Top quark measurements using template method at CDF

(top quark mass, width, and mass diff.)

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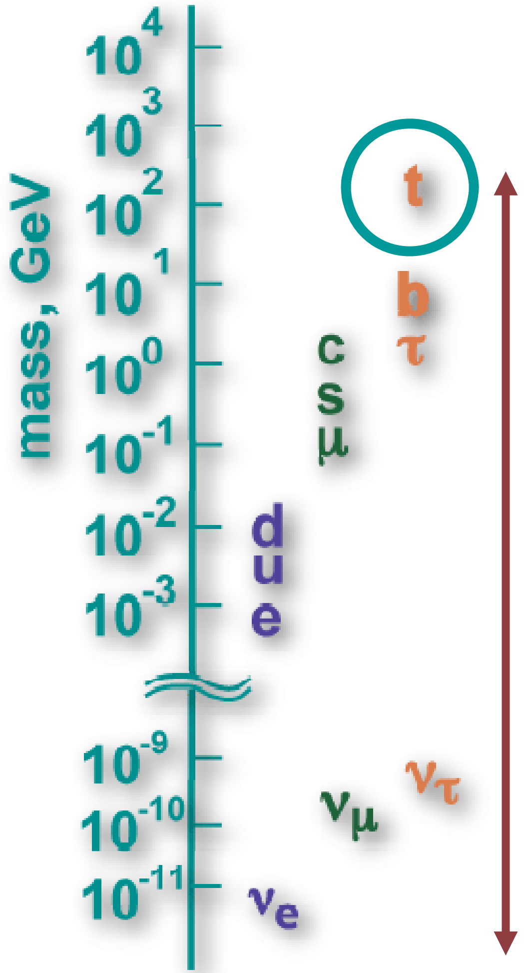
On behalf of the CDF collaboration

Outline

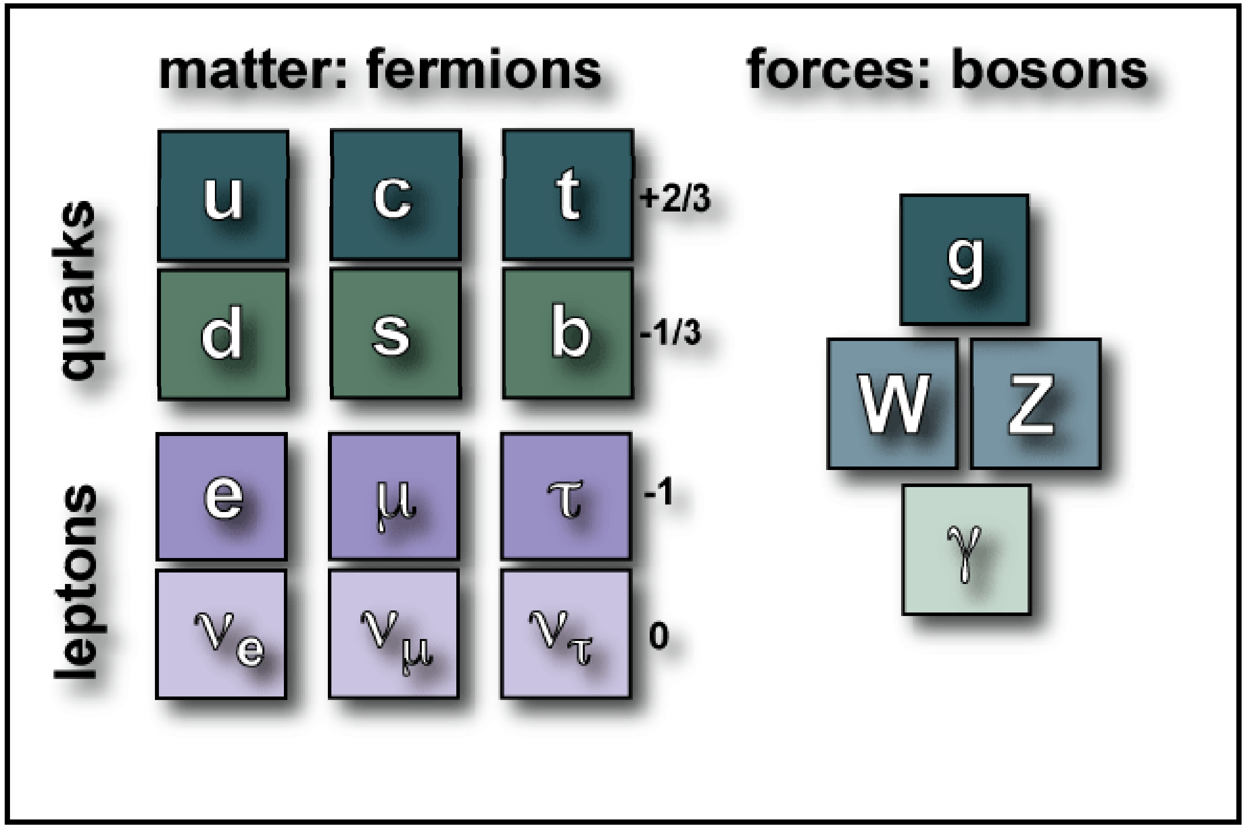
- Top quark and top physics overview
- Top quark mass measurement
  - template method development
- Top quark width measurement
- Top and anti-top quarks mass difference measurement
- Conclusion

Top quark

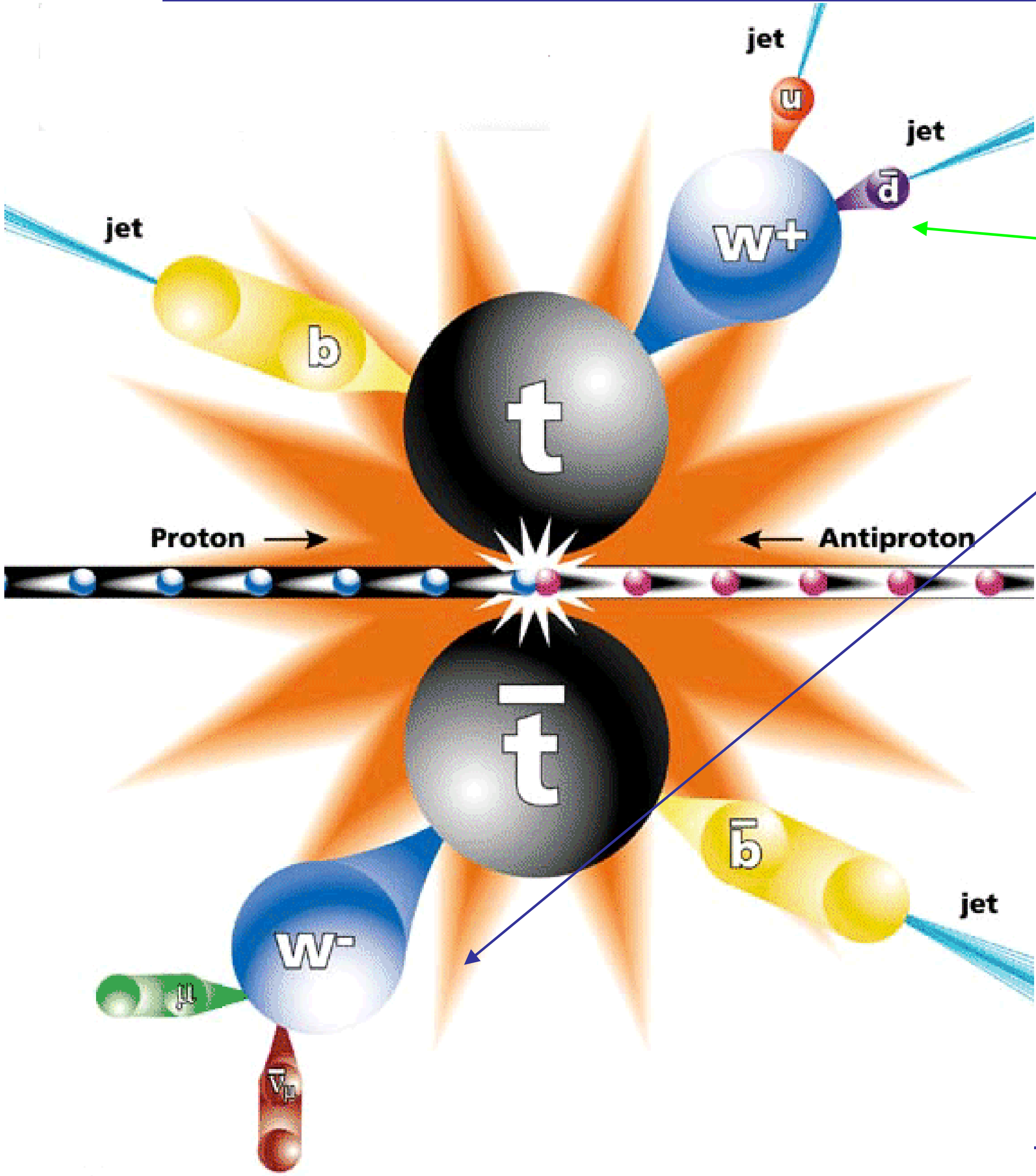


5 orders of magnitude!

Periodic Table of the Particles



Top quark Production and decay



- Tops always decay via t->Wb
- Event topology then depends on W decays
  - Hadronic (quarks)
  - Leptonic (electron or muon + neutrino)

All Jets channle (44%)

6jets

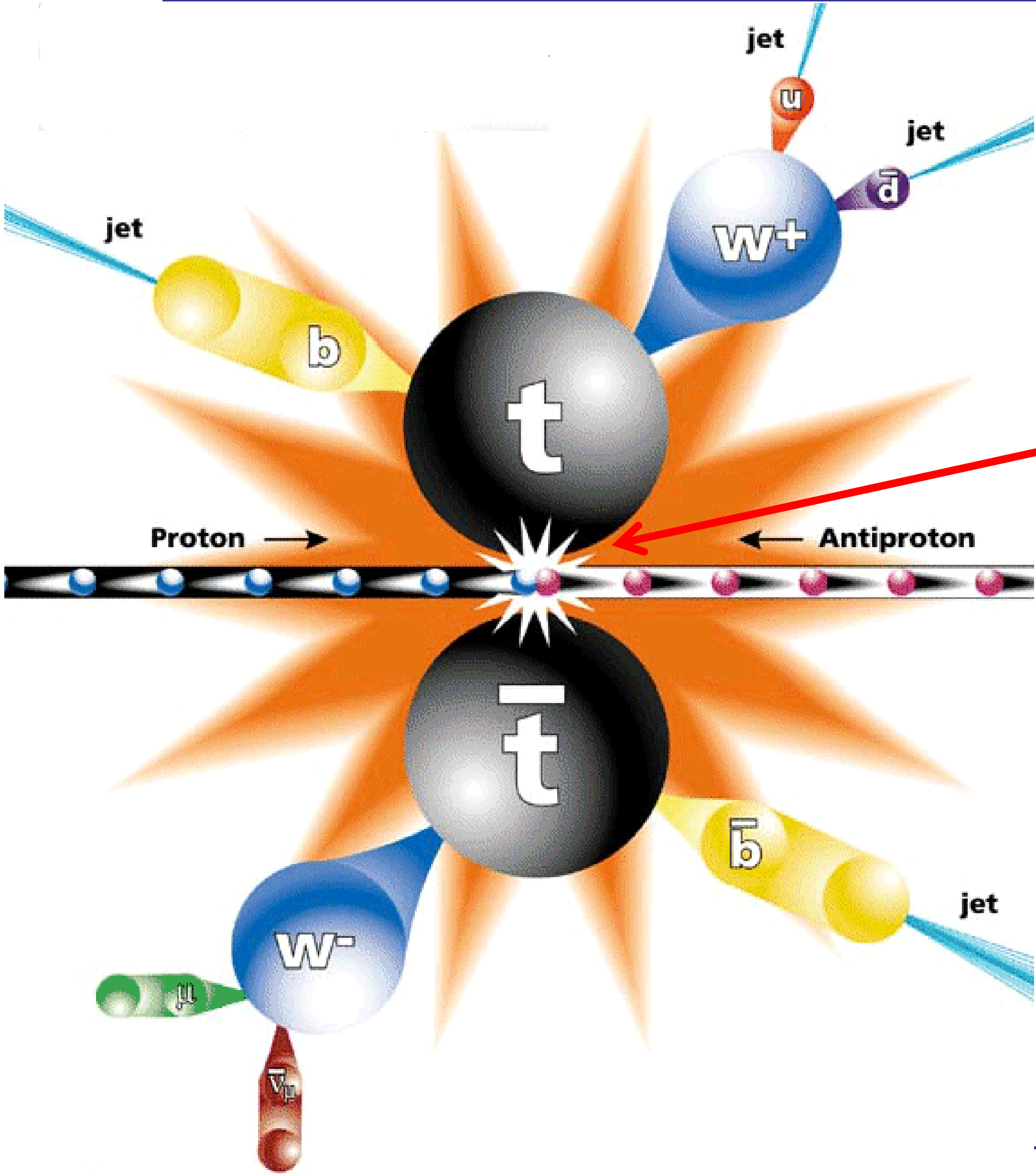
Lepton+Jets channel(30%)

4 quarks, 1 charged lepton + undetected neutrino

Dilepton(5%)

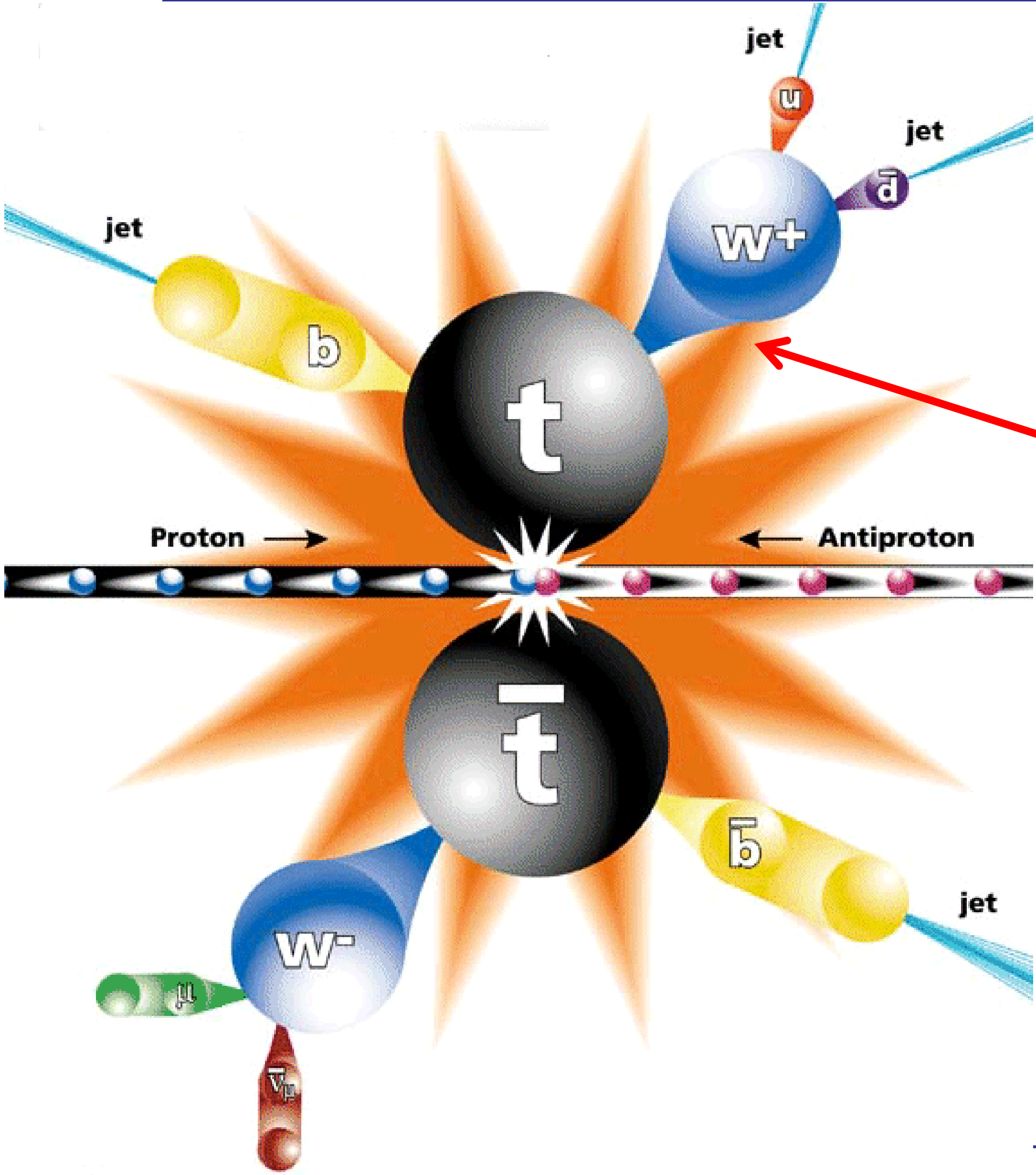
- Both W decay to leptons
- Signature = 2b quarks, 2 charge lepton+2 undetected

Top quark study (Production)



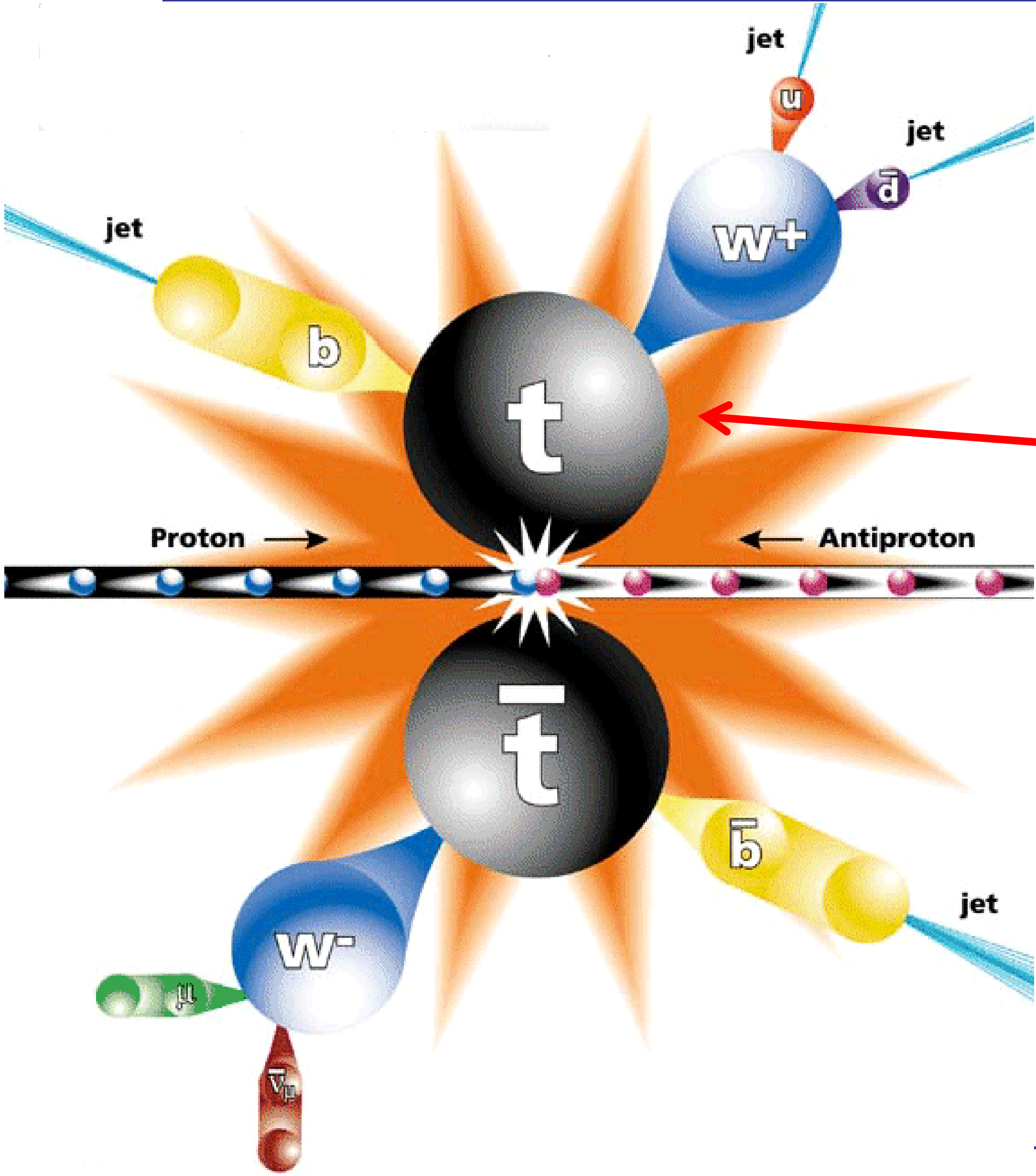
Production Cross Section
Production Mechanism
Forward-Backward Asymmetry
Resonance Production
Spin Correlation

Top quark study (Decay)



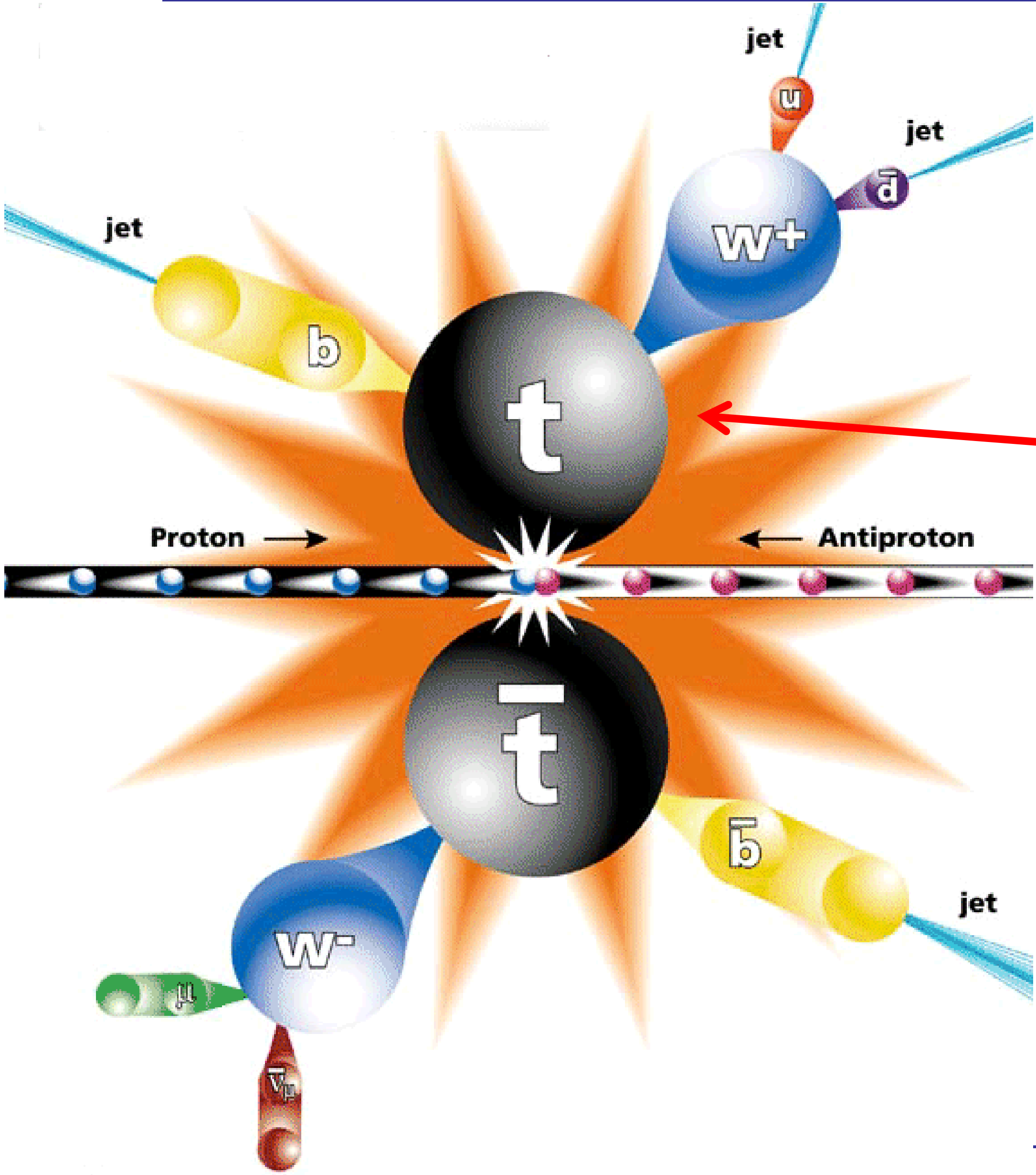
FCNC ?
Charged Higgs ?
Branching fraction of b

Top quark study (Search)



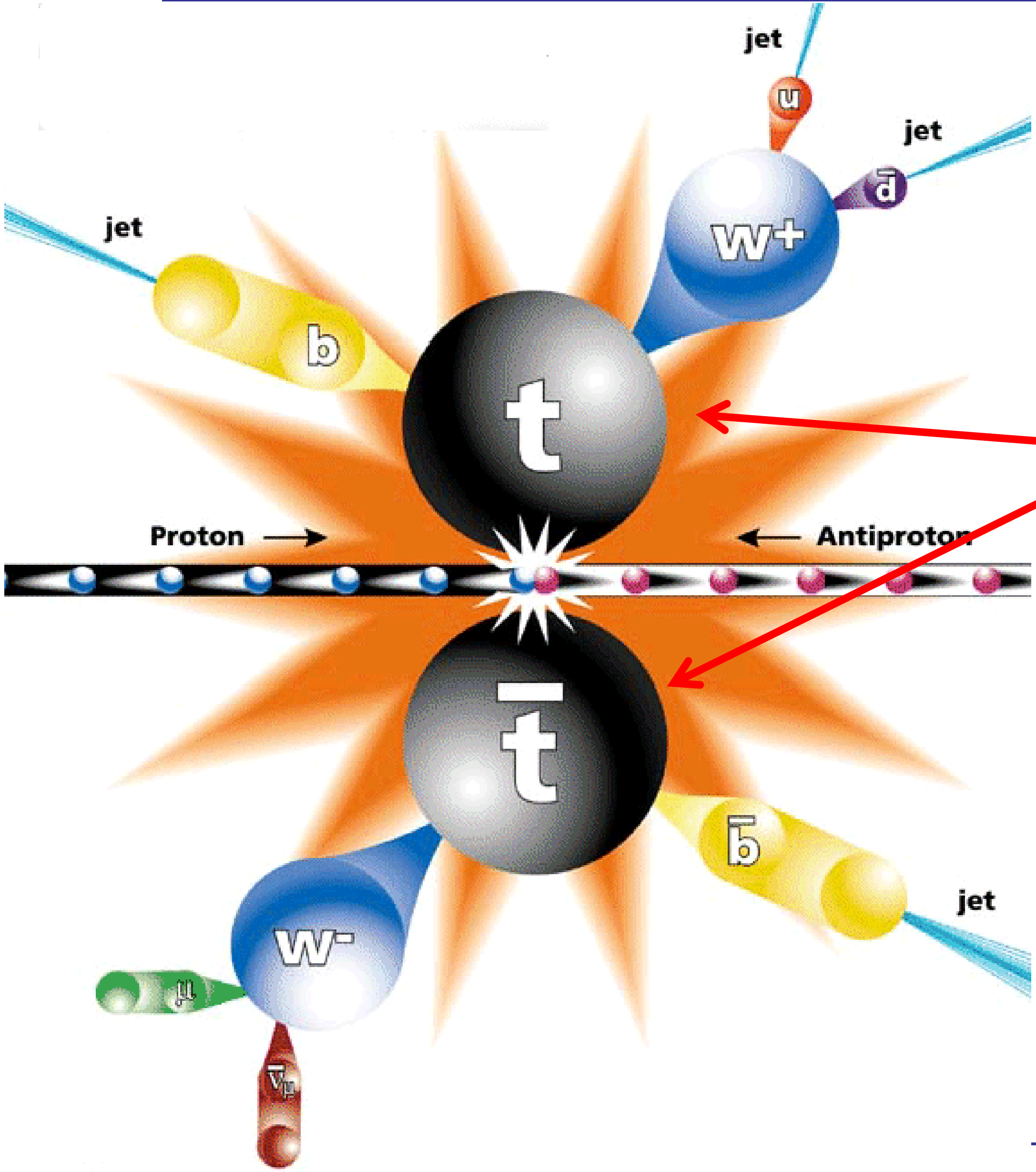
Forth generation ?
SUSY particle ?

Top quark study (Properties)



Mass
Width
Charge

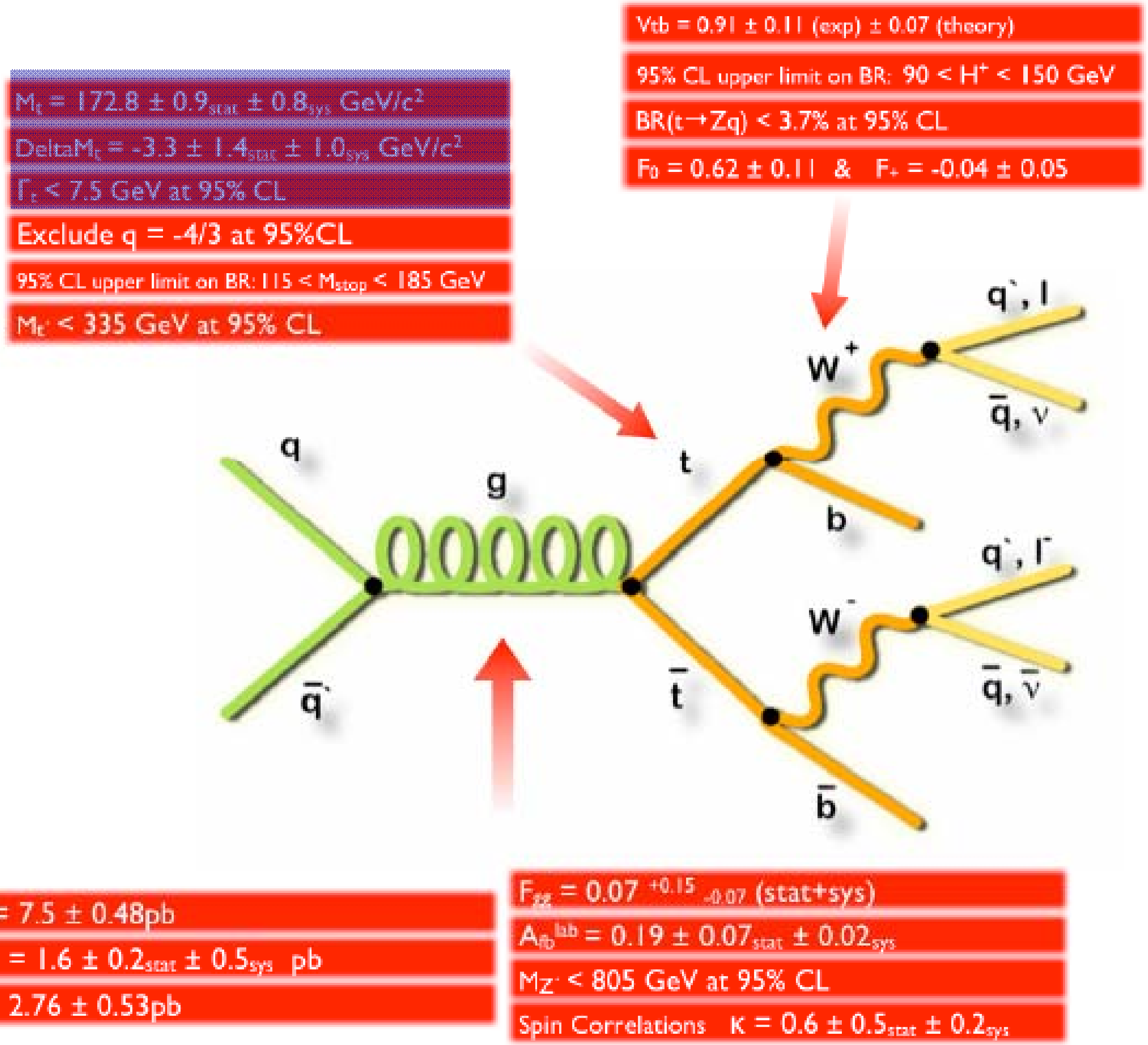
Top quark study



Same mass?

Where we stand (CDF) now

- Today's topic
  (my analysis)



Where we stand (CDF) now

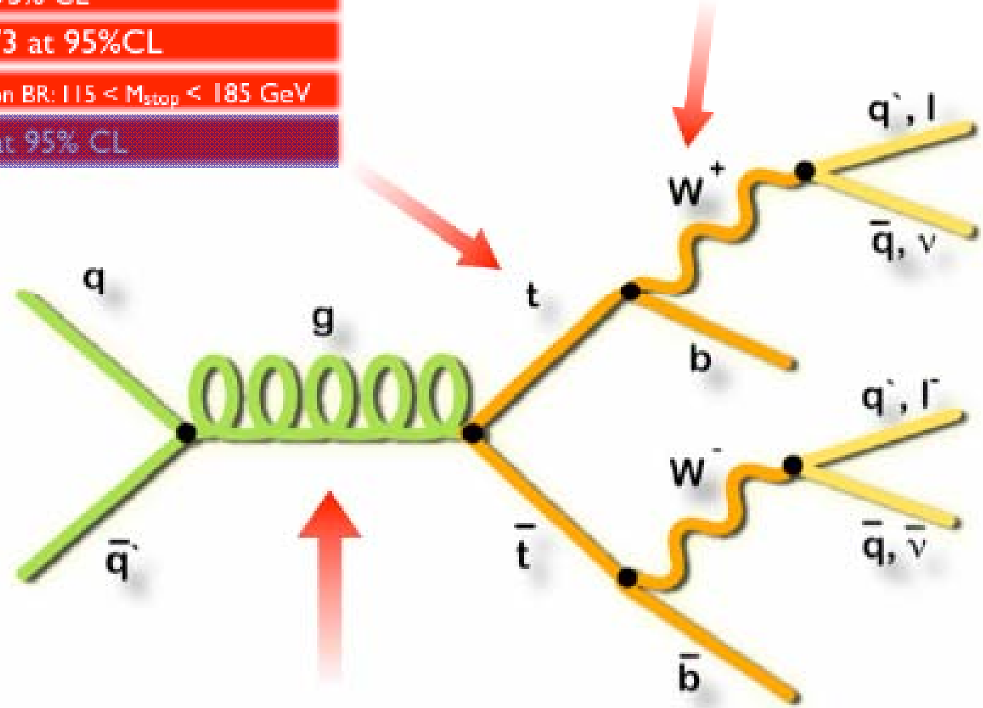
- ~2sigma deviation

  Mass difference

  Fourth generation top

- $M_t = 172.8 \pm 0.9_{stat} \pm 0.8_{sys}$ GeV/c^2
- DeltaM$_t = -3.3 \pm 1.4_{stat} \pm 1.0_{sys}$ GeV/c^2
- $\Gamma_t < 7.5$ GeV at 95% CL
- Exclude q = -4/3 at 95%CL
- 95% CL upper limit on BR: $115 < M_{stop} < 185$ GeV
- $M_{t'} < 335$ GeV at 95% CL

- Vtb = 0.91 ± 0.11 (exp) ± 0.07 (theory)
- 95% CL upper limit on BR: $90 < H^+ < 150$ GeV
- BR(t→Zq) < 3.7% at 95% CL
- $F_0 = 0.62 \pm 0.11$ & $F_+ = -0.04 \pm 0.05$



F/B asymmetry

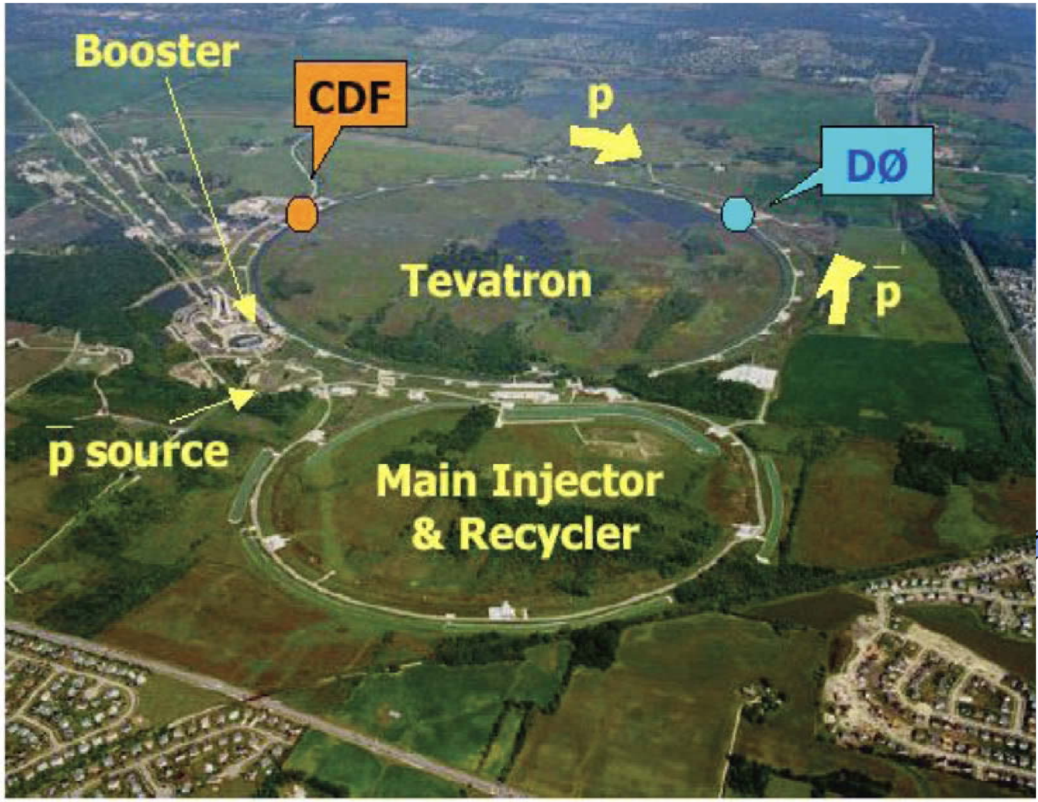
- $\sigma_{t\bar{t}} = 7.5 \pm 0.48$pb
- $\sigma_{t\bar{t}+j} = 1.6 \pm 0.2_{stat} \pm 0.5_{sys}$ pb
- $\sigma_t = 2.76 \pm 0.53$pb

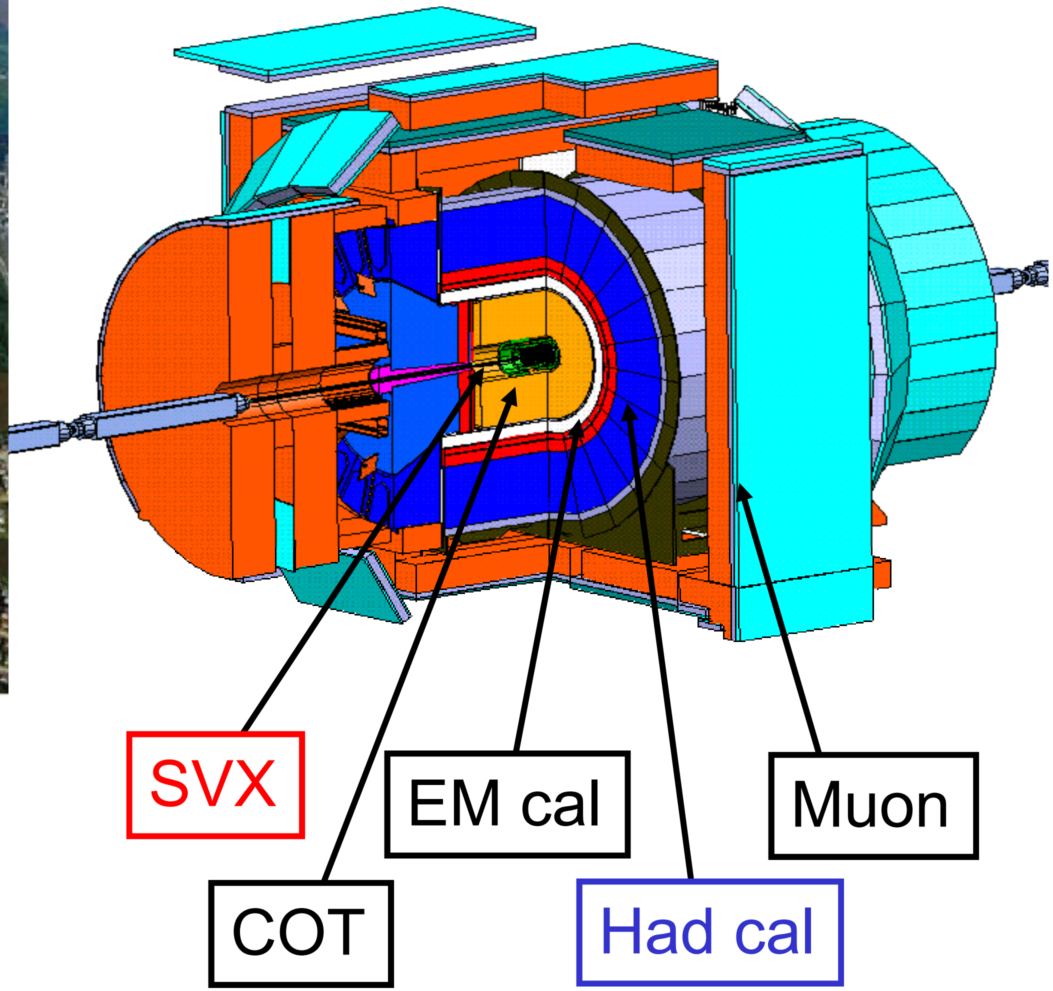
- $F_{gg} = 0.07^{+0.15}_{-0.07}$ (stat+sys)
- $A_{fb}^{lab} = 0.19 \pm 0.07_{stat} \pm 0.02_{sys}$
- $M_{Z'} < 805$ GeV at 95% CL
- Spin Correlations $\kappa = 0.6 \pm 0.5_{stat} \pm 0.2_{sys}$

- Top physics is very rich and give interesting

- More statistics are crucial part of many analyses

Tevatron and CDF II detector





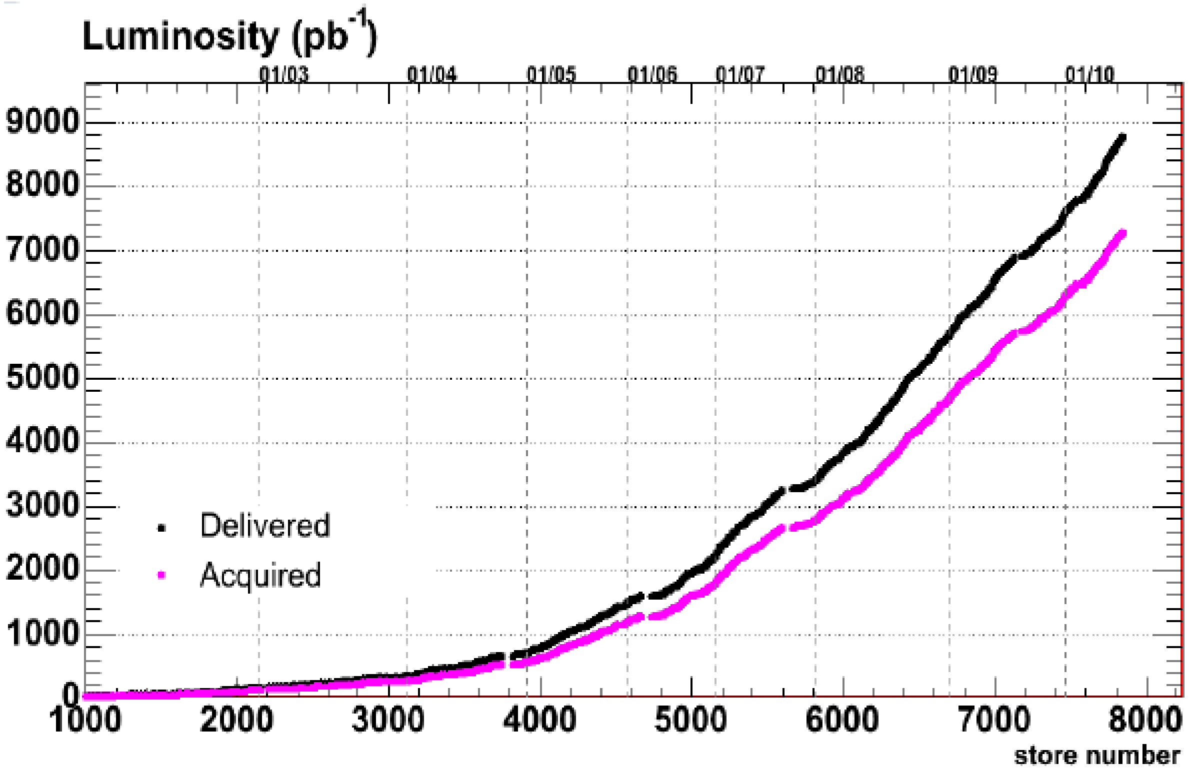
Tevatron is p pbar collider with sqrt(s)=1.96TeV

Now 2nd highest energy in the world

The highest energy of pbar

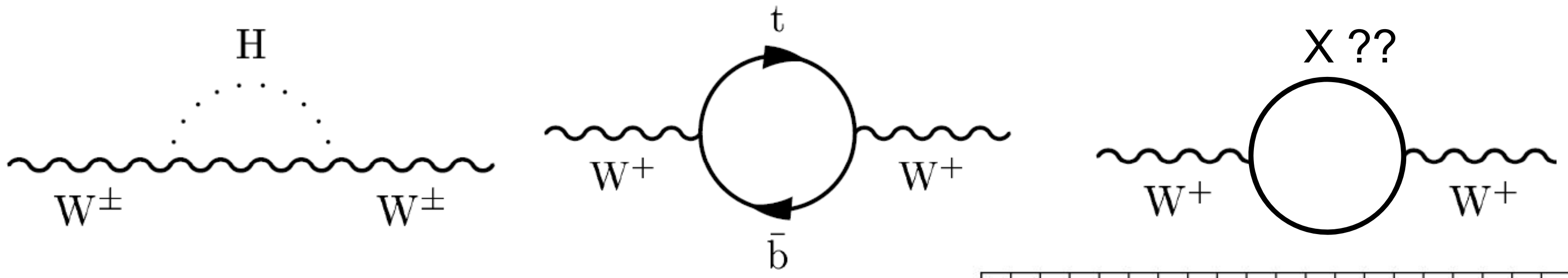
Tevatron Luminosity

- Integrated luminosity $>7fb^{-1}$
- Luminosity is still accelerating
- Now ~ $2fb^{-1}$/year so, 10~12 fb^{-1} by end of 2011
- Possible 3 more year extention is under reviewing ~20 fb^{-1}

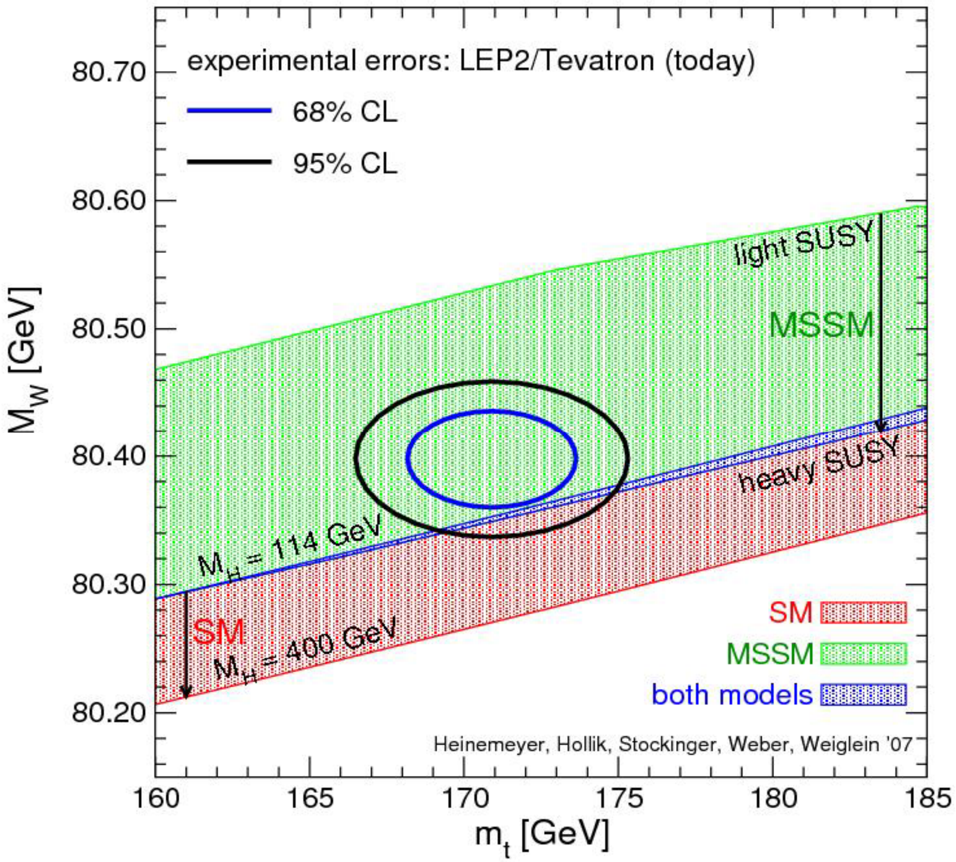


Top quark Mass measurement

Why we measure top quark mass

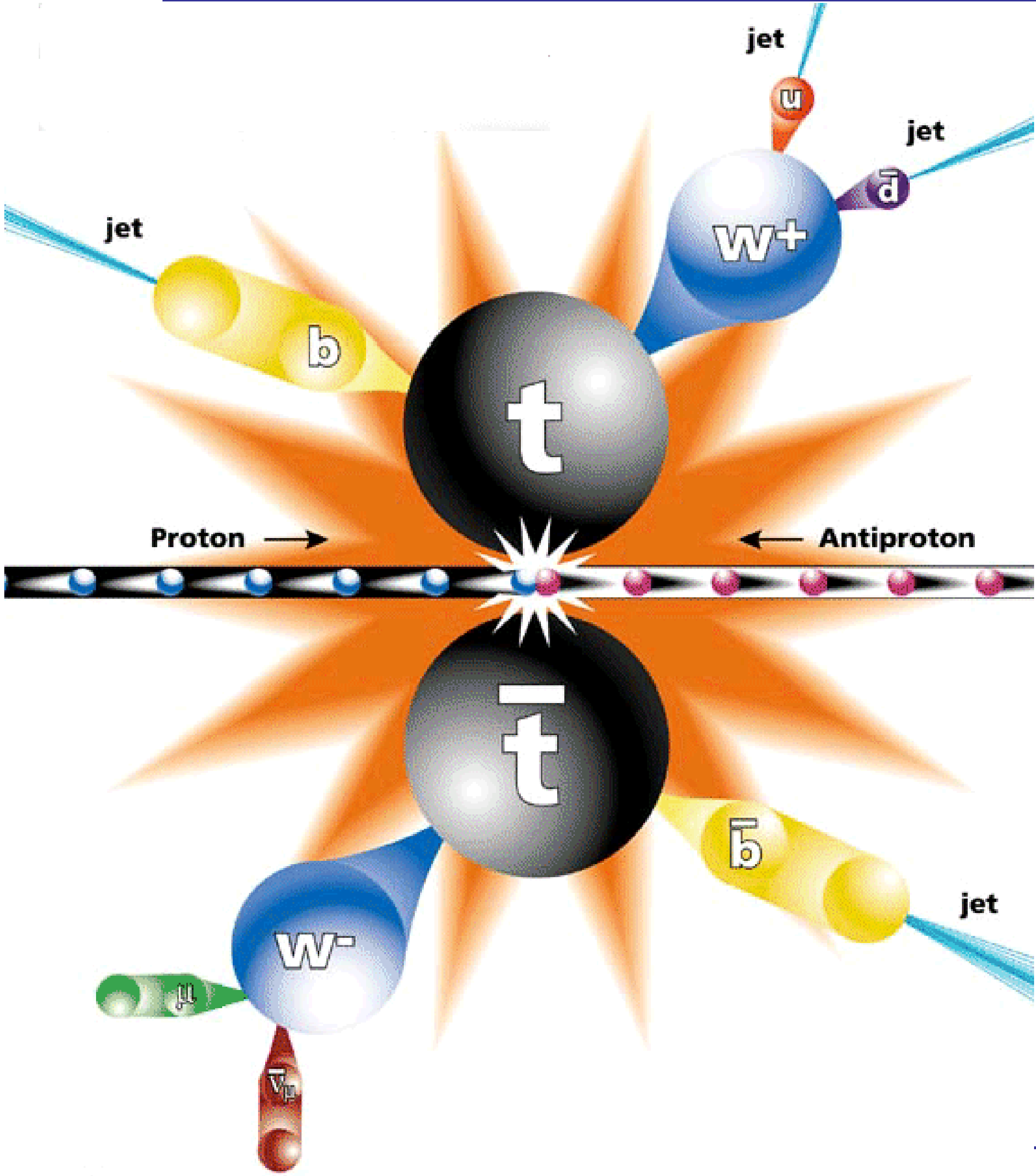


- SM Higgs Mass was constrained by M_{top} and M_W through loop correction of W mass



- Precision top quark mass measurement
  - ❖ Predict SM Higgs mass
  - ❖ Constraints for physics beyond standard model

Golden (Lepton+jets) channel

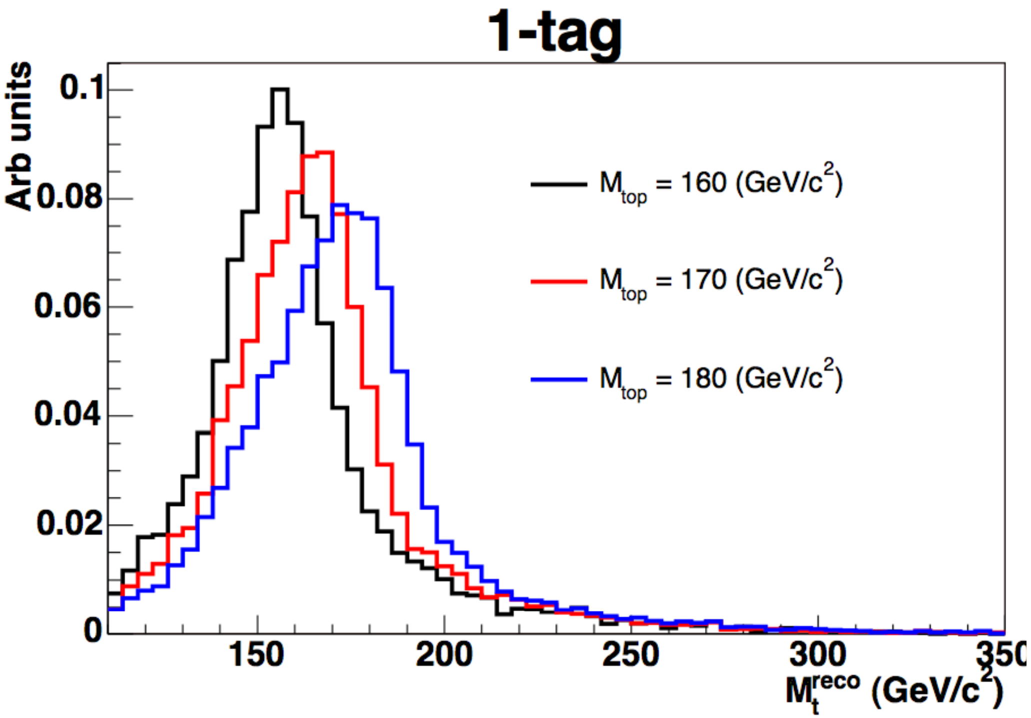


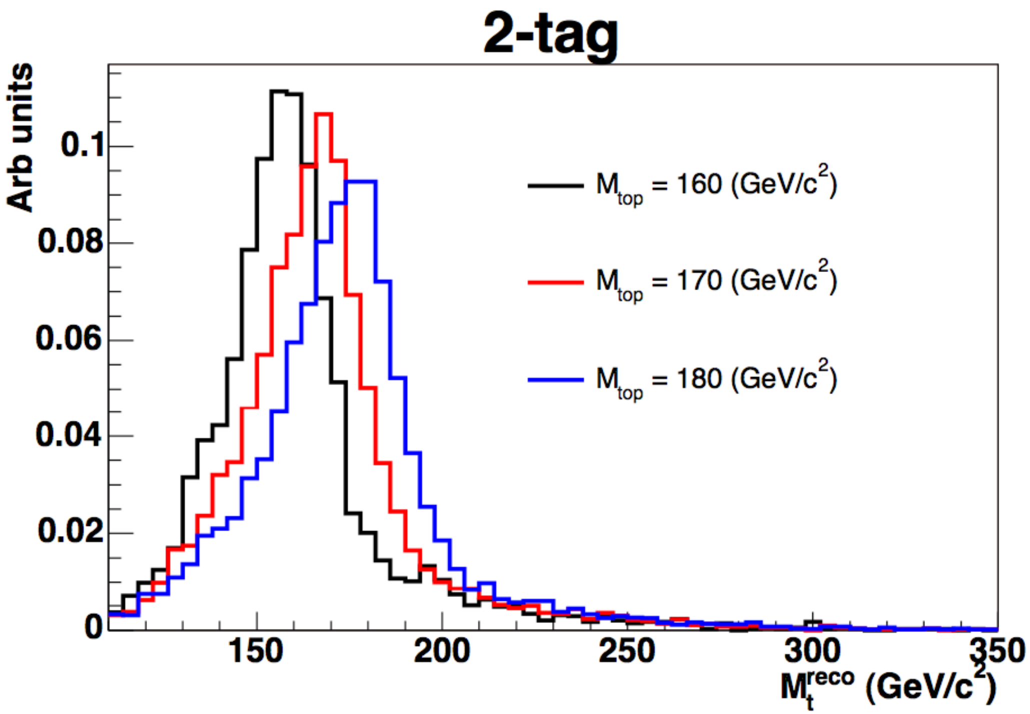
- 4 high p_T jets
  Two of them is b quarks (1>= b tag)
  Light jets is coming from W boson
- One high p_T lepton
- One neutrino
  Large missing transverse energy

Mass reconstruction

- Lepton+jets channel (24 different combinatoric)

$$\chi^2 = \Sigma_{i=\ell,4jets}\frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \Sigma_{j=x,y}\frac{(U_j^{fit} - U_j^{meas})^2}{\sigma_j^2}$$
$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_t)^2}{\Gamma_t^2} + \frac{(M_{b\ell\nu} - M_t)^2}{\Gamma_t^2}$$

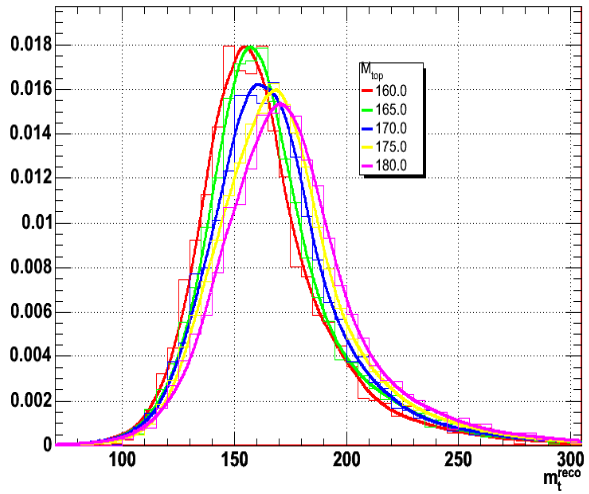




History : Template method (original but still useful)

- •MC datasets
- • ttbar: set of Mtop points
- •backgrounds

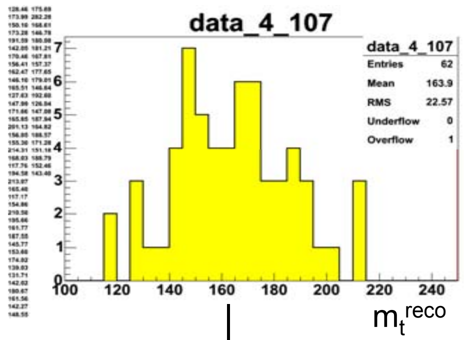
→ **Event reconstruction** → Construct probability density functions for m_t^{reco} for all MC mass points and background



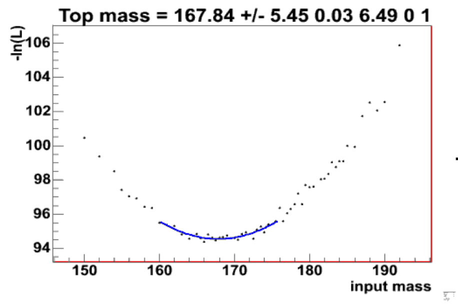
Pick a variable highly correlated to true M_{top}: m_t^{reco}

DATA → **Event reconstruction**

(all plots form MC)

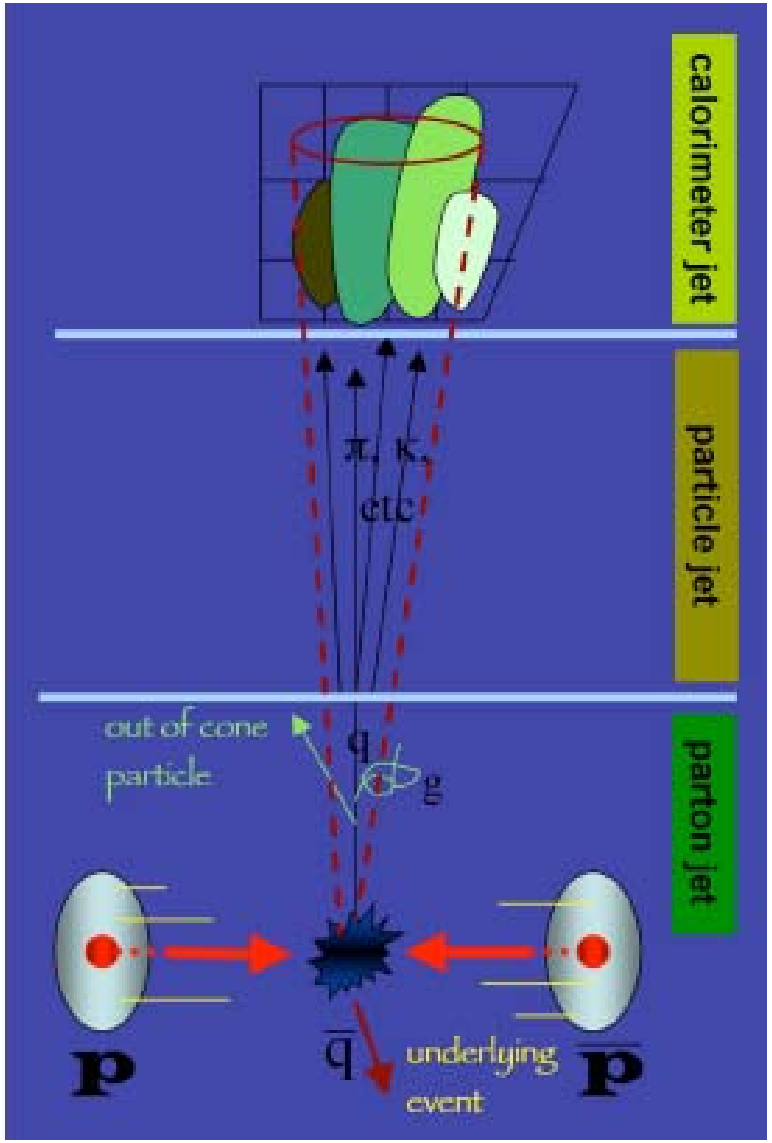


Compare m_t^{reco} distribution from data to each of the PDF's, fit for background fraction

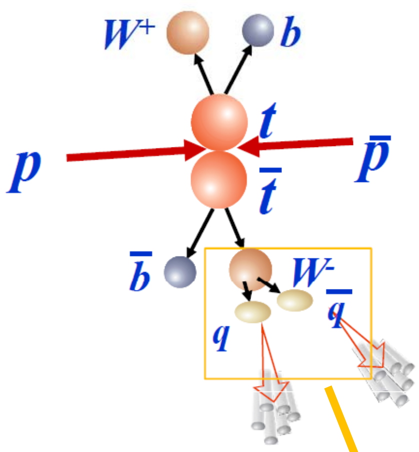


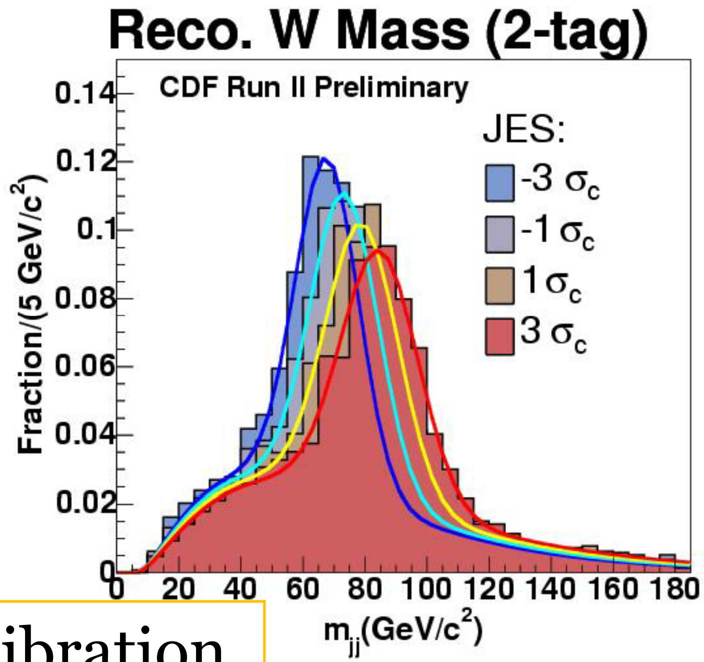
→ Fit –ln(L) to a parabola to extract measurement and statistical error

Jet energy scale



JES uncertainty made bound of top mass resolution



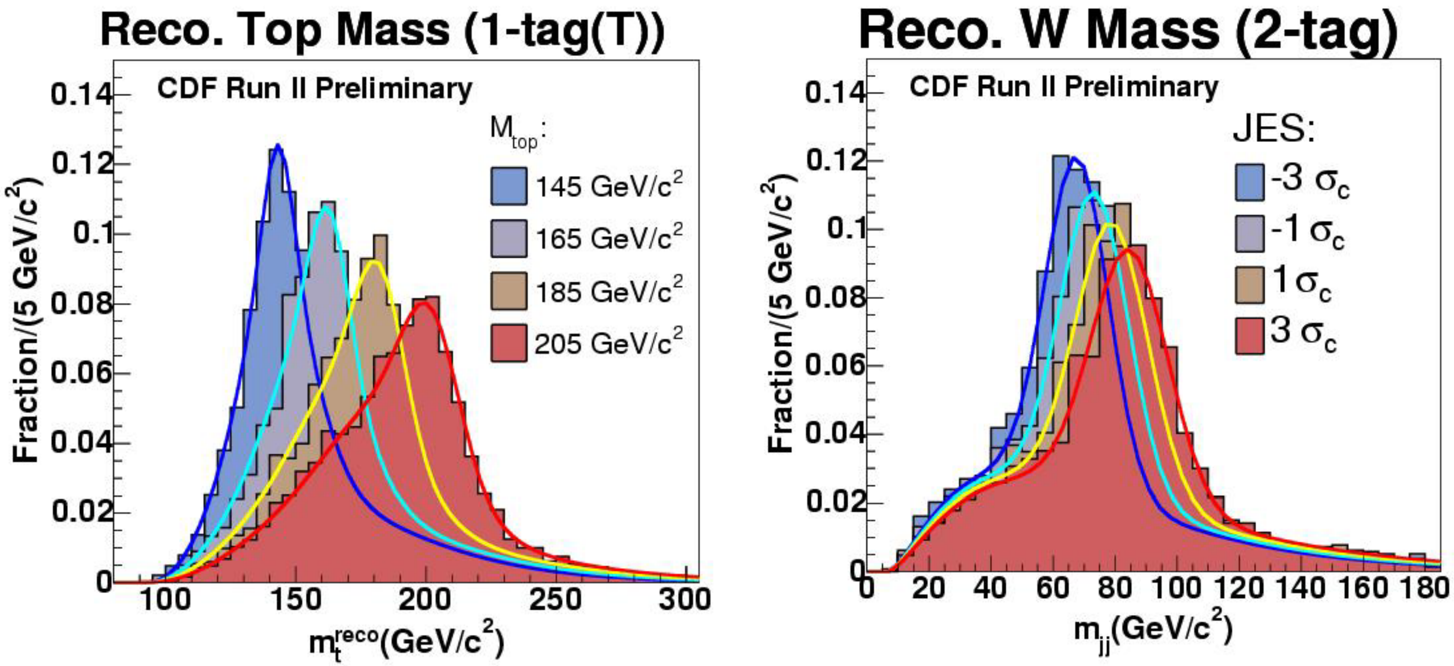


In situ JES calibration

Measured JES uncertainty
Lepton+jets : 1.0 GeV/c^2
Dilepton : 2.9 GeV/c^2
(CDF 4.8 fb^{-1}, template method)

2D(1DX1D) method (340 pb^{-1} in L+Jet channel)

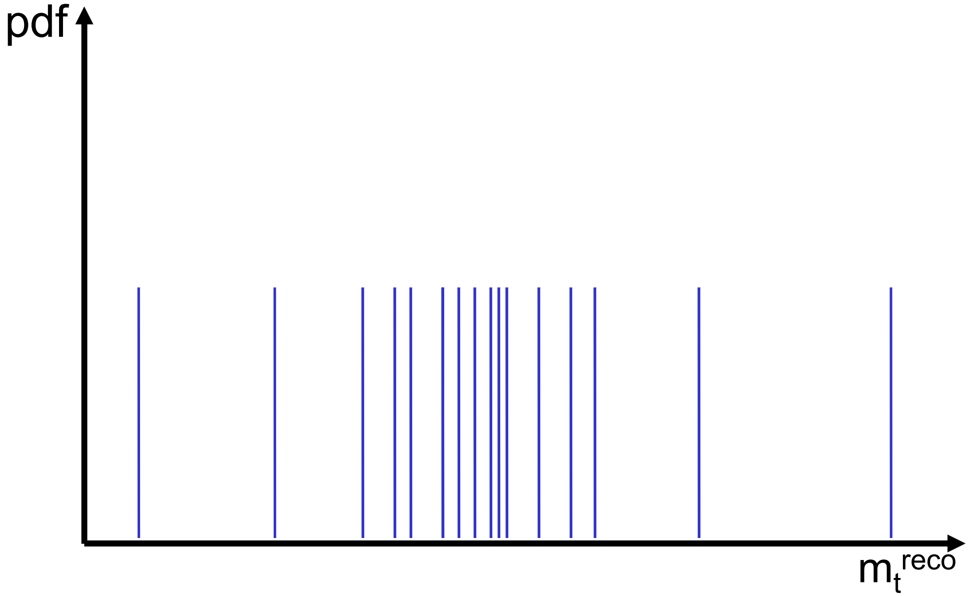
- We build probability for top quark mass using reconstructed top mass and Jet energy scale using dijet mass



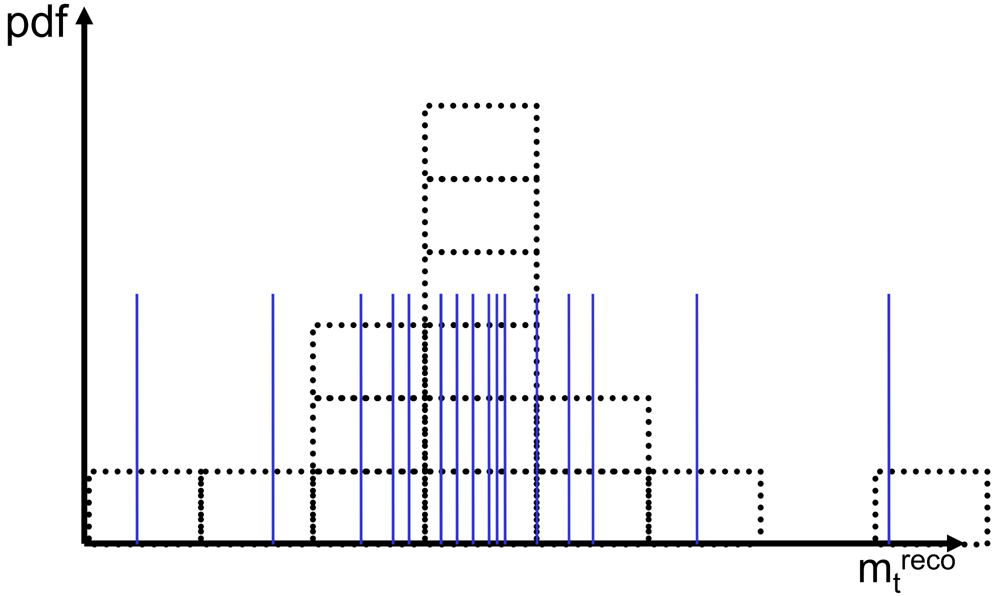
$$P(m_t^{reco}, m_{jj}; M_{top}, \Delta JES) = P(m_t^{reco}; M_{top}, \Delta JES) \times P(m_{jj}; \Delta JES)$$

- We use arbitarary function to build probability density function
- We assume no correlation between reconstructed top mass and dijet mass

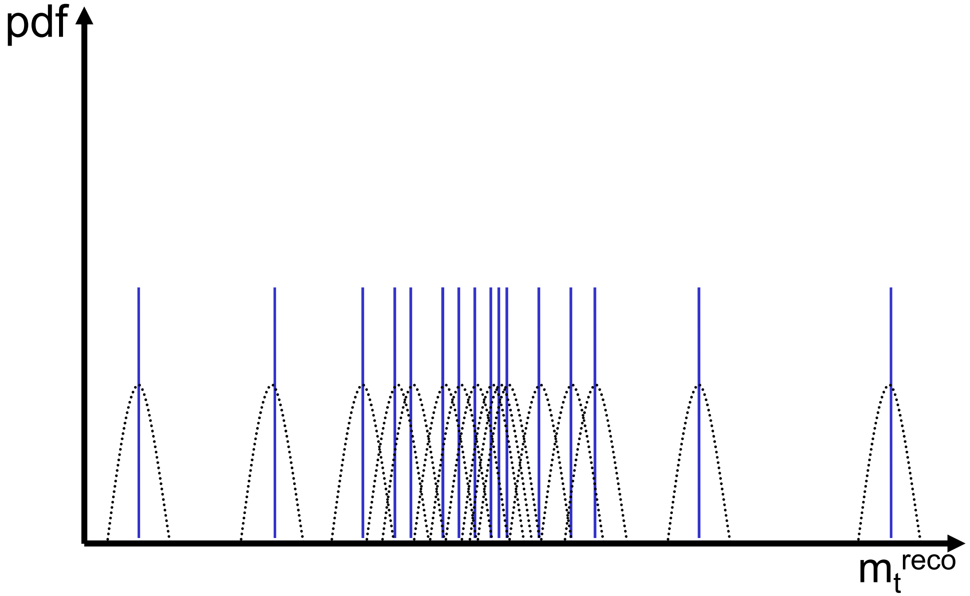
Kernel Density Estimation



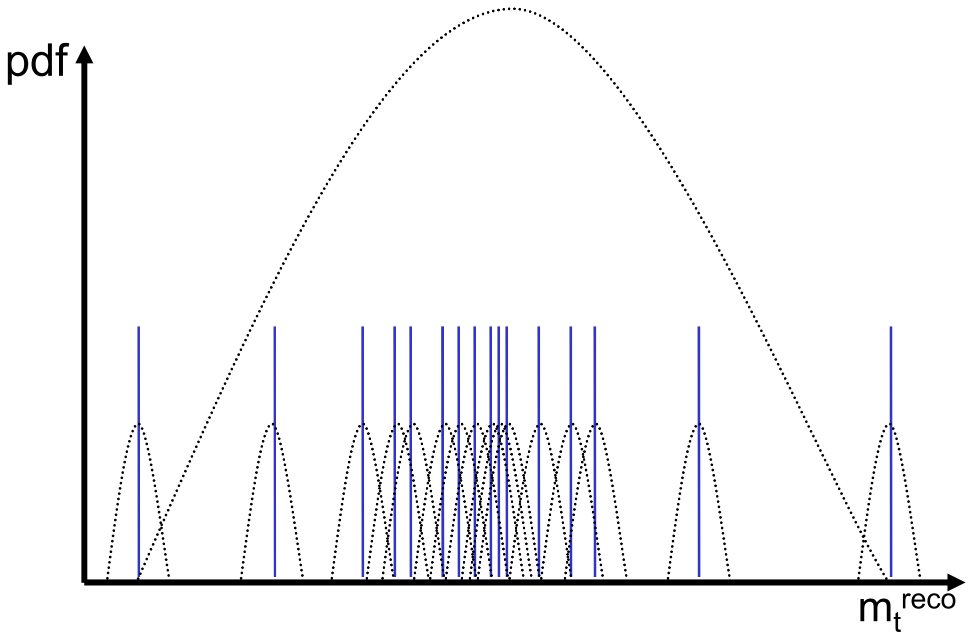
Kernel Density Estimation

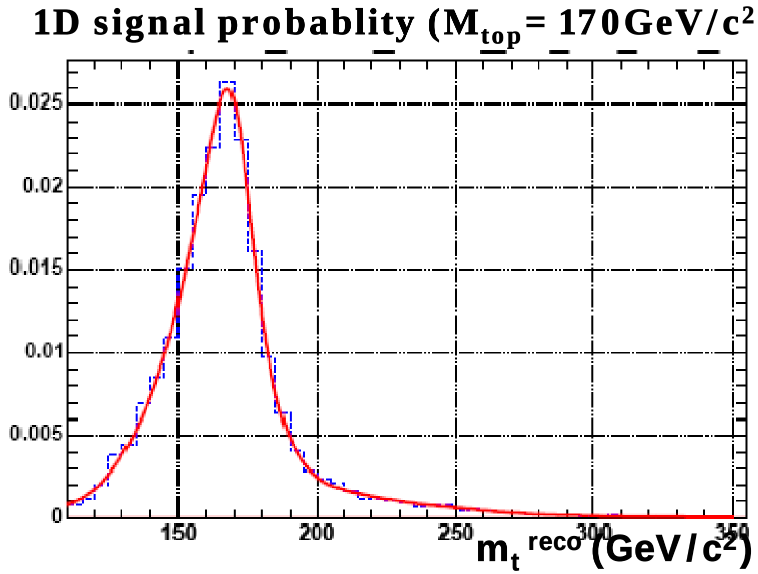


Kernel Density Estimation



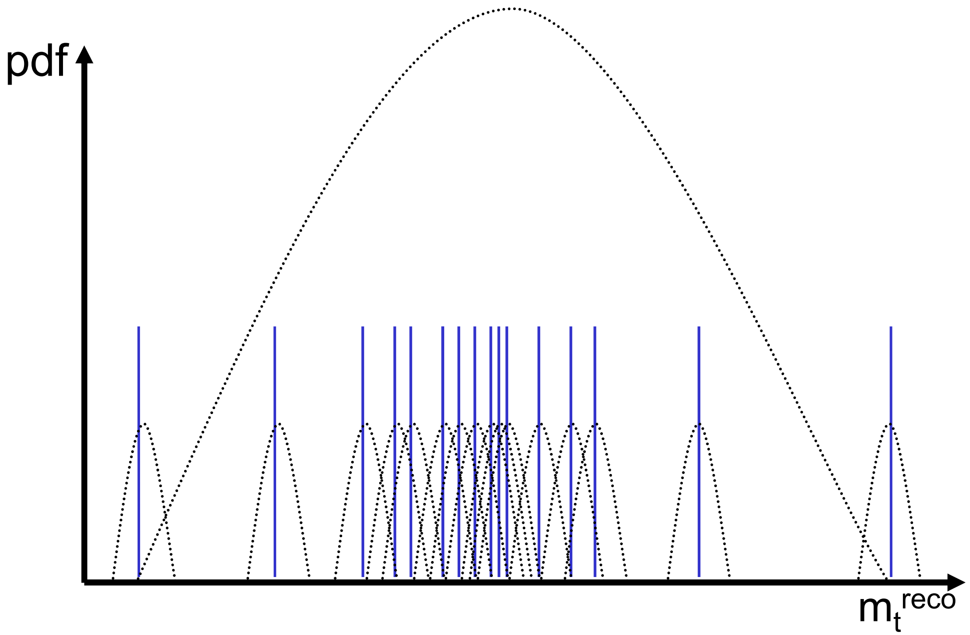
Kernel Density Estimation

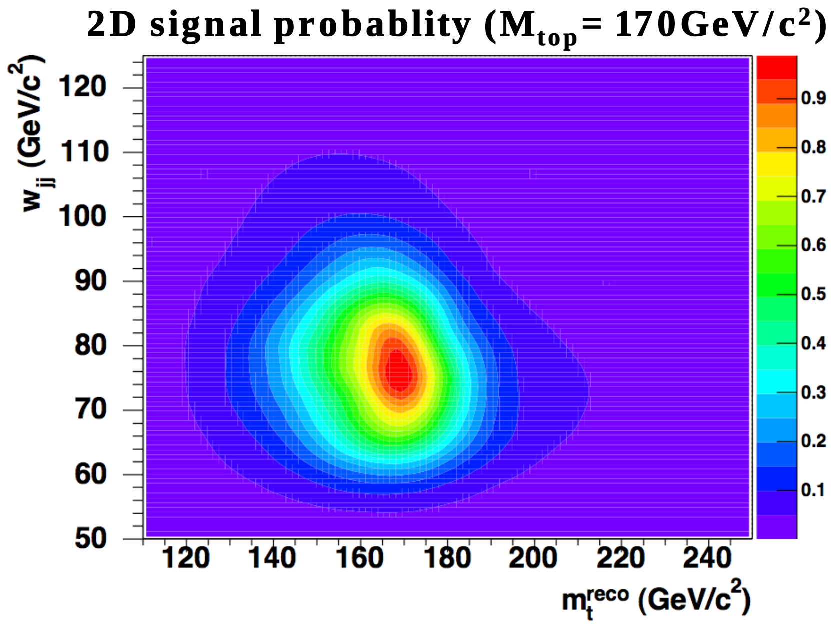




- No need to assume form of the shape
- Naturally extendible to more than 1 dimensions (correlations treated intrinsically)

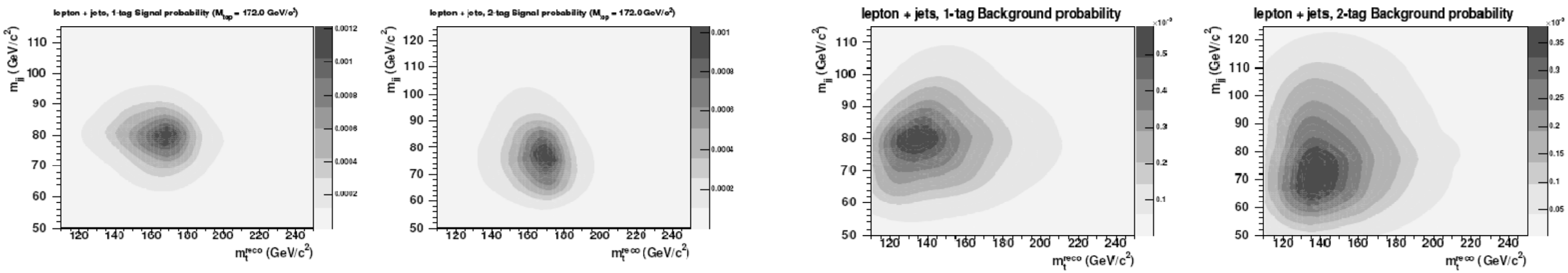
Kernel Density Estimation





- Expand to 2D
  - We can correctly account the correlation between two observables

M_{top} measurement using 1.9 fb^{-1} data



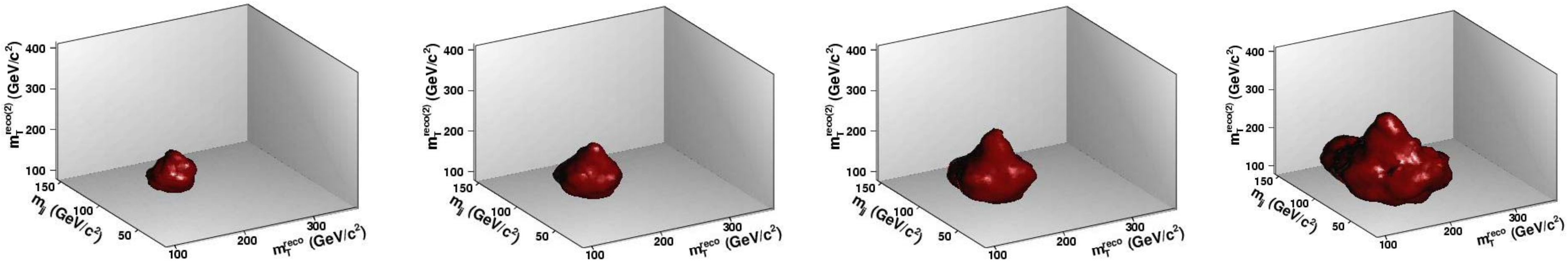
$P(m_t^{reco}, m_{jj}; M_{top}, \Delta JES)$ Fully 2D with Kernal Density Estimation

We apply same technique both lepton+jets and dilepton

We have first simultaneous measurement using lepton+jets and dilepton channel in 1.9 fb^{-1}

PRD 79 112007 (2009)

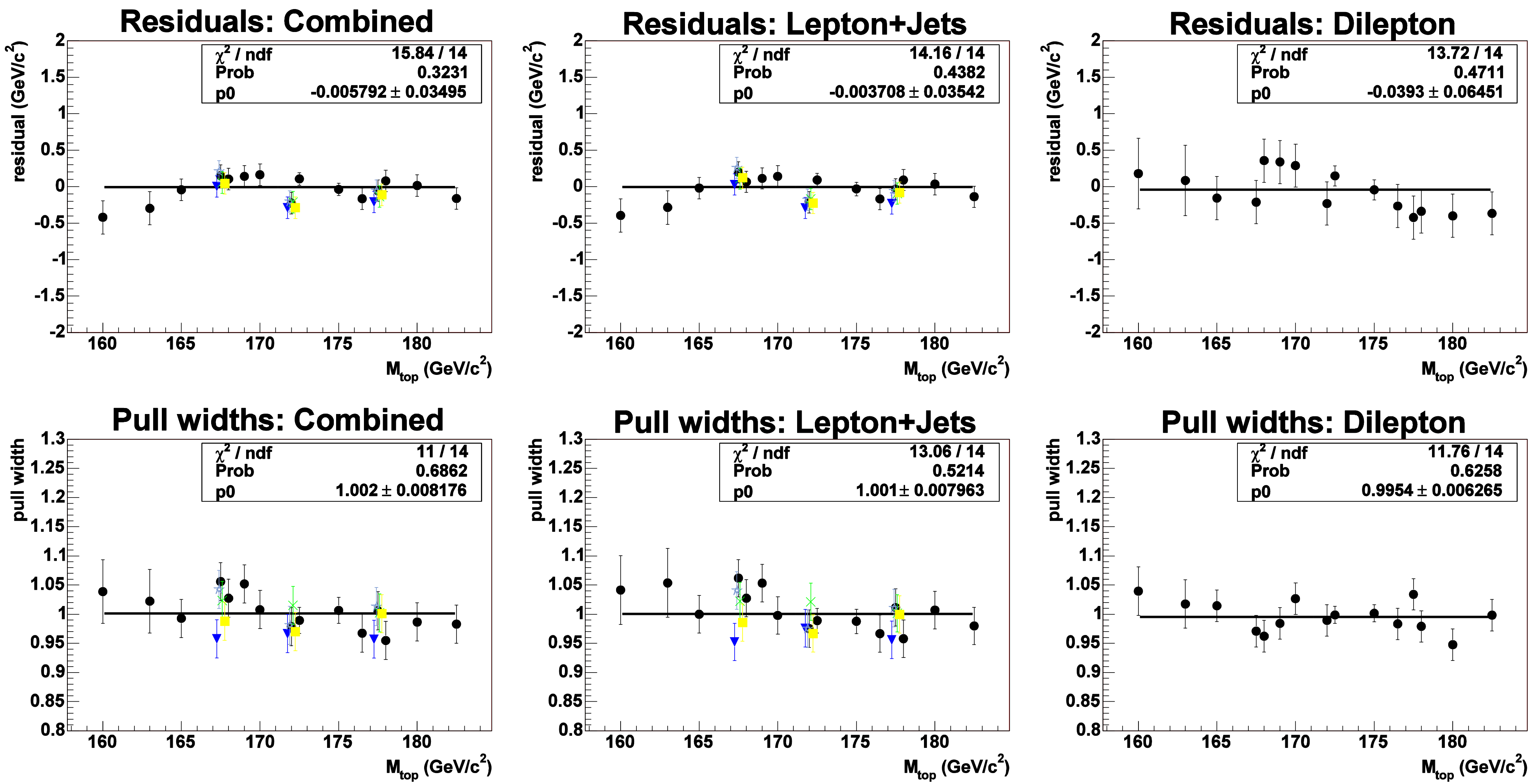
3D template. Why not?



$$P(m_t^{reco}, m_{jj}, m_t^{reco(2)}; M_{top}, \Delta JES)$$

- Three dimensional KDE
  - We use three observables to build probability density function
- We have ~10% improvement in statistical uncertainty by using third observable
  - 2^{nd} minimum chi2 mass in kinematic fit from different combinatoric
- It can be easily extended as multi-variable technique
  - Possible direction(?)
  - Limitation in the MC statistics – not enough with linear increasing

Method checks (after correction)

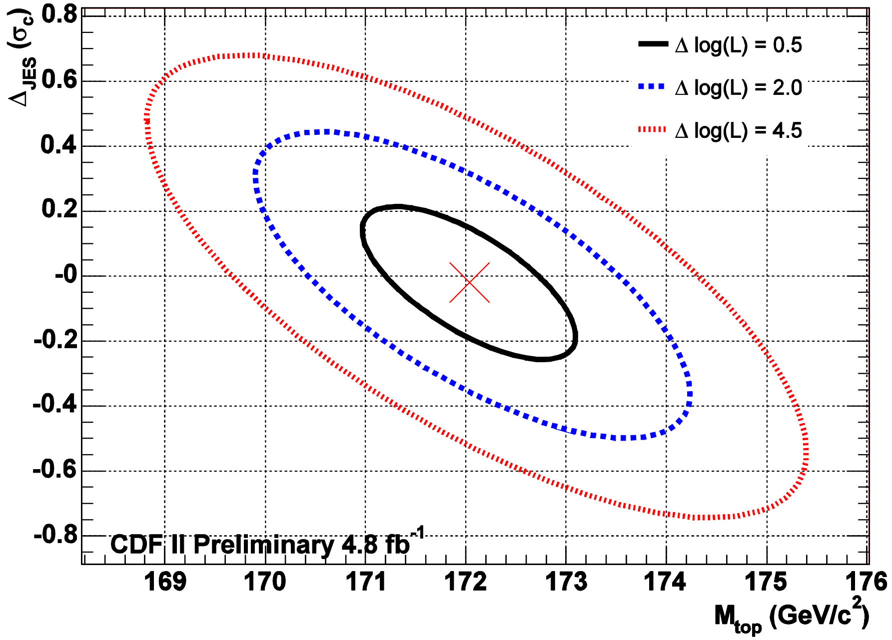


Statistical uncertainty was scaled by 4.1% and 4.8% for LJ and Combined respectively

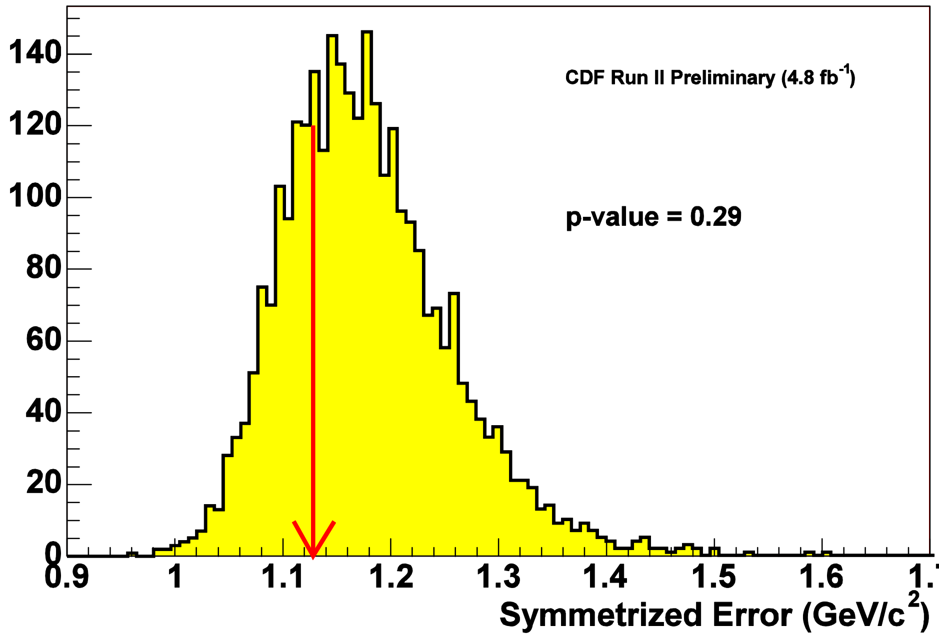
Systematic uncertainties

	CDF II Preliminary 4.8 fb^{-1}		
Systematic	LJ	DIL	Combination
Residual JES	0.6	2.9	0.6
Generator:	0.6	0.6	0.6
PDFs	0.1	0.3	0.1
b jet energy	0.3	0.3	0.3
Background shape	0.1	0.3	0.1
gg fraction	0.1	0.3	$<$0.1
Radiation	0.1	0.3	0.1
MC statistics	0.1	0.3	0.1
Lepton energy	$<$0.1	0.3	$<$0.1
MHI	0.1	0.2	0.1
Color Reconnection	0.2	0.6	0.2
Total systematic	0.9	3.1	0.9

Results (4.8 fb^{-1})



Combined measurement



Combined fit : 171.9 ± 1.5 GeV/c^2

LJ only fit : 172.0 ± 1.5 GeV/c^2

Dilepton fit : 170.6 ± 3.8 GeV/c^2

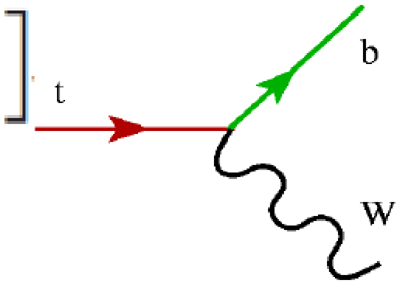
< 0.9% Precision

Top quark width measurement

Why we measure top quark width

- It is intrinsic parameter of SM
  - Very precise estimation using NLO calculation (~1% precision)

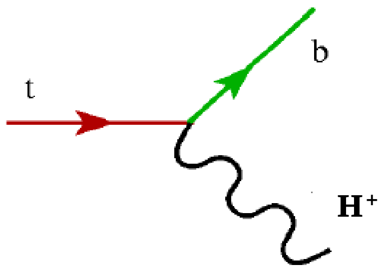
$$\Gamma_t = \Gamma_t^0\left(1 - \frac{M_W^2}{m_t^2}\right)^2\left(1 + 2\frac{M_W^2}{m_t^2}\right)\left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right]$$



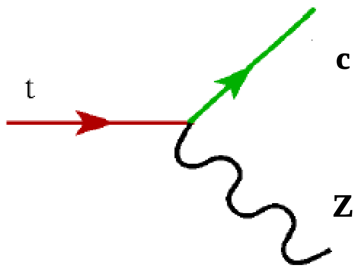
top quark decay

  - 1.4 GeV at M_{top} = 172.5 GeV/c^2

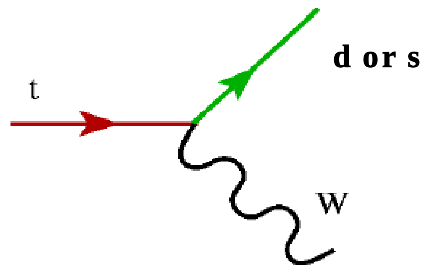
- Deviation from SM indicate new physics
  - Charged Higgs decay, FCNC, and other exotic models



top quark decay



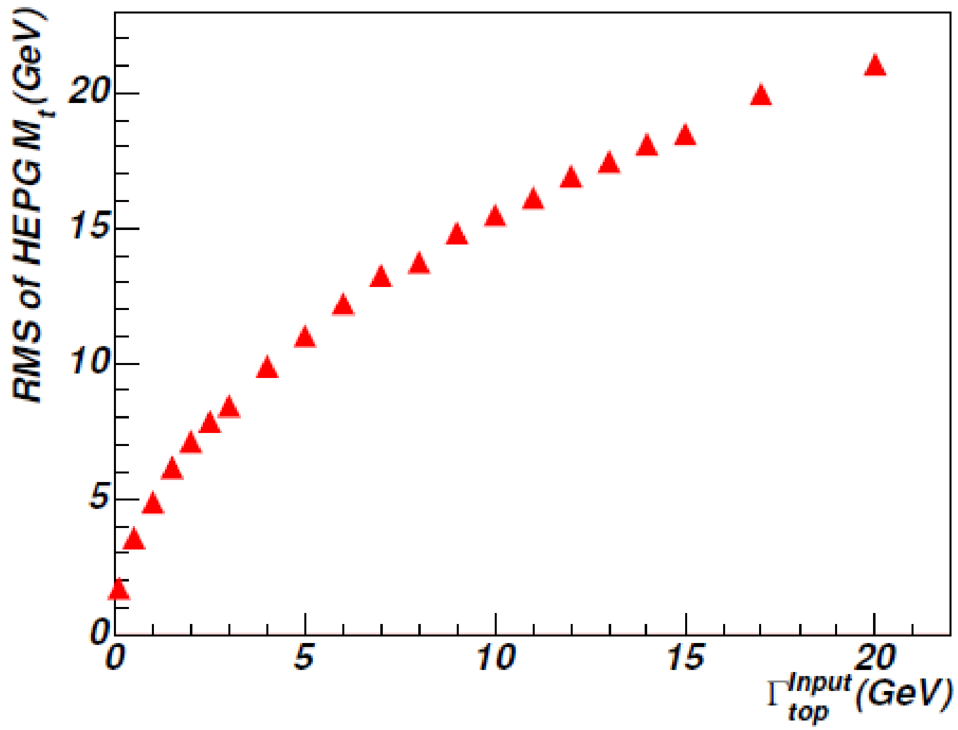
top quark decay

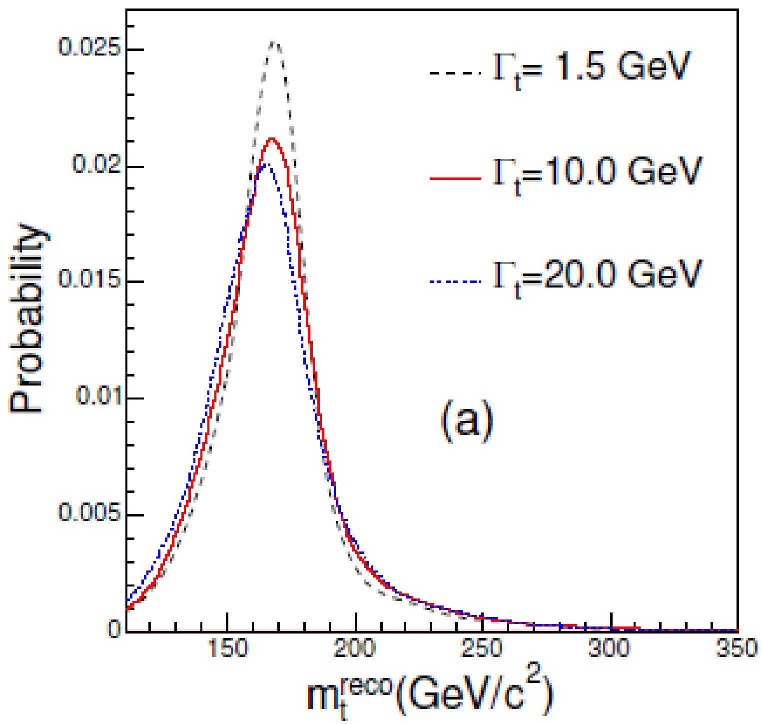


top quark decay

Analysis method

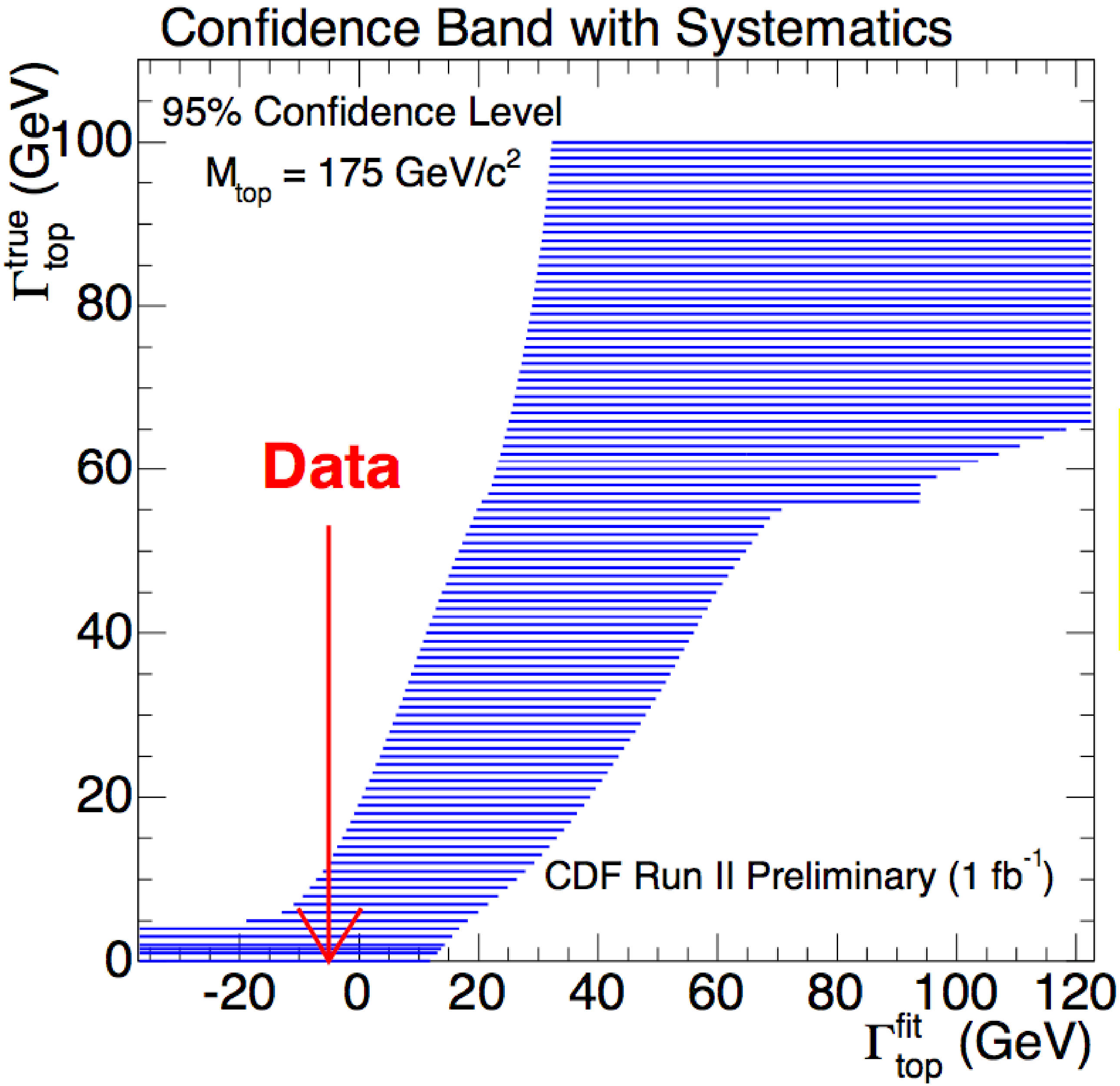
- Same template with top quark mass measurement but different signal samples (varying top width)





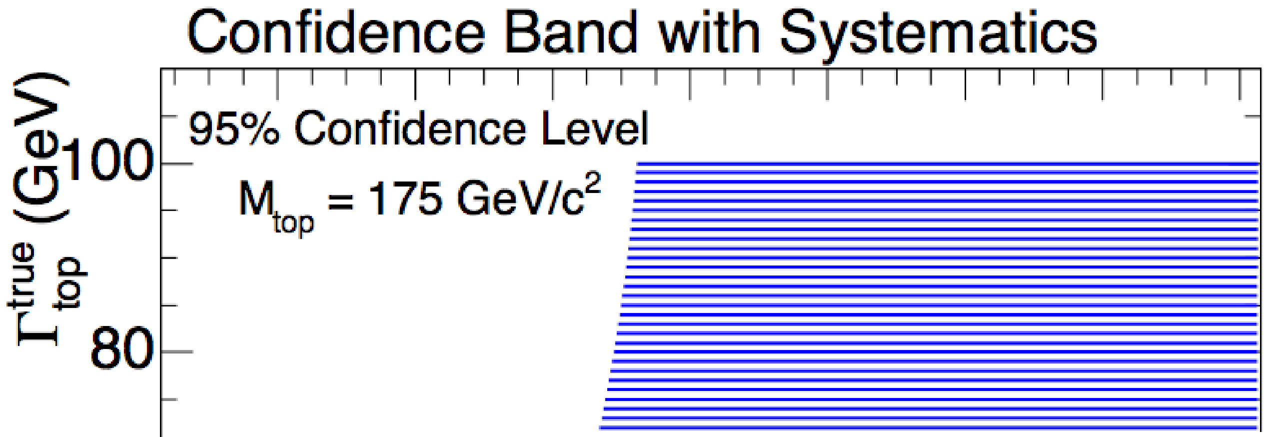
- RMS of reconstructed top mass is measure of top width

First direct bound of top quark width (1 fb^{-1})



Γ_{top} < 13.1 GeV at 95% CL

First direct bound of top quark width (1 fb^{-1})

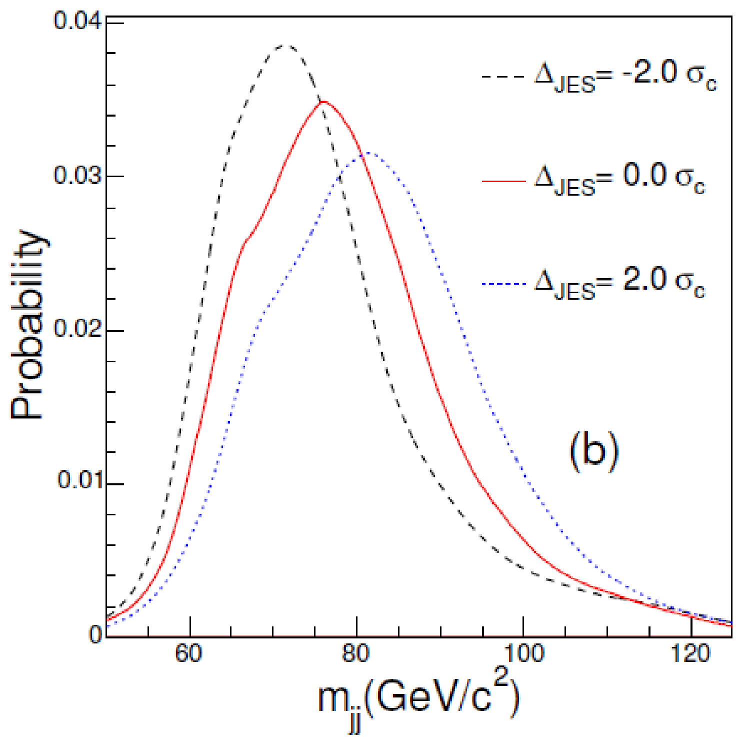


Γ_{top} < 13.1 GeV at 95% CL

Source	$\Delta\Gamma_{top}^{fit}$ (GeV)
*Jet Energy Scale (Γ_t^{input} = 30 GeV)	3.2
*Jet Resolution (Γ_t^{input} = 15 GeV)	2.1
Parton Distribution Functions	1.4
*FSR	0.9
*ISR	0.7
Generator	0.7
Background shape	0.5
MC acceptance	0.5
MC statistics	0.4

Update of top width measurement (4.3 fb^{-1})

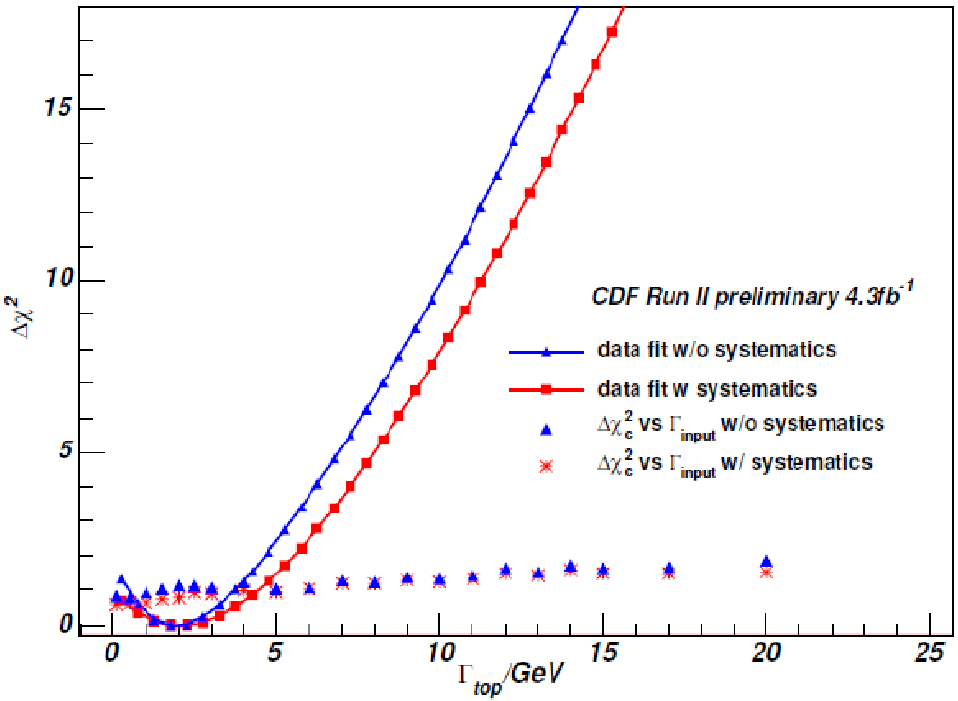
- *In situ* JES calibration using Wjj

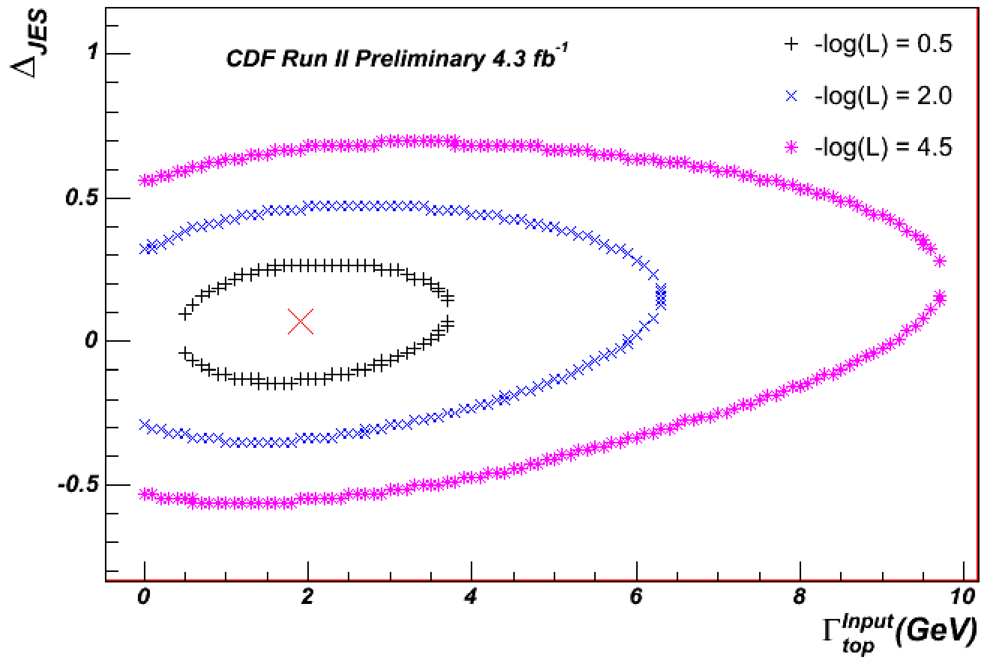


- 2D fit was done

Systematic Effects	Meas. mean top width shift(GeV)
Jet Resolution	1.1
Residual JES	0.3
Generator	0.4
PDF	0.3
B Jet Energy	0.2
LJ Background	0.1
gg Fraction	0.3
IFSR	0.2
Lepton Energy	0.2
Color Reconnection	0.9
Multi. Had. Int.	0.3
Total Systematic	**1.6**

Results





$$0.4 < \Gamma_{top} < 4.4 \text{ GeV @ 68\% CL}$$

$$\Gamma_{top} < 7.4 \text{ GeV @ 95\% CL}$$

First set of low bound limit (68% CL)

ΔM_{top}

Intro.

Our top mass precision allow to test mass difference between top quark and anti top quark

This is testing CPT violation

- Well tested in meson, baryon, and boson
- Not very well in quark and high mass particles
- D0 1fb^{-1} measurement using ME technique

  $\Delta M = 3.8 \pm 3.7$ GeV/c^2

We modified usual kinematic fitter to allow mass difference in the lepton+jets channel

- Two observables (best, 2^{nd} best)

Event Reconstruction

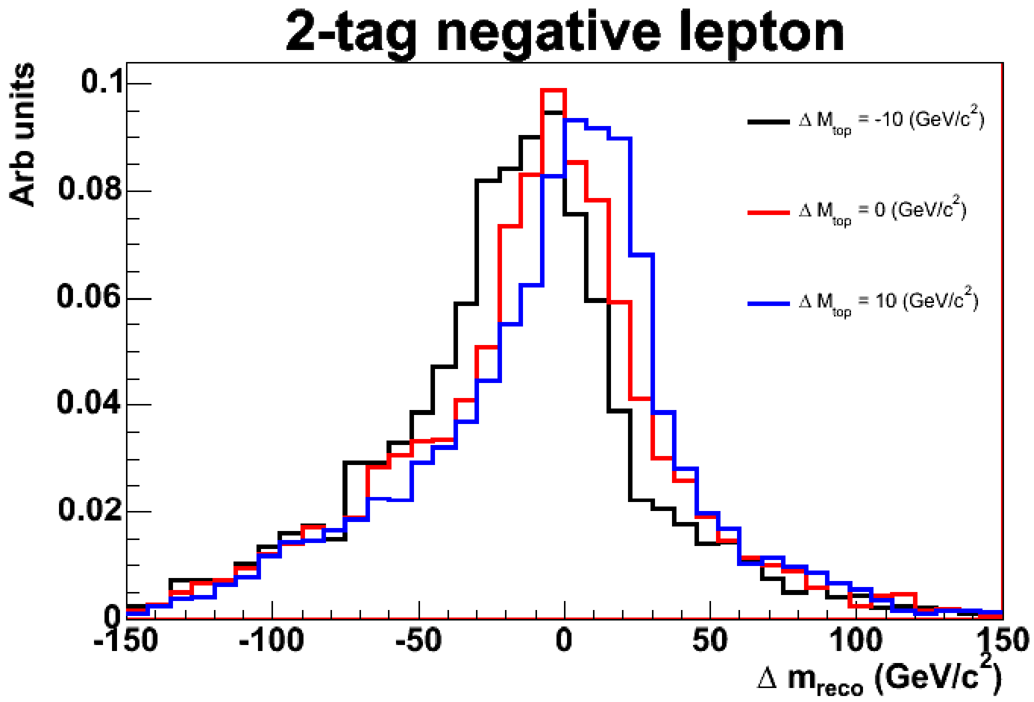
- We modified nominal kinematic fitter to get mass difference

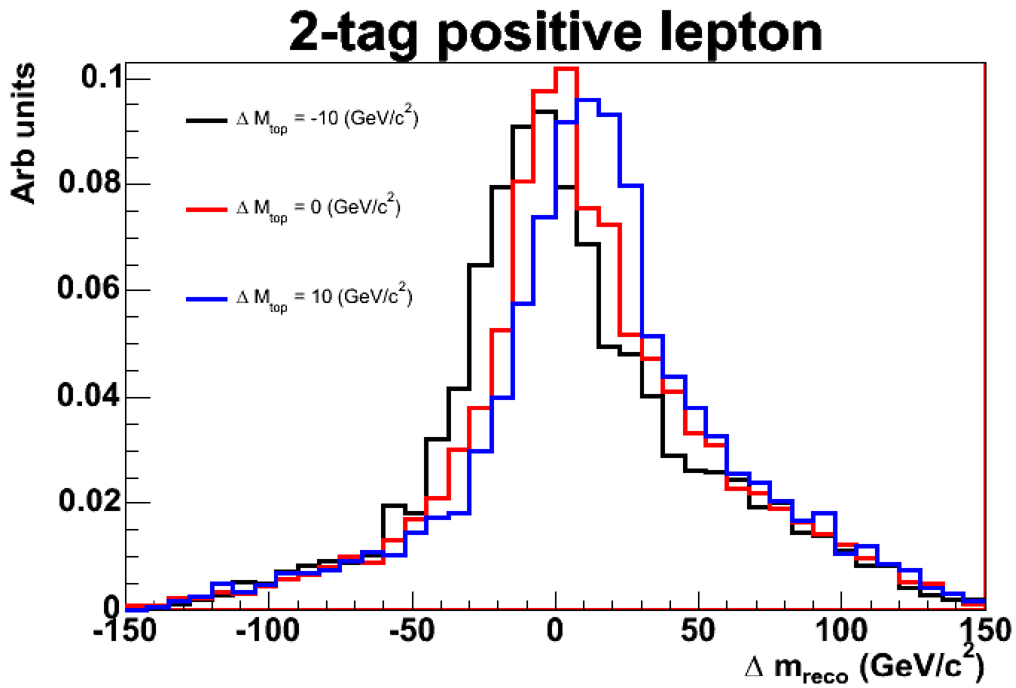
$$\chi^2 = \Sigma_{i=\ell,4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \Sigma_{j=x,y} \frac{(U_j^{fit} - U_j^{meas})^2}{\sigma_j^2}$$
$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2}$$
$$+ \frac{(M_{bjj} - (172.5 + dM_{reco}/2))^2}{\Gamma_t^2} + \frac{(M_{b\ell\nu} - (172.5 - dM_{reco}/2))^2}{\Gamma_t^2}$$

$$\Delta m_{\rm reco} = -Q_{lepton} \times dM_{reco}$$

- This variable is corresponding to top quark mass minus anti-top quark mass in reconstruction level

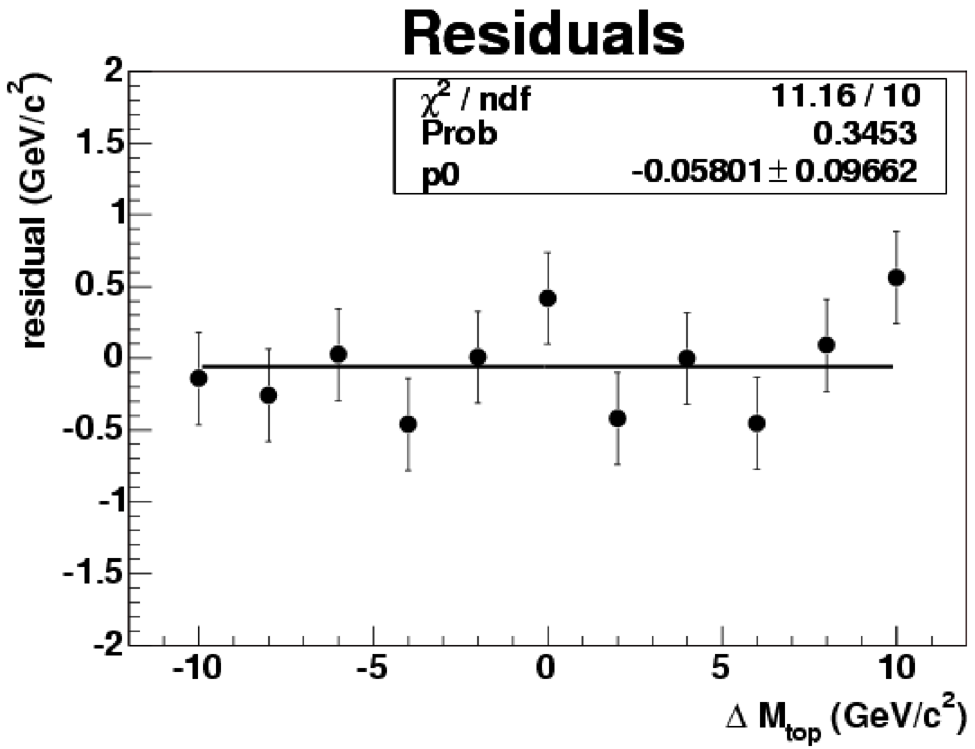
Shape of reconstructed mass diff.

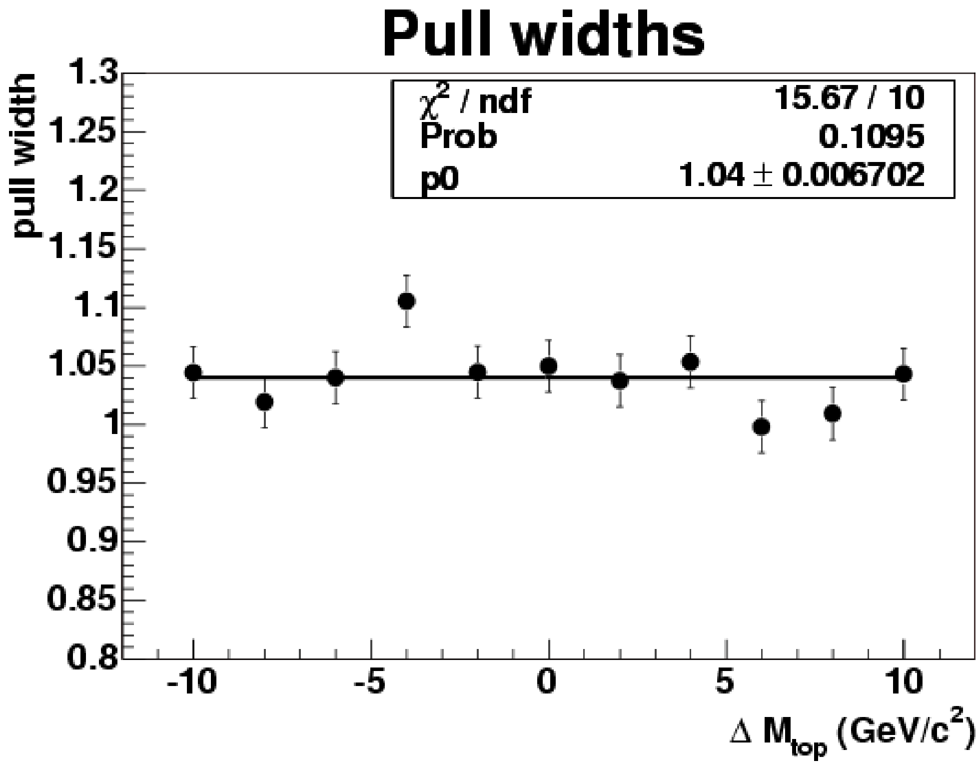




- We divide sample with lepton charge due to different response of hadronic top and leptonic top
  - Different resolution of jets, lepton, and MET

Method checks





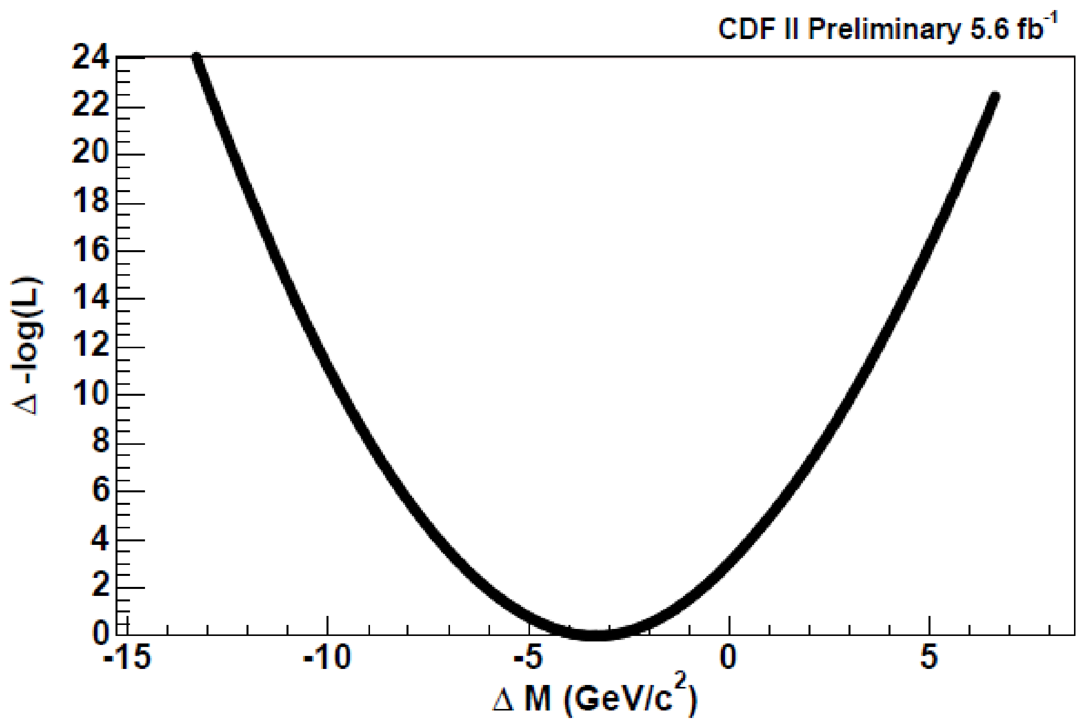
- We assumed the averaged top quark mass as 172.5GeV/c^2
- Working properly – NO Bias
- We increase uncertainties by 4% based on pull widths

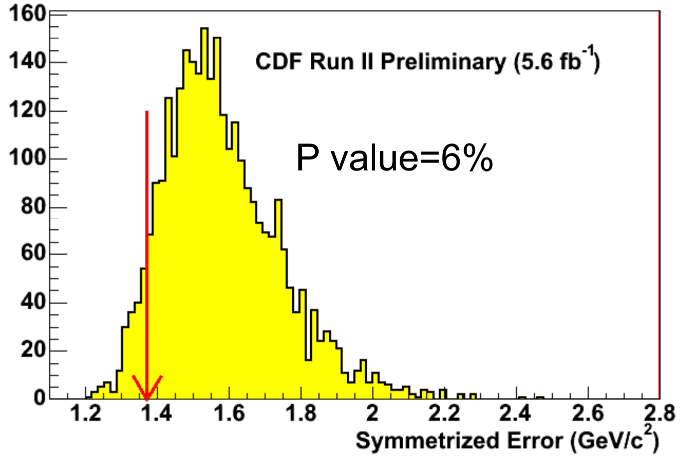
Systematics

CDF II Preliminary 5.6 fb^{-1}	
Systematic	Result (GeV/c^2)
Signal Modeling	0.7
JES	0.2
PDFs	0.1
b jet energy	0.1
$b/\bar{b}$ asymmetry	0.3
Background shape	0.2
gg fraction	0.1
Radiation	0.1
MC statistics	0.1
Lepton energy	0.1
MHI	0.4
Color Reconnection	0.2
Total systematic	1.0

- Very similar way with other top properties
- Possible b/bbar(lepton/anti-lepton) difference was added

Data fit and results

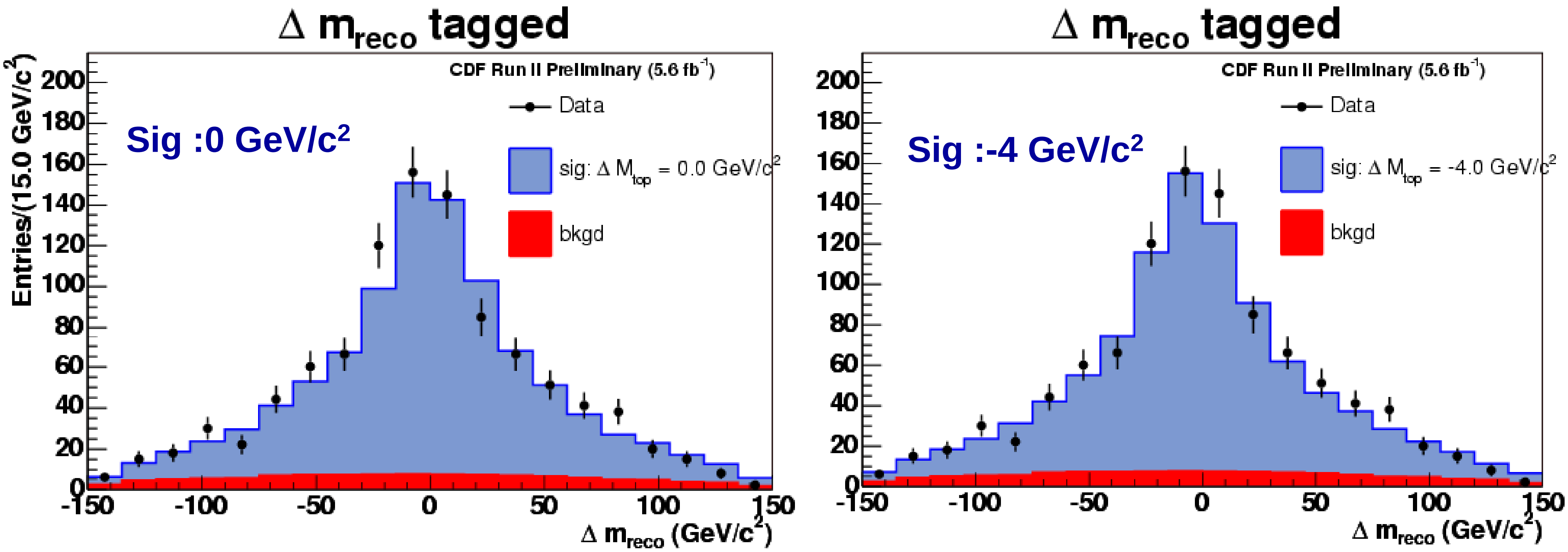




- ~ 2sigma deviation from standard model

$$-3.3 \pm 1.4\ (\text{stat}) \pm 1.0\ (\text{syst})\ \text{GeV}/c^2$$
$$= -3.3 \pm 1.7\ \text{GeV}/c^2$$

Data and expectation comparison



- Comparison was done by adding four sub-categories

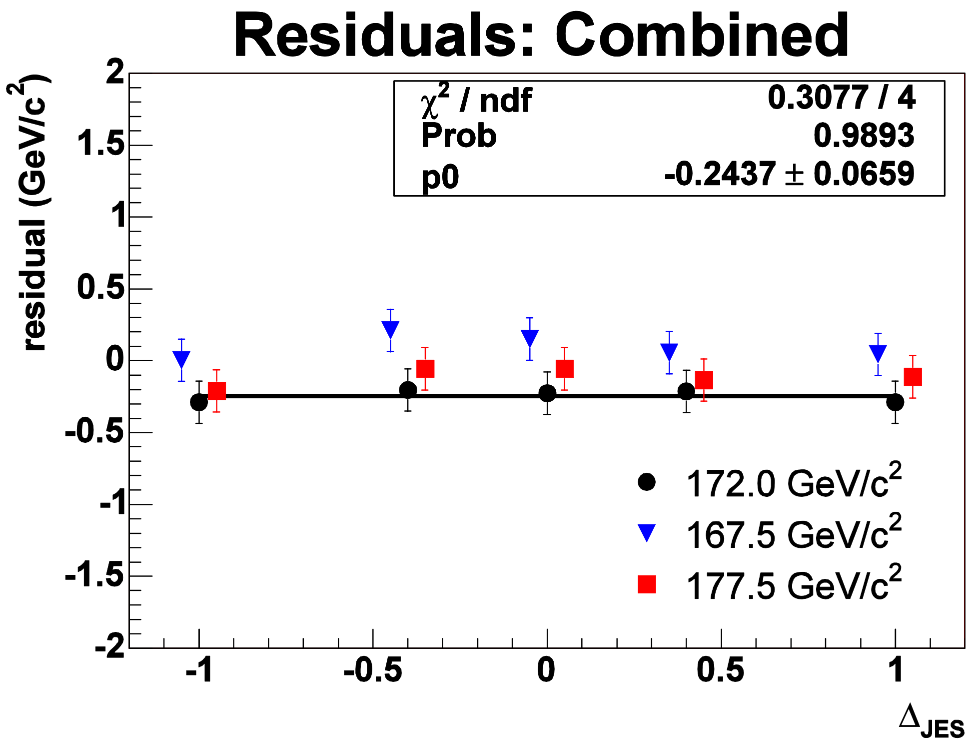
Conclusion

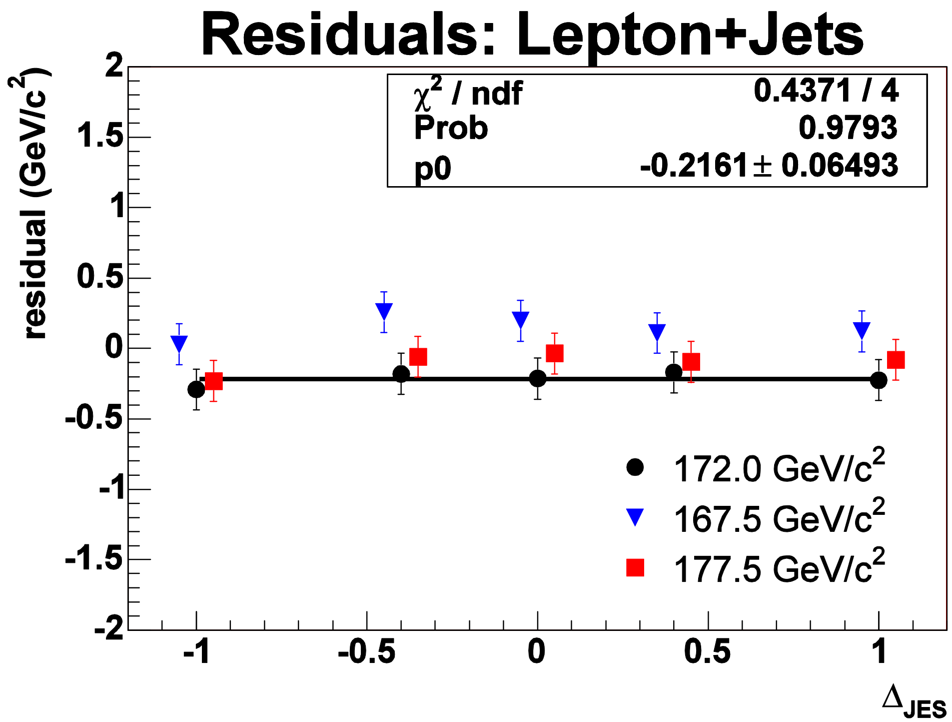
- Top quark mass 172.0 ± 1.5 GeV/c^2
- Top quark width < 7.4 GeV @ 95% CL

  $0.4 < \Gamma_{top} < 4.4$ GeV @ 68% CL
- ΔM_{top} -3.3 ± 1.7 GeV/c^2

Backup

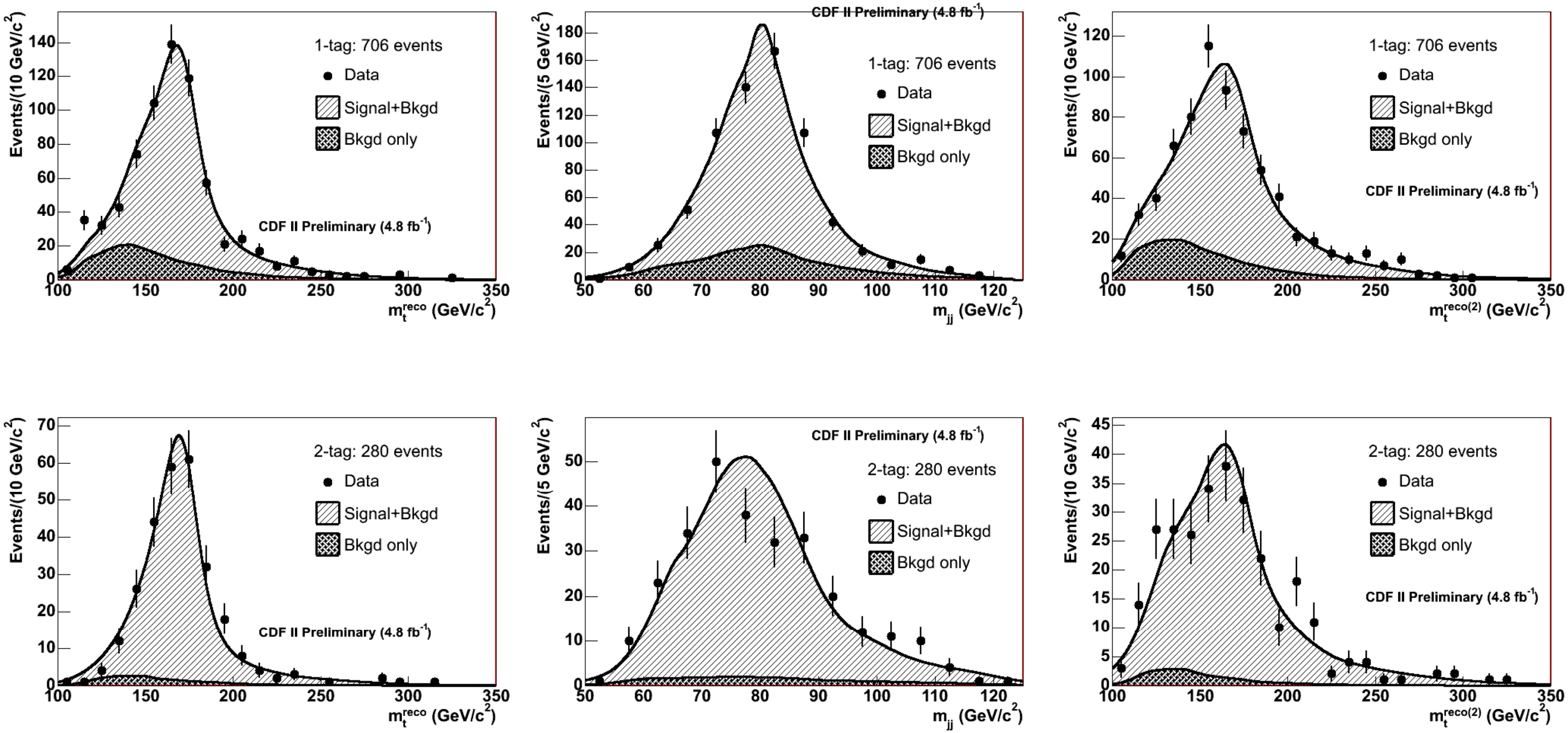
Residual on JES



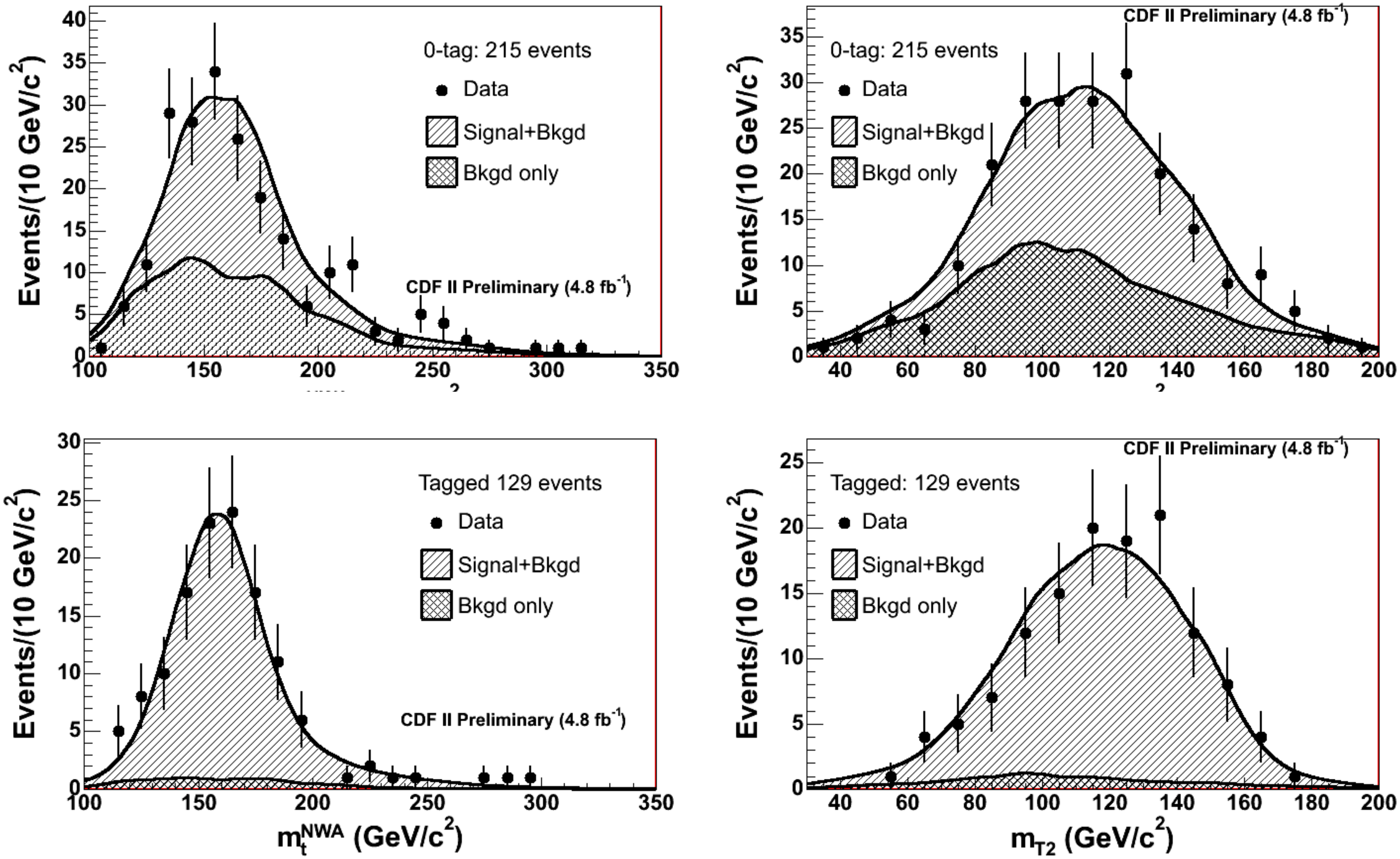


No significant shape on residual

Data and Fit (LJ)



Data and Fit (DIL)

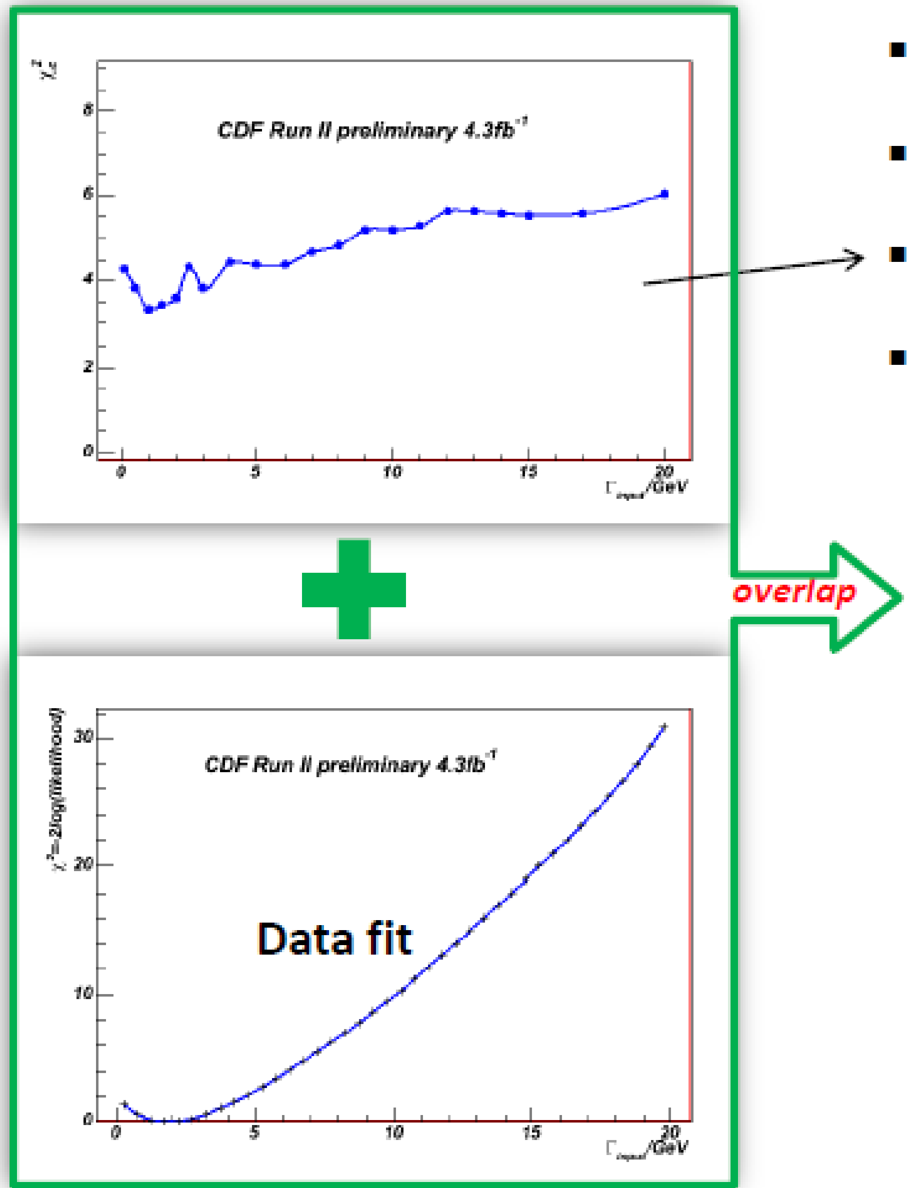


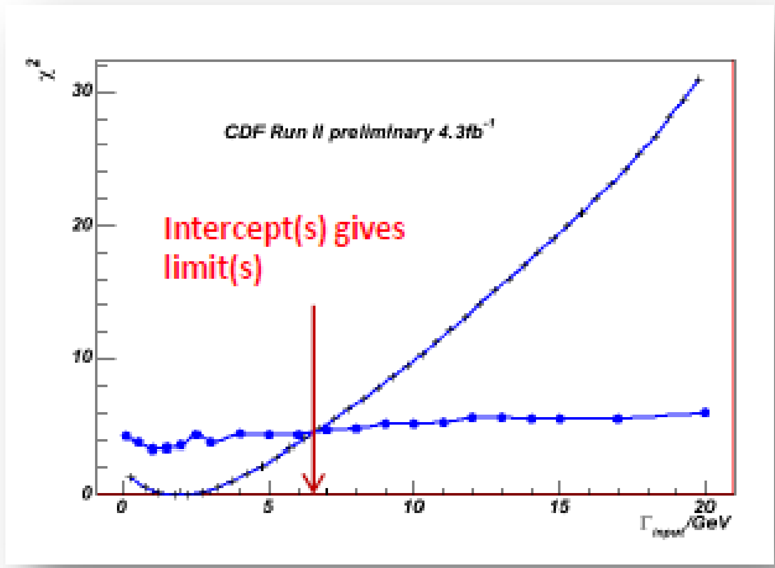
Feldman-Cousins method

- *"ordering principle "* $\Delta\chi^2$

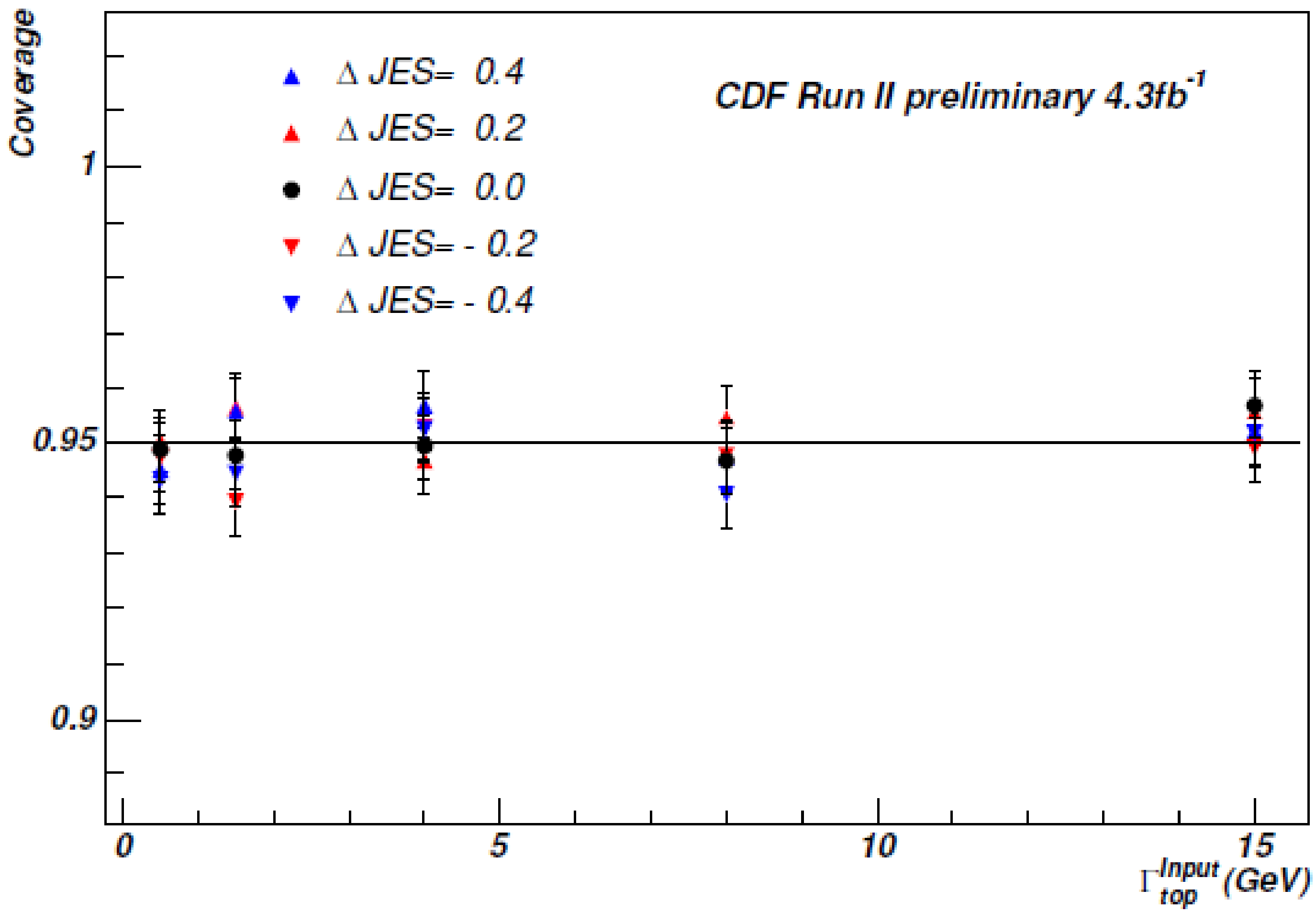
χ^2= -2 Log(Likelihood)

- Each MC sample generates a $\Delta\chi_c^2$
- plot $\Delta\chi_c^2$ vs true Γ
- Overlap with data fit

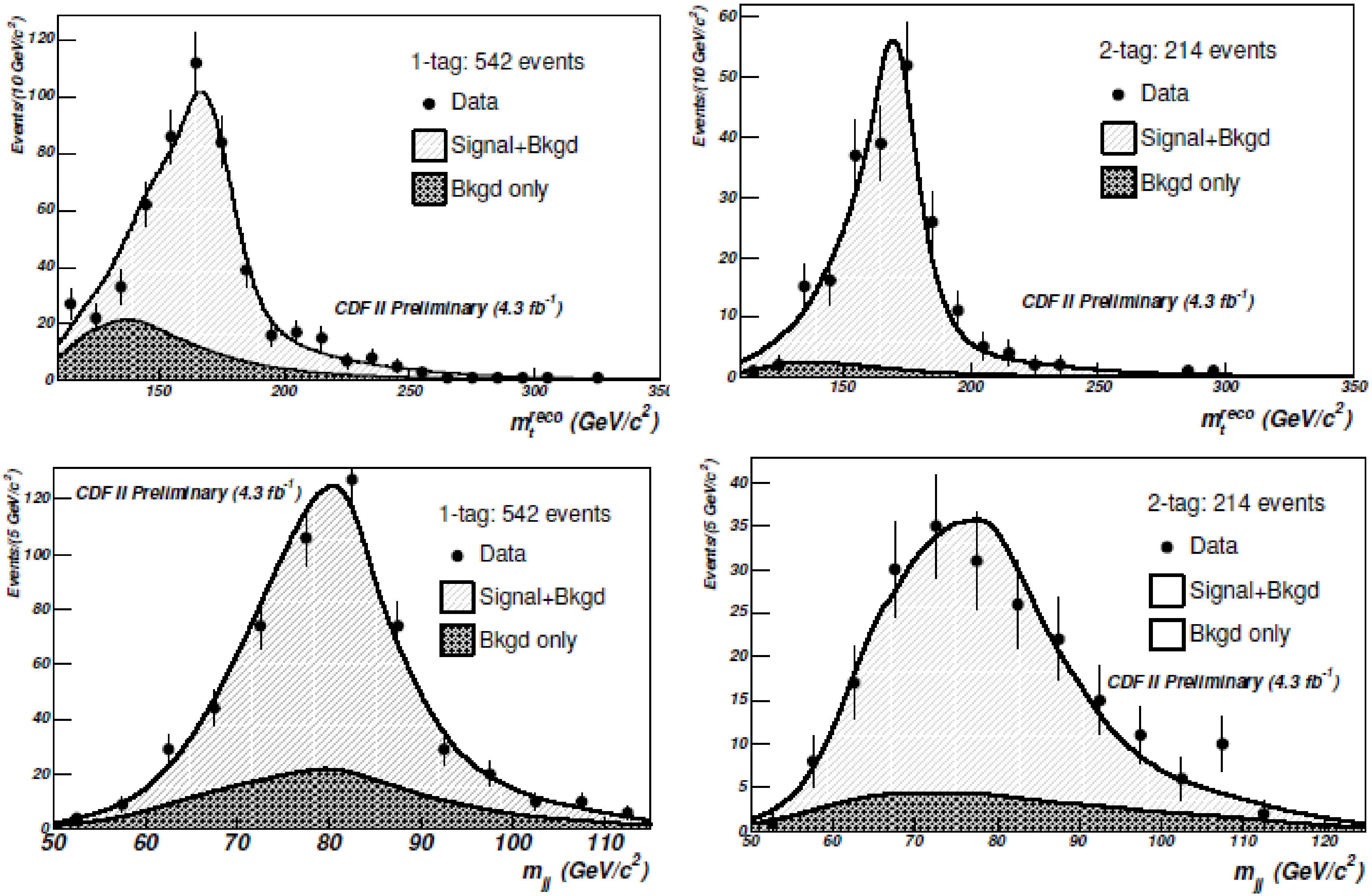




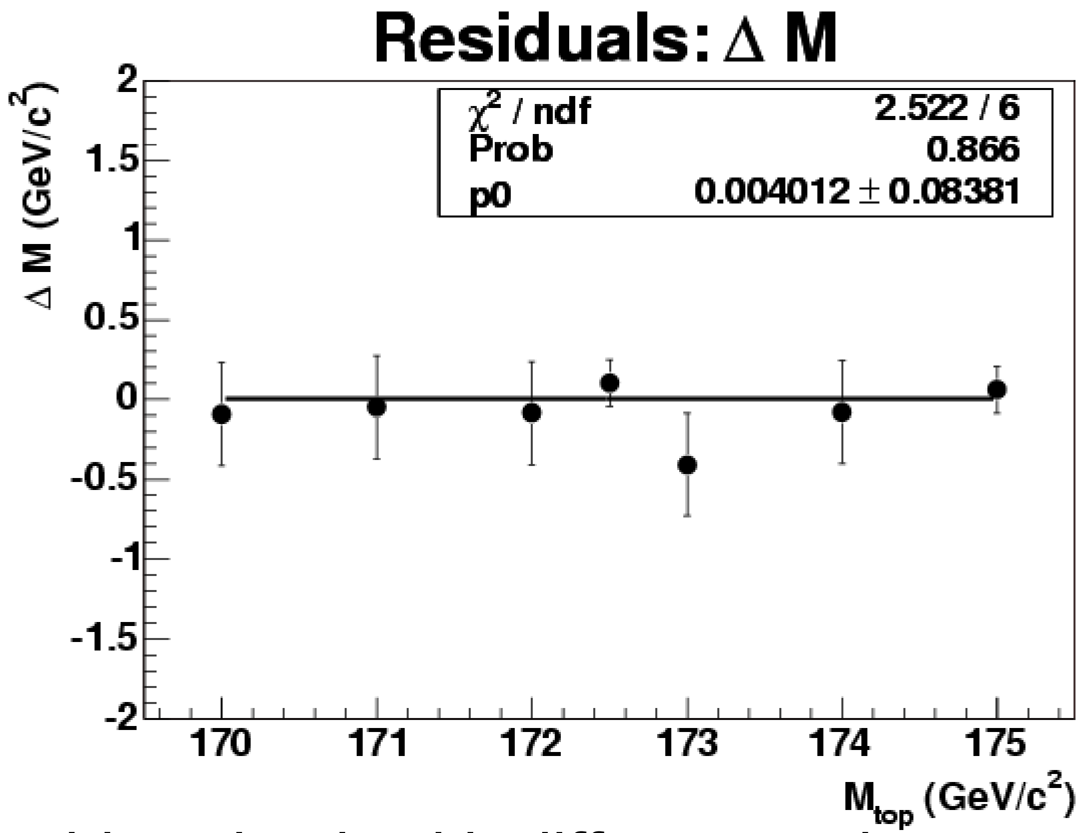
Coverage with different JES



Data fit

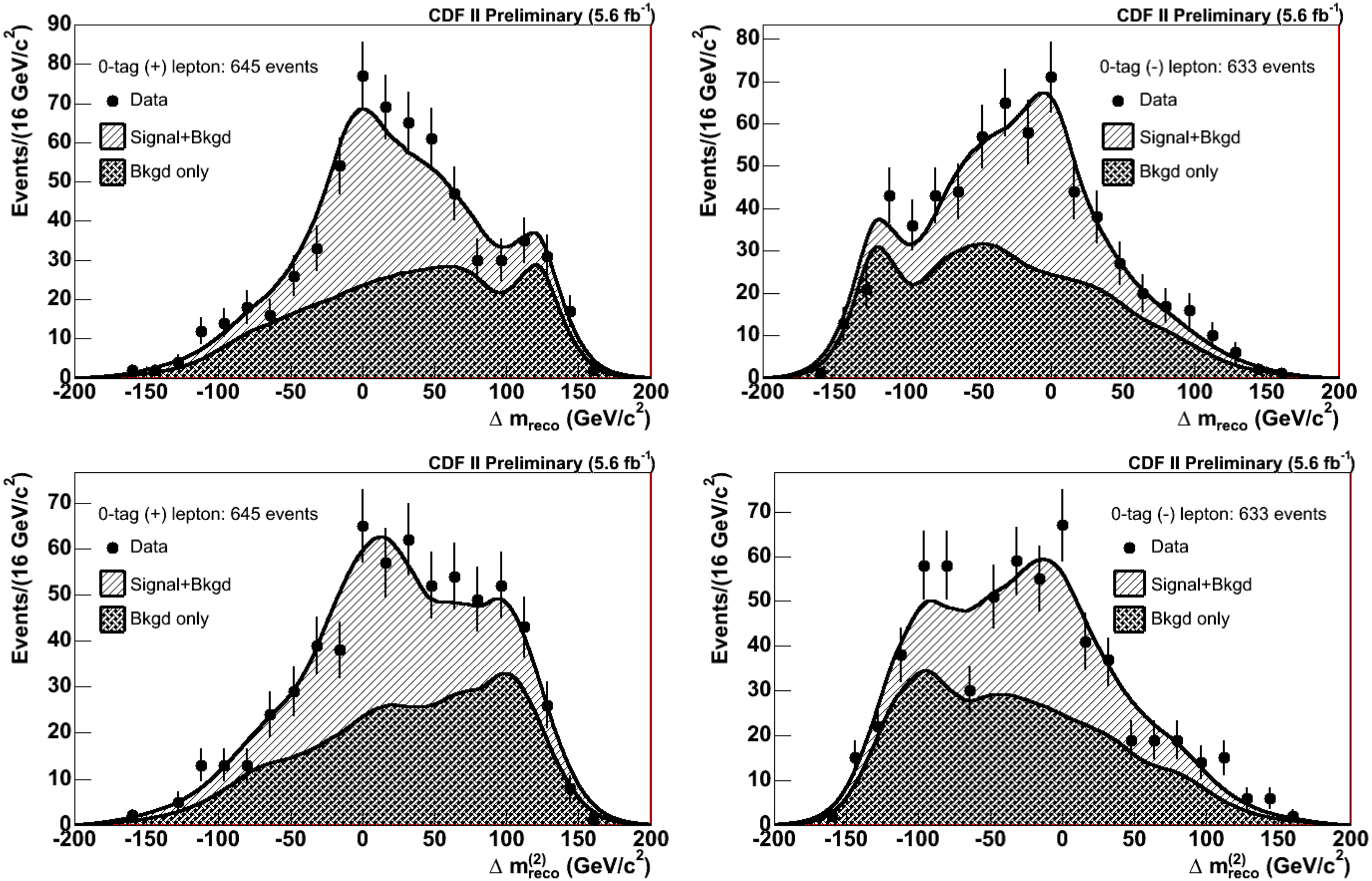

1-tag: 542 events
Data
Signal+Bkgd
Bkgd only
CDF II Preliminary (4.3 fb⁻¹)
Events/(10 GeV/c²)
m_t^{reco} (GeV/c²)
2-tag: 214 events
Data
Signal+Bkgd
Bkgd only
CDF II Preliminary (4.3 fb⁻¹)
Events/(10 GeV/c²)
m_t^{reco} (GeV/c²)
1-tag: 542 events
Data
Signal+Bkgd
Bkgd only
CDF II Preliminary (4.3 fb⁻¹)
Events/(5 GeV/c²)
m_{jj} (GeV/c²)
2-tag: 214 events
Data
Signal+Bkgd
Bkgd only
CDF II Preliminary (4.3 fb⁻¹)
Events/(5 GeV/c²)
m_{jj} (GeV/c²)

Truth mass dependence

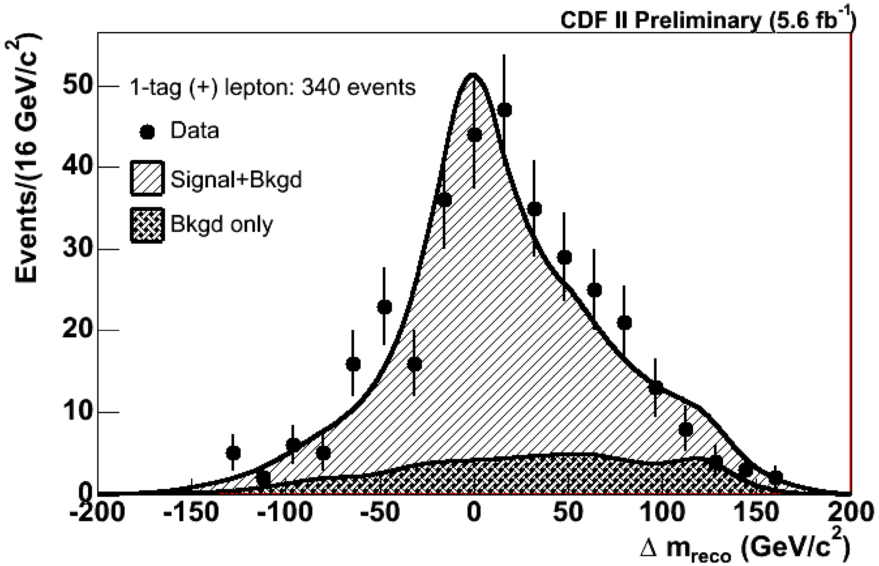


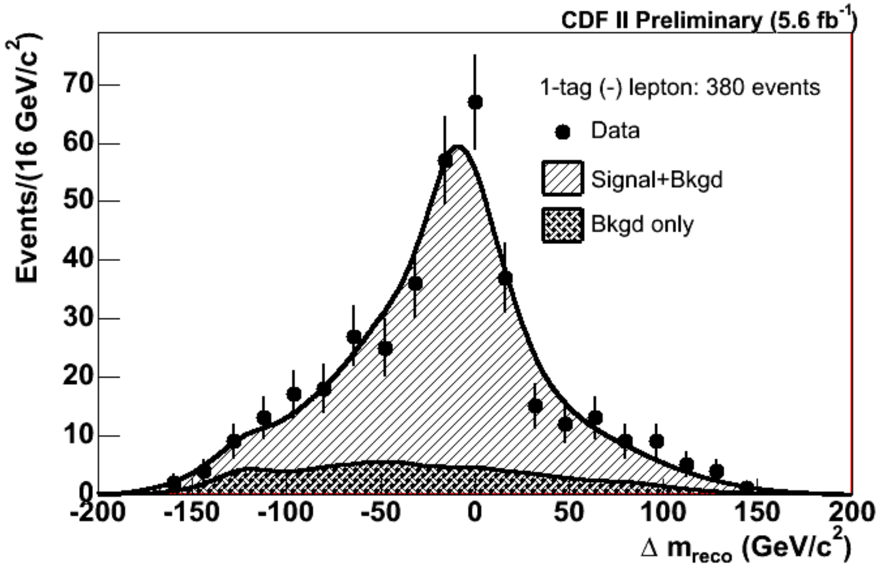
- We perform bias check with different truth top quark mass with ΔM_{top} = 0 GeV/c^2

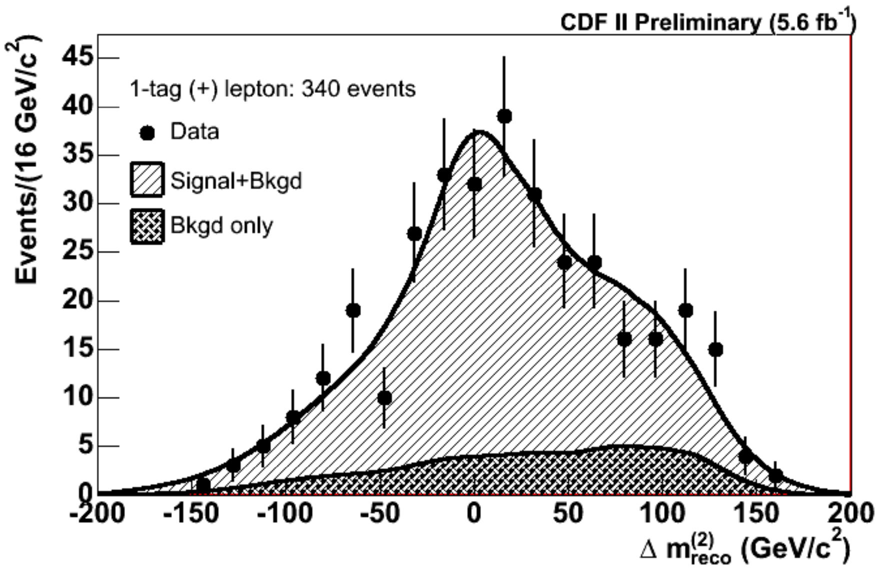
0tag : Data distribution

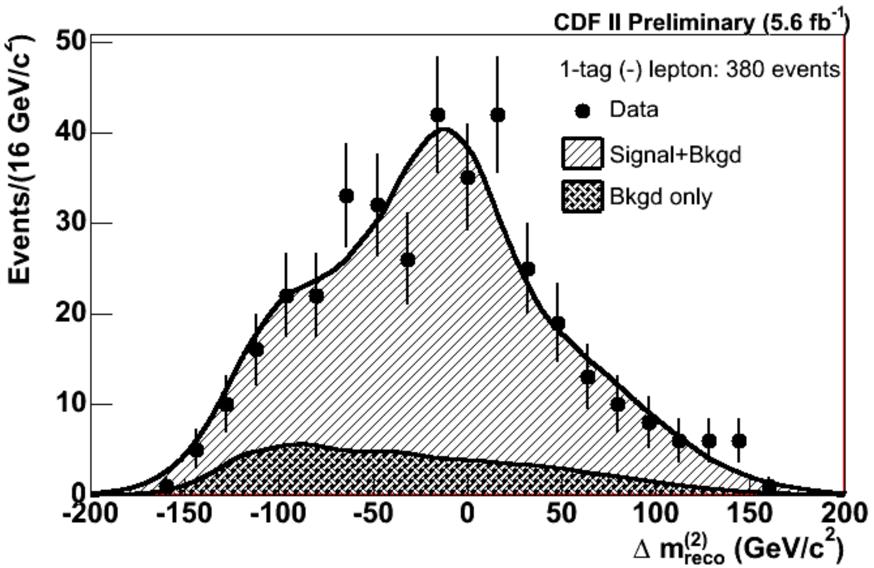


1tag : Data distribution

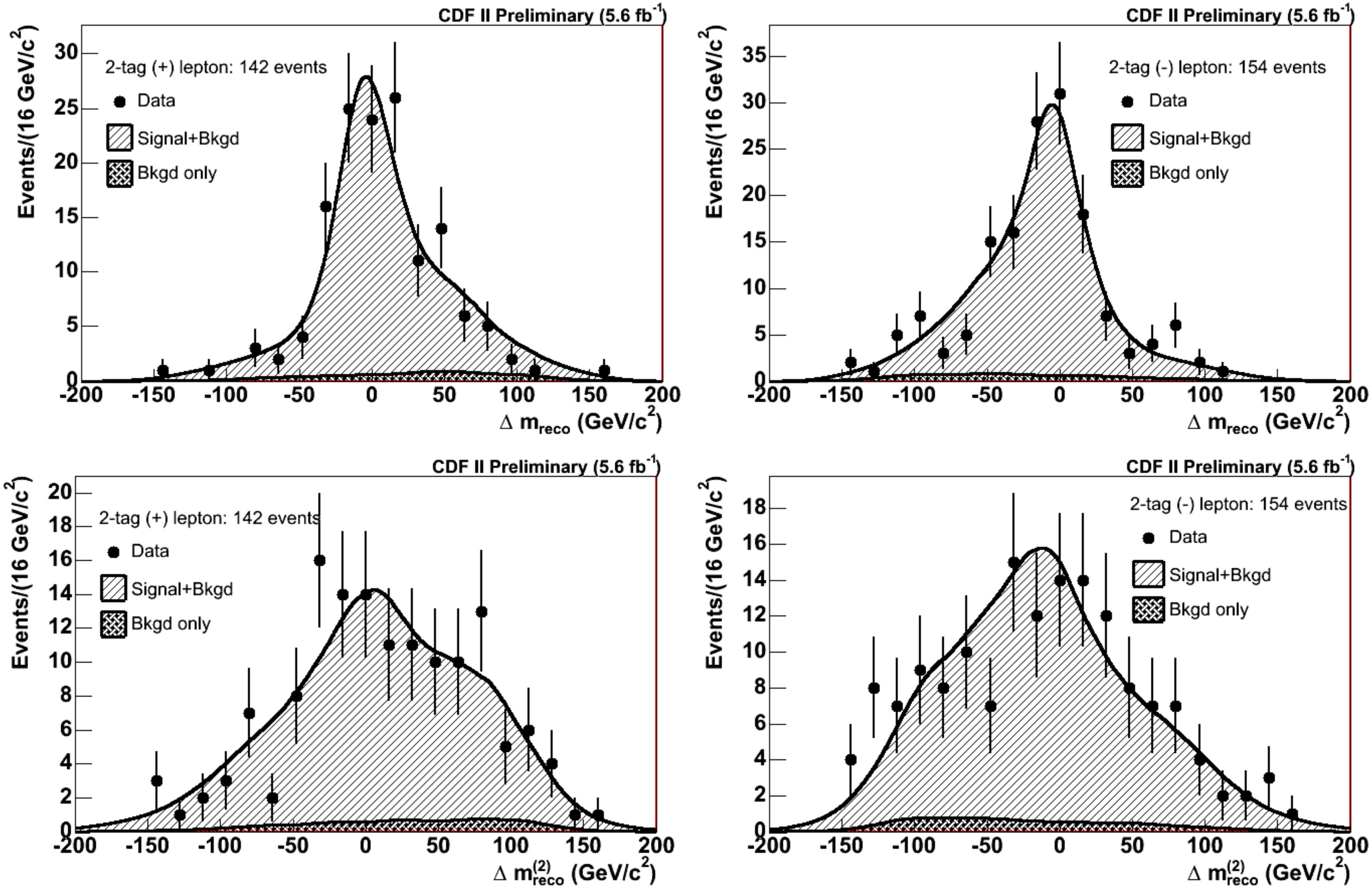






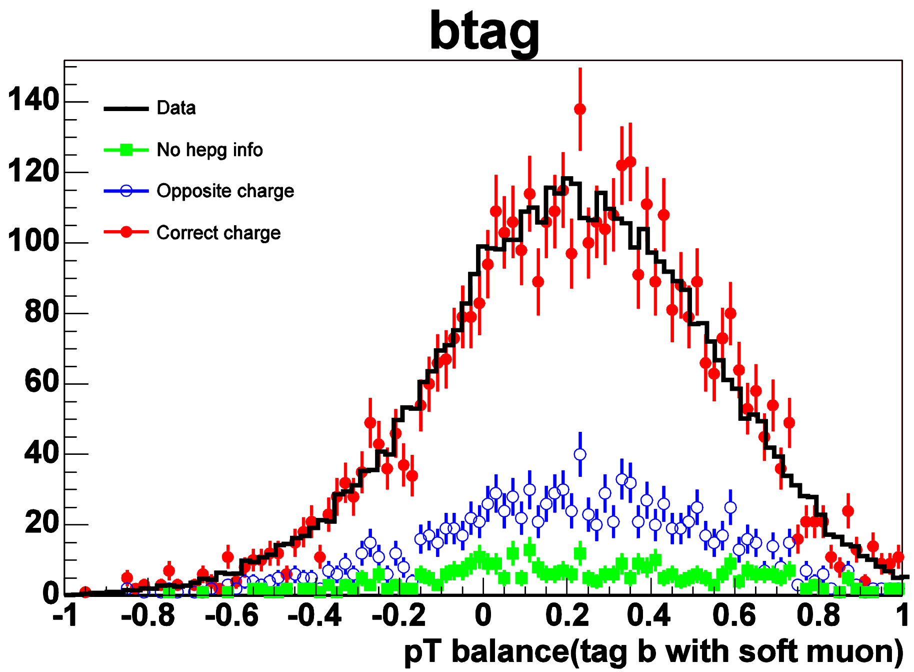


2tag : Data distribution

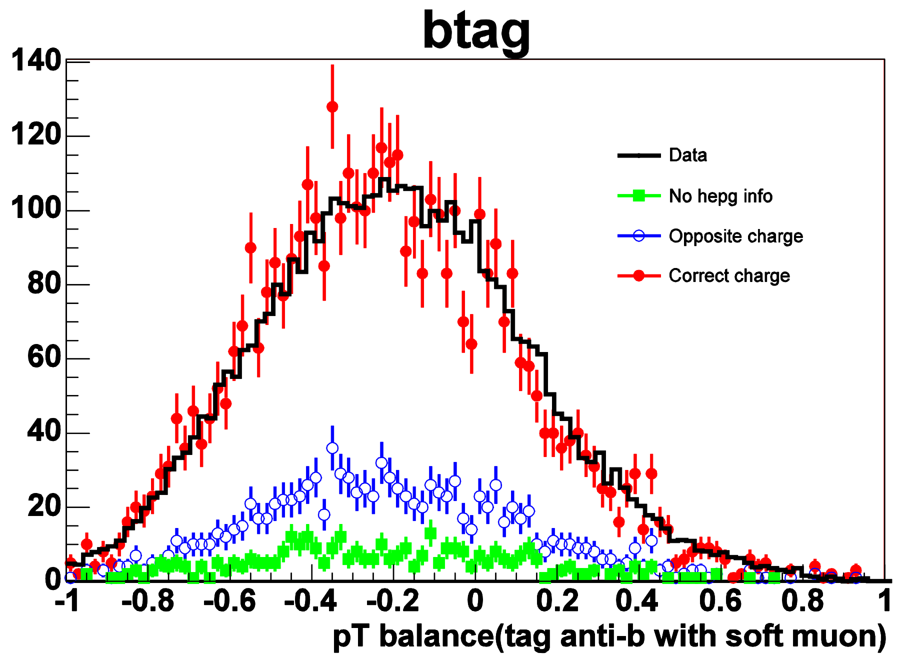


pT balances and assigning systematics

Tag b using soft muon



Tag anti- b



Good agreement between data and MC
Averaged deviation = -0.44 +-0.40%
If we consider anti-tagged(~20%) events, we can assign 0.73% deviation as systematic

B-tagging check for each flavor

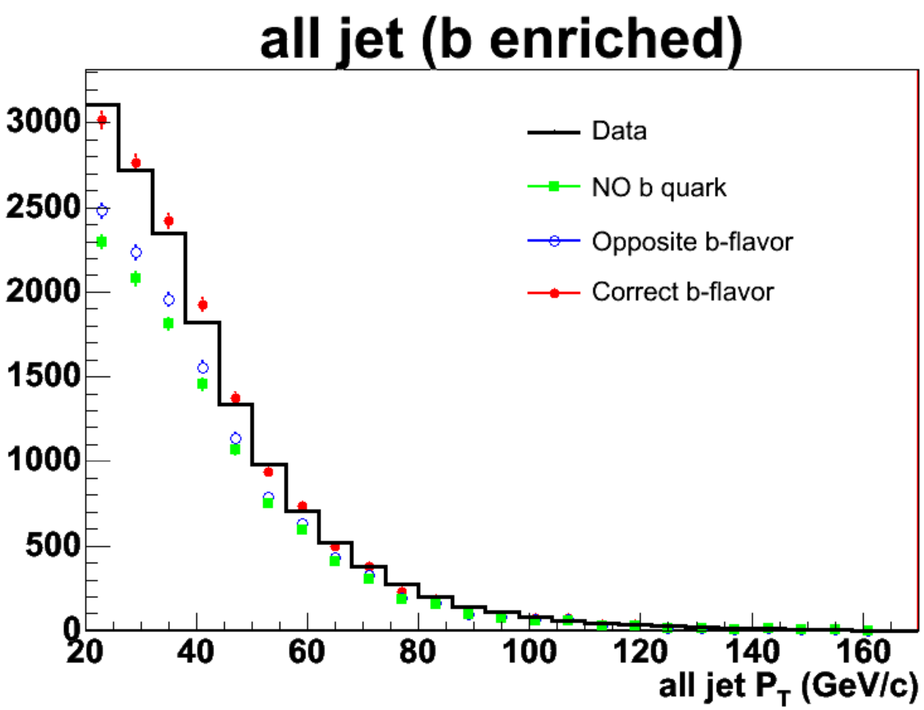
- Use dijet sample from low pt muon triggered data and MC (We require exactly two tight jet in offline)

Tagged jet : SECVTEX tag + soft muon tag

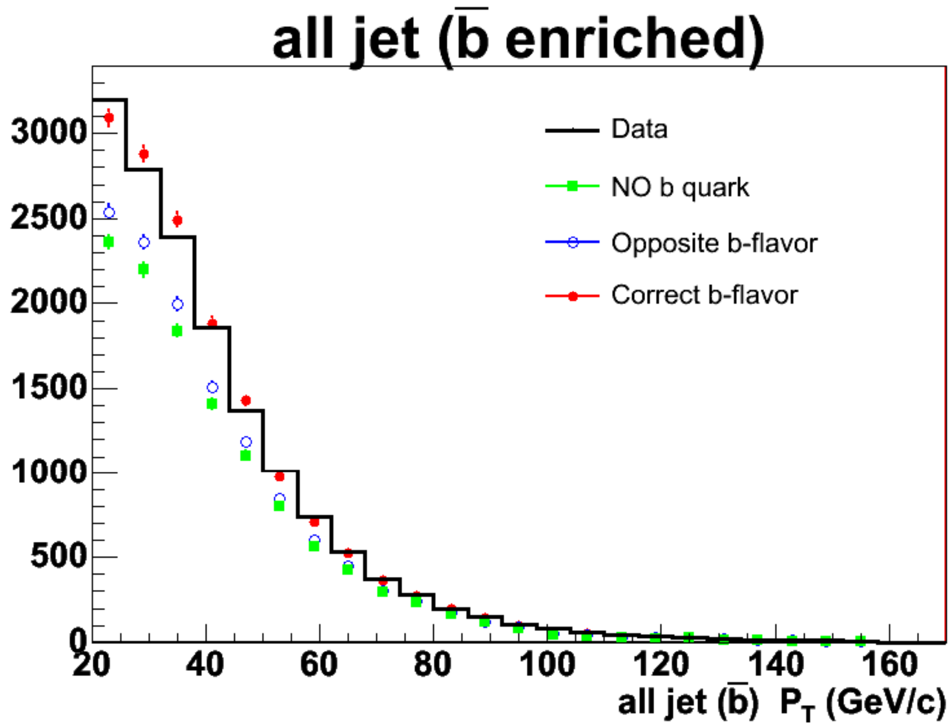
Away jet : jet PT>20GeV

- Depending on charge of soft muon, we can have b or anti b enriched samples

pT distribution of away jets

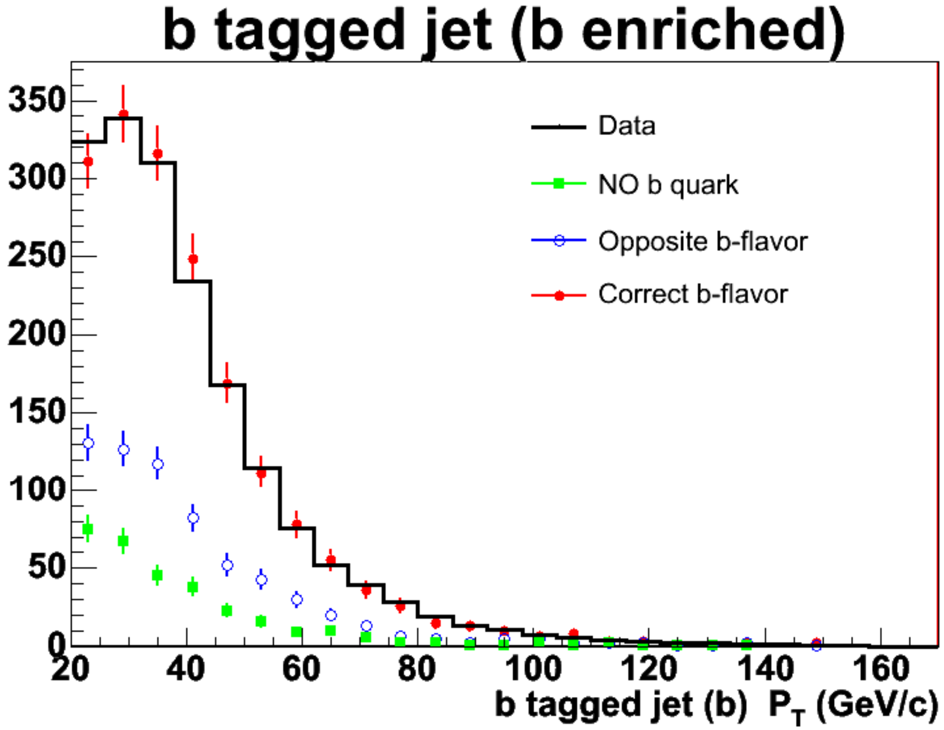


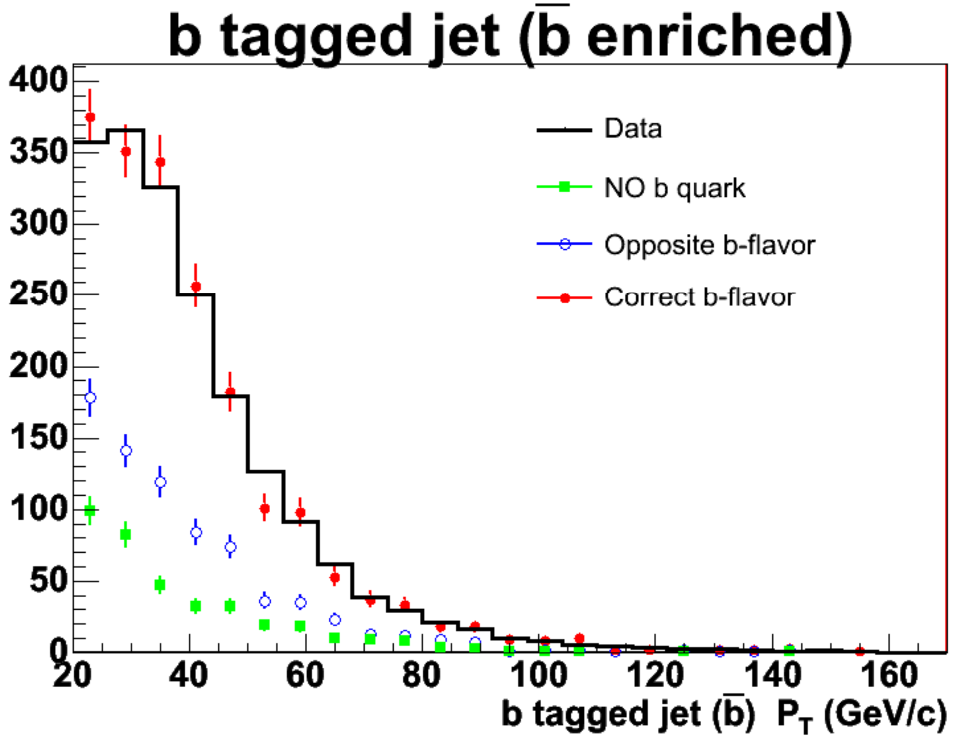
- b : 18%
- Anti b : 5%
- LF : 77%



- Anti b : 17%
- b : 5%
- LF : 77%

pT distribution of away b-jets(btagging)

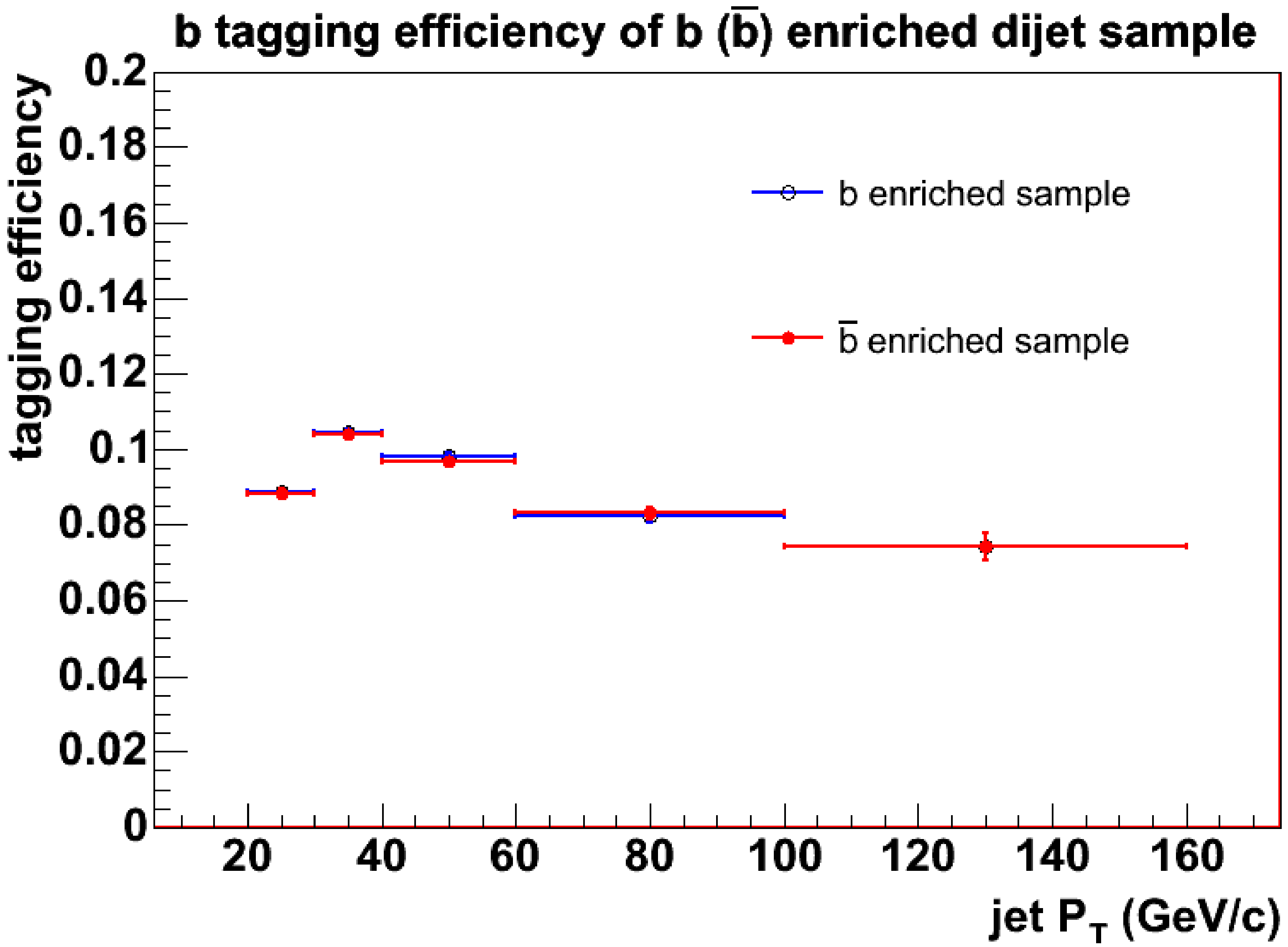




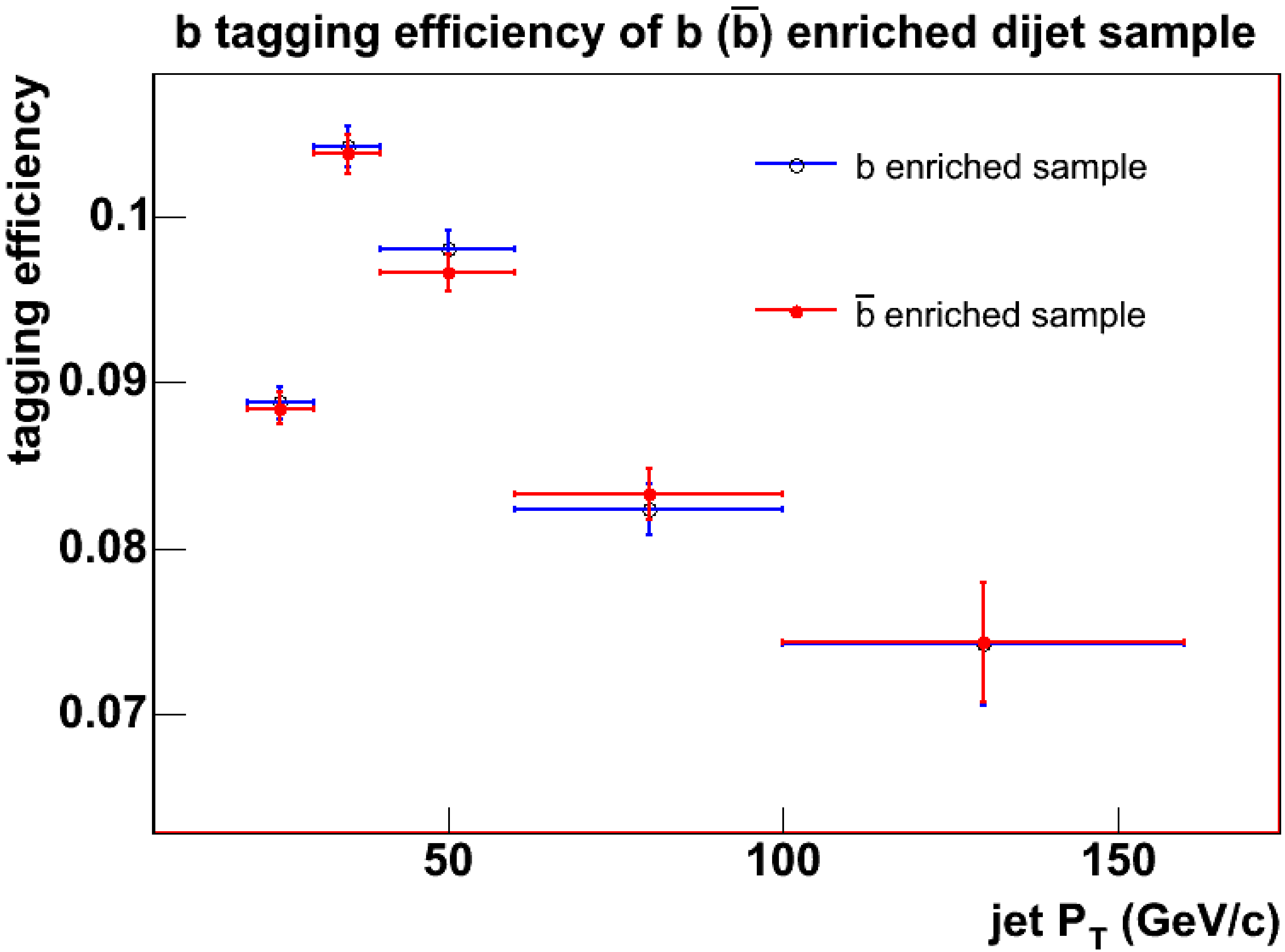
- b : 63(+-3)%
- Anti b : 20(+-2)%
- LF : 17(+-2)%

- Anti b : 61(+-3)%
- b : 20(+-2)%
- LF : 19(+-2)%

B tagging efficiency comparison for two samples



Zoomed plot

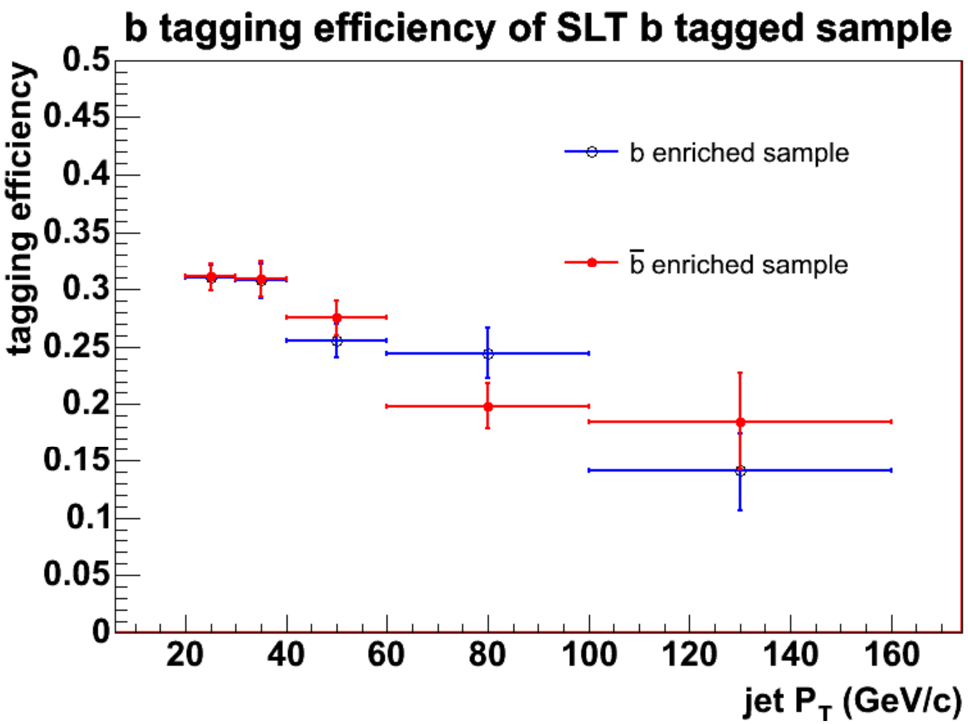


b tagging efficiency of b ($\bar{b}$) enriched dijet sample
tagging efficiency
0.1
0.09
0.08
0.07
b enriched sample
$\bar{b}$ enriched sample
50
100
150
jet P_T (GeV/c)

More pure samples

Tagged jet : SECVTEX tag + soft muon tag

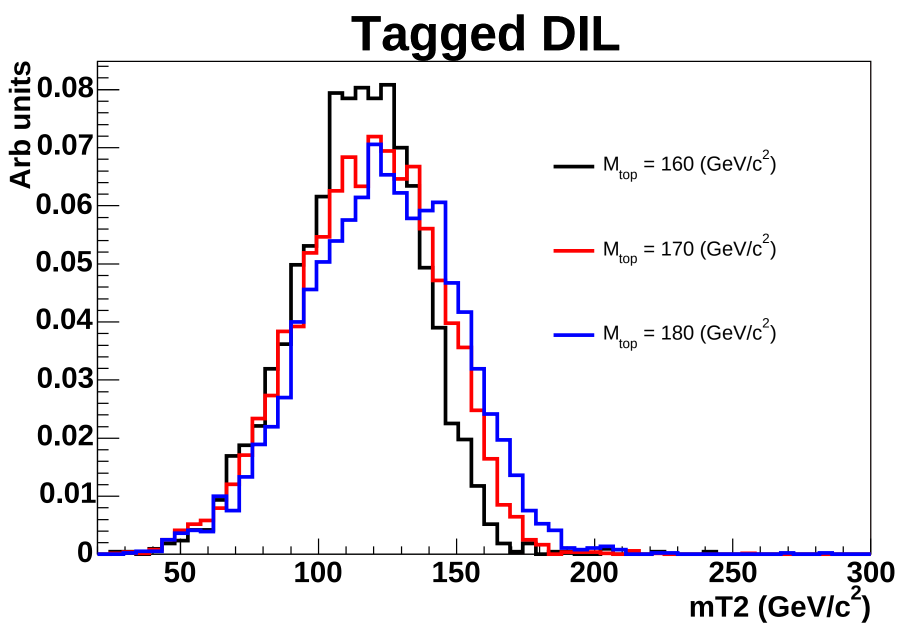
Away jet : jet PT>20GeV+soft muon tag

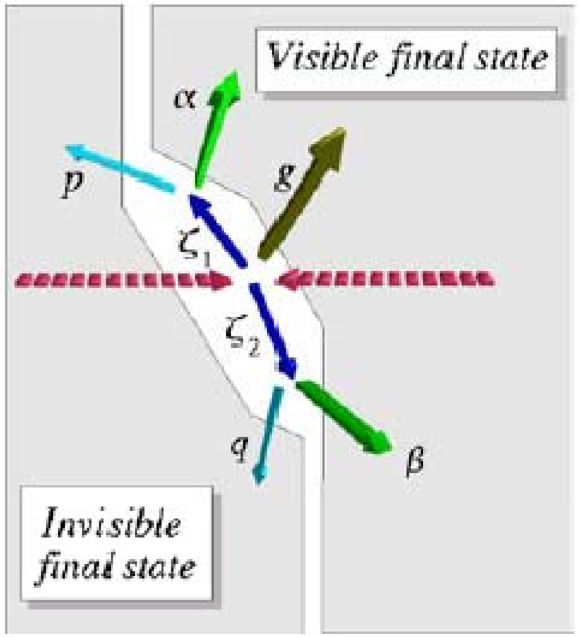


- ~60% of correct b events without b-tagging but low statistics
- Generally good in agreement

m_{T2} in dilepton channel (3.4 fb^{-1})

- m_{T2} was introduced for mass determination of new physics particle pair productions
- We use it as 2nd observable and improve ~15% statistical uncertainty





$$m_{T2} = \min[\max(m_{T(1)}, m_{T(2)})]$$
$$q_T + p_T = \text{missing } p_T$$

- We use m_{T2} first time in data (3.4 fb^{-1})
  - ❖ Phys.Rev.D 81 (2010) 031102