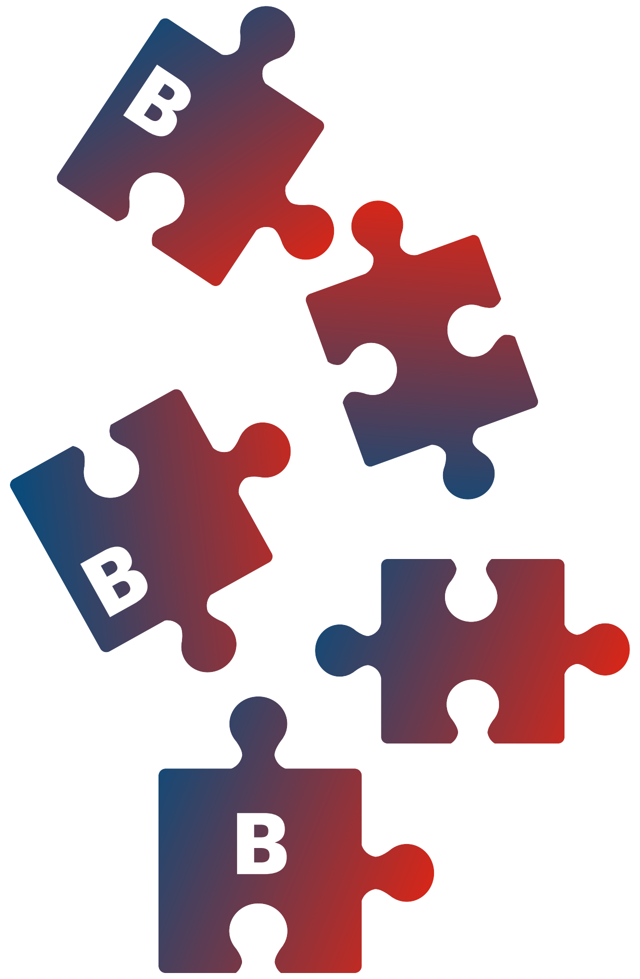


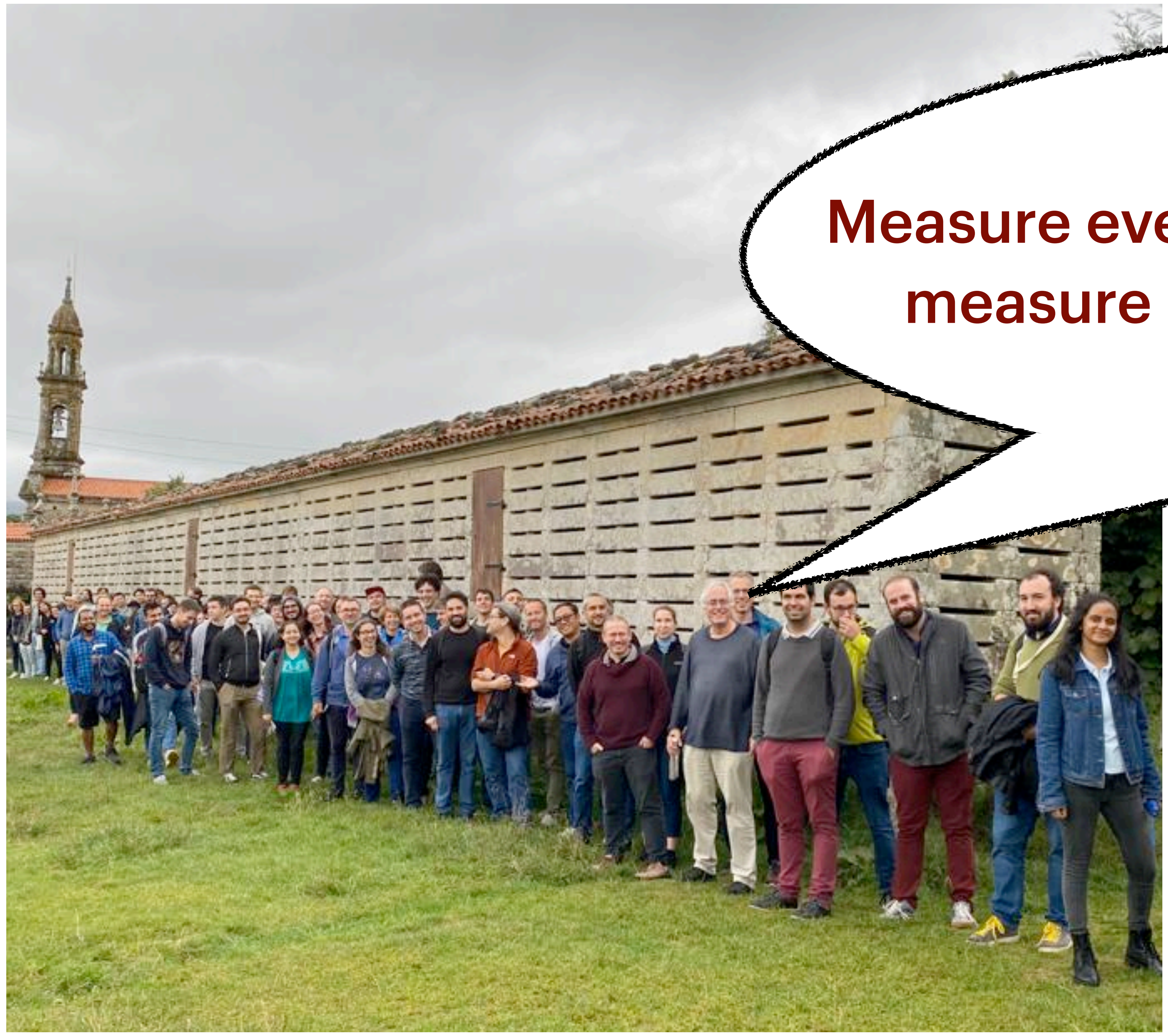
A higher-order present

Exploring New Physics with Flavour - Uli Fest 2026

K. Keri Vos

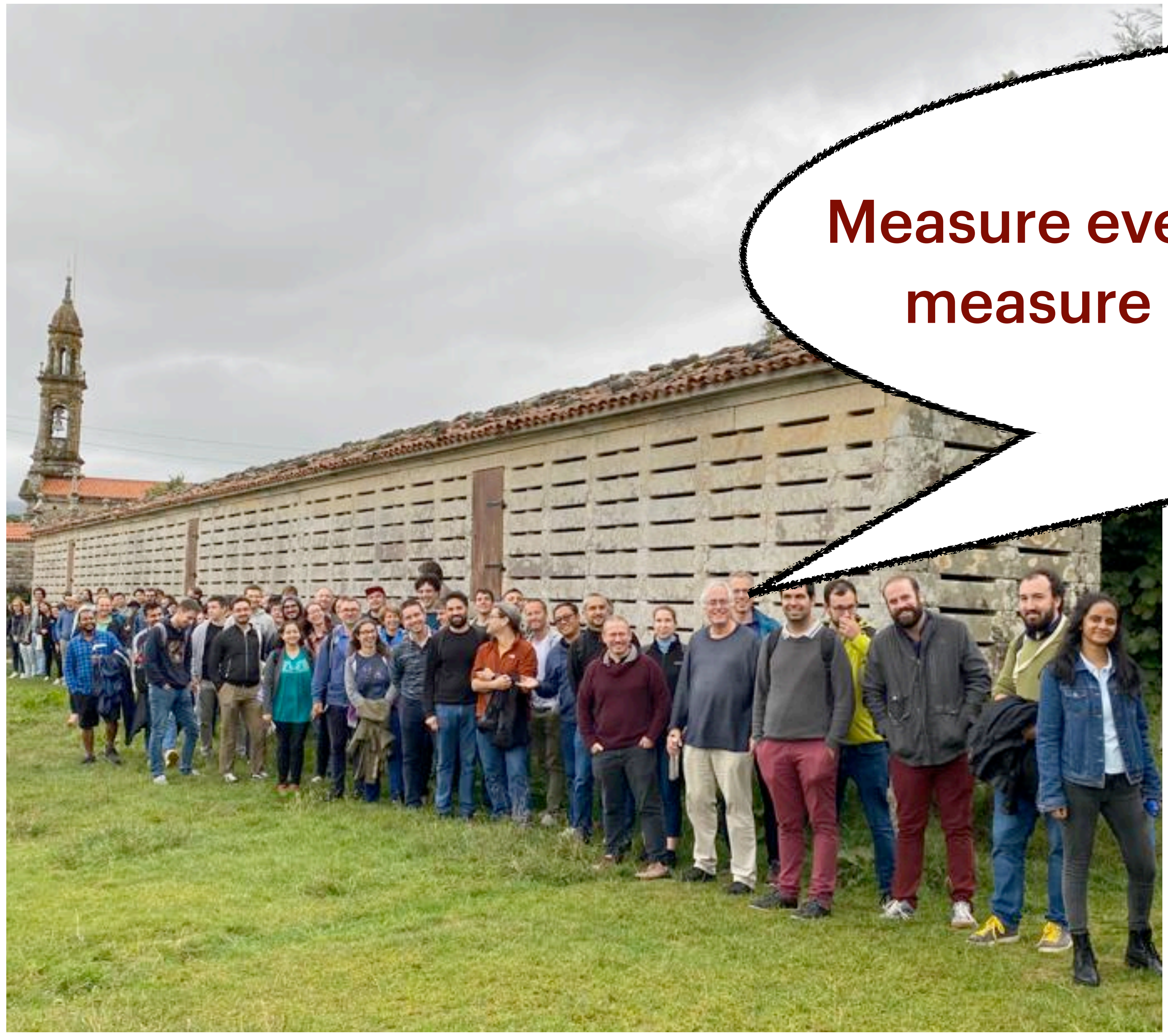
Happy Birthday!

Birthday present?



Measure everything that has been measured better and measure everything that has not been measured*!

Birthday present?



Measure everything that has been measured better and measure everything that has not been measured*!

* Especially Charm CP violation

A higher-order PRESENT

Pushing inclusive B decays to the limit

Why inclusive decays?

- Set up OPE and heavy quark expansion (HQE)
- Well established framework
- Extract CKM parameters $|V_{cb}|$ and $|\mathrm{V}_{\mathrm{ub}}|$
- Extract power corrections directly from data
- Cross check of exclusive decays

The Puzzle...

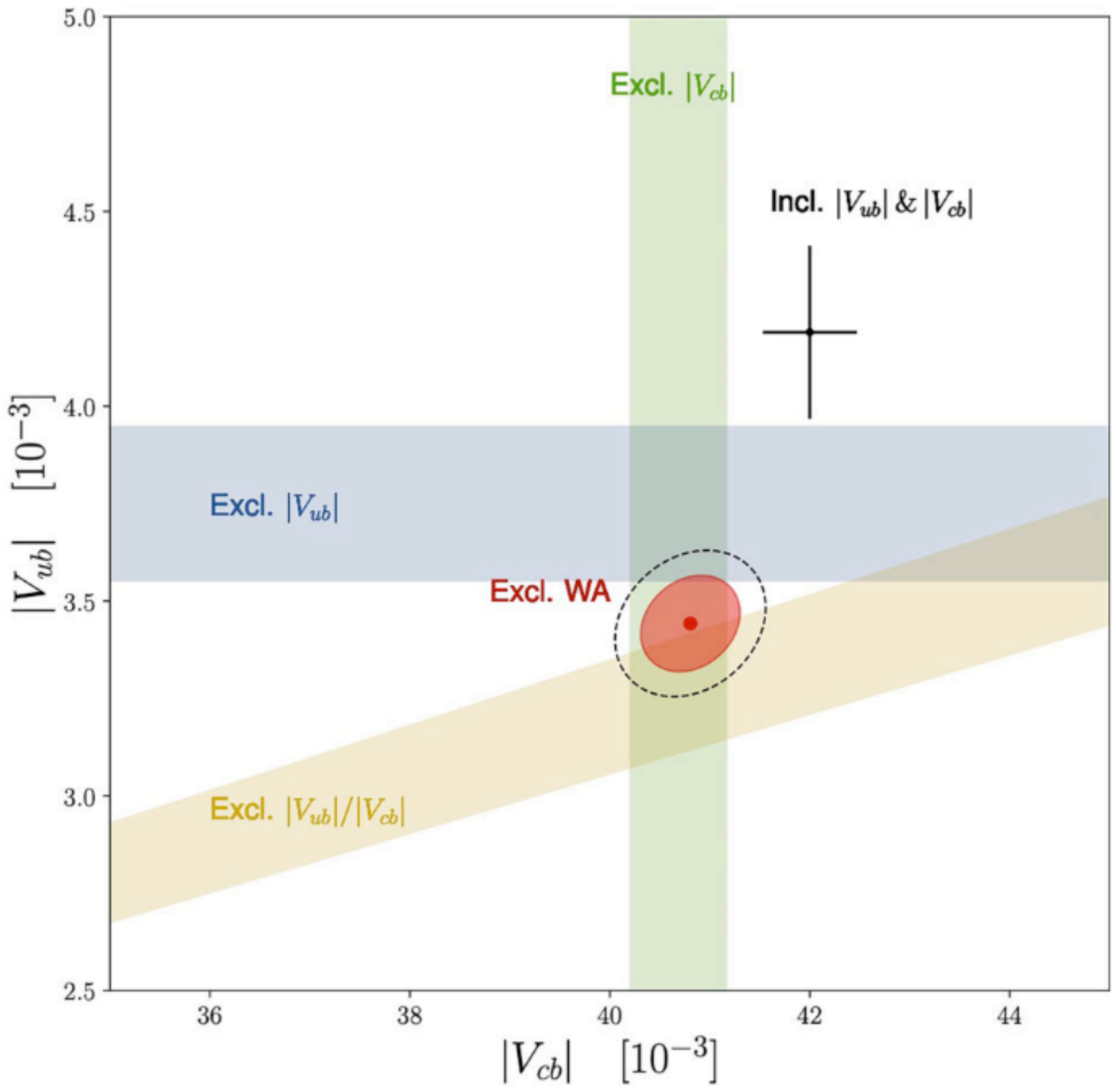
Bernlochner, Prim, Vos (2024)

- Longstanding puzzle between inclusive and exclusive
- Key input to SM predictions

Example:

$$\frac{\mathcal{B}(B^- \to K^-\mu^+\mu^-)^{\rm SM}[1.1, 6.0]_{\rm incl/hybrid}}{\mathcal{B}(B^\pm \to K^\pm\mu^+\mu^-)[1.1, 6.0]} - 1 = 0.54 \pm 0.15 \ ,$$

$$\frac{\mathcal{B}(B^- \to K^-\mu^+\mu^-)^{\rm SM}[1.1, 6.0]_{\rm excl}}{\mathcal{B}(B^\pm \to K^\pm\mu^+\mu^-)[1.1, 6.0]} - 1 = 0.33 \pm 0.13 \ ,$$



Inclusive Decays = Heavy Quark Expansion

- b quark mass large compared to Λ_{QCD}
- Setting up the HQE: $p_b = m_b v + k \qquad k \sim iD$
- Operator product expansion:

$$d\Gamma = d\Gamma_0 + \frac{d\Gamma_1}{m_b} + \frac{d\Gamma_2}{m_b^2} + \ldots \qquad d\Gamma_i = \sum_k C_i^{(k)} \left\langle B \,|\, O_i^{(k)} \,|\, B \right\rangle$$

  - $C_i^{(k)}$ Set up OPE and heavy quark expansion (HQE)
  - HQE matrix elements

$$\langle B \,|\, \mathcal{O}_i^{(n)} \,|\, B \rangle = \langle B \,|\, \bar{b}_v (iD_\mu) \ldots (iD_{\mu_n}) b_v \,|\, B \rangle$$

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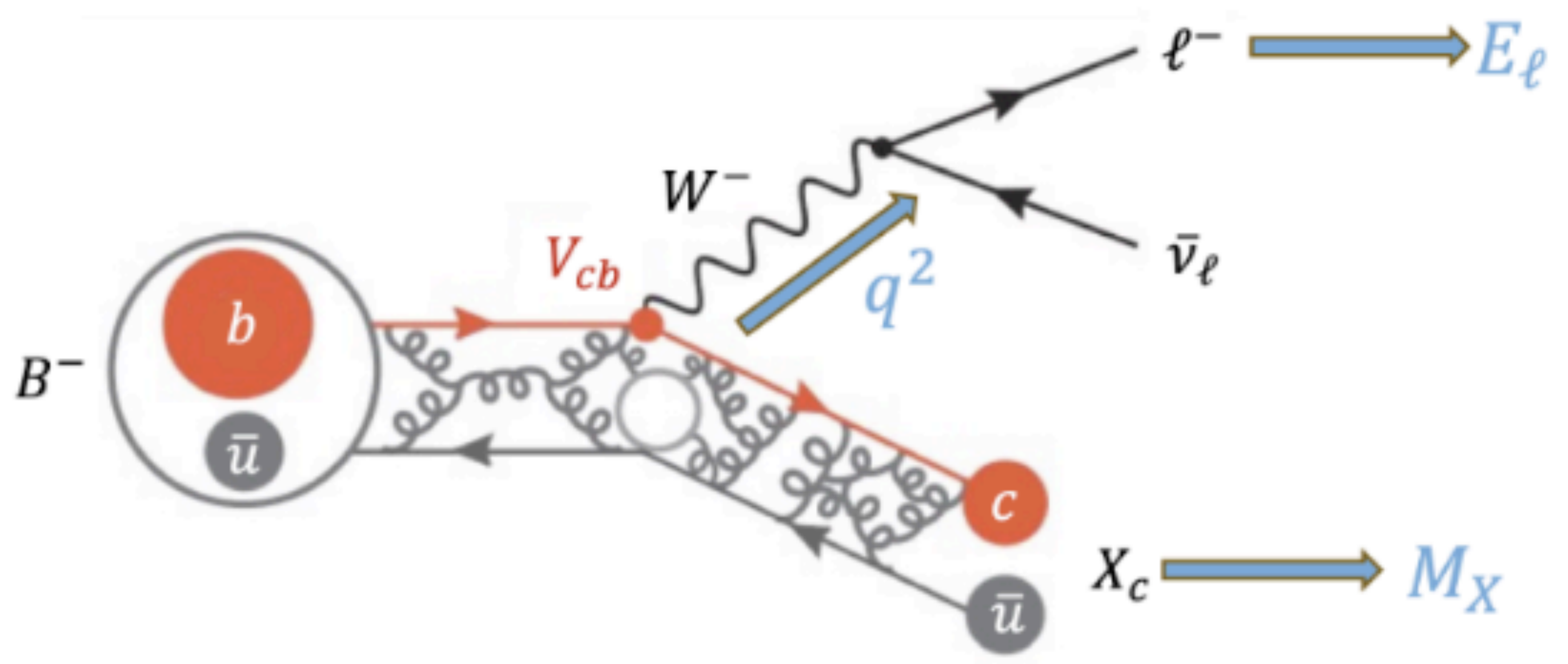
HQE elements:

- Extracted from data (lattice is upcoming!)
- $\Gamma_2 : \mu_\pi^2, \quad \mu_G^2$ at $1/m_b^2$
- $\Gamma_3 : \rho_D^3, \quad \rho_{\text{LS}}^3$ at $1/m_b^3$
- Many more at higher order!

Moments of the Spectrum

Non-perturbative matrix elements obtained from moments of differential rate



$$\langle O^n \rangle_{\text{cut}} = \frac{\int_{\text{cut}} dO\, O^n \frac{d\Gamma}{dO}}{\int_{\text{cut}} dO\, \frac{d\Gamma}{dO}}$$

$M_X^2 = (p_B - q)^2$, $E_\ell = v_B \cdot p_\ell$ and $q^2 = (p_\nu + p_\ell)^2$

hadronic mass, lepton energy and q^2 moments

- Different phase space cuts give additional (correlated) observables
- $\mu_\pi^2, \mu_G^2, \rho_D^3 + \ldots \to$ extracted from data $\to$ total rate $\to |V_{cb}|$

Moments of the Spectrum

$$
\begin{aligned}
L_i =& \frac{1}{\Gamma_0} \int_{E_l \geq E_{\mathrm{cut}}} \mathrm{d}E_l\, \mathrm{d}q_0\, \mathrm{d}q^2\, (E_l)^i\, \frac{\mathrm{d}^3\Gamma}{\mathrm{d}q^2\, \mathrm{d}q_0\, \mathrm{d}E_l} \\
=& (m_b)^i \Bigg[L_i^{(0)} + L_i^{(1)} \frac{\alpha_s(\mu_s)}{\pi} + L_i^{(2)} \left(\frac{\alpha_s(\mu_s)}{\pi}\right)^2 + \frac{\mu_\pi^2}{m_b^2} \left(L_{i,\pi}^{(0)} + L_{i,\pi}^{(1)} \frac{\alpha_s(\mu_s)}{\pi} \right) \\
& + \frac{\mu_G^2(\mu_b)}{m_b^2} \left(L_{i,G}^{(0)} + L_{i,G}^{(1)} \frac{\alpha_s(\mu_s)}{\pi} \right) + \frac{\rho_D^3(\mu_b)}{m_b^3} \left(L_{i,D}^{(0)} + L_{i,D}^{(1)} \frac{\alpha_s(\mu_s)}{\pi} \right) \\
& + \frac{\rho_{LS}^3(\mu_b)}{m_b^3} \left(L_{i,LS}^{(0)} + L_{i,LS}^{(1)} \frac{\alpha_s(\mu_s)}{\pi} \right) + O\left(\frac{1}{m_b^4}\right) \Bigg] ,
\end{aligned}
$$

The present

Jezabek, Kuhn, NPB 314 (1989) 1; Melnikov, PLB 666 (2008) 336; Pak, Czarnecki, PRD 78 (2008) 114015; Becher, Boos, Lunghi, JHEP 0712 (2007) 062; Alberti, Gambino, Nandi, JHEP 1401 (2014) 147; Mannel, Pivovarov, Rosenthal, PLB 741 (2015) 290; Fael, Schonwald, Steinhauser, Phys Rev. D 104 (2021) 016003; Fael, Schonwald, Steinhauser, Phys Rev. Lett. 125 (2020) 052003; Fael, Schonwald, Steinhauser, Phys Rev. D 103 (2021) 014005,

$$\Gamma \propto |V_{cb}|^2 m_b^5 \left[\Gamma_0 + \Gamma_0^{(1)} \frac{\alpha_s}{\pi} + \Gamma_0^{(2)} \left(\frac{\alpha_s}{\pi}\right)^2 + \Gamma_0^{(3)} \left(\frac{\alpha_s}{\pi}\right)^3 + \frac{\mu_\pi^2}{m_b^2}\left(\Gamma^{(\pi,0)} + \frac{\alpha_s}{\pi}\Gamma^{(\pi,1)}\right)\right.$$
$$\left. + \frac{\mu_G^2}{m_b^2}\left(\Gamma^{(G,0)} + \frac{\alpha_s}{\pi}\Gamma^{(G,1)}\right) + \frac{\rho_D^3}{m_b^3}\left(\Gamma^{(D,0)} + \Gamma_0^{(1)}\left(\frac{\alpha_s}{\pi}\right)\right) + \mathcal{O}\left(\frac{1}{m_b^4}\right) + \cdots\right)$$

- Include terms up to $1/m_b^4$ (*)
- Uses kinetic mass scheme [1411.6560, 1107,3100, hep-ph/0401063]
- α_s^3 for total rate and kinetic mass [Fael, Schonwald, Steinhauser (2020,2021)]
- $\alpha_s \rho_D^3$ included [Mannel, Pivovarov, Moreno]

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$$+ \frac{\mu_G^2}{m_b^2}\left(\Gamma^{(G,0)} + \frac{\alpha_s}{\pi}\Gamma^{(G,1)}\right) + \frac{\rho_D^3}{m_b^3}\left(\Gamma^{(D,0)} + \Gamma_0^{(1)}\left(\frac{\alpha_s}{\pi}\right)\right) + \mathcal{O}\left(\frac{1}{m_b^4}\right) + \cdots\Big)$$

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New:
QED corrections in total rate
α_s^2 to q^2 moments

$$|V_{cb}| = (41.64 \pm 0.47) \times 10^{-3}$$

Carvunis, Finauri, Gambino, Jung, Maechler [2507.22123]

Inclusive decays: the Kolya package

Open source Python package:
https://gitlab.com/vcb-inclusive/kolya

- HQE predictions for several observables:
  - Centralized $\langle E_\ell \rangle$ moments
  - Centralized $\langle q^2 \rangle$ moments
  - Centralized $\langle M_X^2 \rangle$ moments
  - Total rate + branching ratio with kinematic cut

Features:

- Includes power corrections up to $1/m_b^5$ Mannel, Milutin, KKV [2311.12002]
- Employs kinetic scheme for m_b and $\overline{\mathrm{MS}}$ for m_c
- Interface with CRunDec for automatic RGE evolution Chetyrkin, Kuhn, Steinhauser, Smidth, Herren

Inclusive decays: the Kolya package

Nir, Pak, Downlin, Egner, Fael, Steinhauser, Gambino, Manohar, Block, Becher, Alberti, Mannel, Turczyk, Dassinger, Schonwald.

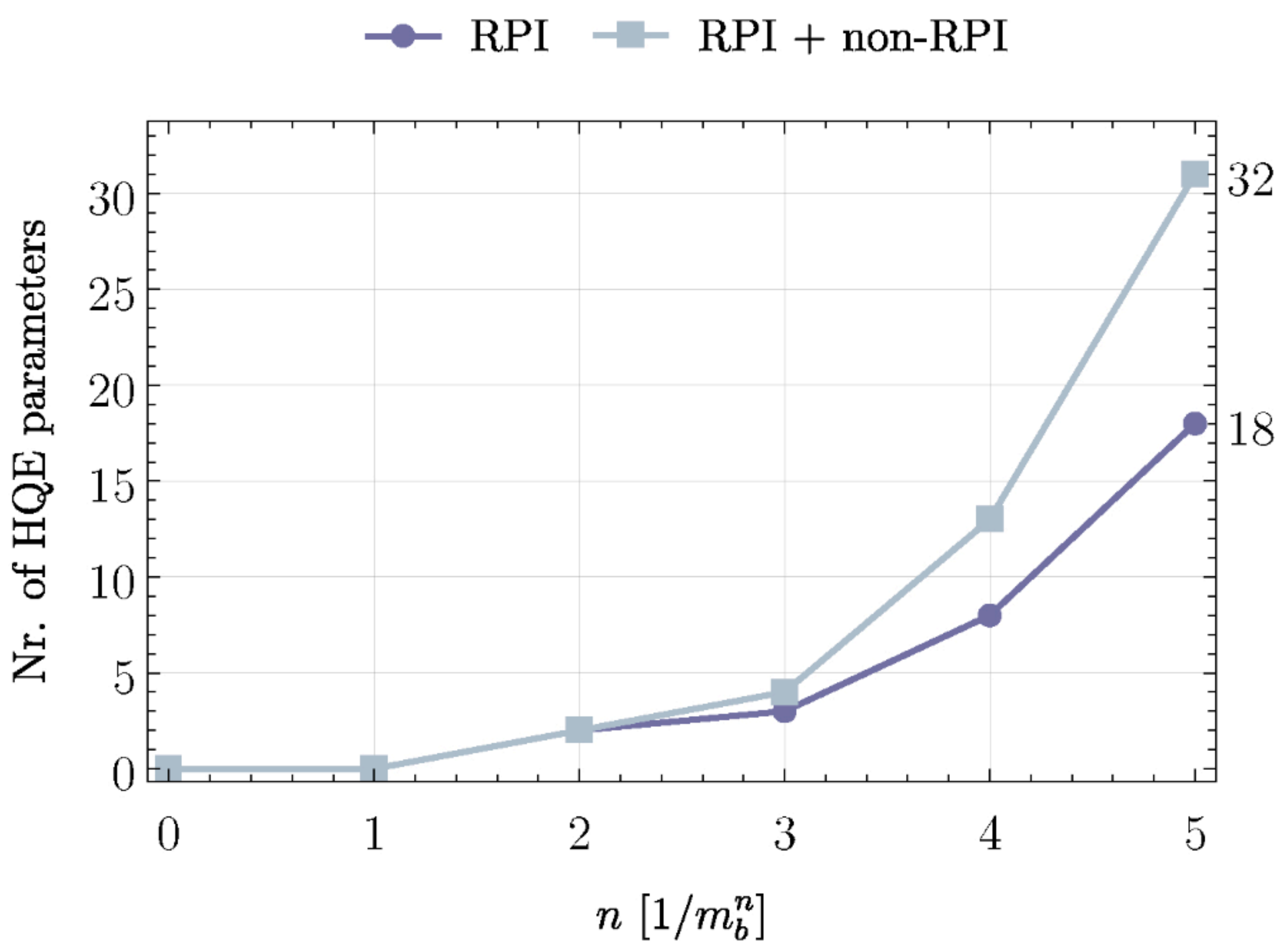
Γ_{sl}	tree	α_s	α_s^2	α_s^3
Partonic				['11]
μ_π^2, μ_G^2		['06, '12,'13,'15]		
ρ_D^3, ρ_{LS}^3		['21]		
$1/m_b^4, 1/m_b^5$	['06,'10,'18,'23]			
$q_n(q^2_{\mathrm{cut}})$	tree	α_s	α_s^2	
Partonic			['24]	
μ_G^2, μ_π^2		['12,'13]		
ρ_D^3, ρ_{LS}		['21]		
$1/m_b^4, 1/m_b^5$	['18, '23]			
$\ell_n(E_{\mathrm{cut}}), h_n(E_{\mathrm{cut}})$	tree	α_s	$\alpha_s^2\beta_0$	α_s^2
Partonic			['05]	['08]*
μ_G^2, μ_π^2		['07,'13]		
ρ_D^3				
$1/m_b^4, 1/m_b^5$	['06, '10,'23]			

- *only known for fixed m_c/m_b and lepton energy cuts

Pushing inclusive B decays to the limit

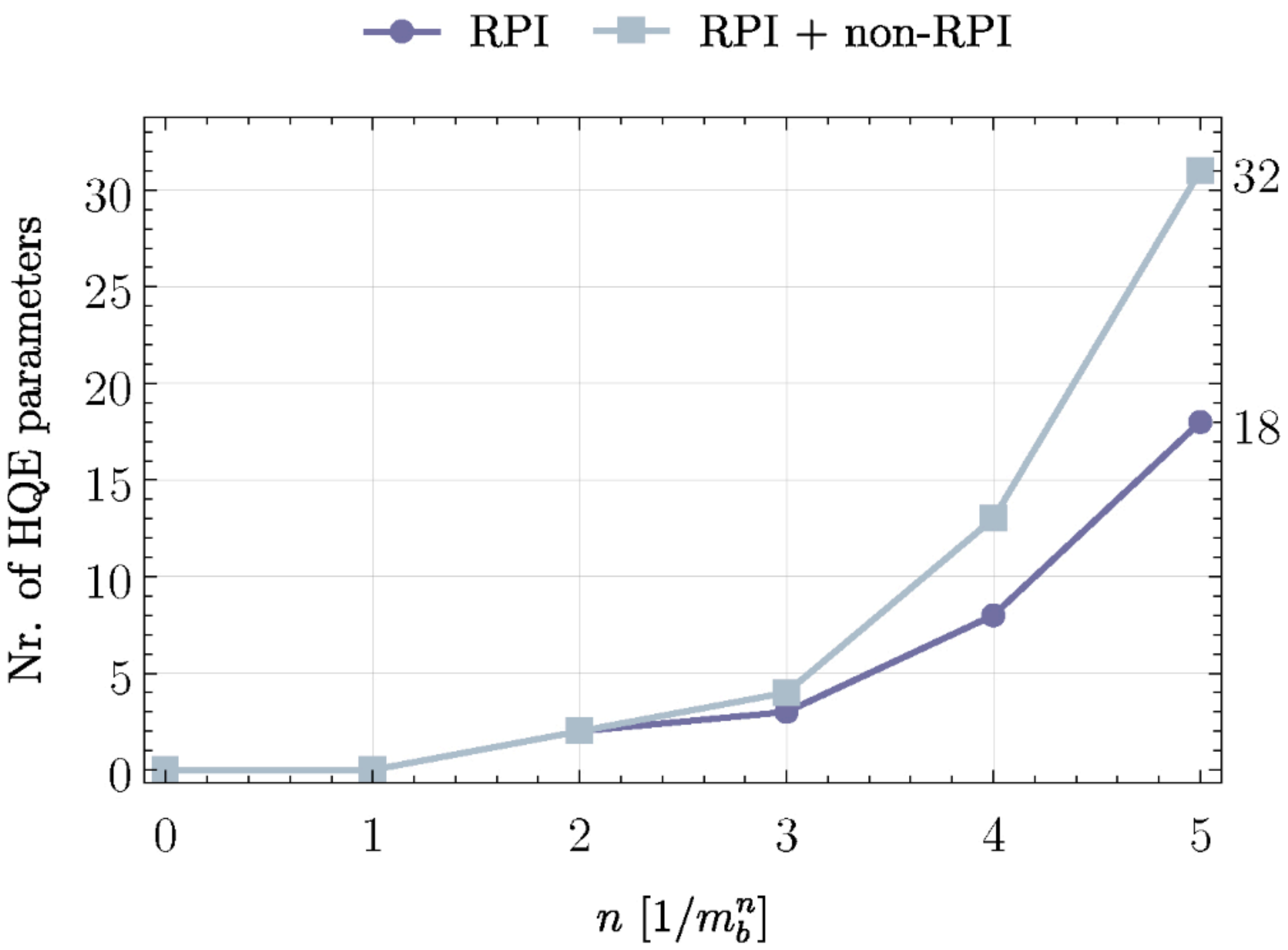
- Include higher-order terms in m_b?
- Include higher orders in α_s? [ask Karlsruhe group]
- Include higher terms in kinetic mass conversion?
- Check for Quark Hadron Duality violation?
- Change HQE fit setup [in progress Fael, Prim, Milutin, KKV]

Getting to higher order



- Large proliferation of terms
- Choice of v in HQE is not unique: Reparametrization Invariance (RPI)
- RPI reduces number of parameters (only for q2 moments!)
- First extraction of $1/m_b^4$ terms done limited sensitivity, no enhancement

Getting to higher order



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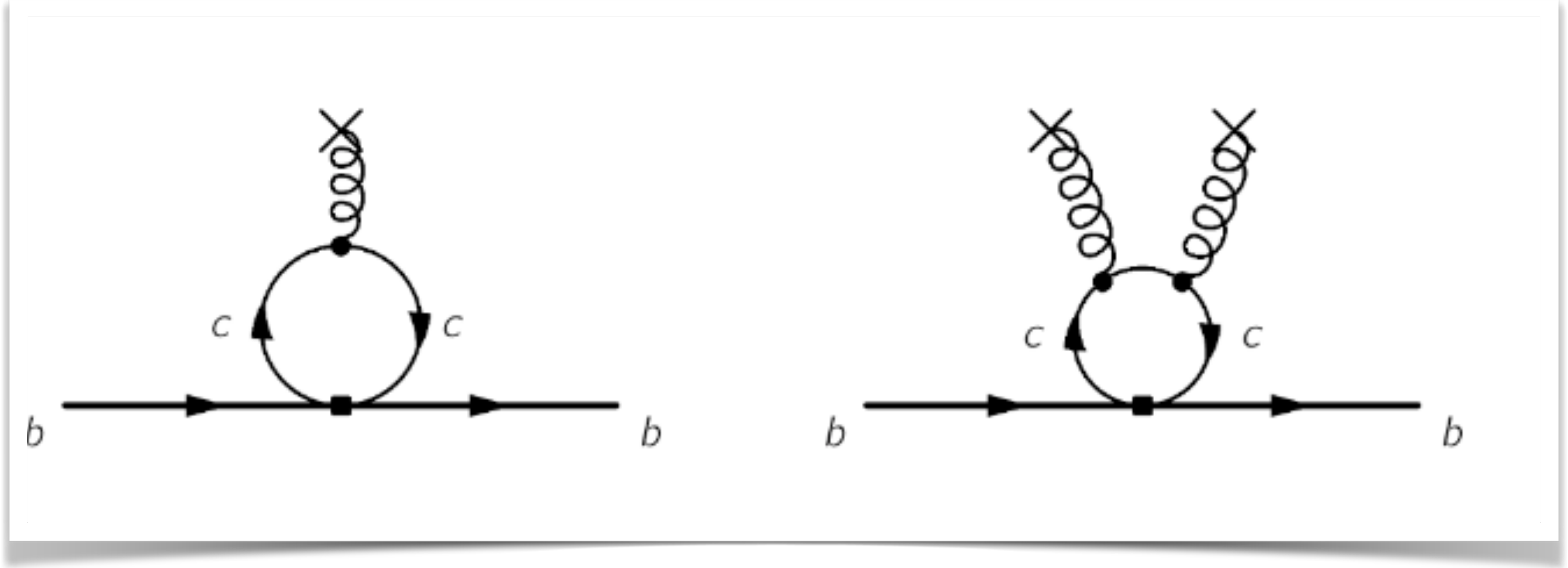
Use higher-order terms to estimate theory uncertainty
[in progress Fael, Prim, Milutin, KKV]

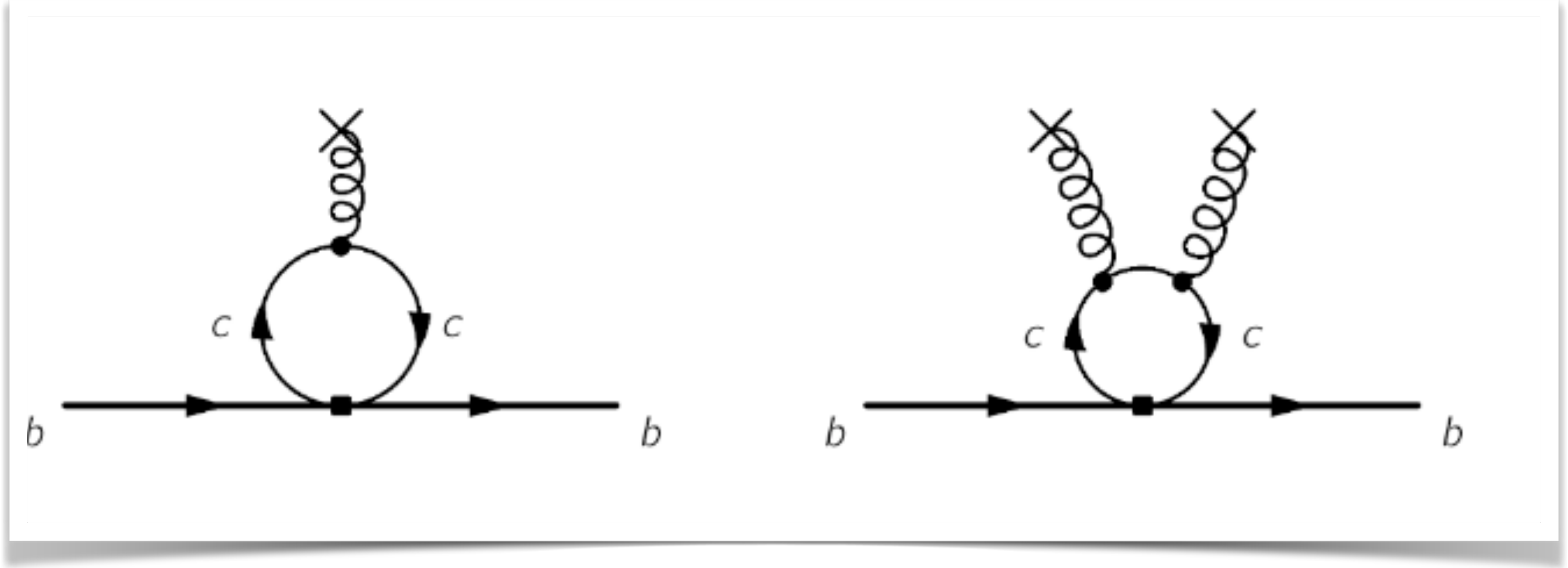
Getting to higher order: dimension 8



- $1/m_b^5$ and $1/m_b^3 m_c^2$ intrinsic charm contributions
- Charm contributions are numerically enhanced $m_c^2 \sim m_b \Lambda_{\rm QCD}$
- Calculate full dimension 8 to get these terms!
- Estimate their effect Lowest-lying state approximation

Mannel, KKV [1802.09409]; Mannel, Milutin, KKV [2311.12002]; Finauri [2501.09090]

Getting to higher order: dimension 8



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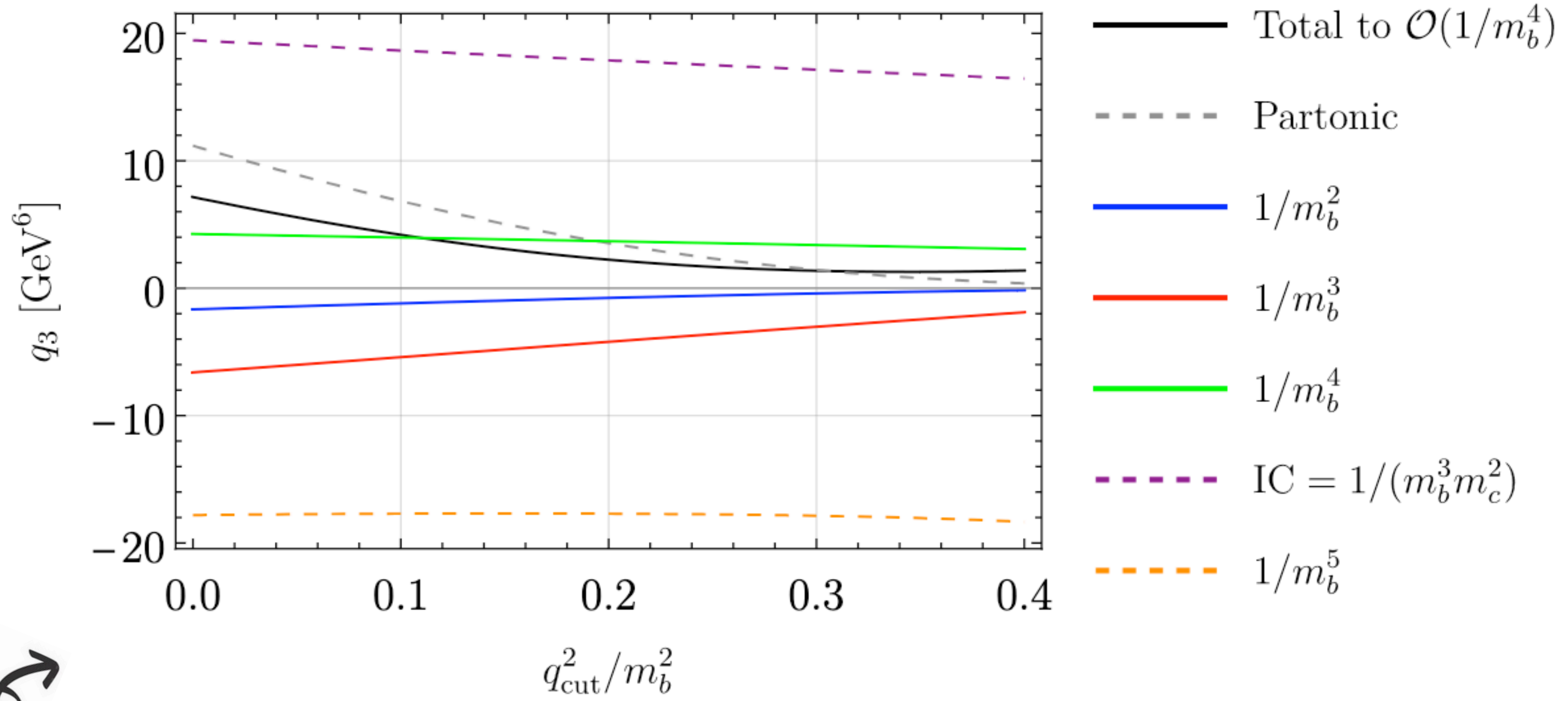


Contributions cancel to large extent, making dim-8 small

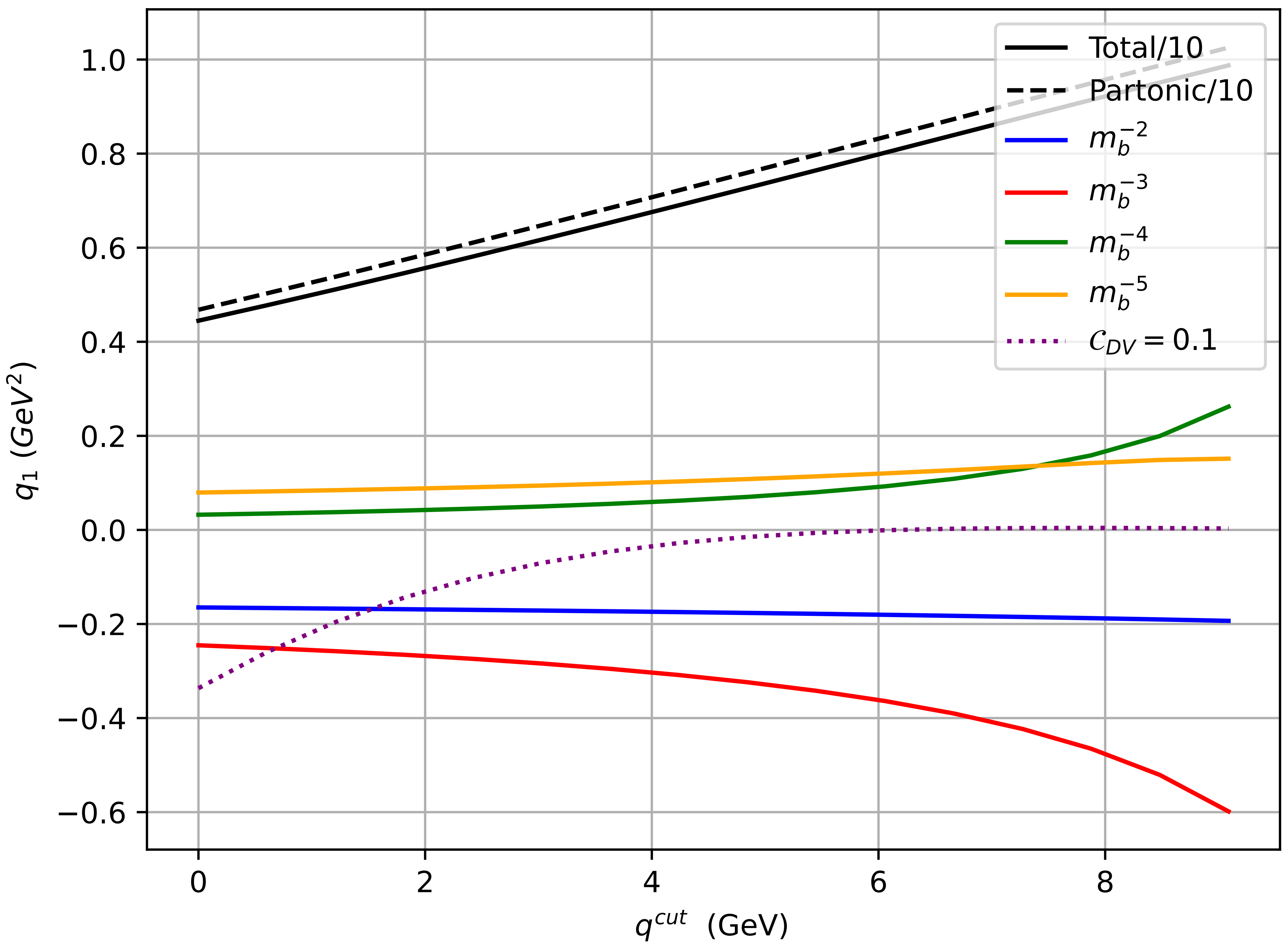
Quark Hadron Duality Violations

- Currently no indications of QHD violations
- Expect QHD violations at some point as the series in $1/m_b$ is not analytic; at some power the series will have factorial behaviour

- Typically this gives sinusoidal fluctuations of the rate
- Constructed a simple model using a Borel transform
- Model parameters based on $1/m_b^5$ terms, with free overal normalization

$Q = m_b v - q$

$$\hat{\Delta}_{\rm DV} W_{1,4}(vQ, Q^2) = -\frac{1}{\pi}\hat{\Delta}_{\rm DV}\mathrm{Im}\left[T_{1,4}(vQ,Q^2)\right] = \frac{1}{\Lambda_{\rm HQE} - vQ}\frac{vQ}{\sqrt{Q^2}}\left(\sin\left(\frac{\sqrt{Q^2}}{\Lambda_{\rm HQE}}\right) - \sqrt{\frac{vQ}{\Lambda_{\rm HQE}}}\sin\left(\frac{1}{\sqrt{\Lambda_{\rm HQE}}}\sqrt{\frac{Q^2}{vQ}}\right)\right)$$



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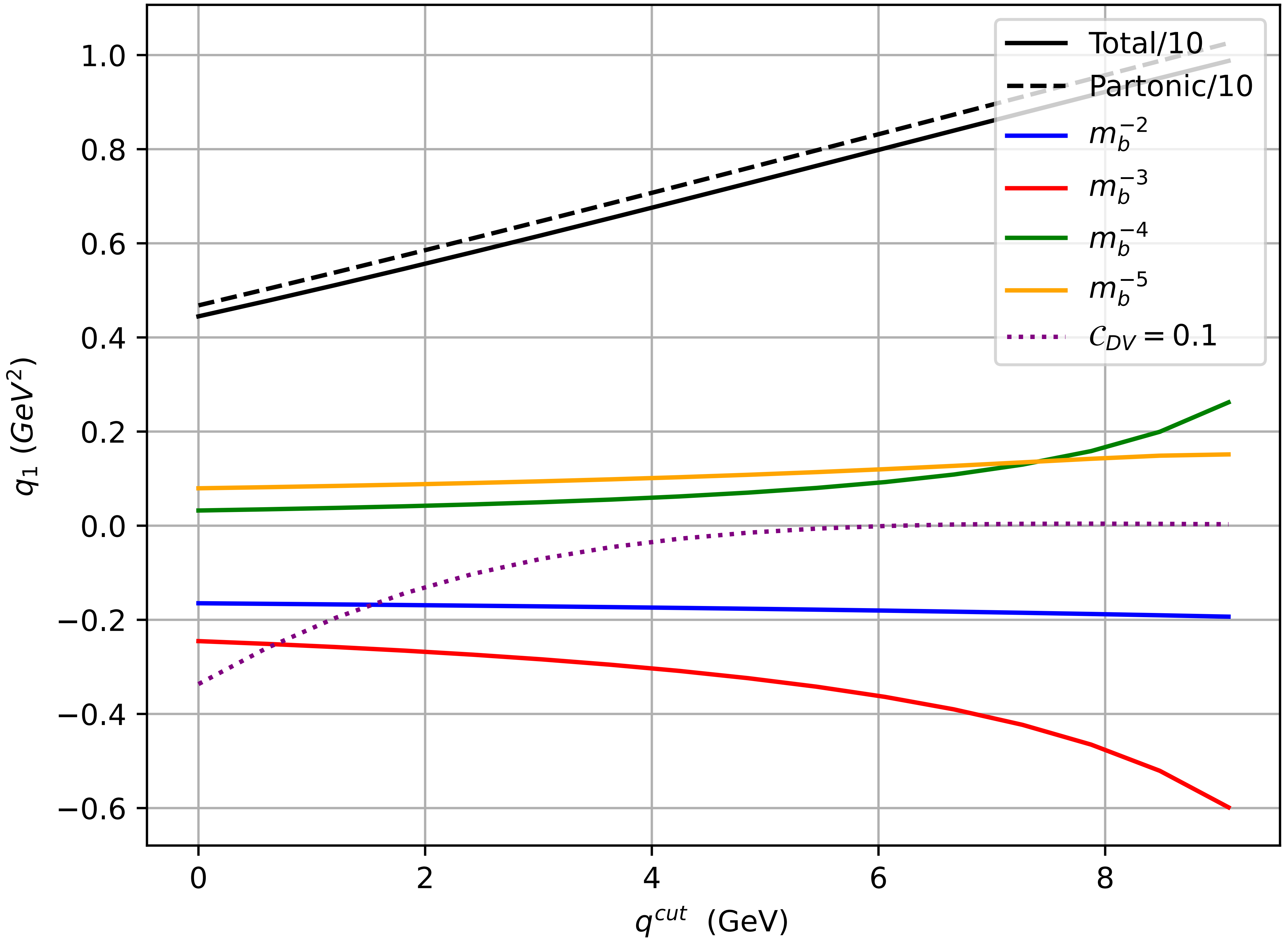
May be challenging to disentangle in data!



Higher-orders in the kinetic mass

- Renormalon ambiguities require a short distance mass
- Large influence on the total rate $\Gamma \propto m_b^5$
- Typically used is the kinetic mass

hep-ph/9405410; hep-ph/9704245

Only terms up to $1/m_b^2$

known up to α_s^3

Standard kinetic mass

$$M_H = m_Q + \bar{\Lambda} + \frac{\hat{\mu}_\pi^2 - \hat{\mu}_G^2}{2m_Q}$$

Defined in HQET limit!

- Start from Hadronic mass formula, identify $M_H \to m_{os}$ $\quad m_Q \to m_{\rm kin}(\mu)$
- Perturbative calculations using Small Velocity (SV) sumrules $v \to 0$ and Wilsonian cutoff μ

$$m_{os} = m_{\rm kin}(\mu) + \bar{\Lambda}_{\rm pert}(\mu) + \frac{\hat{\mu}_\pi^2(\mu)\,|_{\rm pert}}{2m_Q}$$

- Challenging to include higher-order terms

Note: OPE calculation done in terms of full QCD matrix elements!

Extended kinetic mass

Defined in full QCD!

$$M_H = \langle \Theta^\mu_\mu \rangle = M_H = m_Q \frac{\langle \bar{Q}Q \rangle}{2M_H} - \mu \frac{dm_Q}{d\mu} \frac{\langle \bar{Q}Q \rangle}{2M_H} + \mathcal{O}(\alpha_s^2)$$

- Start from trace of energy momentum tensor with full QCD states
- Calculate $\dfrac{\langle \bar{Q}Q \rangle_\mu}{2m} \equiv 1 + \Delta_{\bar{Q}Q}(\mu)$ with Wilsonian cutoff
- Identify $M_H \to m_{os}$ $\quad m_Q \to m_{\rm kin}(\mu)$

$$m_{os} = m_{\rm kin}(\mu) \frac{\langle \bar{Q}Q \rangle_\mu}{2m_{os}} - \left(\mu \frac{d}{d\mu} m_{\rm kin}(\mu) \right) \frac{\langle \bar{Q}Q \rangle_\mu}{2m_{os}}$$

Extended kinetic mass

$$m\Delta_{\bar{Q}Q}(\mu) - \delta m(\mu) + \mu\frac{\partial}{\partial\mu}\delta m(\mu) = 0$$

- All order solution to differential equation:

$$\delta m_{os} = \frac{C_F\alpha_s}{2\pi m}\left(\mu^2 - \mu\sqrt{\mu^2+m^2} + 3m^2\ln\left(\frac{\sqrt{\mu^2+m^2}+\mu}{m}\right)\right) + a\frac{C_F\alpha_s}{\pi}\mu$$

- Linear term ambiguous, μ^2-term agrees with kinetic mass
- Higher order terms new!

hep-ph/9405410; hep-ph/9704245

Extended kinetic mass

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- Linear term ambiguous, μ^2-term agrees with kinetic mass
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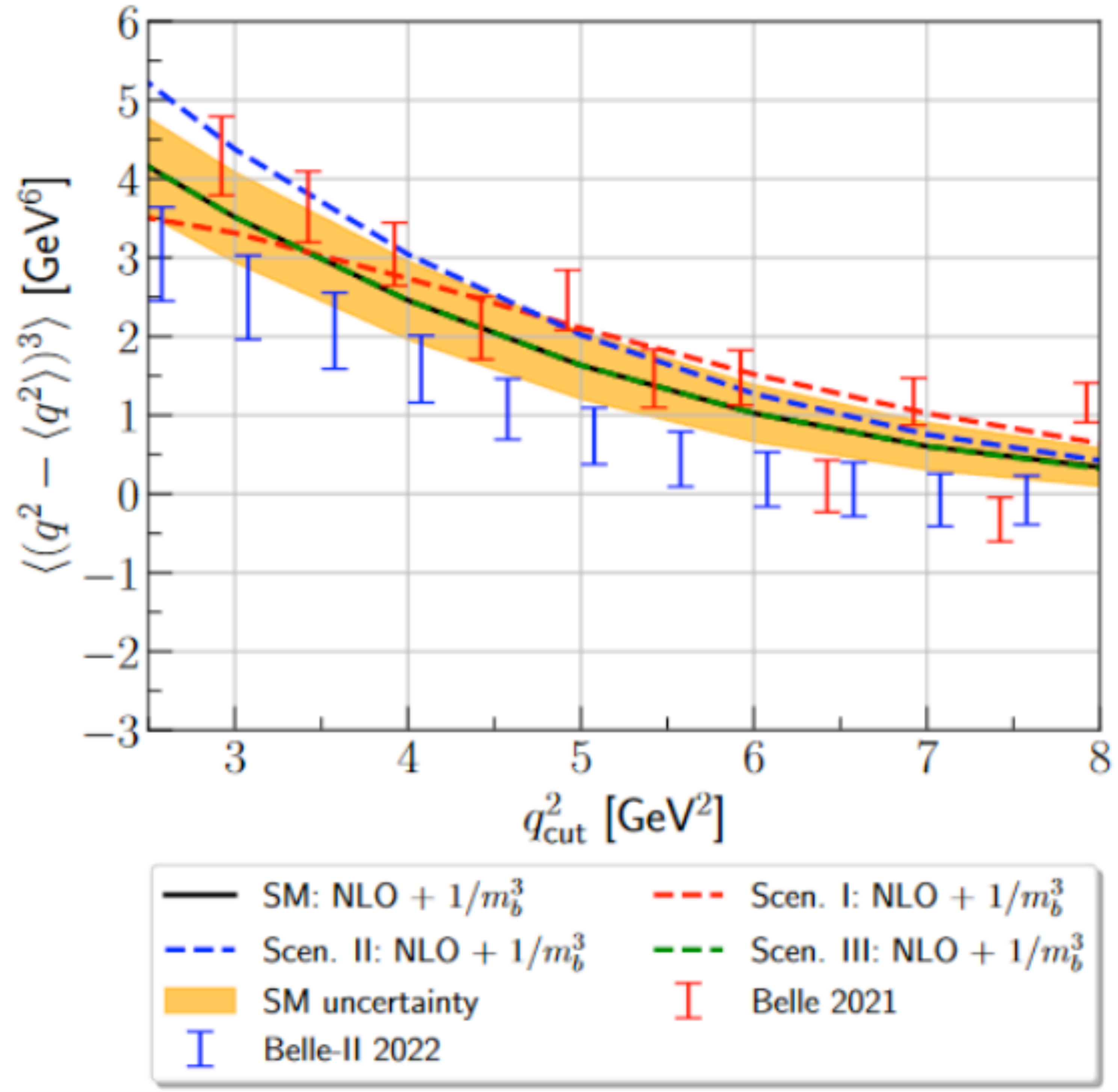
Next extend further in α_s using Gradient Flow Setup?

What about NP?

Fael, Rahimi, KKV [2208.04282]



- NP would influence the moments of the spectrum
- Requires a simultaneous extraction of HQE and NP!

No preference for NP, strong correlation between Vcb and tensor NP

Carvunis, Finauri, Gambino, Jung, Maechler [2507.22123]

Conclusion

- Studied higher-order terms, QHDV and kinetic mass
- Extended kinetic mass formula up to α_s

- In progress: New fit setup estimating theory uncertainties using higher-order HQE parameters
- Further exploration of new kinetic mass formula using gradient flow?

Happy Birthday!

Modelling Quark Hadron Duality Violations

- $F(\lambda)$ is asymptotic, inverse Borel transform contains poles
  $\tilde{B}[F](M) = \dfrac{1}{1-M^2} = \dfrac{1}{1+M}\dfrac{1}{1-M}$
- Define a prescription to deal with these singularities → ambiguity
- Difference between the prescriptions defines the Duality Violation (DV)

$$\frac{1}{1-M+i\epsilon} - \frac{1}{1-M-i\epsilon} = 2i\pi\delta(1-M)$$

$$\Delta_{DV}F(\lambda) = 2i\pi\int dMe^{-M}\frac{1}{1+M\lambda}\delta(1-\lambda M) = \frac{i\pi}{\lambda}\exp\left(-\frac{1}{\lambda}\right)$$

- Note: such a term gives factorial growth of the coefficients!

Modelling Quark Hadron Duality Violations

$$T_{\mu\nu} = \int d^4x e^{-iQ\cdot x}\langle B(p)\,|\,T\bar{b}_v(x)\Gamma_\mu c(x)\bar{c}(0)\bar{\Gamma}_\nu b_v(0)\,|\,B(p) = T_i f_i(g_{\mu\nu}, v_\mu v_\nu, \ldots)$$

- Model: $T_i(t, r^2) = \frac{1}{\Lambda_{\mathrm{HQE}}}\frac{1}{r^2}\sum\left(\frac{1}{r^2}\right)^l (2l)!p_l^{(i)}(t)$ with $r^2 \equiv \frac{Q^2}{\Lambda_{\mathrm{HQE}}^2}$, $t \equiv \frac{vQ}{\Lambda_{\mathrm{HQE}}}$
- Polynomials $p_l^{(i)}(t)$ inspired on LLSA approximation of $1/m_b^5$ terms
- Apply definition of DV from ambiguities in the Borel transform

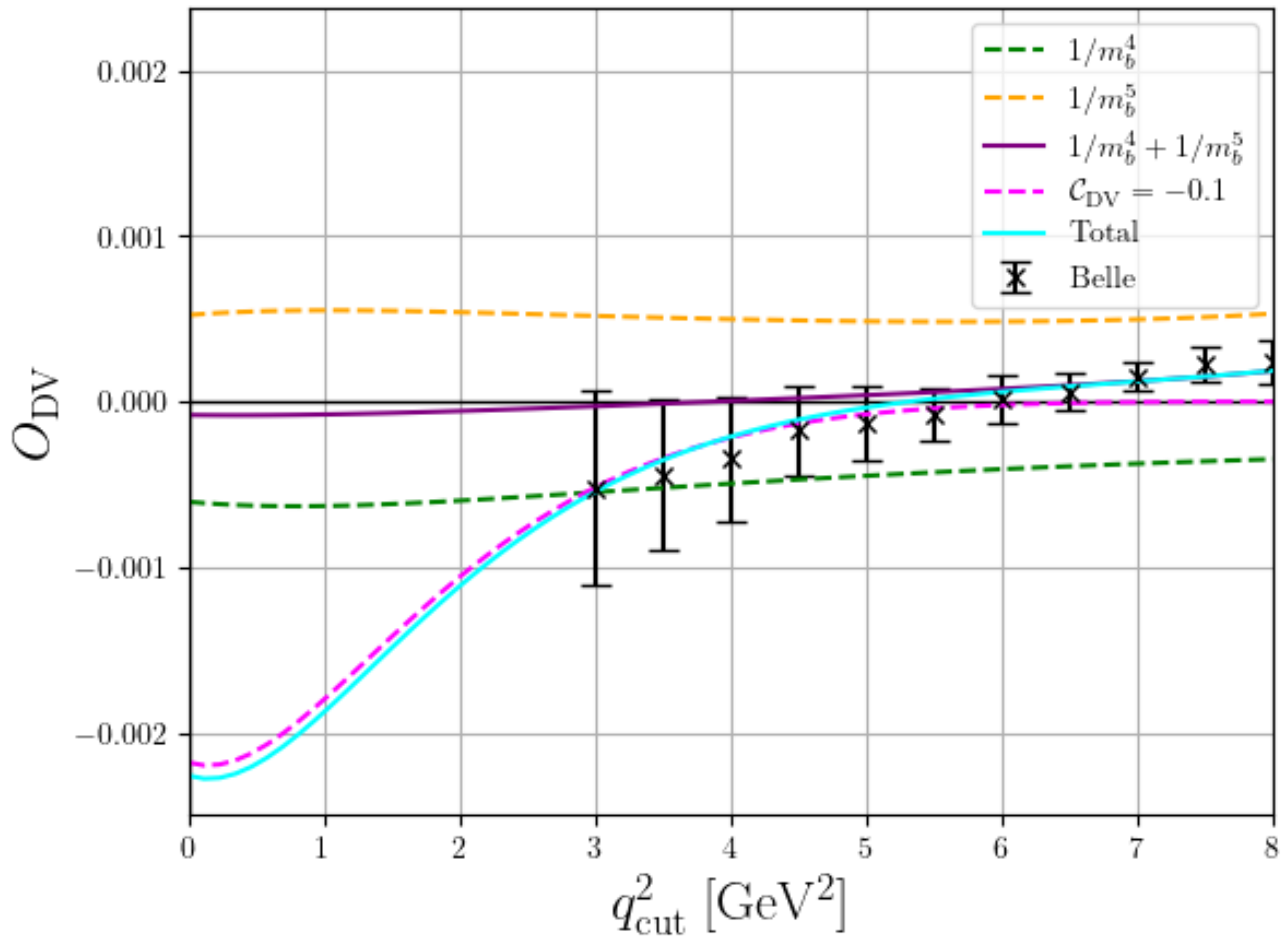
Sensitive observables

Current data: small effect

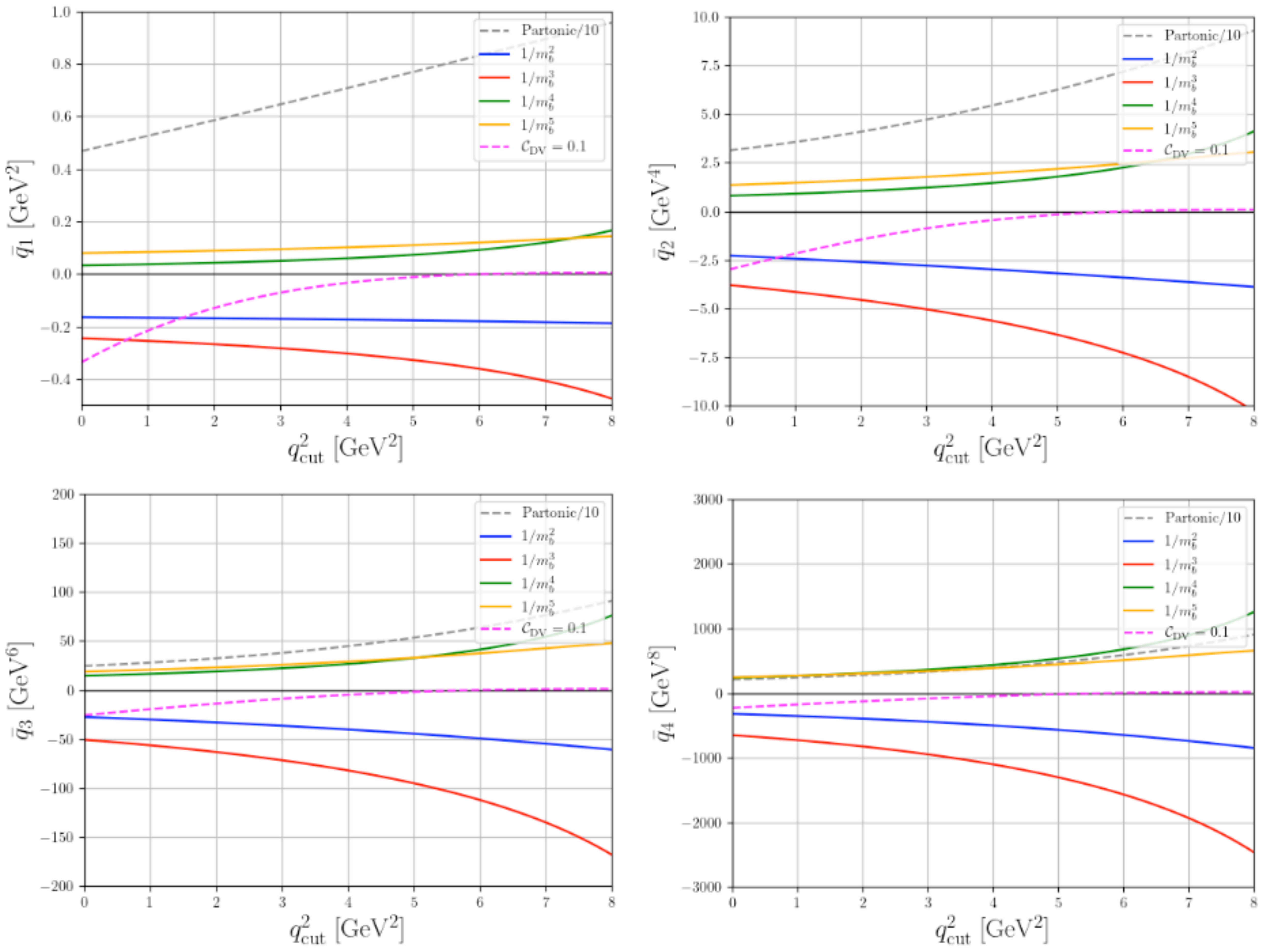
- Construct observables sensitive to higher-order terms and/or QHD violations
- Can express moments as

$$\bar{q}_i = C_i^{(0)} + \frac{\mu_G^2}{m_b^2} C_i^{(2)} + \frac{\rho_D^3}{m_b^3} C_i^{(3)} + R_i$$

- R_i contains both higher HQE terms and QHDV!
- Construct observable $\mathcal{O}_{\rm DV}^{(k)} \sim \Lambda^{k+1}/m_b^{k+1}$ only sensitive to $k+1$ powers

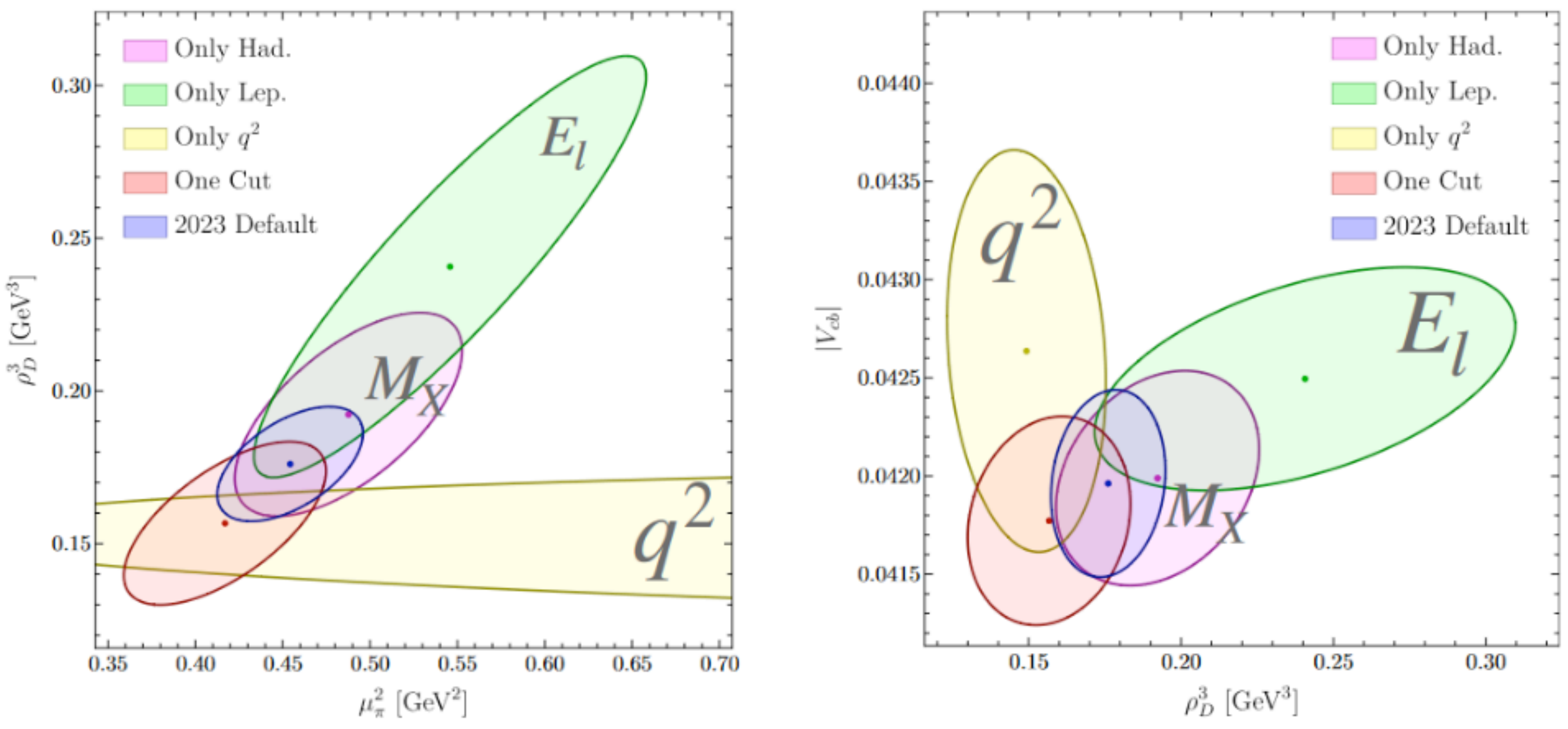


Quark Hadron Duality Violations



Complementarity of moments

Gambino, Finauri [2310.20324]



- Complementary between different measurements
- Extracted $\rho_D^3 = (0.176 \pm 0.019)$ GeV^3 (compare to our $\rho_D^3 = (0.12 \pm 0.20)$ GeV^3)
- Important input for lifetimes and $B \to X_u, B \to X_s$

Theoretical uncertainties

"Known" uncertainties

- Vary scale of α_s to account for perturbative corrections
- Vary m_b^{kin} and scale of charm μ_c

Missing higher order HQE parameters

- Vary ρ_D^3 by 30% to account for missing HQE parameters
- Vary μ_G^2 by 20% to account for missing $\alpha_s \times$ HQE parameters
- Assume theoretical correlations!
  - Strong correlations between different cuts, no correlation between different models see Gambino, Schwanda, Finauri
  - Flexible correlation added as nuisance parameter see Bernlochner, Fael, KKV

Can we use the $1/m_b^{4,5}$ corrections to better access the theory uncertainty?

Lowest State Saturation Approximation (LSSA)

$$\langle B|O_1 O_2|B\rangle = \sum_n \langle B|O_1|n\rangle\langle n|O_2|B\rangle$$

$$\rho_D^3 = \varepsilon\mu_\pi^2, \qquad \rho_{LS}^3 = -\varepsilon\mu_G^2, \qquad \varepsilon \sim 0.4 \text{ GeV}$$

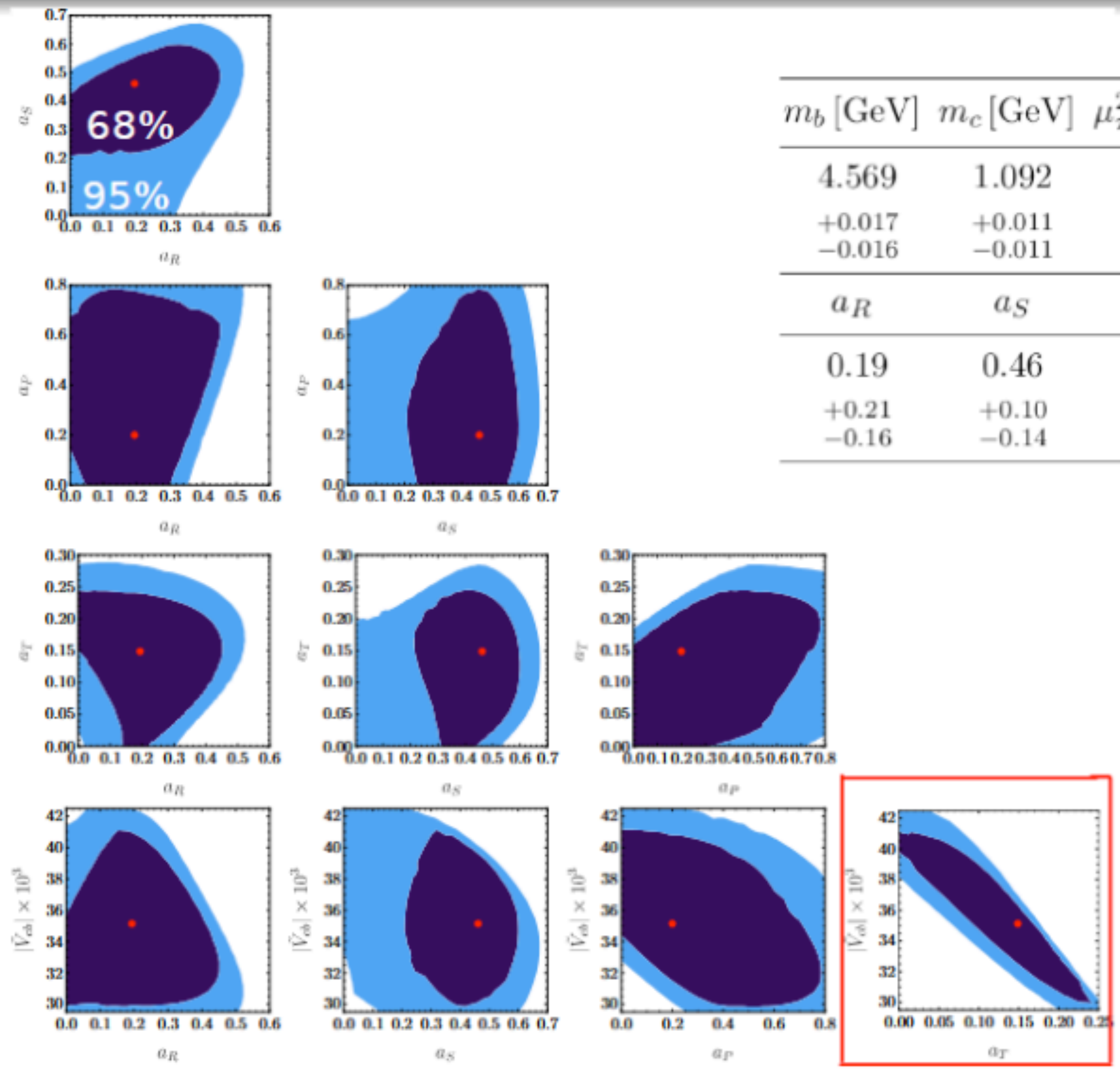
Mannel, Turczyk, Uraltsev JHEP 1011 (2010) 109; Heinonen, Mannel, NPB 889 (2014) 46

- Gives central values but uncertainty challenging to estimate
- $\mathcal{O}(1/m_b^4, 1/m_b^5)$ can then be included in fit Healey, Turczyk, Gambino, PLB 763 (2016) 60
  - LSSA estimated as priors (60% gaussian uncertainty)
  - -0.25% shift on $|V_{cb}|$ due to power corrections

What about NP?

Finauri, Carvunis, Gambino, Jung, Mächler[2507.22123]; slide from CKM 2025

Fit Result with Generic NP



m_b [GeV]	m_c [GeV]	μ_π^2 [GeV^2]	μ_G^2 [GeV^2]	ρ_D^3 [GeV^3]	ρ_{LS}^3 [GeV^3]	BR$_{c\ell\bar\nu}$ [%]
$4.569^{+0.017}_{-0.016}$	$1.092^{+0.011}_{-0.011}$	$0.454^{+0.049}_{-0.050}$	$0.342^{+0.065}_{-0.067}$	$0.195^{+0.027}_{-0.029}$	$-0.126^{+0.096}_{-0.104}$	$10.72^{+0.16}_{-0.16}$
a_R	a_S	a_P	a_T	$\cos(\delta_R)$	$\cos(\delta_{ST})$	$\cos(\delta_{PT})$
$0.19^{+0.21}_{-0.16}$	$0.46^{+0.10}_{-0.14}$	$0.20^{+0.43}_{-0.20}$	$0.15^{+0.07}_{-0.11}$	$0.99^{+0.01}_{-0.81}$	$-0.94^{+0.92}_{-0.06}$	$0.91^{+0.09}_{-1.91}$

first global fit for $\bar B \to X_c \ell \bar\nu$ with generic NP

- $\chi^2_{\text{min}}/\text{d.o.f.} = 36.04/67$
- SM fit: $\chi^2_{\text{min}}/\text{d.o.f.} = 42.58/74$
- first row SM compatible
- strong correlation in $a_T - |\tilde V_{cb}|$
- $\boxed{|\tilde V_{cb}| = (35.1^{+4.2}_{-3.6}) \cdot 10^{-3}}$
- competitive with exclusive
- no preference for NP

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