Measurement of W boson mass with the DØ detector

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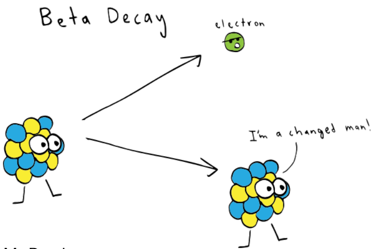
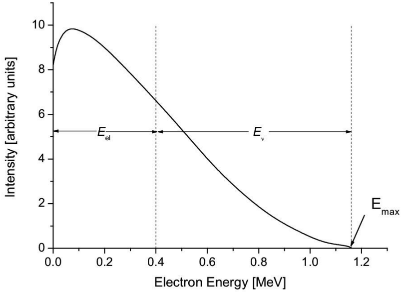
History of the W Boson

Discovery of Radioactivity

- 1896: Henri Becquerel: Uranium; M. and P. Curie: Thorium, Polonium, Radium
- 1899: Ernest Rutherford: Alpha vs. Beta (minus) radiation
- 1900: Paul Villard: Gamma rays (Rutherford identified in 1903)
- 1901: Rutherford and Frederick Soddy: Alpha and Beta change nuclear atomic number!
- Mass number unchanged: angular momentum must change by whole number
- Momentum, angular momentum, not conserved by electron + atom alone.

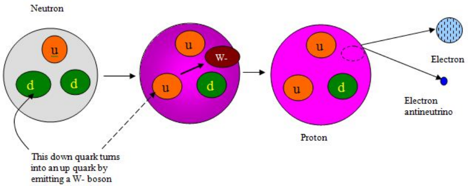


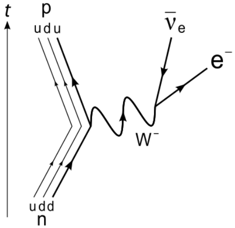


History of the *W* Boson

Discovery of Radioactivity

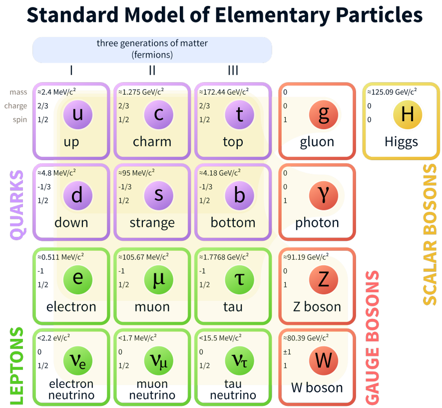
- Wolfgang Pauli and Enrico Fermi: “neutrino” (Pauli called it a “neutron”).
- Enrico Fermi: particle creation and annihilation (not just for photons!)
- Fermi (1930s), Sheldon Glashow (early 1960s), tried to unify EM + weak force
- 1966-7: Abdus Salam, Steven Weinberg, John Ward succeded: SU(2)xU(1)!





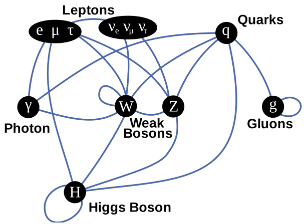
The *W* boson et. al.:

The Particles of the Standard Model and their Interactions



The particles!

- Fermions make up matter
- Interactions mediated by the bosons
  - Massive gauge bosons ($W^{\pm}$ and Z) transmit weak force
  - Massless photon transmits electromagnetic force
  - Unified (before symmetry breaking) as "electroweak" force
  - Gluons transmit strong force - for quarks only
  - Higgs is responsible for mass of all massive particles



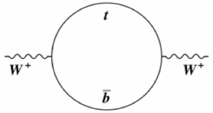
How does the W get its mass?

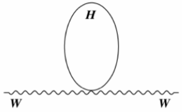
Electroweak Symmetry Breaking!

- Gauge symmetry: Lorentz transformation leaves energy (Lagrangian) unchanged.
- Standard Model Lagrangian: No mass terms (i.e. $\sim m\phi^2$) without Higgs!
- Higgs + Gauge Covariant derivative allows rewriting.
- New form has mass terms!
- Verify relationships between mass terms, validate SM!

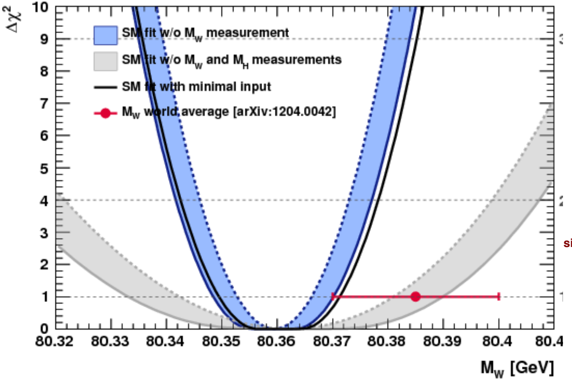
$$M_W \left(1 - M_W^2/M_Z^2\right) = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

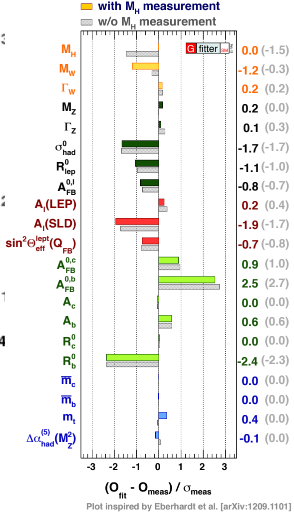
- Δr includes correction terms from the Higgs and top quark





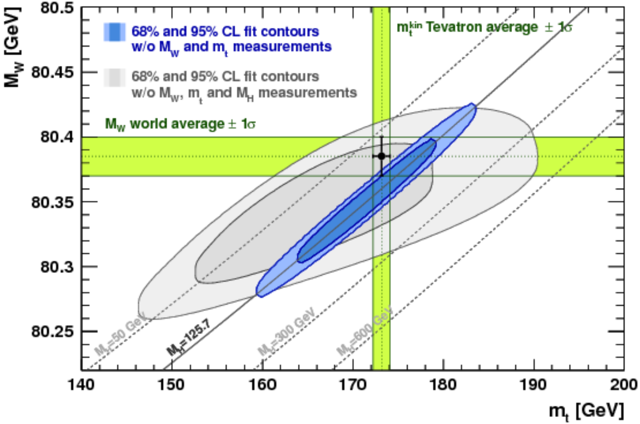
Current tensions between Measurement and theory





- "indirect" determination of W mass:
  - χ^2 computed from tensions between physics observables and standard model
- dotted line: set theoretical uncertainties to 0, band: includes theoretical uncertainties
- solid line: SM fit with "minimal input": M_H, $\alpha_S(M_Z^2)$, M_Z, G_F, $\Delta\alpha_{\text{had}}(M_Z^2)$

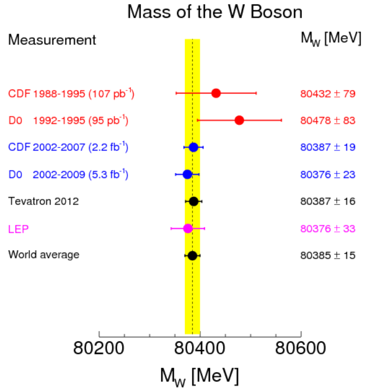
Current Tensions Between Measurement and Theory



- Similarly, simultaneous "indirect" determination of W and Z mass.
- Illustrates potentially stronger effect of narrowing W experimental uncertainty.

Previous Measurements of the W Mass

- 1983: First measurement of W and Z by UA1 and UA2 at CERN's Super Proton Synchrotron (SPS)
- 81 ± 5 GeV and $80 + 10 - 6$ GeV
- Nobel Prize for Carlo Rubbia and Simon van der Meer



- Contributions (in MeV) to the uncertainty in the 4.3fb^{-1} RunIIb12 measurement.

Source	m_T	p_T^e	$\not{E}_T$
Experimental:			
Electron Energy Scale	16	17	16
Electron Energy Resolution	2	2	3
Electron Shower Model	4	6	7
Electron Energy Loss	4	4	4
Recoil Model	5	6	14
Electron Efficiencies	1	3	5
Backgrounds	2	2	2
$\sum$ Experimental	18	20	24
W Production and Decay Model:			
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
$\sum$ Model	13	14	17
$\sum$ Systematic	22	24	29
Statistical	13	14	15
Total	26	28	33

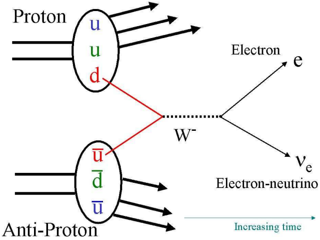
- RunIIb34 will add about 3.7fb^{-1}

Competetiveness with the LHC

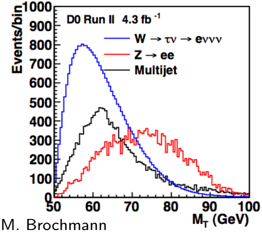
Tevatron Backgrounds

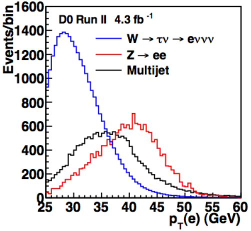
- W Production channels:

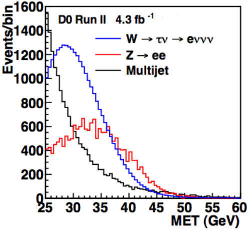
$$\bar{u} + d \rightarrow W^-$$
$$u + \bar{d} \rightarrow W^+$$



- To measure W mass, we need to select W events from data
- Backgrounds are non-W events that look like W events, so they sneak into the data sample
- Main backgrounds: QCD, $Z \rightarrow ee$, and $W \rightarrow \tau 3\nu$

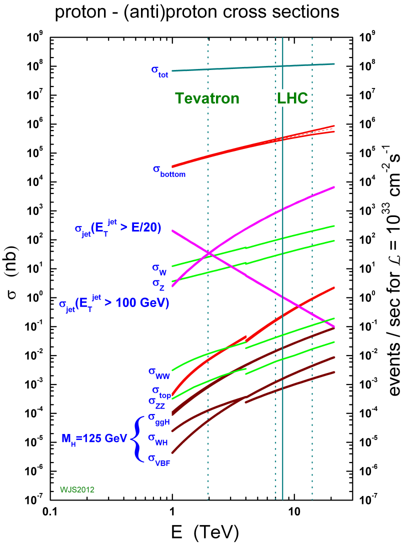




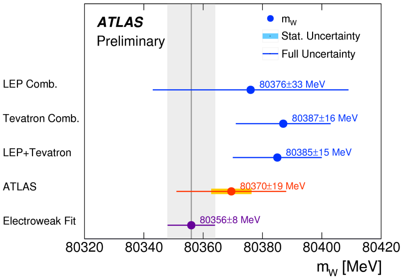


Competitiveness with the LHC

Is it worth it?

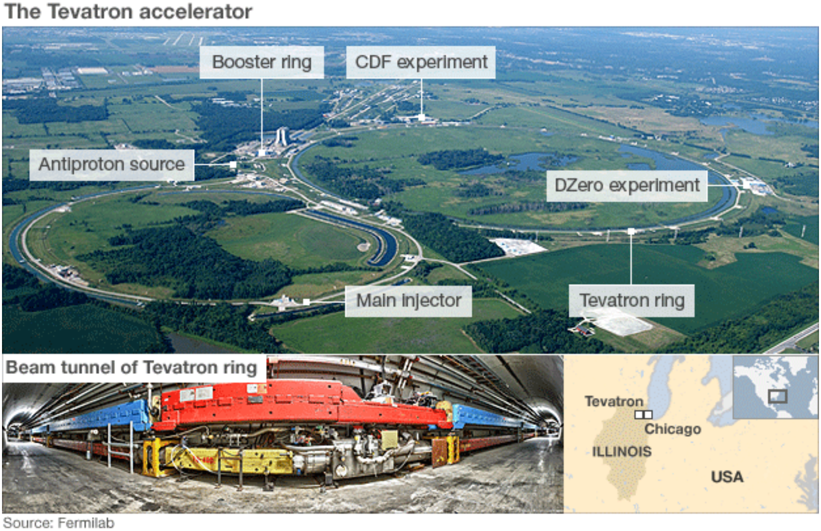


- QCD jet background comparable with W production cross section at Tevatron energies (2 TeV)
- At LHC energies, (13 TeV), an order of magnitude larger!
- (But LHC jets very well modeled.)

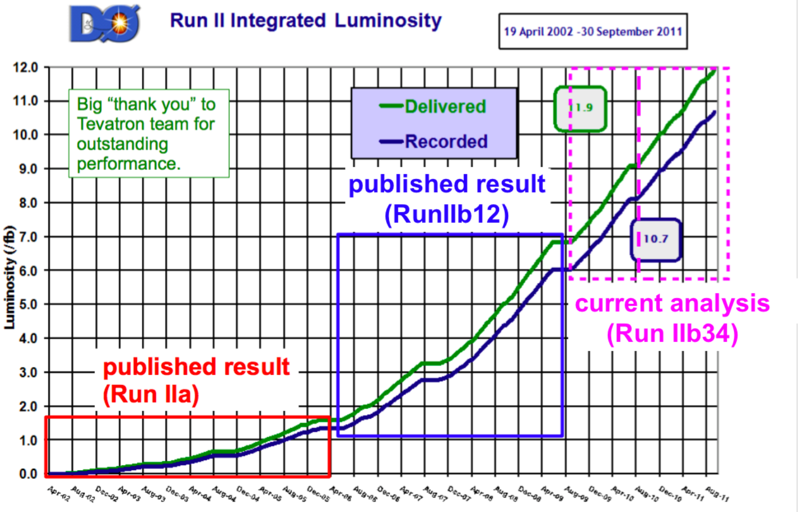


- ATLAS measurement, December 2016

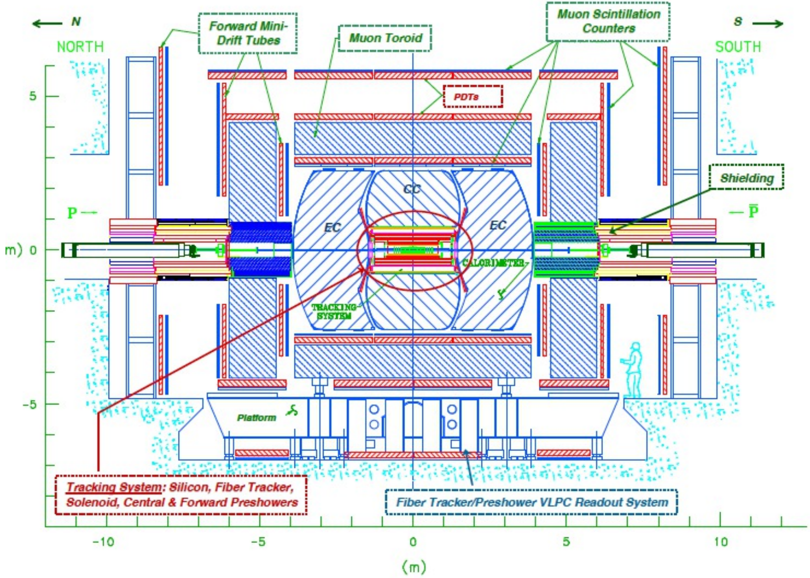
Overview of the Tevatron



Tevatron Luminosities

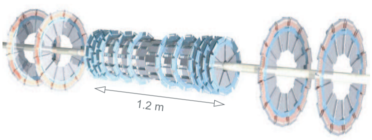


Overview of the D0 Detector

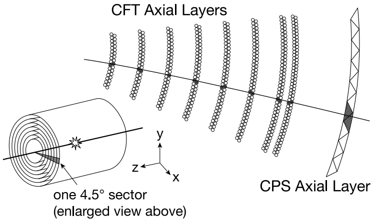


D0 Detector: Trackers

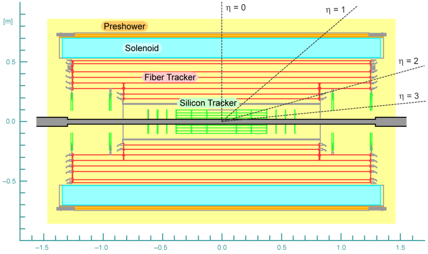
Detailed momentum measurements of charged particles.

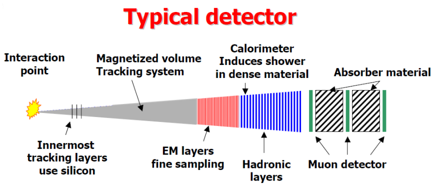


- Silicon Microstrip Tracker (SMT)



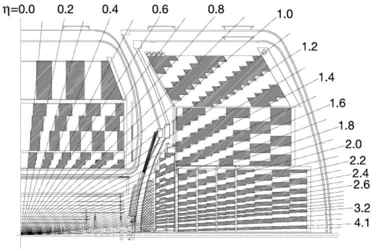
- Center Fiber Tracker

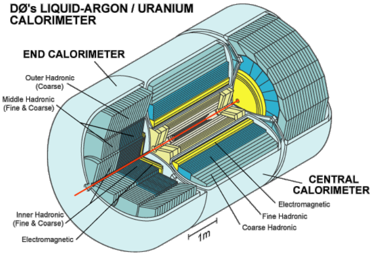




D0 Detector: Central and End Calorimeters

Detailed Energy Measurements from Particle Showers

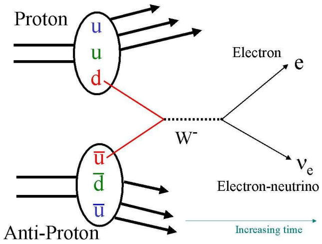




- Liquid Argon - Uranium Calorimeter
- Segmentation in towers of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
- Full coverage up to $\eta \approx 4.0$

W Boson Decay Signature in the Detector

Quantities to measure

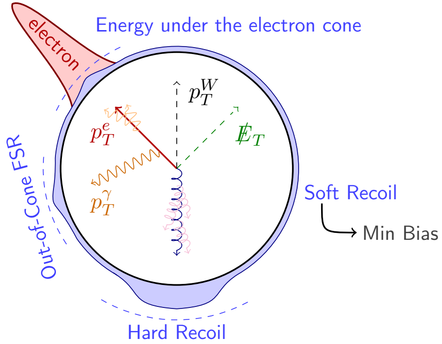


- Missing Transverse Energy (MET):

$$\vec{\not{E}}_T \equiv -(\vec{p}^{\,e}_T + \vec{u}_T)$$

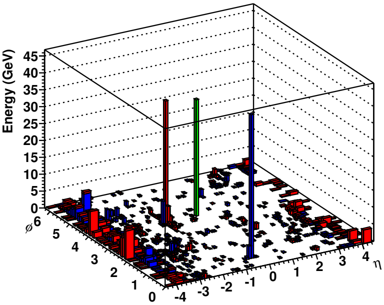
- Transverse *W* mass:

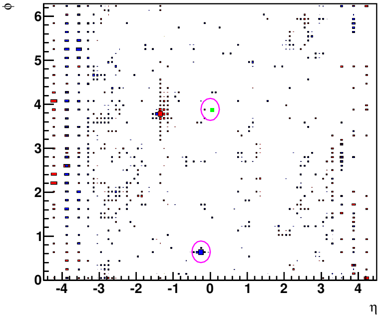
$$m_T = \sqrt{2 p_T^e p_T^\nu (1 - \cos(\phi^e - \phi^\nu))} \tag{1}$$



W Boson Decay Signature in the Detector

The "unrolled" calorimeter



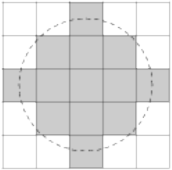


- Red is EM trigger event
- Green represents direction and magnitude of MET (sum of all CC cell momenta)
- Blue is QCD jet - maybe part of the recoil

Calorimeter and Tracker Event Selection Criteria

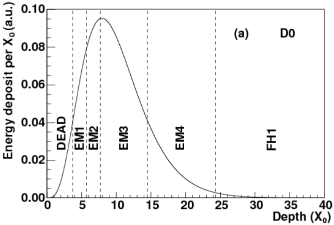
- Isolation: Electron showers deposit most of their energy in a narrow cone:

$$f_{\rm iso} \equiv \frac{E_{\rm tot}^{\rm unc}(\Delta R < 0.4) - E_{\rm EM}^{\rm unc}(\Delta R < 0.2)}{E_{\rm EM}^{\rm unc}(\Delta R < 0.2)} < 0.15$$



- EM fraction: A true electron will deposit nearly all of its energy in the EM layers of the calorimeter. Therefore the EM fraction

$$f_{\rm EM} \equiv \frac{E_{\rm EM}^{\rm unc}(\Delta R < 0.2)}{E_{\rm tot}^{\rm unc}(\Delta R < 0.2)} > 0.9$$



- HMatrix: Multivariate likelihood based on shower shape and energy
- Loose Track Match: track is within 0.05 in $\Delta\eta$ and within 0.05 in $\Delta\phi$.
- Tight Track Match: quality of match satisfies $P(\chi^2_{\rm TM}) > 0.01$, at least one SMT hit.

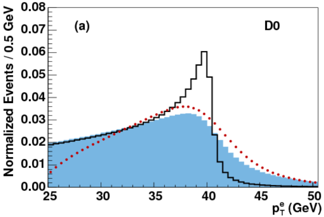
$$\chi^2_{\rm TM} \equiv \left(\frac{\Delta\phi}{\sigma_\phi}\right)^2 + \left(\frac{\Delta\eta}{\sigma_\eta}\right)^2$$

- σ_ϕ and σ_η are measured resolutions of $\Delta\phi$ and $\Delta\eta$.

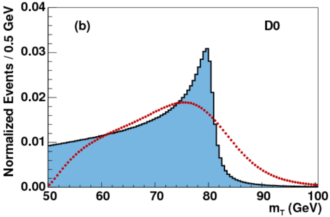
Measurement Strategy: What are we actually measuring?

- Place events into "distributions" - histograms of p_T^e, m_T, and $\not{E}_T$
- Shape is differential cross section (modified by detector effects)

  - p_e^T: e transverse momentum



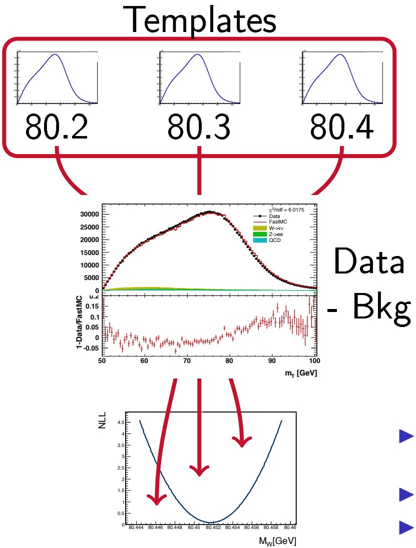
  - m_W^T: W transverse mass

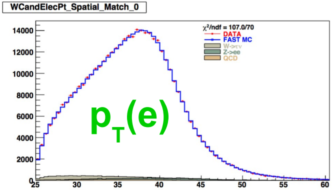


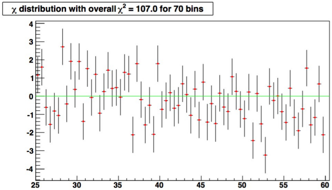
$$\frac{1}{\sigma}\frac{d\sigma}{\left(dp_T^e\right)^2} = \frac{3}{M_W^2}\left(\frac{1-4\left(p_T^e\right)^2}{M_W^2}\right)^{-1/2}\left(\frac{1-\left(2p_T^e\right)^2}{M_W^2}\right)$$

- "Jacobian Peak" at: $p_T^e = \frac{M_W}{2}$
- Simulated spectra (left):
  - Black: w/o p_T^W or detector effects
  - Light blue: include p_T^W
  - Red: include p_T^W and detector effects
- Different systematic uncertainties!
  - m_T^W mainly detector resolution of recoil measurement
  - p_T^e mainly m_T^W, also recoil system, ISR (W radiation)
- Also use MET for cross check. (affected by all systematics)

Measurement Strategy: The Template Method



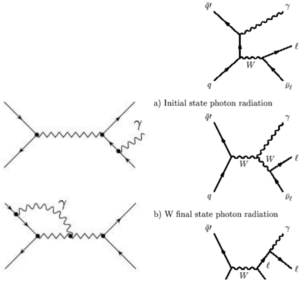




- Create many versions of predected spectra of m_T, p_T^e, and MET, in a range of W masses
- Best spectrum tells us the W mass.
- Templates must include detector effects, so spectrum shape is non-analytic: Need Monte Carlo methods for this.

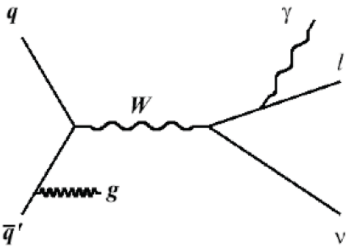
Monte Carlo Simulation: Generators

Simulating W and Z production and decay



- Generator accuracy important for:
  - Total cross section (important for background subtraction)
  - Transverse momentum of vector bosons and hadronic recoil
  - Final State Radiation (FSR) effect on p_T^e spectrum
- Output is 4-vectors of decay products: leptons, hadronic recoil

- Complete Generator level simulation: all electroweak, QCD corrections
- We don't simulate everything, just:
  - QCD corrections
  - up to two FSR photons
- Error $\approx$ 10MeV (`WGRAD`, `ZGRAD` studies)

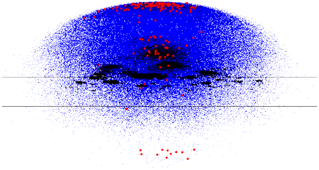


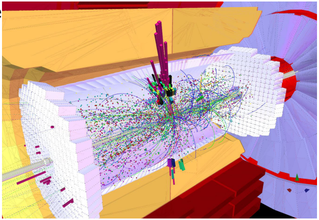
Monte Carlo Simulation: Full Material vs. Parametrized

Simulating the decay products in the detector

- Detector simulation: From 4-vectors of electron(s), recoil (individual particles for FullMC?), simulate response in detector and tracker
- Full Detector Simulation: Material level simulation - detailed simulation of particle interactions and energy flow through tracker and each detector cell.
- We use a simulator called `GEANT` ("GEometry ANd Tracking")

- `GEANT` takes a LONG time to run
- Need FAST generation of samples: less detail, similar output: parametrize output to get observables used for measurement
- Why bother with a FullMC? Two reasons:
  - 1) large number of events with accessible truth values allows us to create high-quality base tune of FastMC, which we then improve to match data
  - 2) we can test our method by using our base tune of the FastMC to measure the Z and W masses from the FullMC
- Next: How to tune the FastMC





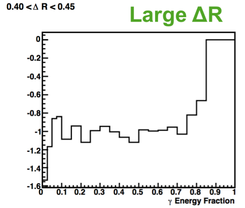
FastMC Detector Simulation Overview

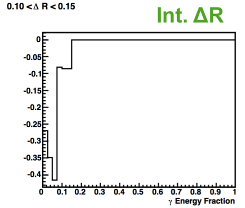
- Primary Vertex simulation: where in z is boson produced?
- FSR: how does it affect p_T^{reco}
- Electron response: How much electron energy does the calorimeter "see"?
- Recoil response: How much energy (u_T) from "everything else"?
- Efficiency: How good are we at "catching" electrons?

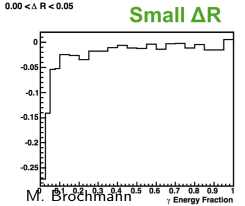
- NOTE: We create two versions:
  - One to model FullMC (the "GEANT" FastMC)
  - One to model collider data (the "data" FastMC)

- Output of FastMC is reconstructed $\vec{p}_T^{\,e}$, $\vec{u}_T$

Final State Radiation (FSR) Simulation







- $\kappa(X, p_T^e, \Delta R, \eta_{\mathrm{phys}}, \mathrm{InstLumi})$ is energy lost by electron in units of the FSR photon energy.
- Measure from dedicated FullMC simulations with and without FSR:

$$\kappa = -\frac{E_{\mathrm{reco}}^{\mathrm{no\ FSR}} - E_{\mathrm{reco}}}{E_{\mathrm{true}}^{\mathrm{no\ FSR}} - E_{\mathrm{true}}} = -\frac{E_{\mathrm{reco}}^{\mathrm{no\ FSR}} - E_{\mathrm{reco}}}{X \cdot E_{\mathrm{true}}^{\mathrm{no\ FSR}}}$$

- X is photon energy fraction.
- ΔR is separation between electron and photon.
- high ΔR: photon outside reconstruction window, all energy "lost"; $\kappa = -1$
- large values of X and intermediate ΔR: cluster reconstructed around photon, most of energy is "caught"; $\kappa \approx 0$
- low ΔR: the larger the photon energy fraction, the less energy is lost to bremsstrahlung; κ depends on X
- For each FSR photon from the generator, modify E_{reco} according to $\kappa(X, p_T^e, \Delta R, \eta_{\mathrm{phys}}, \mathrm{InstLumi})$

The Electron Response Simulation

Determination of the Scale and Offset

- Scale FastMC calorimeter response to match data or FullMC:

$$R_{EM}(E_0) = \alpha \cdot E_0 + \beta \quad (2)$$

- Tune α, β, with 2D distribution of m_Z^{reco}, f_Z

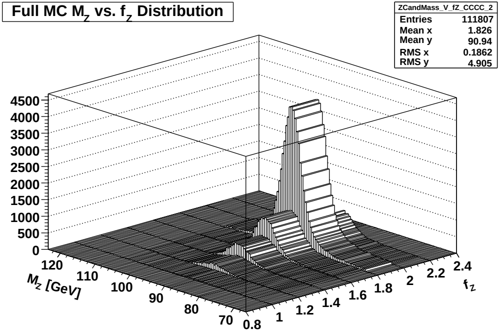
- m_Z^{reco} is invariant dilepton mass

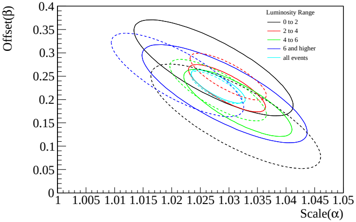
$$m_Z^{\mathrm{reco}} = m_{ee} = \sqrt{2E^{e_1}E^{e_2}(1 - \cos\omega)} \quad (3)$$

- f_Z is sensitive to opening angle

$$f_Z = \frac{(E^{e_1} + E^{e_2}) \cdot (1 - \cos\omega)}{m_Z} \quad (4)$$

- Perform fit in four InstLumi bins.





Efficiencies: Definition

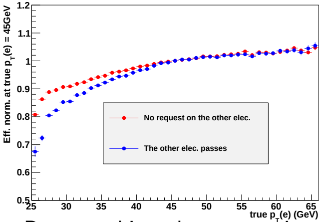
- Efficiency: probability that "signal" (here an electron) will pass a given selection, or "cut".
- Defined relative to base sample (previous selections): ORDER MATTERS!
- If the efficiency depends on a variable that is correlated with a measurement observable, it affects the measurement.
- We need to model efficiencies that affect our measurement observables.
- Simulate with random number between 0 and 1: If rand $<$ eff, keep the event.

Order of efficiencies

- Trigger efficiency
- FSR dependent efficiency
- Electron ID Efficiencies:
  - HMatrix
  - Loose Track-Matching
  - Tight Track-Matching
- Residual ScalarET efficiency
- Residual Efficiency Corrections (for data only)
- Upara efficiency

Efficiencies: How to Measure

- Tag-and-probe method:
  - "tag" $Z \rightarrow ee$ events with a candidate electron that matches the cut.
  - Test whether other "probe" electron passes the cut.
  - Pass/(Pass+Fail) ratio from "probe" electrons = efficiency.

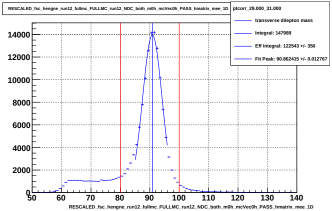


- Beware a bias when measuring a p_T^e dependent eff. for a calo-based selection.
- Low p_T^e electrons have high p_T partners.
- Recoil effects artifically lower the efficiency.

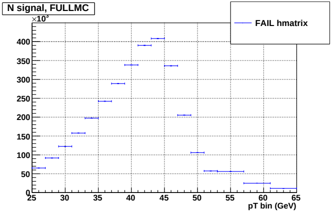
- "Truth" method in FullMC
  - Know which events are signal events.
  - Simply apply selections and calculate Pass/(Pass+Fail) ratio.
- Background subtraction method in data.
  - Predict shape of signal and background distributions in some variable (e.g. m_{ee}).
  - Fit signal and background template to data distribution.
  - No need for "tag".
  - Matches "truth" method in FullMC.
- Ratio methods (for residual final efficiencies).
  - Determine reweighting needed to match FastMC to FullMC distribution.
  - OR measure ratio between FullMC and data efficiency.
  - Apply reweighting as an efficiency.

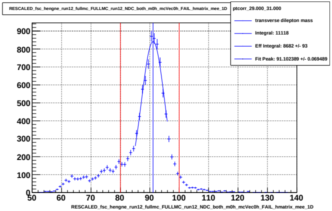
REMINDER: Measuring Hmatrix efficiency in FullMC

- Simply extract signal which passes and fails the Hmatrix cut in the efficiency window:

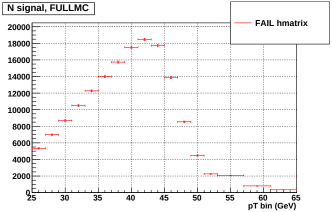


every p_T^e bin $\Longrightarrow$



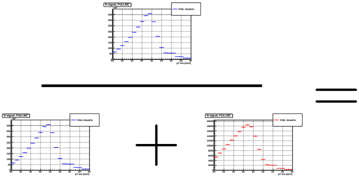


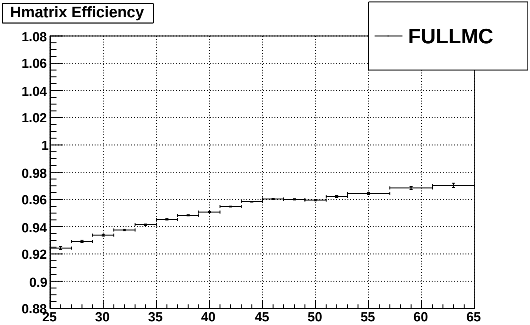
every p_T^e bin $\Longrightarrow$



REMINDER: Measuring Hmatrix efficiency in FullMC

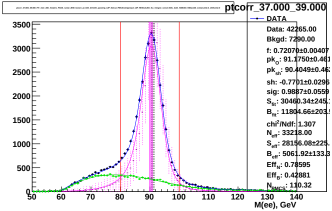
- Hmatrix cut efficiency in Full MC:



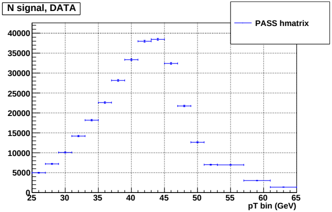


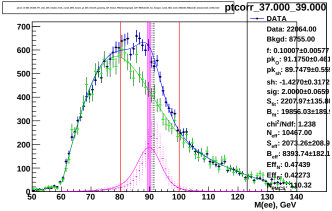
REMINDER: Measuring Track Matching Efficiency in Data

- Must subtract background to extract signal which passes and fails the Hmatrix cut:

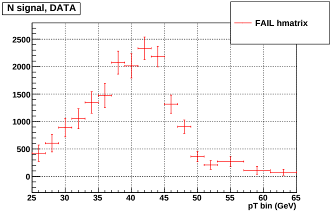


every p_T^e bin $\Longrightarrow$



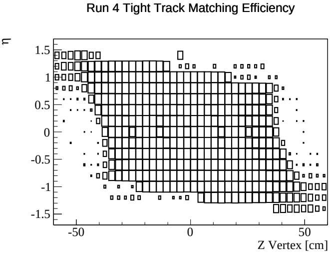


every p_T^e bin $\Longrightarrow$

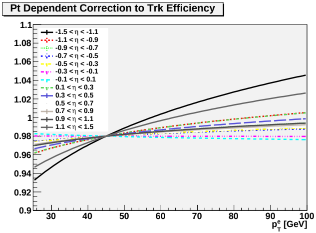


The Electron ID Efficiencies

- HMatrix: p_T^e dependence from single electron FullMC
- Track-Matching: Use Tag-and-Probe method with $Z \rightarrow ee$ FullMC events
- Loose vs. InstLumi, z_{vtx}, η_{phys}
- Tight vs. z_{vtx}, η_{phys}



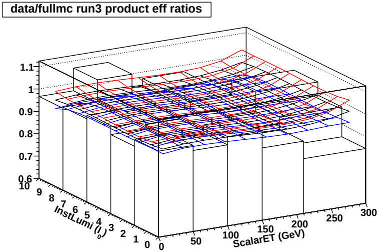
- Additional p_T^e dependence of Loose and Tight:
  - Measure from single electron FullMC in bins of η_{phys}
  - Normalize at Jacobian Peak (mean value of $Z \rightarrow ee$ p_T^e dist.)

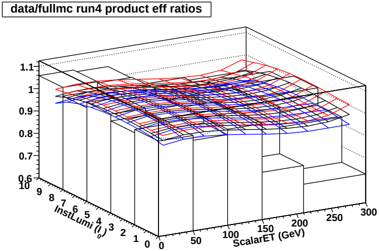


- Also need to model a Residual ScalarET (dependent on 5 correlated variables) efficiency.

The Electron ID Residual Efficiency Corrections

- Ratio of Data/FullMC efficiencies for various sets of correlated variables.
- Measure for HMatrix, Loose Track-Matching, Tight Track-Matching, combine in product.
- η,z_{vtx}, (InstLumi - Loose track-matching only).
- SET-InstLumi, with InstLumi dependence removed for Loose track-matching. (Shown at right)
- Right: Ratio between data efficiency and FullMC efficiency vs. SET and InstLumi (2D "Lego" plot). Residual efficiency correction fit to the ratio and applied in data FastMC (black 2D curve), with upper (red) and lower (blue) 68% confidence intervals of the curve

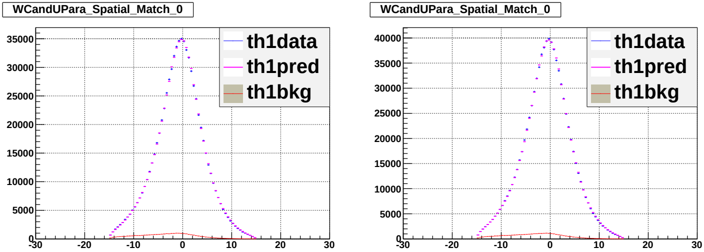




The $u_{\|}$ ("u-para") Efficiency Correction

- Simulation of $u_{\|}$ efficiency dependence is not perfect yet:

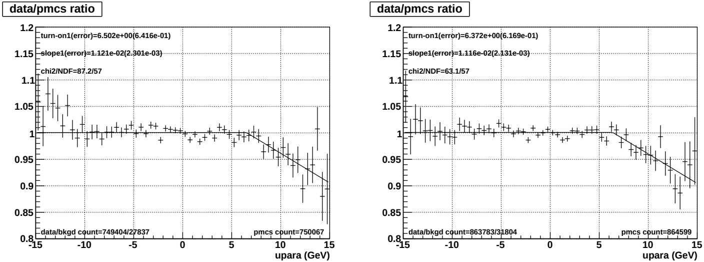
$$u_{\|} = \vec{u}_T \cdot \frac{\vec{p}_T^{\,e}}{p_T^e} \tag{5}$$



Data and FastMC $u_{\|}$ compared, before correction. RunIIb3 is left, RunIIb4 is right. Full InstLumi range.

- Need to apply a final small residual correction.
- Do this for both data and FullMC.
- Presenting data correction here.

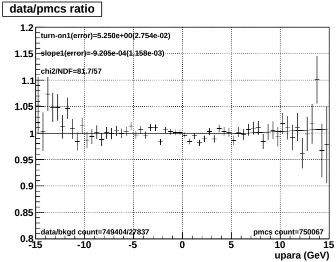
The $u_{\parallel}$ ("u-para") Efficiency Correction

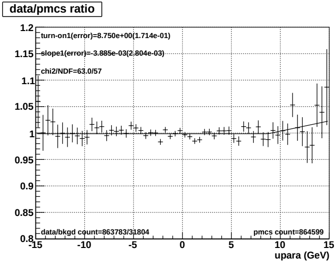


Data/FastMC ratio vs. $u_{\parallel}$, before correction. RunIIb3 is left, RunIIb4 is right. Full InstLumi range.

- Ratio of Data/FullMC $u_{\parallel}$ distributions.
- Two-parameter fit: "Turn-on" plus slope.
- Fit in four InstLumi bins.

The $u_{\parallel}$ ("u-para") Efficiency Correction





Data/FastMC ratio vs. $u_{\parallel}$, after correction. RunIIb3 is left, RunIIb4 is right. Full InstLumi range.

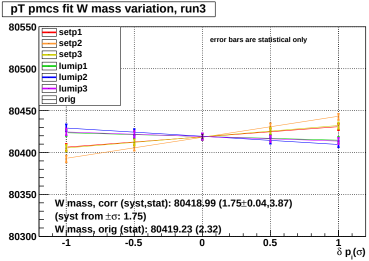
- This is the final modification.
- Must re-derive every time something else changes.

Estimating the Systematic Uncertainties

The Covariance Matrix and $\frac{\delta M_W}{\delta p_i}$

- Parametrized fit $\rightarrow$ covariance matrix C_{ij}:
- Diagonal values: parameter uncertainties (squared): σ_i^2
- Off-diagonal values: describes correlations: $c_{ij} \cdot \sigma_i \sigma_j$
- Need to measure $\frac{\delta M_W}{\delta p_i}$
- Create mock datasets with FastMC, each varies input p_i
- e.g. 5 values of p_i: p_i^0, $p_i^0 \pm \frac{1}{2}\sigma_i$, $p_i^0 \pm \sigma_i$
- n correlated parameters $\rightarrow 4n+1$ mock datasets
- Measure m_W on all mock datasets, central values for template
- Fit slope to $\frac{\delta M_W}{\delta p_i}$

$$\frac{\delta M_W}{\delta p_i} C_{ij} \frac{\delta M_W}{\delta p_j}$$



Monte Carlo Closure:

Test measurements of the W and Z mass on FullMC samples

- Input Z mass: 91.188 GeV

$\mathcal{L}$	Z mass RunIIb3	Z mass RunIIb4
All $\mathcal{L}$	91.191 ± 0.005	91.194 ± 0.004
$0 < \mathcal{L} < 2$	91.188 ± 0.014	91.191 ± 0.016
$2 < \mathcal{L} < 4$	91.190 ± 0.006	91.187 ± 0.006
$4 < \mathcal{L} < 6$	91.189 ± 0.009	91.190 ± 0.008
$\mathcal{L} > 6$	91.191 ± 0.013	91.193 ± 0.010

- Input W mass: 80.450 GeV
- RunIIb3 (top), RunIIb4 (bottom)

$\mathcal{L}$	m_T	$p_T(e)$	MET
All $\mathcal{L}$	80.451 ± 0.006	80.450 ± 0.006	80.439 ± 0.008
$0 < \mathcal{L} < 2$	80.446 ± 0.018	80.457 ± 0.019	80.421 ± 0.021
$2 < \mathcal{L} < 4$	80.454 ± 0.009	80.454 ± 0.009	80.444 ± 0.011
$4 < \mathcal{L} < 6$	80.454 ± 0.012	80.442 ± 0.011	80.443 ± 0.016
$\mathcal{L} > 6$	80.416 ± 0.018	80.439 ± 0.016	80.418 ± 0.026

$\mathcal{L}$	m_T	$p_T(e)$	MET
All $\mathcal{L}$	80.454 ± 0.006	80.452 ± 0.006	80.448 ± 0.008
$0 < \mathcal{L} < 2$	80.460 ± 0.021	80.476 ± 0.021	80.431 ± 0.024
$2 < \mathcal{L} < 4$	80.463 ± 0.009	80.459 ± 0.008	80.457 ± 0.011
$4 < \mathcal{L} < 6$	80.454 ± 0.012	80.452 ± 0.011	80.424 ± 0.016
$\mathcal{L} > 6$	80.434 ± 0.015	80.445 ± 0.013	80.467 ± 0.021

A Small Subset of RunIIb34 Uncertainties

Source	m_T	p_T^e	$\not\!\!E_T$
PDF	14.54	20.78	16.15
QCD (Boson p_T)	1.71	6.41	1.42

Source	m_T	p_T^e	$\not\!\!E_T$
RunIIb3 Residual Eff. Correction	1.35	1.75	4.05
RunIIb4 Residual Eff. Correction	2.07	2.55	5.58

Source	m_T	p_T^e	$\not\!\!E_T$
Statistical	17	17	20

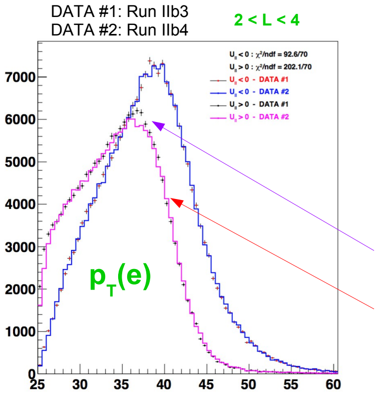
- RunIIb34 recoil parametrization, contribution to m_T: 6.4 MeV

Source	m_T	p_T^e	$\not\!\!E_T$
Experimental:			
Electron Energy Scale	16	17	16
Electron Energy Resolution	2	2	3
Electron Shower Model	4	6	7
Electron Energy Loss	4	4	4
Recoil Model	5	6	14
Electron Efficiencies	1	3	5
Backgrounds	2	2	2
$\sum$ Experimental	18	20	24
W Production and Decay Model:			
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
$\sum$ Model	13	14	17
$\sum$ Systematic	22	24	29
Statistical	13	14	15
Total	26	28	33

Contributions to the uncertainty in the RunIIb12 measurement.

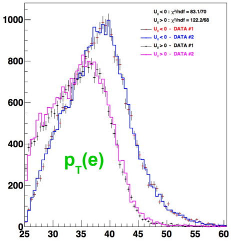
State of the Current Analysis: Unresolved Issues

- 80 MeV tension between RunIIb3 and RunIIb4 data.
- Discrepancy between peaks of RunIIb3 and RunIIb4 distributions when $u_{||} > 0$.
- Possible smearing?
- Also, discrepancy at very low p_T^e, NOT caused by the trigger.

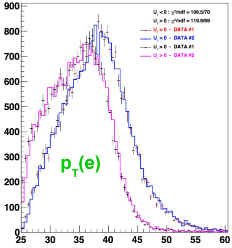


State of the Current Analysis: Unresolved Issues

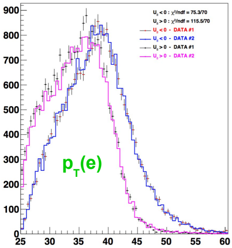
- Problem is strongest at top of detector:



0 < electron phi < 0.785



0.785 < electron phi < 1.570

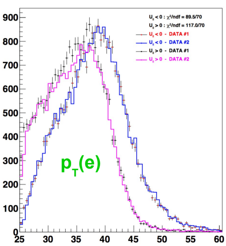


1.570 < electron phi < 2.355

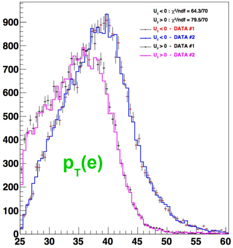
- RunIIb3 and RunIIb4 disagree most when $0 < \phi < \pi$.

State of the Current Analysis: Unresolved Issues

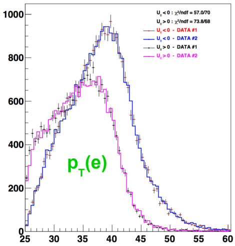
- Problem is strongest at top of detector:



2.355 < electron phi < 3.140



3.140 < electron phi < 3.925

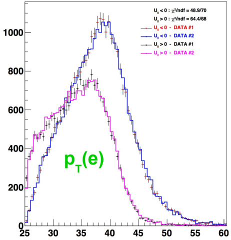


3.925 < electron phi < 4.710

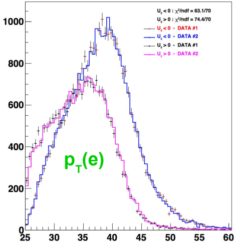
- RunIIb3 and RunIIb4 disagree most when $0 < \phi < \pi$.

State of the Current Analysis: Unresolved Issues

- Problem is strongest at top of detector:



4.710 < electron phi < 5.495

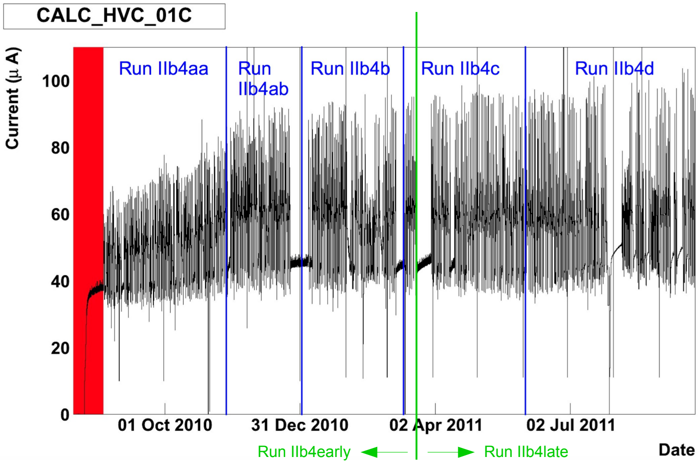


5.495 < electron phi < 6.280

- RunIIb3 and RunIIb4 disagree most when $0 < \phi < \pi$.

State of the Current Analysis: Unresolved Issues

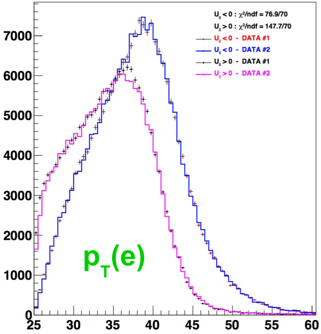
- Problem increases with time - break RunIIb4 into "early" and "late" sample:



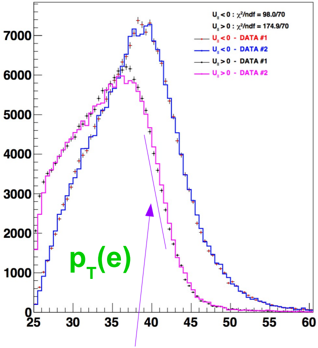
State of the Current Analysis: Unresolved Issues

- Problem increases with time - break RunIIb4 into “early” and “late” sample:

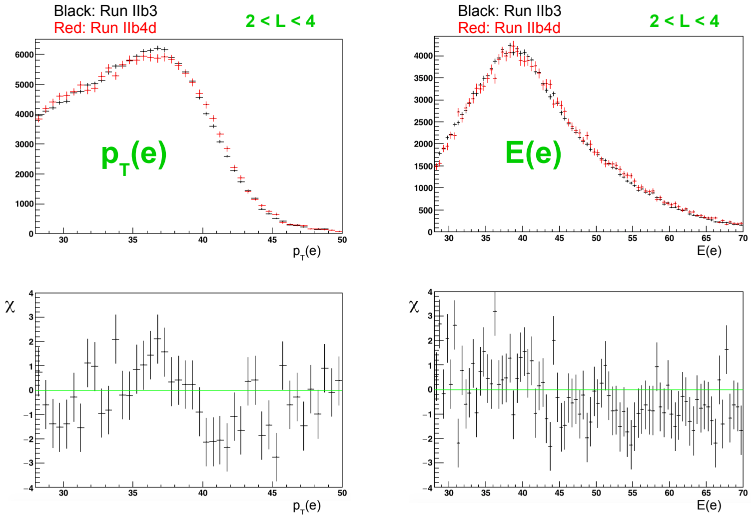
DATA #1: Run IIb3
DATA #2: Run IIb4early
2 < L < 4



DATA #1: Run IIb3
DATA #2: Run IIb4late
2 < L < 4



State of the Current Analysis: Unresolved Issues



- The problem is with the tracker, not calorimeter.

Conclusion

- Discussions about possible next steps are ongoing
- Options:
  - Publish RunIIb3 only
  - Work through problems and publish RunIIb34
  - Not publish ☹
- Would be nice to publish, but...

Conclusion

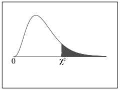
THANK YOU FOR YOUR ATTENTION!!!

Special Thanks to my Committee members: Toby Burnett, Anna Goussiou, Shih-Chieh Hsu, Henry Lubatti, Marcel den Nijs, Stephen Sharpe, LuAnne Thompson

And Extra Special Thanks to my Advisor, Gordon Watts

BACKUP: chi-square probability table

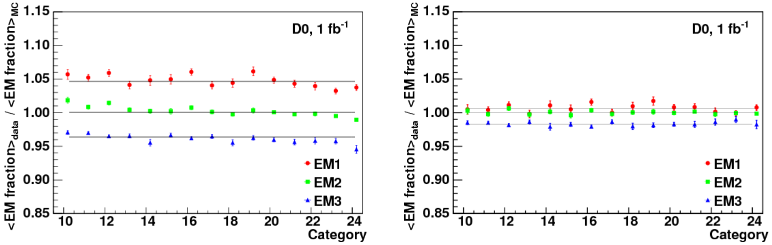
Chi-Square Distribution Table



The shaded area is equal to α for $\chi^2 = \chi^2_\alpha$.

df	$\chi^2_{.995}$	$\chi^2_{.990}$	$\chi^2_{.975}$	$\chi^2_{.950}$	$\chi^2_{.900}$	$\chi^2_{.100}$	$\chi^2_{.050}$	$\chi^2_{.025}$	$\chi^2_{.010}$	$\chi^2_{.005}$
1	0.000	0.000	0.001	0.004	0.016	2.706	3.841	5.024	6.635	7.879
2	0.010	0.020	0.051	0.103	0.211	4.605	5.991	7.378	9.210	10.597
3	0.072	0.115	0.216	0.352	0.584	6.251	7.815	9.348	11.345	12.838
4	0.207	0.297	0.484	0.711	1.064	7.779	9.488	11.143	13.277	14.860
5	0.412	0.554	0.831	1.145	1.610	9.236	11.070	12.833	15.086	16.750
6	0.676	0.872	1.237	1.635	2.204	10.645	12.592	14.449	16.812	18.548
7	0.989	1.239	1.690	2.167	2.833	12.017	14.067	16.013	18.475	20.278
8	1.344	1.646	2.180	2.733	3.490	13.362	15.507	17.535	20.090	21.955
9	1.735	2.088	2.700	3.325	4.168	14.684	16.919	19.023	21.666	23.589
10	2.156	2.558	3.247	3.940	4.865	15.987	18.307	20.483	23.209	25.188
11	2.603	3.053	3.816	4.575	5.578	17.275	19.675	21.920	24.725	26.757
12	3.074	3.571	4.404	5.226	6.304	18.549	21.026	23.337	26.217	28.300
13	3.565	4.107	5.009	5.892	7.042	19.812	22.362	24.736	27.688	29.819
14	4.075	4.660	5.629	6.571	7.790	21.064	23.685	26.119	29.141	31.319
15	4.601	5.229	6.262	7.261	8.547	22.307	24.996	27.488	30.578	32.801
16	5.142	5.812	6.908	7.962	9.312	23.542	26.296	28.845	32.000	34.267
17	5.697	6.408	7.564	8.672	10.085	24.769	27.587	30.191	33.409	35.718
18	6.265	7.015	8.231	9.390	10.865	25.989	28.869	31.526	34.805	37.156
19	6.844	7.633	8.907	10.117	11.651	27.204	30.144	32.852	36.191	38.582
20	7.434	8.260	9.591	10.851	12.443	28.412	31.410	34.170	37.566	39.997
21	8.034	8.897	10.283	11.591	13.240	29.615	32.671	35.479	38.932	41.401
22	8.643	9.542	10.982	12.338	14.041	30.813	33.924	36.781	40.289	42.796
23	9.260	10.196	11.689	13.091	14.848	32.007	35.172	38.076	41.638	44.181
24	9.886	10.856	12.401	13.848	15.659	33.196	36.415	39.364	42.980	45.559
25	10.520	11.524	13.120	14.611	16.473	34.382	37.652	40.646	44.314	46.928
26	11.160	12.198	13.844	15.379	17.292	35.563	38.885	41.923	45.642	48.290
27	11.808	12.879	14.573	16.151	18.114	36.741	40.113	43.195	46.963	49.645
28	12.461	13.565	15.308	16.928	18.939	37.916	41.337	44.461	48.278	50.993
29	13.121	14.256	16.047	17.708	19.768	39.087	42.557	45.722	49.588	52.336
30	13.787	14.953	16.791	18.493	20.599	40.256	43.773	46.979	50.892	53.672
40	20.707	22.164	24.433	26.509	29.051	51.805	55.758	59.342	63.691	66.766
50	27.991	29.707	32.357	34.764	37.689	63.167	67.505	71.420	76.154	79.490
60	35.534	37.485	40.482	43.188	46.459	74.397	79.082	83.298	88.379	91.952
70	43.275	45.442	48.758	51.739	55.329	85.527	90.531	95.023	100.425	104.215
80	51.172	53.540	57.153	60.391	64.278	96.578	101.879	106.629	112.329	116.321
90	59.196	61.754	65.647	69.126	73.291	107.565	113.145	118.136	124.116	128.299
100	67.328	70.065	74.222	77.929	82.358	118.498	124.342	129.561	135.807	140.169

BACKUP: Dead Material Correction



The ratio between the EMF in each layer for $Z \rightarrow ee$ events in data vs. FullMC, for each of the fifteen categories of η_{phys}, before (left) and after (right) the additional material has been added to the simulation. The mean EMF ratio for each layer is shown as a horizontal line.

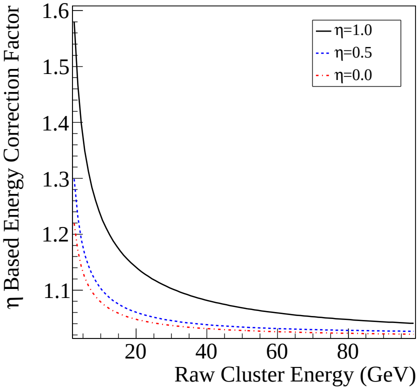
BACKUP: Dead Material Correction

bin 0:	$\lvert\eta_{\text{phys}}\rvert < 0.2$
bin 1:	$0.2 \le \lvert\eta_{\text{phys}}\rvert < 0.4$
bin 2:	$0.4 \le \lvert\eta_{\text{phys}}\rvert < 0.6$
bin 3:	$0.6 \le \lvert\eta_{\text{phys}}\rvert < 0.8$
bin 4:	$0.8 \le \lvert\eta_{\text{phys}}\rvert$

Definition of bins in electron $\lvert\eta_{\text{phys}}\rvert$.

Category	Combination of η_{phys} bins
10	0 - 0
11	0 - 1
12	0 - 2
13	0 - 3
14	0 - 4
15	1 - 1
16	1 - 2
17	1 - 3
18	1 - 4
19	2 - 2
20	2 - 3
21	2 - 4
22	3 - 3
23	3 - 4
24	4 - 4

BACKUP: Dead Material Correction

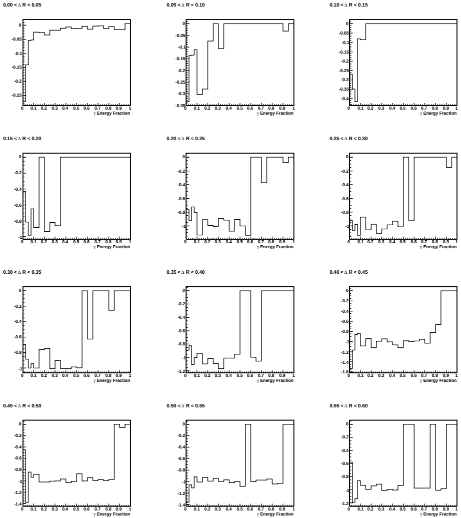


FigureA few examples of the correction functions applied to the energy measurement of reconstructed electrons in collider data in order to correct for energy loss in upstream dead material, as a function of electron p_T^{raw}, for various values of η_{phys}

The Vertex Simulation

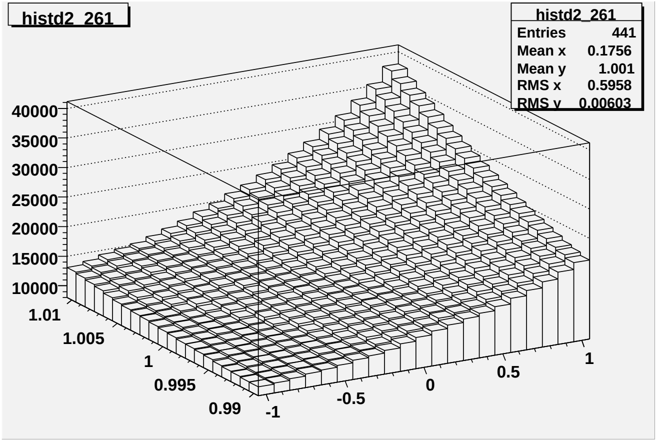
- Important to accurately model kinematics
- z_{vtx} with $\eta_{\mathrm{phys}} \rightarrow \eta_{\mathrm{detector}}$
- Lorentzian transverse beam profile convolved with Gaussian bunch length.
- Spot size of order tens of $\mu\mathrm{m}$.
- z_{vtx} simulated via Gaussian shape.
- For FullMC, center at $z = 0$ and width $25\mathrm{cm}$.
- For data, measure mean and width (in z) from collider data.

BACKUP: FSR simulation plots



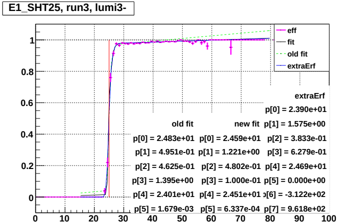
Fraction of FSR photon energy κ that is lost by the electron as a function of photon energy fraction X in bins of ΔR. Dependence is discussed in Section **??**. This is only a subset of the FSR response measurements, corresponding to the bin with $0.1 < |\eta| < 0.3$, $3 < \mathrm{InstLumi} < 3.5$, and $37.5 < p_T^e < 45\,\mathrm{GeV}$. ALSO MAYBE

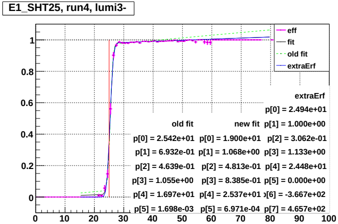
BACKUP: Determining the electron energy response parameters

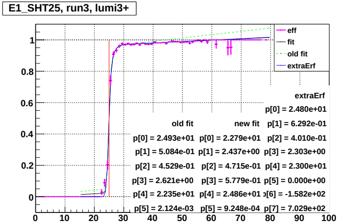


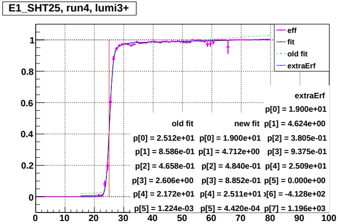
- Computationally intensive - requires creating array of α, β dependent FastMC samples
- To fit, parametrize each m_Z^{reco}, f_Z bin as function of α, β
- i.e. create parametrization at left once for each m_Z^{reco}, f_Z bin

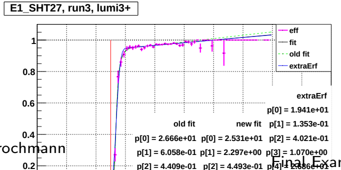
BACKUP: trigger efficiency plots, updated

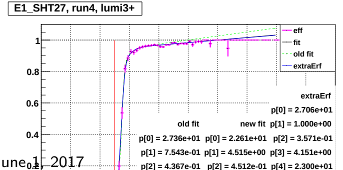




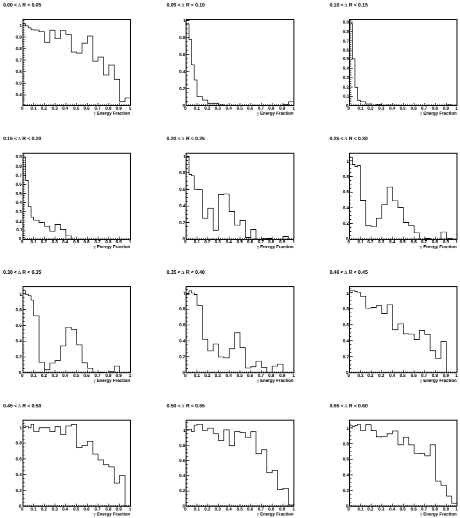






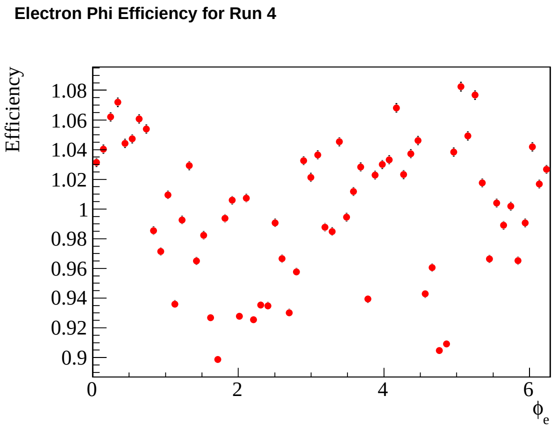


BACKUP: FSR efficiency plots



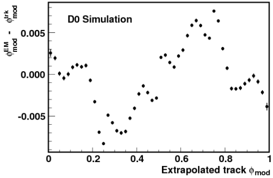
Electron identification efficiency as a function of X, the fraction of electron energy carried by the leading photon, measured from FullMC samples. For discussion, see Section **??**. This is only a subset of the FSR efficiency dependence measurements, in bins with $0.1 < |\eta_{\mathrm{phys}}| < 0.3$, $3 <$ [illegible] < 3.5, $37.5 < p_T^e < 45\,\mathrm{GeV}$, and ΔR

BACKUP: electron ϕ efficiency

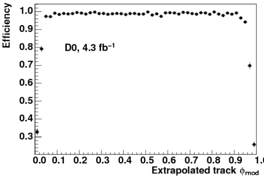


FigureElectron ϕ efficiency used in `GEANT` FastMC, determined from the ratio of the ϕ distributions of FullMC and FastMC. It looks "noisy" because each point corresponds to a single ϕ-module, and the efficiency depends in part on peculiarities to the individual modules.[**?**]

BACKUP: electron ϕ-mod effects



FigureAverage discrepancy between tracker-based (extrapolated to EM3 layer) ϕ^{trk} and calorimeter-based ϕ^{EM} measurements, in units of the calorimeter module width, as function of $\phi^{\mathrm{trk}}_{\mathrm{mod}}$ [?]



FigureElectron reconstruction efficiency as a function of (tracker-based) $\phi^{\mathrm{trk}}_{\mathrm{mod}}$. Note the steep drop in efficiency near the module boundaries. Due to this drop in efficiency, we include only events where electrons satisfy $0.1 < \phi_{\mathrm{mod}} < 0.9$. [?]

BACKUP: ABCD method for $Z \rightarrow ee$ background

make table here

BACKUP: Matrix method for QCD background

make table here

BACKUP: τ background

Overview of Electron Energy Response and Resolution

$$E = R_{EM}\left(E_0\right) \otimes \sigma_{EM}\left(E_0\right) + \Delta E \tag{6}$$

BACKUP (?) Electron Energy Resolution

$$\frac{\sigma_{EM}(E_0)}{E_0} = \sqrt{C_{EM}^2 + \frac{S_{EM}^2}{E_0} + \frac{N_{EM}^2}{E_0^2}} \tag{7}$$

C_{EM}, S_{EM}, and N_{EM} are the constant, sampling, and noise terms for the EM calorimeter.
sampling term does not have the "textbook" $(\sin\theta)^{-\frac{1}{2}}$

$$S_{\mathrm{EM}} = \left(S_1 + \frac{S_2}{\sqrt{E_0}}\right) \cdot \frac{e^{S_{\mathrm{exp}}/\sin\theta}}{e^{S_{\mathrm{exp}}}} \tag{8}$$

$$S_{\mathrm{exp}} = S_3 - S_4/E_0 - (S_5/E_0)^2 \tag{9}$$

$$S_1 = 0.152035 \tag{10}$$
$$S_2 = 0.151266 \tag{11}$$
$$S_3 = 1.39247 \tag{12}$$
$$S_4 = 1.45474 \tag{13}$$
$$S_5 = 10.3506 \tag{14}$$

- In data (in FullMC, negligible):

$$C_{EM} = (2.00 \pm 0.07)\,\% \tag{15}$$

- Noise term included in SoftRecoil model, so set it to 0 here.

BACKUP (?) Other electron response contributions

- Angular resolution
- Window effects

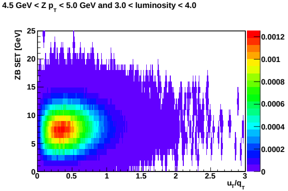
Recoil Simulation: Overview

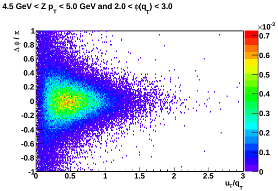
- Hard Recoil:
  - Need to choose values of u_T/q_T (response), $\frac{\Delta\phi}{\pi}$ (angular resolution), $\mathrm{SET} - u_T$ (energy from other parton interactions)
  - Create "Probability Density Functions" (PDFs) by simulating from $Z \to \nu\nu$ events

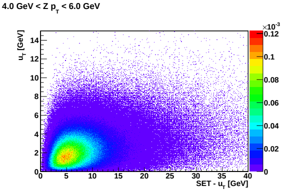
- Other contributions to the recoil:
  - Soft Recoil: Zero-Bias, "De-weighted" (via MB zero-fraction and power) MB library.
  - Electron Window Effects: FSR and non-FSR.
  - Parametric fine tune using FullMC or Data Sample, based on η mean and imbalance.

Recoil Simulation: PDFs for Hard Recoil

"ZB/MB cell-by-cell subtracted reconstruction": Simulate the behavior of Hard Recoil in the detector with underlying energy, create the histograms used below:







"ZB/MB cell-by-cell subtracted reconstruction": Simulate the behavior of Hard Recoil in the detector with underlying energy, create the histograms used below:

Know: p_T^Z, InstLumi $\rightarrow$ grab histogram. From $\mathrm{SET}^{\mathrm{ZB}}$, get PDF, randomly select u_T/q_T:

Know: p_T^Z, recoil angle $\phi(q_T)$ $\rightarrow$ grab histogram. From u_T/q_T (just simulated), get PDF, randomly select $\frac{\Delta\phi}{\pi}$:

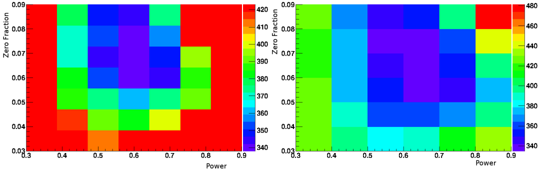
Know: p_T^Z *rightarrow* grab histogram. From u_T (just simulated, since q_T is known), get PDF, randomly select $\mathrm{SET} - u_T$:

BACKUP: Recoil Simulation: ZB and MB library for Soft Recoil

- Fill ZB Library:
- ZB events: Describe Zero Bias Trigger
- No need to reweight: match energy levels in collider data. (This is also used in the FullMC)

BACKUP: Recoil Simulation: ZB and MB library for Soft Recoil

- Fill MB library:
- MB Events: Describe Minimum Bias Trigger
- Fill Library according to:
- MB Zero Fraction: A certain fraction of events have zero soft recoil
- MB reweight: according to certain power (between 0 and 1) of MB (in some units)
- So probability of an MB event $\propto \left(C_{\mathrm{MB}}\mathrm{SET}^{\mathrm{MB}}\right)^{a_{\mathrm{MB}}}$



RunIIb3 (left) and RunIIb4 (right) χ^2 distributions used to find the best values of the zero-fraction and the MB SET power. These values are used when building the MB library.[**?**]

BACKUP: Recoil Simulation: Electron Window Effects

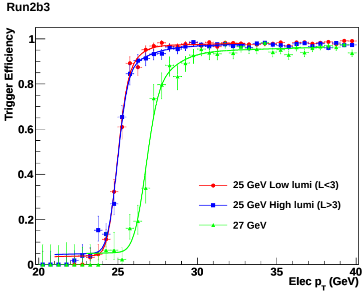
$$\vec{u}_T^{\mathrm{ELEC}} = \sum_e \left[-\Delta u_\parallel \cdot \hat{p}_T(e) + \vec{p}_T^{\mathrm{LEAK}} \right] \quad (16)$$

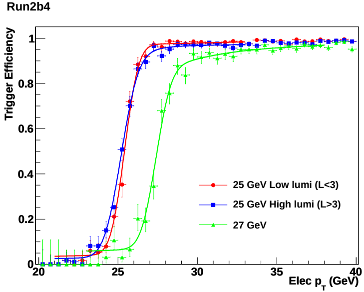
$$\vec{u}_T^{\mathrm{FSR}} = \sum_\gamma \vec{p}_T(\gamma) \quad (17)$$

BACKUP: Recoil Simulation: Fine tuning

$$\frac{u_{\parallel}^{\mathrm{HARD}}}{q_T} = \left(r_0 + r_1 e^{-q_T/\tau_{\mathrm{HAD}}}\right)\left\langle \frac{u_{\parallel}^{\mathrm{HARD}}}{q_T} \right\rangle + \sigma_0 \left(\frac{u_{\parallel}^{\nu\nu}}{q_T} - \left\langle \frac{u_{\parallel}^{\mathrm{HARD}}}{q_T} \right\rangle \right) \tag{18}$$

BACKUP: The Trigger Efficiency



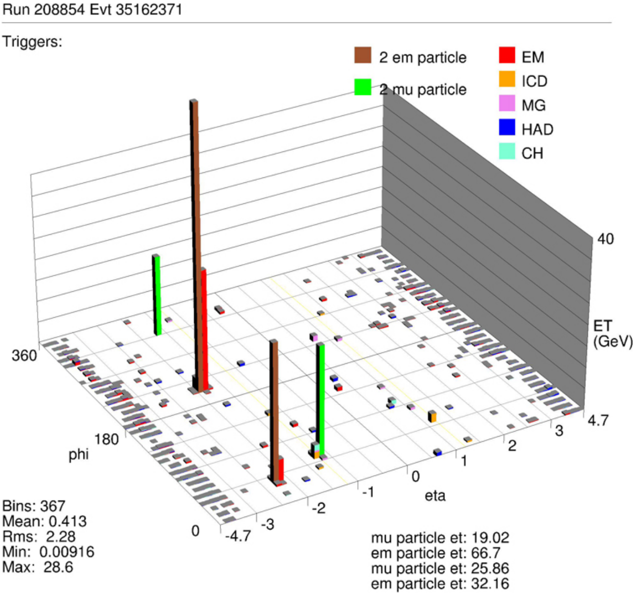


- Not simulated in FullMC - only simulate in data FastMC.
- Measure from data using tag and probe method.
- Model parametrized function - a product of "erfs".
- Trigger efficiency was updated recently in an attempt to understand some fitting problems with RunIIb4
- More discussion about this at end of talk

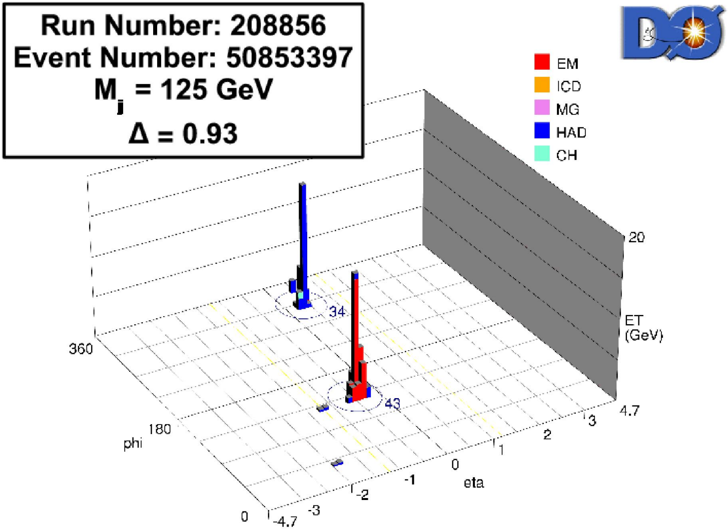
The Residual ScalarET Efficiency

- Residual efficiency dependence of combined selection cuts
- Dependent variables: SET, p_T^e, $\eta_{\rm det}$, InstLumi, $u_{\|}$
- First, determine FullMC/FastMC ratio in four-dimensional binning: p_T^e, $\eta_{\rm det}$, InstLumi, $u_{\|}$
- Parametrize ratio between FullMC and FastMC vs. SET/p_T^e in each bin
- Normalize each bin parametrization to full bin ratio

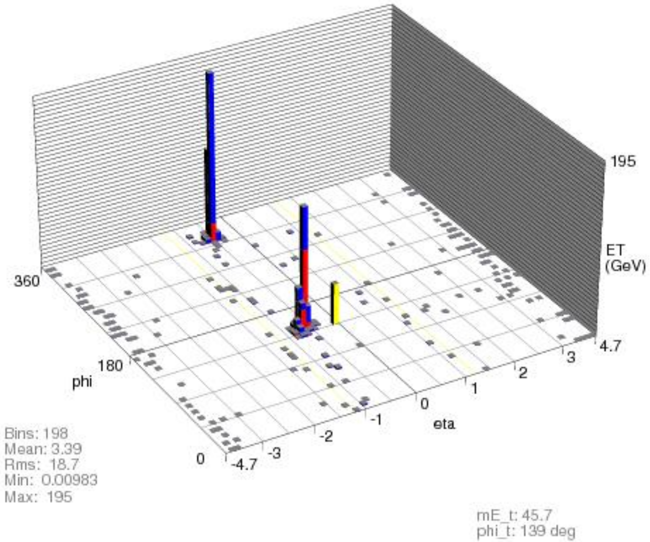
A Z Event in the D0 Calorimeter



A Di-Jet Event in the D0 Calorimeter

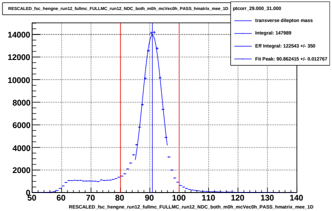


A Di-Jet Event in the D0 Calorimeter

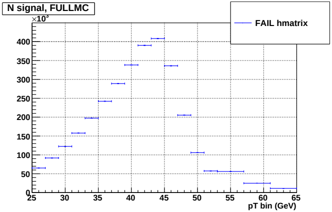


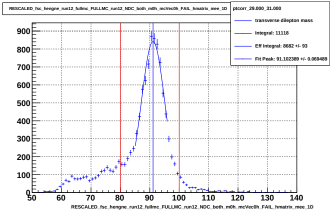
BACKUP: Measuring Hmatrix efficiency in FullMC

- Simply extract signal which passes and fails the Hmatrix cut in the efficiency window:

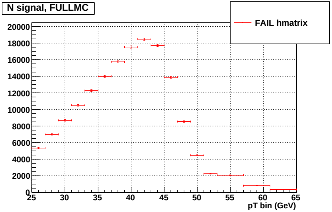


every p_T^e bin $\Longrightarrow$



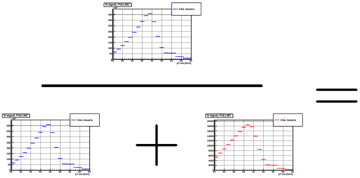


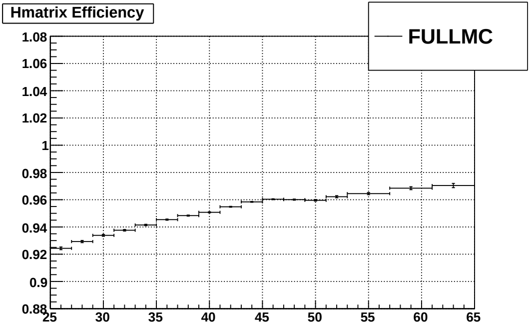
every p_T^e bin $\Longrightarrow$



BACKUP: Measuring Hmatrix efficiency in FullMC

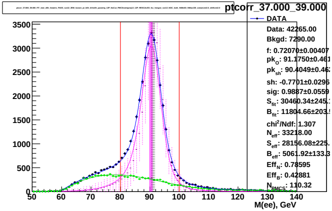
- Hmatrix cut efficiency in Full MC:



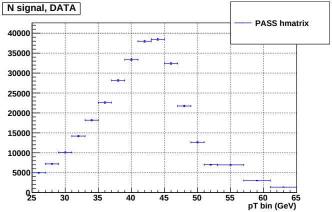


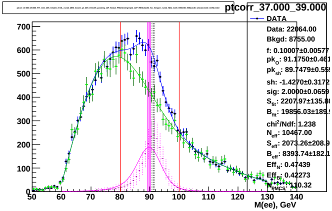
BACKUP: Measuring Track Matching Efficiency in Data

- Must subtract background to extract signal which passes and fails the Hmatrix cut:

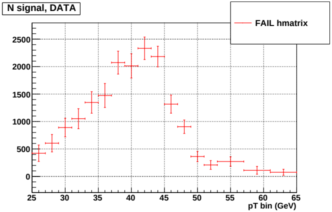


every p_T^e bin $\Longrightarrow$



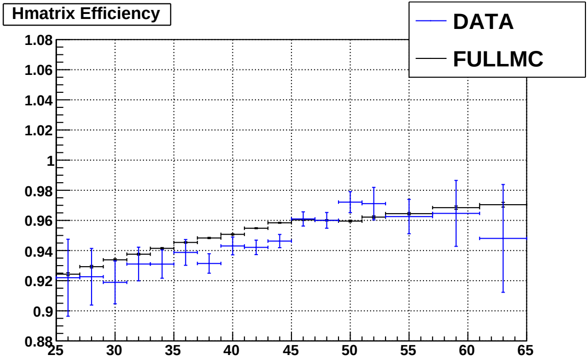


every p_T^e bin $\Longrightarrow$



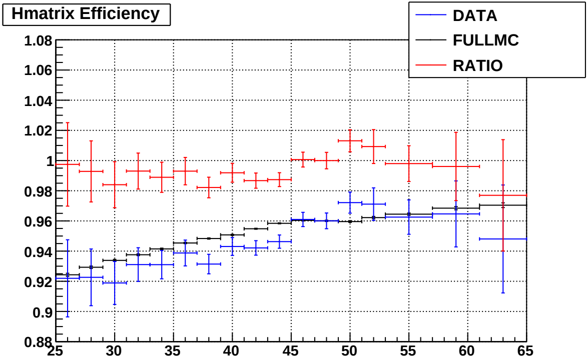
BACKUP: Measuring Track Matching Efficiency in Data

- Hmatrix cut efficiency, DATA compared with FullMC



BACKUP: Measuring Track Matching Efficiency in Data

- Hmatrix cut efficiency, DATA, FullMC, and DATA/FullMC ratio:

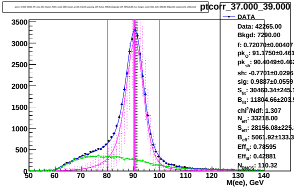


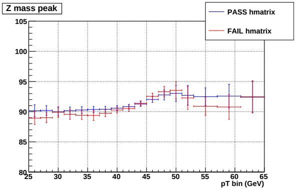
BACKUP: Scale Correction for Data Track Matching Efficiency

- PMCS gets parameters from sample of electrons which passes the Hmatrix cut.
- The efficiency it applies assumes a scaling that is independent of pass/fail status.
- Failing electrons have a different energy scale than passing electrons $\rightarrow$ bin migration.
- We must correct for this so that all electrons are binned according to their pt scaled like passing electrons.

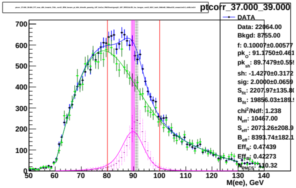
BACKUP: Scale Correction for Data Track Matching Efficiency

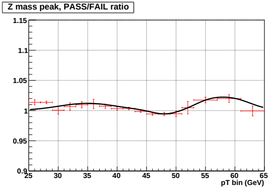
- Get scaling equation by taking ratio of passing Z mass peak to failing Z mass peak:



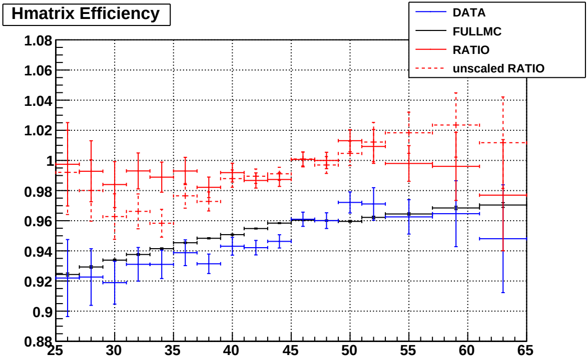


$$\alpha = \frac{Zpass}{Zfail}$$





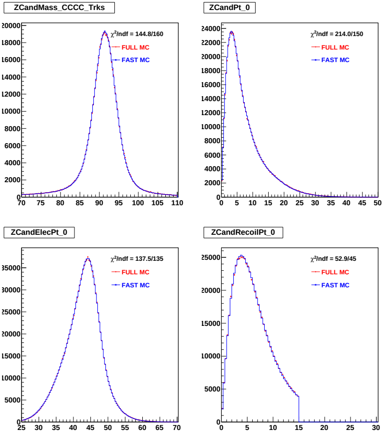
BACKUP: Track Matching Efficiency Correction: Results



- Apply correction factor in PMCS as smoothed function.
- Currently the pT correction is consistent with 1 and is not applied.

Monte Carlo Closure:

A test measurement of the Z mass in FullMC



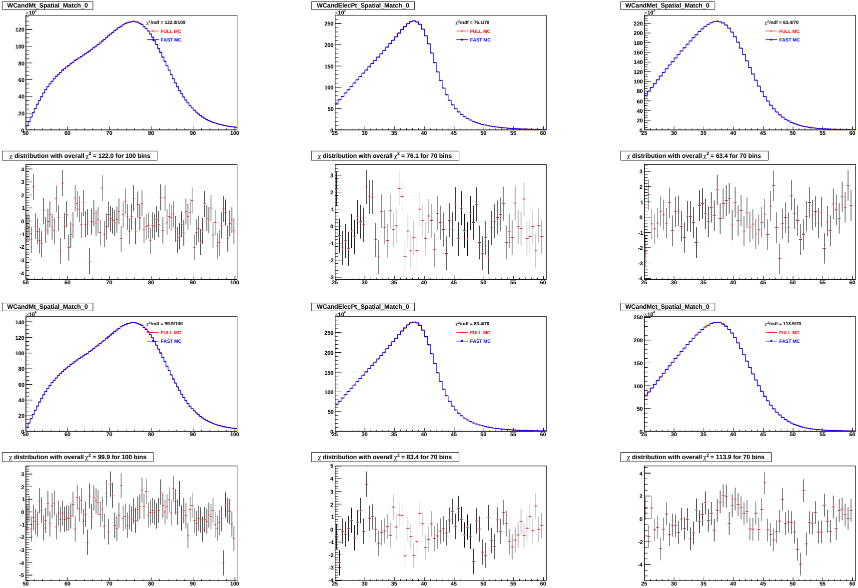
$\mathcal{L}$	Z mass RunIIb3	Z mass RunIIb4
All $\mathcal{L}$	91.191 ± 0.005	91.194 ± 0.004
$0 < \mathcal{L} < 2$	91.188 ± 0.014	91.191 ± 0.016
$2 < \mathcal{L} < 4$	91.190 ± 0.006	91.187 ± 0.006
$4 < \mathcal{L} < 6$	91.189 ± 0.009	91.190 ± 0.008
$\mathcal{L} > 6$	91.191 ± 0.013	91.193 ± 0.010

Result of the fit of the Z mass in bins of InstLumi. The input Z mass value is 91.188 GeV. RunIIb3 and RunIIb4 fit values are in good agreement with the input value.

RunIIb3 comparisons between FullMC and FastMC of the distributions of the Z mass (top left), the Z p_T (top right), the electron p_T (bottom left)), and the hadronic recoil (bottom right). Note the

Monte Carlo Closure:

A test measurement of the W mass in FullMC



Monte Carlo Closure:

A test measurement of the W mass in FullMC

$\mathcal{L}$	m_T	$p_T(e)$	MET
All $\mathcal{L}$	80.451 ± 0.006	80.450 ± 0.006	80.439 ± 0.008
$0 < \mathcal{L} < 2$	80.446 ± 0.018	80.457 ± 0.019	80.421 ± 0.021
$2 < \mathcal{L} < 4$	80.454 ± 0.009	80.454 ± 0.009	80.444 ± 0.011
$4 < \mathcal{L} < 6$	80.454 ± 0.012	80.442 ± 0.011	80.443 ± 0.016
$\mathcal{L} > 6$	80.416 ± 0.018	80.439 ± 0.016	80.418 ± 0.026

TableResult of the MC closure test for RunIIb3, in bins of InstLumi and for the full InstLumi range. The input W mass value is 80.450 GeV.

$\mathcal{L}$	m_T	$p_T(e)$	MET
All $\mathcal{L}$	80.454 ± 0.006	80.452 ± 0.006	80.448 ± 0.008
$0 < \mathcal{L} < 2$	80.460 ± 0.021	80.476 ± 0.021	80.431 ± 0.024
$2 < \mathcal{L} < 4$	80.463 ± 0.009	80.459 ± 0.008	80.457 ± 0.011
$4 < \mathcal{L} < 6$	80.454 ± 0.012	80.452 ± 0.011	80.424 ± 0.016
$\mathcal{L} > 6$	80.434 ± 0.015	80.445 ± 0.013	80.467 ± 0.021

TableResult of the MC closure test for RunIIb4, in bins of InstLumi and for the full InstLumi range. The input W mass value is 80.450 GeV.