University of Glasgow

Christoph Englert

The top quark sector at hadron colliders

Fit(s) for LHC run-2

Edinburgh, 10.10.2016

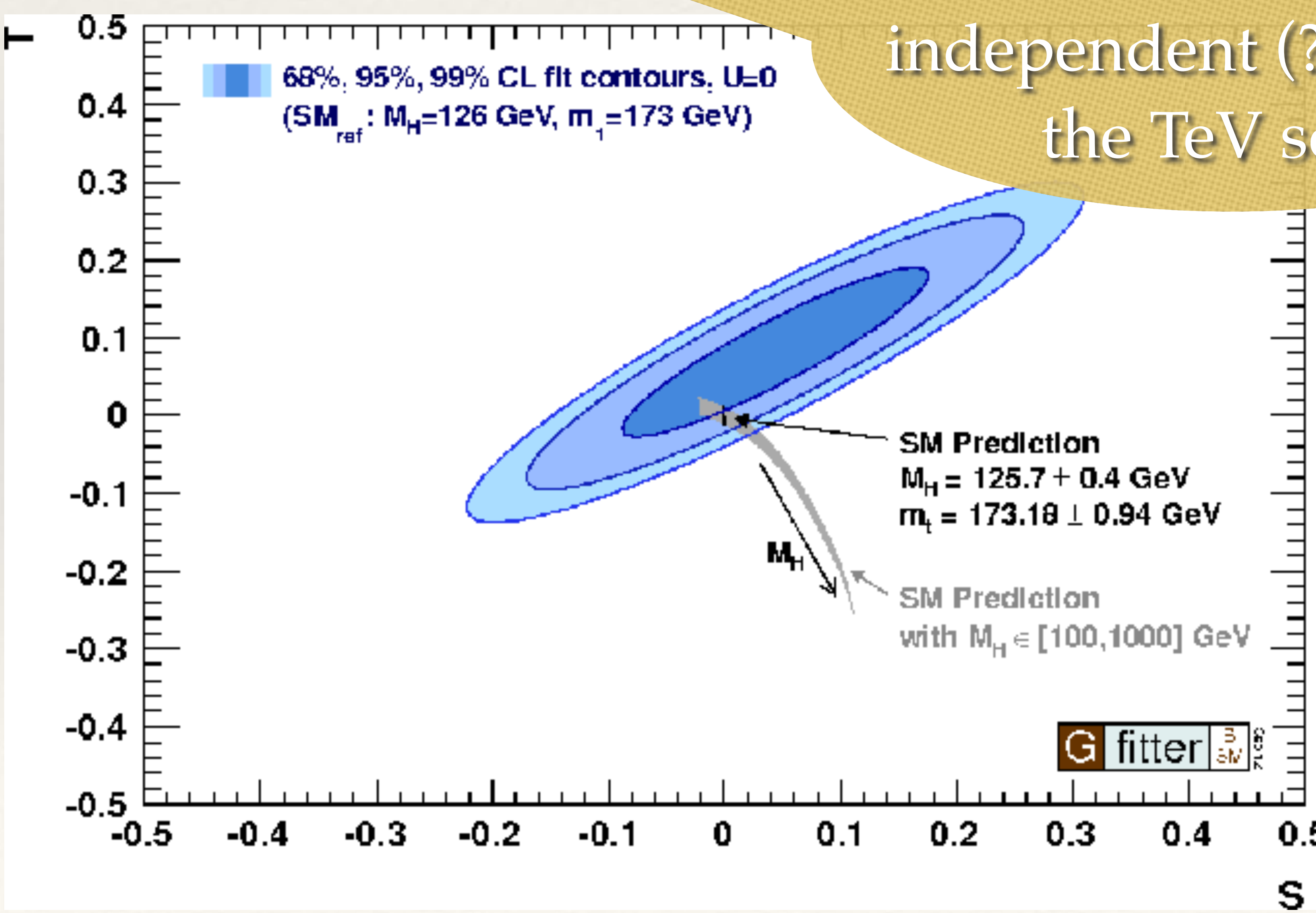
based on [Buckley , CE, Ferrando, Miller, Moore, Russell, White ` 15]^2
[CE, Moore, Nordstrom, Russell ` 16]

Why do we have to have this workshop?

- SM+Higgs works quite well
- that's annoying but not unexpected
- what's the BSM landscape?

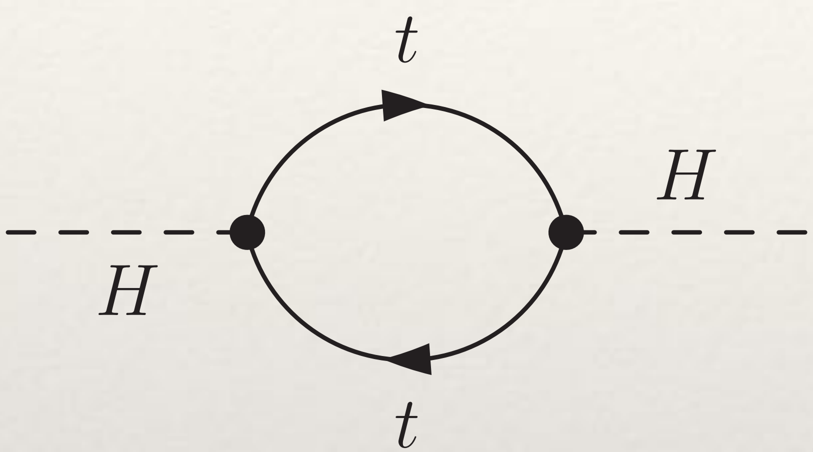
concrete UV complete models

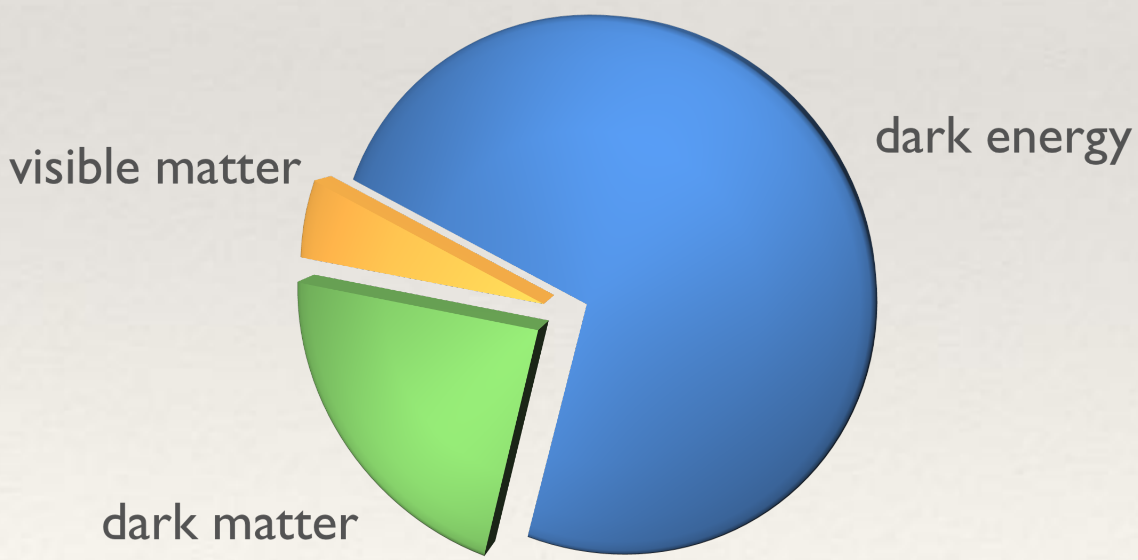
model-independent (?) around the TeV scale



What are good places to look?

- ☛ global fits to hundreds of parameters technically challenging
- ☛ educated guesses





Higgs sector

top sector

dark matter

neutrinos

dark energy

What are good places to look?

top sector

- my talk: what can we learn from the top sector at the LHC

0. top physics is abundant - why not use it **directly**
1. what's the status after the first LHC runs
2. what's the best way to constrain generic BSM phenomena in the top sector in the future

Model - independence?

the SM is flawed

no evidence for exotics

coupling/scale separated BSM physics

Effective Field Theory

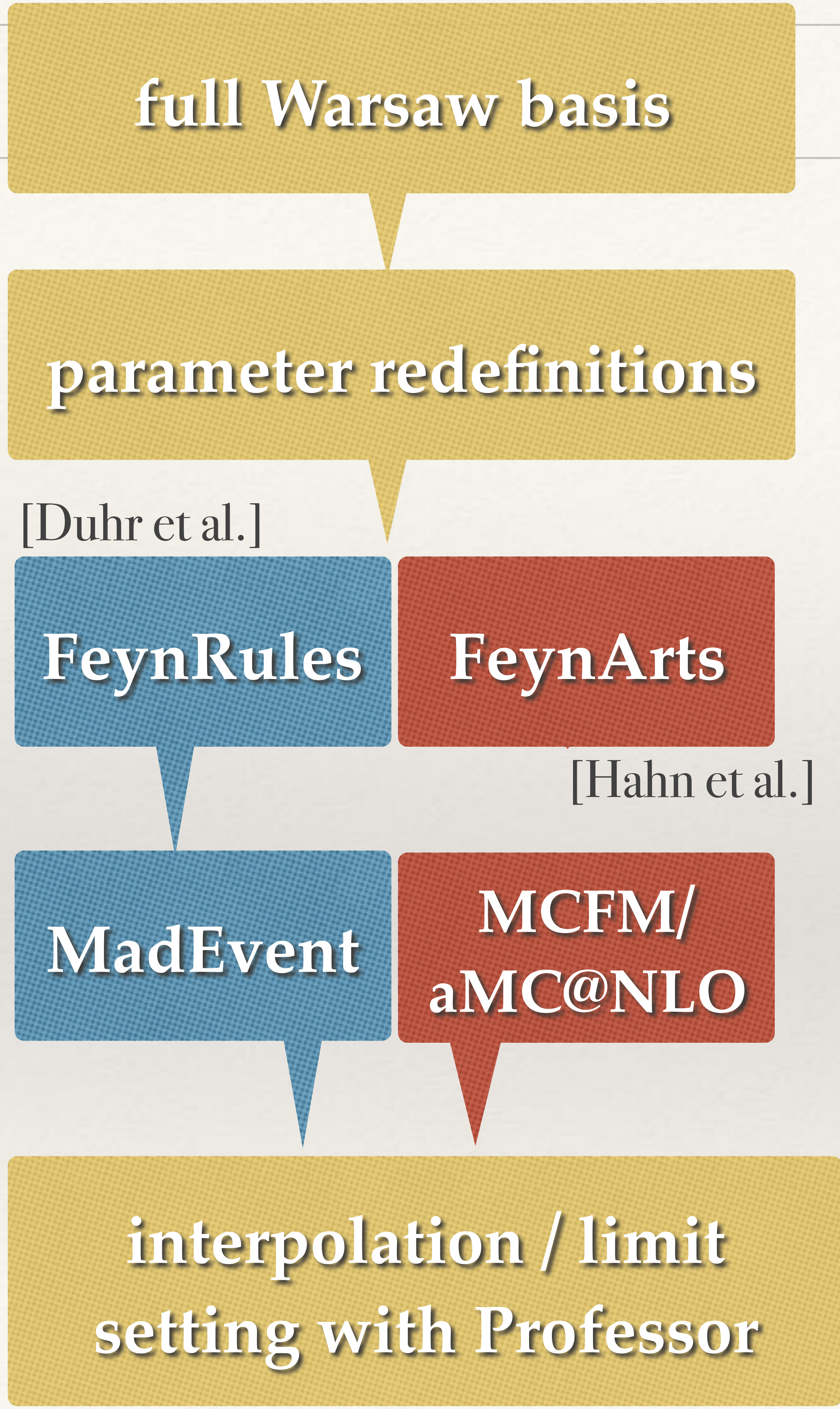
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

[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
- …

set-up outline



general idea

- aim to create a scalable framework
- no random walks, but polynomial interpolation of fully differentiable observables
- we know the outcome!

$$\mathrm{d}\sigma = \mathrm{d}\sigma^{\mathrm{SM}} + \mathrm{d}\sigma^{\mathcal{O}_i}/\Lambda^2 + \mathrm{d}\bar{\sigma}^{\mathcal{O}_i}/\Lambda^4$$

nice interplay with Morse theory

- **"do parameterisation once have it forever"** *scalability*

[Buckley et al.]

Andy's talk

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**”

constrained top EFT status

- operators

$$O_{qq}^{(1)} = (\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu q)$$
$$O_{qq}^{(3)} = (\bar{q}\gamma_\mu \tau^I q)(\bar{q}\gamma^\mu \tau^I q)$$
$$O_{uu} = (\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$$
$$O_{qu}^{(8)} = (\bar{q}\gamma_\mu T^A q)(\bar{u}\gamma^\mu T^A u)$$
$$O_{qd}^{(8)} = (\bar{q}\gamma_\mu T^A q)(\bar{d}\gamma^\mu T^A d)$$
$$O_{ud}^{(8)} = (\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)\,.$$

$$O_{uW} = (\bar{q}\sigma^{\mu\nu}\tau^I u)\tilde{\phi}W^I_{\mu\nu}$$
$$O_{uG} = (\bar{q}\sigma^{\mu\nu}T^A u)\tilde{\phi}G^A_{\mu\nu}$$
$$O_G = f_{ABC}G_\mu^{A\nu}G_\nu^{B\lambda}G_\lambda^{C\mu}$$
$$O_{\tilde{G}} = f_{ABC}\tilde{G}_\mu^{A\nu}G_\nu^{B\lambda}G_\lambda^{C\mu}$$
$$O_{\phi G} = (\phi^\dagger\phi)G^A_{\mu\nu}G^{A\mu\nu}$$

$$O_{\phi q}^{(3)} = i(\phi^\dagger \overleftrightarrow{D}^I_\mu \phi)(\bar{q}\gamma^\mu\tau^I q)$$
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$$O_{uB} = (\bar{q}\sigma^{\mu\nu}u)\tilde{\phi}B_{\mu\nu}$$
$$O_{\phi u} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{u}\gamma^\mu u)$$
$$O_{\phi\tilde{G}} = (\phi^\dagger\phi)\tilde{G}^A_{\mu\nu}G^{A\mu\nu}$$

- 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

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

update late 2016?

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	$p_T(t), M_{t\bar{t}}, \lvert y_{t\bar{t}}\rvert$	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	$M_{t\bar{t}}, p_T(t), \lvert y_t\rvert$	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	$\Gamma_{\rm top}$	1308.4050
CDF + DØ	1.96	Combined world average	1309.7570	CDF	1.96	$\Gamma_{\rm top}$	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				

- total of 195 measurements, 174 based on differential distributions
- **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

- total of 195 measurements, 174 based on differential distributions
- **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

- total of 195 measurements, 174 based on differential distributions
- **fitting** Andy's talk

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

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

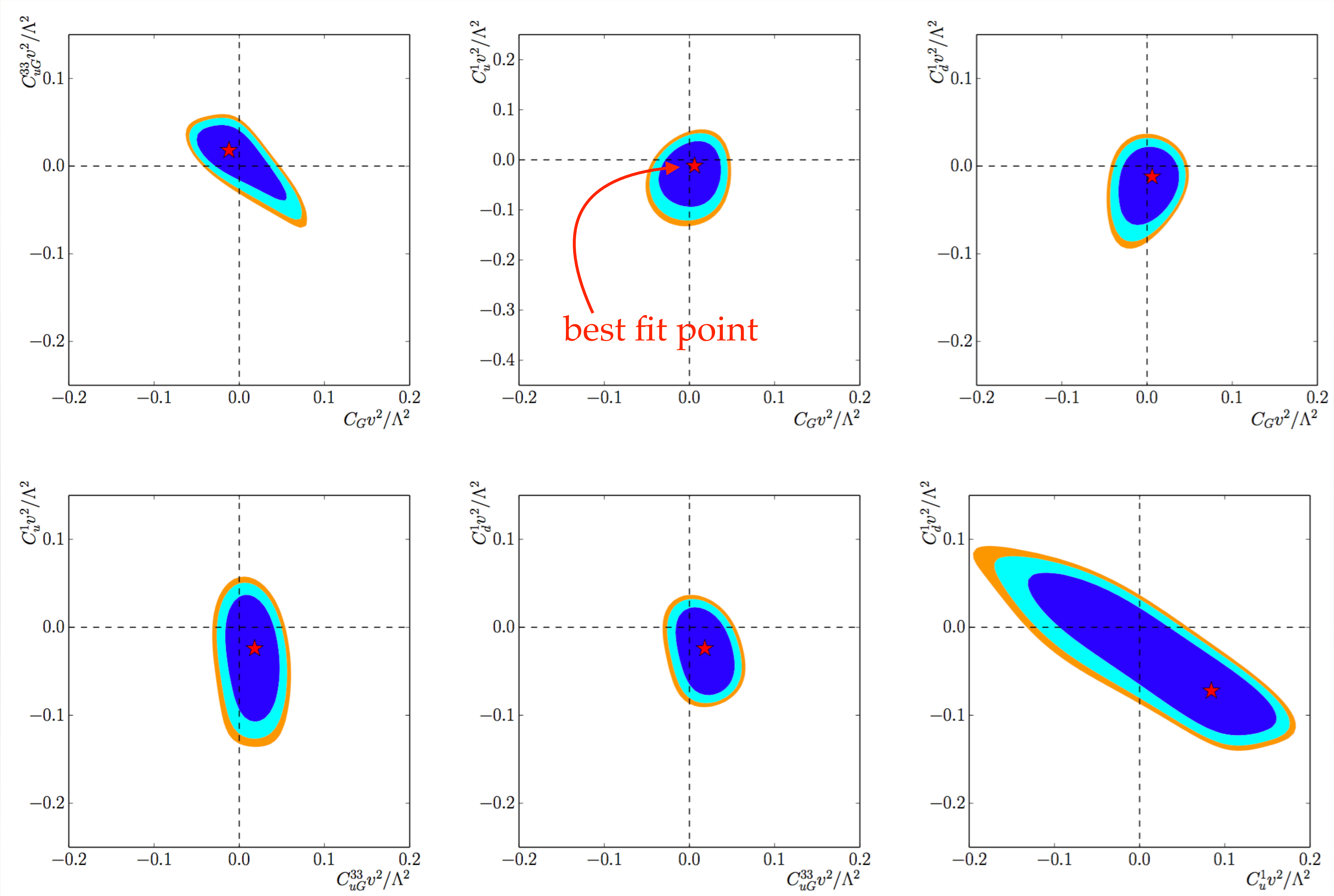
uncertainties (up to order 4)

keep track of dim6² effects

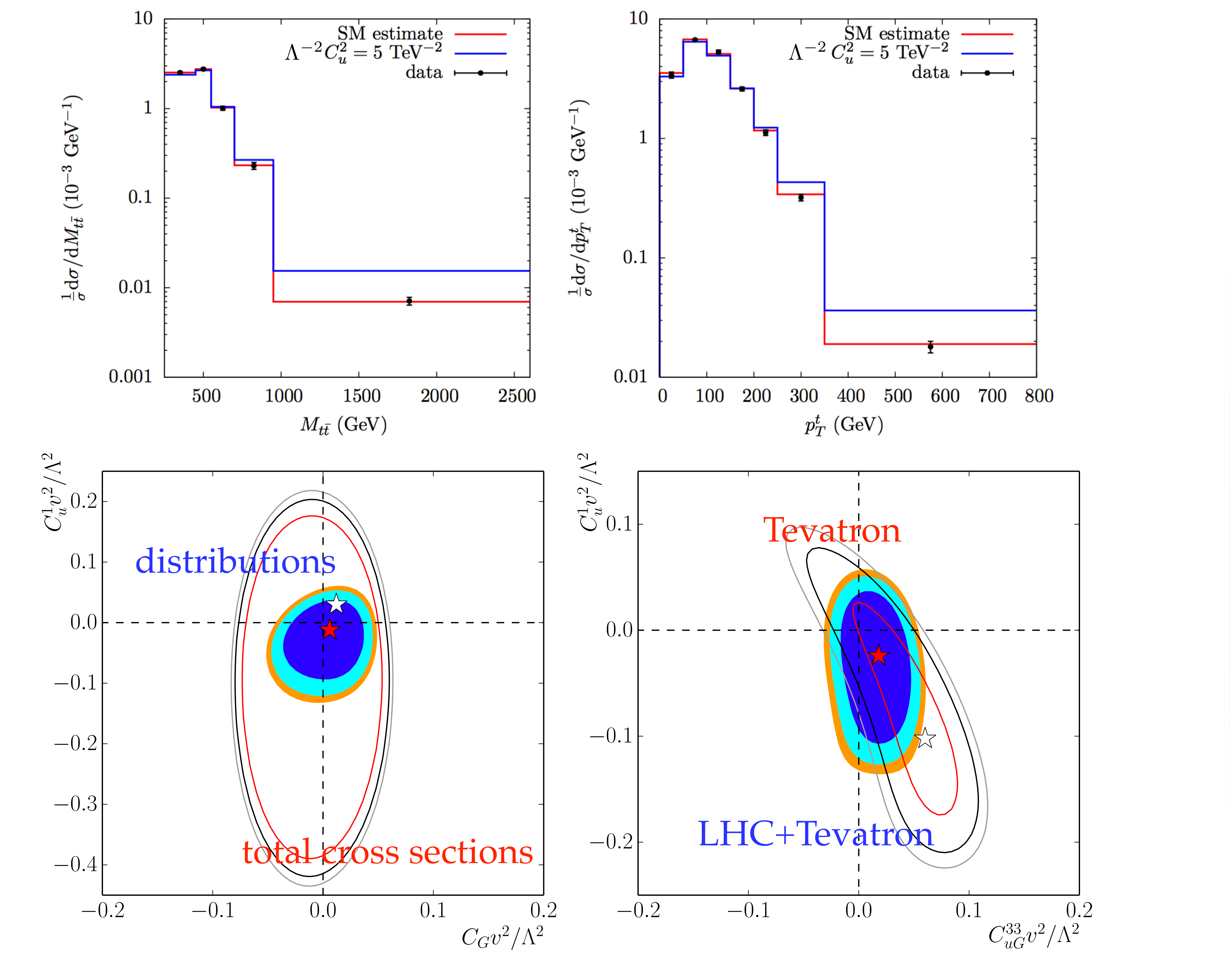
$$\chi^2(\mathbf{C}) = \sum_{\mathcal{O}} \sum_{i,j} \frac{(f_i(\mathbf{C}) - E_i)\rho_{i,j}(f_j(\mathbf{C}) - E_j)}{\sigma_i \sigma_j}$$

[Buckley , CE, Ferrando, Miller, Moore, Russell, White ` 15]

Top quark pair production

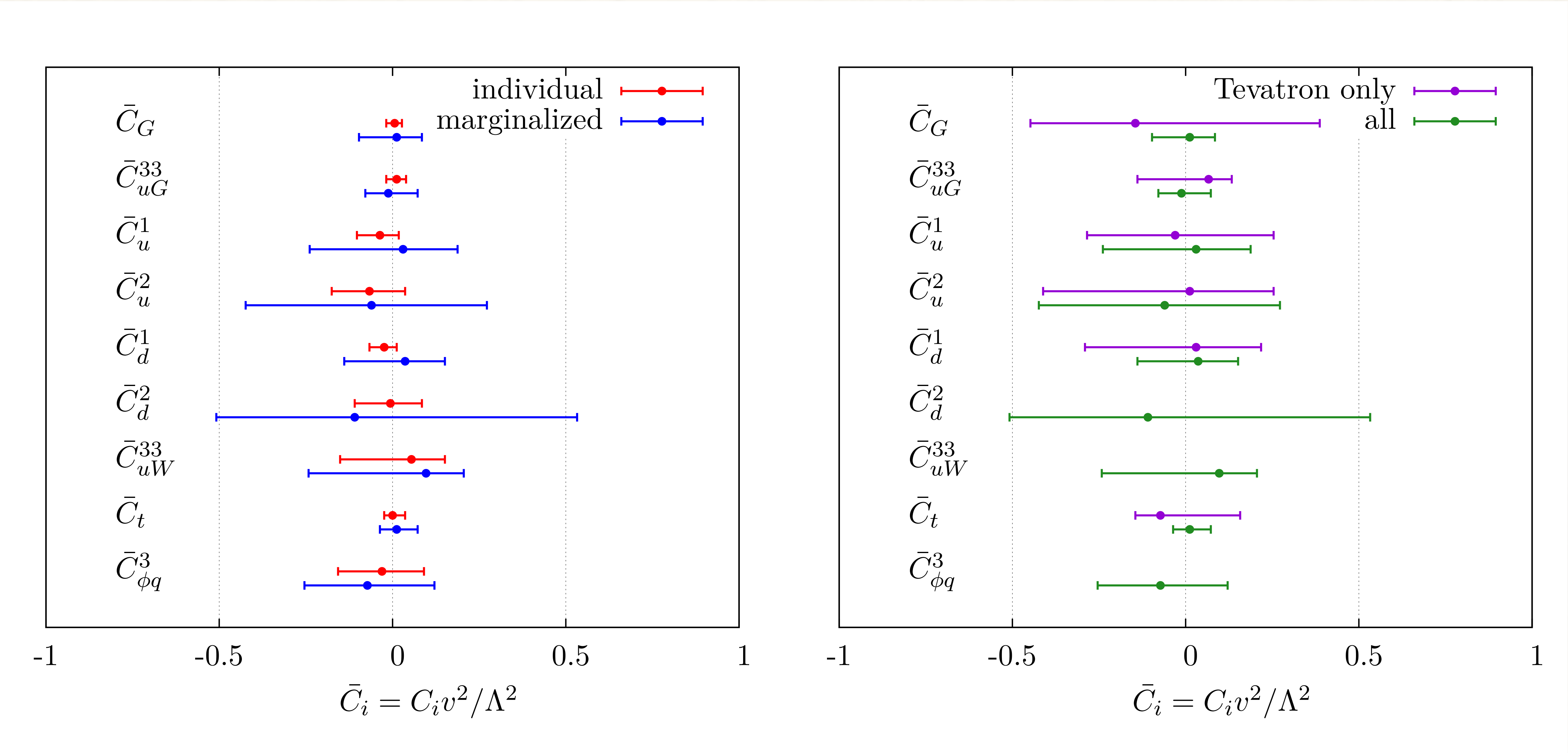


tops: LHC & Tevatron

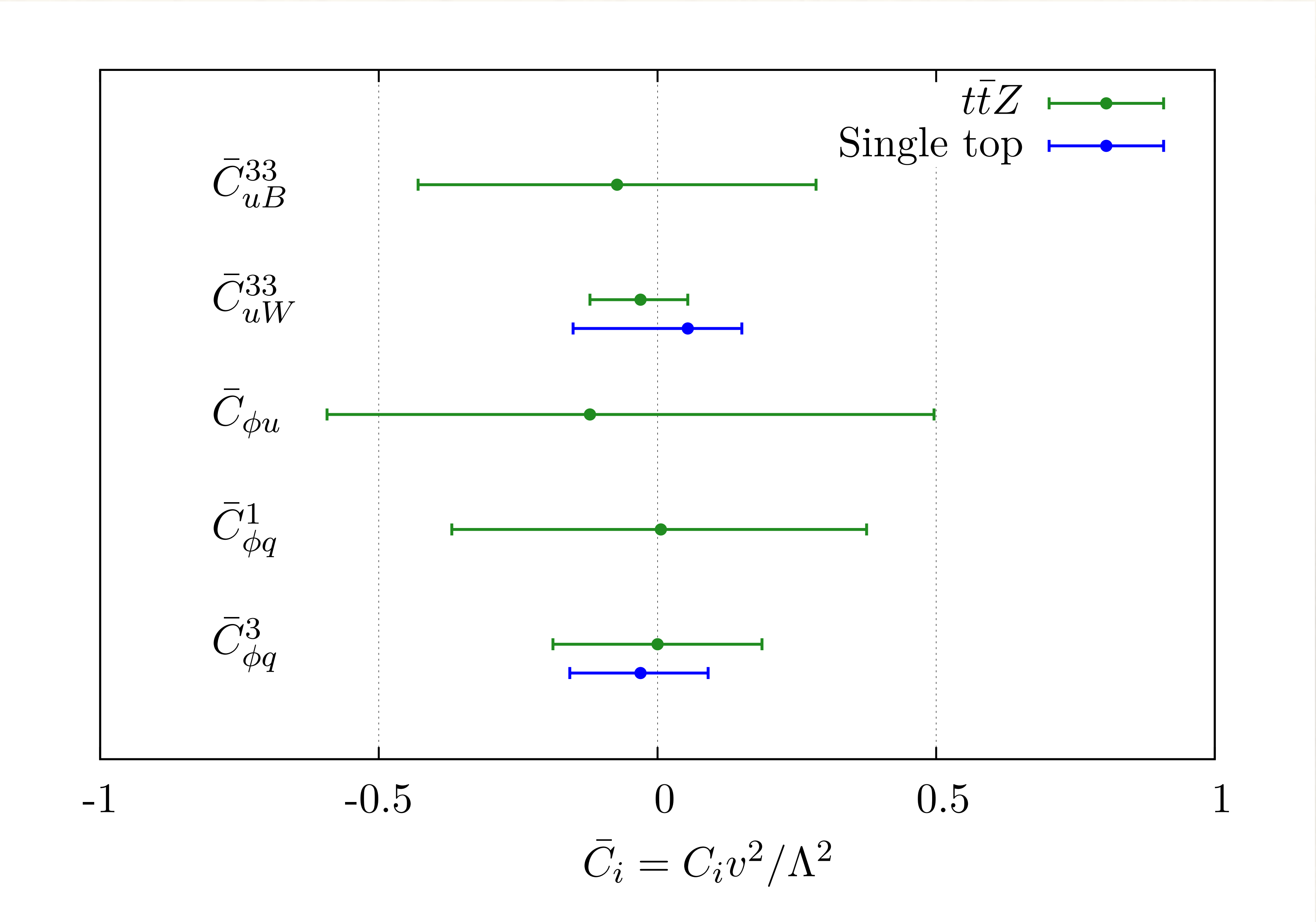


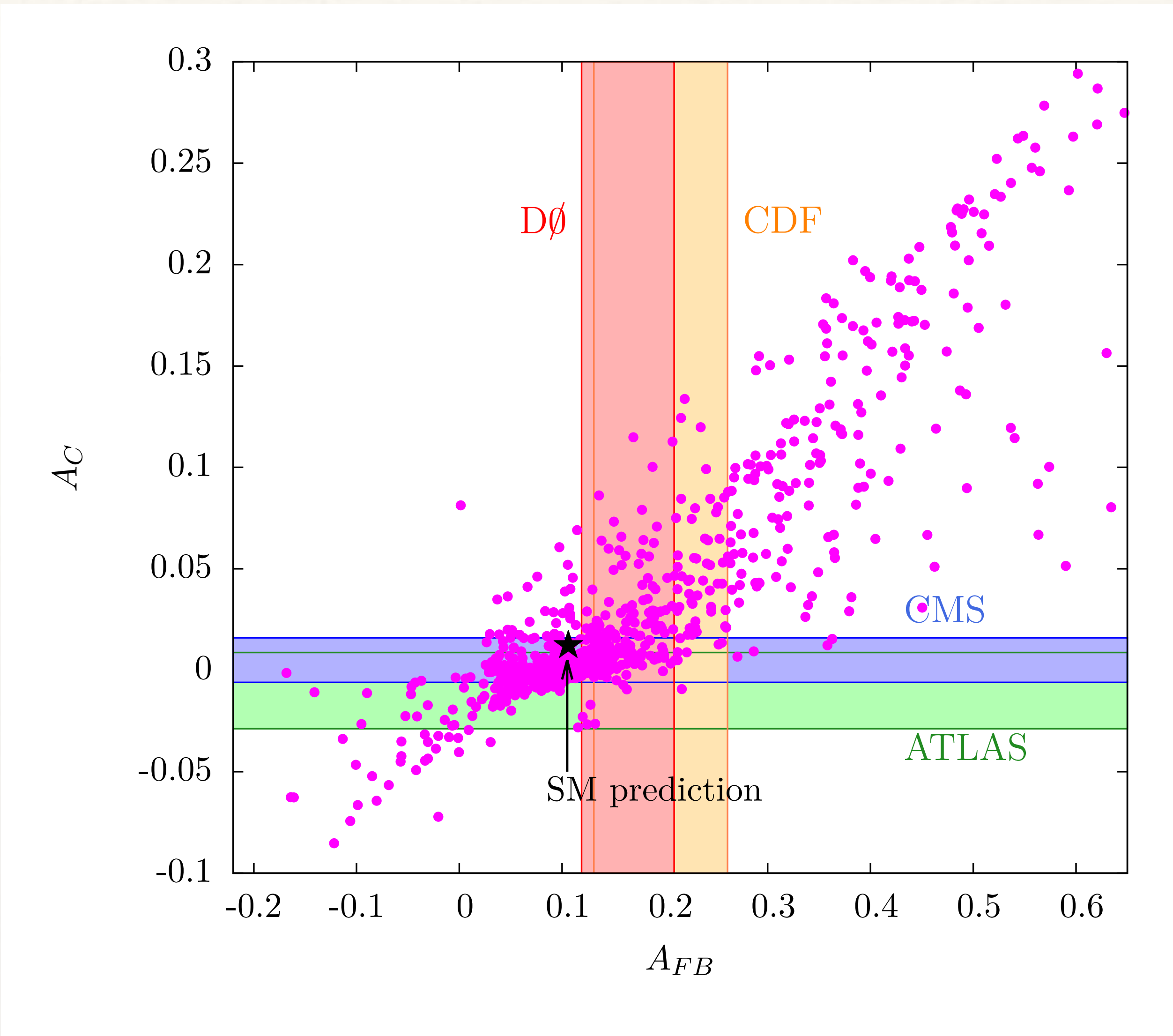
[Buckley , CE, Ferrando, Miller, Moore, Russell, White ` 15]

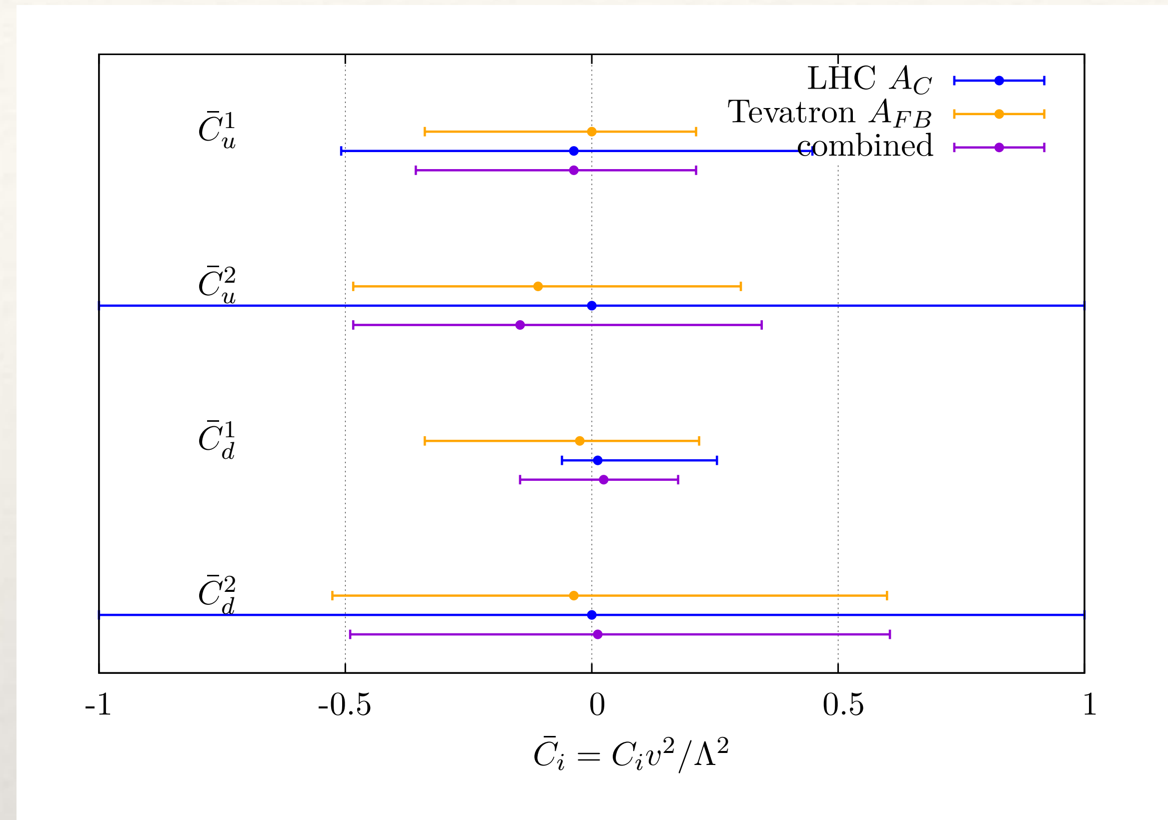
Top quark pair production



single top


$t\bar{t}Z$
Single top
$\bar{C}^{33}_{uB}$
$\bar{C}^{33}_{uW}$
$\bar{C}_{\phi u}$
$\bar{C}^{1}_{\phi q}$
$\bar{C}^{3}_{\phi q}$
-1
-0.5
0
0.5
1
$\bar{C}_i = C_i v^2/\Lambda^2$

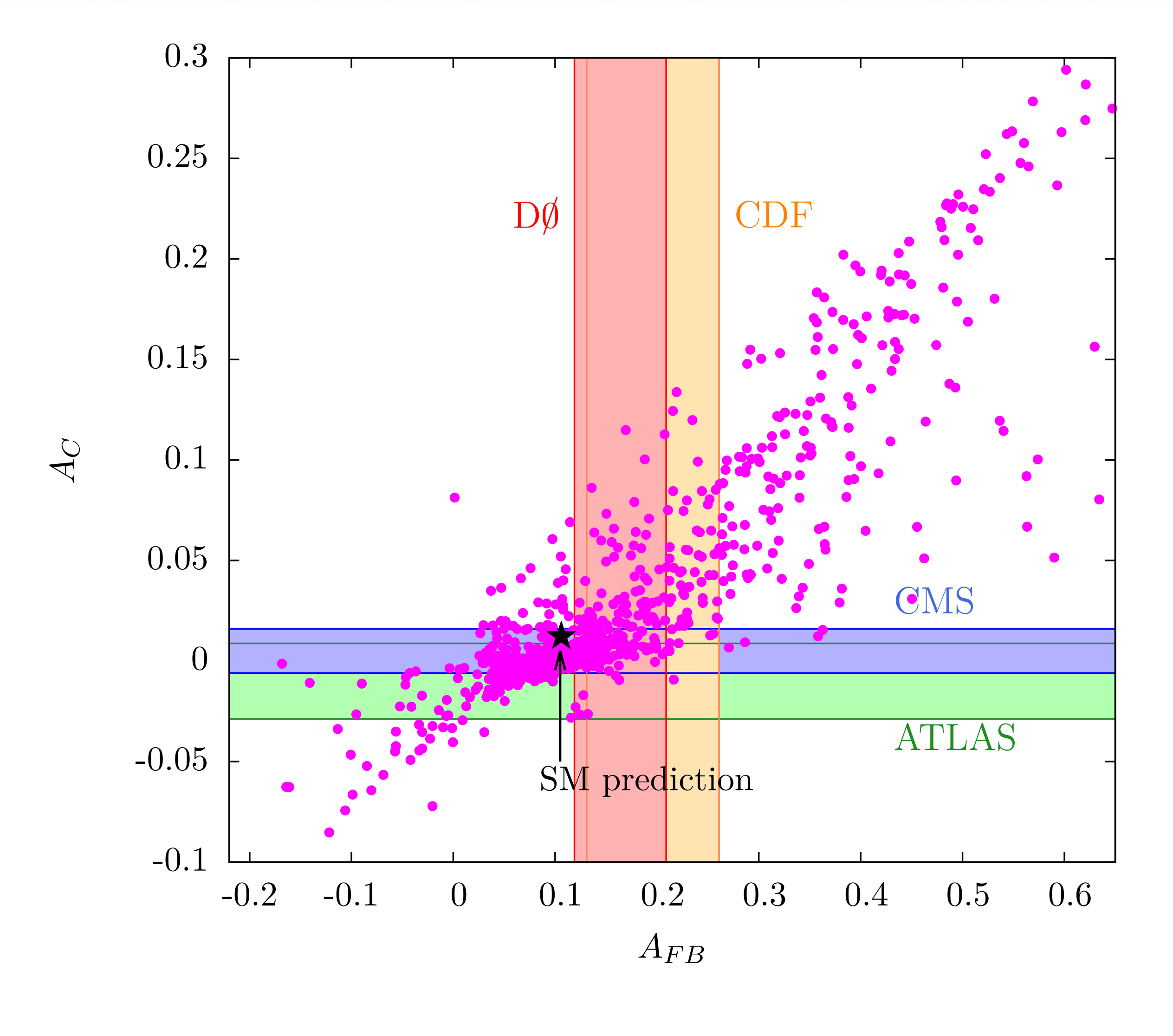


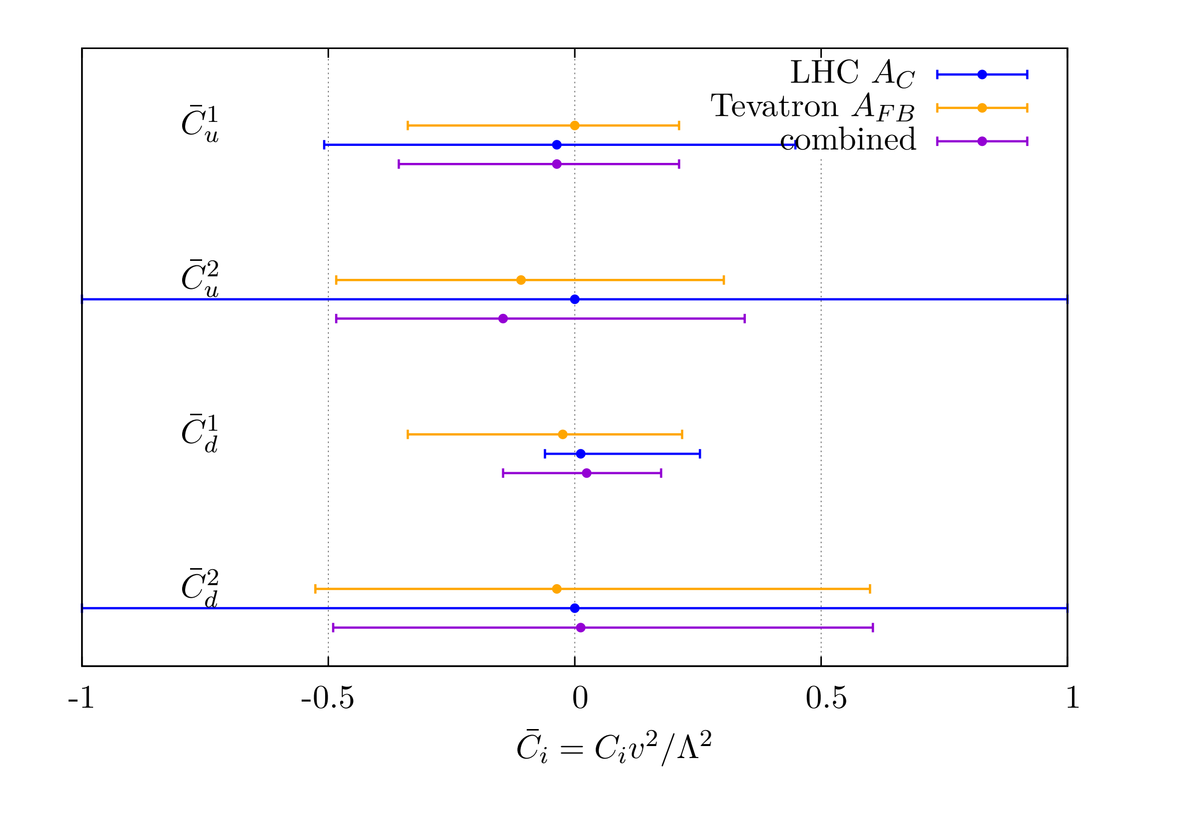


- correlated Tevatron LHC distributions are highly constraining, e.g. LHC central charge asymmetry vs Tevatron forward backward asymmetry

[Czakon, Heymes, Mitov ` 15]

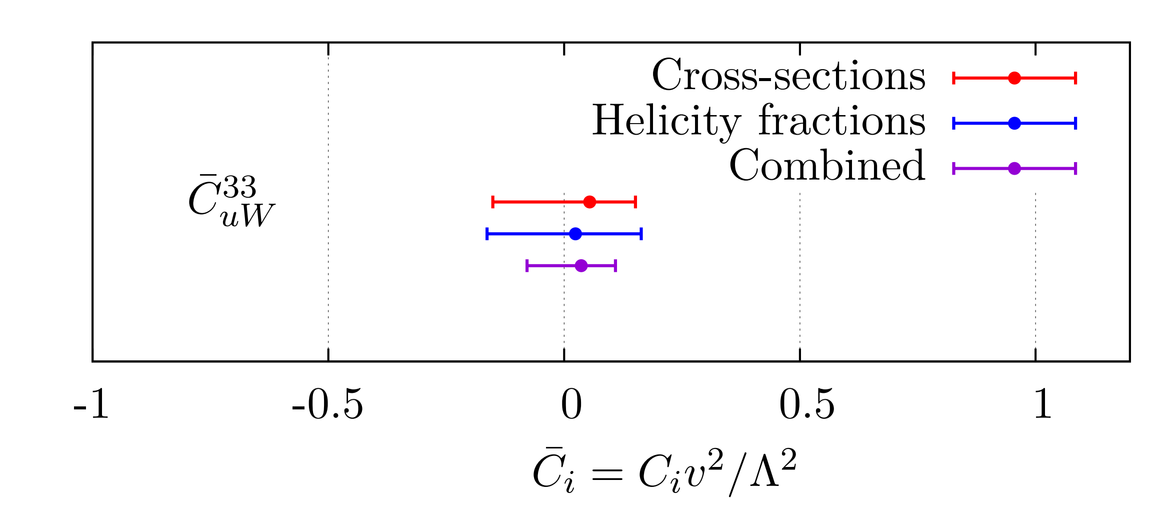
decay observables





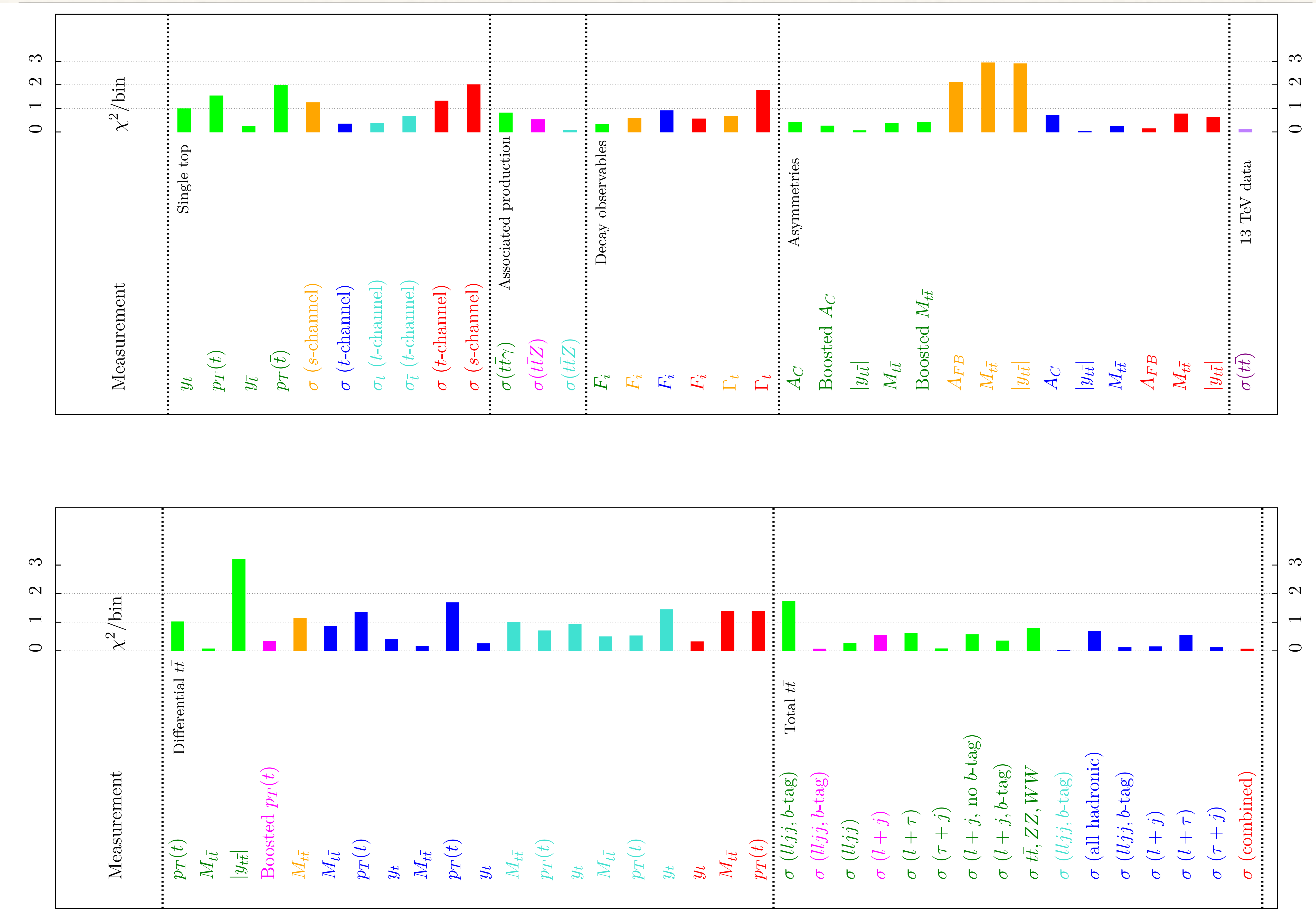
- helicity fractions

  [Zhang, Willenbrock ` 10]

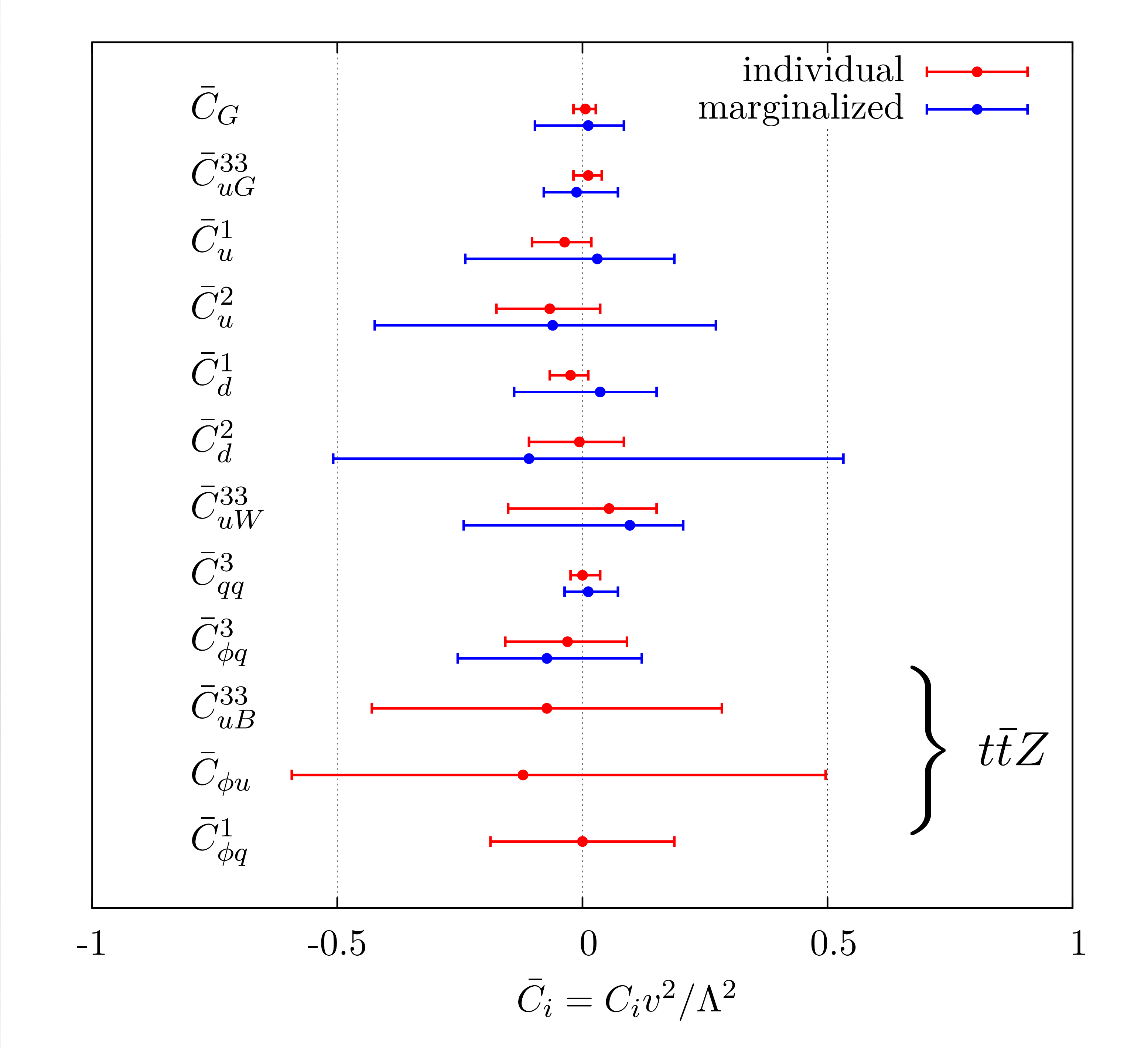


[Buckley , CE, Ferrando, Miller, Moore, Russell, White ` 15]

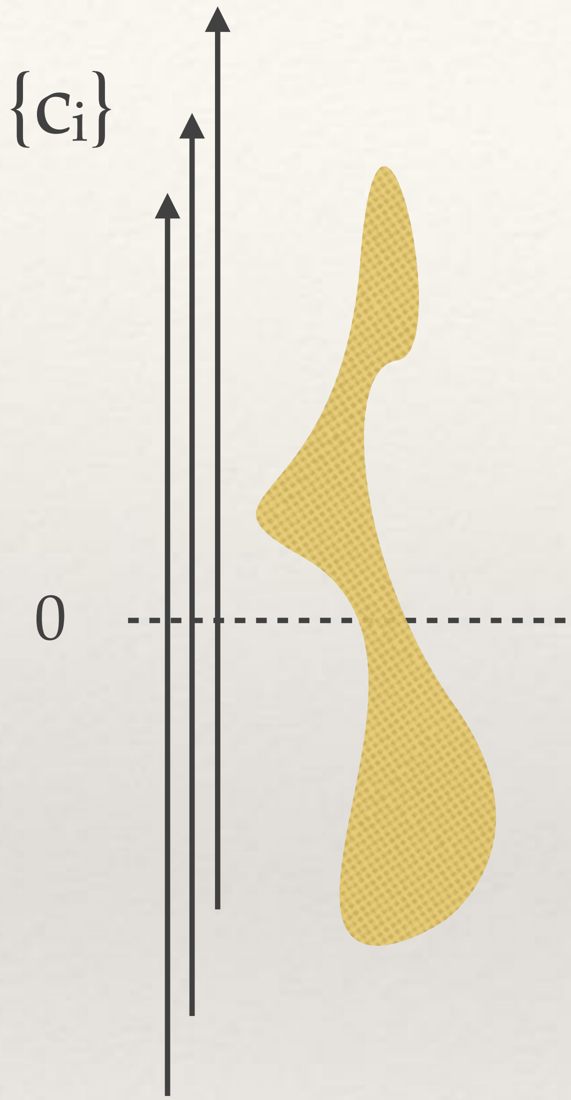
Top fit quality



Summary of the top sector

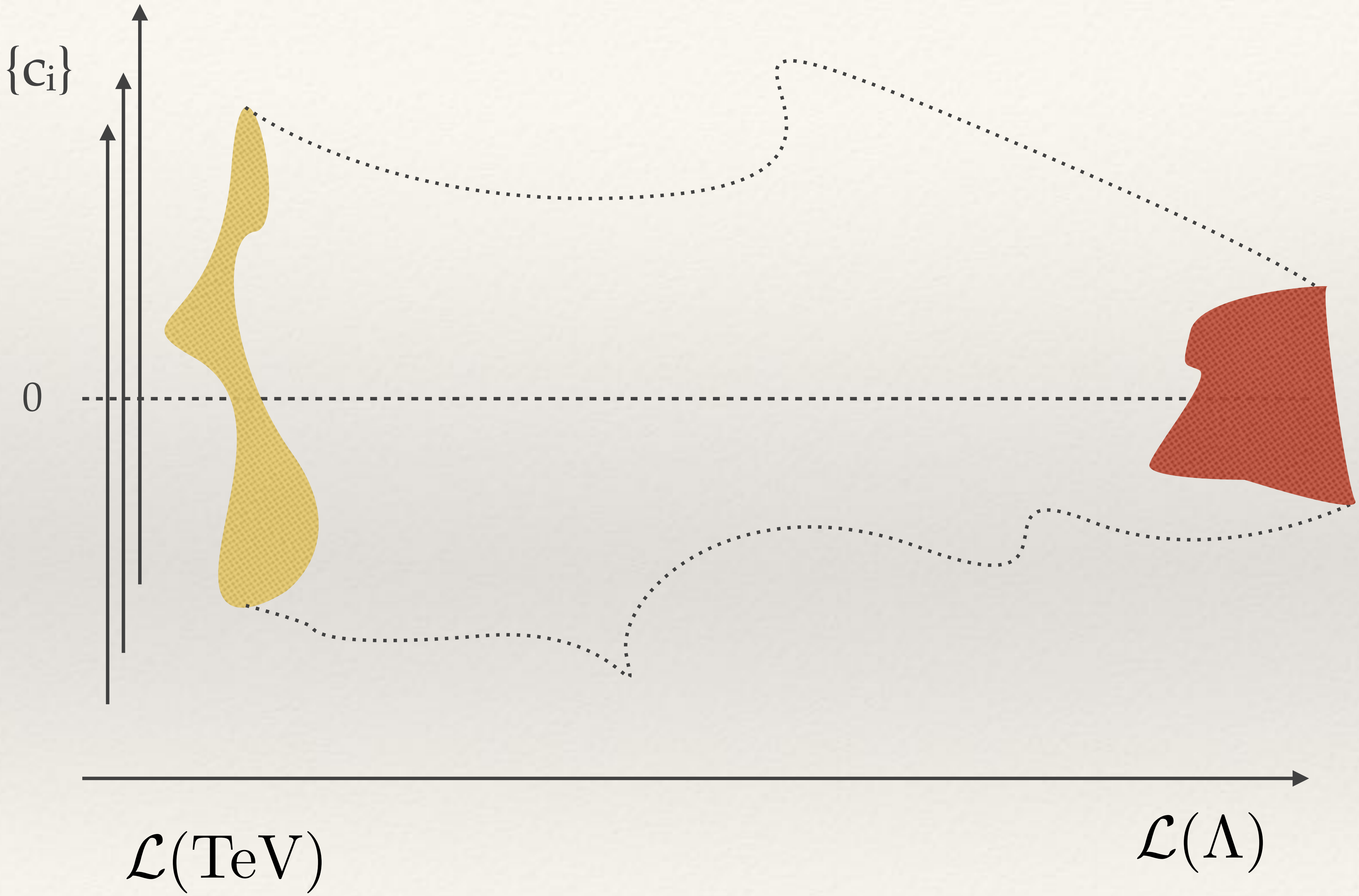


A note on validity



$\mathcal{L}(\text{TeV})$

A note on validity



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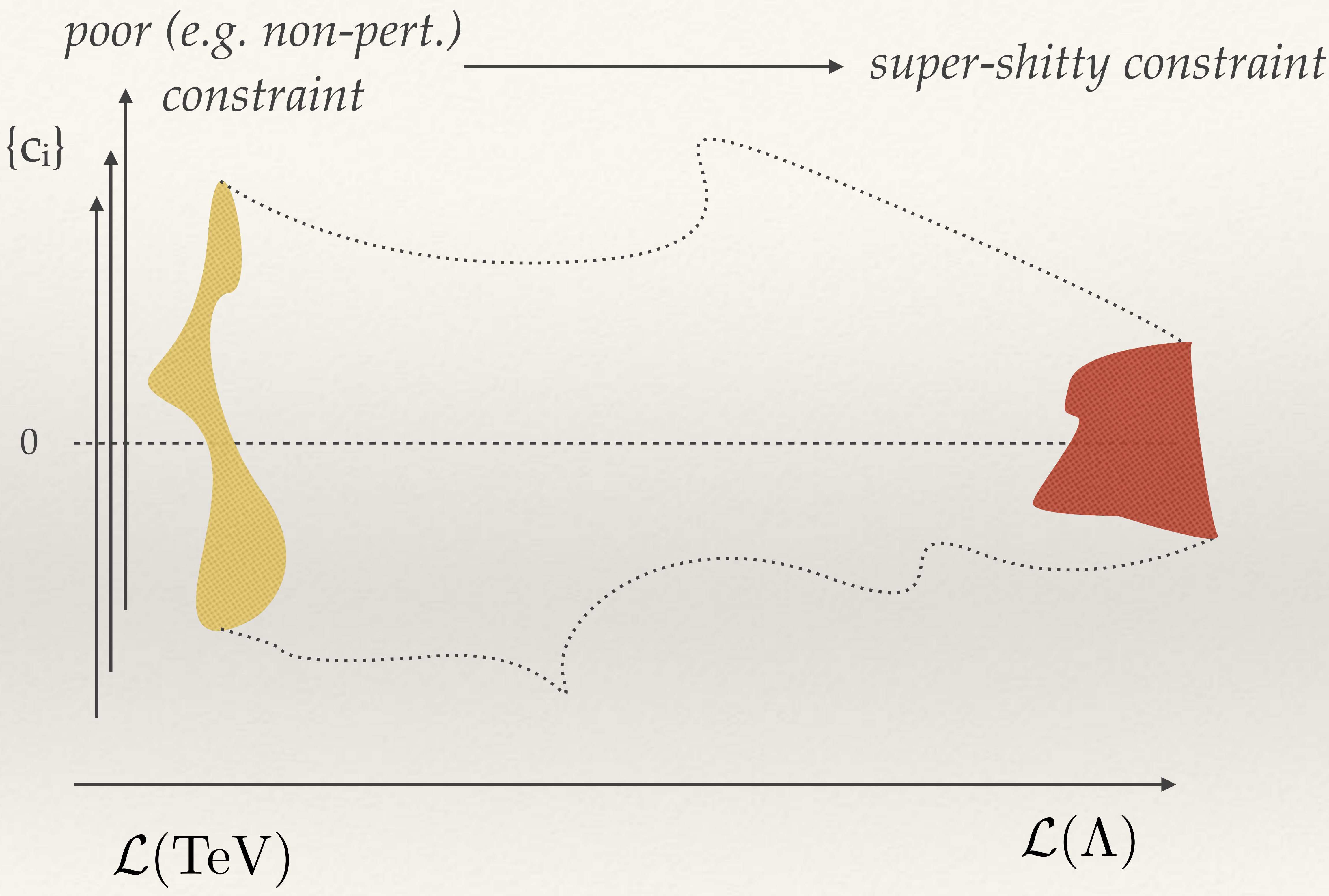

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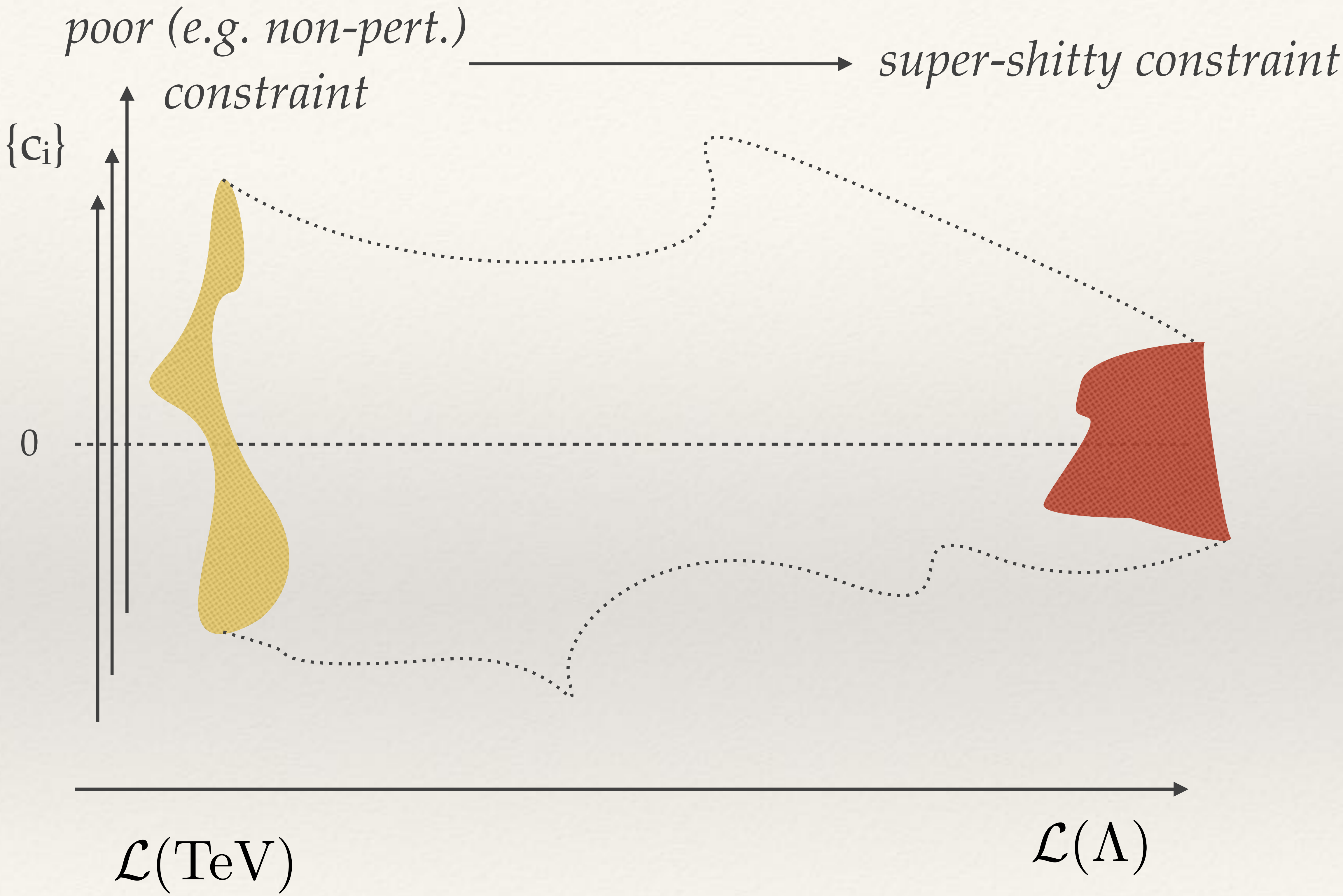
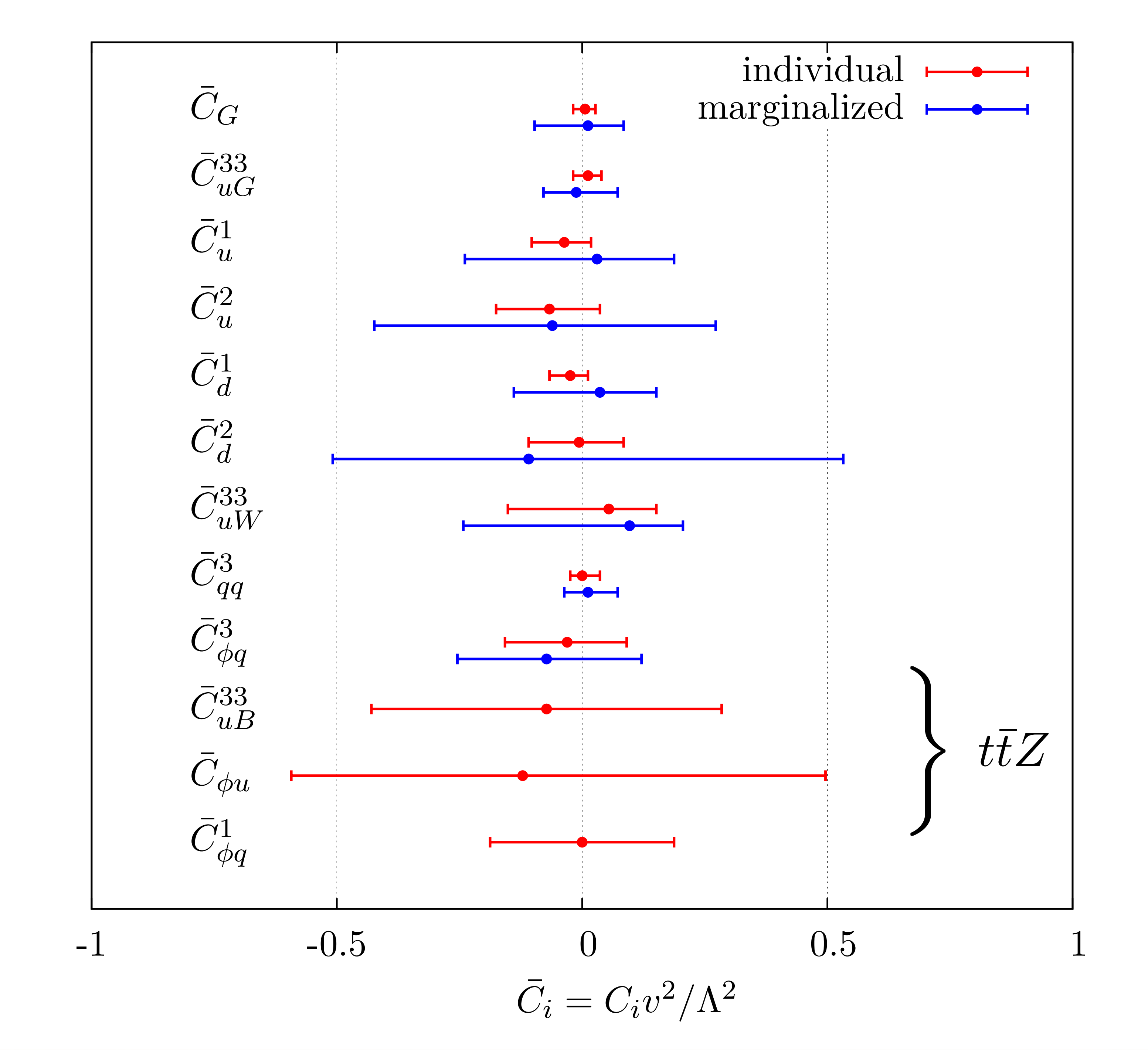


matching calculation tells you how badly you're doing

Summary of the top sector



axigluons

$M \gtrsim 1.6$ TeV

W'

$M \gtrsim 1.5$ TeV

top EFT @ LHC still has a long way to go

[CE, Moore, Nordstrom, Russell ` 15]

Are we set up for the future?

- top quark pheno programme at the LHC is well-developed
- **we can set constraints on all operators relevant for top pairs modulo "blind" directions of operator combinations. But…**

experimental selection

theoretical model

- which phase space region impacts the constraints on on top sector

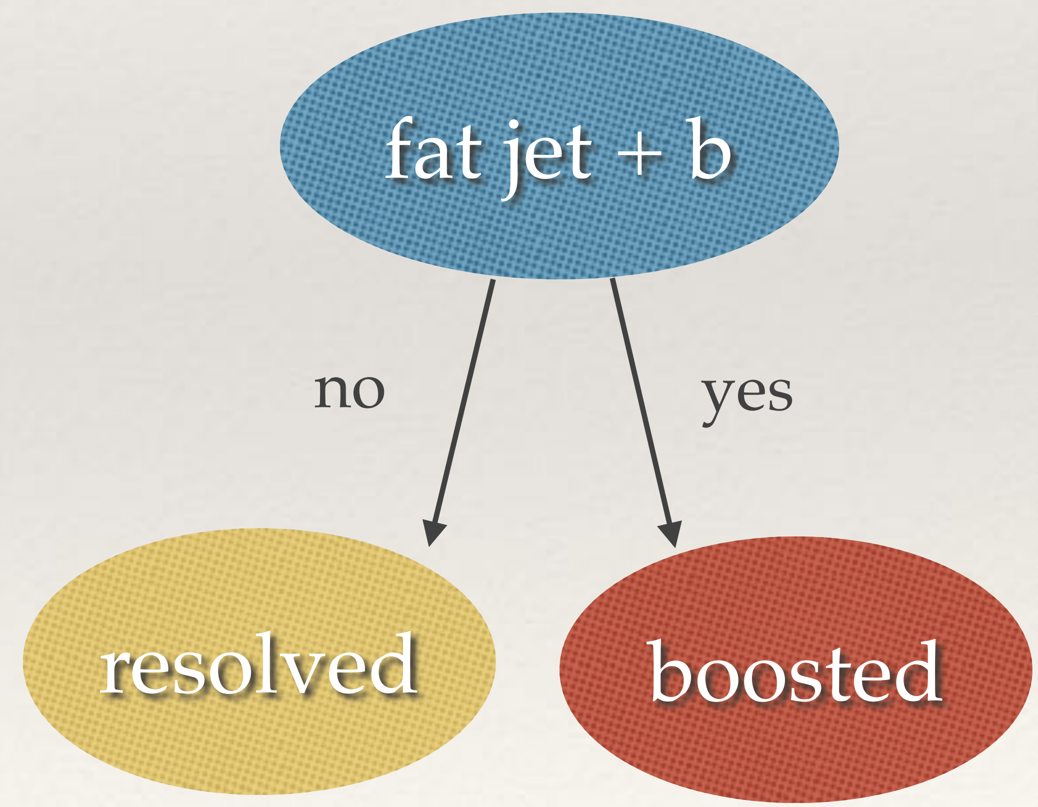
max. abundant

[CE, Moore, Nordstrom, Russell `15]

Are we set up for the future?

- **setup**
  - top pair production extrapolated to 13 TeV, >30/fb
  - split sensitivity range in **fully resolved** and **boosted regime** (HepTopTagger) for semi-leptonic tops [Plehn, Salam, Spannowsky `09]

Leptons	$p_T > 30$ GeV
	$\|\eta\| < 4.2$
Missing energy	$E_T^{\text{miss}} > 30$ GeV
Small jets	anti-k_T $R = 0.4$
	$p_T > 30$ GeV , $\|\eta\| < 2$
Fat jets	anti-k_T $R = 1.2$
	$p_T > 200$ GeV , $\|\eta\| < 2$
Resolved	≥ 4 small jets w/≥ 2 b-tags
Boosted	≥ 1 fat jet, ≥ 1 small jet w/ b-tag



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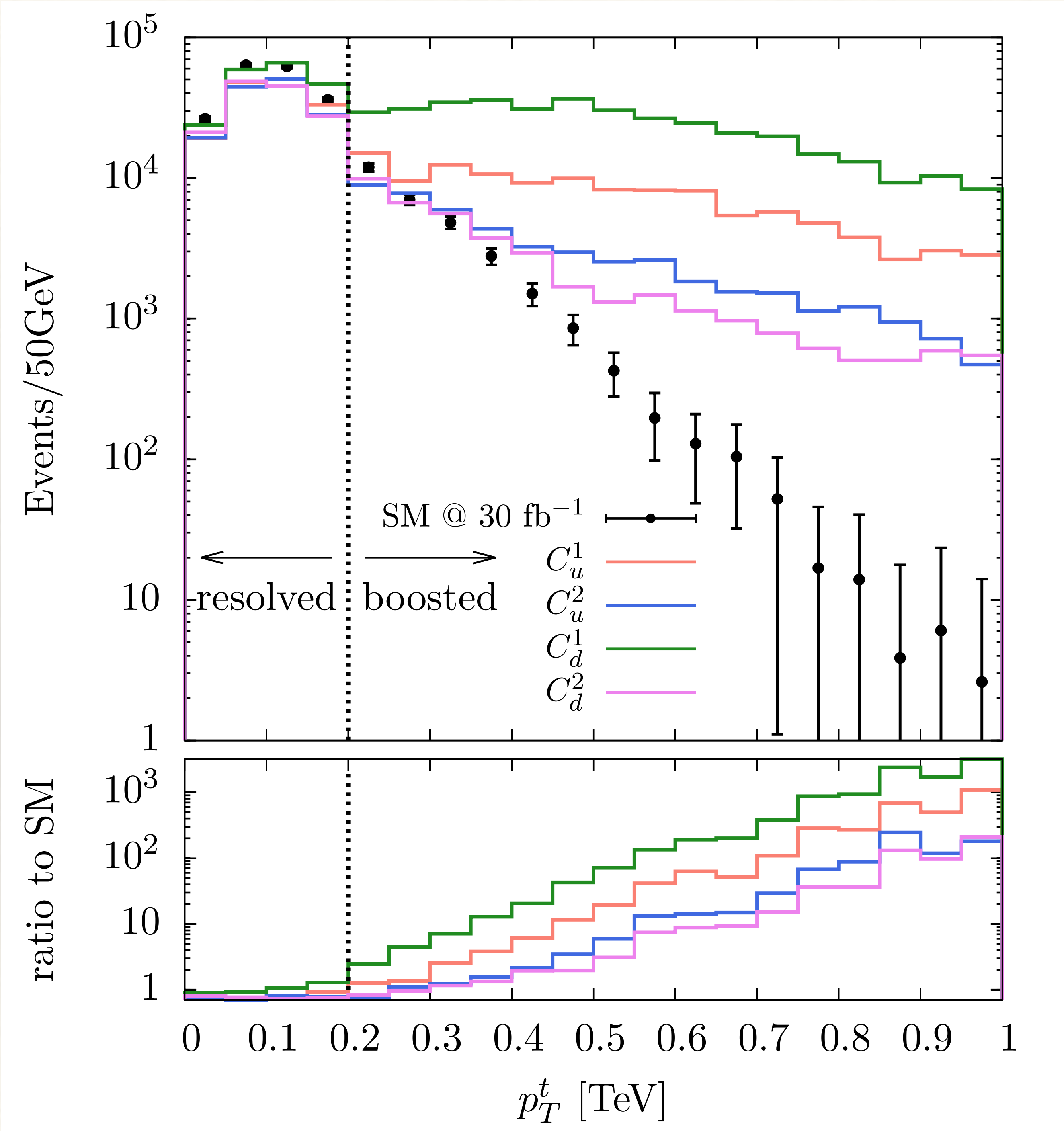
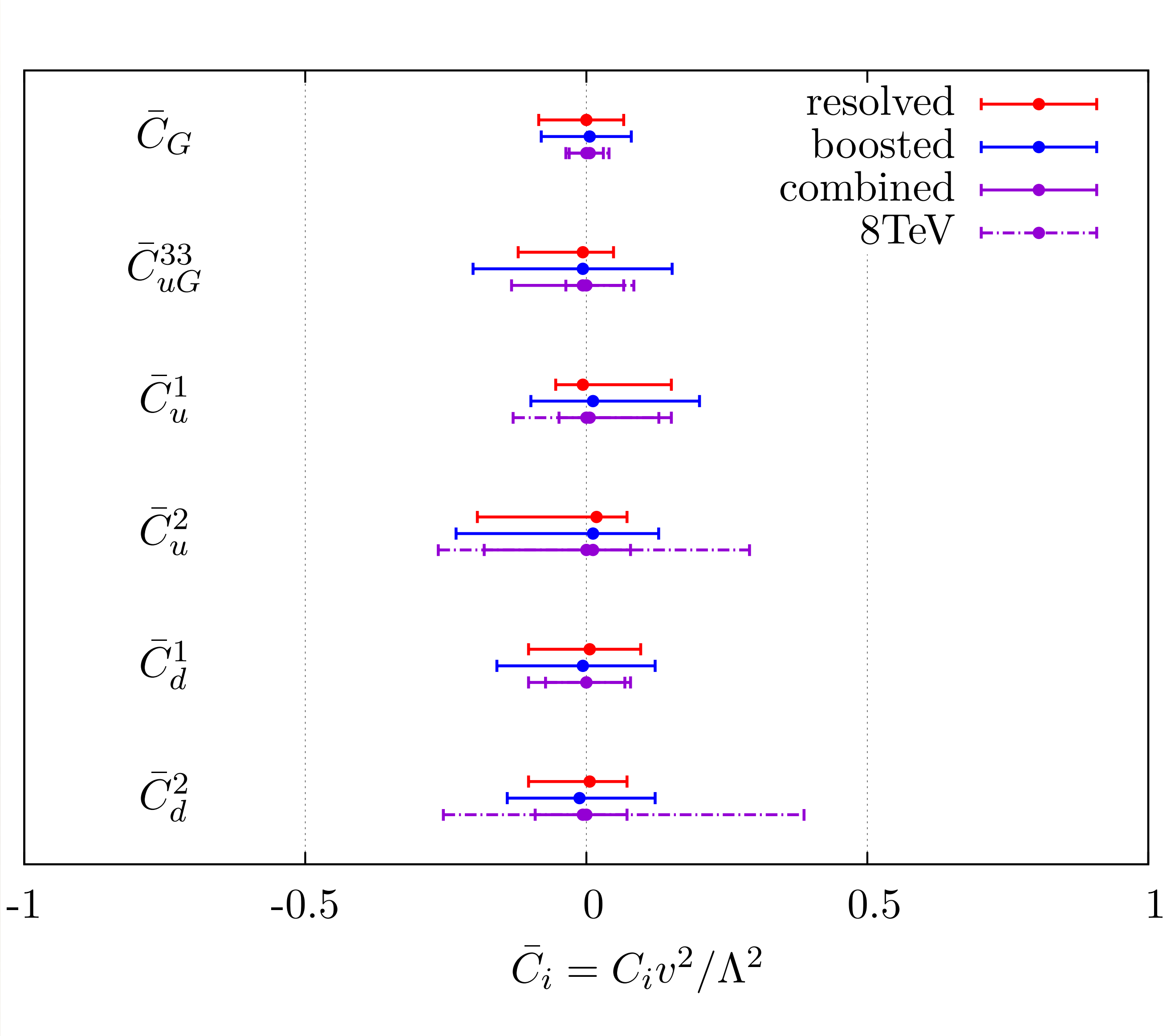
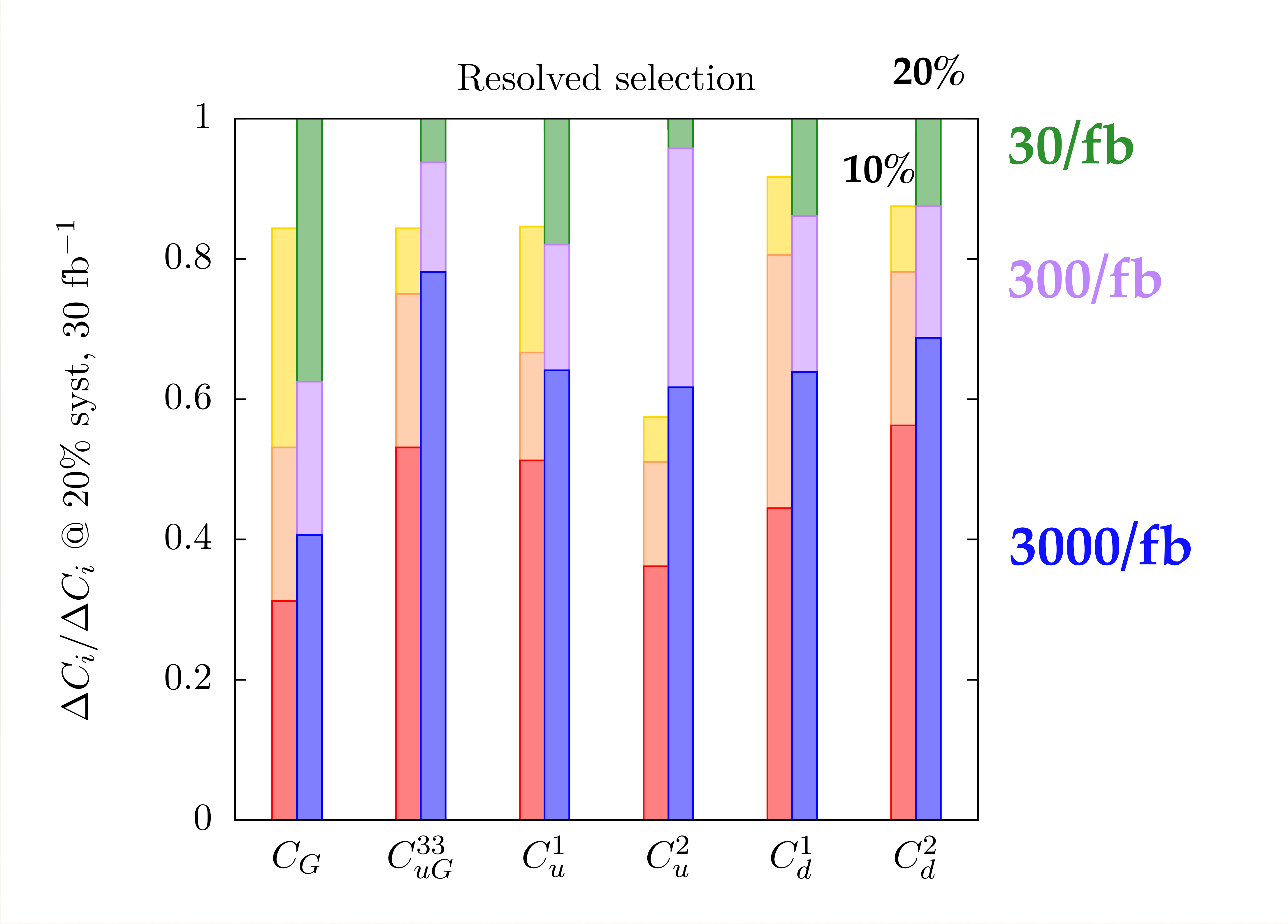




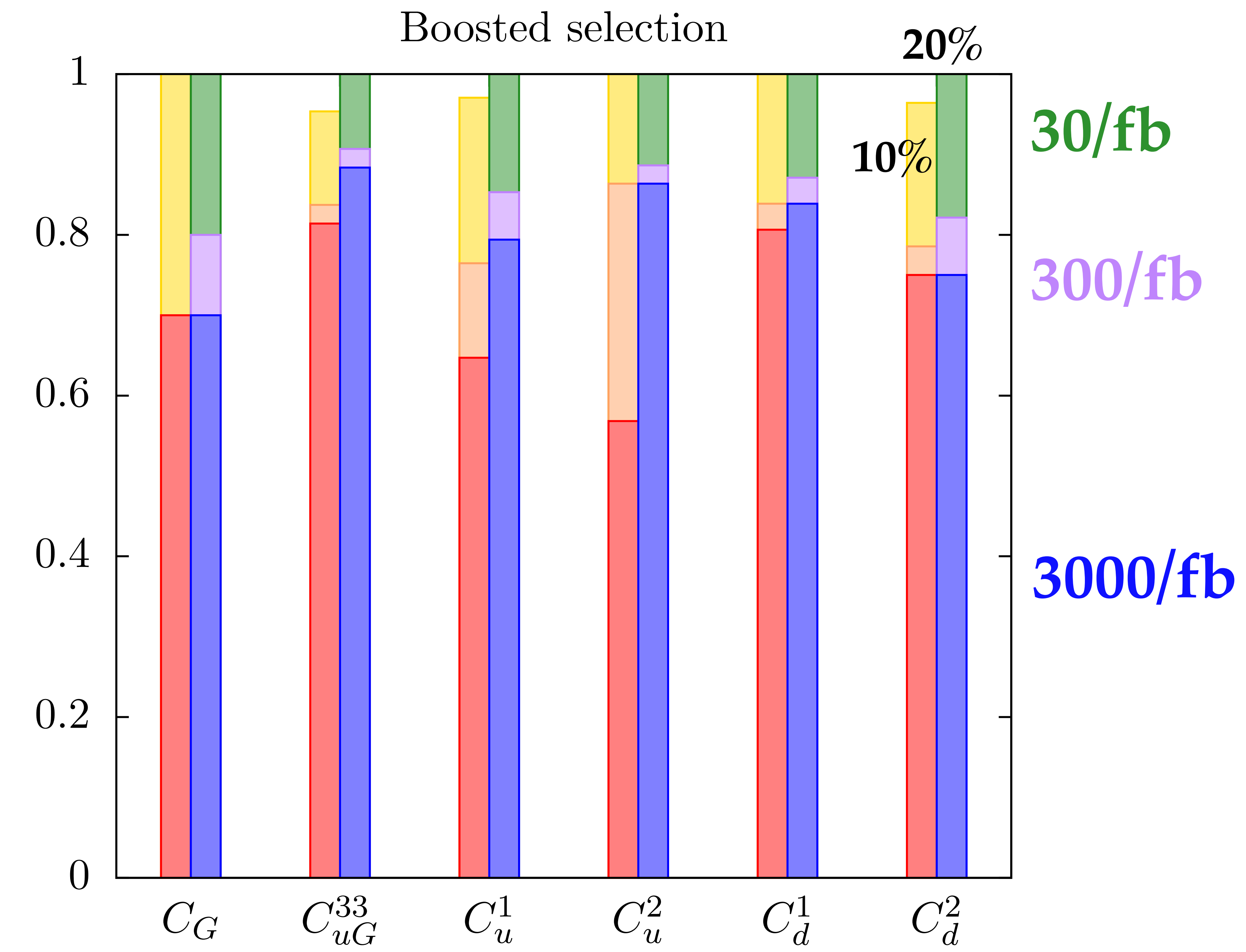
Are we set up for the future?

- **impact of systematics**



Are we set up for the future?

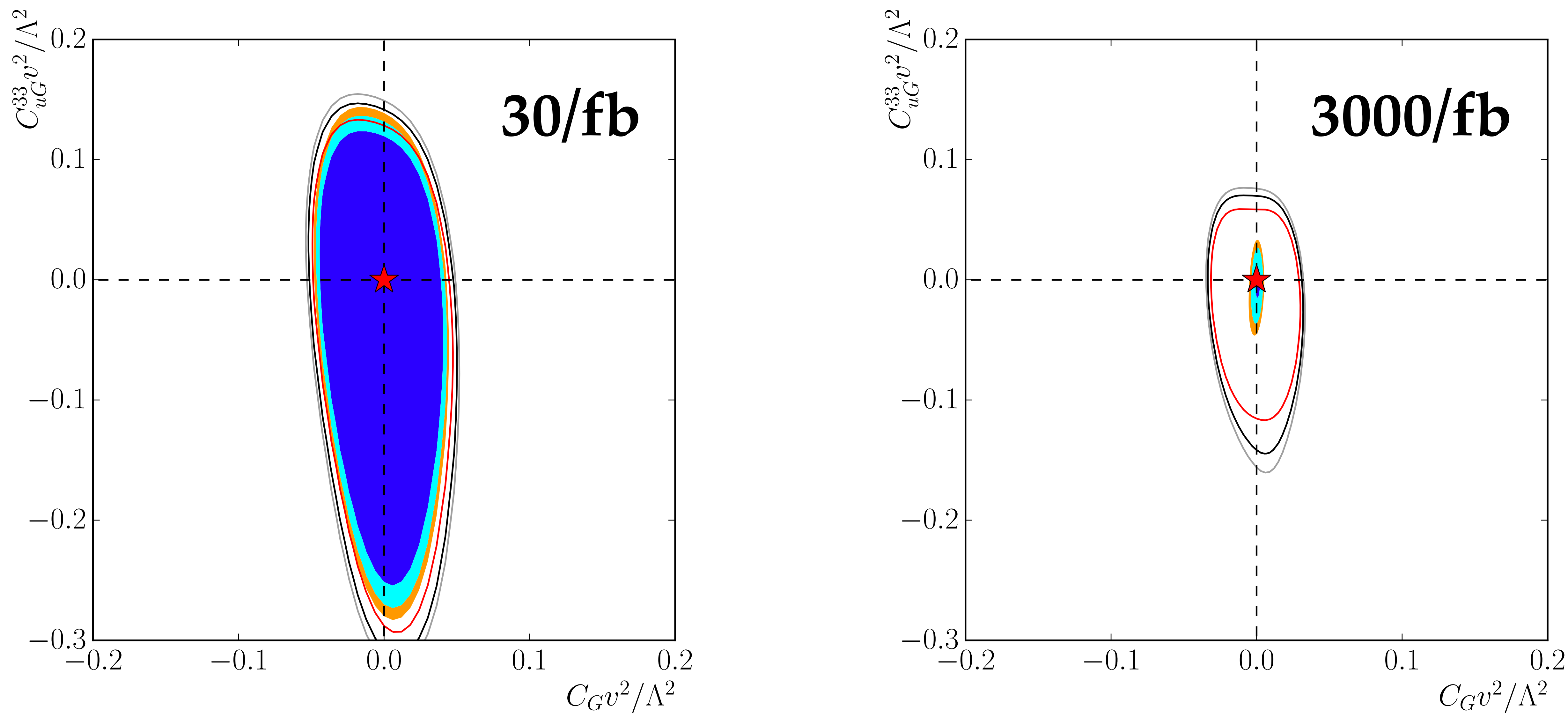
- **impact of systematics**



[CE, Moore, Nordstrom, Russell `15]

Are we set up for the future?

- **impact of systematics**



- **solid: exp. systematics only**

- we’ve started to explore the top sector better than at the Tevatron
- constraints do not tell us an awful lot at the moment
- expect improvement with more data, but probably not much room for theoretical improvements

based on [Buckley , CE, Ferrando, Miller, **Moore, Russell,** White ` 15]^2
[CE, **Moore, Nordstrom, Russell** ` 16]