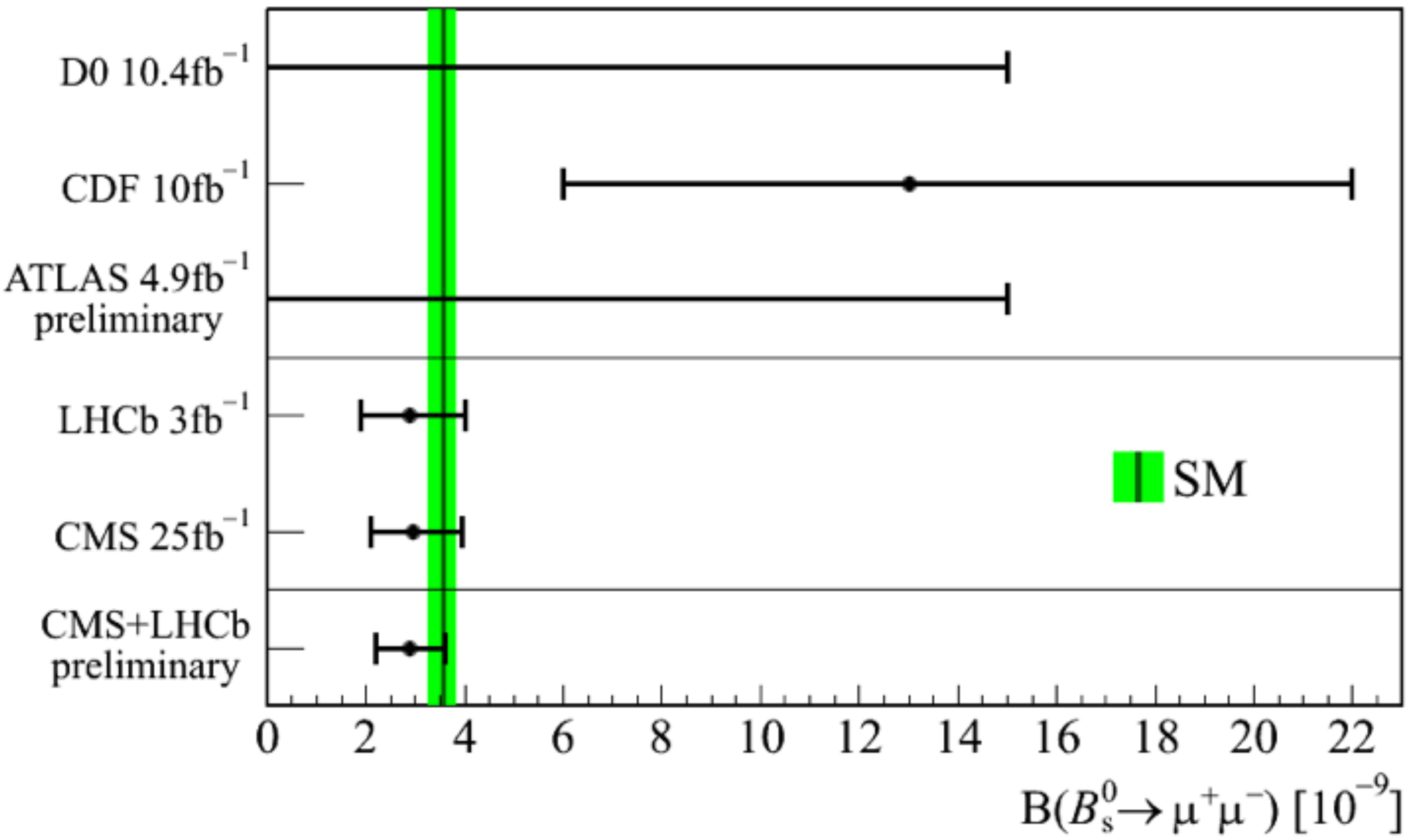
What would permille constraints on flavour observables bring us?

Uli Haisch
University of Oxford

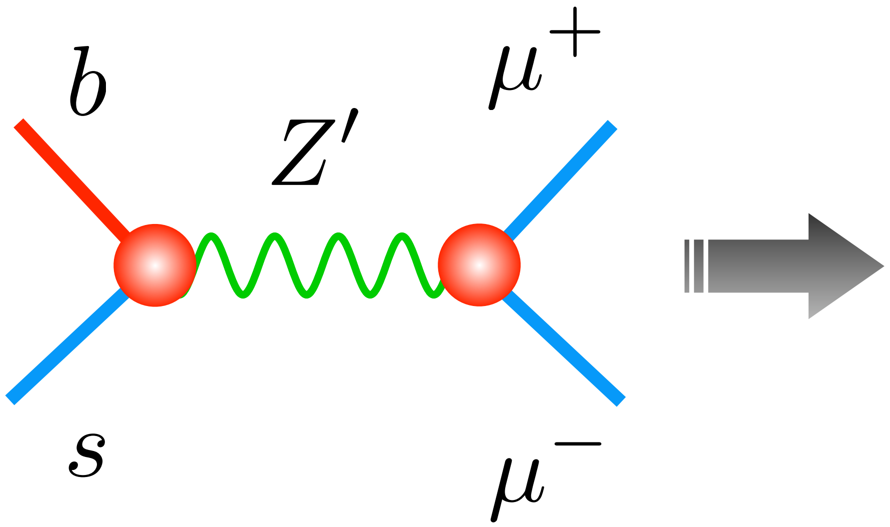
Heavy Flavour physics at HL-LHC, 31 August 2016, CERN

Flavour Run I summary on a slide



$$\boxed{\mu_{B_s \to \mu^+\mu^-} = 0.78 \pm 0.18}$$

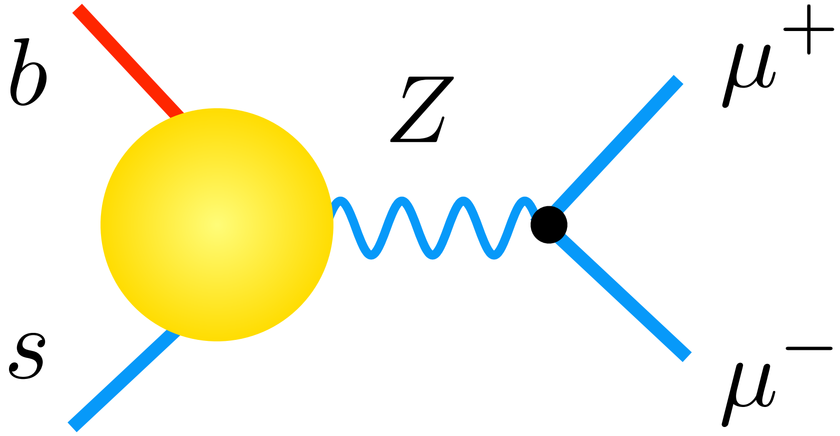
Flavour: new-physics scale?



$$\mu_{B_s \to \mu^+\mu^-} \simeq 1 \pm \frac{4\pi}{g^2\,|V_{tb}^* V_{ts}|^2}\,\frac{v^2}{\Lambda^2}$$

$$\Lambda \gtrsim \frac{v}{\sqrt{0.2}} \times \begin{cases} \dfrac{\sqrt{4\pi}}{g\,|V_{tb}^* V_{ts}|} \\ \\ \end{cases} \simeq \begin{cases} 50\,\text{TeV}\,, & \text{anarchic tree} \\ \\ \end{cases}$$

Flavour: new-physics scale?



$$\mu_{B_s\to\mu^+\mu^-} \simeq 1 \pm \frac{v^2}{\Lambda^2}$$

$$\Lambda \gtrsim \frac{v}{\sqrt{0.2}} \times \begin{cases} \dfrac{\sqrt{4\pi}}{g\,|V_{tb}^* V_{ts}|} \\ 1 \end{cases} \simeq \begin{cases} 50\,\text{TeV}\,, & \text{anarchic tree} \\ 0.6\,\text{TeV}\,, & \text{MFV loop} \end{cases}$$

Estimating new-physics reach

$$\Lambda \gtrsim \frac{v}{\sqrt{\delta}} \times \begin{cases} \dfrac{\sqrt{4\pi}}{g\,|V_{tb}^* V_{ts}|} \\ 1 \end{cases} \simeq \begin{cases} \dfrac{25\,\mathrm{TeV}}{\sqrt{\delta}}\,, & \text{anarchic tree} \\ \dfrac{0.3\,\mathrm{TeV}}{\sqrt{\delta}}\,, & \text{MFV loop} \end{cases}$$

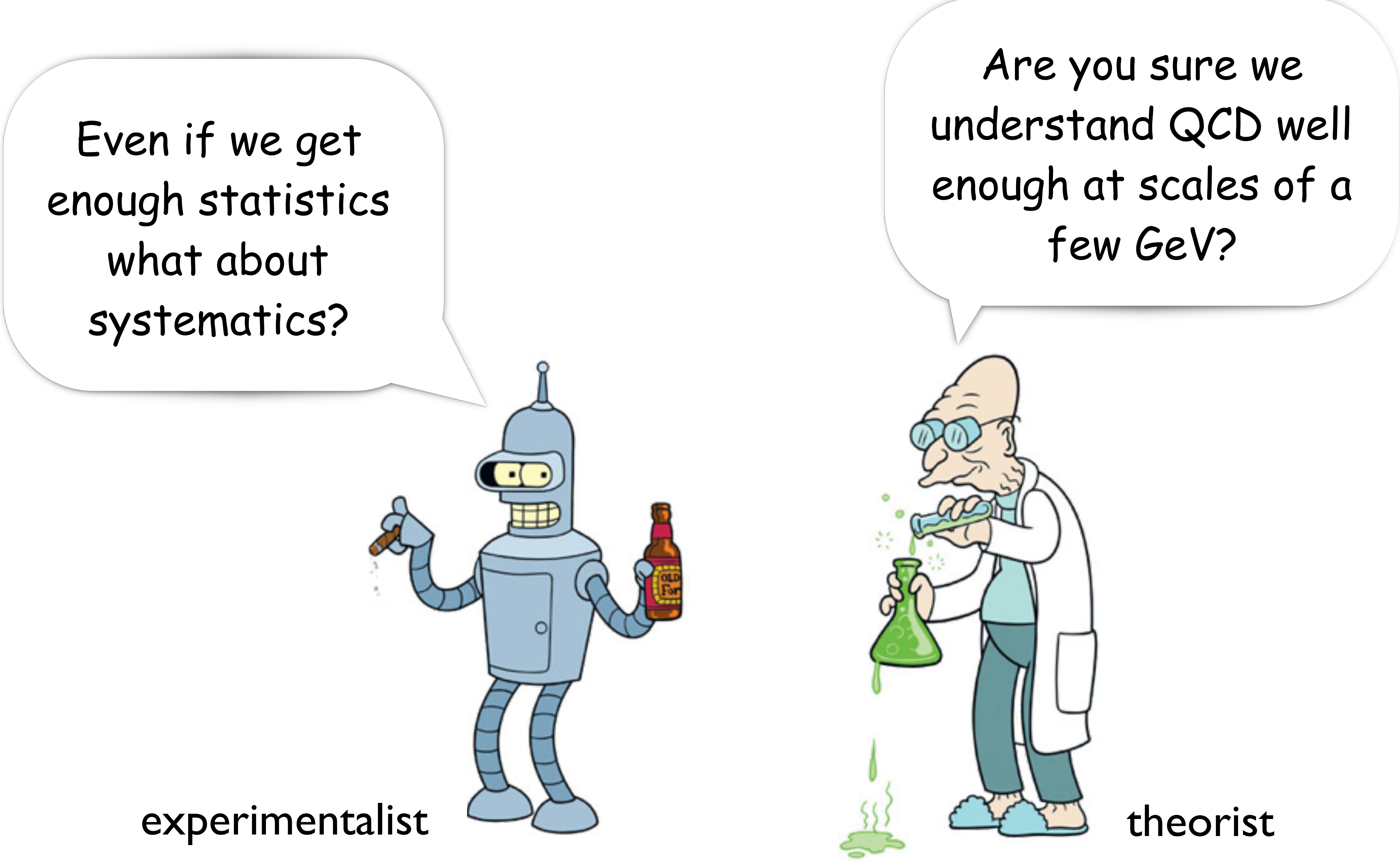
To predict future just need to know total relative uncertainty δ, that's all

Estimating new-physics reach

$$\Lambda \gtrsim \frac{v}{\sqrt{1‰}} \times \begin{cases} \dfrac{\sqrt{4\pi}}{g\,|V_{tb}^* V_{ts}|} \\ 1 \end{cases} \simeq \begin{cases} 700\,\mathrm{TeV}\,, & \text{anarchic tree} \\ 8.5\,\mathrm{TeV}\,, & \text{MFV loop} \end{cases}$$

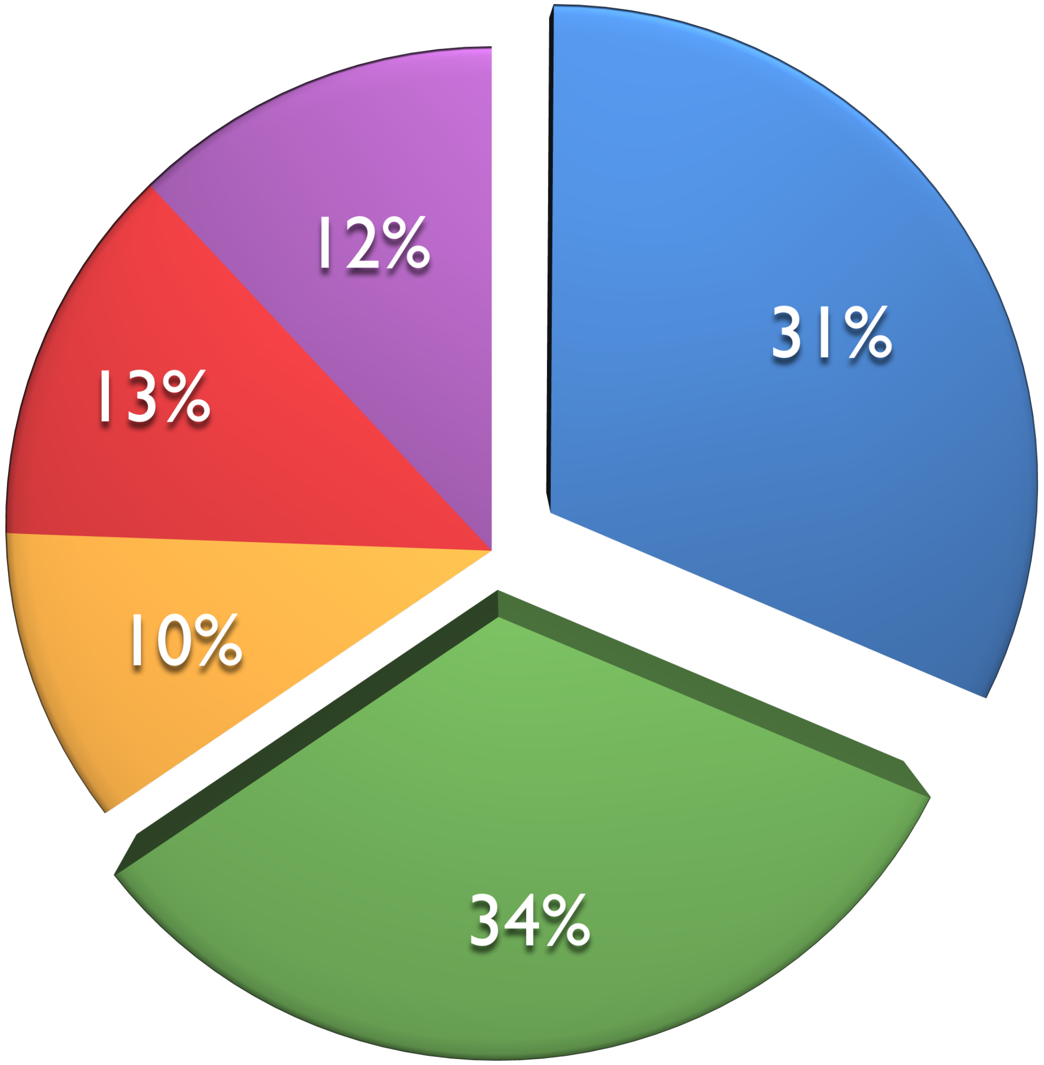
If one takes δ to be a ‰, bounds on new-physics scale improve by a factor of around 15 compared to LHC Run I limits

How realistic is a ‰?



[more on experimental issues in talks by Marc & Patrick]

$B_s \to \mu^+\mu^-$: current SM errors



6.4% total uncertainty

🔵 f_{B_s} 🟢 CKM

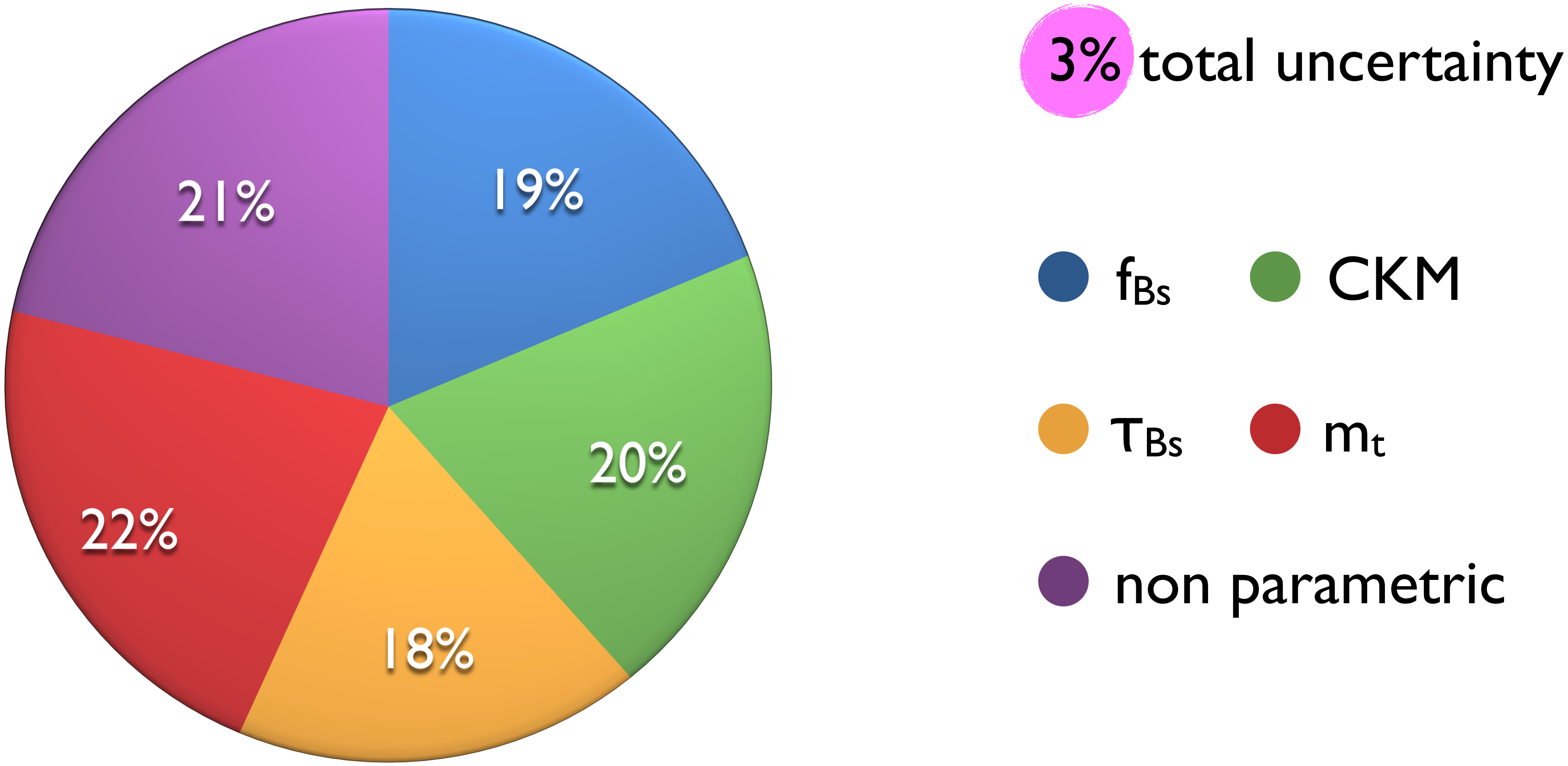
🟠 τ_{B_s} 🔴 m_t

🟣 non parametric

Calculation of 3-loop QCD & 2-loop EW effects reduces perturbative uncertainties to 0.5%. Relative errors due to f_{B_s} & CKM both around 4%

[Bobeth et al., 1311.0903, 1311.1348; Hermann et al.,1311.1347]

$B_s \to \mu^+\mu^-$: future SM errors



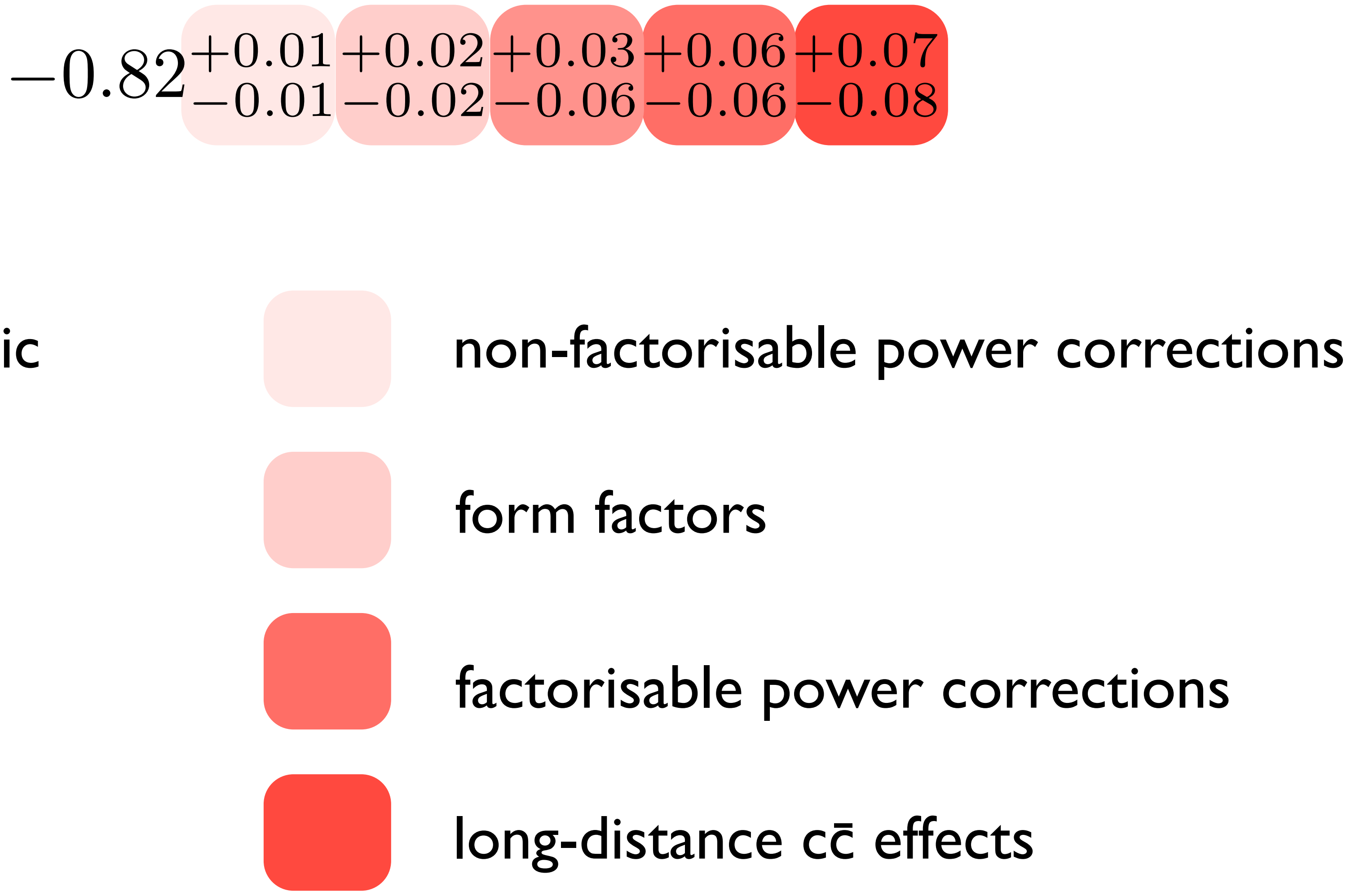
3% total uncertainty

Improvements in lattice QCD calculations may reduce errors due to f_{B_s} & V_{cb}, leading to a future total uncertainty of 3%

[Blum et al., http://www.usqcd.org/documents/13flavor.pdf]

$B \to K^* \mu^+ \mu^-$: current SM errors

For P_5' in [4, 6] GeV^2 bin:



$$-0.82^{+0.01\,+0.02\,+0.03\,+0.06\,+0.07}_{-0.01\,-0.02\,-0.06\,-0.06\,-0.08}$$

🟥 parametric

🟥 non-factorisable power corrections

🟥 form factors

🟥 factorisable power corrections

🟥 long-distance $c\bar{c}$ effects

[Matias, Moriond EW 2015]

$B\to K^*\mu^+\mu^-$: future SM errors

For P_5' in [4, 6] GeV^2 bin:

$$-0.82^{+0.01}_{-0.01}{}^{+0.02}_{-0.02}{}^{+0.03}_{-0.06}{}^{+0.06}_{-0.06}{}^{+0.07}_{-0.08}$$

Dominant uncertainty of O(10%) due to long-distance $c\bar{c}$ contribution cannot be calculated from first principles at present. Achieving % level precision in $B\to K^*\mu^+\mu^-$ & related modes would require breakthrough in our understanding of non-perturbative QCD. Maybe experiment can help by measuring long-distance $c\bar{c}$ effects

[see Patrick's talk & Petridis, Rare B Decays: Theory and Experiment 2016]

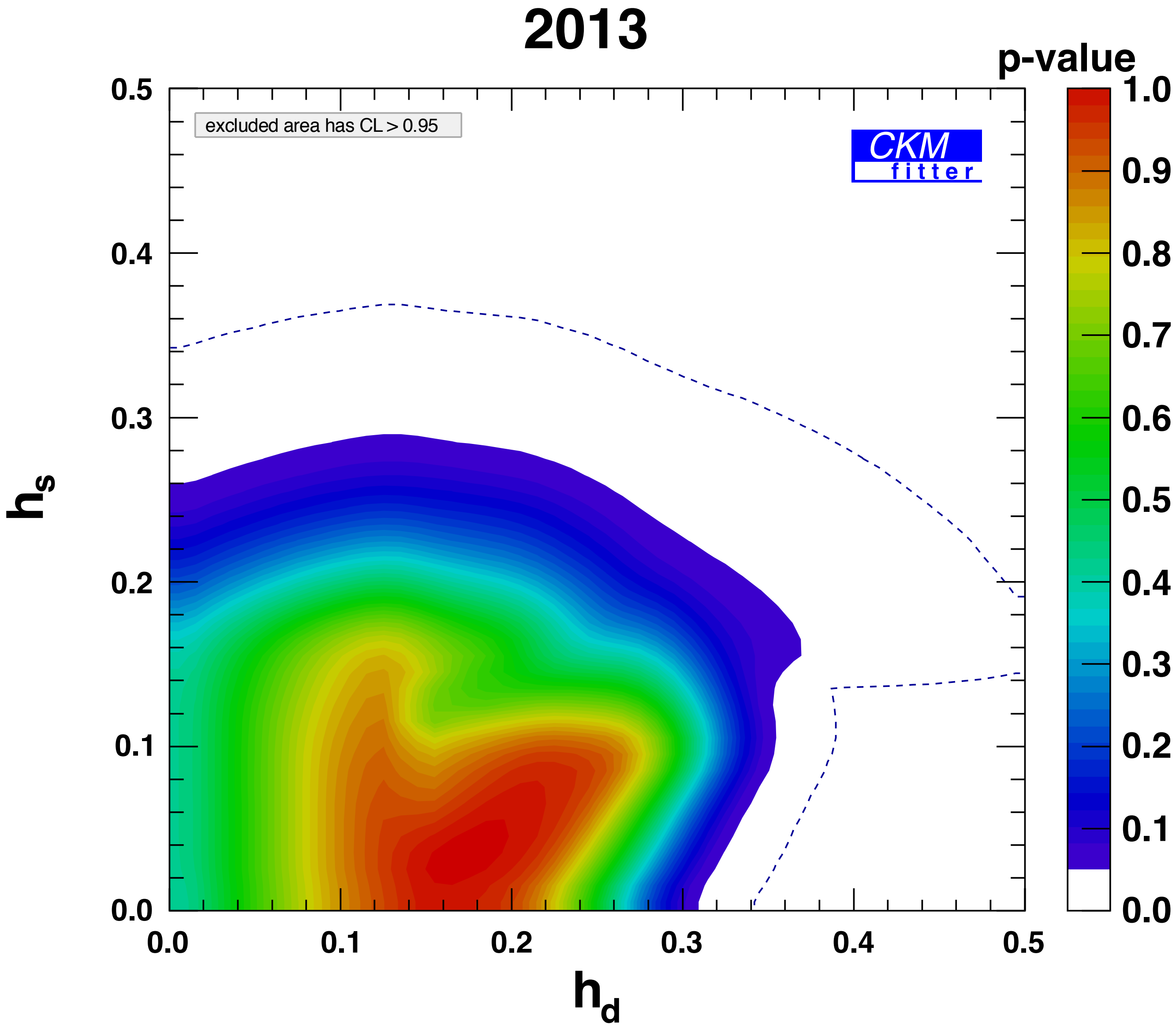
Flavour precision observables

$\delta\gamma$	$\mathcal{O}(10^{-7})$	[Brod & Zupan, 1308.5663]
$\delta\beta$	$\mathcal{O}(1\%)$	[Ciuchini et al., hep-ph/0507290]
δR_{D^*}	$\mathcal{O}(1\%)$	[Fajfer et al., 1203.2654]
$\delta R_K, \delta R_{K^*}, \ldots$	$\mathcal{O}(1\%)$	[Bordone et al., 1605.07633]

Theoretical errors in some observables at % level or below. If measured with a comparable precision one could learn a lot about exotic tree-level effects, penguin pollution, lepton-flavour universality violating couplings, etc.

B mixing: present & future

[Charles et al., 1309.2293]

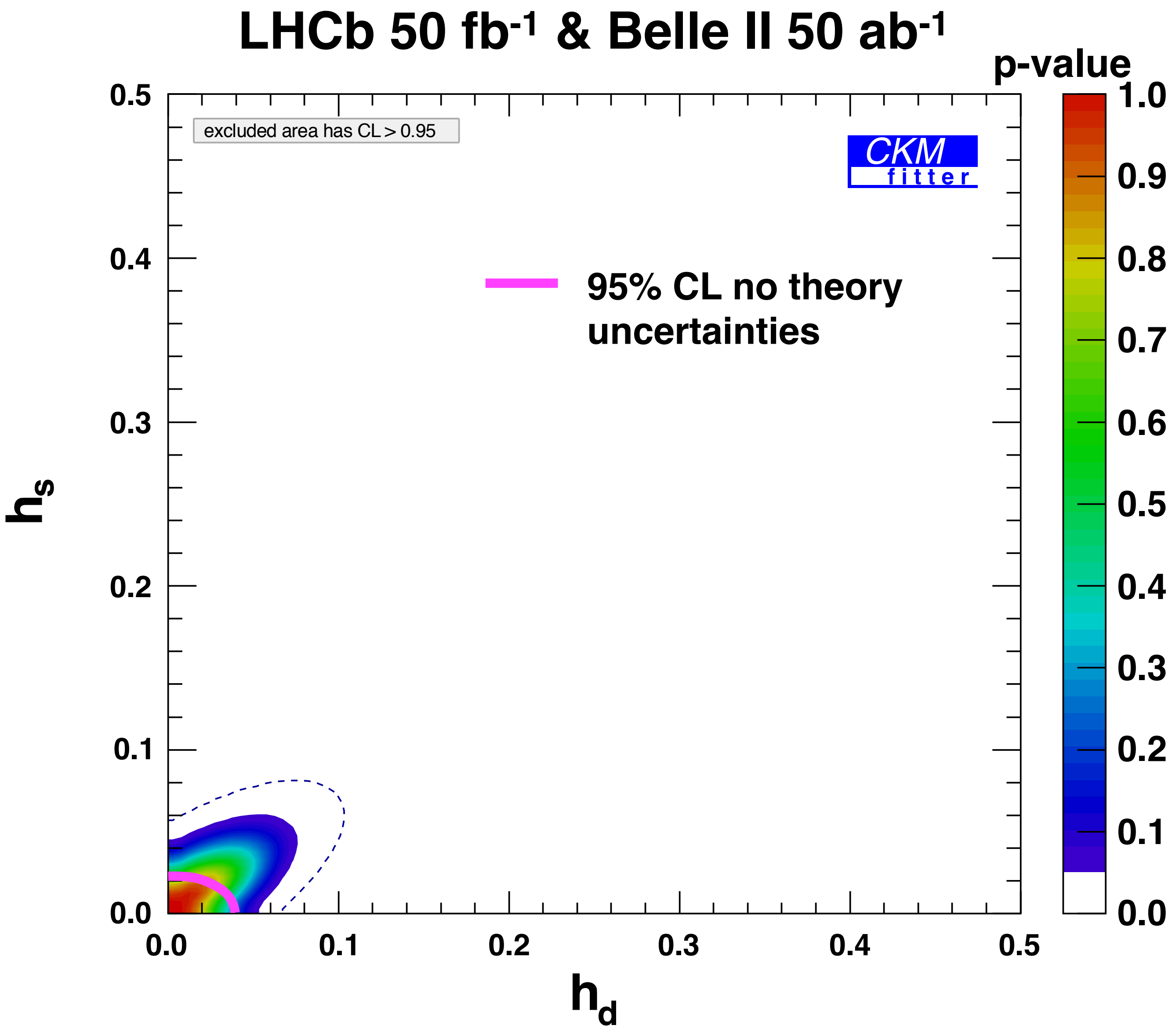


$$M_{12}^q = (M_{12}^q)_{\rm SM}\left(1 + h_q e^{2i\sigma_q}\right)$$

$$h_d \lesssim 30\% \quad \Rightarrow \quad \Lambda \gtrsim \begin{cases} 0.8 \cdot 10^3\,\text{TeV}, & \text{anarchic tree} \\ 0.6\,\text{TeV}, & \text{MFV loop} \end{cases}$$

B mixing: present & future

[Charles et al., 1309.2293]



$$M_{12}^q = (M_{12}^q)_{\rm SM}\left(1 + h_q e^{2i\sigma_q}\right)$$

$$h_d \lesssim 5\% \quad \Rightarrow \quad \Lambda \gtrsim \begin{cases} 2\cdot 10^3\,\mathrm{TeV}, & \text{anarchic tree} \\ 1.4\,\mathrm{TeV}, & \text{MFV loop} \end{cases}$$

Constraints on 2HDM-II

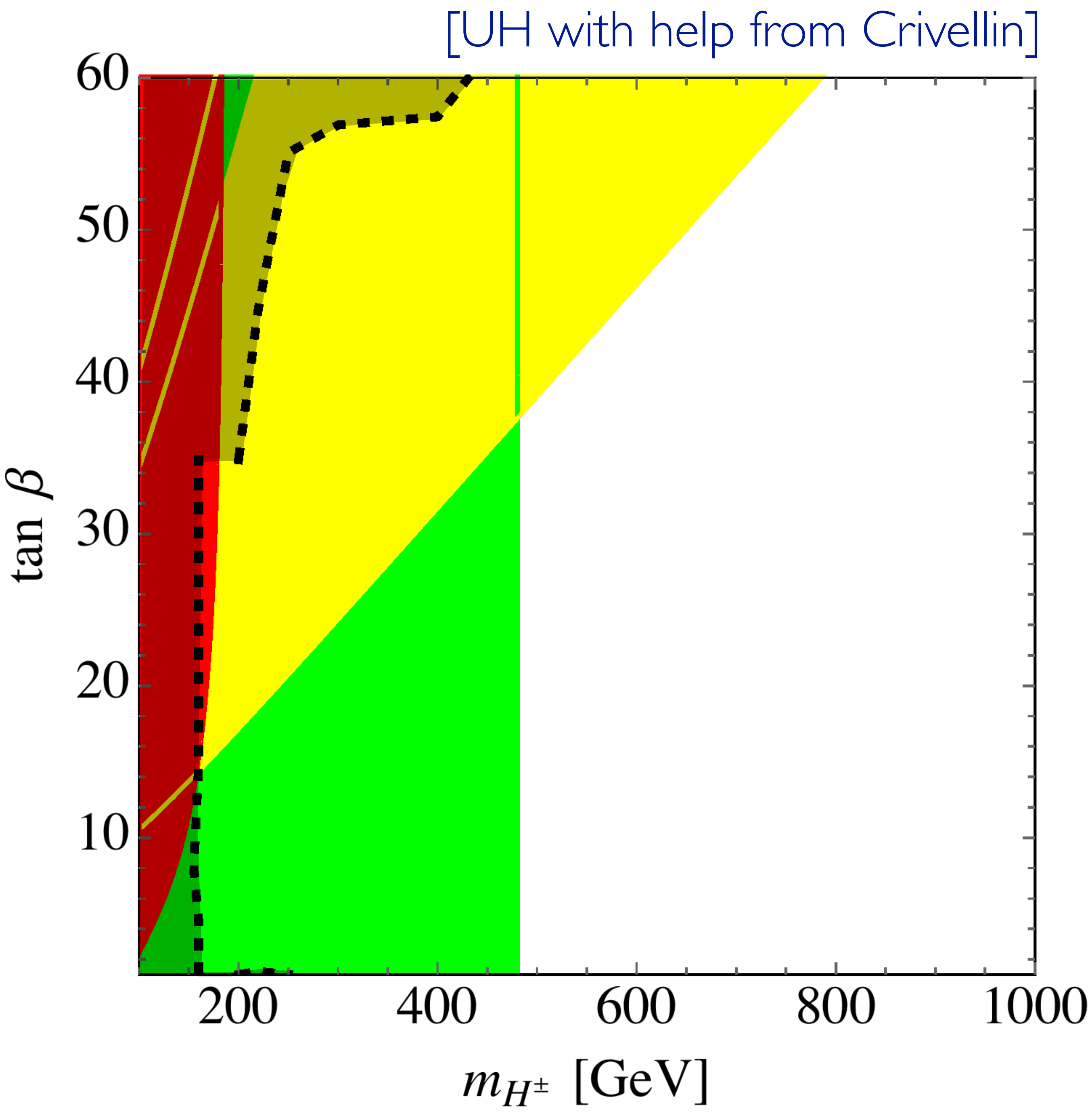
Present 95% CL exclusions:

- 🟩 $B \to X_s \gamma$
- 🟨 $B \to \tau\nu$
- 🟥 $B_s \to \mu^+\mu^-$

▪▪▪▪▪ $\bar{t} \to \bar{b}H^+ \, (\to \tau^+\bar{\nu}_\tau, t\bar{b})$

MSSM updated $m_h^{\max}$

[CMS, 1508.07774]



[UH with help from Crivellin]

Flavour physics provides stringent indirect constraints in $m_{H^\pm}$-tan β plane. Restrictions highly complementary to direct searches by ATLAS & CMS

Constraints on 2HDM-II

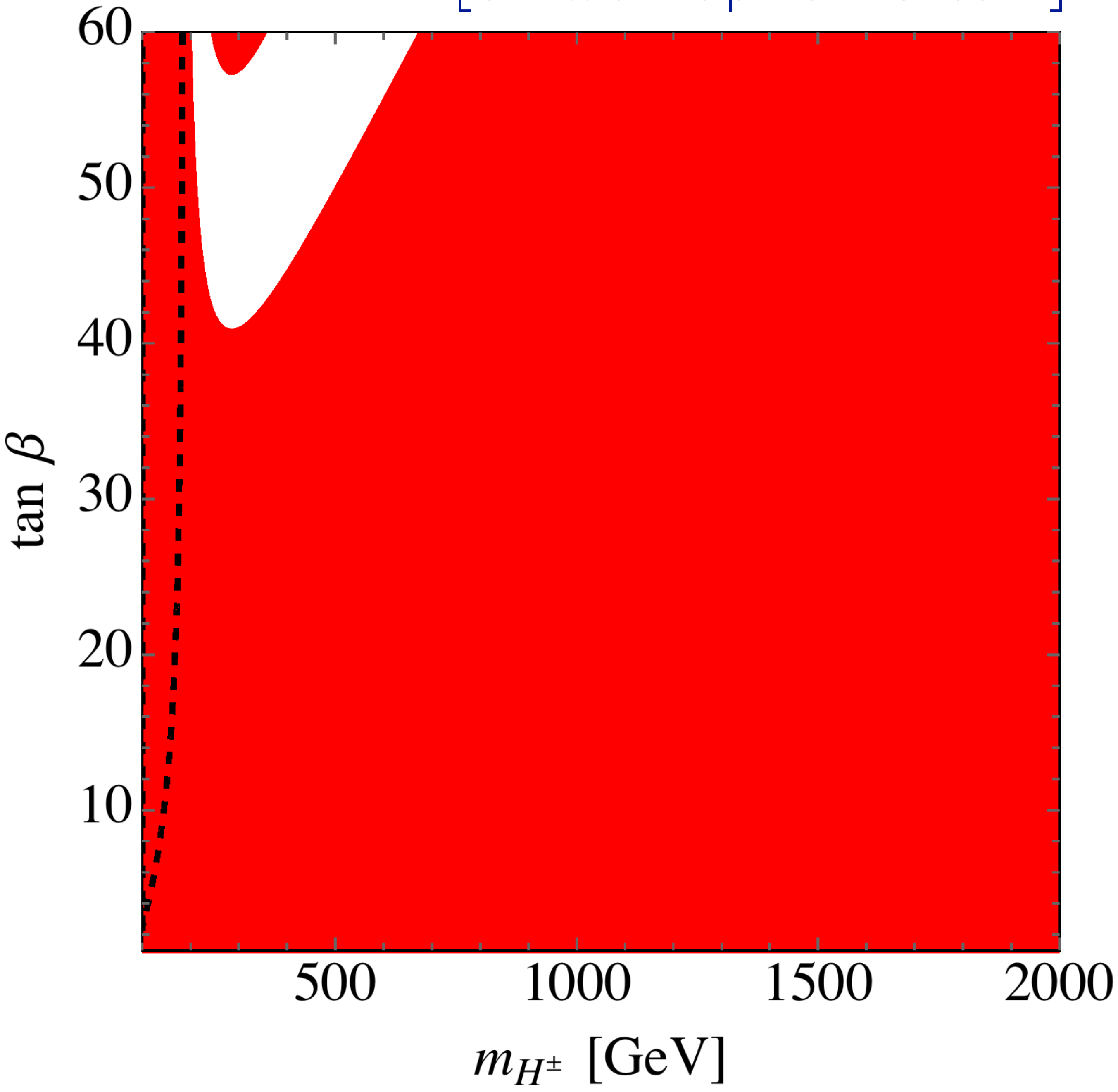
Excluded by

$$\frac{\mathrm{Br}(B_s \to \mu^+\mu^-)}{\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} \in$$

┈ $[0.46,\ 1.16]$

🟥 $[0.46,\ 0.55]$

[UH with help from Crivellin]



Any precision measurement of $B_s \to \mu^+\mu^-$ compatible with Run I 95% CL limit will significantly reduce allowed parameter space in $m_{H^\pm}$-tan β plane

Constraints on 2HDM-II

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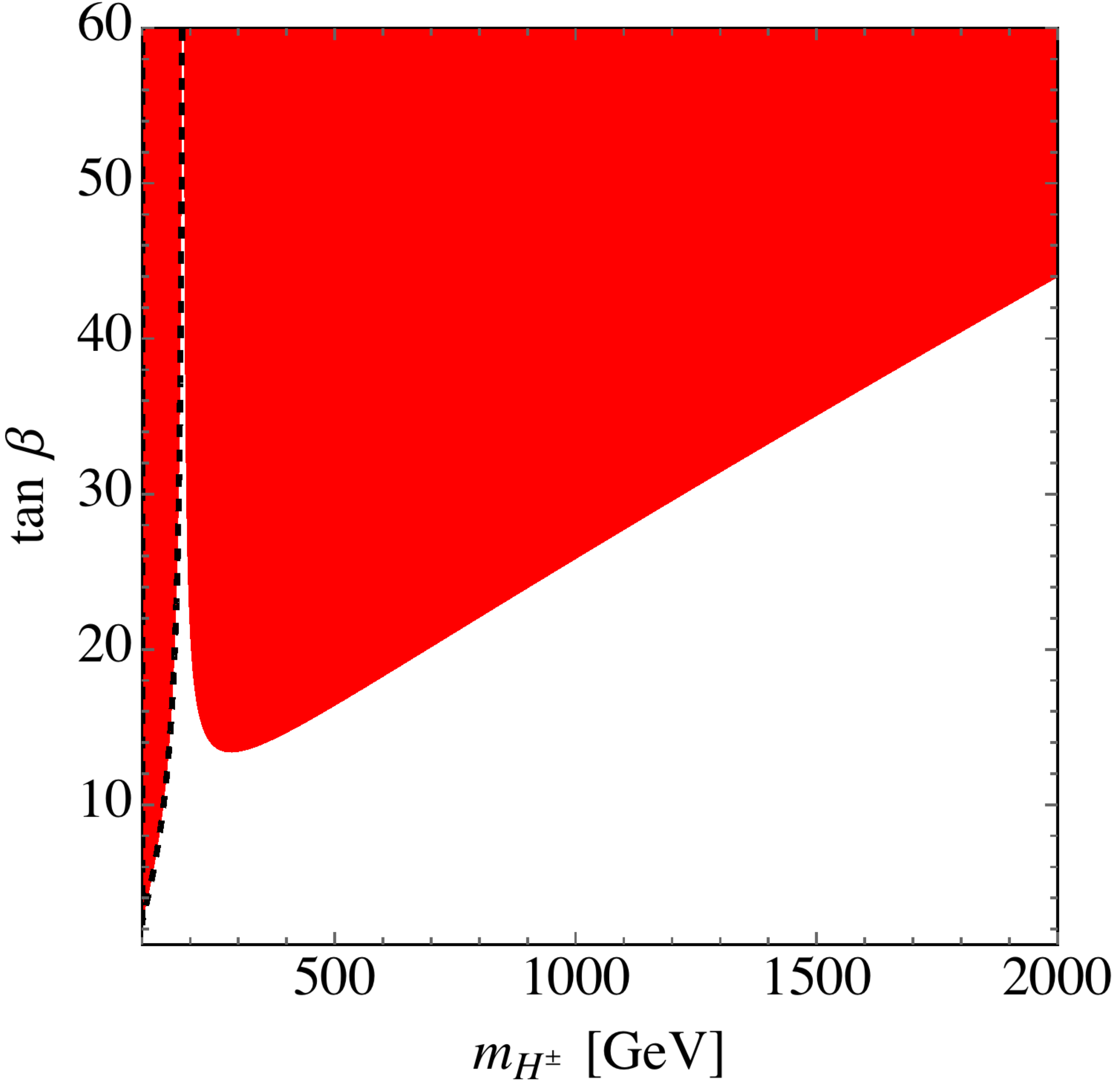
[UH with help from Crivellin]



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Constraints on 2HDM-II

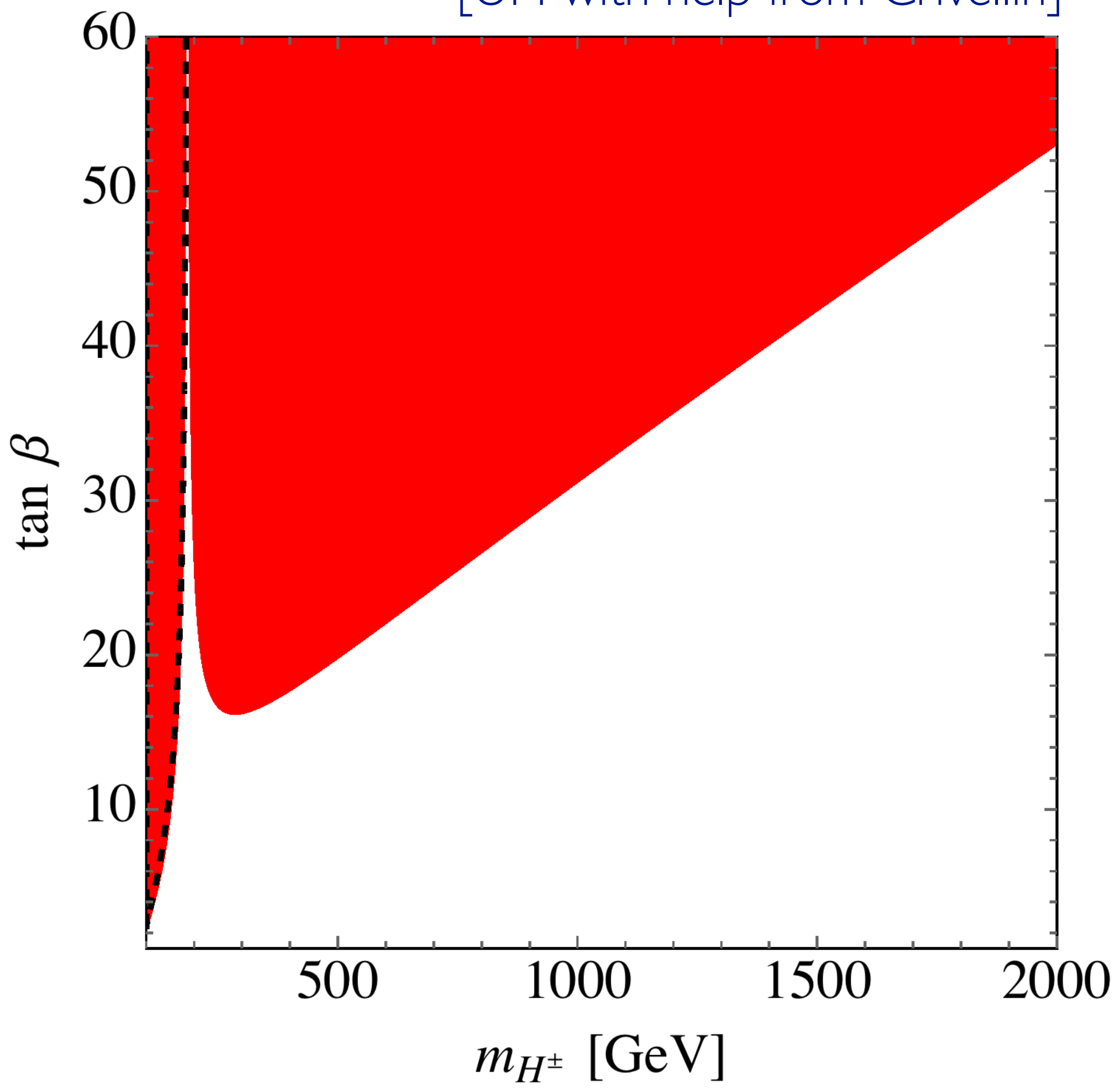
Excluded by

$$\frac{\mathrm{Br}(B_s \to \mu^+\mu^-)}{\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} \in$$

┅ $[0.46,\ 1.16]$

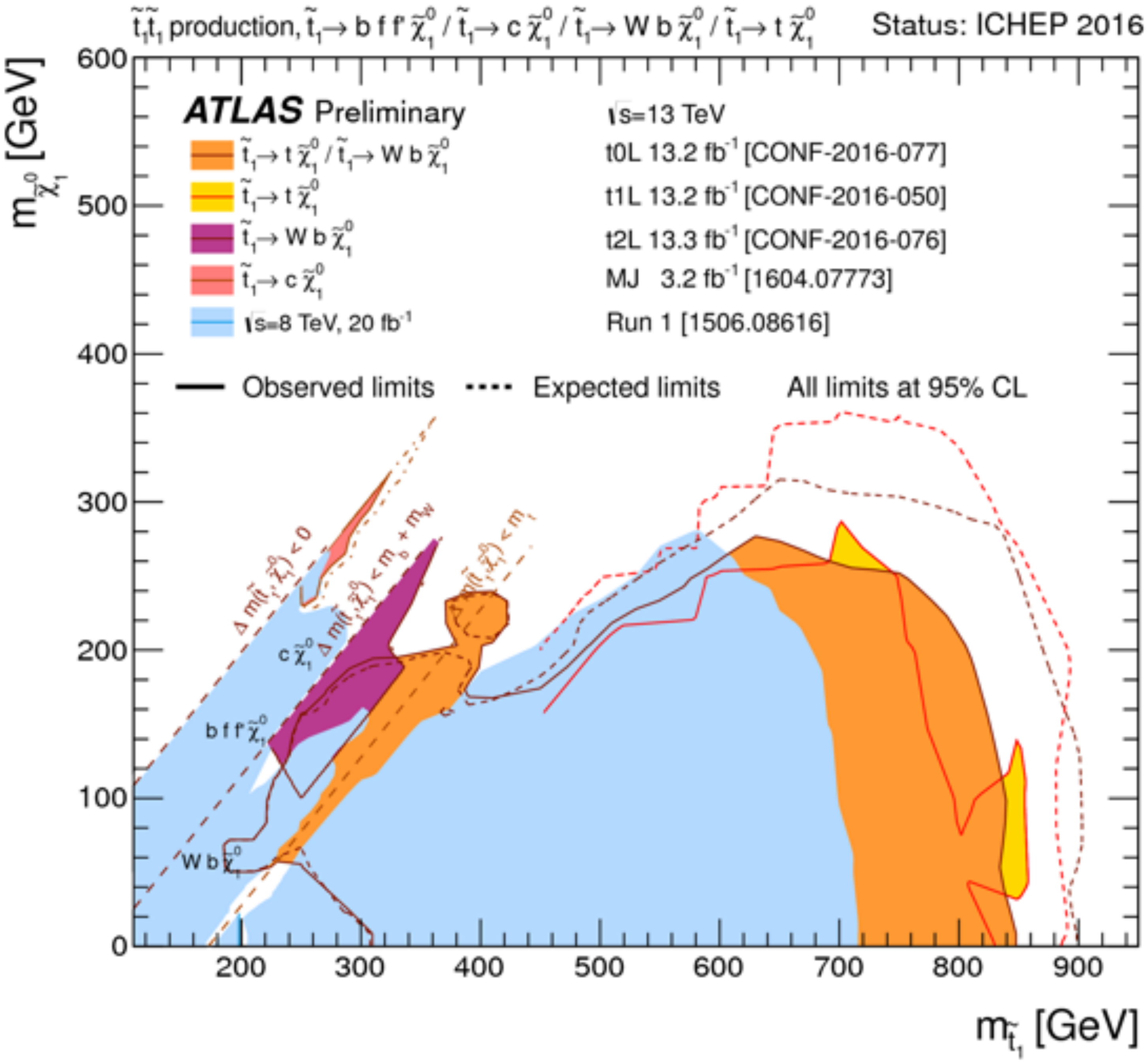
🟥 $[0.9,\ 1.1]$

[UH with help from Crivellin]



Any precision measurement of $B_s \to \mu^+\mu^-$ compatible with Run I 95% CL limit will significantly reduce allowed parameter space in $m_{H^\pm}$-$\tan\beta$ plane

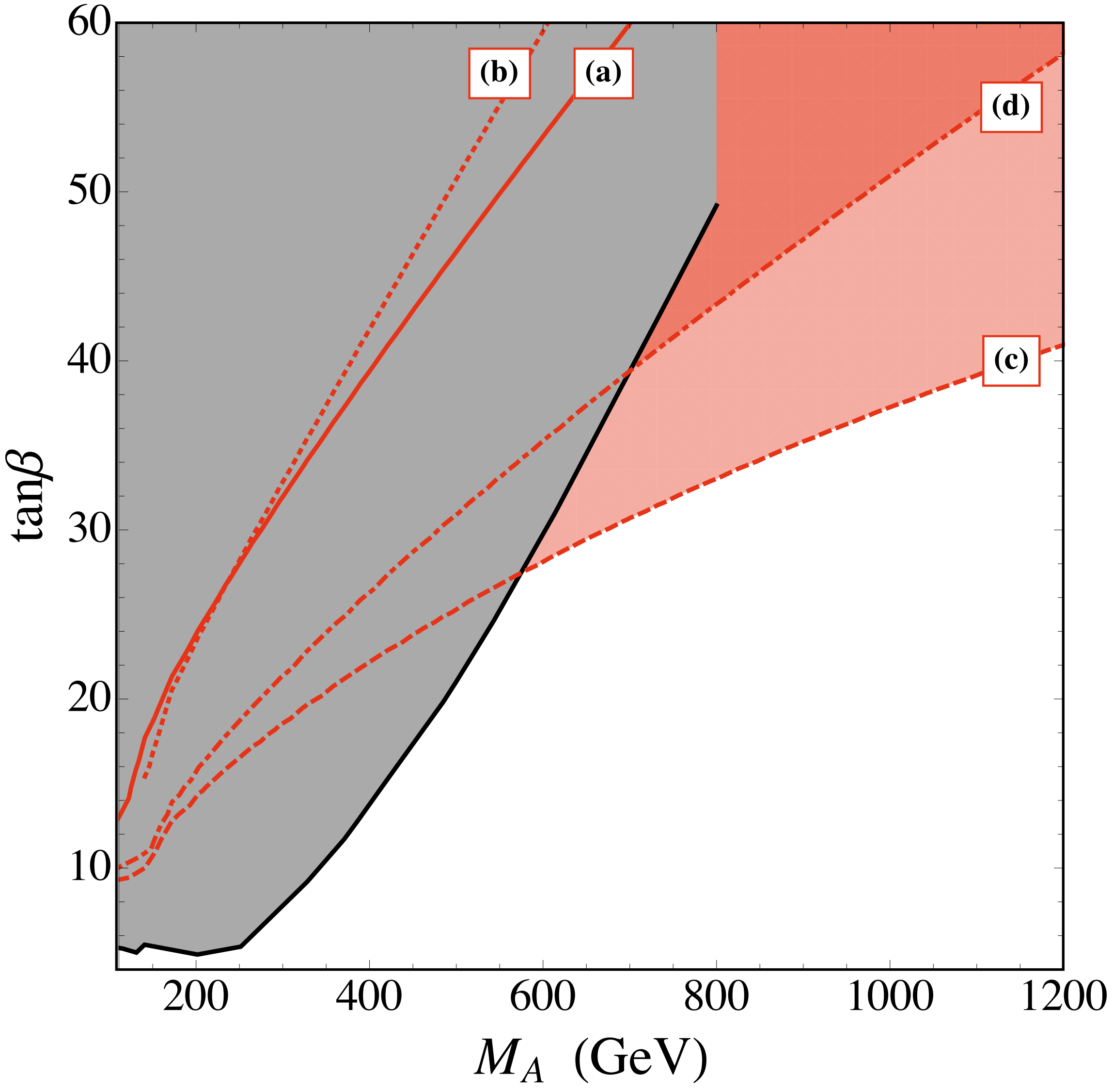
Flavour constraints on MSSM



Since flavour observables involve typically a handful of MSSM parameters such as $m_{\tilde{t}}$, μ, A_t, etc. always more model-dependent than direct searches

$B_s \to \mu^+\mu^-$ constraints on MSSM

[Altmannshofer et al., 1211.1976]



$(a)\ \ \mu = 1\,\mathrm{TeV}\,,\ \ A_t > 0$

$(b)\ \ \mu = 4\,\mathrm{TeV}\,,\ \ A_t > 0$

$(c)\ \ \mu = -1.5\,\mathrm{TeV}\,,\ \ A_t > 0$

$(d)\ \ \mu = 1\,\mathrm{TeV}\,,\ \ A_t < 0$

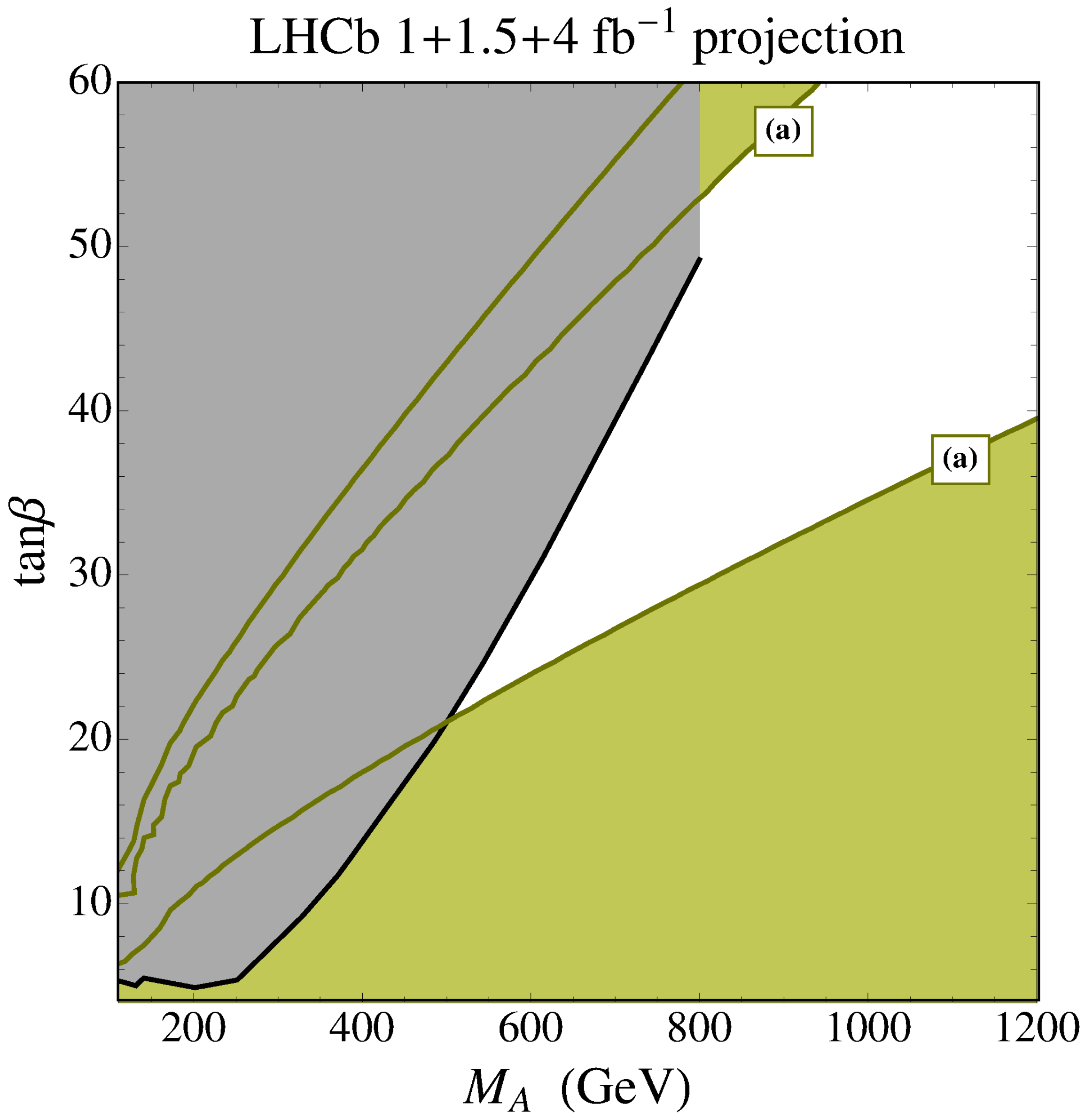
all squarks degenerate with 2 TeV,
A_t such that $m_h = 125\,\mathrm{GeV}$

▨ excluded by LHC Run I
$H, A \to \tau^+\tau^-$ searches

Interference of Higgsino with SM contribution make $B_s \to \mu^+\mu^-$ sensitive probe of μA_t. Currently $\mu A_t < 0$ stronger constrained as interference constructive

$B_s \to \mu^+\mu^-$ constraints on MSSM

[Altmannshofer et al., 1211.1976]



$(a)\ \ \mu = 1\,\mathrm{TeV}\,,\ \ A_t > 0$

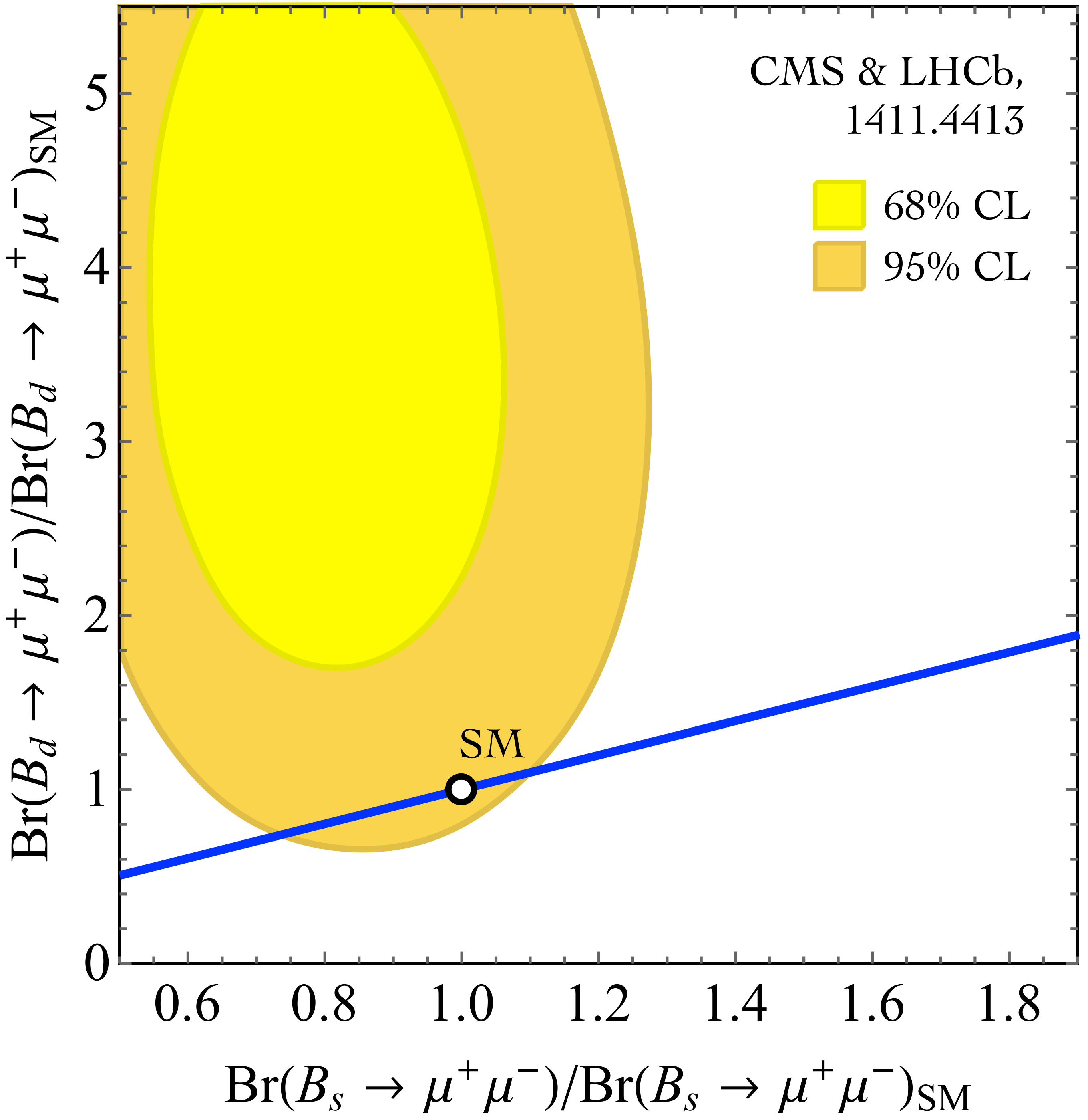
all squarks degenerate with 2 TeV,
A_t such that $m_h = 125\,\mathrm{GeV}$

■ excluded by LHC Run I
$H, A \to \tau^+\tau^-$ searches

🟩 parameters leading to
$\mathrm{Br}(B_s \to \mu^+\mu^-) \in [3.2,\ 4.2] \cdot 10^{-9}$

However also choices with $\mu A_t > 0$ will be constrained significantly if a lower bound of $\mathrm{Br}(B_s \to \mu^+\mu^-)$ above half of SM prediction is established in future

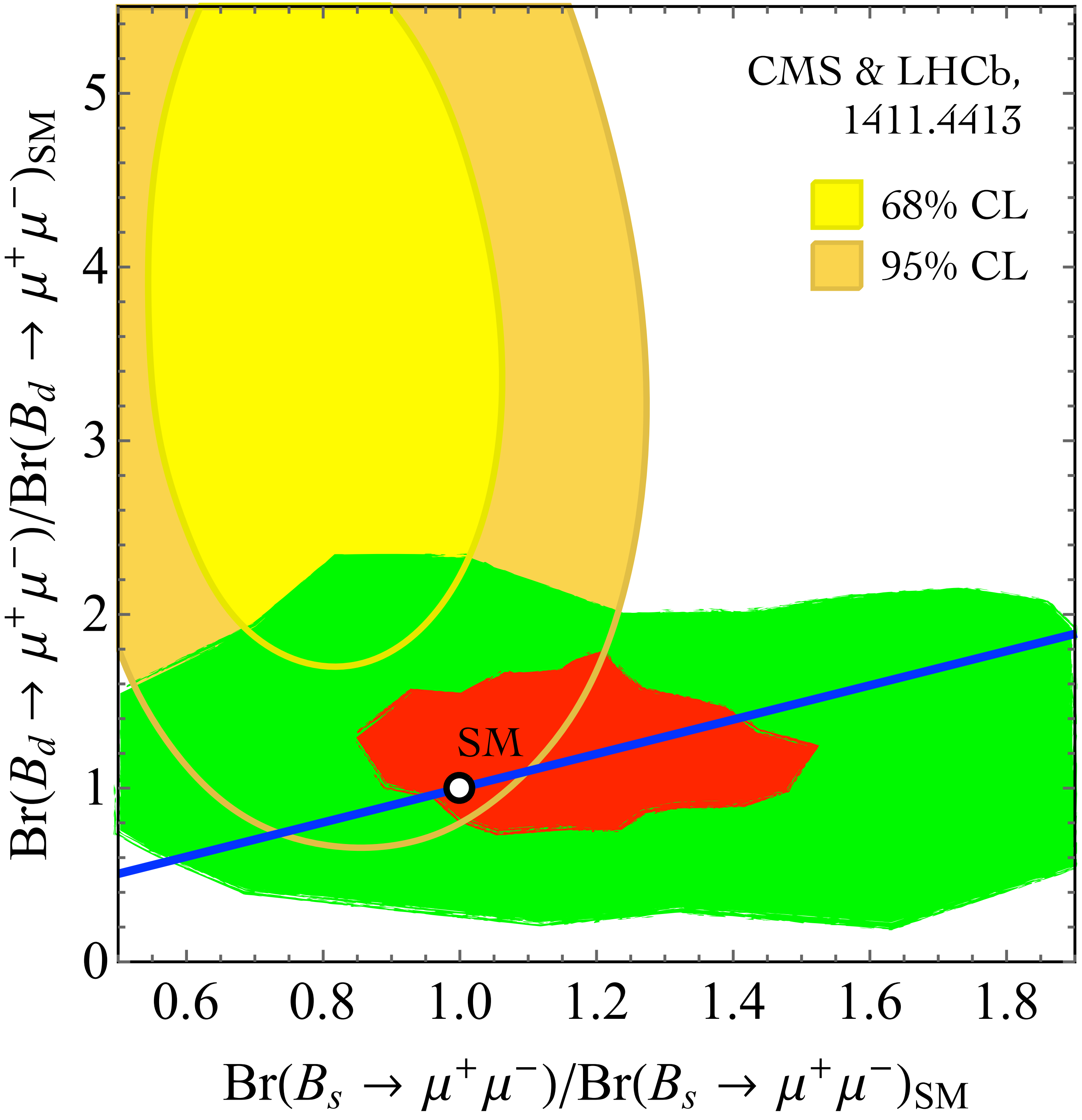
$B_s \to \mu^+\mu^-$ vs. $B_d \to \mu^+\mu^-$



— MFV

in scenarios with MFV deviations in $B_{s,d} \to \mu^+\mu^-$ modes very constrained

$B_s \to \mu^+\mu^-$ vs. $B_d \to \mu^+\mu^-$



— MFV

🟥 little Higgs model with T parity

[Blanke et al., 1507.06316]

🟩 Randall-Sundrum model without custodial protection

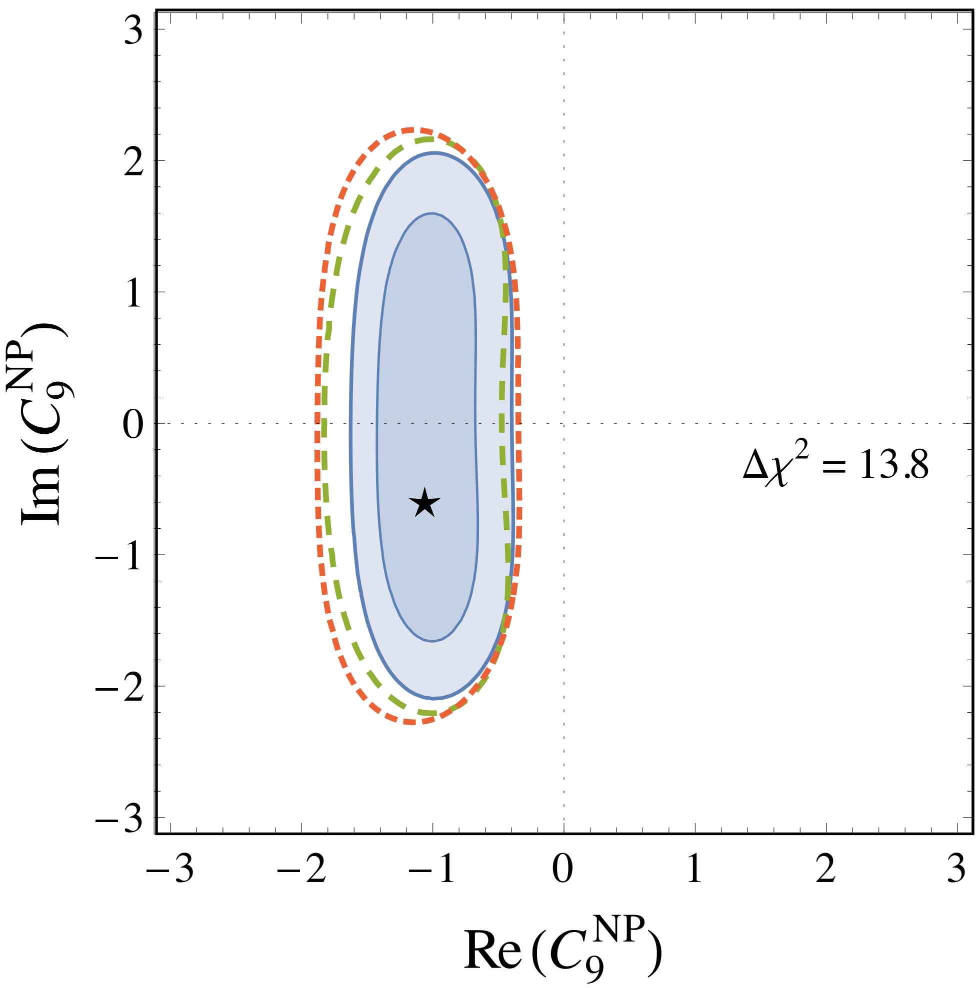
[Bauer et al., 0912.1625]

in models beyond MFV modes are uncorrelated

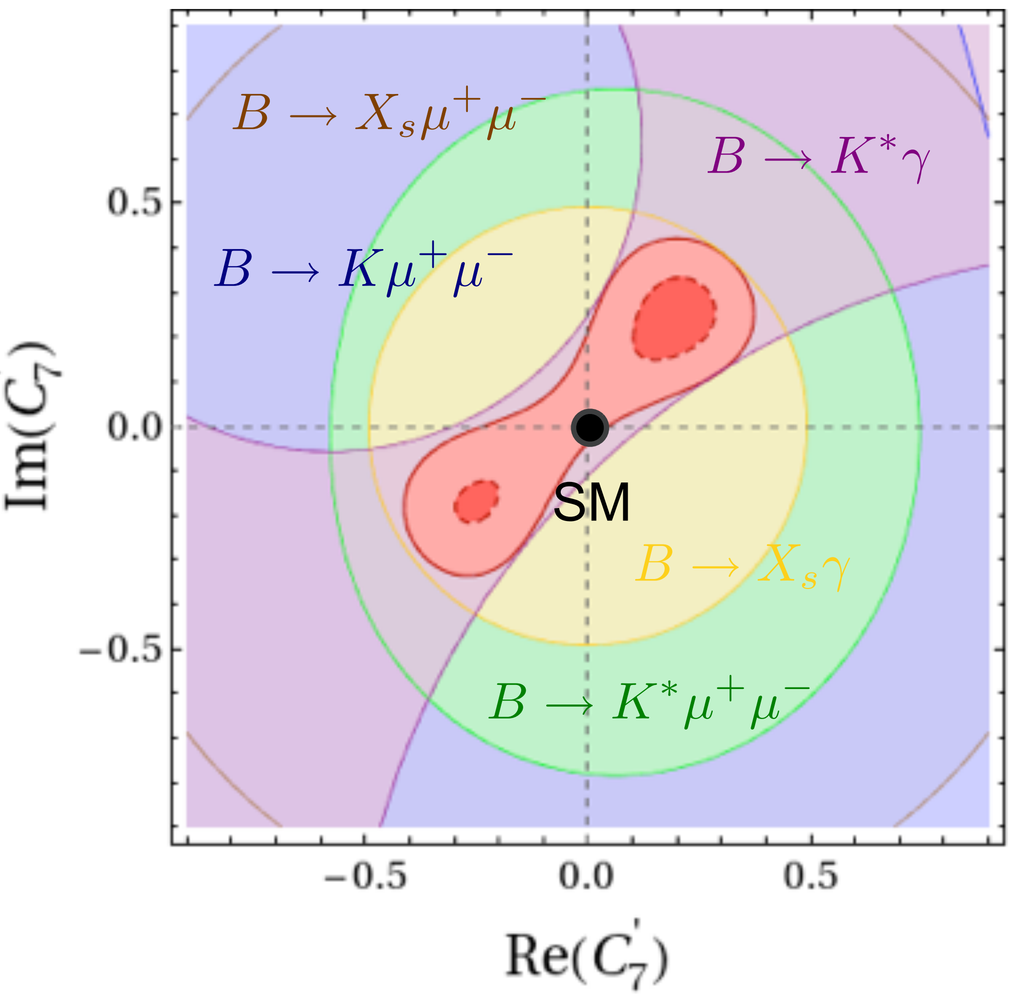
At HL-LHC can rule out or provide precision test of MFV hypothesis

Future directions in $B \to K^* \mu^+ \mu^-$

[Altmannshofer & Straub, 1411.3161]

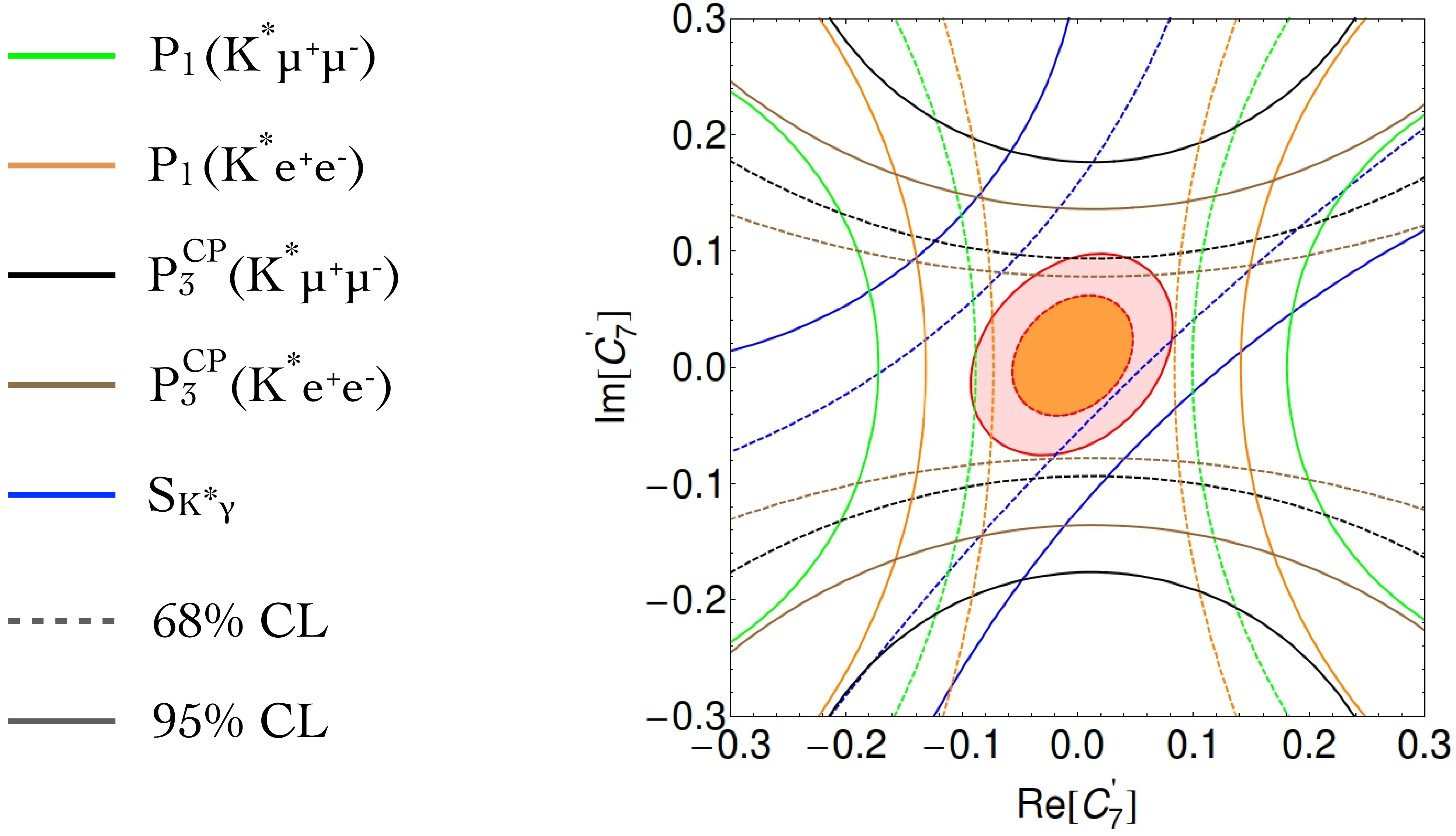


[Altmannshofer & Straub, 1206.0273]



Currently only real parts of Wilson coefficients constrained by global fits. Weak sensitivity to $\mathrm{Im}(C_7^{(\prime)})$ from $B \to K^* \gamma$. Precise measurements of CP-violating observables in $B \to K^* \mu^+ \mu^-$ thus important goal of LHCb

Future directions in $B \to K^* \mu^+ \mu^-$

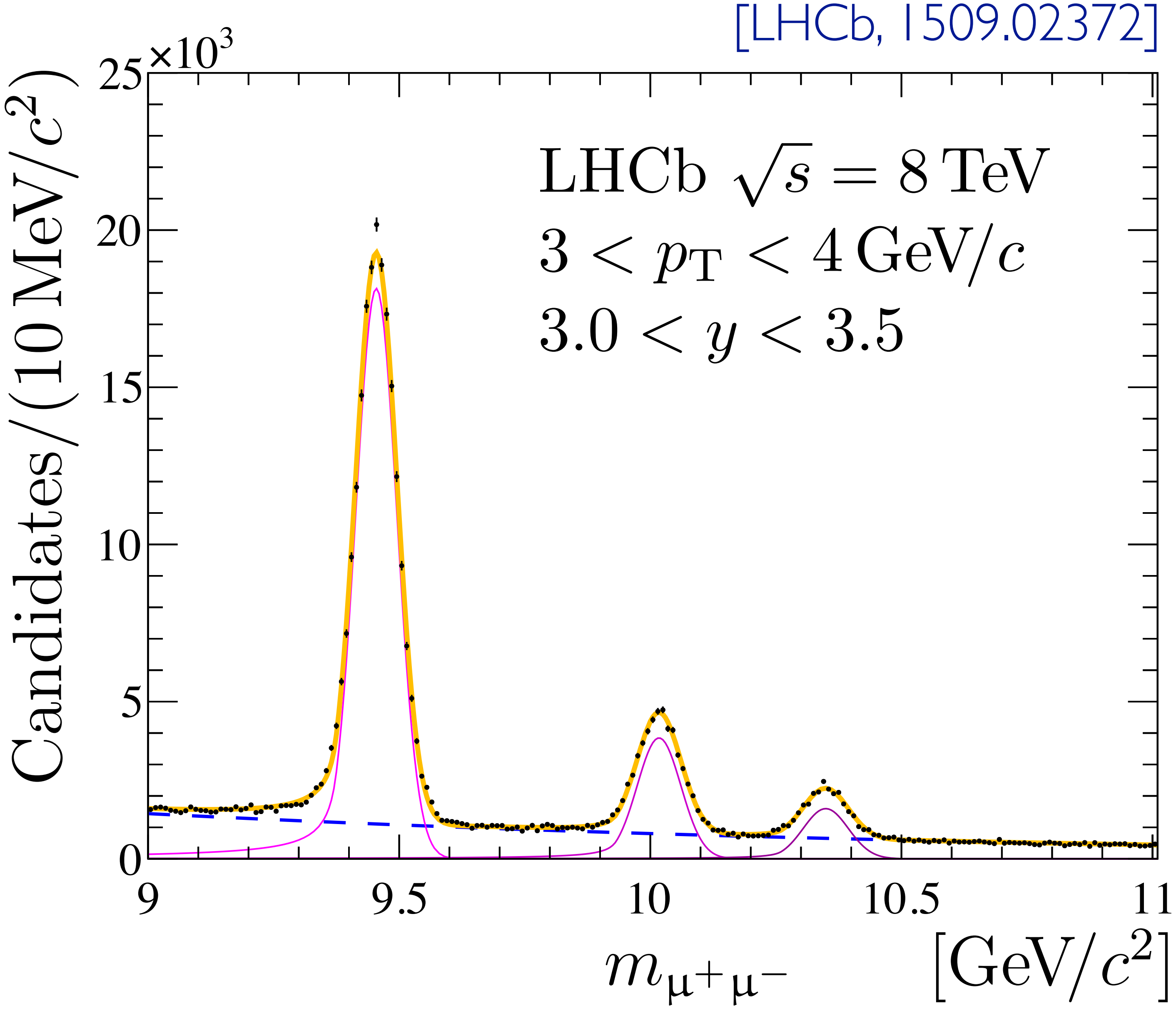


[Camalich & Jäger, 1412.3183]

Low-q^2 observables in $B \to K^* \mu^+ \mu^- / e^+ e^-$ over clean & orthogonal tests of C_7'. Together with $b \to s\gamma$ can probe full $C_7^{(\prime)}$ sector

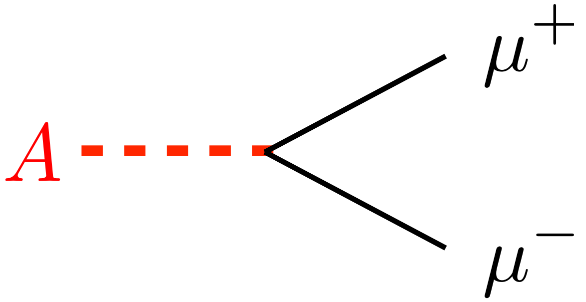
Υ production at LHCb

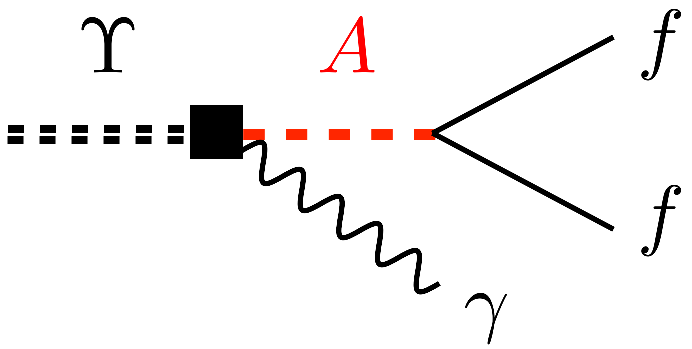
[LHCb, 1509.02372]



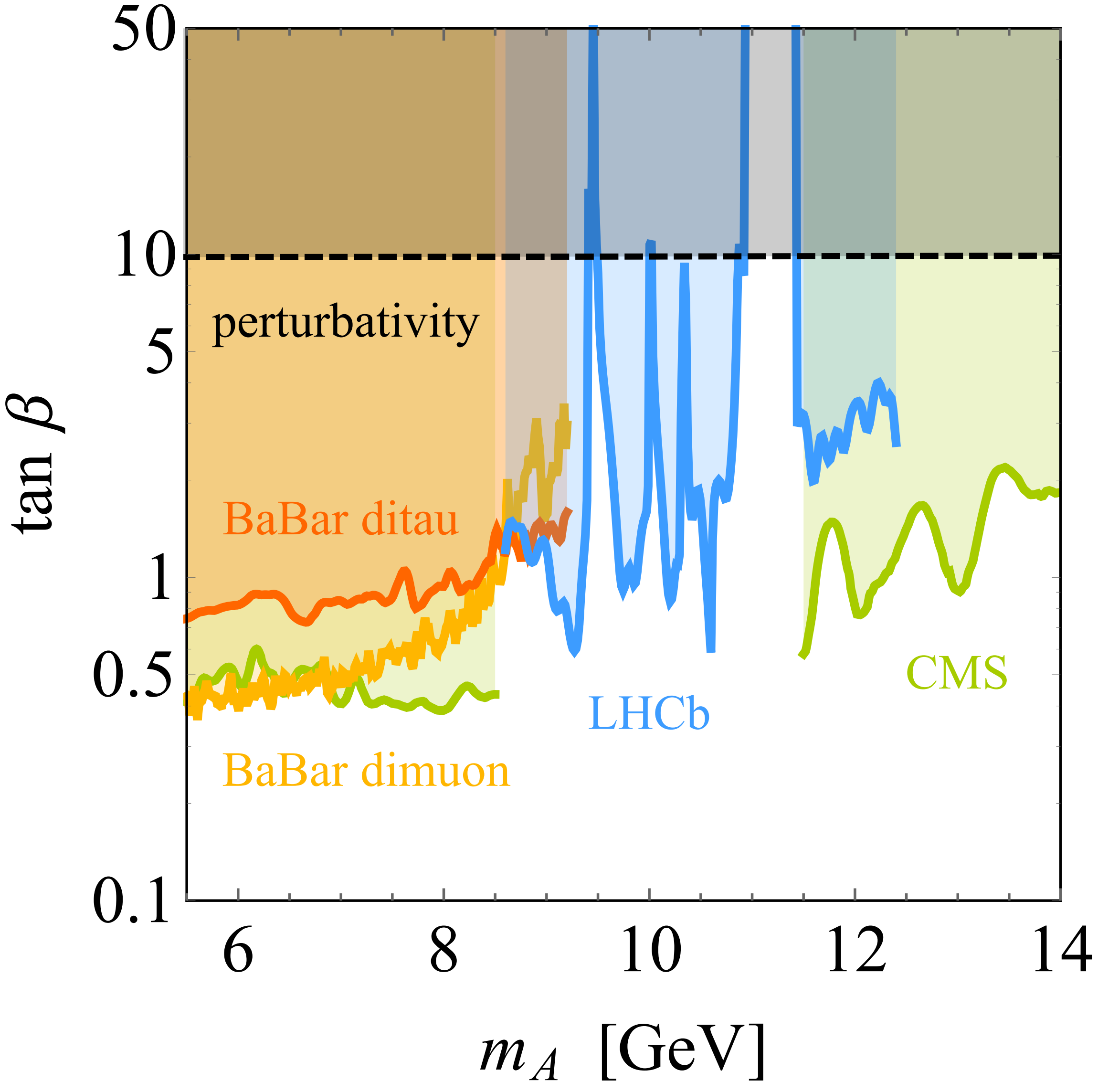
Precision measurement of dimuon spectrum for invariant masses in Υ region with only 3% of 8 TeV data set

Constraints on light pseudoscalars





[UH & Kamenik, 1601.05110]



Existing Υ data provides best bound on 2HDM-II for $m_A \in [8.6, 11]$ GeV.
With more data should be possible to improve & extend limits notably

[for other new-physics searches in dimuon sample see Patrick's talk & backup slides]

Constraining SM parameters

[http://pdg.lbl.gov/2015/reviews/rpp2015-rev-phys-constants.pdf]

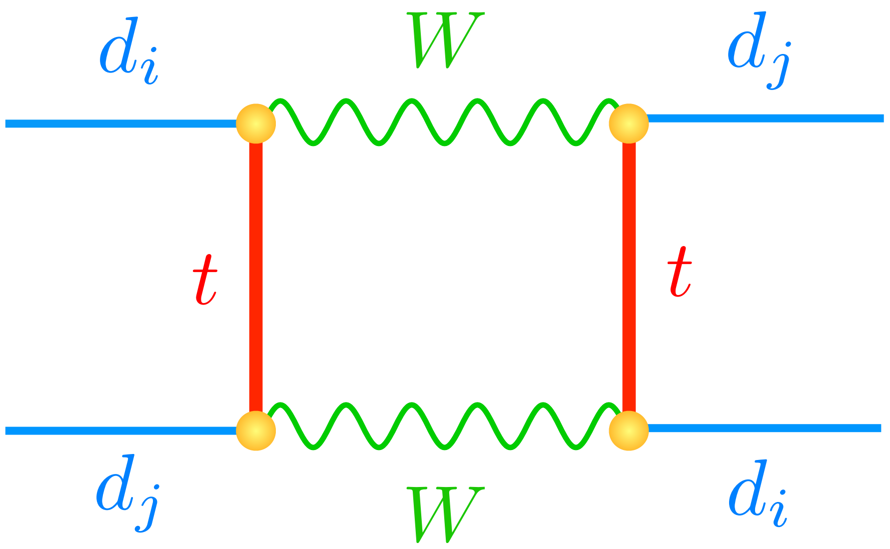
fine structure constant	$1/137.035999139(31)$	$0.23\,\mathrm{ppb}$
electron mass	$0.5109989461(31)\,\mathrm{MeV}$	$6.2\,\mathrm{ppb}$
Fermi constant	$1.1663787(6) \cdot 10^{-5}\,\mathrm{GeV}^{-2}$	$500\,\mathrm{ppb}$
W-boson mass	$80.385(15)\,\mathrm{GeV}$	0.2%
strong coupling constant	$0.1185(6)$	0.5%
top-quark mass	$173.21(87)\,\mathrm{GeV}$	0.5%

Flavour physics obviously allows to constrain CKM elements.
But what about other SM parameters like for instance α_s or m_t?

Boxes & Z penguins

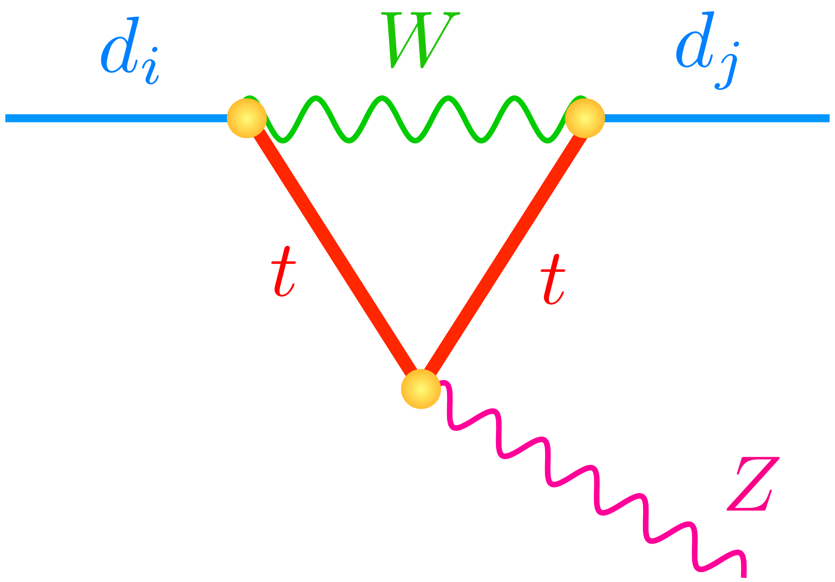
[see e.g. Buras, hep-ph/9806471]

Within SM, only two 1-loop topologies lead to a quadratic dependence on top mass



$$\Downarrow$$

$$\Delta m_K, \Delta m_{B_d}, \Delta m_{B_s}, \epsilon_K$$



$$\Downarrow$$

$$B_{d,s} \to \mu^+\mu^-, B \to K^{(*)}, X_s\mu^+\mu^-,$$
$$K \to \pi\nu\bar{\nu}, K \to \pi\mu^+\mu^-, \epsilon'/\epsilon, Z \to b\bar{b}$$

Top mass from $B_s \to \mu^+\mu^-$

$$\mathrm{Br}\left(B_s \to \mu^+\mu^-\right)_{\mathrm{SM}} = 3.65 \left(\frac{m_t^{\mathrm{pole}}}{173.1\,\mathrm{GeV}}\right)^{3.06} (1 \pm 3\%) \cdot 10^{-9}$$

$$\mathrm{Br}\left(B_s \to \mu^+\mu^-\right)_{\mathrm{exp}} = 3.65\,(1 \pm 4\%) \cdot 10^{-9}$$

[LHCb, 1208.3355]

$$\Downarrow$$

$$\boxed{m_t^{\mathrm{pole}} = (173.1 \pm 2.8)\,\mathrm{GeV}}$$

Indirect determination less stringent than direct measurements, but useful given theoretical ambiguities in extraction of m_t at colliders

[UH, Top at Twenty; Giudice et al., 1508.05332]

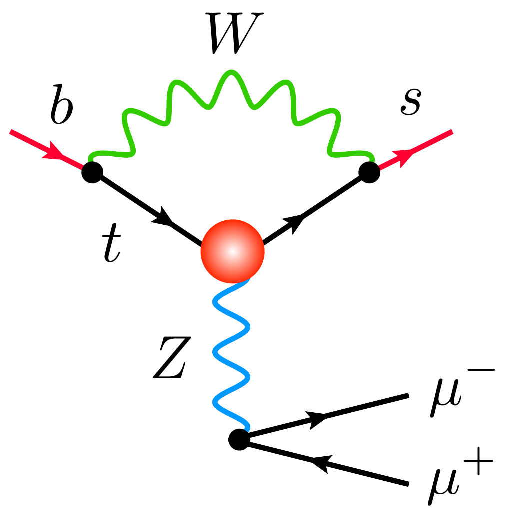
Constraining SM couplings

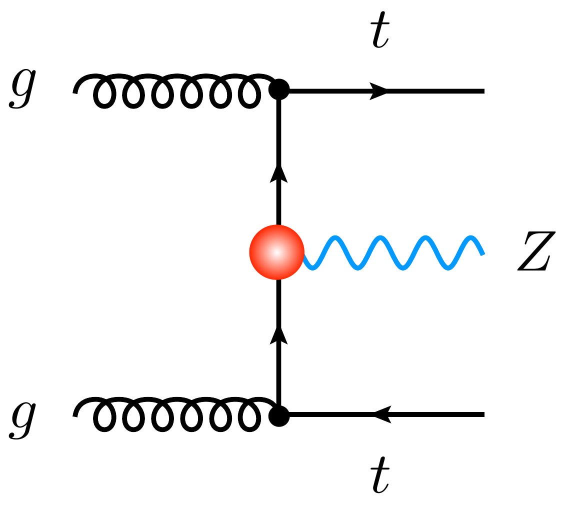
[LEPEWWG, hep-ex/0509008; CMS, 1303.3239; Falkowski et al., 1508.00581]

Ze^+e^- couplings	$(0.1\%)_L, (0.1\%)_R$
$Zc\bar{c}$ couplings	$(1.0\%)_L, (3.2\%)_R$
$Zb\bar{b}$ couplings	$(0.4\%)_L, (6.5\%)_R$
$Zt\bar{t}$ couplings	$> 100\%$
WWZ coupling	2.3%
$WW\gamma$ coupling	3.4%

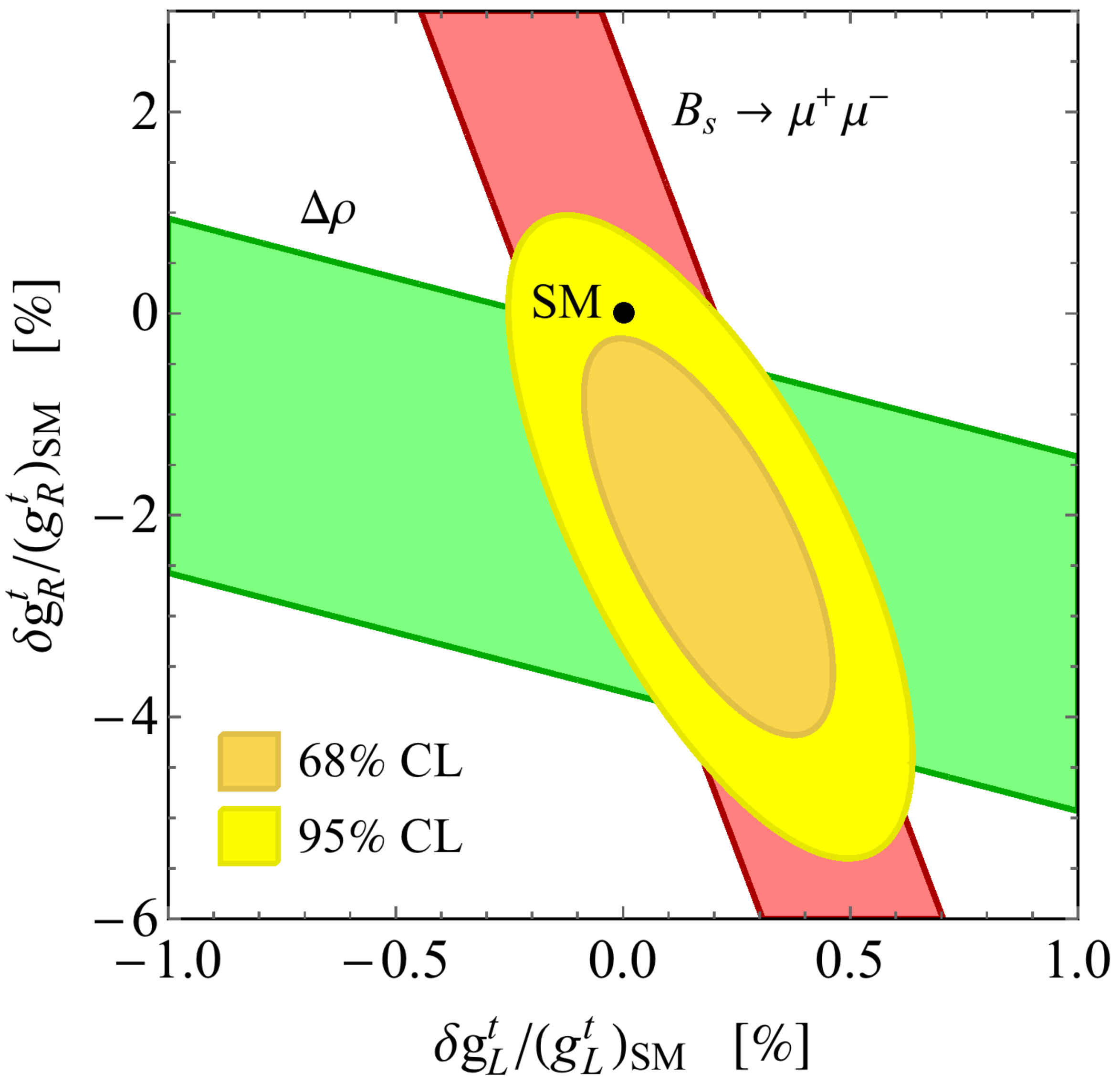
Only couplings of W- & Z-bosons to leptons known with a precision below 1%. Which accuracy can flavour precision measurements achieve?

$Zt\bar{t}$ couplings from $B_s \to \mu^+\mu^-$





[UH based on Brod et al., 1408.0792]

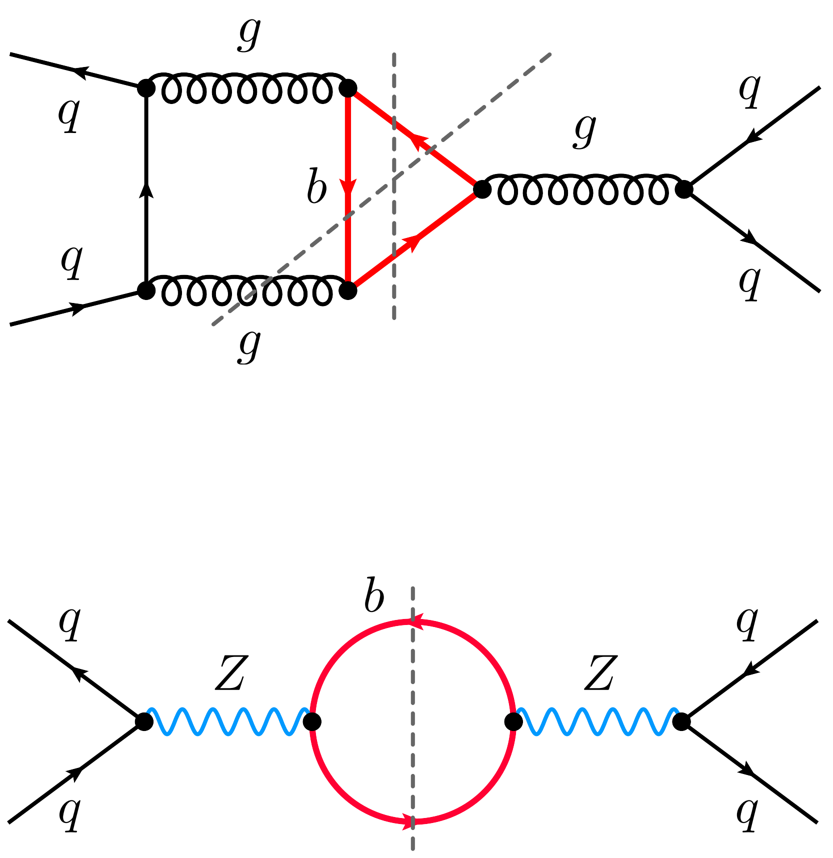


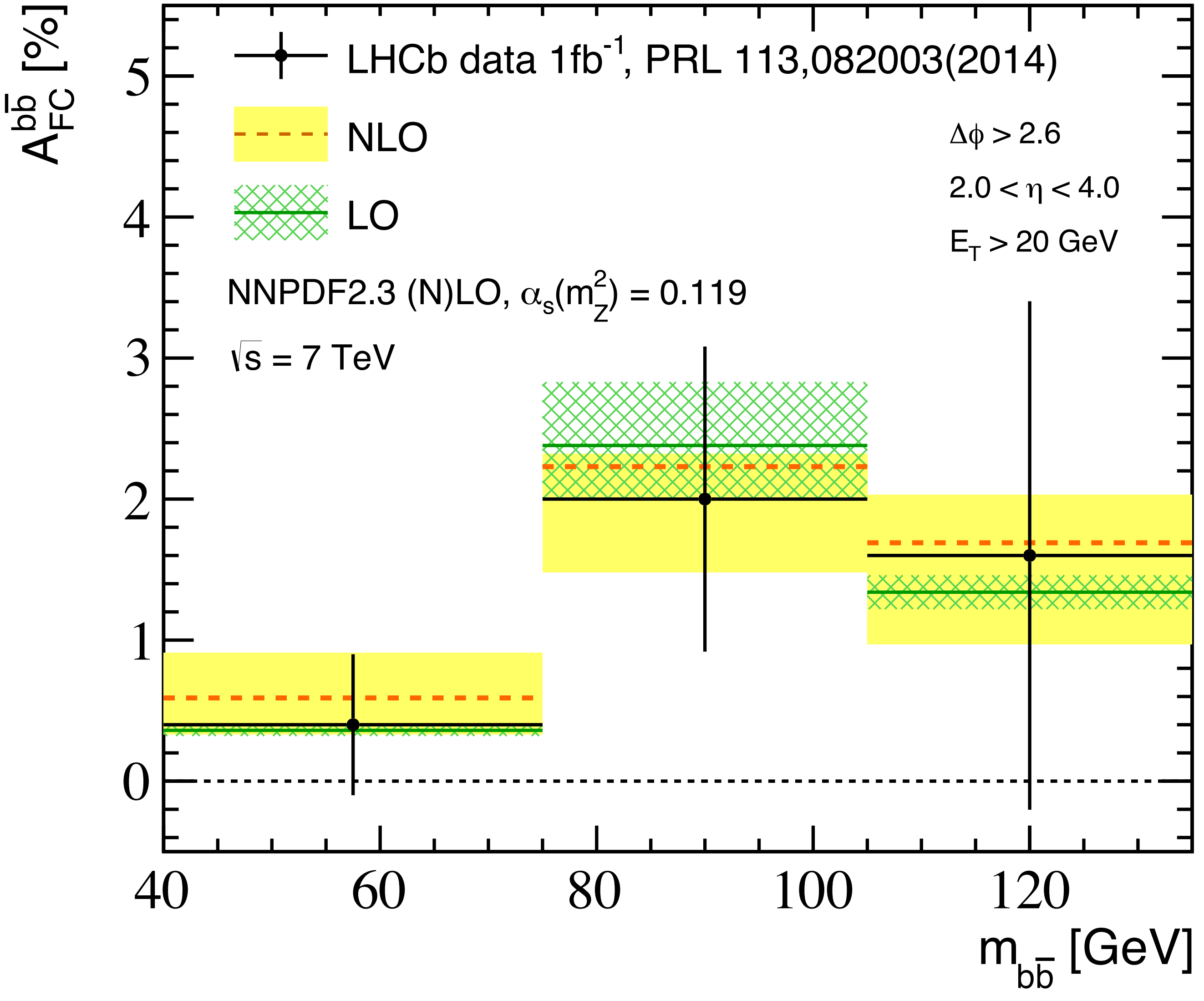
HL-LHC $B_s \to \mu^+\mu^-$ measurements have potential to constrain $Zt\bar{t}$ couplings at few % level. Direct measurements only able to reach O(30%) precision

[Röntsch & Schulze, 1404.1005]

$Zb\bar{b}$ couplings from $A_{FC}^{b\bar{b}}$ at LHCb

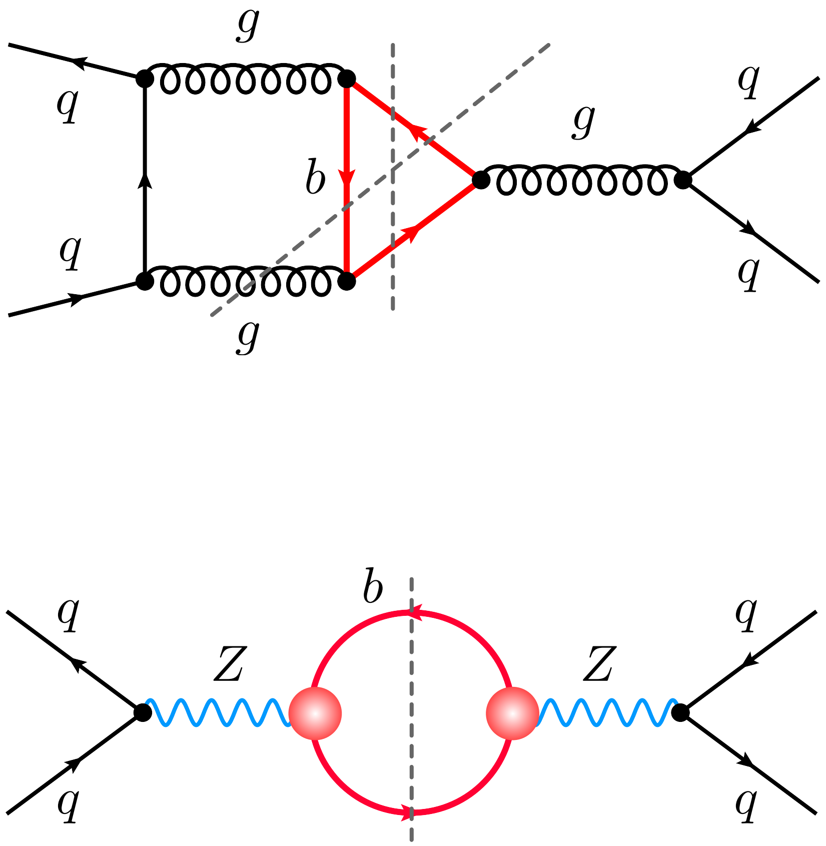
[Gauld et al., 1505.02429]



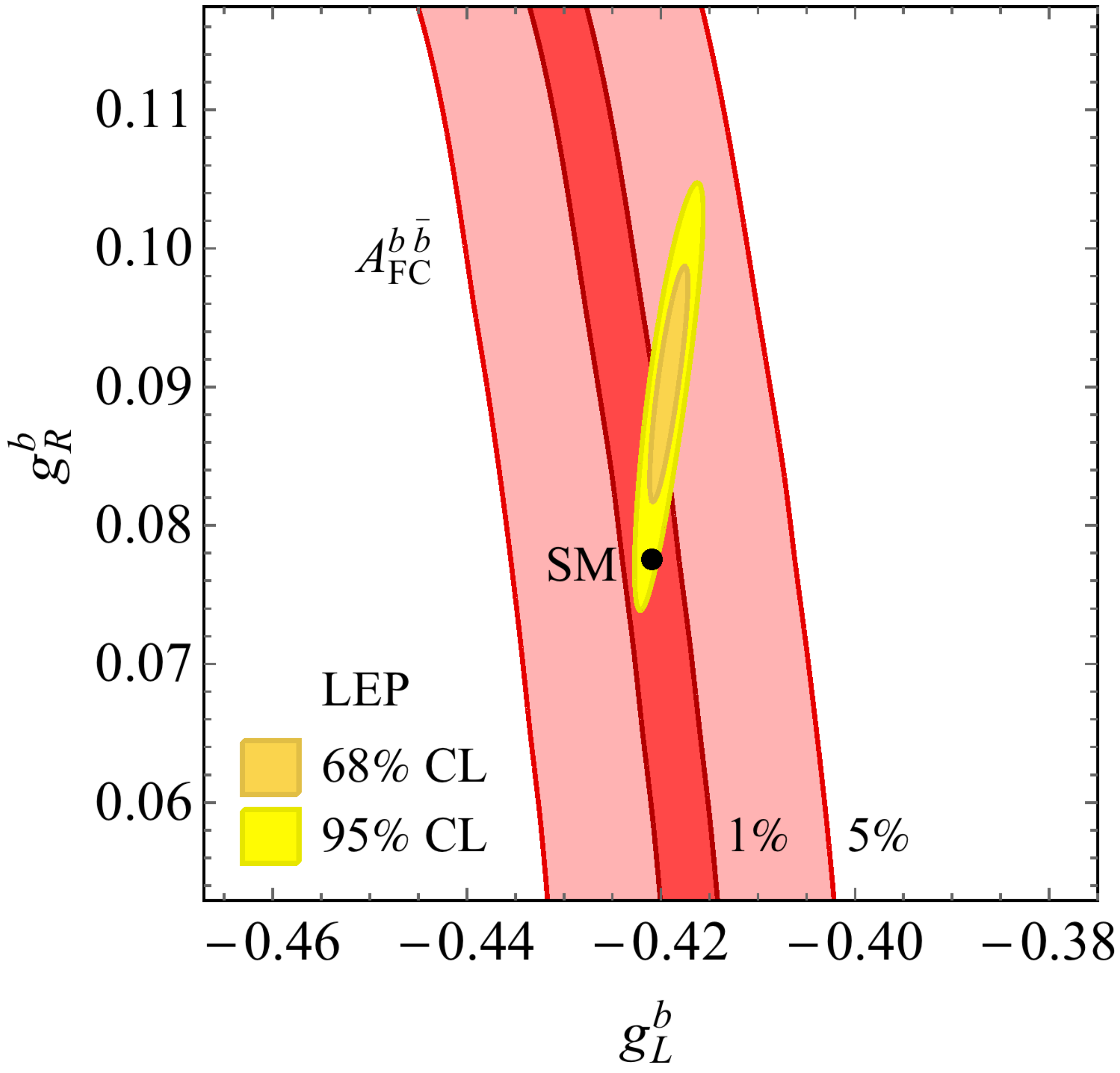


LHCb has measured forward-central $b\bar{b}$ asymmetry with O(50%) precision using 1 fb^{-1} of 7 TeV data, while SM prediction has uncertainty of O(15%)

Z$b\bar{b}$ couplings from $A_{FC}^{b\bar{b}}$ at LHCb

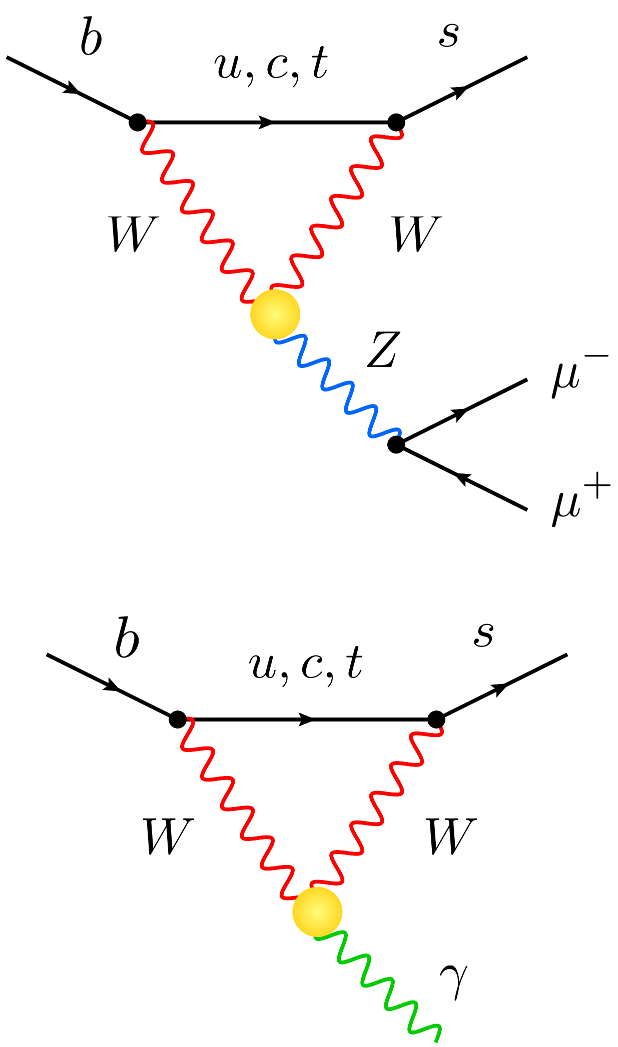


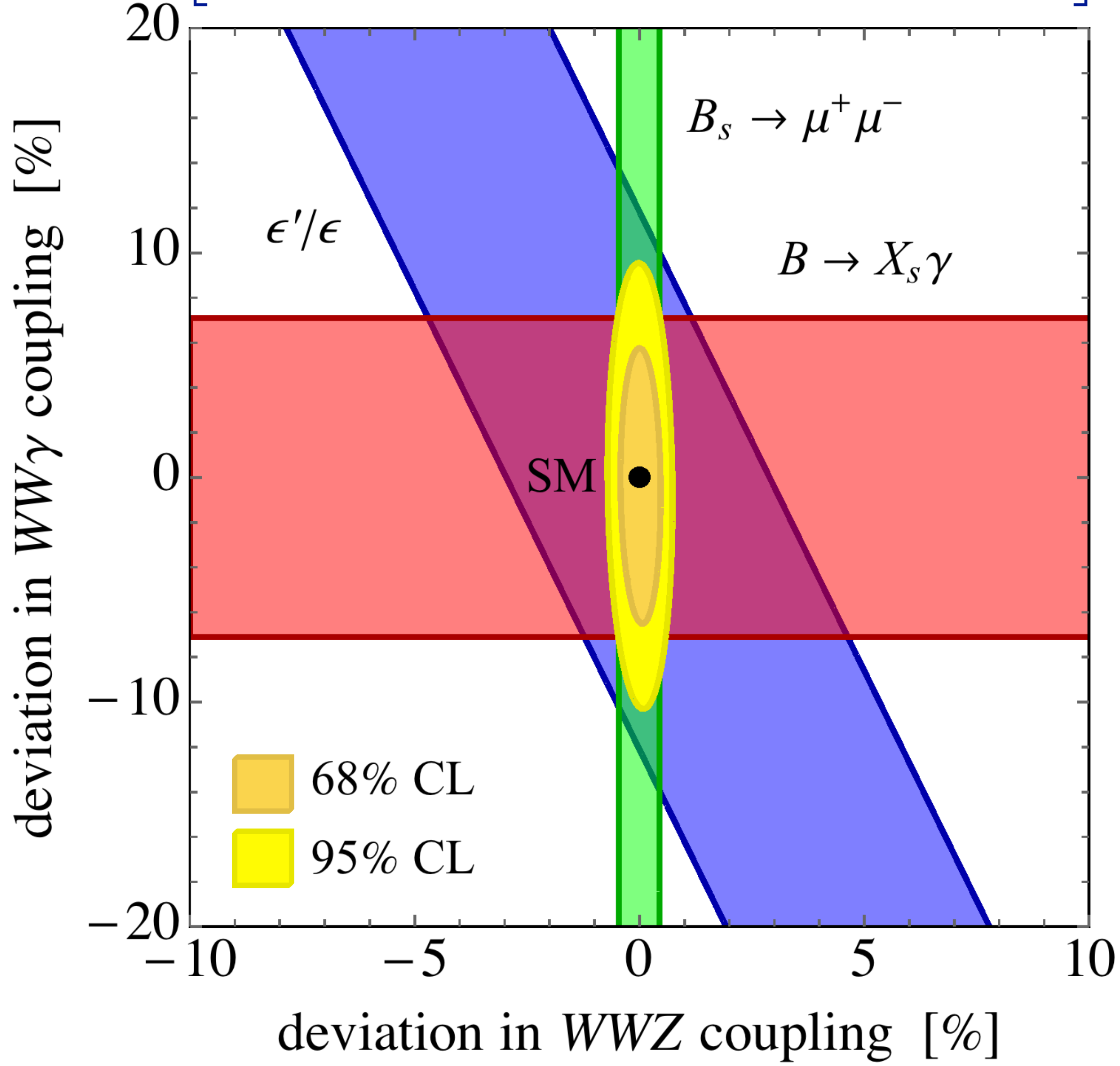
[UH with help from Gauld]



To reach LEP sensitivity need to achieve total relative error on forward-central $b\bar{b}$ asymmetry at % level. A challenge for both LHCb & theory

WWZ/γ couplings from flavour




[Based on Bobeth & UH, 1503.04829]

As deviations in WWZ coupling logarithmically enhanced in $B_s \to \mu^+\mu^-$ may get O(1%) precision at HL-LHC. Only O(10%) sensitivity in case of WWγ

Conclusions

- To shed further light on existing flavour anomalies one needs measurements with higher statistics. LHC upgrade is able to deliver such precision measurements, which can lead to important interplay & complementarity with ATLAS, CMS, Belle II, NA62, etc.

[see Jernej's talk]

- Anomalies could be due to new flavour dynamics at relatively low scale & in such a case one can learn a lot about it at HL-LHC. Conversely if deviations disappear, LHC upgrade will significantly push up effective scale of flavour violation

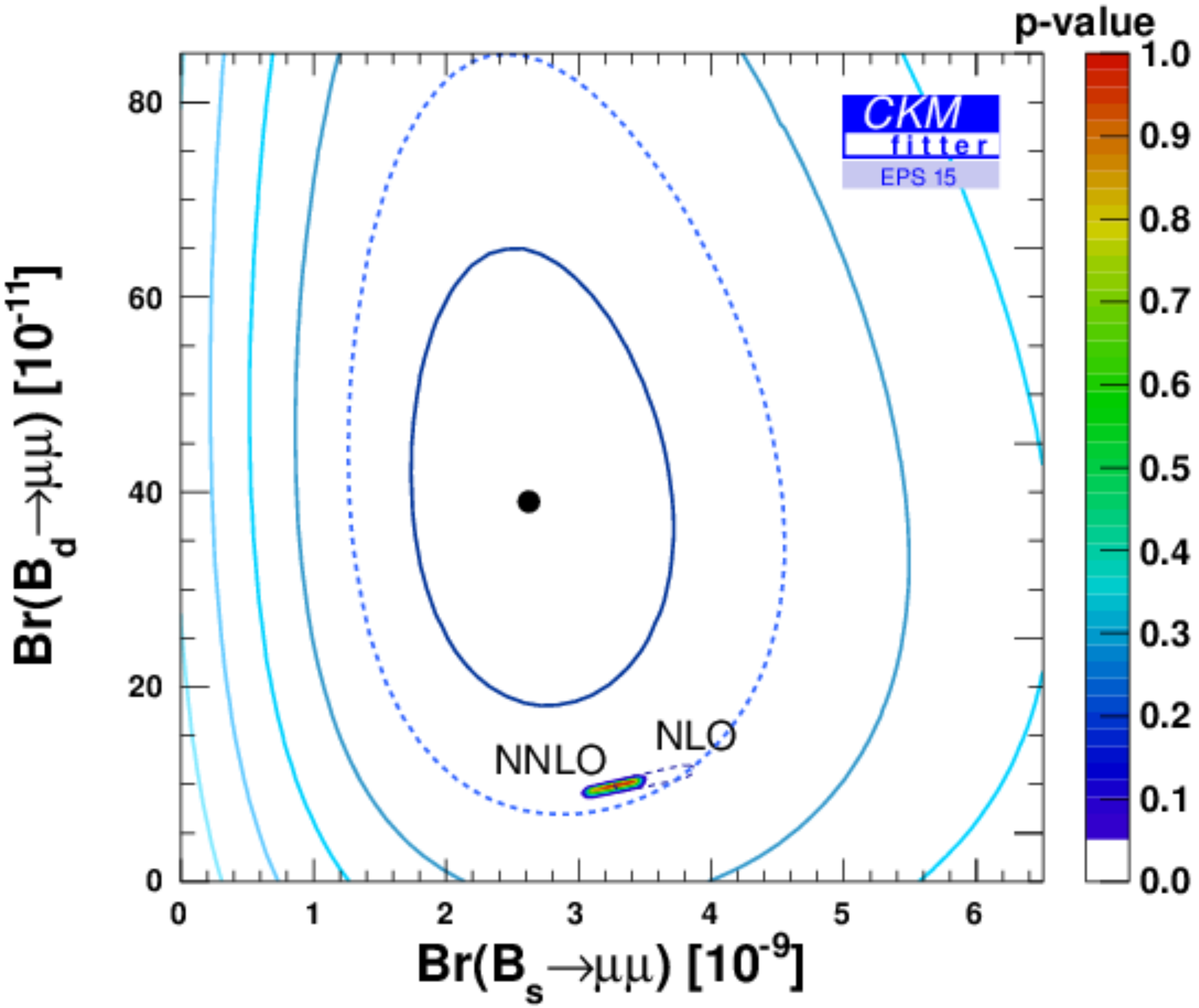
Backup

Future of lattice calculations

[Blum et al., http://www.usqcd.org/documents/13flavor.pdf]

Quantity	CKM element	Present expt. error	2007 forecast lattice error	Present lattice error	2018 lattice error
f_K/f_π	$\lvert V_{us}\rvert$	0.2%	0.5%	0.5%	0.15%
$f_+^{K\pi}(0)$	$\lvert V_{us}\rvert$	0.2%	–	0.5%	0.2%
f_D	$\lvert V_{cd}\rvert$	4.3%	5%	2%	$< 1\%$
f_{D_s}	$\lvert V_{cs}\rvert$	2.1%	5%	2%	$< 1\%$
$D \to \pi\ell\nu$	$\lvert V_{cd}\rvert$	2.6%	–	4.4%	2%
$D \to K\ell\nu$	$\lvert V_{cs}\rvert$	1.1%	–	2.5%	1%
$B \to D^*\ell\nu$	$\lvert V_{cb}\rvert$	1.3%	–	1.8%	$< 1\%$
$B \to \pi\ell\nu$	$\lvert V_{ub}\rvert$	4.1%	–	8.7%	2%
f_B	$\lvert V_{ub}\rvert$	9%	–	2.5%	$< 1\%$
ξ	$\lvert V_{ts}/V_{td}\rvert$	0.4%	2-4%	4%	$< 1\%$
ΔM_s	$\lvert V_{ts}V_{tb}\rvert^2$	0.24%	7–12%	11%	5%
B_K	$\mathrm{Im}(V_{td}^2)$	0.5%	3.5–6%	1.3%	$< 1\%$

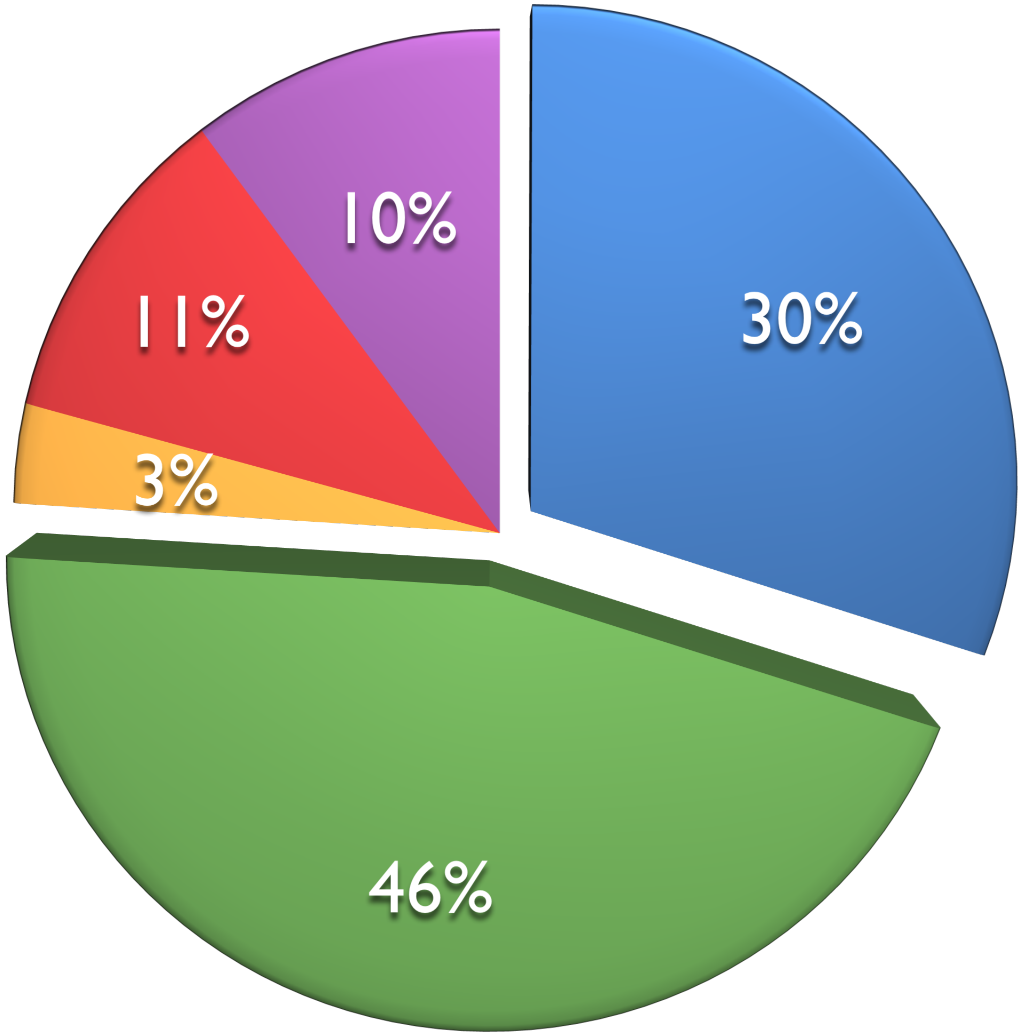
Impact of theory improvement



NNLO QCD & NLO EW effects in $B_{s,d} \to \mu^+\mu^-$ phenomenologically relevant

[Bobeth et al., 1311.0903, 1311.1348; Hermann et al., 1311.1347]

$B_d \to \mu^+\mu^-$: current SM errors



8.5% total uncertainty

● f_{B_d} ● CKM

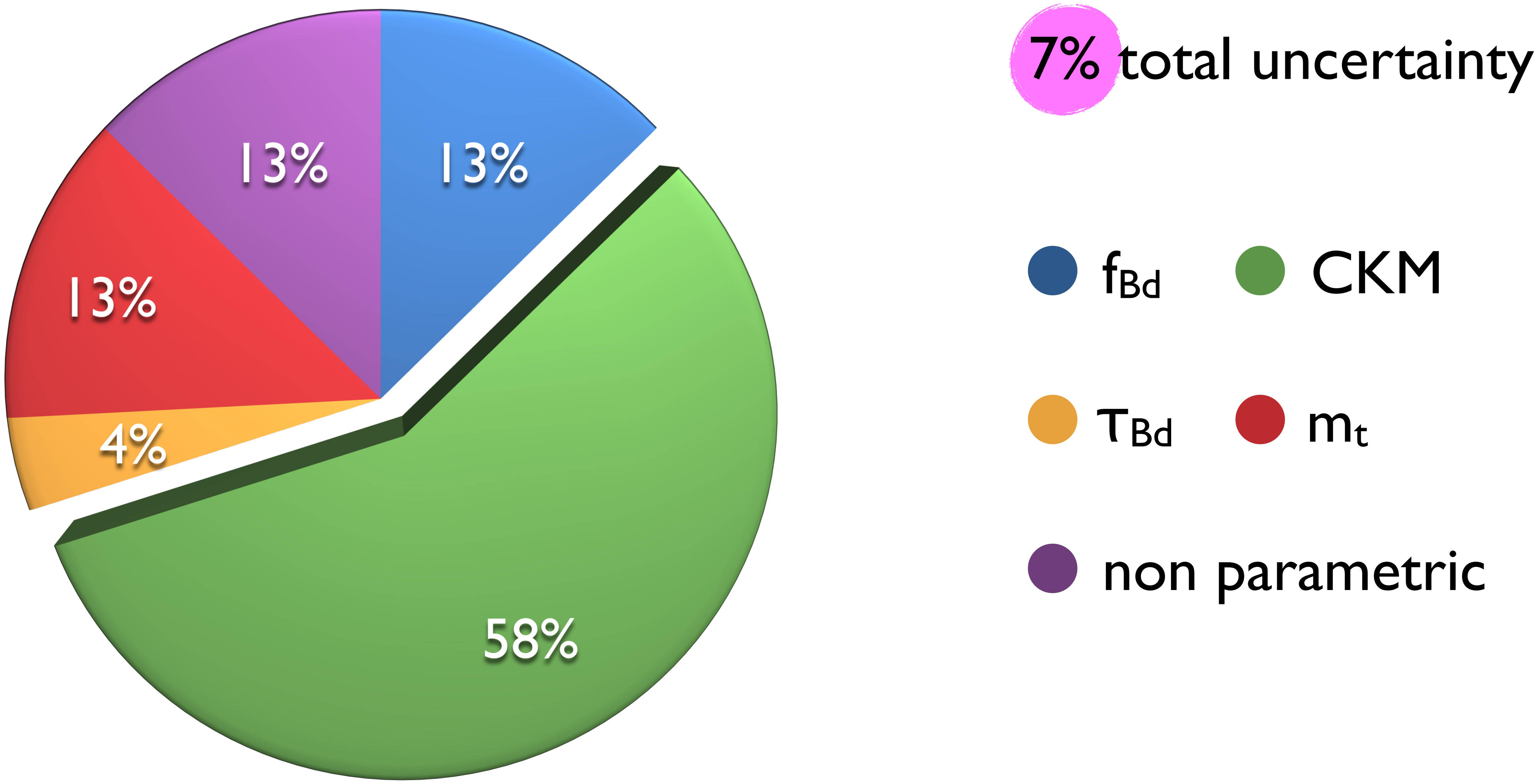
● τ_{B_d} ● m_t

● non parametric

Calculation of 3-loop QCD & 2-loop EW effects reduces perturbative uncertainties to 0.5%. Relative errors due to f_{B_d} & CKM are 4.5% & 6.9%

[Bobeth et al., 1311.0903, 1311.1348; Hermann et al.,1311.1347]

$B_d \to \mu^+\mu^-$: future SM errors



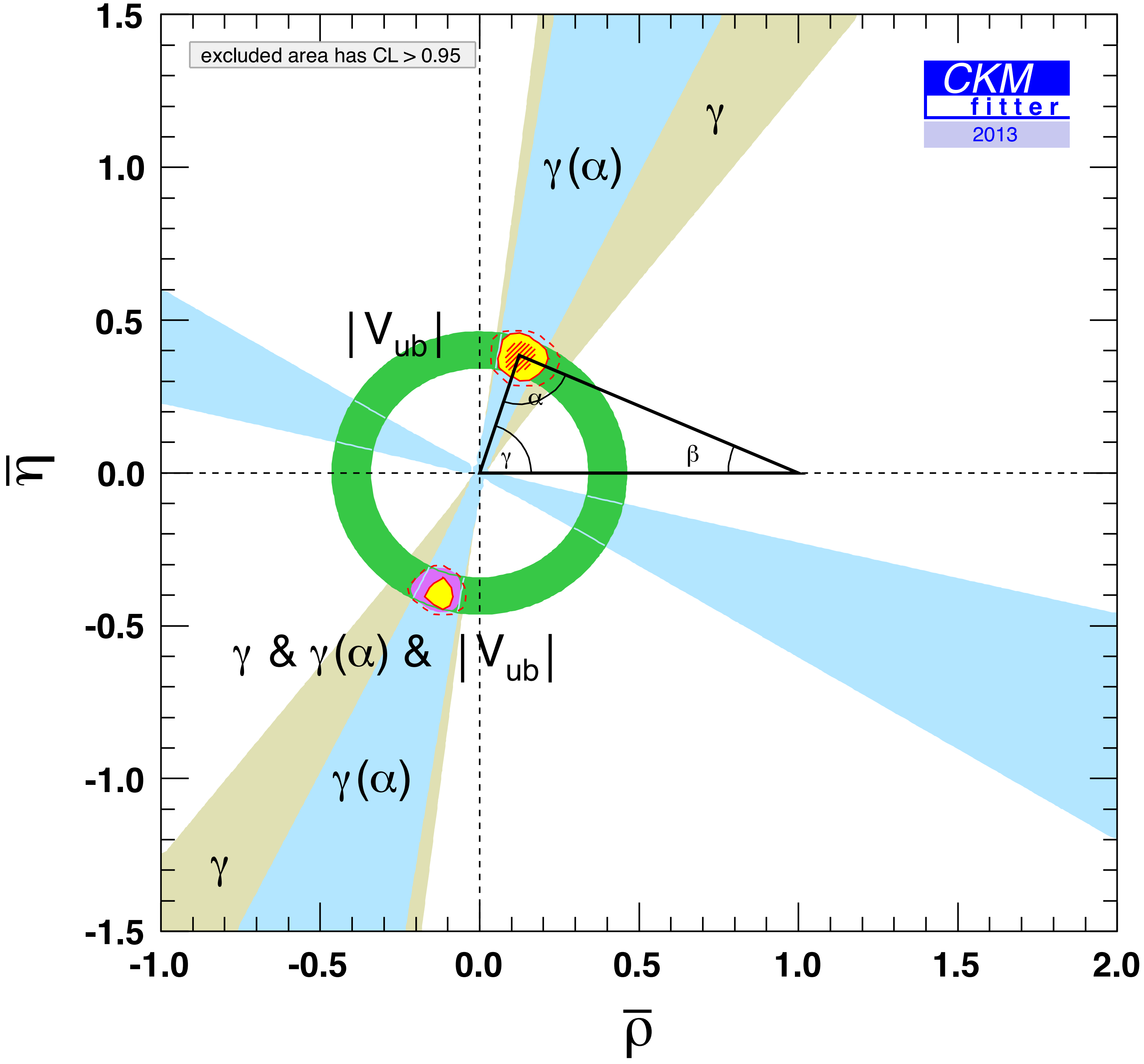
7% total uncertainty

Improvements in lattice QCD calculations may reduce errors due to f_{Bd} leading to a future total uncertainty of 7%

[Blum et al., http://www.usqcd.org/documents/13flavor.pdf]

CKM fit in 2013

[Charles et al., 1309.2293]

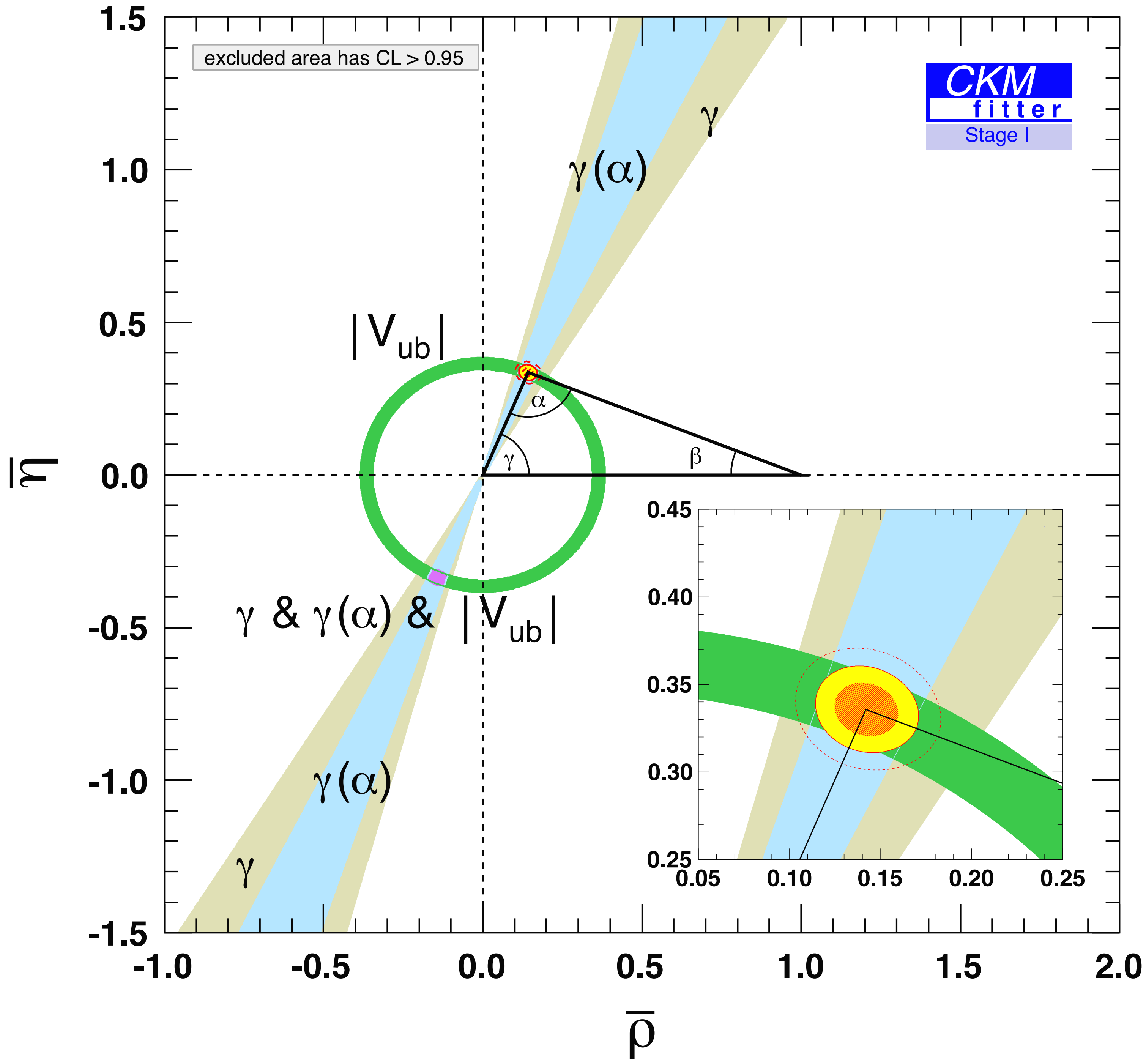


CKM fit in few years

Stage I:

- 7 fb^{-1} of LHCb data
- 5 ab^{-1} of Belle II data
- $\delta f_{B_q} = O(1\%)$,
  $\delta V_{ub} = O(2\%)$

[Charles et al., 1309.2293]



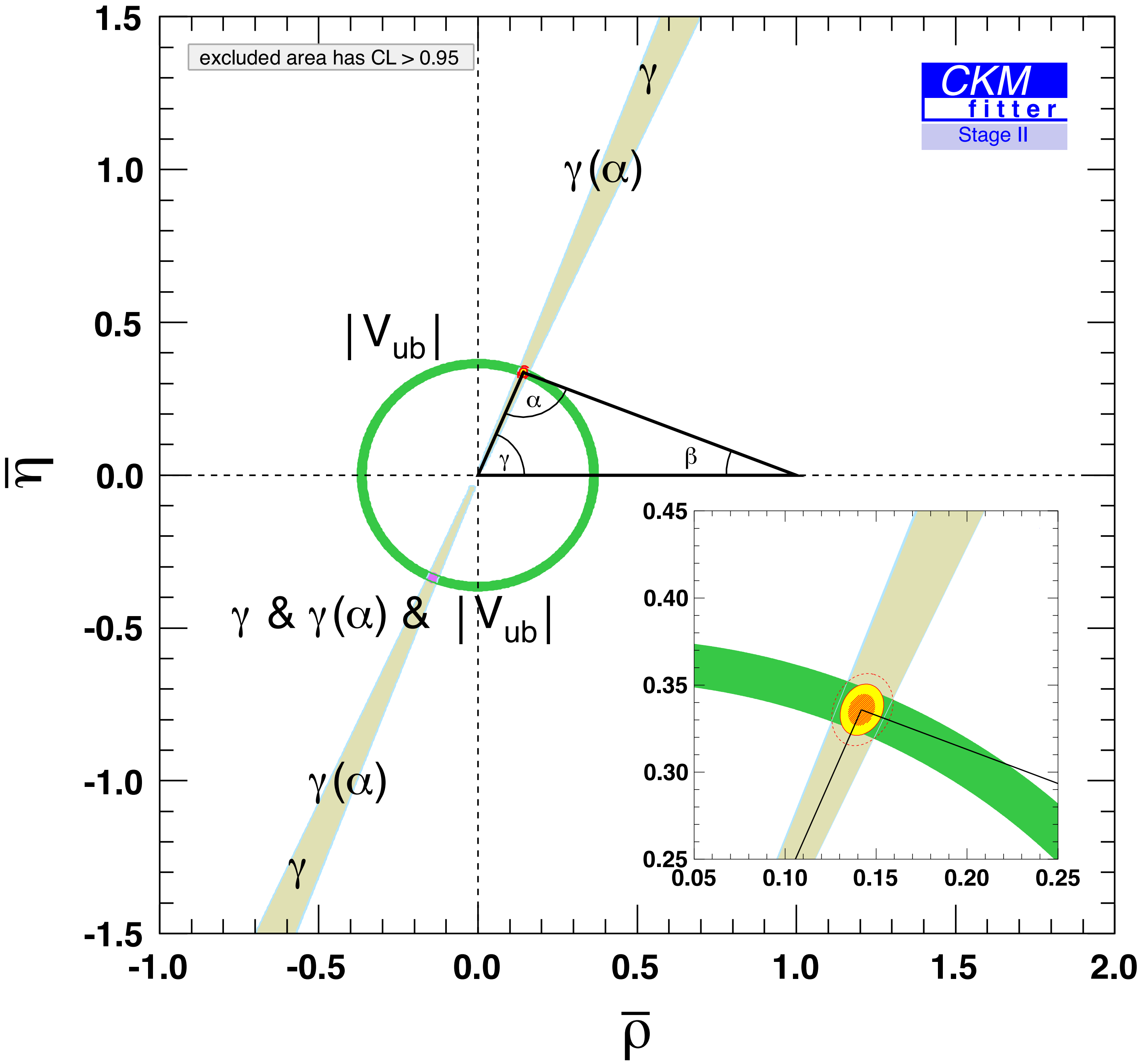
Lattice QCD improvements crucial to obtain such tight constraints

CKM fit in 10 years

[Charles et al., 1309.2293]

Stage II:

- 50 fb^{-1} of LHCb data
- 50 ab^{-1} of Belle II data
- $\delta f_{B_q} = O(1\%)$,
  $\delta V_{ub} = O(2\%)$



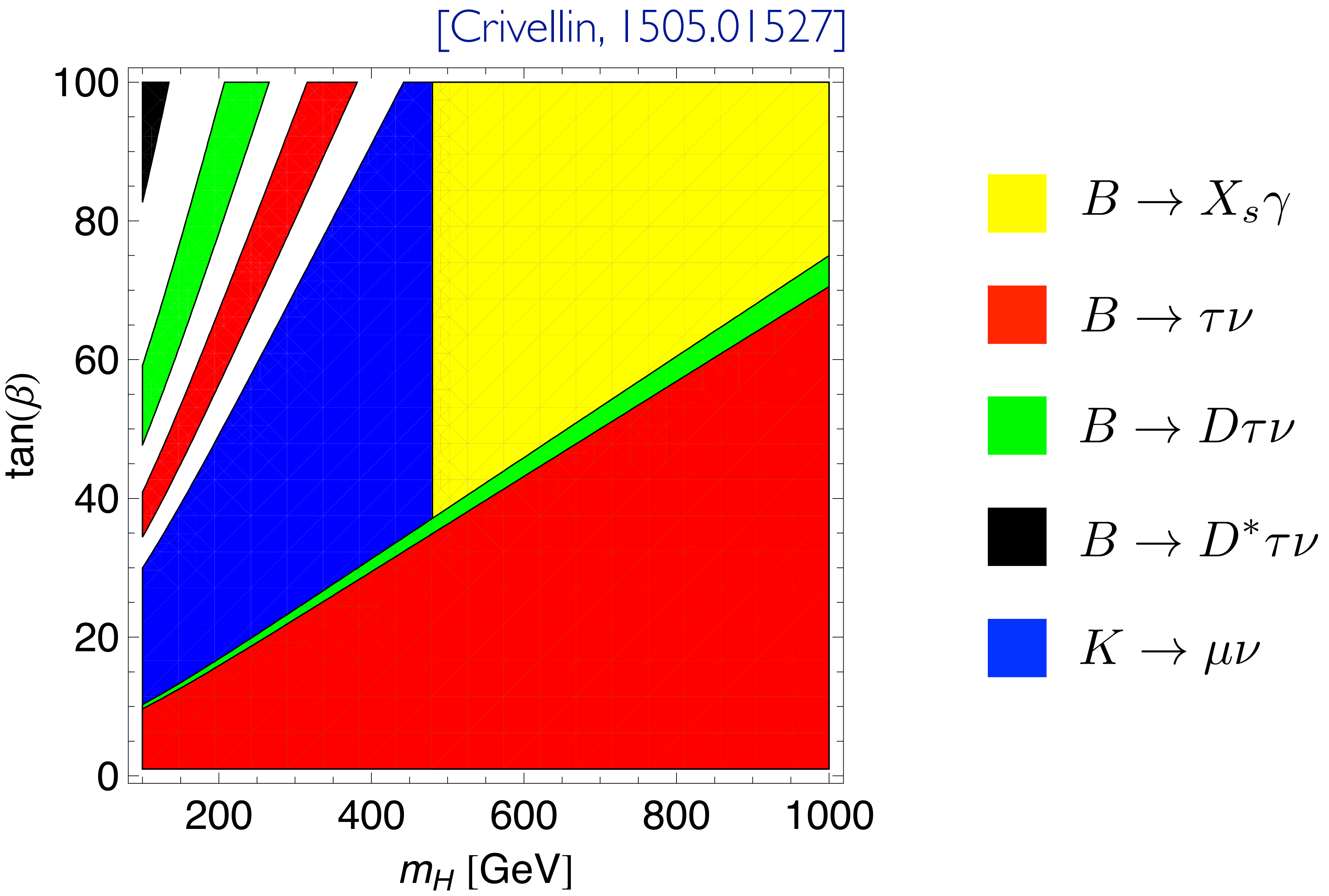
Lattice QCD improvements crucial to obtain such tight constraints

New-physics reach in B mixing

[Charles et al., 1309.2293]

Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	Scales (in TeV) probed by B_s mixing
$\|C_{ij}\| = \|V_{ti}V_{tj}^*\|$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\|C_{ij}\| = 1$ (no hierarchy)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40

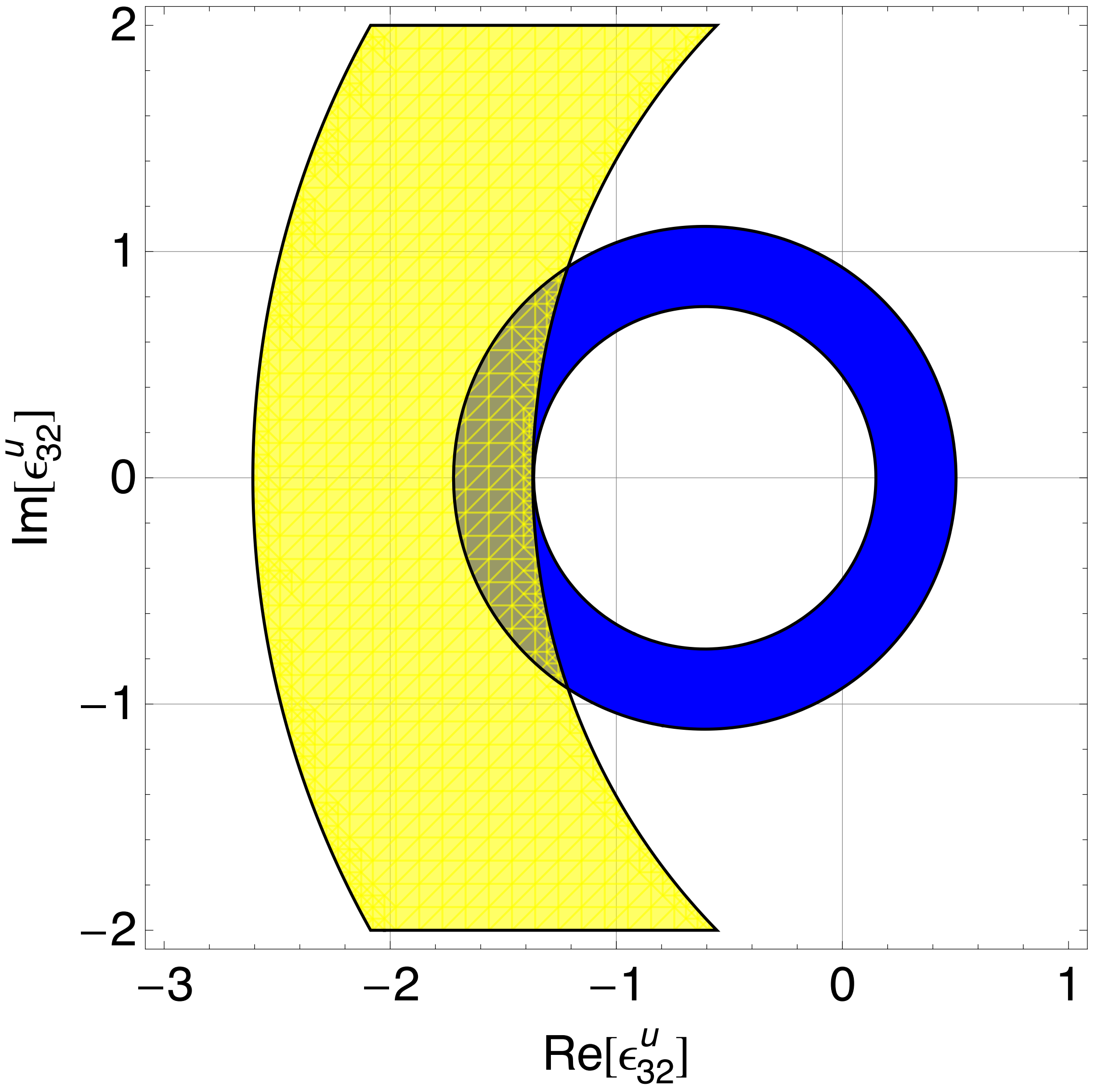
Flavour constraints on 2HDM-II



Explaining B → $D^*\tau\nu$ would require very small m_H & large tanβ.
No region in parameter space compatible with all measurements

B → D$^{(*)}$τν in 2HDM-III

[Crivellin, 1505.01527]



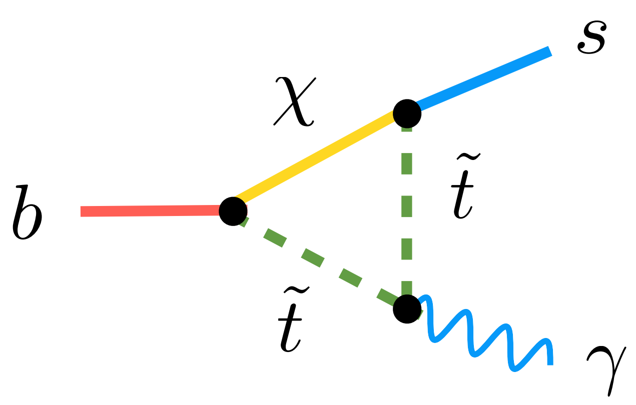
🟦 $$R(D) = \frac{\mathrm{Br}\,(B \to D\tau\nu)}{\mathrm{Br}\,(B \to D\ell\nu)}$$

🟨 $$R(D^*) = \frac{\mathrm{Br}\,(B \to D^*\tau\nu)}{\mathrm{Br}\,(B \to D^*\ell\nu)}$$

$$m_H = 800\,\mathrm{GeV},\ \tan\beta = 40$$

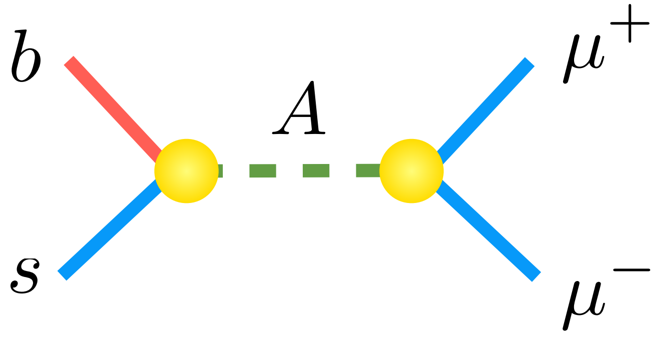
Deviations in B → Dτν & B → D*τν can be explained, using coupling ε^u_{32} of left-handed top to right-handed charm quarks

MSSM: indirect probes



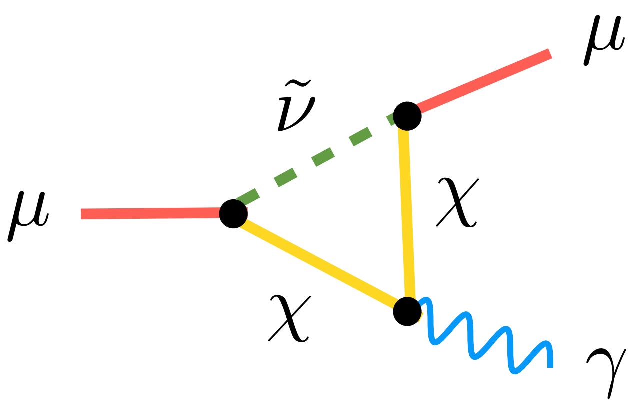
➡

$$\Delta C_7^{\chi} \propto -\mu A_t \, t_\beta \, \frac{m_t^2}{m_{\tilde{t}}^4}$$



➡

$$C_S \approx -C_P \propto \mu A_t \, t_\beta^3 \, \frac{m_t^2}{m_{\tilde{t}}^2} \, \frac{m_b m_\mu}{M_W^2 M_A^2}$$



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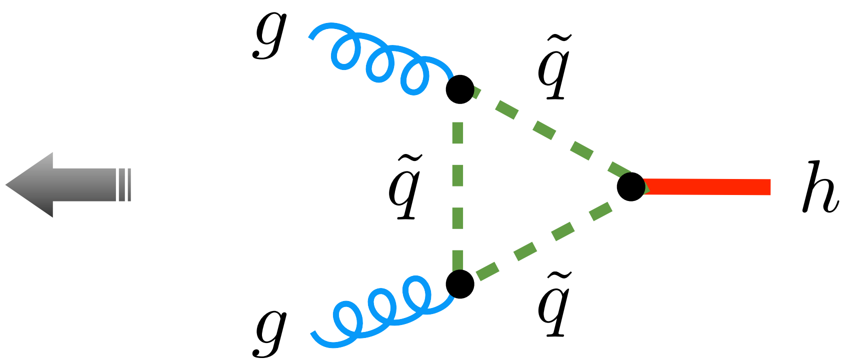
$$\Delta a_\mu^{\chi} \propto \frac{G_F M_W^2}{\sqrt{2}\pi^2} \, \mu M_2 \, t_\beta \, \frac{m_\mu^2}{m_{\tilde{\nu}}^4}$$

MSSM: Higgs properties

$$(\Delta M_h^2)_{\tilde{t}} \approx \frac{3G_F}{\sqrt{2}\pi^2}\, m_t^4 \left[-\ln\left(\frac{m_t^2}{m_{\tilde{t}}^2}\right) + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

$$\kappa_{\tilde{q}} \approx \frac{1}{4}\, m_q^2 \,\frac{\partial}{\partial m_q^2}\, \ln\left[\det\left(\mathcal{M}_{\tilde{q}}^2\right)\right]$$



$$\approx \begin{cases} \dfrac{m_t^2}{4}\left(\dfrac{1}{m_{\tilde{t}_1}^2} + \dfrac{1}{m_{\tilde{t}_2}^2} - \dfrac{X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right), & \tilde{q} = \tilde{t} \\ -\dfrac{m_b^2 X_b^2}{4 m_{\tilde{b}_1}^2 m_{\tilde{b}_2}^2}, & \tilde{q} = \tilde{b} \end{cases}$$

$B_s \to \mu^+\mu^-$ in MSSM

$$R_{\mu^+\mu^-} = \frac{\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{MSSM}}}{\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} \simeq 1 - 13.2\, C_P + 43.6\left(C_S^2 + C_P^2\right)$$

$$C_S \simeq -C_P$$

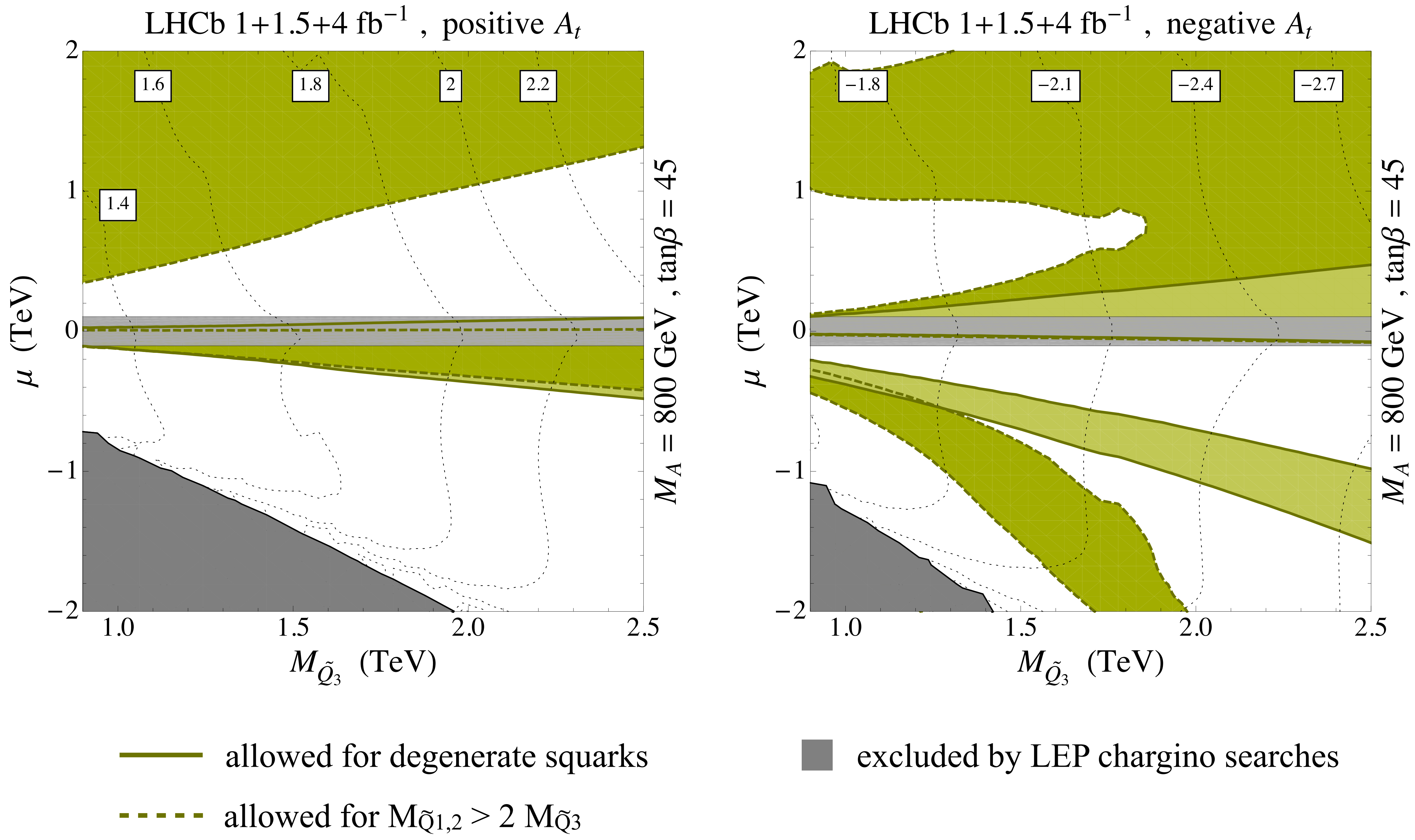
$$\frac{dR_{\mu^+\mu^-}}{dC_P} = -13.2 + 174.4\, C_P = 0 \qquad \Longrightarrow \qquad C_P \simeq 0.076$$

$$\Downarrow$$

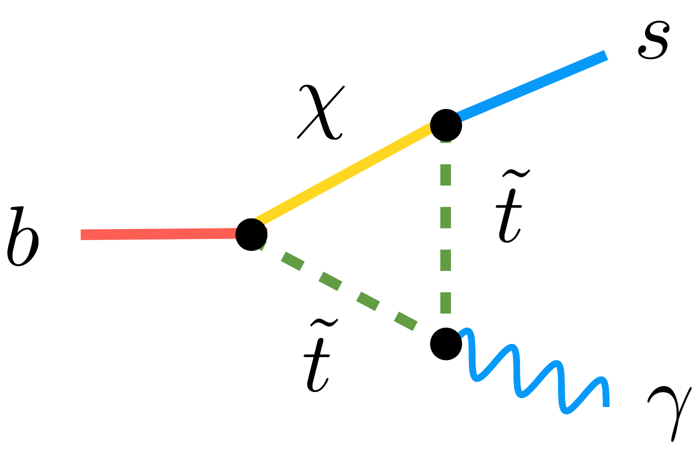
$$(R_{\mu^+\mu^-})_{\mathrm{min}} \simeq 0.5$$

Probing μ & $M_{\tilde{Q}3}$ with $B_s \to \mu^+\mu^-$

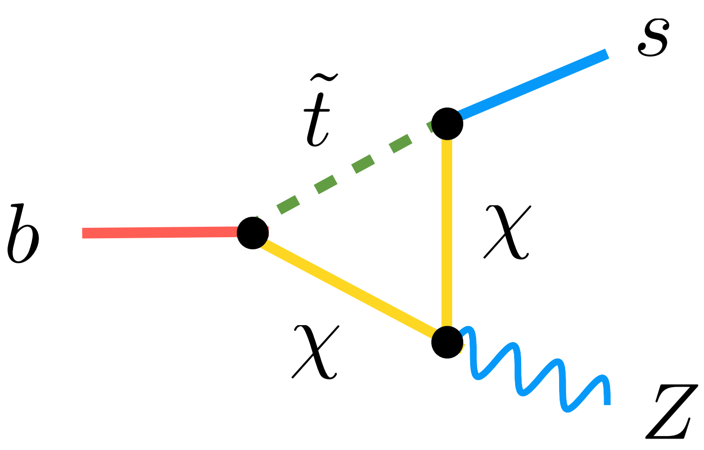
[Altmannshofer et al., 1211.1976]



Stop sector probes

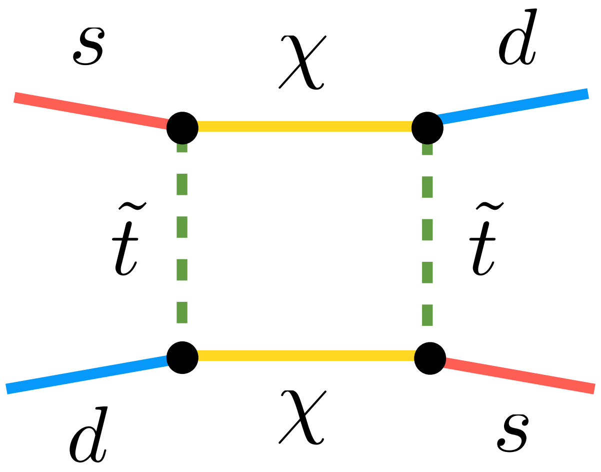


$$\Delta C_7^{\chi} \approx \frac{5}{288}\,\frac{m_t^2}{m_{\tilde{t}_1}^2} - \frac{2}{9}\,t_\beta\, s_{\tilde{t}}\,\frac{\mu m_t}{m_{\tilde{t}_1}^2}$$

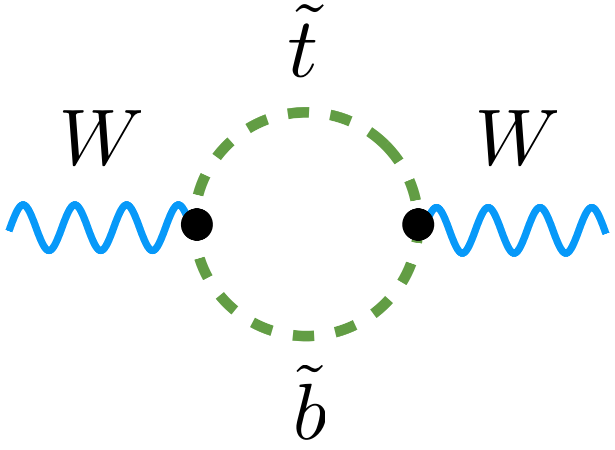


$$\frac{\Delta C}{C_{\mathrm{SM}}} \approx \frac{m_t^2 X_t^2}{12\, s_\beta^2\, m_{\tilde{t}_1}^4}$$

Stop sector probes



$$\frac{\epsilon_K}{(\epsilon_K)_{\rm SM}} \approx 1 + 0.16\,\frac{m_t^2}{m_{\tilde t_1}^2}$$



$$\Delta\rho \approx \frac{G_F}{24\sqrt{2}\pi^2}\,\frac{m_t^4}{m_{\tilde t_1}^2}\left(1 - s_{\tilde t}^2\,\frac{\delta m_{\tilde t}^2}{m_{\tilde t_1}^2}\right)$$

Indirect bounds on stop sector

$$t_\beta = 10$$

$$\mu = 0.2\,\text{TeV}$$

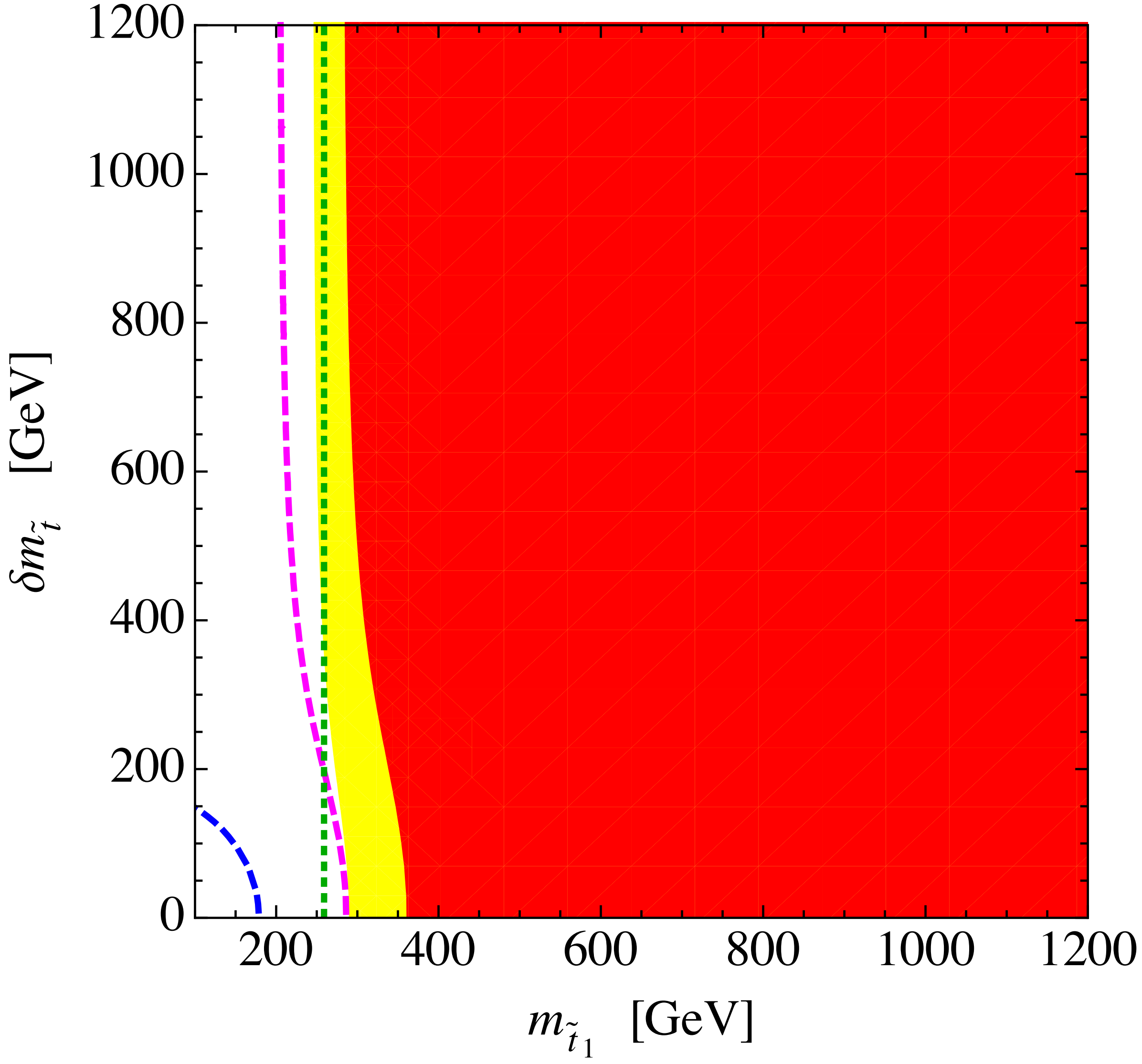
$$\theta_{\tilde{t}} = 0$$

🟨 95% CL 🟥 68% CL

- - - B → $X_s\gamma$

· · · W-boson mass

- - - Higgs signal strengths



[Altmannshofer & UH, unpublished]

Depending on choice of parameters in stop sector, combination of indirect measurements can provide limits on mass of lightest stop eigenstate of around 300 GeV

Indirect bounds on stop sector

$t_\beta = 10$

$\mu = 0.2\,\mathrm{TeV}$

$\theta_{\tilde{t}} = \pi/4$

🟨 95% CL 🟥 68% CL

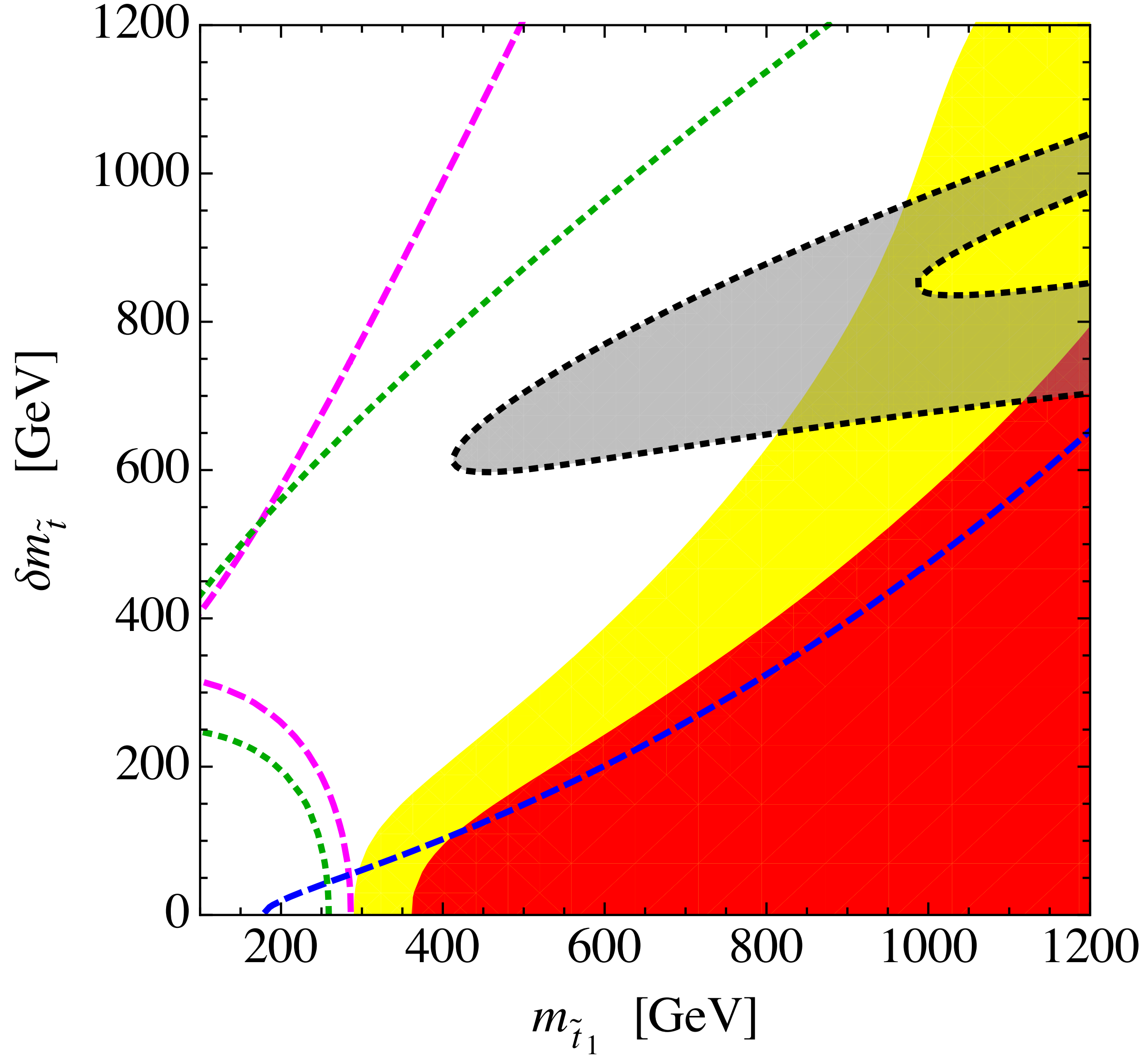
╌ B → $X_s\gamma$

⋯ W-boson mass

╌ Higgs signal strengths

⋯ Higgs mass in MSSM

[Altmannshofer & UH, unpublished]



Depending on choice of parameters in stop sector, combination of indirect measurements can provide limits on mass of lightest stop eigenstate of around 300 GeV

Indirect bounds on stop sector

$$t_\beta = 2$$

$$\mu = -0.2\,\mathrm{TeV}$$

$$\theta_{\tilde{t}} = \pi/4$$

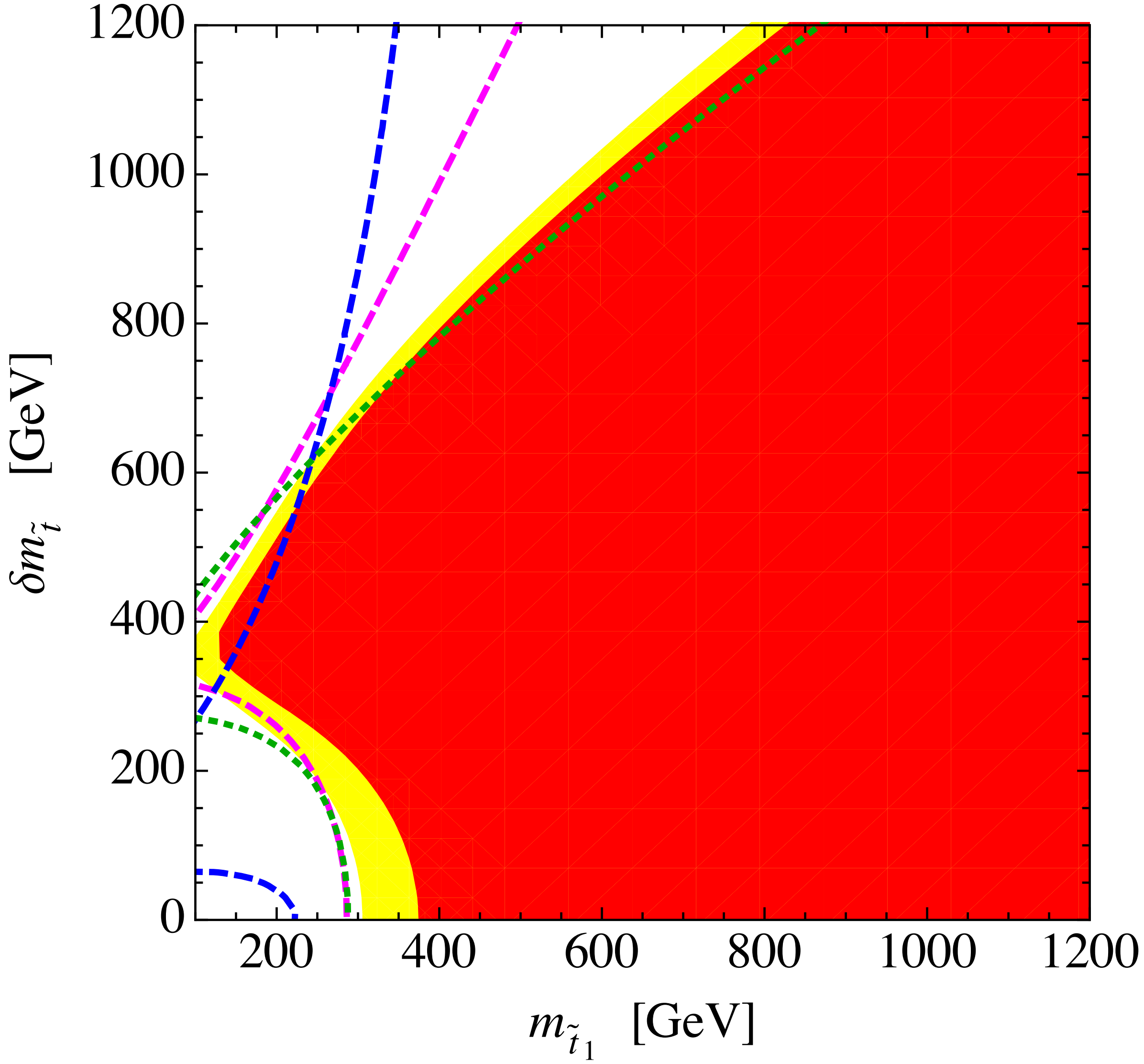
🟨 95% CL 🟥 68% CL

- - - $B \to X_s\gamma$

• • • W-boson mass

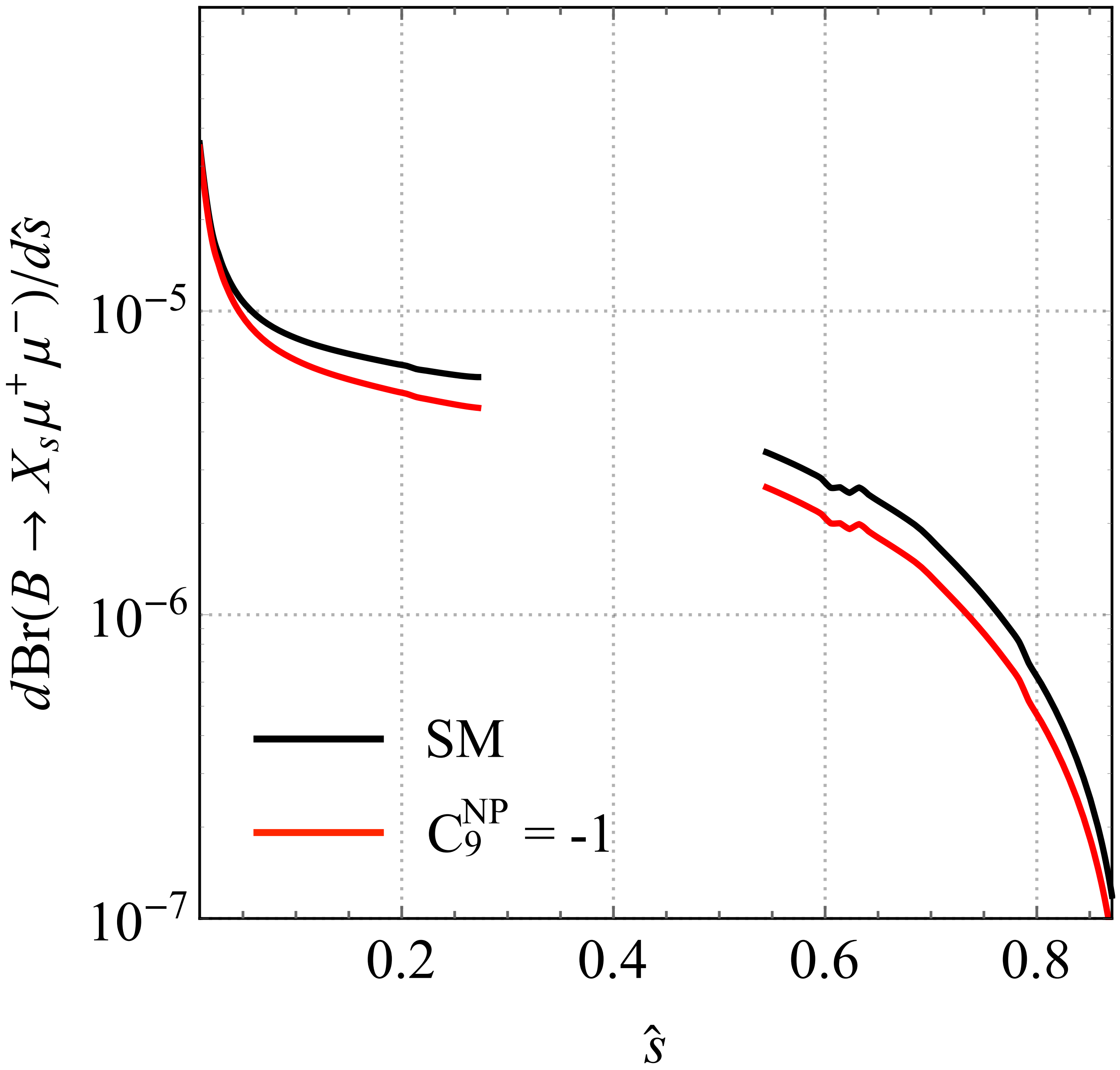
- - - Higgs signal strengths

[Altmannshofer & UH, unpublished]



But if constraint from Higgs-boson mass measurement is ignored (only applies in SUSY with minimal Higgs sector), no relevant model-independent lower bound on stop mass can be found

Implications of b→s$\mu^+\mu^-$ anomalies

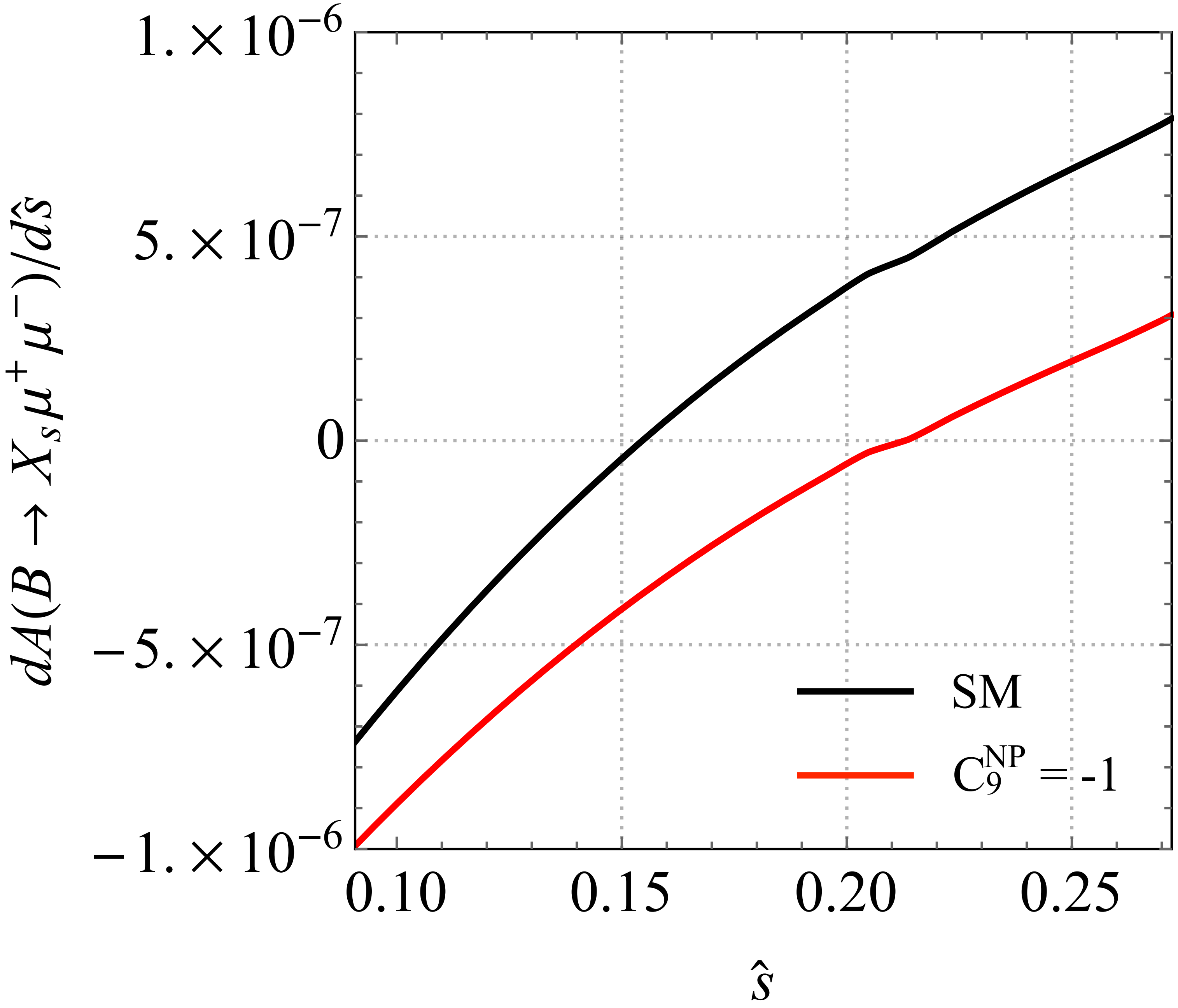


$$\delta\mathrm{Br}_{[1,6]\,\mathrm{GeV}^2} = -17\%$$

$$\delta\mathrm{Br}_{>14.4\,\mathrm{GeV}^2} = -25\%$$

Simplest new-physics explanations of P_5' & R_K anomalies would lead to O(-20%) shifts in Br(B→$X_s\mu^+\mu^-$). Should be observable at Belle II

Implications of b→s$\mu^+\mu^-$ anomalies



$\delta(q_0^2) = 38\%$

Zero of forward-backward asymmetry shifted by even O(35%). Belle II measurements of B→$X_s\mu^+\mu^-$ crucial to shed light on P_5' & R_K anomalies

Low-q^2 observable in $b\to sl^+l^-$

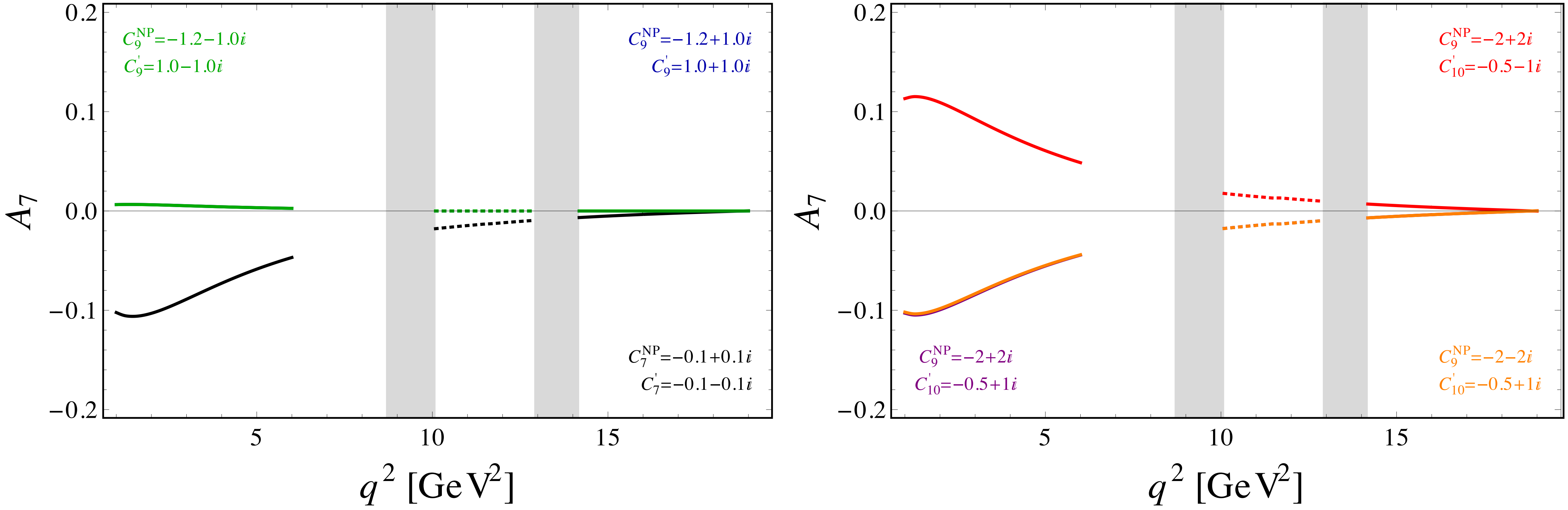
$$S_{K^*\gamma} \simeq \frac{2\,\mathrm{Im}\left(e^{-2i\beta}\,C_7C_7'\right)}{|C_7|^2+|C_7'|^2}$$

$$P_1 \simeq \frac{2\,\mathrm{Re}\,(C_7C_7')}{|C_7|^2+|C_7'|^2} \qquad\qquad P_3^{\mathrm{CP}} \simeq \frac{2\,\mathrm{Im}\,(C_7C_7')}{|C_7|^2+|C_7'|^2}$$

LHCb will reach theoretical limit by end of HL-LHC for P_1 but not for P_3^{CP} which is CP violating but does not require a strong phase

CP violation in $B\to K^*\mu^+\mu^-$

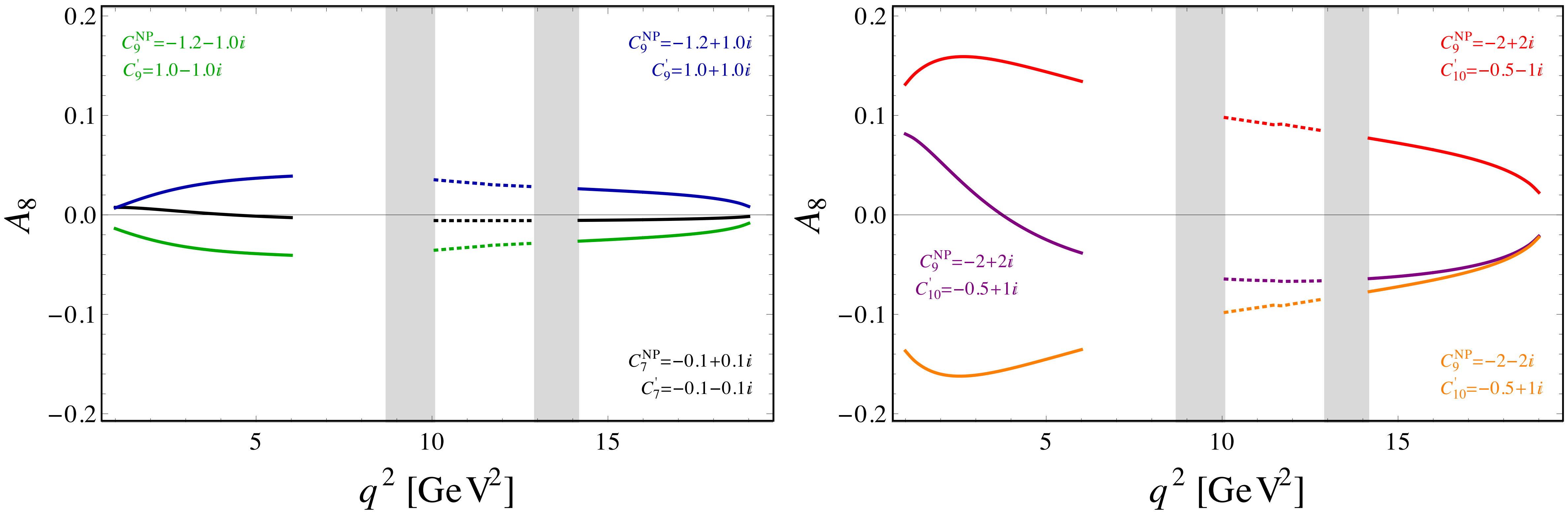
[Altmannshofer & Straub, 1308.1501]



$$\langle A_7\rangle_{[1,6]} \simeq -\,0.44\,\mathrm{Im}(C_7^{\rm NP}) + 0.44\,\mathrm{Im}(C_7') + 0.07\,\mathrm{Im}(C_{10}^{\rm NP}) - 0.07\,\mathrm{Im}(C_{10}')$$

CP violation in $B \to K^* \mu^+ \mu^-$

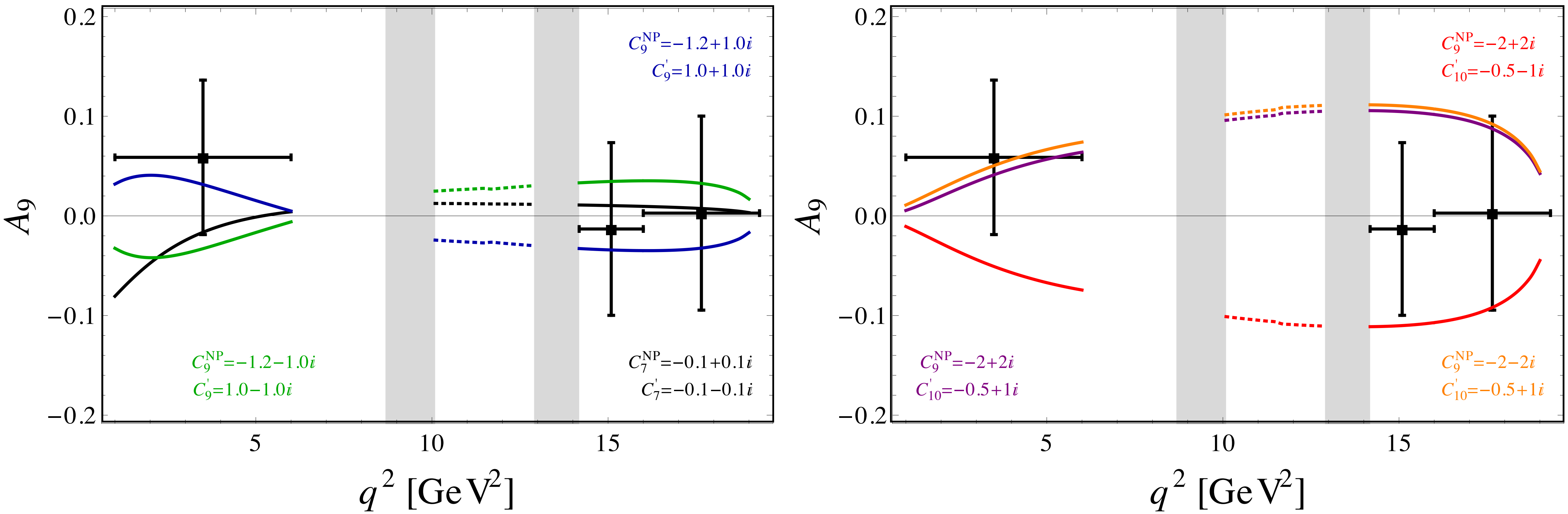
[Altmannshofer & Straub, 1308.1501]



$$\langle A_8\rangle_{[1,6]} \simeq +0.25\,\mathrm{Im}(C_7^{\rm NP}) + 0.23\,\mathrm{Im}(C_7') + 0.04\,\mathrm{Im}(C_9^{\rm NP}) + 0.02\,\mathrm{Im}(C_9') - 0.06\,\mathrm{Im}(C_{10}')$$

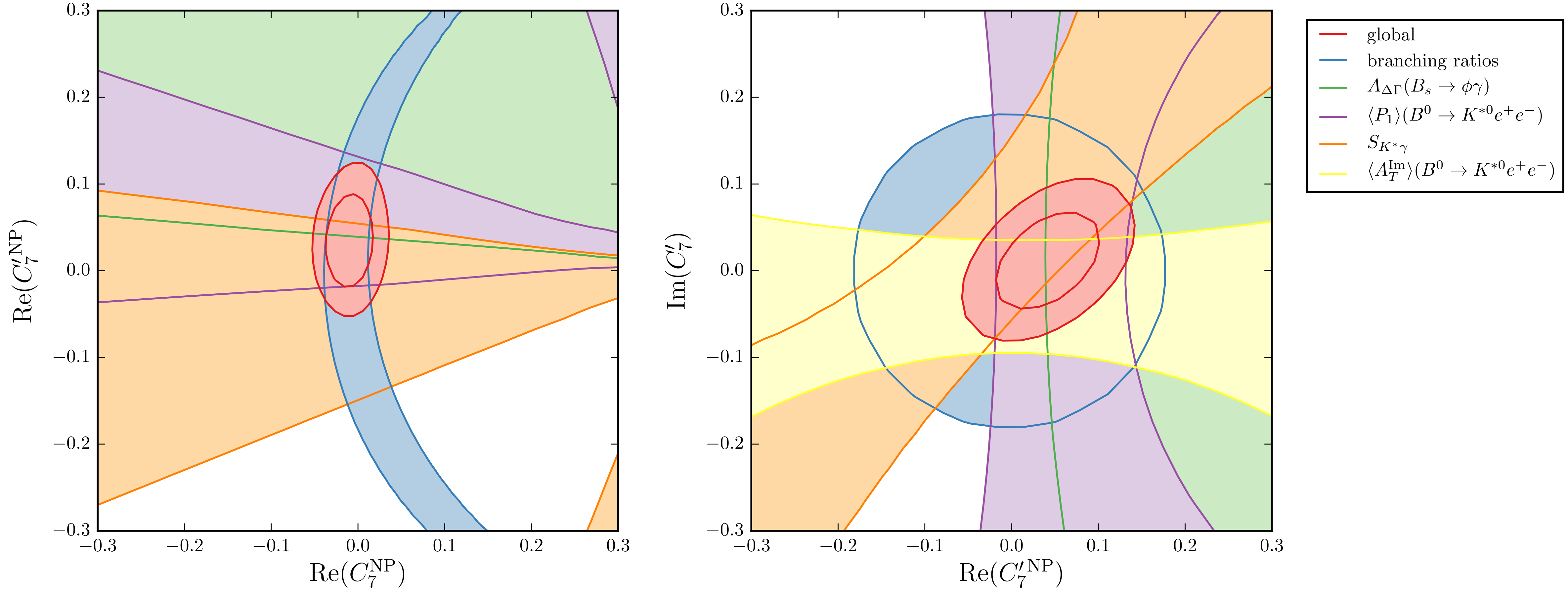
CP violation in $B \to K^* \mu^+ \mu^-$

[Altmannshofer & Straub, 1308.1501]



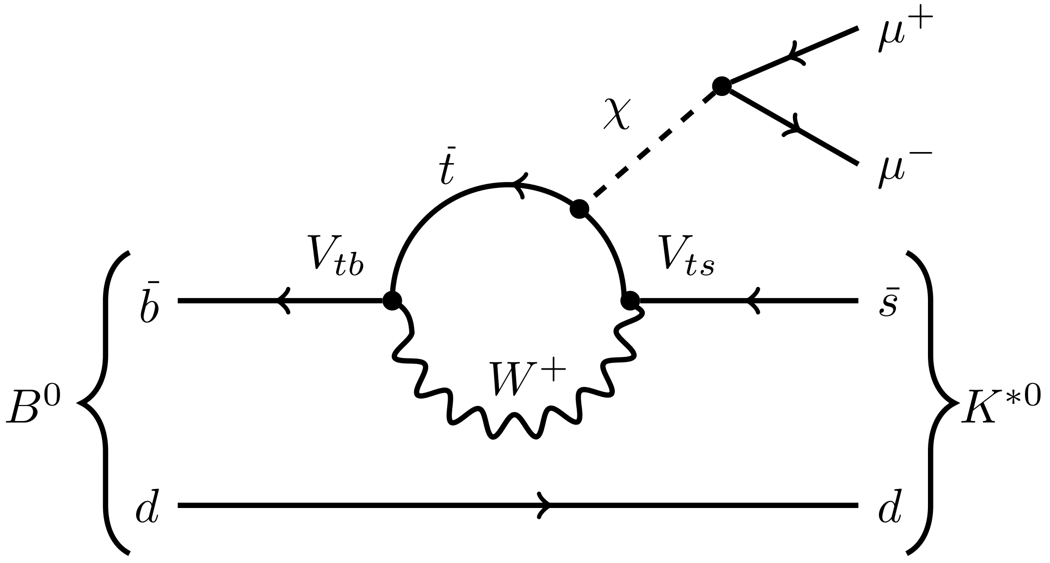
$$\langle A_9 \rangle_{[1,6]} \simeq +\,0.12\,\mathrm{Im}(C_7') + 0.04\,\mathrm{Im}(C_{10}')$$

Constraints from radiative decays

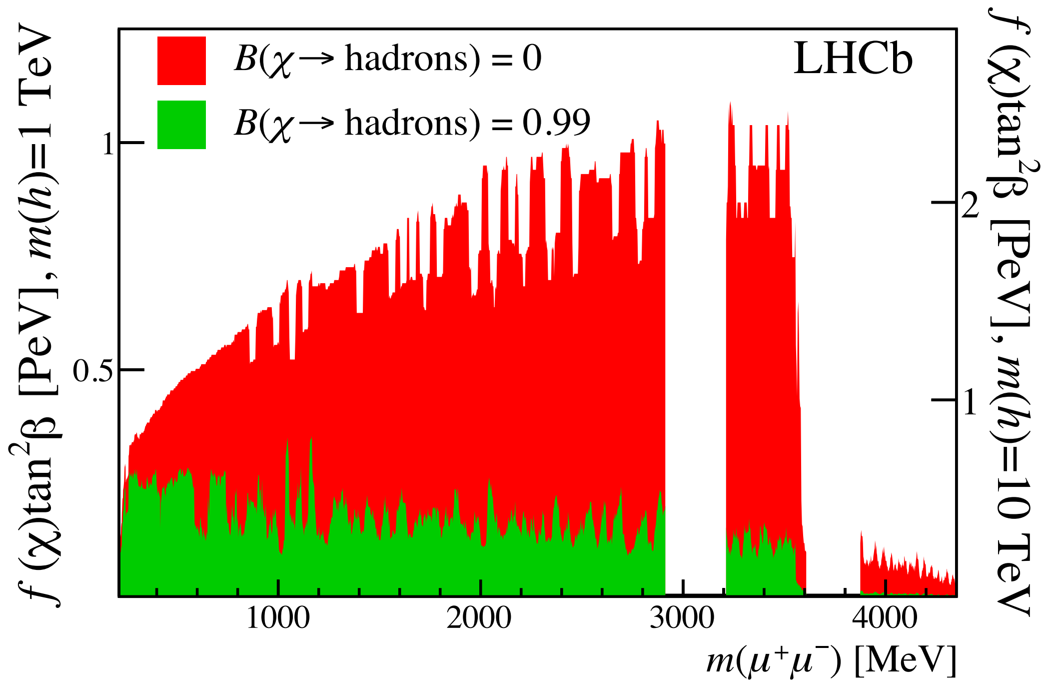


[Paul & Straub, 1608.02556]

Axions in dimuon spectrum



[LHCb, 1508.04094]



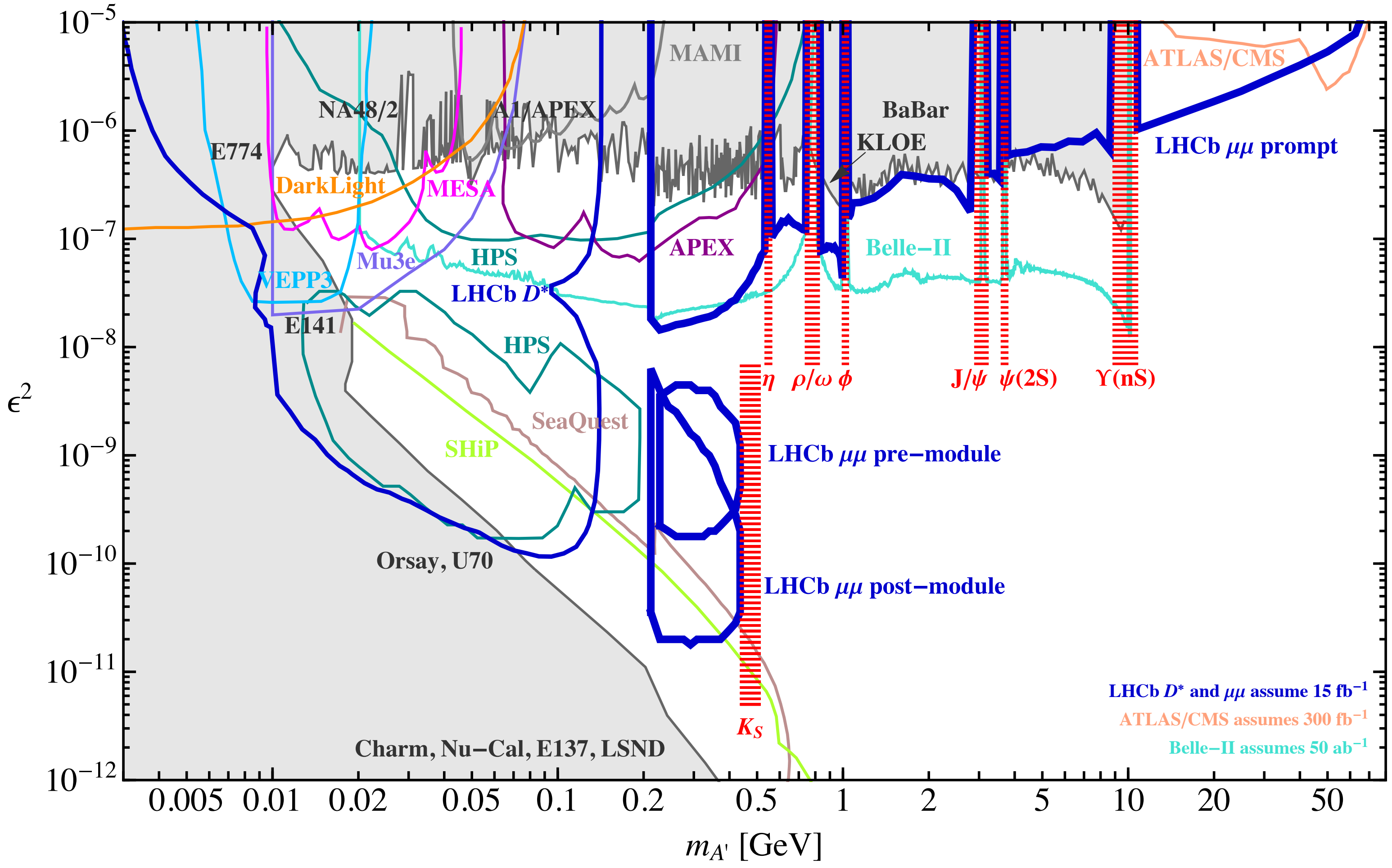
Can use dimuon spectrum as measured by LHCb to set interesting constraint on axion-top couplings in axion-portal models

[Freytsis et al., 0911.5355]

Dark photons at LHCb

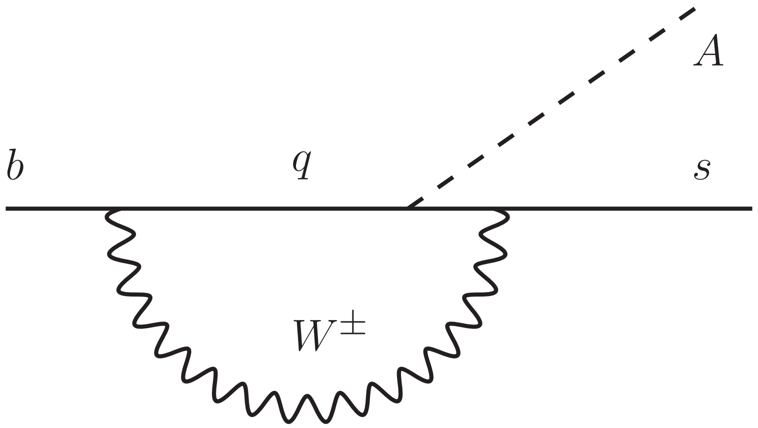
$$\begin{aligned}\mathcal{L} \supset & -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} \\ & + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu \\ & + \epsilon e A'_\mu J^\mu_{\mathrm{EM}}\end{aligned}$$

[Ilten et al., 1603.08926]



LHCb will have sensitivity to large regions of unexplored dark photon A′ parameter space via inclusive dimuon analysis, especially in [210, 520] MeV & [10, 40] GeV mass ranges

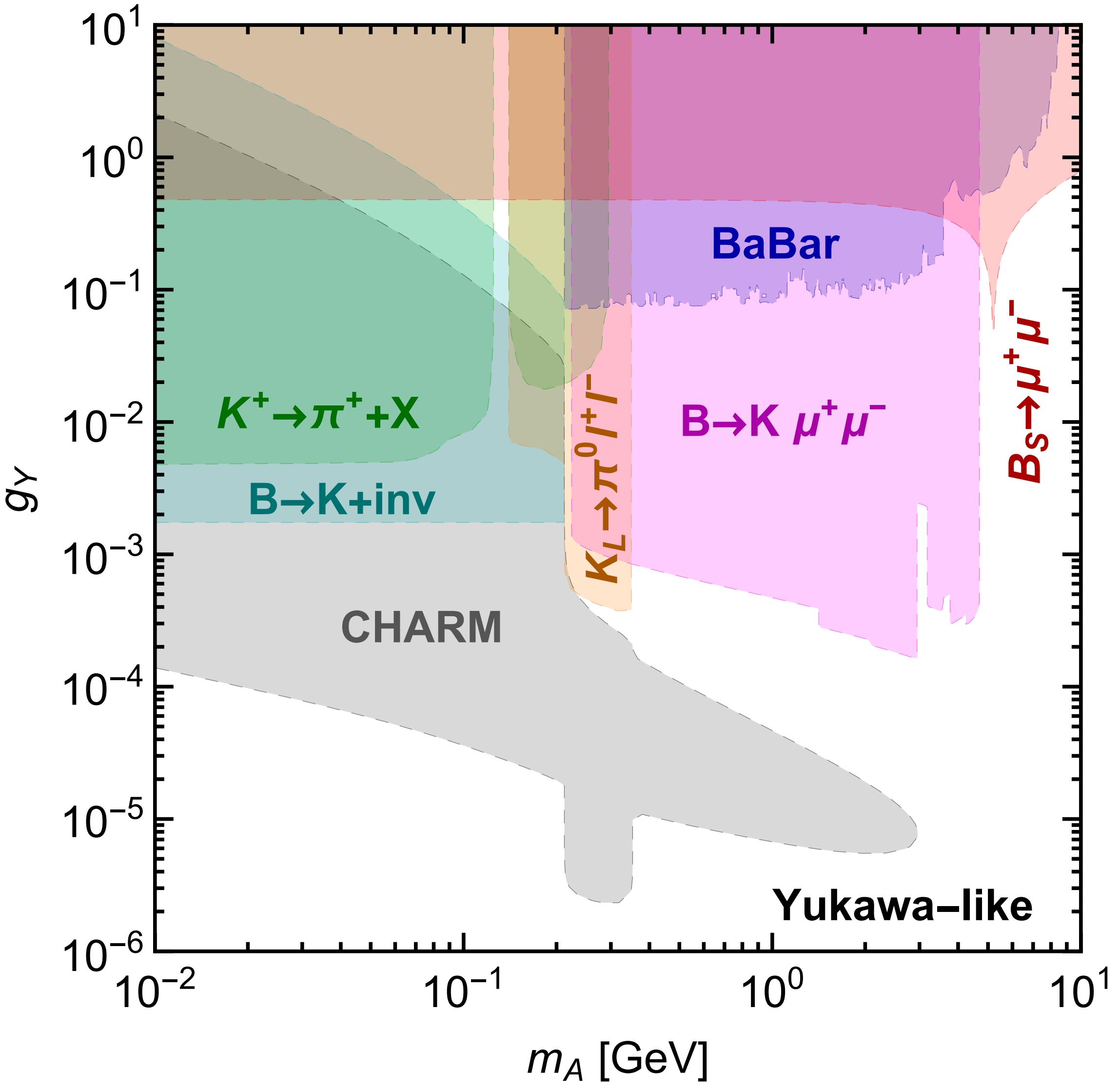
Light spin-0 states & flavour

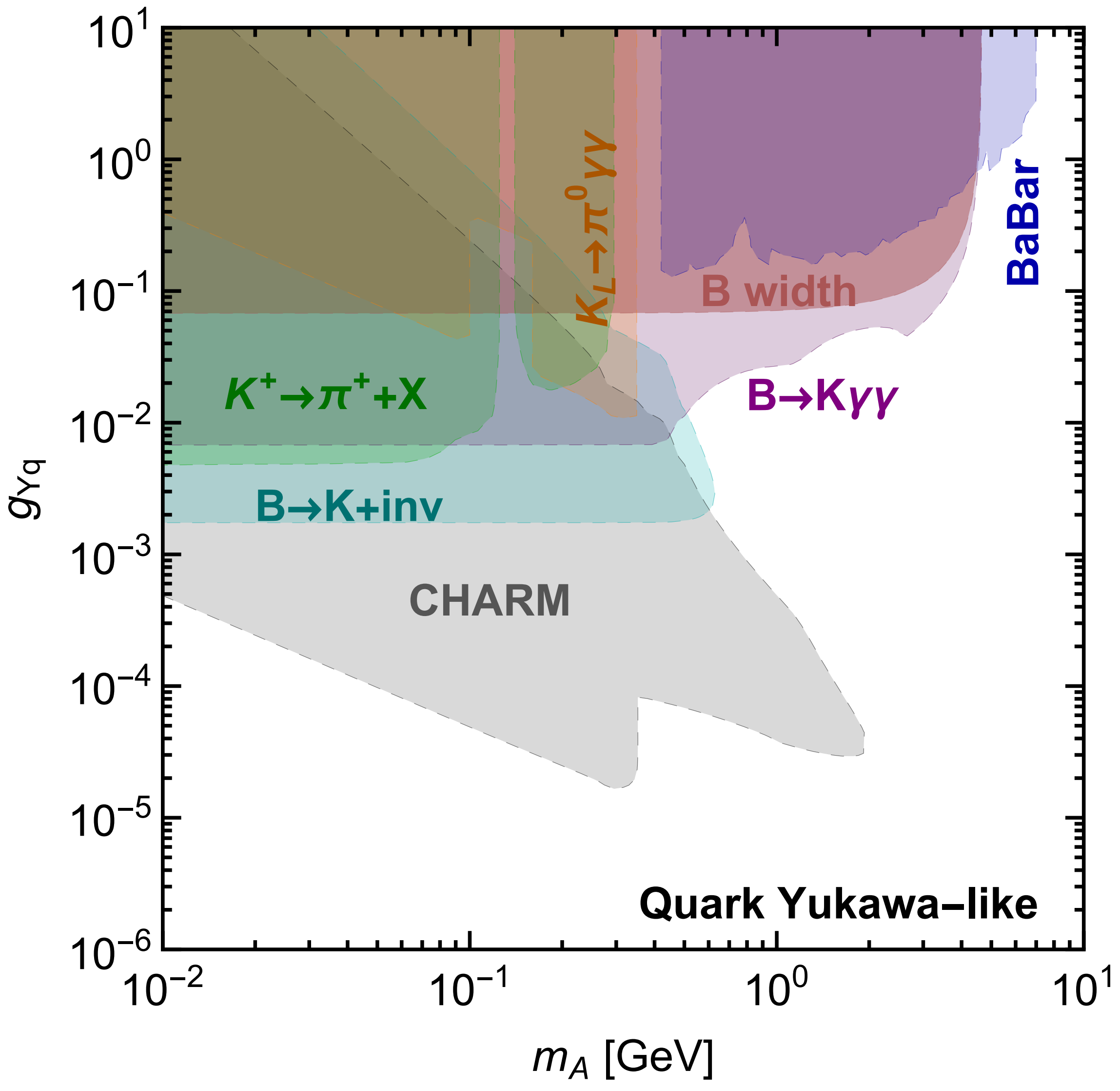


Flavour-changing transitions provide another way to test light spin-0 states. Bounds depend however strongly on assumption on structure of couplings between spin-0 states & SM fermions

Light spin-0 states & flavour

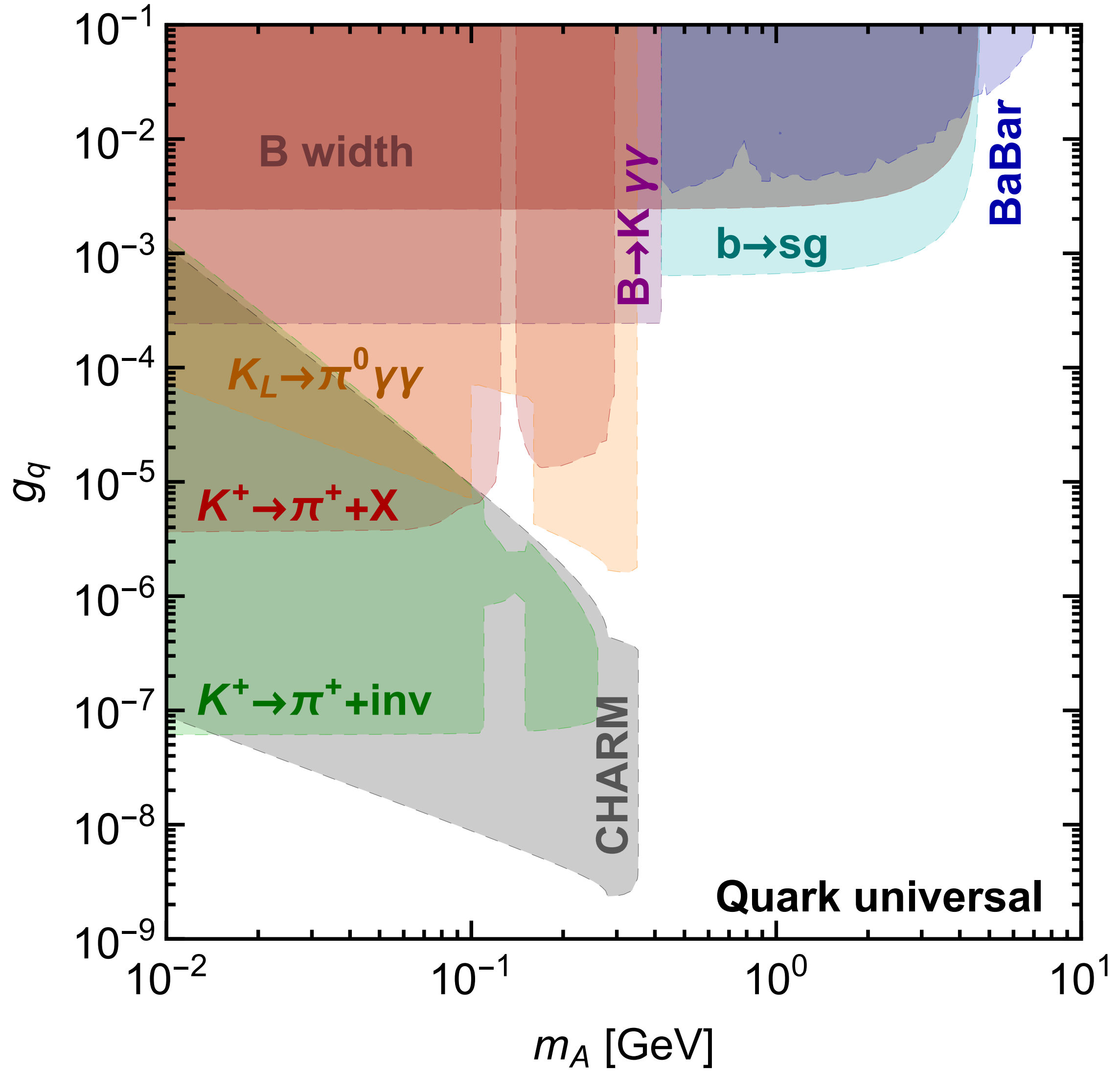
[Dolan et al., 1412.5174]

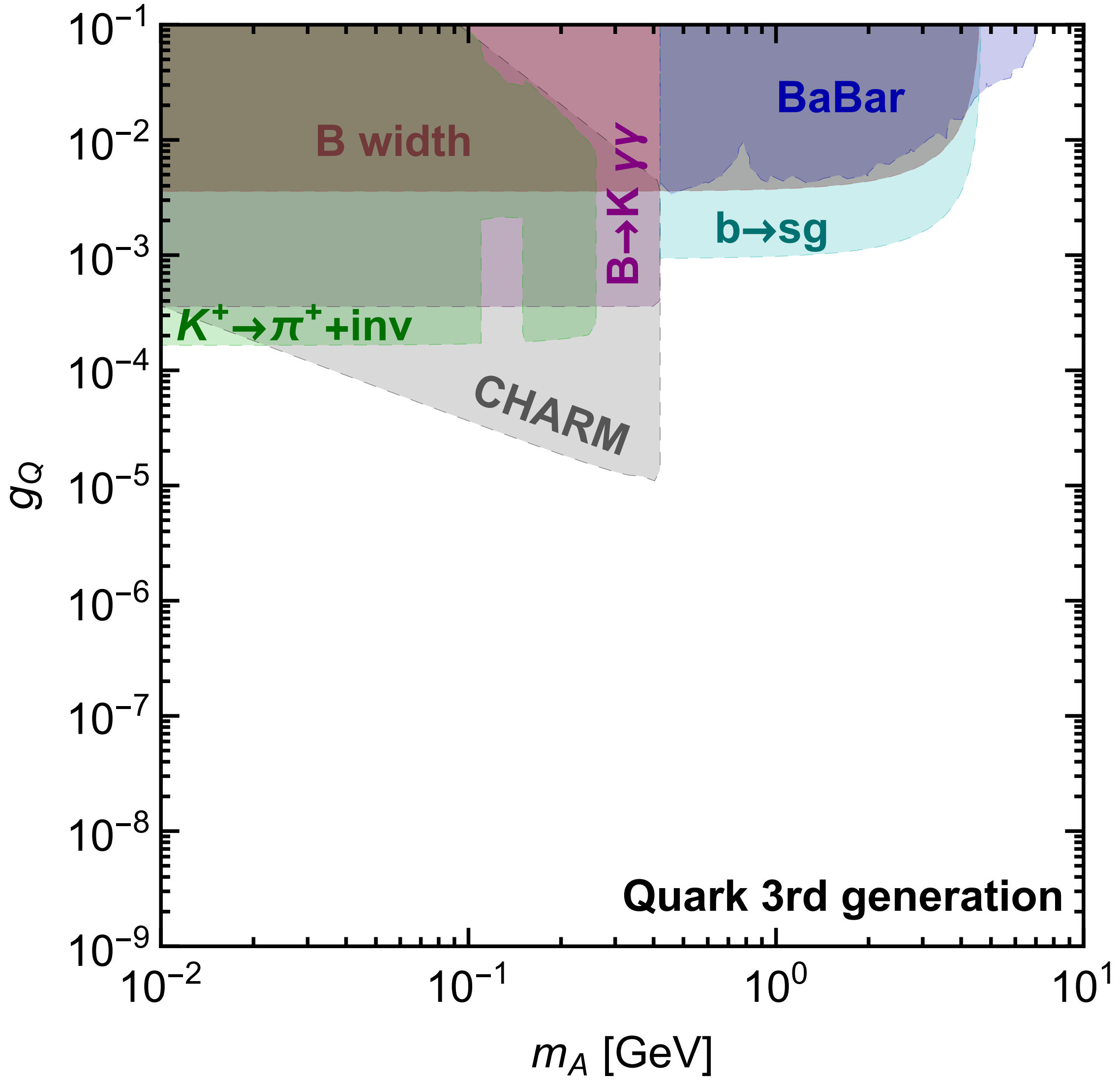




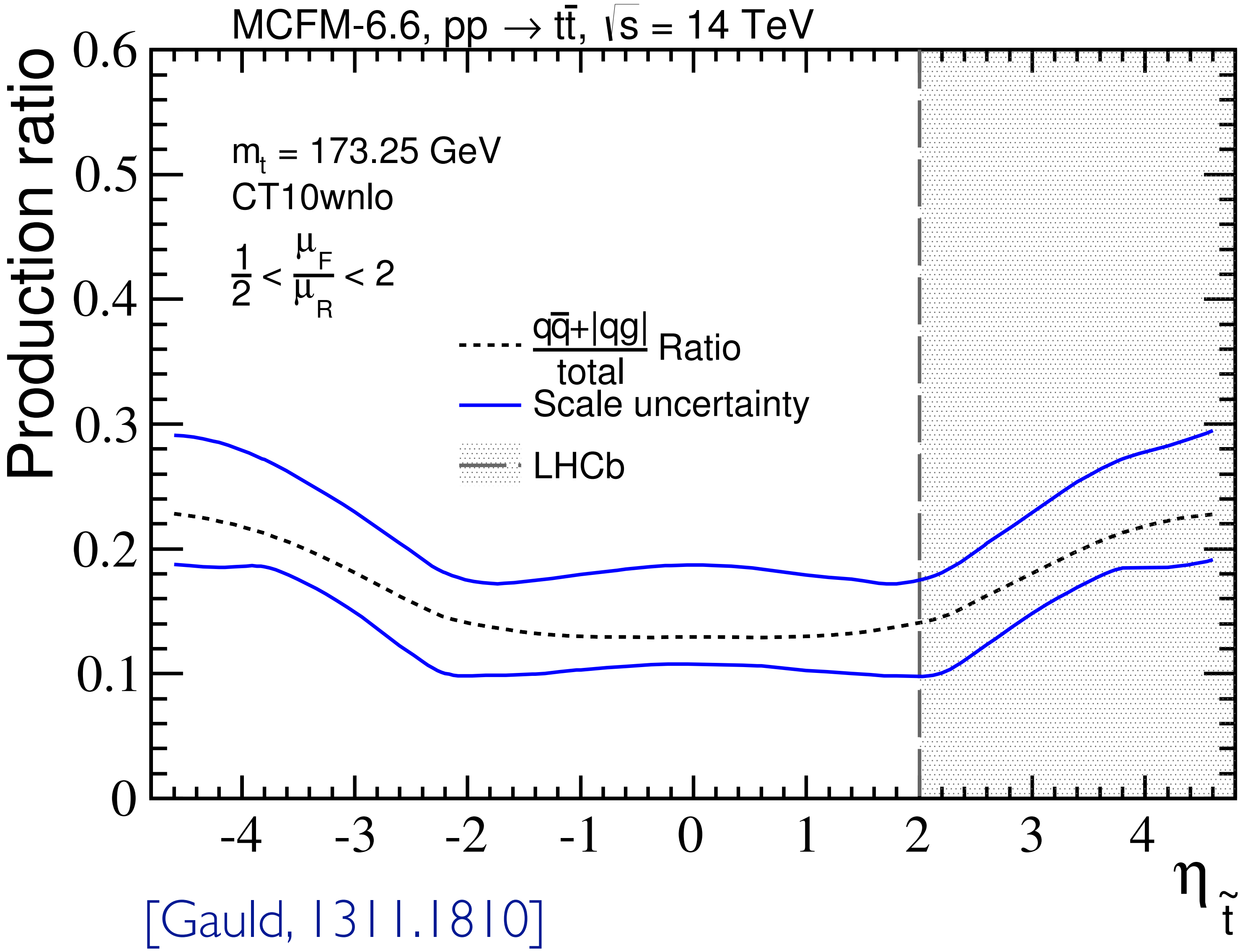
Light spin-0 states & flavour

[Dolan et al., 1412.5174]





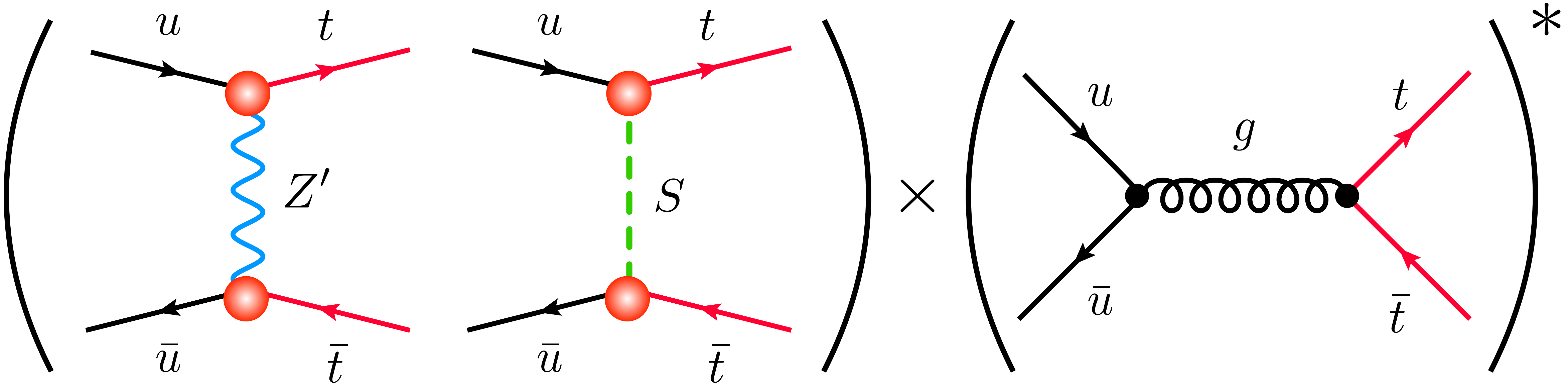
$t\bar{t}$ production at LHCb



[Gauld, 1311.1810]

$t\bar{t}$ production in forward direction advantages because qq + g$\bar{q}$ channels more important, leading to a larger $t\bar{t}$ asymmetry

Why tt̄ production at LHCb?

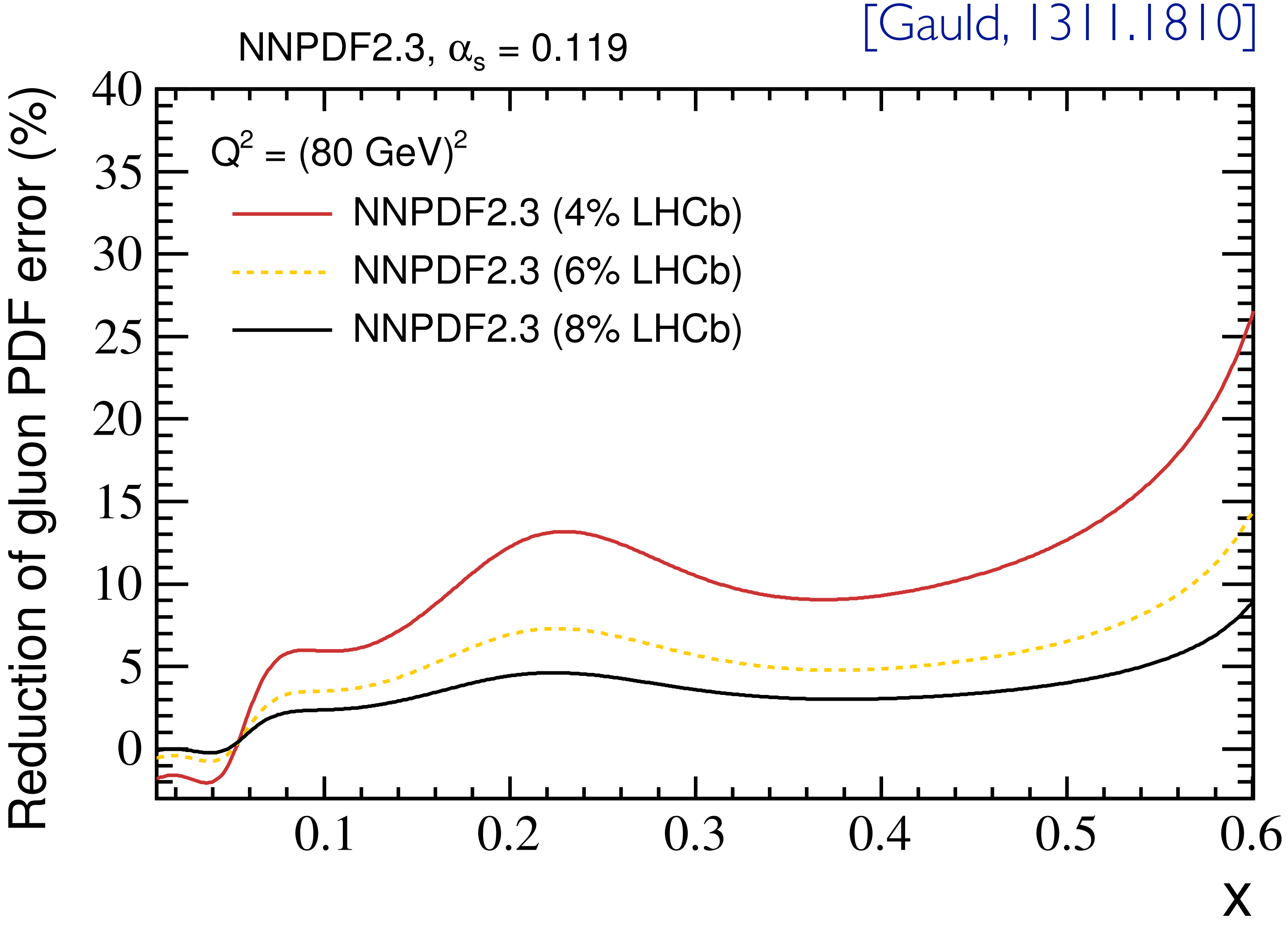


In new-physics scenarios in which top production proceeds via t-channel exchange, cross section enhanced at large η

[in LHCb context see Kagan et al., 1103.3747]

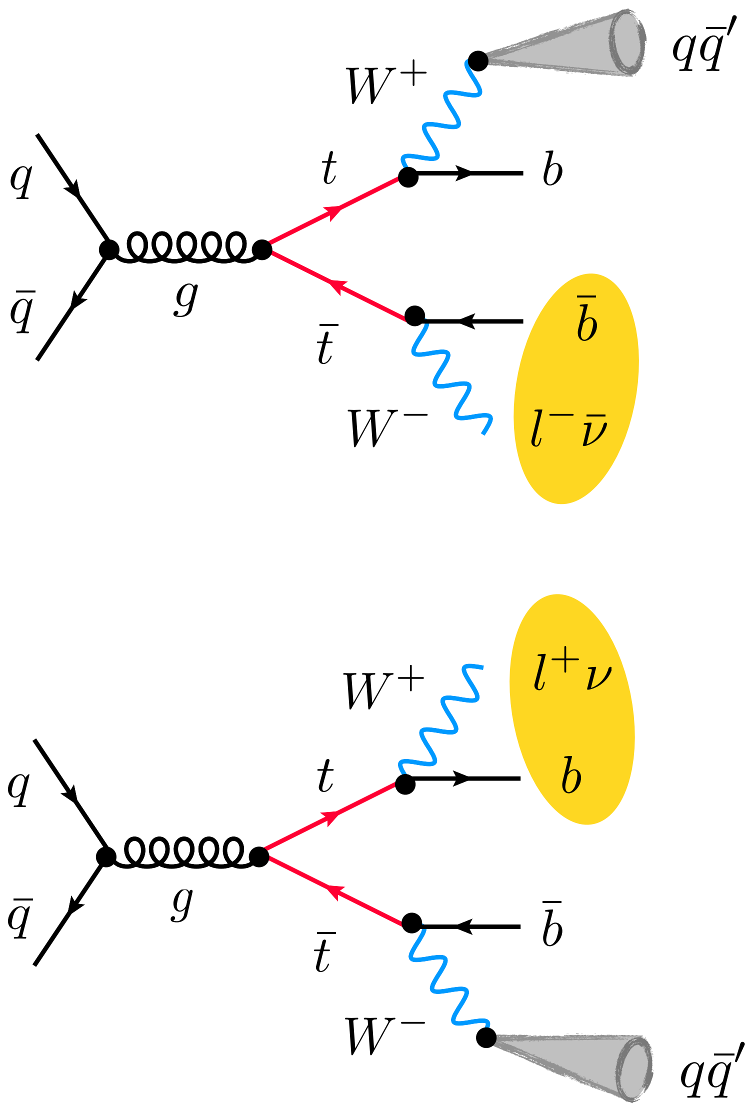
Why $t\bar{t}$ production at LHCb?

[Gauld, 1311.1810]

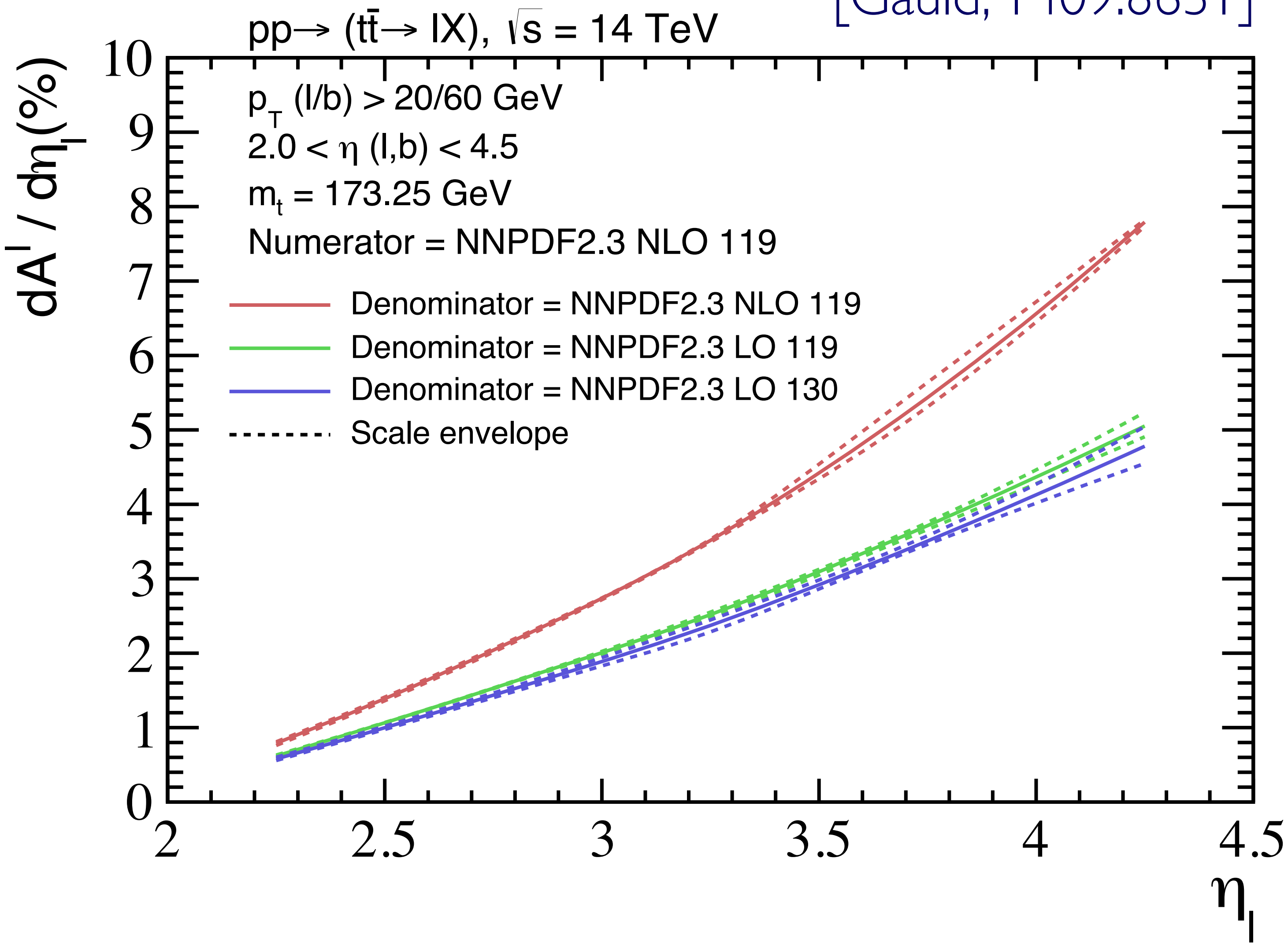


Even if no new physics hides in top sector, could make use of LHCb data by improving our understanding of gluon PDF

Single-lepton asymmetry



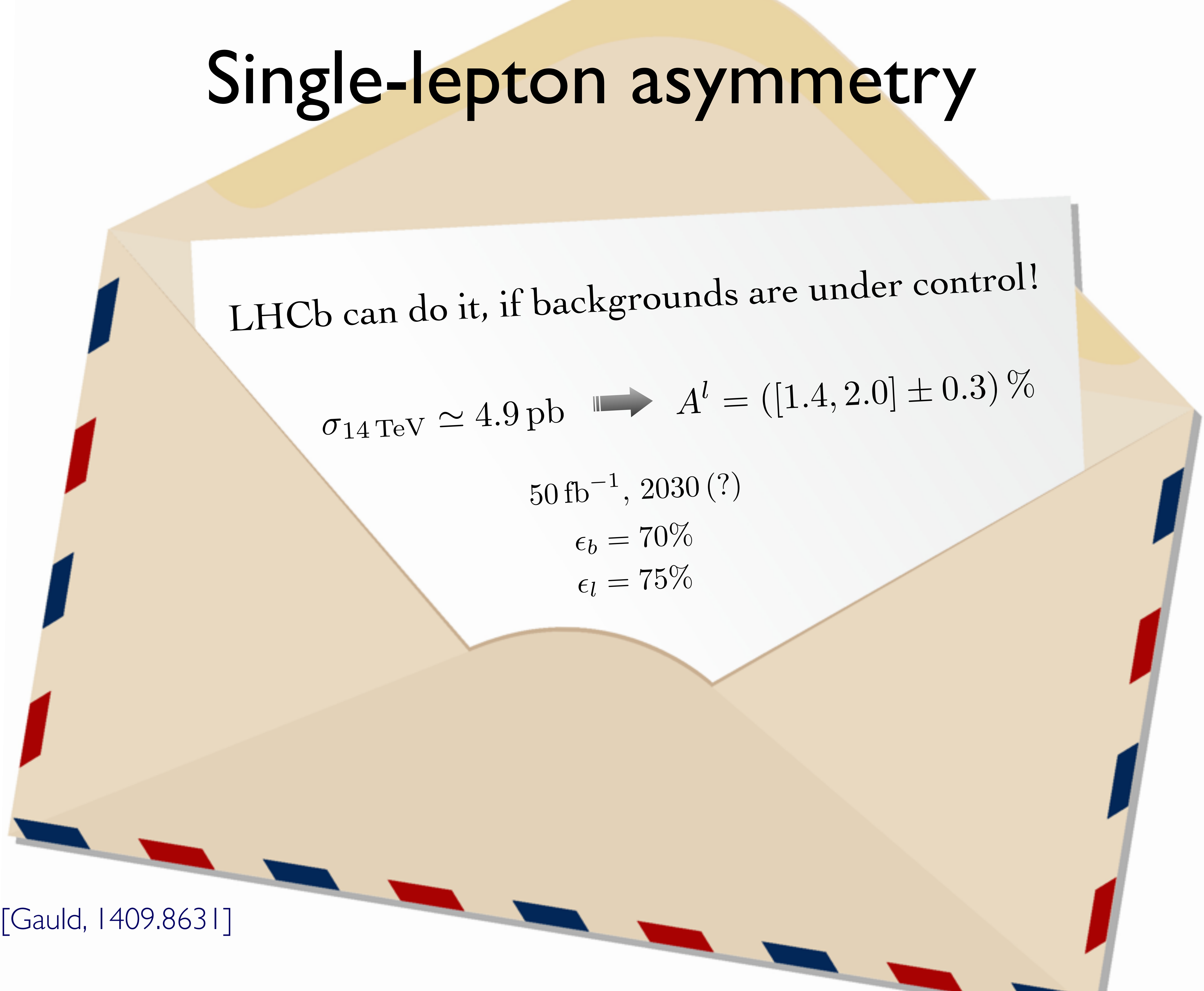
[Gauld, 1409.8631]



Single-lepton channel statistically more promising than dilepton mode.

As background low, second signal should still be looked for

Single-lepton asymmetry



LHCb can do it, if backgrounds are under control!

$$\sigma_{14\,\mathrm{TeV}} \simeq 4.9\,\mathrm{pb} \Rightarrow A^{l} = ([1.4, 2.0] \pm 0.3)\,\%$$

$$50\,\mathrm{fb}^{-1},\ 2030\,(?)$$

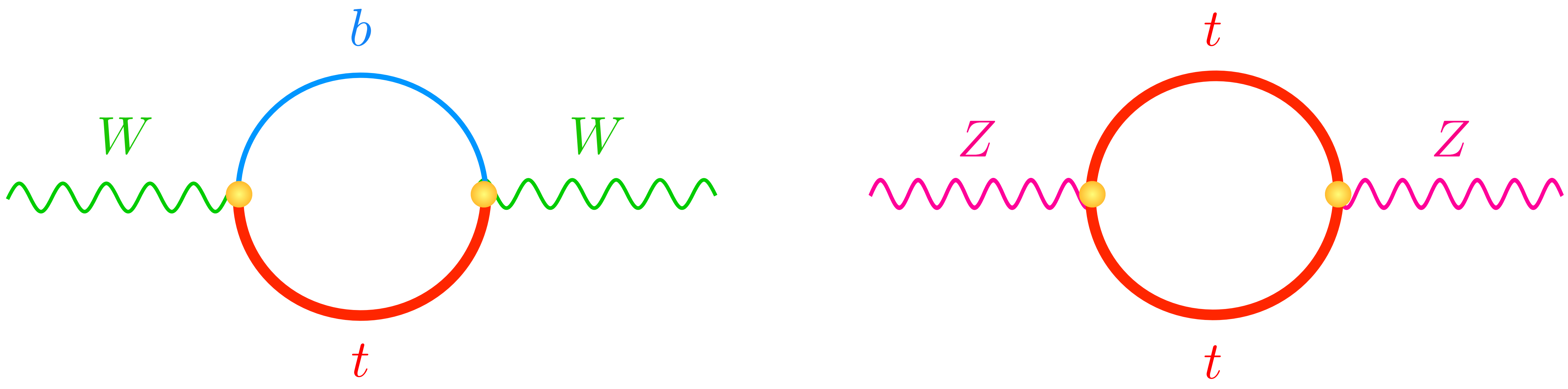
$$\epsilon_b = 70\%$$

$$\epsilon_l = 75\%$$

[Gauld, 1409.8631]

1-loop corrections to ρ

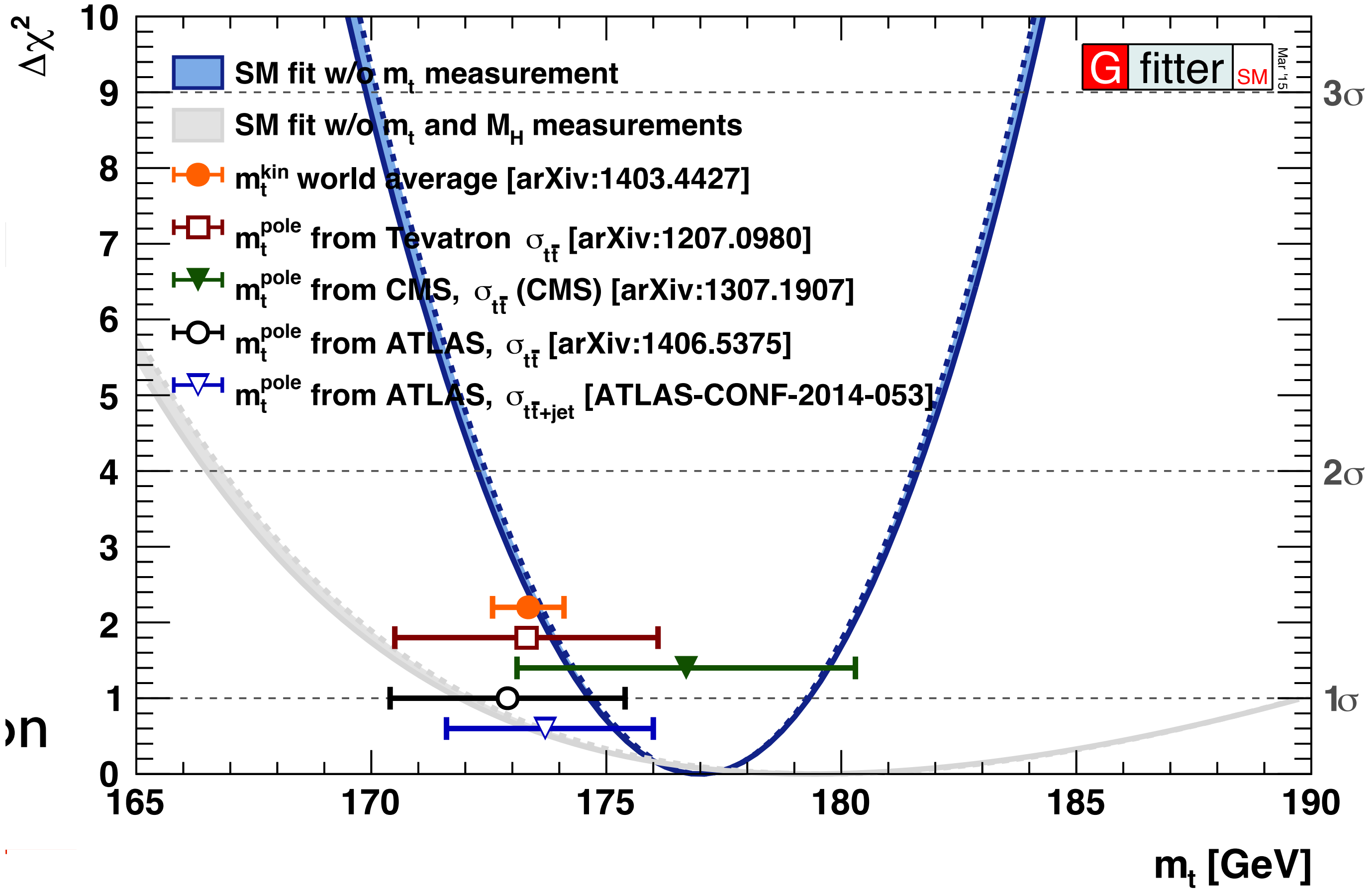
[cf. Veltman, Nucl. Phys. B123, 89 (1977)]



$$\Delta\rho = \alpha\Delta T = \frac{3G_F}{8\sqrt{2}\pi^2}\, m_t^2 \left\{ 1 + \frac{m_b^2}{m_t^2}\left(1 + \frac{2\ln\left(\frac{m_b^2}{m_t^2}\right)}{1-\frac{m_b^2}{m_t^2}} \right) \right\}$$

Dominant 1-loop corrections due to top exchange & proportional to m_t^2. In contrast, Higgs contribution scales as $g_1^2 \ln(m_h^2/m_Z^2)$

Top mass from EW fit



[Kogler, Moriond EW 2015]

$$\Downarrow$$

$$\boxed{m_t^{\text{pole}} = (177.0 \pm 2.5)\,\text{GeV}}$$