Electroweak Couplings of Quarks at Future e^+e^- Colliders

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Motivation

- The Standard Model fixes how strongly the Z boson couples to each quark, *separately* for left- and right-handed quarks:

$$g_L = T_3 - Q \sin^2 \theta_W, \qquad g_R = -Q \sin^2 \theta_W$$

- Precise measurements test this structure: any deviation $\rightsquigarrow$ new physics
- The b quark is special: SU(2) top partner, closely tied to the Higgs sector, and the subject of a long-standing puzzle
- Future e^+e^- colliders will provide huge statistics of Z bosons, run at higher energies than LEP, LC also with polarised beams

What can e^+e^- machines tell us about the EW couplings of quarks?

Current status

- Most of our knowledge still comes from LEP and SLD, e.g.

$R_b = \Gamma(b\bar{b})/\Gamma(\text{hadrons})$ Γ_{12}/Γ_8

OUR FIT is obtained by a simultaneous fit to several c- and b-quark measurements as explained in the note "The Z boson" and ref. LEP-SLC 06.

The Standard Model predicts R_b=0.21581 for m_t=174.3 GeV and M_H=150 GeV.

VALUE		*DOCUMENT ID*		*TECN*	*COMMENT*
0.21629±0.00066 OUR FIT					
0.21594±0.00094±0.00075	[1]	ABE	05F	SLD	E_{cm}^{ee}=91.28 GeV
0.2174 ±0.0015 ±0.0028	[2]	ACCIARRI	00	L3	E_{cm}^{ee}= 89–93 GeV
0.2178 ±0.0011 ±0.0013	[3]	ABBIENDI	99B	OPAL	E_{cm}^{ee}= 88–94 GeV
0.21634±0.00067±0.00060	[4]	ABREU	99B	DLPH	E_{cm}^{ee}= 88–94 GeV
0.2159 ±0.0009 ±0.0011	[5]	BARATE	97F	ALEP	E_{cm}^{ee}= 88–94 GeV

[PDG24]

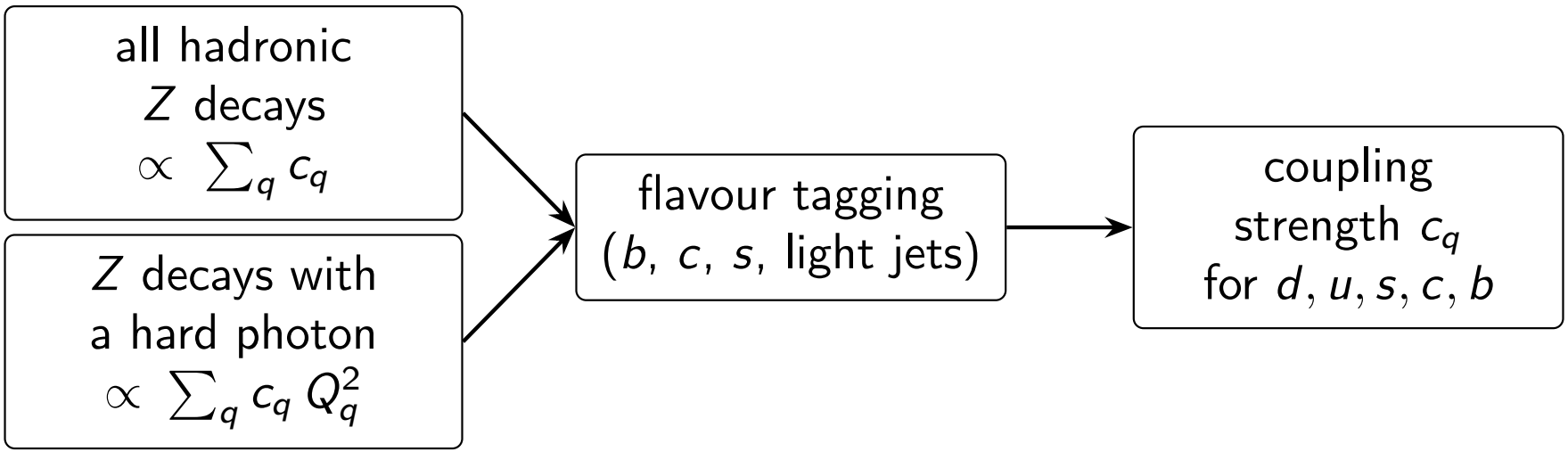
- A long-standing puzzle: the forward–backward asymmetry of b quarks at LEP lies about 2.2σ below the SM

[2011.00530]

- Since then: limited sensitivity from the LHC

Starting point: 5-flavour fit at the Z pole

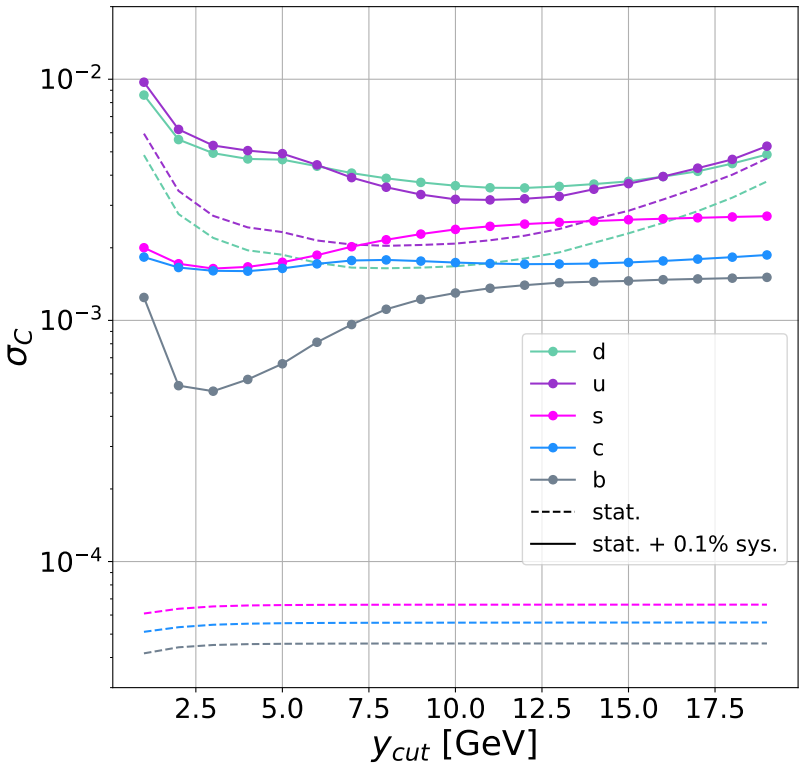
- Photon radiation from a quark scales with its charge squared: up-type radiate about $4\times$ more than down-type
- Combine all hadronic Z decays with those containing a hard photon, plus flavour tagging:

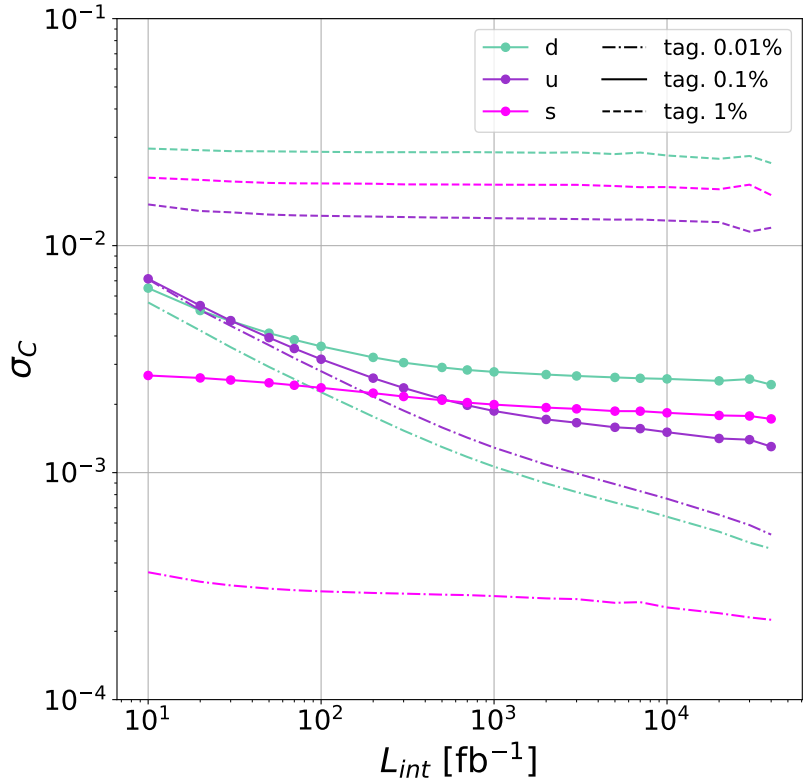


- About an order of magnitude better than LEP for the light quarks

[2504.11365]

5-flavour fit at the Z pole





[2504.11365]

Main limitation: the systematic uncertainty of flavour tagging

Coupling strength vs. chirality

- The Z-pole cross sections depend only on the coupling strength

$$c_q \propto (g_L^q)^2 + (g_R^q)^2$$

- Standard approach: forward–backward asymmetries, polarised beams
- Potential improvements: higher-energy runs
- **This work:** interplay of different approaches, the b-quark example (clean tagging, long-standing puzzle) — very preliminary!

At the Z pole: $e^+e^- \to Z \to q\bar{q}$

Four helicity channels, Z exchange only:

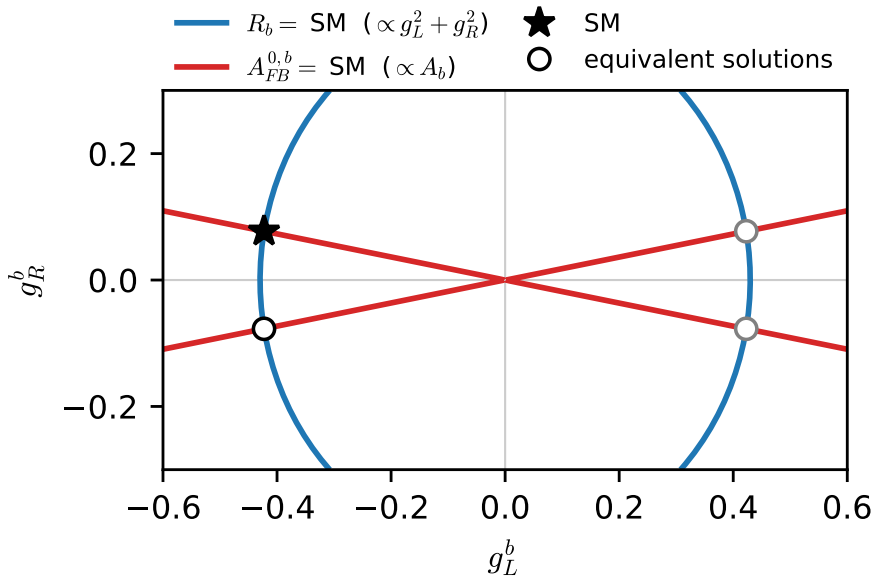
$$\left.\frac{d\sigma}{d\cos\theta}\right|_{ij} \propto (g_i^e)^2\,(g_j^q)^2\,(1 \pm \cos\theta)^2; \quad i,j \in L,R$$

- total rate $\propto (g_L^q)^2 + (g_R^q)^2$
- forward–backward asym. $\propto \frac{(g_L^q)^2 - (g_R^q)^2}{(g_L^q)^2 + (g_R^q)^2}$

At the Z pole: $e^+e^- \to Z \to q\bar{q}$

However, $(g^e)^2$ and $(g^f)^2$ factorise:

	total cross section	FB asymmetry
L	$(g_L^e)^2\left[(g_L^f)^2+(g_R^f)^2\right]$	$\frac{(g_L^f)^2-(g_R^f)^2}{(g_L^f)^2+(g_R^f)^2}$
R	$(g_R^e)^2\left[(g_L^f)^2+(g_R^f)^2\right]$	$-\frac{(g_L^f)^2-(g_R^f)^2}{(g_L^f)^2+(g_R^f)^2}$



Above the Z pole: $e^+e^- \to Z/\gamma \to q\bar{q}$

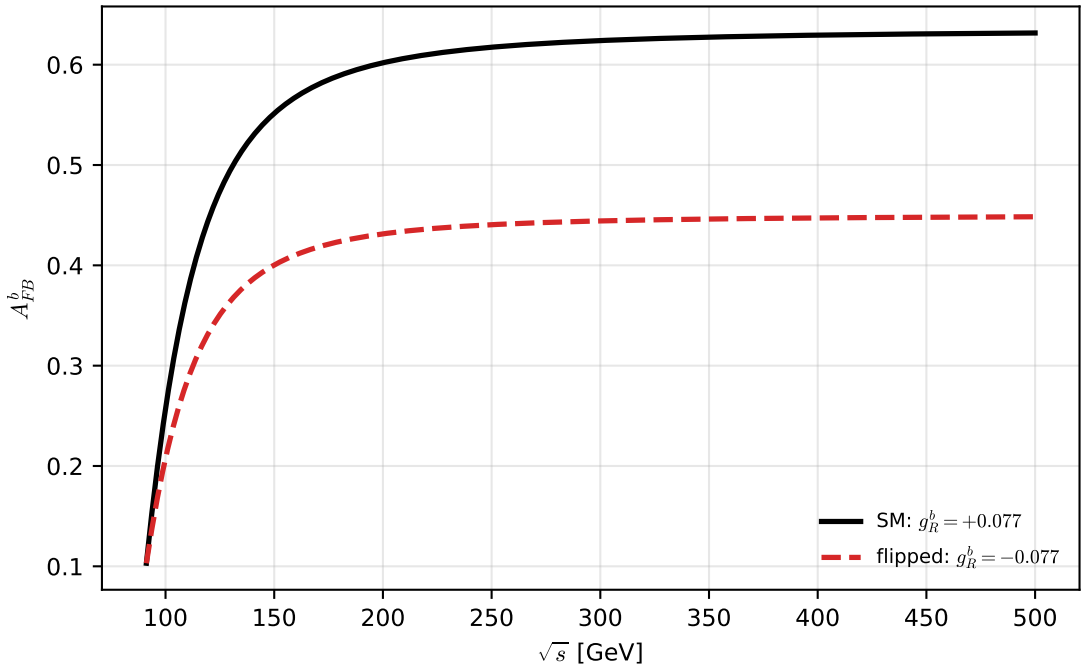
- Both photon and Z contribute and interfere, e.g., for LL:

$$\left.\frac{d\sigma}{d\cos\theta}\right|_{LL} \propto \Big[\underbrace{\frac{Q_q^2}{s^2}}_{\gamma} + \underbrace{\frac{(g_L^e)^2(g_L^q)^2}{(s-M_Z^2)^2}}_{Z} - \underbrace{\frac{2Q_q\, g_L^e\, g_L^q}{s\,(s-M_Z^2)}}_{\text{interference}} \Big](1+\cos\theta)^2$$

- The interference term is *linear* in the couplings: the sign is visible
- The interference term is comparable to the Z term away from the pole
- Electron and quark couplings no longer factorise:
  polarised beams help disentangle the couplings

Energy dependence: the sign becomes visible

E.g. b-quark forward–backward asymmetry for the SM coupling and its mirror image ($g_R^b \to -g_R^b$)



Identical at the peak, very different at high energy

Beam polarisation

- Linear colliders provide highly polarised beams; at circular colliders longitudinal polarisation is challenging
- Polarised beams at the Z pole: the b asymmetry measured directly, without input on the electron (SLD: 30$\times$ fewer Z bosons than LEP, but roughly the same precision)
- Above the Z pole: two polarisations give two independent combinations of g_L^b and g_R^b
  - the FB asymmetry removes the remaining left<>right ambiguity

Interplay of different runs

Run	strength	sign	g_L vs. g_R
Z pole	✓✓	–	$\sim$
Z scan, off-peak	✓	✓	$\sim$
higher energy, unpolarised	✓	✓	✓
higher energy, polarised	✓	✓	✓✓

The combination of different runs brings the best results

Analysis idea

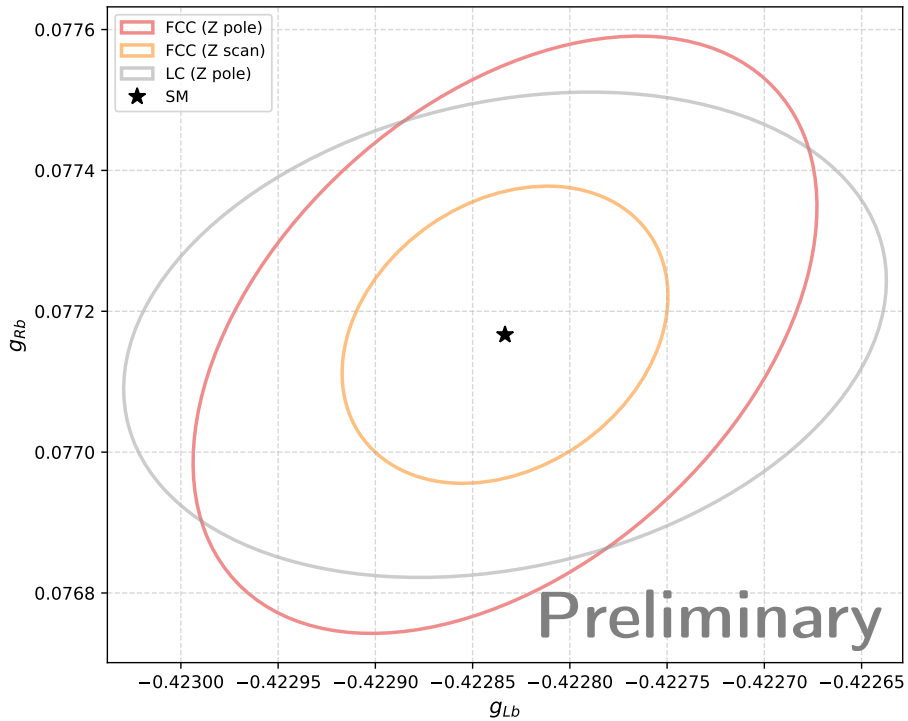
- Same philosophy as the Z-pole study: event categories from flavour tagging, fitted together to constrain systematics
- Same simulation chain: `Whizard` + `Pythia`/`Herwig` + `Delphes`
- New ingredients: quark direction (forward/backward), higher energies, beam polarisation
- Output: expected precision on g_L^b and g_R^b and their correlation
- Any run plan can be studied (LCF, FCC, . . .)

Preliminary results: Z pole

Preliminary inputs: `Whizard` for stat. (no det. simulation), [2206.08326], [2306.11413], [2403.09144], [2504.11365], DOI:10.17181/sq5pm-c8334, etc.
Simplified model: LO+ISR, fixed Z width, etc.

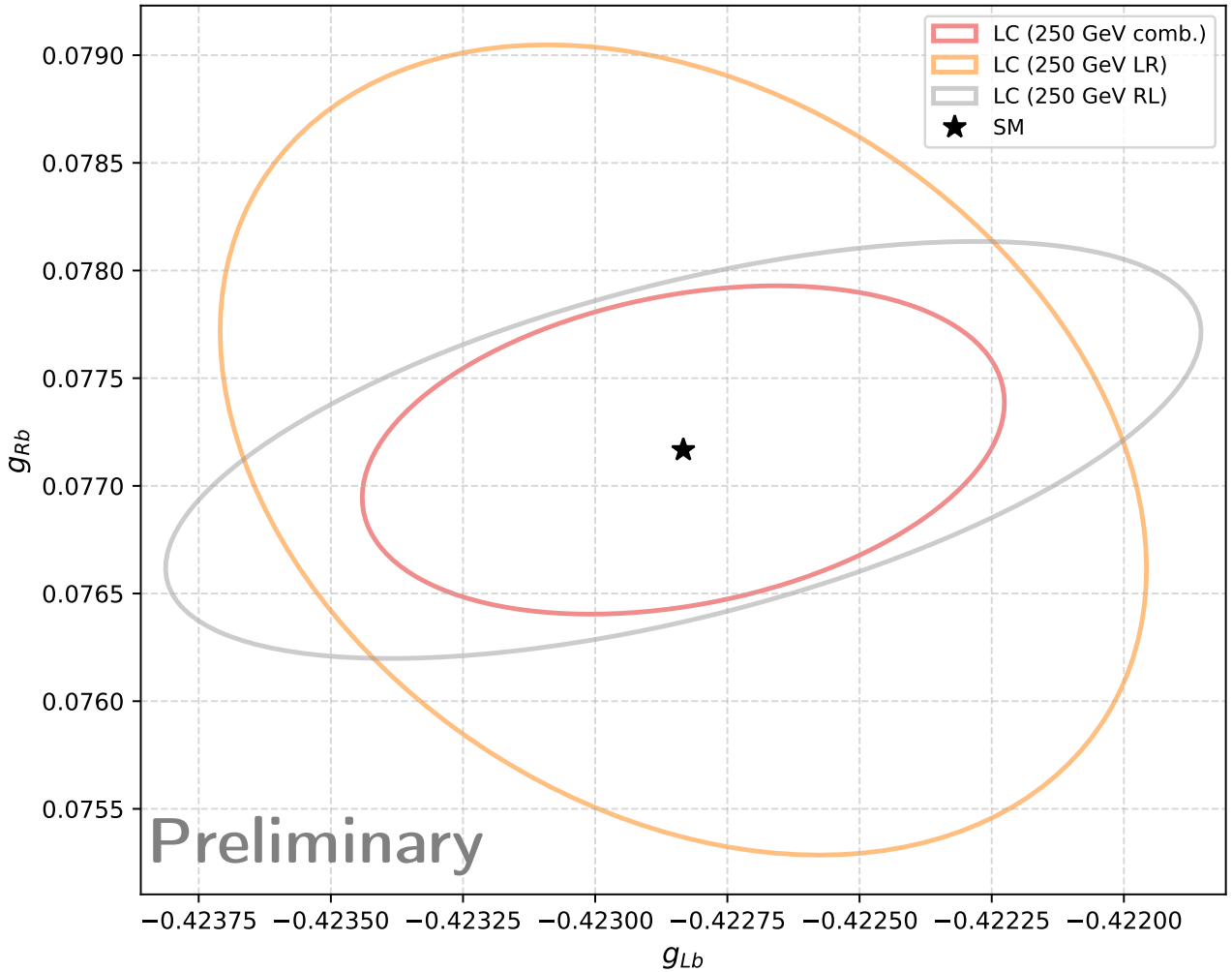
An attempt to unify the assumptions:

but for now, numbers just for **illustration**!



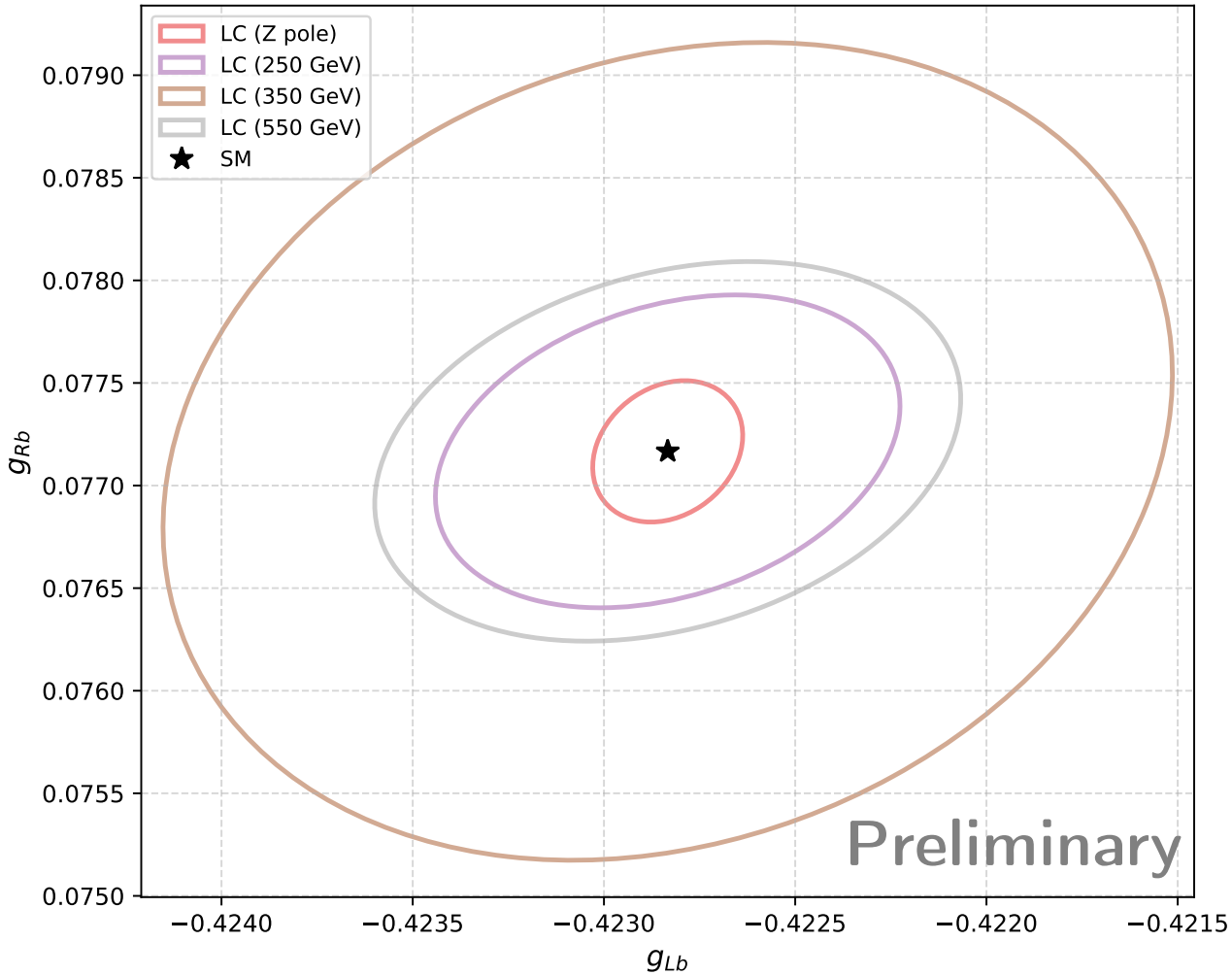
Here, we assume the signs are known.

Preliminary results: 250 GeV



Polarisation significantly helps at 250 GeV, but...

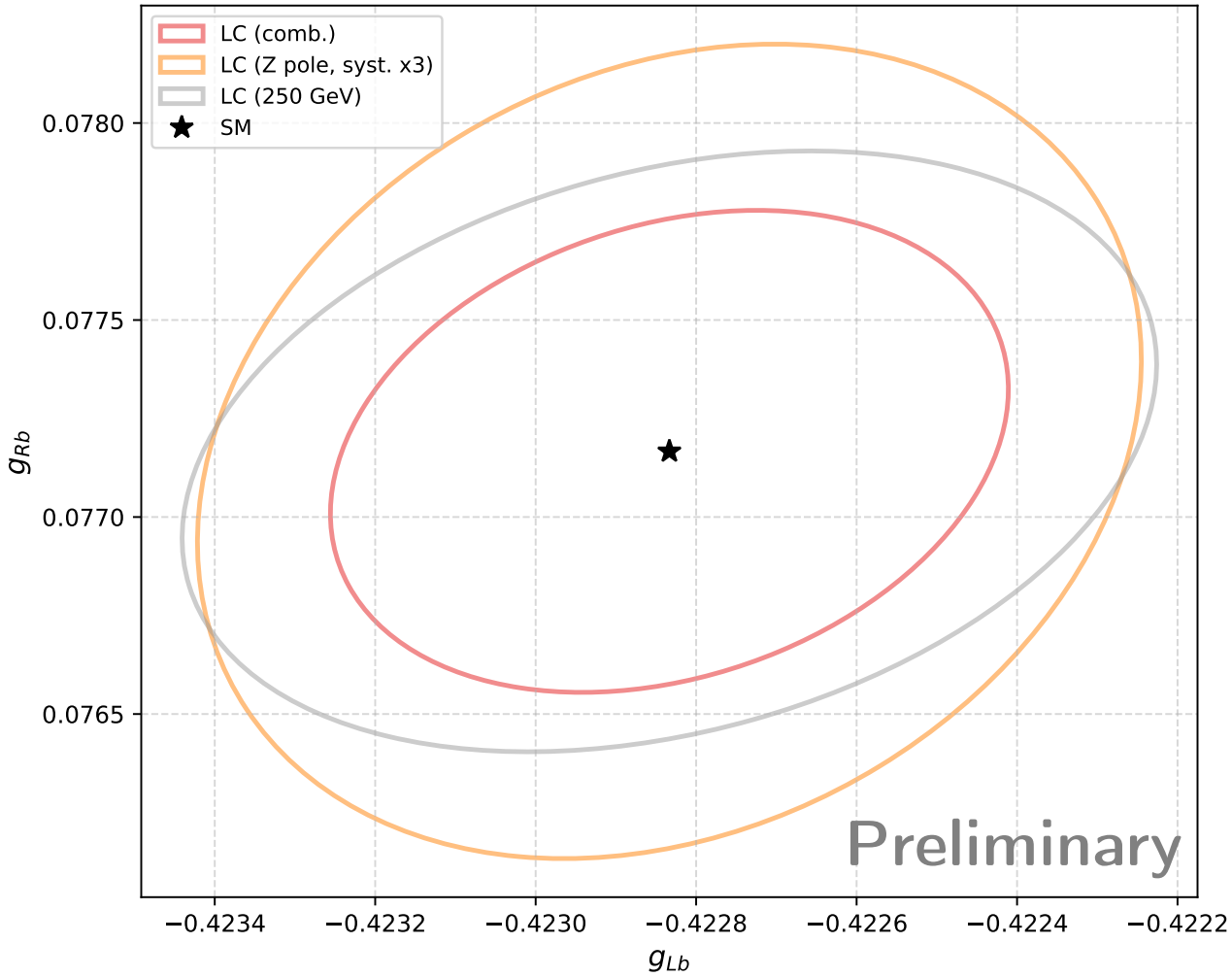
Preliminary results: LC runs



...for the present estimates, the Z pole dominates by far.

Preliminary results: variation of assumptions

Caveat: high-energy inputs well established (A. Irles, R. Pöschl, F.Richard), the Z-pole one — just ~~wishes~~ targets; what if e.g. Z-pole syst. $\times 3$?



Summary and outlook

- At the Z pole, photon radiation plus flavour tagging gives the *strength* of all five quark couplings, about an order of magnitude better than LEP for light quarks
- The *chiral structure* cannot be fully probed at the Z pole; photon–Z interference at other energies and polarised beams solve the ambiguity
- We are developing a framework to quantify this for any run plan, starting with the b quark
- Next steps:
  - proper simulation inputs (`Whizard` + `Delphes`)
  - extension to c and s quarks
  - combination with the photon method for light quarks