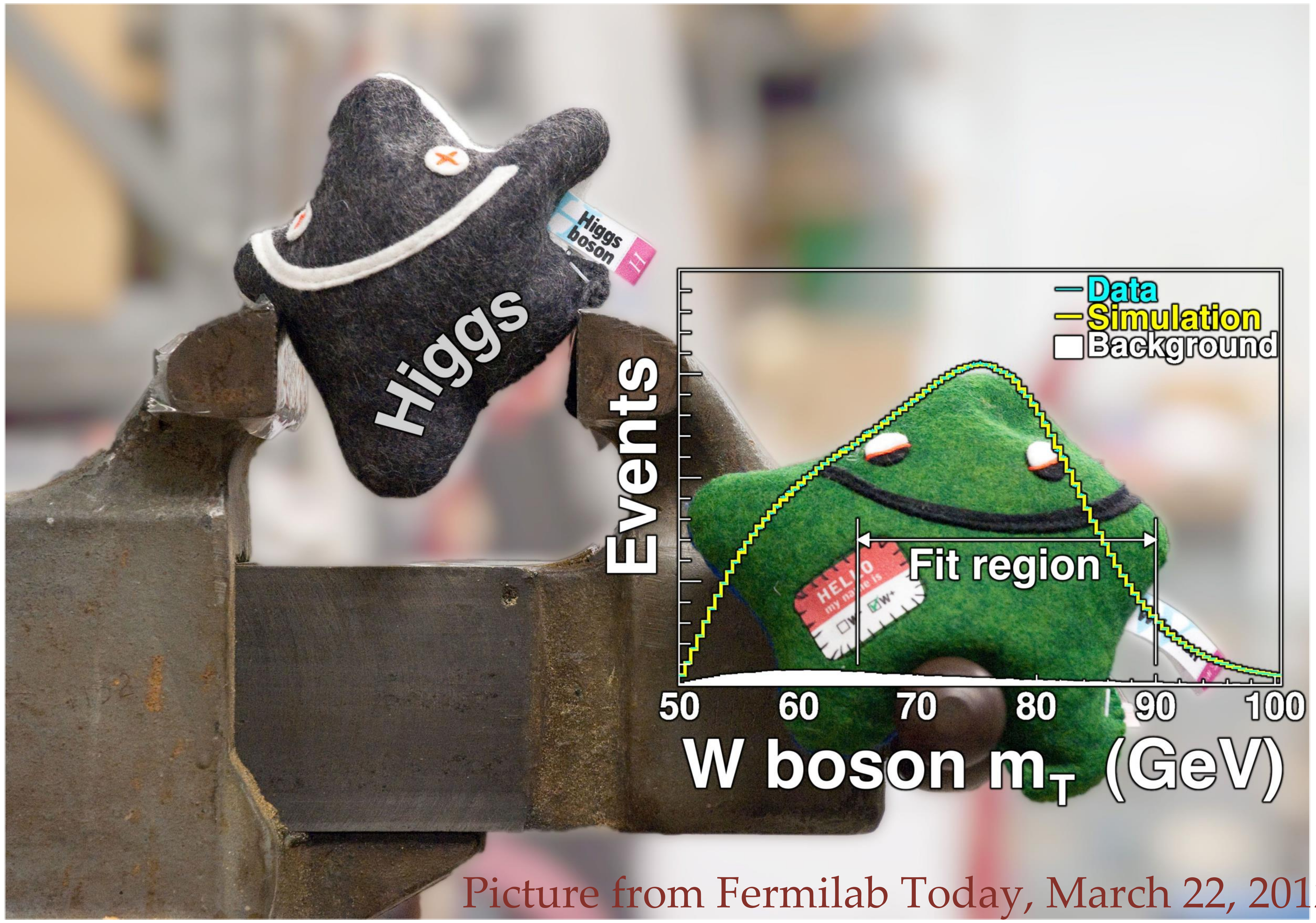
Measurement of the W boson mass with the D0 detector

Hengne Li

(South China Normal University)



Picture from Fermilab Today, March 22, 2012

W mass workshop, 14 Apr. 2022

Motivation

- The Standard Model (SM) predicts a relationship between the W boson mass and other parameters of electroweak theory:

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

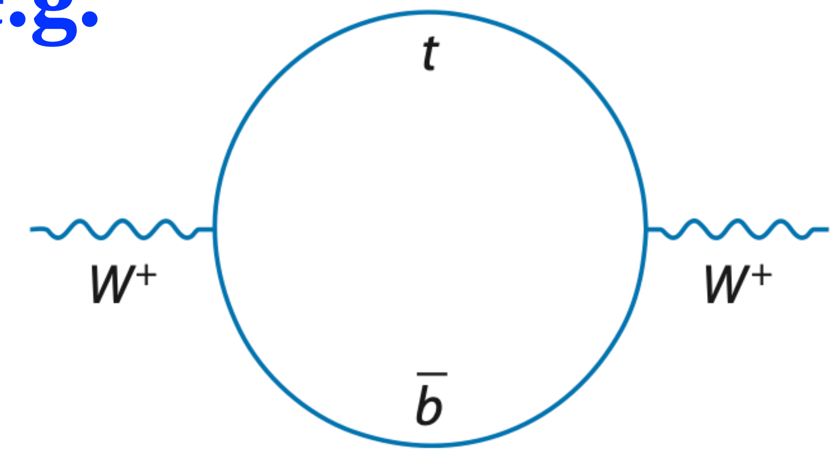
- Contributions to MW through radiative corrections **Δr**.

- Precisely test the electroweak theory at the loop level.
  - In case of SM, the precise W mass and top mass measurements can predict the SM Higgs boson mass.
  - By comparing the prediction and direct Higgs mass measurement, we can know how good is the SM prediction. If disagreement is big, we can infer contributions from theories beyond SM, such as SUSY.

W mass related to Top quark mass:

$$\Delta r \propto M_t^2$$

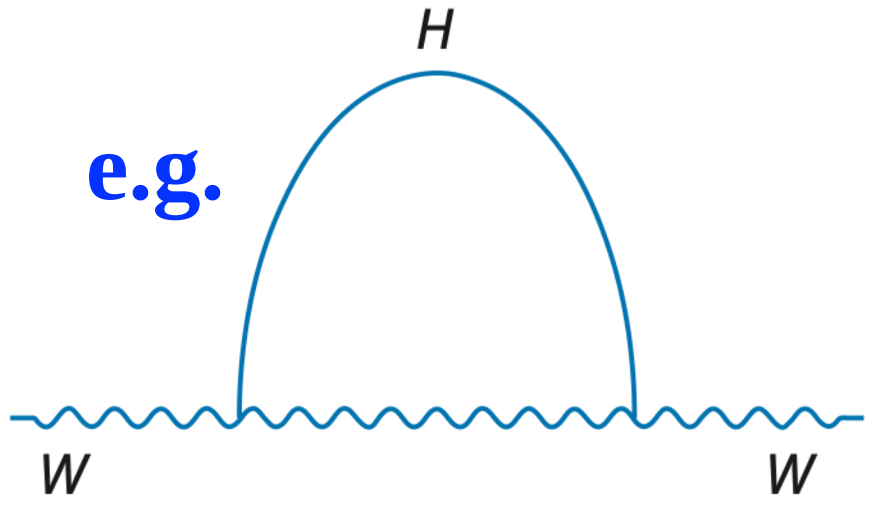
e.g.



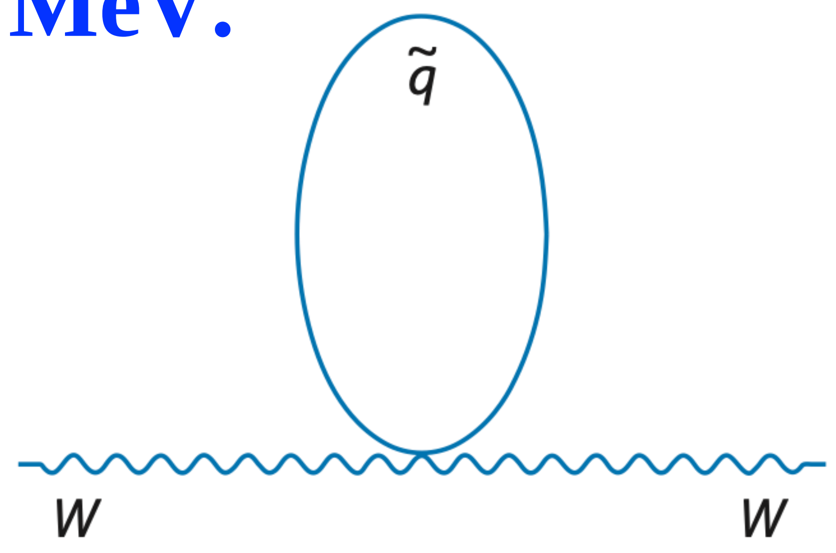
W mass related to SM Higgs mass:

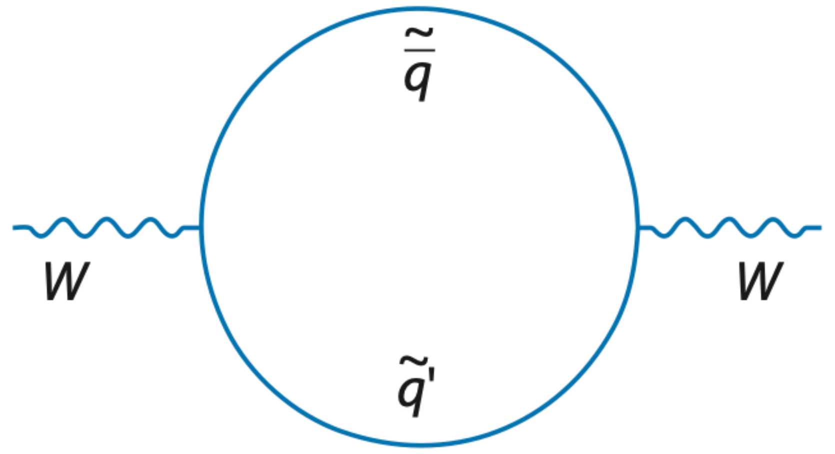
$$\Delta r \propto \ln M_H$$

e.g.



Beyond SM, contribution from SUSY particles can induce a total radiative correction to M_W of 100 to 200 MeV.





Compare predicted and measured
The old state of the art in 2012

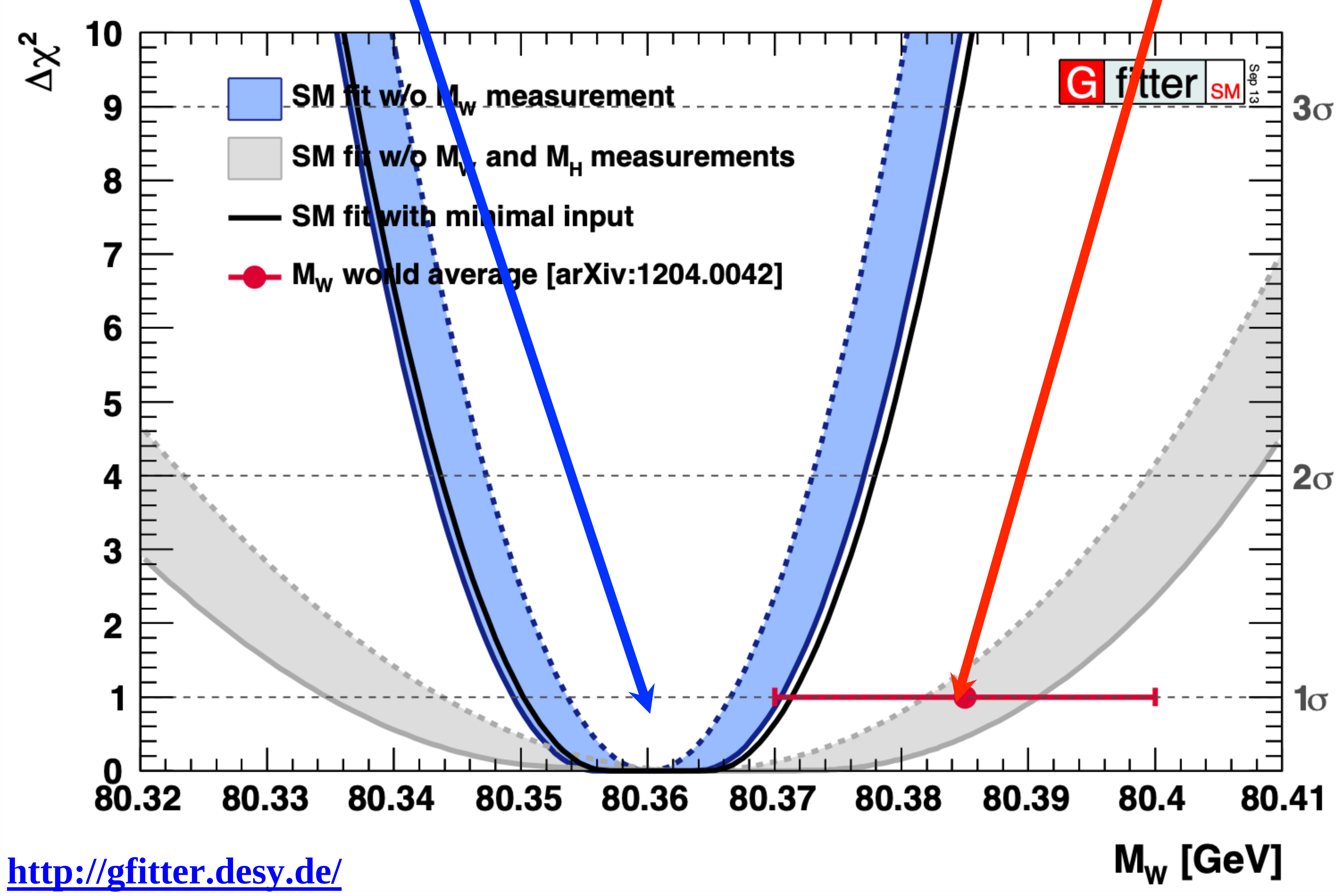
M_W = 80359 MeV ± 11 MeV

Predicted

Comparing with the world average directly measured value in 2012:

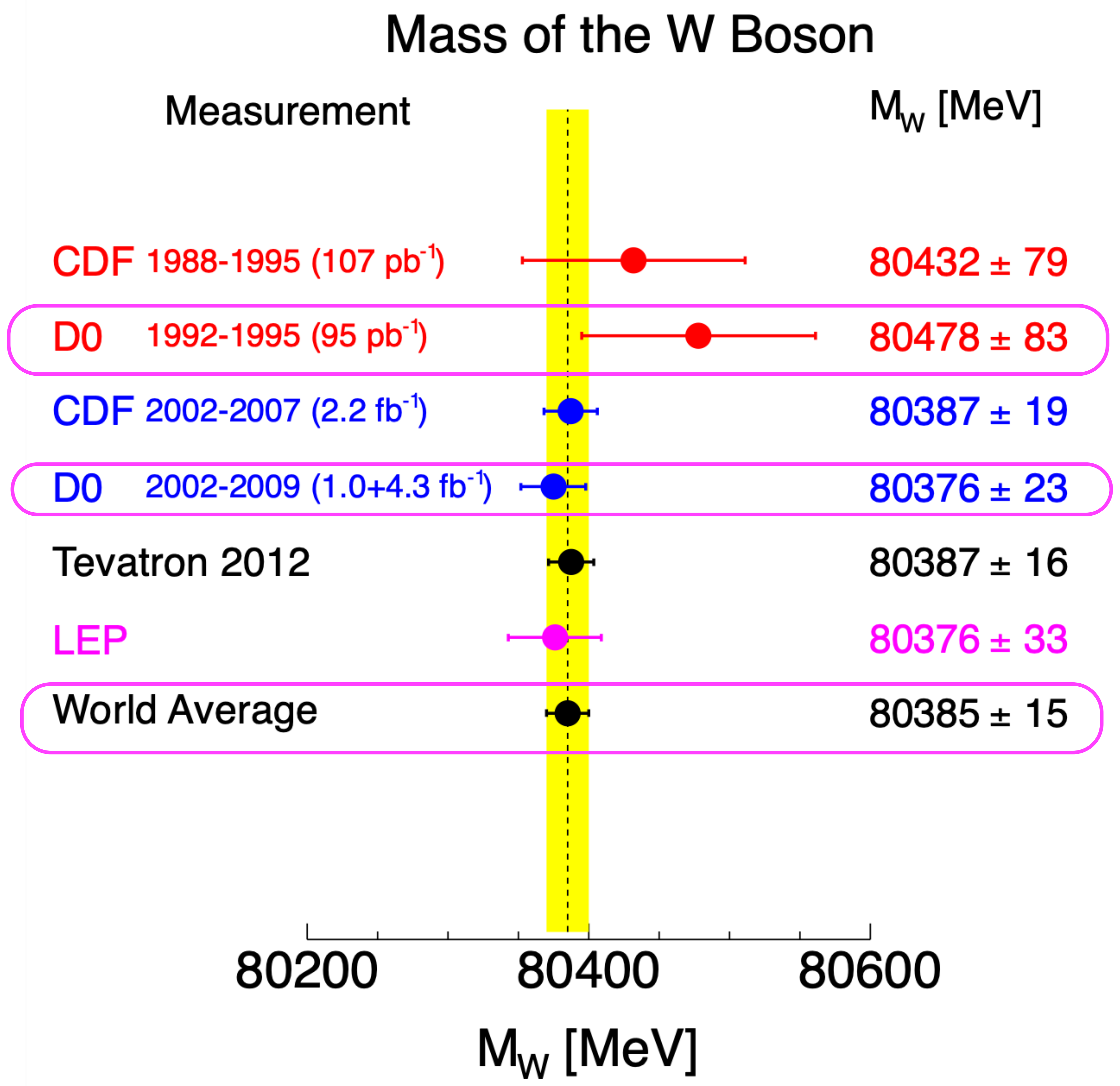
M_W = 80385 MeV ± 15 MeV

Measured



http://gfitter.desy.de/

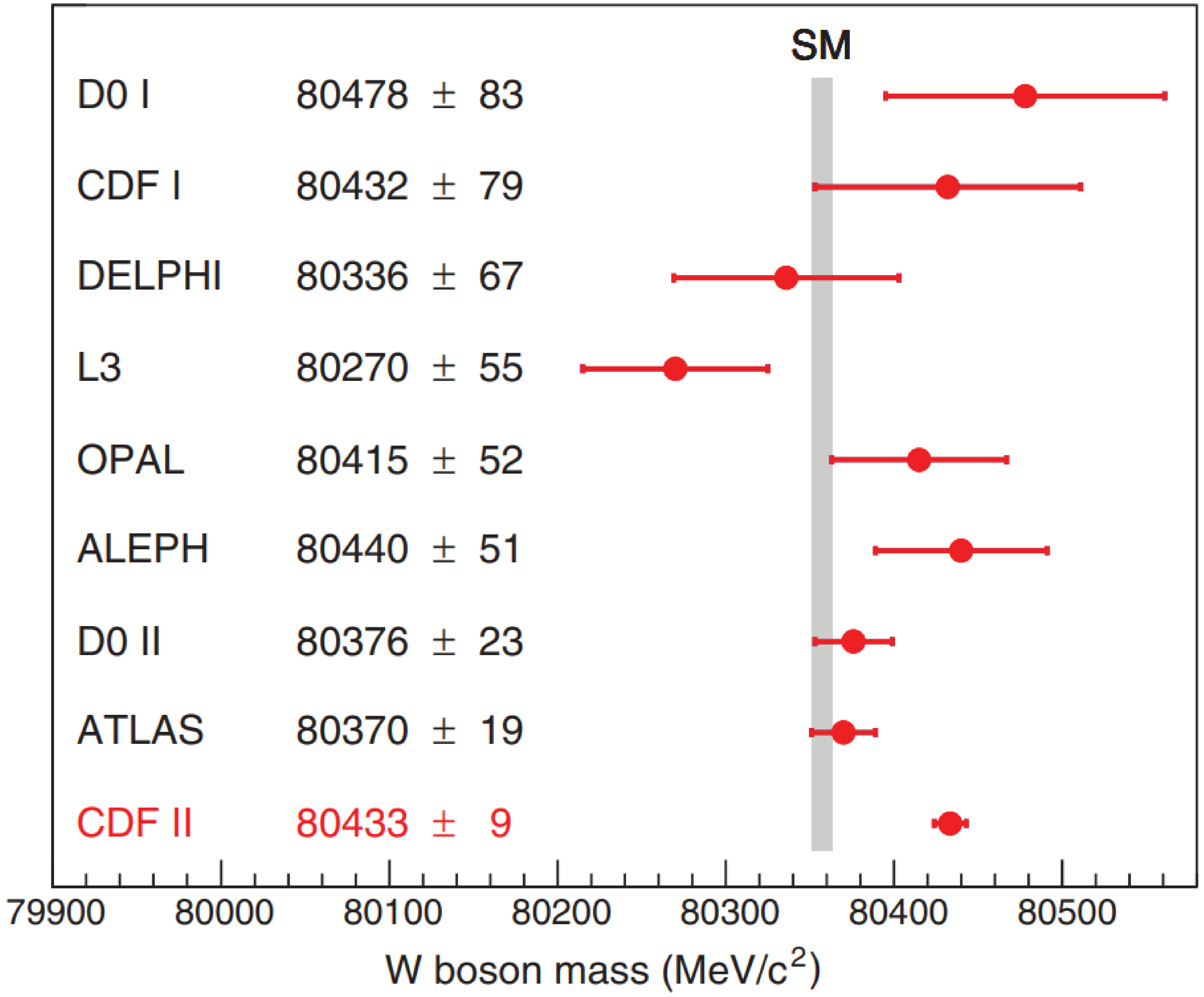
A ~1.3 sigma difference between the two M_W central values.

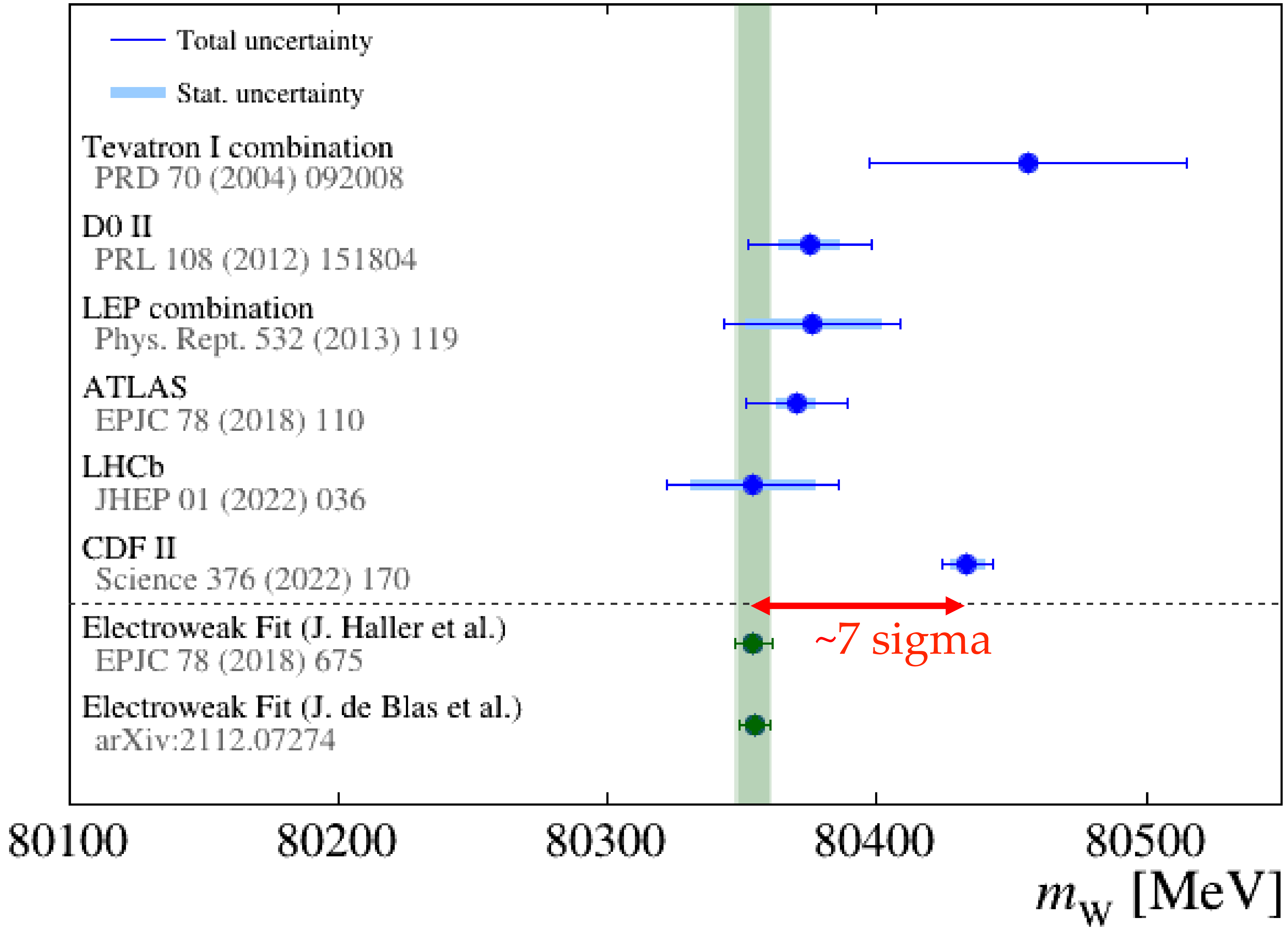


Compare predicted and measured

Current state of the art

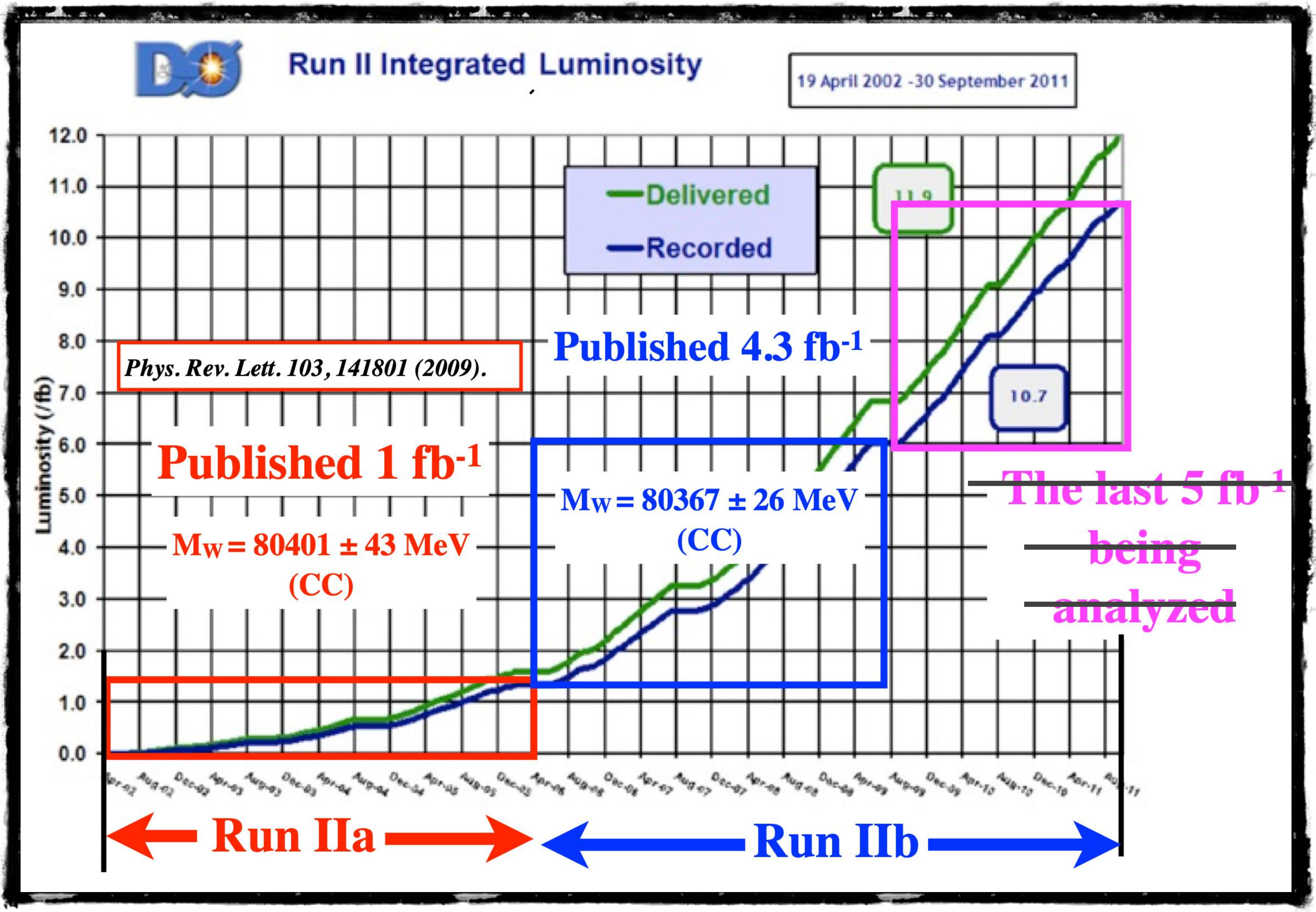
Science 376, 170–176 (2022)





Phys. Rev. Lett. 108, 151804 (2012)

The D0 data sets

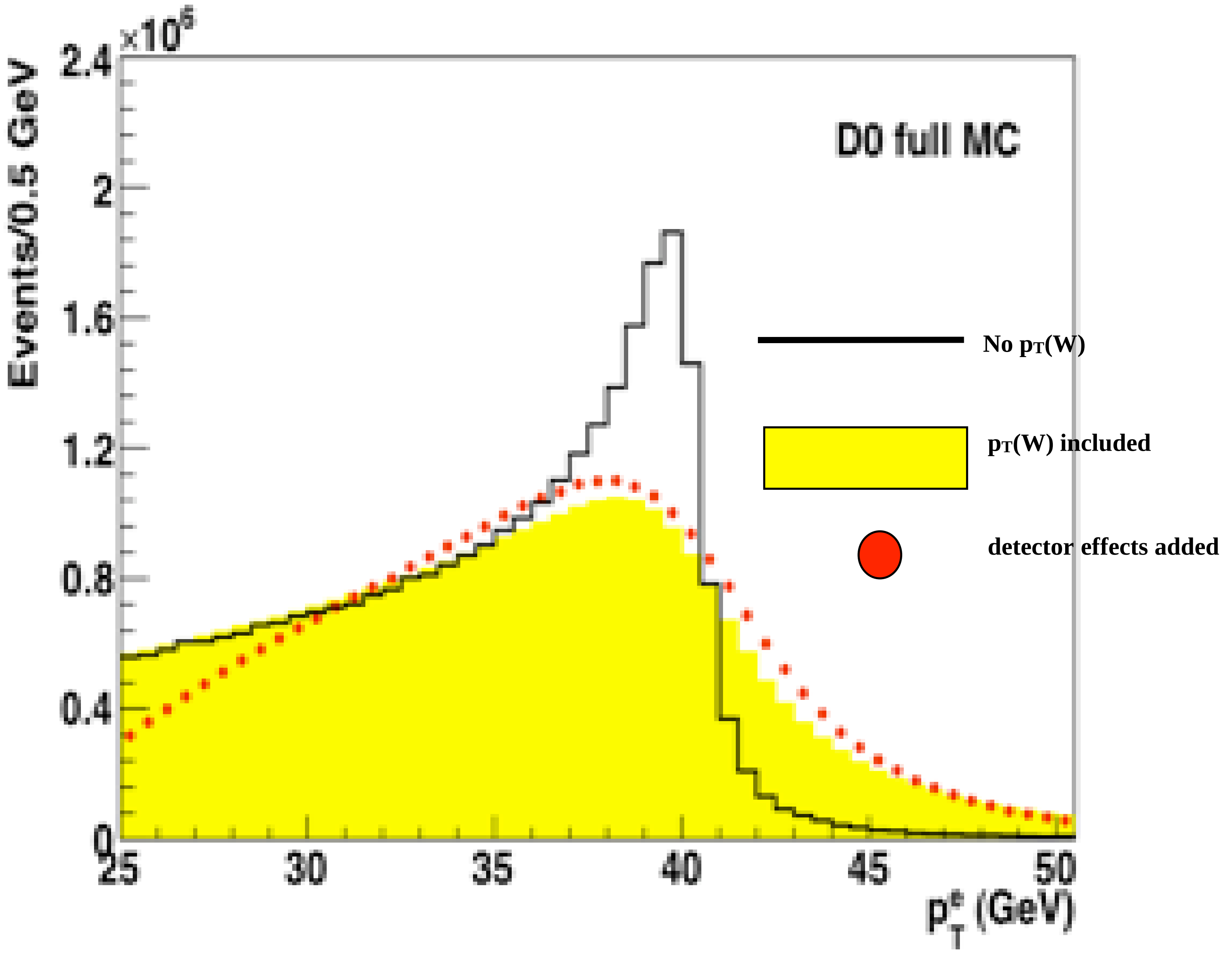


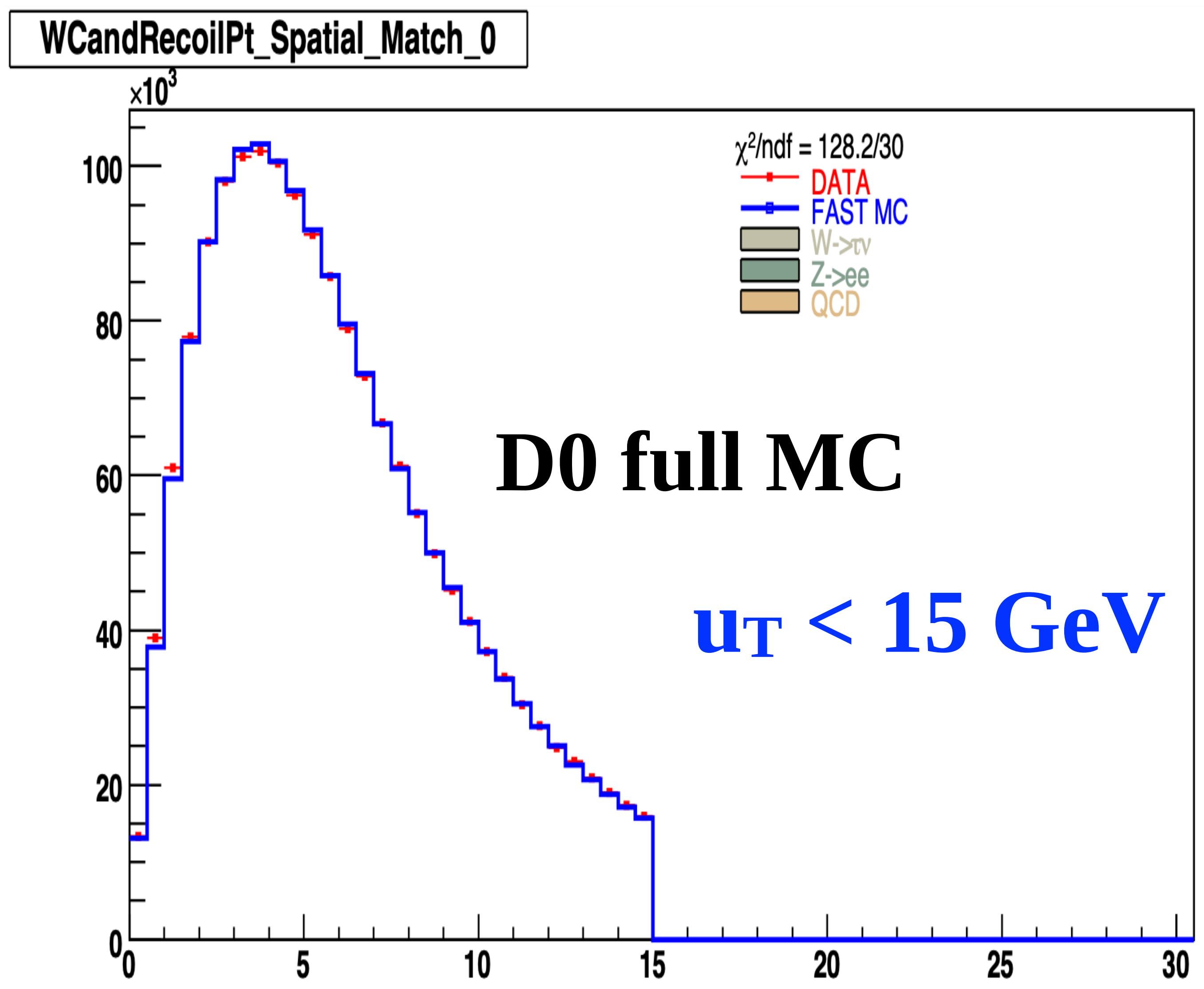
CC:
Central
Calorimeter

Event reconstruction

Event Selection:

- $W \to e\nu$ events
- Central electrons: $|\eta| < 1.05$
- $p_T(e) > 25$ GeV
- Missing $E_T > 25$ GeV
- Hadronic recoil: $u_T < 15$ GeV
- After selection:
  - 1,677,394 $W \to e\nu$ candidates





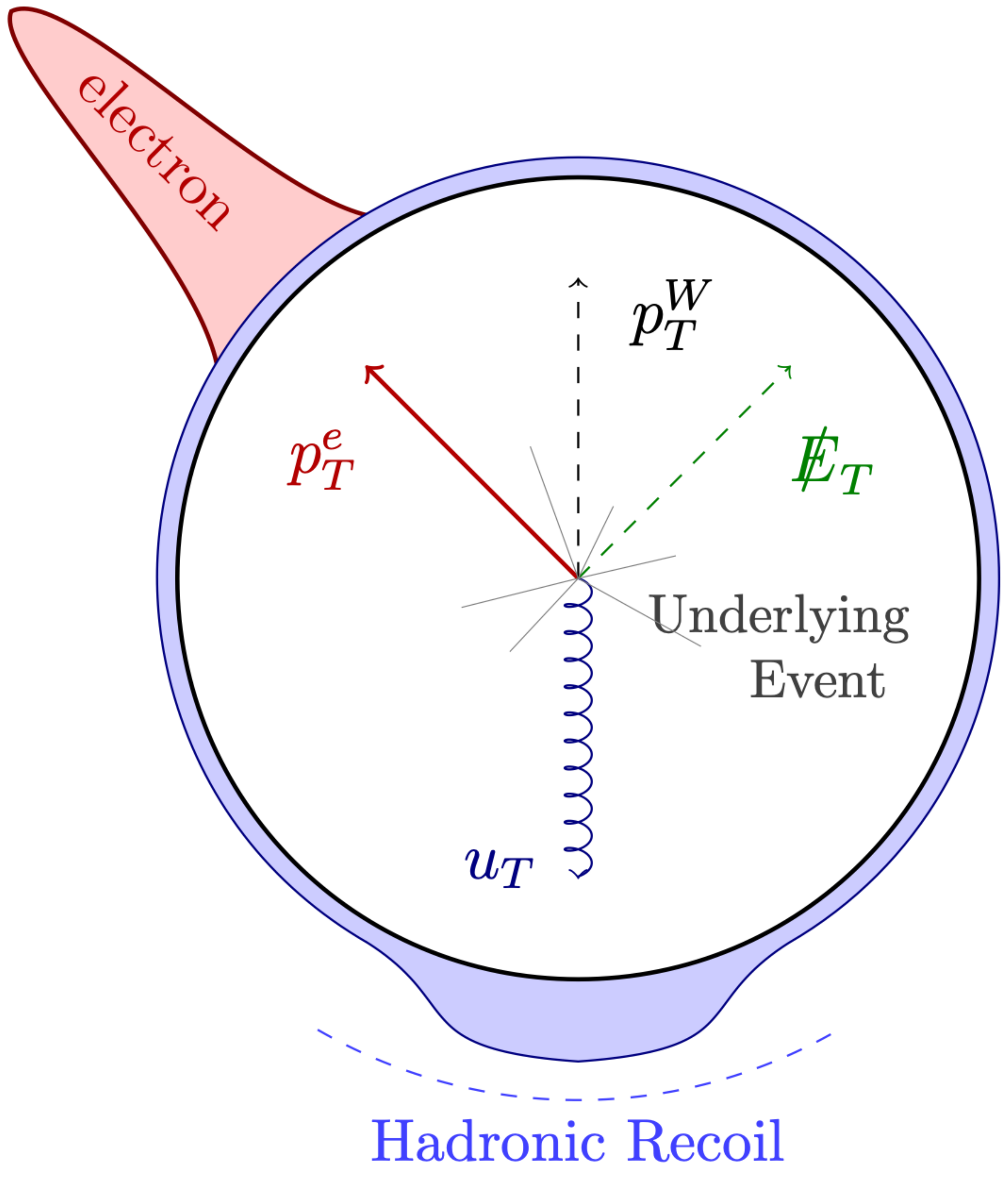
Transverse boost of the W boson degrades the sharpness of the $p_T(e)$ Jacobian edge.

Requiring uT<15 GeV is helpful, however, it also transfers certain recoil modeling uncertainty into $p_T(e)$

Phys. Rev. Lett. 108, 151804 (2012)

Analysis strategy

A Typical W→eν Event in DØ Detector



Reconstruct three observables:

$$M_T,\ P_T^l,\ \not{E}_T$$

$$M_T^W = \sqrt{2P_T^l \not{E}_T(1-\cos\Delta\phi)}$$

using CC electrons with p_T>25GeV

Using Z->ee events for detector calibration

A Fast MC model to generate templates of the 3 observables with different W mass hypotheses.
Fit the templates to the data to extract W mass.

The Fast MC model:
-Event Generator: Resbos(CTEQ6.6)+PHOTOS
-Parameterized Detector Model

Phys. Rev. Lett. 108, 151804 (2012)

The Observables

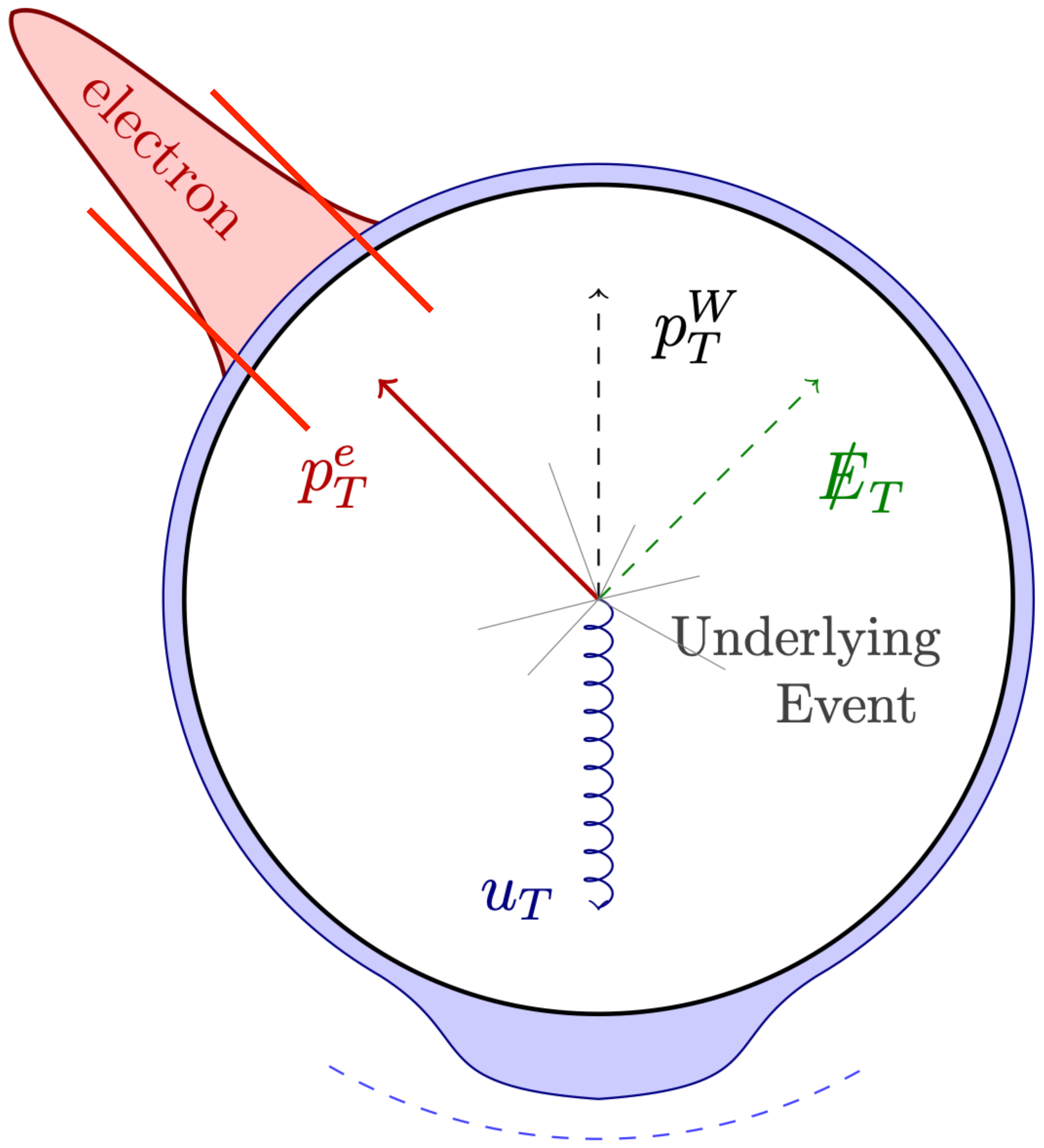
Can directly reconstruct two variables:

Lepton pT can be precisely measured, 0.01% precision.

$$\vec{P}_T^l$$

$$\vec{u}_T$$

Hadronic recoil: vectorial sum of the transverse energies of all the calorimeter cells outside the lepton reconstruction window.
- **less precise, ~1% precision,**
- **low resolution, $\Delta u_T > 3.5$ GeV**
- **hadronic energy response is only ~ 65%**



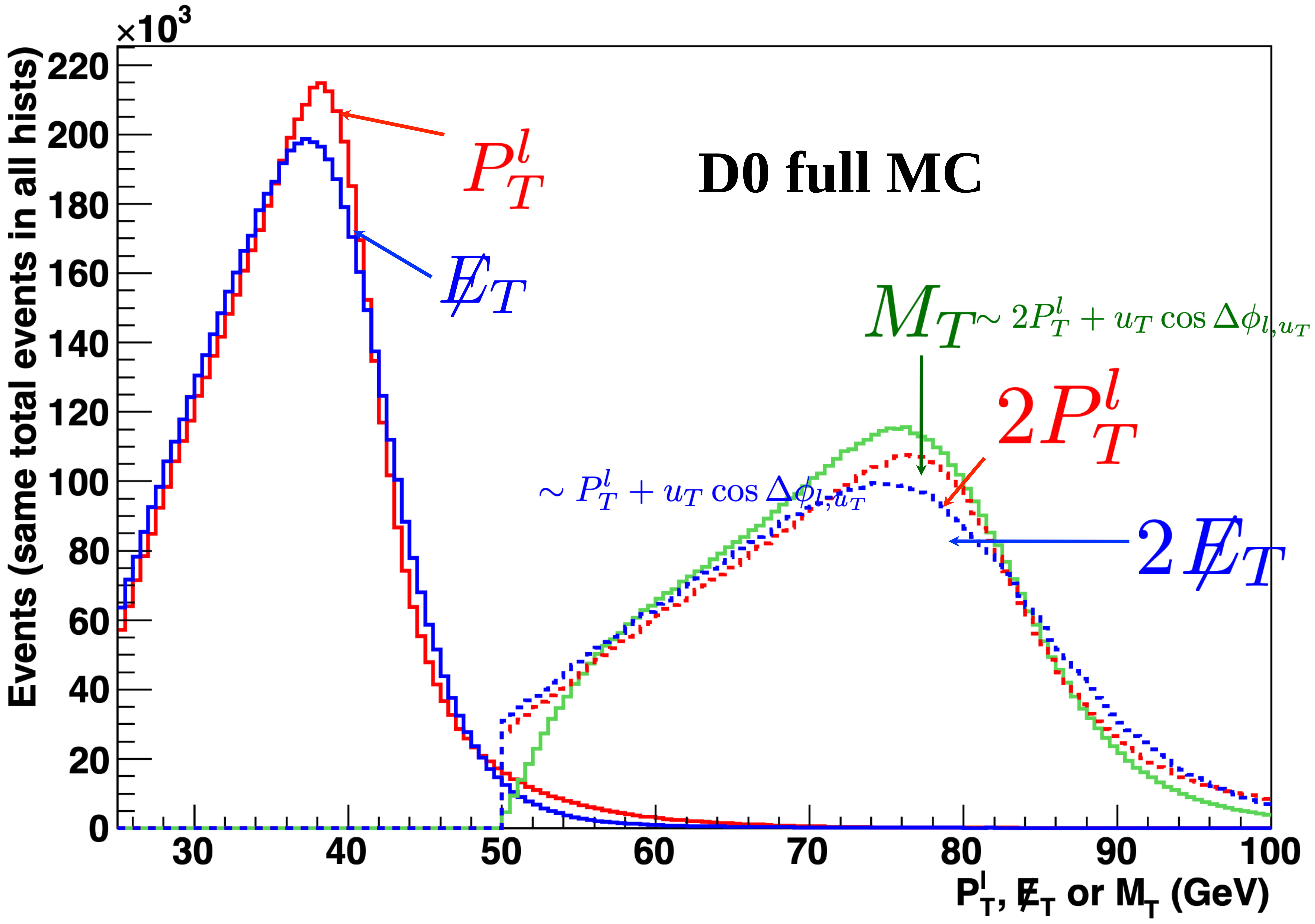
Calculate three observables to extract the W boson mass :

$$P_T^l$$

$$\not{E}_T = |\vec{P}_T^l + \vec{u}_T| \sim P_T^l + u_T \cos\Delta\phi_{(lepton-recoil)}$$

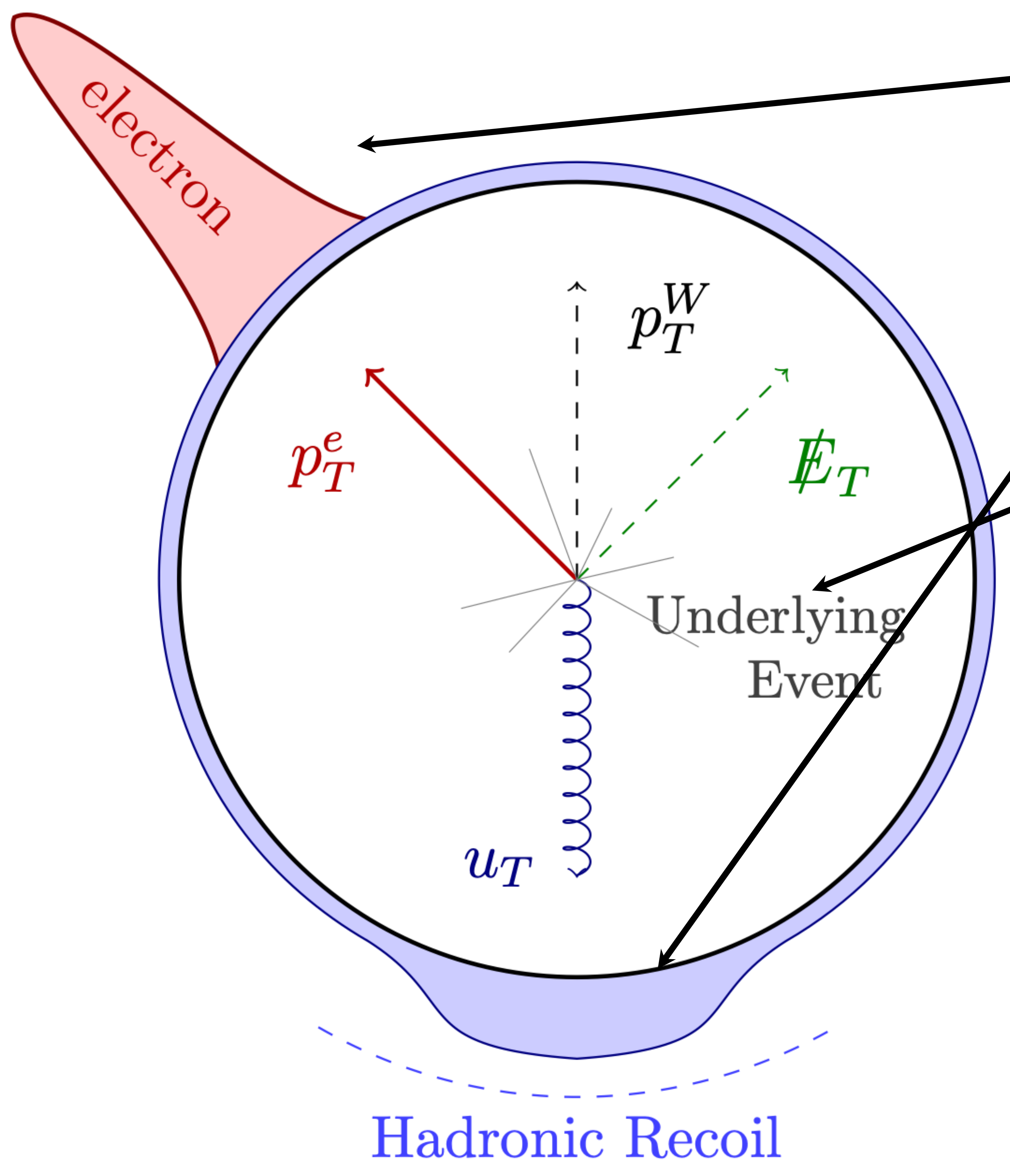
$$M_T = \sqrt{(P_T^l + \not{E}_T)^2 - (\vec{P}_T^l + \vec{\not{E}}_T)^2} \sim 2P_T^l + u_T \cos\Delta\phi_{lepton-recoil}$$

Which observable is more powerful?



Parametrized detector model

The parametrized detector model (PMCS) has to simulate:



- **Electron energy response and smearing**
- **Hadronic recoil energy response and smearing**
- **Underlying energy:**
  - **additional ppbar interactions (pileup):**
    - **average number of primary vertices: >4**
  - **spectator parton interactions**
- **Event selection efficiency**
- **Background**

Phys. Rev. Lett. 108, 151804 (2012)

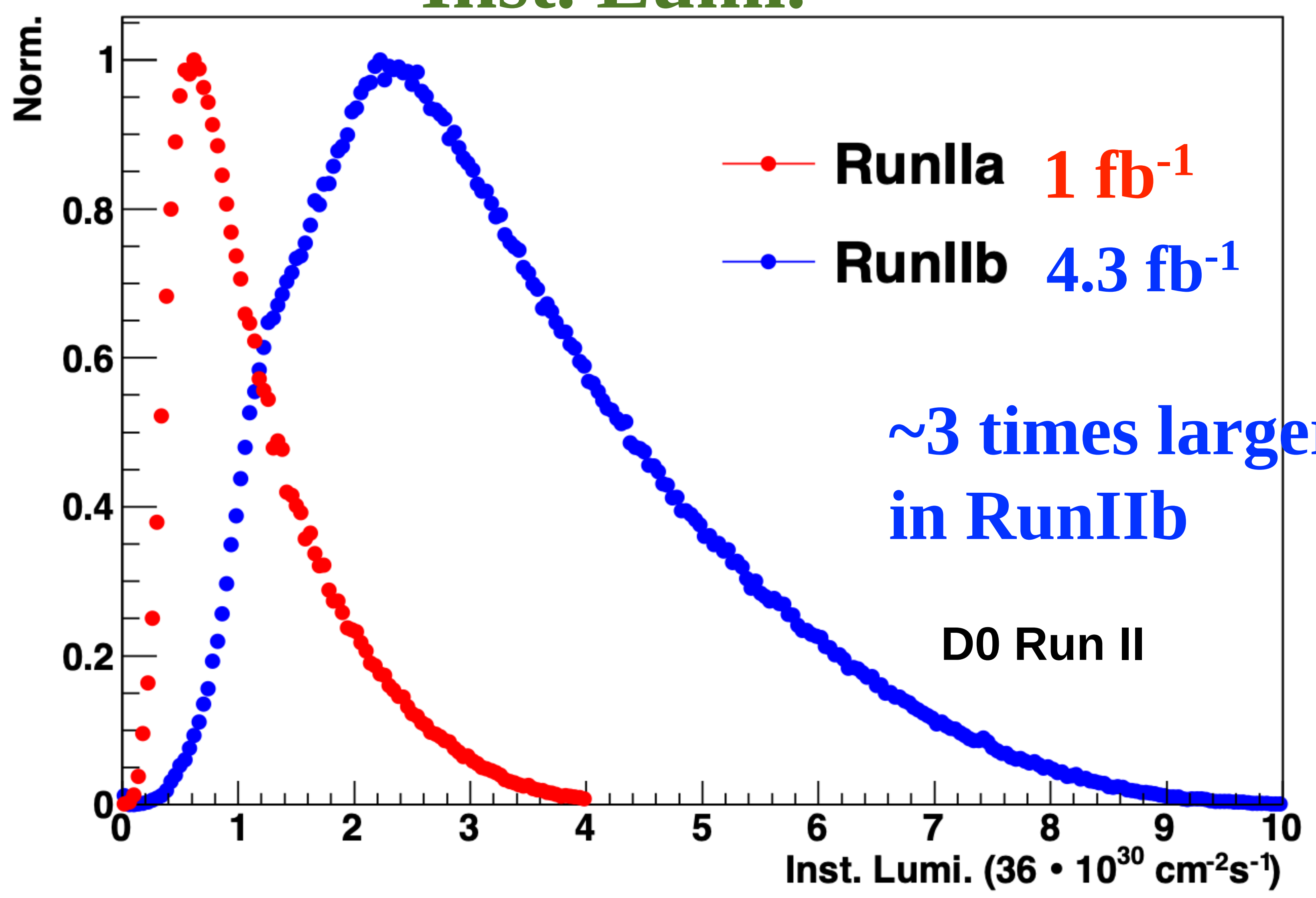
Electron energy model

Correct/model non-linear energy responses:

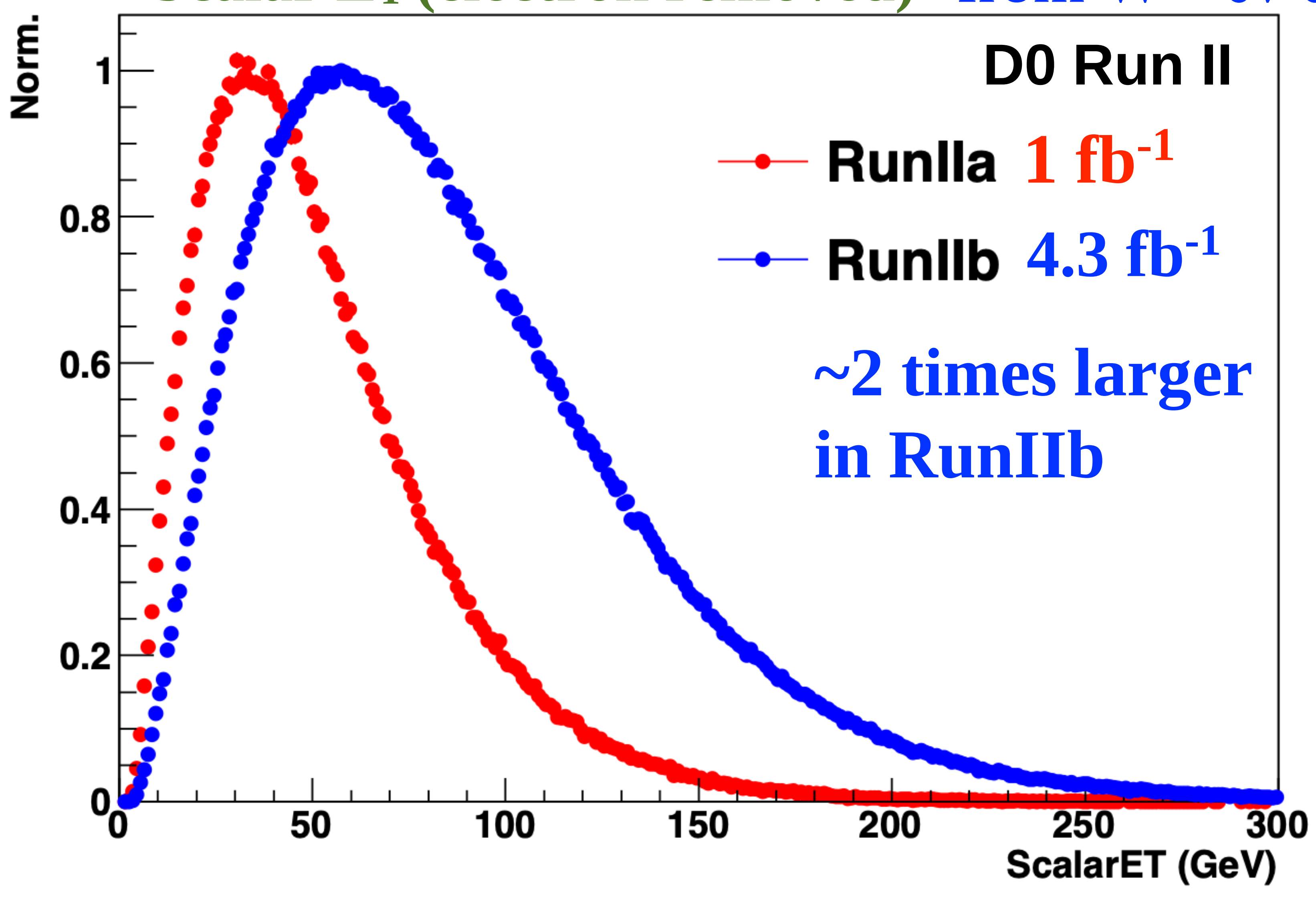
- **Correction of the energy loss due to dead material,**
- **Correction of the response decrease due to pileup**
- **Modeling underlying energy contamination from pileup and hadronic recoil**

Final electron energy response is tuned using Z->ee events assuming a linear response.

Inst. Lumi. from W->eν events



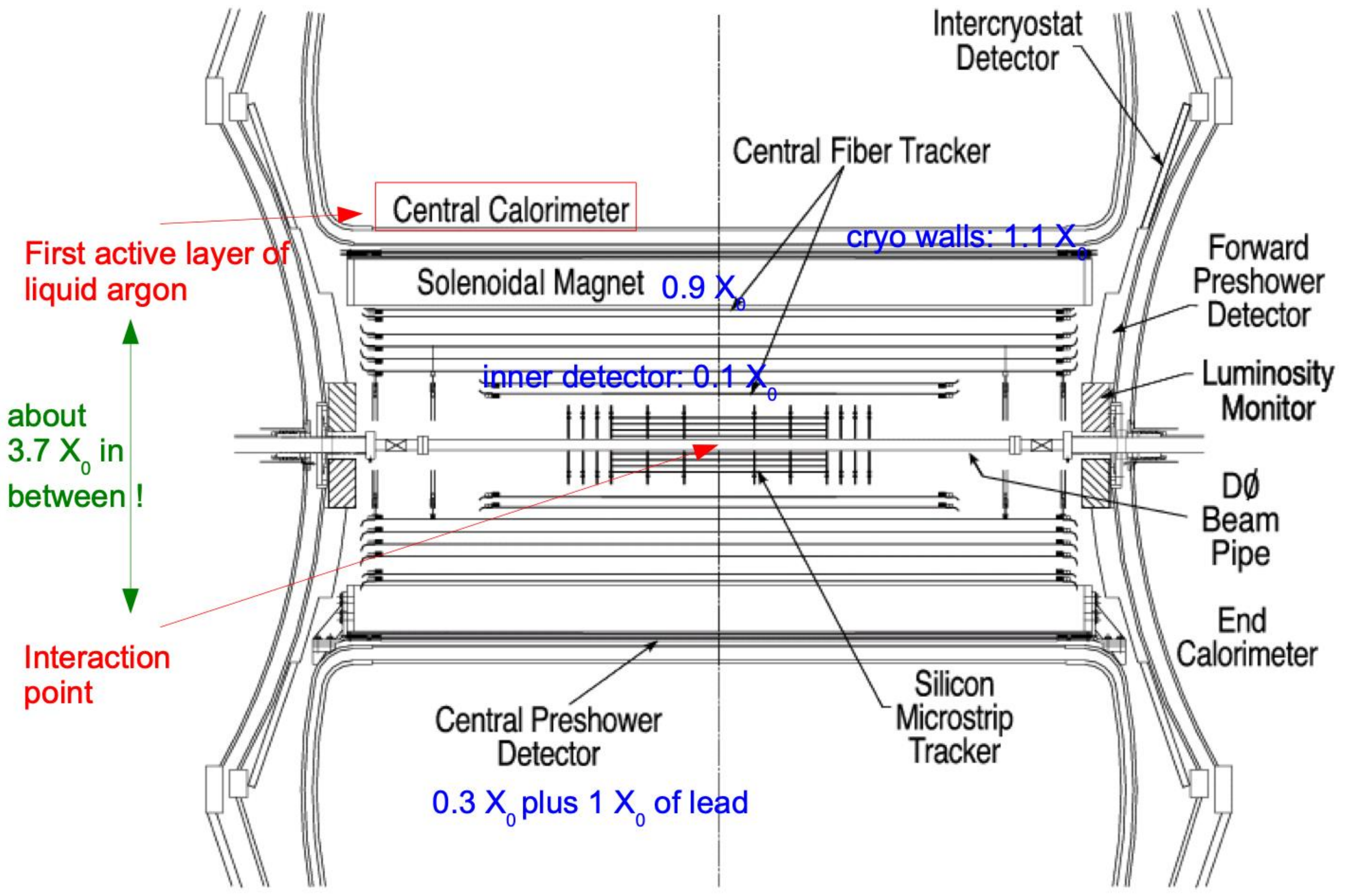
Scalar E_T (electron removed) from W->eν events



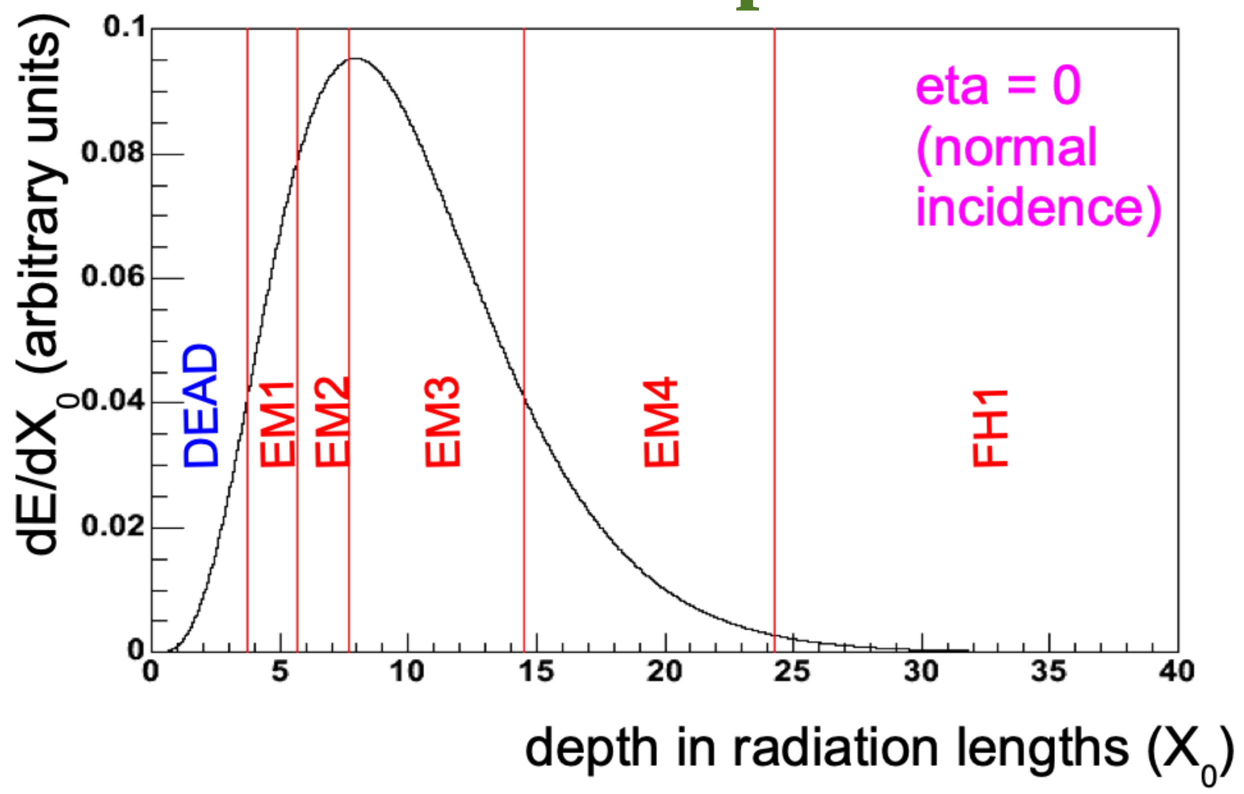
Dead material, electron energy loss

About 3.7 X_0 dead material in front of EM calorimeter

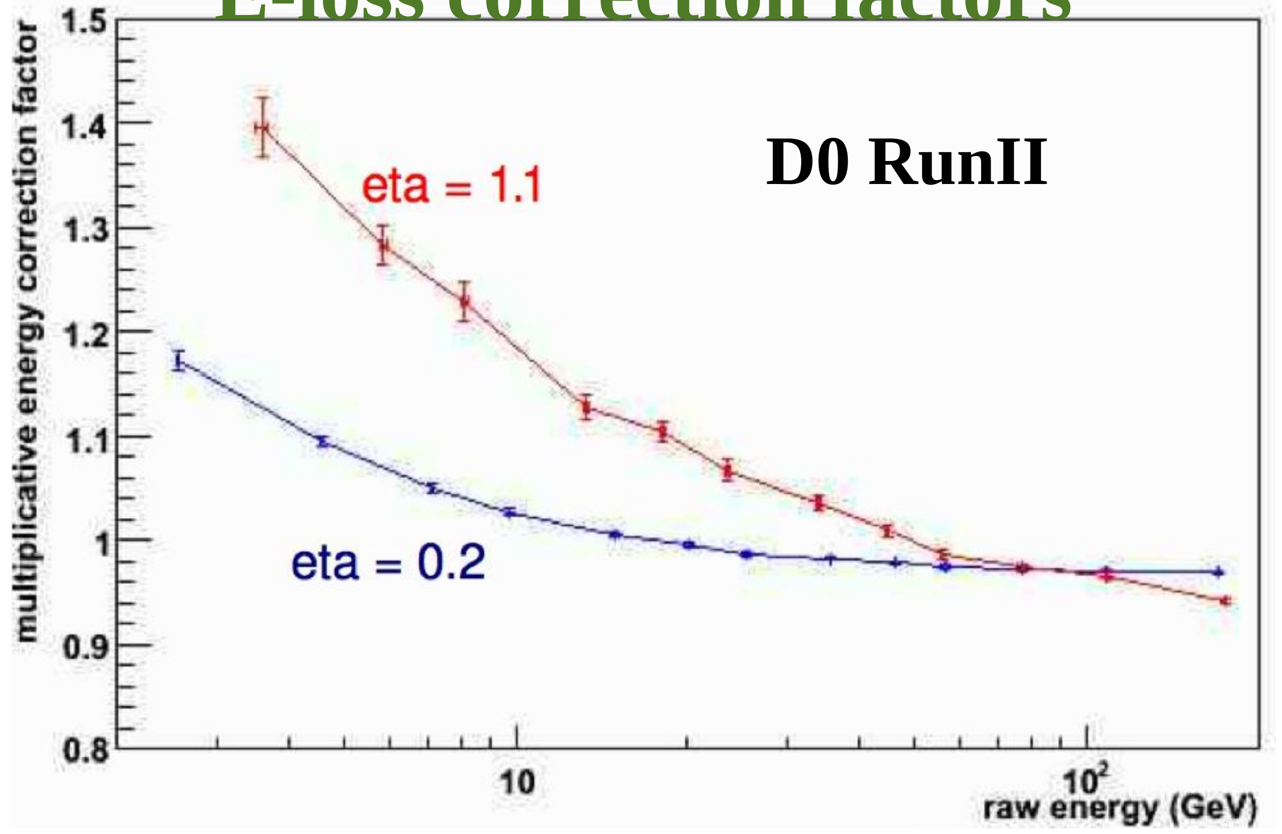
- **Electrons start to loose energy before flying to the EM calorimeter**
- **Depends on electron energy and incidence angle (eta)**



dE/dX vs. depth



E-loss correction factors

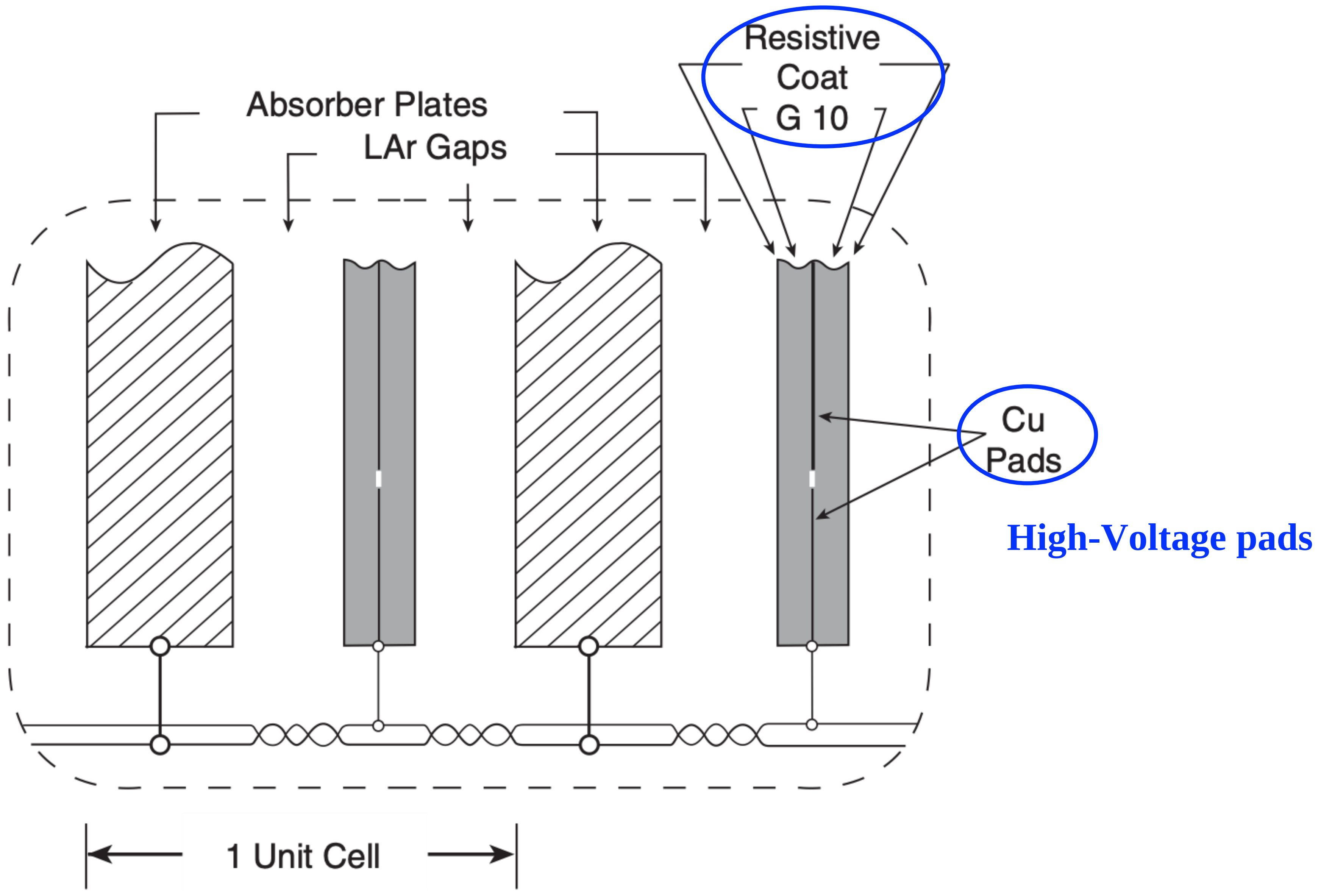


Response reduction due to pileup

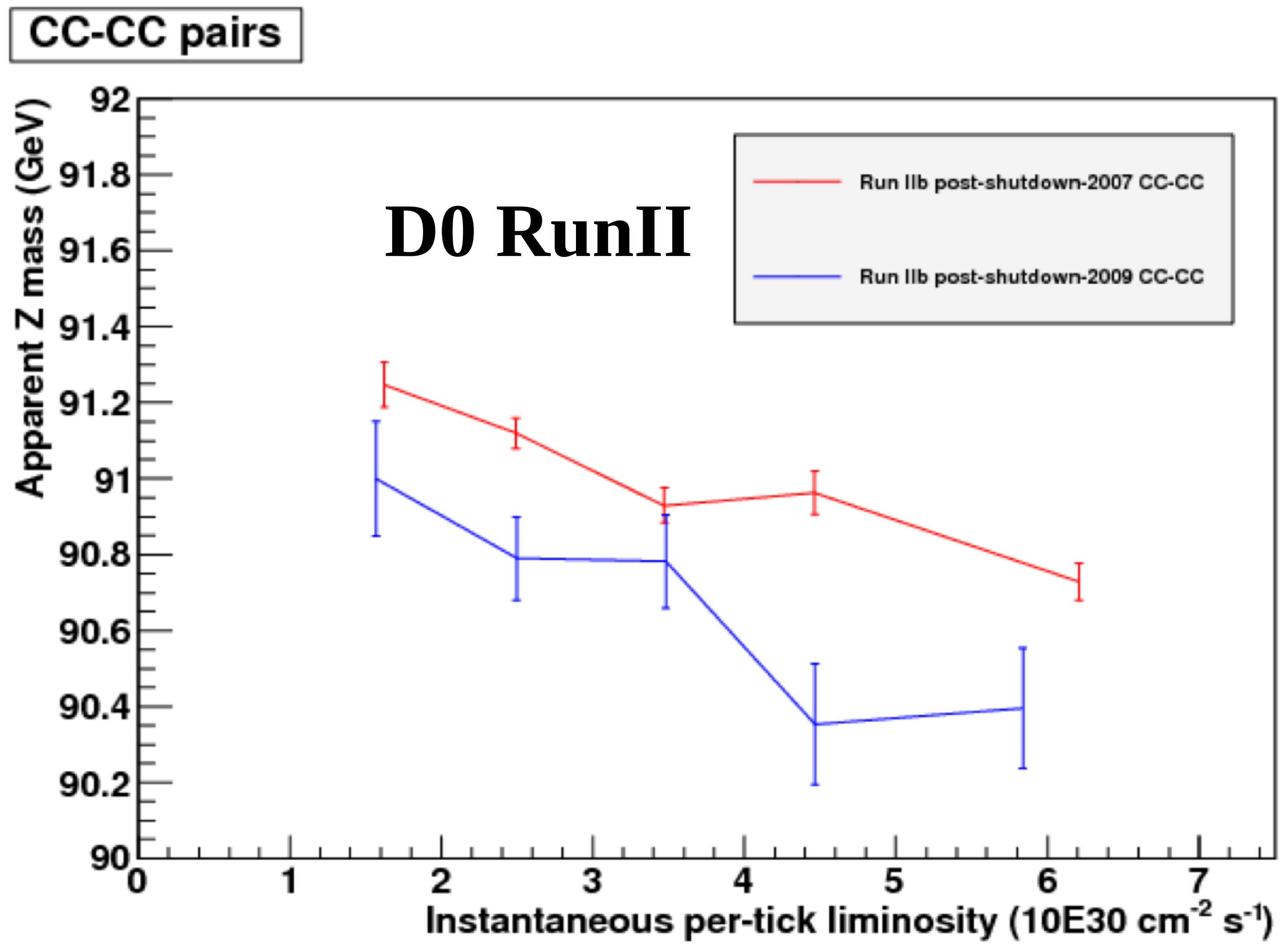
Pileup causes reduction of energy response!

- **Too much pileup creates high current in the readout**
- **The current that flows through resistive coat of the HV pads results in HV drops, thus, reduces the energy response**

Unit cell of the LAr calorimeter readout



Fitted Z mass vs. Inst. Lumi.

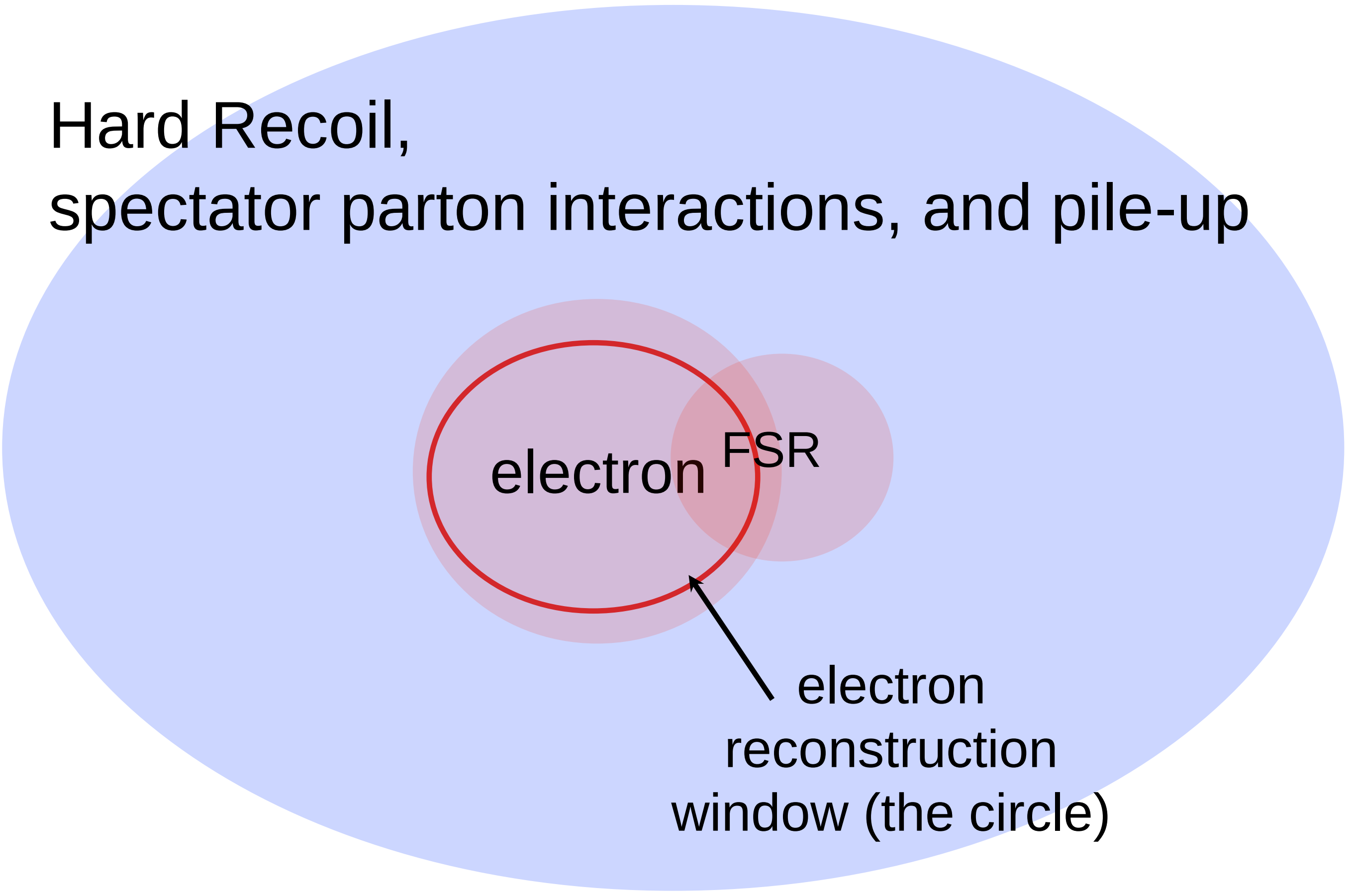


Phys. Rev. Lett. 108, 151804 (2012)

Electron energy model

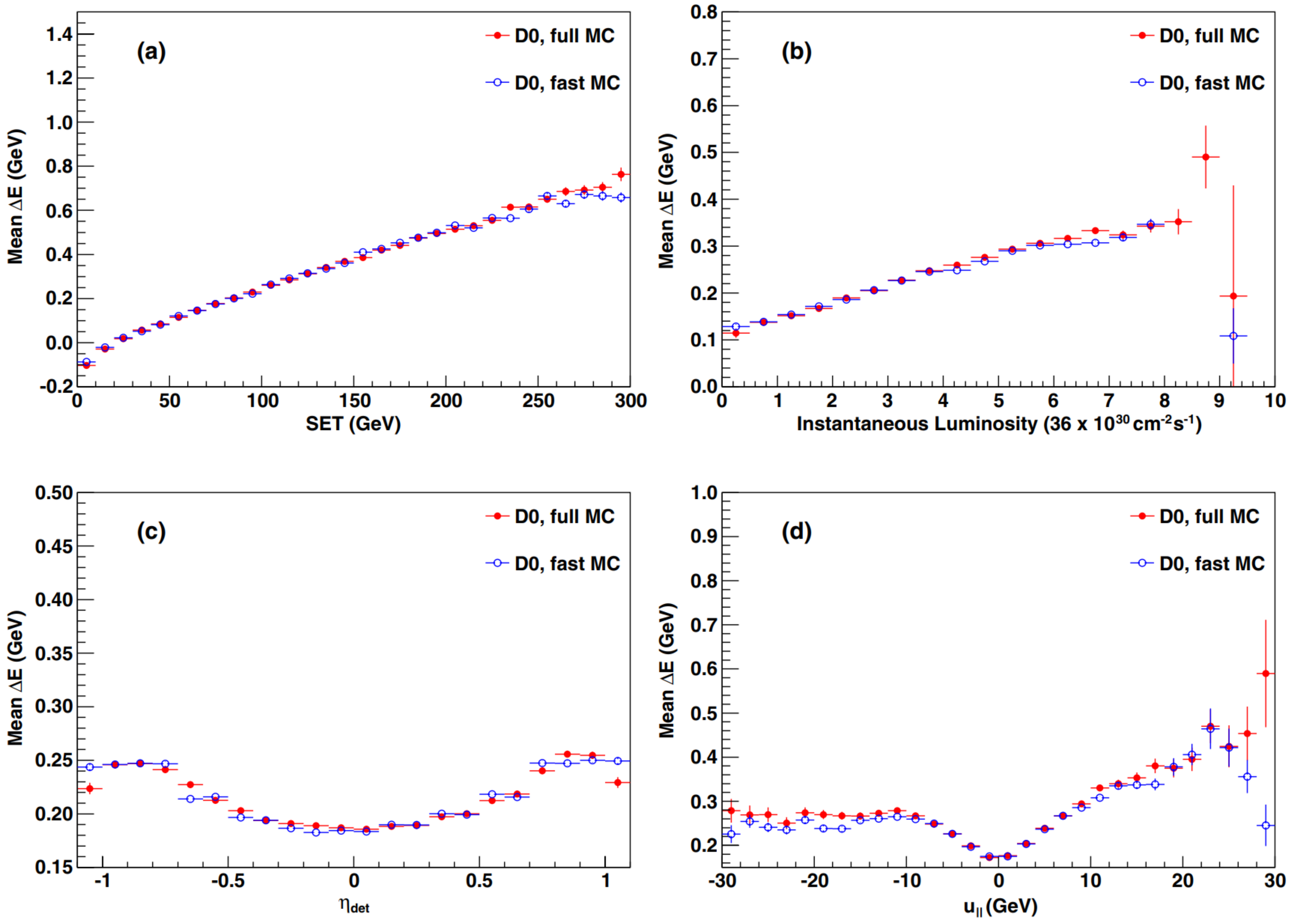
Electron Model: $E_{reco} = R_{EM}(E_{true}) \otimes \sigma_{EM}(E_{true}) + \Delta E_{corr}$

Response **Resolution** **Energy correction**

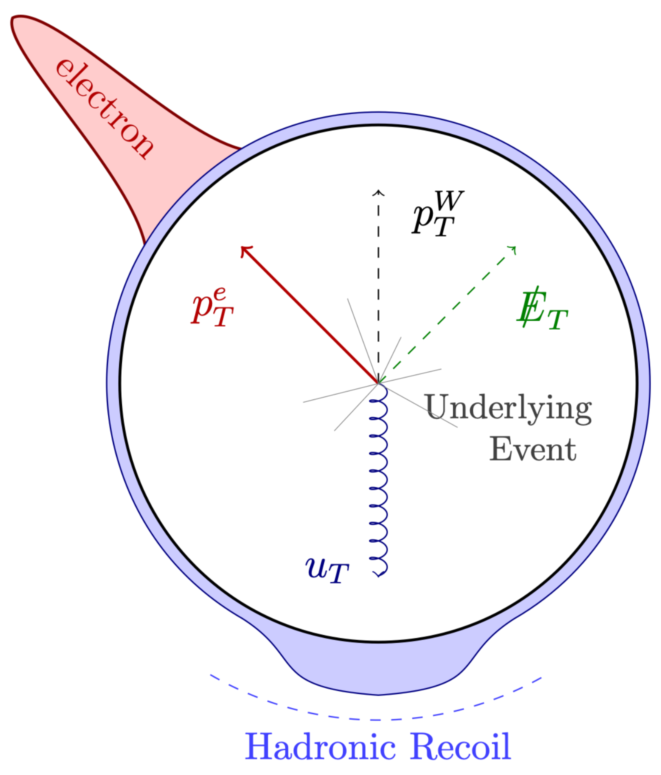


ΔE_{corr} Model:

1. Energy loss due to FSR
2. Recoil, spectator parton interactions and pileup contamination inside the electron reconstruction cone
3. Effects due to electronics noise subtraction and baseline subtraction (to subtract residue energy deposition from previous bunch crossings)



Final electron energy scale

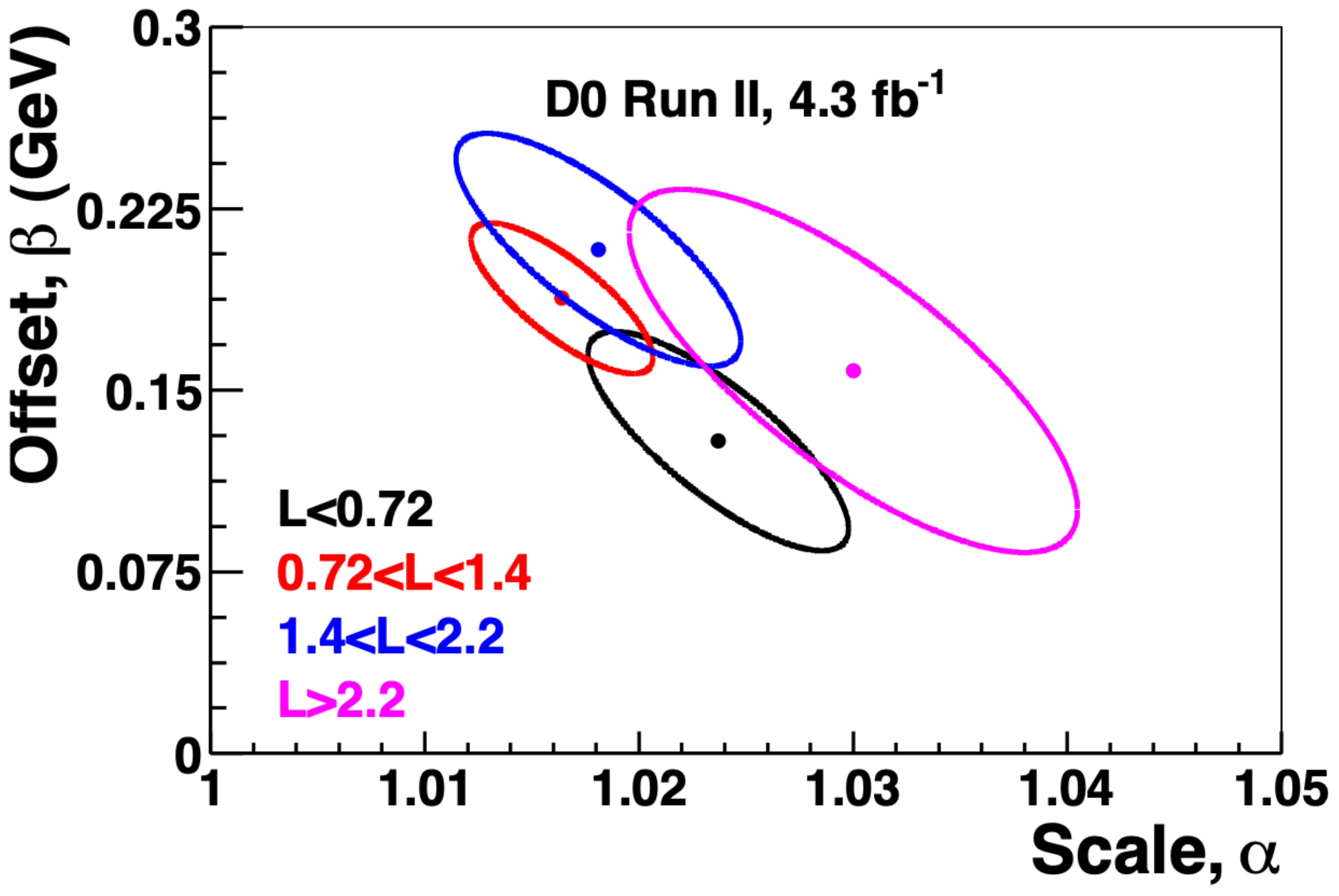


After the correction and modeling of the non-linear energy responses, the final electron energy response is calibrated using Z->ee events assuming a linear response:

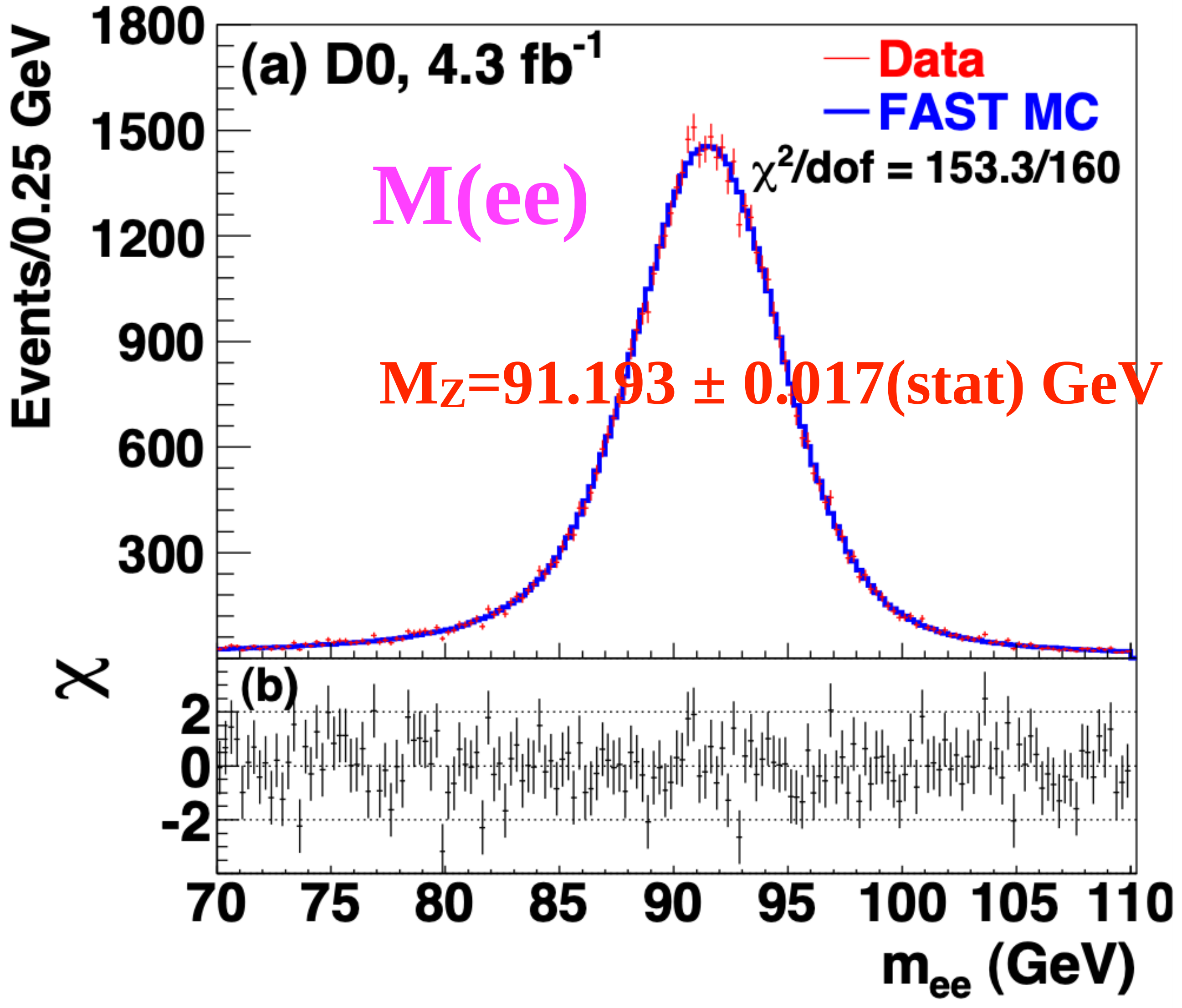
$$R_{EM}(E_{true}) = \alpha \cdot (E_{true} - \bar{E}_{true}) + \beta + \bar{E}_{true}$$

Essentially, measuring the ratio M_W/M_Z , limited by the Z->ee statistics

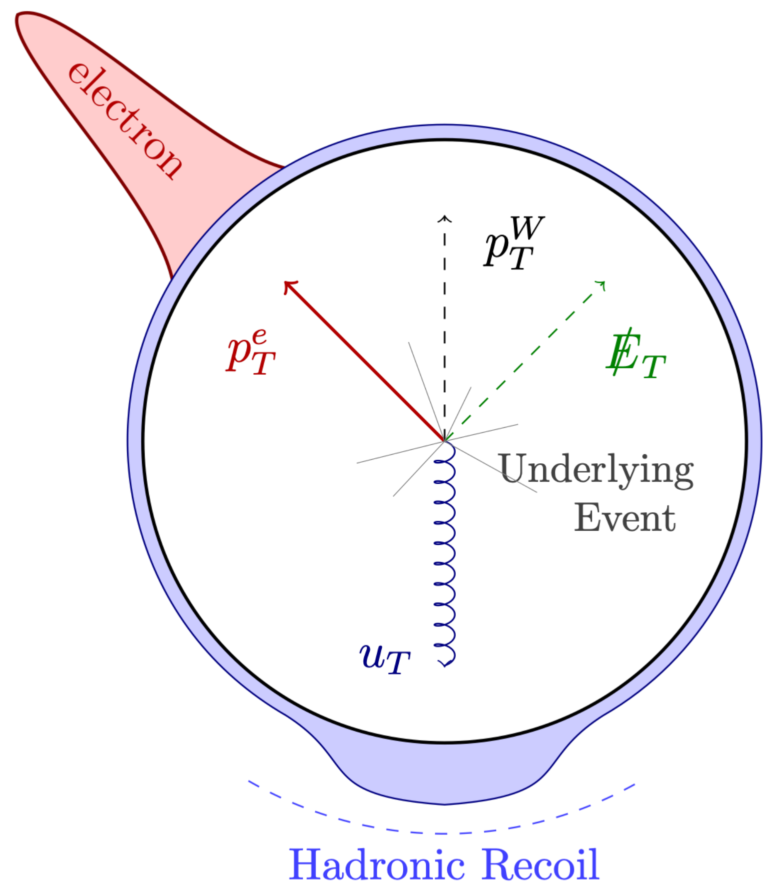
Scale and offset are determined in 4 inst. lumi. bins



Validation: it was calibrated using Z mass, now, we re-determine the Z mass using the calibration, we should find back the Z mass we put in.



Hadronic recoil model



Recoil Model:

$$\vec{u}_T = \vec{u}_T^{\mathrm{Hard}} + \vec{u}_T^{\mathrm{Soft}} + \vec{u}_T^{\mathrm{Elec}} + \vec{u}_T^{\mathrm{FSR}}$$

"pure" Hard Recoil balancing W or Z boson

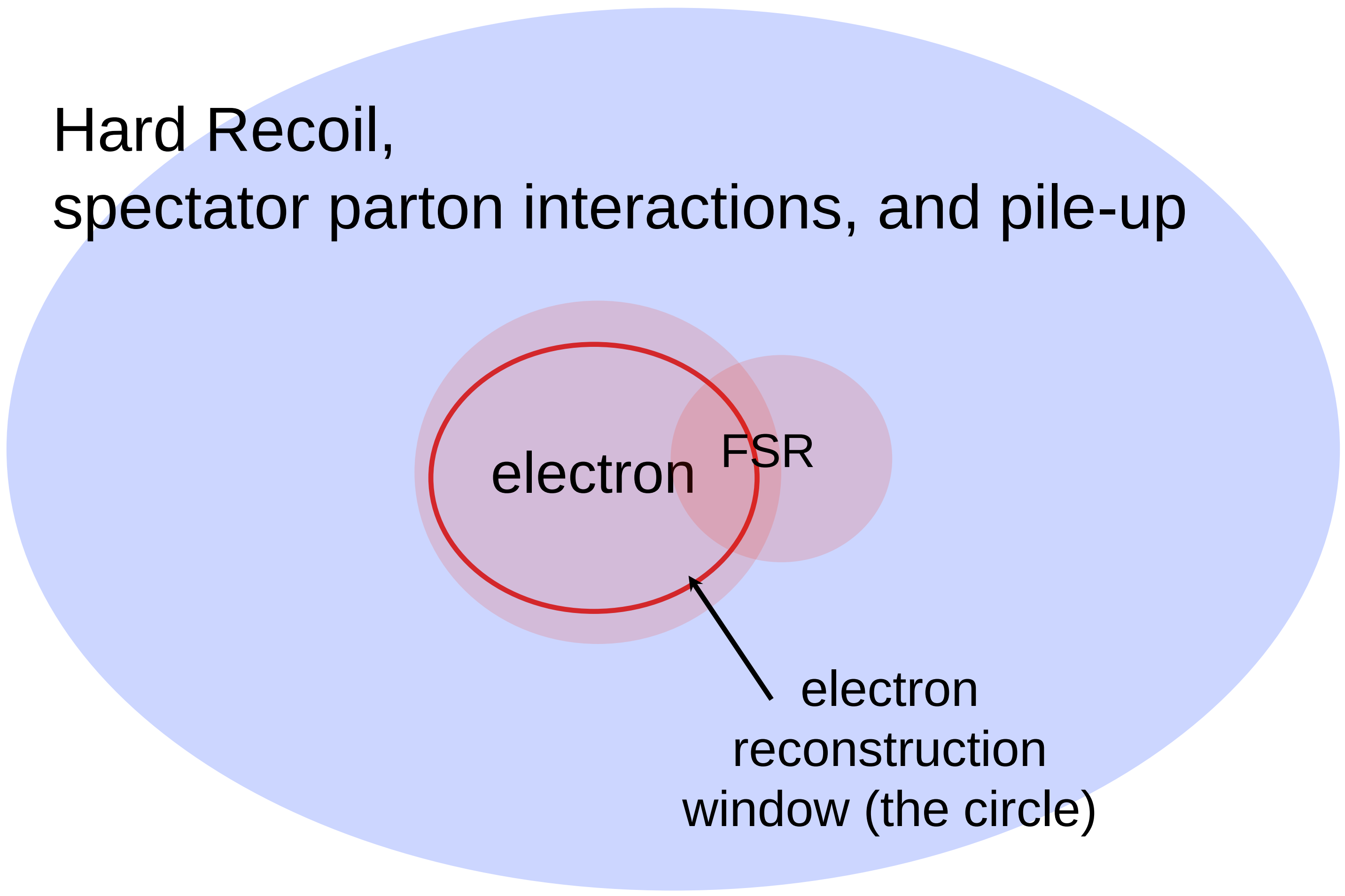
Soft Recoil: pileup and spectator parton interactions

Recoil energy that falls in the electron reconstruction window, as well as electron energy leakage to the recoil.

FSR photons that fly outside the electron reconstruction window.

In the same framework of ΔE_{corr} Modeling

What has been added to (subtracted from) the electron has to be subtracted from (added to) the recoil.



Phys. Rev. Lett. 108, 151804 (2012)

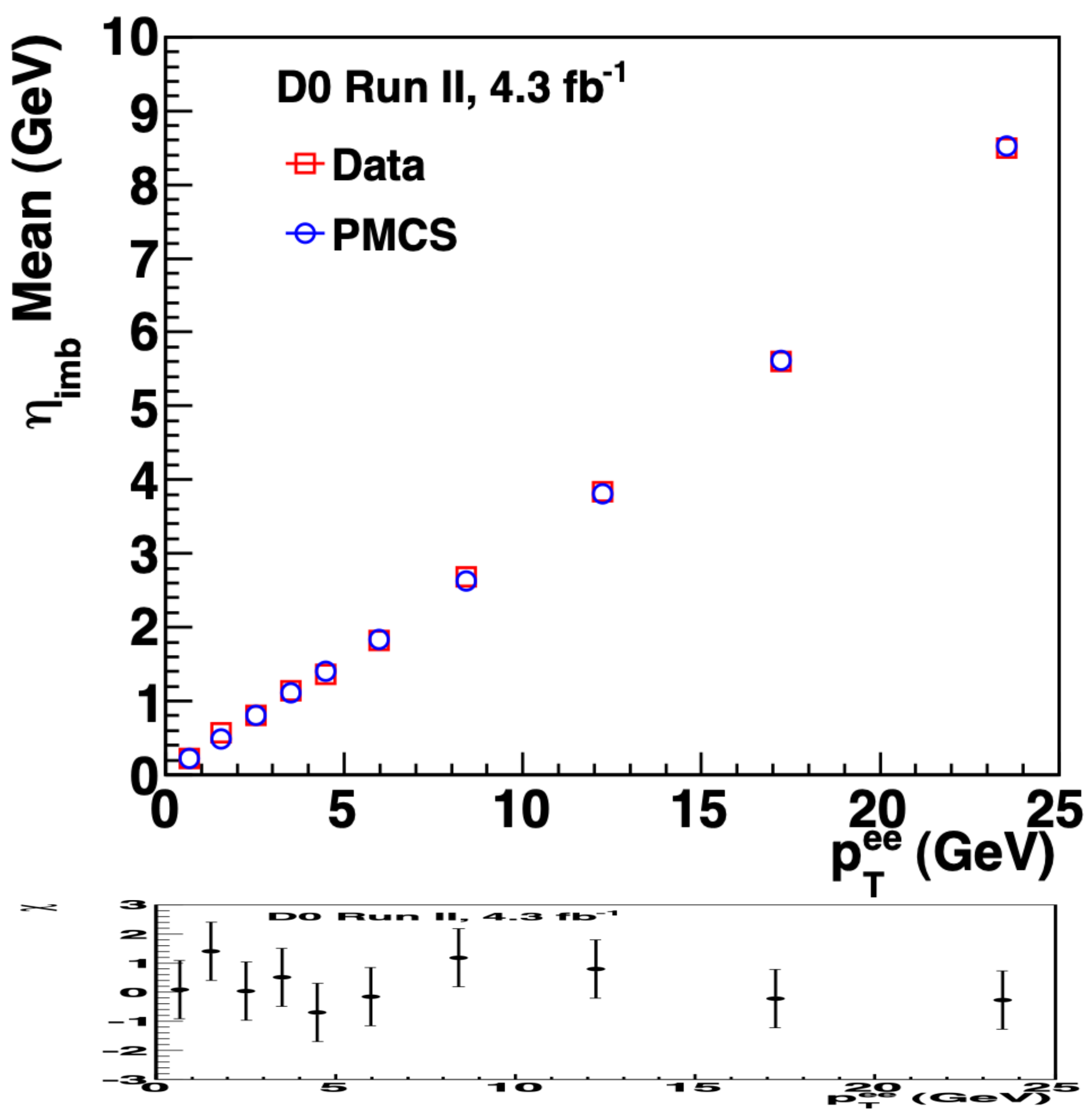
Recoil fine tuning

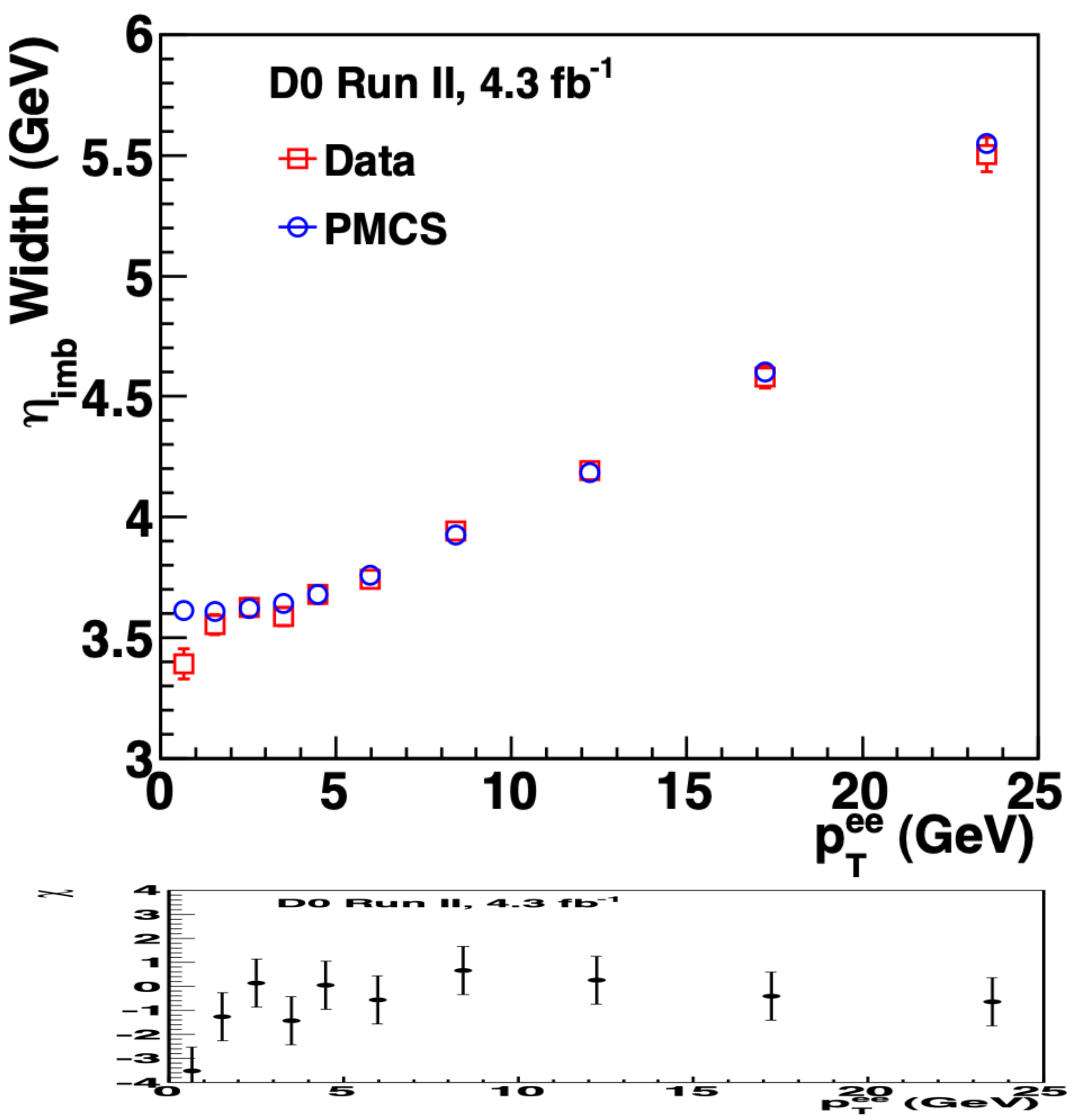
The recoil model is fine tuned using standard UA2 observables

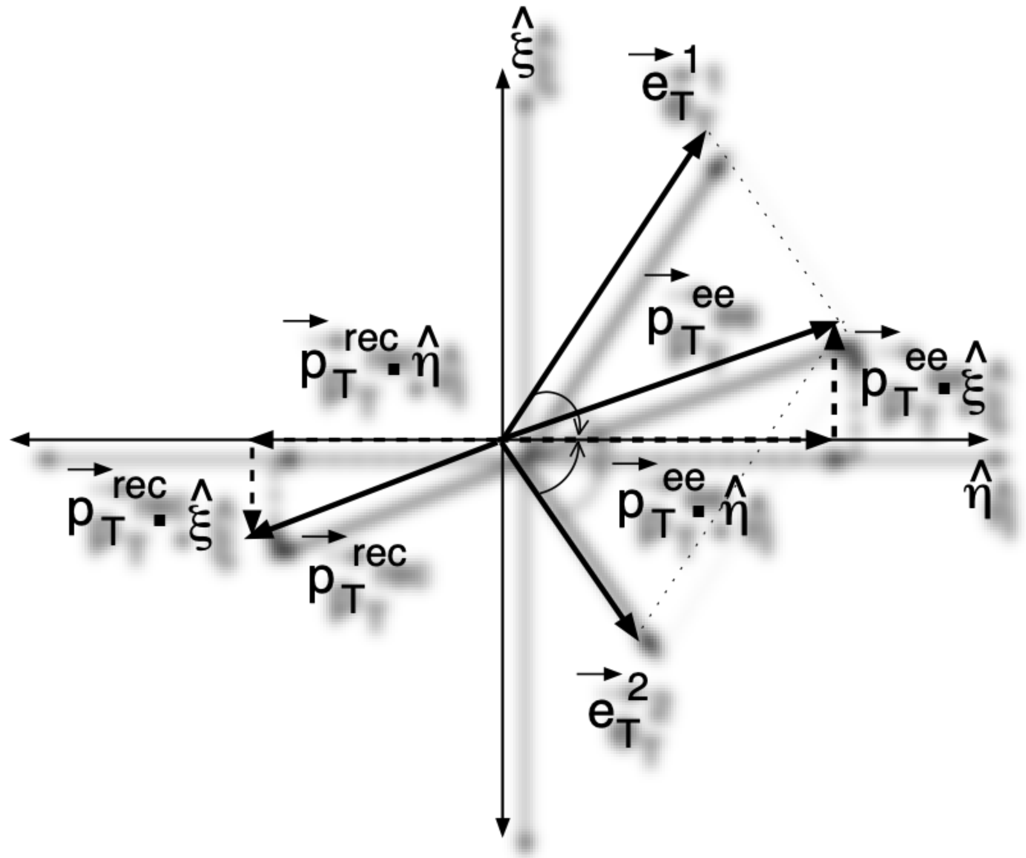
$$\eta_{imb} = (\vec{p}_T^{\,Z} + \vec{u}_T) \cdot \hat{\eta}$$

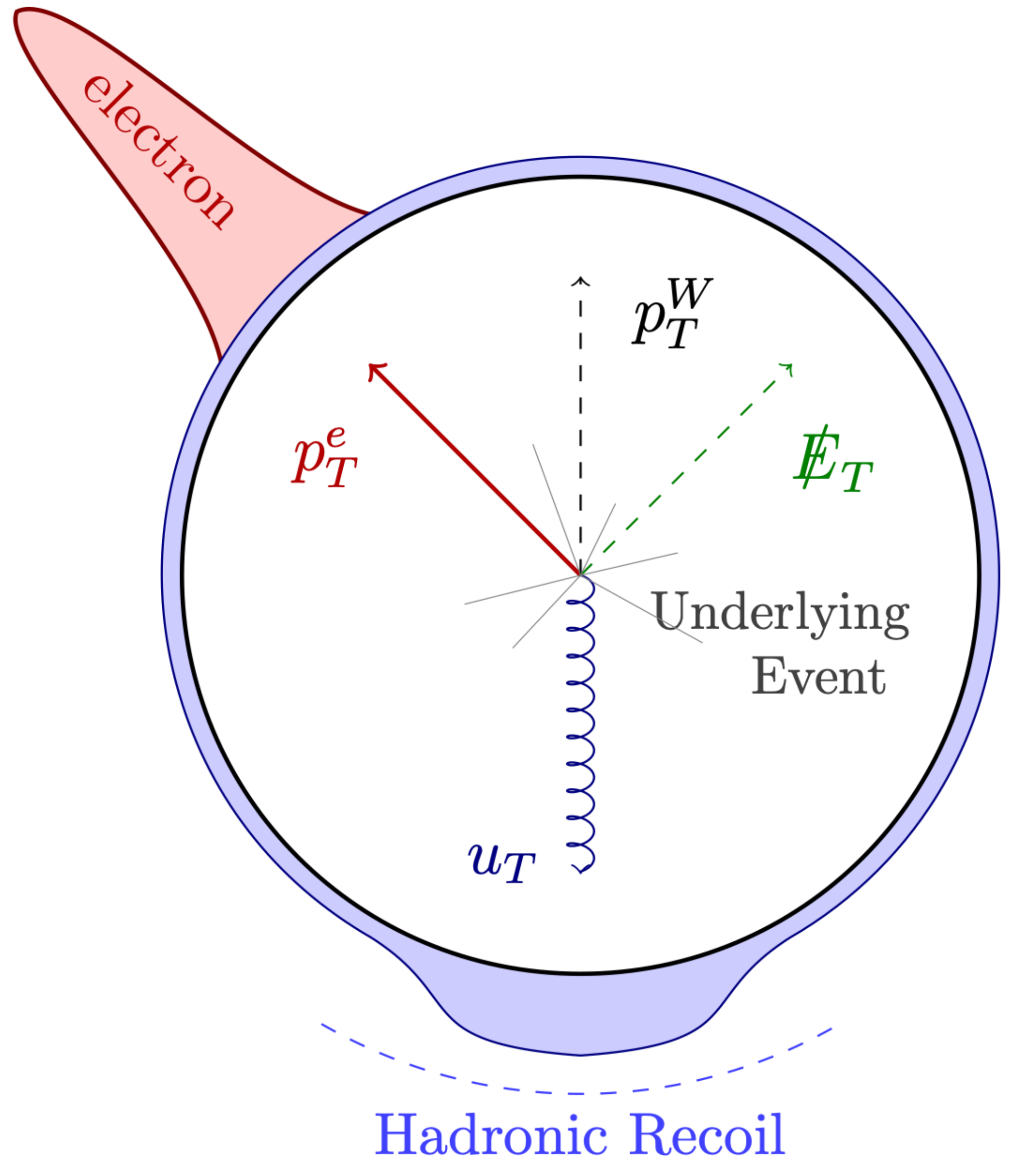
- **Use the mean of η-imbalance to tune the recoil response**
- **Use the width of η-imbalance to tune the recoil resolution**

η-axis: the bisector of two electron momenta of Z->ee events









Electron efficiency model

Efficiency modeling in the high inst. lumi. condition is challenging:

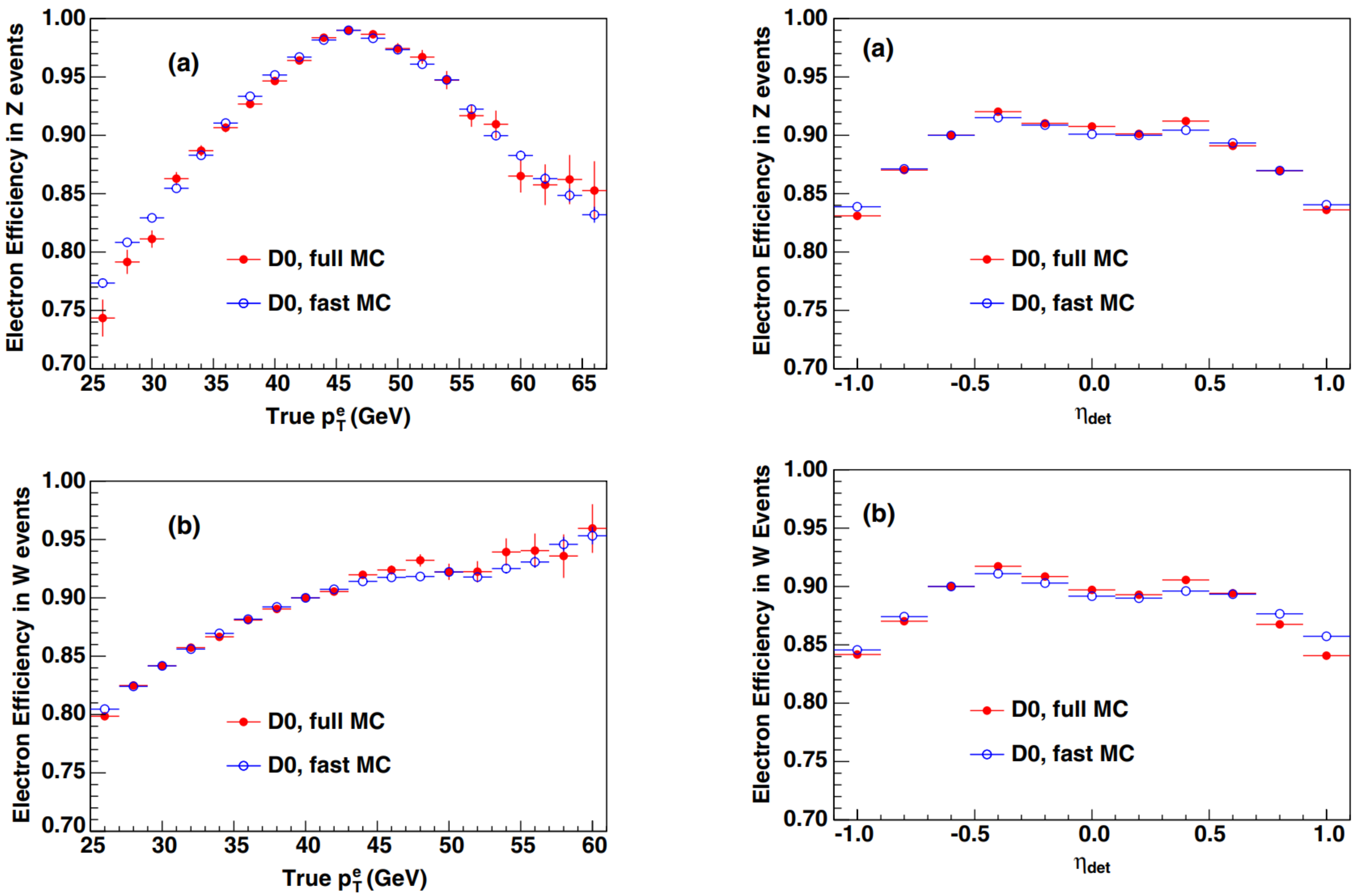
- pileup and hard recoil contaminate the electron reconstruction window,

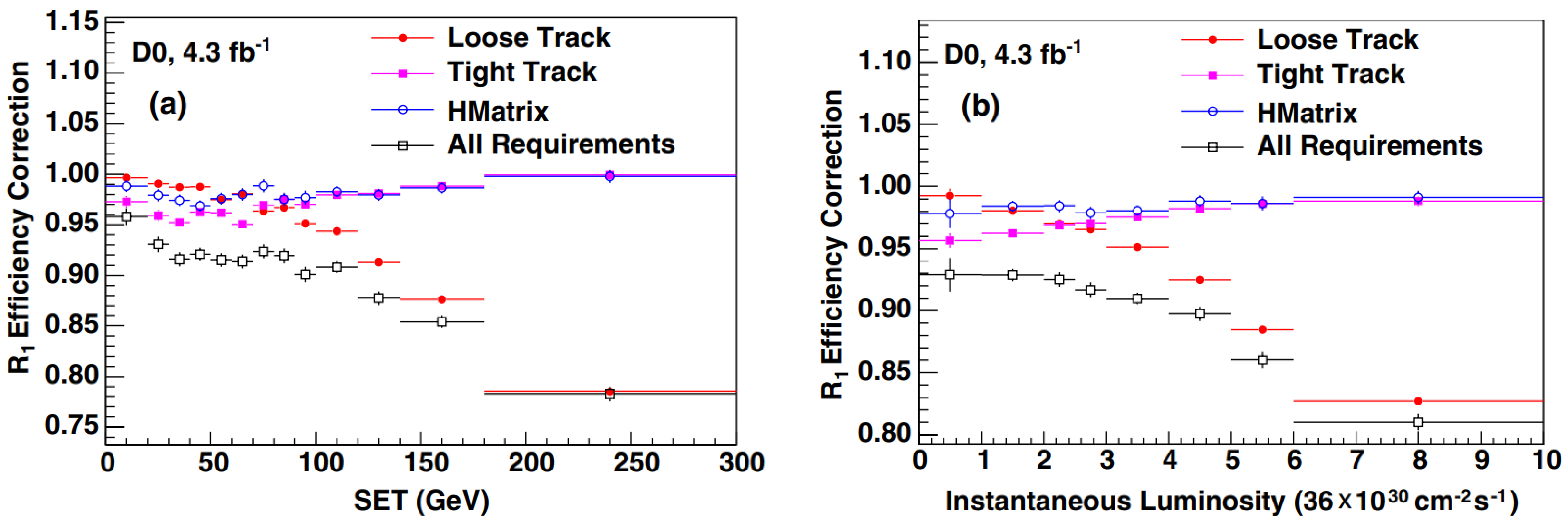
- correlations with electron kinematics.

A two-step modeling:

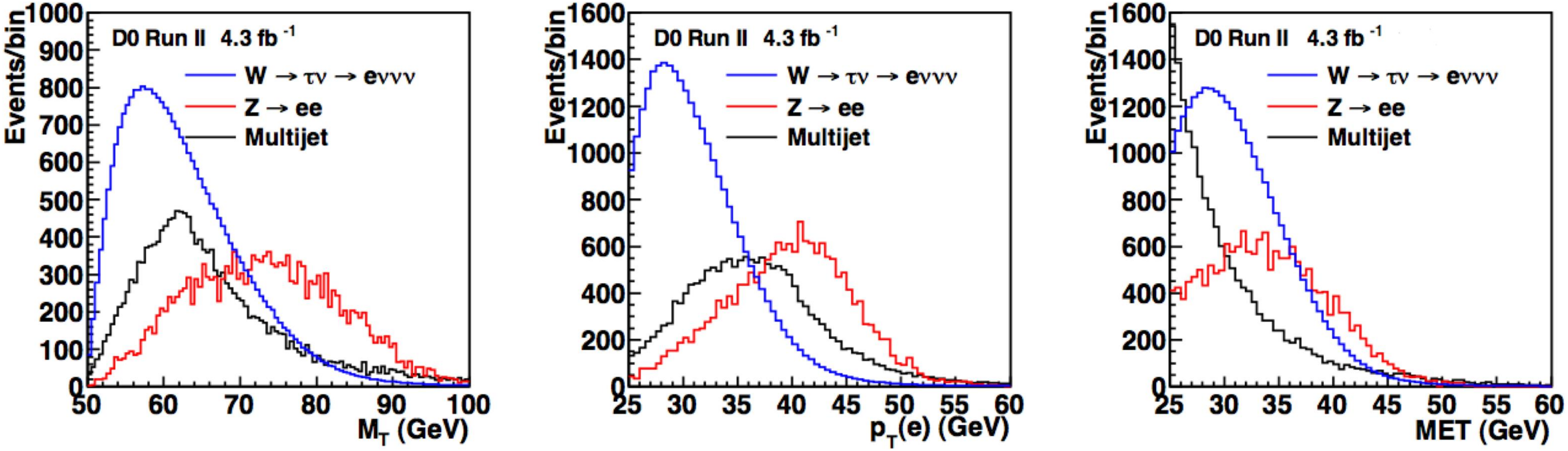
- model the efficiency in a detailed simulation overlaid with pileup from collider data.

- check efficiency dependences using Z->ee events comparing data and detailed simulation.





Backgrounds



Backgrounds:

W->tau nu : 1.67%

Z->ee: 1.08%

Multijet (QCD): 1.02%

Z->ee :
When the other electron falls in the cracks of the EM module
Estimated using electron + electron track

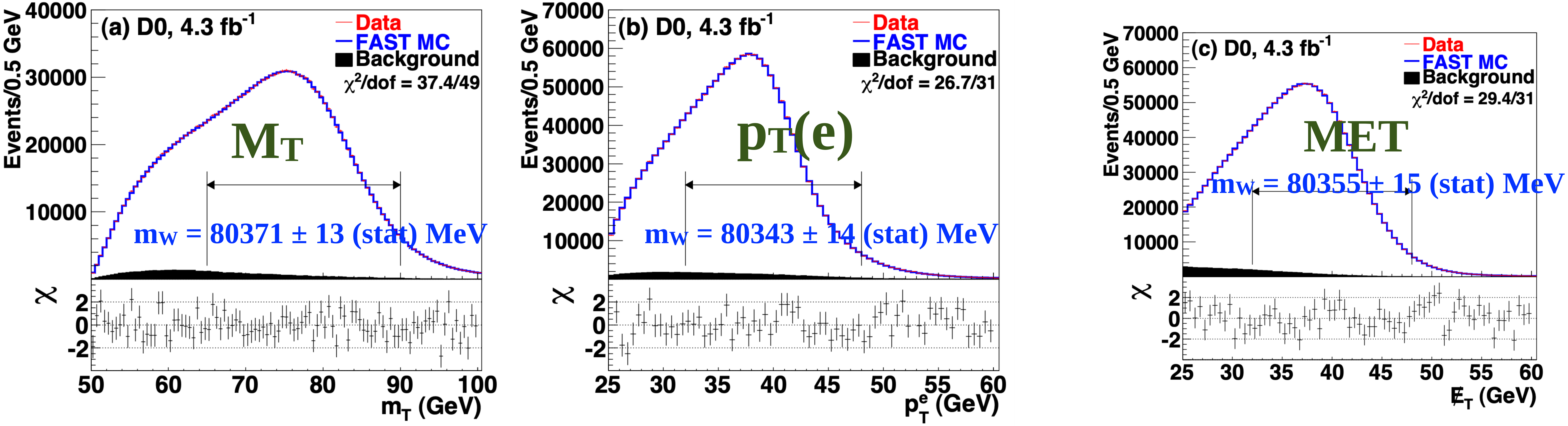
Multijet (QCD): matrix method, solving equation with loose cuts

$$N_L^{(i)} = N_W^{(i)} + N_{\mathrm{MJ}}^{(i)},$$

$$N^{(i)} = \epsilon_e^{(i)} N_W^{(i)} + \epsilon_f^{(i)} N_{\mathrm{MJ}}^{(i)},$$

Results using 1/2 of the D0 full data set

1,677k W events



The combined D0 5.3 fb^{-1} result:

$5.3\ fb^{-1} = 1.0\ fb^{-1}$ (2009) + $4.3\ fb^{-1}$ (2012)

$$\begin{aligned} M_W &= 80.375 \pm 0.011\ (\text{stat}) \pm 0.020\ (\text{syst})\ \text{GeV} \\ &= 80.375 \pm 0.023\ \text{GeV}. \end{aligned}$$

PHYSICAL REVIEW LETTERS 108, 151804 (2012) , PHYSICAL REVIEW D 89, 012005 (2014)

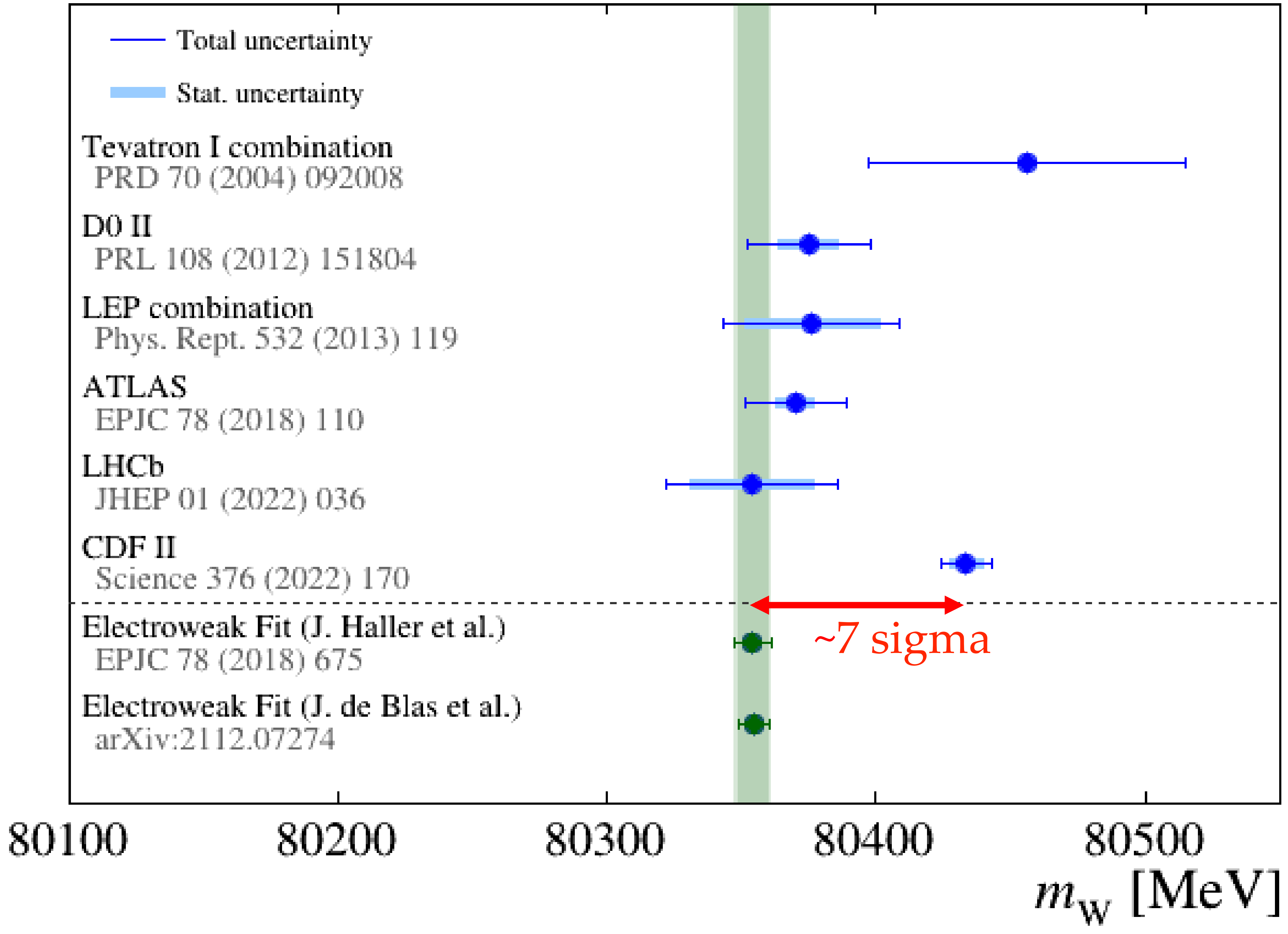
Systematic uncertainties

D0 4.3 fb^{-1}, e-channel

Source	$\sigma(m_W)$ MeV m_T	$\sigma(m_W)$ MeV p_T^e	$\sigma(m_W)$ MeV $\not{E}_T$
Experimental			
Electron Energy Scale	16	17	16
Electron Energy Resolution	2	2	3
Electron Energy Nonlinearity	4	6	7
W and Z Electron energy loss differences	4	4	4
Recoil Model	5	6	14
Electron Efficiencies	1	3	5
Backgrounds	2	2	2
Experimental Total	18	20	24
W production and decay model			
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
W model Total	13	14	17
Total Systematic Uncertainty	22	24	29

Summary

- A highly motivated analysis:
  - Precisely examine the standard model, searching for evidences for new physics.
- CDF Run II gives the most precise measurement at the moment of an uncertainty 9 MeV with ~7 sigma apart from the EW global fit
- For a better understanding of the new CDF results, the D0 measurement using 1/2 D0 data is reviewed in this talk, which gave a 23 MeV precision in 2012.
- Future results are expected from LHC experiments and future e+e- colliders.



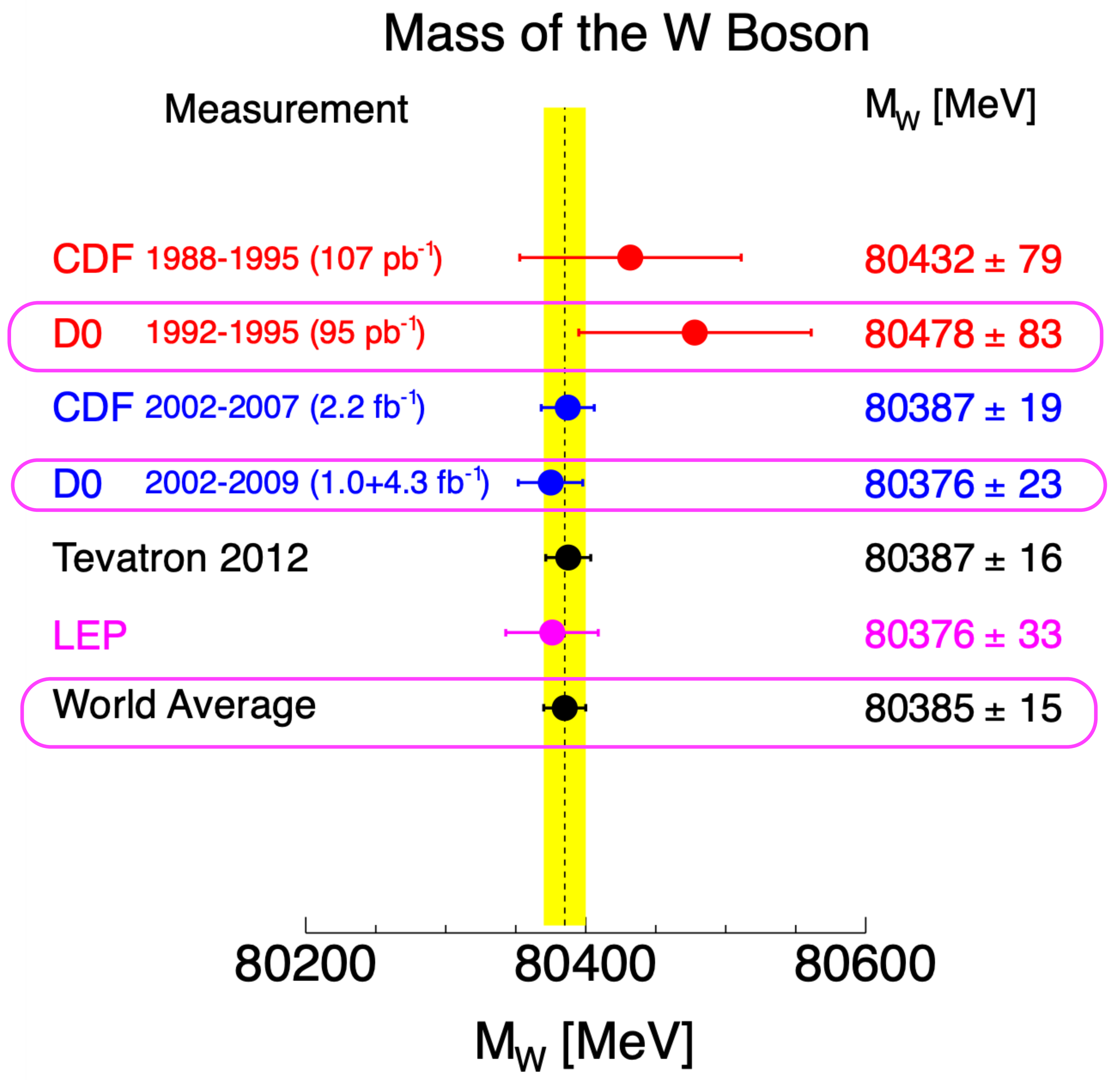
Backup slides

Uncertainties and projection to the D0 full data set

CC: Central Calorimeter
EC: Endcap Calorimeter

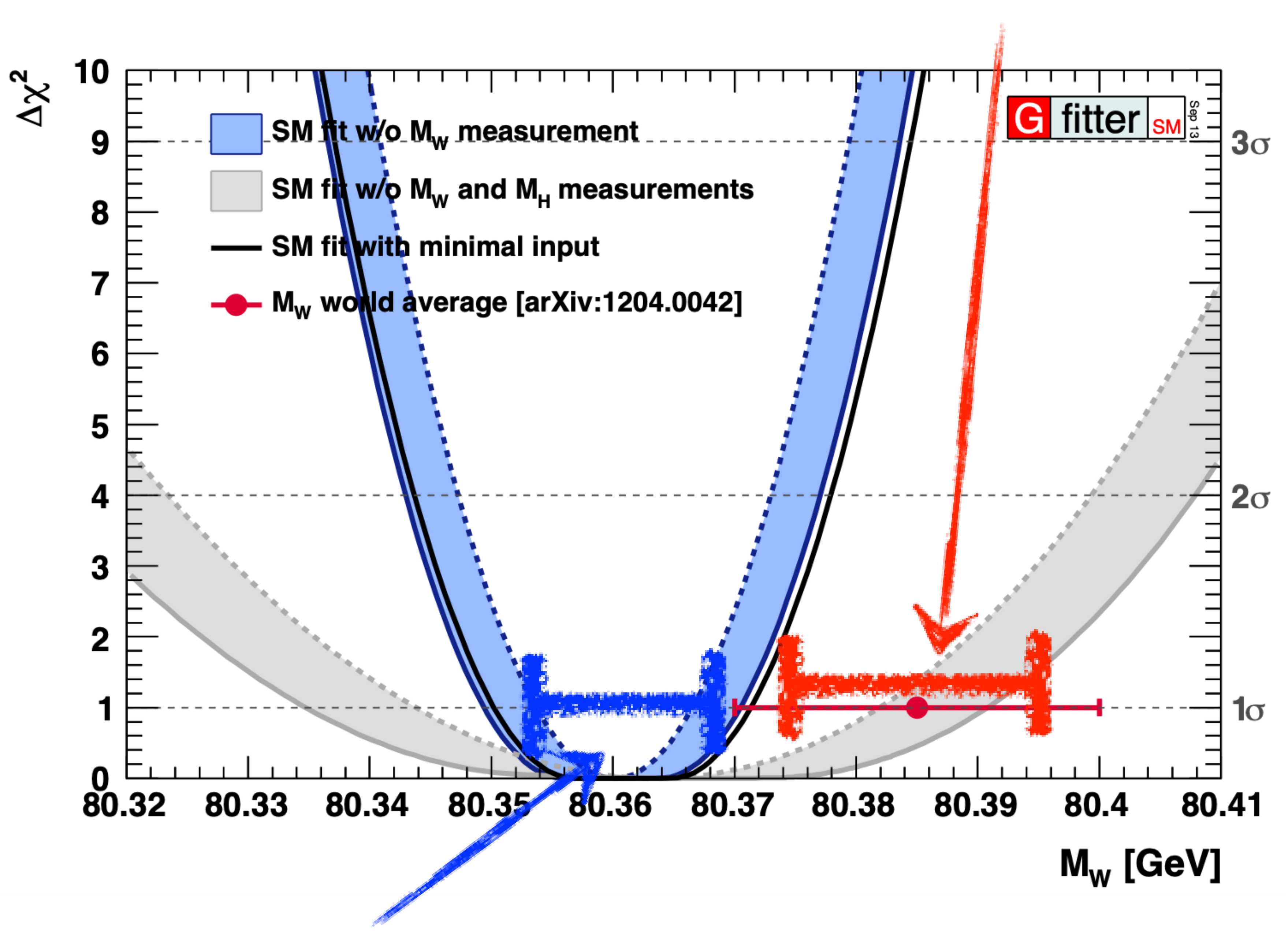
Source (Unit in MeV)	Published (2009) 1 fb^{-1} CC	Published (2012) 4.3 fb^{-1} CC	Projection 10 fb^{-1} CC	Projection 10 fb^{-1} CC+EC
Statistical	**23**	**13**	**9**	**8**
Experimental syst.				
Electron energy scale	34	16	11	10
Electron energy resolution	2	2	2	2
Electron energy nonlinearity	4	4	2	2
W and Z electron energy loss differences	4	4	2	2
Recoil model	6	5	3	2
Electron efficiencies	5	1	1	1
Backgrounds	2	2	2	2
Exp. Syst. Subtotal	35	18	12	11
Theoretical syst.				
PDF	9	11	11	5
QED	7	7	3	3
Boson pT	2	2	2	2
Theo. Syst. Subtotal	12	13	12	6
Systematic total	**37**	**22**	**17**	**13**
Total	**44**	**26**	**19**	**15**

World average and expected new results



Adding the expected new D0 results:

	CC (10 fb^{-1})	CC+EC (10 fb^{-1})
We will have	19 MeV	15 MeV
New world aver. :	14 MeV	12 MeV



If the central value doesn't change in the future, we can expect a 2-sigma divination apart from the SM. But if we expect better discrimination, we need CDF, ATLAS, CMS, and future e+e- colliders: CEPC, ILC, FCC-ee

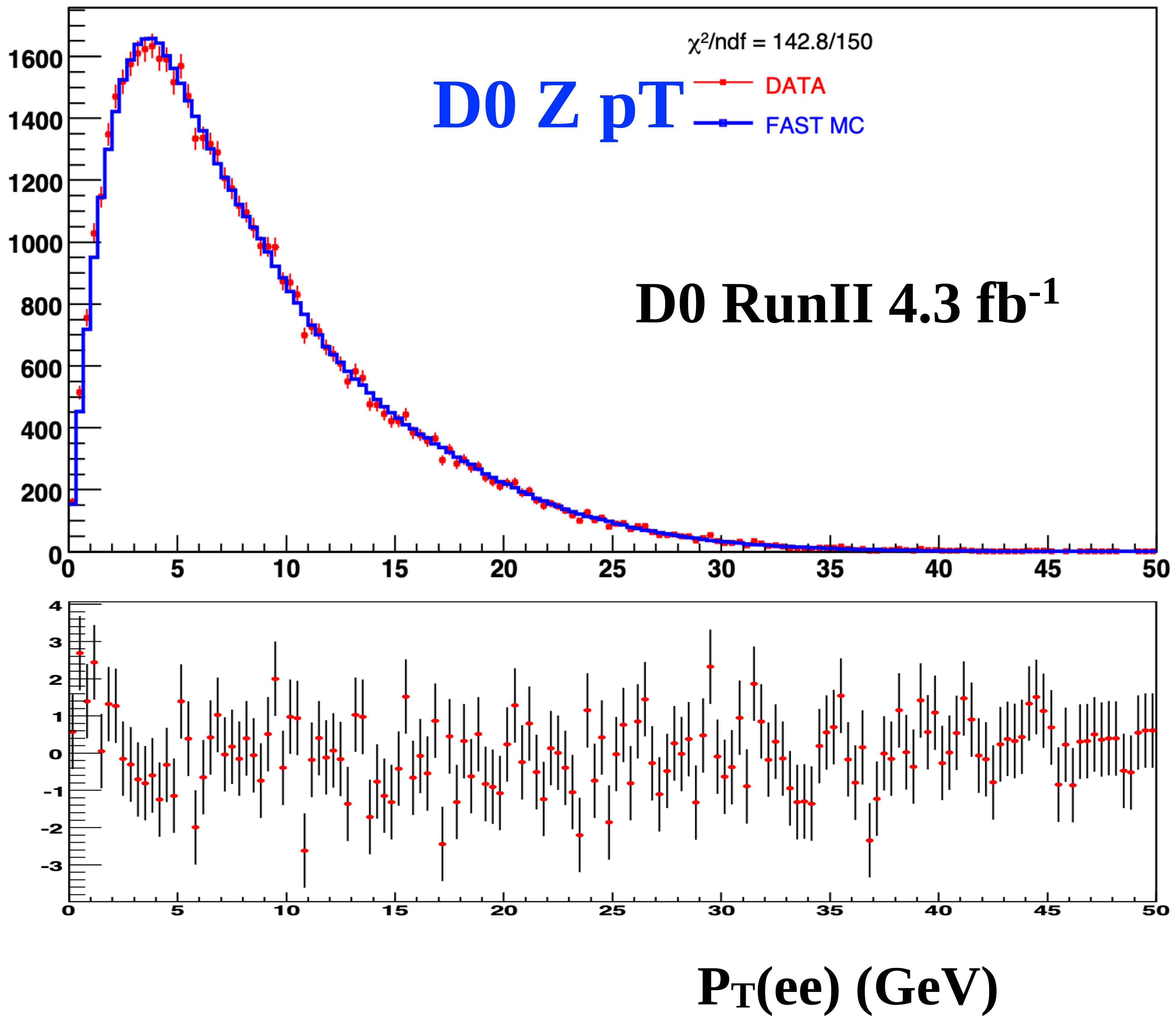
The predicted W mass uncertainty can also be narrowed by improve the Top mass measurement.

Some words about the PDF Uncertainty

- In principle, the transverse observables (e.g. MT, PT(e)) are insensitive to the uncertainties in the (longitudinal) parton distribution functions (PDF).
- However, our cuts on the leptons η ($|\eta|<1.0$) is not invariant under longitudinal boosts. Changes in PDFs can modify the shapes of the transverse observables under η cuts. Therefore, PDF uncertainties are introduced.
- Ways to reduce the PDF uncertainties:
  - Extending the η coverage as much as possible, including end-cap leptons:
  - Can reduce by a factor of two, need to understand the energy scale, pileup, and backgrounds for the end-cap leptons.
- Reduce the PDF uncertainties by other measurements:
  - e.g. W charge asymmetry measurements.

Theoretical modeling

- **Resbos:** **Next-to-leading order event generator with next-to-next-to-leading logarithm resummation of soft gluons, gives the best boson pT description so far.** [C. Balazs and C. P. Yuan, Phys. Rev. D 56, 5558 (1997).]
- **Photos:** **generates up to two final state radiation photons.** [P. Golonka and Z. Was, Eur. Phys. J. C 45, 97 (2006).]



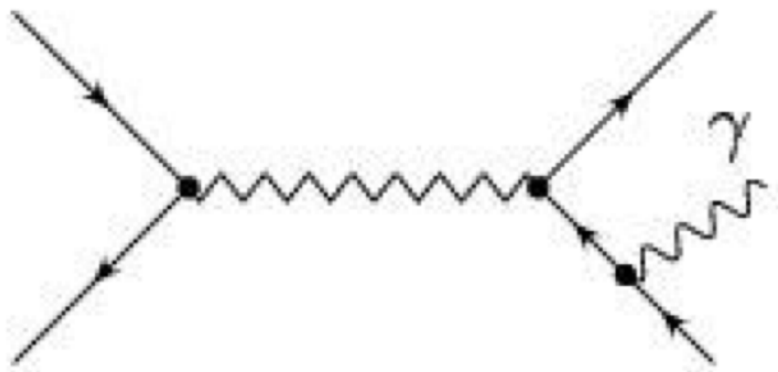
Model of W production and decay

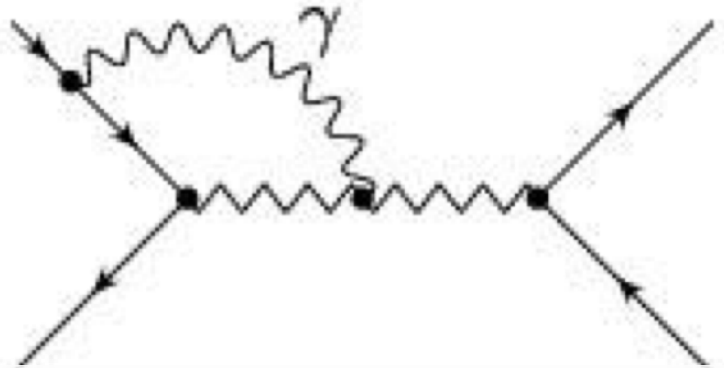
Tool	Process	QCD	EW
RESBOS	W,Z	NLO	-
WGRAD	W	LO	complete $\mathcal{O}(\alpha)$, Matrix Element, ≤ 1 photon
ZGRAD	Z	LO	complete $\mathcal{O}(\alpha)$, Matrix Element, ≤ 1 photon
PHOTOS			QED FSR, ≤ 2 photons

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).





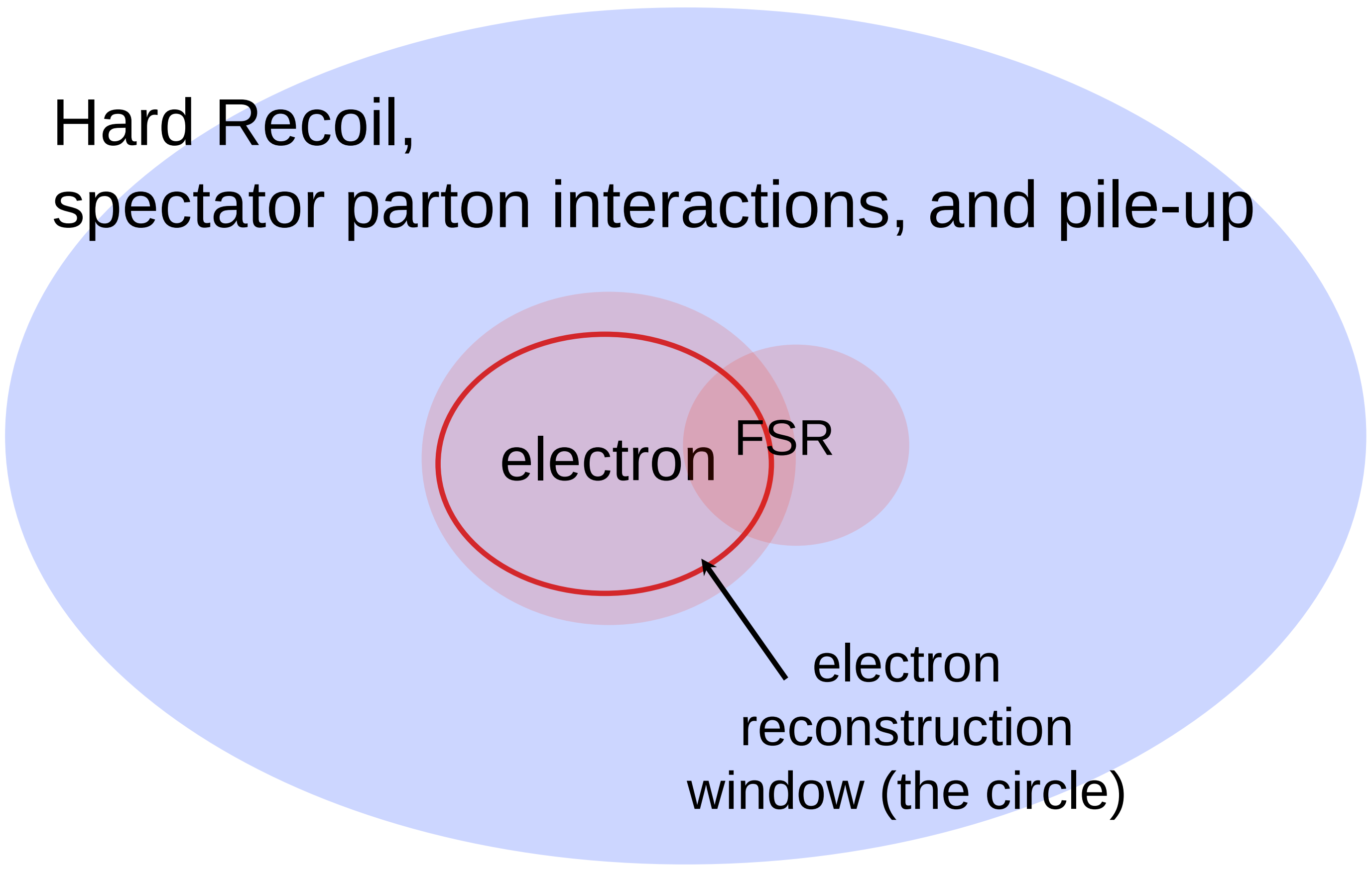
Modeling the pileup contamination

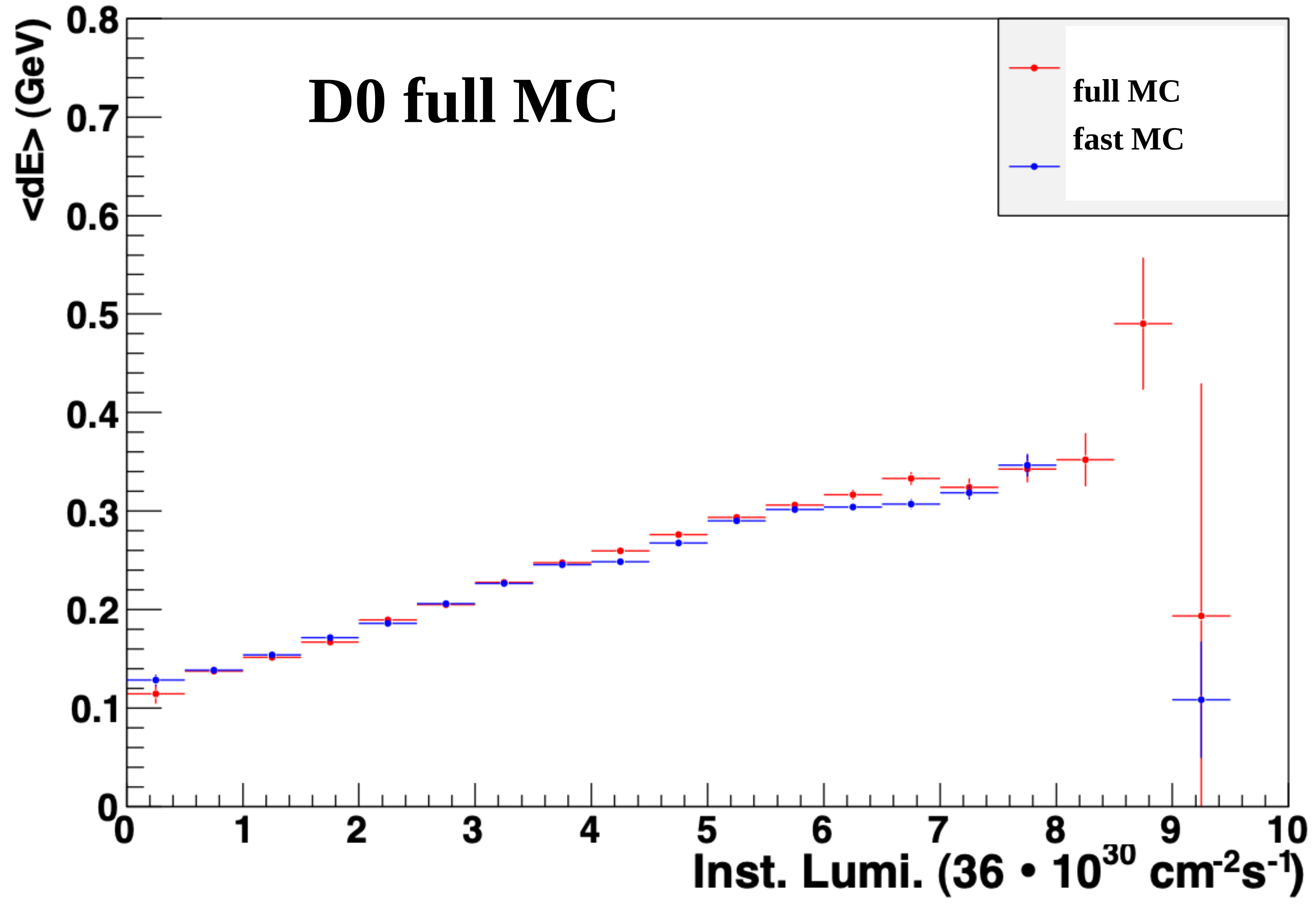
Electron Model: $E_{reco} = R_{EM}(E_{true}) \otimes \sigma_{EM}(E_{true}) + \Delta E_{corr}$

Response **Resolution** **Energy correction**

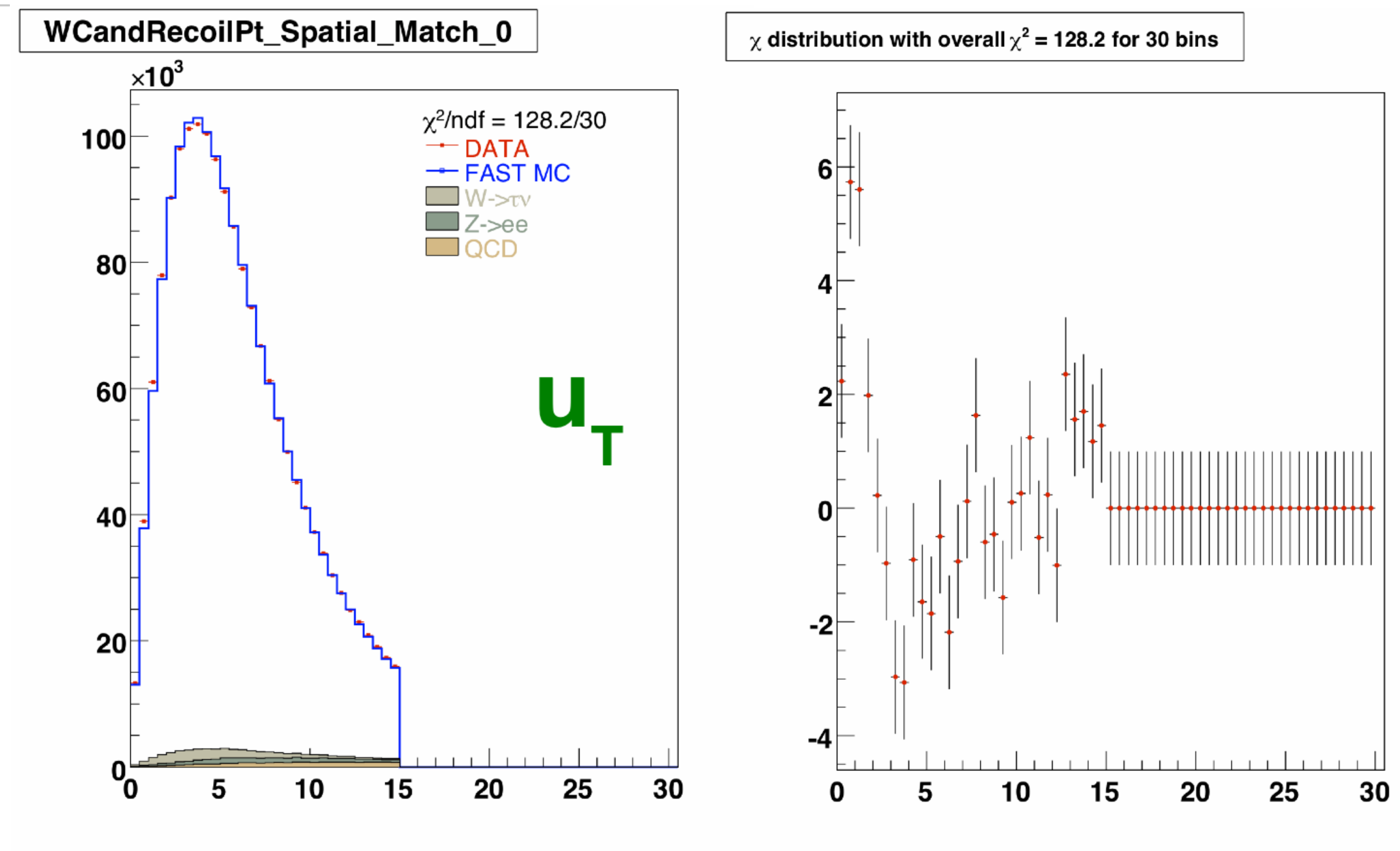
ΔE_{corr} Model:

1. Energy loss due to FSR
2. Recoil, spectator partons interactions and pileup contamination inside the electron reconstruction cone
3. Effects due to electronics noise subtraction and baseline subtraction (to subtract residue energy deposition from previous bunch crossings)

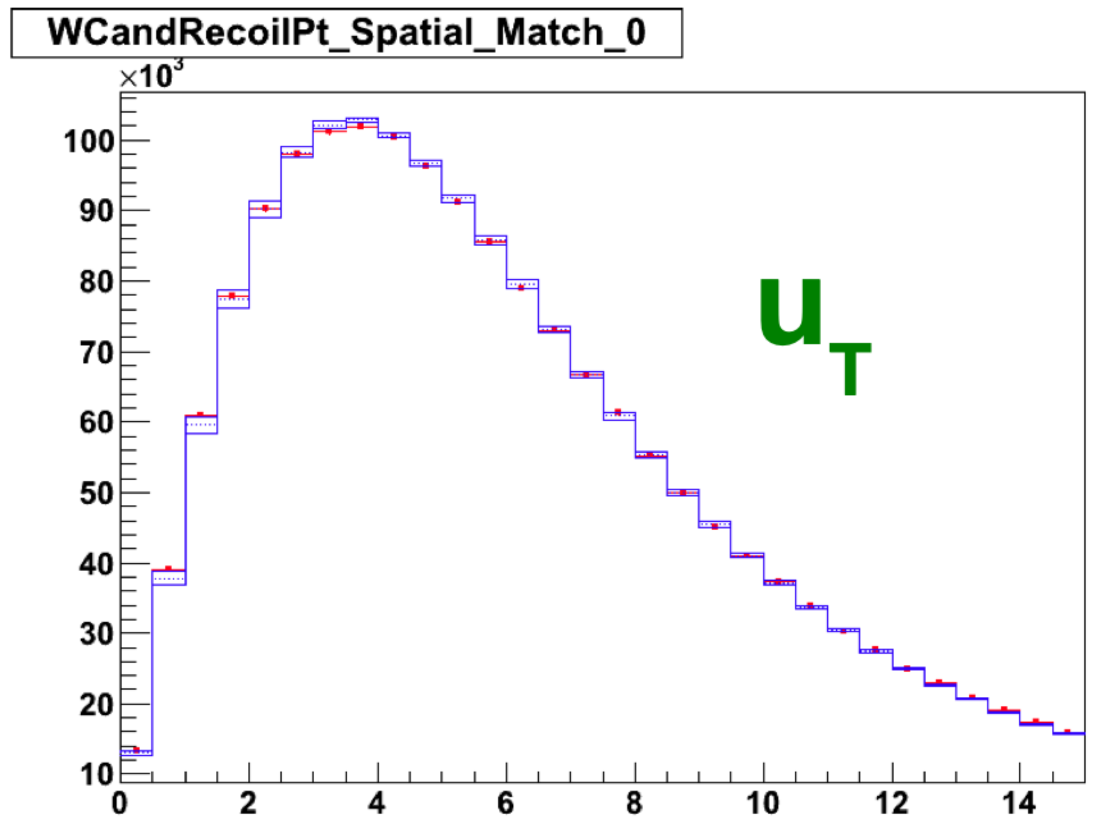




W data



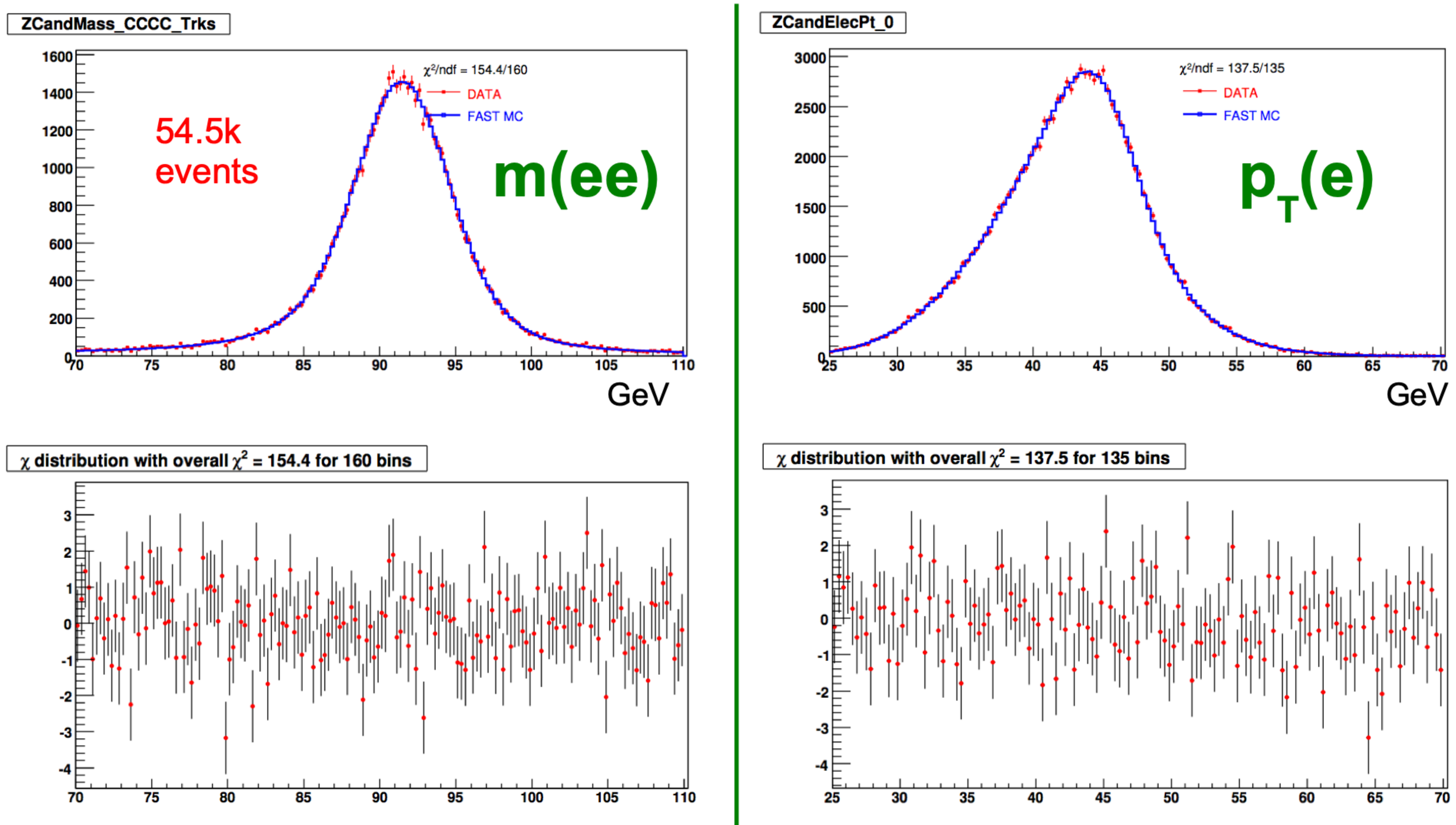
Here the error bars only reflect the finite statistics of the W candidate sample.



These are the same W candidates in the data. The blue band represents the uncertainties in the fast MC prediction due to the uncertainties in the recoil tune from the finite Z statistics.

Good agreement between data and parameterised Monte Carlo.

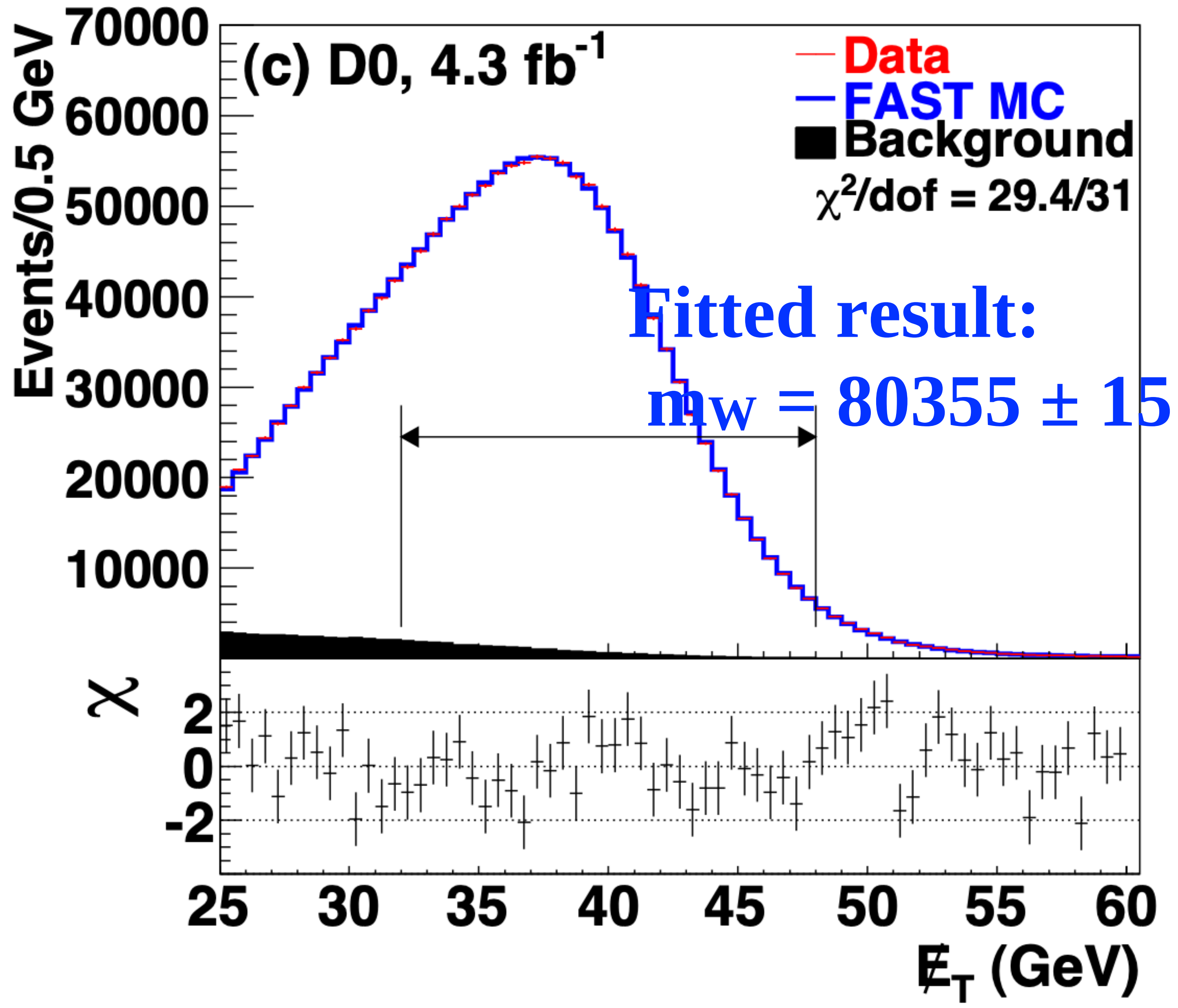
Z data



m(Z) = 91.193 ± 0.017 (stat) GeV

Good agreement between data and parameterised Monte Carlo.

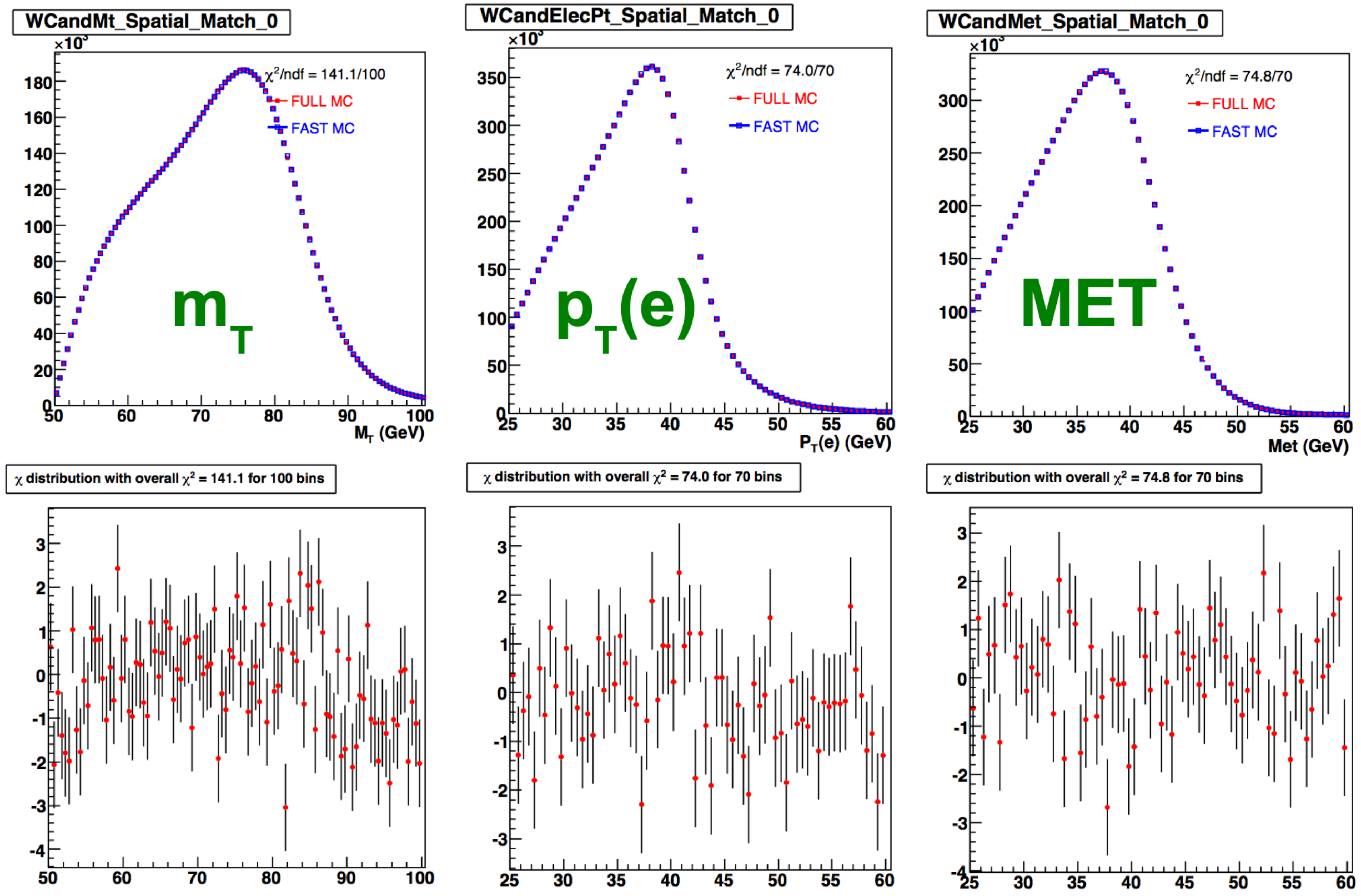
MET



Fitted result:

m_W = 80355 ± 15 (stat) MeV

full MC closure test



9.8 M events after selection

m_T: 80.448 ± 0.005 (stat) GeV

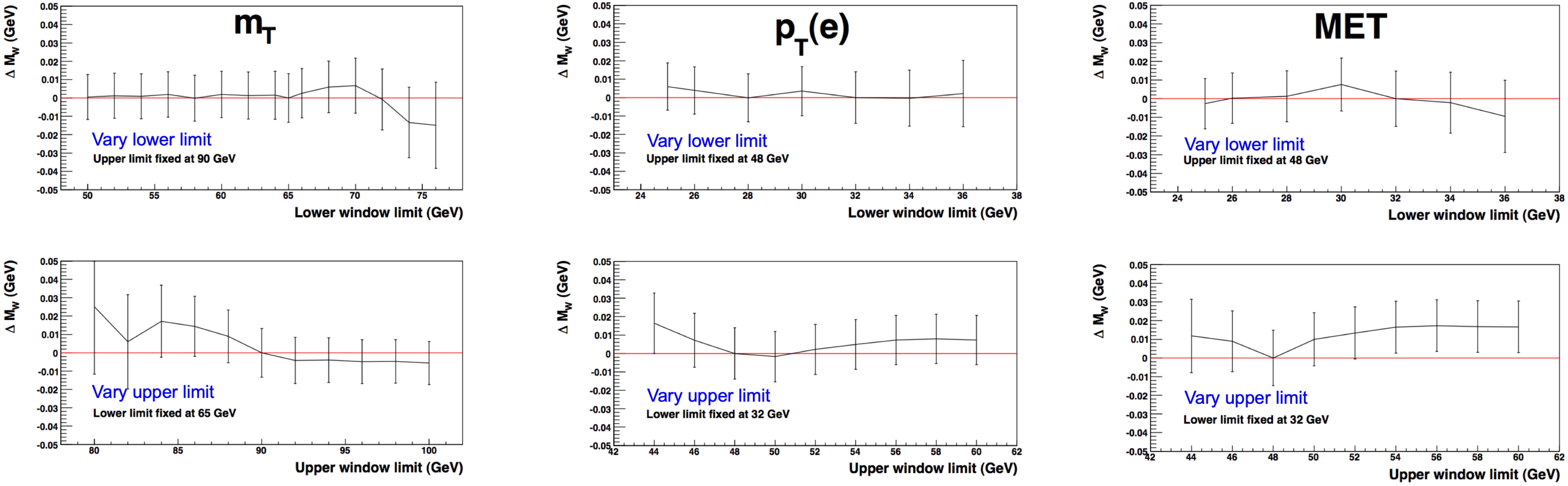
$p_T(e)$: 80.448 ± 0.005 (stat) GeV

Met: 80.455 ± 0.006 (stat) GeV

Input value: 80.450 GeV

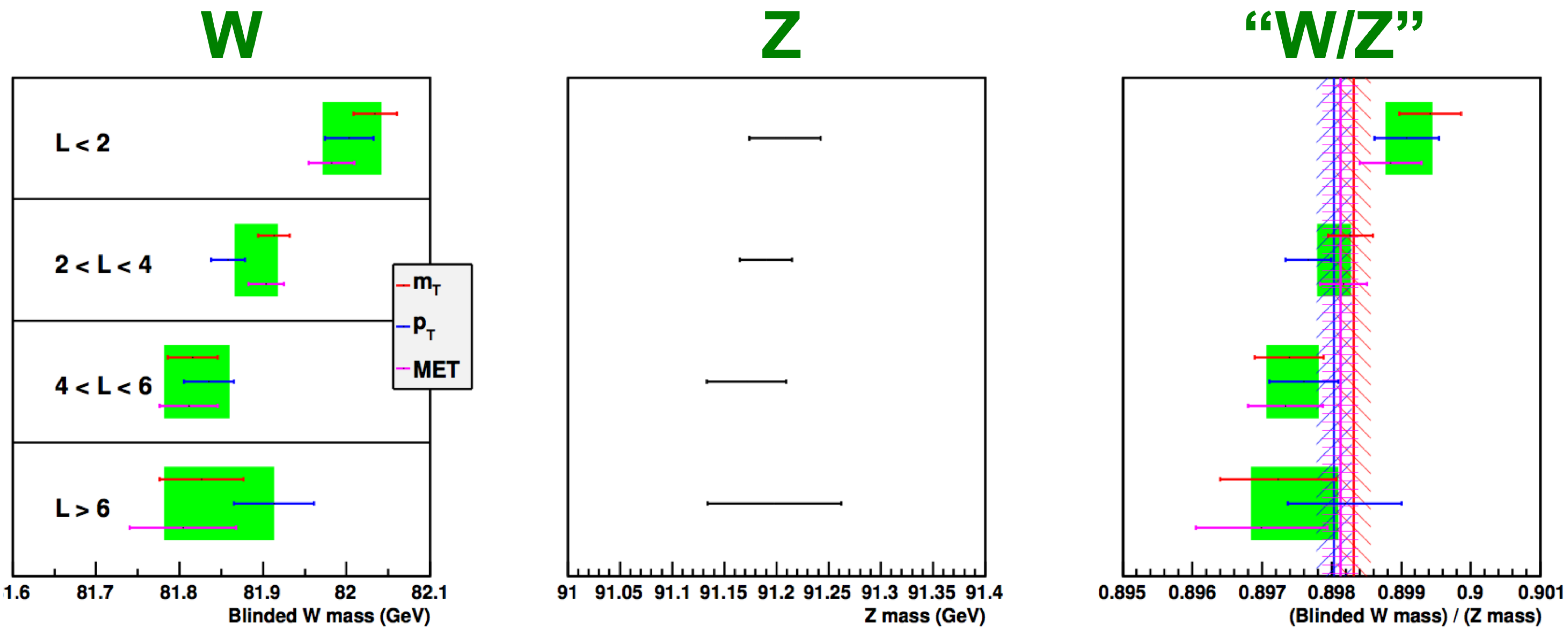
Consistency Check:

W mass fitting window check:



Consistency Check:

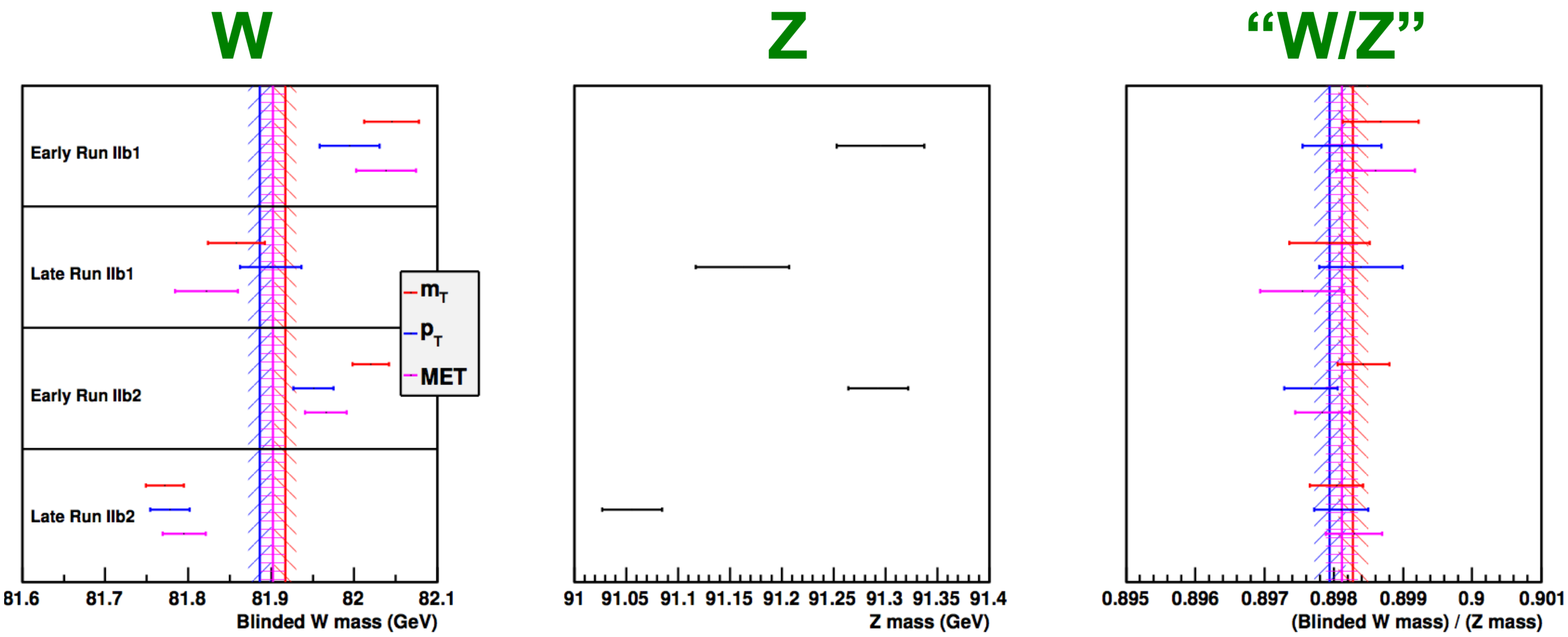
Splitting Dataset according to Inst. Lumi.:



Green band is EM scale uncertainty.

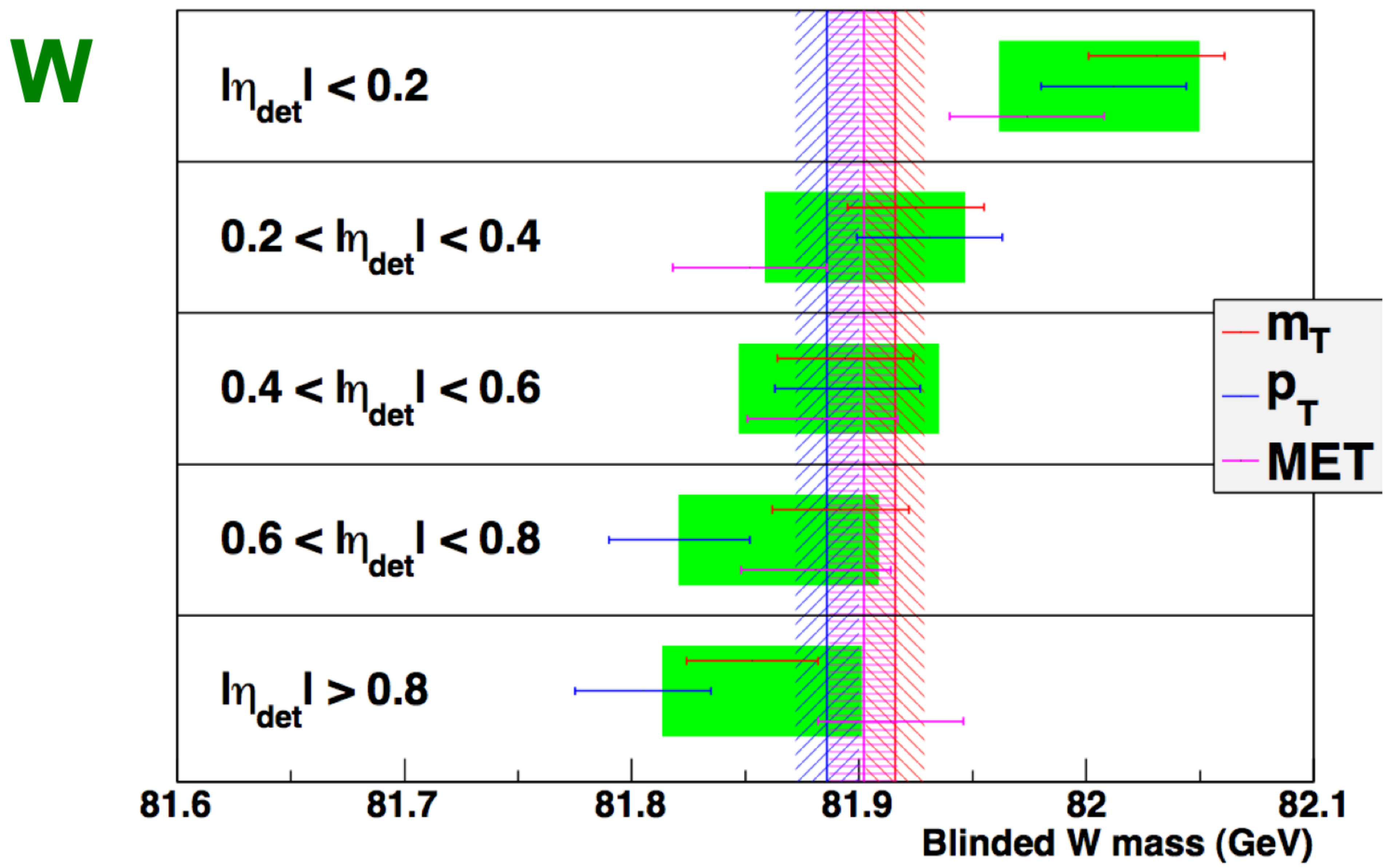
Consistency Check

Splitting Dataset according to Run Periods:

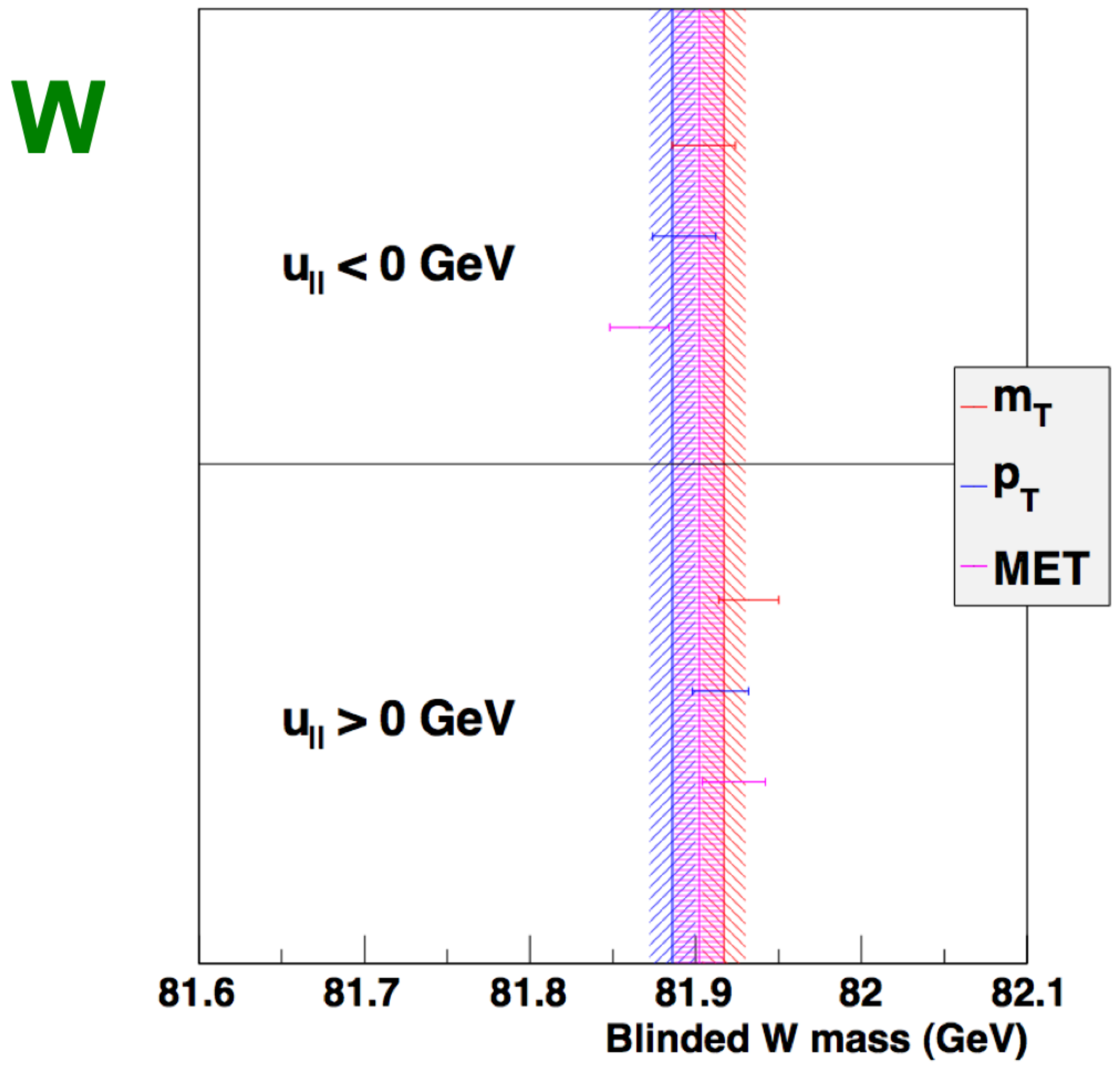


Consistency Check:

Splitting Dataset according to detector Eta:



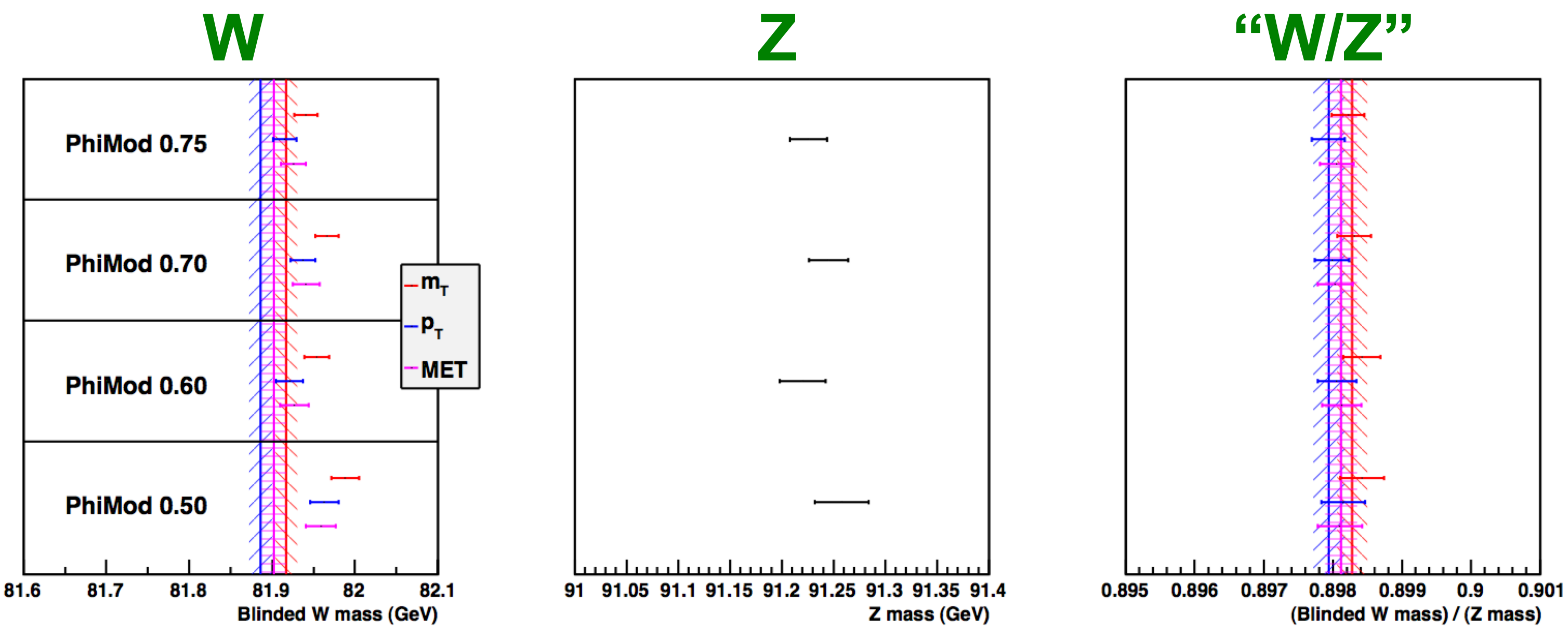
Splitting Dataset according to u_||:



u_||: Hadronic Recoil vector projection to the electron's direction.

Consistency Check:

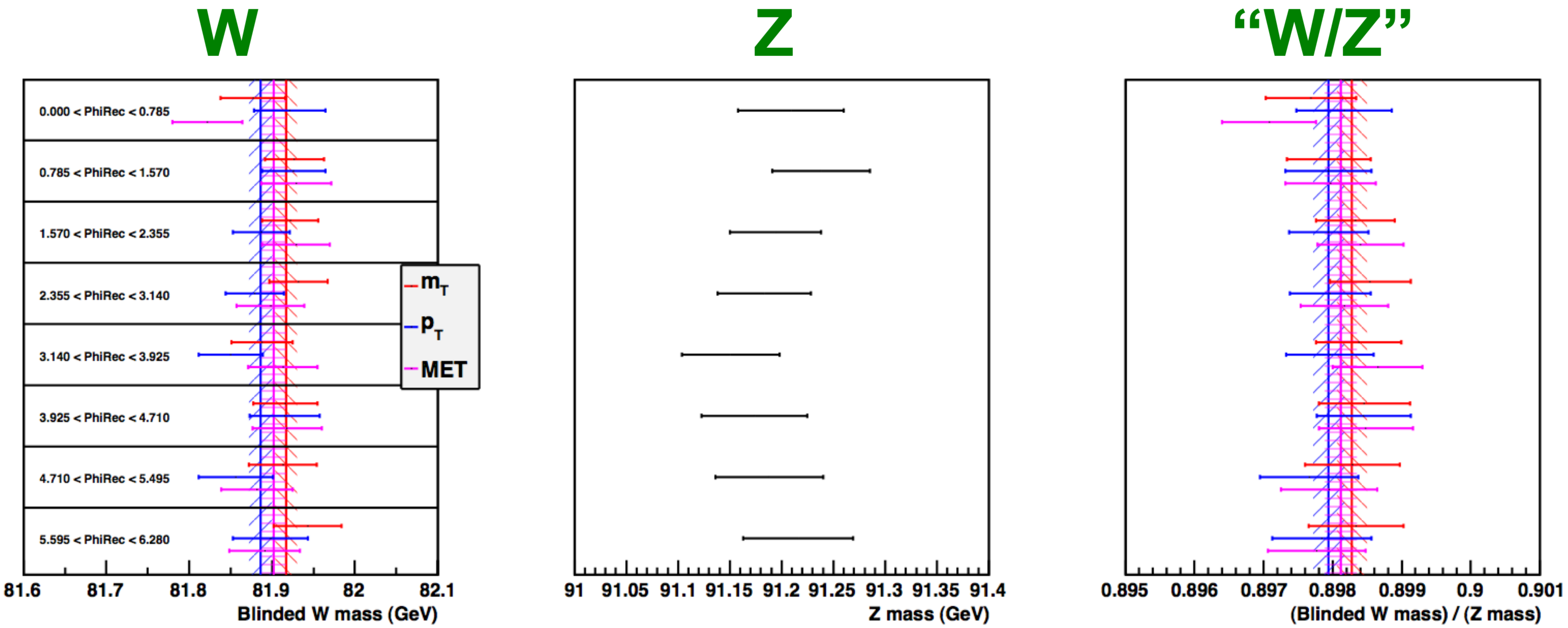
Splitting Dataset according to phi-mod:



An electron shooting to the edge of one calorimeter module in phi would be different in response than to the center of the module. Phi-Mod is the fractional position of one calorimeter module in phi.

Consistency Check:

Splitting Dataset according to the Phi direction of the Hadronic Recoil vector:



Combination

Results from the three observables are highly correlated:

$$\rho = \begin{pmatrix} \rho_{m_T m_T} & \rho_{m_T p_T^e} & \rho_{m_T \not{E}_T} \\ \rho_{m_T p_T^e} & \rho_{p_T^e p_T^e} & \rho_{p_T^e \not{E}_T} \\ \rho_{m_T \not{E}_T} & \rho_{p_T^e \not{E}_T} & \rho_{\not{E}_T \not{E}_T} \end{pmatrix} = \begin{pmatrix} 1.0 & 0.89 & 0.86 \\ 0.89 & 1.0 & 0.75 \\ 0.86 & 0.75 & 1.0 \end{pmatrix}$$

When we consider only the uncertainties which are allowed to decrease in the combination (e.g. not QED), we find that the MET measurement has negligible weight.

We therefore only retain pT(e) and mT for the combination:

Run IIb 4.3 fb^{-1} result:

$$\begin{aligned} M_W &= 80.367 \pm 0.013 \text{ (stat)} \pm 0.022 \text{ (syst) GeV} \\ &= 80.367 \pm 0.026 \text{ GeV}. \end{aligned}$$

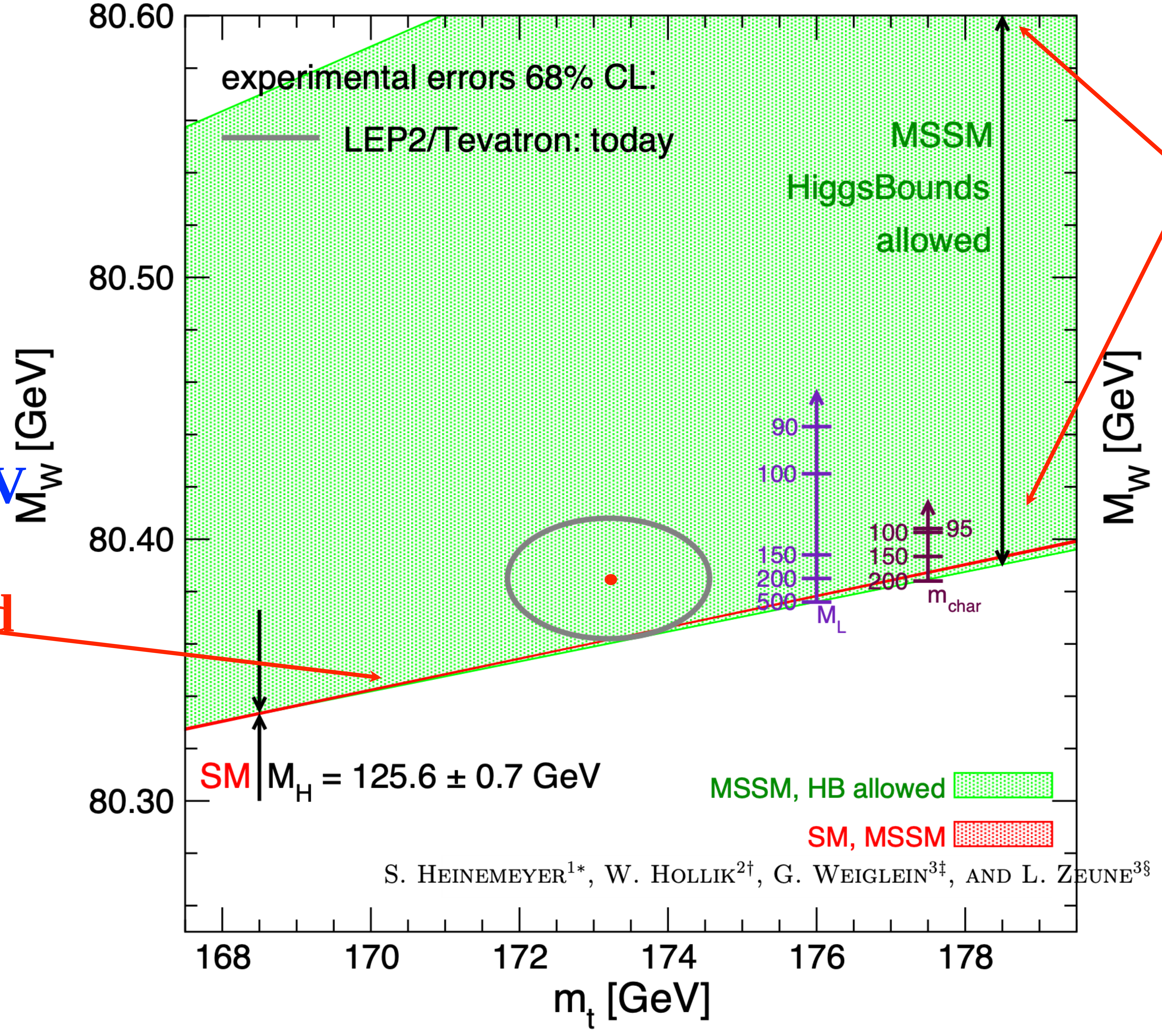
Further combine with Run IIa 1 fb^{-1} result, we obtain

the new Run II 5.3 fb^{-1} result:

$$\begin{aligned} M_W &= 80.375 \pm 0.011 \text{ (stat)} \pm 0.020 \text{ (syst) GeV} \\ &= 80.375 \pm 0.023 \text{ GeV}. \end{aligned}$$

Help to understand the nature of the Higgs

A 125.6 +/- 0.7 GeV Higgs inside SM is this thin line in red color.



But a same 125.6 +/- 0.7 GeV Higgs inside MSSM is this wide band in green color!

(1) The current W mass centrol value points to MSSM, not SM.

(2) But precision is not good, not enough to distinguish SM or models beyond SM, such as MSSM.

Phys. Rev. Lett. 108, 151804 (2012)