Search for WZ + ZZ production with missing transverse energy and *b*-jets at CDF

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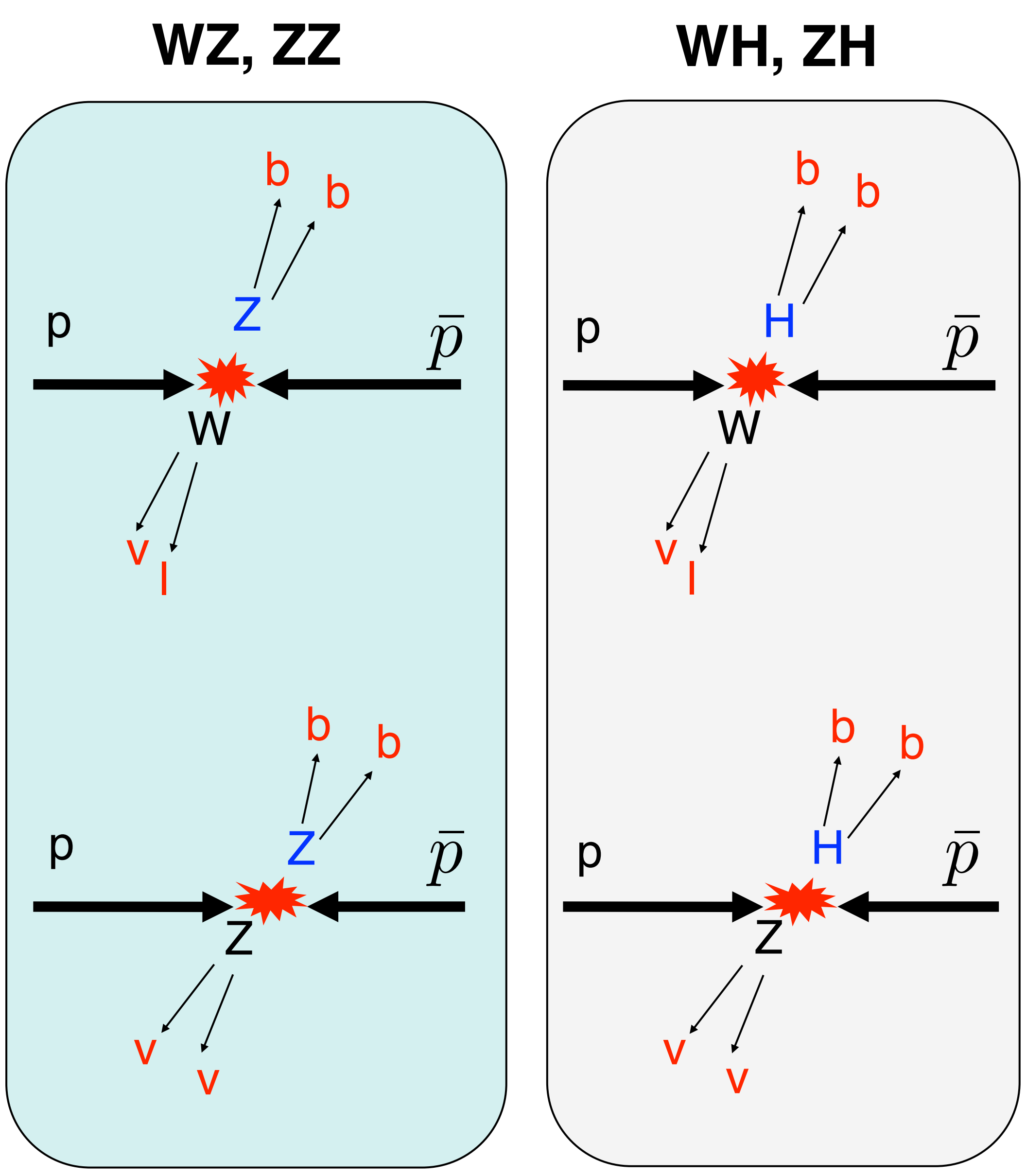
for the CDF collaboration

Outline

- Introduction / Motivation
- Our b-tagger
- Backgrounds
- The fitter
- Systematic uncertainties
- Results

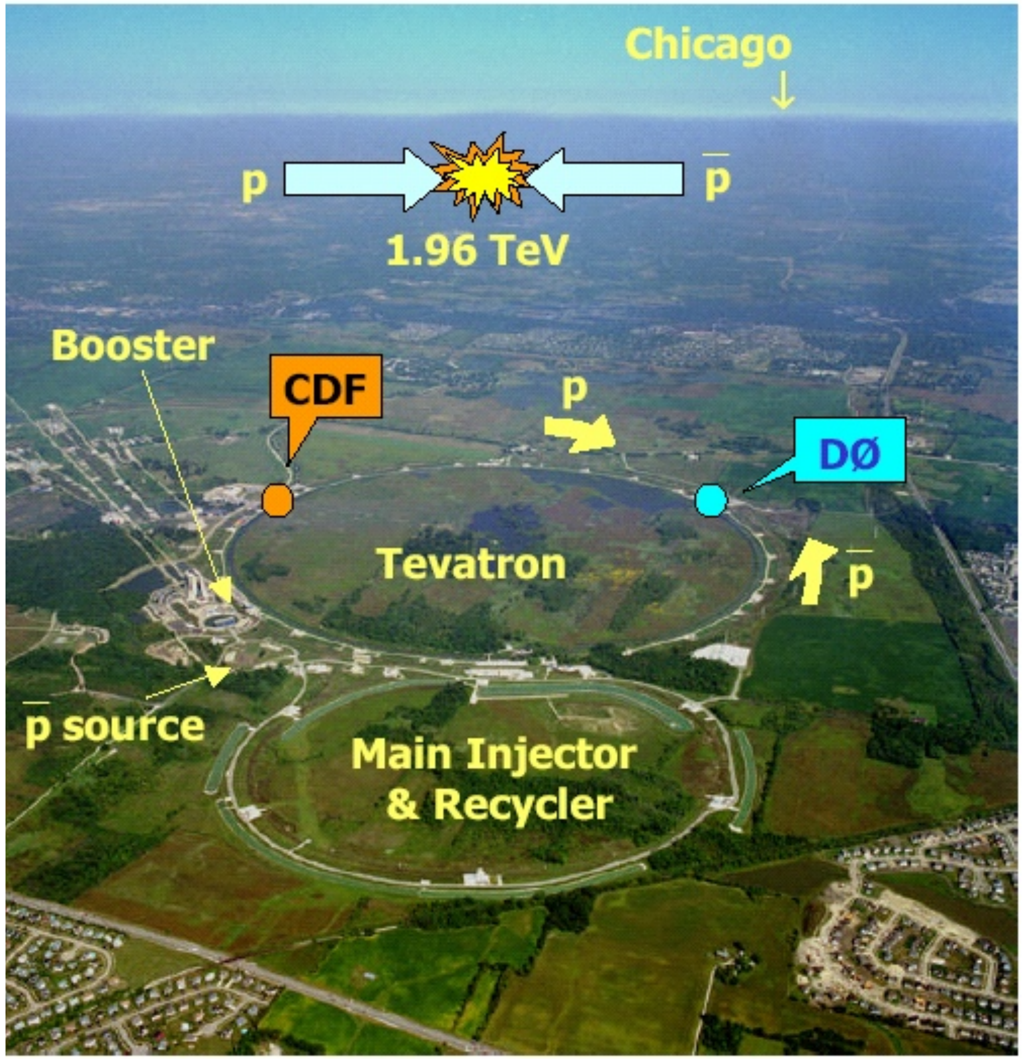
Motivation

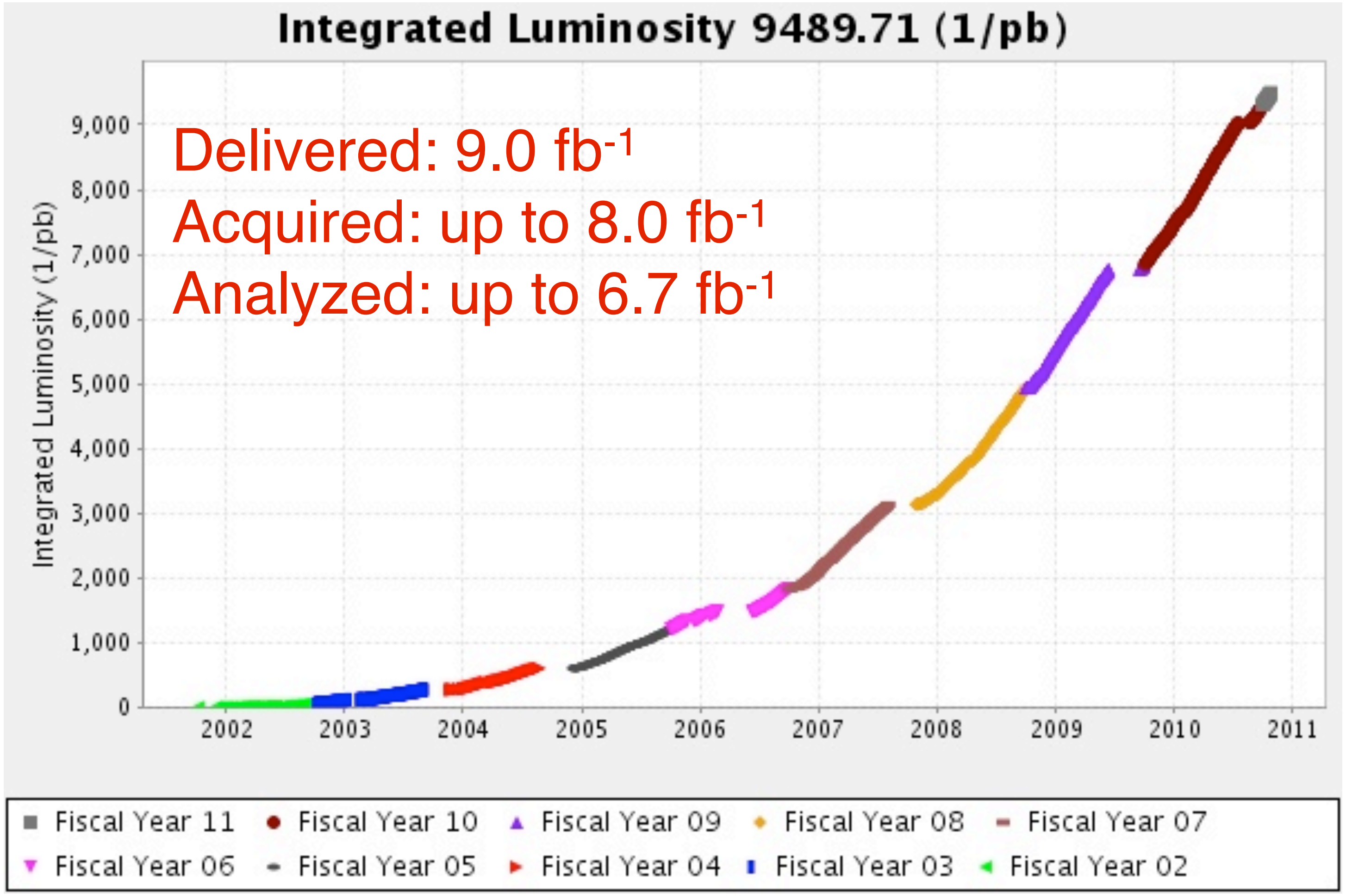
- Cross section for WW+WZ+ZZ in the $\not\!\!E_T$ + jets final state recently measured at CDF
  - Phys. Rev. Lett. 103, 091803 (2009)
- No one has measured WZ+ZZ with jets
- Use b-tagging to reduce WW contribution
  - W doesn't go to 2 b's like Z
  - **WZ+ZZ → $\not\!\!E_\mathbf{T}$ + 2 h.f. jets** enhanced
- Associated Higgs production (WH, ZH) is important for low mass Higgs searches at the Tevatron
  - Observation of WZ+ZZ will be a major milestone

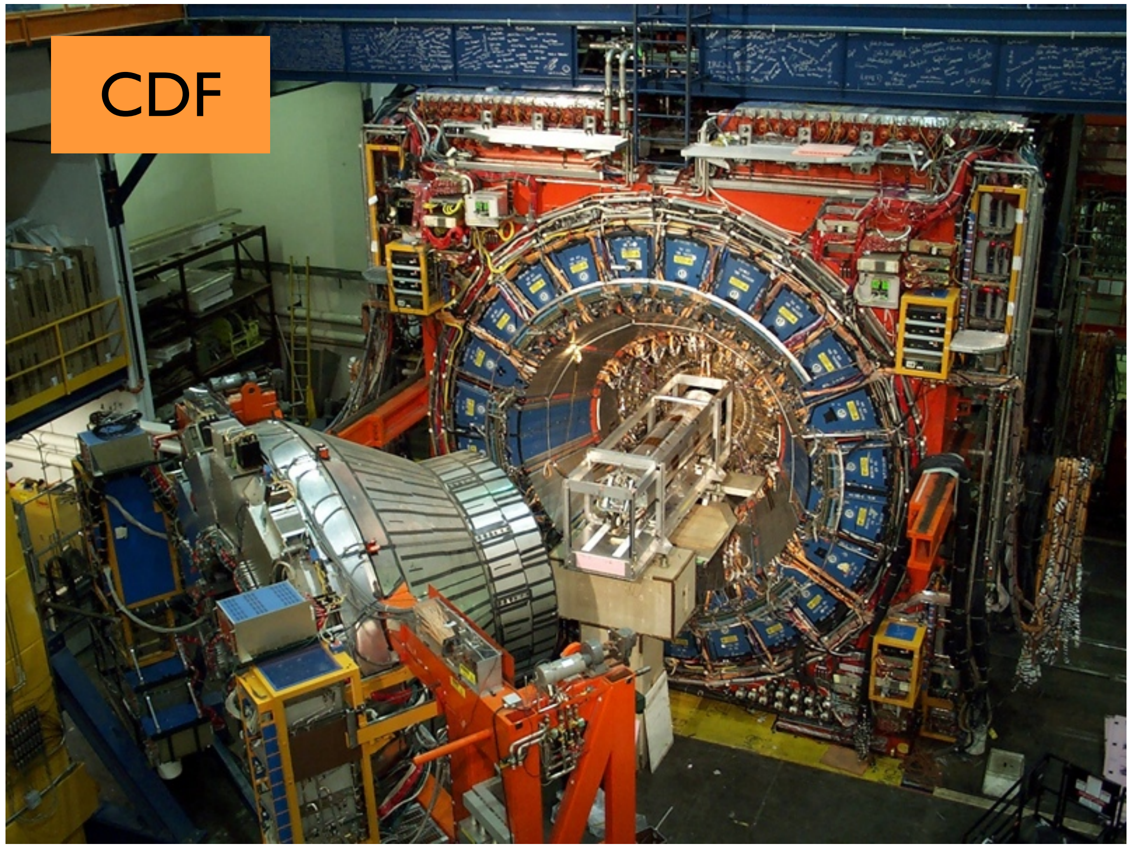


Tevatron & CDF

- p pbar collider operating at 1.96 TeV
- Tevatron will run until September 2011
- Currently have ~8 fb^{-1} data acquired
- Hoping to collect 10 fb^{-1} or more by end of Run II





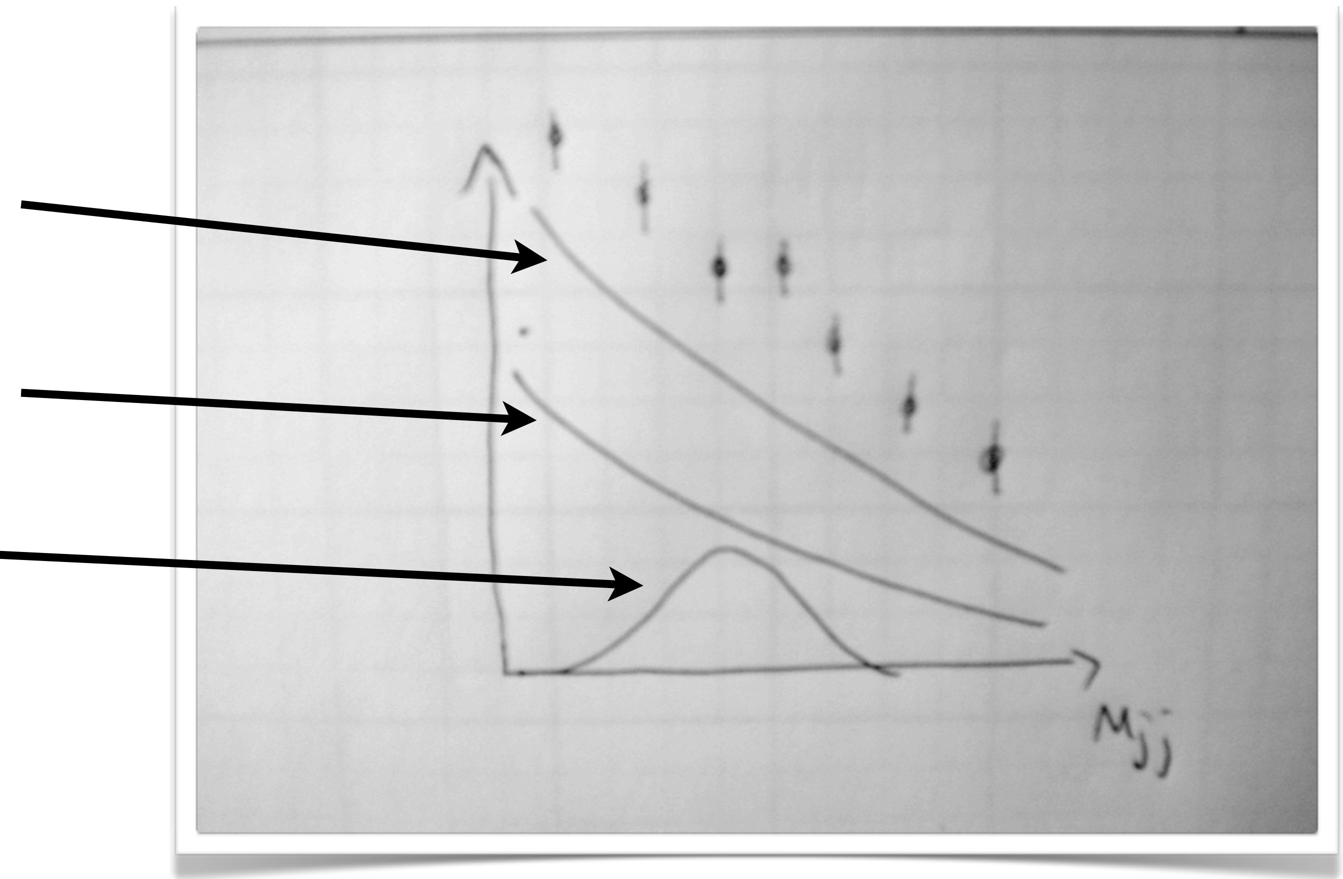


Method overview

- Look for events with
  - large missing transverse energy
  - 2 jets consistent with B hadron decays
- Fit the dijet mass distribution from data using 3 templates
  - **Electroweak background** (mainly from W,Z+jets, from Monte-Carlo)
  - **Multijet background (MJB)** (QCD jet production, estimated from data)
  - **Signal** (WZ+ZZ Monte-Carlo)

⇒ # of signal events

⇒ cross section



The Prequel

Without b-tagging,
measured WW+WZ+ZZ cross section

Signal events:

1516 ± 239 (stat) ± 144(sys)

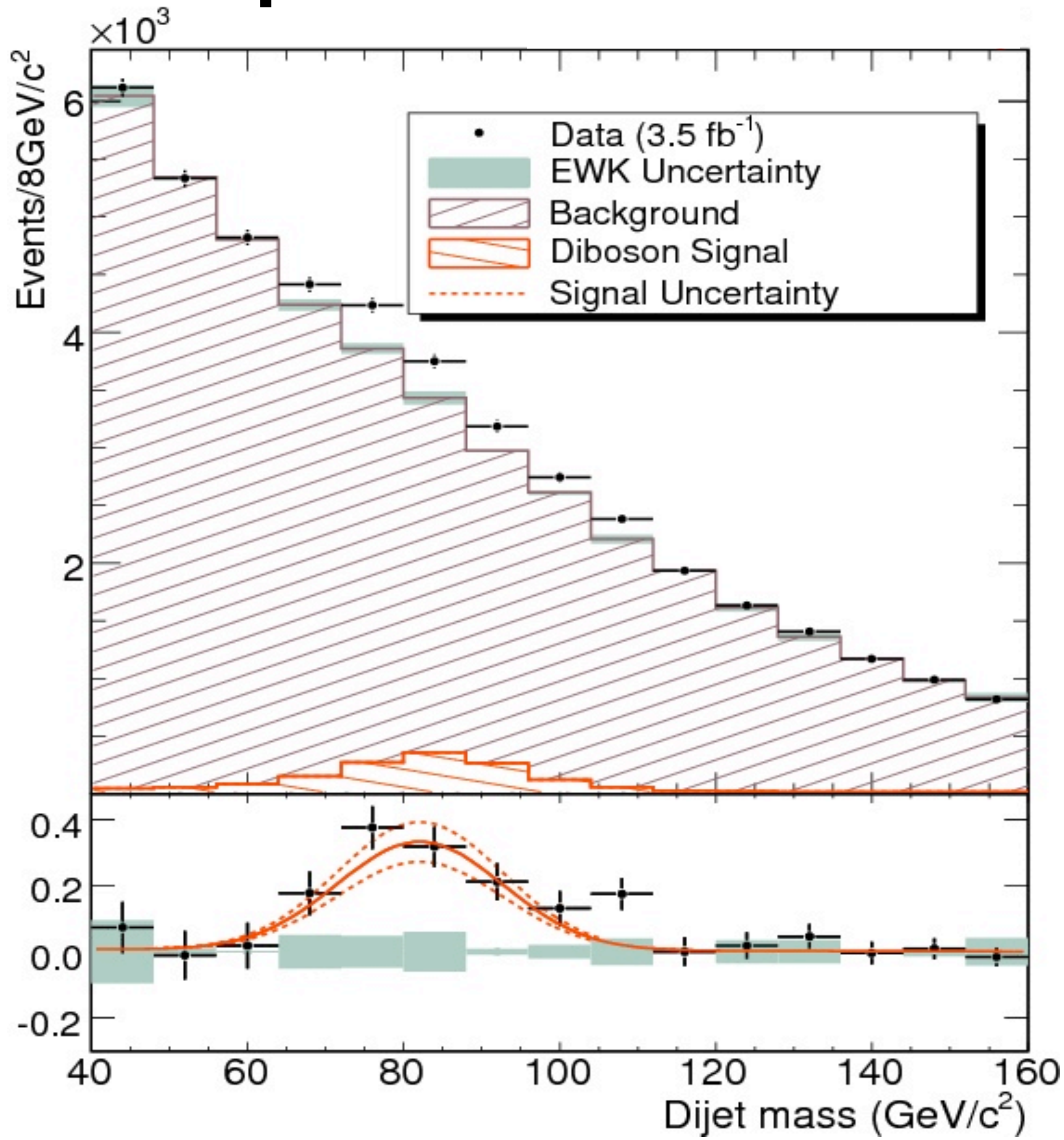
- WW dominates

  σ_{WW} x BR=8.2pb

  σ_{WZ} x BR=2.5pb

  σ_{ZZ} x BR=1.0pb

Data – background →



Theoretical cross section: 16.8 ± 0.5 pb

Measured cross section: 18.0 ± 2.8(stat) ± 2.4(sys) ± 1.1(lum) pb

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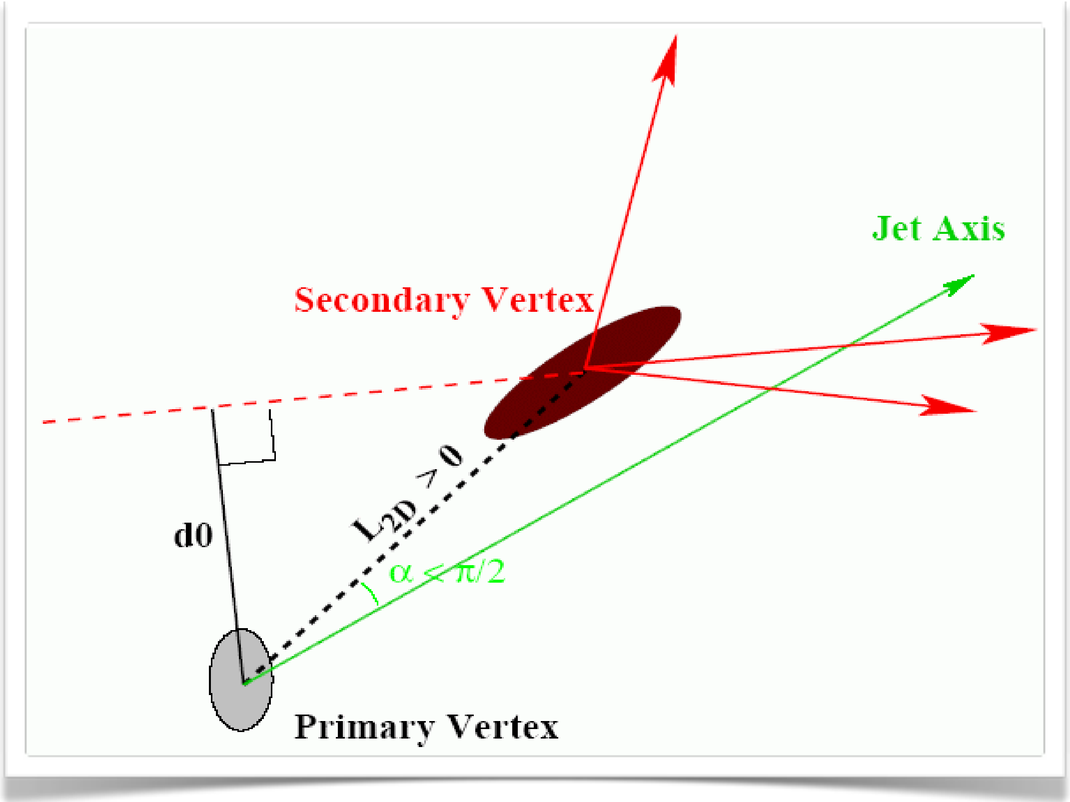
b-tagger

- B hadrons often travel a measurable distance before decaying
- Typical b-taggers look for tracks forming a secondary vertex
  - Use decay length in transverse plane ($\underline{L_{2D}}$)
  - Displaced tracks often have large impact parameter (<u>d0</u>)
- We developed a new b-tagger to further exploit individual track information



Two level neural network:

- **Track "bness"**: distinguish daughter tracks of B's from non-daughters
- **Jet bness**: Combine track bness with jet variables

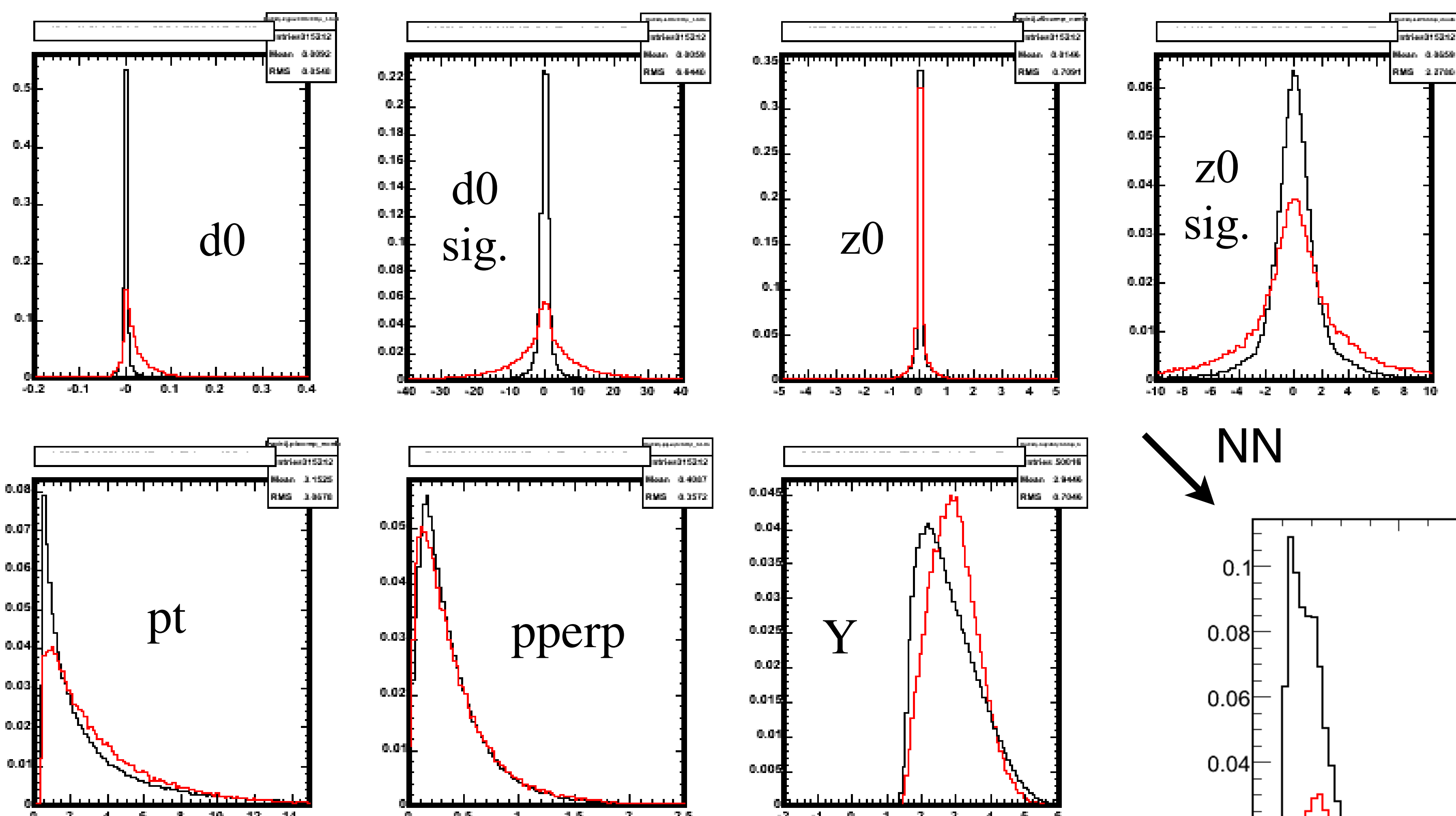
○ **Tune a cut on jet bness to achieve desired b tagging efficiency/mistag rate**

b-tagger: Track bness inputs

Inputs to the track bness NN:

- Signed impact parameter (d0), z position, and their significances (value/uncertainty) ← Take advantage of track displacement
- Track momentum in transverse plane (pt)
- Track momentum transverse to jet axis (pperp)
- Rapidity with respect to the jet axis (Y)

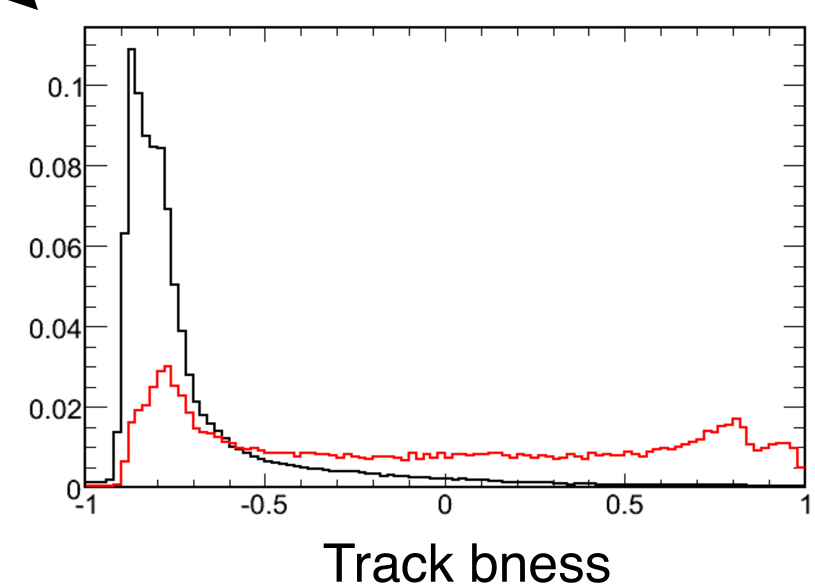
} Take advantage of high B momentum



B tracks

Non-B tracks

NN

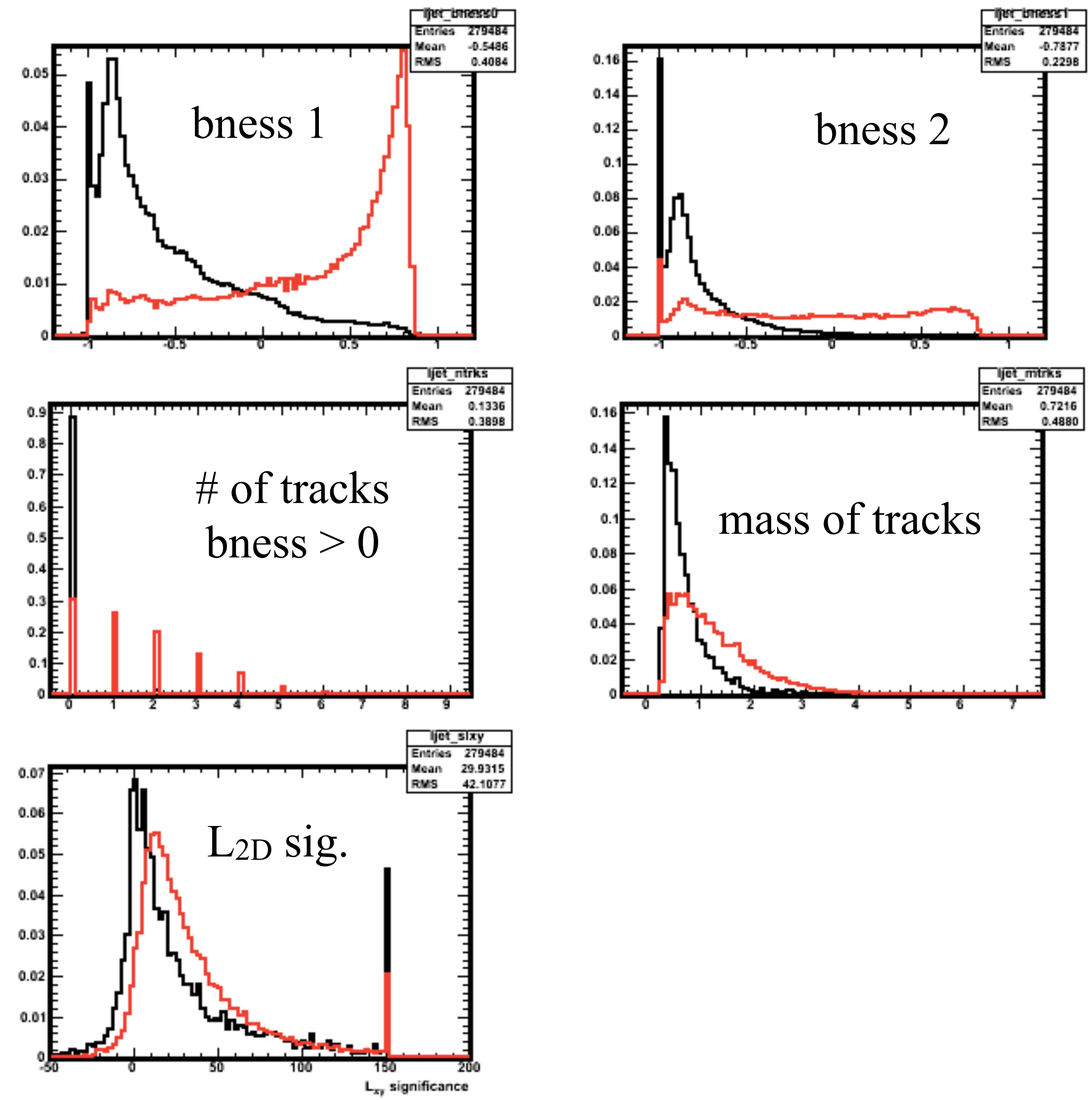


b-tagger: Jet bness inputs

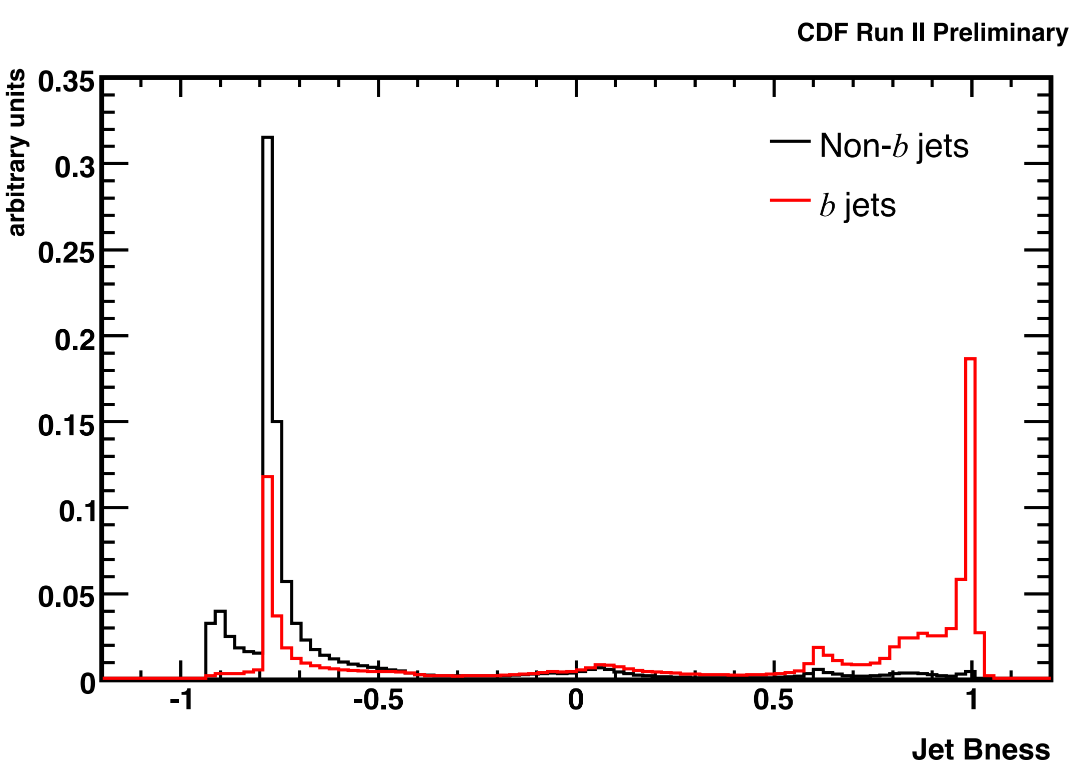
Inputs to the Jet bness NN

- Top 5 track bnesses (“bness 1”, etc.)
- # of tracks of bness > 0 & invariant mass of those tracks
- If secondary vertex found, L_{2D} significance
- Muon likelihood
- # of K_s candidates

B jets   Non-b jets



NN ←



Validity / Uncertainty of b-tagger

- Neural networks are trained on Monte Carlo samples
- How do they actually perform in **data**?
- 2 things you need to know to characterize a b-tagger:
  - What fraction of b-jets does it correctly tag? "efficiency" or "tag rate"
  - What fraction of non-b jets does it incorrectly tag? "mistag rate"
- Also need way to quantify differences between data and MC to take as systematic uncertainty on b-tagger
- Compare data and MC jets in two control regions similar to our data sample:
  - ***Z+1 jet:*** Mostly non-b jets; obtain mistag rate
  - ***t-tbar:*** Mostly b-jets; obtain tag rate

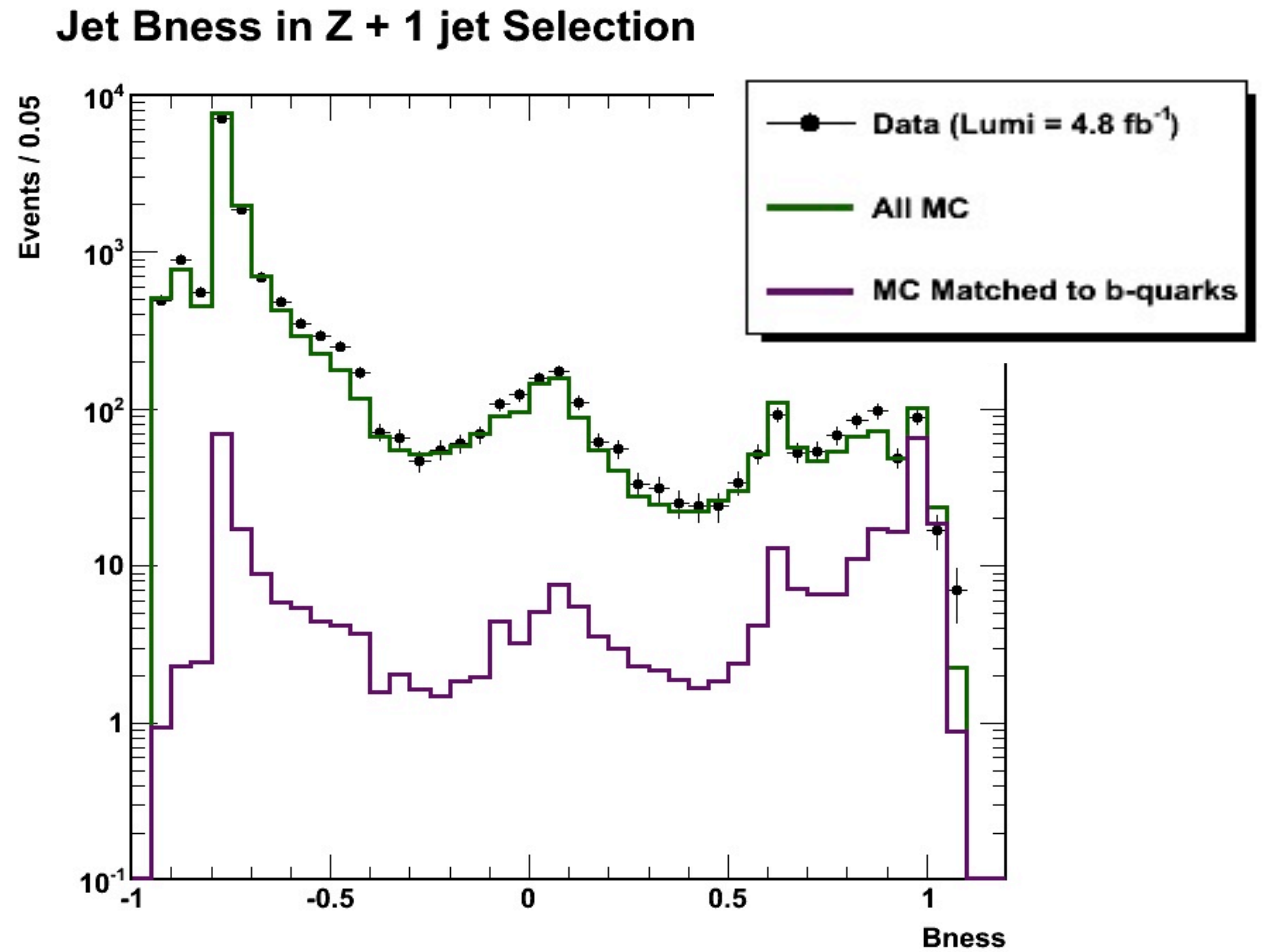
Mistag rate (Z + 1 jet)

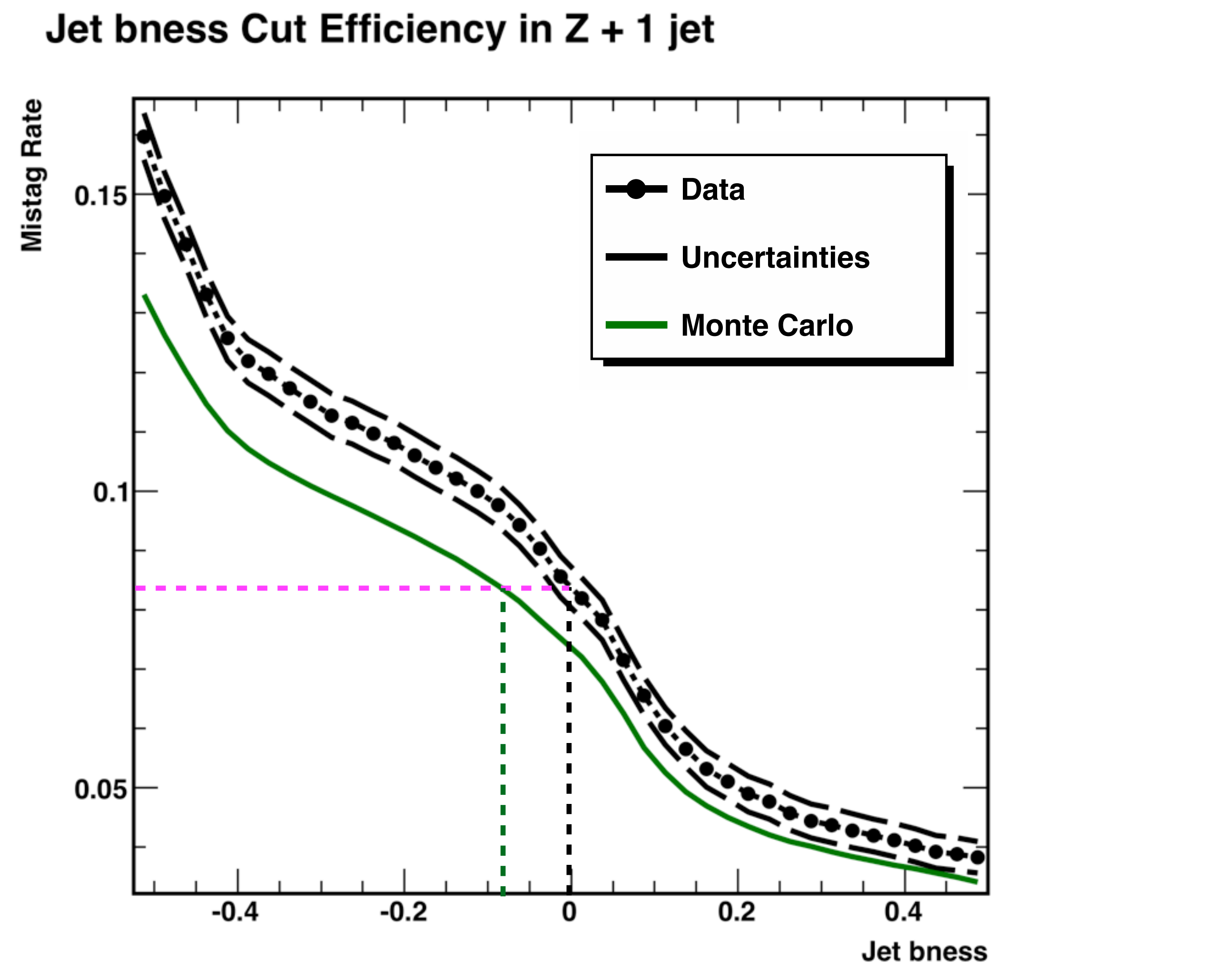
- Typical Z→leptons selection,
  - only one jet with $E_T > 20$ GeV
- Data and MC agreement good
- Still, large number of b's
  - Subtract their contribution when calculating the mistag rate in data

$$\mathrm{MR}(b) \approx \frac{\mathrm{N(non\text{-}b)\ with\ bness} > b}{\mathrm{N(non\text{-}b)}}$$

- For a given bness cut in data, slide the bness cut in MC to match the mistag rate in data
  - Similarly use the uncertainties for the b-tagger systematic uncertainty

*b*ness Cut in Data	Equivalent MC Cut		
	-1σ	Central Value	$+1\sigma$
0.0	−0.114	−0.0795	−0.052
0.85	0.805	0.8325	0.861

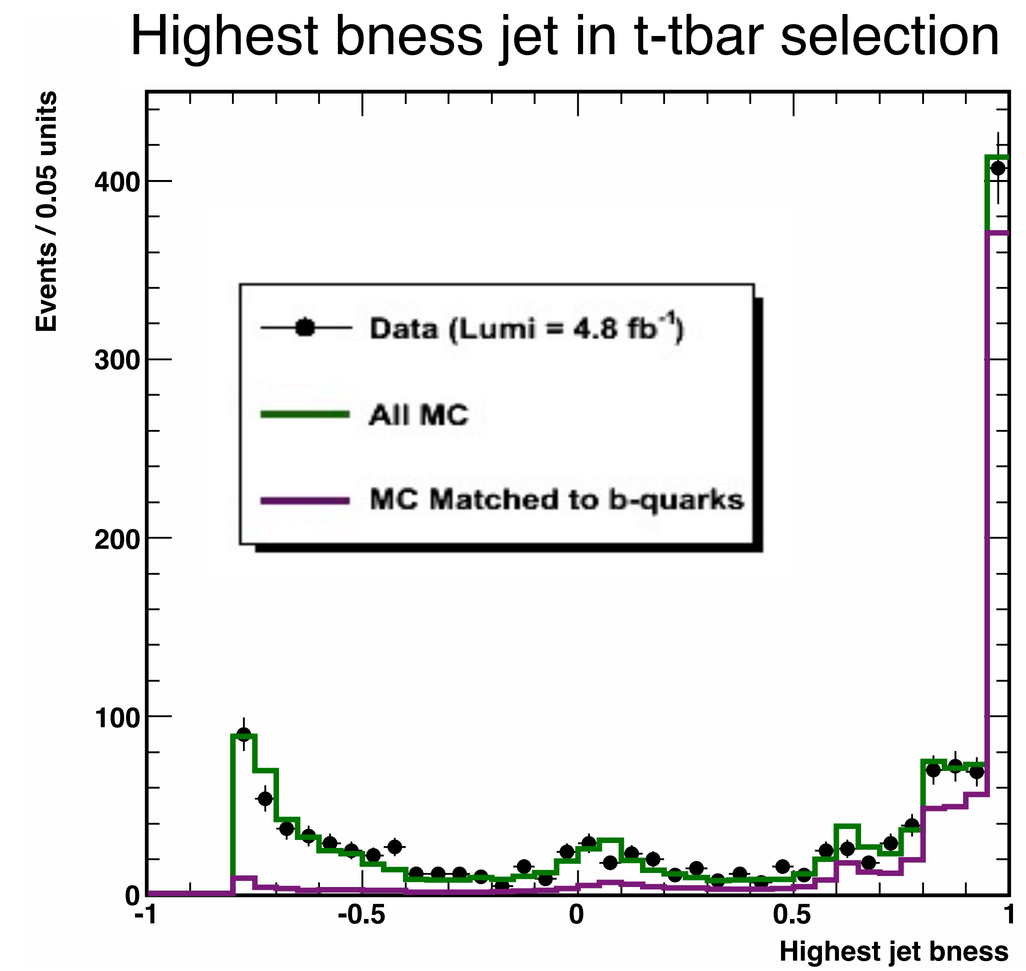


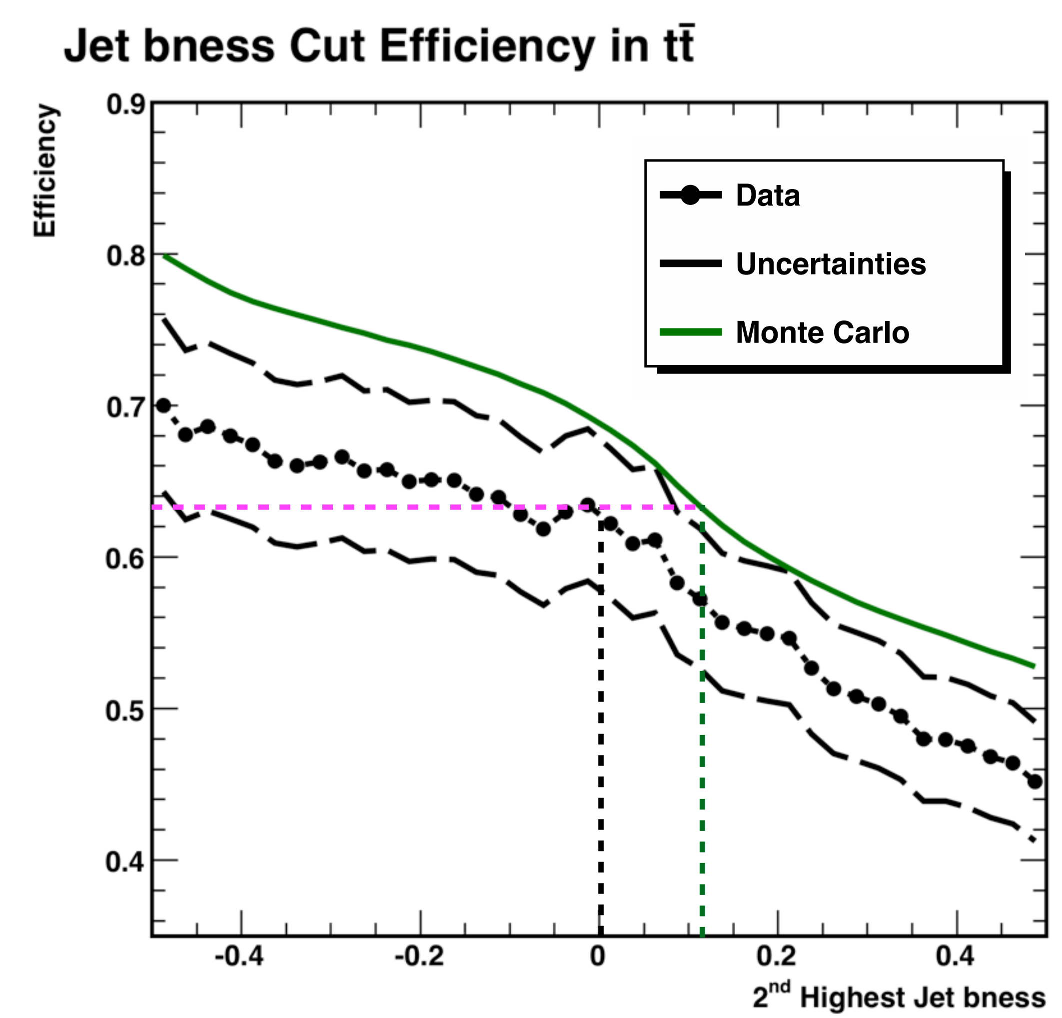


Efficiency (t tbar)

- First application at CDF of this method for obtaining the b-tag efficiency
  - Typically use tag & probe method in generic dijet events, but difficult to get a high purity sample of b jets
- Typical t-tbar→lepton + jets selection
- Data and MC agreement good
- High *b*-jet purity in high bness region
- Subtract the small non-b contribution when calculating efficiency
- For a given bness cut in data, slide the bness cut in MC to match the efficiency in data
  - Similarly use the uncertainties for the b-tagger systematic uncertainty

$b$ness Cut in Data	Equivalent MC Cut		
	-1σ	Central Value	$+1\sigma$
0.0	0.0275	0.1225	0.2675
0.85	0.8465	0.876	0.903





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Basic event selection

2 b-jets

- 2 or more central jets with $E_T > 20$ GeV
  - Sort jets by bness (instead of E_T)
  - Get dijet mass from 2 highest bness jets
- Jet 1 bness > 0.85, Jet 2 bness > 0.0
  - Call this the “two-tag” channel
  - Also exploit a “no-tag” channel for events which fail this cut

neutrinos

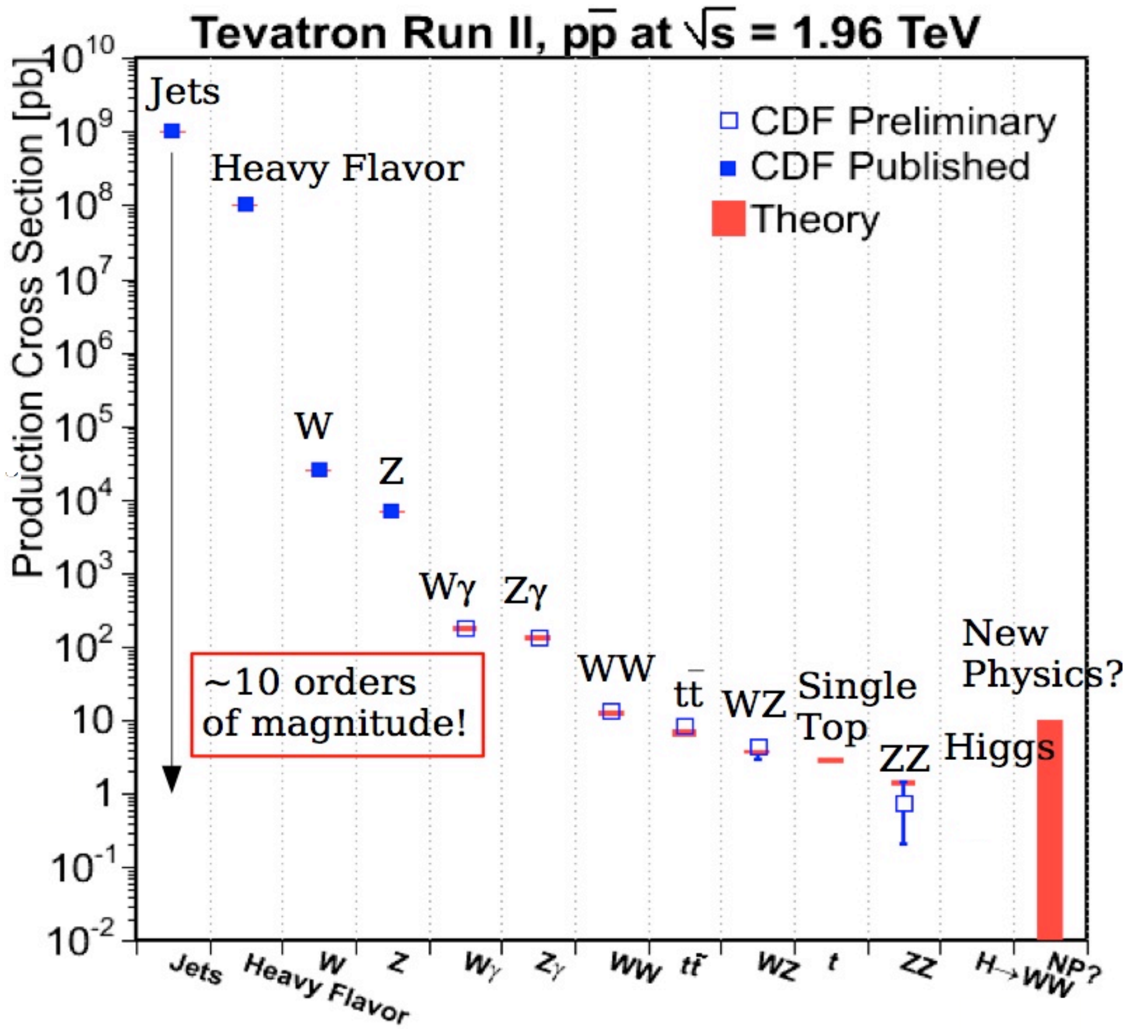
- Missing $E_T > 50$ GeV

define signal region

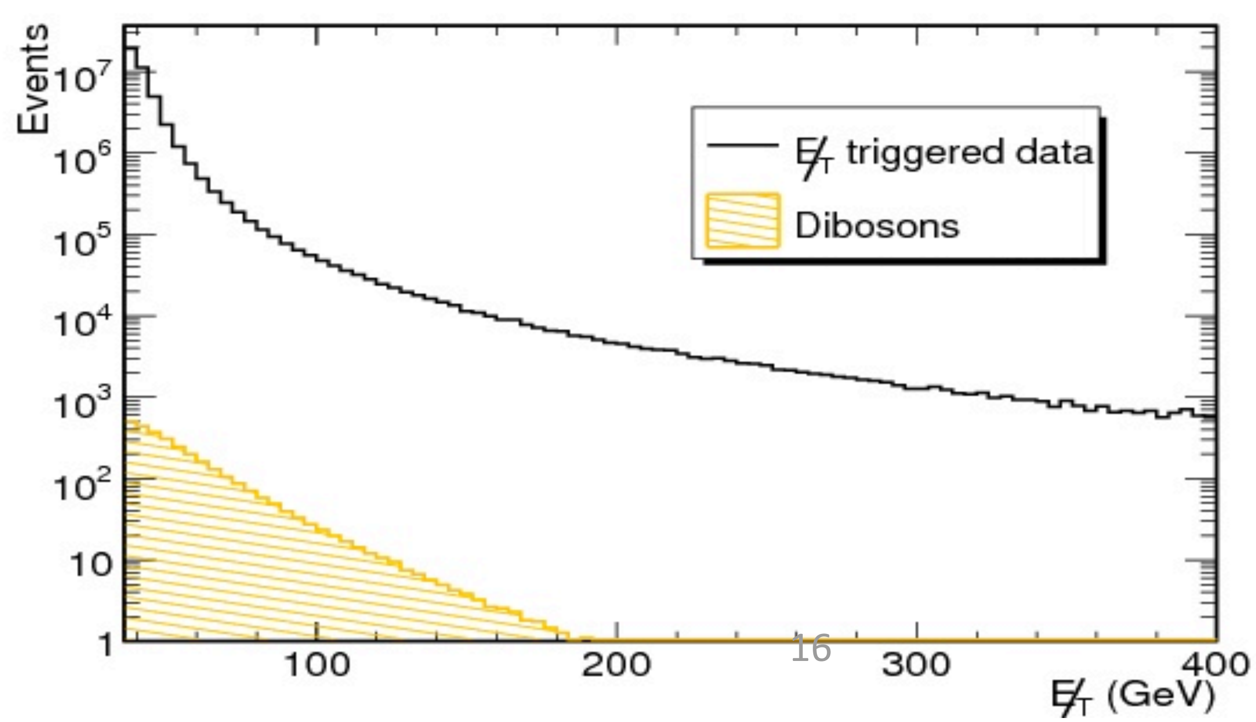
- 40 GeV < dijet mass < 160 GeV

Multi-jet background

- Generic jet production via QCD
- QCD ~9 orders above WW+WZ+ZZ
  - Rare fluctuations × huge rate = large background
  - Difficult to model with Monte Carlo
  - Use a data-driven method instead



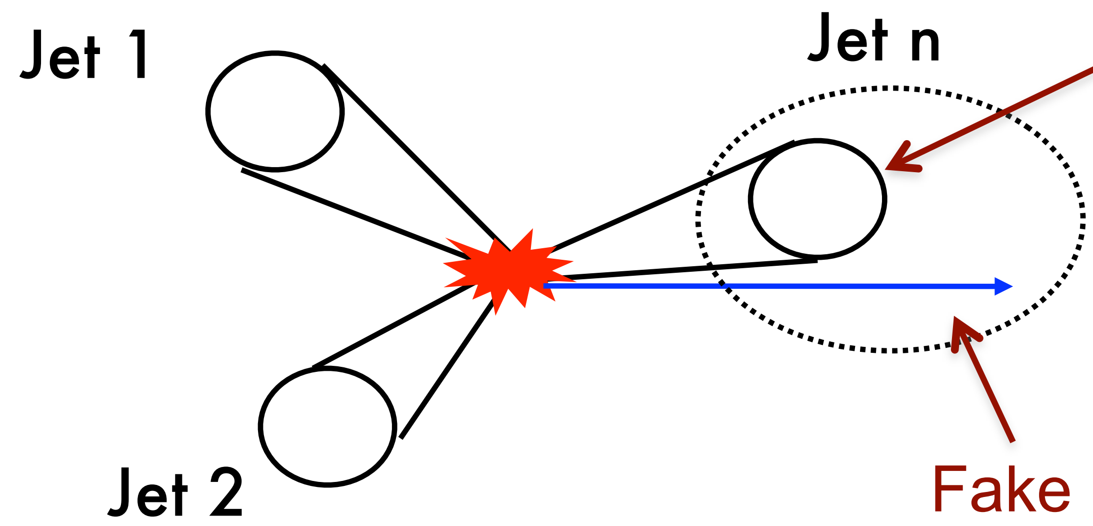
- Before selection the diboson signal is swamped by backgrounds
  - Rejecting QCD multijet events is a major challenge



Multi-jet background

Three handles on Multi-jet background:

1) Δφ(met, closest jet) > 0.4



2) MET-significance > 4

- Uses the jet energy uncertainties to estimate how likely the MET is due to mis-measurement (low significance) or neutrinos (high significance)

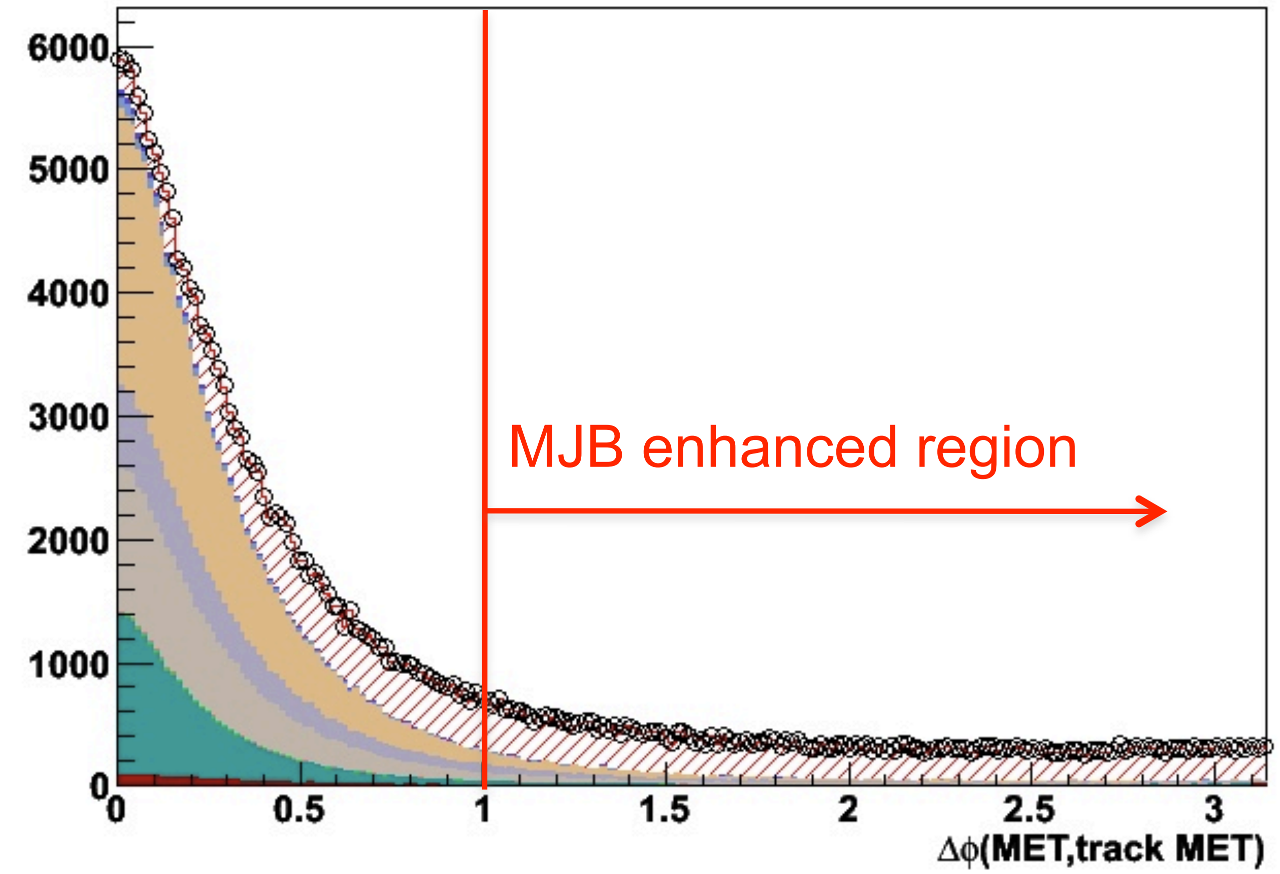
3) Δφ(calorimeter MET, tracker MET)

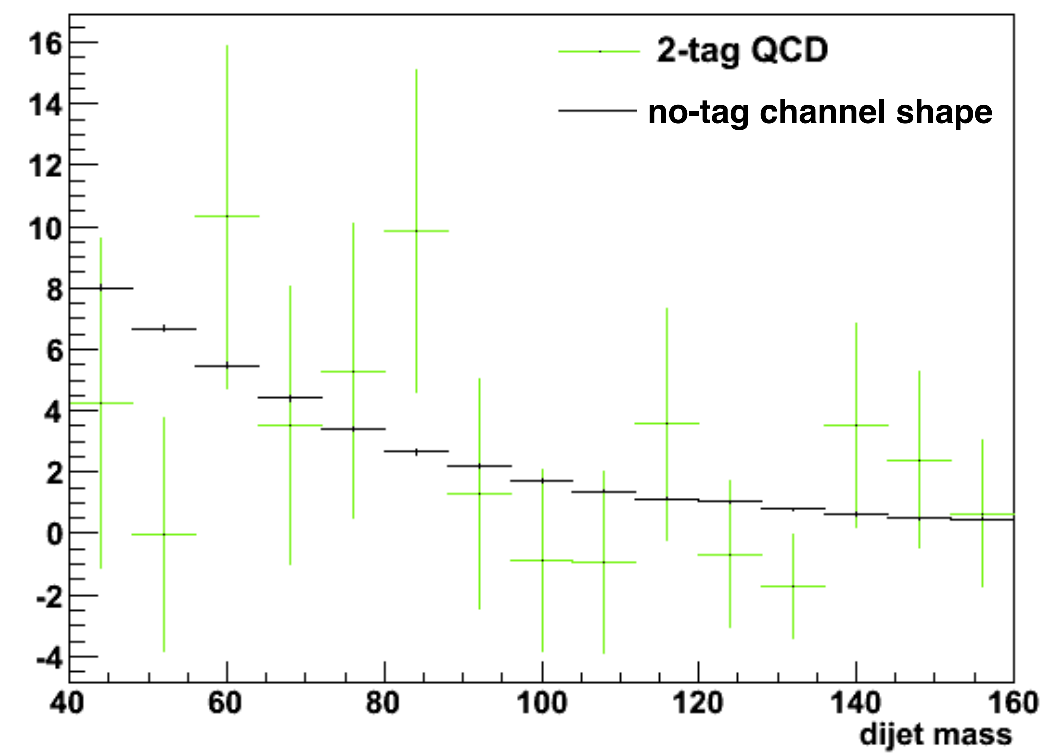
- Two nearly independent ways to detect neutrinos
  - MET: energy imbalance in calorimeter (use towers)
  - Track MET (trkMET): momentum imbalance in tracker (use tracks)
- Small for MET from neutrinos, large for MET from mis-measured jets (MJB)

Data driven Multi-jet background estimate

- There is an excess of data in the region Δφ(MET,track MET)>1 which we take to be from MJB.
- MJB = (data - MC) *dijet mass distribution* for events in this region.
- Scale up to account for events in the region Δφ(MET,track MET)<1.
  - **Correction factor = 1.66 ± 7%**
- Very few MJB events in the 2-tag channel; poor statistics

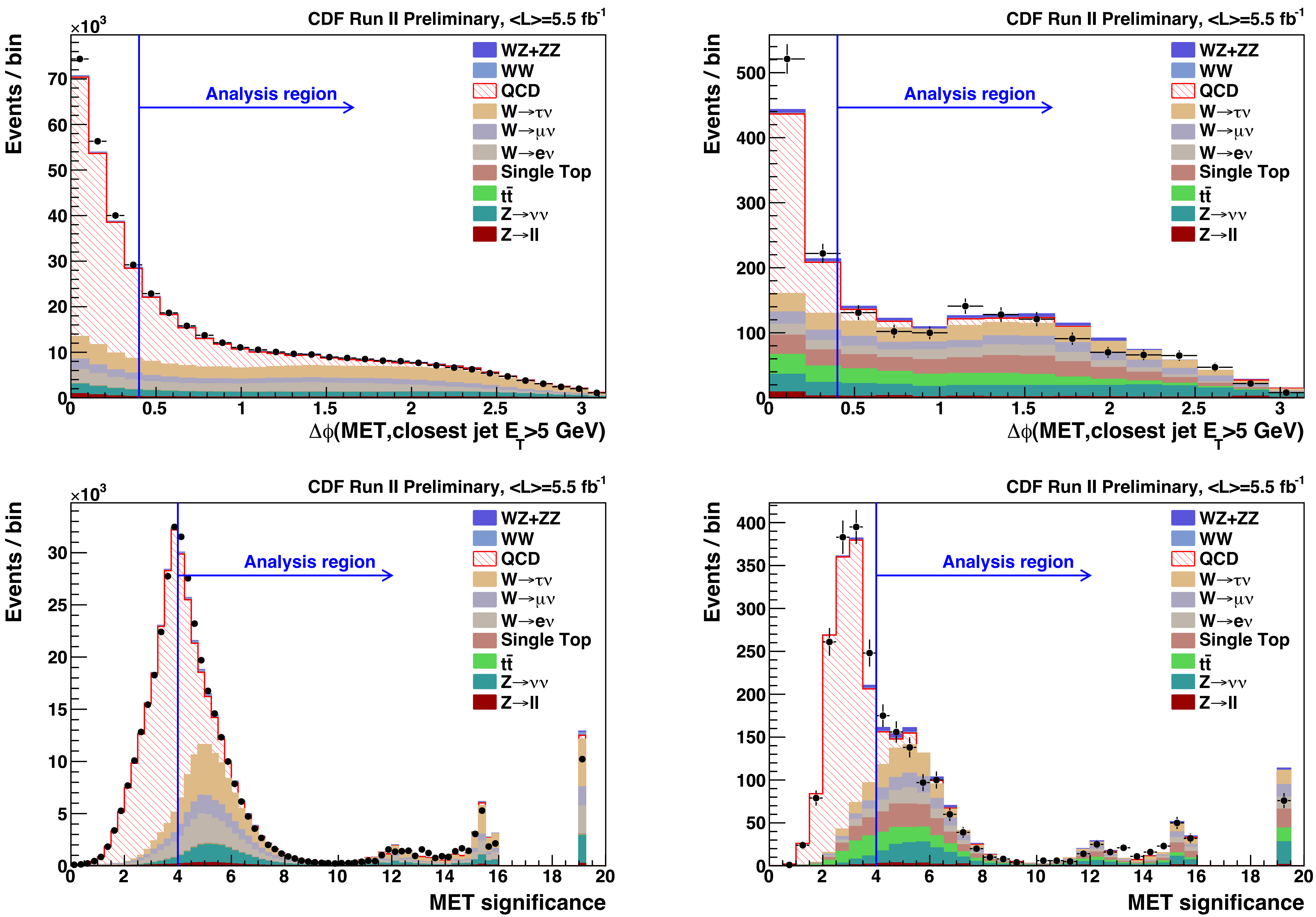
⇒ use shape from no-tag channel →





Checking Background Model: Key MJB plots

no-tag | two-tag



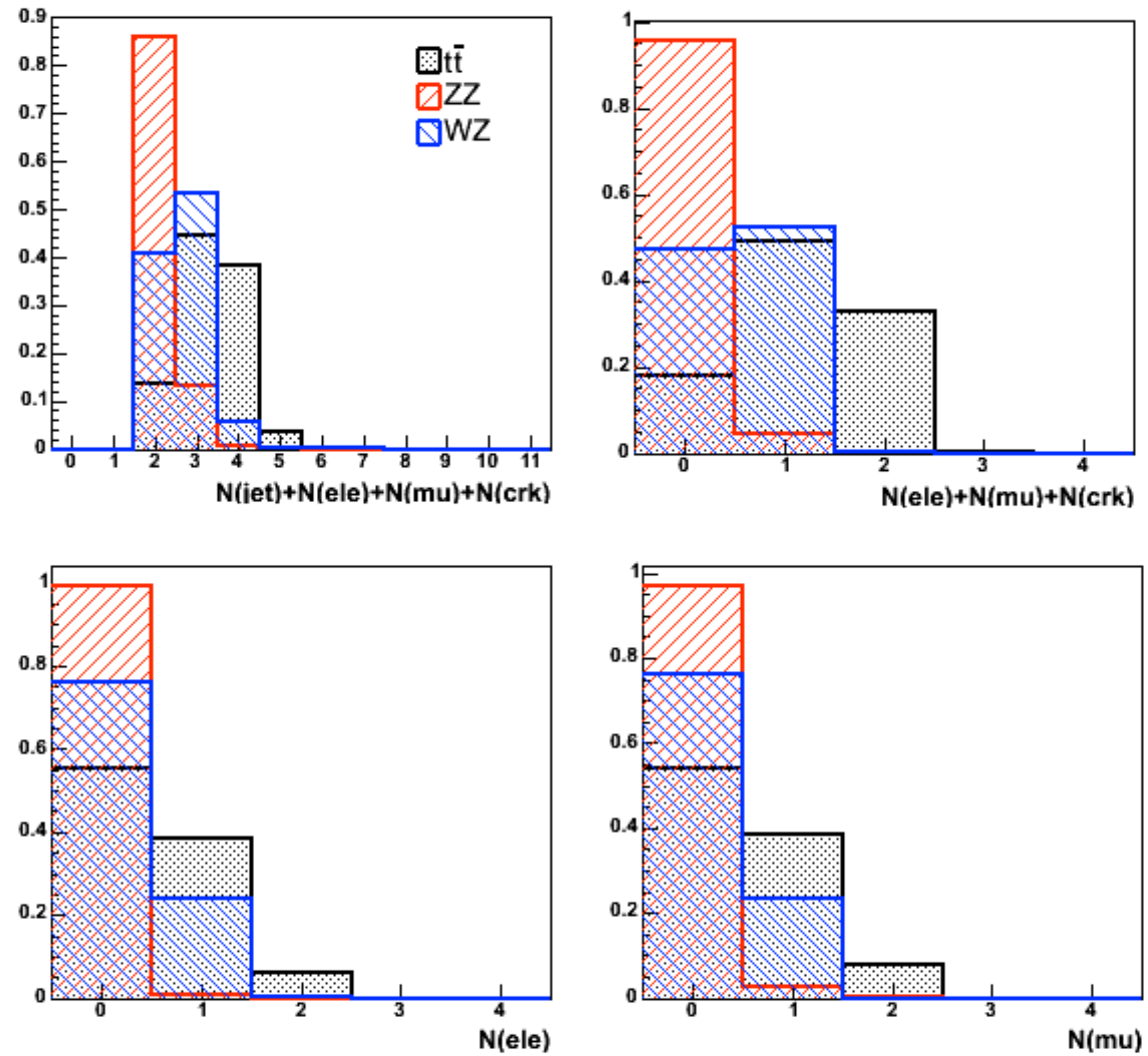
- Great agreement in no-tag & 2-tag regions; little MJB in 2-tag

t-tbar rejection cuts

- t-tbar a large background in 2-tag channel
- t-tbar should give more leptons and jets than signal
- Leptons may be misreconstructed as jets

- $N_{jet(Et>10\ GeV)} + N_{ele} + N_{mu} + N_{crk} < 4$
- $N_{ele} + N_{mu} + N_{crk} < 2$
- $N_{muon} < 2$
- $N_{electron} < 2$

- Odd looking combination of cuts, but it works quite well
    - A neural network offered no improvement



Full event selection

2 b-jets

- 2 or more central jets with $E_T > 20$ GeV
  - Sort jets by bness (instead of E_T)
  - Get dijet mass from 2 highest bness jets
- Jet 1 bness > 0.85, Jet 2 bness > 0.0
  - Or fail these cuts: no-tag channel

neutrinos

- Missing $E_T > 50$ GeV

define signal region

- 40 GeV < dijet mass < 160 GeV

Cuts to reduce:

ttbar

- $N_{jet(Et>10\ GeV)} + N_{ele} + N_{mu} + N_{crk} < 4$
- $N_{ele} + N_{mu} + N_{crk} < 2$
- $N_{ele} < 2$, $N_{muon} < 2$

Multi-jet background

- Missing E_T significance > 4
- $\Delta\phi$(Missing E_T, closest jet) > 0.4

Electroweak backgrounds

- **Model EWK background shape with Monte-Carlo**

Pythia Alpgen MadEvent+Pythia

- In W,Z+jets, can get b's from gluon splitting
- No lepton requirement
- Missing $E_T > 50$ GeV makes events with a neutrino the dominant EWK backgrounds

- Z+jets
  - $Z \rightarrow ee$, $Z \rightarrow \mu\mu$, $Z \rightarrow \tau\tau$
  - $Z \rightarrow \nu\nu$
- W+jets
  - $W \rightarrow e\nu$
  - $W \rightarrow \mu\nu$
  - $W \rightarrow \tau\nu$
- ttbar
- single top

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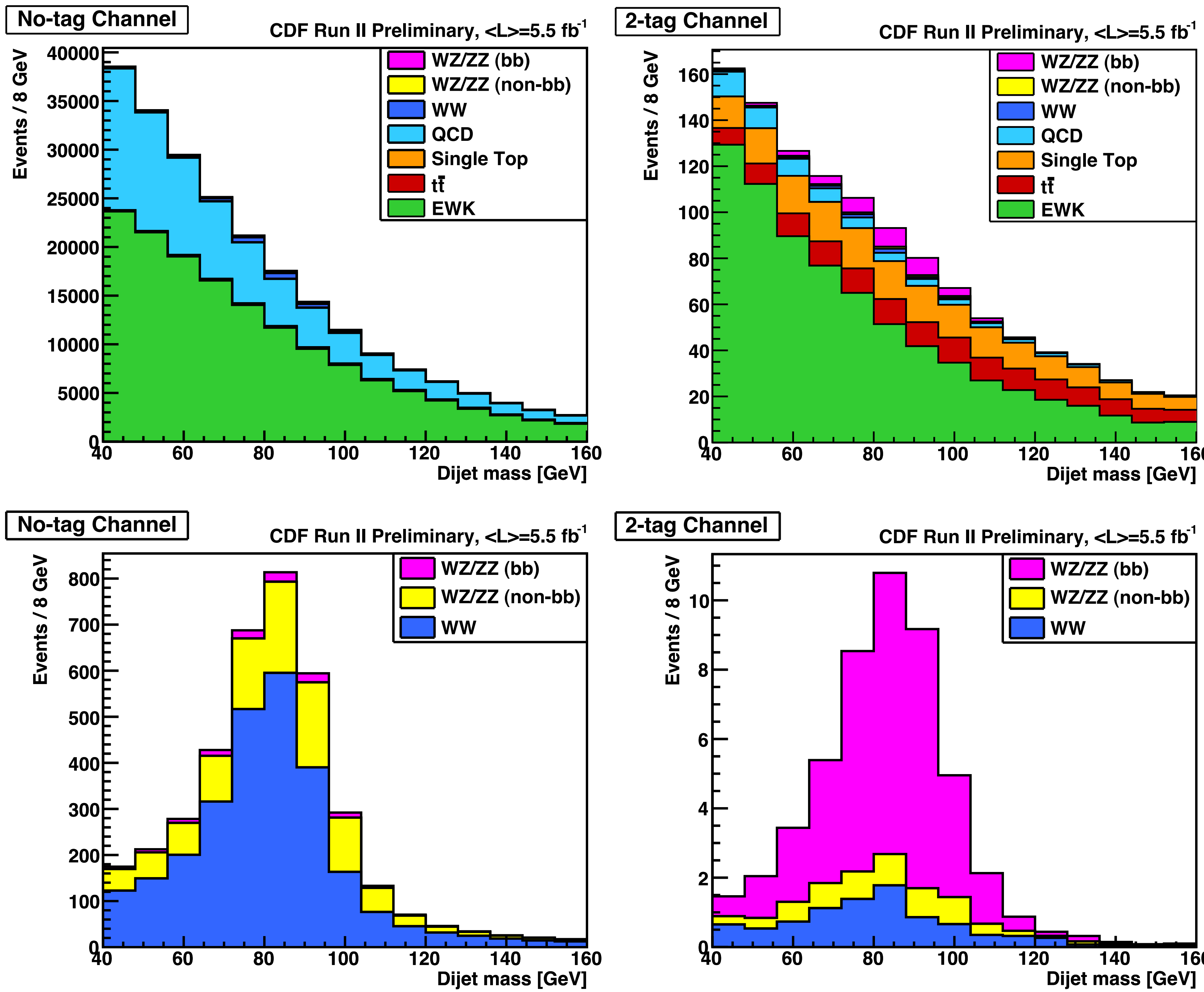
The Fitter: Channels

- Fit the dijet mass distribution in data using templates for the signal and backgrounds
- Also allow backgrounds to vary in the fit
- Simultaneous fit in 2 channels:
    - Two-tag channel: Events with 2 b-tags
    - No-tag channel: Events without 2 b-tags

Just the dibosons →



b-tagging indeed reduces WW

The Fitter: Channels

- Fit in both channels simultaneously:
  - Signal (WZ+ZZ)
  - WW
  - Single top + t-tbar
- Allow to float separately in the two channels:
  - EWK (W,Z+jets): don't trust the modeling of the b-quark content
  - MJB: don't know the b-quark content
- Constrain the backgrounds based on their cross sections, but
- Let EWK float in the fit unconstrained (don't trust the overall normalization)
- Let signal float unconstrained; we're measuring it!

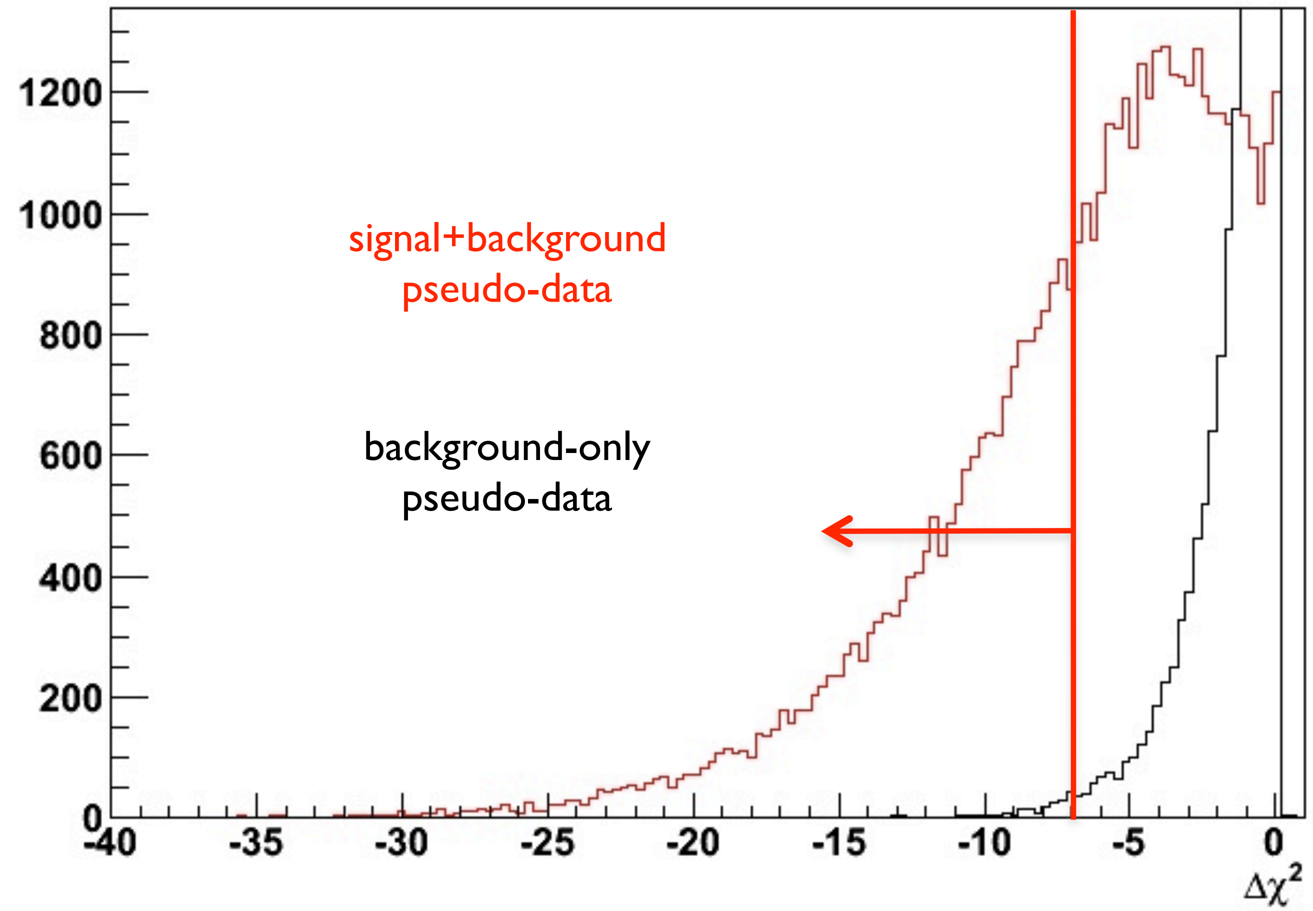
- Systematics go into the fitter:
  - B-tagging uncertainty (already explained)
  - Jet energy scale uncertainty
  - EWK shape uncertainty
  - MJB shape uncertainty

} will explain soon

The Fitter: Sensitivity

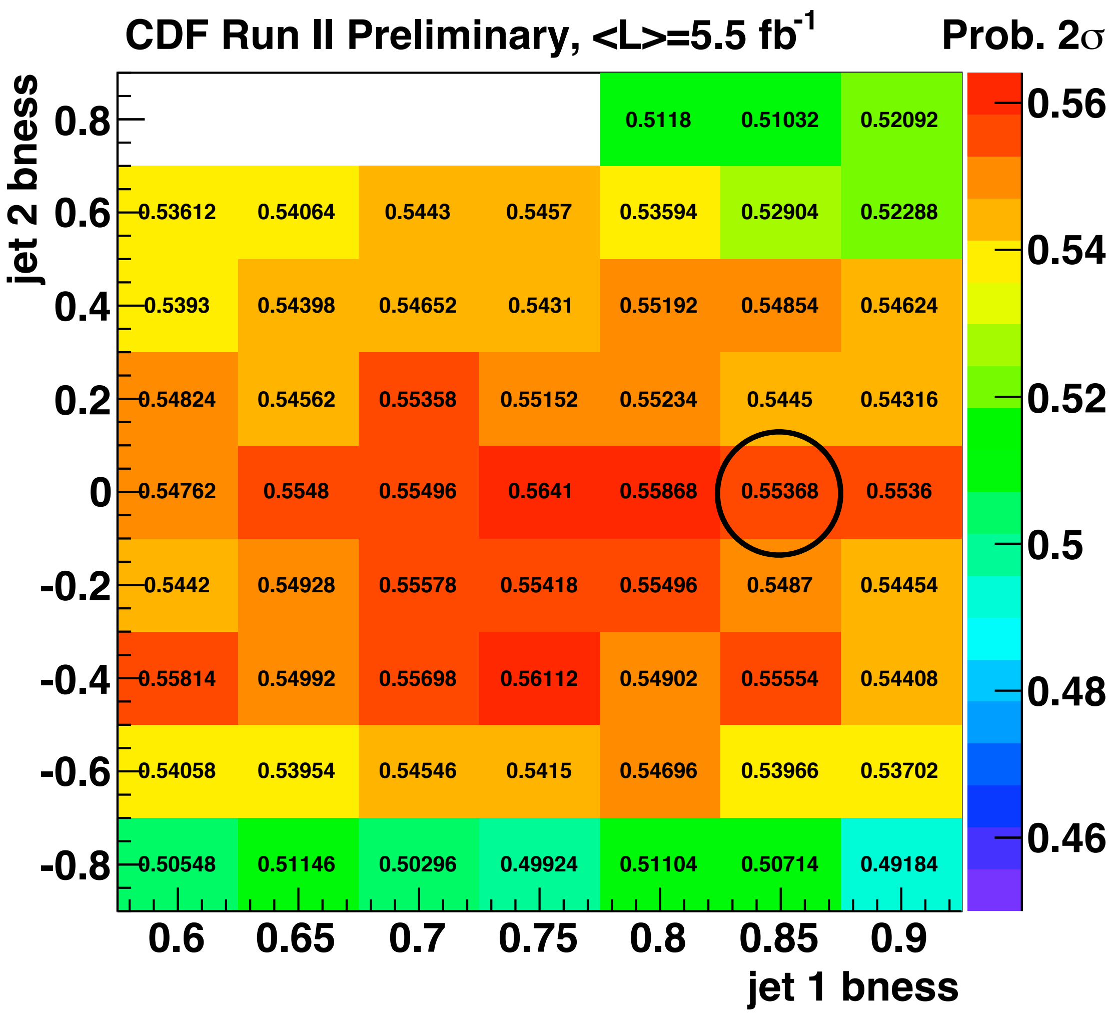
- To optimize the analysis, need an *a priori* estimate of the measurement's sensitivity
- Run many pseudo-experiments and calculate $\Delta\chi^2 = \chi^2_{\mathrm{S+B}} - \chi^2_{\mathrm{B}}$ for pseudo-data generated
  - with signal+background hypothesis, and
  - with background-only hypothesis.
- Obtain the probability of a 3-sigma measurement:
  - Find the $\Delta\chi^2$ where only ~0.3% of background-only PEs lie below
  - Prob 3-sigma = fraction of S+B PEs below this.

Example:



The Fitter: Optimization

- We can now optimize the cuts, specifically: bness
- Scan over jet bness cuts in MC,
- Get the probability of 2 sigma for each set of cuts
  (more accurate than 3 sigma for a given number of PEs)
- Choose Jet 1 bness > 0.85, Jet 2 bness > 0.0



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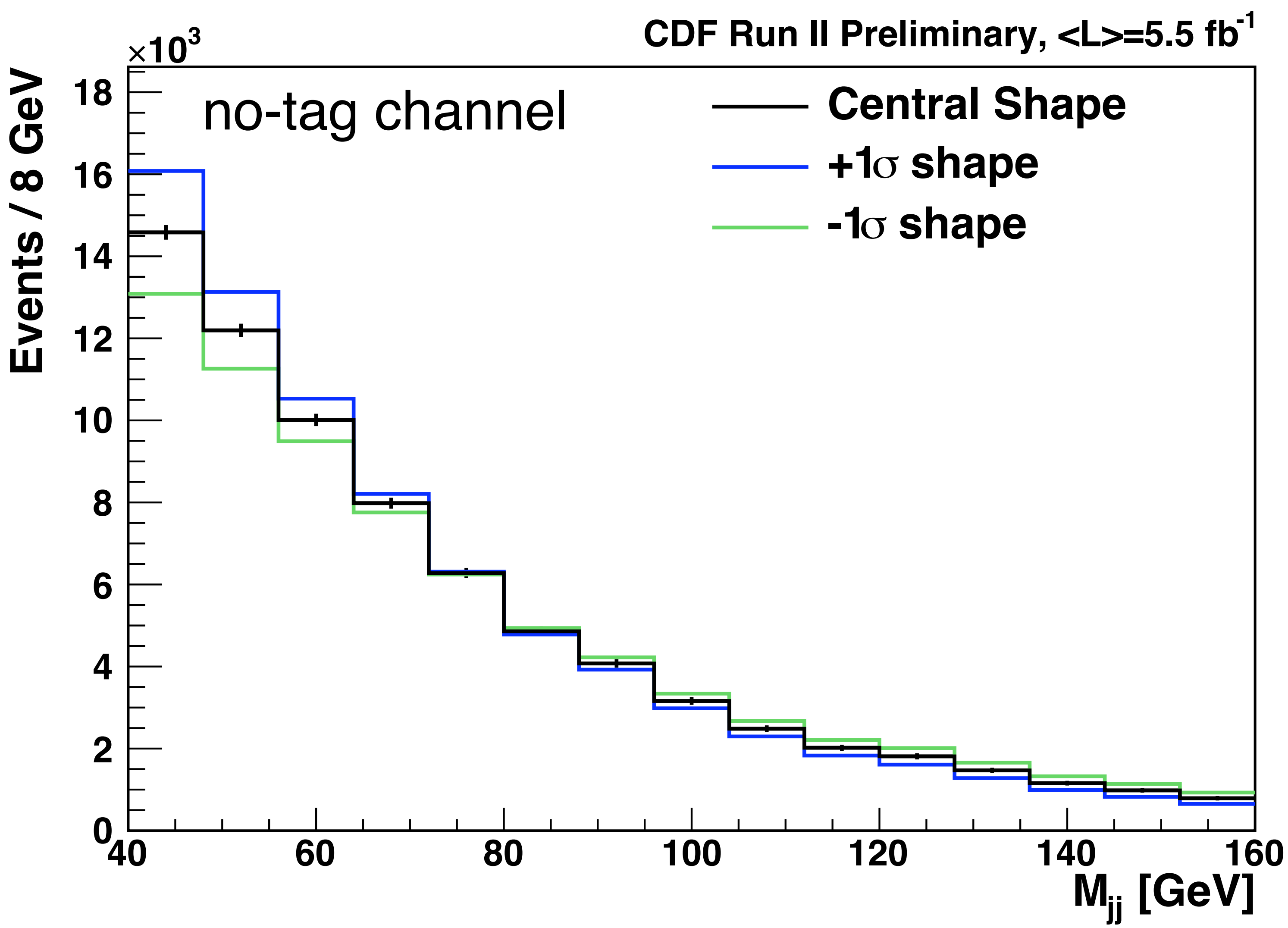
MJB shape uncertainty

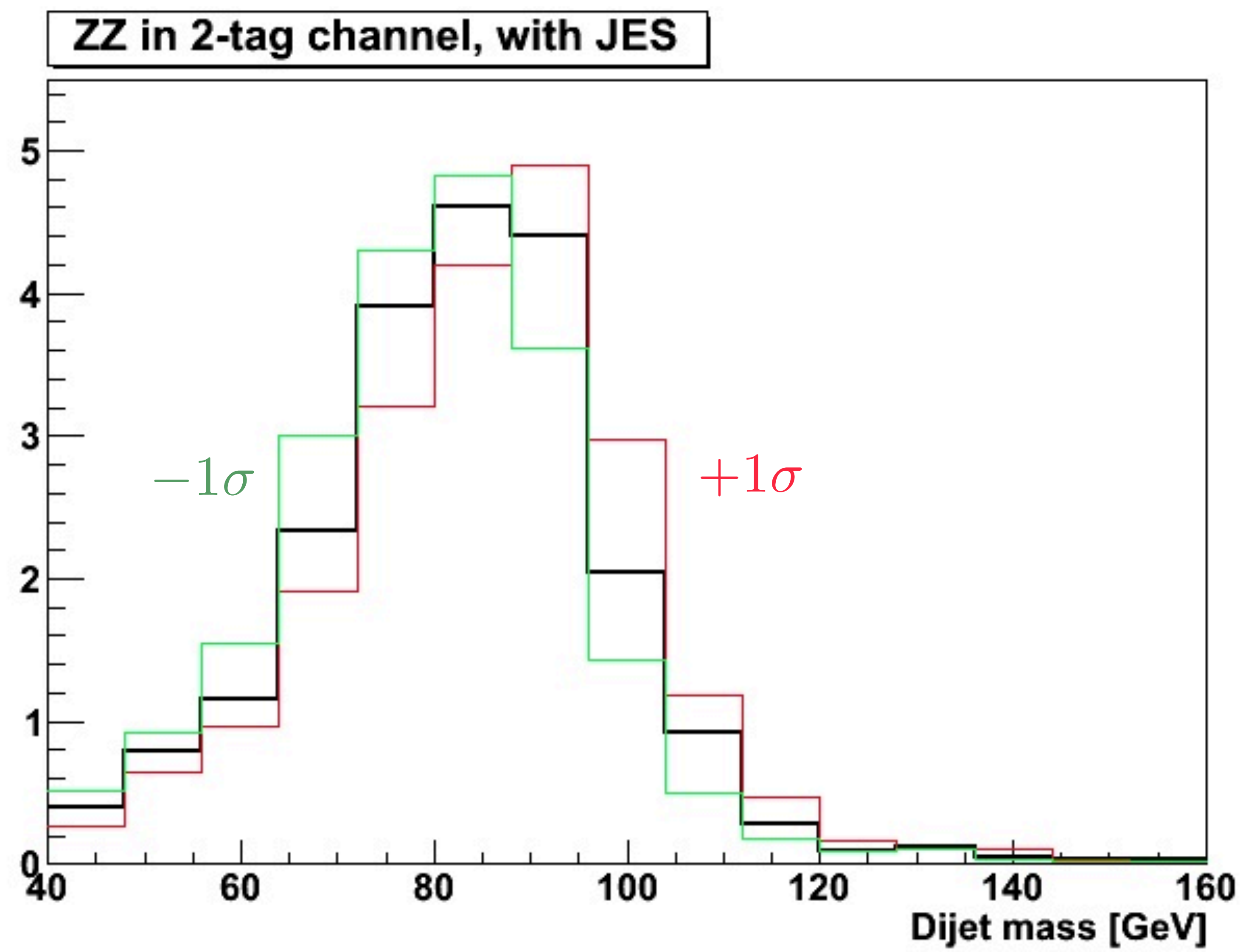
- Need some way of assessing the uncertainty on the MJB estimate
- Look just outside the signal region (3 < MET-significance < 4, whereas the cut is at MET-sig > 4)
- Obtain shape uncertainty by comparing M_{jj} in two different regions:

  $\Delta\varphi$(MET,track MET) > 1 (MJB enhanced region)
  $\Delta\varphi$(MET,track MET) < 1 (EWK dominated region)



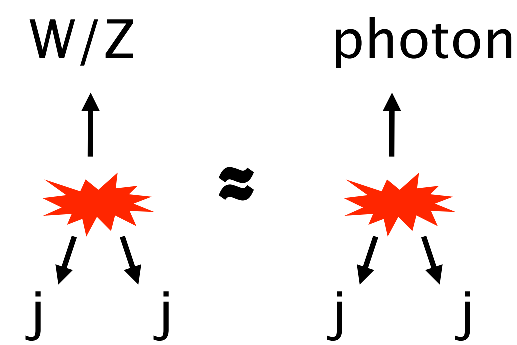
Jet Energy Scale Systematic

- Vary the jet energies according to their uncertainties
- Dijet mass peak in WZ/ZZ and WW will shift



EWK uncertainty via photon+jets

- We use photon+jets data to assess the systematic uncertainty on our W/Z+jets background from Monte-Carlo.
- Idea is that jet kinematics in photon+jets events should be similar to jet kinematics in events with other gauge bosons (W,Z)
  - Z, gamma have same interactions; W slightly different

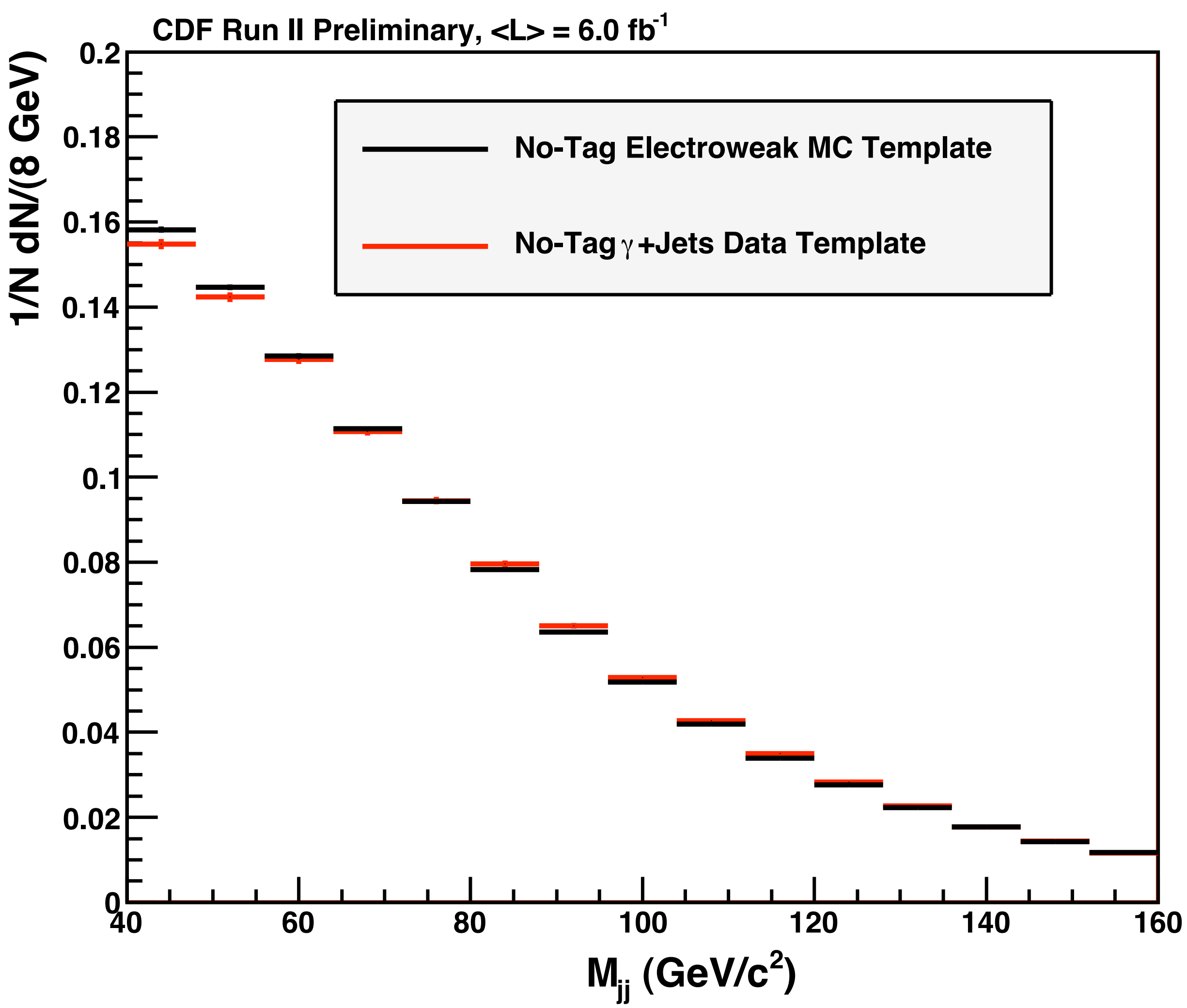


  - Some cuts modified: MET > 50 GeV → MET+photon > 50 GeV

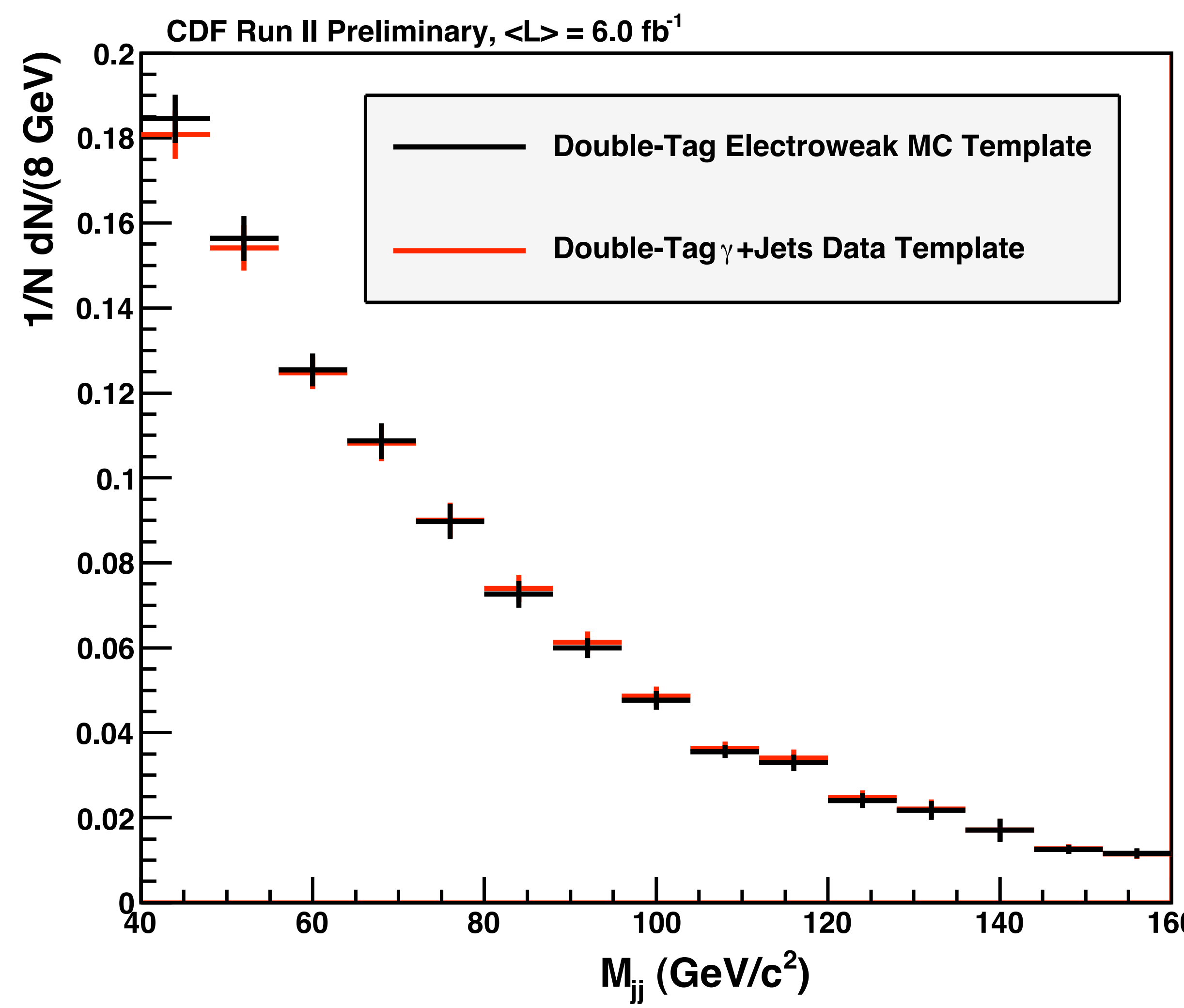
- As photon+jets and W/Z+jets aren't identical (photon is massless), we need a correction
  - Weight photon+jets data by the ratio of the dijet mass distribution of our W/Z+jets MC to photon+jets MC
  - This should compensate for the physical differences, in a MC independent fashion
  - MC uncertainties- PDFs, radiation, etc. - should cancel out in the ratio

EWK MC compared to pho+jets

no-tag

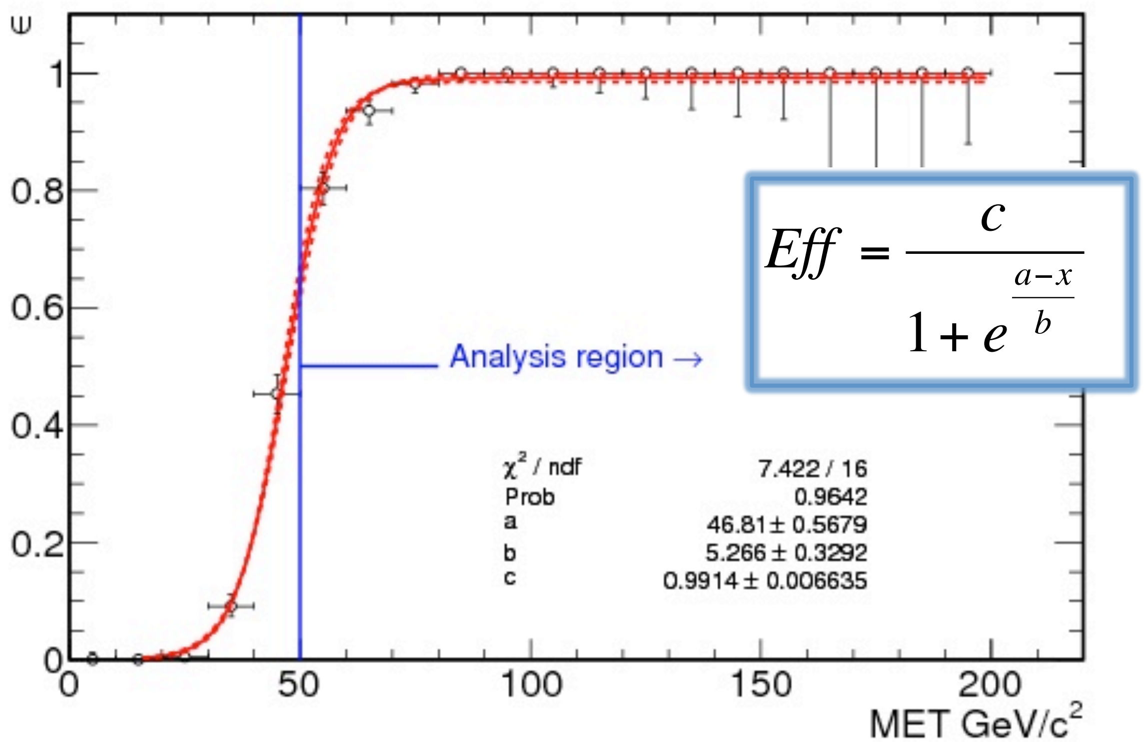


two-tag

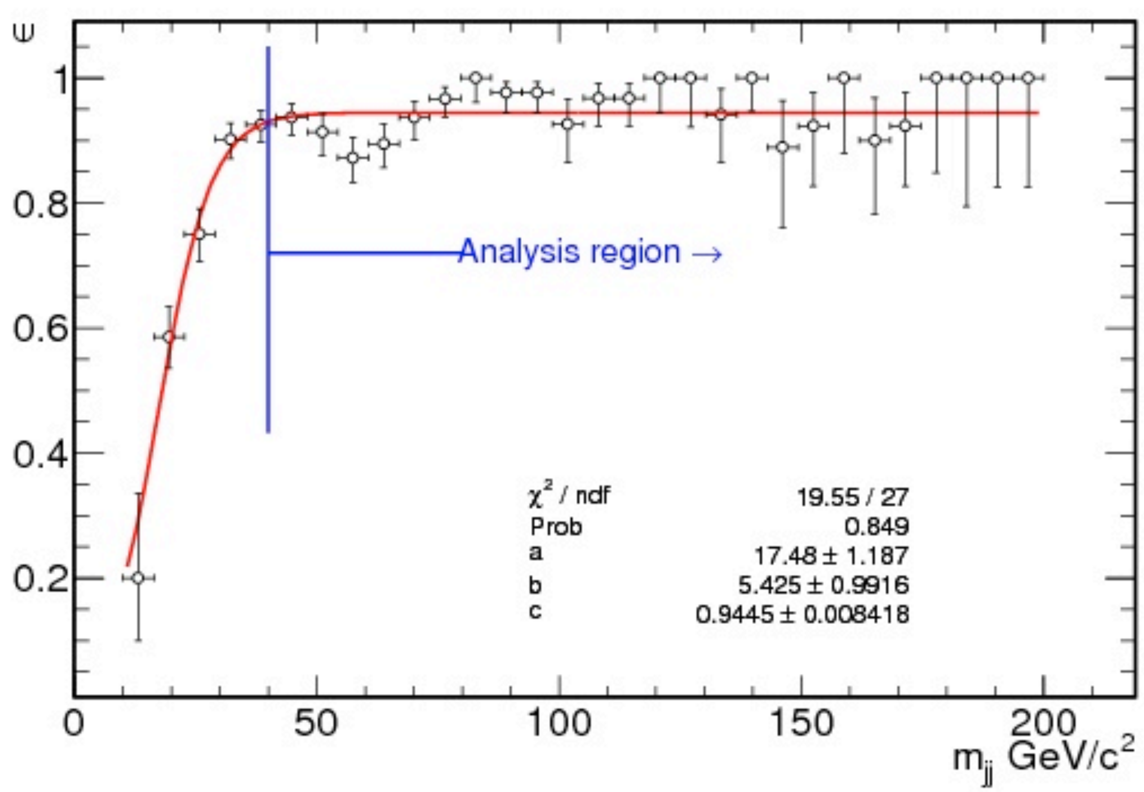


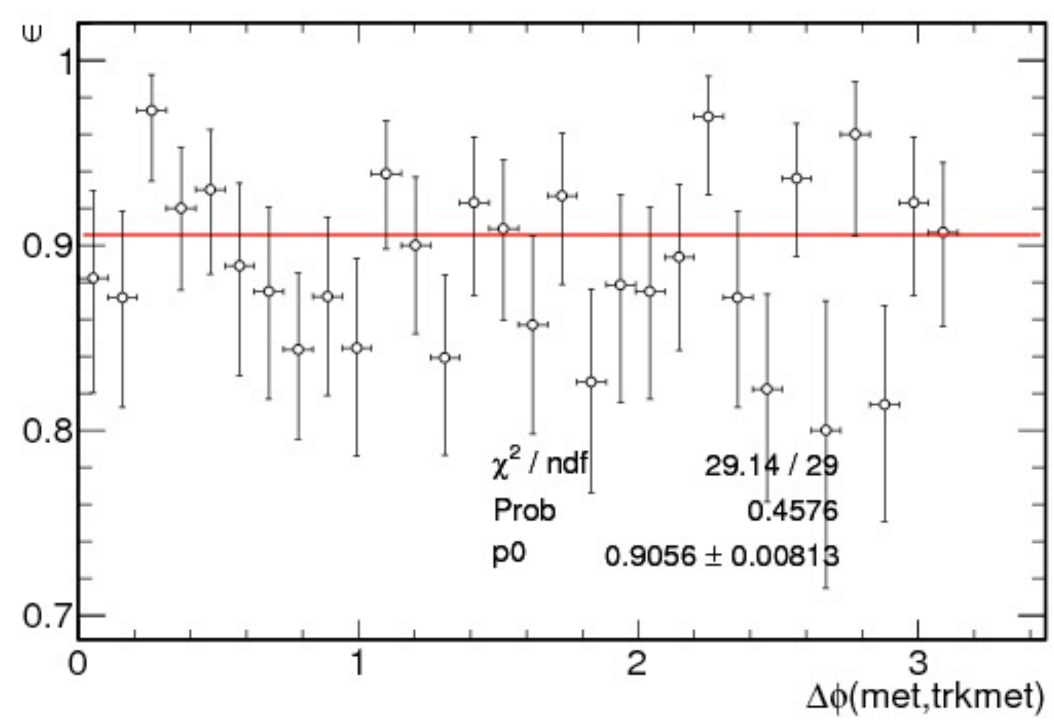
- Excellent agreement
  - but still quantify the difference as a systematic

Trigger efficiency & Luminosity



- Use a combination of MET triggers to get the most data
- MET trigger efficiency: 93.9±0.3%
- 5.5 fb^{-1} of data becomes effectively 5.2 fb^{-1}
  - Cross checked using $Z\to\mu\mu$
- Mjj and Δϕ(MET,track MET) are not sculpted





No sculpting - no effect on QCD

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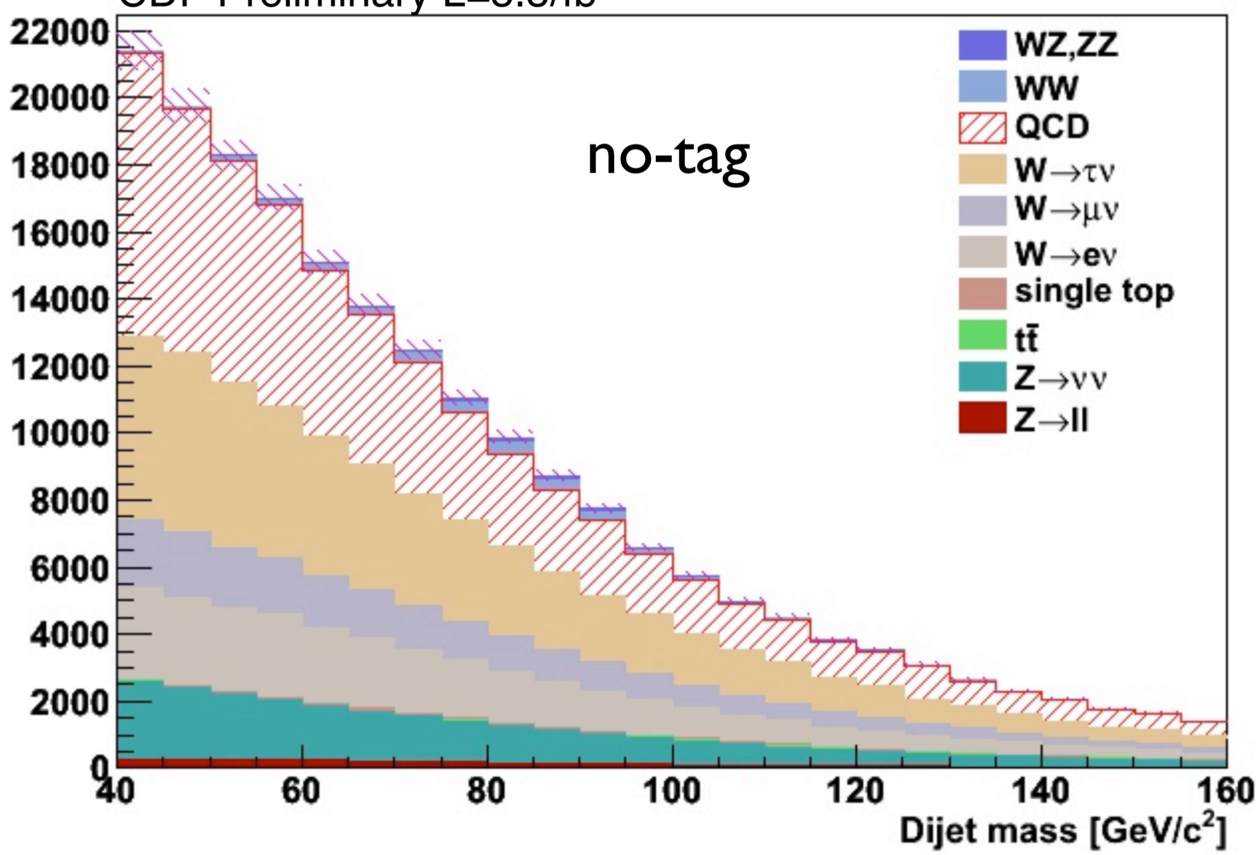
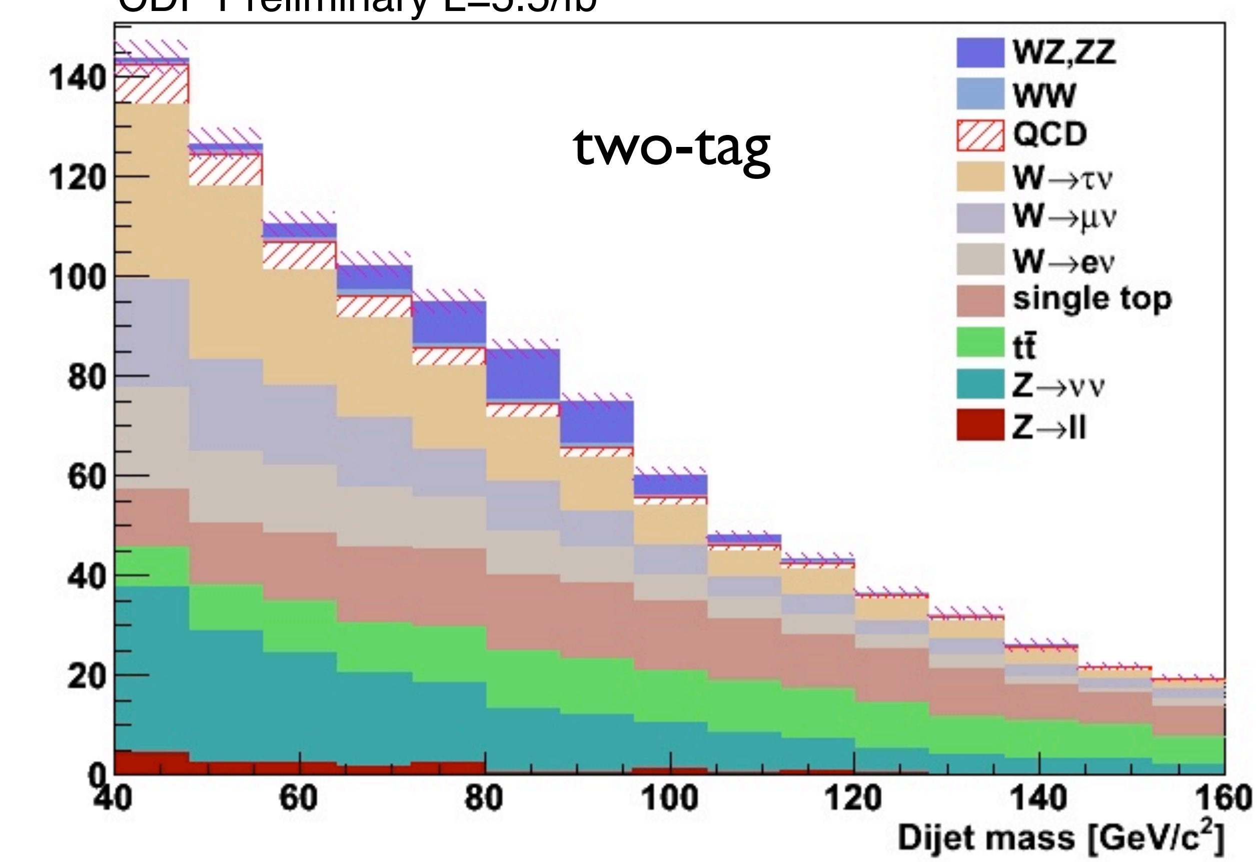
Signal Region Predictions





Sample Description	No-tag channel	Two-tag channel
Z→ee	13.5	0.3
Z→$\mu\mu$	1108.1	9.0
Z→$\tau\tau$	2538.2	12.1
Z→$\nu\nu$	25097.4	204.0
W→eν	34889.1	128.6
W→$\mu\nu$	24299.4	143.4
W→$\tau\nu$	61885.9	216.9
$t\bar{t}$	495.2	154.8
single top	1337.4	200.0
WW	2679.8	6.8
WZ	814.9	23.8
WZ (bb)	58.0	20.6
ZZ	332.3	21.2
ZZ (bb)	50.2	19.6
WZ+ZZ	1147.1	45.0
WZ+ZZ (bb)	108.2	40.2
Non-QCD background	154343.8	1075.8
QCD estimate	73853.5	58.4

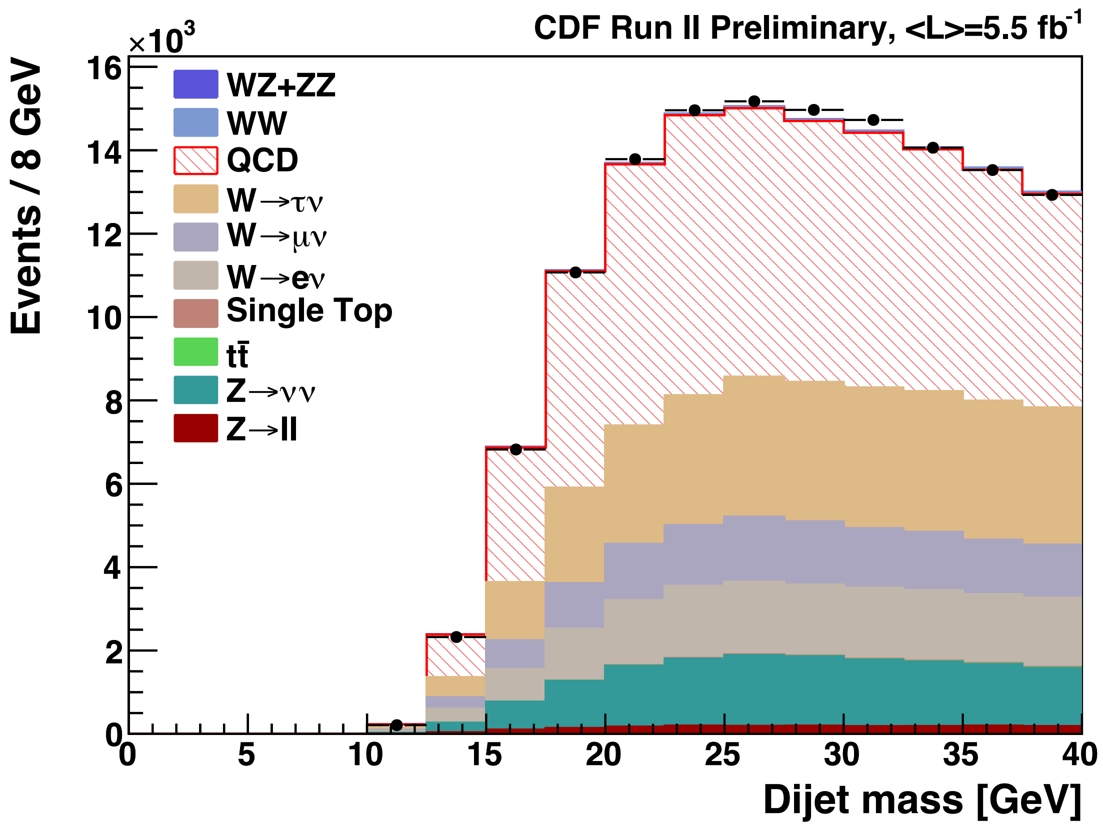
Table 8: Expected contribution of different processes, for 5.5 fb^{-1}.

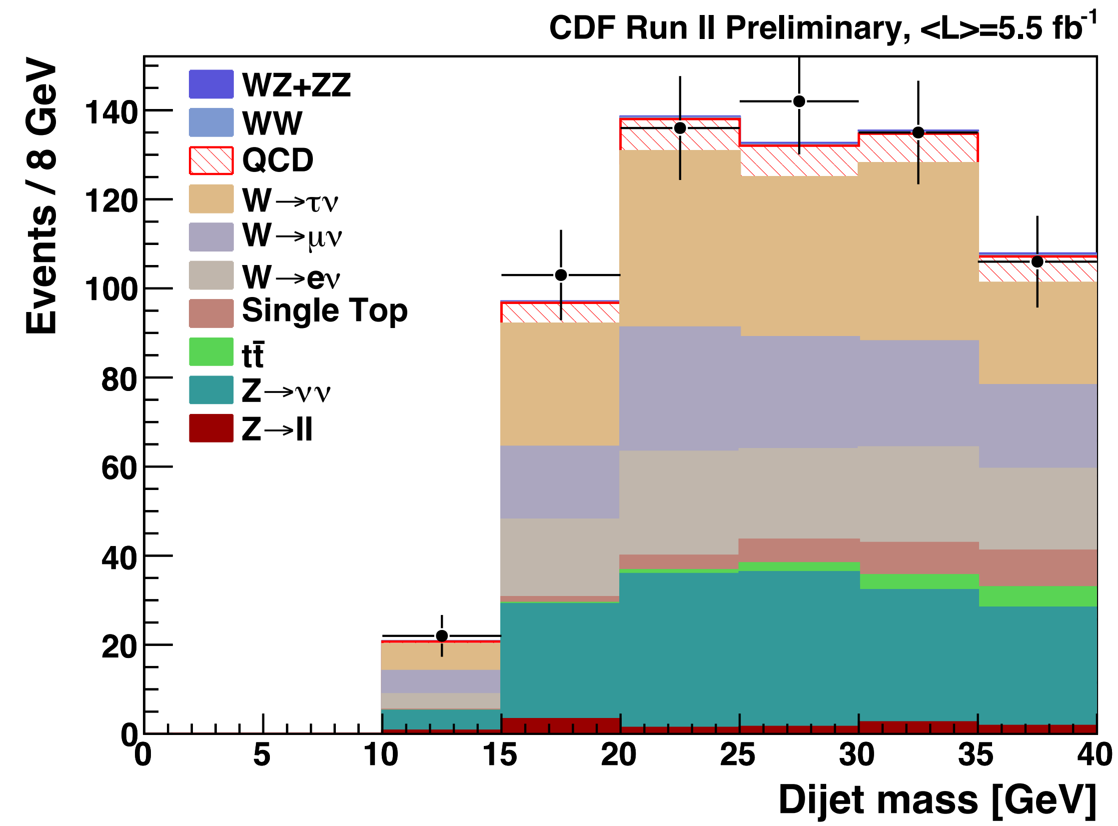
QCD tamed even in no-tag channel;
W+jets the largest background

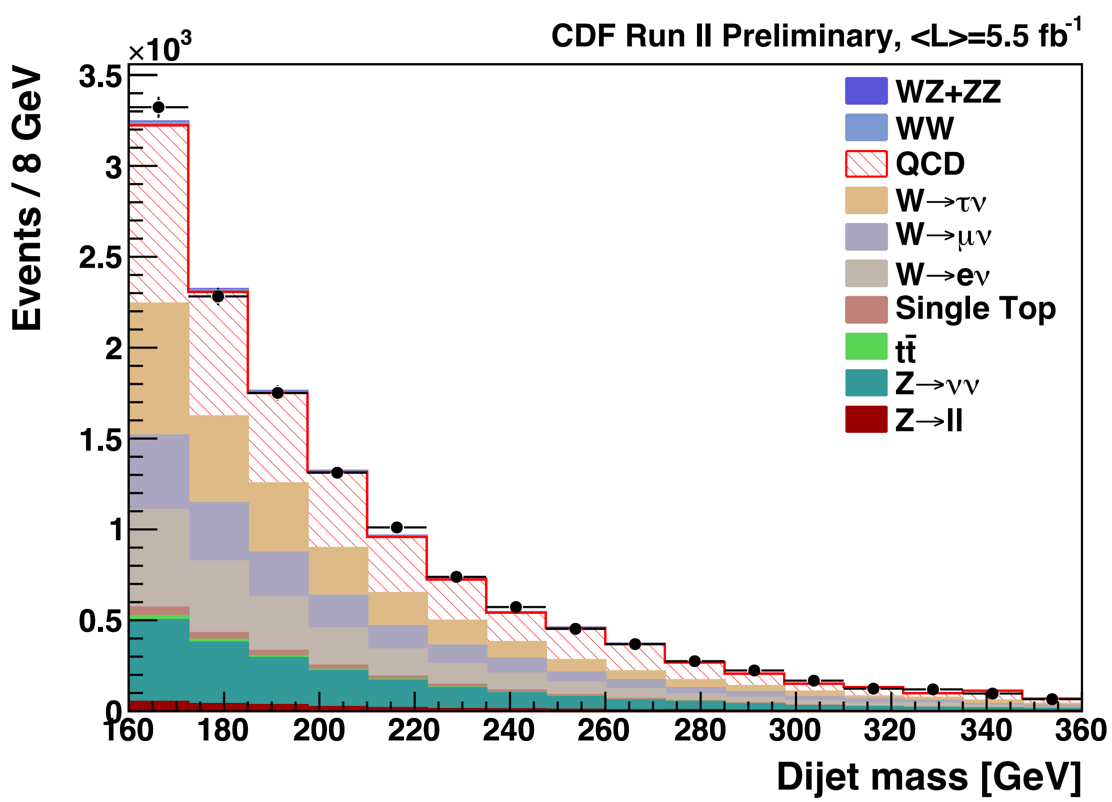
Control regions (Signal region blinded)

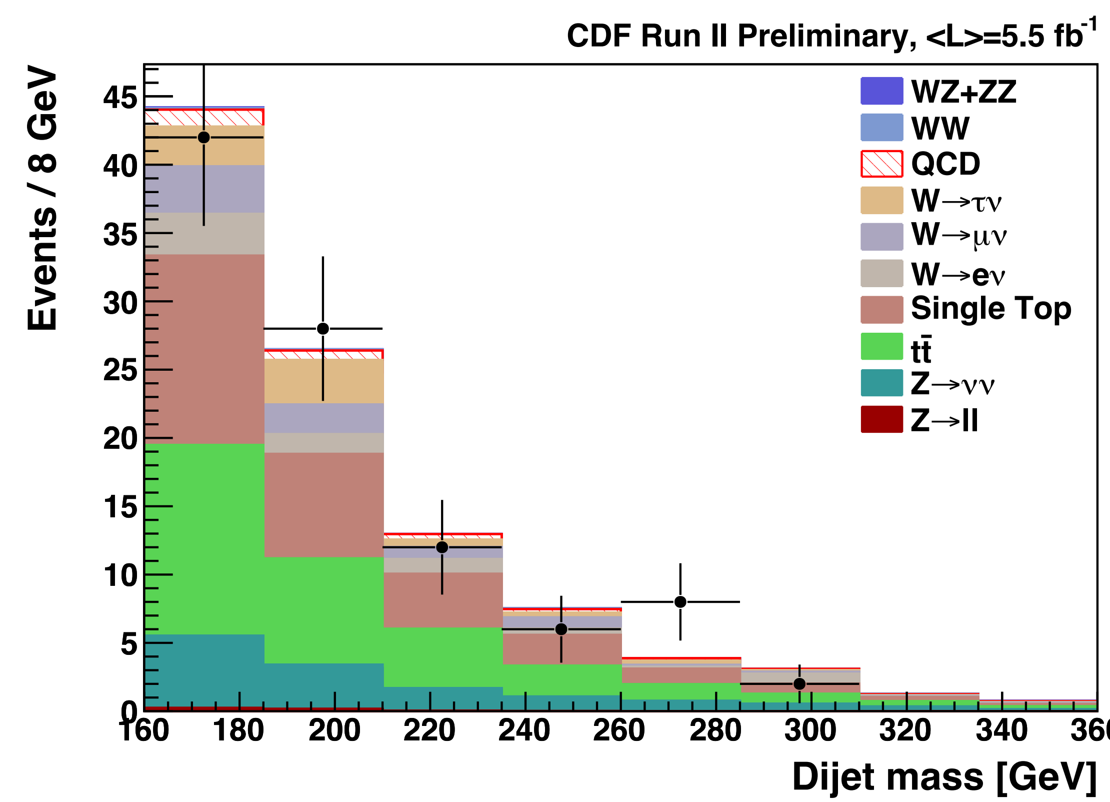
no-tag

two-tag



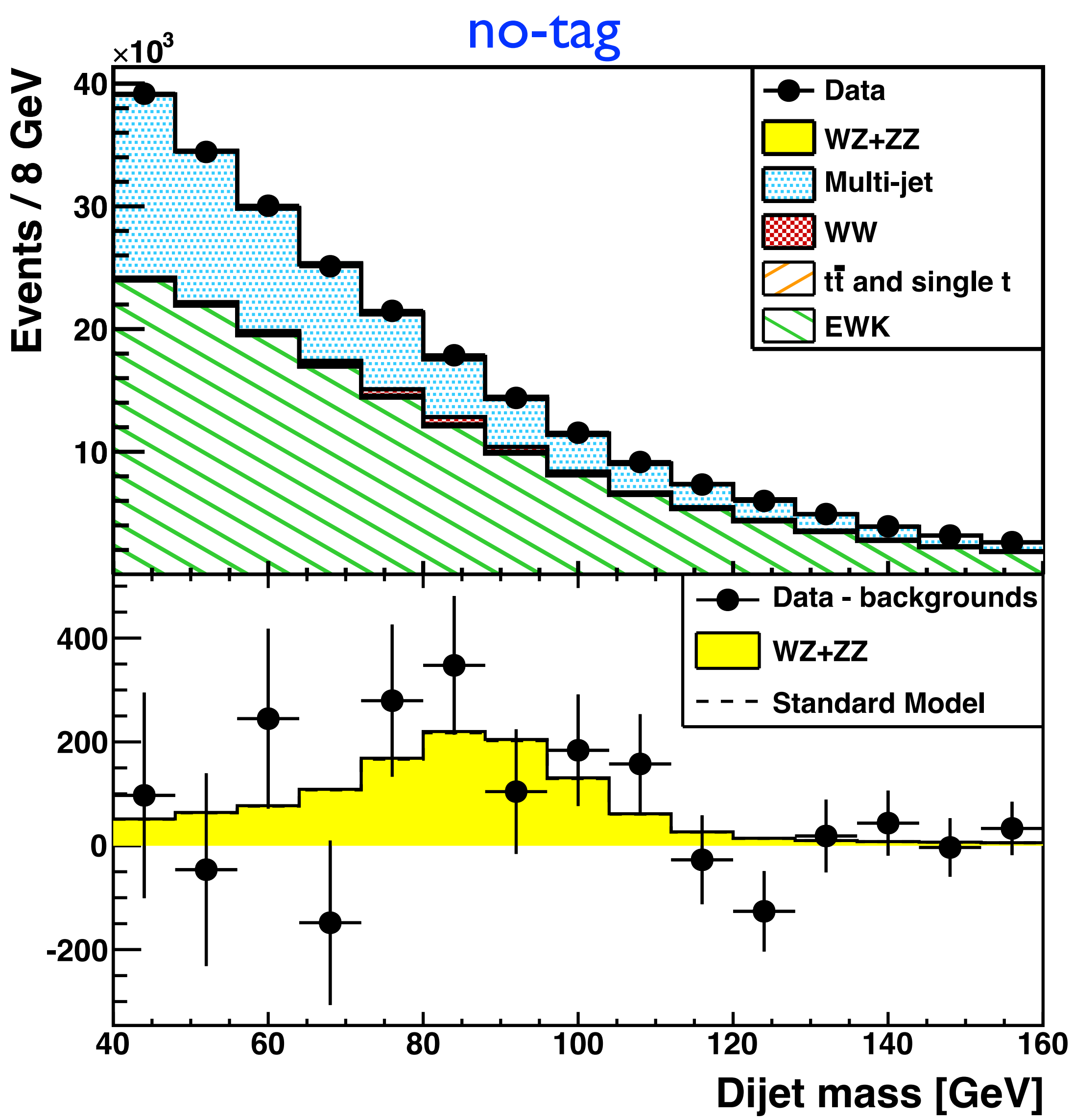


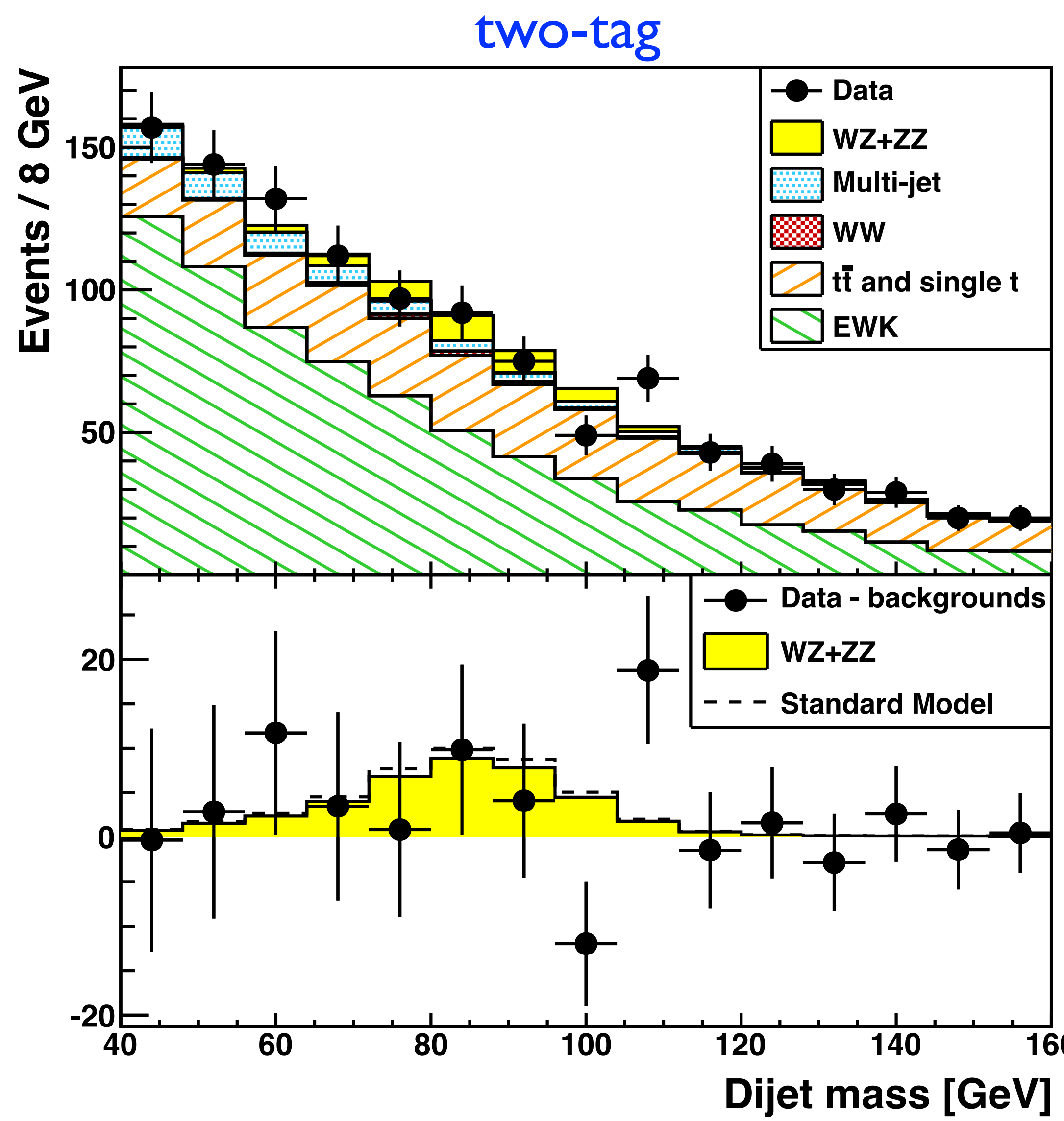




Good agreement between data and MC

Fit results: double fit for WZ/ZZ





CDF Run II Preliminary, $\int L = 5.5\ \text{fb}^{-1}$

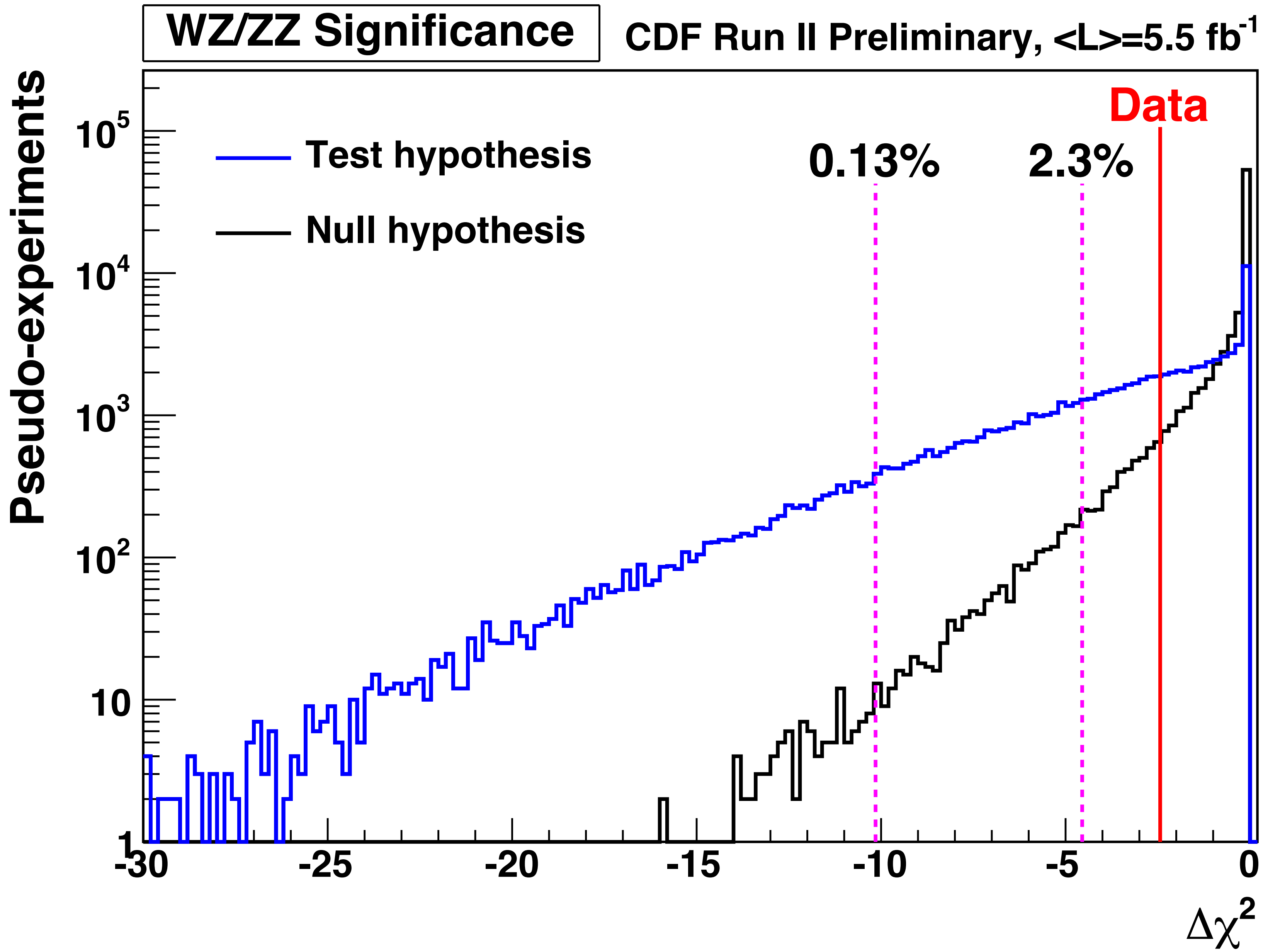
Process(es)	Fit # events (no-tag)	Fit # events (2-tag)
EWK	153312	694.4
$t\bar{t}$	517.3	129.3
single top	1184.4	183.2
QCD	72342.6	54.6
WW	2721.6	8.3
WZ/ZZ	1156.3	39.9

$$\sigma = 0.99\sigma_{\rm SM}$$

$$\sigma_{SM} = \sigma_{WZ} + \sigma_{ZZ} = 5.08\,pb$$

$$\sigma = 5.0^{+3.6}_{-2.5}\ \text{pb}$$

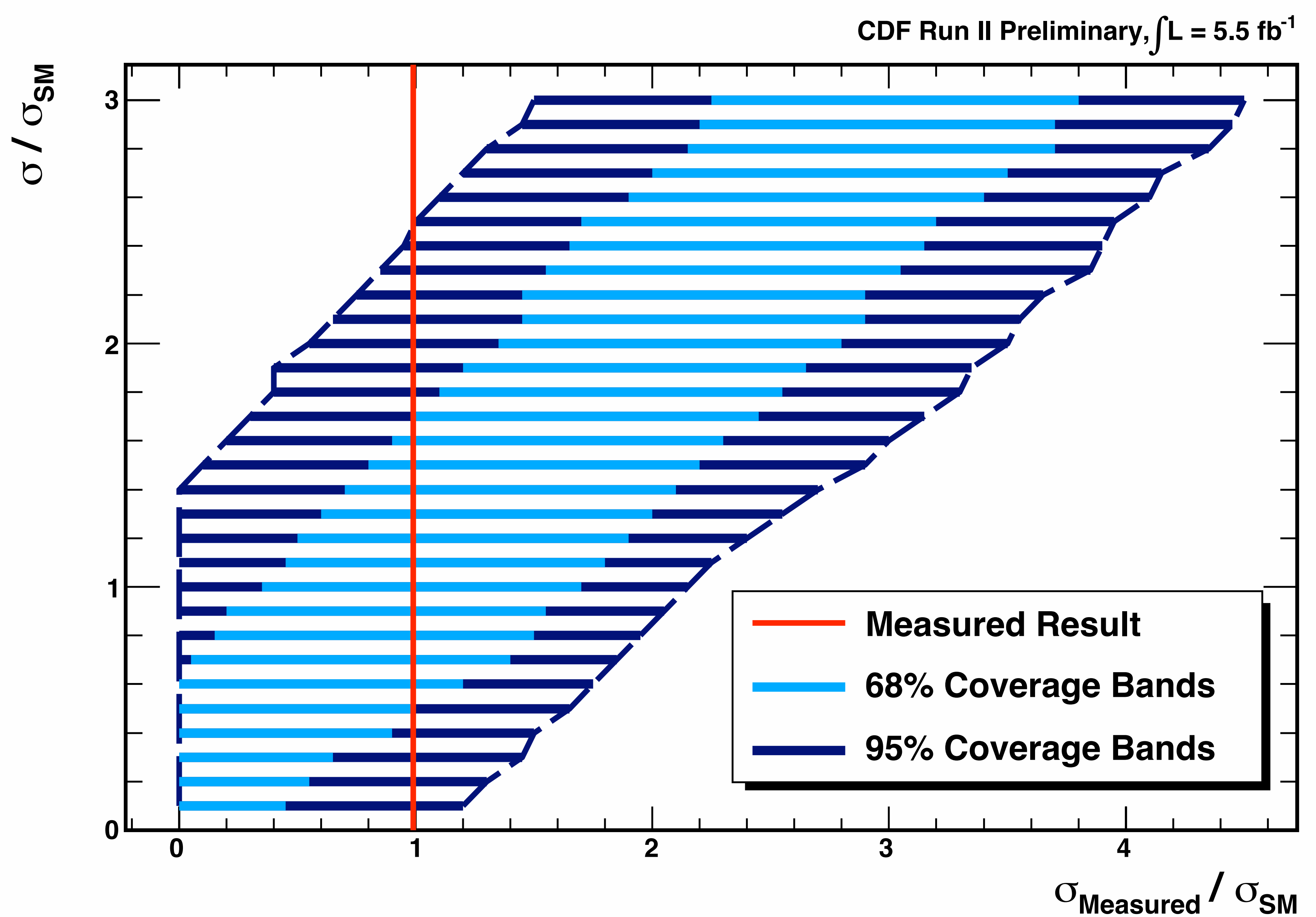
Significance of double fit for WZ/ZZ



- Significance of ~1.5σ

Cross section limit for double fit for WZ/ZZ

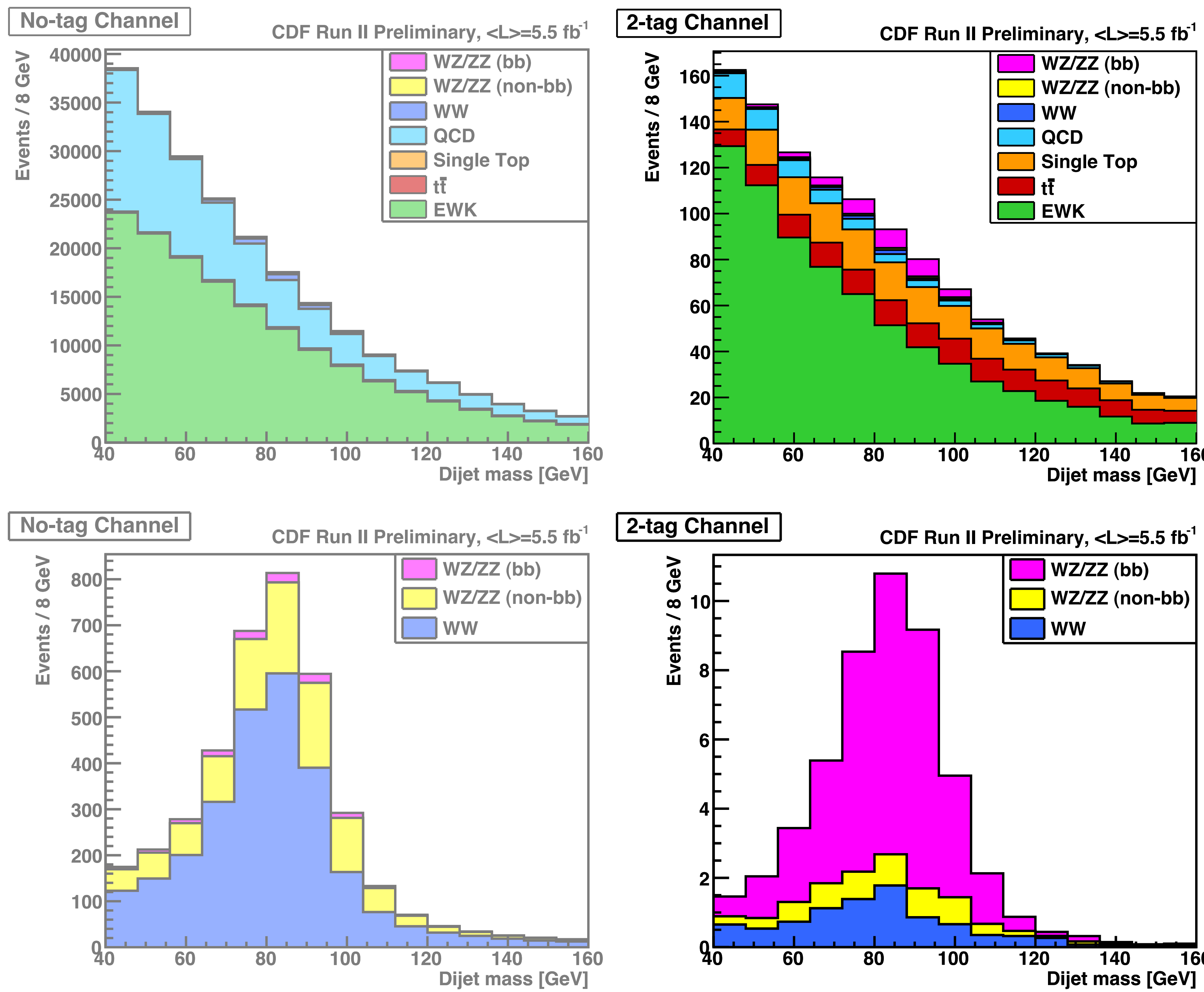
- Use a modified Feldman-Cousins method for determining an upper limit on the cross section
- Perform pseudo-experiments with signal scaled from 0 to 3 times the SM



Measured limit: $\sigma < 2.5\sigma_{SM}$ at 95% CL

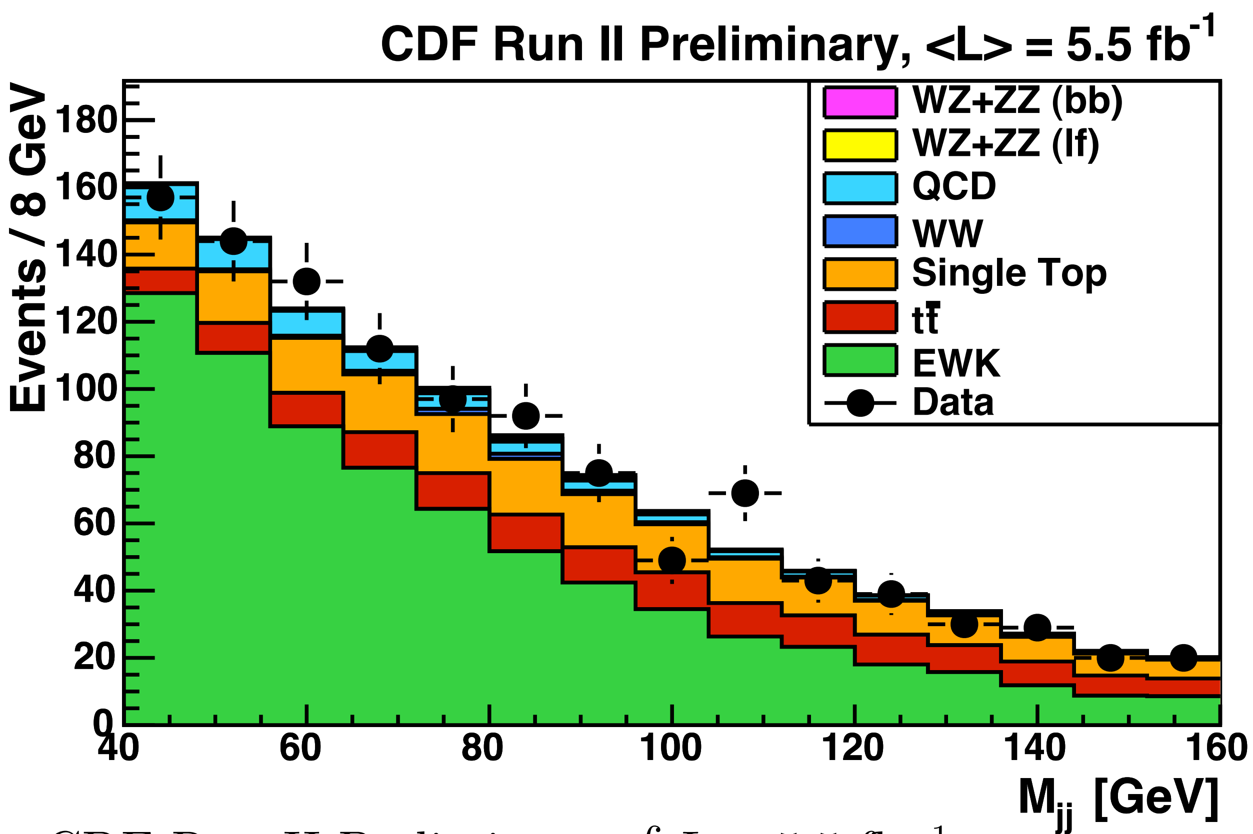
Bonus: WZ+ZZ to MET + bb

- Can also try to measure WZ/ZZ to bb
  - One step closer to WH/ZH to MET + bb
- Fit to only the two-tag channel
- Break WZ/ZZ template into bb (signal) and non-bb (background) templates



Fit results: single fit for WZ/ZZ→MET+bb

two-tag

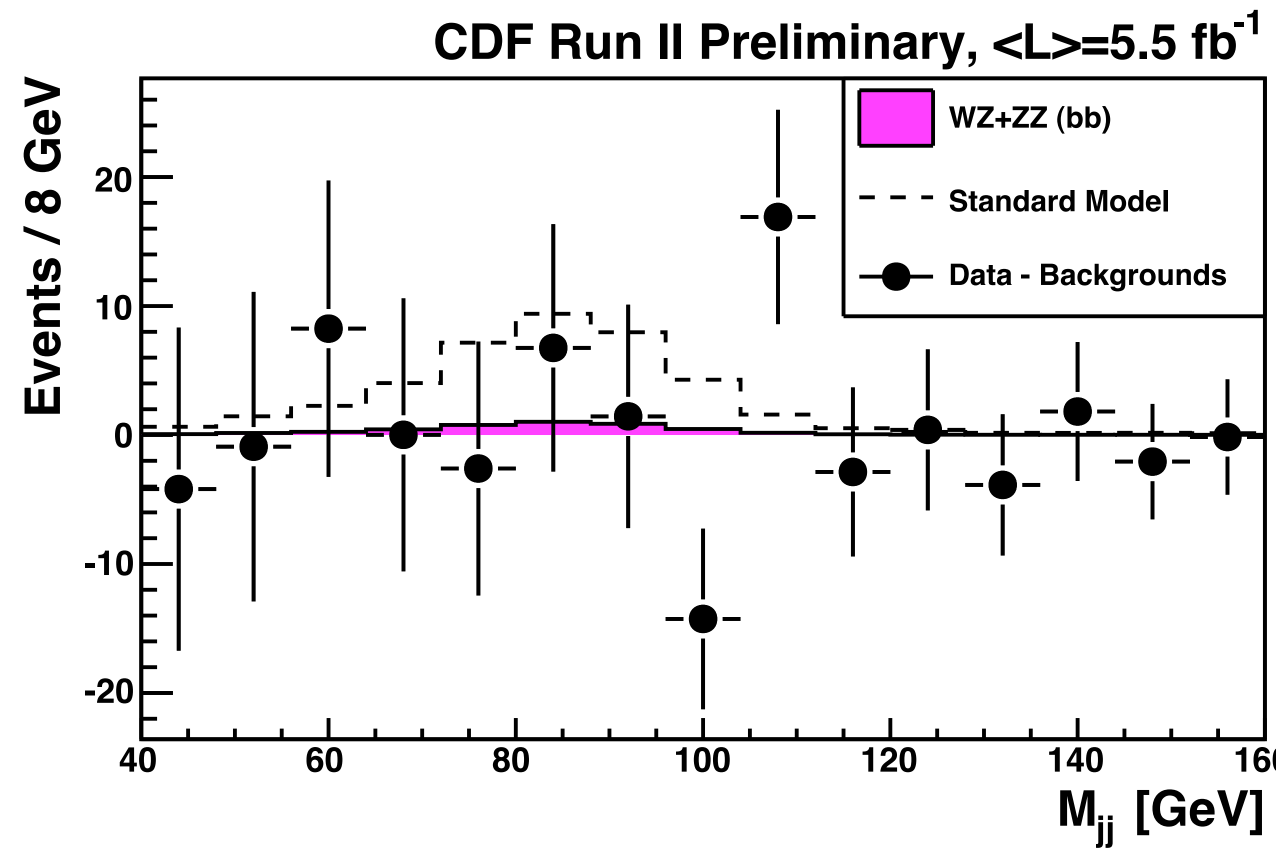


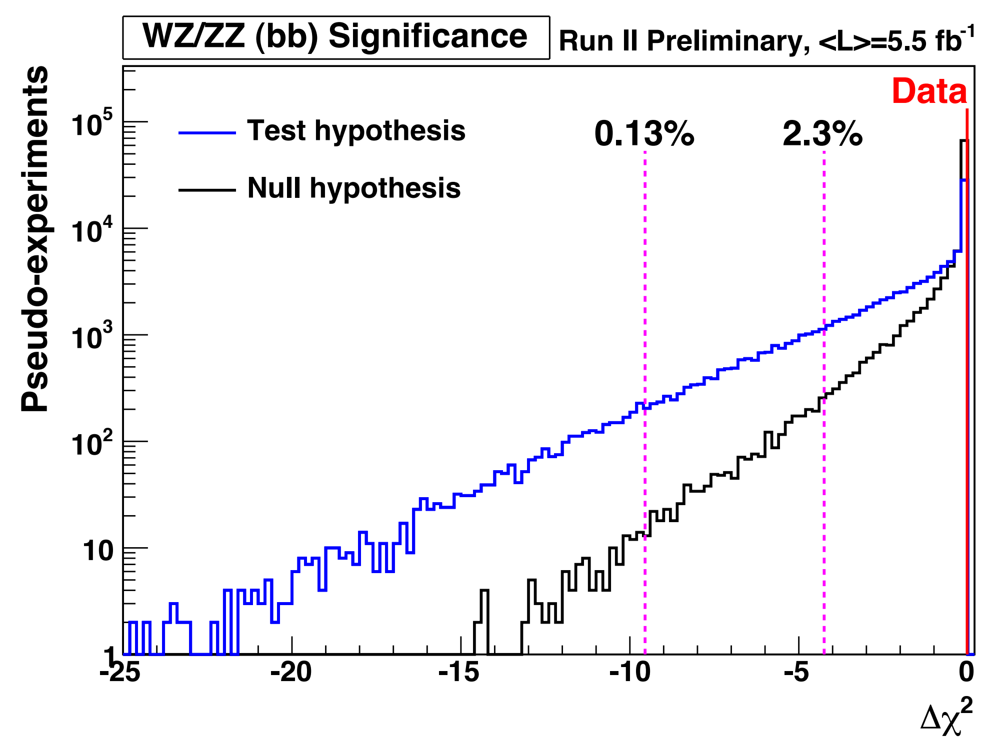
CDF Run II Preliminary, $\int L = 5.5\ \mathrm{fb}^{-1}$

Process(es)	Fit # events (2-tag)
EWK	710.7
$t\bar{t}$	134.3
Single top	189.7
QCD	54.5
WW	8.8
WZ/ZZ (l.f.)	5.7
WZ/ZZ ($b\bar{b}$)	4.4

Measured cross section = $0.12\sigma_{SM}$

Data - backgrounds:

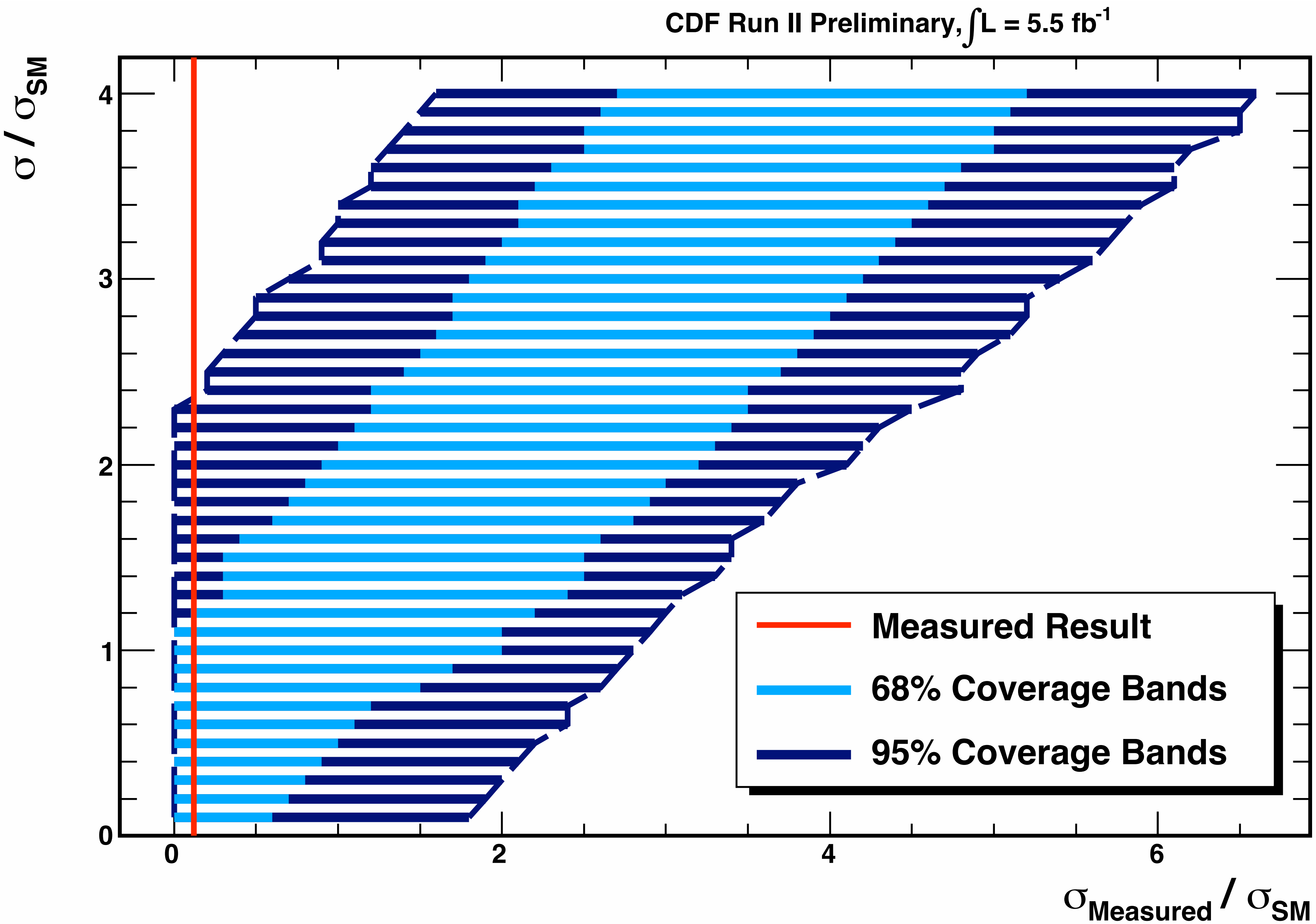




- This measurement has virtually no significance

Cross section limit for single fit for WZ/ZZ→MET+bb

- Still able to set a decent limit though



Measured limit: $\sigma < 2.4\sigma_{SM}$ at 95% CL

Conclusions

- We measured the cross section for WZ+ZZ in the MET plus 2 b-jets enhanced channel
- The key: identify b-jets to reduce WW and measure just WZ+ZZ
  - Developed a custom b-tagger
- Using 5.2 fb^{-1} of data,
  - WZ+ZZ
    - Measured a cross section of $\sigma = 5.0^{+3.6}_{-2.5}\,\mathrm{pb}$, consistent with the SM (5.1 pb)
    - Set a limit of $\sigma < 13$ pb (2.5 σ_{SM}) at 95% CL
  - WZ+ZZ→MET+bb
    - Set a limit of $\sigma < 2.3$ pb (2.4 σ_{SM}) at 95% CL
- Final states for WZ+ZZ the same as WH+ZH in MET + jets channel
  - Our techniques can be used in a future Higgs search