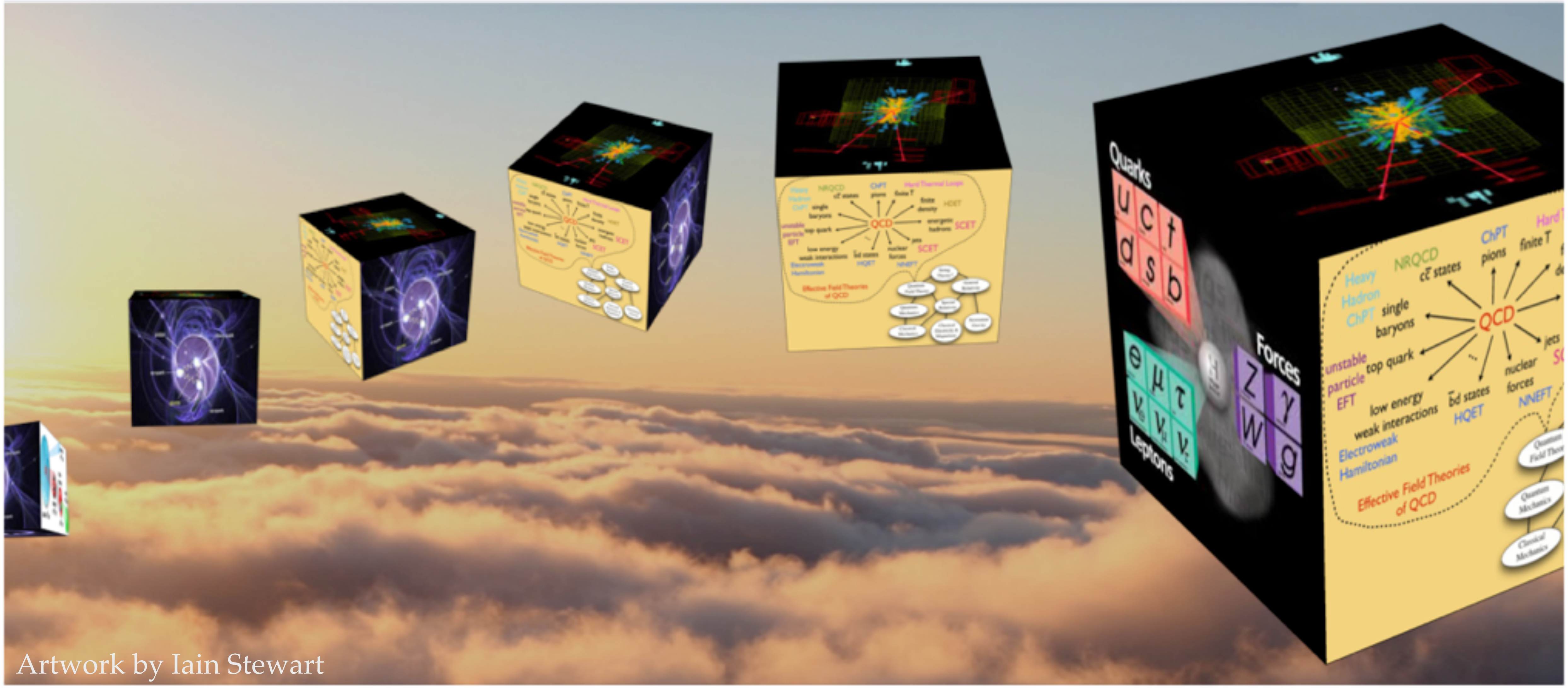


Artwork by Iain Stewart

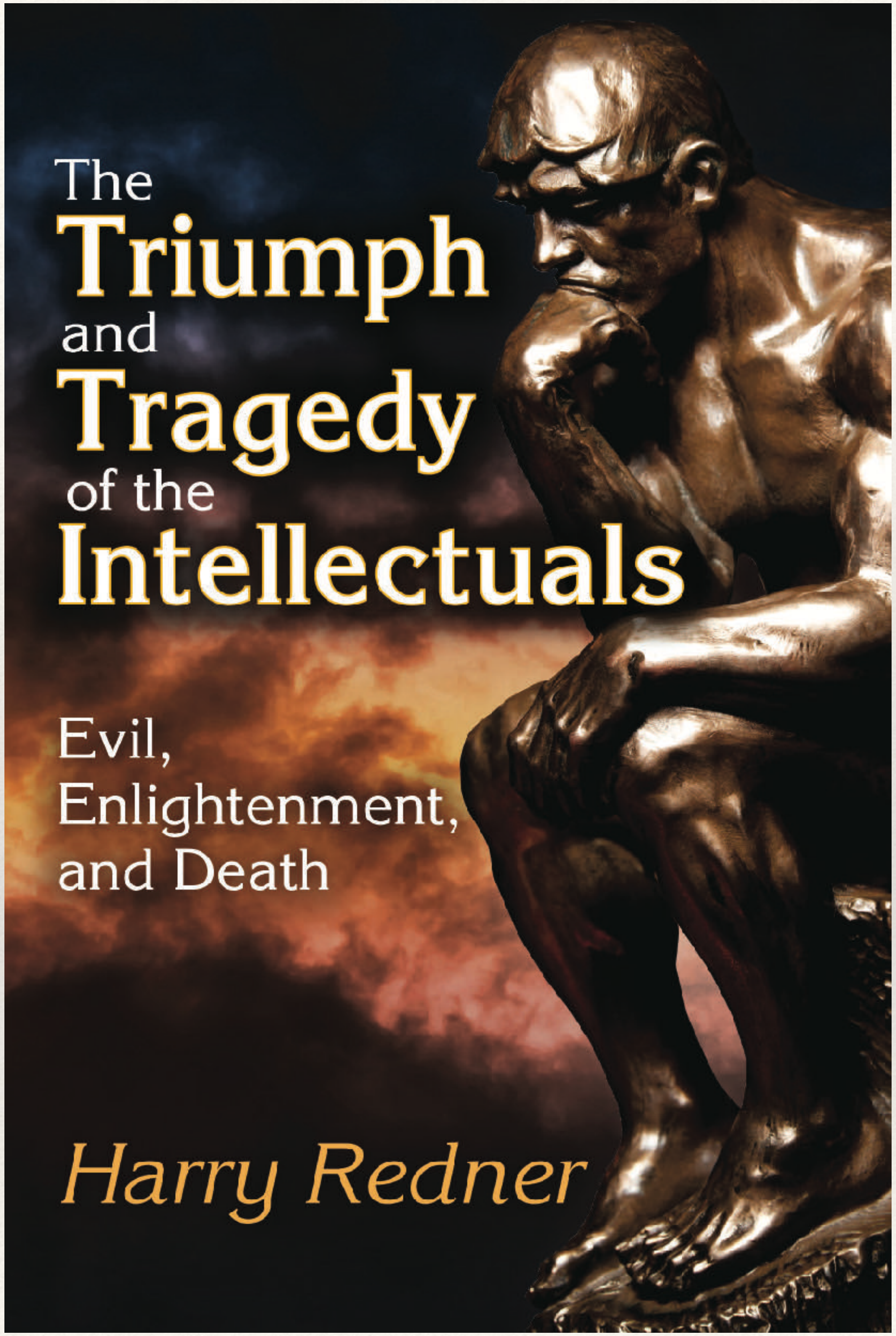
BEAUTY 2018 — La Biodola, Isola d'Elba, 6-11 May 2018

Theory in the LHC Era

Matthias Neubert

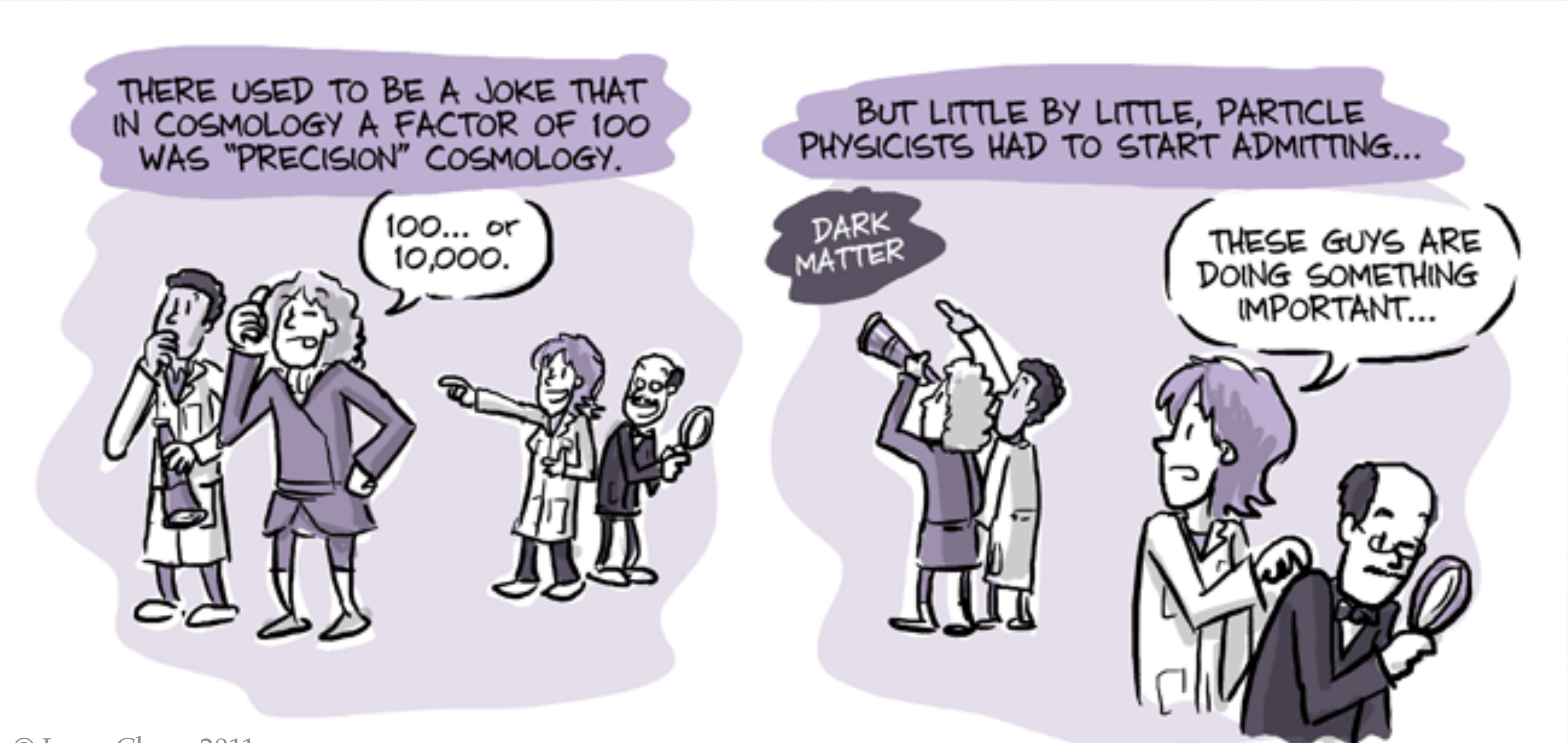
PRISMA Cluster of Excellence
Johannes Gutenberg University Mainz

Triumph & Tragedy

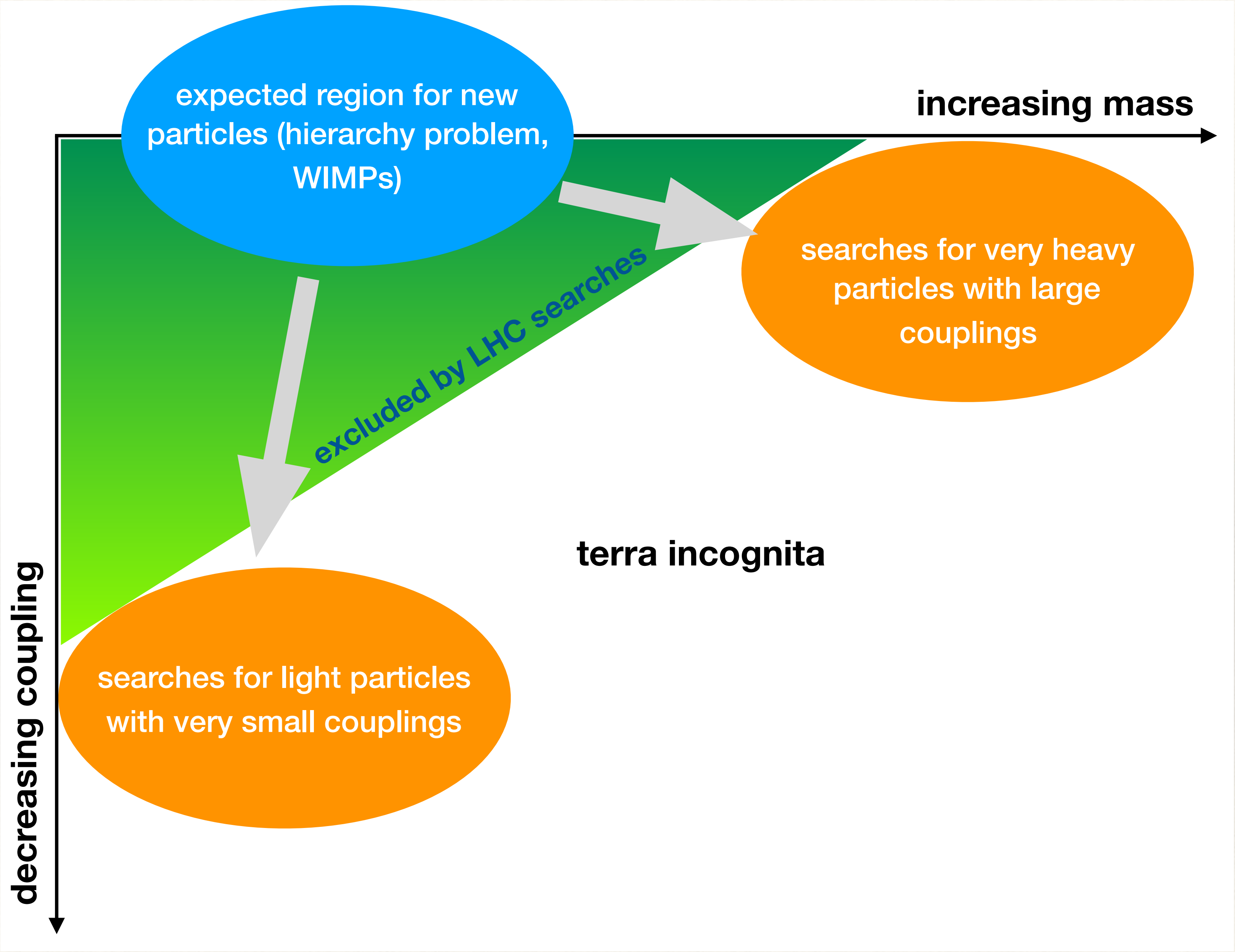


Beyond the SM

→ talk by Alessandro Strumia


THERE USED TO BE A JOKE THAT IN COSMOLOGY A FACTOR OF 100 WAS "PRECISION" COSMOLOGY.
100... or 10,000.
BUT LITTLE BY LITTLE, PARTICLE PHYSICISTS HAD TO START ADMITTING...
DARK MATTER
THESE GUYS ARE DOING SOMETHING IMPORTANT...

Beyond the SM?



SMEFT

- Indirect searches for heavy new physics should be analyzed in context of a systematic extension of the SM as an effective field theory:

[Buchmüller, Wyler 1986;
Grzadkowski, Iskrzynski, Misiak, Rosiek 2010]

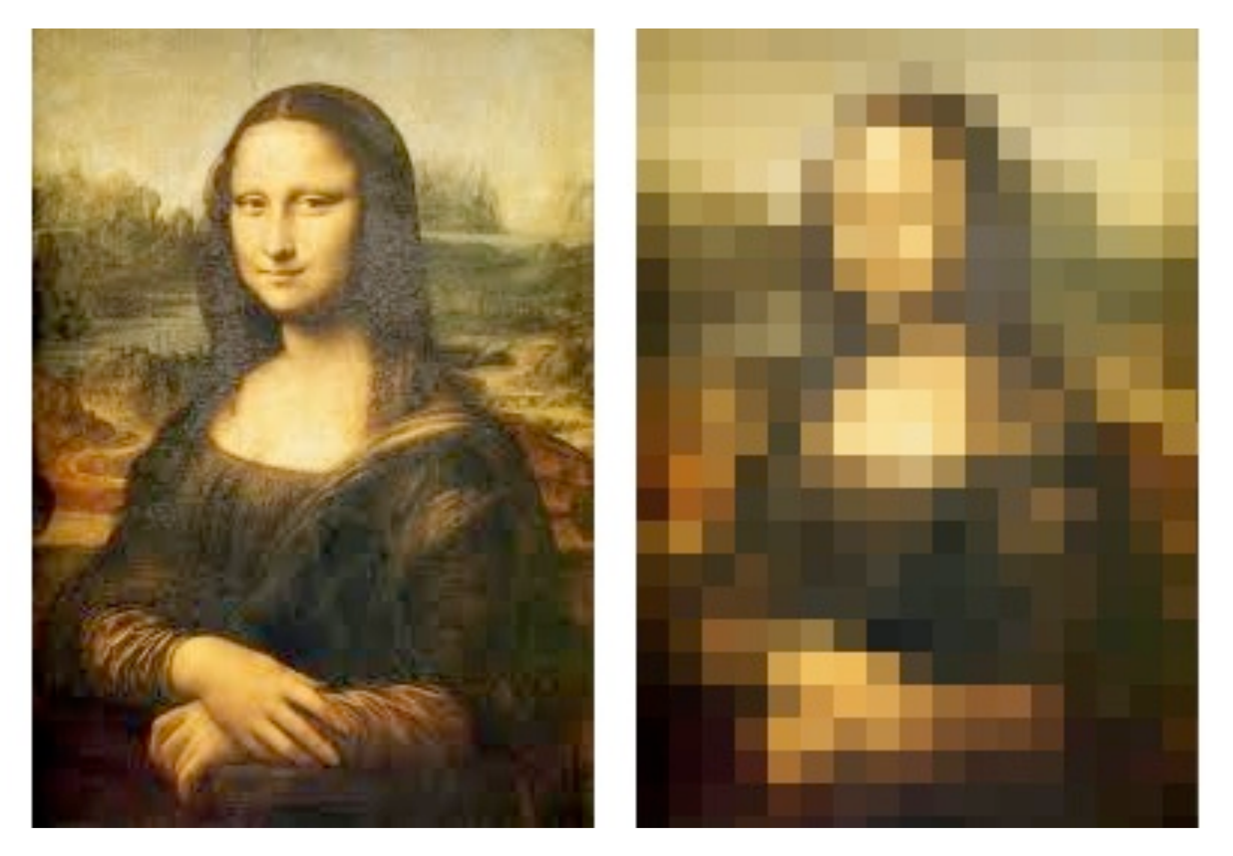
$$\underbrace{\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM}}_{\text{SM without neutrino masses}} + \underbrace{\frac{1}{\Lambda_W}\,\mathcal{O}_W^{(D=5)}}_{\text{Neutrino masses and oscillations}} + \sum_{i=1}^{\rm many} \frac{1}{\Lambda_i^2}\,\underbrace{\mathcal{O}_i^{(D=6)}}_{\text{Generic new-physics phenomena}} + \dots$$

SMEFT

- All scales Λ_i probed so far appear to be rather large:

Order	Observable	New-physics scale for g=O(1)
D=5	Neutrino oscillations	$\Lambda \sim 10^9$ TeV
D=6	Proton decay	$\Lambda > 10^{12}$ TeV
D=6	Flavor physics	$\Lambda > 1$–10^5 TeV
D=6	EWPT	$\Lambda > 1$ TeV
D=6	Higgs couplings	$\Lambda > 0.5$–1 TeV

Searching on all Fronts



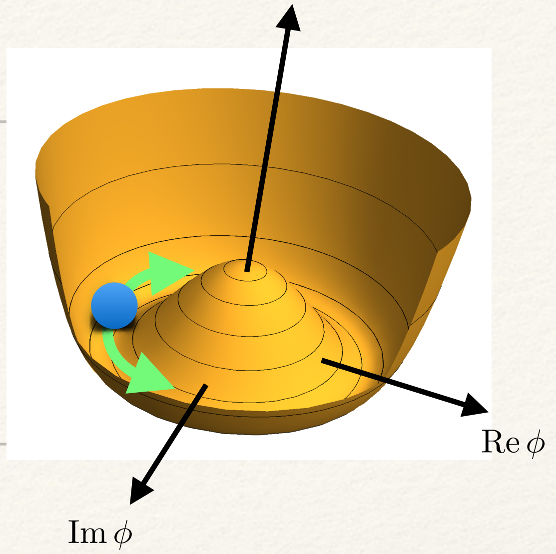
→ nicely reflected in the program of this conference!

Besides theory talks on the B-flavor anomalies, we will also hear about:
CP Violation in B Decays (Keri Vos), Heavy Exotics Spectroscopy (Marek Karliner), Flavor at High p_T (Admir Greljo), Lattice QCD for Heavy Hadrons (Chris Bouchard), Rare Kaon Decays (Giancarlo D'Ambrosio), Rare Leptonic B Decays (Gilberto Tetlalmatzi-Xolocotzi), Charm Decays (Stefan de Boer), Very Rare $B \to K^* \nu\nu$ Decays (Mohammad Ahmady), and lots of beautiful ideas about Physics Beyond the Standard Model (Alessandro Strumia)

Searches for axion-like particles at the LHC

based on work with Martin Bauer and Andrea Thamm
1704.08207 (PRL), 1708.00443 (JHEP)

Motivation



- Why not?
- New pseudoscalar particles appear in many extensions of the SM and are well motivated: strong CP problem, mediators to a hidden sector, pNGB of a spontaneously broken global symmetry, …
- Assume the existence of a new pseudoscalar resonance a, which is a SM gauge singlet and whose mass is kept much lighter than the electroweak scale by means of a shift symmetry $a \to a + c$
- Such particles can explain various low-energy anomalies, such as the muon $(g-2)_\mu$

[Chang, Chang, Chou, Keung 2000; Marciano, Masiero, Paradisi, Passera 2016]

Effective Lagrangian

- The couplings of an axion-like particle (ALP) *a* to the SM start at dimension 5 and are described by the effective Lagrangian (with Λ a new-physics scale): [Georgi, Kaplan, Randall 1986]

$$\mathcal{L}_{\text{eff}}^{D\le 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{\Lambda}\sum_F \bar{\psi}_F\,\boldsymbol{C}_F\,\gamma_\mu\,\psi_F$$
$$+\, g_s^2\,C_{GG}\,\frac{a}{\Lambda}\,G_{\mu\nu}^A\,\tilde{G}^{\mu\nu,A} + g^2\,C_{WW}\,\frac{a}{\Lambda}\,W_{\mu\nu}^A\,\tilde{W}^{\mu\nu,A} + g'^2\,C_{BB}\,\frac{a}{\Lambda}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu}$$

- At dimension-6 order and higher additional interactions arise:

$$\mathcal{L}_{\text{eff}}^{D\ge 6} = \frac{C_{ah}}{\Lambda^2}\,(\partial_\mu a)(\partial^\mu a)\,\phi^\dagger\phi + \frac{C_{Zh}^{(7)}}{\Lambda^3}\,(\partial^\mu a)\left(\phi^\dagger\,iD_\mu\,\phi + \text{h.c.}\right)\phi^\dagger\phi + \dots$$

- Our goal is to probe scales **Λ~1-100 TeV** at the LHC

Effective Lagrangian

- After electroweak symmetry breaking the effective Lagrangian contains couplings to photons and Z-bosons given by:

$$\mathcal{L}_{\text{eff}}^{D\le 5} \ni e^2\, C_{\gamma\gamma}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}\, C_{\gamma Z}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}\, C_{ZZ}\, \frac{a}{\Lambda}\, Z_{\mu\nu}\, \tilde{Z}^{\mu\nu}$$

with:

$$C_{\gamma\gamma} = C_{WW} + C_{BB}\,, \qquad C_{\gamma Z} = c_w^2\, C_{WW} - s_w^2\, C_{BB} \qquad C_{ZZ} = c_w^4\, C_{WW} + s_w^4\, C_{BB}$$

- In the mass basis, the couplings to fermions contain both flavor diagonal and flavor off-diagonal contributions, but the latter must be strongly suppressed; the diagonal couplings can be written as:

$$\mathcal{L}_{\text{eff}}^{D\le 5} \ni \sum_f \frac{c_{ff}}{2}\, \frac{\partial^\mu a}{\Lambda}\, \bar{f}\, \gamma_\mu \gamma_5\, f$$

Higgs decays into ALPs

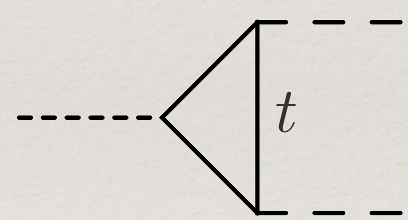
- The effective Lagrangian allows for the decays $h \to aa$ and $h \to Za$ at rates likely to be accessible in the high-luminosity run of the LHC (already with 300 fb^{-1})
- The subsequent ALP decays can be reconstructed largely irrespective of how the ALP decays
- Higgs physics thus provides a powerful observatory for ALPs in the mass range between 1 MeV and 60 GeV, which is otherwise not easily accessible to experimental searches

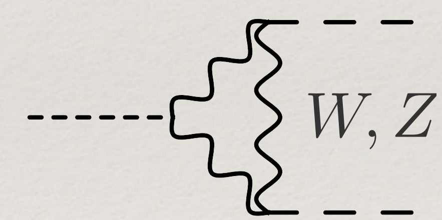
Higgs decays into ALPs

- We compute the relevant production and decay rates of the ALP at one-loop order, e.g.:

$$\Gamma(h \to aa) = \frac{\left|C_{ah}^{\text{eff}}\right|^2}{32\pi} \frac{v^2 m_h^3}{\Lambda^4} \left(1 - \frac{2m_a^2}{m_h^2}\right) \sqrt{1 - \frac{4m_a^2}{m_h^2}}$$

with:

$C_{ah}^{\text{eff}} =$  



$$\approx C_{ah}(\Lambda) + 0.173\, c_{tt}^2 - 0.0025\left(C_{WW}^2 + C_{ZZ}^2\right)$$

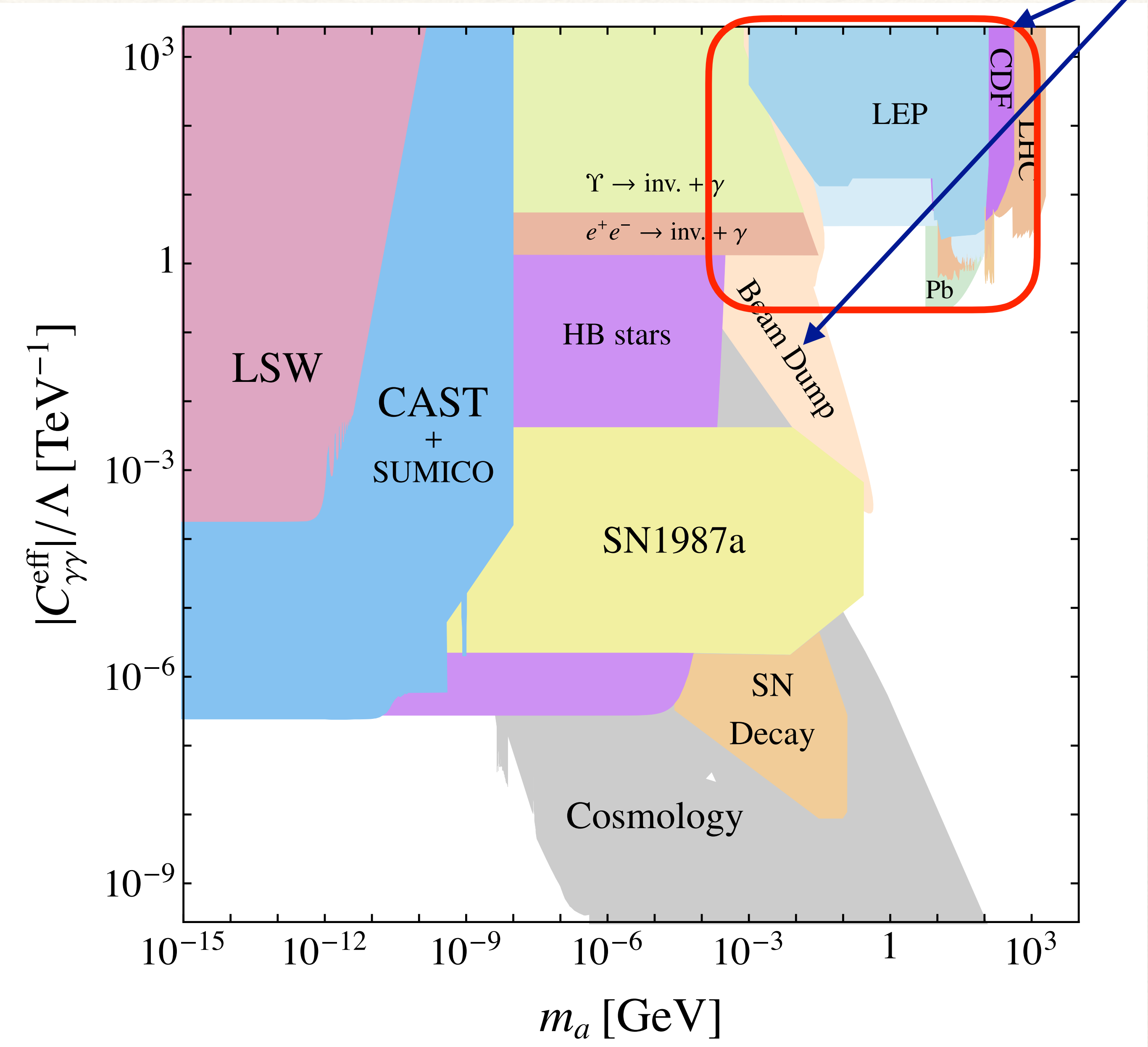
- A 10% branching ratio is obtained for $|C_{ah}^{\text{eff}}| \approx 0.62\,(\Lambda/\text{TeV})^2$

Higgs decays into ALPs

- The effect of the ALP decay length must be carefully taken into account (important for small ALP mass or couplings)
- We require 100 signal events in 300 fb^{-1} of LHC data
- Always probe a pair of ALP couplings, those relevant for the production and decay process; here we focus on $h \to aa$ and $a \to \gamma\gamma$, but $a \to e^+e^-$, $\mu^+\mu^-$ can be probed as well

Probing the ALP-photon coupling

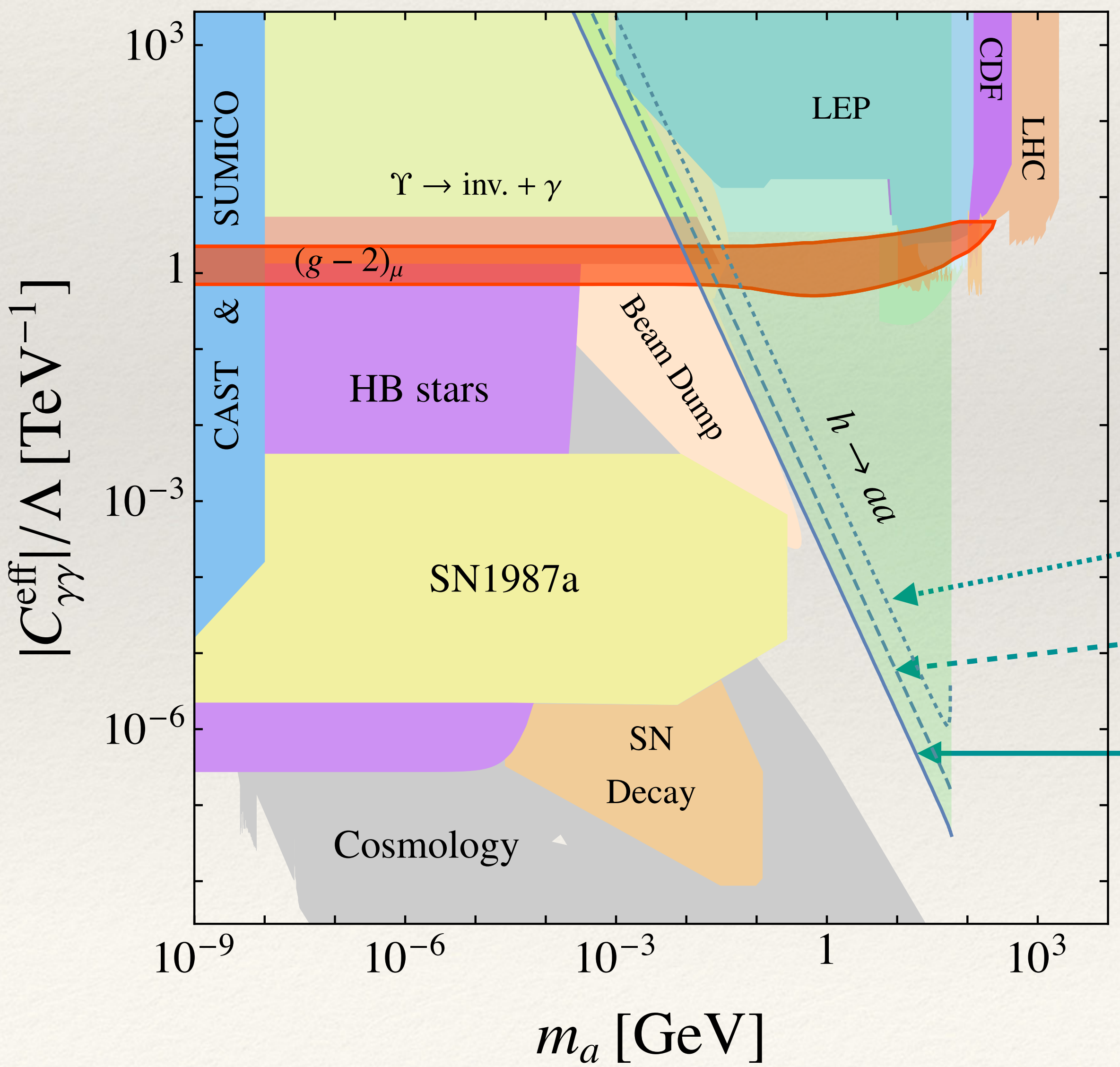
model dependent!



[Armengaud et al. 2013; Jaeckel, Spannovsky 2015; many others …]

Probing the ALP-photon coupling

- Higgs analyses at the LHC (Run-2, 300 fb^{-1}) will be able to explore a large region of uncovered parameter space:



- The ALP-photon coupling can be probed even if the ALP decays predominantly to other particles!
- Region preferred by $(g\text{-}2)_\mu$ can be covered completely!

$|C_{ah}^{\rm eff}| = 0.01,\ \mathrm{Br}(a \to \gamma\gamma) > 0.49$

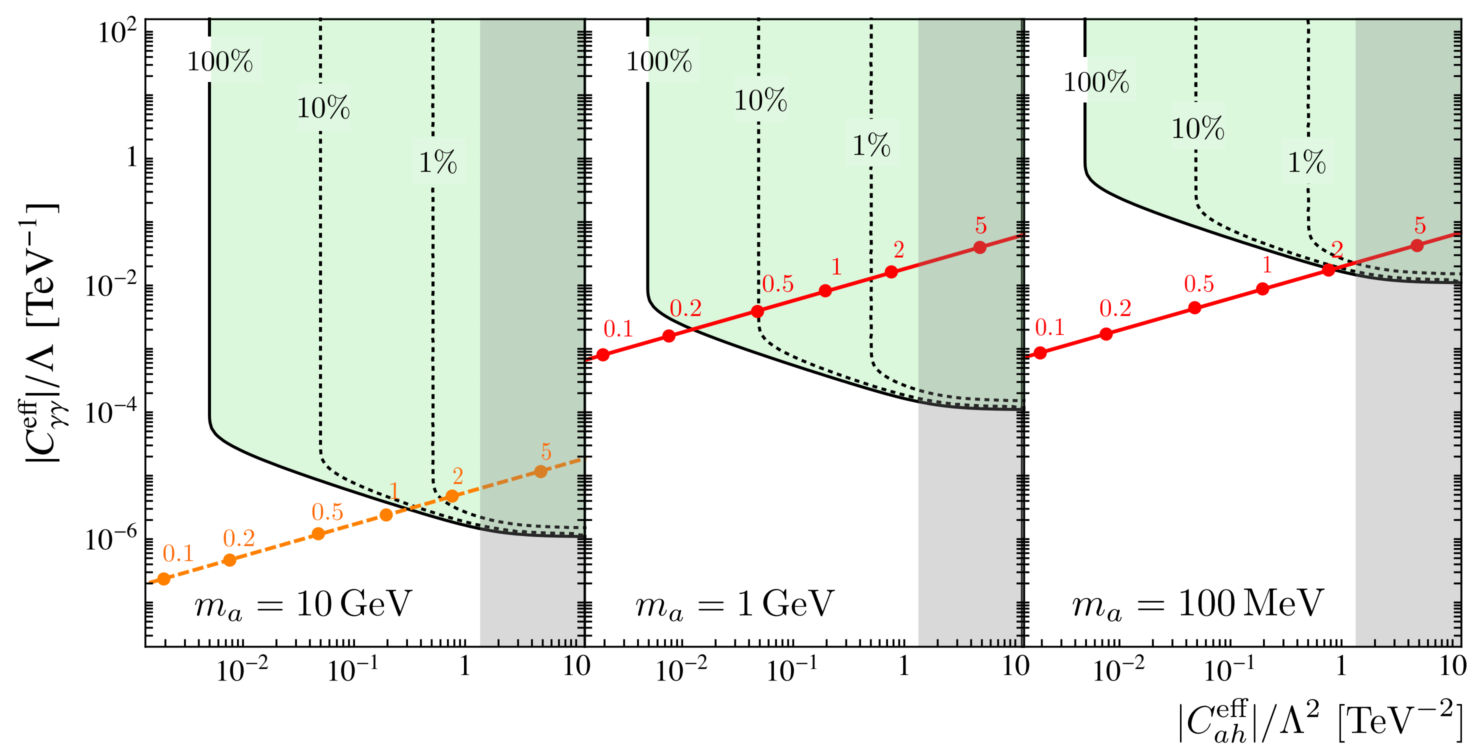
$|C_{ah}^{\rm eff}| = 0.1,\ \mathrm{Br}(a \to \gamma\gamma) > 0.049$

$|C_{ah}^{\rm eff}| = 1,\ \mathrm{Br}(a \to \gamma\gamma) > 0.006$

(for $\Lambda = 1\,\mathrm{TeV}$)

Probing the ALP-photon coupling

- Alternative representation of the parameter space in the ALP-Higgs and ALP-photon coupling plane
- Accessible region depends on the ALP mass and $a \to \gamma\gamma$ branching ratio (dashed contours)
- Lines show predictions for the coefficients in two scenarios with couplings induced by loops of SM fermions



$$h \to aa \to \gamma\gamma + \gamma\gamma$$

Heavy flavor anomalies

→ talks by Olcyr De Lima Sumensari, Admir Greljo, Nazila Mahmoudi, Ferruccio Feruglio, Marco Ciuchini

B-flavor anomalies

- Intriguing hints of anomalies in B decays entered the stage starting in 2012 (R_D, R_{D^*}, P_5', R_K, R_{K^*})

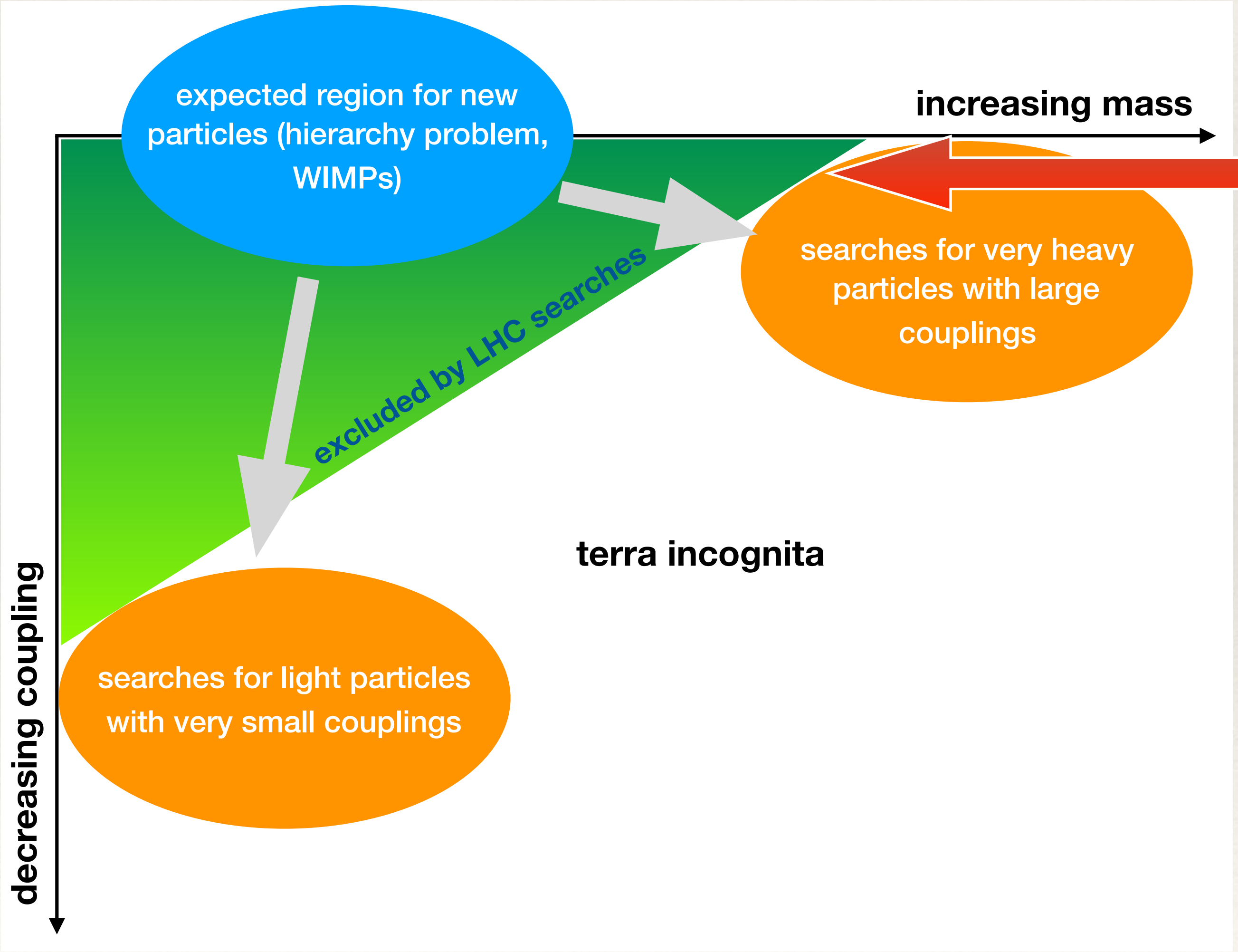
$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}\,; \quad \ell = e, \mu$$

$$R_{K^{(*)}} = \frac{\Gamma(\bar{B} \to \bar{K}^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to \bar{K}^{(*)}e^+e^-)}$$

- If true, they would be hugely important for the future development of high-energy particle physics at large!
- In fact, their importance cannot be overstated …

B-flavor anomalies

- … as they would give a clear target for future searches at energy frontier — exactly what's missing right now!



New physics cannot be too far from here!

(primarily driven by $R_{D^{(*)}}$)

B-flavor anomalies

- It would teach a lesson about the complementarity of different fields (as flavor physics was sometimes considered as being irrelevant in the LHC era)
- Cherish the connection between flavor and high-p_T !

  → talk by Admir Greljo
- Imagine the LHC legacy:
  - discovery of the Higgs boson (2012)
  - discovery of lepton-flavor non-universality (2013+)

B-flavor anomalies

- It would teach a lesson about the complementarity of different fields (as flavor physics was sometimes considered as being irrelevant in the LHC era)
- Cherish the connection between flavor and high-p_T !

→ talk by Admir Greljo

- Imagine the LHC legacy:
  - discovery of the Higgs boson (2012)
  - discovery of lepton-flavor non-universality (2013+)
  - discovery of the predicted Z′ bosons/leptoquarks (2022?)

B-flavor anomalies

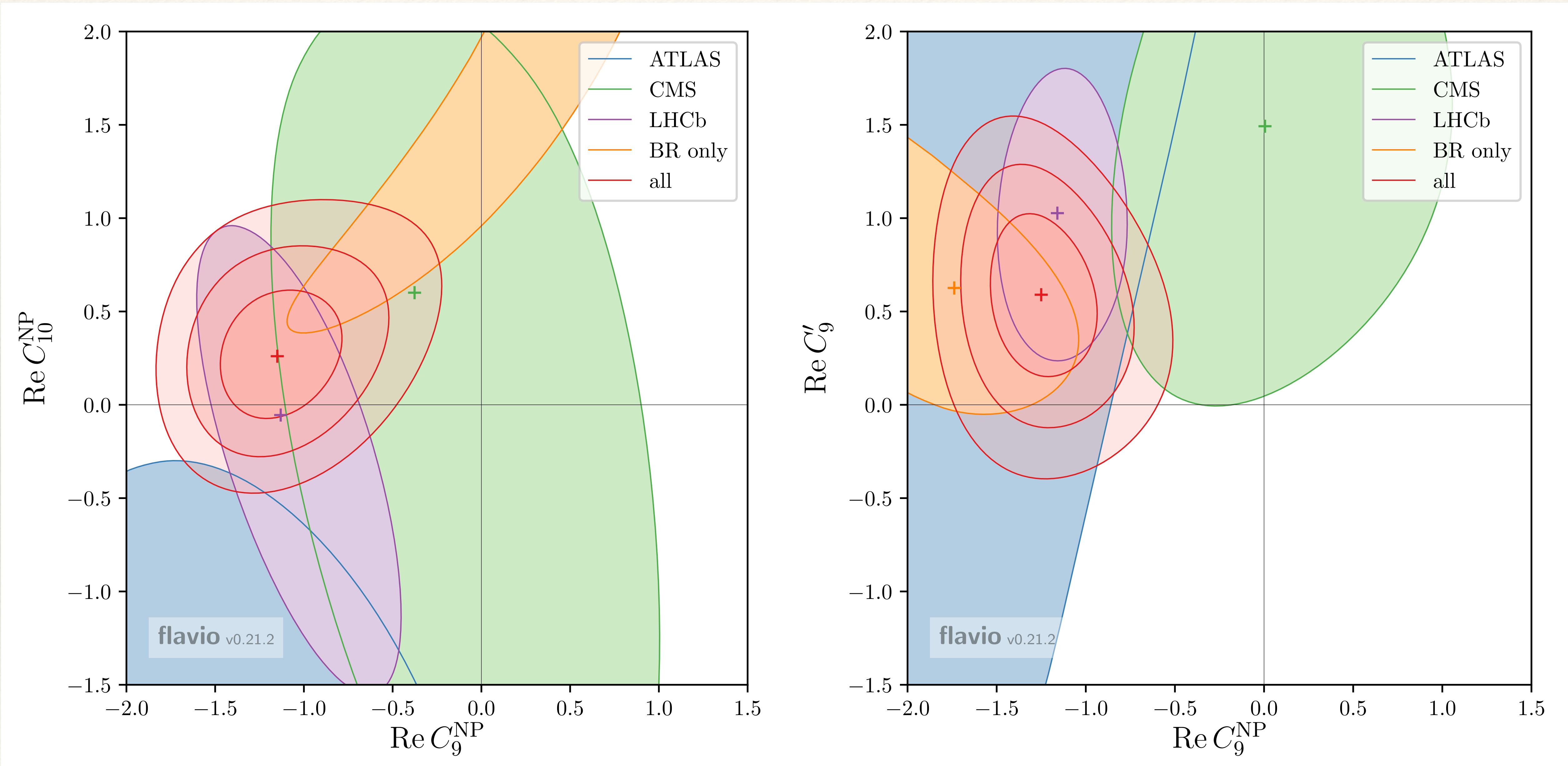
- **Lots of reasons to be excited!**
  - two different sets of anomalies of very different taste
  - many are seen by more than one experiment
  - in case of $b \to sll$ many observables appear to deviate from SM predictions, and the deviations appear to fit a simple pattern → talk by Nazila Mahmoudi

B-flavor anomalies

Coeff.	best fit	1σ	2σ	pull
$C_9^{\rm NP}$	-1.21	$[-1.41, -1.00]$	$[-1.61, -0.77]$	5.2σ
C_9'	$+0.19$	$[-0.01, +0.40]$	$[-0.22, +0.60]$	0.9σ
$C_{10}^{\rm NP}$	$+0.79$	$[+0.55, +1.05]$	$[+0.32, +1.31]$	3.4σ
C_{10}'	-0.10	$[-0.26, +0.07]$	$[-0.42, +0.24]$	0.6σ
$C_9^{\rm NP} = C_{10}^{\rm NP}$	-0.30	$[-0.50, -0.08]$	$[-0.69, +0.18]$	1.3σ
$C_9^{\rm NP} = -C_{10}^{\rm NP}$	-0.67	$[-0.83, -0.52]$	$[-0.99, -0.38]$	4.8σ
$C_9' = C_{10}'$	$+0.06$	$[-0.18, +0.30]$	$[-0.42, +0.55]$	0.3σ
$C_9' = -C_{10}'$	$+0.08$	$[-0.02, +0.18]$	$[-0.12, +0.28]$	0.8σ
$C_9^{\rm NP}, C_{10}^{\rm NP}$	$(-1.15, +0.26)$	—	—	5.0σ
$C_9^{\rm NP}, C_9'$	$(-1.25, +0.59)$	—	—	5.3σ
$C_9^{\rm NP}, C_{10}'$	$(-1.34, -0.39)$	—	—	5.4σ
$C_9', C_{10}^{\rm NP}$	$(+0.25, +0.83)$	—	—	3.2σ
C_9', C_{10}'	$(+0.23, +0.04)$	—	—	0.5σ
$C_{10}^{\rm NP}, C_{10}'$	$(+0.79, -0.05)$	—	—	3.0σ

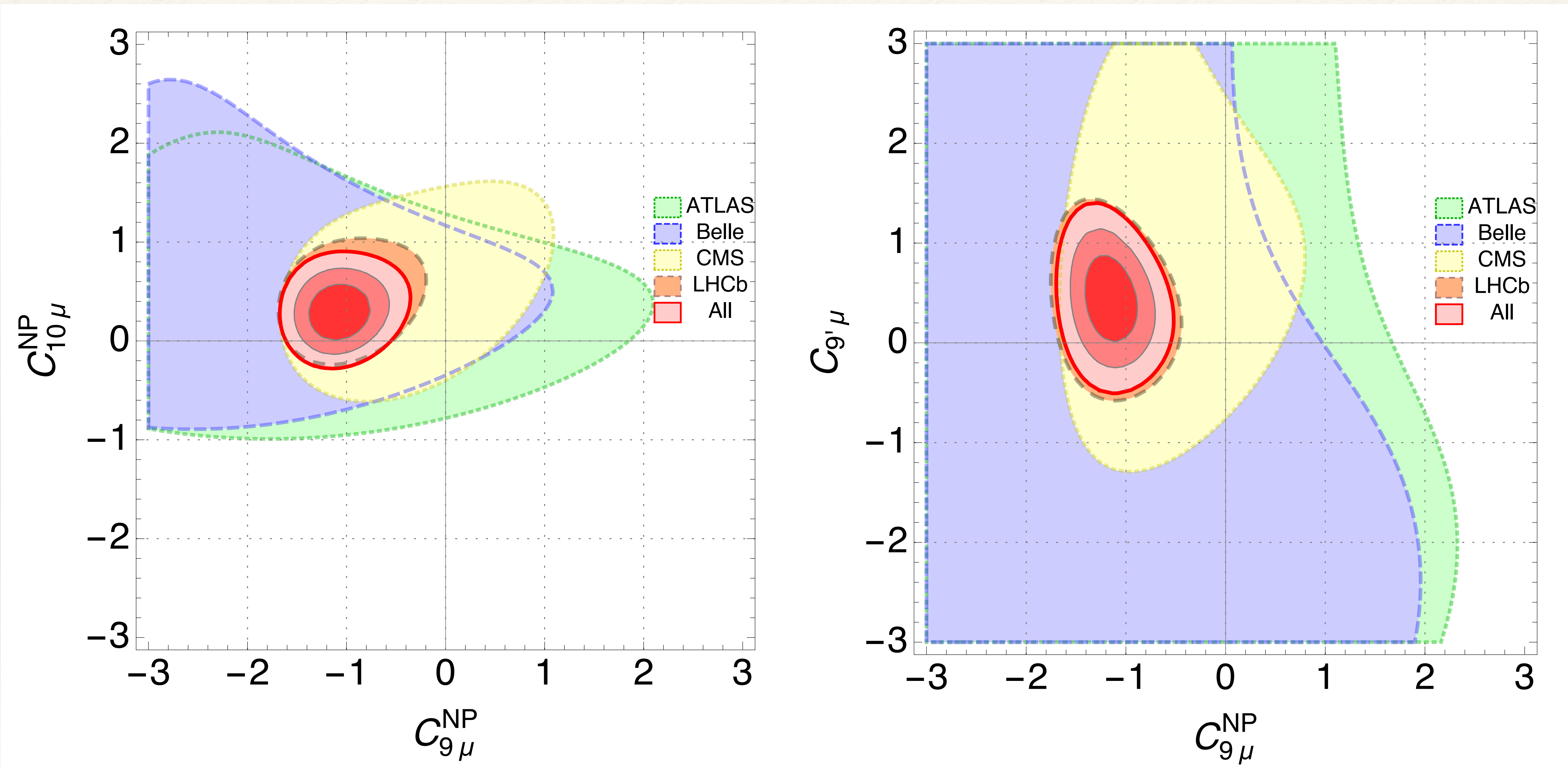
[Altmannshofer, Nies, Stangl, Straub 2017]

B-flavor anomalies



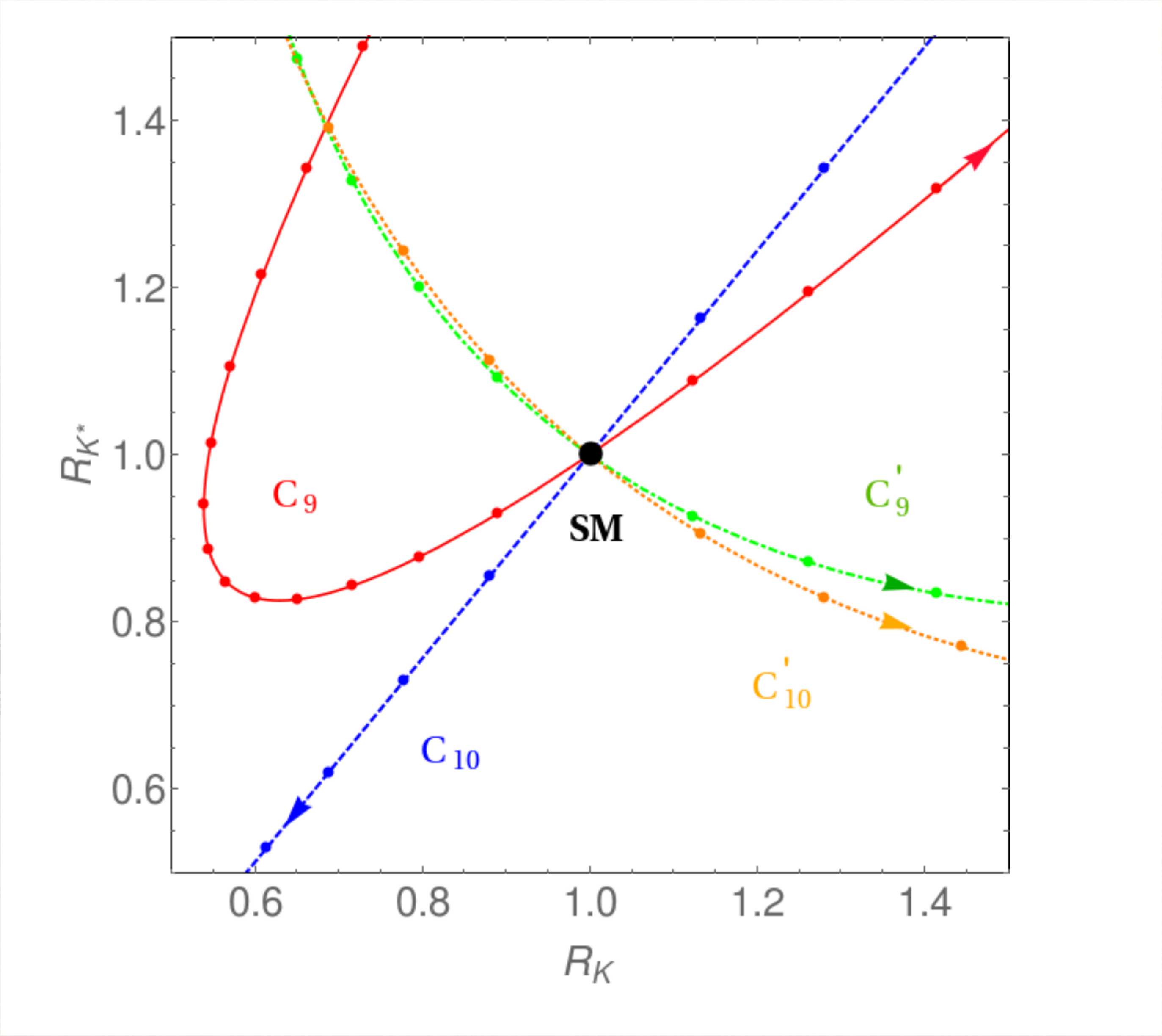
[Altmannshofer, Nies, Stangl, Straub 2017]

B-flavor anomalies



[Capdevila, Crivelin, Descotes-Genon, Matias, Virto 2017]

B-flavor anomalies

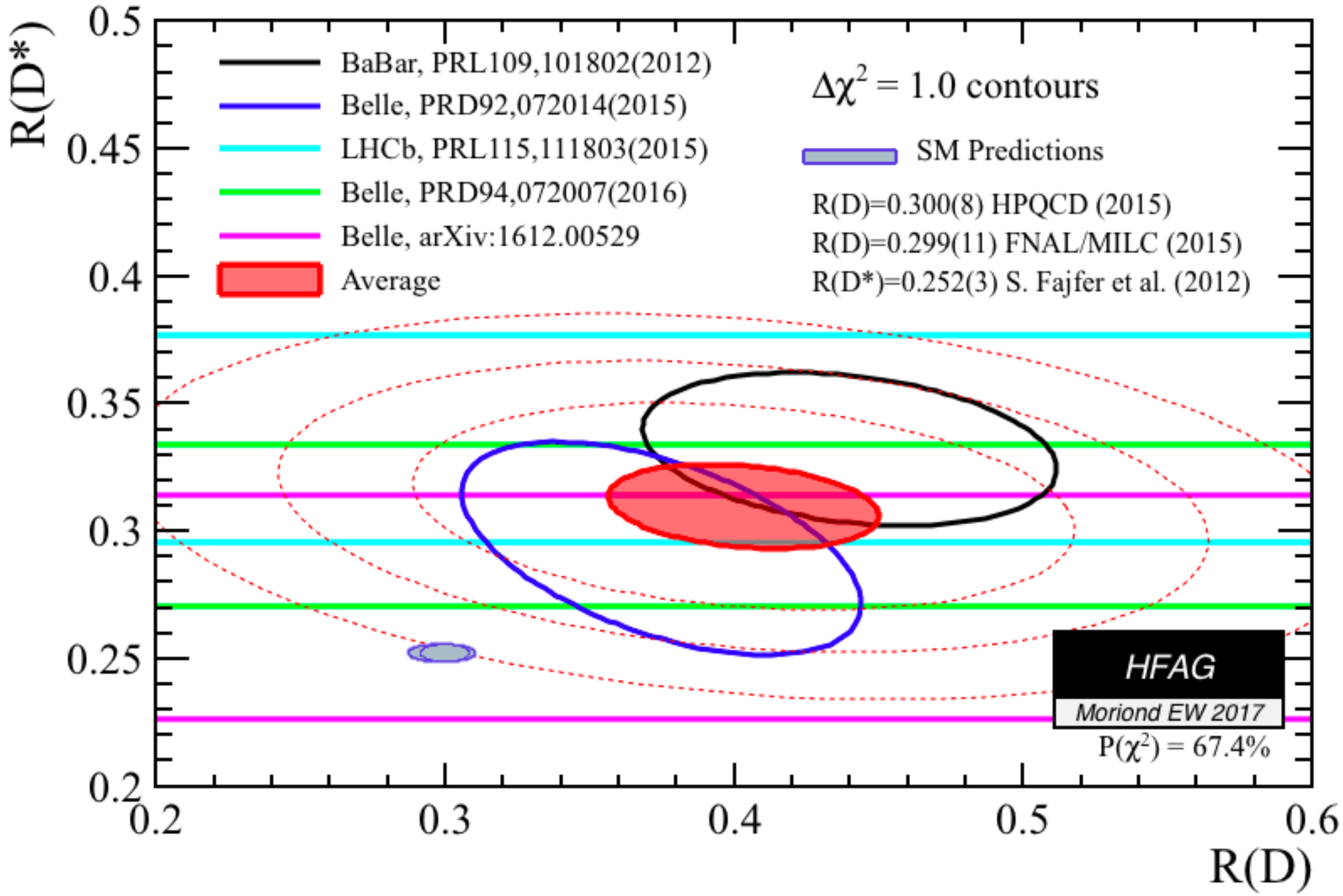


[Geng, Grinstein, Jäger, Martin Camalich, Ren, Shi 2017]

B-flavor anomalies

	$b \to c l \nu$	$b \to s l l$
Observables	R_D, R_{D^*}	R_K, R_{K^*}, angular distributions
SM	tree level, CKM favored	one-loop FCNC, GIM suppressed
LFU violation	τ vs. e/μ	μ vs. e
Caveats	τ reconstruction difficult, oldest experiment (BaBar) shows largest effect	electron reconstruction difficult at LHC*b*, so far no confirmation by another experiment
Benefits	Solid theory	Solid theory for $R_{K^{(*)}}$, some caveats for P_5'

B-flavor anomalies

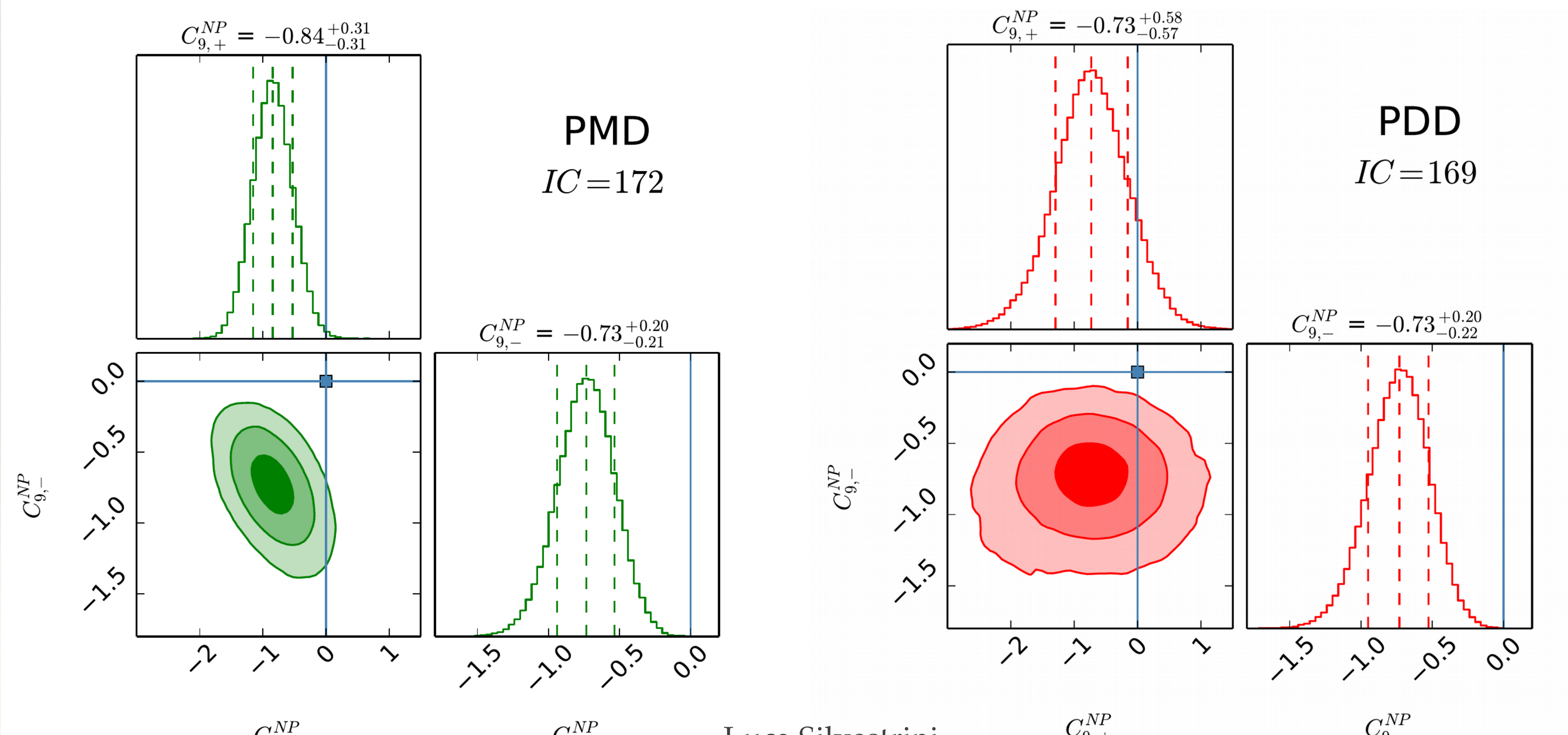


$$R_{D^{(*)}} = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\ell\bar{\nu})}\ ; \quad \ell = e, \mu$$

B-flavor anomalies

- Important theory progress on treatment of non-local hadronic contributions (charm penguins and friends)

→ talk by Marco Ciuchini



B-flavor anomalies

	$b \to c l \nu$	$b \to s l l$
Observables	R_D, R_{D^*}	R_K, R_{K^*}, angular distributions
SM	tree level, CKM favored	one-loop FCNC, GIM suppressed
LFU violation	τ vs. e/μ	μ vs. e
Caveats	τ reconstruction difficult, oldest experiment (BaBar) shows largest effect	electron reconstruction difficult at LHC*b*, so far no confirmation by another experiment
Benefits	Solid theory	Solid theory for $R_{K^{(*)}}$, some caveats for P_5'

B-flavor anomalies

- Challenge to model building, yet several interesting models have been proposed!

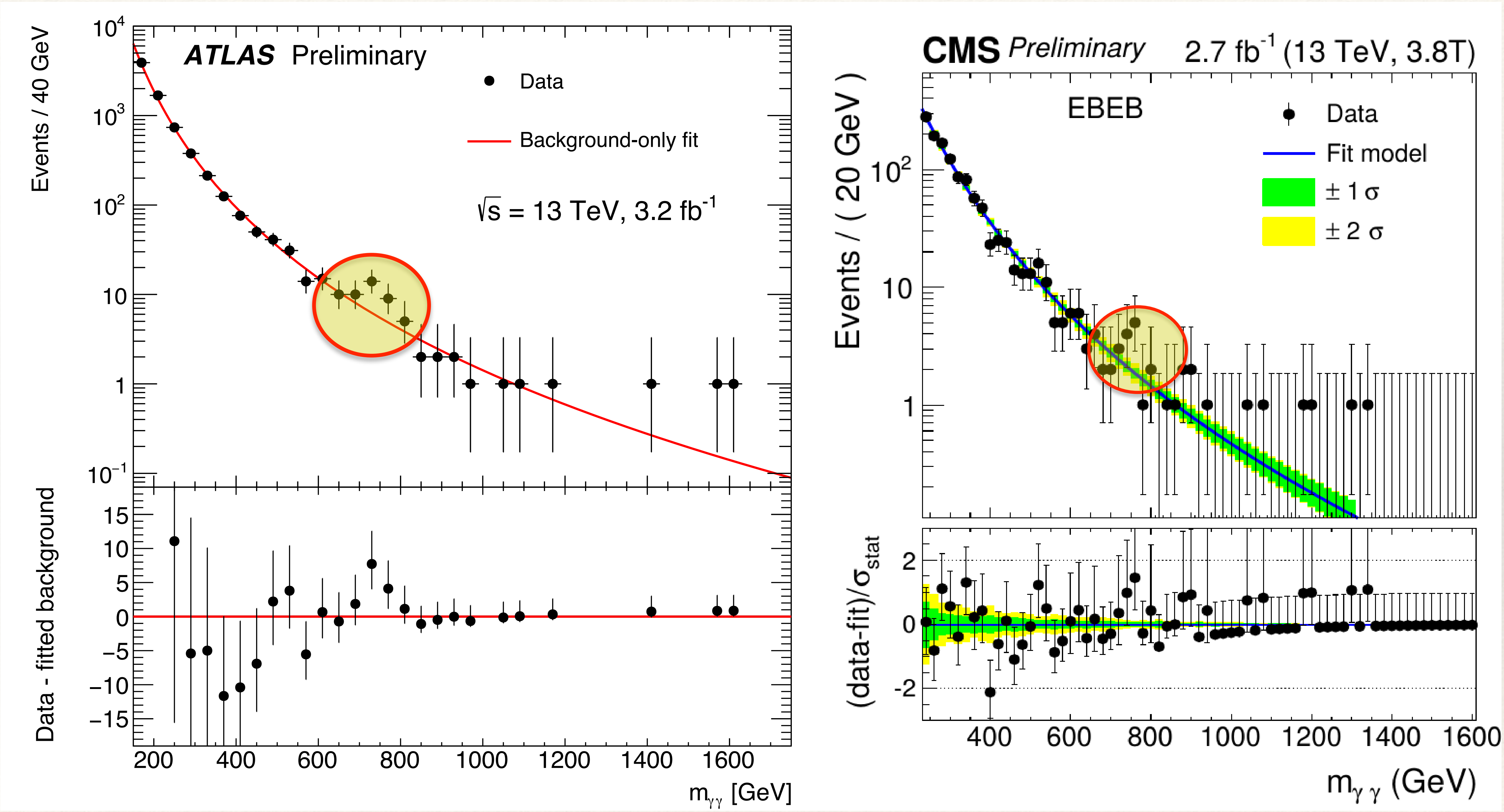
  → talks by Admir Greljo, Ferruccio Feruglio, Alessandro Strumia (?)

- We should not necessarily assume that all anomalies are correct …
- And we should not forget that experimental systematics might be correlated (e.g. between R_K and R_{K^*})
- An independent confirmation of the flavor anomalies by Belle II is as crucial as refining current LHCb analyses

Don't get too excited before you really know what's what

Behappy.me

Remember that thing?



Past (elusive) B-flavor anomalies

- Several anomalies in B physics (many rather persistent, some at the 3-4σ level) have created quite some excitement at their times:
  - puzzle of the too short Λ_b lifetime
  - hints of a too low $\sin 2\beta_{J/\psi\, K_S}$
  - **evidence for a low $\sin 2\beta_{\phi K_S}$ from loop processes**
  - puzzle of the too large $B \to \tau\nu$ branching ratio
  - $\Delta A_{CP}(B \to \pi K)$ puzzle of direct CP asymmetries
  - …

Past (elusive) B-flavor anomalies

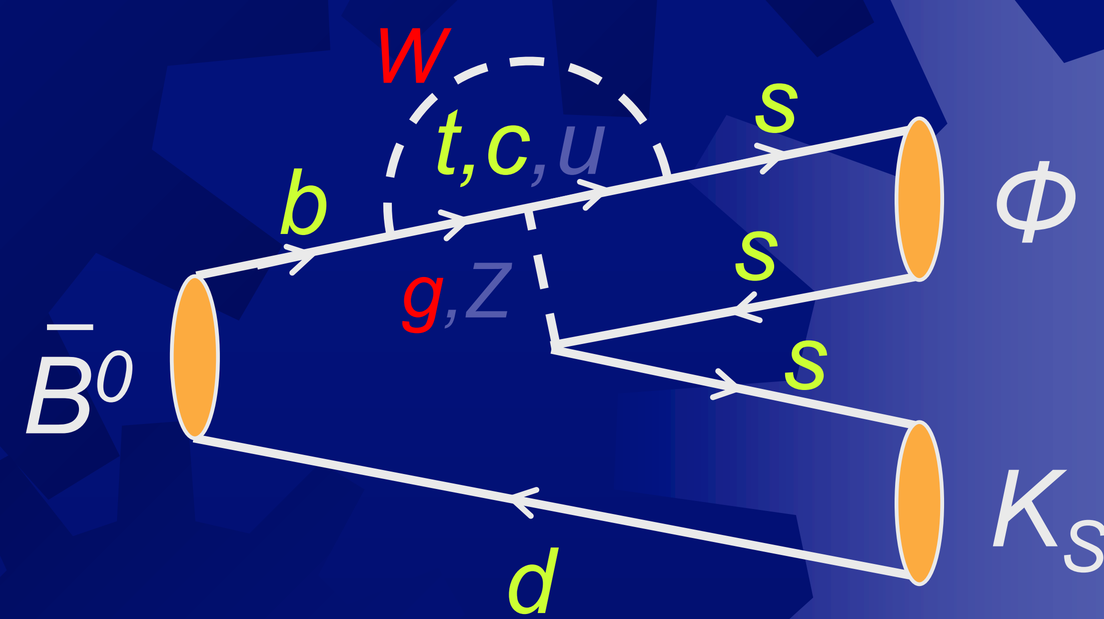
- It is important for theorists to be very careful and question error estimates
- Yet, in all cases above, improved measurements have resolved the tensions (Λ_b story was most impressive) …

CP Asymmetry in $B \to \Phi K_S$

- Interference of mixing and decay:

$$\bar{B}^0 \longleftrightarrow B^0$$
$$\searrow \quad \swarrow$$
$$\Phi K_S$$

- Penguin graph is real to very good approximation!



- Phase structure identical to the decay $B \to J/\psi\, K_S$
- Model-independent result:

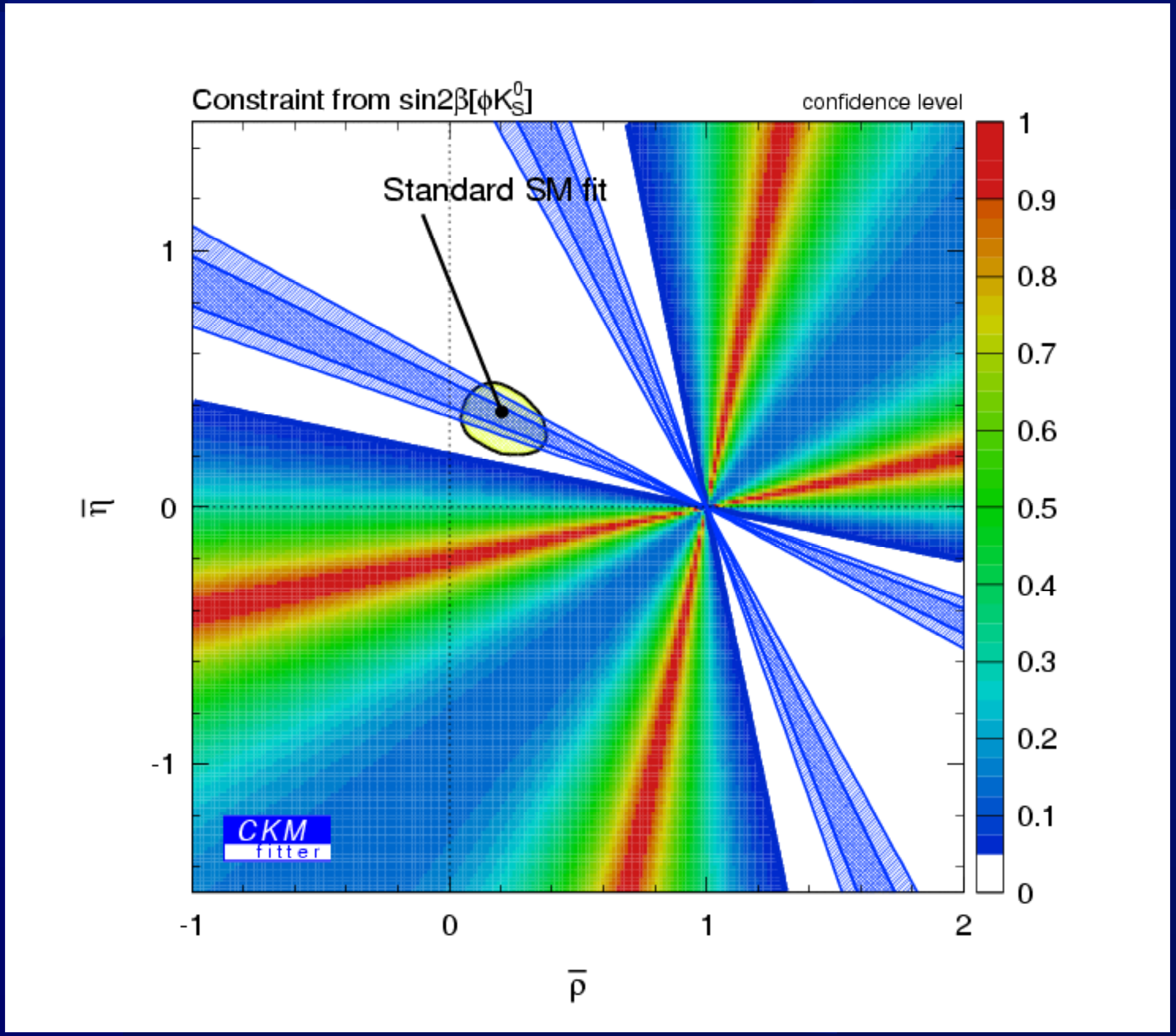
$$\boxed{S(\Phi K_S) - S(J/\psi\, K_S) = 0.02 \pm 0.01}$$

[Beneke, Neubert 2003]

- Experimental situation: (prior to LP 03)
  - $S(\Phi K_S) = -0.18 \pm 0.51 \pm 0.07$ BaBar
  - $S(\Phi K_S) = -0.73 \pm 0.64 \pm 0.22$ Belle

$\left.\begin{matrix} \\ \\ \end{matrix}\right\} -0.38 \pm 0.41$

$S(\Phi K_S) - S(J/\psi\, K_S) = -1.11 \pm 0.41\ (2.8\sigma)$

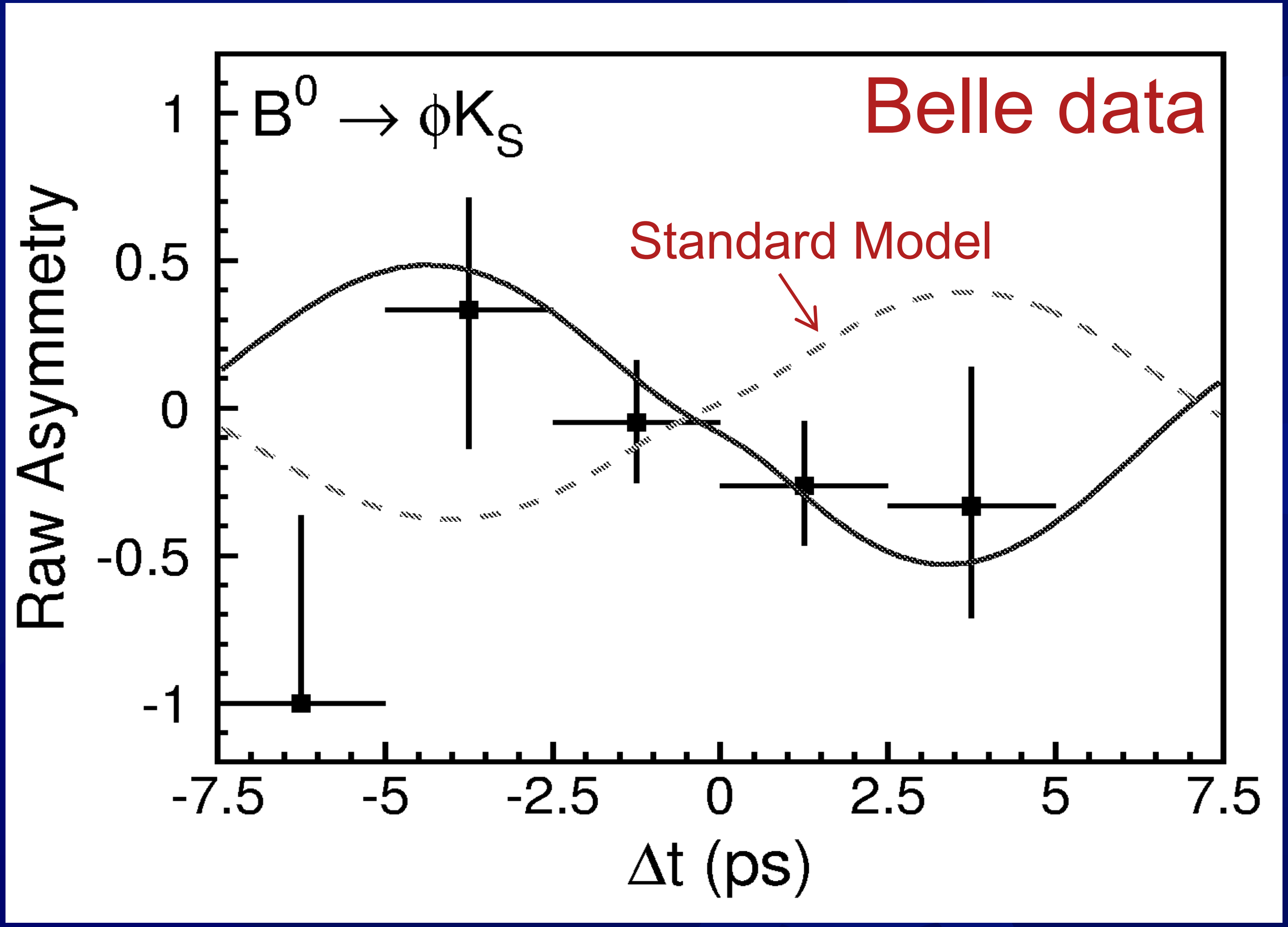


Experimental situation: (after LP 03)

- $S(\Phi K_S)$ =+0.45±0.43±0.07 BaBar
- $S(\Phi K_S)$ = -0.96±0.50±0.10 Belle

$\Big\}$ -0.15±0.33

$S(\Phi K_S)$ - $S(J/\psi\ K_S)$ = -0.88±0.33 (2.7σ)



- Experimental situation: (after ICHEP 04)
  - $S(\Phi K_S)$ =+0.50±0.25±0.06 BaBar
  - $S(\Phi K_S)$ =+0.06±0.33±0.09 Belle

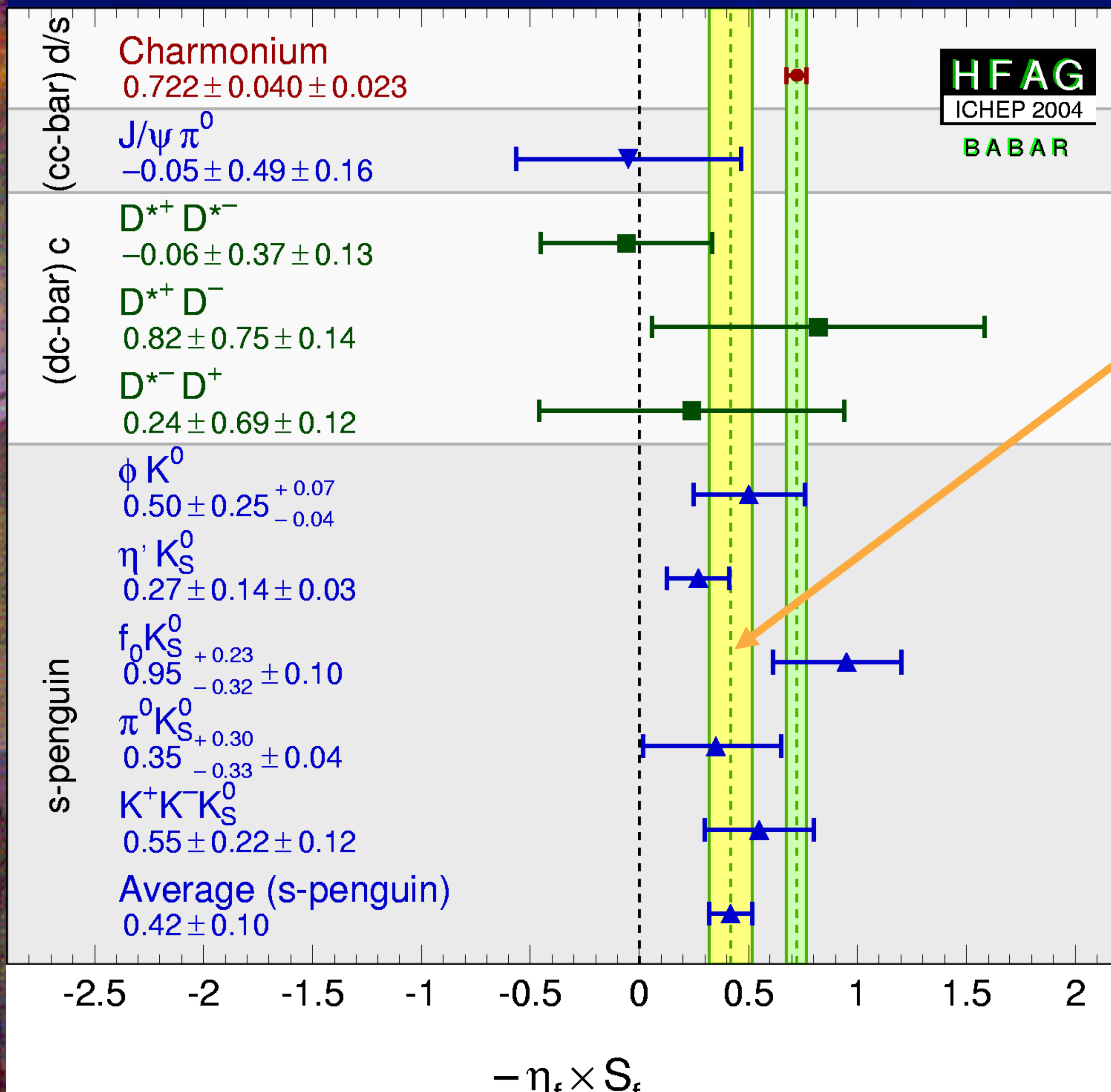
  $\Big\}$ 0.27±0.25

$S(\Phi K_S)$ - $S(J/\psi\ K_S)$ = -0.46±0.25 (1.8σ)

- But, trends for deviations are also seen in other $b \longrightarrow s$ penguin modes, e.g. a 3σ effect for $\eta' K_S$ from BaBar!
- All combined: (after ICHEP 04)
  - $S(b \longrightarrow s)$ = +0.42±0.10 BaBar
  - $S(b \longrightarrow s)$ = +0.43±0.12 Belle

  $\Big\}$ 0.42±0.08
  - deviation from 0.73 is about a 3σ effect

New Physics in penguins?



s-penguin average at 2.7σ different from sin2β[cc] (BABAR)

Similar difference at 2.4 σ seen by Belle

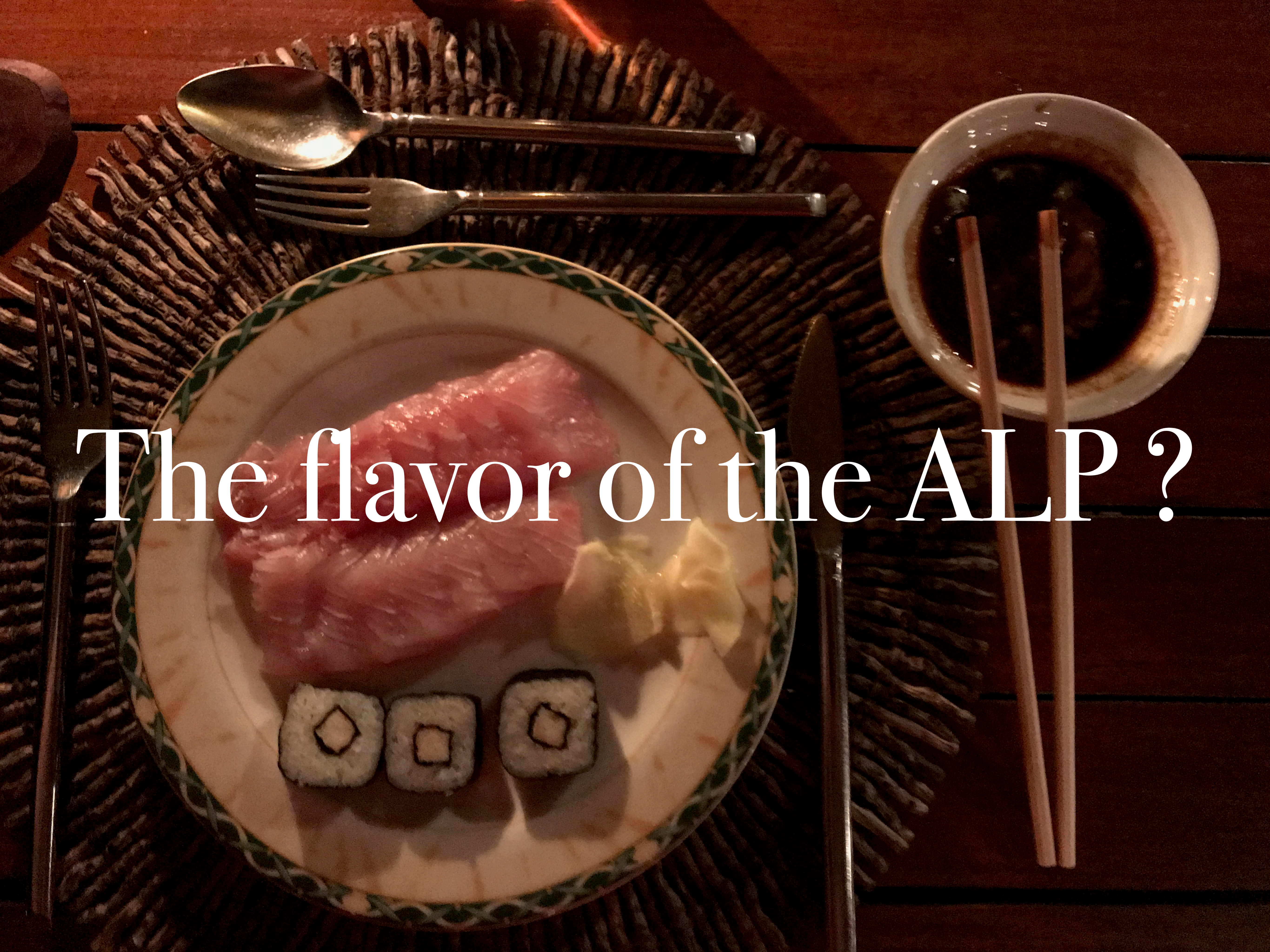
[A. Hoecker, ICHEP 2004]

$B^0 \to \phi K^0$ $B^0 \to K^+K^-K^0$ $B^0 \to \eta' K^0$ $B^0 \to f_0 K^0$ $B^0 \to \pi^0 K^0$

B-flavor anomalies - quo vadis?

- Today we are in a much better situation and the flavor anomalies are **much more compelling**!
- Nevertheless, they will need to mature and be confirmed by independent measurements …


The flavor of the ALP ?

ALP-GIM mechanism

- Derivative couplings of ALPs to fermions give rise to effects suppressed by the masses of the fermions involved
- As a result, the potential effects in B physics are generally rather small compared with other models of TeV-scale new physics
- Potentially large effects can arise in $B_{s,d} \to \mu^+\mu^- / e^+e^-$ decay modes, which are chirally suppressed in the SM ($\Gamma \sim m_{\mu,e}^2$)

$$\frac{\mathrm{Br}(B_s \to \mu^+\mu^-)}{\mathrm{Br}(B_s \to \mu^+\mu^-)_{\mathrm{SM}}} = \left| 1 - \frac{c_{\mu\mu}}{C_{10}} \frac{\pi}{\alpha} \frac{v^2}{\Lambda^2} \frac{1}{1 - m_a^2/m_{B_s}^2} \frac{(K_D - K_d)_{sb}}{V_{ts}^* V_{tb}} \right|^2$$

- Moreover …

Explaining the low-q^2 bin of R_{K^*}

- While the high-q^2 results for R_K and R_{K^*} can be accounted for in terms of effective operators, the low-q^2 bin can only be modified by at most 10% from short-distance physics

$$R_K \equiv \frac{\mathrm{BR}(B \to K\mu^+\mu^-)}{\mathrm{BR}(B \to Ke^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036\,, \quad \text{for } q^2 \in [1,6]\ \mathrm{GeV}^2\,,$$

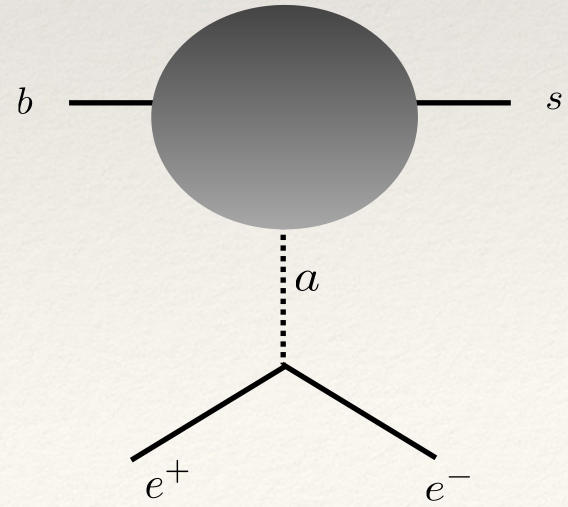
$$R_{K^*} \equiv \frac{\mathrm{BR}(B \to K^*\mu^+\mu^-)}{\mathrm{BR}(B \to K^*e^+e^-)} = \begin{cases} 0.66^{+0.11}_{-0.07} \pm 0.03, & \text{for } q^2 \in [0.045, 1.1]\ \mathrm{GeV}^2 \\ 0.69^{+0.11}_{-0.07} \pm 0.05\,, & \text{for } q^2 \in [1.1, 6]\ \mathrm{GeV}^2\,, \end{cases}$$

$$R_K^{\mathrm{SM}} = 1.00 \pm 0.01\,, \qquad \text{for } q^2 \in [1,6]\ \mathrm{GeV}^2\,,$$

$$R_{K^*}^{\mathrm{SM}} = \begin{cases} 0.91 \pm 0.03\,, & \text{for } q^2 \in [0.045, 1.1]\ \mathrm{GeV}^2 \\ 1.00 \pm 0.01\,, & \text{for } q^2 \in [1.1, 6]\ \mathrm{GeV}^2\,. \end{cases}$$

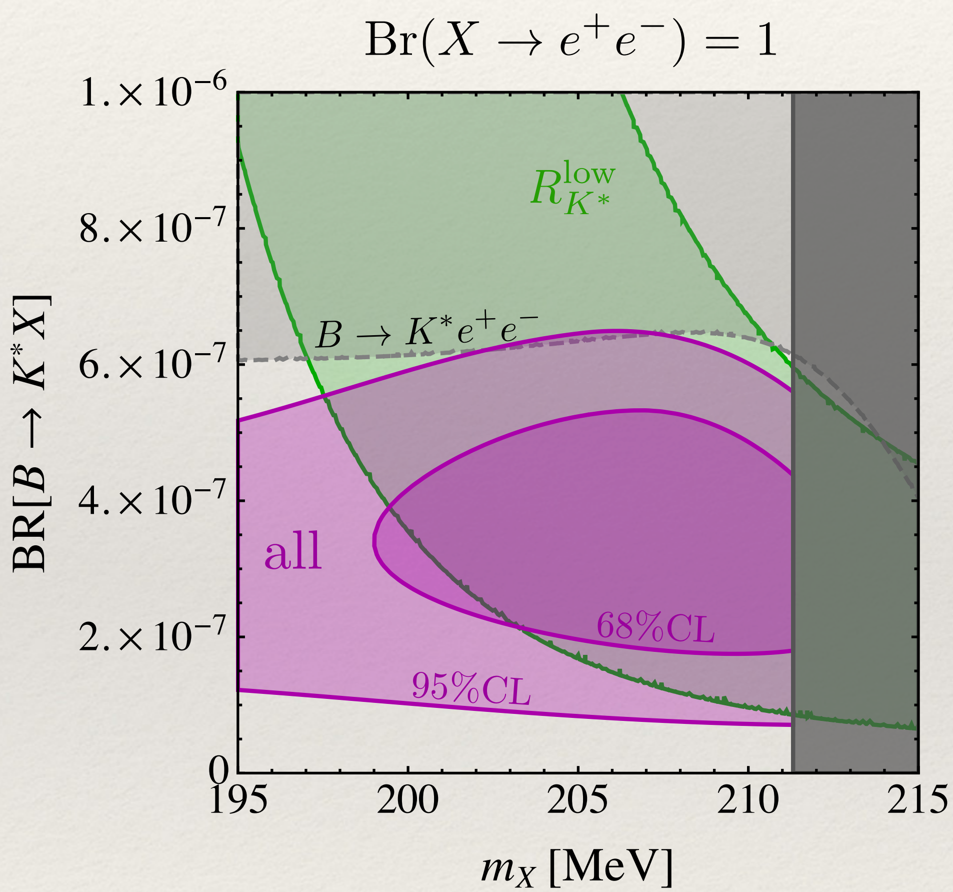
Explaining the low-q^2 bin of R_{K^*}

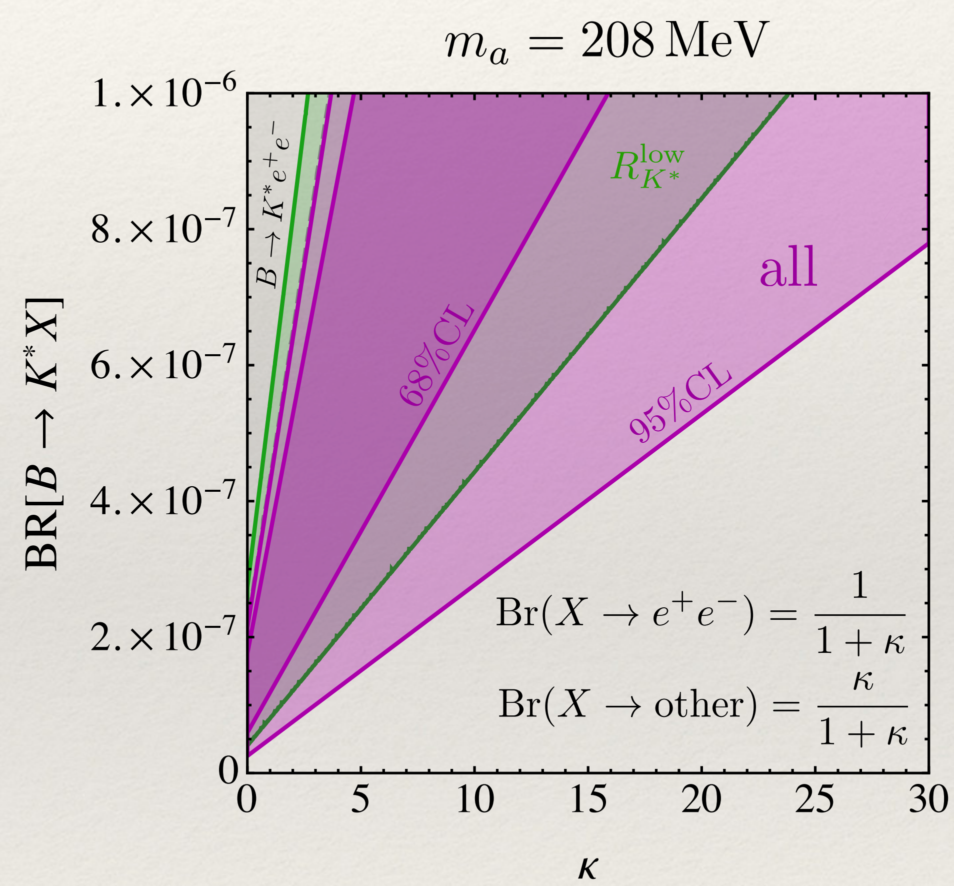
- Several authors have proposed to account for this effect by introducing a light new particle, such as a dark photon [Sala, Straub 2017; Ghosh 2017; Bishara, Haisch, Monni 2017; Datta, Kumar, Liao, Marfatia 2017; …]
- It was argued that a viable scenario must involve a light resonance with mass within 10 MeV of the di-muon threshold, which decays preferentially to electrons
  [Altmannshofer, Baker, Gori, Harnik, Pospelov, Stamou, Thamm 2017]
- An ALP in the mass range around 200 MeV, produced on shell in $B \to K^* a$, is a perfect candidate for such a light resonance!



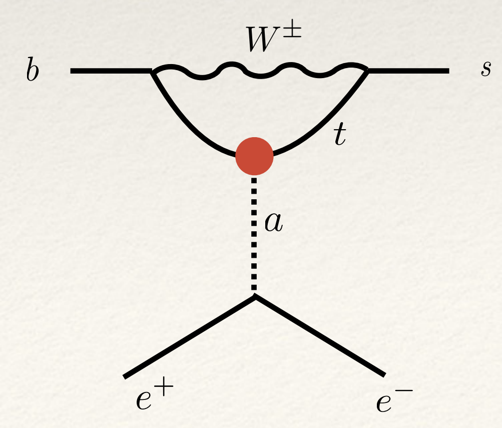
Explaining the low-q^2 bin of R_{K^*}

- One finds: (plots are preliminary; courtesy of Andrea Thamm and Martin Bauer)





- Branching ratios of this magnitude can be generated naturally via top-quark loops!




With some luck, we will soon leave the Standard Model behind us.
If some of the current flavor anomalies survive, there is an
unexplored world out there for us to discover.
It will be a great adventure!
PROPELLER

Thank you!