Measurement of W mass and width at OPAL: the journey from within

PilcherFest, 22nd Sept 2012
Kersten Physics Teaching Center
University of Chicago

- *From Europe to Chicago and back*
- *Francesco meet OPAL*
- *W mass: the works (2000-2004)*
- *Memories and lessons: images of the mind*
- *Coming back to where we began*

Francesco Spanò

Royal Holloway
University of London

From November 1999...

High energy Physics

- My first trip to Chicago and UofC
- Meet Jim PIlcher, Mel Shochet..

Kersten Phys Teaching Center

Internationl House

.. to April 2000

- Join OPAL/ATLAS with Jim Pilcher as advisor.
- ...moving to Hyde Park, start courses, setting down..

You should go to CERN ....

- End of Spring quarter 2000: Jim suggests to go to CERN to make a decision on thesis project.

  - Francesco, meet OPAL !

- Attend OPAL week, talk to phys coordinator, talk to Chicago people resident at CERN
- Mature experiment with large available data set, still more to come *(maybe even some more data taking at WW production threshold..)*

One outsanding topic: W mass and width measurement

- Impressive and fascinating task: **perform measurement using full data set** collected by OPAL extending it from data collected @ $\sqrt{s}$=189 GeV
- Chicago has leading role and one Ph.D. candidate is completing her thesis on that topic (*...who might that be:-)*)

Why W Boson(s)?

W^+ and W^- : SM mediators of weak interactions

Existence confirms (with Z^0) Standard Model SU(2)xU(1) gauge symmetry

Are massive: related to SM EWK symmetry breaking → Higgs

M_W and Γ_W are key parameters of SM

Precise and unbiased measurement by direct production

→

Stringent test of SM, constraints on SM Higgs Boson mass and on physics beyond SM

W mass in SM: the

$$M_W = \sqrt{\frac{\pi\alpha}{G_F\sqrt{2}}} \cdot \frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$

$\delta\alpha/\alpha \sim 0.014\%$ at $Q^2 \sim M^2_Z$

$\sim Cm^2_{top} + D\ln(M^2_H)$

$\sim 1 - M^2_W/M^2_Z$

$\delta M_Z/M_Z \sim 0.004\%$

$\delta G_F/G_F \sim 0.0009\%$

- χ2 test of SM → M_W does not dominate uncertainty on a) test of rad. corrections b) Higgs mass estimate IF $\delta M_W \sim 7\cdot10^{-2}\ \delta M_{top}$
- Indirect determination (LEP1/SLD) : $\delta M_W \sim 32$ MeV

⇒ Need $\delta M_W \sim 15$ MeV if $\delta M_{top} \sim 2$ GeV

Precise and unbiased measurement by direct production

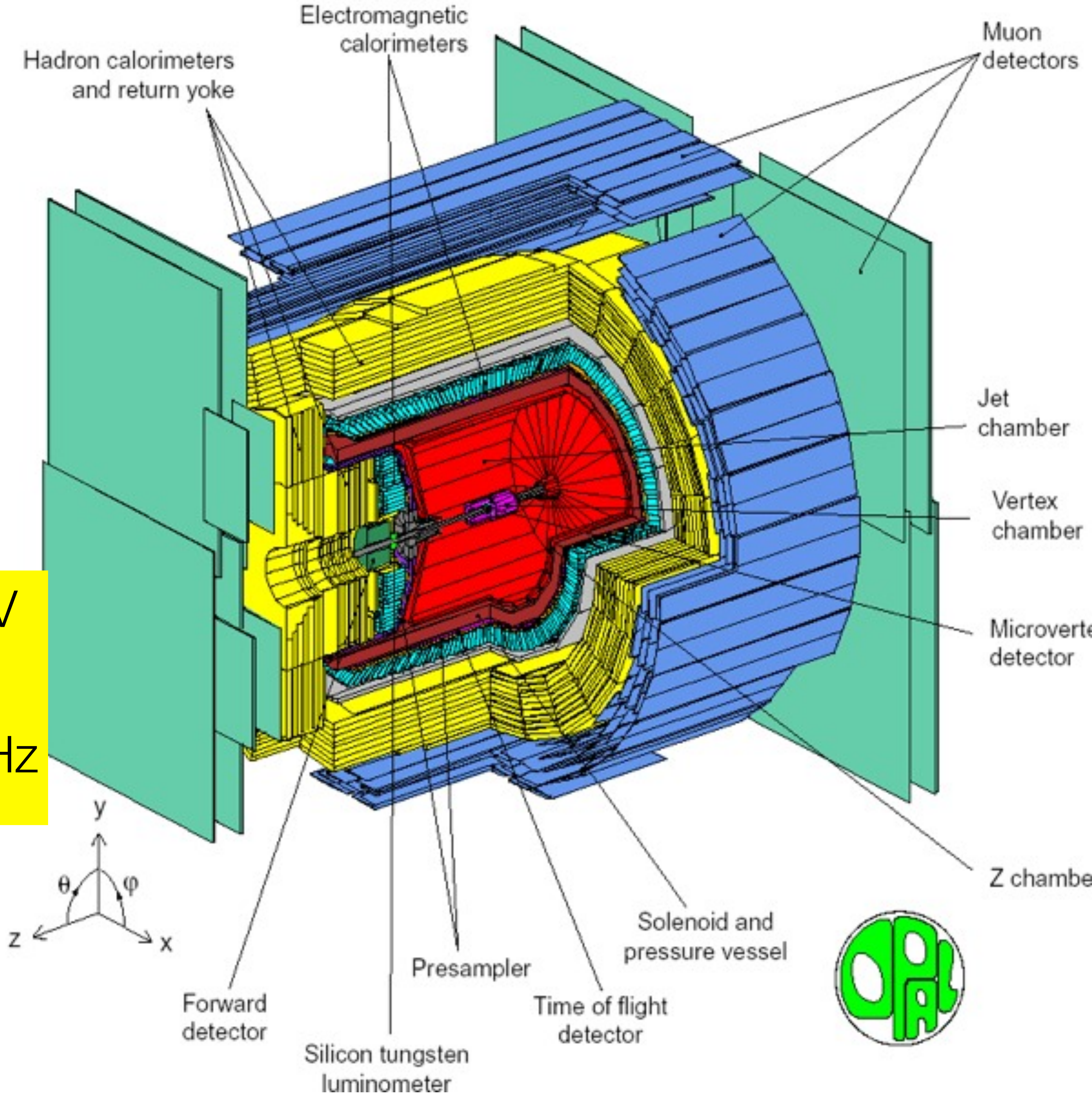
LEP2 (e^+e^- collider): ideal clean, controlled environment for W precision studies.

Hadron colliders (pp and ppbar) : large statistics, sizeable (a-priori) uncertainties

The Omni Purpose Apparatus at LEP

Onion-like detector covering 99% of solid angle with

- Em. Res = 5/6%/√E+0.2%
- Had. Res: ~100-120%/√E
- $\sigma(p)/p^2 = 1.25 \cdot 10^{-3}$ GeV^{-1} (for 45 GeV muons)



LEP

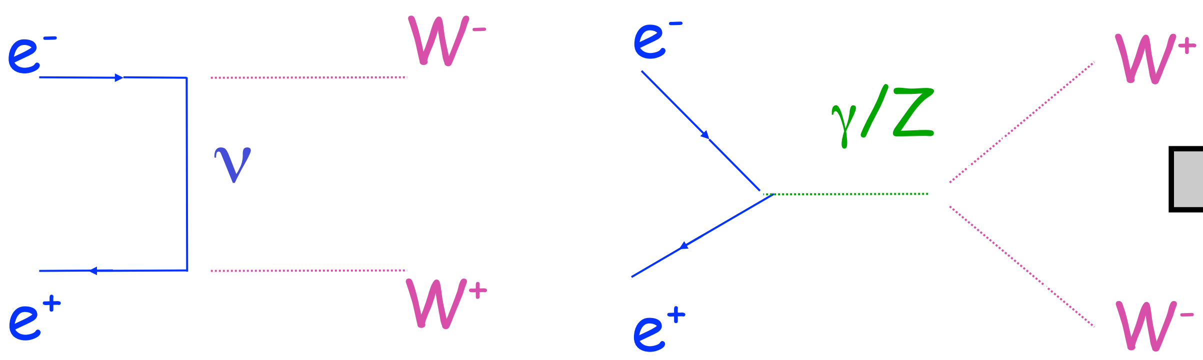
- e^+e^- collider at E_{cm}~ 160-209 GeV
- Peak lumi: ~0.5-1 $\cdot 10^{32}$ cm^{-2} s^{-1}
- Bunch crossing frequency~45 KHz

WW rate ~0.8-1.6 10^{-3} Hz

W physics @ LEP2

@ LEP2 : $e^+e^- \to W^+W^- \to$ 4fermions

At tree level



(CC03 diagrams)

NOT GAUGE INVARIANT $e^+e^- \to 4f$ has other intermediate states

Add other $e^+e^- \to 4f$ for gauge invariant description also of BKG

3 final state topologies

~ 44% ~46% ~ 10%

Add O(α) EWK corr.:**required** for precision measurement

Chan	Main Bkg
lνlν	ZZ, Zee, γγ
qqlν	Weν, Z /γ →qq(γ)
qqqq	Z/γ → qq(γ)

Building the group for W analysis

i.e. your group makes your success..:-)

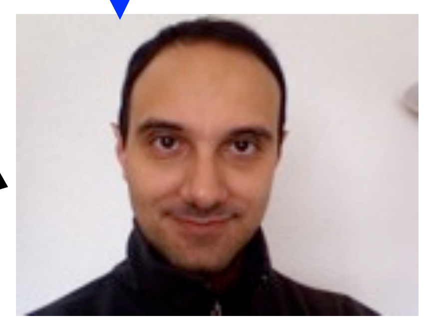
Jim Pilcher

Ambreesh Gupta

Research Associate, then Res Scientist *@ Chicago*

Eric Torrence

McCormick Fellow



FS

Ph.D. Candidate *Chicago, CERN, Chicago*

@ CERN

Richard Teuscher

Research Associate, then Res Scientist

Alain Bellerive

Research Associate

- Jim's insight (my view..)
  - **connect** the relevant **people** to work on the analysis and arrange for smooth continuation of previous work
  - agree with Ambreesh to make **W analysis a priority**
  - arrange for Eric to help FS and AG to start on W analysis
  - send FS to CERN in 2001 to connect with OPAL & Eric

Event selection

Total OPAL ∫Ldt ~ 680 pb^{-1}
(1997-2000) in
E_{cm} ~ 172-209 GeV
~ 10 pb^{-1} @ E_{cm} ~ 161 GeV

~11K WW

~10K 4f bkg

~63K $Z/\gamma \rightarrow qq(\gamma)$

Widest det acceptance

Complex multi-steps event selection (cut based pre-selections, likelihood discriminants) for efficient and clean identification

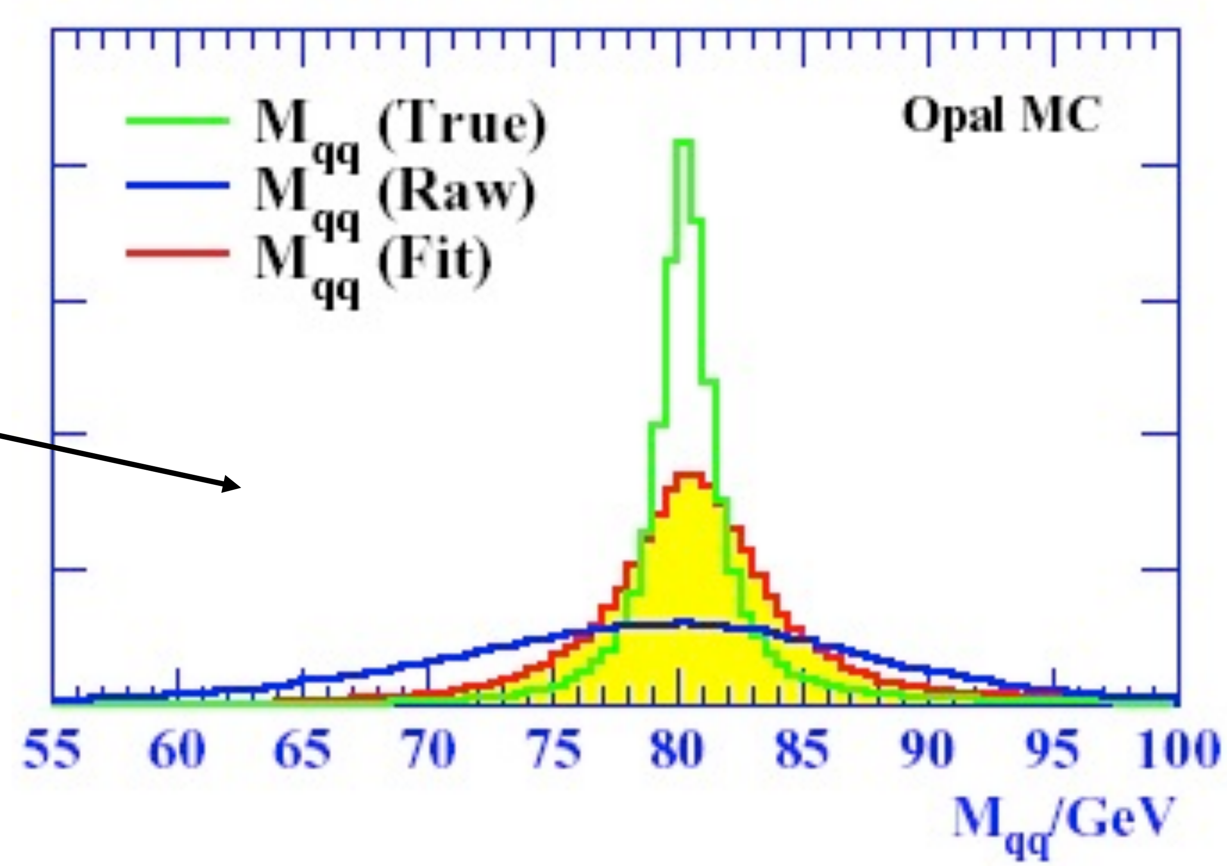
Performance

Chan	Efficiency	Purity	Expected	Selected
qqlν	81%	86%	4836	4822
qqqq	86%	79%	5831	5893

lνlν: two neutrinos → little mass information→ separate analysis

The strategy @ OPAL

- Three main steps
  - Reconstruction: build final state 4f 4-momenta from measured tracks and clusters
  - Kinematic fitting: precise beam energy knowledge to constrain total four momentum → improves mass resolution
  - Mass and width extraction: likelihood



- Three mass extraction methods: Convolution, Reweighting, Breit-Wigner
  - Small differences at reconstruction and kinematic fitting level
  - Clear difference in likelihood building

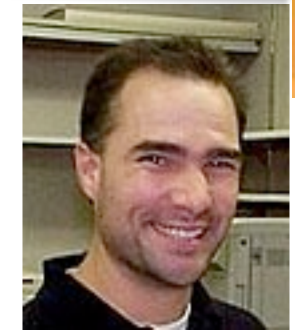
Definitions

- In qqqq: 4-mom. conservation (4C fit) . 4C+ equal mass for Ws (5Cfit)
- In qqlν: neutrino →1C/2C fit

Taking it from Robin's solid foundation..

Robin Coxe
Ph.D. Candidate

- Robin's thesis was OPAL main measurement @ $\sqrt{s}$ =189 GeV
  - Data Set:189 GeV data set $\int L dt$ = 183 pb^{-1}
  - Reco: separate kine fit and jets-to-W lkl pairing for 4 & 5 jets events
  - M_W, Γ_W: **1 dim. Reweighting:**binned lkl scan by re-weighting MC shape for varying (M_W ,Γ_W), least biased, fully exploit MC reco



Doug Glezinski
Res. Associate

..towards a new approach

DataSet: Extend to full data set (680 pb^{-1}, ~11K W pairs)

Reco & kine : fully had: fit as 5jets, merge jets to 4, new lkl for comb bkg handling (matrix el + reco quantities)

M_W, Γ_W: **2d/3d Reweghting** : spread bkg (4j) + more weight to better resolution (qqlv) new flexible binning: enough ev/bin avoid biases

Full analysis of all syst.uncertainties: new data driven (LEP-wide) strategy + Final combination

Event reconstruction in qqlν channel

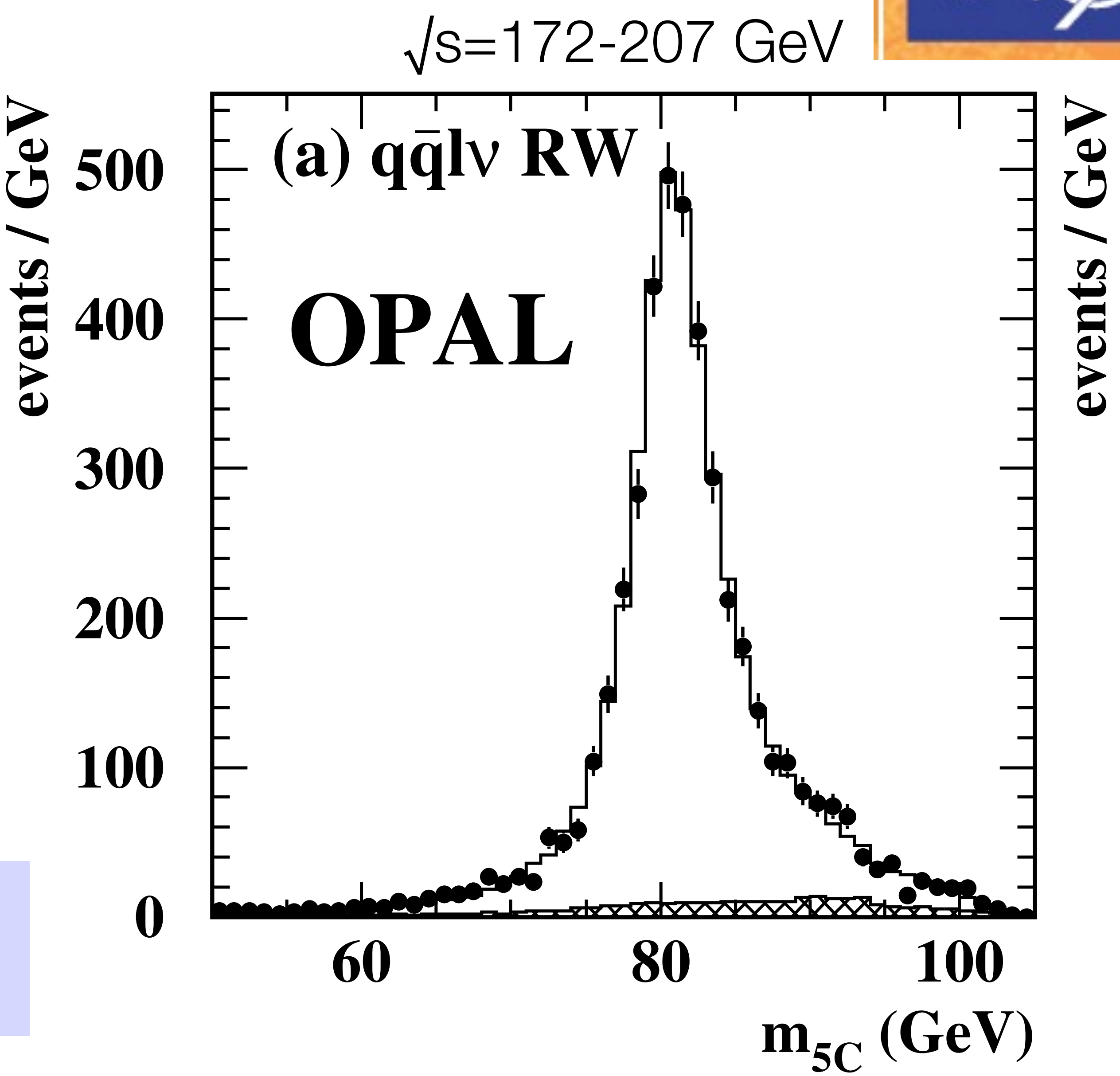
- Identify energy deposits associated with lepton
- Reconstruct lepton (only in qqeν and qqμν)
- Force remainder of event in 2 jets (Durham)

⇓

Apply small calibration corrections to jets and lepton

⇓

Kinematic fit



qqeν and qqμν

χ^2 : 2C and 1C fits (or semi-analytic minimization)

qqτν

χ^2 : simplified analytic minimization using di-jet system only

Event reconstruction in qqqq channel

Force event into

- 5jets to account for additional gluon jet /4jets or 5jets depending on jet res par (5j~23%) (Durham)

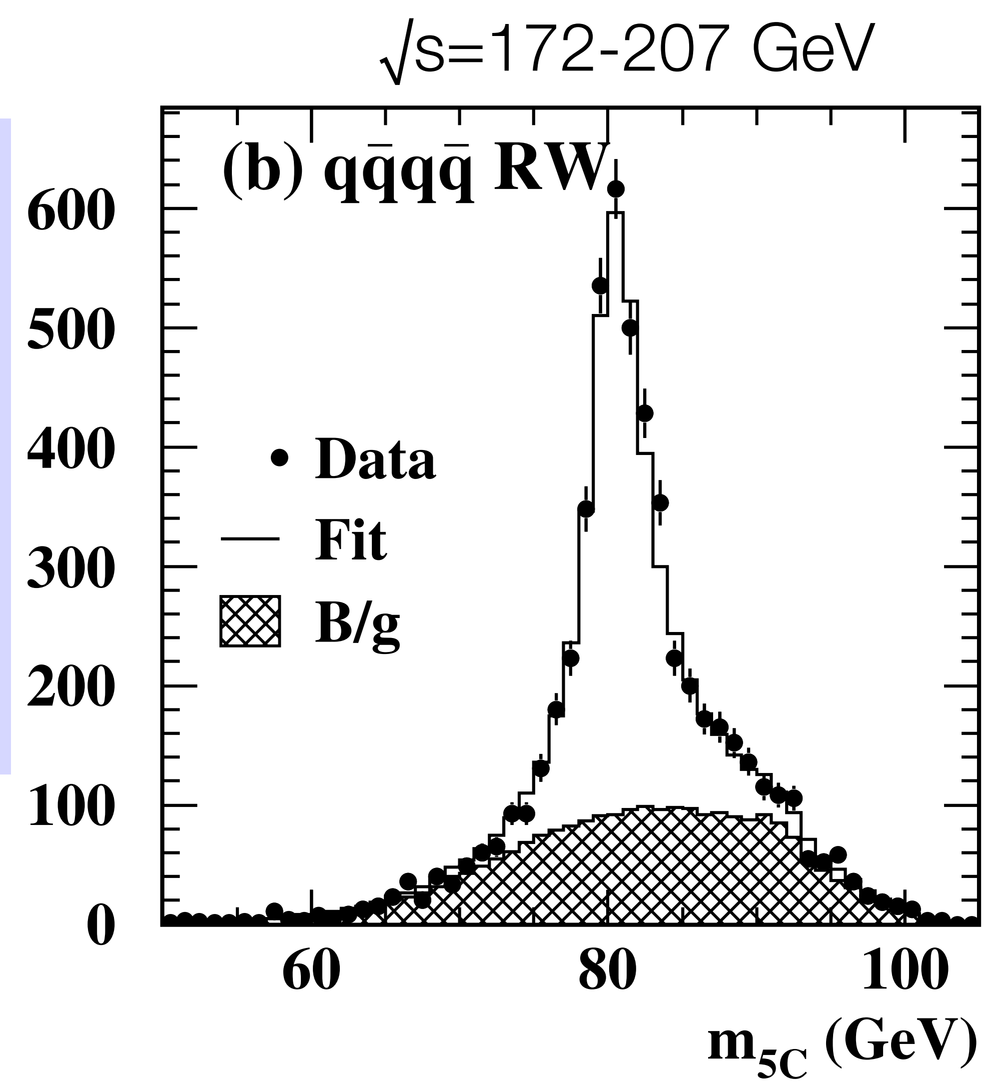
Standard analysis

P_{cut} analysis

jet direction from tracks and clusters with p>2.5 GeV →reduce M_W syst. error from final state interactions, slightly worse angular res.

Apply small calibration corrections to jets

Kinematic fit: 5C and 4C fits implemented



W-Jet Pairing

Event reconstruction in qqqq channel (cont)

Assign jets to Ws with different algorithms

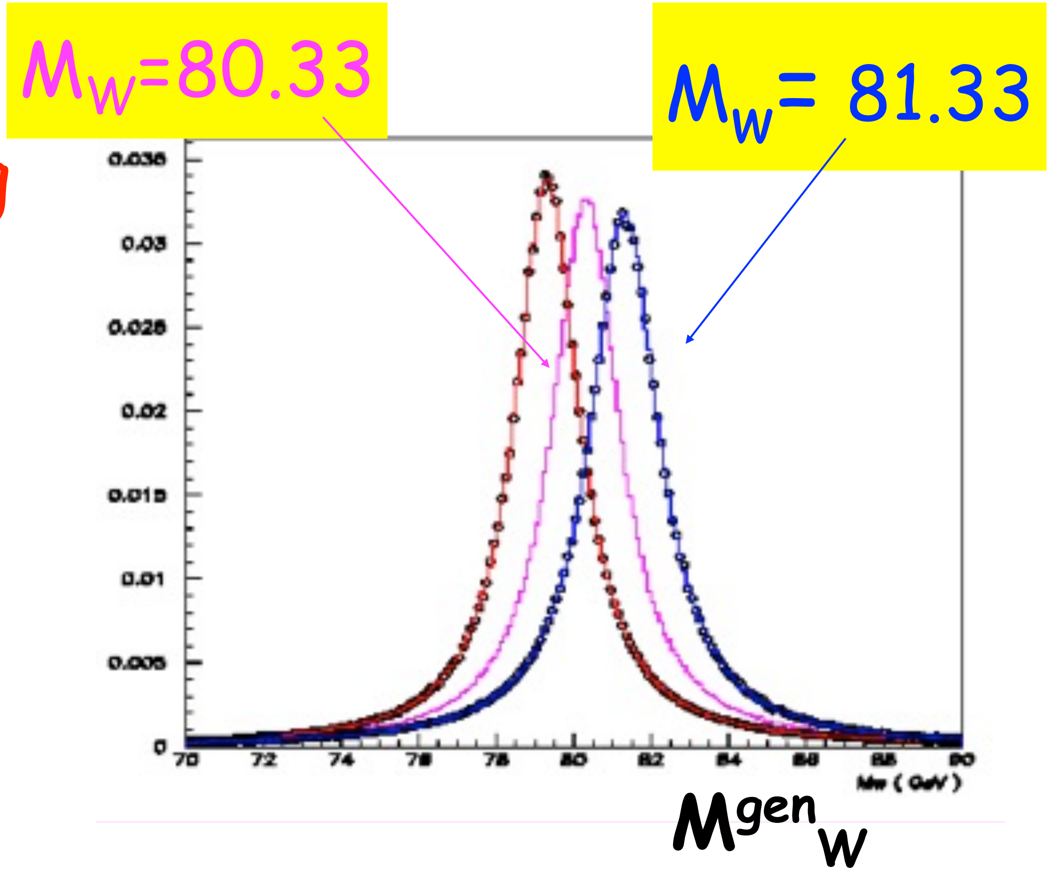
- **Reweighting** and Breit Wigner: **choose one assignment with**
  - **CC03 matrix element and multivariate discriminant** (different treatement for standard and p_{cut}) **(RW)**
  - Kinematic fit probability for 4j , multivariate discriminant for 5j (BW)

- Convolution : use all assignment. Neural Network to give weight to each assignment

Reweighting

- Basic idea: likelihood from MC distribution of (M_W,Γ_W) sensitive variables for signal and bkg. (M_W,Γ_W) lkl. scan performed by reweighting signal MC sample for varying W mass and width hypothesis

- Distributions use multi dimensional binning to spread bkg (mainly qqqq), give more weight to events with better resolution (mainly qqlv)
  - qqev/qqμv: 3D grid (2C mass,error on 2C mass,1C had mass),
  - qqτv: 2D grid (analytic mass and its error)
  - qqqq: 3D grid (5C mass,error on 5C mass,difference between 4C masses)
- Reweighting function is product of Breit-Wigners
- Binned likelihood fit



- No external bias correction needed
- Fully exploit MC power

Systematics and combination, the long and winding road

Jim's advise

- solid connections with the OPAL "family" established
- maximize "in house" coherence/activity (FS + AG)

→ **Time to be back**: FS **in Chicago** at beginning 2002

- **2002-2003: a long effort on systematics**
- Ultimately four "core" groups are left
  - Chicago (RW), CERN (Convolution) , Cambridge (BW), Munich (Convolution measuring width)

- Detailed studies : **show RW can ride the tide**
  - *final state interactions* LEP wide studies: de-sensitize analysis in fully had channel + data driven limits.→ update jet pairing + higher dim RW
  - *hadronization*: different baryon-kaon content in data/MC
  - *higher order corrections*: include WW data driven limit

and more..

W mass and width extraction

- For each event in a data set, build likelihood to have a certain value (be in a certain bin) of one (or more) (M_W, Γ_W) sensitive variables for signal and bkg

- Produce likelihood for each data set and maximize it as a function of $M_W, \Gamma_W \rightarrow$ determine M_W, Γ_W and uncertainties

Two types of fits are performed (consistent results):

- Two parameter fit: (M_W, Γ_W) are independent parameters
- One Parameter fit: fit for M_W (Γ_W fixed to the SM relation : $\Gamma_W \propto M_W^3$) , fit for Γ_W (M_W set to 80.33 GeV)

- Check/correct for bias (Monte Carlo) and expected errors (pulls)
- Evaluate syst. uncertainties

W mass and width extraction (cont)

- Results (years/channels) combined by generalized least-square minimization taking into account correlations and systematic uncertainties

- Strongly correlated methods (65% to 88%) → small stat. gain in combination (~2% decrease in δM_W^{stat}) → Use CV for central values: best expected statistical uncertainty on M_W

Use

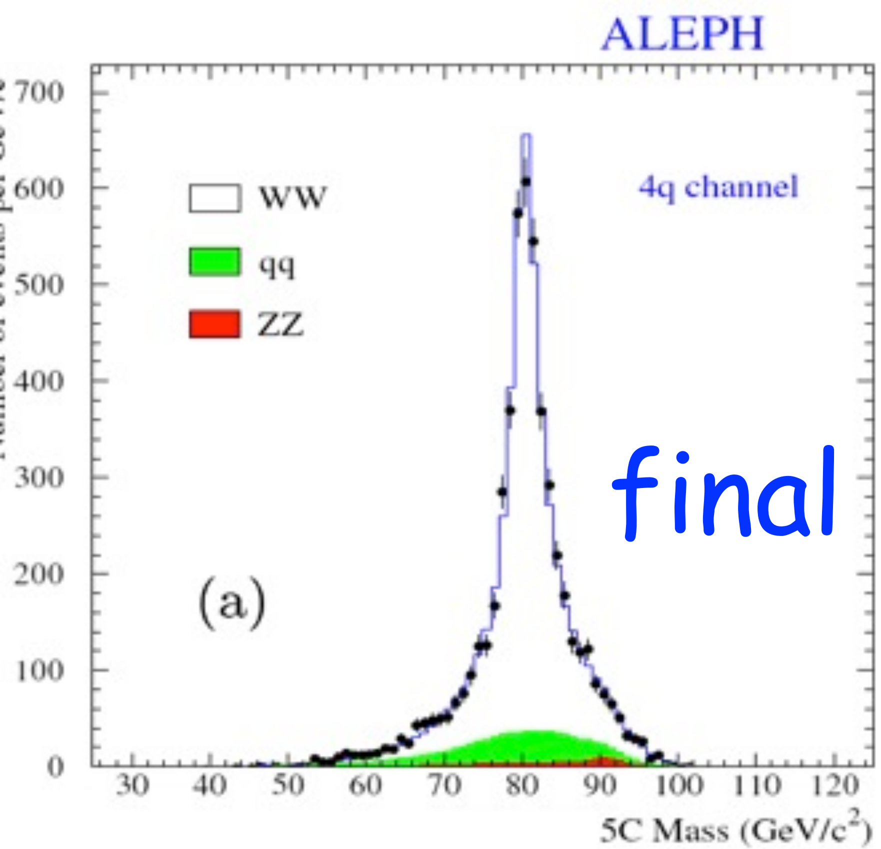
- final LEP beam energy uncertainty and correlation matrix
- M_W p_{cut} analysis to get significant reduction in FSI syst. and improvement of total uncertainty

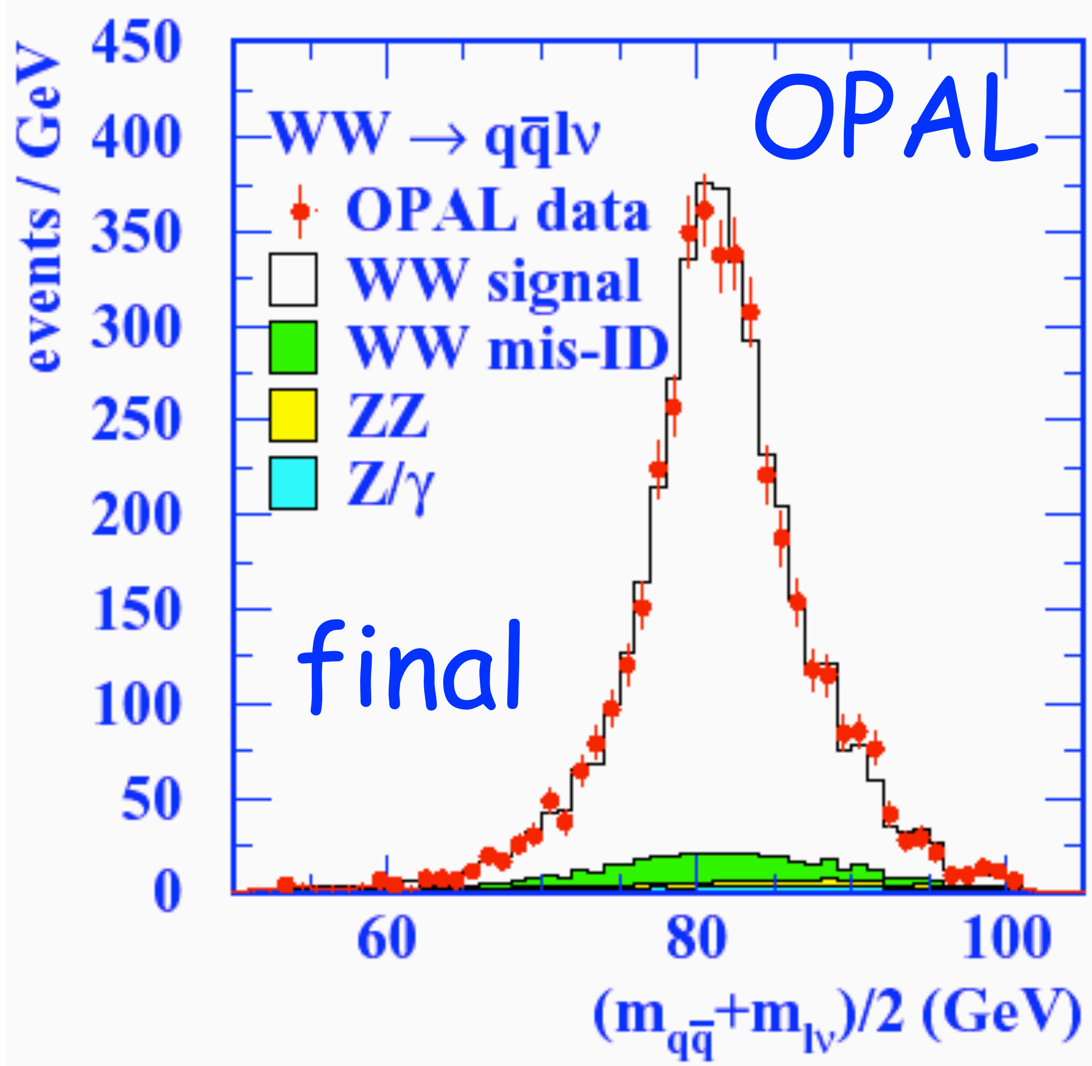
W mass and width extraction (LEP)

Maximum Likelihood fit to extract M_W

Γ_W:from SM relation or 2 parameter Fit

Different likelihood building methods





Breit Wigner (O):
asymmetric BW,
robust for preliminary
estimation

Convolution (D,O):
physics function ⊗
detector response,
statistically
powerful

Reweighting (A,L,O):
MC shape reweighted
for varying assumed W
mass,least biased, fully
exploit MC reco

Uncertainties on M_W

- Use final LEP beam energy uncertainty and correlation matrix

- M_W P_{cut} analysis →significant reduction in FSI syst→qqqq weight in combination: from 10% to 34% (If no FSI, comb. stat~38 MeV, now 42 MeV→use most of qqqq stat power)

Source	Error on M_W (MeV)		
	qqlv	qqqq (p_{cut})	qqqq
Higher Order Corr.	11	9	9
Hadronisation	14	20	6
Detector Syst.	20	10	10
LEP Beam Energy	8	10	10
Colour Reconnection	-	41	125
Bose-Einstein Correlations	-	19	35
Other	5	26	20
Total Systematic	**28 (22,29)**	**58 (56,56)**	**133**
Statistical	**56 (58,64)**	**60 (64,73)**	**51**
Overall	**63 (62,70)**	**83 (85,92)**	**142**

In parenthesis: RW and BW summary values

Detailed discussion uses CV values - RW and BW are consistent

Uncertainties on Γ_W

Source	Error on M_W (MeV)	
	qqlv	qqqq
Higher Order Corr.	11	10
Hadronisation	77	68
Detector Syst.	29	6
LEP Beam Energy	3	2
Colour Reconnection	-	151
Bose-Einstein Correlations	-	32
Other	25	54
Total Systematic	**91 (85)**	**177 (180)**
Statistical	**135 (131)**	**112 (130)**
Overall	**163(156)**	**209 (222)**

In parenthesis: RW summary values. BW does not measure the width

Detailed discussion uses CV values - RW is consistent

OPAL Results

M_W	$M_W \pm \delta M_W^{stat} \pm \delta M_W^{syst}$(GeV)
CV	80.416 ± 0.042 ± 0.032
RW	**80.405 ± 0.044 ± 0.028**
BW	80.390 ± 0.048 ± 0.032

Previous published result
($\sqrt{s}$=161-189 GeV)

M_W= 80.432 ± 0.066(stat) ± 0.045 (syst)

Γ_W=2.04 ± 0.16 (stat) ± 0.09 (syst)

Γ_W	$\Gamma_W \pm \delta \Gamma_W^{stat} \pm \delta\Gamma_W^{syst}$(GeV)
CV	1.996 ± 0.096 ± 0.102
RW	**2.113 ± 0.101 ± 0.097**

Final OPAL results

Combining
lνlν and threshold measurement

M_W= 80.415 ± 0.042 (stat) ± 0.030 (syst) ± 0.009 (E_{beam})

Γ_W=1.996 ± 0.096 (stat) ± 0.102 (syst) ± 0.003 (E_{beam})

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Digital Object Identifier (DOI) 10.1140/epjc/s2005-02440-5

THE EUROPEAN PHYSICAL JOURNAL C

Eur. Phys. J. C 45, 307–335 (2006) hep-ex/0508060

Done!

You do not finish a thesis. You abandon it. (K. Anderson)

Measurement of the mass and width of the W boson

The OPAL Collaboration

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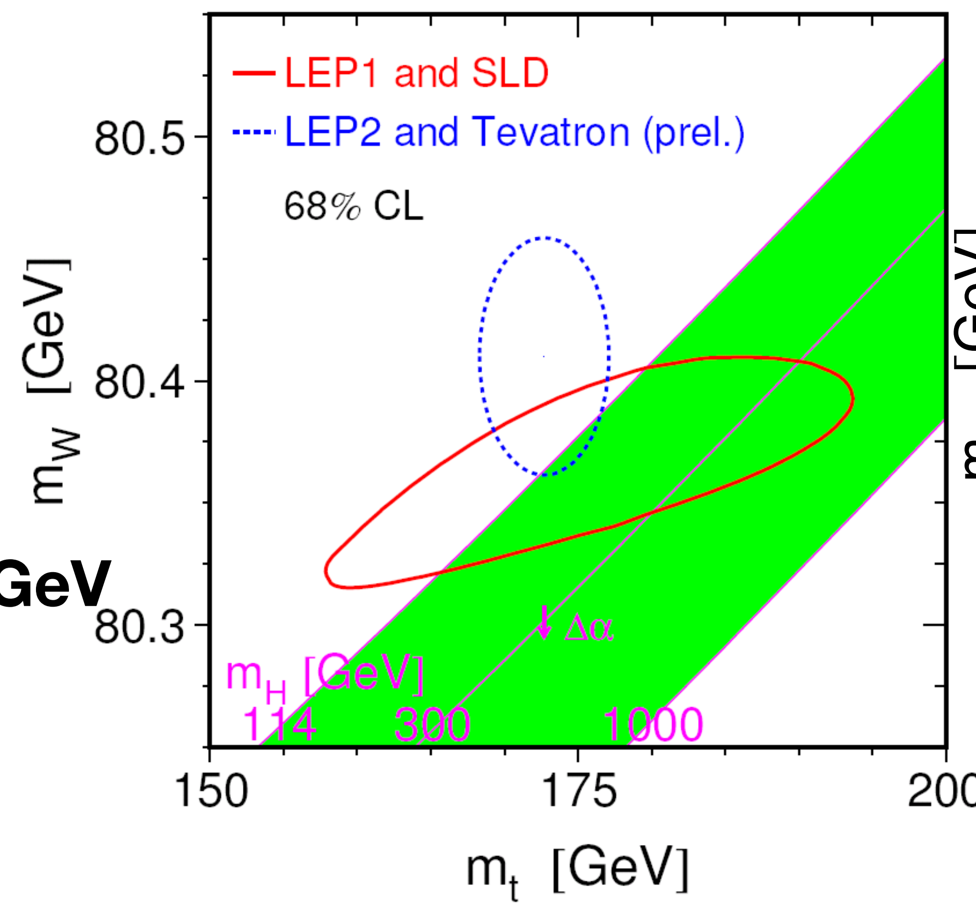
W mass status

summer 2005

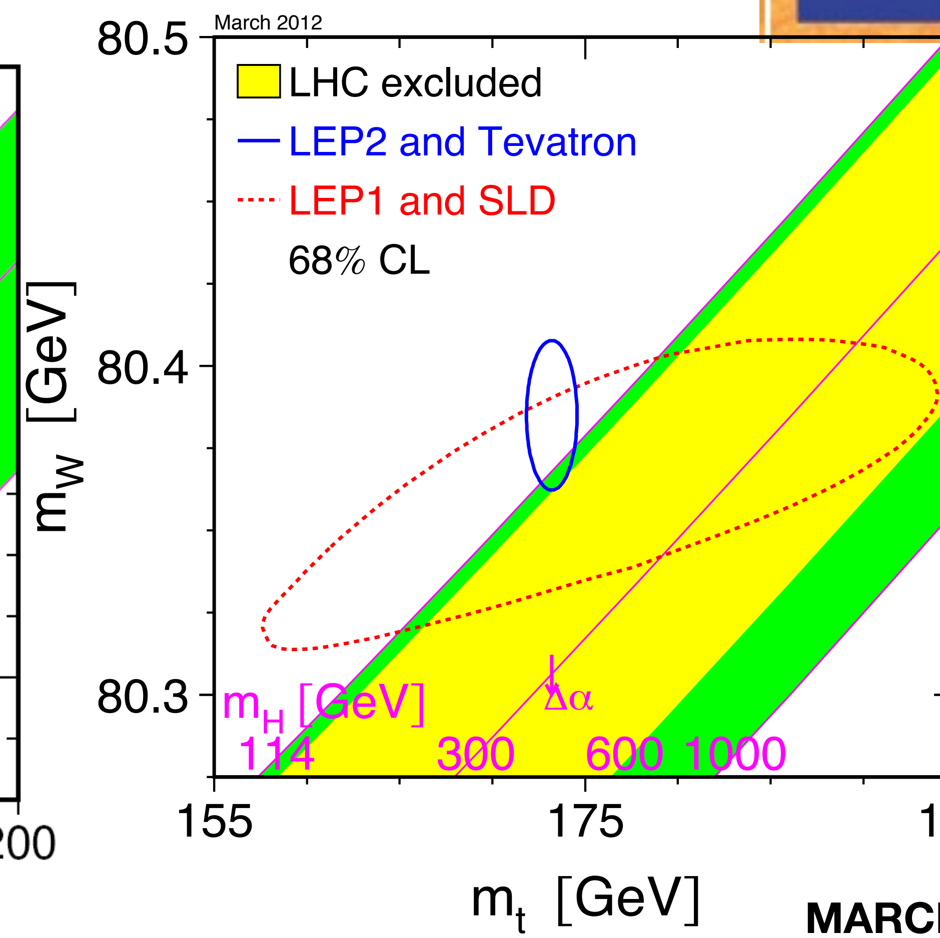


OPAL 2005:
M_W = 80.415 ± 0.052 GeV

Eur. Phys. J. C 45, 307–335 (2006)

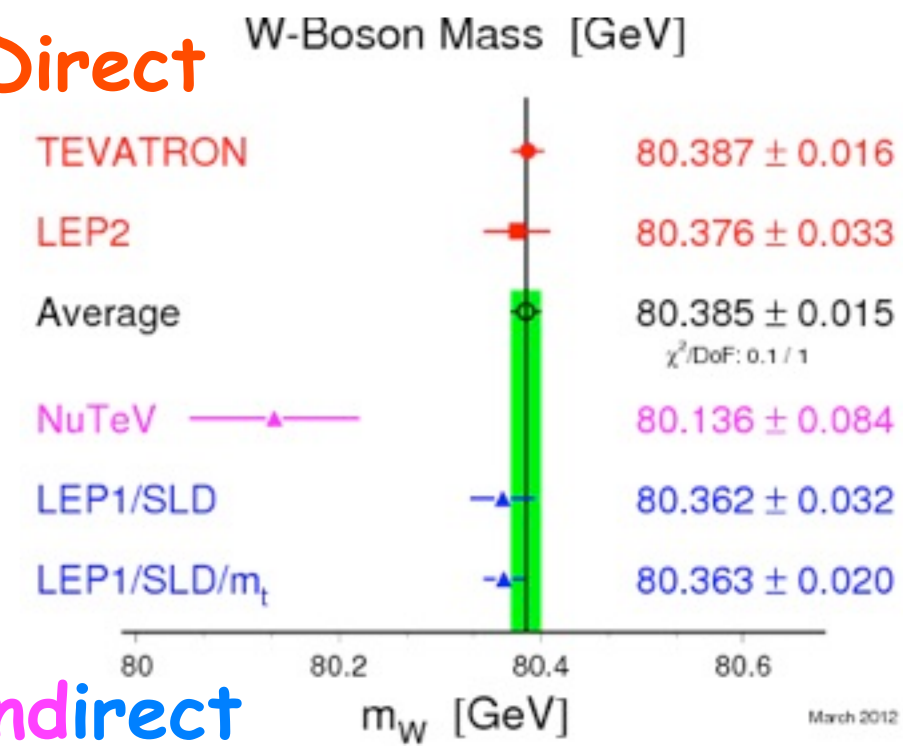
World 2005
Average 80.410 ±0.032 GeV

MARCH 2012

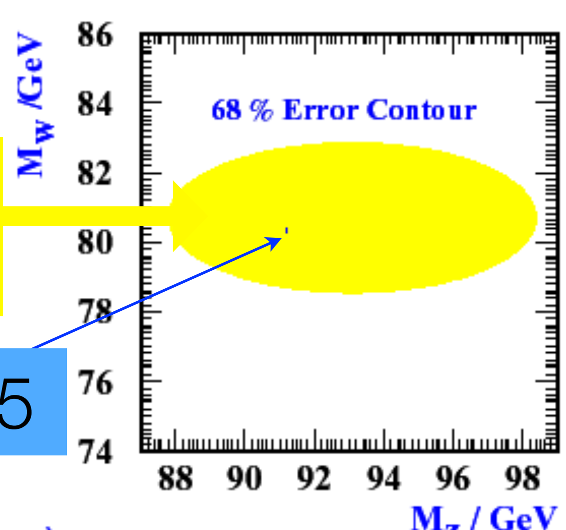


MARCH 2012

Direct



Indirect

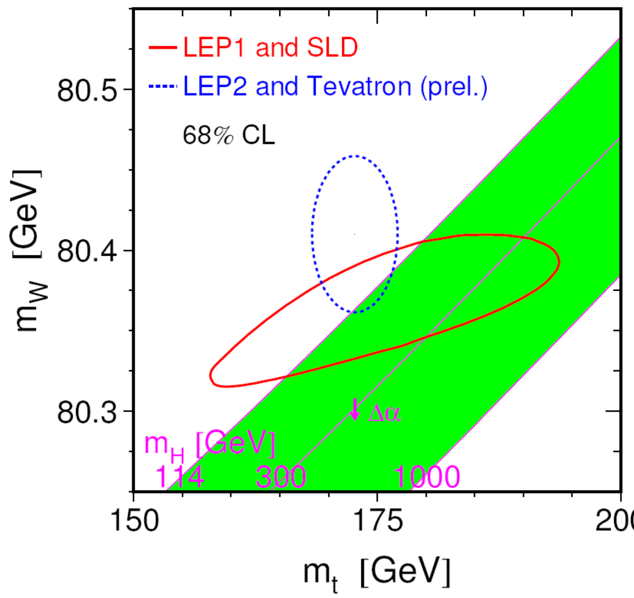


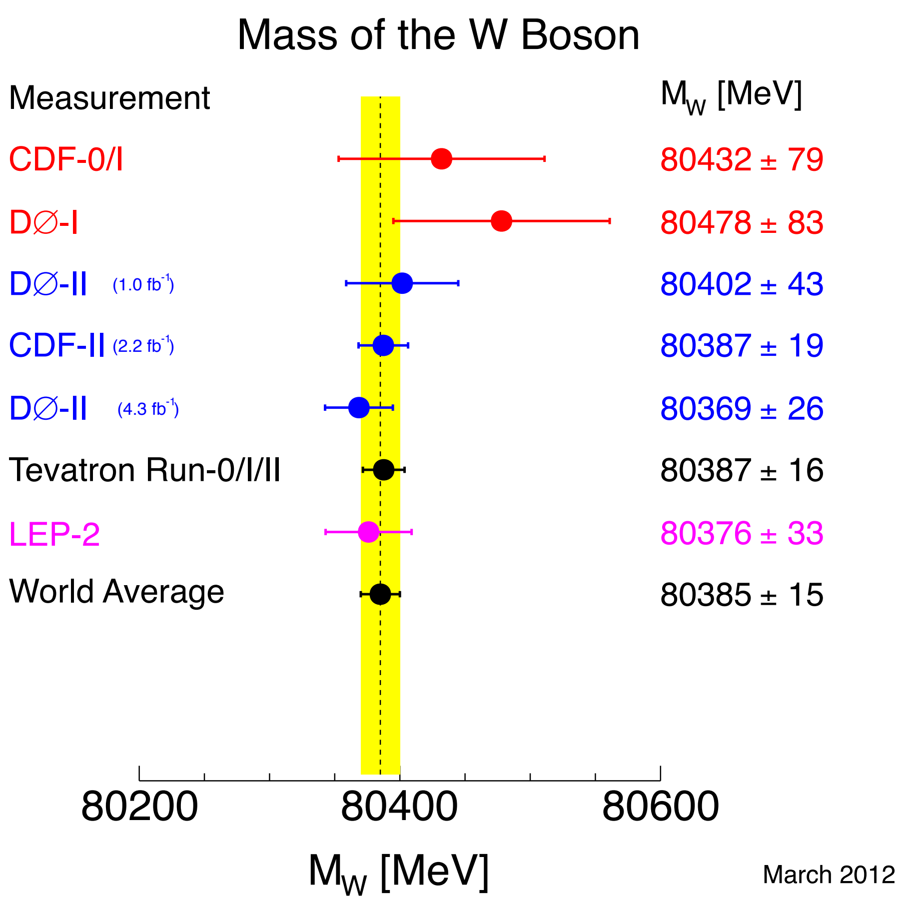
when LEP started...

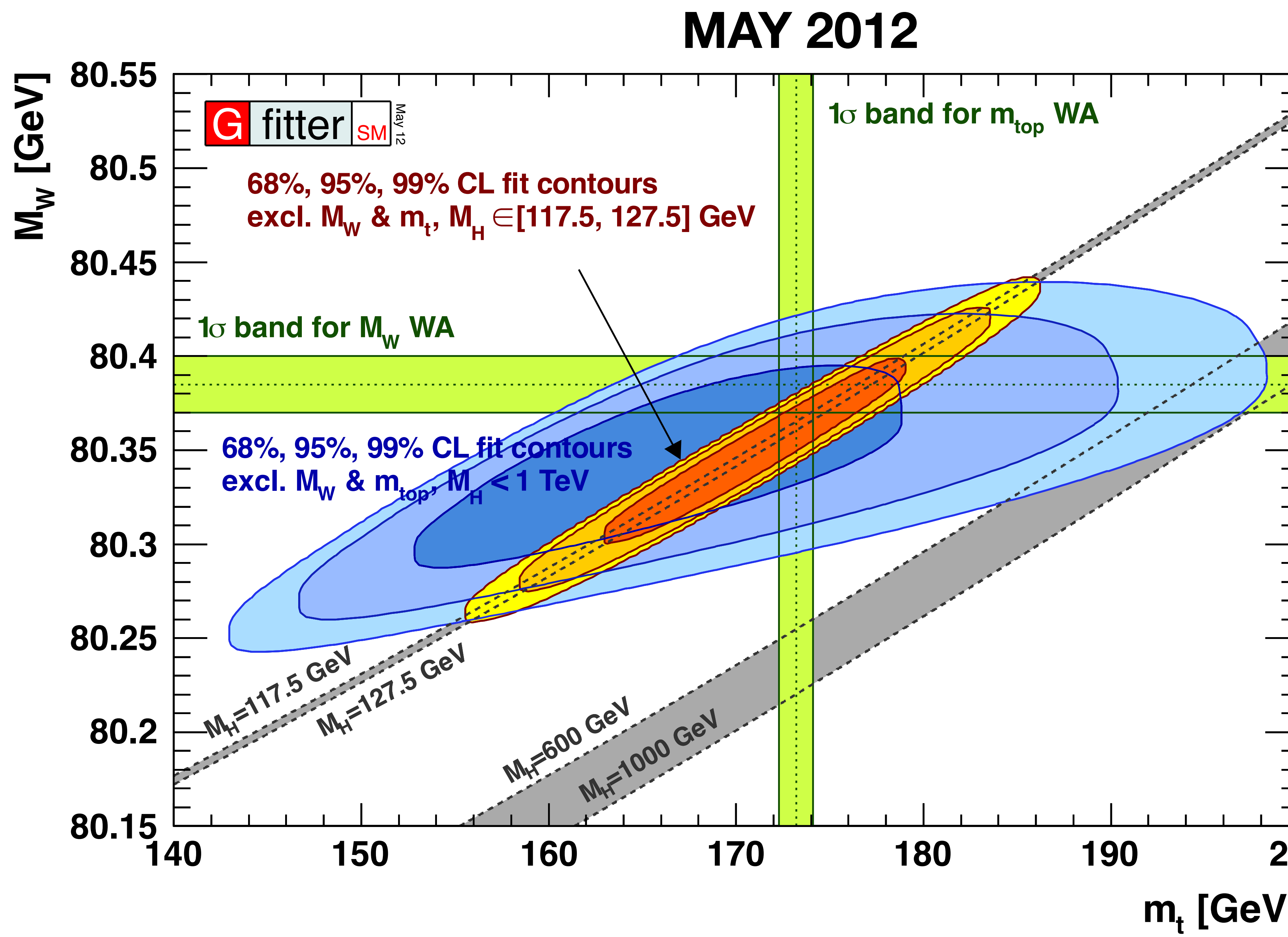
..in 2005

Tevatron includes M_W(UA2) =80.36±0.37

W mass status (cont)







Some personal recollections(I) images

- Jim suggesting to move on from hadronization studies ...

- Jim making time to talk to me in his HEP office..

- Jim arriving by bike on a Saturday sunny afternoon to carry a corrected copy of my thesis to my apartment..

- Jim and Carla inviting me to a reception at their house at a very close time to my handing in my thesis ..

Some personal recollections (II) Making it possible: the Chicago way

- **Solid advise at the right moment**

- **A strongly supportive environment** at "home" (ATLAS/OPAL group, HEP) in the collaboration ("OPAL")
  - nurture independence, while providing tools
    - ❖tools for analysis
    - ❖participation in meetings, conferences, being there where the action is

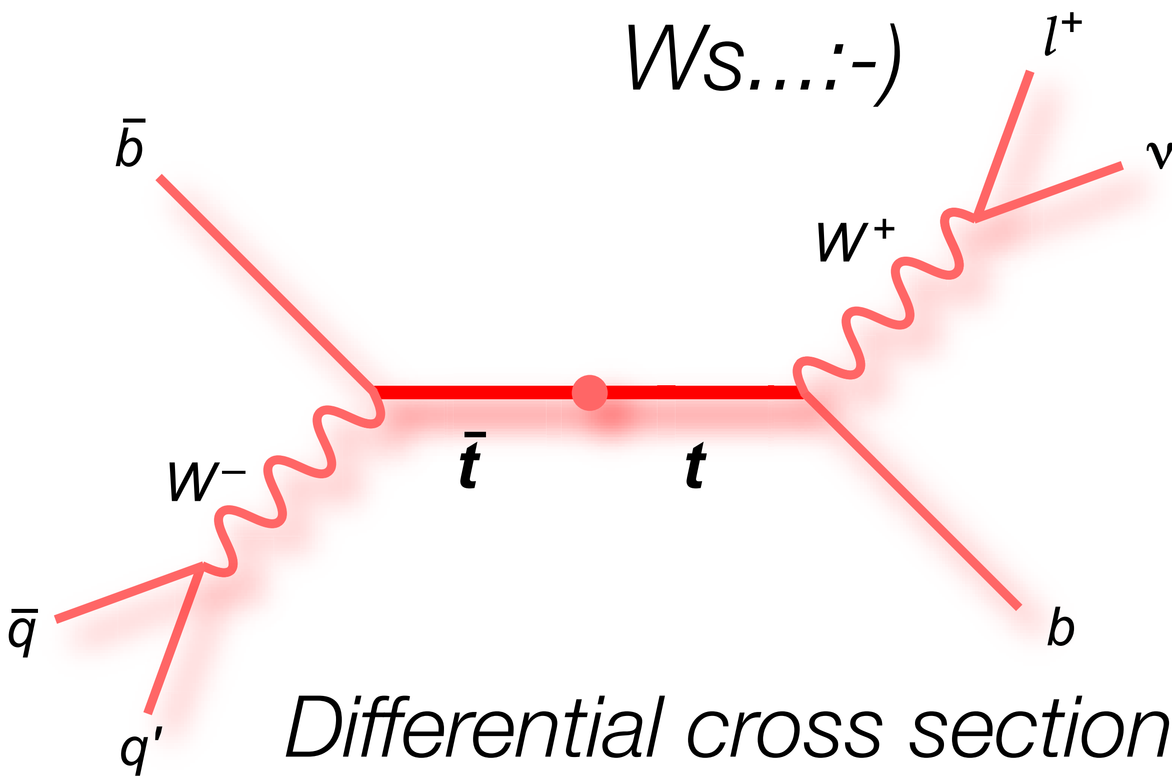
Some personal recollections (III): The lessons

- Concreteness and constructive approach
- Group work
- Solid, careful analysis work
- **Asking the (deep) questions**
- **Independence & trust**
- Teaching by example

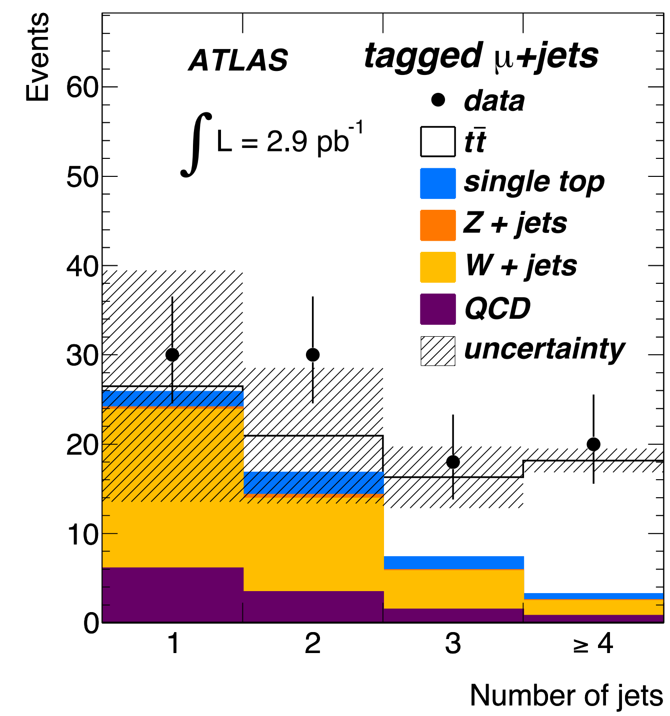
What I am doing now: top pairs i.e. WW bb

Royal Holloway University of London

I can't seem to abandon Ws...:-)

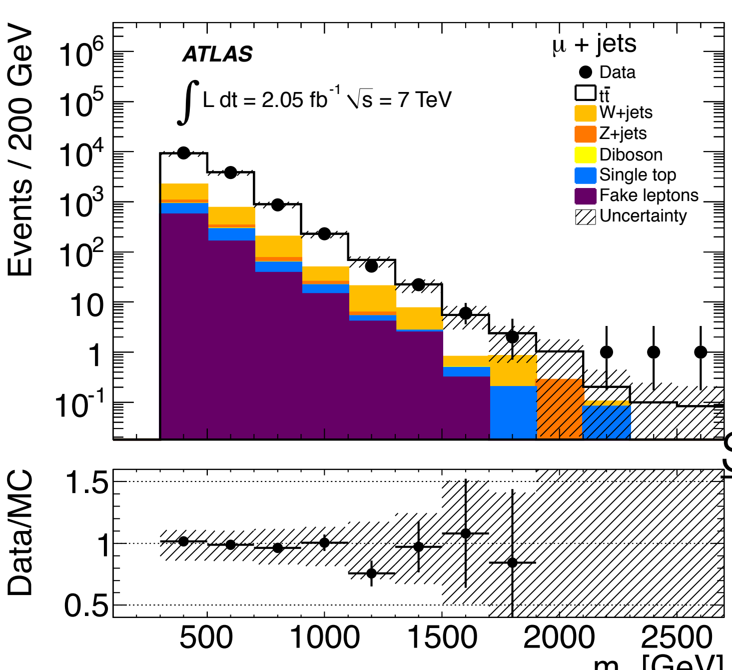


Top re-observation

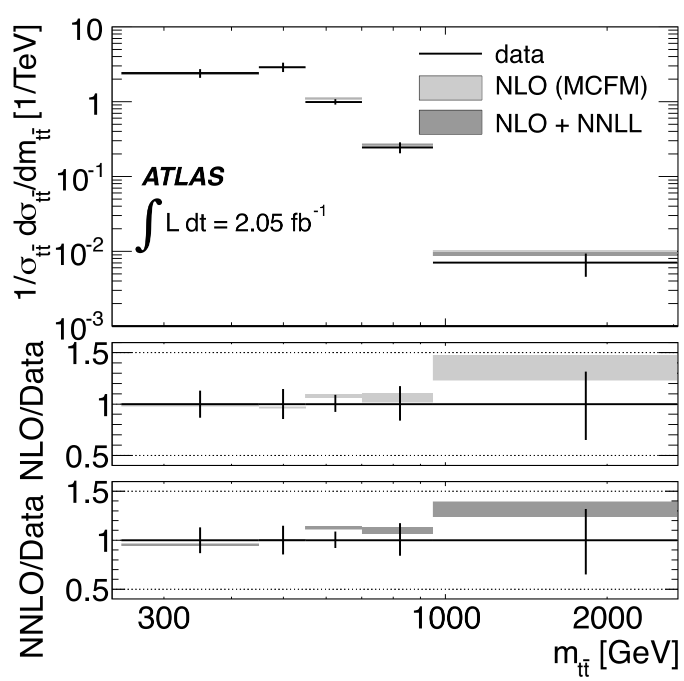


[arXiv1012.1792, EPJC 71, 1577 (2011)]()

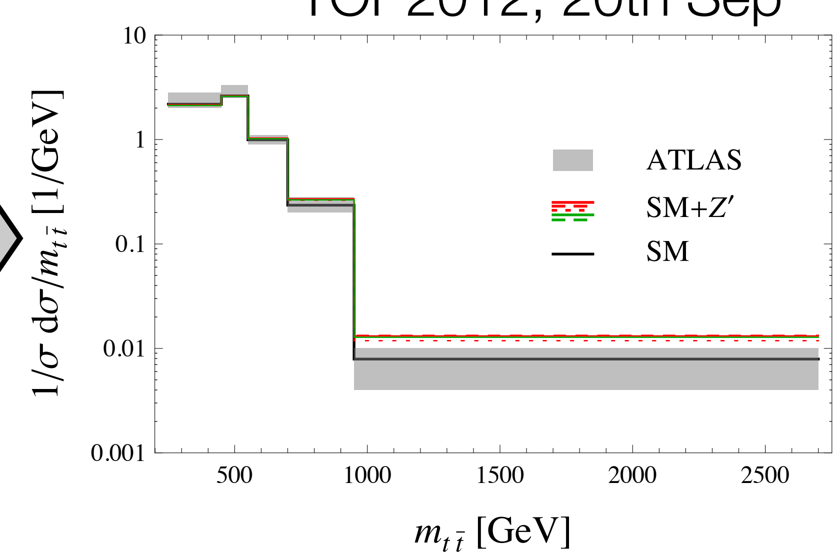
Differential cross sections, for ex. 1/σ dσ/dm$_{tt}$



arXiv: 1207.5644 Submitted to EPJC



J,Kamenik @ TOP2012, 20th Sep



Coming back to where we began

Still I cannot say it better than in 2004

The first person to acknowledge is my adviser James E. Pilcher. I have been privileged to collaborate with him over these four years and to learn from him. My respect and appreciation goes to both the scientist and the man. I benefited from his insight in physics, from the guidance which led me to face all problems and difficulties, also beyond physics. I was advised and supported while I was given the space to grow and make my own decisions. I do hope to be able to collaborate with him again.

THANK YOU JIM !!!

Back up

Jets & metrics

- in Jet clustering combine object i and j with smallest d(i,j)

- Jade

$$y_{ij} = \frac{2E_iE_j(1 - cos\,\theta_{ij})}{s} = \frac{M_{ij}^2}{s}$$

center of mass energy

improper for soft gluons emitted close in angle to high en quarks

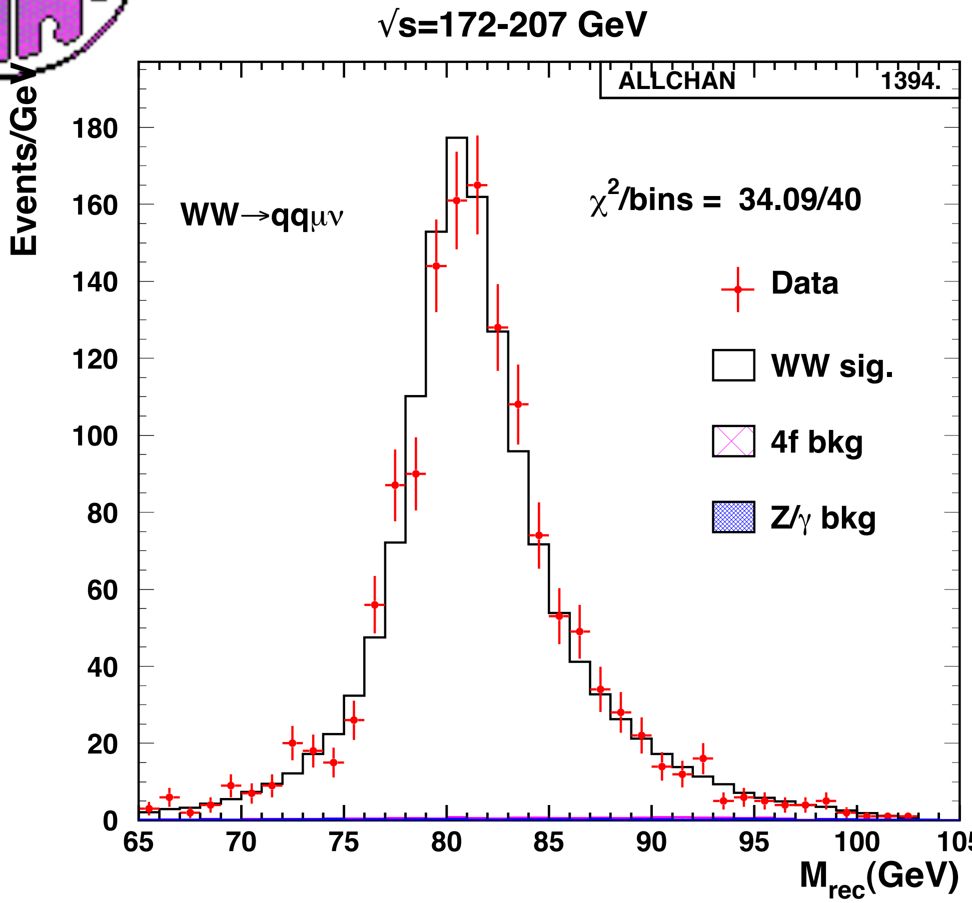
- Durham (KT)

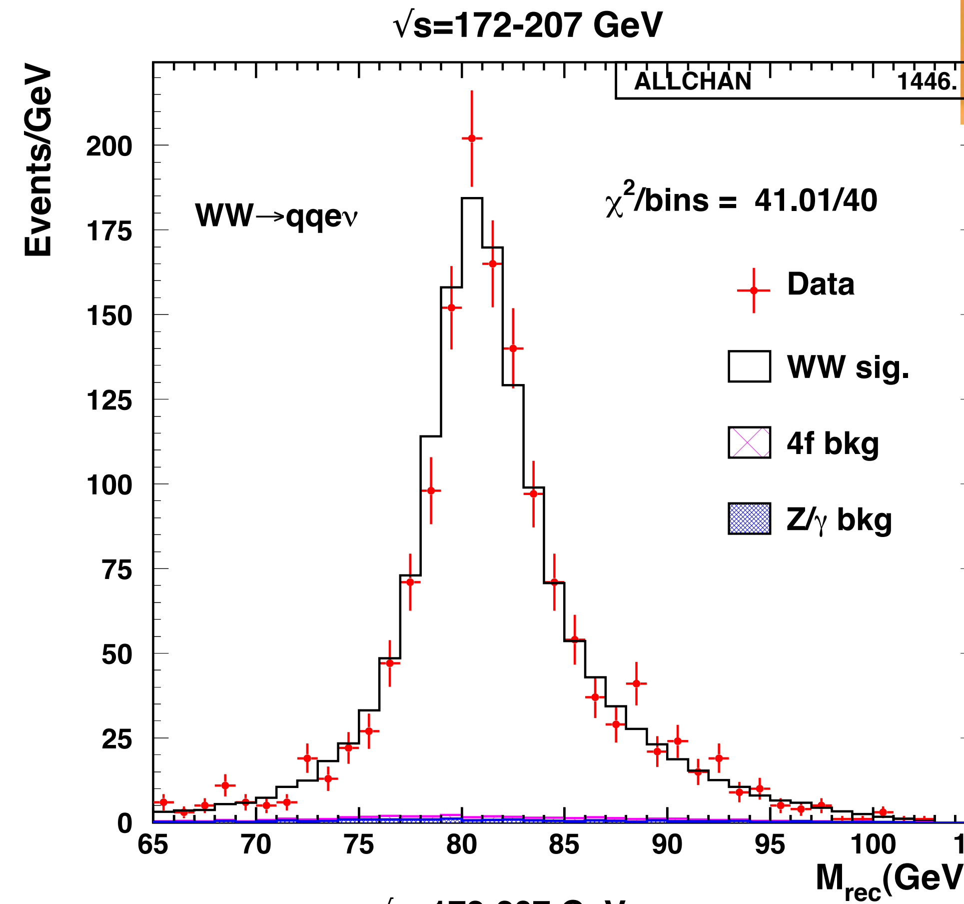
$$(M_T^2)_{ij} = 2\min(E_i^2, E_j^2)(1 - cos\,\theta_{ij})$$

$$y_{Dij} = \frac{(M_T^2)_{ij}}{s}$$

minimum kt of soft particle w.r.t. hard one in the small angle limit

W masses


√s=172-207 GeV
ALLCHAN
1394.
Events/GeV
WW→qqμν
χ2/bins = 34.09/40
Data
WW sig.
4f bkg
Z/γ bkg
0
20
40
60
80
100
120
140
160
180
65
70
75
80
85
90
95
100
105
Mrec(GeV)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1446.
Events/GeV
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χ2/bins = 41.01/40
Data
WW sig.
4f bkg
Z/γ bkg
0
25
50
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150
175
200
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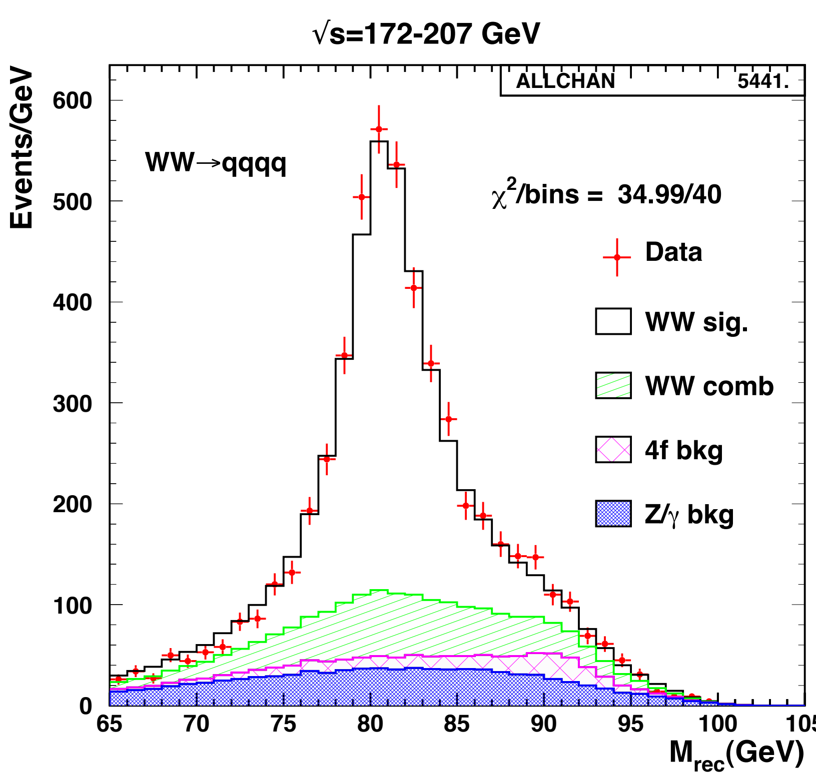
95
100
105
Mrec(GeV)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5441.
Events/GeV
WW→qqqq
χ2/bins = 34.99/40
Data
WW sig.
WW comb
4f bkg
Z/γ bkg
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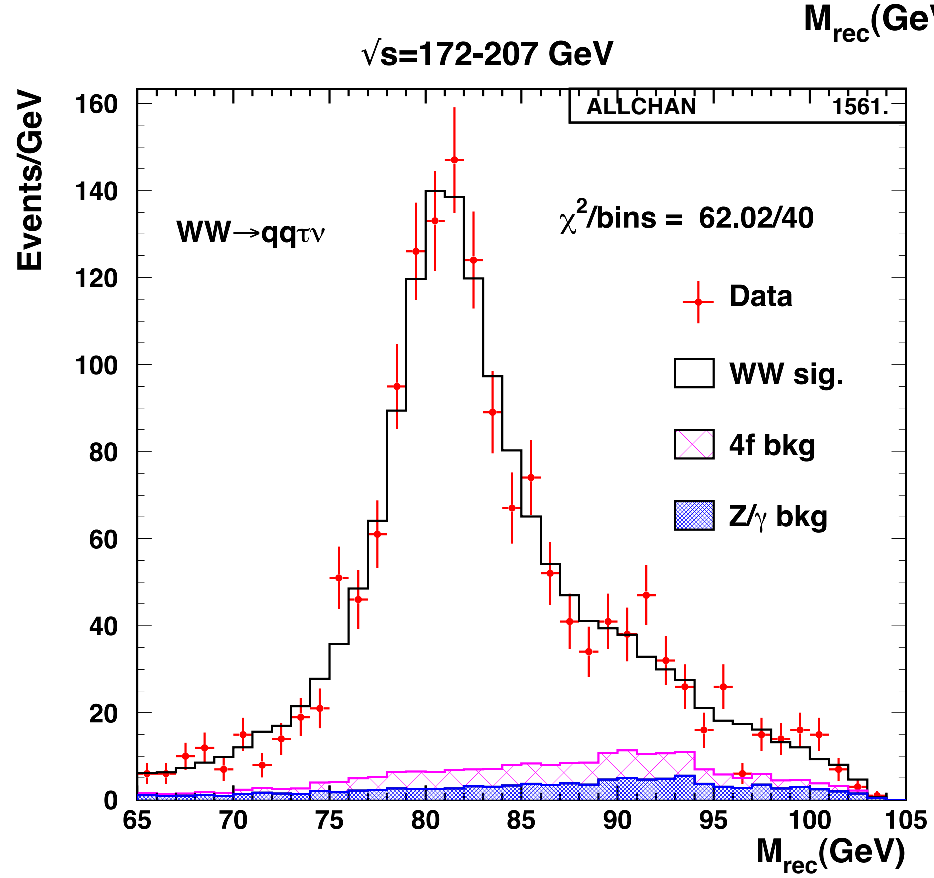
Mrec(GeV)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ALLCHAN
1561.
Events/GeV
WW→qqτν
χ2/bins = 62.02/40
Data
WW sig.
4f bkg
Z/γ bkg
0
20
40
60
80
100
120
140
160
65
70
75
80
85
90
95
100
105
Mrec(GeV)

Event reconstruction in qqqq channel (cont)

Assign jets to Ws with different algorithms

- **Reweighting** and Breit Wigner: **choose one assignment with**
  - **CC03 matrix element and multivariate discriminant (RW)**
  - Kinematic fit probability for 4j , multivariate discriminant for 5j (BW)

- Convolution : use all assignment. Neural Network to give weight to each assignment

RW

- Rec. 5 jets: 4C fit+ merge 2 "closest" jets (JADE) : 4jets →reduce combinatorial bkg
- Choose comb. with

Standard

- highest **CC03 Matrix El**
- If sum of di-jet angles is smallest, choose second-highest ME comb

p_{cut}

- **Highest lkl discr value**
  - CC03 Matrix El,
  - 4C mass diff.
  - sum of di-jet angles

Assign jets to Ws

Event reconstruction

RW

- Rec. 5 jets: 4C fit+ merge 2 "closer" jets : 4jets →reduce combinatorial bkg
- … mb. with

Standard

- highest **CC03 Matrix El**
- If sum of di-jet angles is smallest, choose second-highest ME comb

p_{cut}

- **Highest lkl discr value**
  - CC03 Matrix El,
  - 4C mass diff.
  - sum of di-jet angles

CV

- Rec. 5 jets : 4C fit+ energy ordering (using 4 jet)
- Discard 3 improb. combinations (W made from one split jet+ large energy imbalance)
- Evaluate 7 Mass differences by **Neural Network**: values from 0 (bkg) to 1 (signal).
- Keep all comb with NN value>threshold (most often 3 or 4)

BW

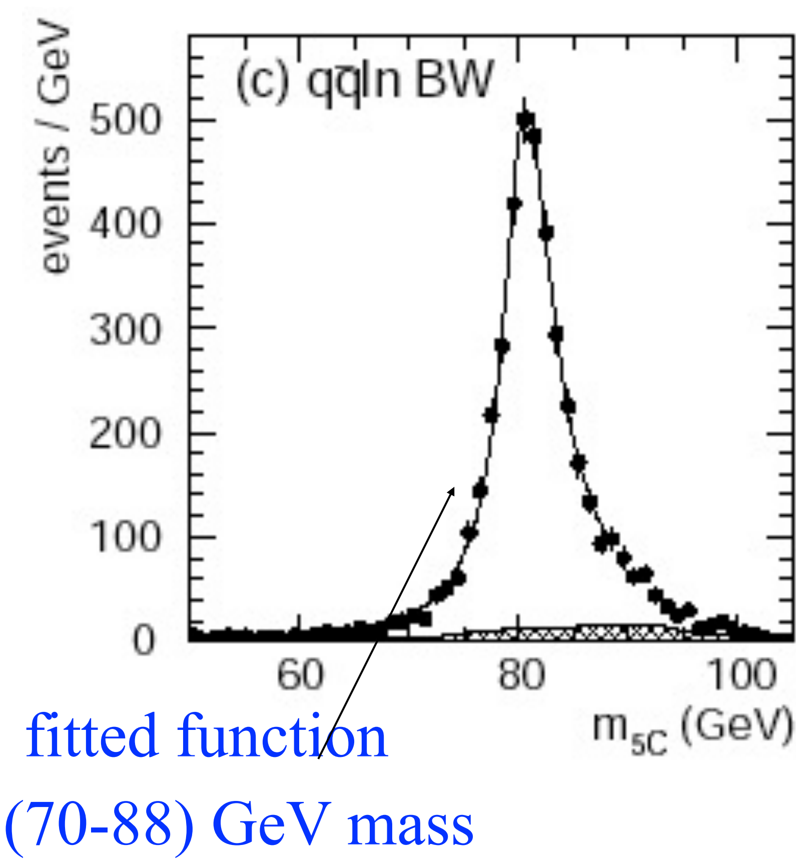
- Rec. 5jets: choose assignment with highest **pairing likelihood >thr**
  - M_W diff in 4C fit
  - Largest inter-jet opening angle in 3-jet system
  - Cosθ of 3-jet system
- 4jets: choose assign, with highest **5C kin fit prob** P(1) >$P_{t(h}$(+ 2[nd] highest P

P_{thr} varies for standard and p_{cut} analysis

Assign jets to Ws

Breit-Wigner

- Basic idea: Likelihood from empirical analytic function: asymmetric BW+ Background term (parameterize from MC)



- qqqq: BW→BW·Gaussian centred at m_W→better description of 5C mass shape
- Unbinned fit to mass distribution: 2C mass for qqlν and 5C mass for qqqq
- Derive bias corrections from MC

Robust and transparent cross-check

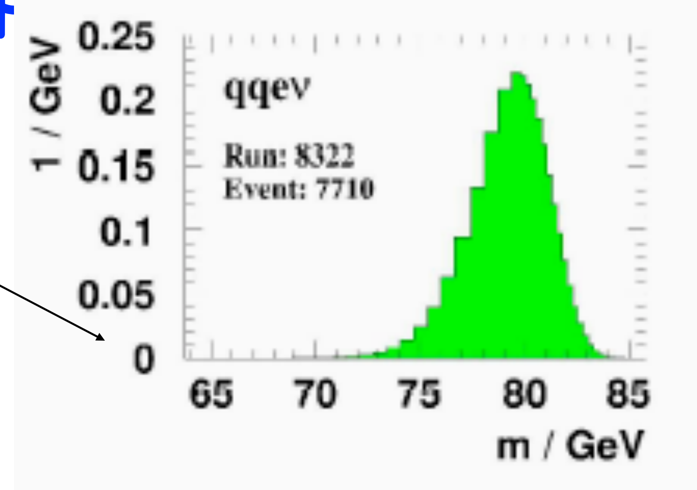
Convolution

Basic idea: likelihood from analytic function.

Bkg: parameterization from MC

Signal: physics function ⊗ detector response:

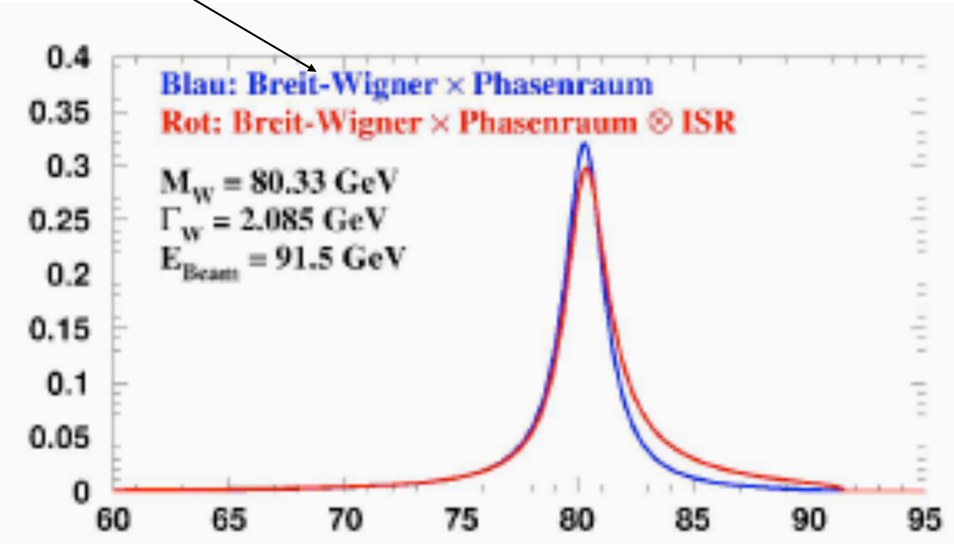
$$P(m_1,m_2|M_W,\Gamma_W)\otimes R(m_1,m_2)$$



- $R(m_1,m_2)$ on event-by-event basis from kin. fit. χ^2 :

  $$\exp\left(\chi_{min}^2-\chi^2(m_1,m_2)\right)$$

  - qqlν: neutrino→ less constraints →non gaussian shape; χ^2 mapped with 6C kin. fits (4-mom cons + fixed mass values)
  - qqqq: double Gaussian centred at (m_{1rec} ,m_{2rec}) from 4C kin fit x combinatorial bkg. parameterization. Likelihood : sum of selected jet assignments weighted with NN output.
- Unbinned likelihood fit



- Exploit all resolution info
- Statistically powerful

Combination : the example of M_W

- M_W is a linear combination of the results from fits to separate data sets

$$y^* = \sum_i y_i w_i \quad \text{with} \quad \sigma^2(y^*) = \sum_i (\sigma_i)^2$$

- Weights and errors ← y^* must be unbiased and have minimum variance

$$w_i = \frac{\sum_k (E^{-1})_{ik}}{\sum_i \sum_k (E^{-1})_{ik}} \qquad (\sigma^l)^2 = \sum_i \sum_k w_i\, w_k\, \sigma^{li}\, \sigma^{lk}\, \rho^{lik}$$

- E is covariance matrix with stat., syst. errors (k) and correlations ρ
  E is 9x9 ($\sqrt{s}$ comb) or 18x18 ($\sqrt{s}$ and chan. comb)

- Equivalent to minimizing $S = \sum_i \sum_k (y^* - y_i)(y^* - y_k)(E^{-1})_{ik}$
  where S_{min} is distributed as a χ^2 with n-1 degrees of freedom

Systematic Uncertainties Estimation

Monte Carlo data

Implement only the variation due to effect under study

Leave as is: default

Build N data-sized varied sub-samples

Build N data-sized default sub-samples

Do N varied fits for (M_W,Γ_W)

Do N default fits for (M_W,Γ_W)

$$(\text{varied} - \text{default}) = \left< \frac{\sum_i (X_i^{varied} - X_i^{default})}{N} \right>_{\sqrt{s}}$$

RMS of (v-d) estimates error

√s-averaged difference ("varied" - default) is taken as syst..

Many "varied"options (models) →take largest diff.

LEP Beam Energy

Kinematic fit: energy scale from E_{beam} ⟹ $\delta M_W/M_W \sim \delta E_{beam}/E_{beam}$

E_{beam} ($\sqrt{s} = 2E_{beam}$) measured by

LEP (directly) : average over 3 different check methods to reduce syst. uncertanties

Experiments (indirectly) : from physics events

All results:

consistent

Uncertainty for each data set (from LEP):

δE_{beam} = 10 to 20 MeV

correlation matrix used in M_W and Γ_W combination

Obtain shift as "use kin fit($E_{beam}+\delta E_{beam}$)" – "use kin fit (E_{beam})" →

δM_W = 9 MeV, $\delta\Gamma_W$ = 3 MeV

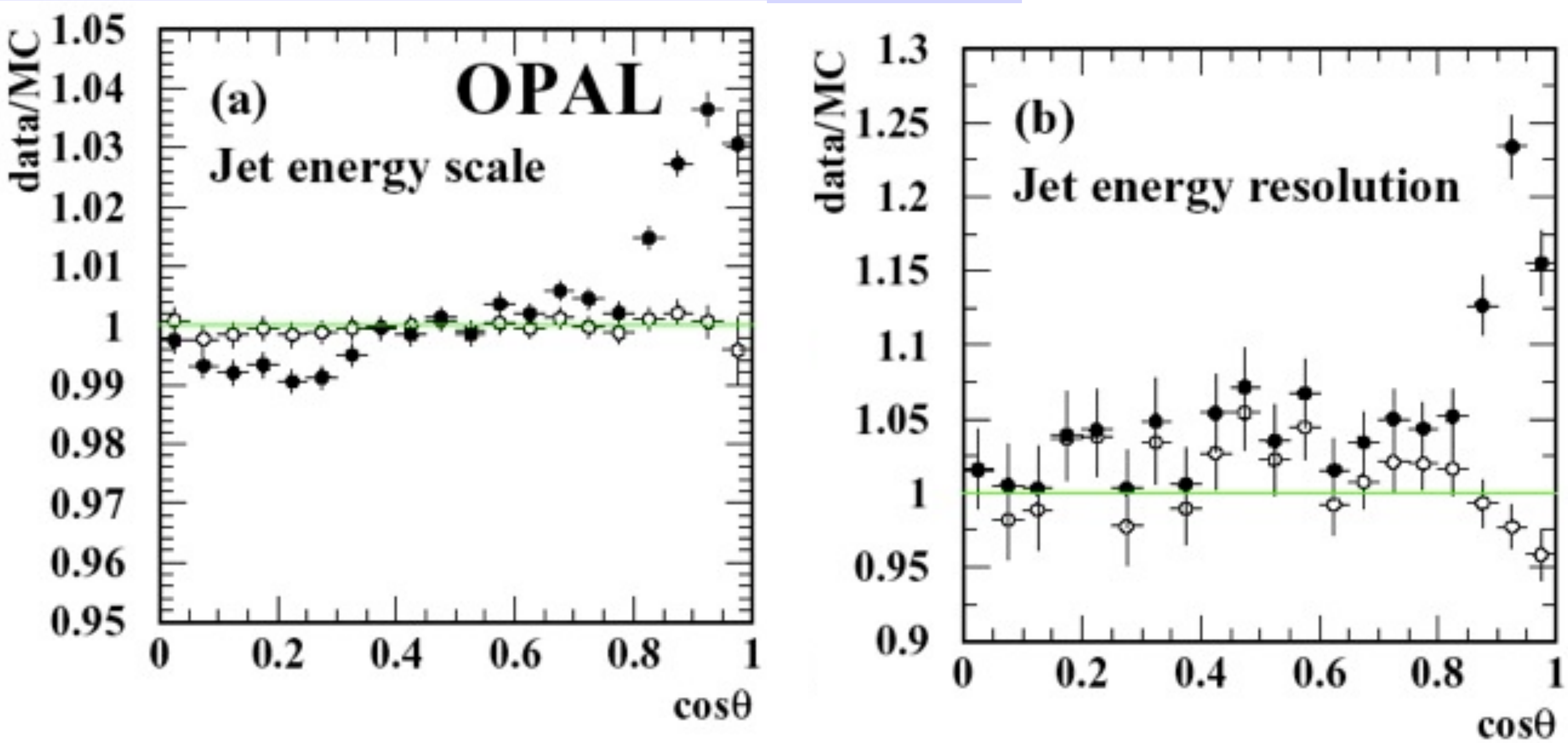
Detector Modelling

Direct reconstruction is sensitive to detector modelling→

Use samples of $e^+e^- \to Z^0$ @Ecm=91.2 (taken year-by-year ∫Ldt~13 pb^{-1} for inst. ~400k Z→had) to calibrate

energy scale, resolution and linearity, angular scale and resolution for leptons and jets, mass scale for jets

Use uncertainties to shift calibrations →
"calib+δ(calib)" - "calib." → δM_W = 20 MeV , $\delta\Gamma_W$=24 MeV



Dominant effects

- For M_W :jet mass and lepton en scale (qqlv)/jet angular bias (qqqq)
- For Γ_W jet and lepton en.res

Higher Order Corrections

Incomplete description of EWK corrections → imperfection in probability shape → δM_w, $\delta\Gamma_W$

- KoralW (Monte Carlo generator for $e^+e^- \rightarrow 4f$) used in the analysis
- Cross check with KandY (KoralW and YFSWW) : improved treatment of photon radiation and photon exchange between Ws

Syst. shifts estimated with KandY : switch on-off improved corrections w.r.t. KoralW and sum in quadrature.
(Use OPAL $\sigma(WW\gamma)$ to constrain shift from photon radiation effects)

δM_W= 10 MeV
$\delta\Gamma_W$ = 11 MeV

Hadronization

Quark→hadrons: not understood mechanism → modelling → δM_W , $\delta\Gamma_W$

Use hadronisation models tuned at Z^0

JETSET (JT): Lund string model

HERWIG (HW): singlet cluster model

Different baryon and kaon rates in models explain part of δM_W → re-weight other MC to JT (def.) ⇒ Residual Largest shift (model – JT): genuine had.

JT baryon/kaon rates different from PDG →apply correction to M_W, ⇒ Syst: error on JT corr.

δM_w = (genuine had err) ⊕ (error on JT corr) = 16 MeV

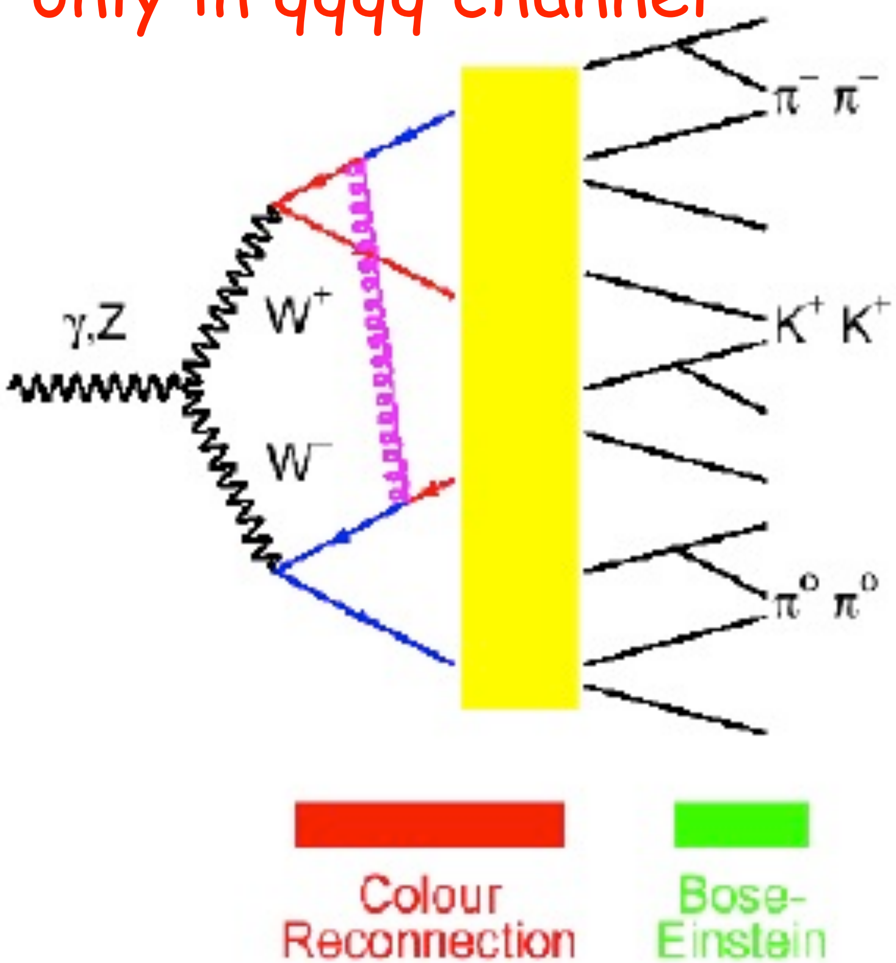
$\delta\Gamma_W$ = largest shift (model –JT) (b/k rates not useful) =74 MeV

Final State Interactions

- $1/\Gamma_W \sim 0.1$ fm « $l_{had} \sim 1$ fm →two (colour singlet) with significant space-time overlap→ possible interaction of final products
- Effect not simulated in Monte Carlo→ possible mass/ width bias only in qqqq channel

Colour Reconnection

- Colour cross-talk between Ws: bias in qqqq but not qqlv .



Bose-Einstein Corrrelations

- QM interference → Momentum space correlation of bosons pairs from **different** W (inter-W) decays: **bias qqqq only**
- Established in Z^0 decays

Colour Reconnection

$\delta M_W, \delta\Gamma_W$ = largest (CR – no CR) shift in different models

Sjostrand-Khoze models (I,II,II'): variable CR strength

HERWIG

ARIADNE

Model	δM_W^{4q}(MeV)	$\delta\Gamma_W^{4q}$(MeV)
Herwig	40	27
Ariadne	66	128
SKI(p_{rec}=58%)	**125**	**150**

p_{rec} = CR probability ← CR strength

Particle Flow technique

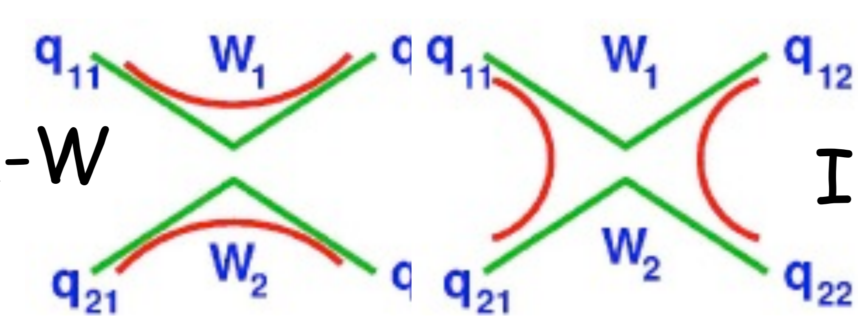
Measure ratio of particle densities in intra- and inter- W planes : sensitive to CR

OPAL PF analysis sets 68% CL upper limit on CR strength in SKI model (p_{rec}< 56%)→ Data Driven $\delta\Gamma_W$ and δM_W for SKI

Final step

Desensitize analysis to CR effects

Intra-W



Inter-W

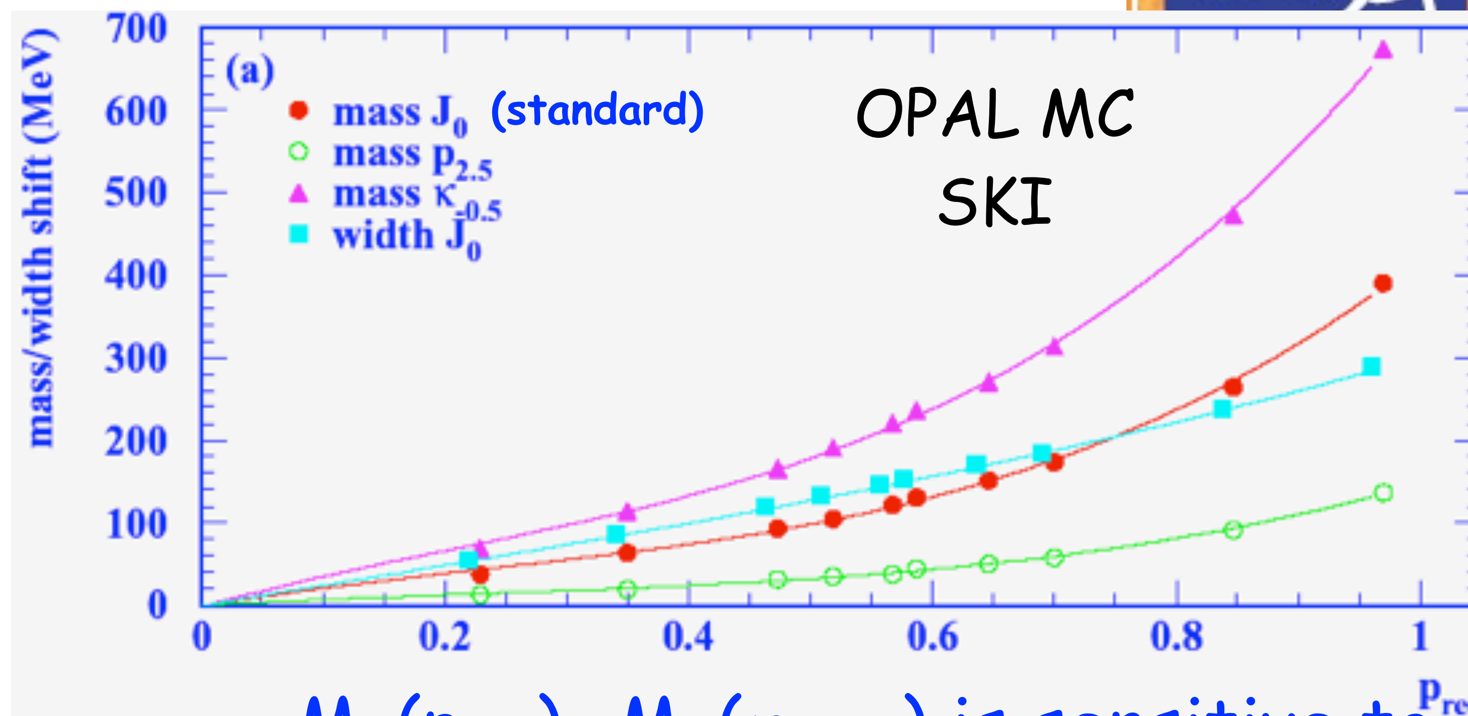
Colour Reconnection (cont)

CR affects mostly soft particles between jets ⇒ changes jet direction

Re-calculate jet dir. from particles:

1. with momentum P larger than P_{thr}
2. by weighted momentum vector sum (weight = $|P|^{\kappa}$)
3. within cone of radius R

Use P_{thr}=2.5 GeV for M_W only (best stat-syst compr). Standard analysis is best for Γ_W.



$M_W(p_{2.5})$- $M_W(\kappa_{-0.5})$ is sensitive to CR → measure in data→ combine with particle flow : Combined 68%CL upper limit on CR strength in SKI (p_{rec}< 58%)

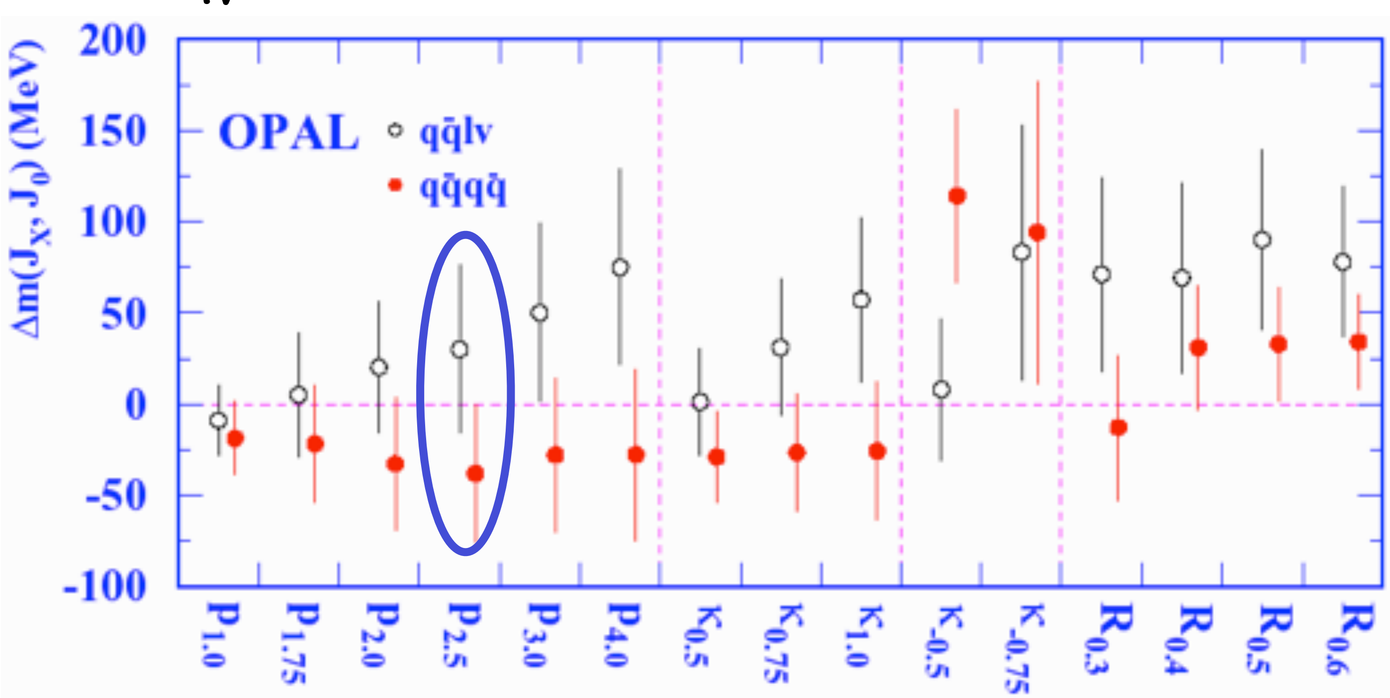
δM_W^{CR} : 125 → 41 MeV

δM_W^{stat} : 51 → 60 MeV

Total δM_W improves:

142 MeV→ 83 MeV

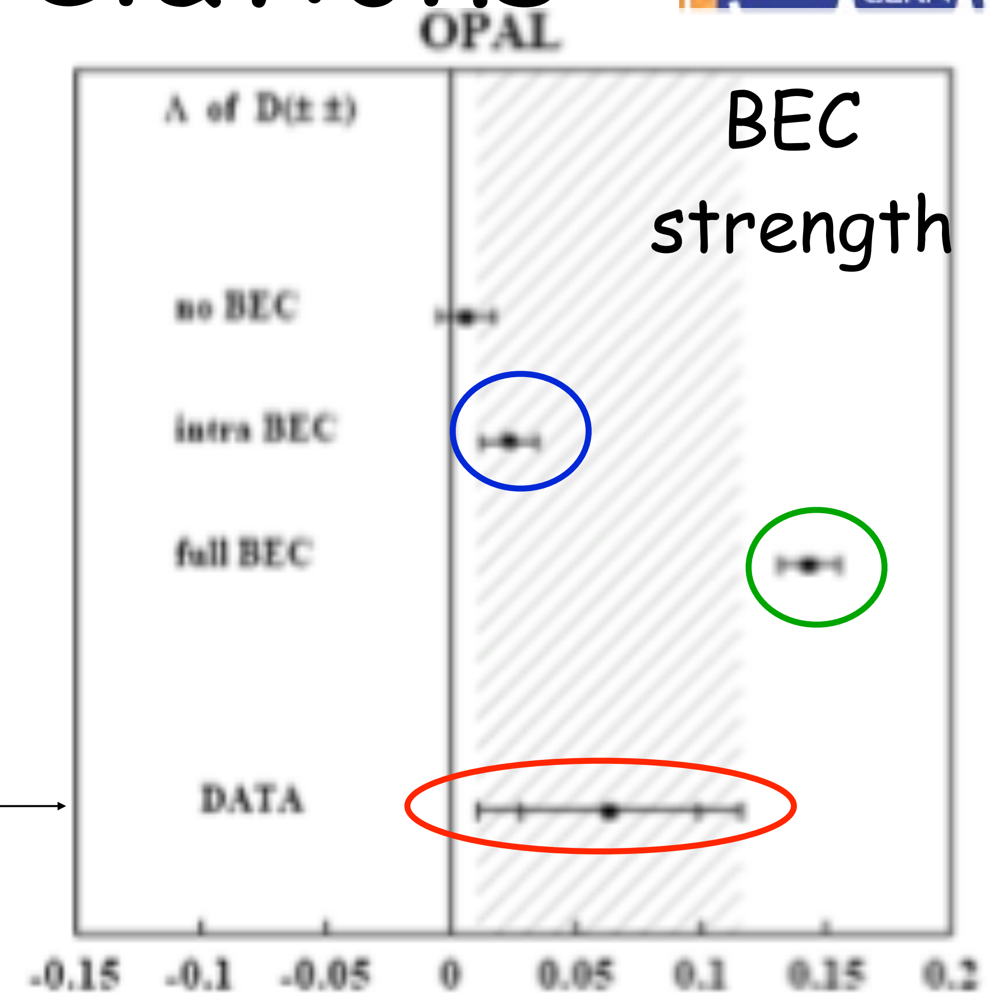
$\delta\Gamma_W^{CR}$ = 151 MeV



Bose Einstein Correlations

Use LUBOEI model tuned to BEC in Z^0 decays:

- obtain shift in (M_W,Γ_W) from samples "with" (full BEC)- "without" (intra BEC) BEC between Ws.
- M_W shift: 40 MeV (std) →~24 MeV (P_{cut}).



BEC investigated at OPAL : No evidence for BEC between Ws as predicted by LUBOEI

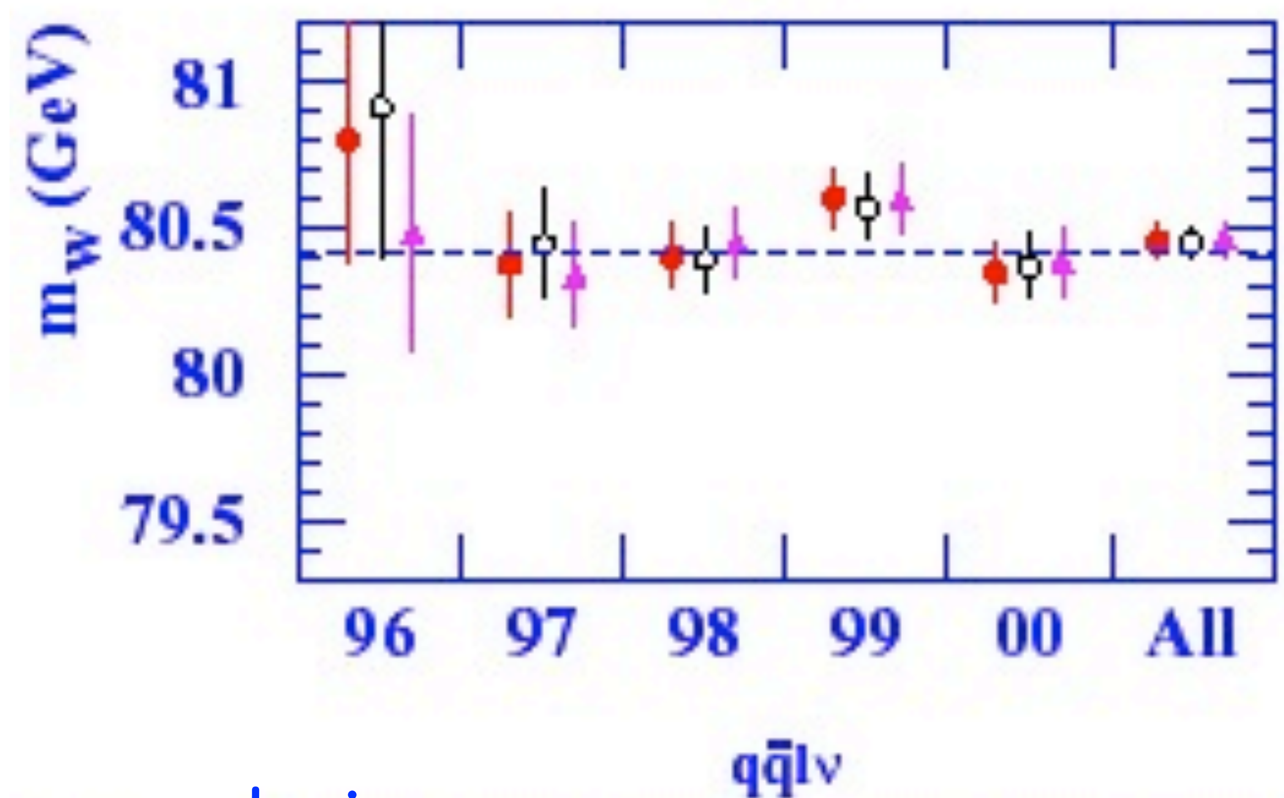
Determine the Fraction of the model: Percentage of LUBOEI inter-W corr. allowed by data (**Linear in** δM_W from LEP studies)

$$\frac{\text{Data-model(intra)}}{\text{model(full)-model(intra)}}$$

OPAL FoM = 0.33±0.45

Use OPAL 1σ limit on FoM : take 0.77 of the shifts in M_w and Γ_W→ δM_W ~ 35 MeV (std) →19 MeV (P_{cut}); $\delta\Gamma_W$~32 MeV

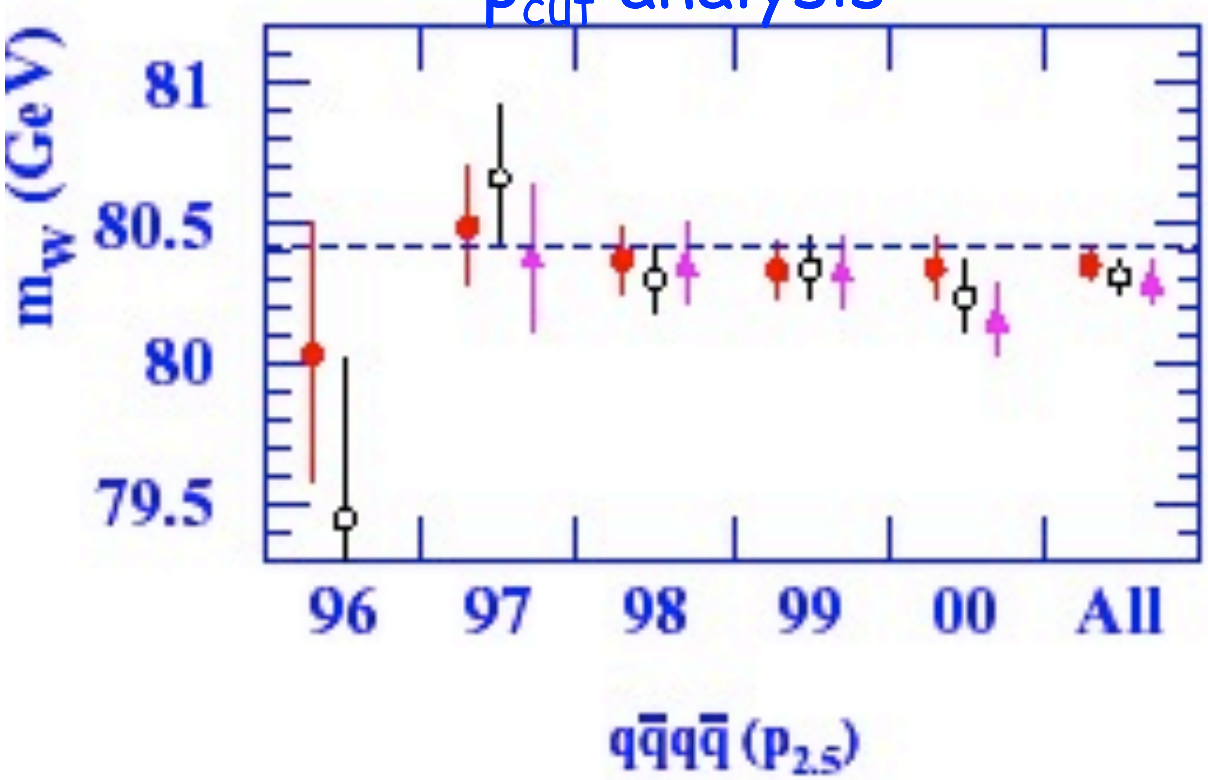
Results for M_W



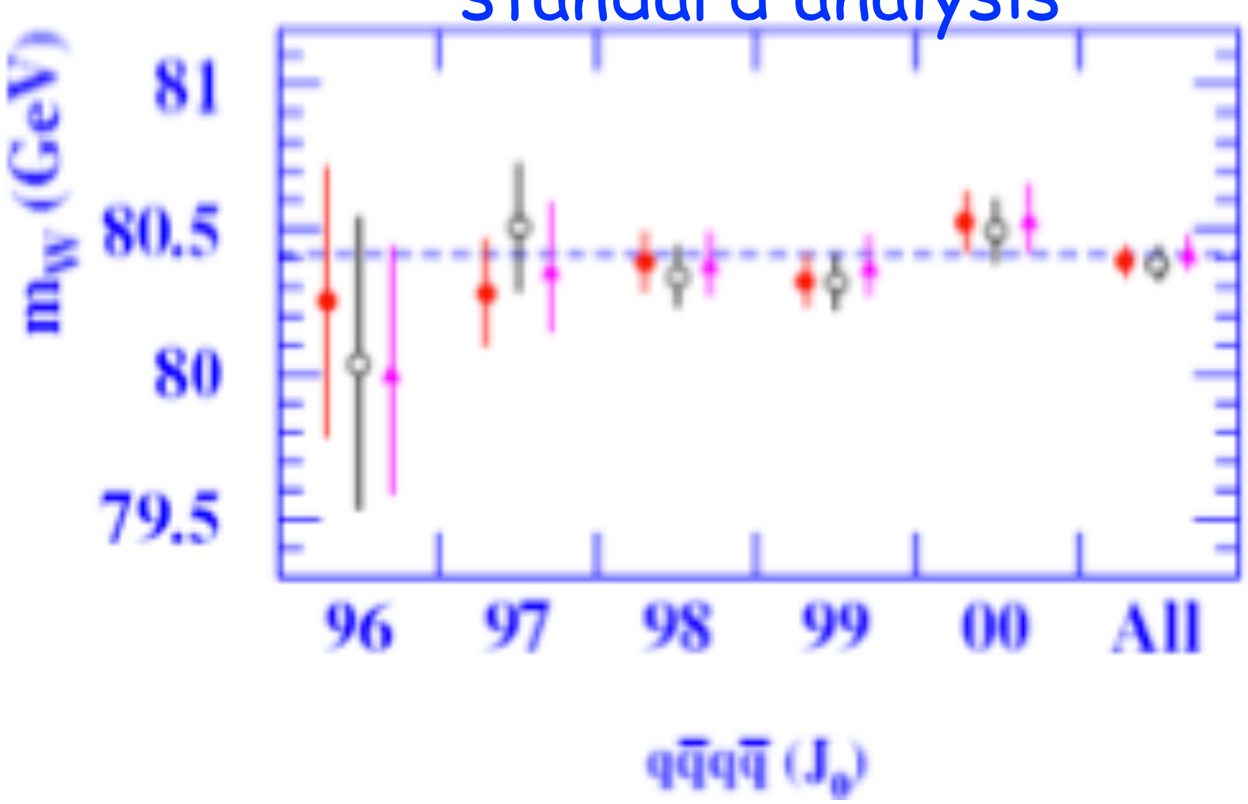
OPAL
• CV ∘ RW ▲ BW

- Very good stability and agreement over data samples and channels

p_{cut} analysis

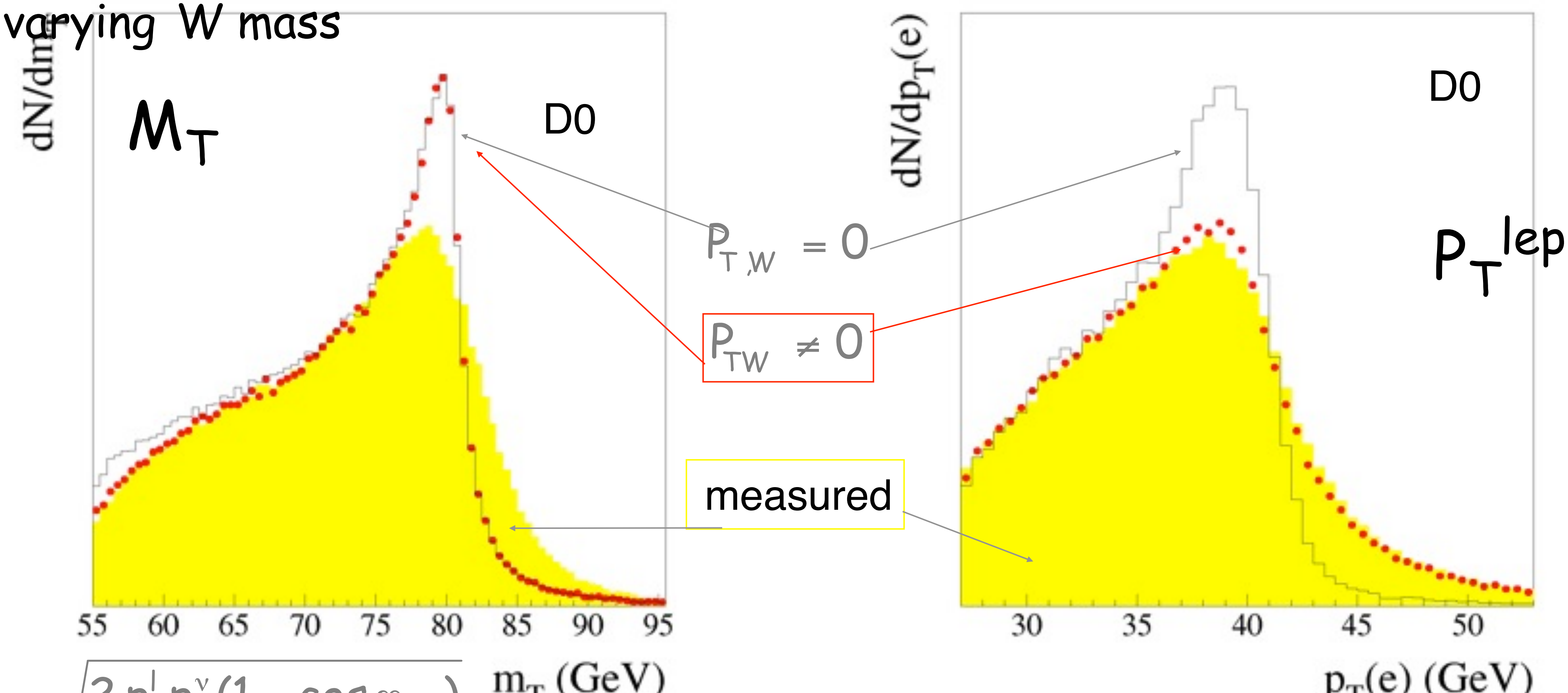


standard analysis



W-mass extraction in $W \to l\nu$

- M_W-sensitive variables:
  - Tranverse mass $M_T = \sqrt{(2 p_T^l p_T^\nu (1 - \cos\theta))}$ (mostly used)
  - Transverse lepton momentum p_T
  - Transverse missing energy
- Use maximum likelihood fit to data. Likelihood built from templates with varying W mass



$$M_T = \sqrt{2 p_T^l p_T^\nu (1 - \cos\varphi_{l\nu})}$$

Sensitive to detector hadronic response and to multiple-interactions etc.
Insensitive to $P_{T,W}$ at Tevatron
…but residual sensitivity at LHC

Insensitive to detector hadronic response
Need correct model for $P_{T,W}$

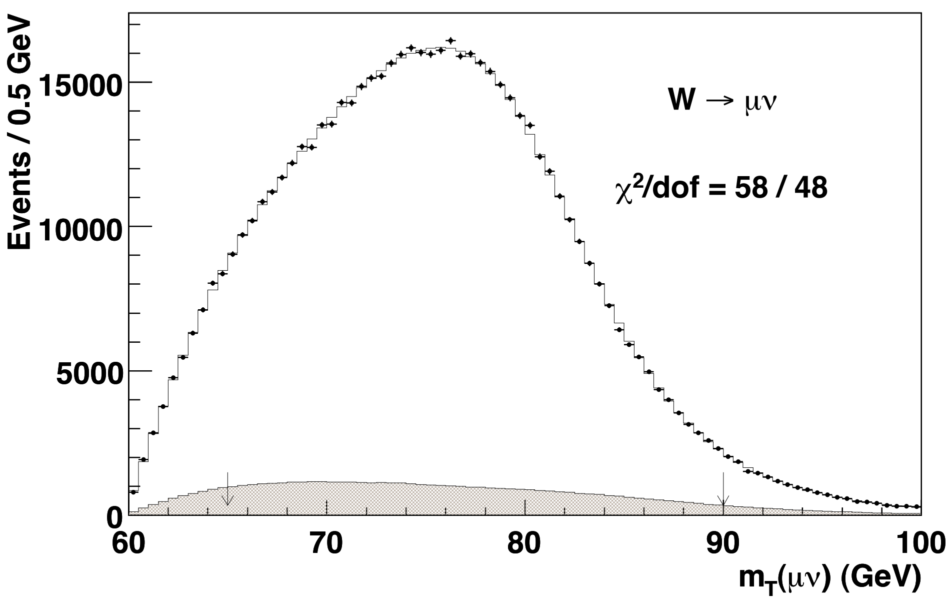
-> need to understand soft hadron production
-> missing higher orders of QCD corrections

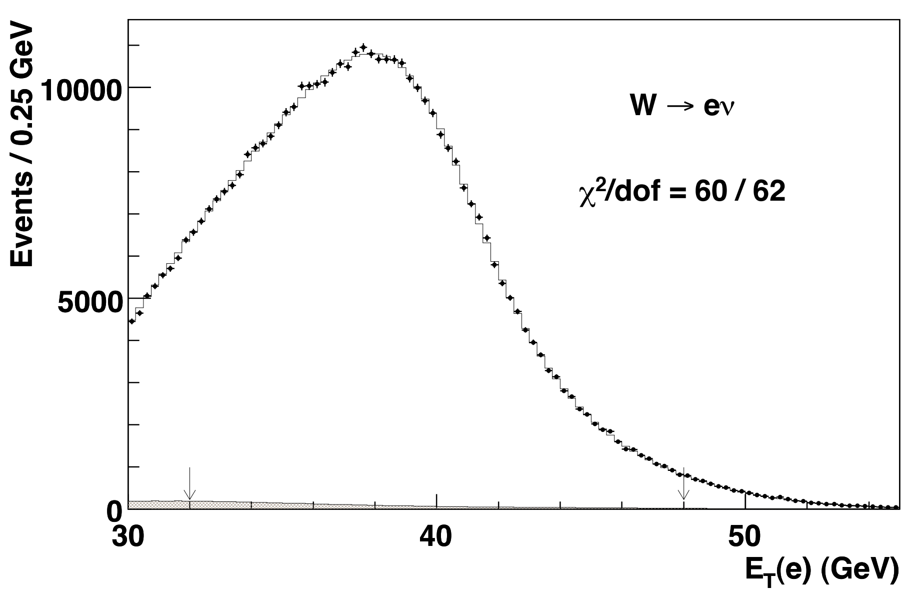
CDF's most precise W mass measurement

http://arxiv.org/abs/1203.0275 2.2 /fb

- Template fits to 6 distrib, combine with belt linear estimator including correl (70% between m_T and p_T, ~30% between p_T^{neu} p_T^{lep})

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





Distribution	W-boson mass (MeV)	χ^2/dof
$m_T(e,\nu)$	$80\ 408 \pm 19_{\rm stat} \pm 18_{\rm syst}$	52/48
$p_T^\ell(e)$	$80\ 393 \pm 21_{\rm stat} \pm 19_{\rm syst}$	60/62
$p_T^\nu(e)$	$80\ 431 \pm 25_{\rm stat} \pm 22_{\rm syst}$	71/62
$m_T(\mu,\nu)$	$80\ 379 \pm 16_{\rm stat} \pm 16_{\rm syst}$	58/48
$p_T^\ell(\mu)$	$80\ 348 \pm 18_{\rm stat} \pm 18_{\rm syst}$	54/62
$p_T^\nu(\mu)$	$80\ 406 \pm 22_{\rm stat} \pm 20_{\rm syst}$	79/62

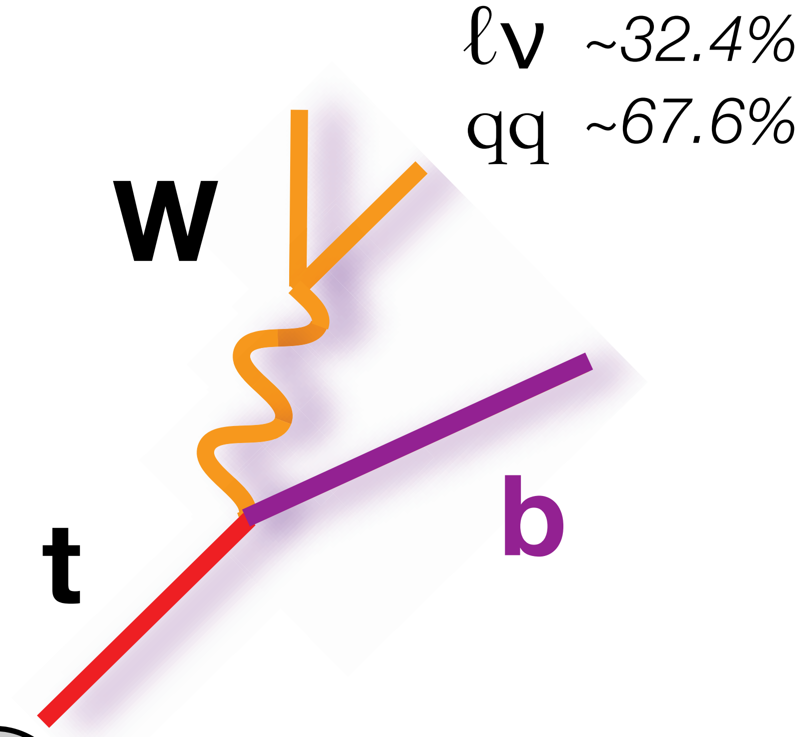
Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal	2
Backgrounds	3
$p_T(W)$ model	5
Parton distributions	10
QED radiation	4
W-boson statistics	12
Total	19

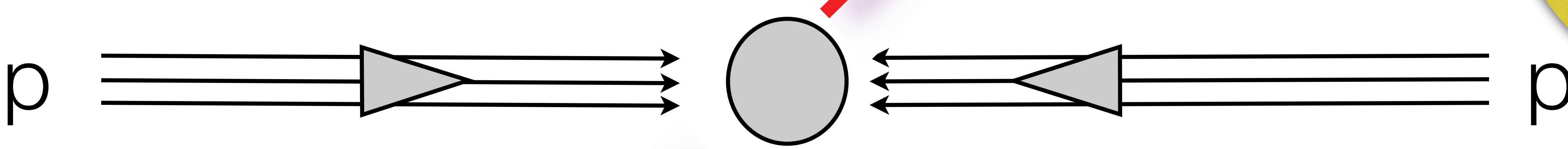
TABLE II: Uncertainties for the final combined result on M_W.

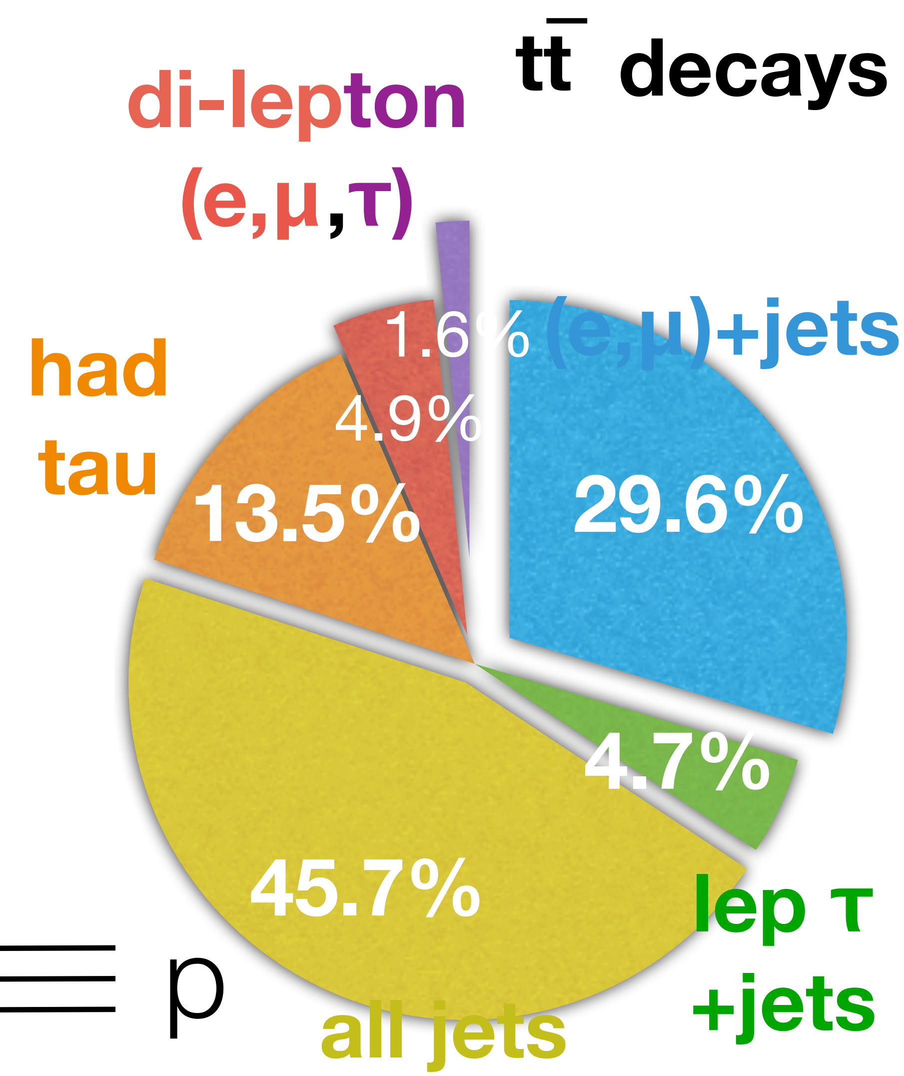
$$M_W = 80\ 387 \pm 12_{\rm stat} \pm 15_{\rm syst} = 80\ 387 \pm 19\ \mathrm{MeV}/c^2.$$

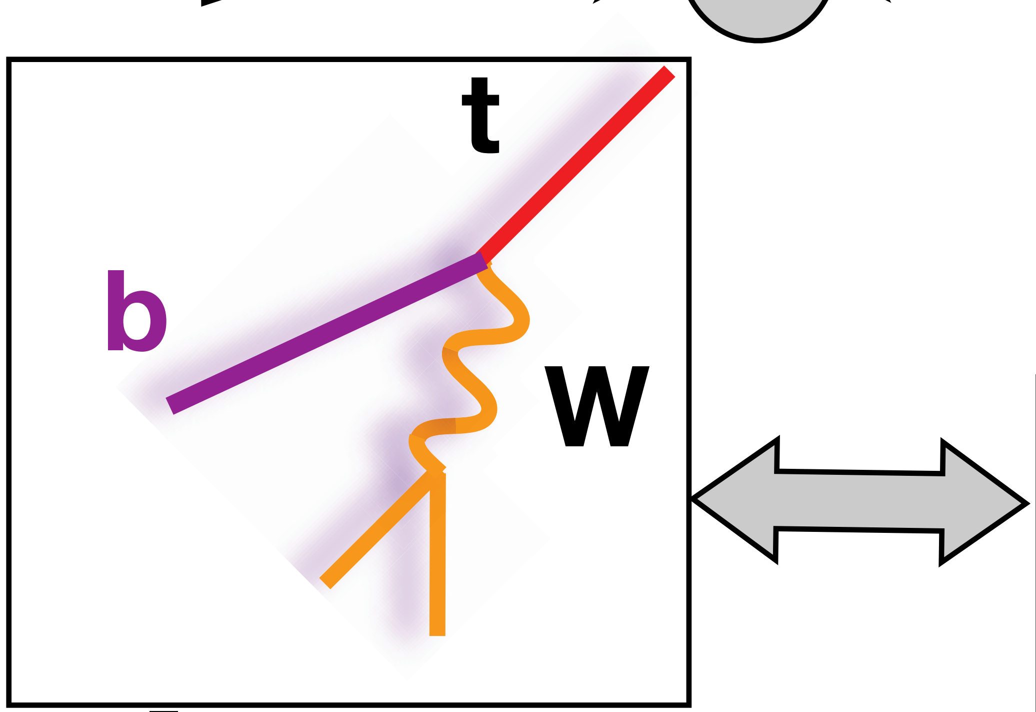
Top signatures

- High P_T jets
- b-jets
- 1 to 2 high P_T leptons
- Missing energy



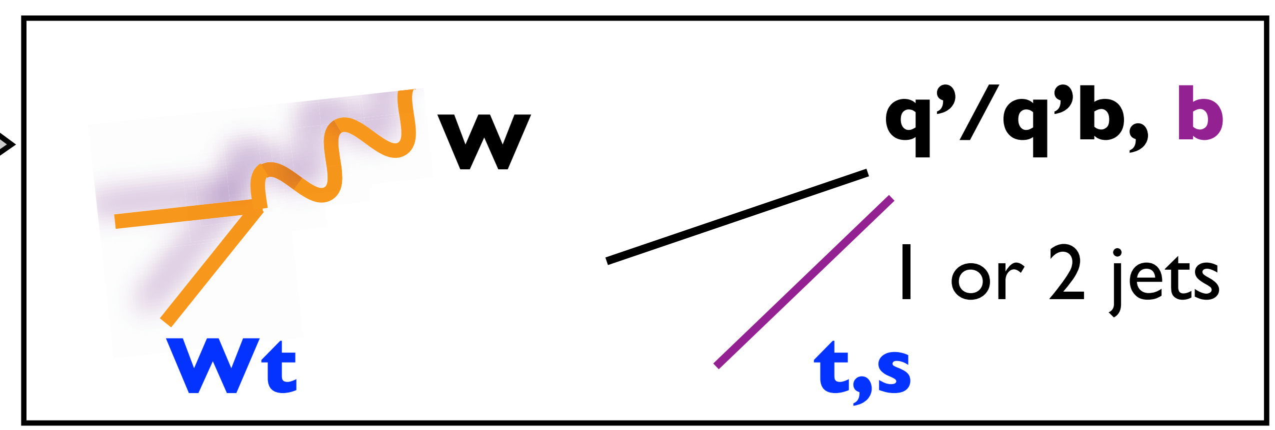






bkgs_tt̄: W/Z(+jets), single top, QCD, Di-bosons

single top



bkgs_single_t: tt +some bkgs_tt

Event reconstruction in qqqq channel (cont)

Assign jets to Ws with different algorithms

- Reweighting and Breit Wigner: choose one assignment with
  - CC03 matrix element and multivariate discriminant (RW)
  - Kinematic fit probability for 4j , multivariate discriminant for 5j (BW)
- Convolution : use all assignment. Neural Network to give weight to each assignment

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RW

- Rec. 5 jets: 4C fit+ merge 2 "closest" jets (JADE) : 4jets →reduce combinatorial bkg
- Choose comb. with

Standard

- highest CC03 Matrix El
- If sum of di-jet angles is smallest, choose second-highest ME comb

p_{cut}

- Highest lkl discr value
  - CC03 Matrix El,
  - 4C mass diff.
  - sum of di-jet angles

Assign jets to Ws