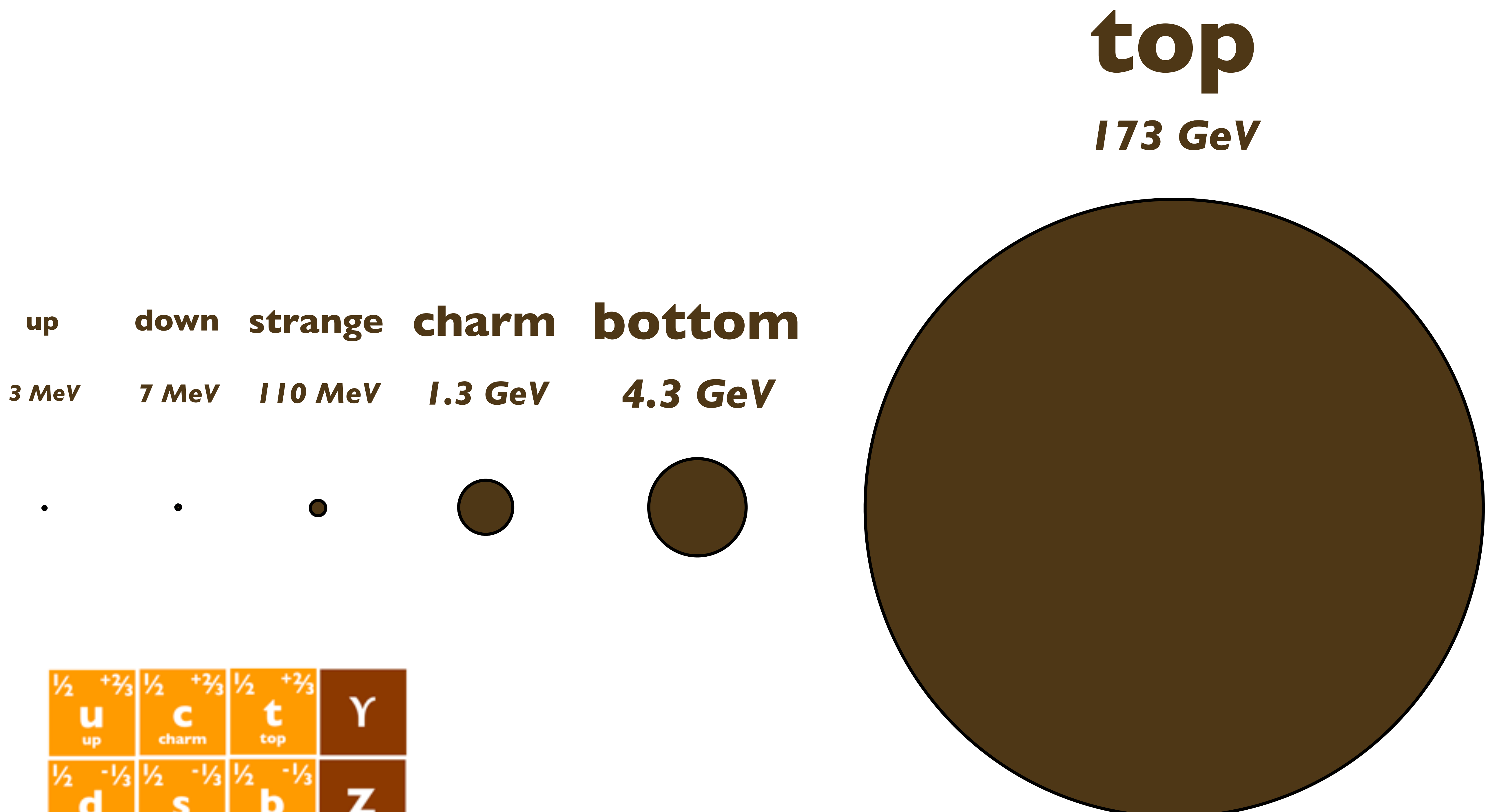
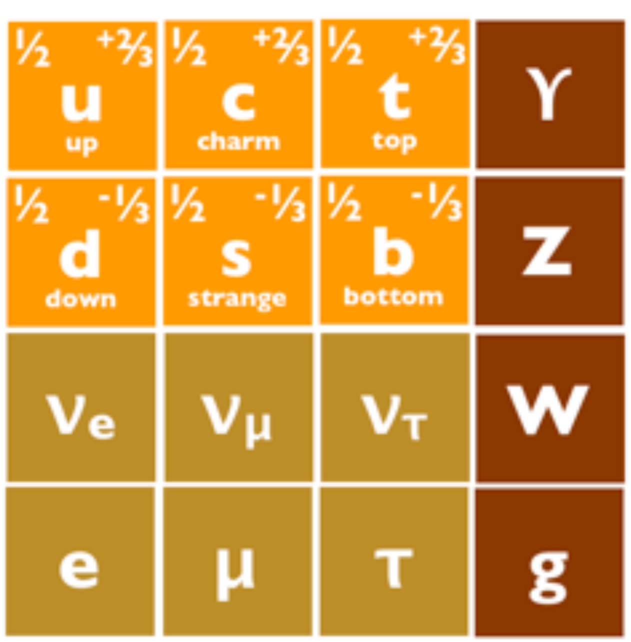
Top Quark Production at the Tevatron

Tom Schwarz
University of California Davis

Fermilab Users Meeting
June 1st, 2011


top
173 GeV
up
3 MeV
down
7 MeV
strange
110 MeV
charm
1.3 GeV
bottom
4.3 GeV


½ +⅔ u up
½ +⅔ c charm
½ +⅔ t top
γ
½ -⅓ d down
½ -⅓ s strange
½ -⅓ b bottom
Z
νe
νμ
ντ
W
e
μ
τ
g

Area ∝ Mass

Coupling to Higgs

Top Mass

$$y_t = \sqrt{2} \cdot \frac{m_t}{v}$$

Higgs Vacuum Expectation

Average Energy in the Higgs Field

Coupling to Higgs

173 GeV

$$y_t = \sqrt{2} \cdot \frac{m_t}{v}$$

243 GeV

Coupling to Higgs

173 GeV

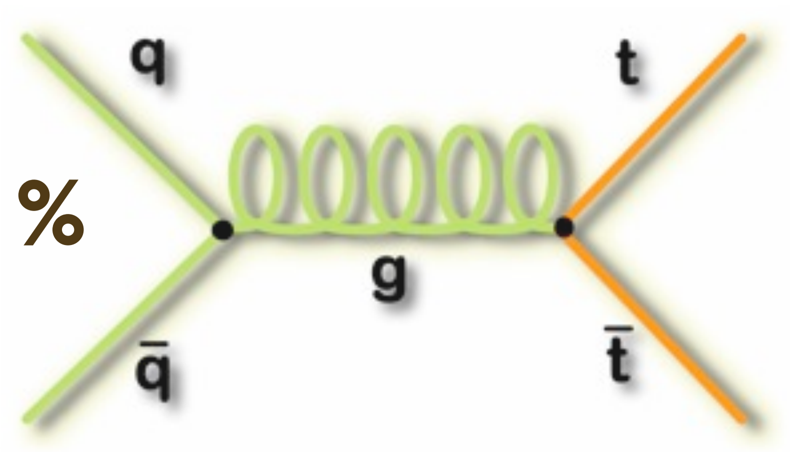
$$y_t = \sqrt{2} \cdot \frac{m_t}{v} \approx 1.0$$

243 GeV

Production & Decay

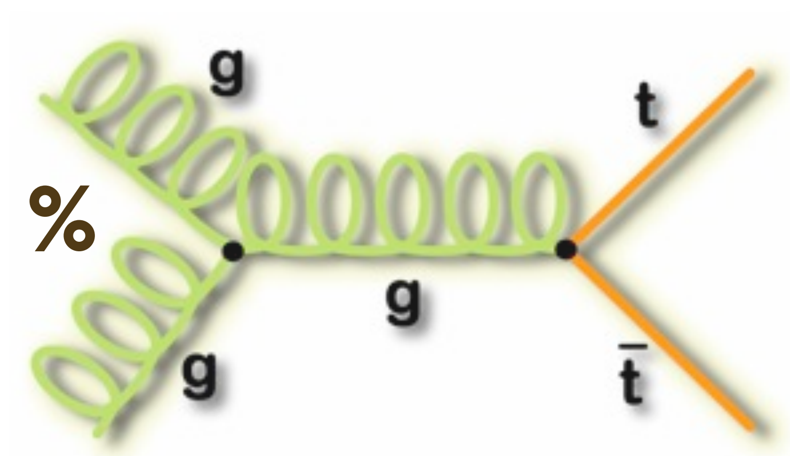
Production

~ 85 %

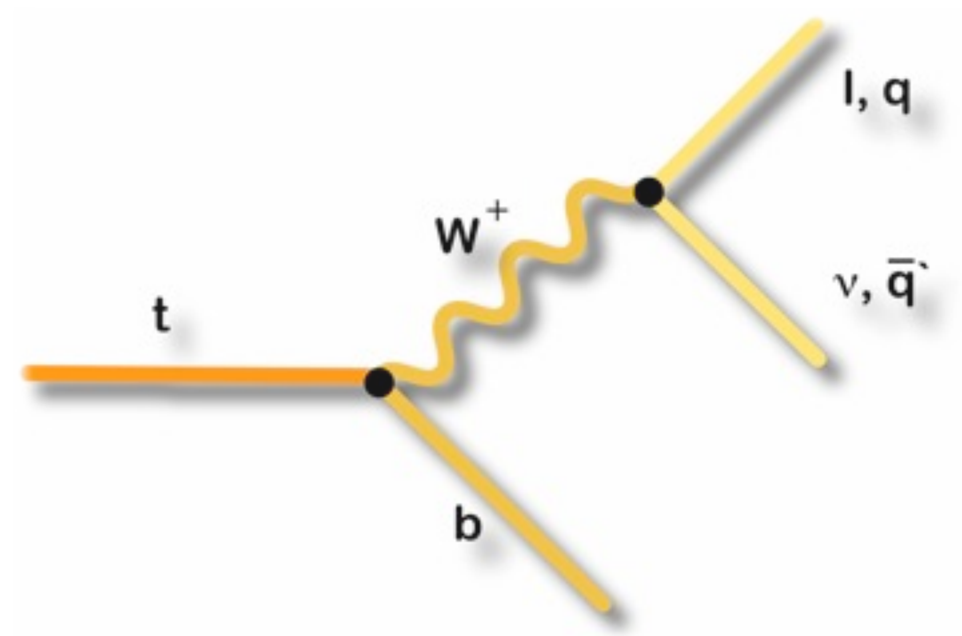


$\sigma_{tt}^{SM} = 7.5$ pb

~ 15 %

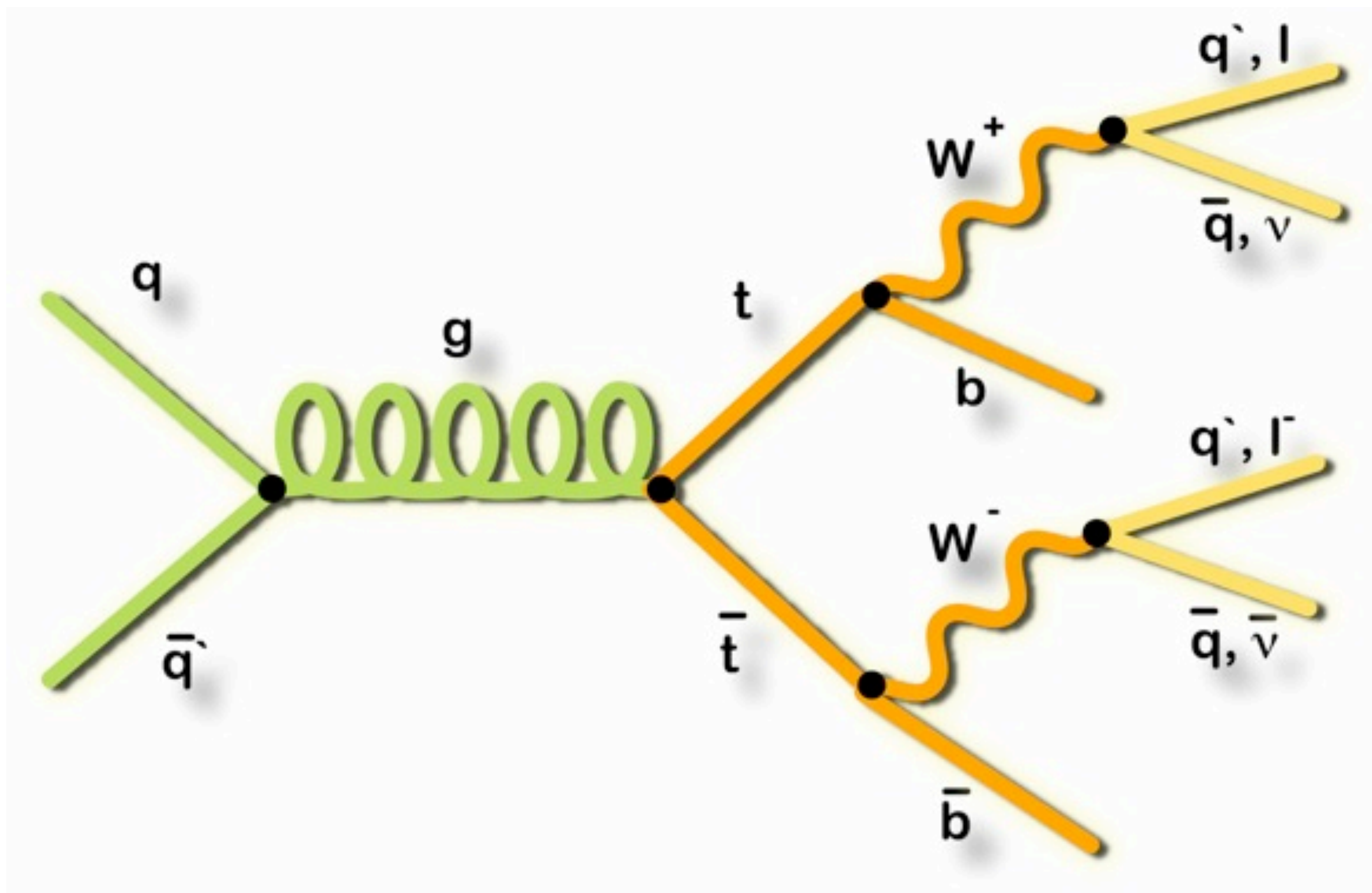


Decay

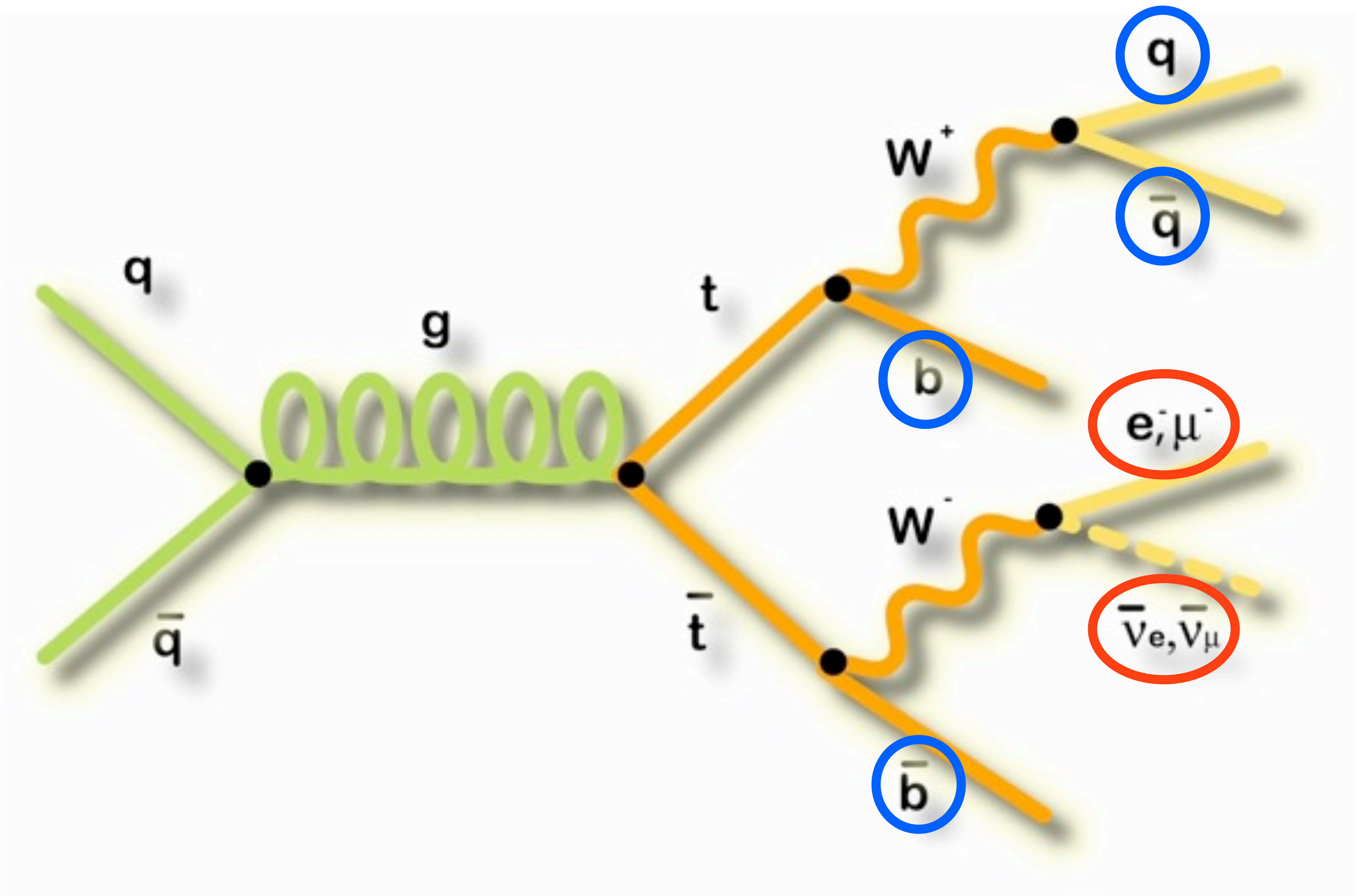


~100 %

Production & Decay

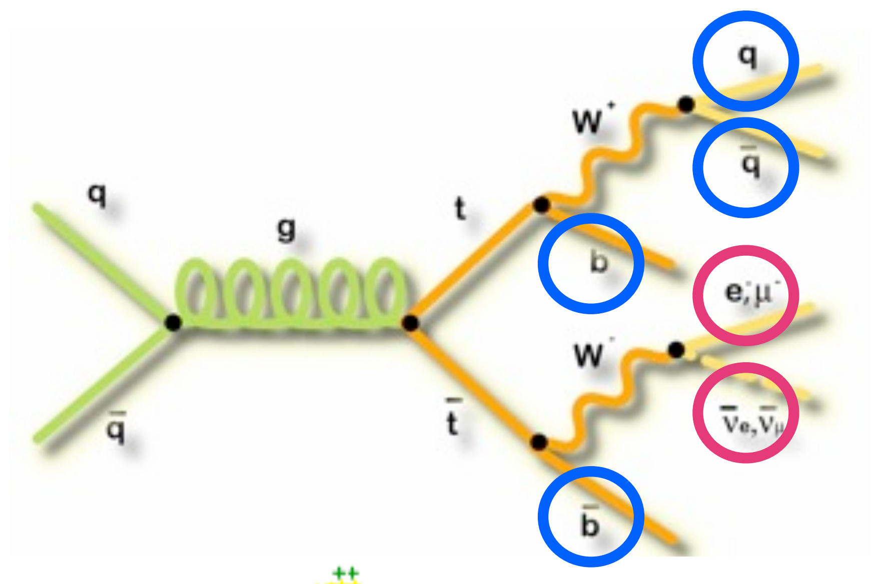


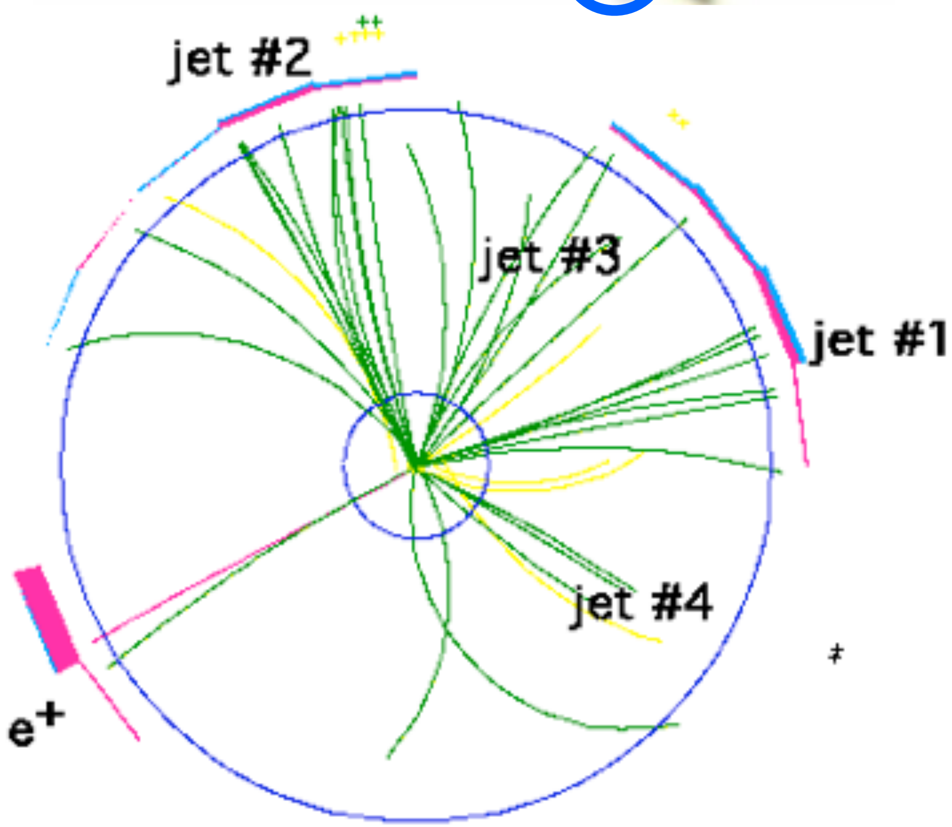
Production & Decay



One Lepton, One Neutrino, and 4 Quarks

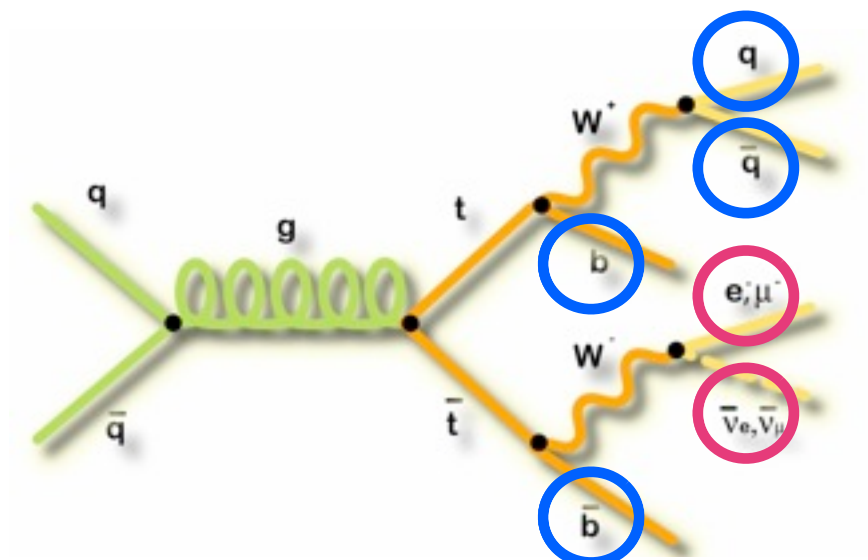
Finding Top

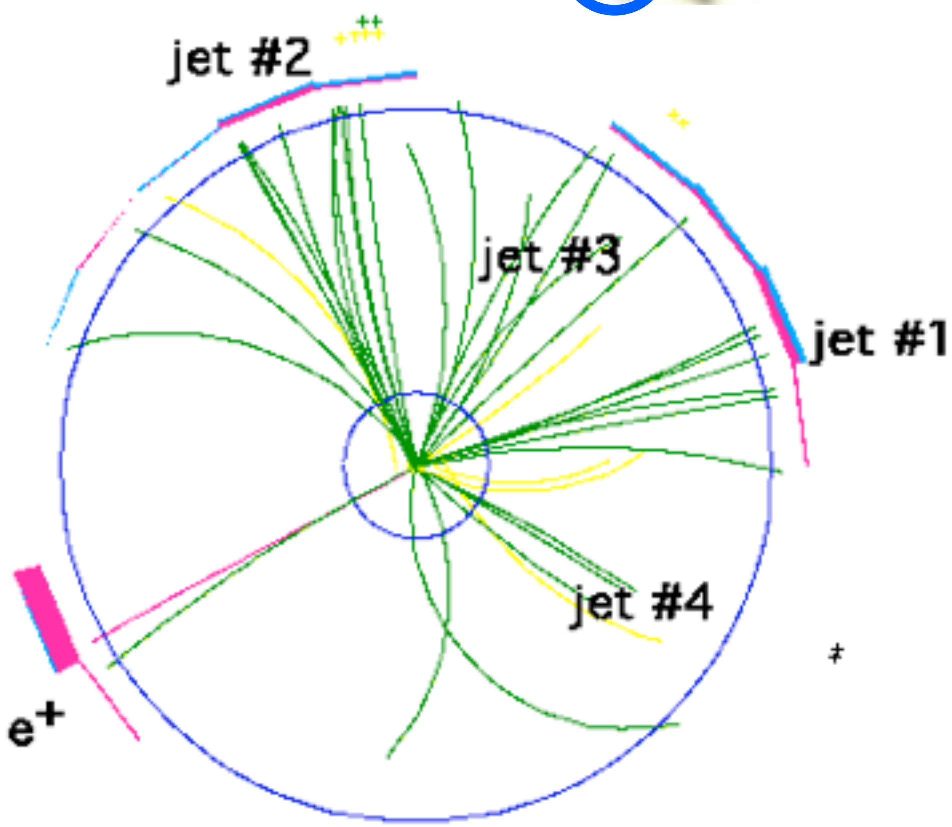




- 1 Electron or Muon ($E_T \geq 20$ GeV, $|\eta| < 1.1$)
- Large “Missing” Energy ($Et \geq 20$ GeV)
- ≥ 4 Jets ($Et \geq 20$ GeV, $|\eta| < 2.0$)
- At least 1 Jet with displaced secondary vertex (Evidence of a ‘b’-jet)

Finding Top



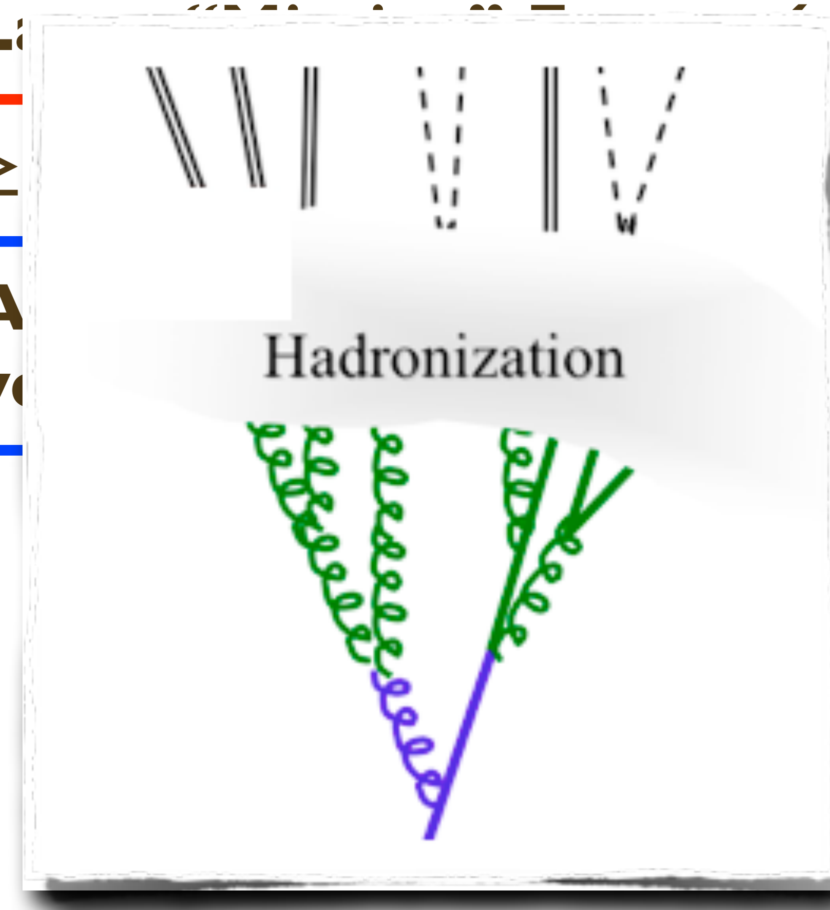


1 Electron or Muon ($E_T \geq 20$ GeV, $|\eta| < 1.1$)

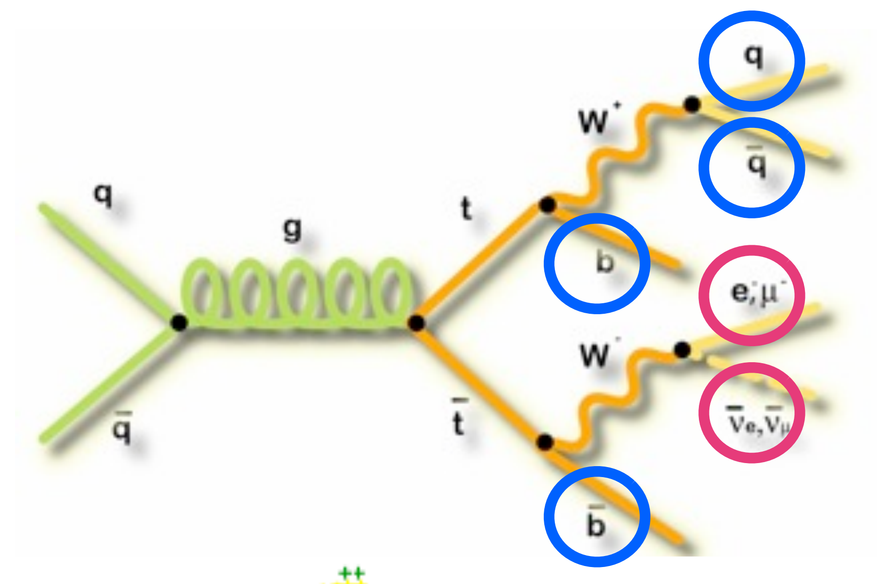
L... ($Et \geq 20$ GeV)

≥ ... < 2.0)

A ... ed secondary
v... jet)



Finding Top



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Large "Missing" Energy ($Et \geq 20$ GeV)

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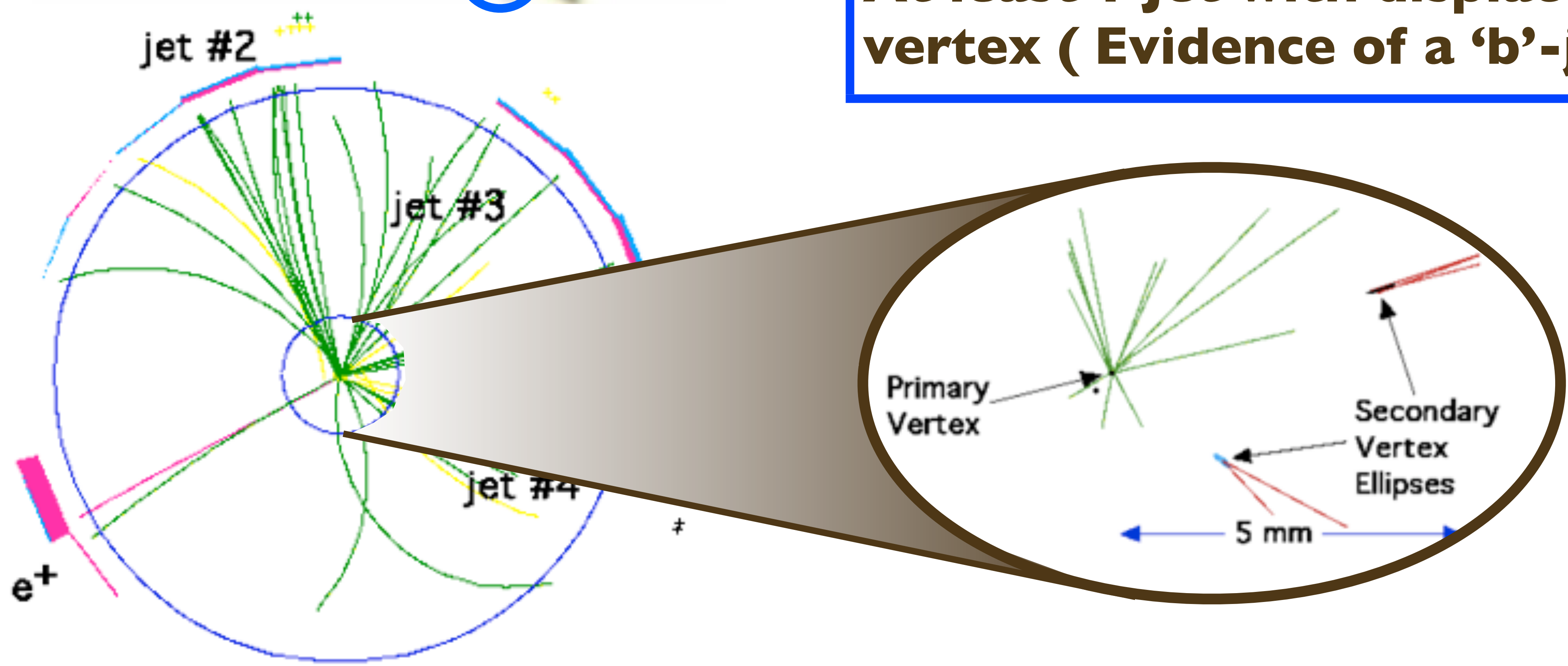
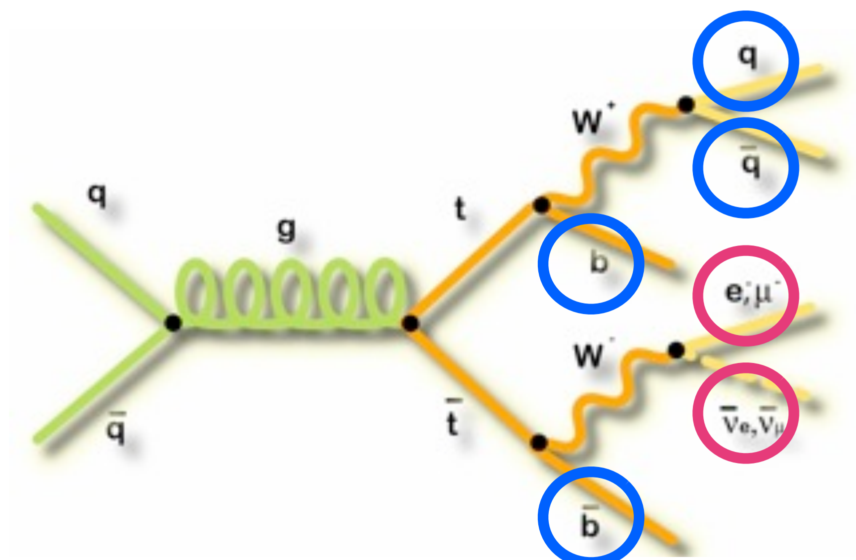
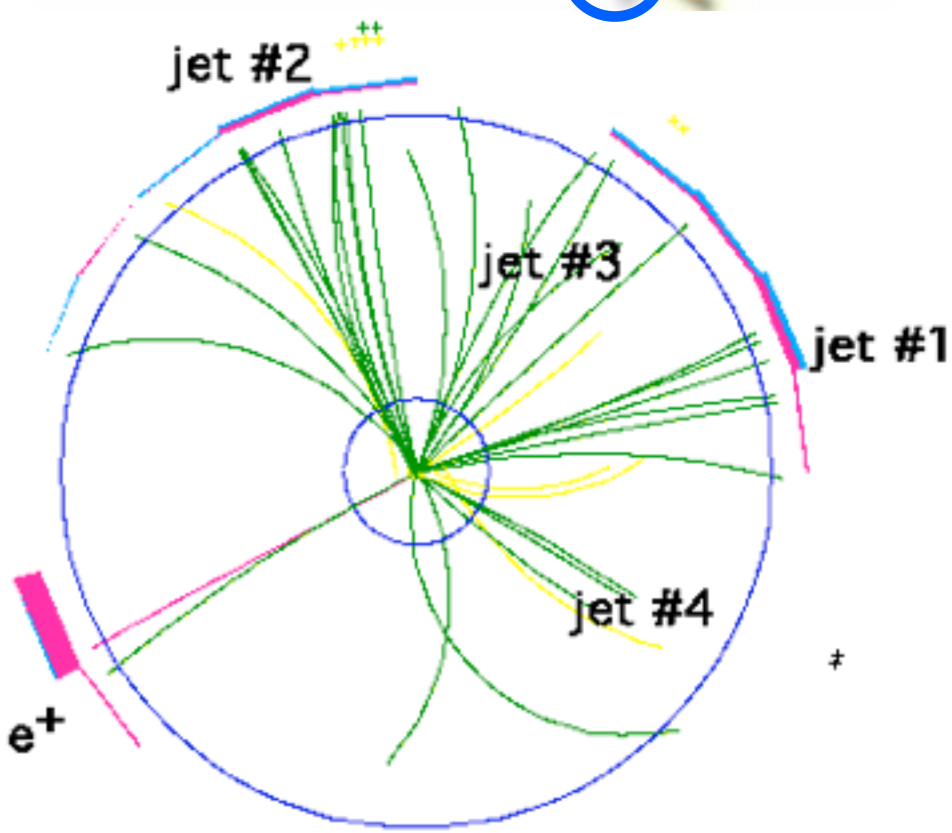


Finding Top

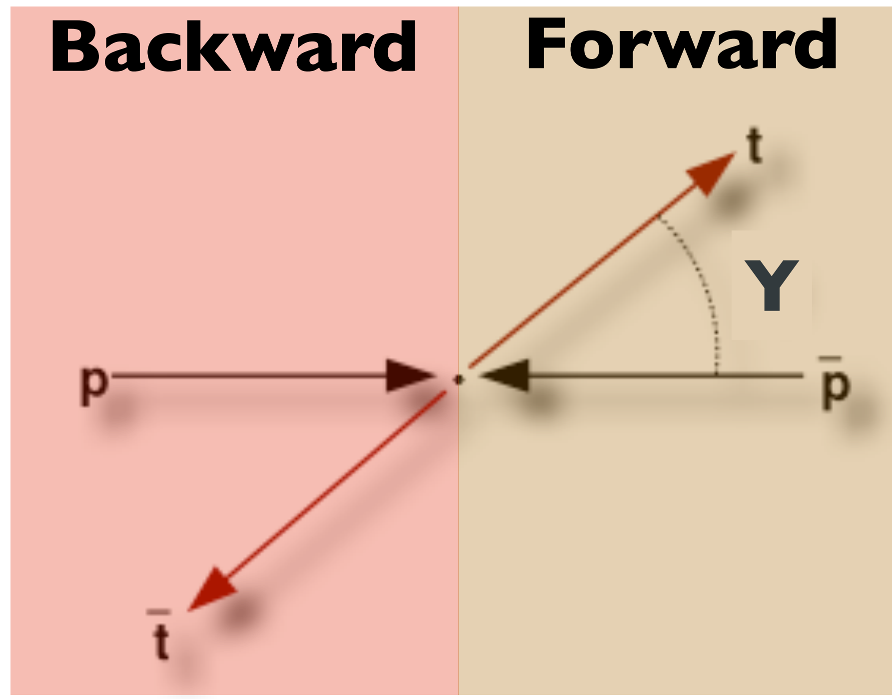




1 Electron or Muon ($E_T \geq 20$ GeV, $\|\eta\| < 1.1$)
Large "Missing" Energy (Et $\geq$ 20 GeV)
$\geq$ 4 Jets (Et $\geq$ 20 GeV, $\|\eta\| < 2.0$)
At least 1 Jet with displaced secondary vertex (Evidence of a 'b'-jet)

1300 Events (5.3 fb^{-1})
20 % Background

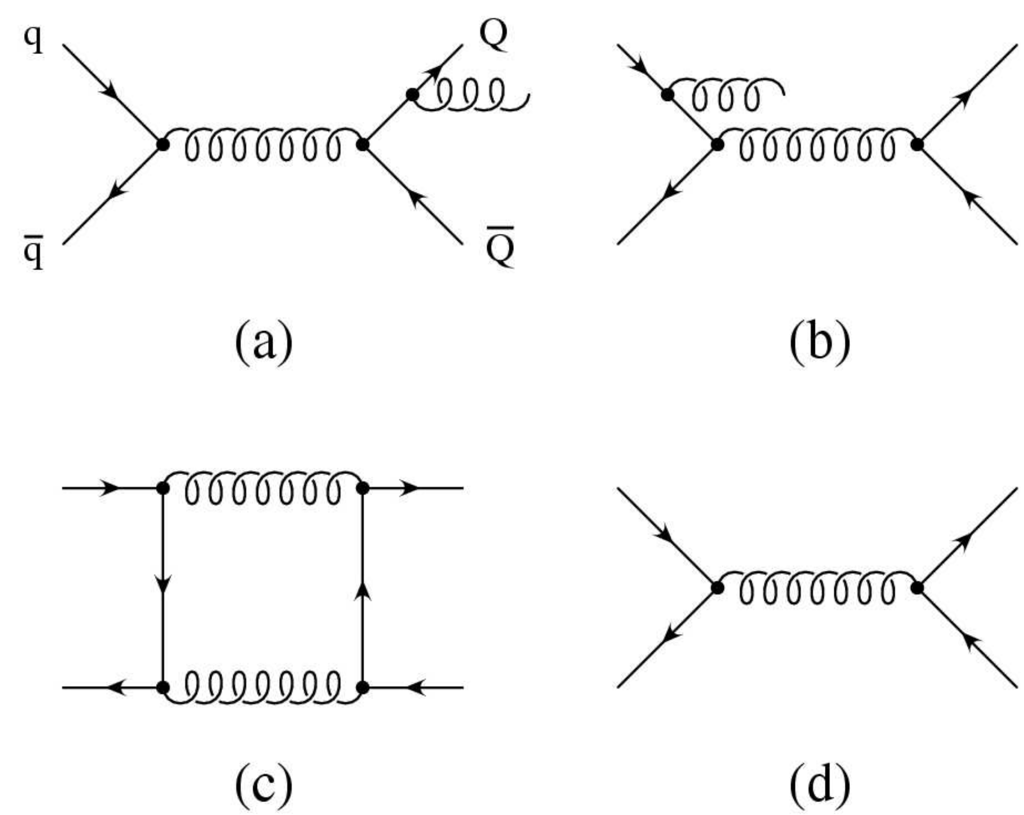
Top Quark Forward Backward Asymmetry



$$A_{FB} = \frac{N_{Y>0} - N_{Y<0}}{N_{Y>0} + N_{Y<0}}$$

Why Measure It?

- **Standard model predicts small (~6%) asymmetry**
- **Evidence of new particles beyond our energy reach can appear in asymmetry measurements**



Kuhn, Rodrigo
PRL 81,89 (1998)

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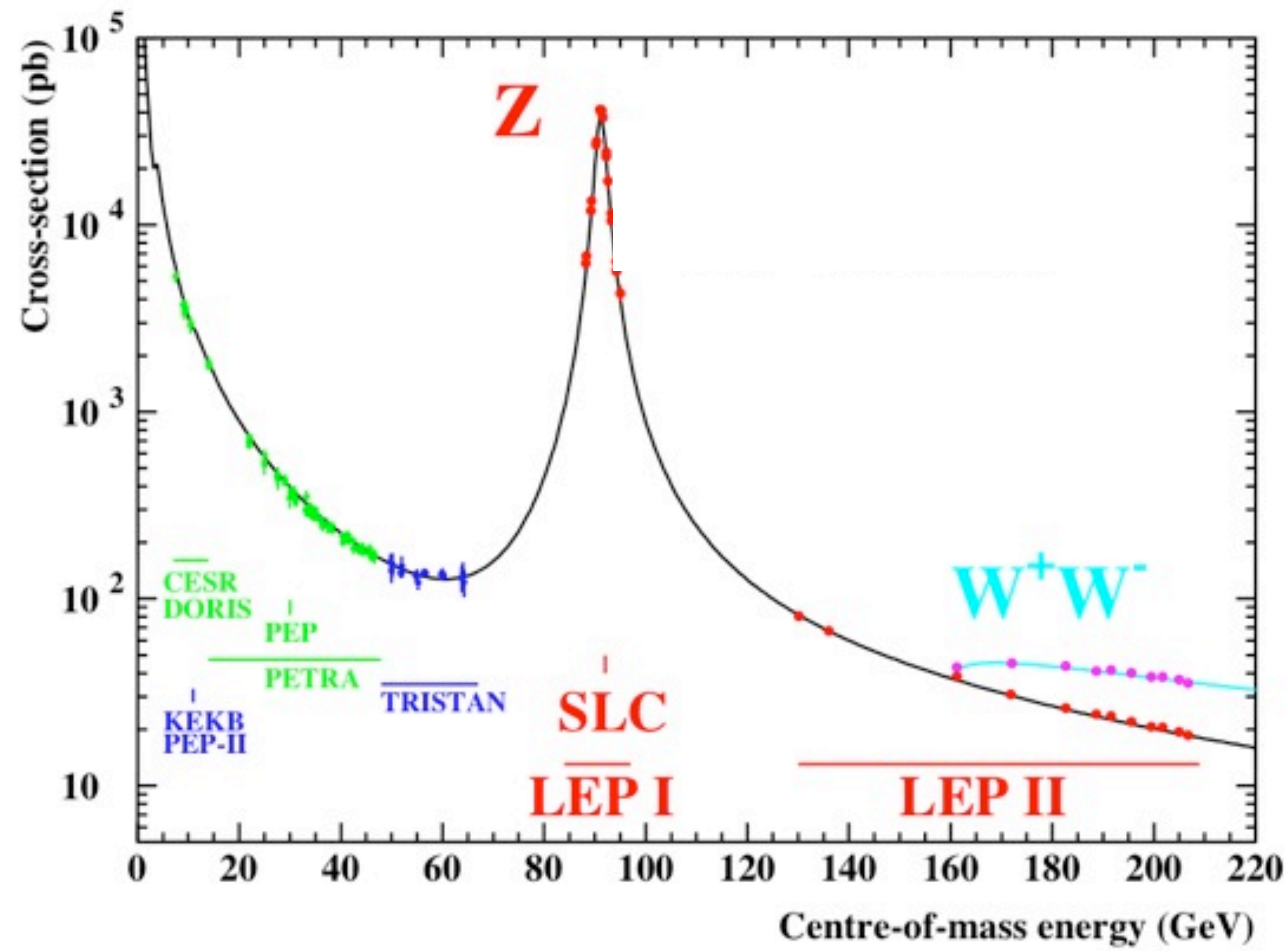

Why Measure It?

- Standard model predicts sm
- Ev
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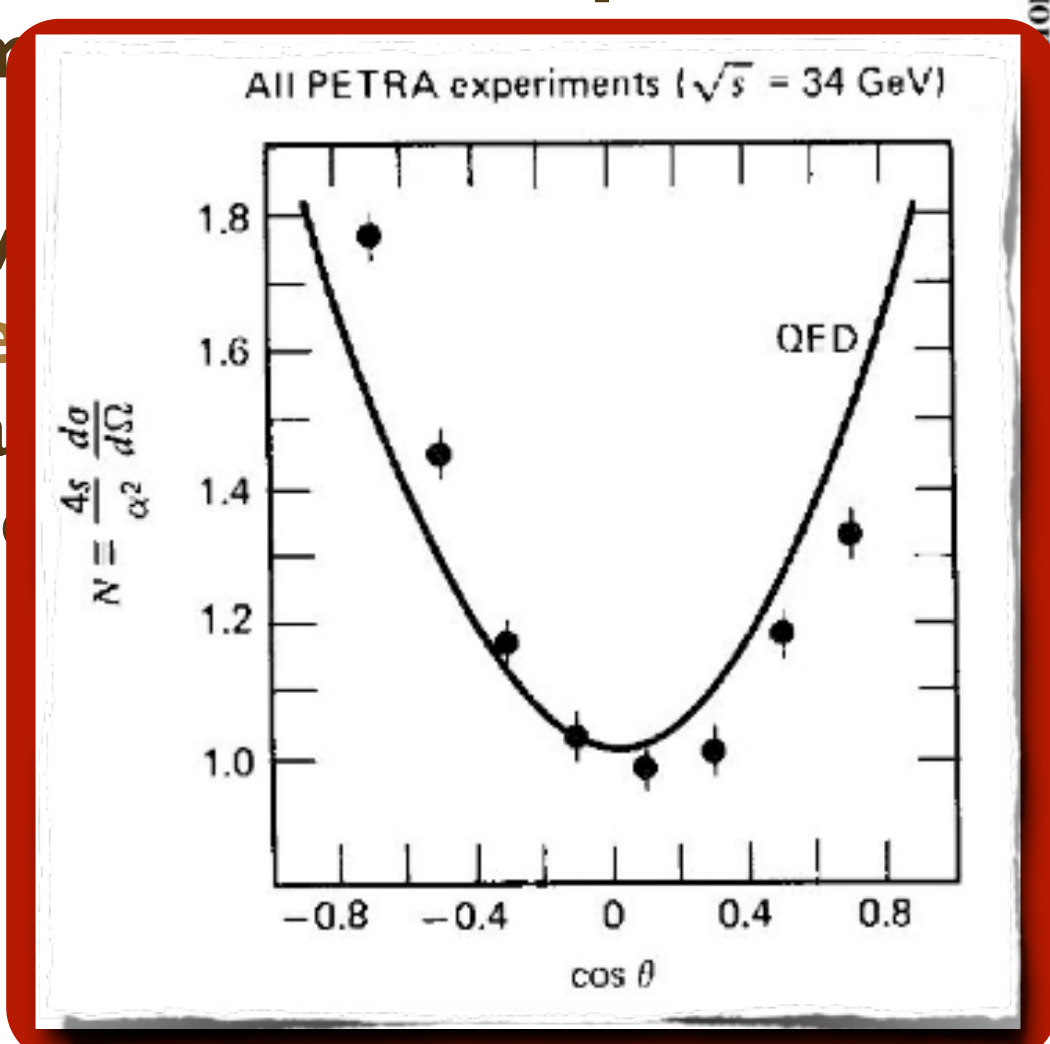
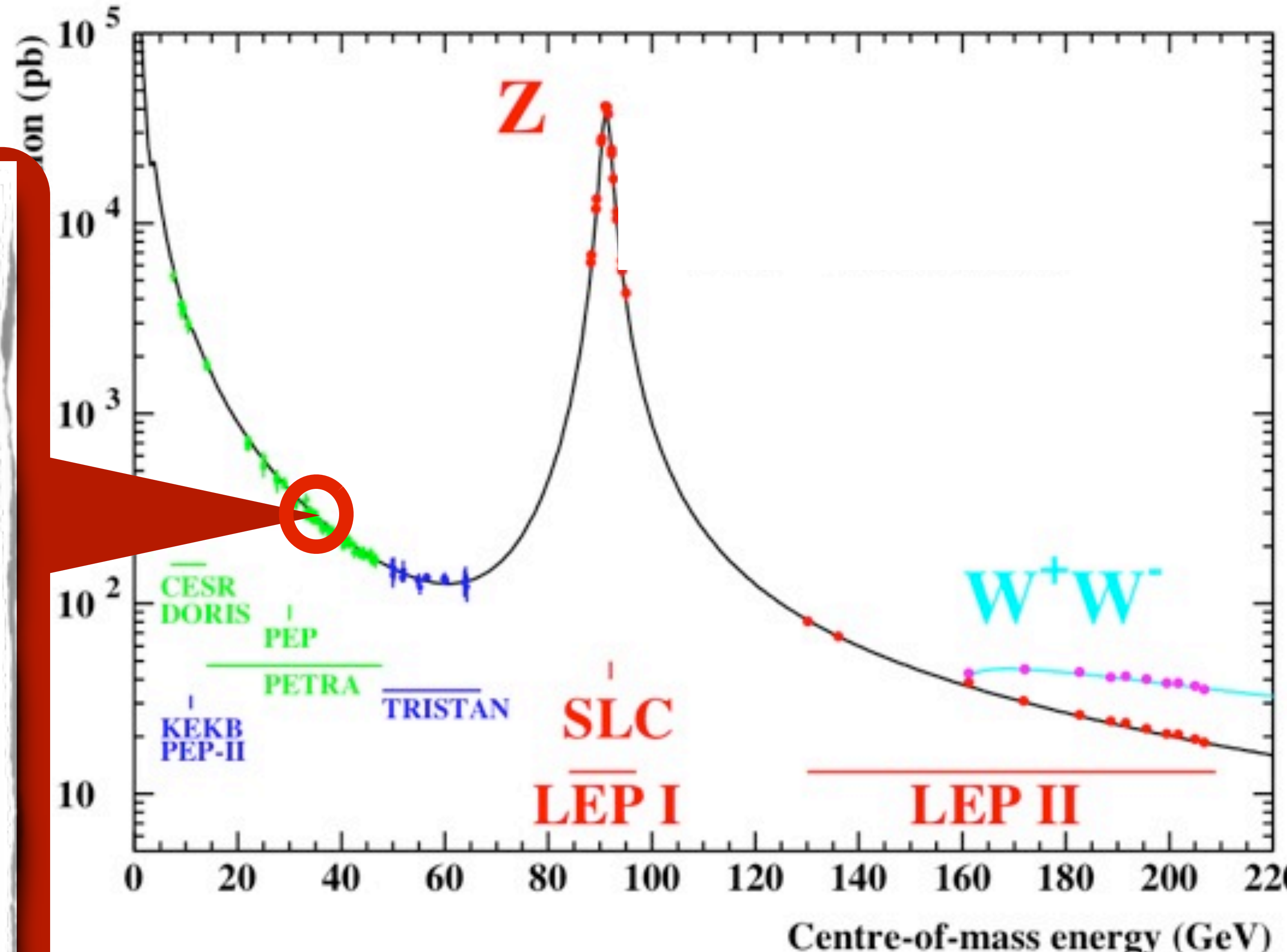
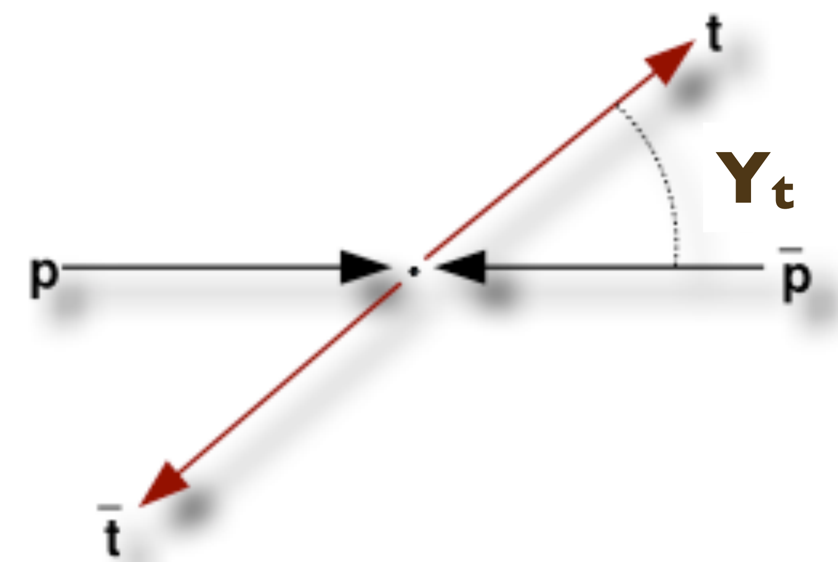


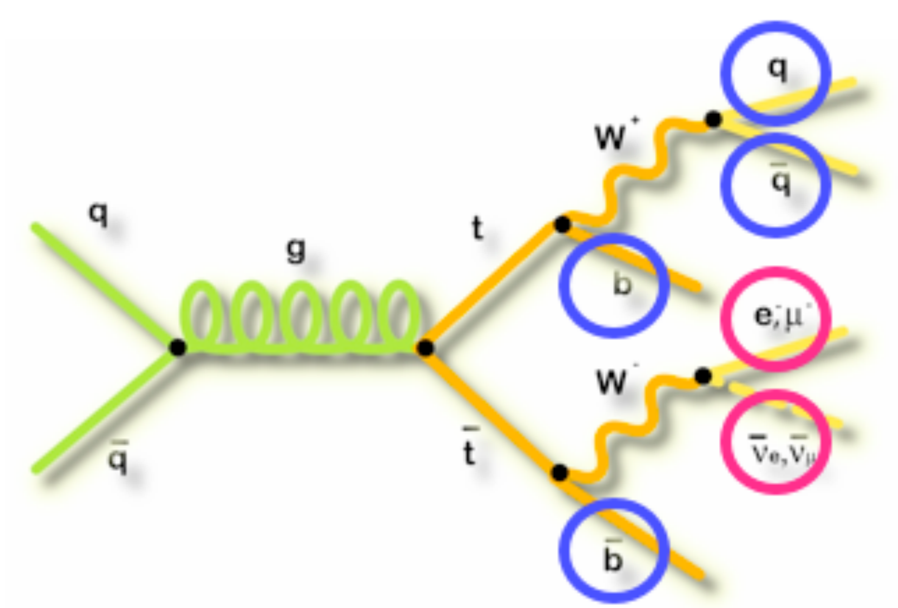


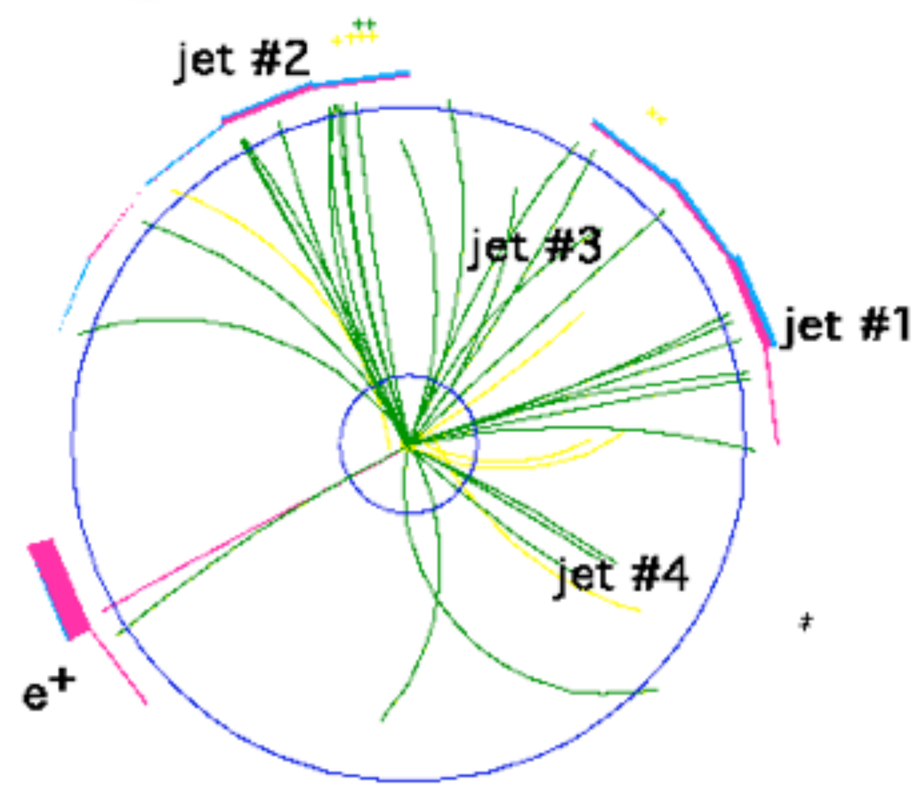
Reconstructing the Top Direction

- **Reconstruct the top direction from the observables in the detector**

- **Algorithm used to match jets to partons → just add 4-vectors to get top direction**







Reconstructing the Top Direction

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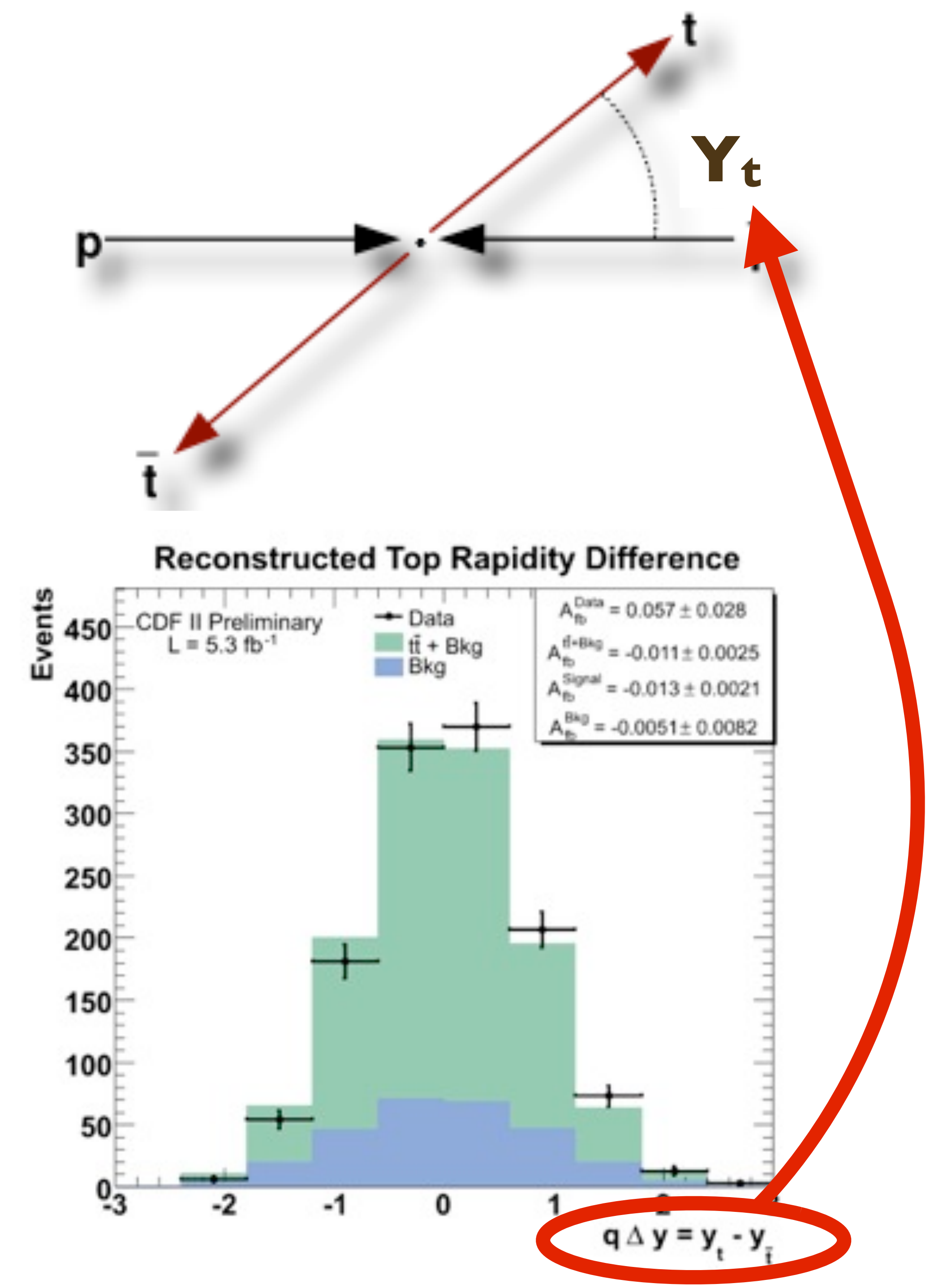
- **Algorithm used to match jets to partons ➔ just add 4-vectors to get top direction**



Measurement

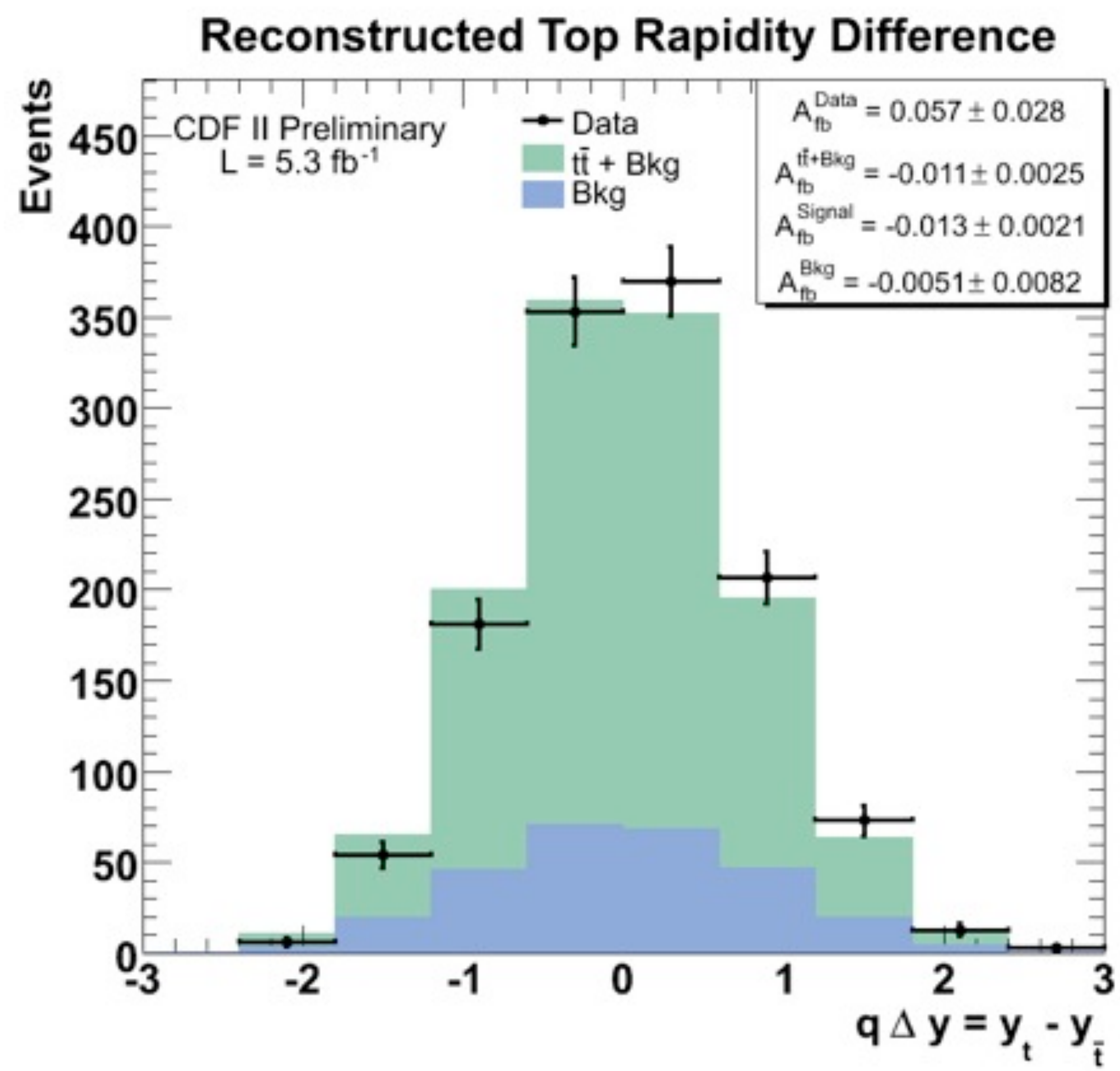
$A_{FB} = 16 \pm 7_{stat} \pm 2_{syst}$ %

5.3 fb^{-1}

Directly comparable to SM

$A_{FB}^{Theory} = 6 \pm 1$ %

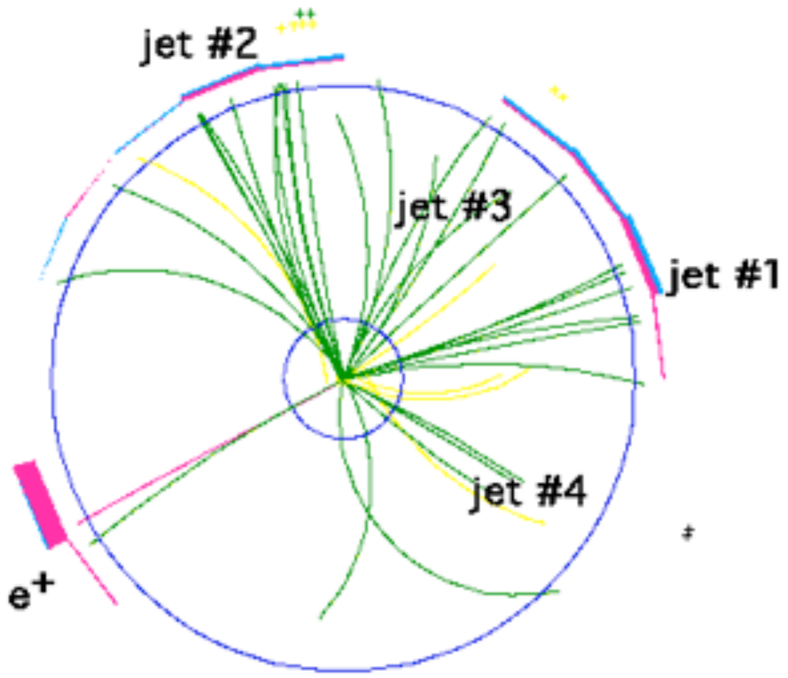
Kuhn, Rodrigo PRL 81,89 (1998)

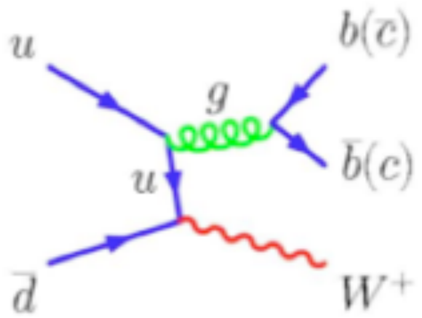


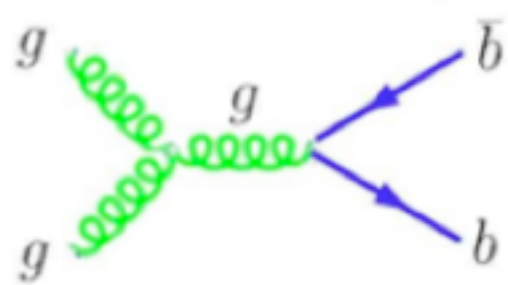
Too much Top?

- Using 4.3 fb^{-1}, select 1390 Events
- Predict ~ 1400
- ~ 28% background

Process	Prediction
W+Jets	269
QCD	74
Other	57
$t\bar{t}$ (7.4 pb)	1000
Data	1390







Rate of Top Production

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

Acceptance

From Simulation

Integrated Luminosity

4.3 fb^{-1}

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W+Jets	269
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W+Jets	269
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Other	57
$t\bar{t}$ (7.4 pb)	1000
Data	1390

σ_{tt} = 7.2 ± 0.8 pb

$$\frac{\Delta\sigma}{\sigma} = 11\%$$

$$\sigma_{t\bar{t}}^{\text{theory}} = 7.4 \pm 0.7 \ \text{pb}$$

Luminosity Uncertainty

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

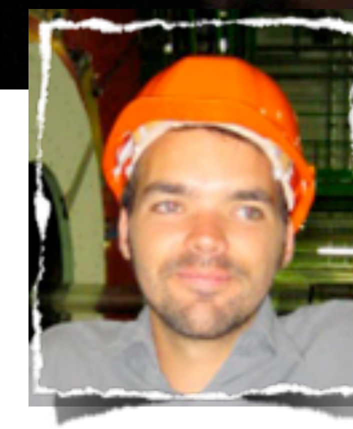
Acceptance

From Simulation

Integrated Luminosity

4.3 fb^{-1}

Luminosity Uncertainty



$$R = \frac{\sigma_{t\bar{t}}}{\sigma_Z} = \frac{\frac{N_t - B_t}{A_t \cdot \cancel{L}}}{\frac{N_Z - B_Z}{A_Z \cdot \cancel{L}}}$$

Trading Luminosity systematic for uncertainty on Z cross section

$$\sigma_{t\bar{t}} = R \cdot \sigma_Z^{theory}$$

Precision Cross Section

σ_{tt} = 7.7 ± 0.5 pb

$$\frac{\Delta\sigma}{\sigma} = 6.5\%$$

$$\sigma_{\mathbf{t\bar{t}}}^{\mathbf{theory}} = \mathbf{7.4 \pm 0.7\ \ pb}$$

Precision Cross Section

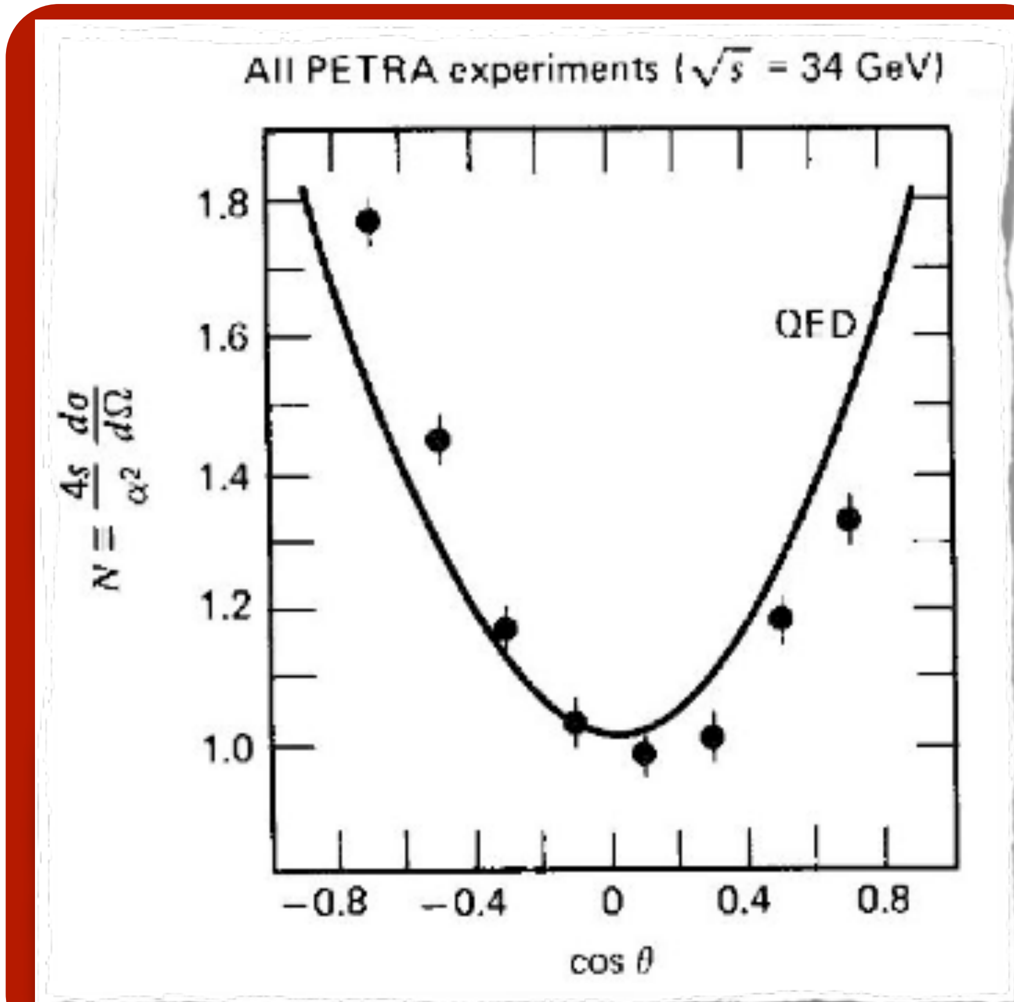
σ_{tt} = 7.7 ± 0.5 pb

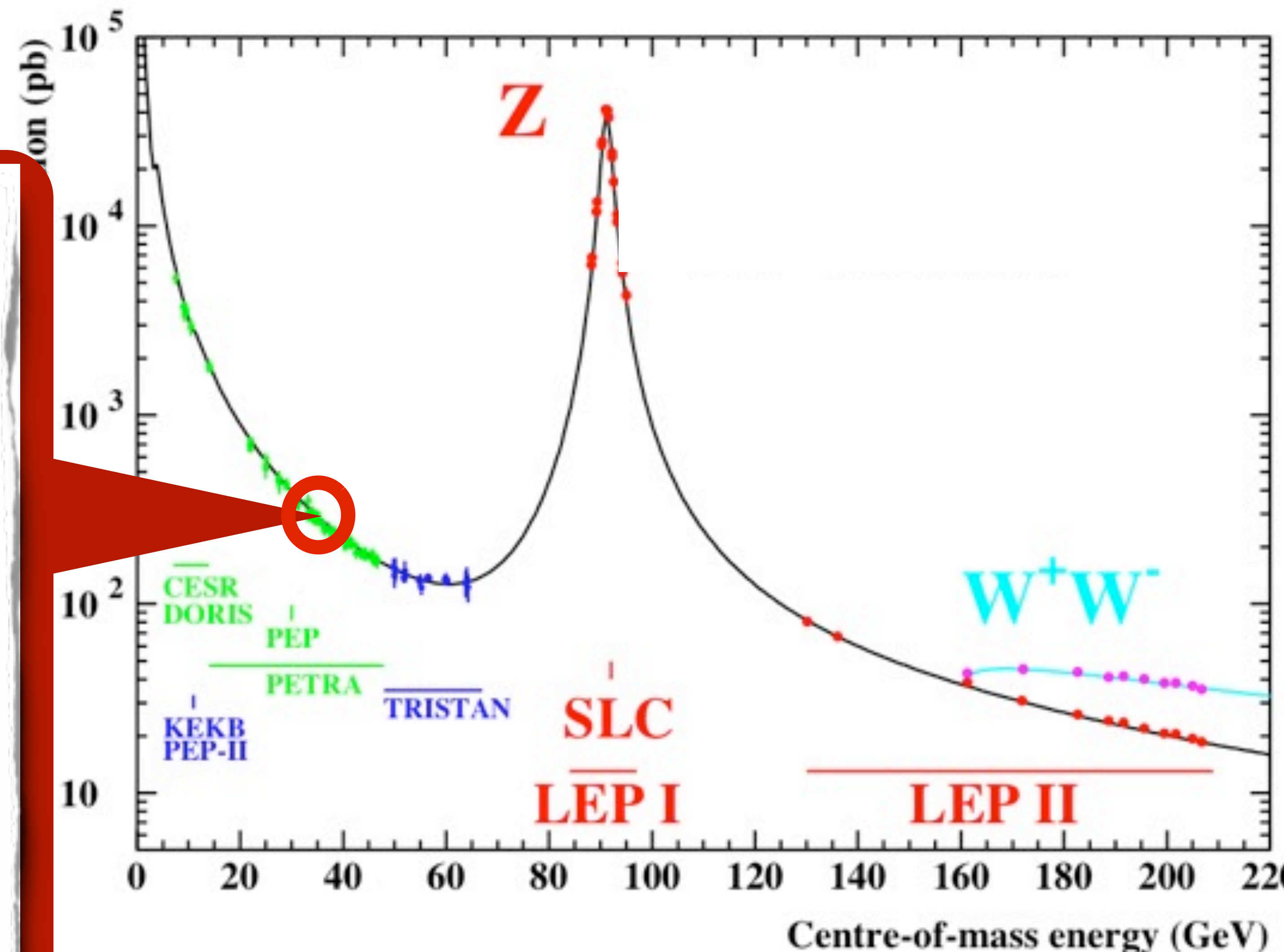
$$\frac{\Delta\sigma}{\sigma} = 6.5\%$$

$$\sigma_{\mathbf{t\bar{t}}}^{\mathbf{theory}} = 7.4 \pm 0.7 \ \ \mathrm{pb}$$

CDF Run II Goal is $\Delta\sigma/\sigma$ < 10%

Anything obvious at High Energy?





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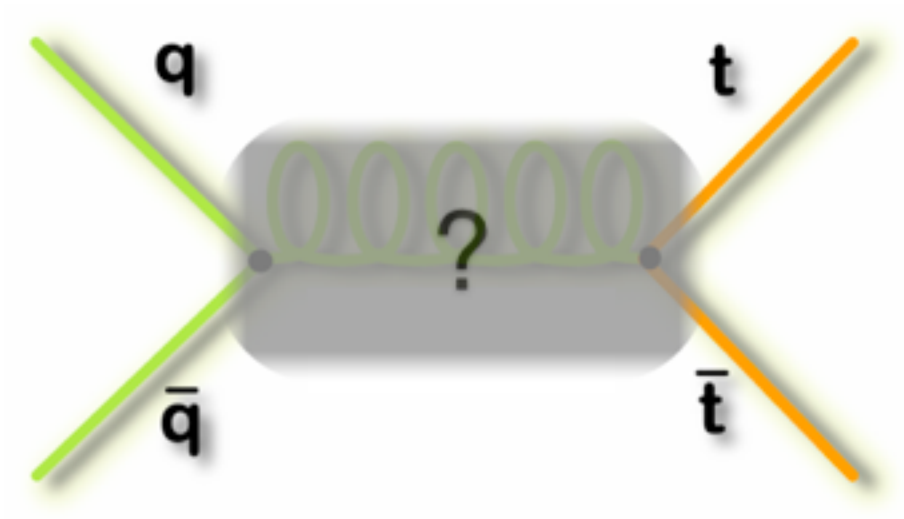
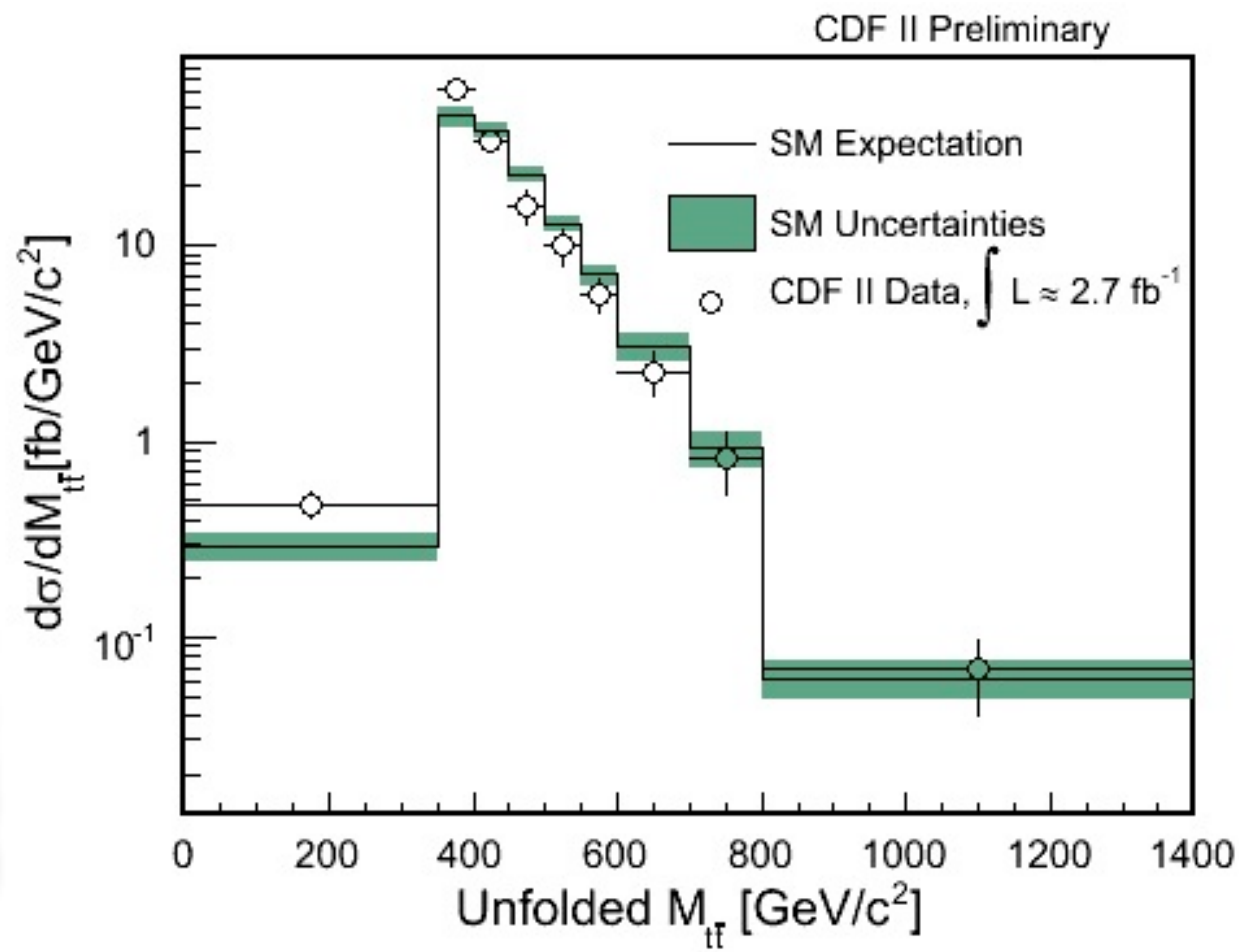
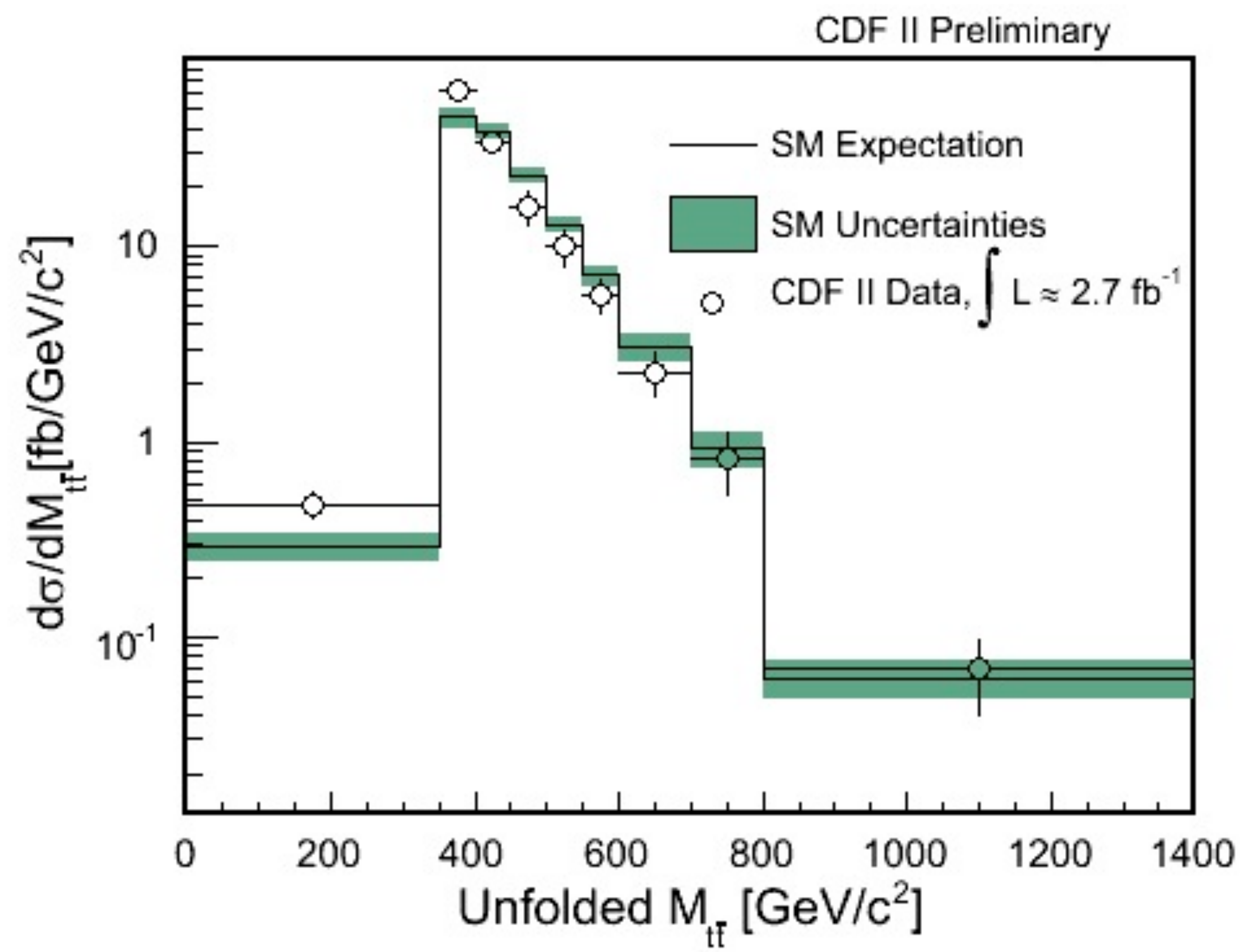


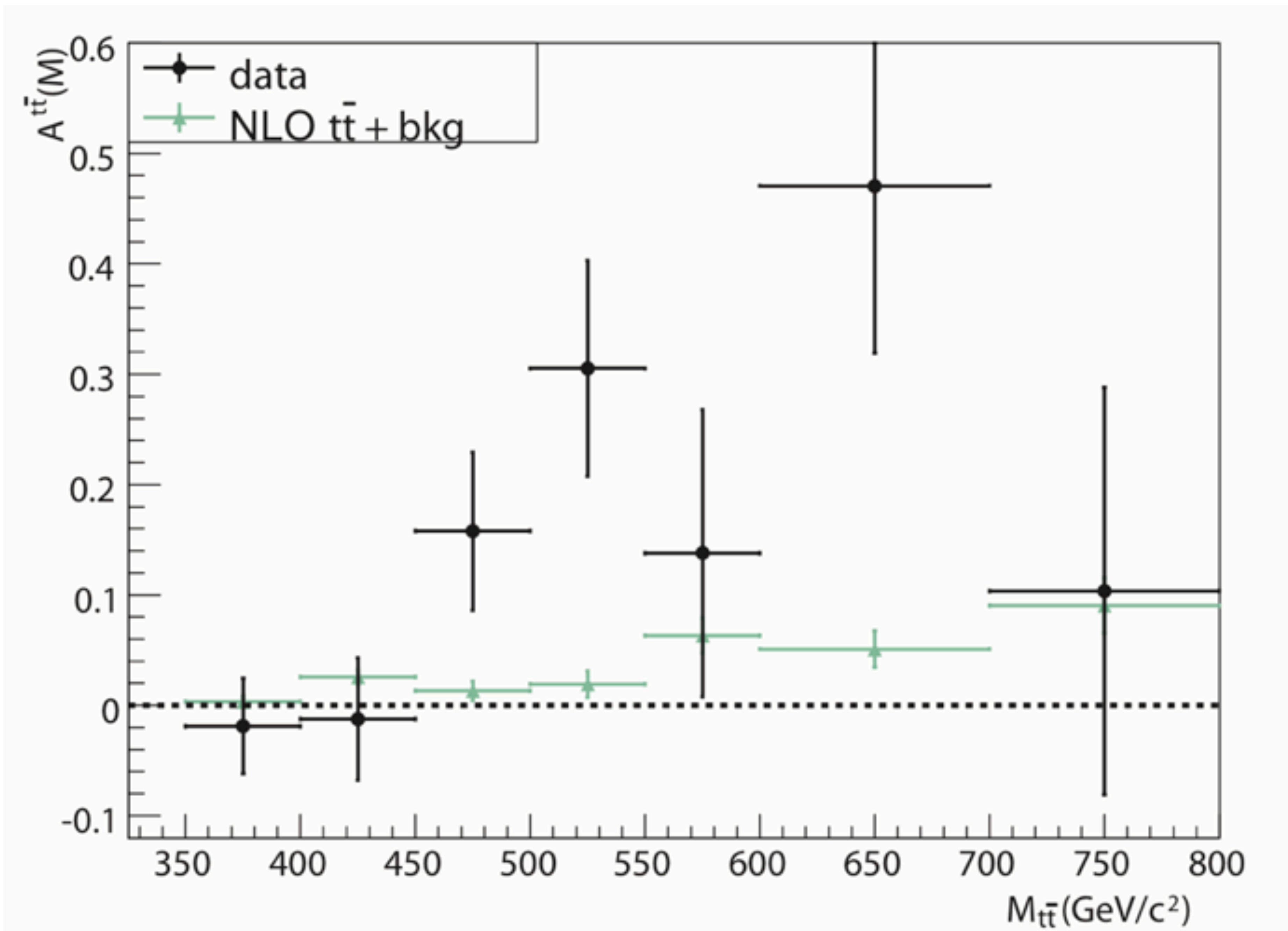


$M_{t\bar{t}}$ Dependence

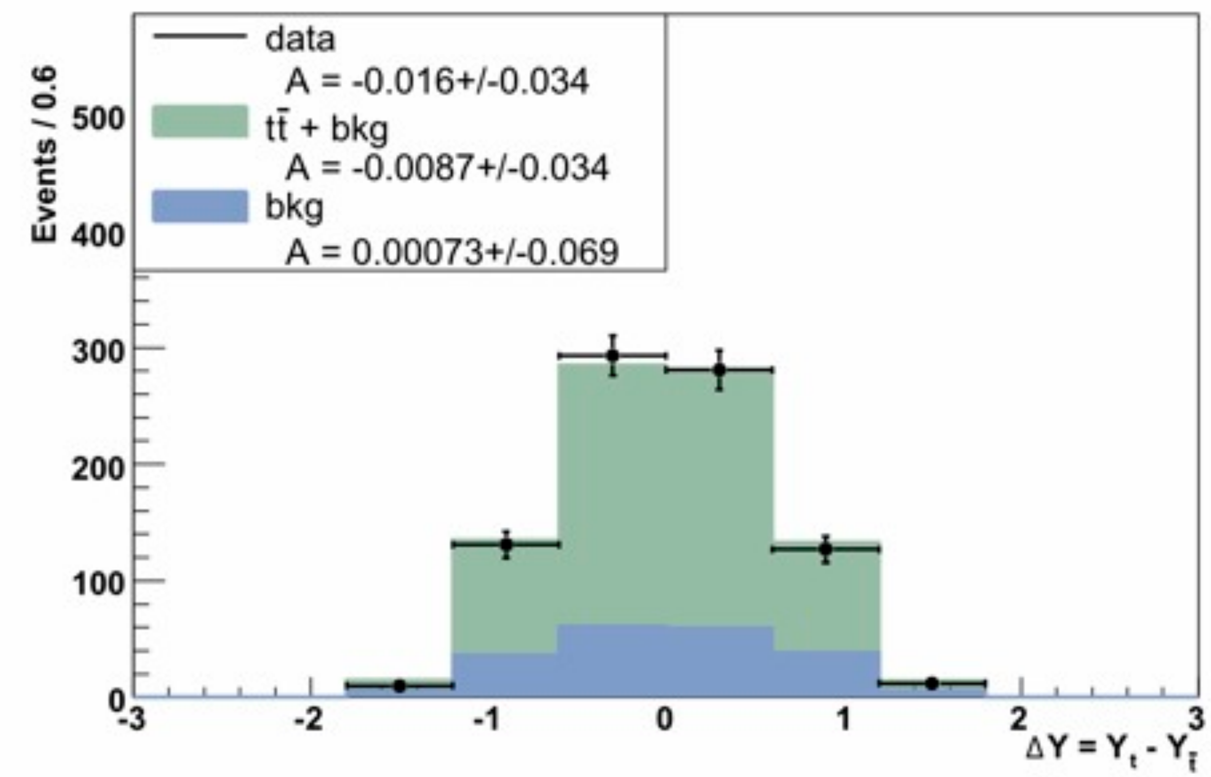
- **Study the asymmetry vs. the mass of the tt system (M_{tt})**
- **Simply divide sample into high/low M_{tt}**
- **450 GeV most sensitive point ➔ based on MC studies**

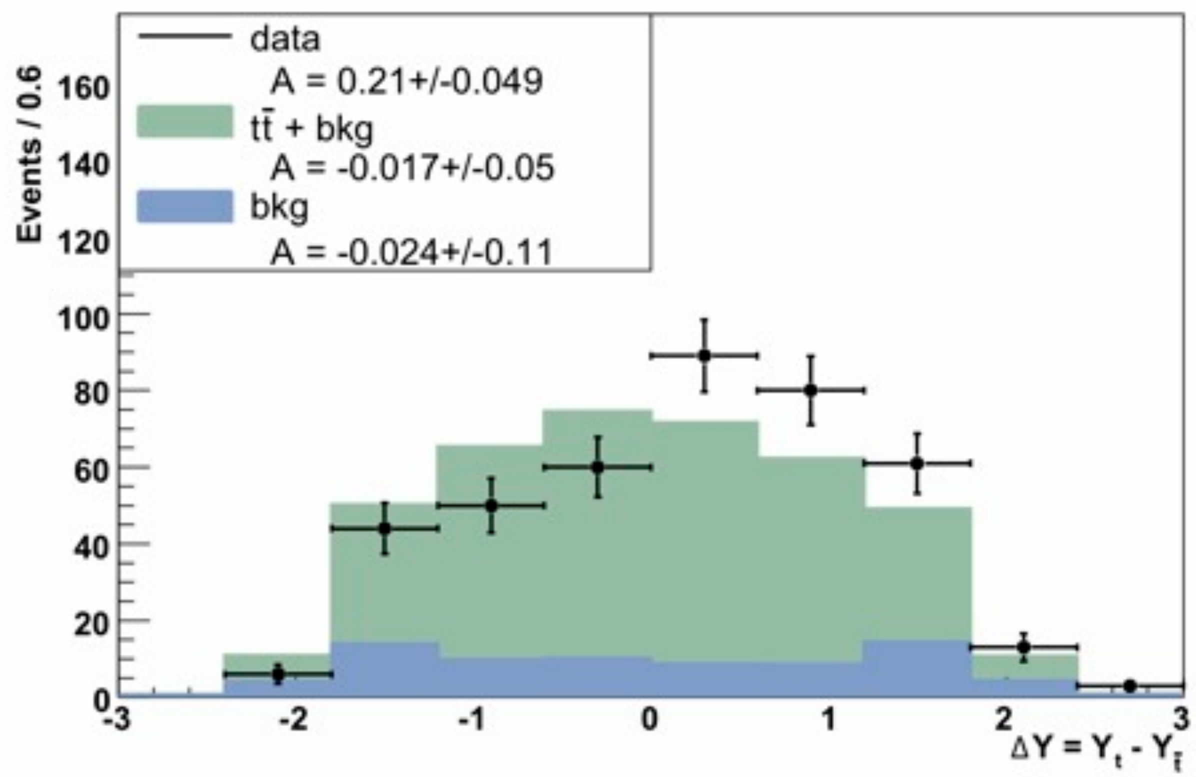


$M_{t\bar{t}}$ Dependence



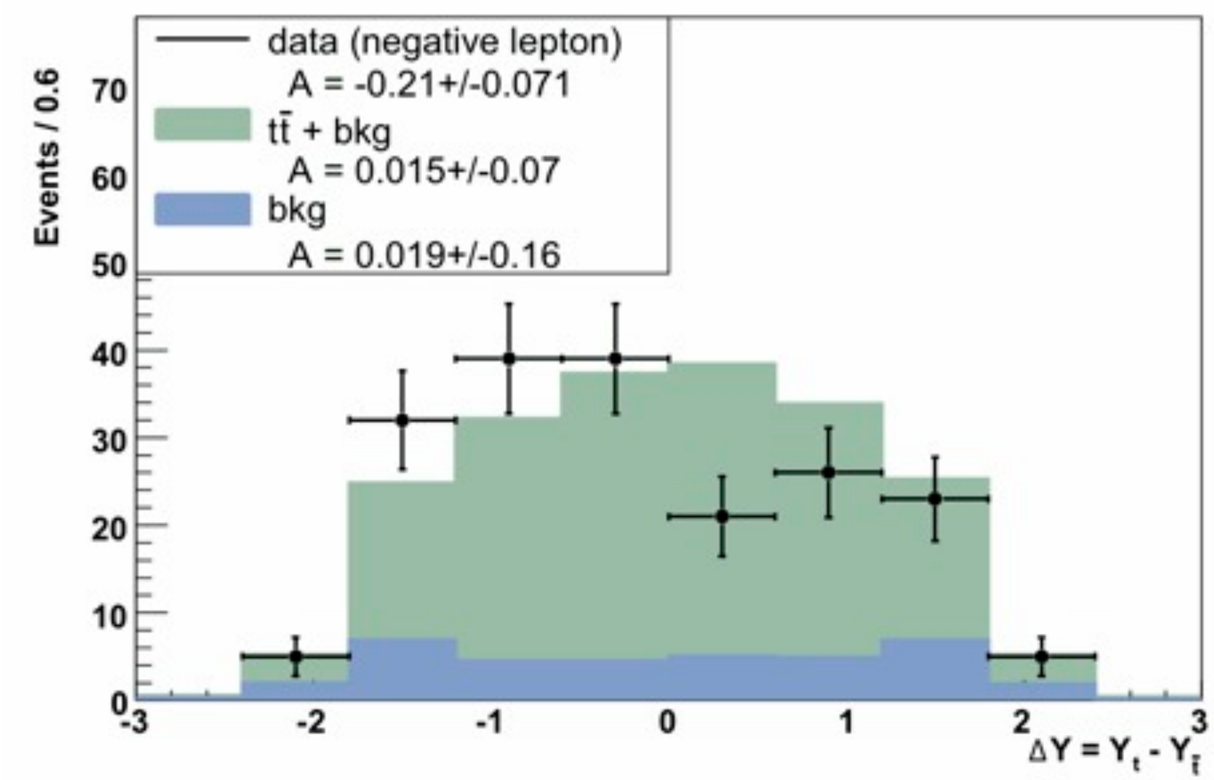
$M_{t\bar{t}}$ Dependence

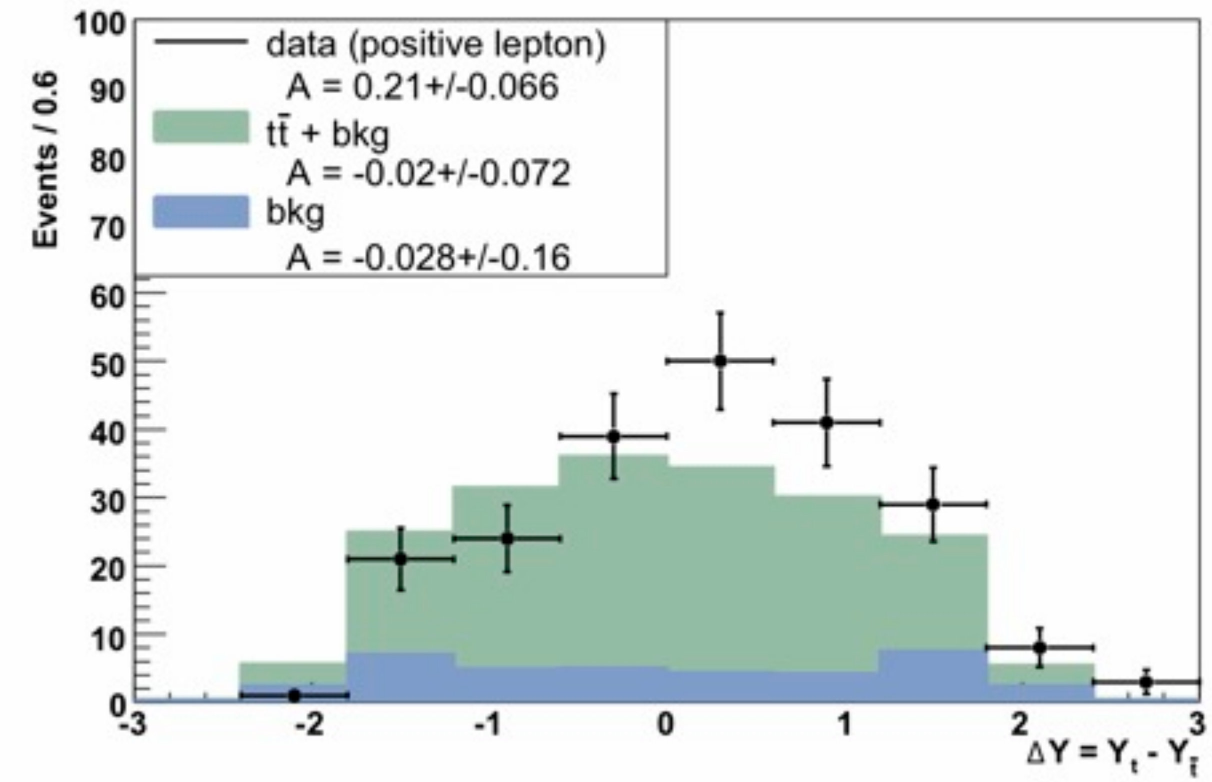




	Inclusive	M < 450 GeV	M > 450 GeV
Data	5.7 ± 2.8 %	-1 ± 3 %	21 ± 5 %
SM MC	2 ± 0.4 %	1 ± 0.6 %	3 ± 0.7 %

$M_{t\bar{t}}$ Dependence





	Inclusive	M < 450 GeV	M > 450 GeV
AFB +	6.7 ± 4 %	-1 ± 5 %	21 ± 7 %
AFB -	-5 ± 4 %	2 ± 5 %	-21 ± 7 %

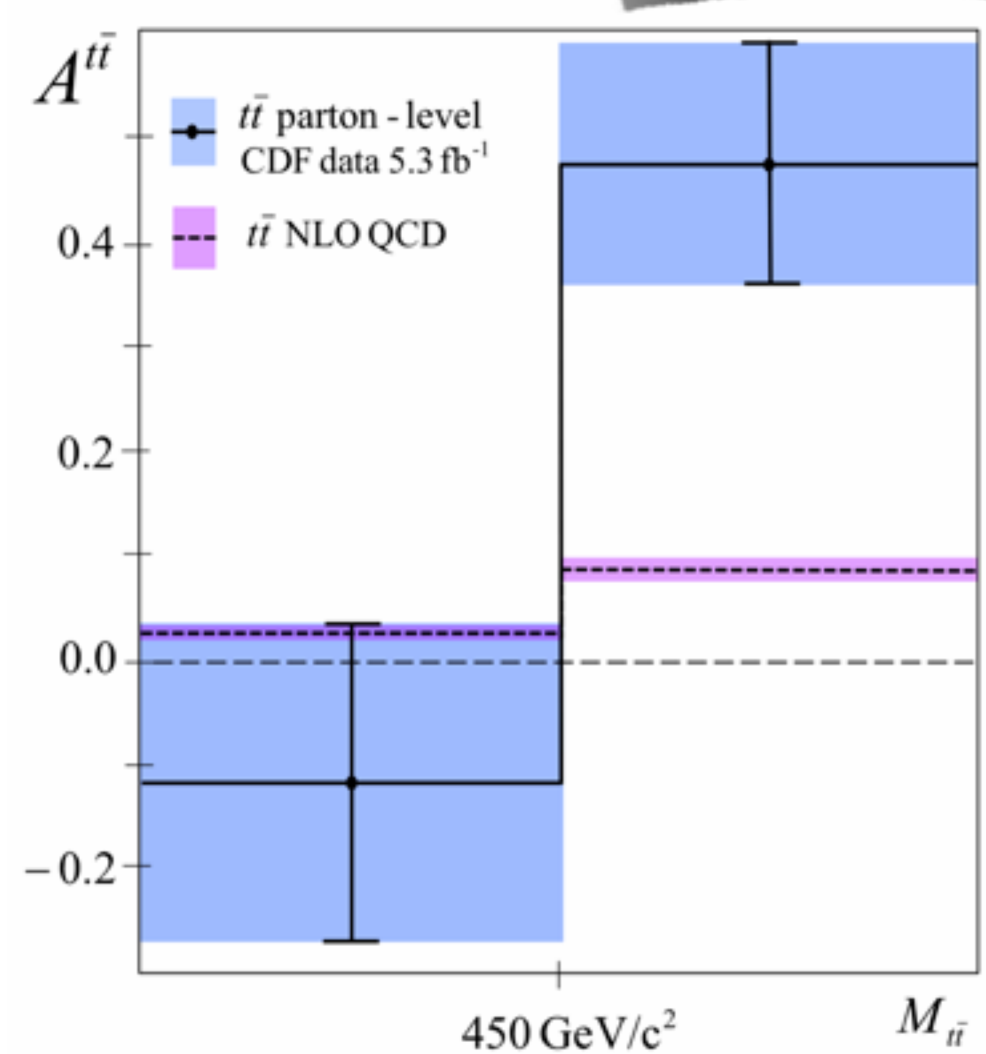
$M_{t\bar{t}}$ Dependence

- **Unfold M_{tt} dependence back to parton level**

A_{FB} = 48 ± 11$_{stat+syst}$ %

5.3 fb^{-1}

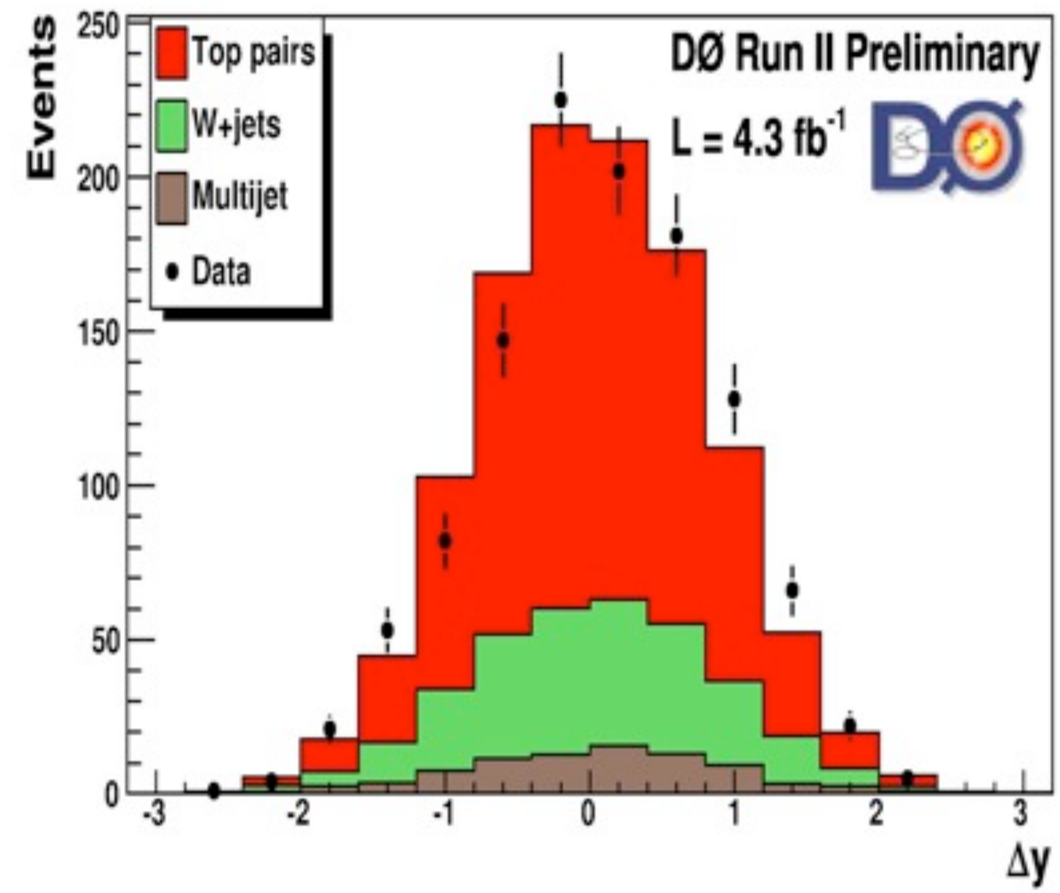
A_{FB}^{Theory} = 9 ± 1 %



Other Signs?

- DØ collaboration has also performed this measurement
- DØ compares the result to the SM as seen by the detector (only corrects for backgrounds)

$A_{FB}^{data\text{-}bkg} = 8 \pm 4_{stat+sys}$ %



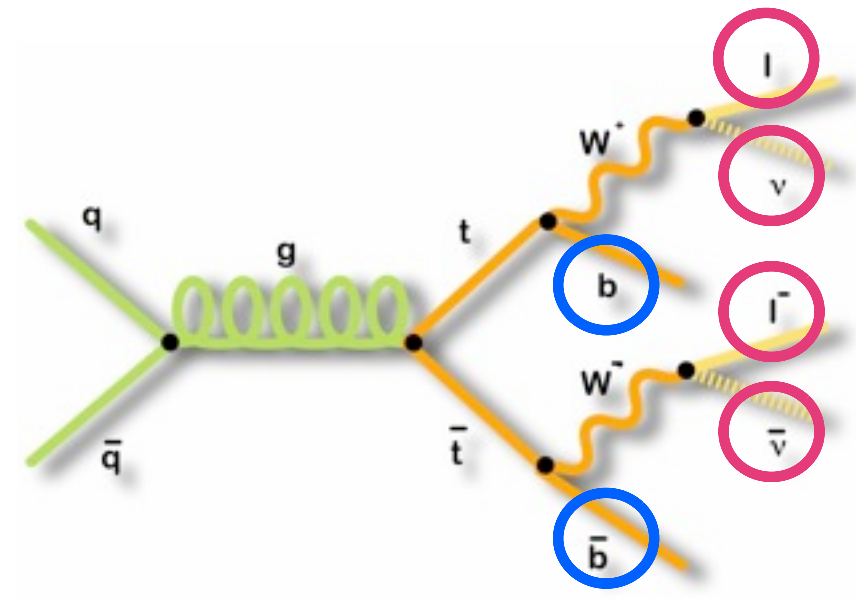
$A_{FB}^{mc@nlo} = 1^{+2.0}_{-1.0}$ %

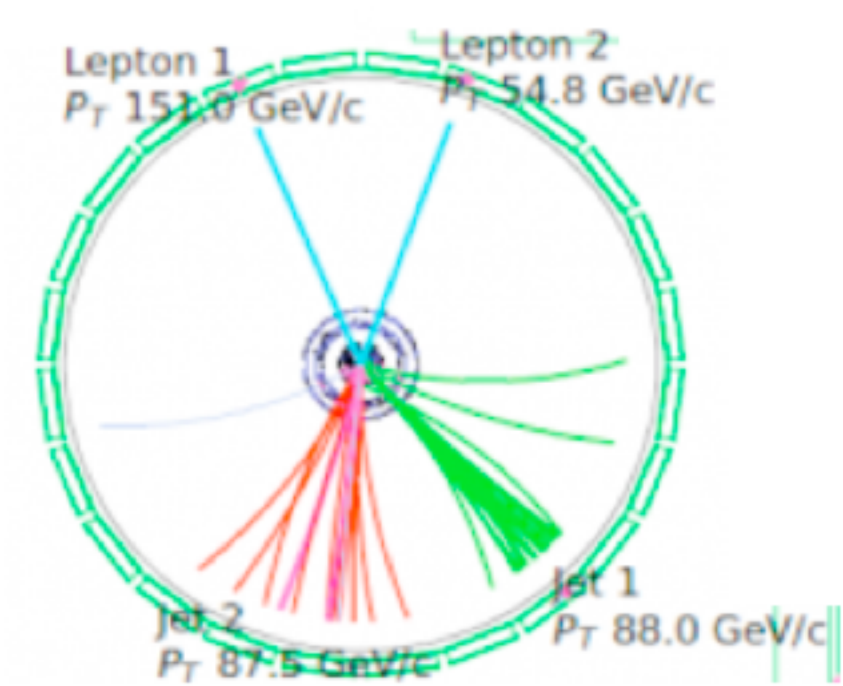
$A_{FB}^{CDF} = 7.5 \pm 3.7$ %

A_{FB} in Dileptons

- **Alternative channel to previous measurement in single lepton+jets events**

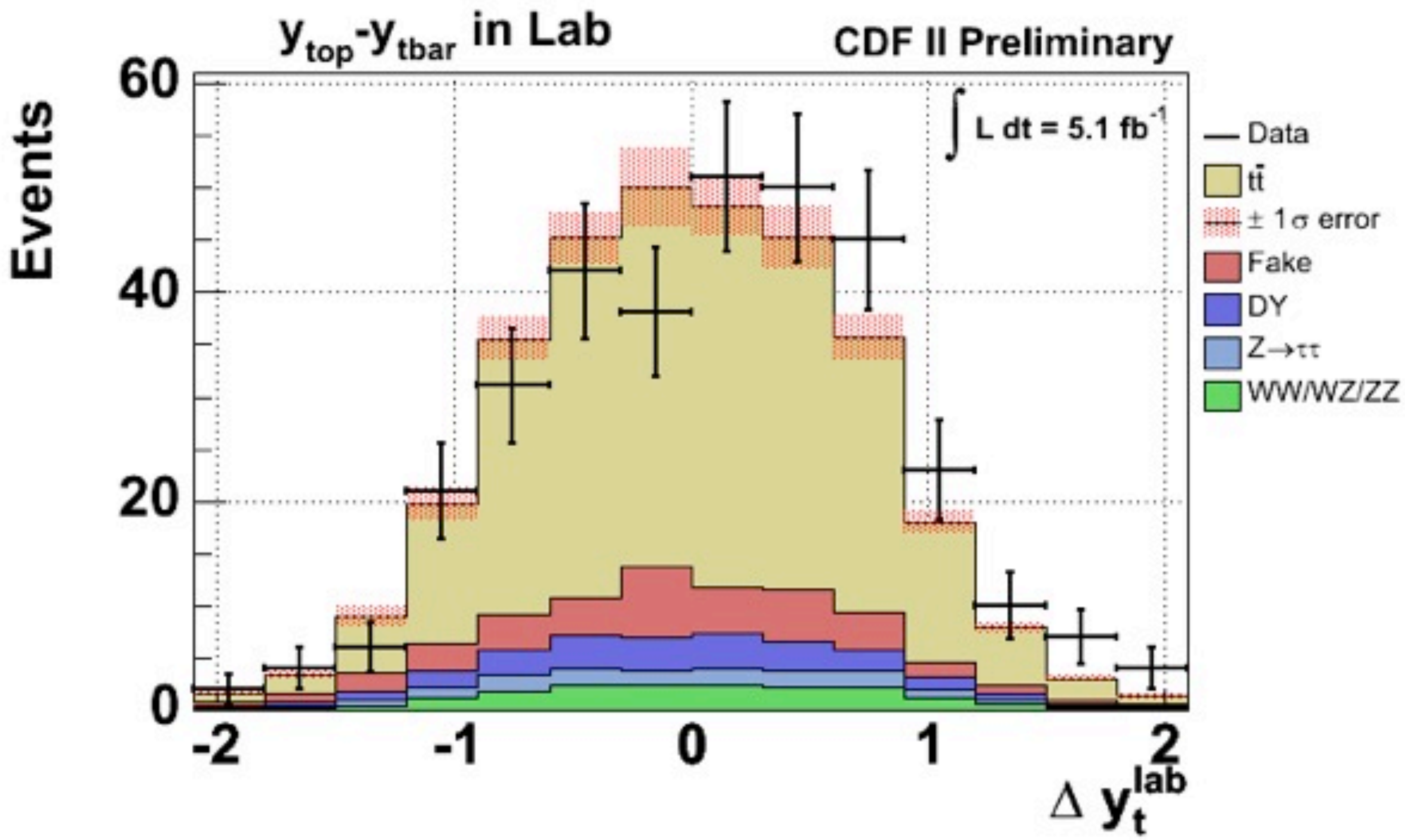
- **Independent events using different reconstruction algorithm**





2 Leptons ($E_T \geq 20$ GeV, $\lvert\eta\rvert < 1.1$)
Large "Missing" Energy ($E_T \geq 50$ GeV)
≥ 2 Jets ($E_T \geq 15$ GeV, $\lvert\eta\rvert < 2.5$)
$\sum E_T$ (jets, leptons) > 200 GeV

A_{FB} in Dileptons



$A_{FB} = 42 \pm 15_{stat} \pm 5_{syst}$ %

5.1 fb^{-1}

$A_{FB}^{Theory} = 6 \pm 1$ %

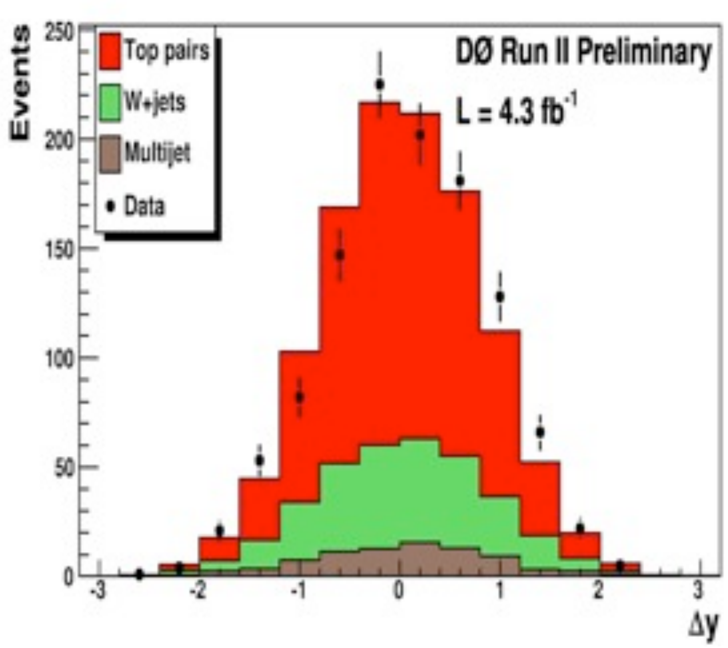
$A_{FB}^{l+Jets} = 16 \pm 7$ %

Summary of Results

Inclusive Asymmetry

A_{FB} = 8 ± 4 %

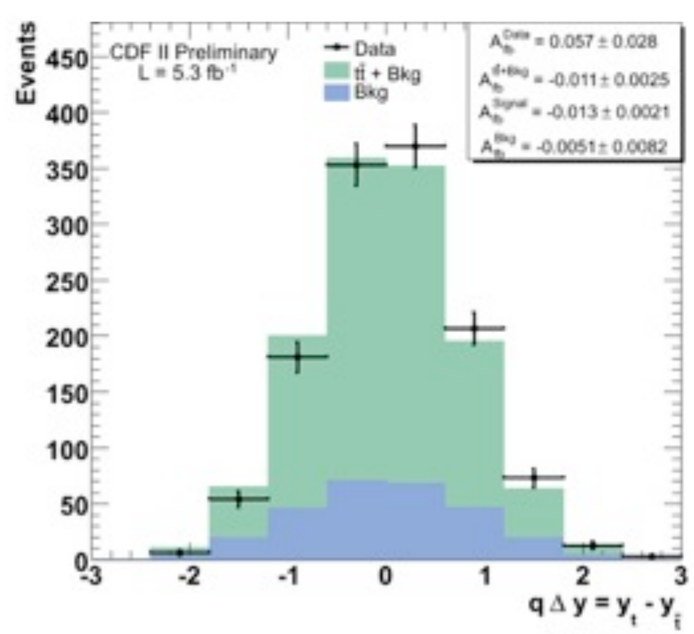
~ 2 σ (4 fb^{-1})



A_{FB}^{sm} ~ 1 %

A_{FB} = 16 ± 7 %

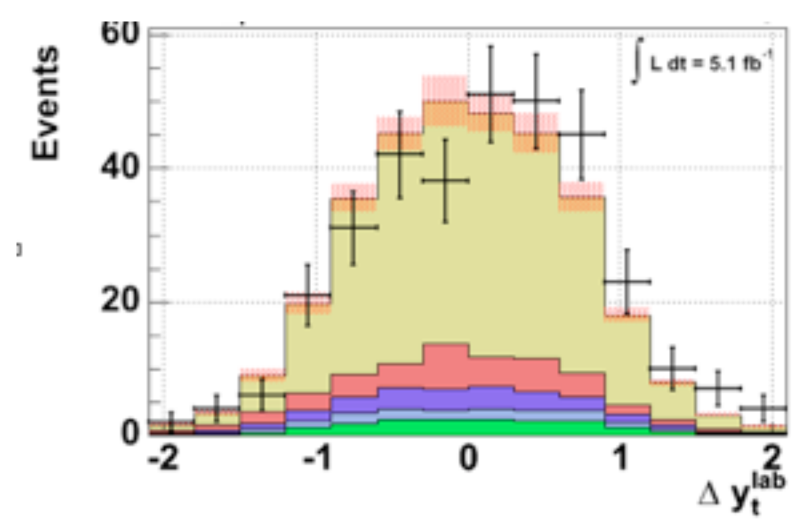
~ 2 σ (5 fb^{-1})



A_{FB}^{sm} ~ 6 %

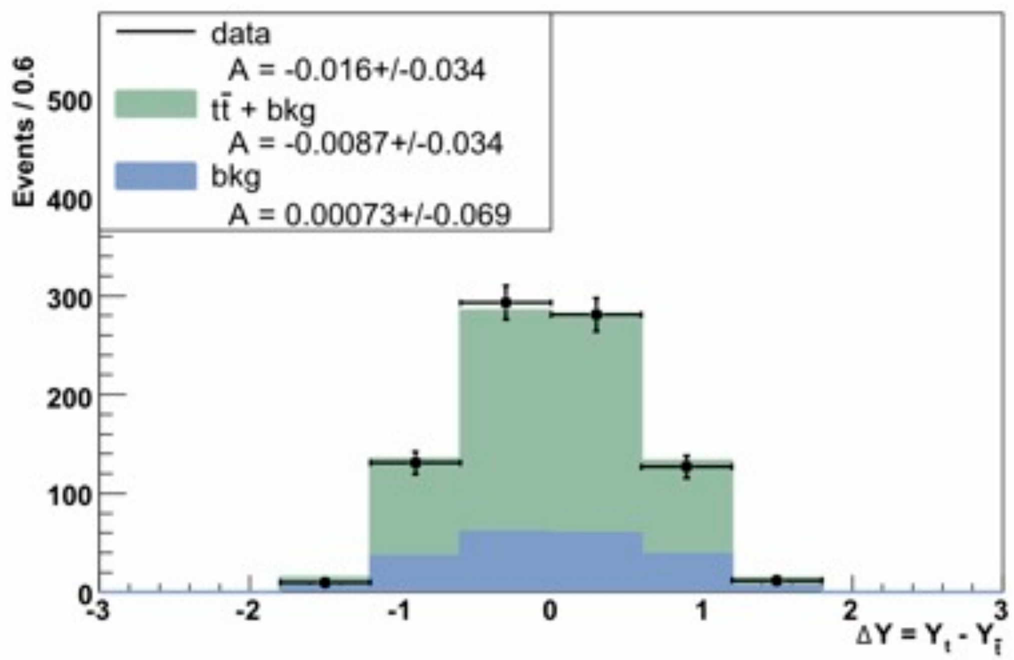
A_{FB} = 42 ± 16 %

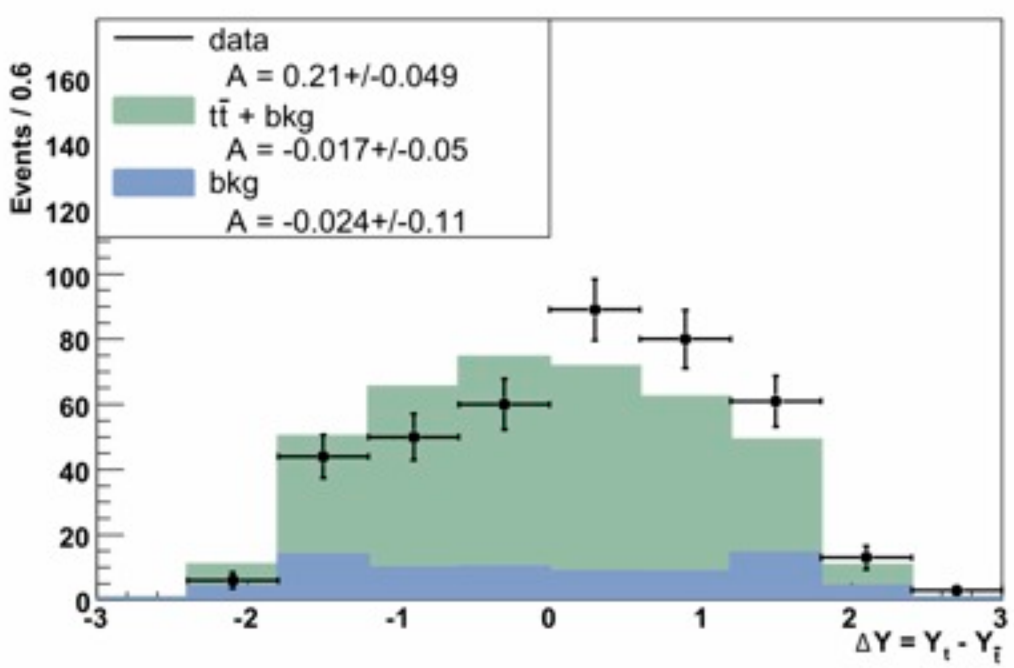
~ 2.7 σ (5 fb^{-1})



A_{FB}^{sm} ~ 6 %

Summary of Results





For M_{tt} > 450 GeV

A_{FB} = 48 ± 11$_{stat+syst}$ %

5.3 fb^{-1}

A_{FB}^{Theory} = 9 ± 1 %

What is A_{FB}?

What is A_{FB}?

I Have No Idea...

What's Next for A_{FB}

- Time and data - really need 4-5σ before we're sure it's not statistics
- D0 will tell us more - comparable results, study mass dependence, combination
- Correlated to other observables → LHC needs to see something

STAY TUNED!


Thanks!!!

Thanks!!!

Rob Roser

Robin Erbacher

Florencia Canelli

Veronica Sorin

Joey Huston

Kevin Lannon

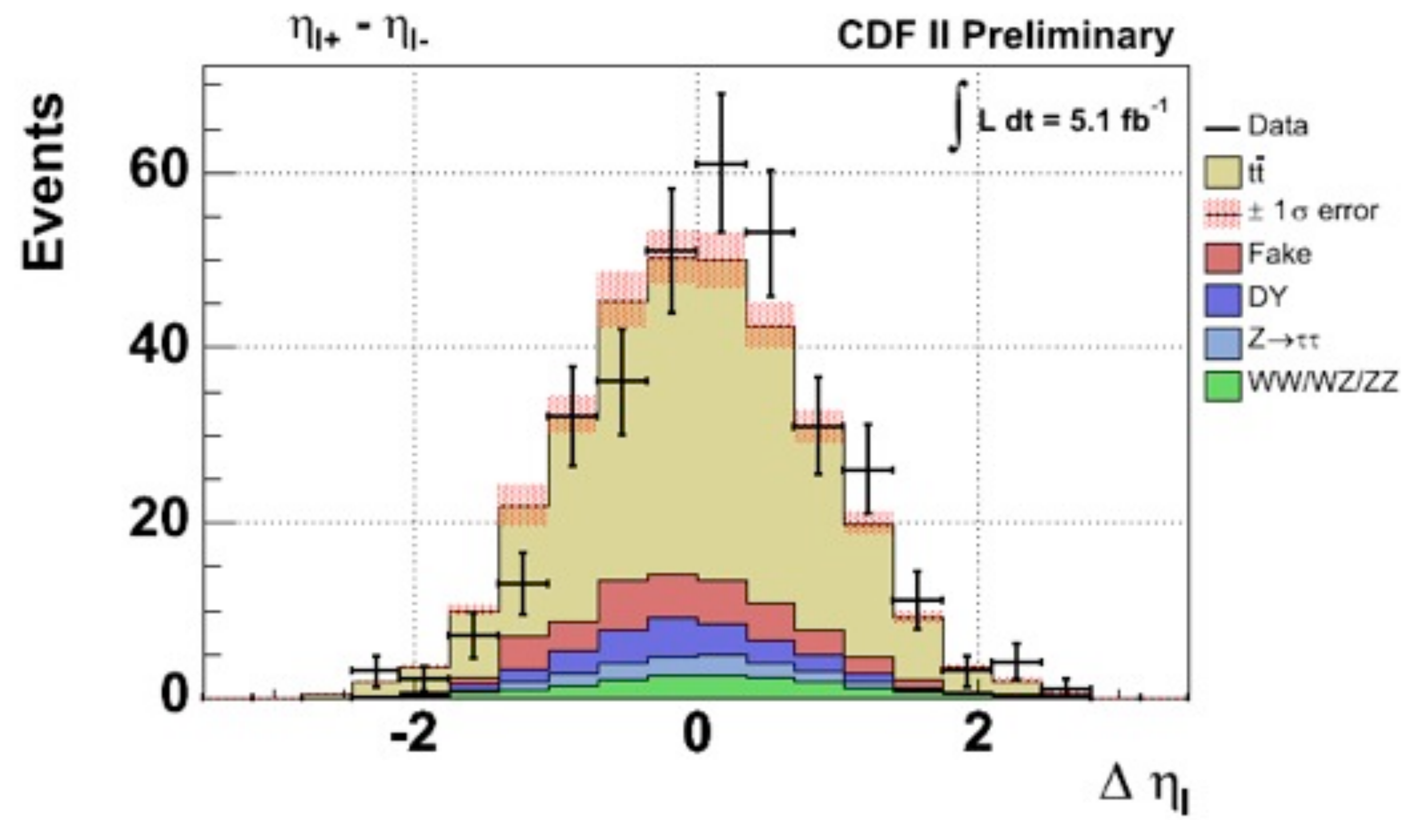
Dan Amidei

Andrew Ivanov

To the Entire CDF Collaboration and wider FNAL Community

A_{FB} in Dileptons

- **Top direction correlated with two leptons**
- **Much simpler than reconstruction algorithm - though correlated**
- **Significance remains**



$A_{FB}^{ll} = 14 \pm 5_{stat}\ \%$

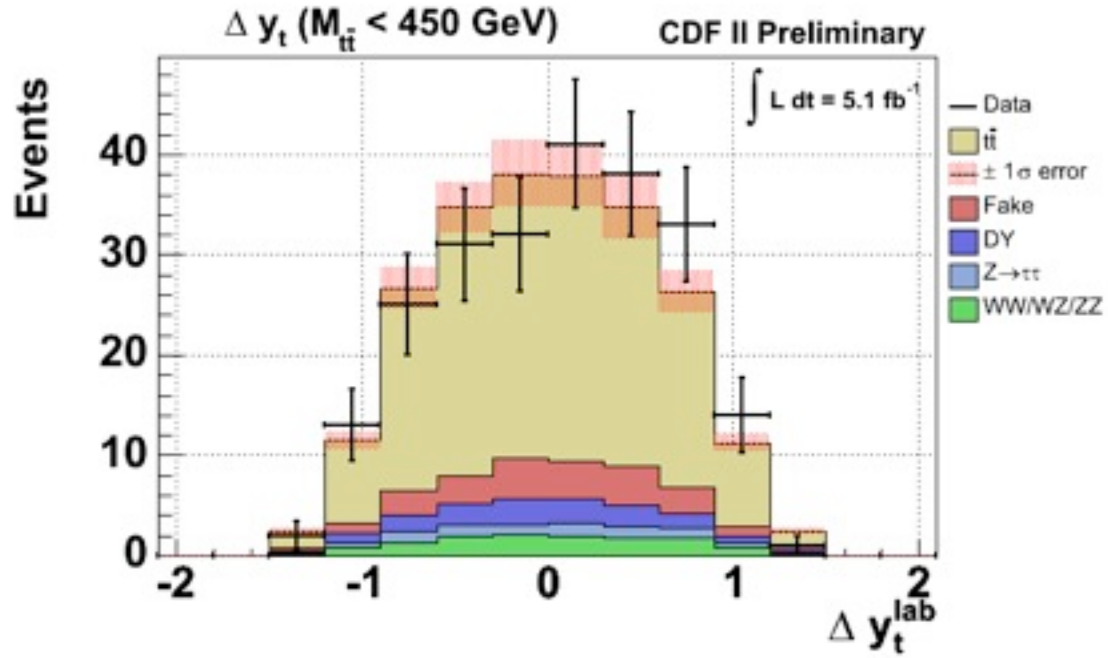
$5.1\ fb^{-1}$

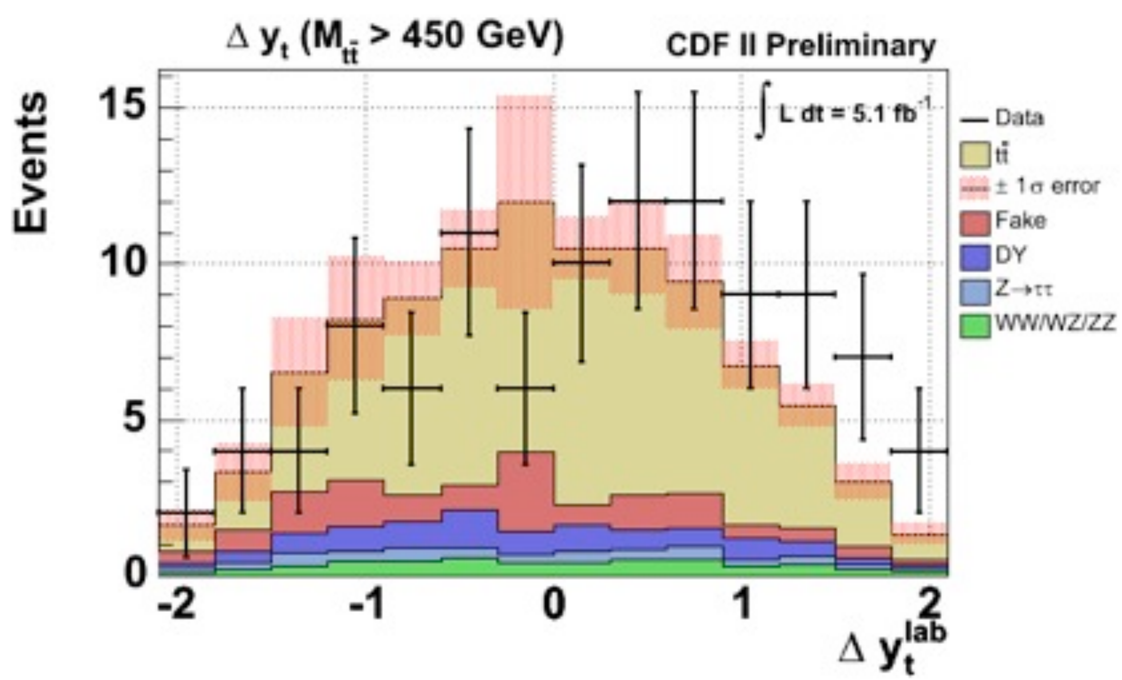
$A_{FB}^{Pred} = -2 \pm 2\ \%$

A_{FB} in Dileptons

- **What is dependence on M_{tt} ?**
- **Raw data here only - we are working on correction methods**
- **Reconstructed M_{tt} for dileptons ≠ lepton+jets → *different algorithms***

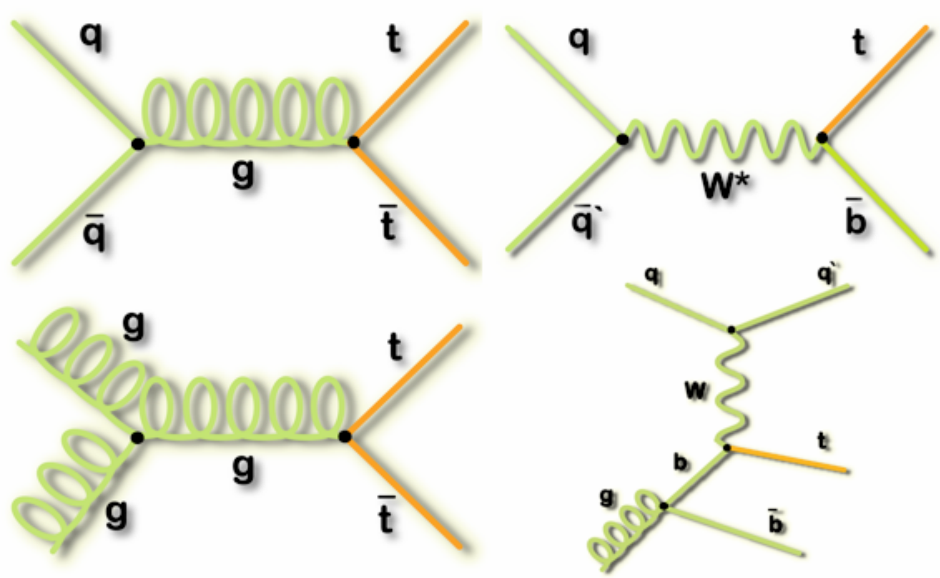
	M < 450 GeV	M > 450 GeV
Data	10 ± 7 %	21 ± 10 %
SM MC	0.3 ± 3 %	-4 ± 6 %





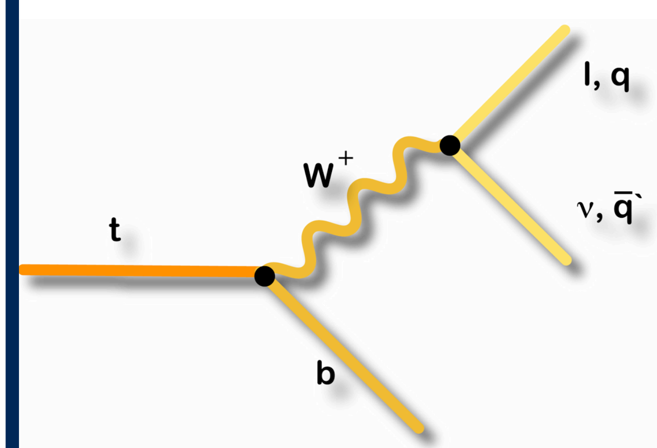
Tevatron Top Physics

How is Top Produced



- **Strong Force**
  $\sigma_{tt} \sim 7.5$ pb
- **Electroweak**
  $\sigma_{s+t} \sim 3$ pb

How Does Top Decay



- **V-A**
  $F_0 \sim 0.7$, $F_+ \sim 0$
- $V_{TB} \sim 1$

What are Top's Intrinsic Properties

- **Mass**
- **Spin** 1/2
- **Charge** +2/3

Tevatron Top Physics

How is Top Produced	How Does Top Decay	What are Top's Intrinsic Properties
$\sigma_{tt} = 7.70$ $\delta \sim 6\ \%$	$F_0 = 0.88$ $\delta \sim 10\ \%$	$M_t = 173.3$ $\delta \sim 0.6\ \%$
$\sigma_{s+t} = 2.8$ $\delta \sim 19\ \%$	$F_+ = -0.15$ $\delta \sim 10\ \%$	$\Gamma_t \sim 2.1$ @ 25%CL
$\sigma_t = 3.1$ $\delta \sim 30\ \%$	$V_{tb} = 0.88$ $\delta \sim 9\ \%$	$\kappa = 0.7$ sig $\sim 1\ \sigma$
		$q \neq -4/3$ @ 95%CL
• Strong Force $\sigma_{tt} \sim 7.5$ pb • Electroweak $\sigma_{s+t} \sim 3$ pb	• V-A $F_0 \sim 0.7$, $F_+ \sim 0$ • $V_{TB} \sim 1$	• Mass • Spin 1/2 • Charge +2/3


Questions

What you shouldn't worry about

- Backgrounds
    - Too small, and the predicted asymmetry in backgrounds goes in the opposite direction
- Reconstruction
    - If it's broken, it's broken for MANY precision measurements that agree with the SM and other well-vetted techniques
- Unfolding
    - The significance of the result is present before the acceptance/reconstruction corrections - they only scale the result

Questions...

- Why do muons have a larger asymmetry than electrons?
- Why is the lab frame asymmetry stronger, yet less dependent on M_{tt} ?
- Why is the result in dileptons so much larger?

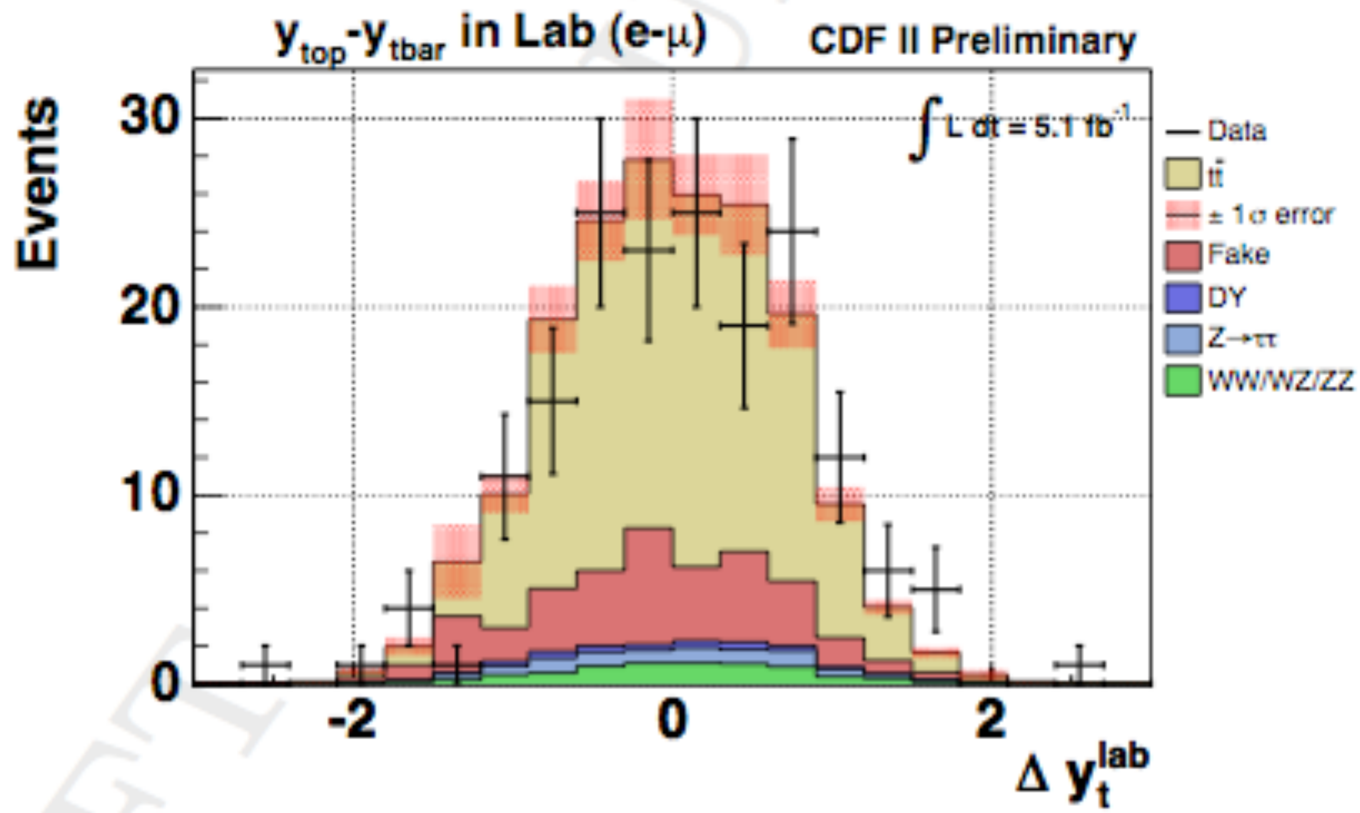
Muons vs Electrons

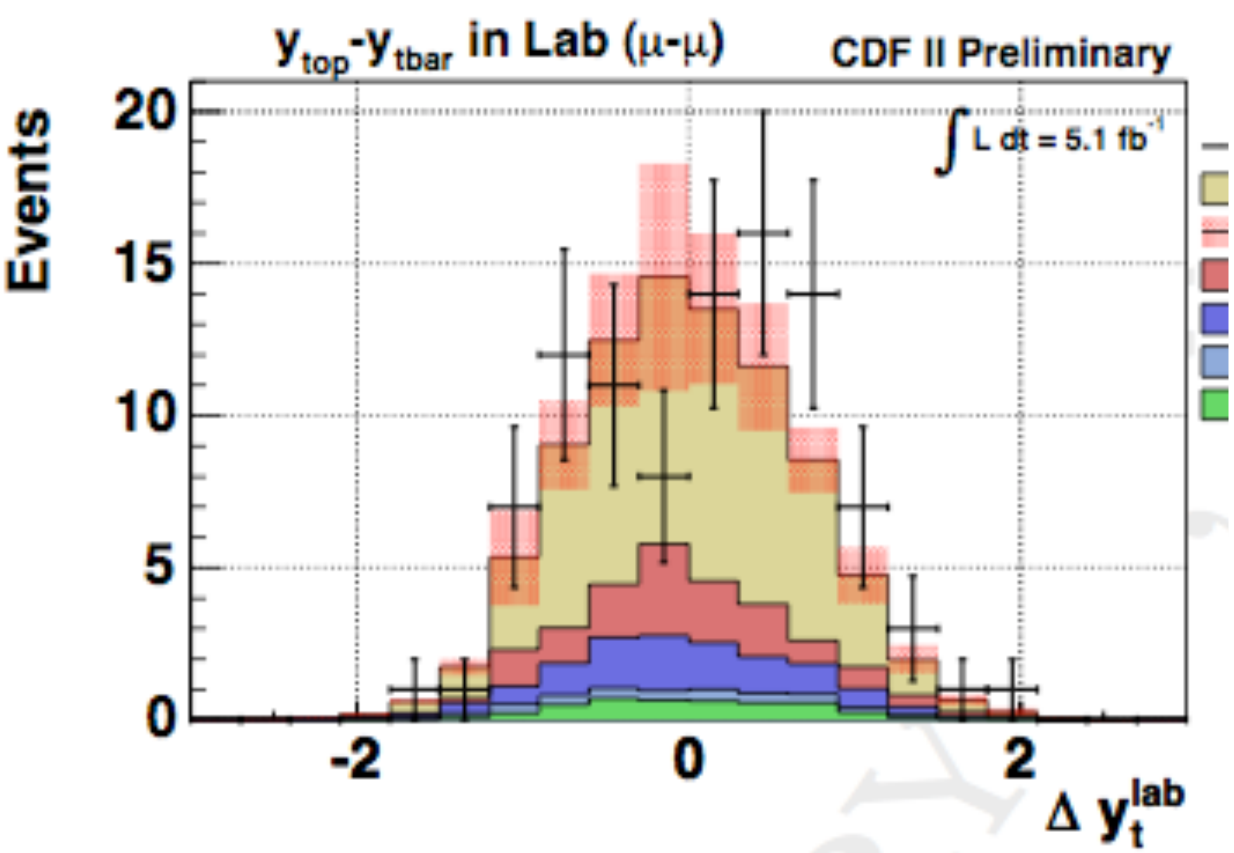
**** before corrections***

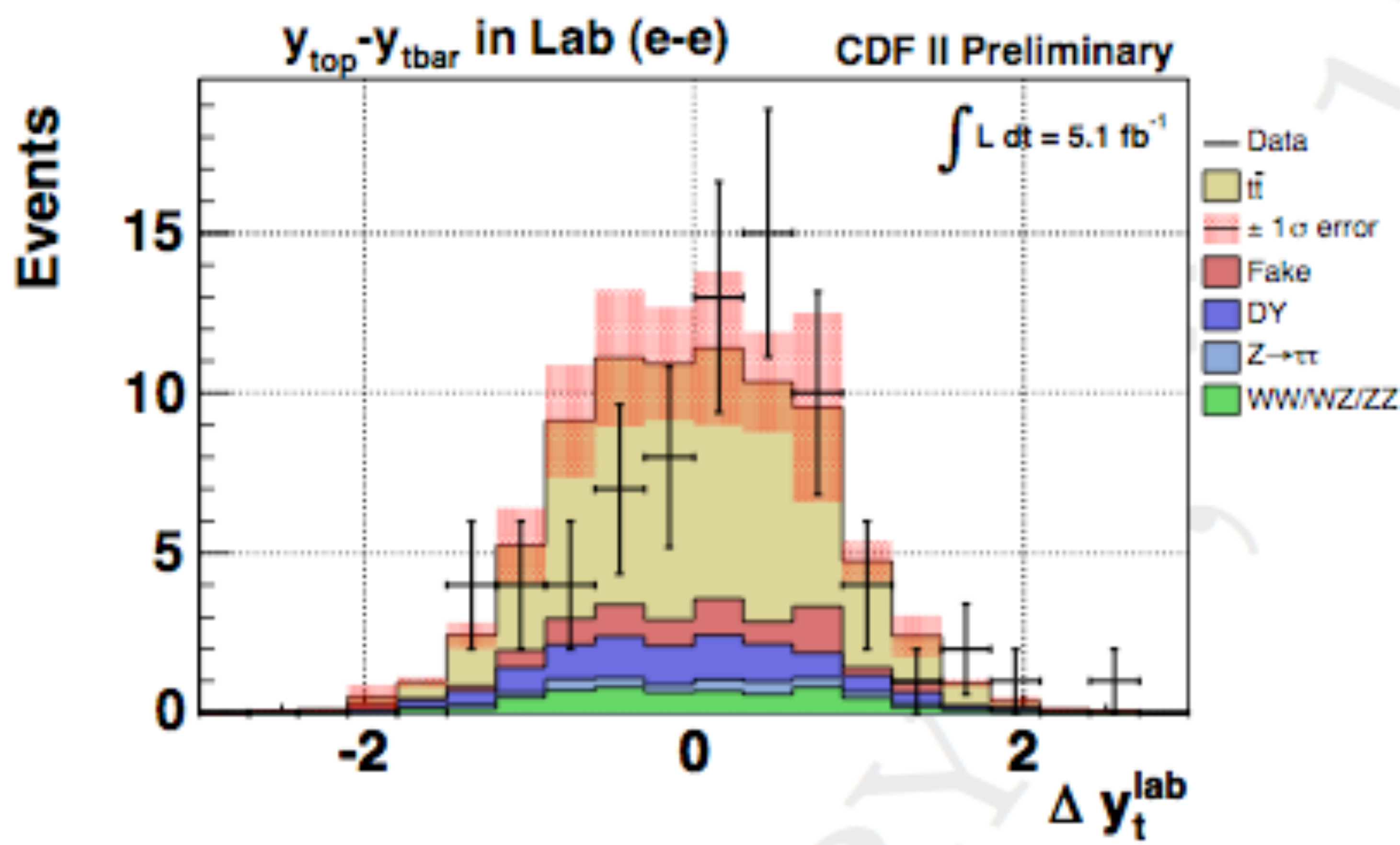
selection	N events	all M	$M < 450$ GeV$/c^2$	$M \geq 450$ GeV$/c^2$
standard	1260	0.057±0.028	-0.016±0.034	0.212±0.049
electrons	735	0.026±0.037	-0.020±0.045	0.120±0.063
muons	525	0.105±0.043	-0.012±0.054	0.348±0.080
data $\chi^2 < 3.0$	338	0.030±0.054	-0.033 ± 0.065	0.180 ± 0.099
data no-b-fit	1260	0.062±0.028	0.006 ± 0.034	0.190 ± 0.050
data single b-tag	979	0.058±0.031	-0.015±0.038	0.224±0.056
data double b-tag	281	0.053±0.059	-0.023±0.076	0.178±0.095
data anti-tag	3019	0.033±0.018	0.029±0.021	0.044±0.035
pred anti-tag	-	0.010±0.007	0.013±0.008	0.001±0.014
pre-tag	4279	0.040±0.015	0.017±0.018	0.100±0.029
pre-tag no-b-fit	4279	0.042±0.015	0.023±0.018	0.092±0.029

What about the di-lepton result?

Flavor	Asymmetry
Inclusive	14 ± 5 %
e-e	27 ± 11 %
e-u	6.4 ± 7.6 %
u-u	17 ± 10 %

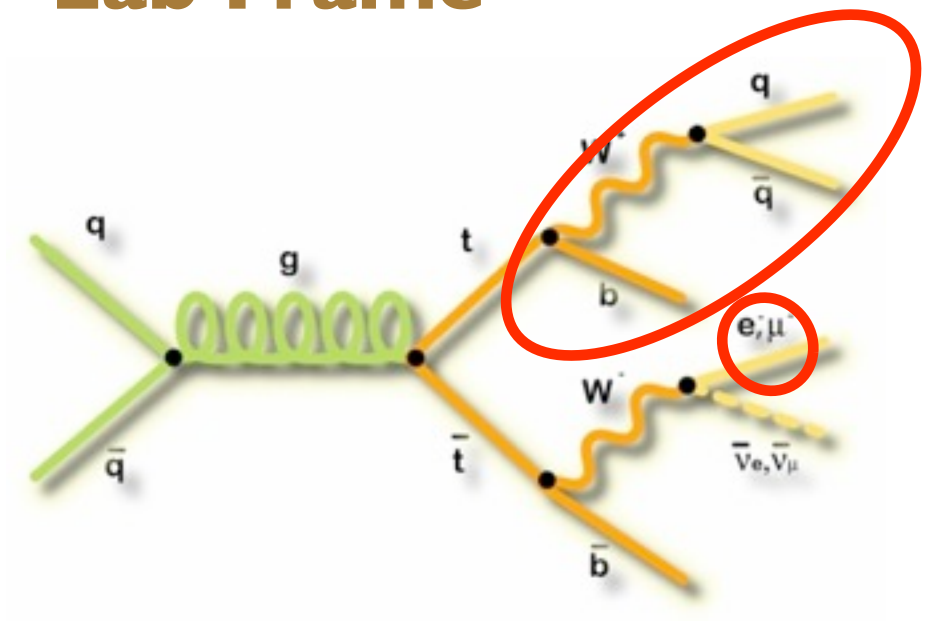


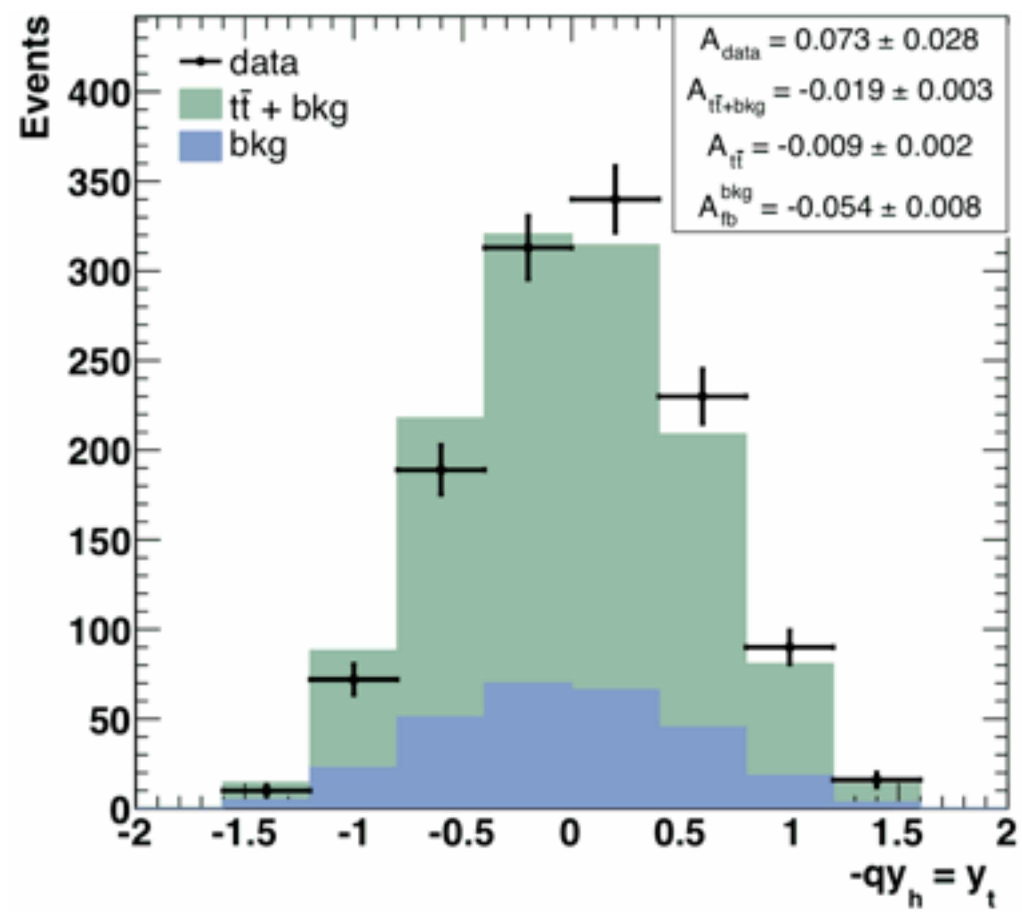




Lab Frame

- **Alternative method**
  - Lab Frame





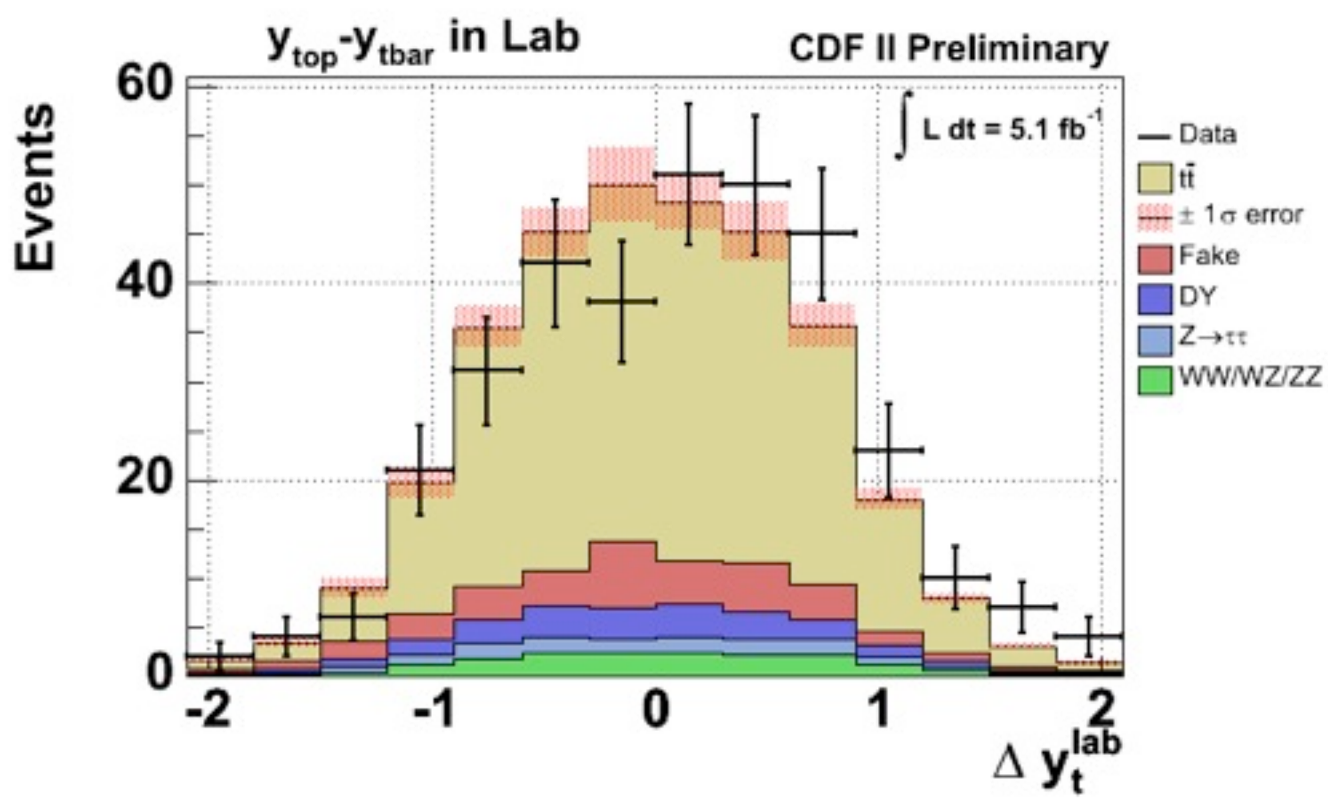
- **Takes the Lepton Pt and Neutrino out of it, still depend on lepton charge**

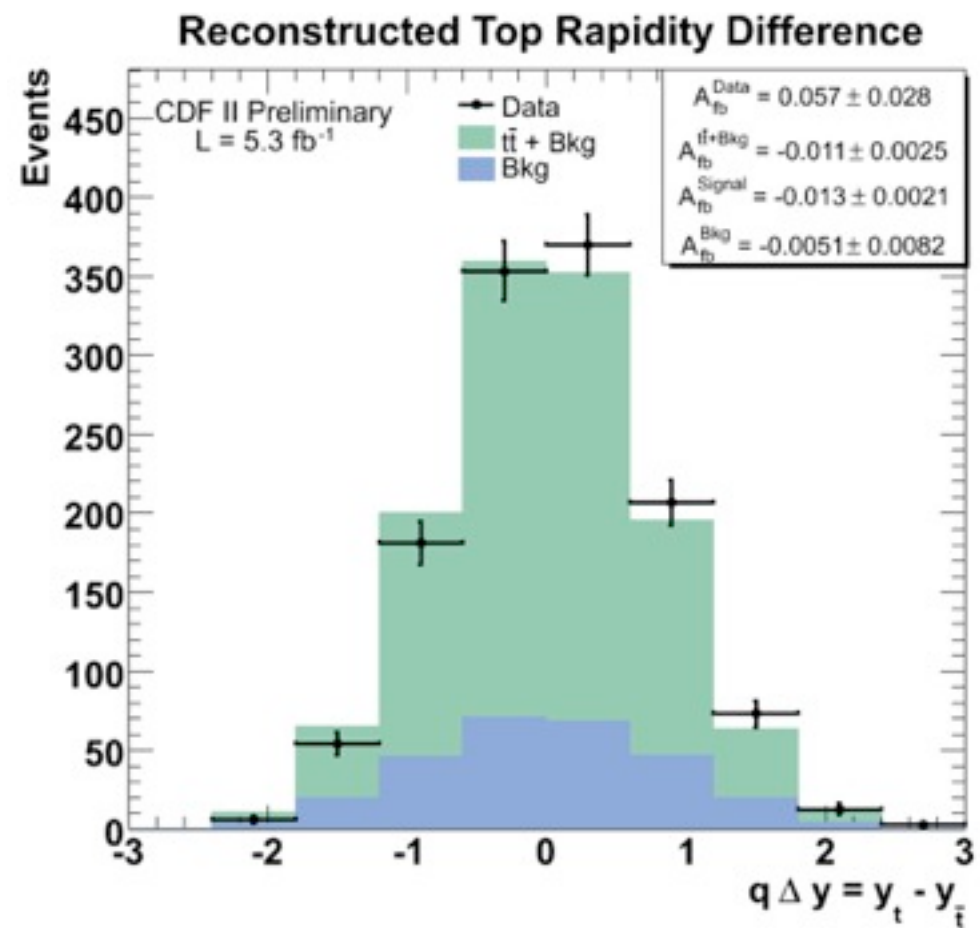
$A_{FB} = 15 \pm 5_{stat+syst}$ %

Lab Frame

	Inclusive	$M < 450$ GeV	$M > 450$ GeV
Data - tt Frame	5.7 ± 2.8 %	-1 ± 3 %	21 ± 5 %
SM Prediction	2 ± 0.4 %	1 ± 0.6 %	3 ± 0.7 %
Data - pp Frame	7.3 ± 2.8 %	5.9 ± 3.4 %	10.3 ± 4.9 %
SM Prediction	2 ± 0.4 %	-1 ± 0.5 %	2 ± 0.7 %

Dileptons vs L+Jets





$A_{FB} = 42 \pm 15_{stat} \pm 5_{syst}$ %

5.1 fb^{-1}

$A_{FB} = 16 \pm 7_{stat} \pm 2_{syst}$ %

5.3 fb^{-1}

$M_{t\bar{t}}$ Dependence

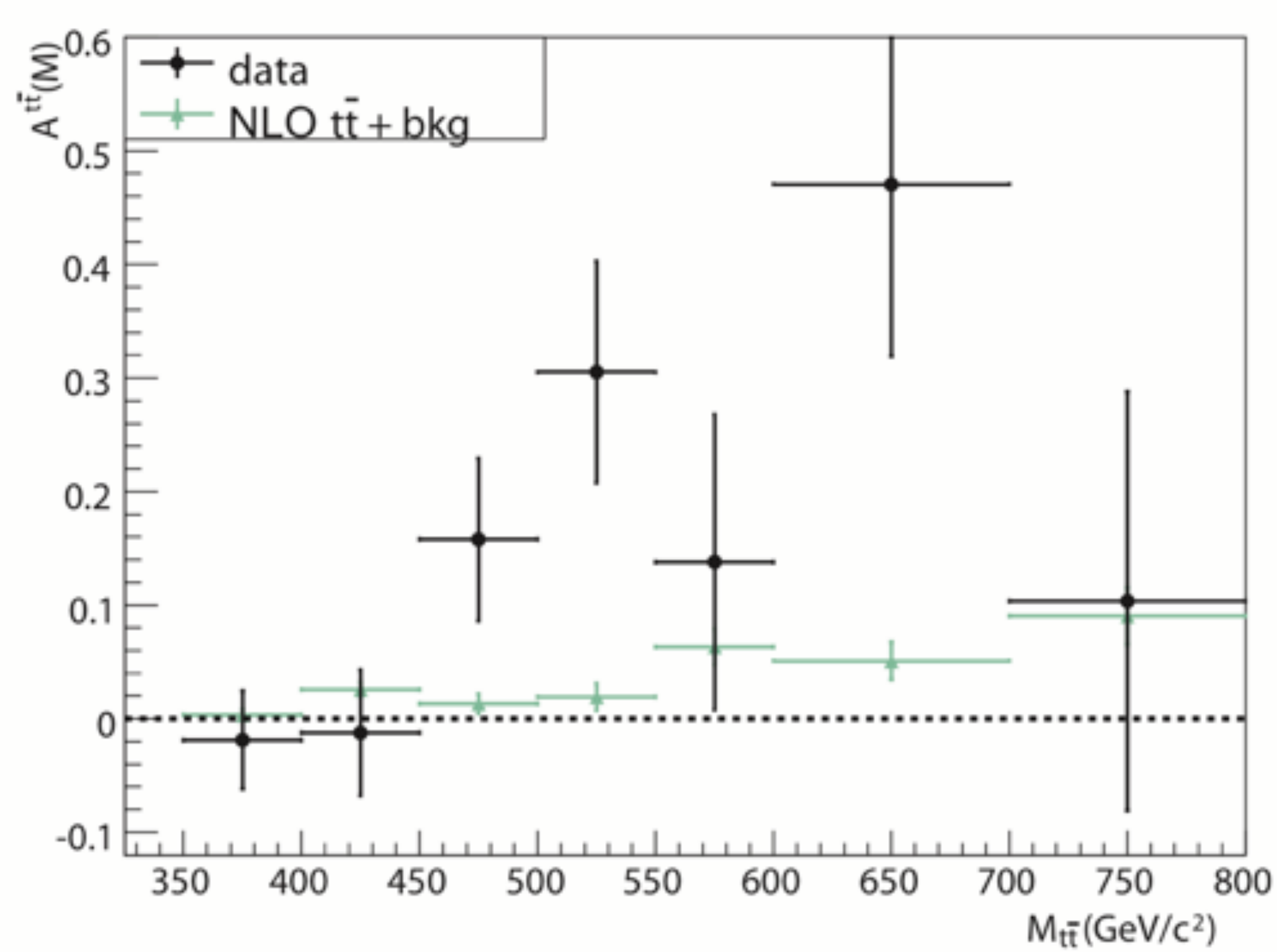
- **What is the optimal high/low bin-edge (based on MC) ?**

	OctetA		OctetB	
bin-edge (GeV/c^2)	A^{tt}	significance	A^{tt}	significance
345	0.082 ± 0.028	2.90	0.168 ± 0.028	5.99
400	0.128 ± 0.036	3.55	0.235 ± 0.035	6.74
450	0.183 ± 0.047	3.91	0.310 ± 0.044	7.08
500	0.215 ± 0.060	3.60	0.369 ± 0.054	6.81
550	0.246 ± 0.076	3.25	0.425 ± 0.066	6.43
600	0.290 ± 0.097	2.97	0.460 ± 0.081	5.70

Models provided by Tim Tait

$M_{t\bar{t}}$ Dependence

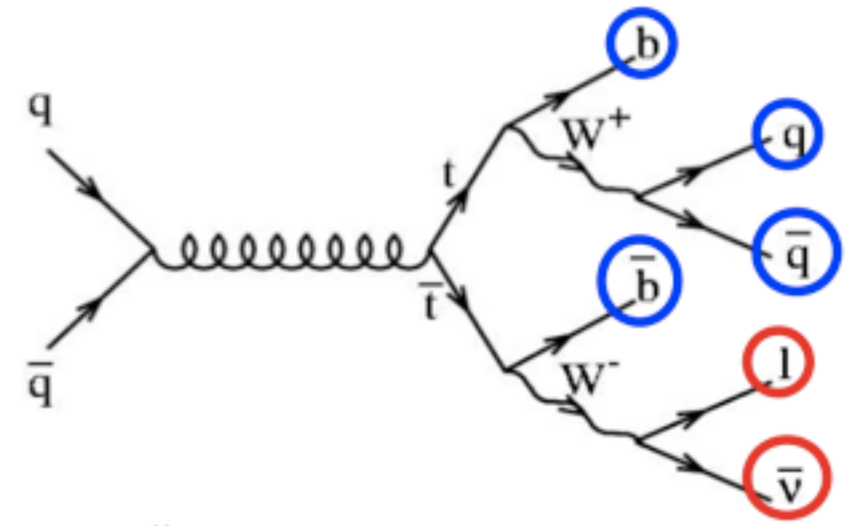
- Interesting effect
- Want to correct this now to compare directly to SM - unfolding
- 450 GeV choice though lies on a weird spot
- We're stuck with what we chose, but this demonstrates the limits of 4-bin unfolding

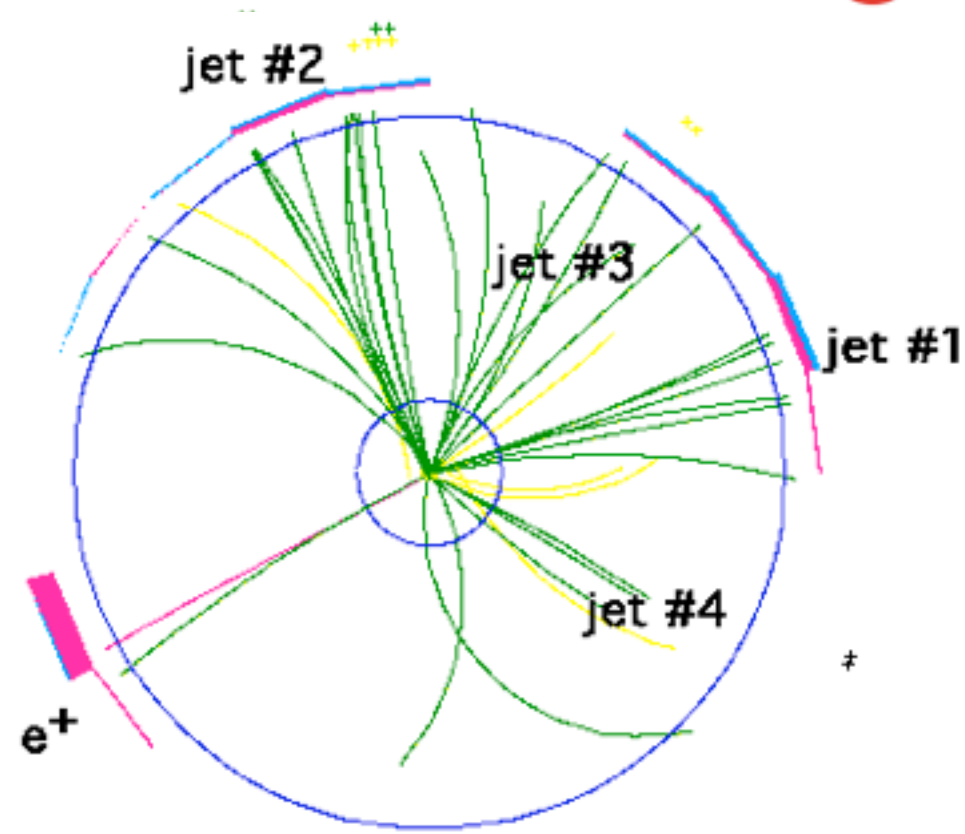


Reconstruction and Corrections

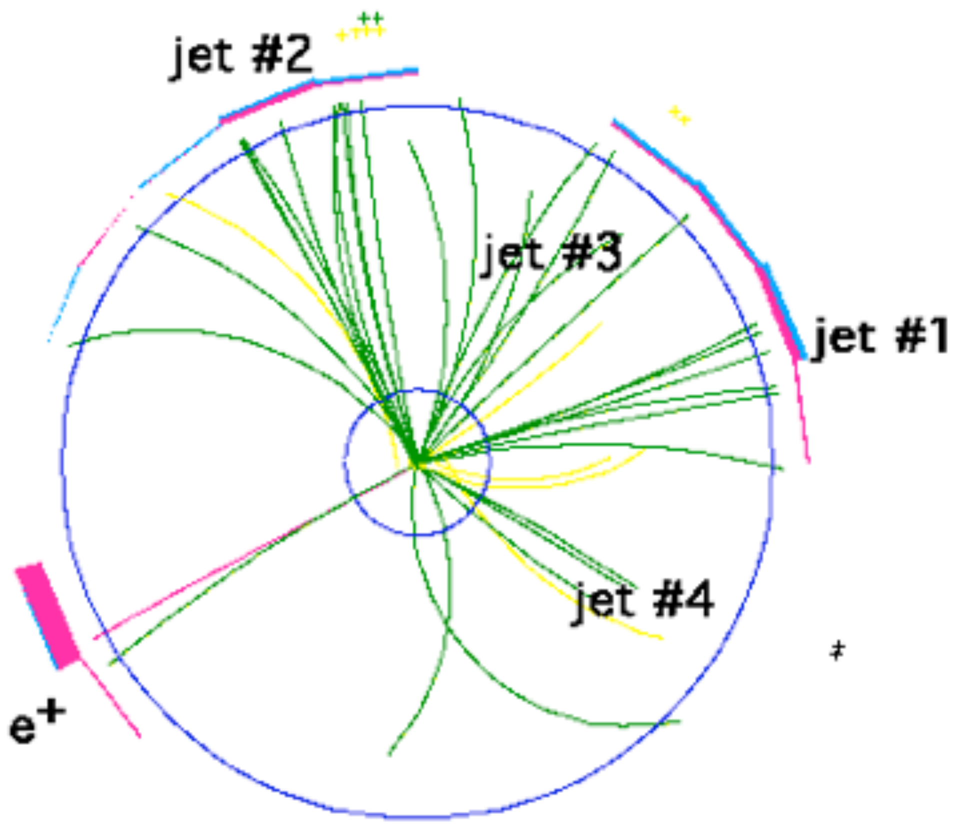
Event Reconstruction

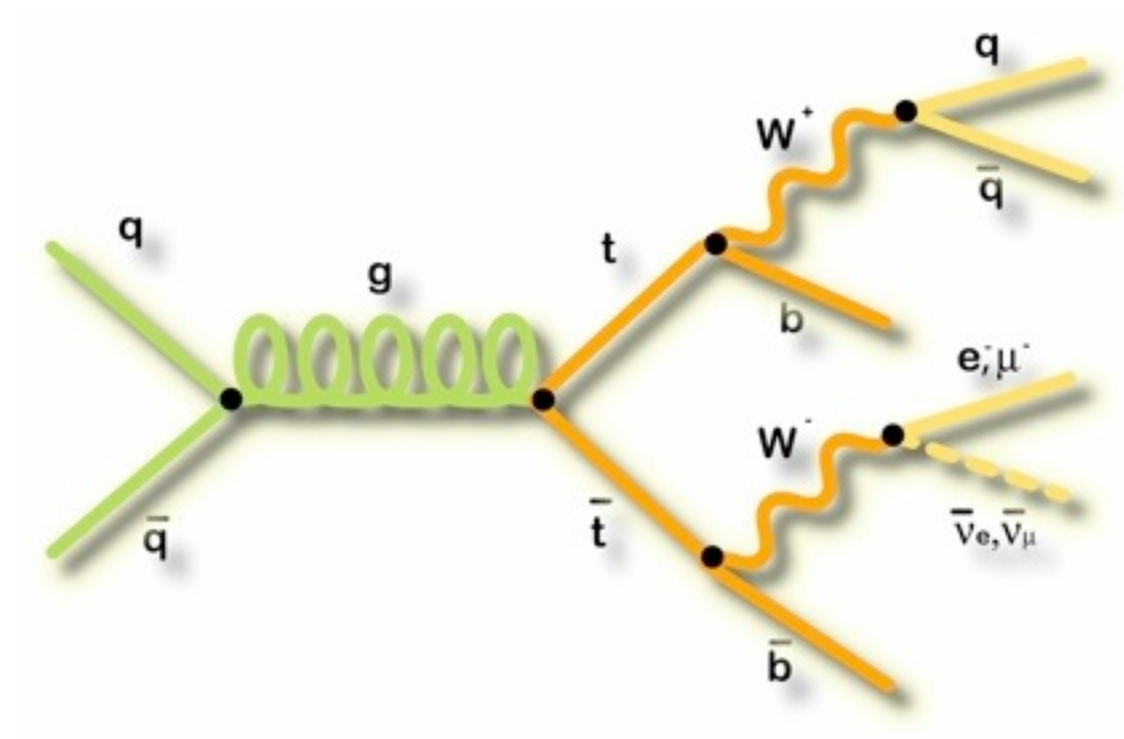
- Reconstruct the top direction from the observables in the detector
- Biggest problem is to match the jets in the detector to the “true” decay products of t and $\bar{t}$?
- 4 Jets to match to 4 quarks leads to 24 combinations
- Use the event topology to build an algorithm!





Event Reconstruction

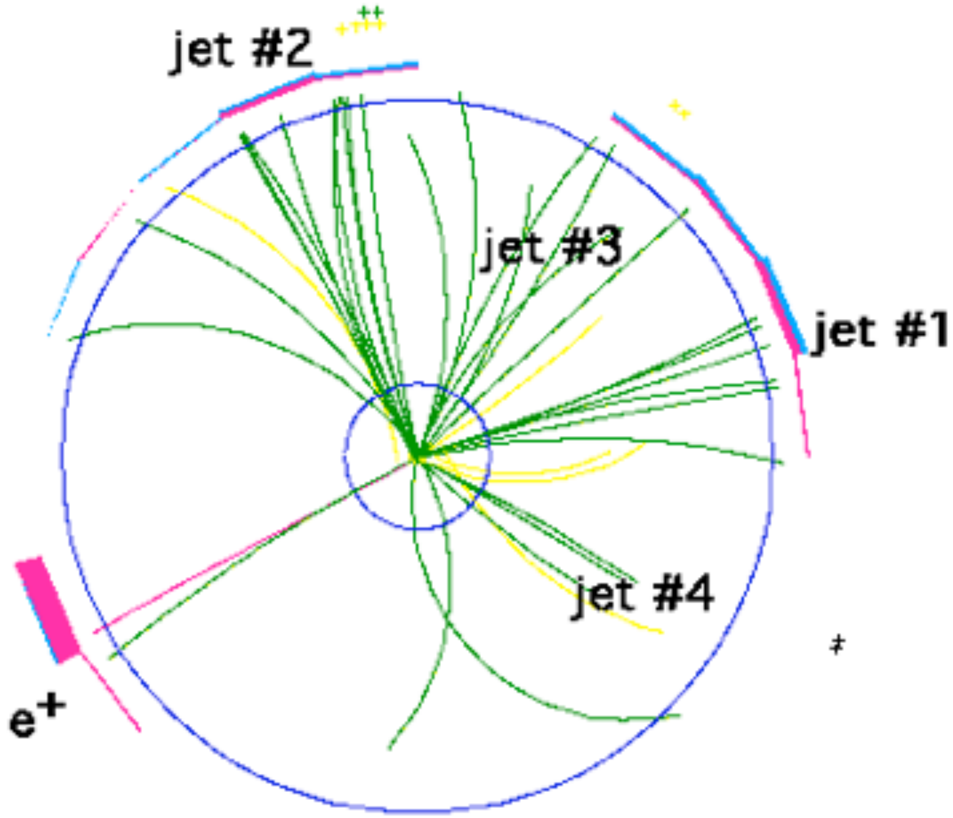


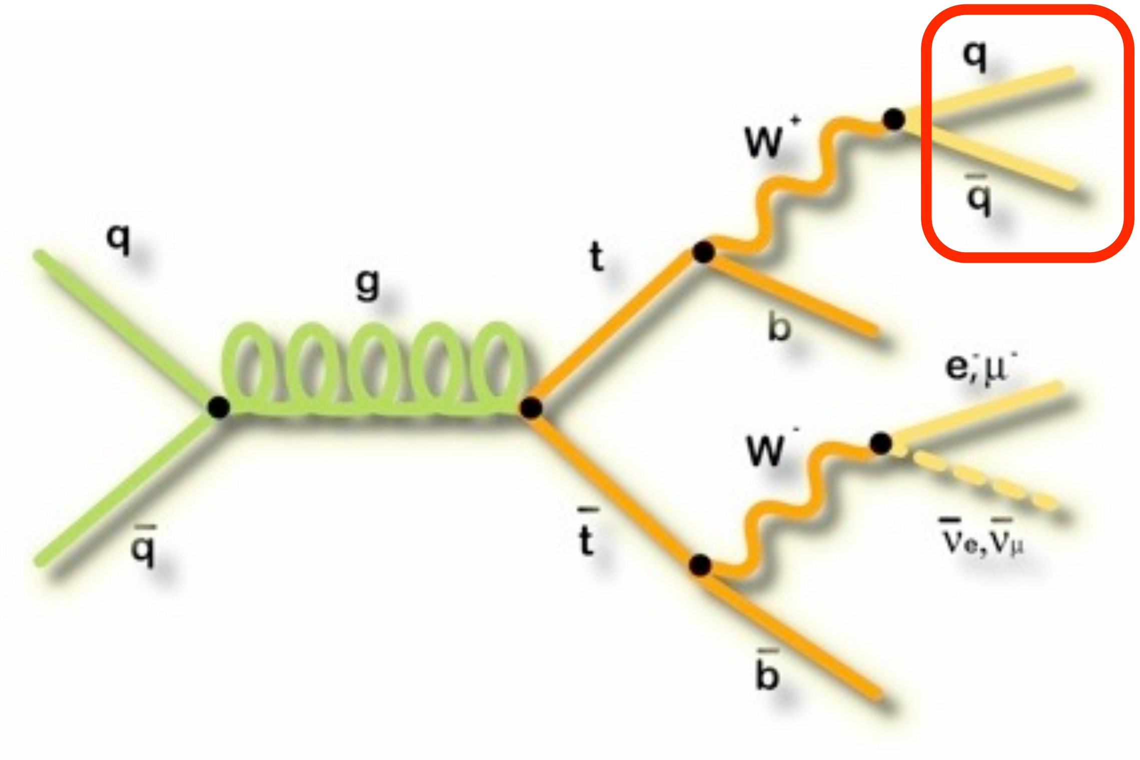


$$\chi^2 = \sum_{i=l,jets} \frac{(p_t^{i,meas} - p_t^{i,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,meas} - p_j^{UE,fit})^2}{\sigma_j^2}$$

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

Event Reconstruction

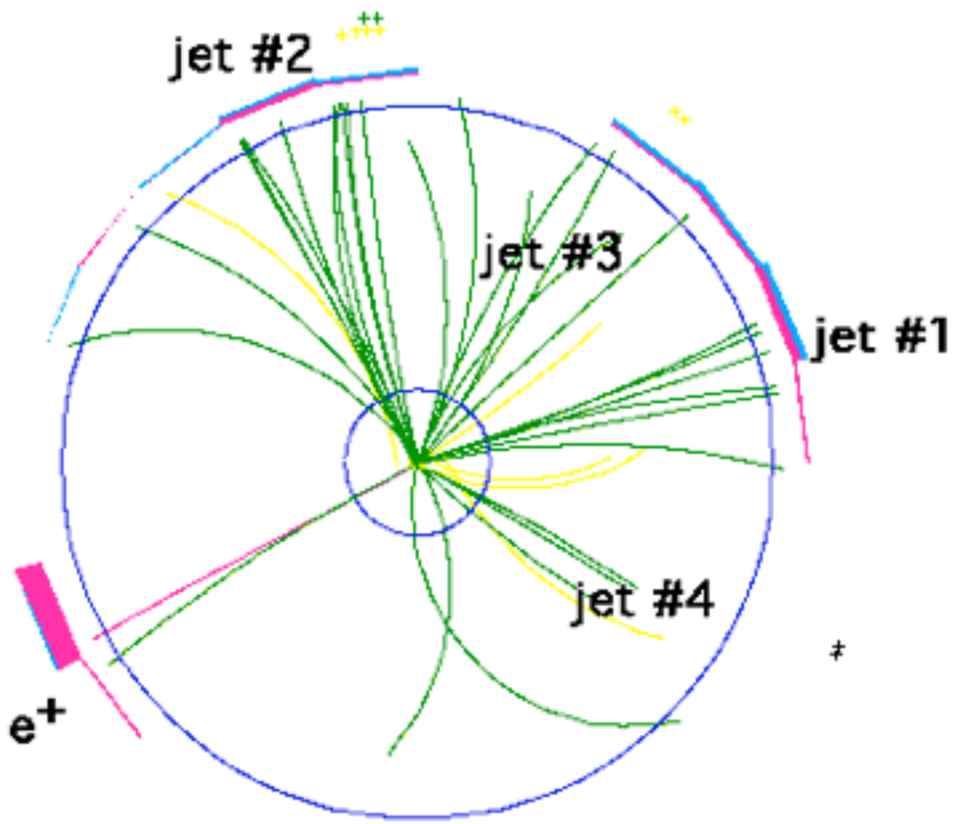


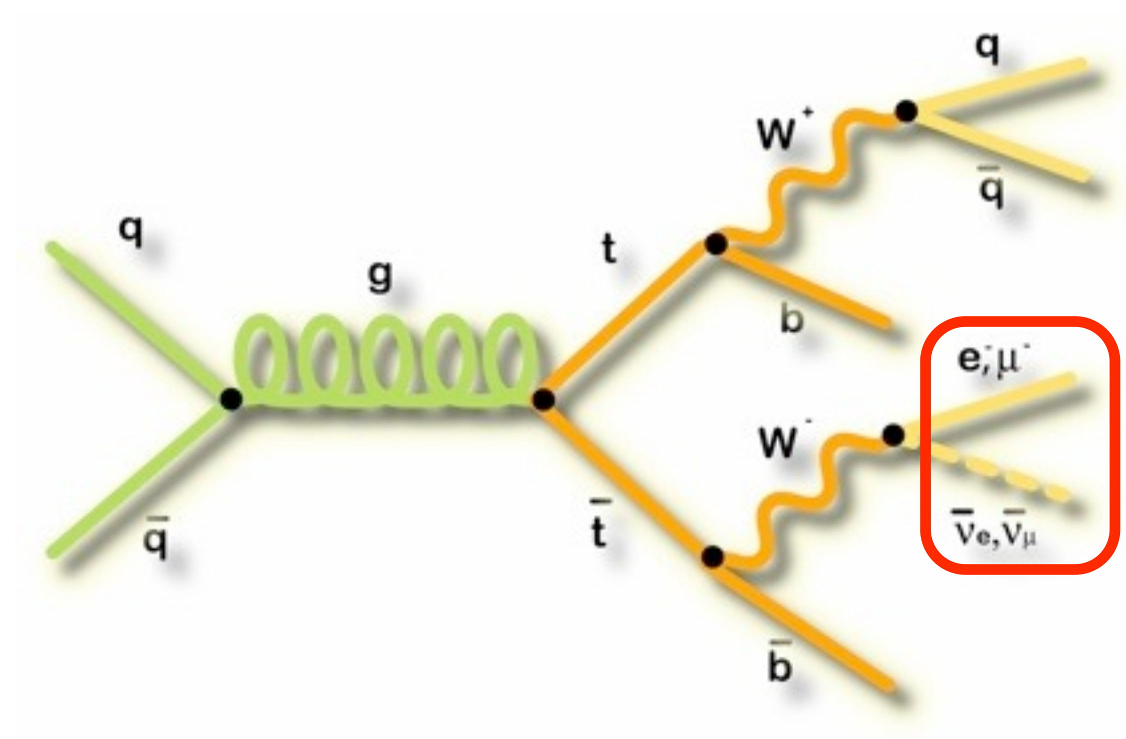


$$\chi^2 = \sum_{i=l,jets} \frac{(p_t^{i,meas} - p_t^{i,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,meas} - p_j^{UE,fit})^2}{\sigma_j^2}$$

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

Event Reconstruction

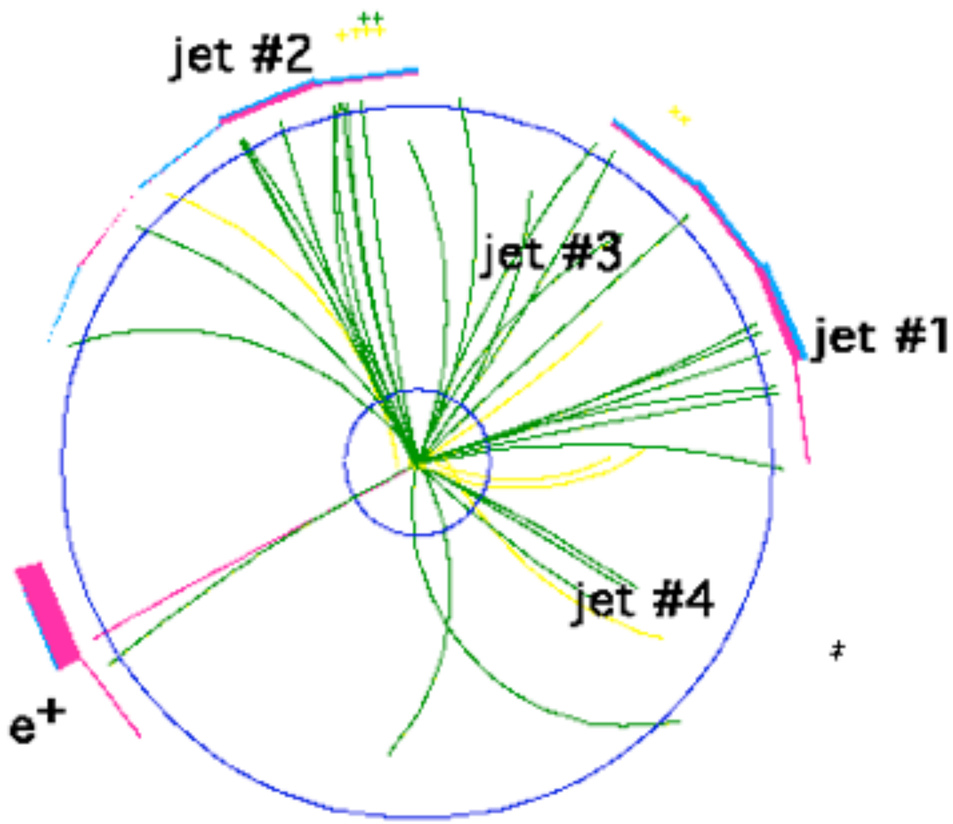


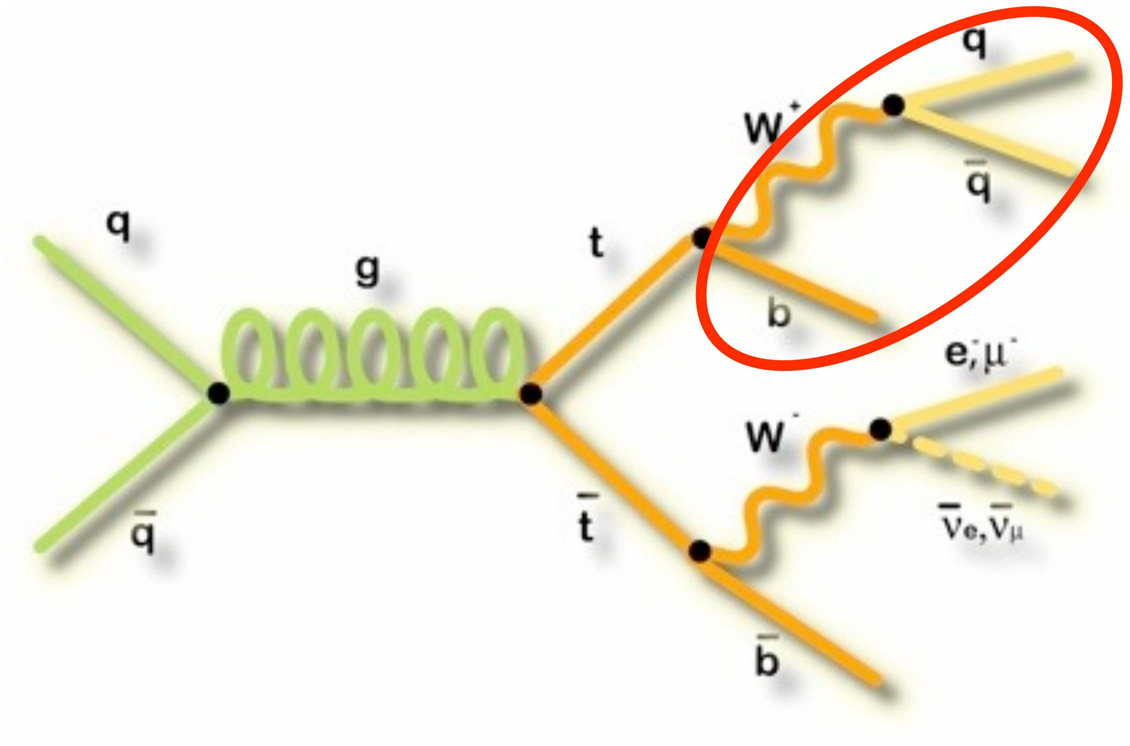


$$\chi^2 = \sum_{i=l,jets} \frac{(p_t^{i,meas} - p_t^{i,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,meas} - p_j^{UE,fit})^2}{\sigma_j^2}$$

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

Event Reconstruction

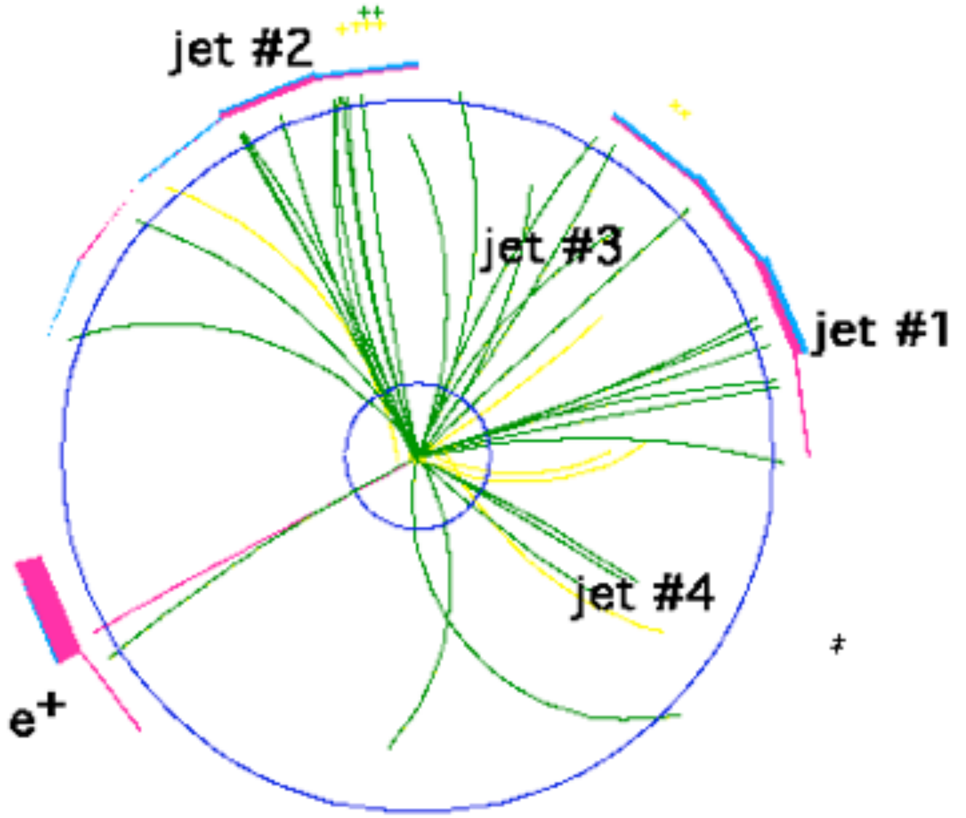


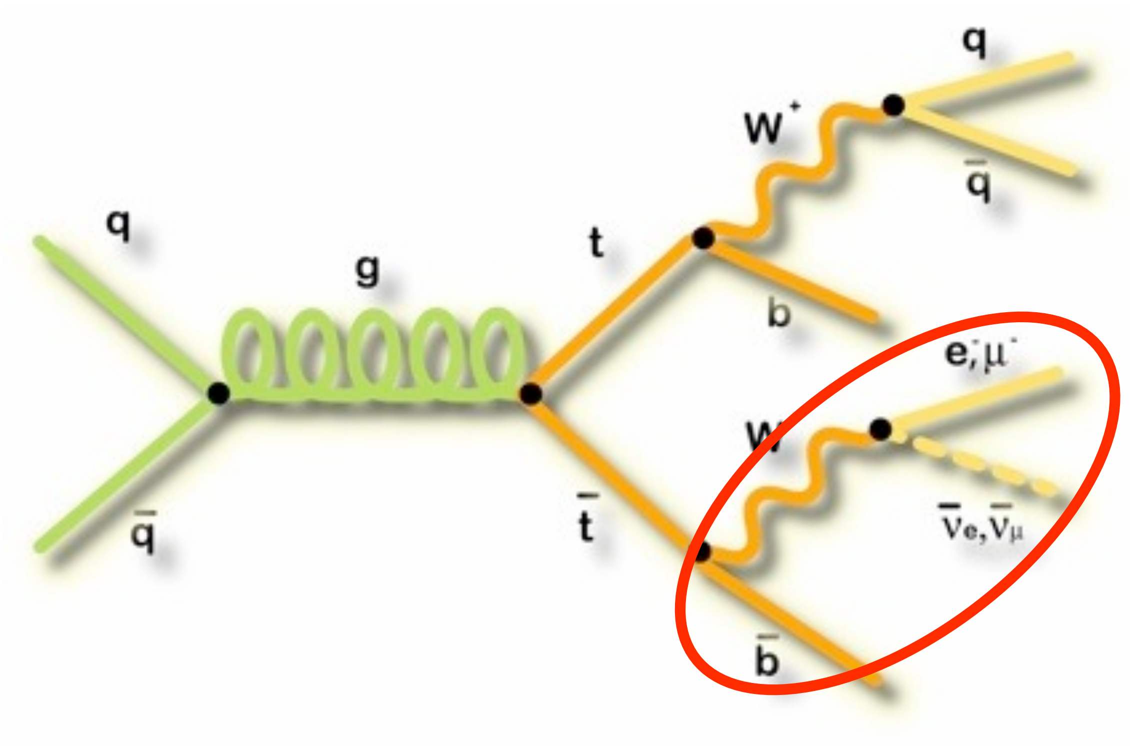


$$\chi^2 = \sum_{i=l,jets} \frac{(p_t^{i,meas} - p_t^{i,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,meas} - p_j^{UE,fit})^2}{\sigma_j^2}$$

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

Event Reconstruction

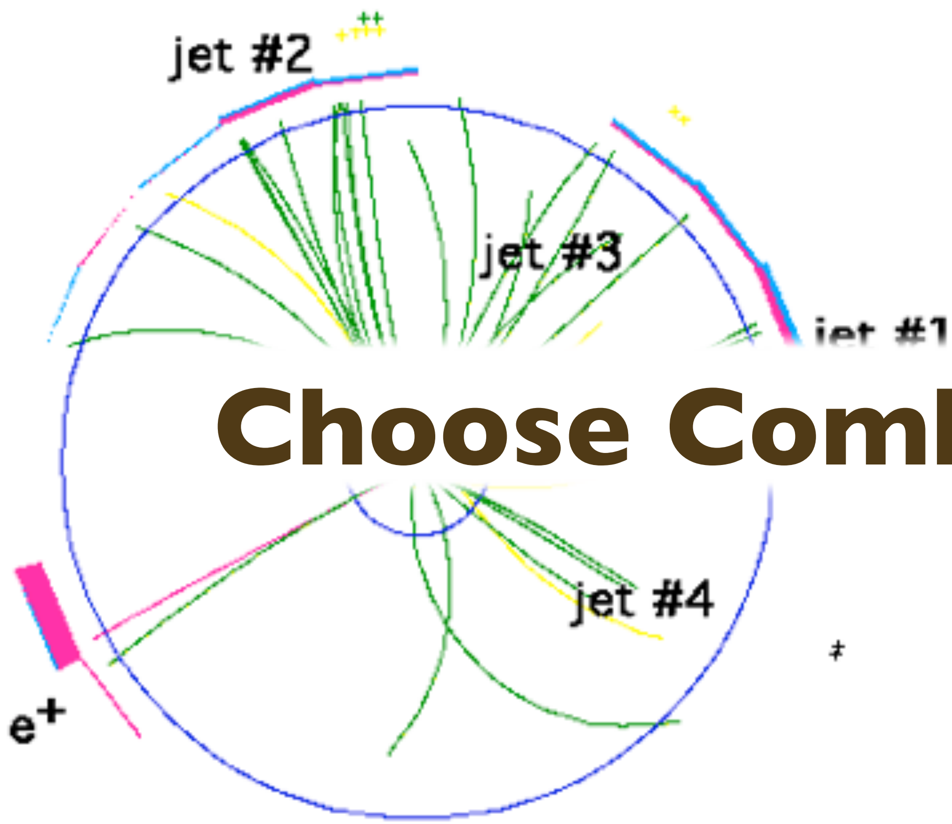




$$\chi^2 = \sum_{i=l,jets} \frac{(p_t^{i,meas} - p_t^{i,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,meas} - p_j^{UE,fit})^2}{\sigma_j^2}$$

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

Event Reconstruction

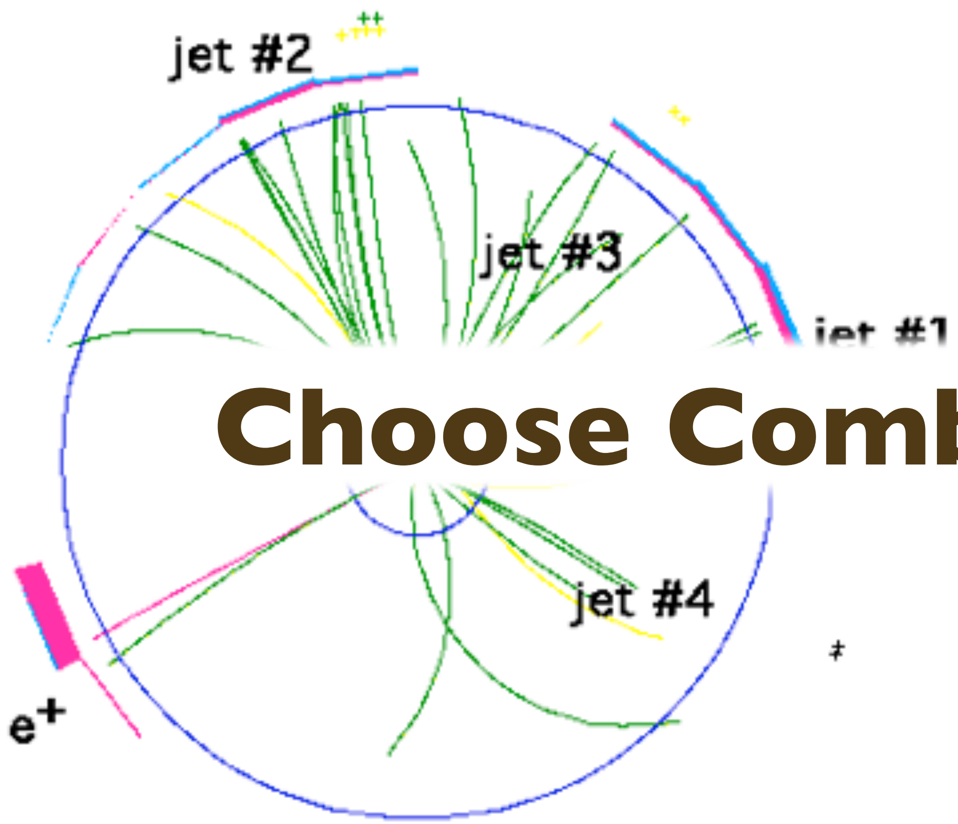


Choose Combination with Best χ^2

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

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

Event Reconstruction



Choose Combination with Best χ^2

All particle energies and angles are available after reconstruction