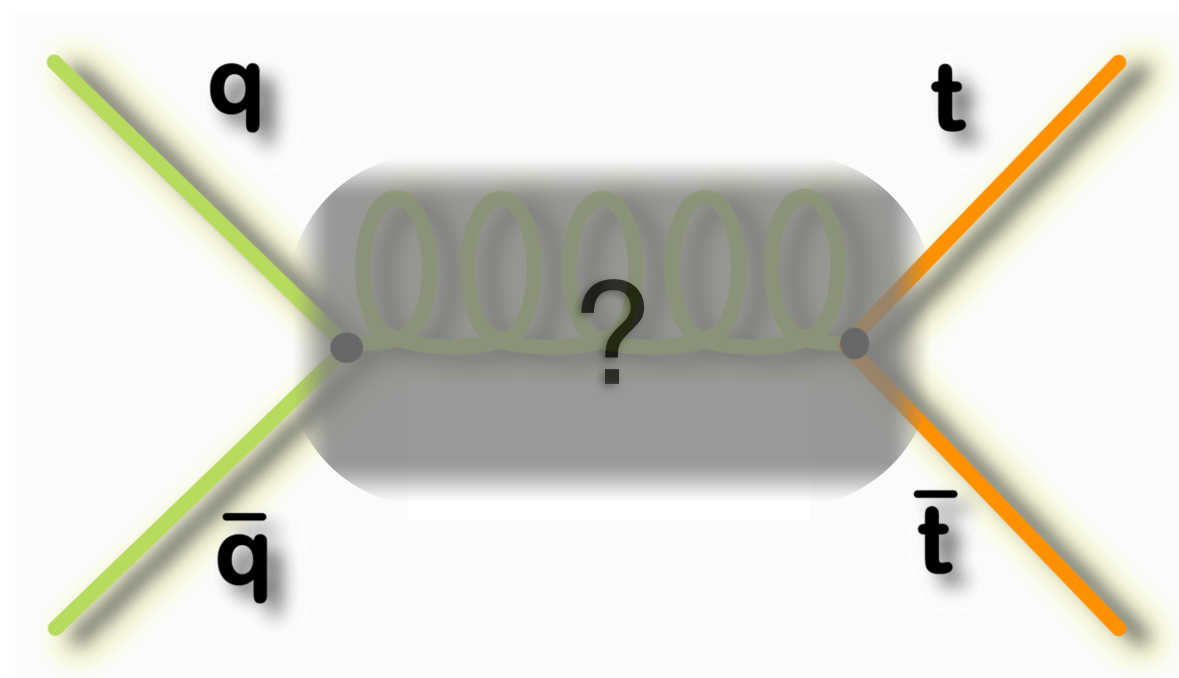


85 % **15 %**

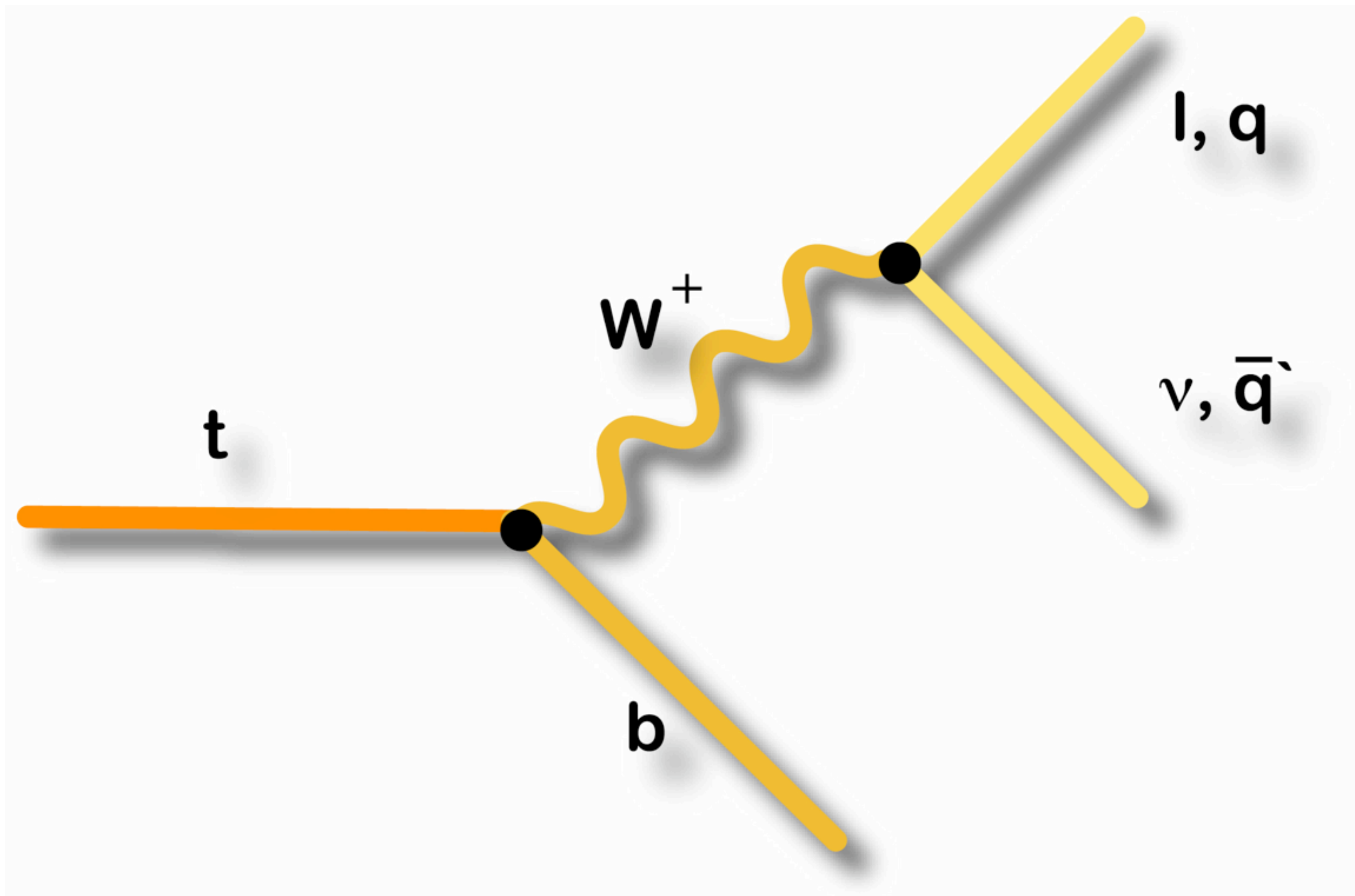
Takes ~350 GeV to make a pair of top quarks

or Maybe there's more....

- New production mechanisms would most likely show up as an enhancement in the cross section
- Kaluza-Klein excitations of gluons from extra dimensional theories
- New gauge boson as a remnant of some higher order symmetry breaking, such as Z′

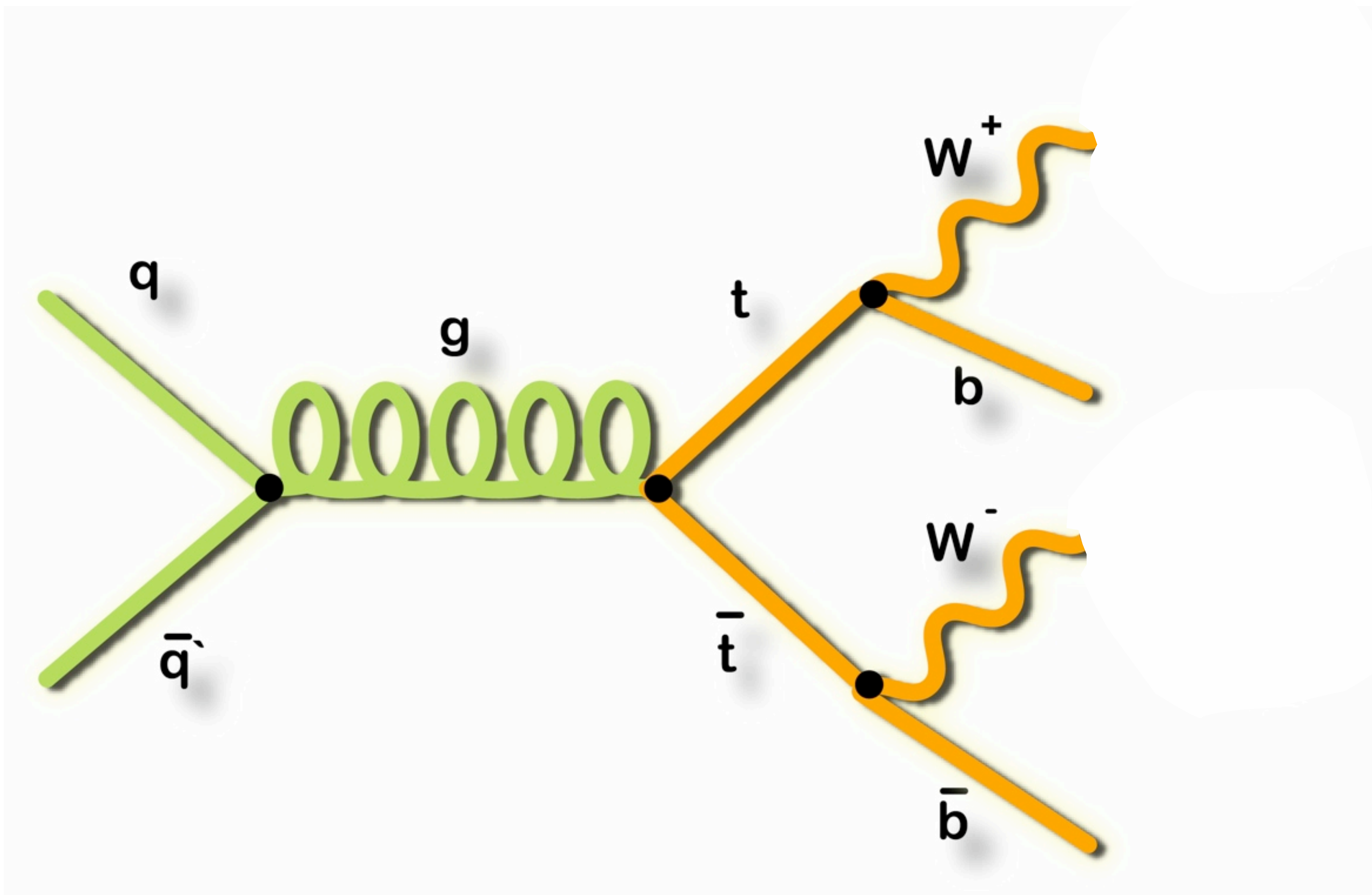


How Does Top Decay?

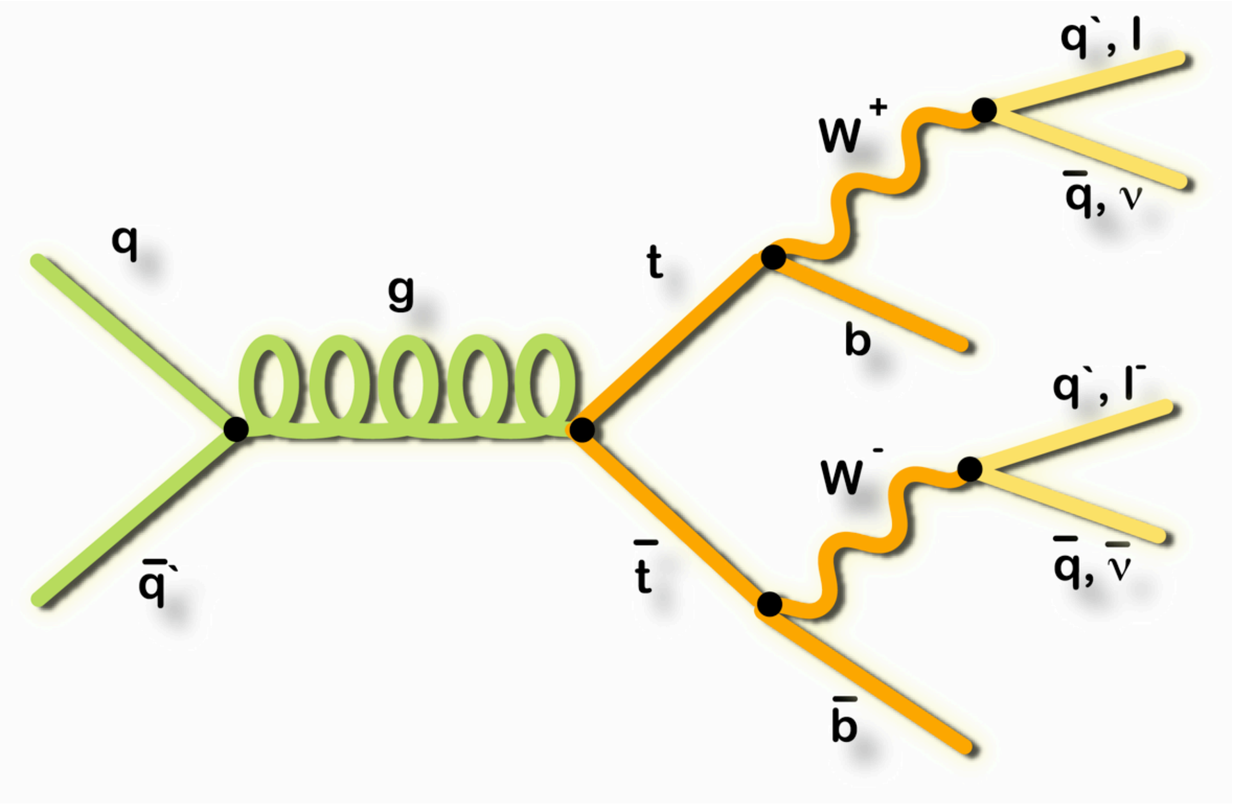


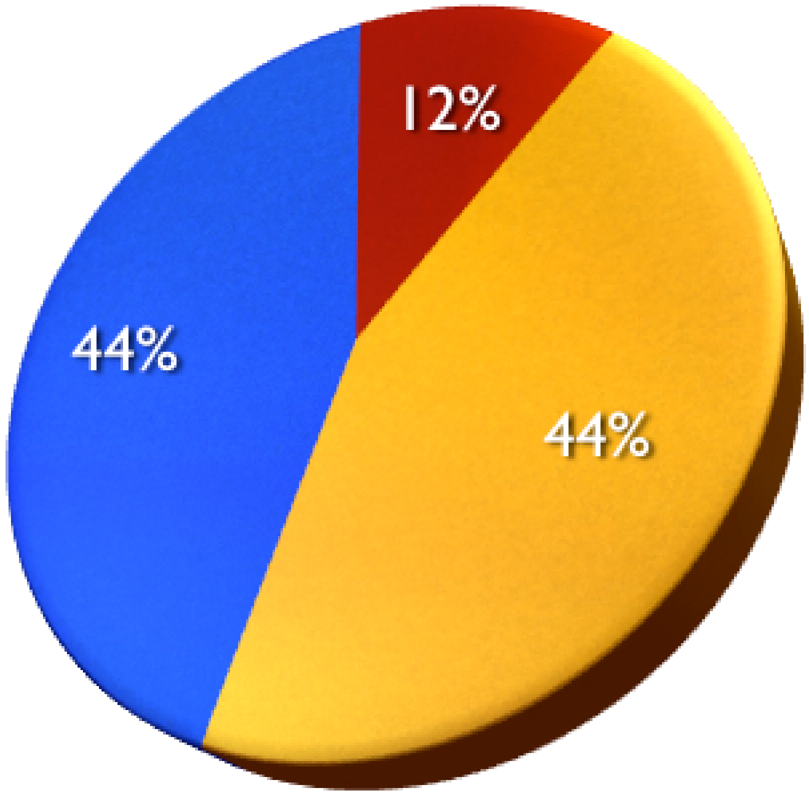
~100 %

Top Events Are Defined By How The W's Decay



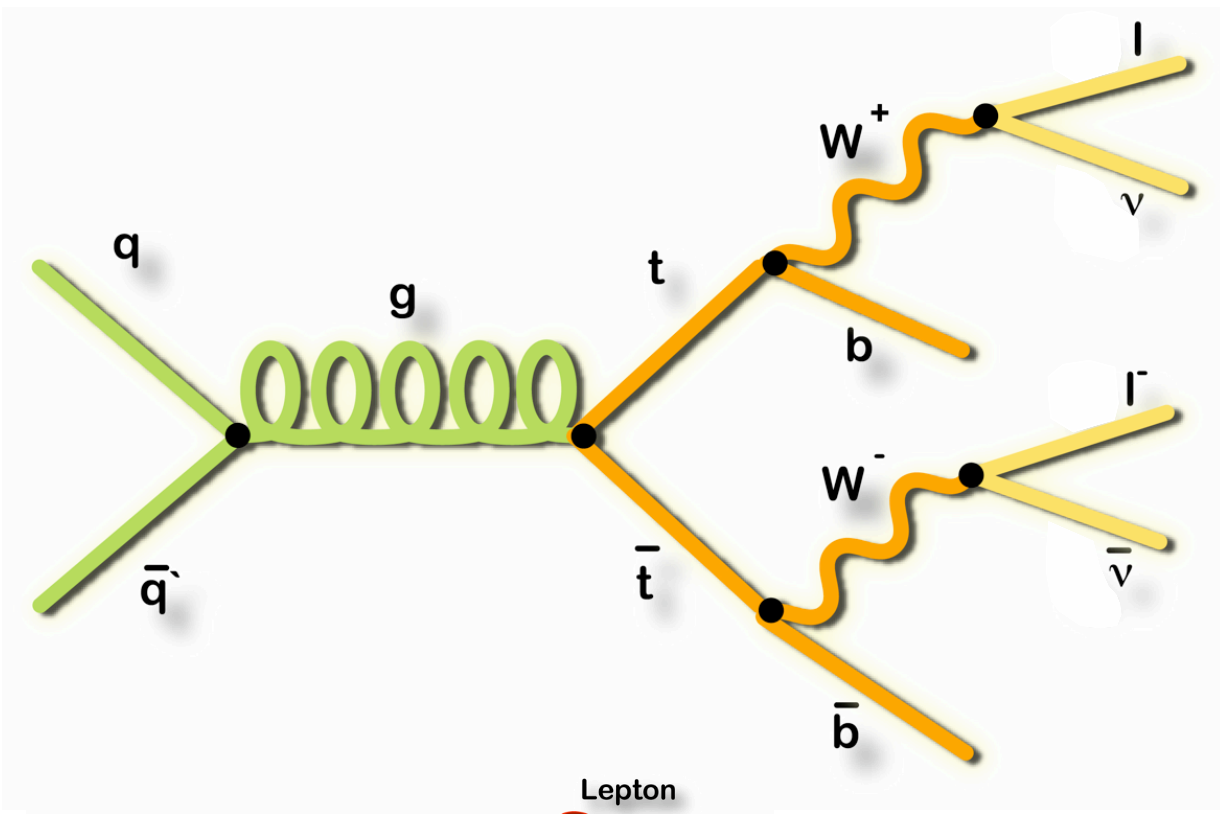
Top Decay Channels

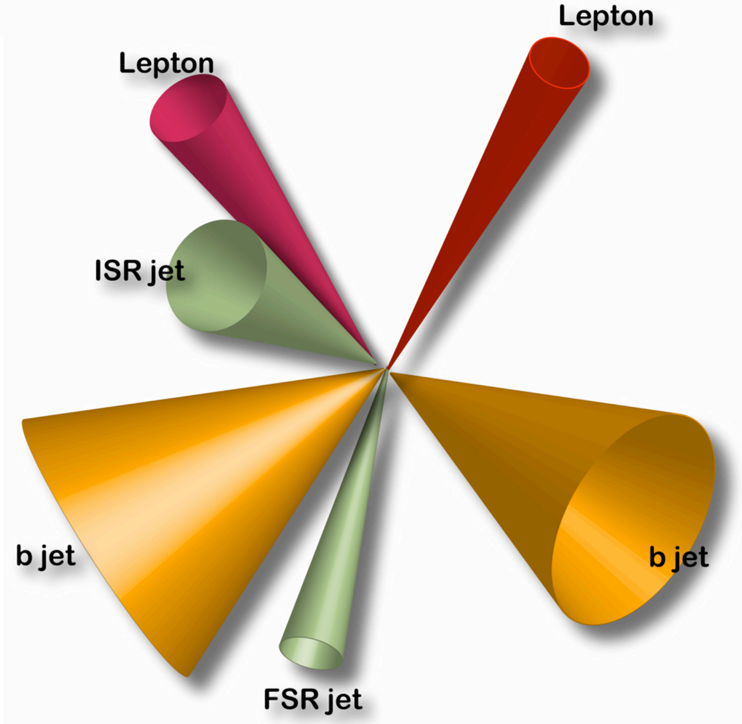


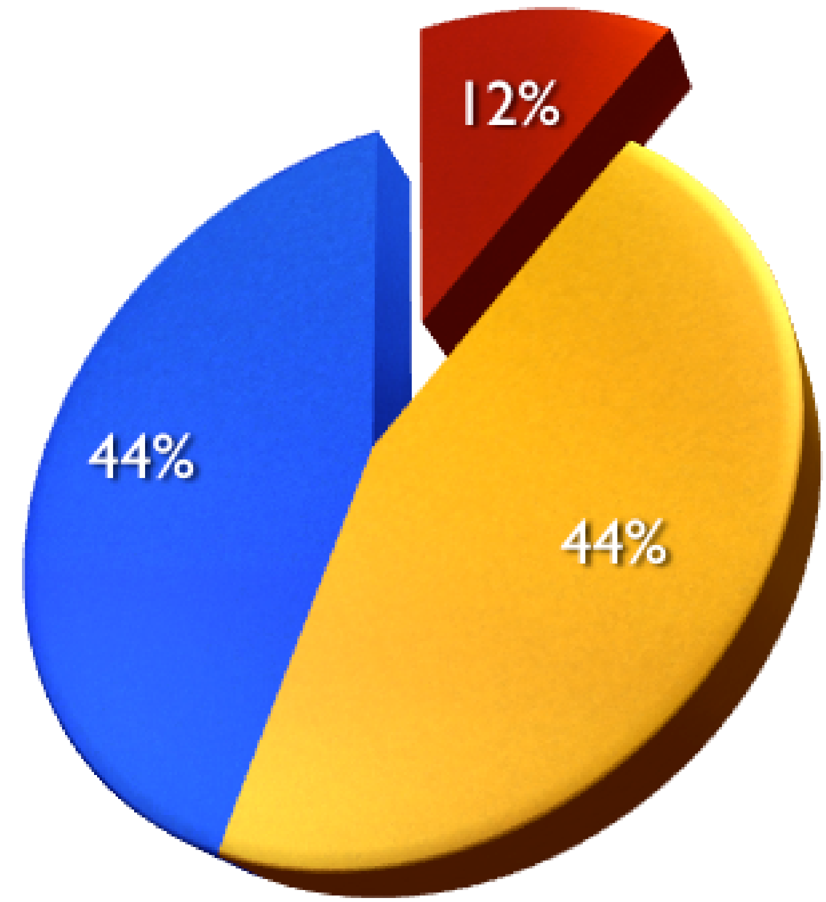


- Di-lepton (W→lν W→lν)
- Lepton + Jets (W→lν W→qq)
- All-hadronic (W→qq W→qq)

Di-lepton Channel







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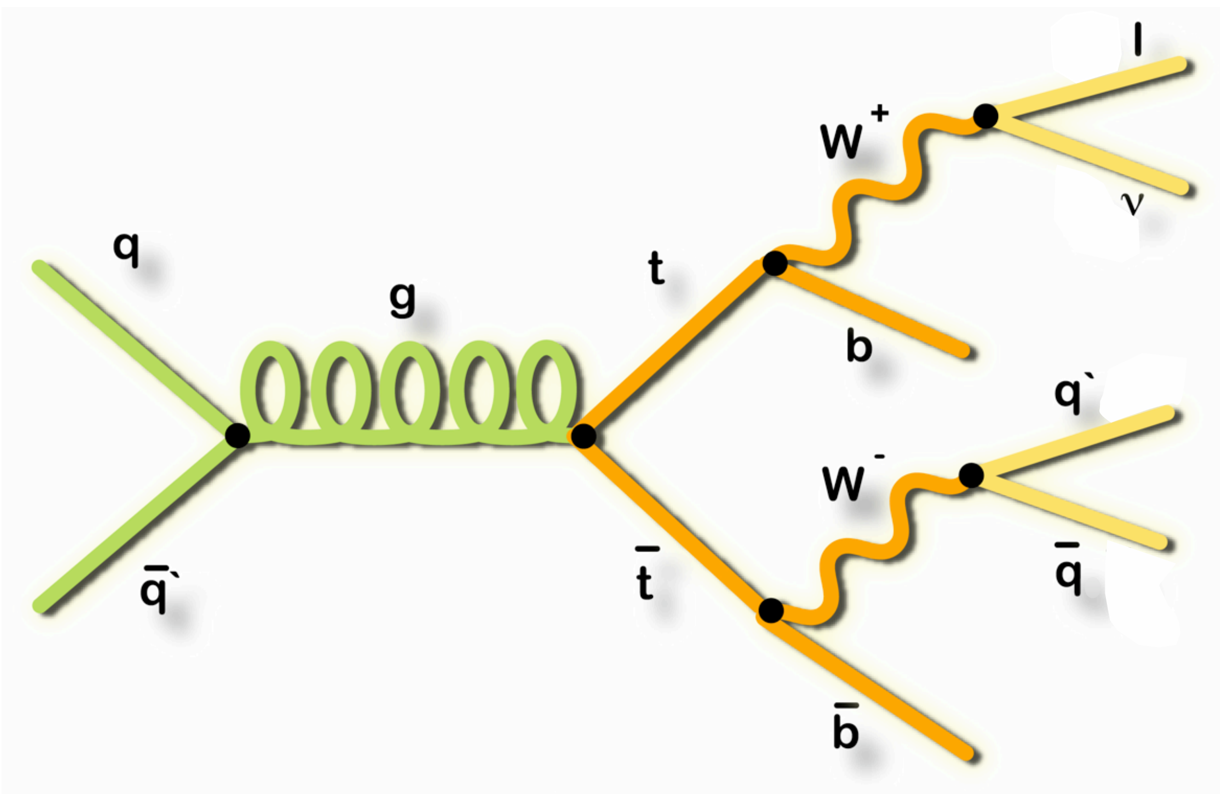
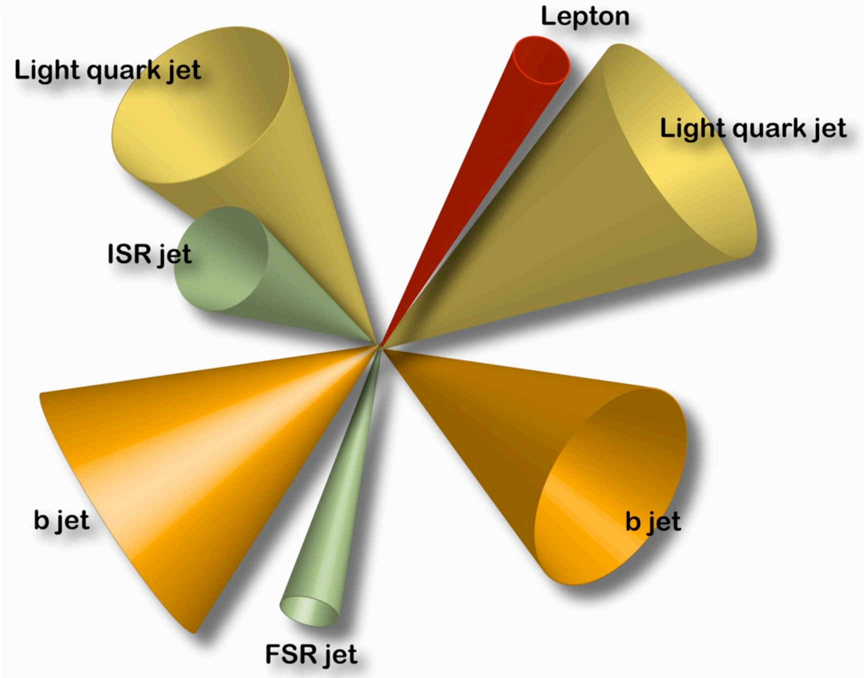
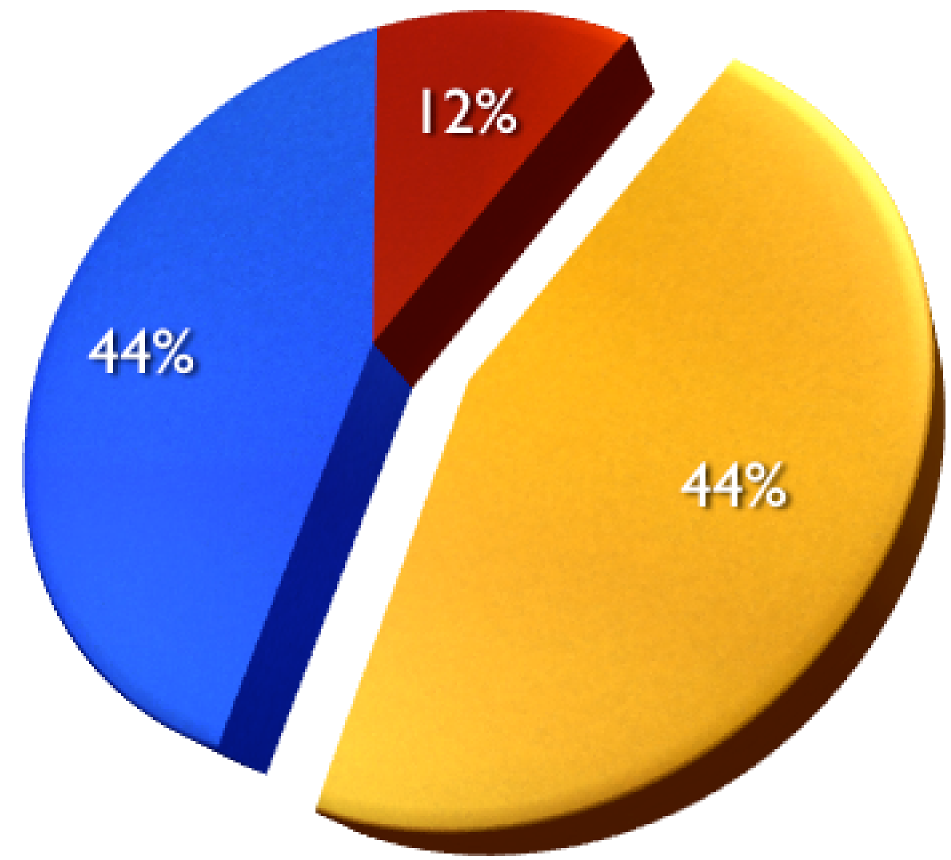
Lepton + Jets Channel







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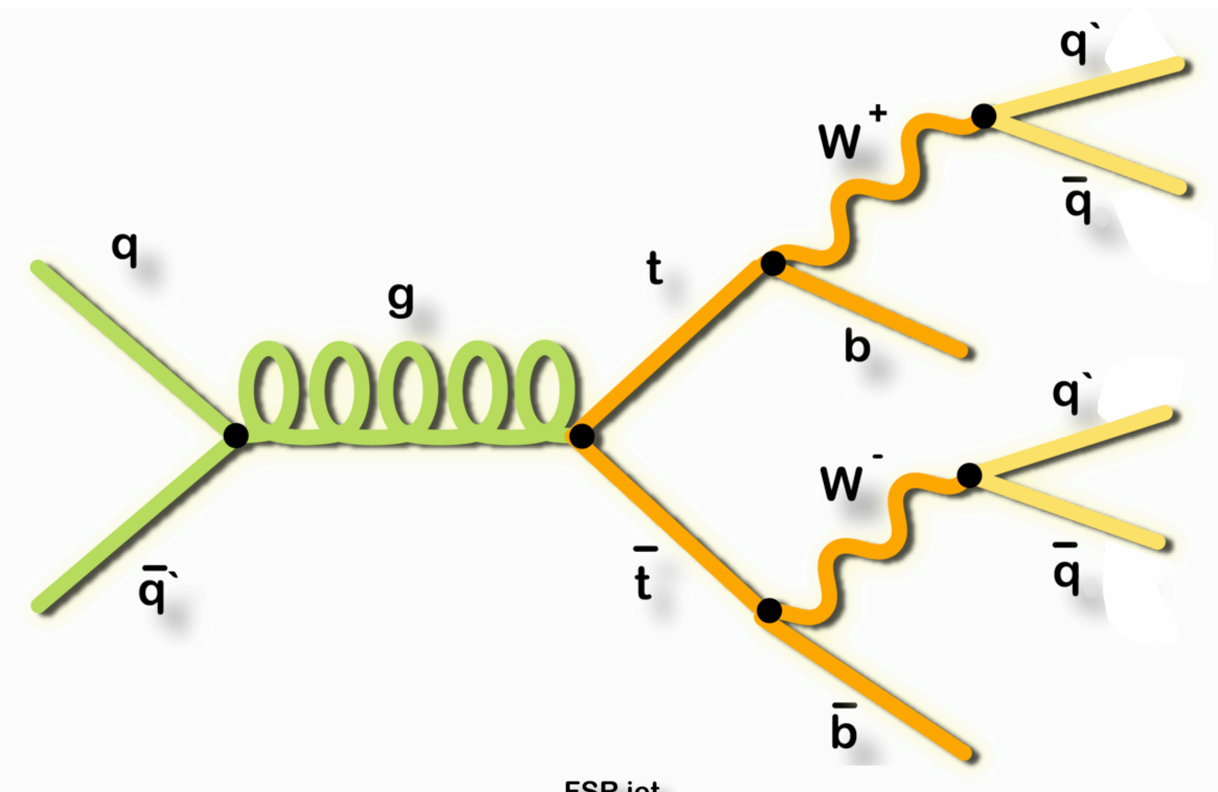
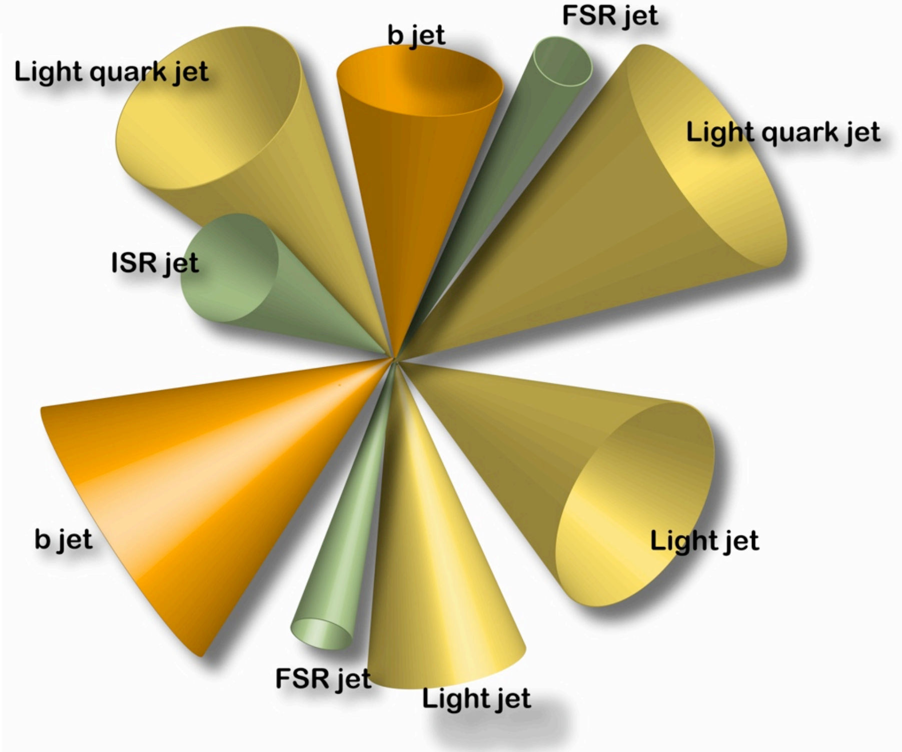
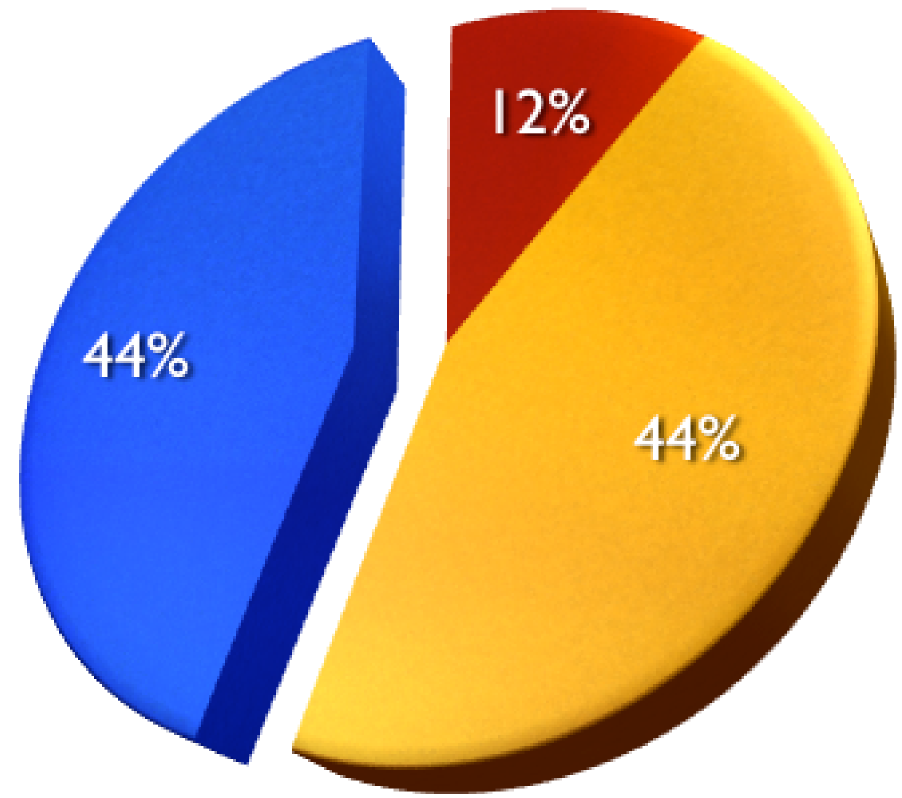
All-Hadronic Channel







- Di-lepton ($W \to l\nu$ $W \to l\nu$)
- Lepton + Jets ($W \to l\nu$ $W \to qq$)
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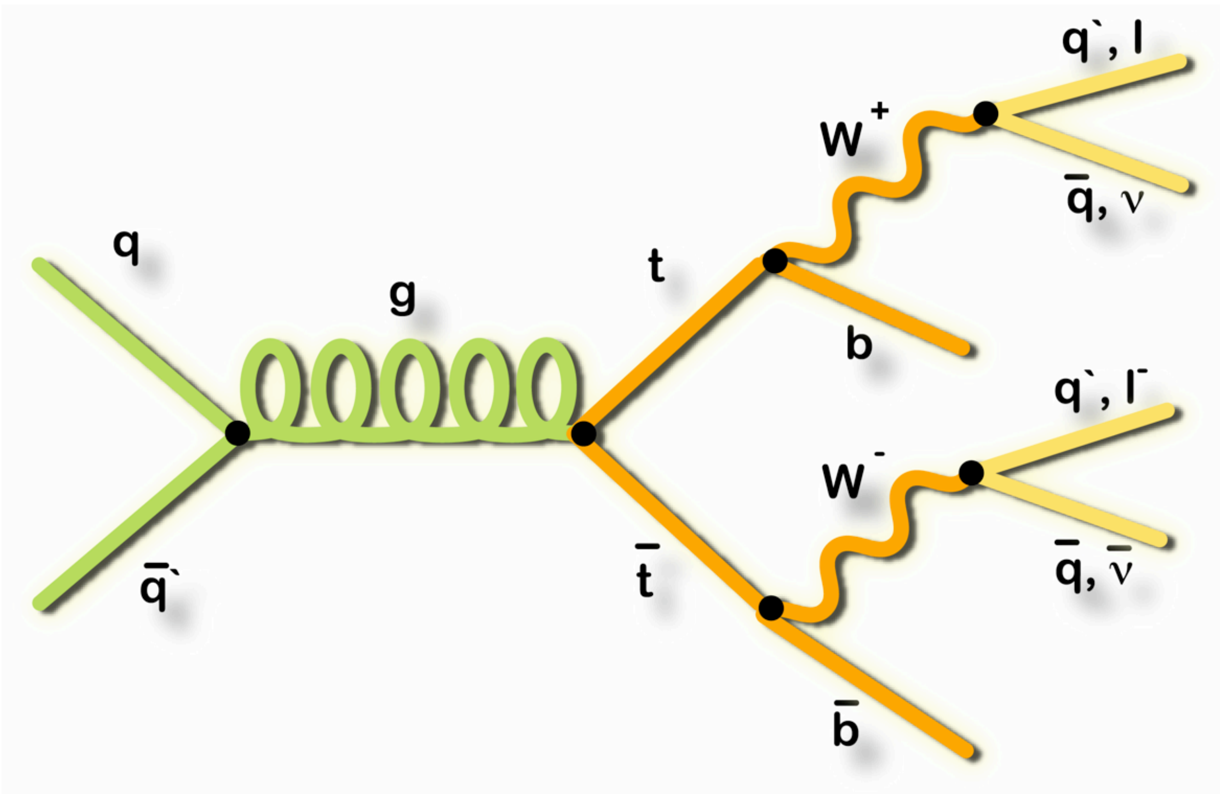
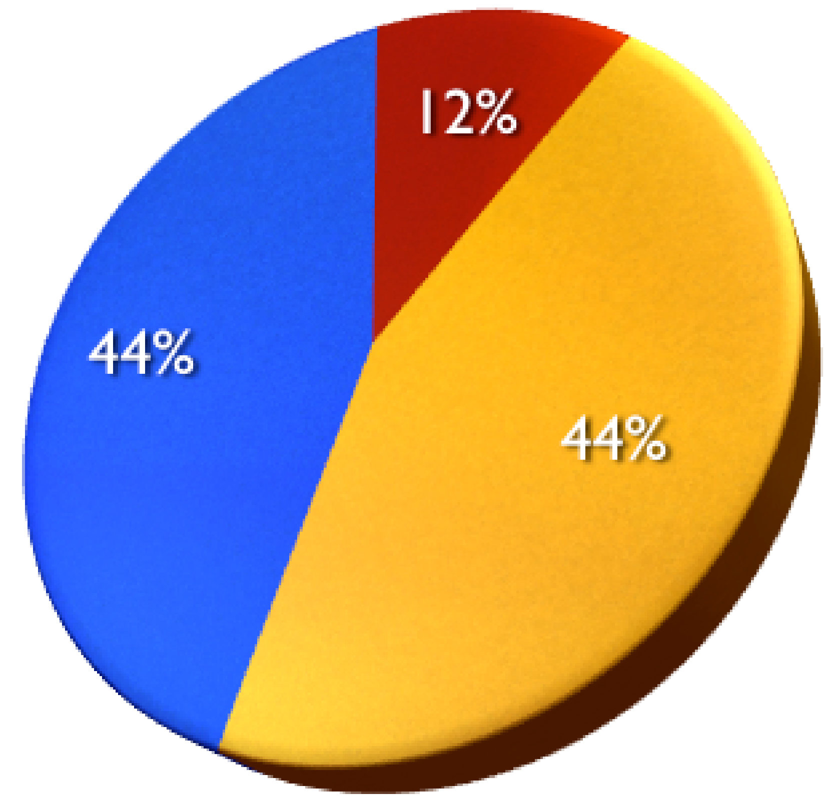
New Physics Can Modify Decay





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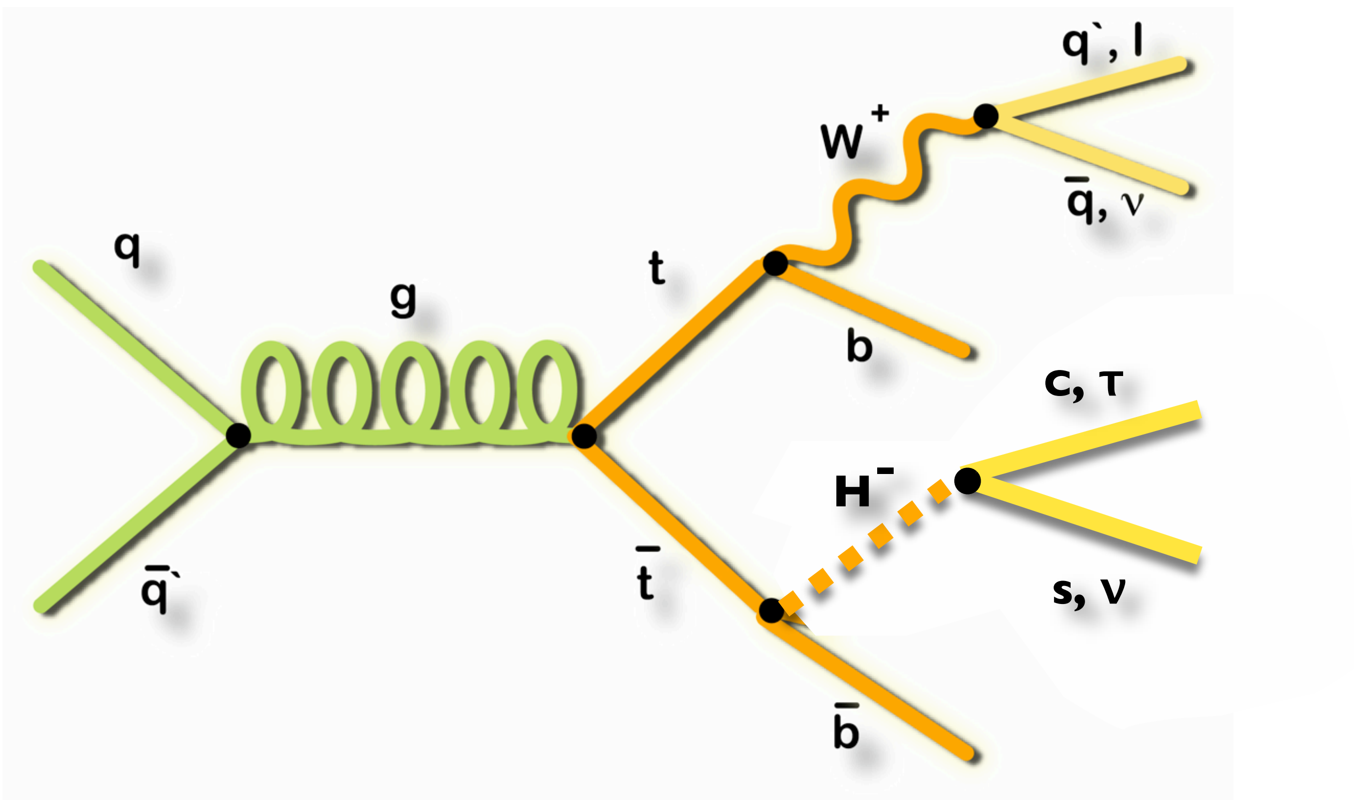
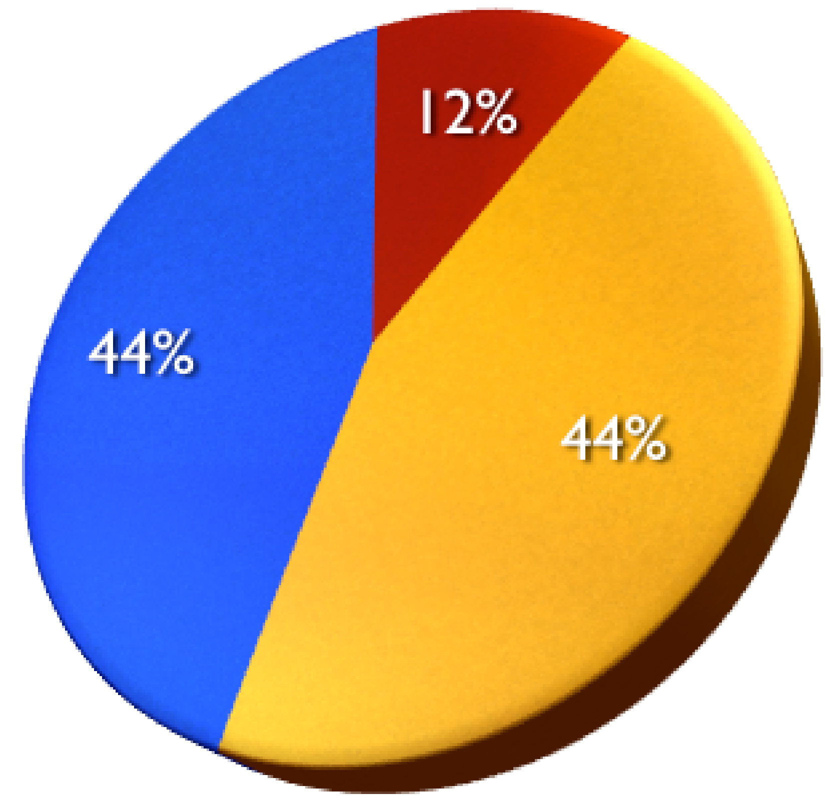


Top decaying to
charged Higgs



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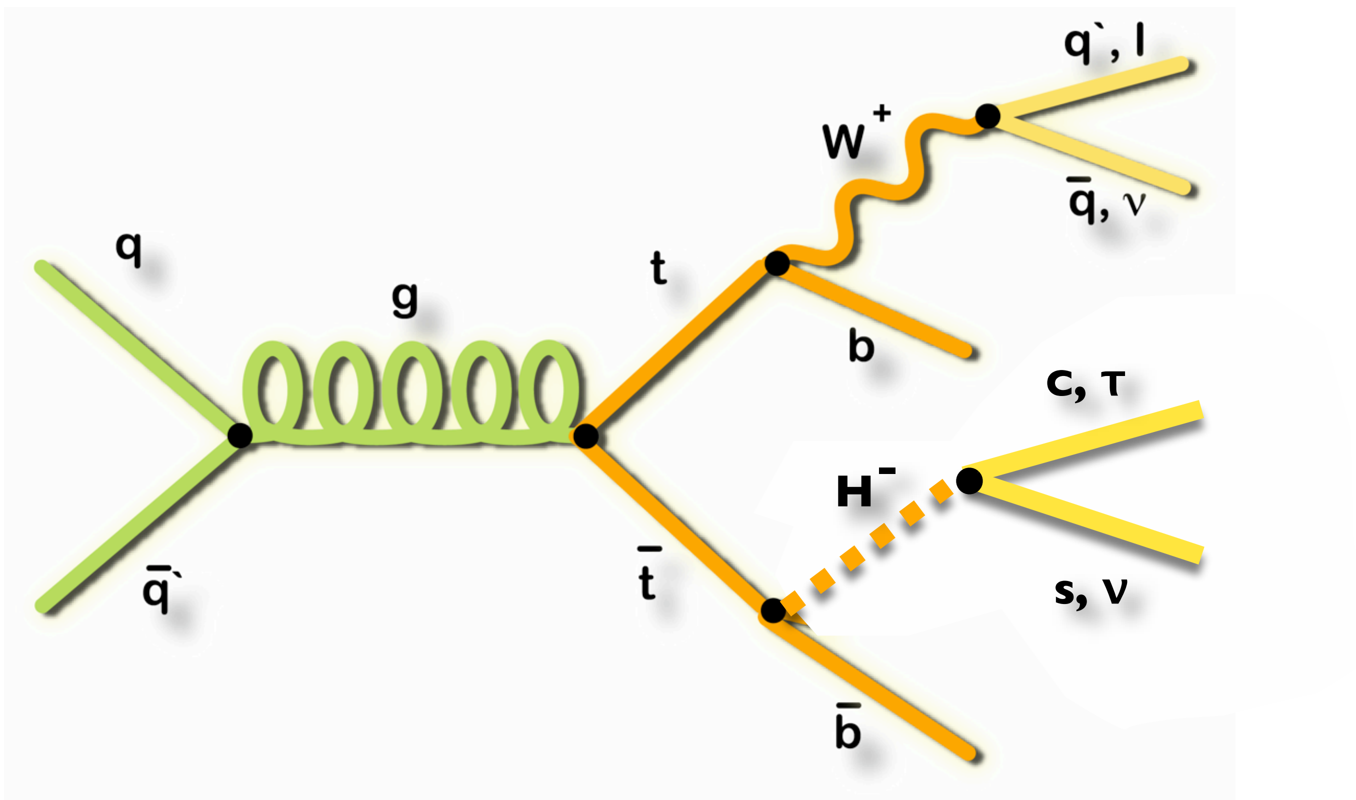

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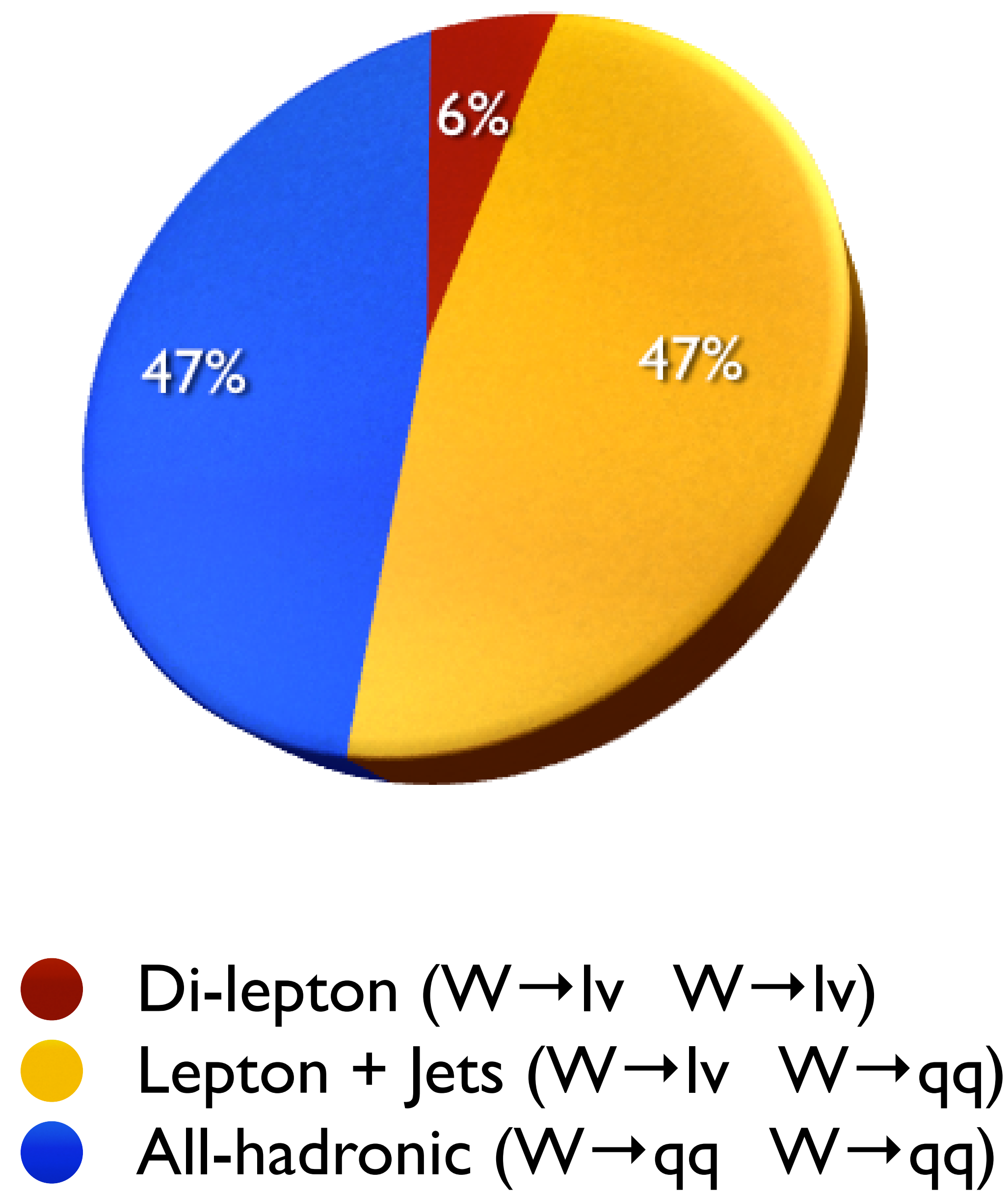
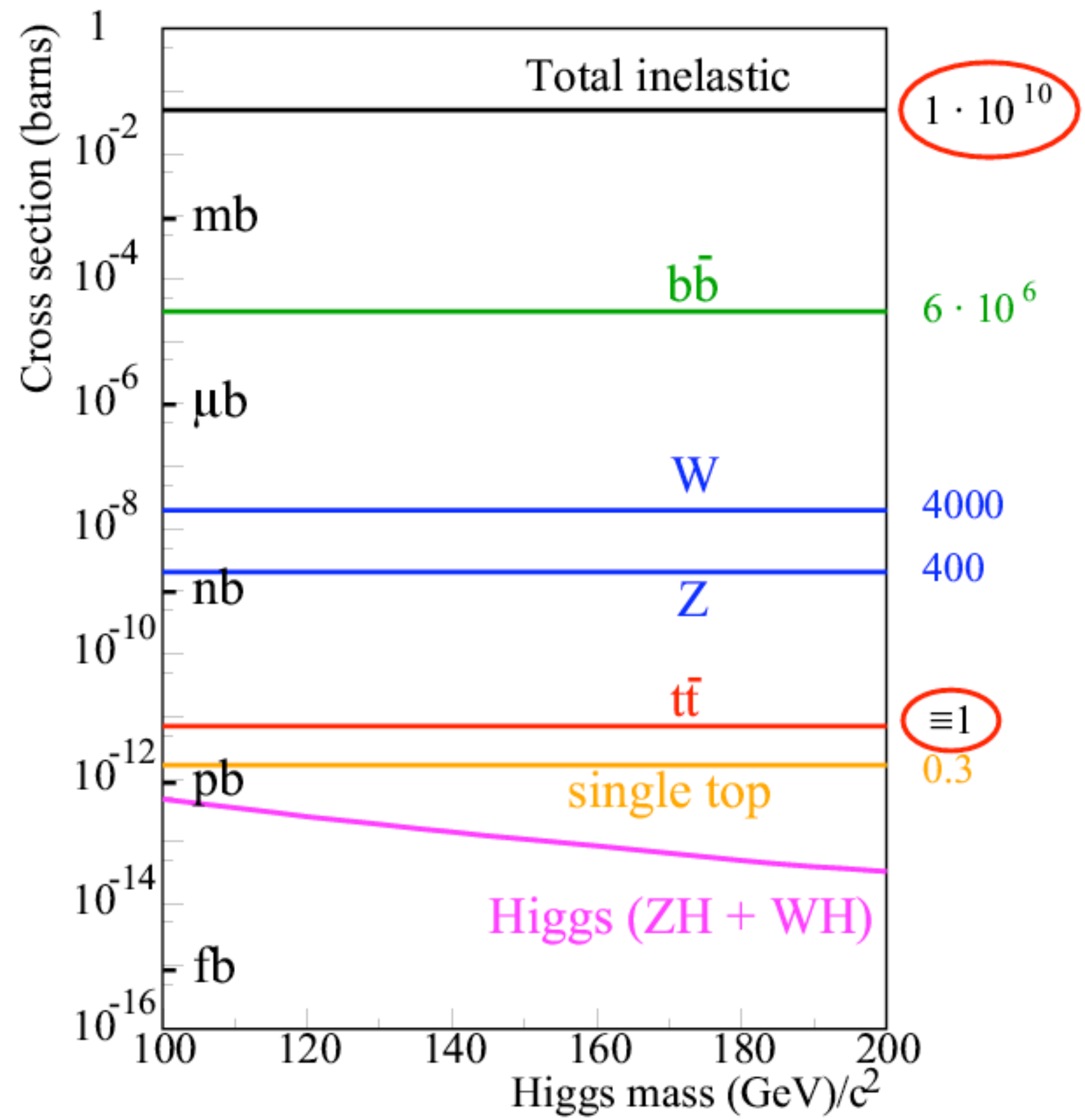


Finding Top Is Difficult

Produce Top
~ 1 in 10 Billion Collisions

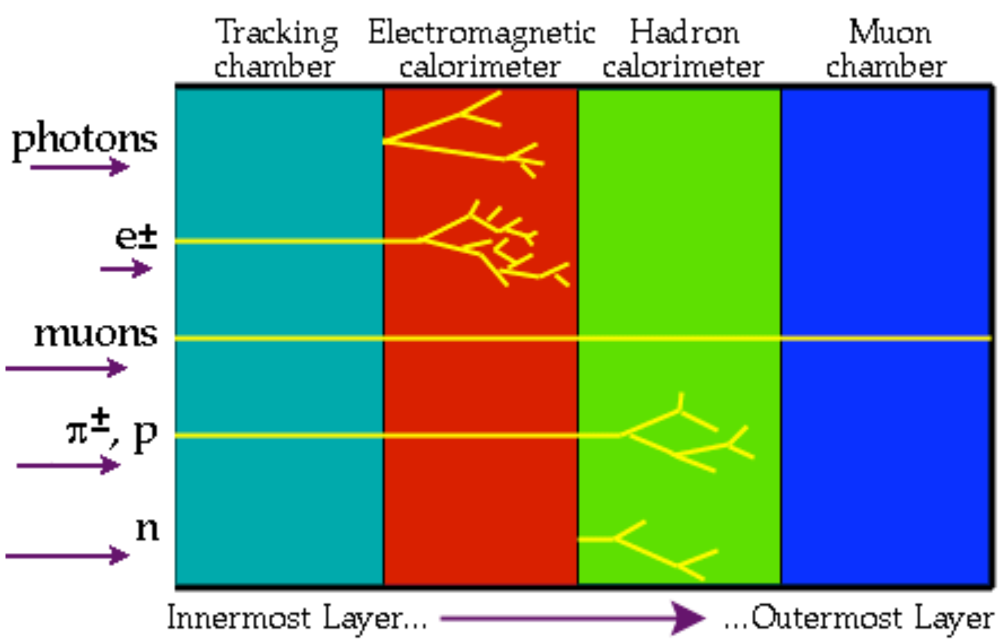
It's all about understanding and reducing backgrounds

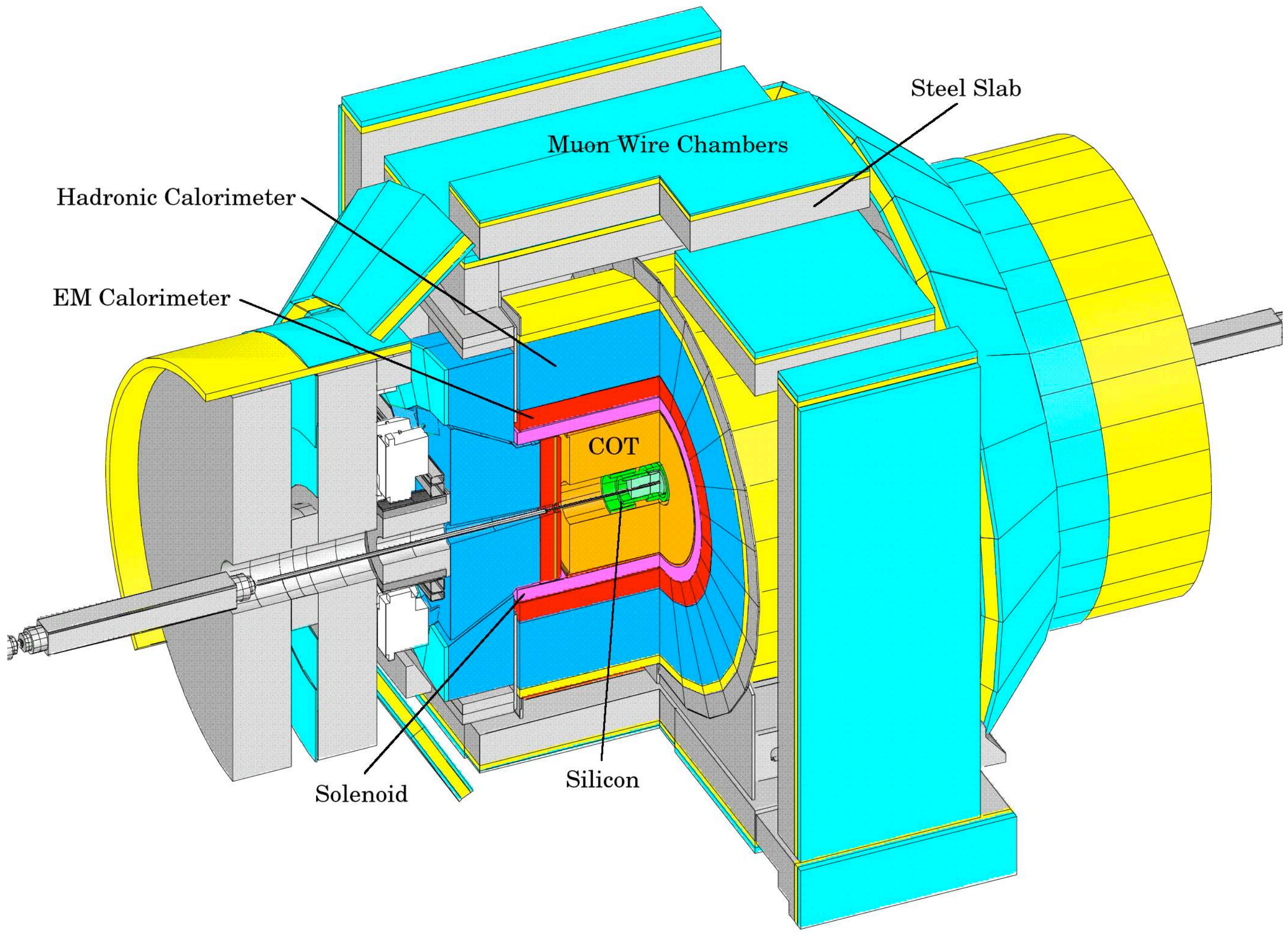


Identifying Top Events

- Top events have a little bit of everything: leptons, quarks that form jets, neutrinos which leave missing transverse energy

- Each piece requires it's own unique method of identification in the detector

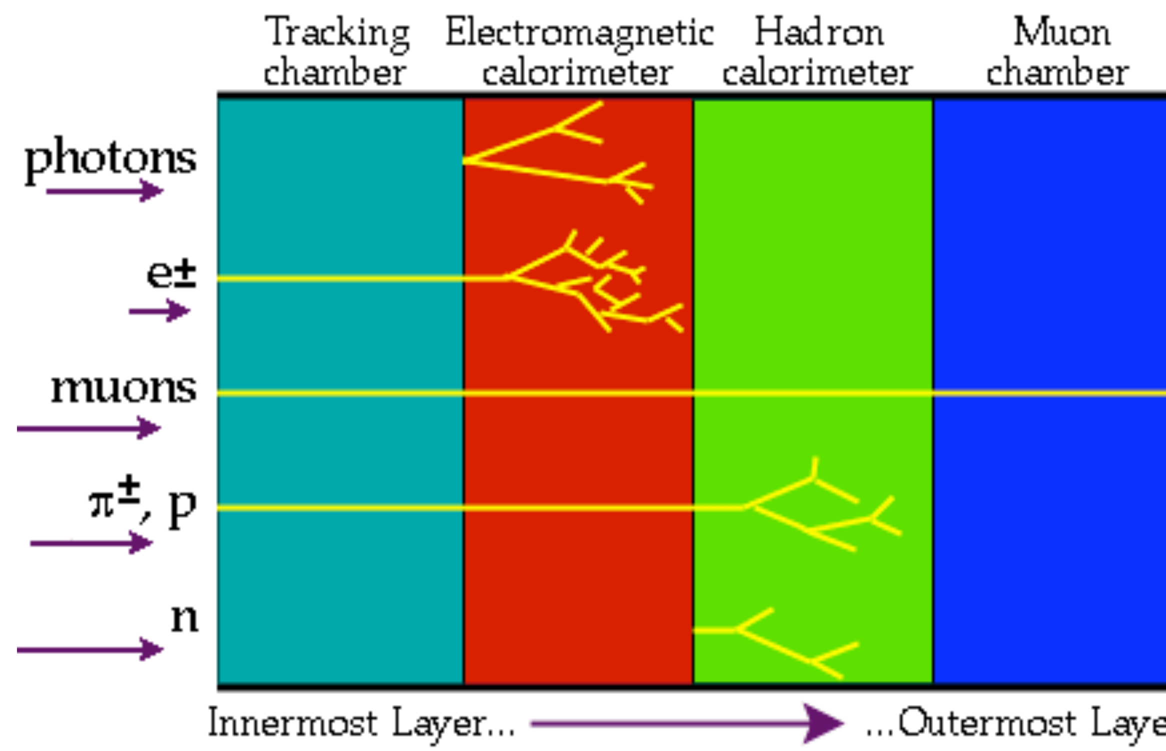




Lepton Identification

Electrons

- Charged track in the tracking chamber
- Deposit energy in the EM calorimeter and little in the hadronic calorimeter

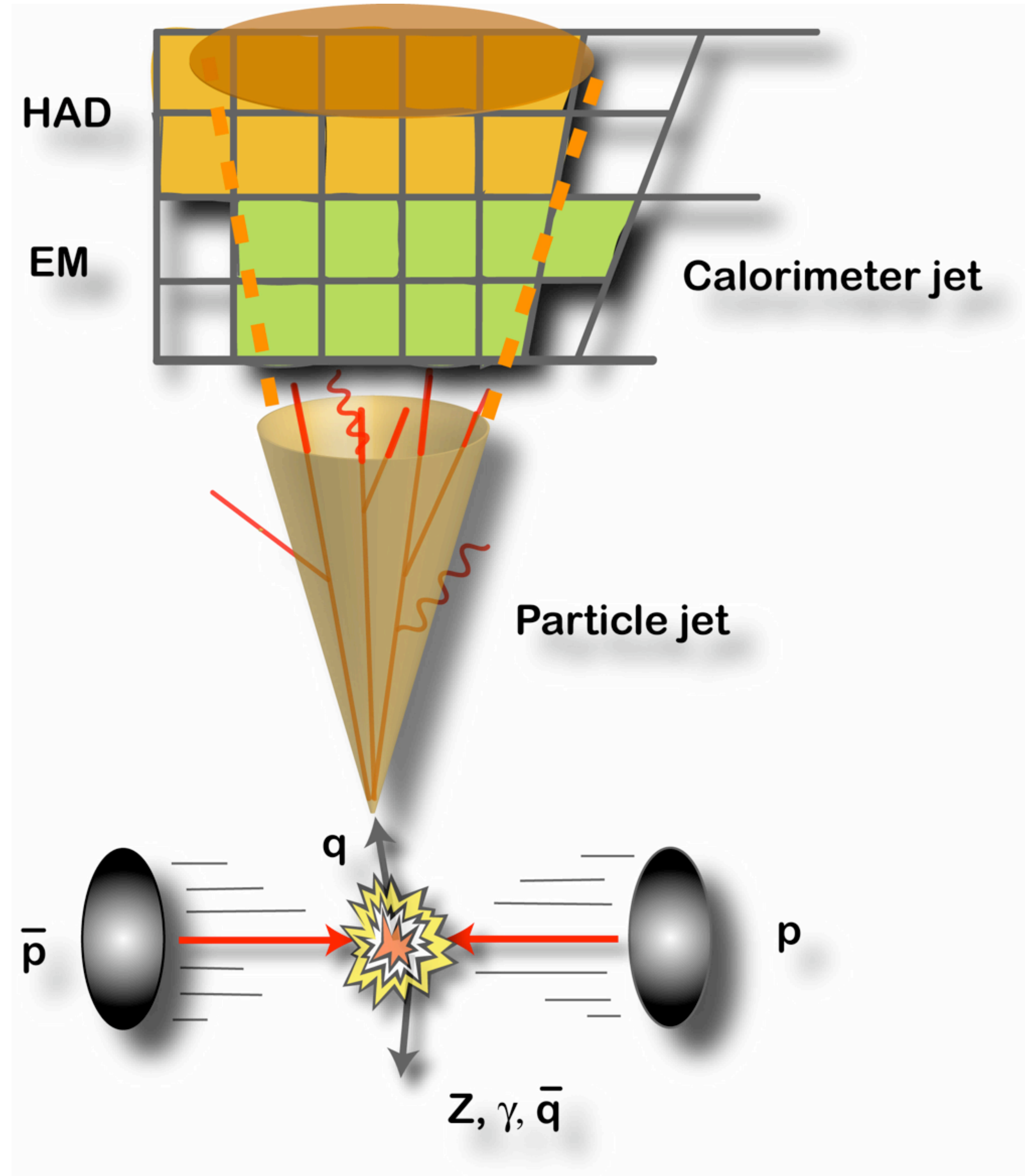


Muons

- Charged track in the tracking chamber
- Minimum amount of energy deposited in calorimeters
- Identified "stub" in muon chambers

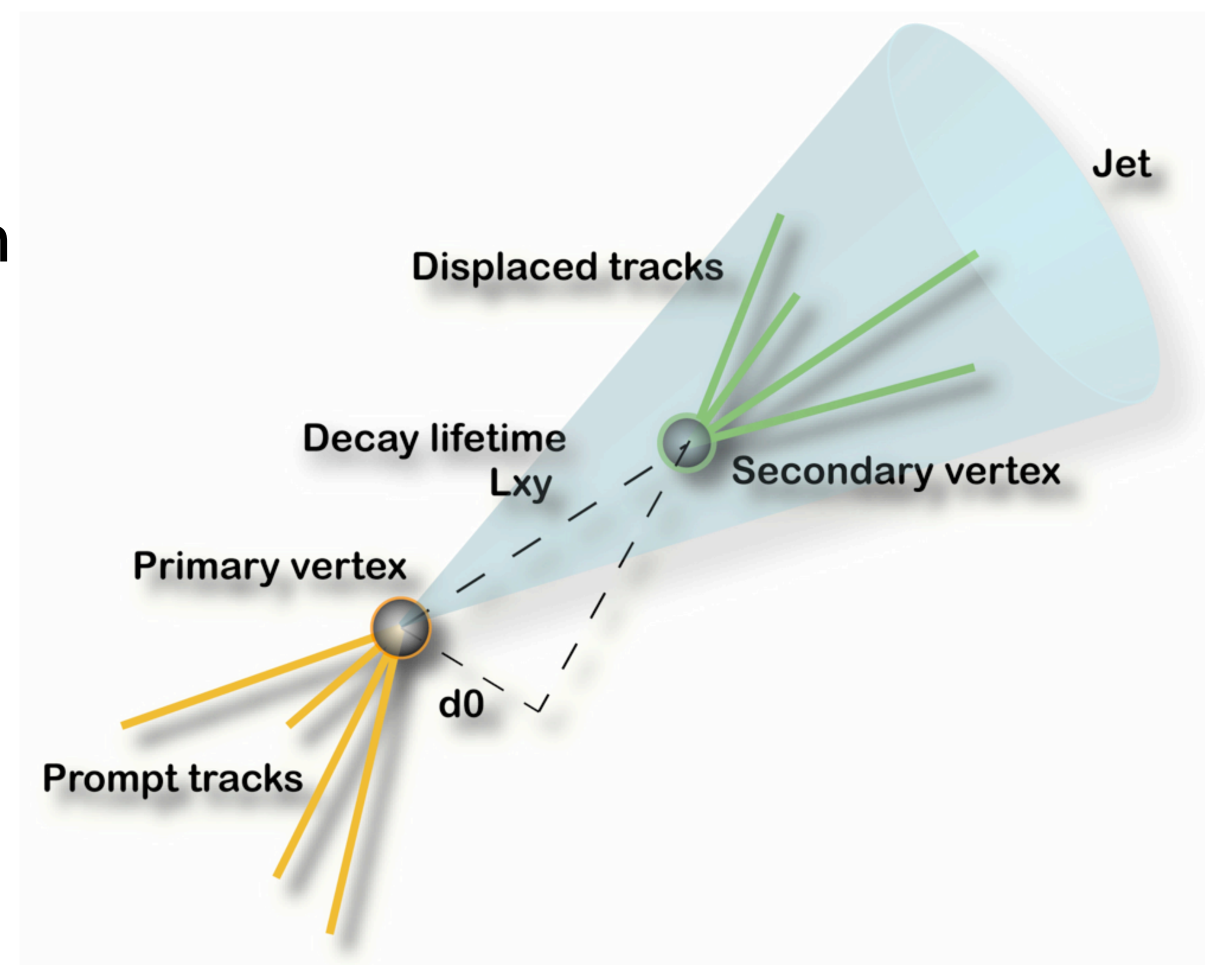
Jet Identification

- We're looking for partons but we observe jets in the detector
- Jets are identified as cones of energy in the calorimeter towers
- Energy of jets are difficult to measure which can generally lead to large systematic uncertainties in our measurements



Bottom Quark Identification (Tagging)

- Bottom quarks generally travel a few millimeters before decay
- Look for a secondary vertex, displaced from primary, formed from two or more displaced tracks
- Suppresses background
  - QCD without bottom/charm
  - W plus light flavor jets



The Cross-Section

$$\sigma_{t\bar{t}} = \frac{N_{data} - N_{bkg}}{\underbrace{A}_{\textit{Acceptance}} \cdot \underbrace{\int \mathcal{L}\, dt}_{\textit{Integrated Luminosity}}}$$

- Measuring the cross-section requires a complete understanding of the physics in our data sample

- Result feeds into all other measurements (mass, properties, searches...)

History of the Top Cross Section at CDF

$\sigma_{SM} = 6.73^{+0.72}_{-0.63}\ pb$ Cacciari et al., arXiv:0804.2800 (2008)

Lepton + Jets B-Tag Measurement In 1.1 fb^{-1}

$$\sigma_{\mathbf{t\bar{t}}} = \mathbf{8.2 \pm 0.5_{stat} \pm 0.8_{syst} \pm 0.5_{lumi}\ \ pb}$$

Lepton + Jets Pretag Measurement In 1.1 fb^{-1}

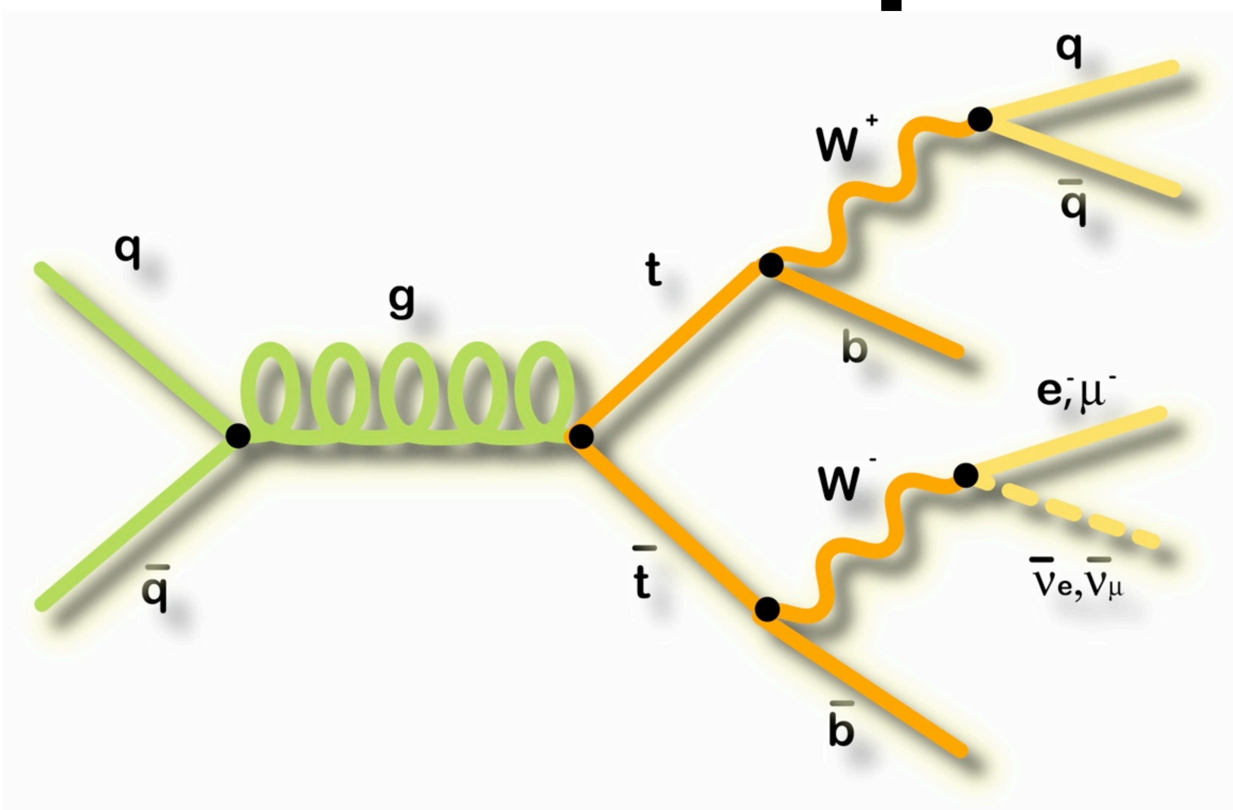
$$\sigma_{\mathbf{t\bar{t}}} = \mathbf{6.0 \pm 0.6_{stat} \pm 0.9_{syst}\ \ pb}$$

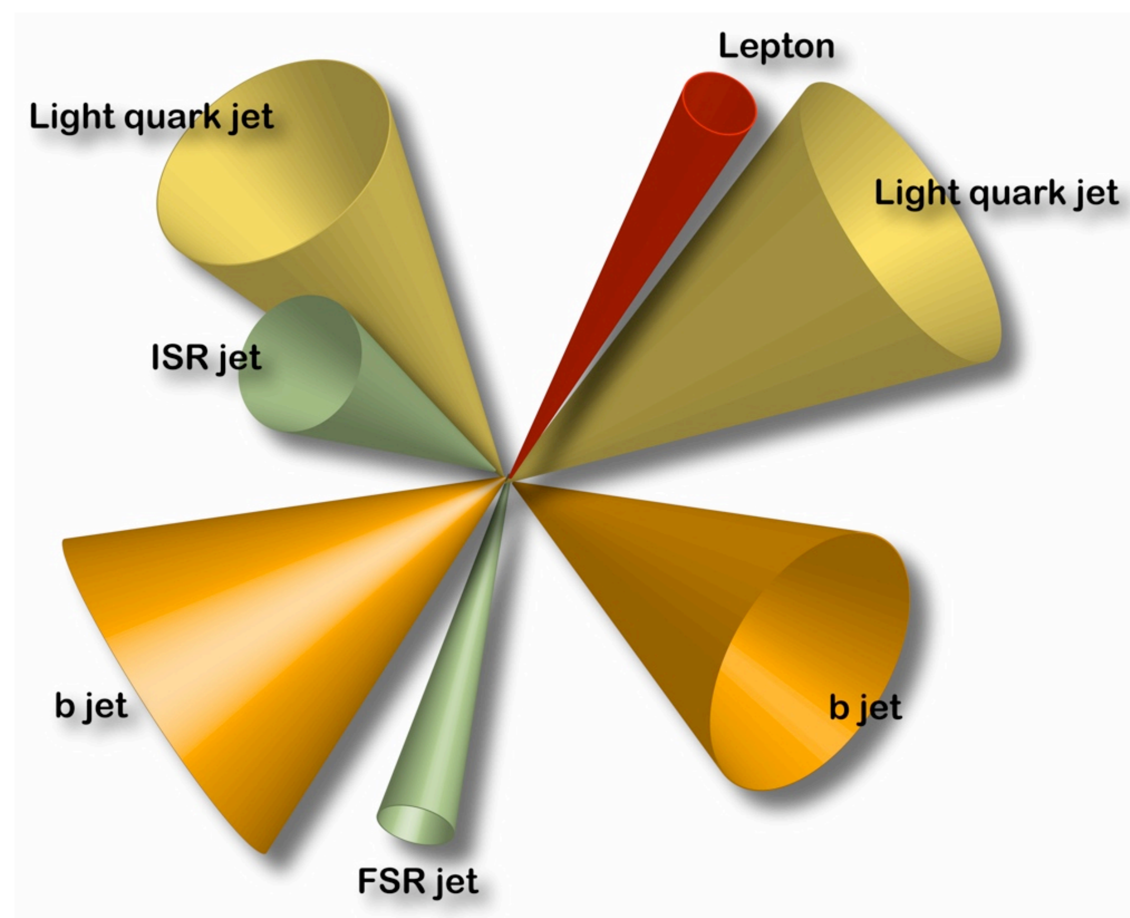
Di-lepton Measurement In 1.2 fb^{-1}

$$\sigma_{\mathbf{t\bar{t}}} = \mathbf{6.2 \pm 1.1_{stat} \pm 0.7_{syst} \pm 0.4_{lumi}\ \ pb}$$

B-Tag Measurement Has Historically Been High...

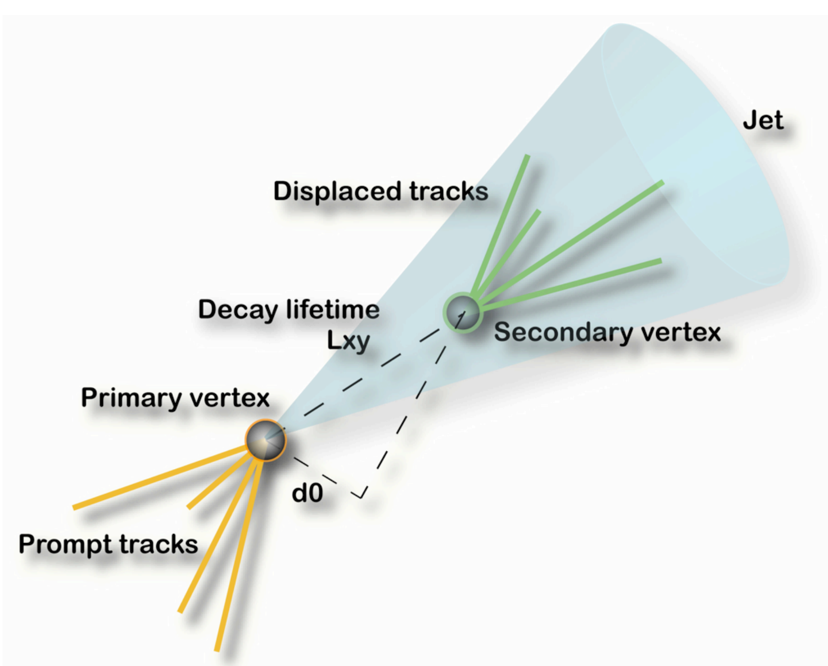
Bottom Tagging in Lepton + Jets

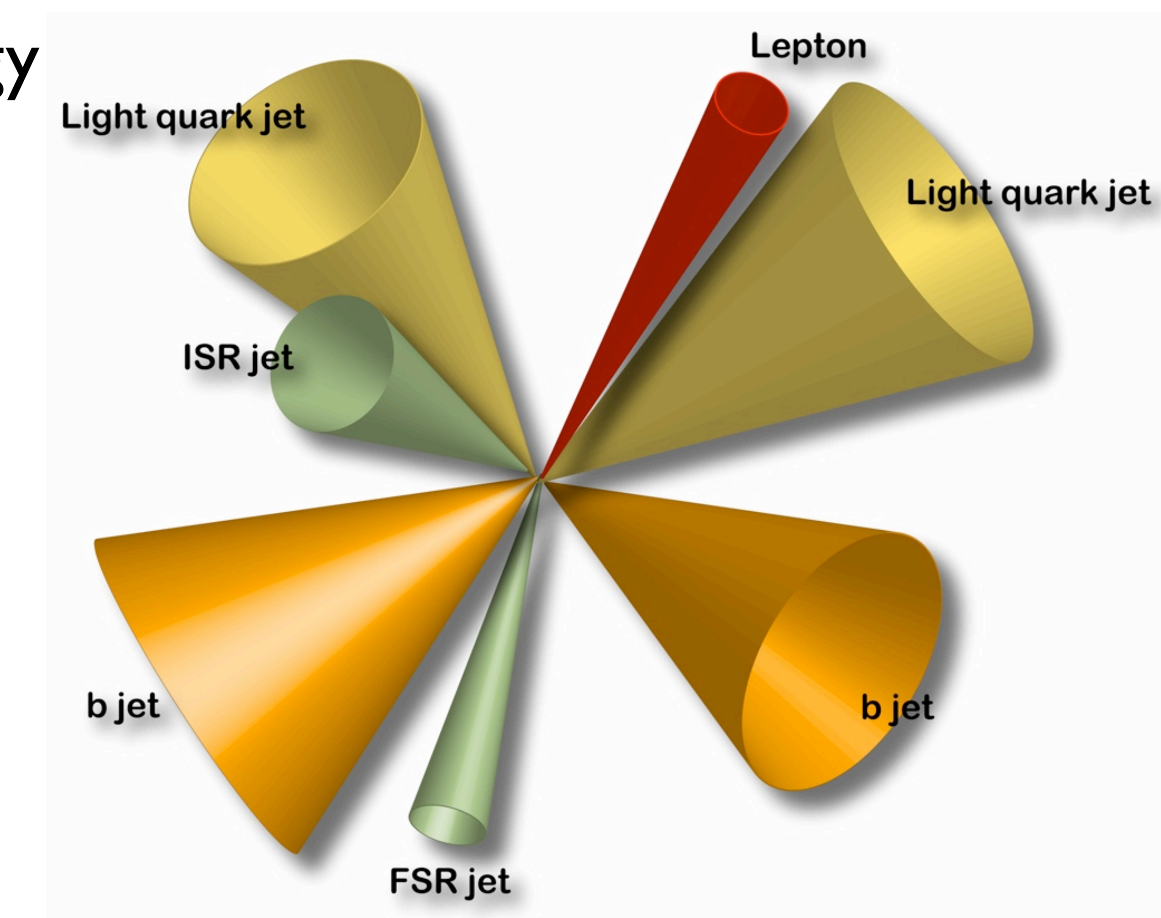




Bottom Tagging in Lepton + Jets

- $\geq$ 3 Jets (Et $\geq$ 20 GeV and η < 2.0)
- 1 Electron or Muon (Pt $\geq$ 20 GeV)
- $\geq$ 25 GeV Missing Transverse Energy
- $\geq$ 1 Bottom Tagged Jet





Physics Processes

- $\geq$ 3 Jets (Et $\geq$ 20 GeV and η < 2.0)
- 1 Electron or Muon (Pt $\geq$ 20 GeV)
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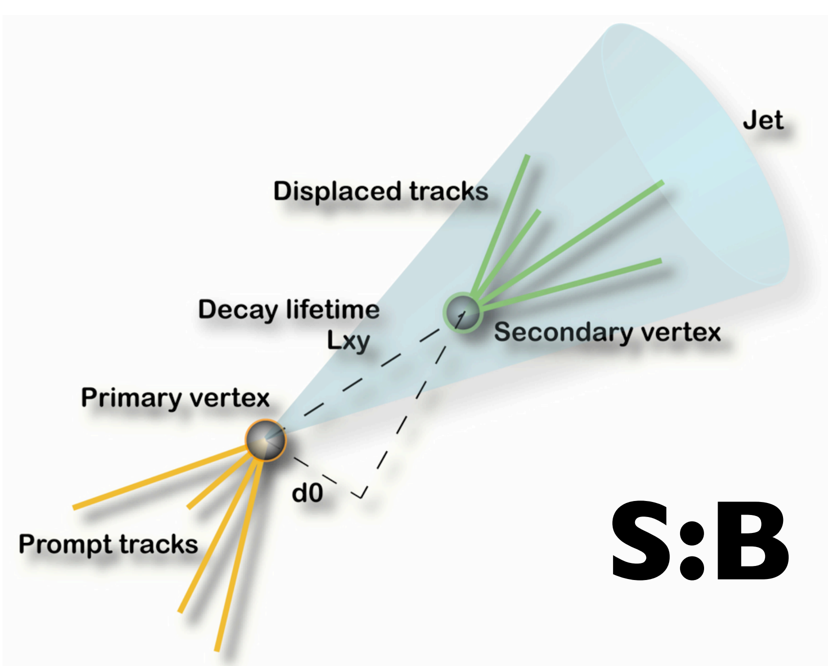
$$t\bar{t}$$
$$W + Jets$$
$$QCD$$
$$Electroweak$$



S:B ~ 1:3 $\xrightarrow{\textit{tagging}}$ 1:1

Monte Carlo Based

$$N = \sigma \cdot \int \mathcal{L}\, dt \cdot A$$

$$W + Jets$$
$$QCD$$
$$Electroweak$$

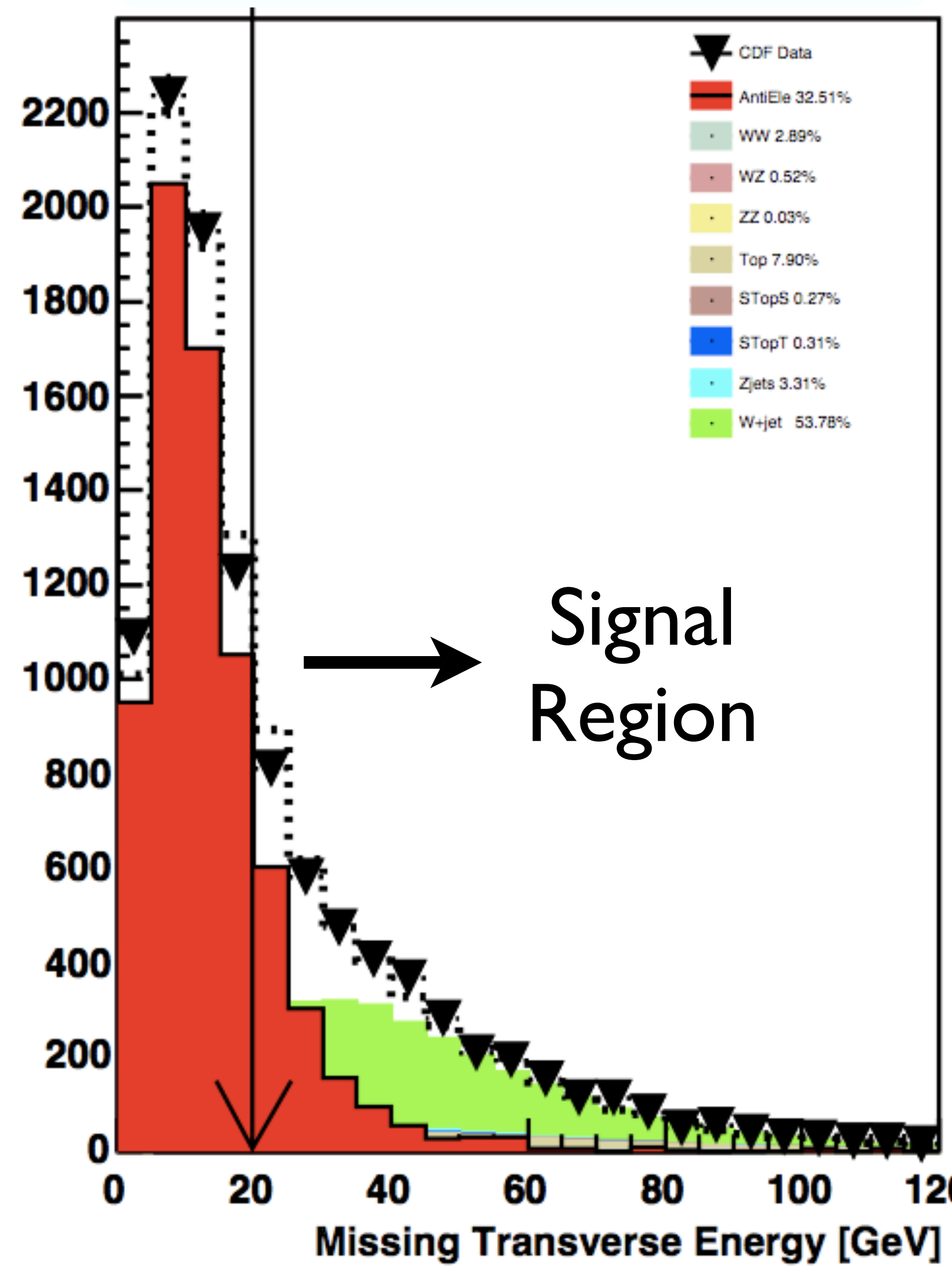
QCD

- QCD is very difficult to model with Monte Carlo
- Use data-driven approach - model QCD by all-jets sample or sample of leptons which failed ID cuts

$$W + Jets$$
$$QCD$$
$$Electroweak$$

QCD

- QCD is very difficult to model with Monte Carlo
- Use data-driven approach - model QCD by all-jets sample or sample of leptons which failed ID cuts
- Fit QCD and W+jets in low MET region - dominated by QCD
- Extract predicted fraction of events from QCD in signal region



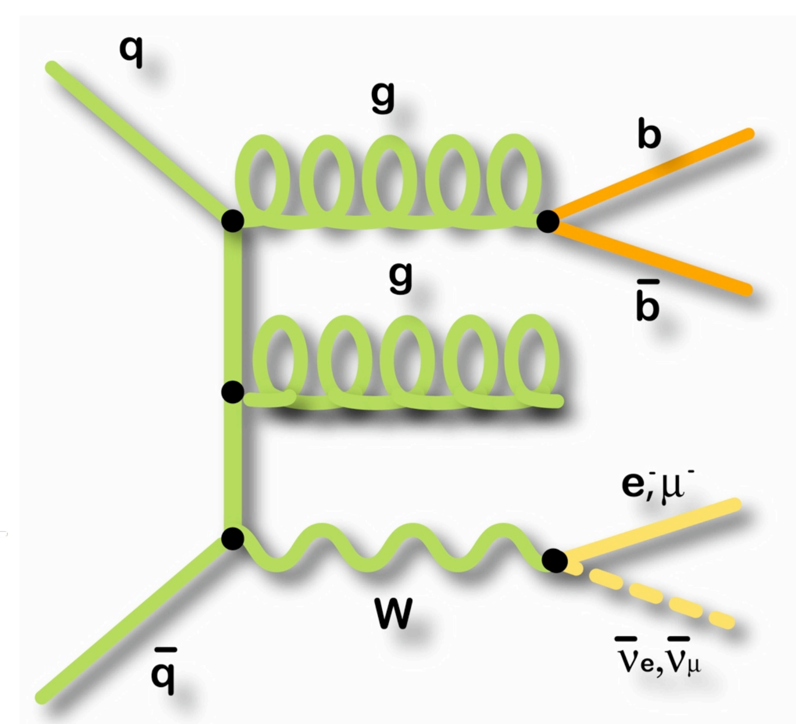
W + Jets

- W + Jets can be modeled by Monte Carlo but there are two difficulties that arise when we require a bottom tag
    - First, the rate of tagging bottom & charm is over-estimated and the rate of mis-identifying them is underestimated
    - Second, the cross-section for W associated with jets from bottom & charm is not well understood

$$W + Jets$$
$$QCD$$
$$Electroweak$$

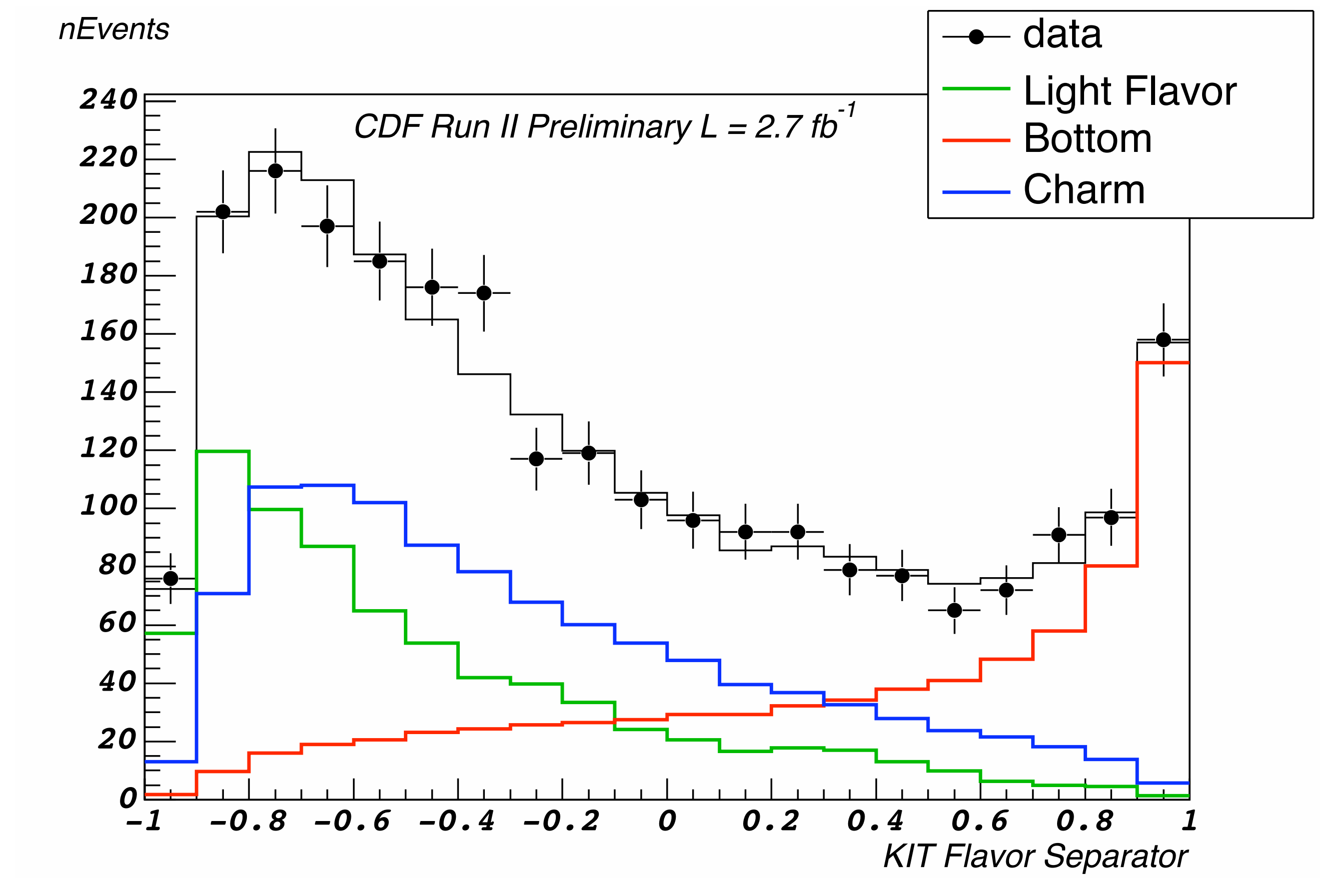
W + bottom/charm

- Because we're tagging bottom quarks, the relative amount of W + heavy flavor events vs W + light flavor becomes important
- This is not well understood theoretically and difficult to model in Monte Carlo
- A data-driven approach is used to correct the fraction of the W+jets sample associated with heavy flavor



W + bottom/charm

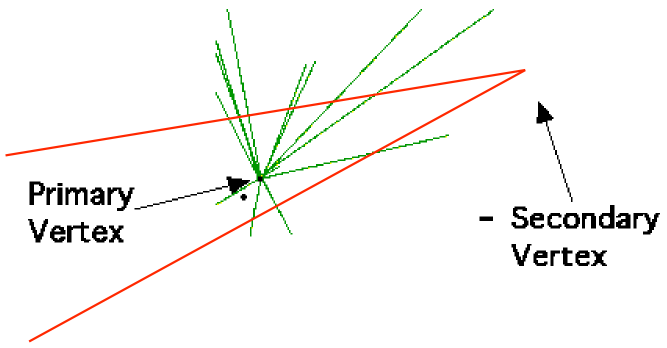
- Effectively, we measure the fraction of W + bottom/charm in W + jets events in a non-signal region (W + 1 jet)
- Neural network used to identify bottom/charm/light flavor events
- Simultaneously fit for bottom, charm, and light flavor fractions



- Compare to Monte Carlo to derive a correction factor and apply this to the W + jets prediction in the signal region

W + light flavor (mistags)

- W + light flavor jets sneak in by a mis-identified bottom/charm jet (call these mistags)
- Unfortunately, monte carlo is not tuned to handle this effect
- Instead, a data-driven parameterization is used to estimate the probability that a given jet will be mis-tagged

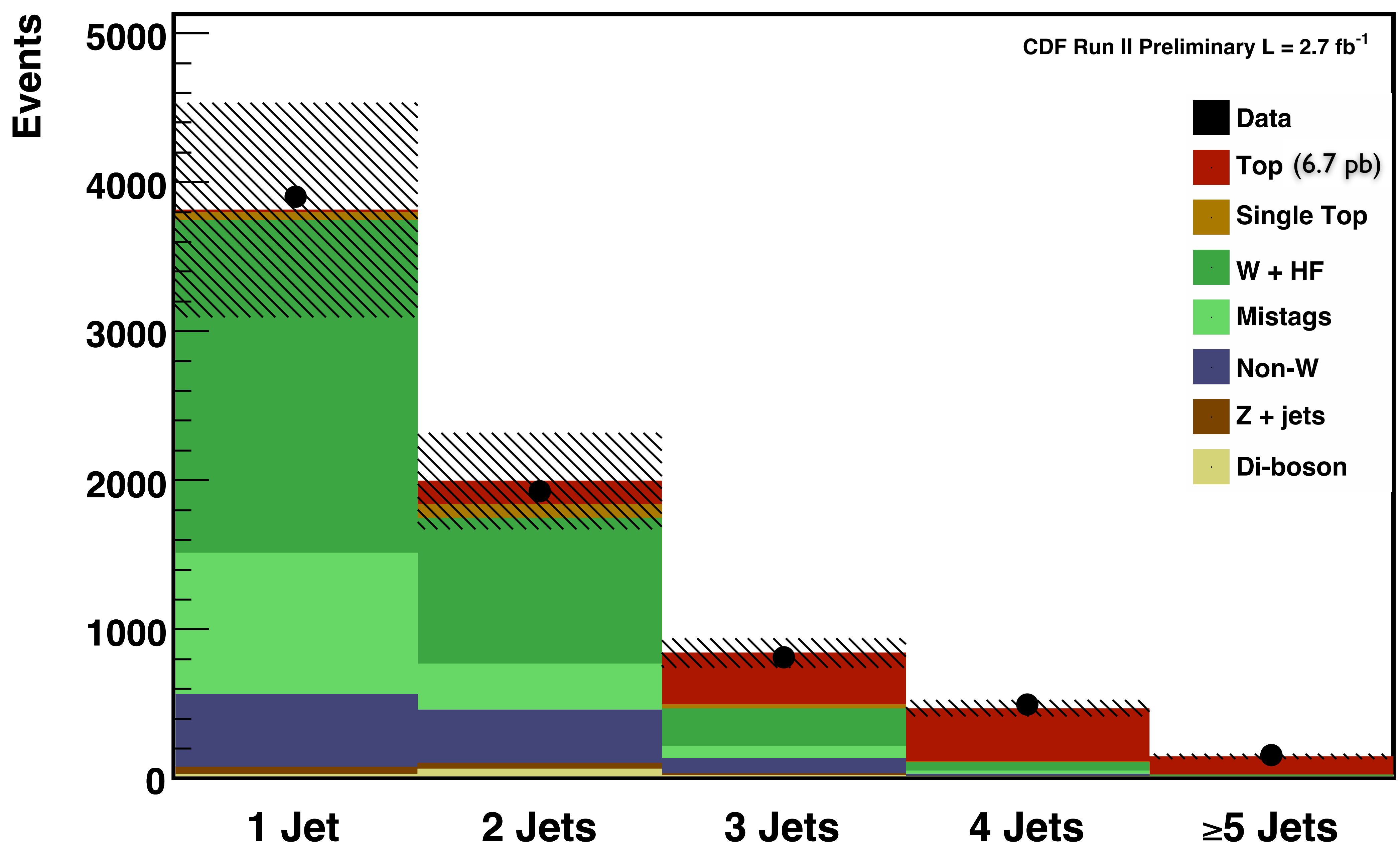


- This is applied to our pre-tag data sample to produce a prediction of the total number of events in our tagged sample that are mistags

Produces a complete prediction of process content across jet multiplicity

Process	1jet	2jets	3jets	4jets	5jets
Pre-tag Data	272347	44868	7605	1686	383
Wbb	802.3 ± 244.6	498.0 ± 154.5	136.9 ± 43.3	32.3 ± 10.5	6.5 ± 2.5
Wcc	431.4 ± 135.2	219.6 ± 69.6	64.3 ± 20.7	16.8 ± 5.6	3.6 ± 1.4
Wc	1002.9 ± 314.4	260.0 ± 82.5	48.8 ± 15.7	8.9 ± 2.9	1.5 ± 0.6
Mistags	946.7 ± 143.6	310.2 ± 53.9	83.5 ± 17.2	18.9 ± 4.8	3.5 ± 1.6
Non-W	487.9 ± 146.4	356.4 ± 106.9	102.2 ± 30.6	20.9 ± 17.5	6.4 ± 6.0
WW	17.7 ± 2.3	44.1 ± 5.7	14.0 ± 1.8	3.5 ± 0.5	1.0 ± 0.1
WZ	9.0 ± 1.0	19.2 ± 2.2	5.1 ± 0.6	1.2 ± 0.1	0.3 ± 0.0
ZZ	0.7 ± 0.1	1.9 ± 0.3	1.0 ± 0.1	0.3 ± 0.0	0.1 ± 0.0
Z+jets	48.7 ± 6.7	36.3 ± 4.6	13.6 ± 1.7	3.3 ± 0.4	0.7 ± 0.1
Single Top (s-channel)	11.4 ± 1.2	42.0 ± 4.1	13.1 ± 1.3	2.8 ± 0.3	0.6 ± 0.1
Single Top (t-channel)	37.6 ± 3.3	52.4 ± 4.6	14.3 ± 1.2	2.8 ± 0.2	0.4 ± 0.0
$t\bar{t}$ (6.7pb)	19.2 ± 2.7	154.9 ± 21.6	345.4 ± 48.0	358.6 ± 49.7	121.5 ± 16.8
Total Prediction	3815.5 ± 720.1	1995.1 ± 325.3	842.0 ± 99.1	470.3 ± 56.5	145.9 ± 18.5
Observed	3906	1926	813	494	156

CDF Run II Preliminary $\mathcal{L} = 2.7\ fb^{-1}$



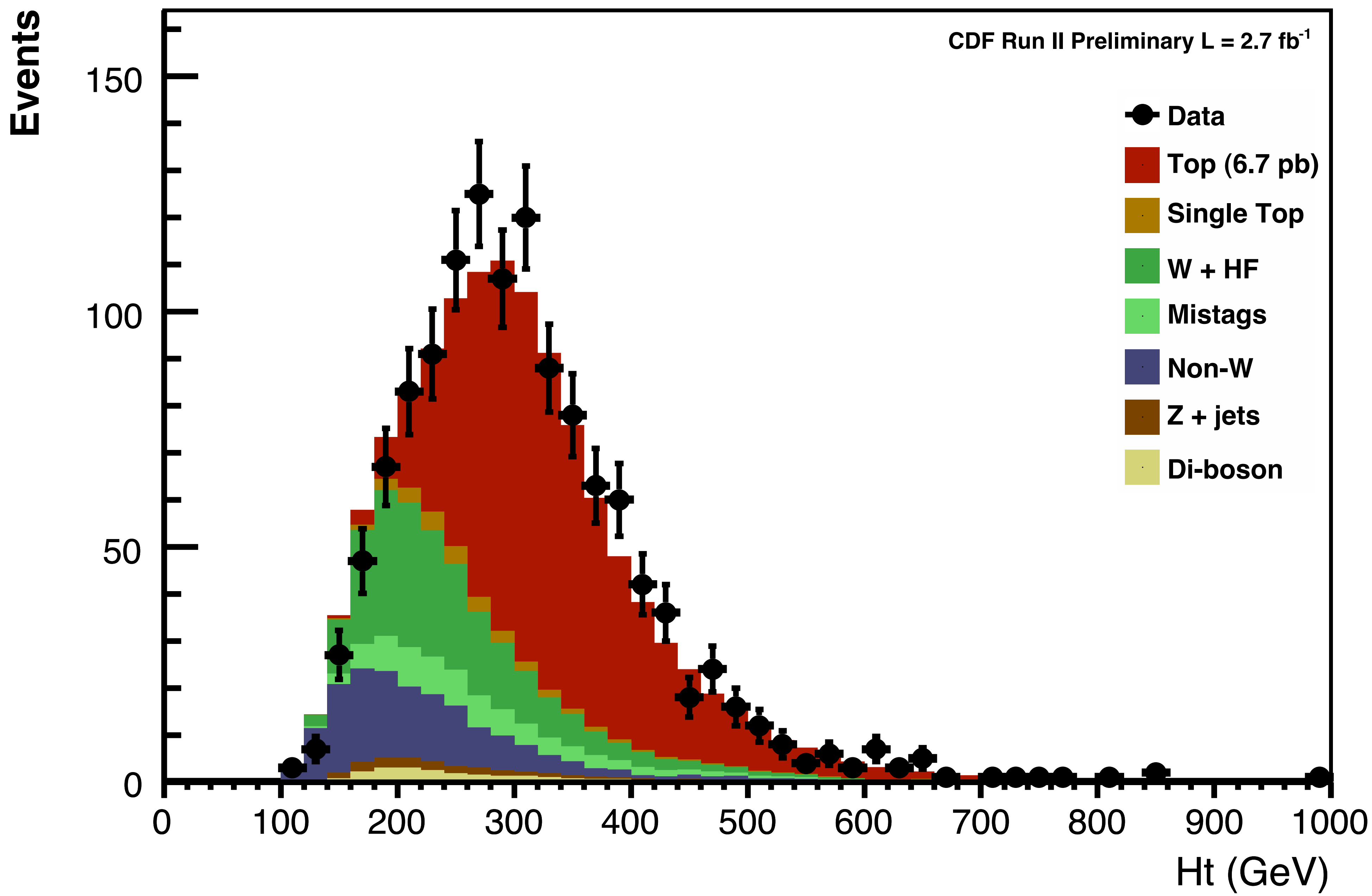
Events
5000
4000
3000
2000
1000
0
CDF Run II Preliminary L = 2.7 fb^{-1}
Data
Top (6.7 pb)
Single Top
W + HF
Mistags
Non-W
Z + jets
Di-boson
1 Jet
2 Jets
3 Jets
4 Jets
≥5 Jets

Signal Region

Process	1jet	2jets	3jets	4jets	5jets
Pre-tag Data	272347	44868	7605	1686	383
Wbb	802.3 ± 244.6	498.0 ± 154.5	136.9 ± 43.3	32.3 ± 10.5	6.5 ± 2.5
Wcc	431.4 ± 135.2	219.6 ± 69.6	64.3 ± 20.7	16.8 ± 5.6	3.6 ± 1.4
Wc	1002.9 ± 314.4	260.0 ± 82.5	48.8 ± 15.7	8.9 ± 2.9	1.5 ± 0.6
Mistags	946.7 ± 143.6	310.2 ± 53.9	83.5 ± 17.2	18.9 ± 4.8	3.5 ± 1.6
Non-W	487.9 ± 146.4	356.4 ± 106.9	102.2 ± 30.6	20.9 ± 17.5	6.4 ± 6.0
WW	17.7 ± 2.3	44.1 ± 5.7	14.0 ± 1.8	3.5 ± 0.5	1.0 ± 0.1
WZ	9.0 ± 1.0	19.2 ± 2.2	5.1 ± 0.6	1.2 ± 0.1	0.3 ± 0.0
ZZ	0.7 ± 0.1	1.9 ± 0.3	1.0 ± 0.1	0.3 ± 0.0	0.1 ± 0.0
Z+jets	48.7 ± 6.7	36.3 ± 4.6	13.6 ± 1.7	3.3 ± 0.4	0.7 ± 0.1
Single Top (s-channel)	11.4 ± 1.2	42.0 ± 4.1	13.1 ± 1.3	2.8 ± 0.3	0.6 ± 0.1
Single Top (t-channel)	37.6 ± 3.3	52.4 ± 4.6	14.3 ± 1.2	2.8 ± 0.2	0.4 ± 0.0
$t\bar{t}$ (6.7pb)	19.2 ± 2.7	154.9 ± 21.6	345.4 ± 48.0	358.6 ± 49.7	121.5 ± 16.8
Total Prediction	3815.5 ± 720.1	1995.1 ± 325.3	842.0 ± 99.1	470.3 ± 56.5	145.9 ± 18.5
Observed	3906	1926	813	494	156

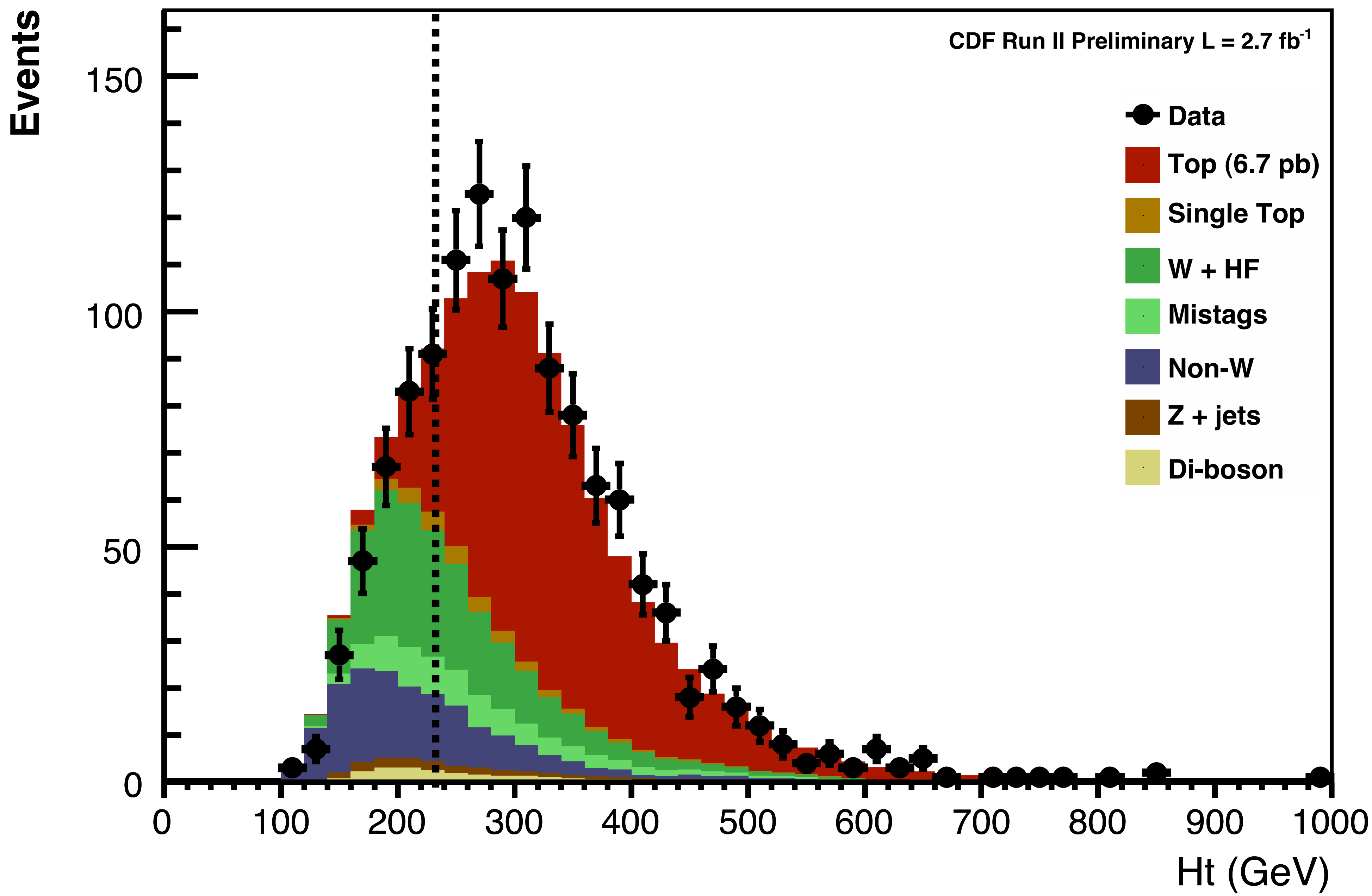
CDF Run II Preliminary $\mathcal{L} = 2.7\ fb^{-1}$

For $\geq$ 3 Jets S:B ~ 1:1

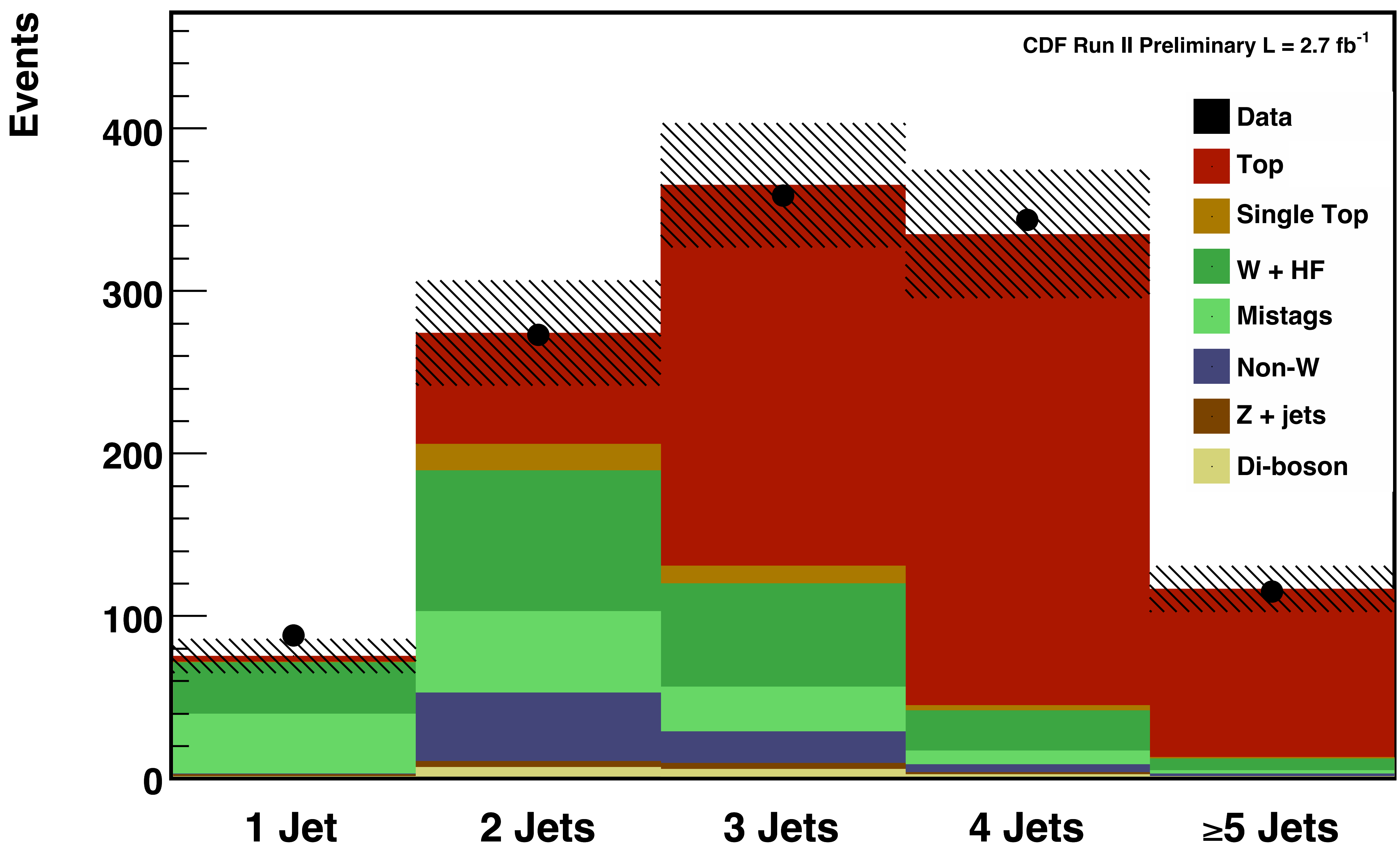


Events
CDF Run II Preliminary L = 2.7 fb^{-1}
Data
Top (6.7 pb)
Single Top
W + HF
Mistags
Non-W
Z + jets
Di-boson
0
50
100
150
0
100
200
300
400
500
600
700
800
900
1000
Ht (GeV)

More Background Reduction



S:B ~ 1:1 → 3:1


CDF Run II Preliminary L = 2.7 fb^{-1}
Events
0
100
200
300
400
1 Jet
2 Jets
3 Jets
4 Jets
≥5 Jets
Data
Top
Single Top
W + HF
Mistags
Non-W
Z + jets
Di-boson

Process	1jet	2jets	3jets	4jets	5jets
Pretag Data	2182	2749	1702	885	271
Wbb	16.7 ± 5.1	47.5 ± 14.8	35.4 ± 11.0	13.7 ± 4.9	4.1 ± 1.7
Wcc	7.1 ± 2.3	20.5 ± 6.5	17.4 ± 5.5	7.3 ± 2.6	2.3 ± 0.9
Wc	7.4 ± 2.4	19.0 ± 6.1	10.6 ± 3.4	3.4 ± 1.2	0.9 ± 0.4
Mistags	37.0 ± 4.3	50.3 ± 7.9	27.8 ± 5.0	8.5 ± 3.1	2.1 ± 1.2
Non-W	0.5 ± 1.0	41.9 ± 12.6	19.3 ± 6.3	4.8 ± 4.3	1.7 ± 1.8
Z+Jets	1.2 ± 0.1	3.6 ± 0.4	3.6 ± 0.4	1.5 ± 0.2	0.5 ± 0.1
WW	1.0 ± 0.1	5.3 ± 0.7	4.3 ± 0.5	1.9 ± 0.2	0.7 ± 0.1
WZ	0.3 ± 0.0	1.6 ± 0.2	1.3 ± 0.1	0.5 ± 0.1	0.2 ± 0.0
ZZ	0.0 ± 0.0	0.2 ± 0.0	0.2 ± 0.0	0.1 ± 0.0	0.0 ± 0.0
Single Top (s-channel)	0.4 ± 0.0	8.7 ± 0.9	5.6 ± 0.5	1.8 ± 0.2	0.5 ± 0.0
Single Top (t-channel)	0.1 ± 0.0	7.3 ± 0.6	5.3 ± 0.4	1.7 ± 0.1	0.3 ± 0.0
$t\bar{t}$	3.6 ± 0.5	68.3 ± 9.0	234.3 ± 30.7	289.9 ± 37.9	103.7 ± 13.6
Total Prediction	75.4 ± 10.6	274.2 ± 32.3	365.1 ± 38.1	335.1 ± 39.5	116.8 ± 14.1
Observed	88	273	359	344	115

CDF Run II Preliminary $\mathcal{L} = 2.7\ fb^{-1}$

Signal Region

Process	1jet	2jets	3jets	4jets	5jets
Pretag Data	2182	2749	1702	885	271
Wbb	16.7 ± 5.1	47.5 ± 14.8	35.4 ± 11.0	13.7 ± 4.9	4.1 ± 1.7
Wcc	7.1 ± 2.3	20.5 ± 6.5	17.4 ± 5.5	7.3 ± 2.6	2.3 ± 0.9
Wc	7.4 ± 2.4	19.0 ± 6.1	10.6 ± 3.4	3.4 ± 1.2	0.9 ± 0.4
Mistags	37.0 ± 4.3	50.3 ± 7.9	27.8 ± 5.0	8.5 ± 3.1	2.1 ± 1.2
Non-W	0.5 ± 1.0	41.9 ± 12.6	19.3 ± 6.3	4.8 ± 4.3	1.7 ± 1.8
Z+Jets	1.2 ± 0.1	3.6 ± 0.4	3.6 ± 0.4	1.5 ± 0.2	0.5 ± 0.1
WW	1.0 ± 0.1	5.3 ± 0.7	4.3 ± 0.5	1.9 ± 0.2	0.7 ± 0.1
WZ	0.3 ± 0.0	1.6 ± 0.2	1.3 ± 0.1	0.5 ± 0.1	0.2 ± 0.0
ZZ	0.0 ± 0.0	0.2 ± 0.0	0.2 ± 0.0	0.1 ± 0.0	0.0 ± 0.0
Single Top (s-channel)	0.4 ± 0.0	8.7 ± 0.9	5.6 ± 0.5	1.8 ± 0.2	0.5 ± 0.0
Single Top (t-channel)	0.1 ± 0.0	7.3 ± 0.6	5.3 ± 0.4	1.7 ± 0.1	0.3 ± 0.0
$t\bar{t}$	3.6 ± 0.5	68.3 ± 9.0	234.3 ± 30.7	289.9 ± 37.9	103.7 ± 13.6
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Observed	88	273	359	344	115

CDF Run II Preliminary $\mathcal{L} = 2.7\ fb^{-1}$

The Cross-Section

$$\sigma_{t\bar{t}} = \frac{N_{data} - N_{bkg}}{A \cdot \int \mathcal{L}\, dt}$$

Acceptance *Integrated Luminosity*

The Cross-Section

$$\sigma_{t\bar{t}} = \frac{N_{data} - N_{bkg}(\sigma_{t\bar{t}})}{A \cdot \int \mathcal{L}\, dt}$$

Acceptance *Integrated Luminosity*

Extracting the X-section

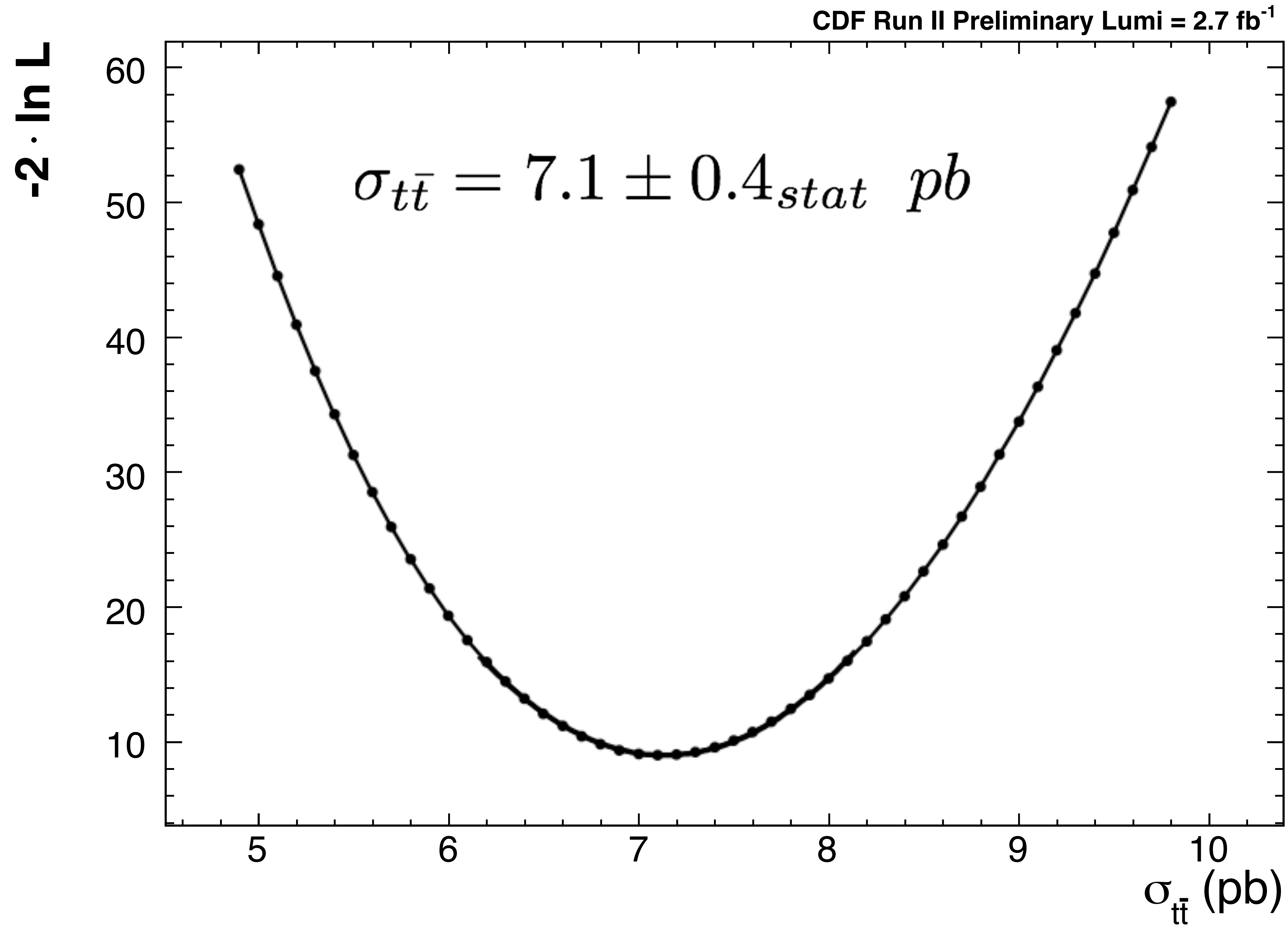
- Because the background estimate is a function of the top cross-section it's not so simple to calculate
- Worse, error propagation basically becomes impossible
- What we can do is construct a Poisson Likelihood from the predicted number of events and the data, evaluate the Likelihood for a range of cross-section values, and extract the minimum value and the statistical uncertainty

$$-2 \cdot lnL = -2 \cdot (N_{data} \cdot ln(D \cdot \sigma + B) - ln(N_{data}!) - (D \cdot \sigma + B))$$

$$D = A \int \mathcal{L}\, dt$$

$$P(\sigma_{t\bar{t}}) = \frac{N_{pred}(\sigma_{t\bar{t}})^{N_{data}} \cdot e^{-N_{pred}(\sigma_{t\bar{t}})}}{N_{data}!}$$

$$B = Background\ estimate\ at\ cross-section\ \sigma$$


CDF Run II Preliminary Lumi = 2.7 fb^{-1}
-2 · ln L
$\sigma_{t\bar{t}} = 7.1 \pm 0.4_{stat}\ pb$
10
20
30
40
50
60
5
6
7
8
9
10
$\sigma_{t\bar{t}}$ (pb)

Measurement in 2.7 fb^{-1}

$$\sigma_{\mathbf{t\bar{t}}} = \mathbf{7.1 \pm 0.4_{stat} \pm 0.6_{sys} \pm 0.4_{lum} \;\; pb}$$

@ M_t = 175 GeV/c^2

$$\frac{\boldsymbol{\Delta}\sigma}{\sigma} = \mathbf{11.6\%}$$

Systematics

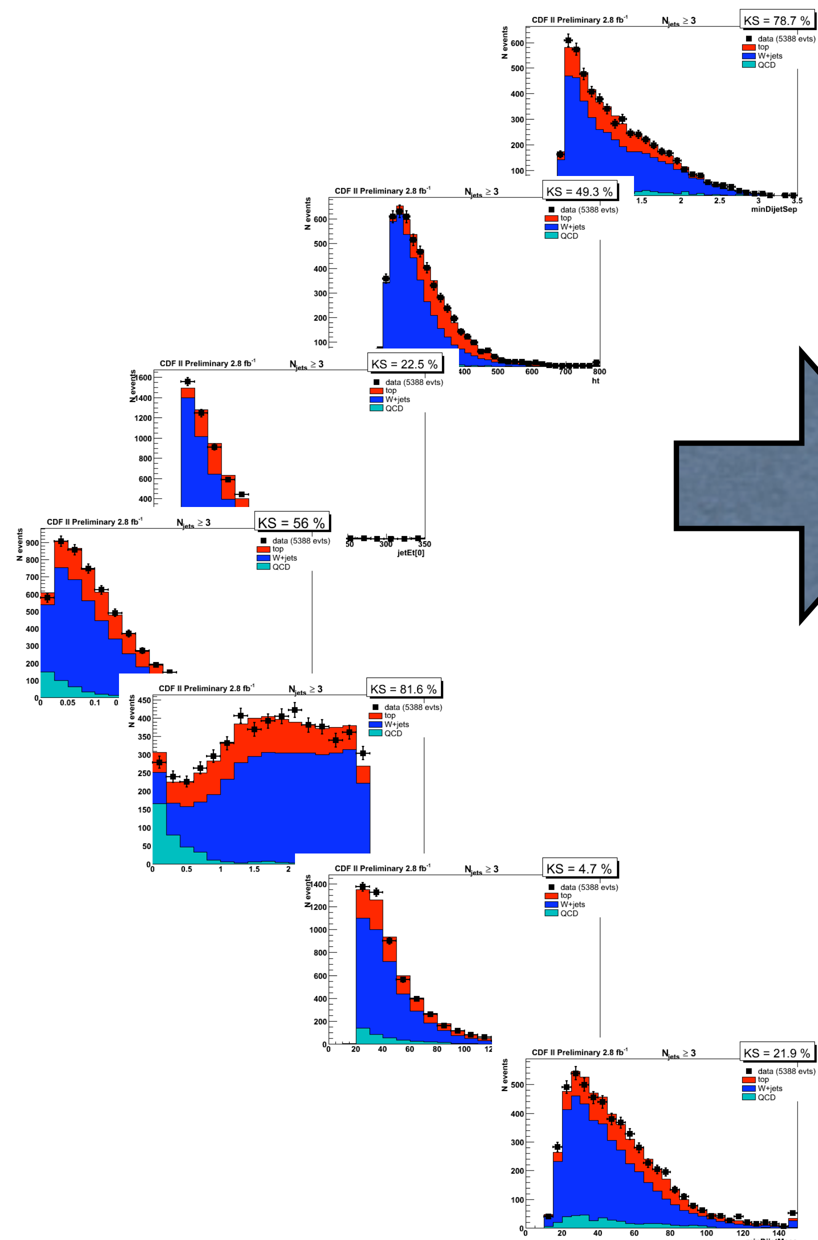
SYSTEMATIC	Δ	Δ%
JET ENERGY SCALE	0.3	4.1
TAGGING	0.4	5.5
MISTAGS	0.2	2.4
HEAVY FLAVOR CORRECTION	0.3	3.8
LUMINOSITY	0.4	6.1
QCD	0.1	0.8
MONTE CARLO GENERATOR	0.2	3.0
INITIAL/FINAL STATE RADIATION	0.1	0.8
LEPTON ID	0.0	0.6
Z0	0.0	0.3
PDF	0.0	0.6
TOTALS	0.8	10.7

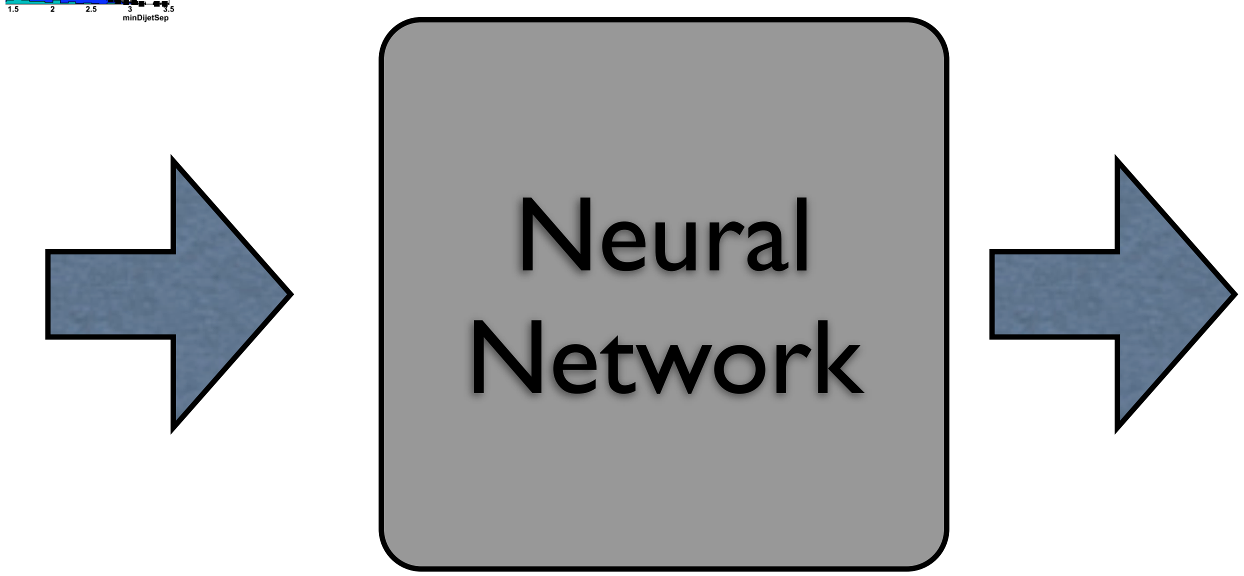
Another Approach

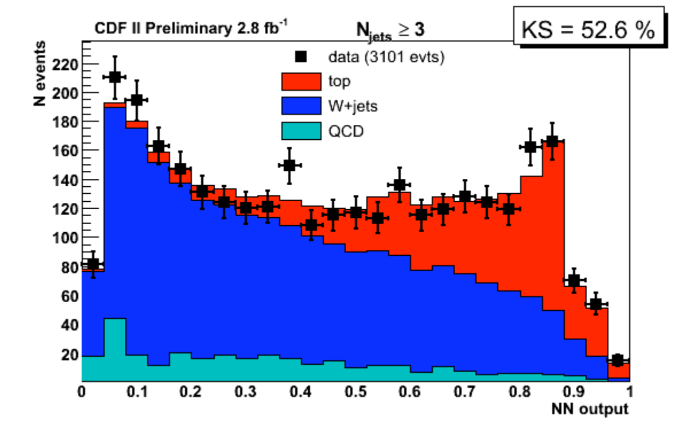
- As opposed to using bottom tagging to reduce backgrounds, use event kinematics to distinguish signal from background

- More model-dependent, but increased statistics and no sensitivity to the last measurements two largest systematics

Topological Measurement







- Feed distributions into Neural Net, trained to distinguish signal from background
- Fit signal and background templates to the data at Neural Net output

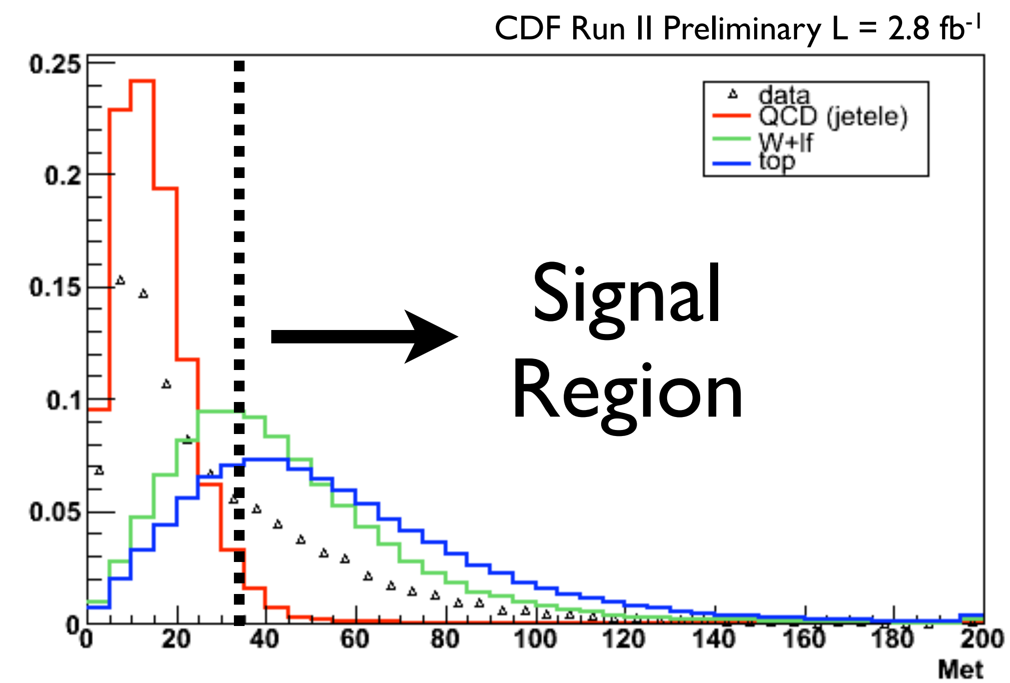
Backgrounds

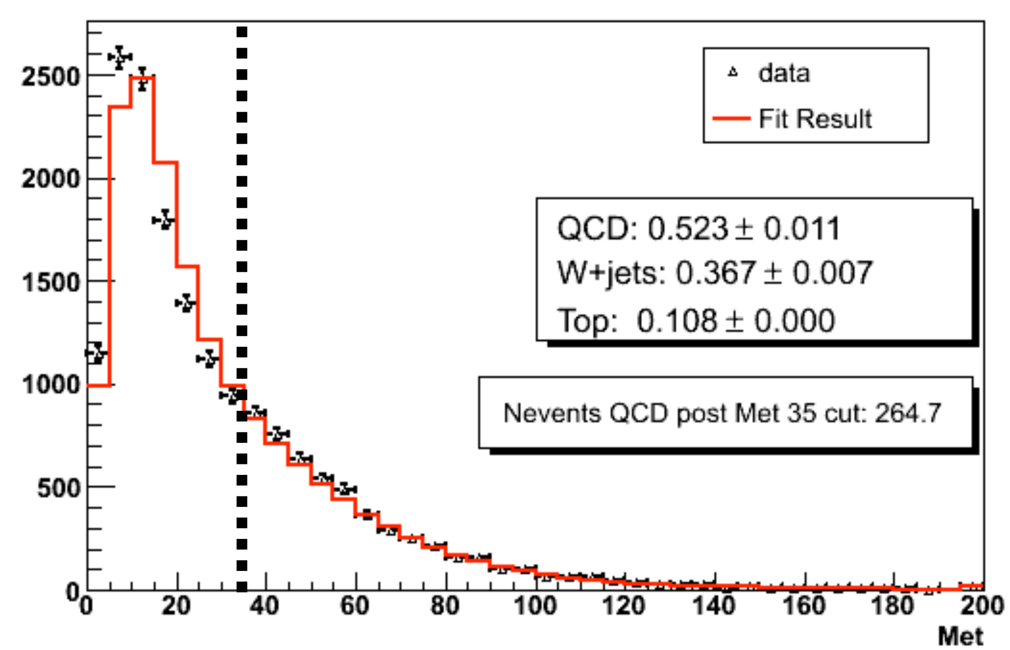
- Absolutely dominated by QCD and W+Jets
- For simplicity, W+Jets is used to model kinematics of all backgrounds except QCD
- QCD is modeled by data
    - All-jet model where one of the jets is kinematically selected to look like a lepton
    - Electron sample where at least two lepton identification cuts fail

$$t\bar{t}$$
$$W + Jets$$
$$QCD$$
$$Electroweak$$

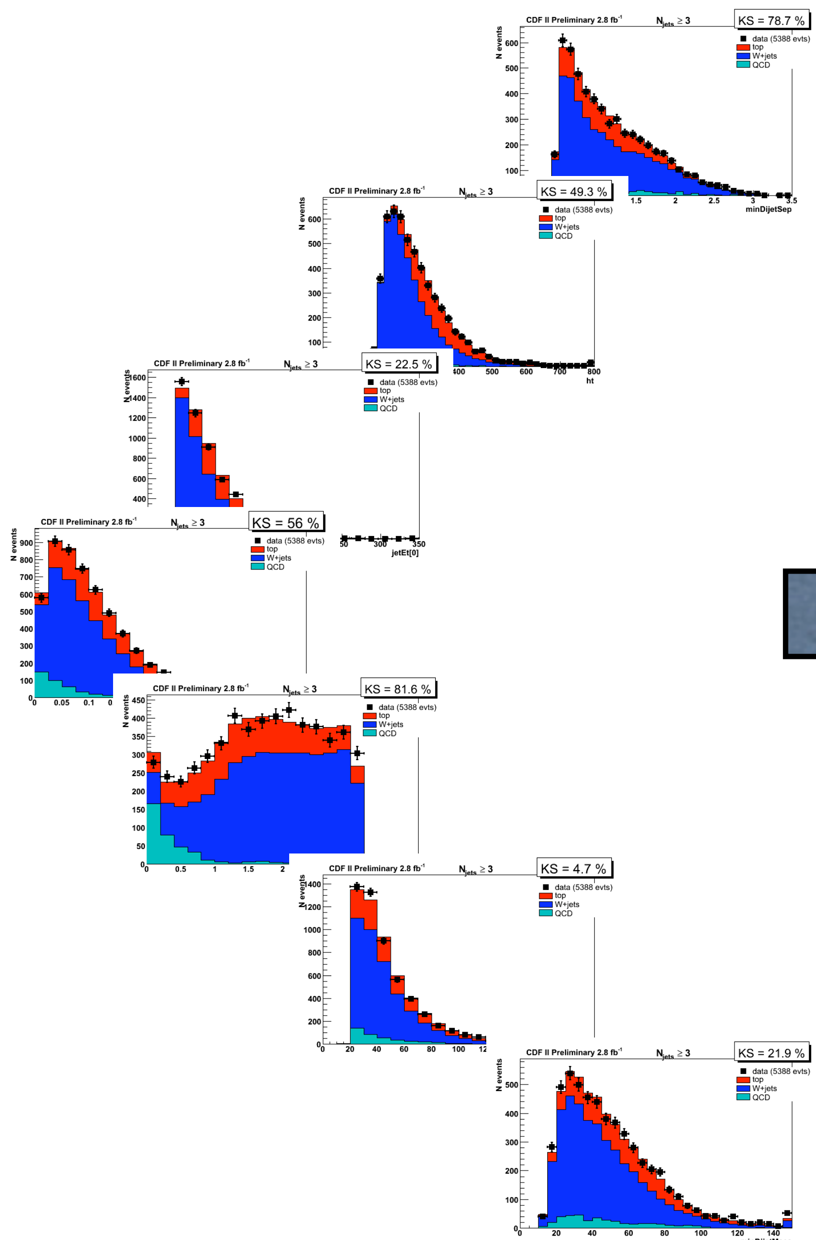
QCD

- As in the previous measurement, QCD is modeled by data
- Could let QCD float in the final fit at neural network output
- Results in a higher systematic
- Use low missing transverse energy region, which is dominated by QCD, to constrain amount of QCD in signal region



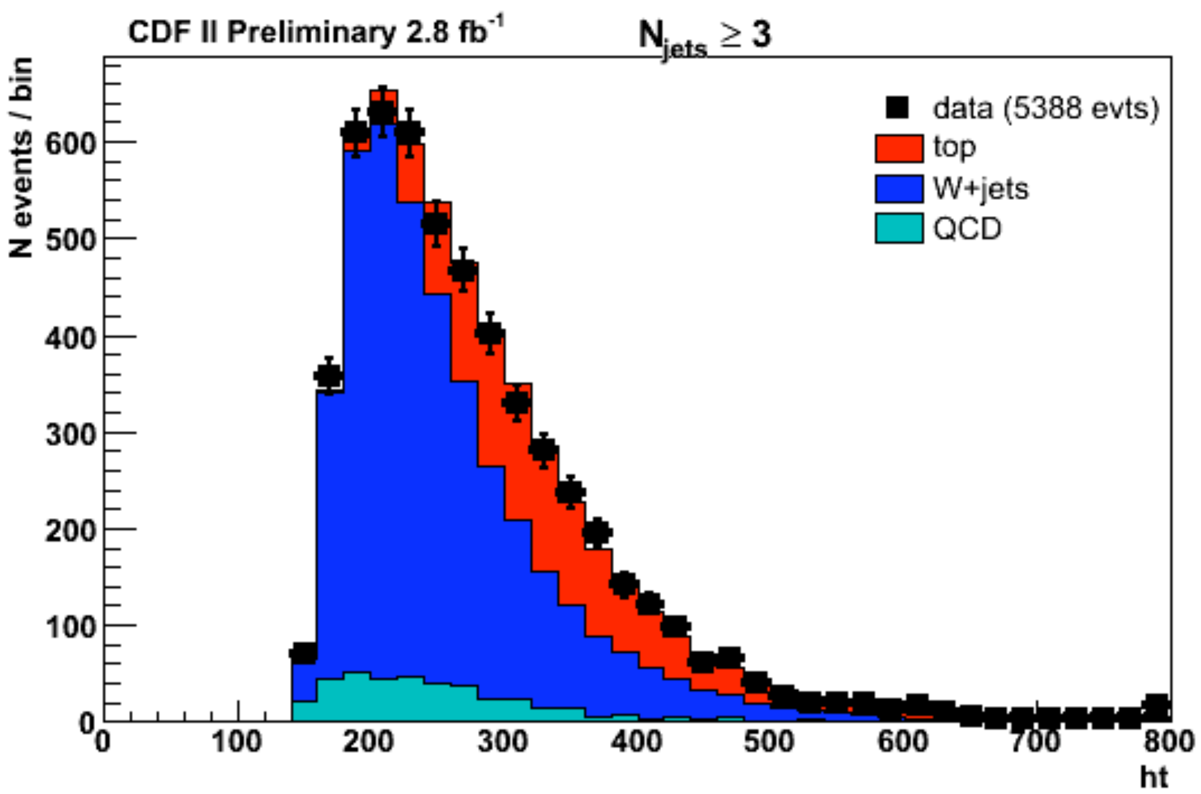


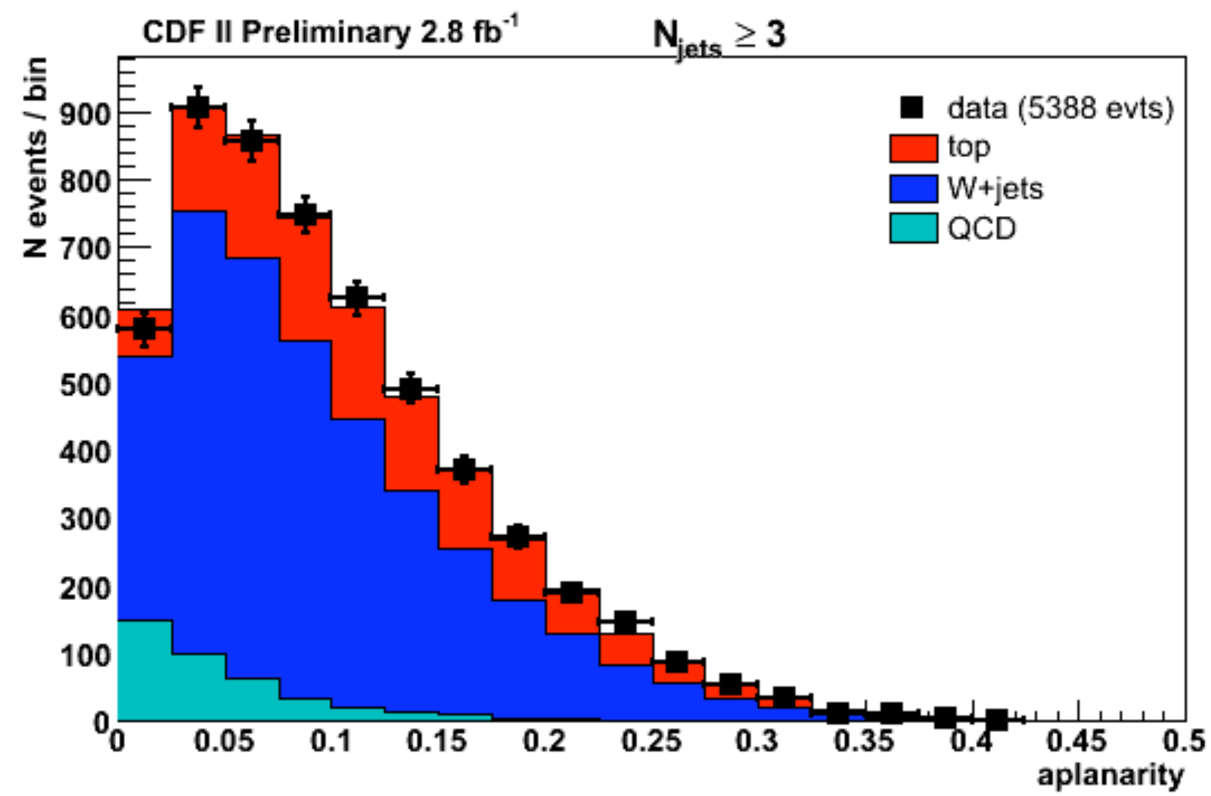
Topological Approach



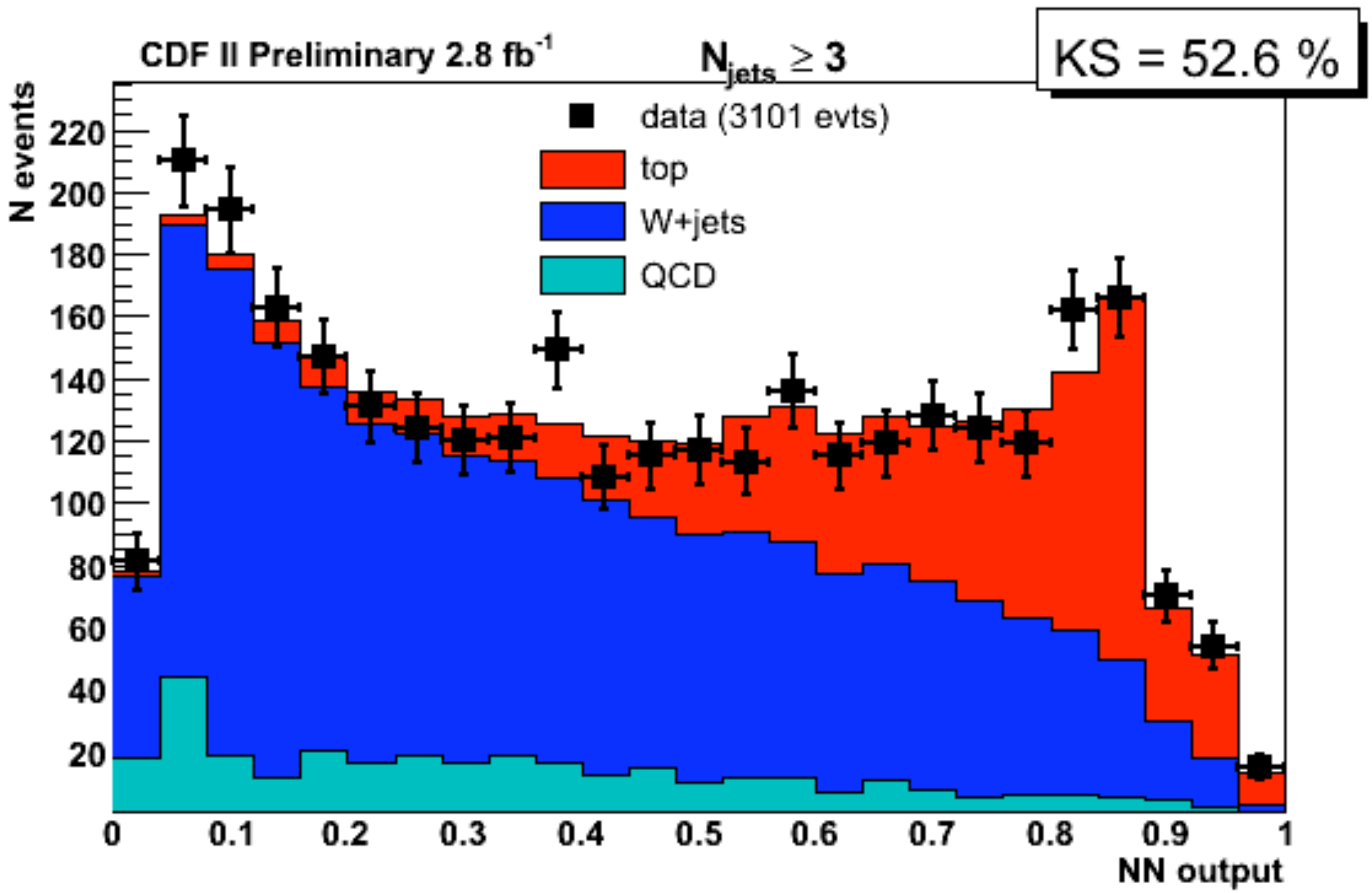
- Total Sum Transverse Energy
- Aplanarity
- Sum Pz / Sum Et of Jets
- Sum Jet Et Excluding Two Highest
- Minimum Di-Jet Mass
- Minimum Angle Between Two Jets
- Maximum Angle of a Jet

Kinematic Shapes In





Neural Net Output



Measurement in 2.8 fb^{-1}

$$\sigma_{\mathbf{t\bar{t}}} = \mathbf{7.1 \pm 0.4_{stat} \pm 0.4_{sys} \pm 0.4_{lum}\ \ pb}$$

$$\frac{\mathbf{\Delta}\sigma}{\sigma} = \mathbf{9.4\%}$$

Systematics

SYSTEMATIC	Δ	Δ%
JET ENERGY SCALE	0.2	3.1
Q^2	0.2	2.2
ISR/FSR	0.1	0.8
QCD	0.1	1.6
MONTE CARLO GENERATOR	0.2	2.9
PDF	0.0	0.5
EWK SHAPE MODELING	0.1	1.0
LEPTON ID	0.0	0.6
LUMINOSITY	0.4	5.8
TOTALS	0.4	7.8

Systematics

SYSTEMATIC	Δ	Δ%
JET ENERGY SCALE	0.2	3.1
Q^2	0.2	2.2
ISR/FSR	0.1	0.8
QCD	0.1	1.6
MONTE CARLO GENERATOR	0.2	2.9
PDF	0.0	0.5
EWK SHAPE MODELING	0.1	1.0
LEPTON ID	0.0	0.6
LUMINOSITY	0.4	5.8
TOTALS	0.4	7.8

Previous measurement tagging systematic ~ 5.5%

History of the Top Cross Section at CDF

Lepton + Jets B-Tag Measurement In 1.1 fb^{-1}

$$\sigma_{\mathbf{t\bar{t}}} = \mathbf{8.2 \pm 0.5_{stat} \pm 0.8_{syst} \pm 0.5_{lumi}\ \ pb}$$

Lepton + Jets Pretag Measurement In 1.1 fb^{-1}

$$\sigma_{\mathbf{t\bar{t}}} = \mathbf{6.0 \pm 0.6_{stat} \pm 0.9_{syst}\ \ pb}$$

Di-lepton Measurement In 1.2 fb^{-1}

$$\sigma_{\mathbf{t\bar{t}}} = \mathbf{6.2 \pm 1.1_{stat} \pm 0.7_{syst} \pm 0.4_{lumi}\ \ pb}$$

Summary

Lepton + Jets Tagging

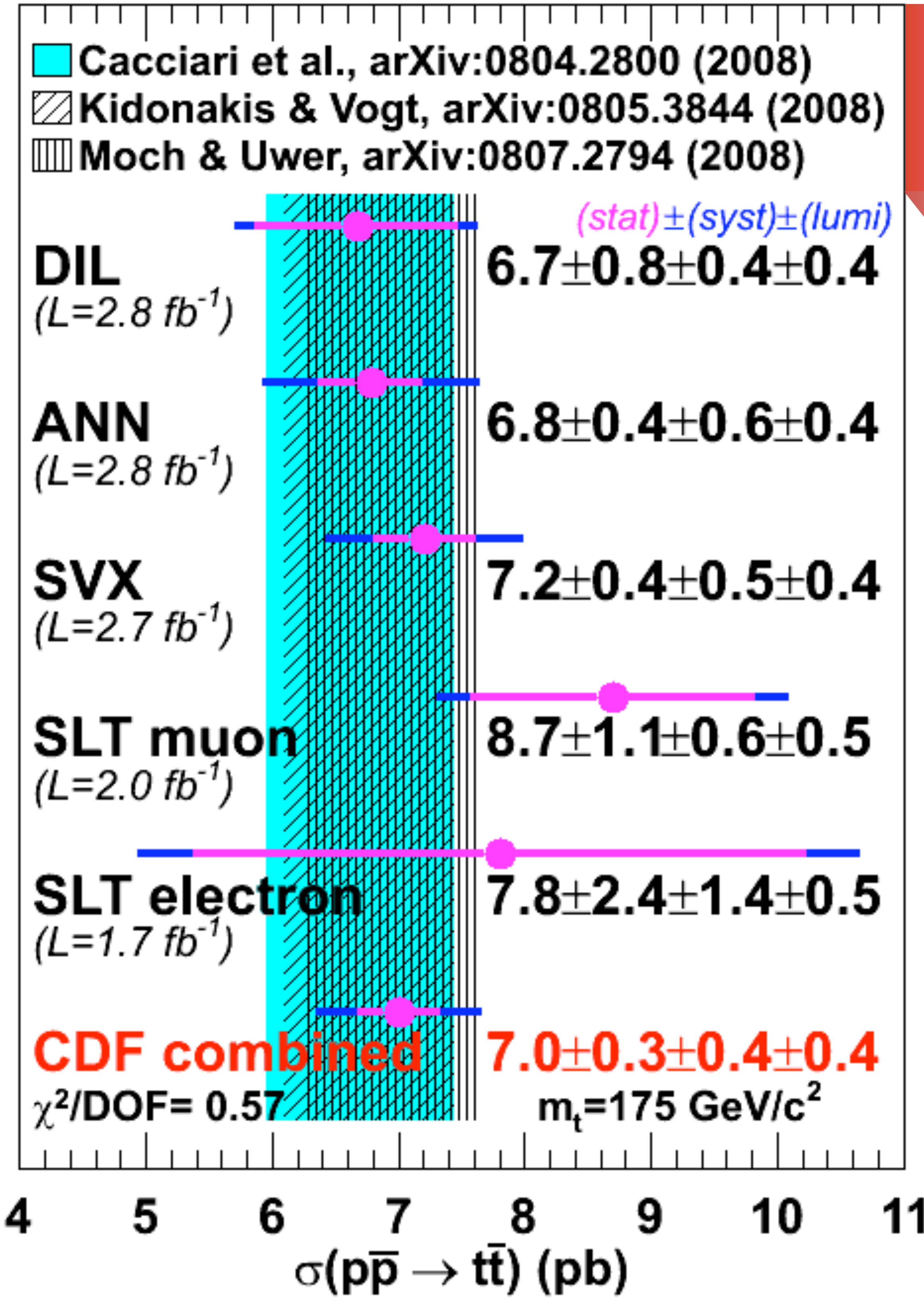
$$\sigma_{\mathrm{t\bar{t}}} = 7.1 \pm 0.4_{\mathrm{stat}} \pm 0.6_{\mathrm{sys}} \pm 0.4_{\mathrm{lum}} \ \ \mathrm{pb}$$

Lepton + Jets Neural Net

$$\sigma_{\mathrm{t\bar{t}}} = 7.1 \pm 0.4_{\mathrm{stat}} \pm 0.4_{\mathrm{sys}} \pm 0.4_{\mathrm{lum}} \ \ \mathrm{pb}$$

Dilepton

$$\sigma_{\mathrm{t\bar{t}}} = 6.7 \pm 0.8_{\mathrm{stat}} \pm 0.4_{\mathrm{sys}} \pm 0.4_{\mathrm{lum}} \ \ \mathrm{pb}$$

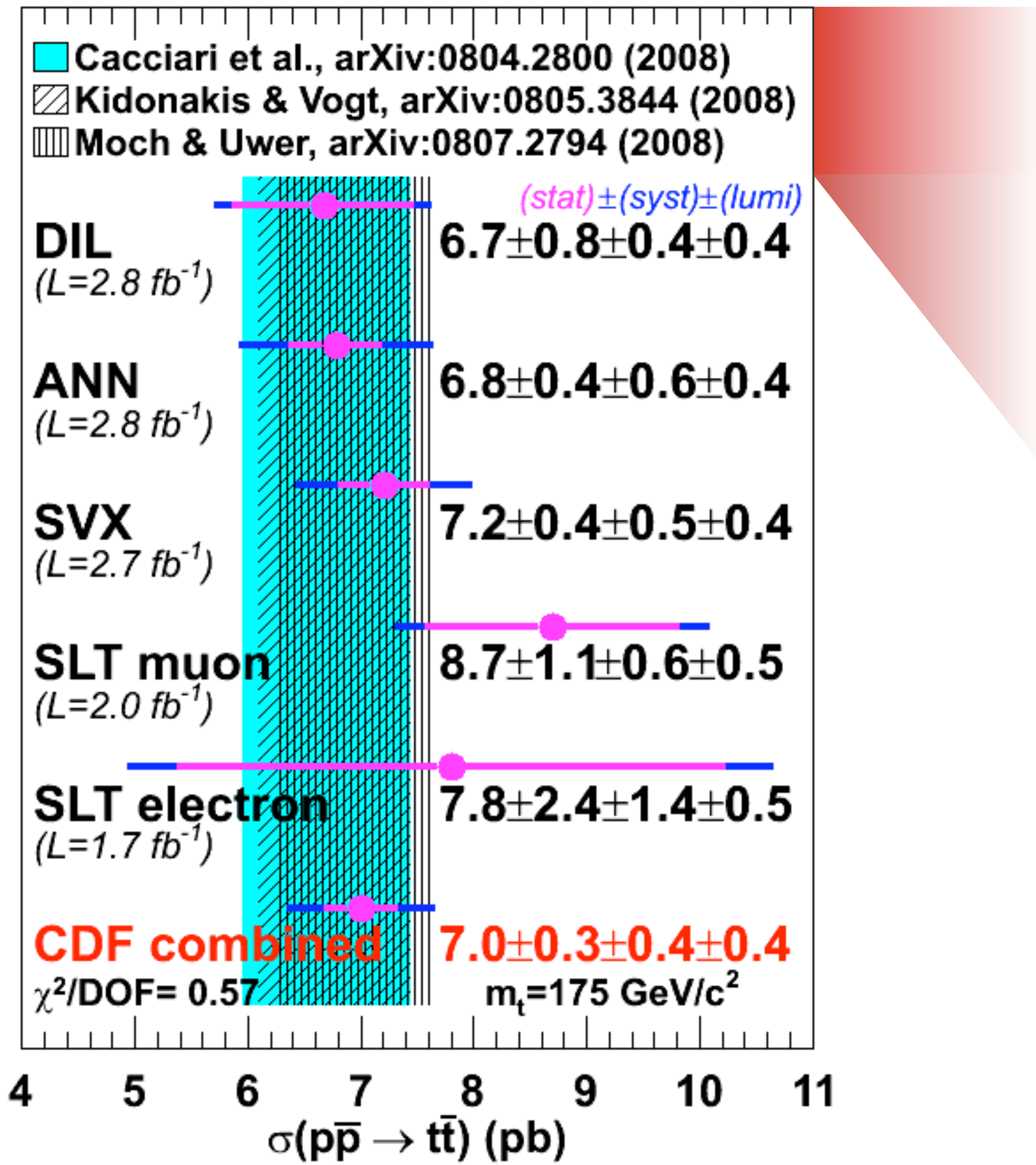


$$\sigma = 6.73^{+0.72}_{-0.63} \ \ pb$$

$$\sigma = 6.90^{+0.46}_{-0.64} \ \ pb$$

$$\sigma = 6.73^{+0.71}_{-0.79} \ \ pb$$

$$\frac{\Delta\sigma}{\sigma} = 9\%$$



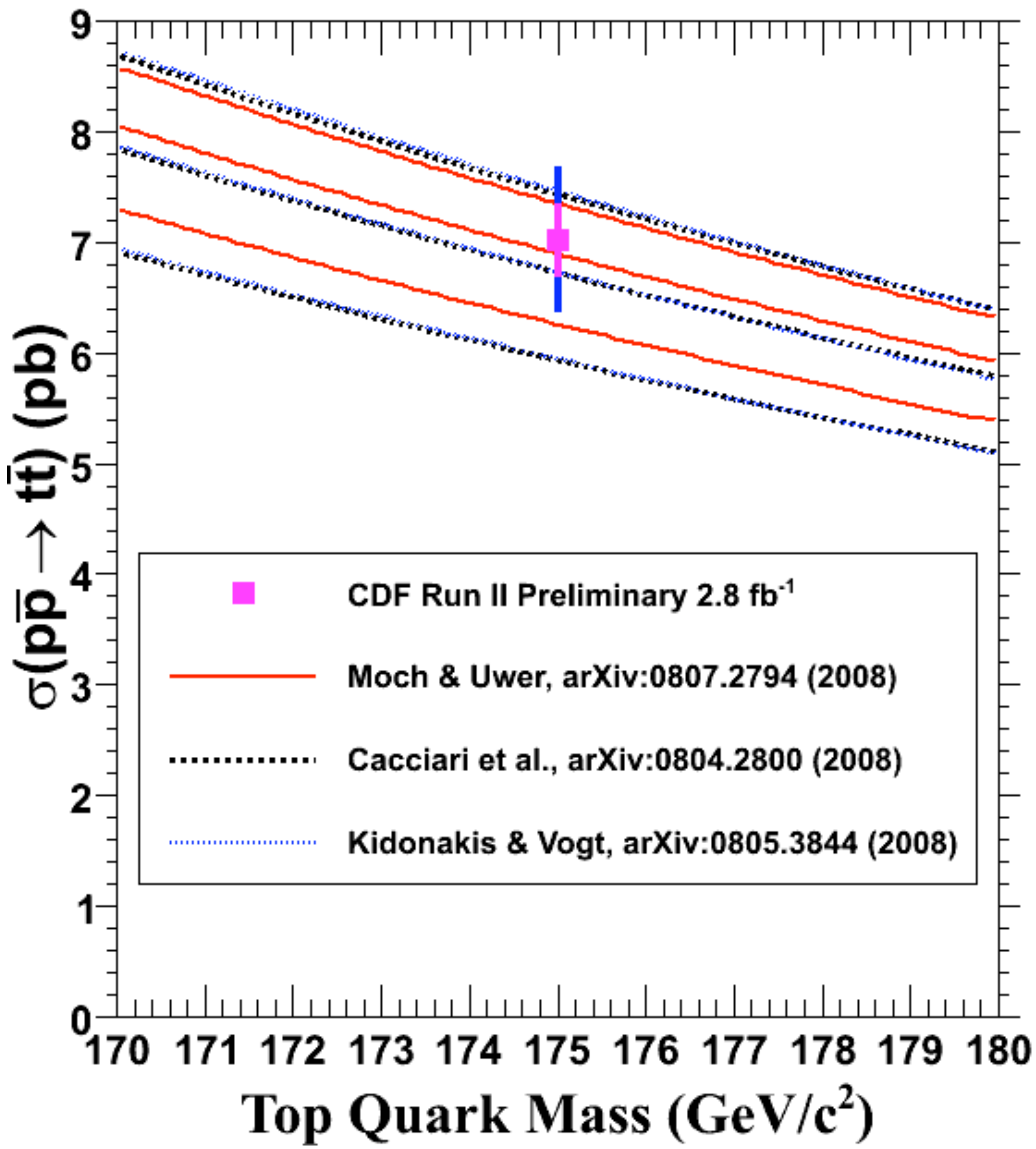
$$\sigma = 6.73^{+0.72}_{-0.63} \; pb$$

$$\sigma = 6.90^{+0.46}_{-0.64} \; pb$$

$$\sigma = 6.73^{+0.71}_{-0.79} \; pb$$

$$\frac{\mathbf{\Delta}\sigma}{\sigma} = \mathbf{8} - \mathbf{10\%}$$

$$\frac{\mathbf{\Delta}\sigma}{\sigma} = \mathbf{9\%}$$

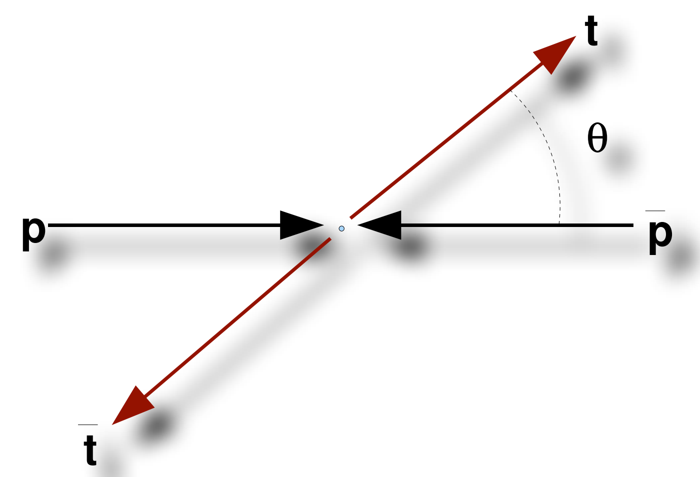


CDF Run II Preliminary 2.8 fb-1
Moch & Uwer, arXiv:0807.2794 (2008)
Cacciari et al., arXiv:0804.2800 (2008)
Kidonakis & Vogt, arXiv:0805.3844 (2008)
Top Quark Mass (GeV/c2)

Ok, so we clearly understand how much

But can we look for cracks from another angle?

The Forward Backward Asymmetry



$$A_{fb} = \frac{N_{Cos\Theta>0} - N_{Cos\Theta<0}}{N_{Cos\Theta>0} + N_{Cos\Theta<0}}$$

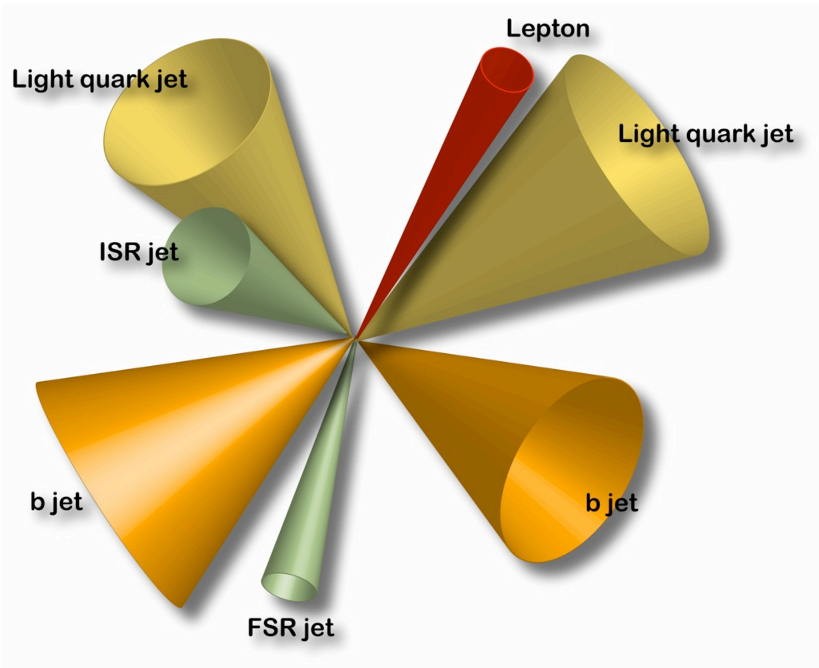
Why Measure It

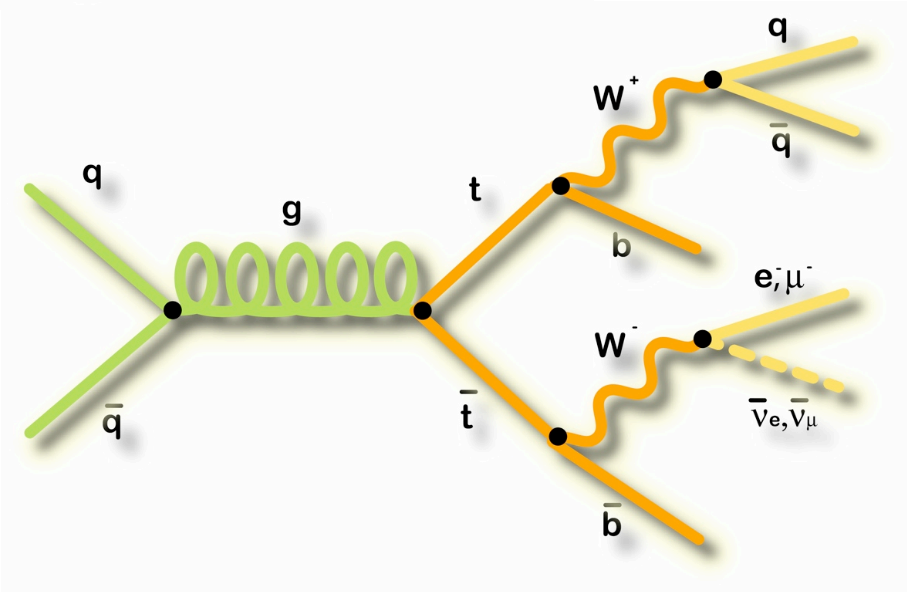
- QCD predicts an observable asymmetry ~ 4-6% due to diagram interference between LO and NLO
- Parity violating new physics can appear as a large asymmetry
- Because the LHC is dominated by gg production this measurement is far more difficult

The Tevatron is special for this measurement

Reconstructing the Event

- We have 4 jets, a lepton, and "Missing" energy
- It is almost impossible to discern the "type" of quark which produced a given jet
- How do we find the top quark production angle from this mess?
- Use the topology to build an algorithm!





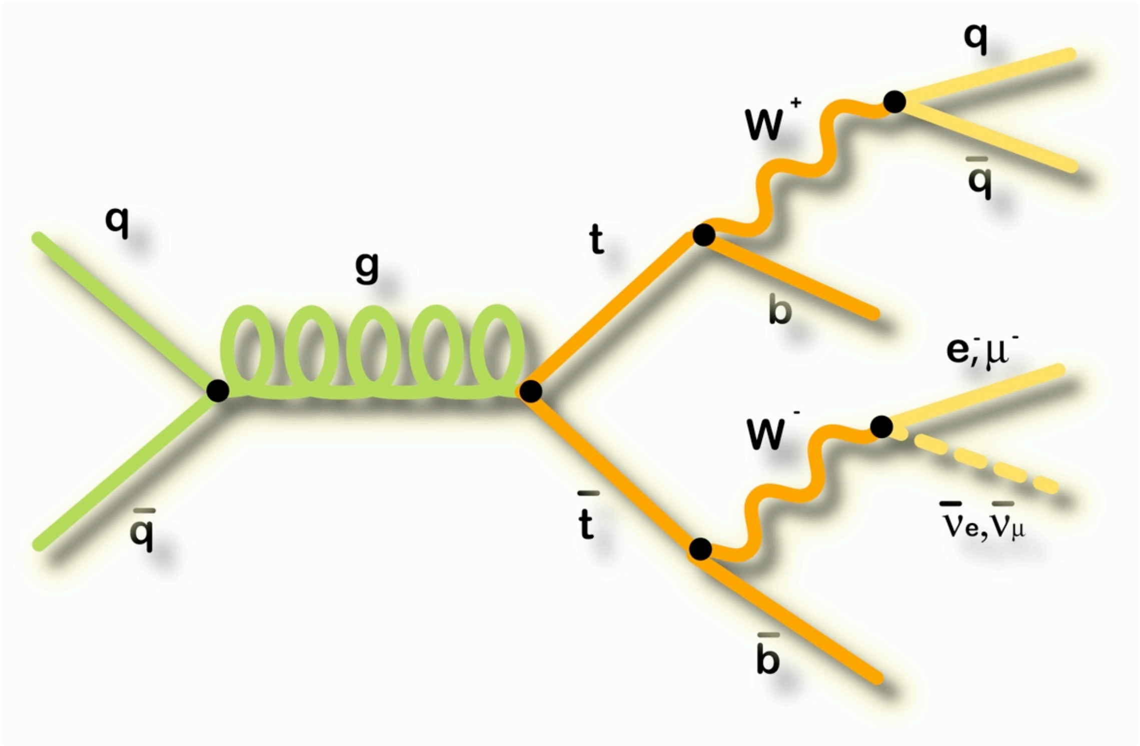
Reconstructing the Event

- 4 jets must be matched to 4 partons
- 24 different combinations to choose from
- Jet and unclustered energies can vary within error
- Known Top Mass can be used as a constraint
- Choose combination with lowest χ^2

$$\chi^2 = \sum_{i=l,jets} \frac{(p_t^{i,meas} - p_t^{i,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,meas} - p_j^{UE,fit})^2}{\sigma_j^2}$$

$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{lv} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_{fit})^2}{\Gamma_t^2} + \frac{(M_{blv} - M_{fit})^2}{\Gamma_t^2}$$

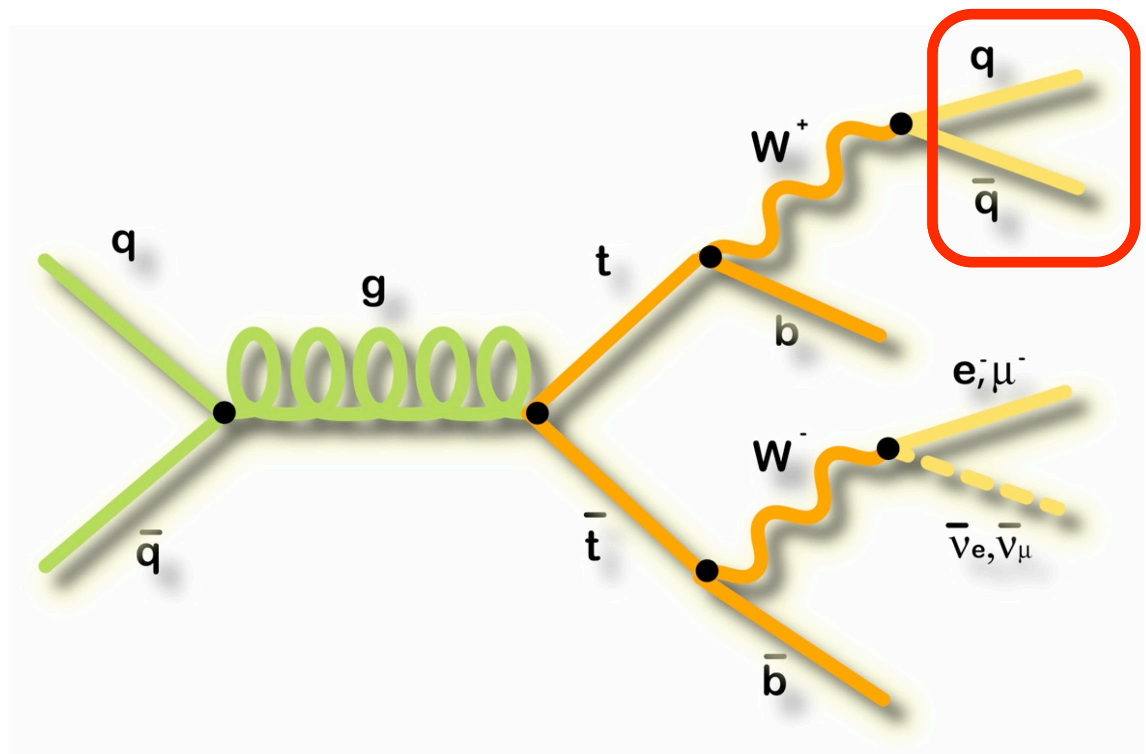
Reconstructing the Event



$$\chi^2 = \sum_{i=l,jets} \frac{(p_t^{i,meas} - p_t^{i,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,meas} - p_j^{UE,fit})^2}{\sigma_j^2}$$

$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_{fit})^2}{\Gamma_t^2} + \frac{(M_{bl\nu} - M_{fit})^2}{\Gamma_t^2}$$

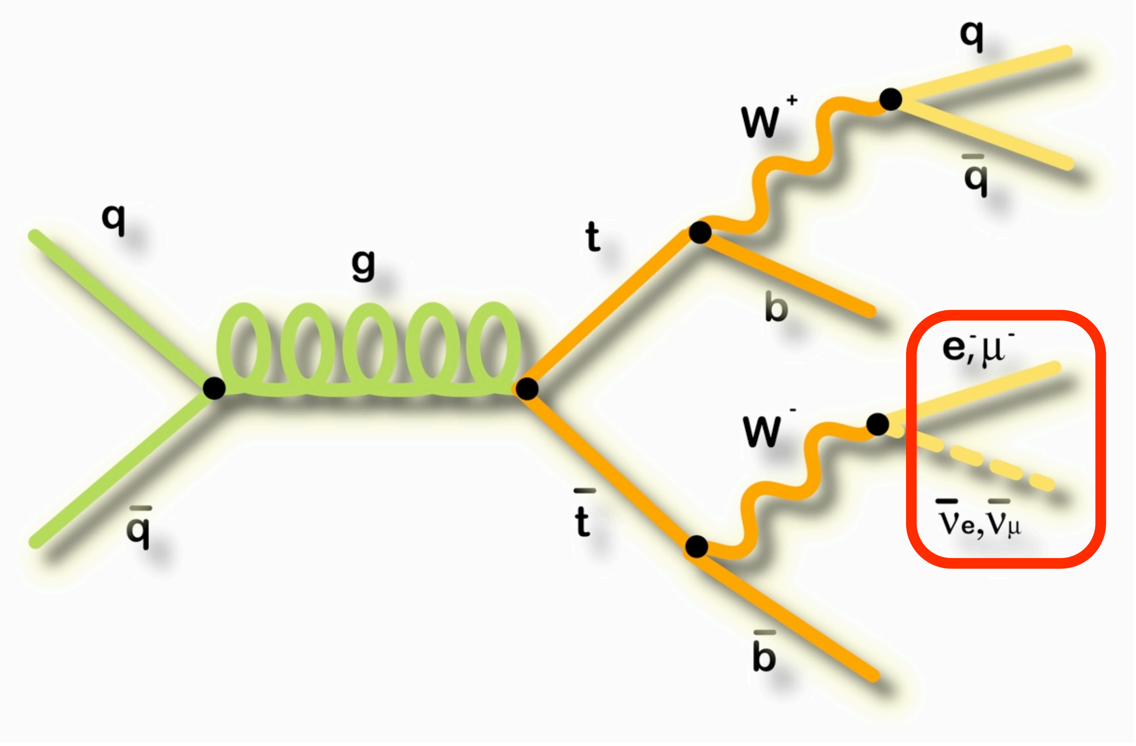
Reconstructing the Event



$$\chi^2 = \sum_{i=l,jets} \frac{(p_t^{i,meas} - p_t^{i,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,meas} - p_j^{UE,fit})^2}{\sigma_j^2}$$

$$+ \boxed{\frac{(M_{jj} - M_W)^2}{\Gamma_W^2}} + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_{fit})^2}{\Gamma_t^2} + \frac{(M_{bl\nu} - M_{fit})^2}{\Gamma_t^2}$$

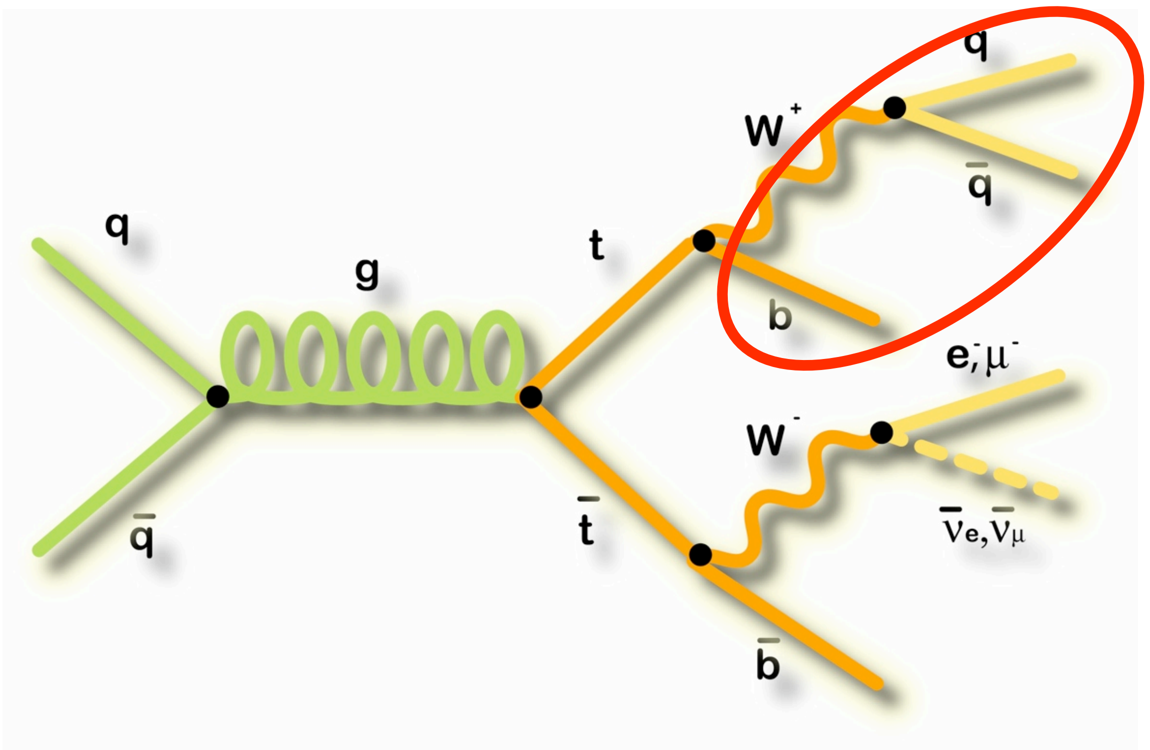
Reconstructing the Event



$$\chi^2 = \sum_{i=l,jets} \frac{(p_t^{i,meas} - p_t^{i,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,meas} - p_j^{UE,fit})^2}{\sigma_j^2}$$

$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \boxed{\frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2}} + \frac{(M_{bjj} - M_{fit})^2}{\Gamma_t^2} + \frac{(M_{bl\nu} - M_{fit})^2}{\Gamma_t^2}$$

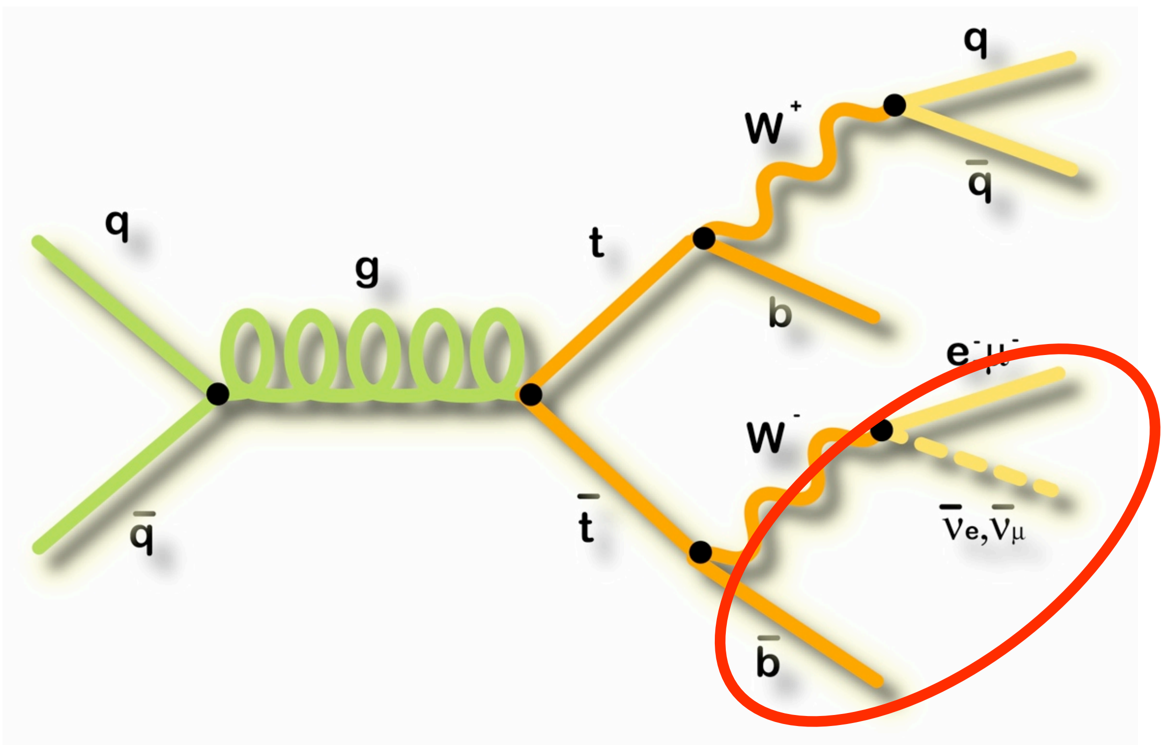
Reconstructing the Event



$$\chi^2 = \sum_{i=l,jets} \frac{(p_t^{i,meas} - p_t^{i,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,meas} - p_j^{UE,fit})^2}{\sigma_j^2}$$

$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \boxed{\frac{(M_{bjj} - M_{fit})^2}{\Gamma_t^2}} + \frac{(M_{bl\nu} - M_{fit})^2}{\Gamma_t^2}$$

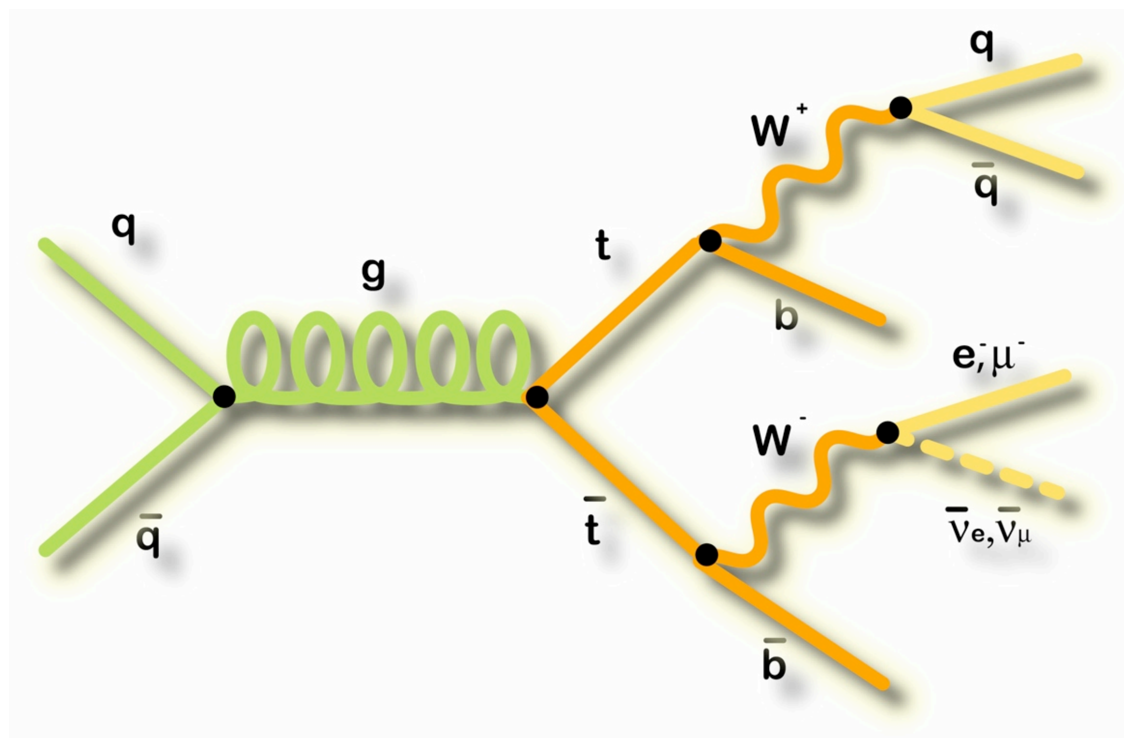
Reconstructing the Event



$$\chi^2 = \sum_{i=l,jets} \frac{(p_t^{i,meas} - p_t^{i,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,meas} - p_j^{UE,fit})^2}{\sigma_j^2}$$

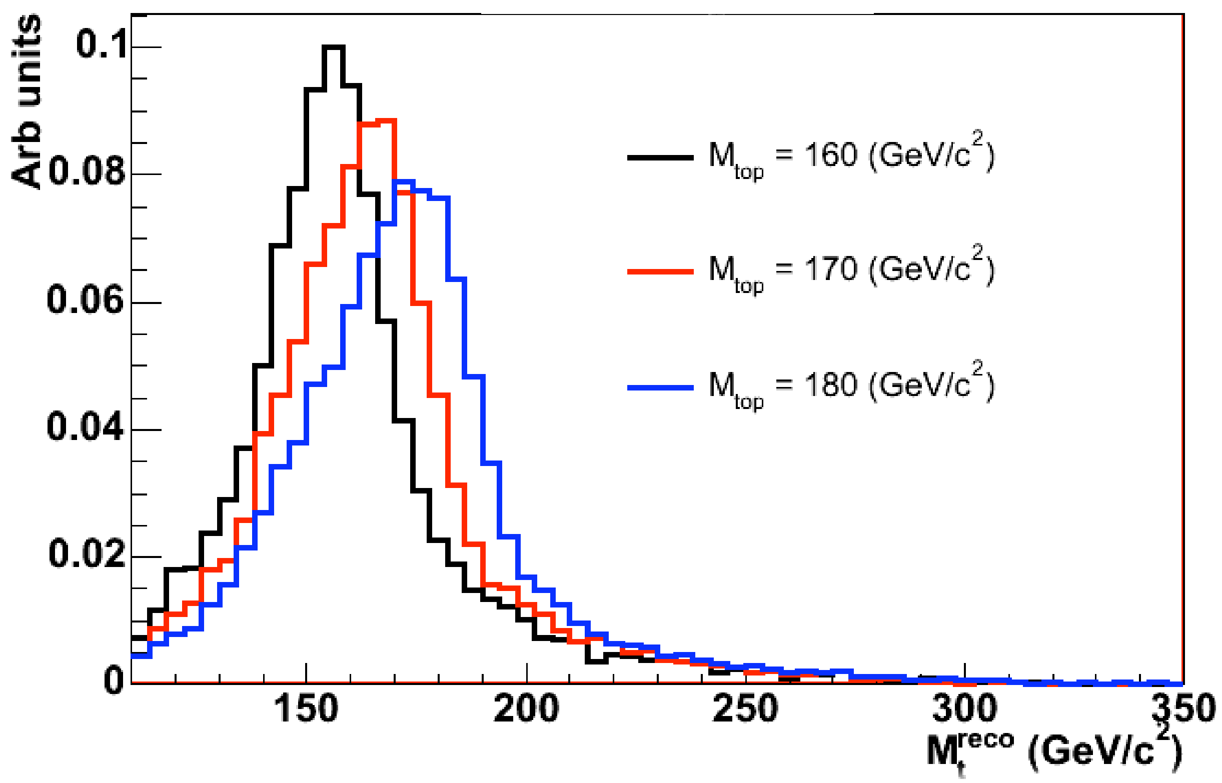
$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_{fit})^2}{\Gamma_t^2} + \boxed{\frac{(M_{bl\nu} - M_{fit})^2}{\Gamma_t^2}}$$

Reconstructing the Event



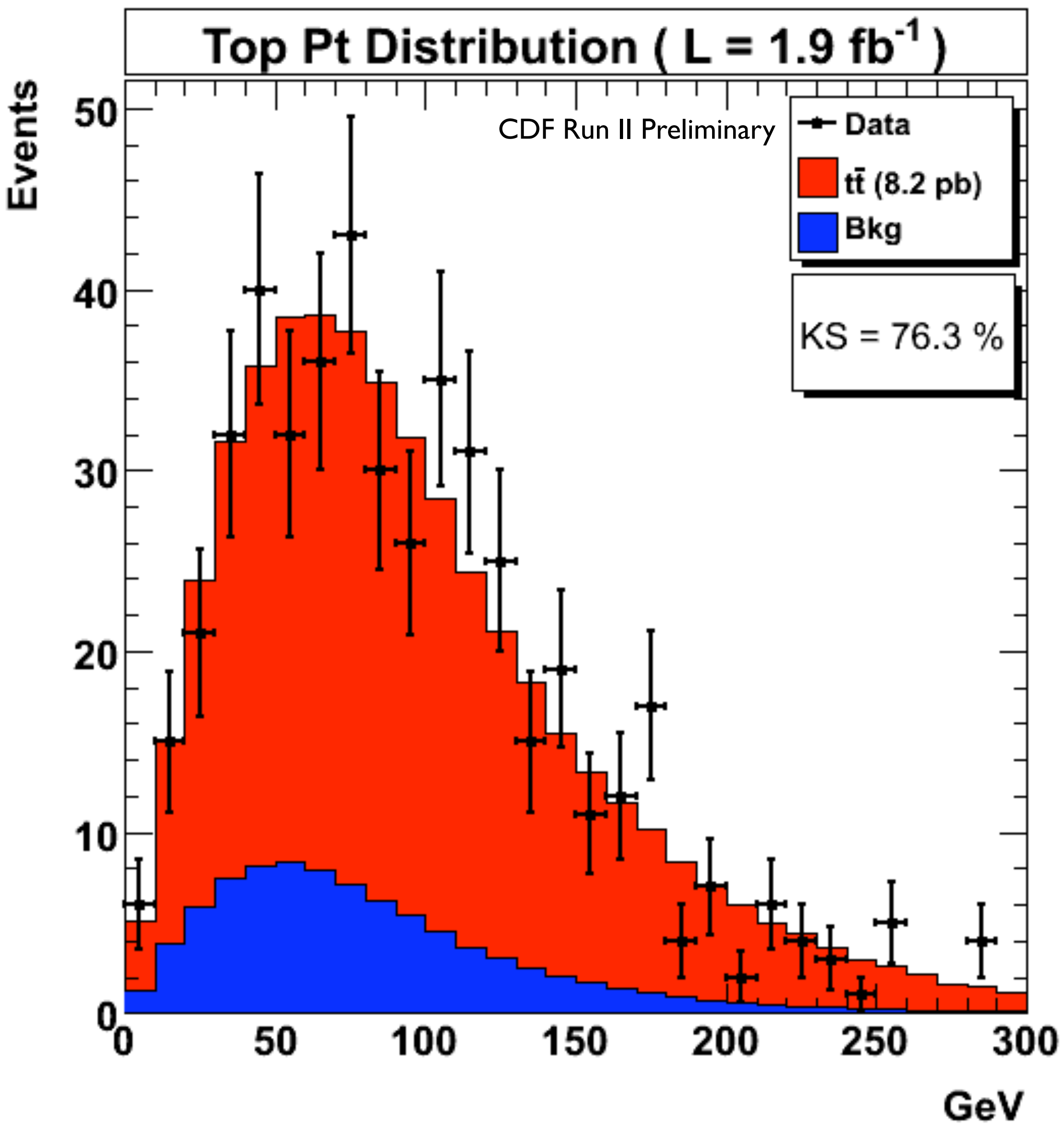
The algorithm reconstructs the entire event: All particle energies and angles are available after reconstruction

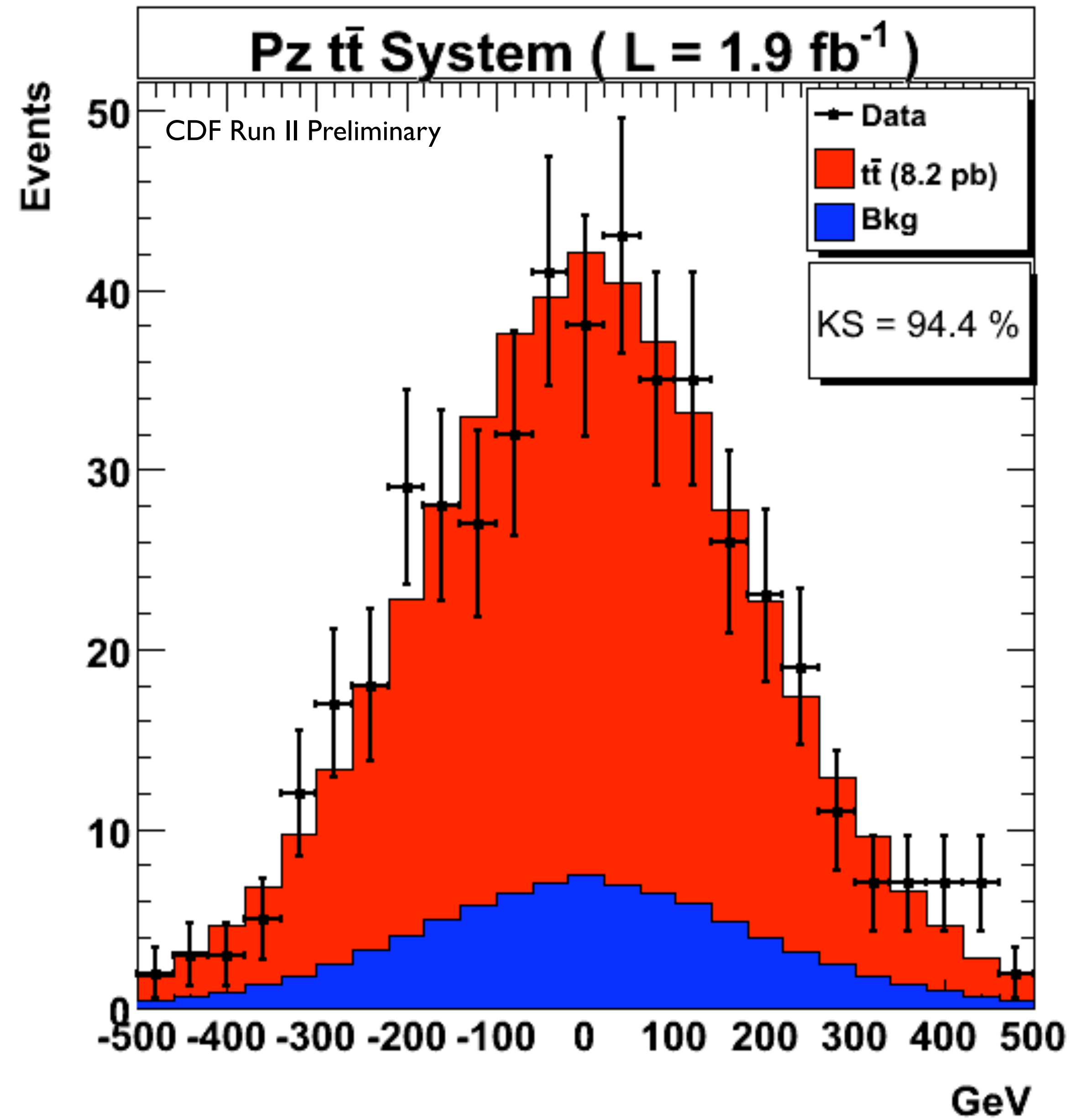
Reconstructed Top Mass



The algorithm is currently used in one of CDF's flagship Top Mass measurements and in over a dozen other analyses

Reconstructing The Event





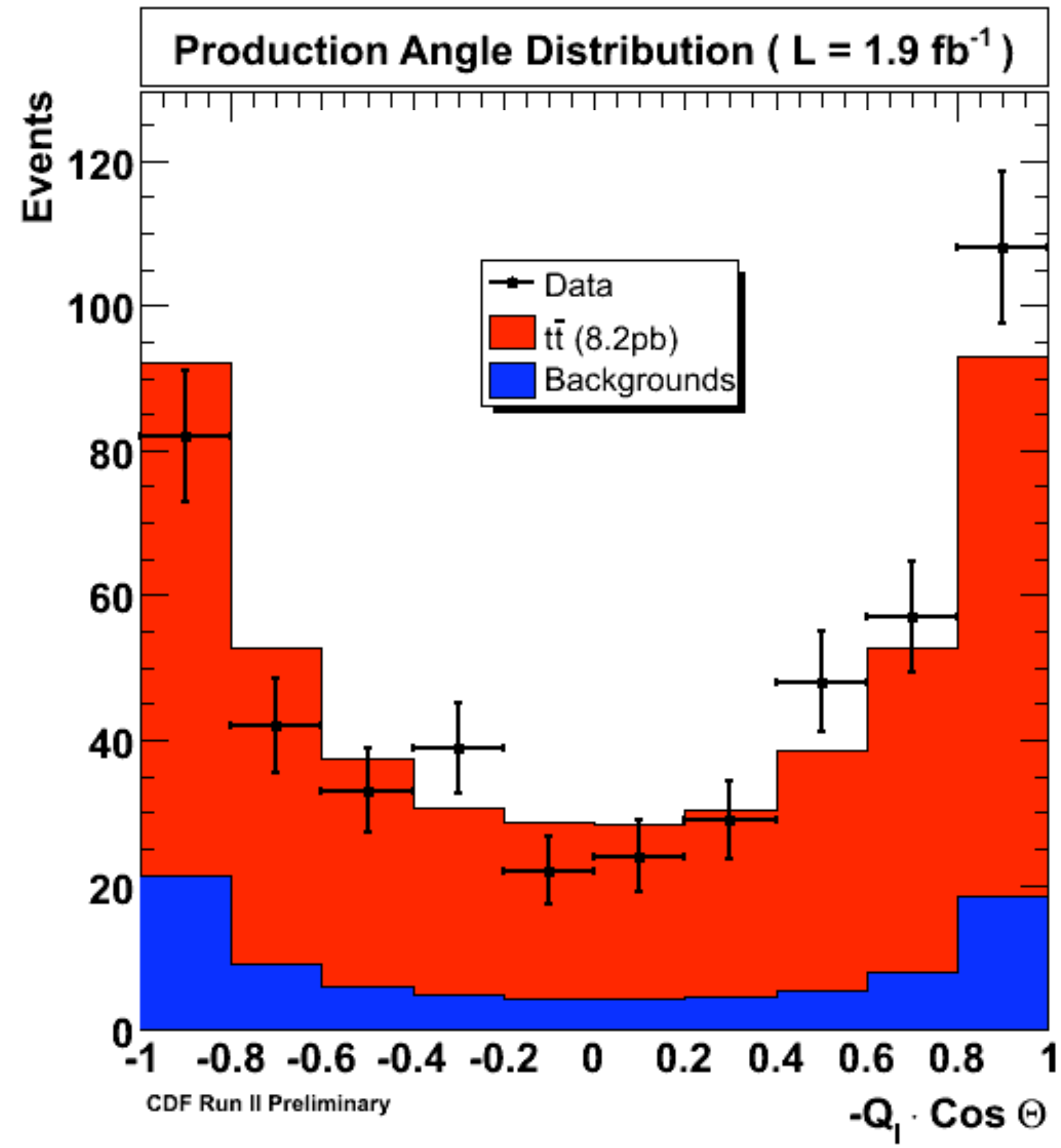
Reconstructing the Angle

Uncorrected

$$\mathbf{A_{fb} = 0.10 \pm 0.05_{stat}}$$

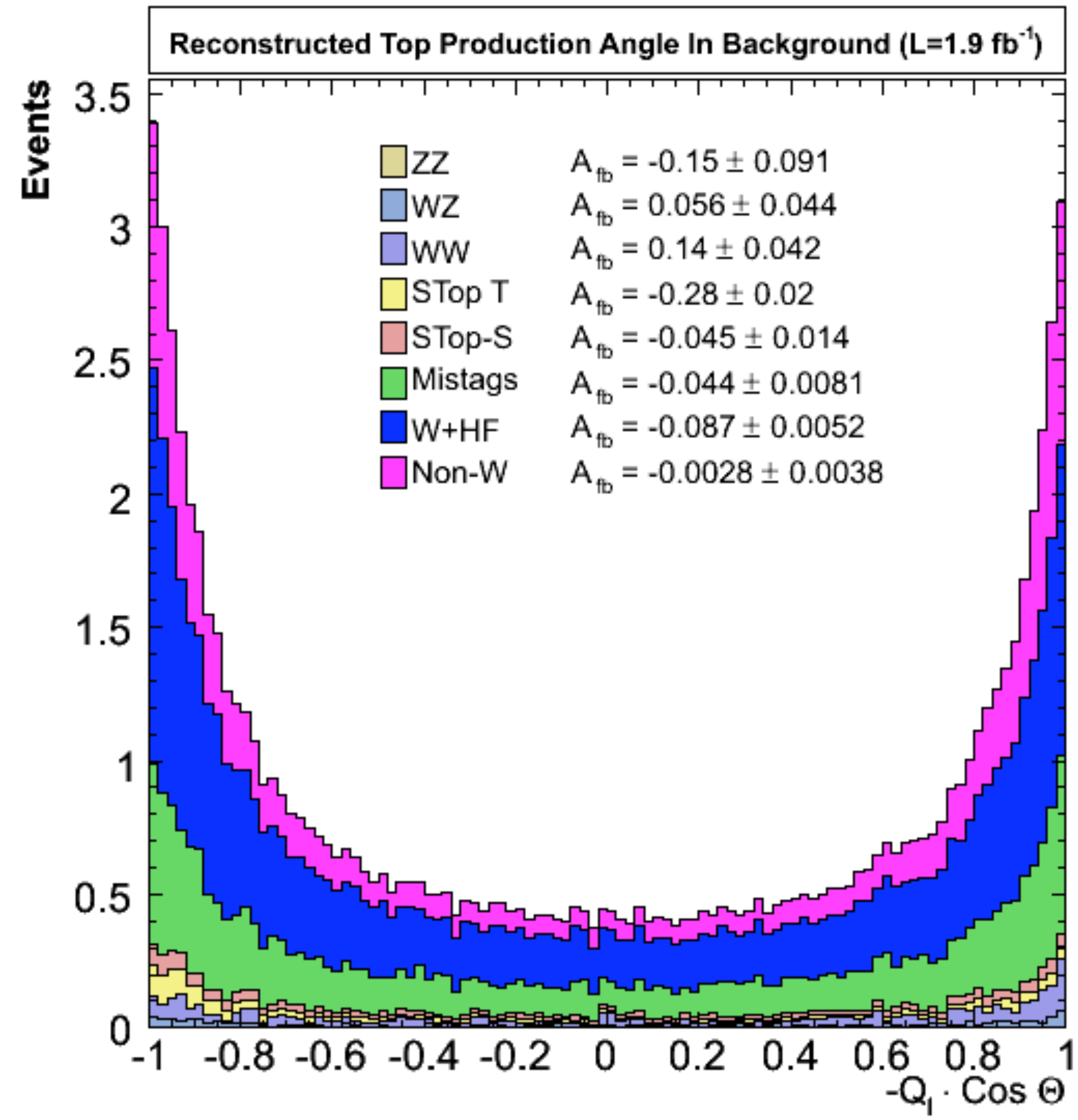
- The shape in data can be biased and/or diluted by backgrounds, acceptance effects, and poor event reconstruction

- Each effect has to be effectively corrected for to get back to a prediction comparable to theory



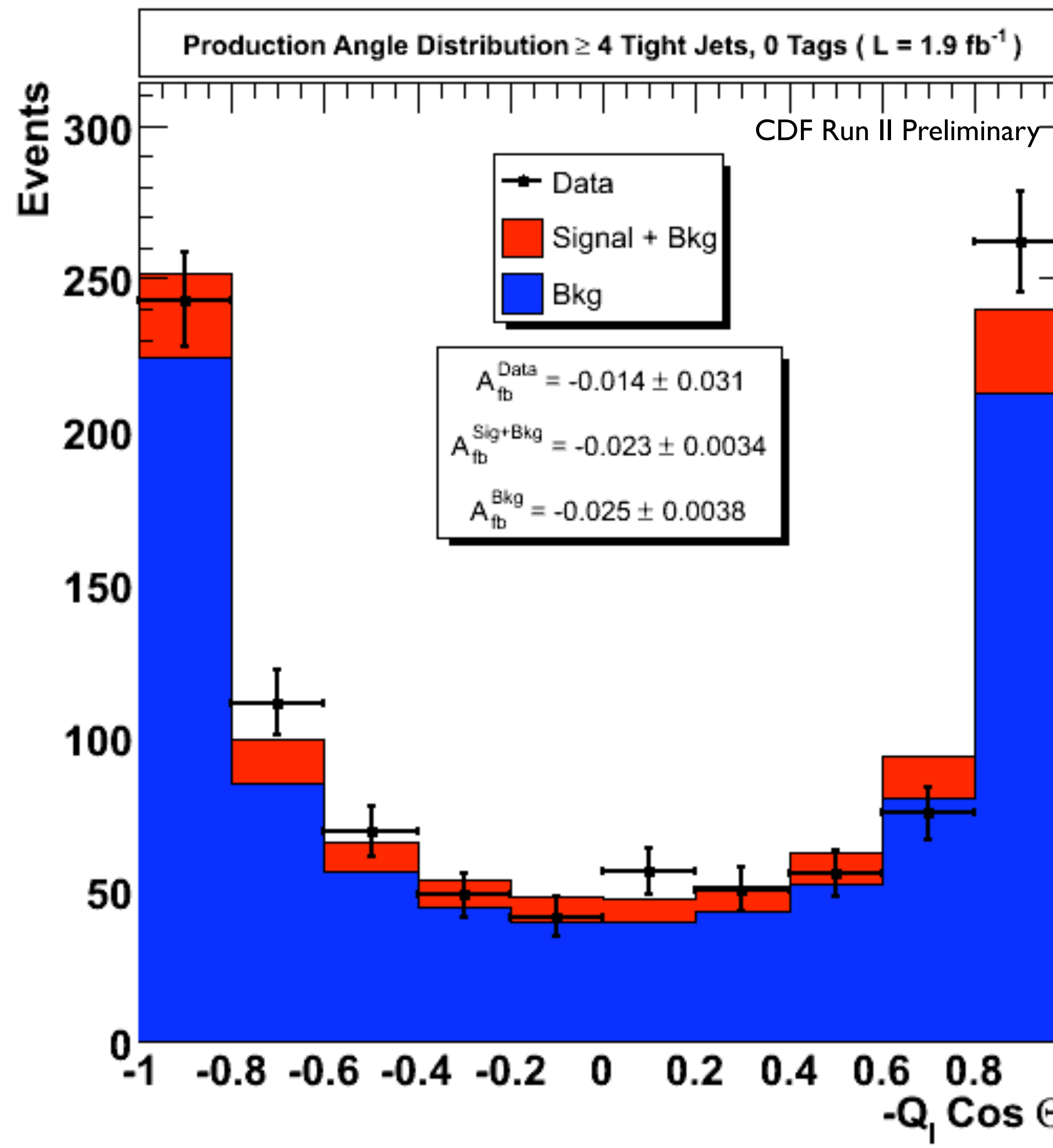
Background Correction

- Backgrounds dilute the signal and, if they have any asymmetric components, bias it
- To properly correct for this effect we need to know the prod angle shape in background
- The background Cos Θ distribution is formed by putting the background models through the entire selection and reconstruction machinery



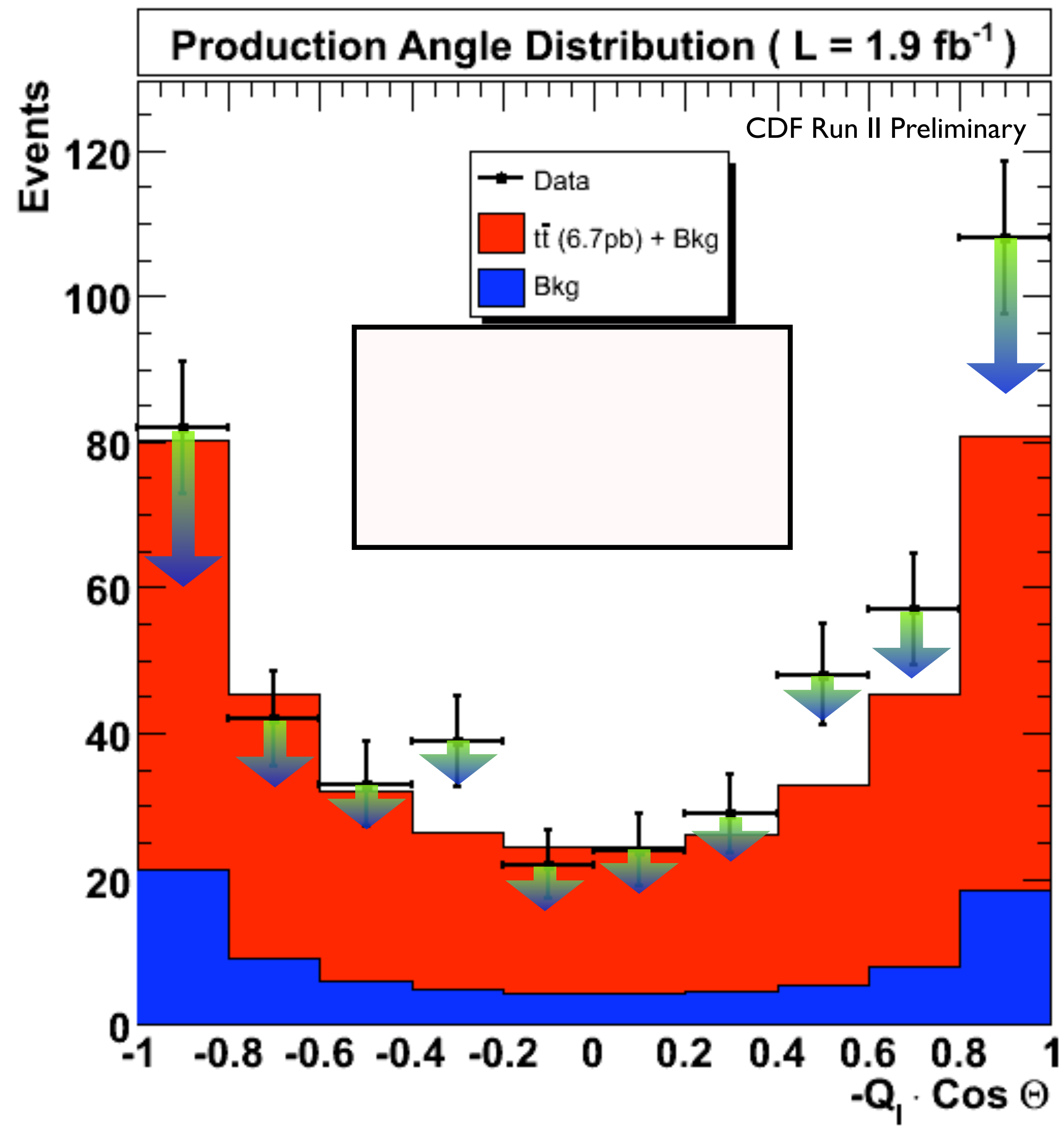
Background Correction

- How do we know the background shape is correct?
- Test in a background dominated side-band region (Anti-Tag Sample)
- Background prediction is consistent in this distribution



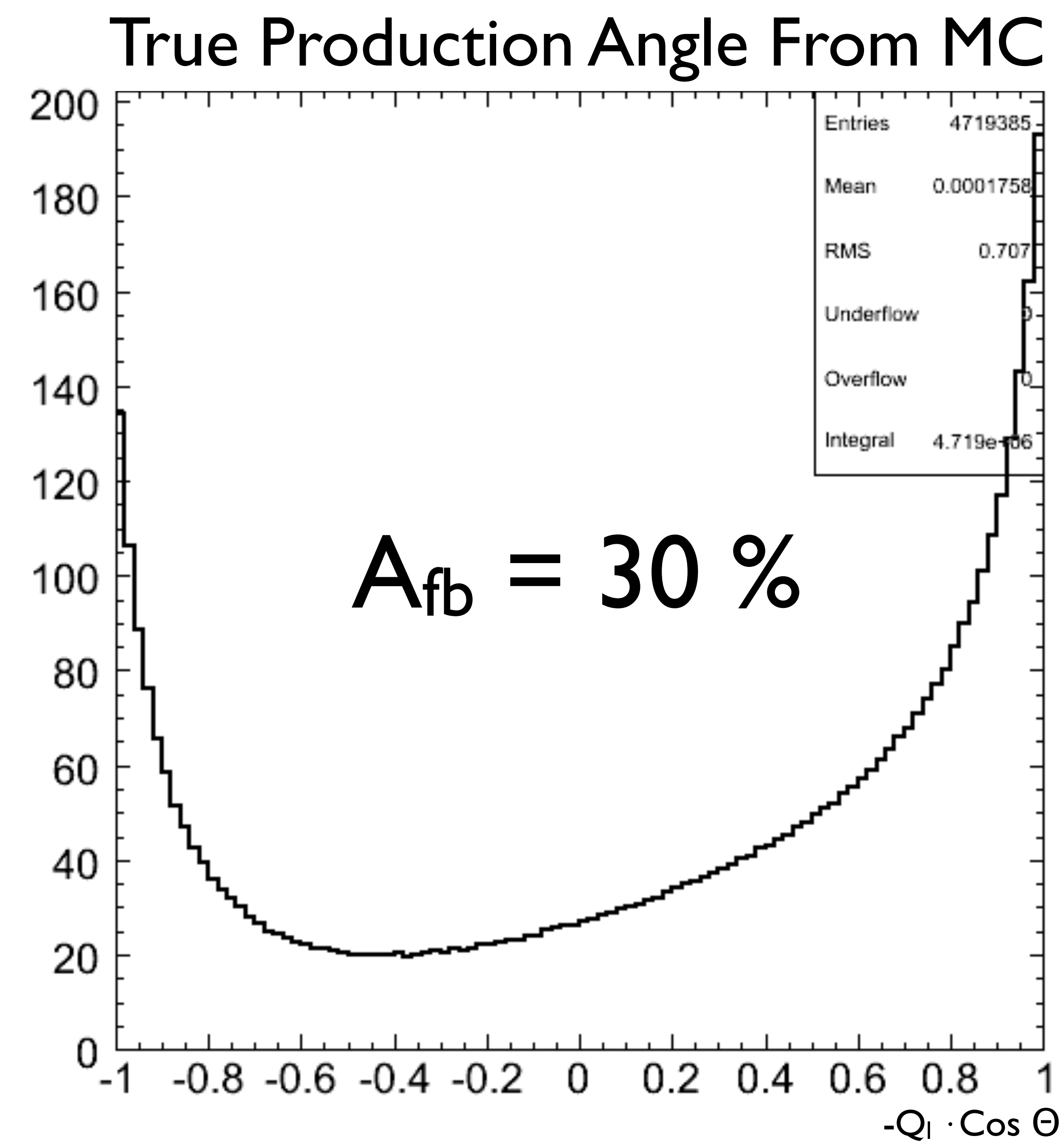
Background Correction

- We correct for backgrounds by subtracting the predicted background shape, normalized by method II, from the data
- The resulting distribution is the predicted production angle shape for ttbar after selection and reconstruction



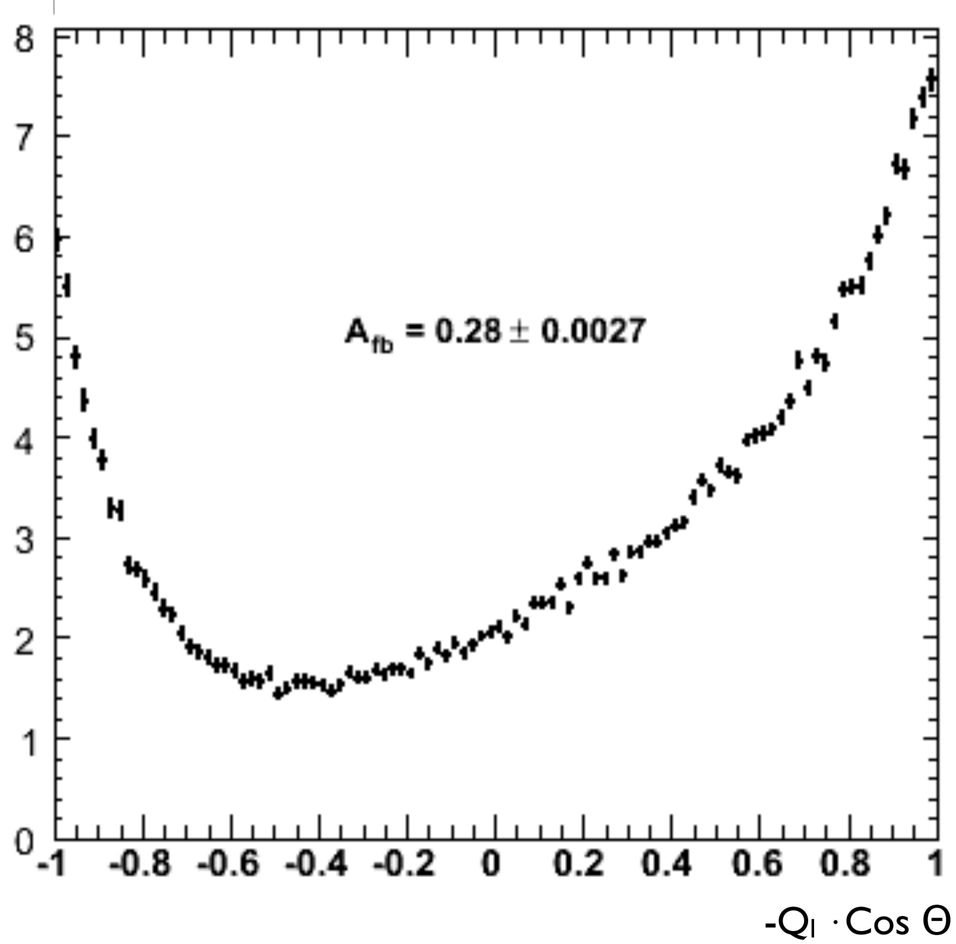
Selection and Reconstruction Effects

- Example production angle distribution with A_{fb} = 30 %
- So what happens as these events are placed through selection and reconstruction?

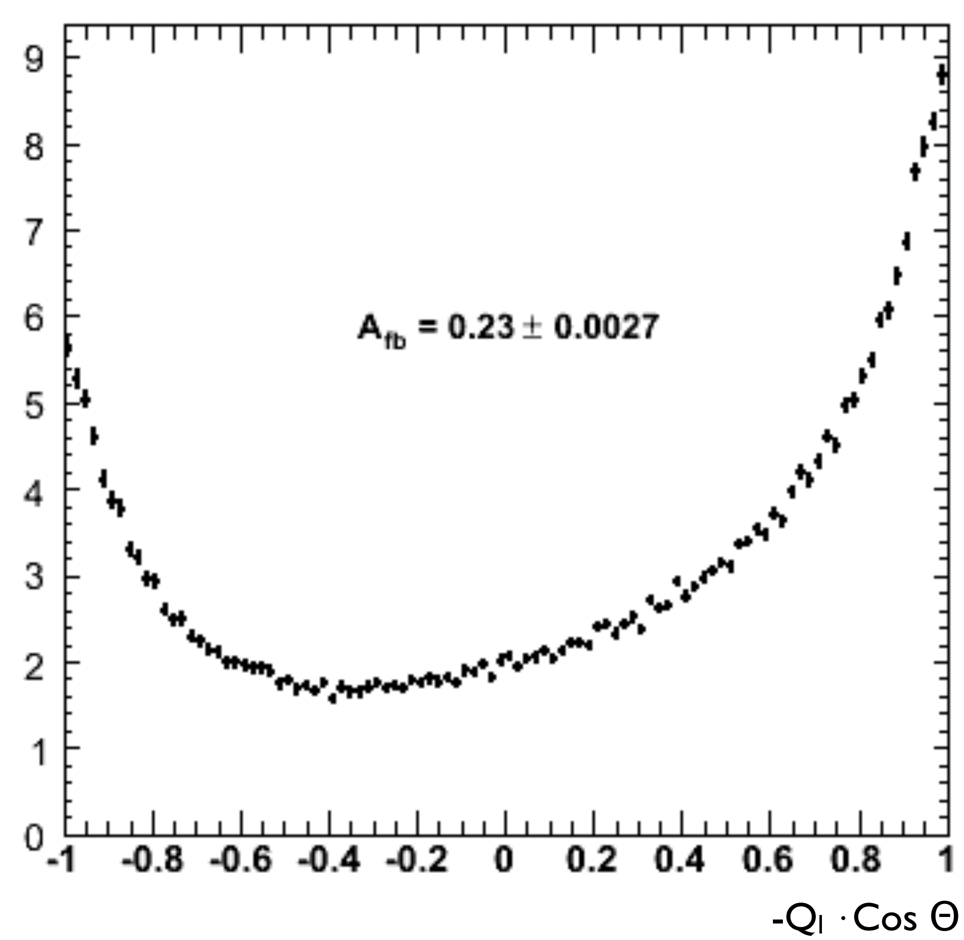


Selection and Reconstruction Effects

After Selection

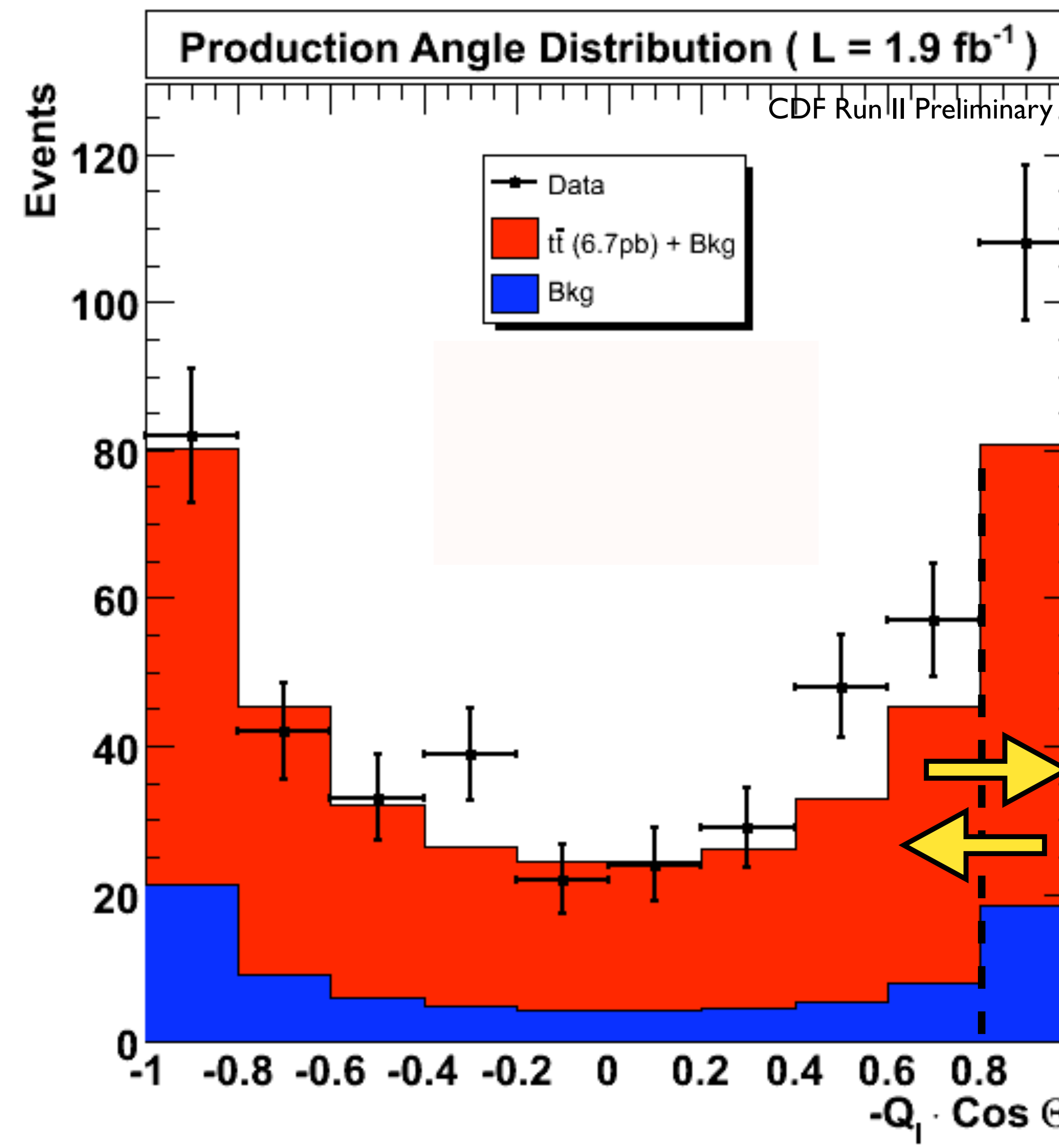


After Reconstruction



Reconstruction Corrections

- The effect of imperfect reconstruction is a smearing of events between bins and therefore a dilution of the front-back asymmetry
- We model this effect in ttbar Monte Carlo in order to correct the data

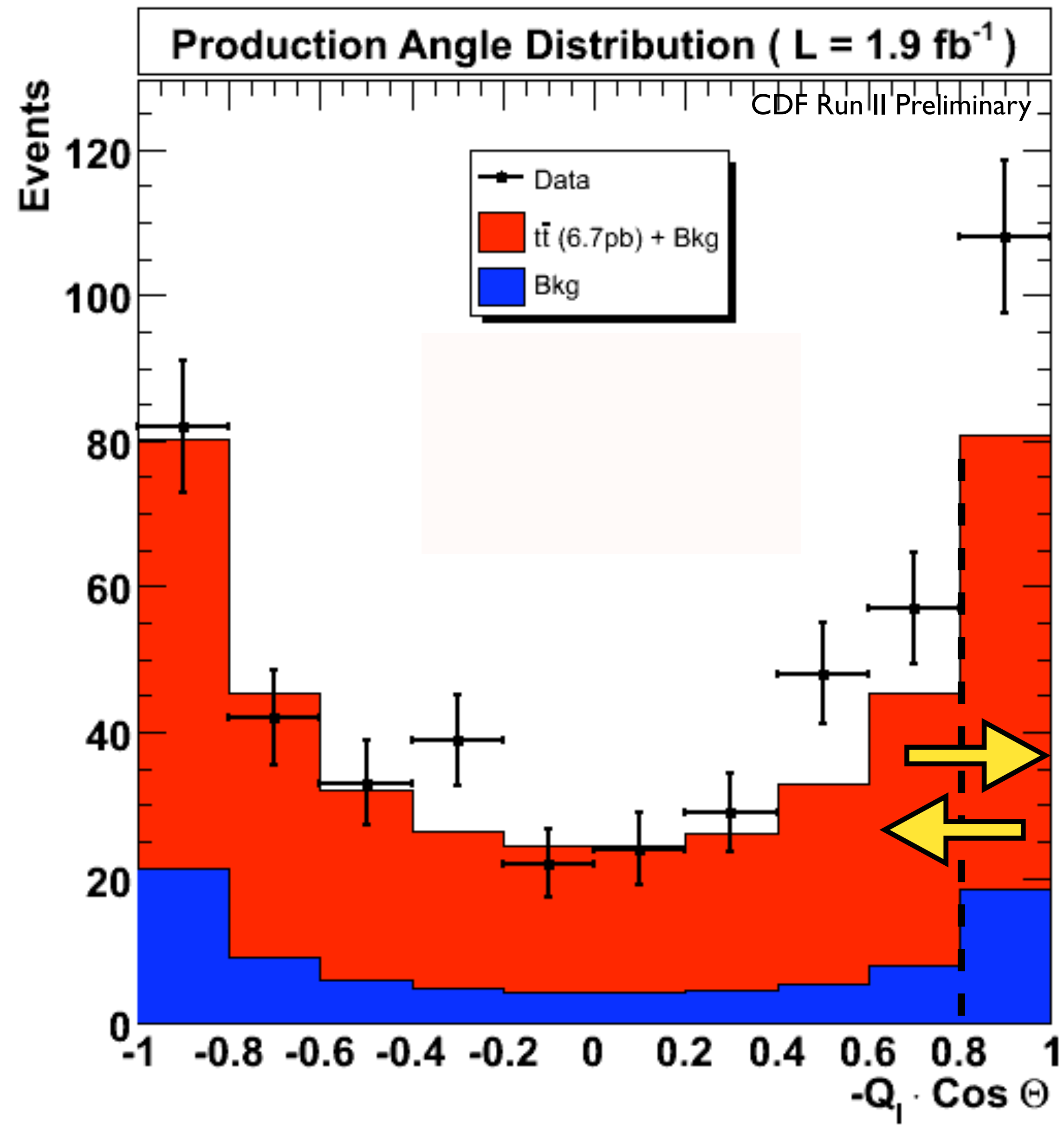


Reconstruction Corrections

- The smearing of the "true" distribution is related to the "reconstructed" distribution by a matrix

$$[Recon] = \begin{bmatrix} s_{0,0} & s_{0,1} & \cdots & s_{0,nbins} \\ s_{1,0} & s_{1,1} & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ s_{nbins0} & \cdots & \cdots & s_{nbins,nbins} \end{bmatrix} [True]$$

- The matrix can be inverted to correct for smearing



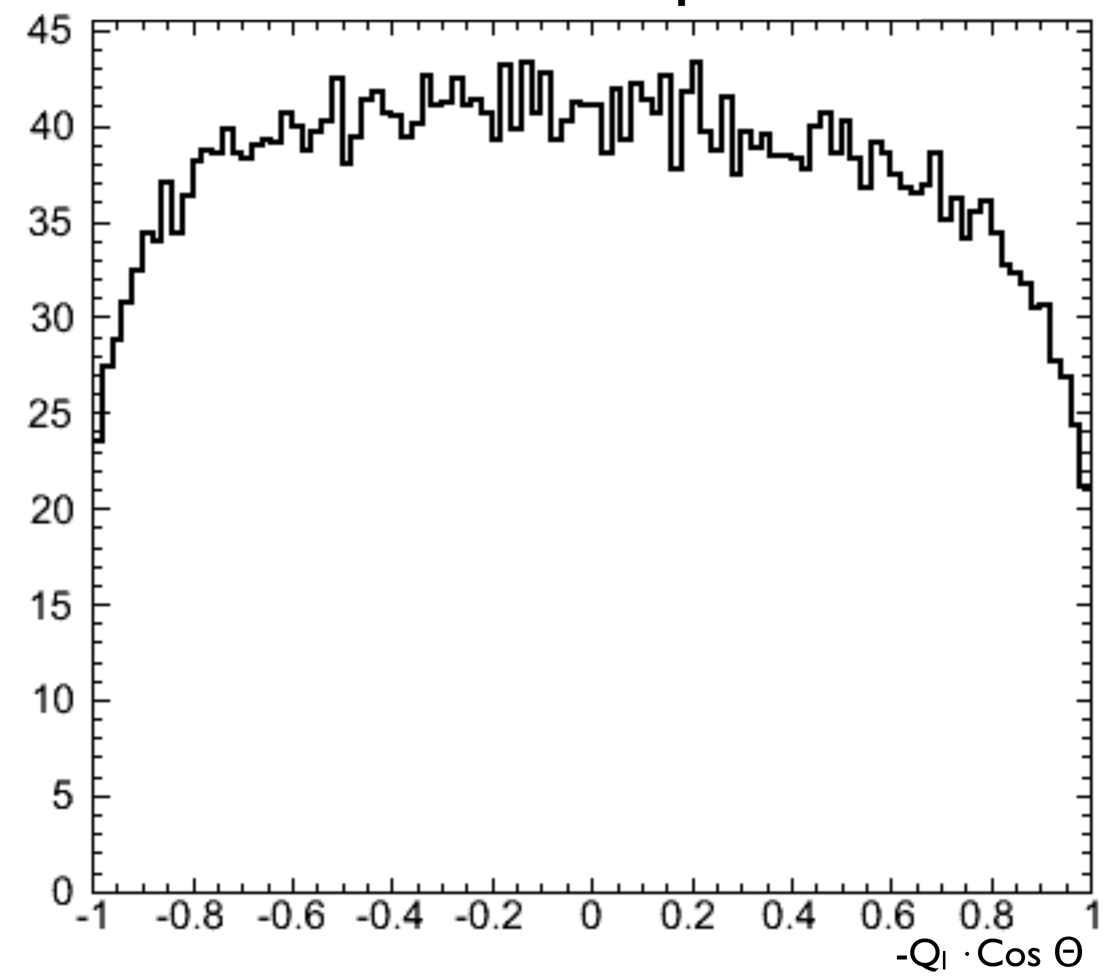
Acceptance Correction

- Can do the same with event acceptance - only no smearing now
- The distribution "after selection" can be related to the "true" distribution again by a matrix

$$[Selected] = \begin{bmatrix} \epsilon_0 & 0 & 0 & 0 \\ 0 & \epsilon_1 & 0 & 0 \\ 0 & 0 & ... & 0 \\ 0 & 0 & 0 & \epsilon_{nbins} \end{bmatrix} [True]$$

- The matrix can be inverted to correct for acceptance

Event Acceptance



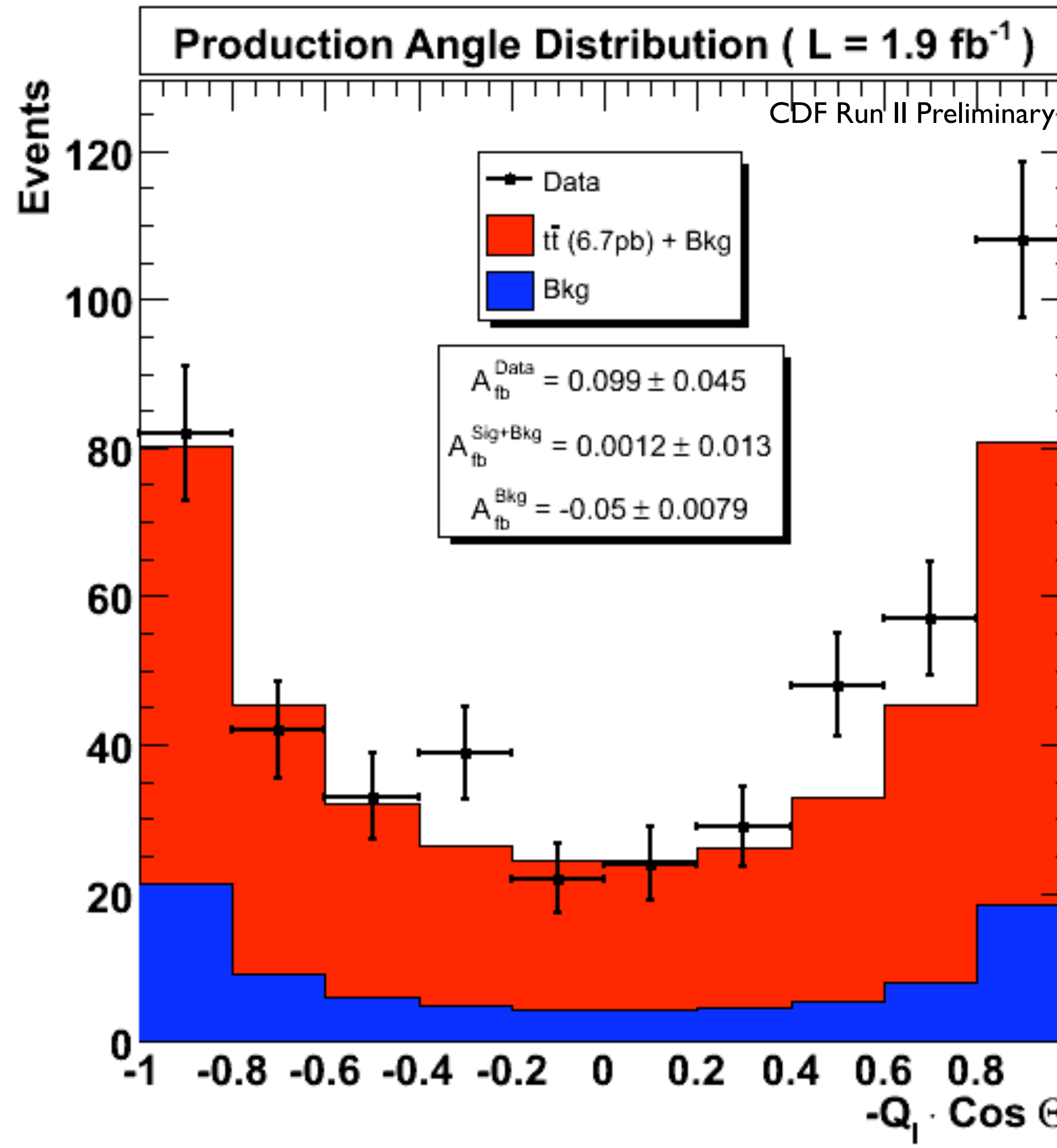
Putting It All Together

- The correction matrices are cascaded and applied to the background corrected data to produce a result independent of the effects of acceptance and reconstruction

$$Corrected = A^{-1} \cdot S^{-1} \cdot (Data - Bkg)$$

Measurement

- Begin with the raw distribution and rebin to create 4 uniform sized bins



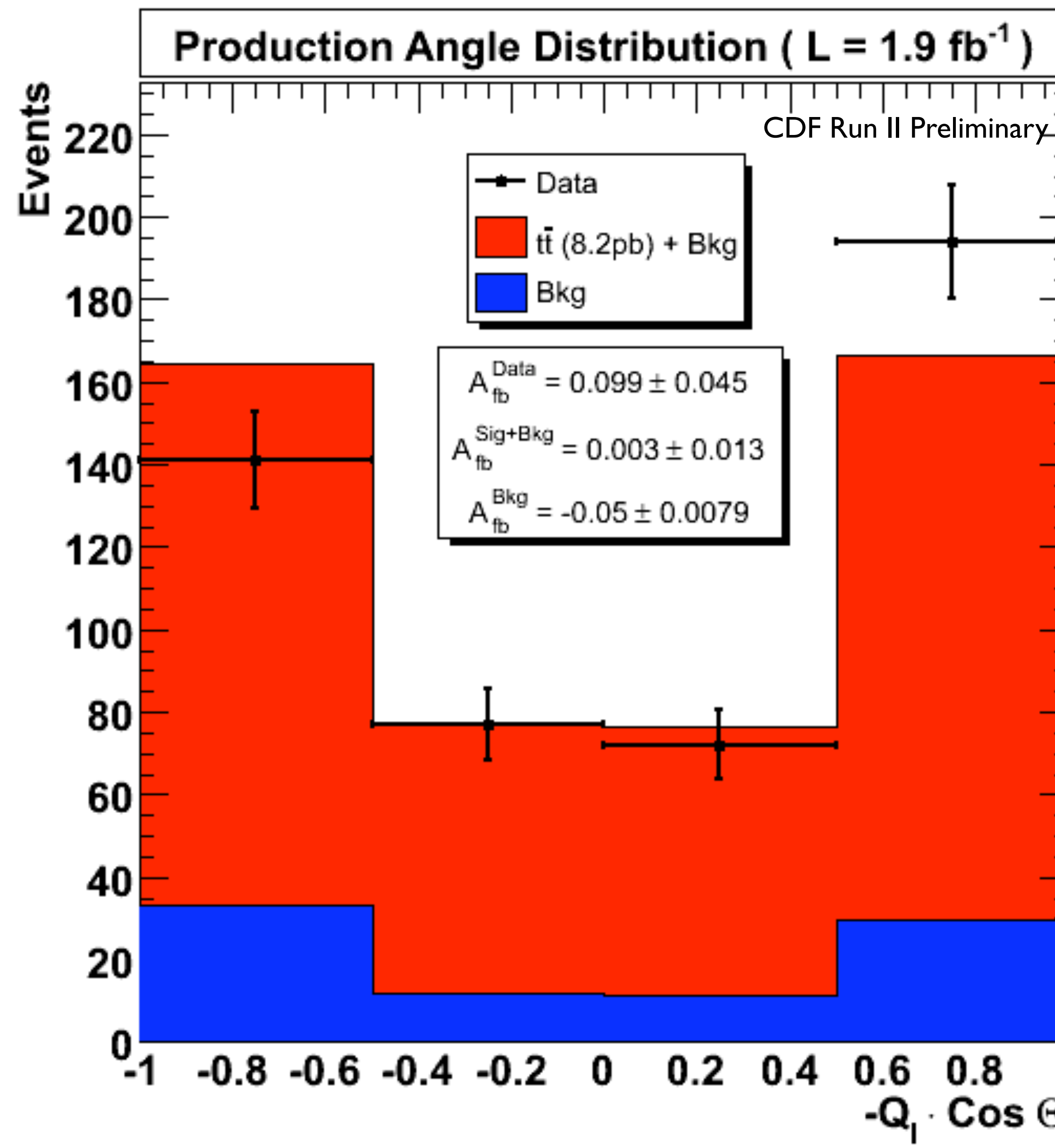
Measurement

- Begin with the raw distribution and rebin to create four uniform sized bins

Event Counts Bin-by-Bin

	bin 0	bin 1	bin 2	bin 3
Data	141	77	72	194
Bkg	33.4	12.0	11.5	29.6
Bkg-Corr	107.6	65.0	60.5	164.4

CDF Preliminary Lumi = 1.9 fb^{-1}



Measurement

- Push background corrected data through acceptance and reconstruction matrices

	bin 0	bin 1	bin 2	bin 3
Data	141	77	72	194
Bkg	33.4	12.0	11.5	29.6
Bkg-Corr	107.6	65.0	60.5	164.4

$$Corrected = A^{-1} \cdot S^{-1} \cdot (Data - Bkg)$$

- And calculate the “corrected” front-back asymmetry......

Measurement of A_{fb} In 1.9 fb^{-1}

$$A_{fb} = 0.17 \pm 0.07_{stat} \pm 0.04_{syst}$$

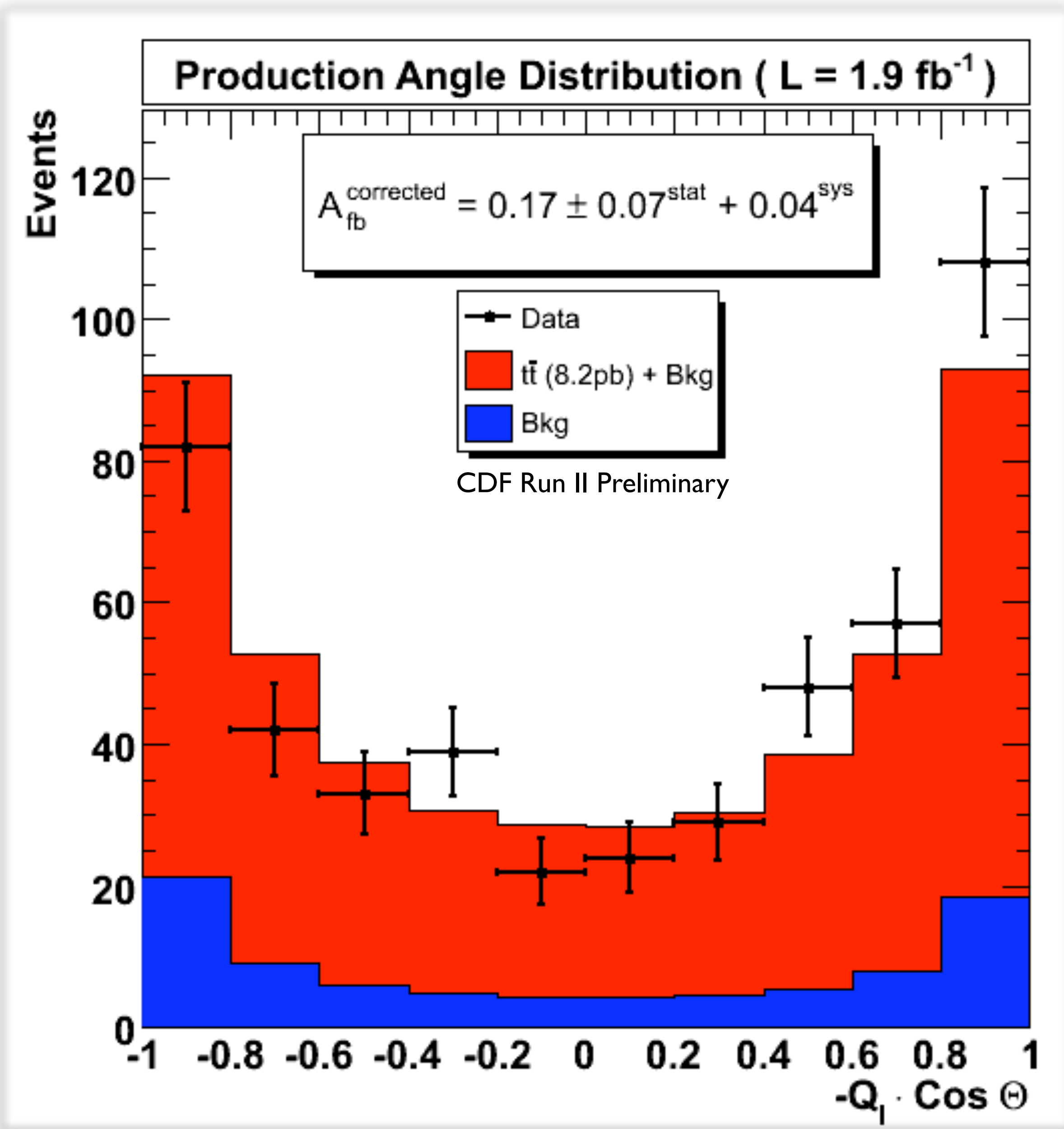
$$A_{fb\ theory} = 0.04 \pm 0.01$$

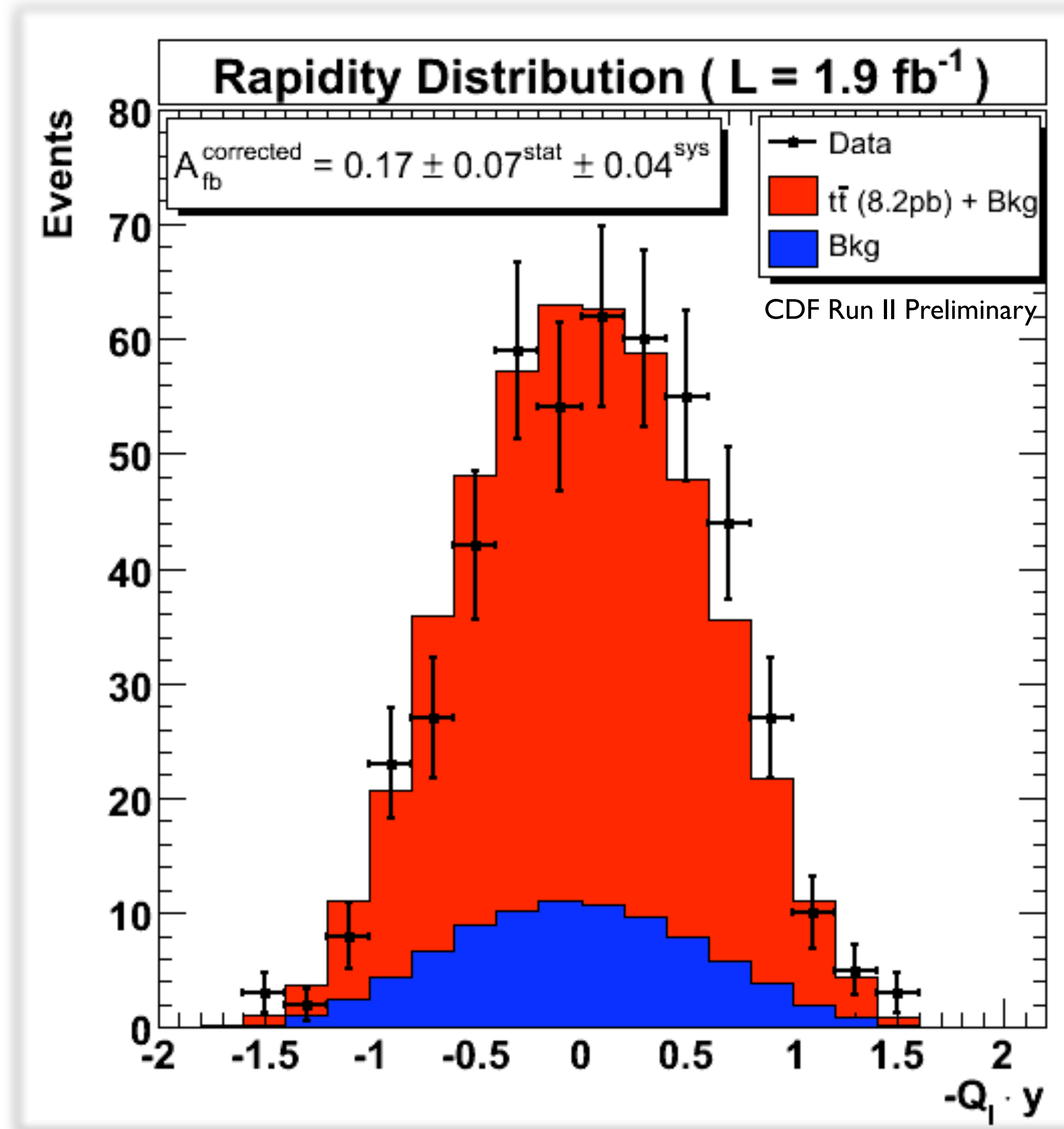
Accepted to PRL

Large Asymmetry observed in two other analyses - one CDF & one D0

Update of this measurement coming soon...

Measurement



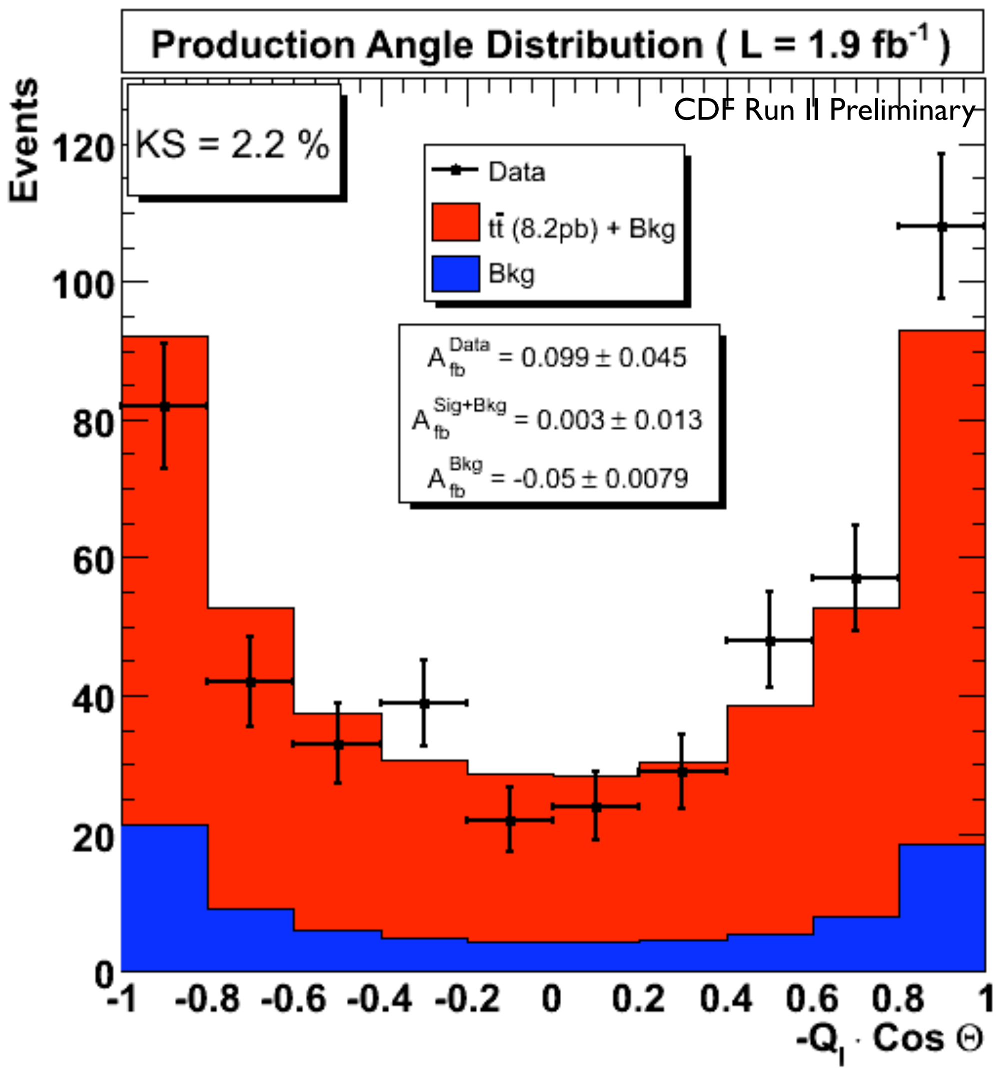


Consistency Check

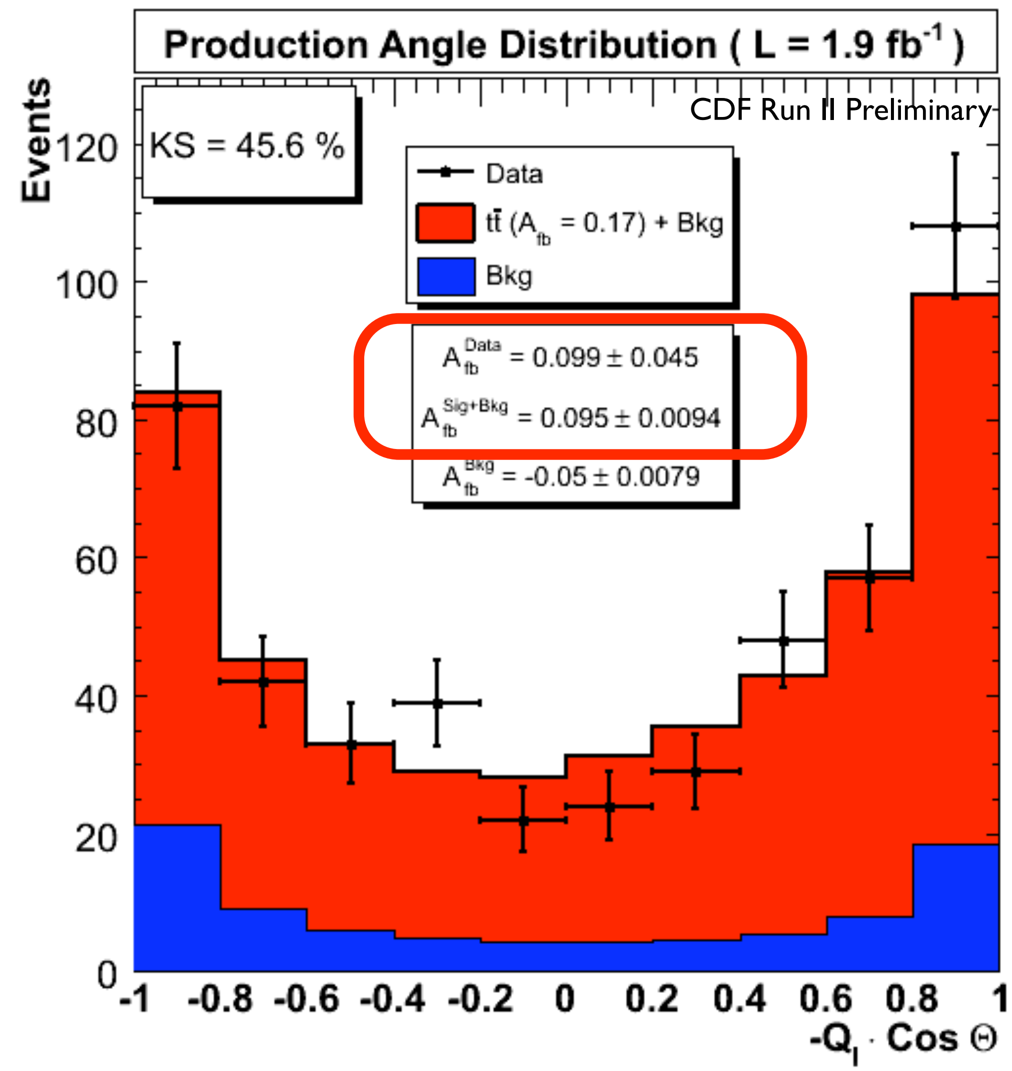
- If I create a Monte Carlo top sample with a 17% asymmetry does it fit the data well at the reconstructed level (before corrections) ?
- This is an alternative technique to the matrix corrections (template method)

Template Check

Normal



Monte Carlo w/ Asymmetry



Template method agrees well with measured value

So Is It Real?

$$A_{fb} = 0.17 \pm (0.07)^{stat} \pm (0.04)^{syst}$$

- The measured value is ~ 2 sigma from the SM and a little over 2 sigma from zero
- With that said, the asymmetry measurement itself does not necessarily reflect the difference in "shape" we see in the production angle
- A KS test of the shape, comparing data to prediction, reveals ~ 1-2 % compatibility
- So I'll hope...

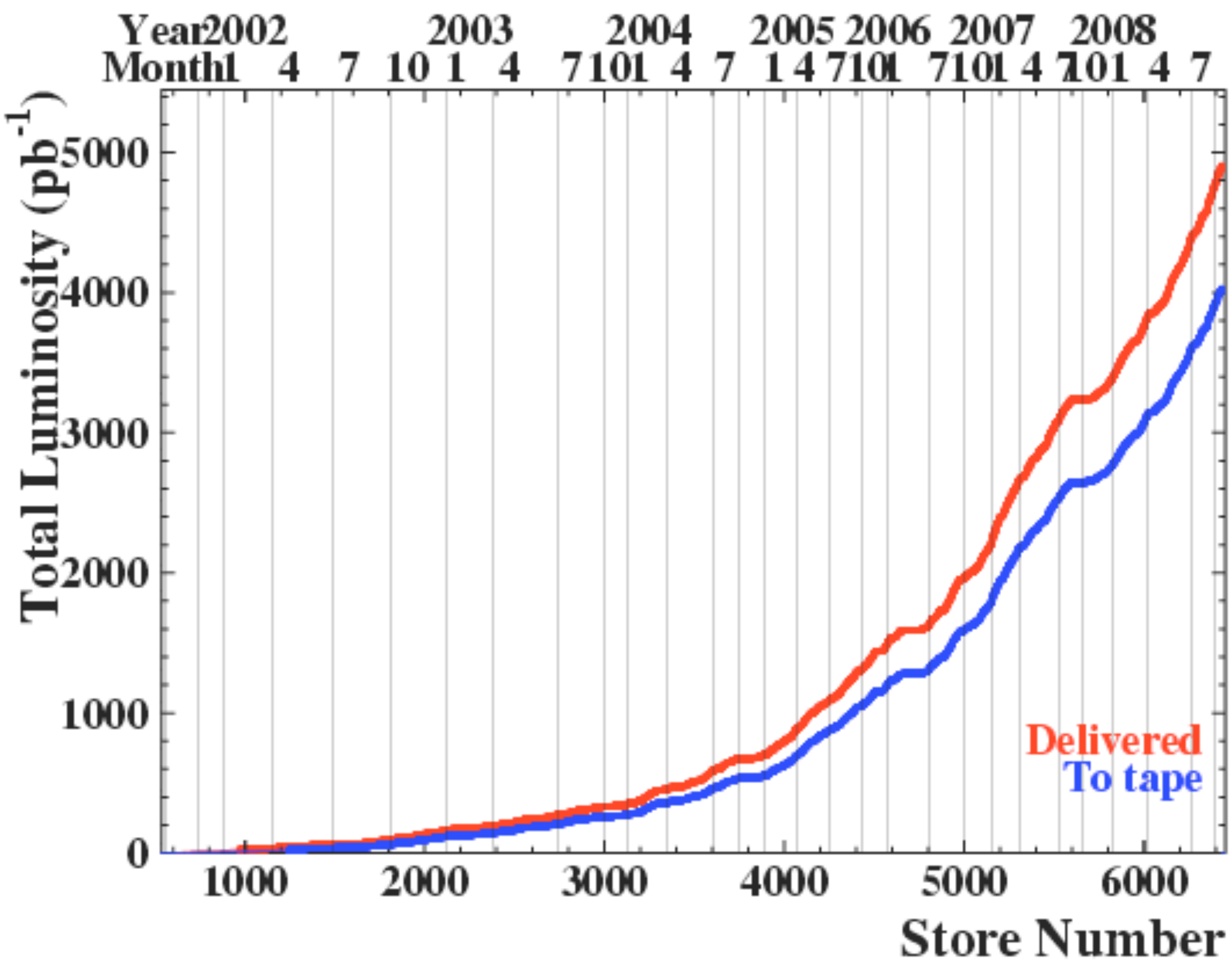
So Does The Standard Model Survive?

Yes, but...

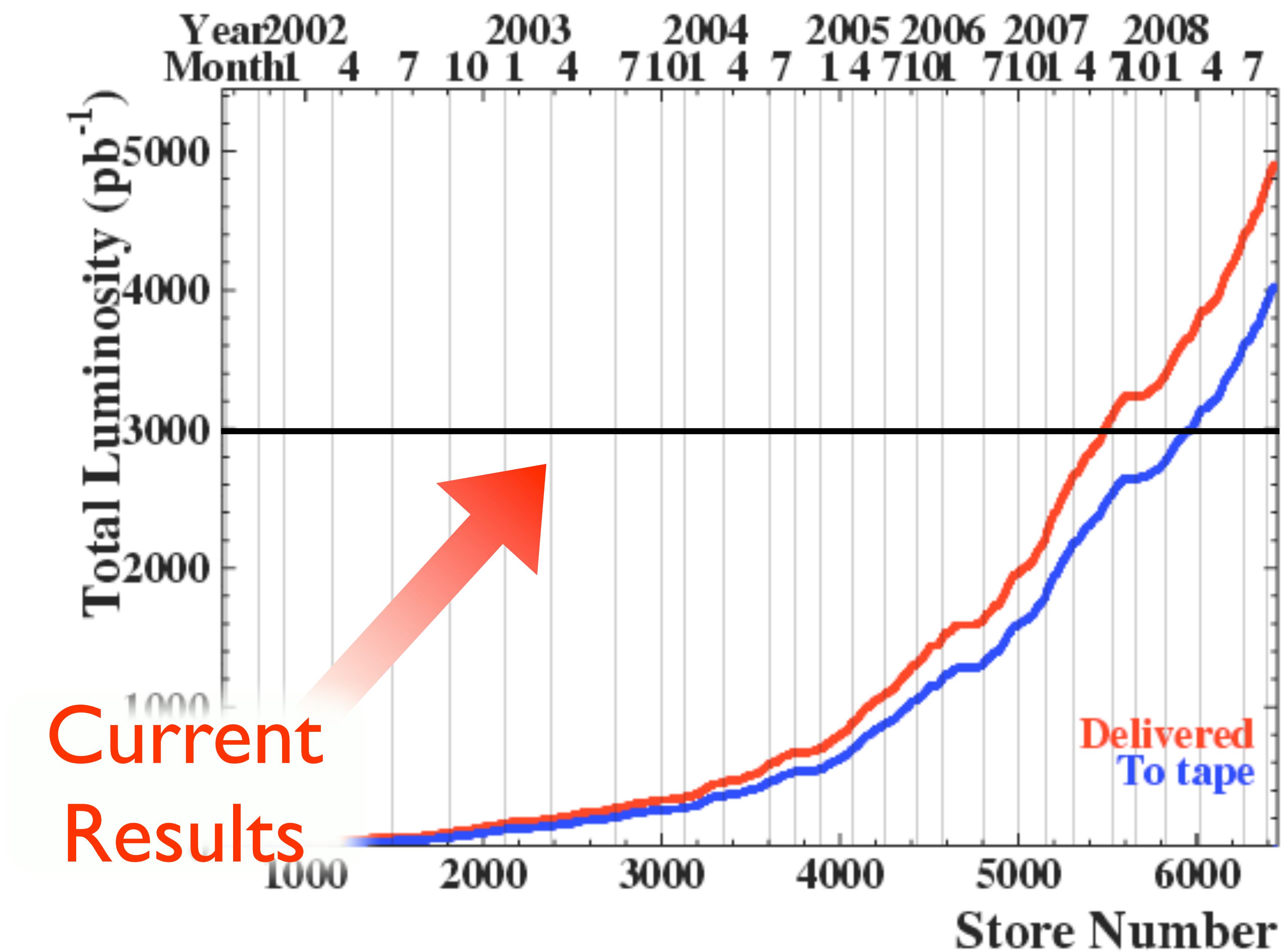
So Does The Standard Model Survive?

- Uncertainty on cross section is still 5-10%, plenty of room for ~ 0.5-1.0 pb additional production mechanism or anomalous decay
- Somewhat discrepant results still present in top physics - many still too statistically limited
  - A_{fb}
  - t´ Search

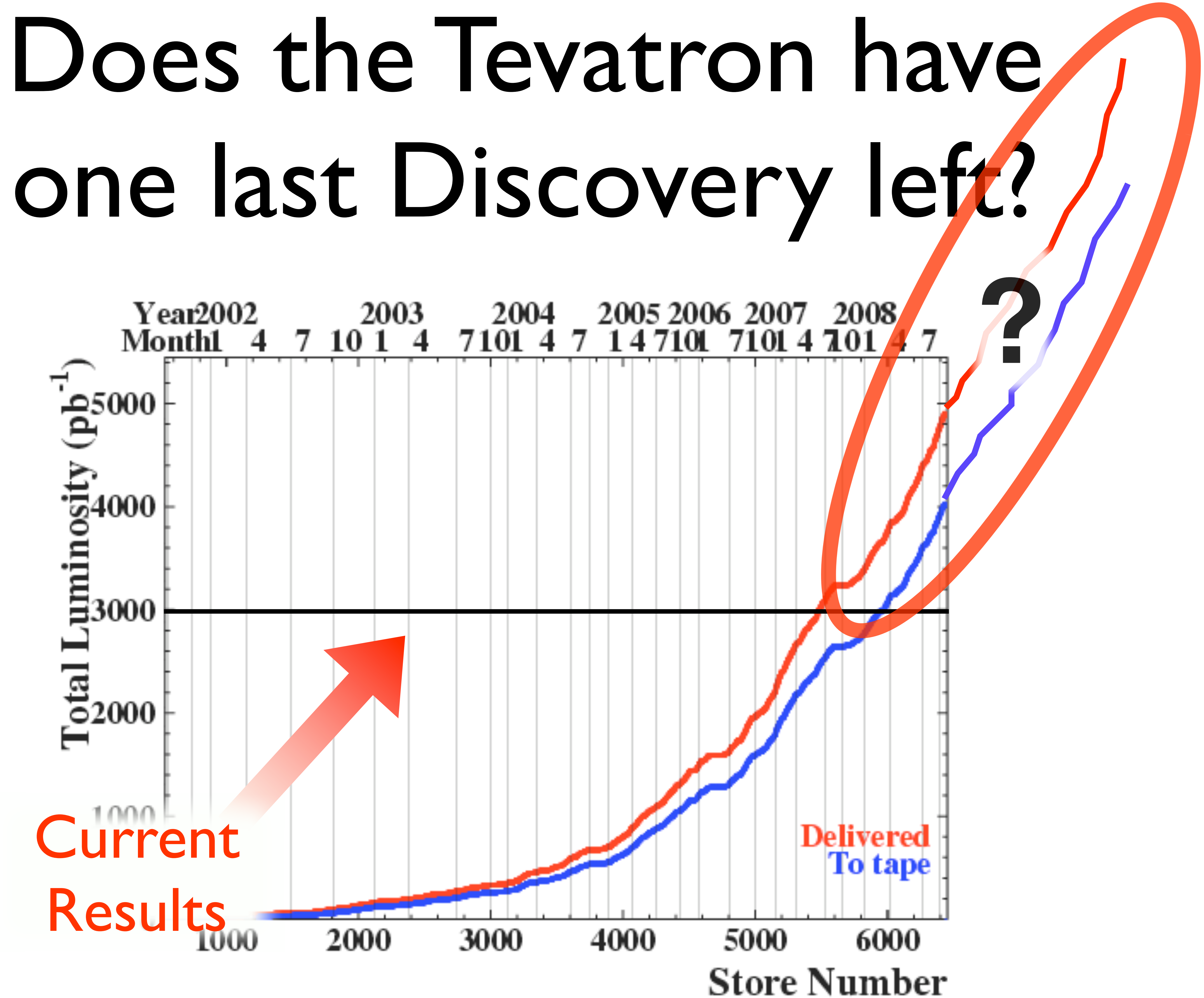
Does the Tevatron have one last Discovery left?



Does the Tevatron have one last Discovery left?

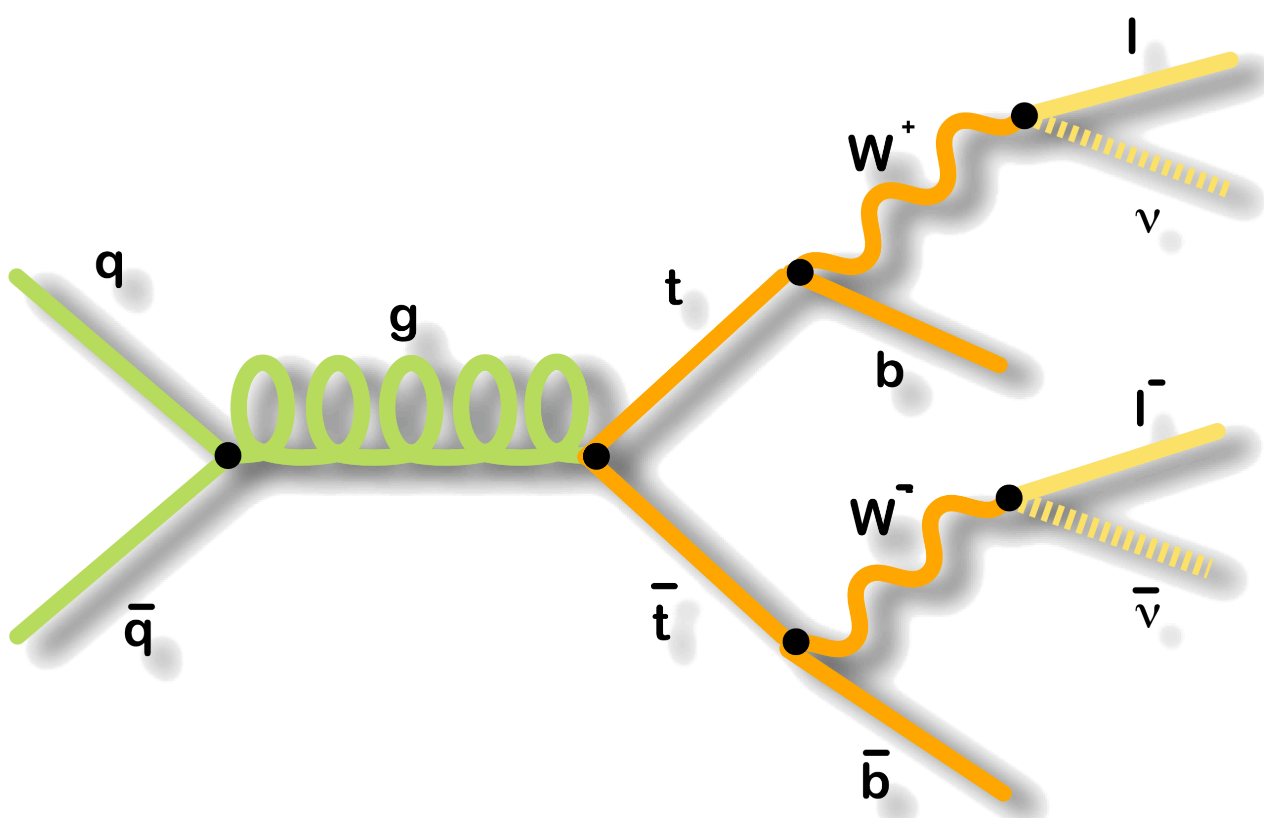


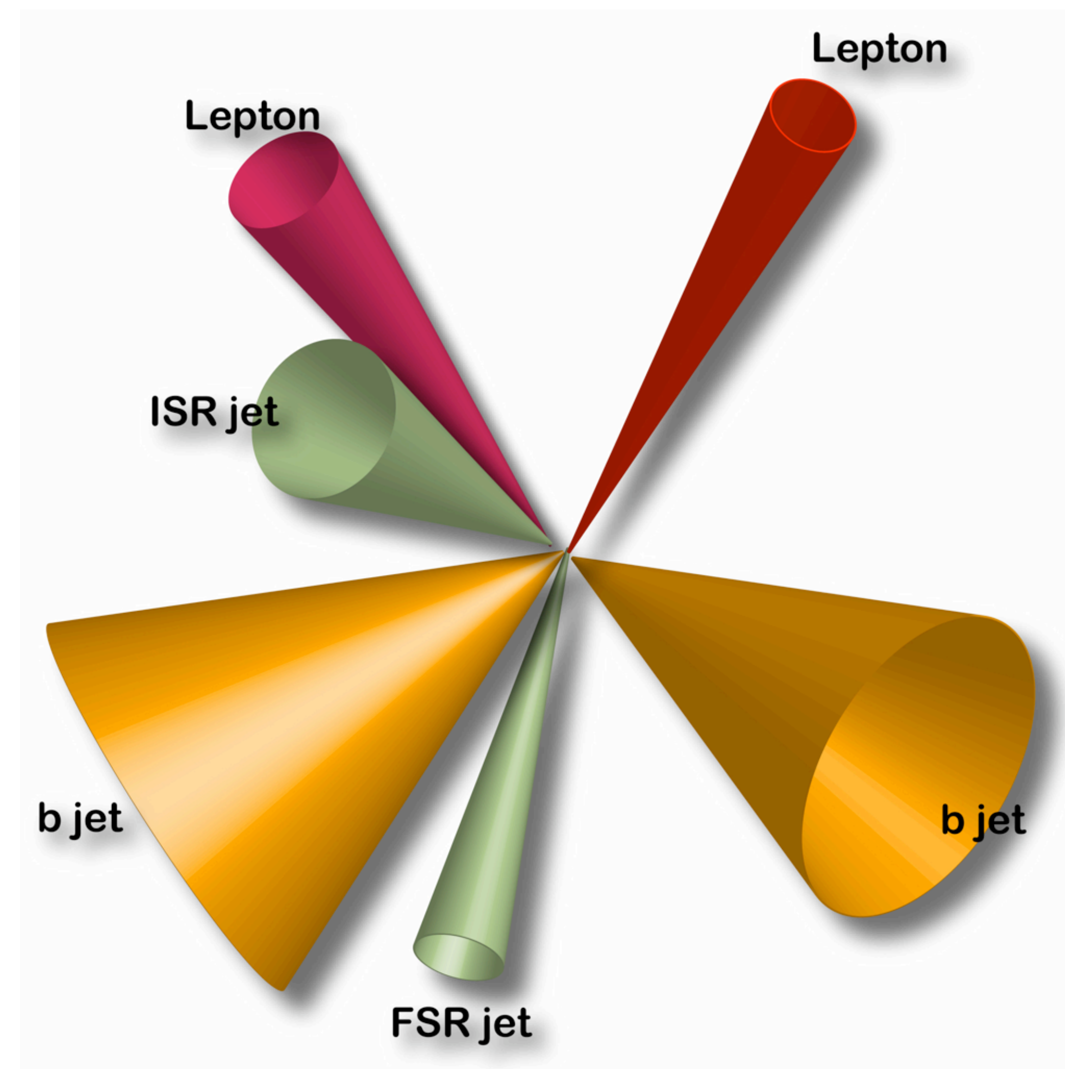
Does the Tevatron have one last Discovery left?



Appendix

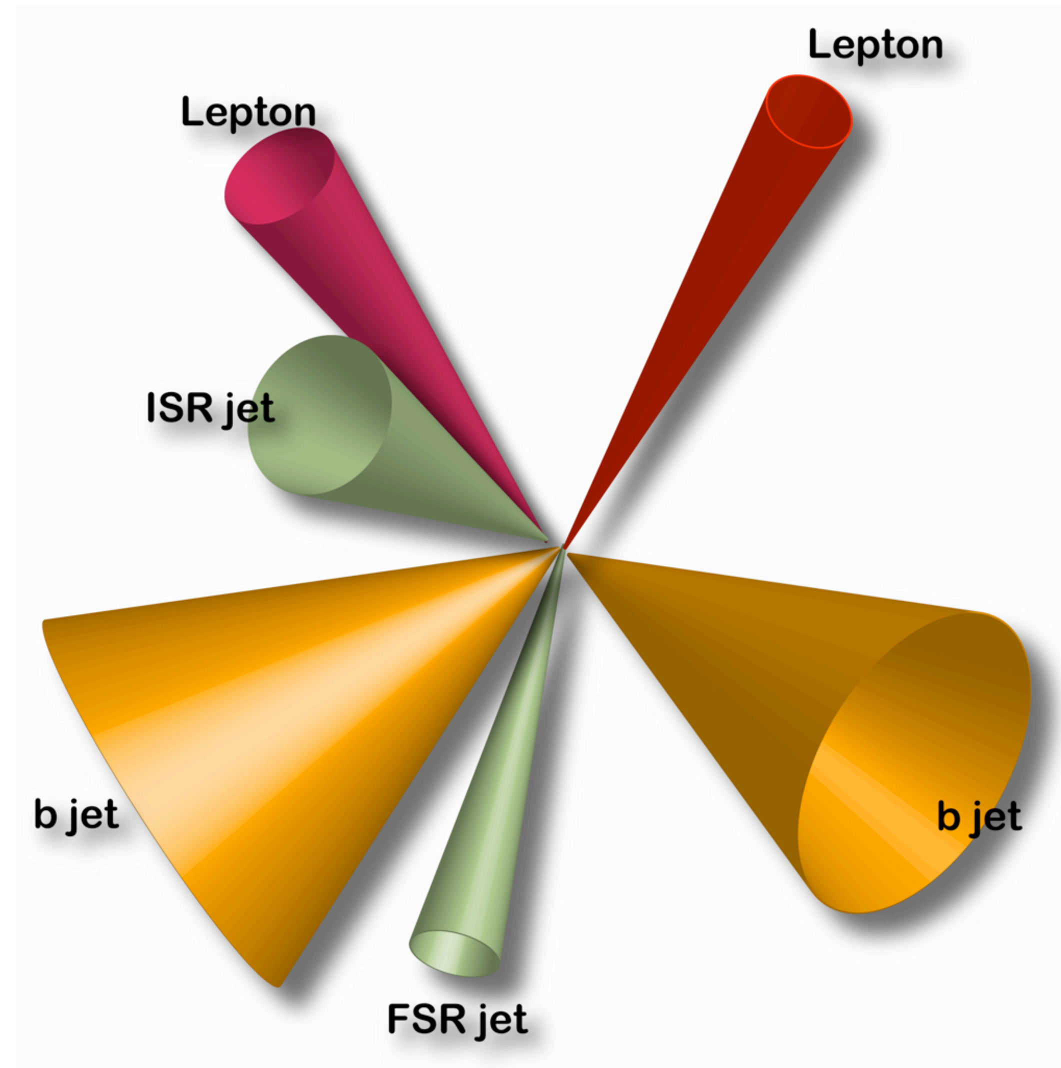
Di-lepton Channel





Di-lepton Channel

- $\geq$ 2 Jets (Et $\geq$ 15 GeV and η < 2.4)
- 2 Electrons or Muons (Pt $\geq$ 20 GeV) of opposite sign
- $\geq$ 25 GeV Missing Transverse Energy
- $|\Delta\Phi|$ > 30° between MET and Leading Jet



Di-lepton Channel

- $\geq$ 2 Jets (Et $\geq$ 15 GeV and η < 2.4)
- 2 Electrons or Muons (Pt $\geq$ 20 GeV) of opposite sign
- $\geq$ 25 GeV Missing Transverse Energy
- |ΔΦ| > 30° between MET and Leading Jet

$t\bar{t}$

Z/γ^*

WW

WZ

ZZ

Fakes

Di-lepton Channel

- $\geq$ 2 Jets (Et $\geq$ 15 GeV and η < 2.4)
- 2 Electrons or Muons (Pt $\geq$ 20 GeV) of opposite sign
- $\geq$ 25 GeV Missing Transverse Energy
- $|\Delta\Phi|$ > 30° between MET and Leading Jet

$t\bar{t}$

Z/γ^*

WW

WZ

ZZ

Fakes

S:B ~ 3:1

Monte Carlo Based Estimates

$$N = \sigma \cdot \int \mathcal{L}\, dt \cdot A$$

$$\begin{gathered} Z/\gamma^* \\ WW \\ WZ \\ ZZ \end{gathered}$$

Monte Carlo Based Estimates

experiment
or
theory

$$N = \sigma \cdot \int \mathcal{L}\, dt \cdot A$$

Measured

From Monte Carlo

Z/γ^*
WW
WZ
ZZ

Backgrounds

Process	Events
$t\bar{t}$ (6.7 pb)	
Z/γ^*	
WW	
WZ	
ZZ	
Fakes	
Sum	
Data	

Backgrounds

Process	Events
$t\bar{t}$ (6.7 pb)	110.6
Z/γ^*	26.6
WW	10.2
WZ	2.9
ZZ	1.5
Fakes	
Sum	
Data	

Fakes

- Anything that can mimick one of the leptons
- Mostly QCD which cannot be estimated by a Monte Carlo approach
- Fakes dominate same-sign dileptons events
- If we assume the fake-rate is independent of charge, we can use the same sign rate to predict fakes in our signal region

Backgrounds

Process	Events
$t\bar{t}$ (6.7 pb)	110.6
Z/γ^*	26.6
WW	10.2
WZ	2.9
ZZ	1.5
Fakes	
Sum	
Data	

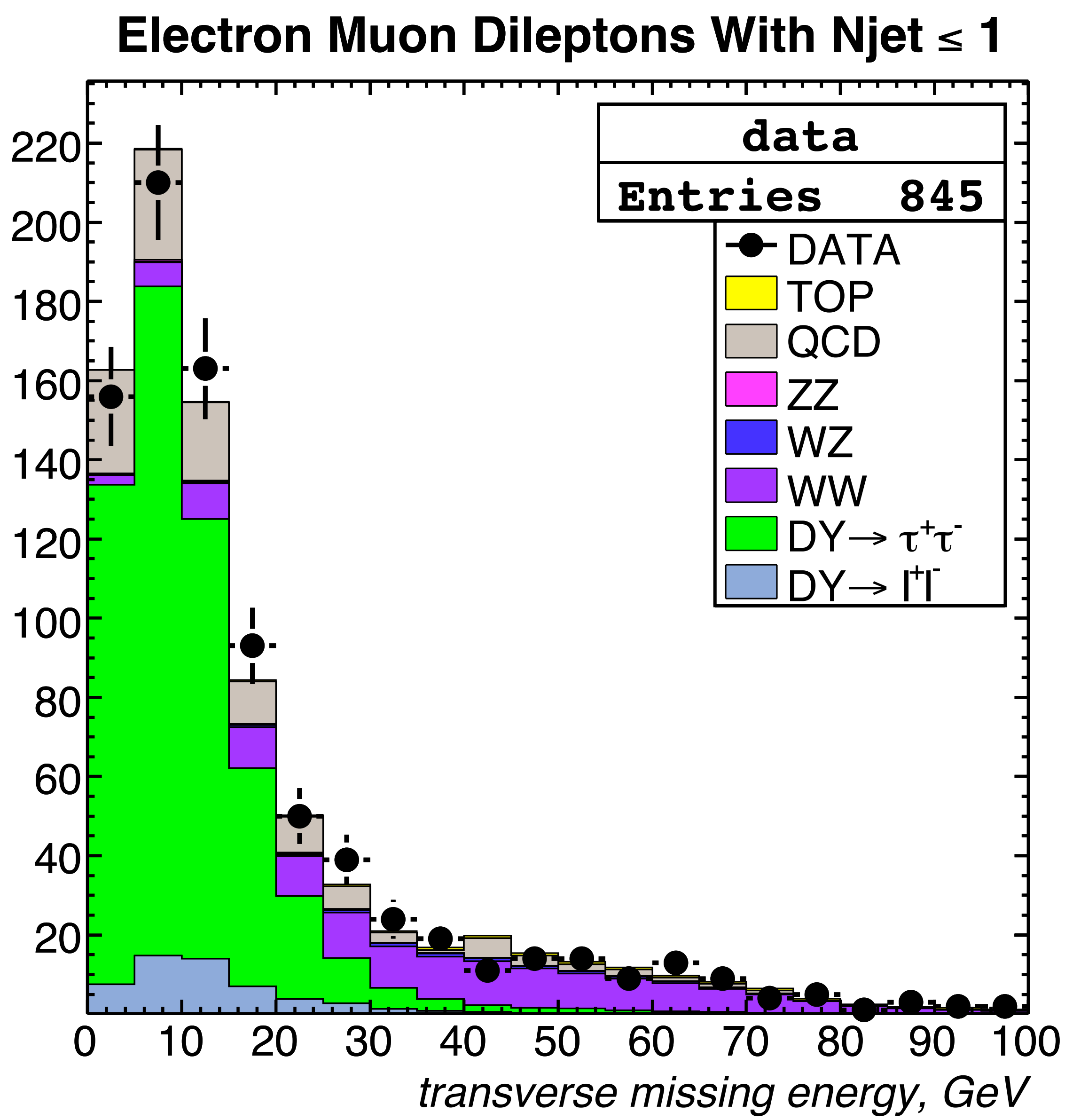
Backgrounds

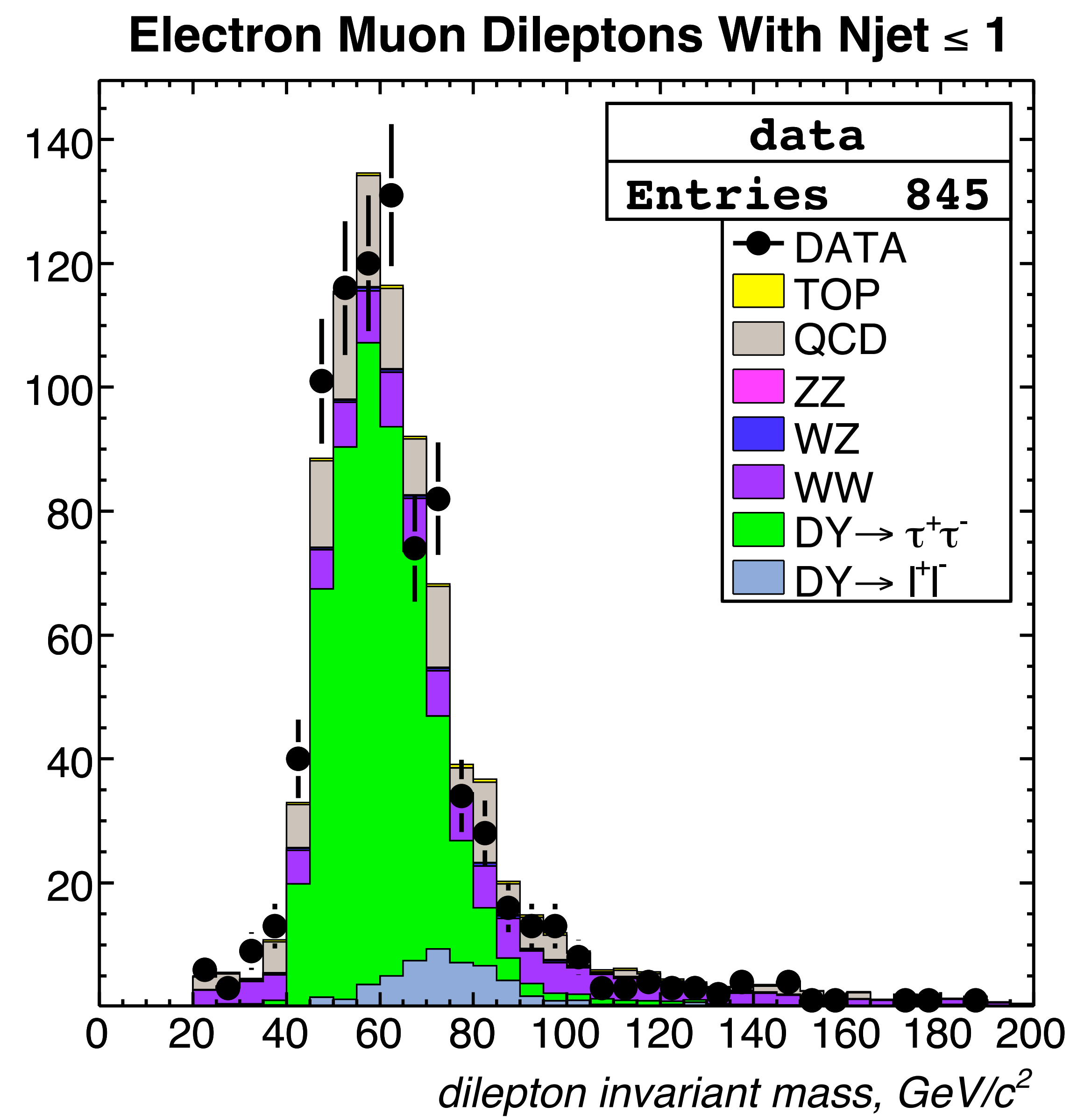
Process	Events
$t\bar{t}$ (6.7 pb)	110.6
Z/γ^*	26.6
WW	10.2
WZ	2.9
ZZ	1.5
Fakes	10.8
Sum	162.5 ± 4.5
Data	

Do we believe it?

- Use a side-band region, dominated by backgrounds, to test method
- Di-lepton events with $\leq$ 1 Jets
    - e^-e^+ and $\mu^-\mu^+$ dominated entirely by Drell-Yan
    - More interesting are $e\mu$ events which have a more diverse process content

Control Region





Backgrounds

Process	Events
$t\bar{t}$ (6.7 pb)	110.6
Z/γ^*	26.6
WW	10.2
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Fakes	10.8
Sum	162.5 ± 4.5
Data	

Backgrounds

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$t\bar{t}$ (6.7 pb)	110.6
Z/γ^*	26.6
WW	10.2
WZ	2.9
ZZ	1.5
Fakes	10.8
Sum	162.5 ± 4.5
Data	162

Measurement in 2.8 fb^{-1}

$$\sigma_{t\bar{t}} = \frac{N_{data} - N_{bkg}}{A \cdot \int \mathcal{L}\, dt}$$

Process	Events
$t\bar{t}$ (6.7 pb)	110.6
Z/γ^*	26.6
WW	10.2
WZ	2.9
ZZ	1.5
Fakes	10.8
Sum	162.5 ± 4.5
Data	162

Measurement in 2.8 fb^{-1}

$$\sigma_{t\bar{t}} = \frac{N_{data} - N_{bkg}}{A \cdot \int \mathcal{L}\, dt}$$

Process	Events
$t\bar{t}$ (6.7 pb)	110.6
Z/γ^*	26.6
WW	10.2
WZ	2.9
ZZ	1.5
Fakes	10.8
Sum	162.5 ± 4.5
Data	162

$$\sigma_{\mathbf{t\bar{t}}} = \mathbf{6.7 \pm 0.8_{stat} \pm 0.4_{sys} \pm 0.4_{lum}\ \ pb}$$

@ M_t = 175 GeV/c^2

How do the Kinematics Look?