Flavour Physics Theory Overview

"Standard Model @ LHC"
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22 April

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Flavour Changing Interactions

Flavour Physics:
Effects of highly virtual particles at lower energies

Measure the standard model $W^{\pm}$ couplings in B and K decays

Test the standard model in process
i) which are suppressed through (accidental) symmetries, and
ii) which can be calculated with high precision

Symmetries: CP, flavour, electroweak symmetry

Flavour Breaking in the Standard Model

All quark gauge interactions derive from a simple Lagrangian

$$\mathcal{L}_g = \sum_{i=1}^{3} Q_i \not{D} Q_i + \sum_{i=1}^{3} u_i \not{D} u_i + \sum_{i=1}^{3} d_i \not{D} d_i + \sum_i \frac{1}{4} g_i \vec{F}^i_{\mu\nu} \vec{F}^{i\,\mu\nu}$$

Only Higgs Yukawa couplings break this symmetry in the SM

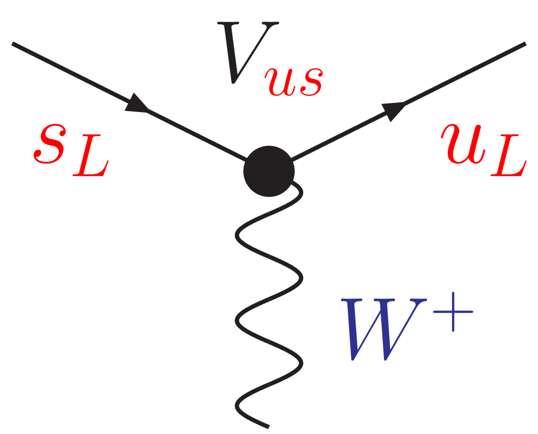
$$-\mathcal{L}_Y^q = \sum_{ij} \bar{u}_i Y_{u_{ij}} \tilde{\varphi}^\dagger Q_j + \sum_{ij} \bar{d}_i Y_{d_{ij}} \varphi^\dagger Q_j$$

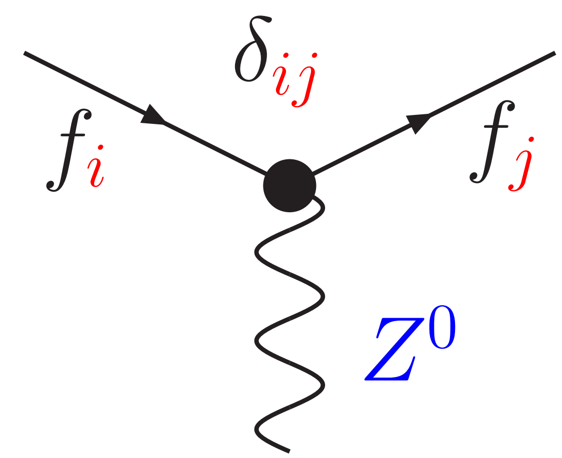
Mass eigenstates $\neq$ flavour eigenstates

for diagonal Y_d: $Y_u = \dfrac{1}{v} \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$

Neutral & Charged Current Interactions

Mass $\neq$ flavour eigenstates





SM: Only charged currents change the flavour ($\propto V_{us}$)

SM: Neutral currents do not change the flavour (i=j) at tree-level

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CKM matrix parametrises CP and flavour violation in the SM

B tree and loop decays: determine CKM matrix

Unitarity Triangle

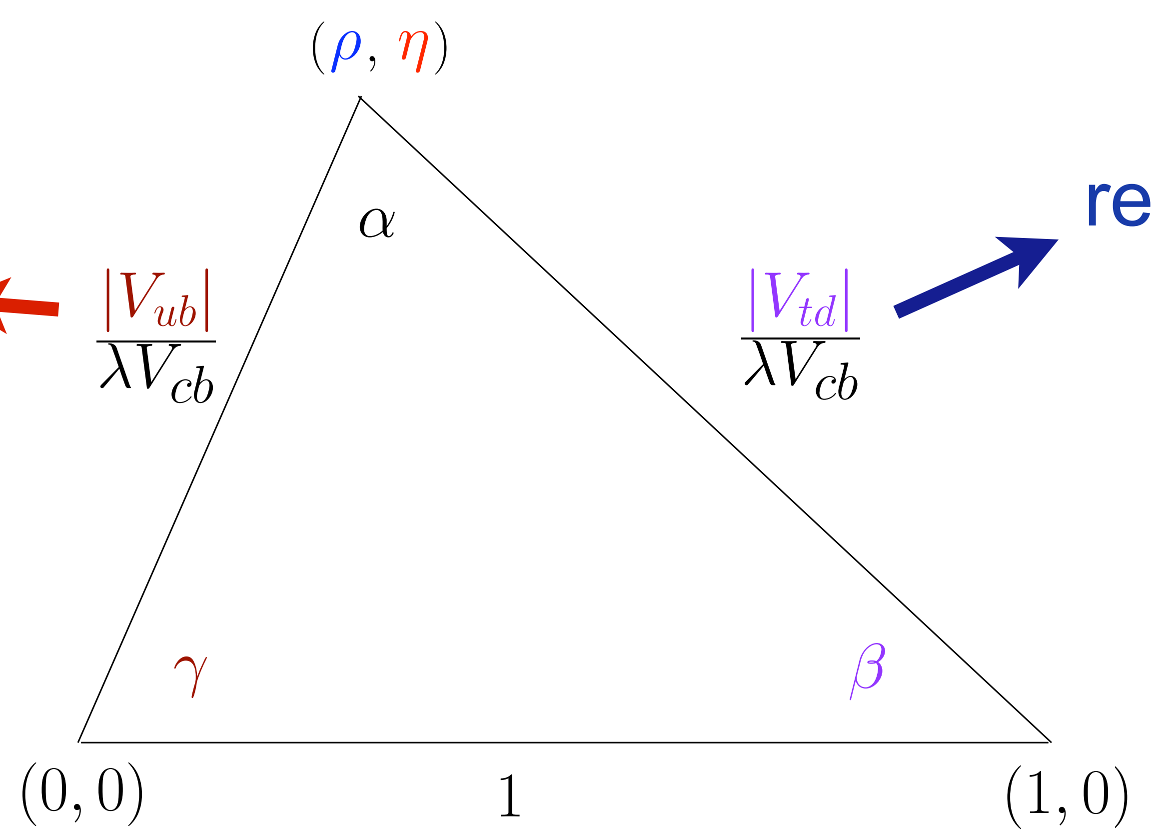
3 CKM angles $|V_{ub}|$, $|V_{cb}|$ & $|V_{us}|$ from (semi)leptonic B & K decays

CP violation in the standard model ∝ area of unitarity triangle

$$\text{Unitarity of } V \Rightarrow \begin{array}{ccccccc} V_{ub}^* V_{ud} & + & V_{cb}^* V_{cd} & + & V_{tb}^* V_{td} & = & 0 \\ A\lambda^3(\rho + i\eta) & - & A\lambda^3 & + & A\lambda^3(1-\rho-i\eta) & = & 0 \end{array}$$

Graphically,

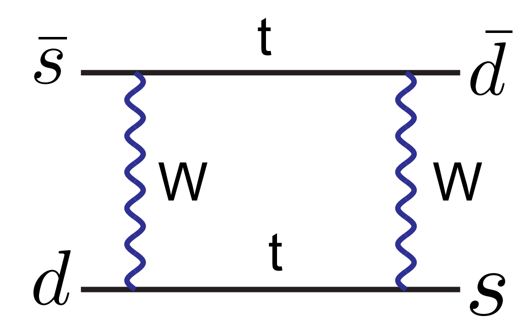
b →u l ν
b →u q q
(tree-level
Weak int.)

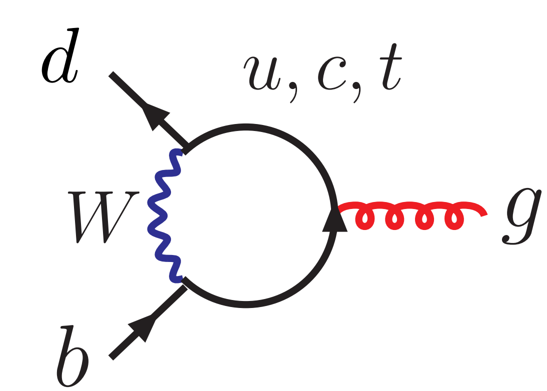


requires top loop

$$V_{ub} = |V_{ub}|e^{-i\gamma}$$

$$V_{td} = |V_{td}|e^{-i\beta}$$

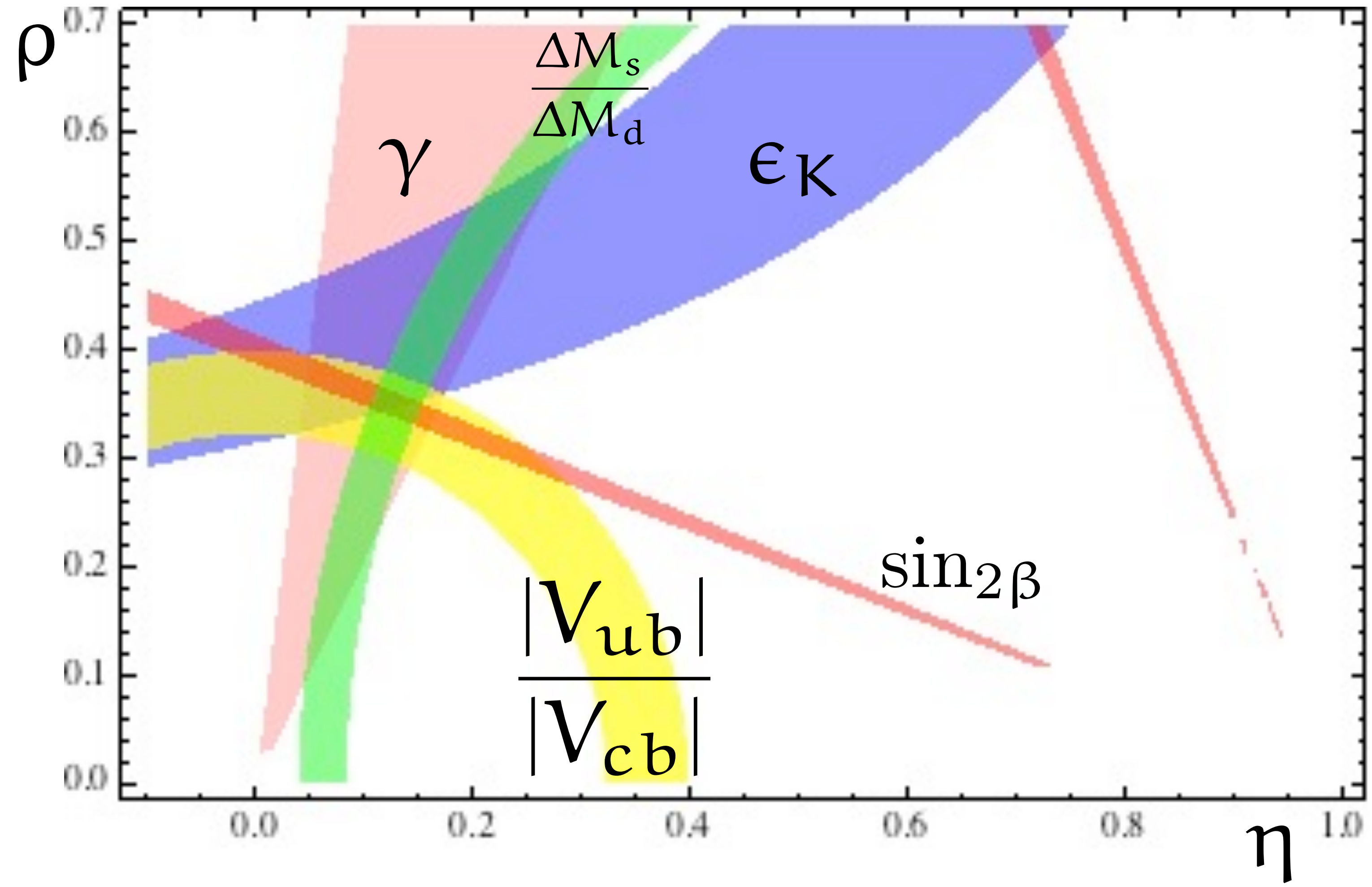




CKM input for tests of SM

CKM parameters: input for new physics insensitive tree level observables – see UUT [hep-ph/0007085]

LHCb exclusive V_{ub}/V_{cb} from semi-leptonic B decays: New $\Lambda_b \to p\, \mu^- \bar{\upsilon}$ results with Lattice QCD input from [Detmold et.al. 1503.01421]



Exclusive determinations consistently smaller then the inclusive one

Gamma determination from $B \to D(\pi/K)$

See Brod [1412.3173] for recent theory work on EW corrections

Can compare observables like ε_K at NNLO [Brod, MG `2012]

New Physics sensitivity

The New Physics (NP) and the Standard Model (SM) compete

$$\delta\mathcal{L} = \frac{C_{NP}}{\Lambda_{NP}^2}(\bar{s}d_L)(\bar{s}d_R) + \frac{C_{SM}}{v_{EW}^2}(\bar{s}d_L)(\bar{s}d_R)\ldots$$

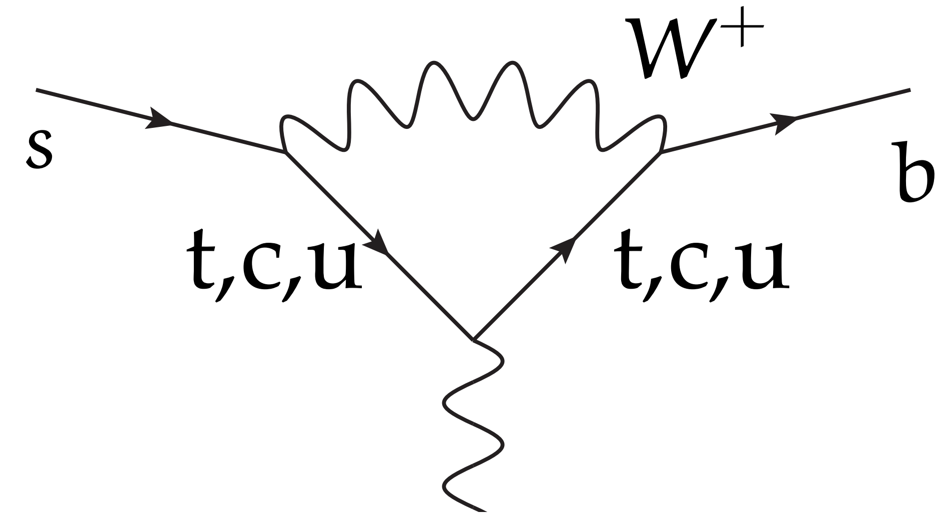
Since we have no direct evidence of new particles we should

- Calculate the SM flavour violation as precisely as possible.
- Understand the origin and correlation of NP flavour violation to be able to interpret small deviations.

Rare FCNC Decays

No tree-level Flavour Changing Neutral Currents in the SM

FCNCs are loop induced in the SM



For b → s transitions:

- short distance top contribution
- charm contribution $\propto \log(\mu/M_W)$

$$\sum_{i=u,c,t} V_{ib}^* V_{is} A(m_i^2/M_W^2) =$$

$$= V_{tb}^* V_{ts} (A_t - A_u)$$

$$+ V_{cb}^* V_{cs} (A_c - A_u)$$

$$-V_{tb} V_{ts}$$

$$\log(\mu/M_W)$$

After unitarity b → s transitions

$$\propto |V_{tb}^* V_{ts}| \simeq \left|1 - \lambda^2 \left(\frac{1}{2} - i\eta - \rho\right)\right| V_{cb}$$

$\lambda = V_{us}$ is the expansion parameter

Rare B Decays

E.g. $B_{(s)} \to l^+ l^-$, $B \to K^{(*)} l^+ l^-$, $B \to X l^+ l^-$, $B \to X_s \gamma$, ...

For rare B decays the operators

$$Q_7 = (\bar{b}_L \sigma_{\mu\nu} s_L) F^{\mu\nu},\ Q_V = (\bar{b}_L \gamma_\mu s_L)(\bar{l}\gamma_\mu l),\ Q_A = (\bar{b}_L \gamma_\mu s_L)(\bar{l}\gamma_\mu \gamma_5 l)$$

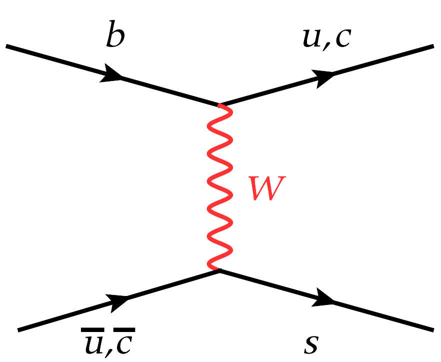
play an important role at at $\mu = m_b$.

In addition four quark operators can also contribute, e.g.

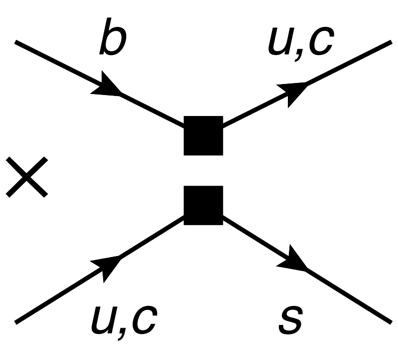
$$Q_2 = (\bar{b}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu s_L)$$

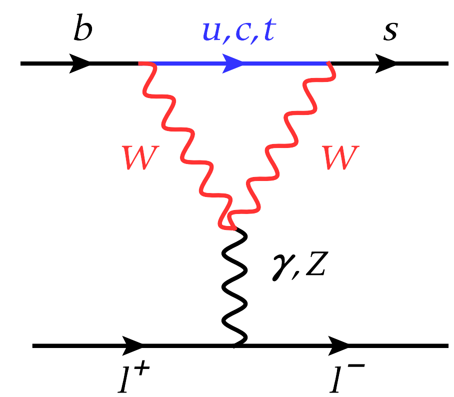
Status of $\mathcal{L}_{\mathrm{eff}}$ for $b \to s\, l^+ l^-$

SM Wilson coefficients: Matching at $\mu \approx M_W$



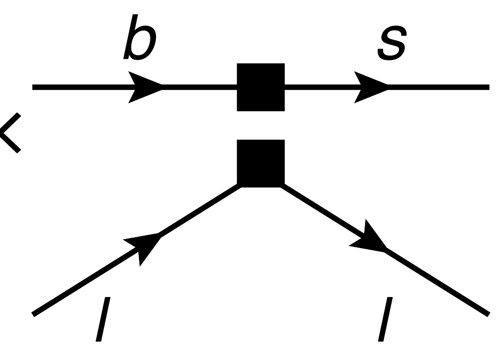
$\to C_2 \times$





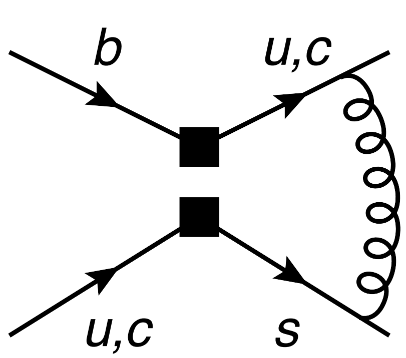
$\to C_{A,V} \times$

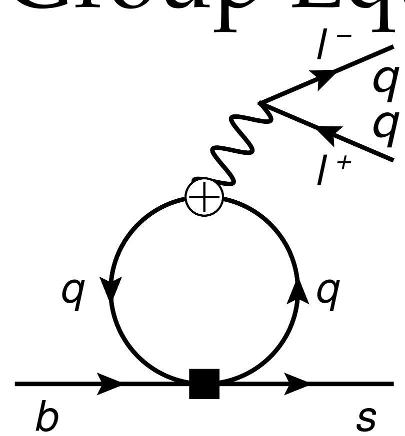
$(C_{10,9})$



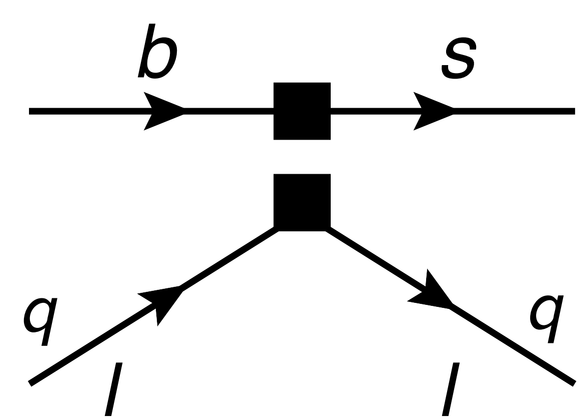
Known at two-loops in QCD for NNLL [Bobeth, Misiak, Urban, `99]

Renormalisation Group Equation $\to \mu \approx M_W$





$\to C_{1\ldots10} \times$



$\mathcal{L}_{\mathrm{eff}}$ @ NNLL in QCD and NLL EW for all but C_9 & C_{10} EW matching

[Gambino Haisch`01; Haisch `05, Bobeth, Gambino, MG, Haisch `04, MG, Haisch `05, Huber et. al. `05]

theory accuracy

$$B_s \to \mu^+\mu^- \quad B \to X\ell^+\ell^- \quad B \to K^{(*)}\ell^+\ell^- \quad B \to hh$$

# of observables

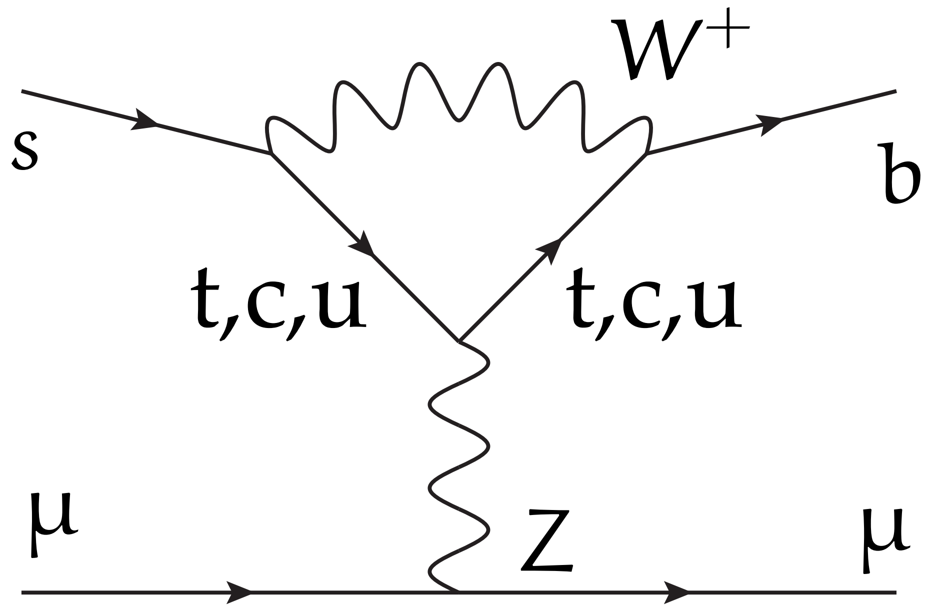
I will concentrate on the purely leptonic decay

Based on work with Christoph Bobeth, Emanuel Stamou [PRD 89, 034023 (2014)]
Christoph Bobeth, Thomas Hermann, Mikolaj Misiak, Emanuel Stamou and Matthias Steinhauser [PRL 112, 101801 (2014)]

and will not discuss purely hadronic decays

See e.g. recent work by Bobeth MG Vickers [1409.3252]

$B_s \to \mu^+ \mu^-$ in the Standard Model



+ Box diagrams

B_s is (pseudo)scalar – no photon penguin

$$Q_A = (\bar{b}_L \gamma_\mu s_L)(\bar{l} \gamma_\mu \gamma_5 l)$$

Dominant operator in the SM

helicity suppression $\left(\propto \frac{m_l^2}{M_B^2}\right)$

$$\propto |V_{tb}^* V_{ts}| \simeq \left|1 - \lambda^2 \left(\tfrac{1}{2} - i\eta - \rho\right)\right| V_{cb}$$

Effective Lagrangian in the SM:

$$\mathcal{L}_{\text{eff}} = G_F^2 M_W^2 \, V_{tb}^* V_{ts} \, (C_A Q_A + C_S Q_S + C_P Q_P) + \text{h.c.}$$

Scalar operators: $Q_S = (\bar{b}_R q_L)(\bar{l} l)$ $\quad Q_P = (\bar{b}_R q_L)(\bar{l} \gamma_5 l)$

Standard Model: C_S & C_P are highly suppressed

$B_s \to \mu^+ \mu^-$ and New Physics

1, Contribution of Q_S and Q_P are not helicity suppressed

Potentially large coefficients C_S and C_P in a 2HDM with an MSSM like Higgs sector – BR $\propto (\tan\beta)^6 \; M_A^{-4}$

2, Absence of tree level contribution to C_A:

Precision test of the Standard Model Z-Penguin
[See Bobeth, Haisch `15 for recent study]

$\rightarrow$ Reduce the (theory) uncertainty:

Either $B_{(s)} \rightarrow \mu^+ \mu^-$ will result in a signal of new physics or in a precision test of the standard model.

Theory Calculation

$$\mathcal{L}_{\text{eff}} = G_F^2 M_W^2 \, V_{tb}^* V_{ts} \left(C_A Q_A + C_S Q_S + C_P Q_P \right) + \text{h.c.}$$

C_S & C_P can be neglected within the Standard Model

For pure QCD determine $< \mu^- \mu^+ | Q_A | B_s >$ from $< 0 \; | \bar{b} \, \gamma^\mu \, \gamma_5 \, s \, | B_s > = i \, p^\mu \, f_{Bs}$ (f_{Bs}= 227.7(4.5)MeV [FLAG])

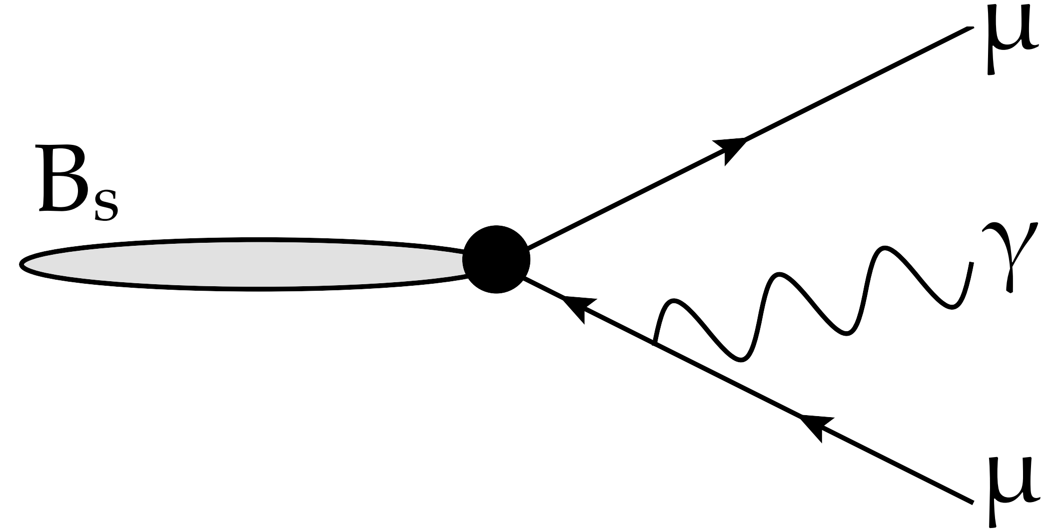
Pure QCD corrections only change $C_A(m_t \, / \, M_W)$ @ $\mu = M_W$
Very good convergence at NNLO [Hermann, Misiak, Steinhauser`14]
if QCD MS-bar $m_t = m_t(m_t)$ is used

QED & Electroweak corrections could potentially be large – i.e. ±2% & ±7%

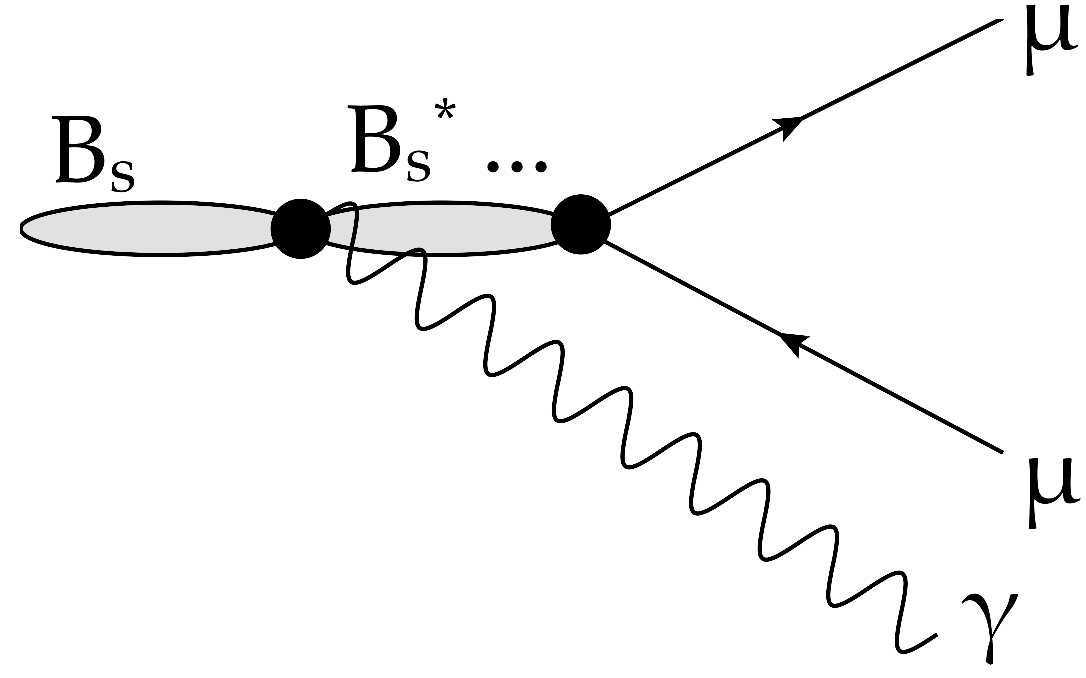
QED corrections I

B_s decay into a 2 lepton final state always helicity suppressed

Soft photon radiation from muons: Theoretical branching ratio is fully inclusive of bremsstrahlung. There would be sizeable corrections otherwise [Buras, Girrbach, Guadagnoli, Isidori] arXiv:1208.0934.



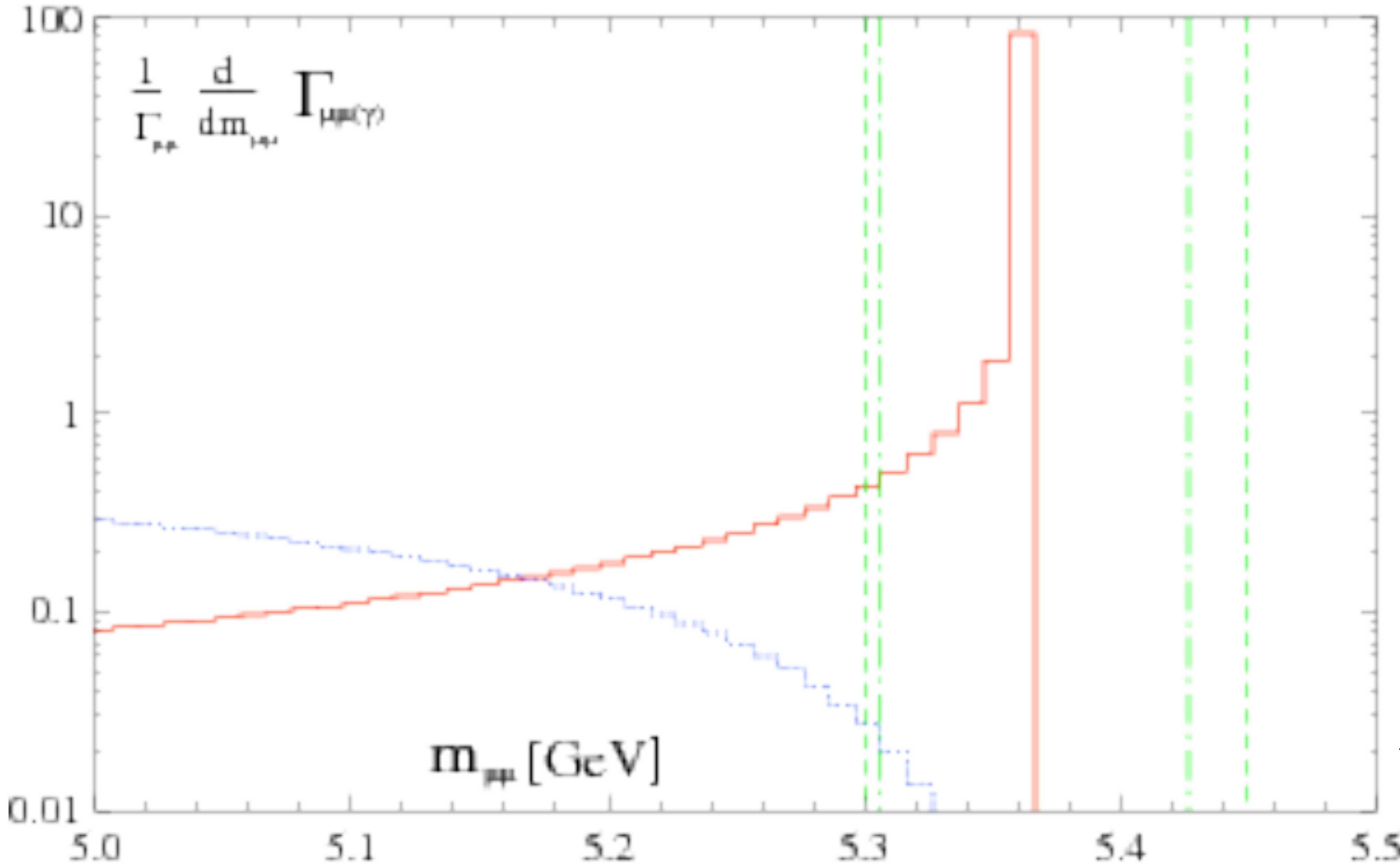
Direct emission is IR safe (B_s is neutral) and phase space suppressed for invariant mass $m_{\mu\mu}$ close to M_{Bs}.
[Aditya, Healey, Petrov] arXiv: 1212.4166



Next correction would be $O(\alpha^3)$

Illustration

Consider an experimental signal window for the invariant mass of the muon pair $m_{\mu\mu}$



Simulate signal fully inclusive of bremsstrahlung (PHOTOS)

Direct emission is a background in the signal window

Electroweak Corrections

$\rightarrow$ Only electroweak corrections and QED to $C_A(\mu_b)$ are potentially large – enhanced by m_{top}/M_W, $1/s_W$, $\alpha_e \log^2(M_W/m_b)$. NNLO is important to remove the scale uncertainty.

Consider $$\mathcal{L}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \frac{\alpha \pi V_{tb}^* V_{ts}}{\sin^2 \theta_W} C_A Q_A + \text{h.c.}$$

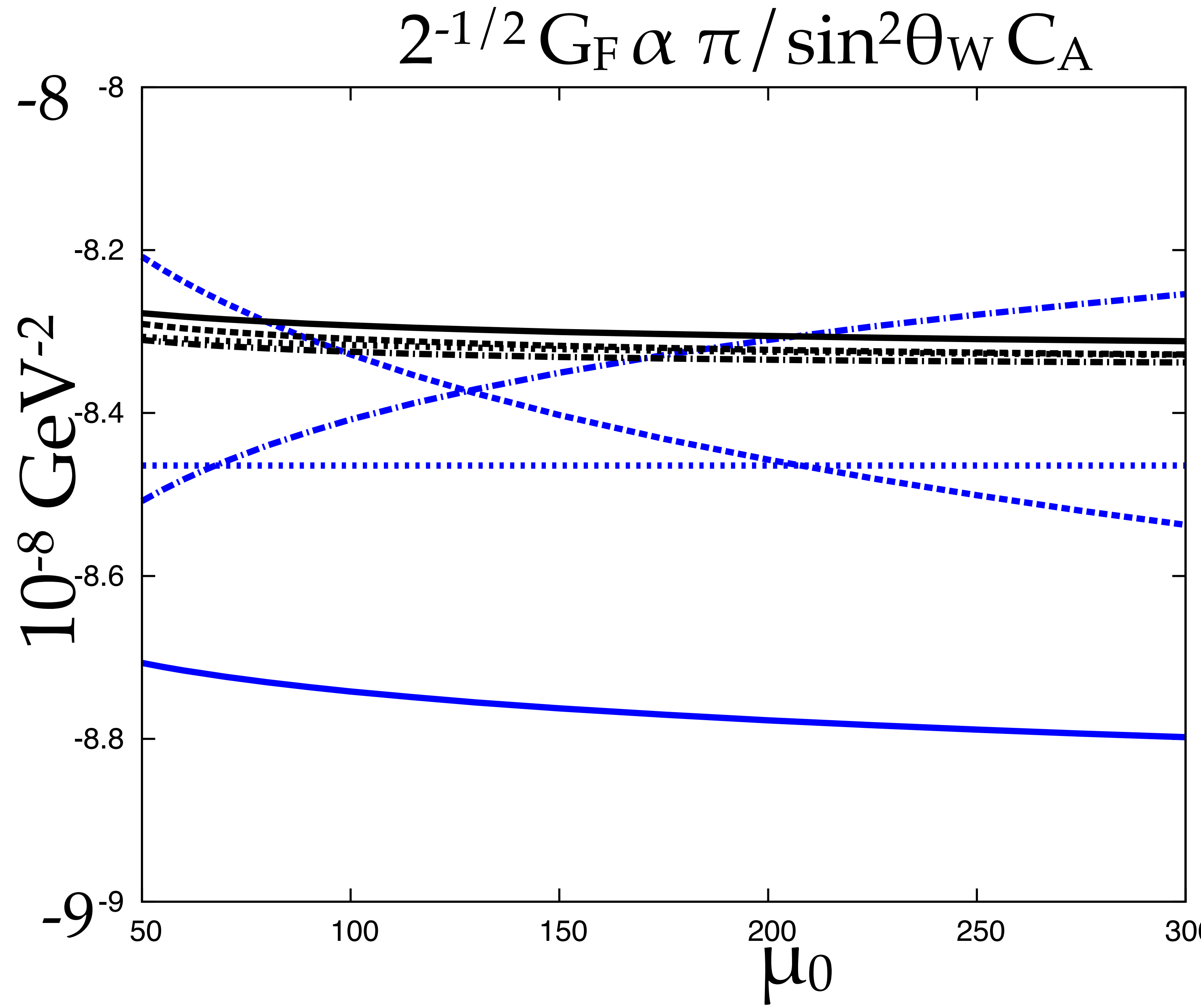
Only $G_F \alpha / \sin^2\theta_W C_A(m_t/M_W)$ invariant under electroweak scheme change

Compare numerical results in different schemes as a function of the matching scale μ

Matching Correction for C_A

There are sizeable shifts and reduction of scale dependence
if we go from 1-loop to 2-loop

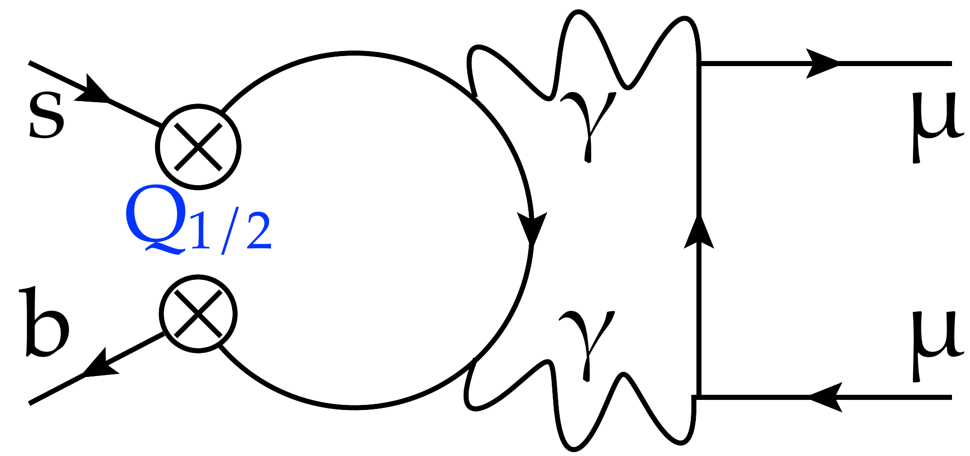
Same input used
(G_F, α, M_Z, M_t, M_H)
for all schemes



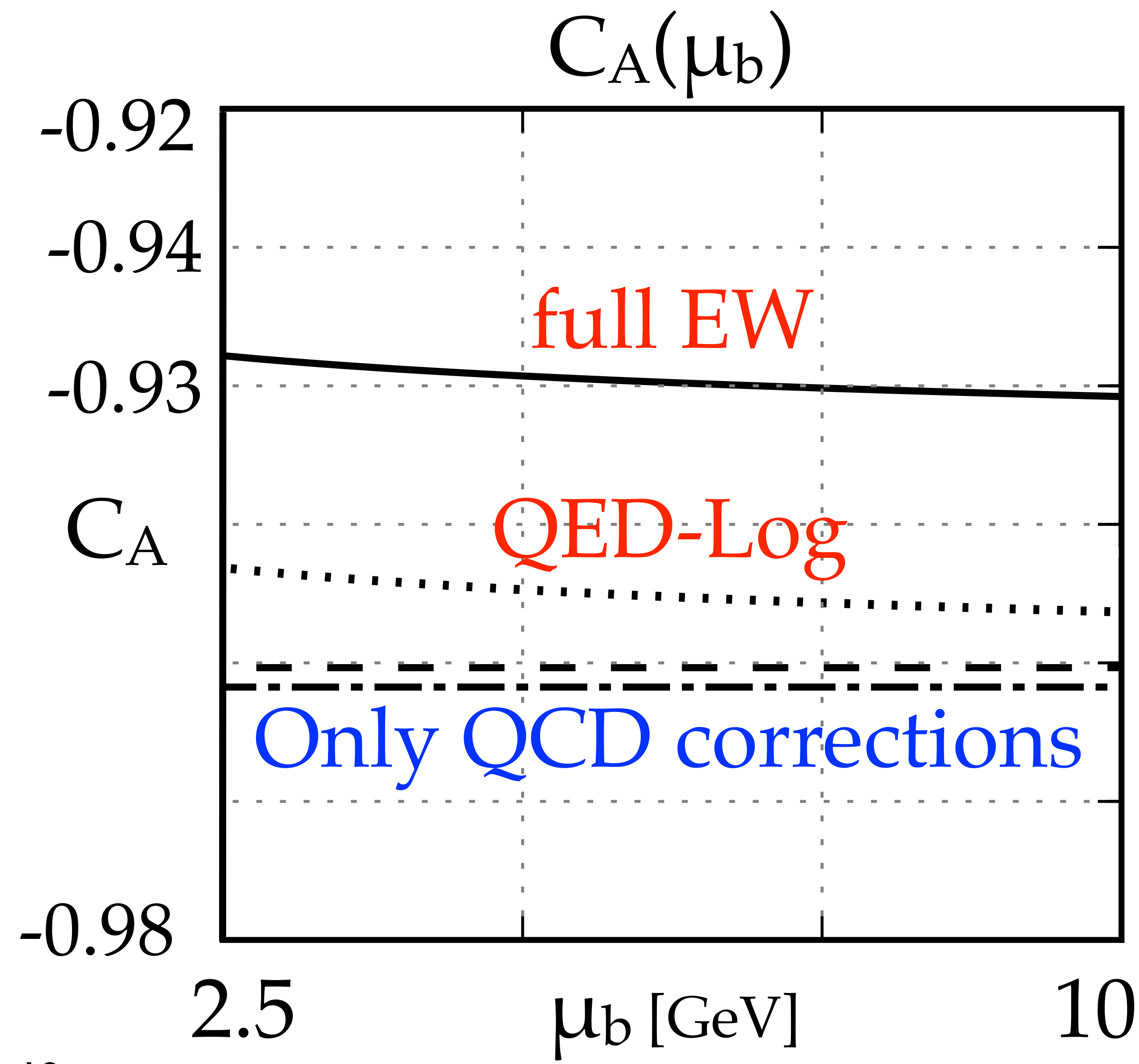
Note: α(nq=6) used for plot

QED RGE for C_A

NLL running cancels matching scale dependence in Q_A



The log enhanced QED corrections reduce the modulus of the Wilson coefficient further.



The remaining 0.3% μ_b scale dependence will only be removed after evaluating non-perturbative QCD⊗QED matrix elements.

Theory Prediction $B_s \to \mu^+\mu^-$

We find for the time integrated BR @ NNLO & EW

[Bobeth MG, Hermann, Misiak, Steinhauser, Stamou `14]

$\mathrm{Br}_{the} = (3.65 \pm 0.23)\, 10^{-9}$

$\mathrm{Br}_{exp} = (\, 2.8\, ^{+0.7}_{-0.6})\, 10^{-9}$

LHCb CMS Combination

	f_{B_q}	CKM	τ_H^q	M_t	α_s	other param.	non-param.	$\sum$
$\overline{\mathcal{B}}_{s\ell}$	4.0%	4.3%	1.3%	1.6%	0.1%	$< 0.1\%$	1.5%	6.4%

f_{Bs} [MeV]	τ_{Bs} [ps^{-1}]	$\lvert V_{tb} V_{ts} \rvert$	M_t [GeV]
227.7(45)	1.516(11)	0.0415(13)	173.1(9)

where we have used $V_{cb} = 0.0424(9)$ [Gambino, Schwanda `13]

Remaining $B_{(s)} \to l^+ l^-$ decays

$$\begin{aligned}
\overline{\mathcal{B}}_{se} \times 10^{14} &= 8.54 \pm 0.55 \\
\overline{\mathcal{B}}_{s\tau} \times 10^{7} &= 7.73 \pm 0.49 \\
\overline{\mathcal{B}}_{de} \times 10^{15} &= 2.48 \pm 0.21 \\
\overline{\mathcal{B}}_{d\mu} \times 10^{10} &= 1.06 \pm 0.09 \\
\overline{\mathcal{B}}_{d\tau} \times 10^{8} &= 2.22 \pm 0.19
\end{aligned}$$

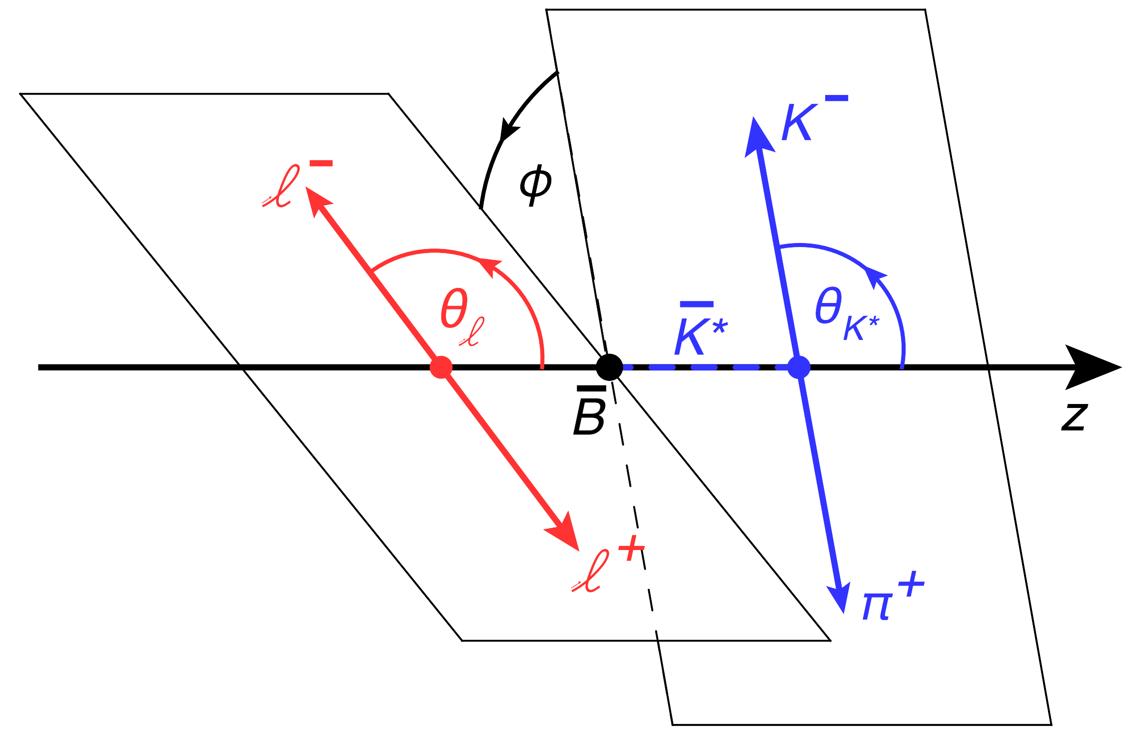
$Br_{the}\,(B_{d\mu}) = (1.06 \pm 0.09)\ 10^{-10}$

$Br_{exp}\,(B_{d\mu}) = (3.9\ ^{+1.6}_{-1.4})\ 10^{-10}$

	f_{B_q}	CKM	τ_H^q	M_t	α_s	other param.	non-param.	$\sum$
$\overline{\mathcal{B}}_{s\ell}$	4.0%	4.3%	1.3%	1.6%	0.1%	$< 0.1\%$	1.5%	6.4%
$\overline{\mathcal{B}}_{d\ell}$	4.5%	6.9%	0.5%	1.6%	0.1%	$< 0.1\%$	1.5%	8.5%

$B \to K^{(*)}[\to K\pi] + \ell^+\ell^-$

Many angular observables
for
$B \to K^{(*)}[\to K\pi] + \ell^+\ell^-$



$$\frac{32\pi}{9}\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_\ell$$
$$+J_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + J_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_\ell + J_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+J_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + J_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi$$

From these one can construct
observables as e.g. forward backward asymmetry

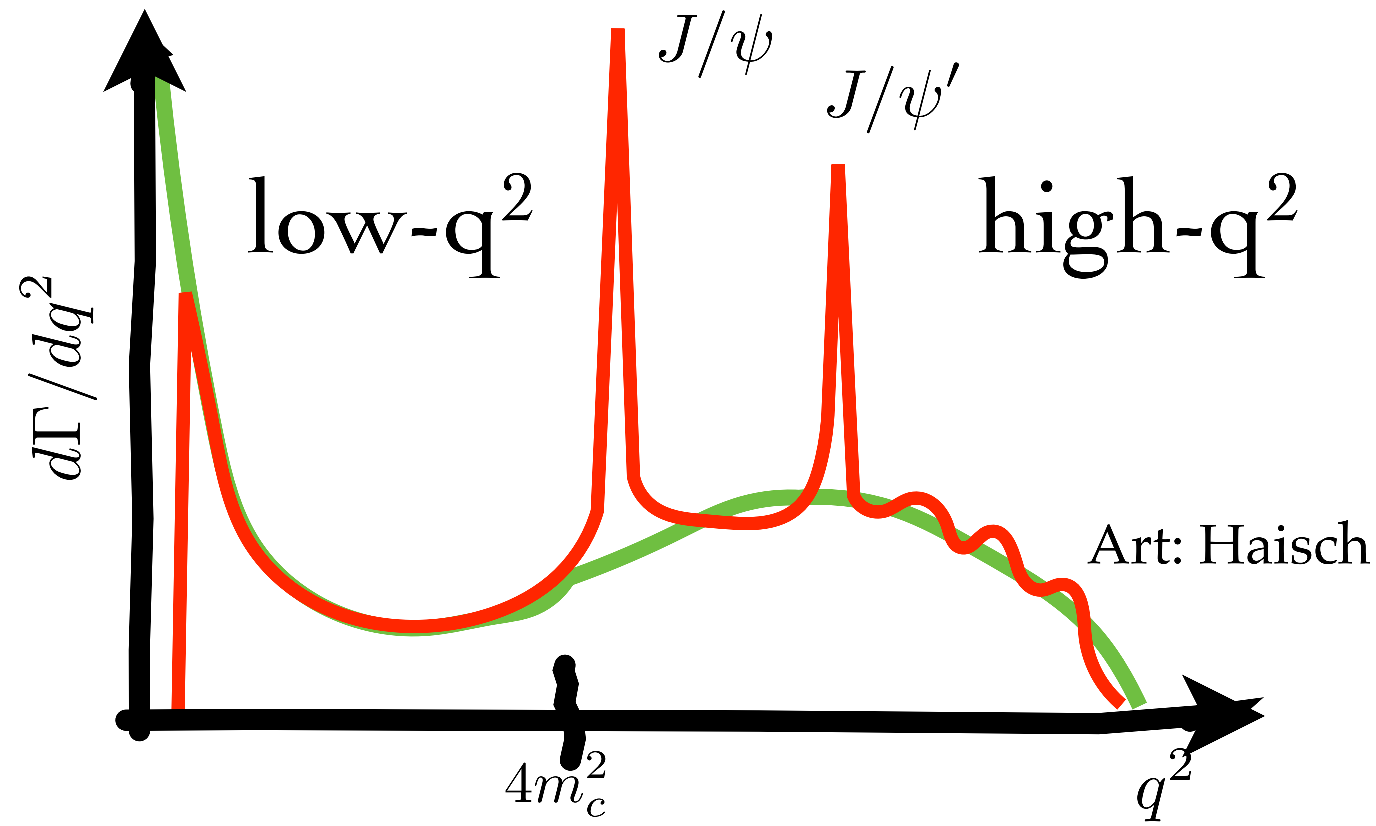
Exclusive B → $K^{(*)}\, l^+ \, l^-$ decays

Systematic heavy-quark expansion in Λ_{QCD}/mb (SCET) for $q^2 << m^2(J/\psi)$

[Benke, Feldmann, Seidel `01]

OPE for $q^2 >> m^2(J/\psi)$

[Grinstein et.al. ; Beylich et. al. `11]



Non-perturbative input: Form factors from sum-rules (small q^2) and Lattice QCD (large q^2)

See e.g. recent work by Bharucha, Straub Zwicky [1503.05534]

Construct form factor insensitive / sensitive quantities

[Krüger, Matias; ... Bobeth et. al.]

Theory uncertainties from power corrections

Exclusive $B \to K^{(*)} l^+ l^-$ decays

Systematic heavy-quark expansion in Λ_{QCD}/mb (SCET) for $q^2 << m^2(J/\psi)$
[Benke, Feldmann, Seidel `01]

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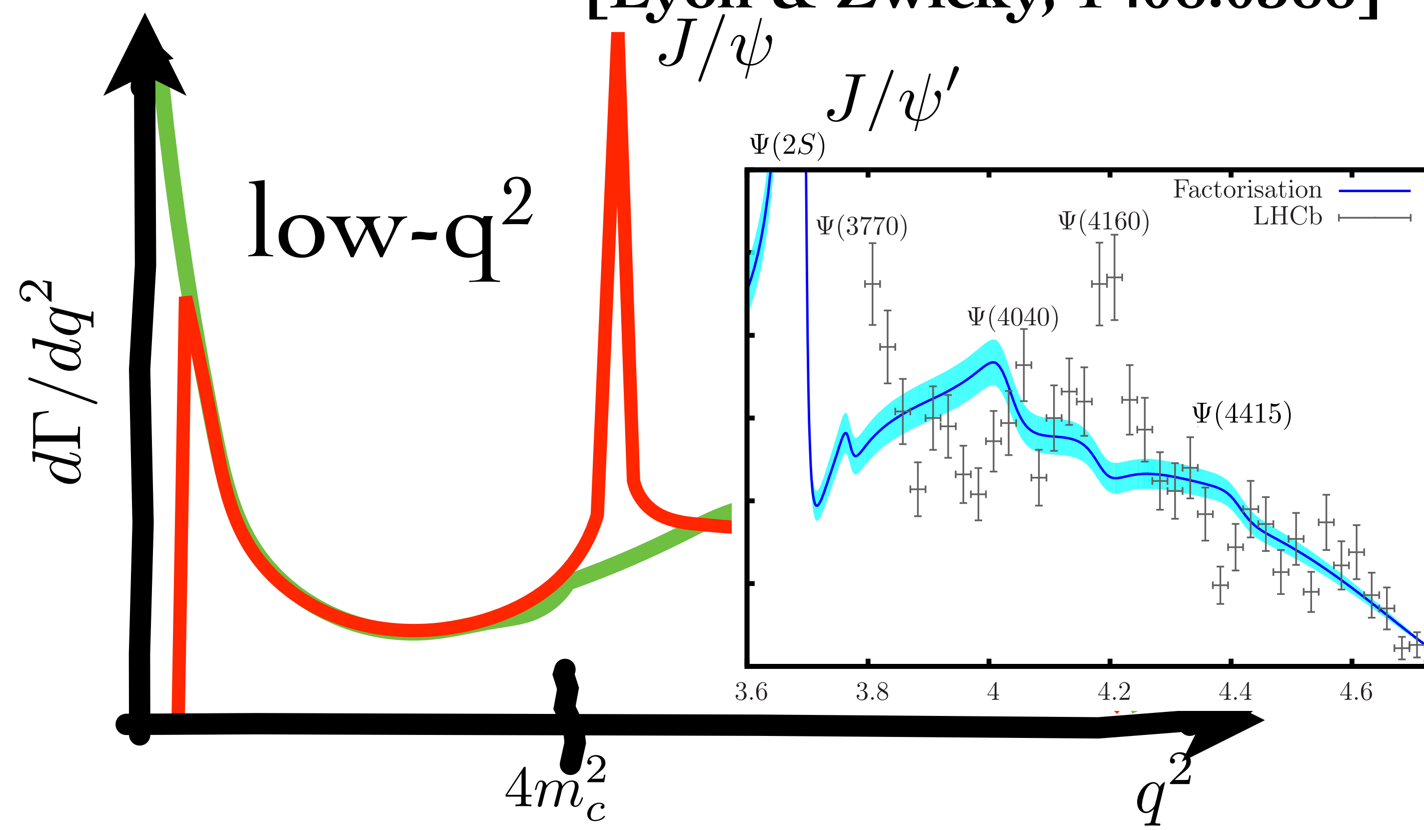
[Lyon & Zwicky, 1406.0566]



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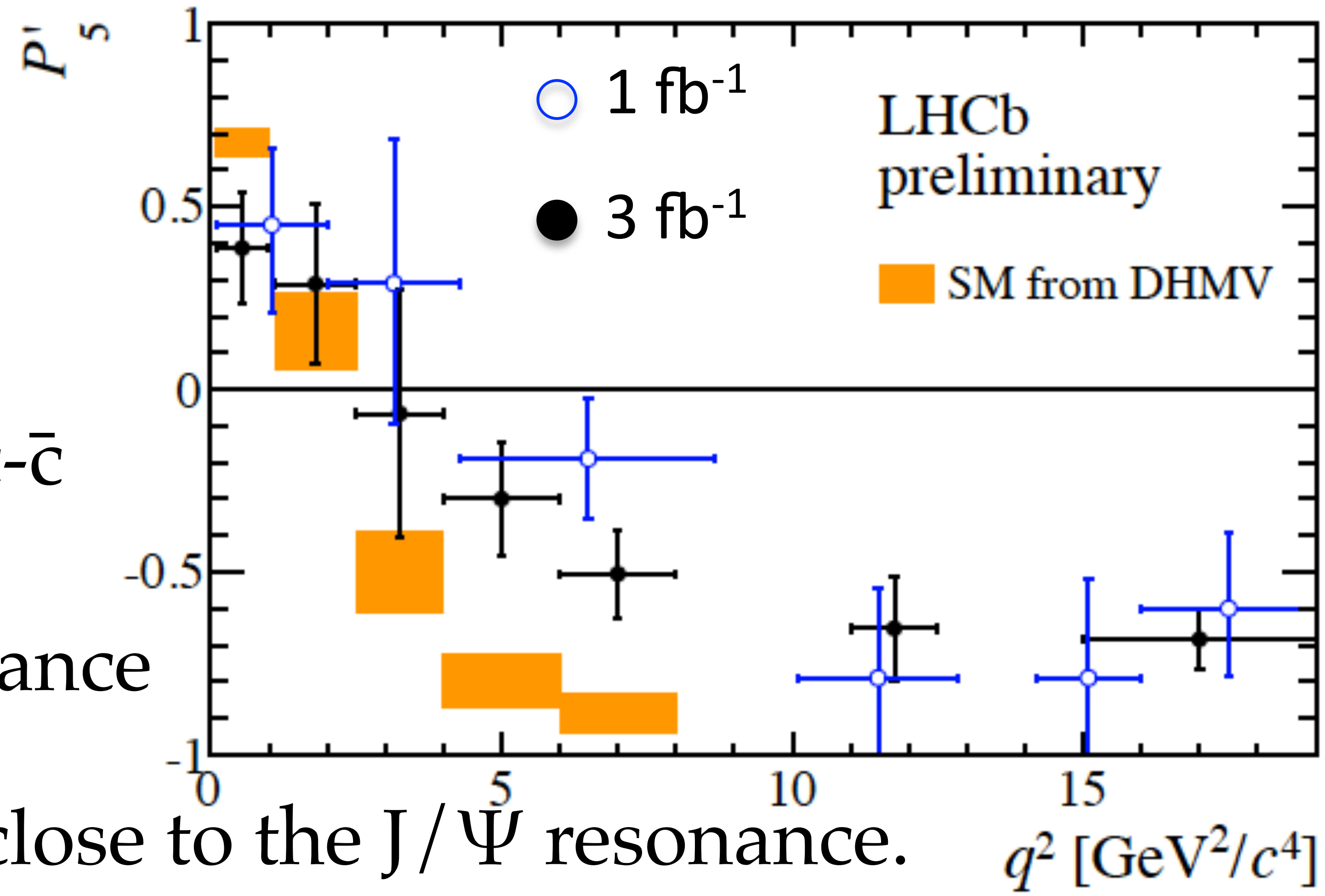
Theory uncertainties from power corrections

P'_5 & R_K

Talk by Passaleva



P'_5 is a clean quantity in the sense that it is insensitive to form factors.

Gluons coupling to on-shell c-$\bar{c}$ states contribute nonperturbatively below the J/Ψ resonance [Khodjamirian et al. [1006.5045]] which pollutes P'_5 in the bin close to the J/Ψ resonance.

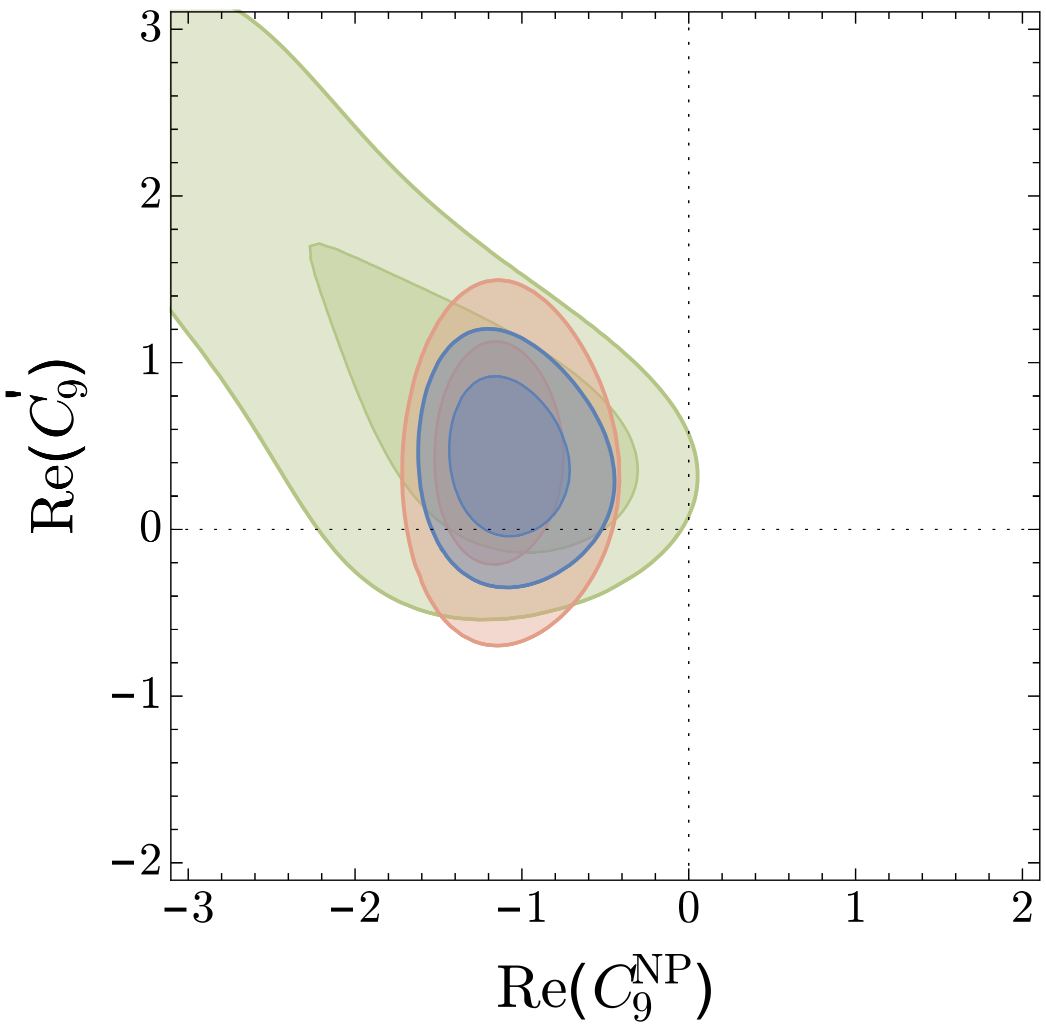
$R_K = \Gamma_\mu / \Gamma_e = 1 + O(10^{-4})$ Bobeth et.al. [JHEP 12 (2007) 040]
Includes only kinematic lepton mass effects – no QED corrections included.

QED corrections are most likely note big enough to explain measurement in $B^+ \to K^+ l^+ l^-$ modes

Modification of C_9 ?

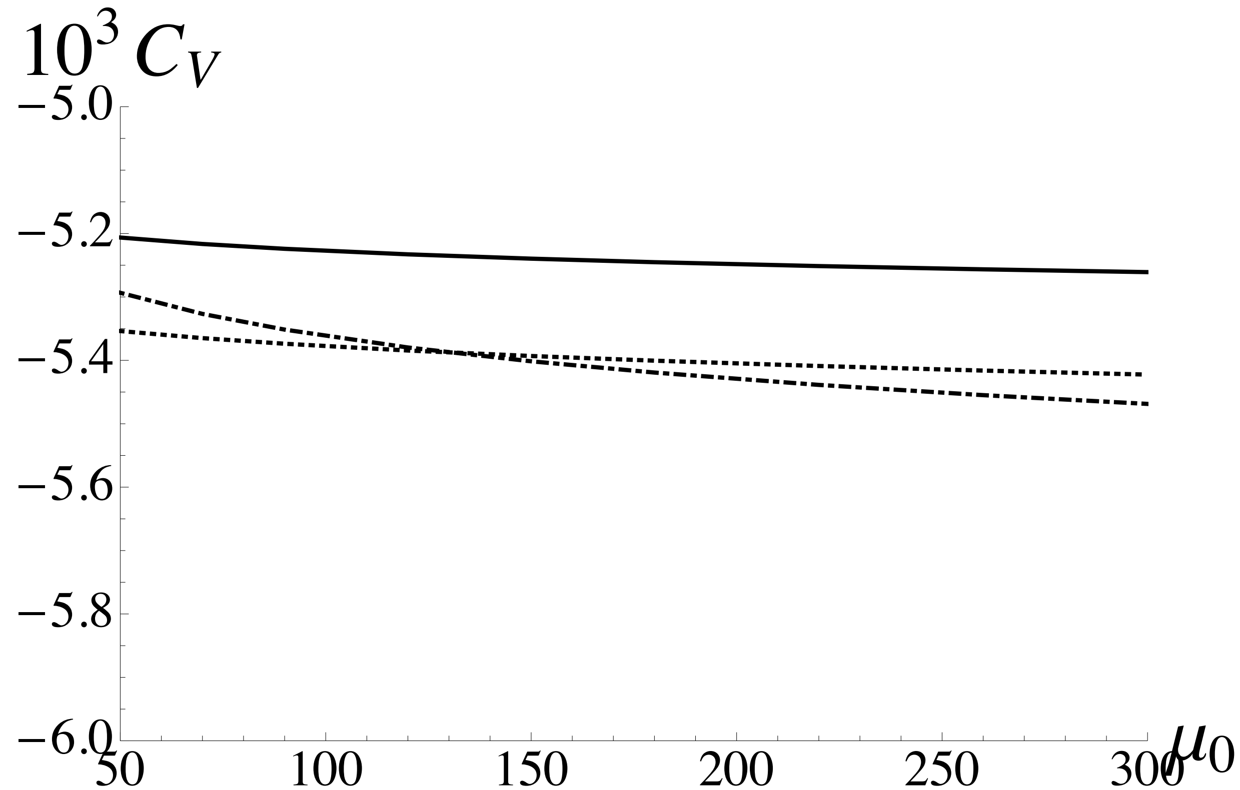
$C_9 \propto C_V$ and the chirality flipped C'_9 can be fitted from data

e.g. Altmanshofer Straub [1503.06199]



→ tension with SM calculation of C_V

EW Uncertainties for LO matching below 5% level



Only the electroweak scheme dependence is shown

Conclusions

The LHC results on flavour physics are super exciting!

Possible tensions with the standard model theory prediction
→ Consider also potentially small contributions to the theory predictions.
→ Quantify uncertainties from sub-leading non-perturbative contributions to clean observables.

$B_q \rightarrow \mu^+ \mu^-$ is the precision probe of flavour violating process and of the Z-Penguin at LHC.

$B / H_b \to X\, l^+ l^-$

$$\mathcal{H}_{eff} = -\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left[\sum_{i=1}^{8} C_i(\mu) Q_i + \frac{\alpha}{2\pi} \tilde{C}_9(\mu) (\bar{s}b)_{V-A} (\bar{l}l)_V + \frac{\alpha}{2\pi} \tilde{C}_{10} (\bar{s}b)_{V-A} (\bar{l}l)_A \right]$$

While the relevant Wilson Coefficients C_7, C_{10} & C_9 are constrained from $B \to X_s \gamma$, $B_s \to \mu^+ \mu^-$ & $B \to K^{(*)} l^+ l^-$.

Inclusive decays are thought to be theoretically clean.

Should we study $B \to X_s l^+ l^-$, or $H_b \to X\, l^+ l^-$ at/for LHC?

Differential Branching Fraction

For an inclusive quantity we use the optical theorem

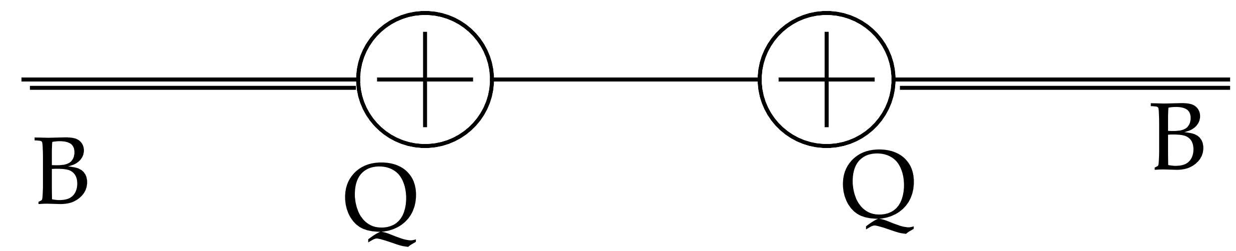
Im M(A → A) ∝ $\Sigma_X \, \Gamma$(A → X)

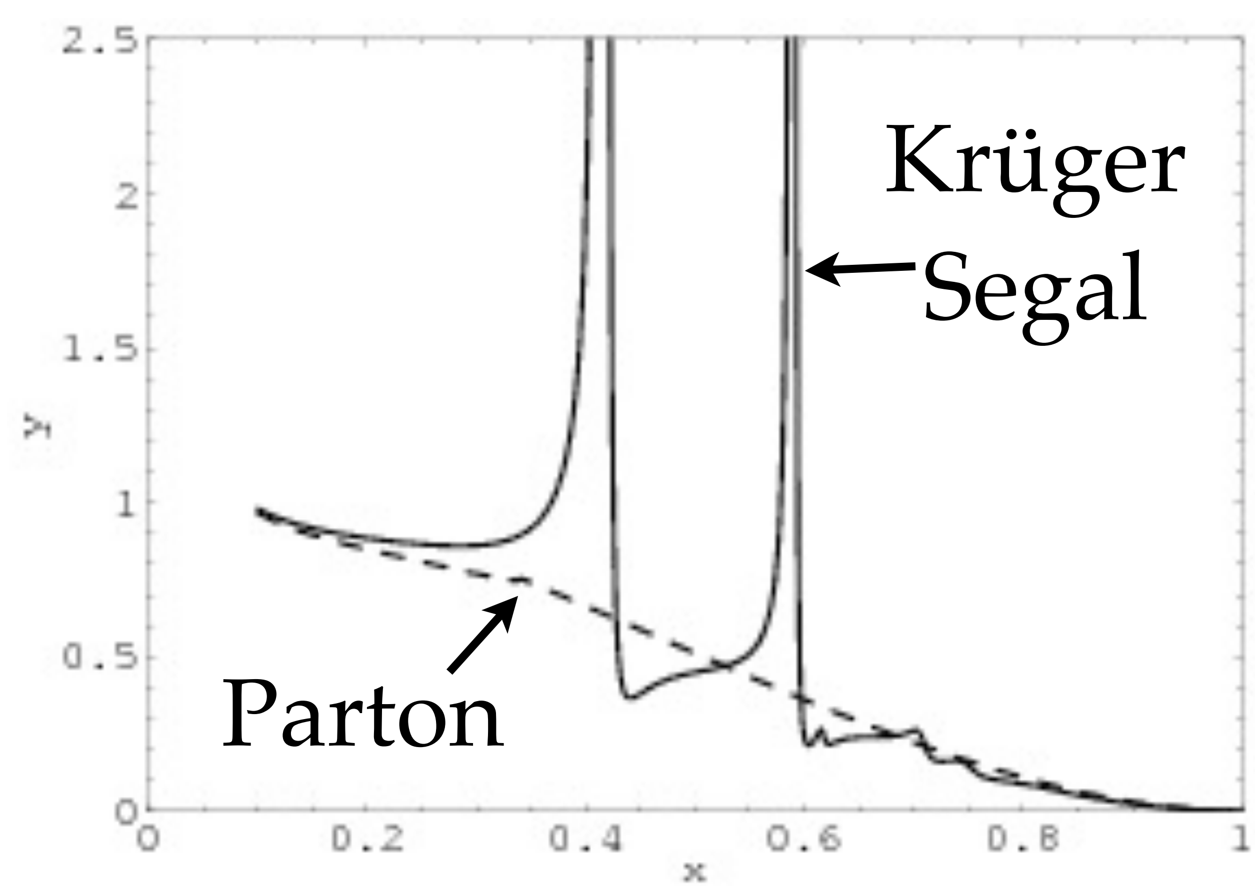
For B Physics: Im M(B → B)

➩ two operator insertions

➩ Operator Product Expansion

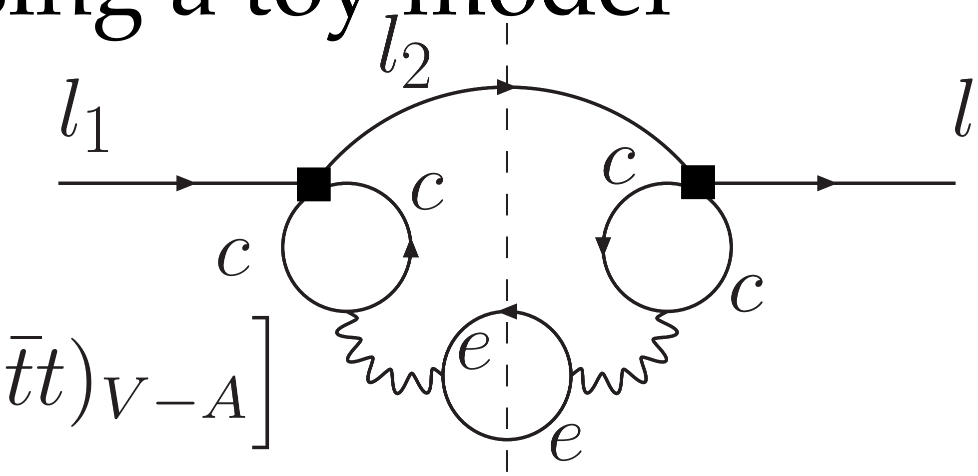
Γ(B → X) = Parton + Λ / m_b





Quark-hadron duality not expected to hold

Discussed e.g. by BBNS [0902.4446] using a toy model



B → X_s l^+ l^- is not inclusive

$$\mathcal{H}_{eff} = \frac{G}{\sqrt{2}} \left[(\bar{l}_2 l_1)_{V-A} \, (\bar{c}c)_{V-A} - (\bar{l}_2 l_1)_{V-A} \, (\bar{t}t)_{V-A} \right]$$

For B → X_s l^+ l^- $\quad R_\psi \equiv \frac{\mathrm{B}(B \to X_s \psi \to X_s \, l^+ l^-)}{\mathrm{B}(B \to X_s \, l^+ l^-)_{\mathrm{SD}}} \approx 93$

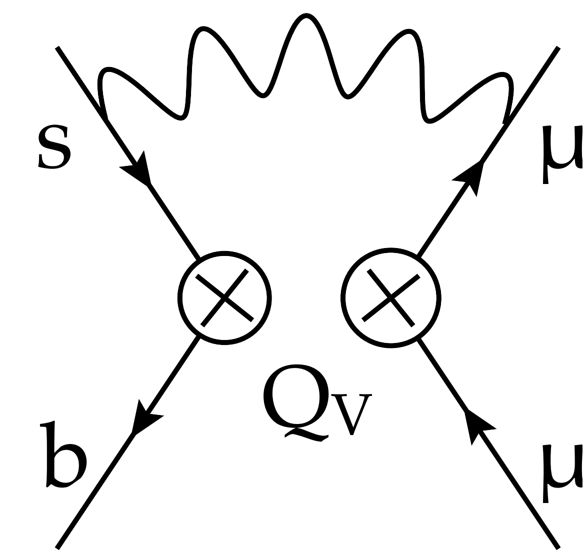
and further contributions for higher resonances

Additionally the OPE breaks down for high q^2

Low q^2 region cleaner, but harder to measure at LHC

Remaining QED uncertainty

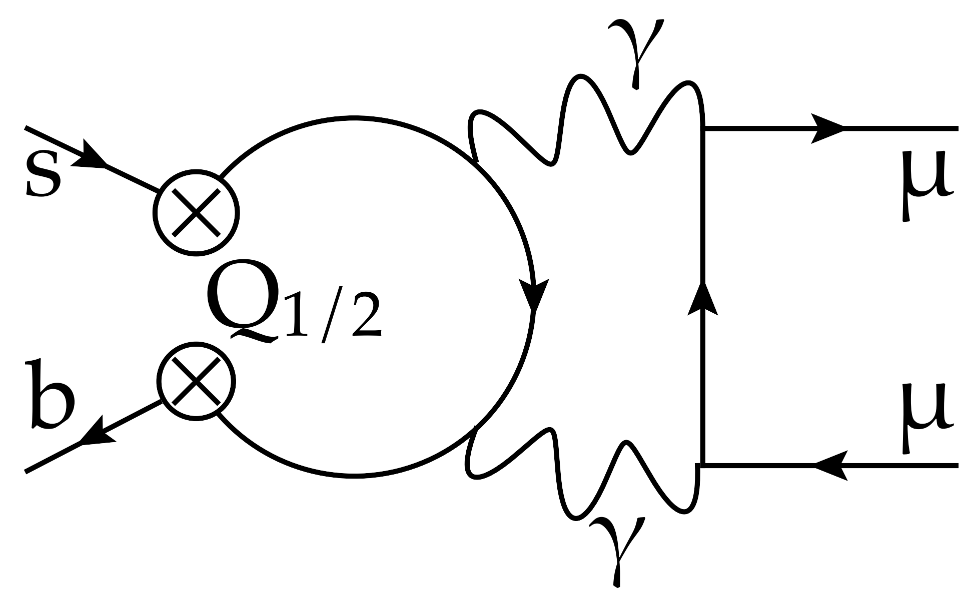
The remaining 0.3% μ_b scale dependence will only be removed after non-perturbative QCD⊗QED corrections are included.



I.e. QED⊗QCD Matrix elements of

$$
\begin{aligned}
Q_1 &= (\bar{b}\gamma_\mu T^a q_L)(\bar{q}\gamma_\mu T^a s_L) \\
Q_2 &= (\bar{b}\gamma_\mu q_L)(\bar{q}\gamma_\mu s_L) \\
Q_V &= (\bar{b}\gamma_\mu s_L)(\bar{l}\gamma_\mu l)
\end{aligned}
$$

could be considered, but they are $O(\alpha/\pi) \lesssim 0.3\%$ (our error estimate)



No relevant lifting of Helicity suppression

Flavour Symmetry

The Standard Model Quark Gauge Sector

The standard model quark sector comprises 9 fermion fields:

3 Generations of left-handed doublets Q_i
3 Generations of right-handed up-type quarks u_i
3 Generations of right-handed down-type quarks d_i

All quark gauge interactions derive from a simple Lagrangian

$$\mathcal{L}_g = \sum_{i=1}^{3} \bar{Q}_i \not{D} Q_i + \sum_{i=1}^{3} \bar{u}_i \not{D} u_i + \sum_{i=1}^{3} \bar{d}_i \not{D} d_i + \sum_i \frac{1}{4} g_i \vec{F}^i_{\mu\nu} \vec{F}^{i\,\mu\nu}$$

and have a large flavour symmetry: $G^{\text{quark}}_{\text{flavour}} = SU(3)_Q \times SU(3)_u \times SU(3)_d$