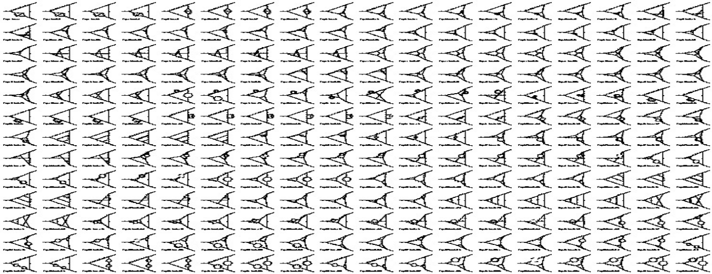
Bound on $M_{H^\pm}$ in the 2HDM from weak radiative *B*-meson decays

QED corrections to (semi-)leptonic *B* decays, Paris, July 8-9, 2019

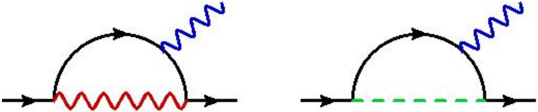
Matthias Steinhauser | in collaboration with Mikolaj Misiak

TTP KARLSRUHE



$\bar{B} \to X_s\gamma$

- $\Gamma(\bar{B}^0 \to X_s\gamma)$, $\Gamma(B^0 \to X_{\bar{s}}\gamma)$, $\Gamma(B^- \to X_s\gamma)$, $\Gamma(B^+ \to X_{\bar{s}}\gamma)$
- $$\Gamma(\bar{B} \to X_s\gamma) \approx \Gamma(b \to X_s^{\rm parton}\gamma) = \Gamma(b \to s\gamma) + \Gamma(b \to s\gamma g) + \ldots$$



- Babar, Belle, CLEO   CP and isospin averaged
  $\mathcal{B}_{s\gamma}^{\rm exp} = (3.32 \pm 0.15) \times 10^{-4}$ [HFLAV'16]
  $\mathcal{B}_{s\gamma}^{\rm exp} = (3.27 \pm 0.14) \times 10^{-4}$ [Misiak,Steinhauser'17]

- SM:
  $\mathcal{B}_{s\gamma}^{\rm SM} = (3.36 \pm 0.23) \times 10^{-4}$ [Misiak et al.'15]

  New: Δ_{0-} from Belle [arXiv:1807.04236v4]   isospin asymmetry: $\Delta_{0-} = [\Gamma(\bar{B}^0) - \Gamma(B^-)]/[\ldots + \ldots]$
  ➪ $+2.1\%$ shift in non-pertubative contribution [Misiak'09; Benzke,Lee,Neubert,Paz'10]

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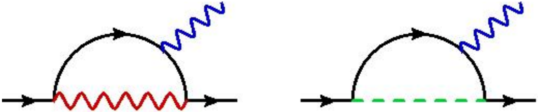
- $\Gamma(\bar{B} \to X_s\gamma) \approx \Gamma(b \to X_s^{\rm parton}\gamma)$
  $= \Gamma(b \to s\gamma) + \Gamma(b \to s\gamma g) + \ldots$



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  this talk

R_γ

- $\mathcal{B}_{s\gamma}$, $\mathcal{B}_{d\gamma}$, $\mathcal{B}_{c\ell\nu}$: CP- and isospin-averaged BR

$$R_\gamma = \frac{\mathcal{B}_{s\gamma} + \mathcal{B}_{d\gamma}}{\mathcal{B}_{c\ell\nu}} \equiv \frac{\mathcal{B}_{(s+d)\gamma}}{\mathcal{B}_{c\ell\nu}}$$

- most precise exp. results from fully inclusive analyses [Babar'12; Belle'16]
  ➪ measure $\mathcal{B}_{(s+d)\gamma}$
- $\mathcal{B}_{c\ell\nu}$: removes 1.5% of parametric uncertainty
  $\delta R_\gamma^{\rm exp}$ not increased

- $R_\gamma^{\rm SM} = (3.31 \pm 0.22) \times 10^{-3}$ [Misiak et al.'15]
  $R_\gamma^{\rm exp} = (3.22 \pm 0.15) \times 10^{-3}$ [Babar,Belle,CLEO] [Misiak,Steinhauser'17]
  $E_\gamma > E_0 = 1.6$ GeV

R_γ — experiment

Karlsruhe Institute of Technology

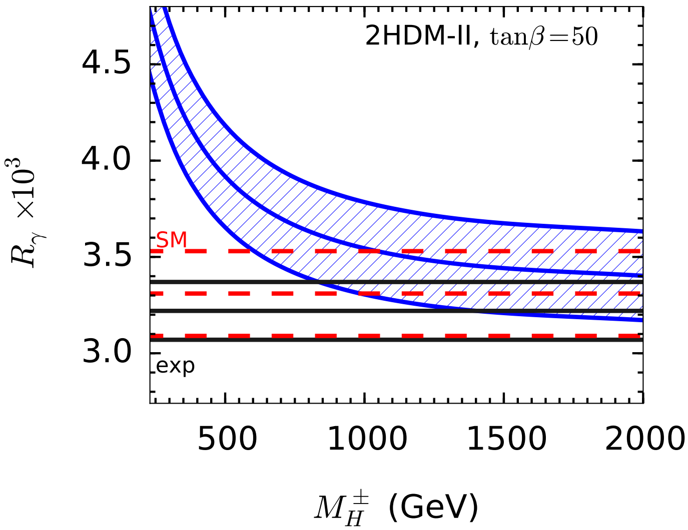
E_0	Babar'12'12'07 incl.	semi-incl.	hadr. tag	aver	Belle'16'14 incl.	semi-incl.	aver	CLEO'01 incl.	w.a. (E_0)
1.7		$\mathcal{B}_{s\gamma} \times 10^6$			306(28)		306(28)		306(28)
		$\mathcal{B}_{(s+d)\gamma} \times 10^6$			320(29)		320(29)		320(29)
1.8	321(34)			321(34)	301(22)		301(22)		307(19)
	335(35)			335(35)	315(23)		315(23)		321(19)
1.9	300(24)	329(52)	366(104)	308(22)	294(18)	351(37)	305(16)		306(13)
	313(25)	344(54)	381(108)	321(23)	307(19)	367(39)	319(17)		320(14)
2.0	280(19)		339(79)	283(18)	279(15)		279(15)	293(46)	281(11)
	292(20)		353(83)	296(19)	292(15)		292(15)	306(49)	294(11)

Note: 313(25) not included in [HFLAV'16]

- compute $\mathcal{B}_{(s+d)\gamma}$ and $\mathcal{B}_{s\gamma}$ for $E_0 = 1.6$ GeV [Buchmüller,Flächer'05]
- compute R_γ

E_0	R_γ ($E_0 = 1.6$ GeV)
1.7	305(28)
1.8	312(19)
1.9	322(15)
2.0	[310(14)]

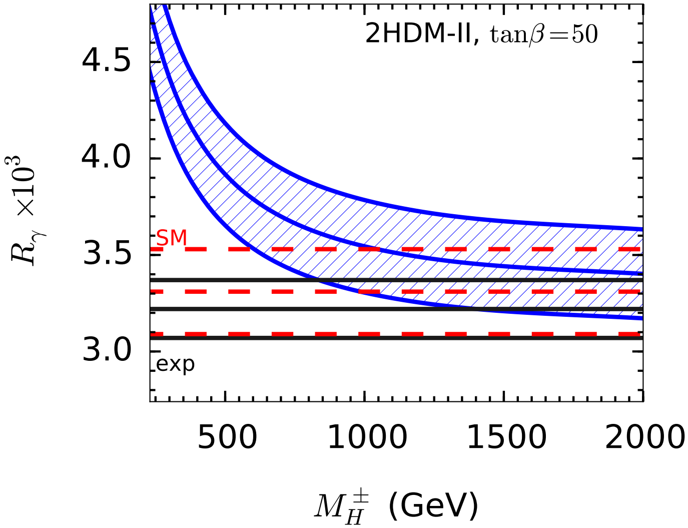
2HDM type II



[Misiak,Steinhauser'17]

2HDM type II

[Misiak,Steinhauser'17]

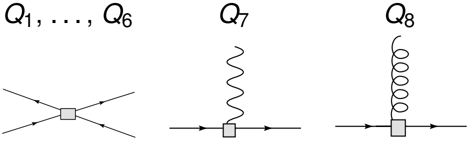


➪ $M_{H^\pm} \geq 570 - 800$ GeV

This talk: how?

SM at NNLO

$\mathcal{L}_{\rm weak} \sim \sum_i C_i Q_i$



Matching — Mixing — Matrix elements

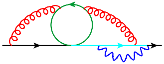
$$\mathcal{B}(\bar{B} \to X_s\gamma)|_{E_\gamma > 1.6\rm GeV} = \mathcal{B}(\bar{B} \to X_c e\bar{\nu})|_{\rm exp} \left(\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to ce\bar{\nu})}\right)_{\rm LO} f\left(\frac{\alpha_s(M_W)}{\alpha_s(m_b)}\right) \times$$

$$\left\{1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\alpha_s^2) + \mathcal{O}(\alpha) + \text{non-pert. corr.}\right\}$$

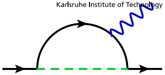
NLO: $\sim$ 30% NNLO: $\sim$ 10% $\sim$ 4% $\sim$ 2.5%

[Asatrian,Bieri,Boughezal,Czakon,Czarnecki,Ewerth,Ferroglia,Fiedler,Gambino,Gorbahn,Greub,Haisch,Hovhannisyan,Huber,Hurth, Kamiński,Misiak,Mitov,Ossola,Poghosyan,Poradziński,Rehman,Schutzmeier,Ślusarczyk,Steinhauser,Virto]

[Misiak et al.'06; Misiak et al.'15]



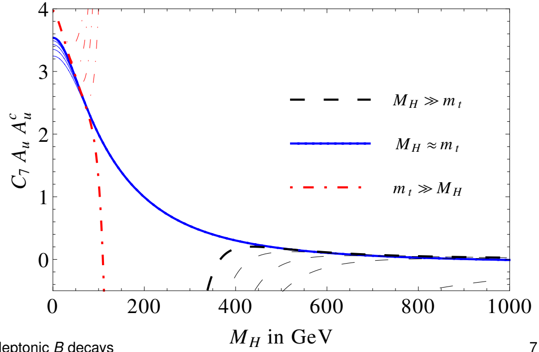
2HDM at NNLO



- QCD corrections to the C_i

[Ciuchini et al.'97; Borzumati,Greub'98; Ciafaloni et al.'97; Bobeth et al.'99; Bobeth et al.'04]

- NNLO: 3 loop corrections to C_7 and C_8 [Hermann,Misiak,Steinhauser'12]
- $C_{7,8} = C_{7,8}(m_t, M_{H^\pm})$
- asymptotic expansion: $m_t \gg M_{H^\pm}$, $m_t \approx M_{H^\pm}$, $m_t \ll M_{H^\pm}$
  ➪ cover full $M_{H^\pm}$ range; analytic results
- 2HDM-I, 2HDM-II



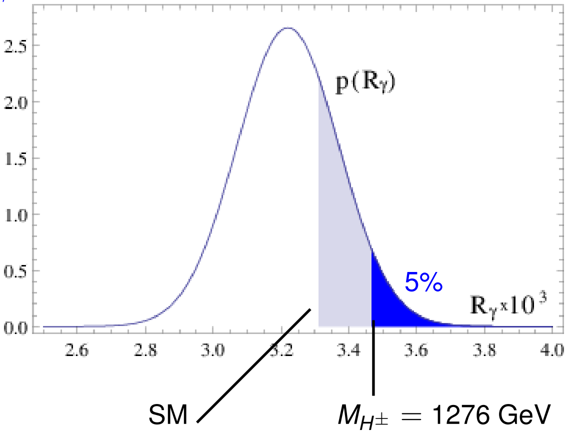
Bound on $M_{H^\pm}$

Bounds on $M_{H^\pm}$: no theory uncertainty

$p(R_\gamma) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-(R_\gamma - R_\gamma^{\rm exp})^2/\sigma^2\right)$

$R_\gamma^{\rm exp} = 3.22 \times 10^{-3}$, $\sigma = 0.15 \times 10^{-3}$ $\quad$ $R_\gamma^{\rm th} = 3.31 \times 10^{-3}$

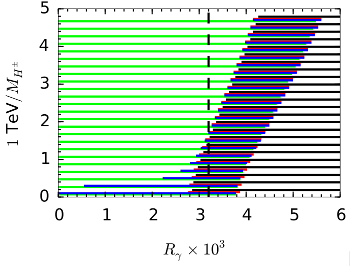
$R_\gamma^{\rm 2HDM-II} > R_\gamma^{\rm SM}$

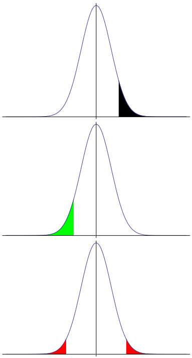


➪ 95% C.L. lower bound for $M_{H^\pm}$: 1276 GeV

Confidence belt construction

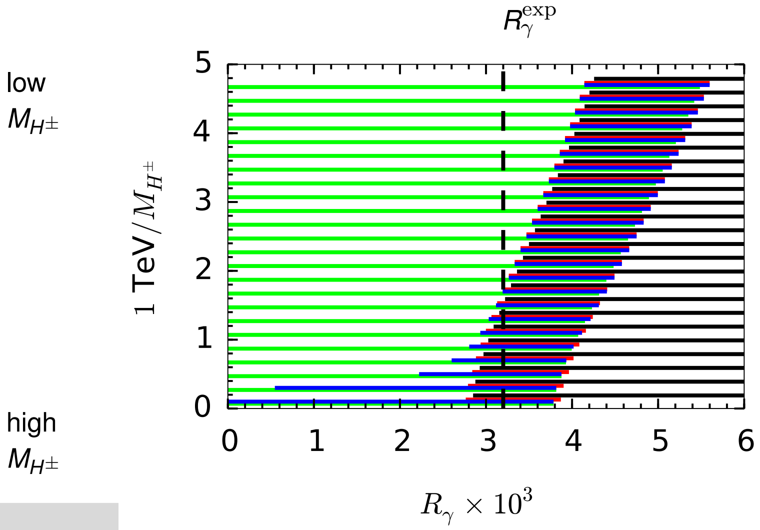
- include theory uncertainties
- For each $M_{H^\pm}$:
  Gaussian probability distribution around the theoretical central value
- $\sigma = \sqrt{(\sigma_{\rm exp})^2 + (\sigma_{\rm th})^2}$
- confidence interval: 95% or 99% integrated probability
  - "1-sided": upper
  - "1-sided": lower
  - "2-sided": centrally
  - "FC": "intermediate" [Feldman,Cousins'98]



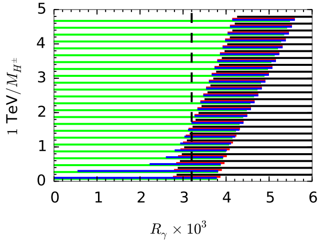


Confidence intervals – 2HDM-II

2-sided upper 1-sided lower 1-sided FC



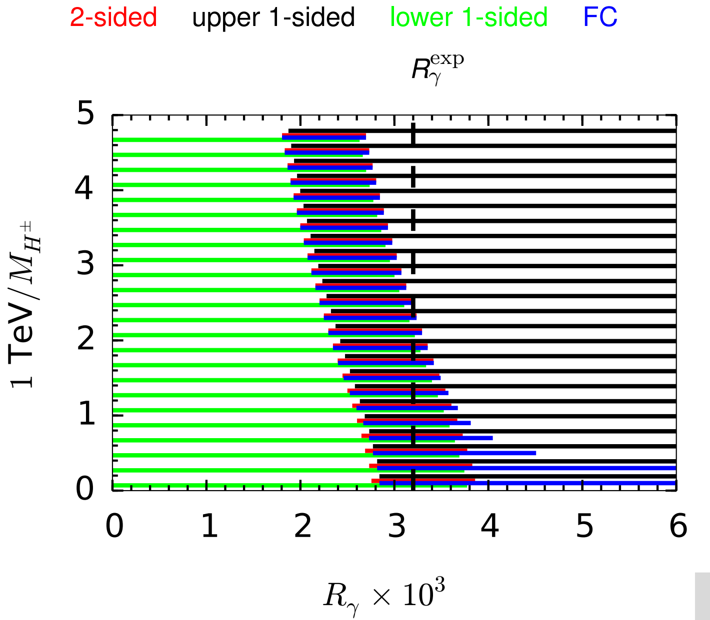
Bounds on $M_{H^\pm}$ – 2HDM-II



- Which interval? ➪ ambiguity
- FC: low values of R_γ^{exp} cannot exclude 2HDM-II
- 2-sided: [Belle'16; Flächer et al.'08]
- 1-sided: [Ciuchini,Degrassi,Gambino,Giudice'97; Gambino,Misiak'01; Hermann,Misiak,Steinhauser'12; Misiak et al'15]

$R_\gamma^{\text{exp}} \times 10^3$	95% C.L. bounds			99% C.L. bounds		
	1-sided	2-sided	FC	1-sided	2-sided	FC
3.05 ± 0.28	740	591	569	477	420	411
3.12 ± 0.19	795	645	628	528	468	461
3.22 ± 0.15	692	583	580	490	440	439

Confidence intervals – 2HDM-I (tan $\beta = 1$)



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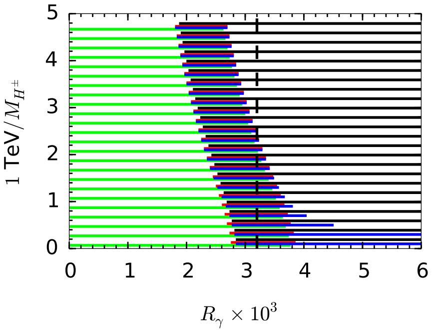
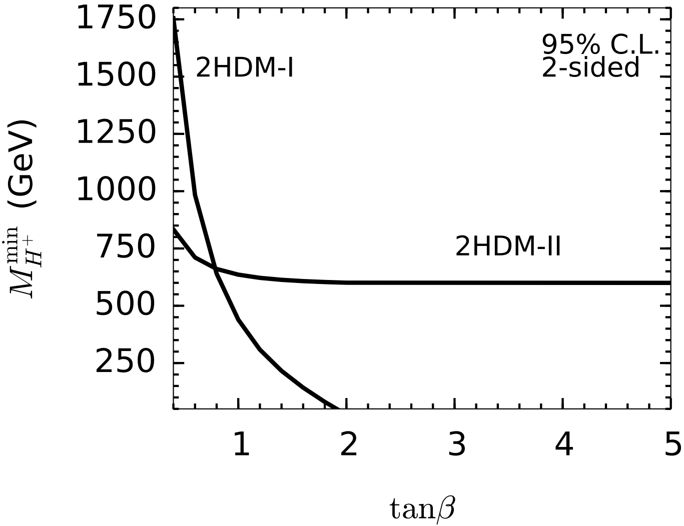


$R_\gamma^{\text{exp}} \times 10^3$	95% C.L. bounds			99% C.L. bounds		
	1-sided	2-sided	FC	1-sided	2-sided	FC
3.05 ± 0.28	307	268	268	230	208	208
3.12 ± 0.19	401	356	356	313	288	288
3.22 ± 0.15	504	445	445	391	361	361

$M_{H^\pm}^{\min}$ – tan β



Switch off QED

Switch off QED
... and EW corrections

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... limit on $M_{H^\pm}$?

no QED/EW: bounds on $M_{H^\pm}$, 2HDM-II

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$\Downarrow$

$R_\gamma^{\rm exp} \times 10^3$	95% C.L. bounds			99% C.L. bounds		
	1-sided	2-sided	FC	1-sided	2-sided	FC
3.05 ± 0.28	1036	761	682	585	504	477
3.12 ± 0.19	1156	855	772	603	531	519
3.22 ± 0.15	941	748	716	788	671	621

Conclusions

- $\mathcal{B}_{s\gamma}$, R_γ: NNLO in SM and 2HDM
- limit on $M_{H^\pm}$
- 2HDM-I: constraints only for $\tan\beta \lesssim 2$
- 2HDM-II: $M_{H^\pm} \geq 580$ GeV (95% C.L., $\tan\beta$-independent)
- 2HDM-II, no QED/EW corrections ➪ $M_{H^\pm} \geq 720$ GeV

Backup

FC confidence intervals

[Feldman,Cousins'97]

- $P(x|\mu) = \frac{1}{\sqrt{2\pi}} \exp\left(-(x-\mu)^2/2\right)$
- μ physically bounded to non-negative values
- $\mu_{\rm best} = \max(0, x)$

  ➩ $P(x|\mu_{\rm best}) = \begin{cases} 1/\sqrt{2\pi}, & x \geq 0 \\ \exp(-x^2/2)/\sqrt{2\pi}, & x < 0 \end{cases}$
- $R = P(x|\mu)/P(x|\mu_{\rm best})$ quantity for ordering principle
  ratio of two likelihoods: the likelihood of obtaining x given the actual mean μ, and the likelihood of obtaining x given the best-fit physically allowed mean.
- fix μ and determine $[x_1, x_2]$ from $R(x_1) = R(x_2)$ with
  $\int_{x_1}^{x_2} P(x|\mu) {\rm d}x = \alpha$

$\mu = R_\gamma^{\rm th} - R_\gamma^{\rm SM} > 0$ for 2HDM-II
$x = R_\gamma - R_\gamma^{\rm SM}$