Tevatron experience: physics modelling choices

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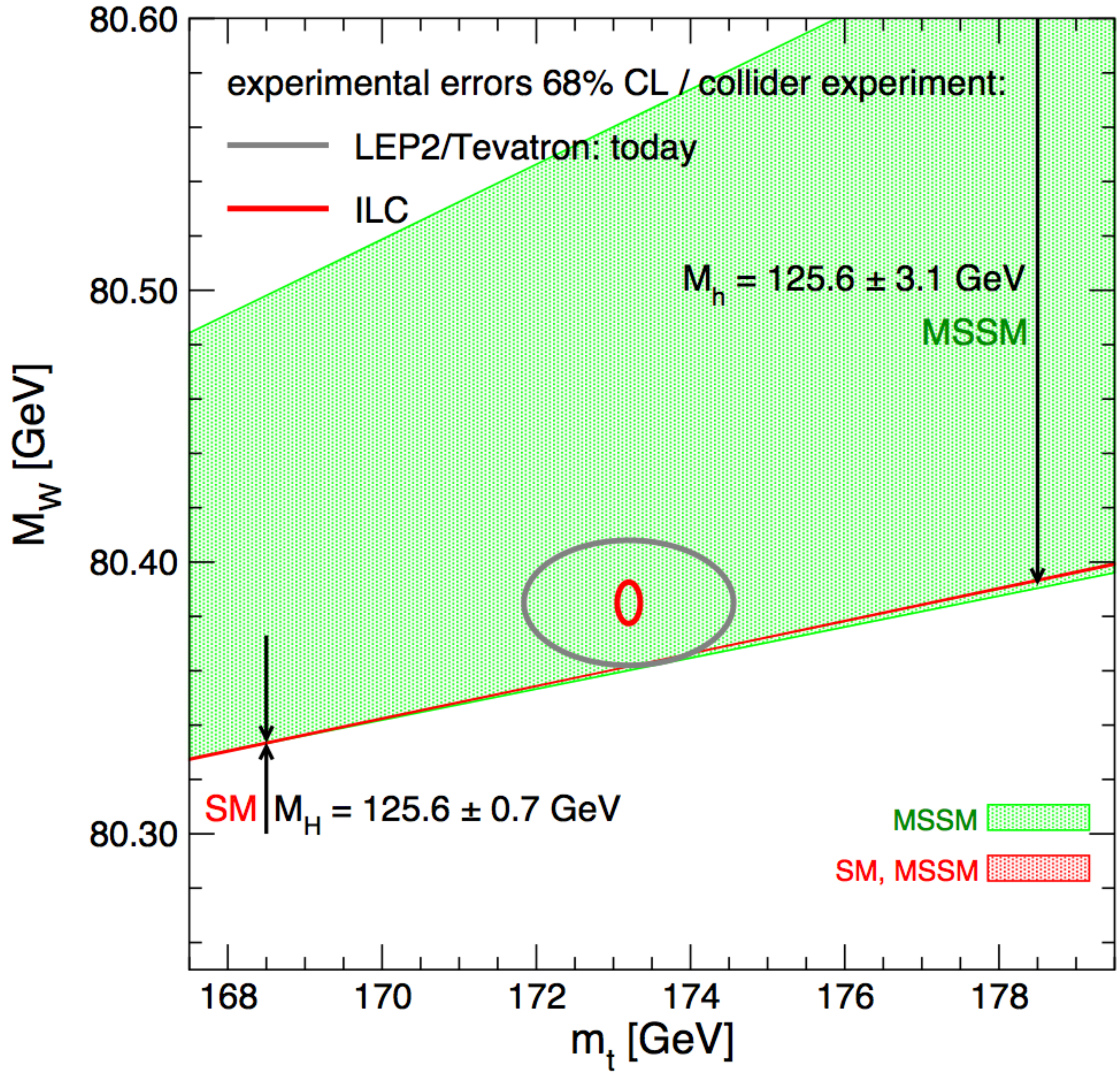
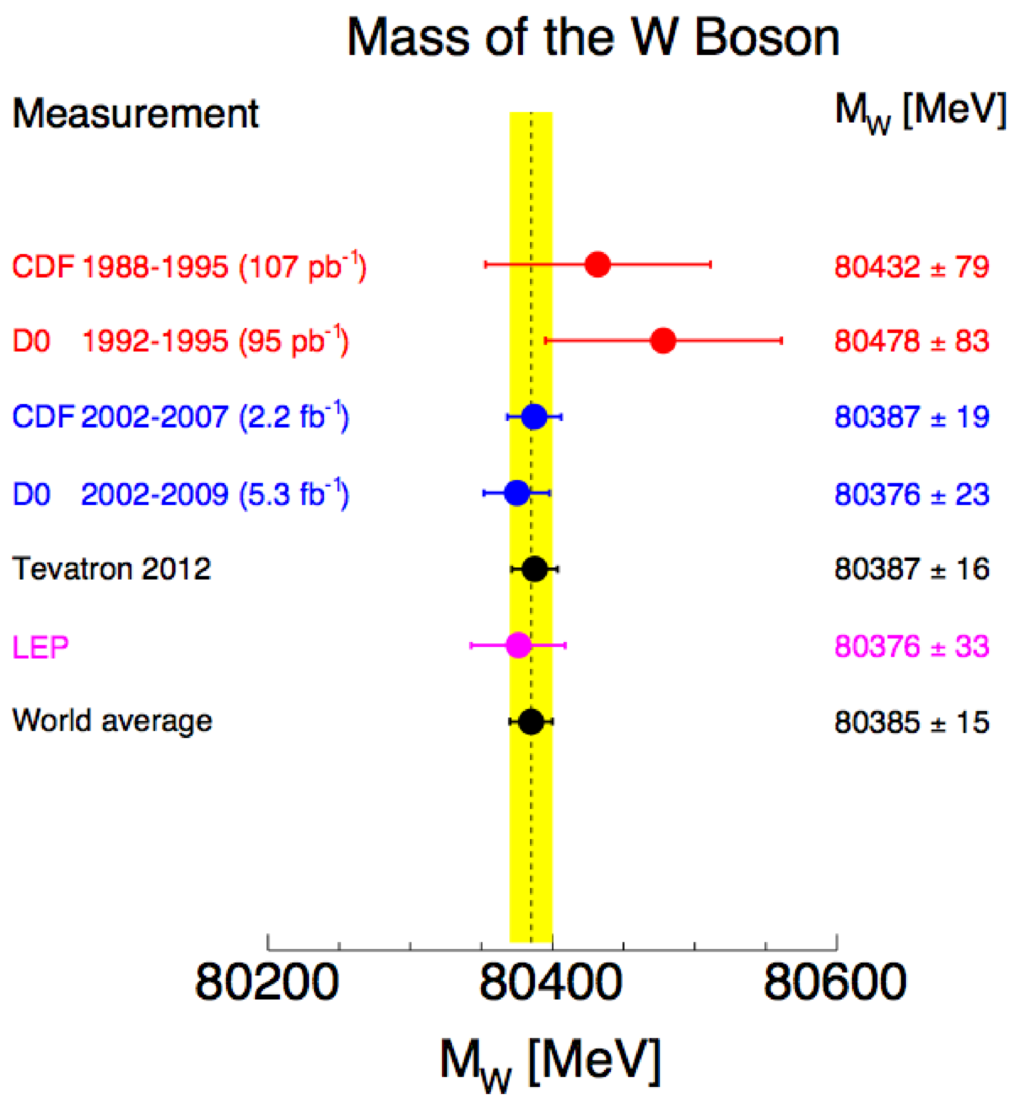
First joint exp+theo meeting on m(W) measurements at the LHC,
October 20-21, 2014, Firenze

Motivation



Heinemeyer, Hollik, Weiglein and Zeune, arXiv:1311.1663 [Nov. 2013]

Current state of the art



Phys. Rev. **D88**, 052018 (2013)

DØ: current uncertainties and projections

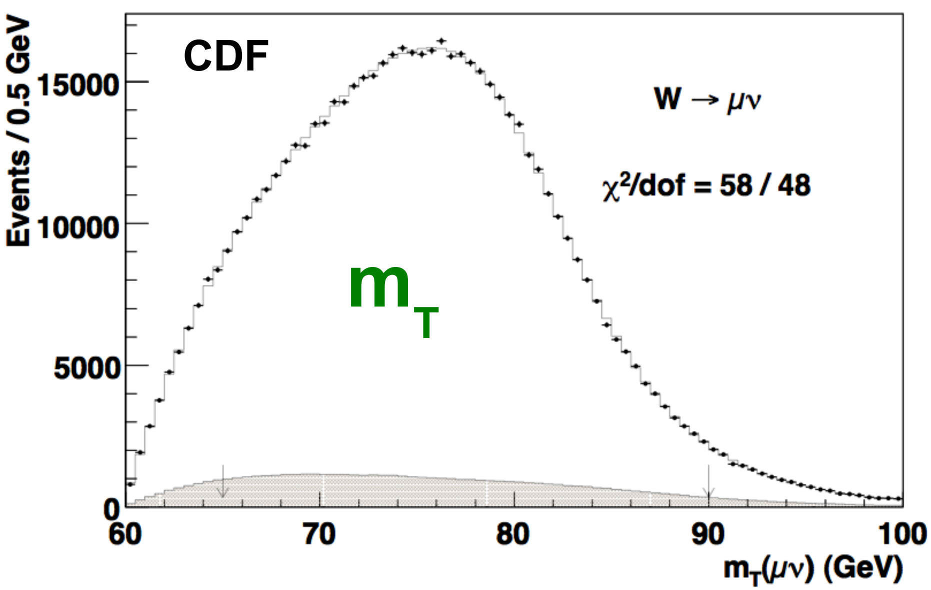
Source	Public. 2009 (1.0 fb^{-1})	Public. 2012 (4.3 fb^{-1})	Proj. 10 fb^{-1}	Proj. 10 fb^{-1} $\boxed{\text{improv.}}$	Proj. 10 fb^{-1} improv. + $\boxed{\text{EC}}$
Statistical	23	13	9	9	8
Experimental syst.					
Electron energy scale	34	16	11	11	10
Electron energy resolution	2	2	2	2	2
EM shower model	4	4	4	$\boxed{2}$	2
Electron energy loss	4	4	4	$\boxed{2}$	2
Hadronic recoil	6	5	3	3	2
Electron ID efficiency	5	1	1	1	1
Backgrounds	2	2	2	2	2
Subtotal experimental syst.	35	18	13	12	11
***W* production and decay model**					
PDF	9	11	11	11	$\boxed{5}$
QED	7	7	7	$\boxed{3}$	3
boson p_T	2	2	2	2	2
Subtotal W model	12	13	13	12	6
Total systematic uncert.	37	22	19	17	13
Total	**44**	**26**	**21**	**19**	$\boxed{\mathbf{15}}$

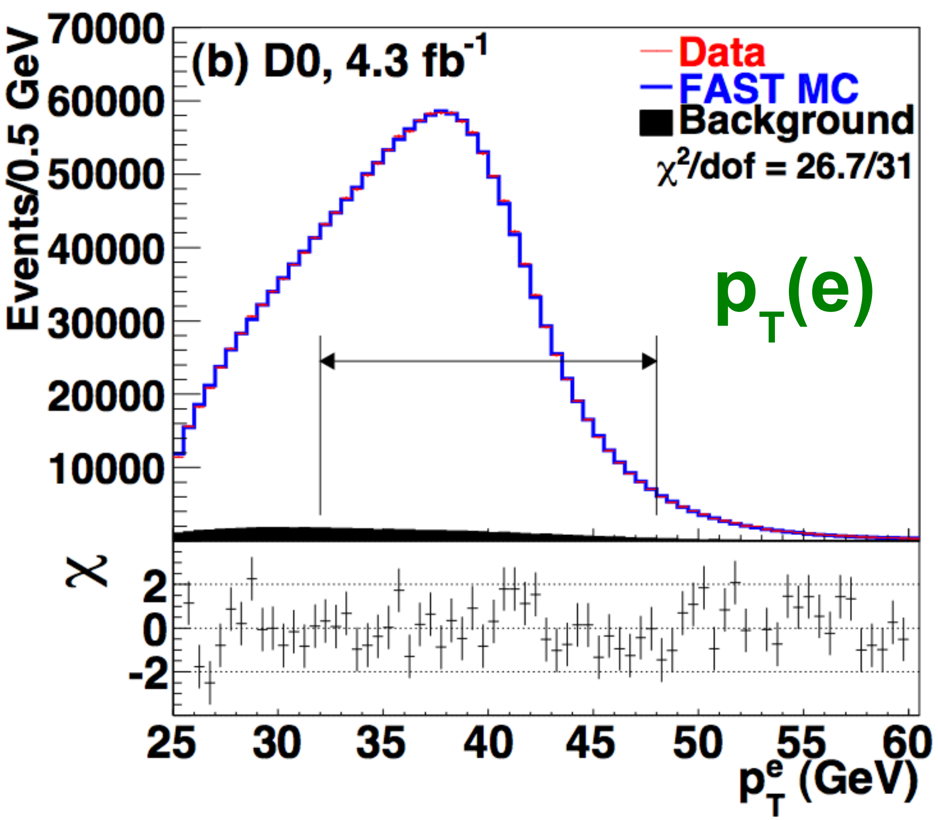
combination: 23

Fits for m(W)

In practice, the measurement of m(W) is extracted from shape fits like the ones below.
We have three observables that are sensitive to the mass: m_T, $p_T(l)$ and missing E_T.

CDF: electron and muon channels. DØ: electron channel only.





Theory; event generators

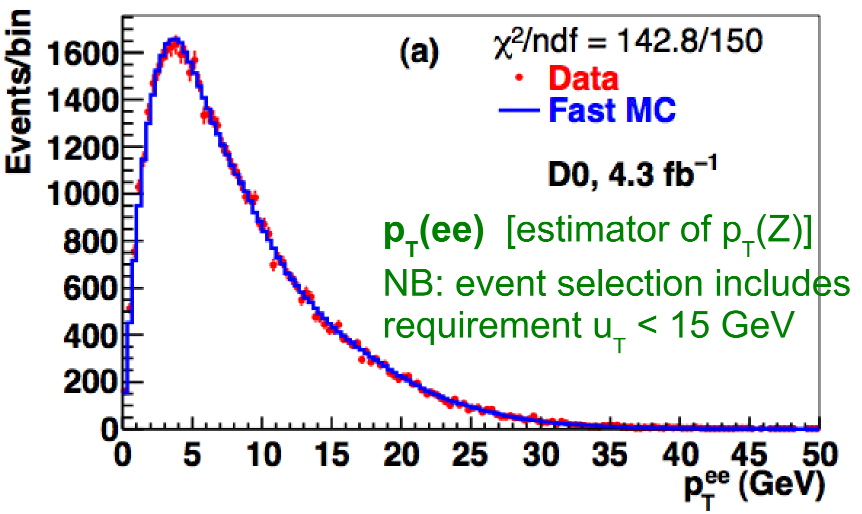
So, what do we need from theory ?

We need an event generator that – for a given value of m(W) – can predict the shape of the distributions of the observables that we use to extract m(W).

This needs to be an "event generator", because the generated events can then be fed to the detector simulation to take into account resolutions, reconstruction efficiencies, cuts.

This event generator needs to simulate W → e nu (signal) and Z → l l (calibration channel).

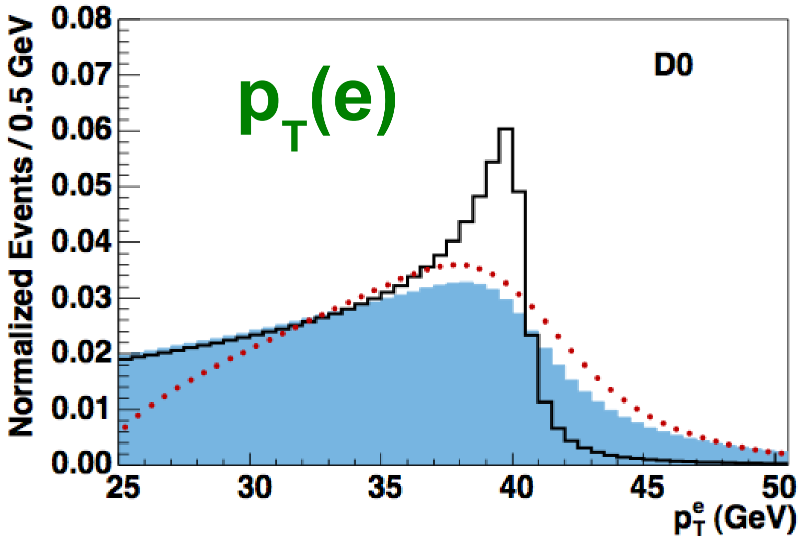
We are interested in the events at low $p_T(Z)$ and $p_T(W)$ … this is where the bulk of the events is anyway, and we further suppress the high-p_T tail using a cut on the hadronic activity recoiling against the vector boson.

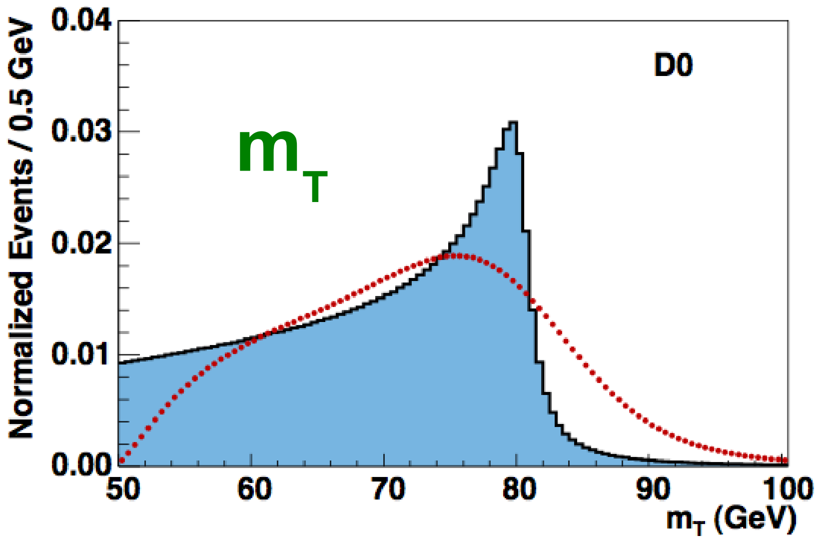


The "ideal generator" that does all this, including all QCD and EWK effects, does not exist.

Need to be pragmatic and build a dedicated generator using the pieces that we do have, making sure that we do include the "most important" effects.

Single-most important QCD effect





Black histogram: no detector resolution and efficiencies, $p_T(W) = 0$.

Blue histogram: with realistic $p_T(W)$ distribution.

Red dots: after inclusion of detector resolutions and efficiencies.

For the purpose of the measurement of m(W), the single-most important QCD effect is the (low-p_T part) of the distribution $p_T(W)$ distribution.

This part of the distribution is driven by the emission of multiple soft gluons.

Single-most important EWK effect

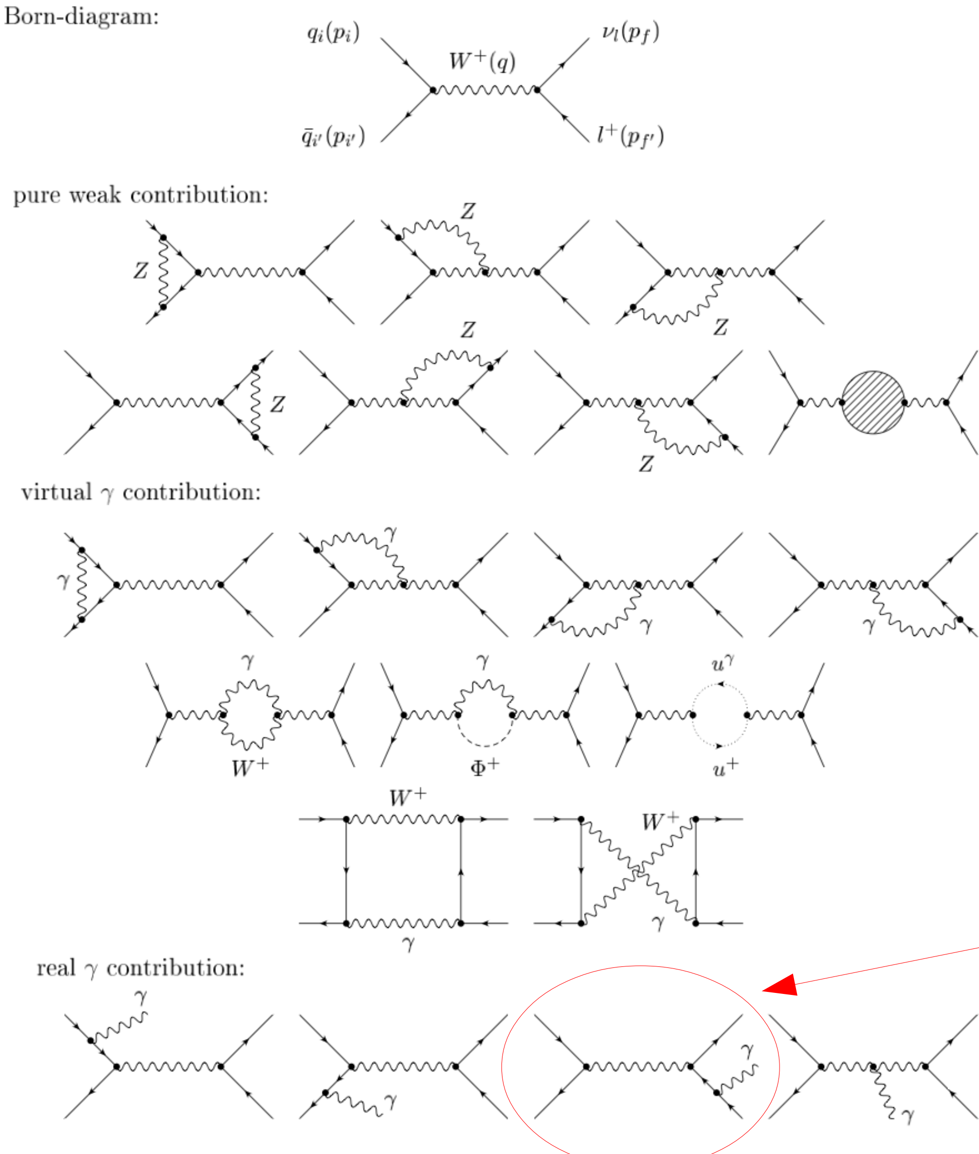


Figure from: Baur, Keller, Wackeroth, hep/ph-9807417.

Electroweak corrections have been studied (and these studies started a long time ago), by the authors of the W/ZGRAD and HORACE event generators and by many others.

For the purpose of the measurement of m(W), the single-most important EWK effect (by far) is this one ("final-state radiation").

"These photons carry away energy that was part of the W boson mass".

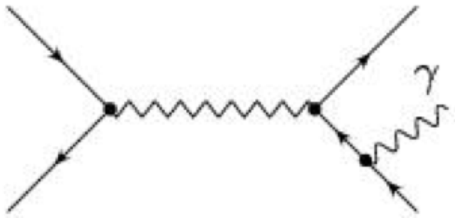
The combination of generators

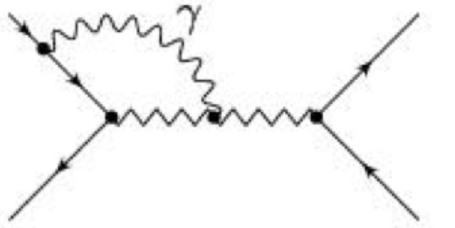
Tool	Process	QCD	EW
RESBOS	W,Z	NLO	-
WGRAD	W	LO	complete $\mathcal{O}(\alpha)$, Matrix Element, ≤ 1 photon
ZGRAD	Z	LO	complete $\mathcal{O}(\alpha)$, Matrix Element, ≤ 1 photon
PHOTOS			QED FSR, ≤ 2 photons

Our main generator is "**ResBos+Photos**". The NLO QCD in **ResBos** allows us to get a reasonable description of the p_T of the vector bosons. The two leading EWK effects are the first FSR photon and the second FSR photon. **Photos** gives us a reasonable model for both.

We use **W/ZGRAD** to get a feeling for the effect of the full EWK corrections.
The final "QED" uncertainty we quote is 7/7/9 MeV (m_T,p_T,MET).
This is the sum of different effects; the two main ones are:

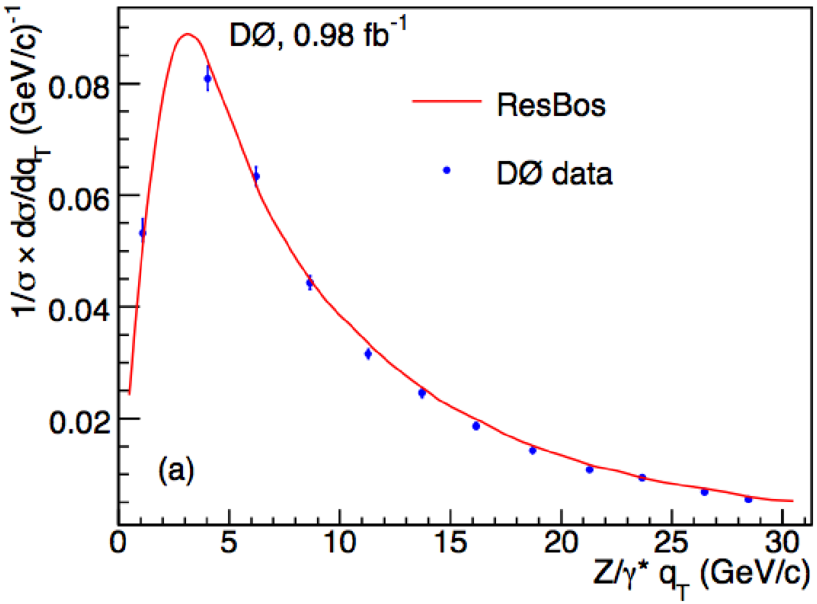
- Effect of full EWK corrections, from comparison of W/ZGRAD in "FSR only" and in "full EWK" modes (5/5/5 MeV).
- Very simple estimate of "quality of FSR model", from comparison of W/ZGRAD in FSR-only mode vs **Photos** (5/5/5 MeV).





How can we help to improve things ?

Phys. Rev. Lett. 100, 102002 (2008)



One region of particular interest in terms of boson p_T is the region at low p_T
(bulk of the sample in measurements like W mass).

Fixed-order QCD calculations diverge;
need resummation.

The measurement above (only 1 fb^{-1} of data) is already limited by systematic uncertainties due to the poor resolution on $p_T(Z)$.

New variable pioneered by DØ:

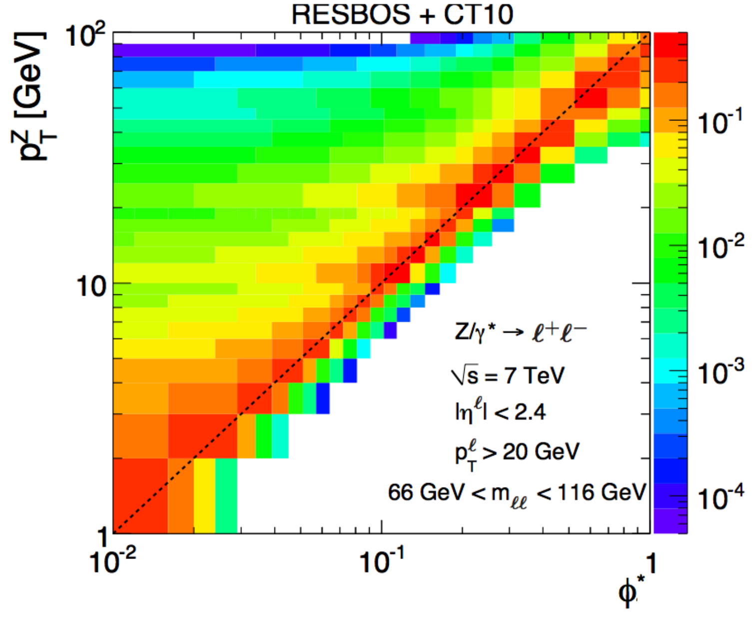
$$\phi^* \equiv tan(\phi_{acop}/2) \cdot sin(\theta^*_\eta)$$

Based on the (precise) measurements of *track directions*.

M. Vesterinen and T.R. Wyatt, NIM A602, 432.

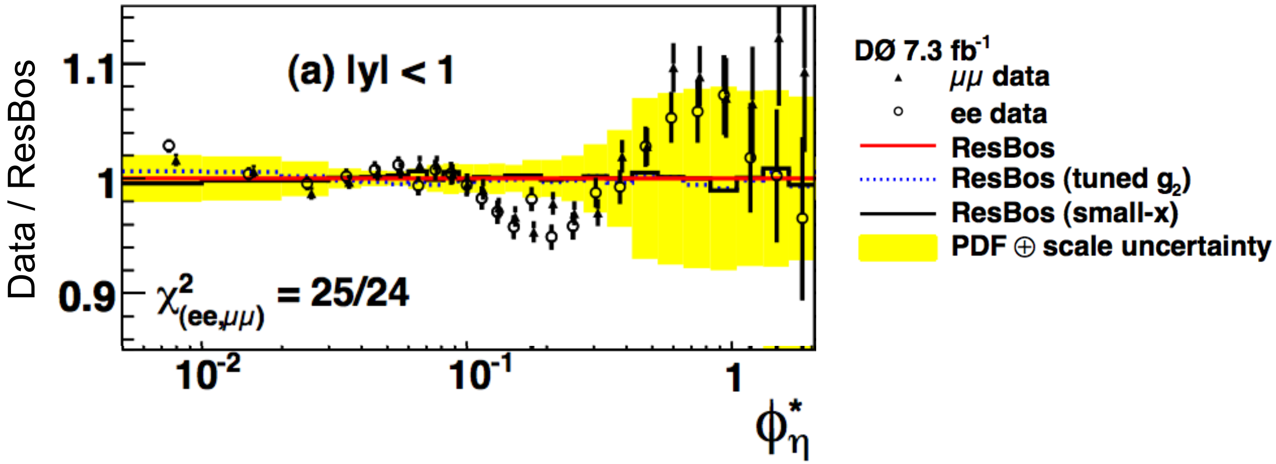
A. Banfi *et al.*, EPJ C71, 1600.

This new variable ϕ^* probes the same physics as $p_T(Z)$, as illustrated in this scatter plot from ATLAS.



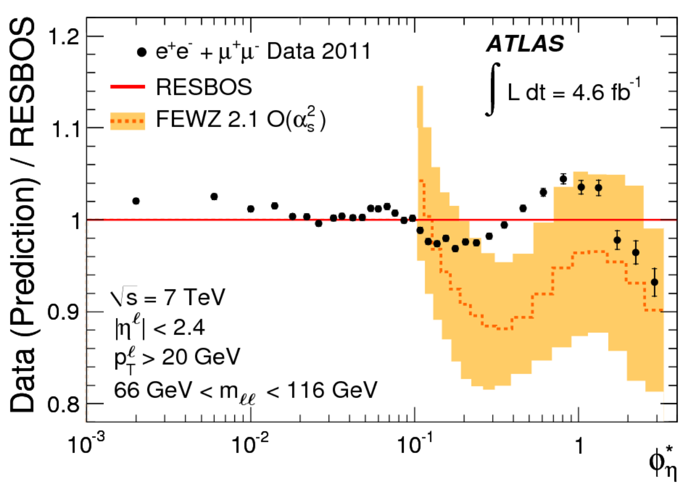
Z transverse momentum: ϕ^*_η

DØ (Phys. Rev. Lett. 106, 122001)

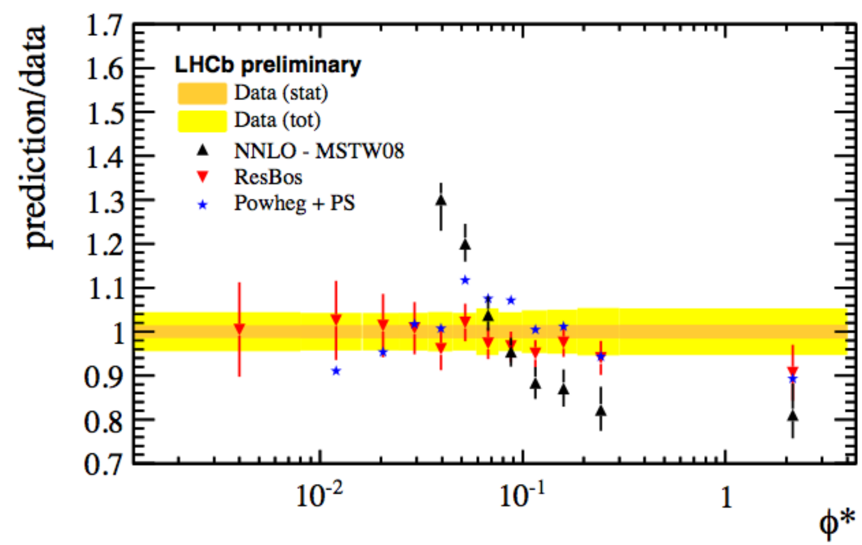


Available measurements more precise than the current best predictions.

ATLAS (Phys. Lett. B720, 32)



LHCb (LHCb-CONF-2013-007)

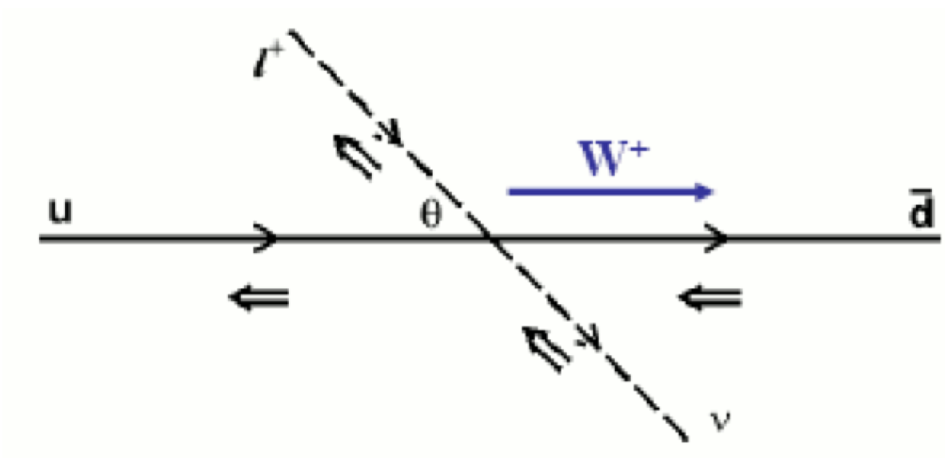


W charge asymmetry

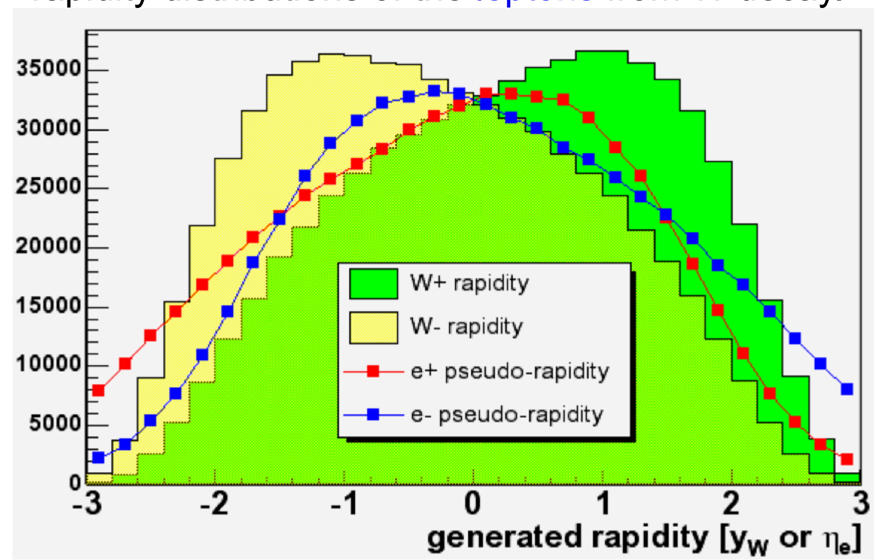
Tevatron ($p\bar{p}$ at “lower energy”): W boson mostly produced by valence quarks.

u quarks tend to carry more momentum than d quarks.

=> W^+ preferentially boosted in proton direction



Asymmetry also present, albeit diluted, in the rapidity distributions of the leptons from W decay.



Define asymmetry:
Often measured as function of lepton rapidity.

$$\mathcal{A}(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) - \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}{\frac{d\sigma}{d\eta}(W^+ \to \ell^+\nu) + \frac{d\sigma}{d\eta}(W^- \to \ell^-\bar{\nu})}$$

This measurement is also critical at the LHC.
Measurements at Tevatron and LHC probe different aspects of PDFs (flavour, Bjorken x).

PDF uncertainties

In principle:
transverse observables (*e.g.* m_T) are insensitive to the uncertainties in the (longitudinal) parton distribution functions (PDFs)

In practice:
the uncertainties are to some extent reintroduced via the limited η coverage of experiments,
which are not invariant under longitudinal boosts

How to reduce the impact of the PDF uncertainties in measurements of the W boson mass ?

- Reduce the uncertainties in the PDFs

  e.g. via measurements of the W charge asymmetry
  at the Tevatron and the LHC (complementarity of the two colliders)

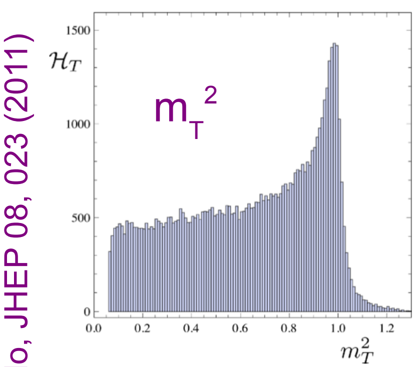
- Reduce the impact of the PDF uncertainties on W boson mass

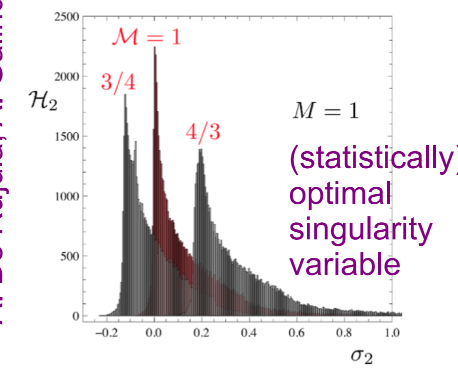
  by extending the η coverage as much as possible
  (challenging: understanding lepton energy scale and pile-up and
  backgrounds in the forward detectors)

- Possibly reduce the impact of the PDF uncertainties on W boson mass

  by exploring even more robust observables
  ("single out events with small longitudinal momentum") to replace/complement m_T

A. De Rújula, A. Galindo, JHEP 08, 023 (2011)





These three approaches are not mutually exclusive, *i.e.* they can be pursued at the same time and gains should "add up".

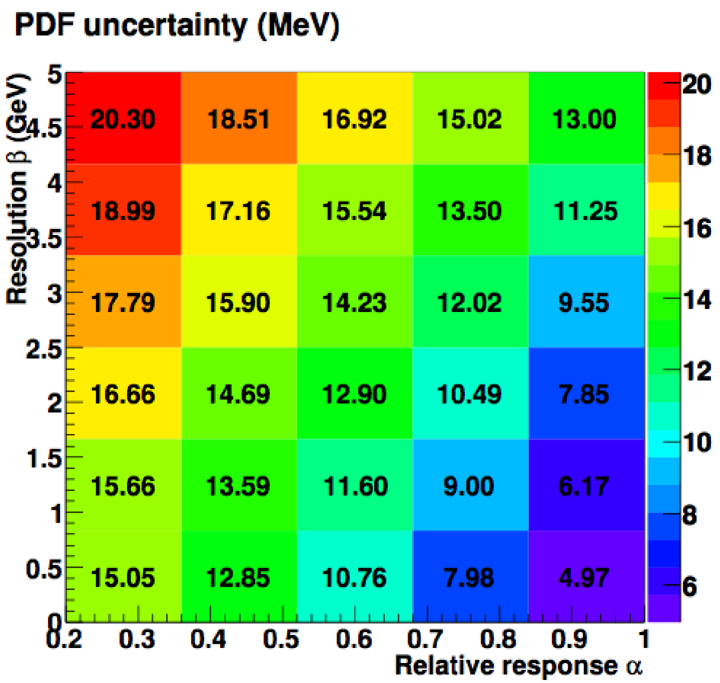
PDF uncertainties

Another comment on PDF uncertainties: one has to keep in mind the interplay between the uncertainties in the PDFs and the detector effects that can make them more or less important in a given measurement.

The Table below shows the PDF uncertainty, using the m_T observable, for different values of

- the average the energy scale for the hadronic recoil,
- and resolution on the hadronic recoil (fluctuations around the average scale).

Ideal detection of the recoil:
$\alpha = 1$
$\beta = 0$ GeV



Huge effect !

For "ideal detection" of the recoil, m_T is close to an invariant mass. For a realistic recoil reconstruction much less so.

And an invariant mass is, well, invariant under certain things.

FIG. 9. Hadronic recoil dependence of the PDF uncertainty. m_T method, ResBos events, CTEQ6.6 PDF set.

(Important) technical comments

Some technical comments/pleas, without any specific order:

- **We need "knobs to turn":**

  It is good that we have ever more precise calculations and event generators that get close to reproducing the data ! But in most cases they will not match *exactly* => want adjustable parameters.

  Of course, the parameters need to make some physics sense ... of you tune them to Z data they should work well for W data.

- **We all need alternatives to compare:**

  It is good that there are multiple experiments per collider (*e.g.* CDF and DØ); we can compare their analyses and results.

  We have learned very valuable lessons from comparing Geant and EGS.

  It would be good if there were multiple generators that are good at EWK and QCD and that, out-of-the-box, give a good description of vector boson data (including boson p_T) ...

- **We need public codes (including event generators):**

  Could not have done the Geant <-> EGS validation/comparison without the source code.

  Even if they contain bells, whistles and switches that we do not have to / want to play with, being able to run ourselves at least allows us to check a few obvious things like numerical stability.

  Also, we need to generate *huge* samples.

Summary

Experimental precision on m(W) is currently driven by the Tevatron :
16 MeV, i.e. two times more precise than LEP.

Still potential for improvement – 10 MeV (CDF+DØ combined) uncertainty looks feasible.

The ideal event generator does not exist. But many building blocks do exist.
Described the strategy for “building” the event generator that has been used,
and the choices that we made.

While the experimental strategy is rather different between CDF and DØ,
(tracking ↔ calorimetry, energy calibrations, ...)
the physics modelling choices are much more similar.
And since I am a DØ person, it was easier for me to show DØ plots/tables.

Close collaboration between theory and experiment has been and is crucial.
This collaboration has been ongoing for many, many years, and it is great to see that many of our long-time theory friends are still onboard and pushing (you know who you are !). And it is good to see all the new faces.

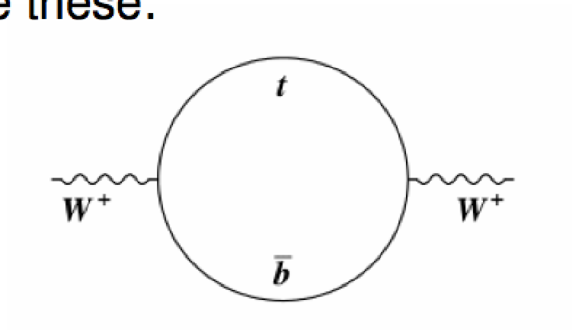
Backup slides

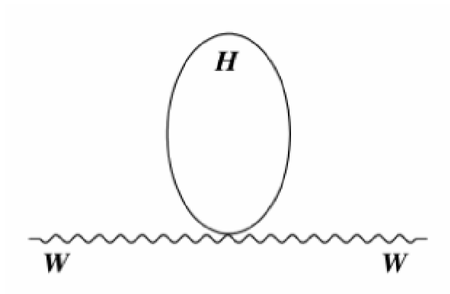
W boson mass

Today's measurements are precise enough to test the electroweak theory at the **loop level**.
At higher orders (including loop diagrams), the mass of the W boson can be expressed as:

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

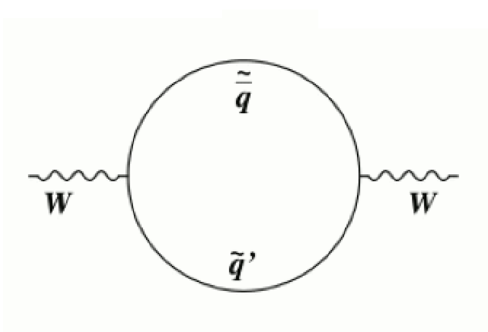
Radiative corrections (Δ r) depend on M_t as $\sim M_t^2$ and on M_H as $\sim \log M_H$. They include diagrams like these:



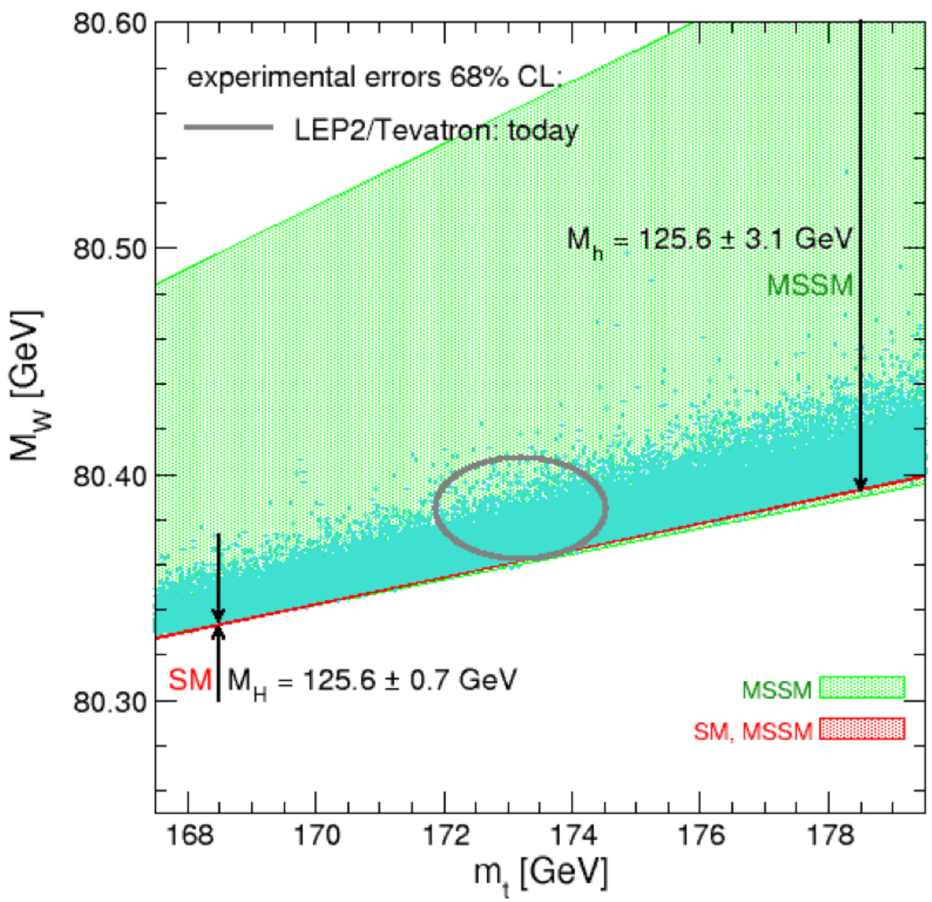


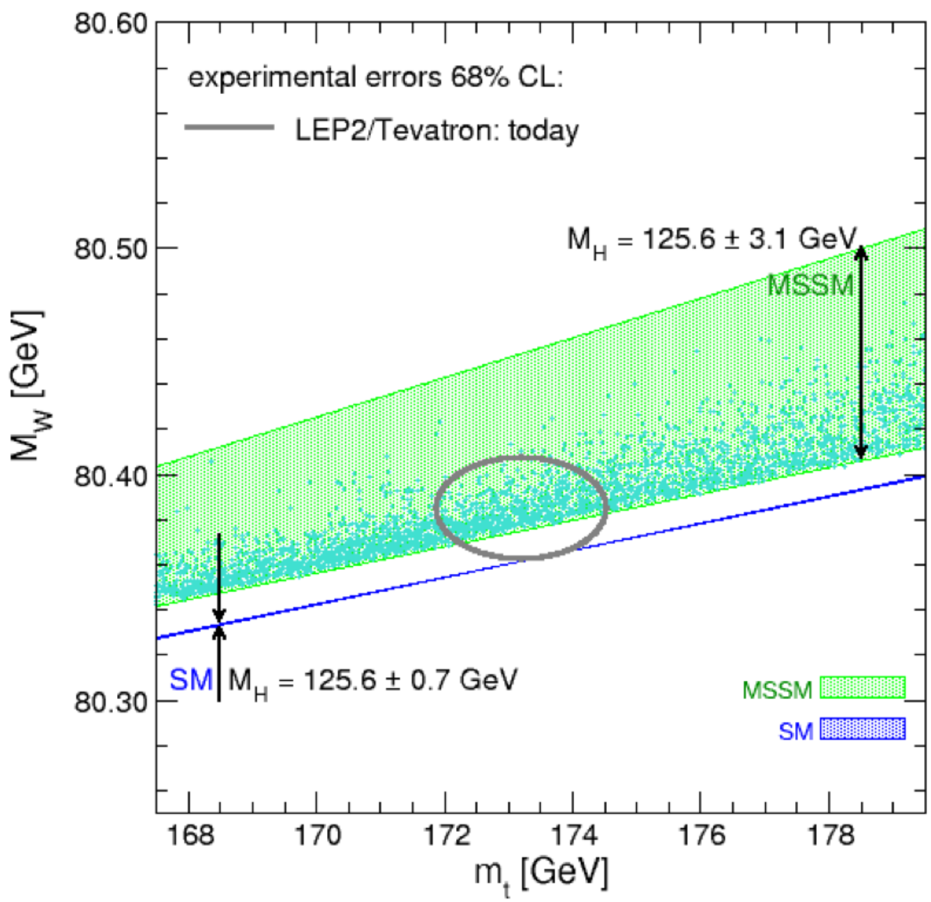
Precise measurements of M_W and M_t constrain SM Higgs mass.

Additional contributions to Δr arise in various extensions to the Standard Model, *e.g.* in SUSY:



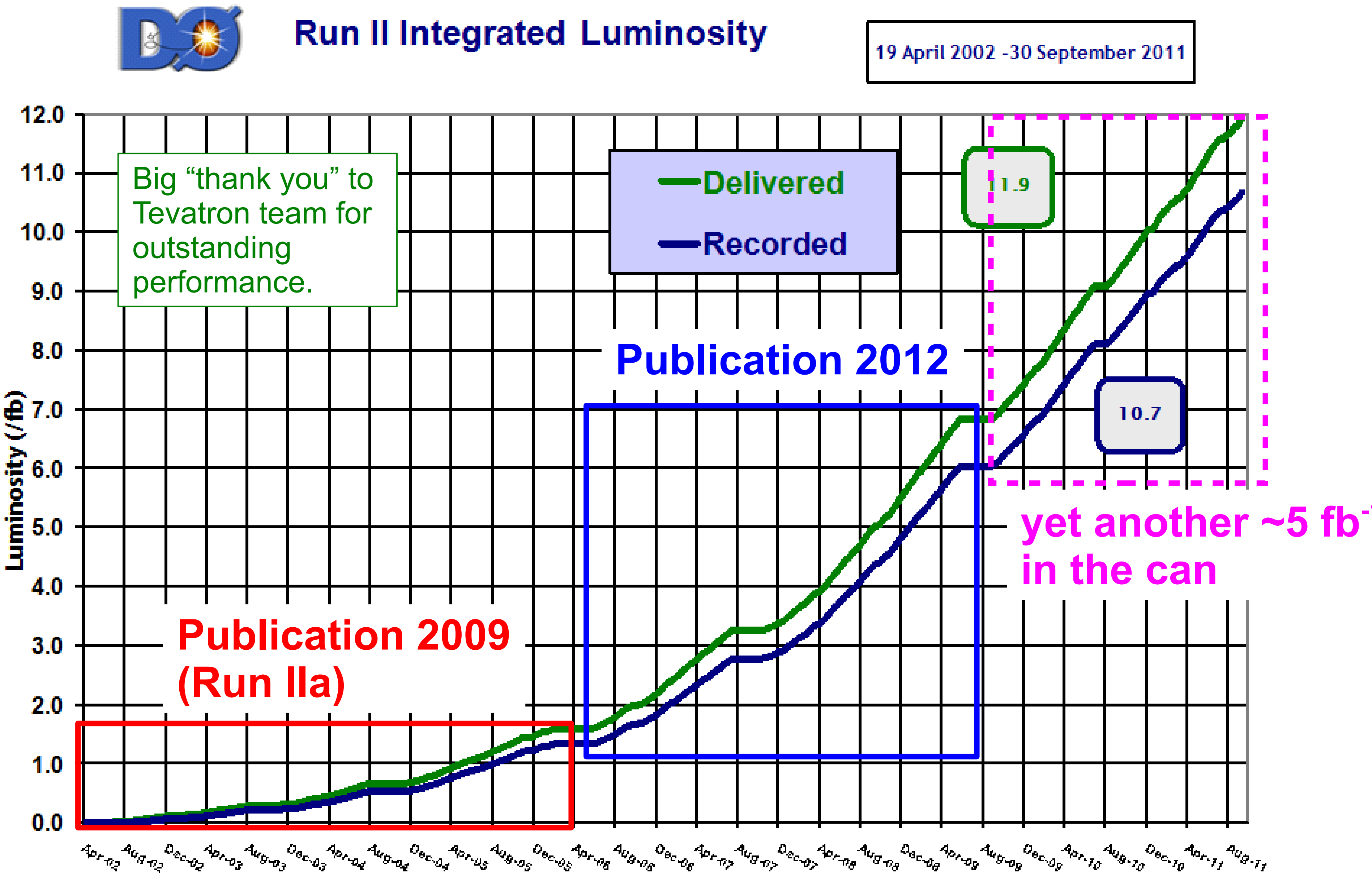
More plots from Heinemeyer *et al*.





Blue points:
stops and sbottoms heavier than 500 GeV, squarks from first two generations and gluino heavier than 1200 GeV

Data periods and analysis iterations



Some control plots from the DØ analysis (this is $Z \rightarrow e^+ e^-$)