Z' Models -@ the LHC and ILC

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Motivations for a Z'

- Strings/GUTS (large underlying groups; $U(n)$ in Type IIa)
  - Harder to break $U(1)'$ factors than non-abelian (remnants)
  - Supersymmetry: $SU(2) \times U(1)$ and $U(1)'$ breaking scales *both* set by SUSY breaking scale (unless flat direction)
  - μ problem
- Alternative electroweak model/breaking (TeV scale): DSB, Little Higgs, extra dimensions (Kaluza-Klein excitations, $M \sim R^{-1} \sim 2\ \mathrm{TeV} \times (10^{-17}\mathrm{cm}/R)$), left-right symmetry
- Connection to hidden sector (weak coupling, SUSY breaking/mediation)
- Extensive physics implications, especially for TeV-scale Z'

Other Models

- **TeV scale dynamics** (Little Higgs, un-unified, strong $t\bar{t}$ coupling, $\cdots$)
- **Kaluza-Klein excitations** (large dimensions or Randall-Sundrum)
- **Decoupled** (leptophobic, fermiophobic, weak coupling, low scale/massless)
- **Hidden sector "portal"** (e.g., SUSY breaking, dark matter, or "hidden valley") [kinetic or HDO mixing, $\tilde{Z}'$ mediation]
- **Secluded or intermediate scale SUSY** (flat directions, Dirac m_ν)
- **Family nonuniversal couplings** (FCNC, apparent CPT violation)
- **String derived** (may be T_{3R}, T_{BL}, E_6 or "random")
- **Stückelberg** (no Higgs)
- **Anomalous $U(1)'$** (string theories with large dimensions)

Additional U(1)'

$$-L_{NC} = eJ^{\mu}_{em}A_{\mu} + g_1 J^{\mu}_1 Z^0_{1\mu} + \sum_{\alpha=2}^{n+1} g_{\alpha} J^{\mu}_{\alpha} Z^0_{\alpha\mu}$$

$$J^{\mu}_{\alpha} = \sum_i \bar{f}_i \gamma^{\mu}[\epsilon^{\alpha}_L(i)P_L + \epsilon^{\alpha}_R(i)P_R]f_i$$

Assuming flavor universality, negligible mixing with Z, charge Q' commutes with SU(2)_L charge

7 Parameters: mass, total width and 5 couplings:

$$g_{\alpha}\epsilon_L^{u,d} = g_{\alpha}\epsilon_L^{q},\ g_{\alpha}\epsilon_L^{e,v} = g_{\alpha}\epsilon_L^{l},\ g_{\alpha}\epsilon_R^{u},\ g_{\alpha}\epsilon_R^{d} \text{ and } g_{\alpha}\epsilon_R^{e}$$

Benchmark Models

	χ	ψ	η	LR
$\hat{\epsilon}/\epsilon$	$2\sqrt{10}$	$2\sqrt{6}$	$2\sqrt{15}$	$\sqrt{5/3}$
$\hat{\epsilon}^q_L$	-1	1	-2	-0.109
$\hat{\epsilon}^l_L$	3	1	1	0.327
$\hat{\epsilon}^u_R$	1	-1	2	0.656
$\hat{\epsilon}^d_R$	-3	-1	-1	-0.874
$\hat{\epsilon}^e_R$	1	-1	2	-0.438

Table 1. Benchmark models and couplings, derived from Ref [1]. g_2 is set at 0.46. The coupling strength is the charge g_2 times $\hat{\epsilon}$ and then divided by the normalization factor $\hat{\epsilon}/\epsilon$, e.g. $g^q_L = g_2 \times \hat{\epsilon}^q_L/(\hat{\epsilon}/\epsilon)$.

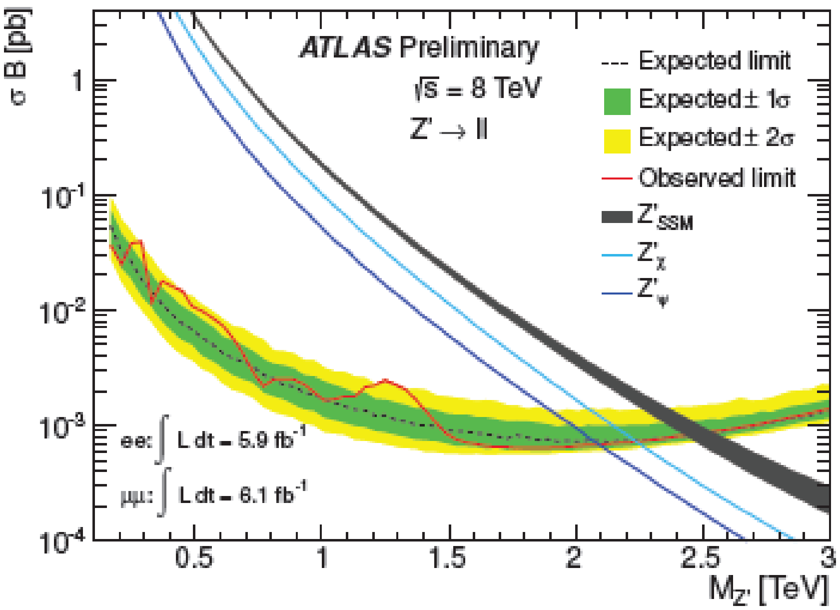
Current Limits (before LHC)

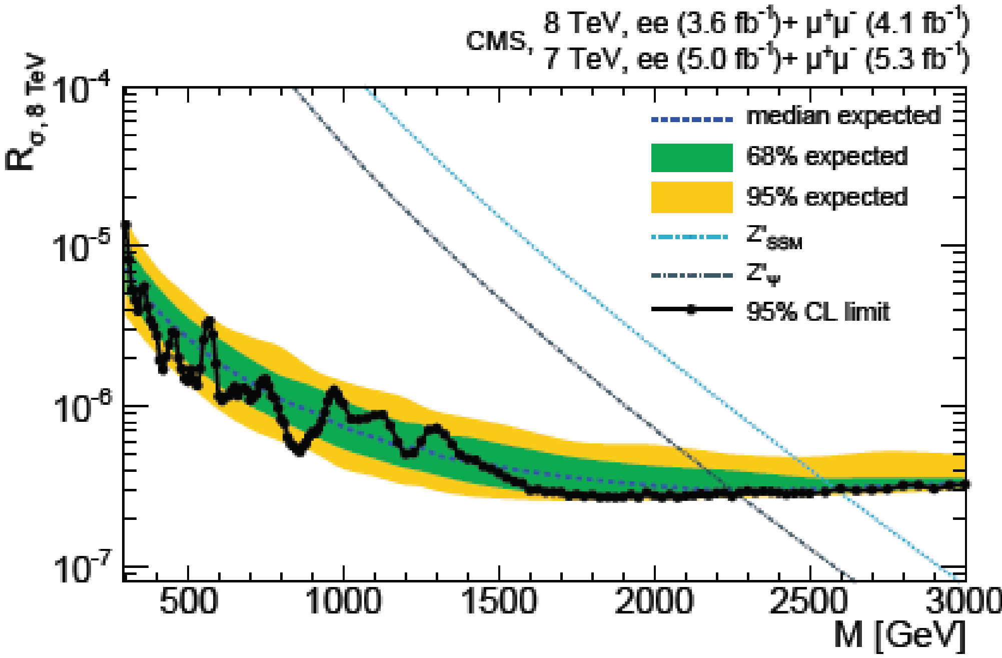
Z'	$M_{Z'}$ [GeV]				$\sin\theta_{ZZ'}$			$\chi^2_{\rm min}$
	EW (this work)	CDF	DØ	LEP 2	$\sin\theta_{ZZ'}$	$\sin\theta_{ZZ'}^{\rm min}$	$\sin\theta_{ZZ'}^{\rm max}$	
Z_χ	1,141	892	640	673	−0.0004	−0.0016	0.0006	47.3
Z_ψ	147	878	650	481	−0.0005	−0.0018	0.0009	46.5
Z_η	427	982	680	434	−0.0015	−0.0047	0.0021	47.7
Z_I	1,204	789	575		0.0003	−0.0005	0.0012	47.4
Z_S	1,257	821			−0.0003	−0.0013	0.0005	47.3
Z_N	623	861			−0.0004	−0.0015	0.0007	47.4
Z_R	442				−0.0003	−0.0015	0.0009	46.1
Z_{LR}	998	630		804	−0.0004	−0.0013	0.0006	47.3
$Z_{\not L}$	(803)	(740)			−0.0015	−0.0094	0.0081	47.7
Z_{SM}	1,403	1,030	780	1,787	−0.0008	−0.0026	0.0006	47.2
Z_{string}	1,362				0.0002	−0.0005	0.0009	47.7
SM	∞				0			48.5

Table 4: 95% C.L. lower mass limits on extra Z' bosons for various models from EW precision data and constraints on $\sin\theta_{ZZ'}$ assuming $\rho_0 = 1$ (fixed). For comparison, we show (where applicable) in the third, fourth and fifth column the limits obtained by CDF, DØ and LEP 2. In the following columns we give, respectively, the central value and the 95% C.L. lower and upper limits for $\sin\theta_{ZZ'}$. Also indicated is the χ^2 minimum for each model. The last row is included for comparison with the standard case of only one Z boson.

Erler et al., 0906.2435;

Current Limits





Benchmark Scenarios

Two Scenarios

(whether Z' can be produced at LHC 14 TeV)

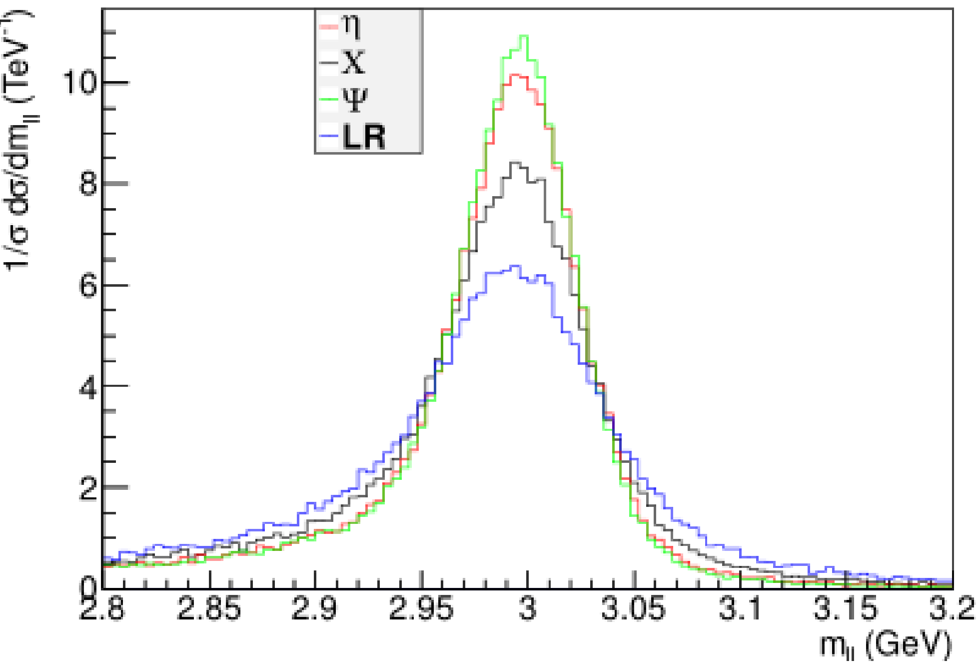
- Z' mass 3 TeV

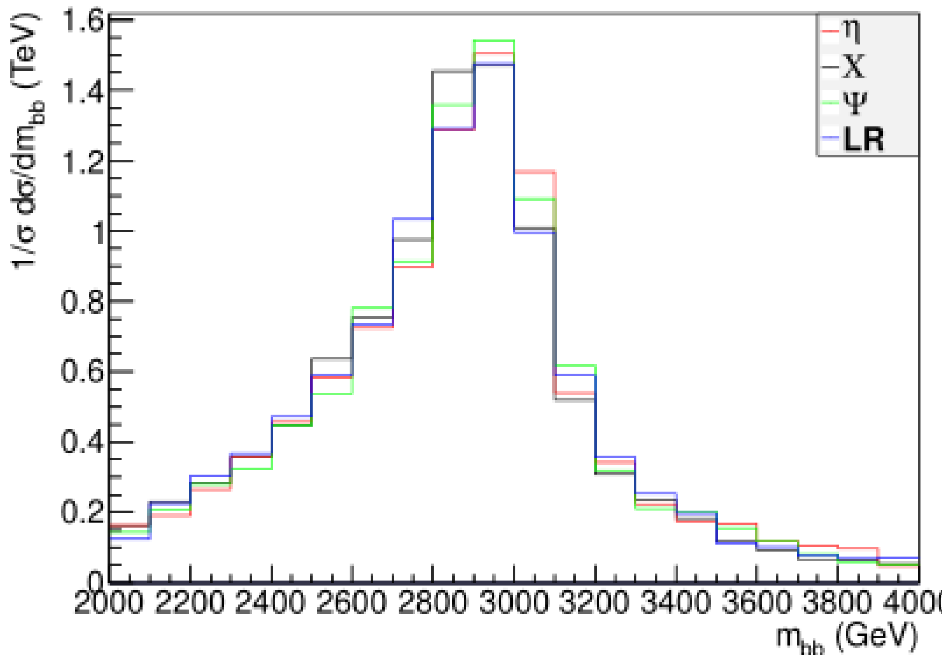
1. LHC 14 TeV 300 fb^-1 and 3000 fb^-1
2. ILC 500 GeV 500 fb^-1

- Z' mass 6 TeV

1. LHC 14 TeV 300 fb^-1 and 3000 fb^-1
2. ILC 500 GeV 500 fb^-1

Benchmark Scenarios (3 TeV Z' @ LHC 14 TeV) – A first Glance





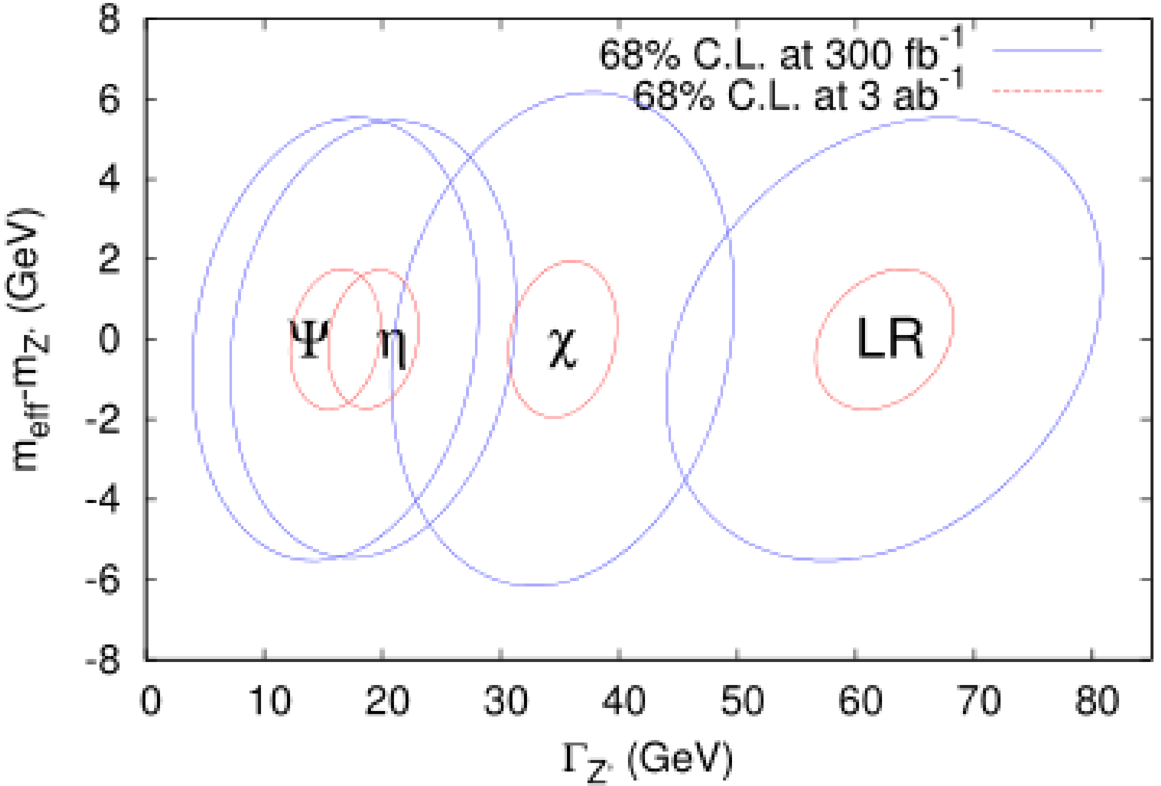
Invariant mass distribution
LEFT: **Dilepton (e+e-)** final State
Right: **Bottom pair** final state

FeynRules->Madgraph5->Pythia->Delphes

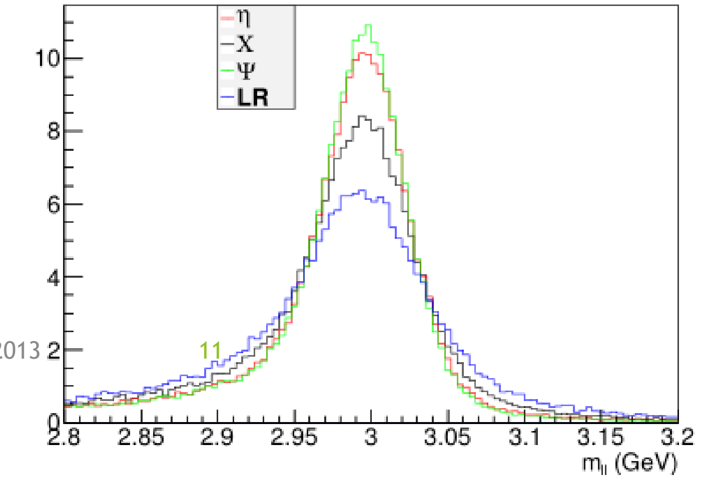
3 TeV Z'---- Leptonic Mode

- Clear Signal
- Good for mass determination
- Good for width determination
- Good for asymmetry→ A product of the Z' chiral hadronic and leptonic couplings. When fitting, need to take the contamination from quark direction definition into account, subjecting to the PDF uncertainties.

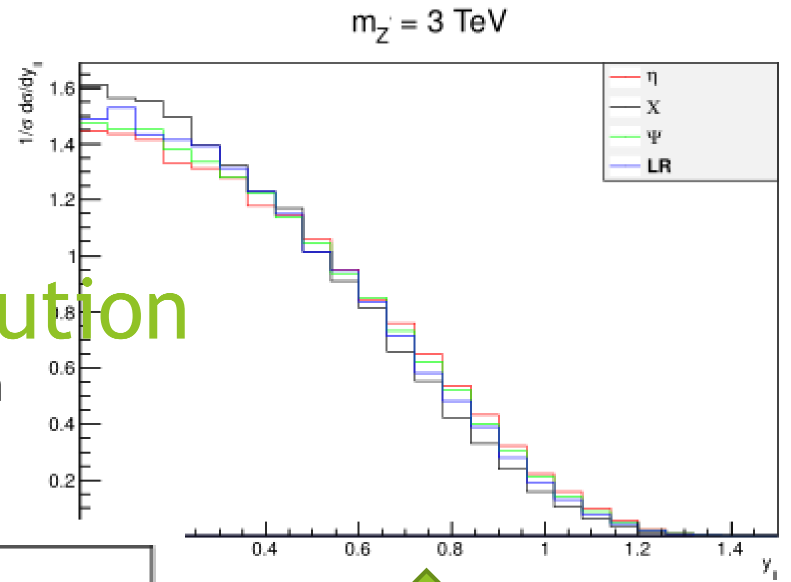
3 TeV Z'----
Leptonic Mode:
Mass and Width Fitting Precisions



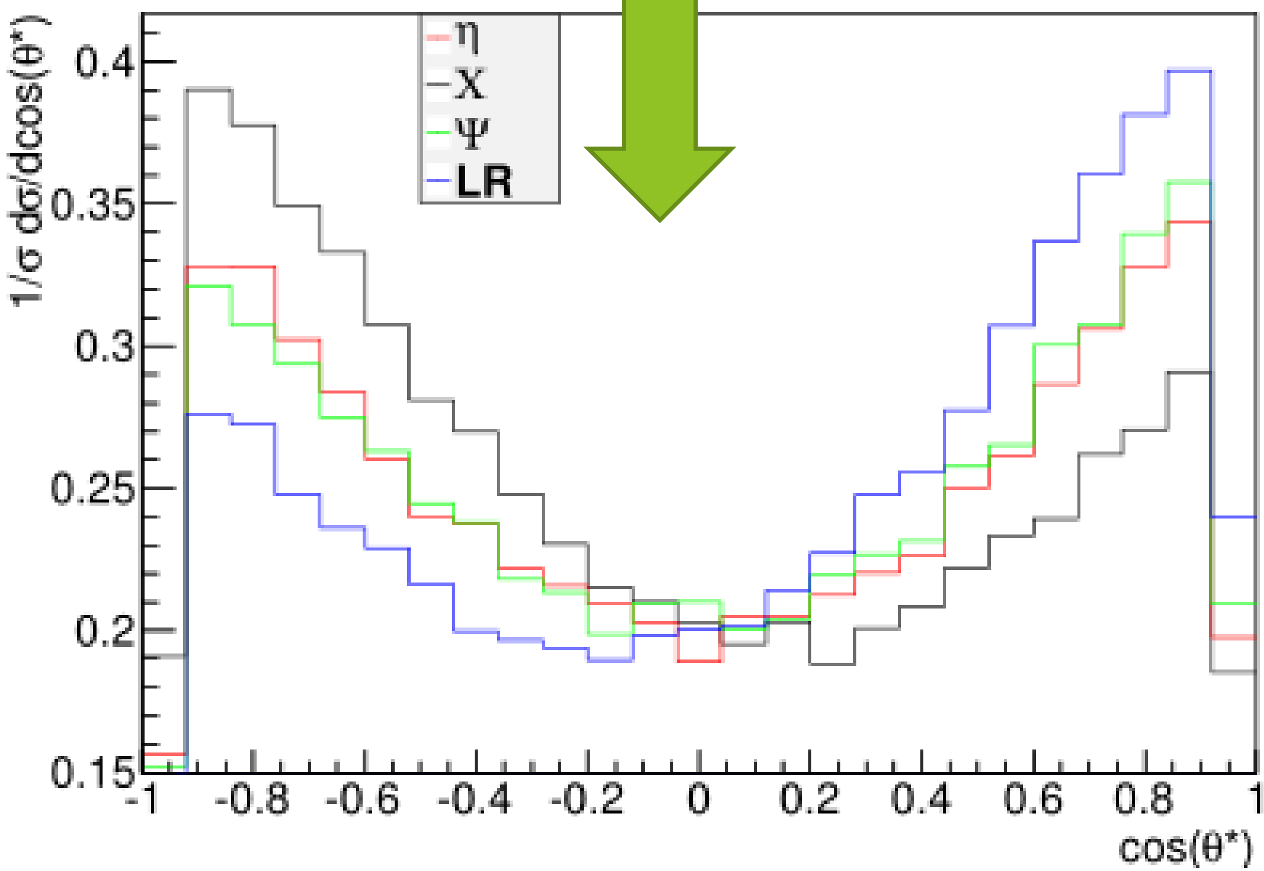
For the 'minimal width'
Width precisions:
30%~80% for 300 fb-1
10%~20% for 3000 fb-1
Mass precisions:
~5 GeV for 300 fb-1
~2 GeV for 3000 fb-1



3 TeV Z'----
Leptonic Mode:
Asymmetry⇔Angular Distribution

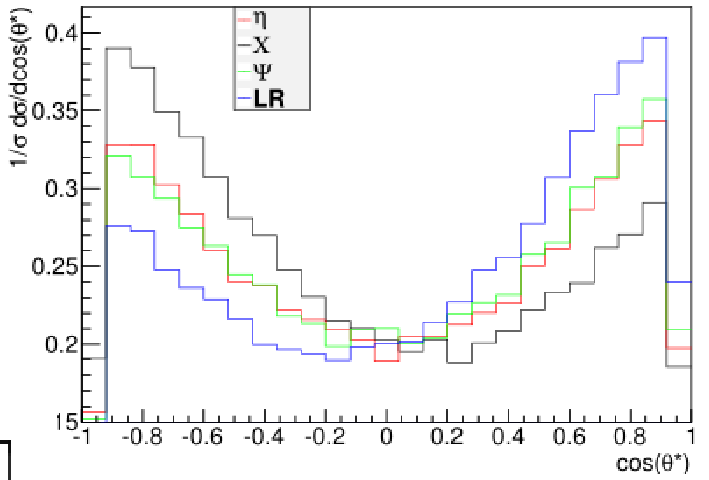


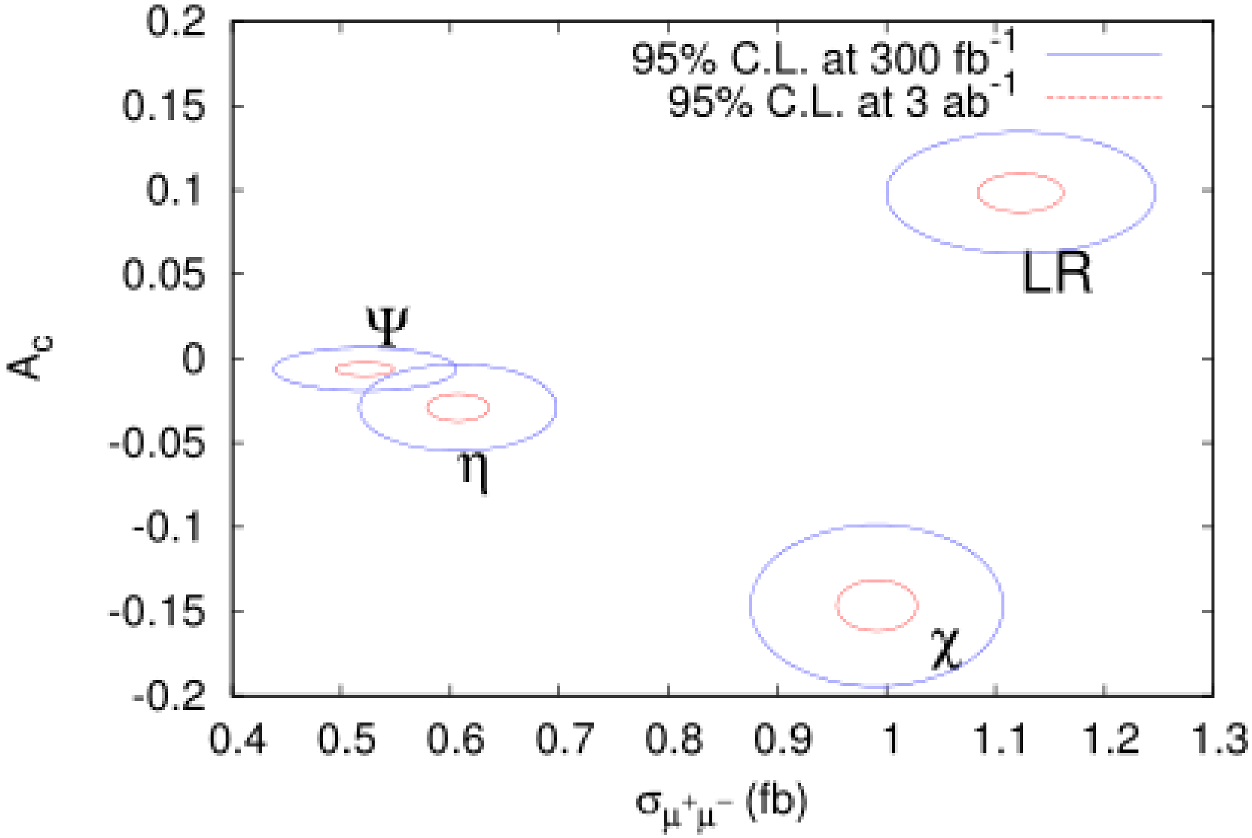
Angular Distribution of the charged lepton (e-) in the Z' rest frame, with positive direction defined as boosting direction



Rapidity Distribution. Difference are small. Differences comes from different relative hadronic coupling strengths from up-type quarks and down-type quarks.

3 TeV Z'----
Leptonic Mode:
Asymmetry and Cross Section





3 TeV Z’----Hadronic Mode

Important and challenging.

With possible b-tagging and top-tagging, the up-type coupling and down-type coupling overall strength determined. With top-quark charge tagging (even more, the polarization tagging), one could determine the chiral coupling of up-type quarks and then derive the down type chiral couplings.

Lack of statistics. Lepton Collider shows complementarity.

	χ	ψ	η	LR
$\sigma_{2j}^{SM+Z'}$ (fb)	1.414×10^6			
$\sigma_{2j}^{SM+Z'}$ (fb)	5102			
$\sigma_{2j;\mathrm{cut}}^{Z'}$ (fb)	6.73	6.42	9.62	16.9
$\sigma_{2b}^{Z'}$ (fb)	2.81	1.61	1.85	5.38
σ_{2b}^{SM} (fb)	1.892			
$\sigma_{2b}^{SM+Z'}$ (fb)	4.50	3.20	3.47	7.27
$\sigma_{2t}^{Z'}$ (fb)	0.56	1.51	2.96	3.07

Hadronic final state cross sections. Mass window of +/- 100 GeV are enforced.

Parton level results here just provide a taste of the S/B. All other studies are with pythia+delphes.

3 TeV Z'----bb Mode

B-tagging necessary to probe the up-type and down-type quark couplings.

Largest background: multi-light jets fake b jets.

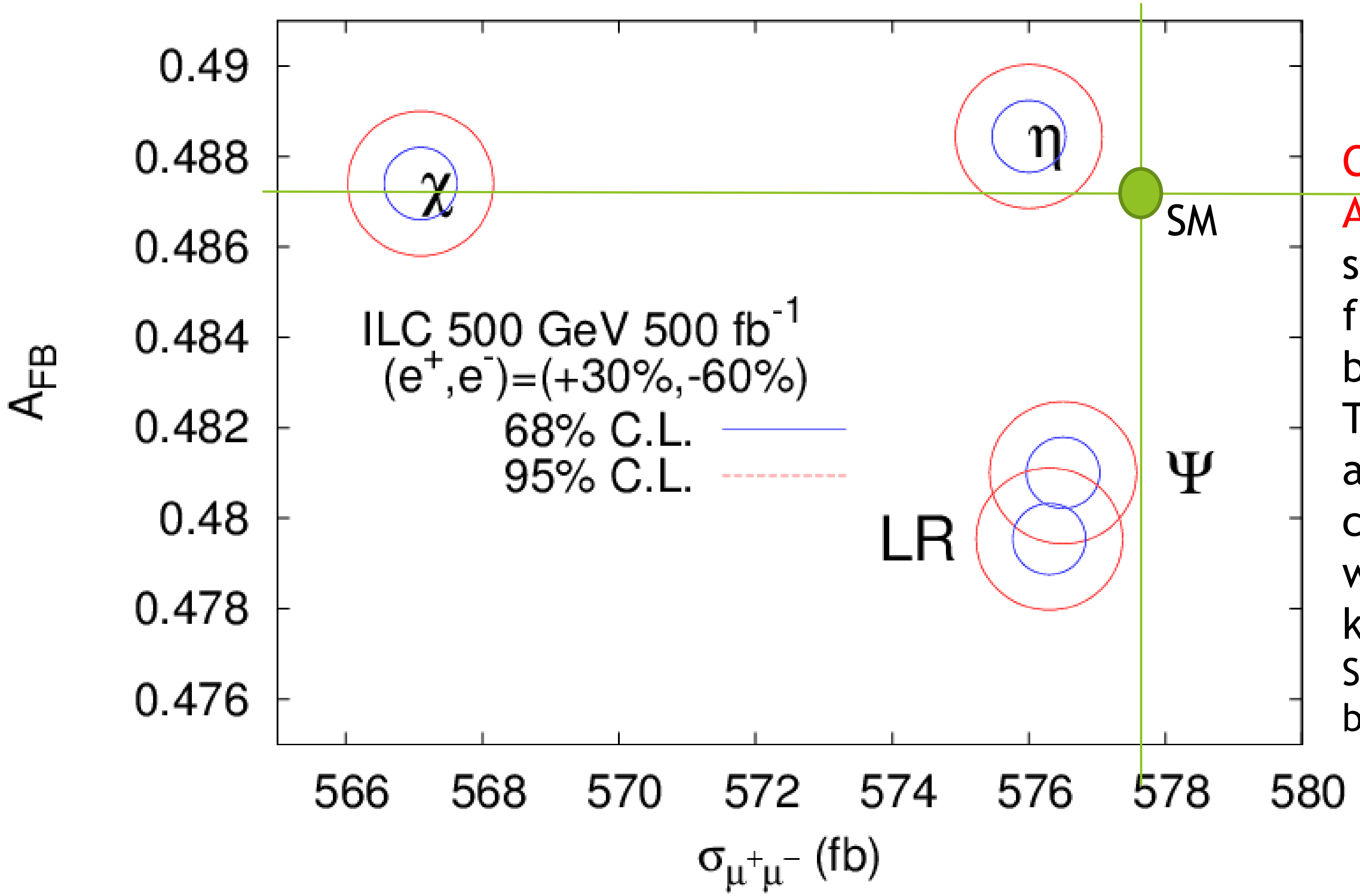
	QCD Dijet	SM $b\bar{b}$	χ	ψ	η	LR
σ (fb)	36300	12.1	3.13	1.66	1.93	9.24
$\epsilon_{b\geq 1}$	7.83%	55.24%	62.46%	63.21%	62.50%	63.06%
$\epsilon_{b\geq 1, P_t^b > 1200 \text{ GeV}}$	0.38%	15.28%	22.24%	22.50%	22.20%	21.74%
$\epsilon_{b\geq 2}$	0.32%	12.27%	15.93%	16.38%	15.71%	15.79%
$\epsilon_{b\geq 2, P_t^b > 1200 \text{ GeV}}$	0.02%	4.77%	7.00%	7.41%	6.77%	6.71%
$\epsilon_{+P_t^{b2} > 800 \text{ GeV}}$	0.01%	4.28%	6.17%	6.53%	5.87%	5.84%
$\epsilon_{+2600 \text{ GeV} < m_{\text{eff}} < 3200 \text{ GeV}}$	0.0035%	2.24%	4.45%	4.81%	4.18%	4.14%
σ_{eff} (fb)	1.283	0.271	0.140	0.080	0.081	0.383
$S/\sqrt{B}$ @300 fb^{-1}			1.94	1.11	1.12	5.31
$S/\sqrt{B}$ @3000 fb^{-1}			6.13	3.50	3.54	16.8

Table 5. Cut flow table and significance for $Z' \to b\bar{b}$ processes at LHC 14 TeV. The cross sections are for bottom pair (dijet) invariant mass within $2.5 \sim 3.5$ TeV.

3 TeV Z’ @ ILC 500 GeV

- Very complementary to LHC results. Especially with good b-tagging efficiency (which also implies good top tagging as well as top charge/polarization tagging) and possible b-charge tagging;
- With combining both ILC and LHC could measure all five couplings;
- However, interferences are small, need to reply on high statistics and subject to systematic uncertainties;

ILC (Diagnosis) mu+mu- final state



Cross section and Asymmetry can be slightly deviated from SM background.
To Extract Vector and Axial-vector couplings strength when the mass is known from LHC.
Systematics need to be added.

ILC (Exclusion Reach)

		SM	Chi	Psi	Eta	LR
$\mu^+\mu^-$	σ (fb)	577.5	567.1	576.5	576	576.3
	$S/\sqrt{B}$(3 TeV Z')	–	9.7	0.9	1.3	1.1
	$m_{Z'}^{\max}$ (TeV)	–	6.6	2.0	2.4	2.2
bb	σ (fb)	717.9	728.7	715	721.1	722.5
	$S/\sqrt{B}$(3 TeV Z')	–	9.0	2.4	2.7	3.8
	$m_{Z'}^{\max}$ (TeV)	–	6.4	3.3	3.5	4.2
tt	σ (fb)	922.5	920.7	923.6	921.8	926.9
	$S/\sqrt{B}$(3 TeV Z')	–	1.3	0.8	0.5	3.2
jj	σ (fb)	3745	3755	3745	3747	3758
	$S/\sqrt{B}$(3 TeV Z')	–	3.8	0.2	0.9	4.9
Combined	$S/\sqrt{B}$(3 TeV Z')	–	19.4	3.0	3.7	7.3
	$m_{Z'}^{\max}$ (TeV)	–	**9.4**	**3.7**	**4.1**	**5.7**

Exclusion through contact operators, which modifies cross sections through interference.

Outlook

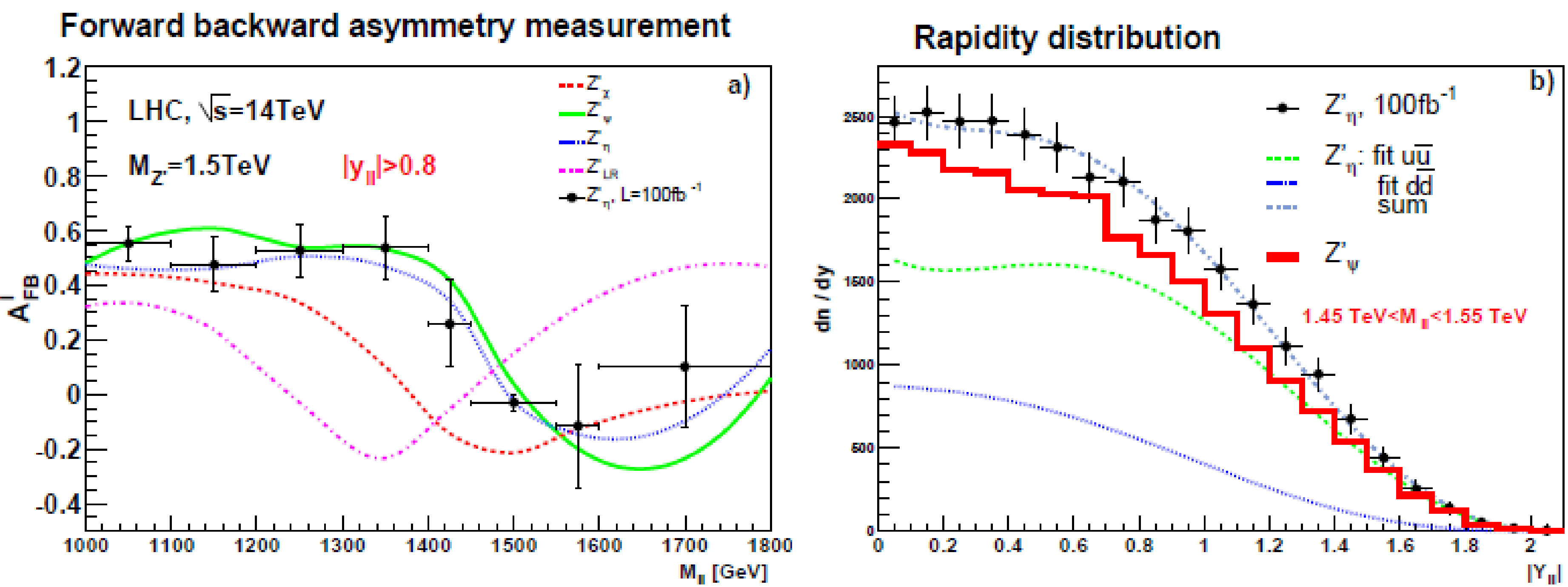
- Z' well motivated
- For 3 TeV Z'
  - Mass and width at LHC 14 TeV from dilepton final states;
  - Lepton charge (Forward-backward) asymmetry well measured; Sensitive to certain product of leptonic and hadronic couplings;
  - Can reach 3-sigma effect for bottom pair at HL-LHC;
  - Complementarity from ILC. Can determine the couplings to bottom quark, top quark much better.
- For 6 TeV Z'
  - Study for both LHC and ILC constraining power on the couplings are under going.

Thank You!

Backup

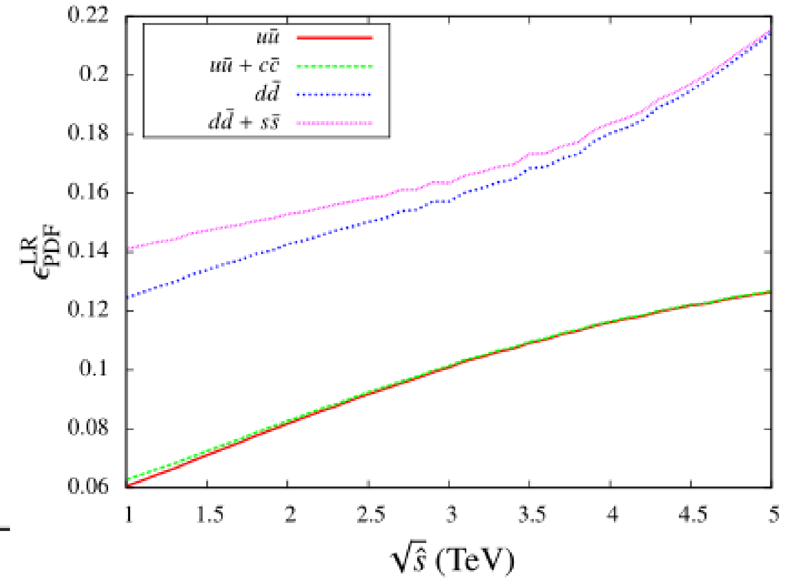
Diagnostics of Z' Couplings

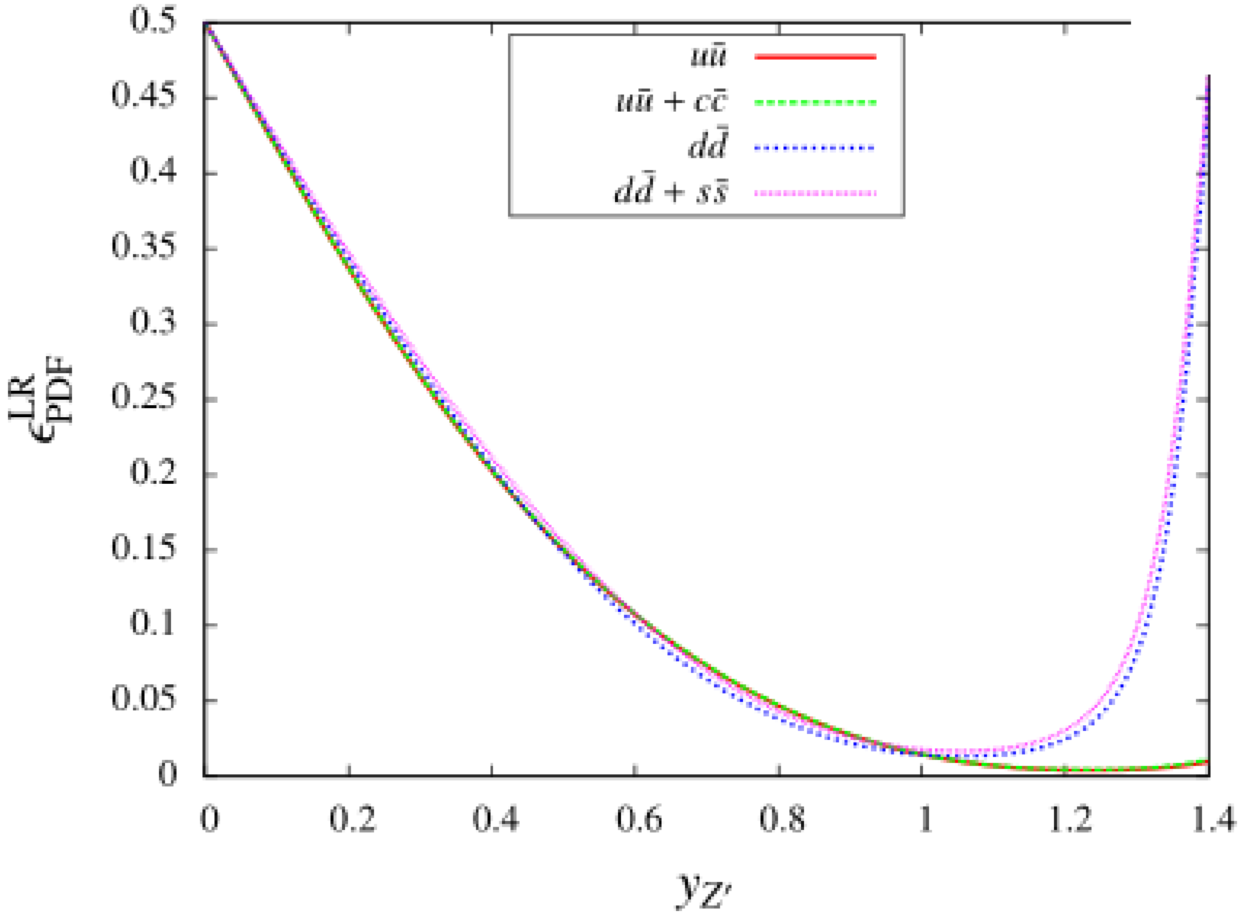
- LHC diagnostics to 2-2.5 TeV
- Forward-backward asymmetries and rapidity distributions in $\ell^+\ell^-$



(LHC/ILC, hep-ph/0410364)

Leptonic mode (Dimuon final state)





The percentage of events with the quark (anti-quark) direction opposite to (same as) the boost direction.
As a function of rapidity;
As a function of partonic center of mass energy.

Correction: the y-axis should be \epsilon^{q_{FB}}_{PDF}

Quantity	Group(s)	Value	Standard Model	pull
m_t [GeV]	Tevatron	173.1 ± 1.4	173.1 ± 1.4	0.0
M_W [GeV]	Tevatron	80.432 ± 0.039	80.380 ± 0.015	1.3
M_W [GeV]	LEP 2	80.376 ± 0.033		−0.1
g_L^2	NuTeV	0.3010 ± 0.0015	0.3039 ± 0.0002	−2.0
g_R^2	NuTeV	0.0308 ± 0.0011	0.0300	0.7
κ	CCFR	0.5820 ± 0.0041	0.5831 ± 0.0003	−0.3
R^ν	CDHS	0.3096 ± 0.0043	0.3091 ± 0.0002	0.1
R^ν	CHARM	0.3021 ± 0.0041		−1.7
$R^{\bar\nu}$	CDHS	0.384 ± 0.018	0.3861 ± 0.0001	−0.1
$R^{\bar\nu}$	CHARM	0.403 ± 0.016		1.1
$R^{\bar\nu}$	CDHS 1979	0.365 ± 0.016	0.3815 ± 0.0001	−1.0
$g_V^{\nu e}$	CHARM II + older	-0.040 ± 0.015	-0.0397 ± 0.0003	0.0
$g_A^{\nu e}$	CHARM II + older	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0
Q_W(Tl)	Oxford + Seattle	-116.4 ± 3.6	−116.8	0.1
Q_W(Cs)	Boulder	-73.16 ± 0.35	-73.16 ± 0.03	0.0
$Q_W(e)$	SLAC E158	-0.0403 ± 0.0053	-0.0472 ± 0.0005	1.3
$\cos\gamma\, C_{1d} - \sin\gamma\, C_{1u}$	Young et al.	0.342 ± 0.063	0.3885 ± 0.0002	−0.7
$\sin\gamma\, C_{1d} + \cos\gamma\, C_{1u}$	Young et al.	-0.0285 ± 0.0043	-0.0335 ± 0.0001	1.2
CKM unitarity	KLOE dominated	1.0000 ± 0.0006	1	0.0
$(g_\mu - 2 - \alpha/\pi)/2$	BNL E821	4511.07 ± 0.74	4509.04 ± 0.09	2.7

Table 2: Non Z-pole precision observables from FNAL, CERN, SLAC, JLab, and elsewhere. Shown are the experimental results, the SM predictions, and the pulls. The SM errors are from the parametric uncertainties in the Higgs boson and quark masses and in the strong and electromagnetic coupling constants evaluated at M_Z.

Erler et al., 0906.2435;