ZZ Observation at the Tevatron

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Outline

Diboson Search at D0
- ZZ→llυυ Signature and Background
- Event Selection
- Instrumental Background Rejection
- Physics Background Seperation
- ZZ → lll'l' Orthogonal Search
  - Limit Setting and Results

Outlook
Conclusions

Diboson Physics

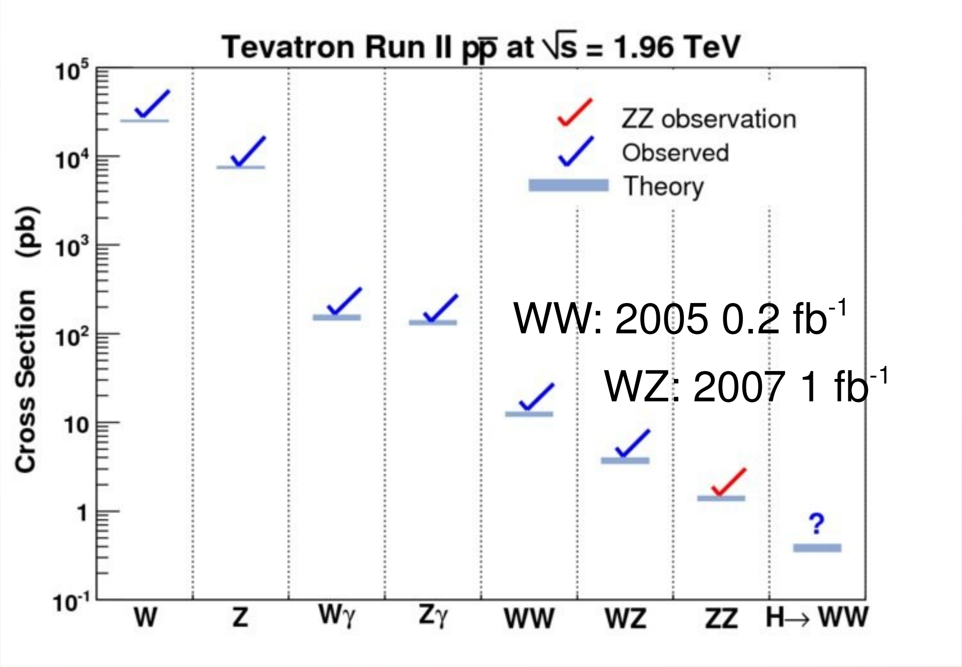
Study of the Electroweak sector:

Pair production of W/Z bosons: WW, WZ, and ZZ
Associated production with a photon: Wɣ and Zɣ

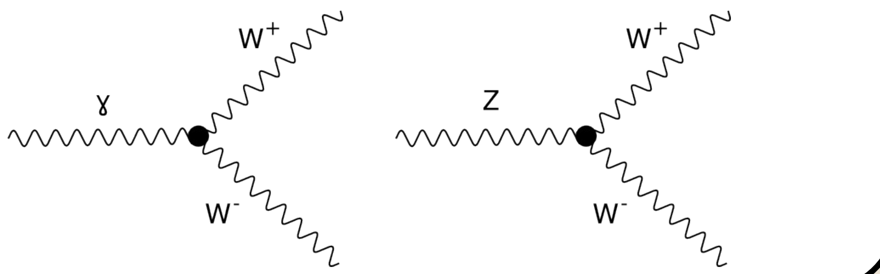
Precision tests of the standard model predictions:
Unexpectedly high cross section could indicate presence of physics beyond the SM.

No trilinear gauge couplings involving ZZ (suppressed at the tree level)

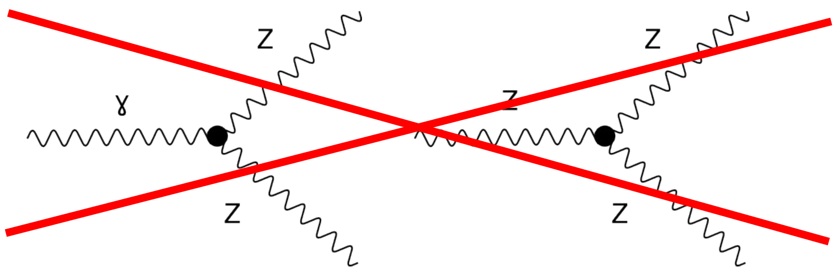
Important to “discover” our SM backgrounds if we are to believe any claims about the Higgs.



Allowed in the Standard Model

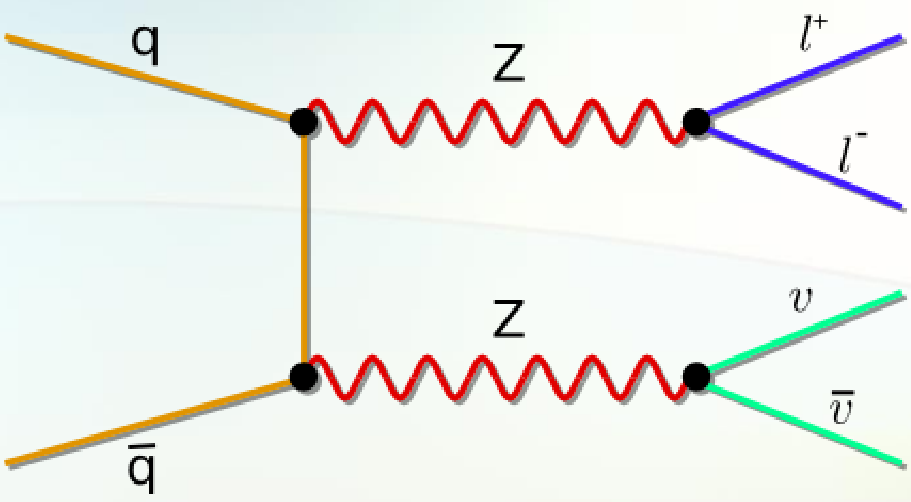


Disallowed in the Standard Model



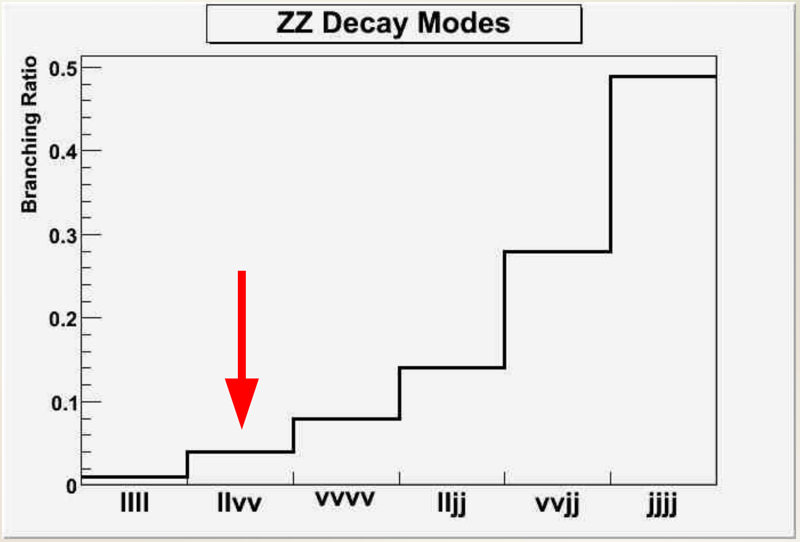
ZZ → llνν : Motivation

Aside from production with a Higgs Boson, the ZZ di-boson process has the lowest cross section and **was** the last remaining unobserved di-boson process at the Tevatron.



Use the fully leptonic mode ZZ→llυυ (where l = electrons and muons):

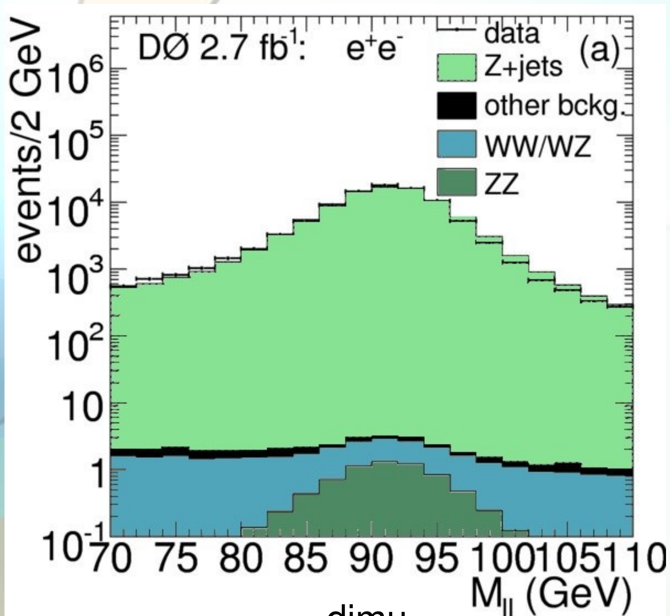
- Small branching fractions w.r.t jet modes
- Larger branching fractions than the ZZ→llll
- Manageable Backgrounds
- Requires a large amount of data



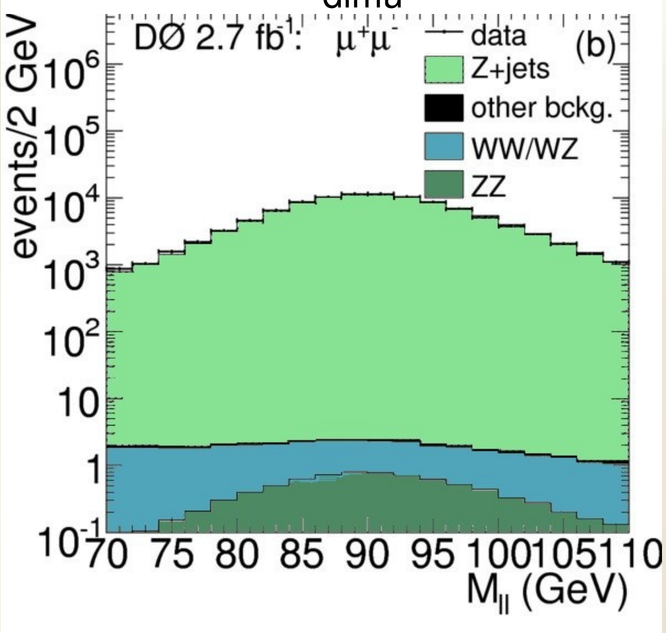
Preselection

2.7 fb^{-1} : Inclusive set of electron / muon triggers
Normalize to the Z peak in Data

diem



dimu



- 2 Leptons w/ p_T > 15 GeV
- Tight Isolation and Shape requirements
- Electrons within the central ($|\eta| < 1.1$) or forward ($1.5 < |\eta| < 2.5$) calorimeter regions
- Muons with at least one 1 hit in the Silicon Microstrop Tracker (SMT)

Reject events with additional low p_T or poorly reconstructed electrons, muon, taus, and isolated tracks

Require # of jets <= 2 w/ p_T > 15 GeV

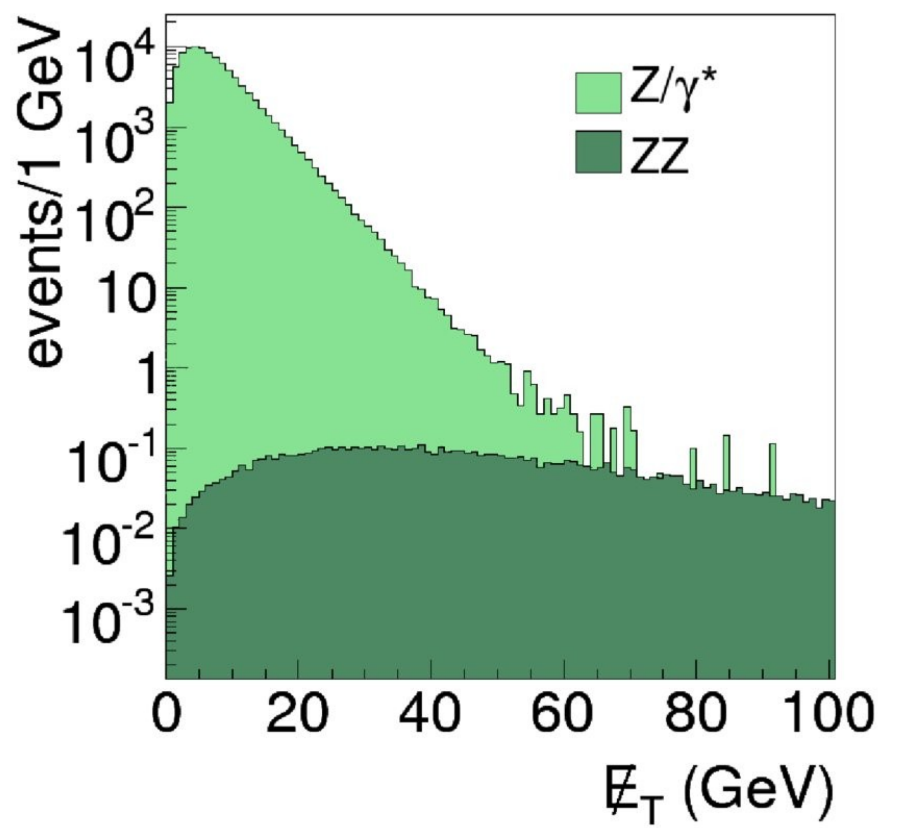
Di-lepton Invariant Mass $70 < M_{ll} < 110$ GeV

Cut on MET?

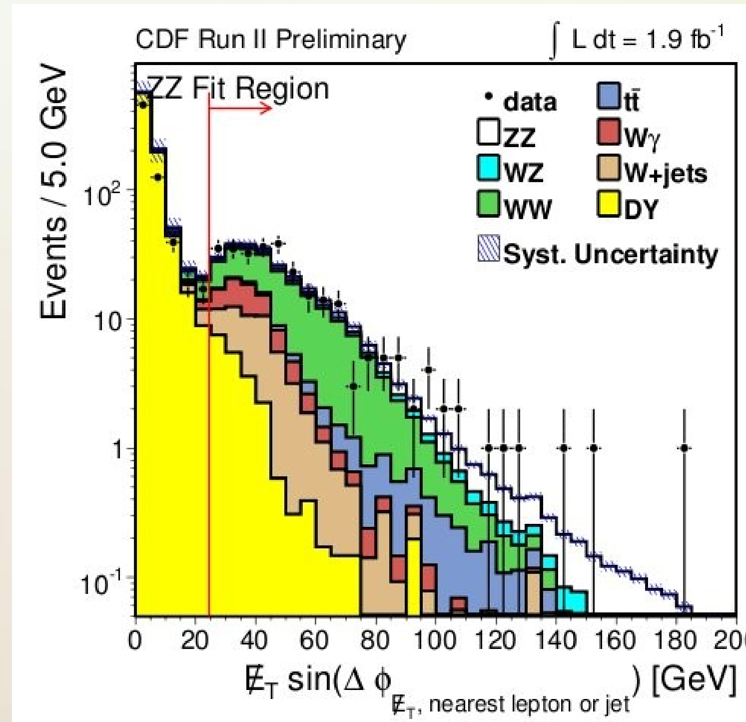
Signal with neutrinos, so expect significant MET in the event

Although the MET mis-measurement tails are small, the signal is still overwhelmed due to the substantially larger cross section of the Z/γ* .

MET for signal and the dominant background



CDF makes a low cut on a MET like variable, relies on a likelihood ratio discriminant to further separate background in the remaining 276 events.

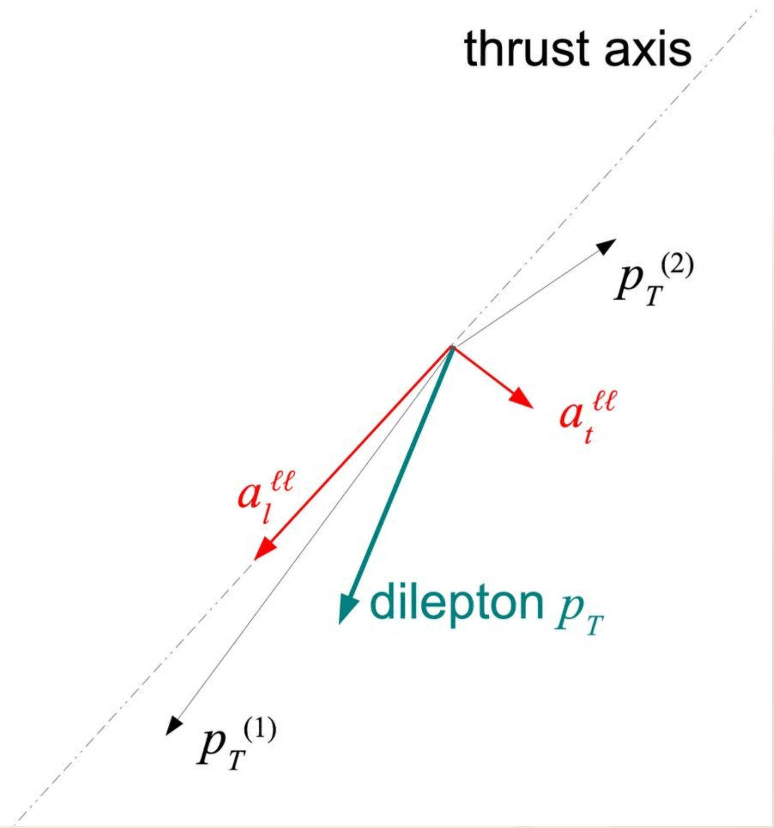


Building a Better MET Indicator

Rather than make an unbiased or accurate estimate of the MET, build a variable which is a measure of the minimum feasible MET robust against reconstruction mistakes.

- decompose di-lepton p_T in 2 components with respect to thrust axis:
  - a_L: sensitive to p_T mis-measurement
  - a_T: sensitive to recoil activity mis-measurement
- Correct a_L and a_T individually for:
  1. Calorimeter recoil activity (MET and Jets)
  2. p_T of recoiling tracks
  3. Lepton transverse momentum uncertainty
- Build a variable which gives more weight to a_T

  $\not{E}_T' = \mathrm{sqrt}(a_L^2 + (1.5\, a_T)^2)$



Result:

- by construction all uncertainties and mis-reconstruction can ONLY reduce the value of $\not{E}_T'$

$$\vec{t} = p_T^{(1)} - p_T^{(2)}$$

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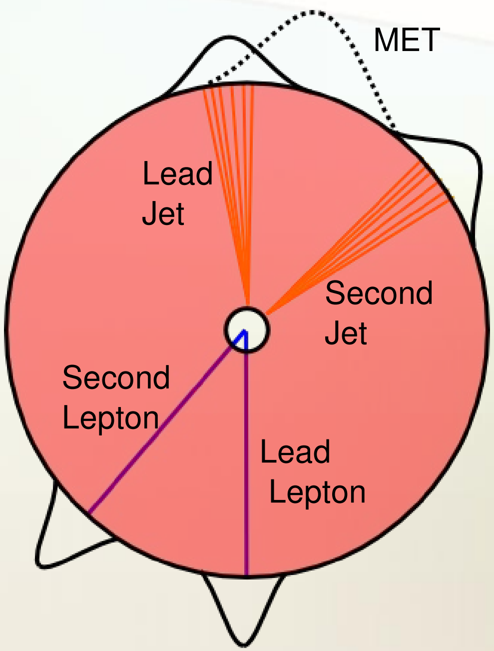

a_L and a_T decomposition:

$$\delta a_t^{cal} = 2 \times min(\Sigma \vec{E_T}^{jets} \cdot \hat{a}_t,\ \vec{\not{E}_T} \cdot \hat{a}_t, 0)$$
$$\delta a_l^{cal} = 2 \times min(\Sigma \vec{E_T}^{jets} \cdot \hat{a}_l,\ \vec{\not{E}_T} \cdot \hat{a}_l, 0)$$

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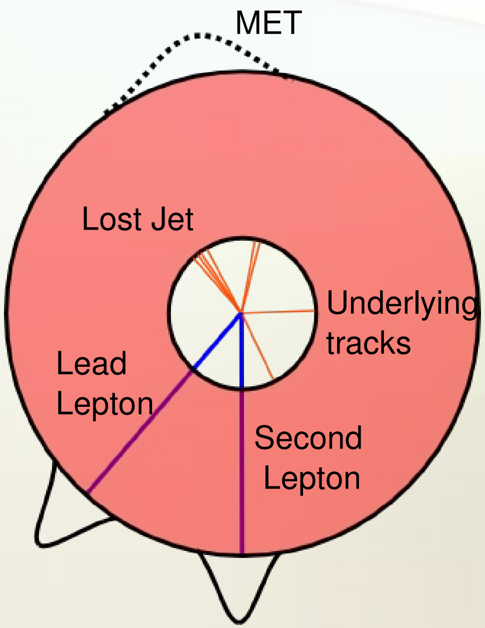

a_L and a_T decomposition:

$$\delta a_t^{trk} = (\Sigma \vec{p_T}^{\,t\,jet}) \cdot \hat{a}_t$$

$$\delta a_l^{trk} = (\Sigma \vec{p_T}^{\,t\,jet}) \cdot \hat{a}_l$$

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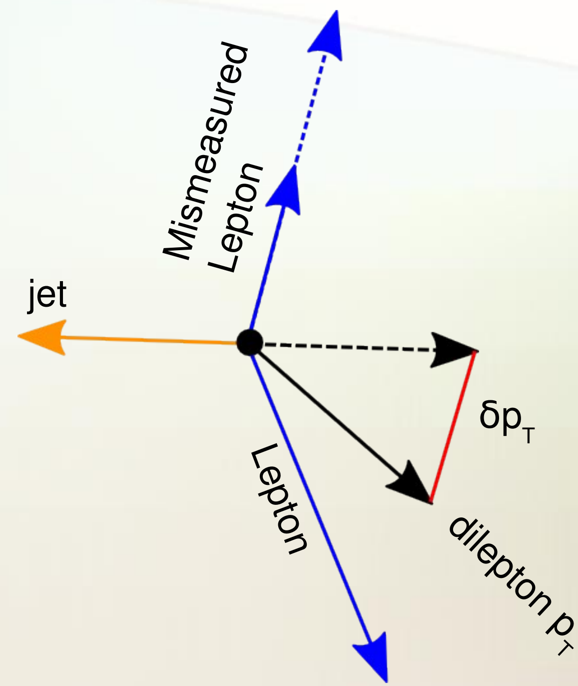

a_L and a_T decomposition:

$$\vec{p_T}' = (1-\sigma)\vec{p_T}\text{, etc...}$$

$$a_t^{\ell\ell'} = \vec{p_T}^{\ell\ell'} \cdot \hat{a}_t'$$

$$\delta a_t^{\ell\ell} = a_t^{\ell\ell'} - a_t^{\ell\ell}$$

$$\delta a_l^{\ell\ell} = (-\sigma_1 \vec{p_T}^{(1)} + \sigma_2 \vec{p_T}^{(2)}) \cdot \hat{a}_l$$

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  - a_L: sensitive to p_T mis-measurement
  - a_T: sensitive to recoil activity mis-measurement
- Correct a and a individually for:

  1

  2

  3

- Bu

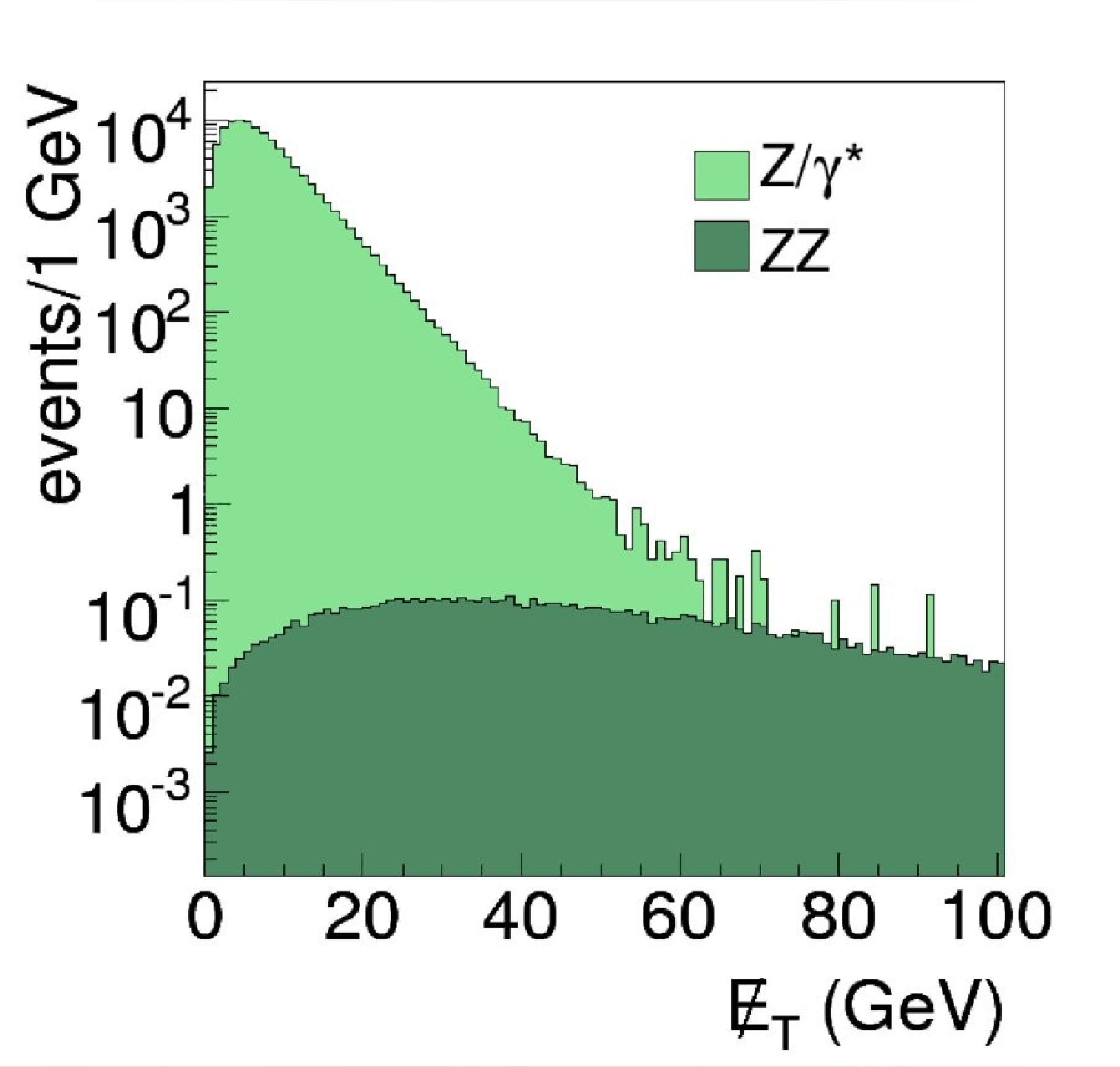
  $\not{E}_T$

$$a_t = a_t^{\ell\ell} + \delta a_t^{cal} + k' \times \delta a_t^{trk} + k \times \delta a_t^{\ell\ell}$$
$$a_l = a_l^{\ell\ell} + \delta a_l^{cal} + k' \times \delta a_l^{trk} + k \times \delta a_l^{\ell\ell}$$

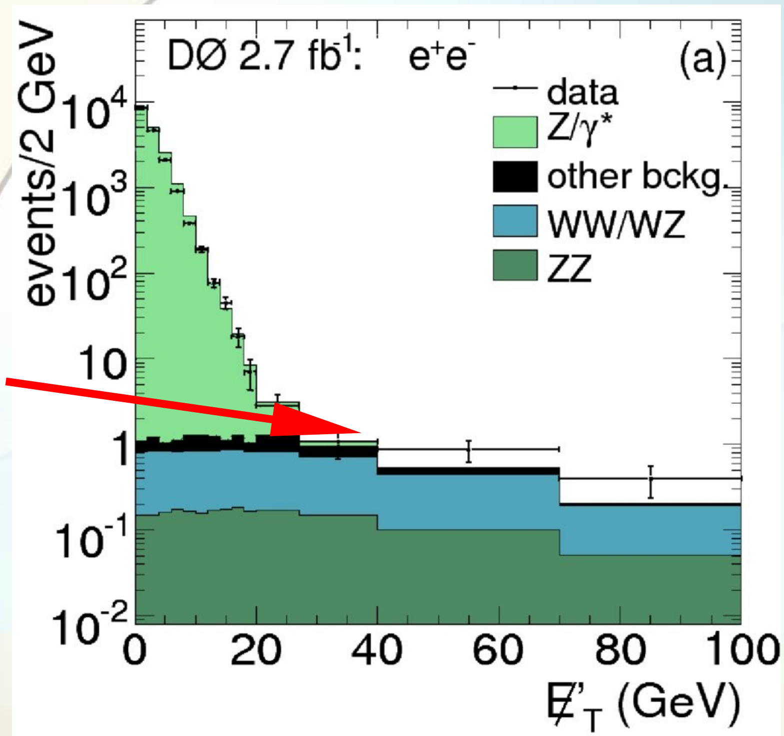
$$a'_t = max(a_t, 0) \qquad a'_l = max(a_l, 0)$$

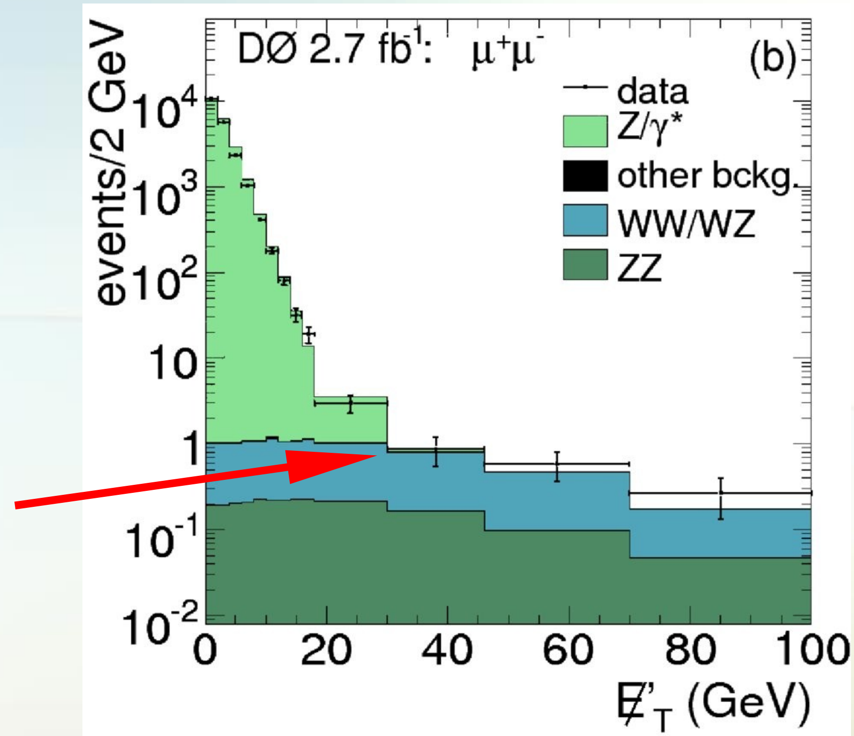
$$\not{E}_T{}' = \sqrt{a'^2_l + (1.5a'_t)^2}$$

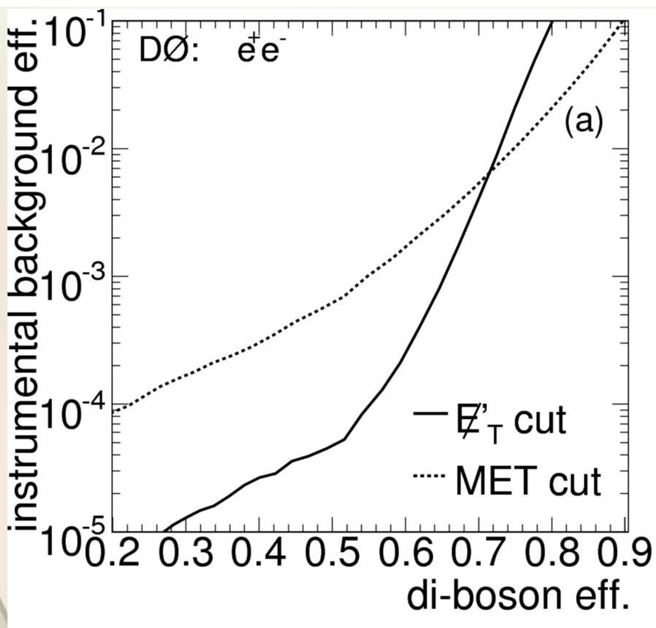
What's The Pay Off?



Instrumental Background Rejection







Yields after the $\not{E}_T$' cut:

Sample	diem	dimu
Z->ll	0.5 ± 0.2	0.1 ± 0.1
ZZ->llvv	4.03	3.39
Tot Bckg	15.6 ± 0.4	10.9 ± 0.3
Bkgd + Signal	19.6 ± 0.4	14.3 ± 0.3
Data	28	15

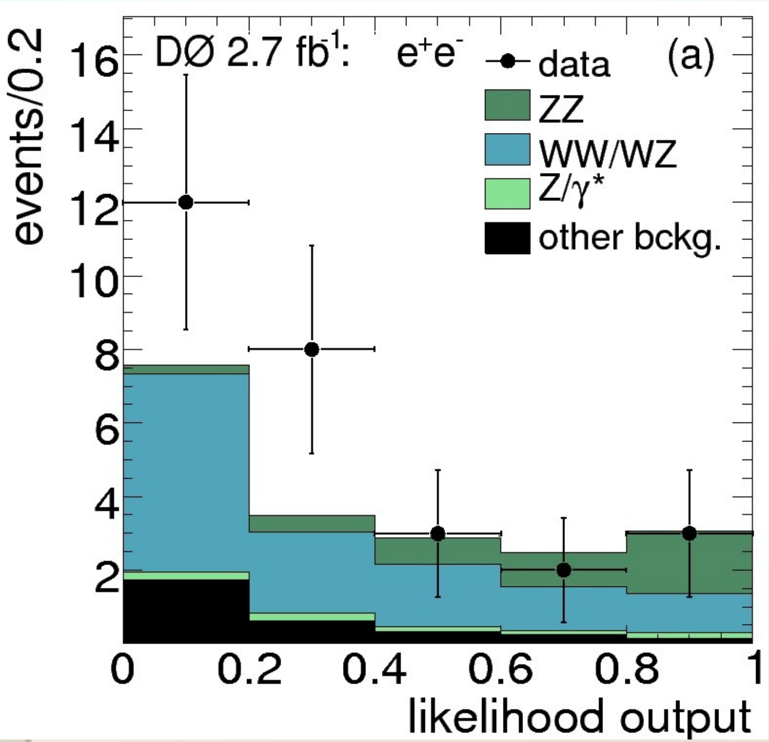
Likelihood Method

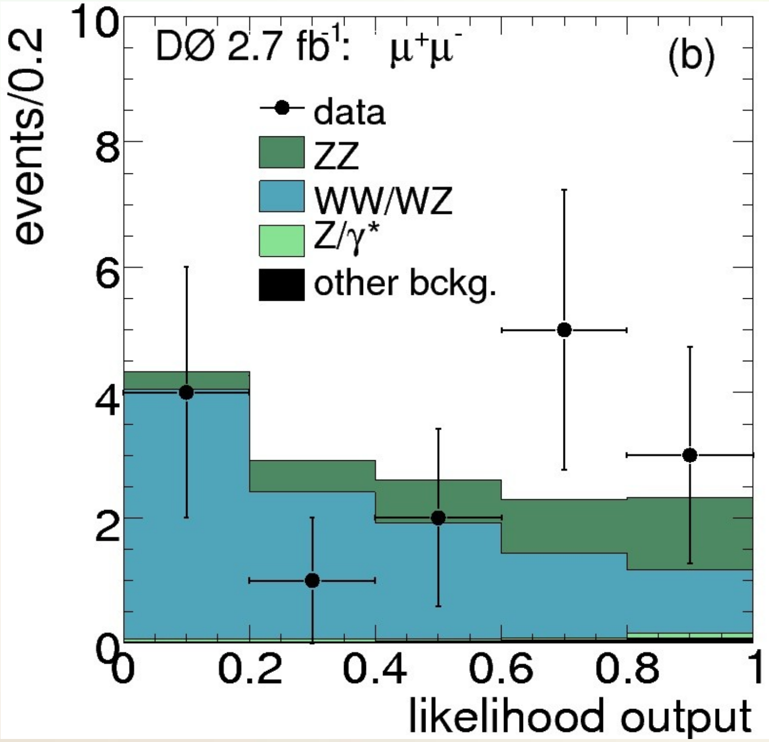
Remaining physics backgrounds are further separated from the signal using a likelihood method.

Calculate and fit S/(S+B) per bin for 4 distributions:
$f(x_1, x_2, ...) = f(x_1) * f(x_2) * ...$

Likelihood Variables:

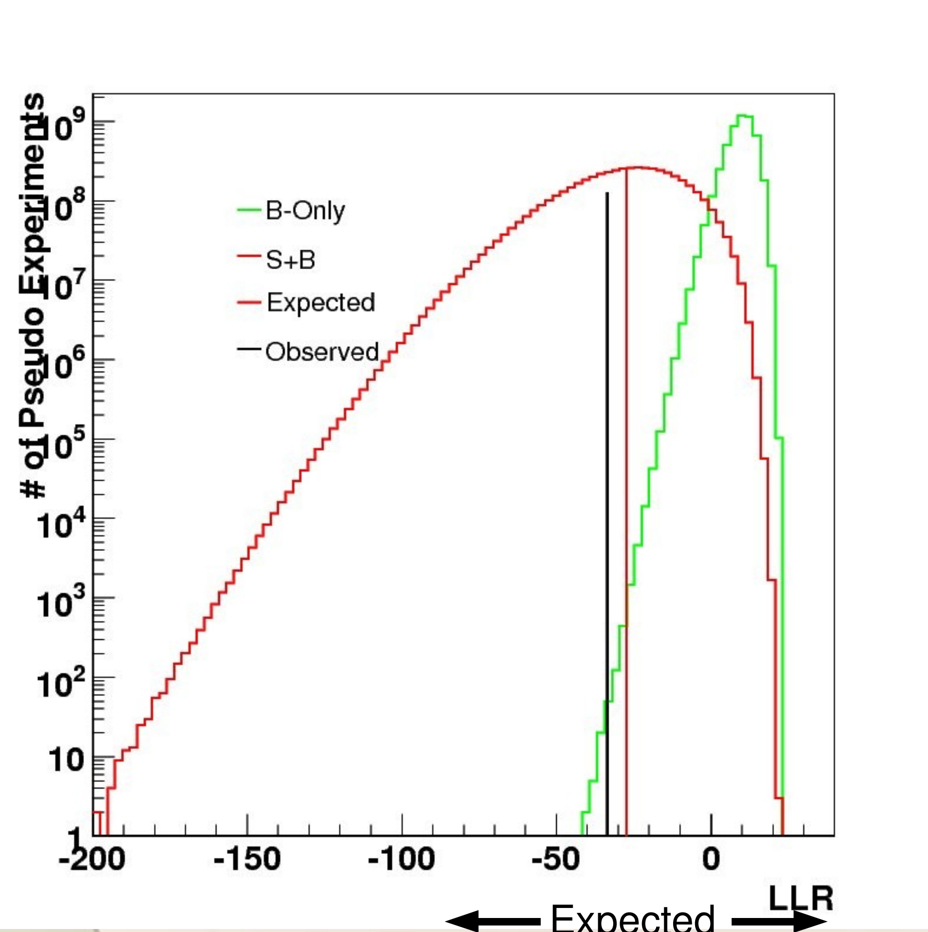
- Di-lepton mass (diem)
- Chi2 probability (dimu)
- Leading lepton p_T
- $\Delta\Phi$(lead lep, di-lep)
- $\cos(\theta^*)$





ZZ → (llυυ, lll'l') Combined Result

An orthogonal search has been performed at D0 in the ZZ to four charged leptons channel in which three candidate events have been found.



← Expected →
Excess Deficit

The combined significance is determined by calculating the probability that the background fluctuate up to our observed values from 3×10^9 pseudo-experiments using a semi-frequentist approach.

First observation at a hadron collider:

ZZ → llυυ:	2.0σ exp	2.6σ obs
ZZ → llll:	4.2σ exp	5.0σ obs
Combined:	4.8σ exp	5.7σ obs

$$\sigma(ZZ) = 1.60 \pm 0.63\ (\text{stat.})^{+0.16}_{-0.17}\ (\text{syst.})\ \text{pb}$$

Predicted Standard Model cross section: 1.4 ± 0.1 pb

Less than 1 order of magnitude different than some high mass Higgs

ZZ → llυυ published in PRD **78**, 072002 (2008)
ZZ → llll and combination published in PRL **101**, 17183 (2008)

vertical red line: expected LLR from pseudo-experiments
vertical black line: value observed from data

Outlook

METPrime is getting an extended lease on life in Higgs searches:

In $H \to WW \to l\upsilon l\upsilon$:

Multiple cuts on MET and related variables could be replaced by one on MET'

Shape difference between signal and background could be used by their NN
Select events with genuine MET

In $ZH \to llbb$ and $ZH \to \upsilon\upsilon bb$:

Feed the shape into a multivariate classifier to improve background rejection.

Two way street:, techniques to extend coverage in Higgs analyses (such as expanded lepton acceptance) could give a significant boost to the sensitivity of the $ZZ \to ll\upsilon\upsilon$ analysis.

Conclusion

Demonstrated an alternate handle on MET.
What METPrime lacks in simplicity, it gains in performance.

Continue to improve the D0 arsenal with 1st observations of processes like ZZ production.

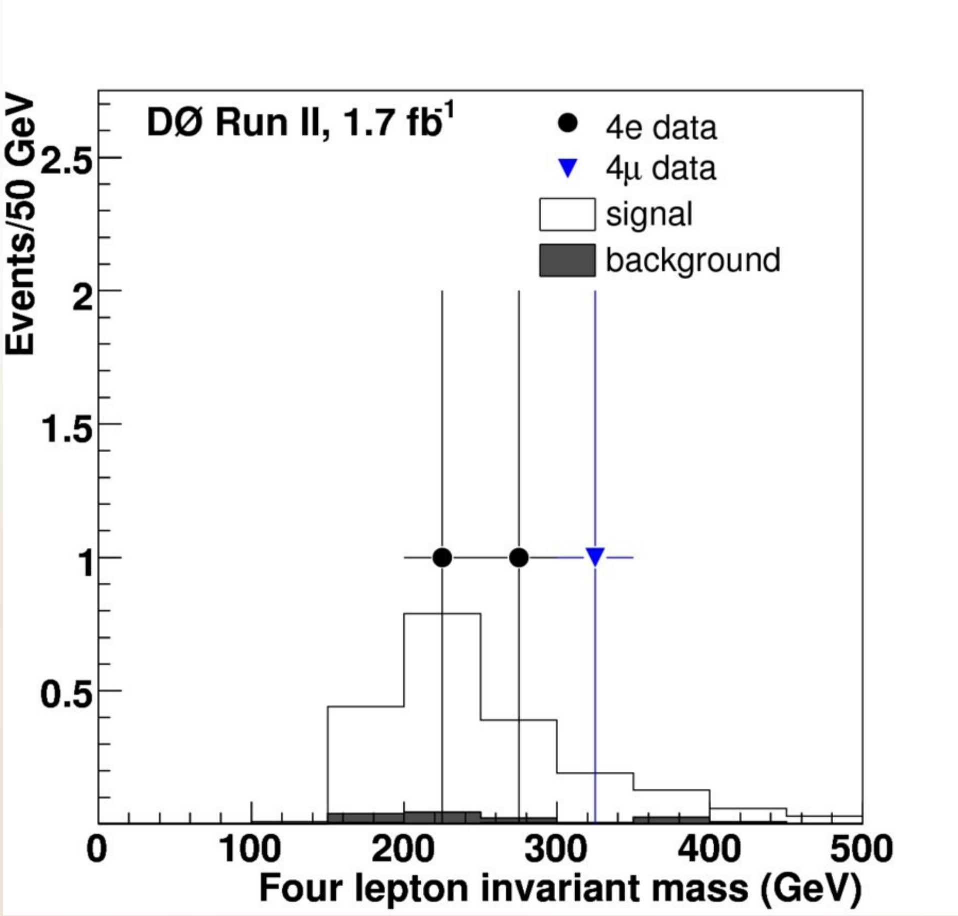
Sharing analysis techniques will lead to further improvements in new physics searches (in both directions).

Higgs analyses using > 6.5 fb^{-1} likely to integrate our instrumental techniques in the Tevatron combination for the Summer 2k9 results.

Backup Slides

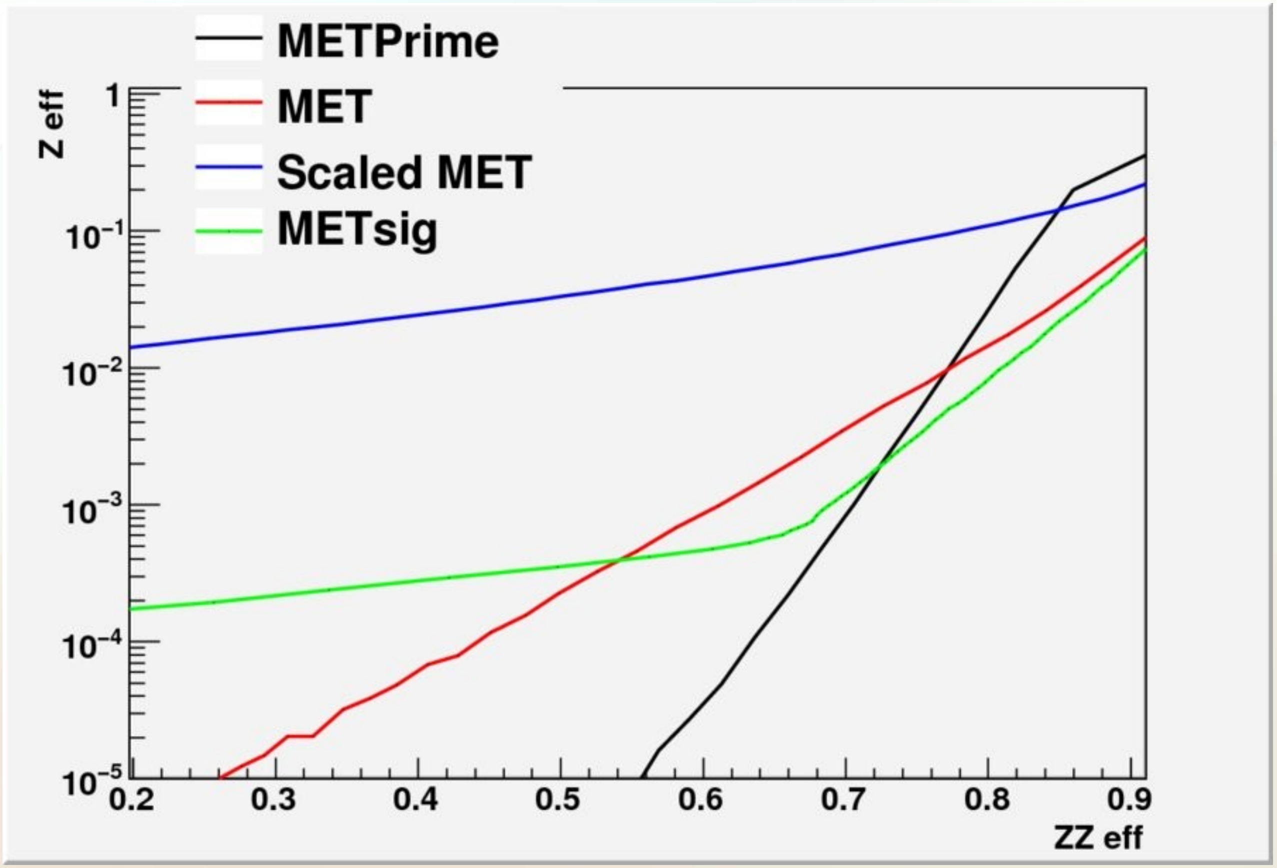
ZZ → llll: Candidate Events

Subchannel	$4e_{2C}$	$4e_{3C}$	$4e_{4C}$	4μ	$2\mu 2e_{0C}$	$2\mu 2e_{1C}$	$2\mu 2e_{2C}$
Luminosity (fb^{-1})	1.75 ± 0.11	1.75 ± 0.11	1.75 ± 0.11	1.68 ± 0.10	1.68 ± 0.10	1.68 ± 0.10	1.68 ± 0.10
Signal	0.084 ± 0.008	0.173 ± 0.015	0.140 ± 0.012	0.534 ± 0.043	$0.058^{+0.007}_{-0.006}$	0.352 ± 0.040	$0.553^{+0.045}_{-0.044}$
$Z(\gamma)$+jets	$0.030^{+0.009}_{-0.008}$	$0.018^{+0.008}_{-0.007}$	$0.002^{+0.002}_{-0.001}$	0.0003 ± 0.0001	$0.03^{+0.02}_{-0.01}$	0.05 ± 0.01	$0.008^{+0.004}_{-0.003}$
$t\bar{t}$	–	–	–	–	$0.0012^{+0.0016}_{-0.0009}$	0.005 ± 0.002	$0.0007^{+0.0009}_{-0.0005}$
Observed events	0	0	$\boxed{2}$	$\boxed{1}$	0	0	0

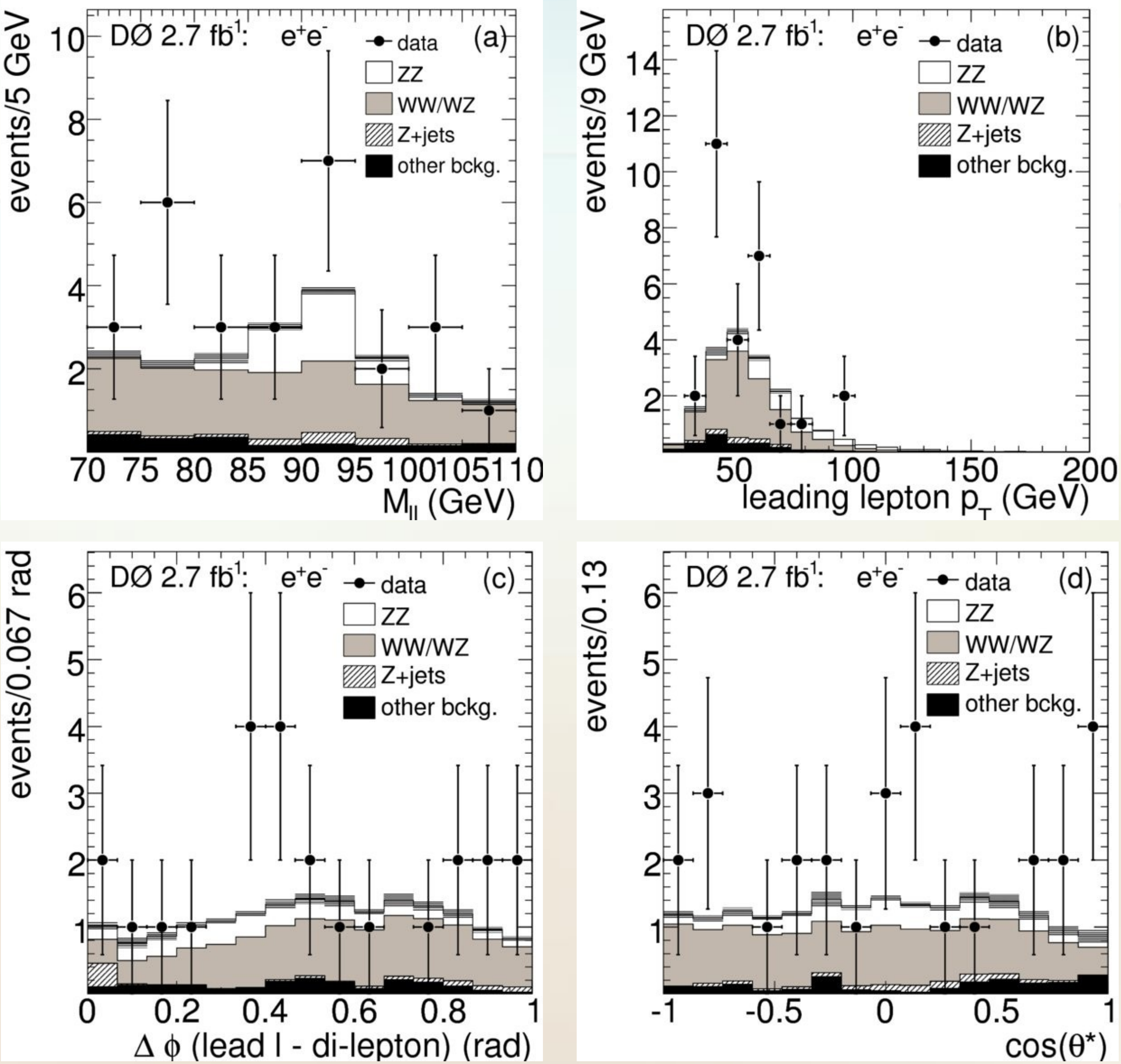


Why METPrime?

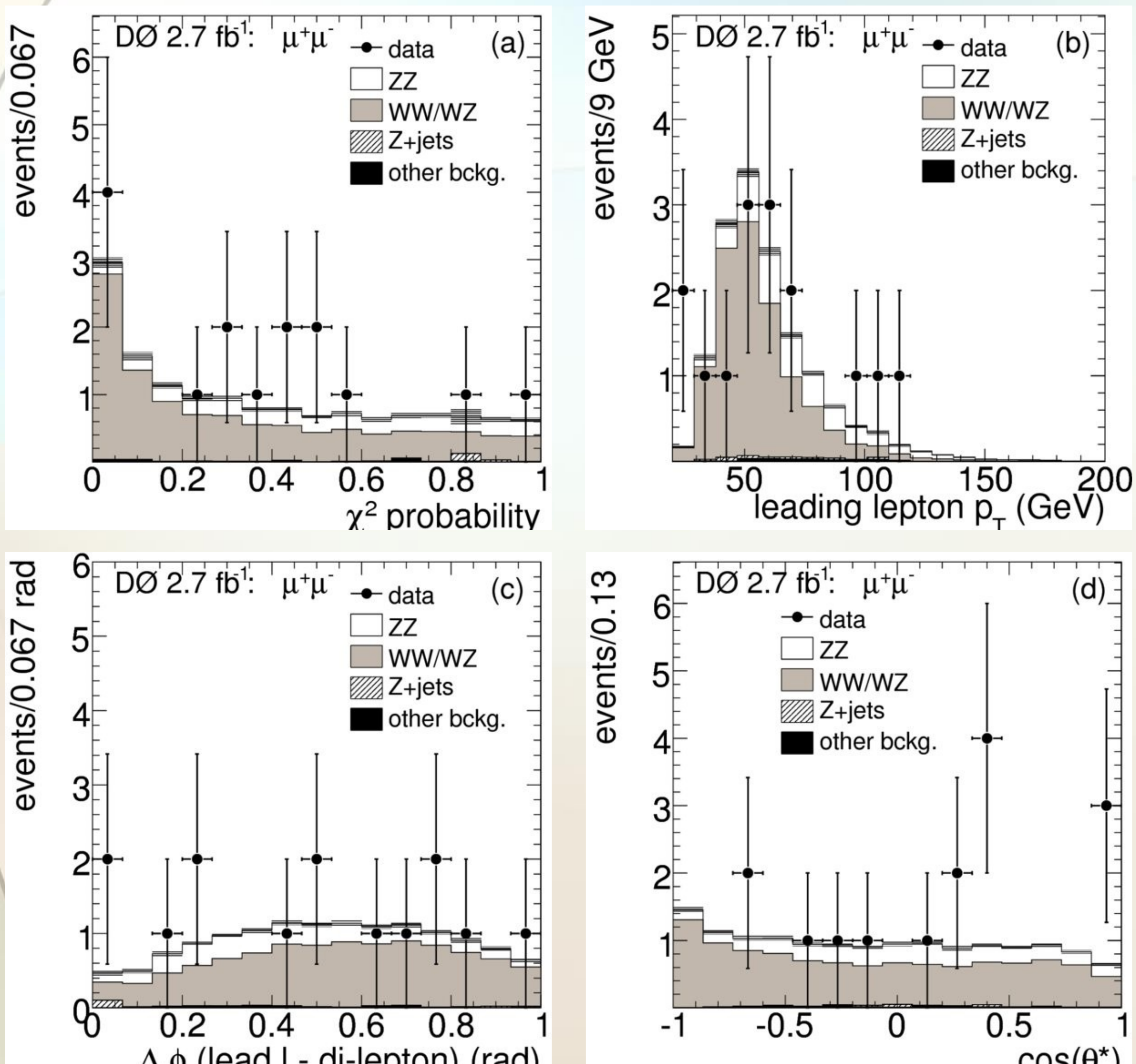
Compute acceptance for Z vs ZZ for several MET types.



ZZ->llυυ: Likelihood Variables - diem



ZZ->llυυ: Likelihood Variables - dimu



For display, not a likelihood var: