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

"Implications of LHCb measurements and future prospects"
CERN
15 October 2014

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

Martin Gorbahn
University of Liverpool

Content

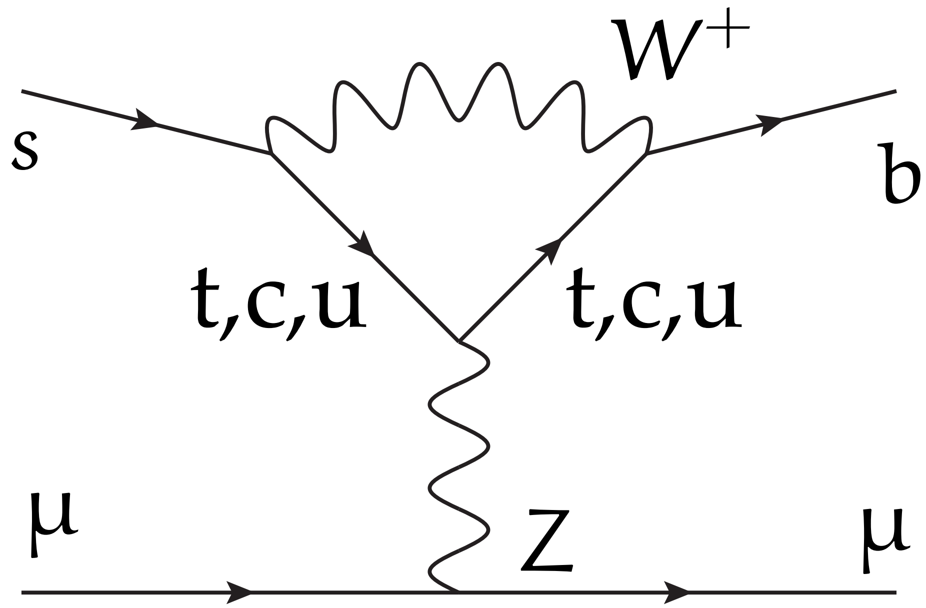
Standard Model Operators

New Physics

Theory status

Conclusions

$B_s \to \mu^+ \mu^-$ 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:

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

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

Contribution of Q_S and Q_P are not helicity suppressed

Potentially large coefficients C_S and C_P in 2HDM

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

Contribution of Q_S and Q_P are not helicity suppressed

Potentially large coefficients C_S and C_P in 2HDM

Yet, only if contribution to ΔM_s is suppressed,
i.e. type 2 Higgs potential, $\lambda_5 \ll 1$ and type 3 Yukawas

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

Contribution of Q_S and Q_P are not helicity suppressed

Potentially large coefficients C_S and C_P in 2HDM

Yet, only if contribution to ΔM_s is suppressed,
i.e. type 2 Higgs potential, $\lambda_5 \ll 1$ and type 3 Yukawas

which is the MSSM at $\tan\beta \gg 1$, with the Branching Ratio

$$BR \propto (\tan\beta)^6 \; M_A^{-4}$$

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

Contribution of Q_S and Q_P are not helicity suppressed

Potentially large coefficients C_S and C_P in 2HDM

Yet, only if contribution to ΔM_s is suppressed,
i.e. type 2 Higgs potential, $\lambda_5 \ll 1$ and type 3 Yukawas

which is the MSSM at $\tan\beta \gg 1$, with the Branching Ratio

$$BR \propto (\tan\beta)^6 \; M_A^{-4}$$

Non-zero $\Delta\Gamma_s$ allows for another untagged observable
beyond the BR via an effective lifetime measurement.
[Bruyn, Fleischer, Knegjens et.al. `12]

Theory Status at NLO

C_S & C_P can be neglected within the Standard Model

$C_A(m_t\ /\ M_W)^{NLO} = 1.0113\ C_A(m_t\ /\ M_W)^{LO}$

– for QCD MS-bar $m_t = m_t(m_t)$ [Buras, Buchalla; Misiak, Urban `99]

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])

QED & Electroweak were so far only known at LO –
this leads to a ±2% & ±7% uncertainty

Improved theory prediction will give us a precision probe of C_A, C_S and C_P (+ flipped Operators ...)

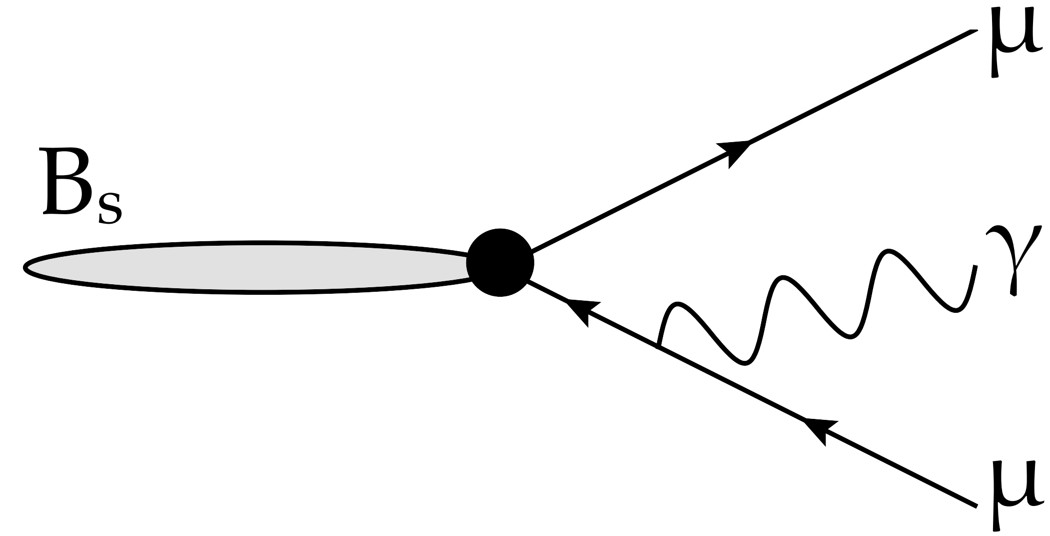
QED corrections

B_s decay into a 2 lepton final state always helicity suppressed

QED corrections

B_s decay into a 2 lepton final state always helicity suppressed

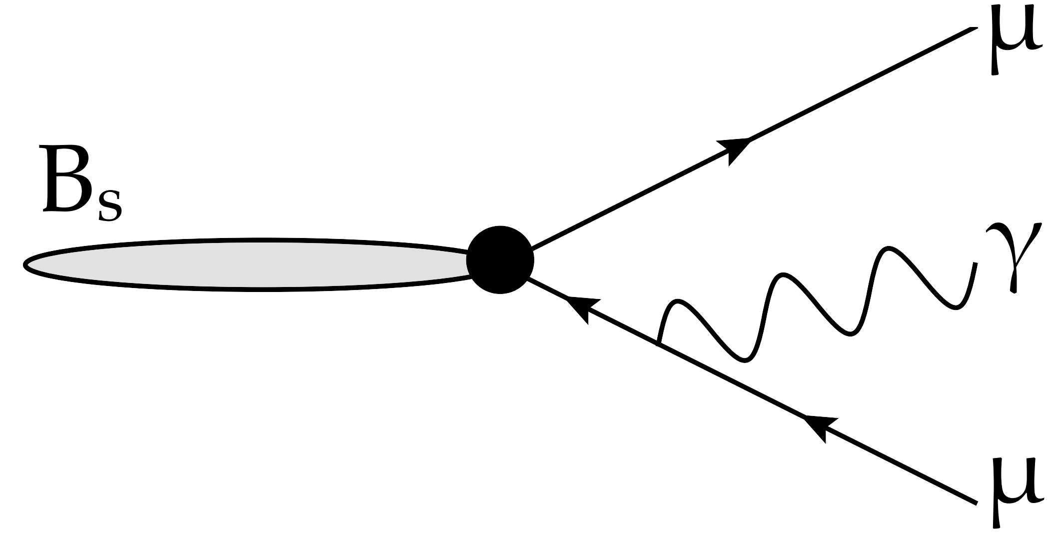
Soft photon radiation from muons: Theoretical branching ratio is fully inclusive of bremsstrahlung. There would be sizeable corrections otherwise [Buras, Girrbach, Guadagnoli, Isidori] arXiv:1208.0934.



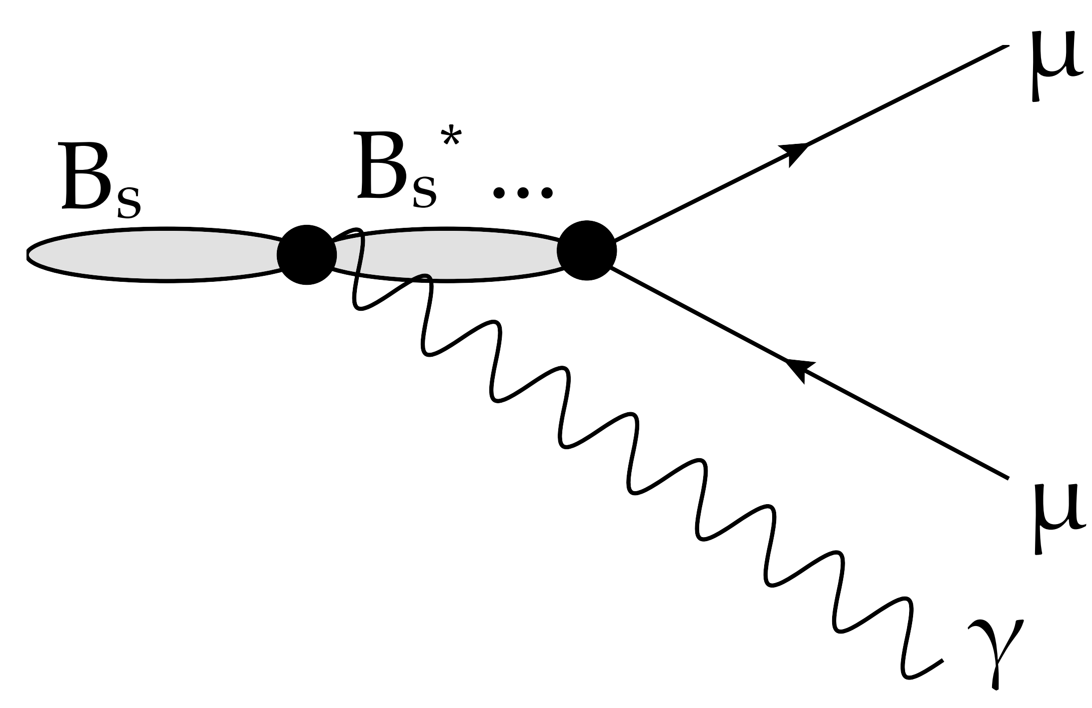
QED corrections

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.

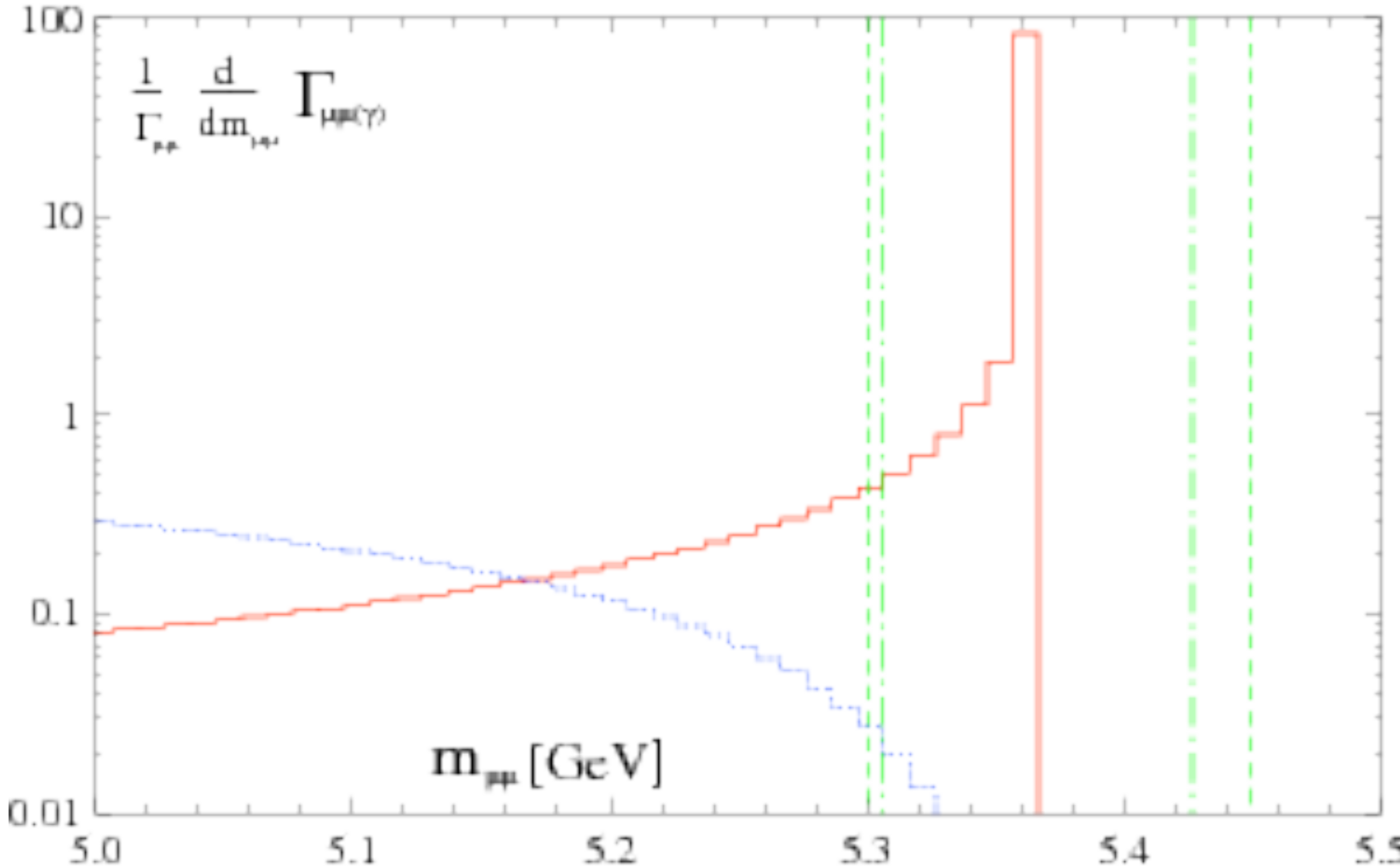


Direct emission is IR safe (B_s is neutral) and phase space suppressed for invariant mass $m_{\mu\mu}$ close to M_{Bs}.
[Aditya, Healey, Petrov] arXiv: 1212.4166



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

Comparing Theory and Experiment

Bremsstrahlung taken into account by the experiment and direct emission treated as background.

The B_s system has a non-zero decay width difference:
$\rightarrow$ instantaneous $\neq$ time integrated branching ratio
[de Bruyn, Fleischer et. al. `12] This correction is precisely known.

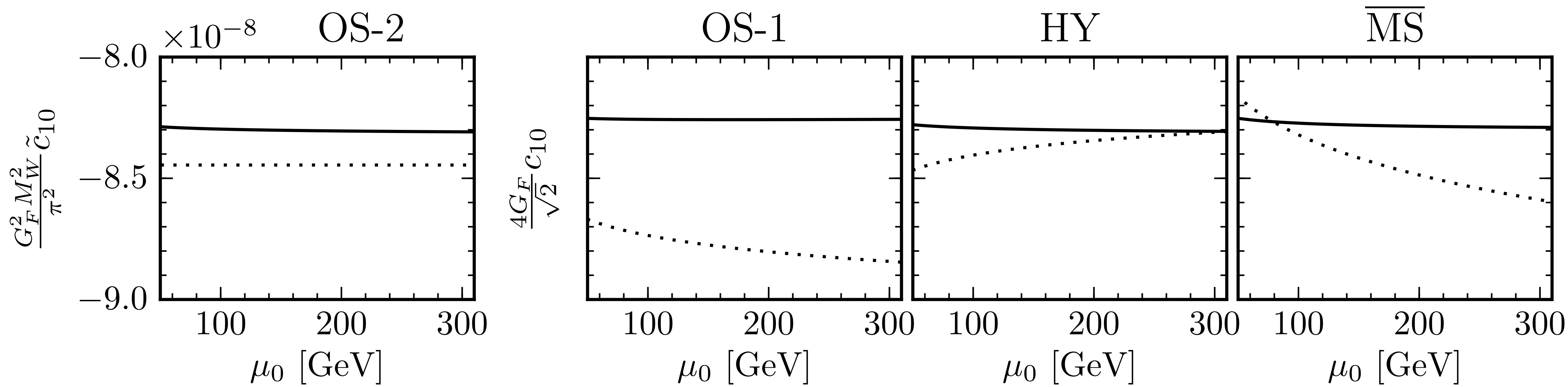
Comparing Theory and Experiment

Bremsstrahlung taken into account by the experiment and direct emission treated as background.

The B_s system has a non-zero decay width difference:
$\rightarrow$ instantaneous $\neq$ time integrated branching ratio
[de Bruyn, Fleischer et. al. `12] This correction is precisely known.

$\rightarrow$ 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.

NLO EW and NNLO QCD

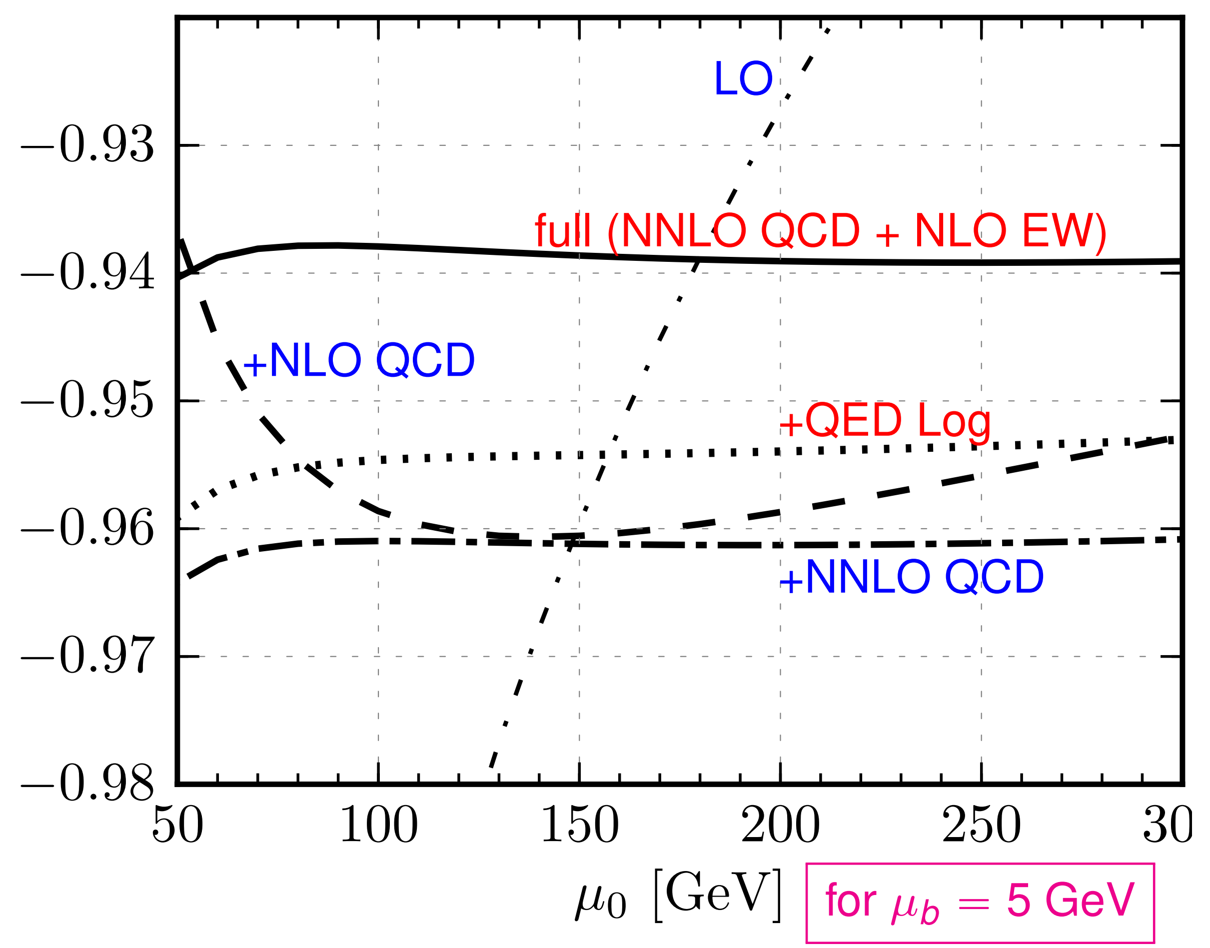


NLO EW calculation removes 7% scheme ambiguities

[Bobeth, MG, Stamou `14]

NNLO calculation removes scale ambiguities – fixes top mass

[Hermann, Misiak, Steinhauser `14]



Theory Prediction

We find for the time integrated BR @ NNLO & EW

[Bobeth MG, Hermann, Misiak, Steinhauser, Stamou `13]

$\mathrm{Br}_{\mathrm{the}} = (3.65 \pm 23)\ 10^{-9}$ $\mathrm{Br}_{\mathrm{exp}} = (\ 2.9 \pm 0.7\ )\ 10^{-9}$

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]

Conclusions

Largest theory uncertainty (@ NLO EW and NNLO) :
- from f_{Bs} (4%), which will be reduced in the future
- rest (<2 %)

But dependence on V_{cb} results in parametric uncertainty, might be reduced in the future or removed by normalising to ΔM_s

Significantly smaller than experimental uncertainty

A reduced experimental uncertainty would by very useful, given the reliable theory prediction.

Precision test of the Z-Penguin, Z', Scalar Operators ...

One should also consider observables beyond the branching ratio.