Parallel Session: Top-Bottom BSM

Thorsten Feldmann and Markus Cristinziani

CPPS Retreat, February 2024

CPPS Center for Particle Physics Siegen

Goals and Guidelines for the Discussions

- What expertise do we have in BSM physics in CPPS?
- Who is working on BSM aspects in CPPS?
- What kind of topics have been / are investigated in the recent past / at present?
- What kind of future research plans do exist / would make sense?
- What would be interesting subjects for special lectures related to the above topics (aiming at PhD students and above)?

Outline Session 1 – Thursday, 13:30 - 15:00

13:30 - 13:40 general intro [TF and MC, 10']

13:40 - 13:55 "$t\bar{t} \rightarrow$ heavy neutral leptons" [Tongbin Zhao, 15']

13:55 - 14:02 discussion of the presentation [Audience, 7']

14:02 - 14:17 "$t\bar{t} \rightarrow$ lepton flavour violation" [Gabriel Gomes, 15']

14:17 - 14:24 discussion of the presentation [Audience, 7']

14:24 - 14:39 "Search for long-lived particles in ATLAS" [Vadim Kostyukhin, 15']

14:39 - 14:46 discussion of the presentation [Audience, 7']

14:46 - 15:00 wrap-up / closing remarks for day 1

Outline Session 2 – Friday, 11:00 - 12:30

11:00 - 11:15	”Beyond the SM - Theory Intro” [Thorsten Feldmann, 15’]
11:15 - 11:22	discussion of the presentation [Audience, 7’]
11:22 - 11:37	“Making friends with flavour structure in BSM” [Tom Tong, 15’]
11:37 - 11:44	discussion of the presentation [Audience, 7’]
11:44 - 11:59	‘’EFT fits” [Jan Hahn, 15’]
11:59 - 12:06	discussion of the presentation [Audience, 7’]
12:06 - 12:21	“Interface between B meson and top physics observables” [Gilberto TX, 15’]
12:21 - 12:28	discussion of the presentation [Audience, 7’]

Universität Siegen

HEP Experimental High Energy Physics

CPPS Center for Particle Physics Siegen

Search for heavy right-headed Majorana neutrinos in $t\bar{t}$ decays

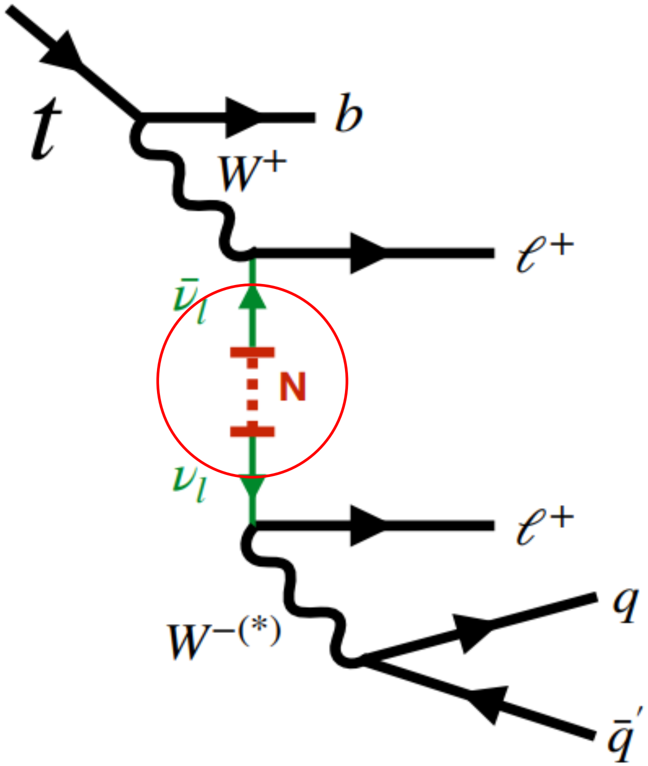
Tongbin Zhao

Universität Siegen

15/02/2024

CPPS Retreat

ATLAS EXPERIMENT

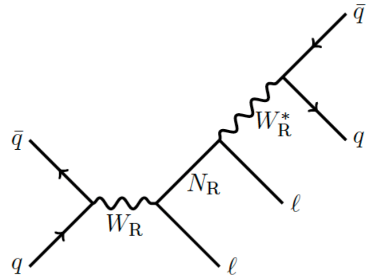


$$V_{\ell,N} = \begin{pmatrix} V_{e,N1} & V_{e,N2} & V_{e,N3} \\ V_{\mu,N1} & V_{\mu,N2} & V_{\mu,N3} \\ V_{\tau,N1} & V_{\tau,N2} & V_{\tau,N3} \end{pmatrix}$$

- ✓ The discovery of neutrino oscillations in solar, atmospheric, reactor and accelerator experimental data indicates that neutrinos are massive and mixed
- ✓ The seesaw mechanism theory provides an explanation for the small mass of neutrinos.
- ✓ The Type-I seesaw is the simplest, adding 3 heavy RH Majorana neutrinos N_1, N_2, N_3. N_i can couple to SM neutrinos via coupling strength $V_{l,N}$
- ✓ The Neutrino-less double-beta decay: a lepton number violation of |ΔL| = 2 along with the process of generating Majorana neutrino.

Other analysis:

- ✓ Mostly search for heavy neutrinos with the Drell-Yan process $q\bar{q} \to W^* \to N\ell$.



- ✓ JHEP10 (2019) 265 (ATLAS) (36.1 fb^{-1}, $[5,50]$GeV, $|V_{iN}|^2 > 1.4 * 10^{-5}$)
- ✓ JHEP01 (2019) 122 (CMS) (35.9 fb^{-1}, $[20,1600]$GeV, $|V_{iN}|^2 > 2.3 * 10^{-5}$)
- ✓ LHC is a top factory and this analysis searches for heavy neutral leptons in the $t\bar{t}$ process.

Summary and Outlook

Search for HNL from $t\bar{t}$ decay in 2ℓSS final states

- ✓ Results of the unblinded fit are in agreement with expectations from the blinded fit
- ✓ Extend the upper limit results on mixing parameters from 50GeV to 75 GeV, compared to other ATLAS experiments
- ✓ The unblinding results have been updated to the INT note and paper draft

Outlook

- ✓ The paper draft has been completed and will be sent into ATLAS circulation soon

Universität Siegen

HEP Experimental High Energy Physics

CPPS Center for Particle Physics Siegen

ATLAS EXPERIMENT

MARKUS CRISTINZIANI, GABRIEL GOMES

SEARCH FOR CHARGED LEPTON FLAVOUR VIOLATION IN TOP-QUARK PRODUCTION AND DECAY WITH THE ATLAS EXPERIMENT

15 FEBRUARY 2024

CPPS RETREAT

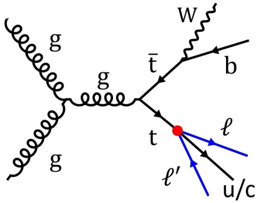
Effective field theory (EFT)

- SM extension in a model-independent approach

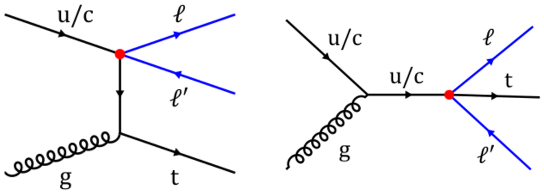
$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\sum_k C_k^{(5)} O_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} O_k^{(6)} + \ldots$$

  - Λ is the mass scale of New Physics; Wilson coefficients, $C_k^{(d)}$, control the strength of the EFT operators, $O_k^{(d)}$
- **Top sector**: $gq_k \to t\ell^{\pm}\ell'^{\mp}$ production and $t \to \ell^{\pm}\ell'^{\mp}q_k$ decay described by $SU(3)_C \times SU(2)_L \times U(1)_Y$ dimension-6 EFT operators
  - 2Q2L operators (subset of the Warsaw basis)

cLFV in top-quark decay



cLFV in top-quark production



EFT operators

$O_{lq}^{1(ijkl)} = \left(\bar{l}_i\gamma^{\mu}l_j\right)\left(\bar{q}_k\gamma_{\mu}q_l\right)$

$O_{lq}^{3(ijkl)} = \left(\bar{l}_i\gamma^{\mu}\sigma^{I}l_j\right)\left(\bar{q}_k\gamma_{\mu}\sigma^{I}q_l\right)$

$O_{eq}^{(ijkl)} = \left(\bar{e}_i\gamma^{\mu}e_j\right)\left(\bar{q}_k\gamma_{\mu}q_l\right)$ — vector

$O_{lu}^{(ijkl)} = \left(\bar{l}_i\gamma^{\mu}l_j\right)\left(\bar{u}_k\gamma_{\mu}u_l\right)$

$O_{eu}^{(ijkl)} = \left(\bar{e}_i\gamma^{\mu}e_j\right)\left(\bar{u}_k\gamma_{\mu}u_l\right)$

$^{\ddagger}O_{lequ}^{1(ijkl)} = \left(\bar{l}_i e_j\right)\varepsilon\left(\bar{q}_k\gamma_{\mu}u_l\right)$ — scalar

$^{\ddagger}O_{lequ}^{3(ijkl)} = \left(\bar{l}_i\sigma^{\mu\nu}e_j\right)\varepsilon\left(\bar{q}_k\sigma_{\mu\nu}u_l\right)$ — tensor

Summary and Conclusion

Summary

- Generated signal MC samples
- Defined analysis regions
- Explored different BDT setups for better signal discrimination
- Achieved good performance with both simple and multi-class BDTs

Outlook

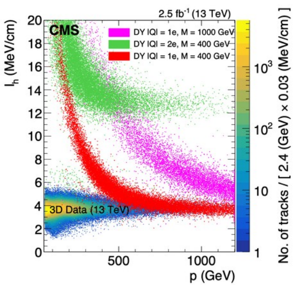
- Compare the fit sensitivity (BDT discriminants vs. H_T)
- Include missing systematics on the fit

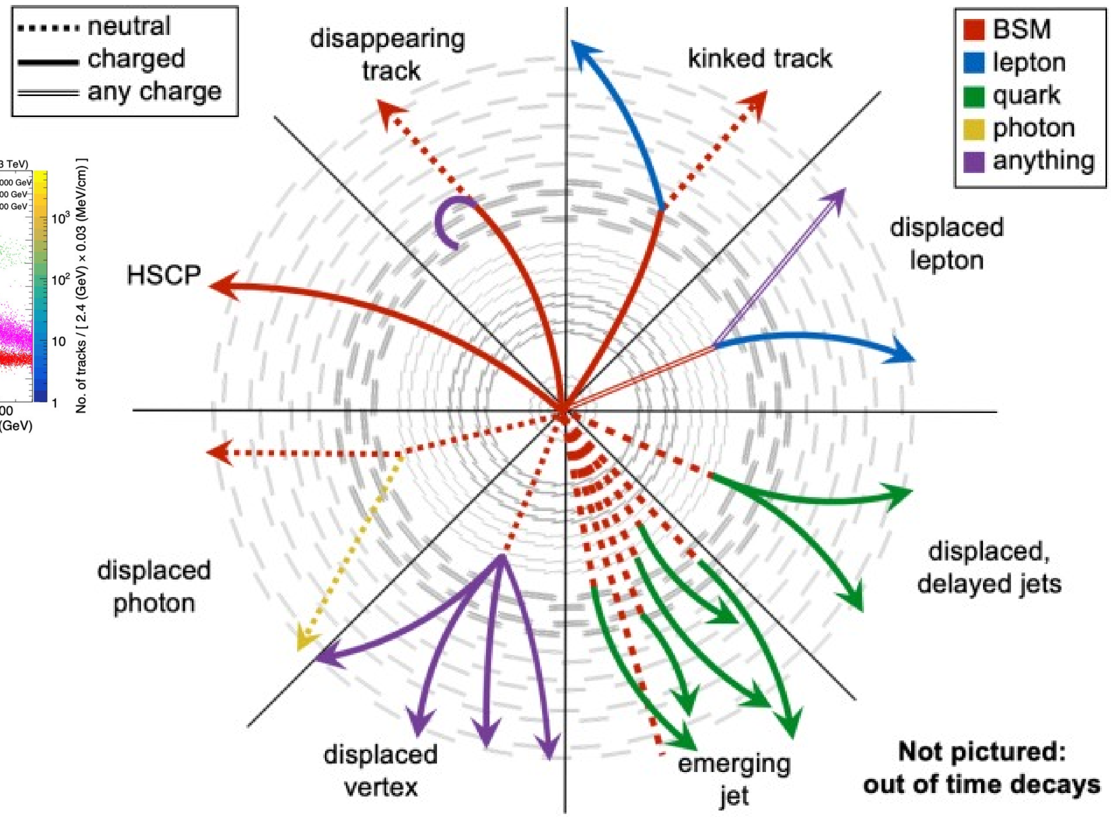
Thank you for your attention!

LLP and top-quark

V. Kostyukhin

Experimental signatures





Some reviews:

2020 J. Phys. G: Nucl. Part. Phys. 47 090501 “Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider”

Front. Phys. 10:967881 (2022) “Searches for long-lived particles at the future FCC-ee”

Current talk – only displaced tracks/leptons/vertices

LLP and top-quark

Some classification:

1) LLP decays to top-quark

2) Top-quark decays to LLP

3) LLP in association with top-quark

ATLAS searches

ATLAS publication database: (13TeV, BSM, LLP) 33 publications; (13TeV, BSM, LLP, Vertex) 16 publications;

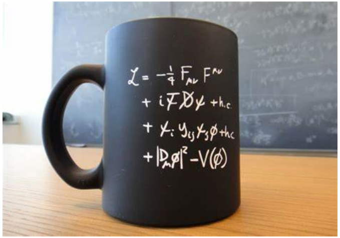
Search for long-lived smuons with millimeter-scale displacement	SUSY	Phys. Lett. B 846 (2023) 138172	2023-05-03	13	139 fb^{-1}
Vertexed non-prompt photons	SUSY	Phys. Rev. D 108 (2023) 012012	2023-04-25	13	139 fb^{-1}
Search for long-lived particles in events with a displaced vertex and jets	SUSY	JHEP 06 (2023) 200	2023-01-31	13	139 fb^{-1}
Displaced heavy neutral leptons	EXOT	Phys. Rev. Lett. 131 (2023) 061803	2022-04-26	13	139 fb^{-1}
Displaced jets in muon system (2vtx)	EXOT	Phys. Rev. D 106, (2022) 032005	2022-03-01	13	139 fb^{-1}
Disappearing track	SUSY	Eur. Phys. J. C 82 (2022) 606	2022-01-07	13	139 fb^{-1}
Search for Higgs (in VH production) decaying to hidden sector bosons in displaced 4b final state	EXOT	JHEP 11 (2021) 229	2021-07-13	13	139 fb^{-1}
Search for stopped long-lived particles decaying to jets in empty bunch crossings	SUSY	JHEP 07 (2021) 173	2021-04-07	13	111 fb^{-1}
Search for displaced leptons	SUSY	Phys. Rev. Lett. 127 (2021) 051802	2020-11-13	13	139 fb^{-1}
Stop pair, long-lived; displaced vertex and displaced muon	SUSY	Phys. Rev. D 102 (2020) 032006	2020-03-26	13	136 fb^{-1}
Displaced Inner Detector +Muon Spectrometer Search	EXOT	Phys. Rev. D 101 (2020) 052013	2019-11-28	13	36 fb^{-1}

All done?

Beyond the Standard Model – (some) Theory Intro

Thorsten Feldmann

CPPS Retreat, February 2024



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TP1 Theoretical Particle Physics

Parameterizing the ”Beyond”

- ”Derive the SM” from a more fundamental underlying (renormalizable) theory ?
- Construct ”Simplified Models” that can address some of the above issues ?
- Consider the SM as a low-energy effective theory
  and include higher-dimensional operators (SM-EFT)

Confront with experimental data:

- Direct Searches for resonances and thresholds in decay spectra,
  due to production and decay of new particles at high energies
- Indirect Searches for deviations from SM predictions in low-energy observables
- measure decays that are forbidden in the SM (”Null Tests”)

Example for flavour-specific couplings

- four-fermion operators with two quark and two lepton fields in SMEFT: (→ LFU violation)

$$\frac{1}{\Lambda_{\rm NP}^2}\,[\mathcal{C}_{\ell q}]^{ij\alpha\beta}\,\left(\bar Q_i\gamma_\mu Q_j\right)\,\left(\bar L_\alpha\gamma^\mu L_\beta\right)$$

(for $i,j,\alpha,\beta = 1\ldots 3$ generations)

- flavour tensor $[\mathcal{C}_{\ell q}]^{ij\alpha\beta}$ introduces $3^4 = 81$ free parameters:

generic EFT:	all coefficients satisfy $\mathcal{C}_{\ell q}^{ij\alpha\beta} \sim \mathcal{O}(1)$ $\to$ flavour constraints require $\Lambda_{\rm NP}$ to be very high $\to$ or: 81 coefficients must be fine-tuned

MFV:	expansion: $\#1\left(\delta^{ij} + \#2\,(Y_U Y_U^\dagger)^{ij} + \#3\,(Y_D Y_D^\dagger)^{ij} + \ldots\right)\left(\delta^{\alpha\beta} + \ldots\right)$ $\to$ reduction to a few unknown numbers $\to$ inherits flavour hierarchies from SM $\to$ independent of flavour bases $\to$ self-consistent under renormalization $\to$ value of $\Lambda_{\rm NP}$ can be reasonably low

Lessons for Top-Bottom Connection

- Generic EFT is already spoiled by the SM Yukawas
- MFV is too special !
- Before adressing the SM-EFT flavour structure, we first have to understand the origin of the SM flavour hierarchies encoded in the Yukawa matrices !
- In the meantime, NP operators with bottom or top quarks have a priori independent coefficients, with no particular correlations between BSM effects in top or flavour observables !
- Keep in mind that any connection between BSM searches in the top or bottom sector is based on (more or less) ad-hoc model assumptions !

. . . but let's see how this works in practice . . .

Making friends with flavor

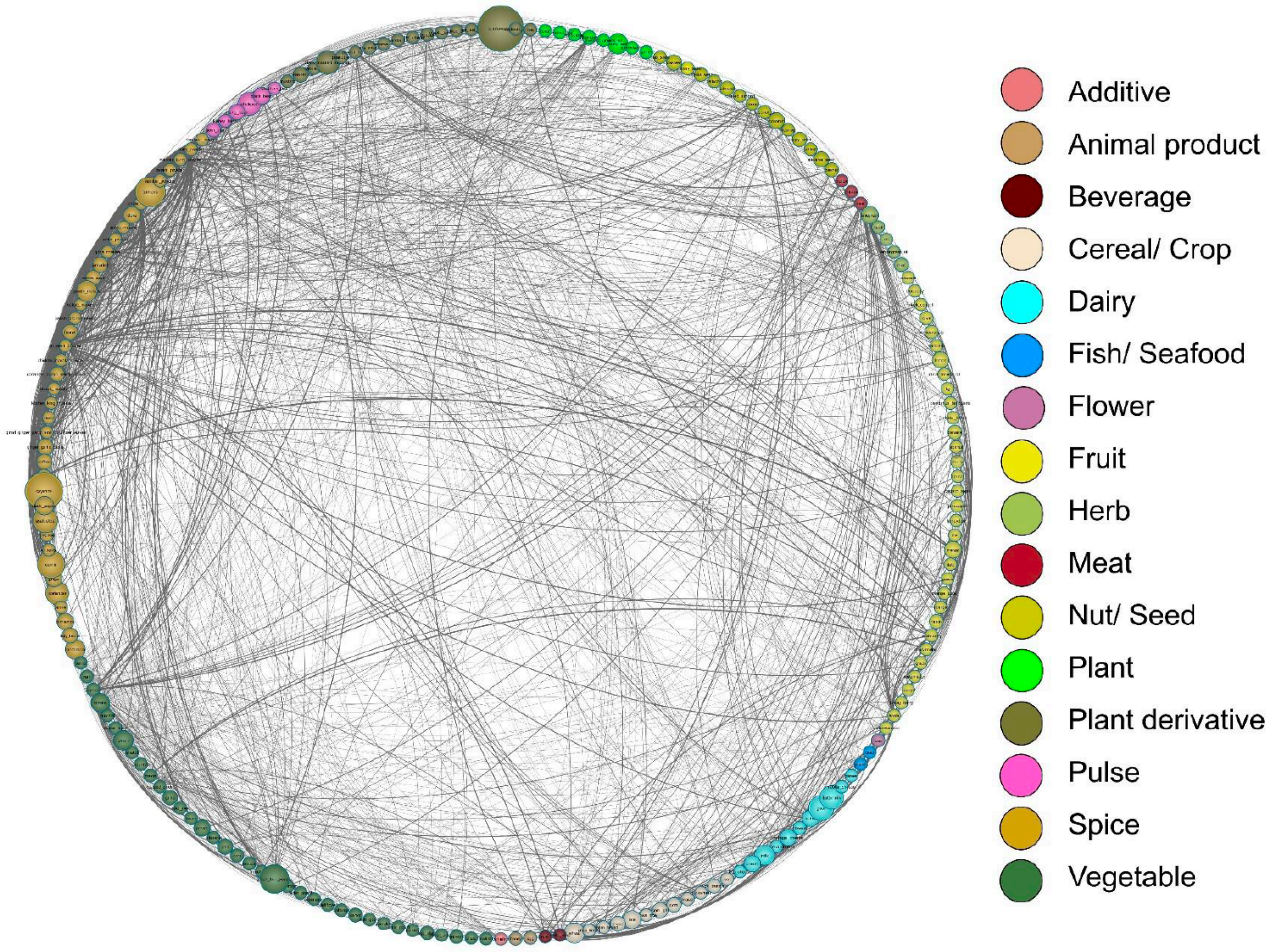
1502.03815

Tom Tong

Center for Particle Physics Siegen, University of Siegen

CPPS Retreat

16 February 2024

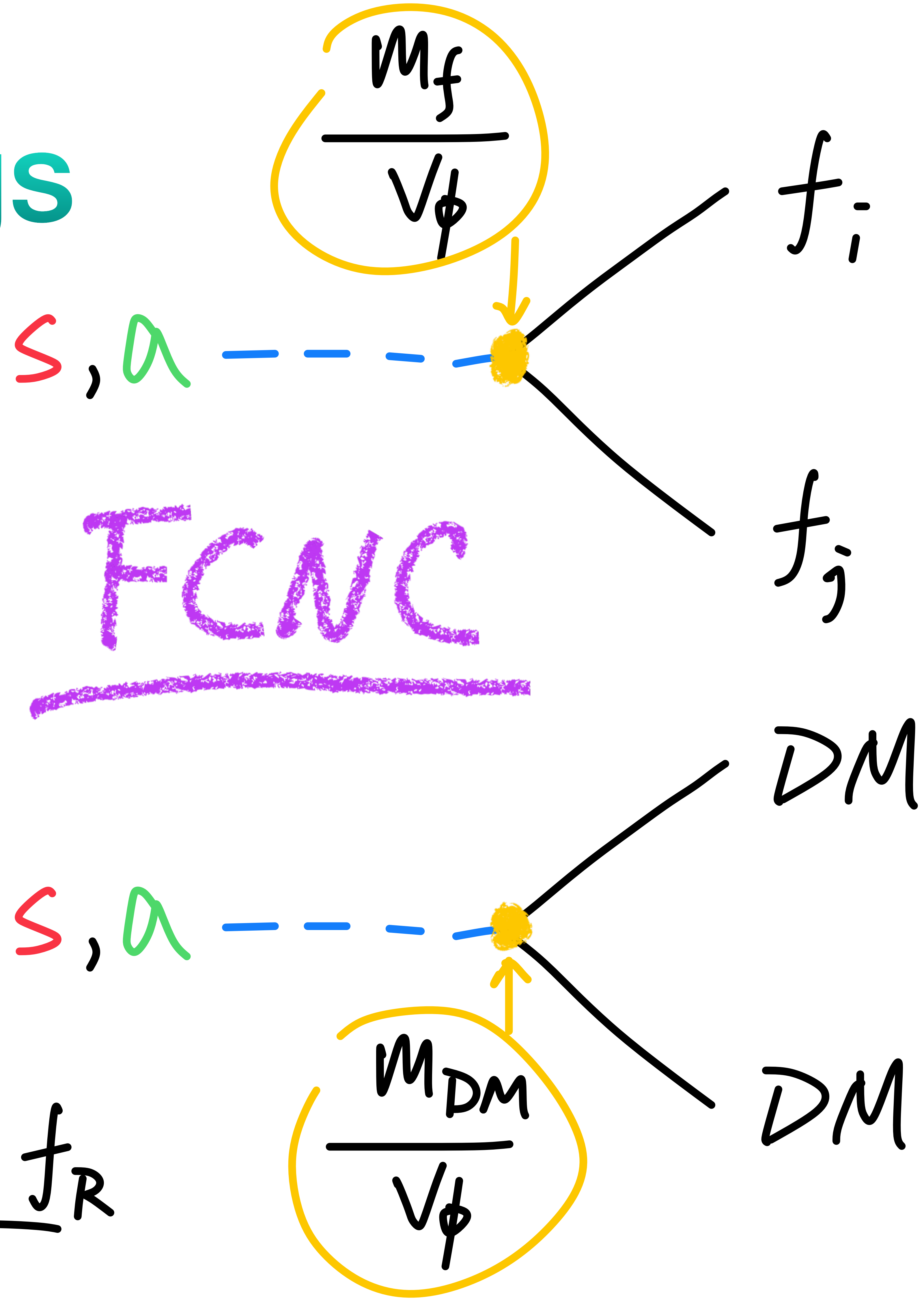


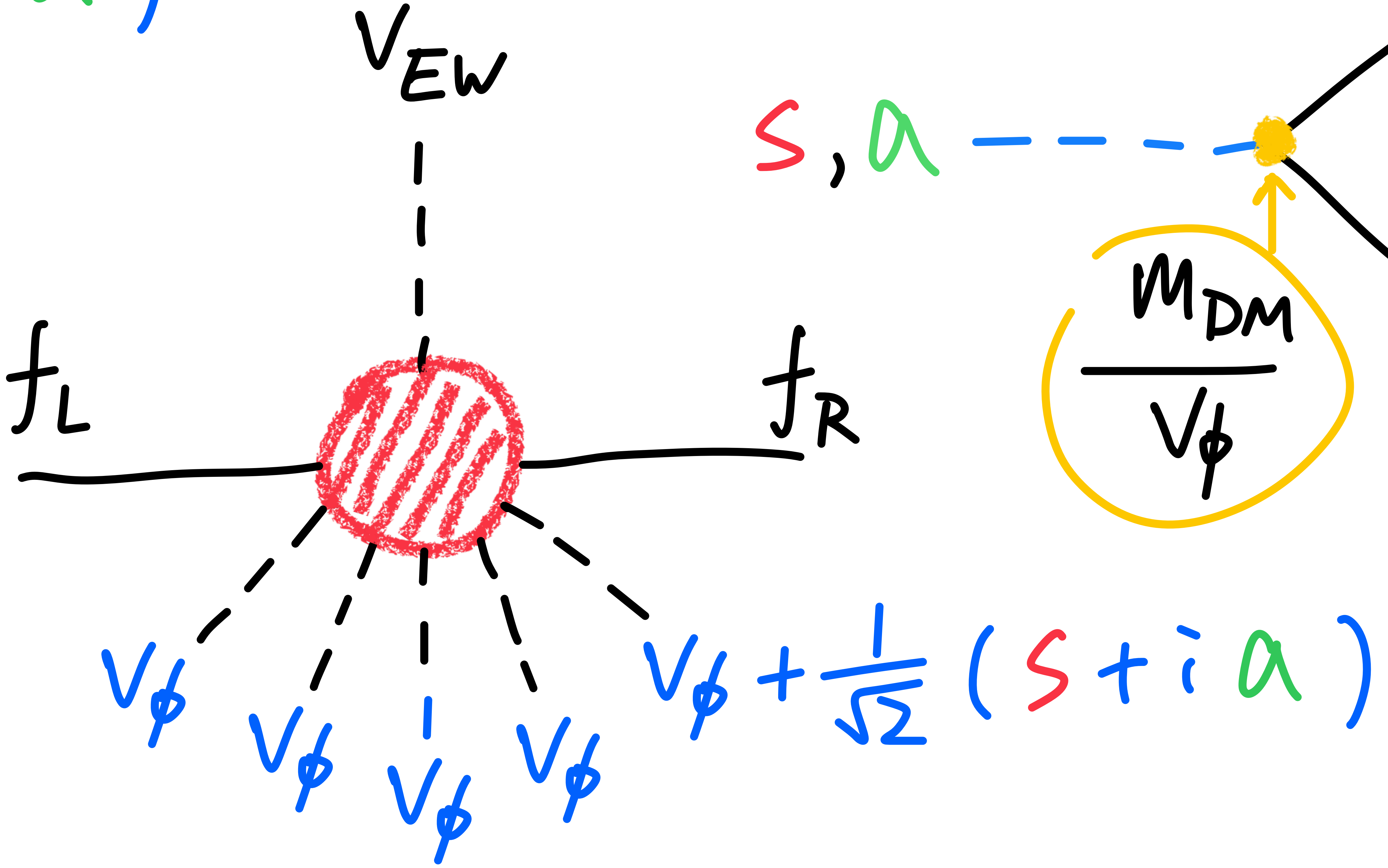
Flavon couplings

$$H \to v_{EW} + \frac{1}{\sqrt{2}}(h + i G_0)$$

$$\phi \to v_\phi + \frac{1}{\sqrt{2}}(s + i a)$$

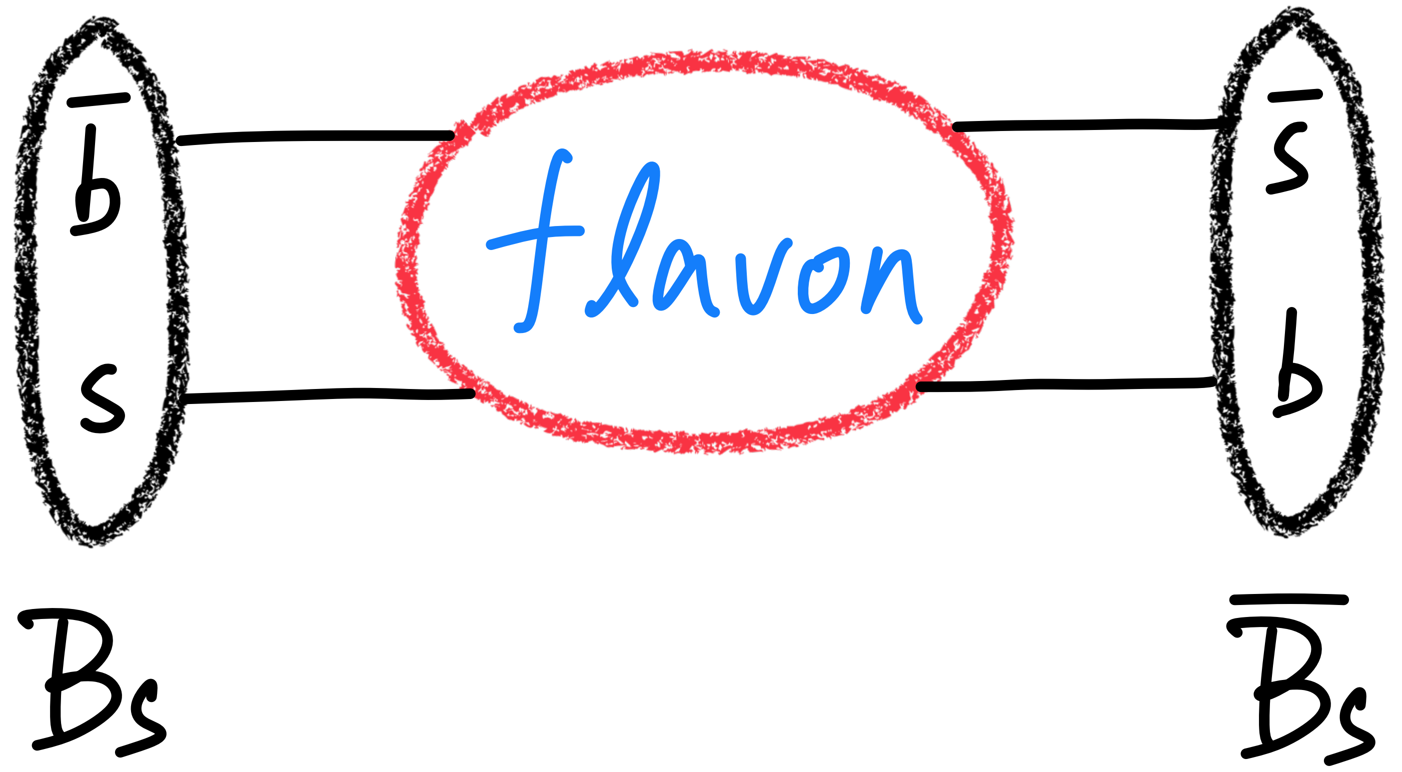
$$\begin{cases} m_s \sim v_\phi \\ 10\,\text{GeV} \leq m_a \ll m_s \end{cases}$$





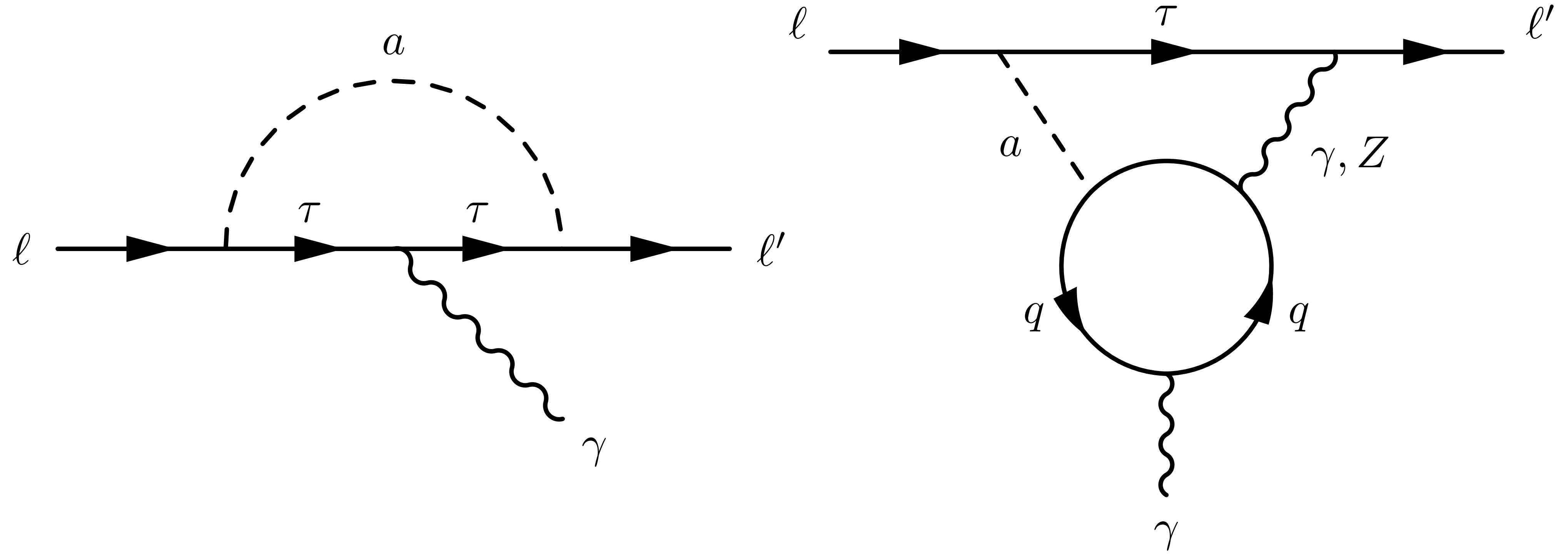
Experimental constraints

B-meson mixing



$$\left(\frac{m_a}{100\,\text{GeV}}\right) \times \left(\frac{v_\phi}{\text{TeV}}\right) > 1.8$$

$\mu \to e\gamma$ (MEG)

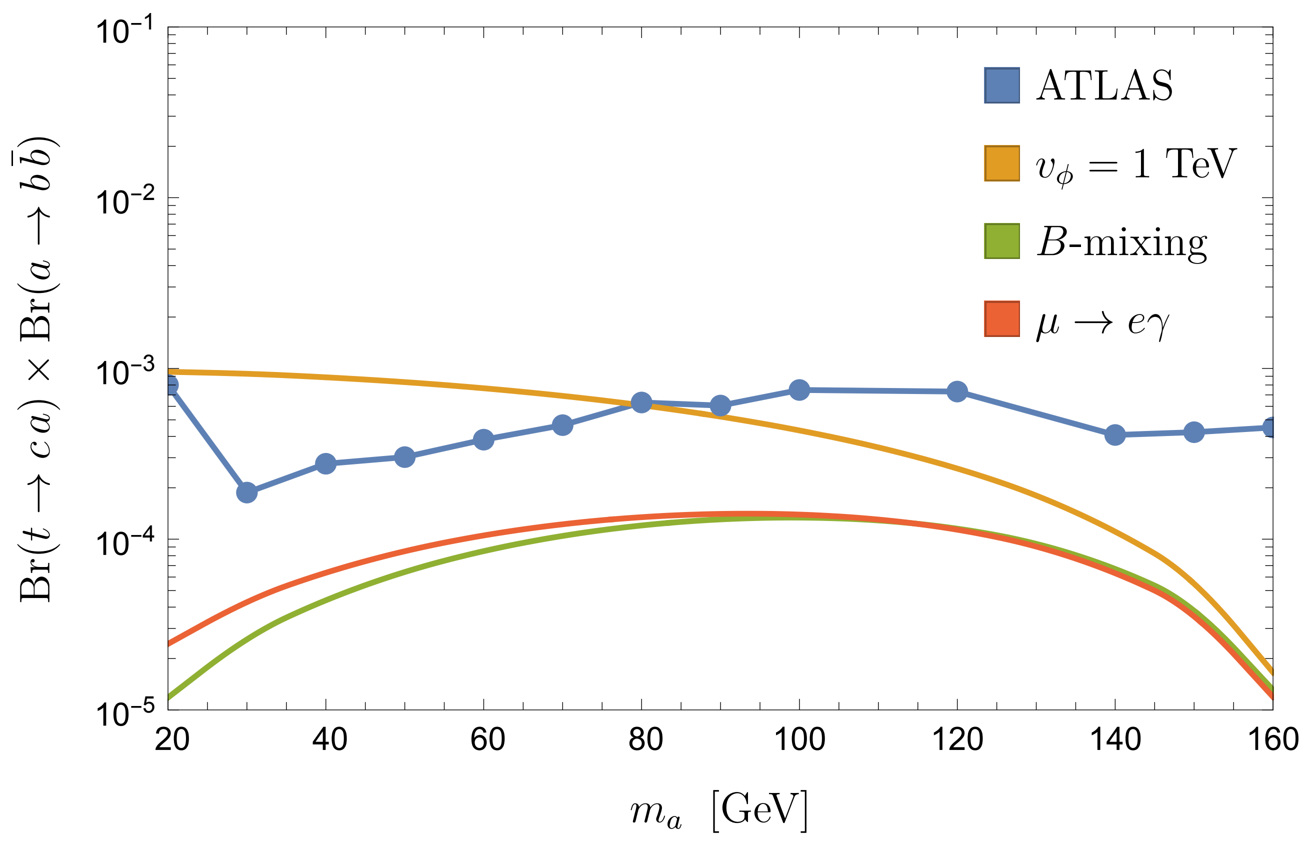


$$\left(\frac{m_a}{100\,\text{GeV}}\right) \times \left(\frac{v_\phi}{\text{TeV}}\right) > 1.9$$

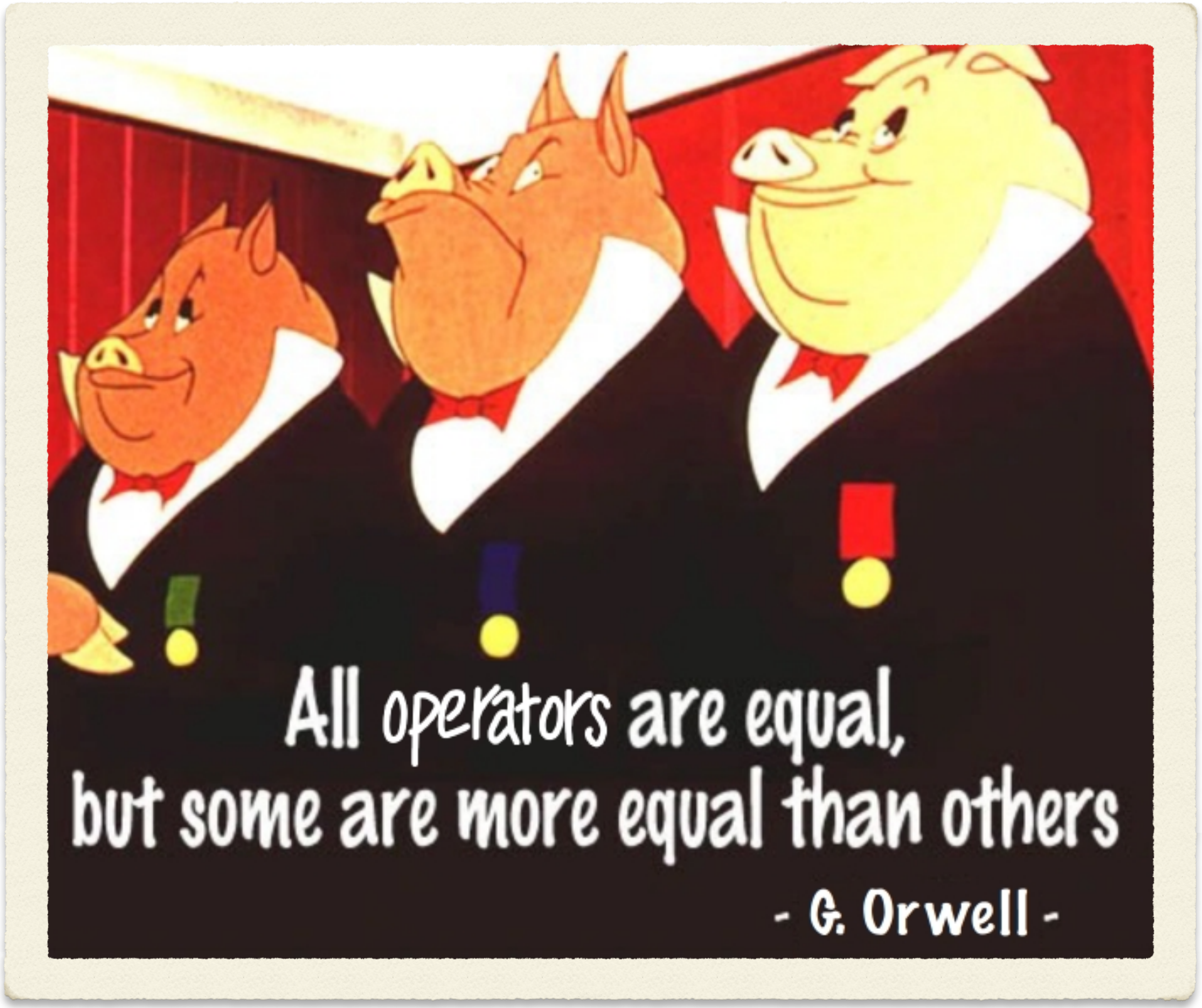
*For $m_a \lesssim 100$ GeV

Top decay ATLAS

$$\text{Br}(t \to c a) \times \text{Br}(a \to b\bar{b})$$



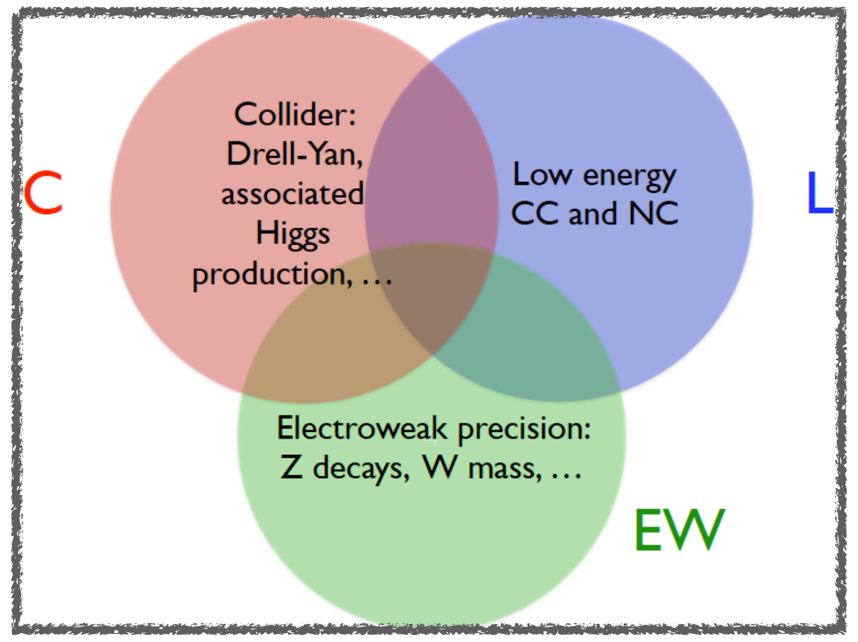
All operators are equal, but...



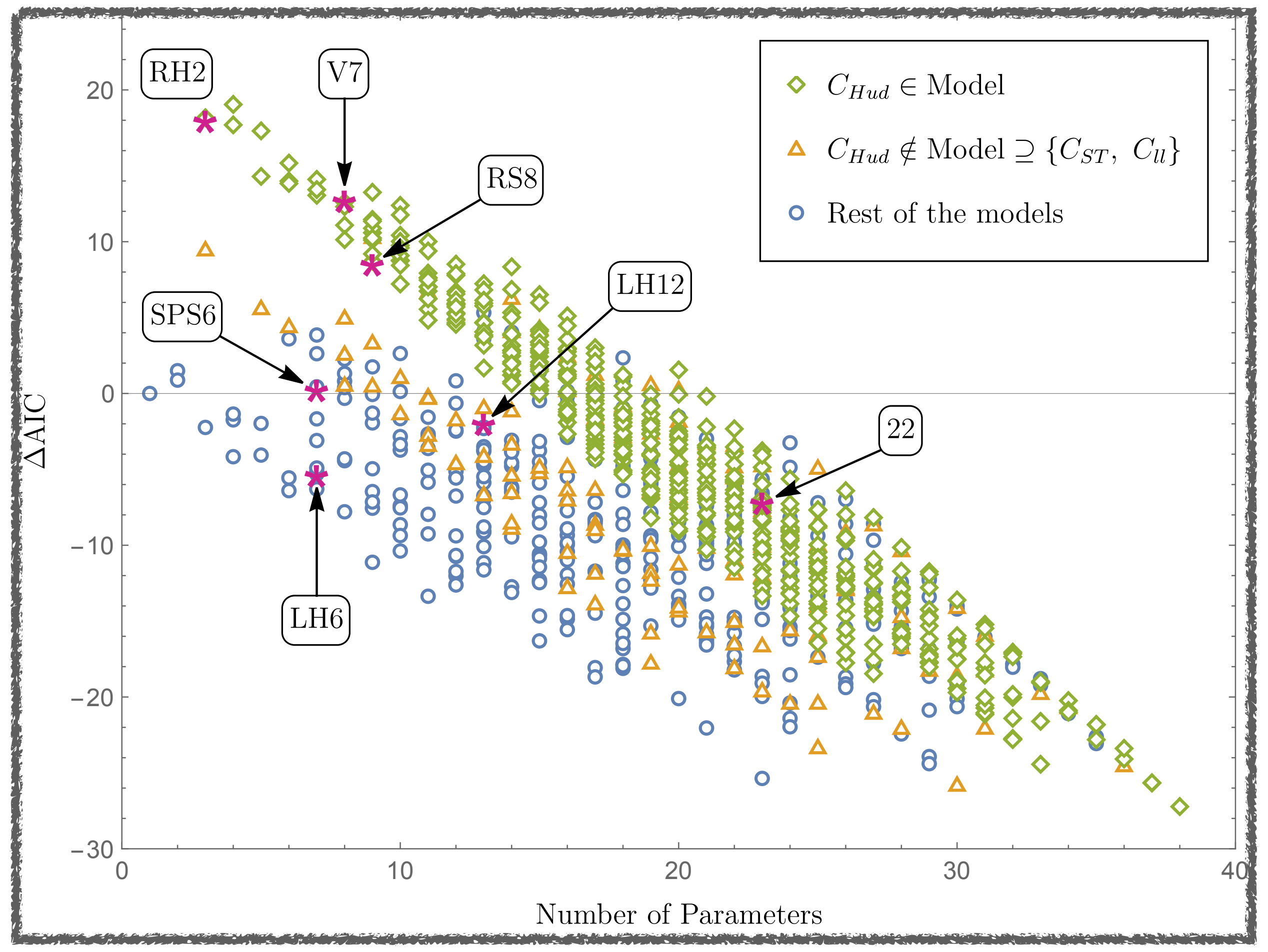
Operators		Low energy CC	EWPO	LHC
H^4D^2				
Q_{HD}	$(H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$	parameter shift (m_Z)		
X^2H^2				
Q_{HWB}	$H^\dagger \tau^I H W^I_{\mu\nu} B^{\mu\nu}$	[illegible]	[illegible]	[illegible]
[illegible]				
[illegible]	[illegible]	✗	✓	✓
[illegible]	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	✓	✓	✓
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	✗	✓	✓
$Q^{(1)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	✗	✓	✓
$Q^{(3)}_{Hq}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	✓	✓	✓
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	✗	✓	✓
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	✗	✓	✓
Q_{Hud} + h.c.	$i(\tilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$	✓	✗	✓
$(\bar{L}L)(\bar{L}L)$				
Q_{ll}	$(\bar{l}_p \gamma^\mu l_r)(\bar{l}_s \gamma_\mu l_t)$	parameter shift ($G_F^{(\mu)}$)		
$Q^{(1)}_{lq}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{q}_s \gamma_\mu q_t)$	✗	✗	✓
$Q^{(3)}_{lq}$	$(\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma_\mu \tau^I q_t)$	✓	✗	✓
$(\bar{L}R)(\bar{R}L)$ + h.c.				
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q_{tj})$	✓	✗	✓
$(\bar{L}R)(\bar{L}R)$ + h.c.				
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\epsilon_{jk}(\bar{q}^k_s u_t)$	✓	✗	✓
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$	✓	✗	✓

With all flavor indices

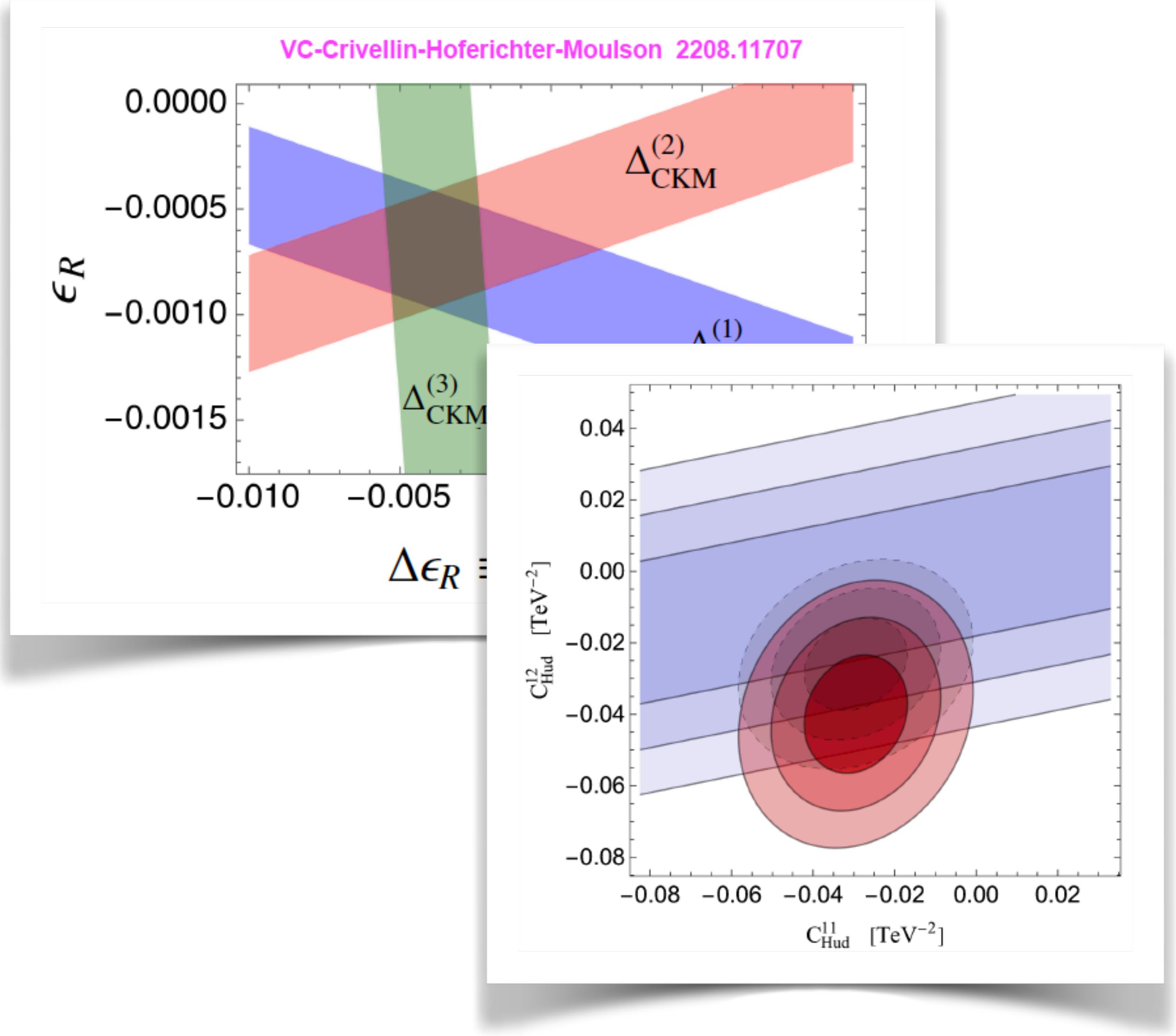
Summary: the CLEW framework



Category	Operators	Description	# of Ops.
I.	C_{ST}	Oblique corrections	1
II.	C_{Hud}	RH charged currents	2
III.	$C_{Hl}^{(1)}$ $C_{Hl}^{(3)}$	LH lepton vertices	6
IV.	C_{He}	RH lepton vertices	3
V.	$C_{Hq}^{(u)}$ $C_{Hq}^{(d)}$	LH quark vertices	5
VI.	C_{Hu} C_{Hd}	RH quark vertices	5
VII.	C_{ll}	Lepton 4-fermion	1
VIII.	$C_{lq}^{(u)}$ $C_{lq}^{(d)}$	Semilepton 4-fermion	6
IX.	C_{ledq} $C_{lequ}^{(1)}$	Scalar 4-fermion	6
X.	$C_{lequ}^{(3)}$	Tensor 4-fermion	2



C_{Hud}



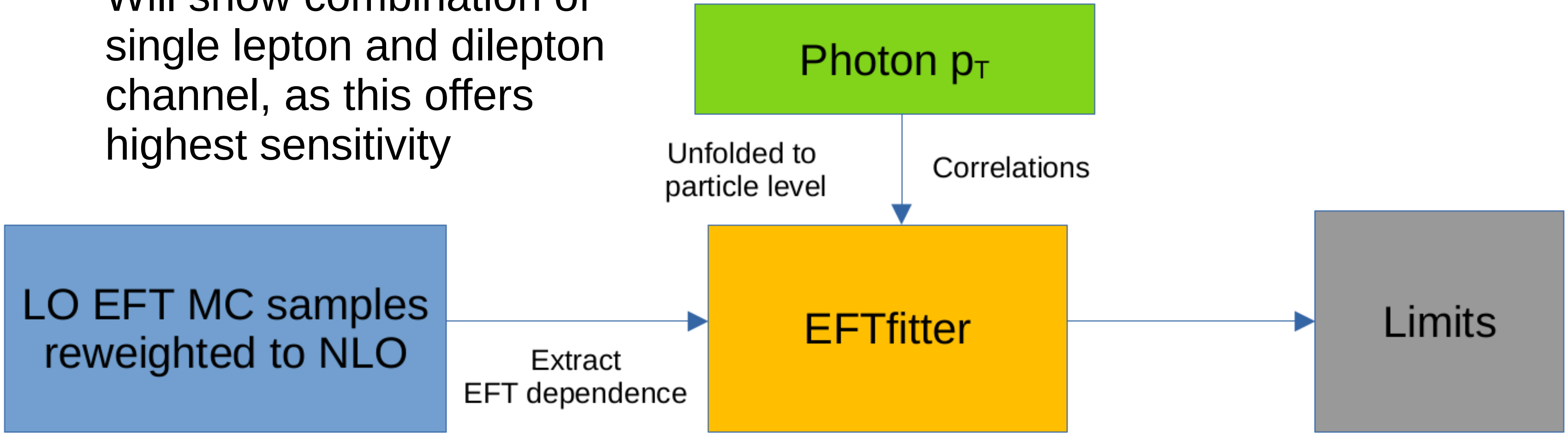
EFT fits

CPPS Retreat, February 2024

Jan Hahn

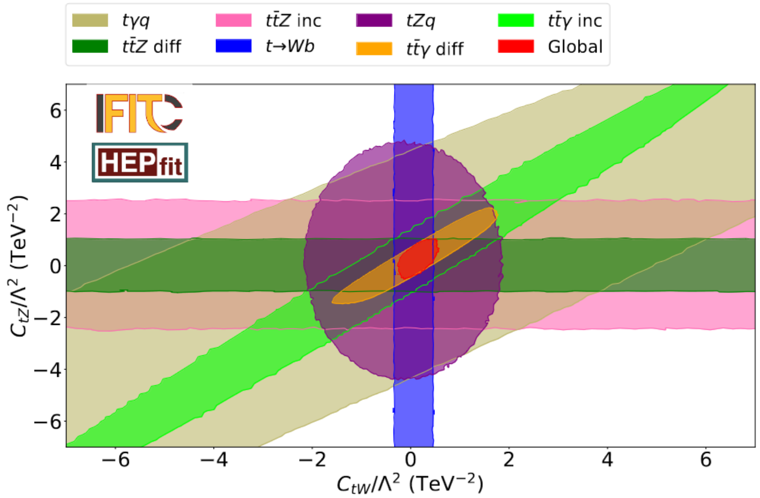
Procedure to extract the limits of EFT parameters

- Procedure to extract the most probable values of the EFT parameters done with Asimov input
  - Photon p_T, uncertainties and correlation between p_T bins from unfolding
  - Parametrisation from EFT samples, scaled to match NLO cross section
  - Will show combination of single lepton and dilepton channel, as this offers highest sensitivity



Combinations of multiple measurement

- Different measurements are sensitive to different operators
- Combine all available measurements to constrain as many operators as possible
- Correlation between different measurements need to be taken into account
  - Some independent (data of different experiments), others highly correlated (e.g. MC generators)
  - Should (partially) be provided by the experiment/group that did the measurement (correlation with uncertainties)
- On the left an example for a combination



Taken from arXiv 2107.13917

Summary

- Many experiments add reinterpretation of their results in terms of EFT to their publications
- Require good prediction of the dependence of the observable with the Wilson coefficient, usually from MC
- Differential measurements offer advantages
  - Parts of phase space may be more sensitive to EFT effects or constrain in different directions
  - More measured points (with well defined correlations)
- In case you want to know more about the ttγ analysis, see us at the poster session

Interface between B meson and top physics observables

Gilberto Tetlalmatzi-Xolocotzi

in collaboration with

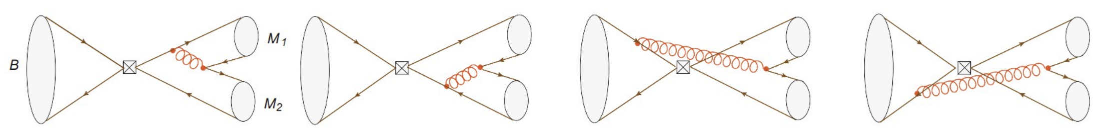
Matthew Kirk,Christoph Englert
and Oliver Atkinson
(work in progress)

The $\bar{B}^0_{(s)} \to D^{(*)+}_{(s)} \{\pi^-, K^-\}$ puzzle

2007.10338 [hep-ph]   (Huber et al.)

Processes such as $\bar{B}^0 \to D^{(*)+} K^-$ and $\bar{B}^0_s \to D_s^{(*)+} \pi^-$ are expected to be extremely clean due to the absence of annihilation topologies

(which in general lead to huge uncertainties, QCDF).



Compare

QCDF predictions

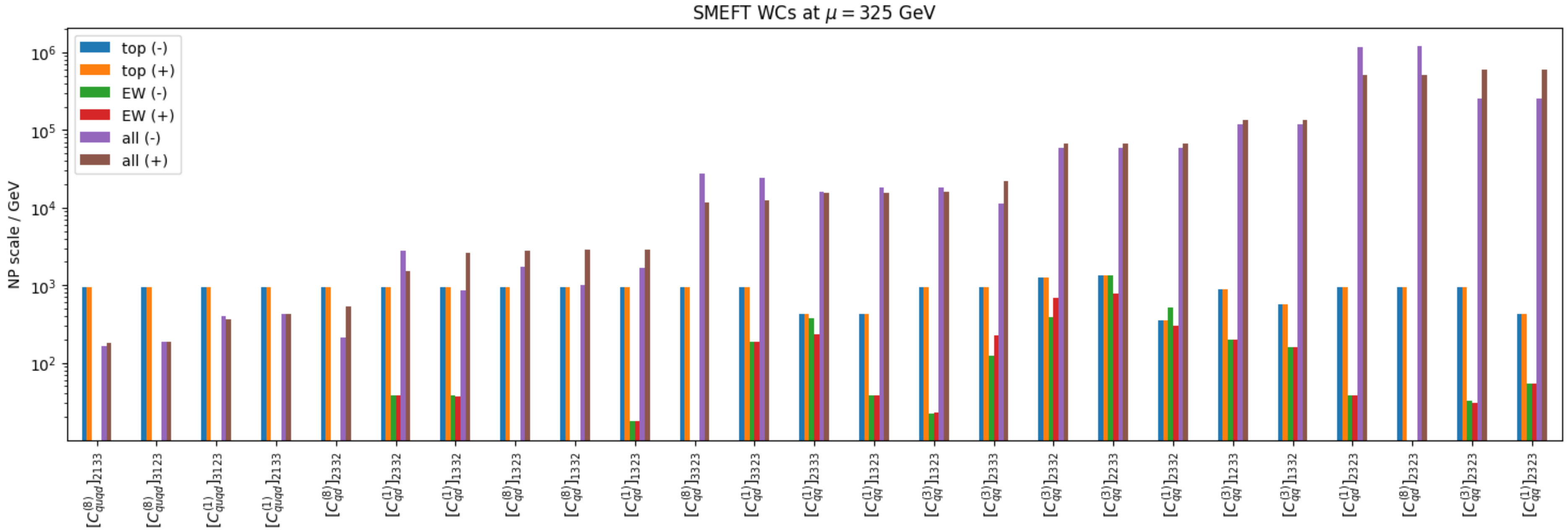
Mode	Theory
$B^- \to \pi^- \bar{K}^0$	$19.3^{+1.9+11.3+1.9+13.2}_{-1.9-\ 7.8-2.1-\ 5.6}$
$B^- \to \pi^0 K^-$	$11.1^{+1.8+5.8+0.9+6.9}_{-1.7-4.0-1.0-3.0}$
$\bar{B}^0 \to \pi^+ K^-$	$16.3^{+2.6+9.6+1.4+11.4}_{-2.3-6.5-1.4-\ 4.8}$
$\bar{B}^0 \to \pi^0 \bar{K}^0$	$7.0^{+0.7+4.7+0.7+5.4}_{-0.7-3.2-0.7-2.3}$
$B^- \to \pi^- \bar{K}^{*0}$	$3.6^{+0.4+1.5+1.2+7.7}_{-0.3-1.4-1.2-2.3}$
$B^- \to \pi^0 K^{*-}$	$3.3^{+1.1+1.0+0.6+4.4}_{-1.0-0.9-0.6-1.4}$
$\bar{B}^0 \to \pi^+ K^{*-}$	$3.3^{+1.4+1.3+0.8+6.2}_{-1.2-1.2-0.8-1.6}$
$\bar{B}^0 \to \pi^0 \bar{K}^{*0}$	$0.7^{+0.1+0.5+0.3+2.6}_{-0.1-0.4-0.3-0.5}$

Arxiv: 0308039 [hep-ph]

$\mathcal{B}(\bar{B}^0_s \to D_s^+ \pi^-)$	10^{-3}	4.42 ± 0.21
$\mathcal{B}(\bar{B}^0_s \to D_s^{*+} \pi^-)$	10^{-3}	$4.30^{+0.9}_{-0.8}$

Arxiv: 2007.10338 [hep-ph]

Combined constraints



“all” refers to the application of all the flavour physics constrains from Smelli

$$C^{\rm SMEFT} \sim \frac{1}{\Lambda^2_{\rm NP}}$$

Flavour structure.

More top observables.

...