Data Analysis II

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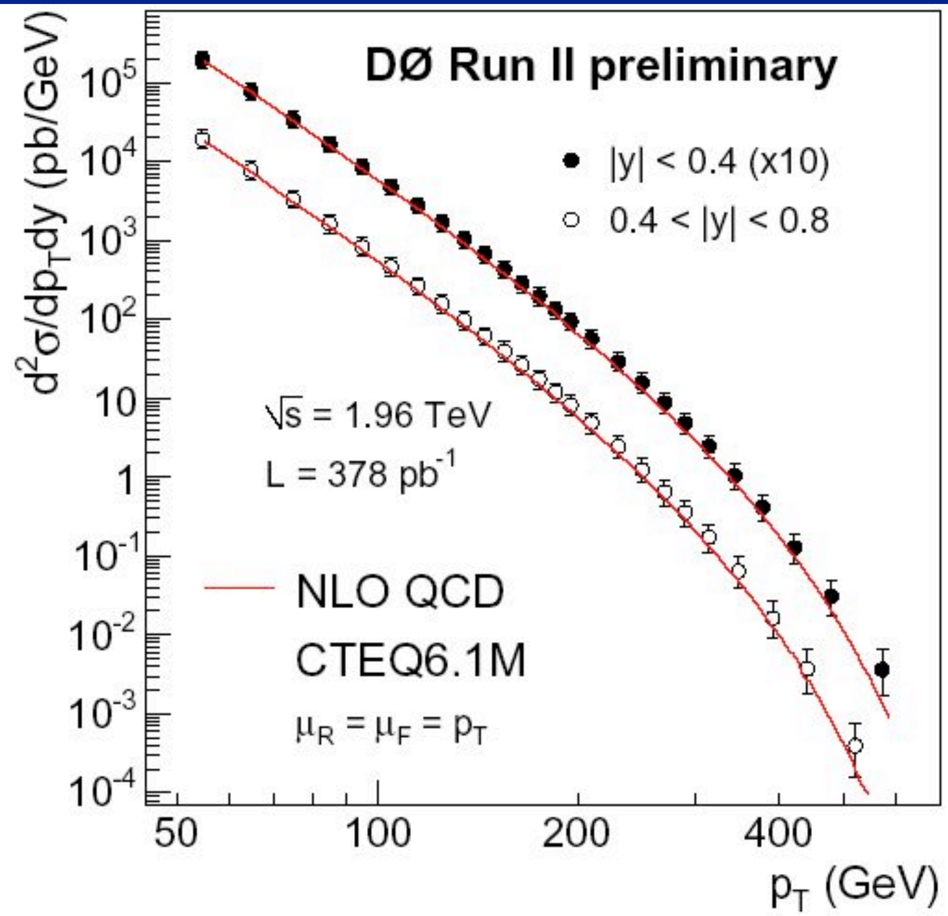
Outline

- Lecture I:
  - Measuring a cross section
    - focus on acceptance
- Lecture II:
  - Measuring a property of a known particle
- Lecture III:
  - Searching for a new particle
    - focus on backgrounds

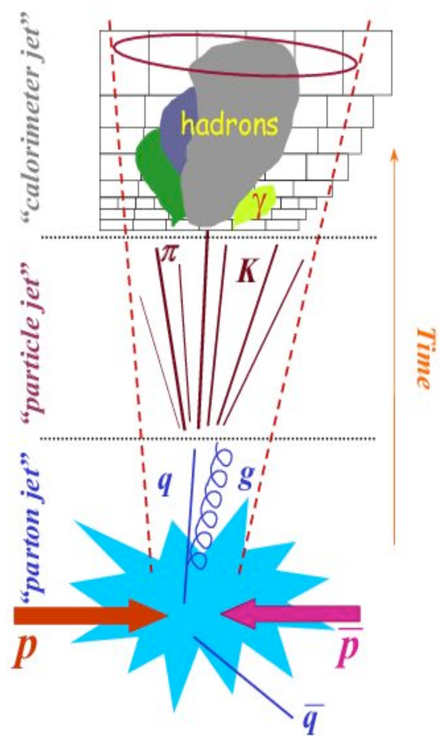
Differential Cross Section



- Measure jet spectra differentially in E_T and η
- Cross section in bin i: $\sigma(i) = \dfrac{N_{obs}(i) - N_{BG}(i)}{\int L dt\, \varepsilon(i)}$

Differential Cross Section: Unfolding

- "Unfolding" critical for jet cross sections
- Measure:
  - Cross section for calorimeter jets
- Want:
  - Cross section for hadron-jets



- Unfolding factor (bin by bin):

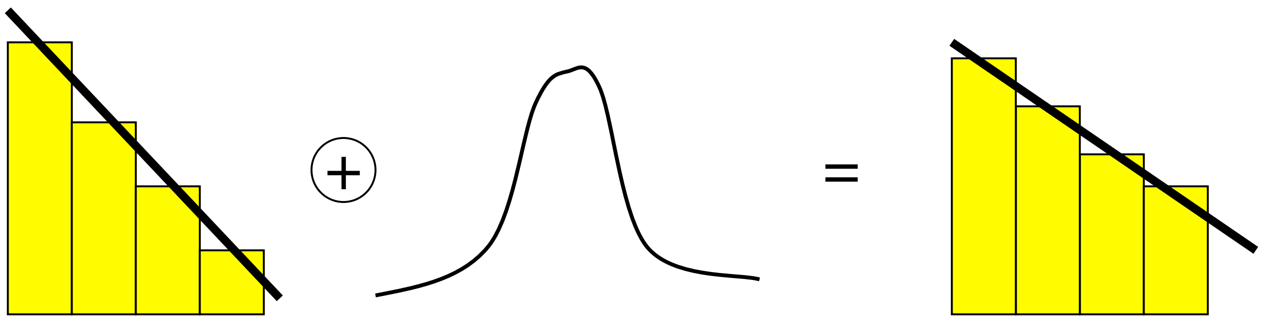
$$C_i = \frac{N^{HAD}_{JET\ i}}{N^{CAL}_{JET\ i}}$$

- Then:

$$N^{DATA\ UNFOLDED}_{JET\ i} = C_i \cdot N^{DATA\ NOT\ UNFOLDED}_{JET\ i}$$

- But, unfolding factors depend on MC E_T spectrum

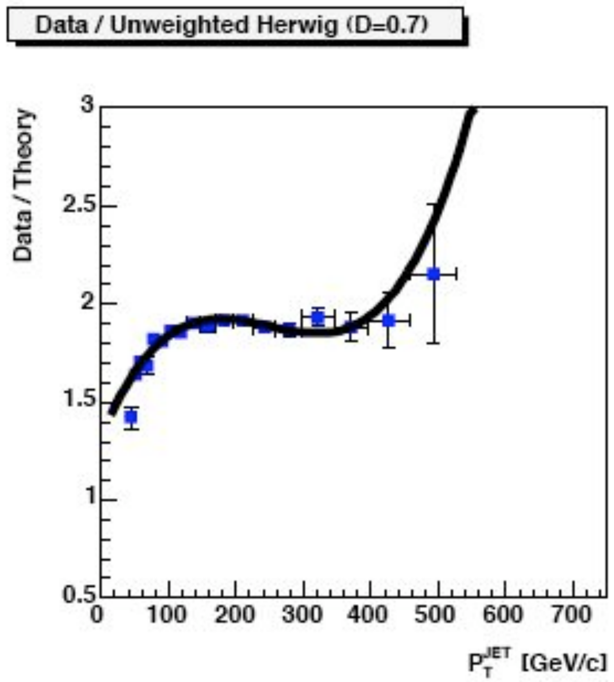
Differential Cross Section: Unfolding

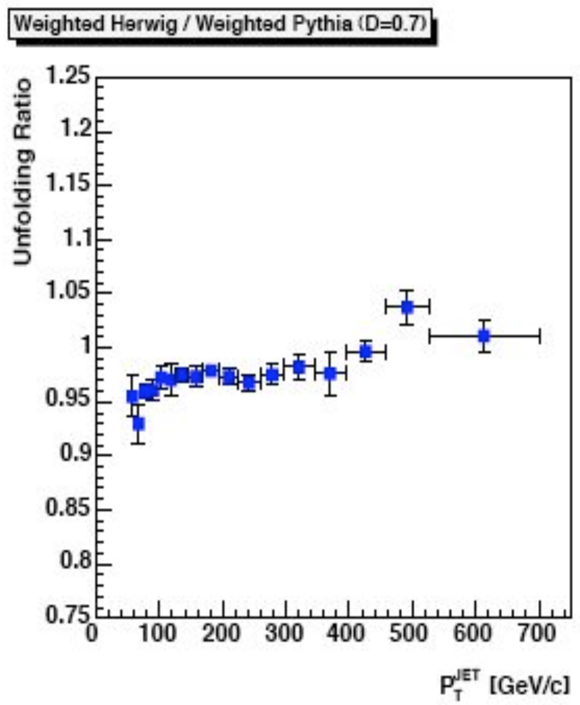


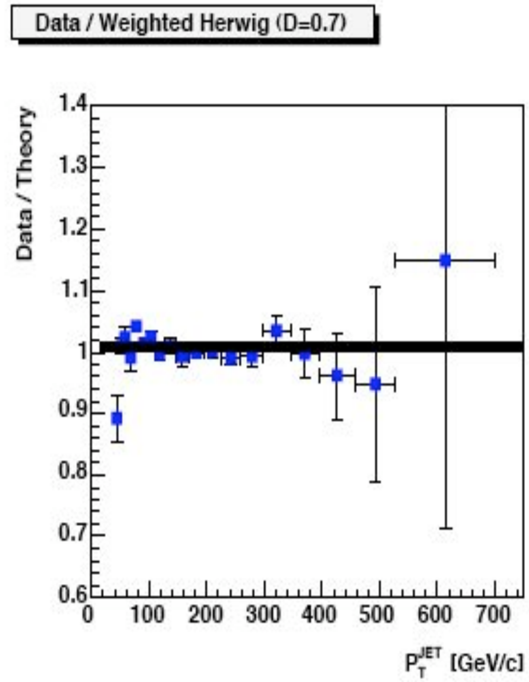
- **Problem:**
  - Steeply falling spectrum causes migrations to go from low to high p_T
    - Measured spectrum “flatter” than true spectrum
  - Size of migration depends on input spectrum

- **Requires iterative procedure** (bin-by-bin unfolding):
  1. Measure using spectrum from MC
  2. Fit measurement
  3. Reweight MC to reflect data measurement => go back to 1.

Example for Bin-by-Bin Unfolding

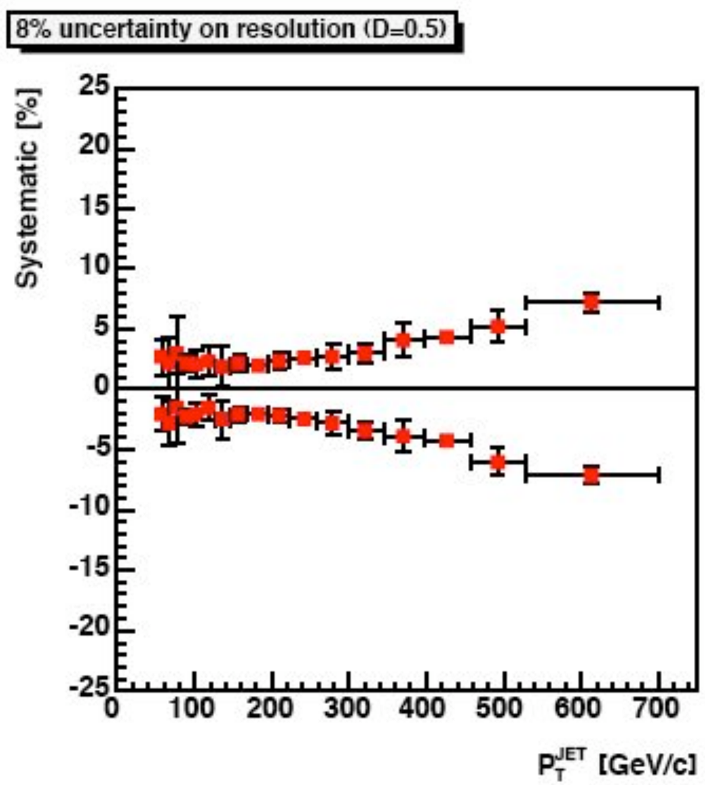


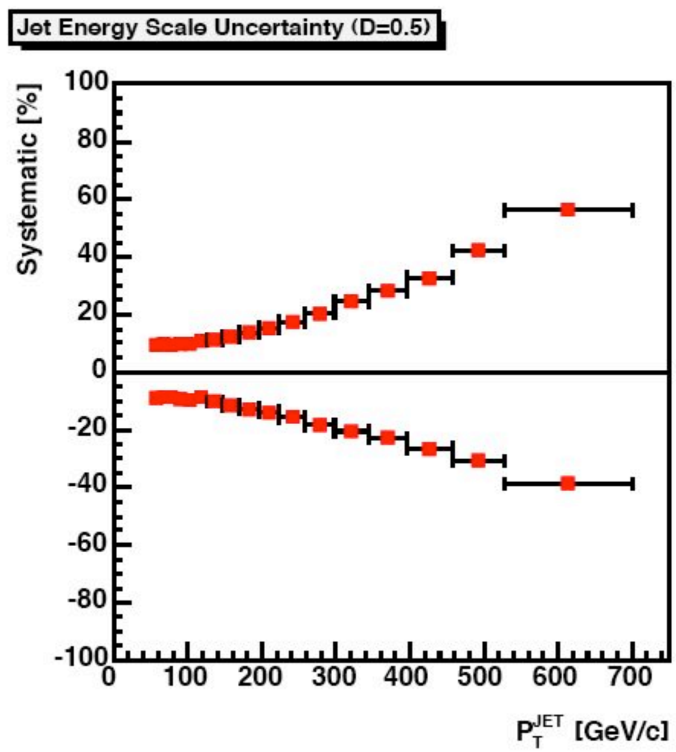




- Correction to unfolding factors <10%
  - One iteration sufficient in this example
  - Starting spectrum was already quite close to data

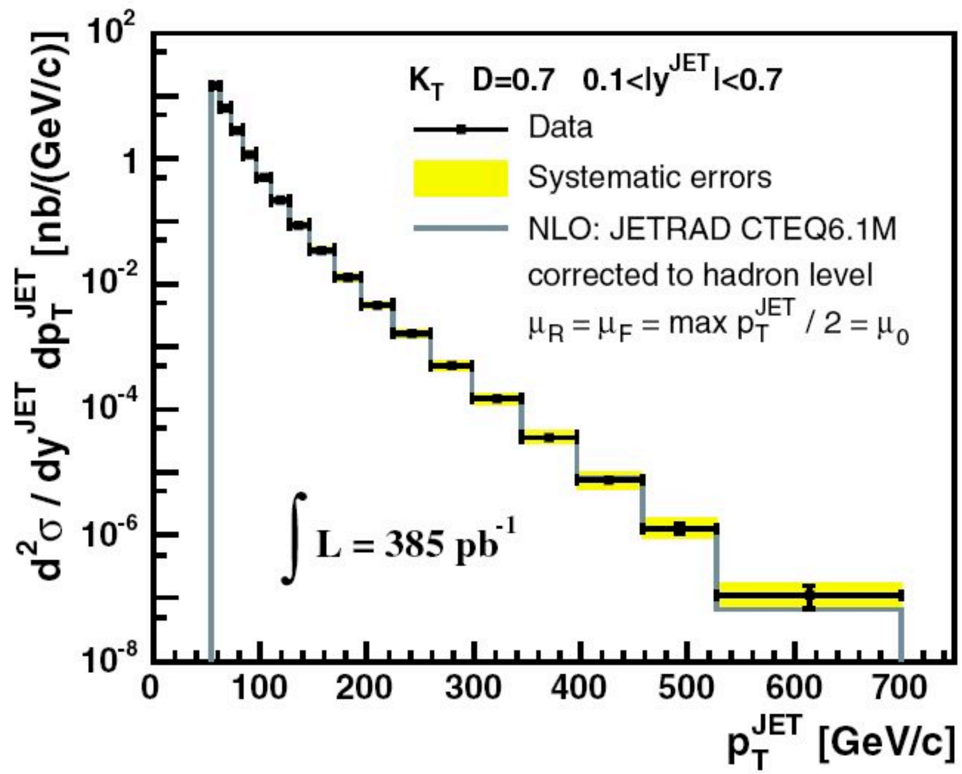
Systematic Uncertainties: Jet Cross Section

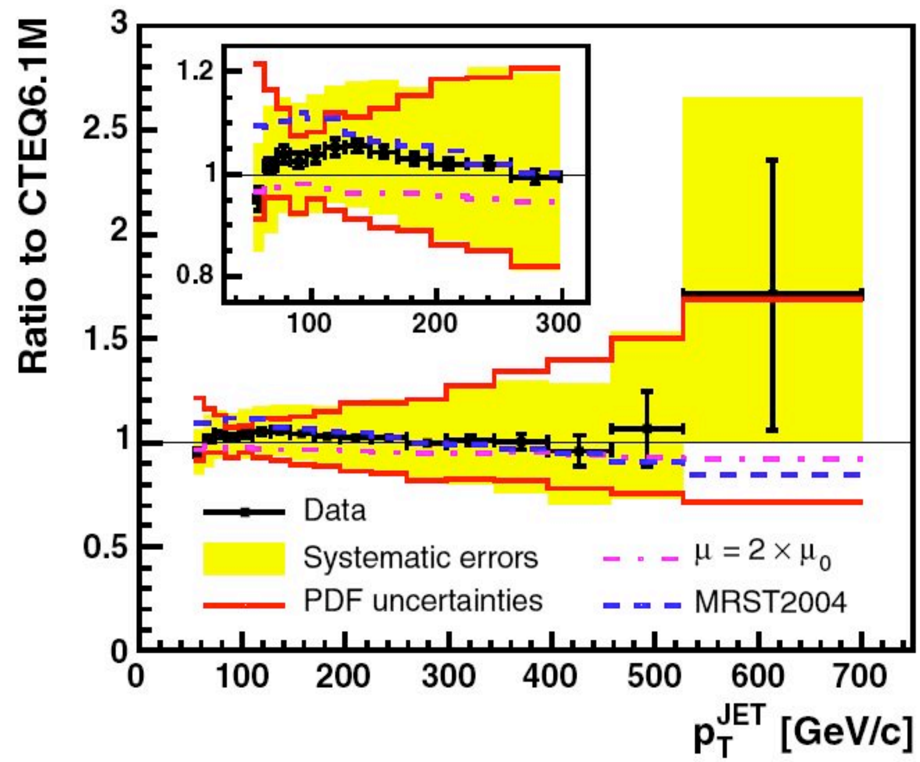




- For Jet Cross Section the Jet Energy Scale (JES) uncertainty is dominant systematic error
  - 3% uncertainty on JES results in up to 60% uncertainty on cross section
  - 8% uncertainty on JE resolution causes <10% uncertainty on cross section

Jet Cross Section Result





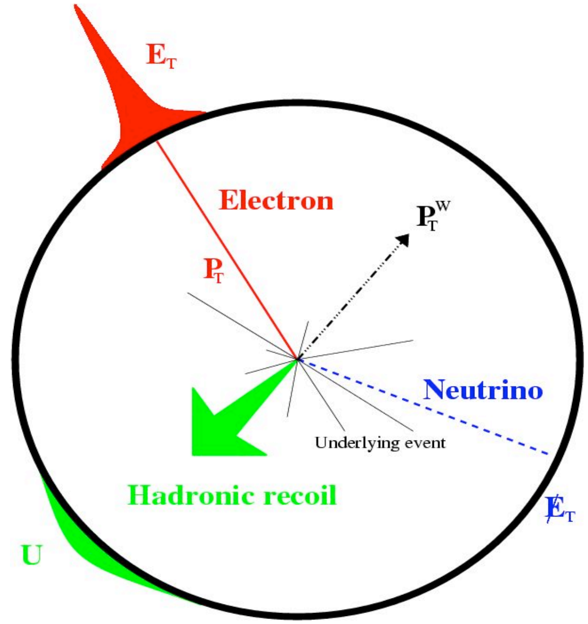
- Cross section falls by 8 orders of magnitude in measured E_T range
- Data in good agreement with QCD prediction
  - Experimental and theoretical errors comparable

Measuring Properties of Particles

The $W^{\pm}$ Boson Mass

W Boson mass

- Real precision measurement:
  - LEP: M_W=80.367±0.033 GeV/c^2
  - Precision: 0.04%
    - => Very challenging!
- Main measurement ingredients:
  - Lepton p_T
  - Hadronic recoil parallel to lepton: $u_{||}$
- Z→ll superb calibration sample:
  - but statistically limited:
    - About a factor 10 less Z's than W's
    - Most systematic uncertainties are related to size of Z sample
      - Will scale with $1/\sqrt{N_Z}$ ($=1/\sqrt{L}$)



$$m_T = \sqrt{2 p_T^l \not{p}_T \,(1-\cos\Delta\phi)},$$

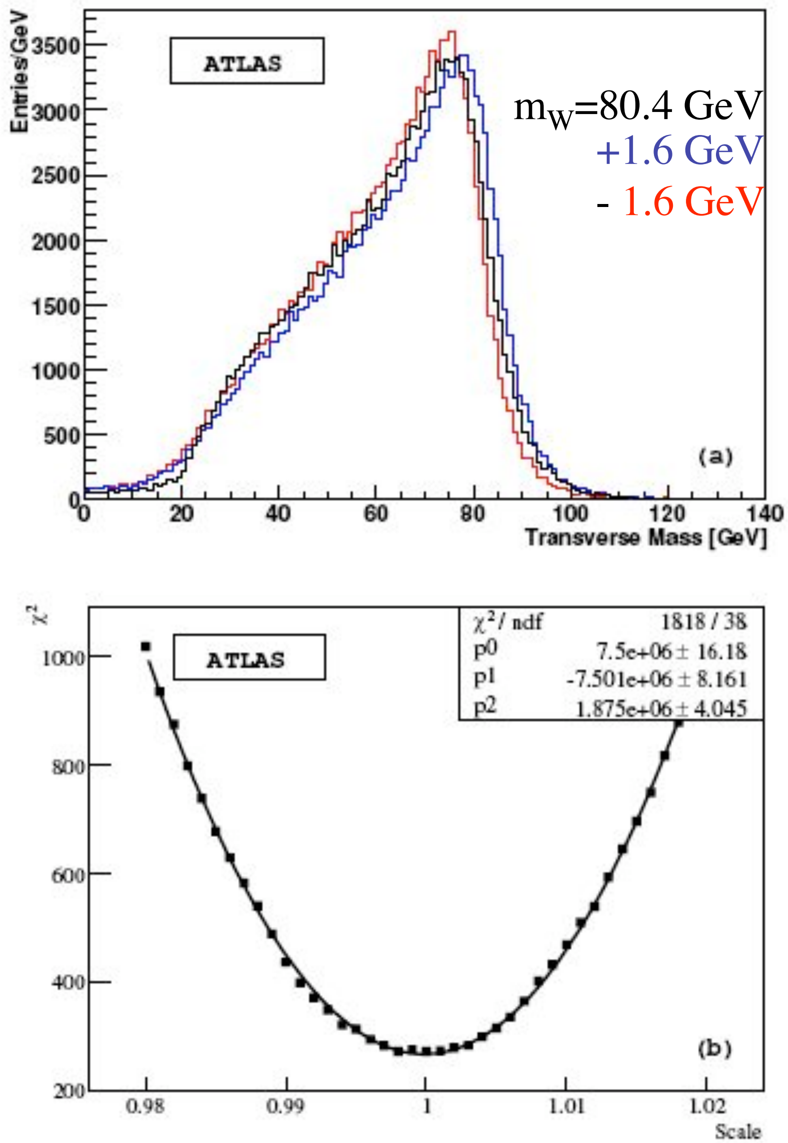
$$\not{p}_T \approx |p_T + u_{||}|$$

$$m_T \approx 2p_T\sqrt{1+u_{||}/p_T} \approx 2p_T + u_{||}$$

How to Extract the W Boson Mass

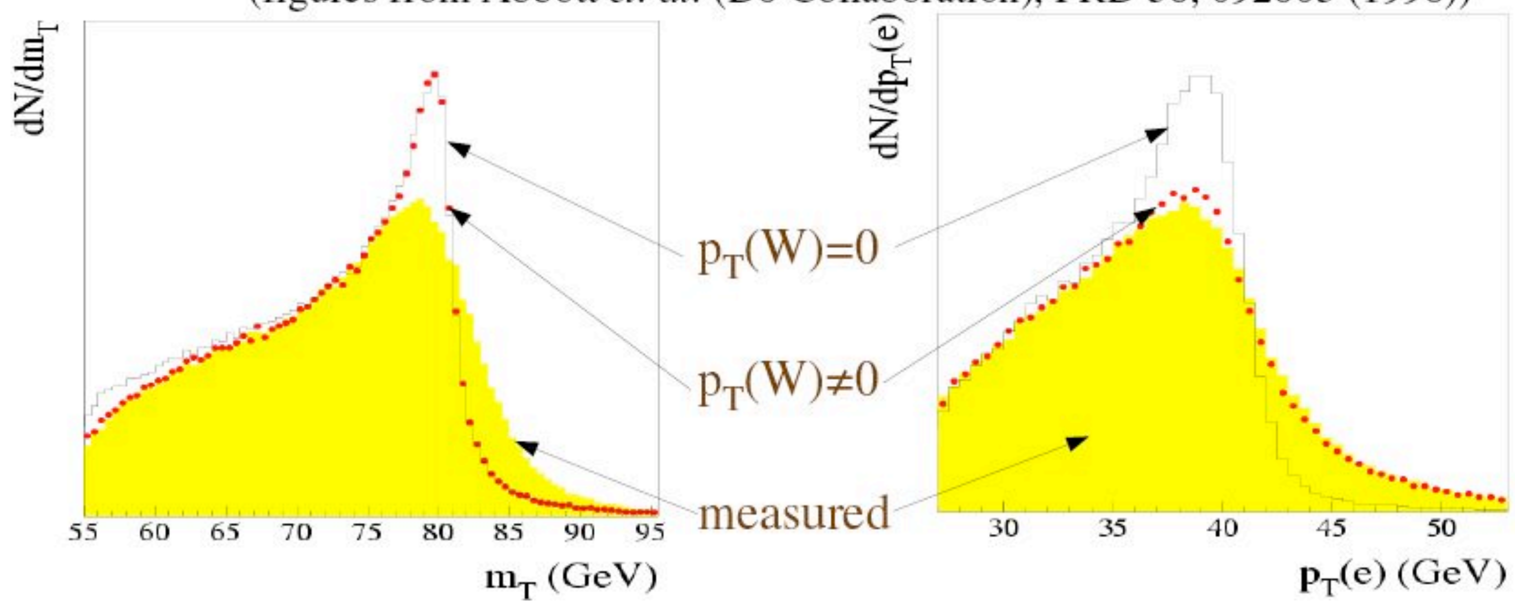
- Uses “Template Method”:
  - Templates created from MC simulation for different mW
  - Fit to determine which template fits best
  - Minimal $\chi^2 \Rightarrow$ W mass!
- Transverse mass of lepton and Met

$$m_T = \sqrt{|p_T^\ell|^2 + |p_T^\nu|^2 - (\vec{p}_T^\ell + \vec{p}_T^\nu)^2}$$



How to Extract the W Boson Mass

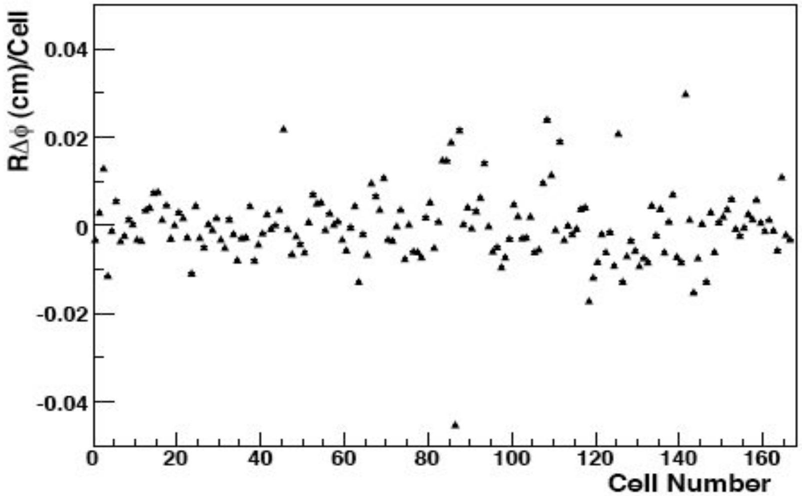
(figures from Abbott *et. al.* (D0 Collaboration), PRD 58, 092003 (1998))

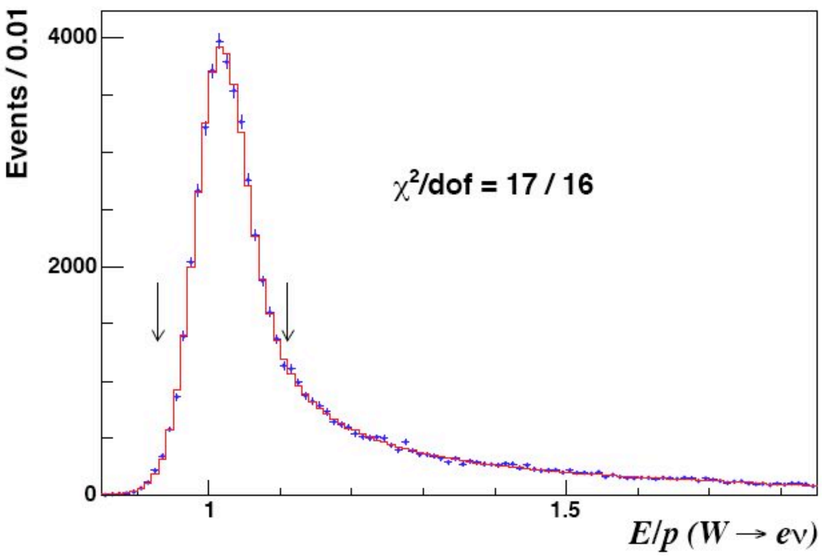


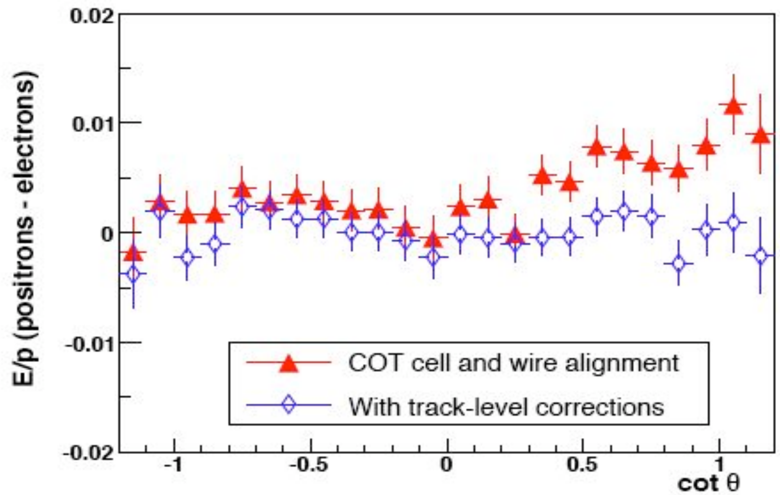
- Alternatively can fit to
  - Lepton p_T or missing E_T
- Sensitivity different to different systematics
  - Very powerful checks in this analysis:
    - Electrons vs muons
    - Z mass
    - m_T vs p_T vs ME_T fits
  - The redundancy is the strength of this difficult high precision analysis

Lepton Momentum Scale

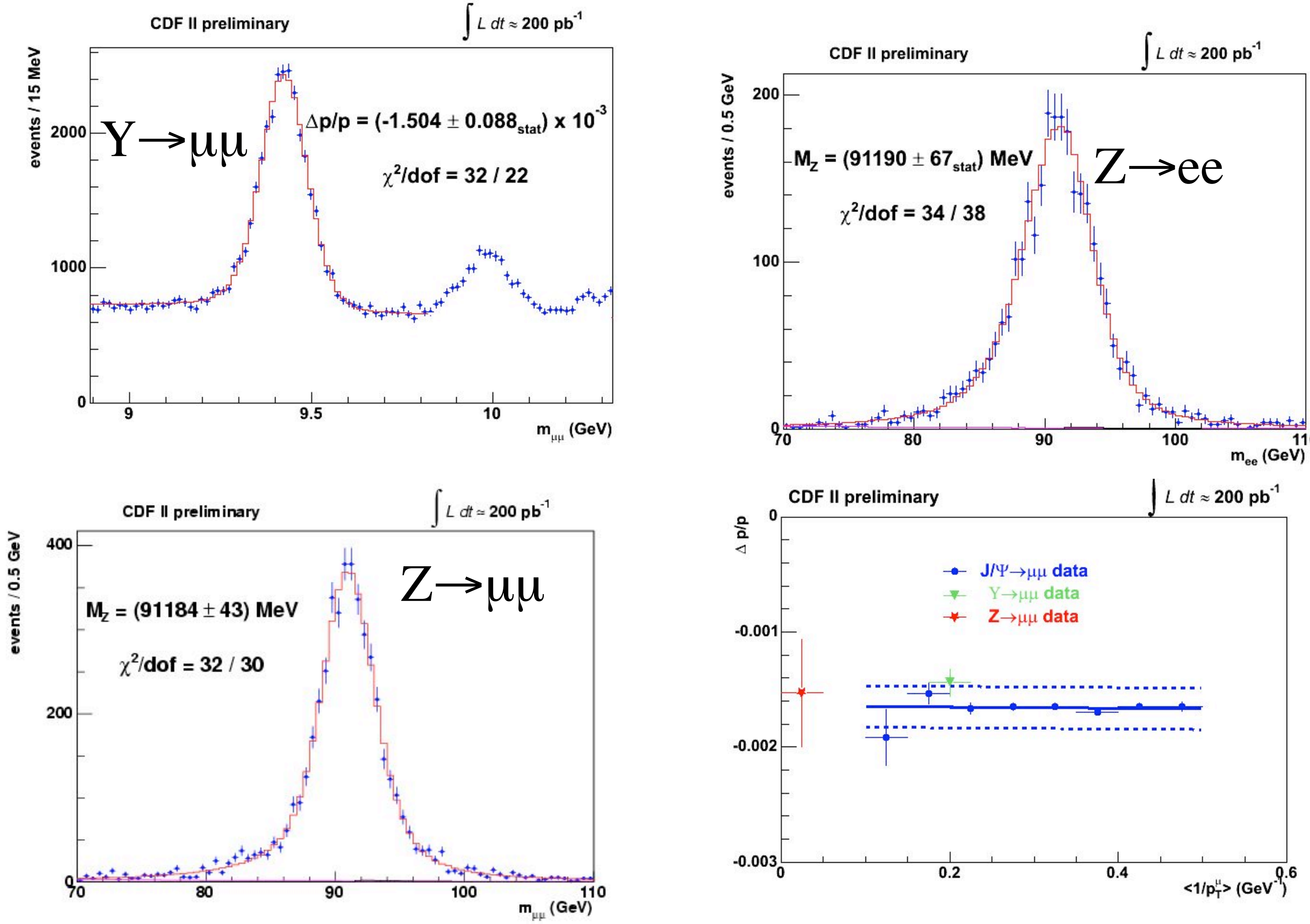
- Momentum scale:
  - Cosmic ray data used for detailed cell-by-cell calibration of CDF drift chamber
  - E/p of e+ and e- used to make further small corrections to p measurement
  - Peak position of overall E/p used to set electron energy scale
    - Tail sensitive to passive material







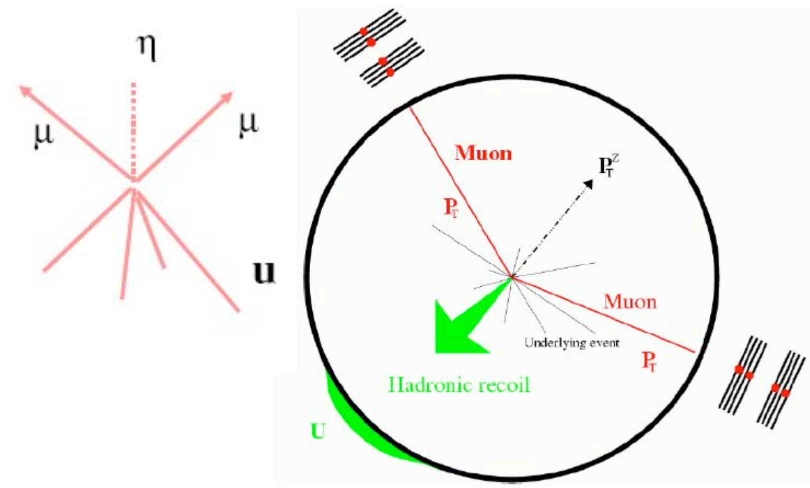
Momentum/Energy Scale and Resolution

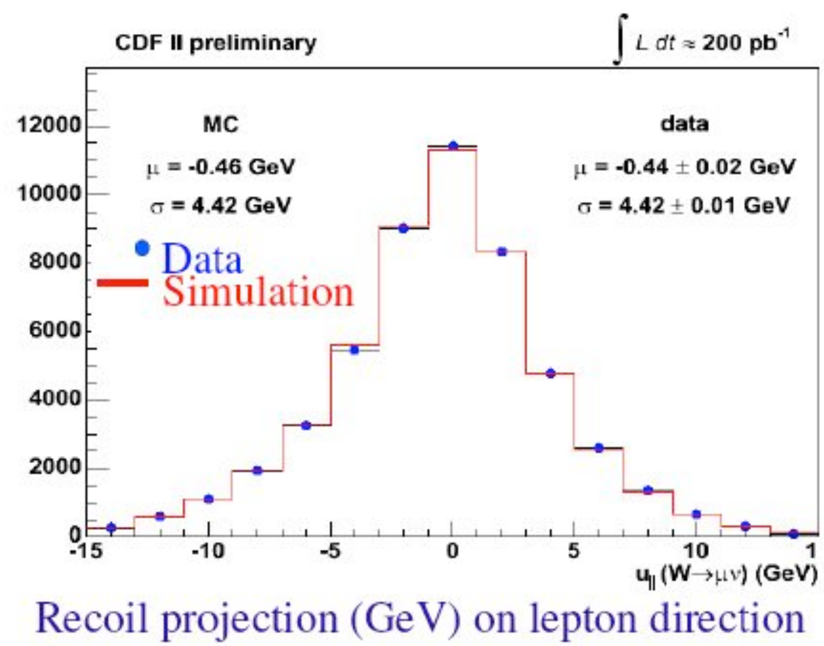


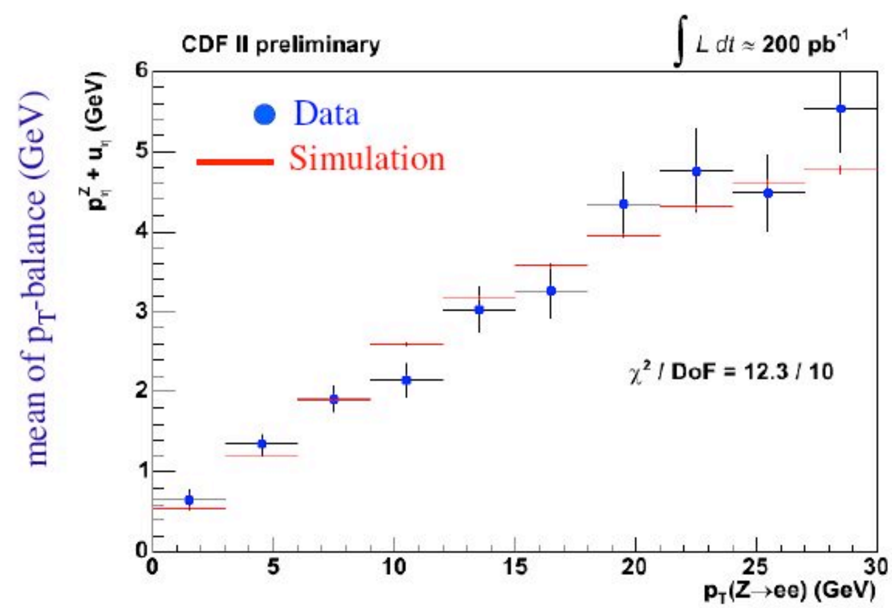
- Systematic uncertainty on momentum scale: 0.04%

Hadronic Recoil Model

- Hadronic recoil modeling
  - Tune data based on Z’s
  - Check on W’s







Systematic Uncertainties

m_T Fit Uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Correlation
Tracker Momentum Scale	17	17	100%
Calorimeter Energy Scale	0	25	0%
Lepton Resolution	3	9	0%
Lepton Efficiency	1	3	0%
Lepton Tower Removal	5	8	100%
Recoil Scale	9	9	100%
Recoil Resolution	7	7	100%
Backgrounds	9	8	0%
PDFs	11	11	100%
W Boson p_T	3	3	100%
Photon Radiation	12	11	100%
Statistical	54	48	0%
Total	60	62	-

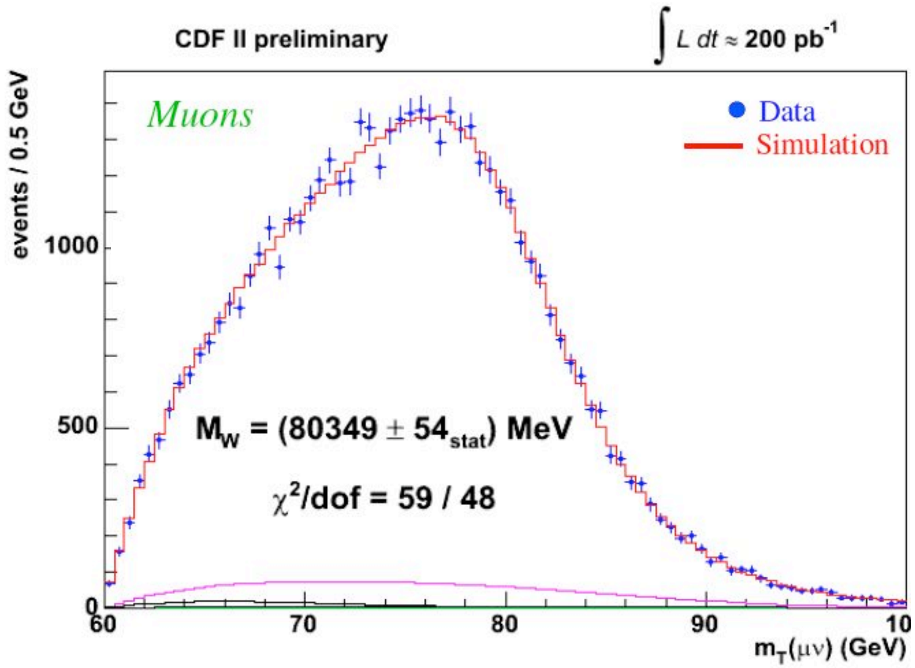
TABLE IX: Uncertainties in units of MeV on the transverse mass fit for m_W in the $W \to \mu\nu$ and $W \to e\nu$ samples.

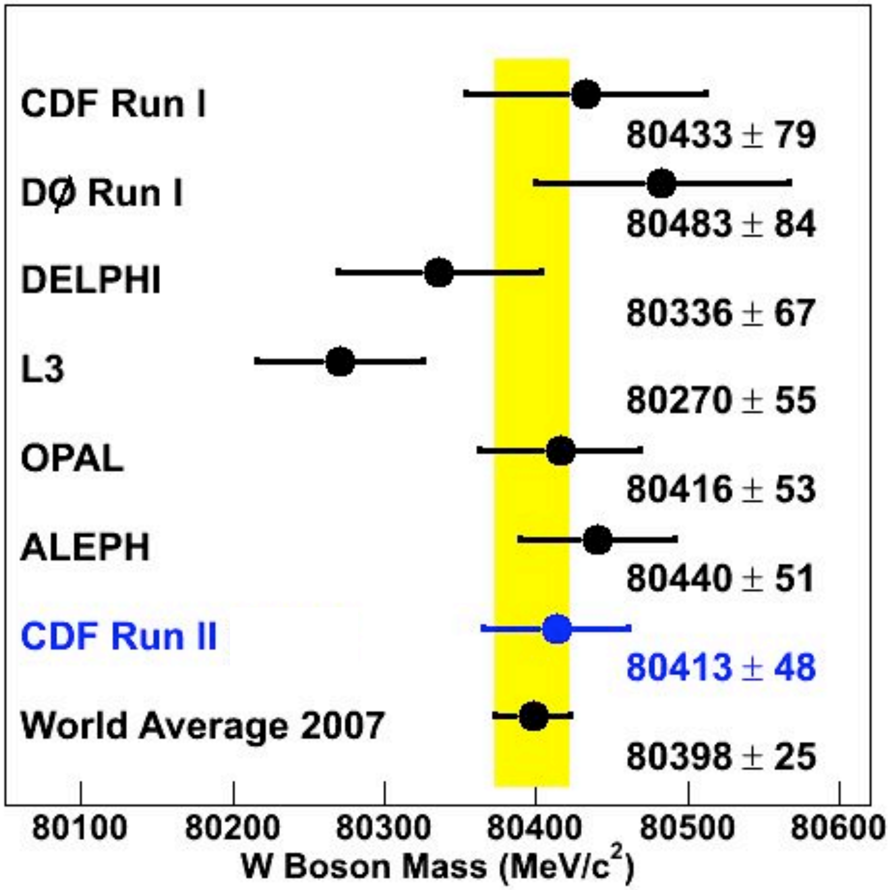
Limited by data statistics (Tracker Momentum Scale through Recoil Resolution)

Limited by data and theoretical understanding (Backgrounds through Photon Radiation)

- Overall uncertainty 60 MeV for both analyses
  - Careful treatment of correlations between them
- Dominated by stat. error (50 MeV) vs syst. (33 MeV)

W Boson Mass





- World average:

  M_W=80398 ± 25 MeV

- Ultimate Run 2 precision:

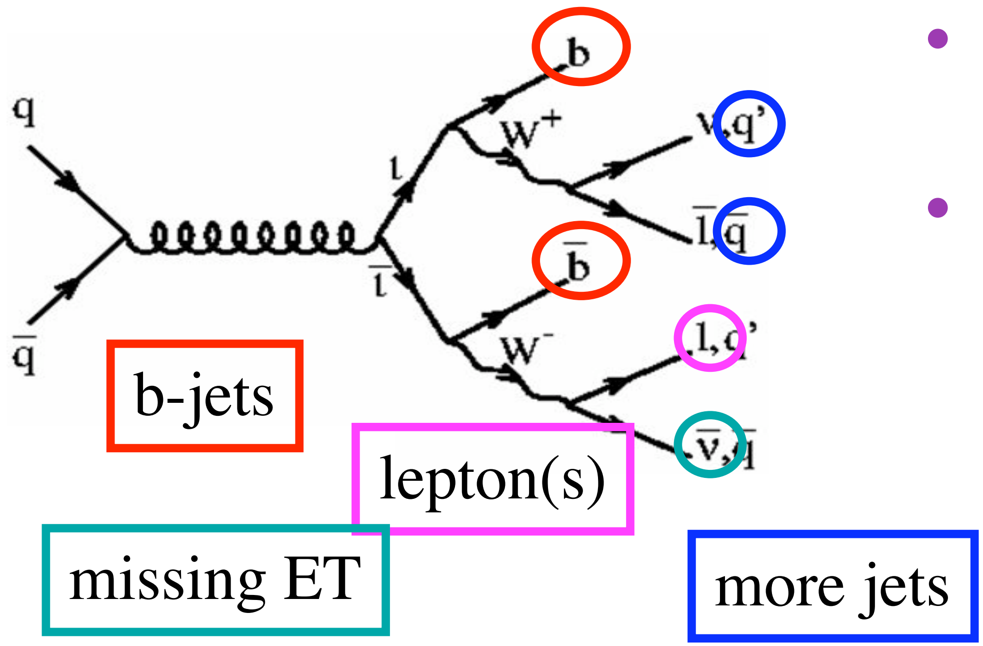
  ~15 MeV

The Top Quark

Top Quark Cross Section

SM: $t\bar{t}$ pair production, Br(t→bW)=100% , Br(W->lν)=1/9=11%

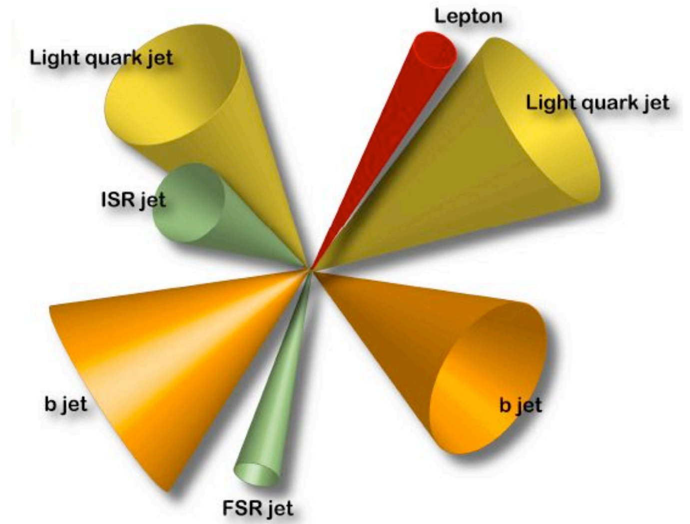
dilepton	*(4/81)*	2 leptons + 2 jets + missing E_T
lepton+jets	*(24/81)*	1 lepton + 4 jets + missing E_T
fully hadronic	*(36/81)*	6 jets

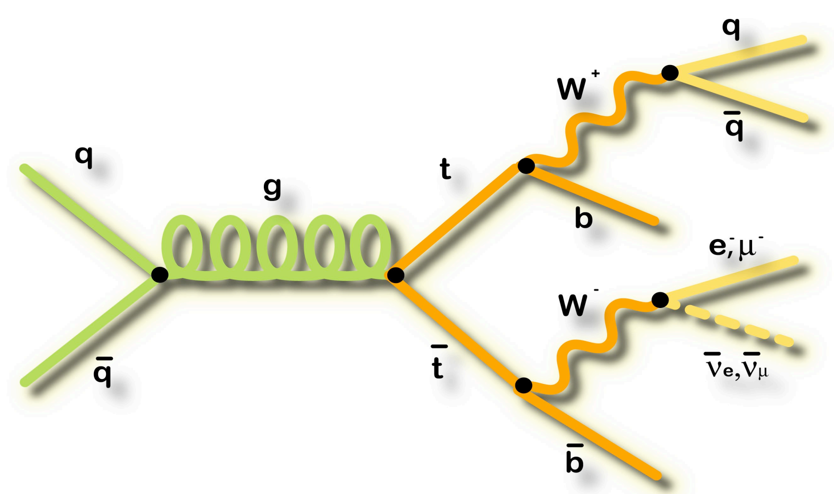


- Trigger on electron/muon
  - Like for Z's
- Analysis cuts:
  - Electron/muon p_T>25 GeV
  - Missing E_T>25 GeV
  - 3 or 4 jets with E_T>20-40 GeV

Top Mass Measurement: tt→(blν)(bqq)

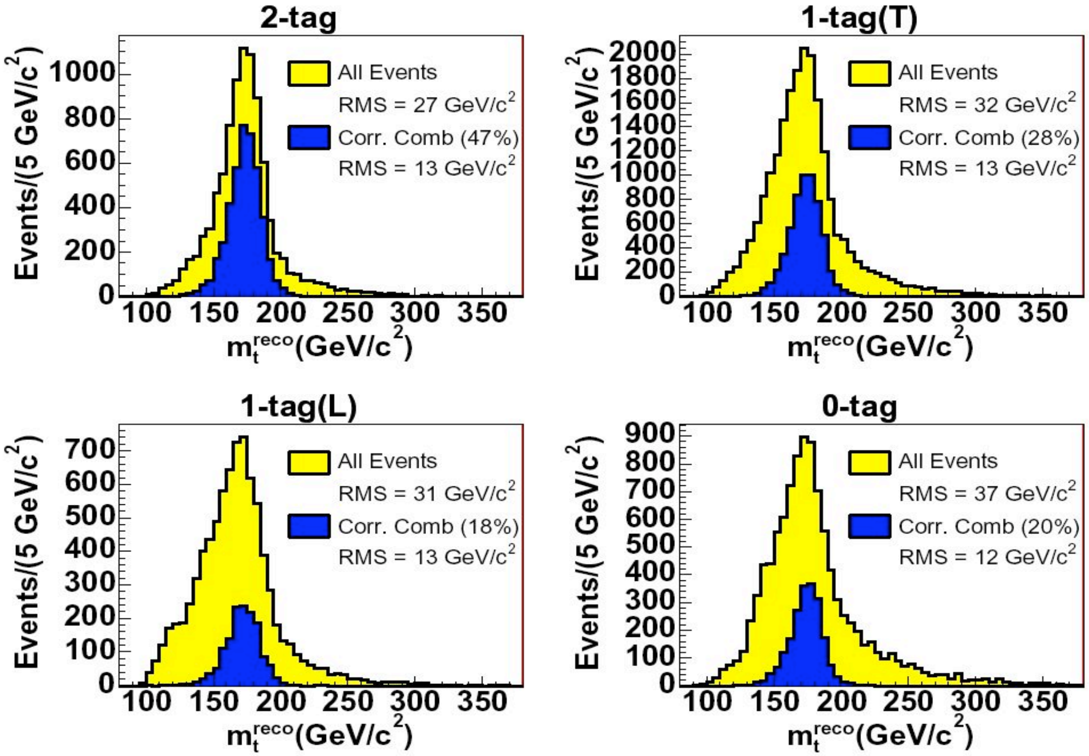
- 4 jets, 1 lepton and missing E_T
  - Which jet belongs to what?
  - Combinatorics!
- B-tagging helps:
  - 2 b-tags =>2 combinations
  - 1 b-tag   => 6 combinations
  - 0 b-tags =>12 combinations
- Two Strategies:
  - Template method:
    - Uses "best" combination
    - Chi2 fit requires $m(t)=m(\bar{t})$
  - Matrix Element method:
    - Uses all combinations
    - Assign probability depending on kinematic consistency with top





Top Mass Determination

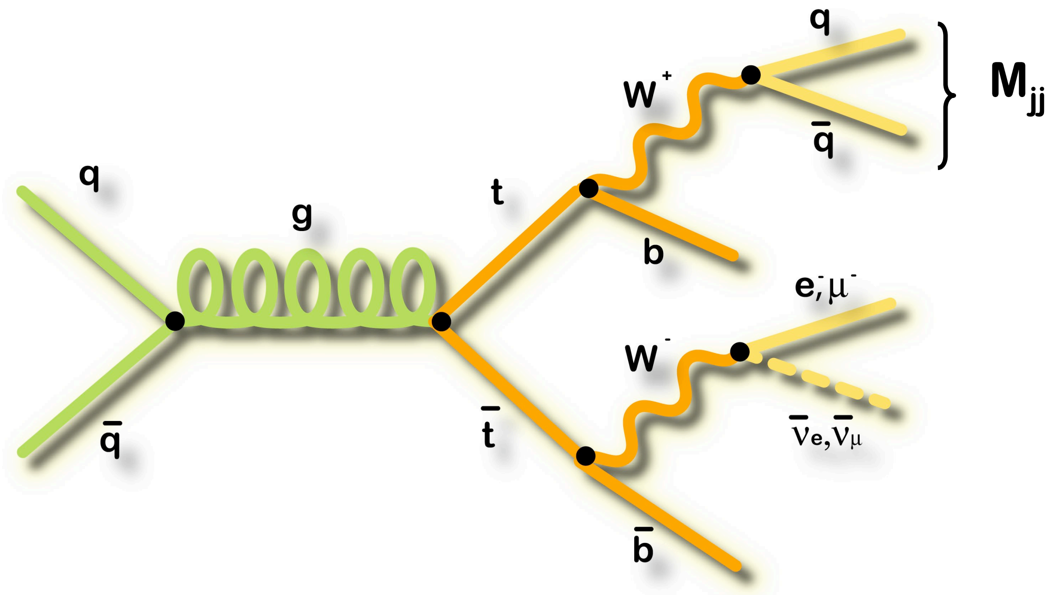
- Inputs:
  - Jet 4-vectors
  - Lepton 4-vector
  - Remaining transverse energy, $p_{T,UE}$:
    - $p_{T,\nu}=-(p_{T,l}+p_{T,UE}+\sum p_{T,jet})$
- Constraints:
  - $M(l\nu)=M_W$
  - $M(q\bar{q})=M_W$
  - $M(t)=M(\bar{t})$
- Unknown:
  - Neutrino p_z
- 1 unknown, 3 constraints:
  - Overconstrained
  - Can measure M(t) for each event: m_t^{reco}



Selecting correct combination 20-50% of the time

In-situ Measurement of JES

- Additionally, use $W \rightarrow jj$ mass resonance (M_{jj}) to measure the jet energy scale (JES) uncertainty

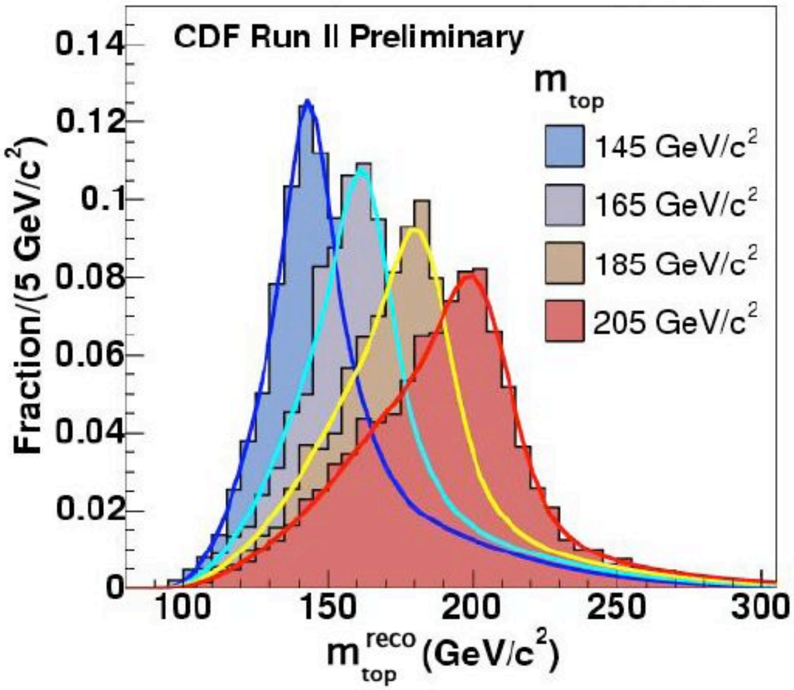


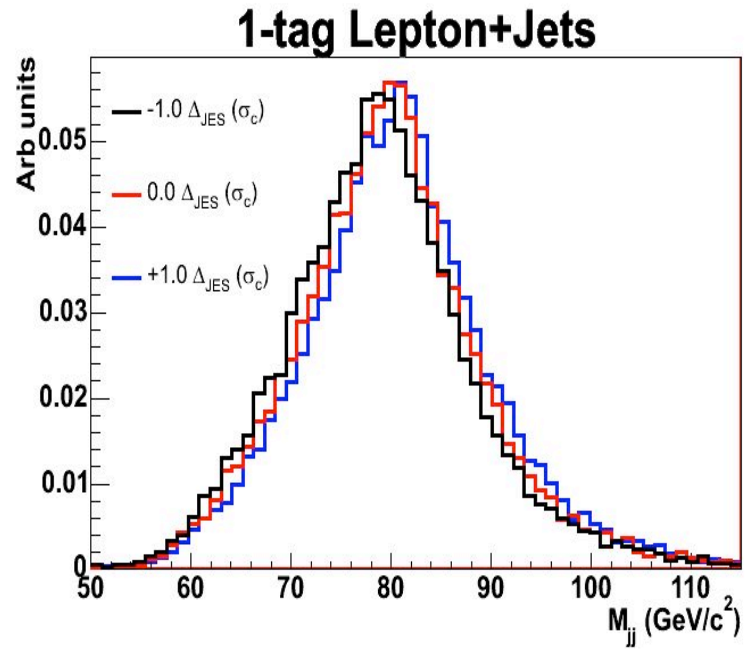
2D fit of the invariant mass of the non-b-jets and the top mass:

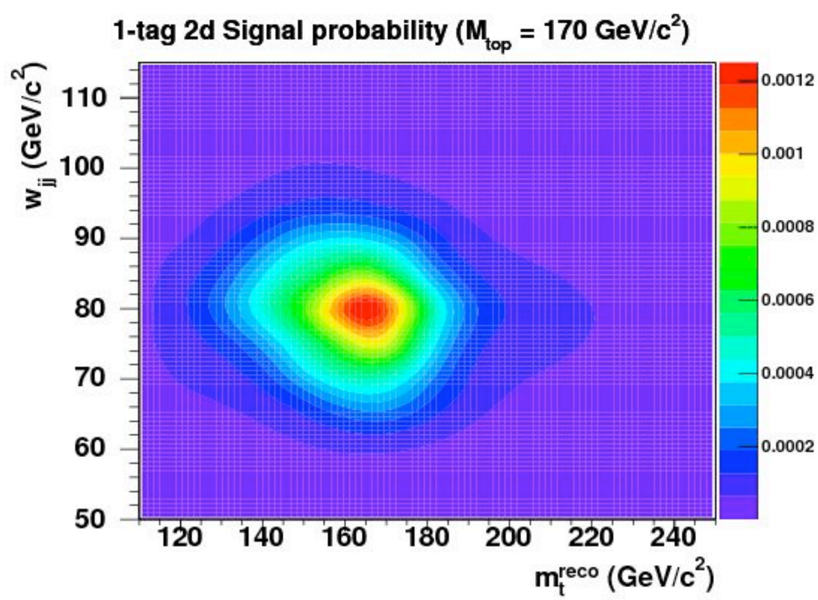
JES $\propto$ M(jj)- 80.4 GeV/c^2

Measurement of JES scales directly with data statistics

Top Mass Templates



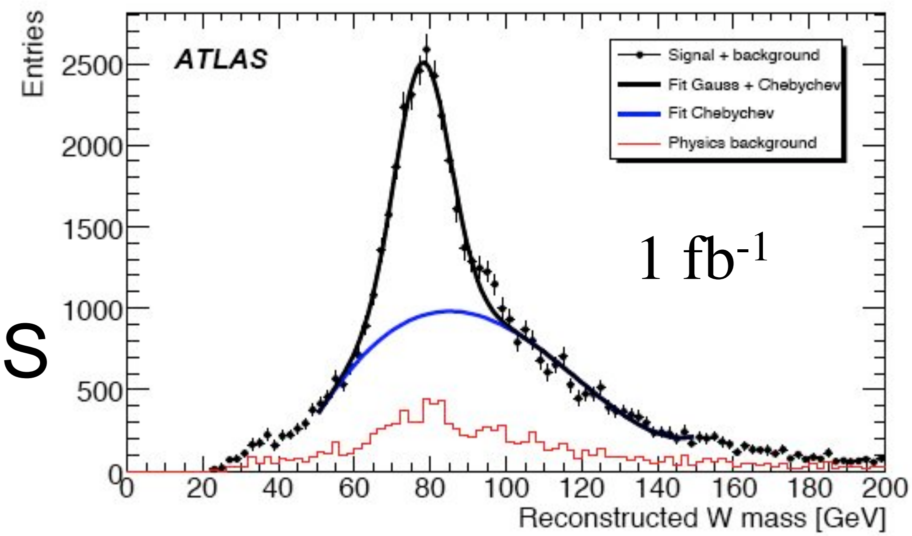


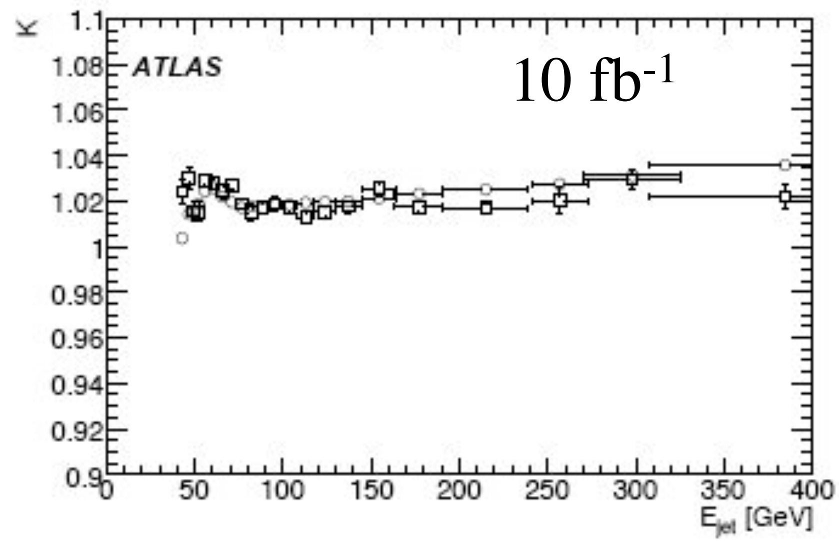


- Fit to those templates for
  - Top mass
  - Jet Energy Scale

Measurement of JES at LHC

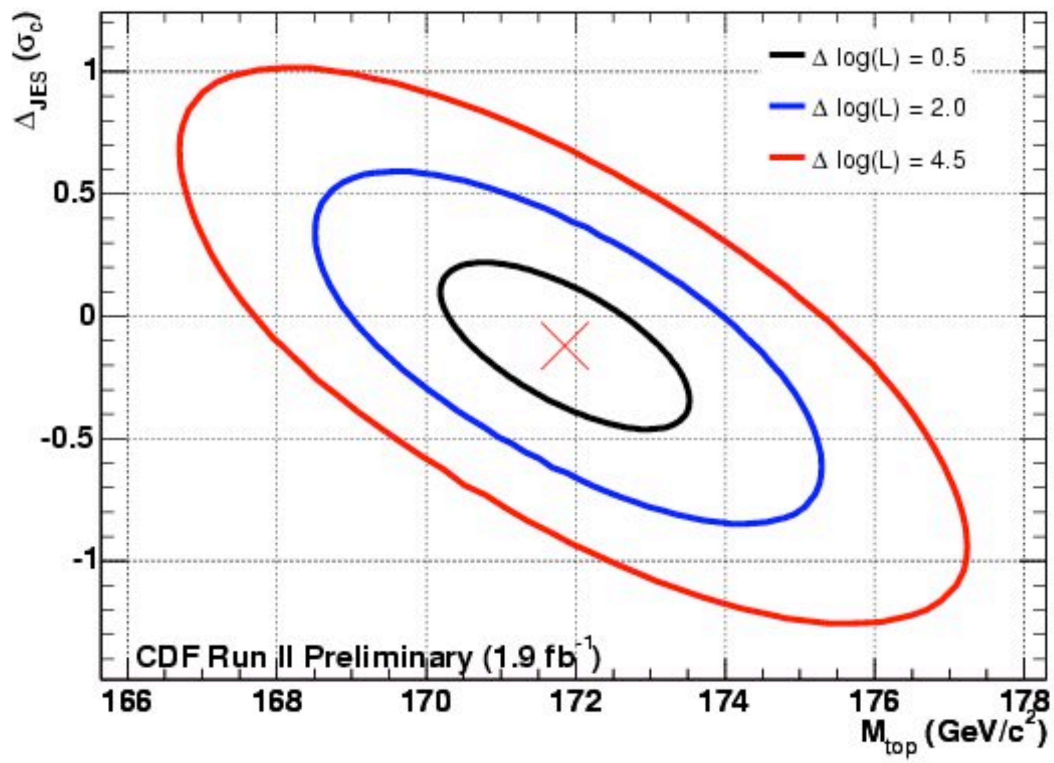
- Large top samples
  - Clean W mass peak
- Allow measurement of JES as function of Jet Energy
- Can achieve 1% precision with 10 fb^{-1}





Template Analysis Results on m_{top}

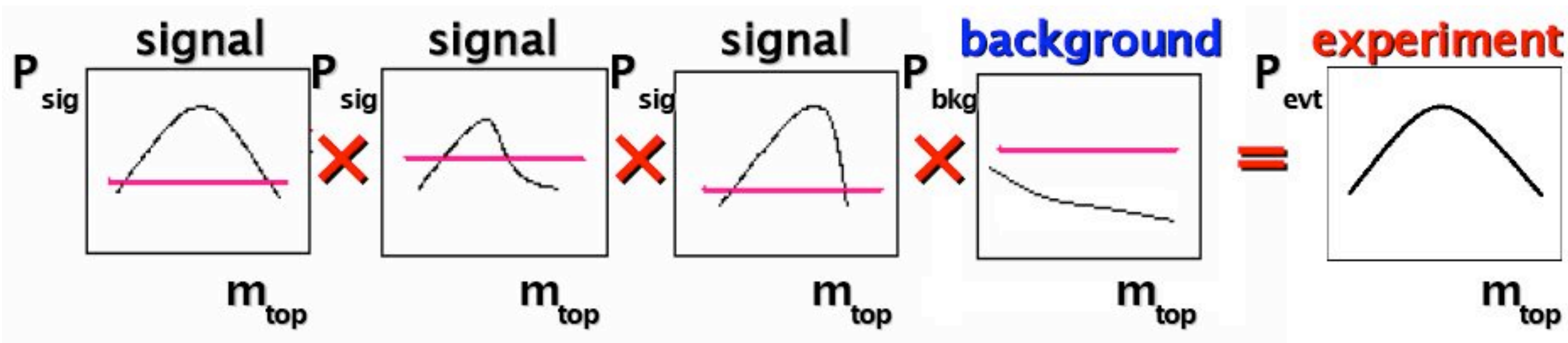
- Using 344 lepton+jets and 144 dilepton candidate events in 1.9 fb^{-1}
- Using in-situ JES calibration results in factor four improvement on JES



$$m_{top} = 171.9 \pm 1.7 \text{ (stat.+JES)} \pm 1.0 = 171.6 \pm 2.0 \text{ GeV/}c^2$$

"Matrix Element Method"

- Construct probability density function as function of m_{top} for each event
- Multiply those probabilities of all events

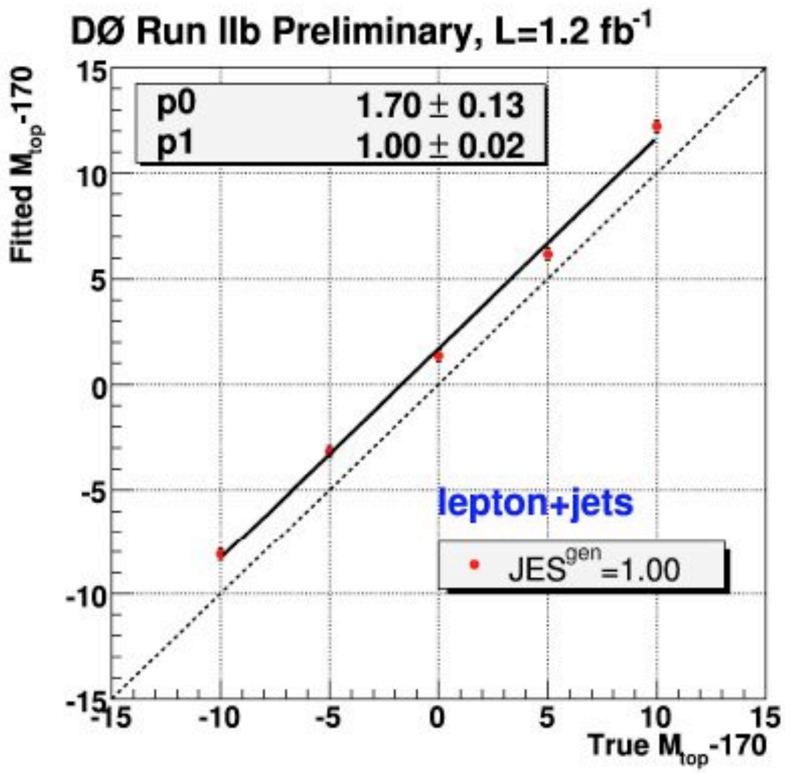


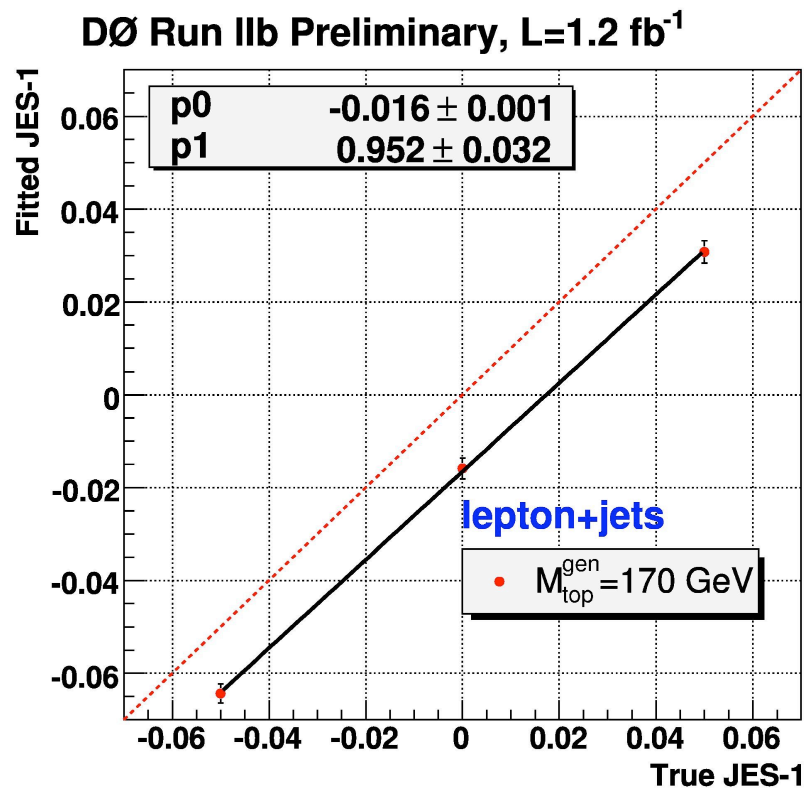
$$P_{sig}(x; m_{top}, JES) = \underbrace{Acc(x)}_{\text{Acceptance (selection, trigger,...)}} \times \frac{1}{\sigma} \int d^n \underbrace{\sigma(y; m_{top})}_{\text{LO-Matrix element x phase space}} \underbrace{dq_1\, dq_2\, f(q_1)\, f(q_2)}_{\text{PDF's}} \underbrace{W(x, y; JES)}_{\text{Transfer Functions (Probability to measure x when y was produced)}}$$

- **maximum Likelihood fit:**

$$L(x_1, .., x_n; m_{top}, JES, f_{top}) = \prod_{i=1}^{n} P_{evt}(x_i; m_{top}, JES, f_{top})$$

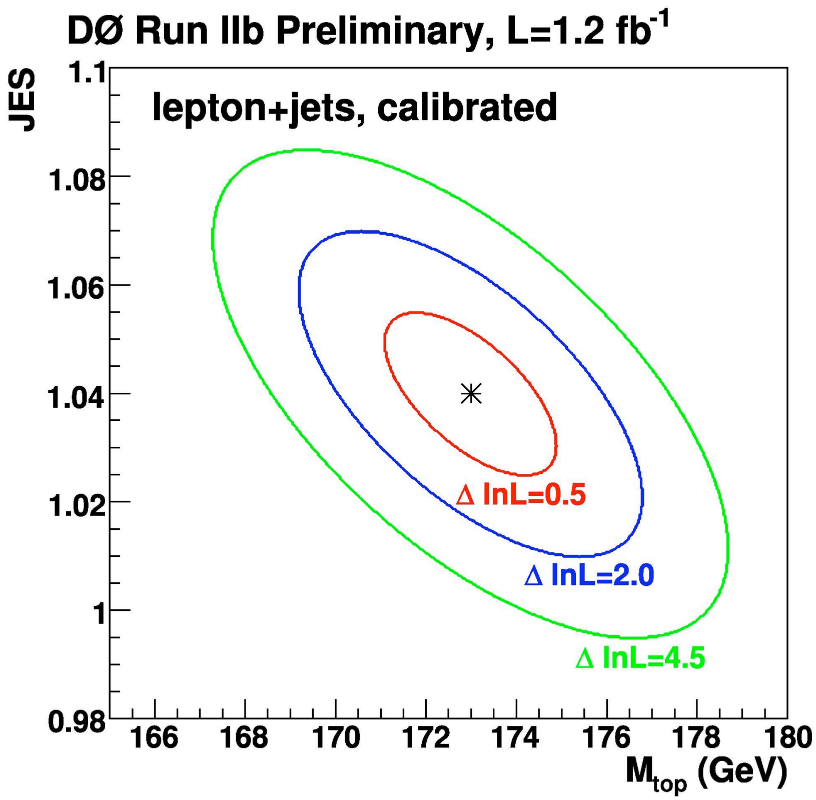
Check you get the right answer

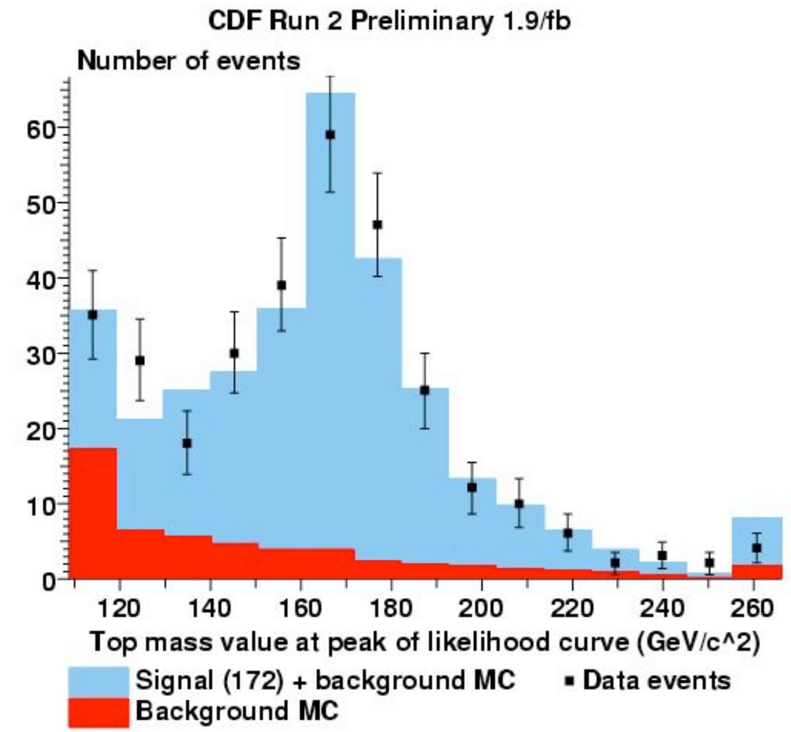




- Run "Pseudo-Experiments" on Monte Carlo to see if you get out the mass that was put in
  - Pretend MC is data and run analysis on it N times
- Non-trivial cross check given the complexity of the method
  - If not: derive "calibration curve" from slope and offset

Matrix Element Top Mass Results





DØ: 2.2 fb^{-1}

m_{top} = 172.2 ± 1.0 (stat) ± 1.4 (syst) GeV

±1.0%

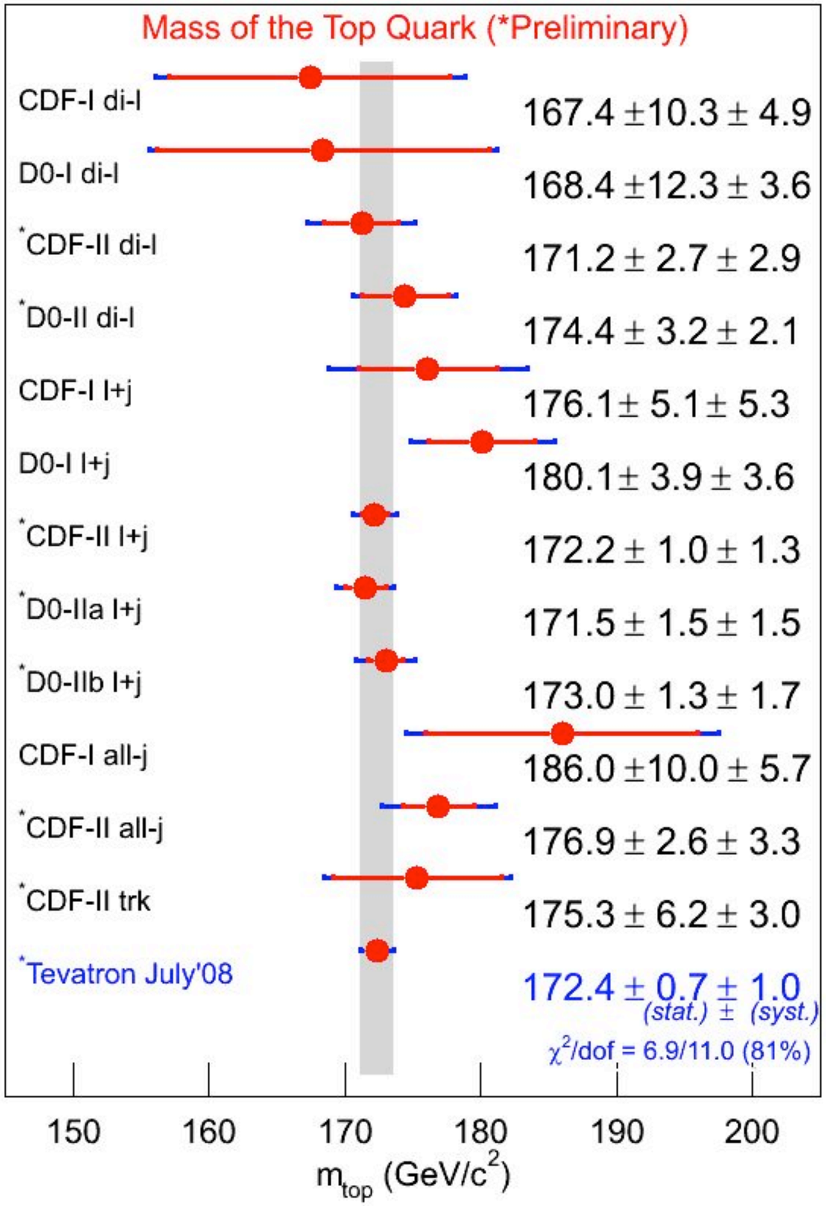
CDF: 2.9 fb^{-1}

m_{top} = 172.2 ± 1.0 (stat) ± 1.3 (syst) GeV

±1.0%

Combining M_{top} Results

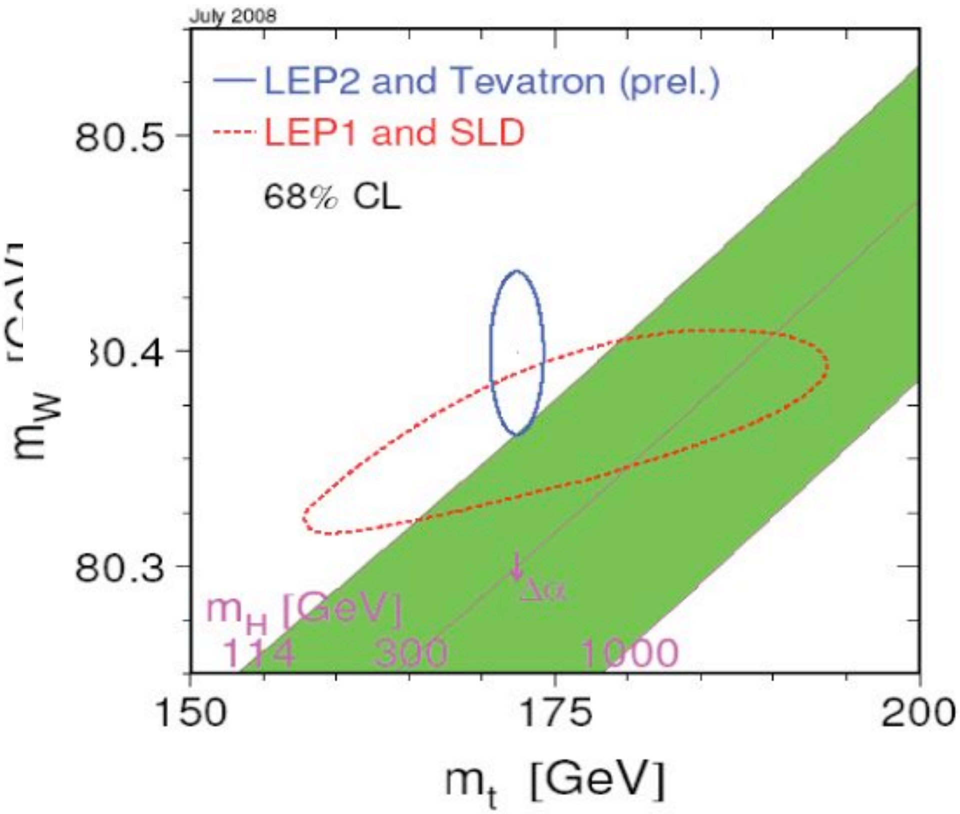
- Excellent results in each channel
  - Dilepton
  - Lepton+jets
  - All-hadronic
- Combine them to improve precision
  - Include Run-I results
  - Account for correlations
- Uncertainty: 1.2 GeV
  - Dominated by systematic uncertainties



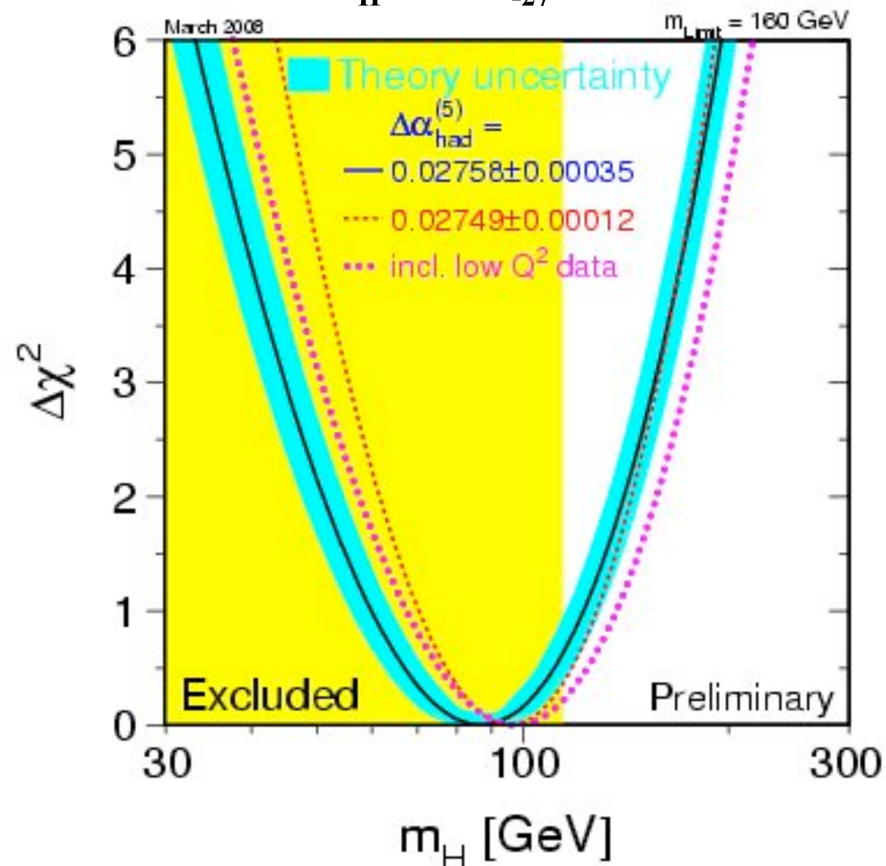
Implications for Higgs Boson

m_H constrained in the Standard Model

LEPEWWG 07/08



$m_H = 87^{+36}_{-27}$ GeV



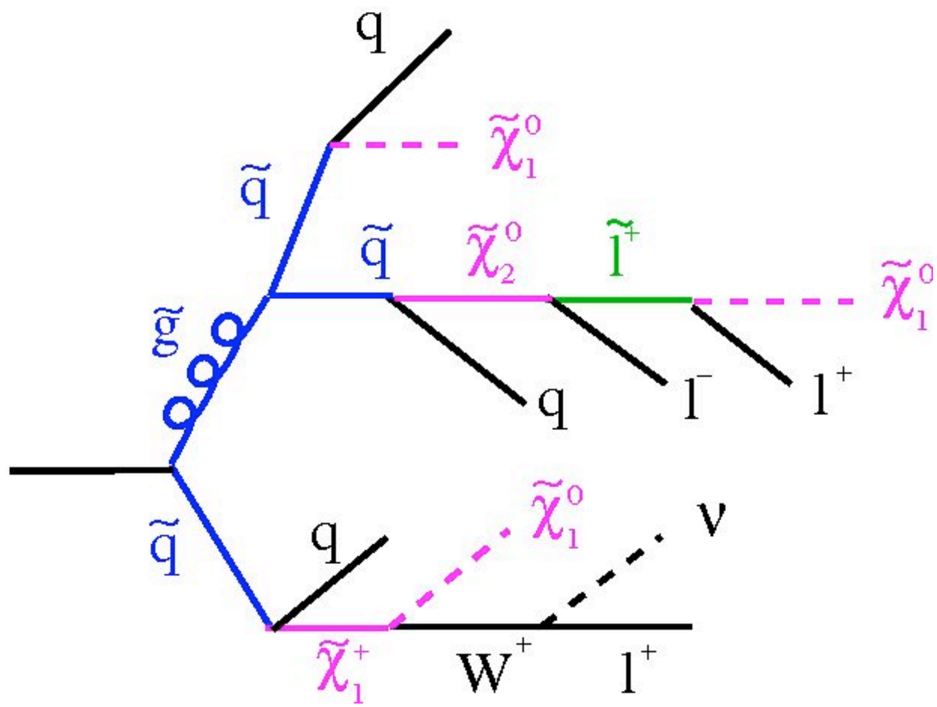
Direct searches at LEP2:
m_H>114.4 GeV @95%CL

Indirect constraints:
m_H<160 GeV @95%CL

Measuring Properties of Supersymmetric Particles (in case they exist)

Spectacular SUSY Events (?)

- Long cascade decays via several SUSY particles
  - In classic models quite possible
    - Would be a wonderful experimental challenge!
  - But of course very possible also that it does not happen



- If Nature is like this:
  - Need to try to reconstruct masses of all those particles

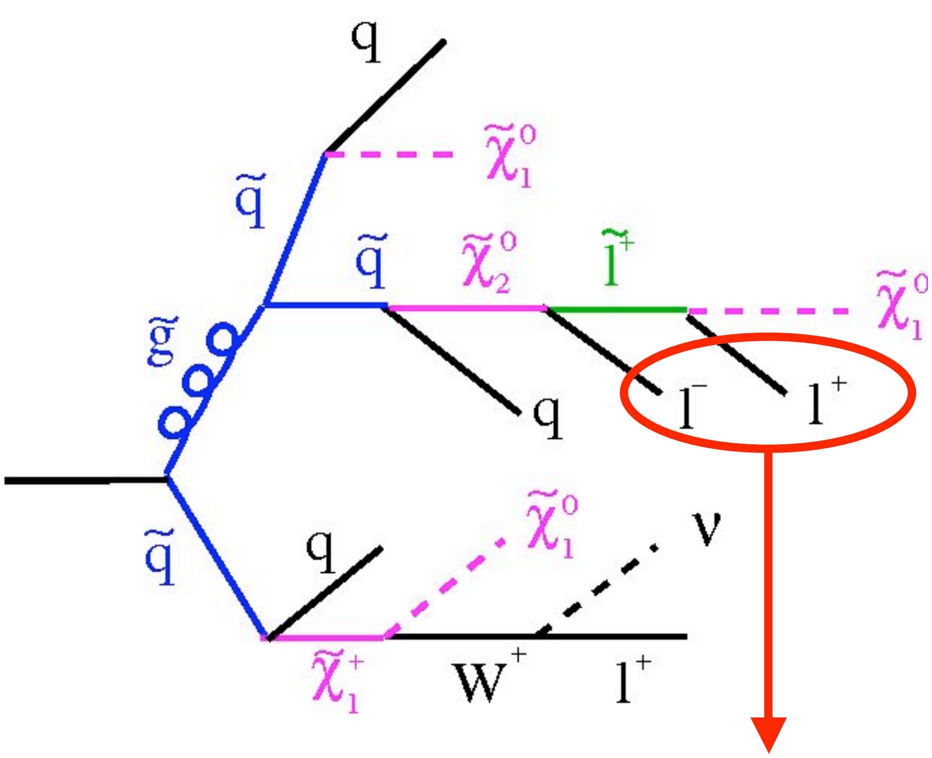
- Main method:
  - Measure “edges”

Spectacular SUSY Events (?)

- Long cascade decays via several SUSY particles, e.g.

$$\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q (\rightarrow \tilde{\ell}^{\pm} \ell^{\mp} q) \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^- q$$

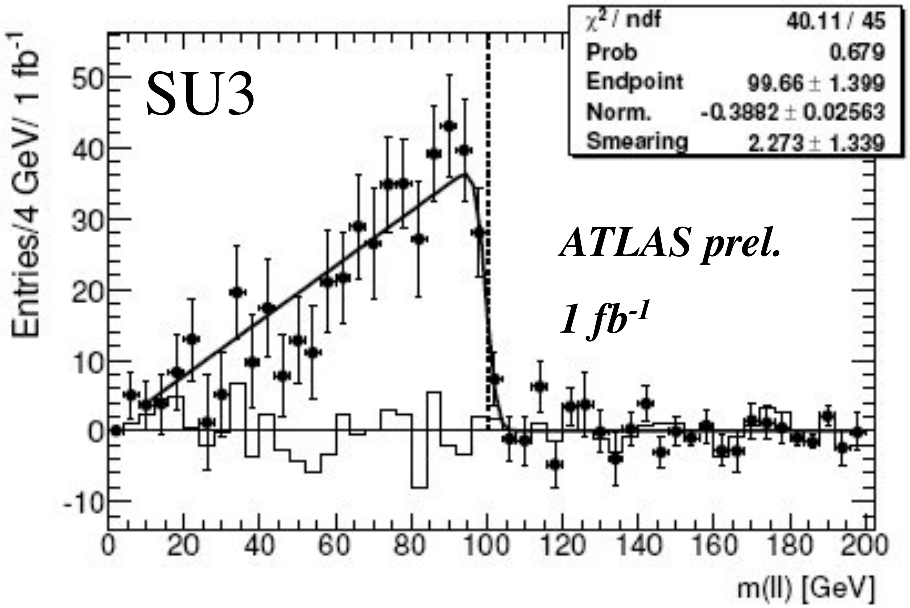
  - In classic models quite possible
    - Would be a wonderful experimental challenge!
  - But of course very possible also that it does not happen
- If Nature is like this:
  - Need to try to reconstruct masses of all those particles
- Main method:
  - Measure “edges”

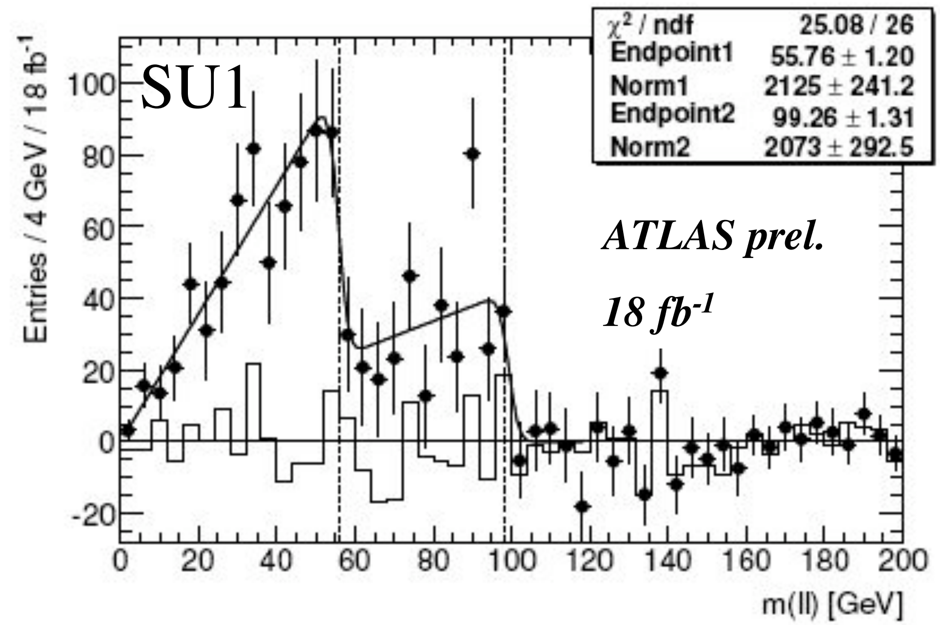


$$m_{\ell\ell}^{\text{edge}} = m_{\tilde{\chi}_2^0} \sqrt{1 - \left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_2^0}}\right)^2} \sqrt{1 - \left(\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2}.$$

Only for opposite sign same-flavor (OSDF) leptons

Dilepton Edge Fit





- Background from different flavors subtracted $\sum e^+e^- + \mu^+\mu^- - e^+\mu^- - \mu^+e^-$
  - Removes random SUSY backgrounds, top backgrounds,..
- Fit for dilepton edge
  - With many such edges one can maybe get a beginning of an understanding what is happening!
  - Different models look differently

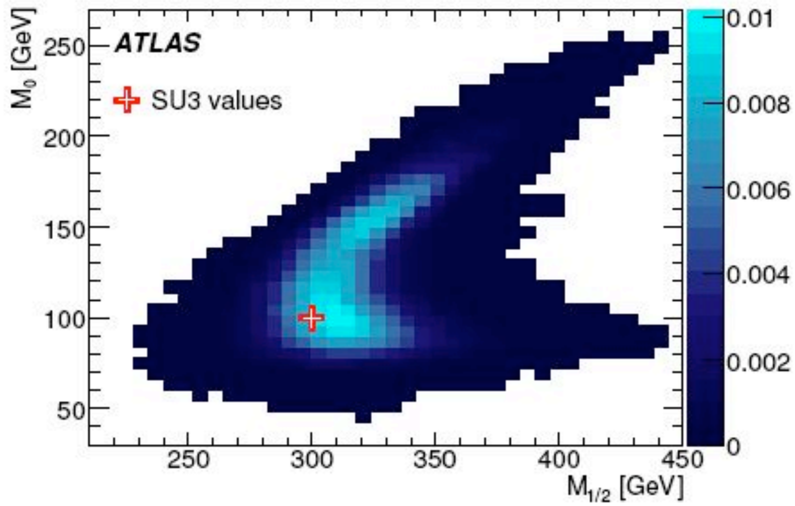
$$m_{\ell\ell}^{\text{edge}} = m_{\tilde{\chi}_2^0}\sqrt{1-\left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_2^0}}\right)^2}\sqrt{1-\left(\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2}.$$

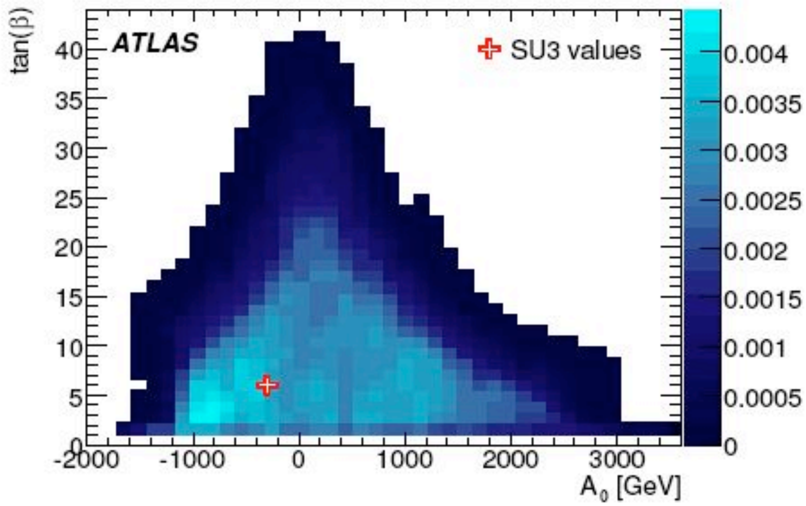
How well does this work?

Endpoint	SU3 truth	SU3 measured	SU4 truth	SU4 measured
$m_{\ell\ell q}^{\mathrm{edge}}$	501	$517 \pm 30 \pm 10 \pm 13$	340	$343 \pm 12 \pm 3 \pm 9$
$m_{\ell\ell q}^{\mathrm{thr}}$	249	$265 \pm 17 \pm 15 \pm 7$	168	$161 \pm 36 \pm 20 \pm 4$
$m_{lq(\mathrm{low})}^{\mathrm{max}}$	325	$333 \pm 6 \pm 6 \pm 8$	240	$201 \pm 9 \pm 3 \pm 5$
$m_{lq(\mathrm{high})}^{\mathrm{max}}$	418	$445 \pm 11 \pm 11 \pm 11$	340	$320 \pm 8 \pm 3 \pm 8$

- Works reasonably well…
- Can even try to extract high-level theory parameters

SUSY Parameters at GUT scale!?!





Parameter	SU3 value	fitted value	exp. unc.
	$\mathrm{sign}(\mu) = +1$		
$\tan\beta$	6	7.4	4.6
M_0	100 GeV	98.5 GeV	±9.3 GeV
$M_{1/2}$	300 GeV	317.7 GeV	±6.9 GeV
A_0	−300 GeV	445 GeV	±408 GeV
	$\mathrm{sign}(\mu) = -1$		
$\tan\beta$		13.9	±2.8
M_0		104 GeV	±18 GeV
$M_{1/2}$		309.6 GeV	±5.9 GeV
A_0		489 GeV	±189 GeV

- Depends if we understand our model well enough
- Personally I am very skeptical that we can do this
  - But would be great to have that problem!

Conclusions

- Several methods of extracting property of particle
  - Template method is widely used
  - Matrix Element technique extracts more information
  - For known shapes simple fits can also be done
- Examples:
  - W boson mass (precision ~0.06%)
  - Top quark mass (precision ~0.7%)
  - SUSY particles
- I hope we will be able to measure properties of many new particles!
  - Let's see how to find them first in the next lecture