Heavy Z’ Boson Searches at CDF

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For the CDF Collaboration

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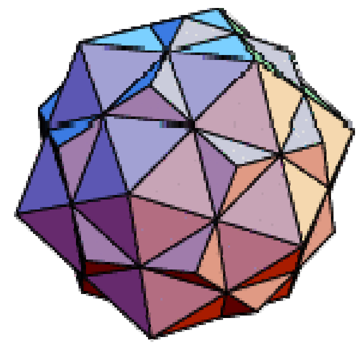
Motivation

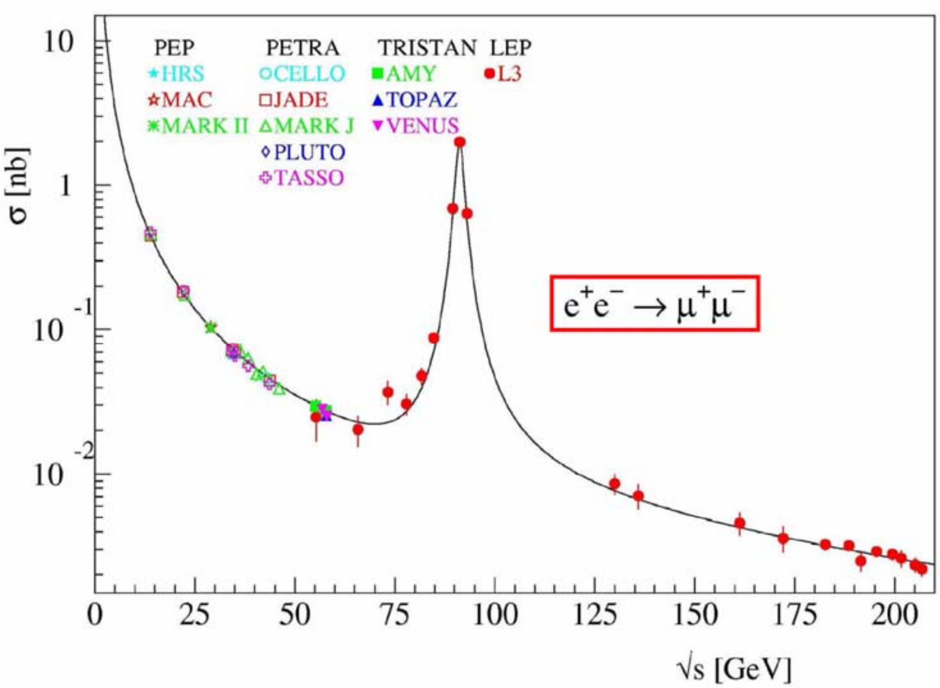
- Z' is a heavy neutral vector boson
- Z' (or other gauge) are remnants from the top-down:
  - String, GUT, DSB, little Higgs, LED often involve Z'
  - Example: Grand Unified Theory E_6:
    - $E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi$
  - Or little Higgs:
    - $[SU(2) \times U(1)]^2 \rightarrow SU(2)_L \times U(1)_Y$

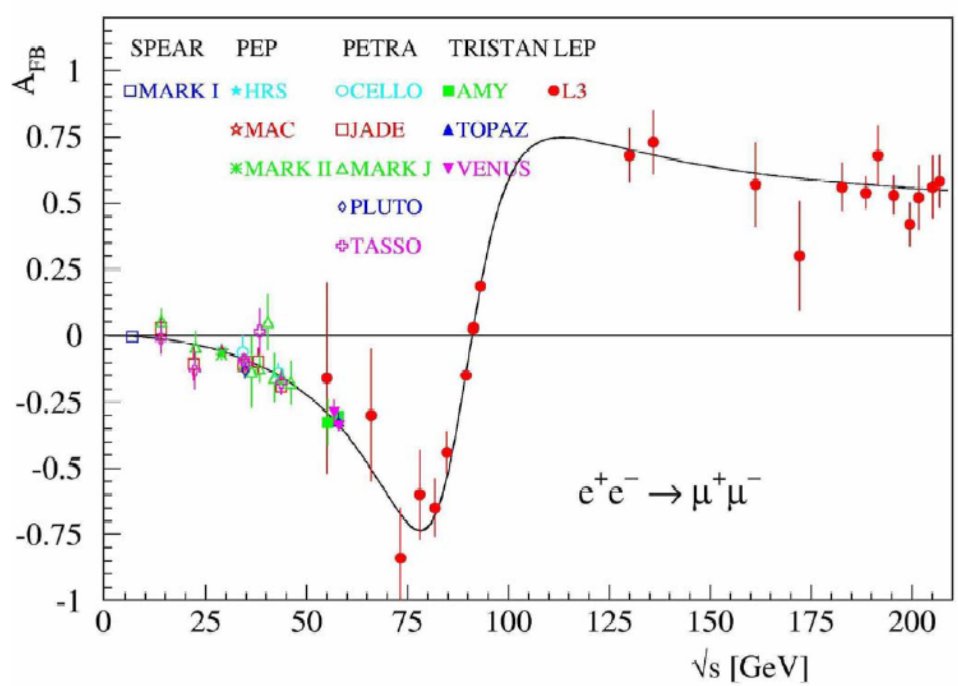


- If it exists, Z' interferes with the SM Z^0
  - Mixing angle $\theta \sim 10^{-3}$
- Northwestern University workshop on Z' Nov.04
  - Very fruitful interaction between theory-experiment

Searching for Z'

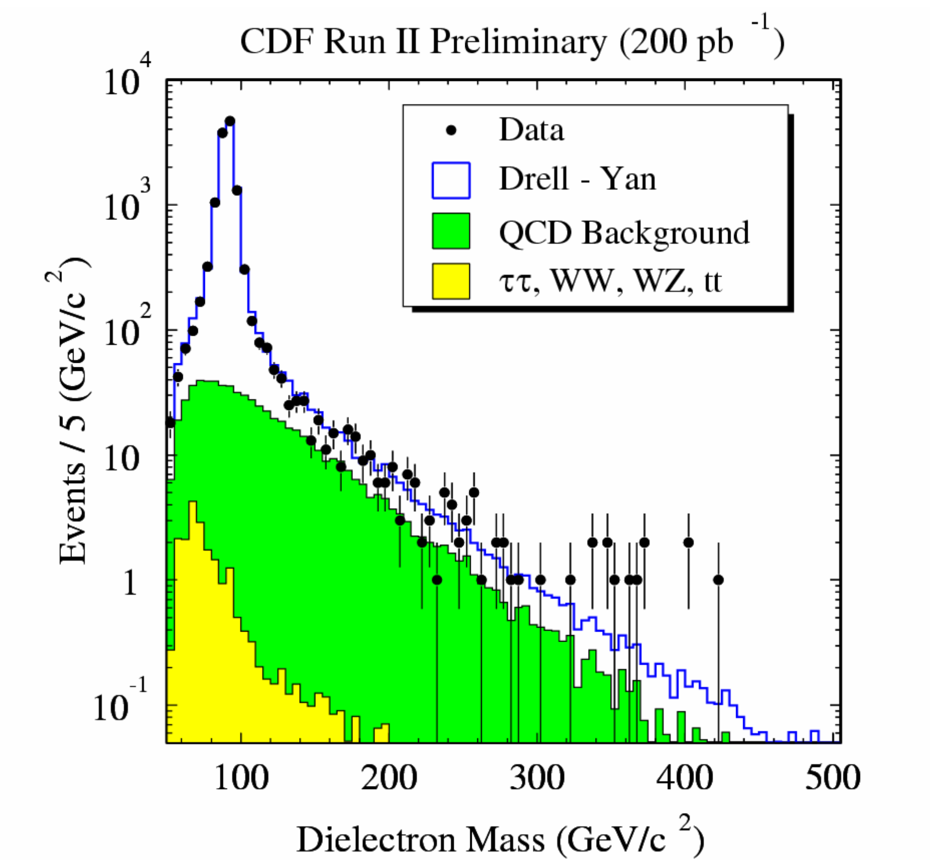
- Direct searches at LEPII restricted to M_{ee} <207 GeV
- Tevatron can extend the direct search closer to 1 TeV
- Z' can show up as a peak, or
- Z' can be detected through ee angular distribution





M_{ee} and A_{FB} at CDF

- M_{ee} used in setting limits in 200 pb^{-1} PRL 95, 252001 (2005)
- A_{FB} asymmetry in 72 pb^{-1} PRD 71, 051104 (2005)
- Put them together? *hepex/0602045* to appear in PRL (May 2006)



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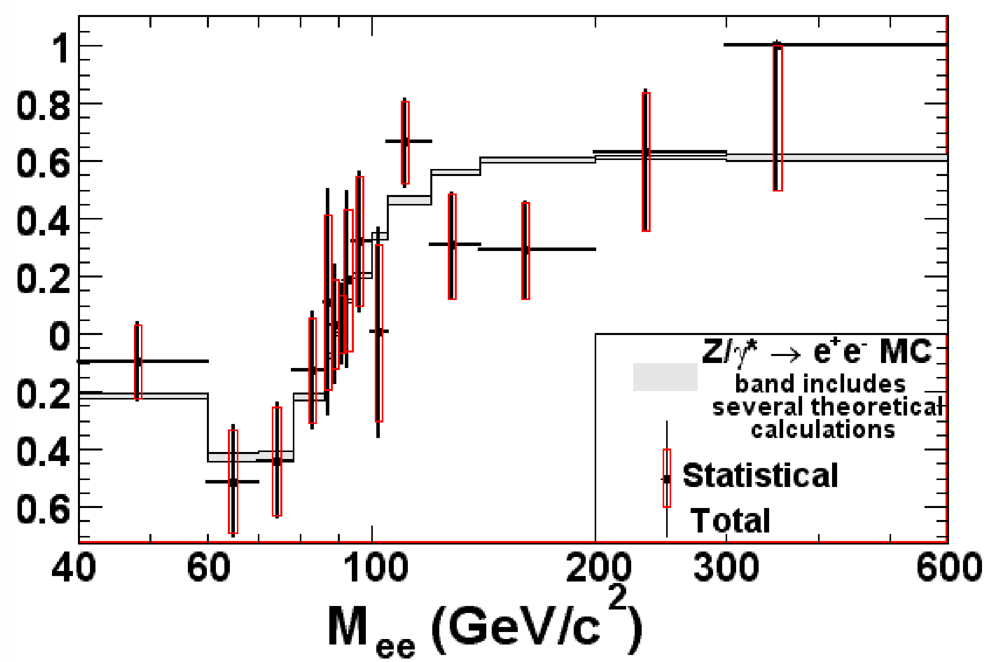
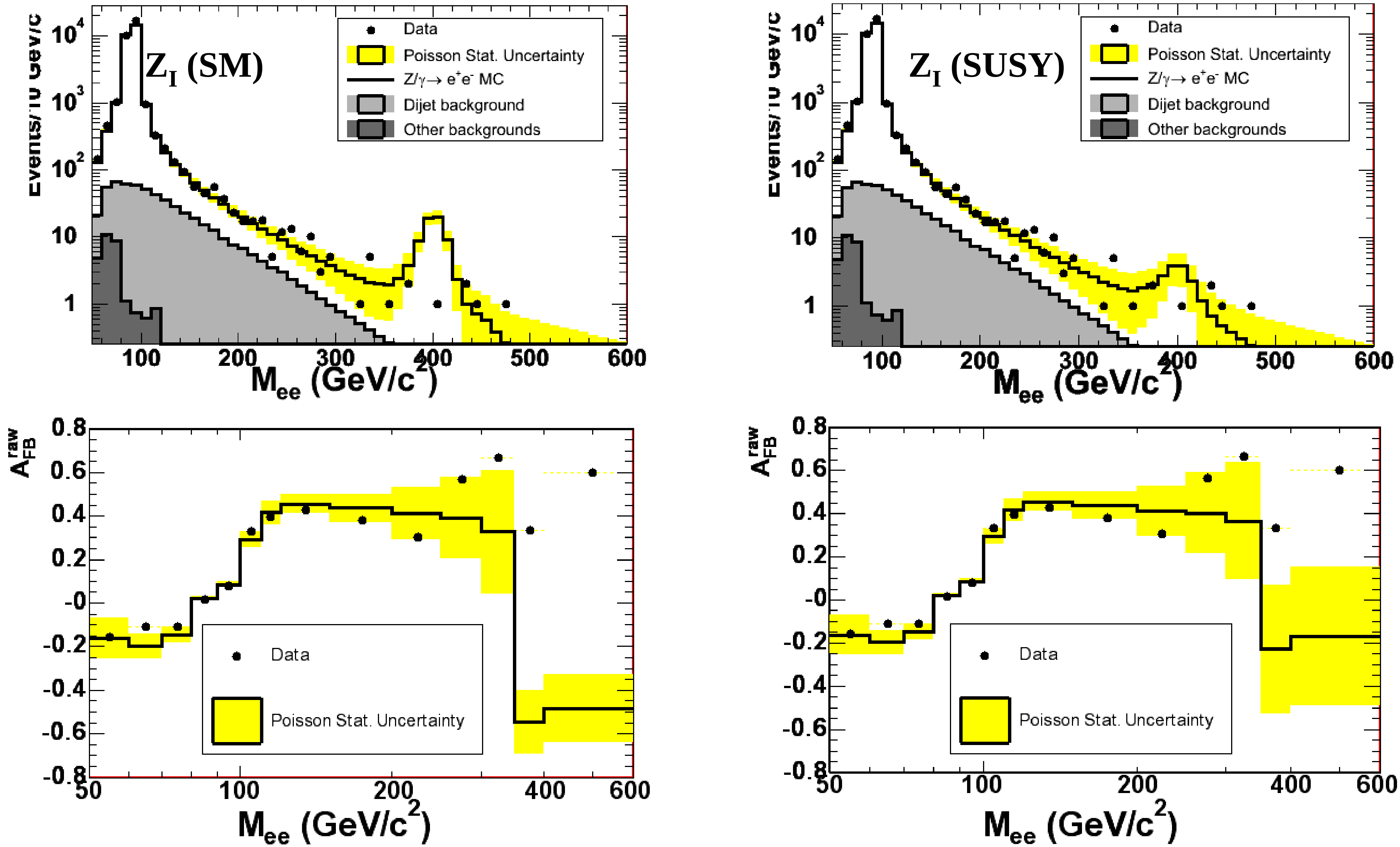
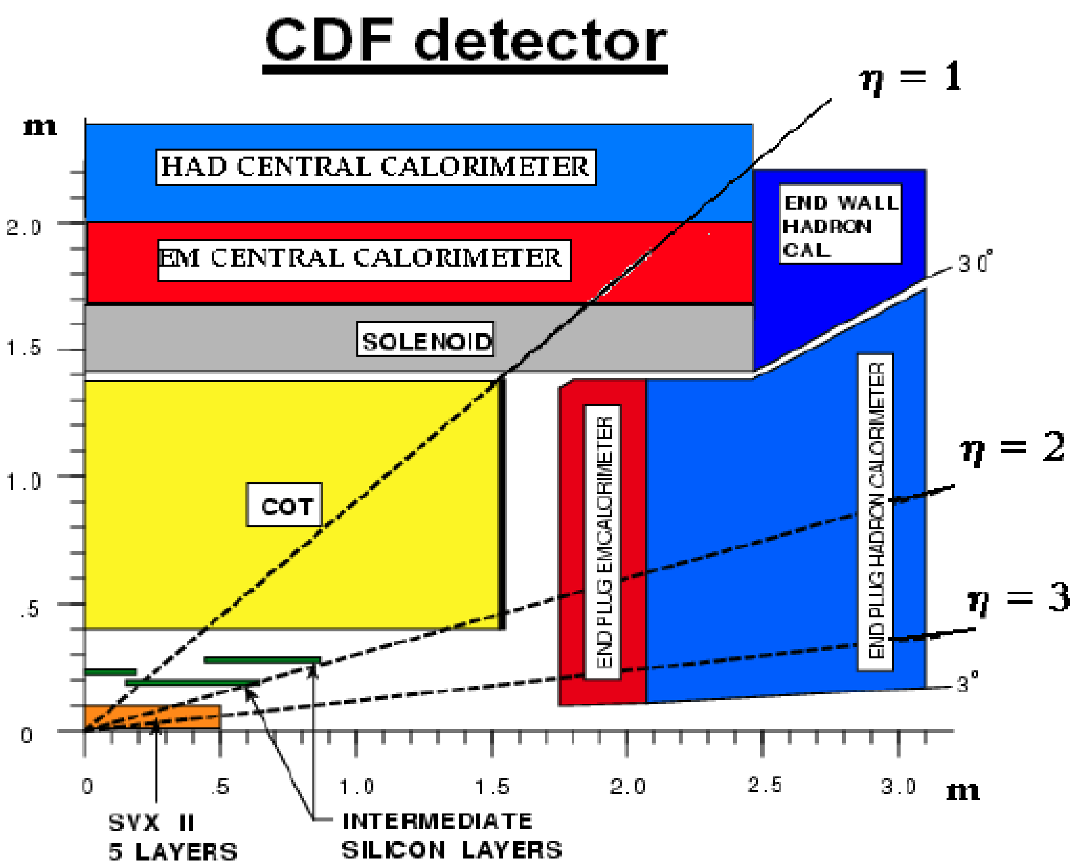


An Example: Z_I





- Selection
  - 2 high P_T isolated electrons
    - E_T > 25 GeV
    - Central electrons (|η|<1) require a charged track
    - Plug electrons (1<|η|<3) have no track requirement
  - Central-Central, or Central-Plug pairs
  - Require opposite sign for Central-Central
- Sample: 448 pb^{-1}
  - 30745 candidates

Event selection. Backgrounds

- Baseline:
  - Require two opposite sign electrons
  - E_T > 25 GeV, at least one with $|\eta|<1.0$
  - **Luminosity 448 pb^{-1}**

- Backgrounds are fit to exponentials to estimate the cross section in the high mass region
- Angular distribution taken from Monte Carlo samples
- Compare to Z/γ^*, expect 80 events

Back-ground	Source	# of events		M_{ee}>200 GeV
		C-C	C-P	
Dijet	Data	42.5	453	28.5
$W\rightarrow e\nu+\gamma$	MC	1.9	48.3	4.9
$Z\rightarrow\tau\tau$	MC	11.6	17.6	0.13
WW	MC	7.7	9.3	1.2
Top	MC	5.1	3.3	0.65
WZ	MC	6.3	7.9	0.19
Total		75	540	35.6

Signal and Background

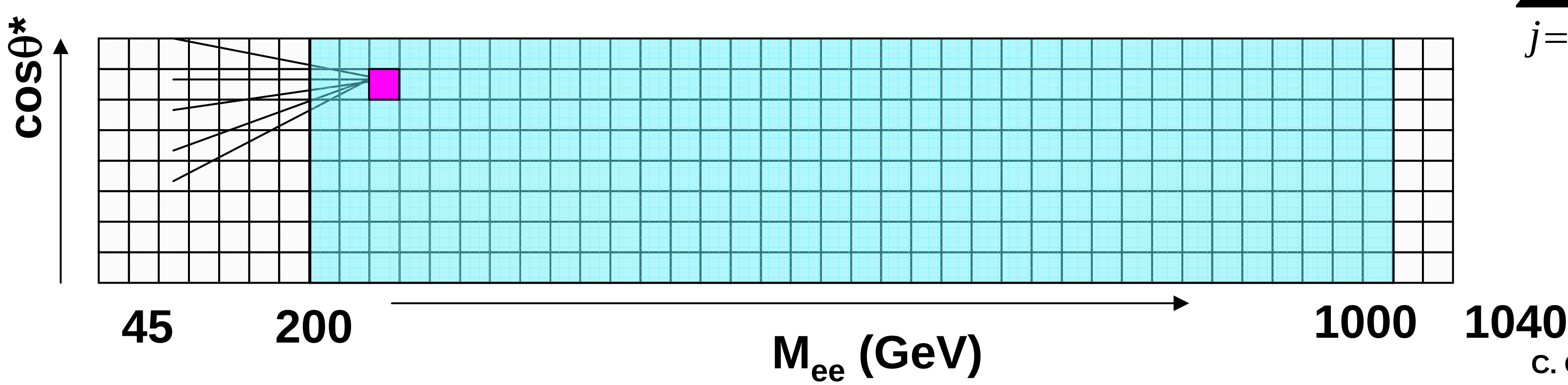
- Most searches compare
  - SM processes (Z/γ* + dijet + ewk +…)
  - SM processes + signal (Z/γ* + dijet + ewk +… + Z')
- Can't do this:
  - To interfere or not to interfere
  - Correct way is to generate full interference Z'/ Z/γ* (call it Z' signal)
- But then, how are we going to add the Z'/ Z/γ* on top of the dijet+ewk? What if there is no Z'?
- The solution:
  - Z/γ* + (dijet + ewk +…) == SM DY+backgrounds
  - Z'/Z/γ* + (dijet + ewk +…) == Z' signal + backgrounds

Solving the MC Problem

- Two issues:
  - 1) We have to generate Z'/Z/ γ^* - which suffers from low stat at high mass
  - 2) We have to test a large number of models (thousands)
- **Solution:**
  - Start with a LO calculation
  - Include a NNLO mass dependent K-factor
  - Then parameterize the simulation in terms of (M_{ee}, cosθ^*)
- **Parameterization obtained running Pythia (~7 million events)**
  - Tweak switches to generate in steps of 5 GeV, from 45-1045 GeV.

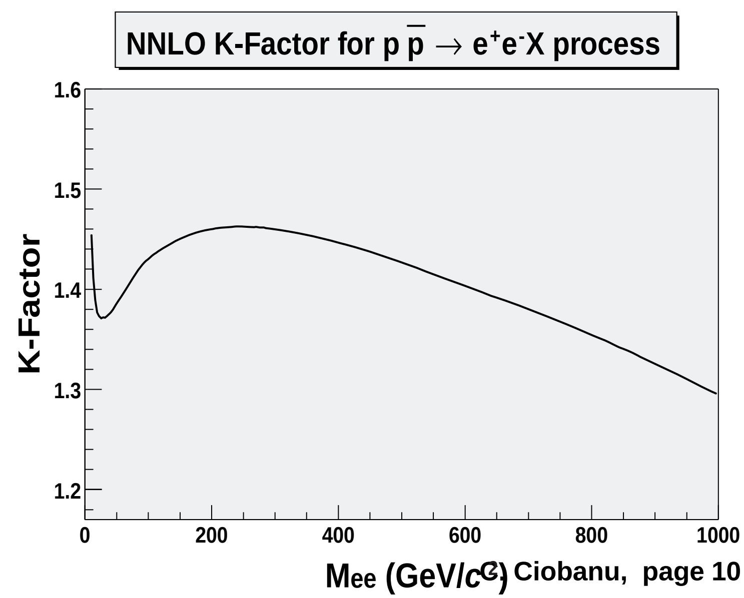
n_i* = sim. events in bin *i ***N_j* = gen. events in bin *j***

$$n_i = \sum_{j=1}^{N_{bins}} A_{ij} N_j$$



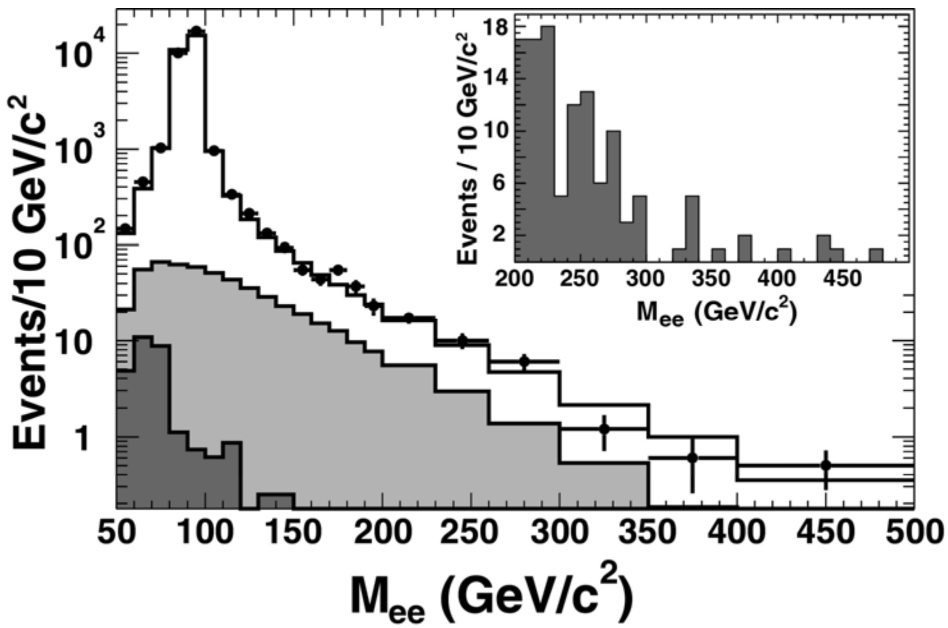
2D Signal Templates

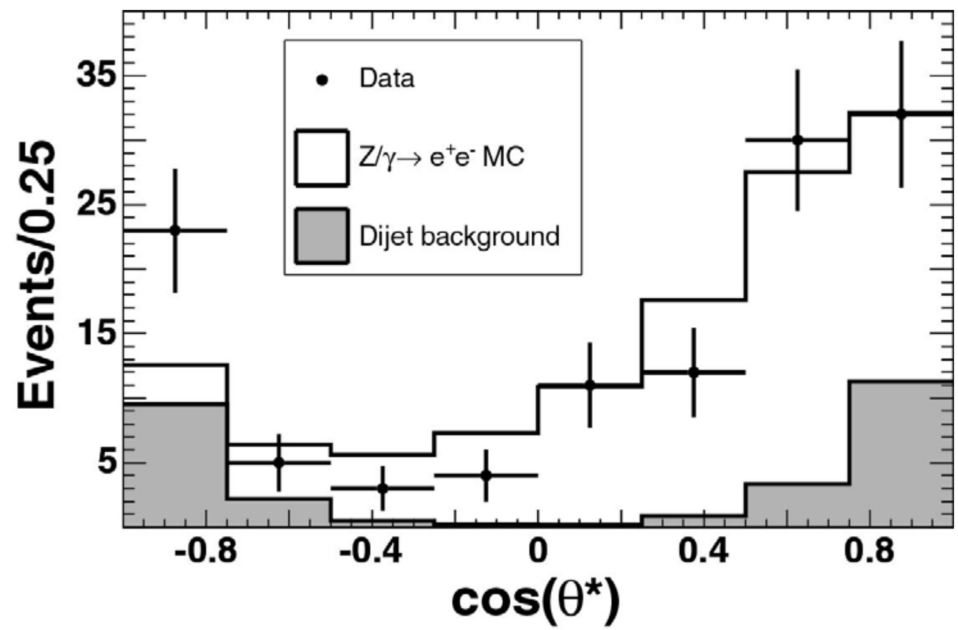
- Pick a Z' model.
- Start with the LO calculation $d\sigma/(dMd(\cos\theta))$, and compute cross section in each (M_{ee}^{gen}, $\cos\theta^*$) bin
- Account for the NNLO correction by multiplying each bin with a mass-depended k-factor (ZPROD from C.D.D.T.):
  - Obtain "NNLO" (M_{ee}^{gen}, $\cos\theta^*$) template
- Use detector parameterization and luminosity (448 pb-1) to obtain the expected template (M_{ee}^{reco}, $\cos\theta^*$)
  - **10 GeV M bins, and 8 $\cos\theta^*$ bins**



- Systematic uncertainties: luminosity, background estimations, electron energy scale and resolution, pdf's

Data versus SM





Source	$Z/\gamma^* \rightarrow e^+e^-$	Dijet	Diboson	Total SM	Observed
Events	80.0 ± 8.0	28^{+14}_{-17}	6.8 ± 1.4	115^{+16}_{-19}	120

Very good agreement with SM: 87% SM pseudo-exp have a lower P(data|SM)

95% C.L. Limits

SEQUENTIAL Z': 850 GeV (825). Mass alone needs >25% more L.

Compared to PRL 95, 252001 (2005) – ee+μμ channel

E_6 Z' Model	$Z\chi$	$Z\psi$	$Z\eta$	Z_I	Z_N	Zsec
Observed Limit	740	725	745	650	710	680
	690	675	720	615		

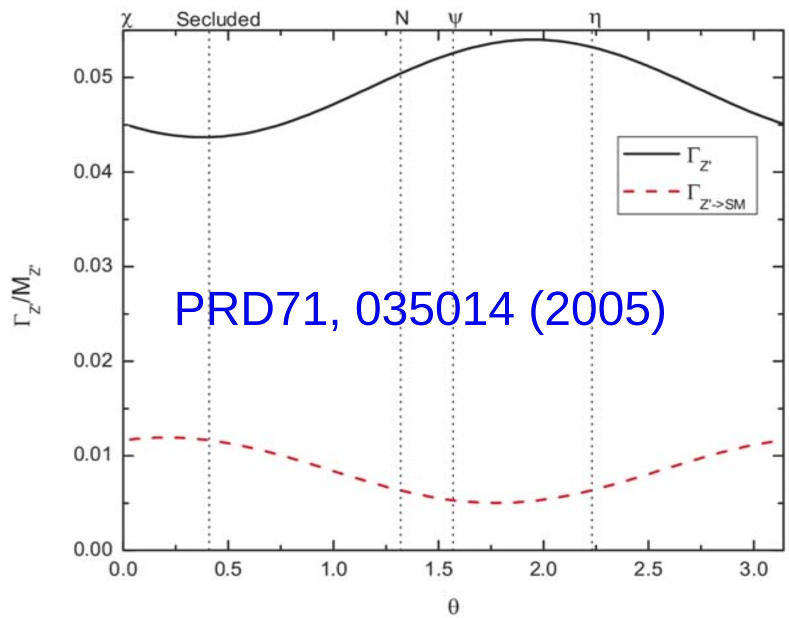
Mass alone:

5% more L.

Littlest Higgs Z'	$\cot\theta_H$=0.3	$\cot\theta_H$=0.5	$\cot\theta_H$=0.7	$\cot\theta_H$=1.0
Observed Limit	625	760	830	900
		725	805	885

Decays to SUSY particles?

- Previous page: Z' decays to SM particles only.
- Including superparticle decays enlarges the Z' width, reducing the branching ratio to quark and lepton pairs; limit gets weaker.
  - The width dependence on θ_{E6} provided by P. Langacker

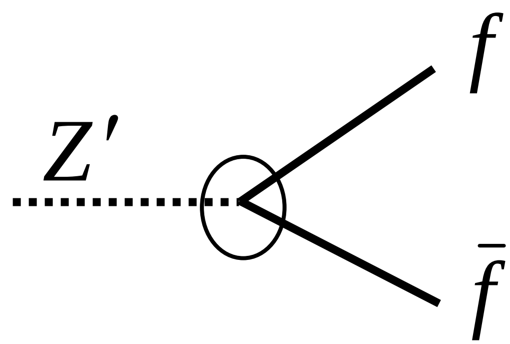


E_6 Z' Model	Zχ	Zψ	Zη	Z_I	Z_N	Zsec
Observed Limit	740(610)	725(435)	745(520)	650(525)	710(450)	680(565)

Searching for Generic Z'

- A more generalized approach to Z':
  - **PRD 70, 093009 (2004) Carena, Dobrescu, Tait, Daleo**
  - **A general Z' described by M_Z, Γ_Z, 15 couplings :**

$$\sum_f z_f g_z Z_\mu' \bar{f} \gamma^\mu f$$



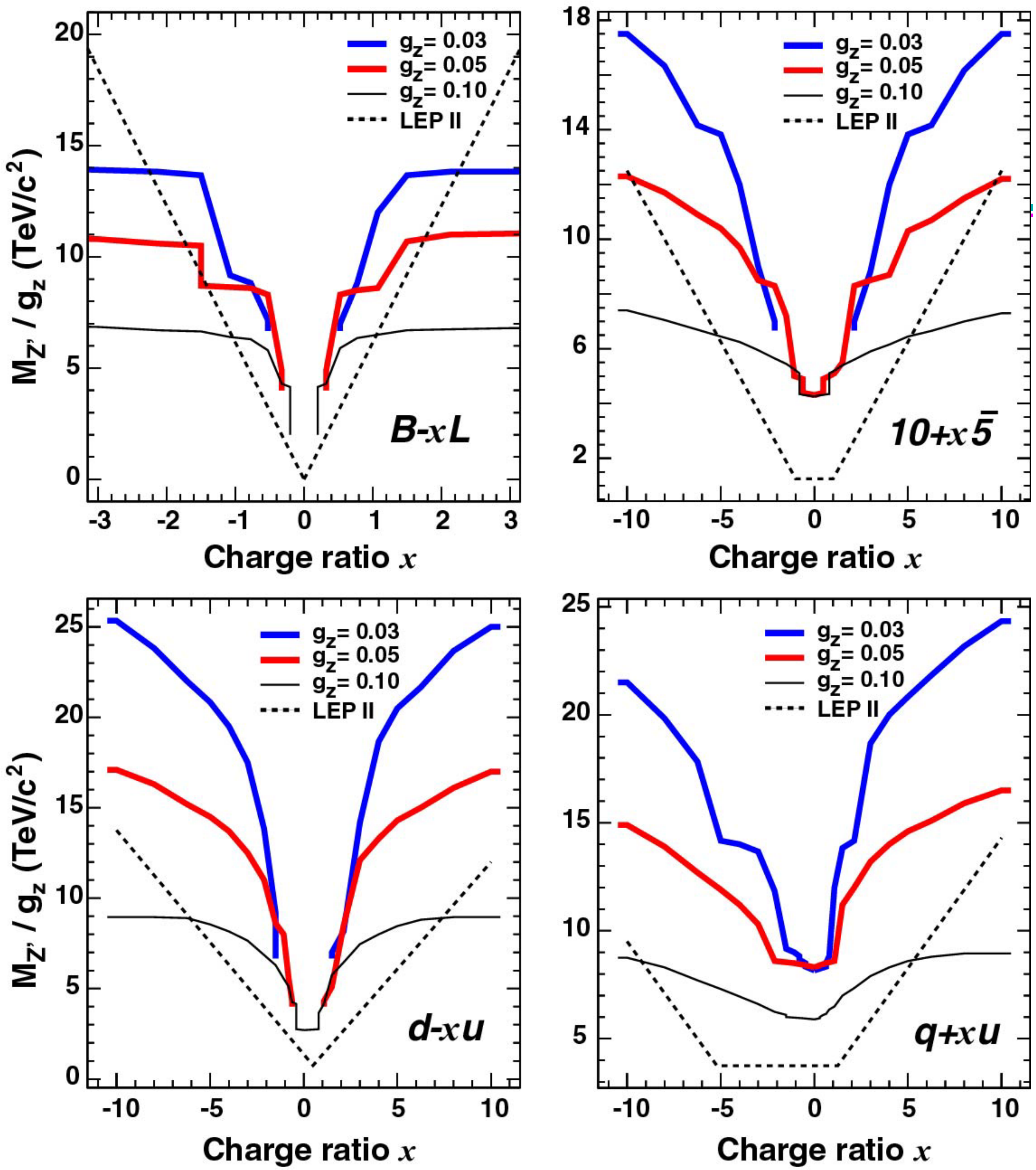
- Too many parameters.
- Sensible assumptions to eliminate some of them:
  - **No new particles Z' can decay into (-1)**
  - **No FCNC (-6)**
  - **Anomaly cancelations: 6 equations involving fermion charges (-6?)**
  - **3rd degree equations – only particular solutions (4 classes, or model-lines)**

Model-lines

- Charges expressed as first order polynomials in *x*
- Canonical E6 models are particular cases :
  - D-xu models: Z_I (x=0)
  - 10+x5 models: Z_η(x=-0.5), Z_ψ(x=1), Z_χ(x=-3)

Few parameters: Z' = model-line, M_Z, g_Z, x

	B-*x*L	q+*x*u	10+*x*$\bar{5}$	d-*x*u
$q_L=(u_L,d_L)$	+1/3	+1/3	+1/3	0
u_R	+1/3	+*x*/3	-1/3	-*x*/3
d_R	+1/3	(2-*x*)/3	-*x*/3	+1/3
$l_L=(e_L,\nu_L)$	-*x*	-1	+*x*/3	(*x*-1)/3
e_R	-*x*	-(2+*x*)/3	-1/3	+*x*/3



CDDT general Z’:

Comparisons to LEP

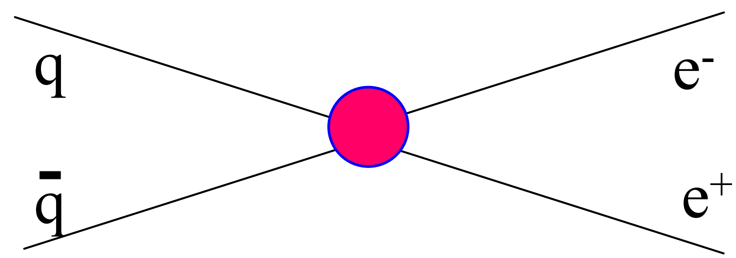
- better for |x|<1

- better for small g_z

Contact Interactions?

- If the CI scale is >> 1TeV, we can detect it through distortions of the $M_{ee}/\cos\theta^*$ spectrum

$$\sum_q \sum_{i,j=L,R} \frac{4\pi\eta}{\Lambda_{ij}^2} \bar{e}_i \gamma^\mu e_i \bar{q}_j \gamma_\mu q_j$$

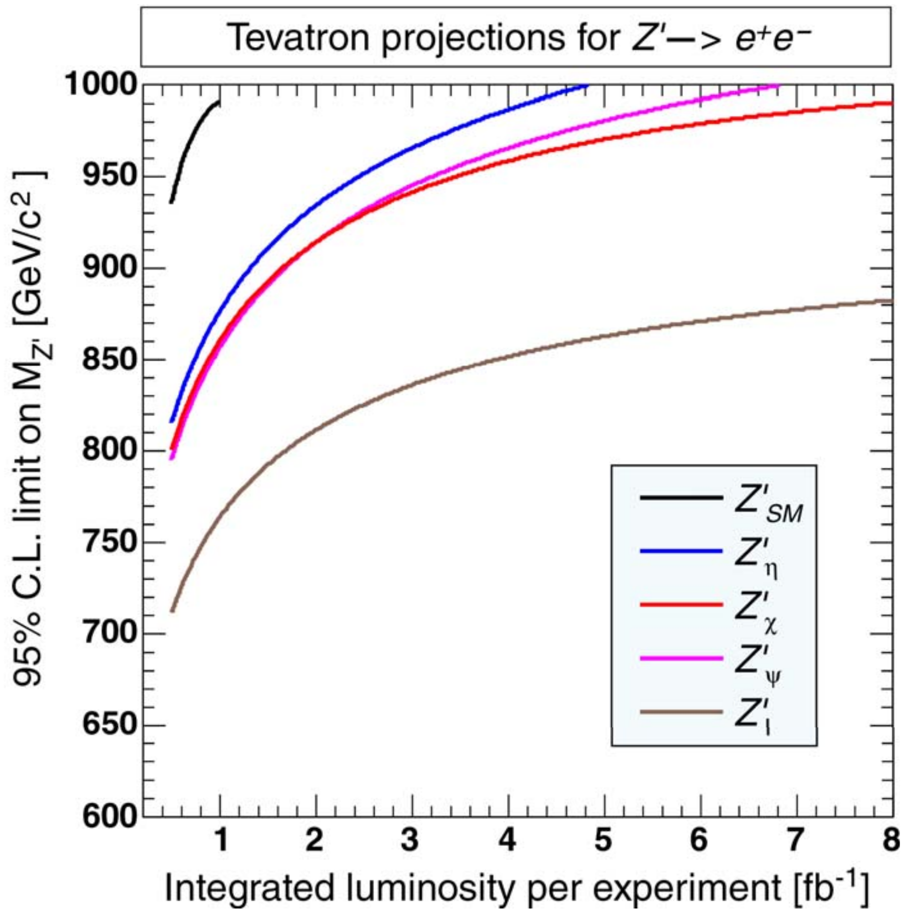


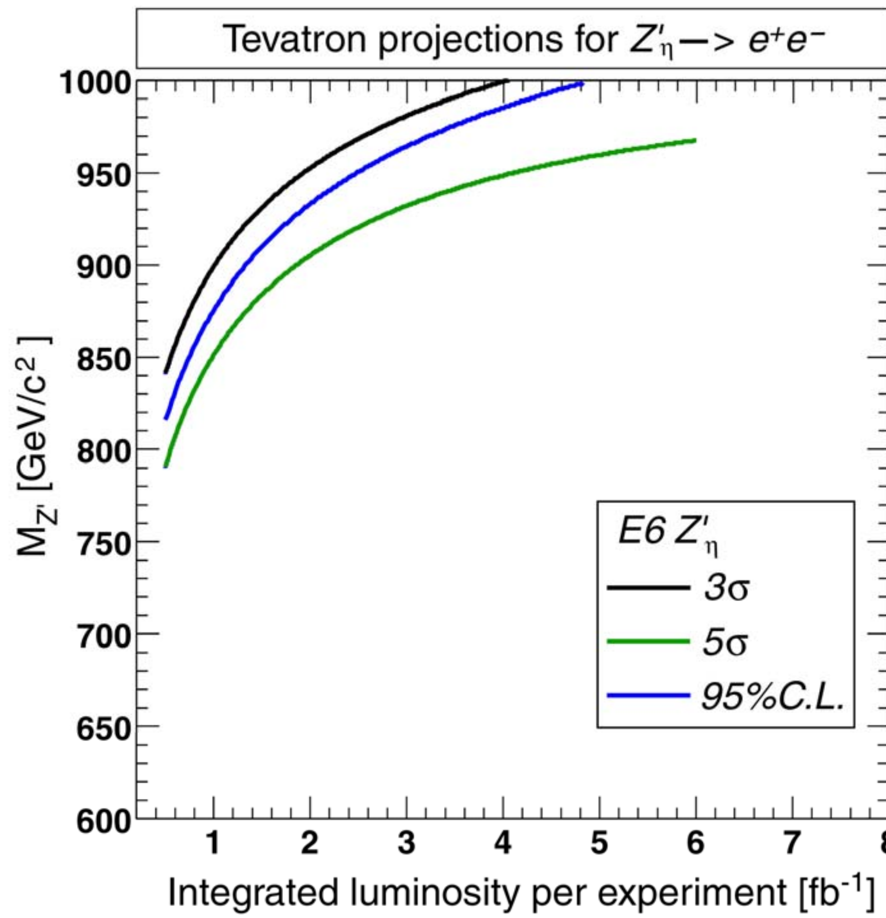
Interaction	LL	LR	RL	RR	VV	AA
Λ_{qe}^+ limit (TeV/c^2)	3.7	4.7	4.5	3.9	5.6	7.8
Λ_{qe}^- limit (TeV/c^2)	5.9	5.5	5.8	5.6	8.7	7.8

Surpass LEP

What's next?

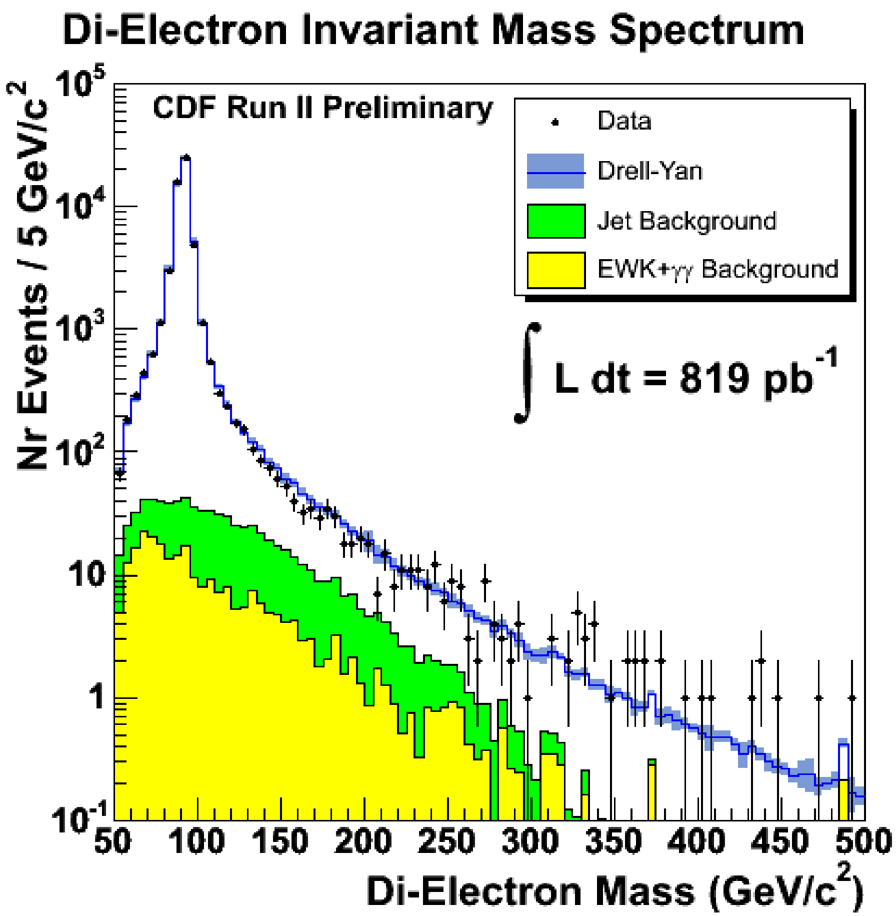
- Keep taking good data.
- Z'->ee Run II projections:
  - ***http://www-cdf.fnal.gov/physics/projections/***

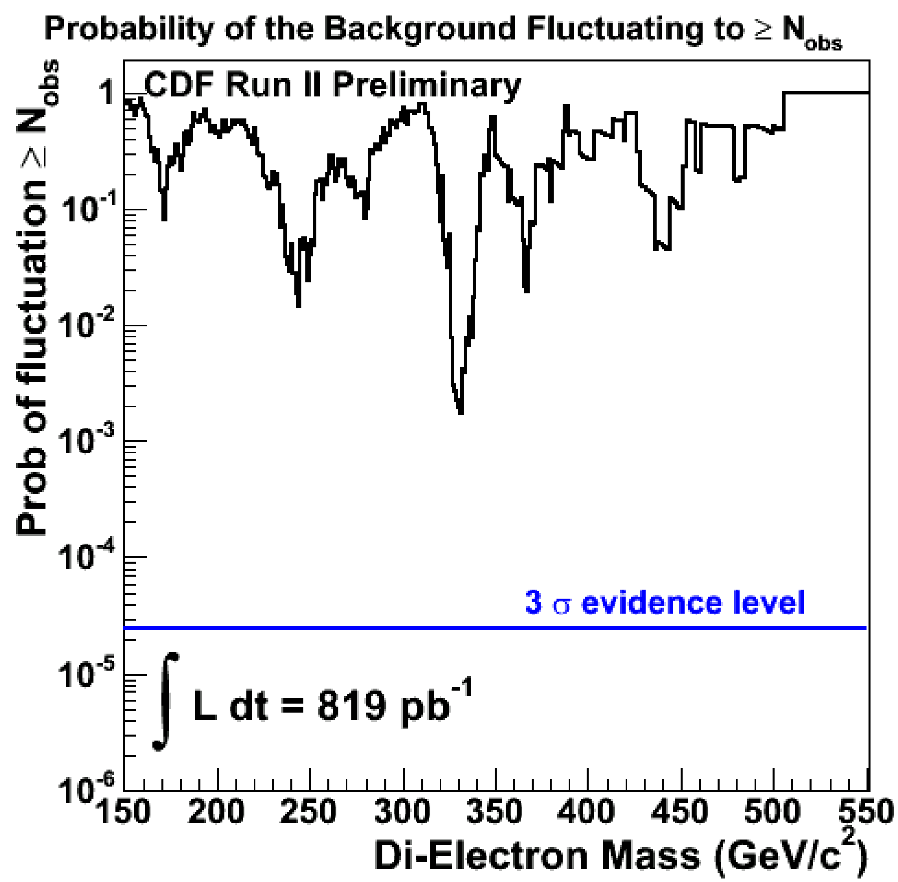




Latest CDF Dielectron Results

- Using mass alone. Adding angular info in progress.





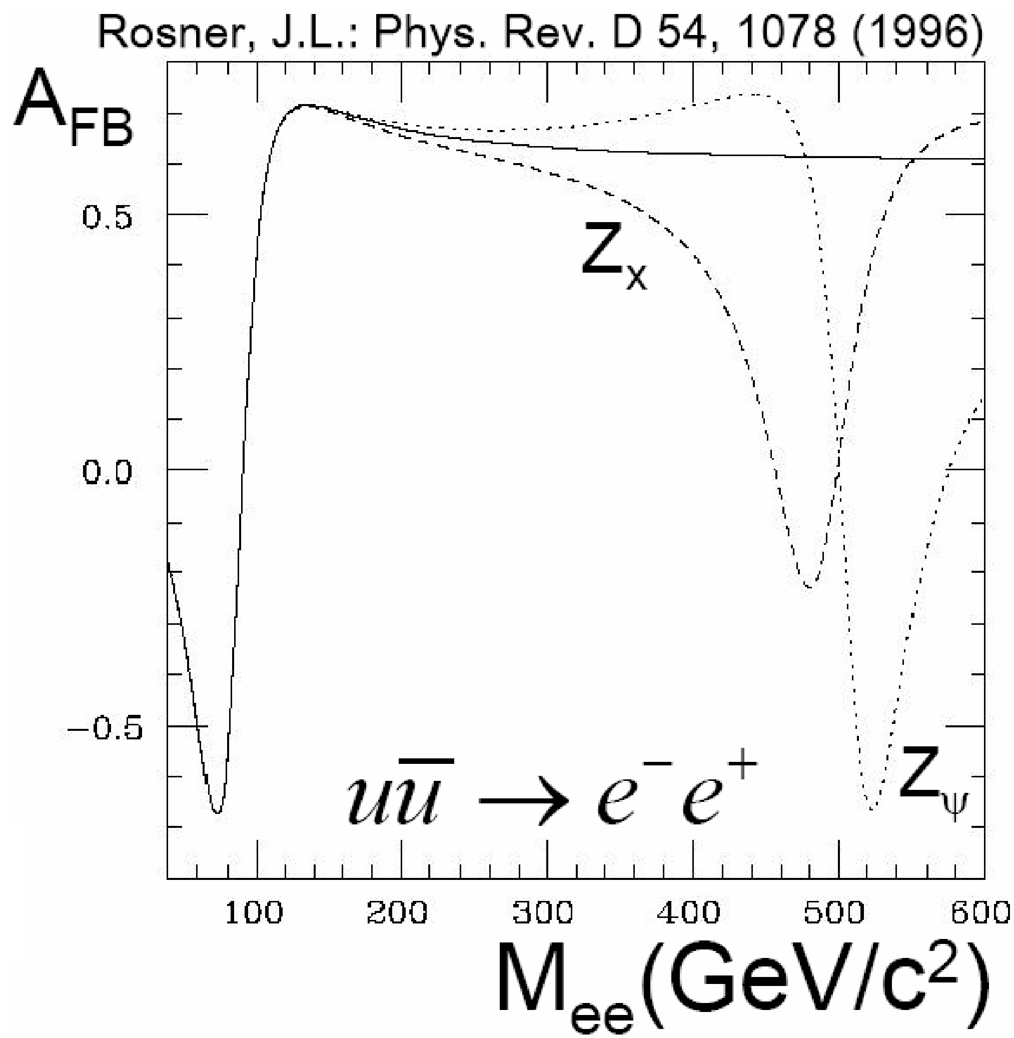
Conclusions

- Results shown for 0.45 fb^{-1} luminosity
- Several additions:
  - New way of modeling Z' signal
  - Use mass and angular distribution
- Data consistent with SM
- Stringent limits on many Z' models
  - Seq. Z'_{SM}, Z_{ψ}, Z_{χ}, Z_{I}, Z_{η}, Z_{N}, Z_{sec}, Littlest Higgs Z'
  - CDDT models – mapped exclusion versus Z' mass, gauge coupling, and certain ratio of U(1) charges
    - Allows comparison to LEP2
  - Contact interaction qqee results
- Many Thanks to all theorists who helped us (Marcela C., Bogdan D., Tim T., Paul L. , Heather L.).

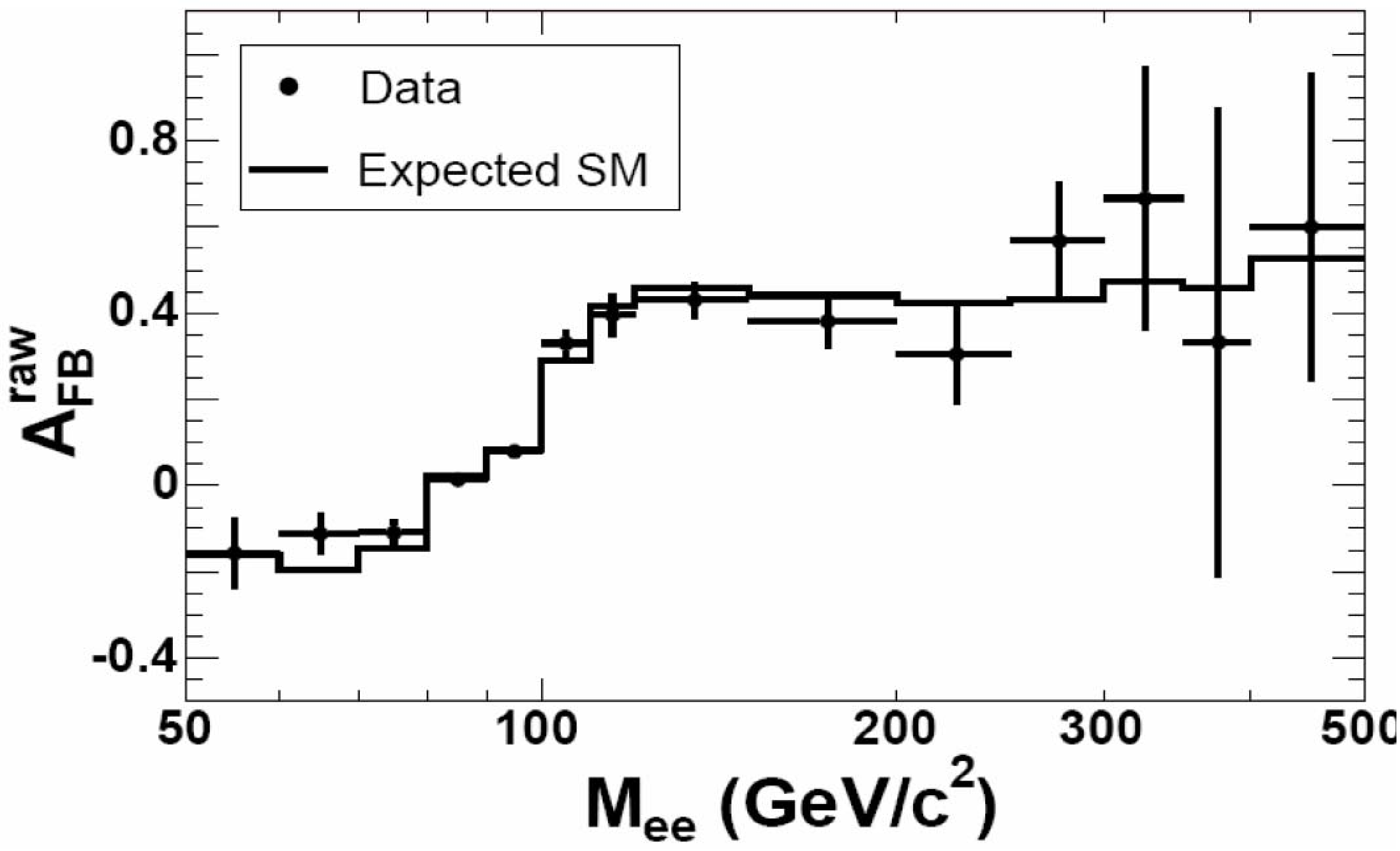
A_{FB} for Z′

500 GeV/c^2 Z'

- Looking for symmetries beyond the SM
- New resonance could interfere with γ and Z.
- Information about the angular distribution will strengthen the search
- Can be used to distinguish between different models
- Can see evidence below Z' pole



A_{FB}



Test Statistic

- CL$_s$ method used in Higgs searches at LEP
- Test between two hypotheses:
  - H1: Data is described by Z'/Z/γ and backgrounds
  - H2: Data is described by SM Z/γ and backgrounds

- Poisson probabilities:

$$P(data \mid H1) = \prod_{i=i}^{N_{bins}} P^i = \prod_{i=1}^{N_{bins}} \frac{\mathbf{e}^{n_i^{H1}} \cdot (n_i^{H1})^{d_i}}{d_i!}$$

- Test statistics Q = - 2ln[P($data$|$H1$)/P($data$|$H2$)]

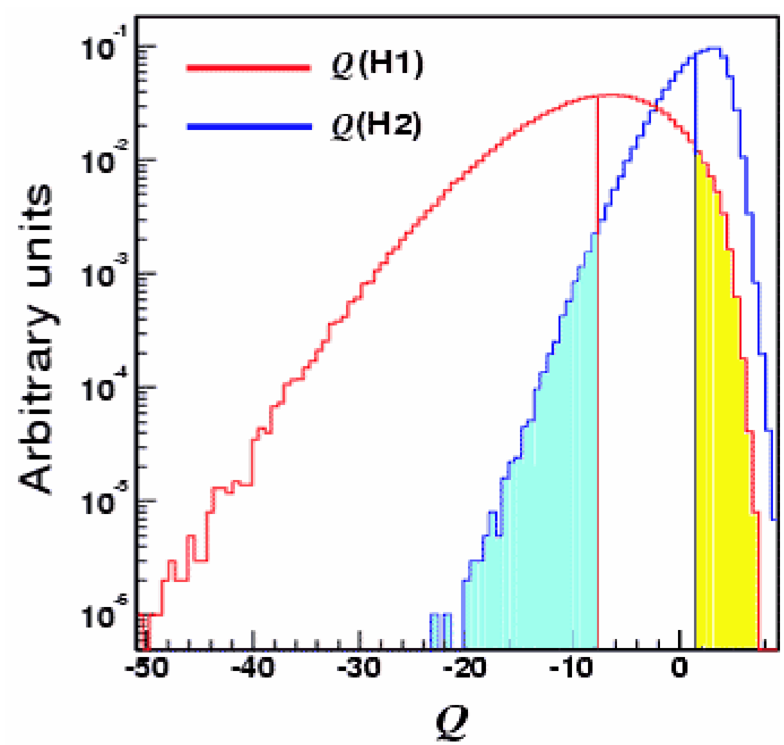
$$Q = const - 2 \cdot \sum_{i=1}^{N_{bins}} d_i \ln \frac{n_i^{H1}}{n_i^{H2}}$$

Pseudo-Experiments

- Throw pseudo-exp. assuming either H1 or H2. Get Q distribution in each case
- The separation defines sensitivity between H1 and H2
  - B-xL model. Example: $M_{Z'}$=440 GeV, g_z=0.03, x=10
- For a measured Q_o, CL_s is given by

$$CL_s(Q_o) = \frac{\text{Prob}(Q < Q_o | H1)}{\text{Prob}(Q < Q_o | H2)}$$

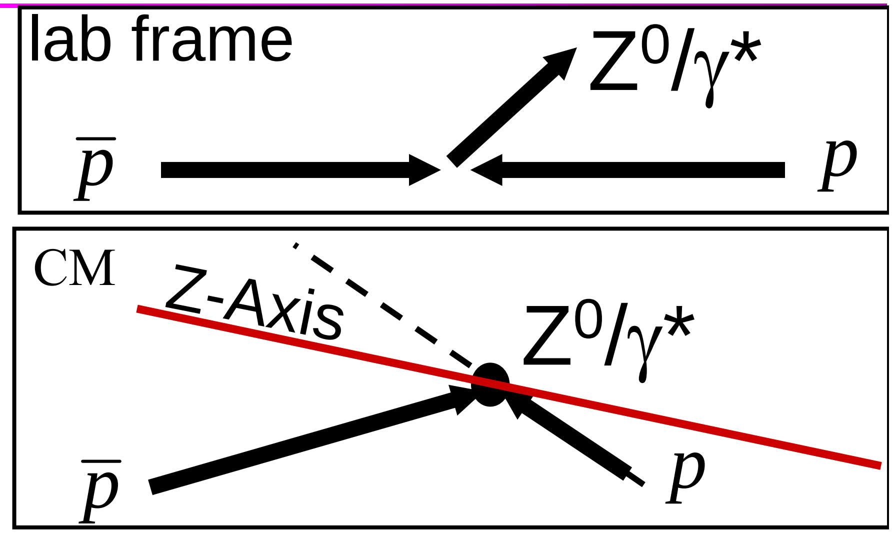
- Median CL_s in H2 hypothesis (SM) defines exclusion (<5%)
- CL_s =2·yellow area.
  - CL_s < 0.05 excluded at 95% C.L.



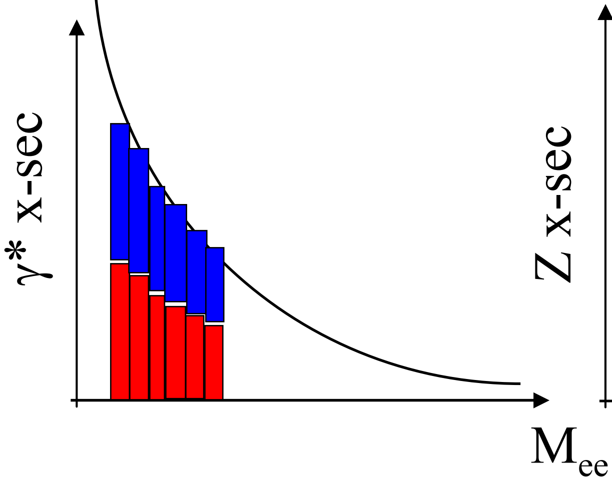
A_{FB} and cosθ^*

- Collins–Soper frame.
- If $P_t^{total} = 0$, then cosθ^* measured wrt the beam
- If cos$\theta^* > 0 \rightarrow$ forward event
- If cos$\theta^* < 0 \rightarrow$ backward event

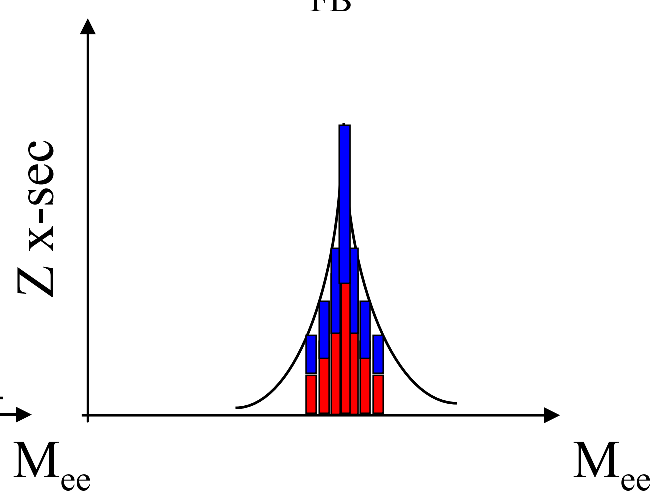
$$A_{FB} = (F-B)/(F+B)$$



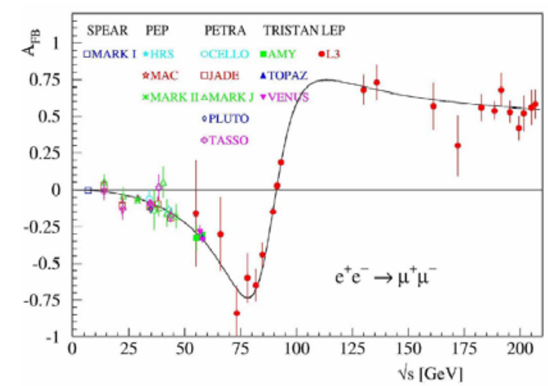
$A_{FB} = 0$



$A_{FB} = 0$



High mass F = 4B !

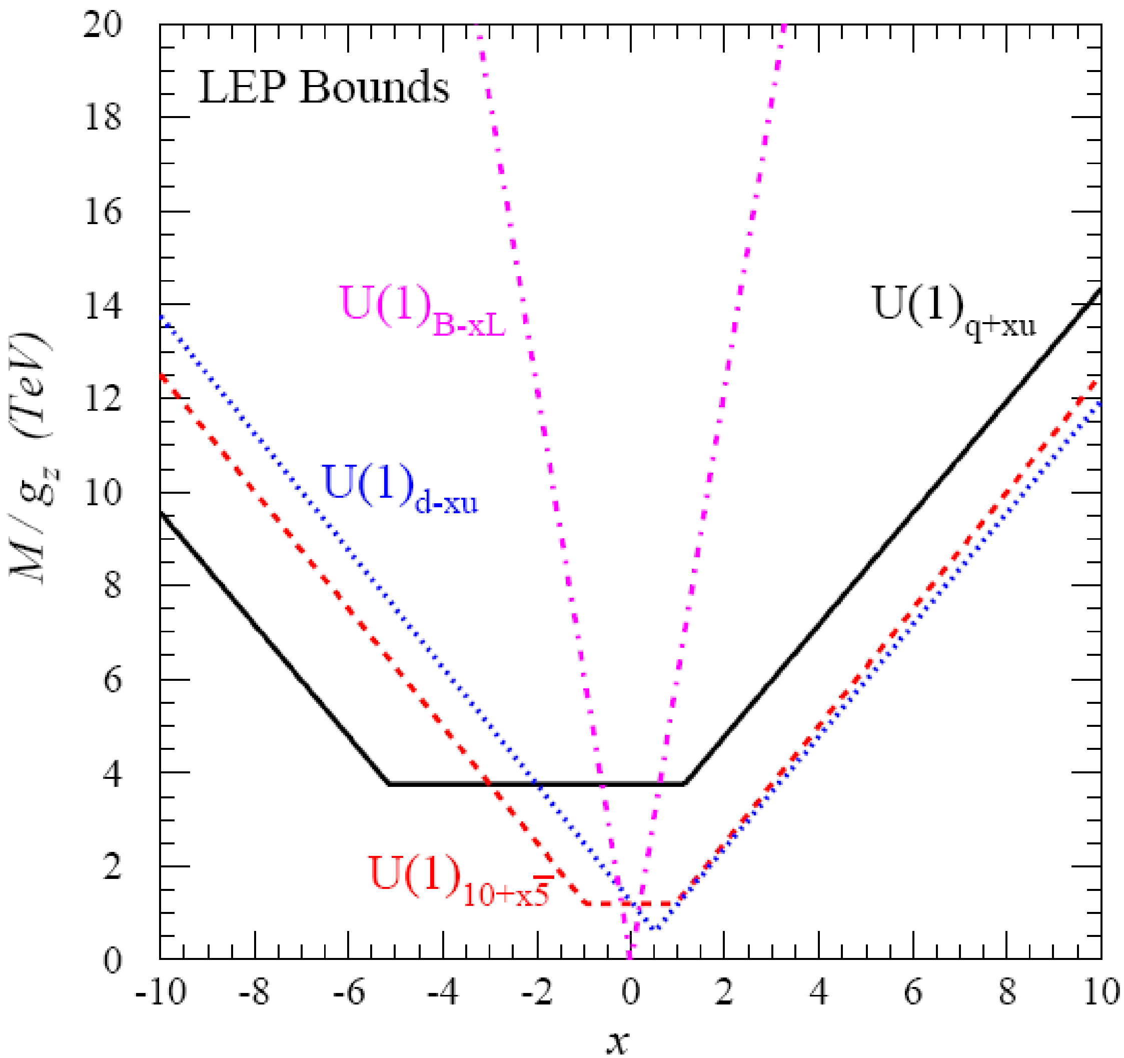


Electron selection

Variable	Central	Plug
Fiducial	**Fid = 1,2**	**$1.18 < \eta_{det} < 3.0$**
E_T	**> 25 GeV**	**> 25 GeV**
$\|Track Z_0\|$	**$\leq$ 60 cm**	
P_T	**> 10 GeV**	
E_{had}/E_{em}	**$\leq 0.055 + 0.00045 \times E$**	**$\leq 0.05 + 0.026 \times \ln(E/100)$**
Isol E_T	**$\leq 3 + 0.02 x E_T$ GeV**	**$\leq 1.6 + 0.02 x E_T$ GeV**
E/P	**$\leq 2.5 + 0.015 x E_T$**	
CES $\|\Delta X\|$	**$\leq$ 3 cm**	
CES $\|\Delta Z\|$	**$\leq$ 5 cm**	
L_{shr}	**$\leq$ 0.2**	
χ^2_{Pem3x3}		**$\leq$ 25**

Systematic Uncertainties

- Luminosity and lep trigger + ID:
  - 10% (SU'05=20%)
  - Acceptance and efficiency uncertainties: 5%
  - The A matrix reproduces full simulation down to 3%
  - Found a 4% difference in the high mass region between out LO calculation and LO Pythia.
  - $6\% \oplus 4\% \oplus 3\% \oplus 5\% = 9.3\%$.
- Electron energy scale and resolution
  - Shifts of 3% for the scale in the central and plug regions
  - Cal. resolutions varies by 3% in both central and plug
- Uncertainties in the background estimations
  - Use jet-electron fake rates. At least 50% uncertainty
- Pdf uncertainty found to have a small effect.


LEP Bounds
$U(1)_{B-xL}$
$U(1)_{q+xu}$
$U(1)_{d-xu}$
$U(1)_{10+x\bar{5}}$
M / g_z (TeV)
x
0
2
4
6
8
10
12
14
16
18
20
-10
-8
-6
-4
-2
0
2
4
6
8
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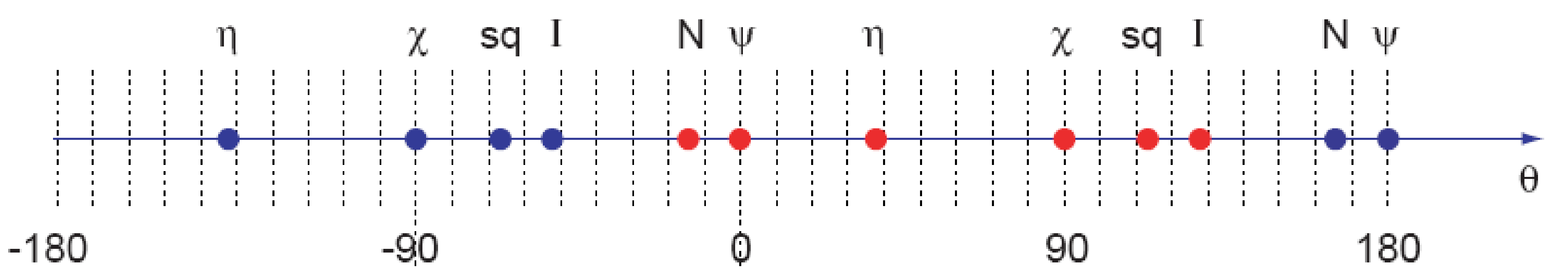
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