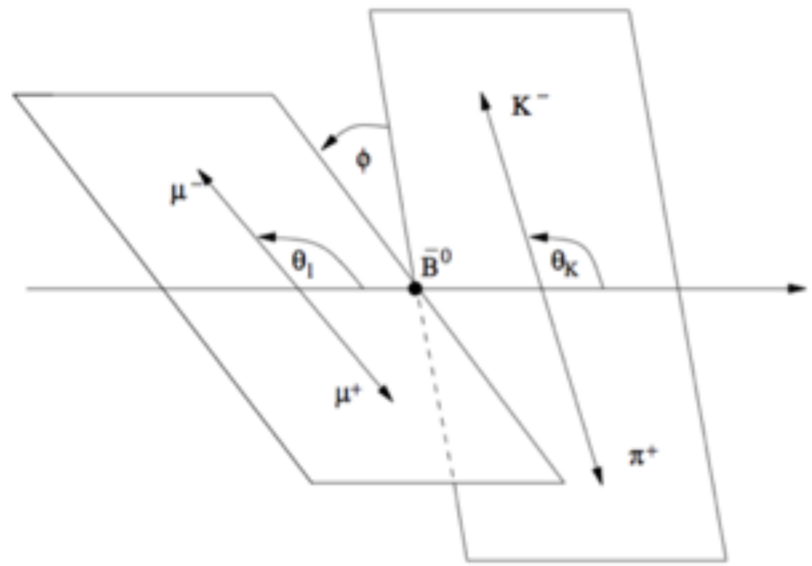
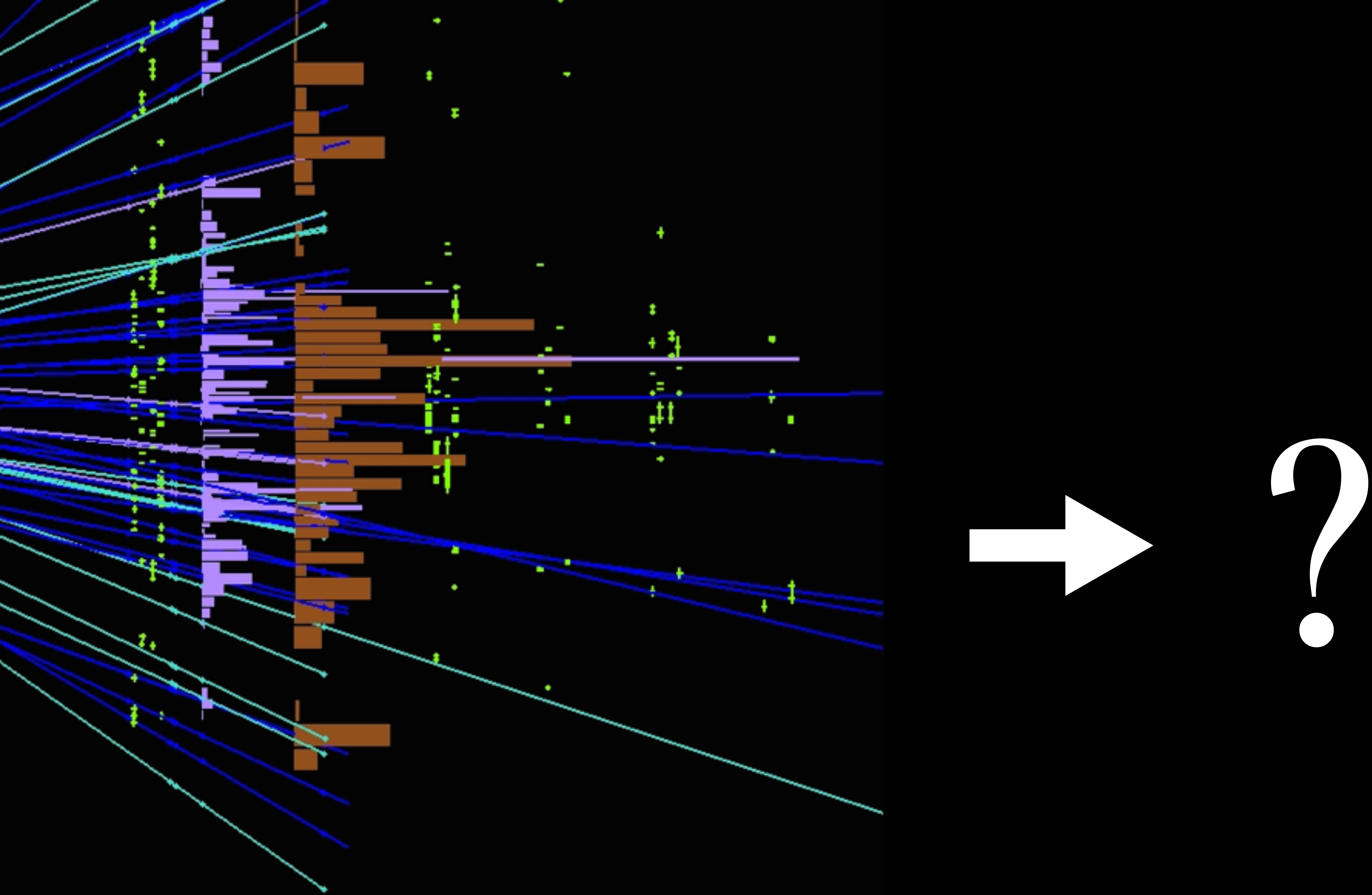
What is P_5'?



$$
\begin{aligned}
\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} =& \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell \\
& - F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi \\
& + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi \\
& + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi \\
& + S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]
\end{aligned}
$$

$$
P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}
$$

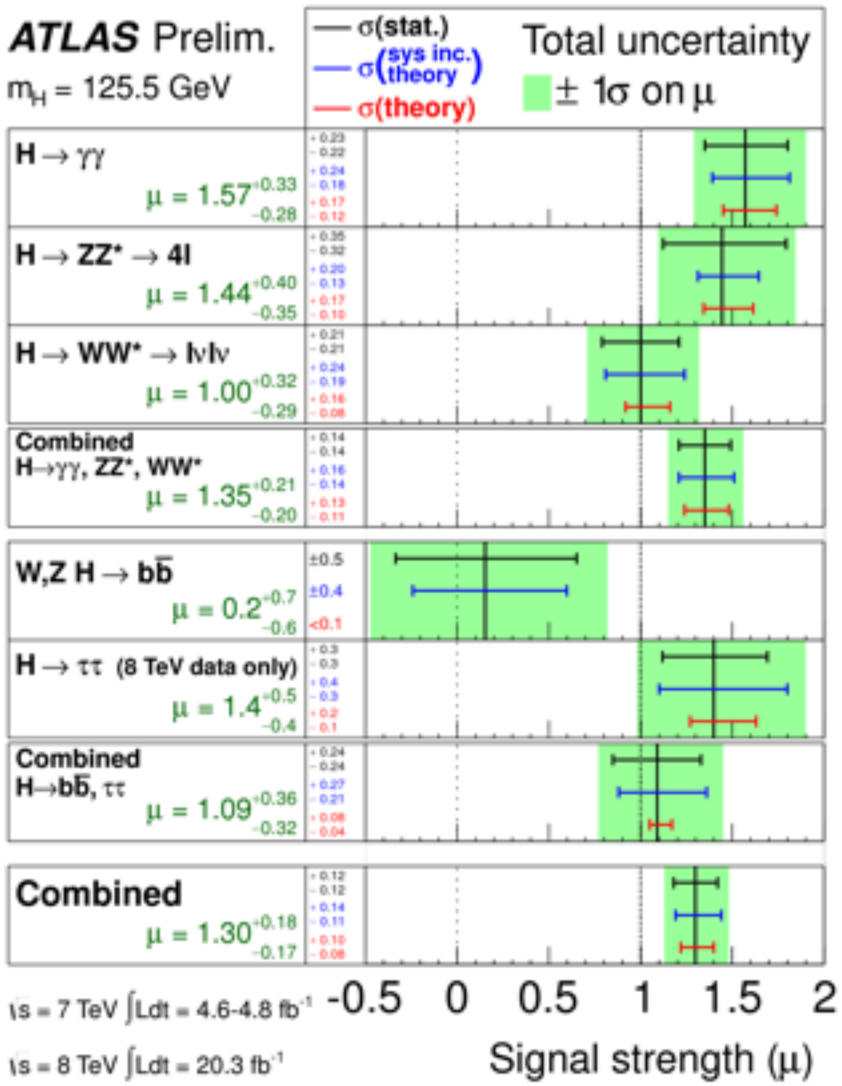


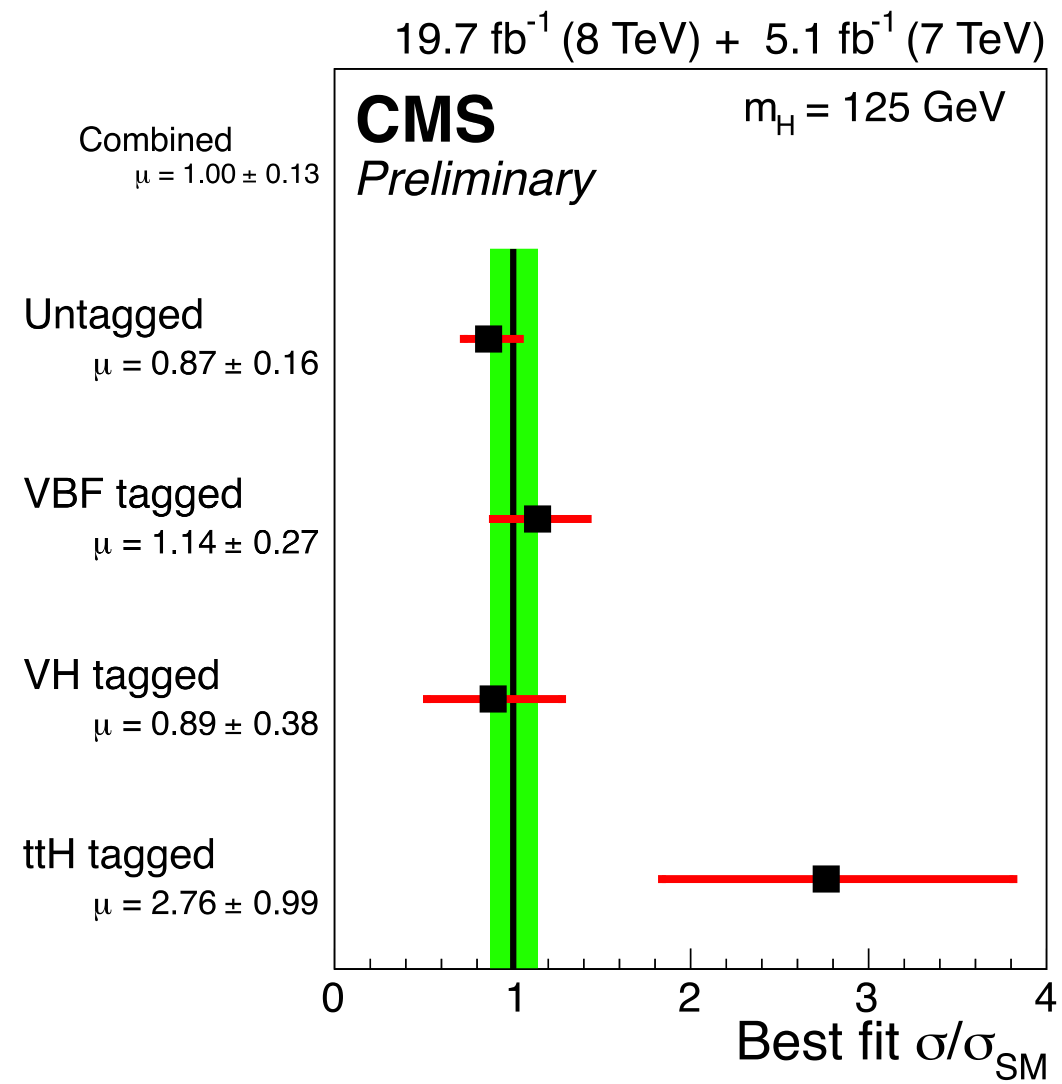
Implications of Heavy Flavor Measurements

Uli Haisch, Oxford University

Experimental Challenges for the LHC Run II,
28 March 2016

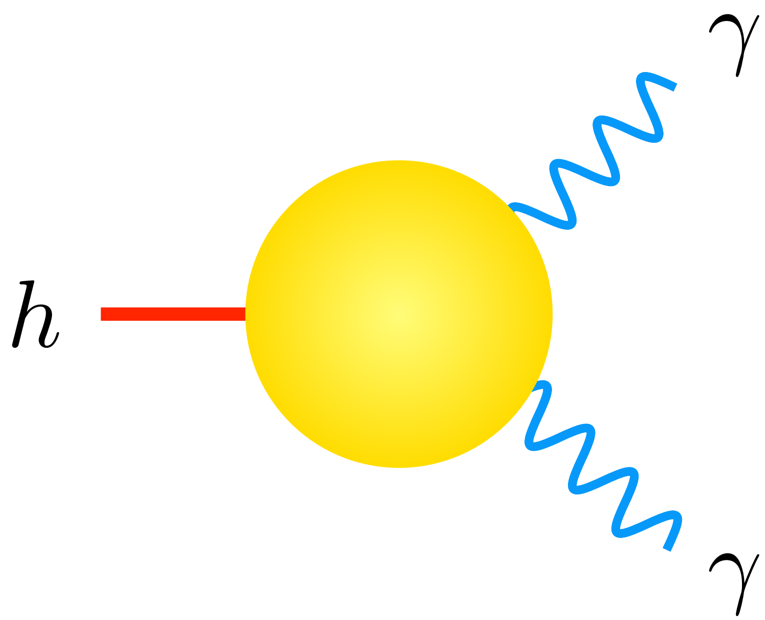
Higgs data





$$\mu_{\text{Higgs}} = 1.1 \pm 0.1$$

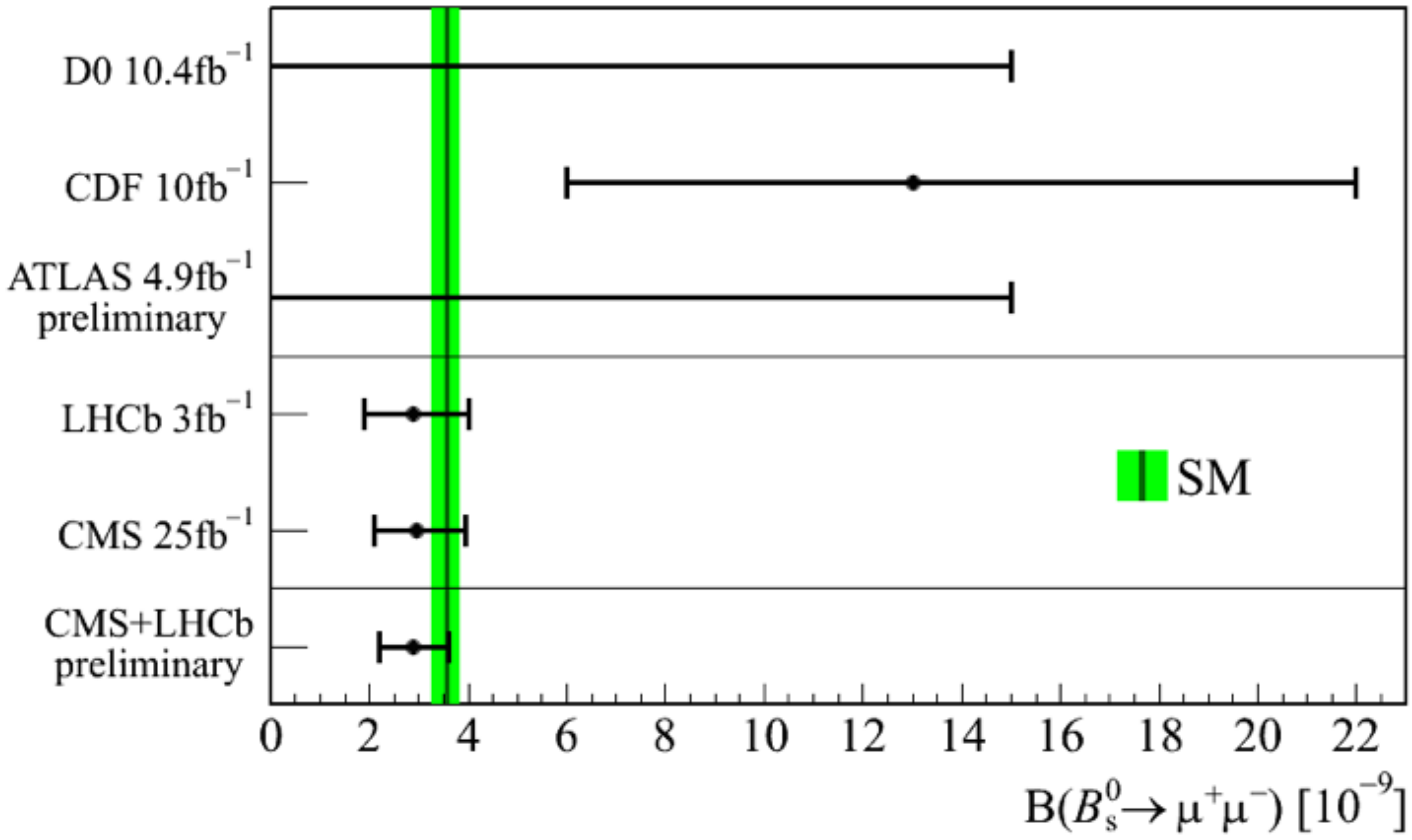
Higgs: new-physics scale?



$$\mu_{h\to\gamma\gamma} \simeq 1 \pm N\,\frac{v^2}{\Lambda^2}$$

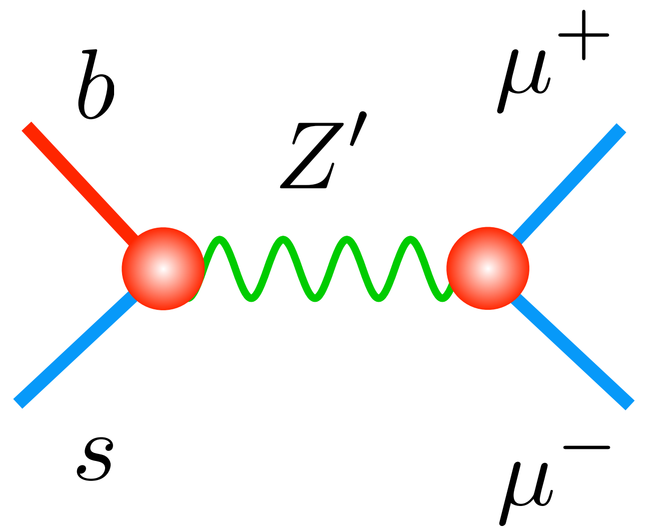
$$\Lambda \gtrsim \sqrt{\frac{N}{0.1}}\,v \simeq \begin{cases} 0.8\,\mathrm{TeV}\,, & N=1 \\ 3\,\mathrm{TeV}\,, & N=4\pi \end{cases}$$

Flavor data



$$\mu_{B_s \to \mu^+\mu^-} = 0.79 \pm 0.20$$

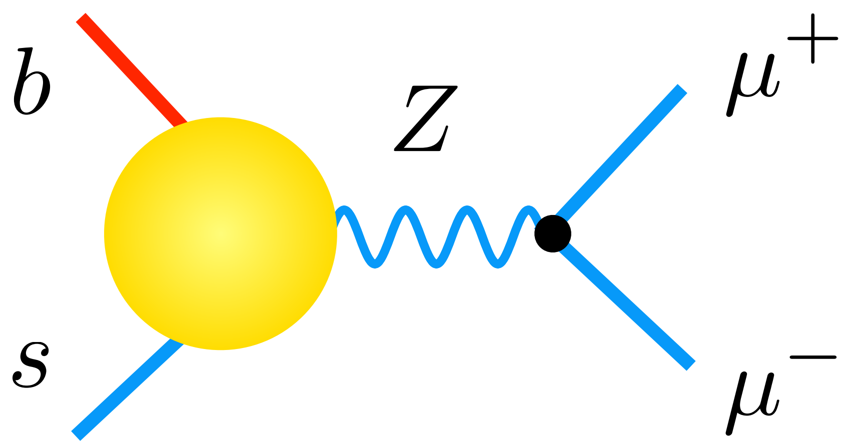
Flavor: new-physics scale?



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

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

Flavor: new-physics scale?



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

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

Upshot

Even in most pessimistic scenario, i.e. minimal-flavor violation (MFV), LHCb sensitivity to new-physics scale comparable to those of Higgs coupling measurements by ATLAS & CMS. Like in case of Higgs, we are now in era of precision physics. Further progress likely to depend on how well experimentalists can measure & theorists can predict — of course, there is still room for surprises!

Flavor precision tests: an example

- Effects of anomalous $t\bar{t}Z$ couplings can be described by

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{i={}^{(3)}_{\phi Q},\phi Q,\phi u} \frac{C_i}{\Lambda^2} O_i + \dots$$

$$O_{\phi Q}^{(3)} = \left(\phi^\dagger i \overleftrightarrow{D}_\mu \sigma^a \phi\right)\left(\bar{Q}_{L,3}\gamma^\mu \sigma^a Q_{L,3}\right) ,$$

$$O_{\phi Q} = \left(\phi^\dagger i \overleftrightarrow{D}_\mu \phi\right)\left(\bar{Q}_{L,3}\gamma^\mu Q_{L,3}\right) ,$$

$$O_{\phi u} = \left(\phi^\dagger i \overleftrightarrow{D}_\mu \phi\right)\left(\bar{t}_R\gamma^\mu t_R\right)$$

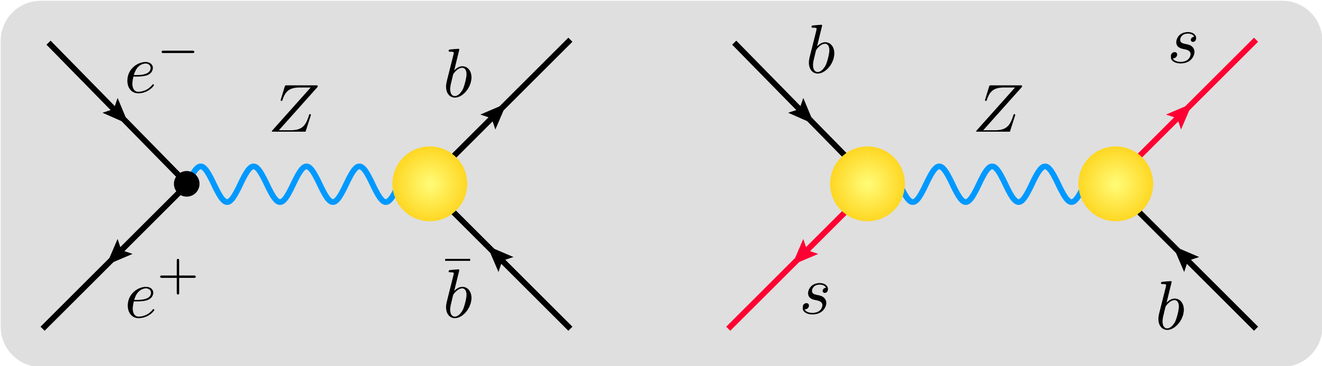
[Buchmüller & Wyler, NPB (1986) 268;
Grzadkowski et al., 1008.4884; ...]

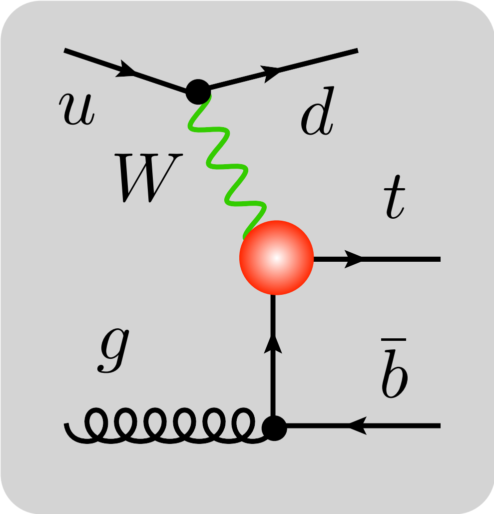
Closed $t\bar{t}Z$ couplings

$$\mathcal{L}_{t\bar{t}Z} = g_L \bar{t}_L \not{Z} t_L + g'_L V^*_{ti} V_{tj} \bar{d}_{L,i} \not{Z} d_{L,j} + g_R \bar{t}_R \not{Z} t_R$$

$$+ \left(k_L \bar{t}_L \not{W}^+ b_L + \text{h.c.} \right)$$

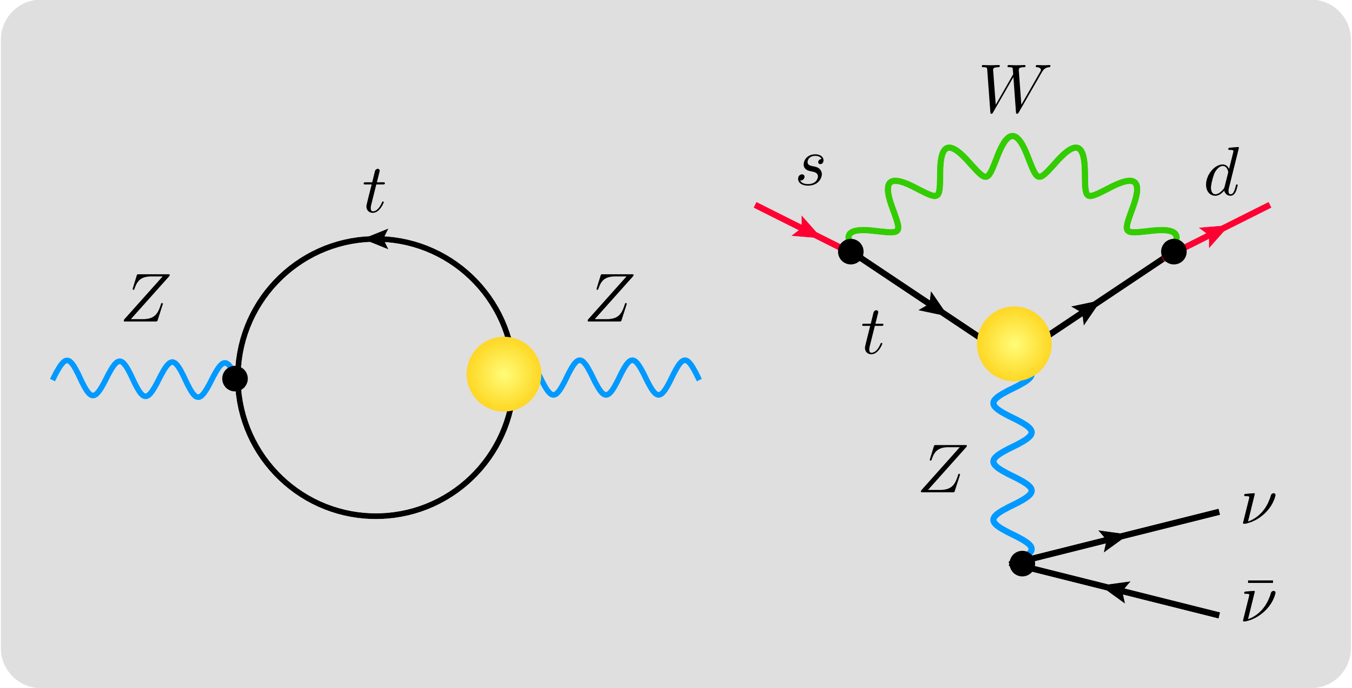
$$g'_L \propto \frac{v^2}{\Lambda^2} \left(C^{(3)}_{\phi Q} + C_{\phi Q} \right) \simeq 0 \,, \qquad k_L \propto \frac{v^2}{\Lambda^2} C^{(3)}_{\phi Q} = -0.006 \pm 0.038$$

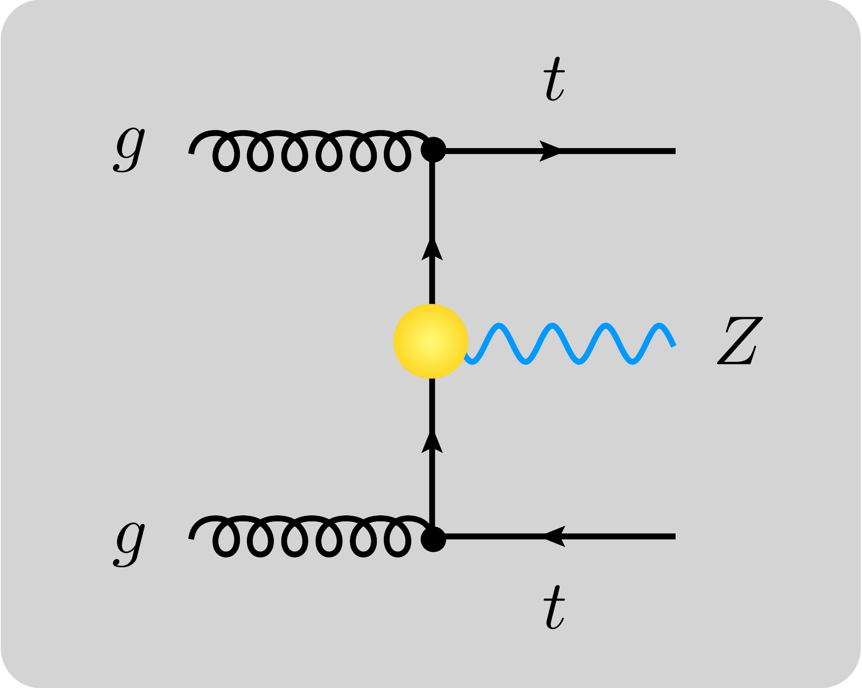




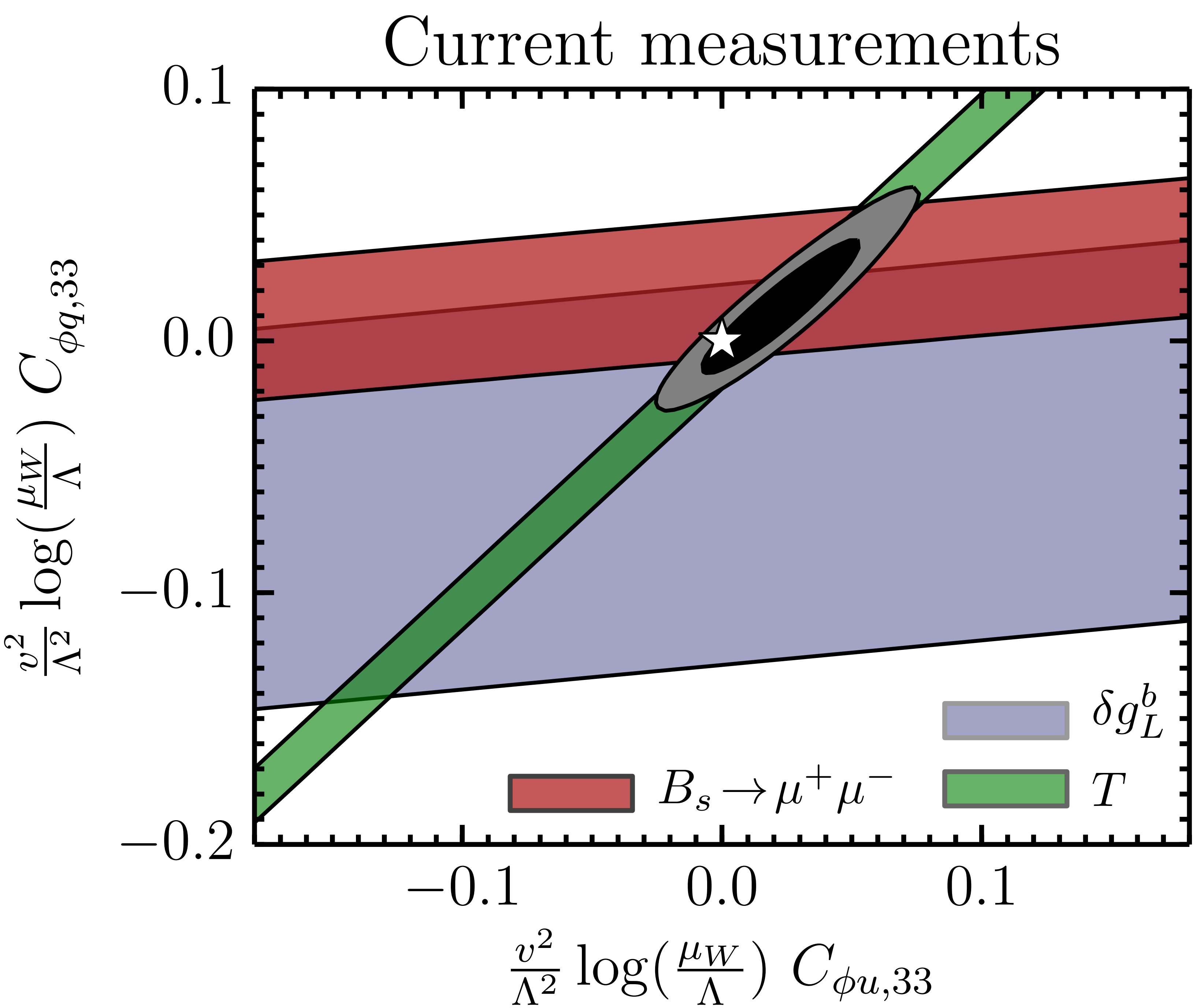
Open tt̄Z couplings

$$g_L \propto \frac{v^2}{\Lambda^2}\left(C^{(3)}_{\phi Q} - C_{\phi Q}\right) , \qquad g_R \propto \frac{v^2}{\Lambda^2} C_{\phi u}$$





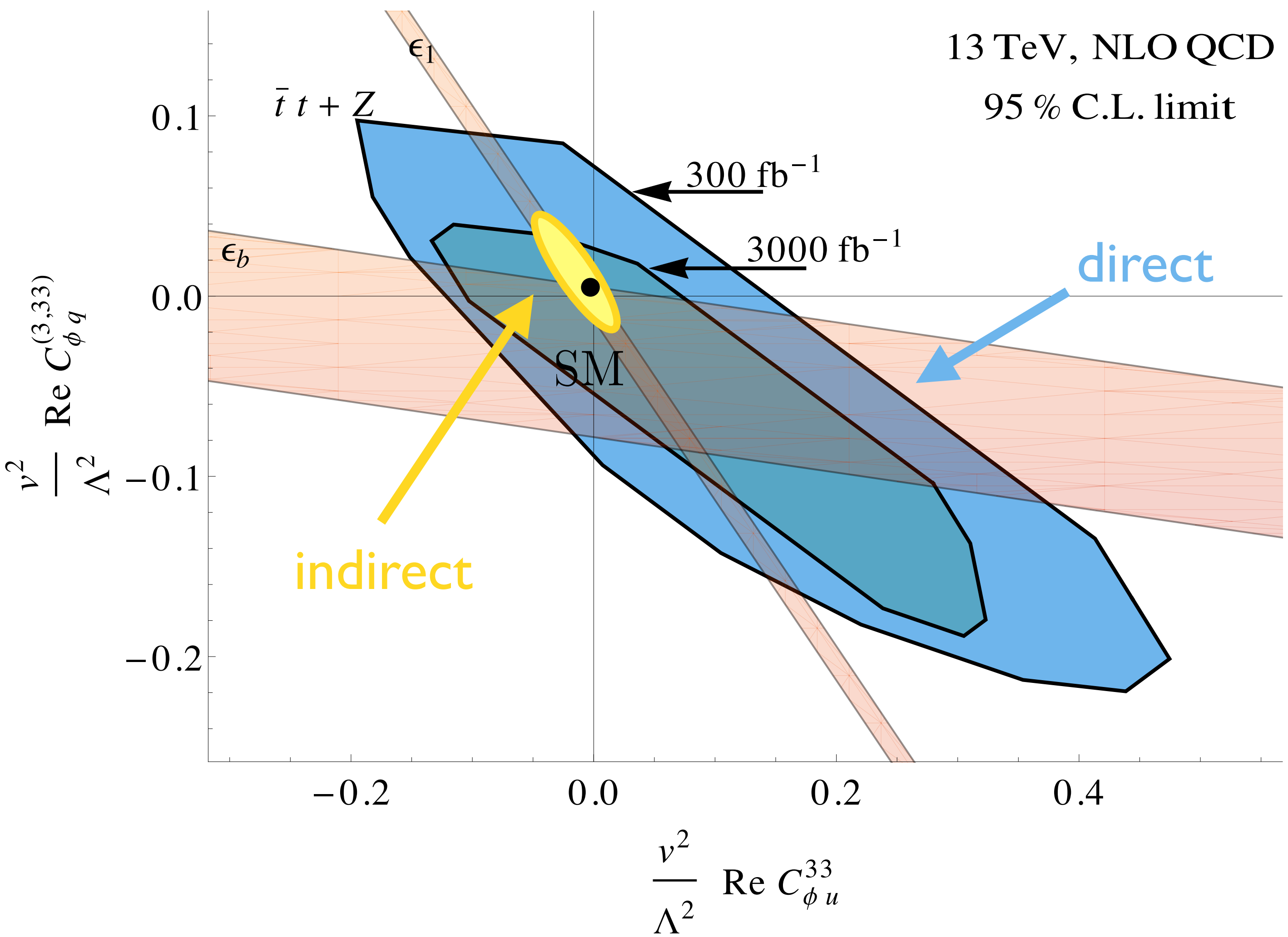
$t\bar{t}Z$ couplings: indirect tests



[Brod et al., 1408.0792]

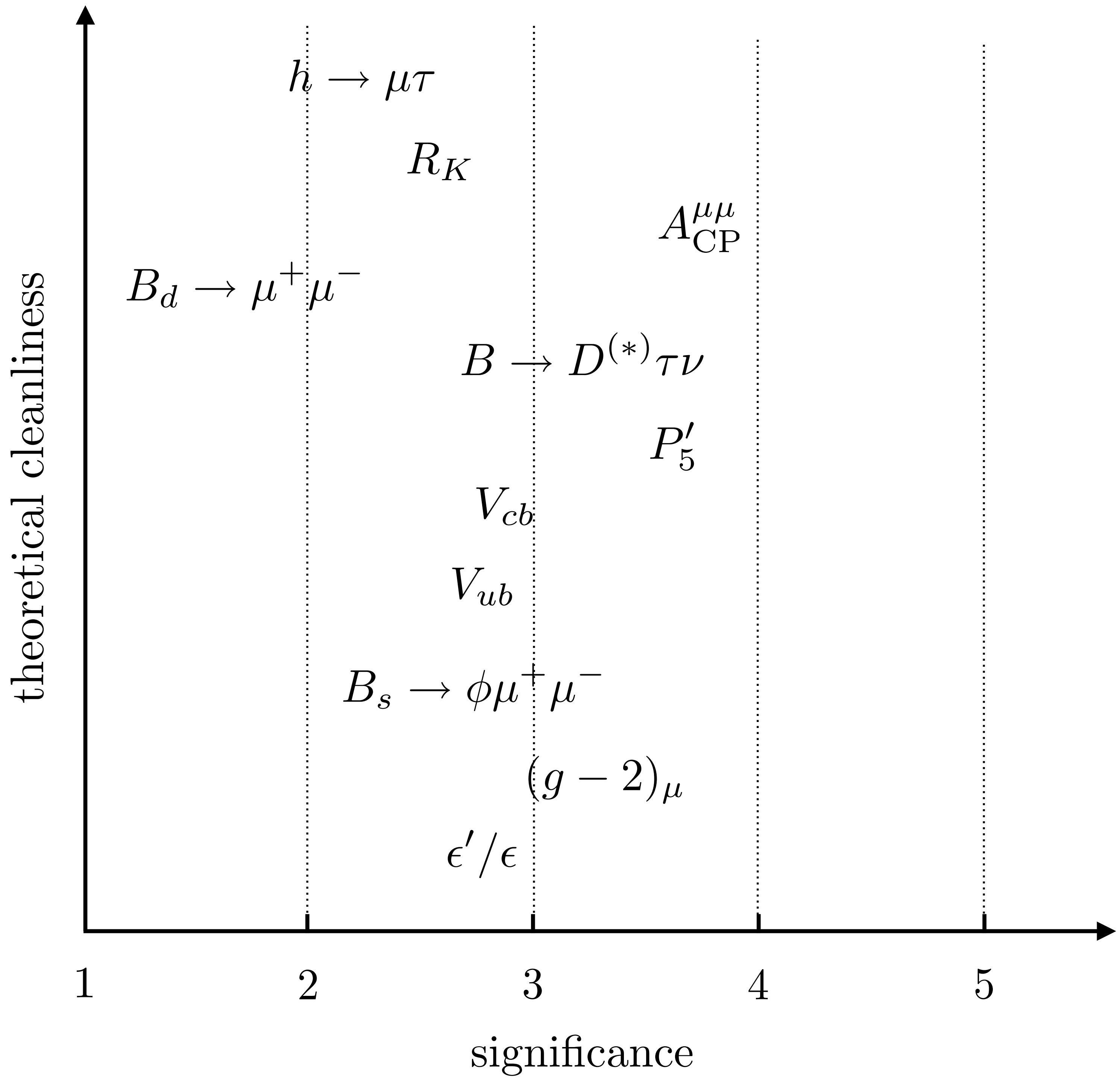
$t\bar{t}Z$ couplings: Comparison

[Röntsch & Schulze, 1404.1005]



- Indirect bounds stronger than direct limits for $t\bar{t}Z$ couplings. Still worth looking at $pp \to t\bar{t}Z$, as cancellation in former case possible

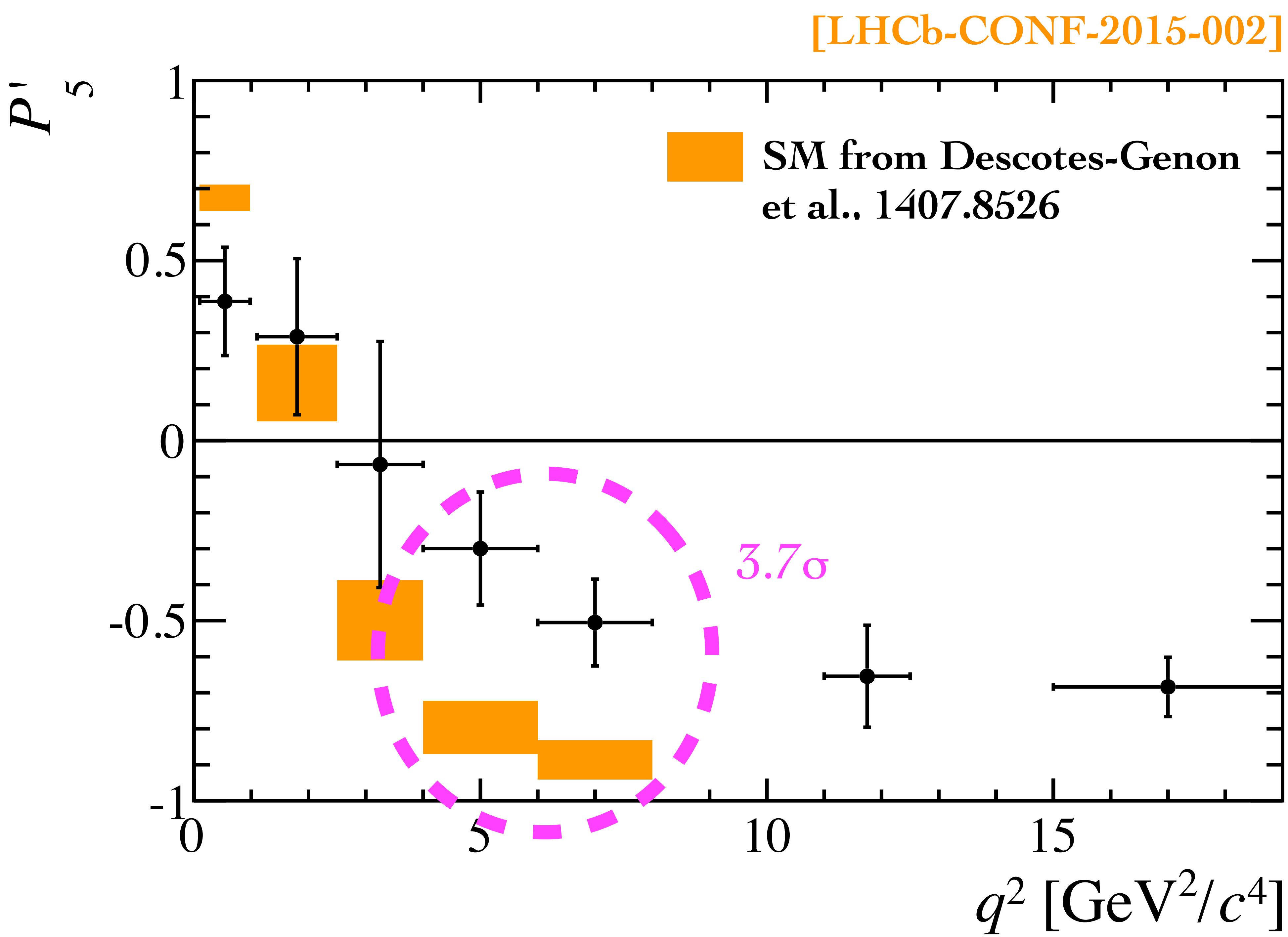
Flavor anomalies



Flavor anomalies

- No new-physics model can simultaneously explain all anomalies
- Notoriously difficult to construct new physics that accommodates deviations in like-sign dimuon CP asymmetry ($A_{CP}^{\mu\mu}$) & V_{cb}, V_{ub}
- Progress in lattice gauge theory will improve understanding of for instance ε'/ε & $(g\text{-}2)_\mu$, so keep an eye on “R-rated” quantities
- In following will only discuss anomalies in $b \to sl^+l^-$ — but have backup slides on some of other observables that show deviations

$B \to K^* \mu^+ \mu^-$ anomaly



$B \to K^* \mu^+ \mu^-$ anomaly: Errors

- Error budget of P_5' in [4, 6] GeV^2 bin:

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

parametric

non-factorizable power corrections

form factors

factorizable power corrections

long-distance $c\bar{c}$ effects

[Matias, talk at Moriond EW 2015]

$B \to K^{*}\mu^{+}\mu^{-}$ anomaly: Errors

- Dominant uncertainties of theoretical origin. What to do?

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

all errors are Gaussian

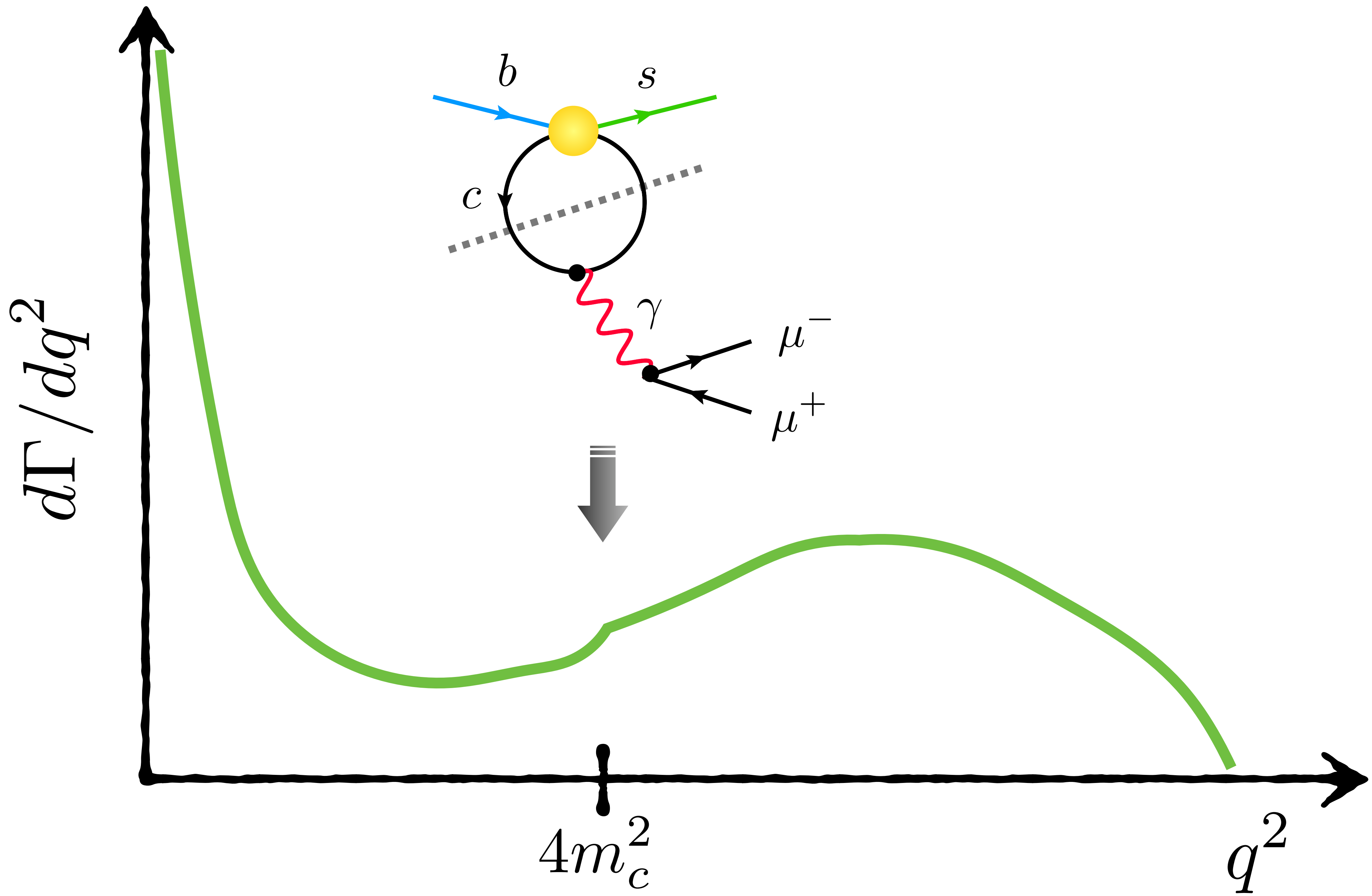
$$-0.82\,(1 \pm 13\%)$$

maybe better to add errors linearly

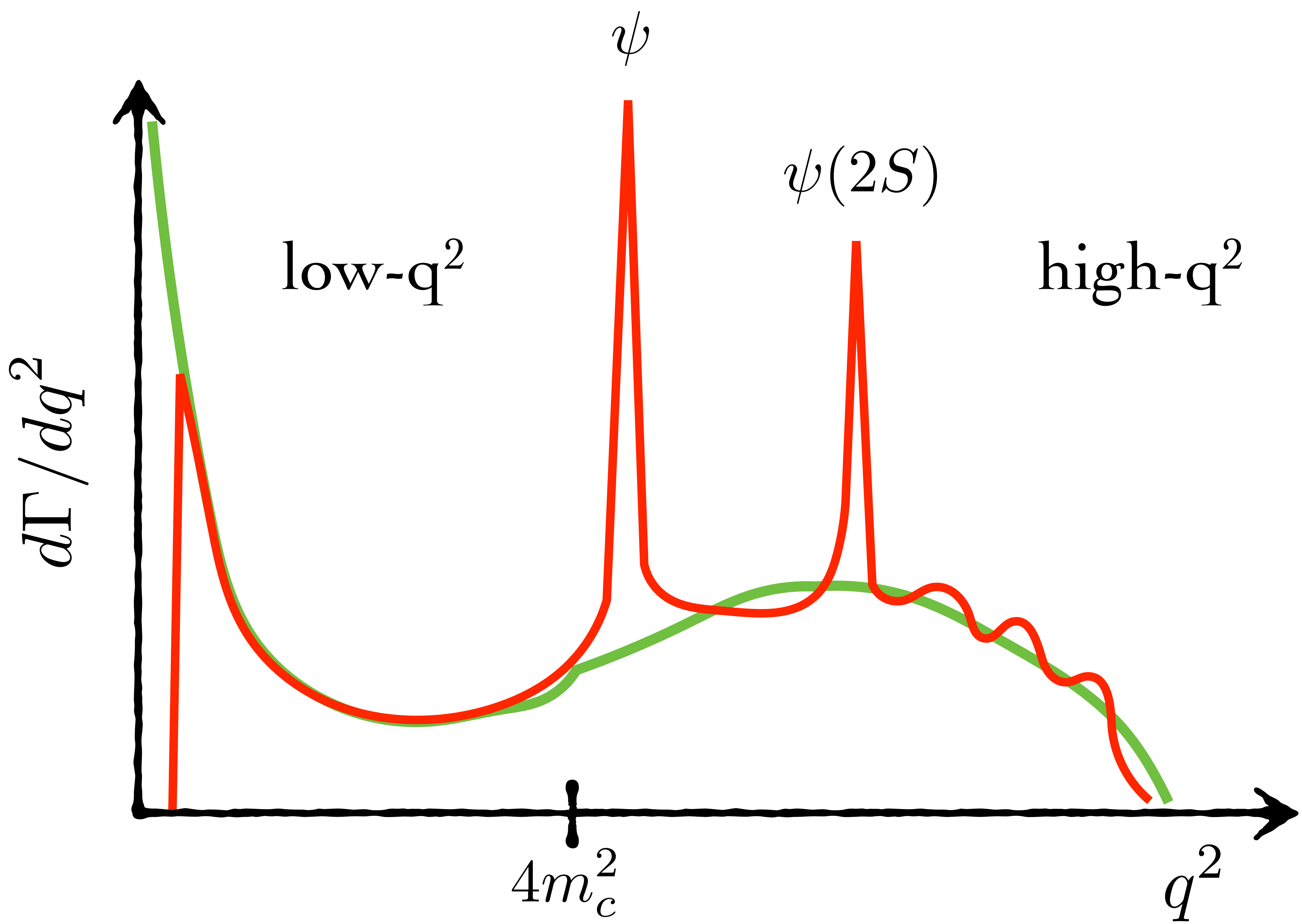
$$-0.82\,(1 \pm 26\%)$$

- Largest individual uncertainty due to long-distance $c\bar{c}$ effects. What is the problem & what does this mean for the error?

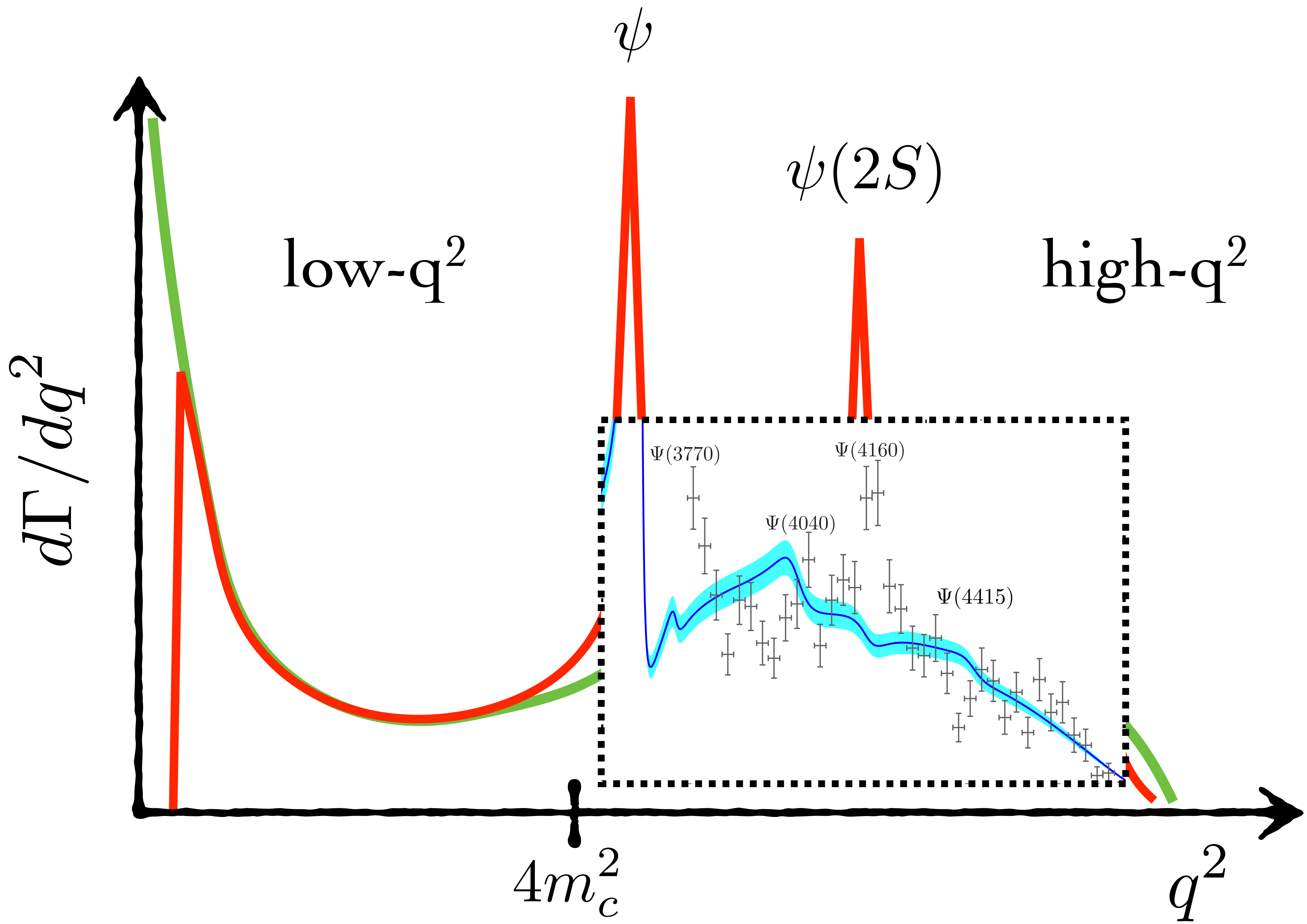
In an ideal world ...



… in reality

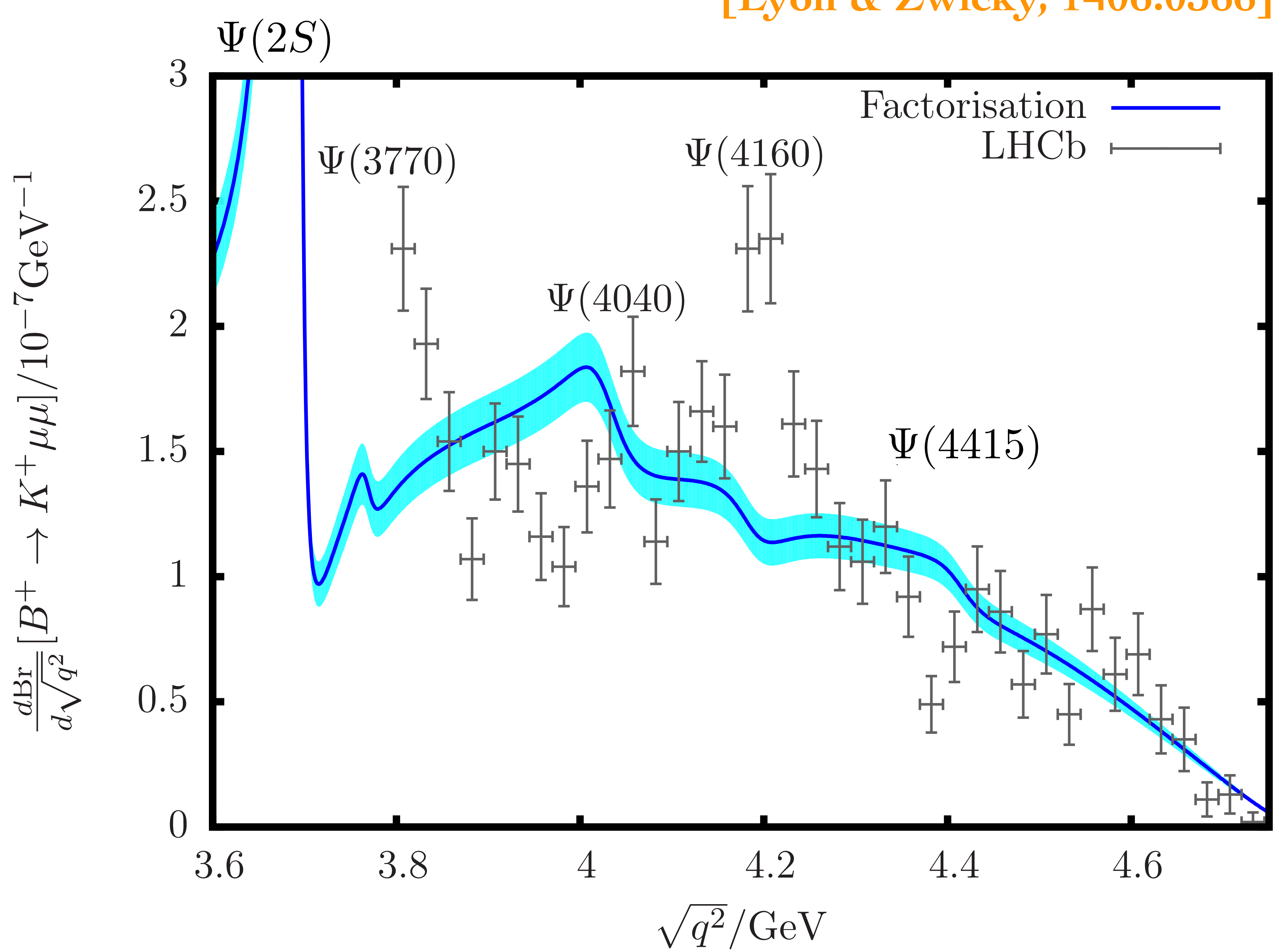


A closer look

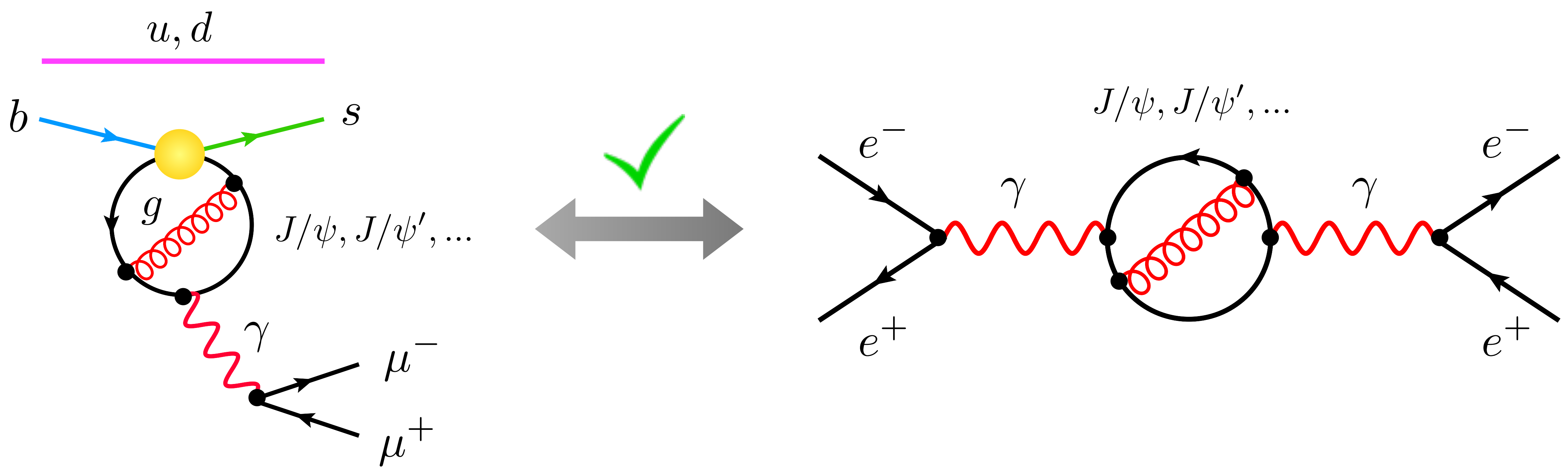


Resonances gone topsy-turvy

[Lyon & Zwicky, 1406.0566]

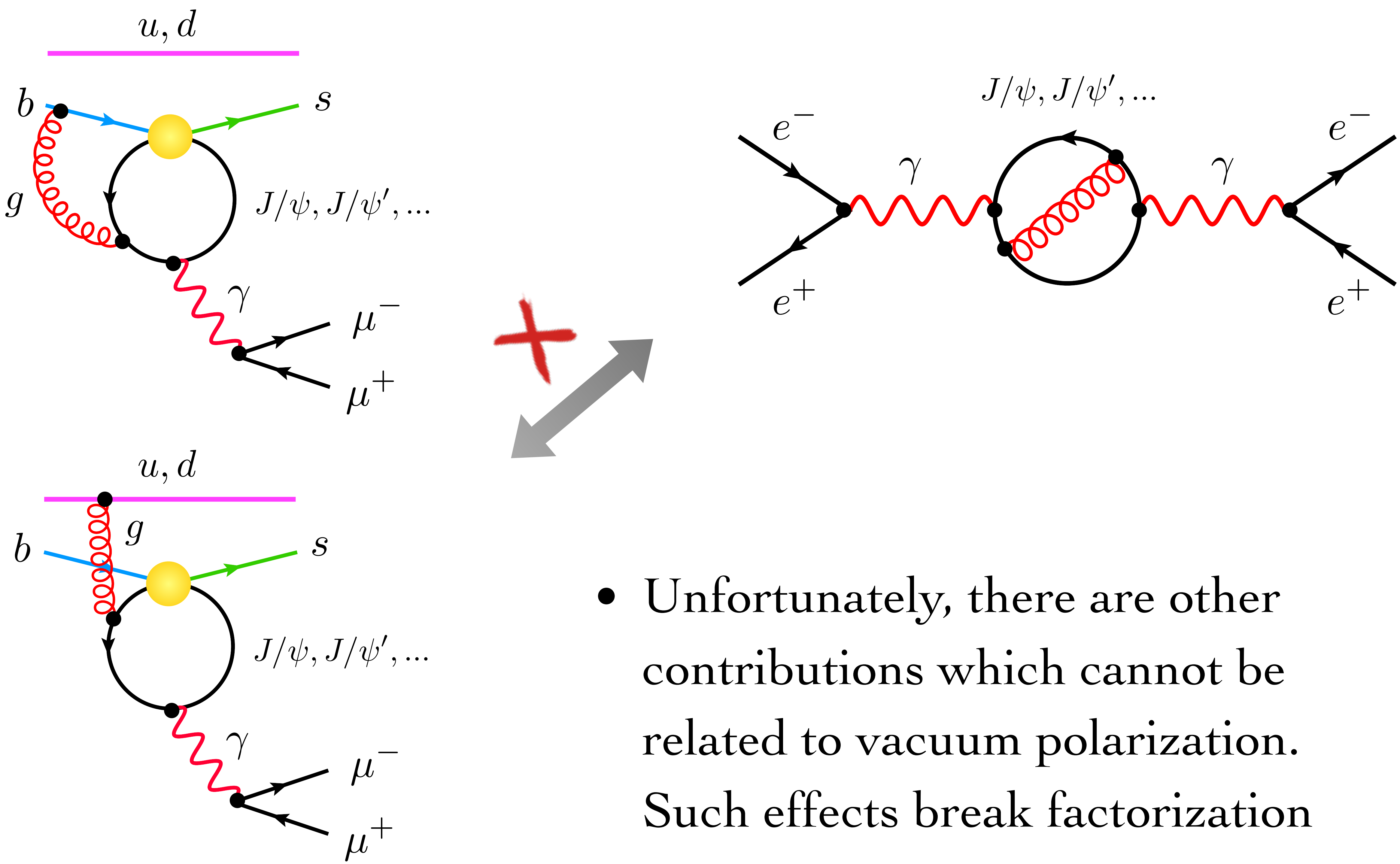


Breakdown of factorization



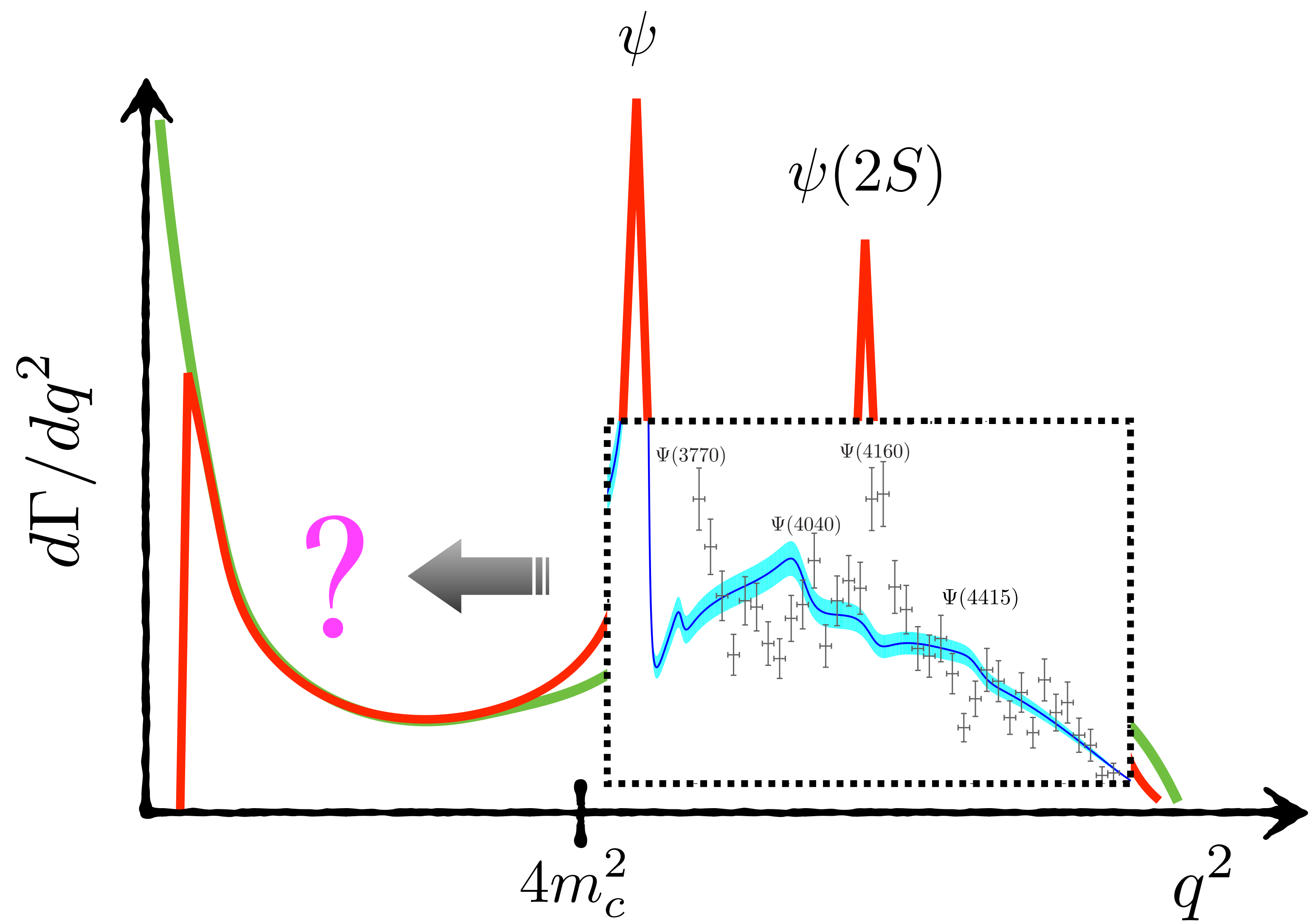
- Factorizable effects can be related to (full non-perturbative) charm vacuum polarization via a standard dispersion relation & extracted from BESII data on $e^+e^- \to$ hadrons

Breakdown of factorization



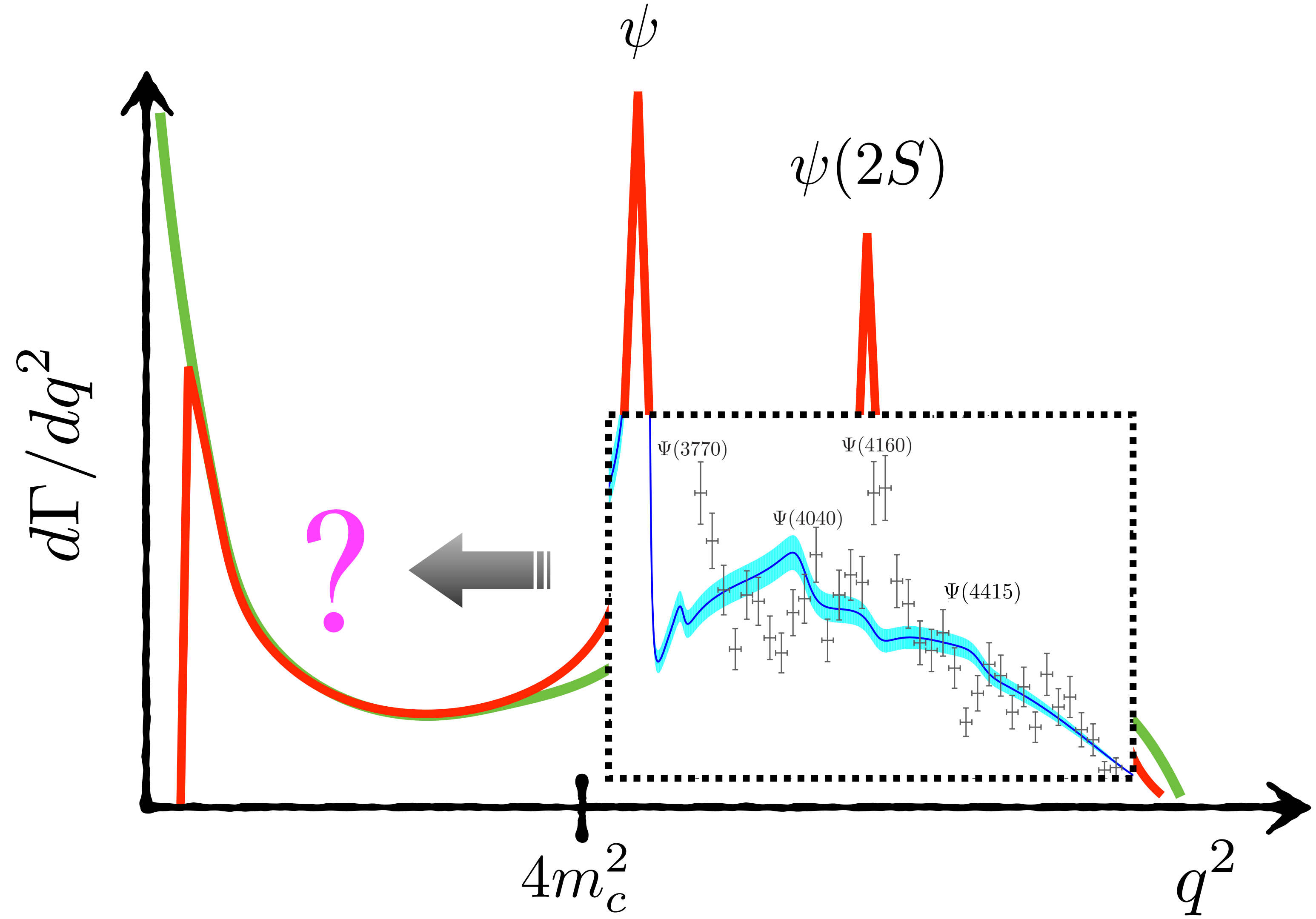
- Unfortunately, there are other contributions which cannot be related to vacuum polarization. Such effects break factorization

Breakdown of factorization



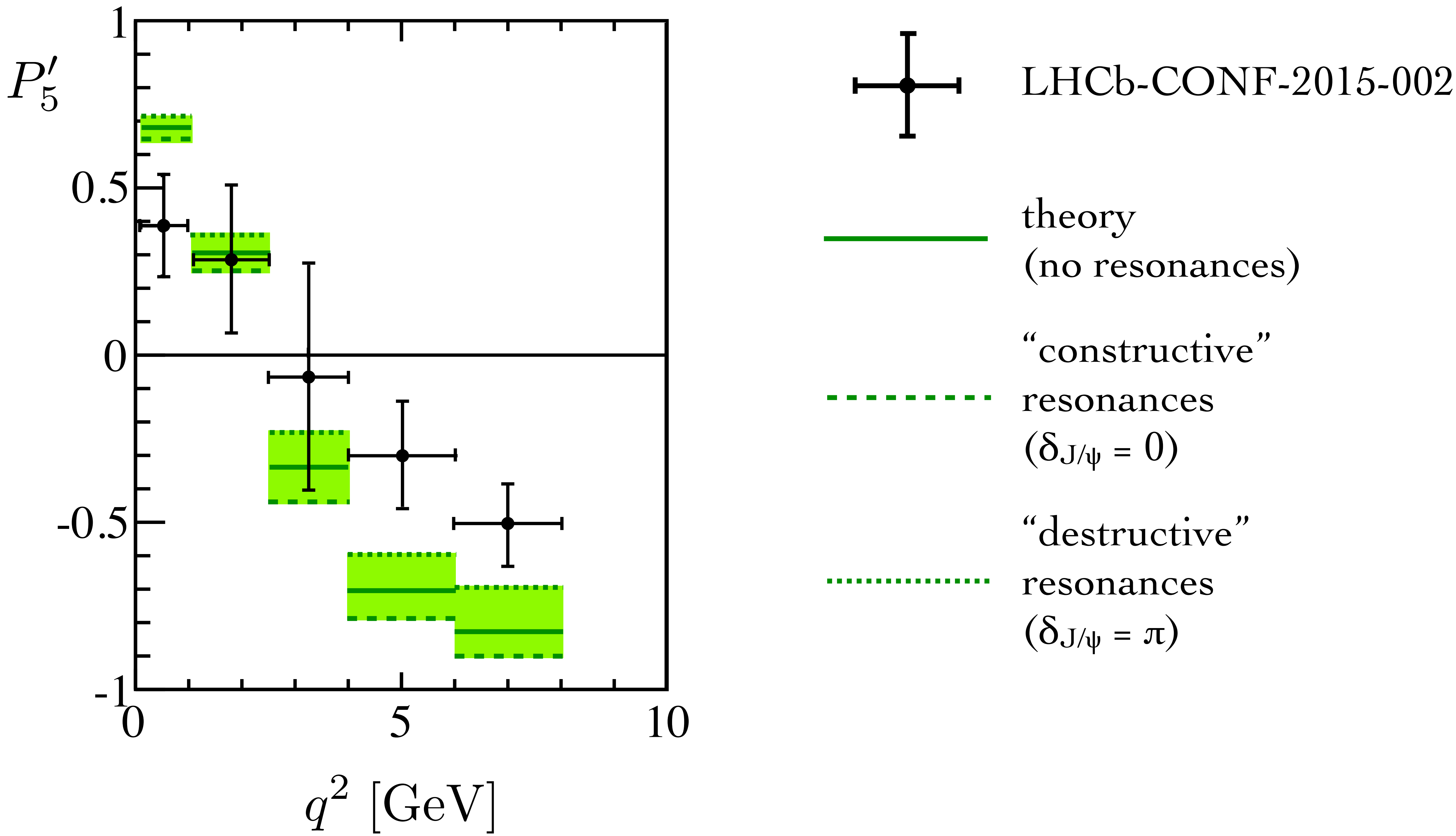
- As we are dealing with strong coupling, not a big surprise that factorization is badly broken in resonance region. To which extent does this pollute $B \to K^*\mu^+\mu^-$ observables at low q^2?

Breakdown of factorization



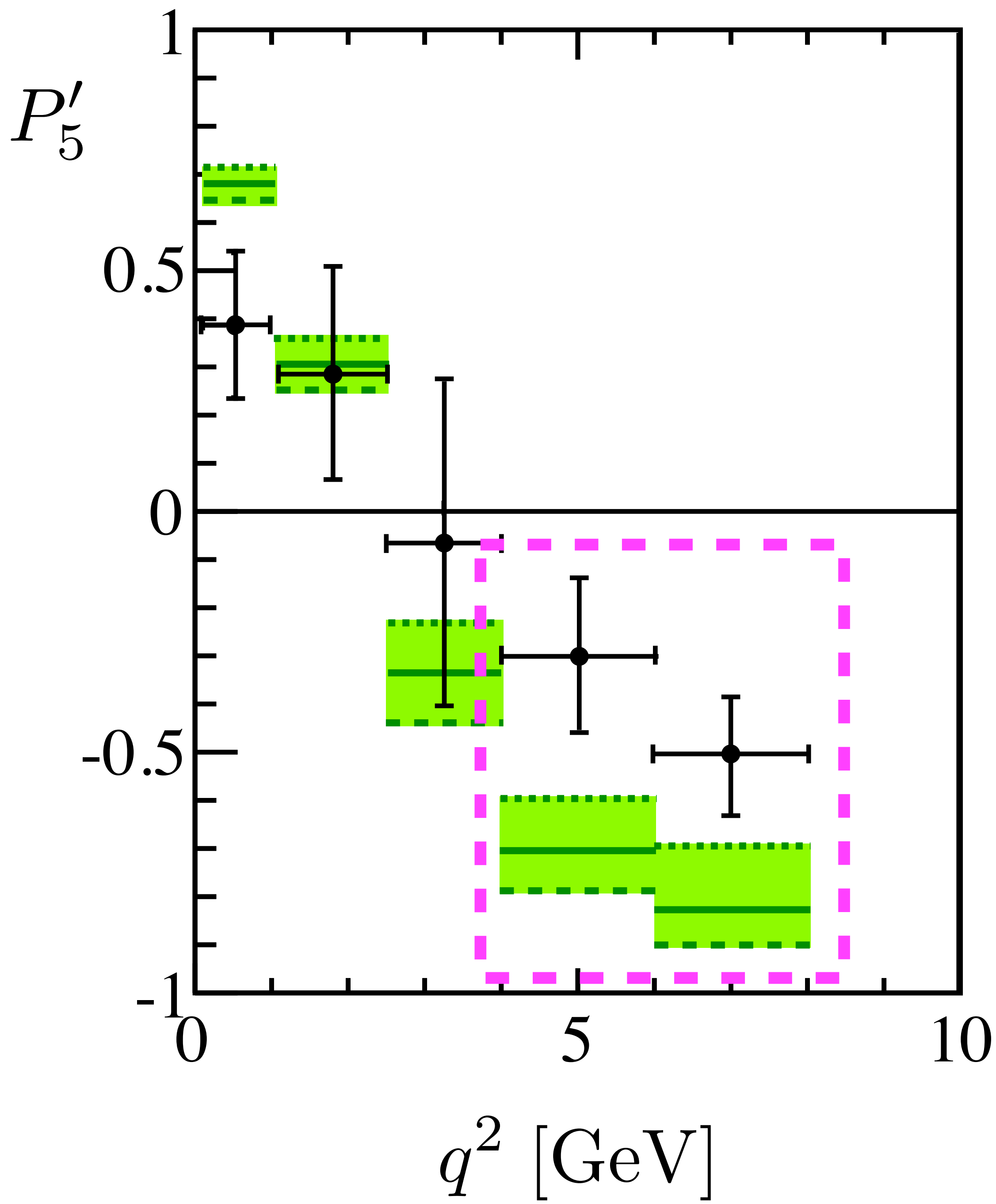
- At present, question cannot be answered from first principles. But can use models to calculate size of pollution & may utilize information to arrive at a guesstimate of induced theory error

My error guesstimates



[UH based on light-cone sum rule calculation of Khodjamirian et al., 1006.5045]

My error guesstimates



- My guesstimate gives an uncertainty of 14% in bin 4 & 5 from $c\bar{c}$ effects only — i.e. larger than total Gaussian error quoted before

- Topsy-turvy analysis suggests even much larger $c\bar{c}$ effects, potentially resolving anomaly — I think that this “model” is more shaky than my guess

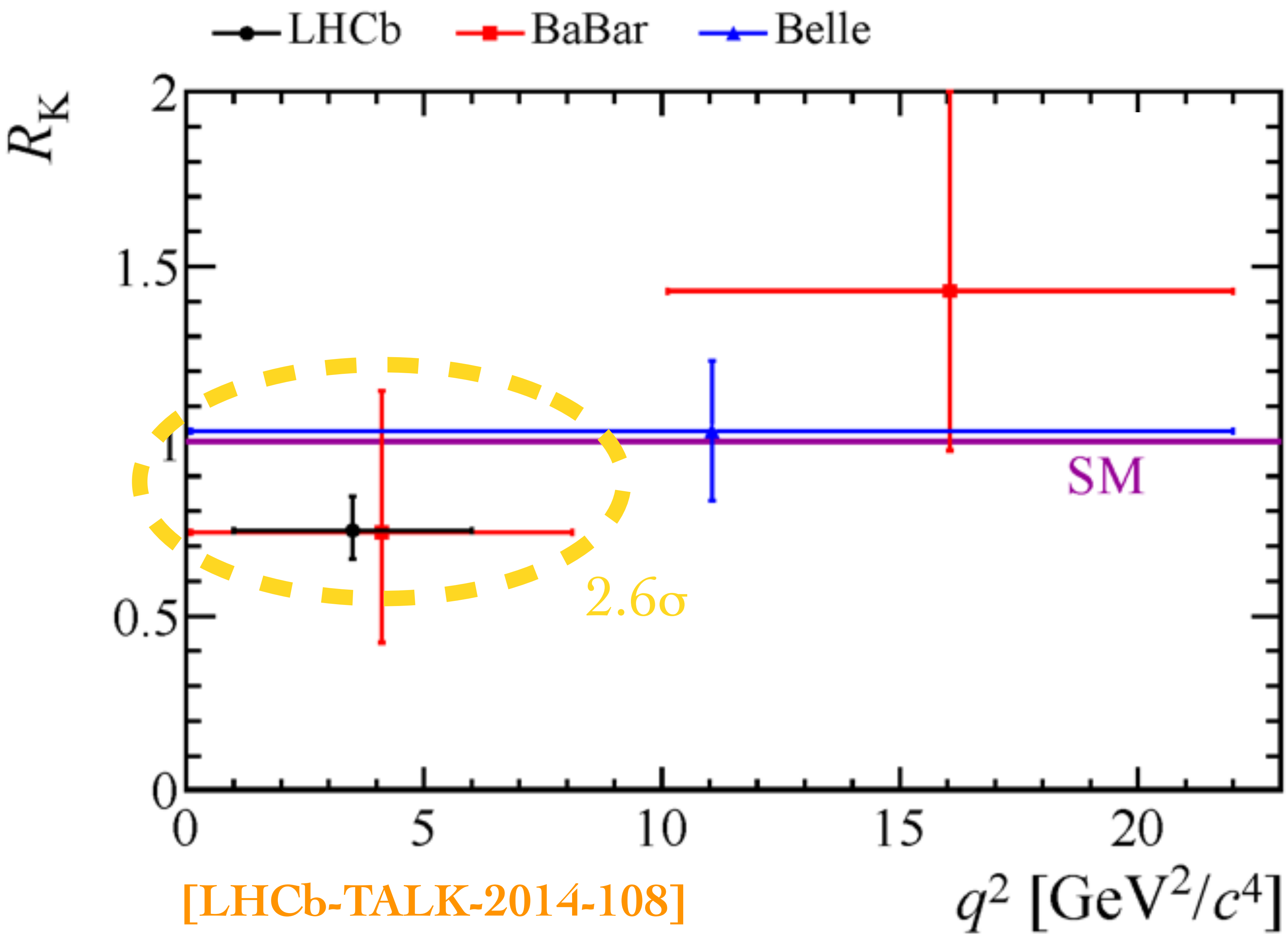
[UH based on light-cone sum rule calculation of Khodjamirian et al., 1006.5045]

My error guesstimates

- In my opinion my exercise indicates that theory uncertainties in some analysis are too small — by how much is hard to say

- Notice that one could gain already quite a bit, if one could pin down whether interference between long-distance & short-distance physics is constructive or destructive. All ideas are very welcome!

R_K anomaly



[LHCb-TALK-2014-108]

Maybe R_K not alone

$$R_{X_s} = \frac{\int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2} dq^2 \, \frac{d\Gamma\left(B \to X_s \mu^+ \mu^-\right)}{dq^2}}{\int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2} dq^2 \, \frac{d\Gamma\left(B \to X_s e^+ e^-\right)}{dq^2}} = 0.34 \pm 0.16$$

$$R_{X_s}^{\mathrm{SM}} = 1 - 4.3\%$$

⟷ 3.9σ

[http://belle.kek.jp/belle/theses/doctor/2009/Nakayama.pdf]

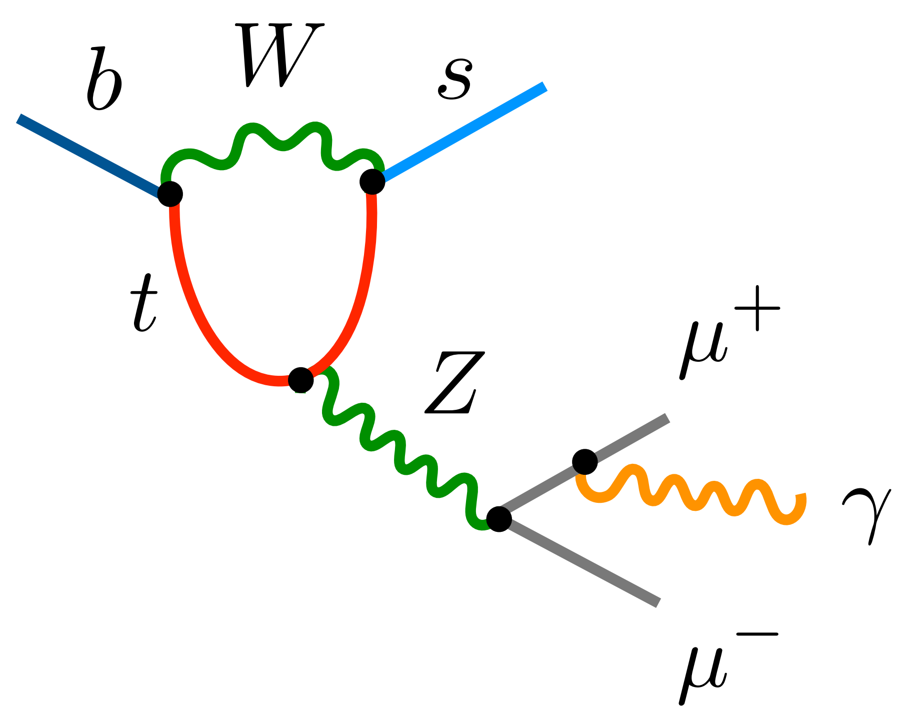
R_K: null test in SM?

$$R_K^{\mathrm{SM}} = 1 + \mathcal{O}\left(\frac{m_\mu^2}{m_b^2}\right) = 1.0003 \pm 0.0001$$

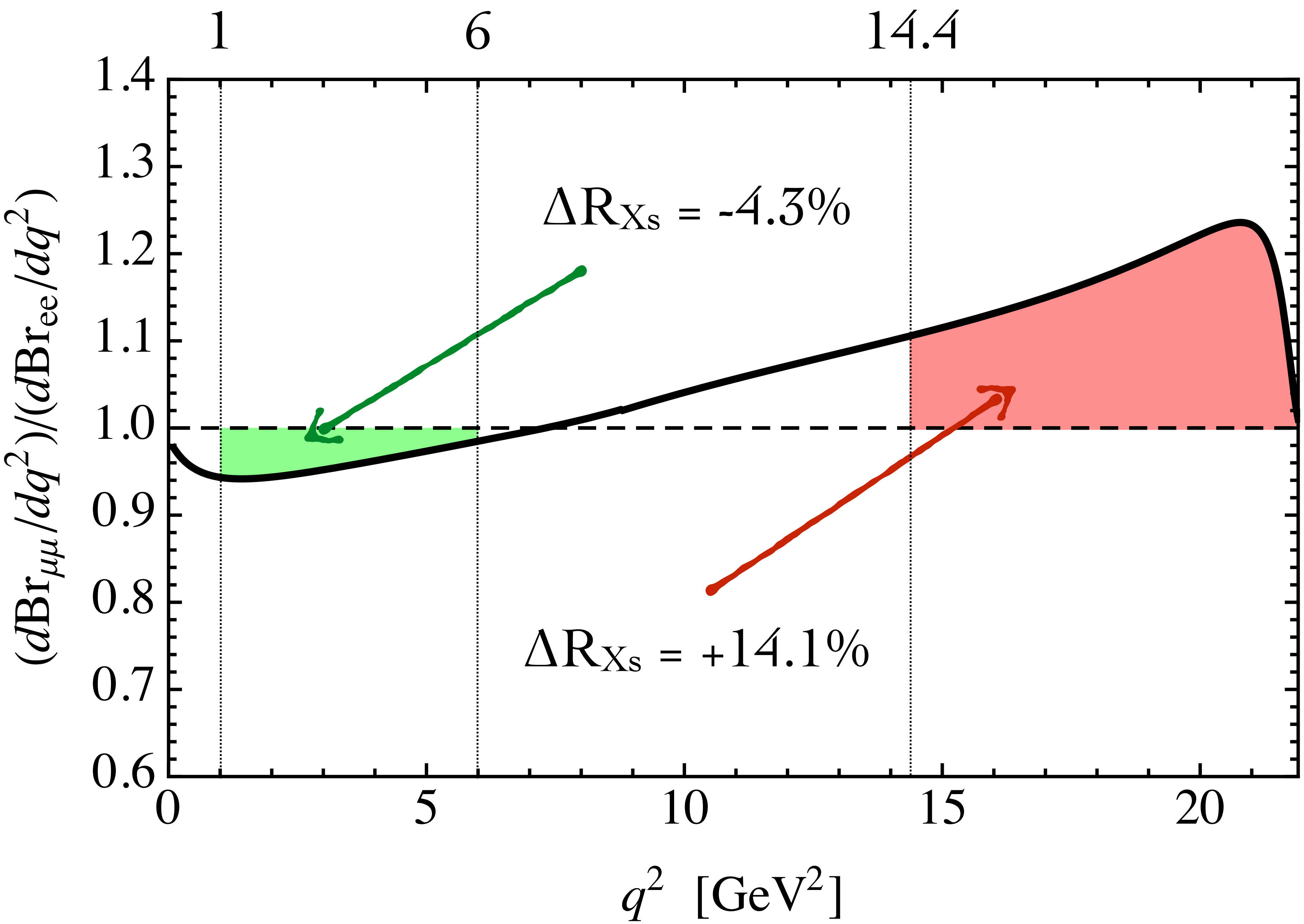
[Bobeth et al., arXiv:0709.4174]

R_K: null test in SM?

$$R_K^{\rm SM} = 1 + \mathcal{O}\left(\frac{m_\mu^2}{m_b^2}\right) + \mathcal{O}\left(\alpha \ln \frac{m_\mu^2}{m_b^2}\right) = 1 + \mathcal{O}(0.01)$$

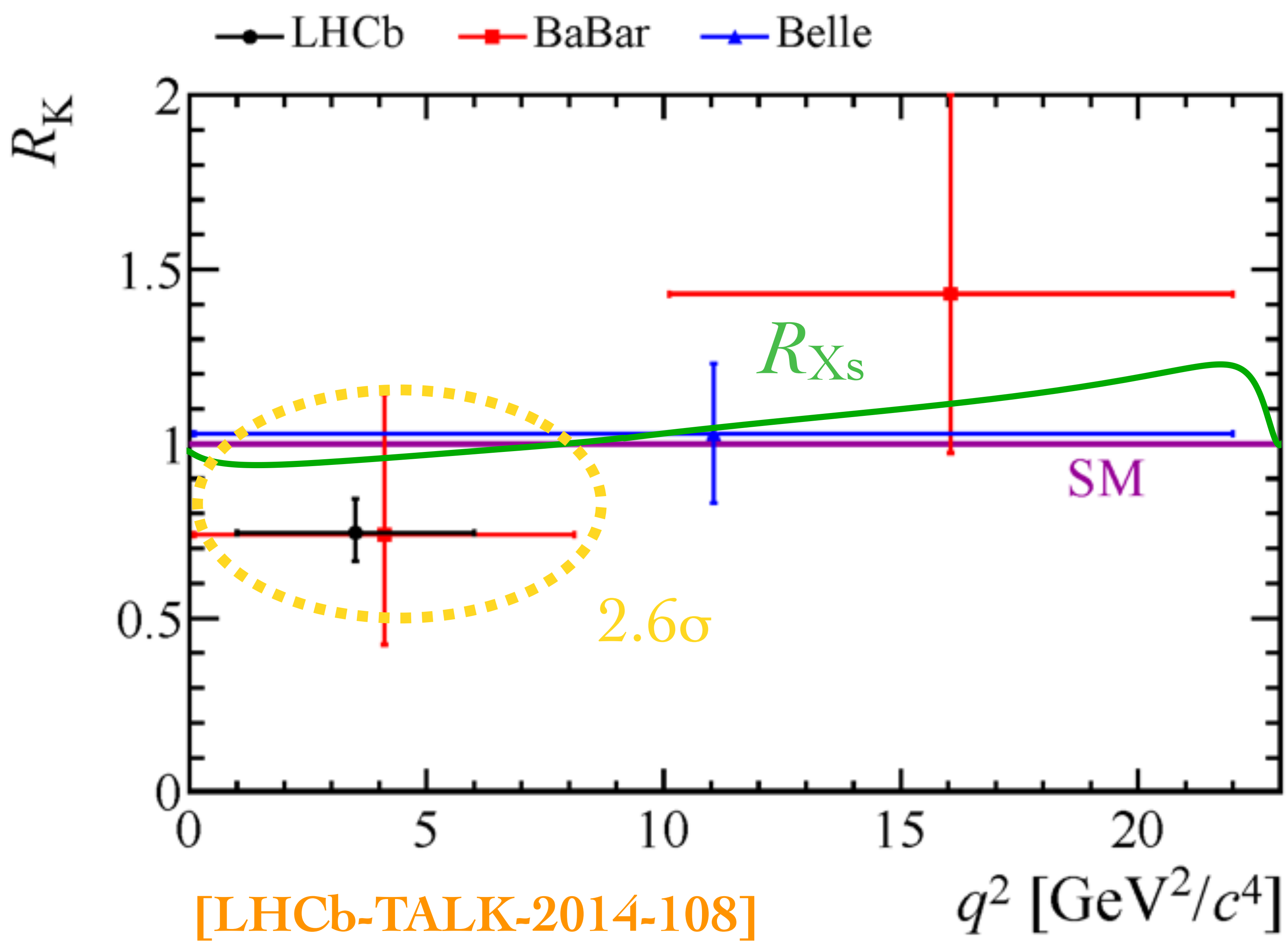


How big is O(0.01)?



[UH based on Huber et al., hep-ph/0510266]

How big is O(0.01)?



[LHCb-TALK-2014-108]

- Naive inclusion of collinear QED logarithms (from R_{Xs}) fails to explain anomaly, but corrections seem to improve tension in R_K

In practice …

- … things are again much more complicated:
  - Ratio between $B^+ \to K^+\mu^+\mu^-$ & $B^+ \to K^+e^+e$ not directly measured, but a double ratio involving $B^+ \to J/\psi\ (\to l^+l^-)\ K^+$ — this is necessary because for each electron pair LHCb "sees" O(50) muon pairs
  - To correct for this mismatch, LHCb uses a Monte Carlo (PHOTOS), which contains QED effects. Bremsstrahlungs photons are also part of detector simulation
- What SM prediction would one get if one uses full LHCb chain to calculate R_K instead of taking $R_K = 1$ from literature?

If its new physics, it should nail it!

Fit to 88 $b \to s\mu^+\mu^-$ observables

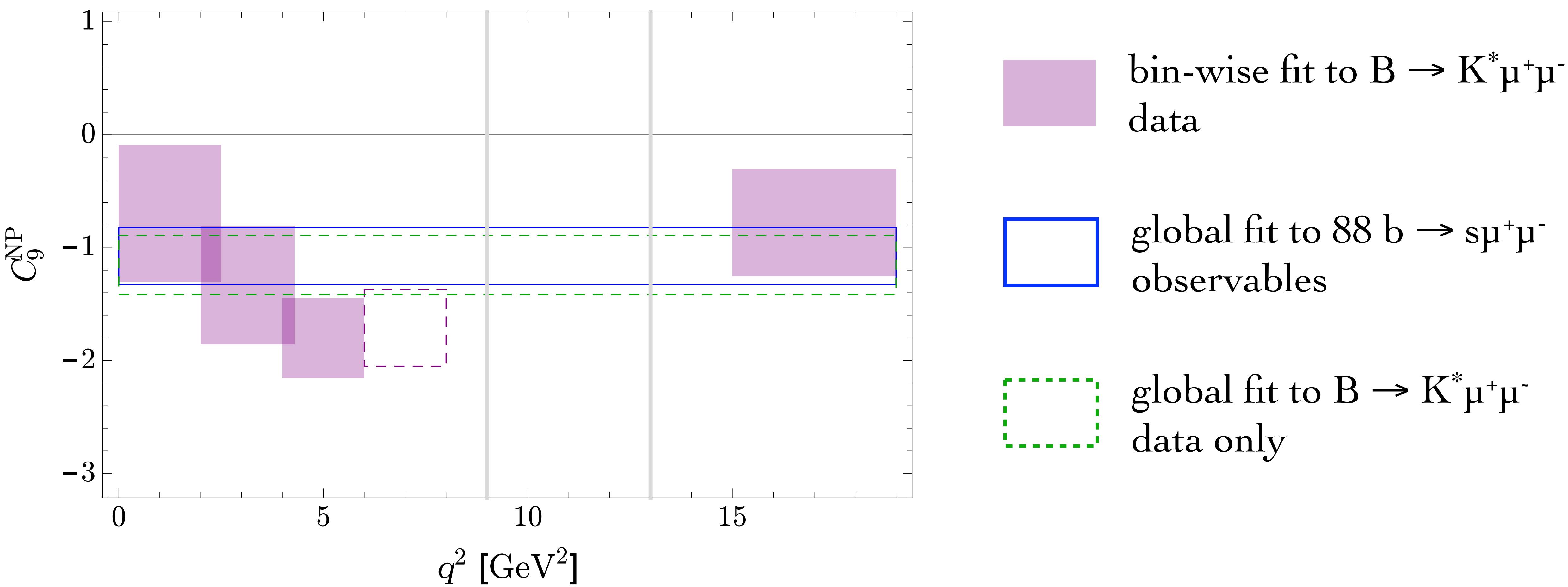
[Altmannshofer & Straub, 1503.06199]

Coeff.	best fit	1σ	2σ	$\sqrt{\chi^2_{\text{b.f.}} - \chi^2_{\text{SM}}}$	p [%]
C_7^{NP}	-0.04	$[-0.07, -0.01]$	$[-0.10, 0.02]$	1.42	2.4
C_7'	0.01	$[-0.04, 0.07]$	$[-0.10, 0.12]$	0.24	1.8
C_9^{NP}	-1.07	$[-1.32, -0.81]$	$[-1.54, -0.53]$	3.70	11.3
C_9'	0.21	$[-0.04, 0.46]$	$[-0.29, 0.70]$	0.84	2.0
C_{10}^{NP}	0.50	$[0.24, 0.78]$	$[-0.01, 1.08]$	1.97	3.2
C_{10}'	-0.16	$[-0.34, 0.02]$	$[-0.52, 0.21]$	0.87	2.0
$C_9^{\text{NP}} = C_{10}^{\text{NP}}$	-0.22	$[-0.44, 0.03]$	$[-0.64, 0.33]$	0.89	2.0
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	-0.53	$[-0.71, -0.35]$	$[-0.91, -0.18]$	3.13	7.1
$C_9' = C_{10}'$	-0.10	$[-0.36, 0.17]$	$[-0.64, 0.43]$	0.36	1.8
$C_9' = -C_{10}'$	0.11	$[-0.01, 0.22]$	$[-0.12, 0.33]$	0.93	2.0

- Since p-value of SM is 2.1%, no solution really nails it. Scenario with a -25% shift in C_9 (vector current) preferred

A line is a line, is a line, is a line

[Altmannshofer & Straub, 1503.06199]



- If $B \to K^*\mu^+\mu^-$ anomalies due to new physics, best-fit values for C_9 should be q^2-independent. If effect grows towards resonance region smells like long-distance $c\bar{c}$ effect

First main message

At present only real parts of Wilson coefficients bounded by global fits of $b \to s\gamma$ & $b \to sl^+l^-$ data. Weak sensitivity to $\mathrm{Im}(C_7^{(\prime)})$ from time-dependent CP asymmetry $S_{K^*\gamma}$. An important future goal of LHCb has to be measurements of CP-violating observables in $B \to K^*\mu^+\mu^-$, … . Looking at $B \to K^*\mu^+\mu^-/e^+e^-$ also mandatory because channels over theoretically clean way to extract C_7'

Second main message

If only $SU(2)_L \times U(1)_Y$ invariant operators are present get:

$$\Delta C_9 \ll \Delta C_{10} \quad \text{or} \quad \Delta C_9 = \pm \Delta C_{10}$$

Neither pattern is preferred by fit & therefore new-physics models such as MSSM & simple-minded realisations of compositeness, lepto-quark scenarios, ... seem disfavored. Observed deviations can be addressed in Z'-boson models that have vector-like couplings to muons

Proposed Z' models

<u>“3-3-1” model</u>

$$SU(3)_L \times U(1)_X$$

$$\downarrow v_\chi \gg v$$

$$SU(2)_L \times U(1)_Y$$

$$\downarrow v_\rho, v_\eta \ll v_\chi$$

$$U(1)_Q$$

[Gauld et al., 1310.1082;
Buras et al., 1311.6729]

<u>“L_μ-L_τ” model</u>

$$SU(2)_L \times U(1)_Y \times U(1)_{L_\mu - L_\tau}$$

$$\downarrow v_\Phi \gg v$$

$$SU(2)_L \times U(1)_Y$$

$$\downarrow v$$

$$U(1)_Q$$

[Altmannshofer et al., 1403.1269;
Crivellin et al., 1501.00993, 1503.03477]

Proposed Z' models

<u>"3-3-1" model</u>

- $l\bar{l}Z'$ couplings almost vector-like after suitable charge normalization
- $s\bar{b}Z'$ couplings can be made MFV-like by alignment (favorable in view of B_s mixing)

[Gauld et al., 1310.1082;
Buras et al., 1311.6729]

<u>"L_μ-L_τ" model</u>

- At tree-level, muons & taus couple vectorially (no electron couplings)
- $s\bar{b}Z'$ vertex from mixing with vector-like quarks (mixings dialled or due to horizontal symmetries)

[Altmannshofer et al., 1403.1269;
Crivellin et al., 1501.00993, 1503.03477]

Proposed Z' models

"3-3-1" model

- P_5' anomaly explained by a Z' of 7 TeV (minimal model has Landau pole at 4 TeV, but curable)
- No explanation for R_K anomaly, since lepton couplings universal

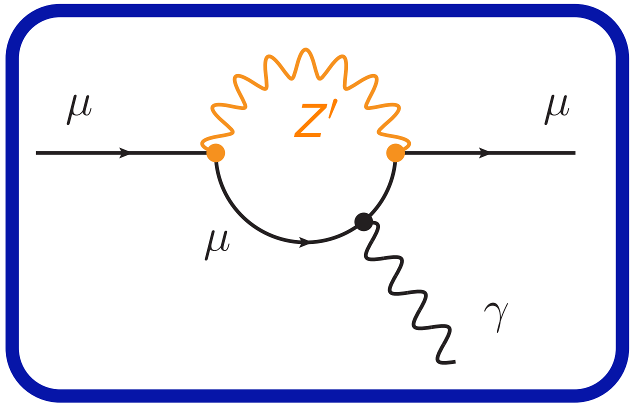
[Gauld et al., 1310.1082; Buras et al., 1311.6729]

"L_μ-L_τ" model

- If mixing is dialled, get $M_{Z'} > 40$ GeV, while if horizontal symmetries are used, Z' searches imply $M_{Z'} > 2.5$ TeV
- Both P_5' & R_K anomaly can be addressed

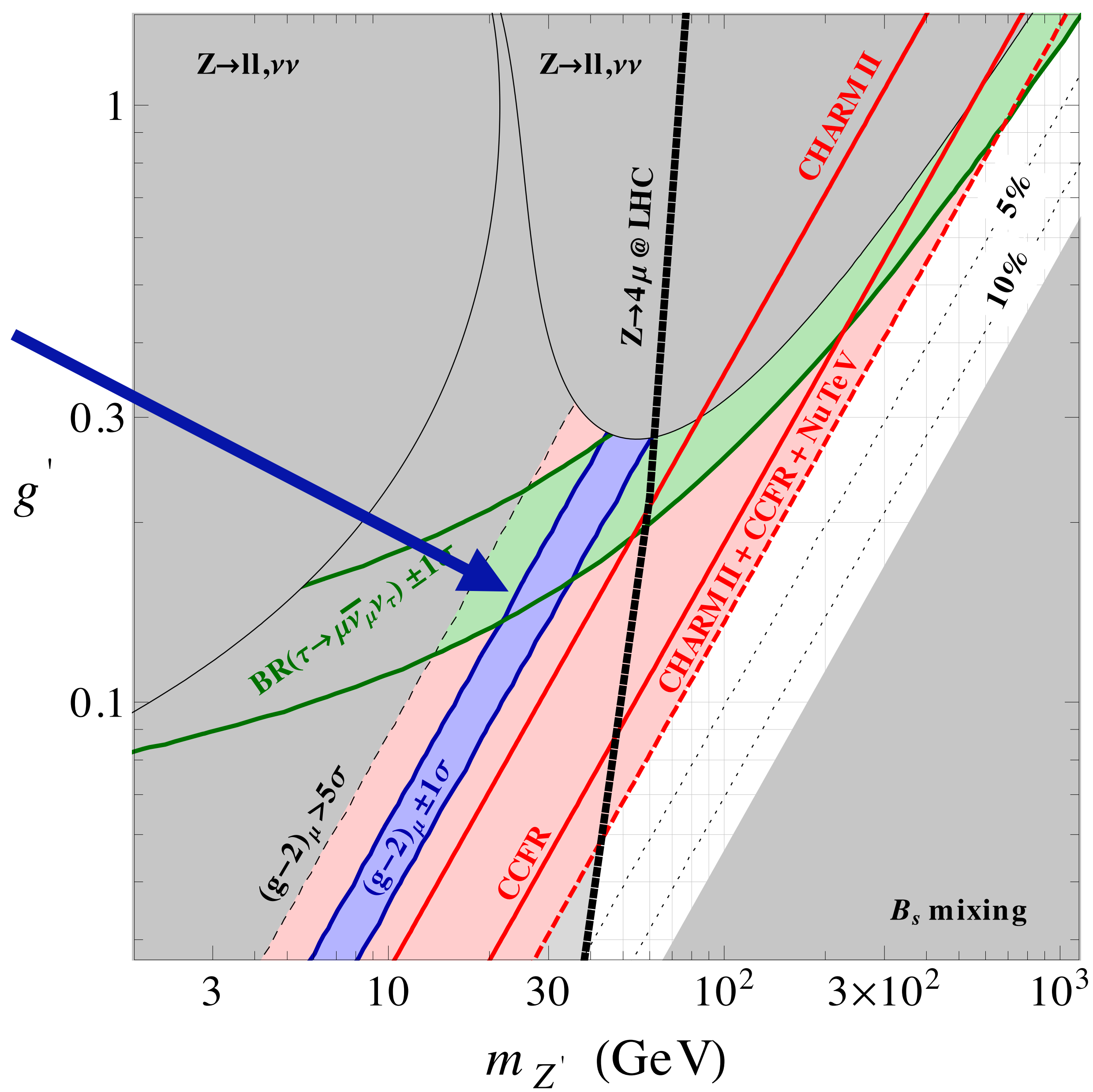
[Altmannshofer et al., 1403.1269; Crivellin et al., 1501.00993, 1503.03477]

"L_μ-L_τ" models: phenomenology



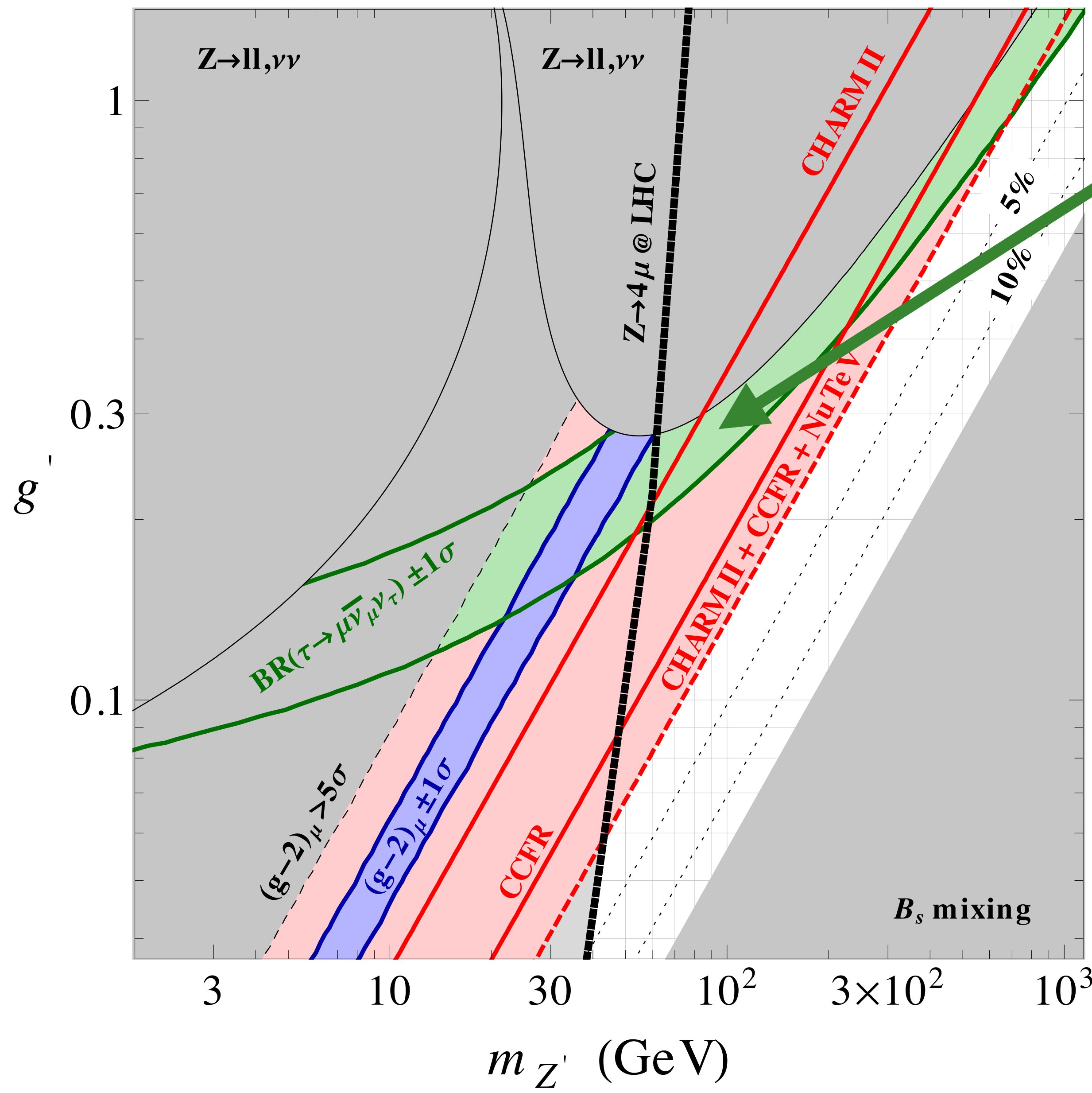
favored by
$(g\text{-}2)_\mu$ anomaly

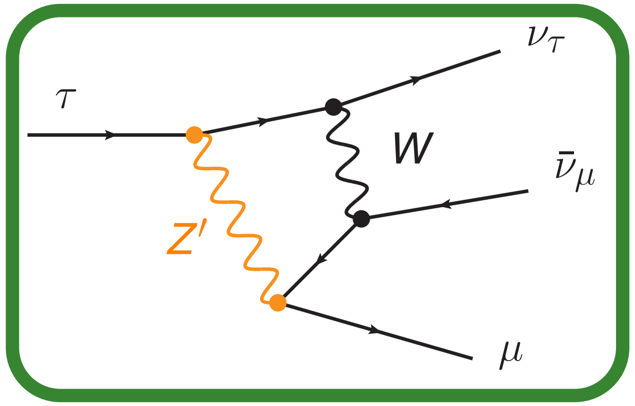
[Altmannshofer et al., 1403.1269]



"L_μ-L_τ" models: phenomenology

[Altmannshofer et al., 1403.1269]

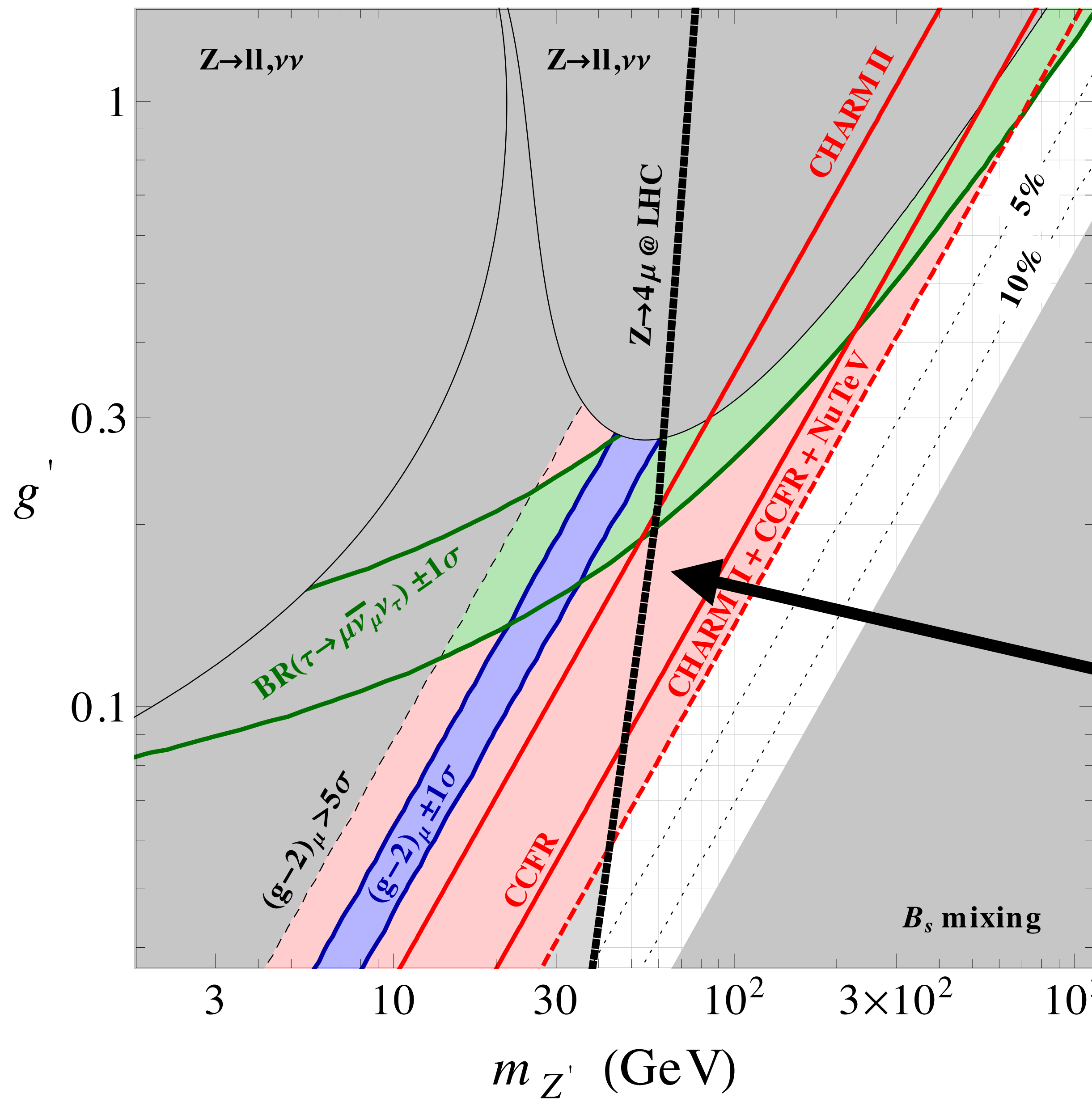


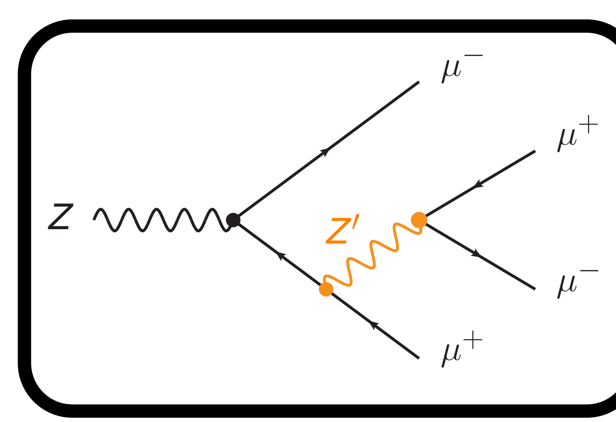


favored by anomaly in τ decay

"L_μ-L_τ" models: phenomenology

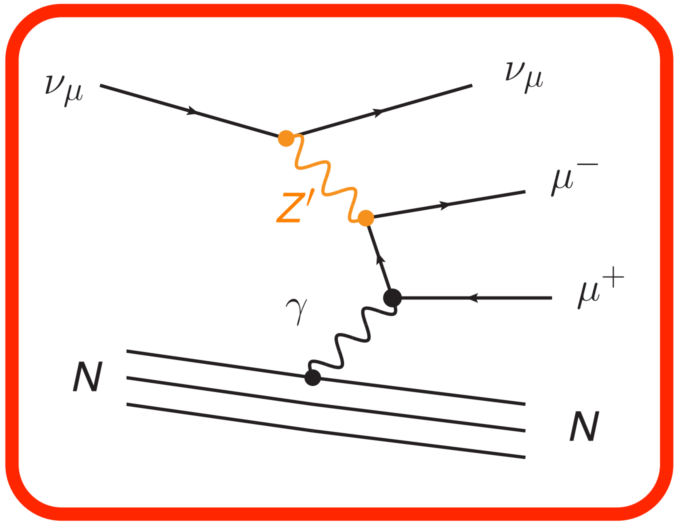
[Altmannshofer et al., 1403.1269]





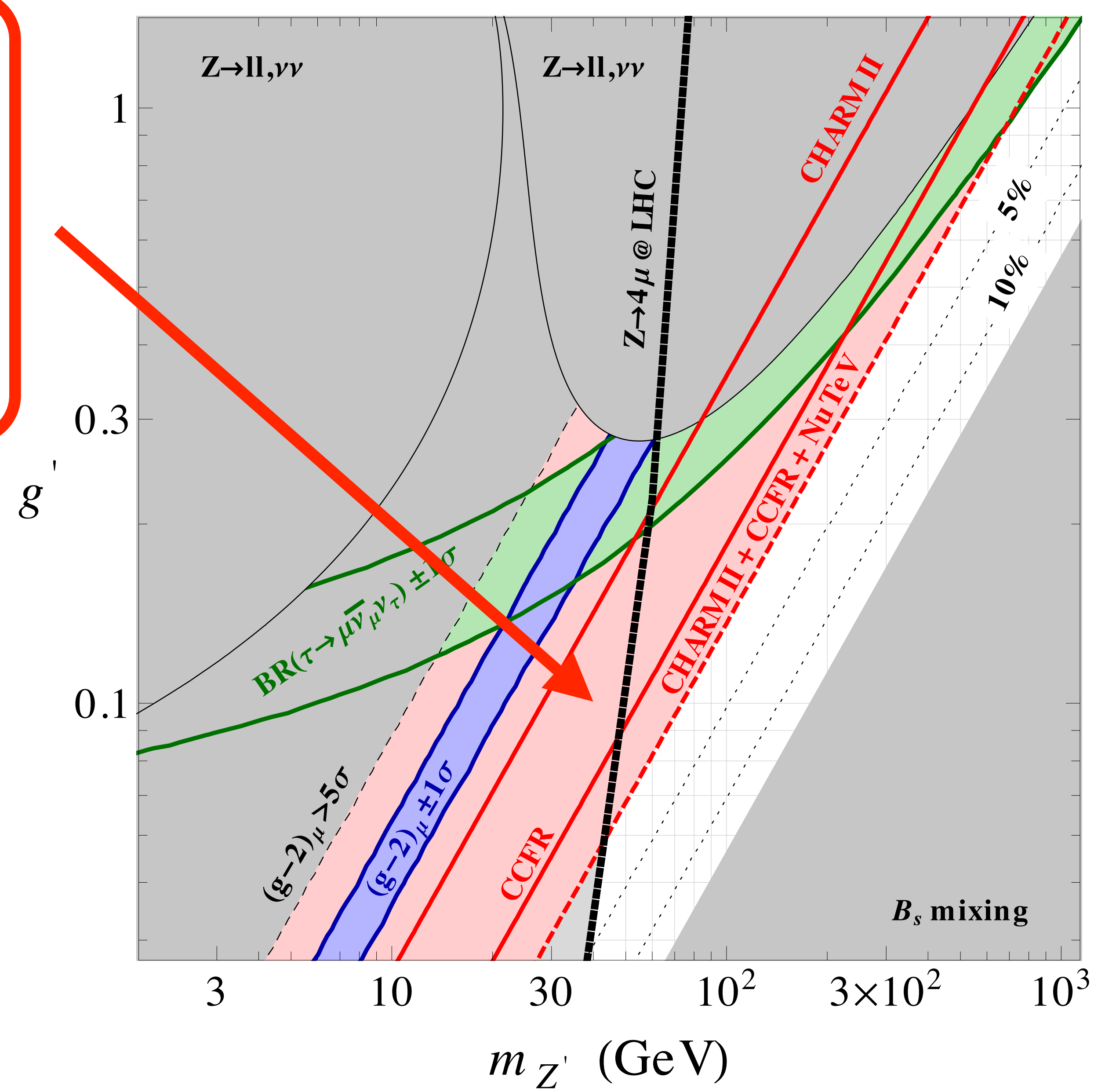
LHC bound from $Z \to 4l$

"Lμ-Lτ" models: phenomenology



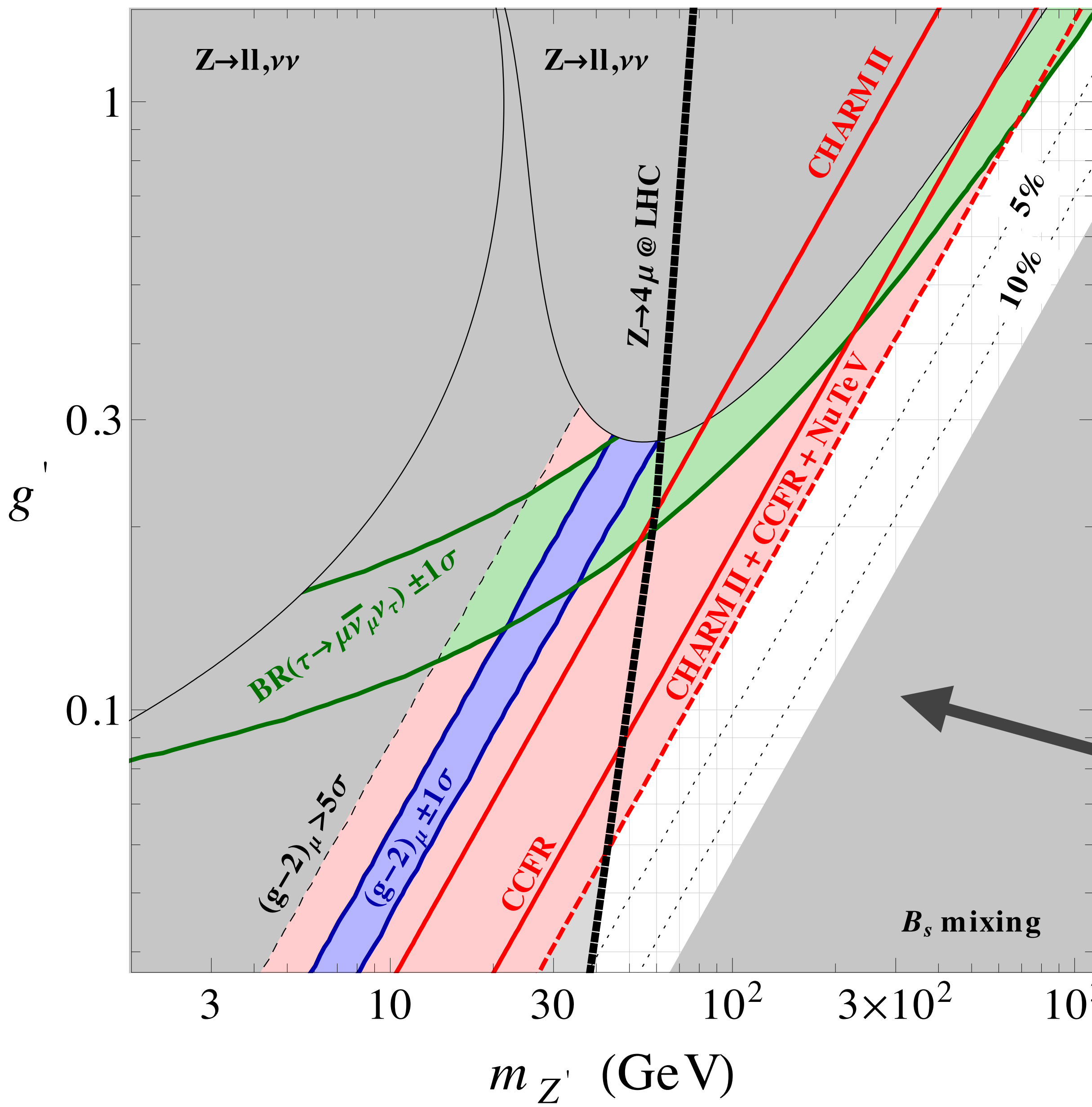
limits from neutrino trident production

[Altmannshofer et al., 1403.1269]

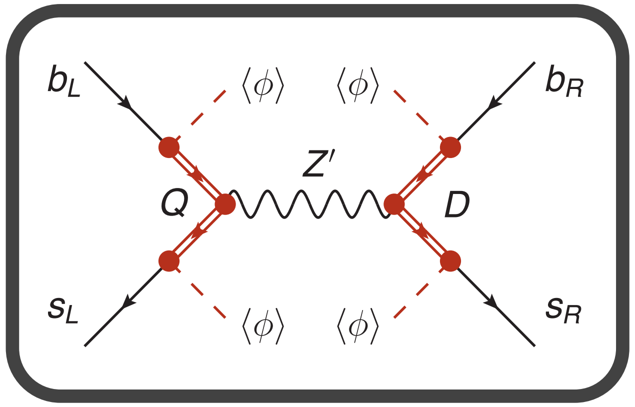


"L_μ-L_τ" models: phenomenology

[Altmannshofer et al., 1403.1269]

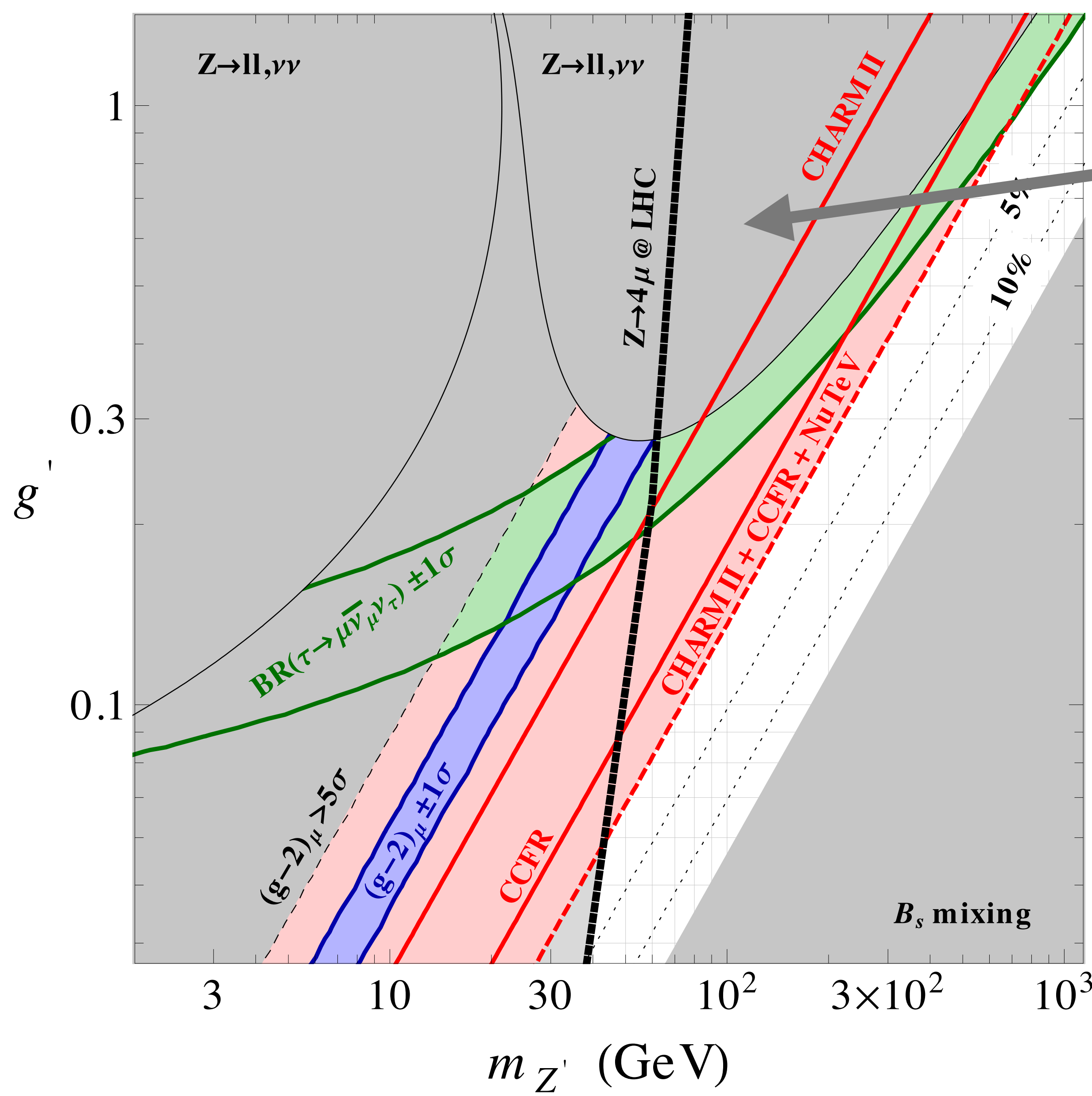


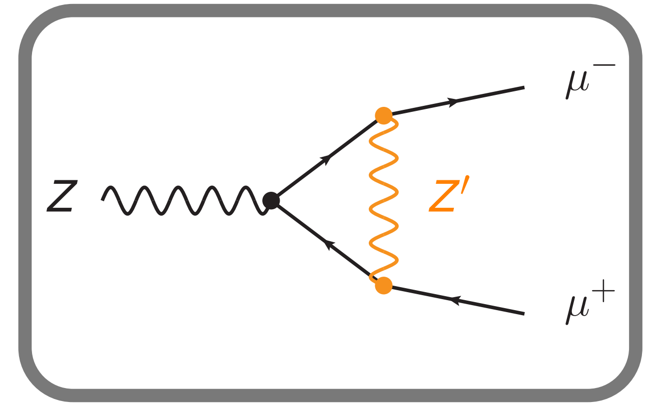
inconsistent with B_s-meson mixing



"L_μ-L_τ" models: phenomenology

[Altmannshofer et al., 1403.1269]

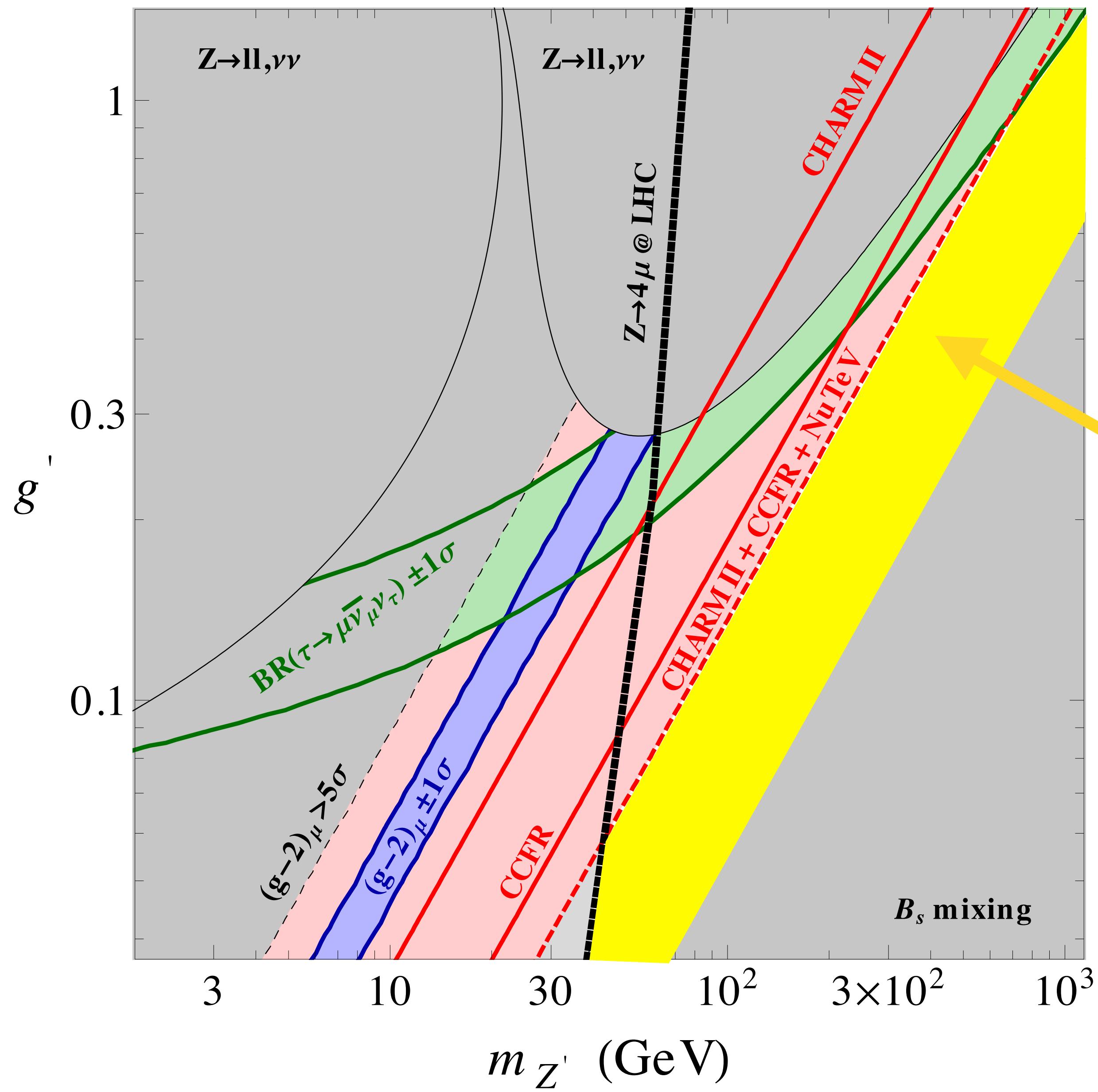




excluded by LEP measurements of Z couplings

"L_μ-L_τ" models: phenomenology

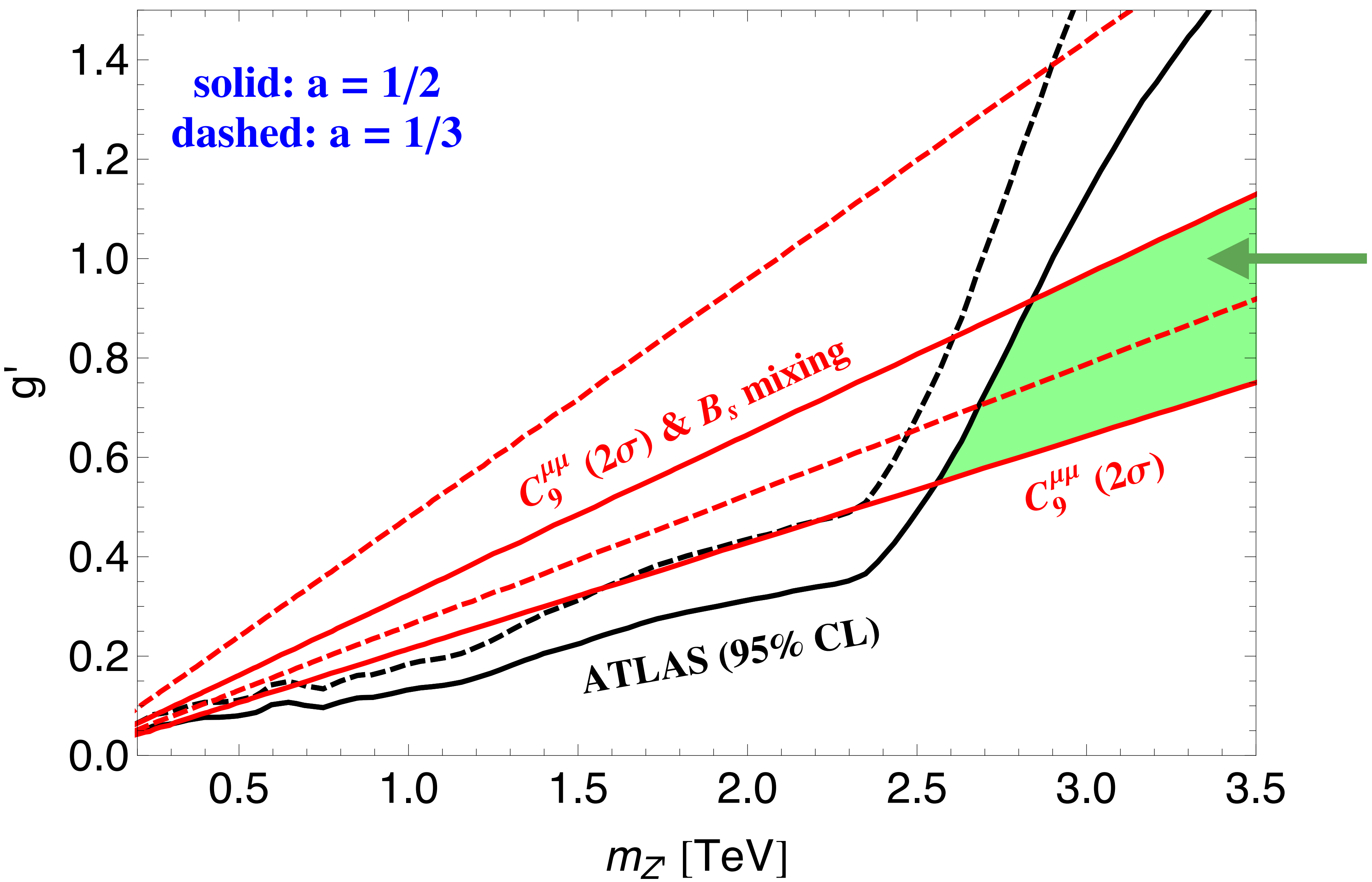
[Altmannshofer et al., 1403.1269]



various constraints, but plenty of viable parameter space, if Z'-quark coupling not fixed by symmetry

“L_μ-L_τ” models: phenomenology

[Crivellin et al., 1503.03477]



if Z'-quark couplings are constrained by horizontal symmetry, LHC Drell-Yan Z' searches cut severely into parameter space

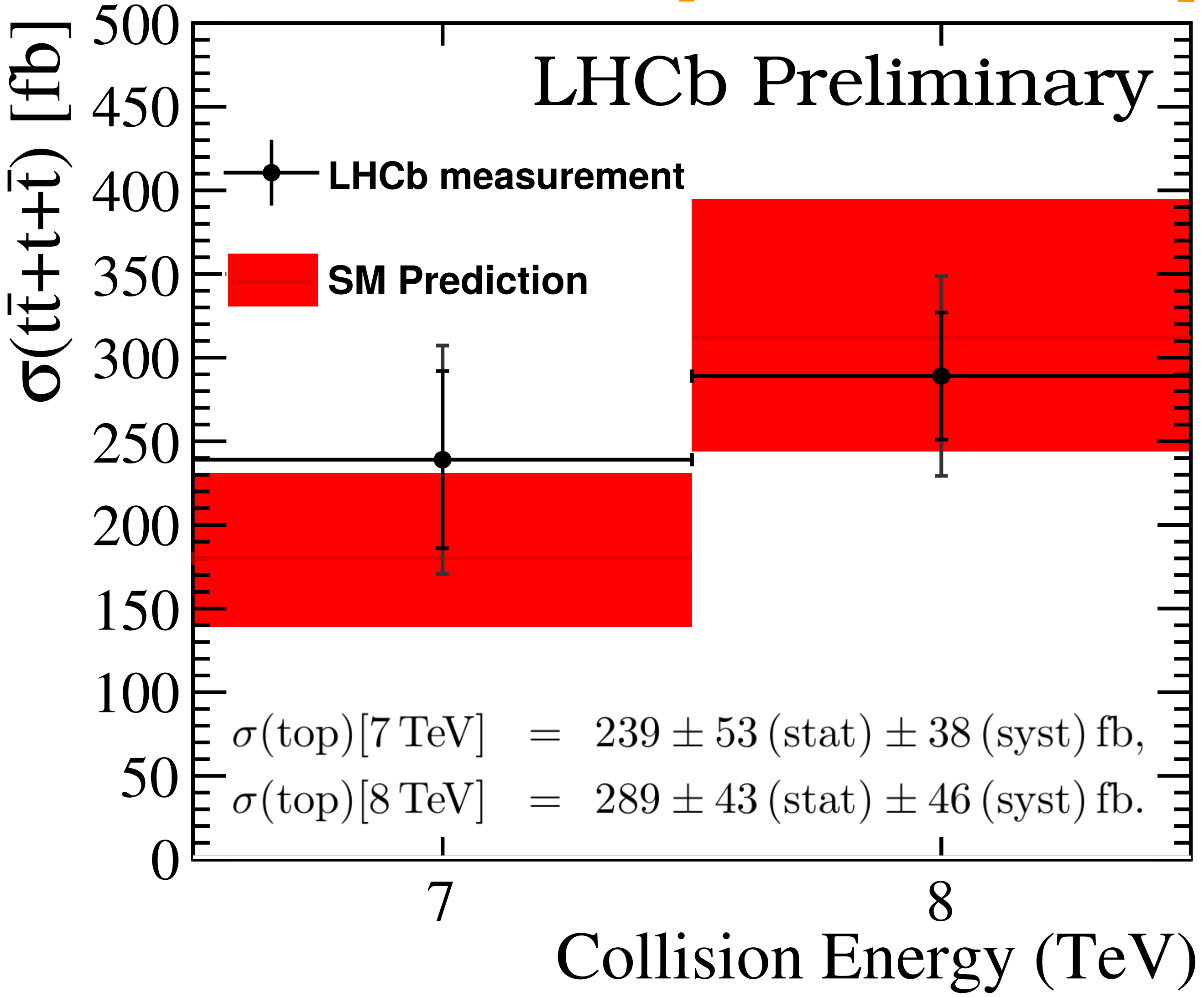
LHCb can do more than B's

33 papers of QCD, Electroweak and Exotica Working Group:

- W, Z production in forward region **[1511.08039]**
- Determination of weak mixing angle **[1509.07645]**
- Forward top & bottom production **[1509.07645; 1406.4789]**
- Searches for light dimuon resonances **[1508.04094]**
- Limits on neutral Higgs decays to tau pairs **[1304.2591]**
- …

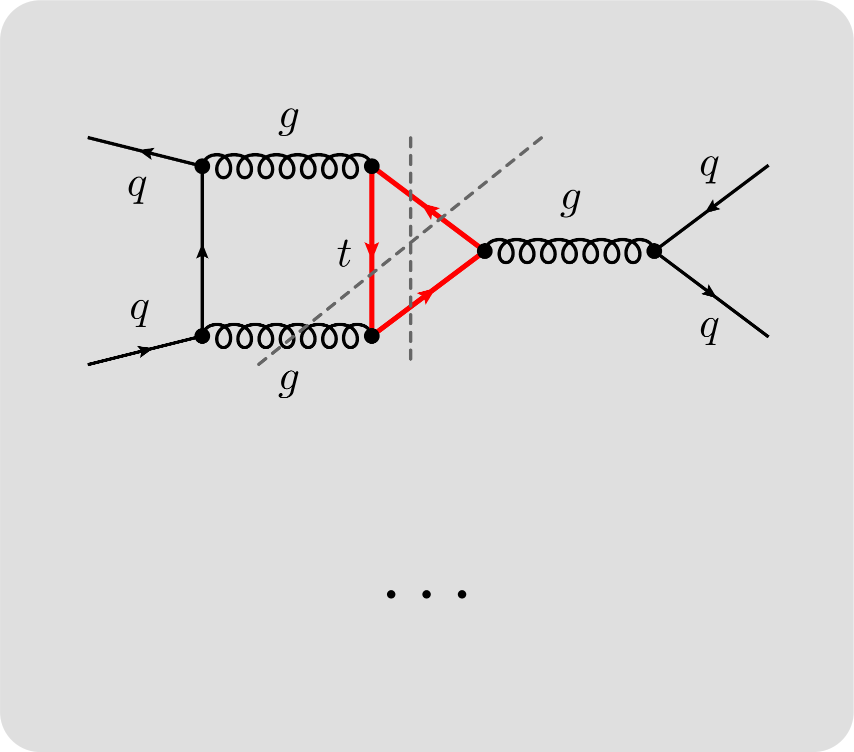
Top production at LHCb

[LHCb, 1506.00903]



- Using Run I data, 5.4σ observation of top production in forward region. Cross sections consistent with NLO QCD predictions

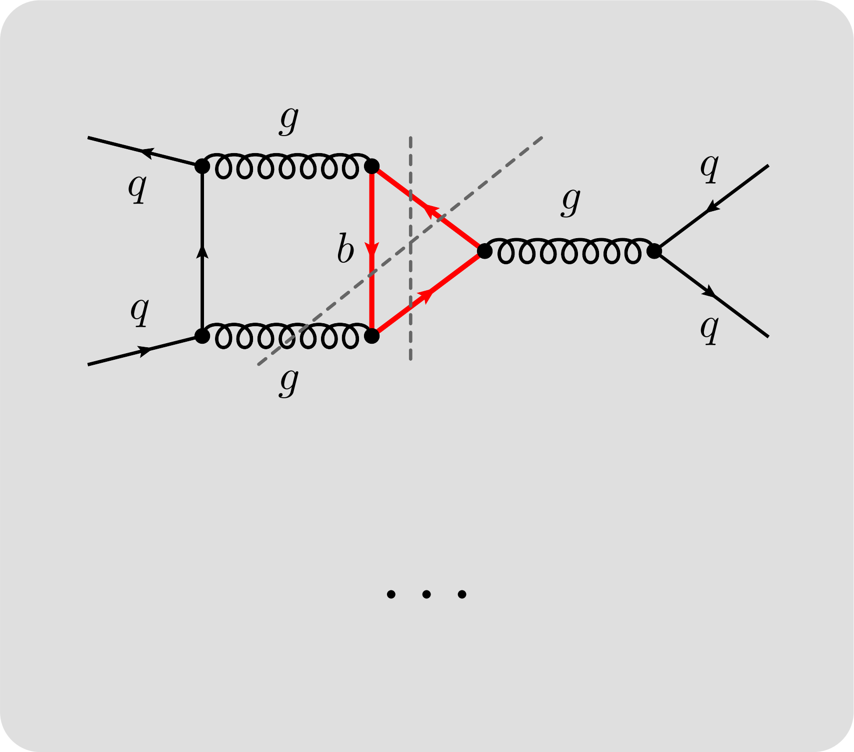
$t\bar{t}$ vs. $b\bar{b}$ asymmetry

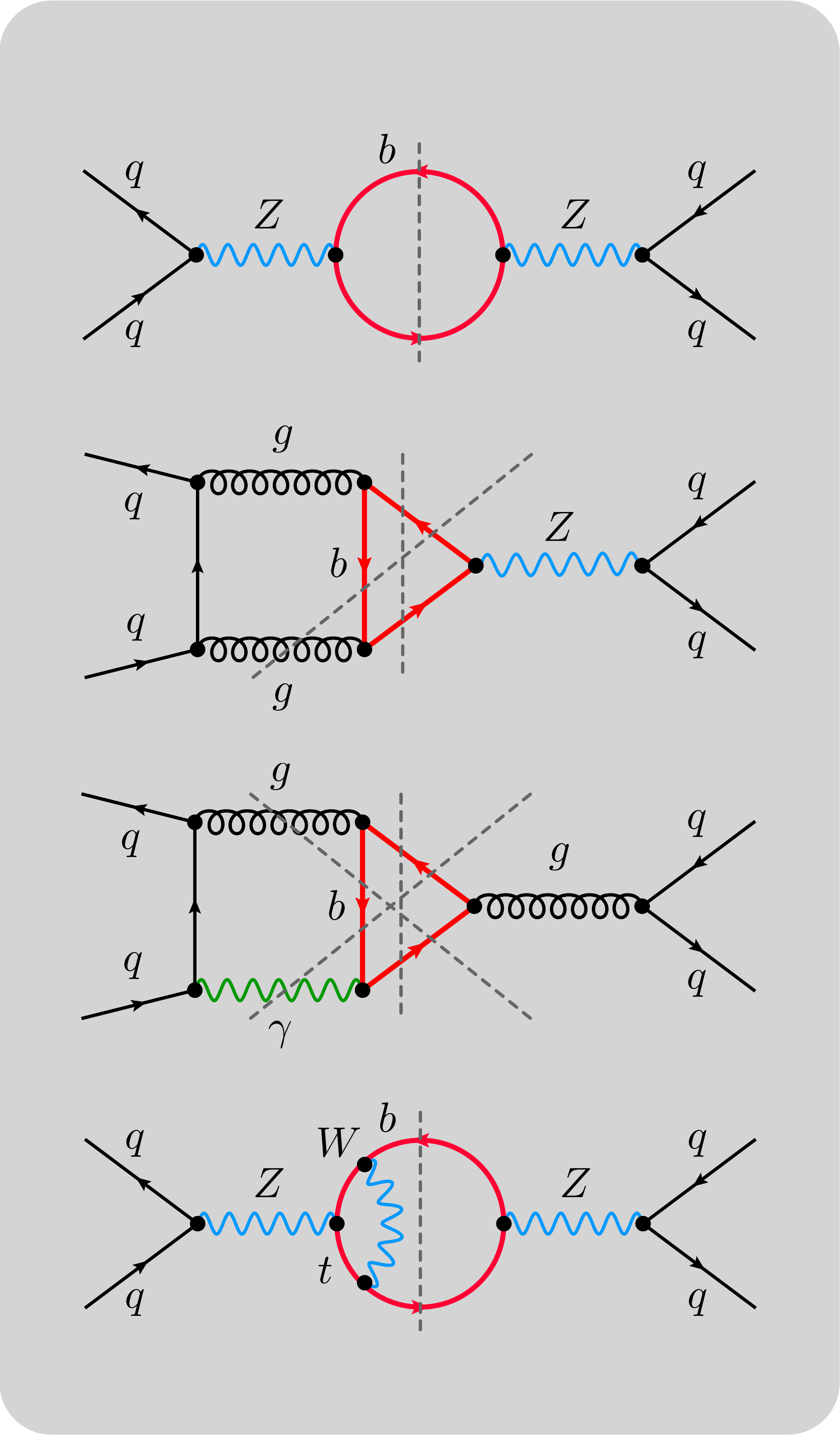


- Top-quark asymmetry fully dominated by QCD. Electroweak corrections amount to only around 20%. Now known to NNLO in QCD, i.e. 2 loops for what concerns virtual effects

[Czakon et al., 1411.3007]

$t\bar{t}$ vs. $b\bar{b}$ asymmetry

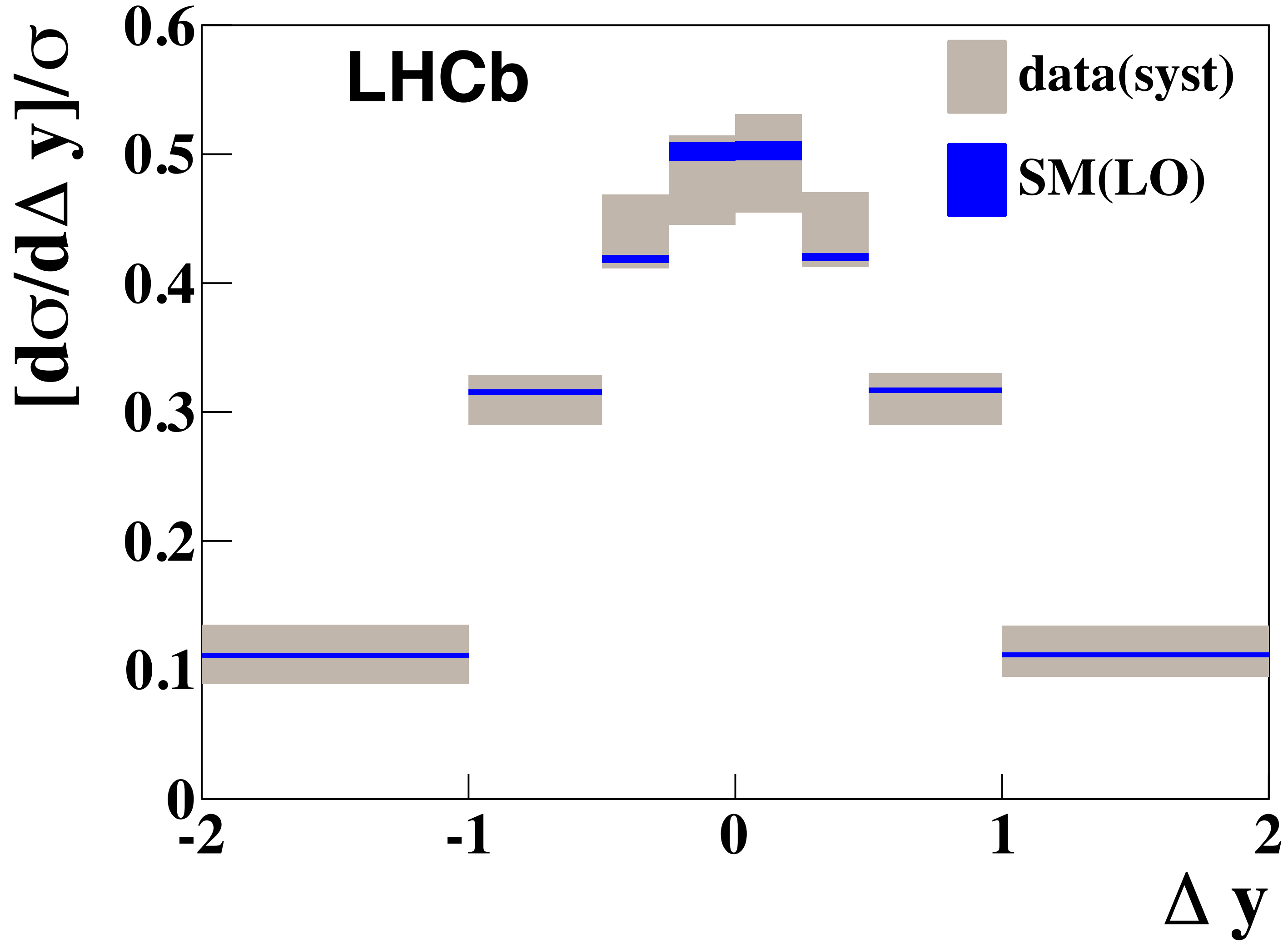




- $b\bar{b}$ asymmetry receives large corrections from on-shell Z bosons. Rich electroweak structure both in standard model & beyond

$t\bar{t}$ vs. $b\bar{b}$ asymmetry

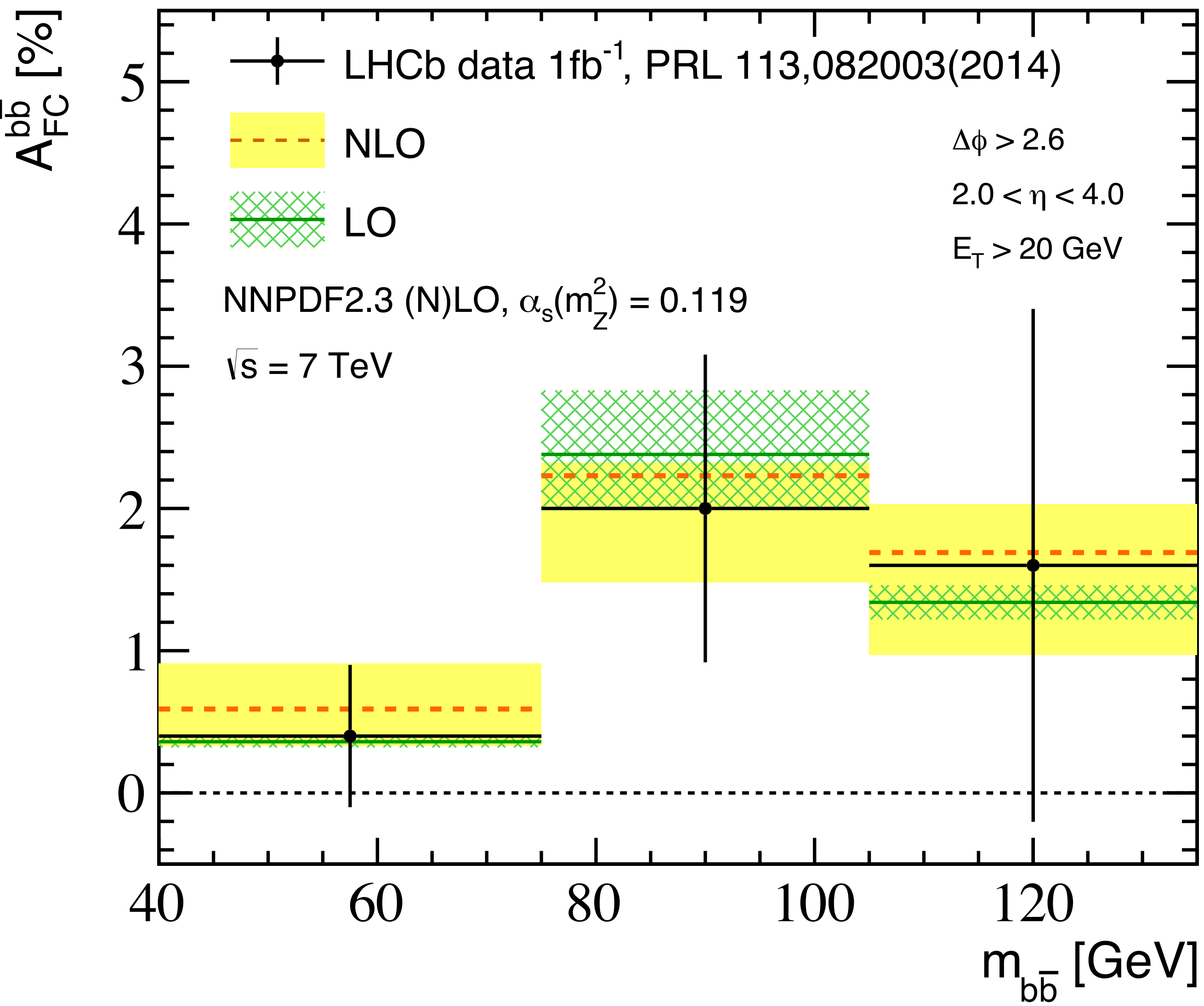
[LHCb, 1406.4789]



- In contrast to top asymmetry, bottom asymmetry has already been measured by LHCb & also D0, CDF [1411.3021; 1504.06888]

$b\bar{b}$ asymmetry: LHCb vs. SM

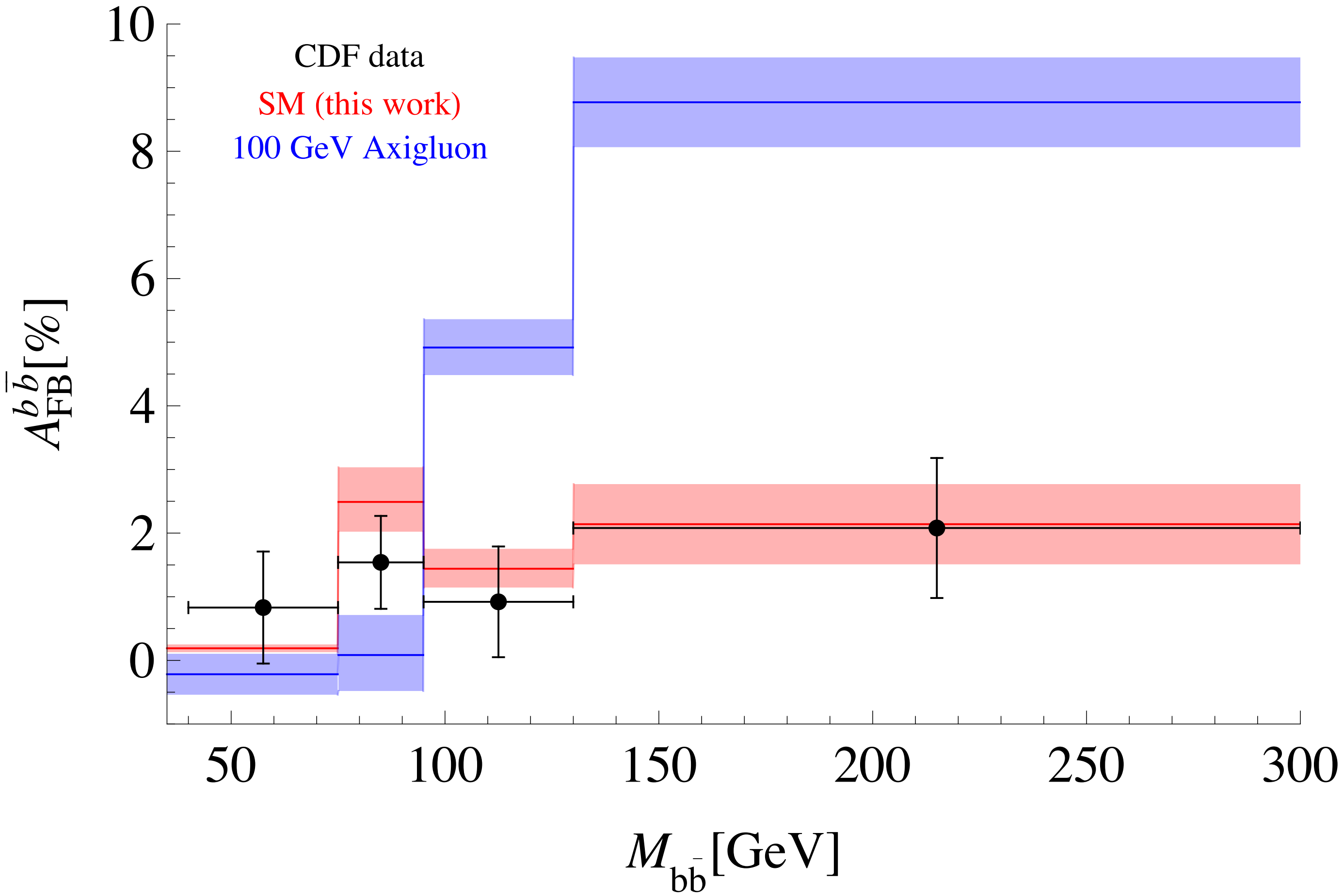
[Gauld et al., 1505.02429]



- Within uncertainties good agreement between state-of-the-art SM prediction (NLO QCD, QED & EW) & LHCb measurement

$b\bar{b}$ asymmetry: implications

[Murphy, 1504.02493]



- Tough no dedicated analysis exists (yet), obvious that LHCb measurement puts non-trivial constraints on for instance light axigluon solutions of Tevatron "anomaly" in $t\bar{t}$ asymmetry

Conclusions

- Beautiful measurements of phase φ_s in B_s mixing, $B_{s(d)} \to \mu^+\mu^-$, $B \to K^{(*)}\mu^+\mu^-$, R_K, $B \to D^{(*)}\tau\nu$, V_{ub} from $\Lambda_b \to p\mu\nu$, etc. We are now in flavor precision era. In some cases these measurements are a serious challenge for theory & improvements are needed to fully exploit existing (future) data

- Growing LHCb program beyond standard flavor applications. Robust heavy flavor tagging used for instance to measure $b\bar{b}$ forward-central asymmetry & W+ udsg, c, b. More to come in Run II — $c\bar{c}$, maybe even Higgs, etc. Think outside the box!

Backup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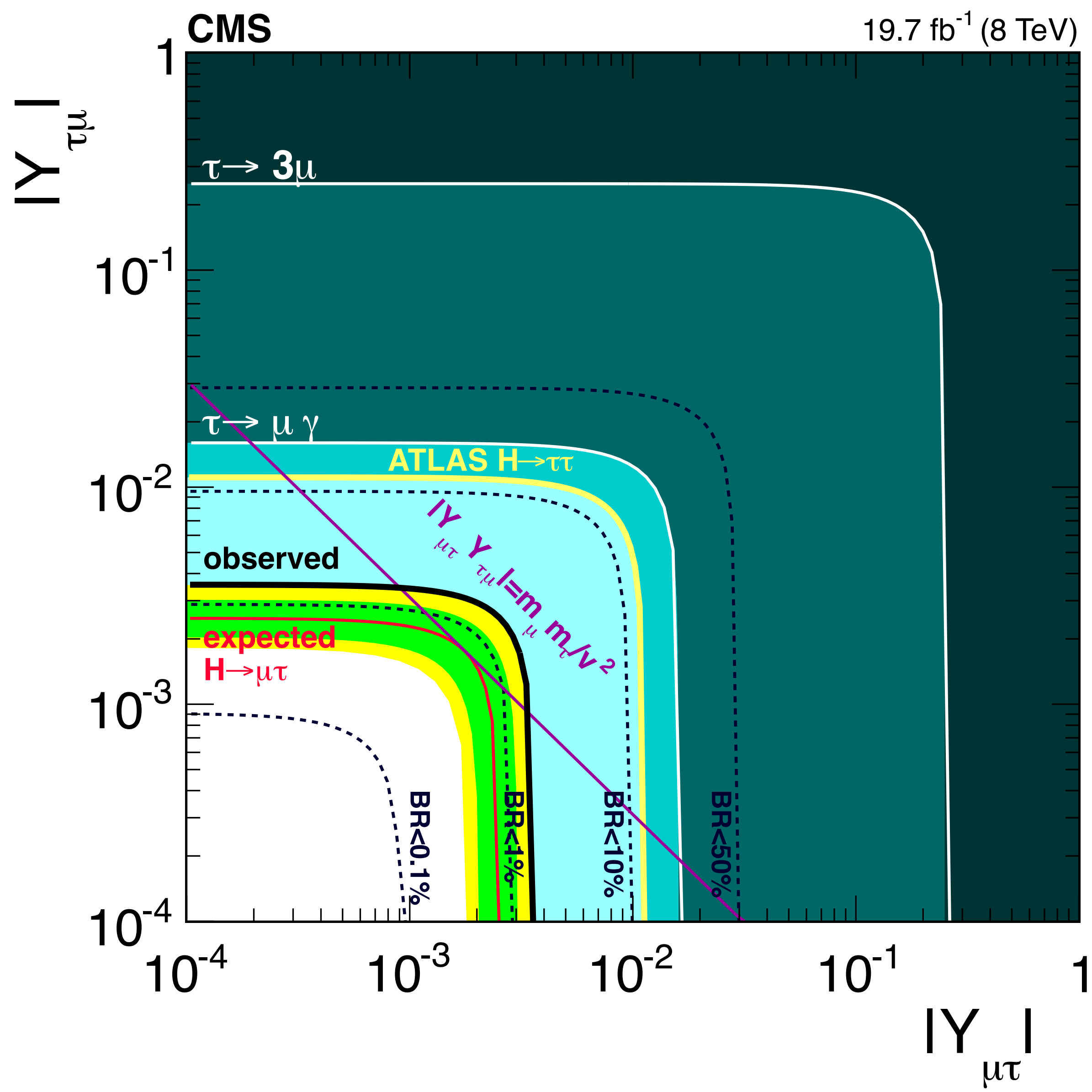
REISS

Hints for h → τμ

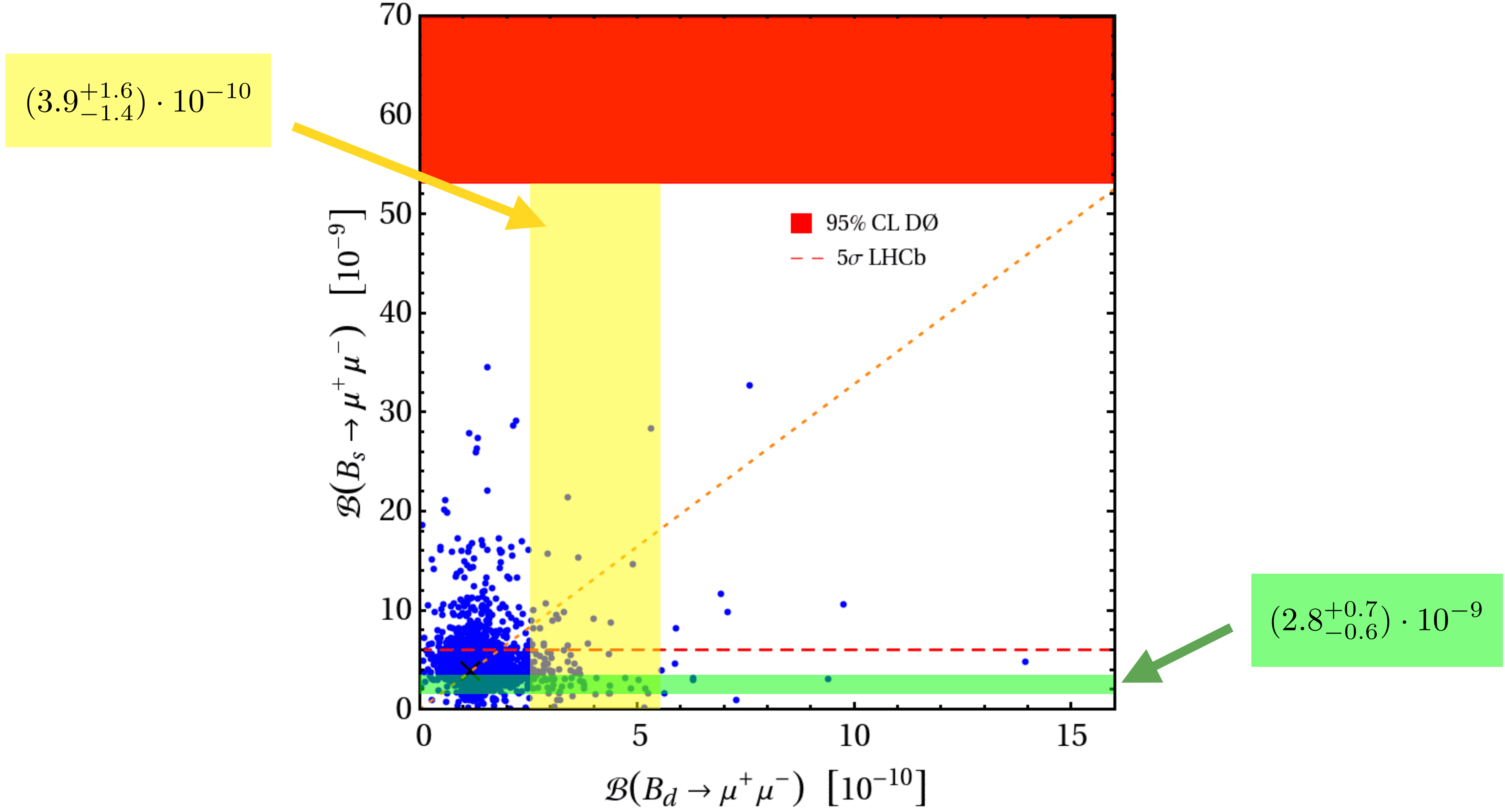
[CMS,1502.07400]



- Branching ratios of O(1%) are not easy to get in new physics & may need tuning to get hierarchical tau & muon masses

$B_{s/d} \to \mu^+\mu^-$ in RS models

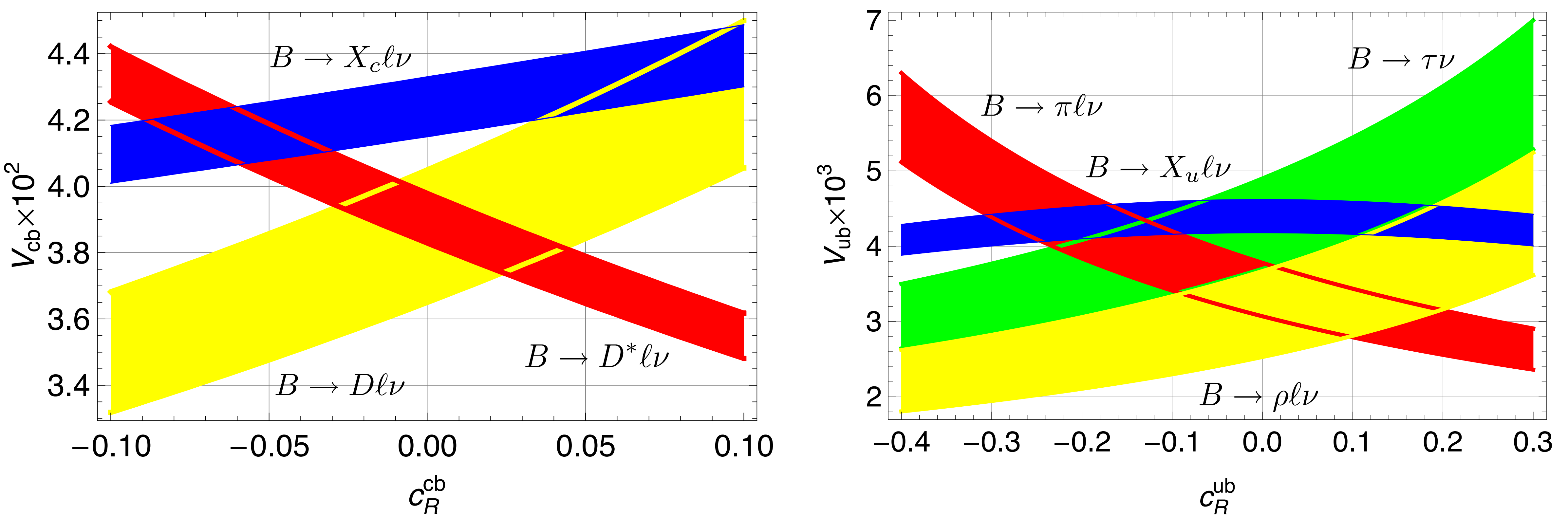
[Bauer et al., 0912.1620]



- Suppression (enhancement) of $B_s \to \mu^+\mu^-$ ($B_d \to \mu^+\mu^-$) can be explained for instance in Randall-Sundrum (RS) scenarios

Right-handed couplings in $V_{c(u)b}$

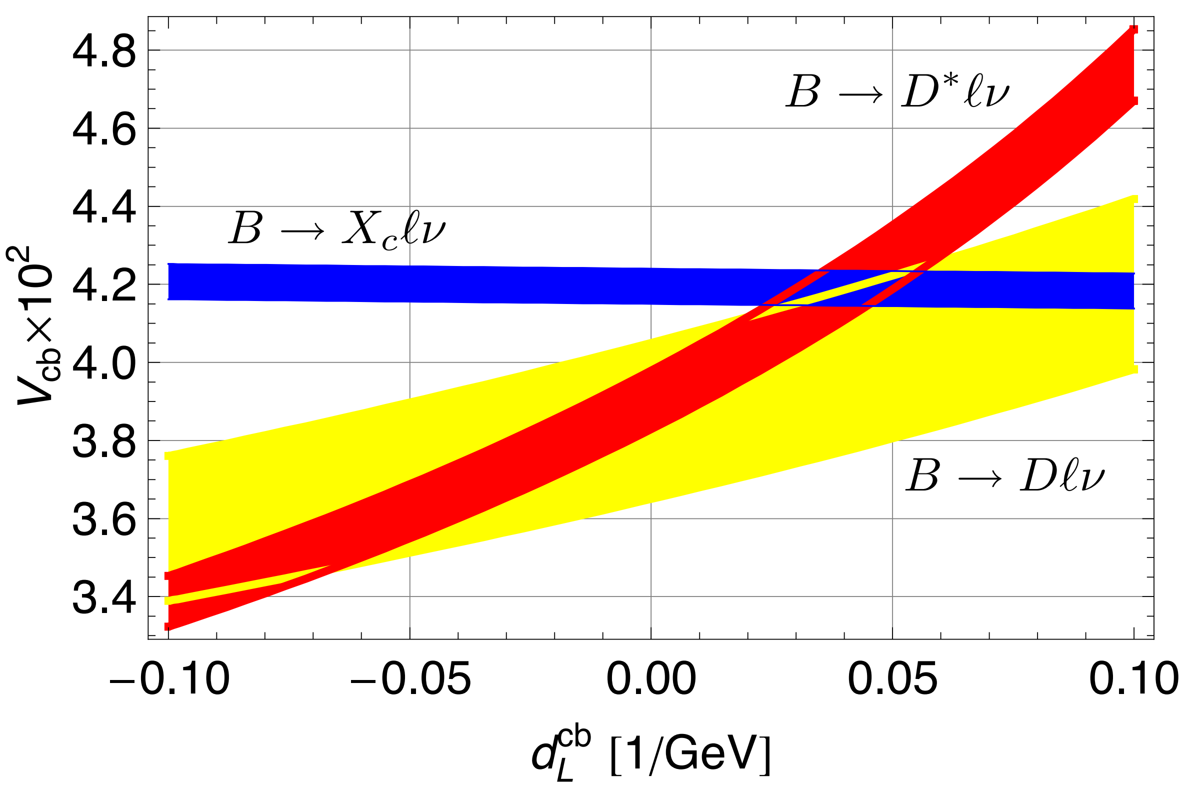
[Crivellin & Pokorski,1407.1320]

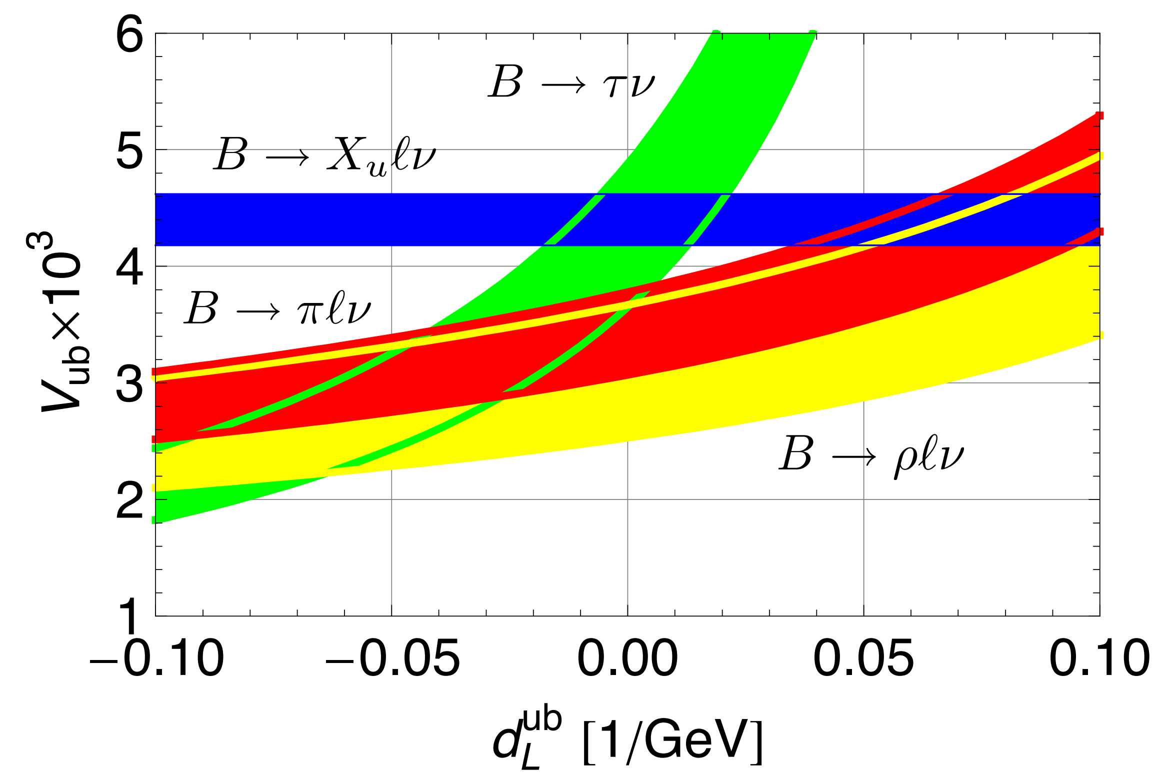


- Right-handed Wcb & Wub couplings cannot explain deviations found in inclusive vs. exclusive extractions of V_{cb} & V_{ub}

Off-shell interactions in $V_{c(u)b}$

[Crivellin & Pokorski,1407.1320]

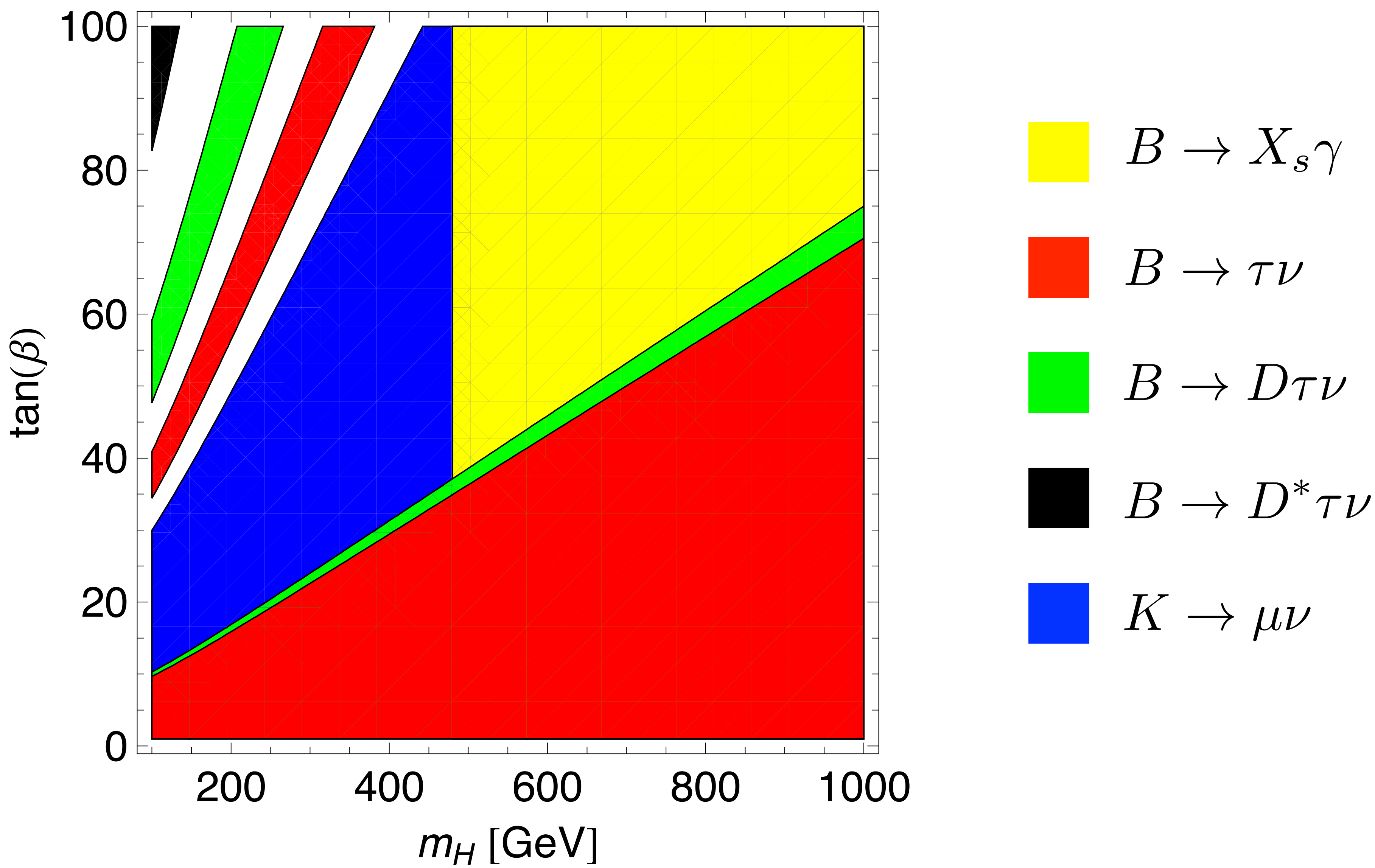




- V_{cb} anomaly can be addressed by off-shell operators $\partial^\mu \bar{c} \sigma_{\mu\nu} P_L b$, but such interactions lead to unacceptable effects in $Z \to b\bar{b}$

Flavor in 2HDM of type II

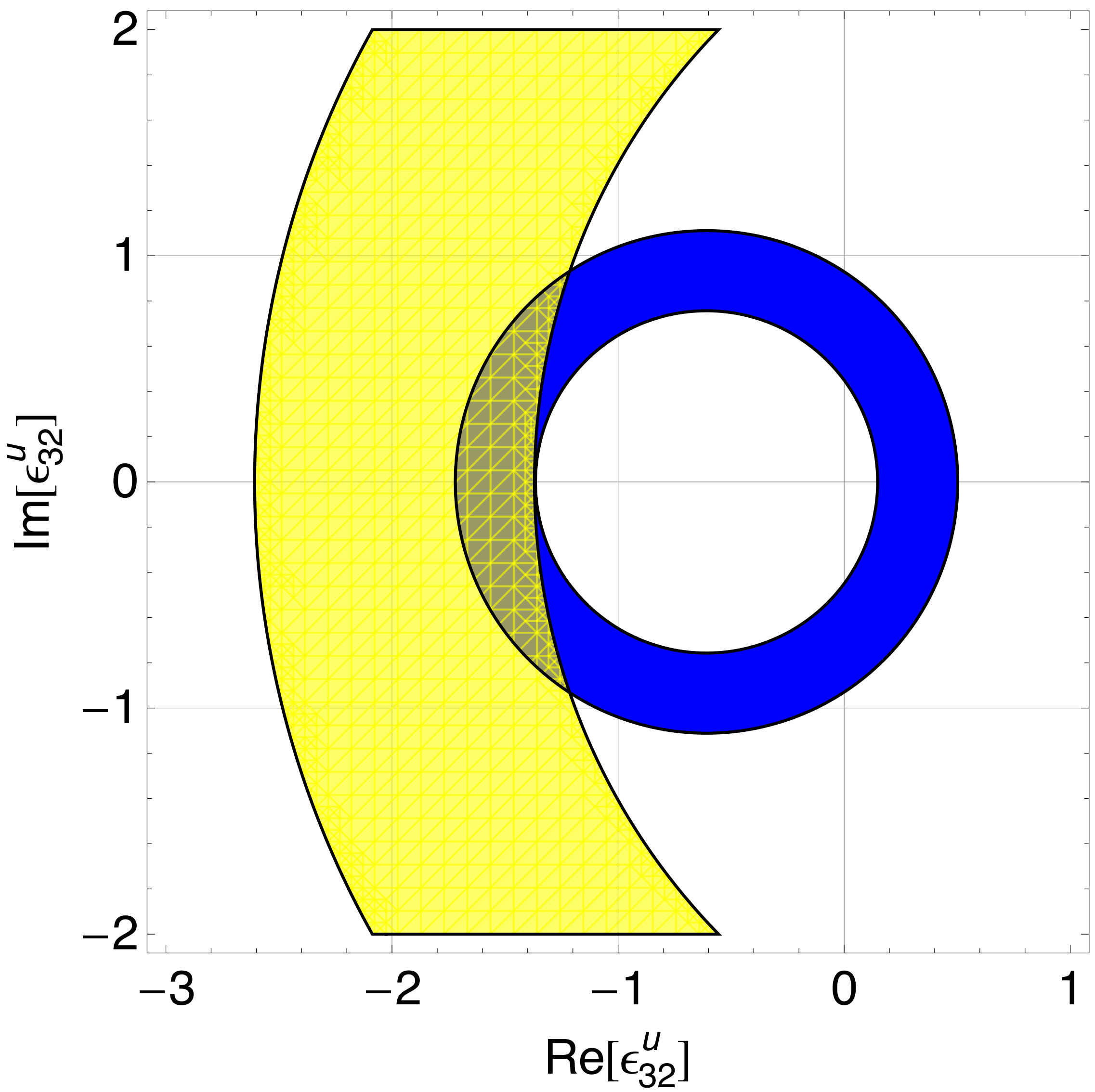
[Crivellin,1505.01727]



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

$B \to D^{(*)}\tau\nu$ in 2HDM of type III

[Crivellin,1505.01727]



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

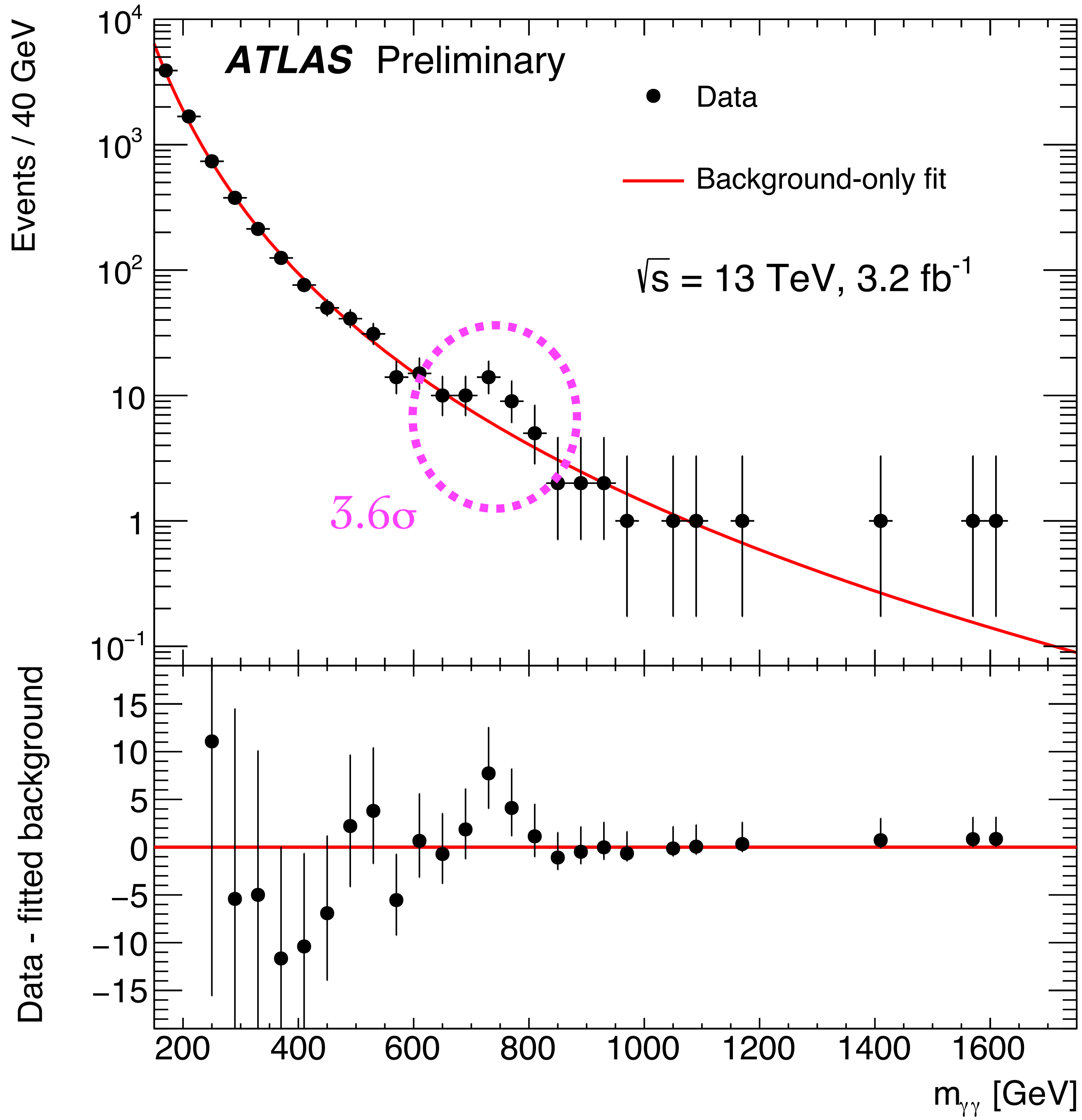
$$R(D^*) = \frac{\mathrm{Br}\,(B \to D^*\tau\nu)}{\mathrm{Br}\,(B \to D^*\ell\nu)}$$

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

- Deviations in $B \to D\tau\nu$ & $B \to D^*\tau\nu$ can be explained, utilizing coupling ε^u_{32} of left-handed top to right-handed charm quarks

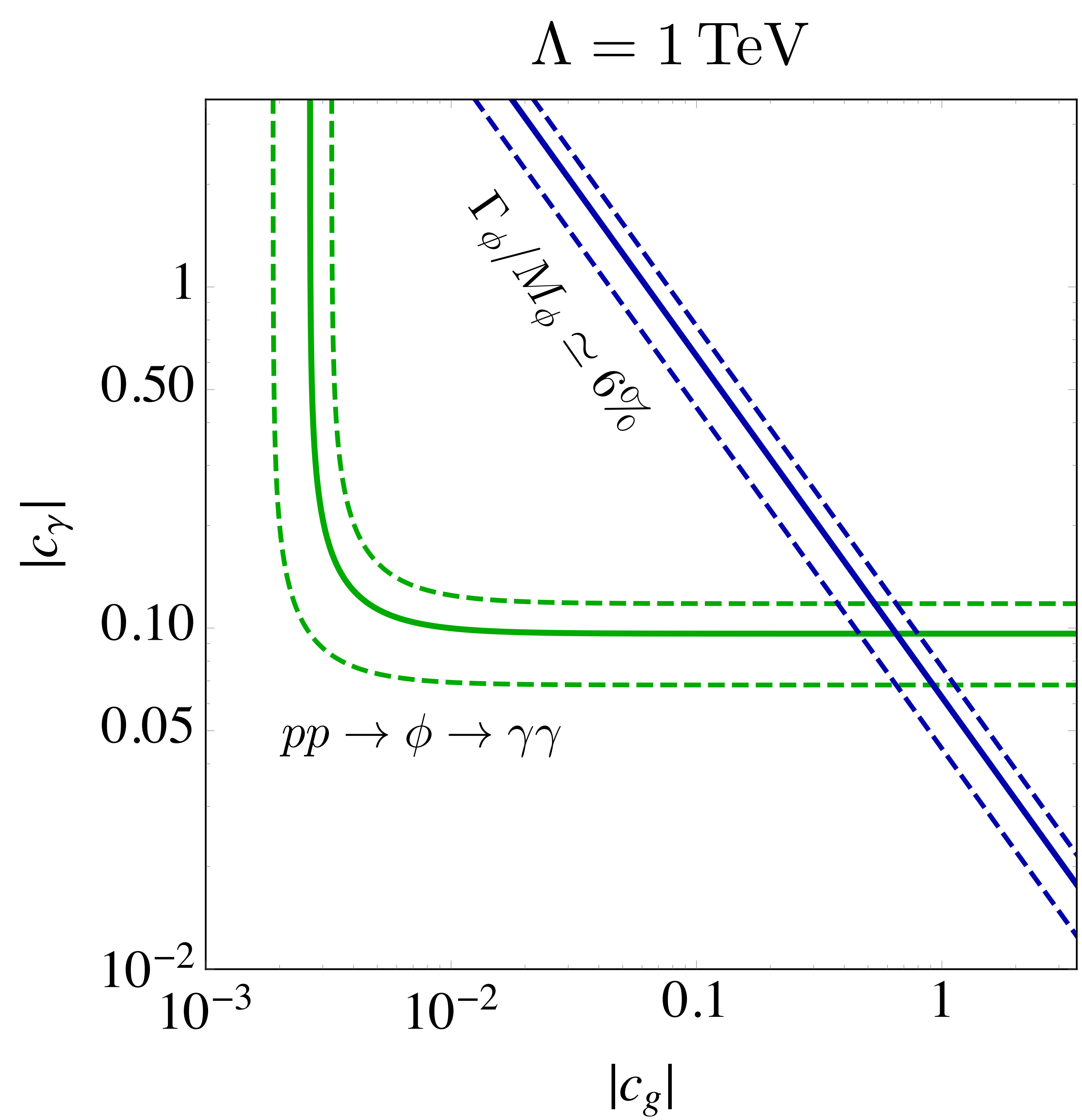
Who ordered that?

[ATLAS-CONF-2015-081]



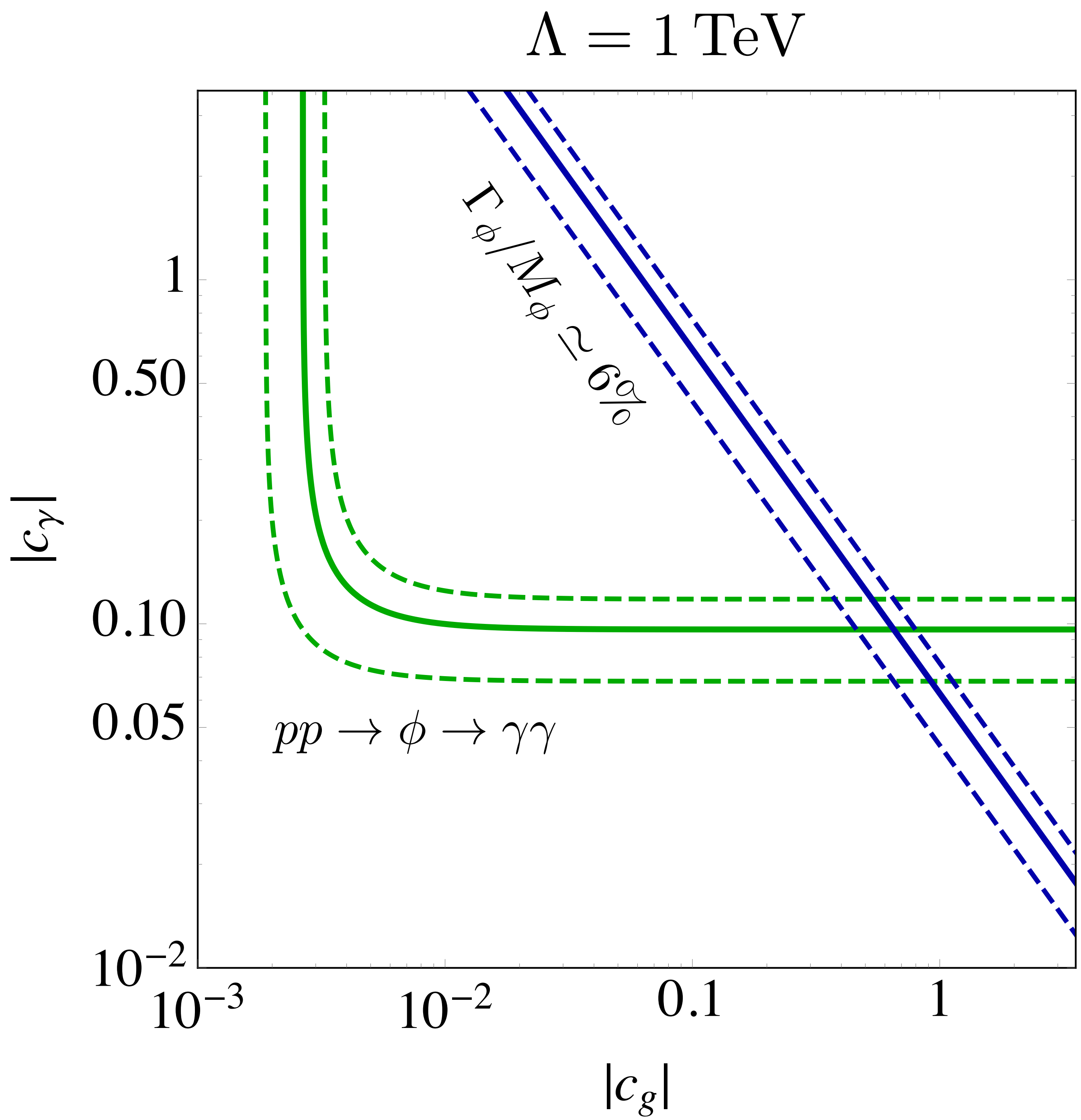
A toy model for 750 GeV excess

$$\mathcal{L}_{\rm eff} \supset -\frac{e^2 c_\gamma}{2\Lambda}\,\phi F_{\mu\nu}F^{\mu\nu} - \frac{g_s^2 c_g}{2\Lambda}\,\phi\, G^a_{\mu\nu}G^{a,\mu\nu}$$

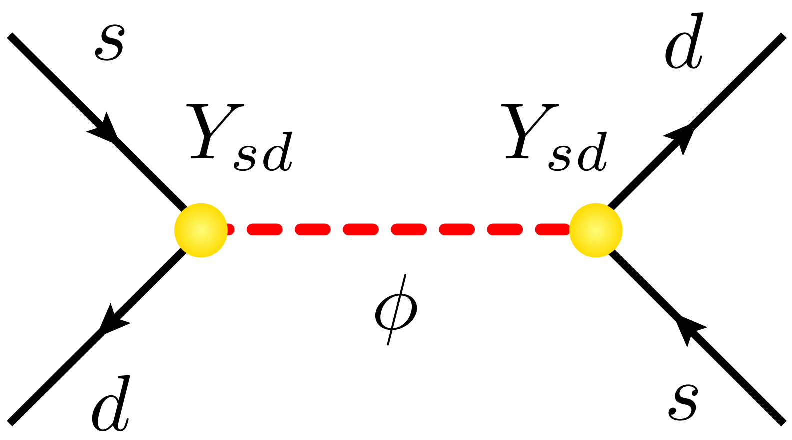


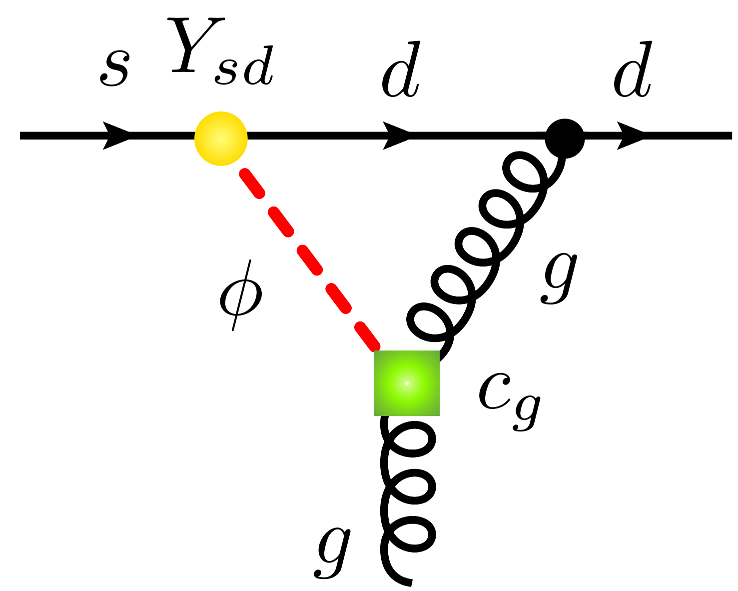
Let's add flavor violation

$$\mathcal{L}_{\rm eff} \supset -\frac{e^2 c_\gamma}{2\Lambda}\,\phi F_{\mu\nu}F^{\mu\nu} - \frac{g_s^2 c_g}{2\Lambda}\,\phi\, G^a_{\mu\nu}G^{a,\mu\nu} - Y_{sd}\,\phi\,\bar{s}_L d_R + \text{h.c.}$$



We get contributions to ε_K & ε'/ε





from ε_K

from ε'/ε

$$\sqrt{|\mathrm{Im}\,(Y_{sd}^2)\,|} < 6.4 \cdot 10^{-6}$$

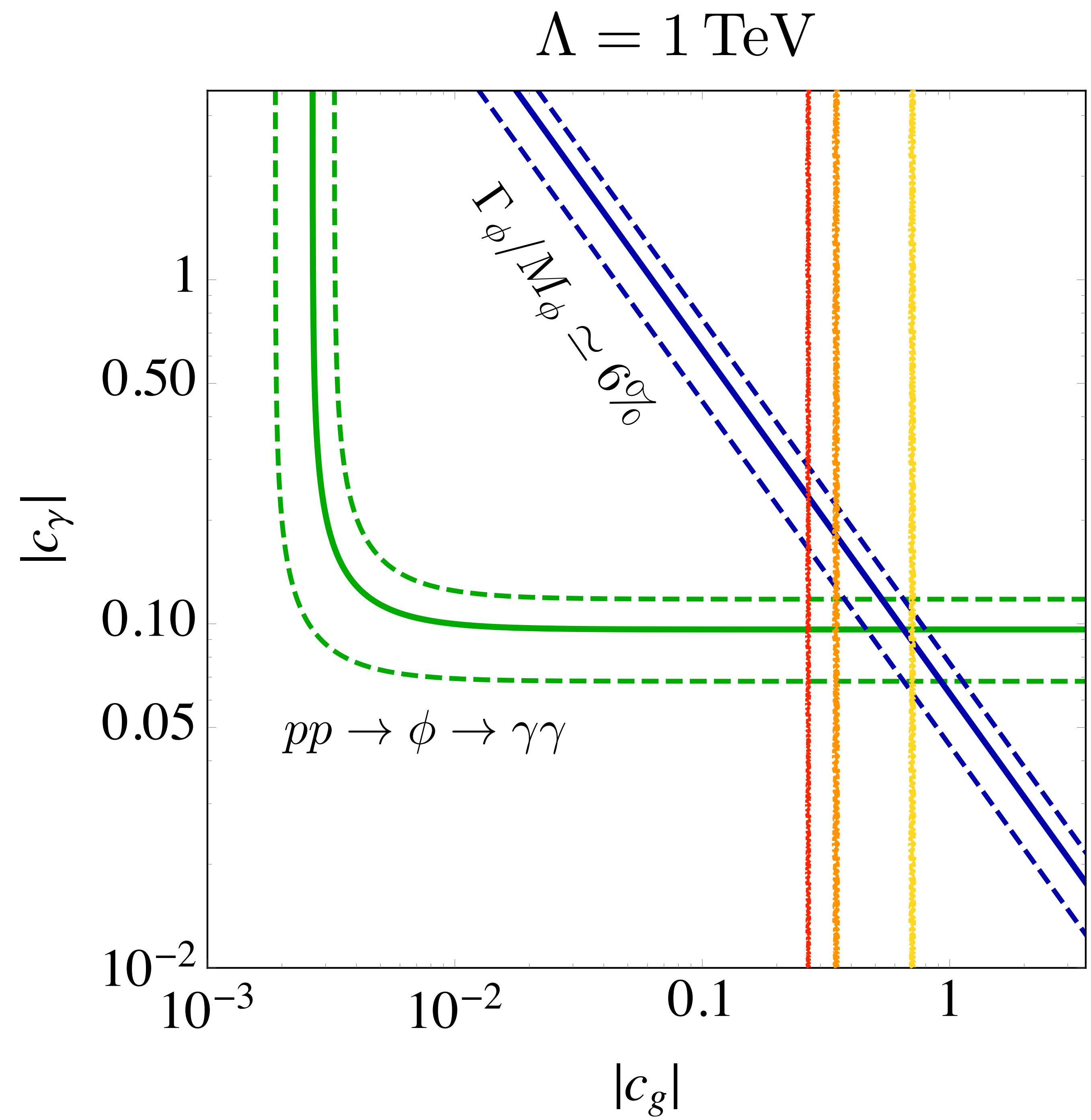
$$|c_g\,\mathrm{Im}\,(Y_{sd})\,| < \{1.1, 2.2, 4.4\} \cdot 10^{-6}\;{}^{\dagger}$$

†numbers assume shifts of $\{0.25, 0.5, 1\} \cdot 10^{-3}$ in ε'/ε & $B_{8g^-} = 0.3$

We get contributions to ε_K & ε'/ε

- shift of $0.25 \cdot 10^{-3}$ in ε'/ε
- shift of $0.5 \cdot 10^{-3}$ in ε'/ε
- shift of $1 \cdot 10^{-3}$ in ε'/ε

ε_K constraint satisfied, $|c_g|$ values to right disfavoured



Power corrections from $b \to \bar{c}c\,s \to \bar{\ell}\ell\,s$ for $q^2 \lesssim 6$ GeV^2

Parameterisation of power corrections $\lambda = \pm, 0$

$$h_\lambda(q^2) = \frac{\epsilon^*_\mu(\lambda)}{m_B^2} \int \mathrm{d}^4x\, e^{i\,q\cdot x} \left\langle K_\lambda^{(*)} \middle| \mathrm{T}\left\{ j_\mu^{\mathrm{em}}(x), \sum_i C_i \mathcal{O}_i(0) \right\} \middle| B(p) \right\rangle$$

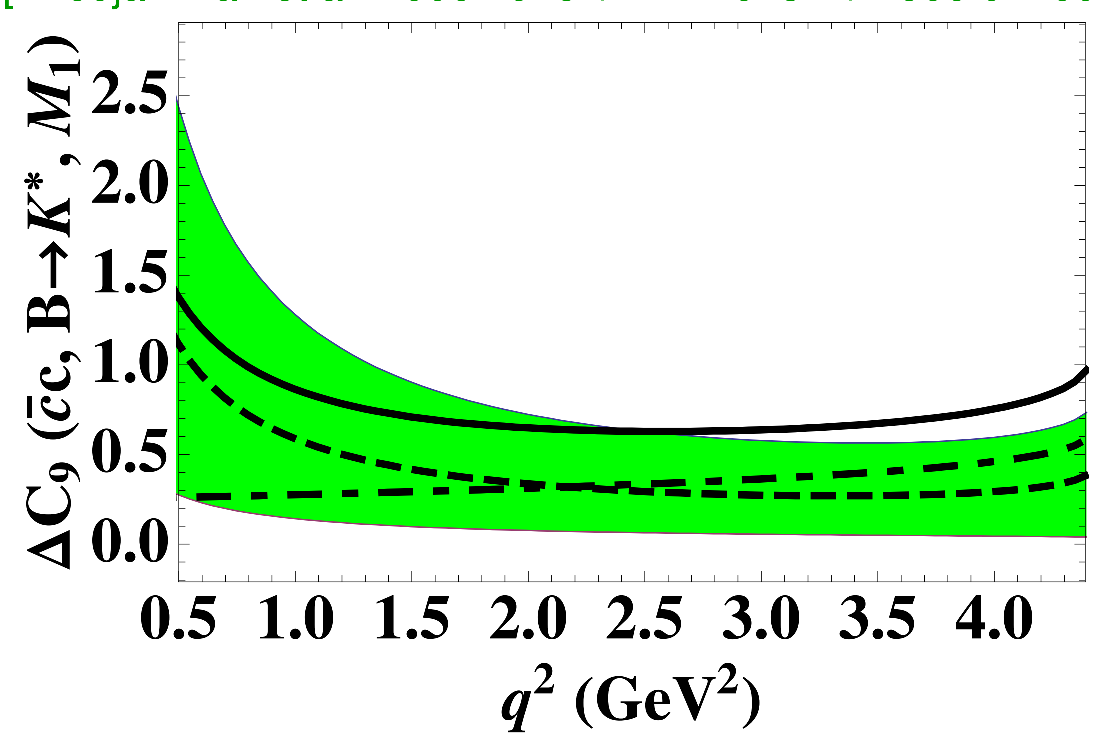
$$\approx \underbrace{\left[\text{LO in } 1/m_b\right]}_{\text{QCDF}} + h_\lambda^{(0)} + \frac{q^2}{1\mathrm{GeV}^2} h_\lambda^{(1)} + \frac{q^4}{1\mathrm{GeV}^4} h_\lambda^{(2)}, \qquad h_\lambda^{(0,1,2)} \in \mathbb{C}$$

⇒ Soft-gluon emission off $\bar{c}c$-pairs enhanced by tree-level current-current $C_{1,2}$

1) contributions to $h_\lambda(q^2)$ via OPE

- works for $\Lambda_{\mathrm{QCD}} \ll 4m_c^2 - q^2$, also at $q^2 < 0$ GeV^2
- gives q^2-dependent shift to C_9
  $\Delta C_9^1(q^2) = (C_1 + 3C_2)g_{\mathrm{fact}}(q^2) + 2C_1\tilde{g}_1(q^2)$
  with $\tilde{g}_1(q^2) \propto h_-(q^2) - h_+(q^2)$
- $g_{\mathrm{fact}}(q^2)$ = LO in $1/m_b$ = *dashed*
- soft-gluon emission $\tilde{g}_1(q^2)$ = *dashed-dotted*

[Khodjamirian et al. 1006.4945 + 1211.0234 + 1506.07760]



⇒ power corrections from soft gluons about 20% of C_9 at $1.0 \le q^2 \le 4.0$ GeV^2

2) interpolation up to $q^2 \approx 12$ GeV^2 via dispersion relation

Power corrections from $b \to \bar{c}c\,s \to \bar{\ell}\ell\,s$ for $q^2 \lesssim 6$ GeV^2

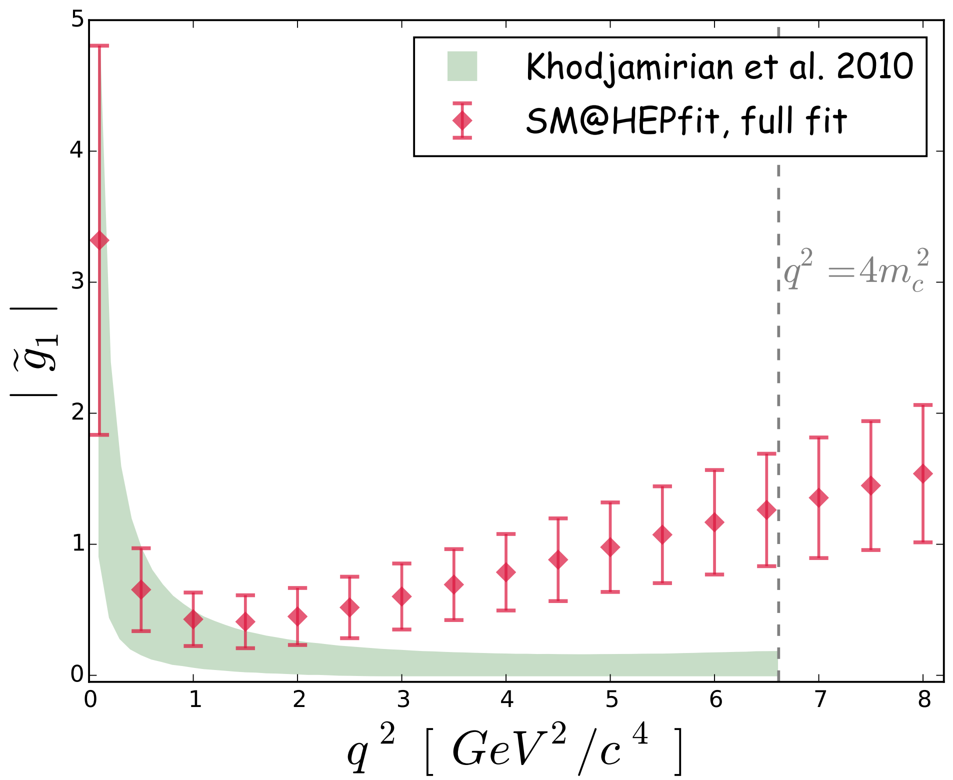
Parameterisation of power corrections $\lambda = \pm, 0$

$$h_\lambda(q^2) = \frac{\epsilon^*_\mu(\lambda)}{m_B^2} \int d^4x\, e^{i q\cdot x} \left\langle K_\lambda^{(*)} \right| \mathrm{T}\Big\{ j_\mu^{\mathrm{em}}(x), \sum_i C_i \mathcal{O}_i(0) \Big\} \left| B(p) \right\rangle$$

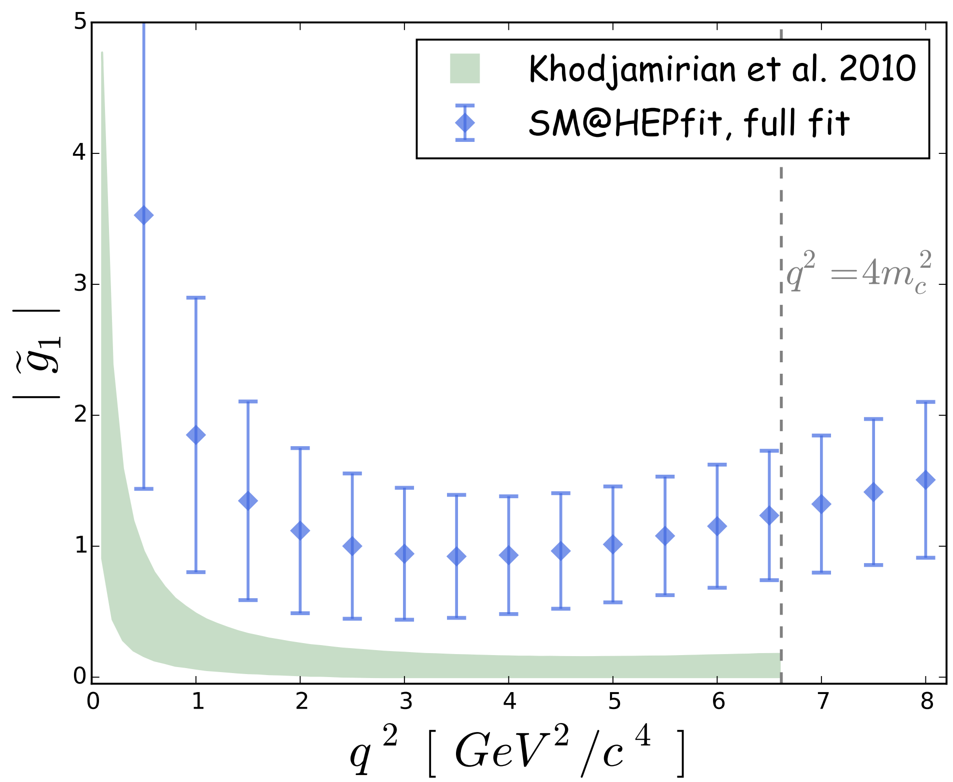
$$\approx \underbrace{[\text{LO in } 1/m_b]}_{\text{QCDF}} + h_\lambda^{(0)} + \frac{q^2}{1\text{GeV}^2} h_\lambda^{(1)} + \frac{q^4}{1\text{GeV}^4} h_\lambda^{(2)}, \qquad h_\lambda^{(0,1,2)} \in \mathbb{C}$$

$\Rightarrow$ Can fit $h_\lambda^{(0,1,2)}$ from data (assuming $C_9^{\mathrm{NP}} = 0$) [Ciuchini et al. 1512.07157]

with OPE-result at $q^2 = 0, 1$ GeV^2



without OPE-result



$\Rightarrow$ leads $(5 - 10) \times$ larger power corrections than predicted by Khodjamirian et al. for $\tilde{g}$'s

Data: Likelihood fit *vs* method of moments

[LHCb 1512.04442]

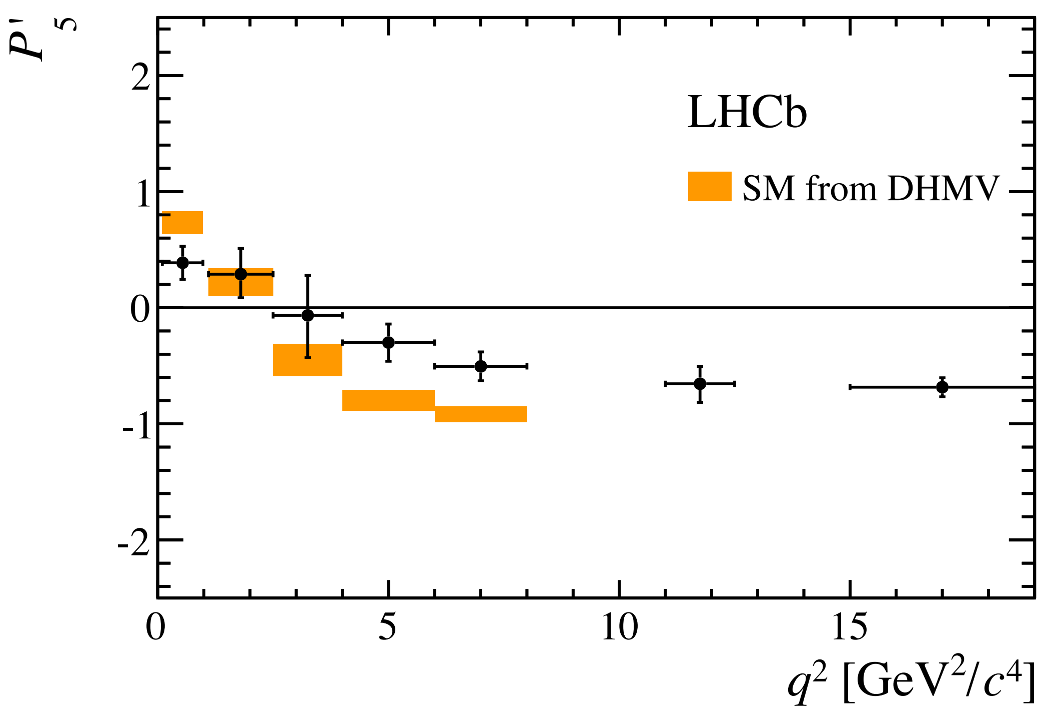
⇒ LHCb measured angular distribution with **two methods**

[see talk C. Langenbruch]

“Unbinned maximum likelihood fit”

involves model-dependent assumptions:

- lepton mass = 0, important for $q^2 \lesssim 1$ GeV^2
- no scalar and tensorial operators

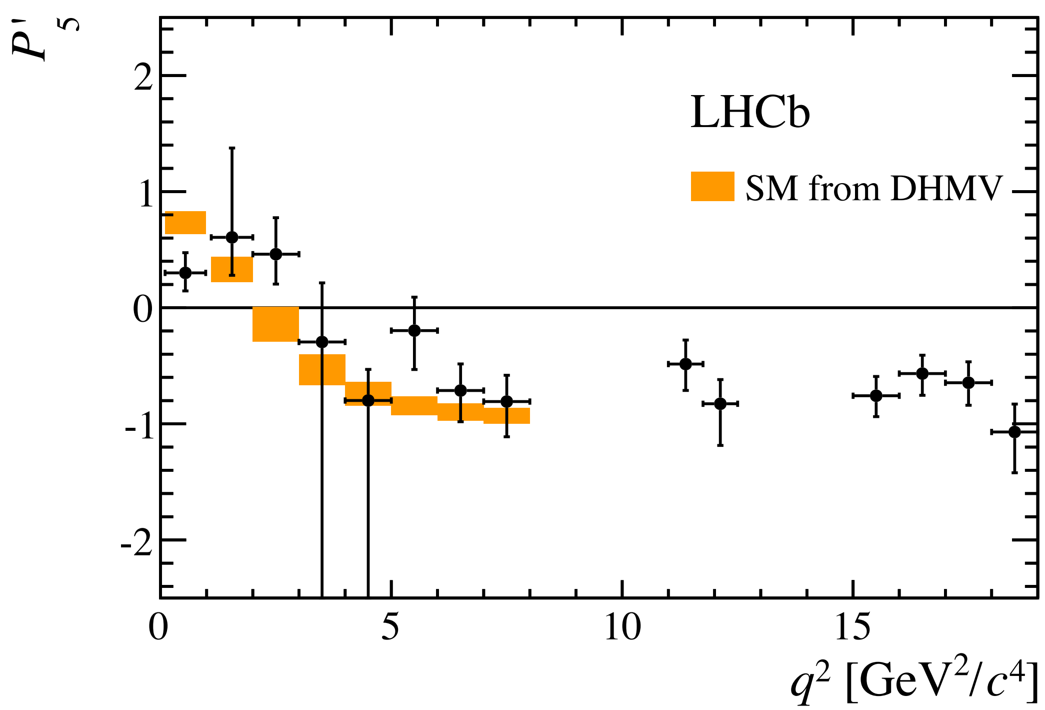


“Principal moments”

no model-dependent assumptions

!!! but larger uncertainties

[Beaujean/Chrzaszcz/Serra/van Dyk 1503.04100]



$P'_5 = S_5/\sqrt{F_L(1 - F_L)}$

longitudinal K^* polarisation fraction $F_L \in [0, 1]$

⇒ in some q^2-bins measurement $F_L > 1$

⇒ “Principal moments”-data has less tension with “standard” SM predictions

Data: Likelihood fit *vs* method of moments

[LHCb 1512.04442]

⇒ LHCb measured angular distribution with **two methods**

[see talk C. Langenbruch]

"Unbinned maximum likelihood fit"

involves model-dependent assumptions:

- lepton mass = 0, important for $q^2 \lesssim 1$ GeV^2
- no scalar and tensorial operators

"Principal moments"

no model-dependent assumptions

!!! but larger uncertainties

[Beaujean/Chrzaszcz/Serra/van Dyk 1503.04100]

How does choice of method affect fits? ⇒ tension decreases with "principal moments"-data

1) LHCb fit or real-valued C_9 finds ($C_9^{\rm NP} = 4.27$)

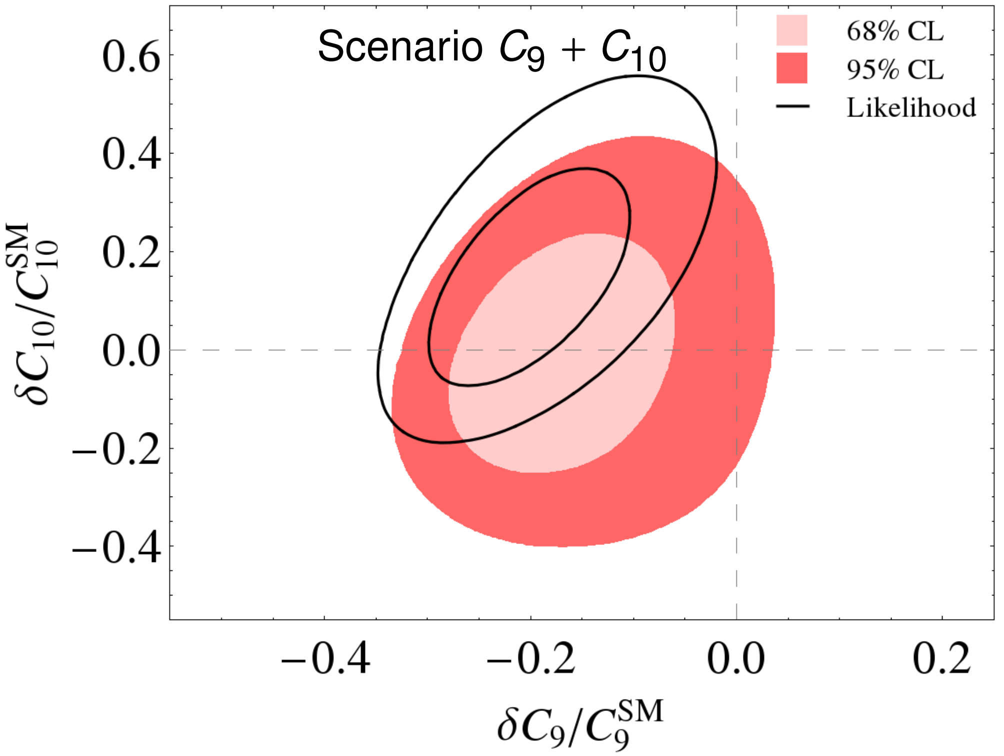
[LHCb 1512.04442]

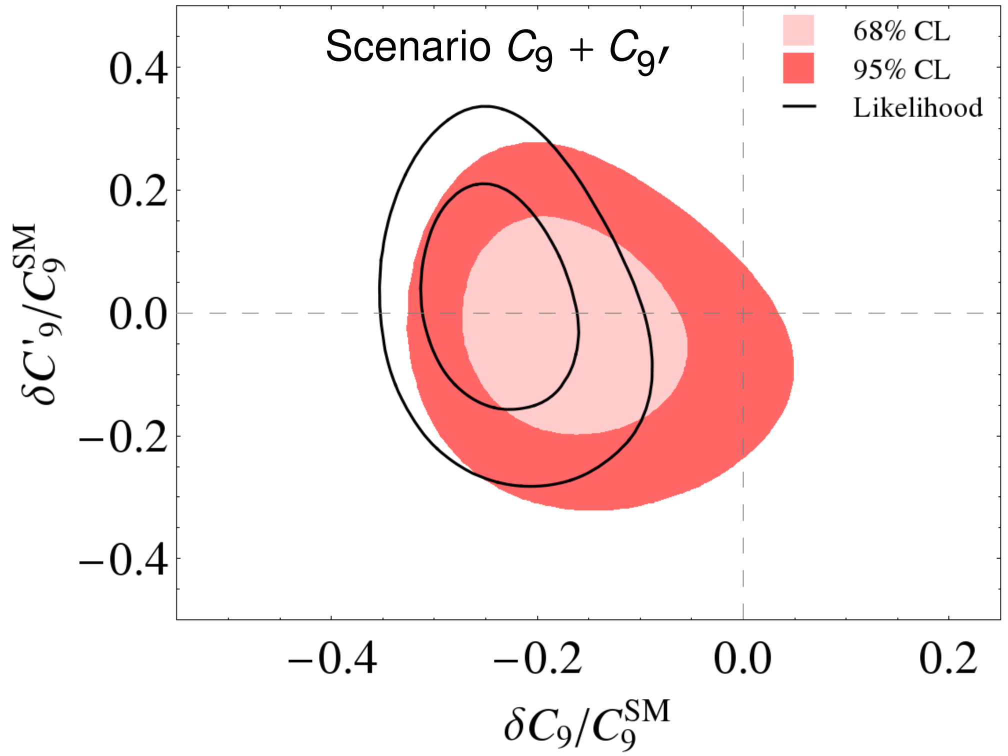
$C_9^{\rm NP} = -1.04 \pm 0.25$ ($3.4\,\sigma$)

$C_9^{\rm NP} = -0.68 \pm 0.35$

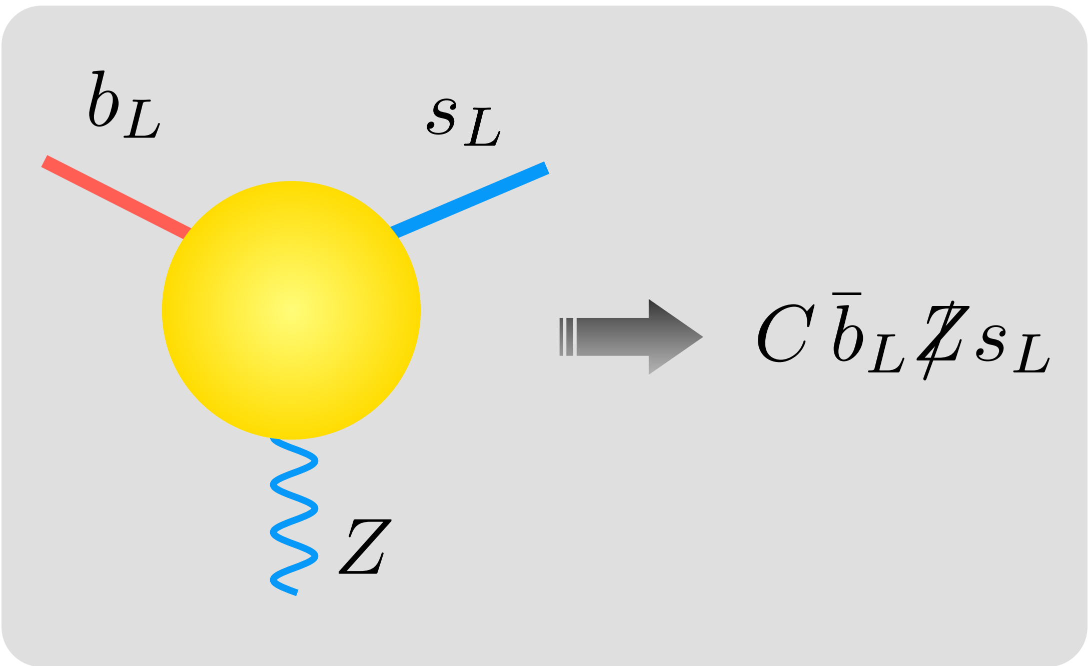
2)

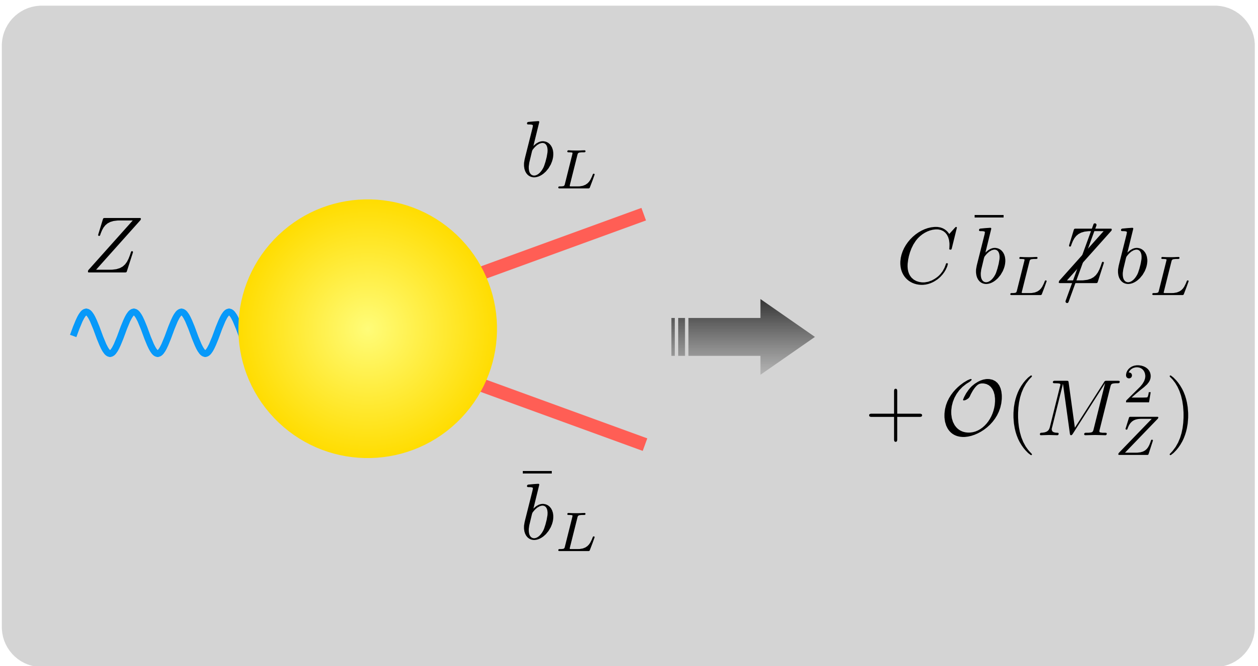
[Hurth/Mahmoudi/Neshatpour 1603.00865]





Flavor precision tests

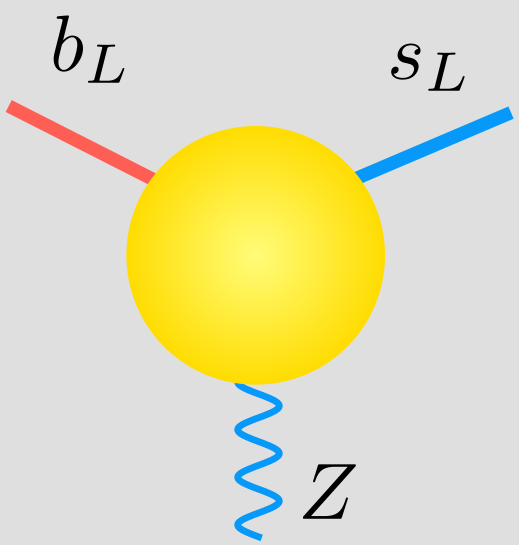




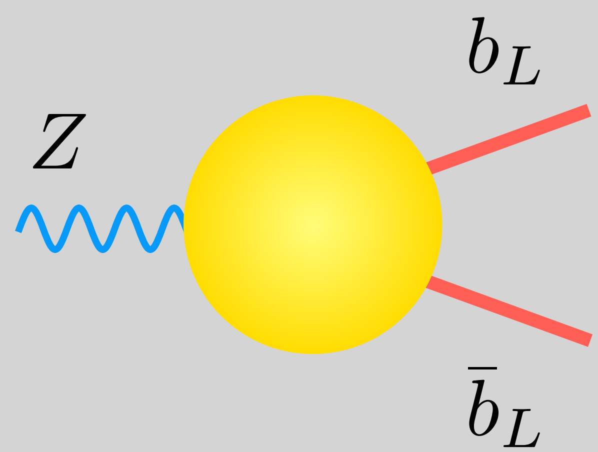
- In many new-physics models (MFV, compositeness, ...), flavor-changing & flavor-conserving Z penguins closely related

[UH & Weiler, 0706.2054]

Flavor precision tests



$$C\,\bar{b}_L \not{Z} s_L$$



$$C\,\bar{b}_L \not{Z} b_L + \mathcal{O}(M_Z^2)$$

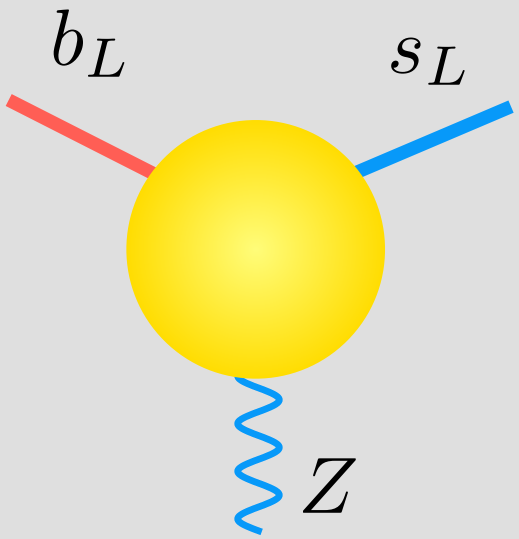
$$\Delta C = (-0.16 \pm 0.53) \cup (-2.15 \pm 0.08)$$

$$\Delta C = -0.04 \pm 0.26$$

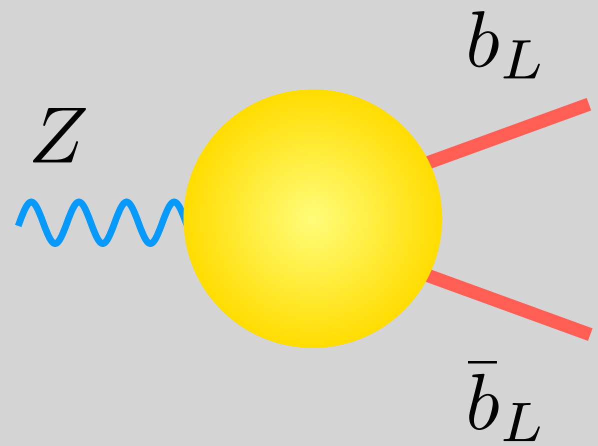
- Pre LHC, flavor not competitive with electroweak precision data

[Bobeth et al., hep-ph/0505110; UH & Weiler, 0706.2054]

Flavor precision tests



$$C\,\bar{b}_L \not{Z} s_L$$



$$C\,\bar{b}_L \not{Z} b_L + \mathcal{O}(M_Z^2)$$

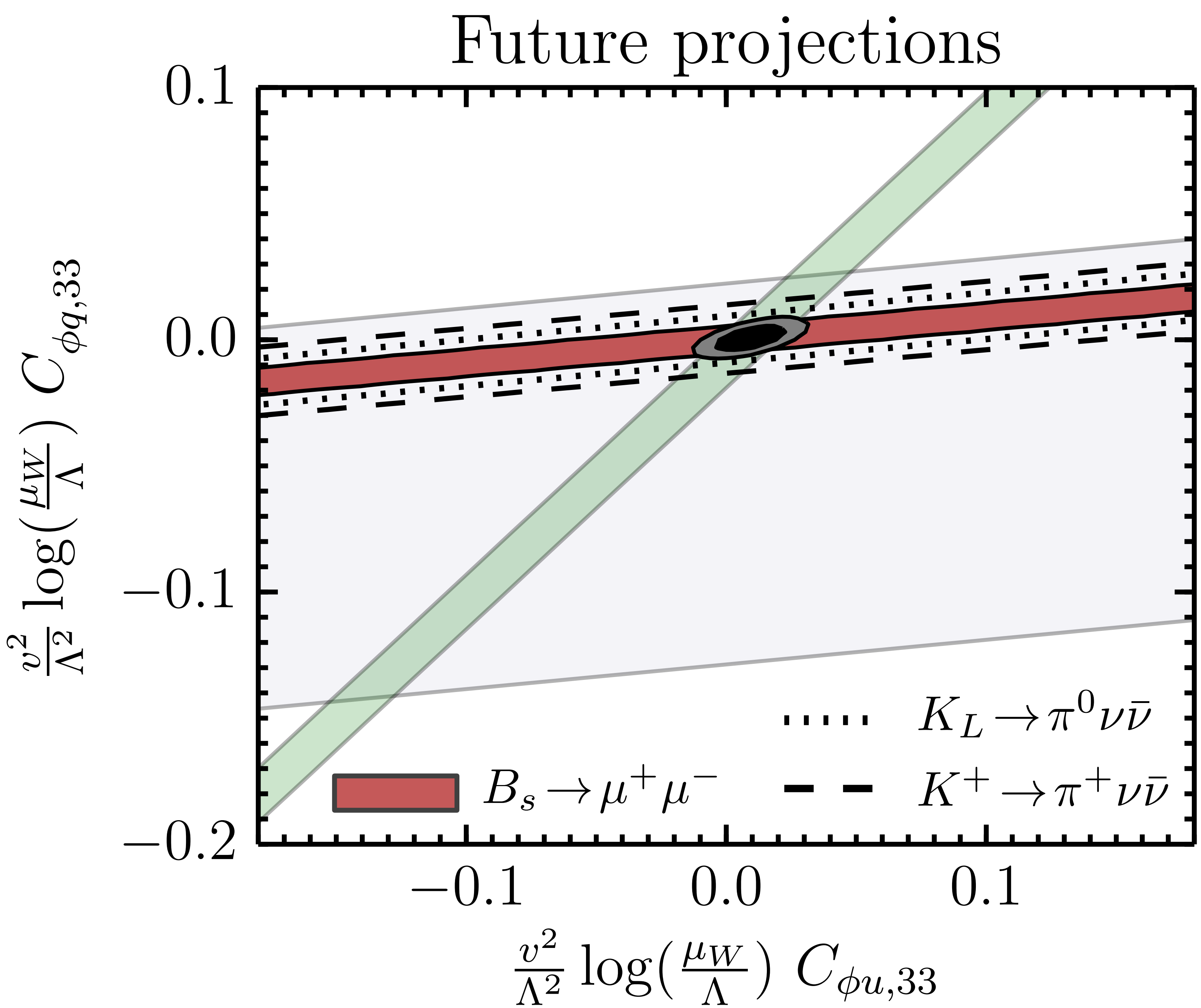
$$\Delta C = -0.11 \pm 0.11$$

$$\Delta C = 0.28 \pm 0.30$$

- Today situation reversed: $B_s \to \mu^+\mu^-$ provides stronger constraint

[Guadagnoli & Isidori, 1302.3909]

$t\bar{t}Z$ couplings: indirect tests



[Brod et al., 1408.0792]

Triple gauge couplings (TGCs)

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{i=\phi B, \phi W, 3W} \frac{C_i}{\Lambda^2} O_i + \ldots$$

$$O_{\phi B} = (D_\mu \phi)^\dagger (D_\nu \phi) \hat{B}^{\mu\nu} \,,$$

$$O_{\phi W} = (D_\mu \phi)^\dagger (D_\nu \phi) \hat{W}^{\mu\nu} \,,$$

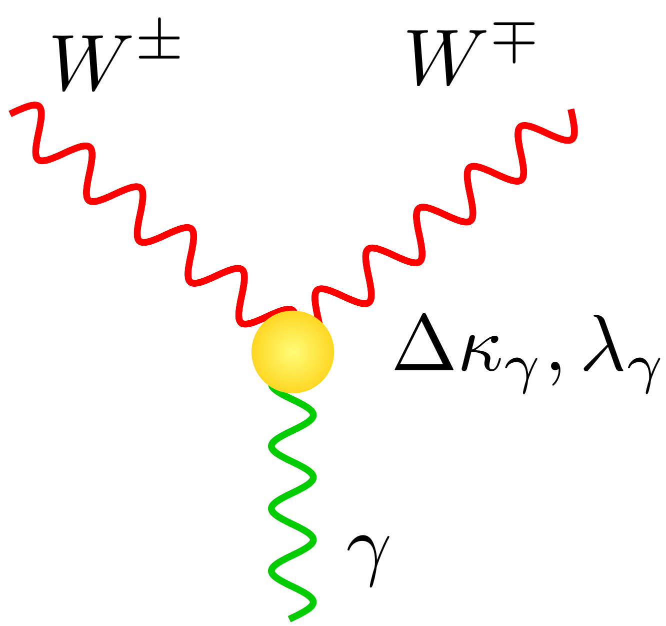
$$O_{3W} = \text{Tr}\left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho{}^\mu\right)$$

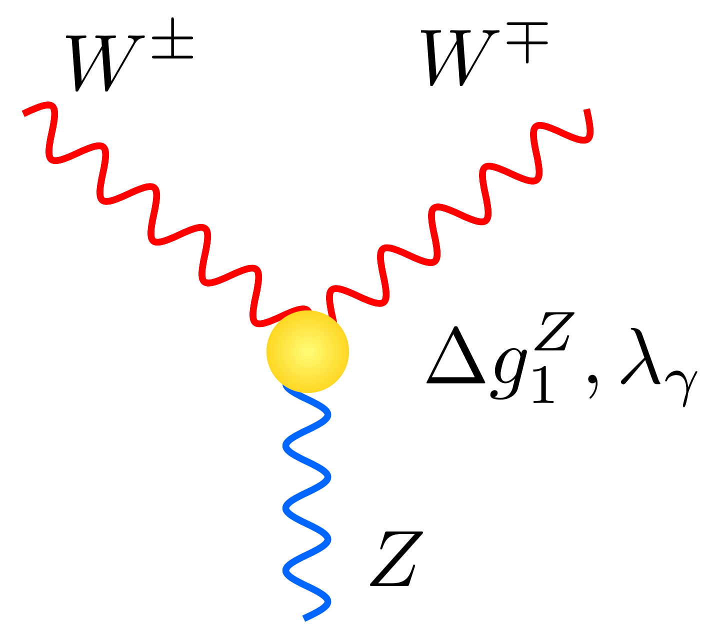
[Buchmüller & Wyler, NPB (1986) 268;
Hagiwara et al., NPB (1987) 282;
Hagiwara et al., PRD (1993) 48;
...
Grzadkowski et al., 1008.4884;
...]

Triple gauge couplings (TGCs)

$$\mathcal{L}_{WWV} = -ig_{WWV}\left[g_1^V\left(W^+_{\mu\nu}W^{-\mu}V^{\nu} - W^+_{\mu}V_{\nu}W^{-\mu\nu}\right)\right.$$

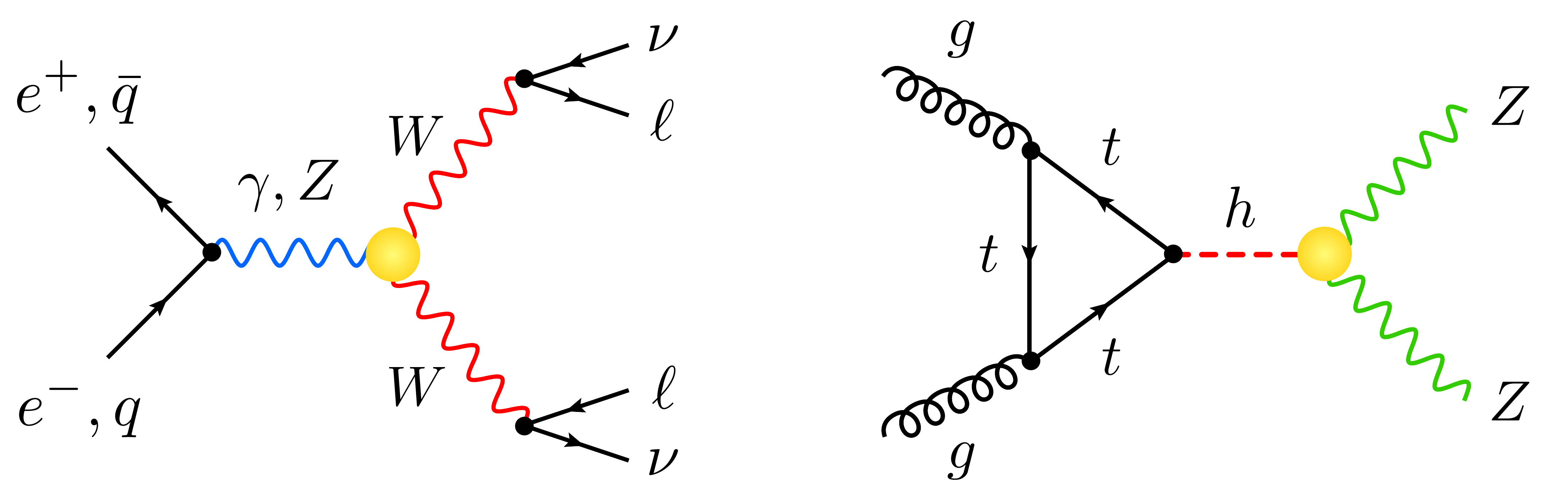
$$\left. + \kappa_V W^+_{\mu}W^-_{\nu}V^{\mu\nu} + \frac{\lambda_V}{m_W^2}W^+_{\mu\nu}W^{-\nu\rho}V_{\rho}{}^{\mu}\right]$$





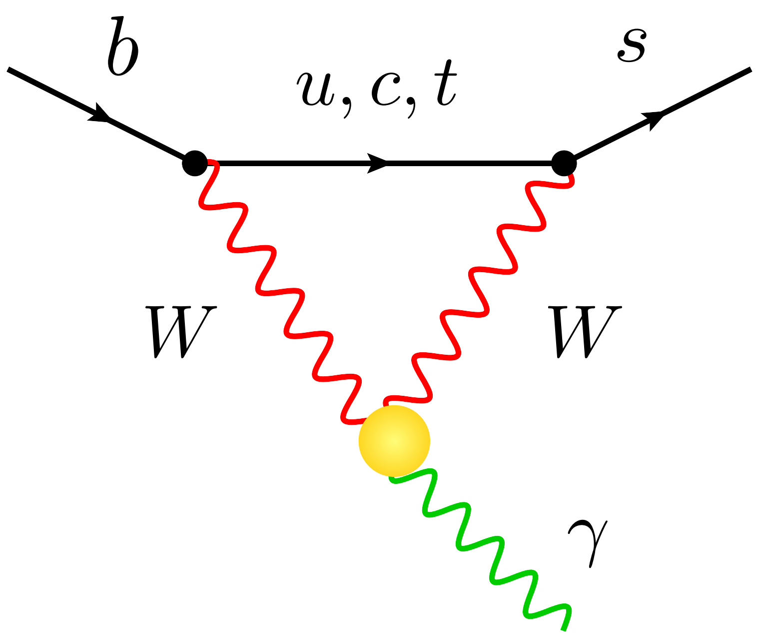
B20/B62

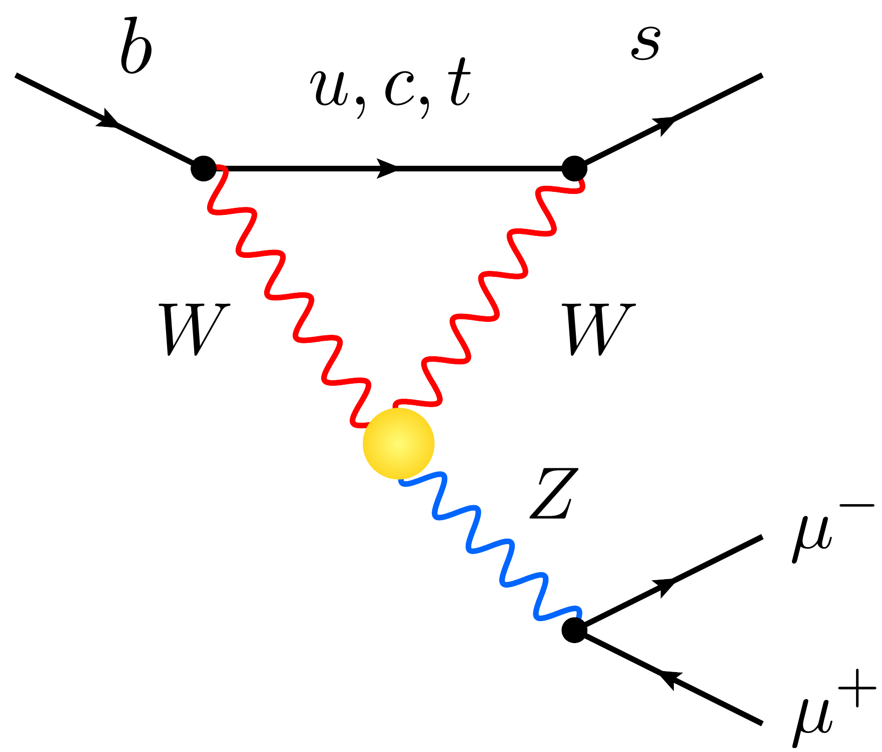
Direct probes of anomalous TGCs



- Searches for anomalous TGCs have been performed at LEP, Tevatron & LHC (WW, WZ, Wγ, Zγ, … production). They can also be probed in Higgs physics ($pp \to h \to ZZ$, …)

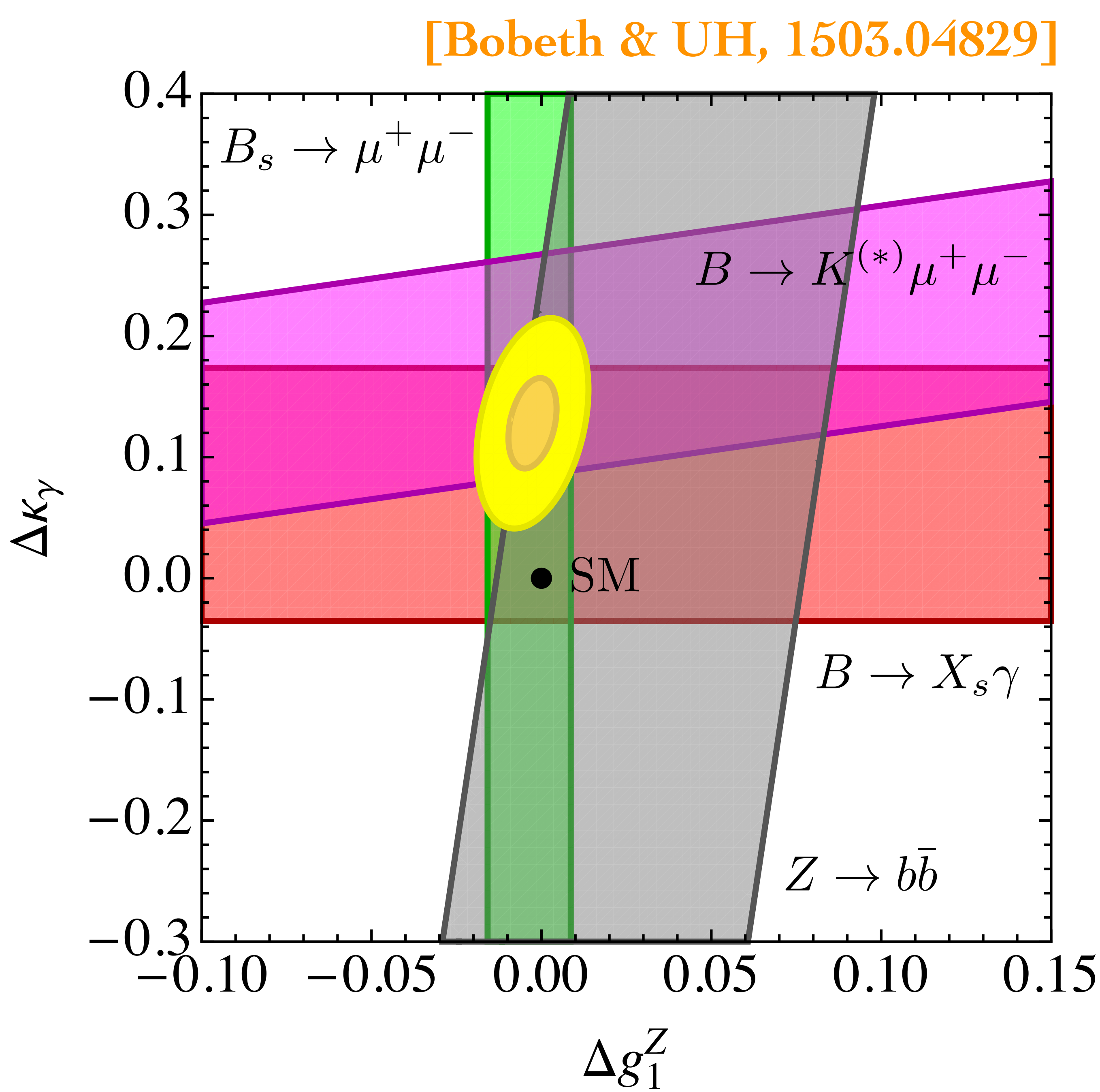
Indirect tests of anomalous TGCs





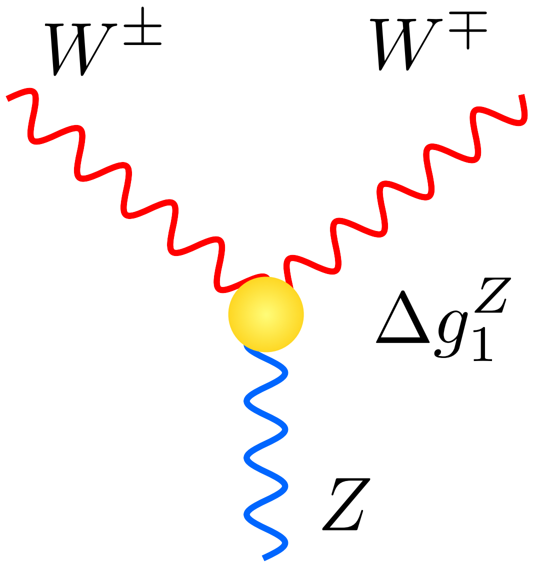
- Anomalous TGCs contribute to observables such as $B \to X_s\gamma$, $B \to K^*\mu^+\mu^-$, $B_s \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$ & ε'/ε as well as $Z \to b\bar{b}$ from one-loop level & beyond

Anomalous TGCs from flavor



- b → s$\mu^+\mu^-$ anomalies lead to 3σ deviation of best fit from SM

Bounds on TGCs: Comparison



- Indirect bound on Δg_1^Z from $B_s \to \mu^+\mu^-$ alone slightly better than direct LEP II constraint

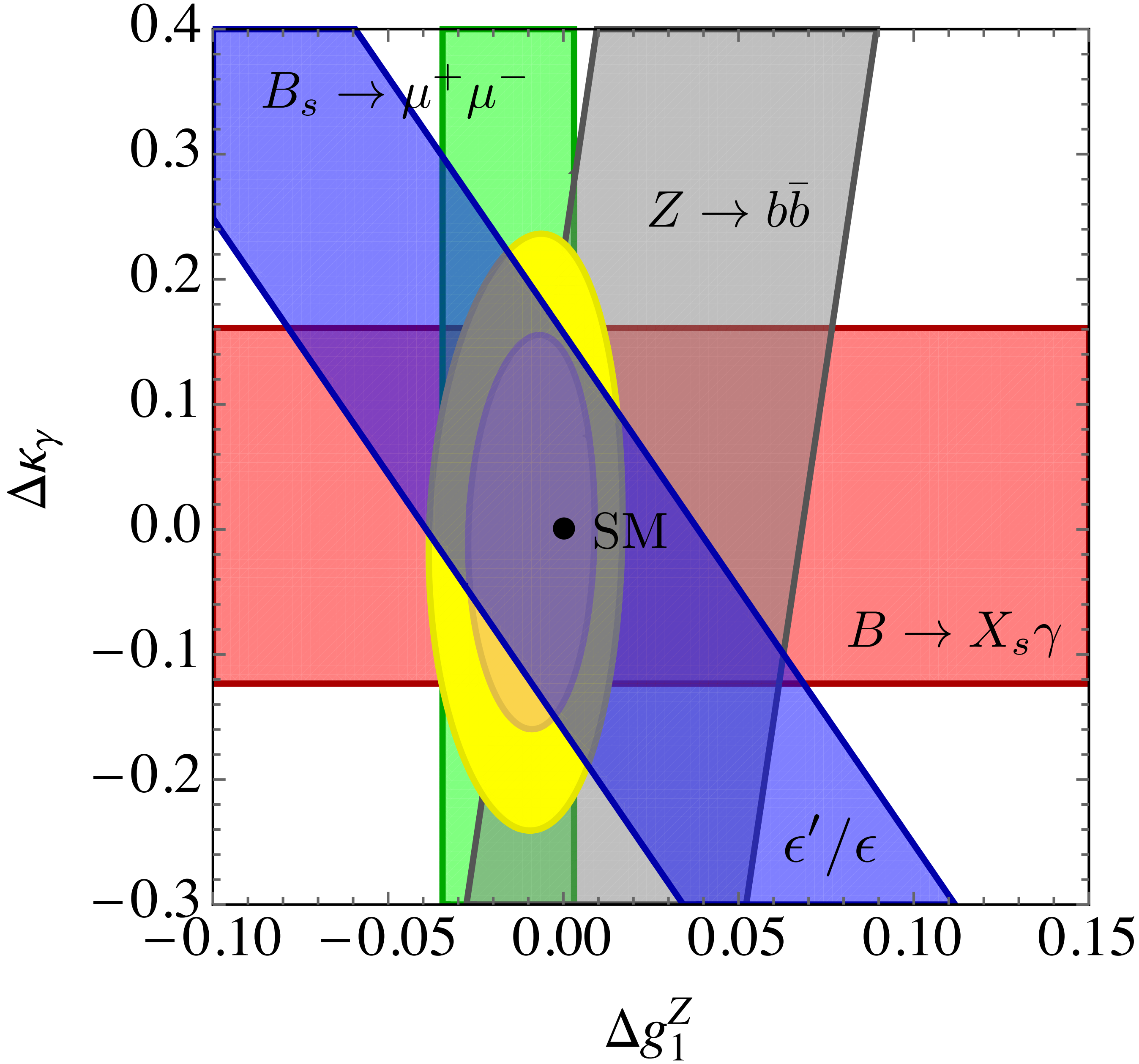
[Falkowski et al., 1508.00581]

$$\Delta g_1^Z = \frac{M_Z^2}{2\Lambda^2} c_{HW} = \begin{cases} 0.017 \pm 0.023 & \text{(direct)} \\ -0.009 \pm 0.019 & \text{(indirect)} \end{cases}$$

[Bobeth & UH, 1503.04829]

Anomalous TGCs from ε′/ε

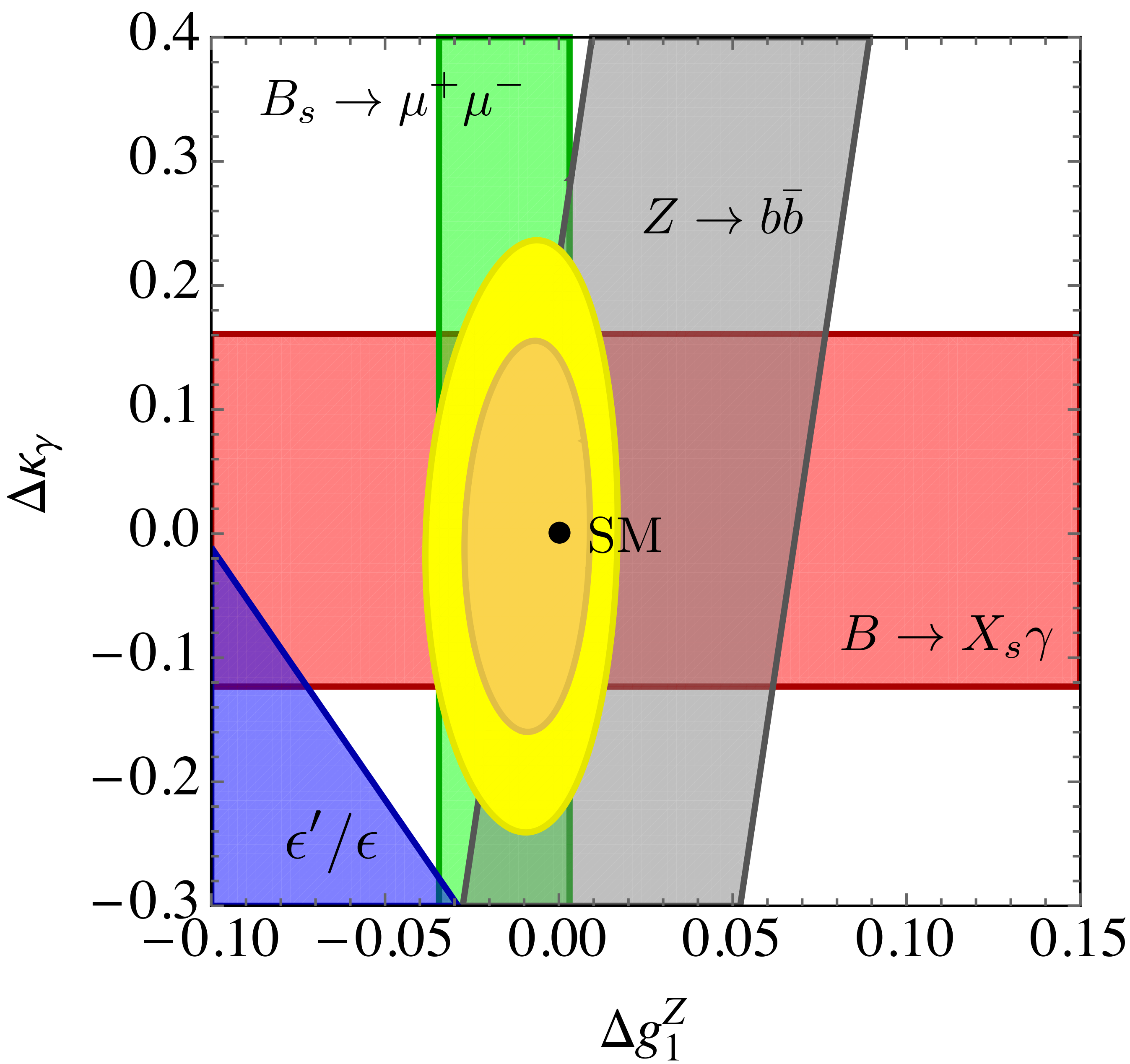
[Bobeth & UH, 1503.04829]



$$\left(\frac{\epsilon'}{\epsilon}\right)_{\rm SM} = (16.5 \pm 2.6) \cdot 10^{-4}$$

- ε′/ε can provide meaningful additional constraints on anomalous TGCs & resolve blind directions

Anomalous TGCs from ε′/ε



$$\left(\frac{\epsilon'}{\epsilon}\right)_{\text{SM}} = (1.9 \pm 5.4)\cdot 10^{-4}$$

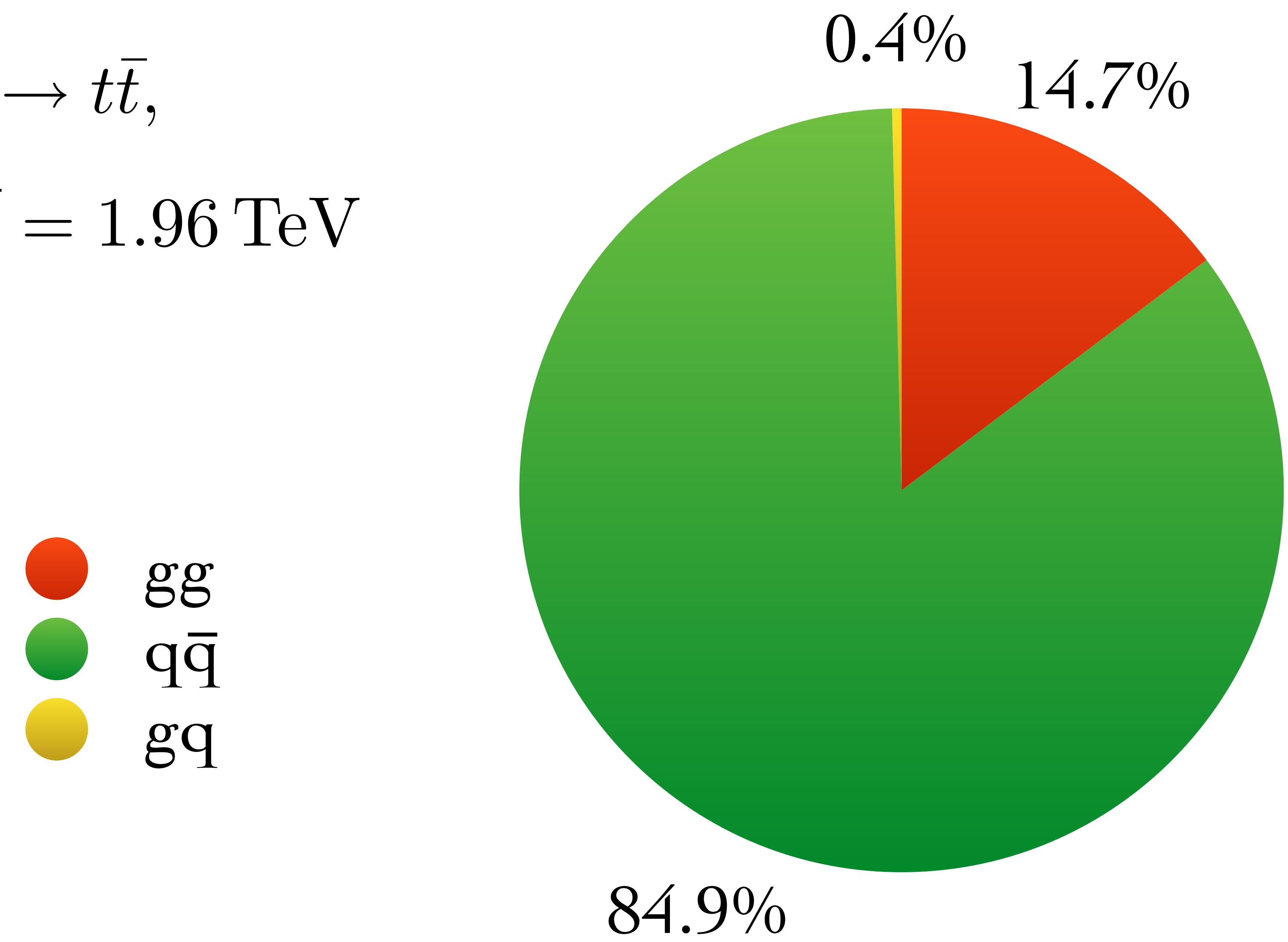
[Buras et al., 1507.06345]

- ε′/ε can provide meaningful additional constraints on anomalous TGCs & resolve blind directions

$\mathrm{t\bar{t}}$ production at Tevatron

$p\bar{p} \to t\bar{t},$

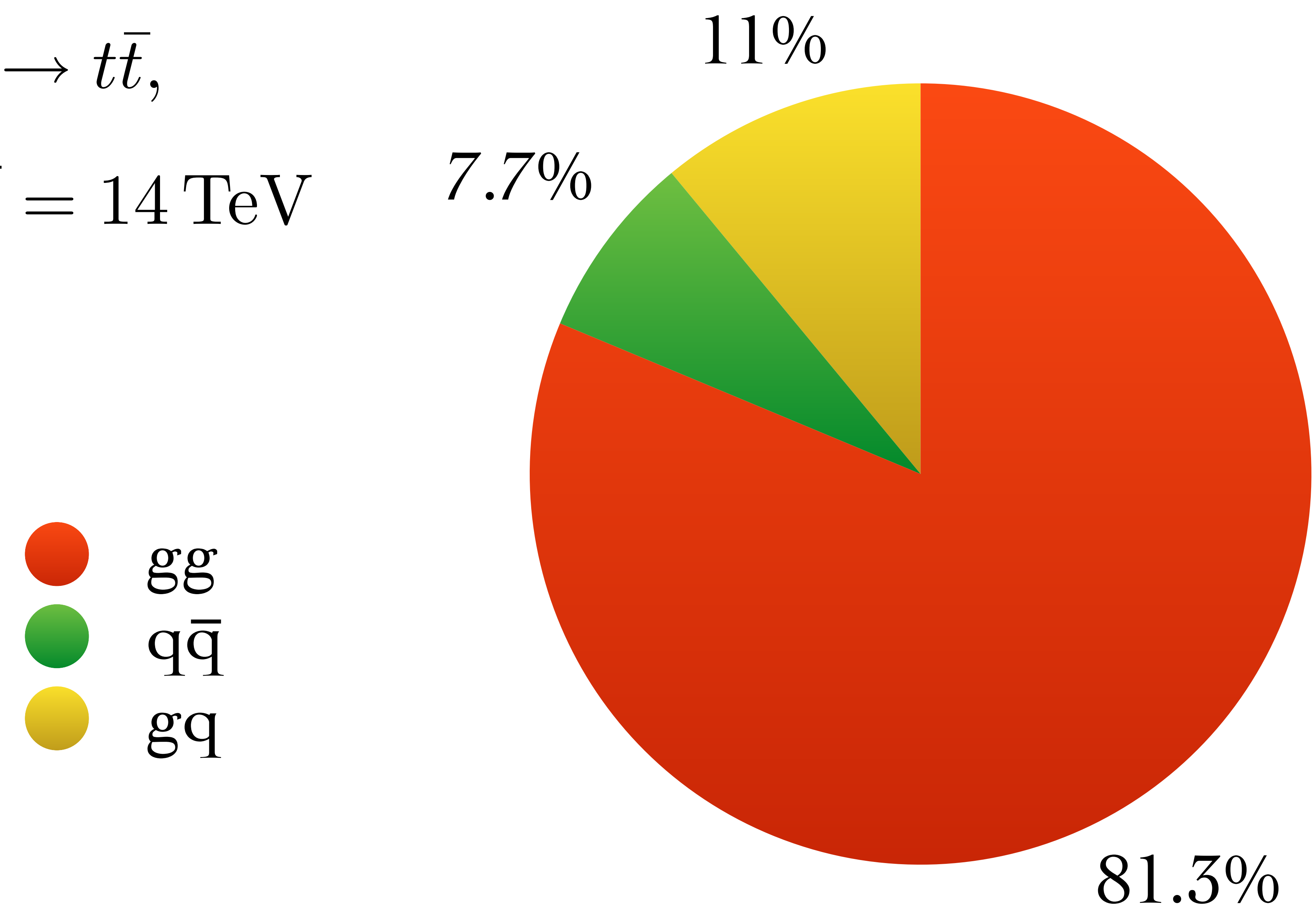
$\sqrt{s} = 1.96\,\mathrm{TeV}$



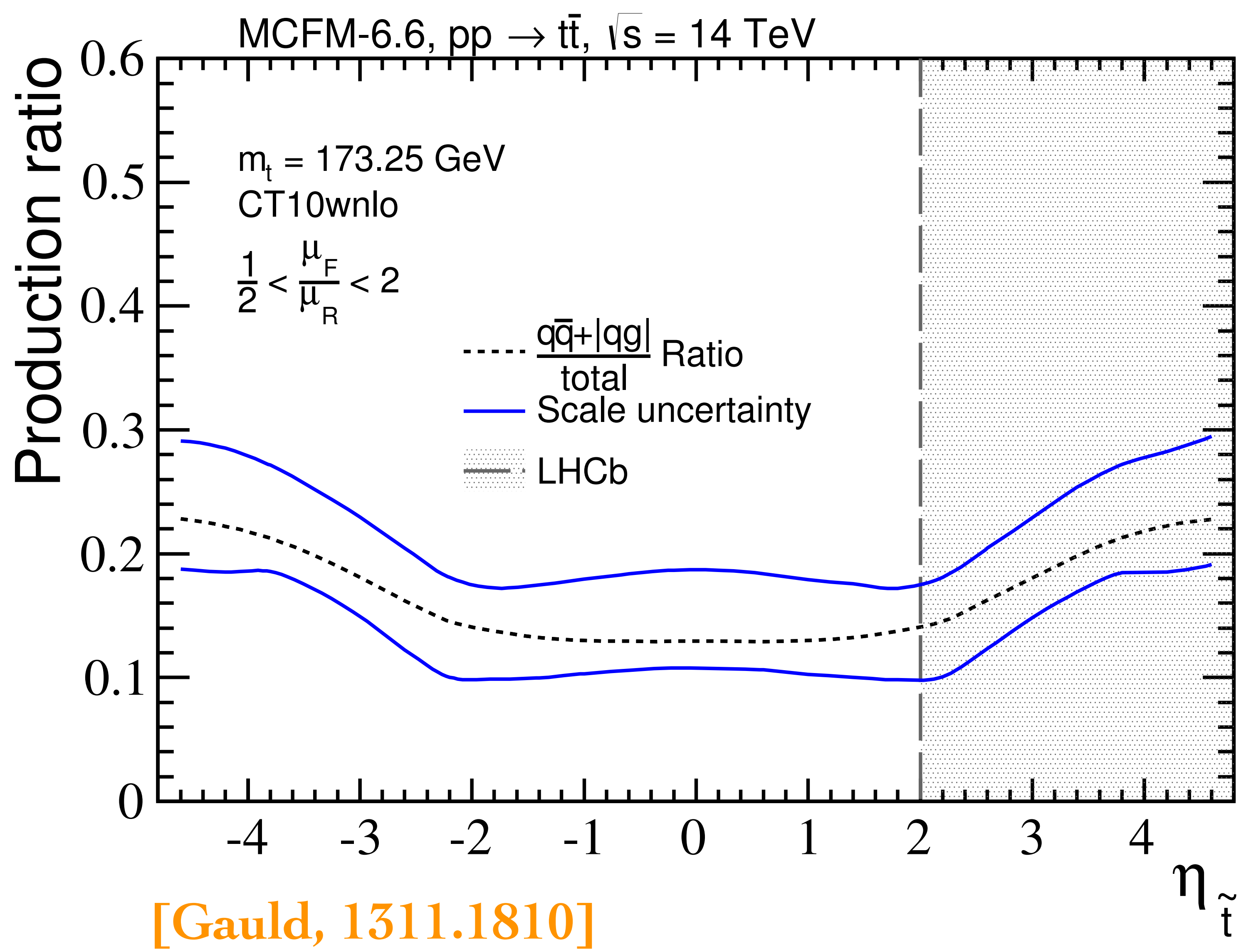
$t\bar{t}$ production at ATLAS & CMS

$pp \to t\bar{t},$

$\sqrt{s} = 14\,\mathrm{TeV}$



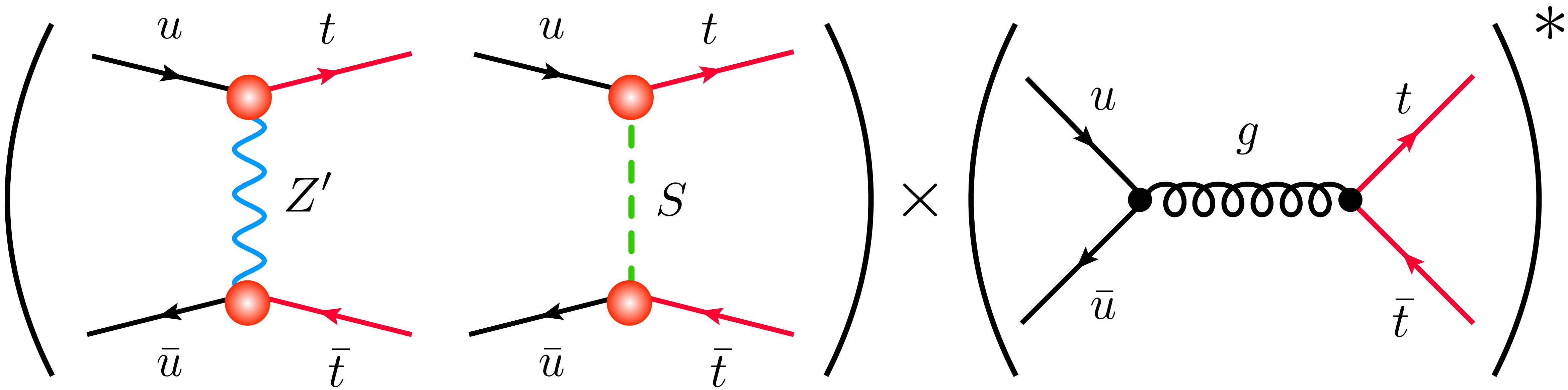
$t\bar{t}$ production at LHCb



[Gauld, 1311.1810]

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

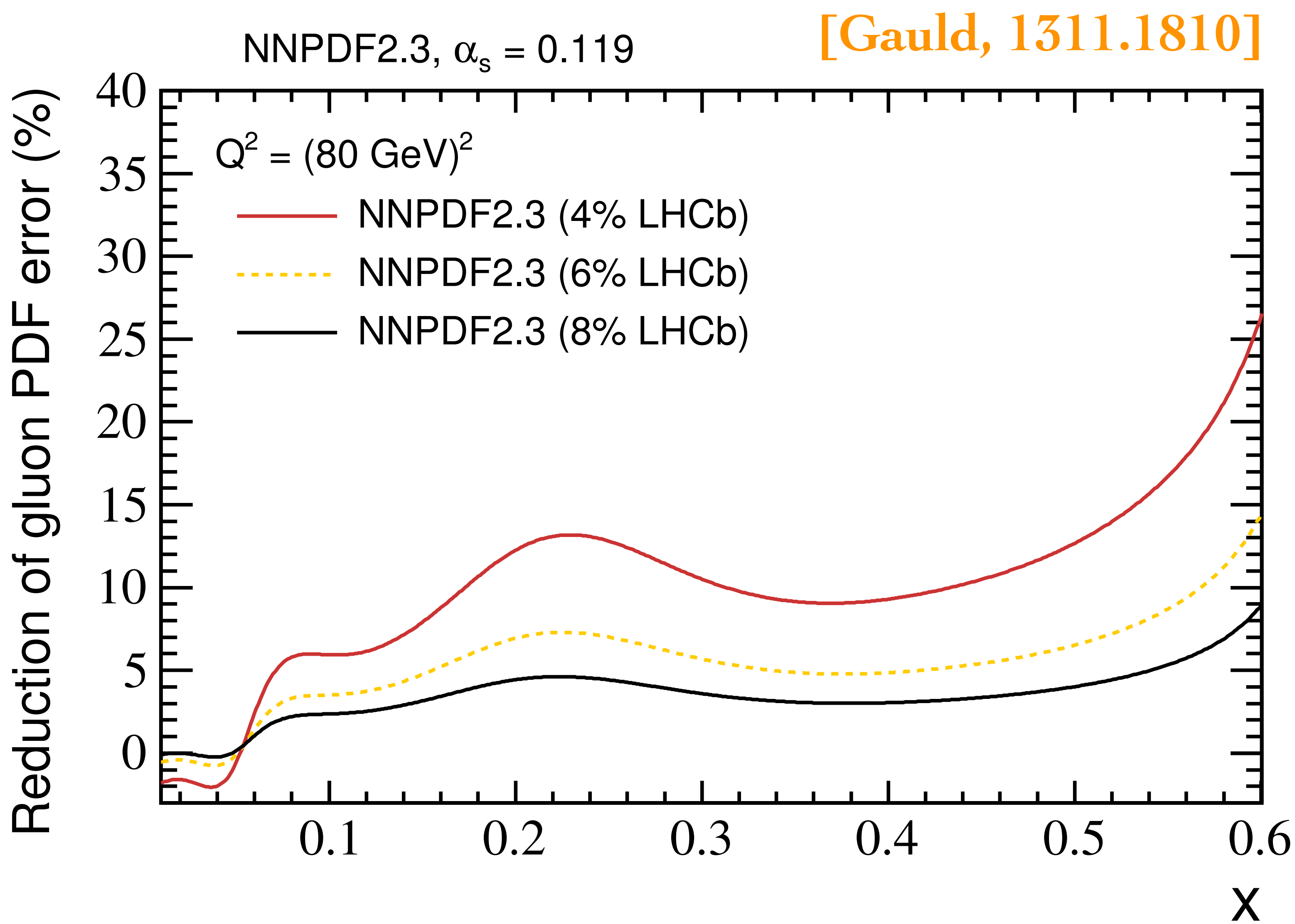
Why $t\bar{t}$ production at LHCb?



- In new-physics scenarios in which top production proceeds via t-channel exchange, cross section enhanced in forward direction

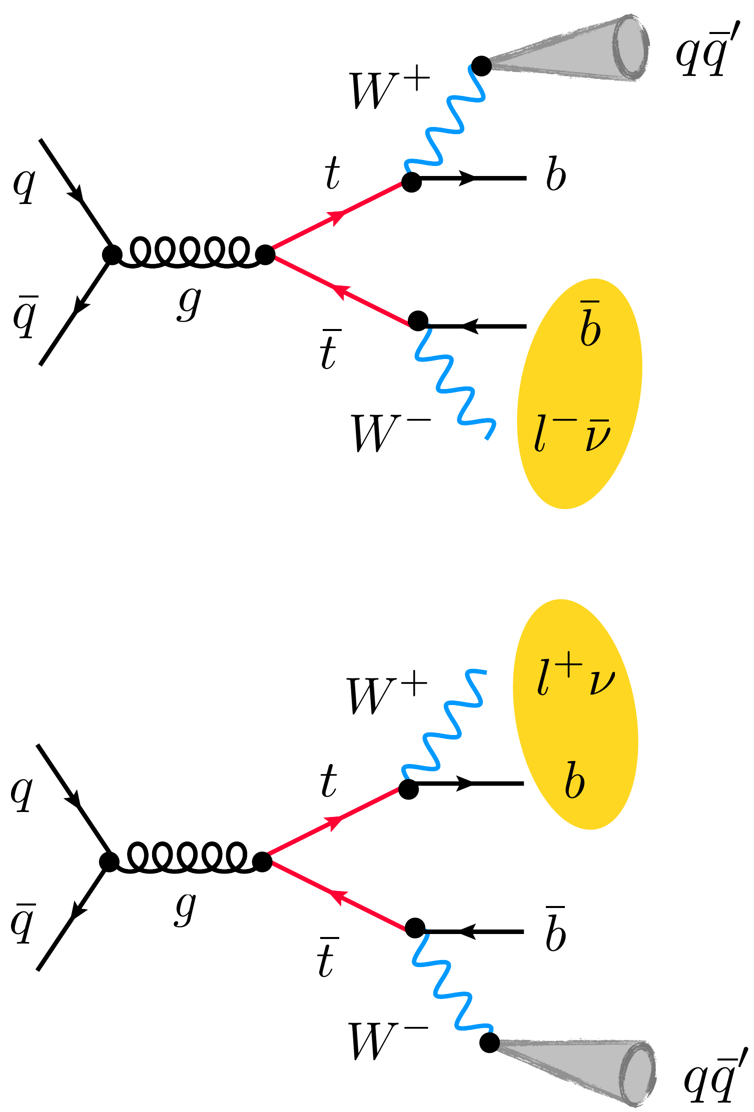
[in LHCb context see Kagan et al., 1103.3747]

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

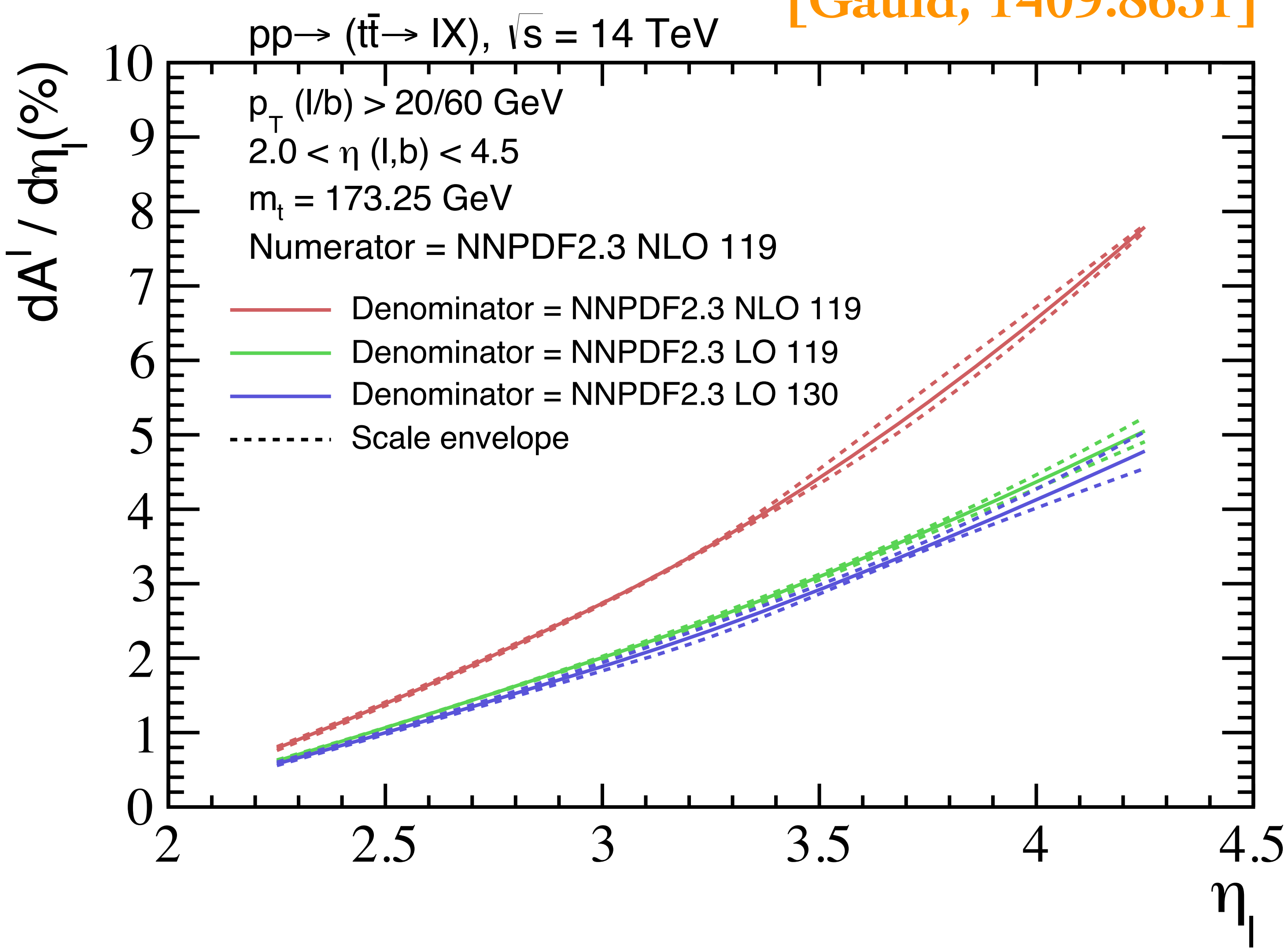


- Even if no new physics hides in top sector, could make use of LHCb data by improving our understanding of gluon PDF

Single-lepton asymmetry



[Gauld, 1409.8631]



- Single-lepton channel statistically more promising than di-lepton mode. As background low, 2nd signal should still be looked for

Single-lepton asymmetry

LHCb can do it, if backgrounds are under control!

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

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

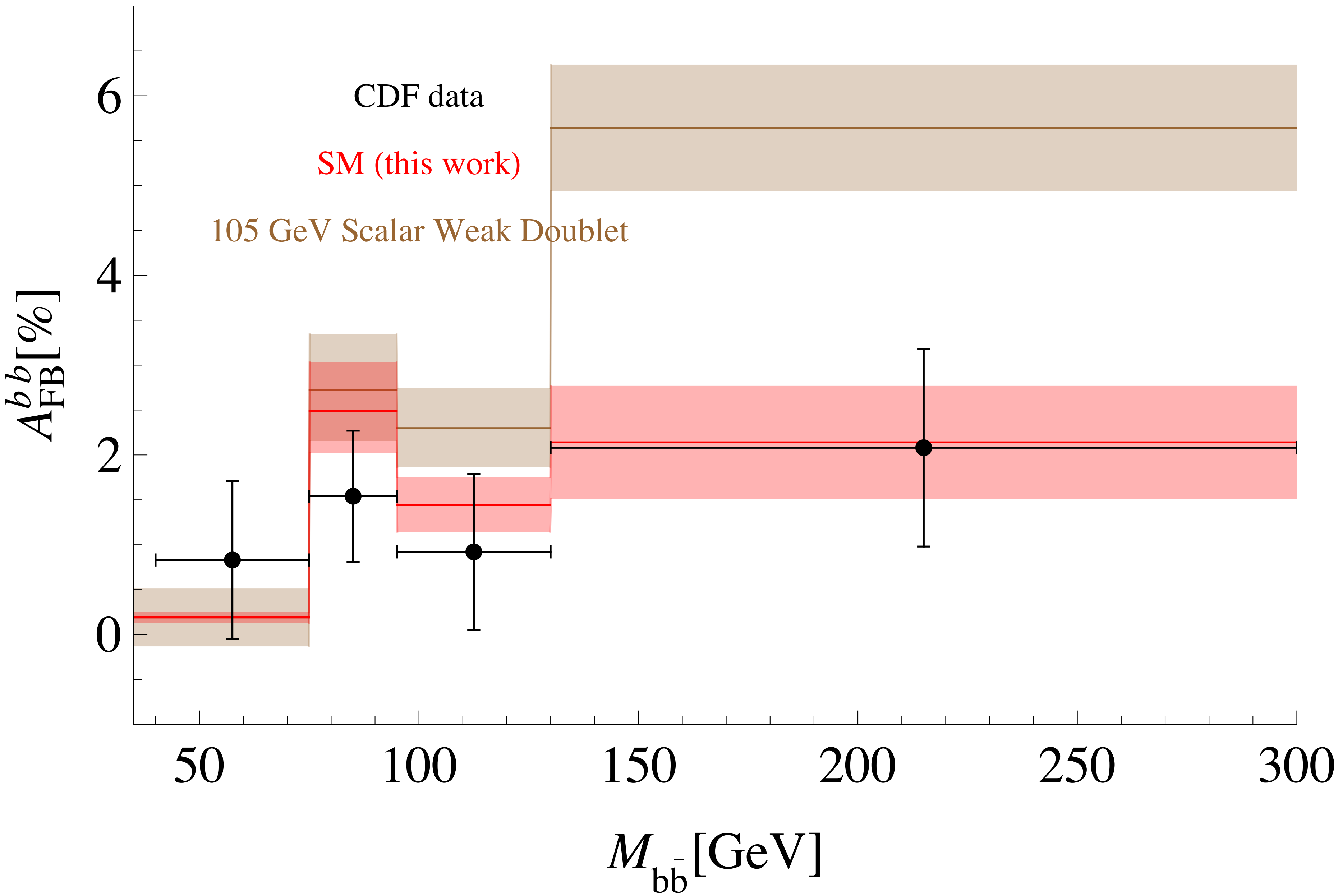
$$\epsilon_b = 70\%$$

$$\epsilon_l = 75\%$$

[Gauld, 1409.8631]

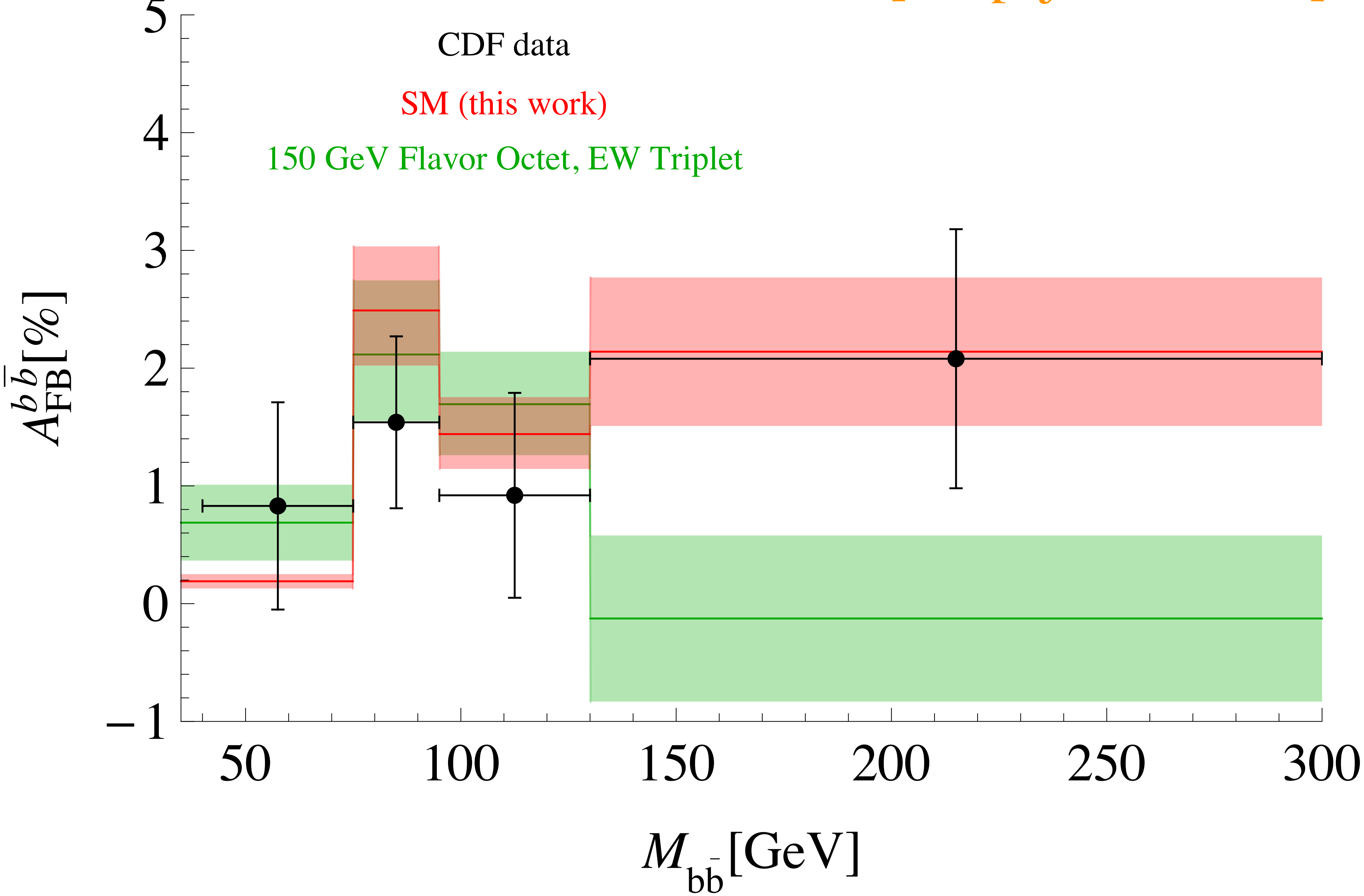
$b\bar{b}$ asymmetry: implications

[Murphy, 1504.02493]



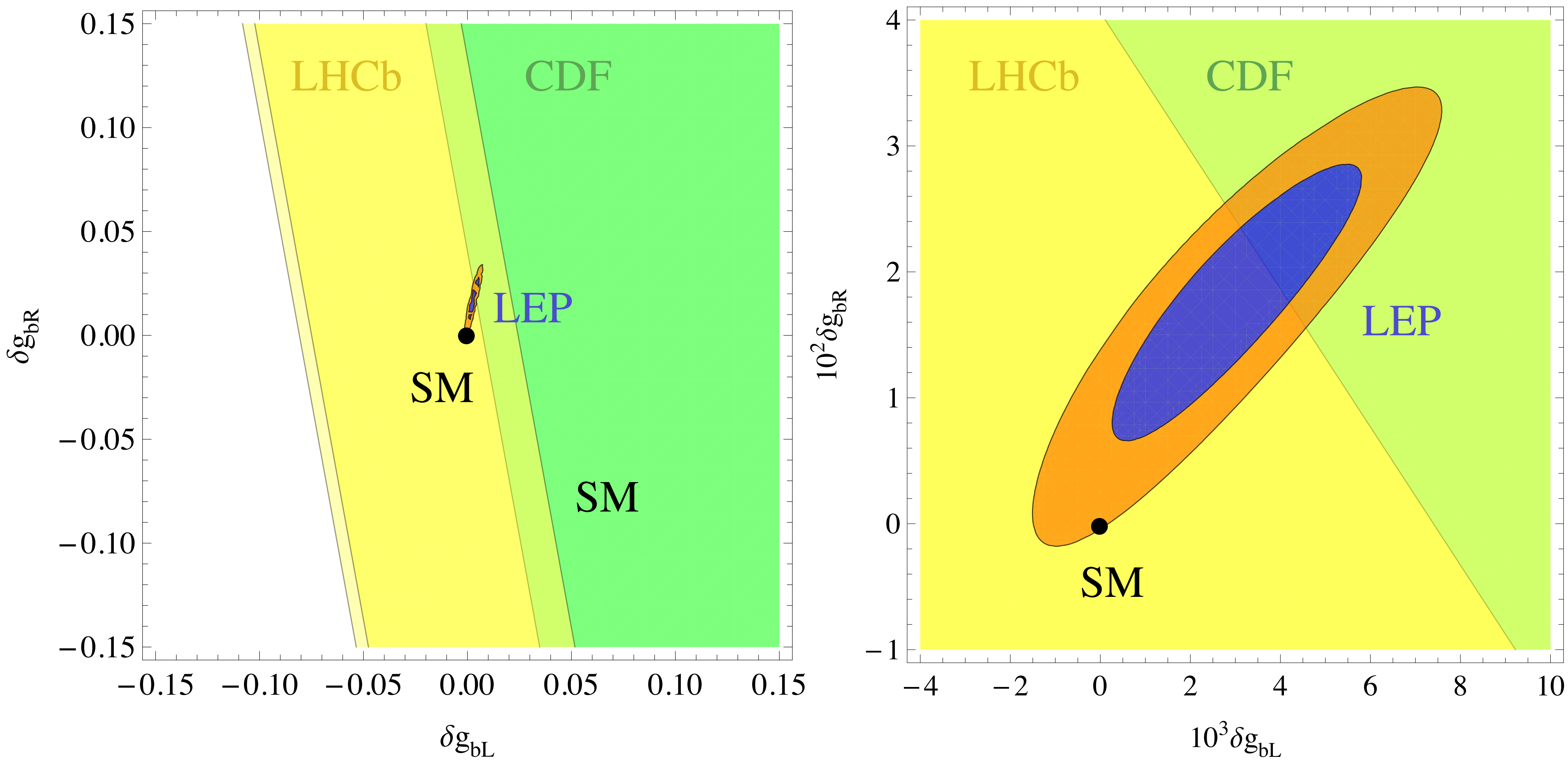
$b\bar{b}$ asymmetry: implications

[Murphy, 1504.02493]



$b\bar{b}$ asymmetry: implications

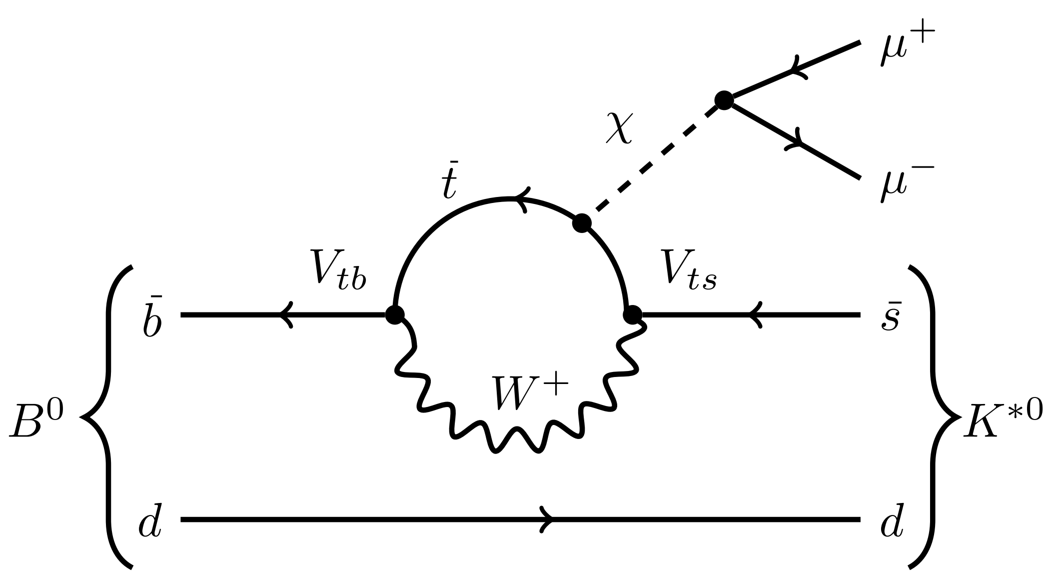
[Murphy, 1504.02493]

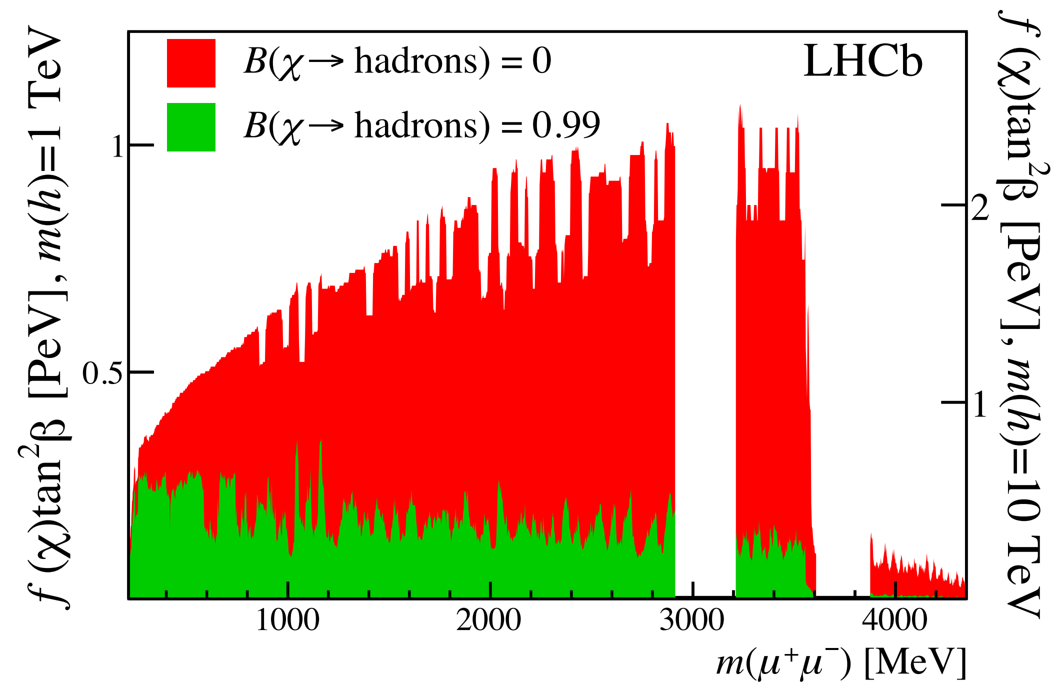


- CDF & LHCb measurements of $b\bar{b}$ asymmetries not yet sensitive to probe longstanding anomaly in $Z \to b\bar{b}$ pseudo observables

Axions in dimuon spectrum

[Freytsis et al., 0911.5355]



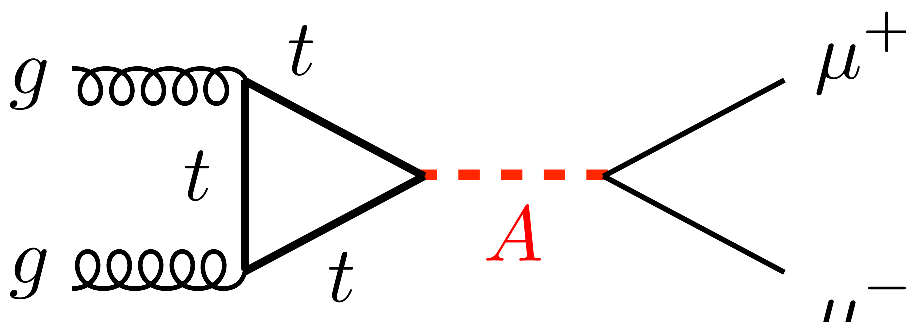


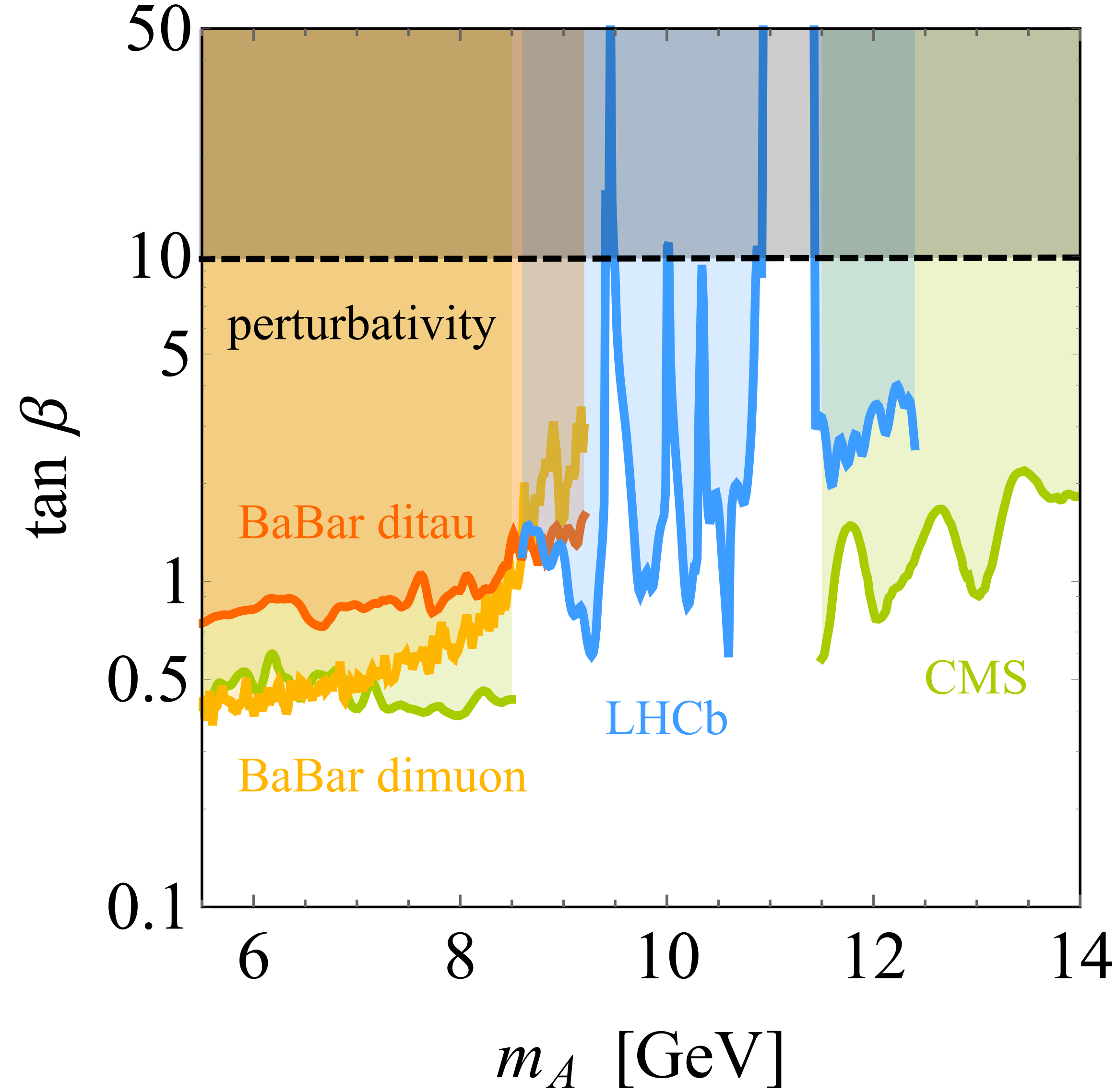
[LHCb, 1508.04094]

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

Search for light spin-0 states

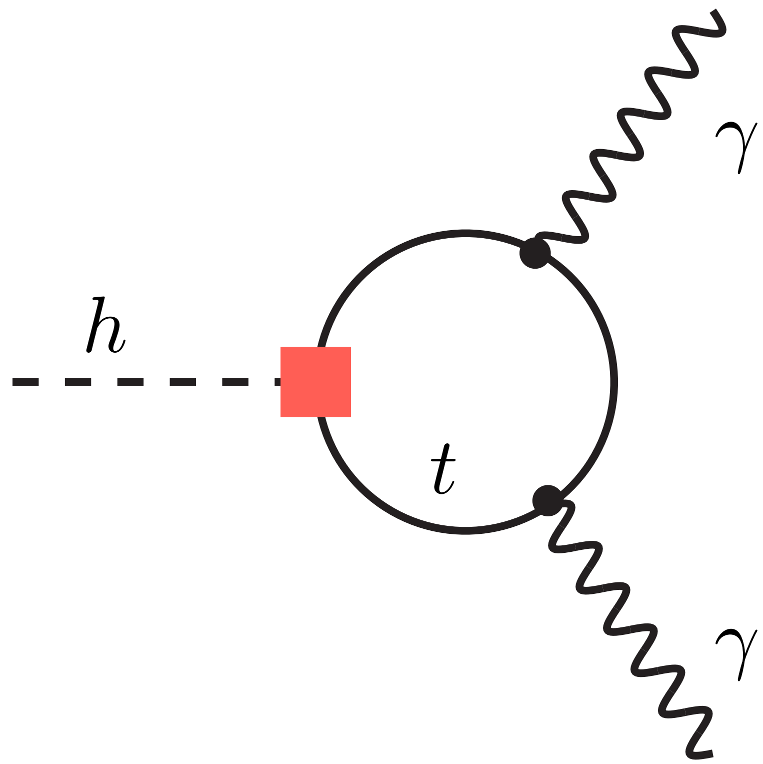
[UH & Kamenik, 1601.05110]





- Using LHCb Υ data can probe dimuon resonances in [8.6, 11] GeV range. Improvements possible as only 3% of Run I data published

From h→γγ to …

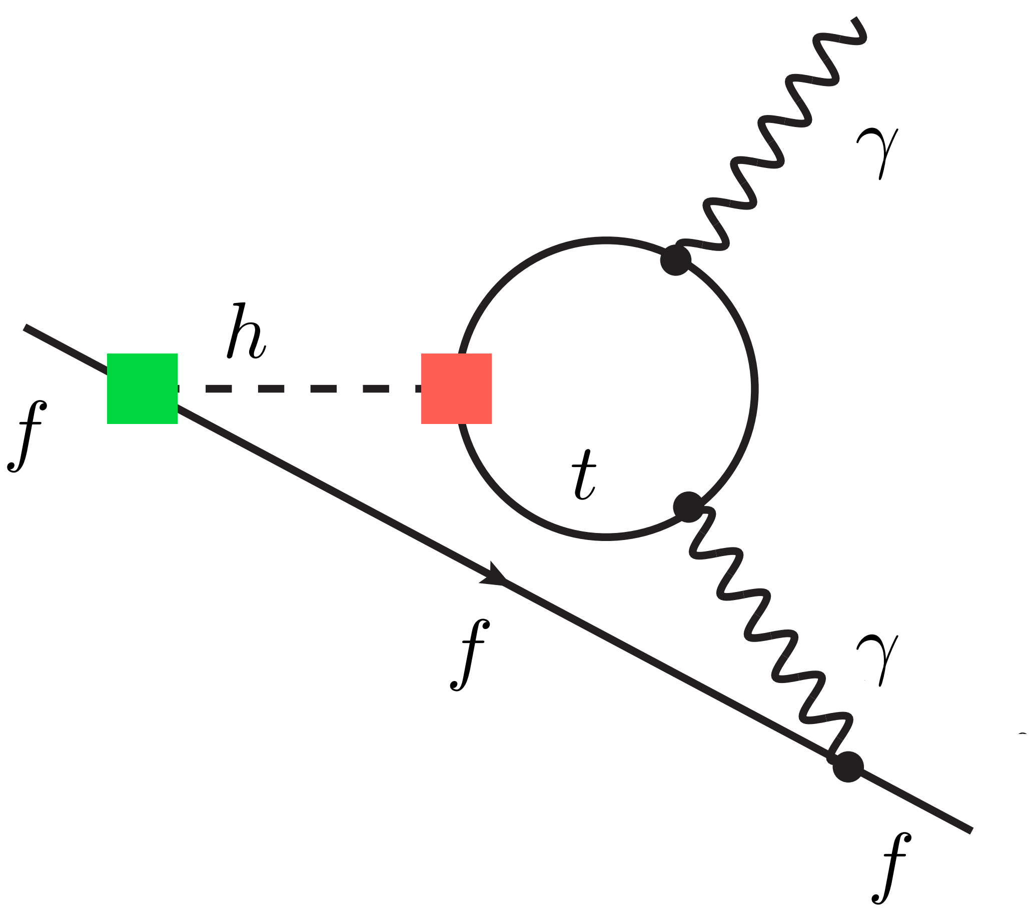


- Modified Higgs-fermion couplings

$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}} \left(\kappa_f \bar{f} f + i \tilde{\kappa}_f \bar{f} \gamma_5 f \right) h$$

alter Higgs production & decay

… to electric dipole moments (EDMs)



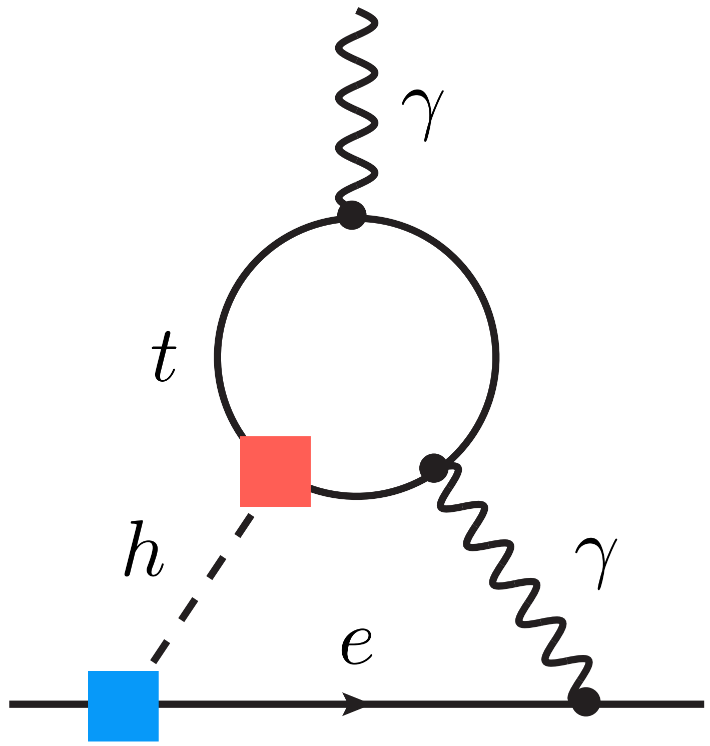
- Modified Higgs-fermion couplings

$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}} \left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right) h$$

alter Higgs production & decay

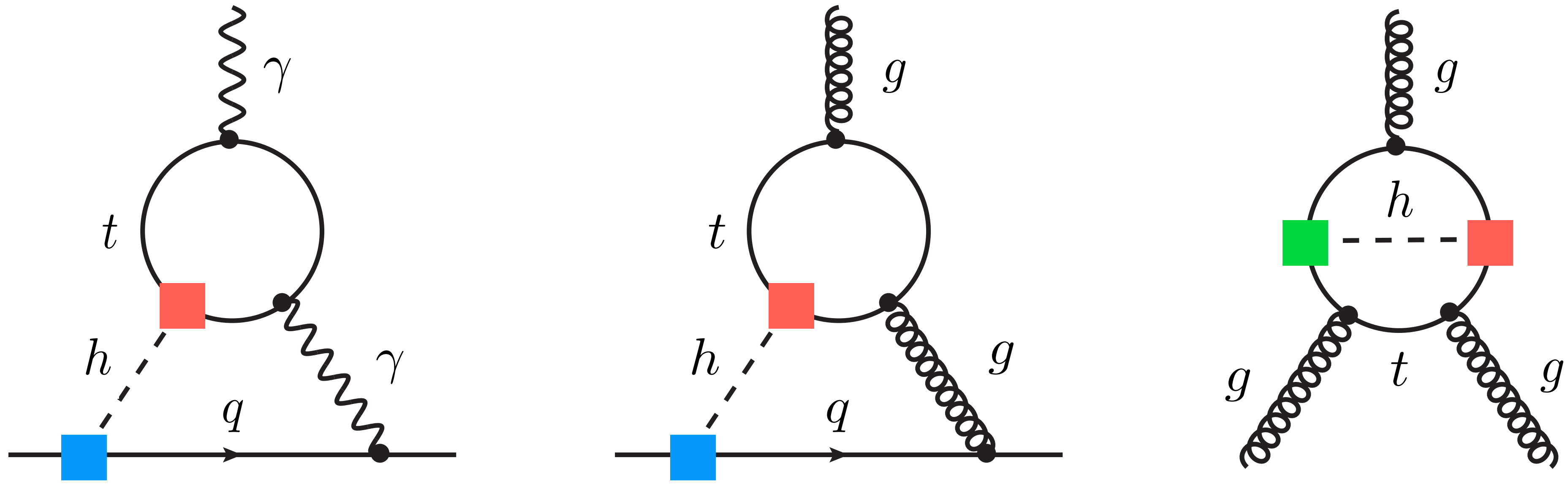
- Attaching fermion line generates EDM. As SM background 3-loop suppressed, EDMs offer unique indirect probe of CP-violating Higgs-fermion couplings

Electron EDM (d_e)



- d_e induced via two-loop diagrams of Barr-Zee type
- At present $|d_e/e| < 8.7 \cdot 10^{-29}$ cm at 90% CL **[ACME, 1310.7534]**
- Constraint vanishes if Higgs does not couple to electron

Neutron EDM (d_n)

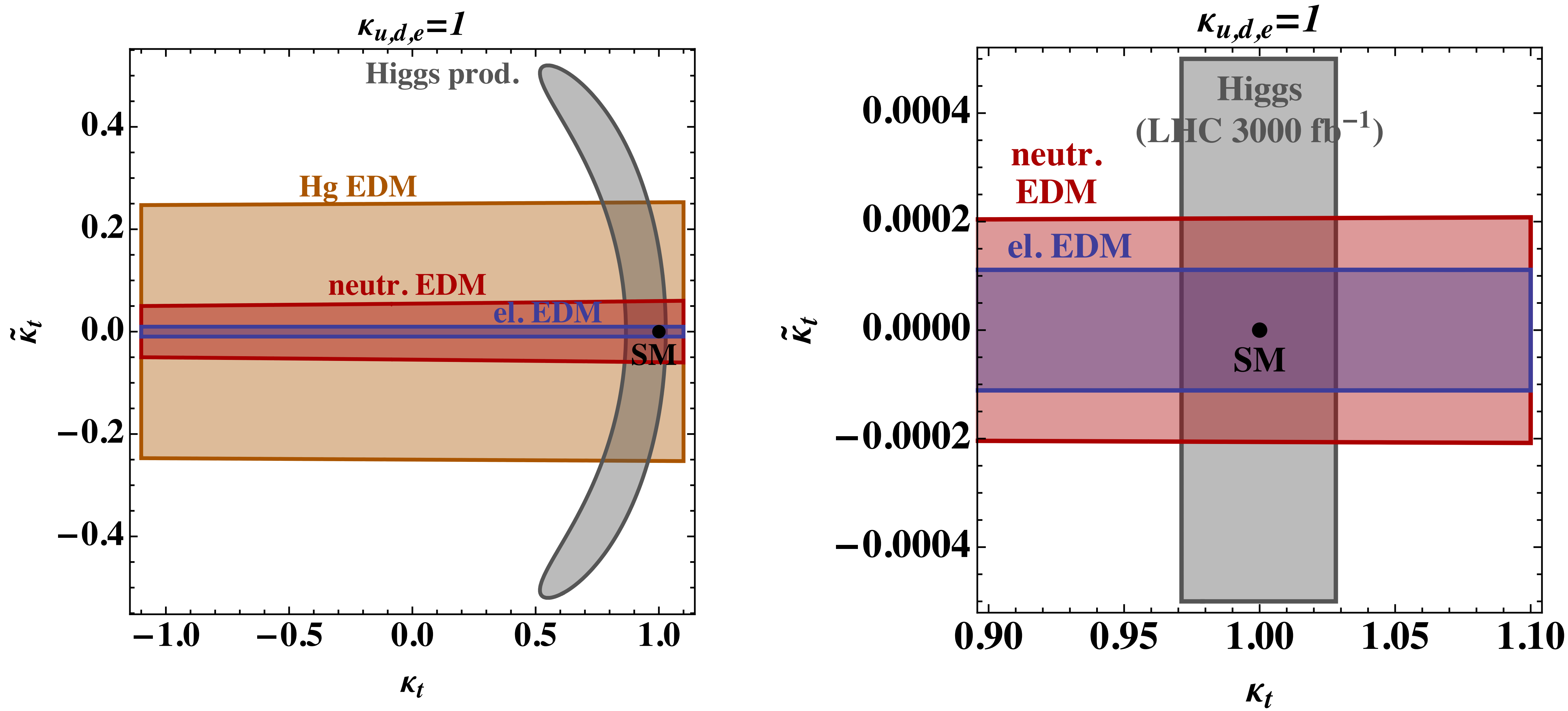


$$\frac{d_n}{e} = \Big\{ (1.0 \pm 0.5) \left[-(1.0\,\kappa_u + 4.3\,\kappa_d)\,\tilde{\kappa}_t + 5.1 \cdot 10^{-2}\,\kappa_t \tilde{\kappa}_t \right]$$

$$+ (22 \pm 10)\, 1.8 \cdot 10^{-2}\,\kappa_t \tilde{\kappa}_t \Big\} \cdot 10^{-25}\,\text{cm}$$

- $\kappa_t \tilde{\kappa}_t$ contributions due to Weinberg operator subdominant
- At 90% CL have $|d_n/e| < 2.9 \cdot 10^{-26}$ cm **[Baker et al., hep-ex/0602020]**

Fits to $h\bar{t}t$ couplings



- Plots assume SM couplings to electron & light quarks ($\kappa_{e,d,u} = 1$)
- Projection for 3000 fb^{-1} at HL-LHC [Olsen, talk at Snowmass2013]
- Factor 90 (300) improvement on d_e (d_n) [Hewett et al., 1205.2671]

$t \to qh$ from dimension-6 operators

- Adding higher-dimensional operators to SM Lagrangian will generically lead to top-Higgs FCNCs:

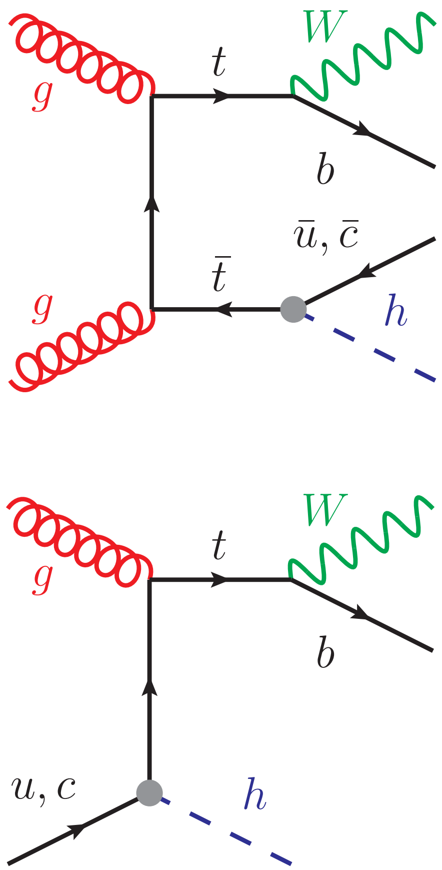
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{\lambda_{ij}}{\Lambda^2}\left(\phi^\dagger \phi\right) \bar{Q}_L^i u_R^j \tilde{\phi} + \text{h.c.}$$

symmetry breaking ↓ rotation to mass basis

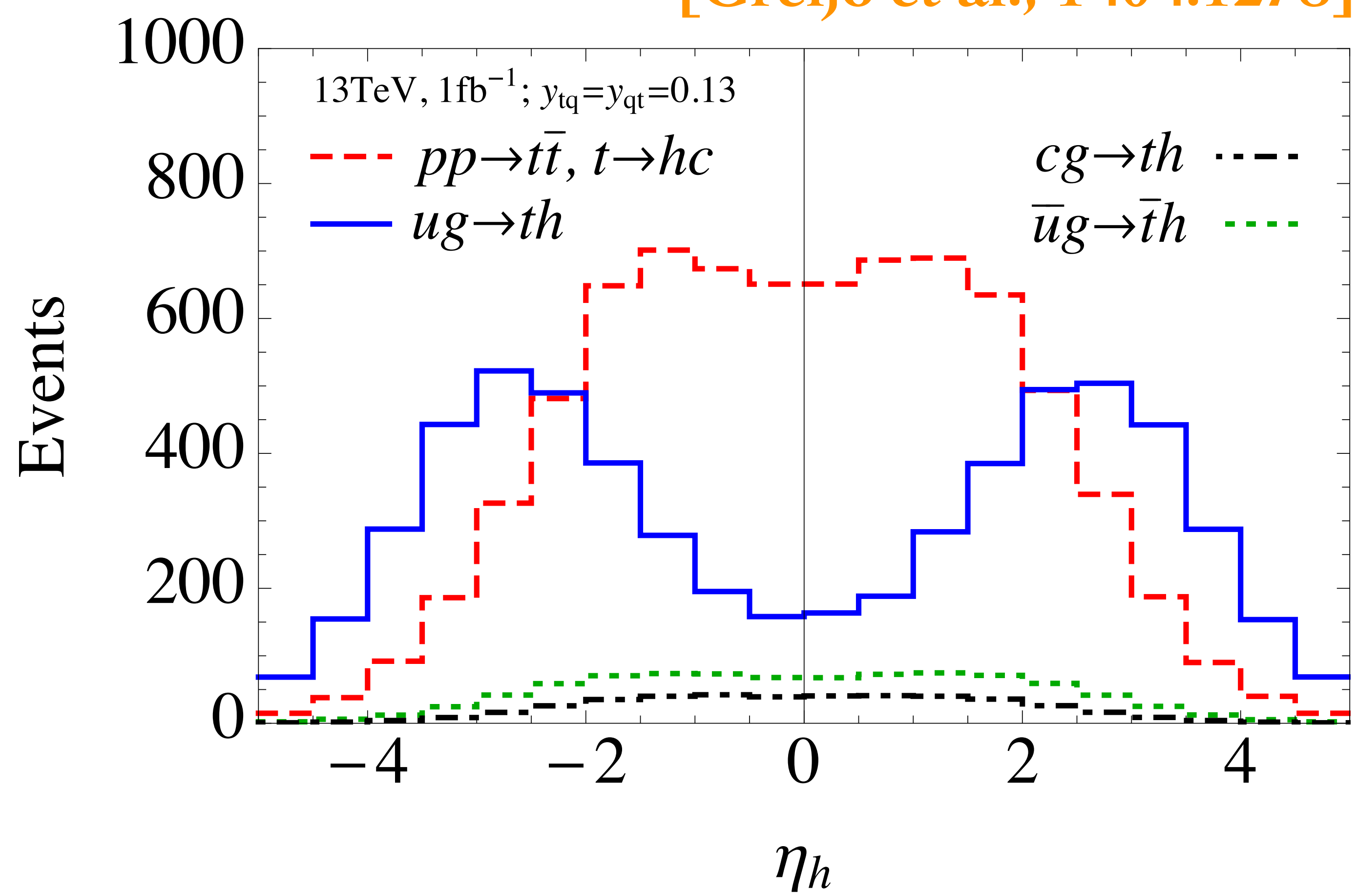
$$\mathcal{L} \supset -\sum_{q=c,u} \left(Y_{tq}\, \bar{t}_L q_R h + Y_{qt}\, \bar{q}_L t_R h \right) + \text{h.c.}$$

$$Y_{ij} = \frac{m_i}{v}\,\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\,\bar{\lambda}_{ij}\,, \qquad \bar{\lambda} = U_L \lambda U_R^\dagger \not\propto \mathbf{1}$$

LHC searches

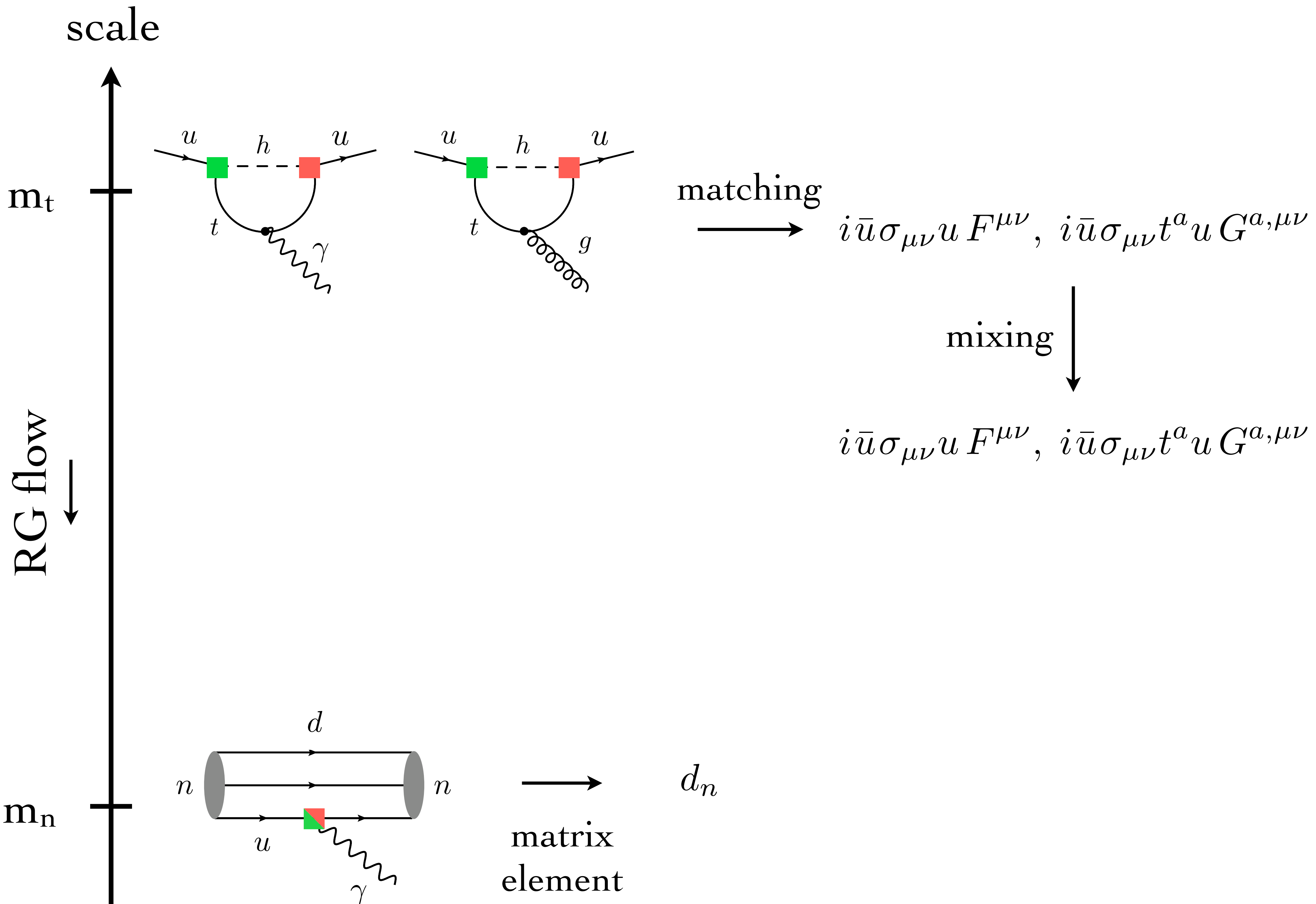


[Greljo et al., 1404.1278]

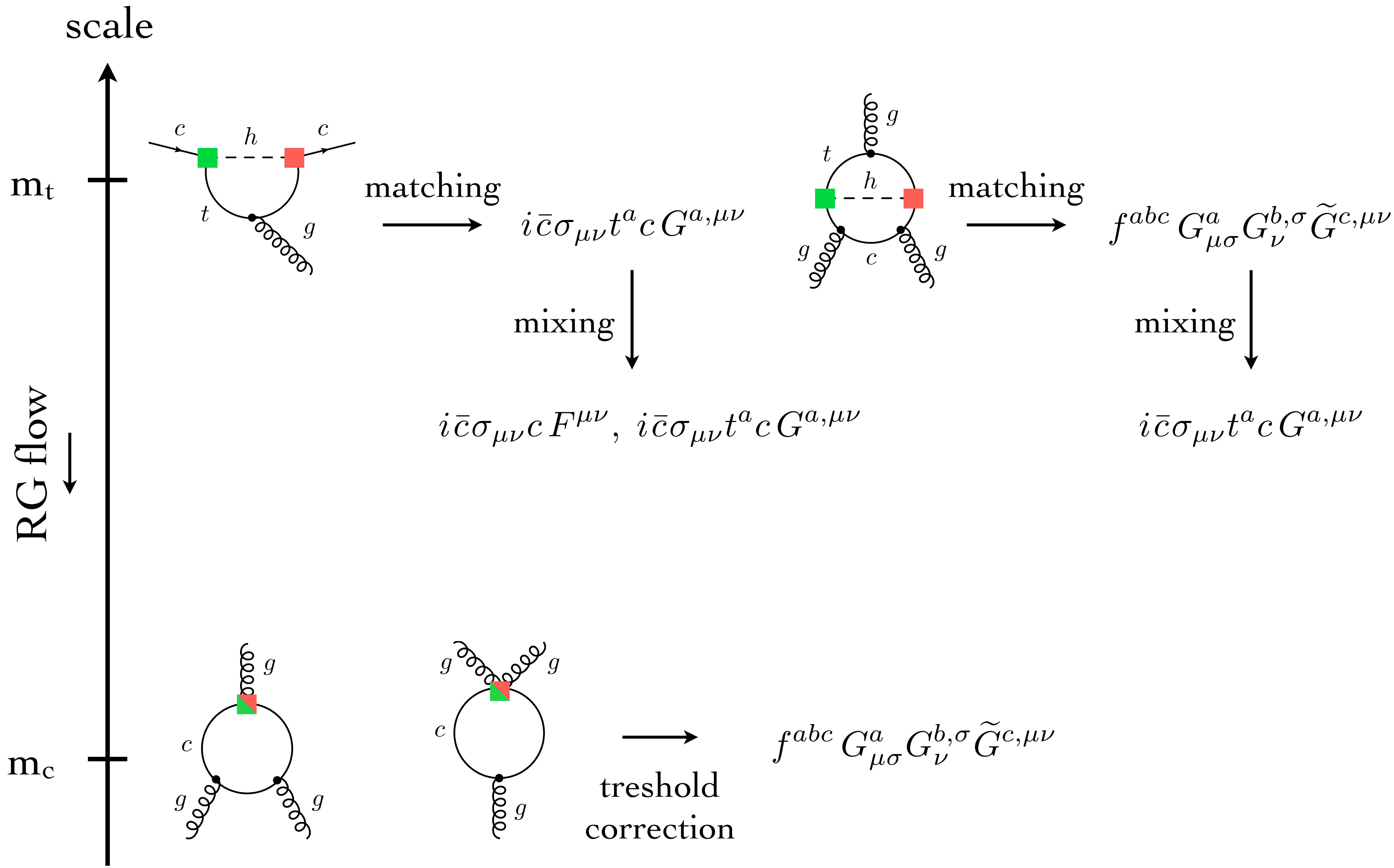


- tc(u)h couplings have been looked for in $t\bar{t}$ & single-top samples
- Best LHC Run I bound reads Br(t → qh) < 0.56% at 95% CL
- Can distinguish t → c/uh by considering e.g. Higgs pseudo-rapidity

Constraints from d_n on $t \to uh$



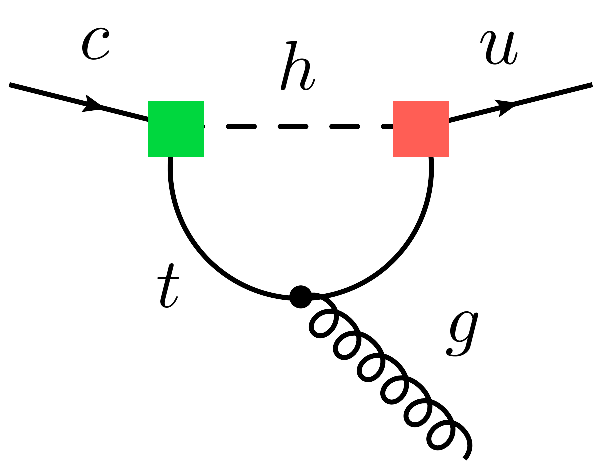
Constraints from d_n on $t \to ch$



B46/B62

Constraints from D → $\pi^+\pi^-$, K^+K^-

- Top-Higgs couplings contribute to difference ΔA_{CP} between direct CP asymmetries in D → $\pi^+\pi^-$ & D → K^+K^-:



matching ⟶

$$Q_8 = \frac{g_s}{(4\pi)^2}\, m_c\, \bar{u}_L \sigma^{\mu\nu} t^a c_R G^a_{\mu\nu}$$

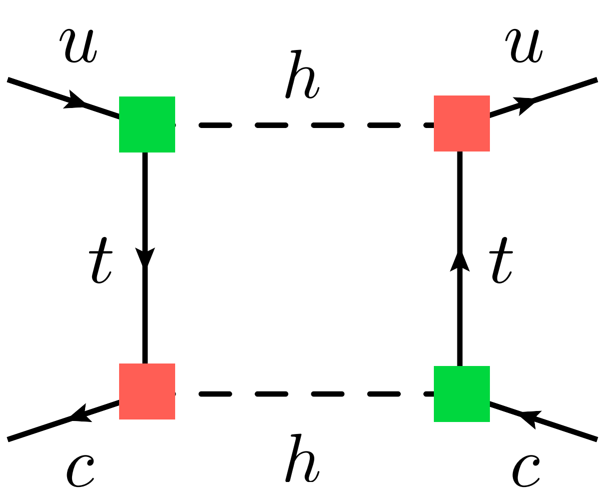
$$|\Delta A_{\rm CP}| \simeq \mathrm{Im}\big(\Delta C_8(m_t)\big) \simeq \frac{|\mathrm{Im}\,(Y^*_{ut} Y_{tc})|}{3.7 \cdot 10^{-4}}\,\% \lesssim 1\%$$

↑ **[HFAG]**

$$\Delta A_{\rm CP} = -(0.33 \pm 0.12)\%$$

Constraints from D-$\bar{\text{D}}$ mixing

- Also D-$\bar{\text{D}}$ mixing receives contribution from Higgs-top loops. Dominant effect due to mixed-chirality operator:



matching $\longrightarrow$ $Q_4 = (\bar{c}_L u_R)(\bar{c}_R u_L)$

$$\Delta C_4(m_t) \simeq \frac{1}{32\pi^2} \frac{\sqrt{2}}{4G_F} \frac{1}{3m_h^2} Y_{tc}^* Y_{ut}^* Y_{tu} Y_{ct}$$

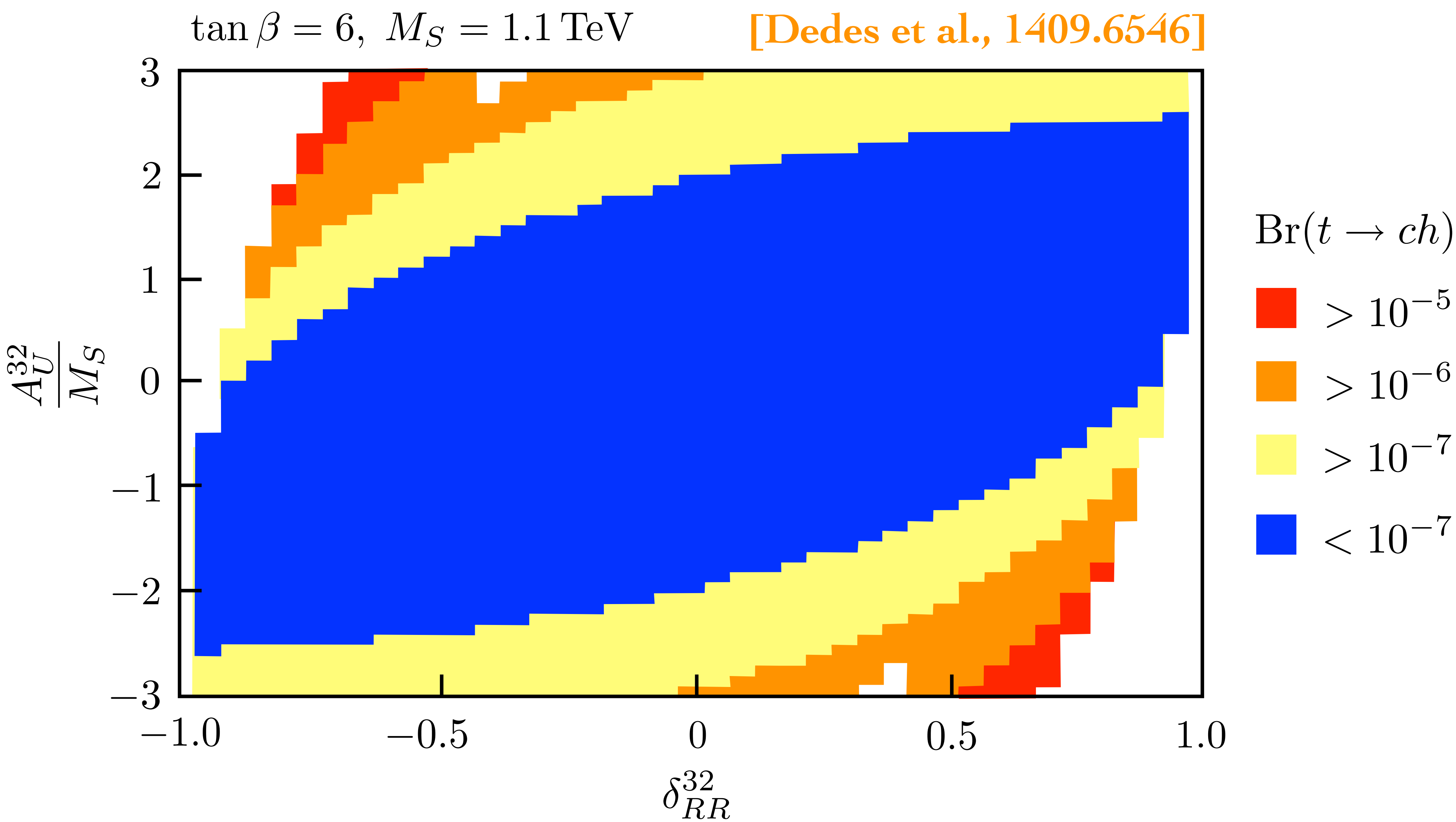
[Gedalia et al., 0906.1879]

$$|\text{Im}\,(\Delta C_4(m_t))\,| \lesssim 3.4 \cdot 10^{-10}$$

Summary of constraints

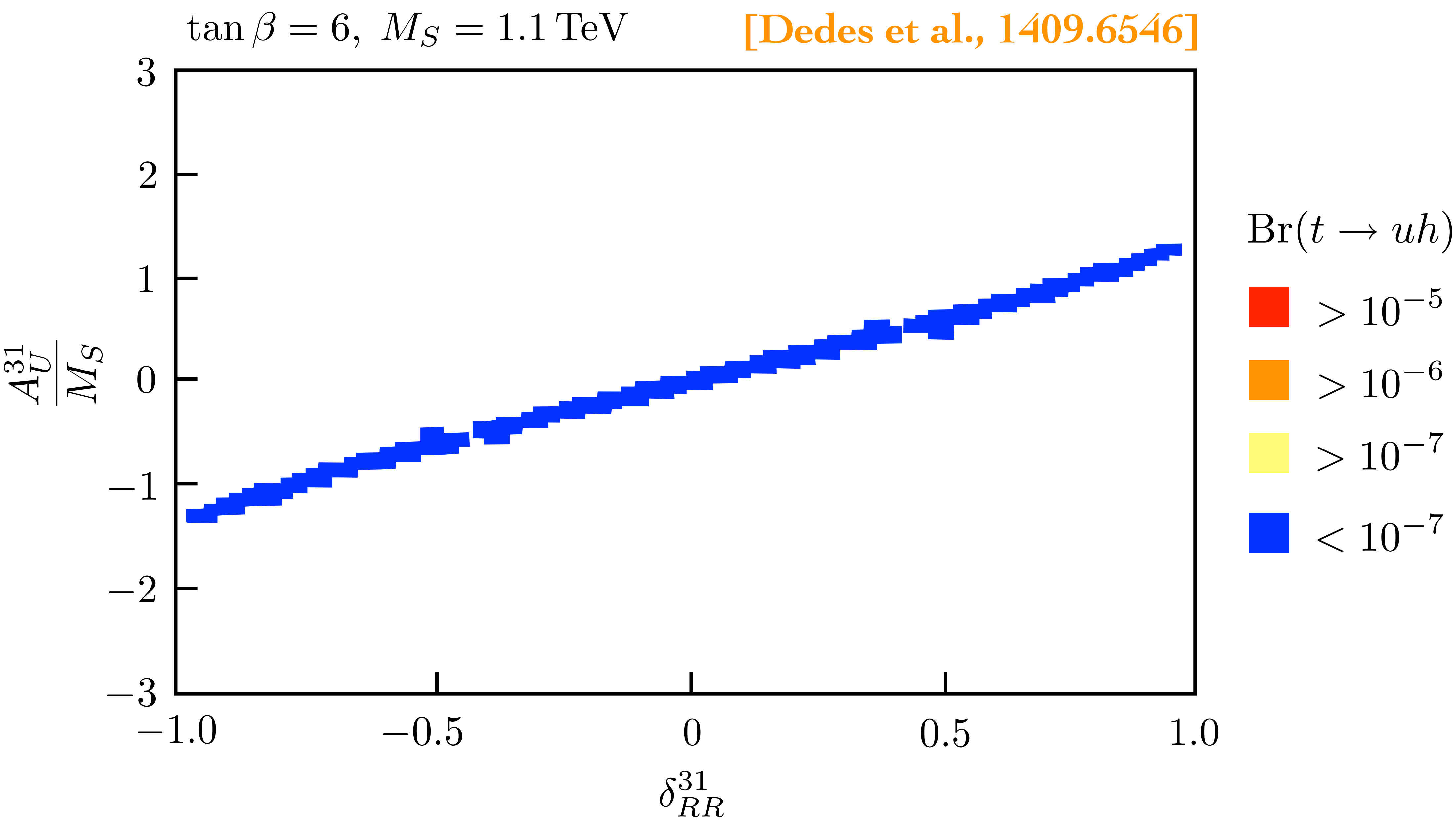
Observable	Coupling	Present bound	Future sensitivity
LHC searches	$\sqrt{\lvert Y_{tc}\rvert^2 + \lvert Y_{ct}\rvert^2}$	0.14	$2.8 \cdot 10^{-2}$
	$\sqrt{\lvert Y_{tu}\rvert^2 + \lvert Y_{ut}\rvert^2}$	0.13	$2.8 \cdot 10^{-2}$
d_n	$\lvert \mathrm{Im}\,(Y_{tc} Y_{ct})\rvert$	$5.0 \cdot 10^{-4}$	$1.7 \cdot 10^{-6}$
	$\lvert \mathrm{Im}\,(Y_{tu} Y_{ut})\rvert$	$4.3 \cdot 10^{-7}$	$1.5 \cdot 10^{-9}$
d_D	$\lvert \mathrm{Im}\,(Y_{tc} Y_{ct})\rvert$	—	$1.7 \cdot 10^{-7}$
	$\lvert \mathrm{Im}\,(Y_{tu} Y_{ut})\rvert$	—	$1.7 \cdot 10^{-11}$
ΔA_{CP}	$\lvert \mathrm{Im}\,(Y_{ut}^* Y_{ct})\rvert$	$4.0 \cdot 10^{-4}$	—
D–$\bar{D}$ mixing	$\sqrt{\lvert \mathrm{Im}\,(Y_{tc}^* Y_{ut}^* Y_{tu} Y_{ct})\rvert}$	$4.1 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$

$t \to ch$ in MSSM



- Regions with $\mathrm{Br}(t \to ch) > 10^{-6}$ require $|A_U^{32}| > 2M_S$. Such large A_U^{32} terms naively trigger color & charge breaking minima

t → uh in MSSM

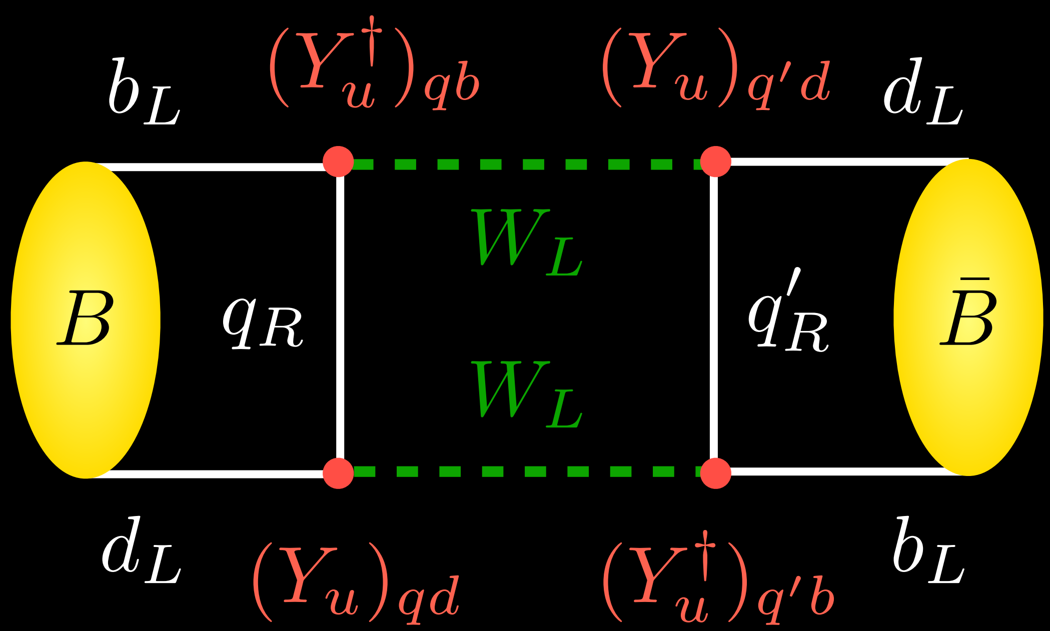


- Even for real A_U^{31} & δ_{RR}^{31}, higher-order terms in mass insertion expansion depend on δ_{CKM}. d_n rules out $\mathrm{Br}(t \to uh) > 10^{-7}$

Flavor changing neutral currents

[see e.g. D'Ambrosio et al., hep-ph/0207036]

In fact, neutral meson mixing & other flavor changing processes test structure of Yukawa interactions beyond tree level

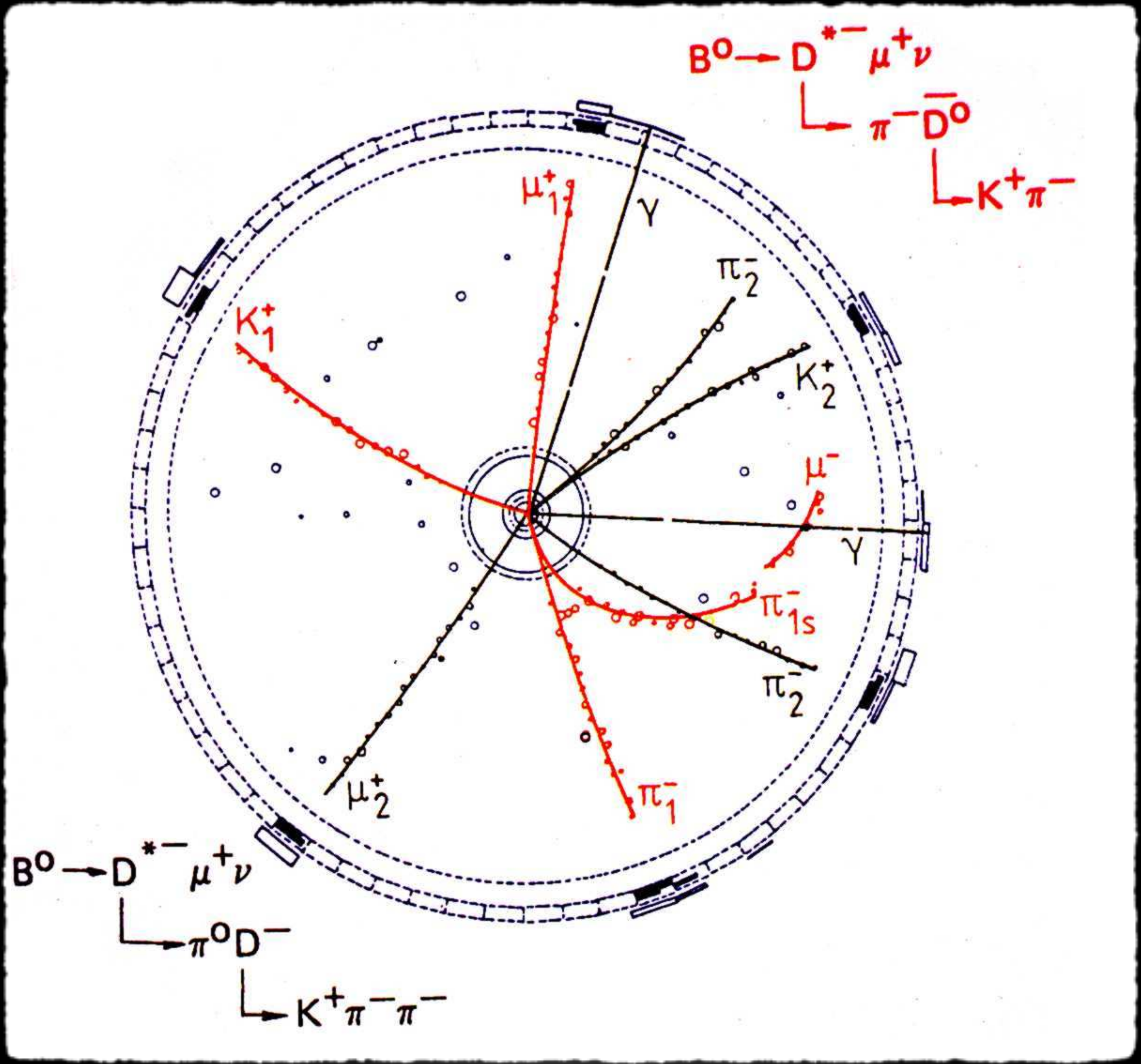


$$Y_u = V^\dagger \, \mathrm{diag}\,(y_u, y_c, y_t)$$
$$\approx V^\dagger \, \mathrm{diag}\,(0, 0, y_t)$$

$$\Longrightarrow \quad \frac{m_t^2}{16\pi^2 m_W^4 m_t^4}\, y_t^4 \left(V_{tb}^* V_{td}\right)^2 \propto \frac{g_2^2}{16\pi^2 m_W^4} m_t^2 \left(V_{tb}^* V_{td}\right)^2$$

$\Upsilon(4S) \to B^0\overline{B}^0 \to B^0B^0$

[ARGUS, Phys. Lett. B192, 245 (1987)]



Implications for top mass

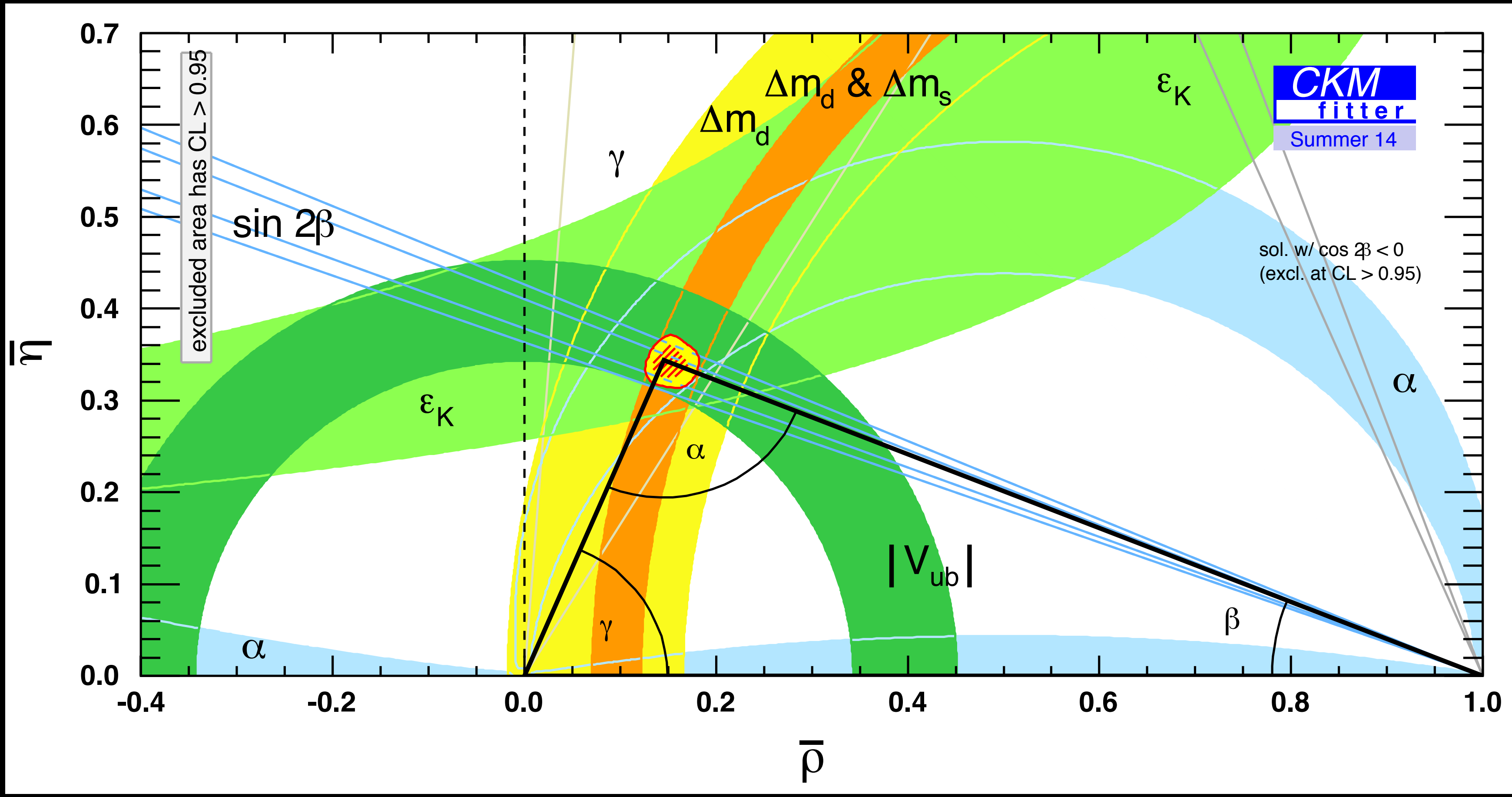
[ARGUS, Phys. Lett. B192, 245 (1987)]

$r > 0.09$ (90%CL)	this experiment
$x > 0.44$	this experiment
$B^{1/2} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_b < 5$ GeV/c^2	b-quark mass
$\tau < 1.4 \times 10^{-12}$s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi–Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor
$m_t > 50$ GeV/c^2	t quark mass

By 1987 it was general belief that top mass was much smaller than 50 GeV, but ARGUS found that it is (probably significantly) larger

Top mass from unitarity triangle

[CKMfitter, CKM14 results]



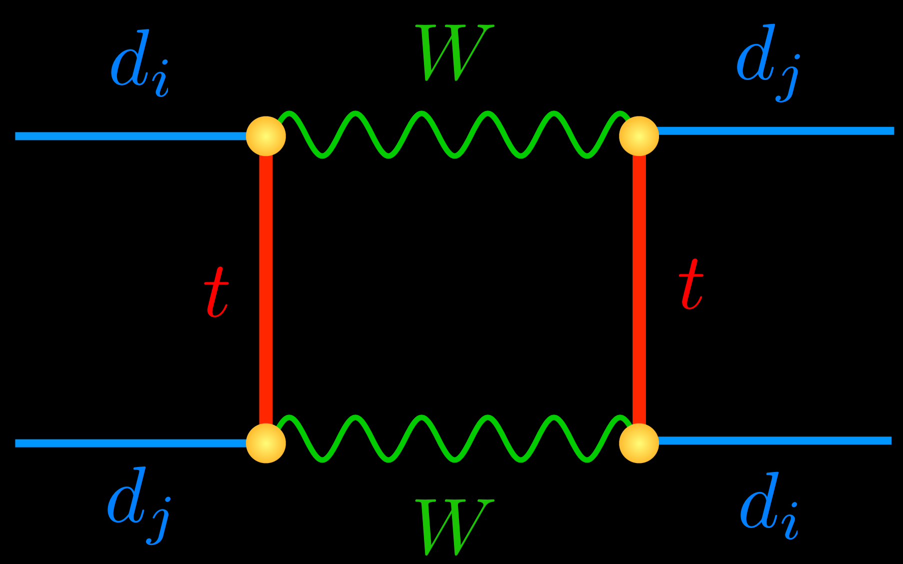
$$\Downarrow$$

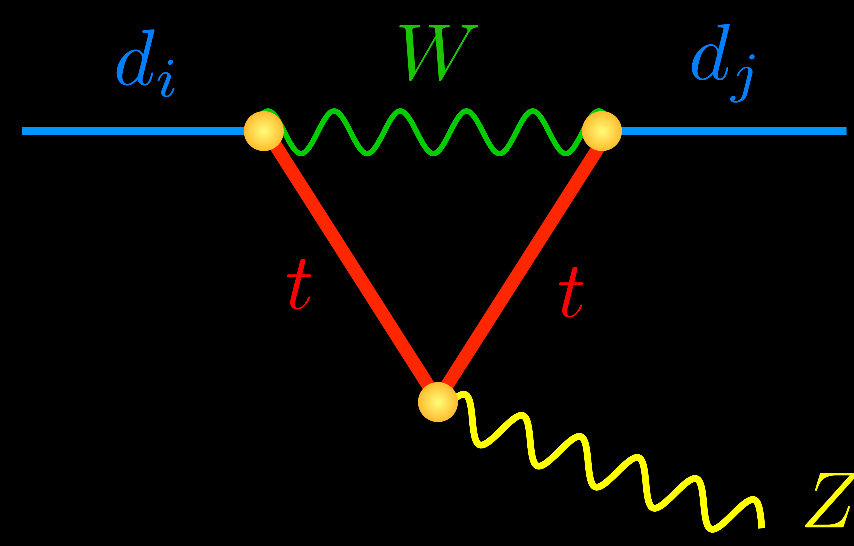
$$m_t^{\rm pole} = (169 \pm 5)\ {\rm GeV}$$

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





$$\Downarrow$$

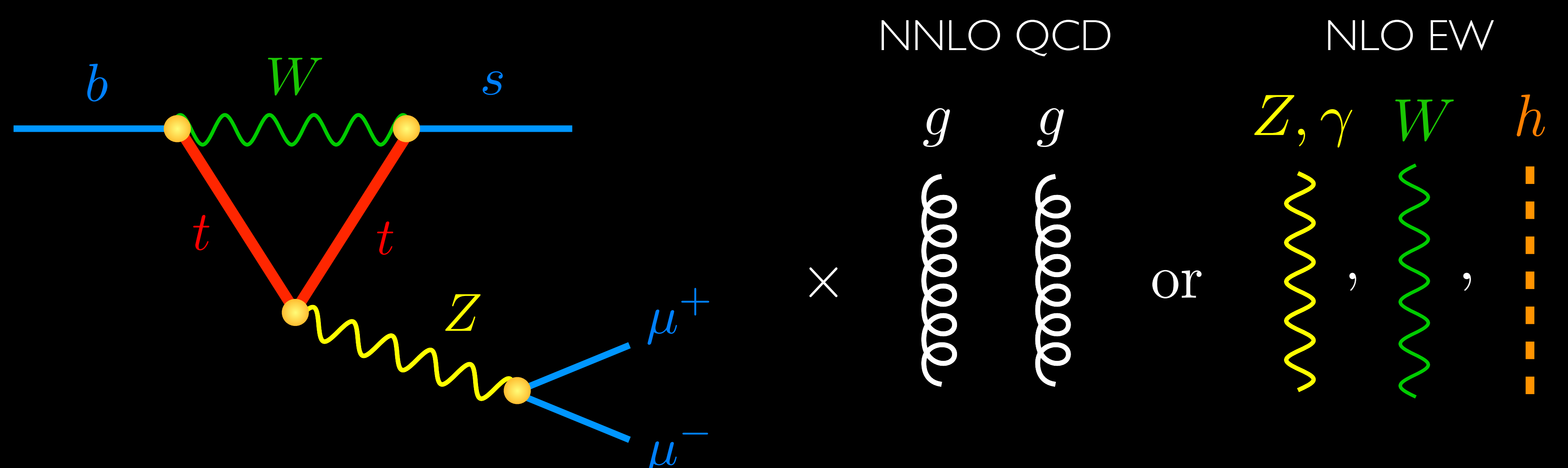
$$\Delta M_K, \Delta M_{B_d}, \Delta M_{B_S}, \epsilon_K$$

$$\Downarrow$$

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

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

[Bobeth et al., 1311.0903]



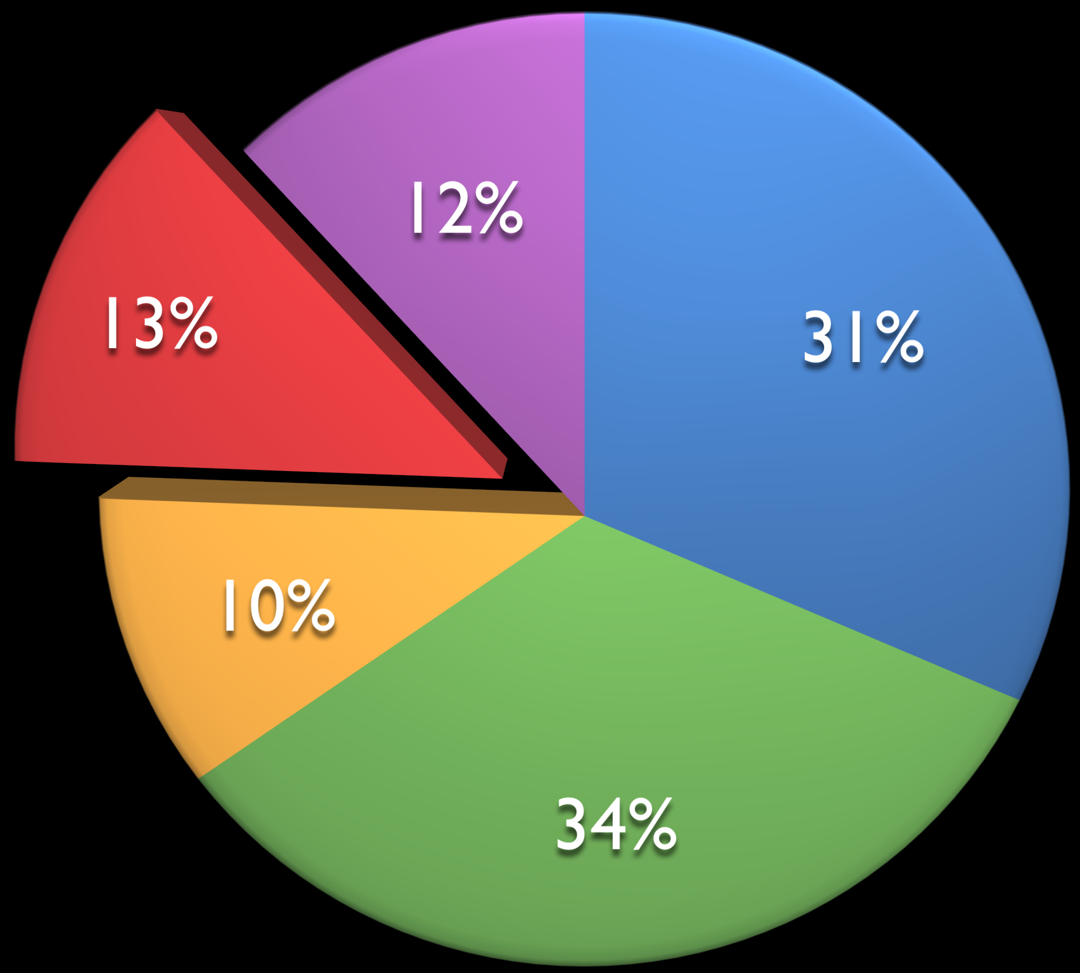
$$\mathrm{Br}\left(B_s \to \mu^+\mu^-\right)_{\mathrm{SM}} = 3.65 \left(\frac{m_t^{\mathrm{pole}}}{173.1\,\mathrm{GeV}}\right)^{3.06} (1 \pm 6.4\%) \cdot 10^{-9}$$

$$\mathrm{Br}\left(B_s \to \mu^+\mu^-\right)_{\mathrm{exp}} = 2.8 \left(1^{+25\%}_{-21\%}\right) \cdot 10^{-9}$$ [CMS & LHCb, 1411.4413]

$$\Longrightarrow \boxed{m_t^{\mathrm{pole}} = (158 \pm 13)\ \mathrm{GeV}}$$

$B_s \to \mu^+\mu^-$ relative error budget

[Bobeth et al., 1311.0903]



6.4% total uncertainty

- f_{Bs}
- CKM
- τ_{Bs}
- m_t
- non parametric

Improvements in lattice QCD calculations may reduce errors due to decay constant f_{Bs} & V_{cb}. Might result in future total uncertainty of 3%

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

[Bobeth et al., 1311.0903]

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

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

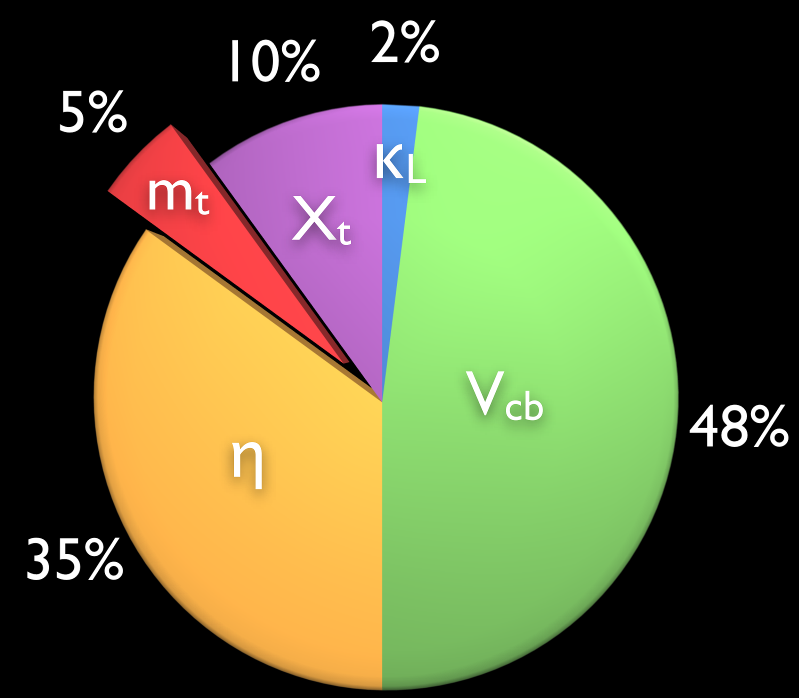
[LHCb, 1208.3355]

$$\Downarrow$$

$$m_t^{\mathrm{pole}} = (173.0 \pm 2.8)\ \mathrm{GeV}$$

Top mass from $K_L \to \pi^0 \nu\bar{\nu}$

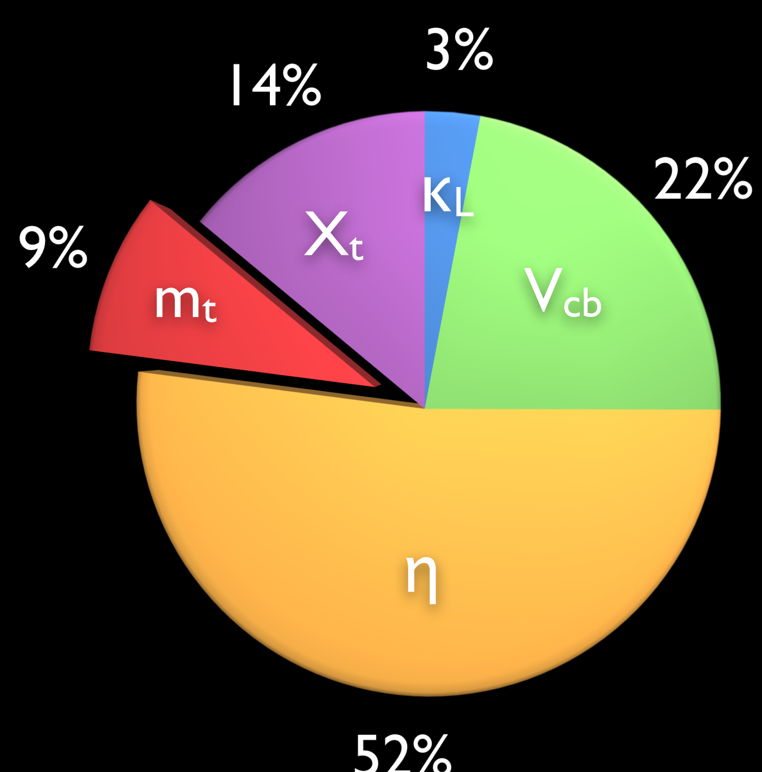
[Brod et al., 1009.0947]



$$\mathrm{Br}\big(K_L \to \pi^0 \nu\bar{\nu}\big)_{\mathrm{SM}} = 2.4\,(1 \pm 15\%) \cdot 10^{-11}$$

$$\underset{10\%\ \text{measurement}}{\Longrightarrow} \qquad \boxed{\delta m_t^{\mathrm{pole}} = 14\ \mathrm{GeV}}$$

$$\Big\Downarrow \quad \text{if } V_{cb} \text{ known to } 1\%$$

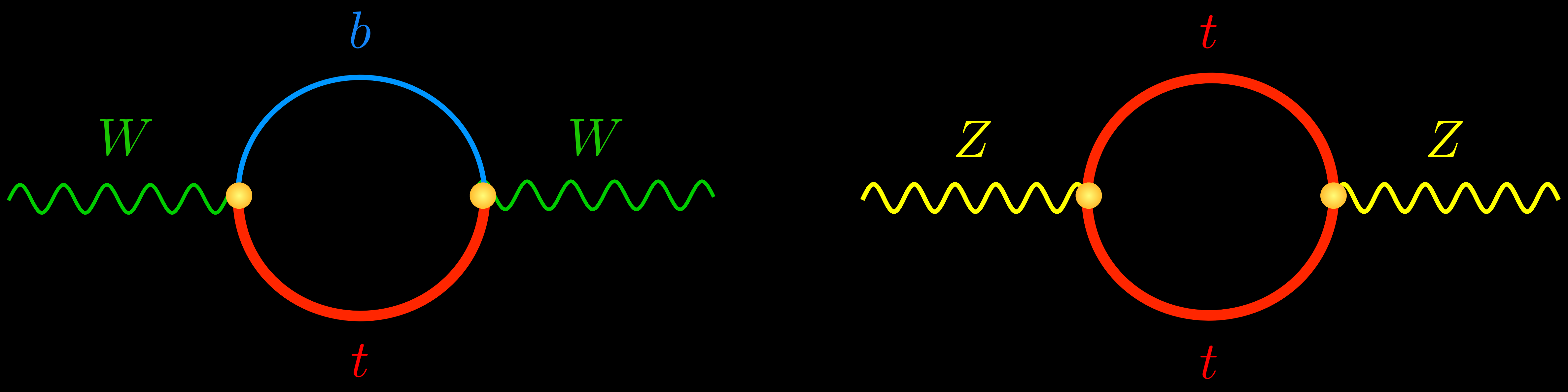


$$\mathrm{Br}\big(K_L \to \pi^0 \nu\bar{\nu}\big)_{\mathrm{SM}} = 2.4\,(1 \pm 10\%) \cdot 10^{-11}$$

$$\underset{10\%\ \text{measurement}}{\Longrightarrow} \qquad \boxed{\delta m_t^{\mathrm{pole}} = 11\ \mathrm{GeV}}$$

1-loop corrections to ρ

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



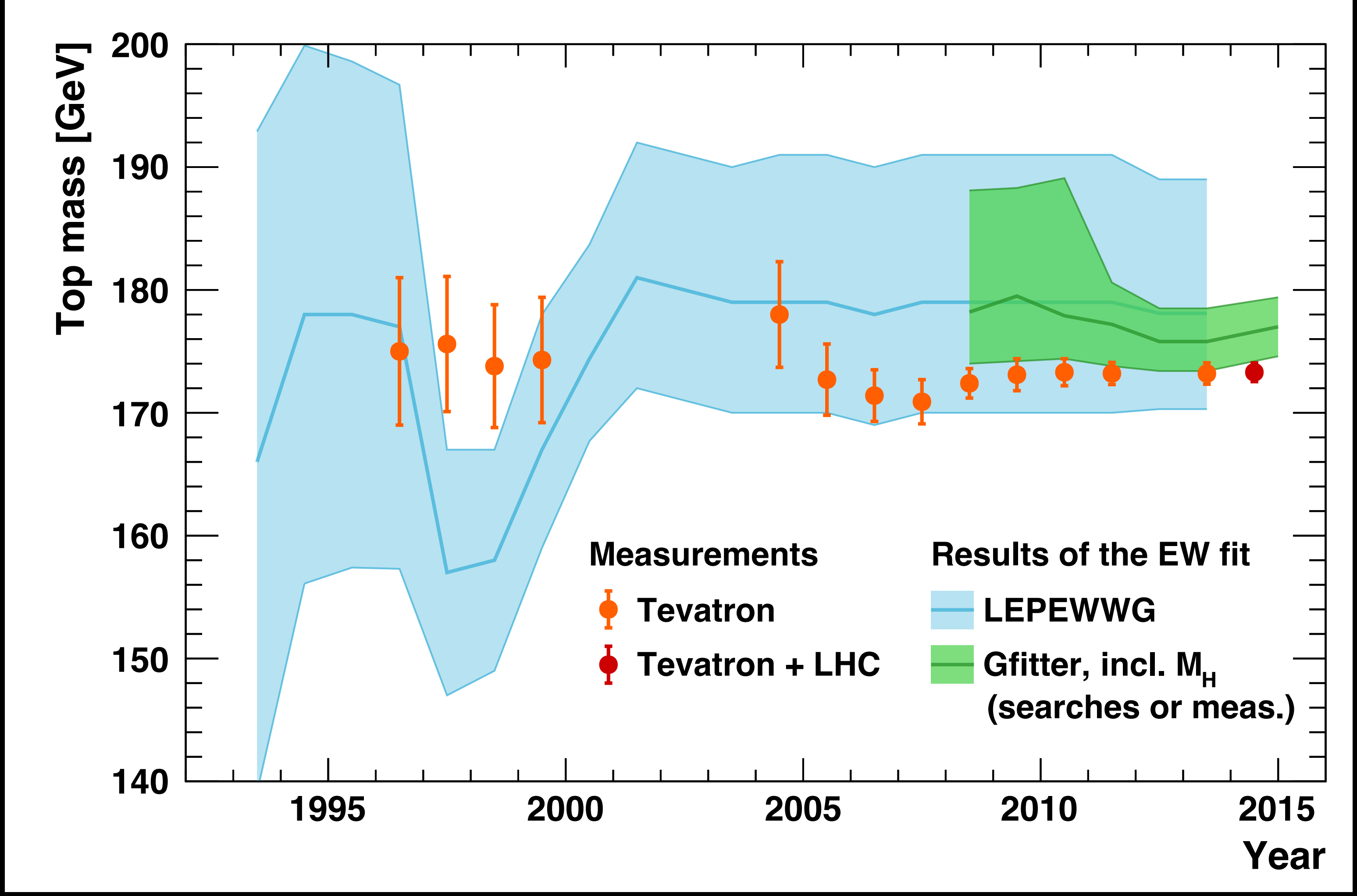
$$\Delta\rho = \alpha \Delta T = \frac{3G_F}{8\sqrt{2}\pi^2} m_t^2 \left\{ 1 + \frac{m_b^2}{m_t^2} \left[1 + \frac{2\ln\left(\frac{m_b^2}{m_t^2}\right)}{1 - \frac{m_b^2}{m_t^2}} \right] \right\}$$

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

B60/B62

History of m_t from electroweak fit

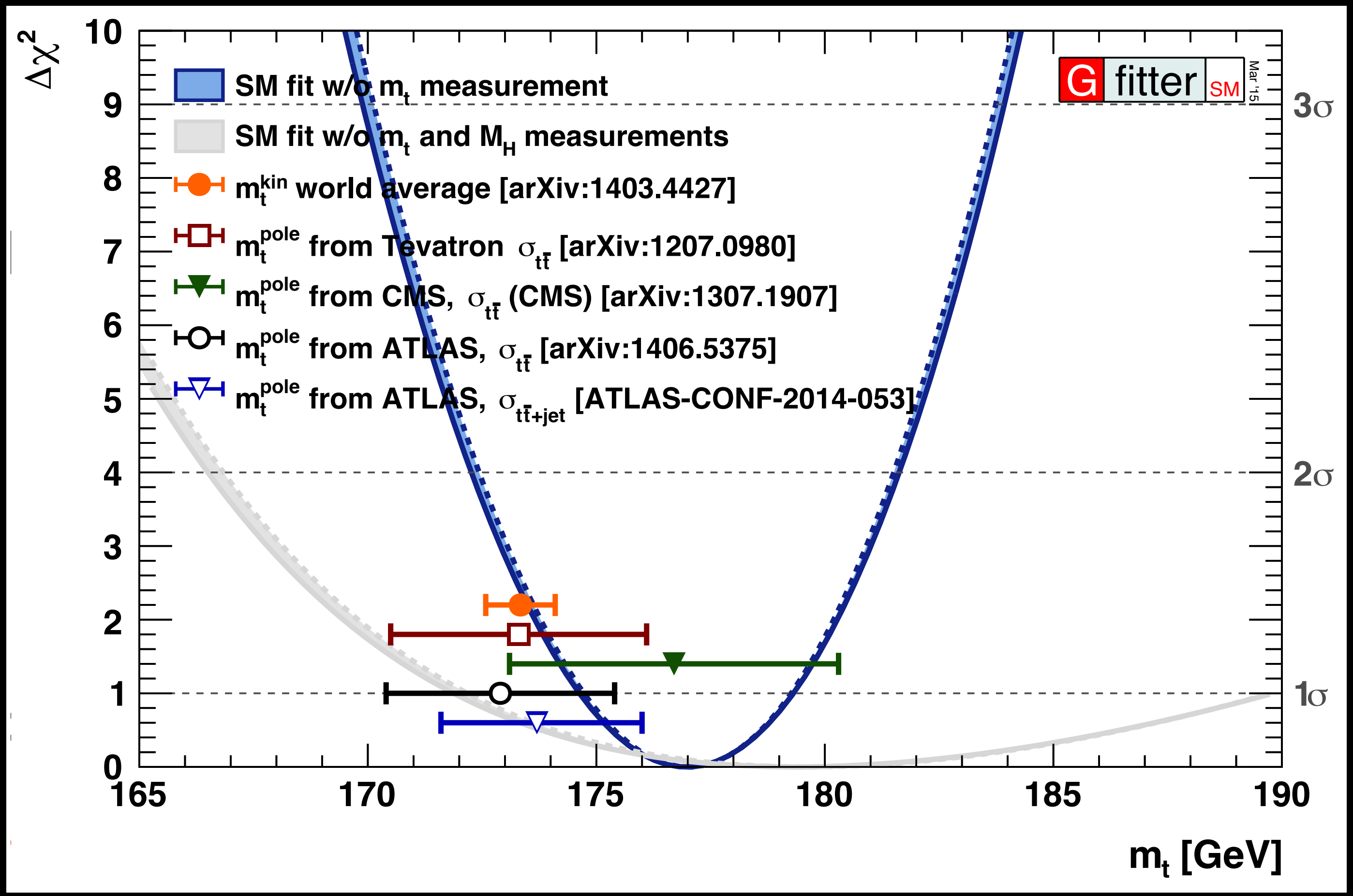
[Gfitter, November 2014]



Even before top discovery at Fermilab in 1995, global electroweak (EW) fits have always been able to predict mass correctly

Top mass from EW fit: Present

[Kogler, Moriond EW 2015]



$\Downarrow$

$$m_t^{\text{pole}} = \left(177.0 \pm 2.3_{M_W, \sin^2\theta^f_{\text{eff}}} \pm 0.6_{\alpha_s} \pm 0.5_{\Delta\alpha_{\text{had}}} + 0.4_{M_Z}\right)\ \text{GeV}$$