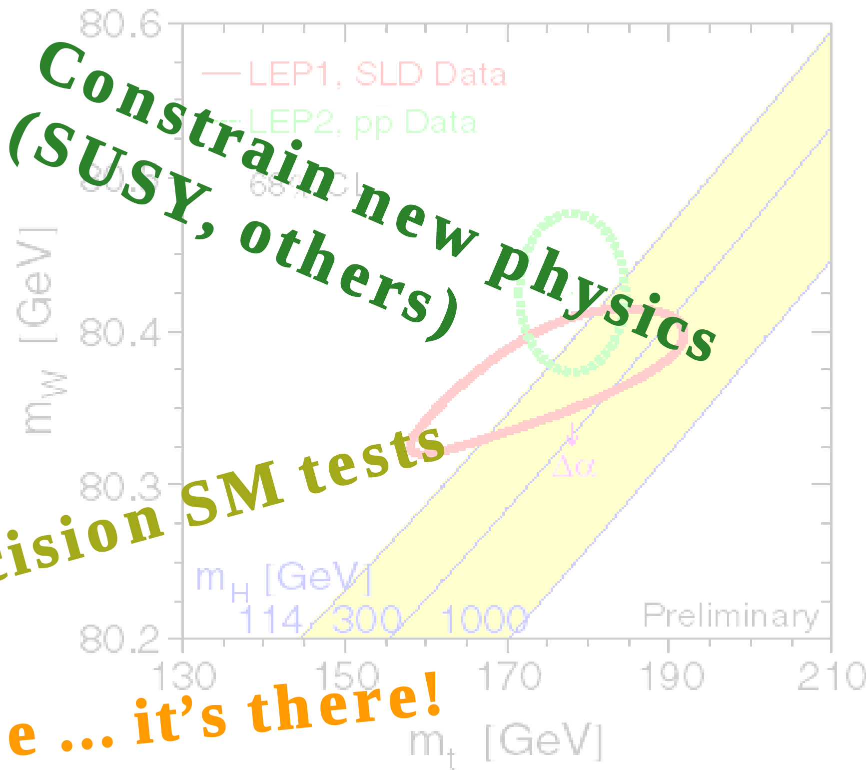
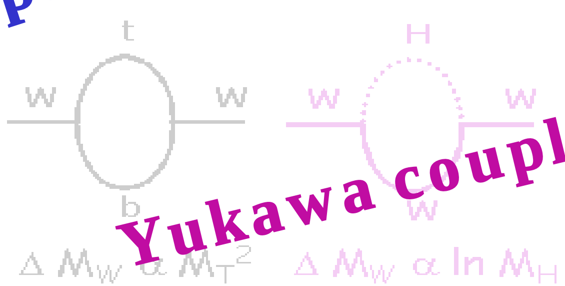
Top quark mass measurement in the Lepton+Jets Channel Using the Template Method

For the CDF Collaboration

Why m_{top}?





Produced only at the Tevatron

Constrain new physics (SUSY, others)

Pinpoint Higgs mass

Heaviest fundamental particle

Precision SM tests

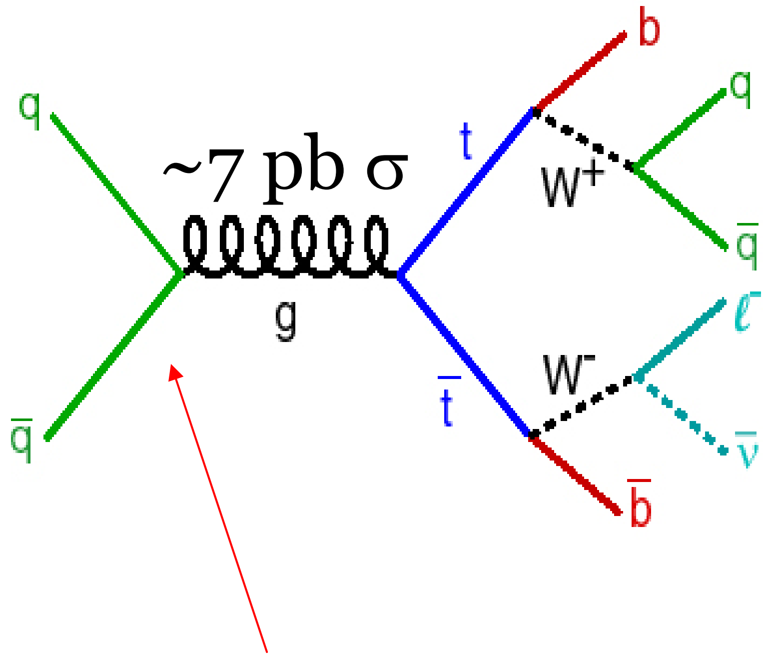
Because … it's there!

Yukawa coupling ~1

Benchmark for LHC at startup

Measurement Challenges

- Measure m_{top} in the Lepton+Jets channel, $t\bar{t} \rightarrow WbW\bar{b} \rightarrow l\nu q\bar{q}'b\bar{b}$
  - Neutrino escapes detection
  - Event signature: 4 jets (2 light/2 b), energetic lepton and MET
    - Watch out for combinatorics (12)!!!
    - Due to uncertain jet measurements, combinatorics and background, can't simply reconstruct Breit-Wigners
- Big systematic - the uncertain jet energy scale (JES) in the detector
  - How to get from complicated jets measured in the detector back to partons?
    - Need to measure quantities sensitive not only to the top quark mass, but also to ΔJES



Can also have additional ISR or FSR (leading 4 jets in the event may not correspond to any of the partons in the ttbar system)

Overview (2)

- **MC: tt MC at discrete M_{top} and JES, necessary backgrounds**

Kinematic fitter
(selects best single jet-parton assignment)

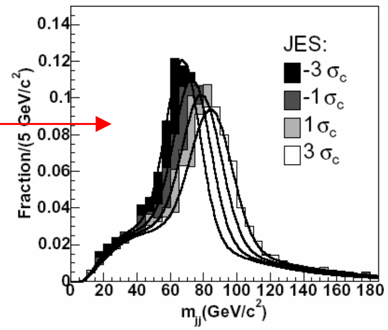
Output: Reconstructed top mass distribution

Strongly sensitive to true M_{top} and ΔJES

W->jj dijet mass
(use all pairs of untagged jets from leading 4 jets)

W_{jj} template weakly sensitive to true M_{top}

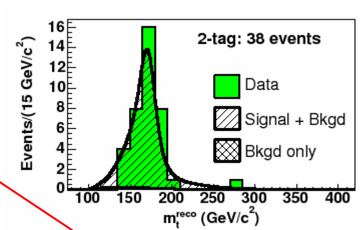
strongly correlated with ΔJES

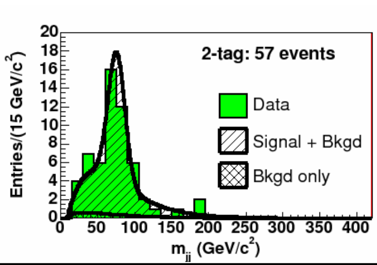


Parameterization

- form two 1-D PDFs for each template
- Shapes vary as a function of true M_{top} and JES

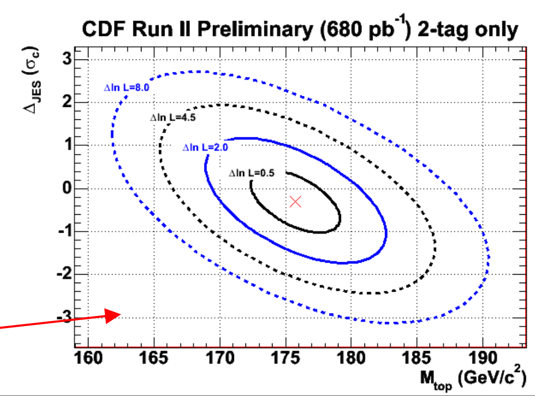
- **Run Lepton+Jets data through kinematic fitter, form dijet masses**





Likelihood fit

- Fit for signal fraction, M_{top} and JES
- Constrain # background evts, JES with Gaussian priors



Event selection

- High Pt lepton trigger for 680 pb^{-1} of data:
  - Track and electromagnetic cluster match
  - Track and muon stub match
- Jets:
  - 3 leading jets: Et>15GeV
    - Corrected back to particle-jet level, roughly ~21 GeV
  - 4^{th} jet Et>8 GeV
    - Corrected back to particle-jet level, roughly ~12 GeV
- Electrons:
  - Cluster Et > 20GeV
  - E/p < 2
  - HAD/EM <0.055+0.00045 $E_{cluster}$.
  - Isolation: <10% of cluster energy on R<0.4 cone
- Muons:
  - Pt>20GeV track matched to hits in the Muon chambers
  - Isolated MIP deposition in the calorimeter
- Missing transverse energy > 20GeV

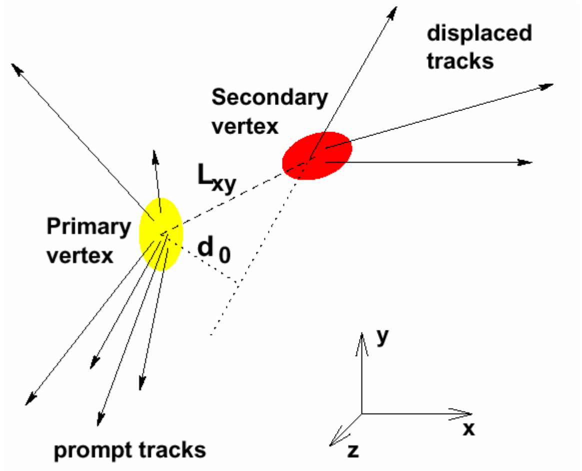
Sample division

- Use b-tagging in silicon to reduce combinatorics and increase S:B
- Divide events into 4 subsamples with different S:B and template shapes

	2-tag	1-tag (Tight 4^{th} jet)	1-tag (Loose 4^{th} jet)	0-tag
B-tags	2	1	1	0
Jet E_T (GeV) (jets 1-3)	>15	>15	>15	>21
Jet E_T (GeV) (jet 4)	> 8	> 15	8-15	> 21
Expected S:B	10.6:1	3.7:1	1.1:1	0.6:1
Observed Evts	57	120	75	108

$t\bar{t}$ efficiency for at least 1 tag: ~60%

False Tag Rate (per jet): ~0.5%



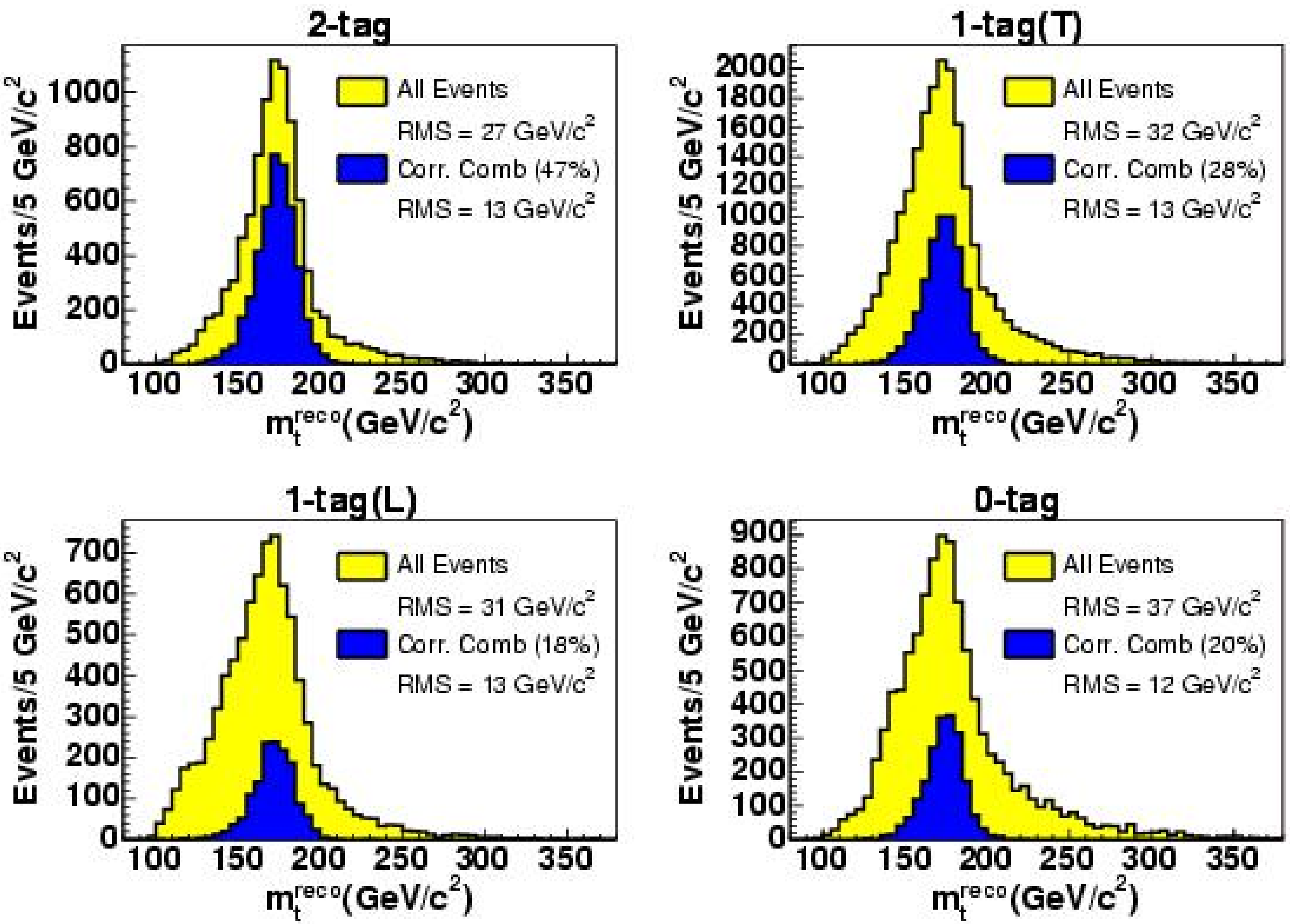
How we get m_t^{reco}

- Our system is over-constrained
    - We know M(W) = M($W^\pm$)
    - Set M(t)=M($\bar{t}$)
    - Accounting for ν, balance energy in transverse plane
- Form a χ^2 for each jet-parton assignment (only leading 4 jets) consistent with b-tagging
- Select assignment with lowest χ^2, yielding **one number (m_t^{reco}) per event**
- Make additional cut ($\chi^2 < 9$) on best jet-parton assignment to reject poorly measured events

Keep in mind that m_t^{reco} is a good estimator for the true top quark mass, but it is NOT the true top quark mass

$$\chi^2 = \sum_{i=\ell,4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_j^{UE,meas})^2}{\sigma_{UE}^2} + \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{b\ell\nu} - m_t^{reco})^2}{\Gamma_t^2} + \frac{(M_{bjj} - m_t^{reco})^2}{\Gamma_t^2}$$

M_t^{reco} MC - signal distributions

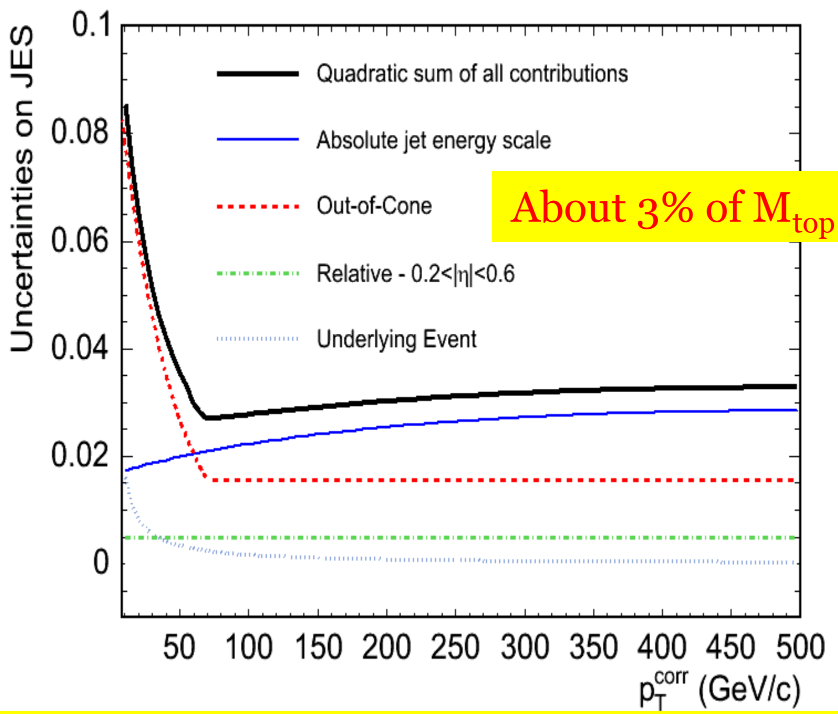


B-tagging helps quite a bit ... but even in cleanest (2-tag) sample, we correctly match all 4 jets to partons only ~1/2 the time.

Jet Energy Scale

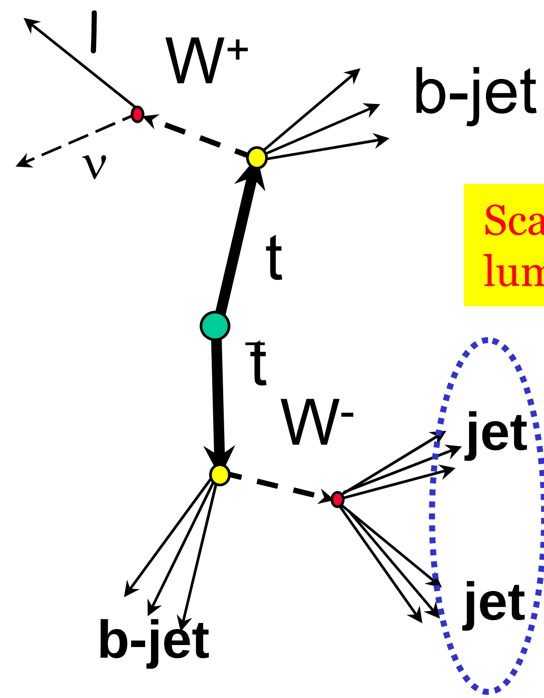
Jets are hard to measure! Fragmentation, hadronization, color flows, radiation, divergences, all difficult to model in MC. Big, overlapping objects in the detector, and we want to correct back to the partons

Standard Calibration



About 3% of M_{top}

In-situ Calibration

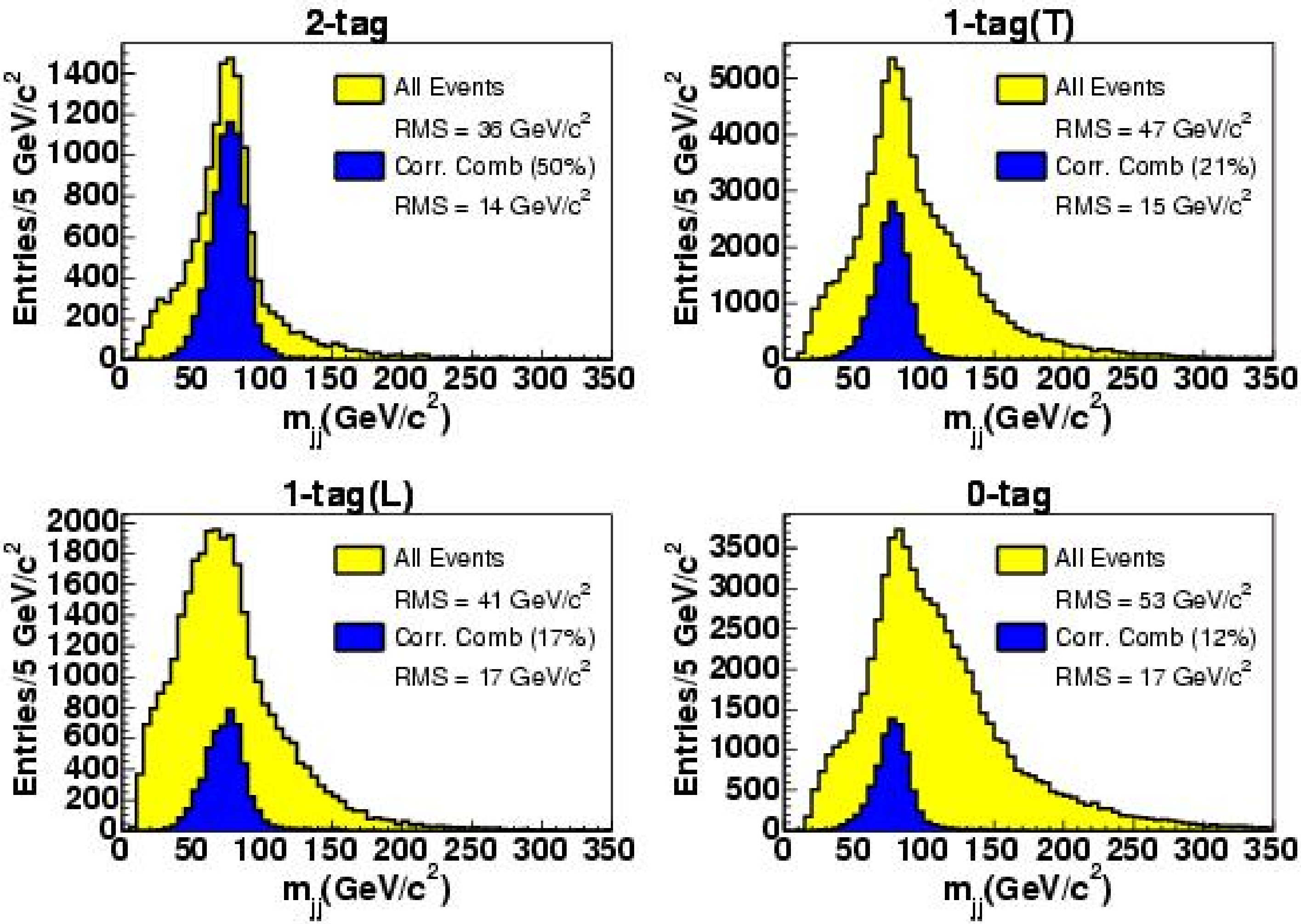


Scales with luminosity!

$M_{jj}(W)$ resonance!

Measure JES in terms of ΔJES ≡ JES shifts from 0 in units of nominal calibration CDF Jet Energy Scale Calibration (σ_c)

W_{jj} signal MC distributions



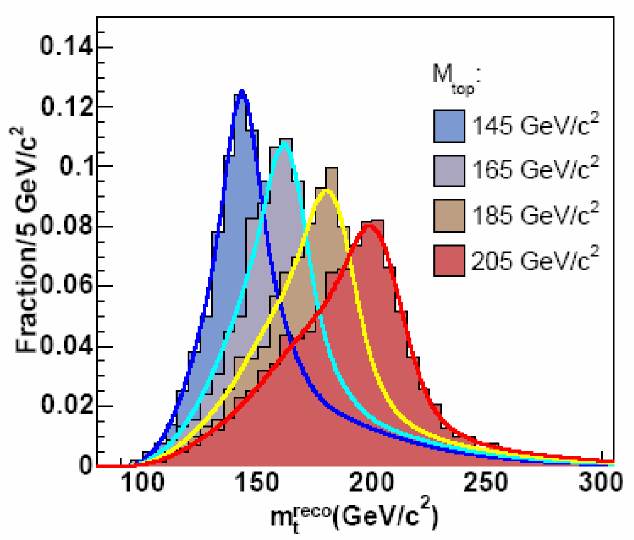
W resonance is visible despite our jet resolution (even in 0-tag sample, with 6 entries per event).

b-tagging really helps!

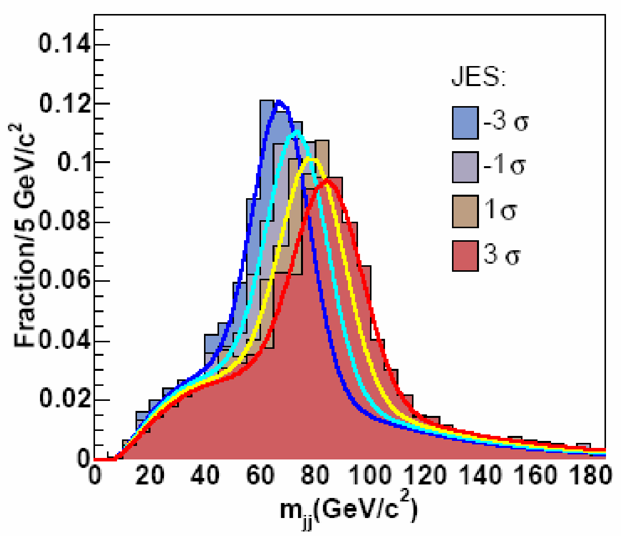
Make NO χ^2 cut when forming W_{jj} distributions

Parameterizations

m_{top}^{reco} templates for ΔJES=0



W_{jj} templates for true M_{top} = 180



- Generate tt MC at a grid of points in true top quark mass-ΔJES space
- Form signal (m_t^{reco} and W_{jj}) distributions at each point
- Interpolate between the points by parameterizing the templates as functions of true top mass and ΔJES

Backgrounds

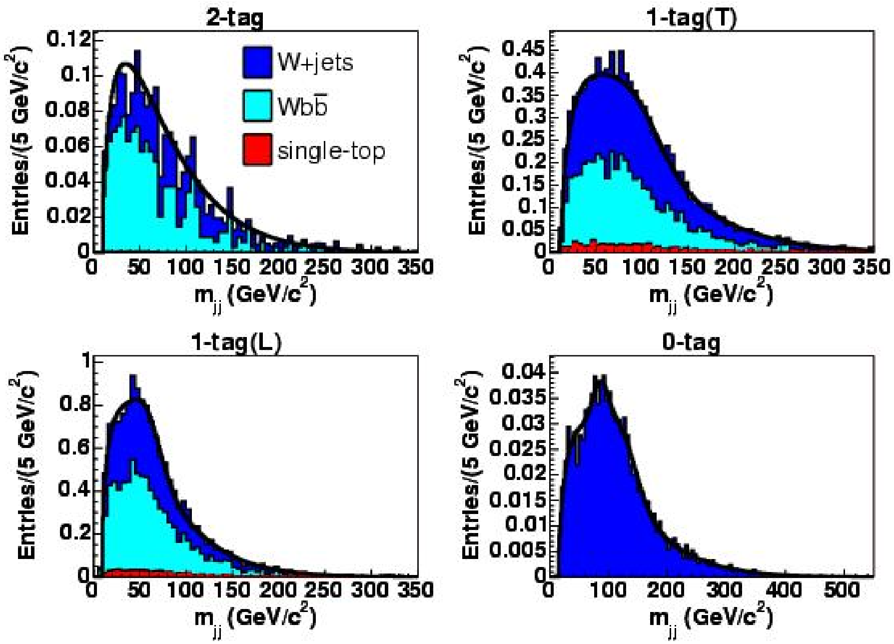
Sample:	2-tag	1-tag(T)	1-tag(L)
Non-W (QCD)	0.6 ± 0.2	5.0 ± 1.4	4.4 ± 1.4
W+Heavy Flavor	2.4 ± 1.0	8.4 ± 3.0	14.6 ± 4.7
W+light jets	0.9 ± 0.2	6.9 ± 1.4	8.9 ± 1.9
WW/WZ	0.11 ± 0.03	1.0 ± 0.3	1.5 ± 0.4
Single top	0.02 ± 0.01	1.1 ± 0.3	1.3 ± 0.3
Total expected background (680 pb^{-1})	4.0 ± 1.3	22.2 ± 4.7	30.6 ± 6.7
Observed events	57	120	75

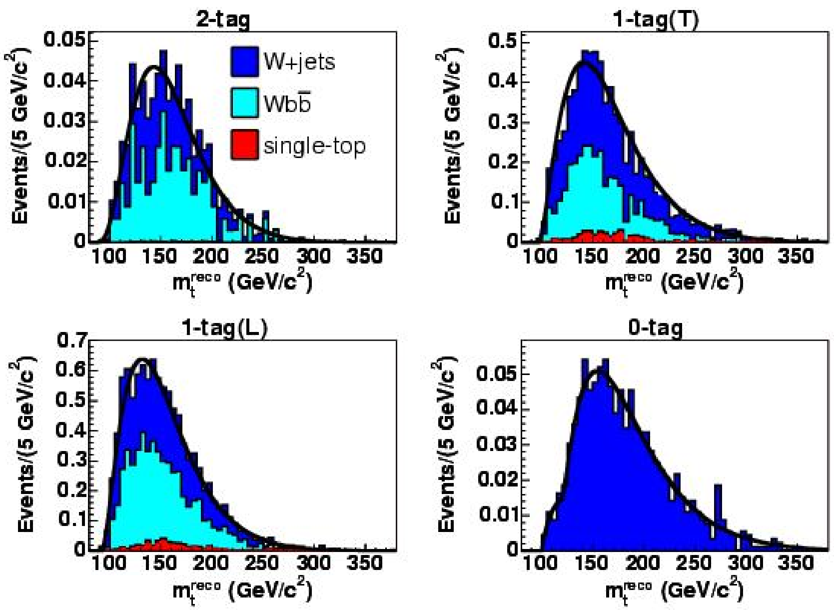
We can cleanly fit for most of the background – not extremely sensitive to exact number of events

Used as Gaussian constraint on number of background events

Background templates

To form templates: Use backgrounds in their expected proportions after χ^2 cut, parameterize combined template (no top mass or ΔJES dependence)





Backgrounds peak lower than signal

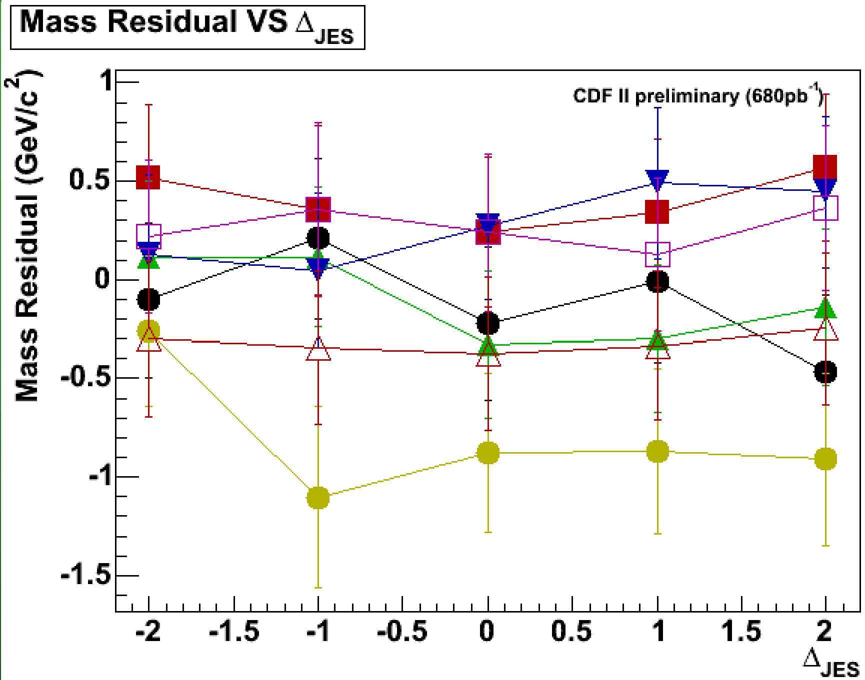
Likelihood Form

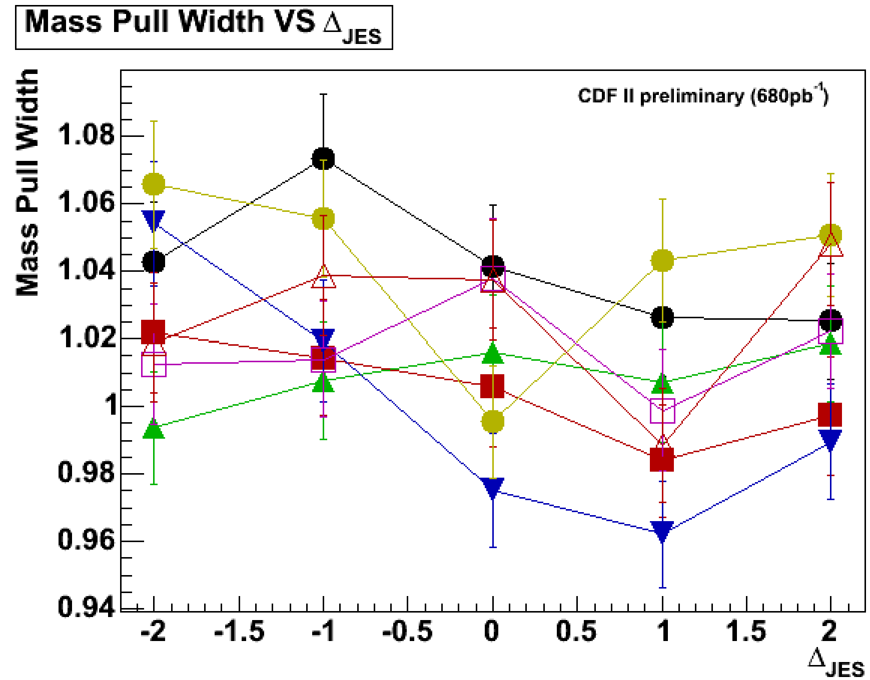
For each of the subsamples define: $\mathcal{L}_{\text{sample}} = \mathcal{L}_{\text{shape}}^{m_t^{\text{reco}}} \times \mathcal{L}_{\text{shape}}^{m_{\text{jj}}} \times \mathcal{L}_{\text{nev}} \times \mathcal{L}_{\text{bg}}$

$\mathcal{L}_{\text{shape}}^{m_t^{\text{reco}}}$	Looping over reconstructed top masses for events passing χ^2 cut, likelihood that the event is background, or signal of a given true top mass and ΔJES
$\mathcal{L}_{\text{shape}}^{m_{\text{jj}}}$	Looping over all dijet masses for all events, likelihood that the mass comes from background, or signal of a given true top mass and ΔJES
$\mathcal{L}_{\text{nev}}$	Likelihood relating the possibility of observing some number of signal and background events passing the χ^2 cut given the χ^2 efficiencies
$\mathcal{L}_{\text{bg}}$	Gaussian constraint on number of background events in the sample (for all samples but 0-tag)

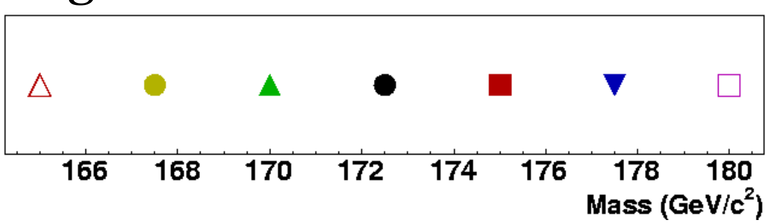
- Total likelihood is the product of the 4 subsample likelihoods with a Gaussian constraint on ΔJES: Gaus(0,1)
- Maximize total likelihood, fit for Mtop and ΔJES and the number of signal and background events

Sanity checks





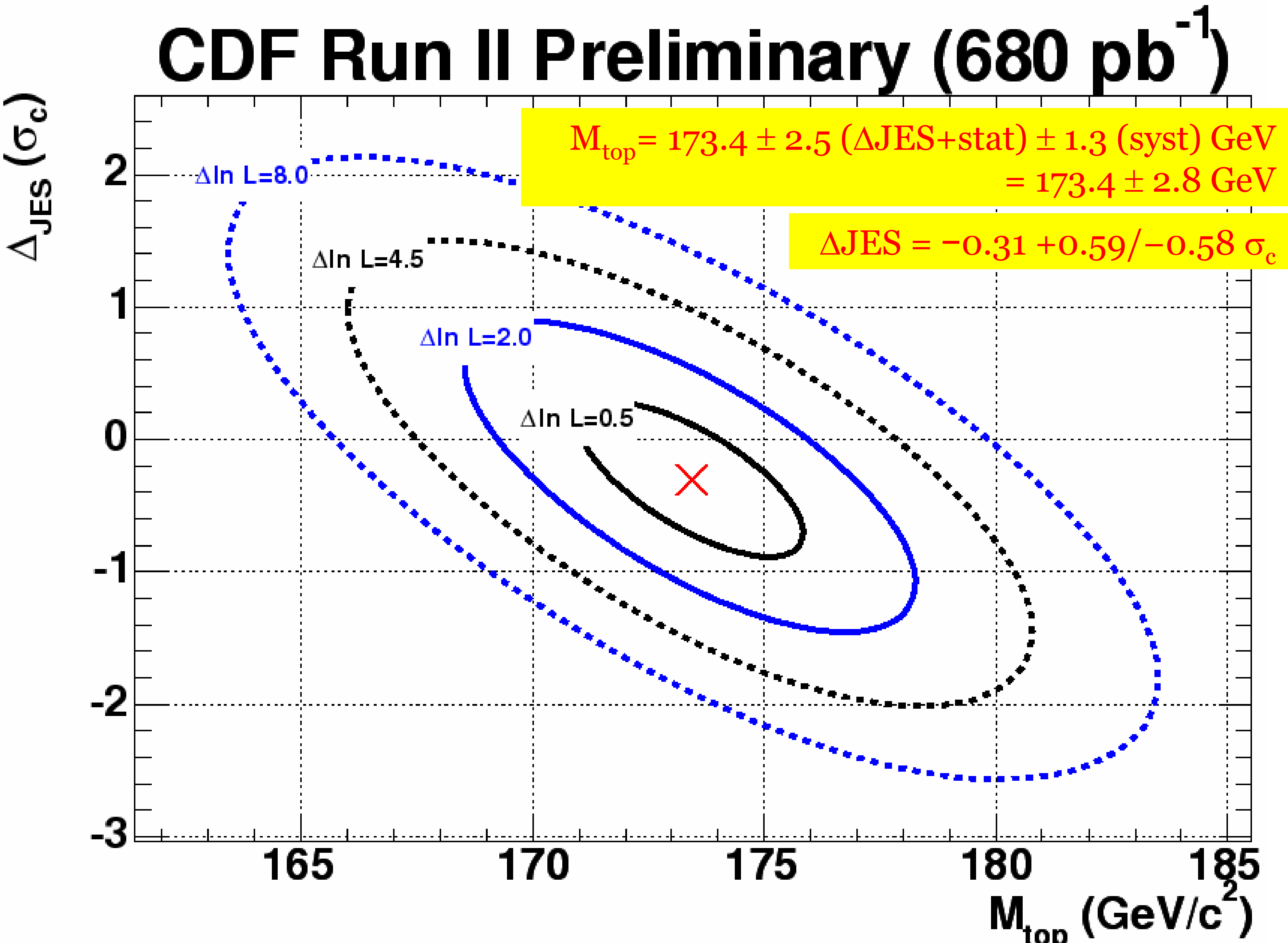
Legend



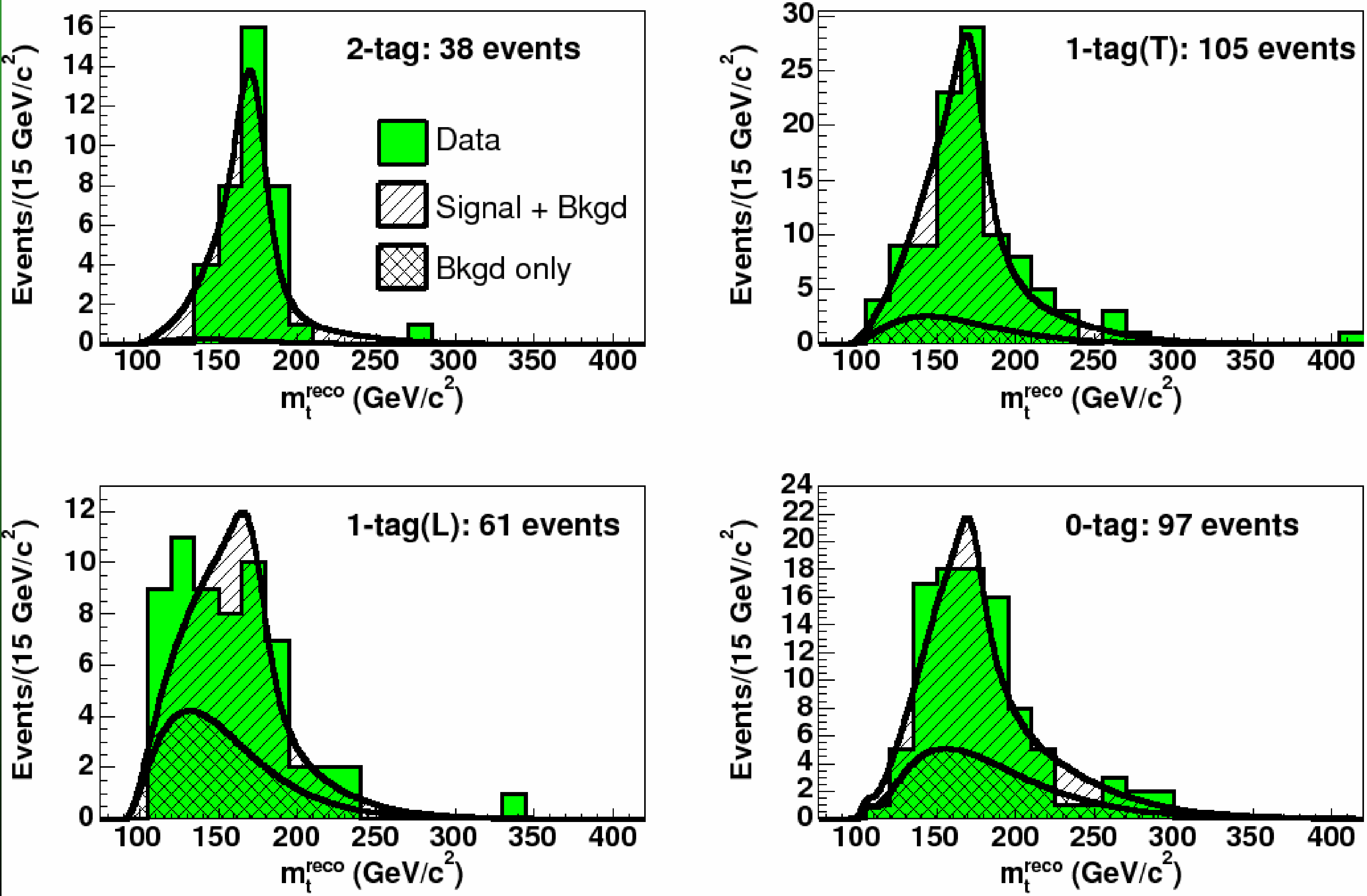
- Method is not biased
- Statistical error will be inflated by 2% due to non-unit mass pull widths
    - Non-Gaussian L
    - Effect will disappear with larger statistics

Systematics

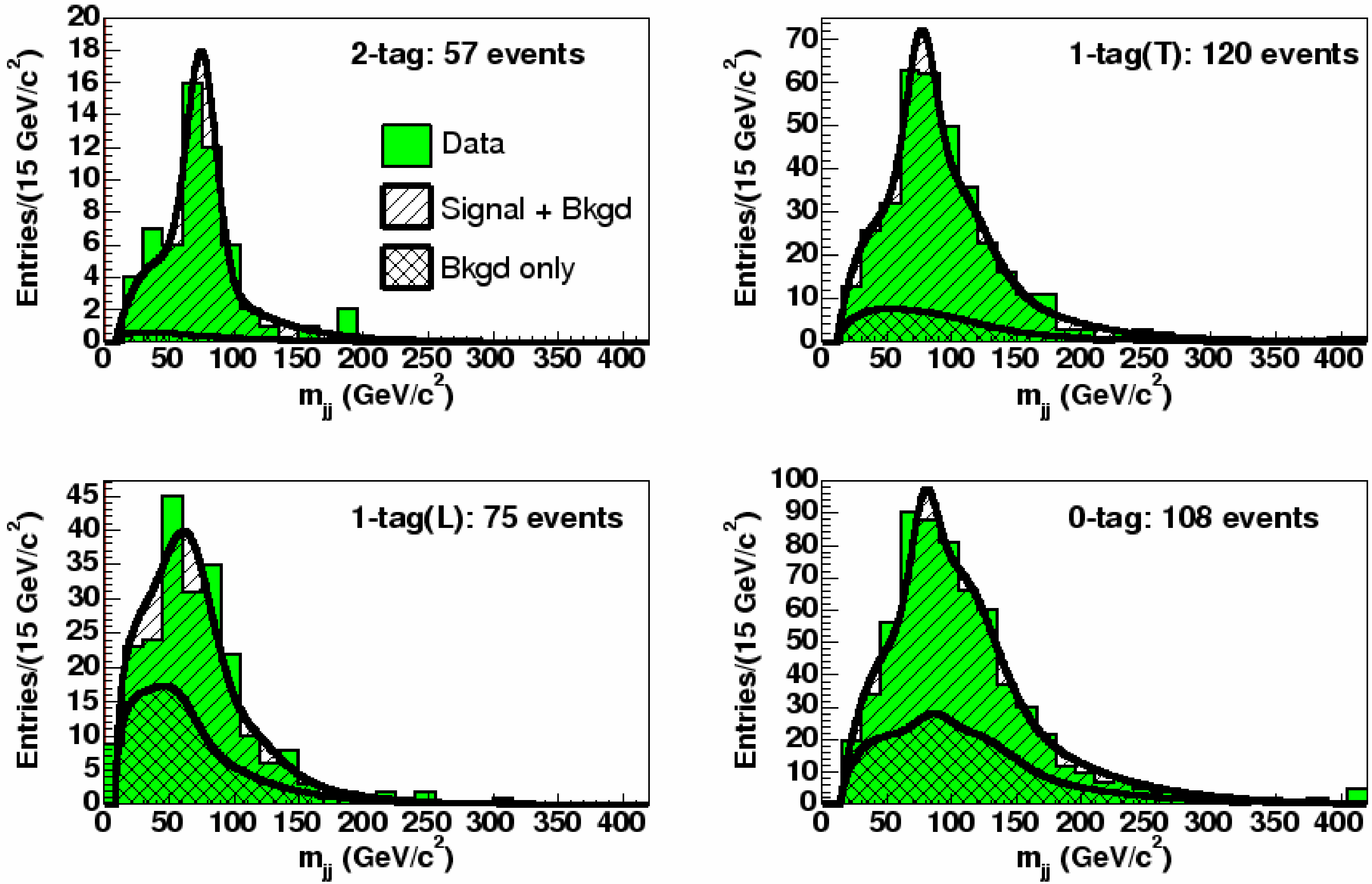
Systematic source	ΔMtop (GeV)
Residual Jet Energy Scale	0.7
b-jet energy (uncertainties arising from b-jet modeling)	0.6
Background shape	0.5
Initial State Radiation	0.5
Background Jet Energy Scale	0.4
Final State Radiation	0.2
Parton Distribution Functions	0.3
Monte Carlo generator differences (HERWIG vs PYTHIA)	0.2
b-tagging	0.1
MC statistics	0.3
TOTAL	**1.3**


CDF Run II Preliminary (680 pb^{-1})
M_{top} = 173.4 ± 2.5 (ΔJES+stat) ± 1.3 (syst) GeV
= 173.4 ± 2.8 GeV
ΔJES = −0.31 +0.59/−0.58 σ_c
Δln L=8.0
Δln L=4.5
Δln L=2.0
Δln L=0.5
Δ_{JES} (σ_c)
M_{top} (GeV/c^2)
2
1
0
-1
-2
-3
165
170
175
180
185

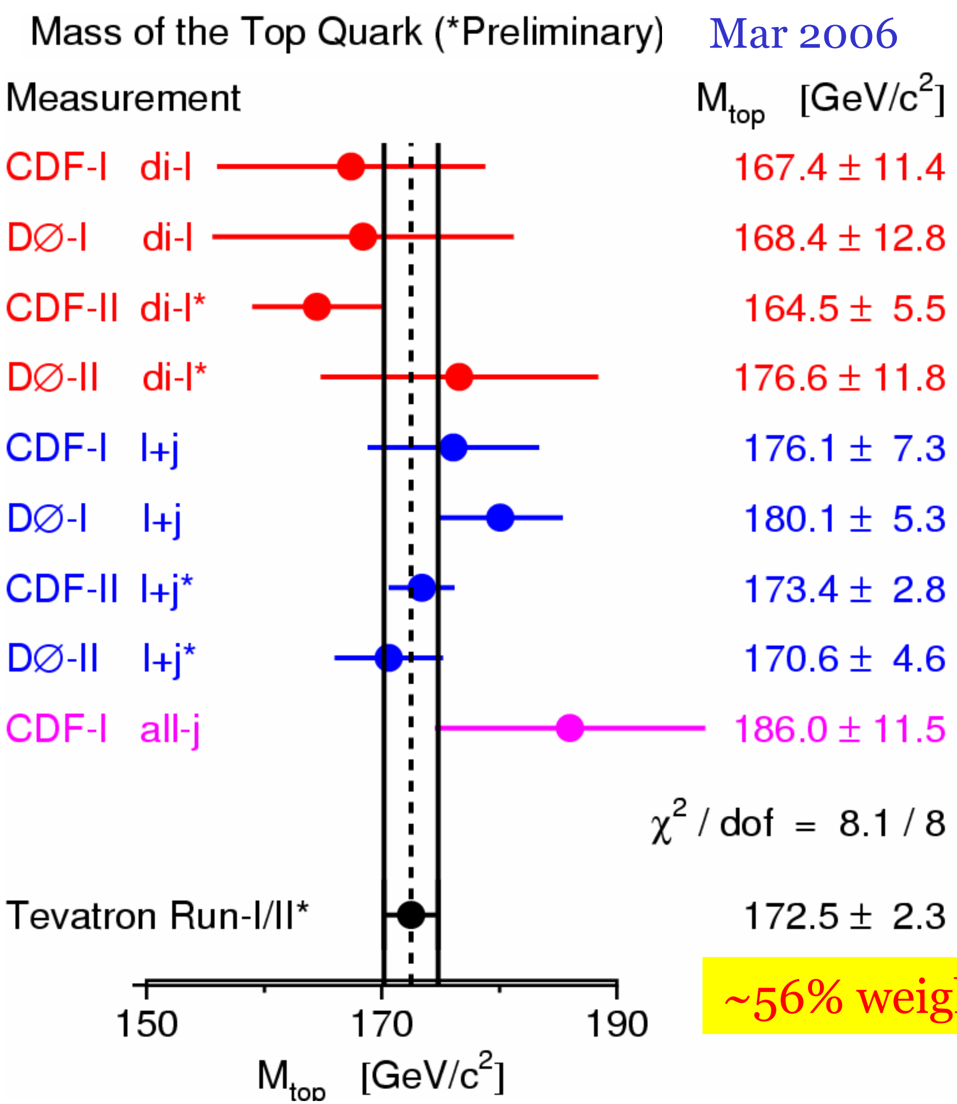
CDF Run II Preliminary (680 pb^{-1}) Reconstructed top mass fits



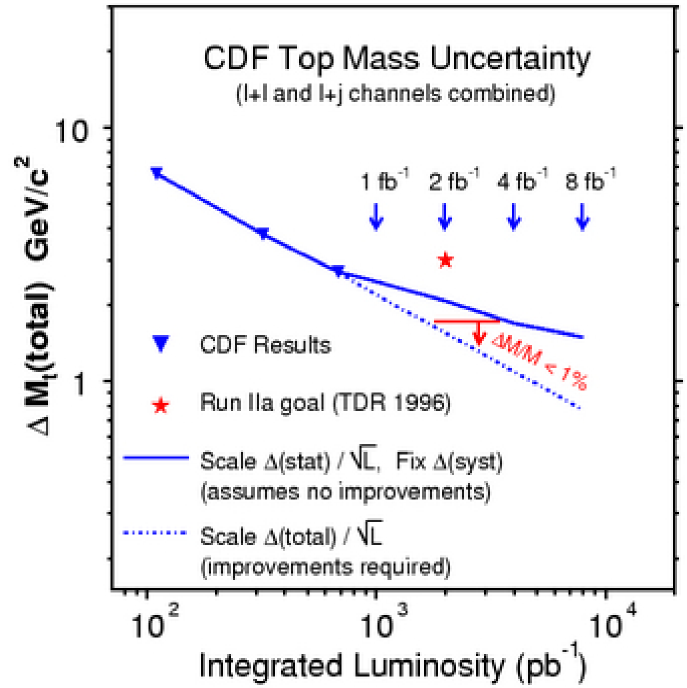
CDF Run II Preliminary (680 pb^{-1}) Dijet fits



M_{top} = 173.4 ± 2.8 GeV/c²



~56% weight!



We're already quite ahead of the Run IIa goal, but don't want to stop where we are …

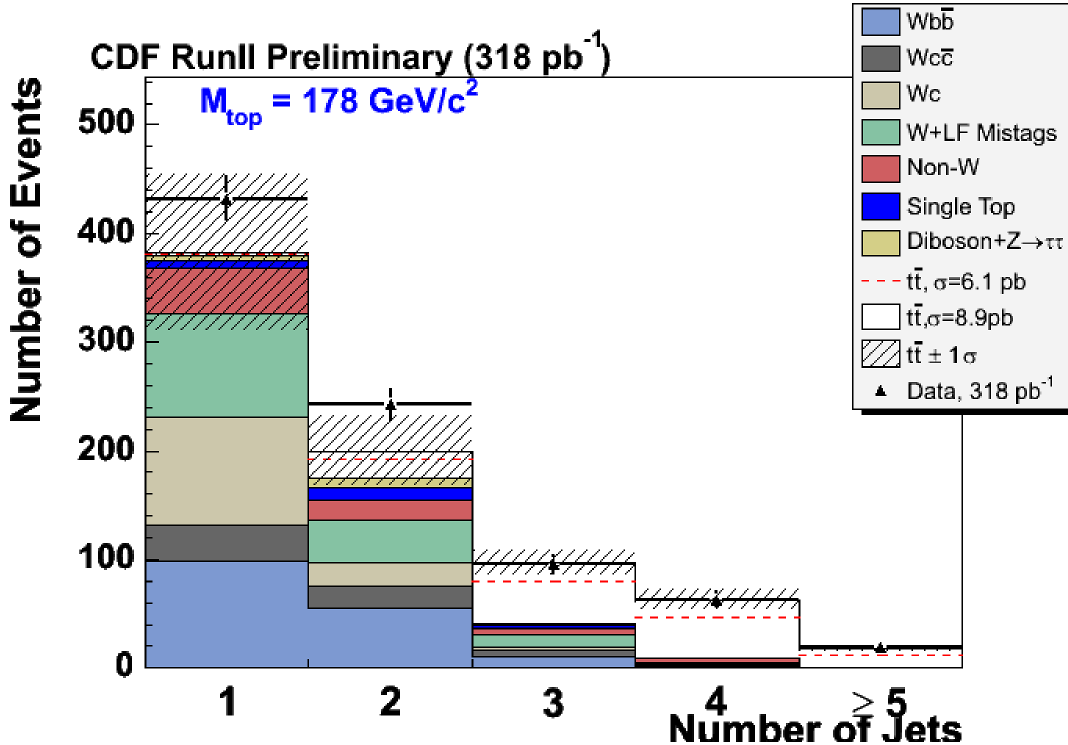
Conclusion

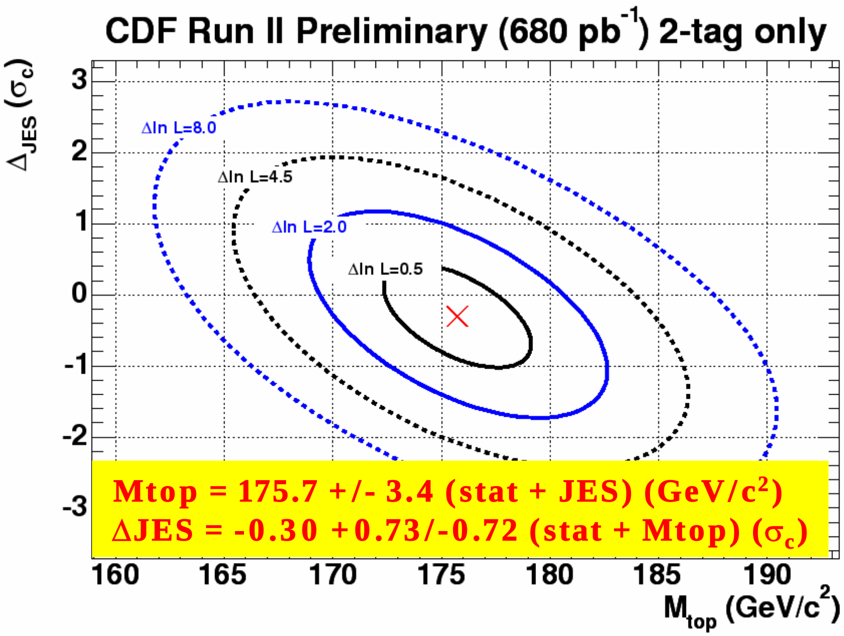
- For the future, some things we're thinking about:
  - More luminosity! (probably helps more than anything else)
  - Measure top mass in the dilepton channel using a template method in one joint likelihood machinery (can dileptons take advantage of W resonance to constrain JES?)
  - Get away from parameterizations (they're not fun), and move to non-parametric methods (specifically Kernel Density Estimation)
  - Measure top quark mass and $t\bar{t}$ x-section simultaneously (they're correlated in the SM)
  - Revisit event selection, subdivision?
  - Different b-tagging algorithms?
- For now:
  - **We measure $m_{top} = 173.4 \pm 2.8$ GeV/c2**

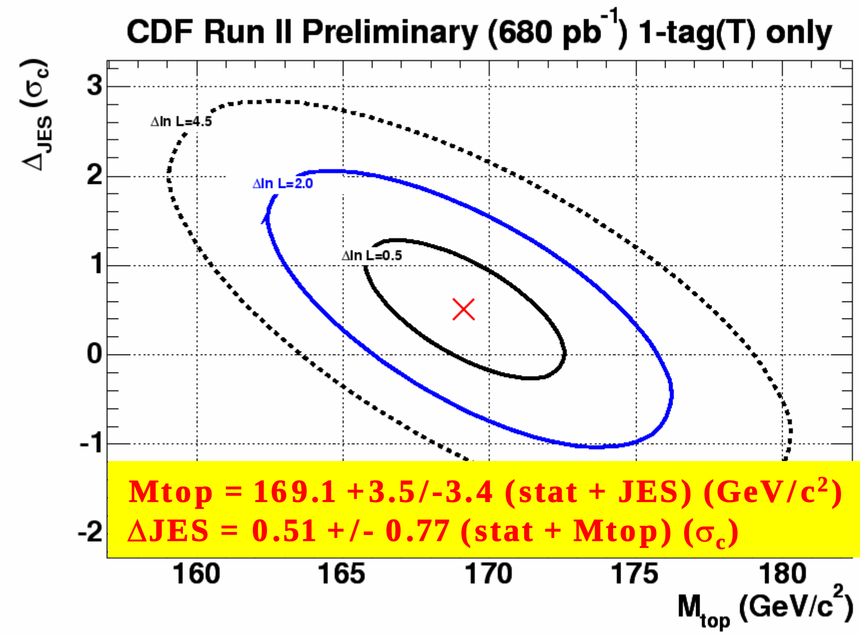
BACKUP SLIDES

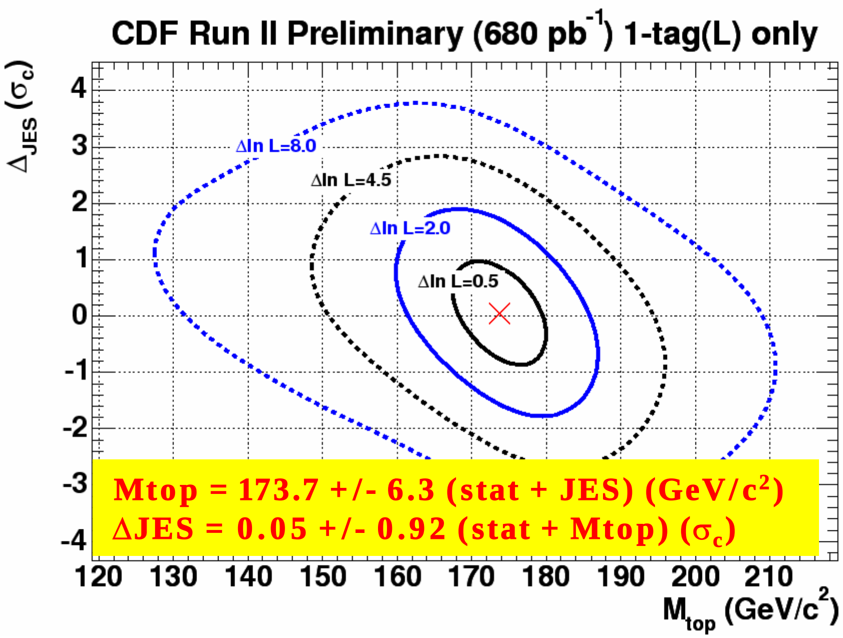
More on backgrounds

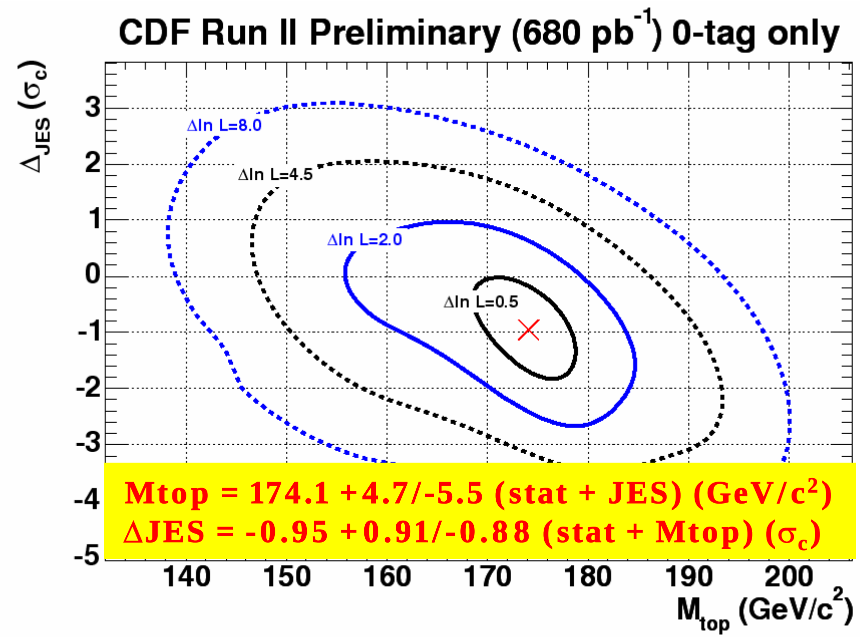
- W+multijets: ALPGEN+HERWIG with absolute normalization from pre-tag W+multijets data
  - W+Heavy flavor: Heavy flavor fraction from ALPGEN x tagging efficiency x pretag number from data
  - W+light jets: Mistag rate parametrized as a function of kinematic variables and applied to the pretag data in the signal region
- QCD: Sidebands of lepton isolation and MET used to estimate QCD in the signal region
- Diboson and Single top backgrounds estimated using ALPGEN



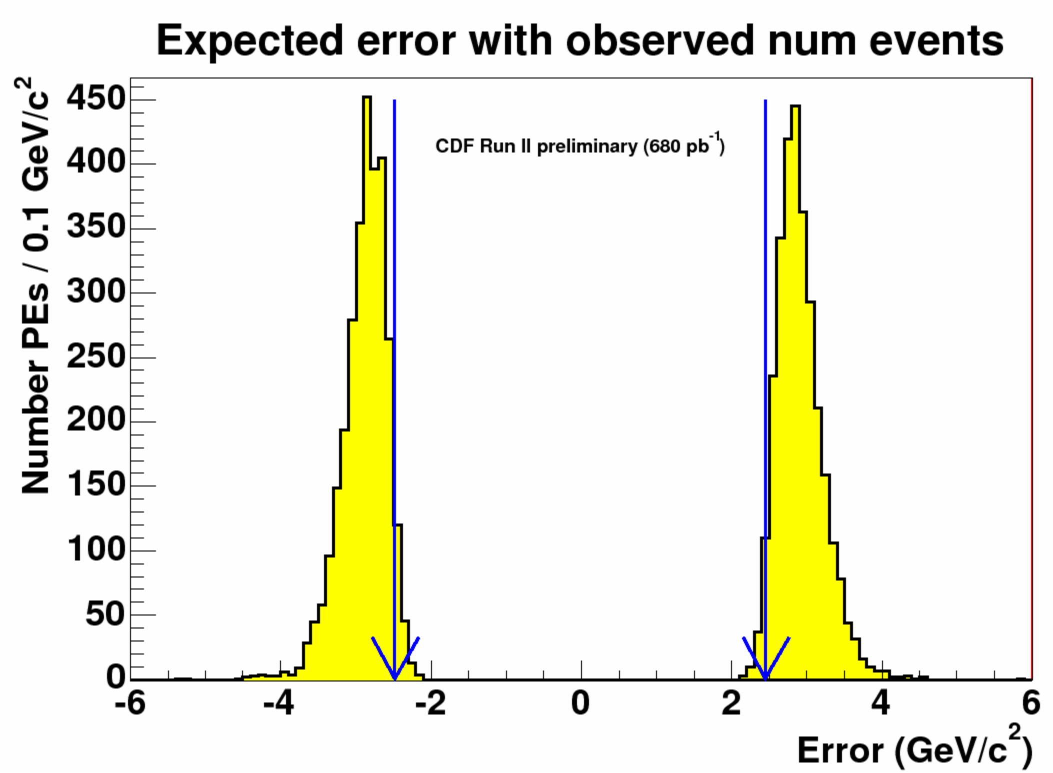

CDF Run II Preliminary (680 pb^{-1}) 2-tag only
Δ_{JES} (σ_c)
M_{top} (GeV/c^2)
Δln L=8.0
Δln L=4.5
Δln L=2.0
Δln L=0.5
Mtop = 175.7 +/- 3.4 (stat + JES) (GeV/c^2)
ΔJES = -0.30 +0.73/-0.72 (stat + Mtop) (σ_c)


CDF Run II Preliminary (680 pb^{-1}) 1-tag(T) only
Δ_{JES} (σ_c)
M_{top} (GeV/c^2)
Δln L=4.5
Δln L=2.0
Δln L=0.5
Mtop = 169.1 +3.5/-3.4 (stat + JES) (GeV/c^2)
ΔJES = 0.51 +/- 0.77 (stat + Mtop) (σ_c)


CDF Run II Preliminary (680 pb^{-1}) 1-tag(L) only
Δ_{JES} (σ_c)
M_{top} (GeV/c^2)
Δln L=8.0
Δln L=4.5
Δln L=2.0
Δln L=0.5
Mtop = 173.7 +/- 6.3 (stat + JES) (GeV/c^2)
ΔJES = 0.05 +/- 0.92 (stat + Mtop) (σ_c)

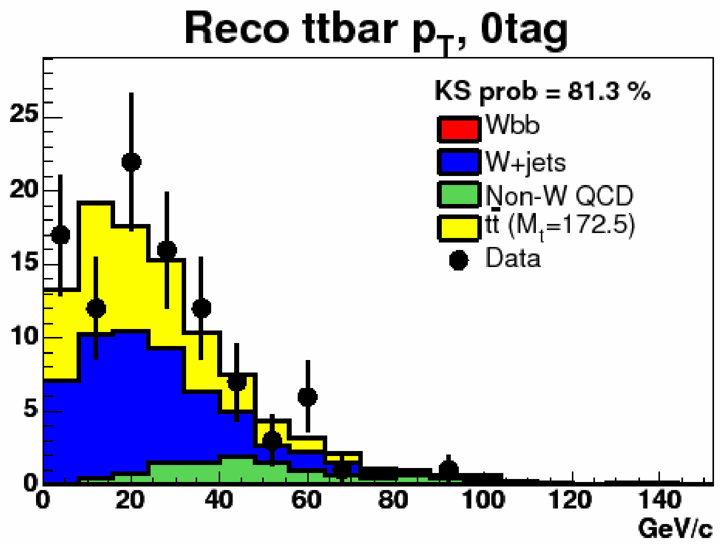

CDF Run II Preliminary (680 pb^{-1}) 0-tag only
Δ_{JES} (σ_c)
M_{top} (GeV/c^2)
Δln L=8.0
Δln L=4.5
Δln L=2.0
Δln L=0.5
Mtop = 174.1 +4.7/-5.5 (stat + JES) (GeV/c^2)
ΔJES = -0.95 +0.91/-0.88 (stat + Mtop) (σ_c)

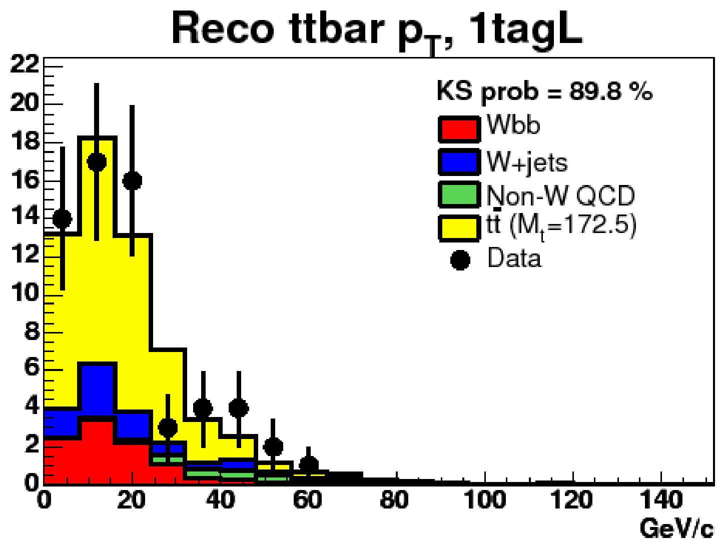
Expected errors

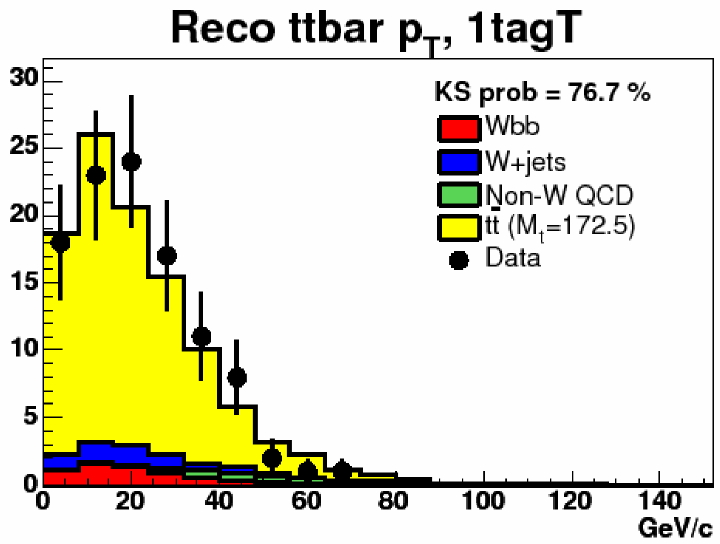


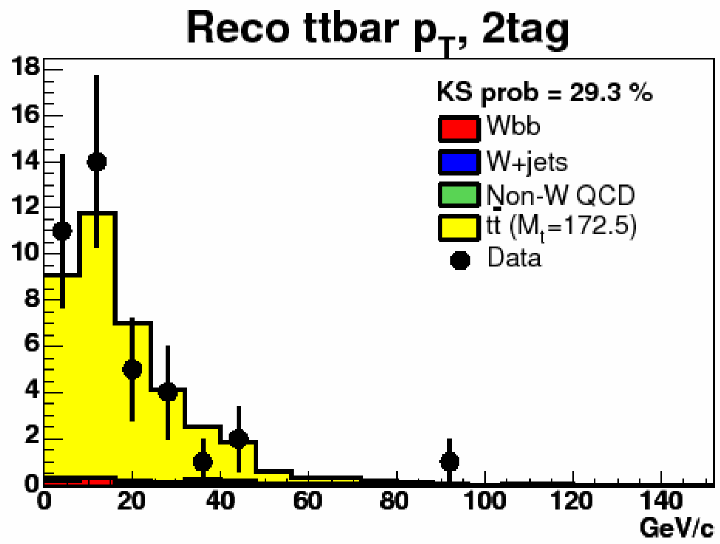
3.9% of pseudoexperiments give smaller error

ttbar pt

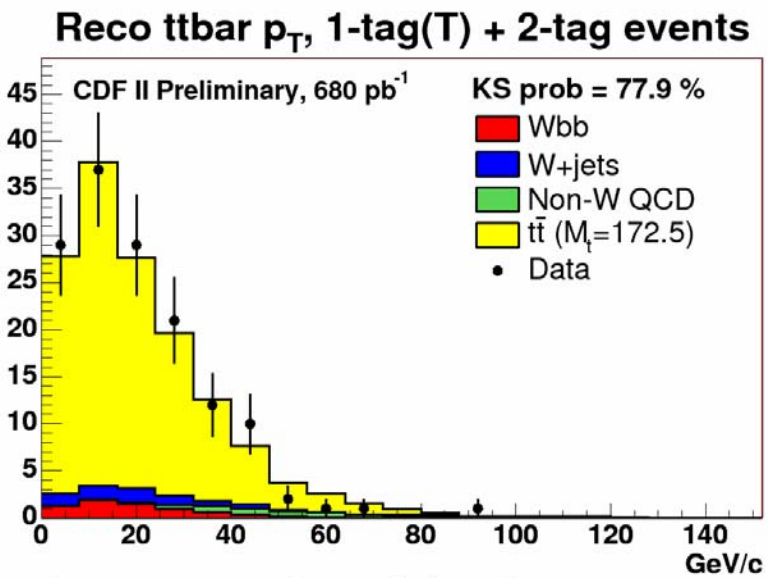

Reco ttbar p_T, 0tag
KS prob = 81.3 %
Wbb
W+jets
Non-W QCD
tt (M_t=172.5)
Data
GeV/c

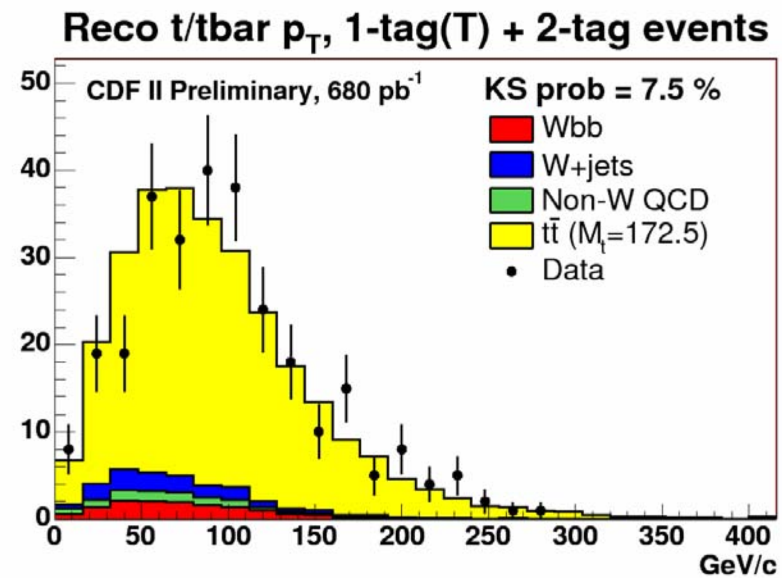

Reco ttbar p_T, 1tagL
KS prob = 89.8 %
Wbb
W+jets
Non-W QCD
tt (M_t=172.5)
Data
GeV/c

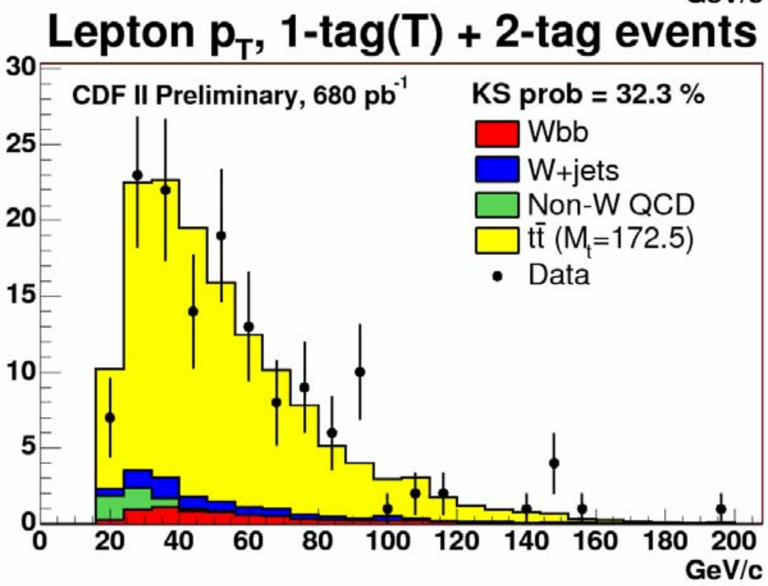

Reco ttbar p_T, 1tagT
KS prob = 76.7 %
Wbb
W+jets
Non-W QCD
tt (M_t=172.5)
Data
GeV/c

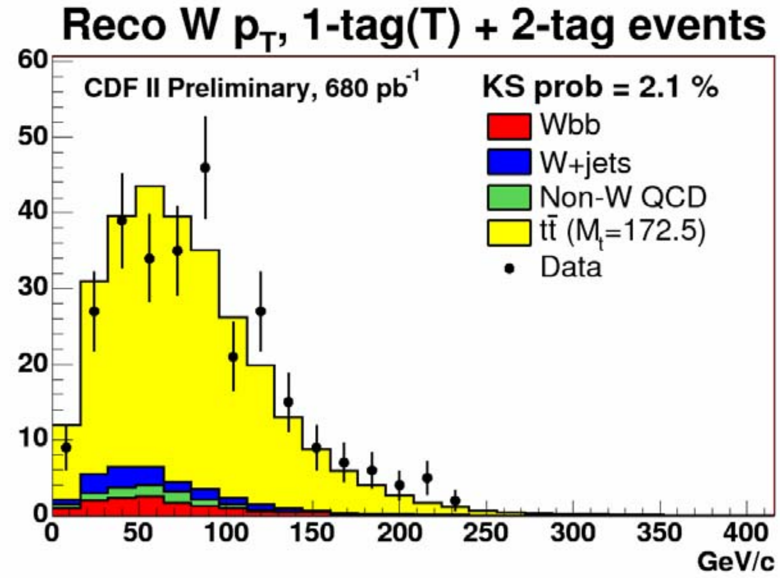

Reco ttbar p_T, 2tag
KS prob = 29.3 %
Wbb
W+jets
Non-W QCD
tt (M_t=172.5)
Data
GeV/c

More kinematic plots









One more kinematic plots