Top cross section and mass measurement in the all hadronic channel at CDF

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For the CDF collaboration

Top is special!

- **Top lifetime very short: decays before hadronizing**

$$\tau_{top} \sim 10^{-24}\,\mathrm{s}\,,\ \ \Gamma^{-1} \approx \left(1.5\ \mathrm{GeV}\right)^{-1} \ll \Lambda_{QCD}^{-1} \sim \left(200\ \mathrm{MeV}\right)^{-1}$$

  - **No spectroscopy**
  - **Spin is transferred to decay products**

- **Probes physics at highest allowable mass scale**
  - **Top (or heavy top) protagonist of EWSB models:**

- Higgs, Top Color, ….

Top pair decays

- **Dileptons:**

BR = 5% **(ee/eμ/μμ only) cleanest sample, lowest statistics**

- **Lepton+Jets:**

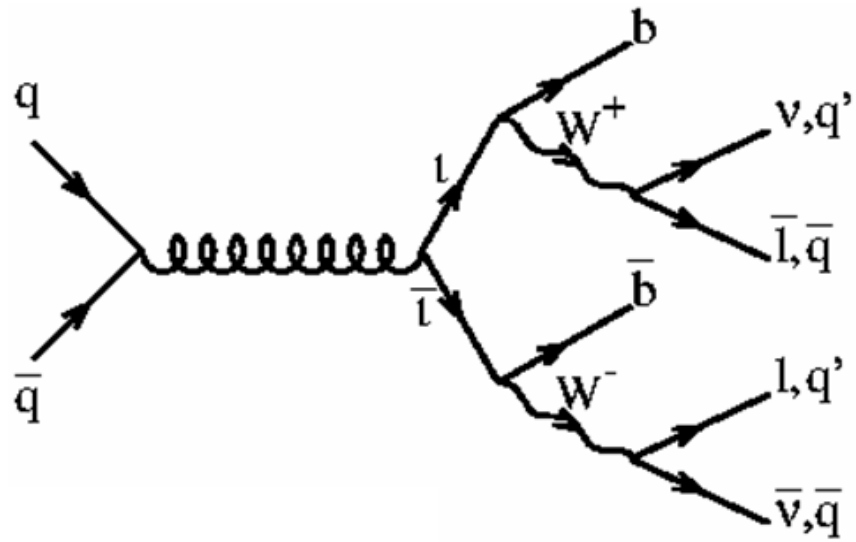
BR = 29% **(e/μ + jets only)**

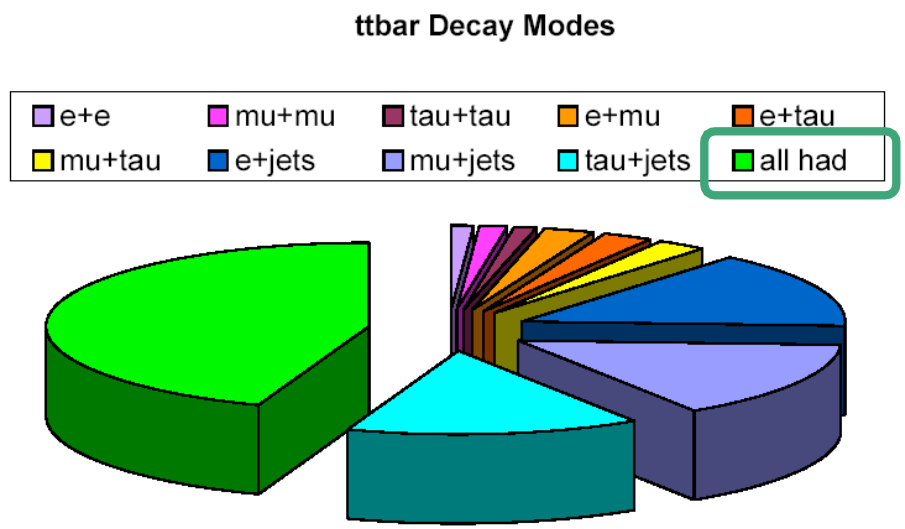
golden channel w/ high statistics and reasonable S/B

- **All-hadronic:**

BR = 46%, challenging channel w/ high statistics but large backgrounds

BR(W → leptons) = 1/3
BR(W → quarks) = 2/3





The all hadronic channel

It is important to measure the top mass (and production xsec) in all possible channel not only for completeness but also because:

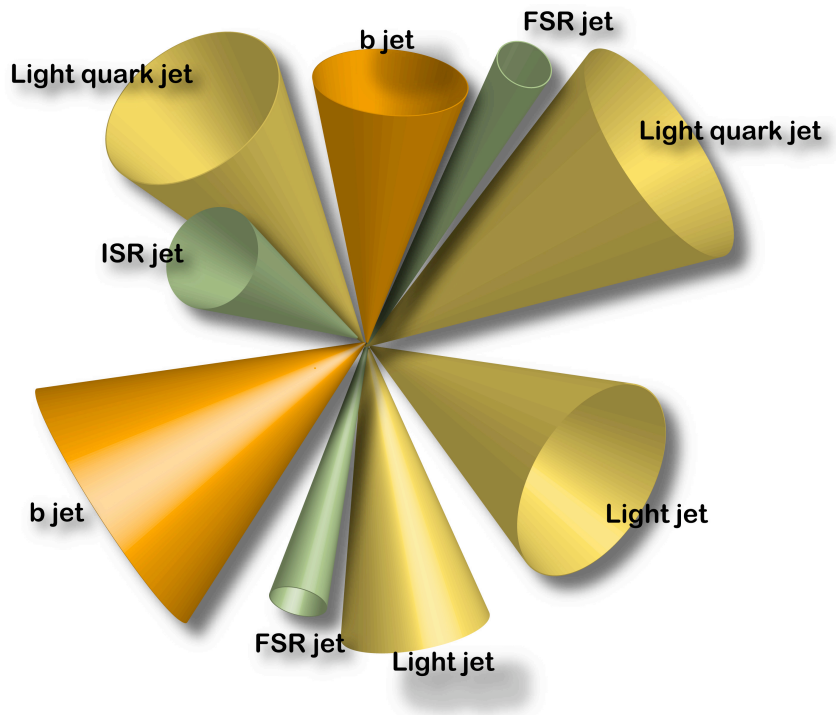
- **all-hadronic channel is where most of the events are!!**
- **check the consistency between various channels with different metodology/backgrounds/systematics. Moreover, each channel has different sensitivity to new physics**
- **reduce the overall uncertainty combining various channels**

The challenge we're facing

All-hadronic channel is difficult

The signature:

- many jets in the calorimeter
- b-quark jets-identify with b-tagging



Advantage:

- no neutrinos,
- fully reconstruct

Disadvantage:

- Huge QCD background of light and heavy flavour production
- Combinatoric background due to large number of jet-to-parton association

Overview

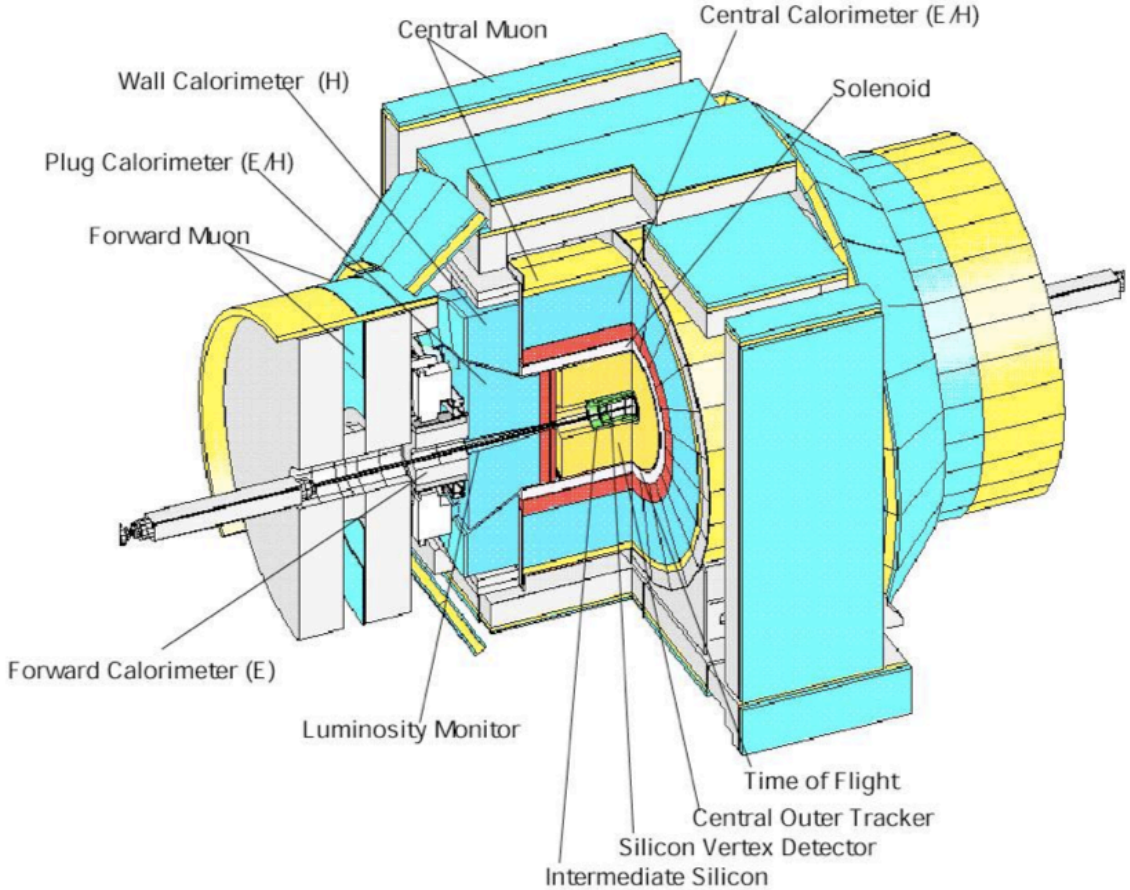
common strategy for event selection

1) Trigger
2) Kinematic selection (with NN)
3) b jet identification
4) Background estimate

latest cross section measurement
latest mass measurement

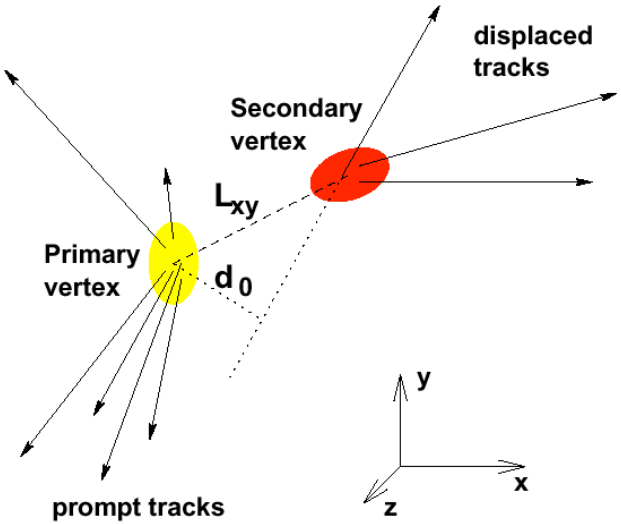
CDF detector

Multi purpose detector

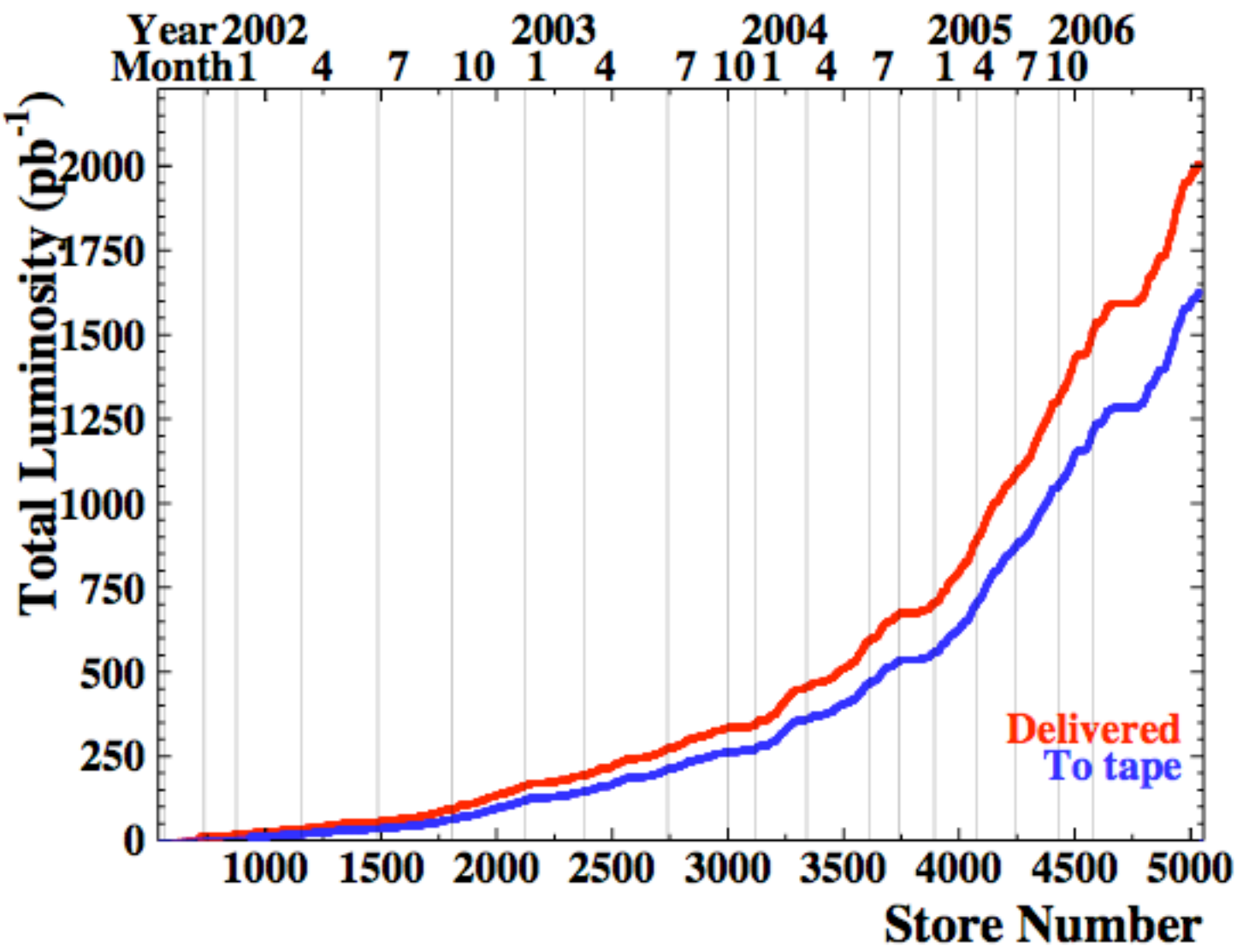


- Calorimeters:
  Central, wall, plug
  Coverage: $|\eta|<3.6$

- b-quark identification
  Silicon detector (SVX)
  top event b-tag: ~ 55%



Luminosity



2.0 fb^{-1} delivered

1.6fb^{-1} on tape

1.0fb^{-1} used in this analysis

Multijet Trigger

A multi-jet trigger based on calorimetric information has been developed specifically for this channel:

- **<u>L1</u>: ≥ 1 cal. tower with E_T≥10 GeV**
- **<u>L2</u>: ≥ 4 cal. clusters with E_T ≥ 15 GeV, $\sum E_T$ ≥ 175 GeV**
- **<u>L3</u>: ≥ 4 jets, cone radius=0.4, E_T ≥10 GeV**

This trigger has a cross section of about **4.3 nb** and an efficiency of about **58% for all tt events** and of about **80% in the case of all-hadronic tt** decays. The signal-to-background ratio (S/B) is about **1/1100**.

Selection and Topology requirement

- ✓ well reconstructed vertex (|Zvert|<60 cm)
- ✓ no high-Pt leptons (e or mu) **orthogonality to leptonic channels**
- ✓ no significant missing energy $\frac{\not{E}_T}{\sqrt{\sum E_T}} < 3\sqrt{\mathrm{GeV}}$
- ✓ E_T^{jet}>=15GeV,|η|<2.0 for all jets

SIGNAL region	6<=Njet<=8	has 0.5M events
CONTROL region	4 or 5 jets	has 2.9M events

Signal and Background Modeling

- We model the signal with PYTHIA tt events (mt=175). samples to derive systematics on the efficiency
- The background after b-tagging can be derived:

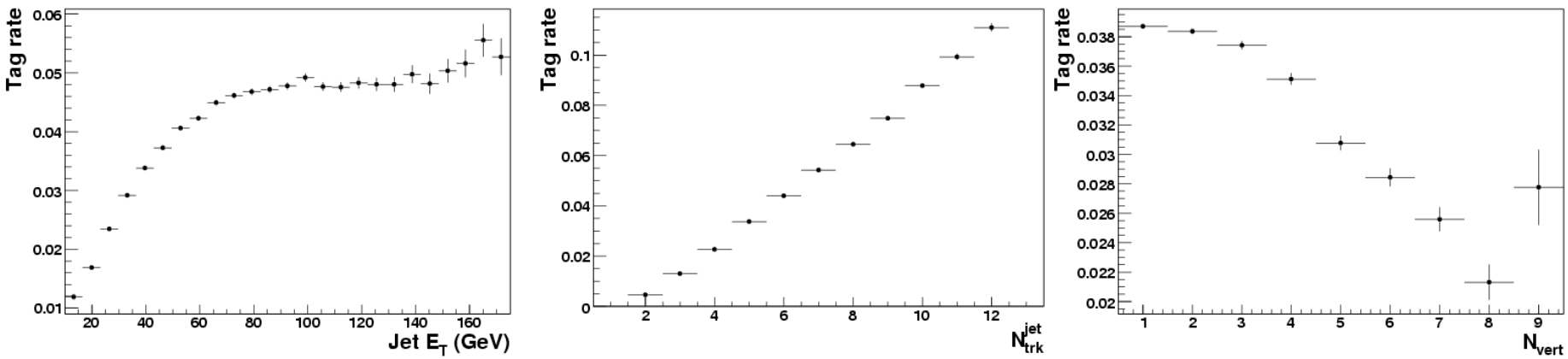
MC modeling
poorly known cross-sections, suitable generation of huge QCD samples.
Allows separation of heavy flavour from fakes

Data driven background has no such complications (but do not distinguish between real heavy flavour and fakes)

Background estimate

Events with ≥ 6 jets have still a poor S/B (0.3%), so:

- the dataset is background dominated and the data themselves can be used as representation of the background
- Since we require ≥ 1 b-tag, we parametrize the probability of a jet being tagged as a function of the kinematic and event variables
- We do so in the CONTROL region with exactly 4 jets



Background estimate

This tag rate matrix is used to estimate the probability that a fiducial jet in the signal sample is tagged.

Summing this probability over all fiducial jets we obtain the expected *number of tags* from non-signal processes, that is *QCD heavy flavor production* and *light quark mistags*:

We end with an inclusive prediction on tags and not events:

$$N_{exp} = \sum_{i}^{Nevents} \sum_{j}^{Ntaggable} P(E_T^j, N_{trk}^j, N_{vert})$$

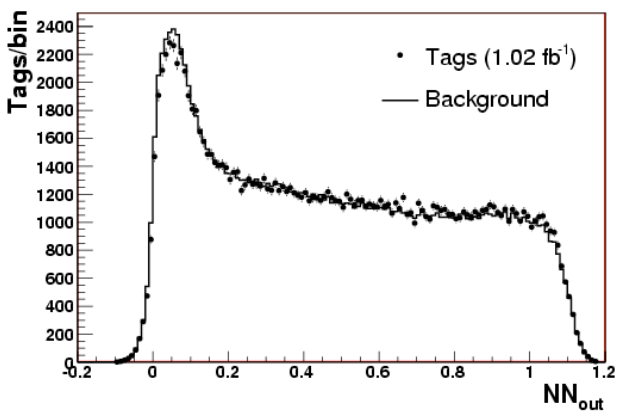
Background determined from the data

We assume that the tagging-rate is independent from the jet multiplicity. Apply technique to samples with higher multiplicities.

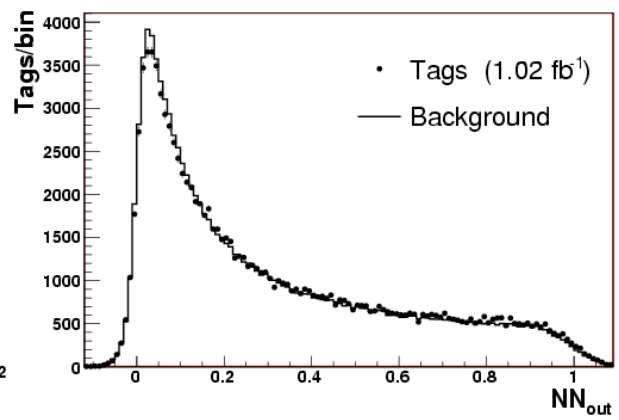
This procedure works: the agreement between data (~observed background) and the expected background is evaluated and treated as systematic uncertainty

We estimate a 2.5% uncertainty on the background normalization

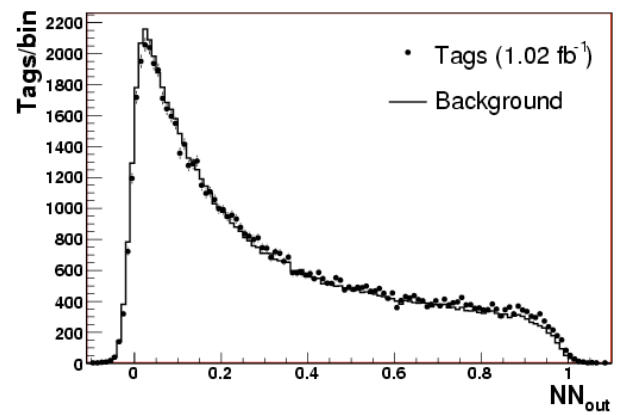
4 jets



5 jets



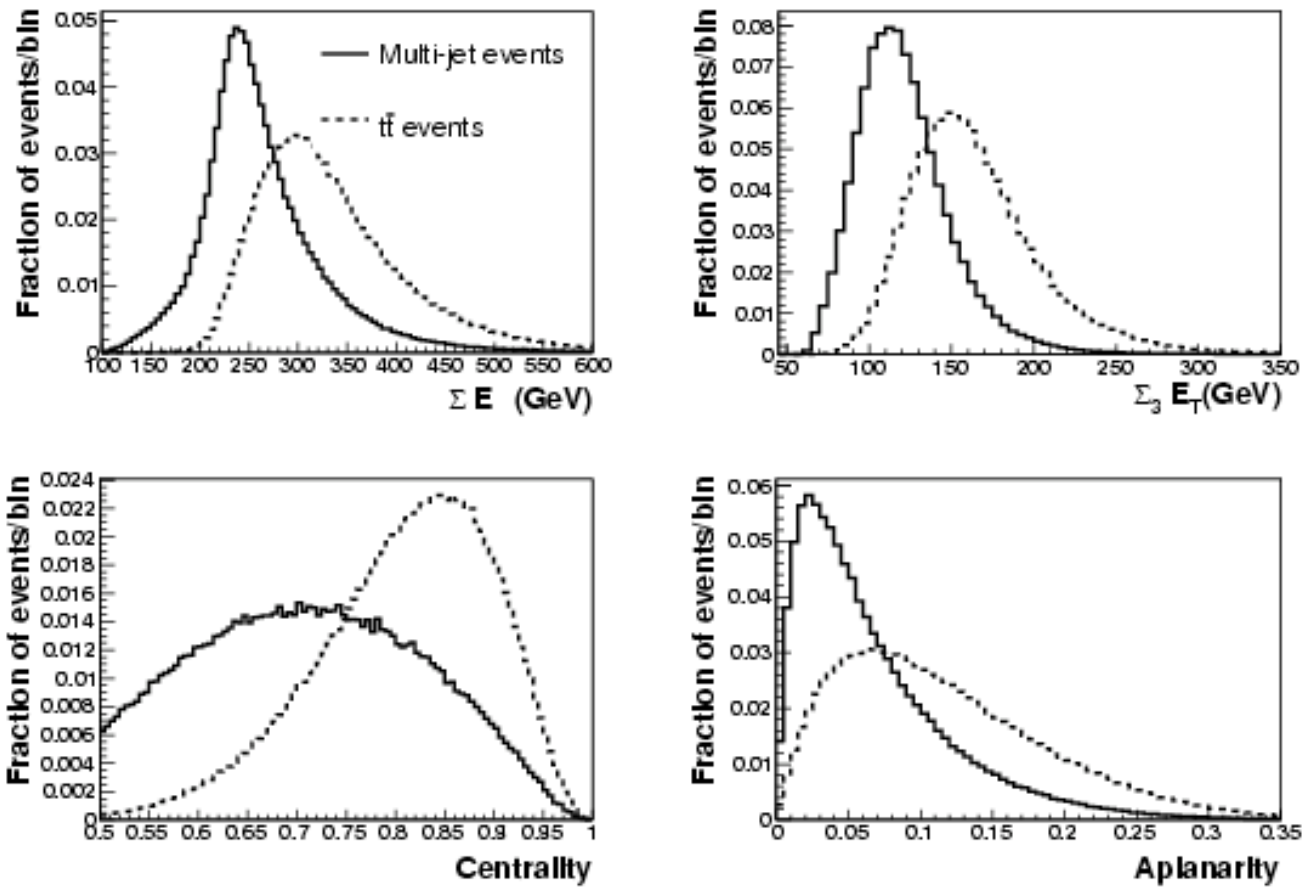
6 or more jets



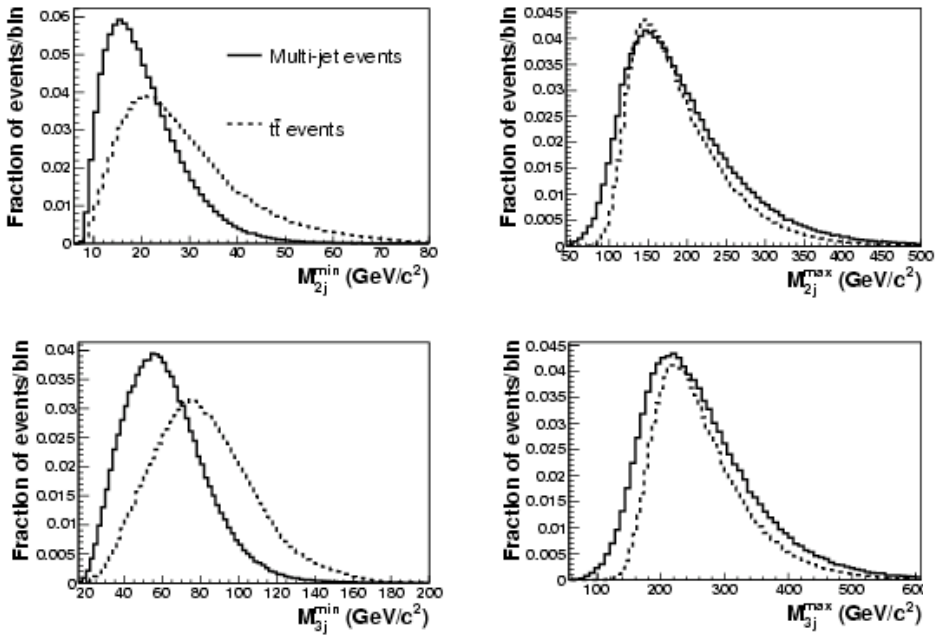
Discriminating signal from background

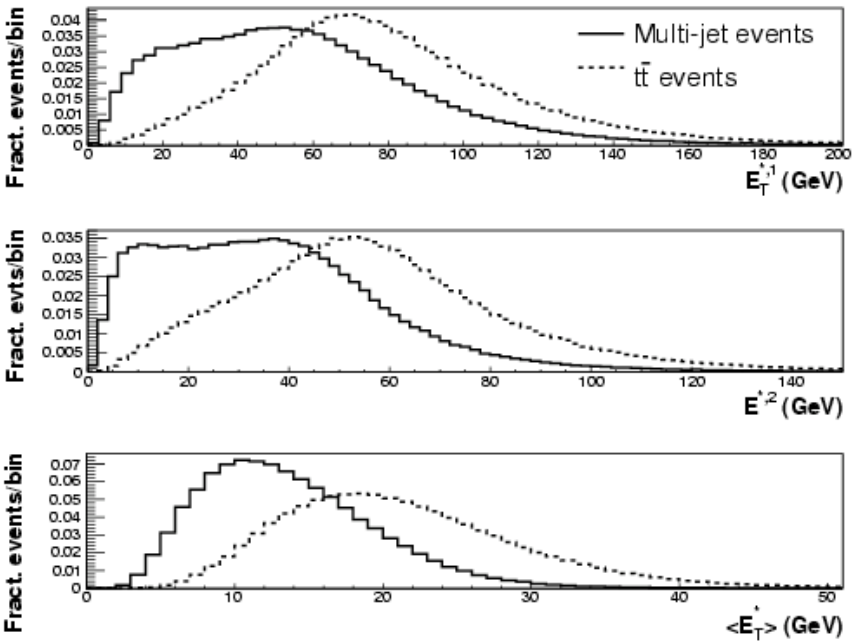
We define a kinematical selection based on dynamical and topological properties of the event. We build a neural network based on the following(11 variables):

CDF used these 4 variables in previous measurement



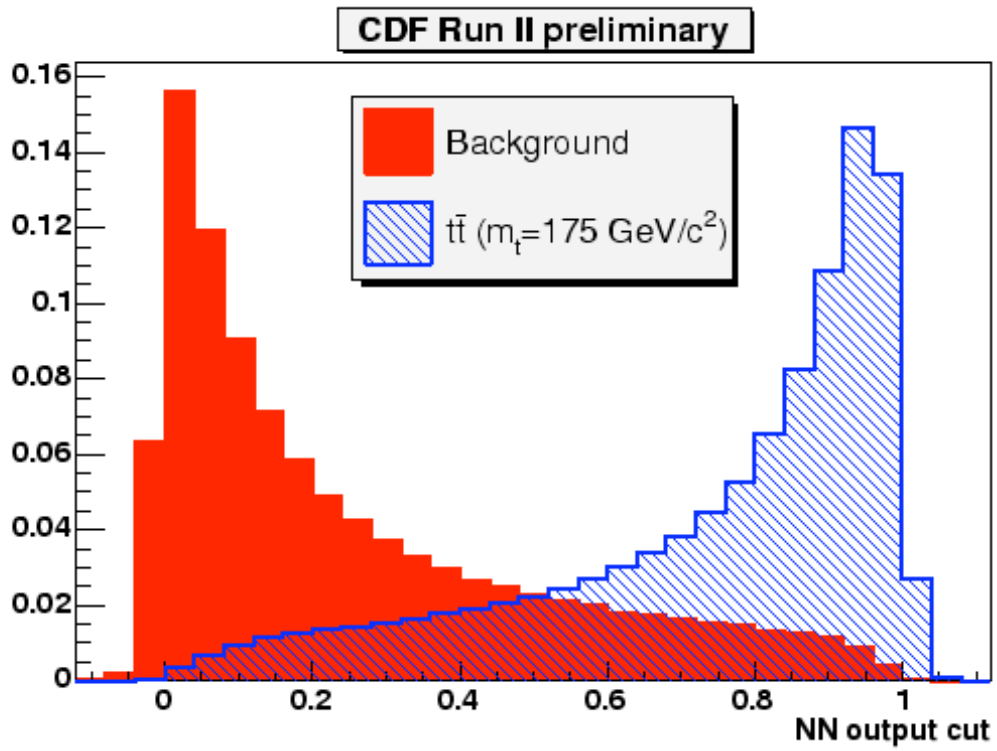
Discriminating signal from background





Neural network output distribution

The training is based on same size (~500,000) samples of signal (tt MC-PYTHIA) and data-driven background



S/B~1/16 - improvement 50% keeping with same efficiency!

ROOT class TMultiLayerPerceptron

Production cross section

$$\sigma(tt) = \frac{N_{evts} - N_{back}}{\mathcal{L}uminosity * \varepsilon}$$

Why is it important to measure production rate?

- tt production tests QCD

- Cross sections significantly differing from expected values may indicate new physics

  - Resonant X→ tt OR Anomalous QCD coupling

Previous CDF results

Run I pair production all-hadronic cross section L=110pb^{-1}

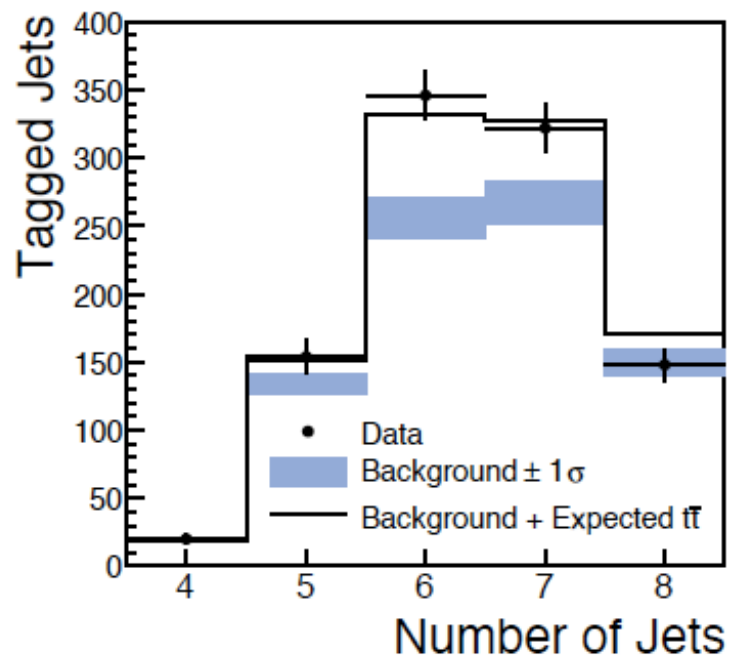
$$\sigma_{t\bar{t}} = 7.6 + 3.5 - 2.7$$

phys.rev.lett.79, 1992 (1997)
phys.rev.D 63, 032003 (2001)
phys.rev.D 64, 032001(2001)

Run II pair production all-hadronic cross section measurement L=310pb^{-1}

$$\sigma_{t\bar{t}} = 7.5 \pm 2.1(stat.)^{+3.3}_{-2.2}(syst.)^{+0.5}_{-0.4}(lumi.)pb$$

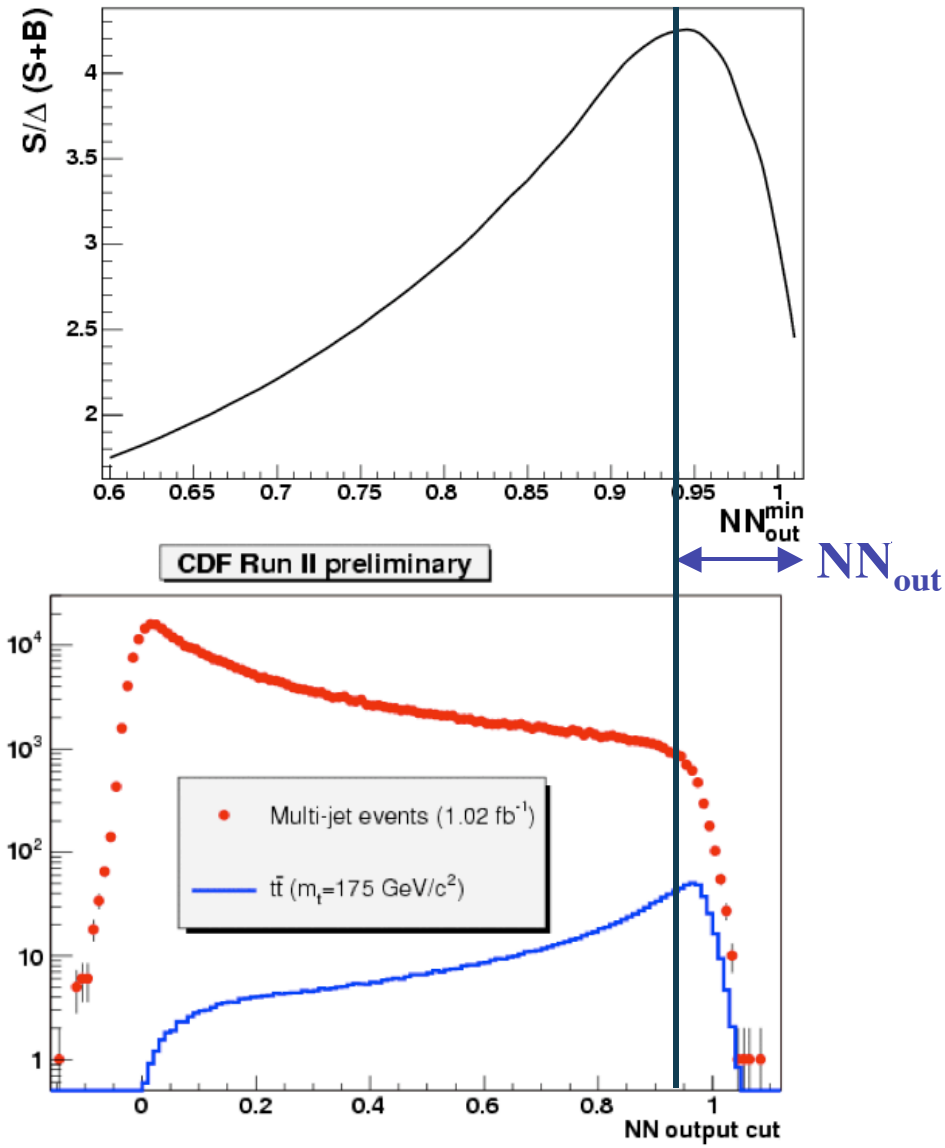
phys. Rev. D **74**, 072005 (2006)



Neural Network based Kinematical Selection

The xsec measurement is a counting experiment.

We choose the cut on NNout which provides the smallest relative total uncertainty on the xsec, i.e. after the request of btagging: NNout>=0.94



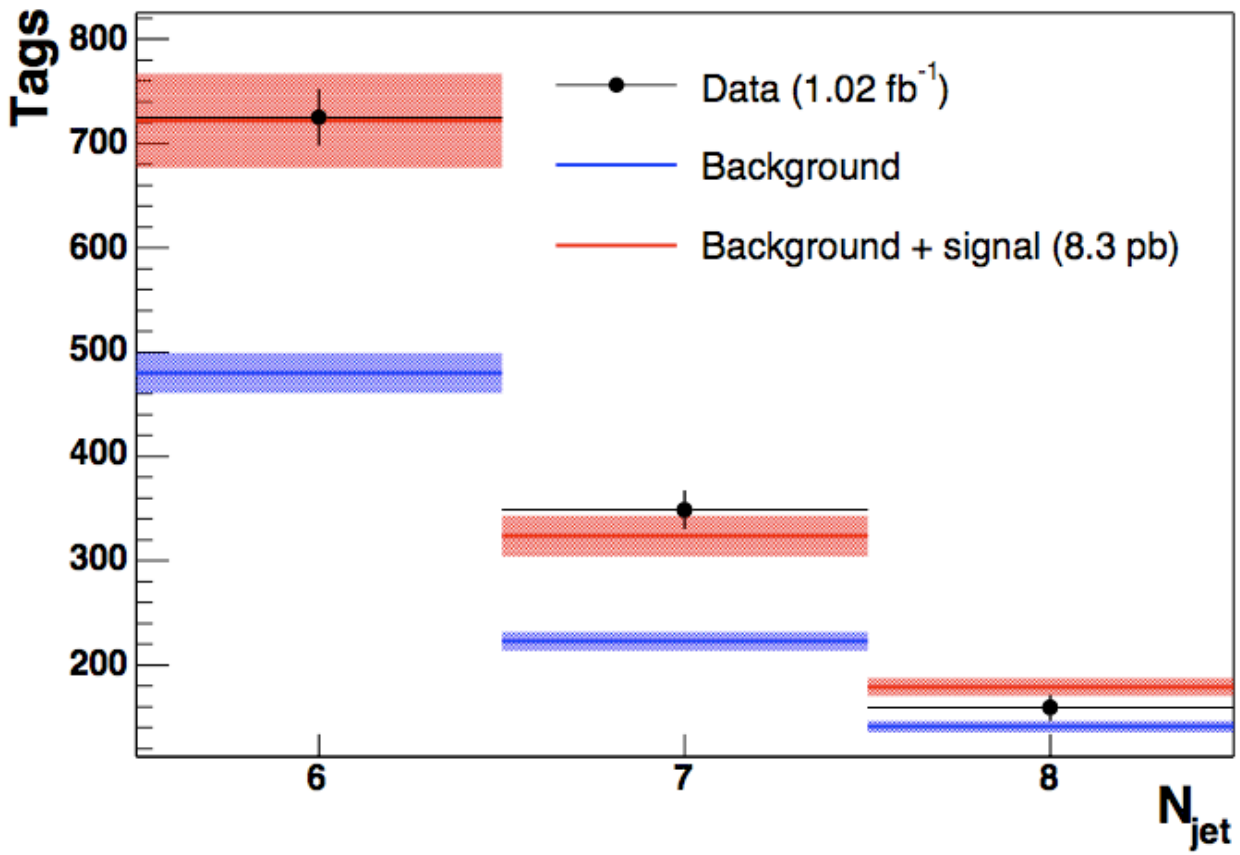
How we measure it

$$\sigma_{tt}=(N_{obs}-N_{bck})/(\varepsilon_{NN}*n_{ave}^{tag}*L)$$

N_{evts} pre tag	**-**	**4205**
Obs tags	**Nobs**	**1233**
Exp tags	**-**	**937 ± 30**
Exp tags corr*	**Nbck**	**846 ± 37**
Efficiency	**εNN**	**4.8 ± 0.8 %**
Average tags	**n_{av}^{etag}**	**0.95 ± 0.07**
Luminosity	**L**	**1.02 ± 0.06 fb-1**

*We subtract the signal contribution with an iterative technique to find **846 ± 37 tag**

Cross section measurement

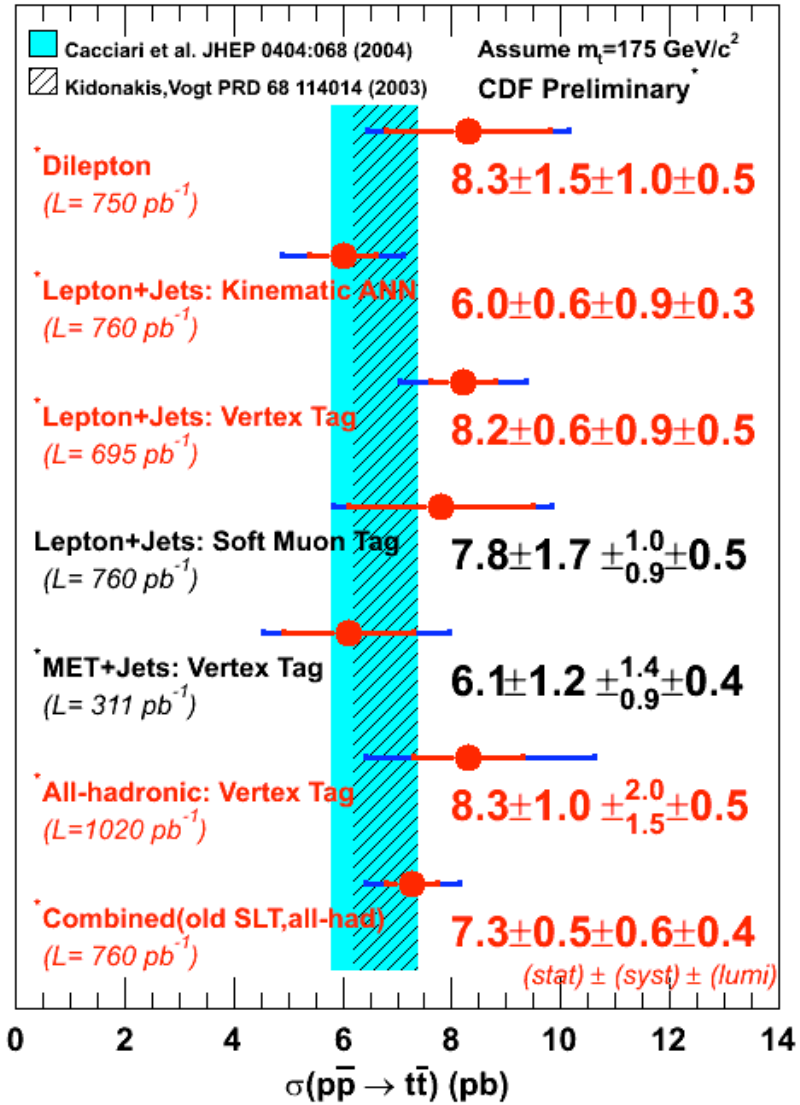


σ_{tt}= 8.3 ± 1.0(stat)$^{+2.0}_{-1.5}$(syst)± 0.5(lumi) pb

(top mass=175GeV/c^2)

Cross section summary

- not included yet in combination
- consistent with other channels



TOP: Mass measurement

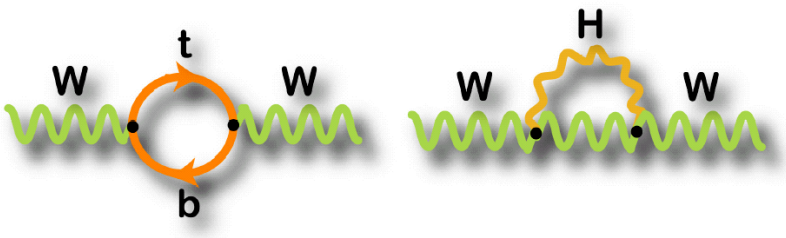
Free parameter in SM

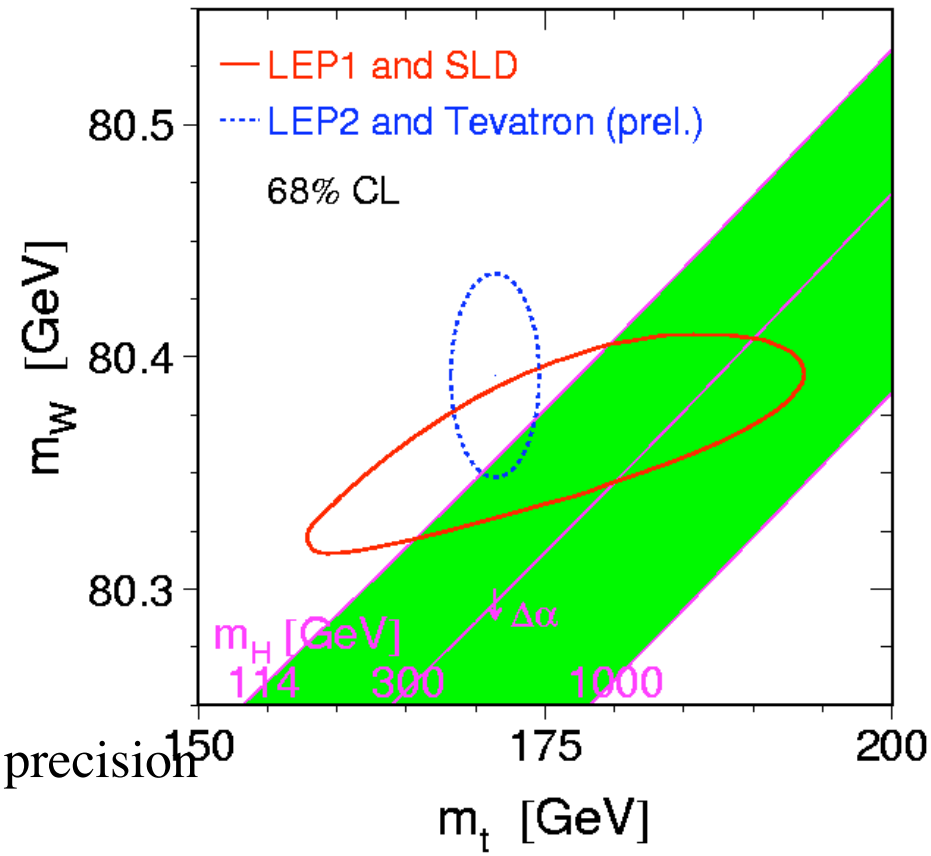
allows SM consistency check

Yukawa coupling~1

M_{top} enter in radiative corrections:

$$\Delta M_W \propto M_{top}^2 \qquad \Delta M_W \propto \ln M_H$$





Together with M_w and other electroweak precision measurements, it constrains M_{Higgs}

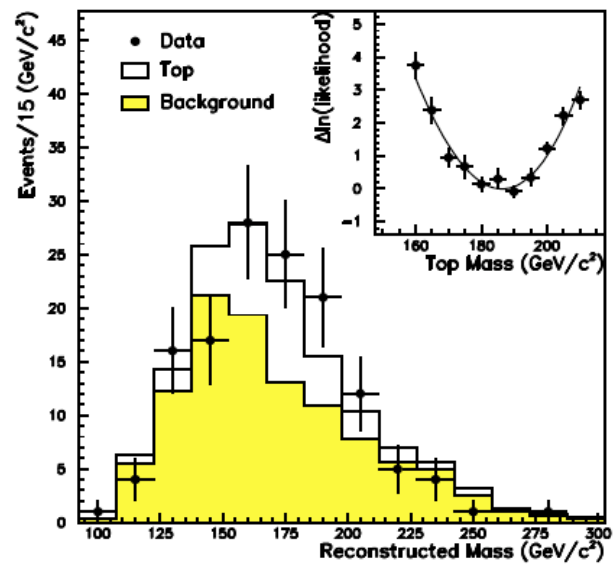
A key to understand electroweak symmetry breaking

CDF mass results in all-had

First RunI mass measurement L=110pb^{-1}

m_t=186.0 ± 10.0(stat.) ± 5.7(syst.) GeV/c^2

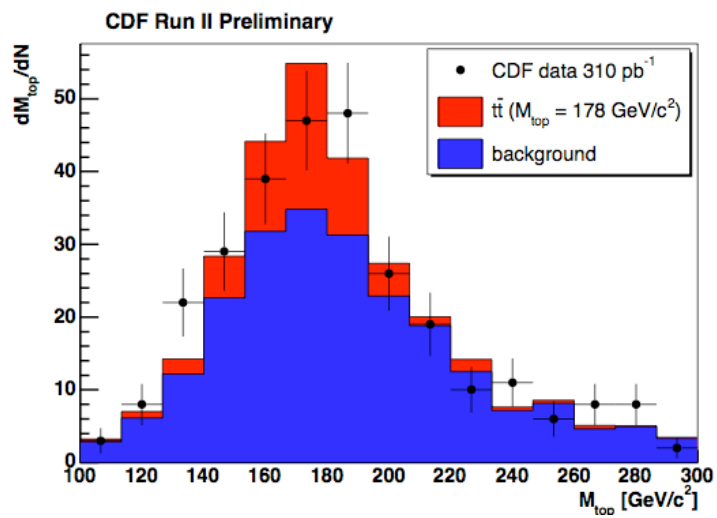
S~30 events



First Run II mass measurement L=310pb^{-1}

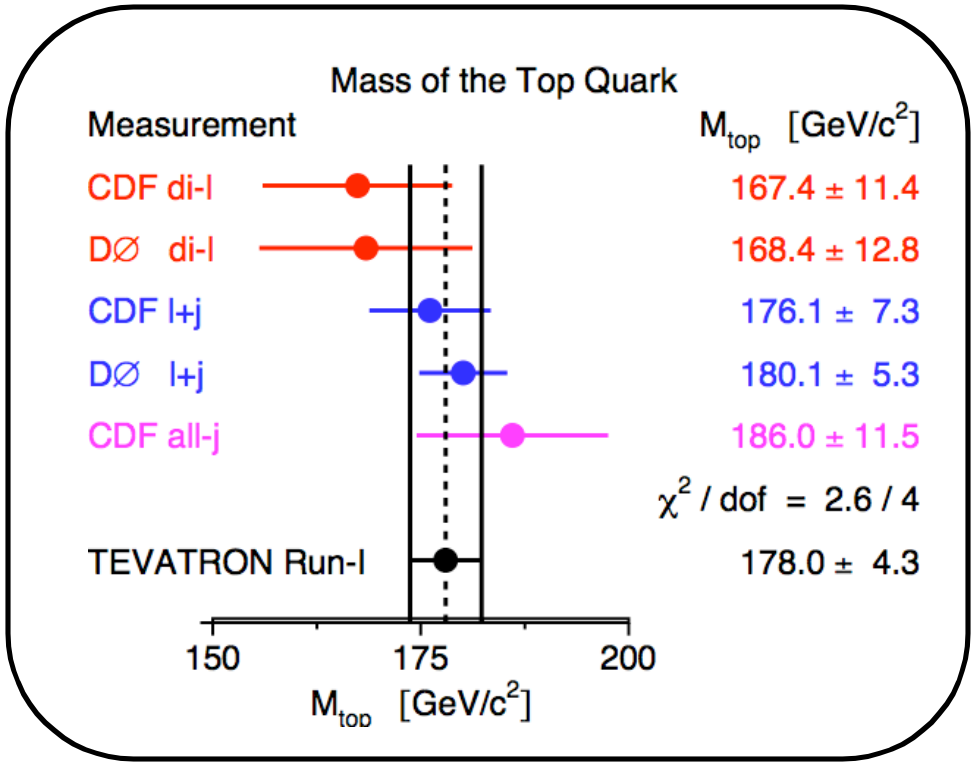
m_t=177.1 ± 4.9(stat.) ± 4.7(syst.) GeV/c^2

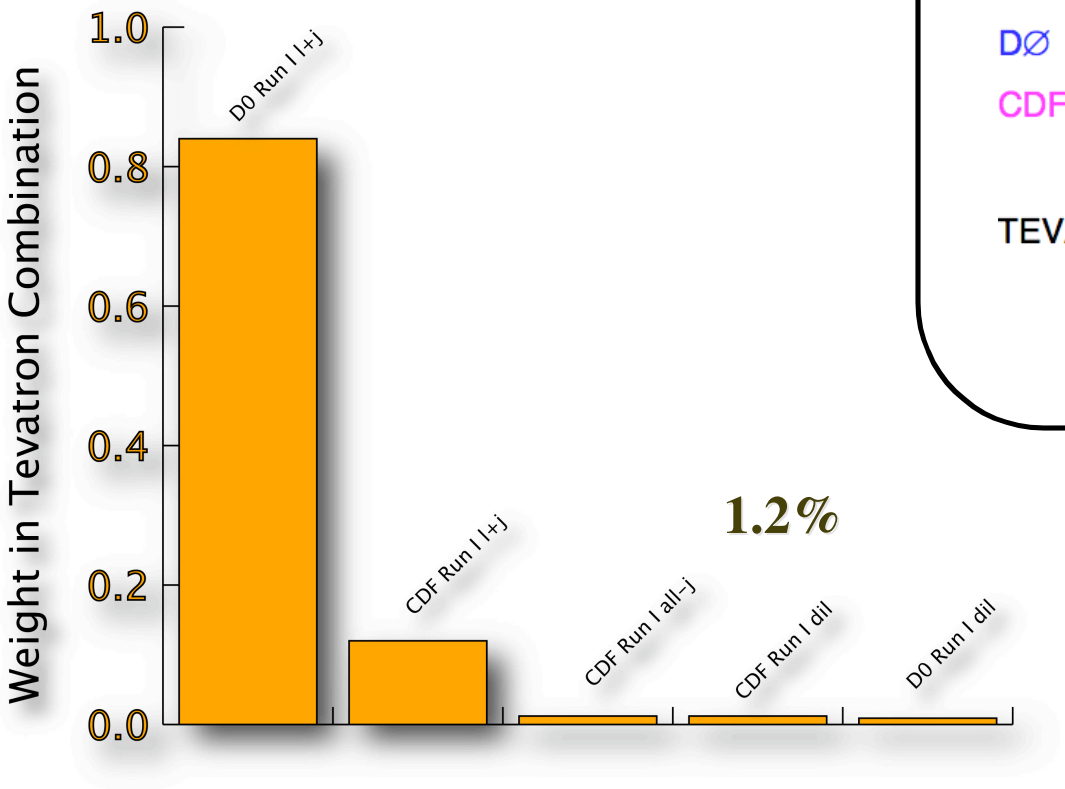
S~60 events



All-had mass and Run I average

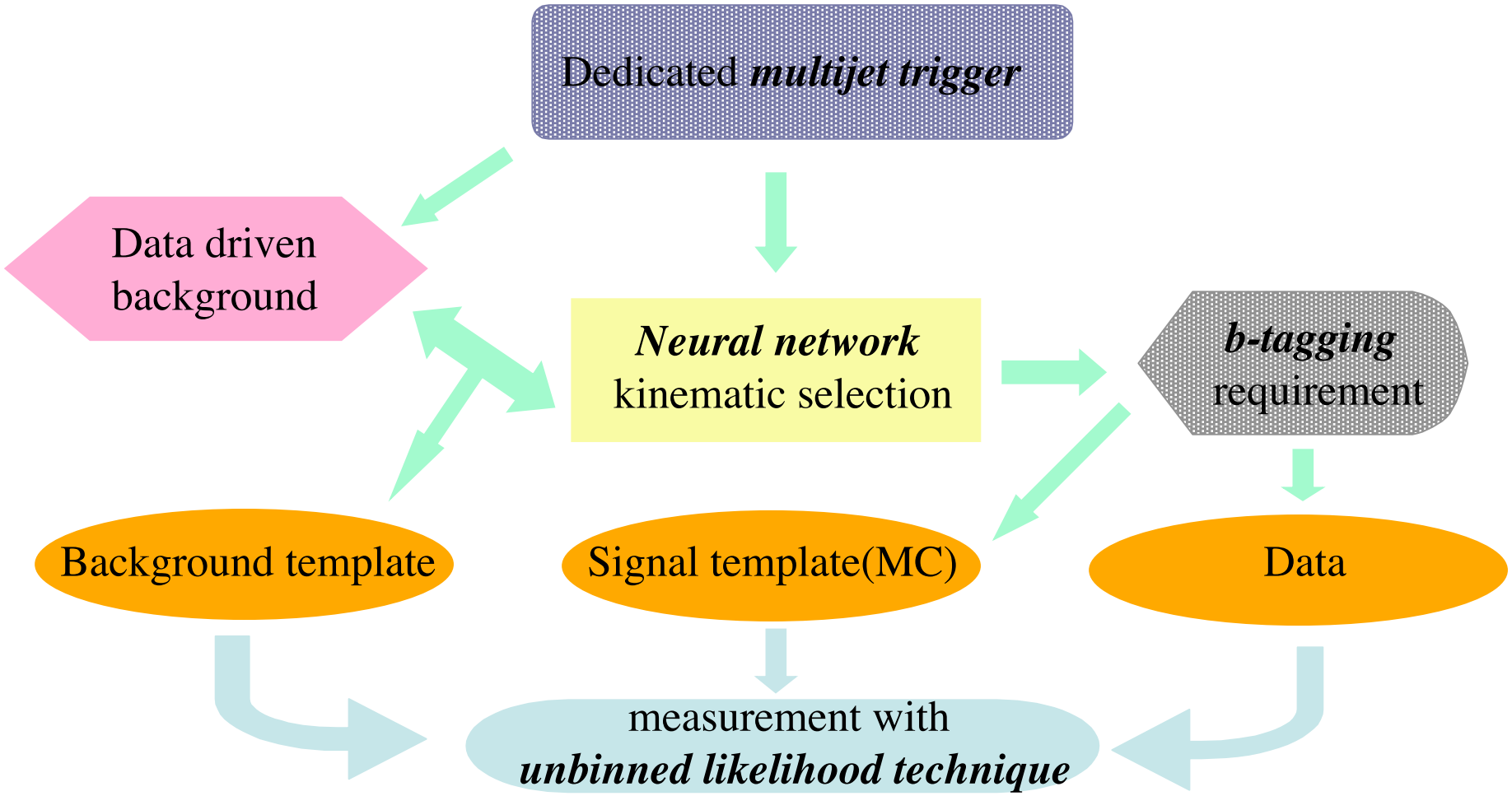
Tevatron mass average in Run I. Important cross-check between channels..





...but other channel contribution to measurement precision negligible

Mass Analysis overview



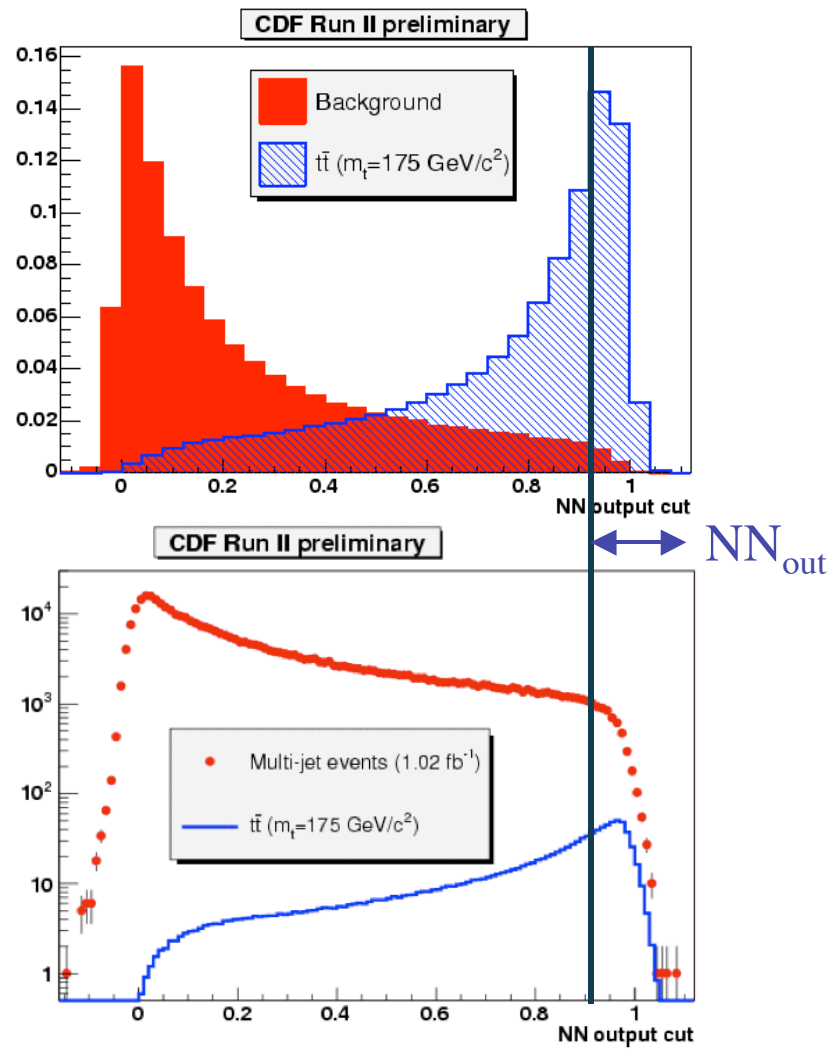
Reducing background

Cut at 0.94 was optimized for the x-sec measurement

Now we want to look for best cut for MASS measurement

Use pseudoexperiments spanning a range of high NN_{out}

NN_{out}>0.91 found to be the cut that offers best stastistical sensitivity



Fitter definition

- We reconstruct event kinematics according to $t\bar{t} \to b\,b\,q_1\bar{q}_2\,q_3\bar{q}_4$ hypothesis.
- Assume b-tagged jets come from b quarks (reduce combinatories)

$$\chi^2 = \frac{(m_{jj1} - m_W)^2}{\Gamma_W^2} + \frac{(m_{jj2} - m_W)^2}{\Gamma_W^2} + \frac{(m_{jjj1} - m_t)^2}{\Gamma_t^2} + \frac{(m_{jjj2} - m_t)^2}{\Gamma_t^2} + \Sigma\frac{(p_i^{fit} - p_i^{data})^2}{\sigma_i^2}$$

m_W , Γ_W fixed to known values - Γ_t theoretical value

m_{top} - p_T^{fit} fit parameters

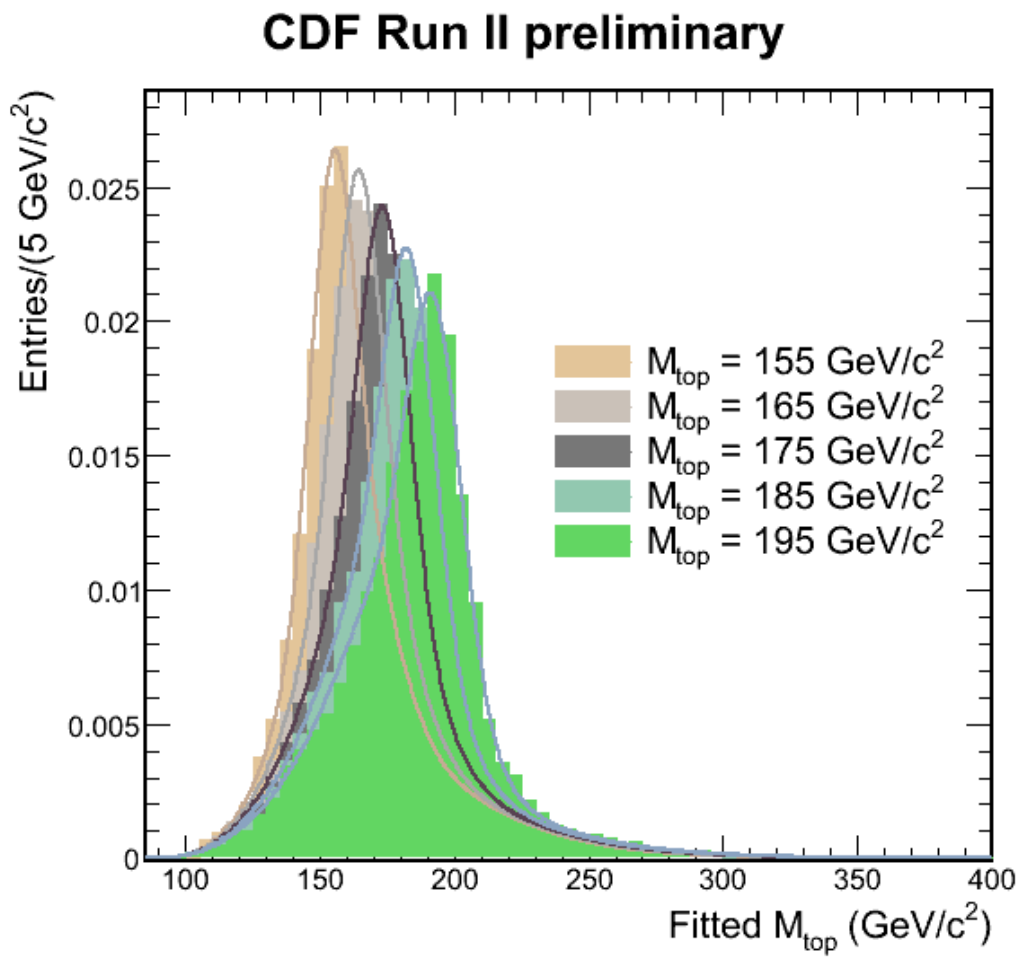
- Pick up the combination with the lowest χ^2 enters an invariant mass of fitted mop distribution, i.e. our template

- Use pseudoexperiments to determine best χ^2 cut -> $\chi^2 < 16$

Signal templates

Use MC Herwig with masses ranging from 150 to 200 GeV/c^2 as signal.

Parametrize resulting shape to obtain a pdf smoothly varying with input M_{top}



Background estimation

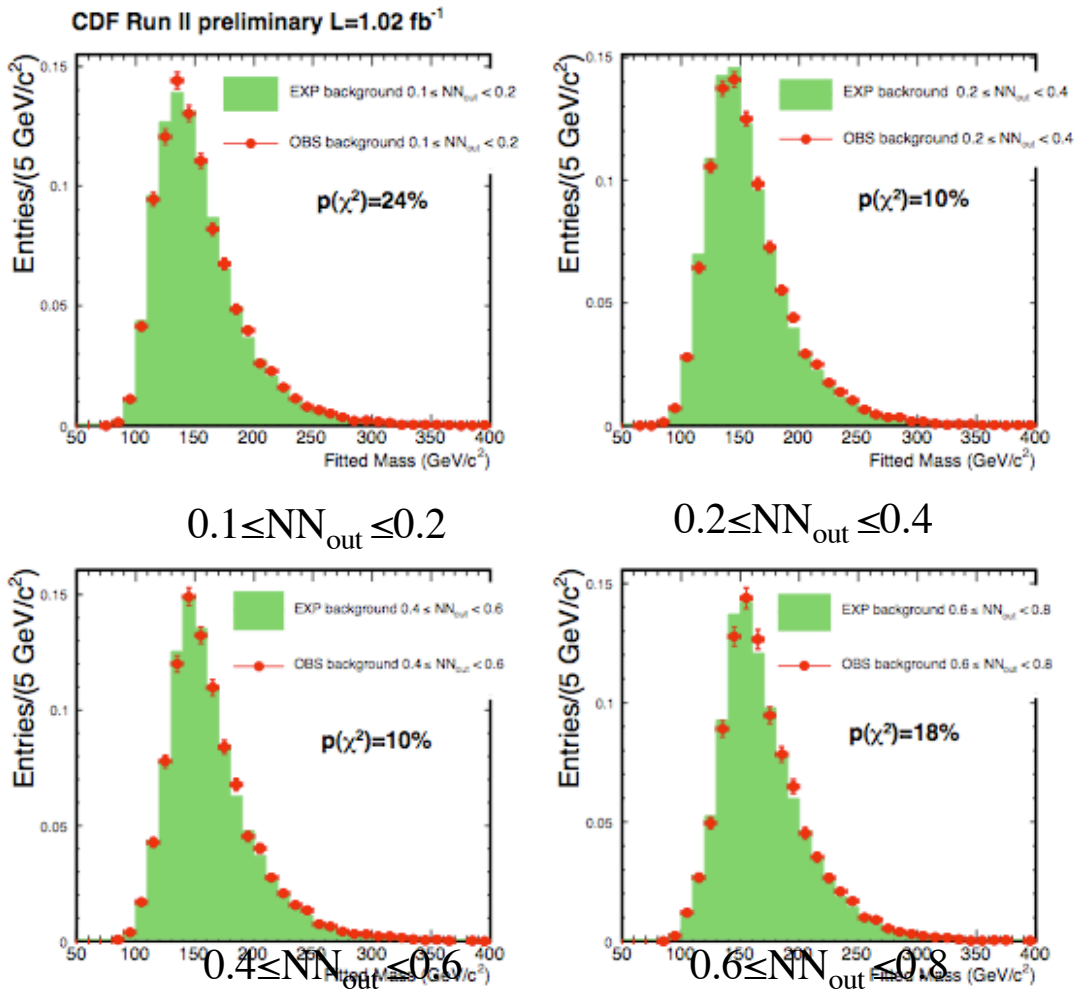
In this region S/B<<5%

red real >=1tag data

green expected background

no b quark i.d.

Resulting distribution is validated in data samples NN_{out} control regions



$0.1 \le NN_{out} \le 0.2$ $0.2 \le NN_{out} \le 0.4$

$0.4 \le NN_{out} \le 0.6$ $0.6 \le NN_{out} \le 0.8$

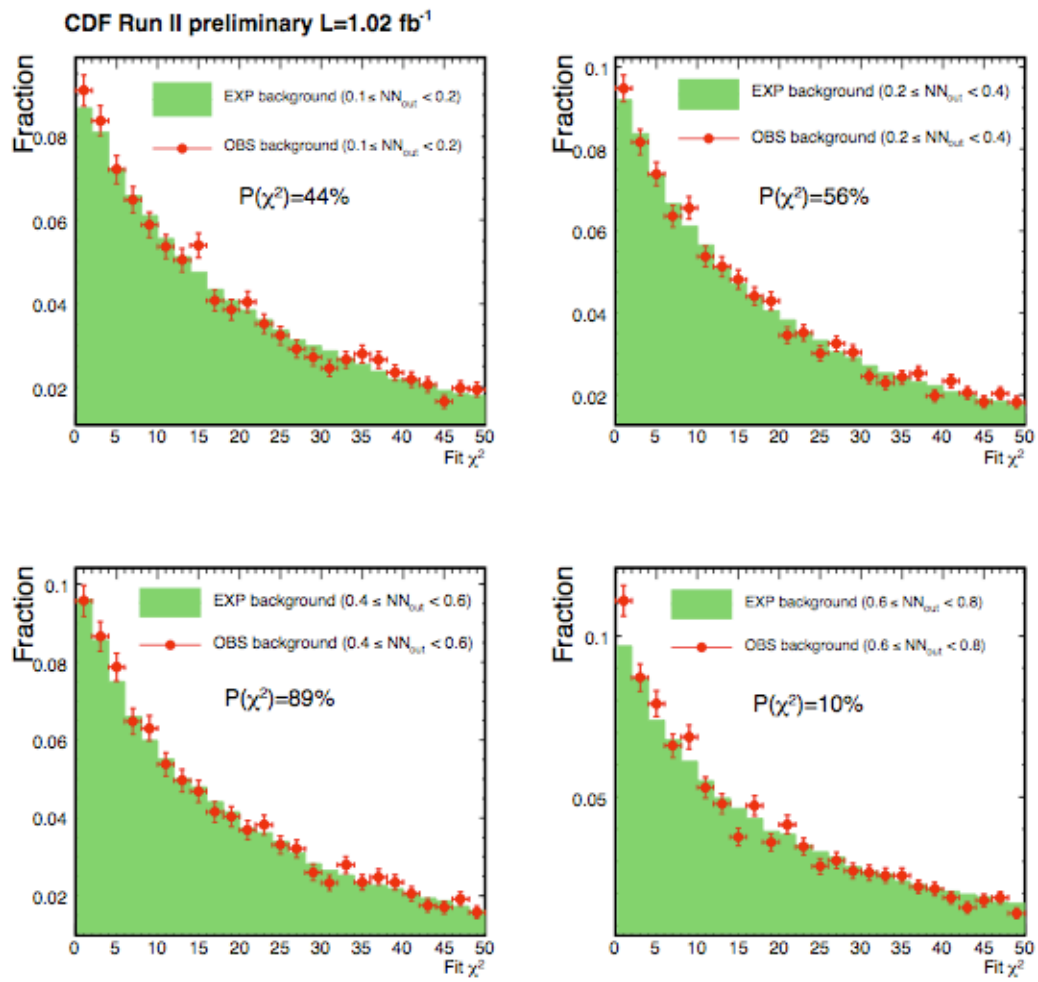
More validation

Same check performed also in other kinematic distribution

red real >=1tag data

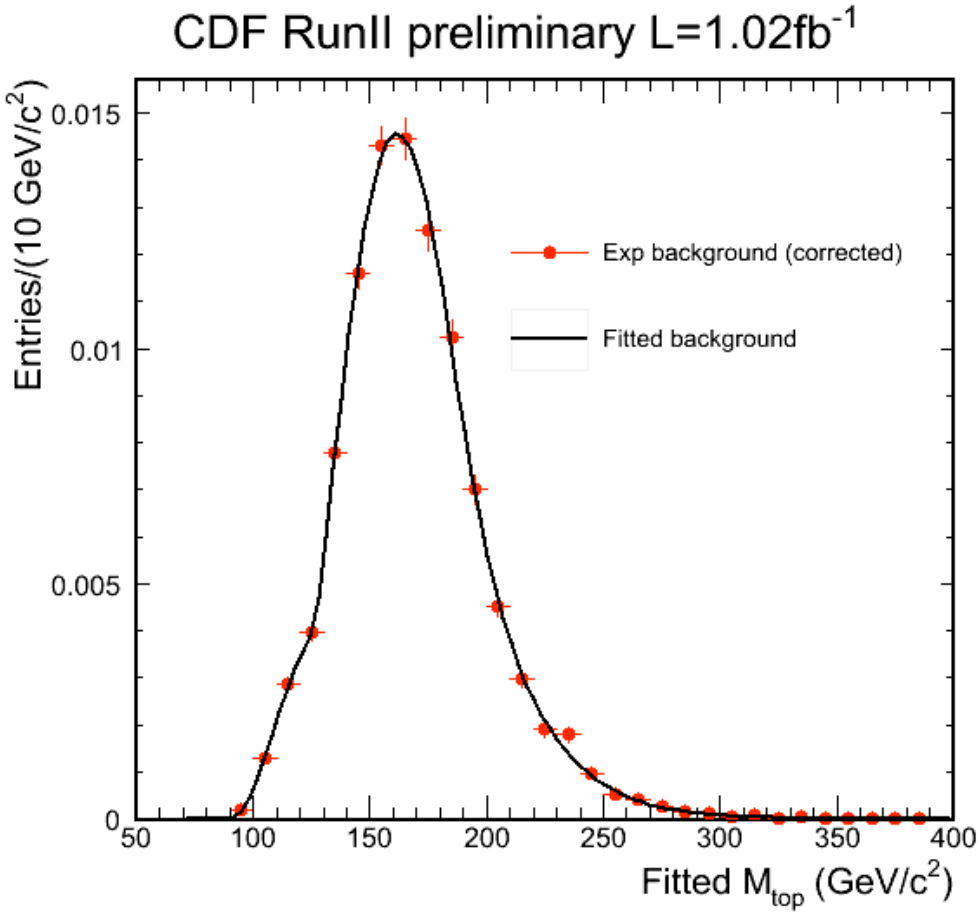
green expected background no b quark i.d.

Agreement good over the whole control region $0.1 \leq NN_{out} \leq 0.8$



Final background

- Signal contribution estimated and subtracted
- Fit with an analythical curve



Likelihood fit

Finally compare the data invariant masses to signal and background templates

$$L_{sample} = L_{norms} \cdot L_{shapes}$$

$$L_{sample} = e^{-\frac{(n_b - N_b)^2}{2\sigma^2_{N_b}}} \cdot e^{-\frac{(n_b + n_s - N)^2}{2\sigma^2_N}} \cdot \prod_{i=1}^{N} \frac{n_b P_b(m_i) + n_s P_s(m_i, M_{top})}{n_b + n_s}$$

n_s, n_b are #s,b tags, N obs tags

M_{top} true top mass

$\{m_i\}$ input mass from data

P_b P_s prob. dist. func.

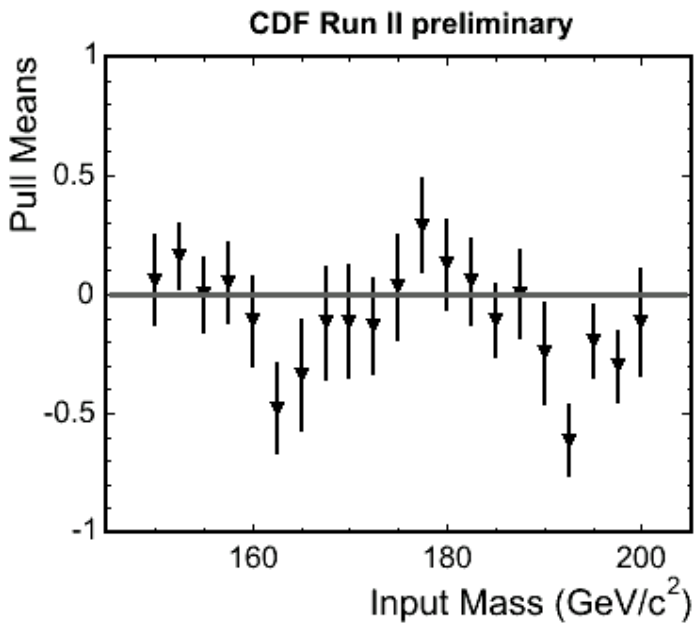
Find a maximum for L_{sample} with respect to n_s, n_b, M_{top}

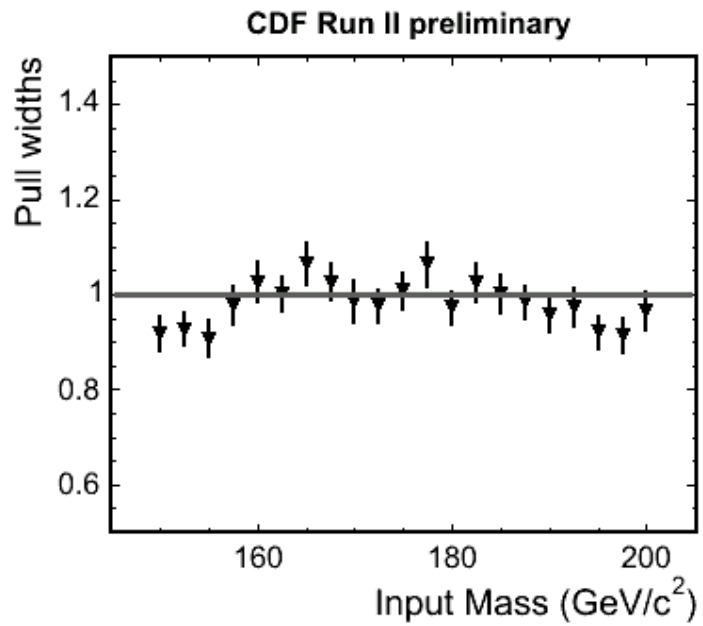
Pseudo-experiments

Plot ***pull*** $\frac{M_{fit} - M_{input}}{\sigma_{M_{fit}}}$

means to check if method is biased

widths to check if statistical sensitivity prediction is accurate





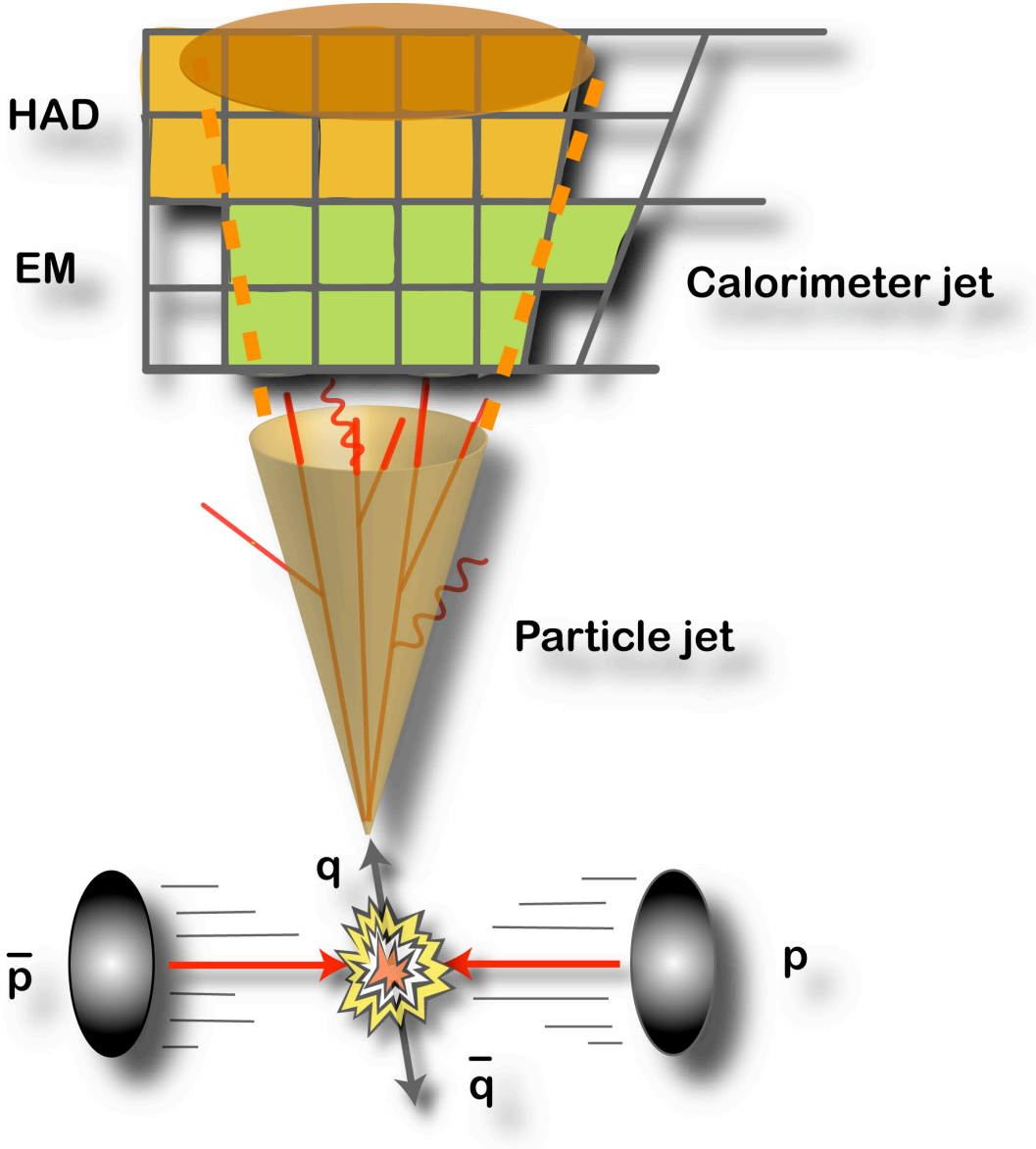
Residual discrepancy accounted in systematics

Systematic uncertainties

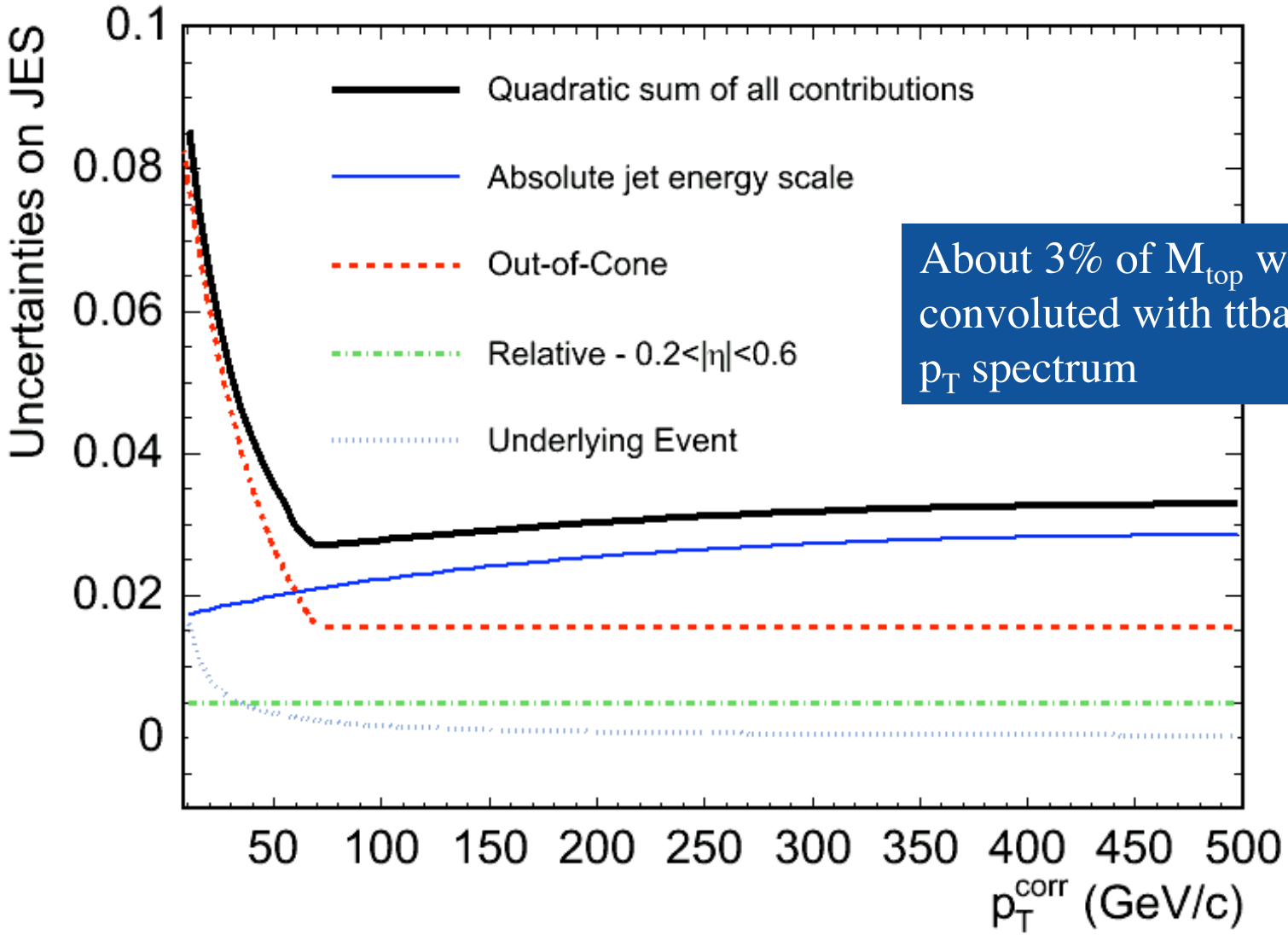
Source	Systematics (GeV/c^2)
Jet energy scale	4.5
Generator	1.0
b-jet energy scale	0.5
Parton Distribution Function	0.5
Background shape	0.5
Background fraction	0.5
ISR	0.5
FSR	0.5
b-tag	0.5
MC statistics	0.1
Template parametrization	0.1
Total	4.8

Jet energy scale

- Jet energy scale
  - Determine the energy of the quarks produced in the hard scattered
  - We use the Monte Carlo and data to derive the jet energy scale
- Jet energy scale uncertainties
  - Differences between data and Monte Carlo from all these effects



Jet energy scale uncertainty

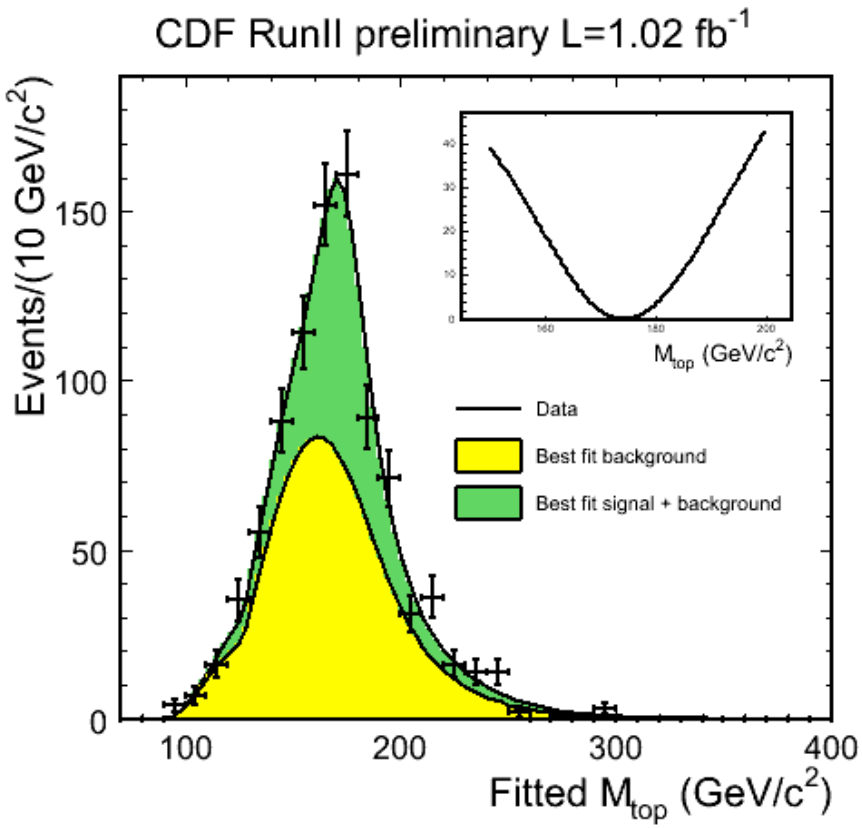


About 3% of M_{top} when convoluted with ttbar p_T spectrum

Results

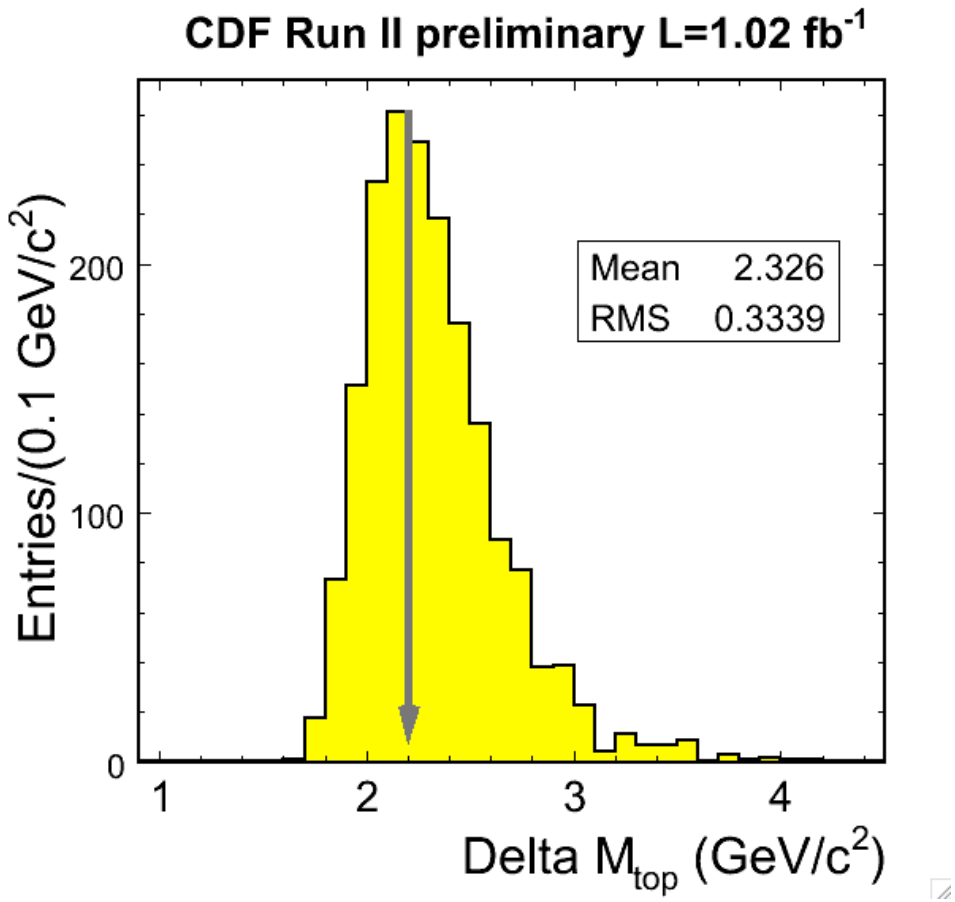
Apply to L=1.02 fb^{-1} of data. Find 926 tags in 772 events. We measure:

m_{top}=174.0 ± 2.2 (stat.) ± 4.8 (syst.) GeV/c^2



What did we expect?

About 40% of the pseudo-experiments have lower σ_{stat}

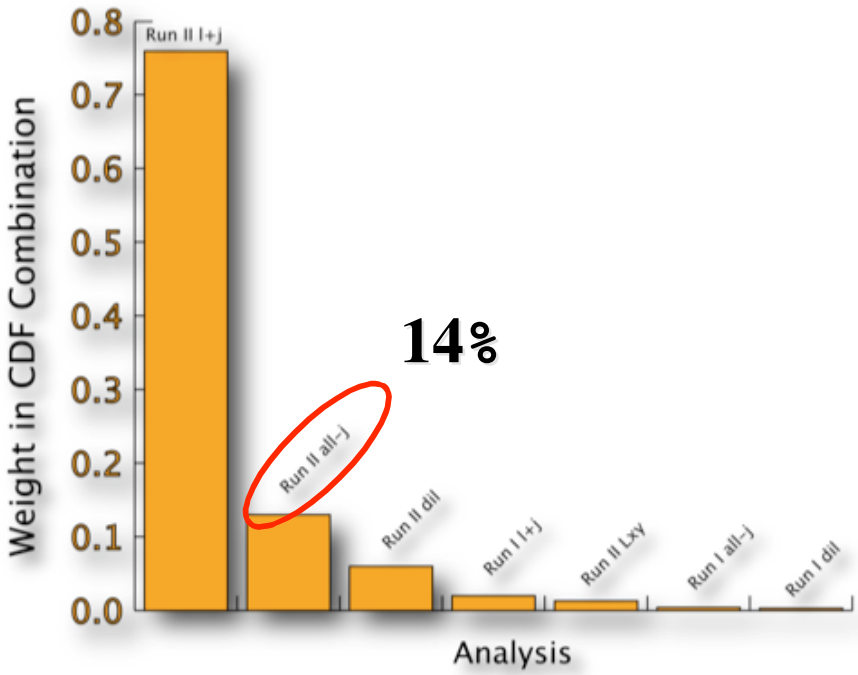


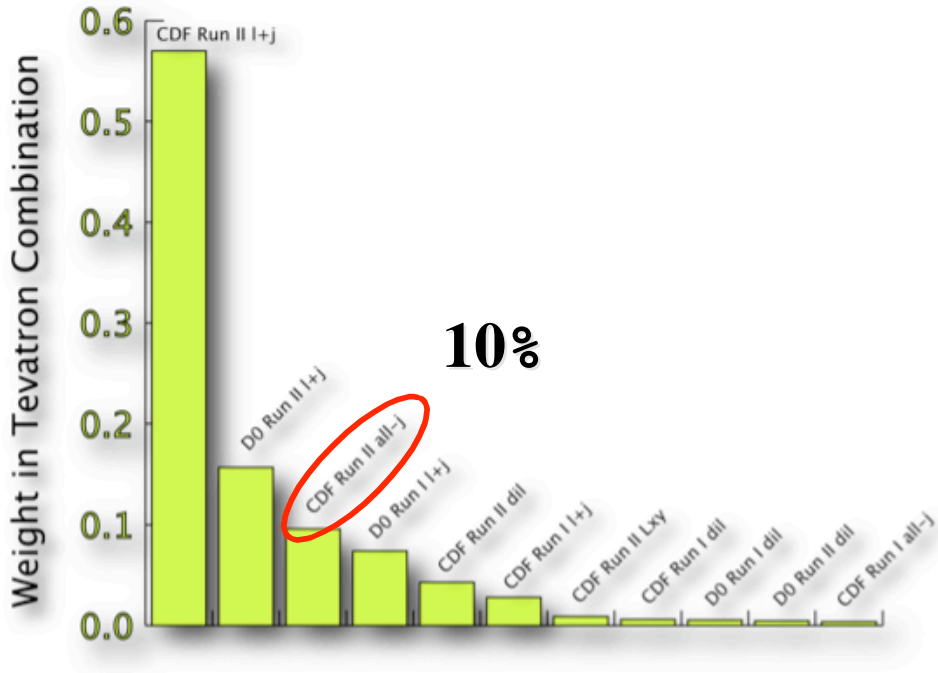
grey arrow:
measured σ_{stat}

All-hadronic mass and world average

This measurement enters the most recent Tevatron combination

All-hadronic channel now second main contributor



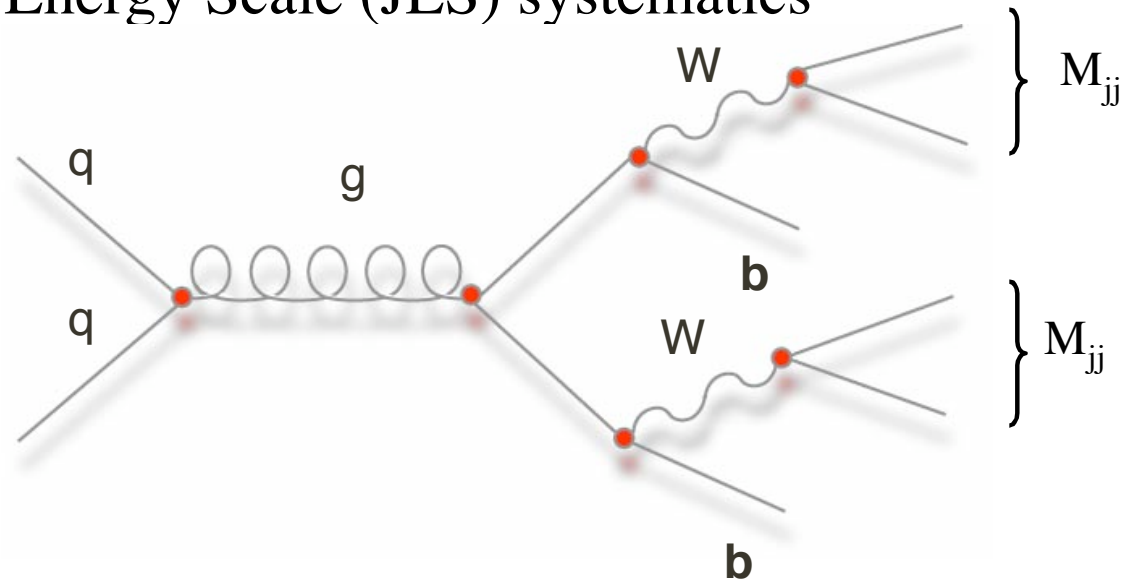


Yesterday	Run I	$110pb^{-1}$	$w_i \rightarrow 1\%$
Today	Run II	$1000pb^{-1}$	$w_i \rightarrow 10\%$

And...what about tomorrow?

Addressing jet energy scale issue

Jet energy can be calibrated *in situ* using jets from hadronic W decays. CDF & D0 already use W→jj in the lepton+jet channel to reduce Jet Energy Scale (JES) systematics



Constrain the invariant mass of the non-b-tagged jets to be 80.4 GeV/c^2

In this channel there are two hadronic W decays

more sensitive to the jet energy scale!

CDF measurements

RunI 110pb^{-1}	stat. (GeV/c^2)	JES (GeV/c^2)	other syst. (GeV/c^2)
dilepton	10.3	3.8	2.9
all-hadronic	10.0	5.0	2.7
lepton+jets	5.1	4.4	3.0

RunII 1fb^{-1}	stat. (GeV/c^2)	JES (GeV/c^2)	other syst. (GeV/c^2)
dilepton	3.9	3.5	1.7
all-hadronic	2.2	4.5	1.7
lepton+jets	1.6	1.4	1.4

without *in situ* calibration

with *in situ* calibration

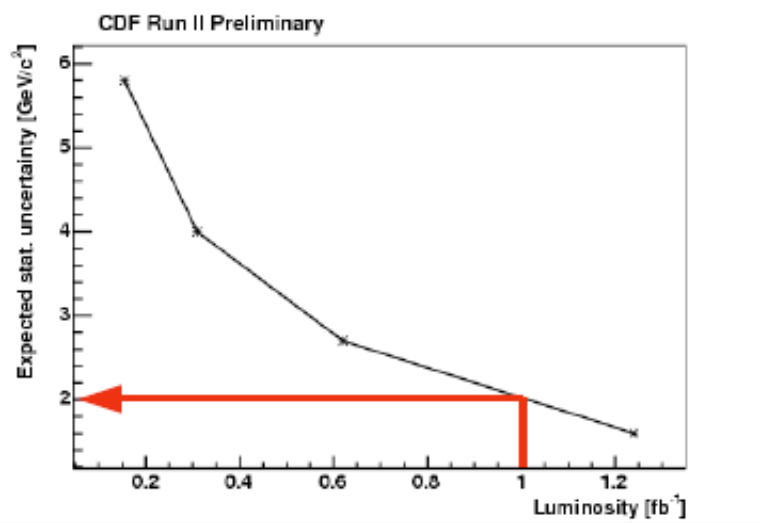
Other measurements ongoing

"*Ideogram*"

- Cascade cuts
- Statistical tagging algorithm
- Mixed background: MC+data-driven

Sensitivity with L=1 fb^{-1}

assuming no improvements to the technique: **stat~2GeV/c²**



"*FLAME*": Mixed technique

- Cascade cuts
- Secondary vertex tagger
- Data-driven background

- Templates weighted by Matrix Element event probabilities

- Already using W→jj *in situ* calibration to measure the jet energy scale

Coming soon!

Conclusion

- Overall 6 measurement (RunI + RunII) of top quark properties at the CDF detector in the all-hadronic channel
- Recent results: σ_{tt}= 8.3 ± 1.0(stat)$^{+2.0}_{-1.5}$(syst)± 0.5(lumi) pb

  m_{top}=174.0 ± 2.2 (stat.) ± 4.8 (syst.) GeV/c^2

Precision measurements where we've been swamped by background

Latest mass measurement in CDF contributes 10% to world average

HUGE POTENTIAL we just started to uncover

more results with ***different techniques*** coming soon!

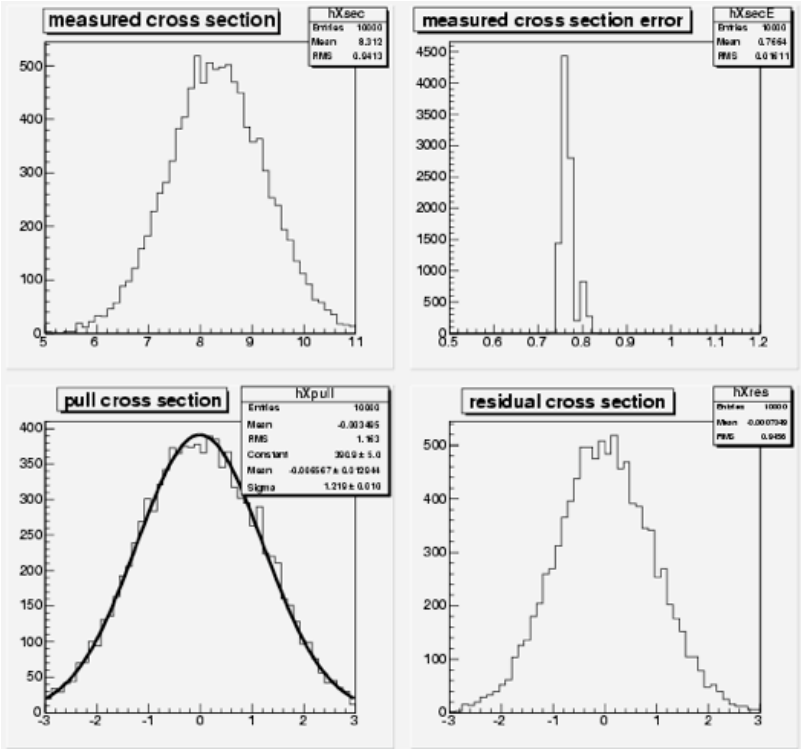
Back up slides

Tags-events

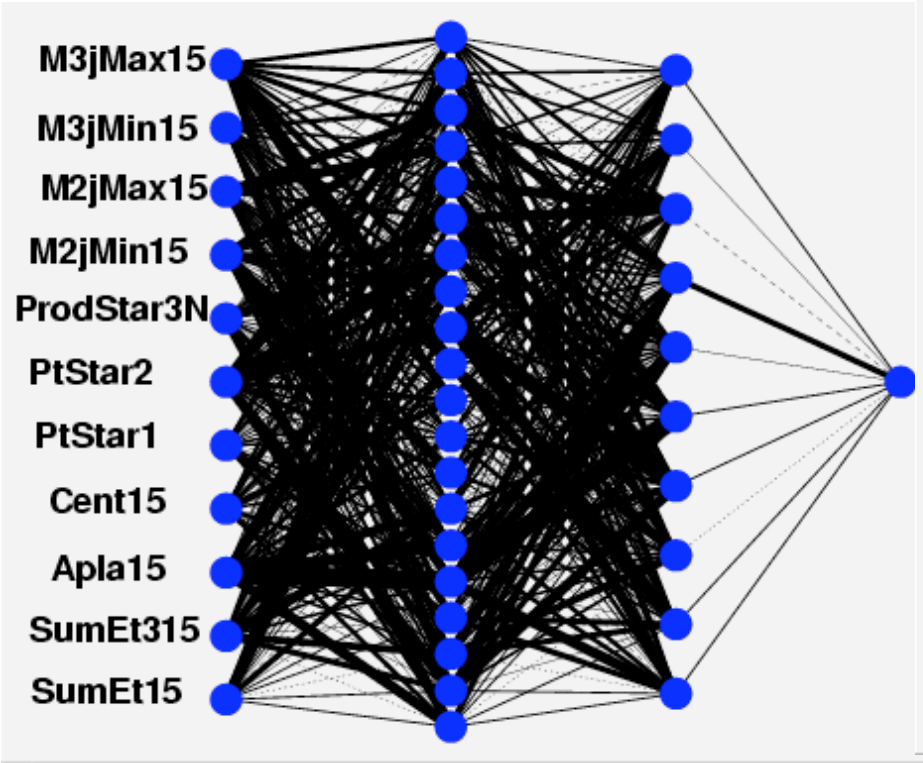
- This data driven background has the inconvinient of having to use tags instead of events.

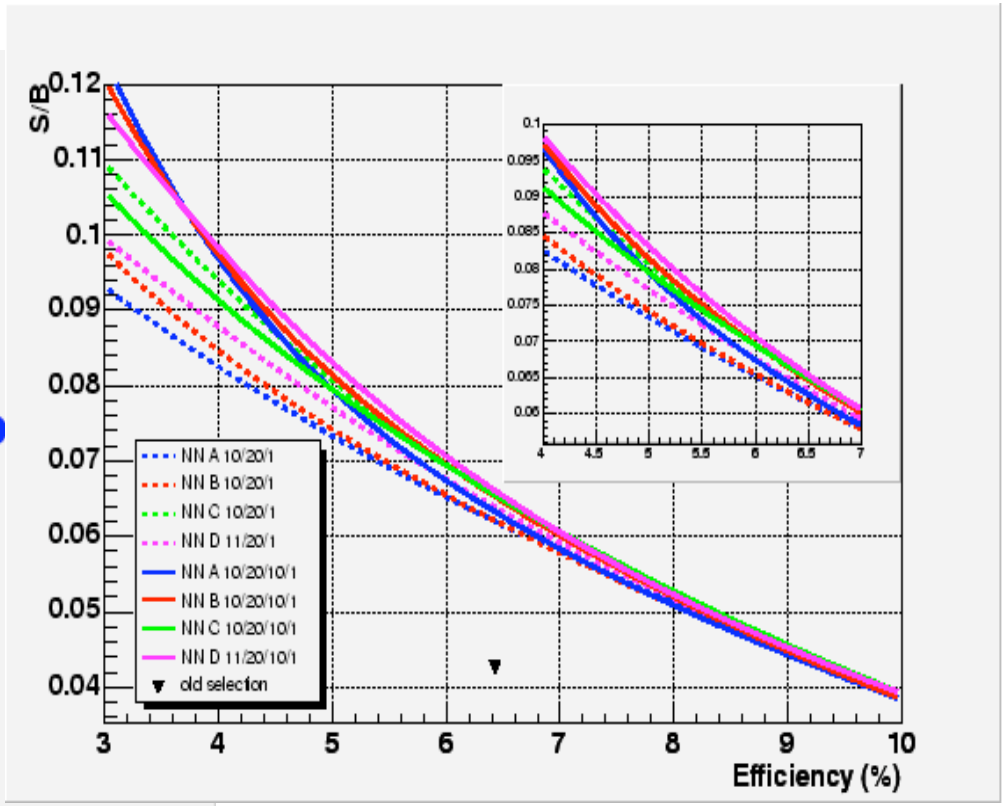
- Proved that this choice do not introduce a bias using pseudo-experiments (have to make assumptions on # of 1tag and 2 tag events for background)

- Found that stat error has to be inflated by 20%

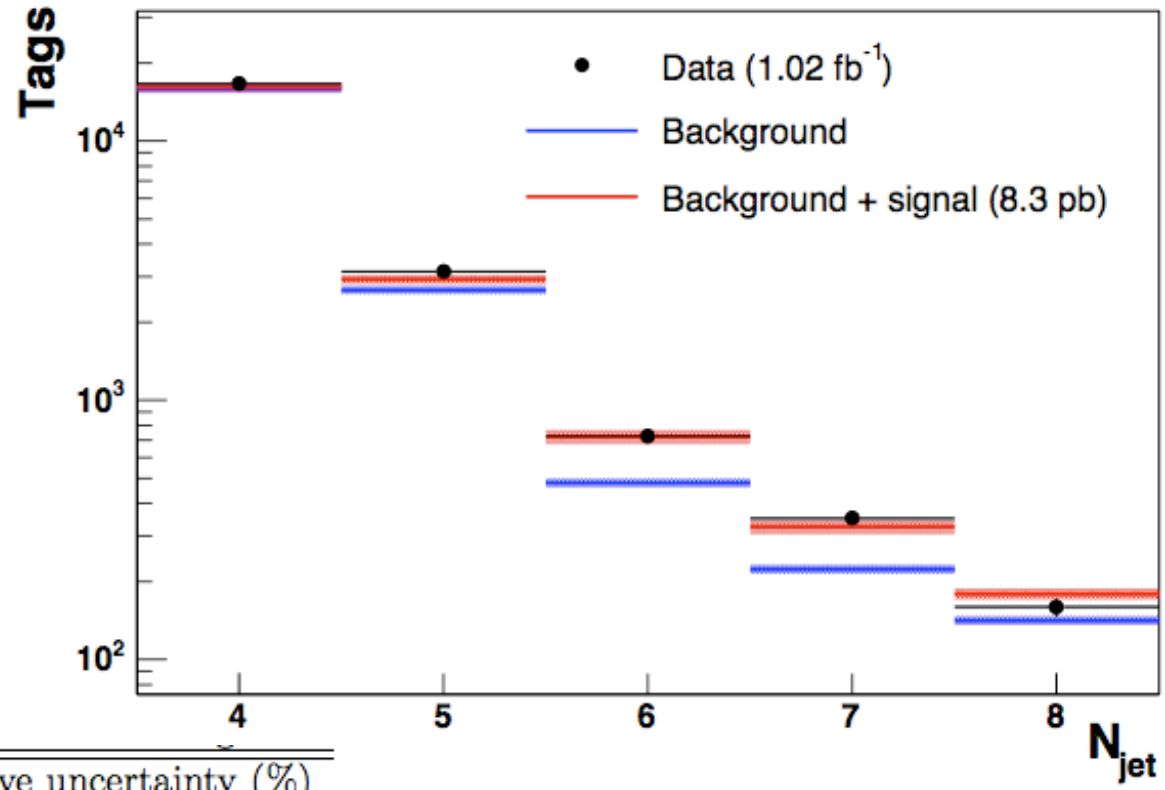


11 var / 20 nodes/ 10 nodes/ 1output



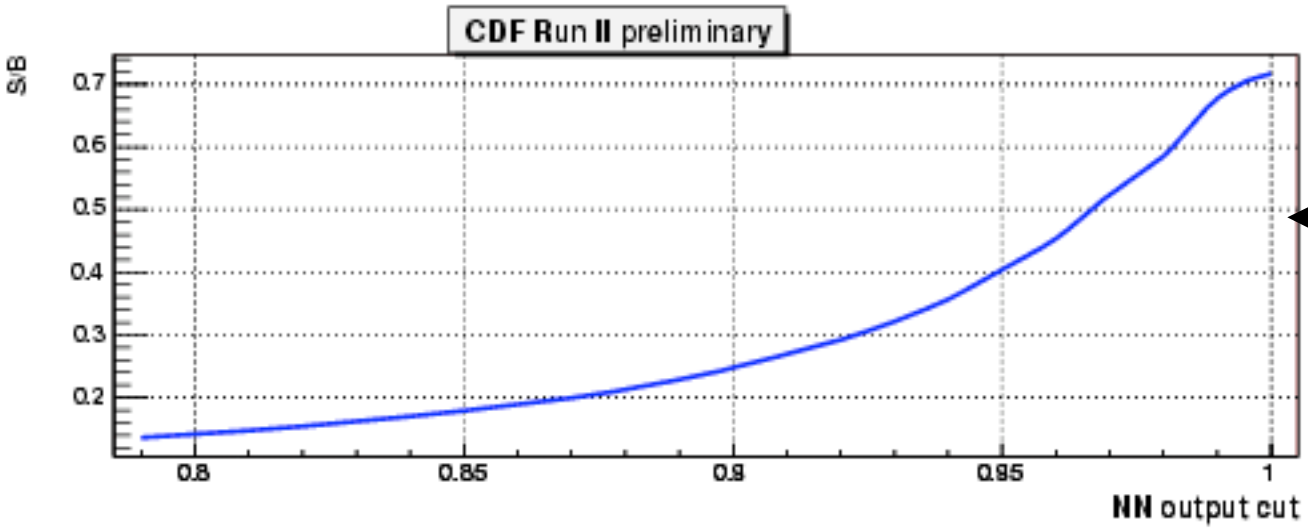


xsec meas.

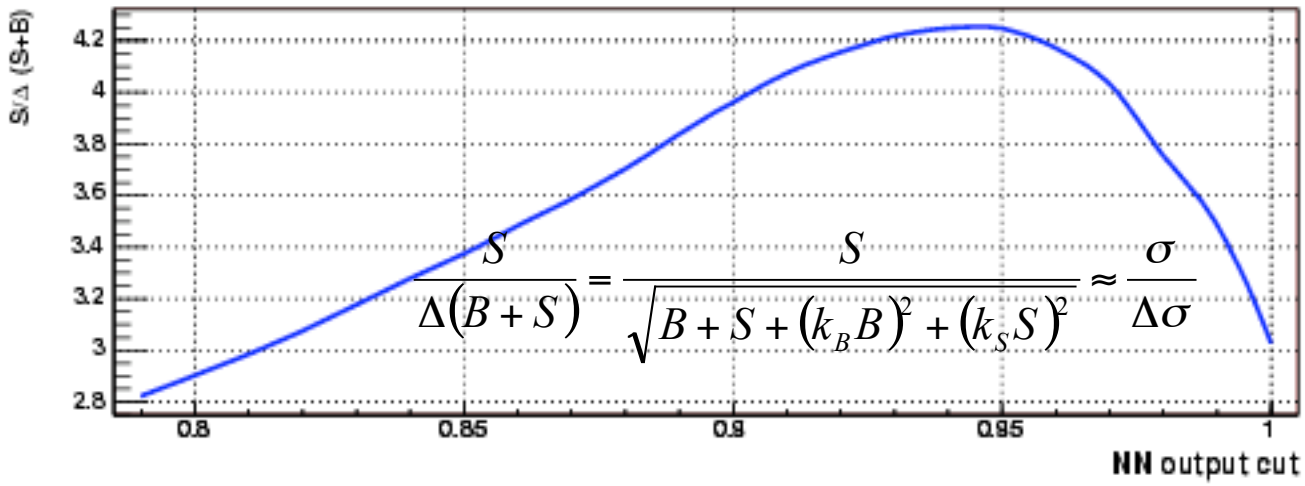


Source	Relative uncertainty (%)
Energy Scale	16.3
PDFs	1.4
ISR/FSR	2.9
Monte Carlo Modeling	1.1
Multiple interactions	2.5
Total	17.0

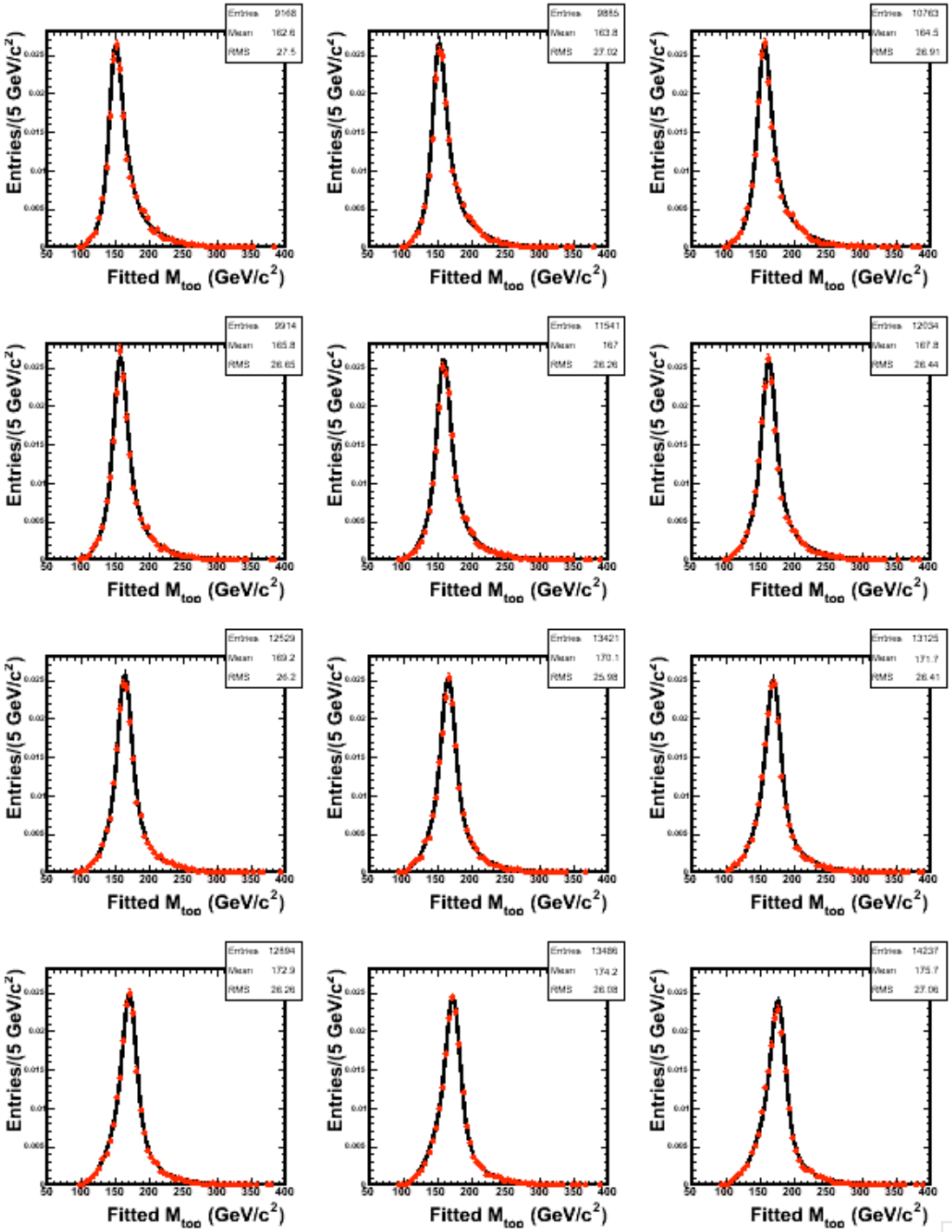
We use data to validate

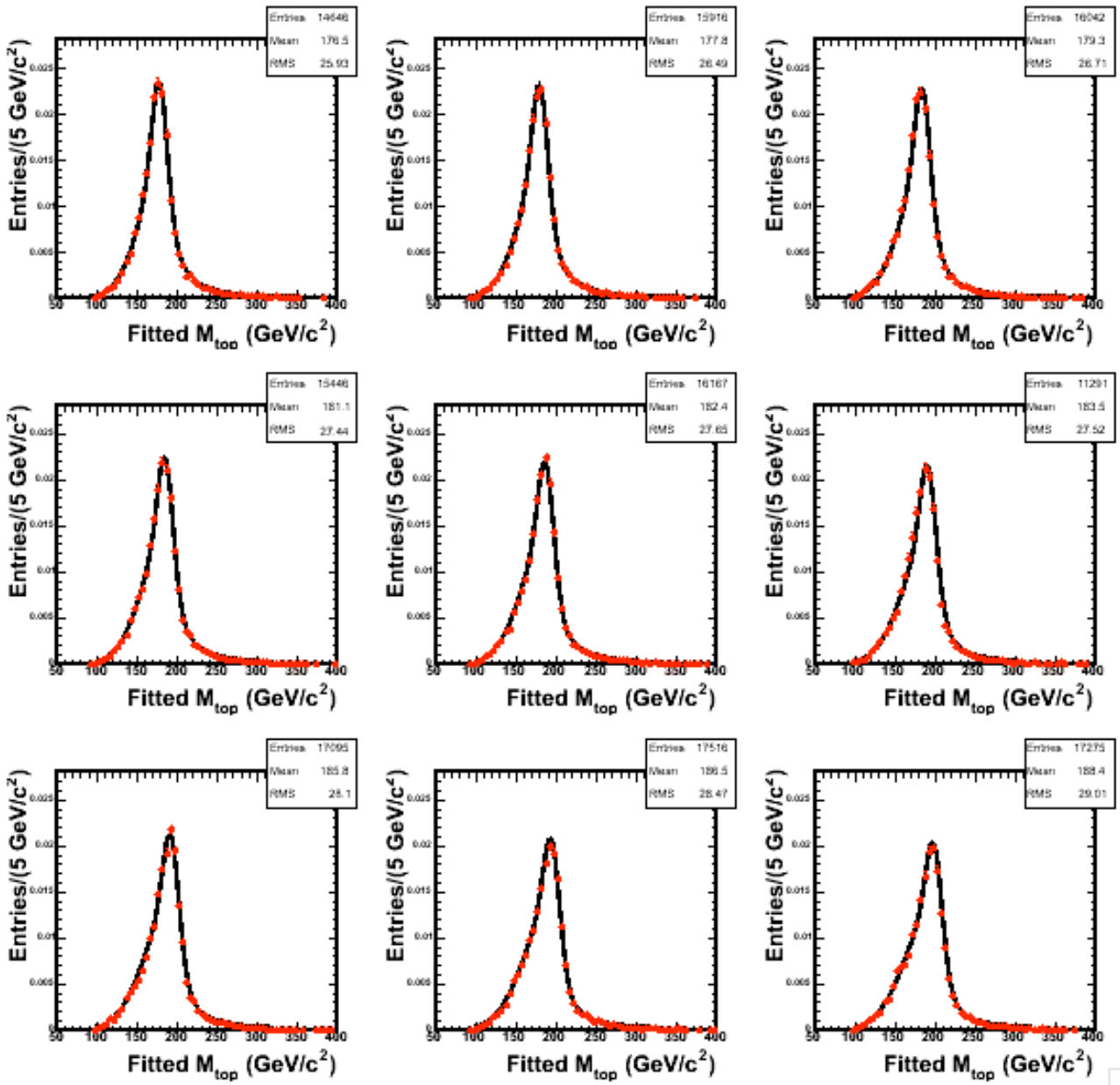


After requiring at least 1 tag

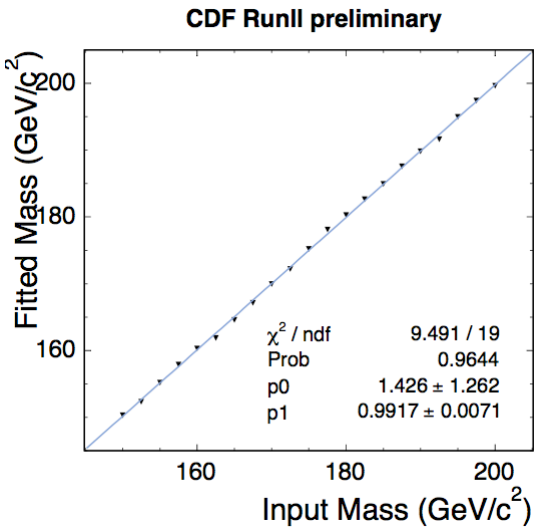


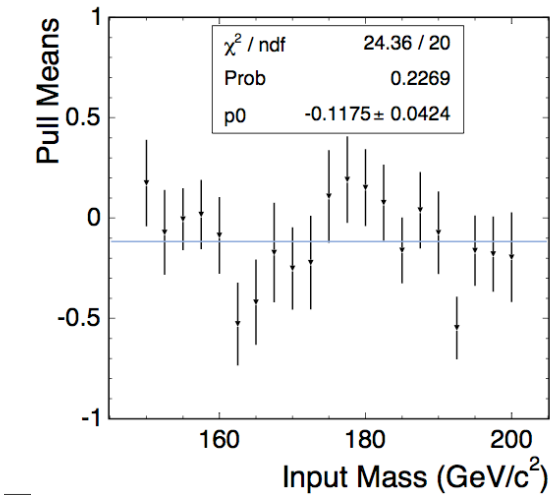
$$\frac{S}{\Delta(B+S)} = \frac{S}{\sqrt{B+S+(k_B B)^2+(k_S S)^2}} \approx \frac{\sigma}{\Delta\sigma}$$

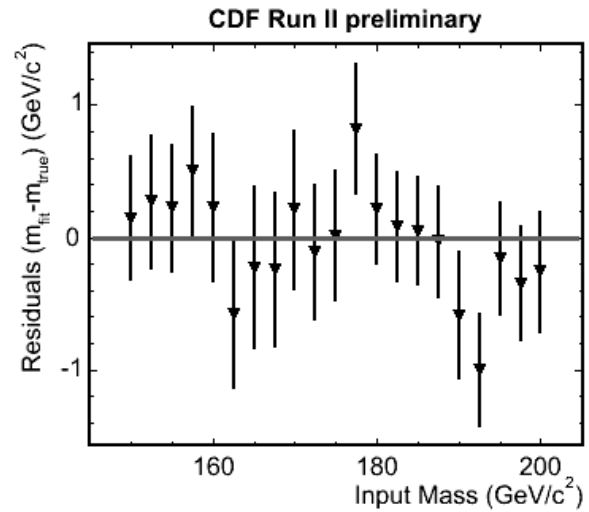

Entries/(5 GeV/c²)
Fitted M_too (GeV/c²)

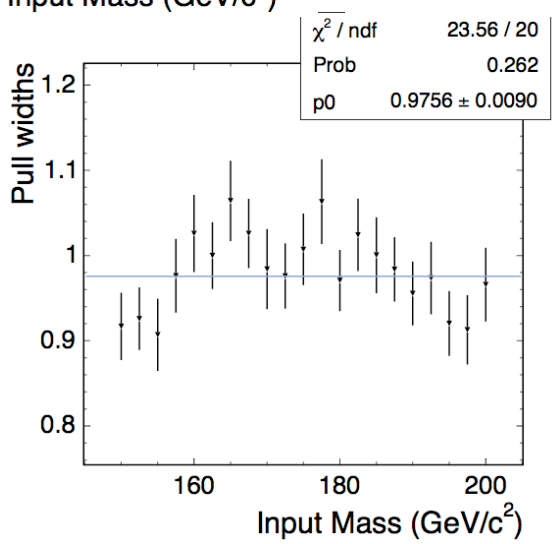

Entries/(5 GeV/c²)
Fitted M_top (GeV/c²)

Mass pseudo-experiments









add sigma rms