New Vector Boson Near the Z-pole
and the Puzzle in Precision Electroweak Data

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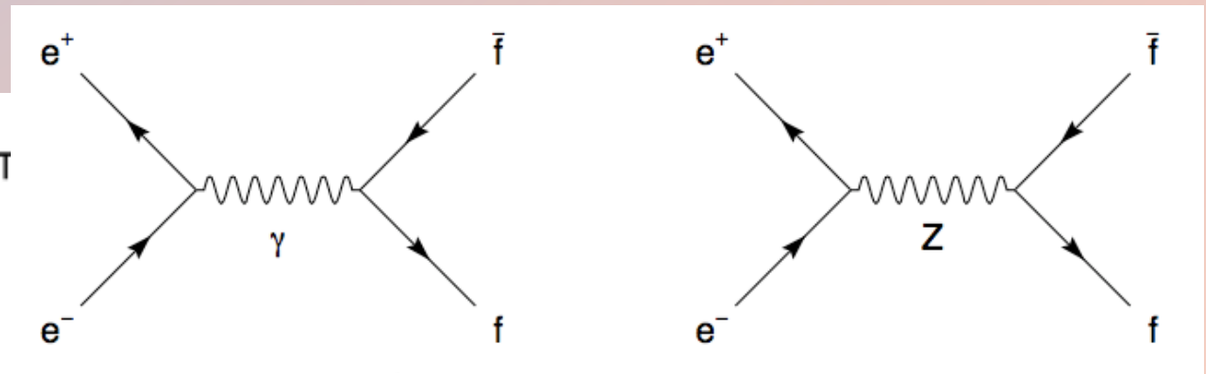
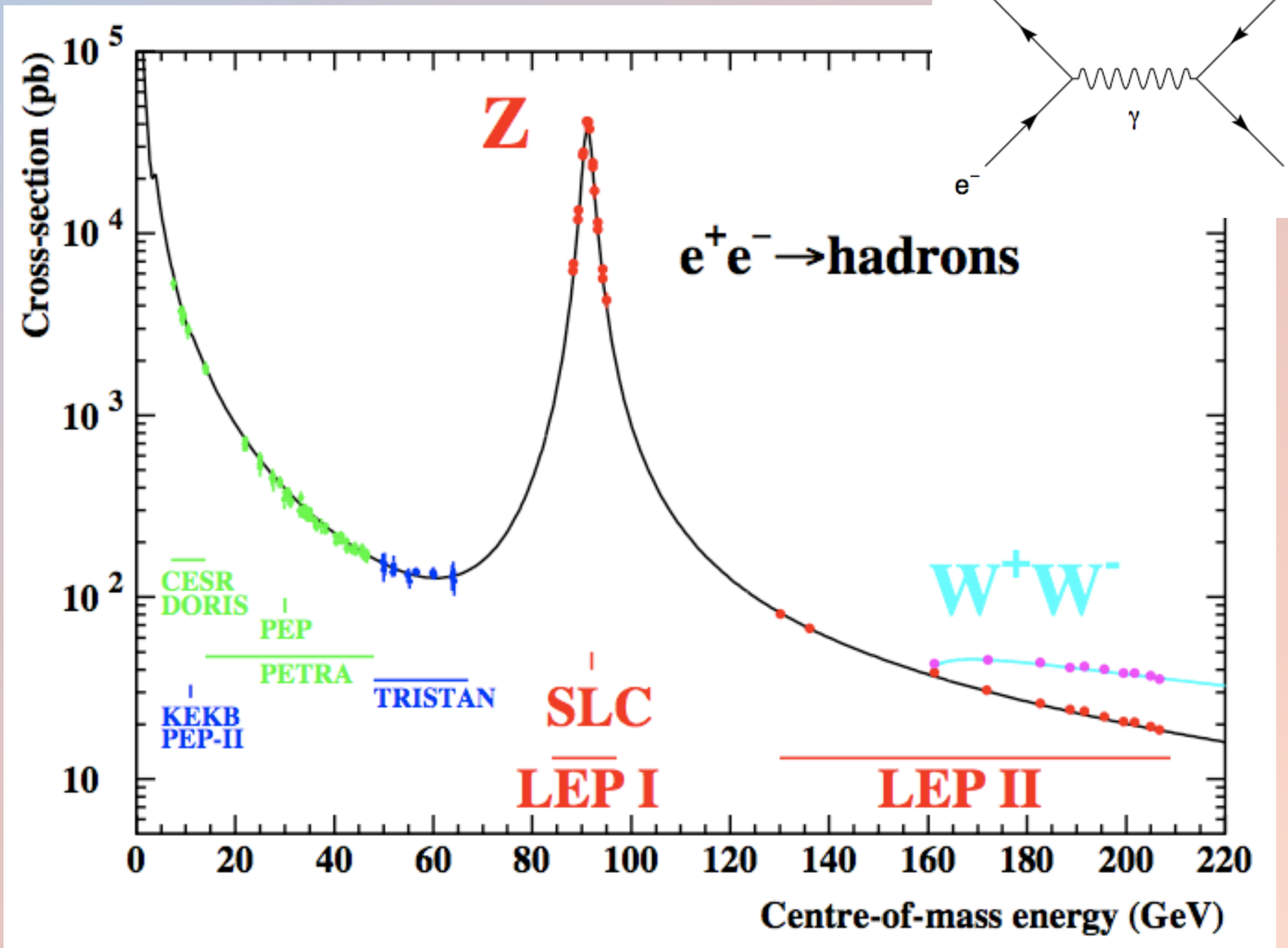
SUSY 2011, Fermilab, Sep 1, 2011

Puzzle in Precision Electroweak Data

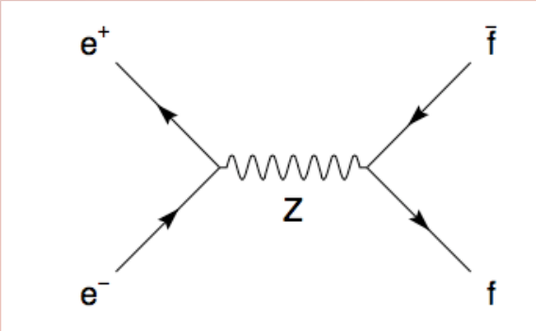
Precision EW data from LEP and SLC





Cross sections and Asymmetries

$$\frac{d\sigma_{Ll}}{d\cos\theta} \propto g_{Le}^2 g_{Lf}^2 (1+\cos\theta)^2$$
$$\frac{d\sigma_{Rr}}{d\cos\theta} \propto g_{Re}^2 g_{Rf}^2 (1+\cos\theta)^2$$
$$\frac{d\sigma_{Lr}}{d\cos\theta} \propto g_{Le}^2 g_{Rf}^2 (1-\cos\theta)^2$$
$$\frac{d\sigma_{Rl}}{d\cos\theta} \propto g_{Re}^2 g_{Lf}^2 (1-\cos\theta)^2.$$



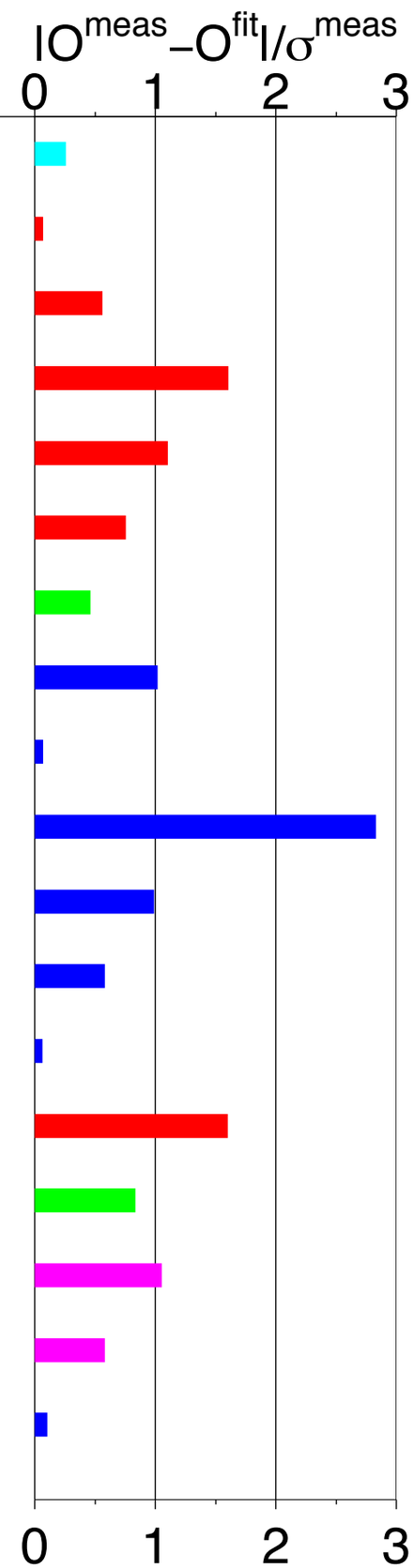
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$
$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}\frac{1}{\langle|\mathcal{P}_e|\rangle}$$
$$A_{LRFB} = \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R}\frac{1}{\langle|\mathcal{P}_e|\rangle}$$

Z-boson only

$$A_{FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$
$$A_{LR}^{0} = \mathcal{A}_e$$
$$A_{LRFB}^{0} = \frac{3}{4}\mathcal{A}_f$$

$$A_f = \frac{g_L^{f2} - g_R^{f2}}{g_L^{f2} + g_R^{f2}}$$

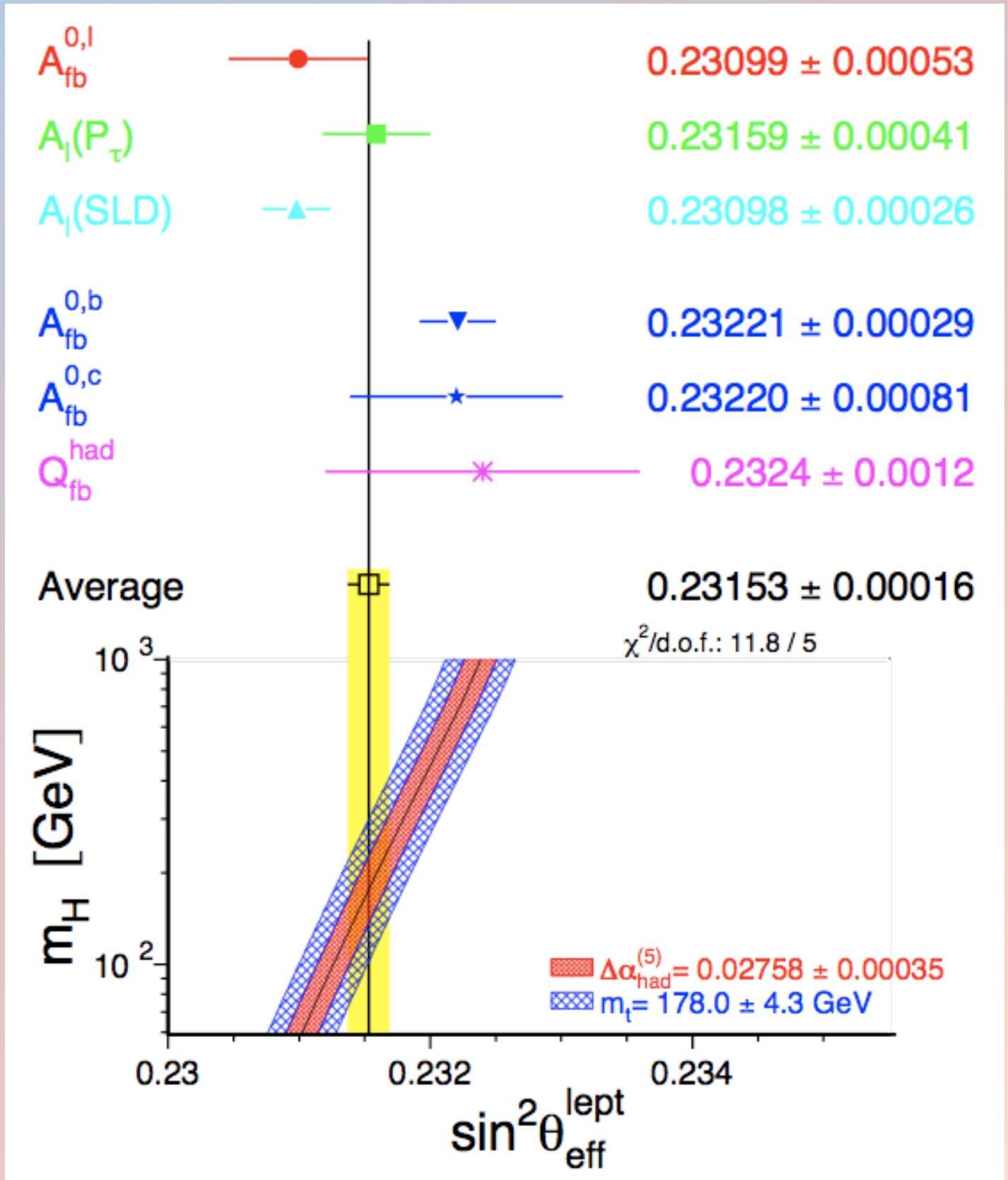
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ^0_{had} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5



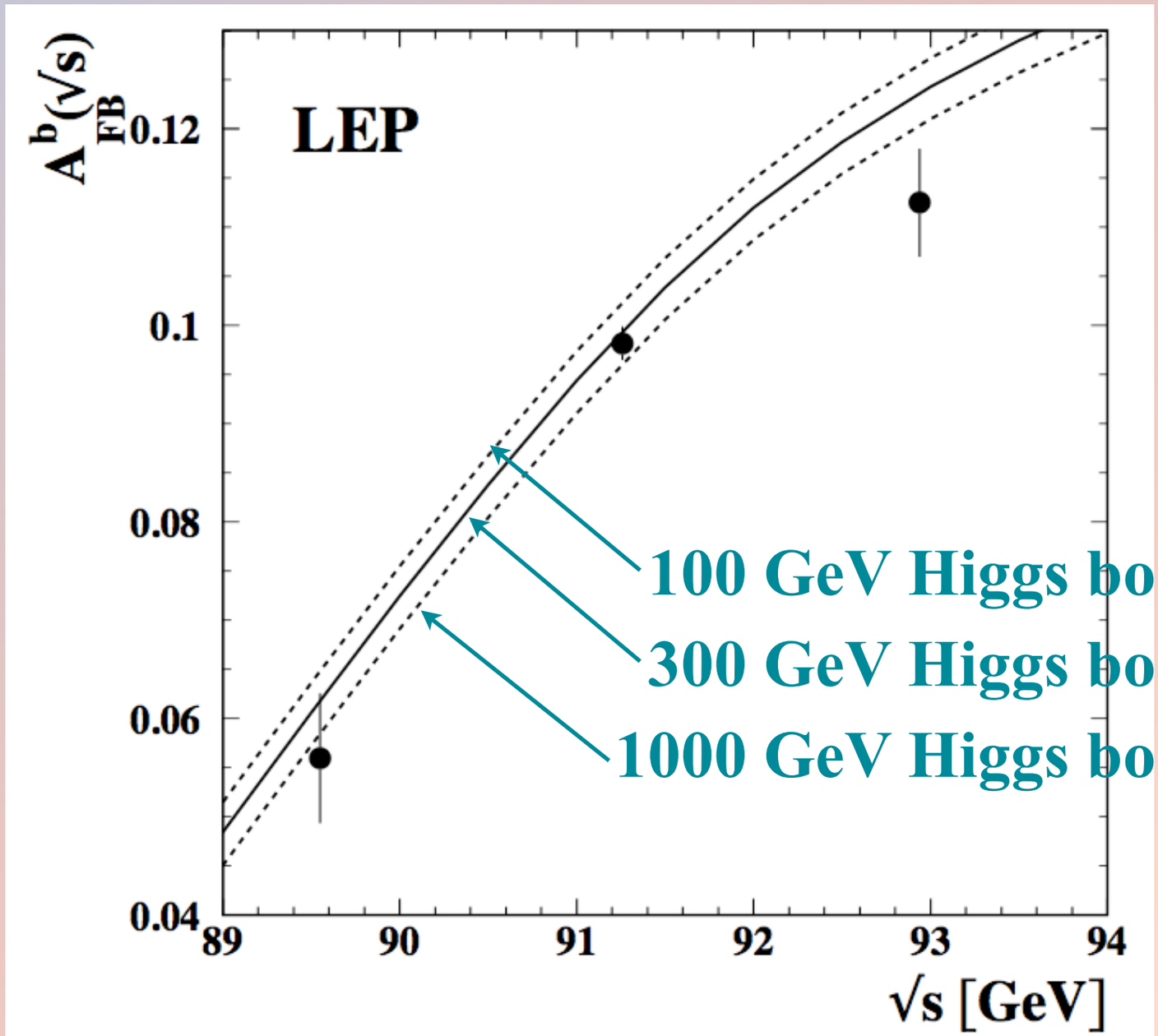
→ + 0.3%

→ - 4%

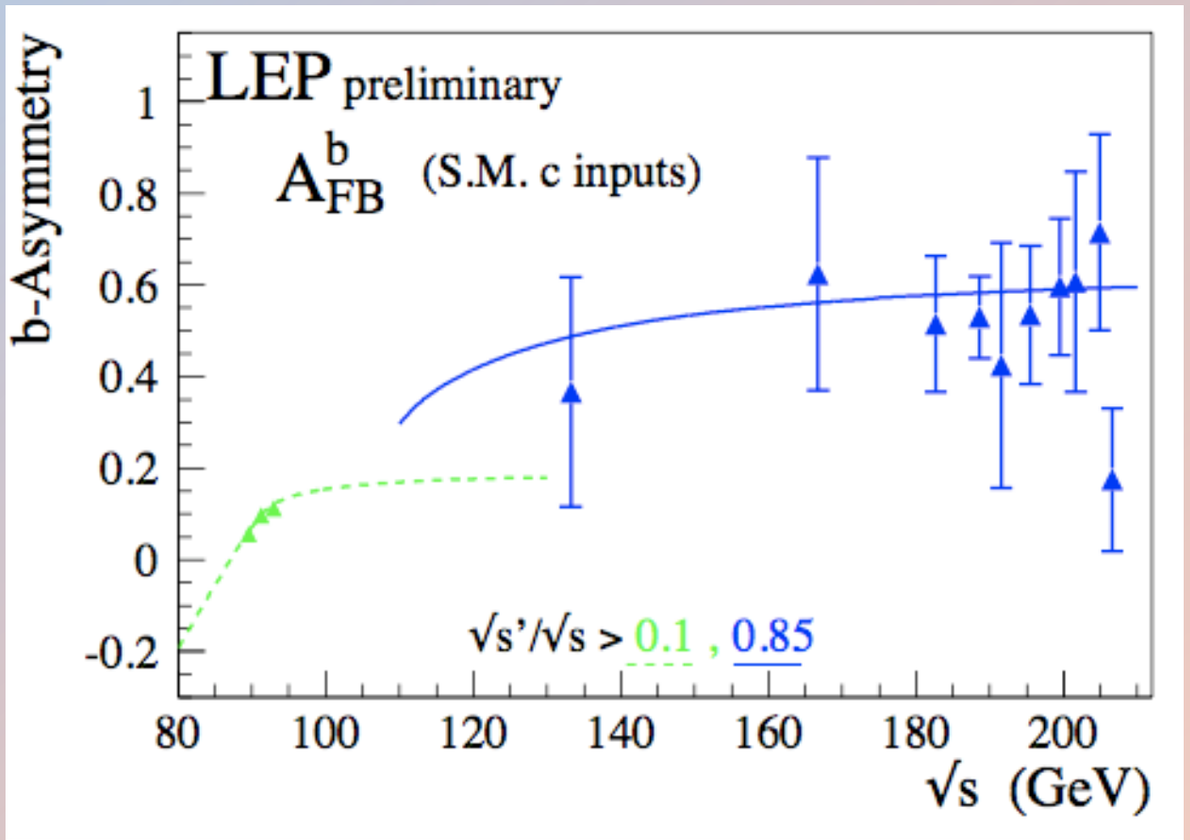
→ +2%

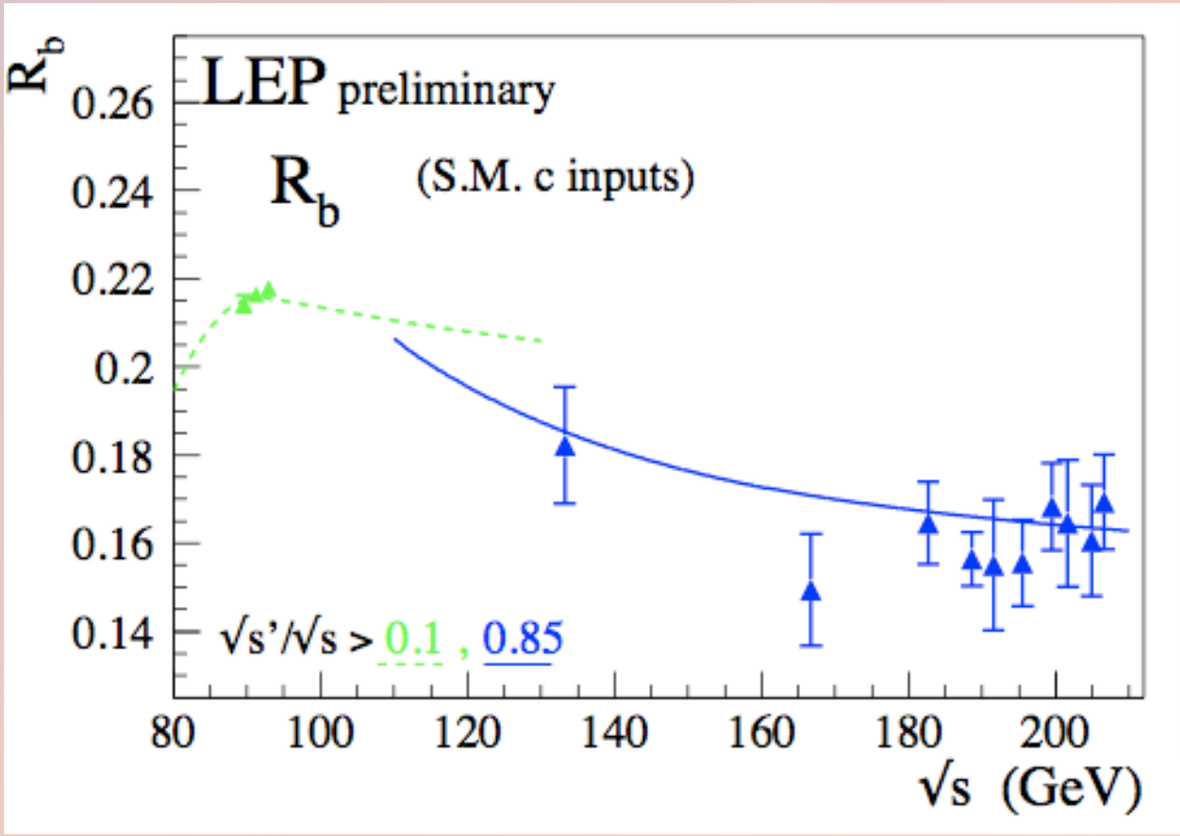

$A_{fb}^{0,l}$
0.23099 ± 0.00053
$A_l(P_\tau)$
0.23159 ± 0.00041
A_l(SLD)
0.23098 ± 0.00026
$A_{fb}^{0,b}$
0.23221 ± 0.00029
$A_{fb}^{0,c}$
0.23220 ± 0.00081
Q_{fb}^{had}
0.2324 ± 0.0012
Average
0.23153 ± 0.00016
χ^2/d.o.f.: 11.8 / 5
m_H [GeV]
10^3
10^2
$\Delta\alpha_{had}^{(5)}$= 0.02758 ± 0.00035
m_t= 178.0 ± 4.3 GeV
0.23
0.232
0.234
$\sin^2\theta_{eff}^{lept}$

Near the Z-pole measurements



Above the Z-pole measurements



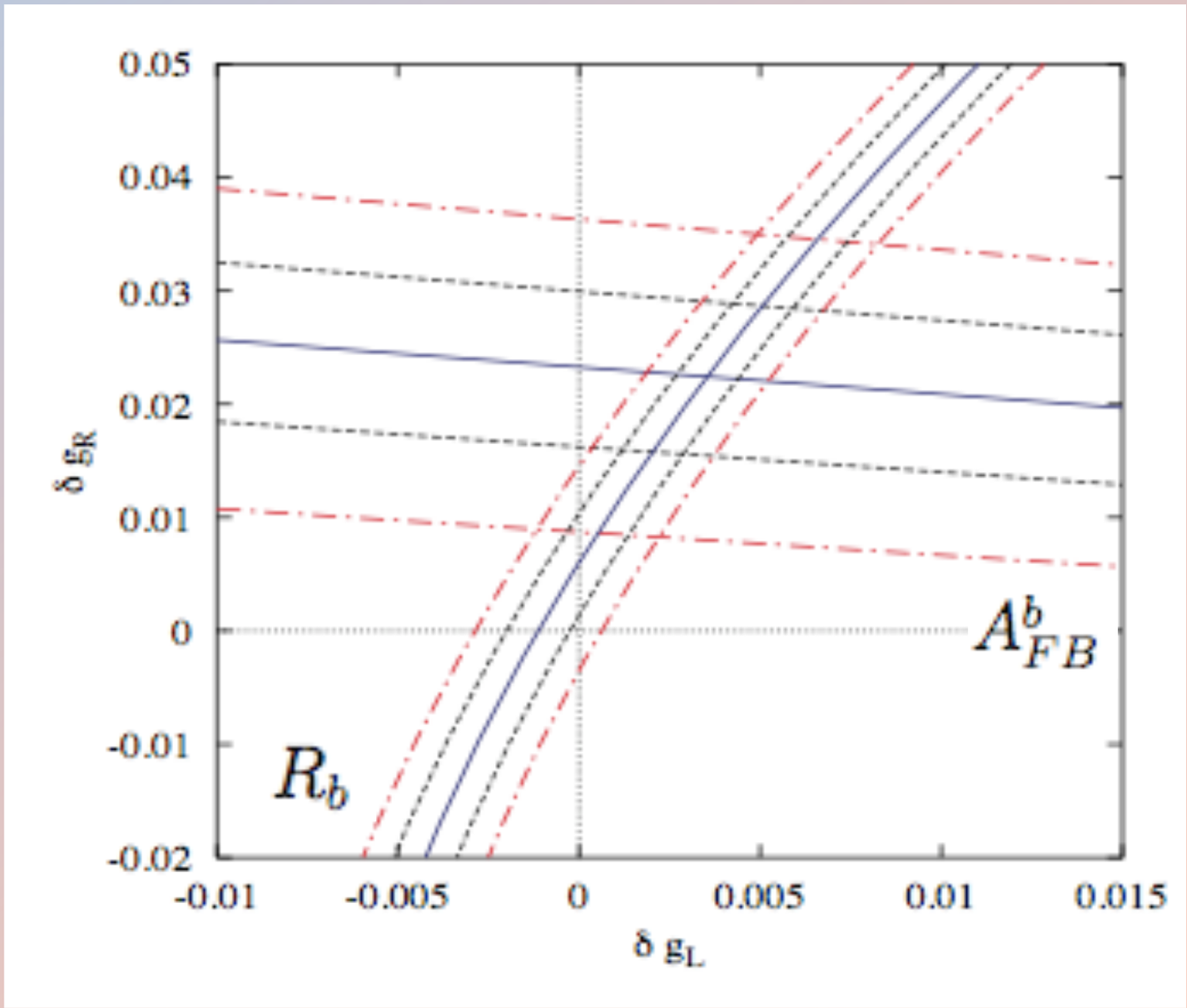


average is 1.6σ below SM

average is 2.1σ below SM

Previous explanations of A_{FB}^{b}

focused on modifying the right handed b-quark coupling to Z:



$$A_f = \frac{g_L^{f2} - g_R^{f2}}{g_L^{f2} + g_R^{f2}}$$

mixing of b-quark with extra fermions

D. Choudhury, T. Tait, and C. Wagner 2002

Z-Z' mixing

X.G. He and G. Valencia 2002

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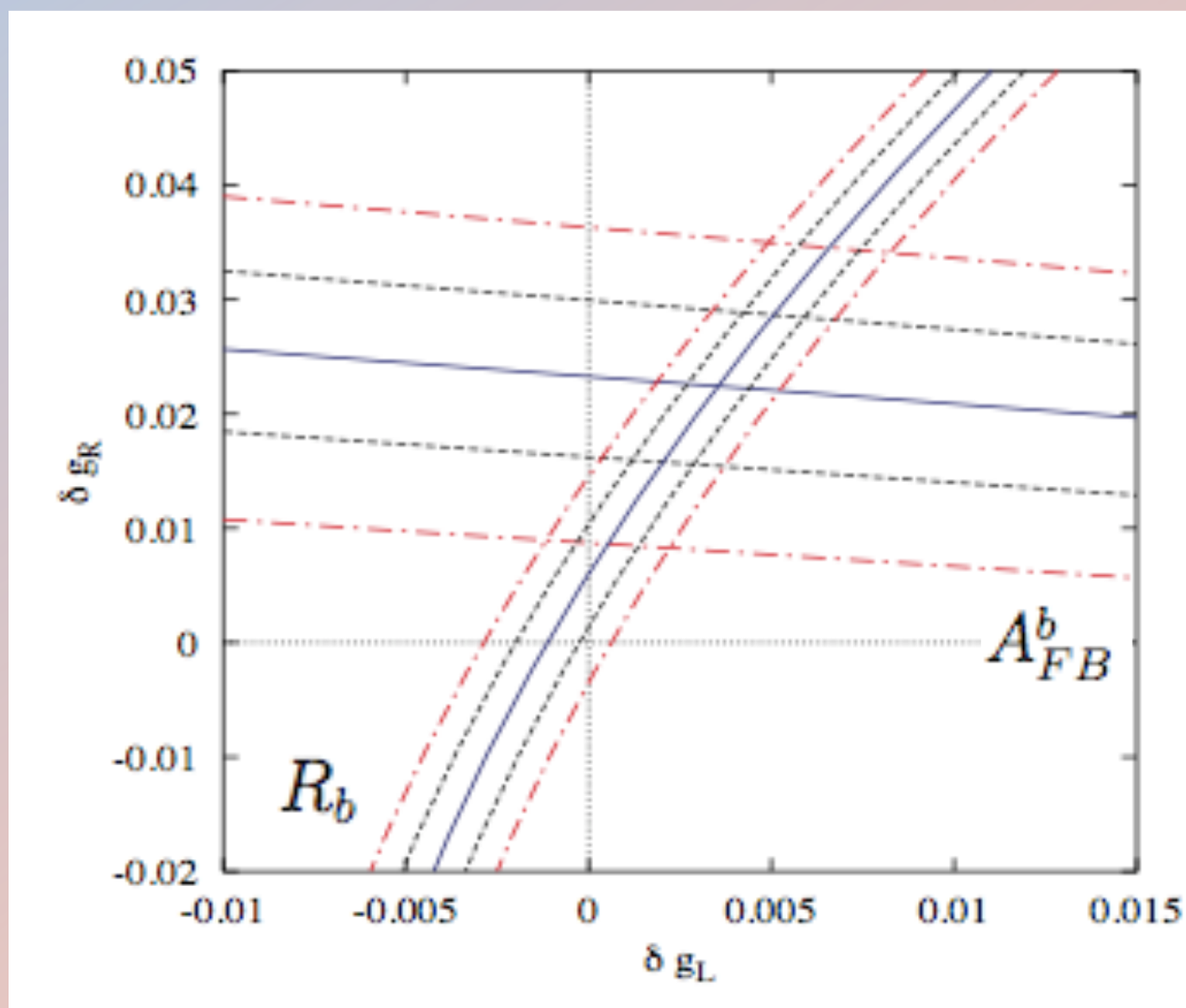

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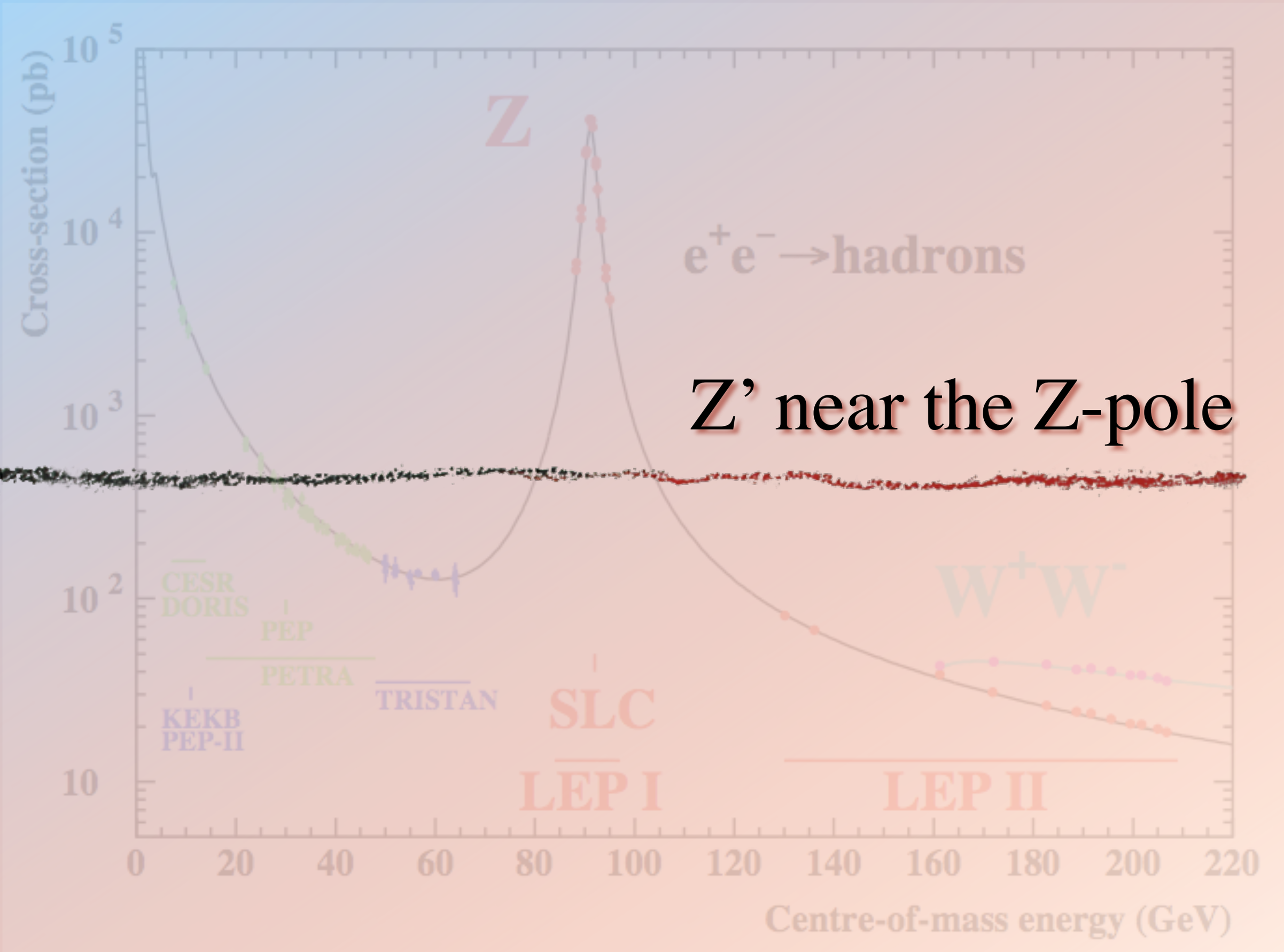
Any new physics that reduces to modification of bottom quark couplings does not affect the $\mathbf{A_e}$ (LR – had.). Only a partial solution!



Z' near the Z-pole

The model

$$\mathcal{L} \supset Z'_\mu \bar{e}\gamma^\mu (g'^e_L P_L + g'^e_R P_R) e + Z'_\mu \bar{b}\gamma^\mu (g'^b_L P_L + g'^b_R P_R) b.$$

all 4 couplings and the mass are free parameters

all other couplings and the Z - Z' mixing negligible

(discussion of typical couplings and flavor violation later)

A possible complete model - not charging SM fields under U(1)' directly, but rather through a mixing with extra heavy fermions:

Effective Z', P. J. Fox, J. Liu, D. Tucker-Smith and N. Weiner, 2011

- **complete control over the couplings, flavor violation can be small**
- **standard Yukawa couplings are preserved**
- **anomaly free**

$$A^b_{FB} = \frac{3}{4}\frac{\hat\sigma^b_{LL} - \hat\sigma^b_{LR} - \hat\sigma^b_{RL} + \hat\sigma^b_{RR}}{\hat\sigma^b_{LL} + \hat\sigma^b_{LR} + \hat\sigma^b_{RL} + \hat\sigma^b_{RR}} \xrightarrow{Z\ only} \frac{3}{4}A_e A_b,$$

$$A^b_{LR} = \frac{\hat\sigma^b_{LL} + \hat\sigma^b_{LR} - \hat\sigma^b_{RL} - \hat\sigma^b_{RR}}{\hat\sigma^b_{LL} + \hat\sigma^b_{LR} + \hat\sigma^b_{RL} + \hat\sigma^b_{RR}} \xrightarrow{Z\ only} A_e,$$

$$A^b_{LRFB} = \frac{3}{4}\frac{\hat\sigma^b_{LL} - \hat\sigma^b_{LR} + \hat\sigma^b_{RL} - \hat\sigma^b_{RR}}{\hat\sigma^b_{LL} + \hat\sigma^b_{LR} + \hat\sigma^b_{RL} + \hat\sigma^b_{RR}} \xrightarrow{Z\ only} \frac{3}{4}A_b,$$

$$R_b = \frac{\hat\sigma^b_{LL} + \hat\sigma^b_{LR} + \hat\sigma^b_{RL} + \hat\sigma^b_{RR}}{\sum_f (\hat\sigma^f_{LL} + \hat\sigma^f_{LR} + \hat\sigma^f_{RL} + \hat\sigma^f_{RR})}.$$

$$\begin{aligned}
A_{\rm FB} &= \frac{\sigma_{\rm F} - \sigma_{\rm B}}{\sigma_{\rm F} + \sigma_{\rm B}} \\
A_{\rm LR} &= \frac{\sigma_{\rm L} - \sigma_{\rm R}}{\sigma_{\rm L} + \sigma_{\rm R}}\frac{1}{\langle|\mathcal{P}_{\rm e}|\rangle} \\
A_{\rm LRFB} &= \frac{(\sigma_{\rm F} - \sigma_{\rm B})_{\rm L} - (\sigma_{\rm F} - \sigma_{\rm B})_{\rm R}}{(\sigma_{\rm F} + \sigma_{\rm B})_{\rm L} + (\sigma_{\rm F} + \sigma_{\rm B})_{\rm R}}\frac{1}{\langle|\mathcal{P}_{\rm e}|\rangle}.
\end{aligned}$$

$$\begin{aligned}
\frac{{\rm d}\sigma_{\rm Ll}}{{\rm d}\cos\theta} &\propto g^2_{\rm Le} g^2_{\rm Lf}(1+\cos\theta)^2 \\
\frac{{\rm d}\sigma_{\rm Rr}}{{\rm d}\cos\theta} &\propto g^2_{\rm Re} g^2_{\rm Rf}(1+\cos\theta)^2 \\
\frac{{\rm d}\sigma_{\rm Lr}}{{\rm d}\cos\theta} &\propto g^2_{\rm Le} g^2_{\rm Rf}(1-\cos\theta)^2 \\
\frac{{\rm d}\sigma_{\rm Rl}}{{\rm d}\cos\theta} &\propto g^2_{\rm Re} g^2_{\rm Lf}(1-\cos\theta)^2.
\end{aligned}$$

$$A^b_{FB} = \frac{3}{4}\frac{\hat{\sigma}^b_{LL} - \hat{\sigma}^b_{LR} - \hat{\sigma}^b_{RL} + \hat{\sigma}^b_{RR}}{\hat{\sigma}^b_{LL} + \hat{\sigma}^b_{LR} + \hat{\sigma}^b_{RL} + \hat{\sigma}^b_{RR}} \xrightarrow{Z\ only} \frac{3}{4}A_e A_b,$$

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+ 0.4%

better than SM

$$A^b_{FB} = \frac{3}{4}\frac{\hat\sigma^b_{LL} - \hat\sigma^b_{LR} - \hat\sigma^b_{RL} + \hat\sigma^b_{RR}}{\hat\sigma^b_{LL} + \hat\sigma^b_{LR} + \hat\sigma^b_{RL} + \hat\sigma^b_{RR}} \xrightarrow{Z\ only} \frac{3}{4}A_e A_b,$$

- 4%

just what is needed

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+4%/5 = + 0.8%

better than SM

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+ 0.4%

better than SM

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- 4%

just what is needed

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+4%/5 = + 0.8%

better than SM

$$A^b_{LRFB} = \frac{3}{4}\frac{\hat\sigma^b_{LL} - \hat\sigma^b_{LR} + \hat\sigma^b_{RL} - \hat\sigma^b_{RR}}{\hat\sigma^b_{LL} + \hat\sigma^b_{LR} + \hat\sigma^b_{RL} + \hat\sigma^b_{RR}} \xrightarrow{Z\ only} \frac{3}{4}A_b,$$

- 0.4%

little better than SM

$$R_b = \frac{\hat\sigma^b_{LL} + \hat\sigma^b_{LR} + \hat\sigma^b_{RL} + \hat\sigma^b_{RR}}{\sum_f (\hat\sigma^f_{LL} + \hat\sigma^f_{LR} + \hat\sigma^f_{RL} + \hat\sigma^f_{RR})}.$$

+ 0.4%

better than SM

Quantities included in the fit

Quantity	Exp. value	SM	χ^2_{SM}
$\sigma^0_{\rm had}$ [nb]	41.541(37)	41.481	**2.6**
$R_b(-2)$	0.2142(27)	0.2150	0.1
R^0_b	0.21629(66)	0.21580	0.6
$R_b(+2)$	0.2177(24)	0.2155	0.8
$A_{FB}(-2)$	0.0560(66)	0.0638	**1.4**
$A^b_{FB}(\rm pk)$	0.0982(17)	0.1014	**3.5**
$A^b_{FB}(+2)$	0.1125(55)	0.1255	**5.6**
A_b	0.923(20)	0.9346	0.3
R^0_e	20.804(0.050)	20.737	1.8
$A^{0,e}_{FB}$	0.0145(25)	0.0165	0.7
$A_e(\rm LR-had.)$	0.15138(216)	0.14739	**3.4**
$A_e(\rm LR-lept.)$	0.1544(60)	0.1473	1.4
total χ^2			22.1

The best fit

$m_{Z'} = 92.2$ GeV, $g_L'^e = 0.0059$, $g_R'^e = 0.0073$, $g_L'^b = 0.040$, and $g_R'^b = -0.54$;

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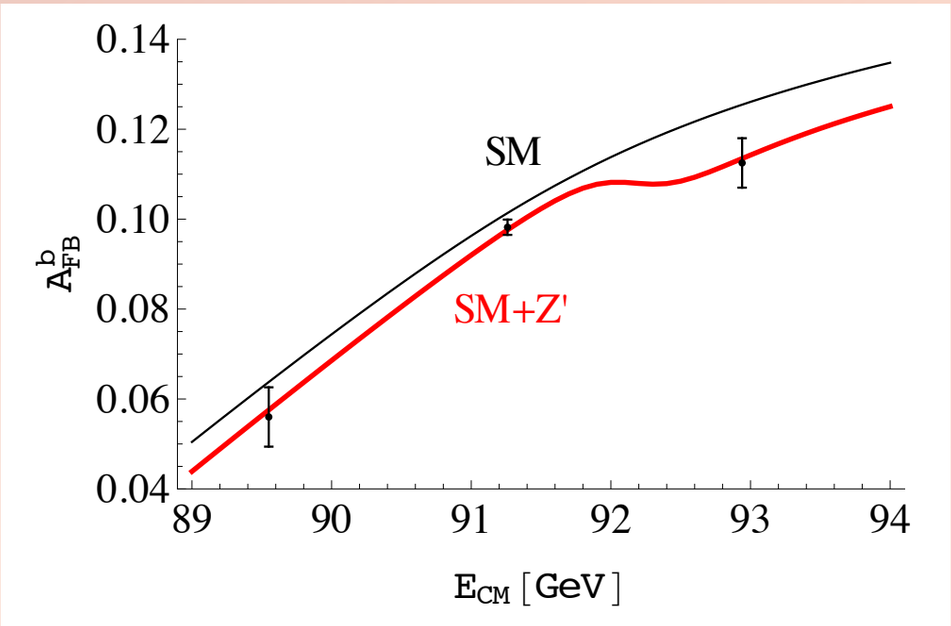

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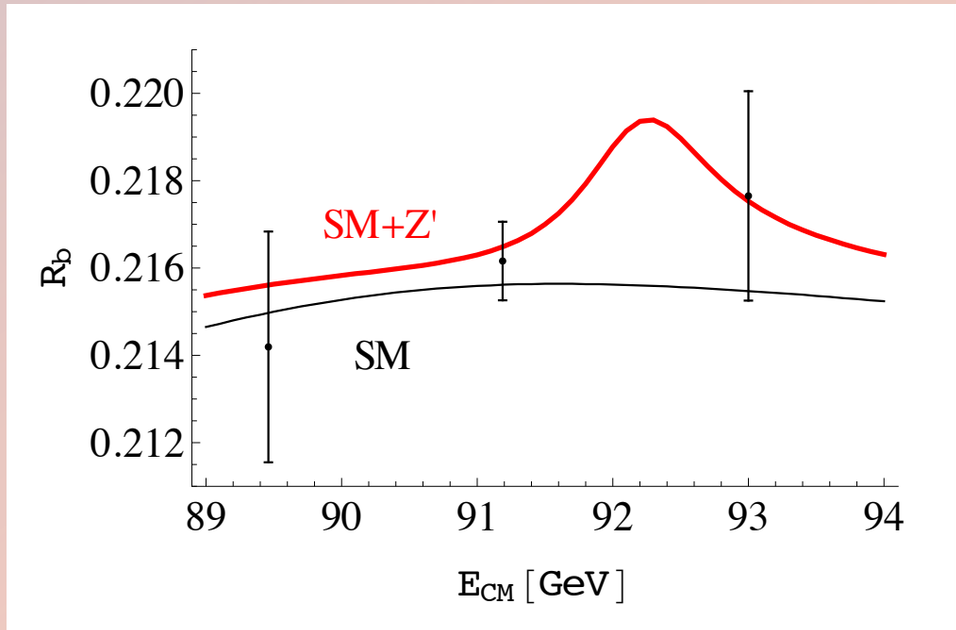

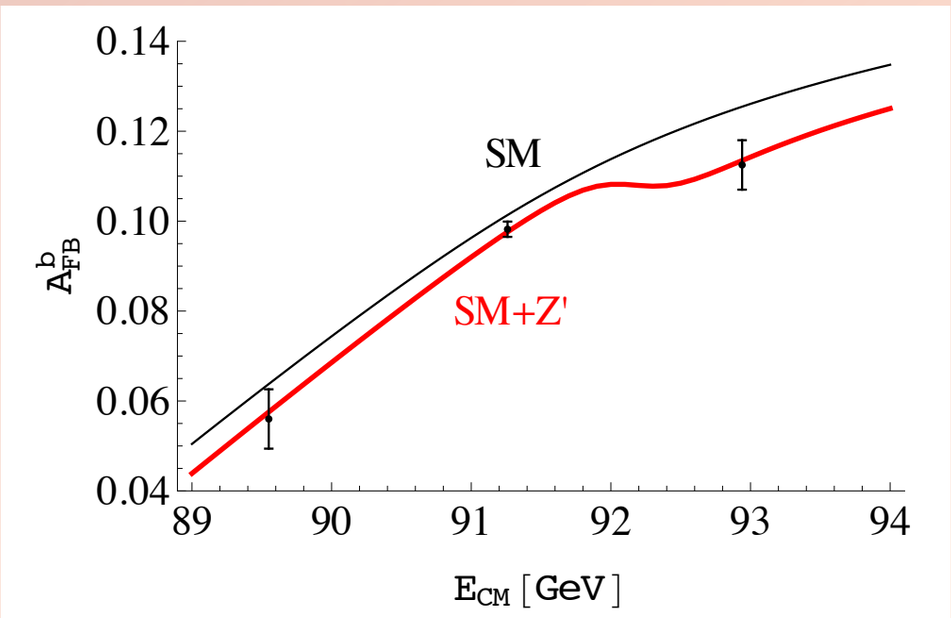

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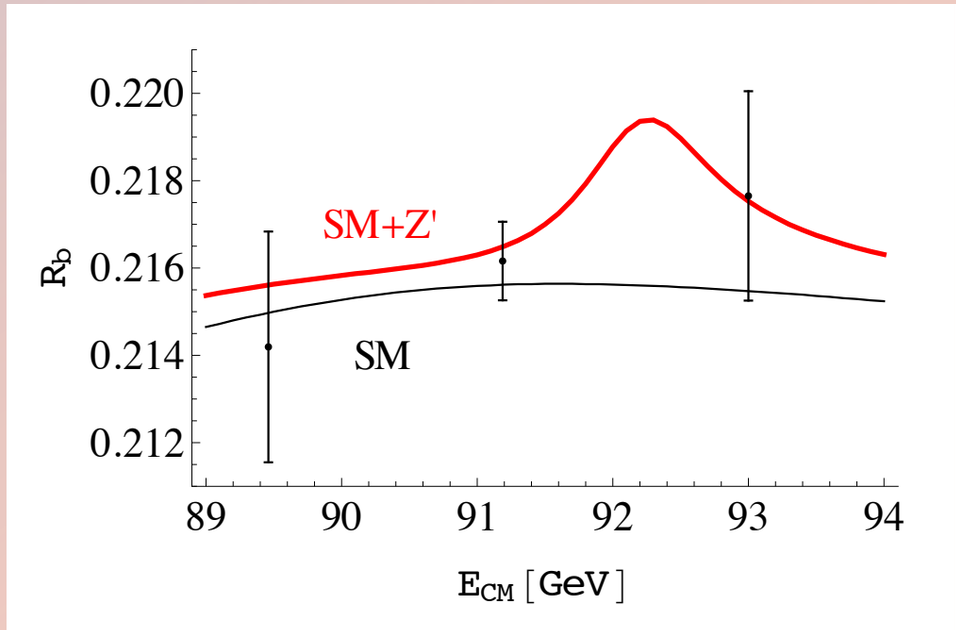
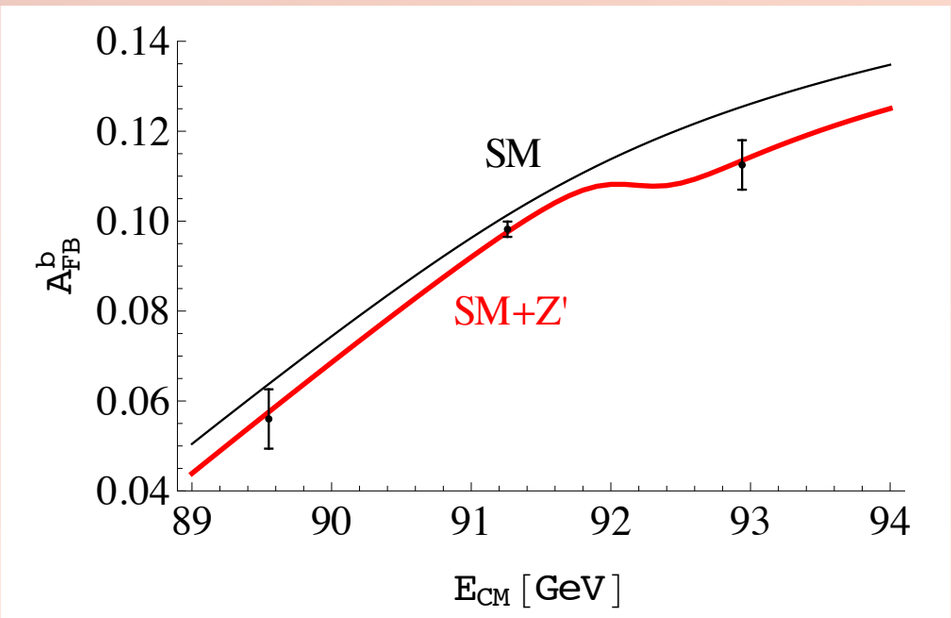
total χ^2			22.1		

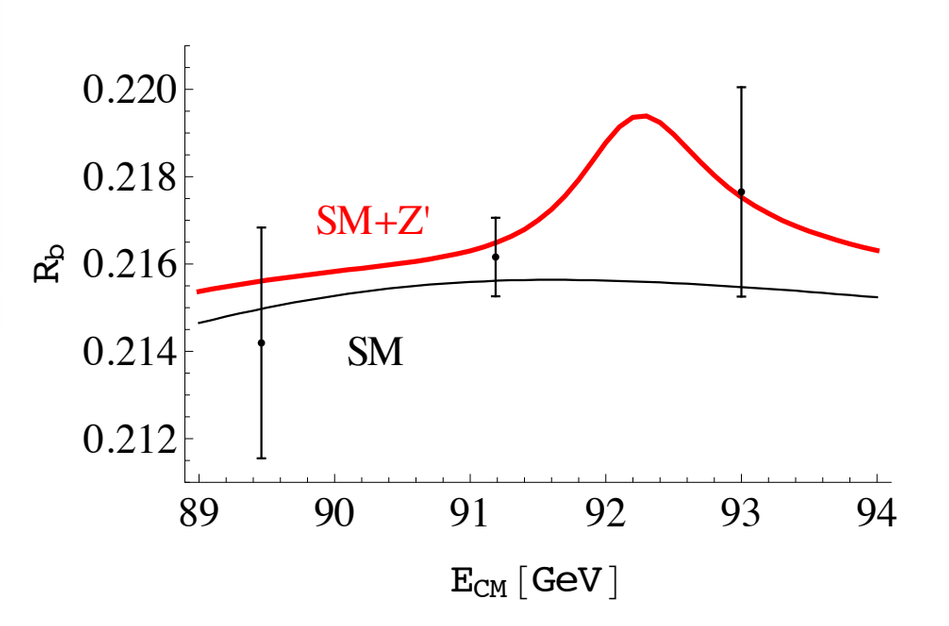


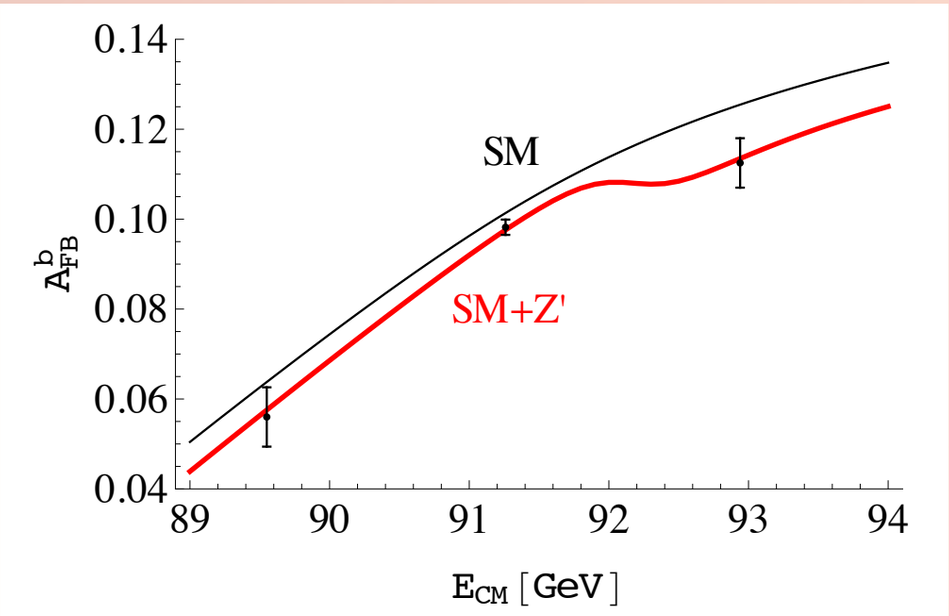


The best fit

$m_{Z'} = 92.2$ GeV, $g_L'^e = 0.0059$, $g_R'^e = 0.0073$, $g_L'^b = 0.040$, and $g_R'^b = -0.54$;

Quantity	Exp. value	SM	χ^2_{SM}	Z'	$\chi^2_{Z'}$
$\sigma^0_{\rm had}$ [nb]	41.541(37)	41.481	**2.6**	41.529	**0.1**
$R_b(-2)$	0.2142(27)	0.2150	0.1	0.2156	0.3
R^0_b	0.21629(66)	0.21580	0.6	0.21670	0.4
$R_b(+2)$	0.2177(24)	0.2155	0.8	0.2177	0.0
$A_{FB}(-2)$	0.0560(66)	0.0638	**1.4**	0.0577	**0.1**
$A^b_{FB}(\rm pk)$	0.0982(17)	0.1014	**3.5**	0.0979	**0.0**
$A^b_{FB}(+2)$	0.1125(55)	0.1255	**5.6**	0.1136	**0.0**
A_b	0.923(20)	0.9346	0.3		
R^0_e	20.804(0.050)	20.737	1.8		
$A^{0,e}_{FB}$	0.0145(25)	0.0165	0.7		
$A_e(\rm LR-had.)$	0.15138(216)	0.14739	**3.4**	0.15014	**0.3**
$A_e(\rm LR-lept.)$	0.1544(60)	0.1473	1.4		
total χ^2			22.1		





The best fit

$m_{Z'} = 92.2$ GeV, $g_L'^e = 0.0059$, $g_R'^e = 0.0073$, $g_L'^b = 0.040$, and $g_R'^b = -0.54$;

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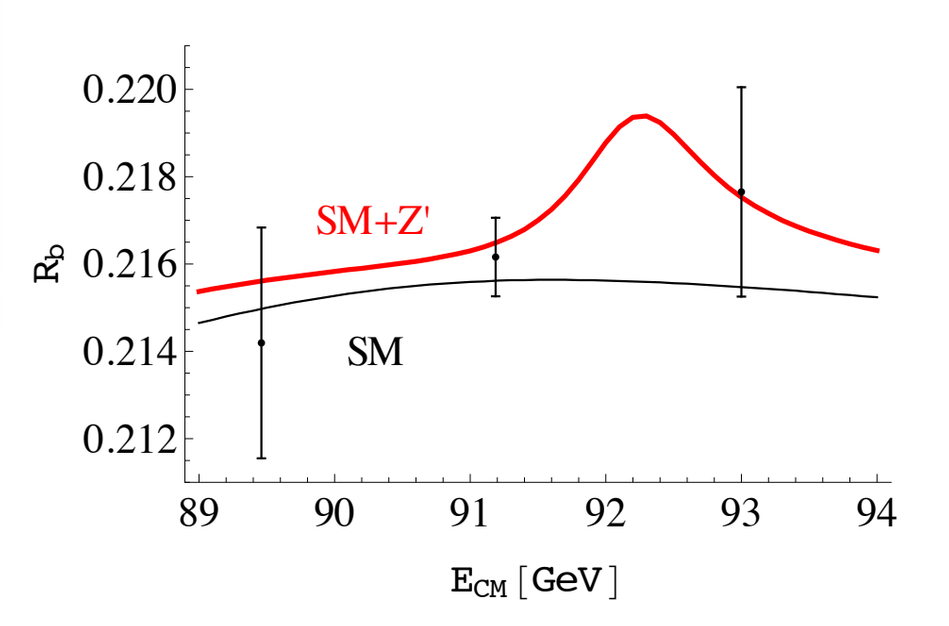
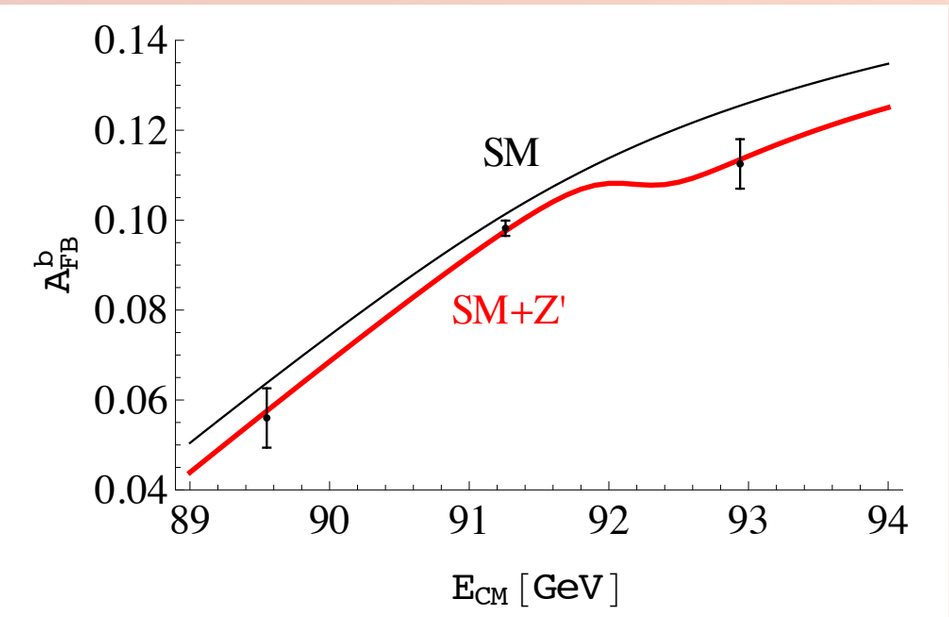
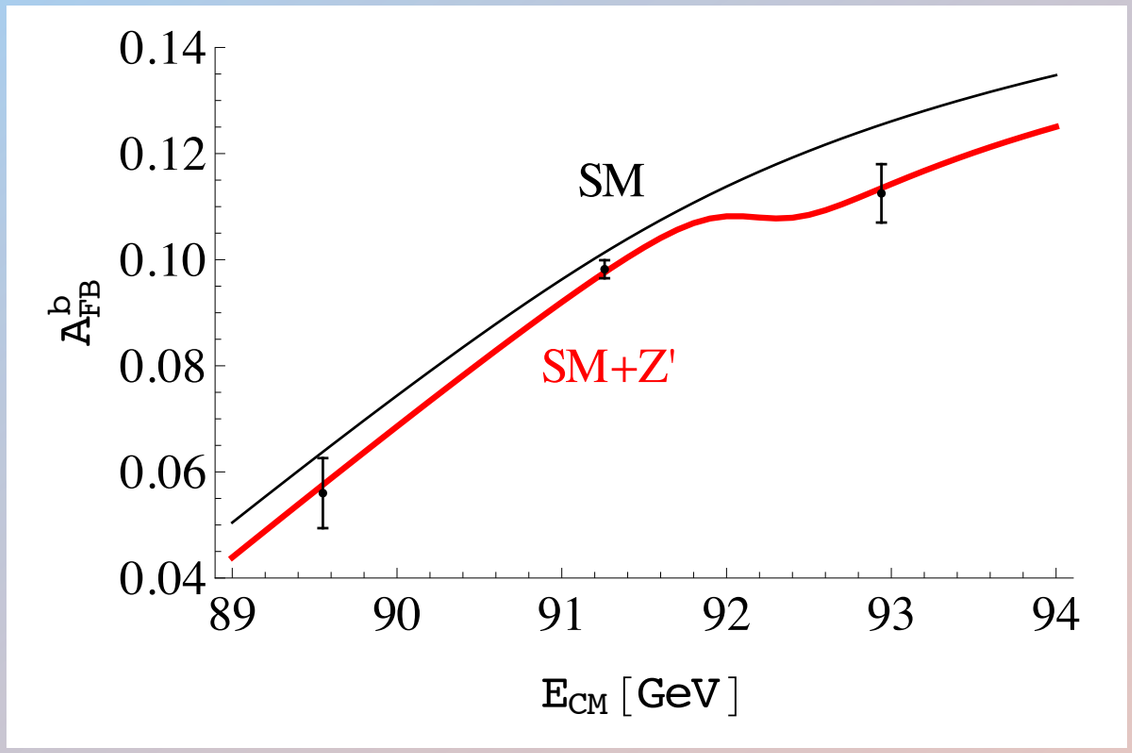
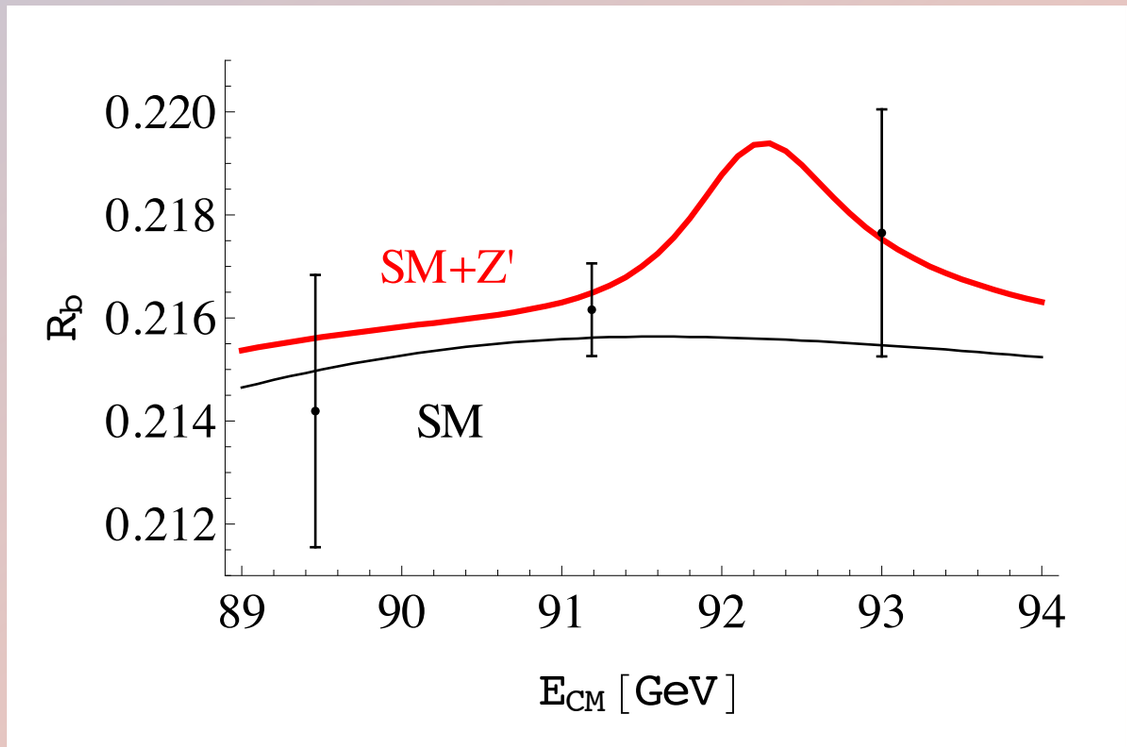
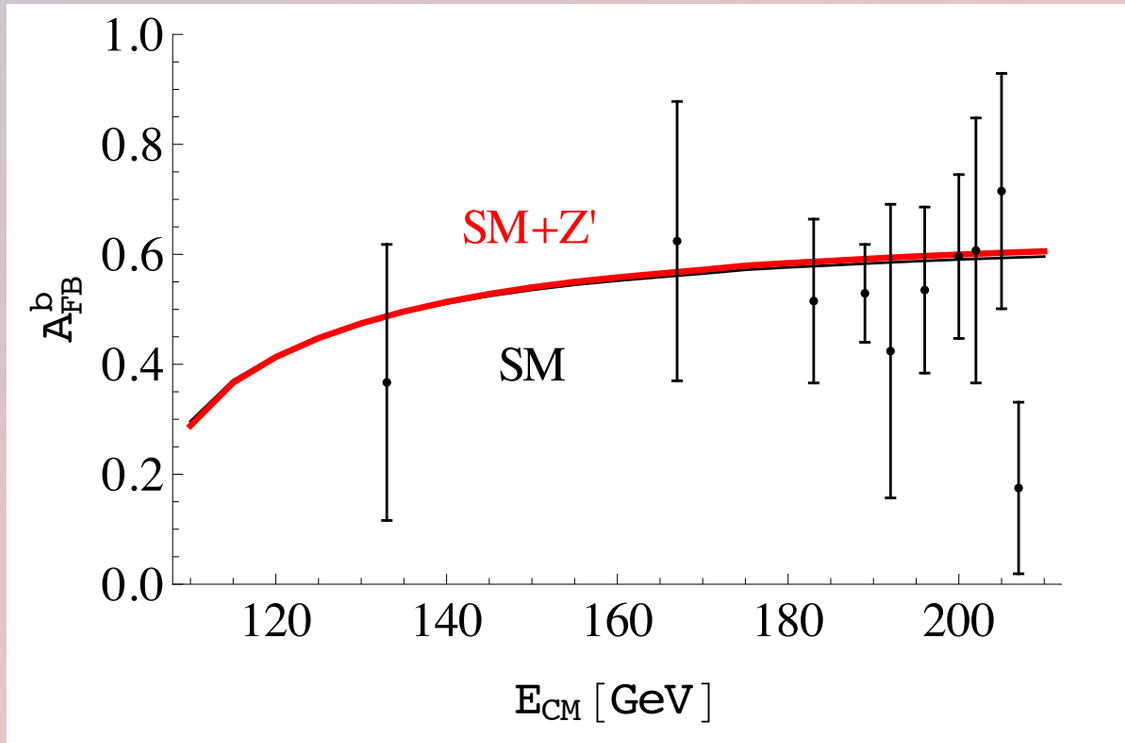
$A^b_{FB}(+2)$	0.1125(55)	0.1255	**5.6**	0.1136	**0.0**
A_b	0.923(20)	0.9346	0.3	0.9237	0.0
R^0_e	20.804(0.050)	20.737	1.8	20.765	0.6
$A^{0,e}_{FB}$	0.0145(25)	0.0165	0.7	0.0174	1.4
$A_e(\rm LR-had.)$	0.15138(216)	0.14739	**3.4**	0.15014	**0.3**
$A_e(\rm LR-lept.)$	0.1544(60)	0.1473	1.4	0.1473	1.4
total χ^2			22.1		4.61

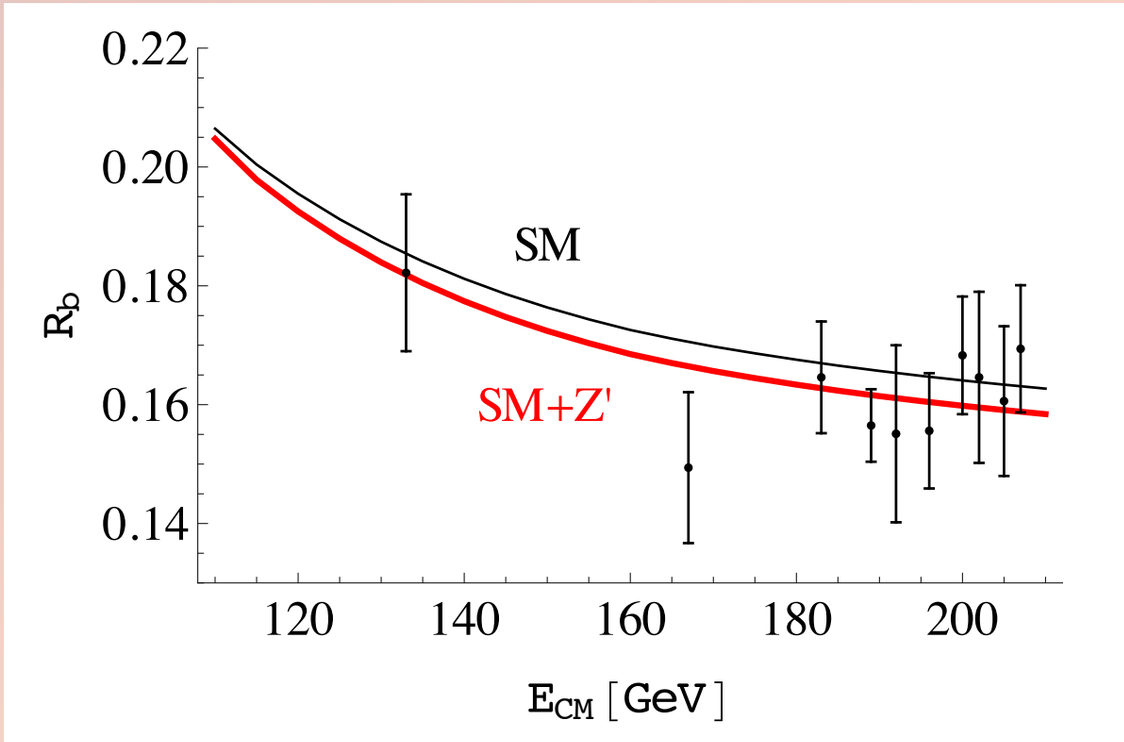





0.14
0.12
0.10
0.08
0.06
0.04
A^b_{FB}
SM
SM+Z'
89
90
91
92
93
94
E_{CM} [GeV]


0.220
0.218
0.216
0.214
0.212
R_b
SM+Z'
SM
89
90
91
92
93
94
E_{CM} [GeV]


1.0
0.8
0.6
0.4
0.2
0.0
A^b_{FB}
SM+Z'
SM
120
140
160
180
200
E_{CM} [GeV]


0.22
0.20
0.18
0.16
0.14
R_b
SM
SM+Z'
120
140
160
180
200
E_{CM} [GeV]

The model

$$\mathcal{L} \supset Z'_\mu \bar{e}\gamma^\mu (g'^e_L P_L + g'^e_R P_R) e + Z'_\mu \bar{b}\gamma^\mu (g'^b_L P_L + g'^b_R P_R) b.$$

with minimal set of couplings
no new sources of flavor violation
(in principle)

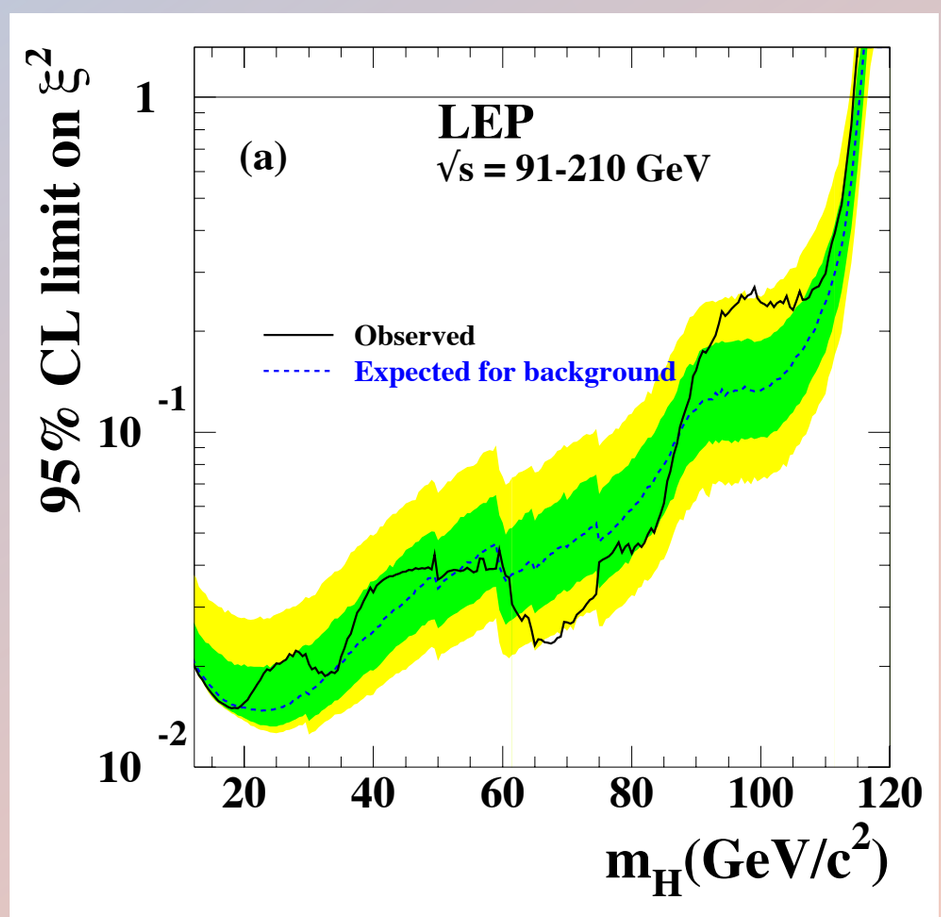
with all couplings,
in effective Z' framework,
flavor violation is small

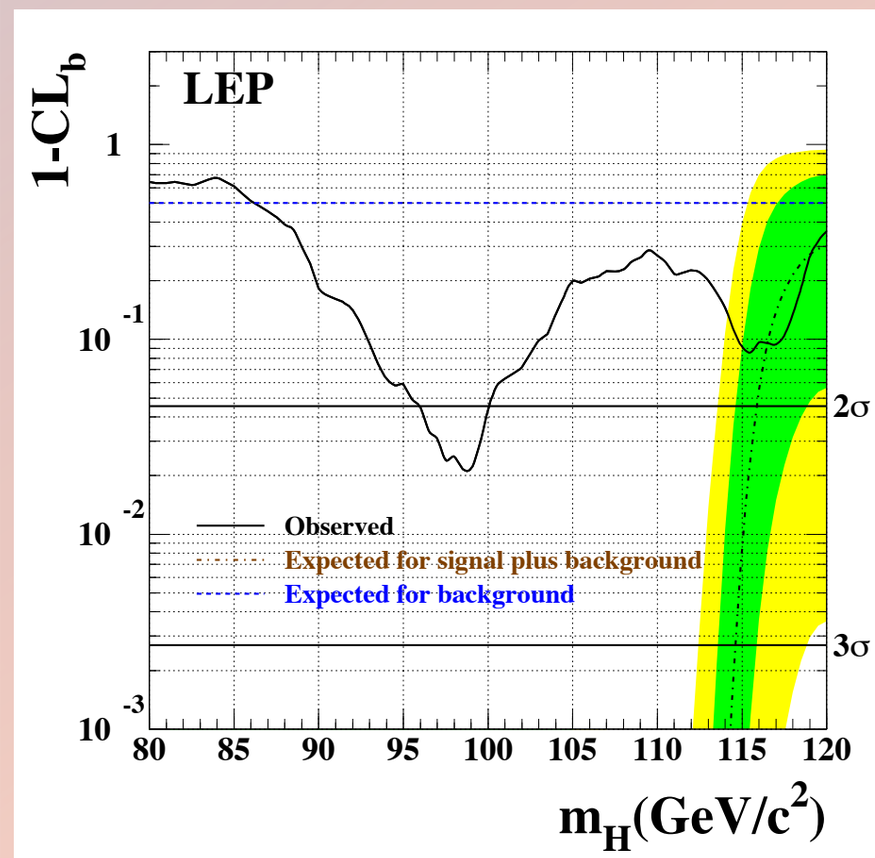
small flavor violating couplings can be useful
to explain other deviations from the SM

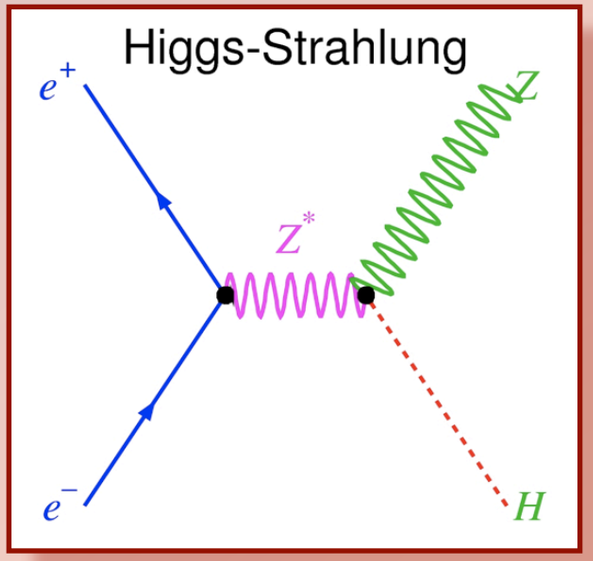
talk of S.G. Kim

Further constraints from LEP

$$e^+e^- \to ZZ' \to Zb\bar{b}$$





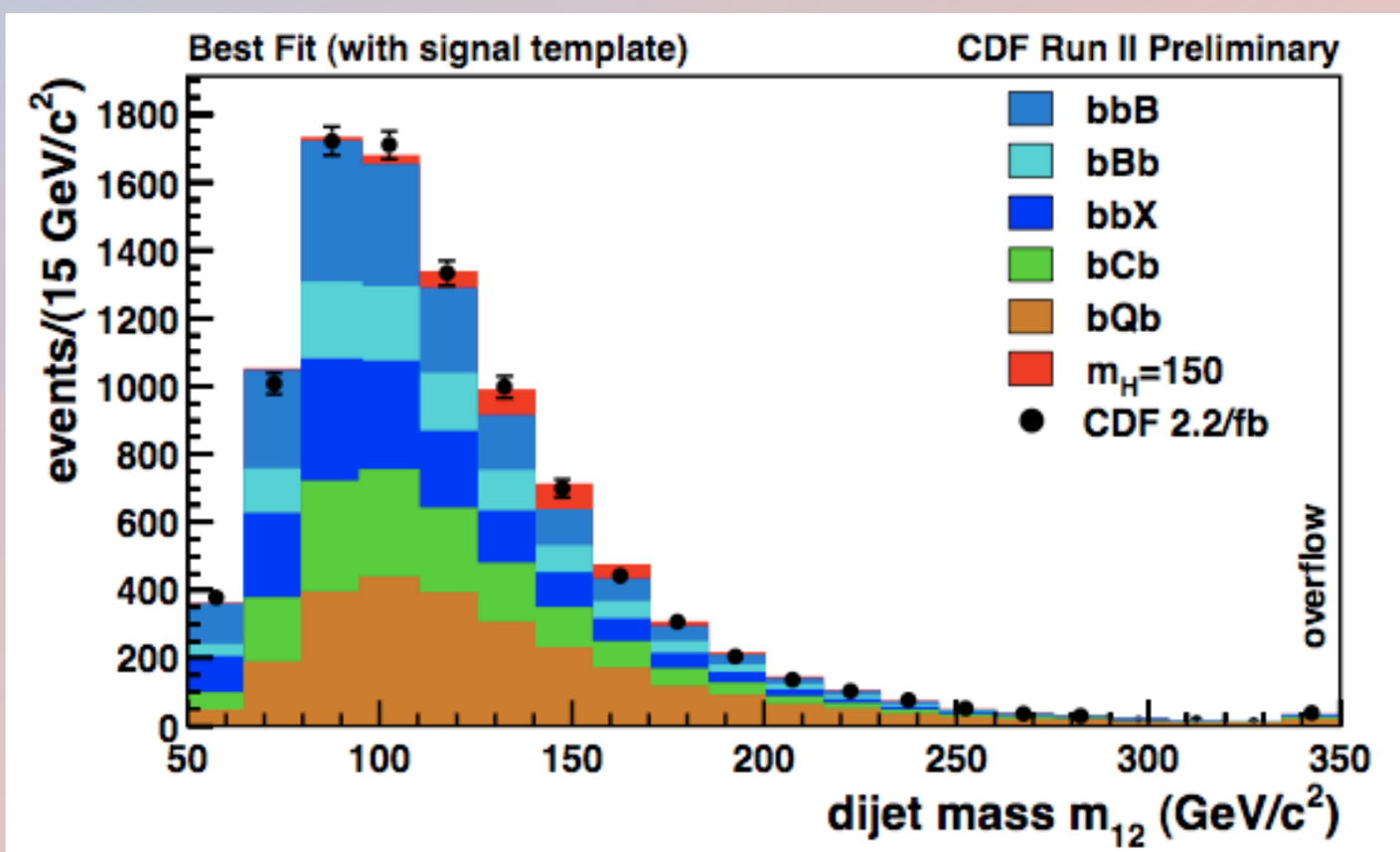


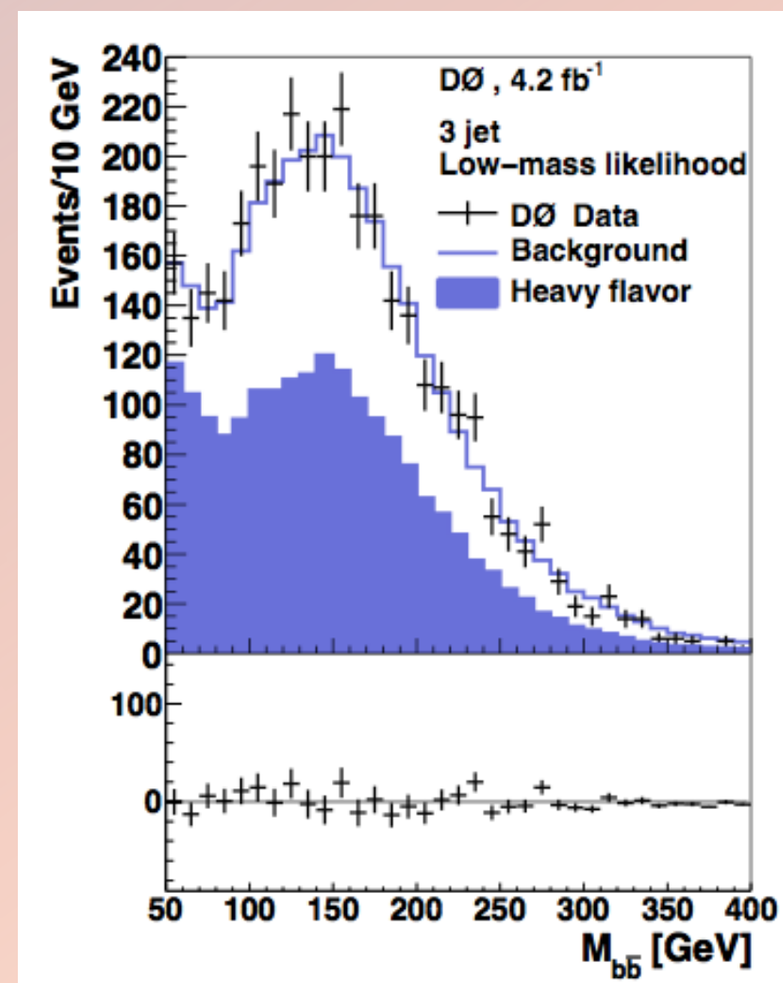
Higgs like excess can be explained by Z'!

Z' at the Tevatron and the LHC

$$p\bar{p} \to Z'b \to bb\bar{b}$$

typical prediction $\sigma(p\bar{p} \to Z'b) \simeq 20 - 30$ pb





$$\sigma(p\bar{p} \to Hb) \times B(H \to b\bar{b}) < 30 - 50 \text{ pb}$$

constraints on this Z' soon!

Conclusions

- **Z' near the Z-pole is a strange but viable scenario that explains the puzzle in $\mathbf{A_{FB}^b}$ and $\mathbf{A_e}$ $(\mathrm{LR-had.})$**
- **needed couplings do not necessarily introduce new sources of flavor violation**
- **extra Zbb events can (partially) explain the Higgs-like excess at LEP above the Z-pole**
- **optional flavor violating couplings can explain other deviations from the SM**

  talk of S.G. Kim
- **testable at the Tevatron and LHC in 3b, 4b events**