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Top pair production

non-resonant new physics from LHC to CLIC

Physics at CLIC

CERN, 17.07.2017

SM $\rightarrow$ see Alexander Mitov's talk

BSM ?

top sector | *Higgs sector* | *neutrinos* | *dark matt*

☛ <u>my talk</u>: direct EFT constraints from top pairs (mostly)

[Hikasa et al. `98]
[Degrande et al. `10]
[Kamenik `11]
....

0. top physics @ LHC is abundant - LHC sets the stage

1. what's the status after the first LHC runs

[Bernardo et al. `14]
[Buckley et al. `15]
[Castro et al. `16]

2. constrain generic BSM phenomena in the top pairs at a future using lepton colliders

→ *focus top electroweak couplings*

see also [Aguilar-Saavedra `08] [Greiner et al. `11] [Zhang et al. `12] [Aguilar-Saavedra et al.` 12] [Khiem et al. `15] [de Blas et al. `15] [Perello et al. `15] [Bylund et al. `16] the SM is flawed

no evidence for exotics

coupling/scale separated BSM physics

Effective Field Theory

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

[Buchmüller, Wyler `87]
[Hagiwara, Peccei, Zeppenfeld, Hikasa `87]
[Giudice, Grojean, Pomarol, Rattazzi `07]
[Grzadkowski, Iskrzynski, Misiak, Rosiek `10]

concrete models

- (N)MSSM
- Higgs portals
- compositeness
- …

constrained top EFT status

- operators

$$O_{qq}^{(1)} = (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q) \qquad O_{uW} = (\bar{q}\sigma^{\mu\nu}\tau^I u)\tilde{\phi}W^I_{\mu\nu} \qquad O_{\phi q}^{(3)} = i(\phi^\dagger \overleftrightarrow{D}^I_\mu \phi)(\bar{q}\gamma^\mu \tau^I q)$$

$$O_{qq}^{(3)} = (\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q) \qquad O_{uG} = (\bar{q}\sigma^{\mu\nu}T^A u)\tilde{\phi}G^A_{\mu\nu} \qquad O_{\phi q}^{(1)} = i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{q}\gamma^\mu q)$$

$$O_{uu} = (\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u) \qquad O_G = f_{ABC}G^{A\nu}_\mu G^{B\lambda}_\nu G^{C\mu}_\lambda \qquad O_{uB} = (\bar{q}\sigma^{\mu\nu}u)\tilde{\phi}B_{\mu\nu}$$

$$O_{qu}^{(8)} = (\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u) \qquad O_{\tilde{G}} = f_{ABC}\tilde{G}^{A\nu}_\mu G^{B\lambda}_\nu G^{C\mu}_\lambda \qquad O_{\phi u} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{u}\gamma^\mu u)$$

$$O_{qd}^{(8)} = (\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d) \qquad O_{\phi G} = (\phi^\dagger \phi)G^A_{\mu\nu}G^{A\mu\nu} \qquad O_{\phi\tilde{G}} = (\phi^\dagger \phi)\tilde{G}^A_{\mu\nu}G^{A\mu\nu}$$

$$O_{ud}^{(8)} = (\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)\,.$$

- consider CP even operators for the moment
- neglect operators with chiral suppression for the interference with SM
- top pair production, single top production, top pair + Z production decay observables, "**corrected to top level**"

non-trivial for BSM: Whizard/OpenLoops: [Nejad et al. `15]

constrained top EFT status

- operators

$$O_{qq}^{(1)} = (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q) \qquad O_{uW} = (\bar{q}\sigma^{\mu\nu}\tau^I u)\tilde{\phi}W_{\mu\nu}^I \qquad O_{\phi q}^{(3)} = i(\phi^\dagger \overleftrightarrow{D}_\mu^I \phi)(\bar{q}\gamma^\mu \tau^I q)$$

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$$O_{ud}^{(8)} = (\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)\,.$$

- only sensitive to a superposition of operators (at LO)

top pairs

$$C_u^1 = C_{qq}^{(1)1331} + C_{uu}^{1331} + C_{qq}^{(3)1331}$$

$$C_u^2 = C_{qu}^{(8)1133} + C_{qu}^{(8)3311}$$

$$C_d^1 = C_{qq}^{(3)1133} + \frac{1}{4}C_{ud}^{(8)3311}$$

$$C_d^2 = C_{qu}^{(8)1133} + C_{qd}^{(8)3311}\,.$$

top single top

$$C_t = C_{qq}^{(3)1133} + \frac{1}{6}(C_{qq}^{(3)1331} - C_{qq}^{(3)1331})$$

234 measurements

constrained top EFT status

Dataset	$\sqrt{s}$ (TeV)	Measurements	arXiv ref.	Dataset	$\sqrt{s}$ (TeV)	Measurements	Ref.
Top pair production							
Total cross-sections:				Differential cross-sections:			
ATLAS	7	lepton+jets	1406.5375	ATLAS	7	$p_T(t), M_{t\bar{t}}, \|y_{t\bar{t}}\|$	1407.0371
ATLAS	7	dilepton	1202.4892	CDF	1.96	$M_{t\bar{t}}$	0903.2850
ATLAS	7	lepton+tau	1205.3067	CMS	7	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1211.2220
ATLAS	7	lepton w/o b jets	1201.1889	CMS	8	$p_T(t), M_{t\bar{t}}, y_t, y_{t\bar{t}}$	1505.04480
ATLAS	7	lepton w/ b jets	1406.5375	DØ	1.96	$M_{t\bar{t}}, p_T(t), \|y_t\|$	1401.5785
ATLAS	7	tau+jets	1211.7205				
ATLAS	7	$t\bar{t}, Z\gamma, WW$	1407.0573	Charge asymmetries:			
ATLAS	8	dilepton	1202.4892	ATLAS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1311.6742
CMS	7	all hadronic	1302.0508	CMS	7	A_C (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1402.3803
CMS	7	dilepton	1208.2761	CDF	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1211.1003
CMS	7	lepton+jets	1212.6682	DØ	1.96	A_{FB} (inclusive+$M_{t\bar{t}}, y_{t\bar{t}}$)	1405.0421
CMS	7	lepton+tau	1203.6810				
CMS	7	tau+jets	1301.5755	Top widths:			
CMS	8	dilepton	1312.7582	DØ	1.96	Γ_{top}	1308.4050
CDF + DØ	1.96	Combined world average	1309.7570	CDF	1.96	Γ_{top}	1201.4156
Single top production				W-boson helicity fractions:			
ATLAS	7	t-channel (differential)	1406.7844	ATLAS	7		1205.2484
CDF	1.96	s-channel (total)	1402.0484	CDF	1.96		1211.4523
CMS	7	t-channel (total)	1406.7844	CMS	1.96		1308.3879
CMS	8	t-channel (total)	1406.7844	DØ	1.96		1011.6549
DØ	1.96	s-channel (total)	0907.4259				
DØ	1.96	t-channel (total)	1105.2788				
Associated production				*Run II data*			
ATLAS	7	$t\bar{t}\gamma$	1502.00586	CMS	13	$t\bar{t}$ (dilepton)	1510.05302
ATLAS	8	$t\bar{t}Z$	1509.05276				
CMS	8	$t\bar{t}Z$	1406.7830				

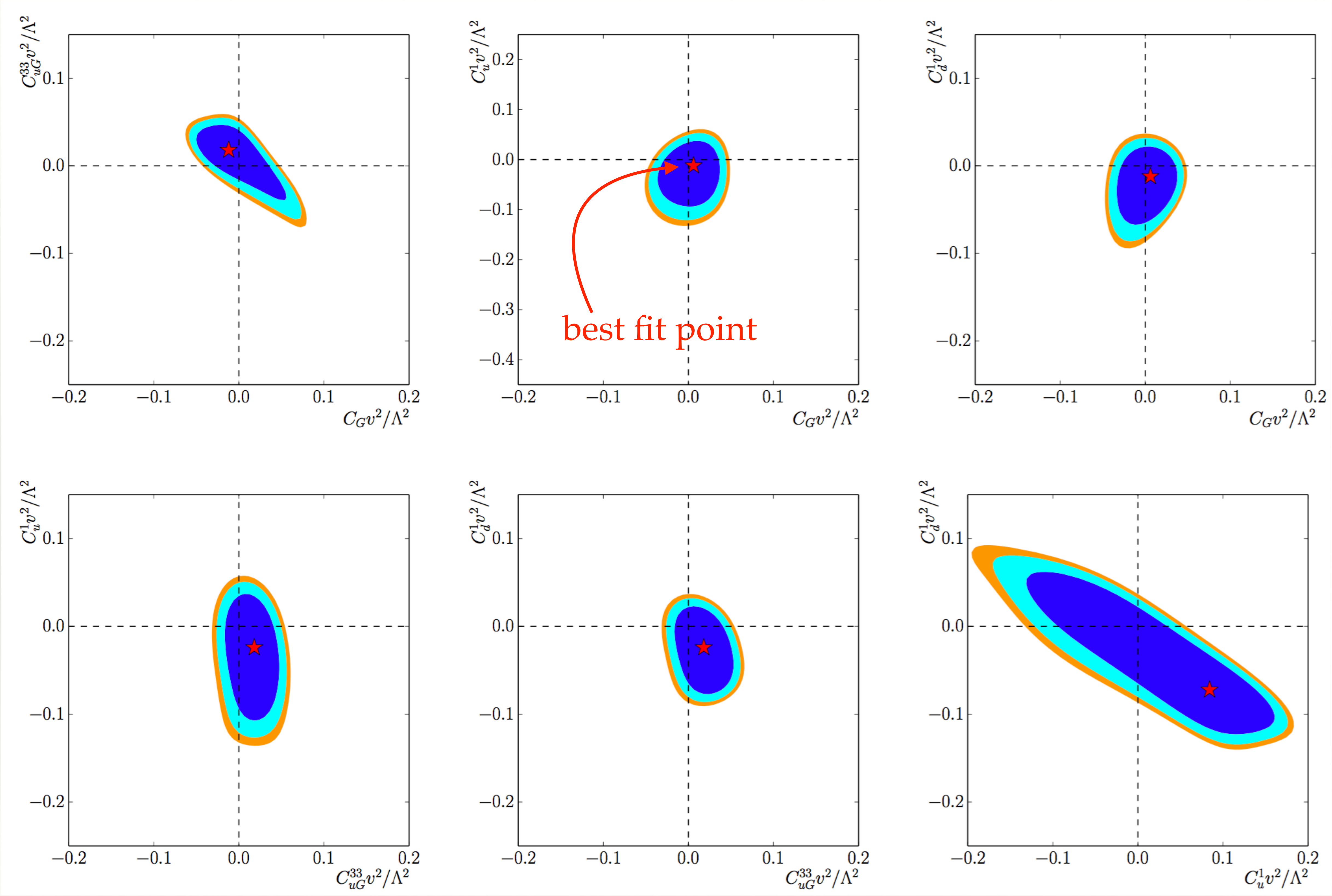
- **treatment of uncertainties and systematics**

1. **experimental systematics**
    - in general no control
    - available experimental systematics/uncertainties added in quadrature when available
    - uncertainties of top parton-level matching included when available
    - correlation between different signal regions not included
    - bin-by-bin migration effects do not impact the fit result

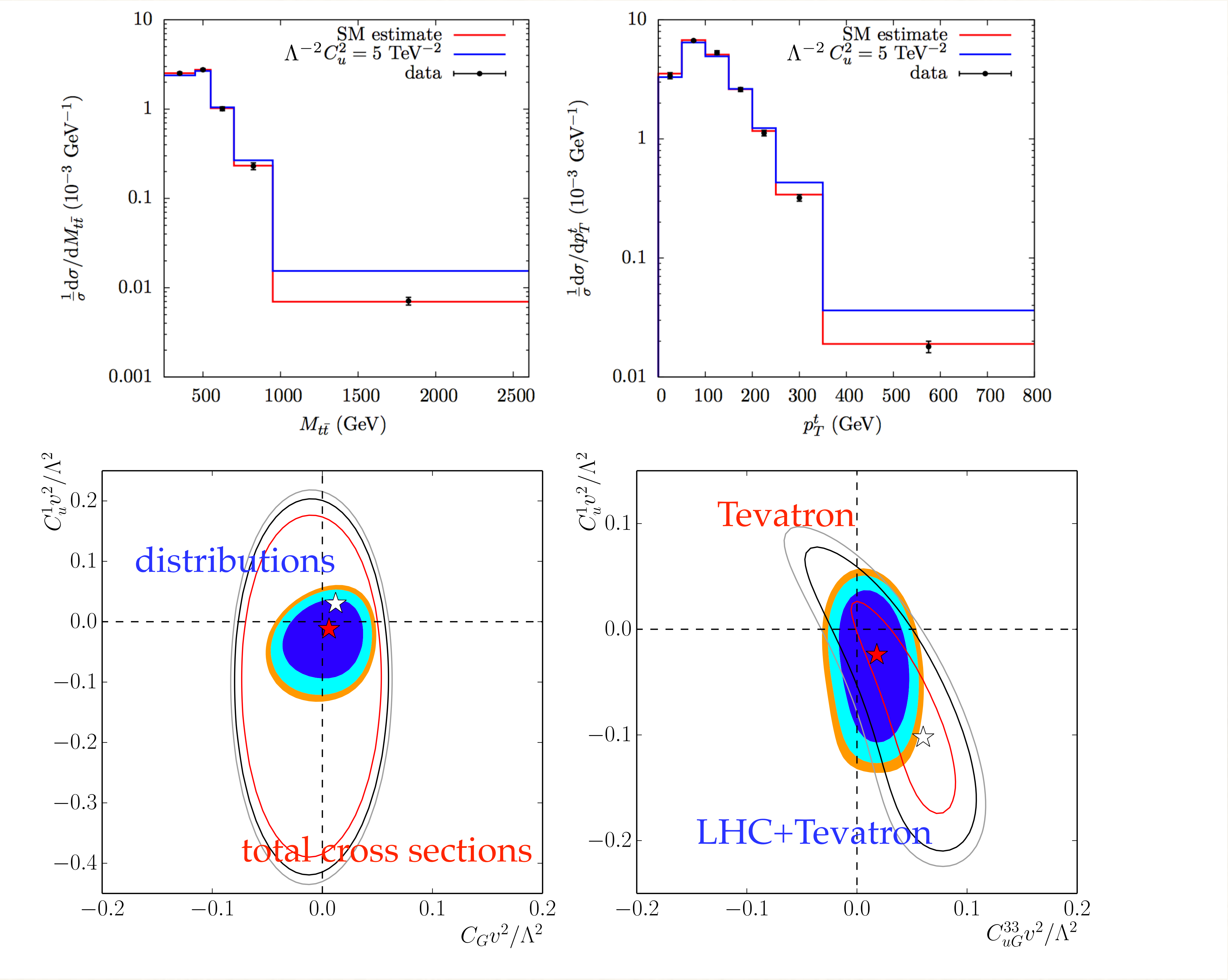
- **treatment of uncertainties and systematics**

2. **SM theoretical uncertainties** [Butterworth et al. ` 15]
    - PDF and scale uncertainties following the PDF4LHC recommendation: full scale + PDF uncertainty band
    - no electroweak corrections
    - no strong/electroweak operator mixing effects: reasonable to assume that they are small for direct searches [CE, Spannowsky ` 15] [Bylund et al ` 16]
    - interpolation error estimated to 5%
    - uncorrelated with experimental systematics

top quark operators



LHC vs Tevatron

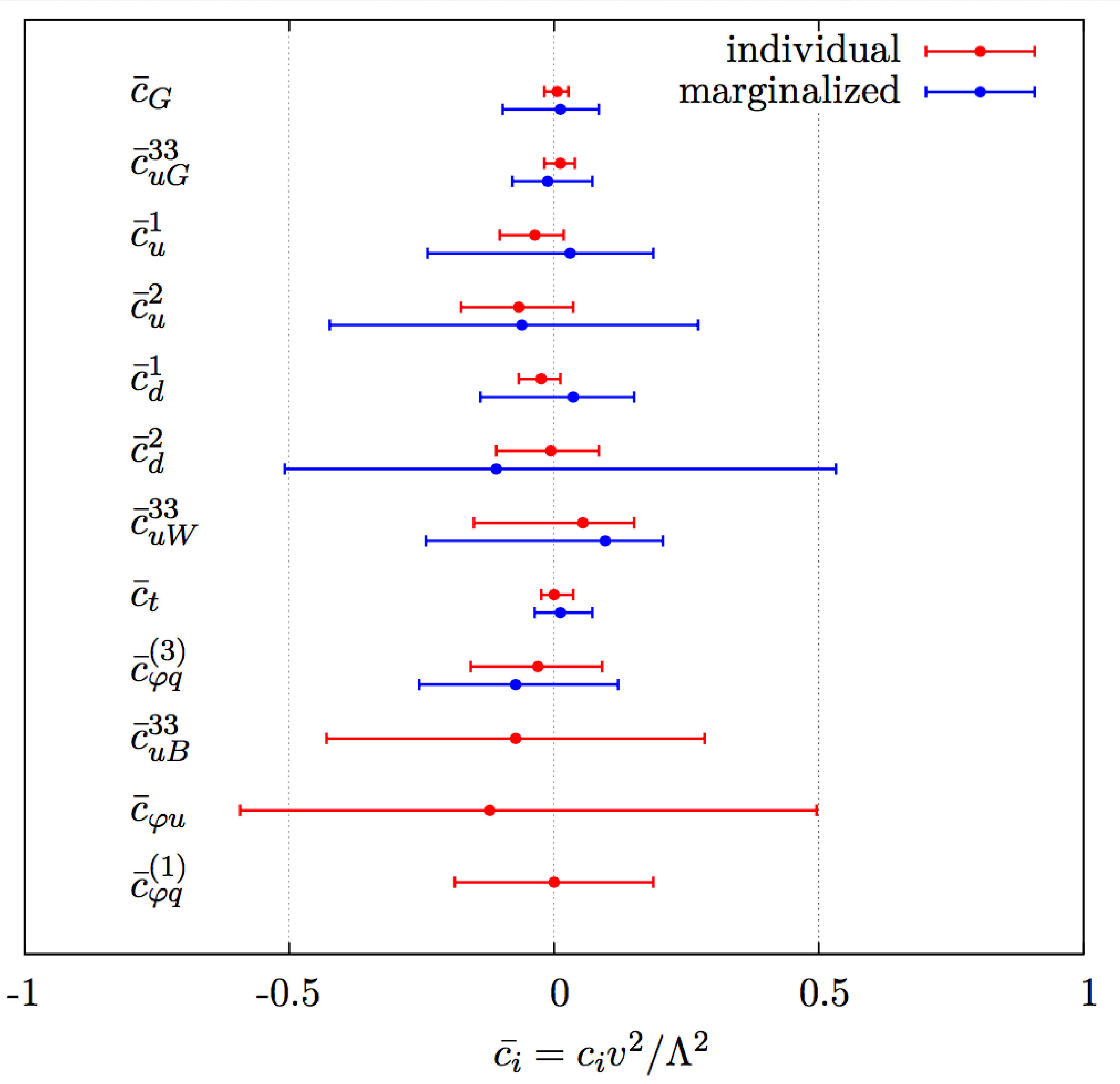


summary of the top sector (early Run-2)

$t\bar{t} + X$

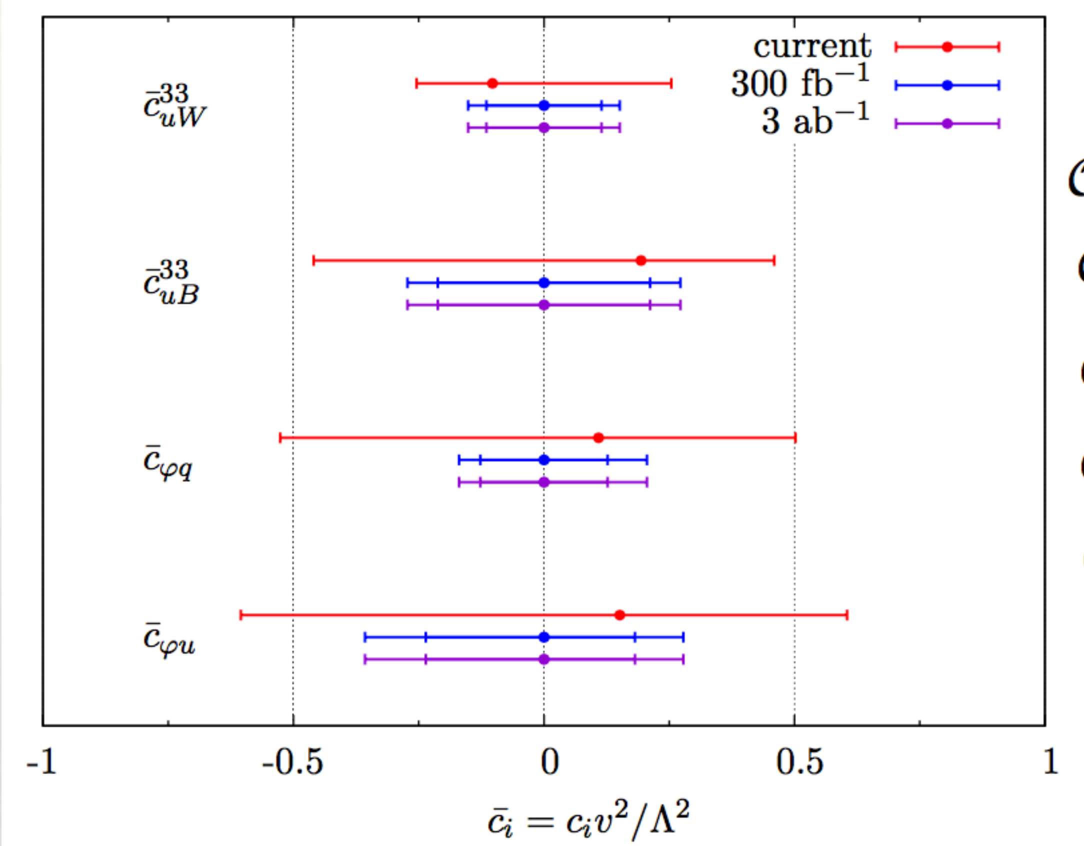
$tX, t\bar{t}Z, t\bar{t}\gamma$

$t\bar{t}Z$ only



top electroweak couplings

- fast forward through LHC lifetime

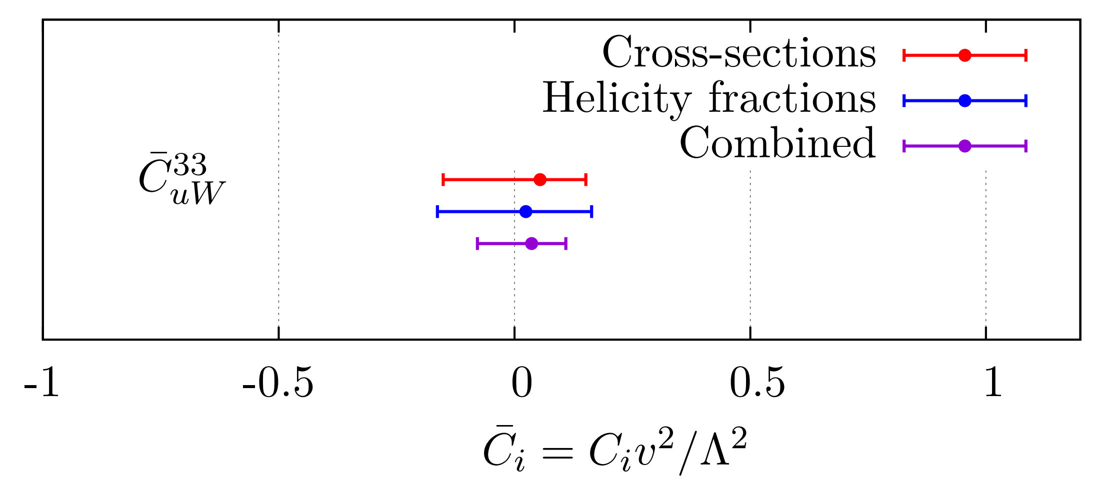


[CE, Russell ` 17]

$$\mathcal{O}_{uW} = (\bar{Q}\sigma^{\mu\nu}u)\tau^I\tilde{\varphi}W^I_{\mu\nu}$$
$$\mathcal{O}_{uB} = (\bar{Q}\sigma^{\mu\nu}u)\tilde{\varphi}B_{\mu\nu}$$
$$\mathcal{O}^{(3)}_{\varphi q} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{Q}\tau^I\gamma^\mu Q)$$
$$\mathcal{O}^{(1)}_{\varphi q} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{Q}\gamma^\mu Q)$$
$$\mathcal{O}_{\varphi u} = (\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}\gamma^\mu u).$$

top pairs: $\mathcal{O}^{(3)}_{\varphi q} - \mathcal{O}^{(1)}_{\varphi q} \equiv \mathcal{O}_{\varphi q}$

cf. LHC *W* helicity fractions [full fit]



[Zhang, Willenbrock ` 10]

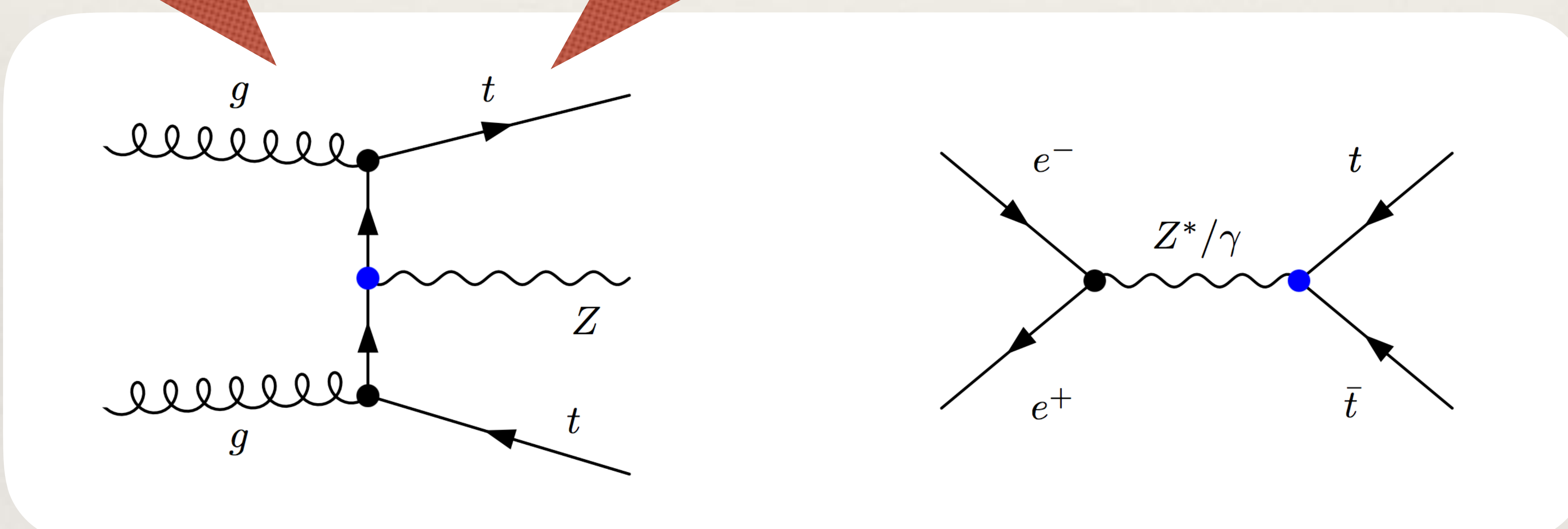
- lots of space left for (systematic) improvement!

- complementary to involved LHC measurements

systematics

"marginalising" over cms energy

[Contino, Falkowski, Goertz, Grojean, Riva ` 16]



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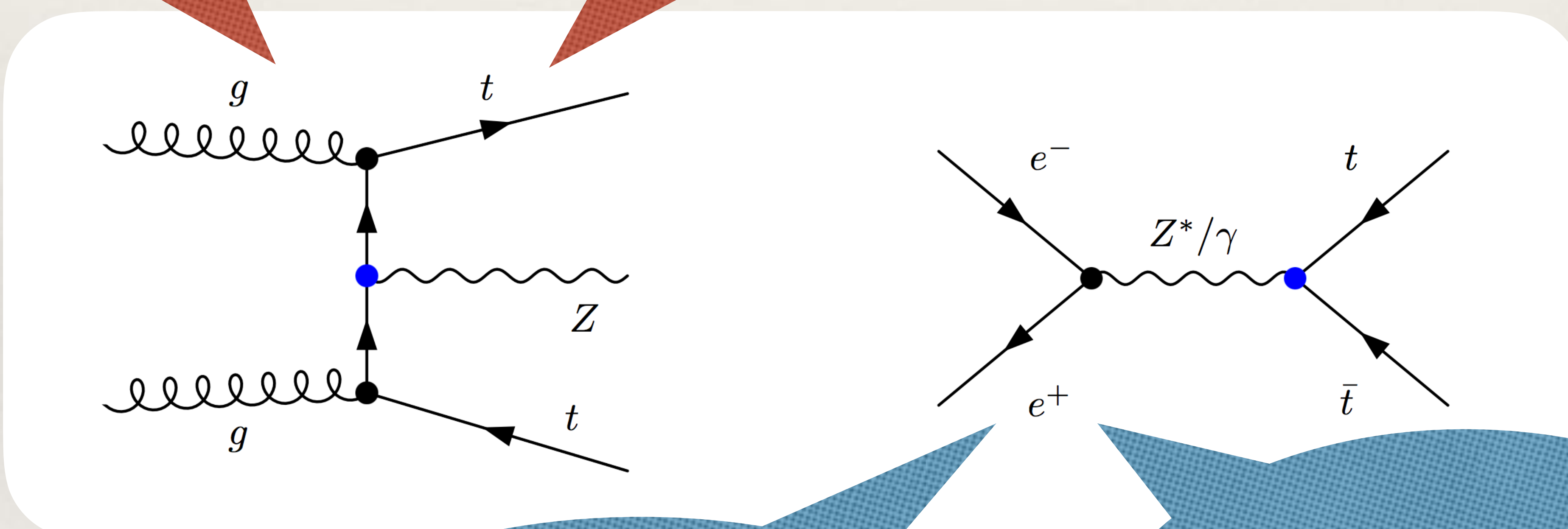

high precision!

transparent validity

- **setup**
  - *energy:* ILC 500 GeV and CLIC 3 TeV
  - *polarisation:* unpolarised and $P_{e^-} = \pm 0.8$, $P_{e^-} = \mp 0.3$
  - *observables:* total cross sections and forward-backward asymmetry

$$A^t_{FB} = \frac{N(\cos\theta_t > 0) - N(\cos\theta_t < 0)}{N(\cos\theta_t > 0) + N(\cos\theta_t < 0)}$$

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e.g. [Bernreuther et al. ` 06]
[Fleischer, et al. ` 03]
[Gao, Zhu ` 14]

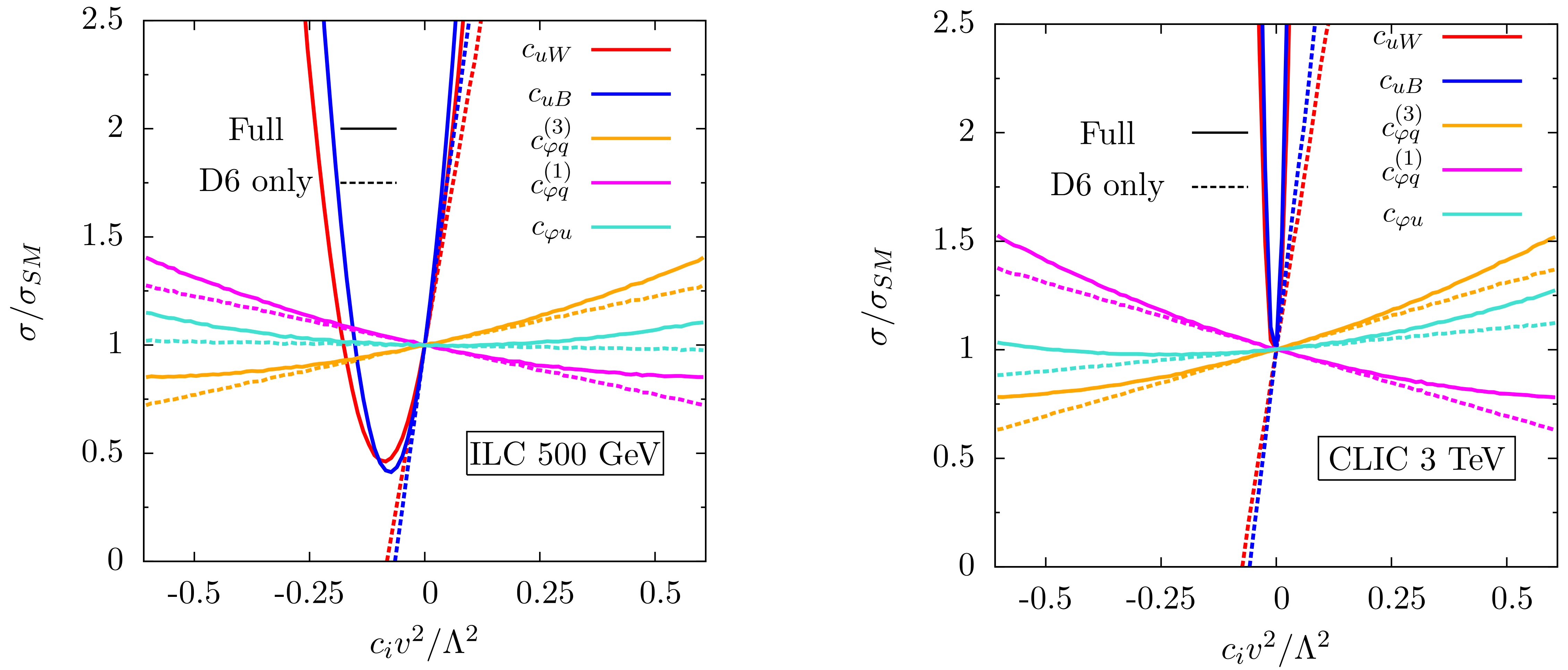
[Alexander Mitov's talk]

- **constraints from SM pseudodata 1% theory and exp. uncertainty**

e.g. [Amjad et al, ` 15]

- **only modified top electroweak couplings, LO in EFT**

why these observables?

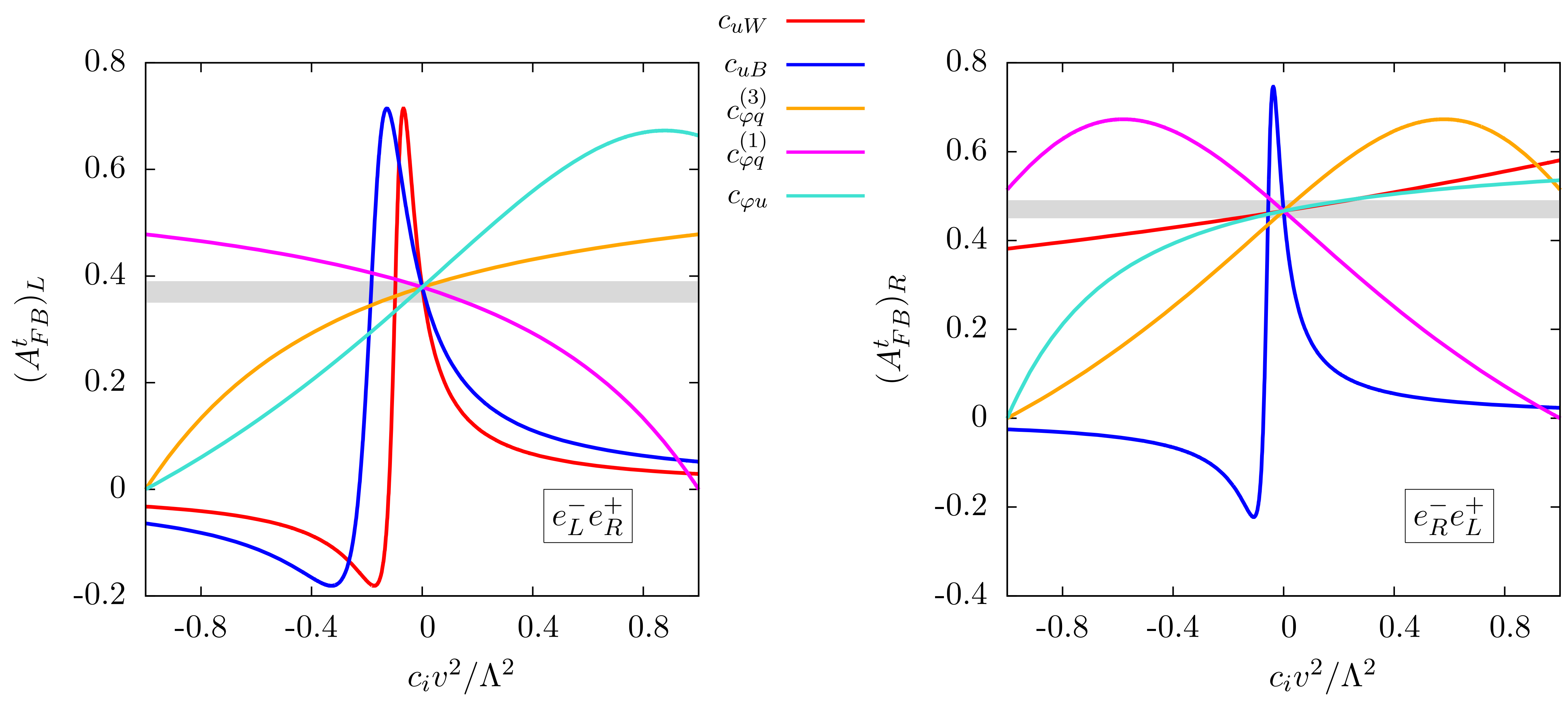


$\longrightarrow$ see also Philipp Roloff's talk

why these observables?

- helicity fractions are already in good shape at the LHC…
- asymmetries encode orthogonal information compared to cross sections

for LHC: [Perelló, Roselló, Vos, `15]



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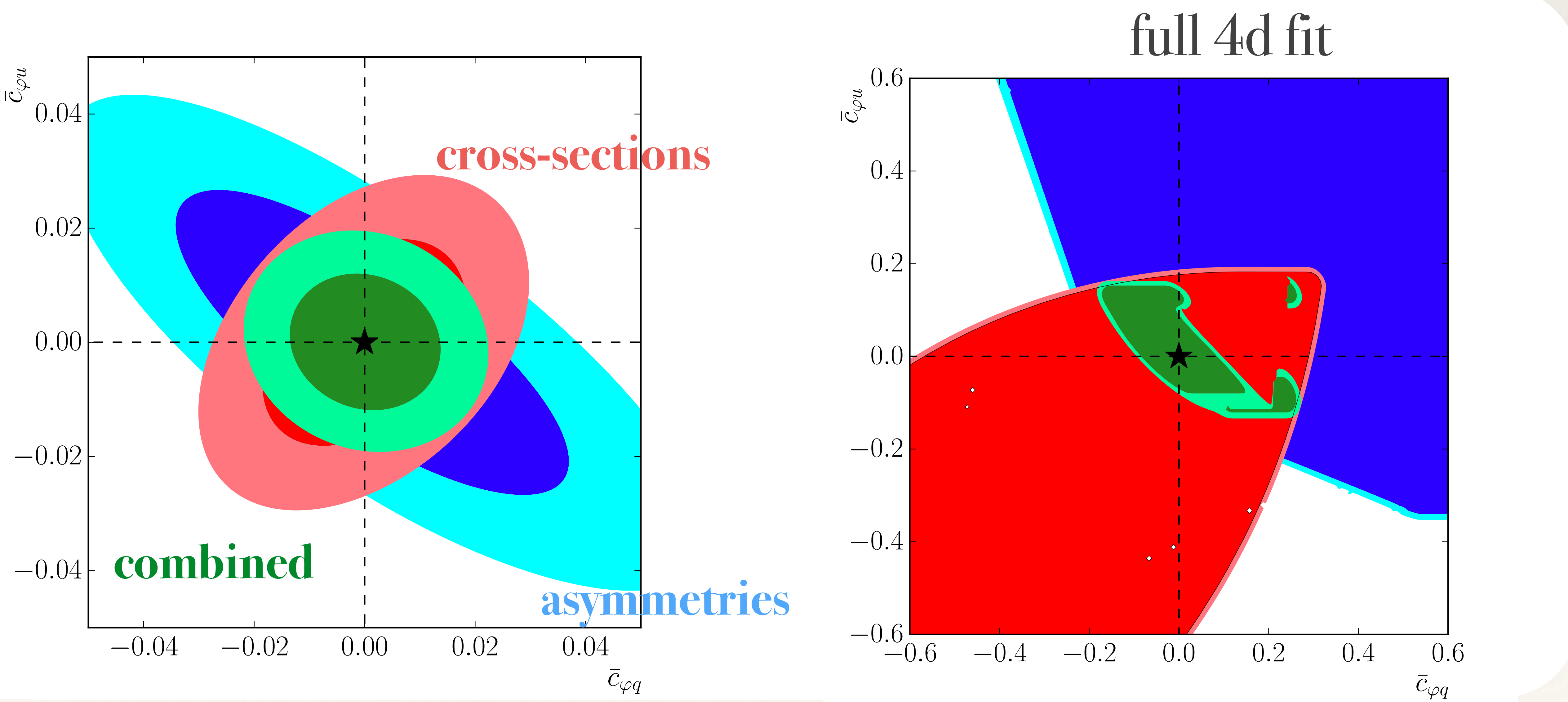
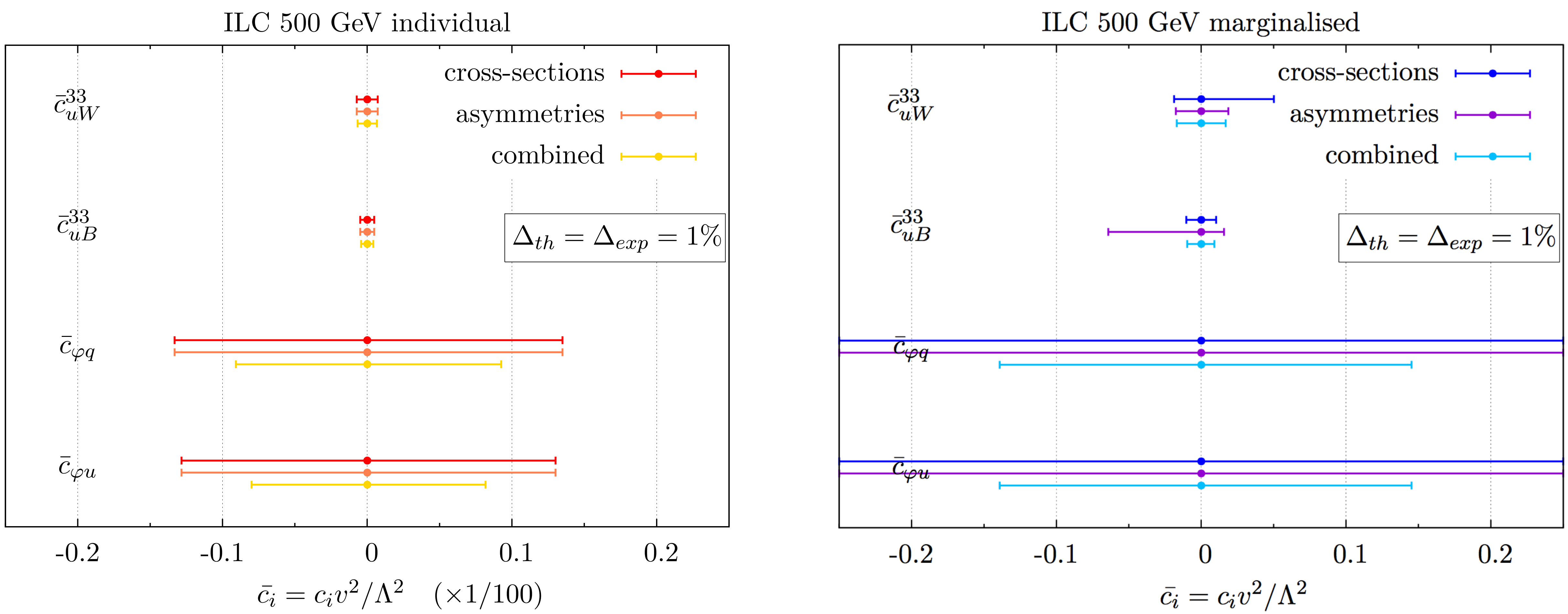


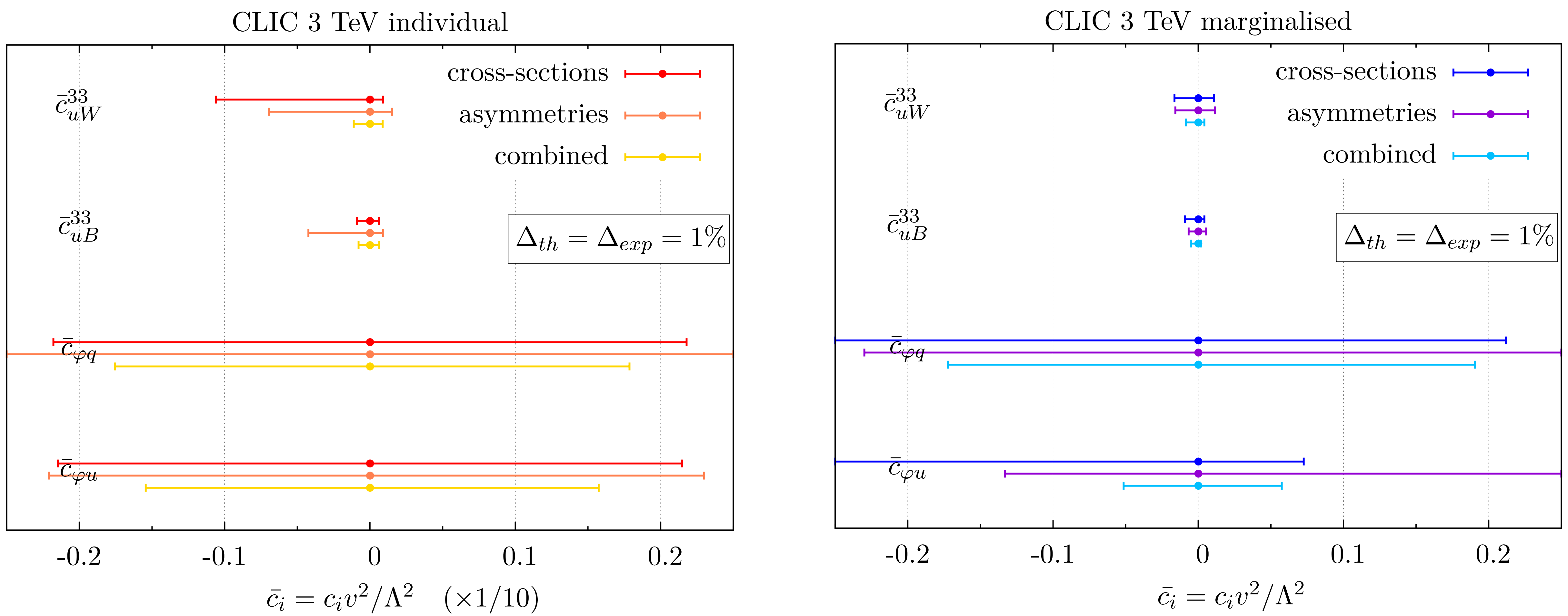
ILC 500 GeV



see also [Aguilar-Saavedra, Fiolhais, Onofre. ` 12]

- improvement by up to a factor of 10^3 compared to LHC
- marginalised results weaker, but overly conservative (BSM matching)

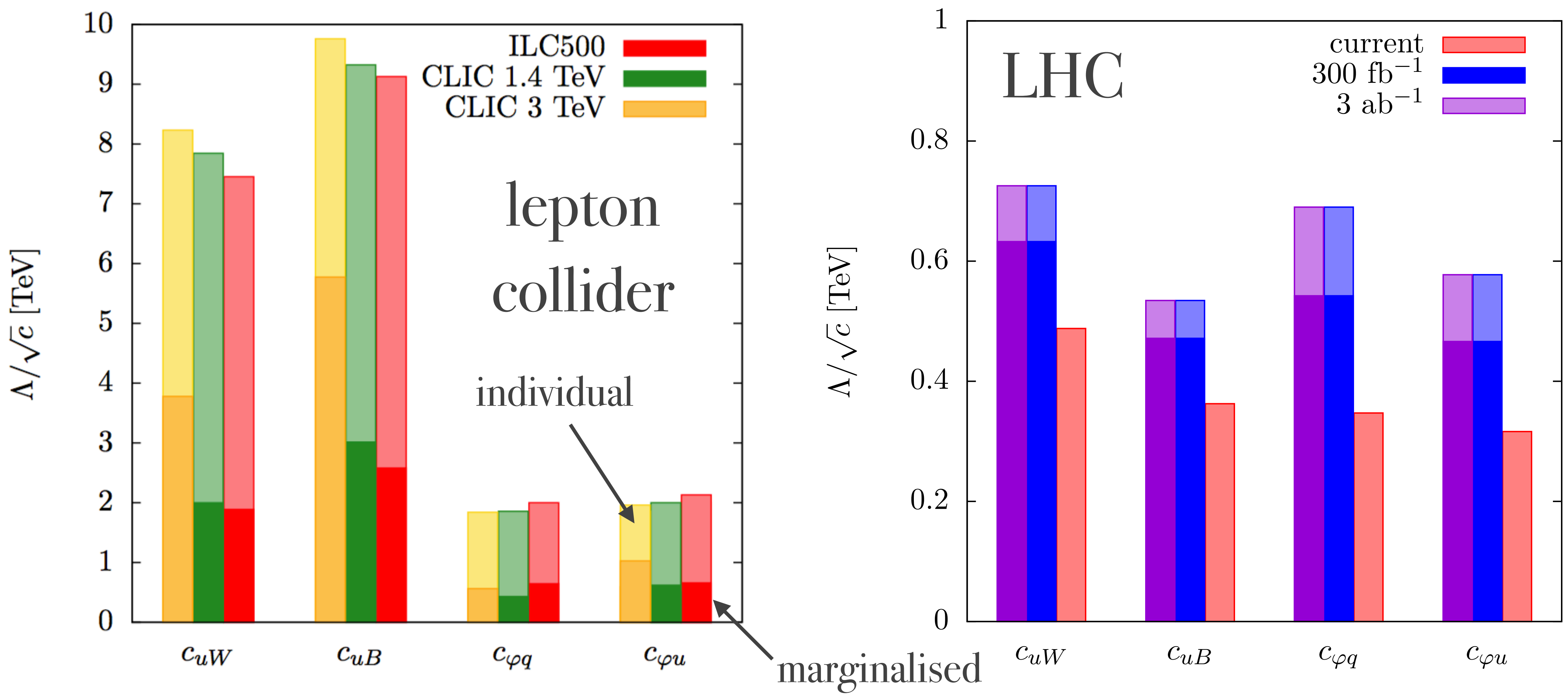
CLIC 3 TeV



- momentum dependent operators further improved, feeds into marginalised results
- pay price for decreased total cross section sensitivity within the assumptions of our fit [highly off-shell Z - run at threshold?]

.....[Beneke et al, `15] [Reuter et al. `16]

comparison of sensitivity

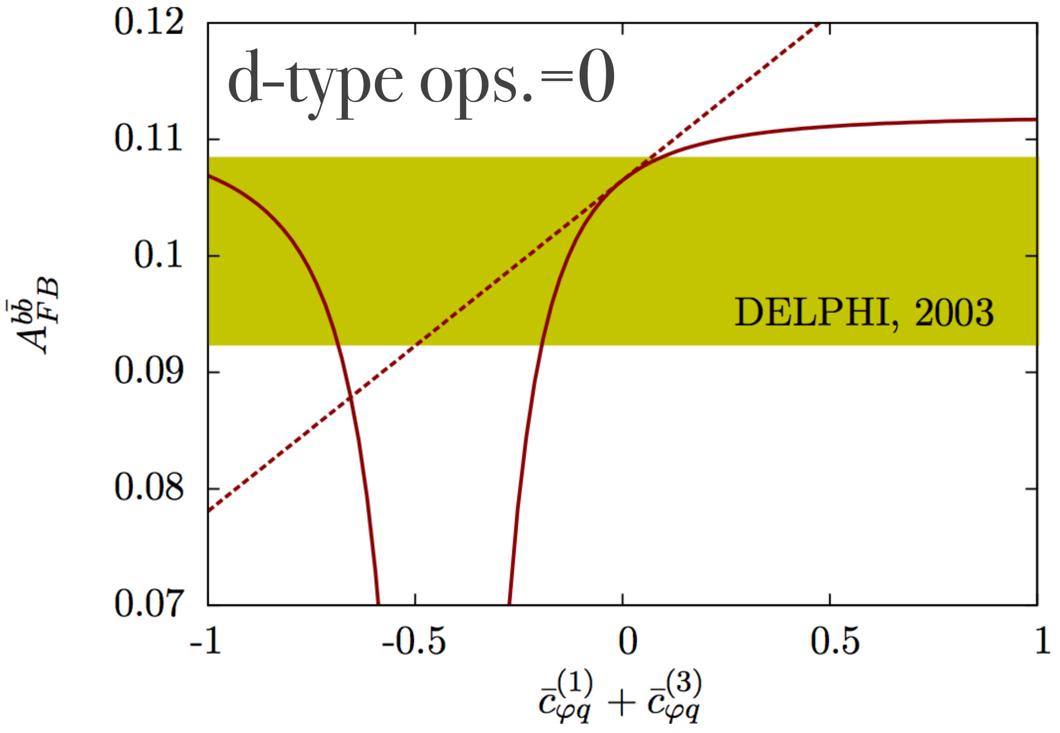


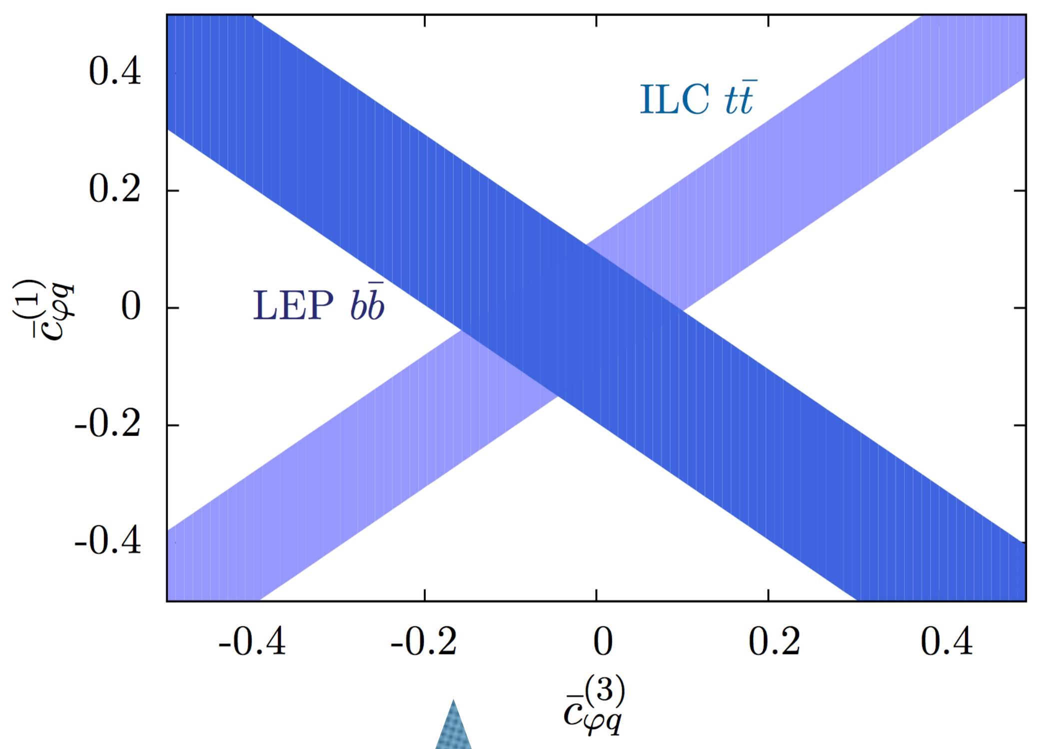
- constraints much stronger than LHC, big opportunity of BSM physics
- large sensitivity to marginalisation → power counting

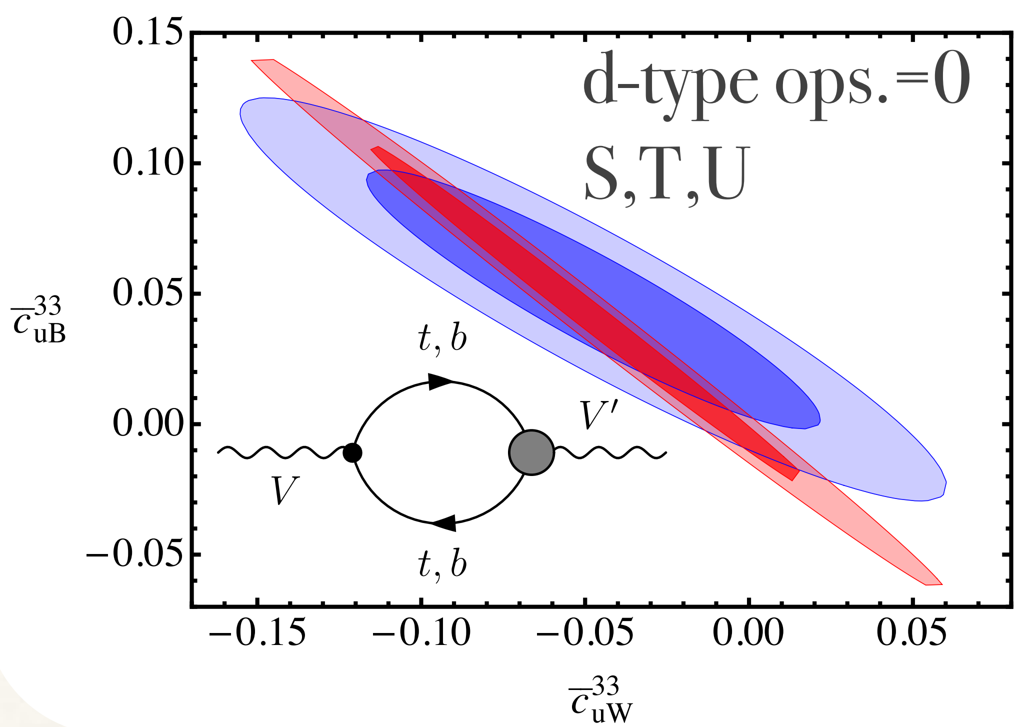
what about EWPO?

- intrinsically tedious, all operators need to be considered, not only top sector ones
- that said….

what about EWPO?







- potential improvement but probably restricted to UV-biased fit
- potentially break blind directions

see also [de Blas et al. `15]

Summary

- fully differential fitting techniques have seen great progress, interpolation approaches are scalable
- direct LHC constraints will leave a lot of space for non-standard top quark physics
- sensitivity at CLIC provides a huge potential for searches for non-resonant new physics in the top sector
- sensitivity to marginalisation shows that the potential of UV-informed fits is even bigger

BACKUP

fitting procedure in a nutshell

multidimensional interpolation & fit

adapted random walks in parameter space

[SFITTER, Lafaye, Plehn, Zerwas `04]

parameterisation-based interpolation

[PROFESSOR, Buckley et al. `09]

$$\sigma \sim \sigma_{\mathrm{SM}} + C_i \sigma_{D6} + C_i^2 \sigma_{D6^2}$$

$$f_b(\{C_i\}) = \alpha_0^b + \sum_i \beta_i^b C_i + \sum_{i \leq j} \gamma_{i,j}^b C_i C_j + \dots$$

$$\chi^2(\mathbf{C}) = \sum_{\mathcal{O}} \sum_{i,j} \frac{(f_i(\mathbf{C}) - E_i)\rho_{i,j}(f_j(\mathbf{C}) - E_j)}{\sigma_i \sigma_j}$$

uncertainties (up to order 4)

keep track of dim6² effects

analytic results where possible