Experimental aspects from Heavy Flavour in EFT

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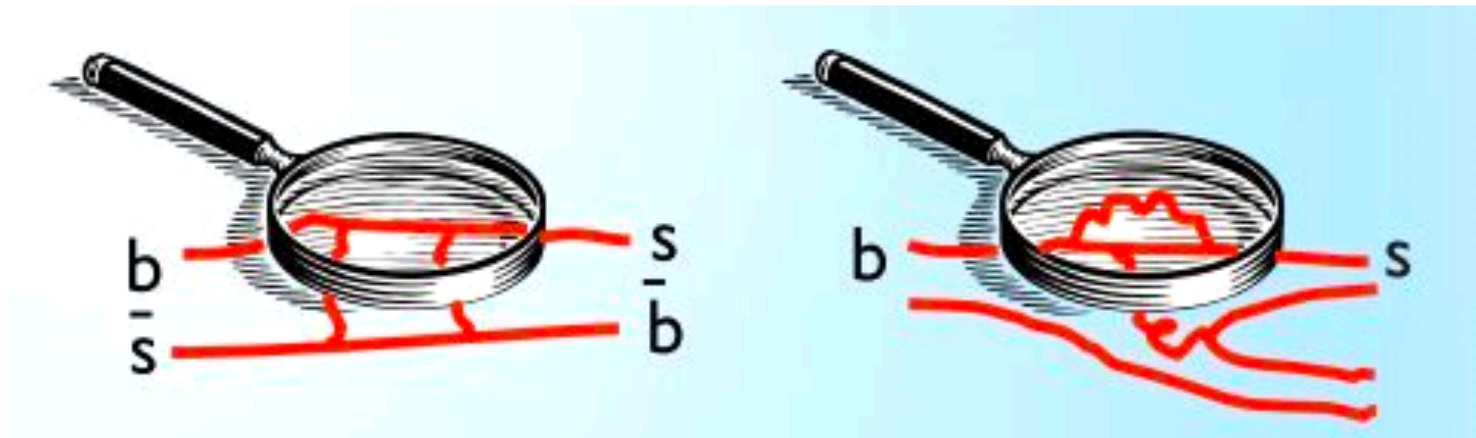
Heavy flavour physics

- Precision frontier physics via the decays of heavy flavour (b and c) hadrons.

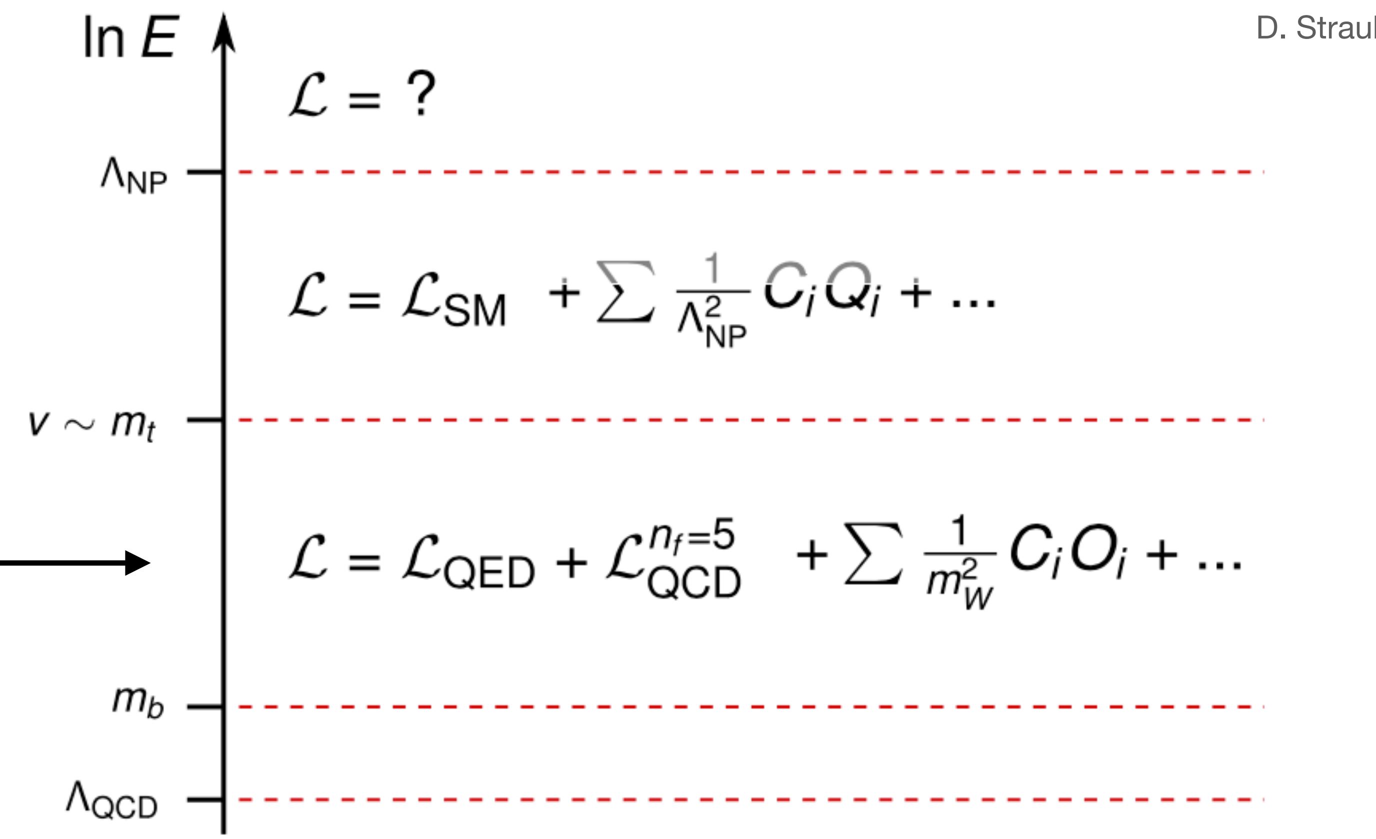


- Interesting because:
  - Complementary to direct searches/high PT precision due to reduced production of beauty/charm quarks.
  - Complementary to low energy physics as probe 2nd/3rd generation fermion couplings.
  - Experimental reach significantly improve on short timescale (LHCb, CMS, ATLAS, Belle-II, BES-III ..).
- Main challenge: Low energy QCD.
  - Comparison of experiment and SM often complicated by hadronic effects.
  - Rely on non-perturbative QCD techniques (e.g. Lattice) - theoretically challenging.

The Weak Effective Theory (WET)

- Typically work at a different EFT compared to high-PT physics.

Integrate out everything above the b/c-hadron mass scale (WET).



Typical operators

Rare decays ($b \to s, d\ell\ell$)

$$O_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$$

$$\mathcal{O}_9^\ell = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)\,, \qquad \mathcal{O}_{10}^\ell = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

$$\mathcal{O}_9^{\ell\prime} = (\bar{s}_R\gamma_\mu b_R)(\bar{\ell}\gamma^\mu\ell)\,, \qquad \mathcal{O}_{10}^{\ell\prime} = (\bar{s}_R\gamma_\mu b_R)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

$$\mathcal{O}_{\hat{S}}^\ell = (\bar{s}_L b_R)(\bar{\ell}_R\ell_L)\,, \qquad \mathcal{O}_{\hat{S}}^{\ell\prime} = (\bar{s}_R b_L)(\bar{\ell}_L\ell_R)\,.$$

Semileptonic decays

$$\mathcal{O}_{C_{V_L}} = \bar{c}_L\gamma^\mu b_L\,\bar{\ell}_L\gamma_\mu\nu_L\,,$$
$$\mathcal{O}_{C_{V_R}} = \bar{c}_R\gamma^\mu b_R\,\bar{\ell}_L\gamma_\mu\nu_L\,,$$

$$\mathcal{O}_{C_{S_L}} = \bar{c}_R b_L\,\bar{\ell}_R\nu_L\,,$$
$$\mathcal{O}_{C_{S_R}} = \bar{c}_L b_R\,\bar{\ell}_R\nu_L\,,$$
$$\mathcal{O}_{C_{T_L}} = \bar{c}_R\sigma^{\mu\nu}b_L\,\bar{\ell}_R\sigma_{\mu\nu}\nu_L\,.$$

Why directly fit WC?

Flavour observables are (usually) model independent - why fit WC?

Broadly two reasons

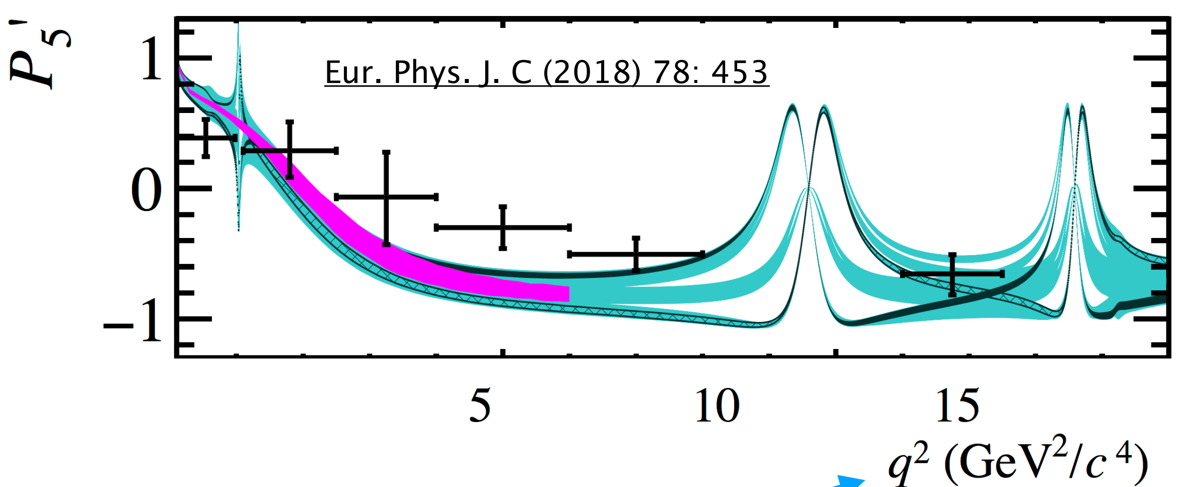
Rare decays: Exploit full information	Semileptonics: Avoid unfolding of observables

Observables binned in kinematic regions (e.g. q^2).

Fitting WC allows to perform unbinned fits:

Gain information lost in the integration.

Allows to fit hadronic model directly in data.

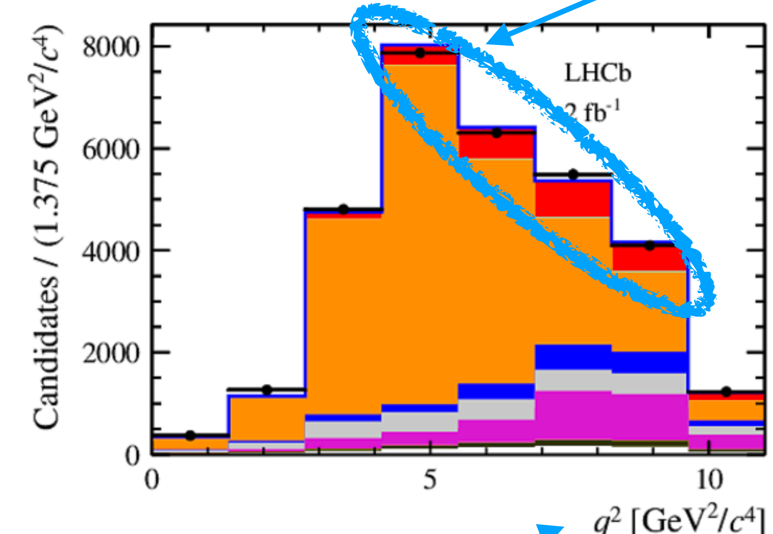


q^2 reco ~ q^2 true

Observables *not* model dependent in some cases (semitauonic decays)

Signal (red) kinematics fixed to SM.

arXiv:2305.0146



q^2 here suffers from considerable resolution

Fitting for WC in this case **improves** interpretability.

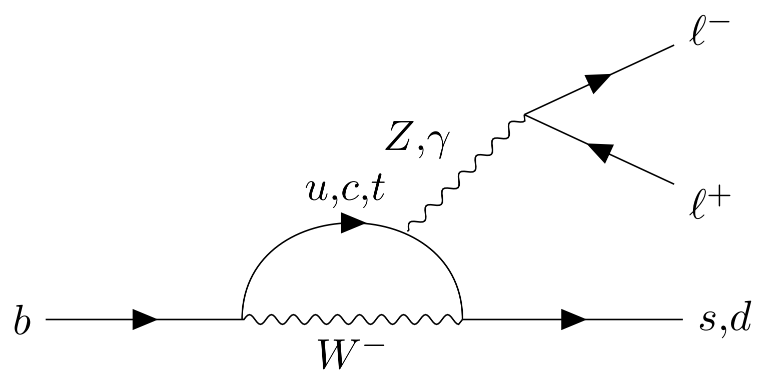
Today: go through these routes and point out high-p_T connections.

$b \to (s,d)\ell\ell$ decays

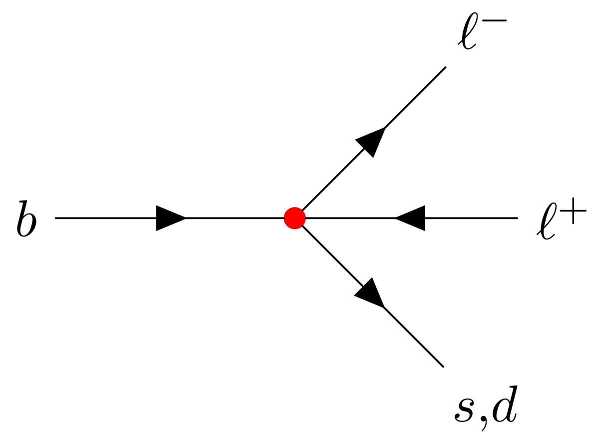
For latest status see F. Reiss talk at plenary III

Rare $b \to (s,d)\ell\ell$ decays are fully reconstructed.

SM

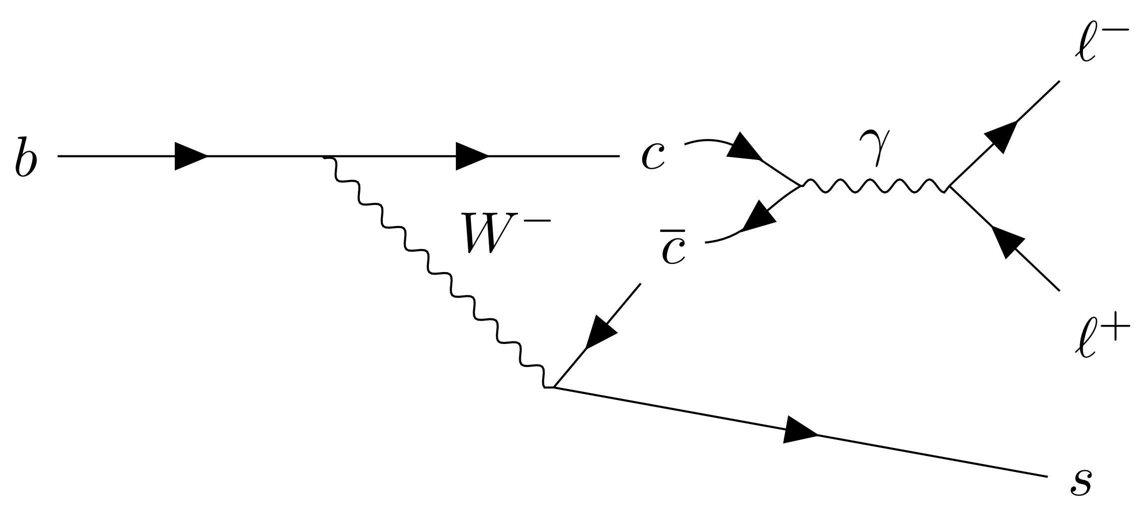


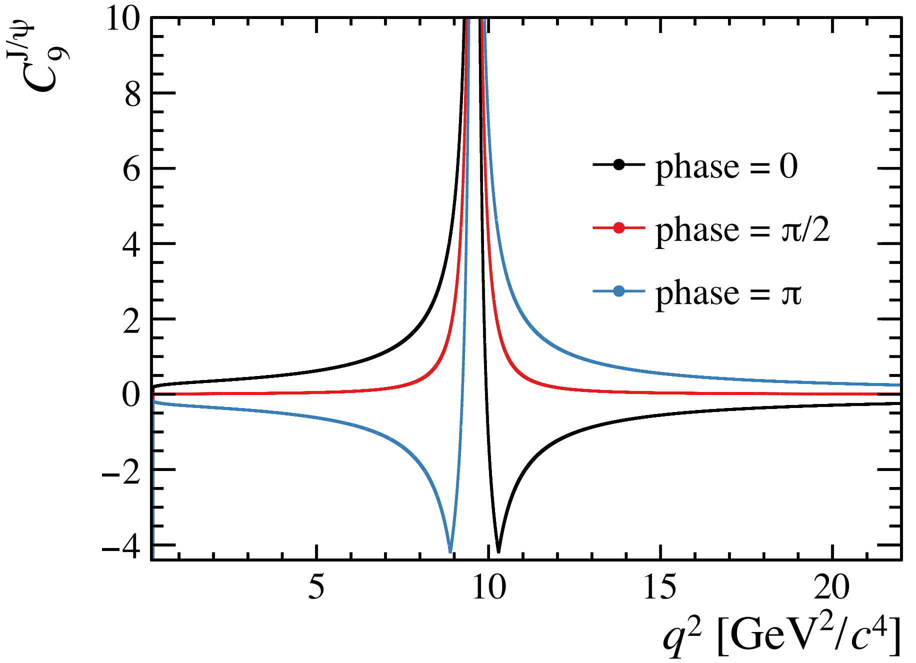
WET



Main SM operators $\quad \mathcal{O}_9^\ell = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\ell)\,, \quad \mathcal{O}_{10}^\ell = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu\gamma_5\ell)$

Long-distance contributions absorbed into the WC C_9.

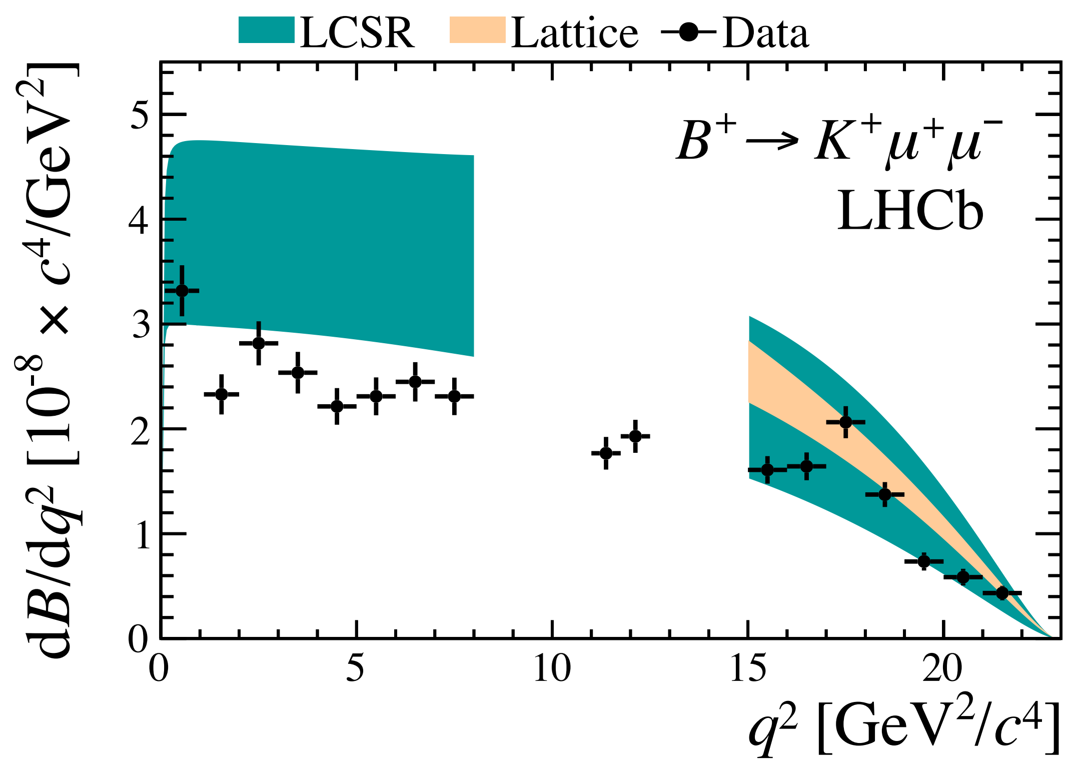




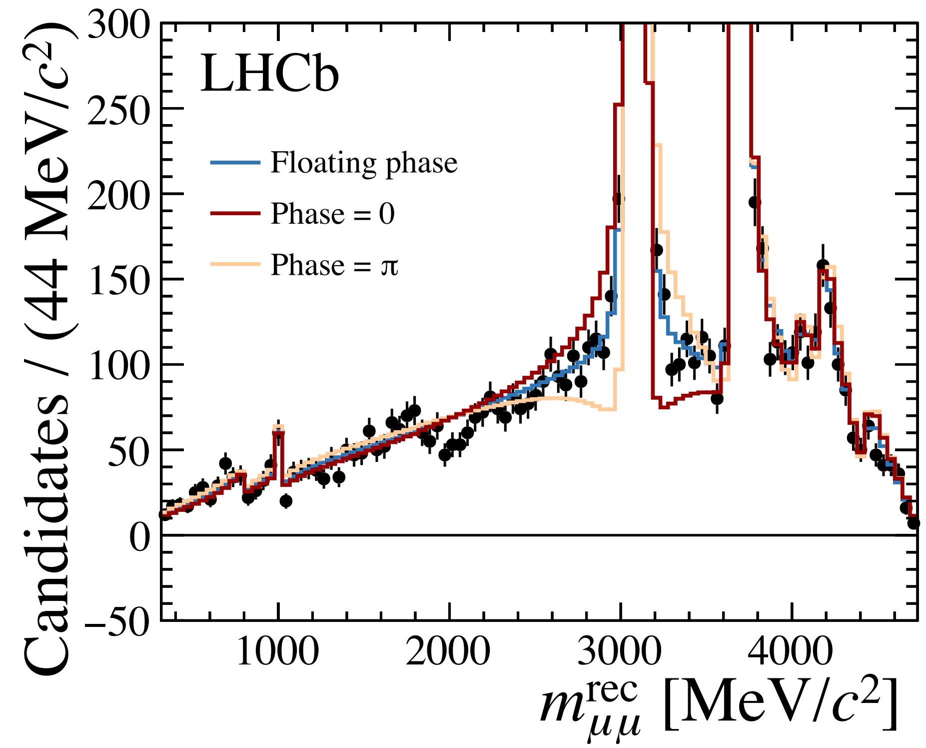
Direct fit to q^2 (and $C_{9,10}$)

Previously were comparing binned dBF/dq^2 measurements to theory.

Binned method JHEP 06 (2014) 133

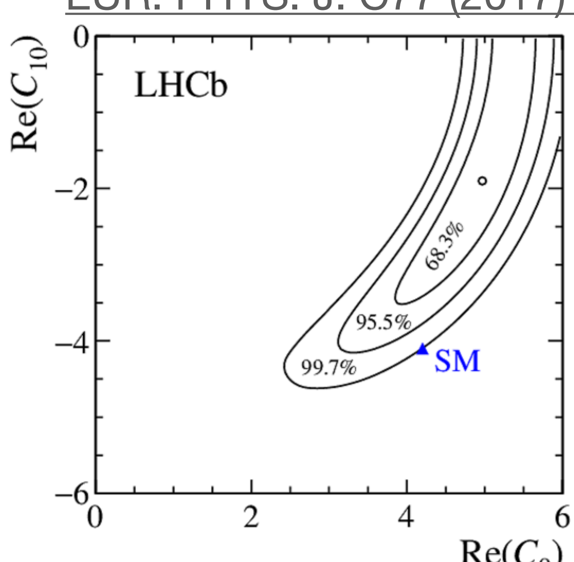


Unbinned method EUR. PHYS. J. C77 (2017) 161



Fitting unbinned: Gain access to crucial region which determines key hadronic nuisance parameters.

EUR. PHYS. J. C77 (2017) 161



Measurement not without controversy due to model dependence - updates ongoing with full run II data using improved models.

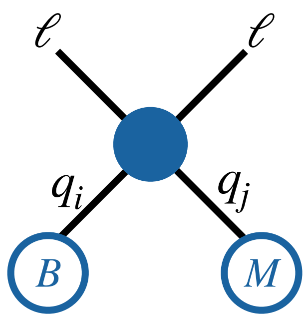
This remains LHCb's only direct WC fit so-far, many more are coming soon.

High p_T connection

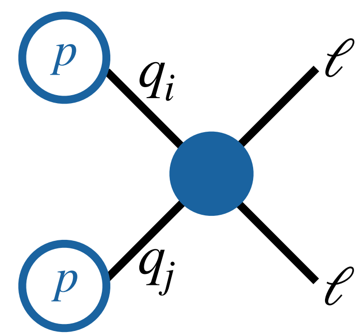
Measurements sensitive to particles up to O(1-10TeV) scale (e.g. Z', leptoquark).

E.g. can manifest as di-lepton mass resonance.

For more details see A. Smolkovic talk at the LHC EFT meeting



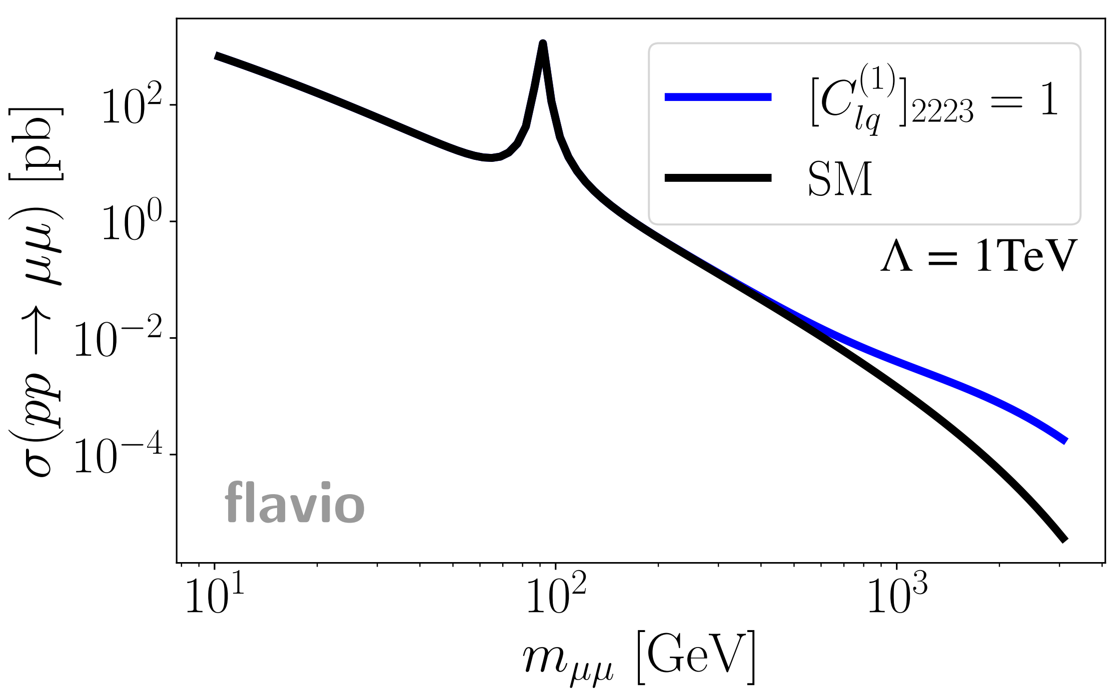
$B \to K\mu\mu, \ldots$

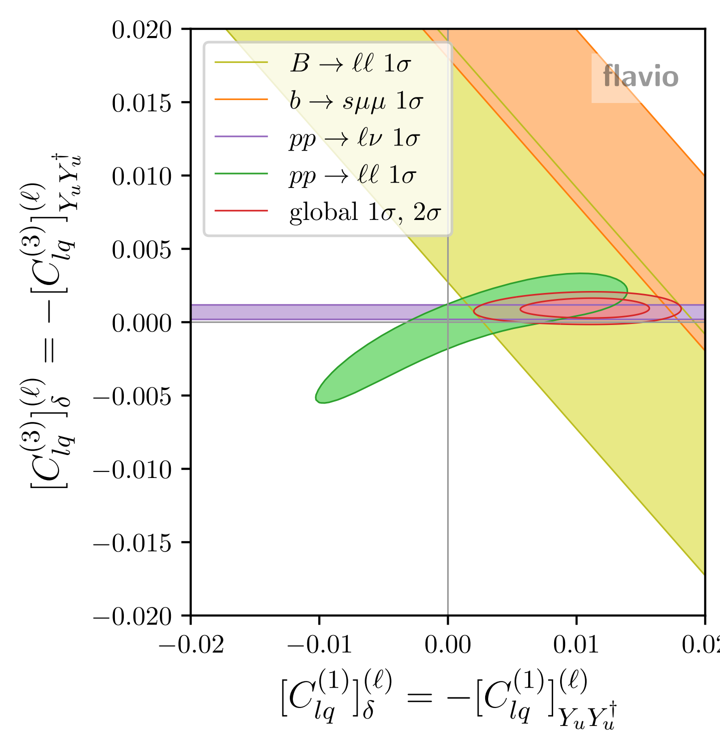


$pp \to \ell\ell, \ell\nu$

Example for $b \to d\ell\ell$, complementarity of fields visible on constraints available in SMEFT operators.

Greljo, Salko, Smolkovic, Stangl



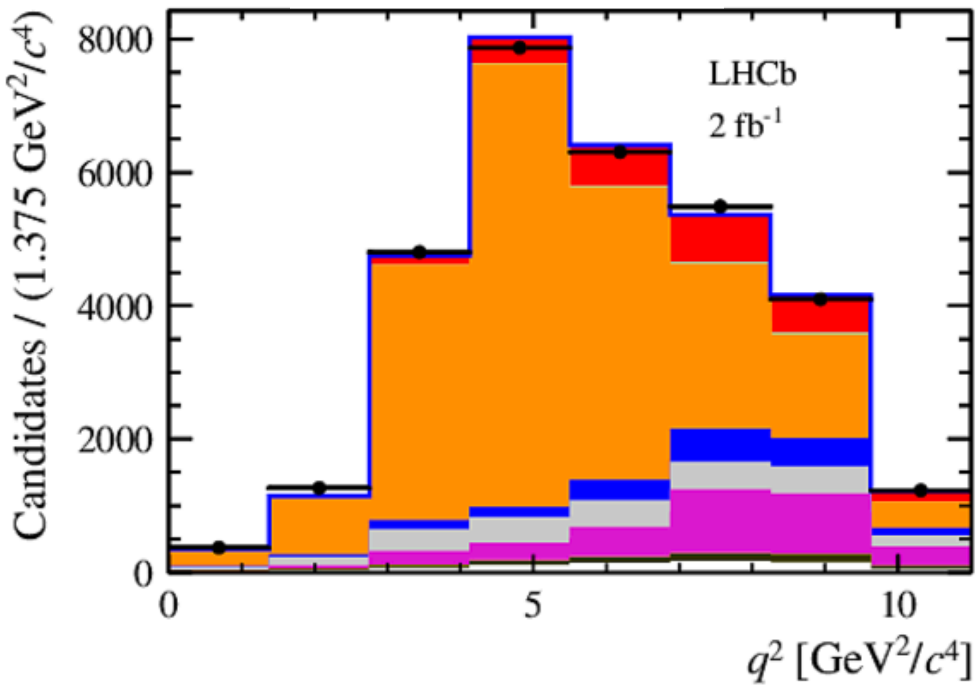


R(D$^{(*)}$) measurements

For latest status see R. Mohammed's talk on Thursday

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

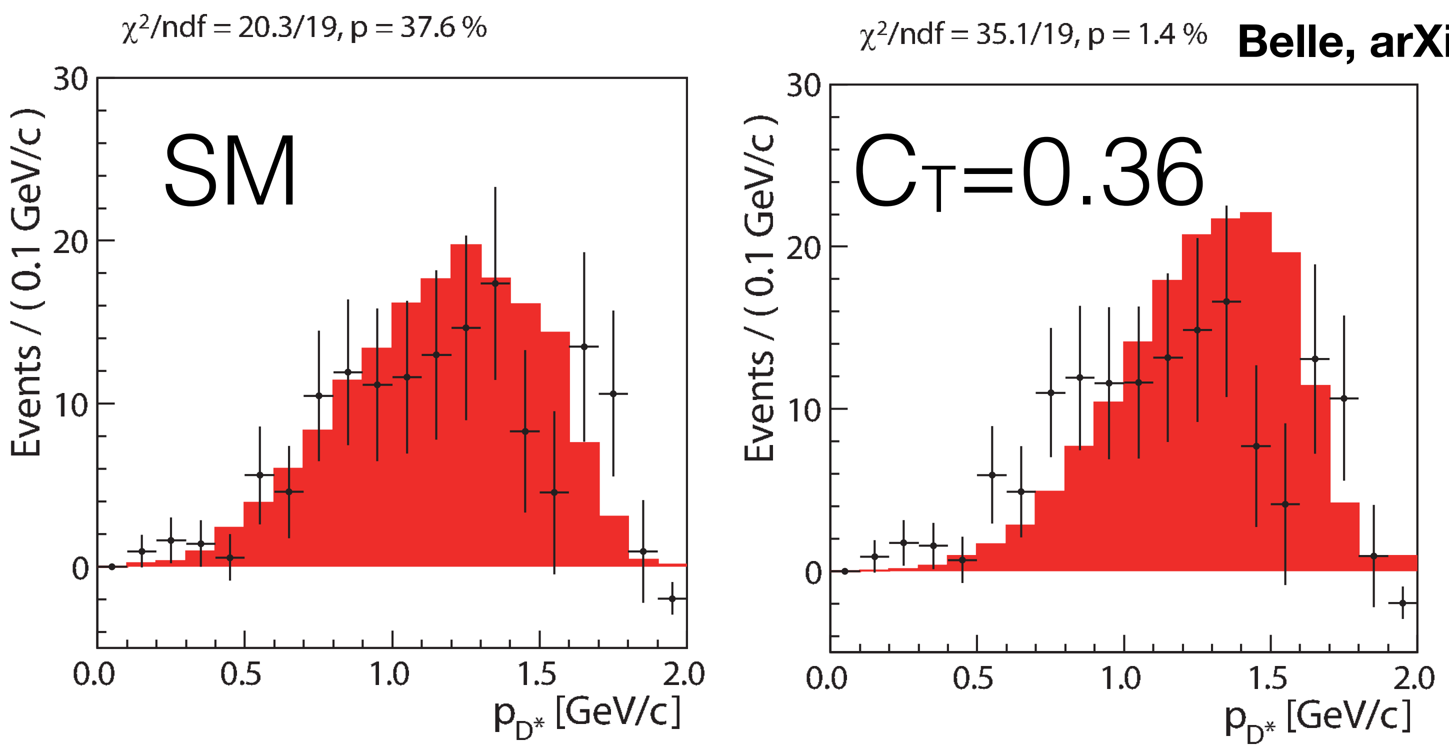
arXiv:2305.0146



- Determined from a 3D fit.
- Signal assumed to be SM-like when extracting R(D*).
  - Inconsistent!

- Less of an issue at B-factories due to kinematic tagging.
- E.g: effect of Tensor operator on D* momentum distribution.

Belle, arXiv:1607.07923

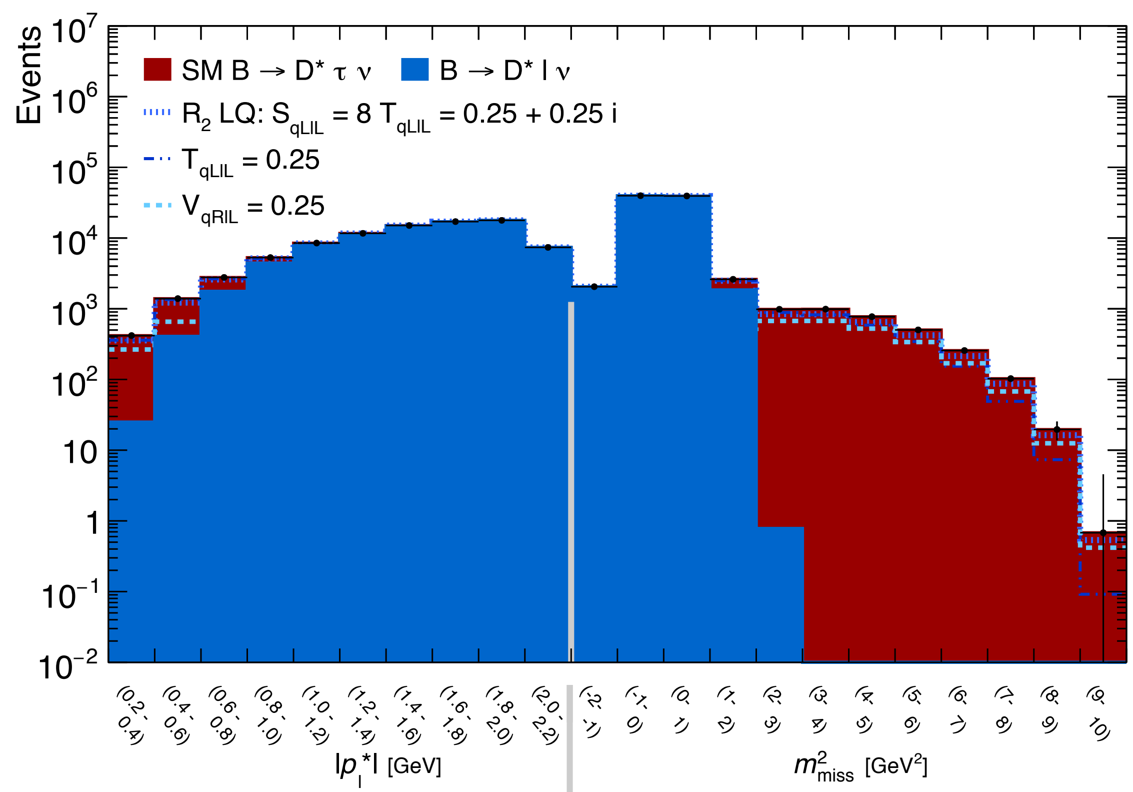


How to deal with this

See talk by D. Robinson at LHC-EFT meeting

- Unfolding and background subtraction out of the question.
- One possible way is the HAMMER (Helicity Amplitude Module for Matrix Element Reweighting) tool: HAMMER website
    - Allows for faster reweighting of templates.

Bernlochner, F.U., Duell, S., Ligeti, Z. et al.



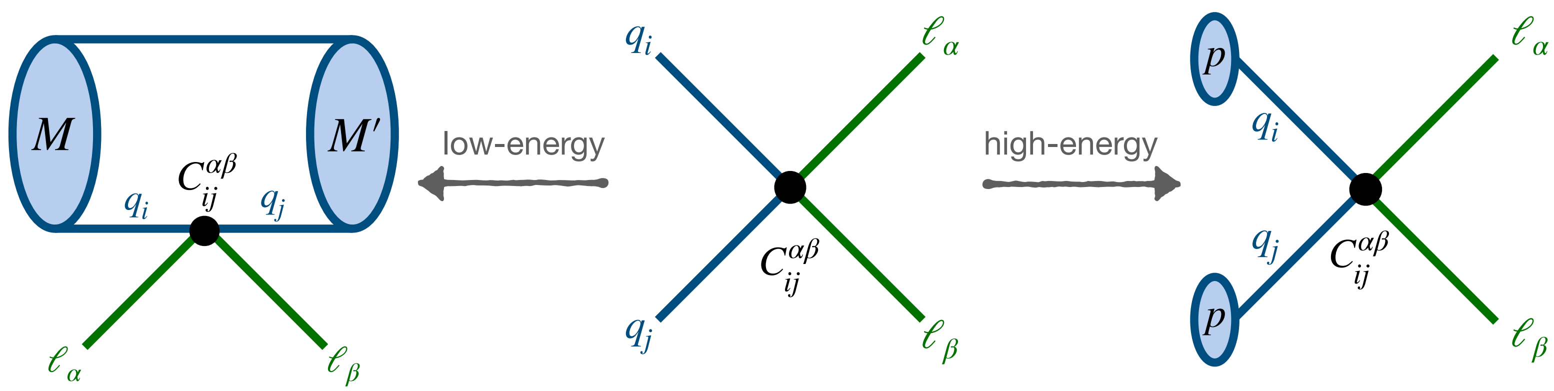
- Have interfaced this with RooFit [2022 JINST 17 T04006] in order to get it integrated into our analyses.
    - For next round mainly using for systematics, then we move onto WC fitting.
- The idea is to directly fit Wilson Coefficients and provide likelihood surface. (Still vulnerable to QCD updates).

High p_T connection

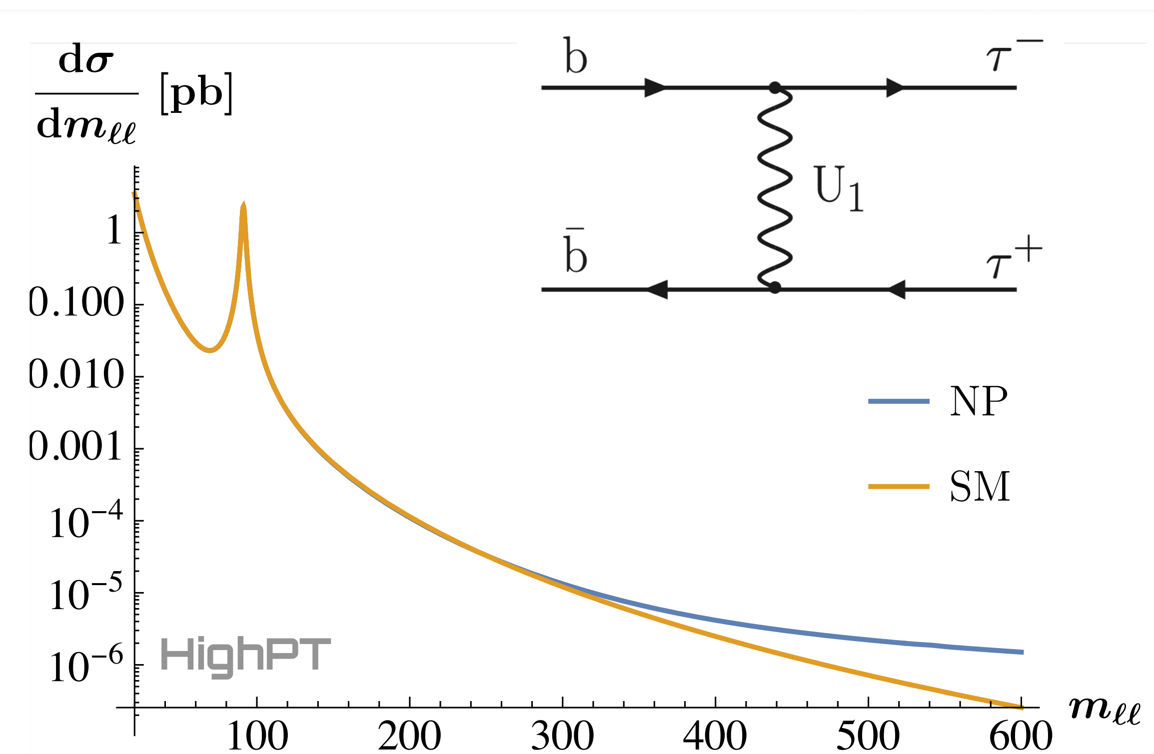
See F. Wilsch's talk at LHC EFT meeting

Measurements sensitive to particles up to O(1TeV) scale (e.g. W', leptoquark).

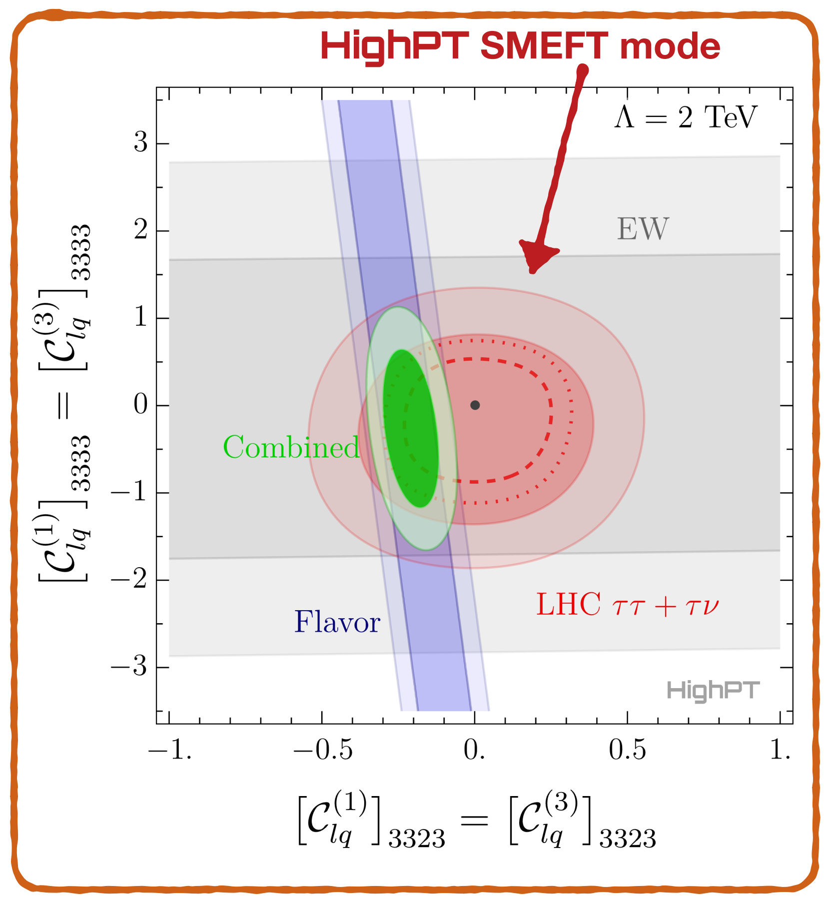
Can manifest as di-lepton enhancement (can be non-resonant).



L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, F. Wilsch



SMEFT fit

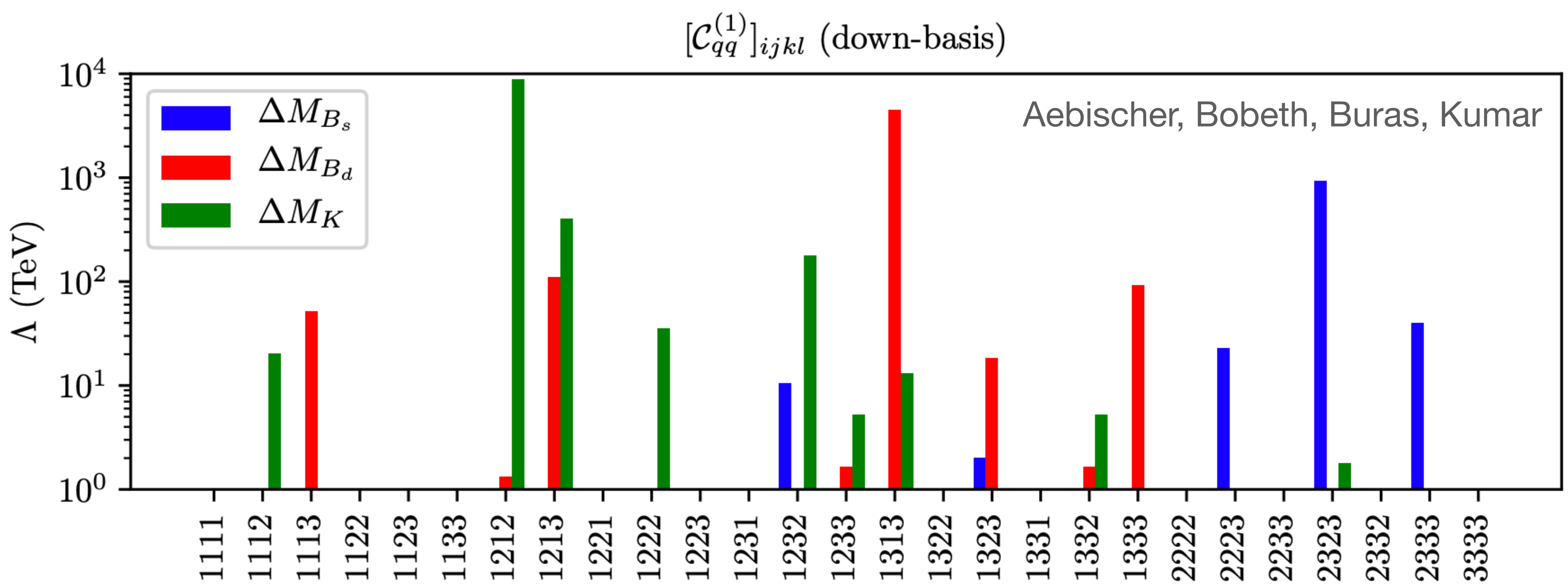


Mixing constraints

Aebischer, Bobeth, Buras, Kumar
See also Silverstrini, Valli

- Mostly focussed on Δ(F)=1 processes as more motivation to fit WC.
  - However, in general Δ(F)=2 constraints probe higher scales.
- Some operators completely dominated by mixing constraints .

$$\frac{c_{qq}^{(1)}}{\Lambda^2}(\bar{q}_i\gamma_\mu q_j)(\bar{q}_k\gamma^\mu q_l)$$



- Also see complementarity of mixing constraints between up and down sectors.

Summary

- Heavy flavour physics been parameterised in WET for a long time.
- Starting to get into direct fits of WC.
  - Exploit full information and determine theory nuisances.
  - Relax assumptions in fits with missing energy.
- Complementary to high p_T but there are a few connections to direct searches.
- Reinterpetrability takes non-trivial work to preserve.