Radiative Corrections and Z′

Jens Erler

Departamento de Física Teórica
Universidad Nacional Autónoma de México

Instituto de Física
(IF-UNAM)

Bar Harbor, ME

June 22−26, 2009

PAVI09

Outline

- Introduction
- Radiative Corrections
  - Vertex and box corrections
  - Running weak mixing angle
- Z' Physics
  - Introduction and overview of popular Z' models
  - Formalism and electroweak data
  - Results and discussion

Introduction

Weak Lagrangian

- $\mathscr{L} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{fermion}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{Yukawa}}$
- $\mathscr{L}_{\text{fermion}} + \mathscr{L}_{\text{Yukawa}} \equiv \mathscr{L}_{\psi} + \mathscr{L}_{\text{QED}} + \mathscr{L}_{W} + \mathscr{L}_{Z}$

$$= \mathscr{L}_{\psi} - g/2\, (2 \sin\theta_W\, J^{\mu}_{\text{QED}}\, A_{\mu}$$

$$+ J^{\mu}_{W}\, W^{-}_{\mu} + J^{\mu}_{W^{\dagger}}\, W^{+}_{\mu} + J^{\mu}_{Z}\, Z_{\mu}/\cos\theta_W)$$

- electromagnetic current:

$$J^{\mu}_{\text{QED}} = \sum_i \left(\tfrac{2}{3}\, \overline{u}^i \gamma^{\mu} u^i - \tfrac{1}{3}\, \overline{d}^i \gamma^{\mu} d^i - \overline{e}^i \gamma^{\mu} e^i\right)$$

- weak charged current:

$$J^{\mu}_{W^{\dagger}} = \sqrt{2} \sum_i \left(\overline{u}^{i0} \gamma^{\mu} P_L\, d^{i0} + \overline{\nu}^{i0} \gamma^{\mu} P_L\, e^{i0}\right) \qquad [P_{L,R} \equiv \tfrac{1}{2}\,(1 \mp \gamma^5)]$$

Weak neutral current

- weak neutral current:

$$J^\mu_Z = \sum_i (\overline{u}^i \gamma^\mu P_L u^i - \overline{d}^i \gamma^\mu P_L d + \overline{\nu}^i \gamma^\mu P_L \nu^i - \overline{e}^i \gamma^\mu P_L e^i)$$

$$- 2 \sin^2\theta_W J^\mu_{QED}$$

$$\equiv \sum_i \overline{\psi}^i \gamma^\mu [g_L^i P_L + g_R^i P_R] \psi^i \equiv \sum_i \overline{\psi}^i \gamma^\mu [g_V^i - g_A^i \gamma^5] \psi^i$$

- $g_L^i = \tau_3^i - 2 Q^i \sin^2\theta_W$ (τ_i: Pauli matrices)
- $g_R^i = - 2 Q^i \sin^2\theta_W$
- $g_V^i = ½ \tau_3^i - 2 Q^i \sin^2\theta_W = ½ (g_L^i + g_R^i)$
- $g_A^i = ½ \tau_3^i = ½ (g_L^i - g_R^i)$

Effective interactions

- $\mathscr{H}_{eff}^{NC} = \frac{1}{2} (g/2 \cos\theta_W M_Z)^2 J^\mu{}_Z J_{\mu Z} = G_F/\sqrt{2}\, J^\mu{}_Z J_{\mu Z}$

  $\equiv G_F/\sqrt{2} \sum_{abij} h_{ab}^{ij}\, \bar{\psi}^i \gamma^\mu P_a \psi^i\, \bar{\psi}^j \gamma_\mu P_b \psi^j$

  [a, b = L, R] where $h_{ab}^{ij} = g_a^i\ g_b^j$

  $\equiv G_F/\sqrt{2} \sum_{MNij} h_{MN}^{ij}\, \bar{\psi}^i \Gamma^M \psi^i\, \bar{\psi}^j \Gamma_N \psi^j$

  [$\Gamma^M, \Gamma^N = \gamma^\mu$ (V), $\gamma^\mu\gamma^5$ (A)] where $h_{AB}^{ij} = g_A^i\ g_B^j$

- $\mathscr{H}_{eff}^{CC} = (g/2 M_W)^2 J^\mu{}_W{}^\dagger J_{\mu W} \equiv \sqrt{2}\, G_F J^\mu{}_W{}^\dagger J_{\mu W}$

  $\equiv \sqrt{2}\, G_F \sum_{abijkl} h_{ab}^{ijkl}\, \bar{\psi}^i \gamma^\mu P_a \psi^j\, \bar{\psi}^k \gamma_\mu P_b \psi^l$

  $\equiv \sqrt{2}\, G_F \sum_{MNijkl} h_{MN}^{ijkl}\, \bar{\psi}^i \Gamma^M \psi^j\, \bar{\psi}^k \Gamma_N \psi^l$ (Michel, Sirlin)

Radiative Corrections

Radiative corrections to PVDIS

$\omega_{PVDIS} \equiv (2\, C_{1u} - C_{1d}) + 0.84\, (2\, C_{2u} - C_{2d})$

- $2\, C_{1u} - C_{1d} = -\frac{3}{2}\, [\rho_{NC} - \frac{\alpha}{2\pi}]\, [1 - \frac{20}{9}\, (\sin^2\bar{\theta}_W(0) - \frac{2\alpha}{9\pi})]$

  $+ \frac{5\bar{\alpha}}{9\pi}\, [1 - 4 \sin^2\bar{\theta}_W(M_Z)]\, [\ln\, (M_Z/m_e) + \frac{1}{12}]$

  $+ \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$ **Marciano & Sirlin, PRD 1984** $[\bar{\alpha} \equiv \bar{\alpha}(M_Z)]$

- $2\, C_{2u} - C_{2d} = -\frac{3}{2}\, [\rho_{NC} - \frac{\alpha}{6\pi}]\, [1 - 4\, (\sin^2\bar{\theta}_W(0) - \frac{2\alpha}{9\pi})]$

  $+ \frac{5\bar{\alpha}}{9\pi}\, [1 - \frac{12}{5} \sin^2\bar{\theta}_W(M_Z)]\, [\ln\, (M_Z/m_q) + \frac{1}{12}]$

  $- \frac{8\bar{\alpha}}{9\pi}\, [\ln\, (M_W/m_q) + \frac{1}{12}] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$

- $\rho_{NC} \approx 1.0007$ (oblique + vertex relative to μ-decay)

Box contributions

- $2\,C_{1u} - C_{1d}$:
  - $\Box_{WW} = -\,9\bar{\alpha}/[8\pi \sin^2\bar{\theta}_W(M_Z)]\,[1 - \tfrac{1}{3}\,\bar{\alpha}_s(M_Z)/\pi]$
  - $\Box_{\gamma Z} = -\,\tfrac{3\bar{\alpha}}{4\pi}\,[1 - 4 \sin^2\bar{\theta}_W(M_Z)]\,[\ln (M_Z/M_\rho) + \tfrac{3}{4}]$
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  - $\Box_{ZZ} \ll \Box_{WW}$

Marciano & Sirlin, PRD 1984; JE, Kurylov & Ramsey-Musolf, PRD 2003

Box contributions to C_{2q}

	$2\,C_{1u} - C_{1d}$	$2\,C_{2u} - C_{2d}$	ω_{PVDIS}
tree + QED	-0.7060	-0.0715	-0.7660
charge radii	+0.0013	-0.0110	-0.0079
$\Box_{WW}$	-0.0120	-0.0120	-0.0220
$\Box_{\gamma Z}$	-0.0008	-0.0029	-0.0032
other	-0.0009	-0.0011	-0.0018
TOTAL	-0.7184	-0.0985	-0.8011

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➡ running of $\overline{\alpha}$ (e^+e^- and/or τ data) $\Longrightarrow$ running of $\sin^2\overline{\theta}_W$ if

- either no mass threshold is crossed
- or perturbation theory applies (W±, leptons, b & c quarks)
- or all coefficient are equal (RGE factorizes) like for (d,s)
- or there is a symmetry like $SU(2)_I$ or $SU(3)_F$

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  - heavy quark limit for $\bar{m}_s$: $\xi^s \longrightarrow \xi^c \Longrightarrow \bar{m}_s < 387$ MeV
  - $SU(3)_F$ limit: $\xi^s \longrightarrow \xi^d \approx \xi^u$ + dispersion result for $\Delta\bar{\alpha}^{(3)}(\bar{m}_c) \Longrightarrow \bar{m}_s > 240$ MeV

JE & Ramsey-Musolf, PRD 2005

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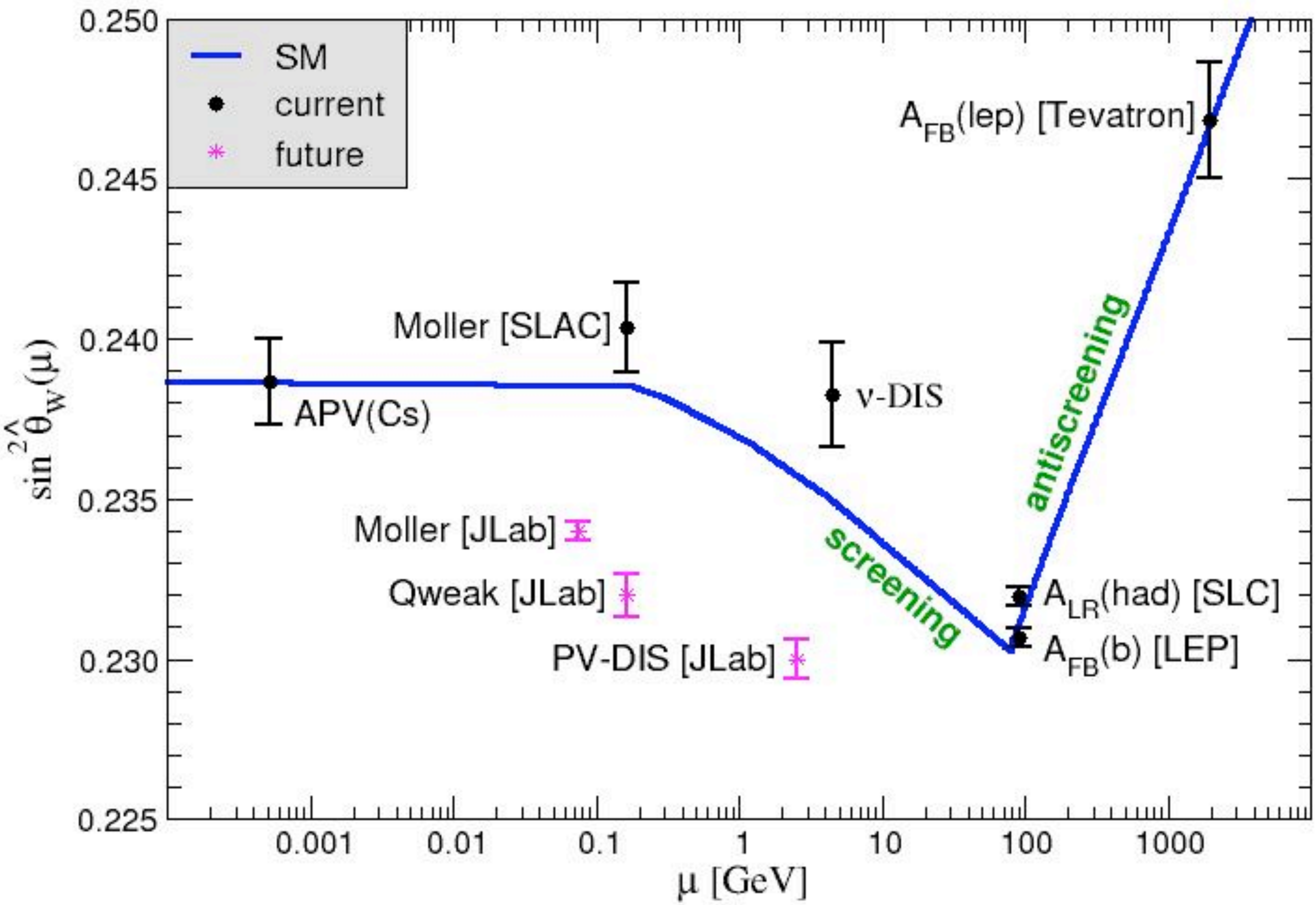

SM
current
future
A_{FB}(lep) [Tevatron]
Moller [SLAC]
APV(Cs)
ν-DIS
antiscreening
screening
Moller [JLab]
Qweak [JLab]
PV-DIS [JLab]
A_{LR}(had) [SLC]
A_{FB}(b) [LEP]
$\sin^2\hat{\theta}_W(\mu)$
μ [GeV]
0.250
0.245
0.240
0.235
0.230
0.225
0.001
0.01
0.1
1
10
100
1000

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◉ correct PVDIS asymmetry for $Q^2 \neq 0$ effects — or define new C_{2q}, which could supersede less precise old ones

Z′ Physics

The search for a fifth force

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  - Diagnostic tools: leptonic FB asymmetries, heavy quark final states Barger, Han & Walker, PRL 2008; Godfrey & Martin, PRL 2008

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- $\beta \approx 75.5° \Longrightarrow Z_N$ [no couplings to ν_R: see-saw possible]

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- $Z_{LR} \propto \bar{\alpha} \, Z_R - Z_{B\text{-}L}/2\bar{\alpha}$, where $\bar{\alpha} = \sqrt{(g_R^2/g_L^2 \cot^2\theta_W - 1)} \approx 1.53$ (for $g_R = g_L$); [$(\alpha, \beta) \approx (-39.2°, 0°) \Longrightarrow Z_{B\text{-}L} \perp Z_R$]

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Chaudhuri, Chung, Hockney & Lykken, NPB 1995; Cleaver et al., PRD 1999

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- $\rho/(1 - \alpha T) \neq 1$ has relatively little impact on extracted Z′ parameters $\Longrightarrow$ will mostly set $\rho/(1 - \alpha T) = 1$

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  $|v|^2 + |\bar{v}|^2 + |x|^2 = (\sqrt{2}\, G_F)^{-1} = (246.22\ \text{GeV})^2$ ($\mathbf{27}$ of E_6)

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- Z_I for illustration: $C = \tau + 2\,\omega - 1 \Longrightarrow -1 \leq C \leq 1$

  restricted range for SUSY ($\omega = 0, \tau \geq ½$) $\Longrightarrow -½ \leq C \leq 0$

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  - $\delta a_\mu = 5/36\,\lambda\,(v_\mu^2 - 5\,a_\mu^2)\,\alpha_Y/\pi\,m_\mu^2/M_{Z'}^2$

Pivotal data

Quantity	Group(s)	Value	SM	pull
g_L^2	NuTeV	0.3010(15)	0.3039(2)	-2.0
g_R^2	NuTeV	0.0308(11)	0.0300	0.7
$Q_W(e)$	SLAC E158	-0.0403(53)	-0.0472(5)	1.3
$Q_W(Cs)$	Boulder	-73.16(35)	-73.16(3)	0.0
$\cos\gamma\, C_{1d} - \sin\gamma\, C_{1u}$	Young et al.	0.342(63)	0.3885(2)	-0.7
$\sin\gamma\, C_{1d} + \cos\gamma\, C_{1u}$	($\tan\gamma \approx 0.445$)	-0.0285(43)	-0.0335(1)	1.2
CKM unitarity	various	1.0000(6)	1	0.0
$a_\mu - \alpha/(2\pi)$	BNL E821	4511.07(74)	4509.04(9)	2.7
M_W [GeV]	LEP 2, Tevatron	80.399(25)	80.380(15)	0.8

Z′ limits

Z'	EW	CDF	LEP 2	$\theta_{ZZ'}^{min}$	$\theta_{ZZ'}^{max}$	χ^2_{min}
Z_χ	1,141	892	673	-0.0016	0.0006	47.3
Z_ψ	147	878	481	-0.0018	0.0009	46.5
Z_η	427	982	434	-0.0047	0.0021	47.7
Z_I	1,204	789		-0.0005	0.0012	47.4
Z_S	1,257	821		-0.0013	0.0005	47.3
Z_N	623	861		-0.0015	0.0007	47.4
Z_R	442			-0.0015	0.0009	46.1
Z_{LR}	998	Run I: 630	804	-0.0013	0.0006	47.3
$Z_{\not L}$	C^2 = 3/8: 803	jj (Z_{SM}): 740		-0.0094	0.0081	47.7
Z_{SM}	1,403	1,030	1,787	-0.0026	0.0006	47.2

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- The various mass limits are highly complementary (e.g., limits from EW and LEP 2 scale with coupling strength)

M_H with LEP 2 bound removed

Z'	M_H [GeV]	χ^2_{min}
Z_χ	171^{+493}_{-89}	47.3
Z_ψ	97^{+31}_{-25}	46.1
Z_η	423^{+577}_{-350}	47.7
Z_I	141^{+304}_{-61}	47.4
Z_S	149^{+353}_{-68}	47.3
Z_N	117^{+222}_{-40}	47.4

Z'	M_H [GeV]	χ^2_{min}
Z_R	84^{+31}_{-24}	45.1
Z_{LR}	110^{+174}_{-35}	47.3
$Z_{\not L}$	126^{+276}_{-52}	47.7
Z_{SM}	331^{+669}_{-246}	47.2
Z_{string}	134^{+299}_{-58}	47.7
SM	96^{+29}_{-25}	48.0

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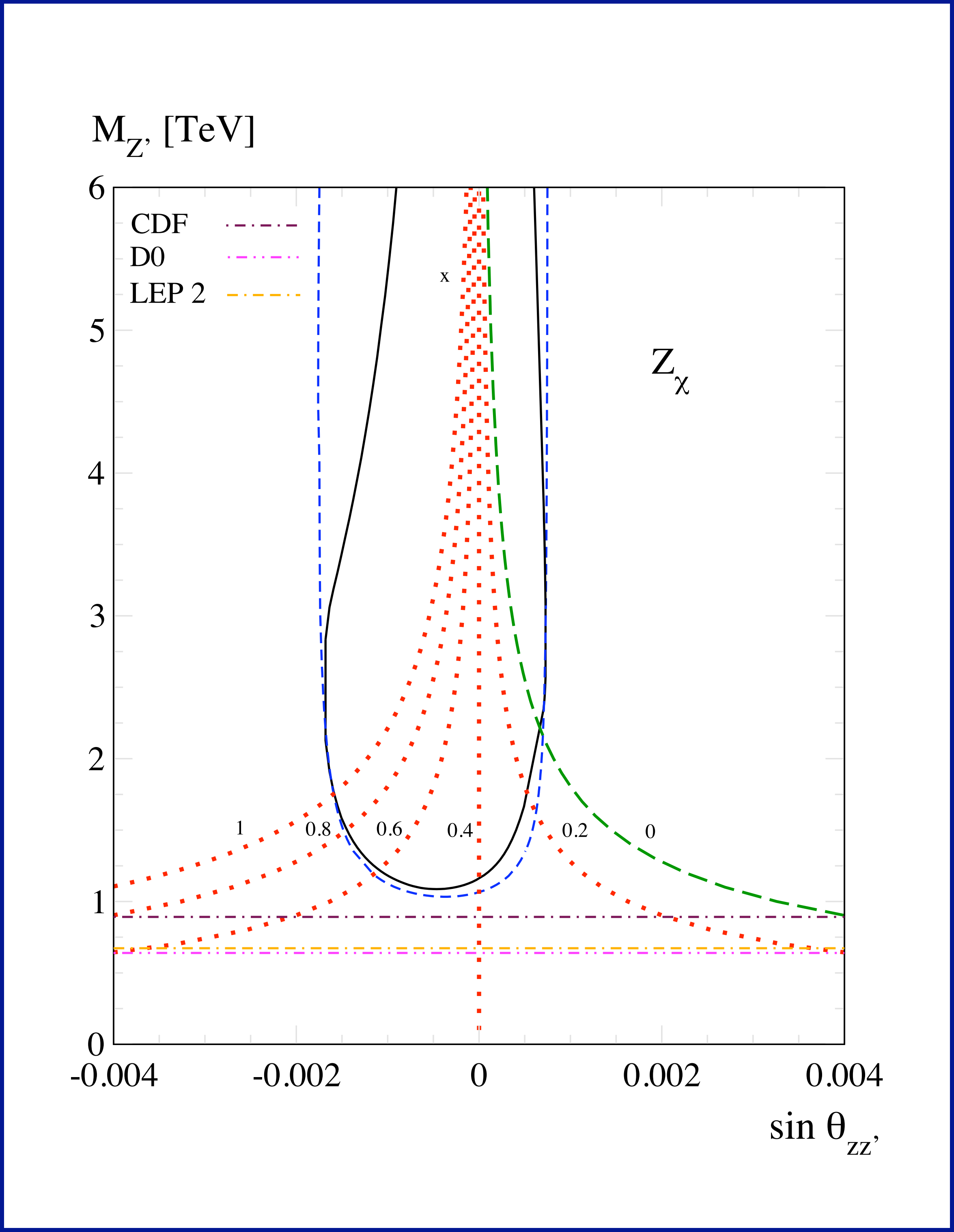
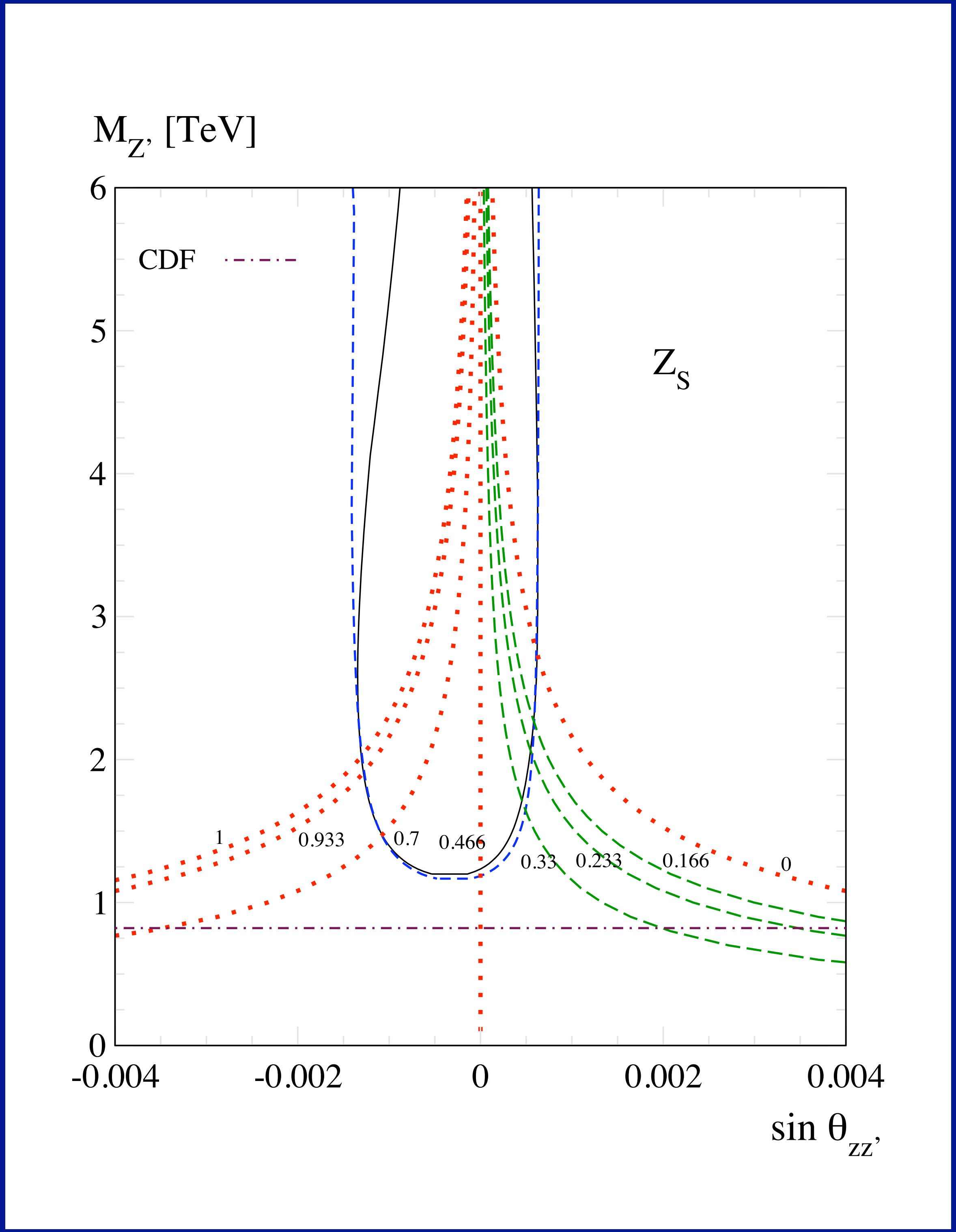
- $M_{Z'} = 1$ TeV ⟹ shifts of -0.0033 (3.0 & 1.1 σ) and -0.0090 (1.9 σ), respectively


M_Z' [TeV]
CDF
D0
LEP 2
x
Z_χ
1
0.8
0.6
0.4
0.2
0
sin θ_zz'


M_Z' [TeV]
CDF
Z_S
1
0.933
0.7
0.466
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0.166
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