Observation of Single Top at CDF

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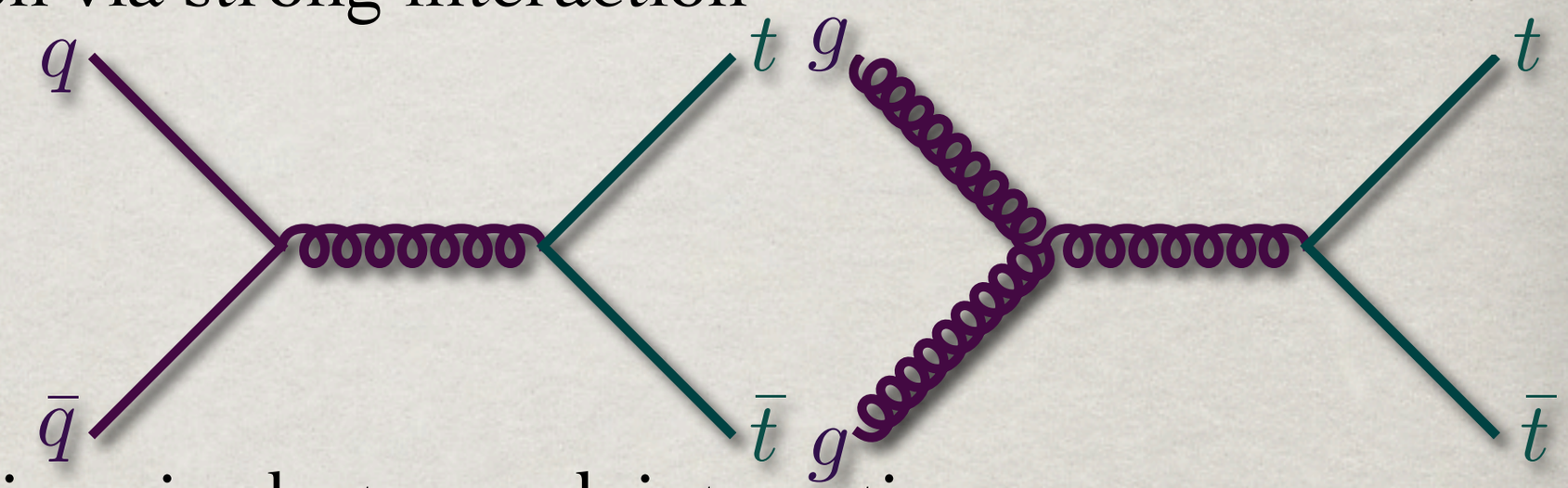
on behalf of the
CDF Collaboration

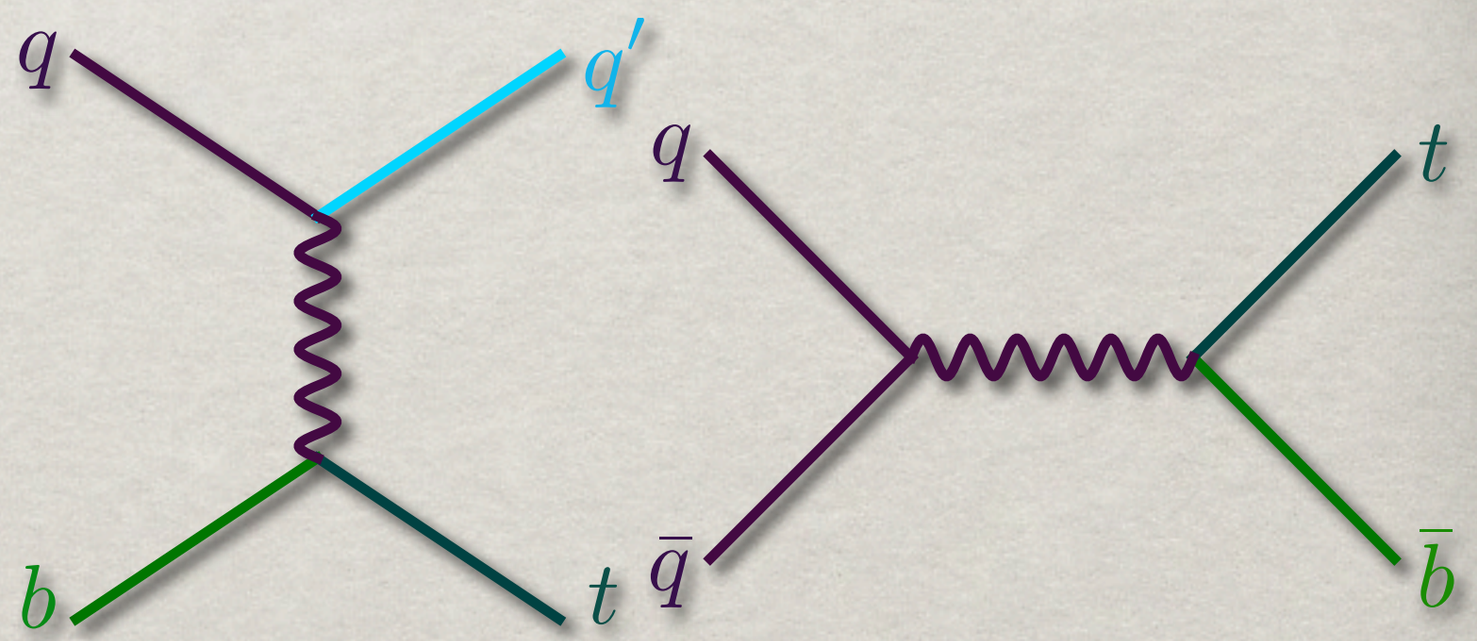
Top Quark Production

(At the Tevatron)

- Top pair production via strong interaction
  - σ_{NLO}=6.7 ± 0.8 pb
  - Observed in 1995



- Single top production via electroweak interaction
  - s-channel:
    σ_{NLO}= 0.88 ± 0.07 pb
  - t-channel:
    σ_{NLO}= 1.98 ± 0.21 pb
  - Evidence in 2006
  - Observed March 2009

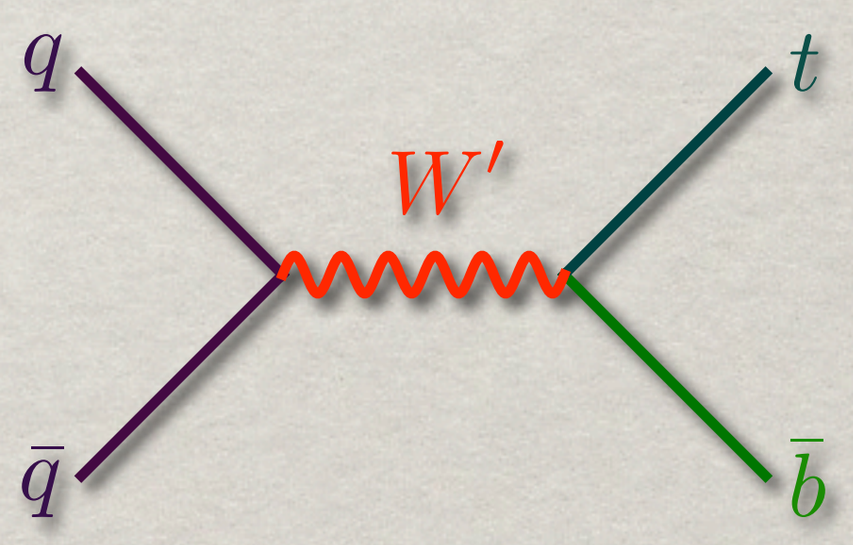


For M_{top}=175 GeV. Top Pair: Cacciari, *et al.* arXiv:0804:2800 (2008); Single Top: Z. Sullivan, Phys. Rev. D70, 114012 (2004). Compatible Predictions: Top Pair: Kidonakis &Vogt, arXiv: 0805.3844 (2008); Single Top: Campbell/Ellis/Tramontano, Phys. Rev. D70, 094012 (2004), N. Kidonakis, Phys. Rev. D74, 114012 (2006).

Why Study Single Top?

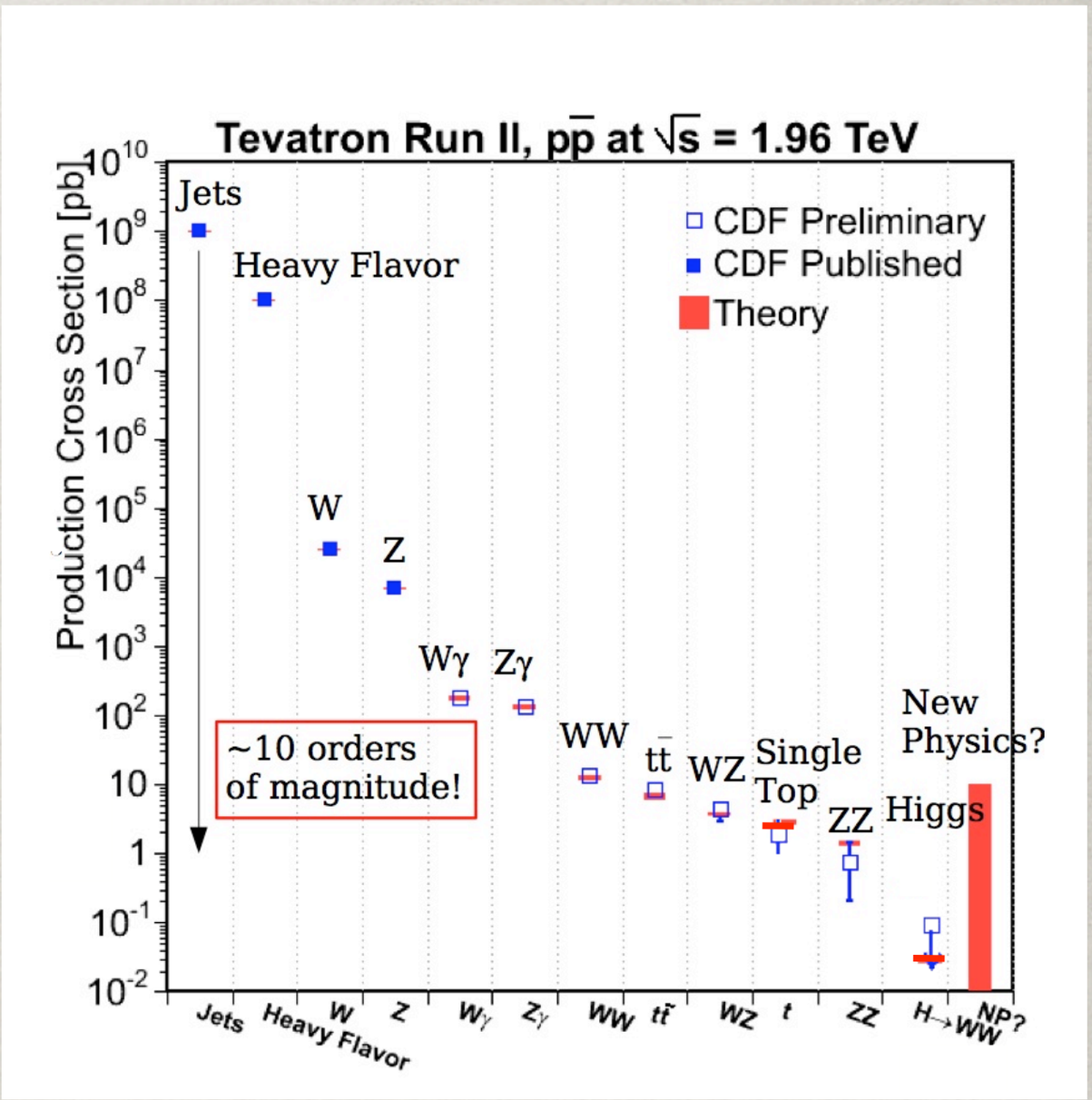
- Rate of single top production sensitive to new physics
- SM rate proportional to $|V_{tb}|^2$
  - $|V_{tb}|$ poorly constrained by other measurements
  - Sensitive to 4th generation of quarks
- Extra production from physics beyond SM
  - Extra heavy gauge bosons (W′)
  - Flavor changing neutral currents
  - Charge Higgs

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{uX}? \\ V_{cd} & V_{cs} & V_{cb} & V_{cX}? \\ V_{td} & V_{ts} & V_{tb} & V_{tX}? \\ V_{Yd}? & V_{Ys}? & V_{Yt}? & V_{YX}? \end{pmatrix}$$



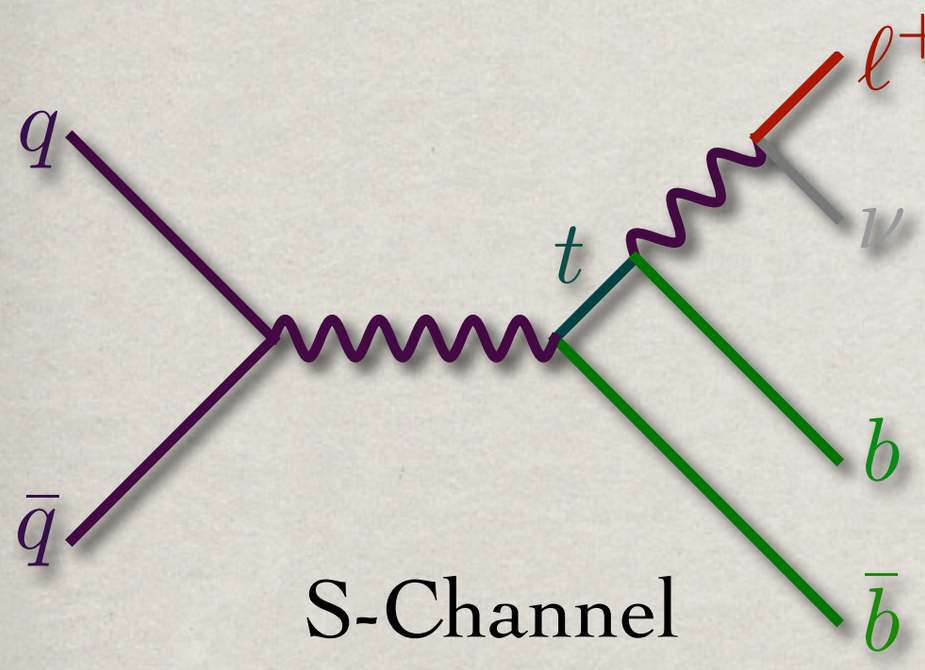
Why Study Single Top?

- Observing single top paves way for Higgs
  - Share same backgrounds and final state (WH)
  - Higgs cross section ~10× smaller
- Single top is the last SM process to be observed before Higgs

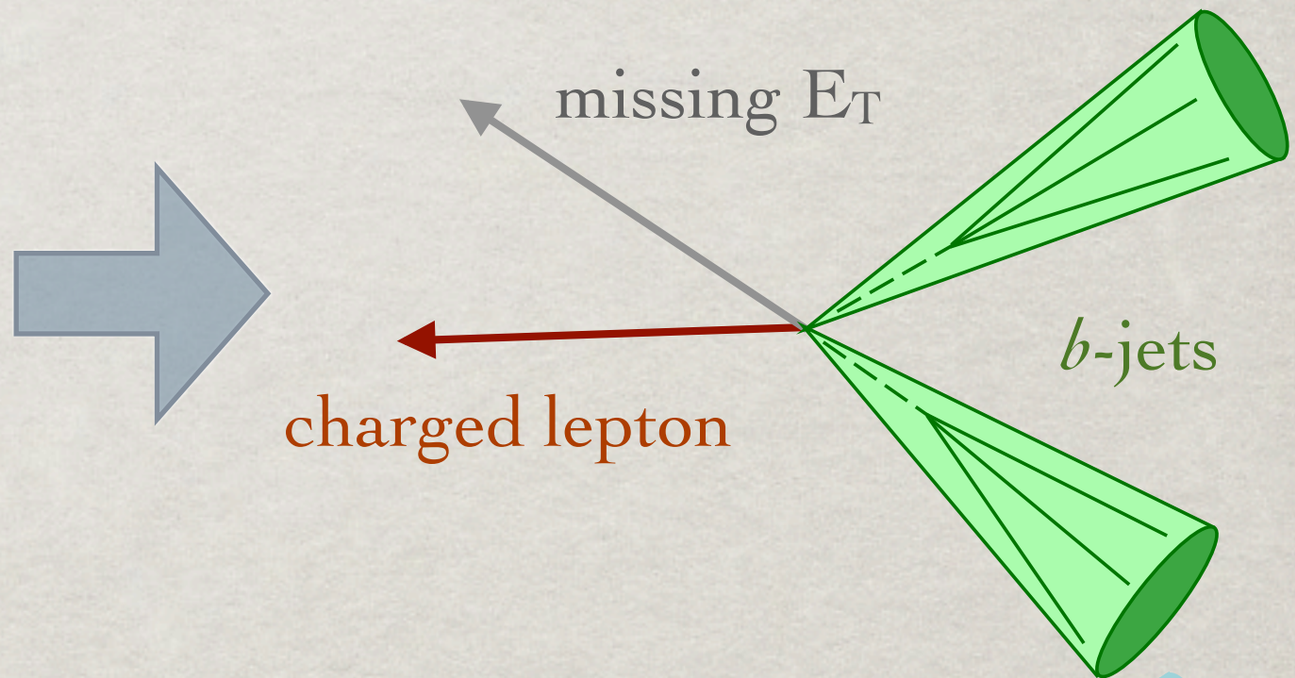


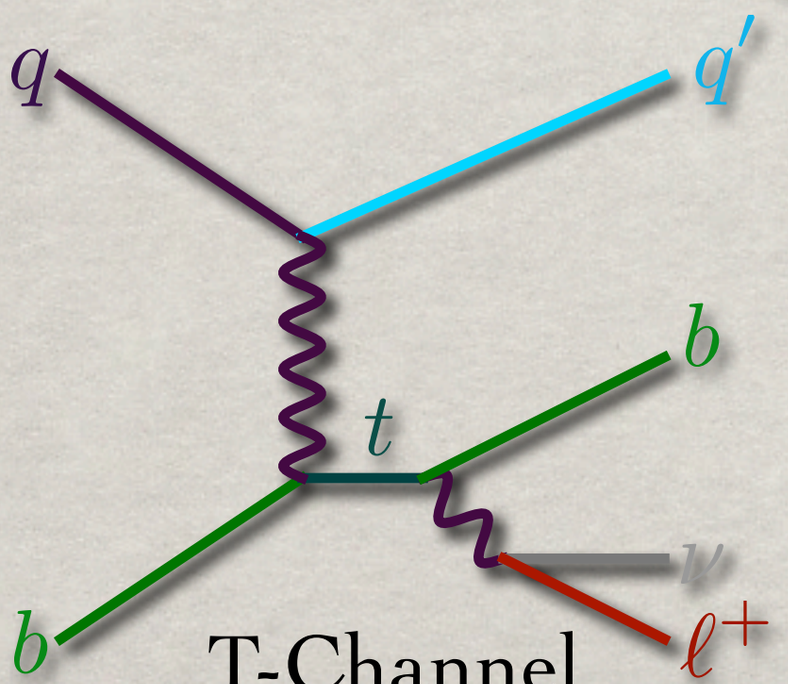
Single Top Signature

- W (lepton + Missing E_T) + 2 jets (≥ 1 b-jet)

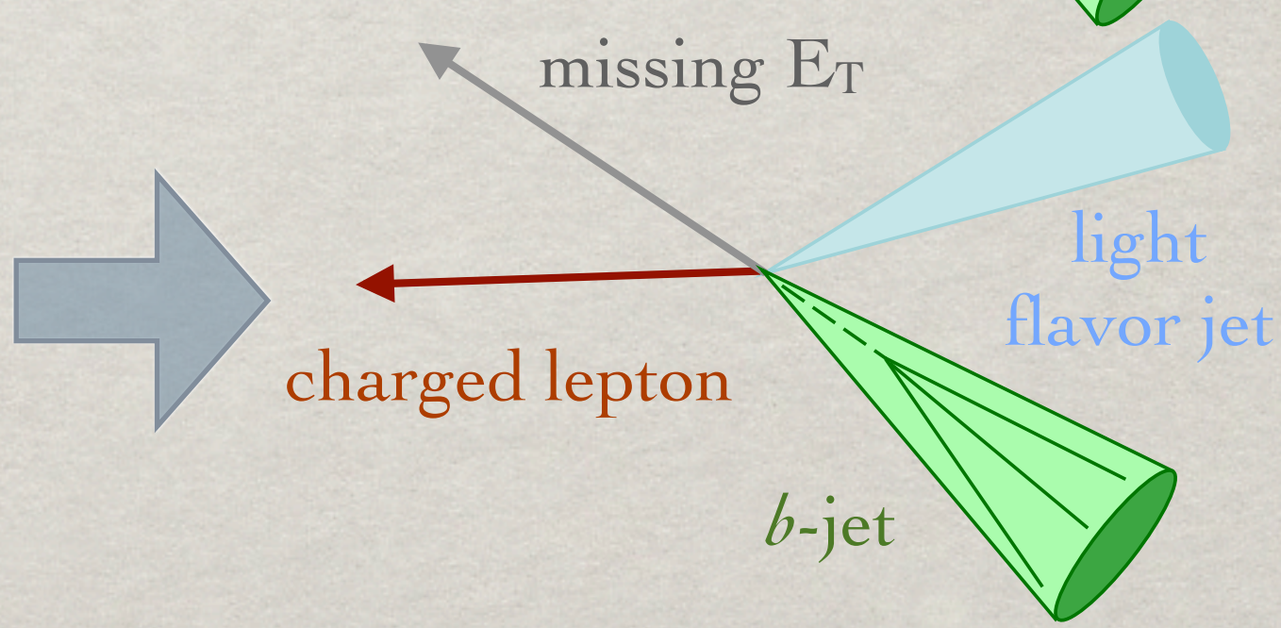


S-Channel



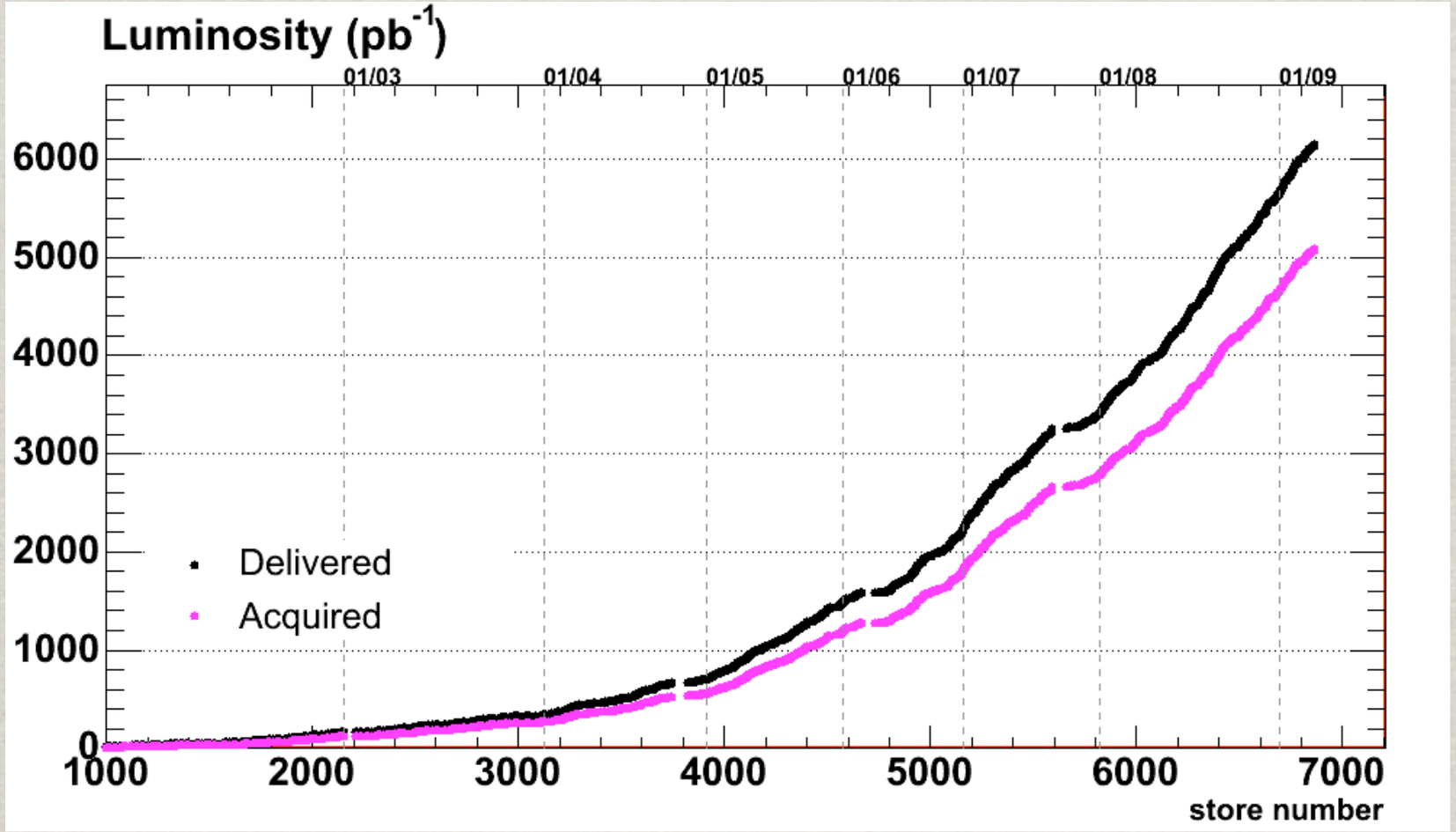


T-Channel



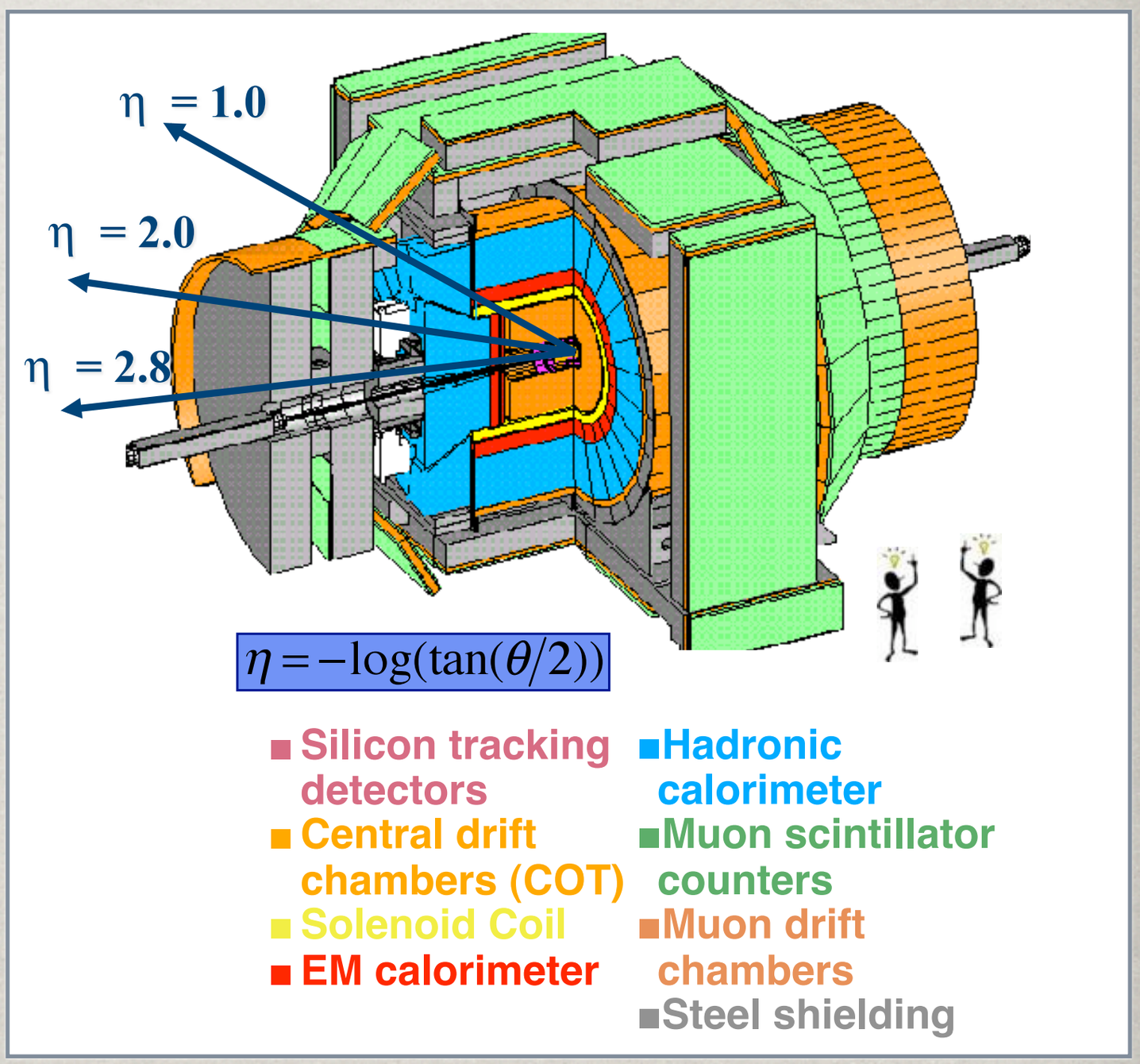
Takes Many Collisions to Make Single Top

- Single top production occurs approximately once in every 20 billion collisions at Tevatron
- Thanks to Fermilab accelerator division for producing enough collisions to give us a sample

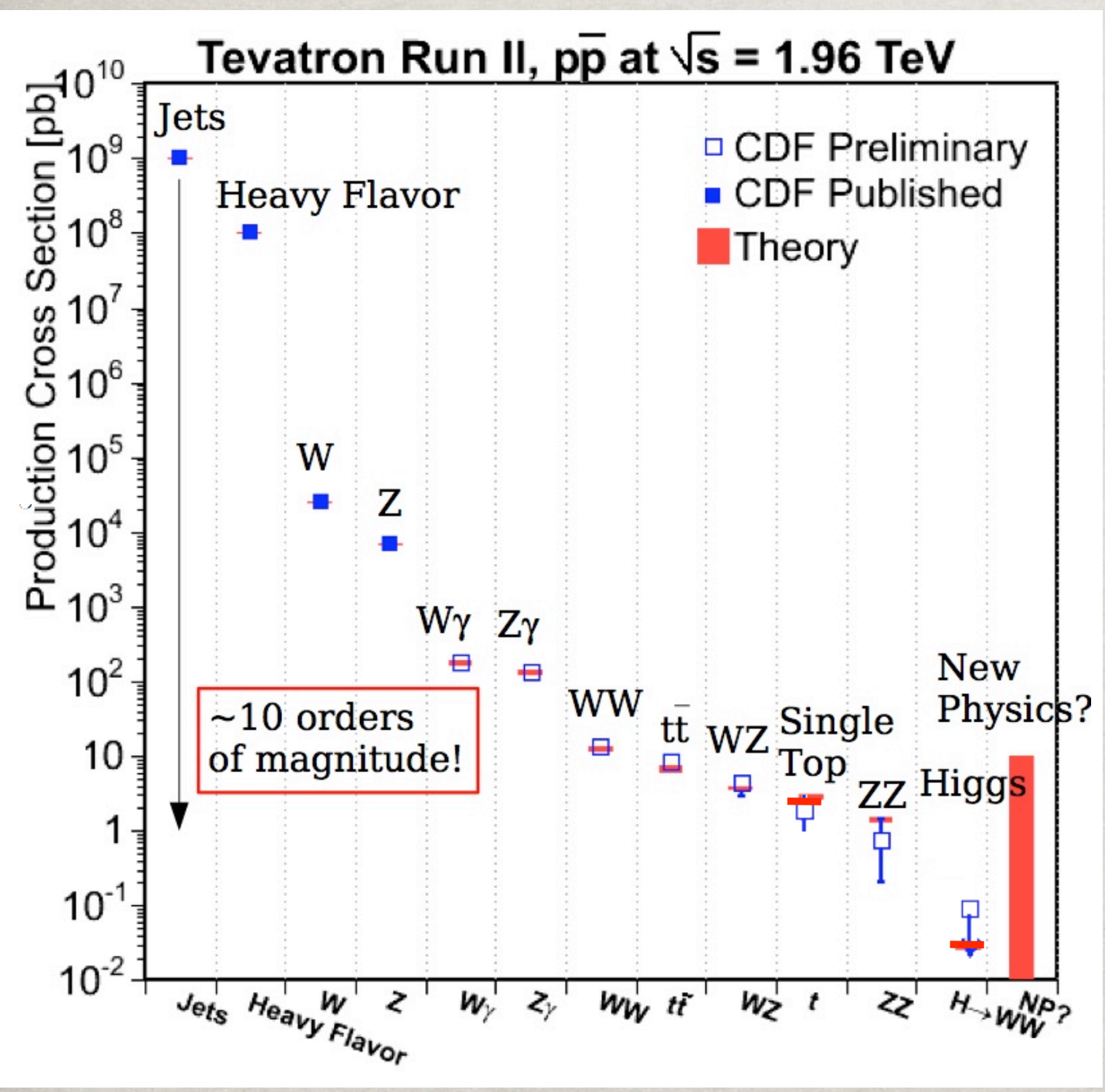


CDF Detector

- CDF dataset
  - ~5 fb^{-1} on tape
  - Single top analyses use 3.2 fb^{-1}
    - Up to Aug. 2008
    - All detector components on
- Currently takes 6 weeks to calibrate, validate, and process raw data

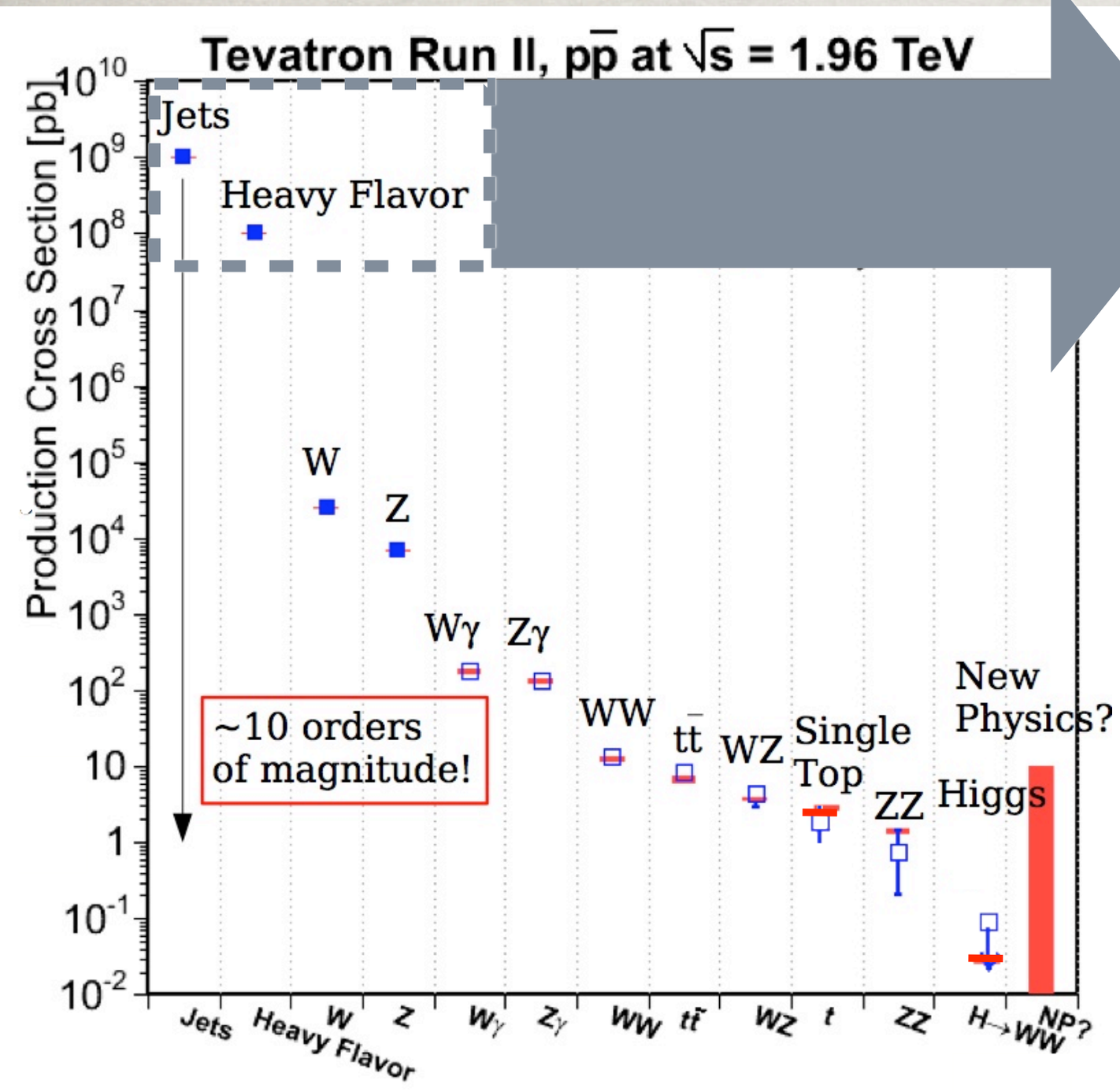


Extracting Single Top



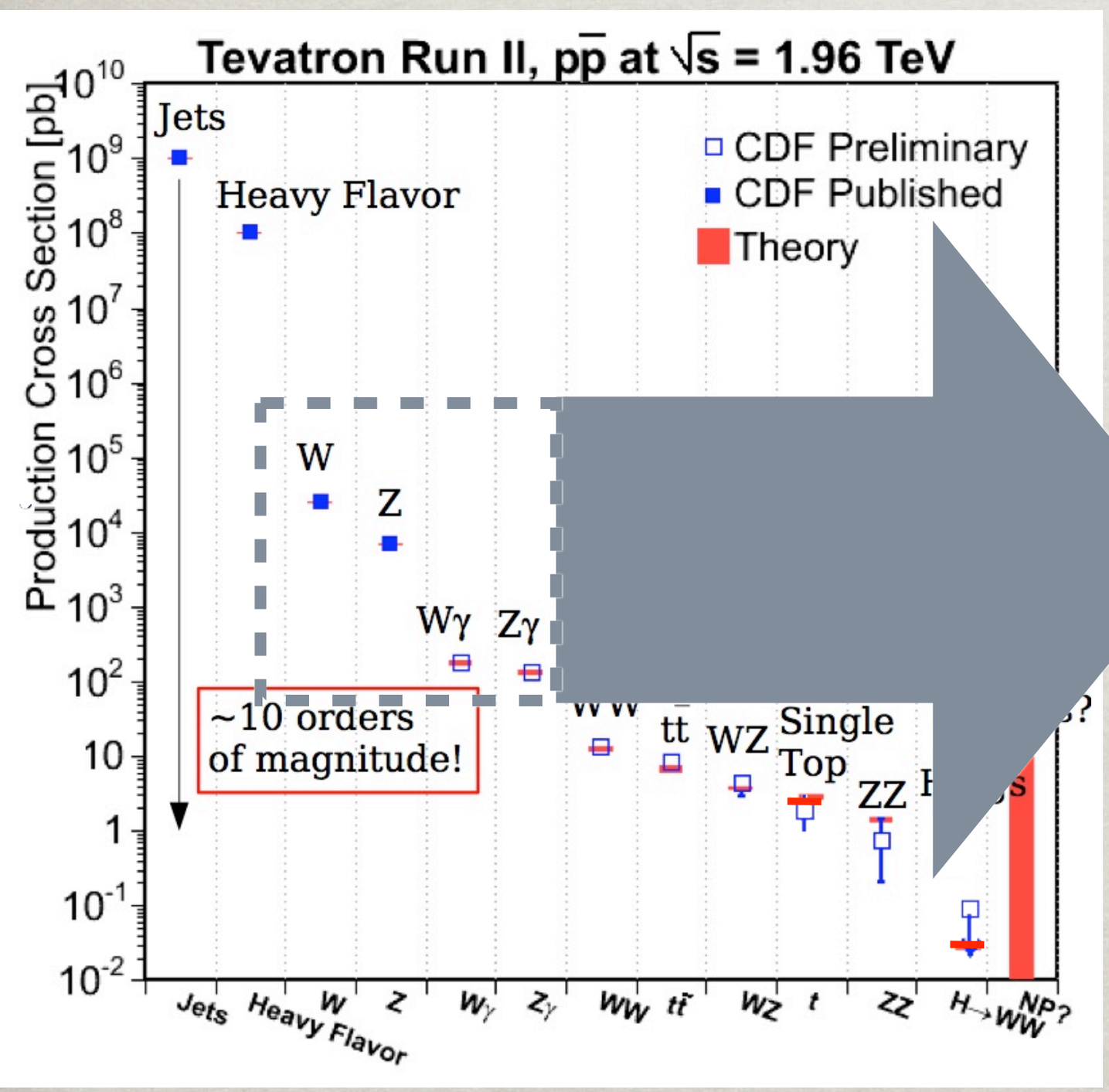
- Experimental challenge to separate small single top signal from huge backgrounds

Jet Background



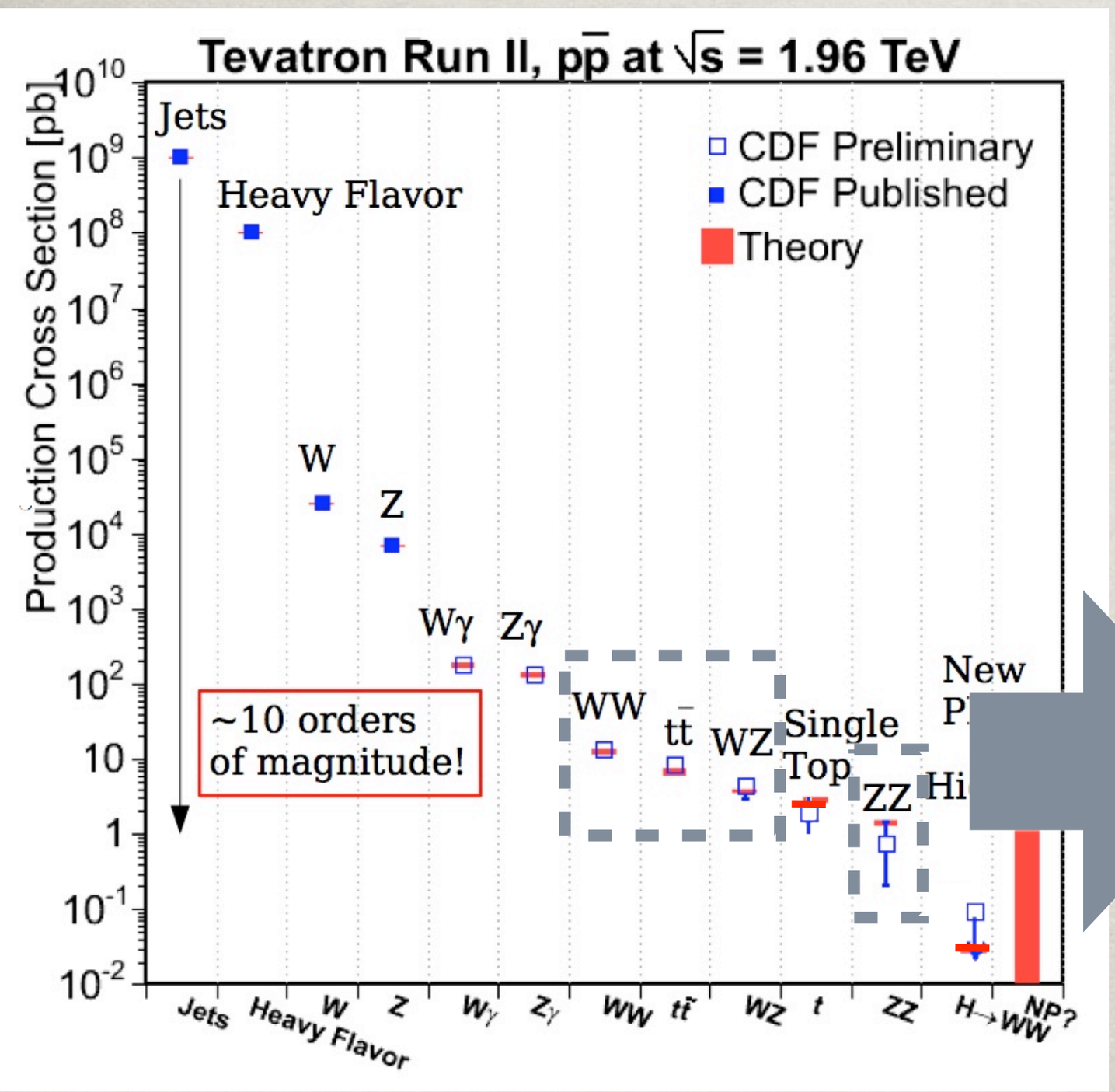
- Rejected by trigger
  - Require lepton or MET+jets
- Rejected by W selection (lepton + MET)
- Residual contribution:
  - Jets faking leptons
  - MET from jet mismeasurement
  - Estimated from data

W Background



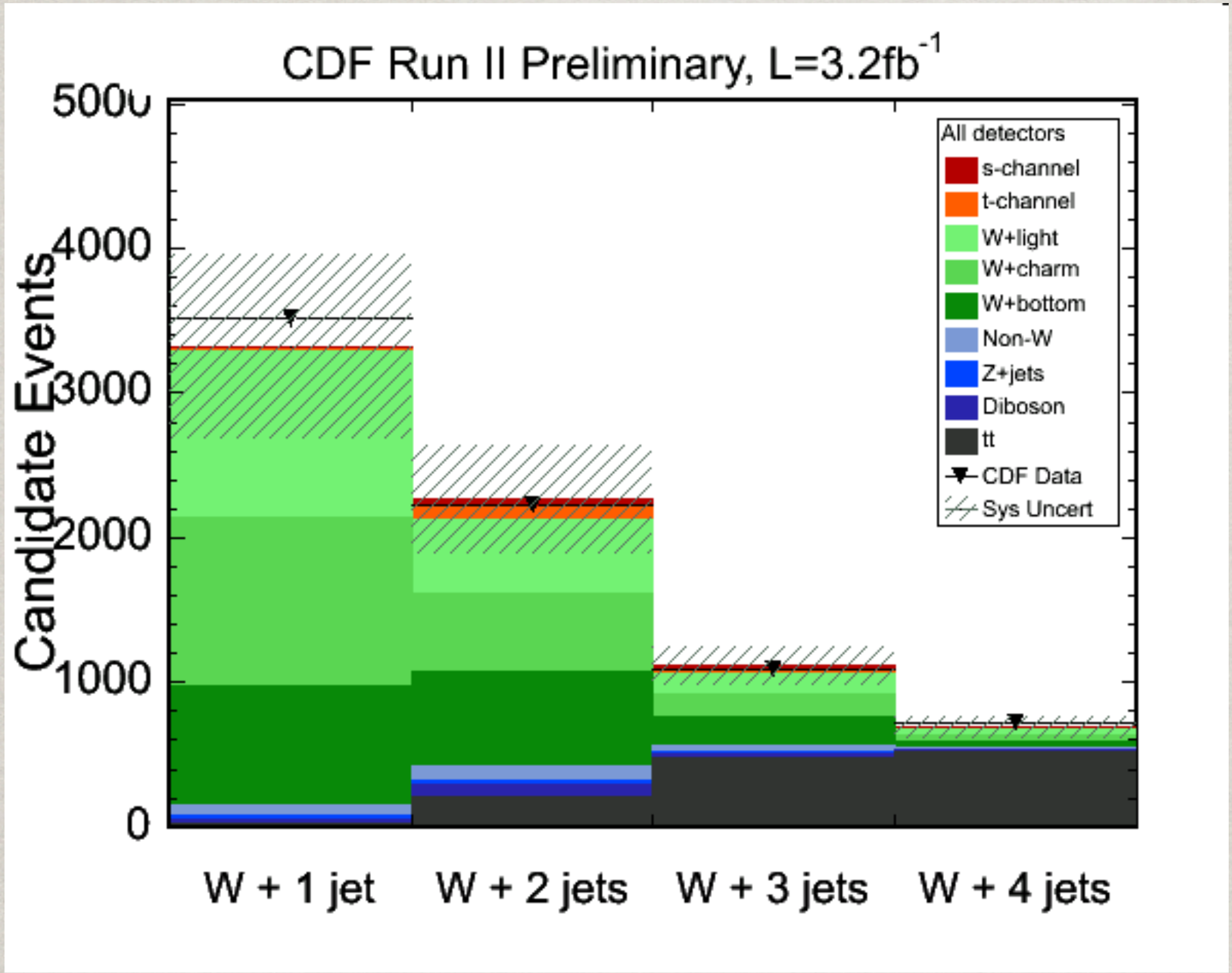
- Rejected by requiring two jets with at least one b-tag
- Residual contributions:
  - W+ 2 jets (fake *b*-tag)
  - W+bottom, charm
  - Estimated from mixture of data and MC

Top and Diboson Background

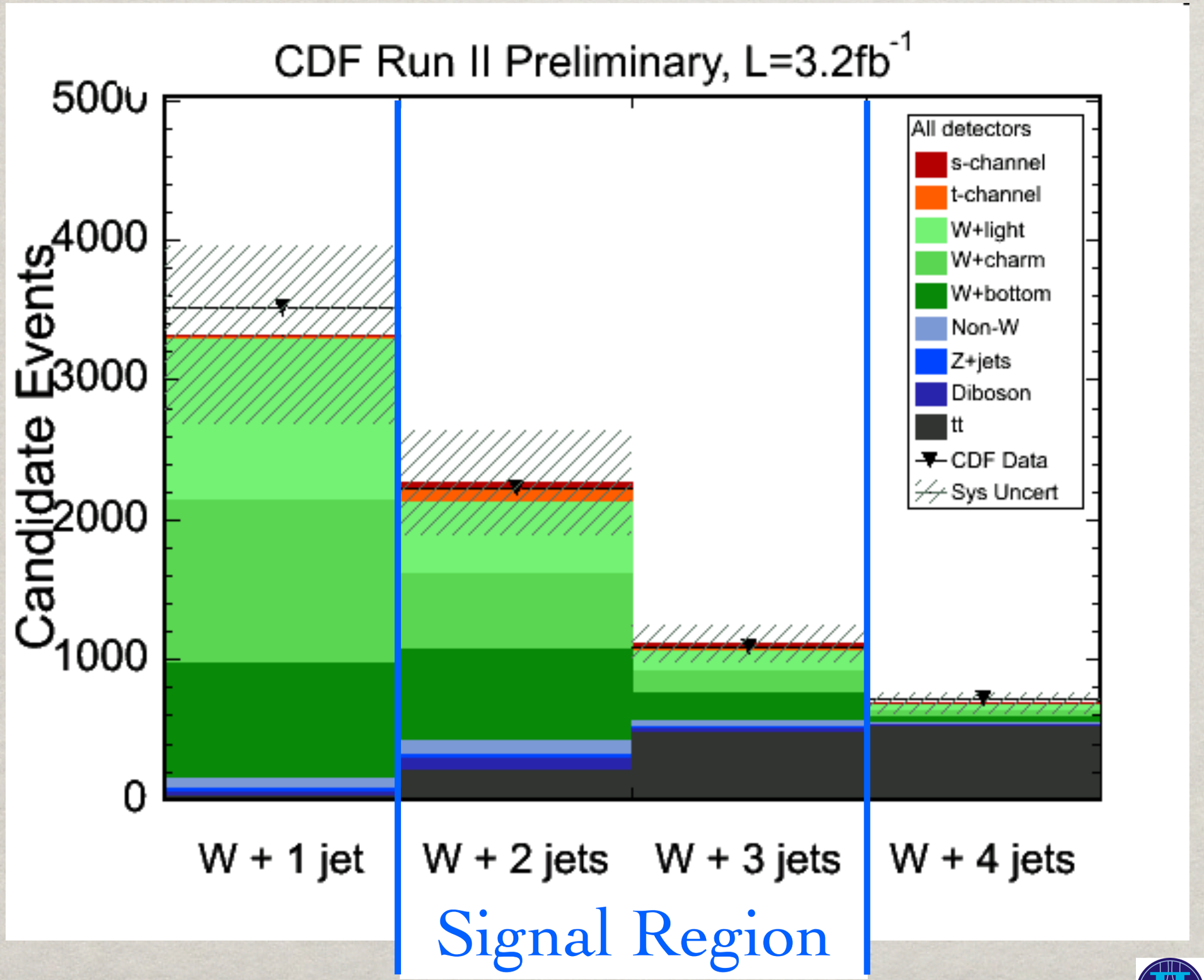


- Difficult to reject
  - Top pair: Require 2-3 jets (not 4)
  - Dibisons: Require 1 *b*-jets
- Residual contributions:
  - Irreducible W+2 jets and top backgrounds
  - Estimated from MC

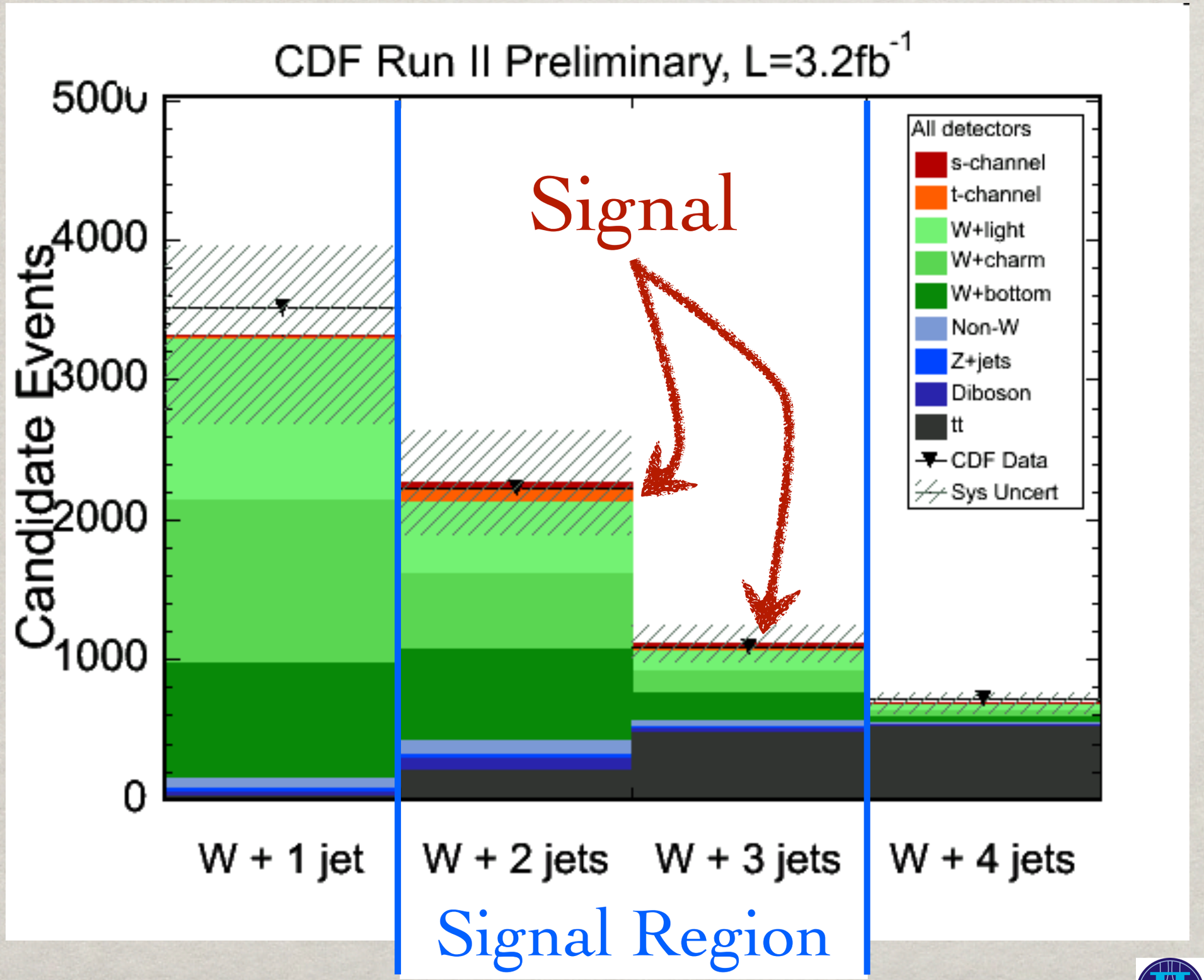
Remaining Background



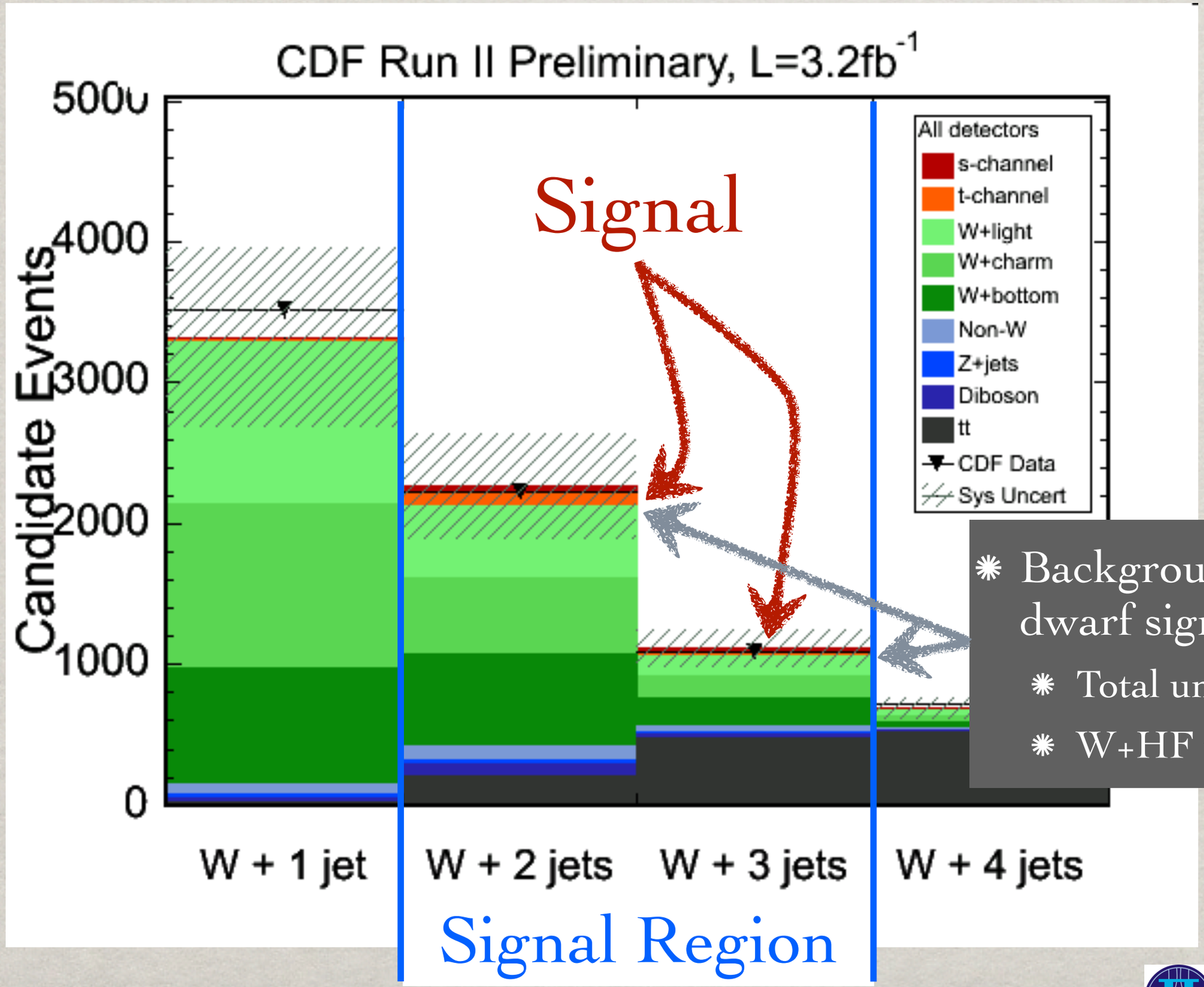
Remaining Background



Remaining Background

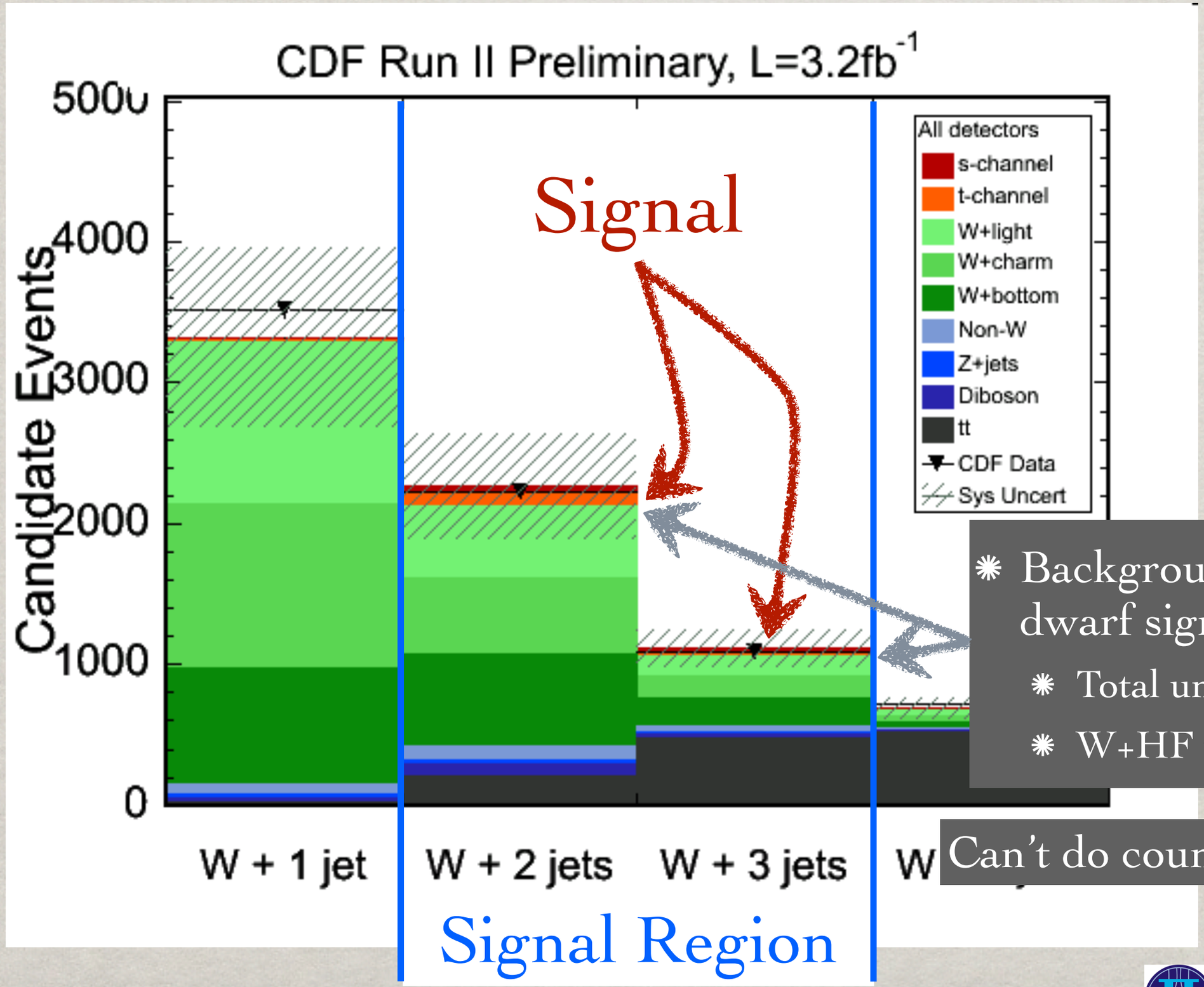


Remaining Background



- Background uncertainties dwarf signal
  - Total uncertainty ~17%
  - W+HF uncertainty ~30%

Remaining Background

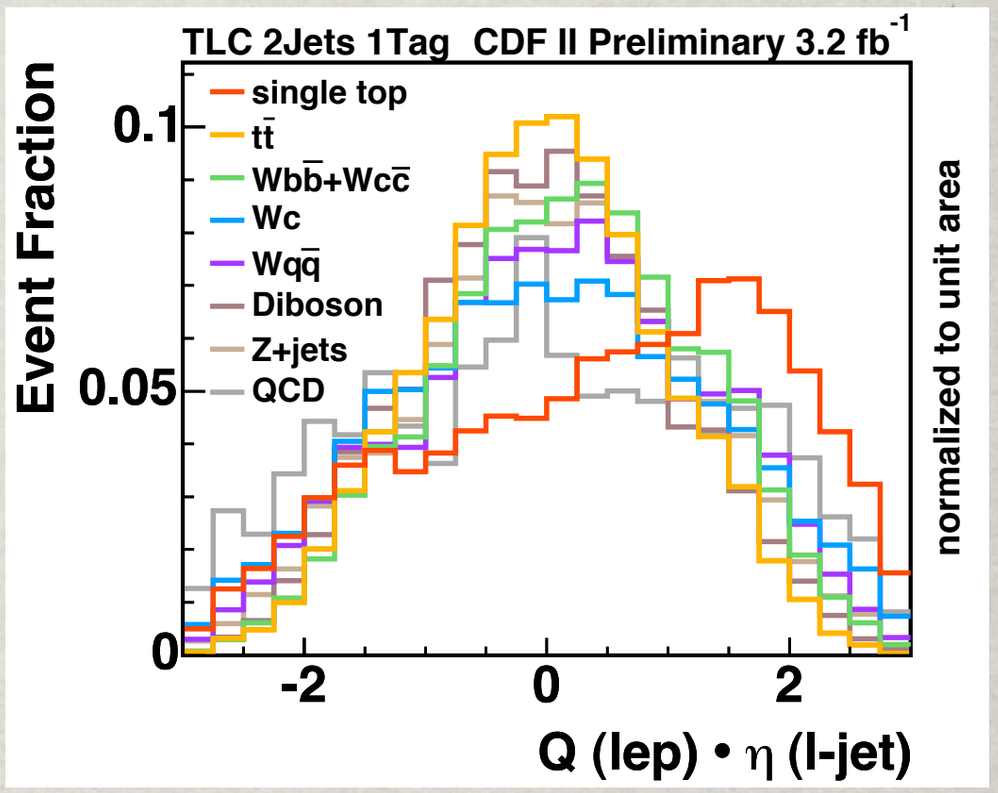


- Background uncertainties dwarf signal
  - Total uncertainty ~17%
  - W+HF uncertainty ~30%

Can't do counting experiment

Shape Fit

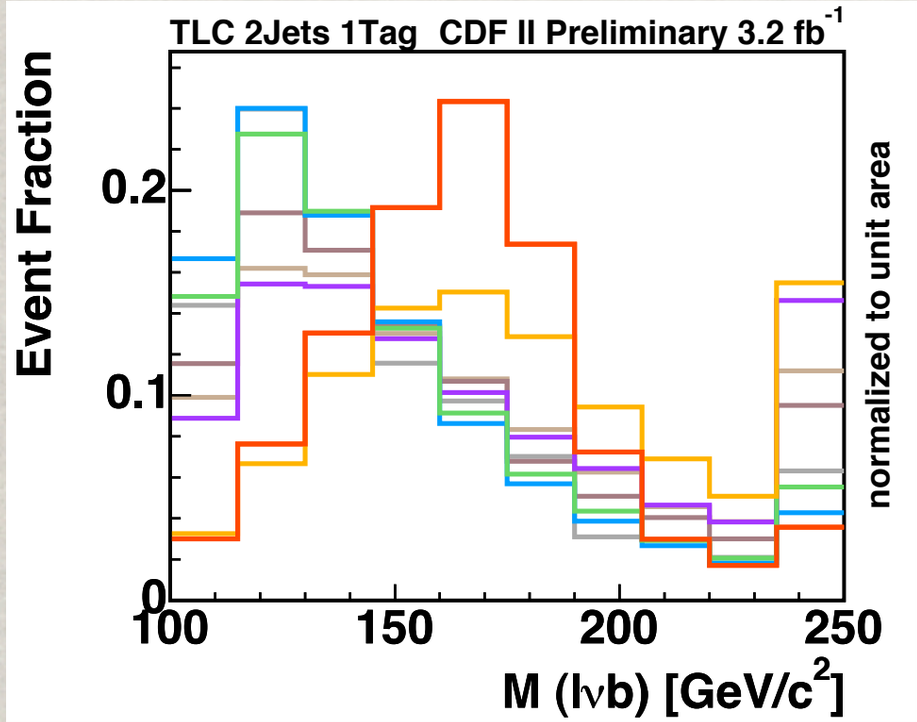
- To go beyond counting experiment, use shape fit
  - Provides in-situ constraint on background
  - Parts of the distribution (hopefully) have much better purity
- Which variable is best?



- Perform binned likelihood fit

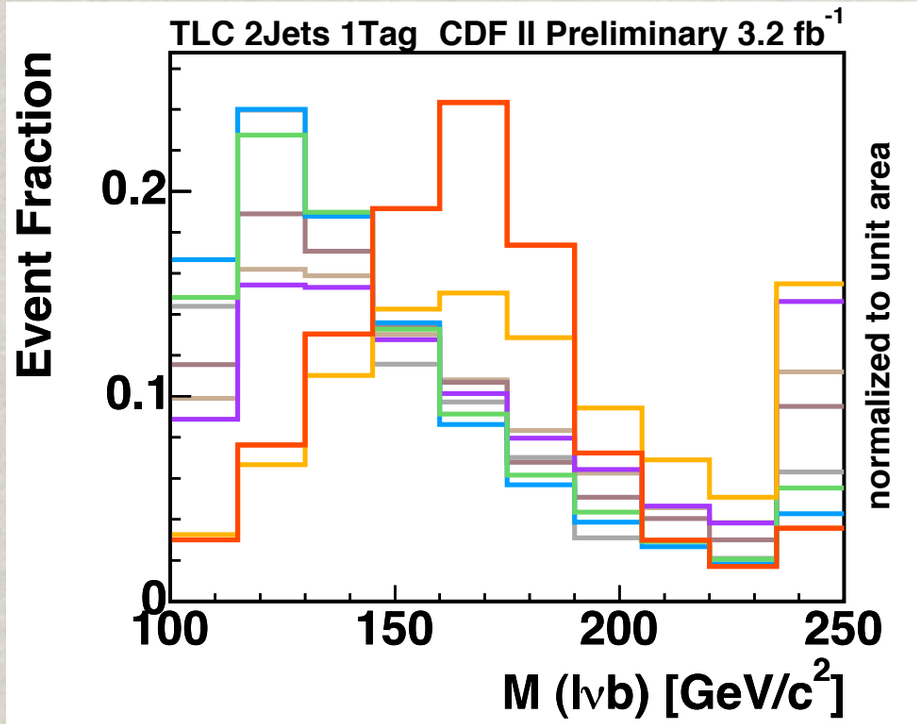
$$L(sig, bkg_1, \ldots, bkg_N) = \prod_{k=1}^{N+1} \frac{e^{-\mu_k}\mu_k^{n_k}}{n_k!} \prod_{j=1}^{M} G(bkg_j|1, \Delta_j)$$

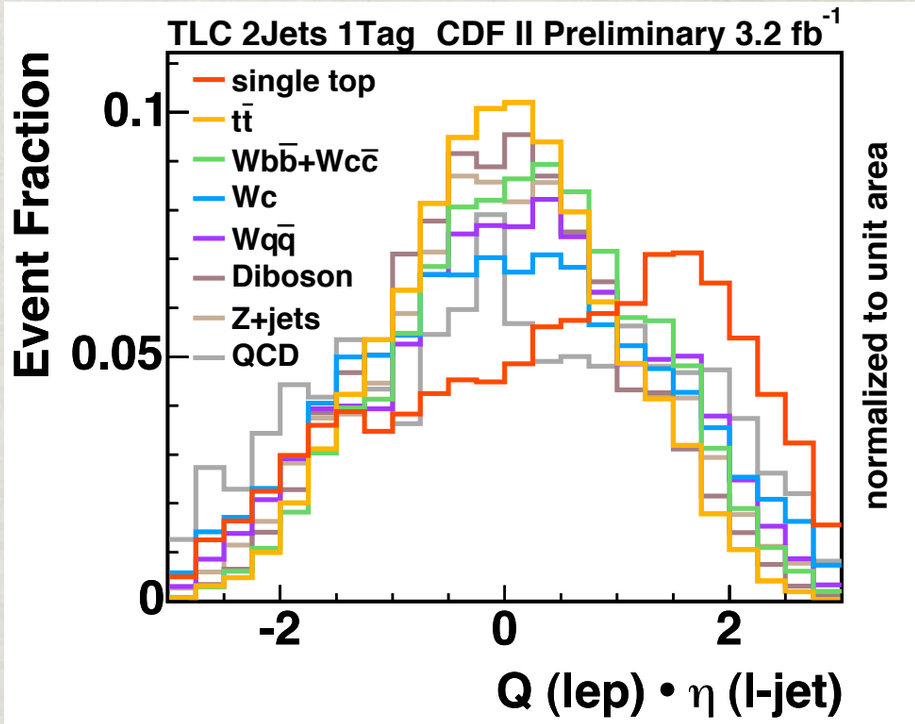
Discriminating Variables

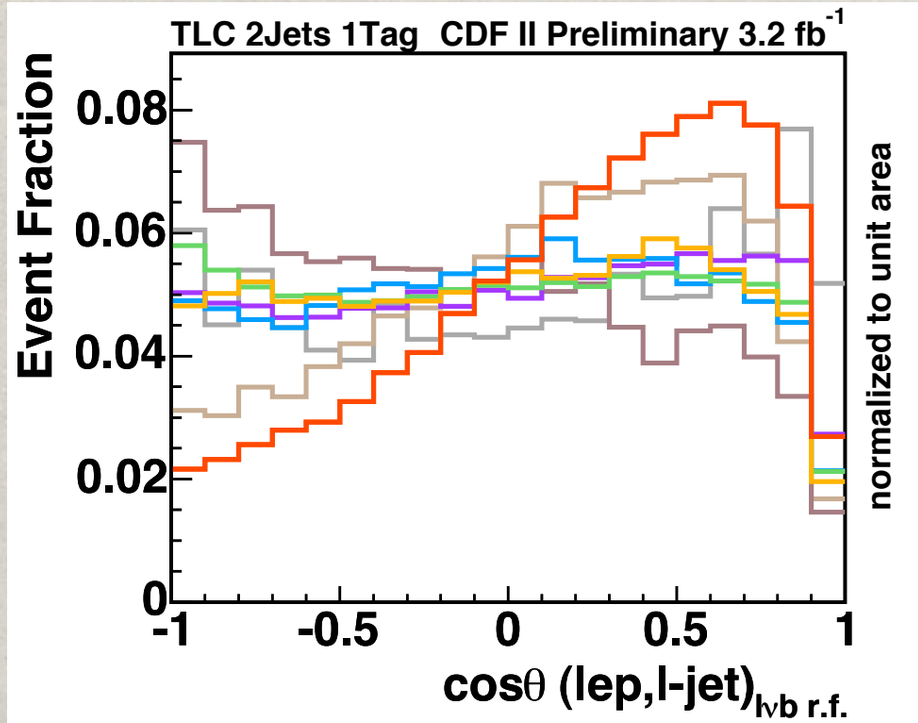


- Invariant mass of lepton, neutrino, and b-jet
  - Shows top mass peak for signal
  - Top pair background also has peak
- Difficult to reconstruct
  - Neutrino → MET (no z component)
  - Which jet goes with top?
  - MET and jet resolutions

Discriminating Variables

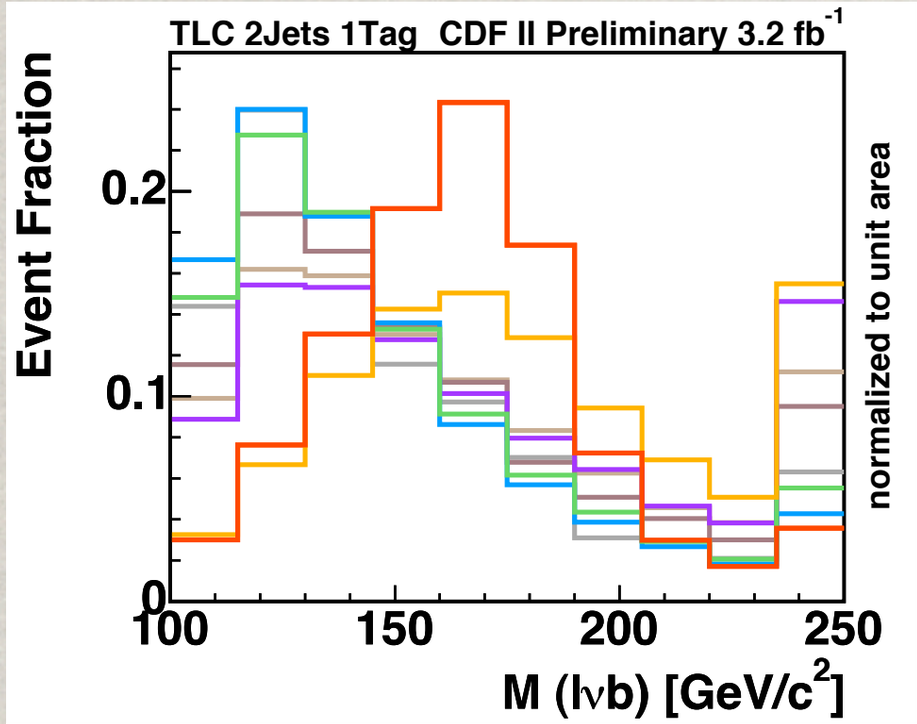


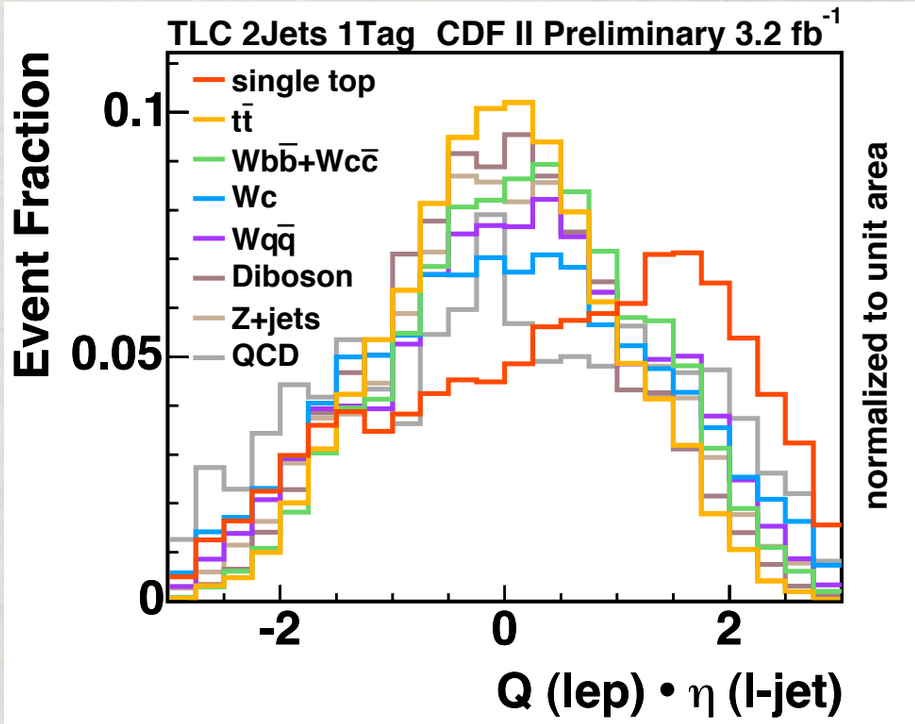


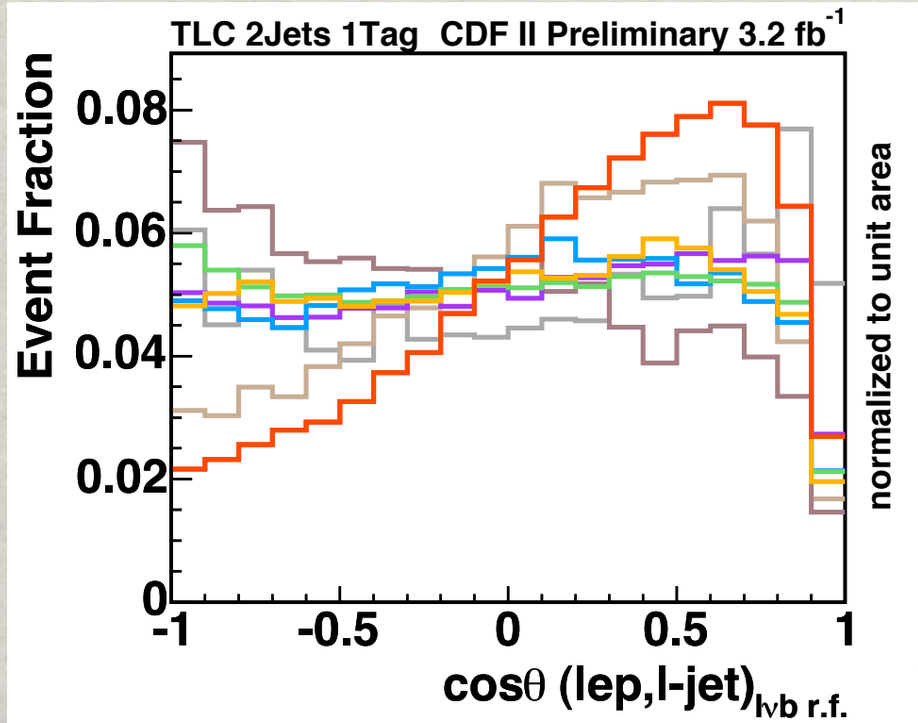


- Angular correlations:
  - Lepton charge times η of light jet
  - Cos(polar angle) between lepton and light jet in top rest-frame
- Take advantage of production characteristics

Discriminating Variables



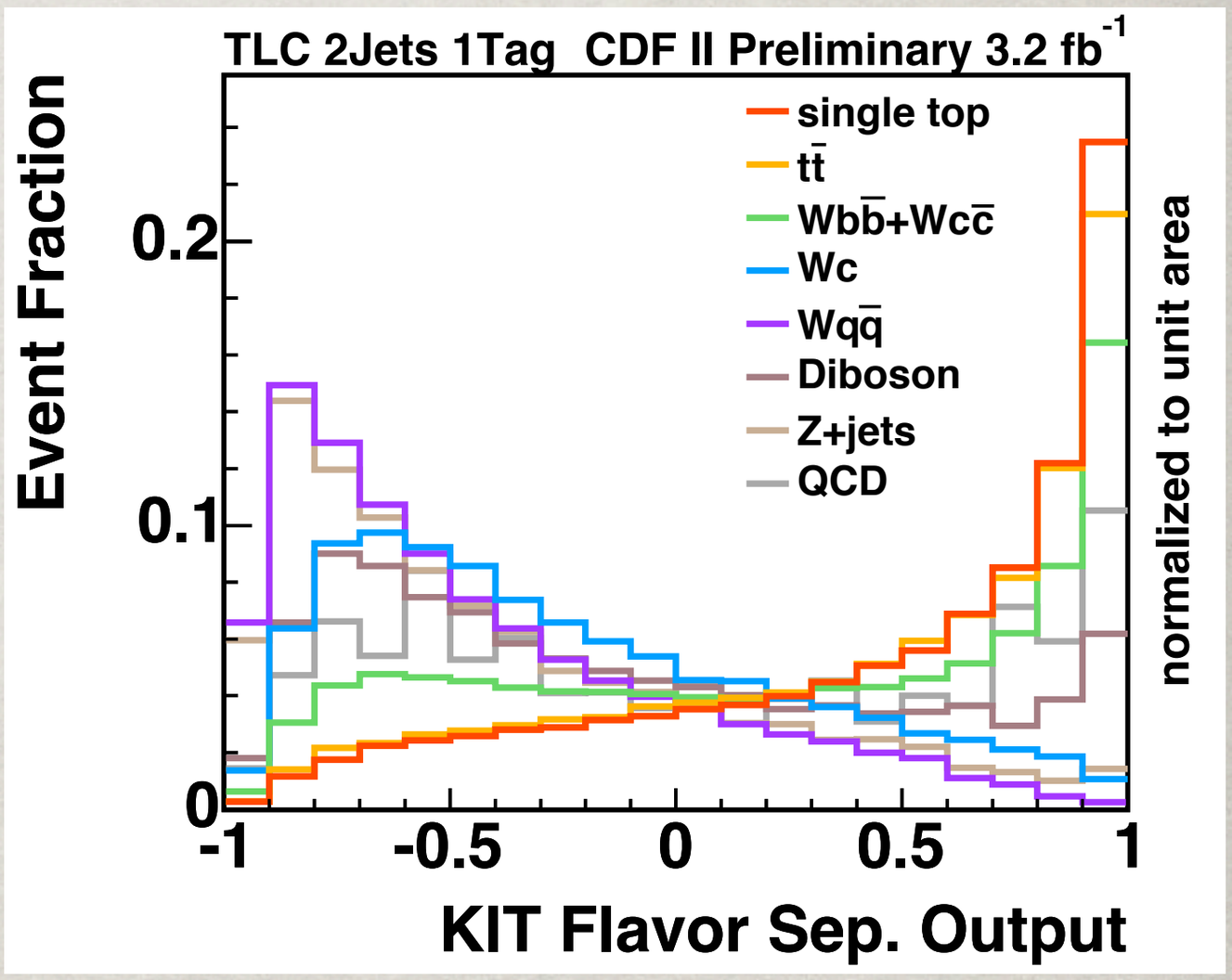




- What about non-kinematic variables?

Flavor Separation

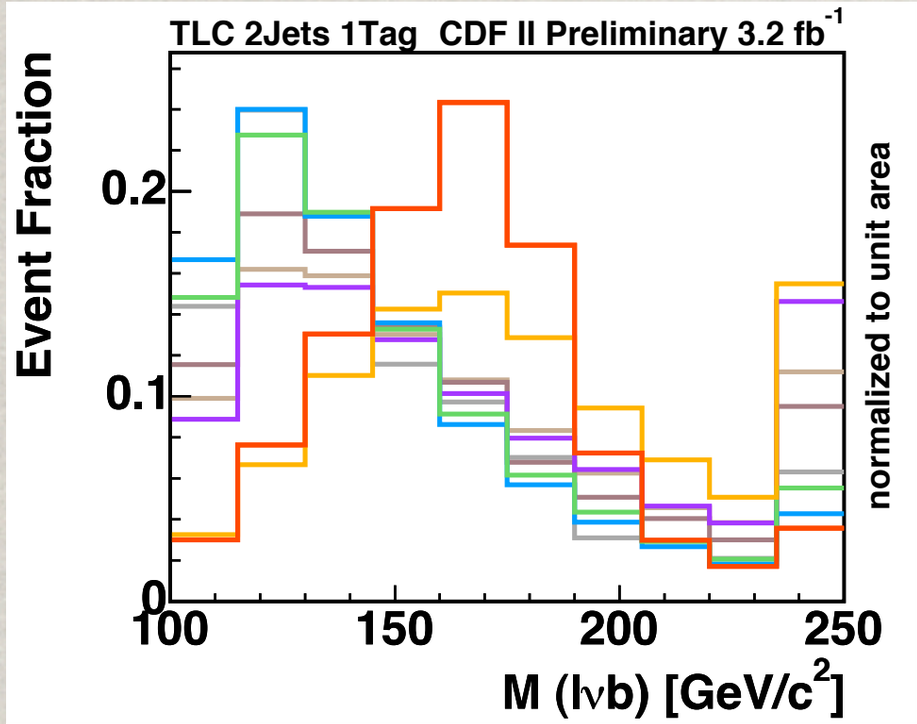
- All events contain at least one *b*-tagged jet
- Only about half of backgounds contain real *b*-jet
- Can we distinguish real *b*-tags from non-*b*?
- Neural network: combine several variables

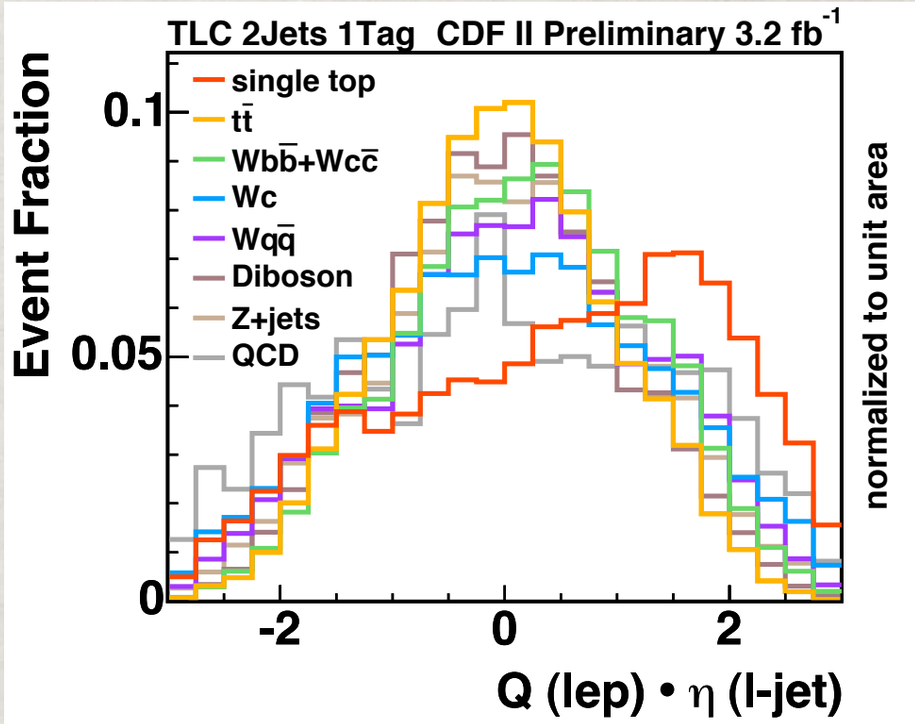


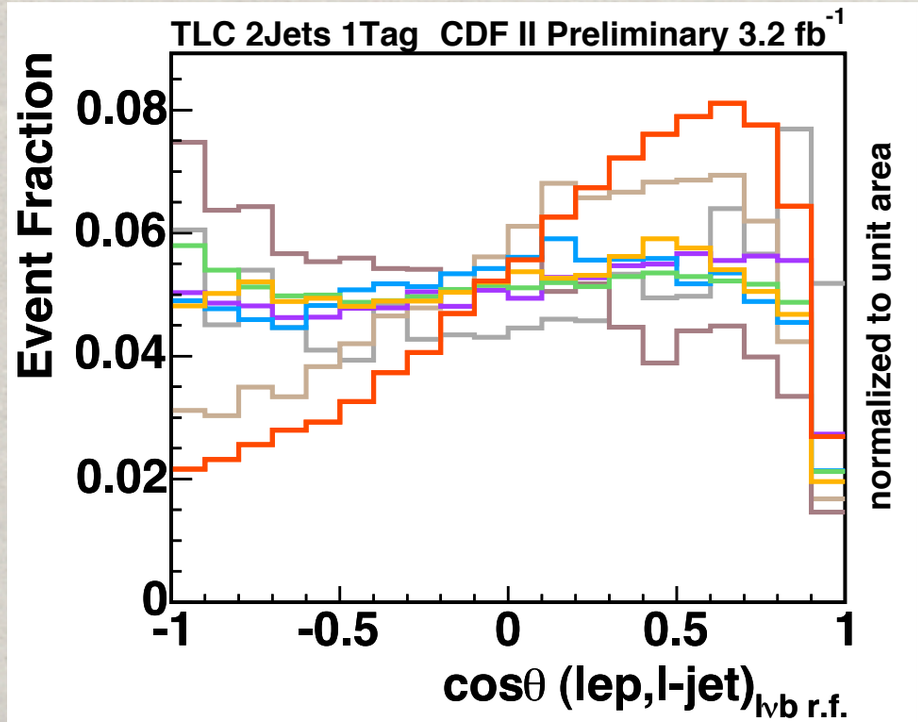
Mistag/Charm.....Bottom

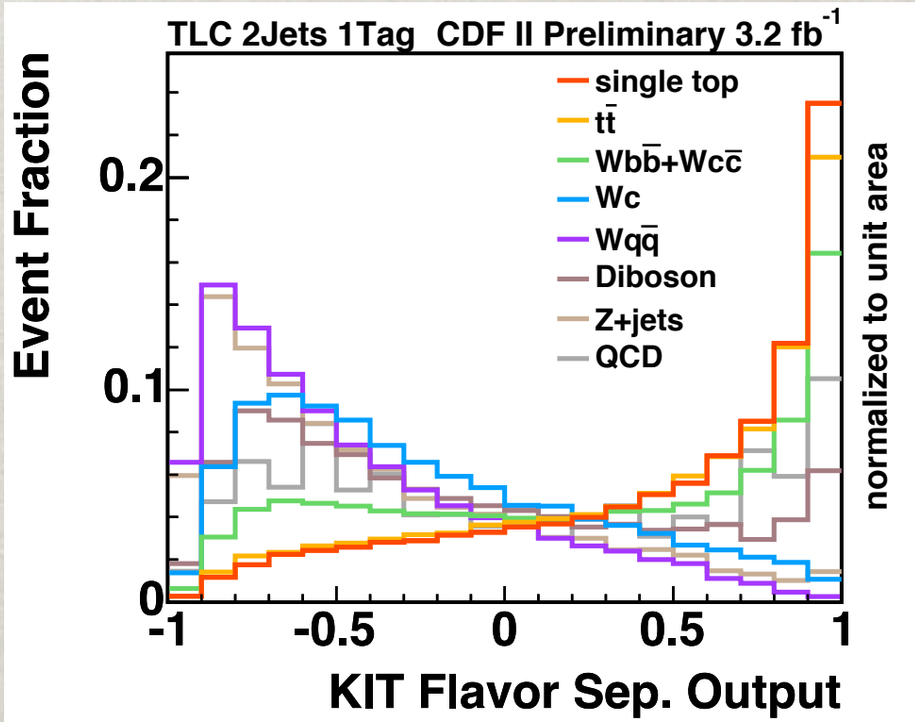
L_{xy}, vertex mass, track multiplicity, impact parameter, semi-leptonic decay information, etc...

Normalized to Equal Area

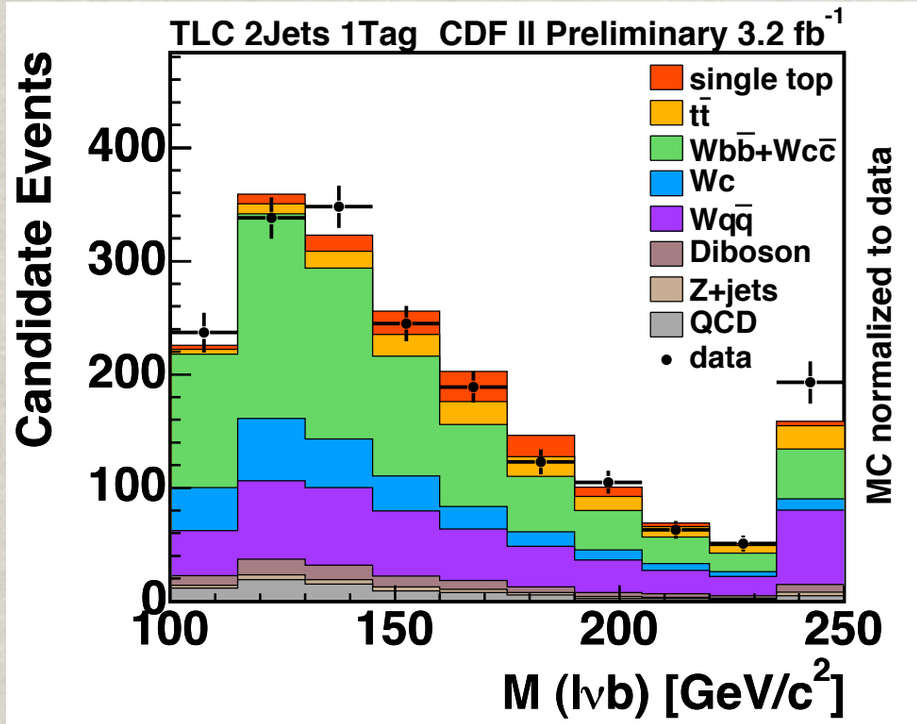


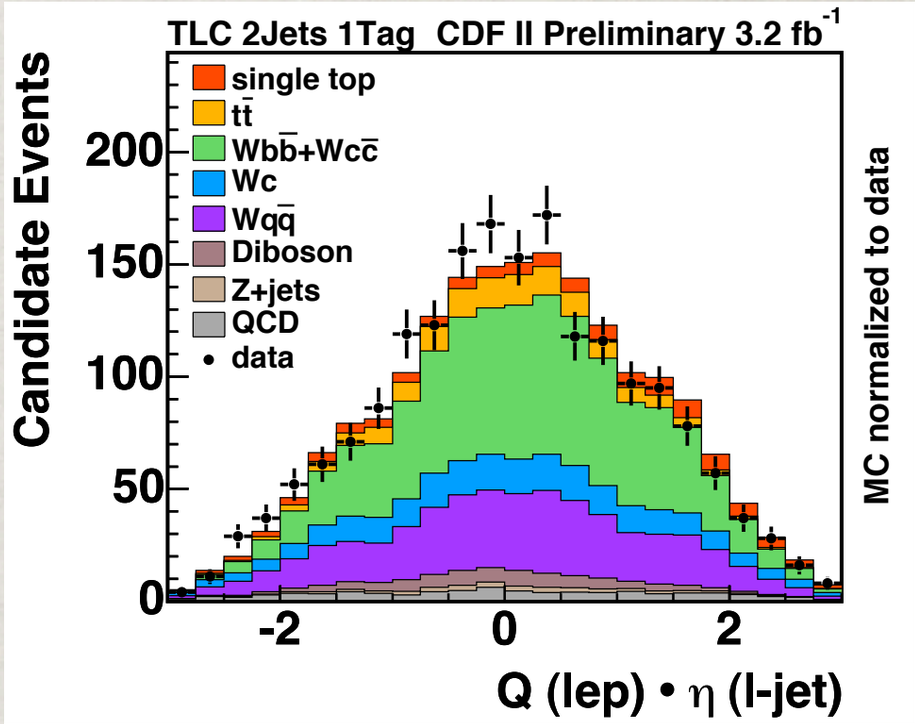


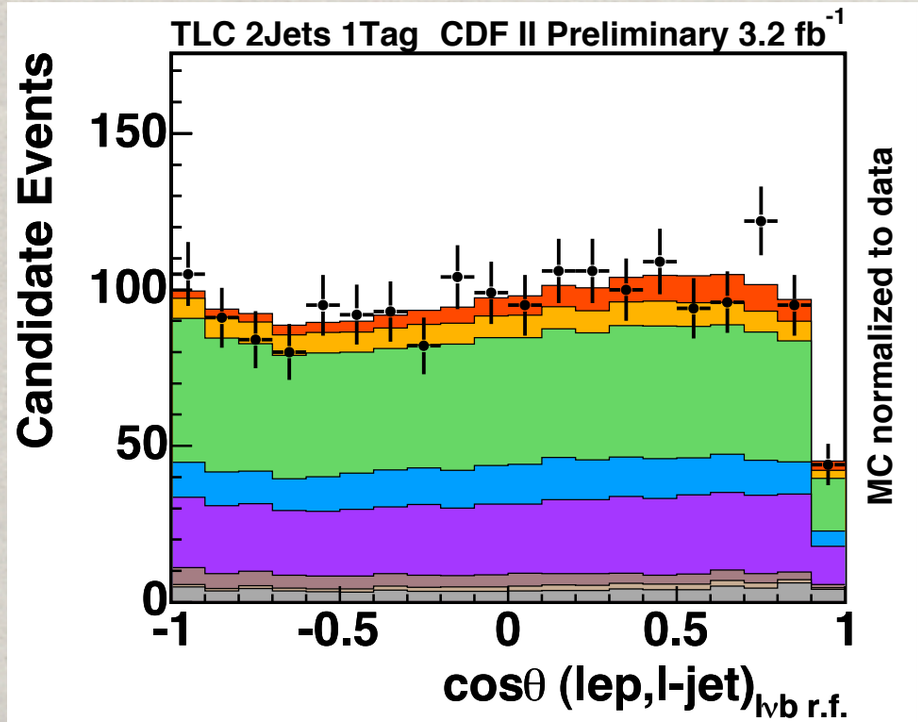


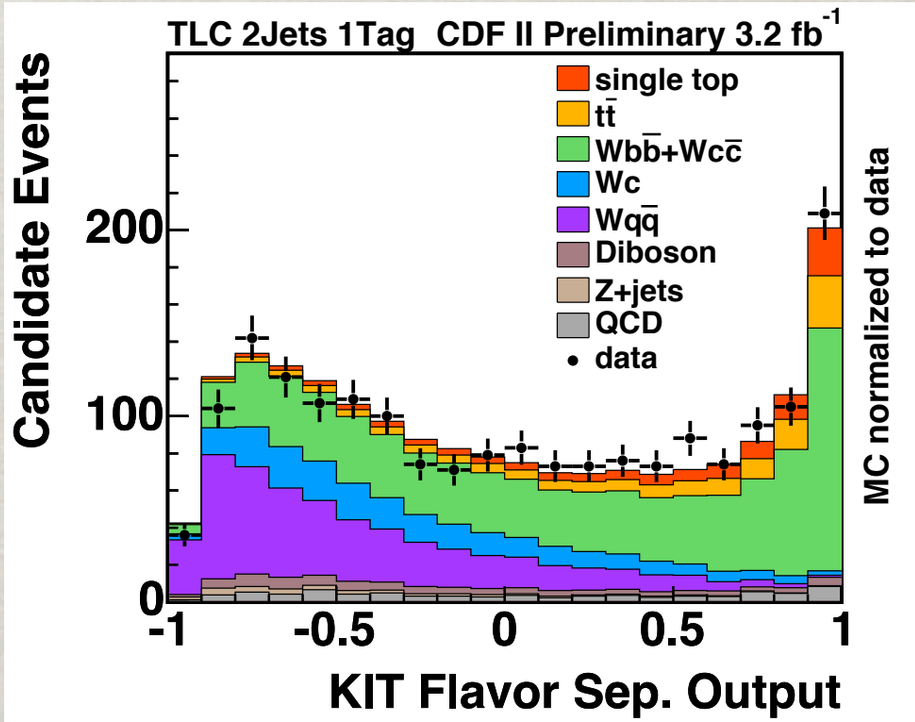


Normalized to Expectation

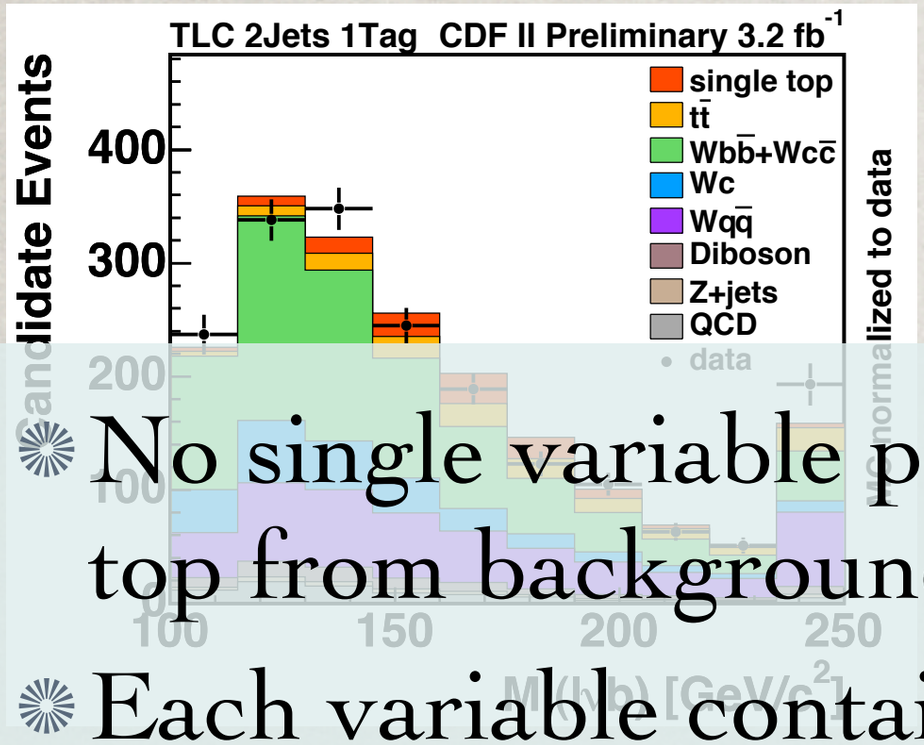


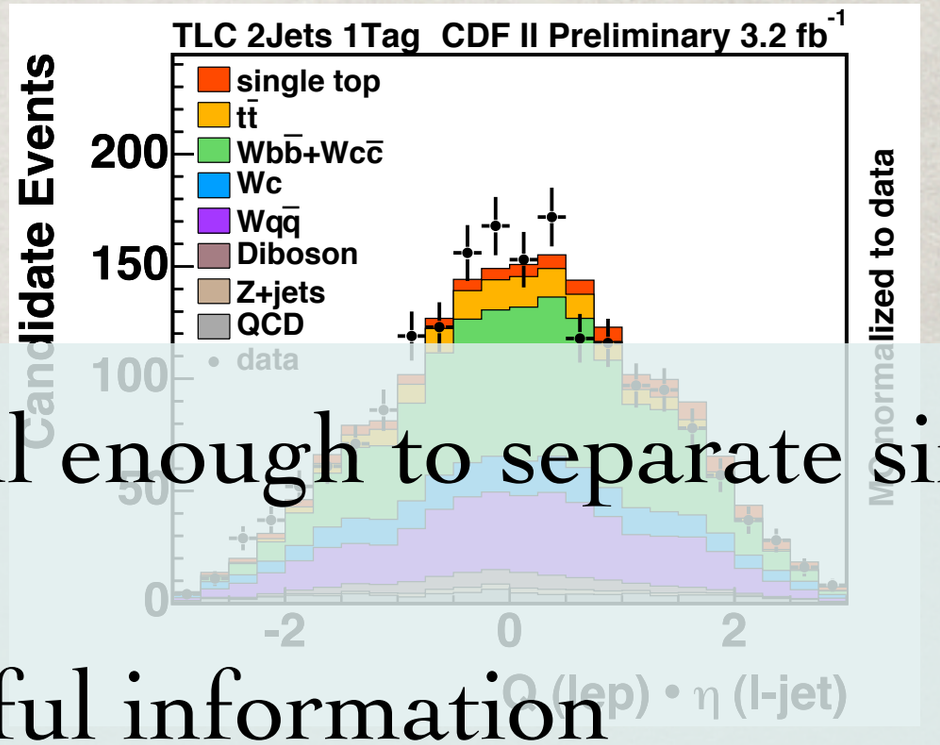




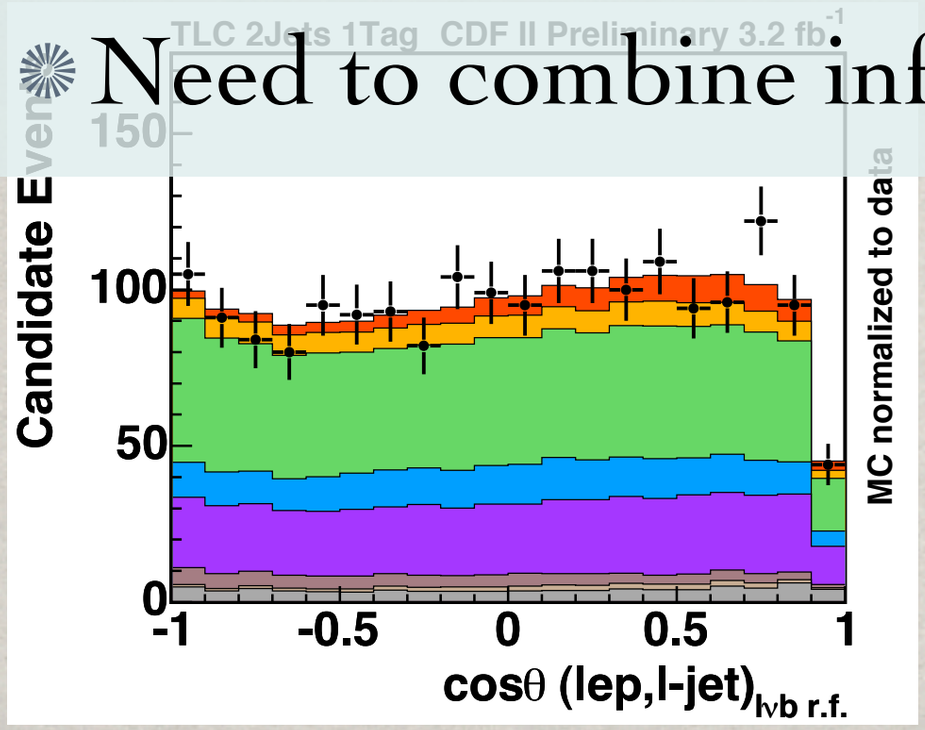


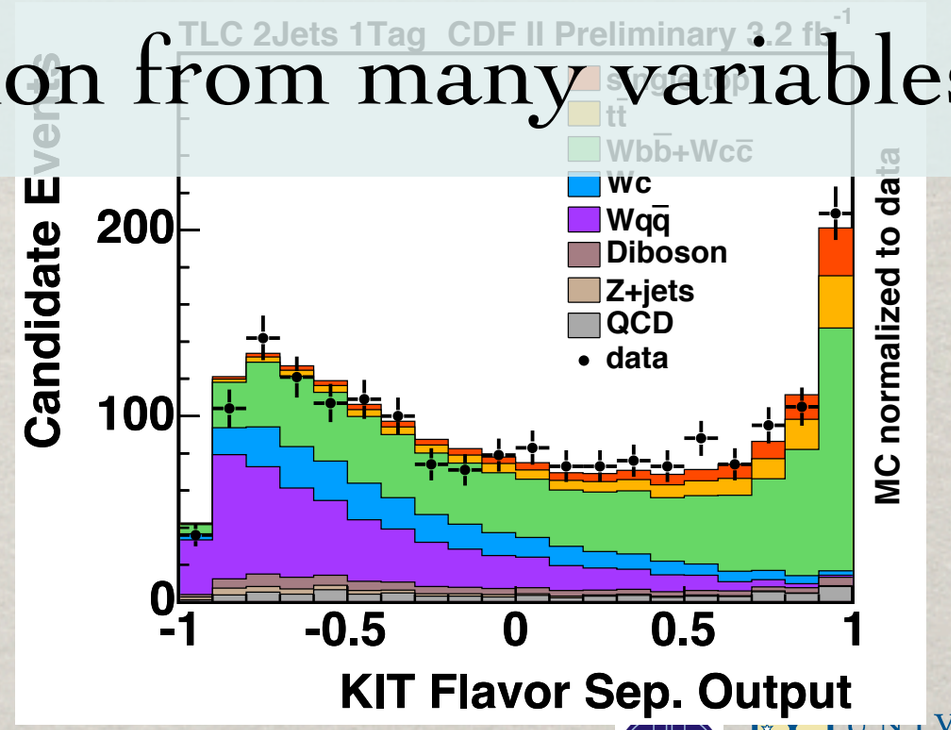
Normalized to Expectation



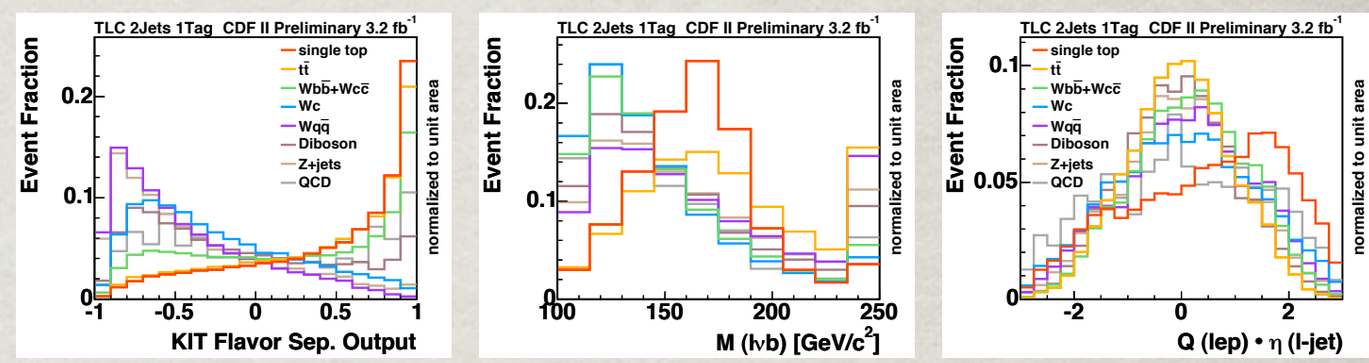


- No single variable powerful enough to separate single top from backgrounds
- Each variable contains useful information
- Need to combine information from many variables



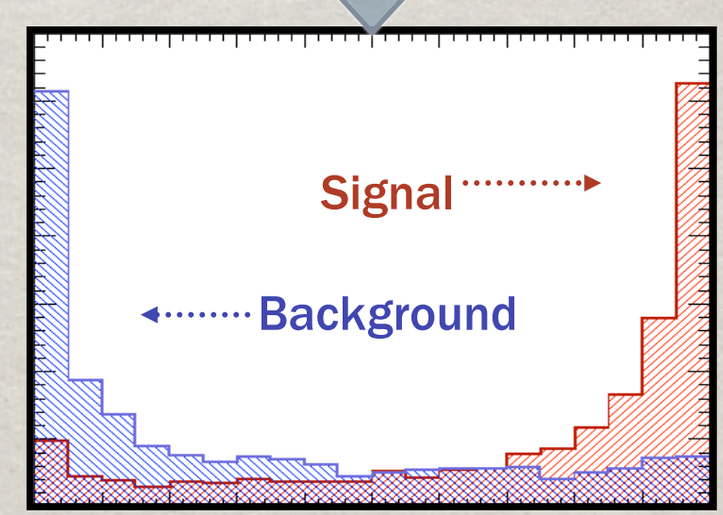


Multivariate Techniques



x y z $\ldots$

$$f(x, y, z, \ldots)$$



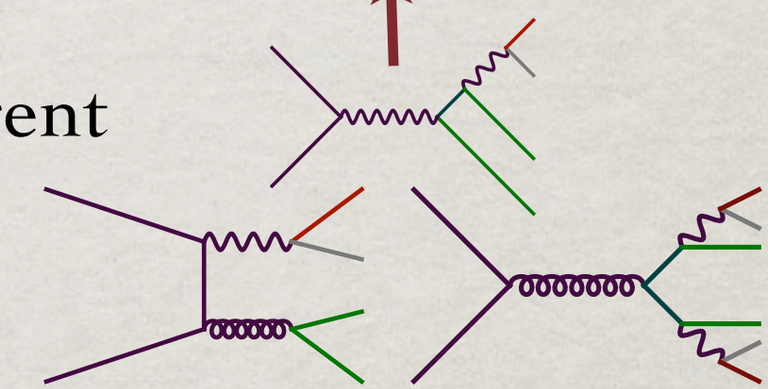
- Goals:
  - Combine multiple variables into single, more powerful discriminant
  - Reduce dimensionality of problem

Different Techniques

- Matrix Element

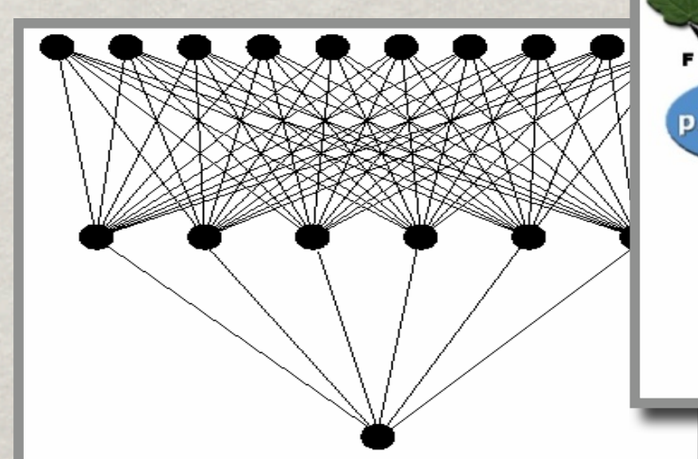
$$P_i(x) = \frac{1}{\sigma_i} \int d^n\sigma_i(y) dq_1 dq_2 f(q_1) f(q_2) W(x|y)$$

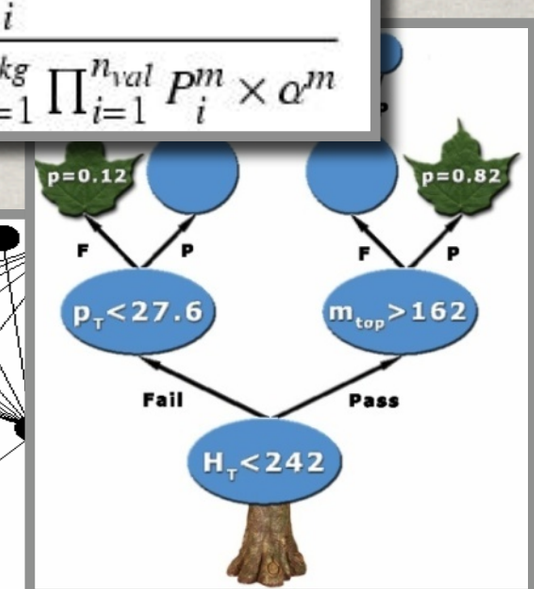
PDFs



  - Uses LO matrix elements to calculate probability for different processes
  - Includes detector resolutions (transfer functions)
- Neural Network, Boosted Decision Tree, Multivariate Likelihood function
  - General purpose multivariate techniques
  - Train using realistic MC for signal and backgrounds

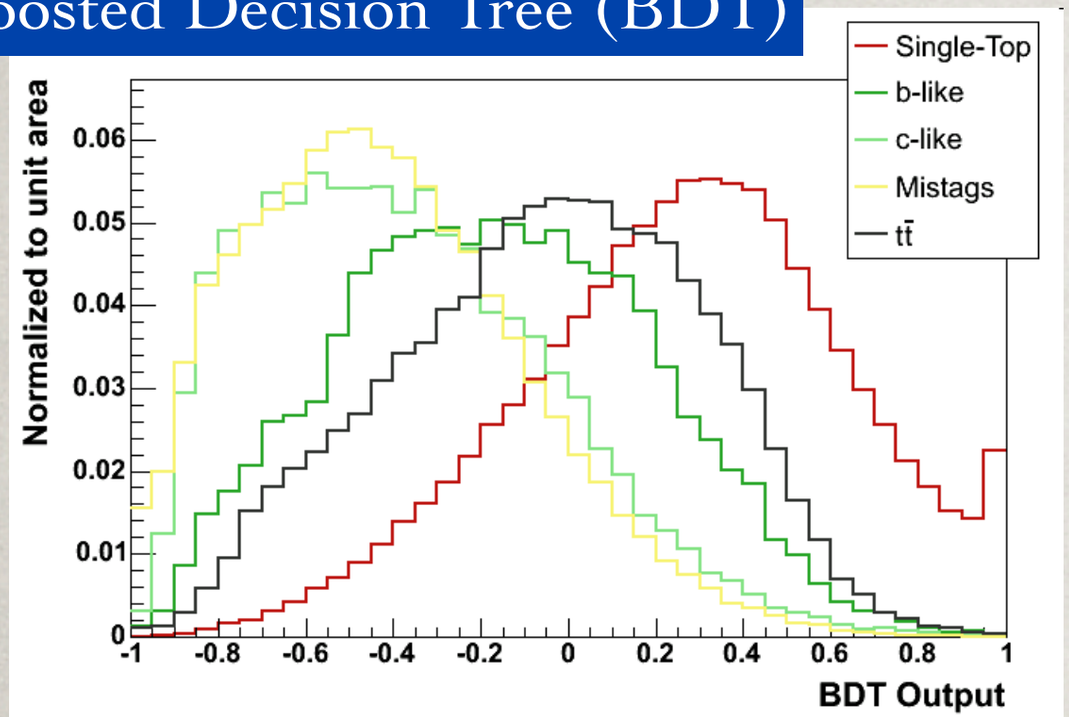
$$\mathcal{L}^{signal} = \frac{\prod_{i=1}^{n_{val}} P_i^{\text{signal}}}{\prod_{i=1}^{n_{val}} P_i^{\text{signal}} + \sum_{m=1}^{n_{bkg}} \prod_{i=1}^{n_{val}} P_i^m \times \alpha^m}$$



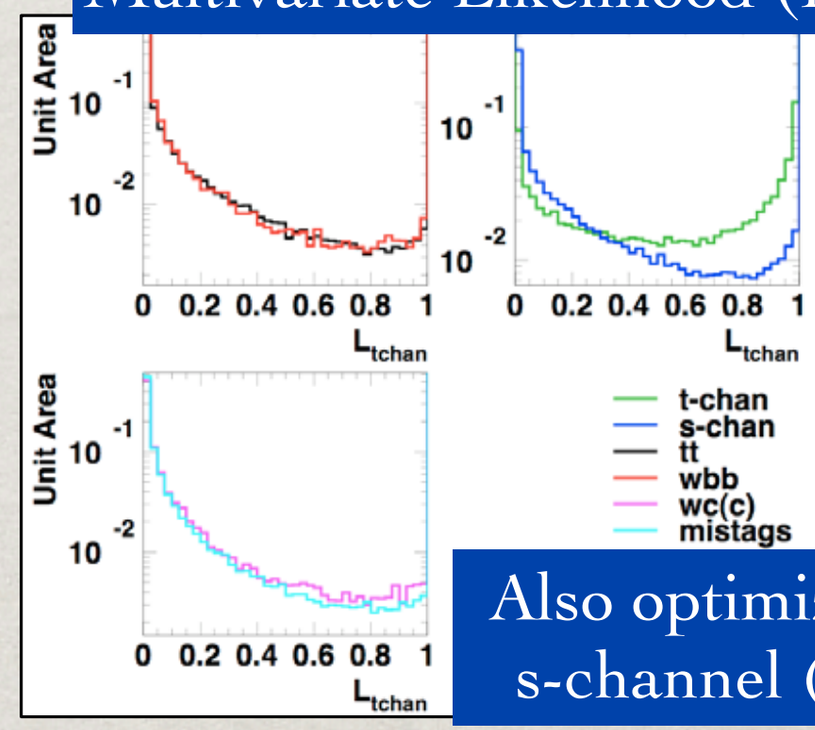


Use Each Technique

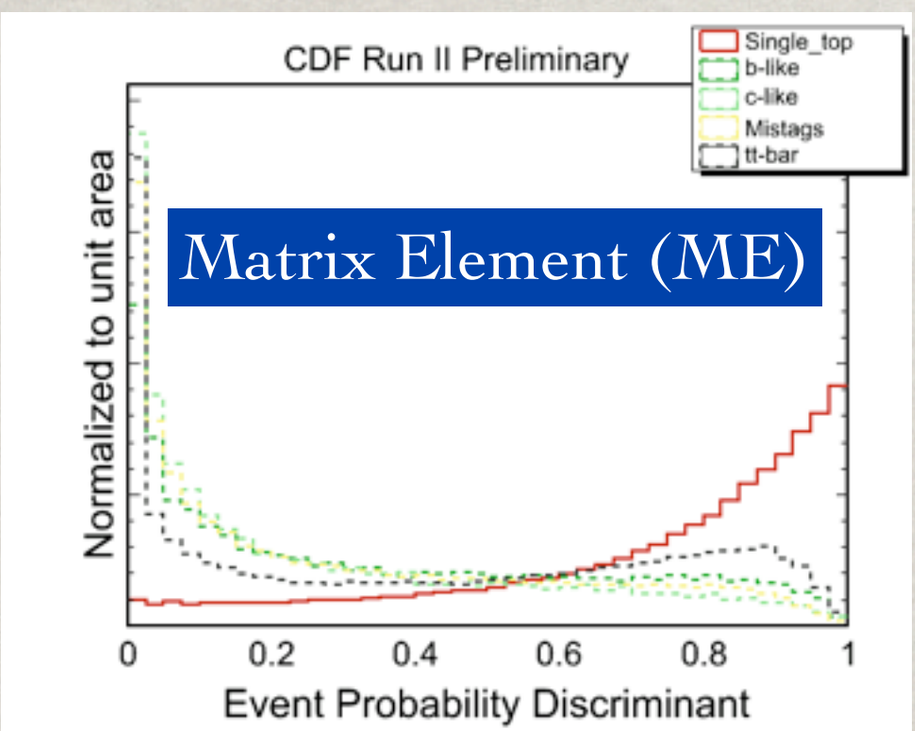
Boosted Decision Tree (BDT)



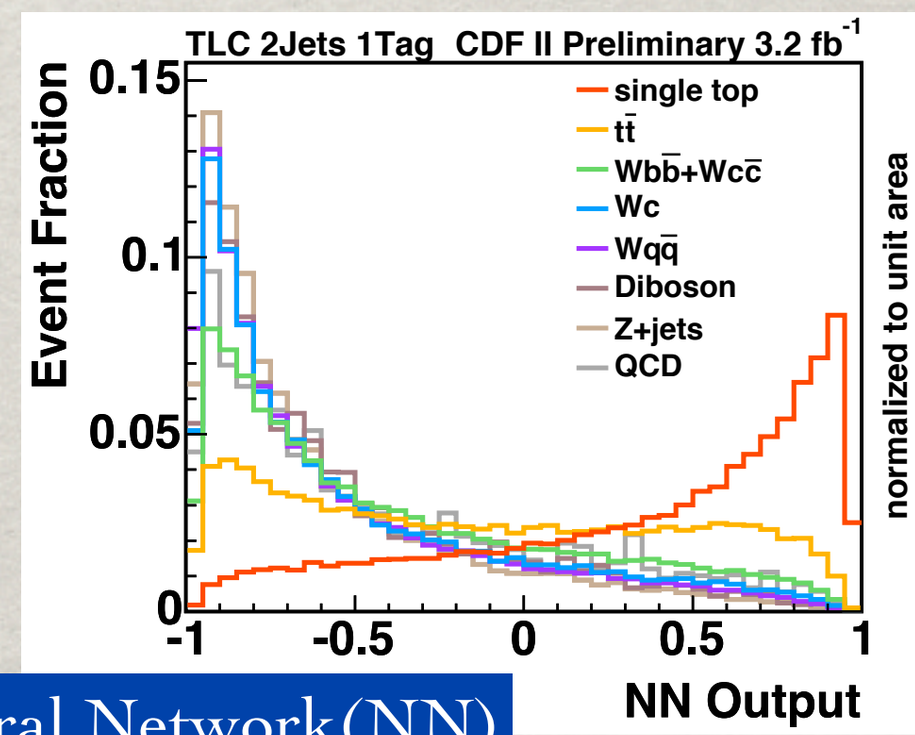
Multivariate Likelihood (LF)



Also optimized for s-channel (LFS)



Matrix Element (ME)



Neural Network (NN)

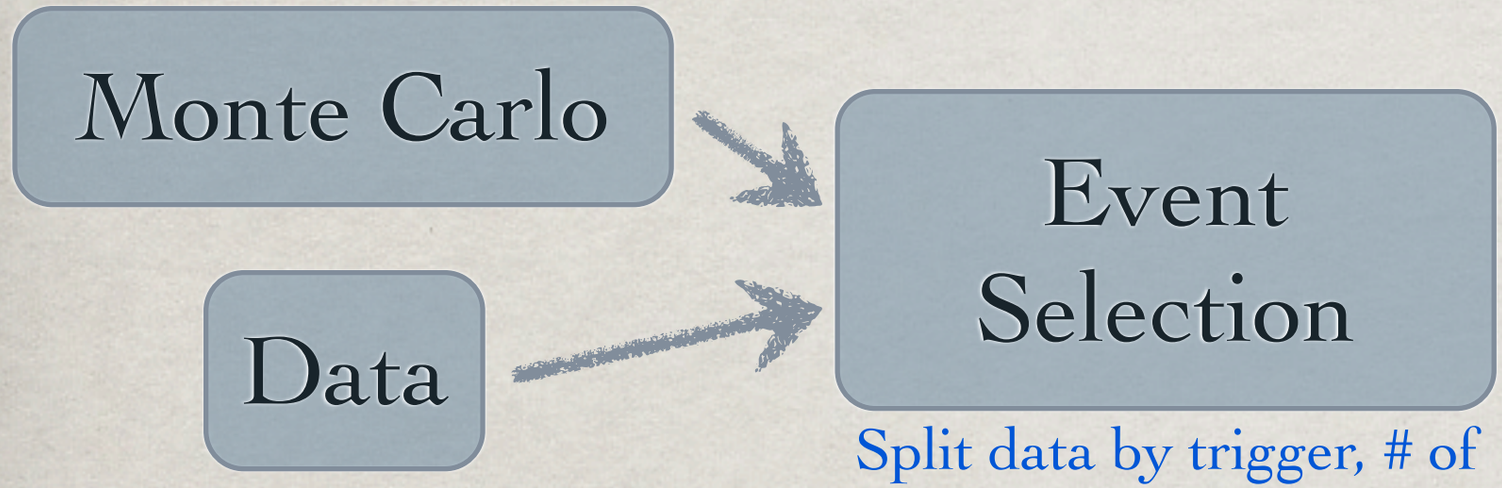
Analysis Strategy

Monte Carlo

Data

Signal regions
Side-bands/Control Regions

Analysis Strategy



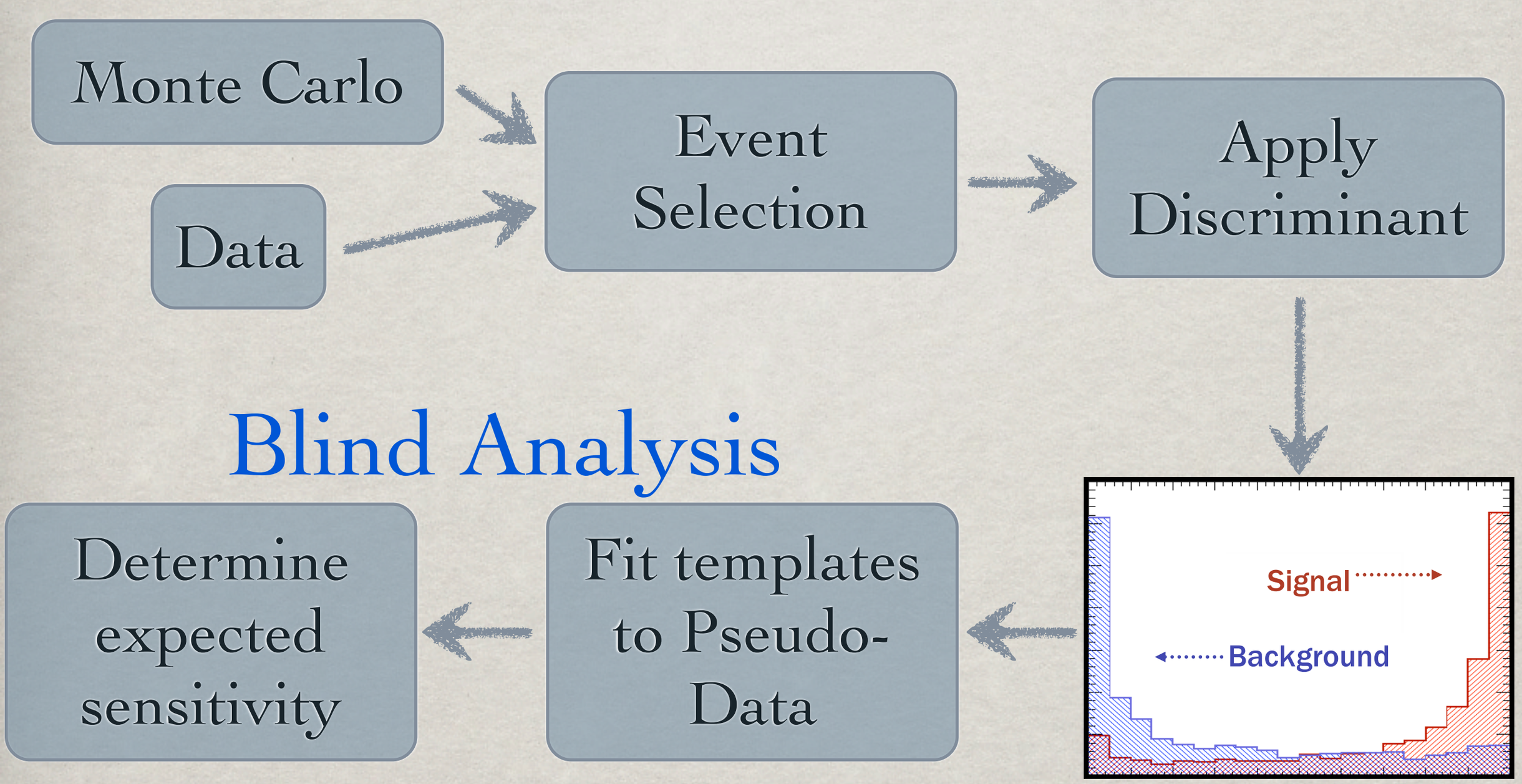
Split data by trigger, # of *b*-tags, # of jets

8 channels total

Analysis Strategy

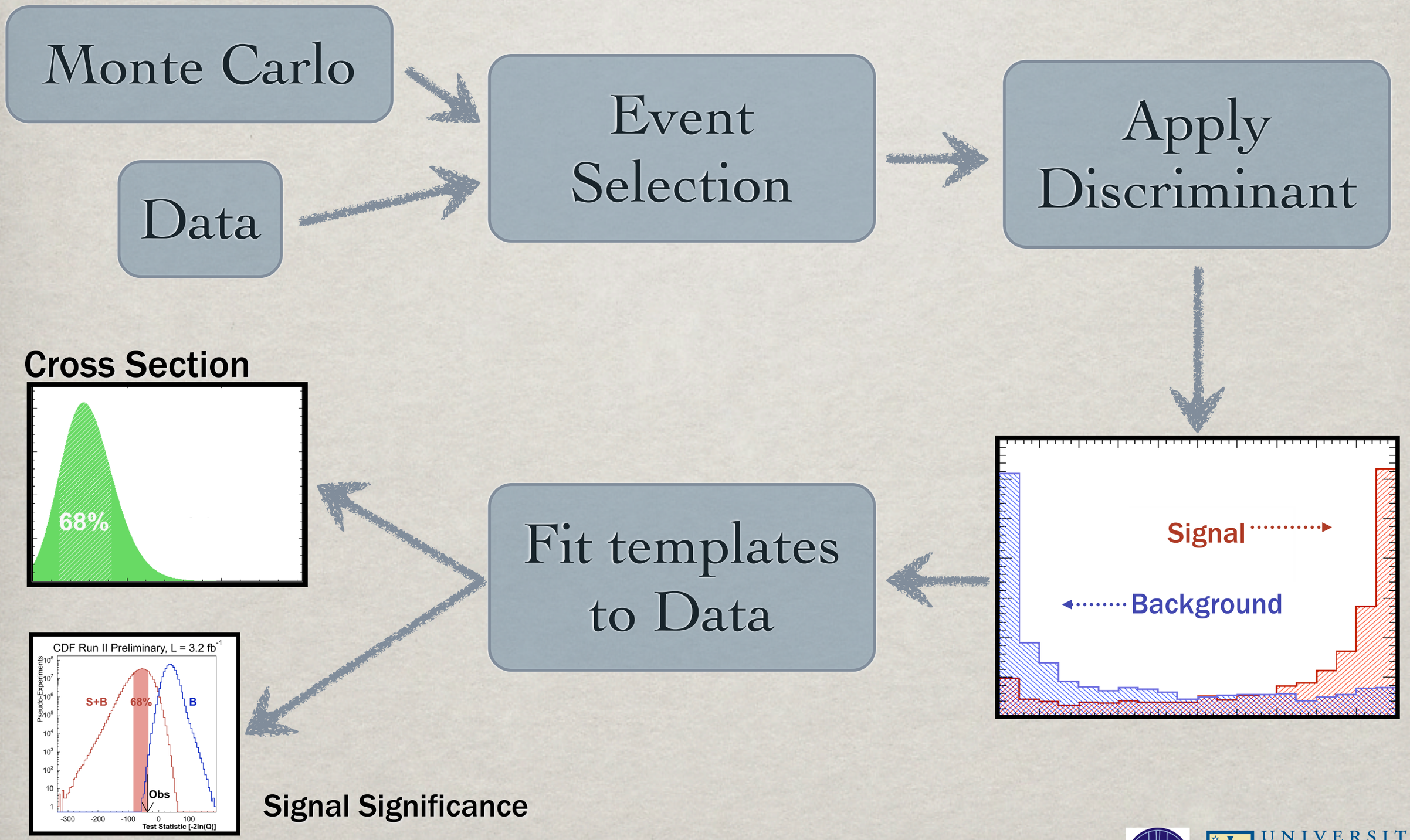
Do separately for each multivariate technique:
Boosted Decision Tree
Likelihood function
Matrix Element
Neural Network
S-Channel Likelihood Function

Analysis Strategy



Blind Analysis

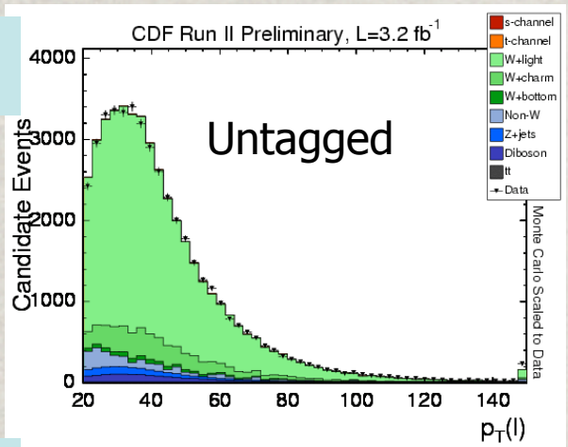
Analysis Strategy

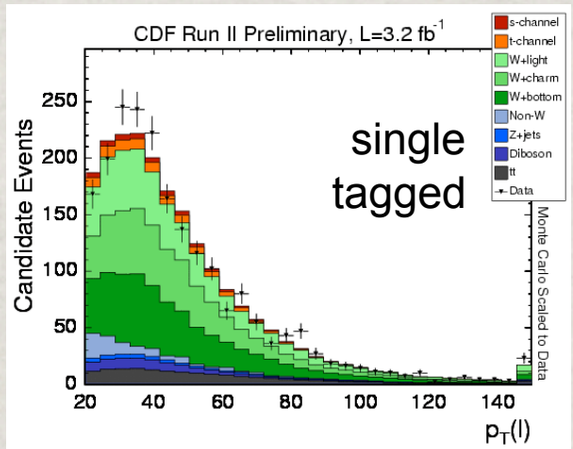


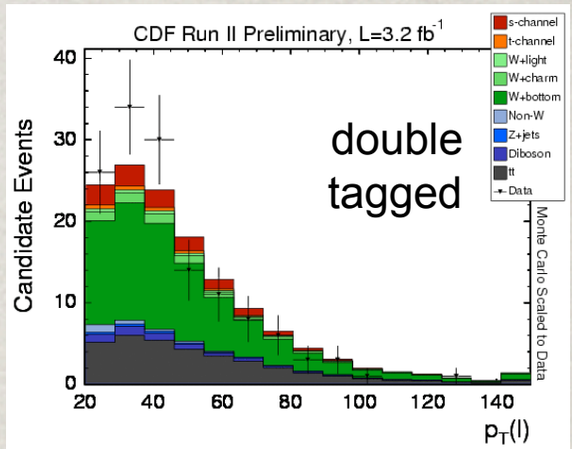
Validation of Inputs

- Critical that all inputs be well modeled within uncertainties

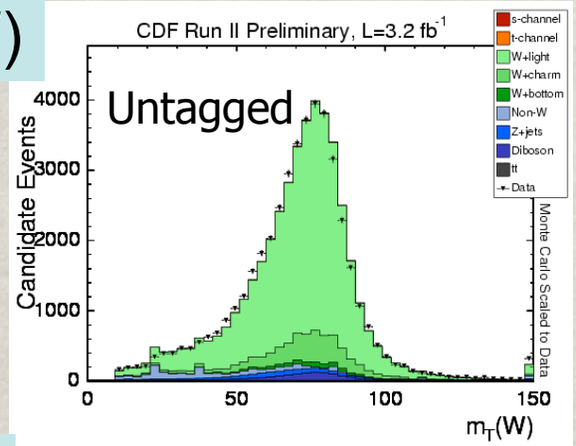
P_T lepton

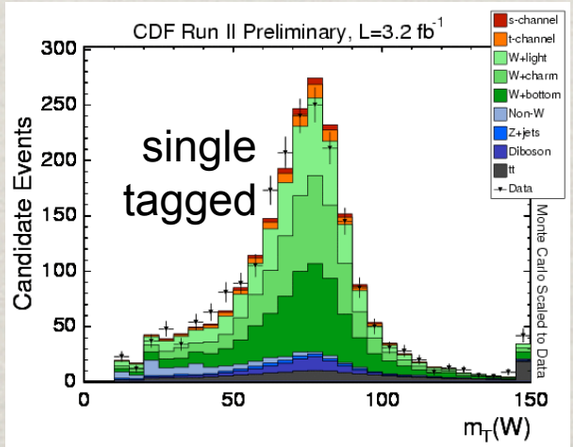


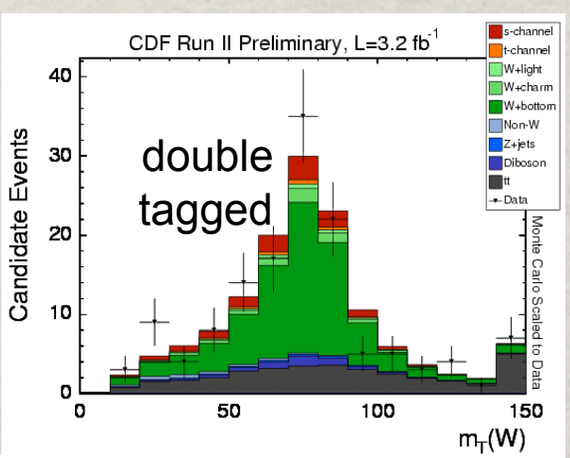




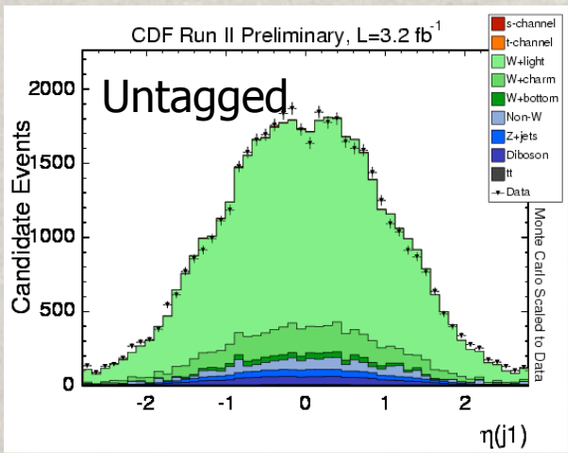
$M_T(W)$

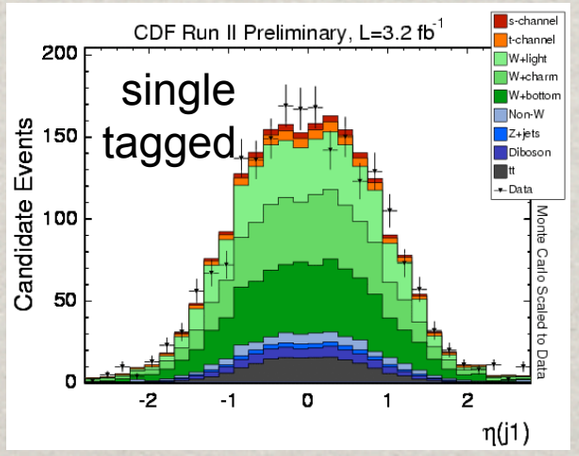


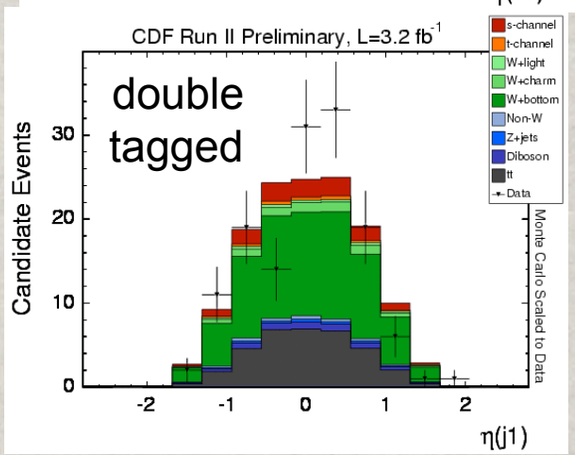




$J_1(\eta)$



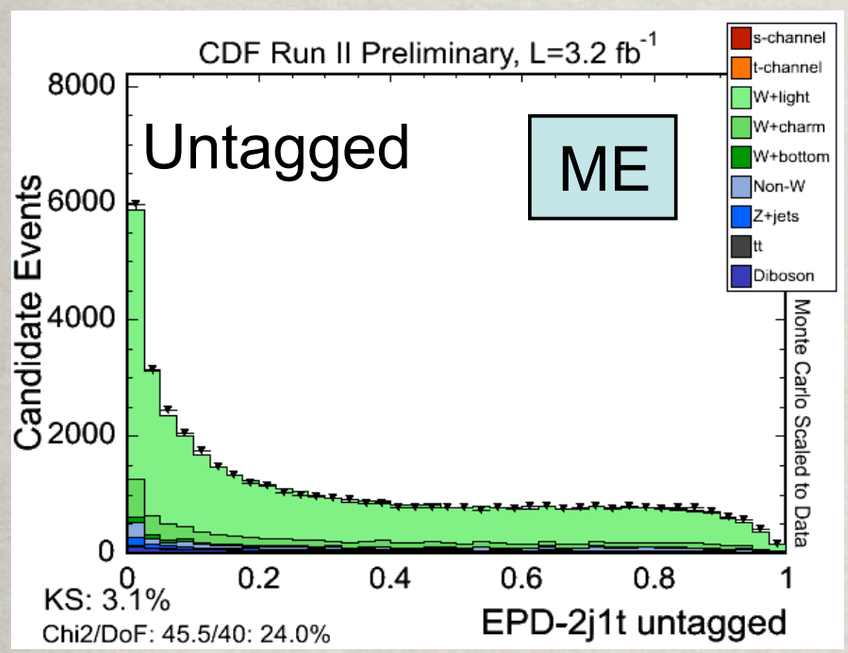


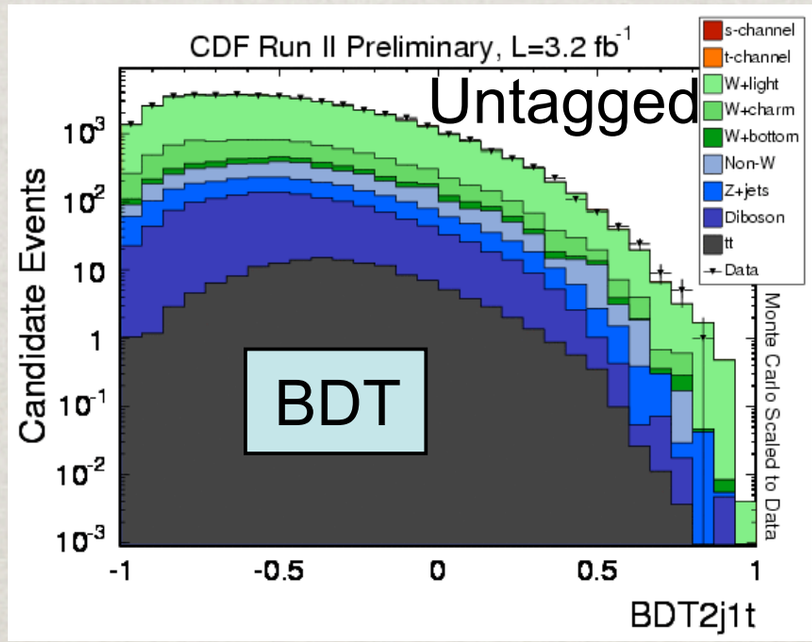


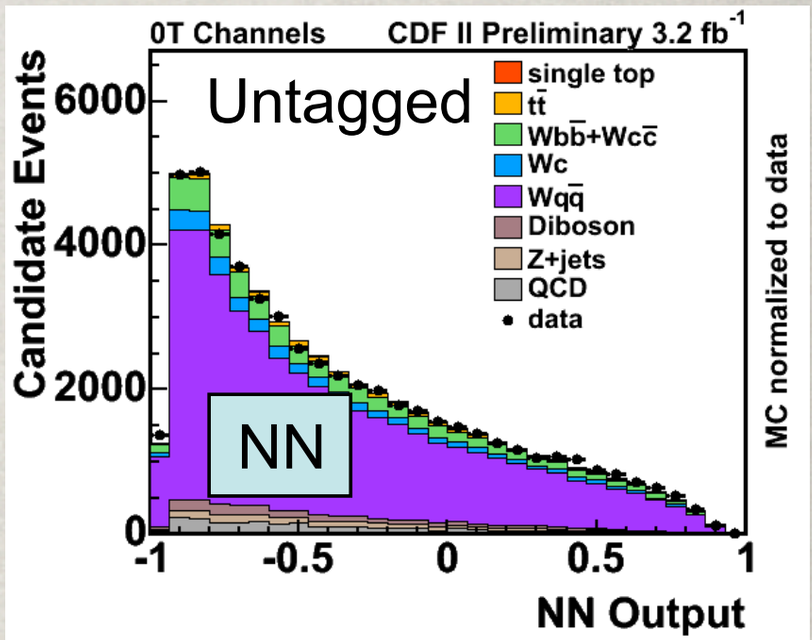
Checked hundreds of distributions

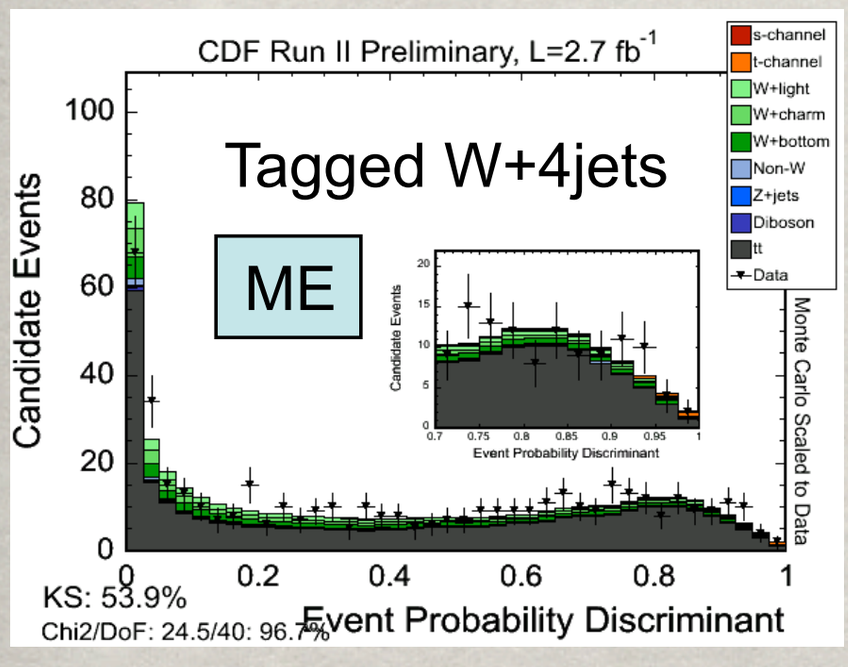
Validation of Outputs

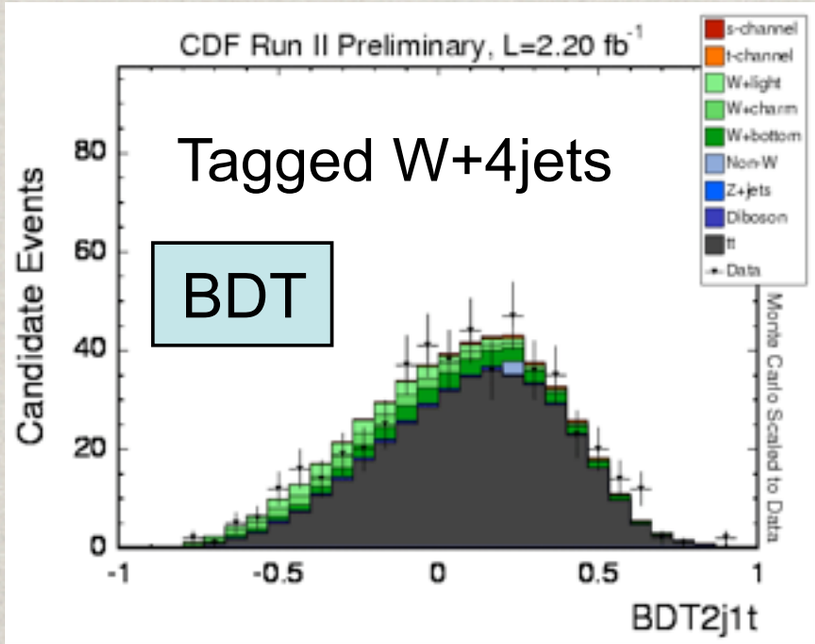
- Also need to check all variables together (correlations)

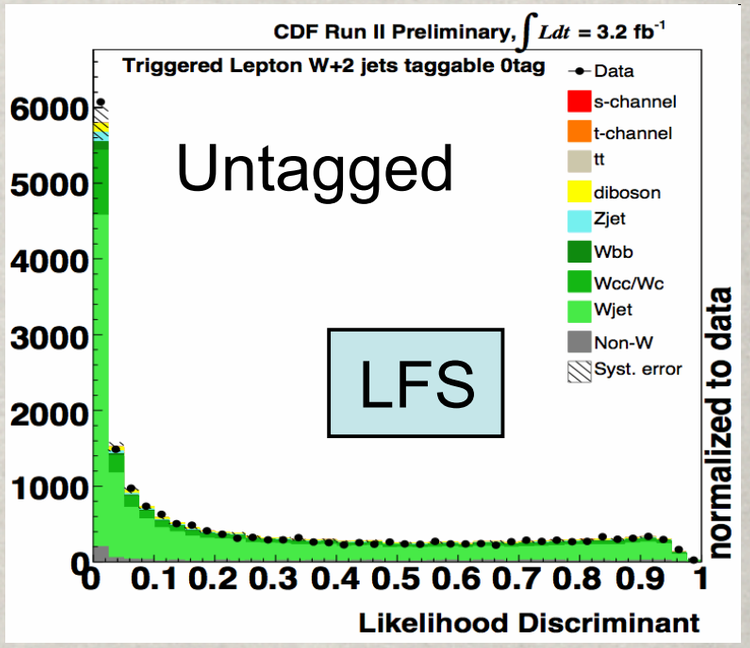






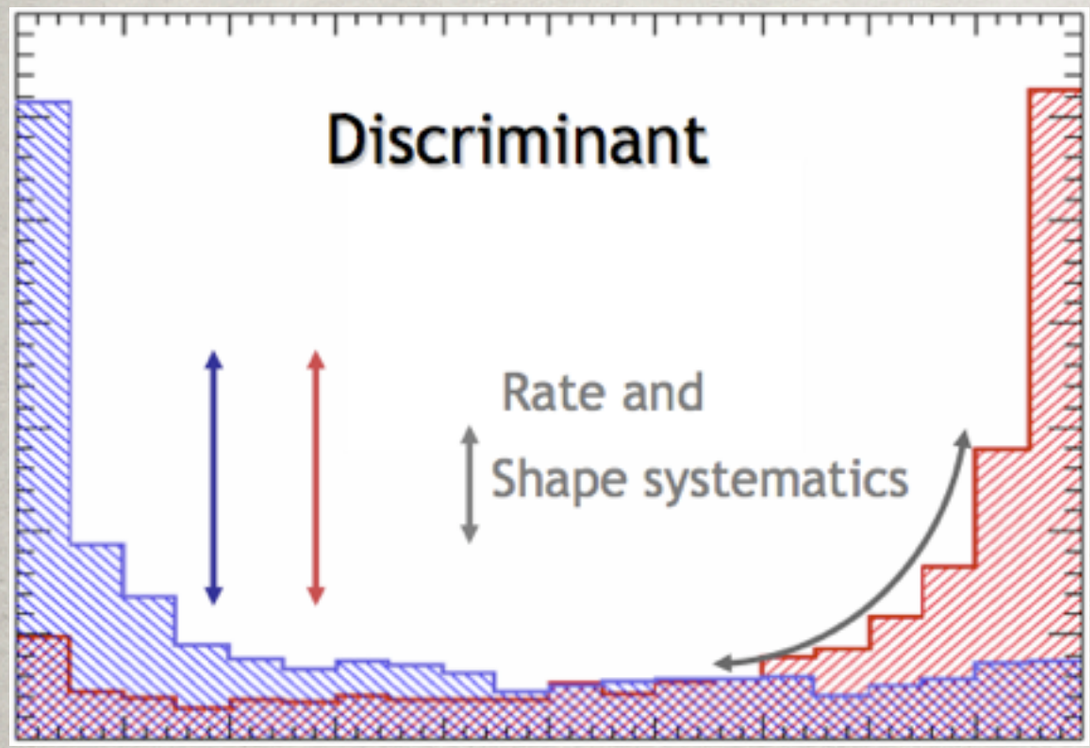






Systematic Unceratinties

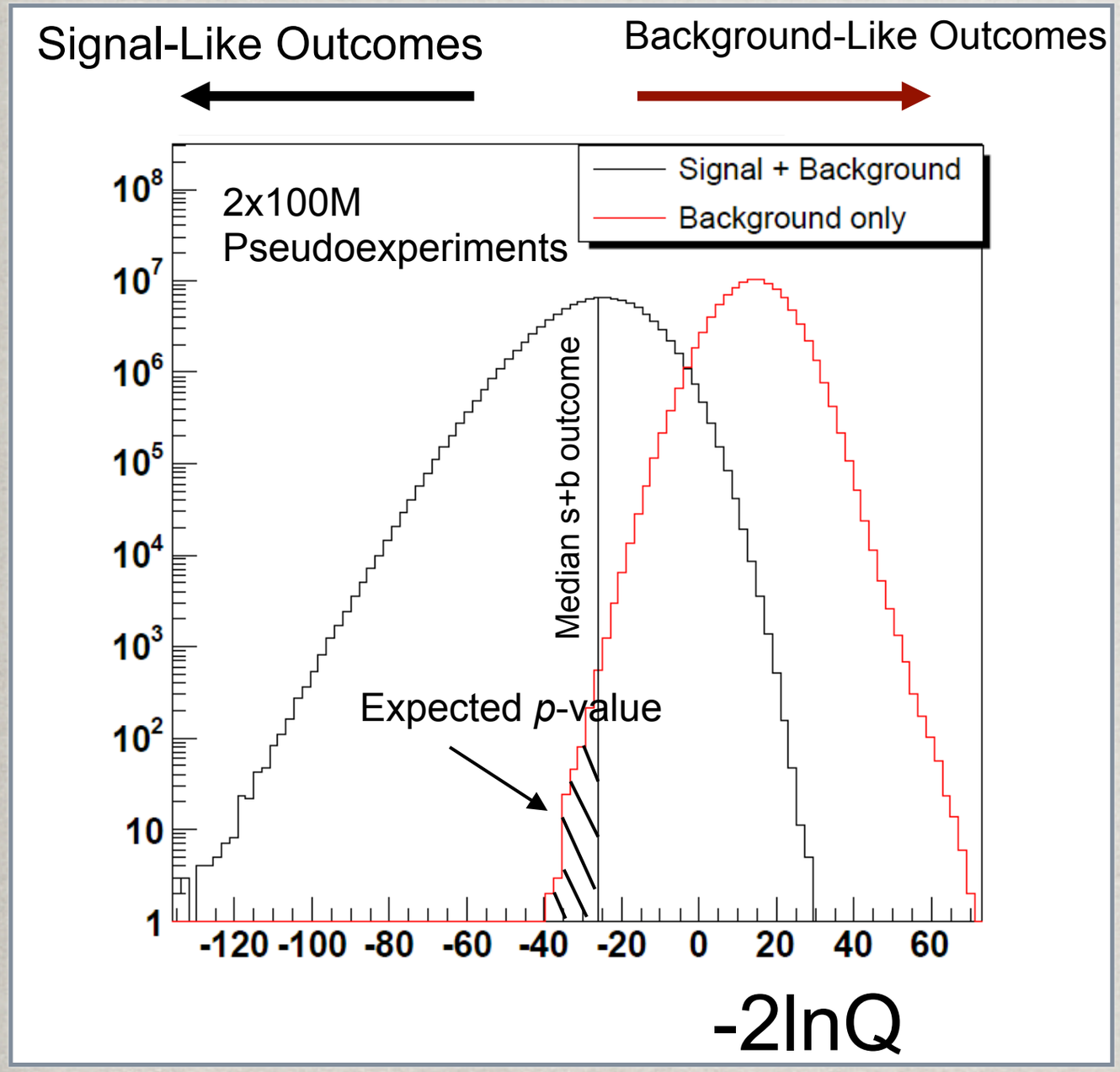
- After working hard to achieve best agreement between data and background model, carefully assess systematics



Consider sources that affect rate, discriminant shape, or both

Systematic Uncertainty	Rate	Shape
Jet Energy Scale	0-10%	✓
Initial + Final State Radiation	0-15%	✓
Parton Distribution Functions	2-3%	✓
Monte Carlo Generator	1-5%	
Event Detection Efficiency	0-9%	
Luminosity	6%	
Neural Net B-Tagger		✓
Mistag Model		✓
Q^2 Uncertainty		✓
Input Variable Mismodeling		✓
Wbb+Wcc Normalization	30%	
Wc Normalization	30%	
Mistag Normalization	17-29%	
Top Pair Normalization and m_{Top}	23%	✓

Hypothesis Testing



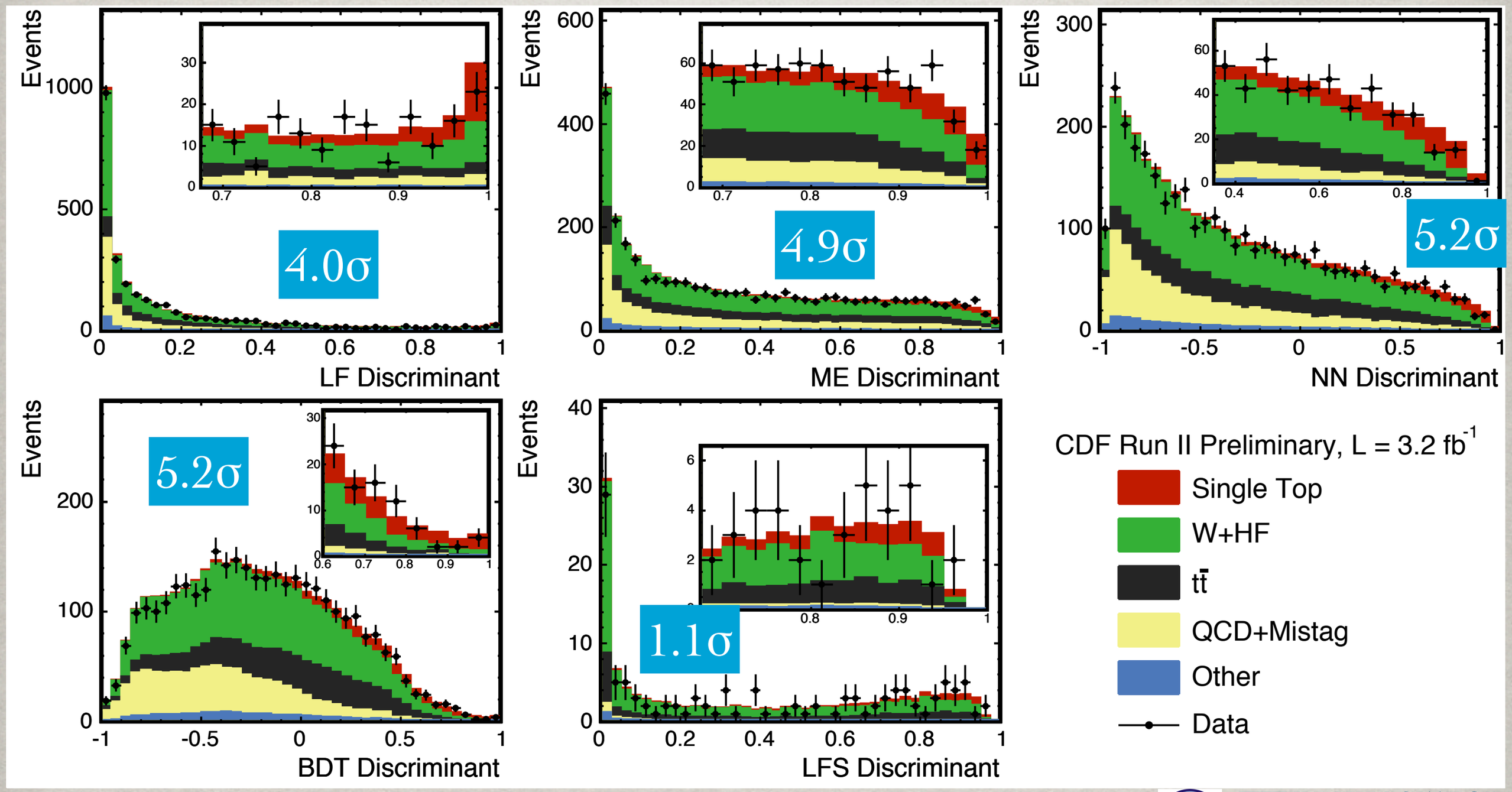
- Quote p-value: Probability of upward fluctuation of background to data or something more signal like

$$Q = \frac{P(\text{data} \mid s+b, \hat{\theta})}{P(\text{data} \mid b, \hat{\hat{\theta}})}$$

$\theta \equiv$ Nuisance parameters

Sensitivity

- Expected sensitivity for each discriminant



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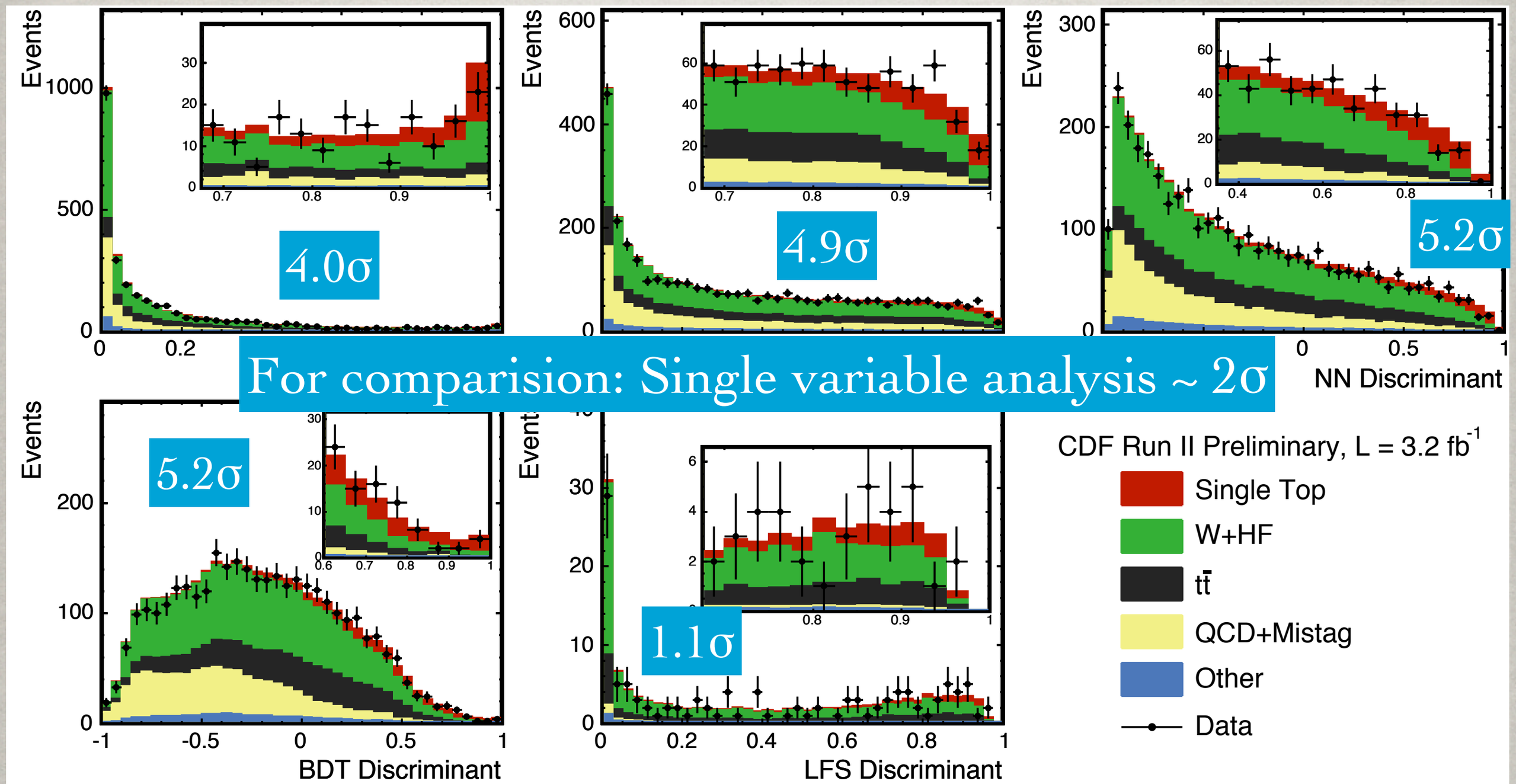

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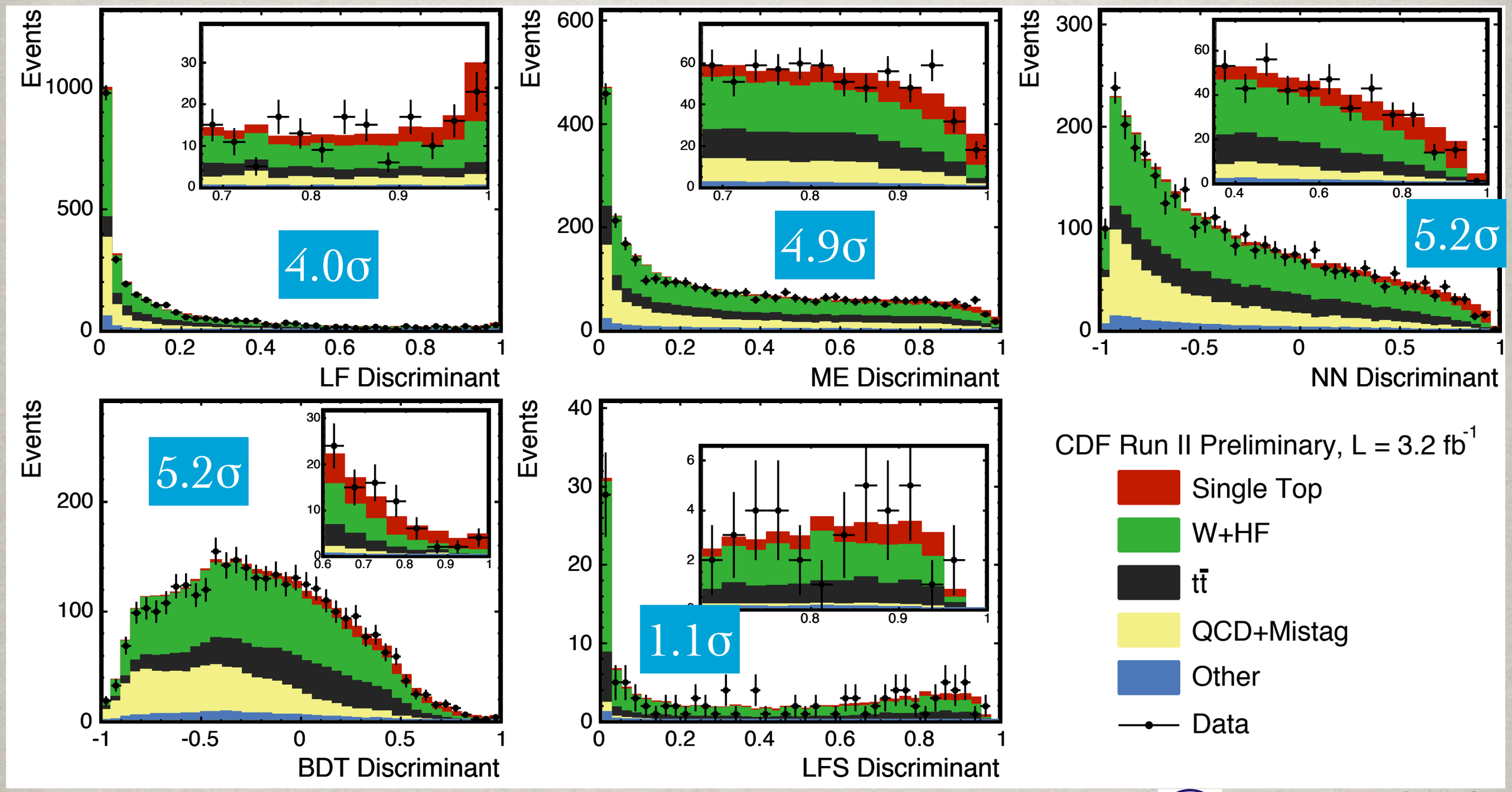
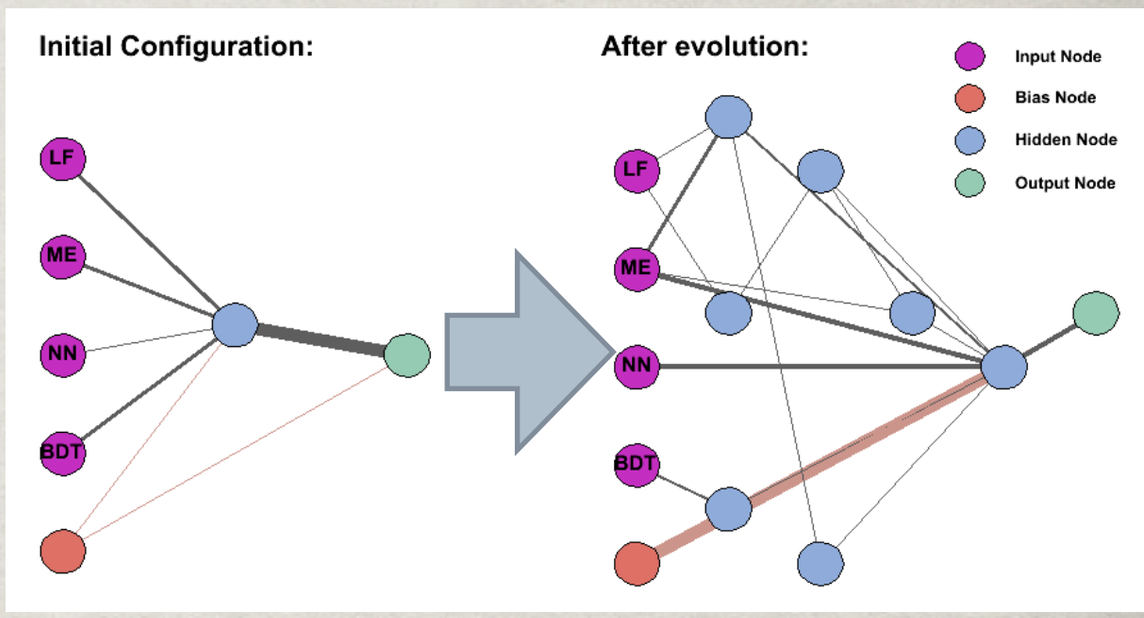
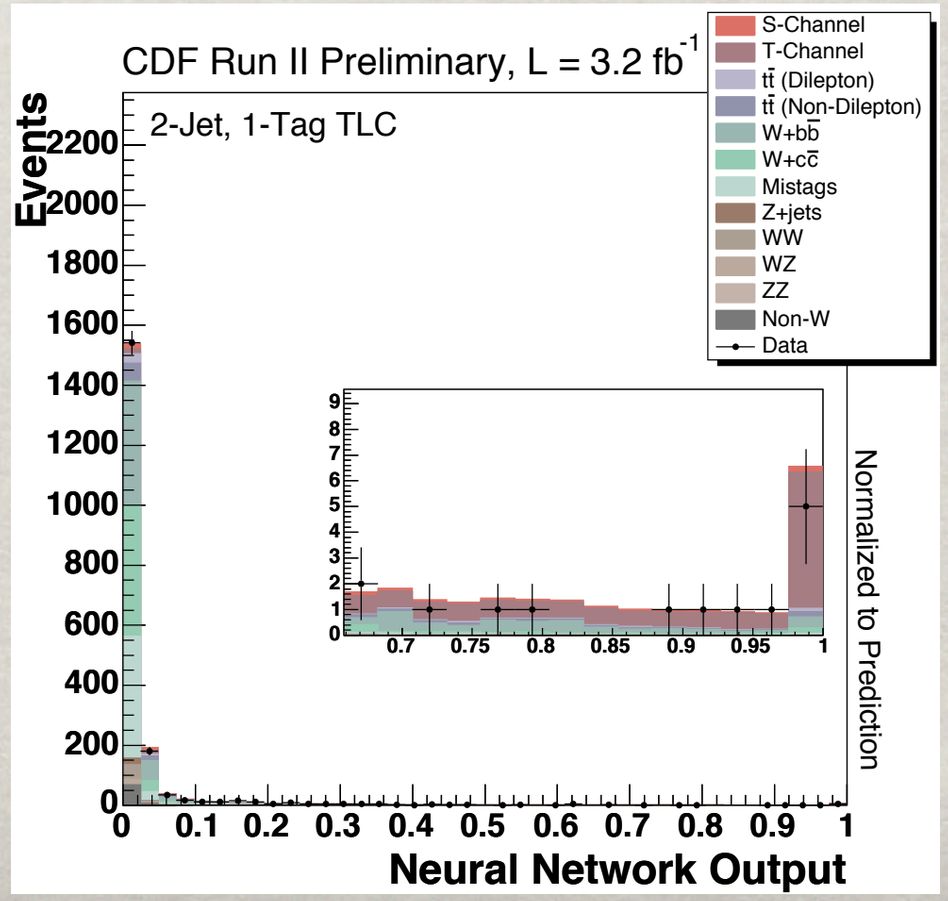


Combination

- Super Discriminant (SD): Treat outputs of discriminants as inputs to new discriminant
  - Use Neural Network for SD
  - Optimize for best expected p-value using genetic algorithms
    - Network weights
    - Network topology
    - Histogram binning



Neuro-Evolution of Augmenting Topologies (NEAT)
K O. Stanley and R. Miikkulainen, Evolutionary Computation **10 (2)** 99-127(2002)



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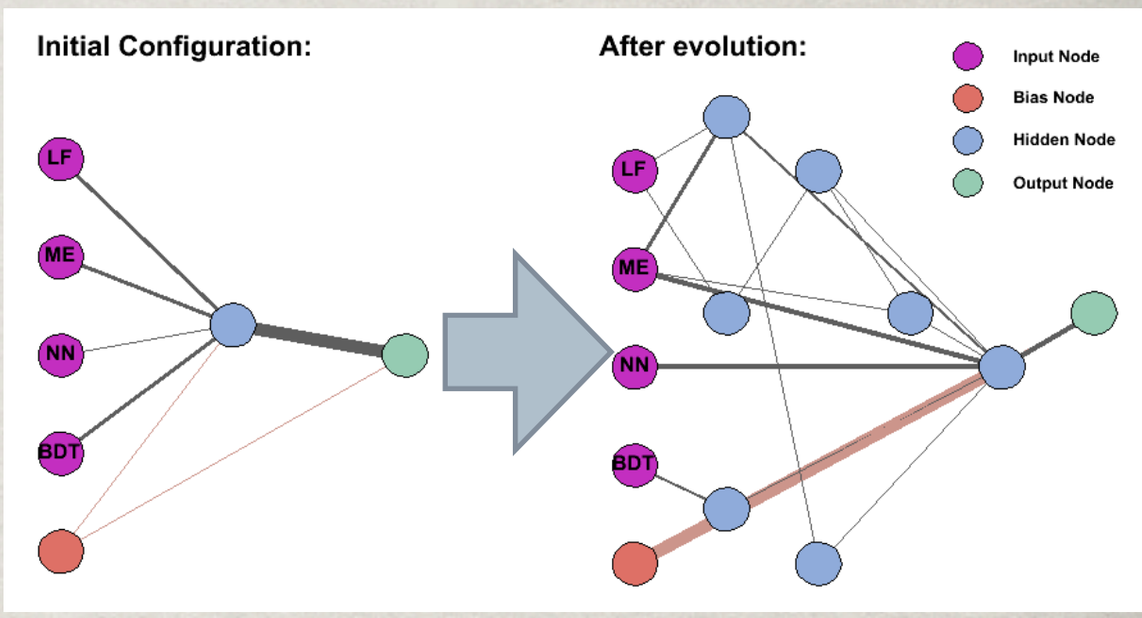

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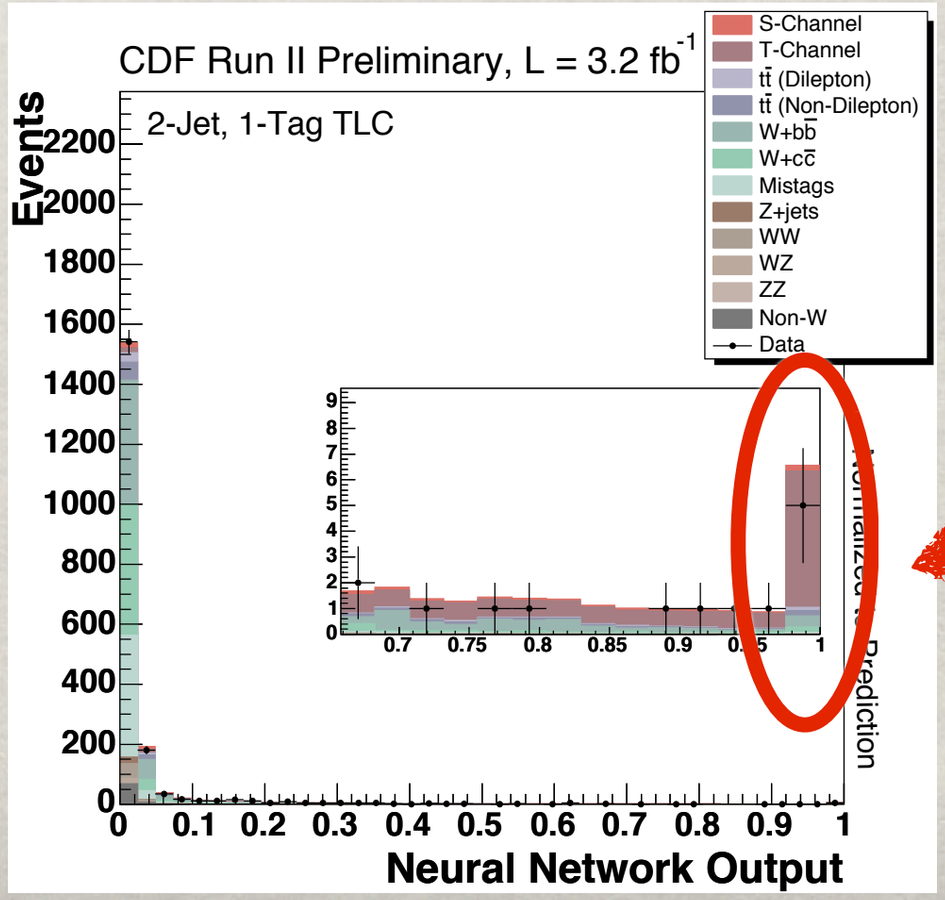
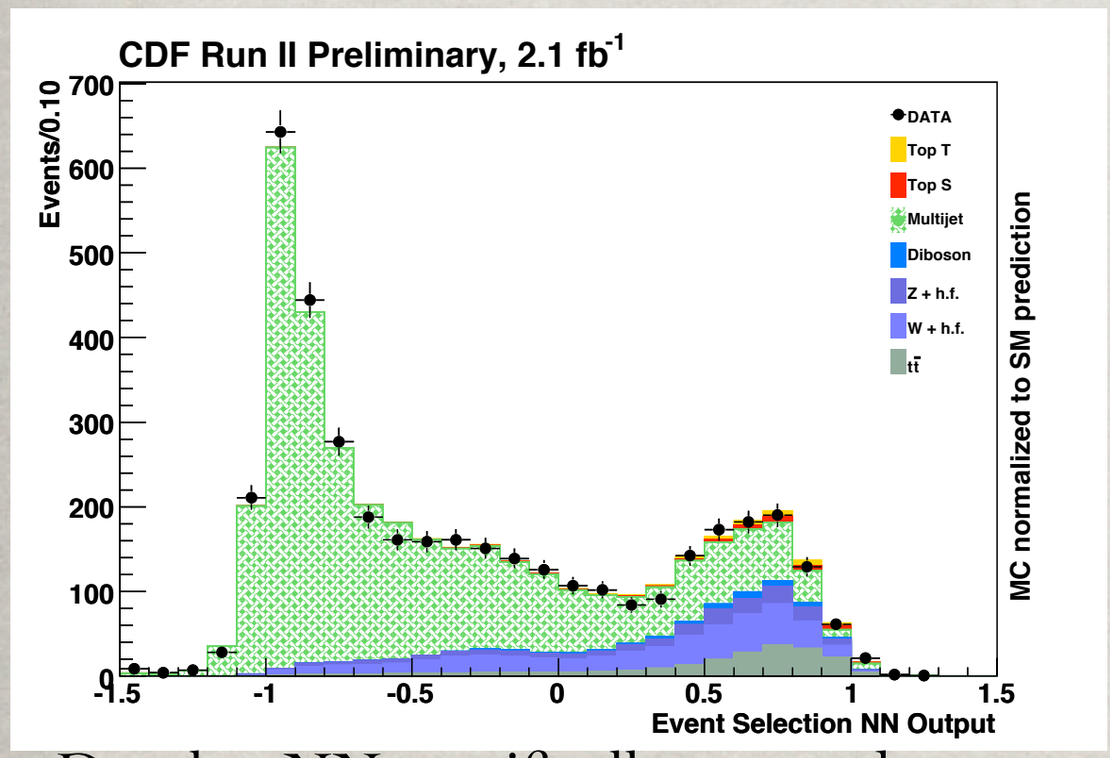


$$\frac{S}{B} = 5.2$$

MET+Jets

- Recover single top events with no reconstructed lepton
  - Lepton outside detector acceptance
  - W decays to tau + neutrino

Must deal with overwhelming QCD background: mismeasured jet → MET



Develop NN specifically targeted at removing QCD: uses angular correlations and difference between calorimeter MET and missing track momentum

MET+Jets

- Recover single top events with no reconstructed lepton
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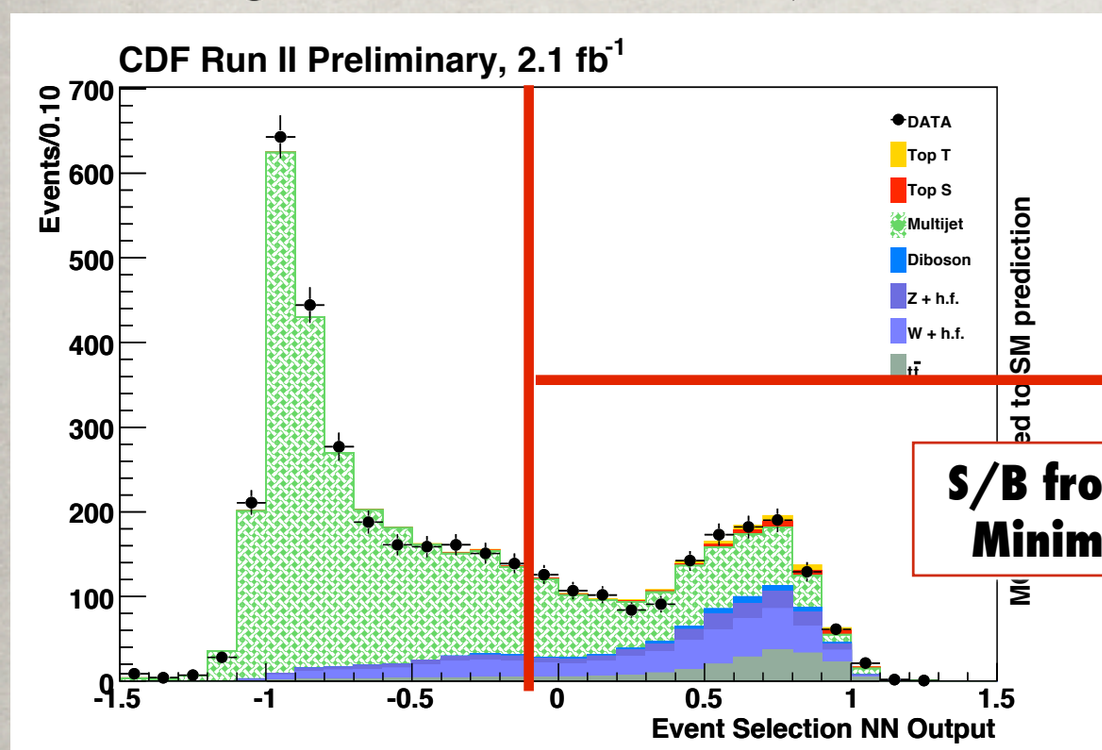
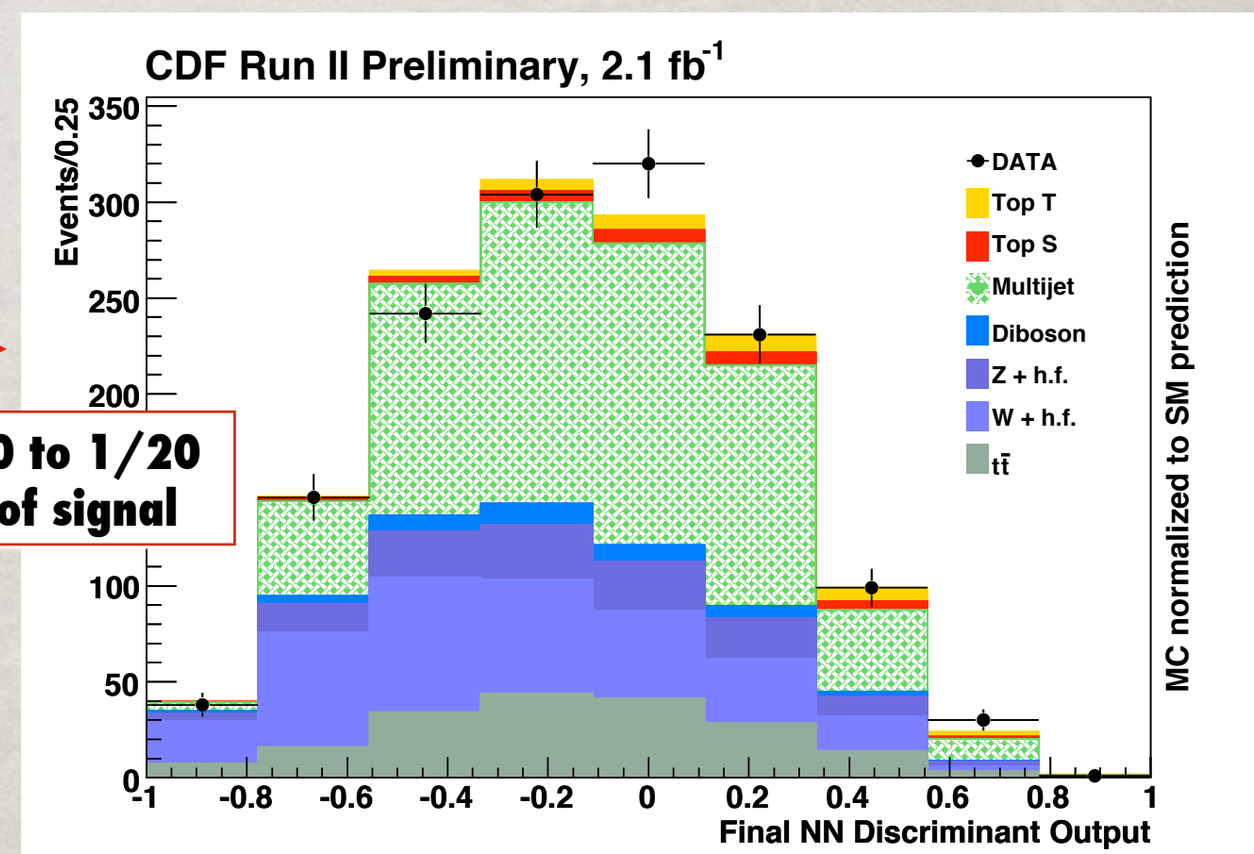


Final discriminant is NN using kinematic quantities, similar to other channels

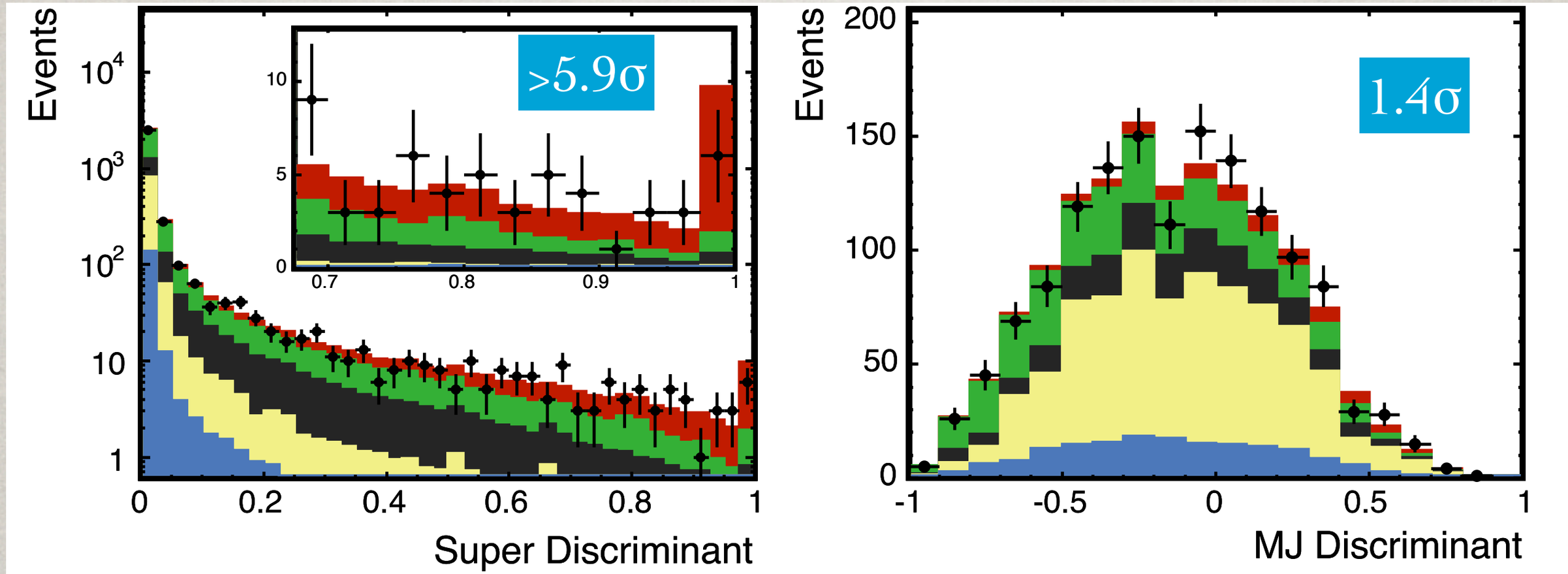


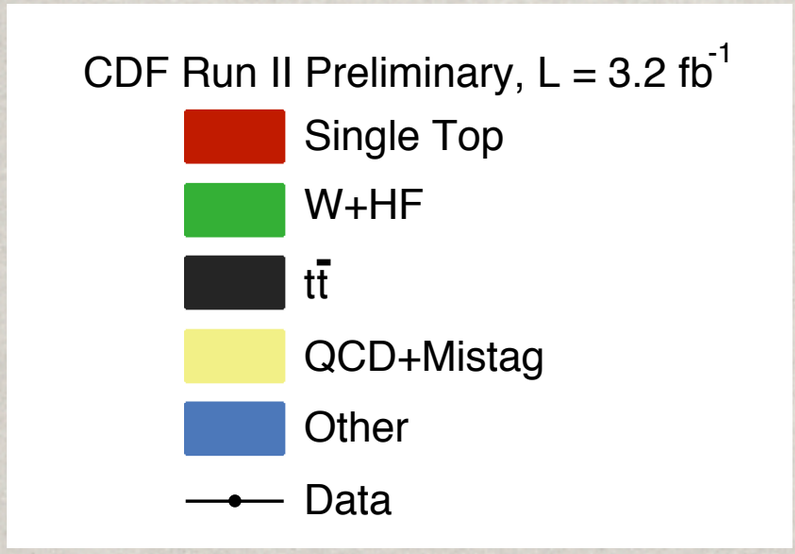
S/B from 1/50 to 1/20
Minimal loss of signal

Develop NN specifically targeted at removing QCD: uses angular correlations and difference between calorimeter MET and missing track momentum

Background.....Signal

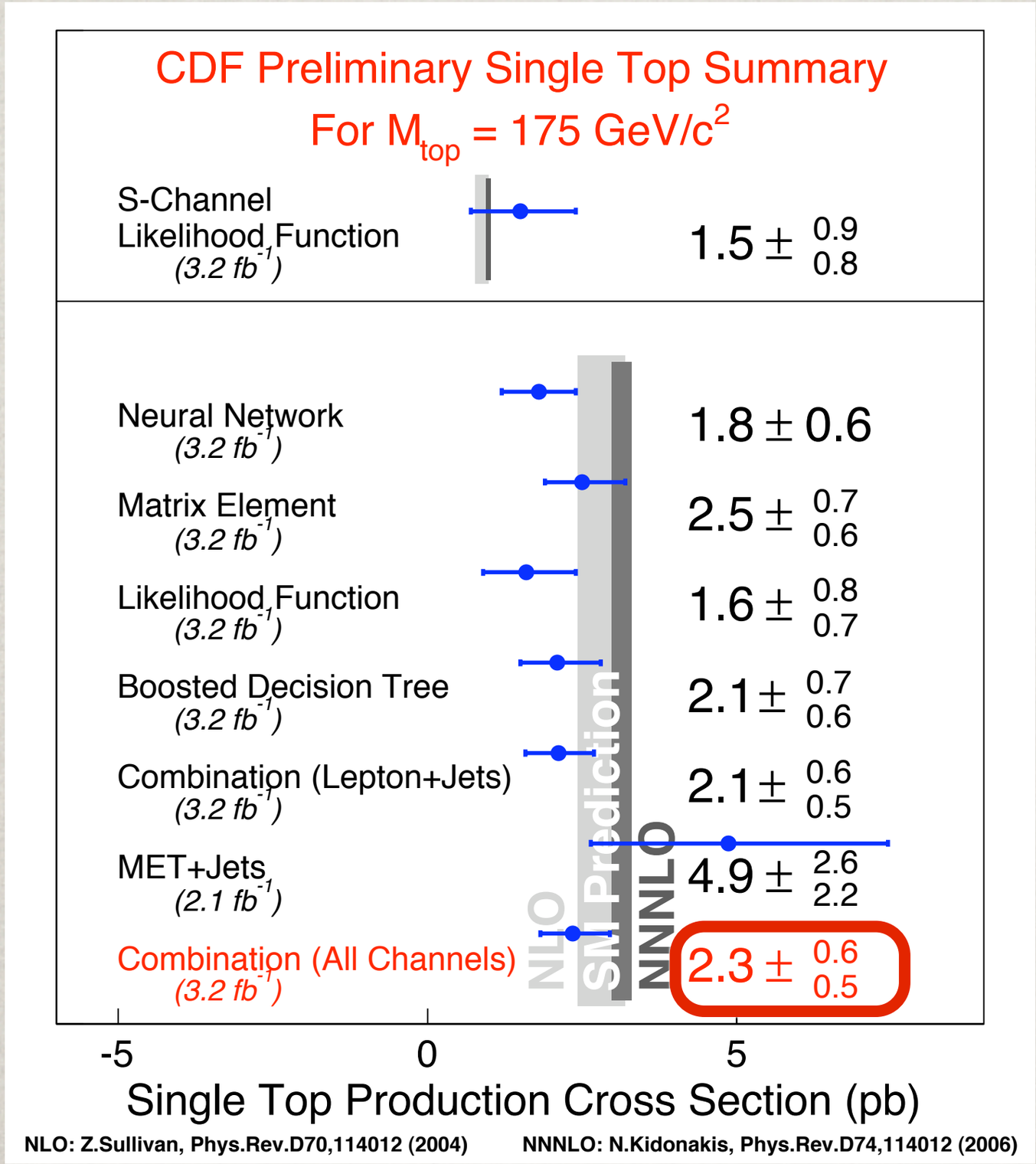
Combined Fit





- Do a simultaneous fit to independent data sets to obtain final CDF result

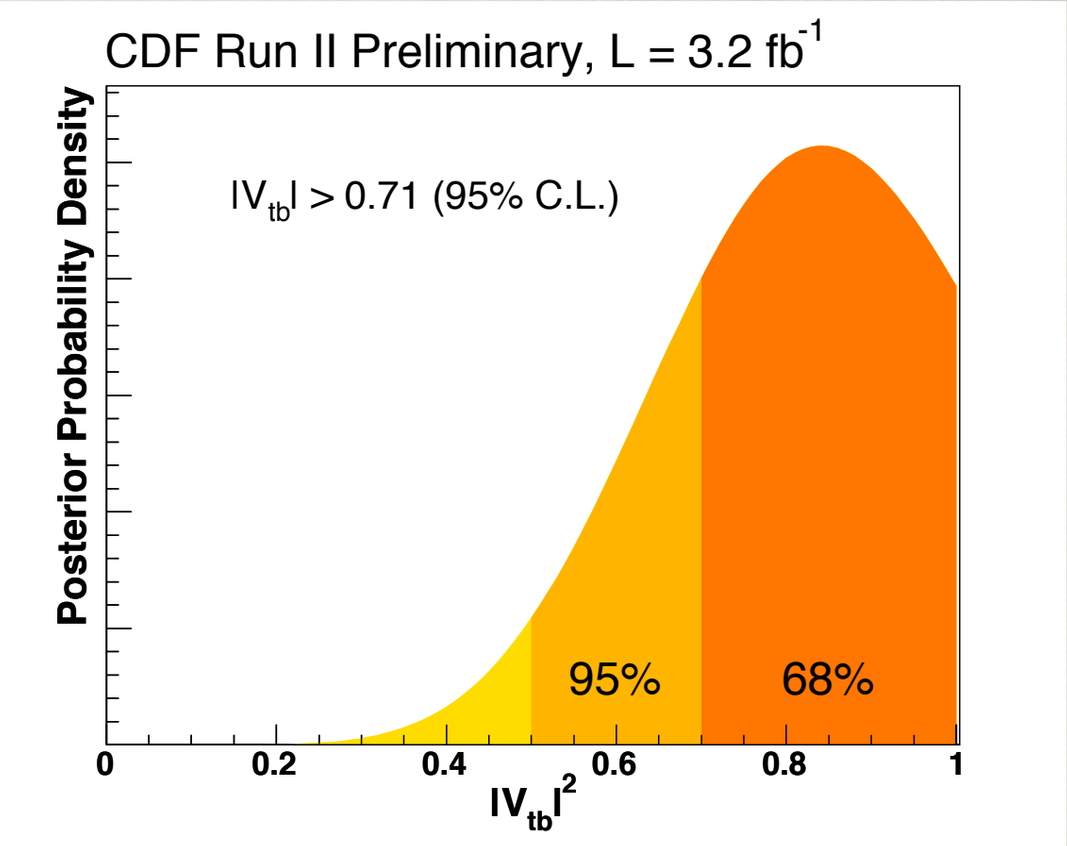
Cross Section Result



$|V_{TB}|$

- Assumptions:
  - Standard Model (V-A) coupling
  - $|V_{tb}| >> |V_{tu}| + |V_{ts}|$ (from $B(t \rightarrow Wb)$ measurements)

$$|V_{tb,meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} \cdot |V_{tb,SM}|^2$$

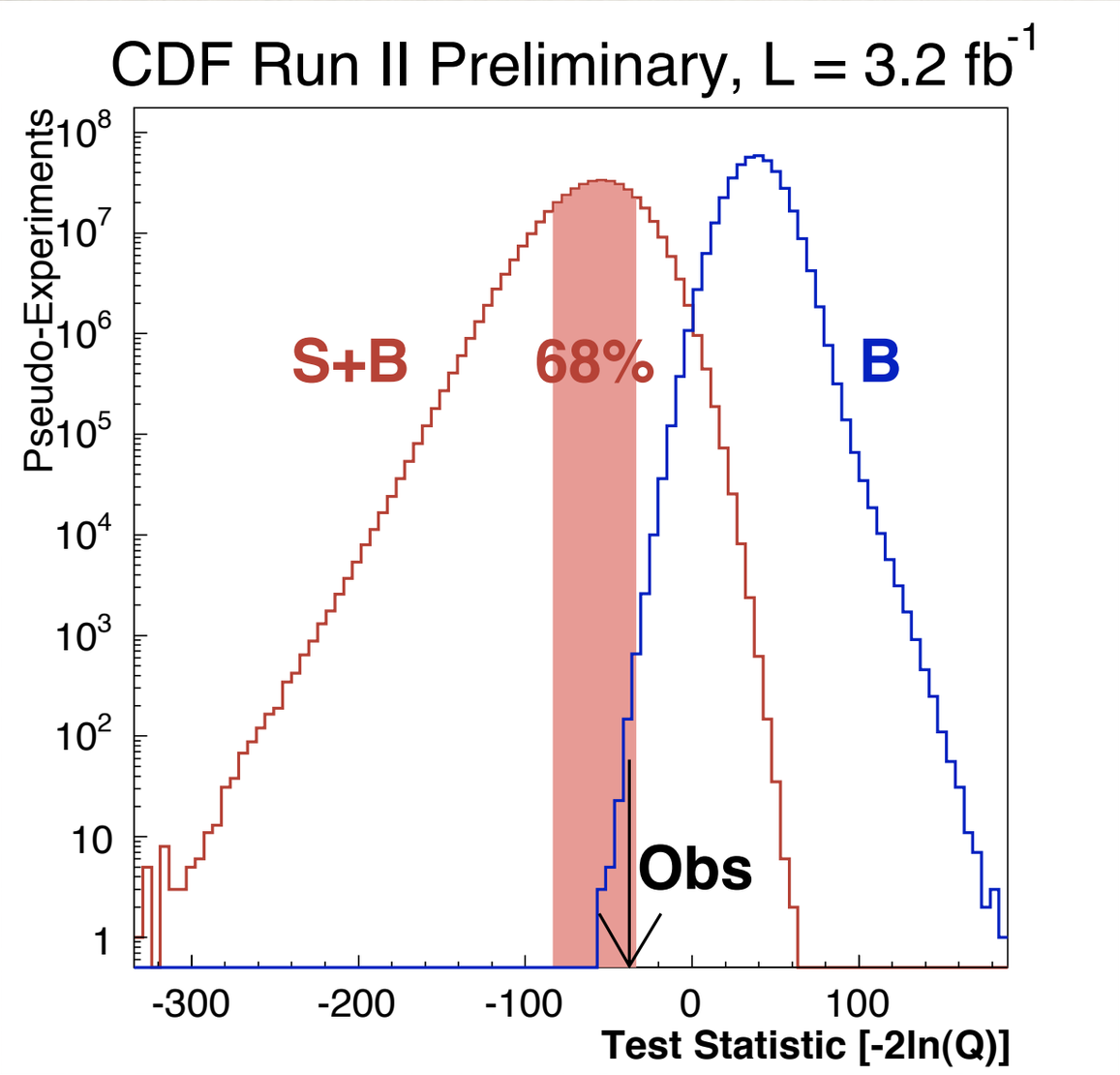


Central value: $|V_{tb}| = 0.91 \pm 0.11\ (\text{exp}) \pm 0.07\ (\text{theory})$

95% C.L. lower limit: $|V_{tb}| > 0.71$

Z. Sullivan, Phys.Rev. D70 (2004) 114012

Significance

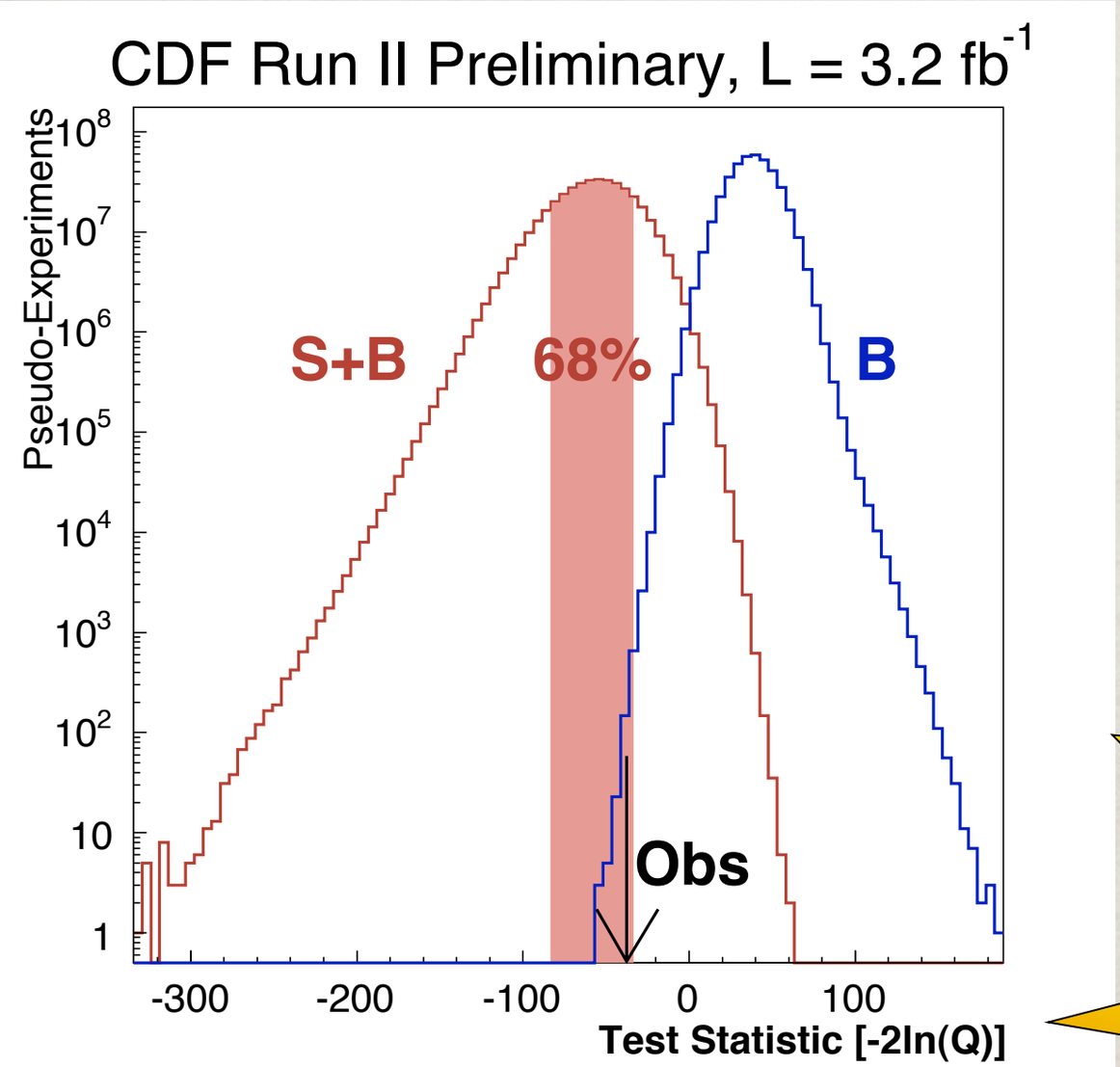


Analysis	Significance	Sensitivity
NN	3.5σ	5.2σ
ME	4.3σ	4.9σ
LF	2.4σ	4.0σ
LFS	2.0σ	1.1σ
BDT	3.5σ	5.2σ
SD	4.8σ	> 5.9σ
MJ	2.1σ	1.4σ
Combined	5.0σ	>5.9σ

Expected p-value : xxx x10^{-10}: >5.9σ
Observed p-value: 3.1 x10^{-7} : 5.0σ

400 Million pseudo-experiments!
(130,000 CPU hrs)

Significance



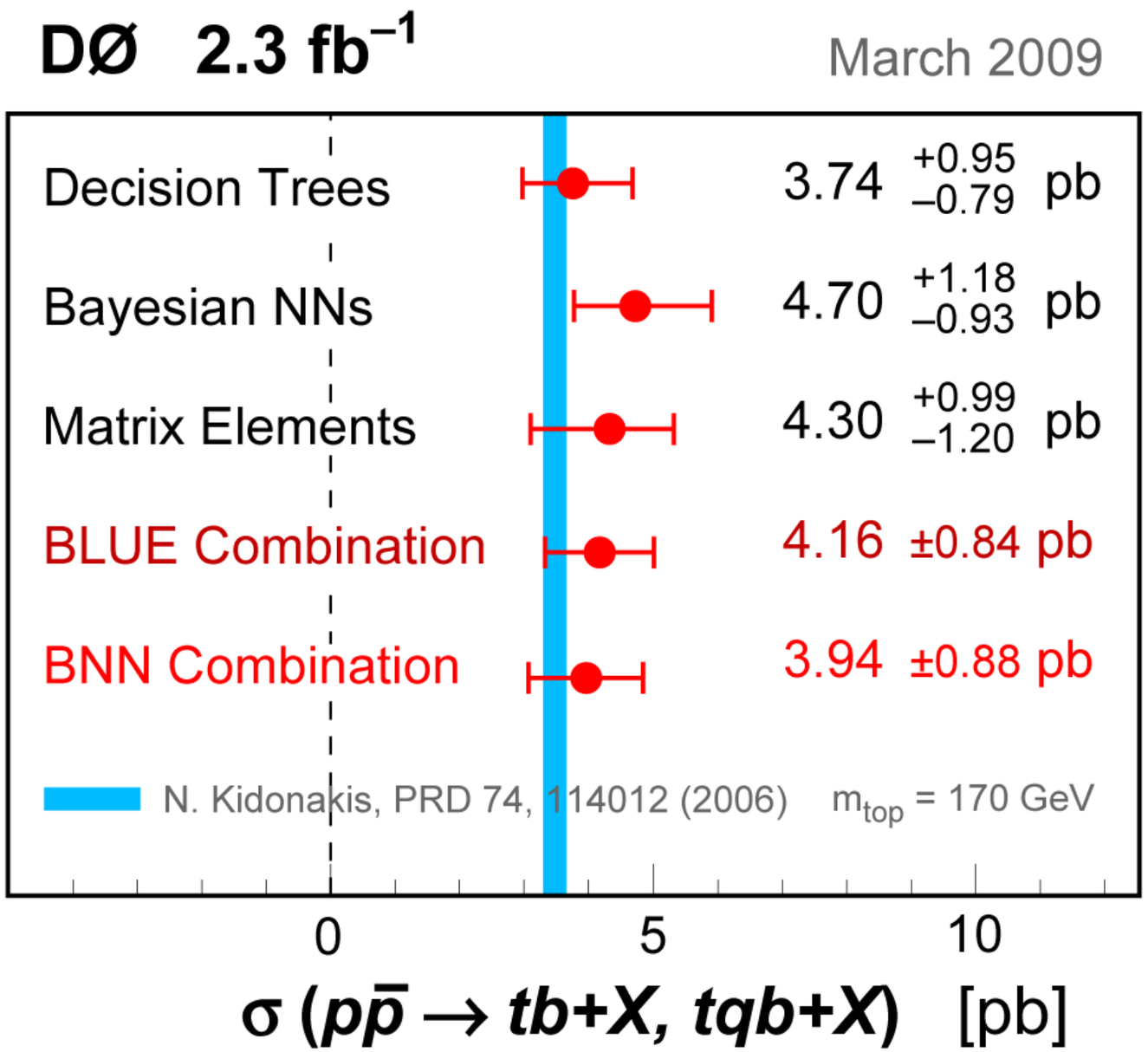
Analysis	Significance	Sensitivity
NN	3.5σ	5.2σ
ME	4.3σ	4.9σ
LF	2.4σ	4.0σ
FS	2.0σ	1.1σ
B		.2σ
		5.9σ
4		
	(130	U

5σ Observation!

Expected p-value : xxx x10 $^{-10}$: >5.9σ

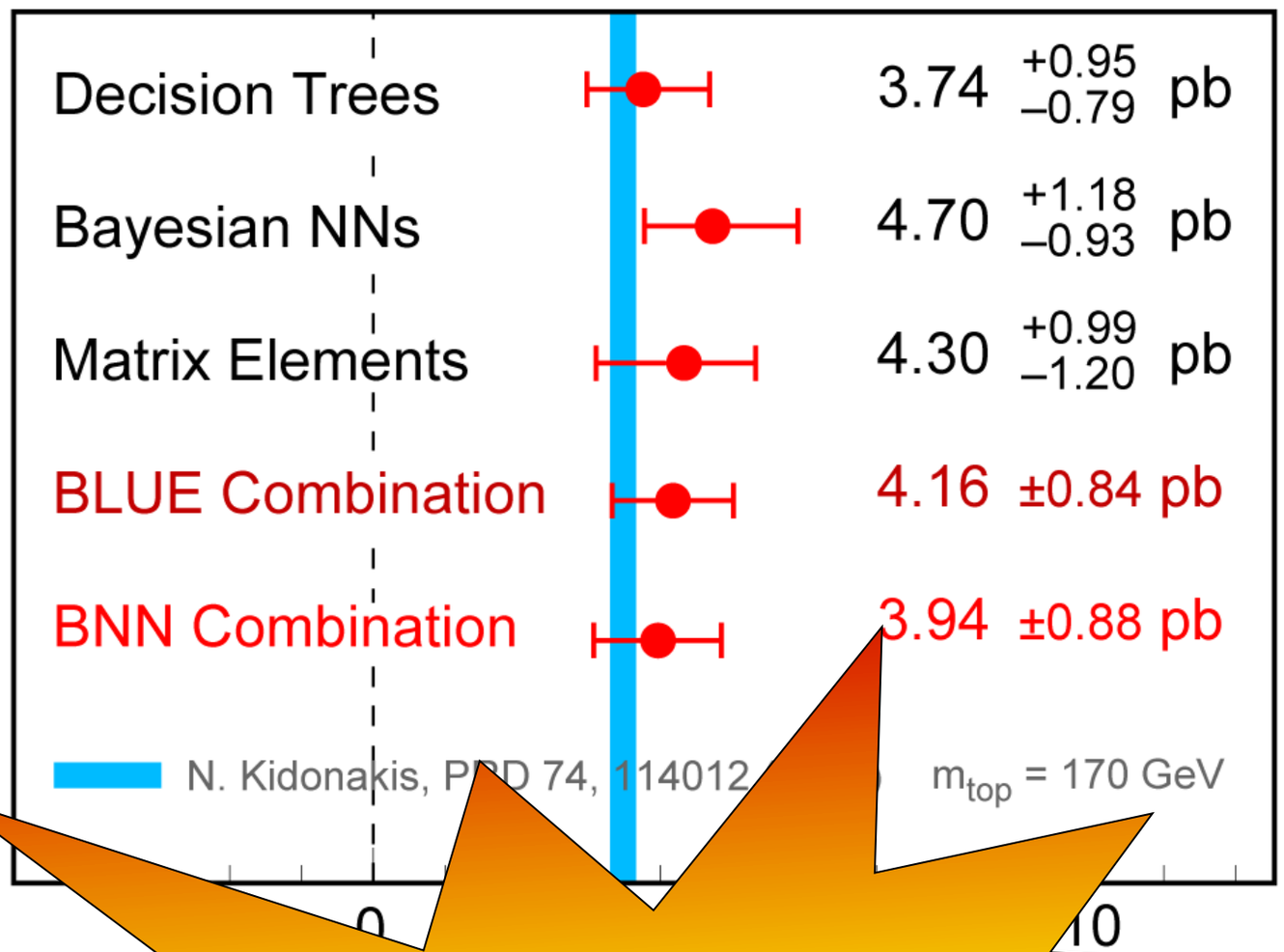
Observed p-value: 3.1 x10^{-7} : 5.0σ

Results from DØ



MVA	Expected Signif.	Observed Signif.
BDT	4.3σ	4.6 σ
BNN	4.1σ	5.2 σ
ME	4.1σ	4.9 σ
BNNComb	4.5σ	**5.0 σ**

Results from DØ



MVA	Expected Signif.	Observed Signif.
BDT	4.3σ	4.6 σ
BNN	4.1σ	5.2 σ
ME	4.1σ	4.9 σ
BNNComb	4.5σ	**5.0 σ**

5σ Observation!

photo: Reidar Hahn; artwork: Jan Lueck

Celebrate!

* CDF and DØ both submitted papers to PRL on March 4th
* Another 5σ discover from the Tevatron
* Direct measurement of $|V_{tb}|$
* Look forward to more single top results in future
  * Precise s- and t-channel measurements
  * Top polarization
  * Tevatron single top combination
* Last SM process to observe before the Higgs....

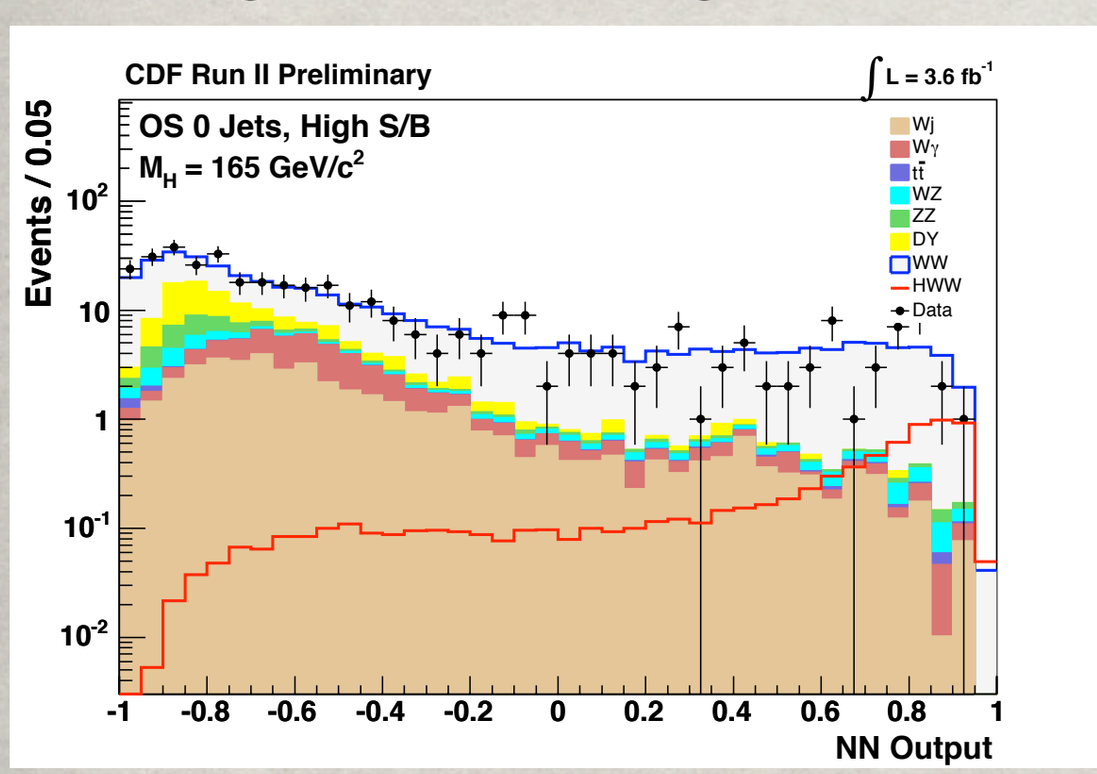
photo: Reidar Hahn; artwork: Jan Lueck

On to the Higgs

- Major effort to find the Higgs at CDF (and DØ) both through direct searches and indirect means....

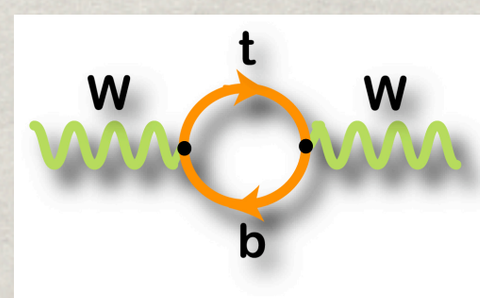
Direct searches: Like single top.

- Multivariate techniques
- Looking for excess of Higgs signal above background

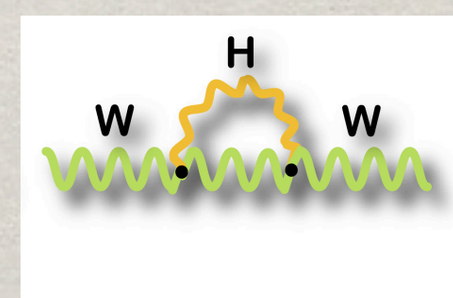


Indirect constraints:

- Precision electroweak measurements sensitive to Higgs mass
- In particular, for Tevatron, Higgs and Top provide radiative corrections to W mass
- Precise measurements of M_W and M_T give hints about Higgs



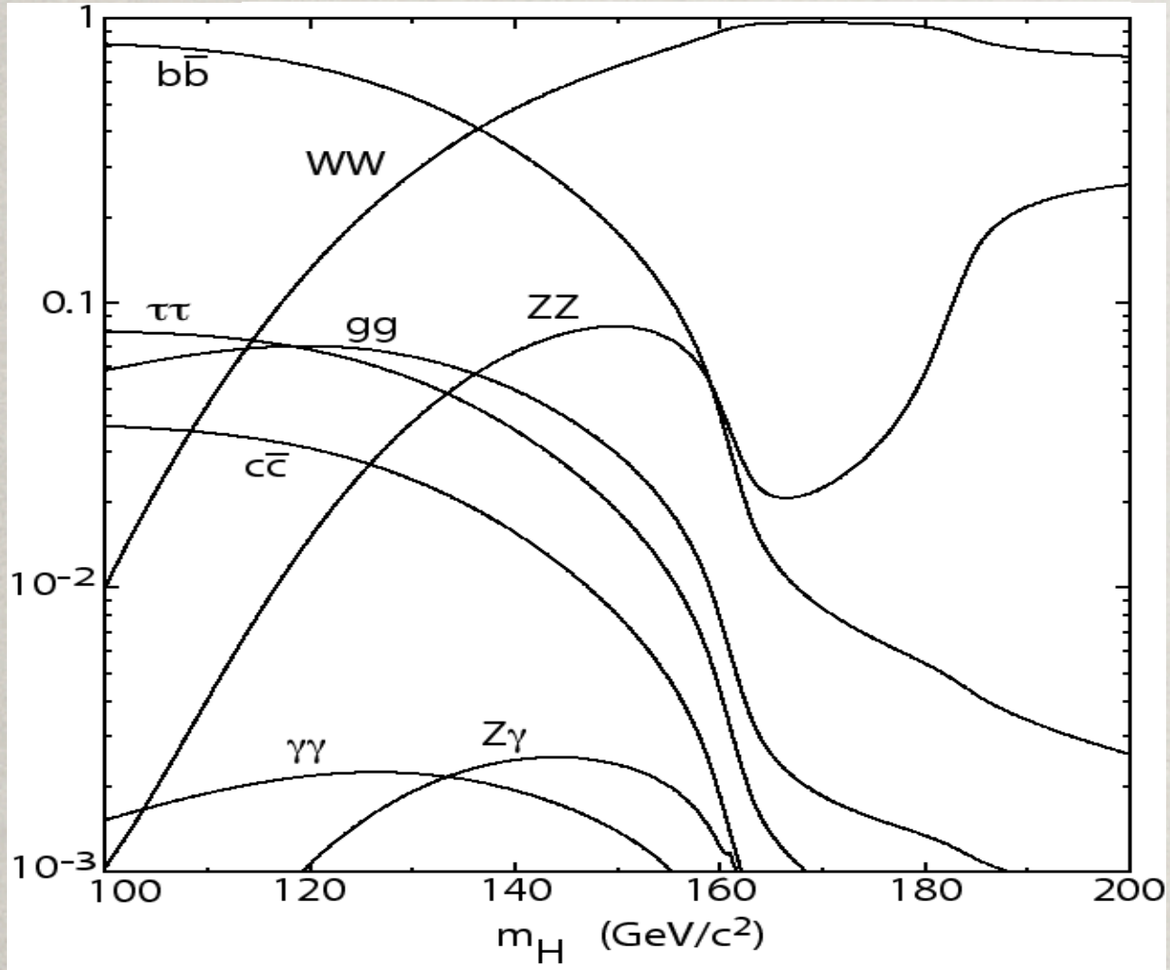
$\Delta M_W \propto M^2_{top}$

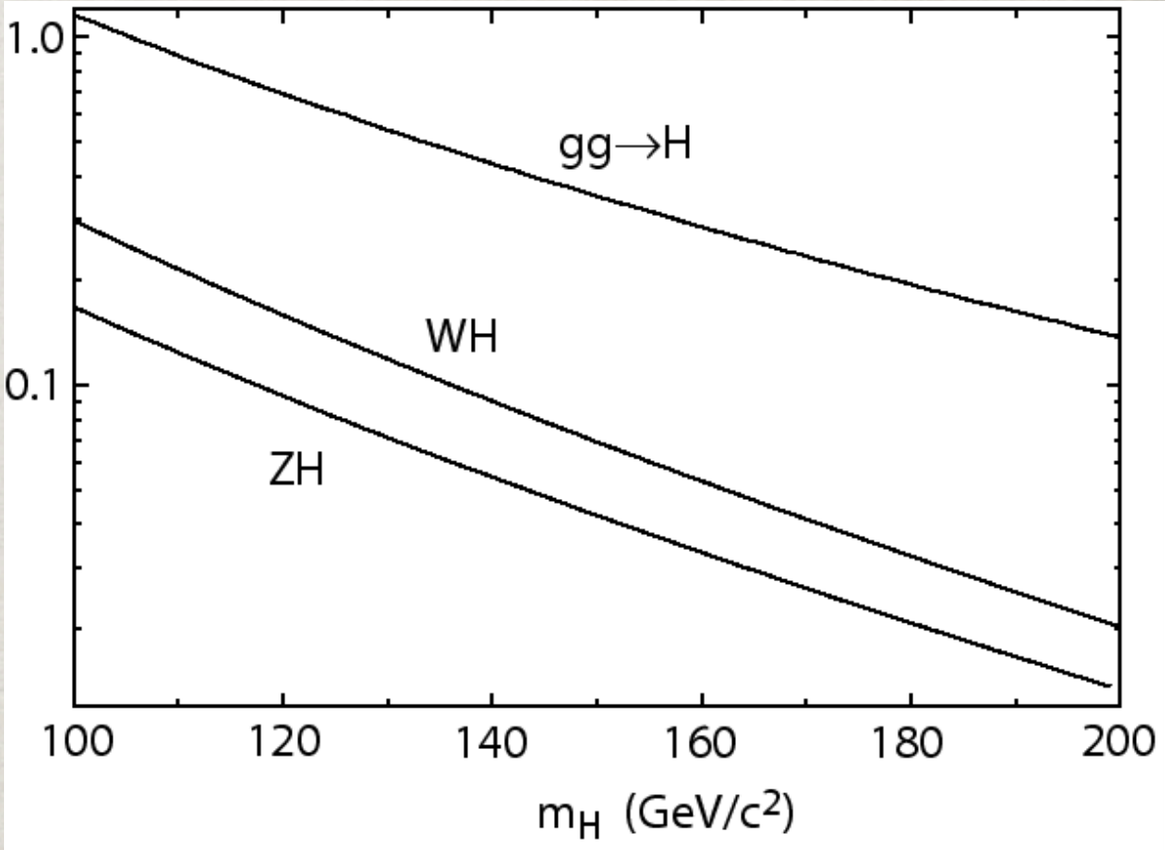


$\Delta M_W \propto \ln M_{Higgs}$

Direct Search for Higgs

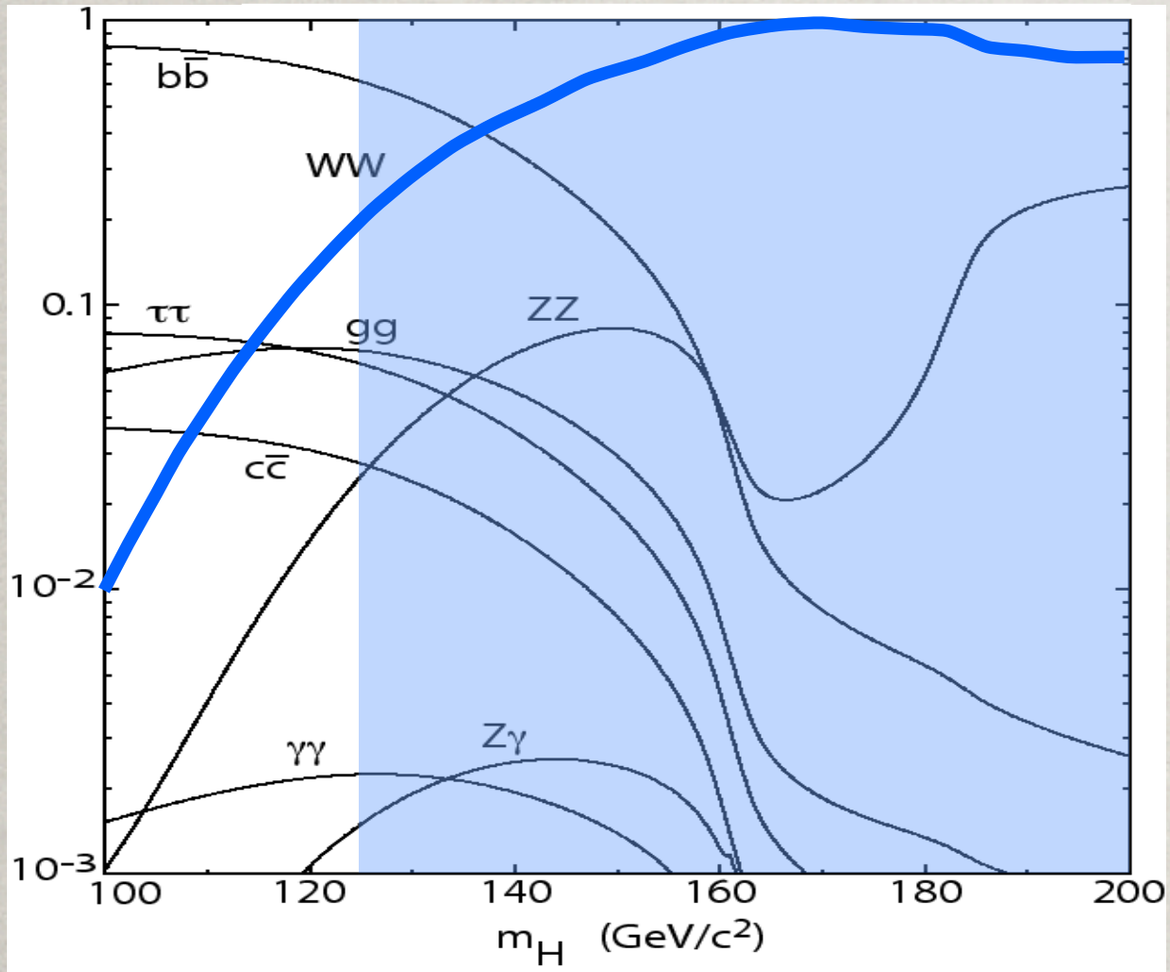
- Different search strategies in for high mass and low mass

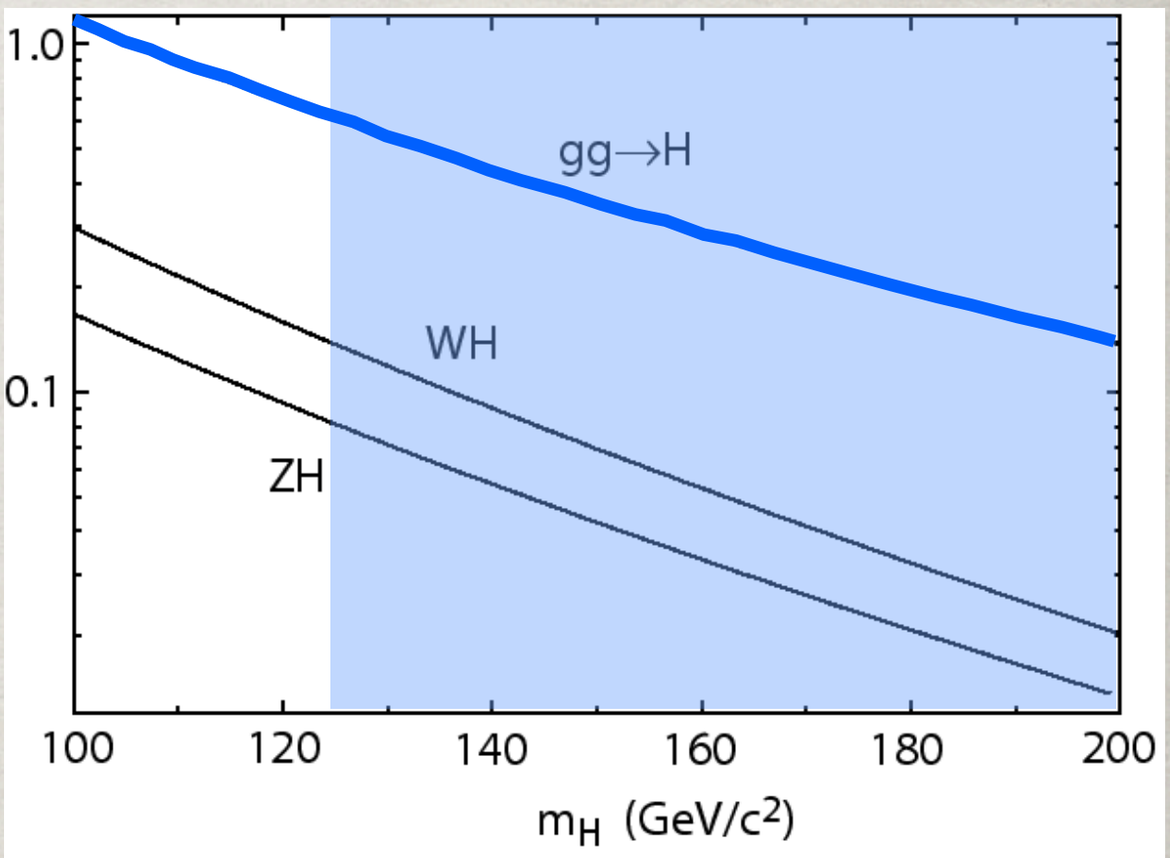




Direct Search for Higgs

- Different search strategies in for high mass and low mass

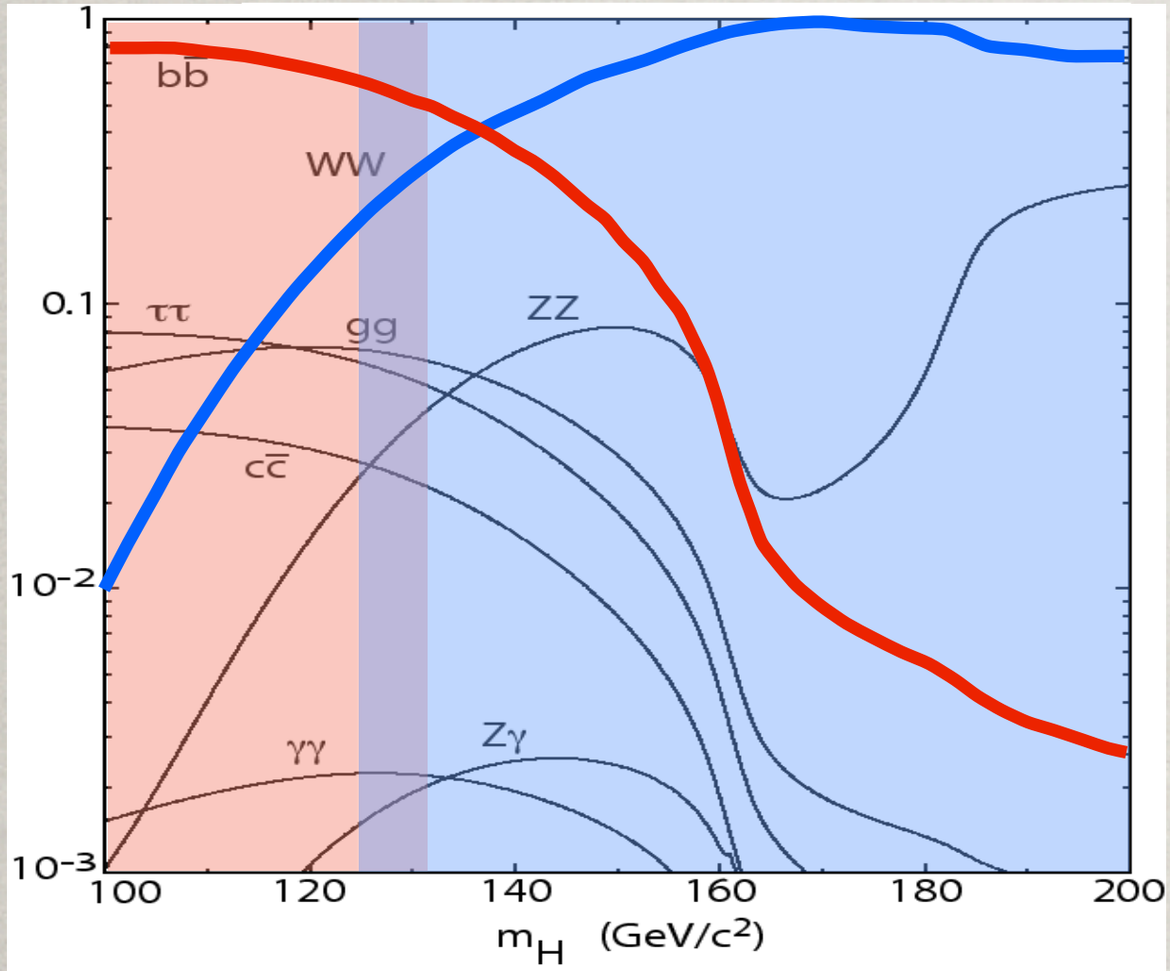


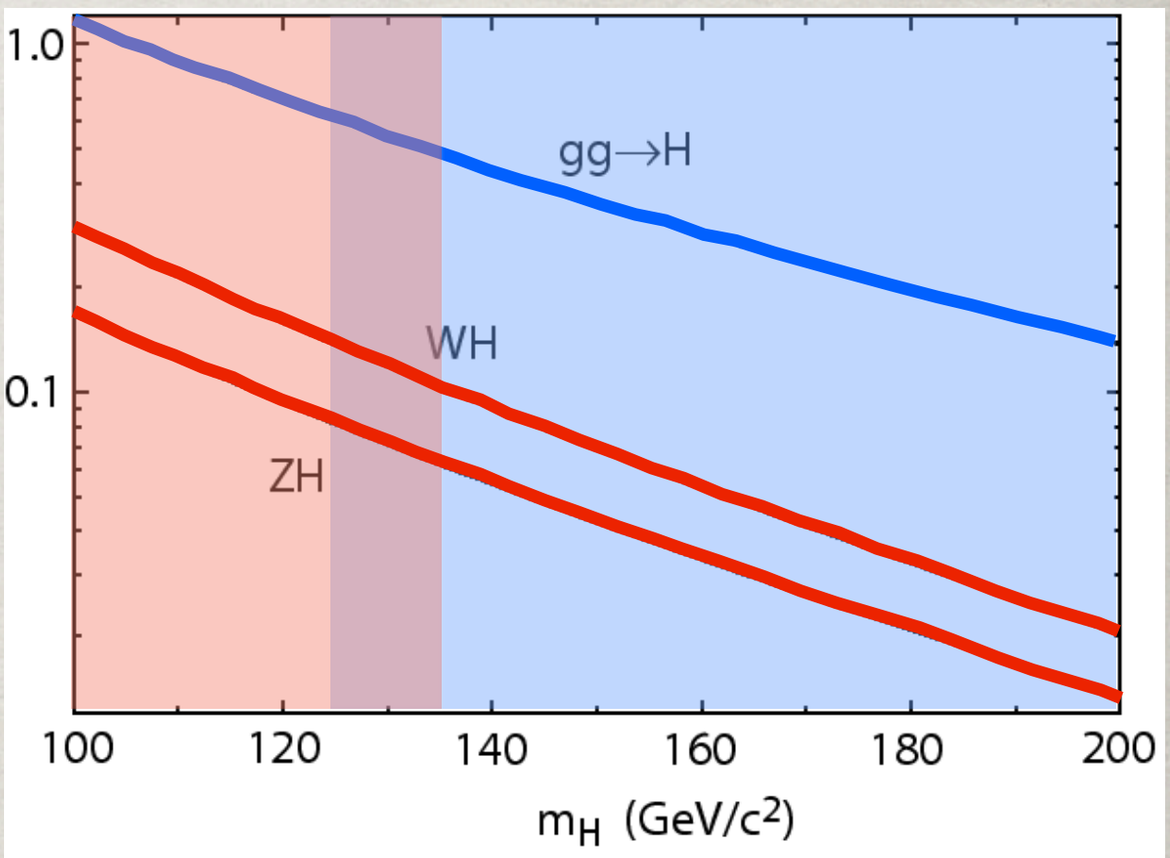


- High mass:
  - H→WW dominant decay
  - Search using direct production: gg→W

Direct Search for Higgs

- Different search strategies in for high mass and low mass



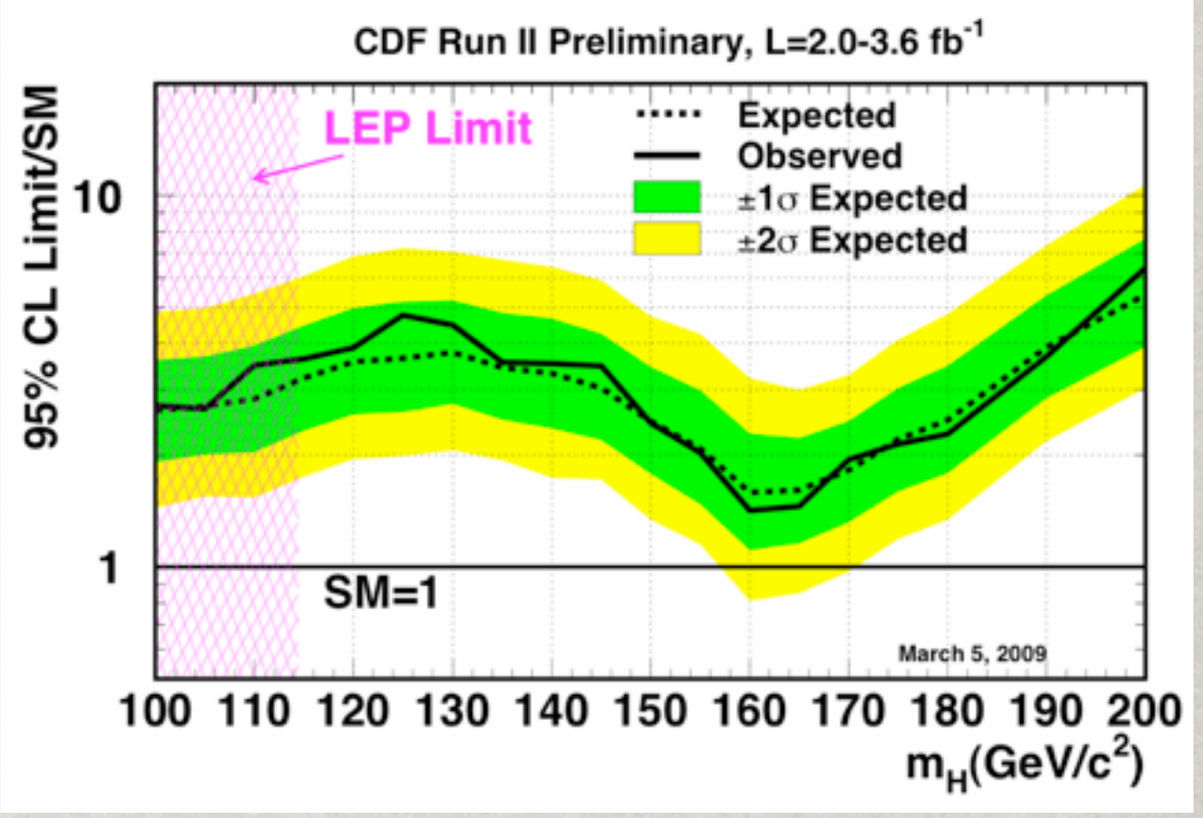


- High mass:
  - H→WW dominant decay
  - Search using direct production: gg→W

- Low mass:
  - H→bb dominates
  - Search using associated production: WH→lνbb, ZH→llbb or ZH→ννbb

Recent Progress

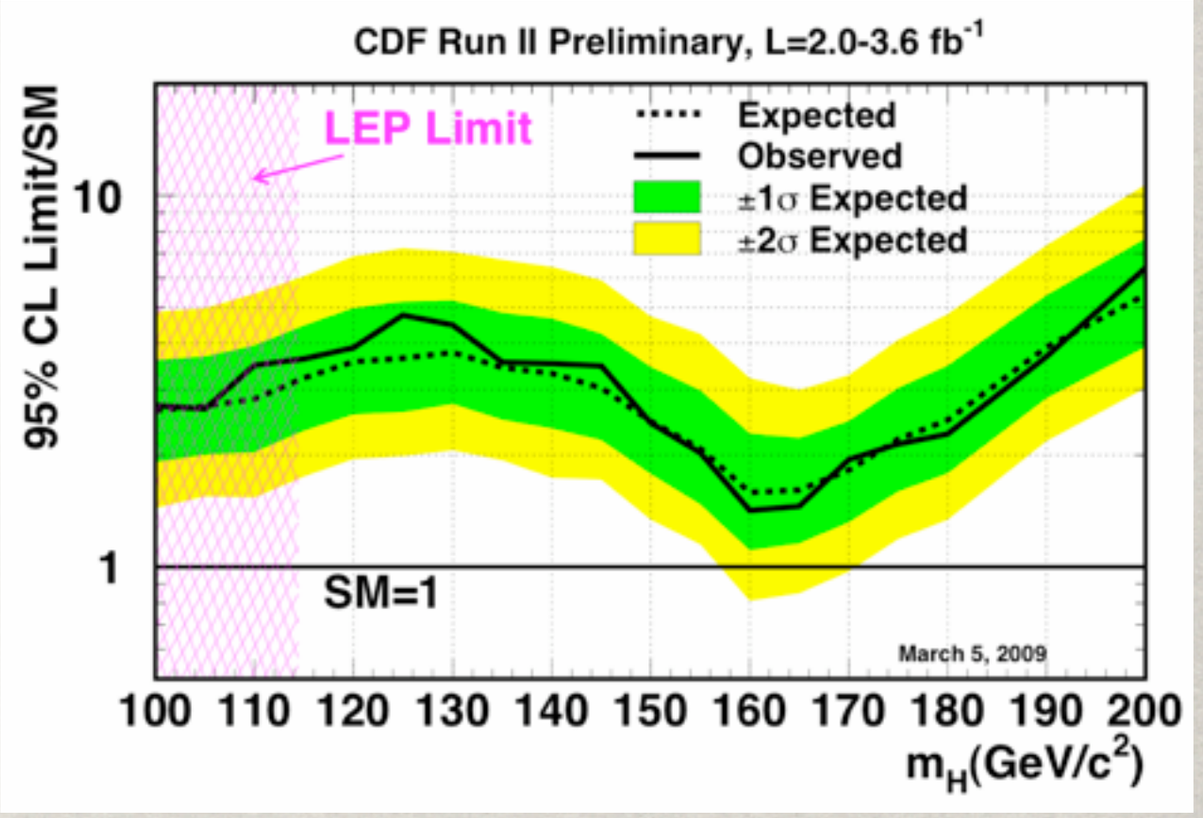
- More acceptance
  - Additional Triggers
  - Additional lepton selection
  - New final states/channels
- Better reconstruction
  - Jet corrections
  - QCD rejection
- Advanced multivariate techniques
  - ME + NN/BDT
- Combine all channels using information about SM ratios



Recent Progress

- More acceptance
  - Additional Triggers
  - Additional lepton selection
  - New final states/channels
- Better reconstruction
  - Jet corrections
  - QCD rejection
- Advanced multivariate techniques
  - ME + NN/BDT

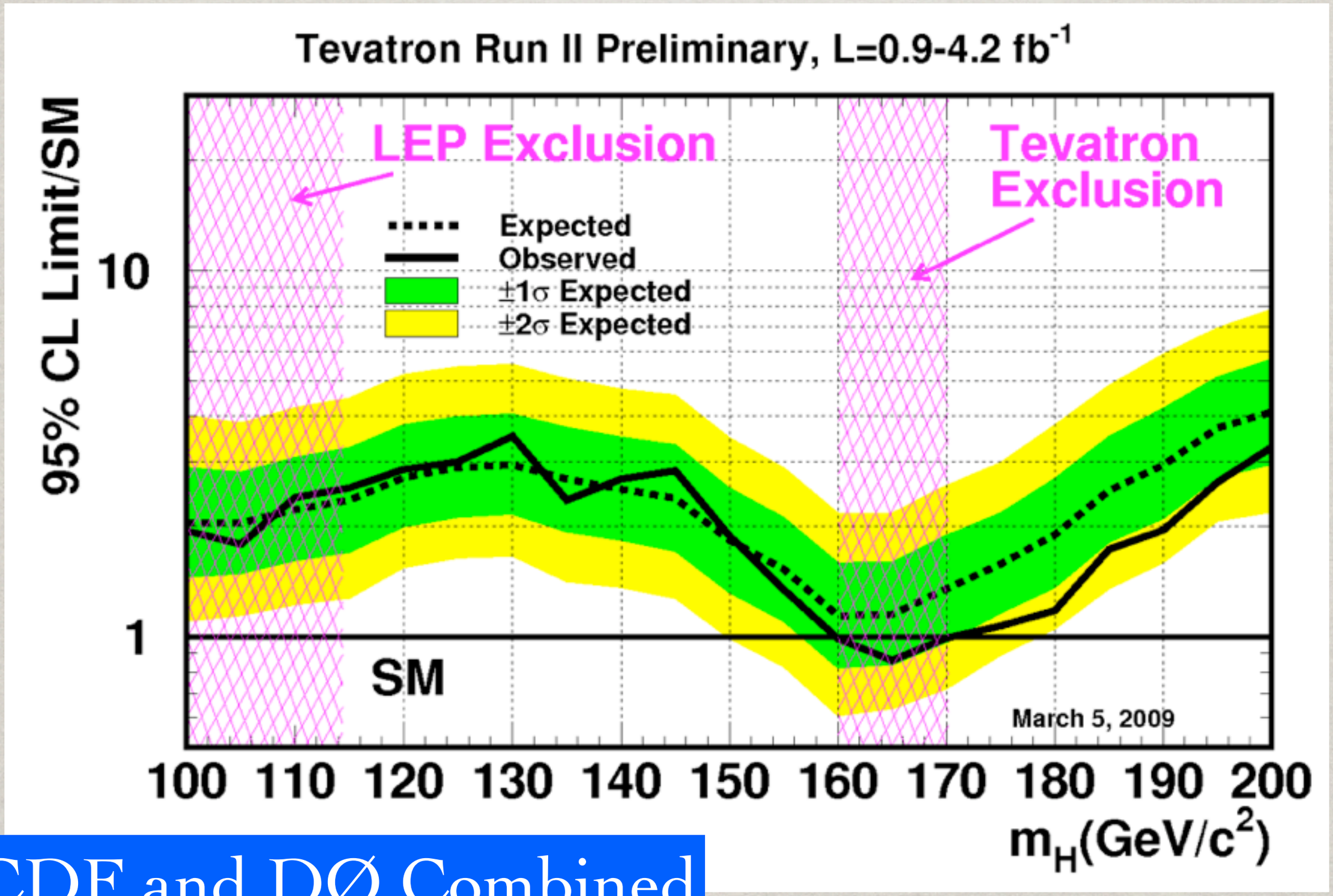
- Combine all channels using information about SM ratios



In the past year:

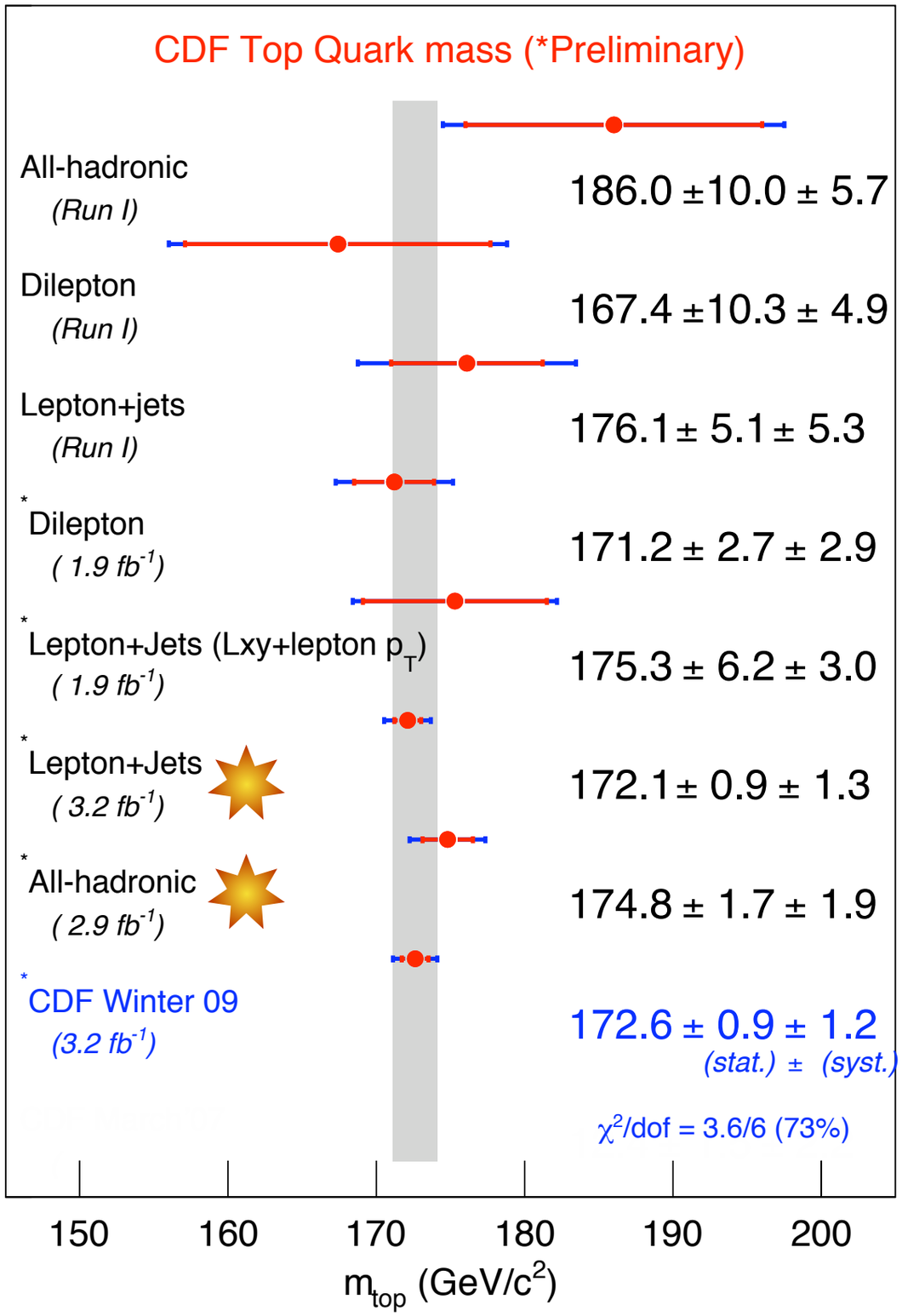
Higgs Mass	Winter 08	Winter 09
115 GeV/c^2	5.0×SM	3.2×SM
160 GeV/c^2	2.6×SM	1.6×SM

Tevatron Exclusion!



CDF and DØ Combined

Latest Top Mass Results



- Measure the mass with different techniques in different channels
- Combine for best precision
- Tevatron combination:

$173.1 \pm 0.6\ (\text{stat}) \pm 1.1\ (\text{syst})\ \text{GeV}/c^2$

- Real work now involves understanding and reducing systematic uncertainties

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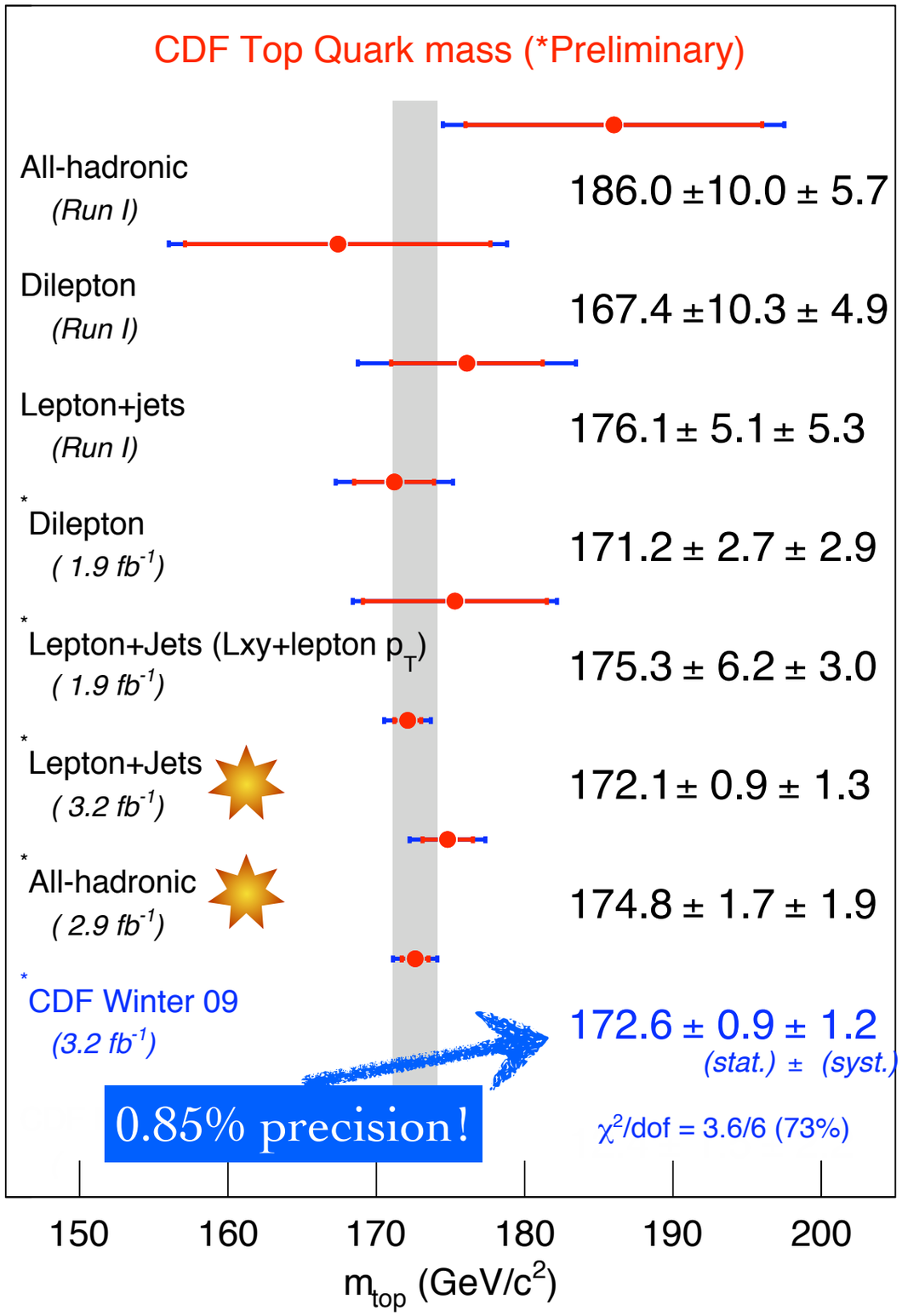
Latest Top Mass Results



- Measure the mass with different techniques in different channels
- Combine for best precision
- Tevatron combination:

$173.1 \pm 0.6\ (\text{stat}) \pm 1.1\ (\text{syst})\ \text{GeV}/c^2$

- Real work now involves understanding and reducing systematic uncertainties

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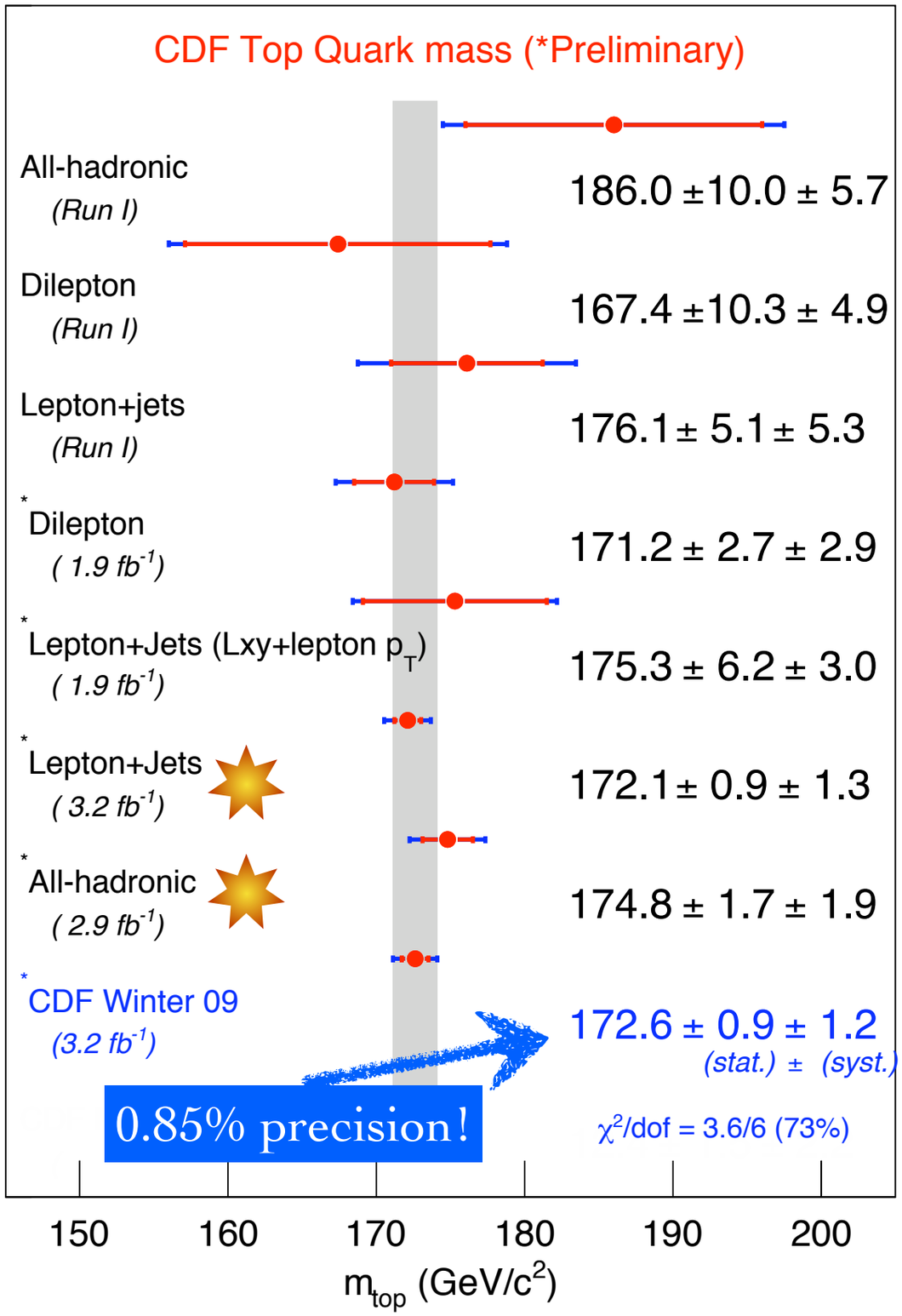
Latest Top Mass Results



- Measure the mass with different techniques in different channels
- Combine for best precision
- Tevatron combination:

$173.1 \pm 0.6\ (\text{stat}) \pm 1.1\ (\text{syst})\ \text{GeV}/c^2$

0.75% precision!

- Real work now involves understanding and reducing systematic uncertainties

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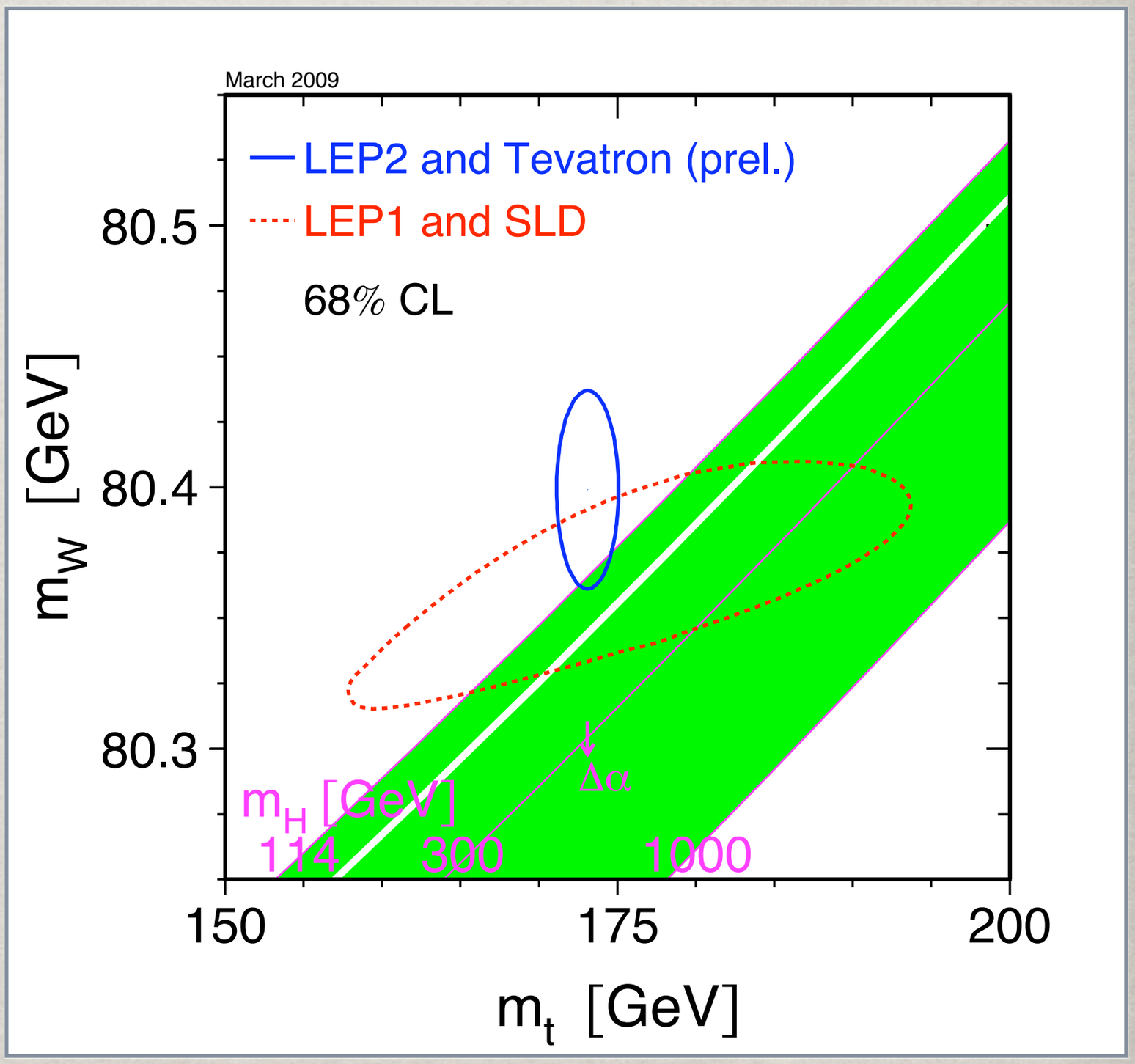
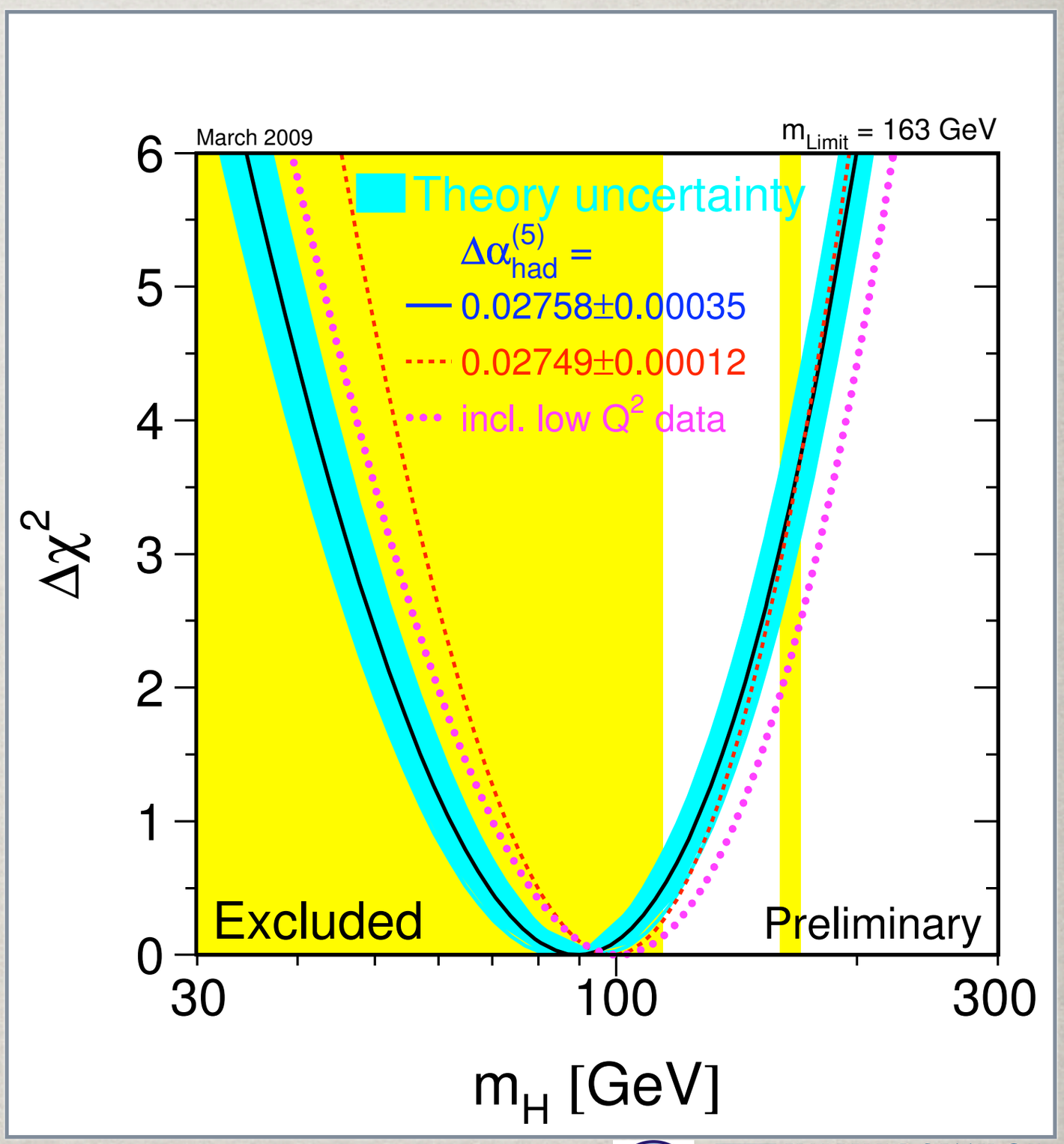
Constraint on Higgs Mass

- Includes Tevatron combined top mass and world average W mass
- New DØ W mass measurement not yet included



Conclusions

- CDF excited and motivated by recent single top observation
- Progress being made on search for Higgs (both direct and indirect)
  - Tevatron-wide effort
  - More data to come
- Look forward to future discoveries