COMPLEMENTARY CONSTRAINTS ON $Zb\bar{b}$ COUPLING AT THE LHC

Zhuoni Qian @ Terascale WS 2021 November 2021
Work in progress with Fady Bishara
arXiv: 2011.XXXXX

Table of Contents:

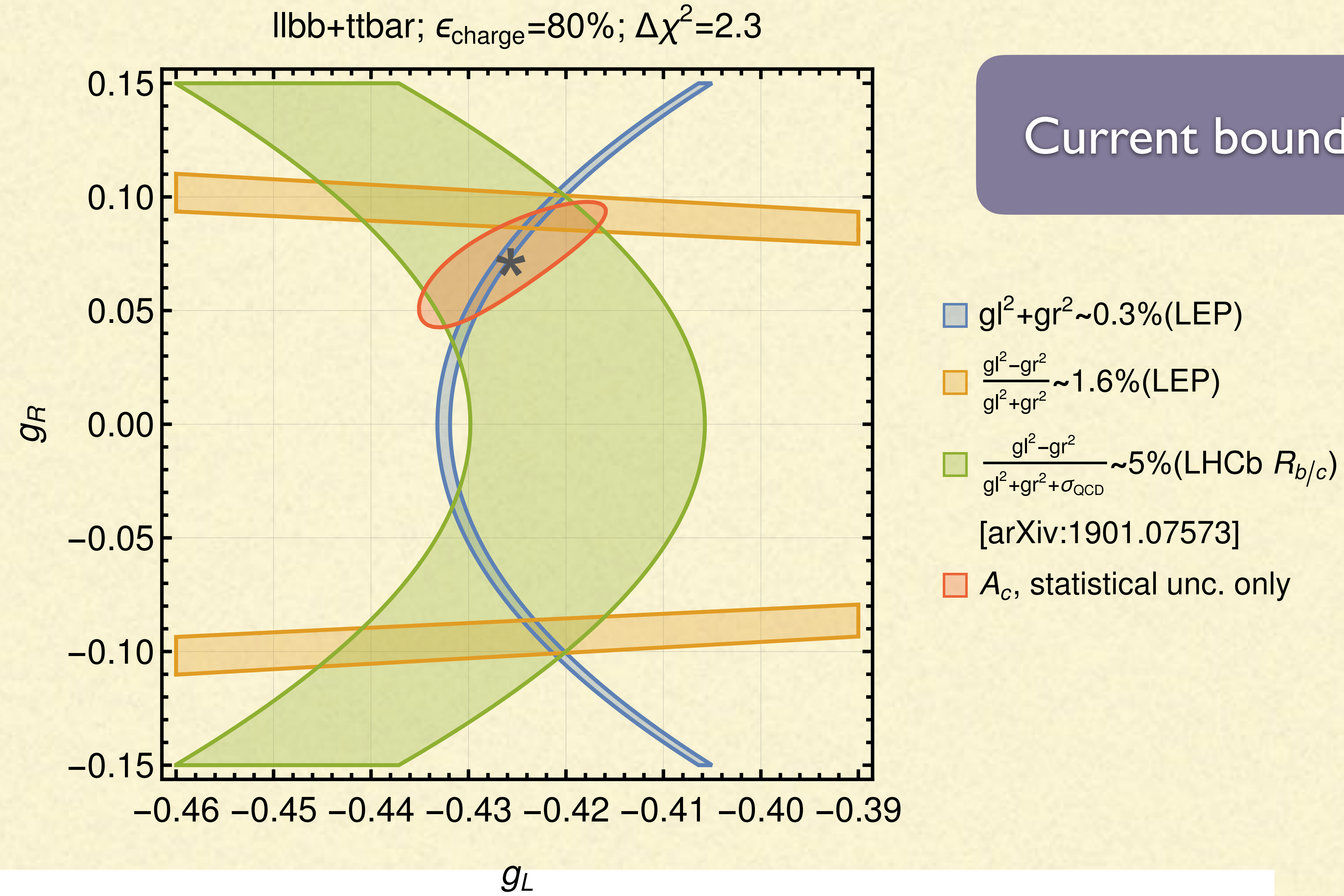
Motivation: A persistent discrepancy between Exp. and SM prediction: $Zb\bar{b}$ coupling

L,R $Zb\bar{b}$ Coupling and the SM prediction:

$$\mathcal{L}_{Zb\bar{b}} = \frac{-e}{s_W c_W} Z_\mu (g_L \bar{b}_R \gamma^\mu b_L + g_R \bar{b}_L \gamma^\mu b_R)$$

$$g_{L,SM} = -1/2 + s_W^2/3$$

$$g_{R,SM} = s_W^2/3$$



Current bounds

Symmetric / asymmetric observable

$$(\text{LEP}) \quad \frac{\sigma_Q^{inc}}{\sigma_q^{inc}} = R_Q \propto (g_{Q,L}^2 + g_{Q,R}^2)$$

$$(\text{LEP}) \quad \frac{\sigma^A}{\sigma^{inc}} = A_{FB} \propto \frac{(g_{Q,L}^2 - g_{Q,R}^2)(g_{e,L}^2 - g_{e,R}^2)}{(g_{Q,L}^2 + g_{Q,R}^2)(g_{e,L}^2 + g_{e,R}^2)}$$

$$(\text{Tevatron, LHCb}) \quad A_{FB} \propto \frac{(g_{Q,L}^2 - g_{Q,R}^2)}{(g_{Q,L}^2 + g_{Q,R}^2) + \sigma_{\text{QCD}}}$$

$$(\text{LHCb}) \quad R_{b/c} \propto A_b / A_c$$

$$\delta R_Q \sim g_{Q,L}\delta g_{Q,L} + g_{q,R}\delta g_{q,R}$$

$$\delta A_{FB}(\text{LEP}) \sim \frac{4 g_{Q,L}^2 g_{Q,R}^2}{g_{Q,L}^2 + g_{Q,R}^2}\left(\frac{\delta g_{Q,L}}{g_{Q,L}} - \frac{\delta g_{q,R}}{g_{q,R}}\right)$$

$$\delta A_{FB}(\text{LHCb}) \sim \frac{2}{\sigma_{\text{QCD}}}(g_{Q,L}\delta g_{Q,L} - g_{q,R}\delta g_{q,R}) \ (\text{for } \sigma_{\text{QCD}} \gg \sigma_Z),$$

For small deviation, R_Q and A_{FB} give orthogonal bounds

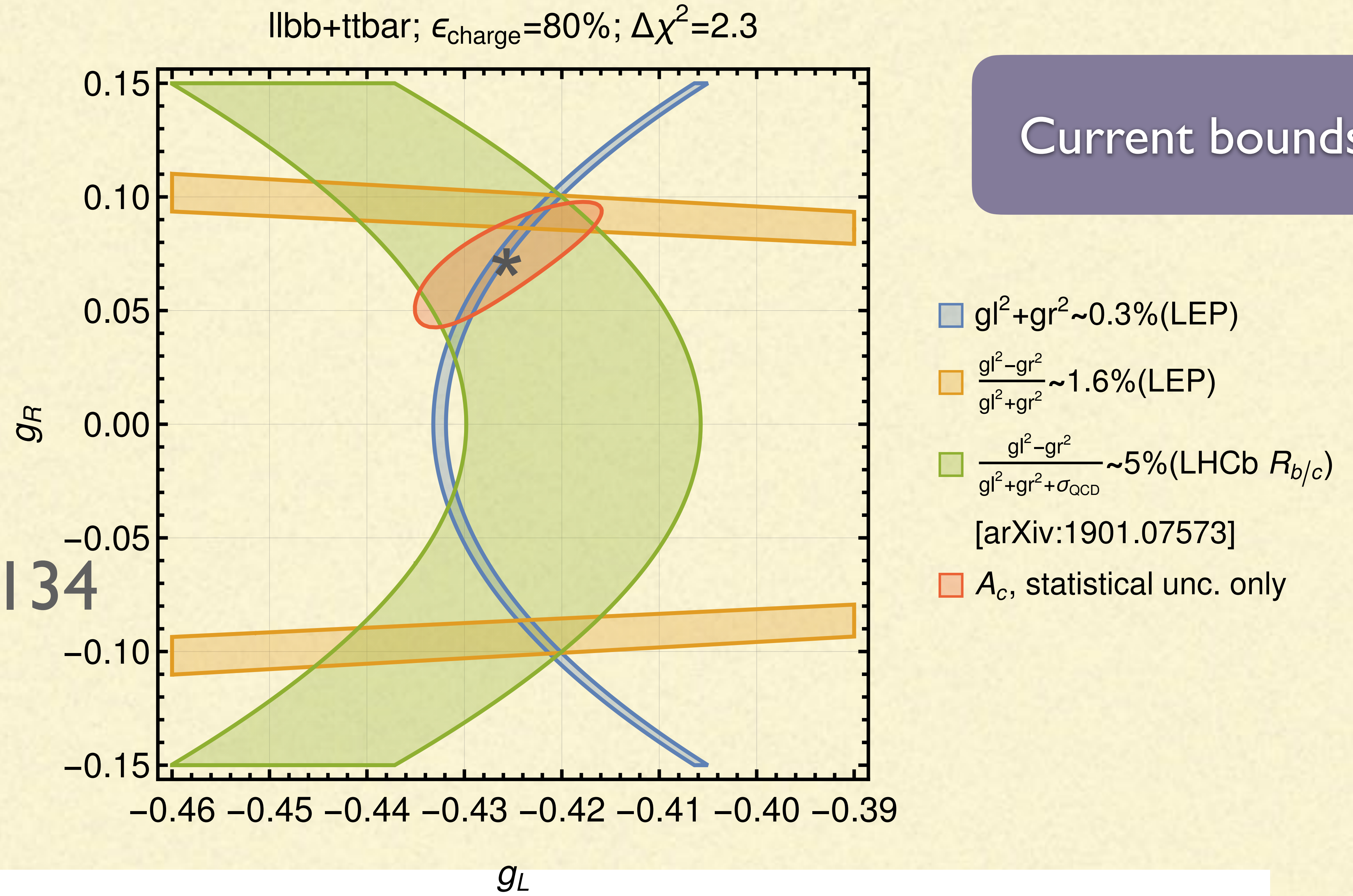
Motivation: A persistent discrepancy between Exp. and SM prediction: $Zb\bar{b}$ coupling

LEP(2.9σ) SLD(1σ) @ Z-pole: $e^-e^+ \to Z^* \to b\bar{b}$
[hep-ex/0509008] ,1407.3792

Tevatron/LHCb: $q\bar{q} \to Z^* \to b\bar{b}$
1504.06888,1505.02429, 1504.02493, 1901.07573

Future Proposal e^-e^+ collider:1508.07010, 2107.02134
HL-LHC processes: 2101.06261 ($gg \to Zh$)

Symmetric / asymmetric observable: $\sqrt{s} \approx m_z$



Current bounds

$$\text{(LEP)} \quad \frac{\sigma_Q^{inc}}{\sigma_q^{inc}} = R_Q \propto (g_{Q,L}^2 + g_{Q,R}^2)$$

$$\text{(LEP)} \quad \frac{\sigma^A}{\sigma^{inc}} = A_{FB} \propto \frac{(g_{Q,L}^2 - g_{Q,R}^2)(g_{e,L}^2 - g_{e,R}^2)}{(g_{Q,L}^2 + g_{Q,R}^2)(g_{e,L}^2 + g_{e,R}^2)}$$

$$\text{(Tevatron, LHCb)} \quad A_{FB} \propto \frac{(g_{Q,L}^2 - g_{Q,R}^2)}{(g_{Q,L}^2 + g_{Q,R}^2) + \sigma_{\rm QCD}}$$

$$\text{(LHCb)} \quad R_{b/c} \propto A_b/A_c$$

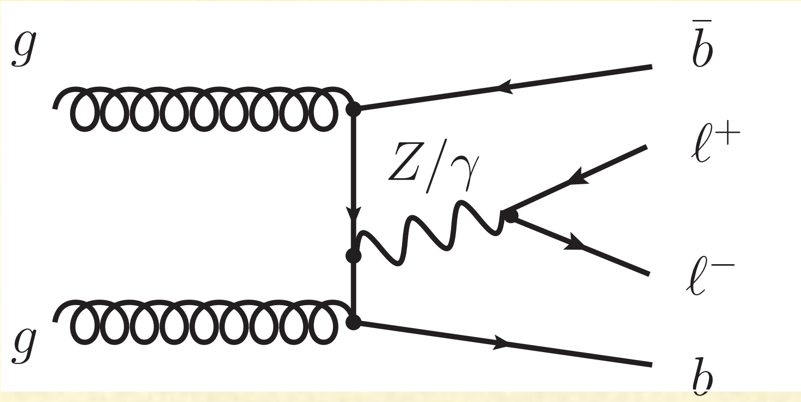
$$\delta R_Q \sim g_{Q,L}\delta g_{Q,L} + g_{q,R}\delta g_{q,R}$$

$$\delta A_{FB}(\text{LEP}) \sim \frac{4g_{Q,L}^2 g_{Q,R}^2}{g_{Q,L}^2 + g_{Q,R}^2}\left(\frac{\delta g_{Q,L}}{g_{Q,L}} - \frac{\delta g_{q,R}}{g_{q,R}}\right)$$

$$\delta A_{FB}(\text{LHCb}) \sim \frac{2}{\sigma_{\rm QCD}}(g_{Q,L}\delta g_{Q,L} - g_{q,R}\delta g_{q,R}) \ (\text{for } \sigma_{\rm QCD} \gg \sigma_Z),$$

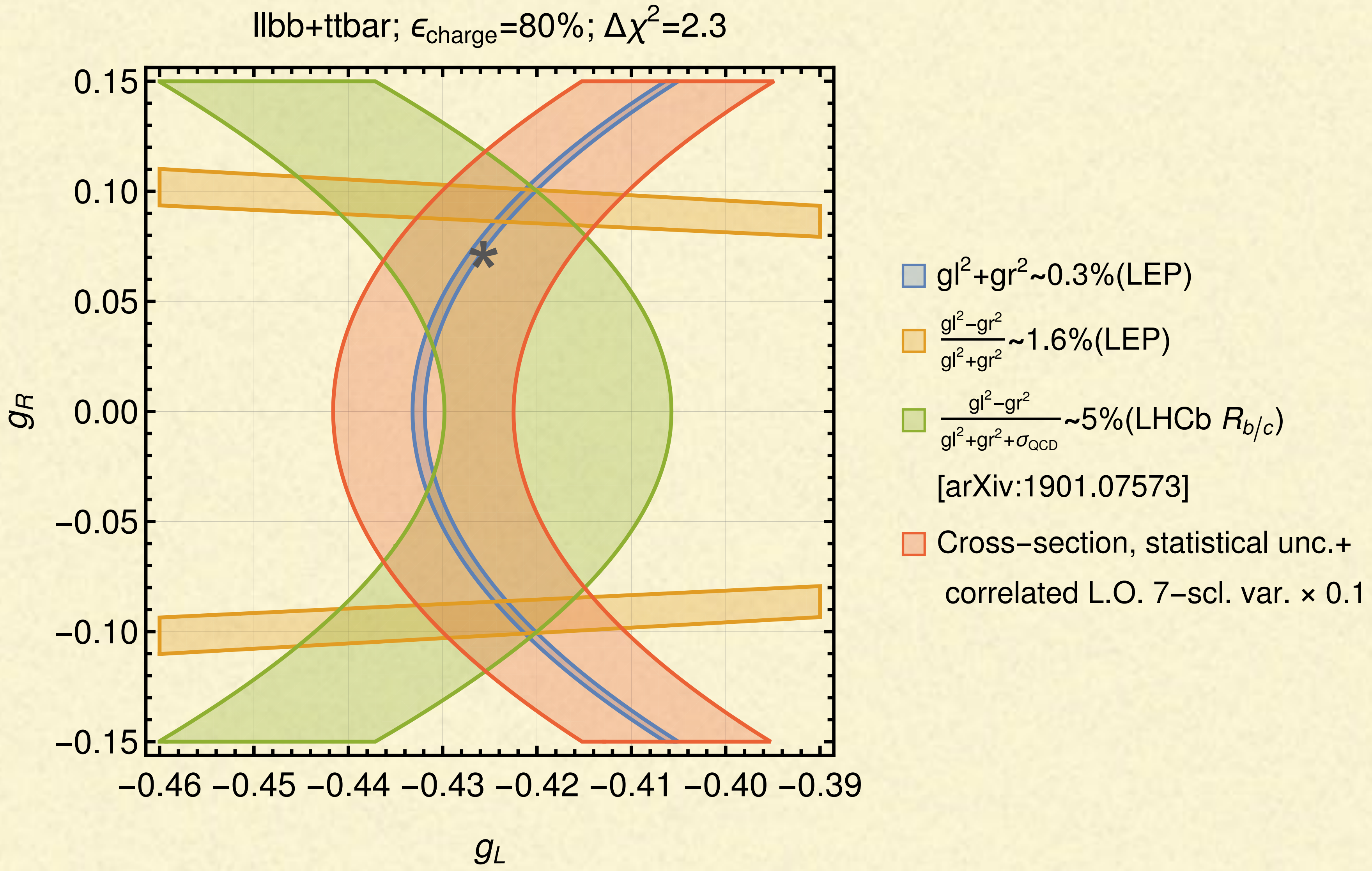
For small deviation, R_Q and A_{FB} give orthogonal bounds

Observable for the $gg \to b\bar{b}\ell^-\ell^+$ process:



Total cross section: $\propto g_L^2 + g_R^2$

Systematics dominant (>2-3%) and not competitive with LEP (0.3%)



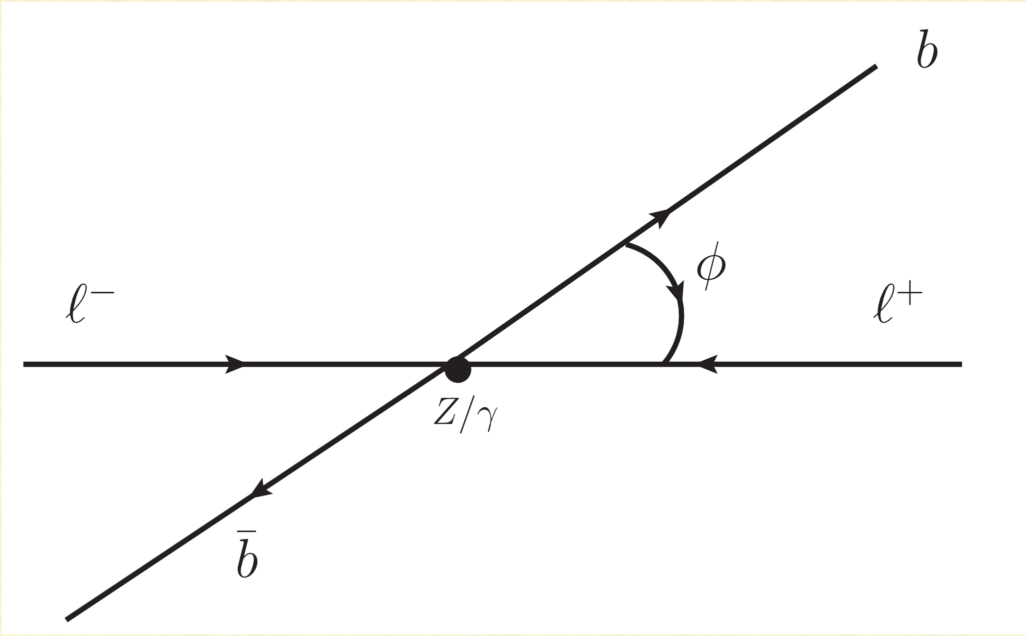
Asymmetric observable:

In the massless fermion limit, for the Z-mediated channel:

$g_L \to b_L, \bar{b}_R \to b(-), \bar{b}(+)$; $g_R \to b_R, \bar{b}_L \to b(+), \bar{b}(-)$

Chirality of the coupling $\{g_L, g_R\}$ corresponds to charge ordering:

$\mathcal{M}_L^{-+}(b, \bar{b}) = \mathcal{M}_R^{-+}(\bar{b}, b)$



$\{g_L, g_R\}$ asymmetric term <=> $\{b, \bar{b}\}$ Asymmetric observable:

A_{FB}: whether $b/\bar{b}$ is closer to the ℓ^-(Forward) direction: $sign(\cos\phi)$

Or in Lorentz invariant form $(p_b - p_{\bar{b}})(p_{\ell^-} - p_{\ell_+})$

Observable for the $gg \to b\bar{b}\ell^-\ell^+$ process:

Polarisation summed $\overline{|\mathscr{M}|}^2(\ell^-\ell^+ \to Z^*/\gamma^* \to b\bar{b})$:

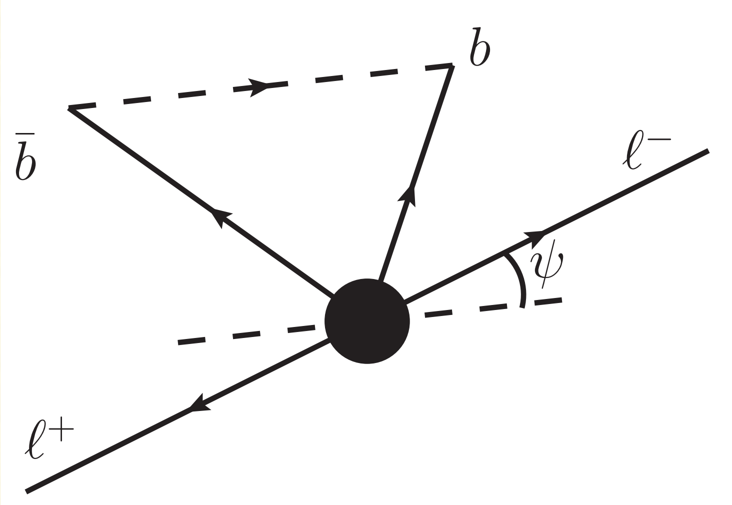
$$\mathcal{M}_{\mathcal{S}}(p_b, p_{\bar{b}}, p_{\ell^-}, p_{\ell^+}) = \mathcal{M}_{\mathcal{S}}(p_{\bar{b}}, p_b, p_{\ell^-}, p_{\ell^+}),$$
$$\mathcal{M}_{\mathcal{A}}(p_b, p_{\bar{b}}, p_{\ell^-}, p_{\ell^+}) = -\mathcal{M}_{\mathcal{A}}(p_{\bar{b}}, p_b, p_{\ell^-}, p_{\ell^+}).$$

$$|\mathcal{M}|^2 = |\mathcal{M}_S|^2(p_b, p_{\bar{b}}, p_{\ell^-}, p_{\ell^+})$$
$$\left(\frac{1}{m_{\ell\ell}^4} + \frac{9/4}{\sin\theta_W^4\cos\theta_W^4}\frac{(g_{Q,L}^2+g_{Q,R}^2)(g_{e,L}^2+g_{e,R}^2)}{(m_{\ell\ell}^2-M_Z^2)^2+\Gamma_Z^2M_Z^2} + \frac{3/2}{\sin\theta_W^2\cos\theta_W^2}\frac{(m_{\ell\ell}^2-M_Z^2)(g_{Q,L}+g_{Q,R})(g_{e,L}+g_{e,R})}{m_{\ell\ell}^2((m_{\ell\ell}^2-M_Z^2)^2+\Gamma_Z^2M_Z^2)}\right)$$
$$+ |\mathcal{M}_A|^2(p_b, p_{\bar{b}}, p_{\ell^-}, p_{\ell^+})$$
$$\left(\frac{9/4}{\sin\theta_W^4\cos\theta_W^4}\frac{(g_{Q,L}^2-g_{Q,R}^2)(g_{e,L}^2-g_{e,R}^2)}{(m_{\ell\ell}^2-M_Z^2)^2+\Gamma_Z^2M_Z^2} + \frac{3/2}{\sin\theta_W^2\cos\theta_W^2}\frac{(m_{\ell\ell}^2-M_Z^2)(g_{Q,L}-g_{Q,R})(g_{e,L}-g_{e,R})}{m_{\ell\ell}^2((m_{\ell\ell}^2-M_Z^2)^2+\Gamma_Z^2M_Z^2)}\right).$$

Similar to the LEP process:
The asymmetric Lorentz invariant coefficient for $\{g_L, g_R\}$ asymmetric term

$$(p_b - p_{\bar{b}}).(p_{l^-} - p_{l^+})$$

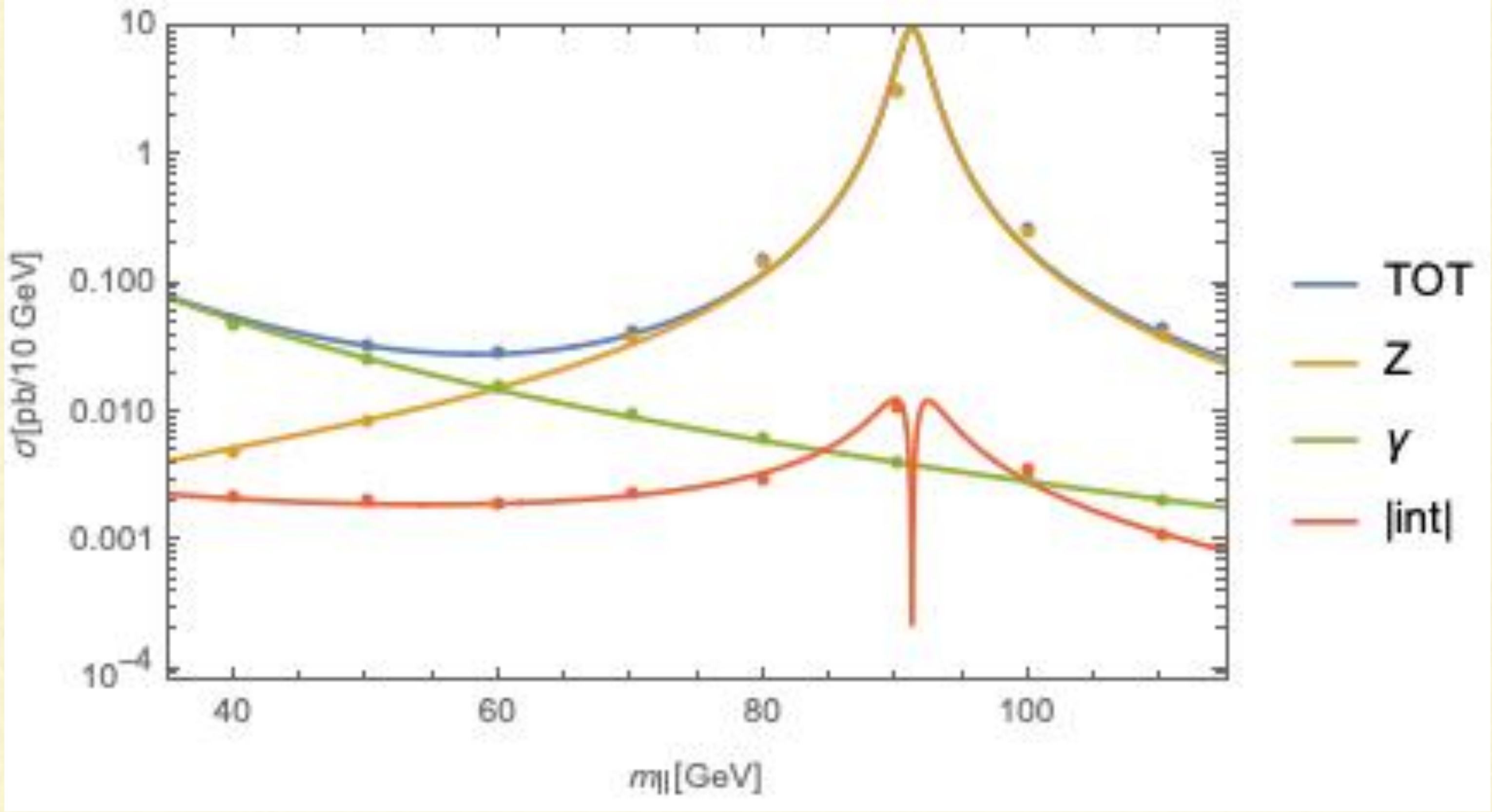
Define angle in the Z^* $(m_{\ell\ell})$ rest frame: $sign(cos\psi)$ between $\vec{p}_b - \vec{p}_{\bar{b}}$ and $\vec{p}_{\ell^-}$



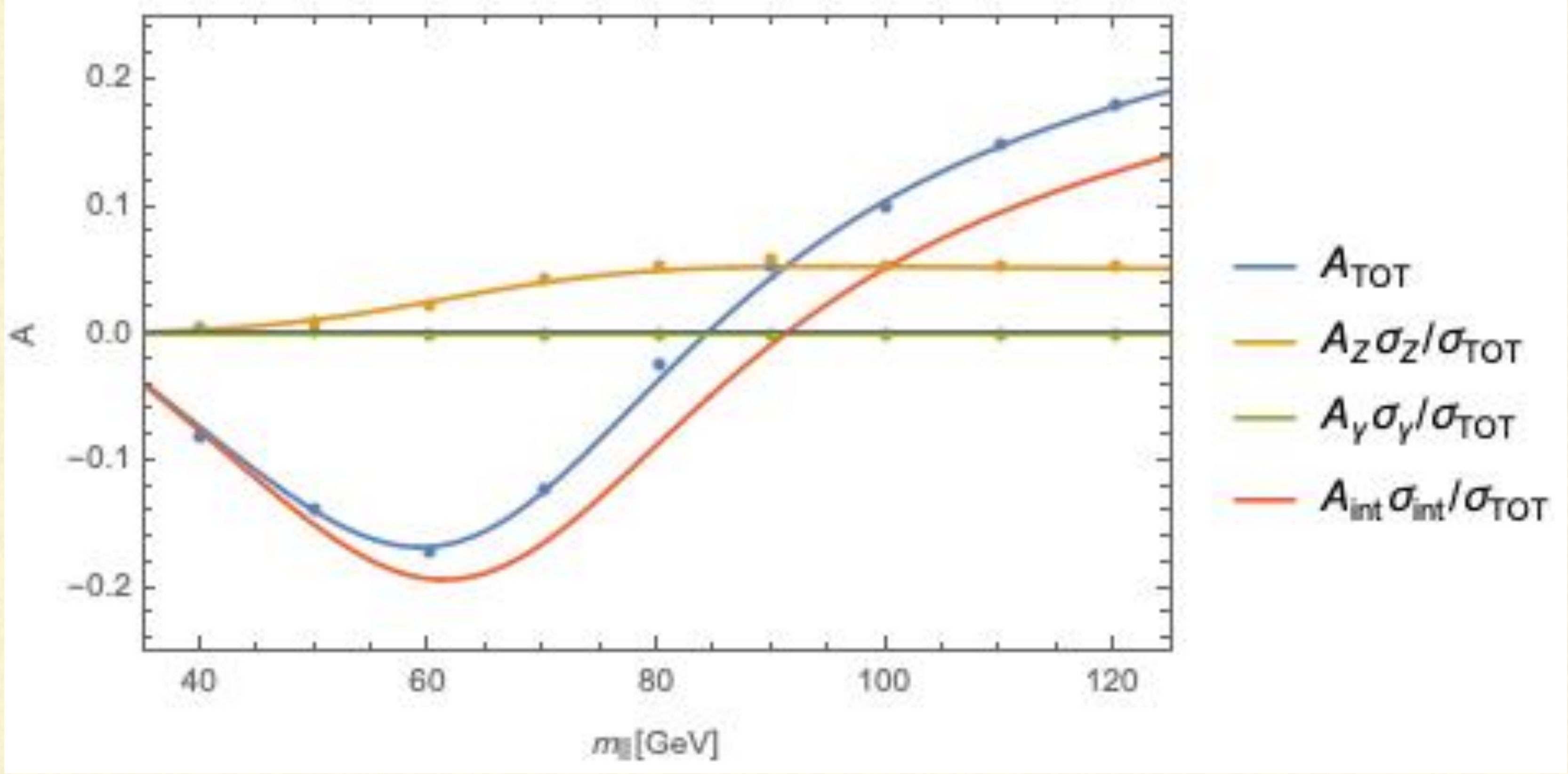
Through $m_{\ell\ell}$ Analysis:

γ, Z and interference contribution $gg \to Zb\bar{b}, Z \to \ell^-\ell^+$

$$\frac{d\sigma_\gamma}{dm_{\ell\ell}} = F(m_{\ell\ell})\frac{1}{m_{\ell\ell}^4}$$
$$\frac{d\sigma_Z}{dm_{\ell\ell}} = F(m_{\ell\ell})\frac{9/4}{(\sin\theta_W^2\cos\theta_W^2)^2}\frac{(g_{Q,L}^2+g_{Q,R}^2)(g_{e,L}^2+g_{e,R}^2)}{(m_{\ell\ell}^2-M_Z^2)^2+\Gamma_Z^2M_Z^2}$$
$$\frac{d\sigma_{\rm int}}{dm_{\ell\ell}} = F(m_{\ell\ell})\frac{3/2}{\sin\theta_W^2\cos\theta_W^2}\frac{(m_{\ell\ell}^2-M_Z^2)(g_{Q,L}+g_{Q,R})(g_{e,L}+g_{e,R})}{m_{\ell\ell}^2((m_{\ell\ell}^2-M_Z^2)^2+\Gamma_Z^2M_Z^2)}.$$



$$\frac{d\sigma_\gamma^A}{dm_{\ell\ell}} = 0$$
$$\frac{d\sigma_Z^A}{dm_{\ell\ell}} = G(m_{\ell\ell})\frac{9/4}{(\sin\theta_W^2\cos\theta_W^2)^2}\frac{(g_{Q,L}^2-g_{Q,R}^2)(g_{e,L}^2-g_{e,R}^2)}{(m_{\ell\ell}^2-M_Z^2)^2+\Gamma_Z^2M_Z^2}$$
$$\frac{d\sigma_{\rm int}^A}{dm_{\ell\ell}} = G(m_{\ell\ell})\frac{3/2}{\sin\theta_W^2\cos\theta_W^2}\frac{(m_{\ell\ell}^2-M_Z^2)(g_{Q,L}-g_{Q,R})(g_{e,L}-g_{e,R})}{m_{\ell\ell}^2((m_{\ell\ell}^2-M_Z^2)^2+\Gamma_Z^2M_Z^2)}$$



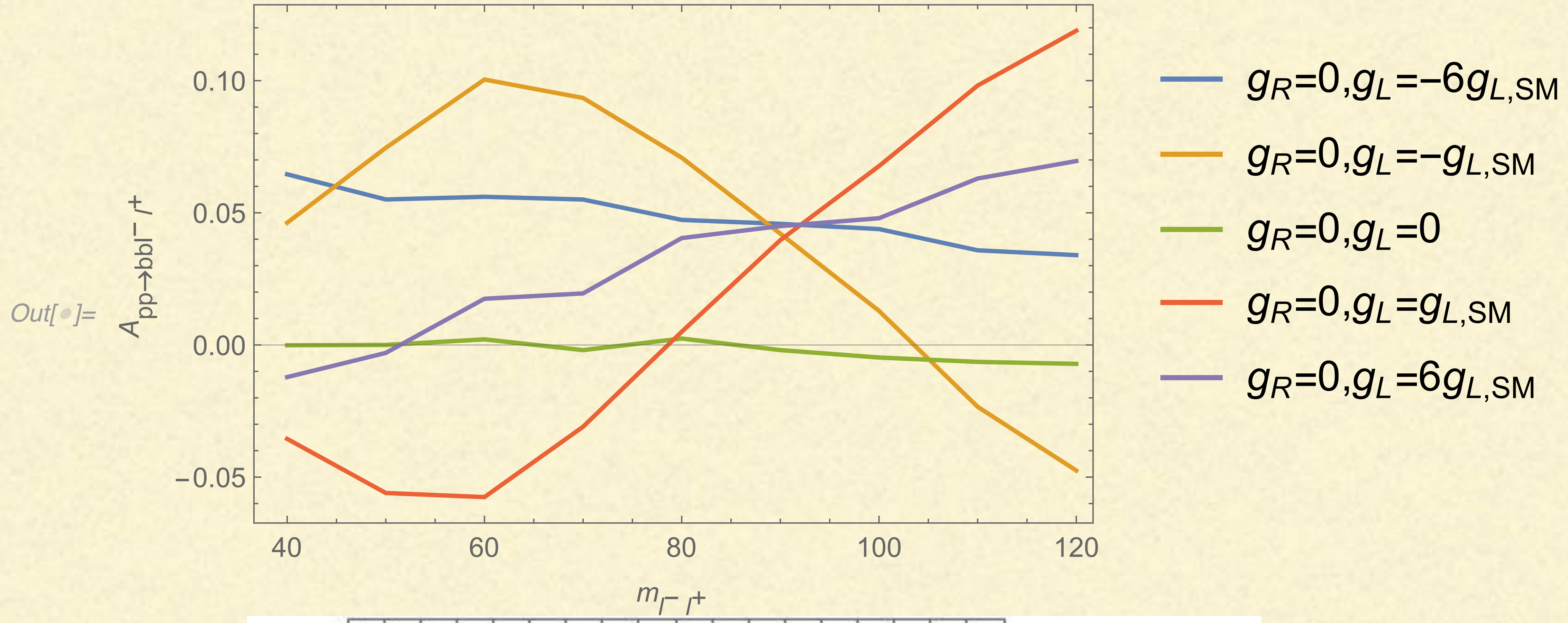
$$A(m_{\ell\ell}) = \frac{d\sigma_{tot}^A}{d\sigma_{tot}} = \frac{d\sigma_\gamma^A+d\sigma_Z^A+d\sigma_{\rm int}^A}{d\sigma_\gamma+d\sigma_Z+d\sigma_{\rm int}},$$

Simulation and Realistic effects

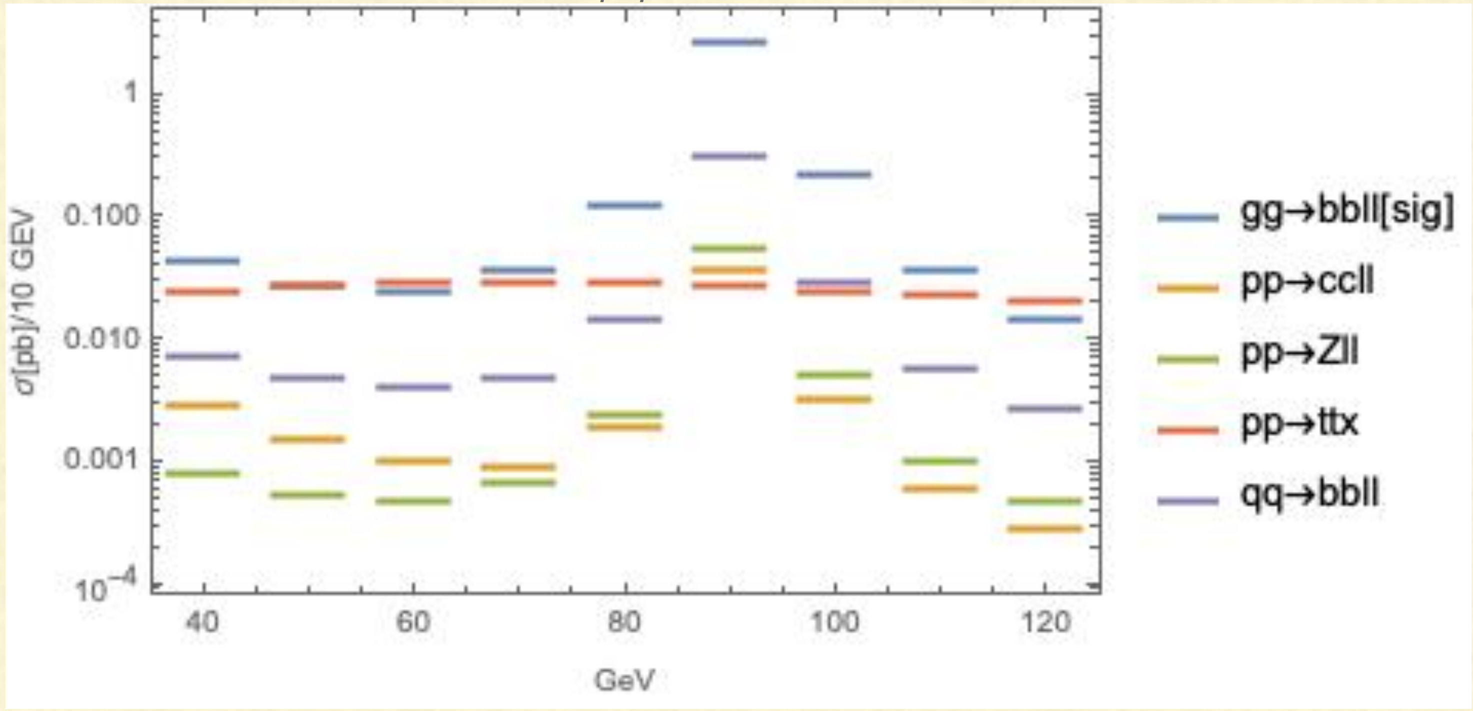
Benchmark fit $pp \to b\bar{b}\ell^-\ell^+$ with LO simulation

$$\sigma = A + B(g_L + g_R) + C(g_L^2 + g_R^2)$$

$$\sigma^A = D + E(g_L + g_R) + F(g_L^2 + g_R^2)$$



Parton analysis for 10 GeV bin from 35-125 GeV: σ, σ_A, A



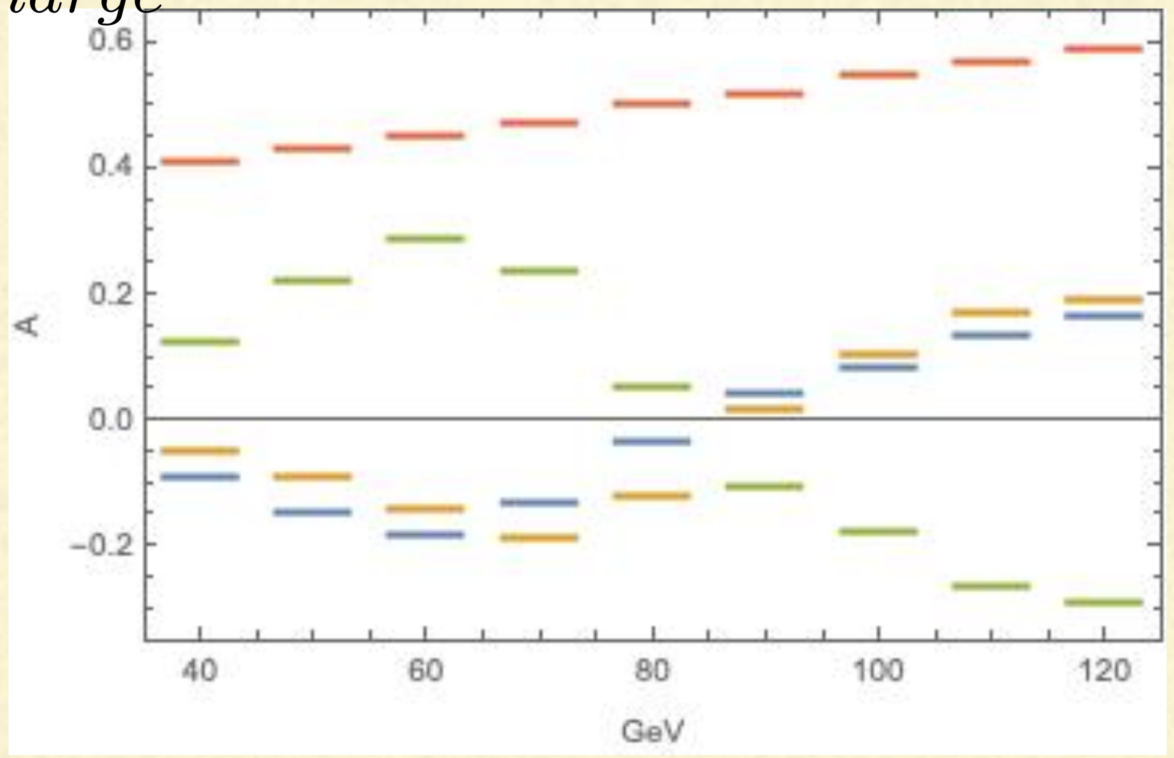
Total Asymmetry contribution $A_p = \frac{\sum_c A_c \sigma_c}{\sum_c \sigma_c}$

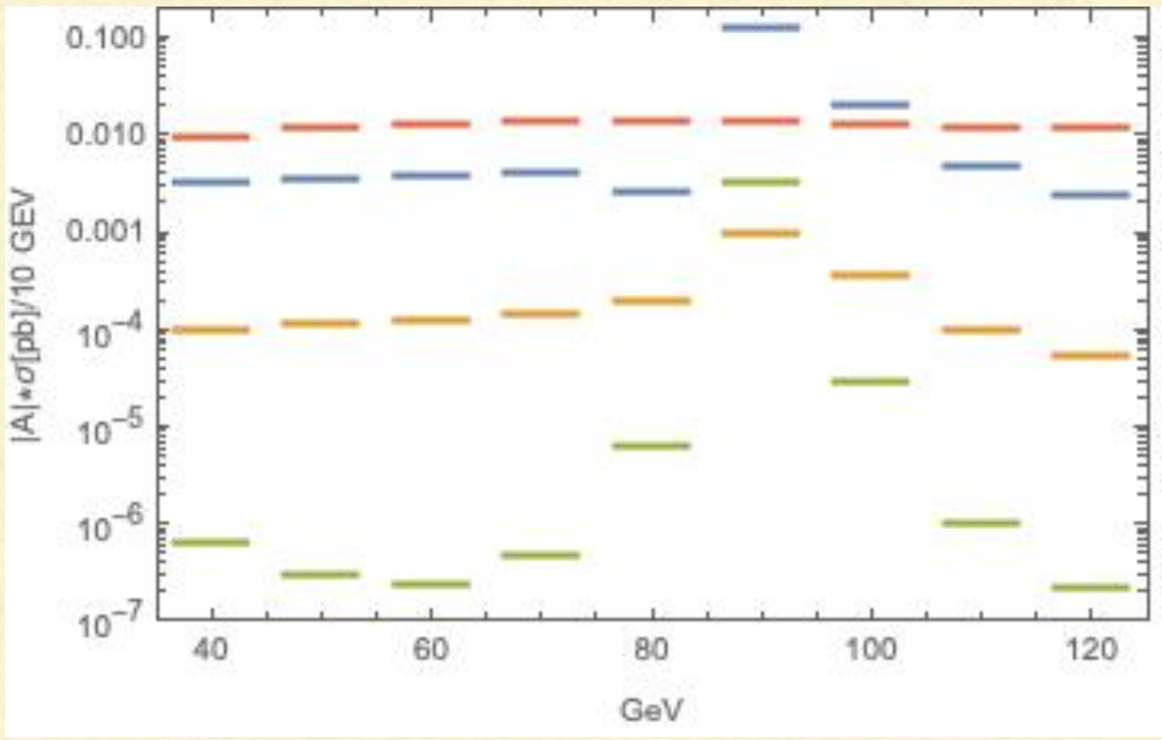
(Charge) Tagging efficiency: $A_{obs} = \frac{2\varepsilon_{charge} - 1}{1 - 2\varepsilon_{charge} + 2\varepsilon_{charge}^2} A_p$

Basic Selection Cuts:

$p_{T,bjet} > 20, p_\ell > 10$ GeV and $|\eta|_{bjet,\ell} < 2.5$

MET>30 GeV (for reducing $t\bar{t}$ background)





Simulation and Realistic effects

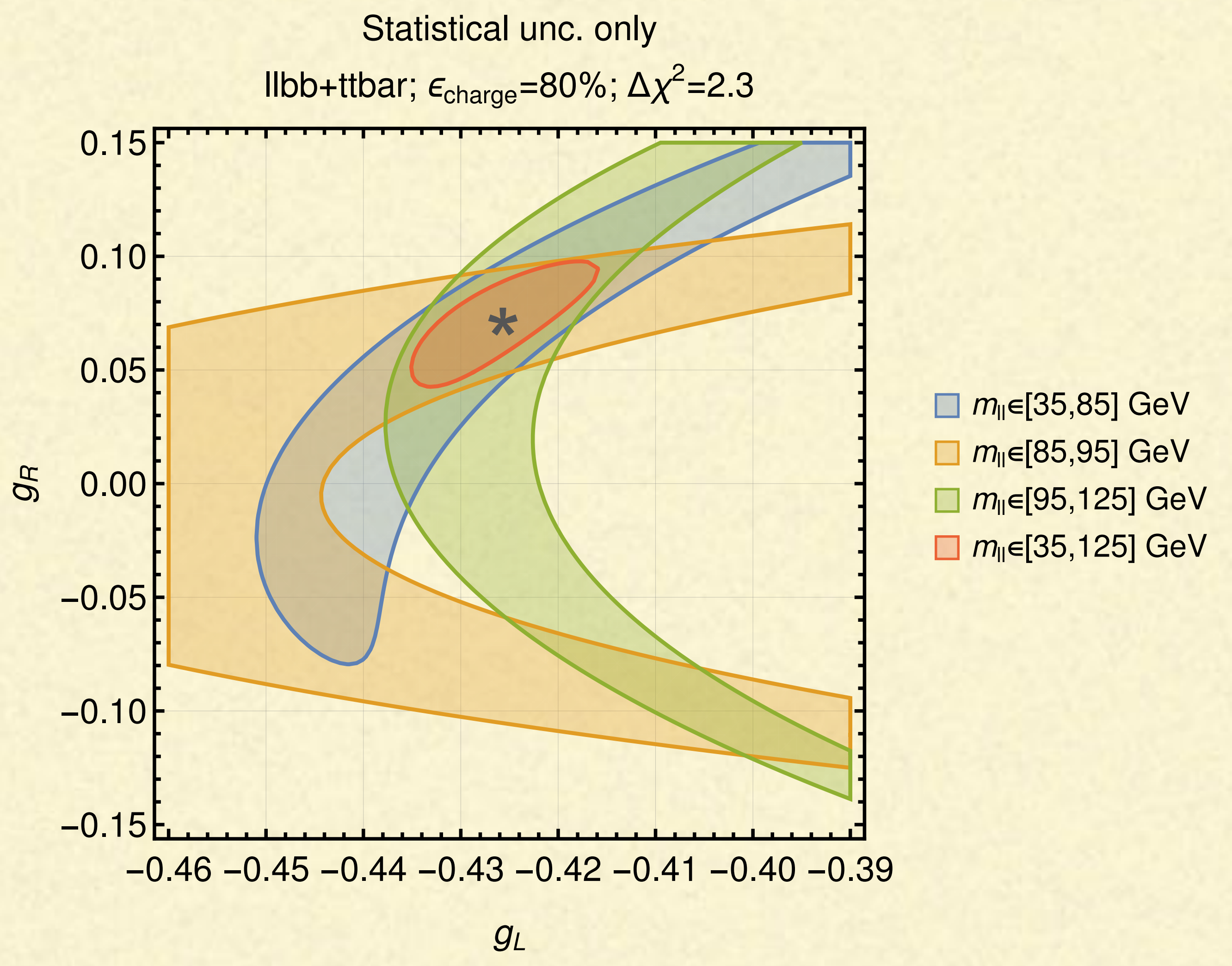
$$\chi^2 = \sum_{I=bins} \frac{\left(A^I_{obs}(g_L, g_R) - A^{I,SM}_{obs}\right)^2}{\left(\delta A^I_{stat}\right)^2 + \left(\delta A^I_{syst}\right)^2}.$$

Statistic error and results

$$(\delta\sigma^{stat})^2 = \frac{(\sigma_{bbZ} + \sigma^{\mathrm{SF}}_{t\bar{t}})^2}{N}$$

$$A_{\mathrm{SF}} = \frac{\sigma^A_{\mathrm{SF}}}{\sigma_{\mathrm{SF}}} = \frac{A_{Zb\bar{b}}\sigma_{Zb\bar{b}} + A_{t\bar{t}}\sigma_{t\bar{t}}}{\sigma_{Zb\bar{b}} + \sigma_{t\bar{t}}}$$

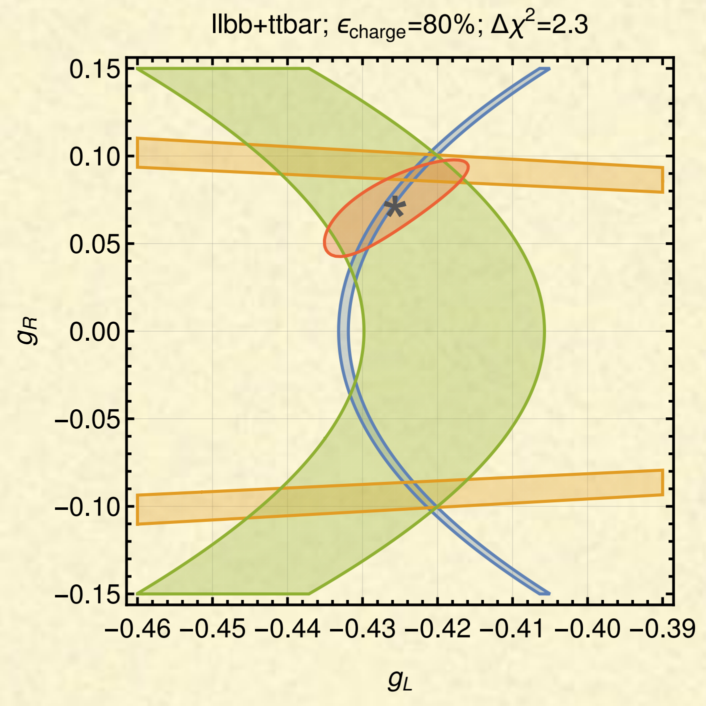
$$(\delta A^{\mathrm{stat}}_{\mathrm{SF}})^2 = \frac{1 - A^2_{SF}}{N_{SF}}$$



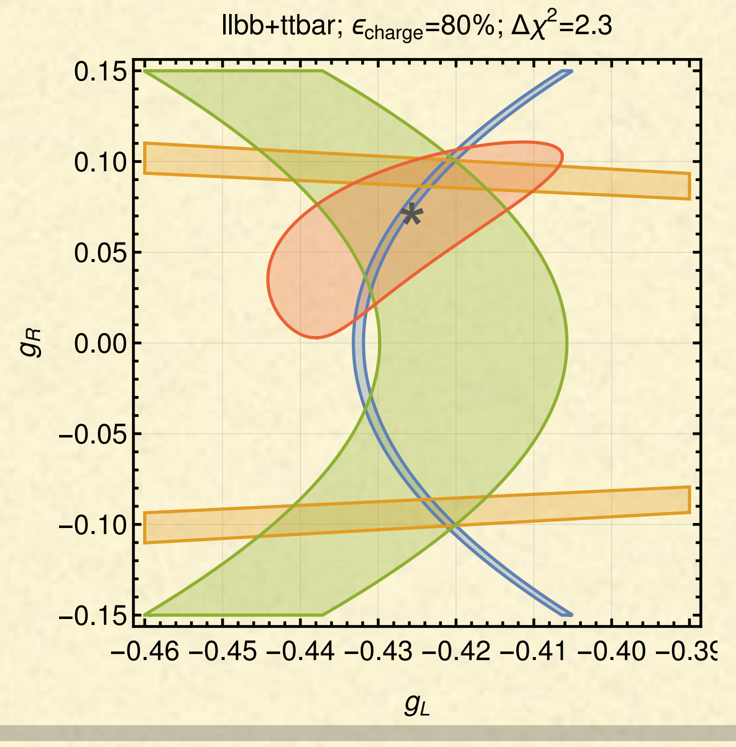
Low, High, Z-pole bins give complementary constraints

Systematic error: (Higher order correction, PDF, m_b correction, experimental error)

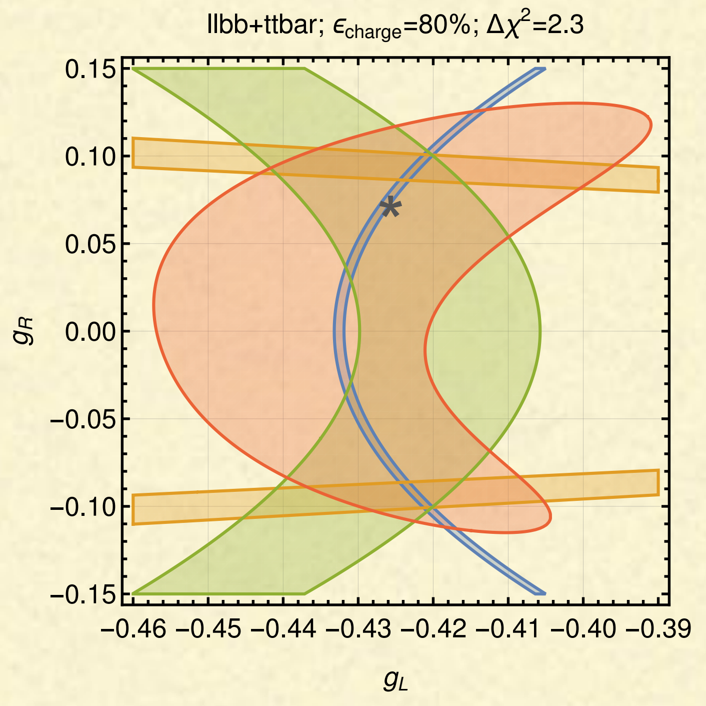
Estimate with LO scale variation (20-30% on $\delta\sigma_{t\bar{t}}$ and $\delta\sigma_{Zb\bar{b}}$)



Stat. Only



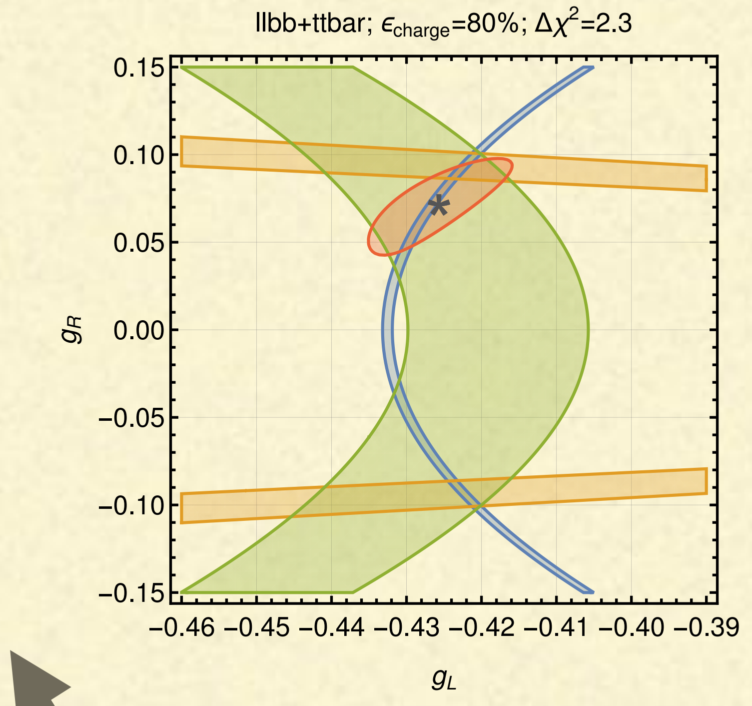
LO Sys/2. Inc

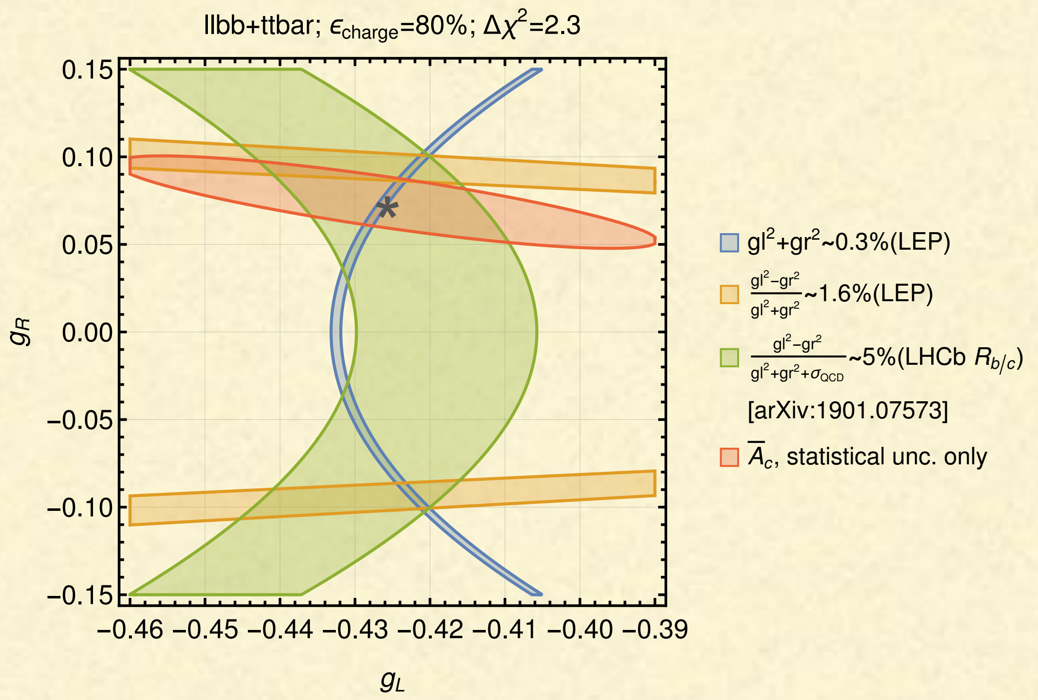


LO Sys. Inc.

Alternative observable: subtracting $t\bar{t}$ (DF)

Different flavor $t\bar{t}$ ($b\bar{b}e\mu\nu\nu$: DF) as "sideband" subtraction:
(correlated systematics between $t\bar{t}$-SF and $t\bar{t}$-DF)





$$\bar{\sigma} = \sigma_{\rm SF} - \sigma_{\rm DF} \approx \sigma_{bbZ} \qquad (\delta\bar{\sigma}^{\rm stat})^2 = (\delta\sigma_{\rm SF}^{\rm stat})^2 + (\delta\sigma_{\rm DF}^{\rm stat})^2 = \frac{\sigma_{SF}^2}{N_{SF}} + \frac{\sigma_{DF}^2}{N_{DF}}$$

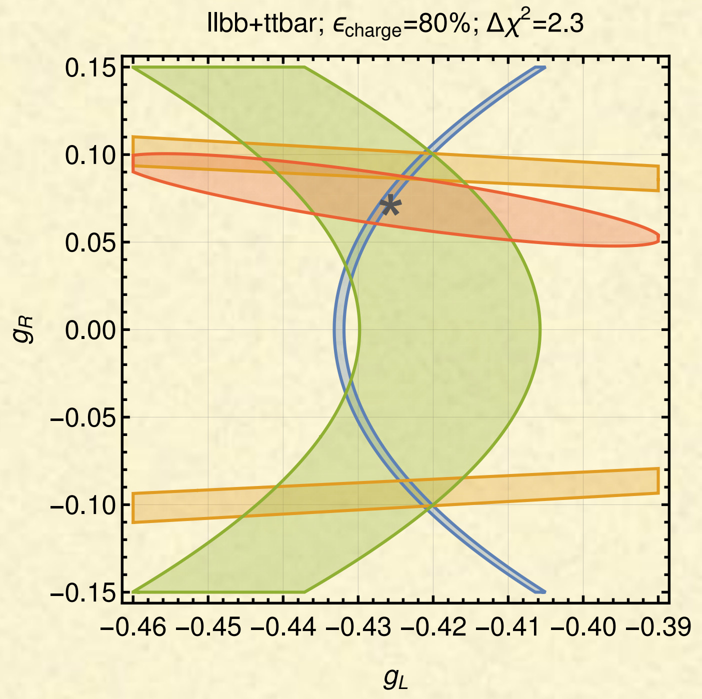
$$\bar{A} = \frac{\bar{\sigma}^A}{\bar{\sigma}} = \frac{(\sigma_{\rm SF}^+ - \sigma_{\rm DF}^+) - (\sigma_{\rm SF}^- - \sigma_{\rm DF}^-)}{(\sigma_{\rm SF}^+ + \sigma_{\rm SF}^-) - (\sigma_{\rm DF}^+ + \sigma_{\rm DF}^-)} \approx A_{Zb\bar{b}}$$

Worsened statistic

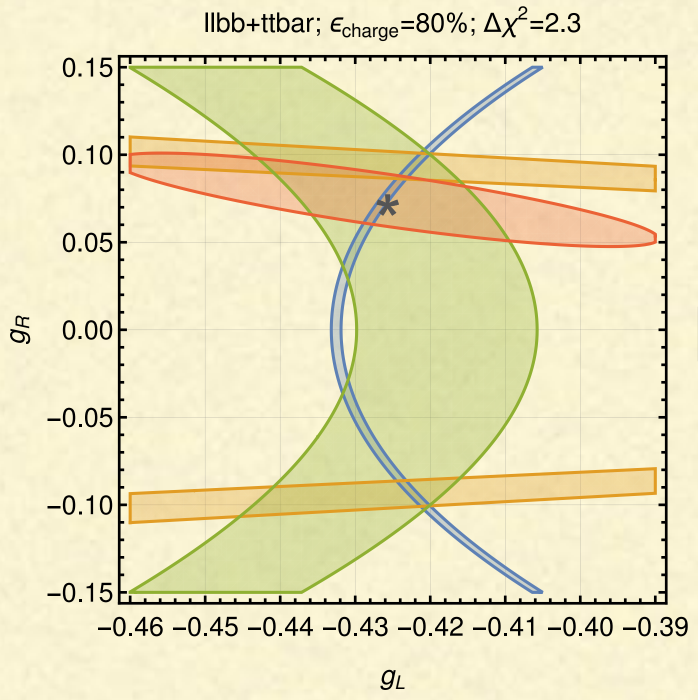
$$(\delta\bar{A}^{\rm stat})^2 = \frac{1}{N_{Zbb}} \frac{\sigma_{Zbb}(1 - A_{Zbb}^2) + \sigma_{t\bar{t}}(2 - 4A_{t\bar{t}}A_{Zbb} + 2A_{Zbb}^2)}{\sigma_{Zbb}}$$

Improved systematics

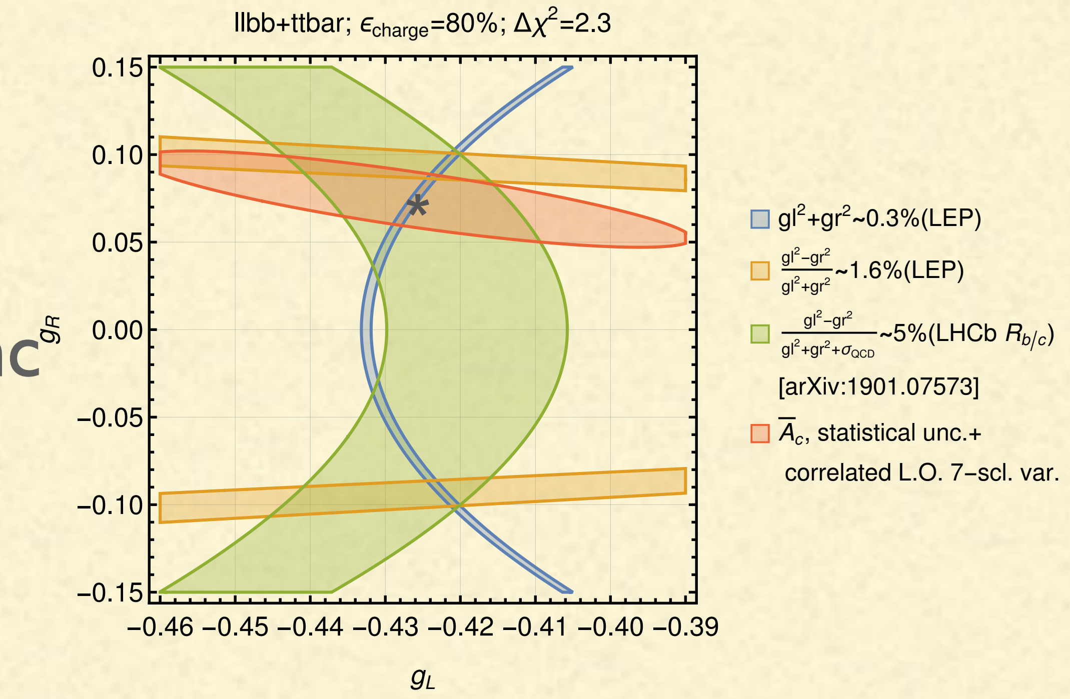
$$\delta\bar{\sigma}^{\rm sys} \approx \delta\sigma_{bbZ}^{\rm sys} \gg \delta\bar{\sigma}^{\rm stat} \qquad \delta\bar{A}^{sys} = \delta A_Z^{sys}$$



Stat. Only



LO Sys/2. Inc



LO Sys. Inc.

Conclusion

- The $Zb\bar{b}$ coupling measurement at LEP has persistent anomaly which remain a poorly constrained at the hadron collider era
- The study at Tevatron, LHCb huge QCD contribution and associated systematics
- Asymmetric observable $\mathcal{O}_{[b,\bar{b}]}$ provide orthogonal information to total cross section measure on the $\{g_L, g_R\}$ coupling, also the main source of anomaly
- $b\bar{b}\ell^-\ell^+$ study at LHC provides complimentary probe through $m_{\ell\ell}$ spectra
- Systematic error as dominant source can be availed by $t\bar{t}$(DF) subtraction
- Realistic systematic error prospects give competitive HL-LHC constraints