The first four years of the CRC

TRR 257 P3H: Particle Physics Phenomenology after the Higgs discovery

KIT Karlsruher Institut für Technologie

RWTH AACHEN UNIVERSITY

UNIVERSITÄT SIEGEN

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

Welcome!

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

This presentation will address the results of the first funding period of the CRC.

- The funding of the Collaborative Research Center has been extended by the DFG for another four years (01/01/2023 - 31/12/2026).
- The goal of this meeting its to reflect on the first four years of the CRC and discuss the new elements of the research program.
- In fact, detailed presentations of new projects is an important part of the meeting.

Welcome!

This presentation will address the results of the first funding period of the CRC.

- Reviewers' comments were very positive, overall.
- However, it was pointed out to us that stronger collaboration between the sites is expected.
- We also need to keep working on improving gender balance.
- It was recommended to create an Advisory Board and staff it with renowned scientists with whom we can consult on strategic questions regarding the CRC development.
- The choice of the next spokesperson (Gudrun) was very strongly commended.

Structure of the CRC

- The Collaborative Research Center is a joint venture of KIT, the University of Aachen, the University of Siegen and Heidelberg University.
- It is the only CRC in Germany devoted to broad phenomenological aspects of particle physics.
- The research interests of the four sites are similar but not identical.
- They include high-precision SM physics (collider (KIT, Aachen, Heidelberg), flavour (Siegen, KIT)), physics beyond the SM, dark matter physics, machine learning (Aachen, Heidelberg, KIT).

Structure of the CRC

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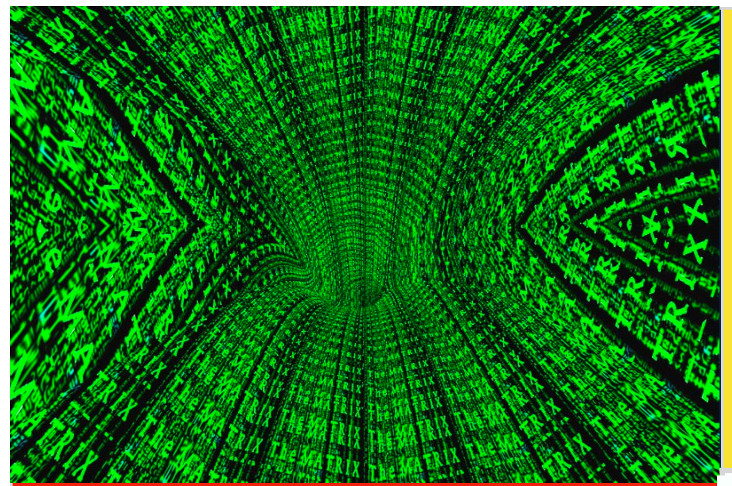
- From the very conception of the CRC, the combination of depth and breadth that the four sites together provide, was considered a very important and attractive aspect of the CRC and its research program.

- The composition of the CRC reflects the fact that already four years ago it was getting clear that expected rapid discoveries of new particles at the LHC will not happen.

- As the result, it was getting important to focus on the development of a "better SM theory" that describes hadron collisions and/or physics of B-mesons, and on the exploration of a landscape of possible BSM physics models, to have a better idea of what we are looking for.

The matrix structure of the Collaborative Research Center



	1: Perturbative QFT	2: Effective Field Theories	3: Explicit BSM models
A: Higgs			
B: Top, QCD, electroweak			
C: Flavour			

Projects of the CRC

Electroweak symmetry breaking

Properties of the Higgs force

The hierarchy problem

Hidden sectors, dark matter

Yukawa sector of the Standard Model

CP-violation

Matter-anti-matter asymmetry

The first funding period: 2019-2022

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Scientists of the Collaborative Research Center produced an impressive number of the highest-quality results during the first funding period.

Constraining flavour patterns of scalar leptoquarks in the effective field theory
Marzia Bordone,[a,b] Oscar Catà,[a] Thorsten Fel…
[a] Theoretische Physik 1, Naturwissenschaftlich-Techn… Walter-Flex-Straße 3, D-57068 Siegen, Germany
[b] Dipartimento di Fisica, Università di Torino & IN…

NNLO QCD corrections to three-photon productio… at the LHC
Herschel A. Chawdhry,[a] Michał Czakon,[b] Alexander Mitov[a] and Rene Poncelet[a]

Non-factorisable contribution to t-channel single-top production
Christian Brønnum-Hansen,[a] Kirill Melnikov,[a] Jérémie Quar… Chiara Signorile-Signorile[a,b] and Chen-Yu Wang[a]

SciPost Phys. 12, 129 (2022)
…integrals with neural networks
…, Vitaly Magerya[4], Emilio Villa[4], Stephen P. Jones[5], …Anja Butter[1,2], Gudrun Heinrich[2,4] and Tilman Plehn[1,2]

PHYSICAL REVIEW D 104, 016003 (2021)
Editors' Suggestion
Third order corrections to the semileptonic $b \to c$ and the muon decays
Matteo Fael, Kay Schönwald, and Matthias Steinhauser

PHYSICAL REVI…
Anomalous cou… …on with Higgs bo… …NLO in QCD
…Kirill Melnikov, and Raoul Rö…

…EFT predictions for $gg \to hh$ at full NLO QCD and truncation uncertainties
Gudrun Heinrich,[a] Jannis Lang[a] and Ludovic Scyboz[b]

Autoencoders for unsupervised anomaly detection in high energy physics
Thorben Finke, Michael Krämer, Alessandro Morandini, Alexander Mück and Ivan Oleksiyuk

…-siegen.de
…Standard Model with… …ed in terms of Frogg… …toquark. we find esse…

Higgs-pair production via gluon fusi… colliders: NLO QCD correction…
Julien Baglio,[a] Francisco Campanari… Jonathan Ronca,[b] Michael Spi…
[a] Theoretical Physics Depart…

PHYSICAL REVIEW LETTERS 127, 152…
Next-to-Next-to-Leading Order Study of Three-Jet…
…eitner,[c]
Institut für Theoretische Teilchenphysik un… Alexan…

Tasting flavoured Majorana dark matter
Harun Acaroğlu[a] and Monika Blanke[a,b]

On phase-space integrals with Heaviside functions
Daniel Baranowski,[a] Maximilian Delto,[a,b] Kirill Melnikov[a] and Chen-Yu Wang[a]

O new physics, where art thou? A global search in the top sector
Ilaria Brivio,[a] Sebastian Bruggisser,[a] Fabio Maltoni,[b,c] Rhea Moutafis,[a,d] Tilman Plehn,[a] Eleni Vryonidou,[e] Susanne Westhoff[a] and Cen Zhang[f]

PHYSICAL REVIEW LETTERS 127, 16200…
Exact Top-Quark Mass Dependence in Hadronic H…
M. Czakon, R. V. Harlander, J. Klappert, and M. N…

…-scale long-lived pa…
…rasco Mejia, Felix Kahlhoefer, Michael Krämer and

Higher Order Corrections to Spin Correlations in Top Quark Pair Production at the LHC
Arnd Behring
Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen University, D-52056 Aachen, Germany and Institute for Theoretical Particle Physics, KIT, D-76128 Karlsruhe, Germany
Michał Czakon
Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen University, D-52056 Aachen, Germany
Alexander Mitov and Rene Poncelet
Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, United Kingdom
Andrew S. Papanastasiou
Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, United King… and MRC Institute of Genetics and Molecular Medicine, University of Edinb… Crewe Road, Edinburgh EH4 2XU, United Kingdom

Computer Physics Communications
Volume 266, September 2021, 108024
…duction with Kira 2.0 and finite field methods
…abian Lange, Philipp Maierhöfer, Johann Usovitsch

Towards ruling out the charged Higgs interpretation of the $R_{D^{(*)}}$ anomaly
Monika Blanke,[a,b] Syuhei Iguro[a,b] a…
[a] Institute for Theoretical Particle Physi… Engesserstraße 7, 76131 Karlsruhe, Ge…
[b] Institute for Astroparticle Physics (IA… Hermann-von-Helmholtz-Platz 1, 7634…
E-mail: monika.blanke@kit.edu, … hantian.zhang@kit.edu
ABSTRACT: Motivated by the notor… $R_{D^{(*)}}$, we study the sensitivity of the… Higgs boson H^- lighter than 400 GeV… of current constraints from the B_c –… di-jet searches at the LHC allows t… low-mass charged Higgs. In this co…

$t\bar{t}b\bar{b}$ at the LHC: on the size of corrections and b-jet definitions
Giuseppe Bevilacqua,[a] Huan-Yu Bi,[b] Heribertus Bayu Hartanto,[c] Manfred Kraus,[d] Michele Lupattelli[b] and Malgorzata Worek[b]

SU(3) breaking effects in B and D meson lifetimes
Daniel King,[a] Alexander Lenz[b] and Thomas Rauh[c]
[a] IPPP, Department of Physics, University of Durham,

PHYSICAL REVIEW LETTERS…
Nonfactorizable QCD Effects in Higgs Boson Produ…on via Vector Boson Fus…
Tao Liu,[1,*] Kirill Melnikov,[2,†] and Alexander A. Penin[1,2,3,‡]

Recurring themes

- Perturbative computations at high orders in pQCD/SM which contribute to the development of a better theory of hadron collisions at the LHC and of heavy flavour physics.

- Studies of validity, applicability and practicality of effective field theories as an agnostic tool to analyse potential effects of physics beyond the Standard Model at the LHC.

- Use of global fits with inputs that range from cosmology and astro-particle physics to collider and flavour physics.

- Development of novel technical tools (from understanding Feynman integrals to machine learning methods, to global fitting programs) is an omnipresent topic.

Project A1a: Quark-mass effects in Higgs-boson production in gluon fusion

Principal investigators: Czakon, Harlander

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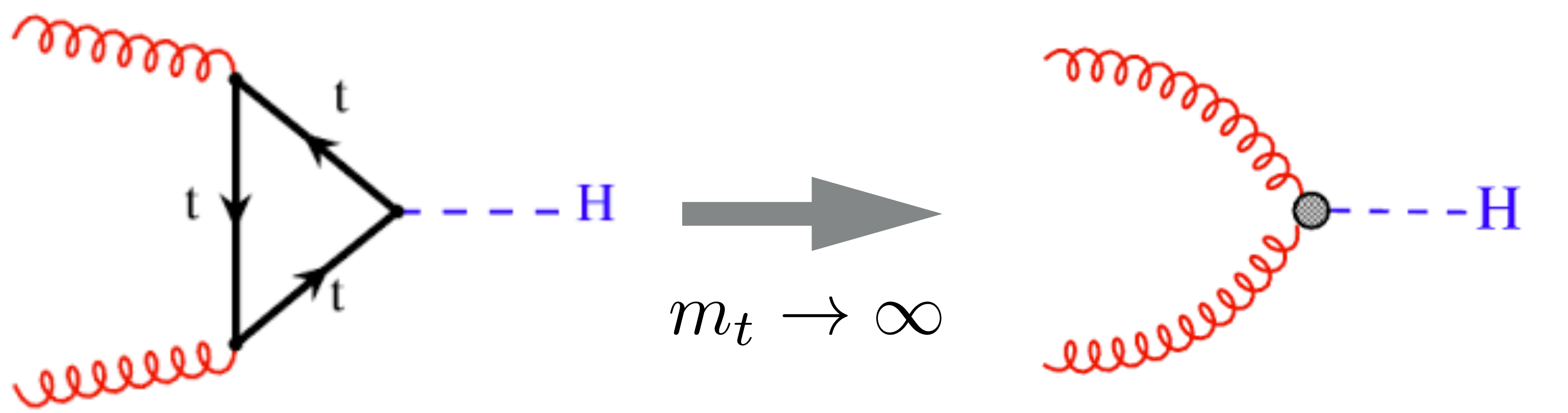
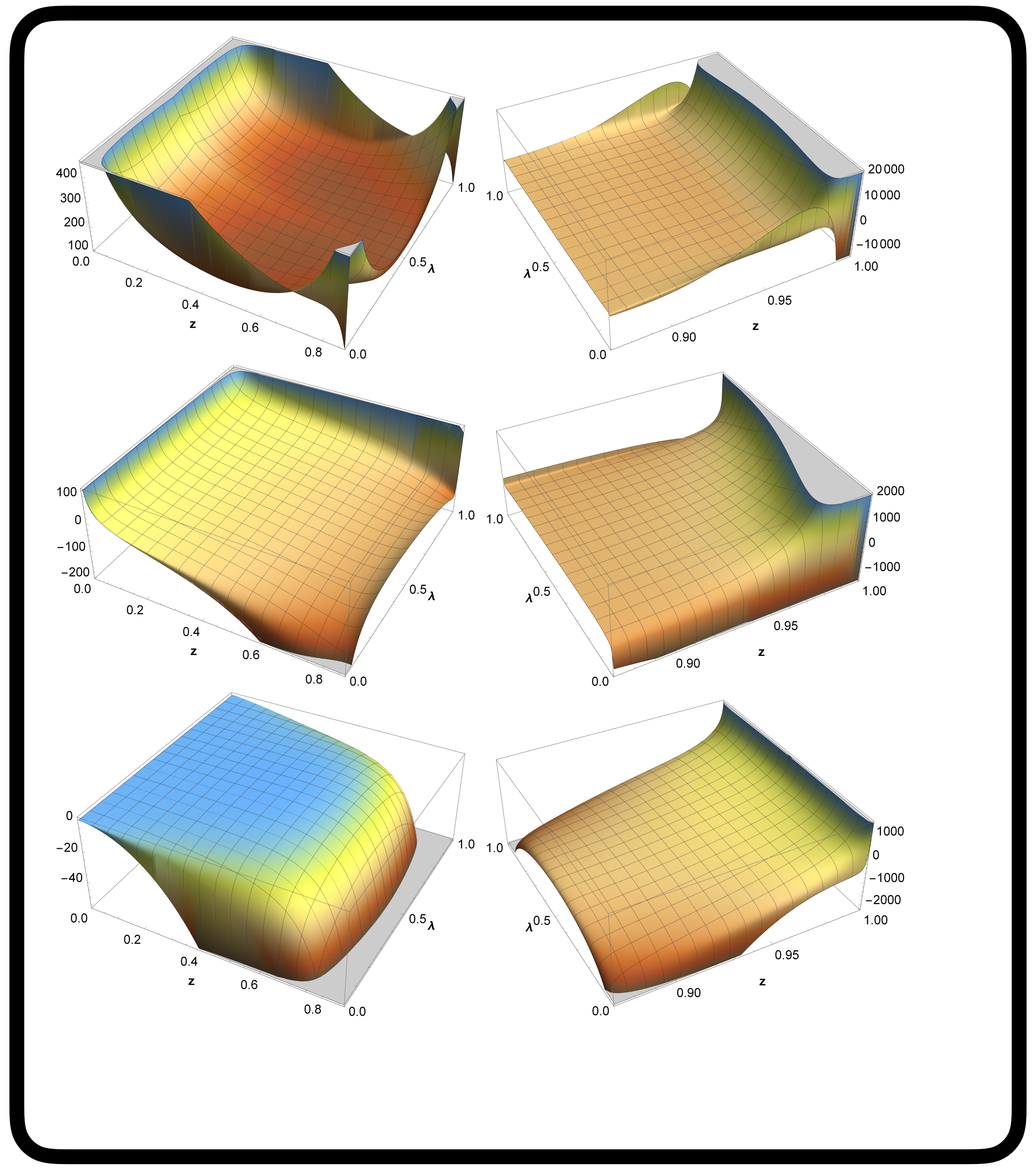


$$\sigma = 48.58\ \text{pb}^{+2.22\ \text{pb}(+4.56\%)}_{-3.27\ \text{pb}(-6.72\%)}(\text{theory}) \pm 1.56\ \text{pb}\ (3.20\%)(\text{PDF} + \alpha_s)$$

Anastasiou et al.

....

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t, b, c)$	$\delta(1/m_t)$
+0.10 pb −1.15 pb	±0.18 pb	±0.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
+0.21% −2.37%	±0.37%	±1.16%	±1%	±0.83%	±1%

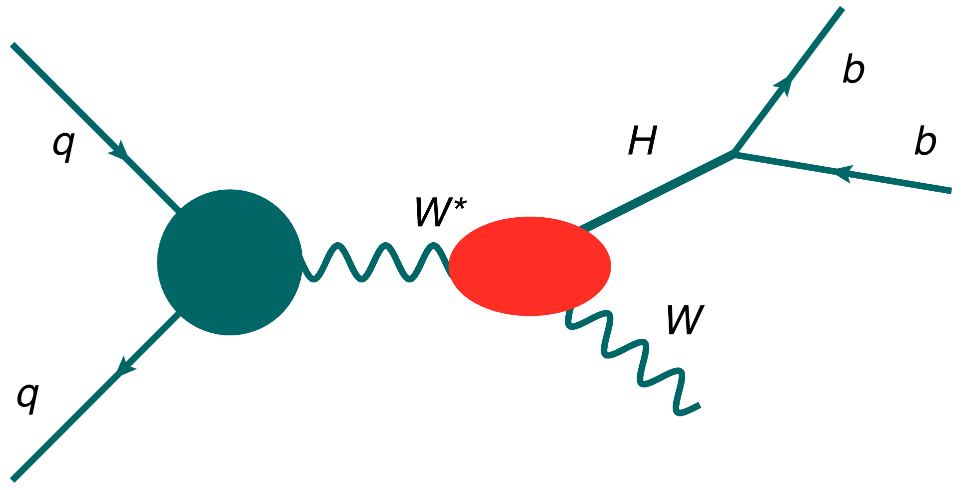


channel	$\sigma^{\text{NNLO}}_{\text{HEFT}}$ [pb] $\mathcal{O}(\alpha_s^2)+\mathcal{O}(\alpha_s^3)+\mathcal{O}(\alpha_s^4)$	$(\sigma^{\text{NNLO}}_{\text{exact}} - \sigma^{\text{NNLO}}_{\text{HEFT}})$ [pb] $\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$(\sigma^{\text{NNLO}}_{\text{exact}}/\sigma^{\text{NNLO}}_{\text{HEFT}} - 1)$ [%]
	$\sqrt{s} = 8$ TeV			
gg	7.39 + 8.58 + 3.88	+0.0353	+0.0879 ± 0.0005	+0.62
qg	0.55 + 0.26	−0.1397	−0.0021 ± 0.0005	−18
qq	0.01 + 0.04	+0.0171	−0.0191 ± 0.0002	−4
total	7.39 + 9.15 + 4.18	−0.0873	+0.0667 ± 0.0007	−0.10
	$\sqrt{s} = 13$ TeV			
gg	16.30 + 19.64 + 8.76	+0.0345	+0.2431 ± 0.0020	+0.62
qg	1.49 + 0.84	−0.3696	−0.0115 ± 0.0010	−16
qq	0.02 + 0.10	+0.0322	−0.0501 ± 0.0006	−15
total	16.30 + 21.15 + 9.79	−0.3029	+0.1815 ± 0.0023	−0.26

Czakon, Harlander, Klappet, Niggetiedt

Project A1b: Higgs boson physics with higher order corrections and anomalous couplings

Principal investigators: Harlander*, Melnikov, Heinrich**



$$\mathcal{L}_{\rm anom} = -\frac{1}{4\Lambda} g^{(1)}_{hzz} Z_{\mu\nu} Z^{\mu\nu} h - \frac{1}{2\Lambda} g^{(1)}_{hww} W^{\mu\nu} W^{\dagger}_{\mu\nu} h - \frac{1}{\Lambda} g^{(2)}_{hzz} Z_{\nu} \partial_{\mu} Z^{\mu\nu} h - \frac{1}{\Lambda}\left[g^{(2)}_{hww} W^{\nu} \partial^{\mu} W^{\dagger}_{\mu\nu} h + {\rm h.c.}\right] - \frac{1}{4\Lambda} \tilde{g}_{hzz} Z_{\mu\nu} \tilde{Z}^{\mu\nu} h - \frac{1}{2\Lambda} \tilde{g}_{hww} W^{\mu\nu} \tilde{W}^{\dagger}_{\mu\nu} h \,.$$

Setup 1: $g^{(1)}_{hww} = -1.20\,, \quad g^{(2)}_{hww} = -0.25\,, \quad \tilde{g}_{hww} = +0.00\,,$

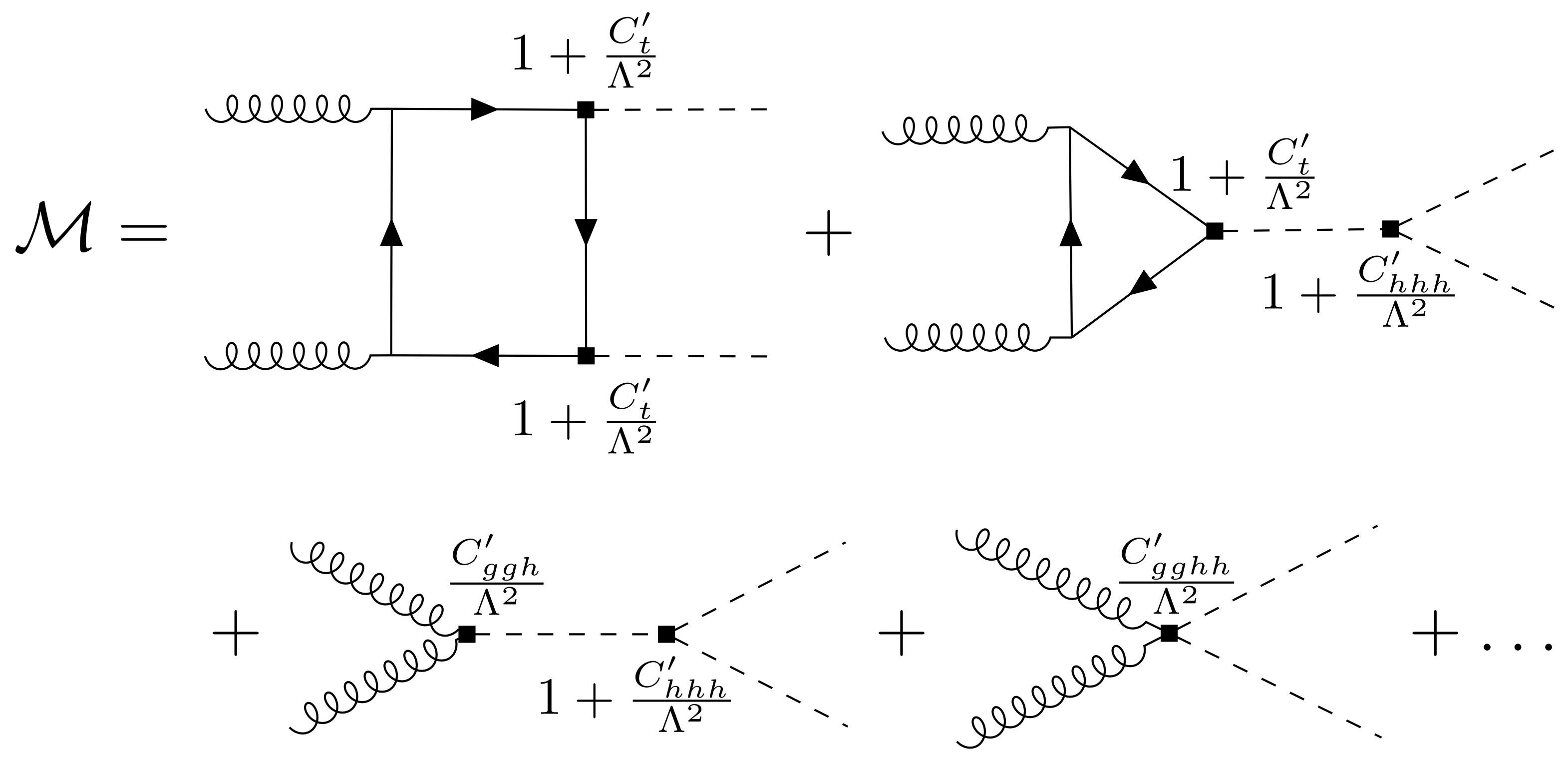
Setup 2: $g^{(1)}_{hww} = +1.00\,, \quad g^{(2)}_{hww} = +0.00\,, \quad \tilde{g}_{hww} = +0.80\,,$

Setup 3: $g^{(1)}_{hww} = +0.00\,, \quad g^{(2)}_{hww} = -0.10\,, \quad \tilde{g}_{hww} = -1.10\,,$

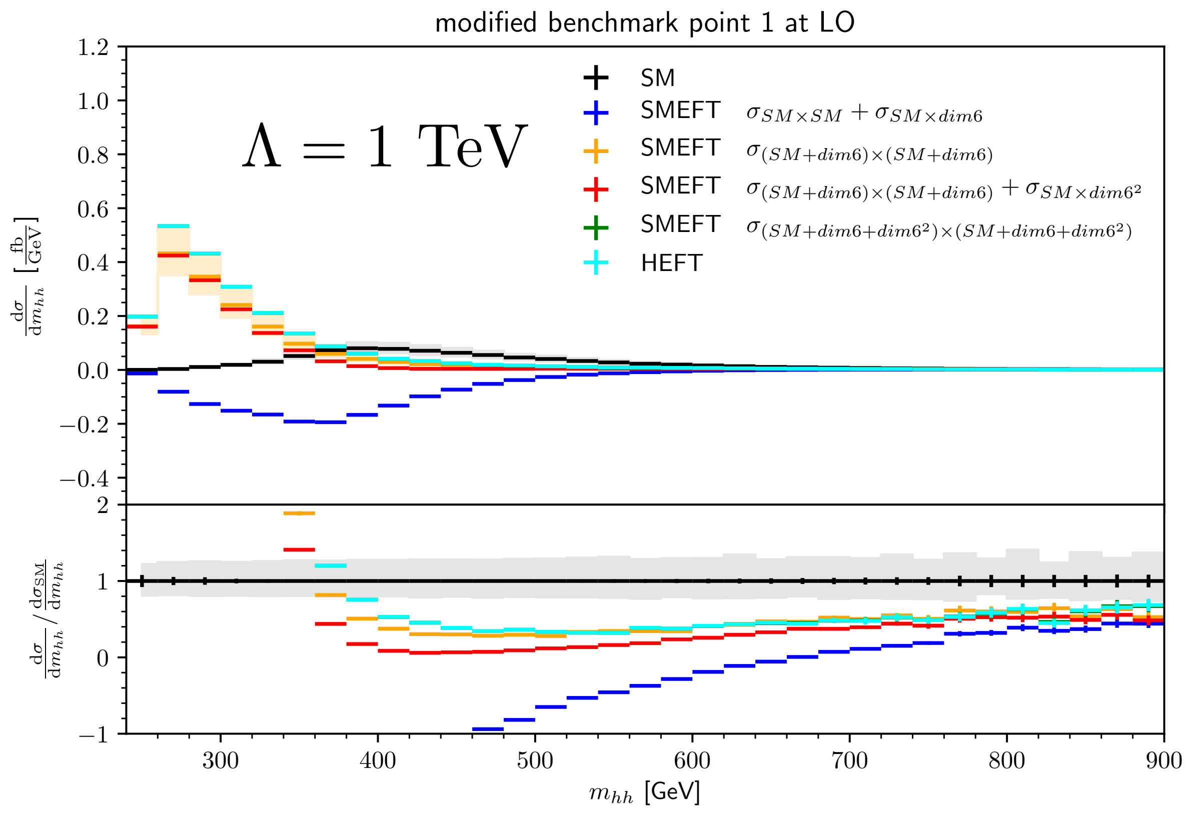
Setup 4: $g^{(1)}_{hww} = +0.70\,, \quad g^{(2)}_{hww} = -0.05\,, \quad \tilde{g}_{hww} = -1.05\,.$

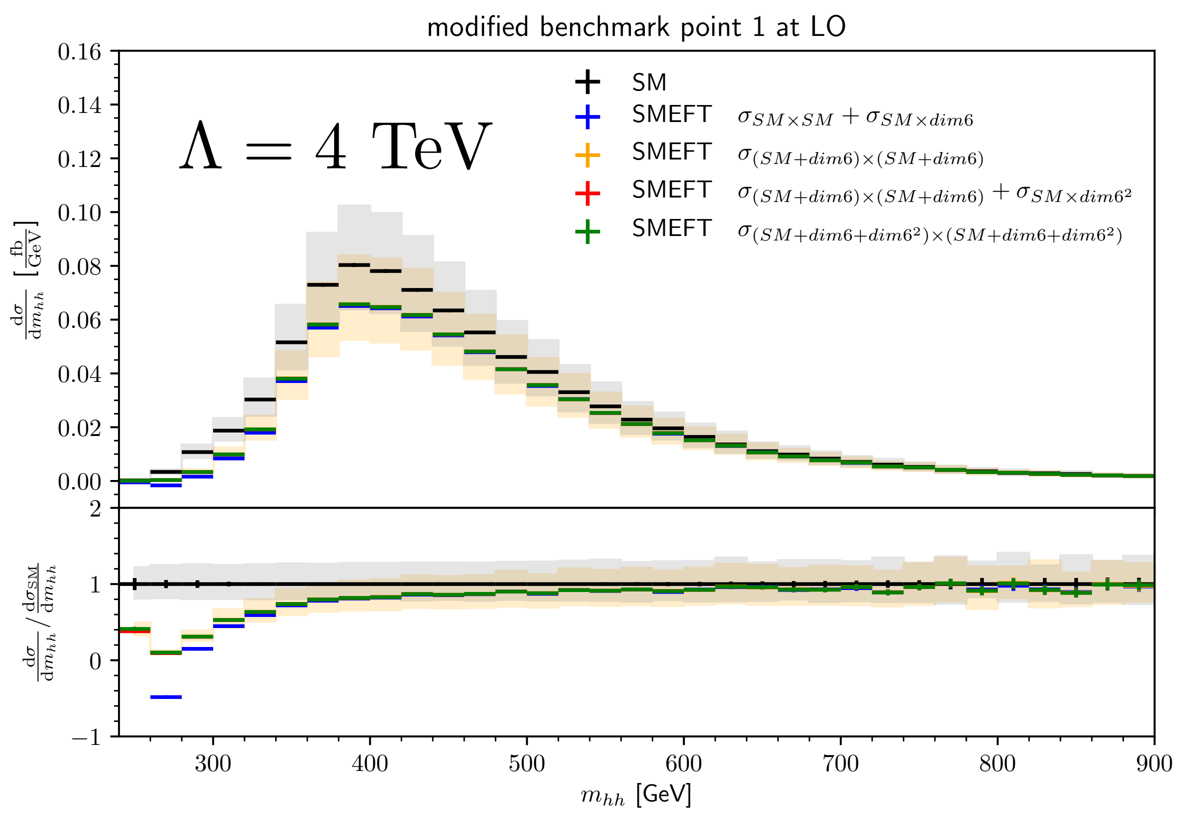
$\sigma^{W^+H}_{\rm fid}$ [fb]	SM	Setup 1	Setup 2	Setup 3	Setup 4
LO	$2.813^{+0.023}_{-0.039}$	$2.657^{+0.012}_{-0.024}$	$2.999^{+0.007}_{-0.021}$	$2.898^{+0.012}_{-0.026}$	$2.958^{+0.007}_{-0.021}$
NLO	$3.434^{+0.089}_{-0.064}$	$3.419^{+0.110}_{-0.080}$	$3.466^{+0.070}_{-0.048}$	$3.501^{+0.088}_{-0.063}$	$3.458^{+0.074}_{-0.052}$
NNLO	$3.409^{+0.024}_{-0.025}$	$3.436^{+0.028}_{-0.034}$	$3.387^{+0.004}_{-0.015}$	$3.463^{+0.015}_{-0.031}$	$3.390^{+0.003}_{-0.018}$

Bizon, Caola, Melnikov, Rontsch



$$= \mathcal{M}_{\rm SM} + \mathcal{M}_{\rm dim6} + \mathcal{M}_{\rm dim6^2}\;,$$





Heinrich, Lang, Scyboz

Project A1c: Higher order QCD corrections to Higgs boson production in weak boson fusion

Principal investigator: Melnikov

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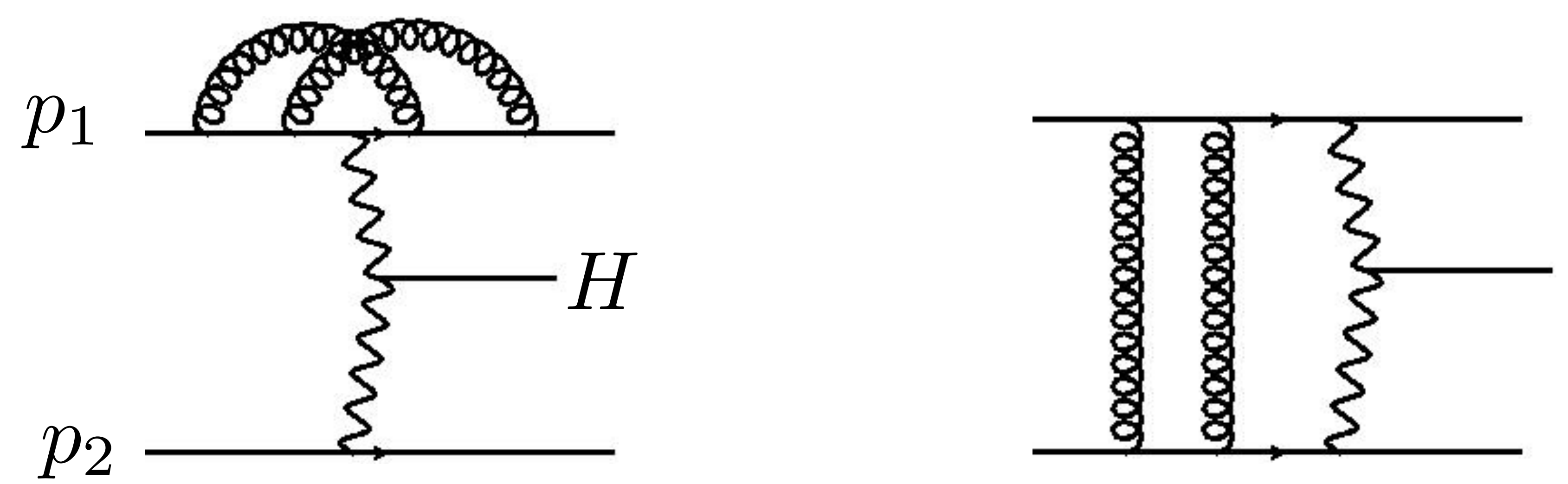
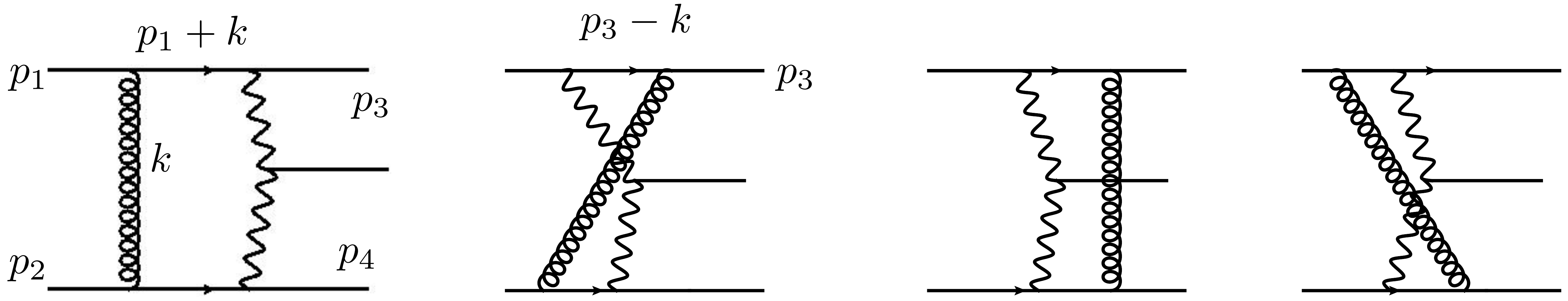


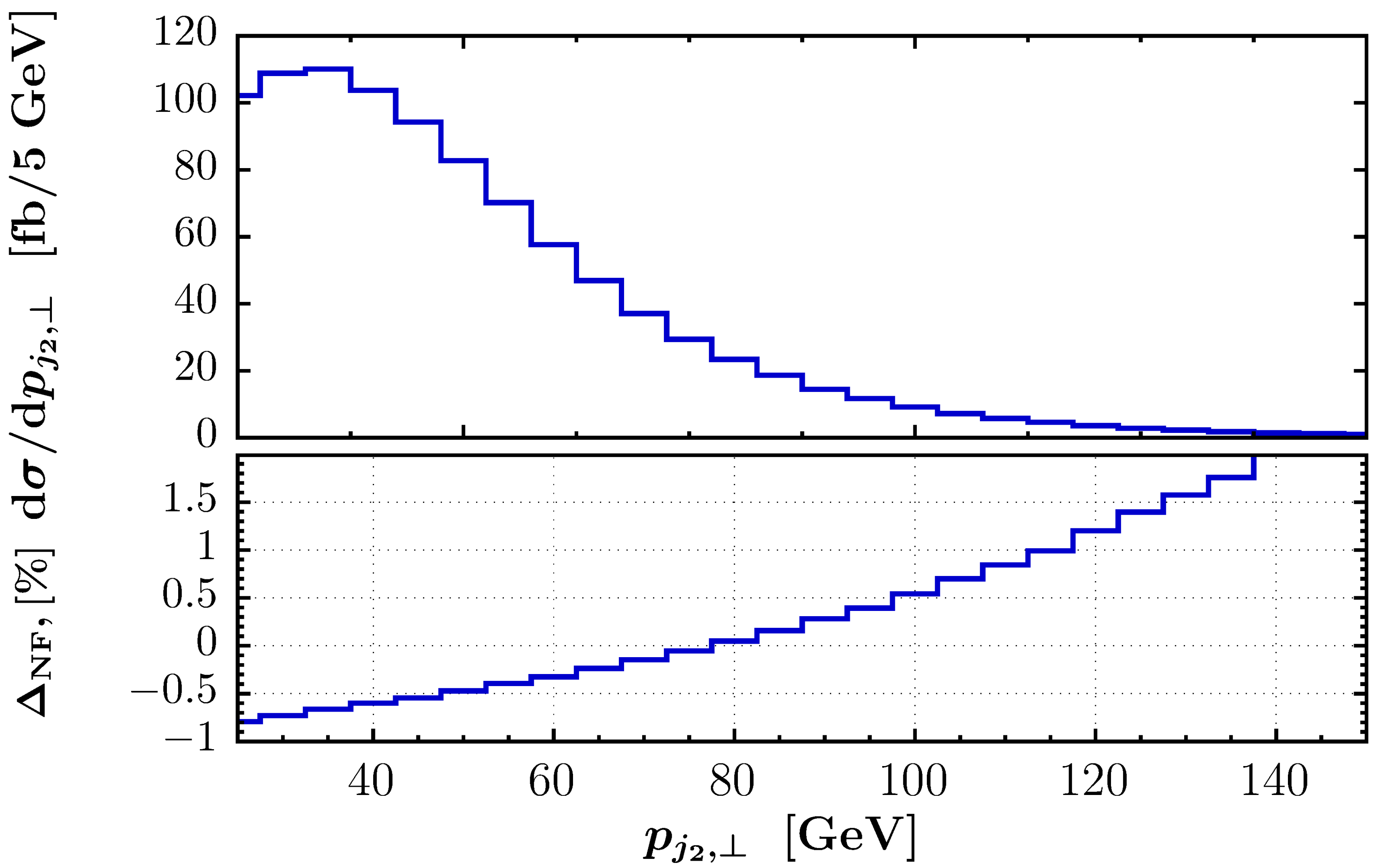
Example of factorizable and non-factorizable corrections. Non-factorizable contributions are color suppressed. Are there any enhancement mechanisms?



$$\int \frac{d^4k}{(2\pi)^4}\,\frac{1}{k_\perp^2}\,\frac{1}{(k_\perp - q_{3,\perp})^2 + M_V^2}\,\frac{1}{(k_\perp + q_{4,\perp})^2 + M_V^2}\left[\frac{1}{2p_1k + i0} + \frac{1}{-2p_3k + i0}\right]\left[\frac{1}{-2p_2k + i0} + \frac{1}{2p_4k + i0}\right]$$

The leading term in the expansion around the forward limit is remarkably simple.

Melnikov, Penin



Transverse momentum distribution of the second hardest jet

$$\lim_{p_3 \to p_1}\left[\frac{1}{2p_1k + i0} - \frac{1}{-2p_3k + i0}\right] = -\frac{2i\pi}{s}\delta(\beta)$$

$$k = \alpha p_1 + \beta p_2 + k_\perp$$

$$p_\perp^{j_1,j_2} > 25 \text{ GeV}, \quad |y_{j_1,j)2}| < 4.5$$
$$|y_{j_1} - y_{j_2}| > 4.5, \quad m_{j_1j_2} > 600 \text{ GeV}$$

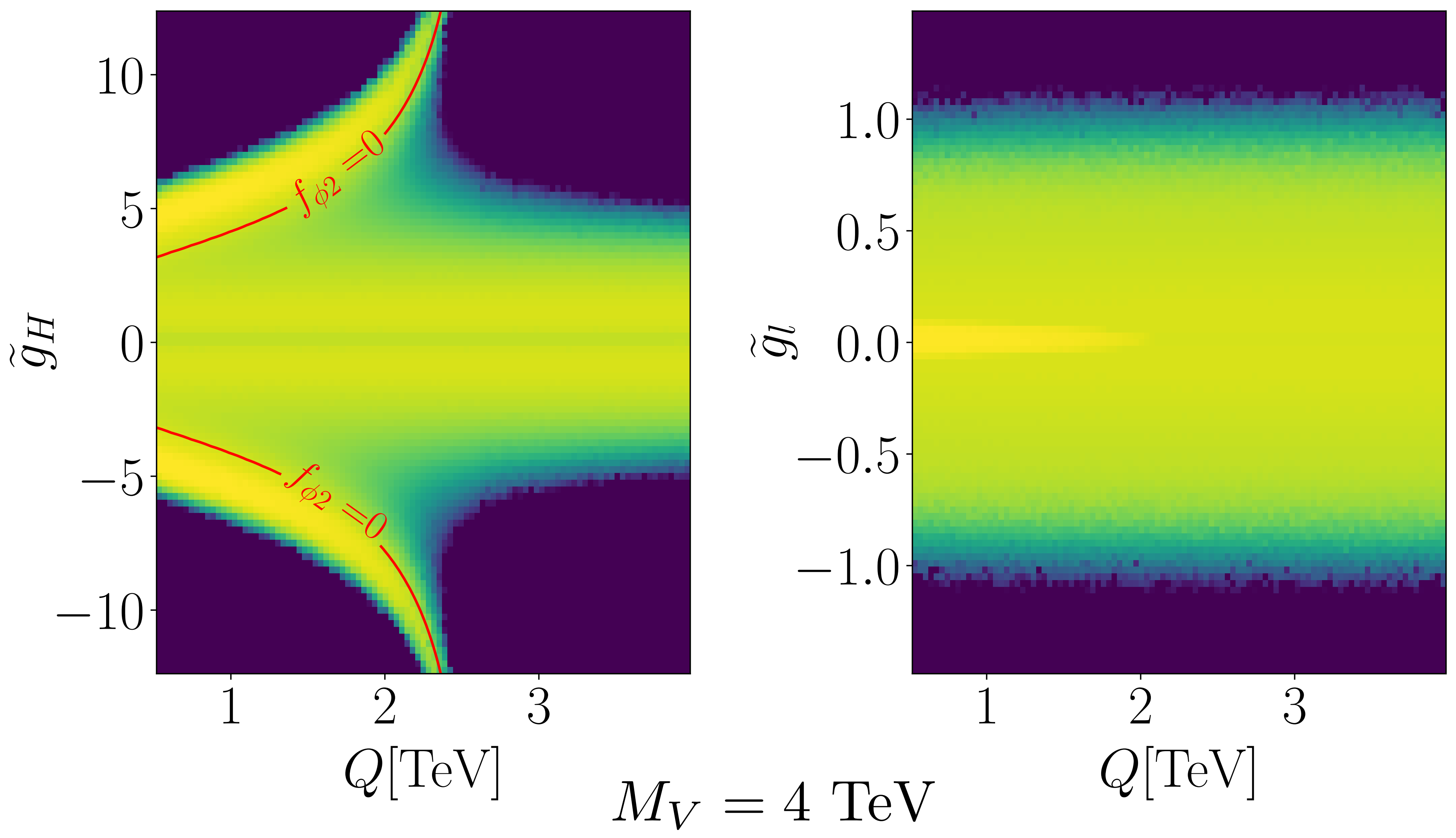
Project A2a: The effective electroweak Lagrangian in the light of the LHC

Principal investigators: Krämer, Plehn, Killian**

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

The goal: explore practicalities of using SMEFT to analyse the LHC data.

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\widetilde{V}^{\mu\nu A}\widetilde{V}^{A}_{\mu\nu} - \frac{\tilde{g}_M}{2}\,\widetilde{V}^{\mu\nu A}\widetilde{W}^{A}_{\mu\nu} + \frac{\tilde{m}_V^2}{2}\widetilde{V}^{\mu A}\widetilde{V}^{A}_{\mu} + \sum_f \tilde{g}_f\,\widetilde{V}^{\mu A}J^{fA}_{\mu} + \tilde{g}_H\,\widetilde{V}^{\mu A}J^{HA}_{\mu} + \frac{\tilde{g}_{VH}}{2}\,|\phi|^2\widetilde{V}^{\mu A}\widetilde{V}^{A}_{\mu}\,,$$



Impact of the matching scale variation on the allowed/excluded regions for the couplings

- SFITTER in action
- One-loop matching
- Precision EW observables
- WH and WW production
- Direct WW resonance search

Significant impact of the matching scale on the interpretation of SMEFT analysis.

Important role of precision EW observables.

Complementarity of resonance searches and shape fits.

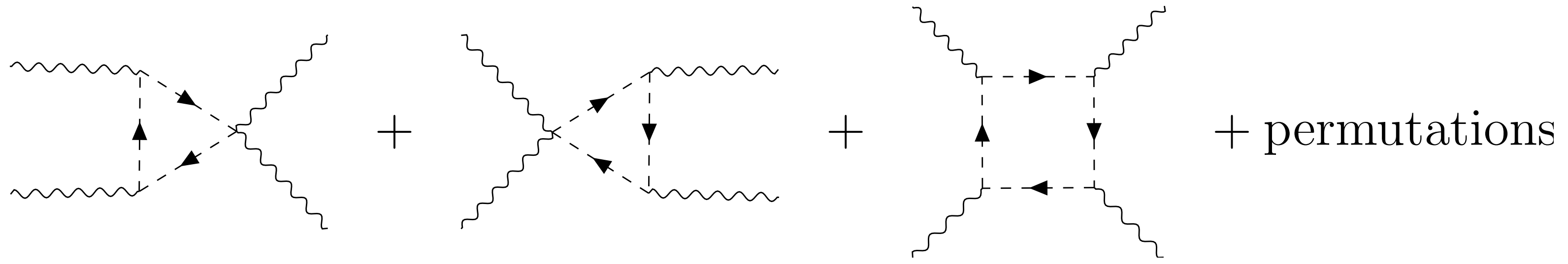
Brivio, Bruggisser, Geoffray, Kilian, Krämer, Luchmann, Plehn, Summ

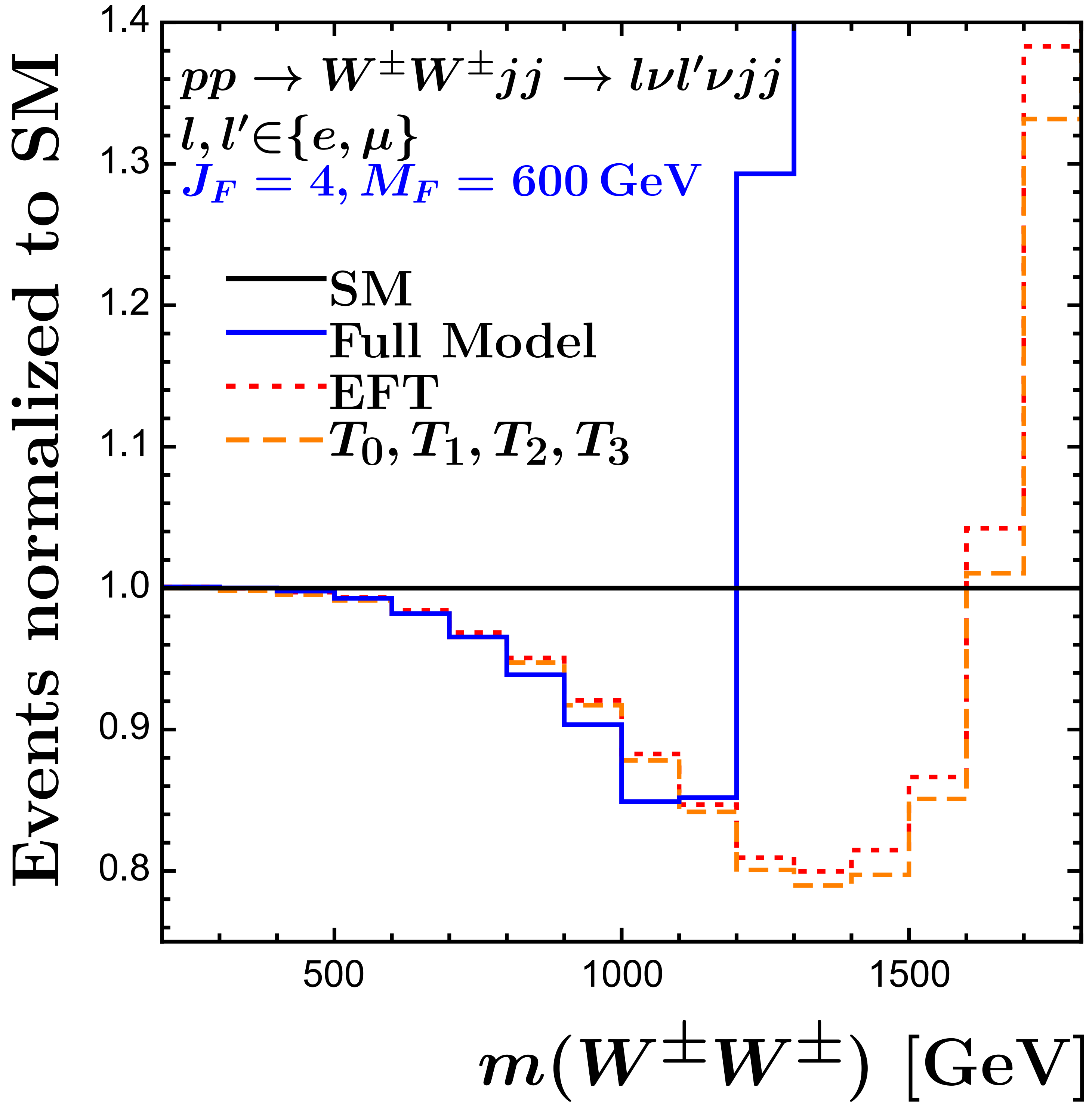
Project A2b: (Vector-boson scattering and) multi-boson physics at the LHC

Principal investigators: Killian, Zeppenfeld*, Butter**, Heinrich**

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu H\right)^2 - \frac{m_H^2}{2} H^2 - \frac{1}{2}\mathrm{Tr}\left(\hat{W}^{\mu\nu}\hat{W}_{\mu\nu}\right) + \frac{m_W^2}{2}\left(\sum_{a=1}^{3} W_\mu^a W^{a\mu}\right)\left(1 + \frac{H}{v}\right)^2$$
$$+ \bar{\Psi}\left(i\gamma_\mu D^\mu - M_F\right)\Psi + (D^\mu\Phi)^\dagger(D_\mu\Phi) - {M_S}^2\Phi^\dagger\Phi\,.$$



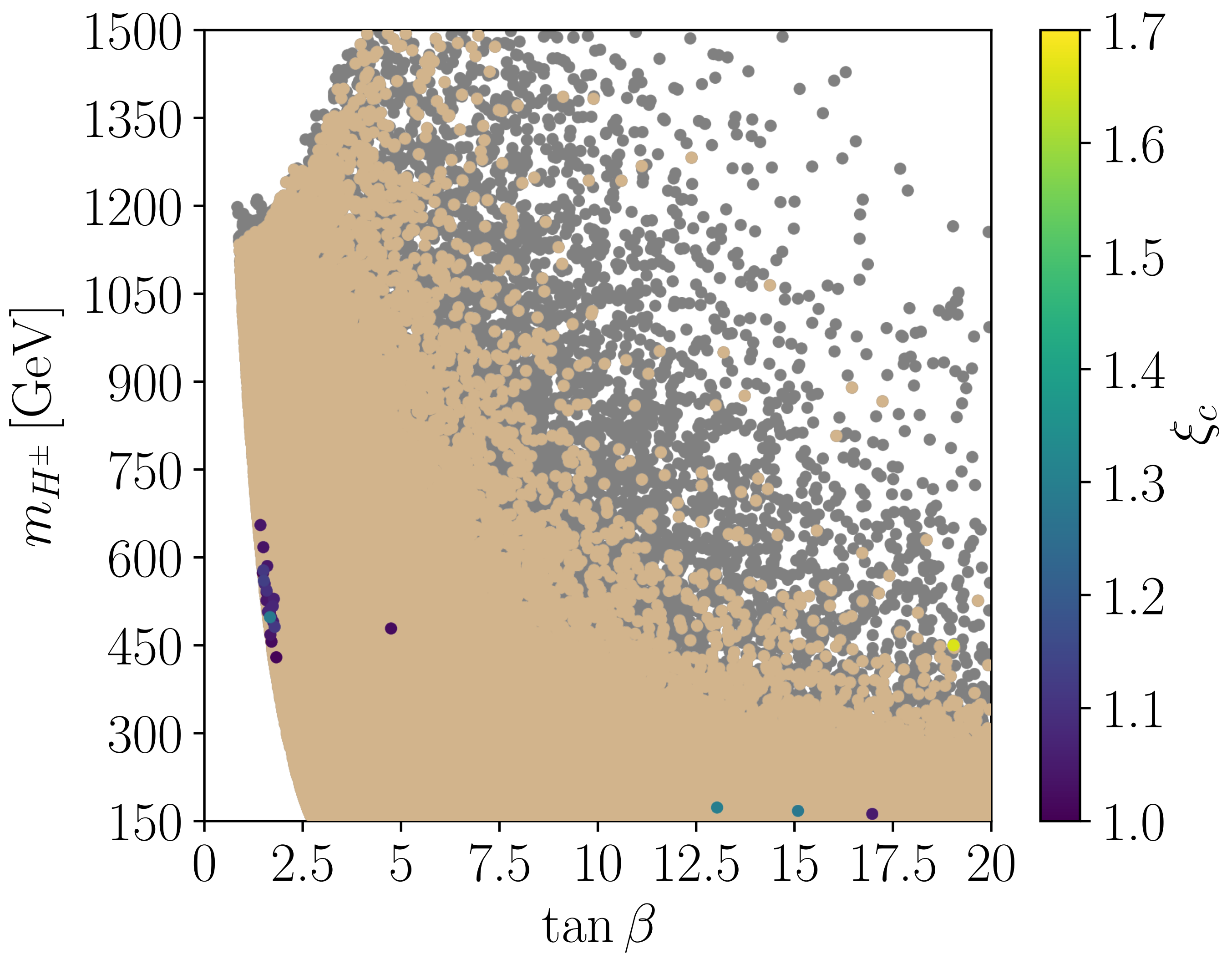


Lang, Liebler, Schäfer-Siebert, Zeppenfeld

- In the second funding period, the project will change significantly.
- It will become more focused on the technical aspects of simulations for multi-particle final states with the idea to use advances in machine learning for optimization.
- Are there machine-learning alternatives to good old Vegas?
- Can one use machine-learning ideology to sample amplitudes across multi-dimensional phase-spaces?
- Phenomenology: better description of VBS within and beyond the SM.

Project A3a: Extended Higgs sectors at the LHC

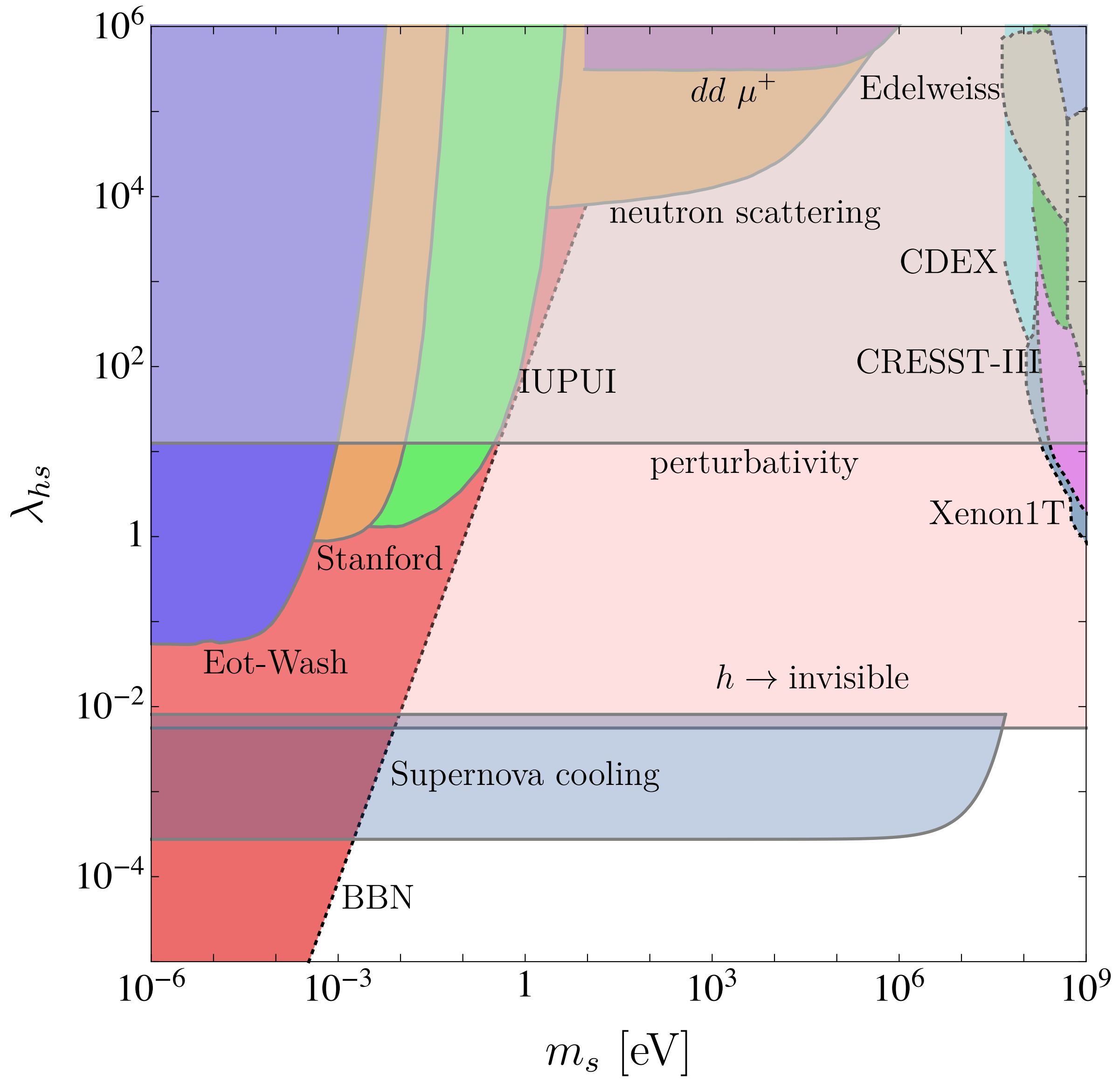
Principal investigators: Mühlleitner, Plehn



$$V_{\rm C2HDM} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)^2 + \left[\frac{\lambda_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2\right) + h.c.\right],$$

Higgs production constraints, flavour constraints, requirement of a stable EW vacuum, existence of strong first-order EW phase transition, the CKM matrix.

Basler, Mühlleitner, Müller



$$\mathcal{L} \supset \frac{1}{2}\partial_\mu s \partial^\mu s - \frac{1}{2}m_s^2 s^2 - \frac{1}{4!}\lambda_s s^4 . \qquad \mathcal{L} \supset -\frac{1}{2}\lambda_{hs}\, s^2\, H^\dagger H .$$

Direct detection, BBN, supernova, invisible Higgs decays, “macroscopic” forces.

Bauer, Foldenauer, Plehn

Project A3b: Precision predictions for Higgs boson properties as a probe for New Physics

Principal investigators: Mühlleitner, Steinhauser

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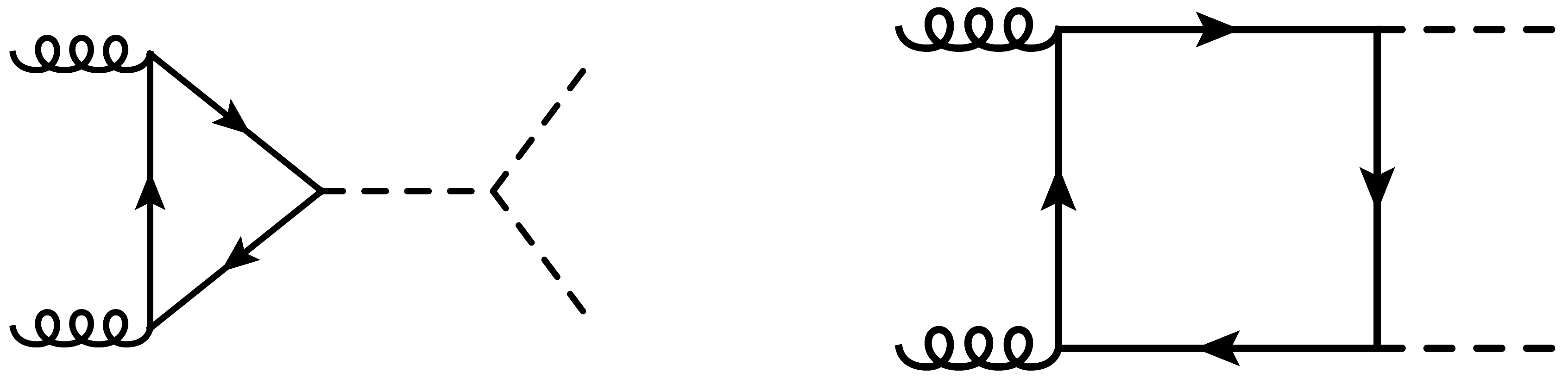
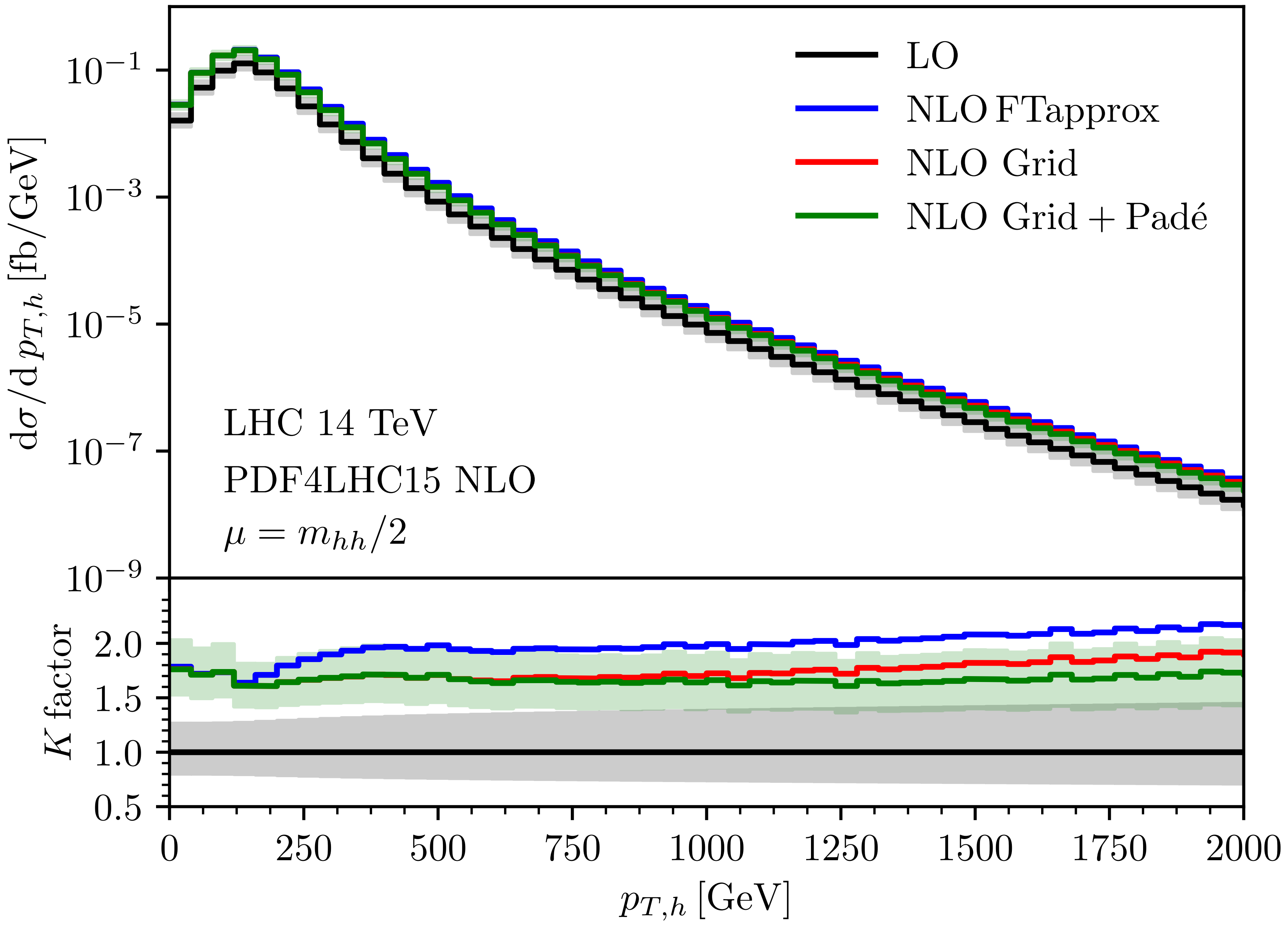
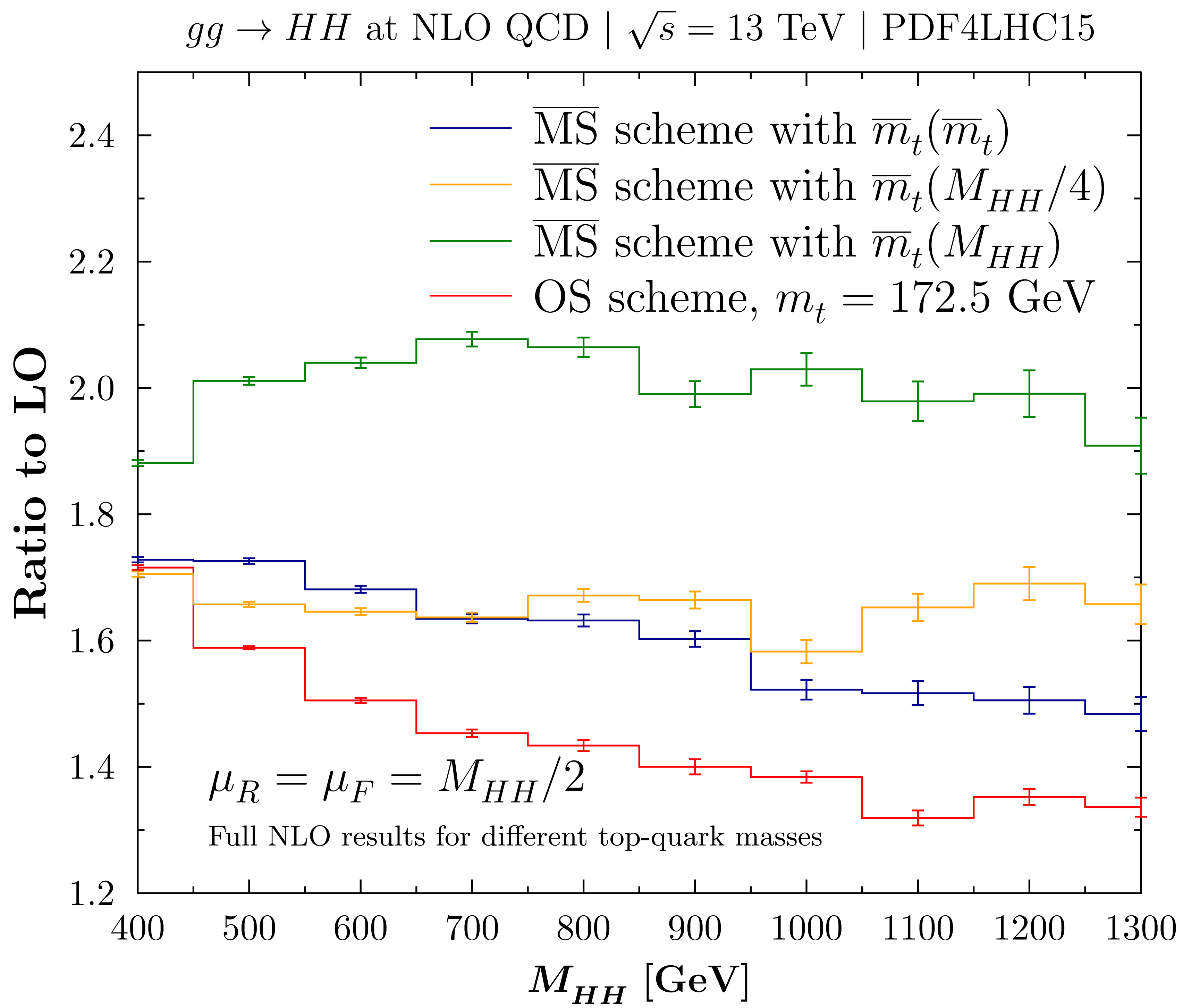


Kinematic expansions, generic numerical loop integration, "dedicated" numerical loop integration.



Davies, Heinrich, Jones, Kerner, Mishima, Steinhauser, Wellmann



Strong sensitivity to the choice of the top-quark mass renormalization scheme.

Baglio, Companario, Glaus, Mühlleitner, Ronca, Spira

Project B1a: N3LO QCD corrections to color-singlet production at the LHC

Principal investigators: Bell,Czakon, Melnikov**

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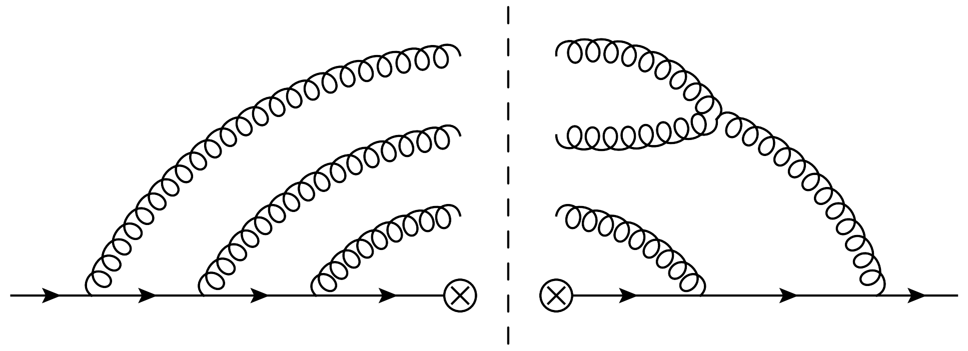
$$\mathcal{T} = \sum_j \min_{i\in\{1,2\}} \left[\frac{2p_i\cdot k_j}{Q_i}\right]$$



$$I_N(t,z) \sim \int\limits_{i=1}^{N} [\mathrm{d}k_i]\delta(s(1-z) - \sum_{i=1}^{N} 2p_2\cdot k_i)\delta(t - z\sum_{i=1}^{N} 2p_1\cdot k_i)P_{\text{split}}(z_1, z_2, ..)$$

Calculation of beam function(s) at N3LO QCD an axial gauge.

Behring, Baranowsky, Tancredi, Wever, K.M..

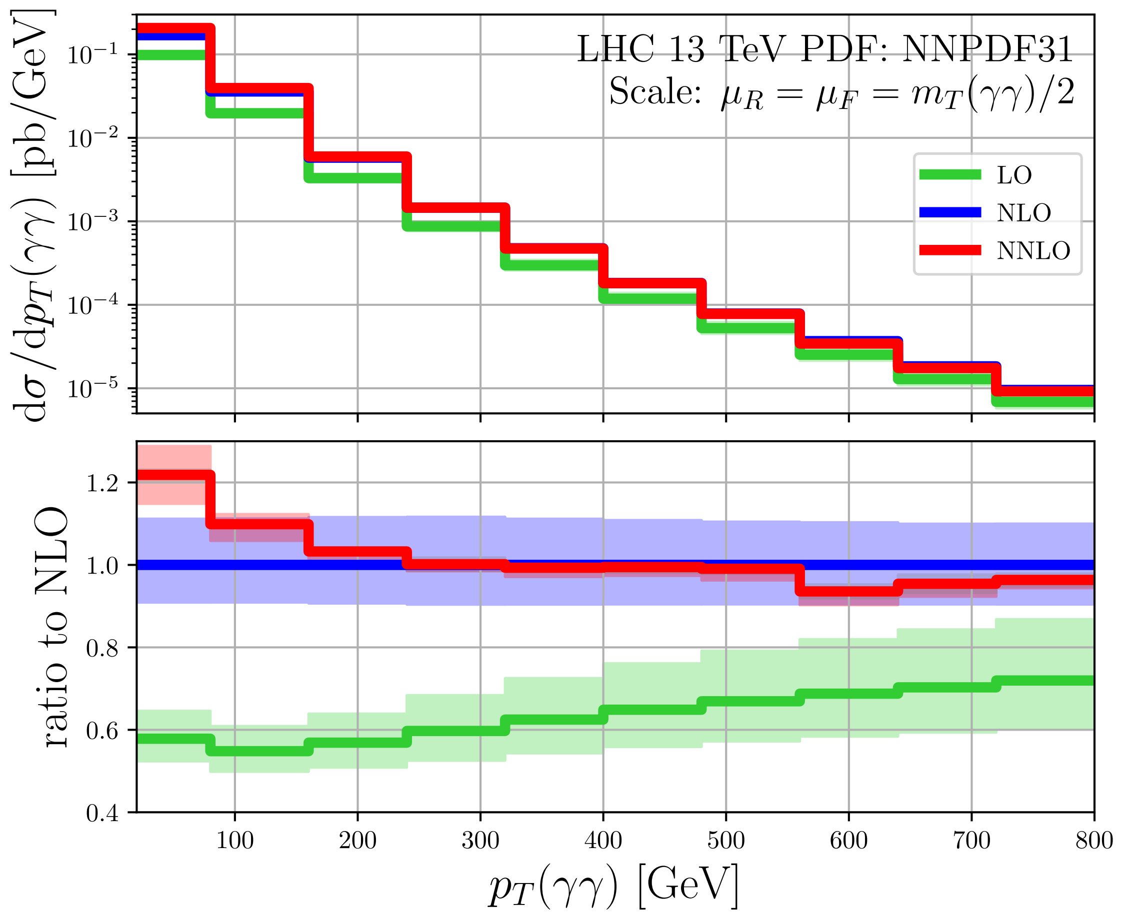
$$S_{RRR}(\tau) = \int \prod_{i=1}^{3} \frac{\mathrm{d}^d k_i}{(2\pi)^d}\,\delta(k_i^2)\,\delta(\mathcal{T}-\tau)\,\mathrm{Eik}(\{k_i\},p_1,p_2)$$

$$k_i = \alpha_i p_1 + \beta_i p_2 + k_{i,\perp}$$

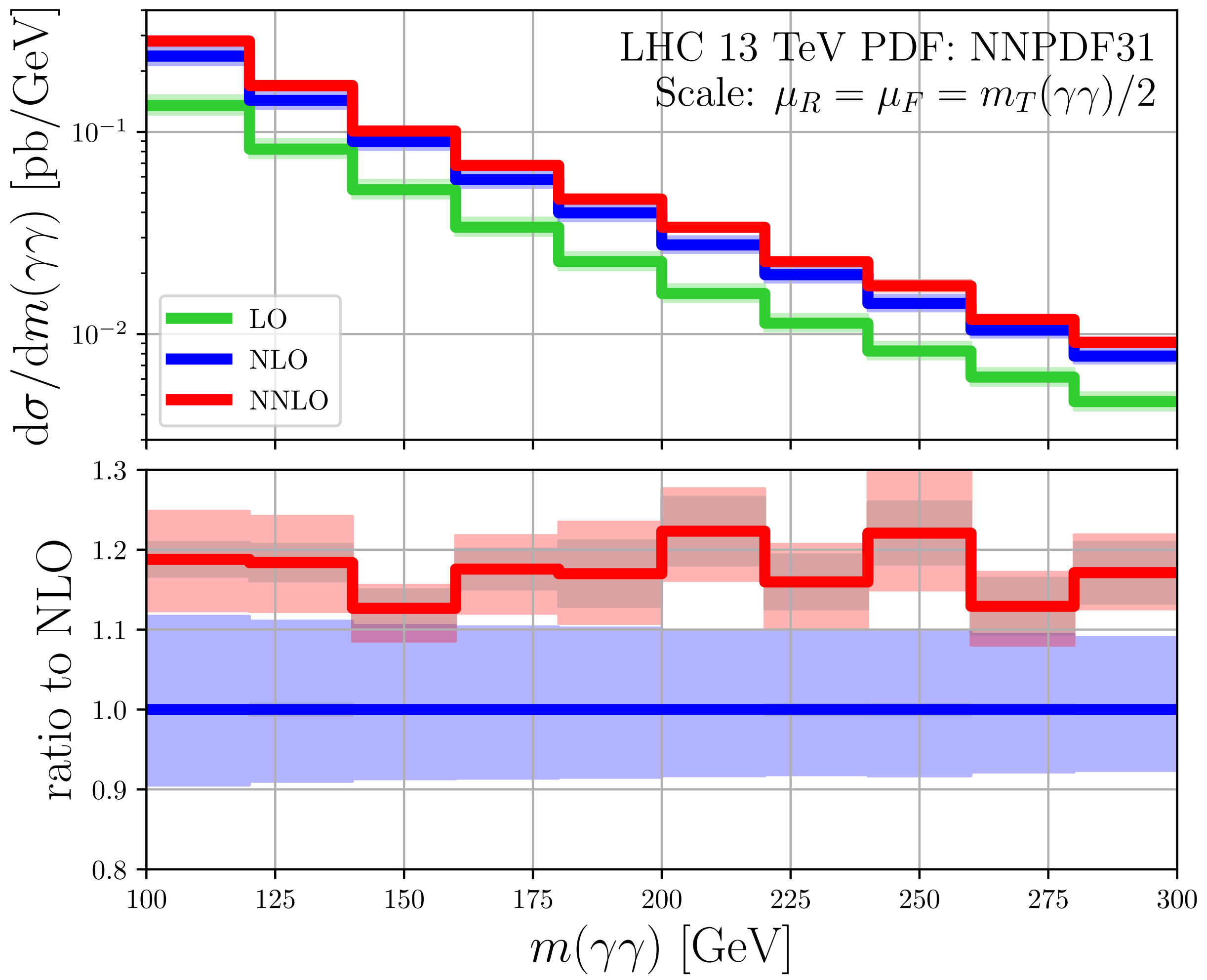
$$\delta(\mathcal{T}-\tau) = \theta(\alpha_1-\beta_1)\theta(\alpha_2-\beta_2)\theta(\alpha_3-\beta_3)\delta(\beta_1+\beta_2+\beta_3-\tau) + \theta(\beta_1-\alpha_1)\theta(\alpha_2-\beta_2)\theta(\alpha_3-\beta_3)\delta(\alpha_1+\beta_2+\beta_3-\tau)+\ldots$$

Jettiness soft function calculation at N3LO in pQCD.

Baranowski, Delto, Wang, K.M.



Calculation of NNLO QCD corrections to $pp \to \gamma\gamma + j$ opens up a way for a computation of N3LO QCD corrections to $pp \to \gamma\gamma$



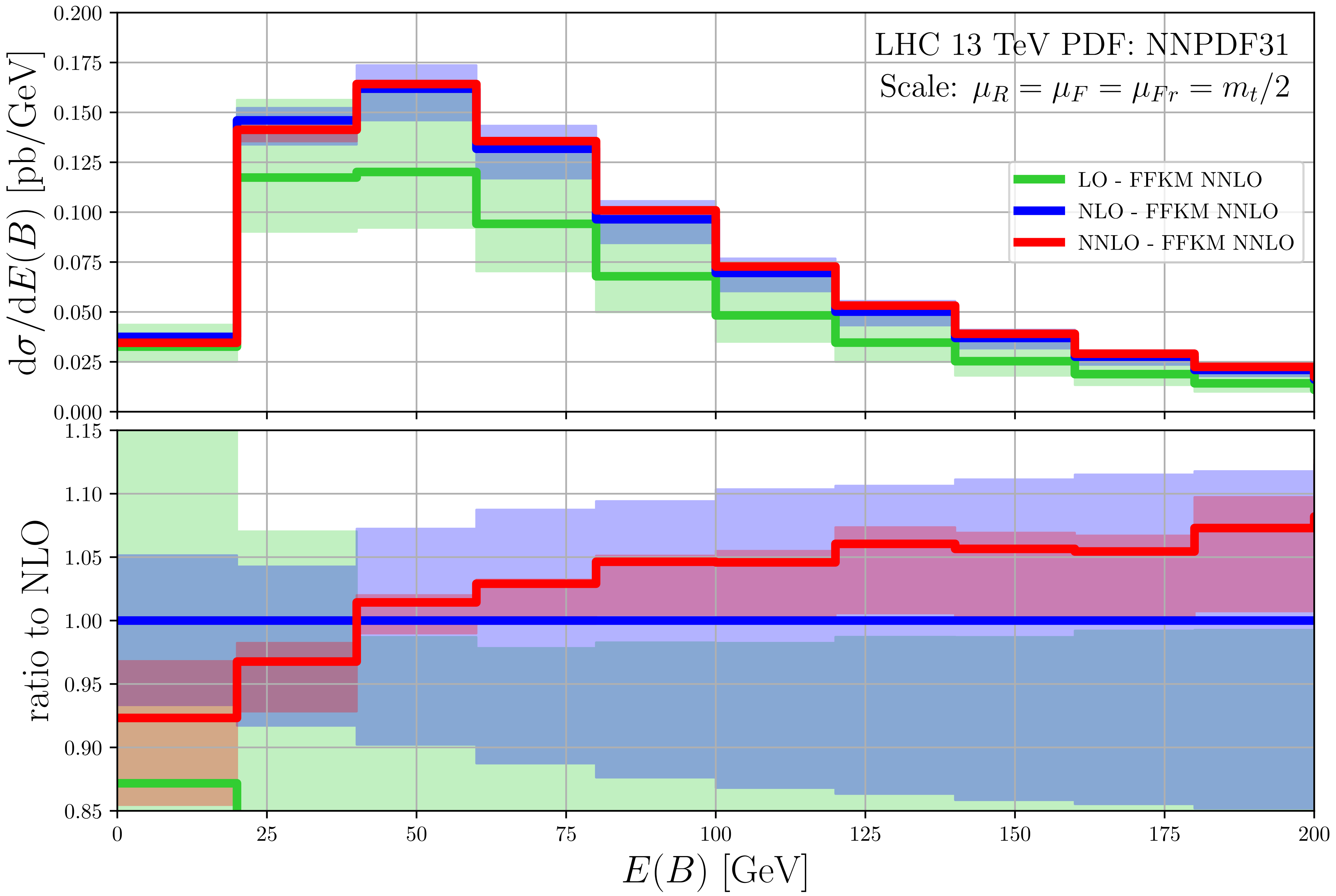
$p_\perp(\gamma_1) > 30$ GeV,
$p_\perp(\gamma_2) > 18$ GeV,
$|\eta(\gamma)| < 2.4$,
$\Delta R_\gamma = 0.4$,
$E_\perp^{\max} = 10$ GeV,
$p_\perp(\gamma\gamma) > 20$ GeV

Chadwhry, Czakon, Mitov, Poncelet

Project B1b: Precision top quark physics at the LHC

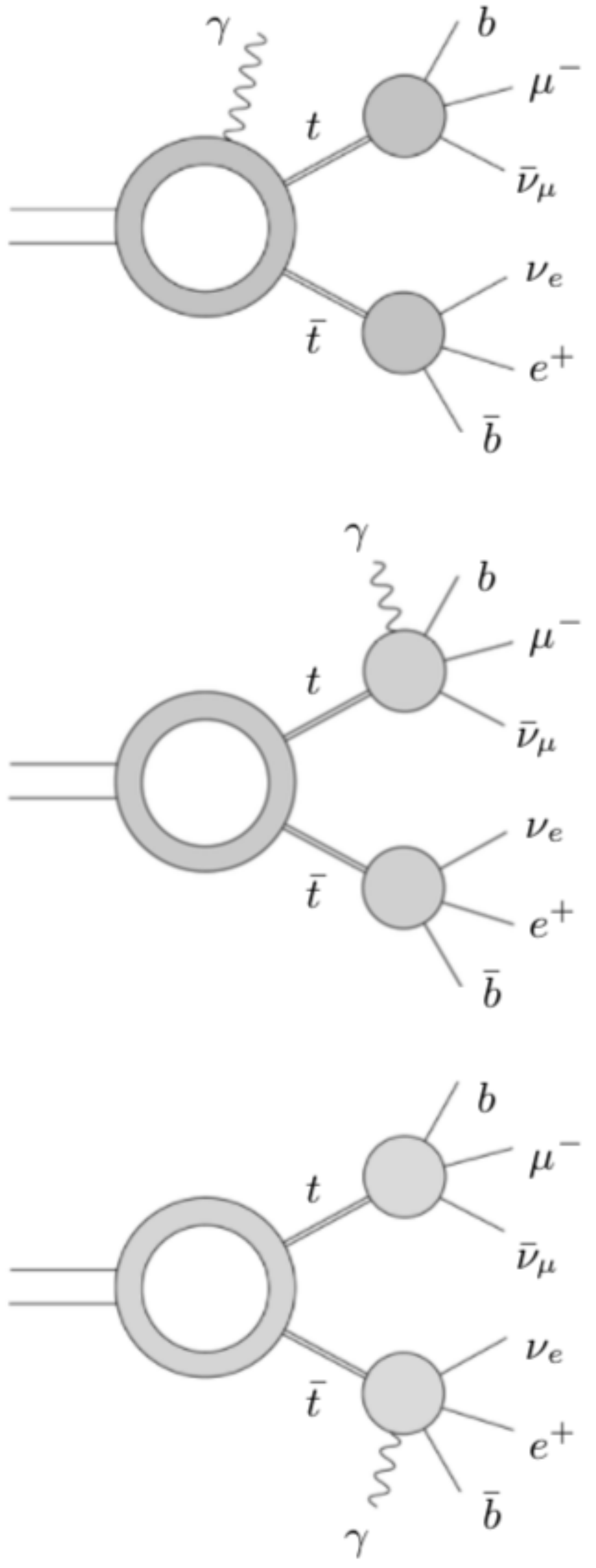
Principal investigators: Czakon, Heinrich**, Worek

$pp \to t\bar{t} \to B + X$

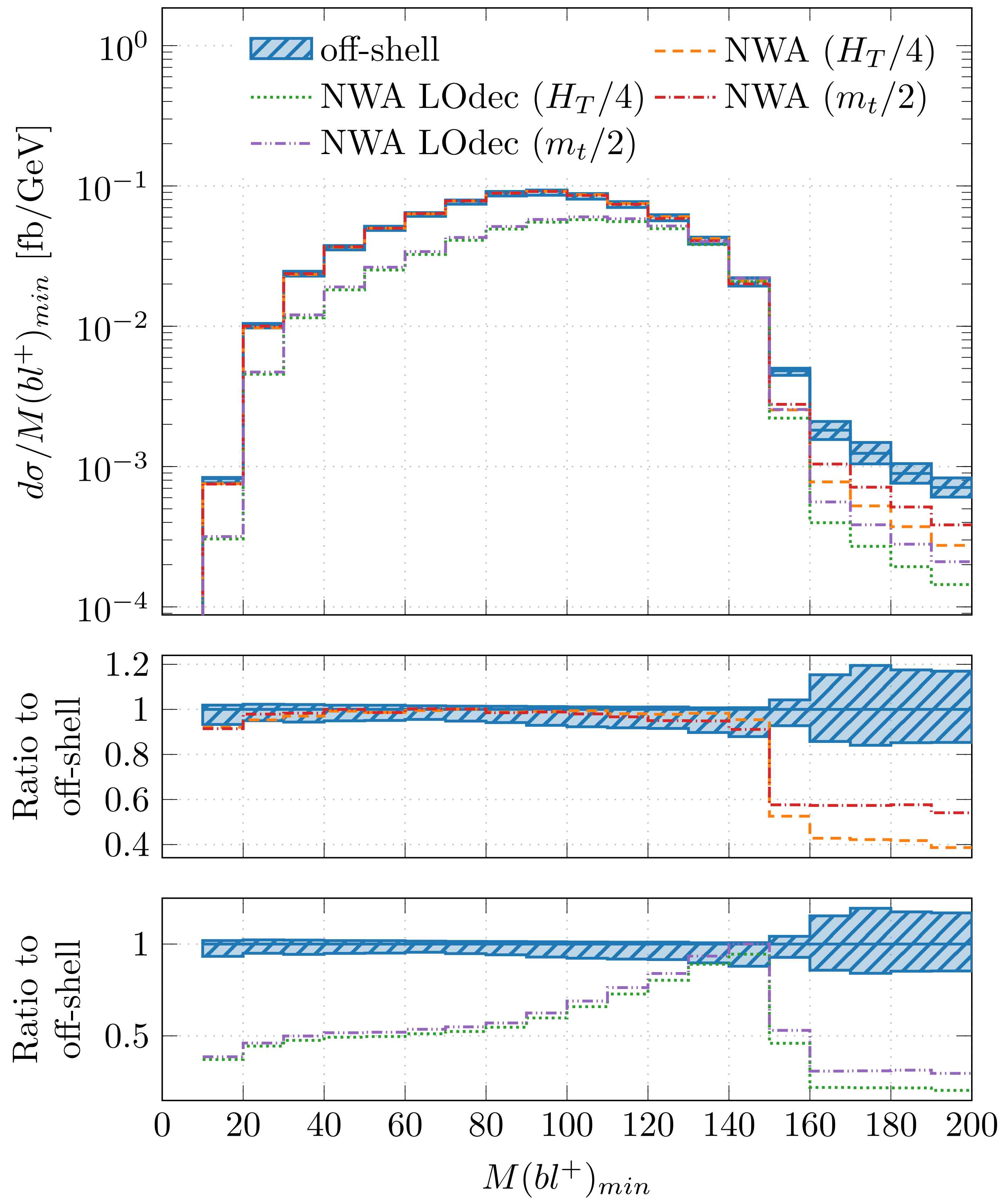


Fragmentation to B-mesons in top quark decays can be combined with the description of top production at the LHC through NNLO QCD.

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



$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}\gamma$



Radiation of photons in the decay needs to be suppressed to study the anomalous couplings.

Czakon, Generet, Mitov, Poncelet

Bevilacqua, Hartano, Kraus, Weber, Worek

Project B2a: Automated calculations in Soft-Collinear Effective Theory

Principal investigator: Bell

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

$$\mathrm{d}\sigma = H \prod_{k=1,2} B_k \otimes \prod_{j=1}^{N_f} J_j \otimes S$$

Automated calculation of soft, beam and jet functions for arbitrary observables.

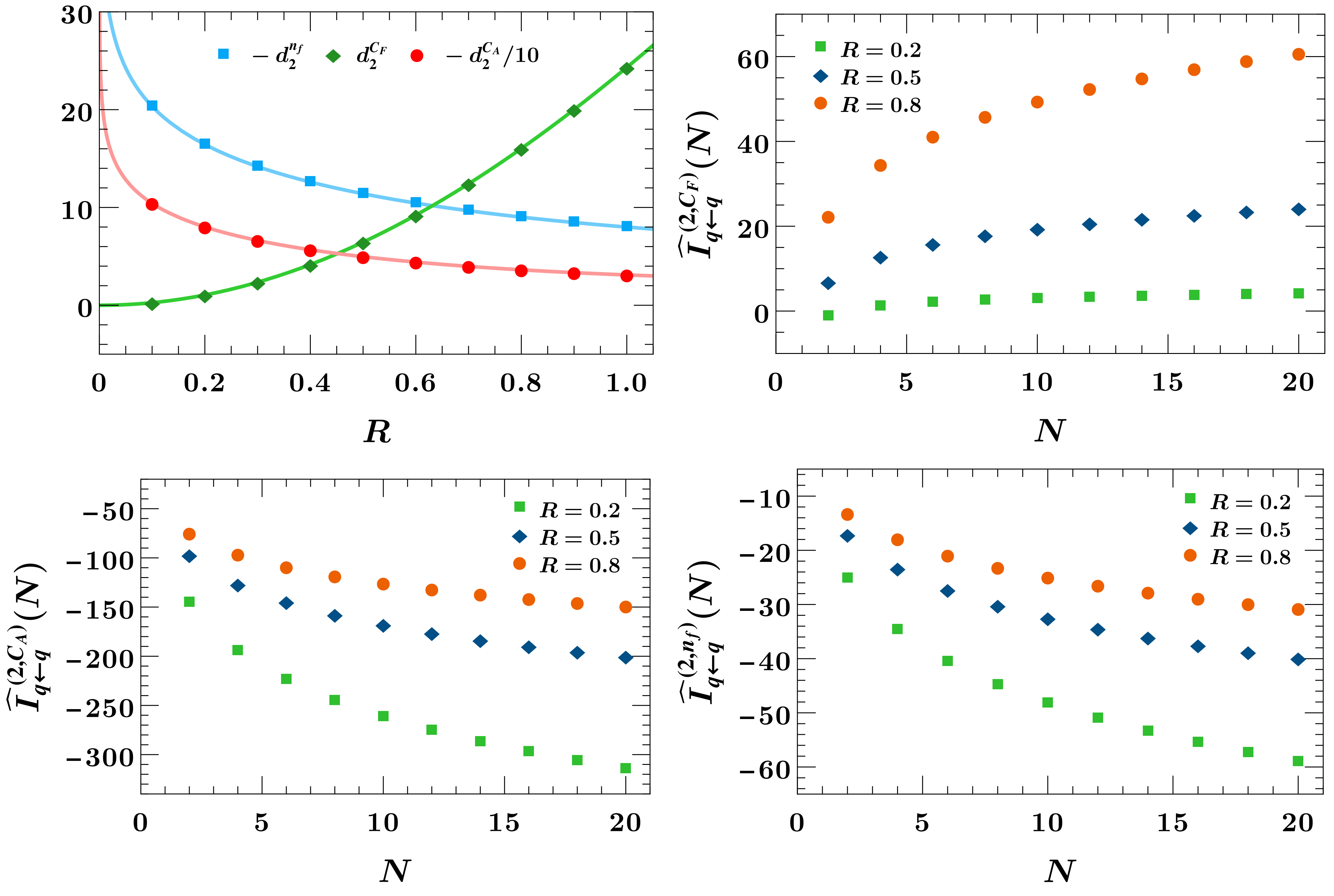
$$B,\ J,\ S \sim \int (\mathrm{Eik}, P_{f_1 \to f_2})\ \mathrm{PhSp}\ \mathrm{Observable}$$

In principle, same divergencies as in QCD, therefore a generic NNLO problem. On the other hand, SCET-related phase-space modifications lead to “UV” divergencies which must be extracted as well.

$$\frac{d^2\sigma(p_T^{\rm veto})}{dQ^2 dY} = \sum_{i,j} H_{ij}(Q,\mu)\, \mathcal{B}_{i/h_1}(x_1, p_T^{\rm veto}, \mu)\, \mathcal{B}_{j/h_2}(x_2, p_T^{\rm veto}, \mu)\, \mathcal{S}_{ij}(p_T^{\rm veto}, \mu)\,,$$

$$\theta\big(p_T^{\rm veto} - \omega(\{k_i\})\big)$$

$$\omega_2(k,l) = \theta(\Delta - R)\ \max\big(|\vec{k}^\perp|, |\vec{l}^\perp|\big) + \theta(R-\Delta)\ |\vec{k}^\perp + \vec{l}^\perp|\,, \qquad \Delta = \sqrt{\frac{1}{4}\ln^2\frac{k^- l^+}{k^+ l^-} + \theta_{kl}^2}\,,$$



Bell, Brune, Das, Wald

Project B2b: Operator analysis of New physics in top quark observables

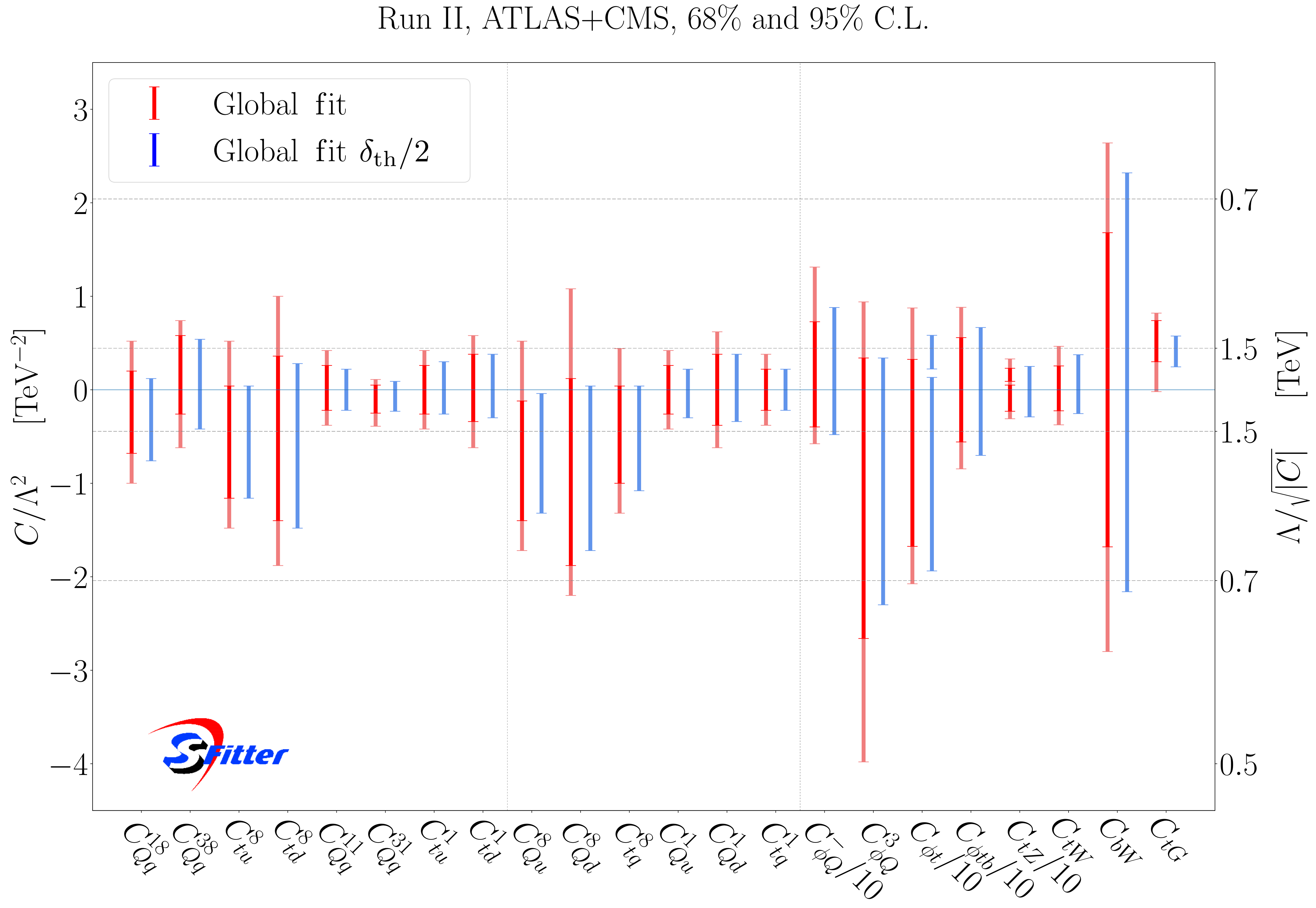
Principal investigator: Westhoff

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

parameter	$t\bar{t}$	single t	tW	tZ	t decay	$t\bar{t}Z$	$t\bar{t}W$
$C^{1,8}_{Qq}$	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
$C^{3,8}_{Qq}$	Λ^{-2}	Λ^{-4} $[\Lambda^{-2}]$	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}
C^{8}_{tu}, C^{8}_{td}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
$C^{1,1}_{Qq}$	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
$C^{3,1}_{Qq}$	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-2}	–	Λ^{-2}	Λ^{-2}	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
C^{1}_{tu}, C^{1}_{td}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	–
C^{8}_{Qu}, C^{8}_{Qd}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
C^{8}_{tq}	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
C^{1}_{Qu}, C^{1}_{Qd}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	–
C^{1}_{tq}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
$C^{-}_{\phi Q}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C^{3}_{\phi Q}$	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
$C_{\phi t}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi tb}$	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tZ}	–	–	–	Λ^{-2}	–	Λ^{-2}	–
C_{tW}	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
C_{bW}	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tG}	Λ^{-2}	$[\Lambda^{-2}]$	Λ^{-2}	–	$[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}

Table 1. Wilson coefficients in our analysis and their contributions to top-quark observables via SM-interference (Λ^{-2}) and via dimension-6 squared terms only (Λ^{-4}). A square bracket indicates that the Wilson coefficient contributes via SM-interference at NLO QCD. All quark masses except m_t are assumed to be zero. 'Single t' stands for $s-$ and $t-$channel electroweak top production.

$$O^{1,8}_{Qq} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i\gamma^\mu T^A q_i) \qquad O^{1,1}_{Qq} = (\bar{Q}\gamma_\mu Q)(\bar{q}_i\gamma^\mu q_i)$$
$$O^{3,8}_{Qq} = (\bar{Q}\gamma_\mu T^A\tau^I Q)(\bar{q}_i\gamma^\mu T^A\tau^I q_i) \qquad O^{3,1}_{Qq} = (\bar{Q}\gamma_\mu \tau^I Q)(\bar{q}_i\gamma^\mu \tau^I q_i)$$
$$O^{8}_{tu} = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i\gamma^\mu T^A u_i) \qquad O^{1}_{tu} = (\bar{t}\gamma_\mu t)(\bar{u}_i\gamma^\mu u_i)$$
$$O^{8}_{td} = (\bar{t}\gamma^\mu T^A t)(\bar{d}_i\gamma_\mu T^A d_i) \qquad O^{1}_{td} = (\bar{t}\gamma^\mu t)(\bar{d}_i\gamma_\mu d_i)\ ;$$

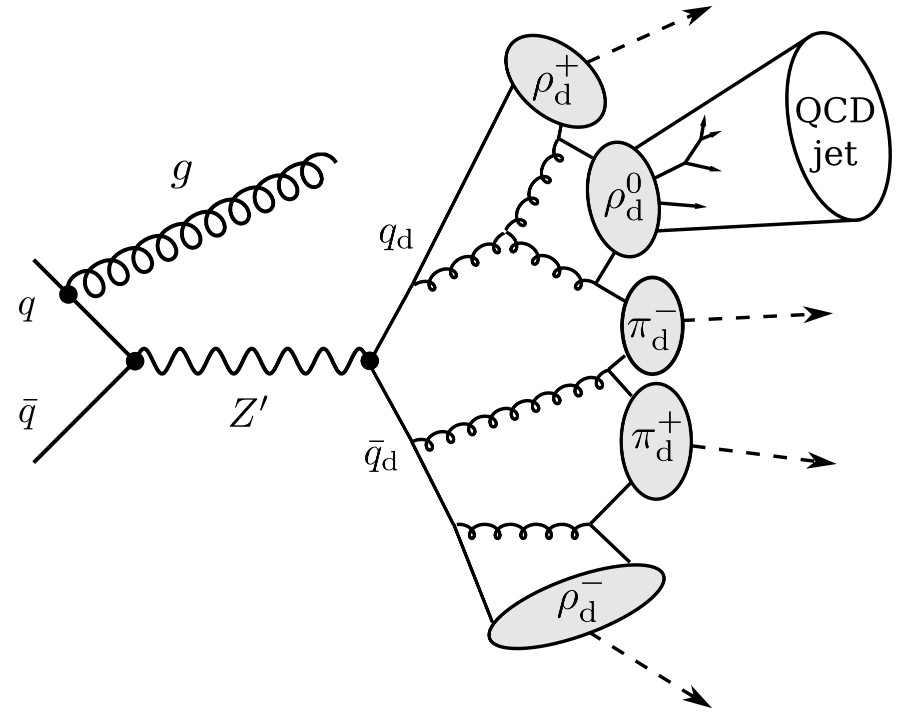


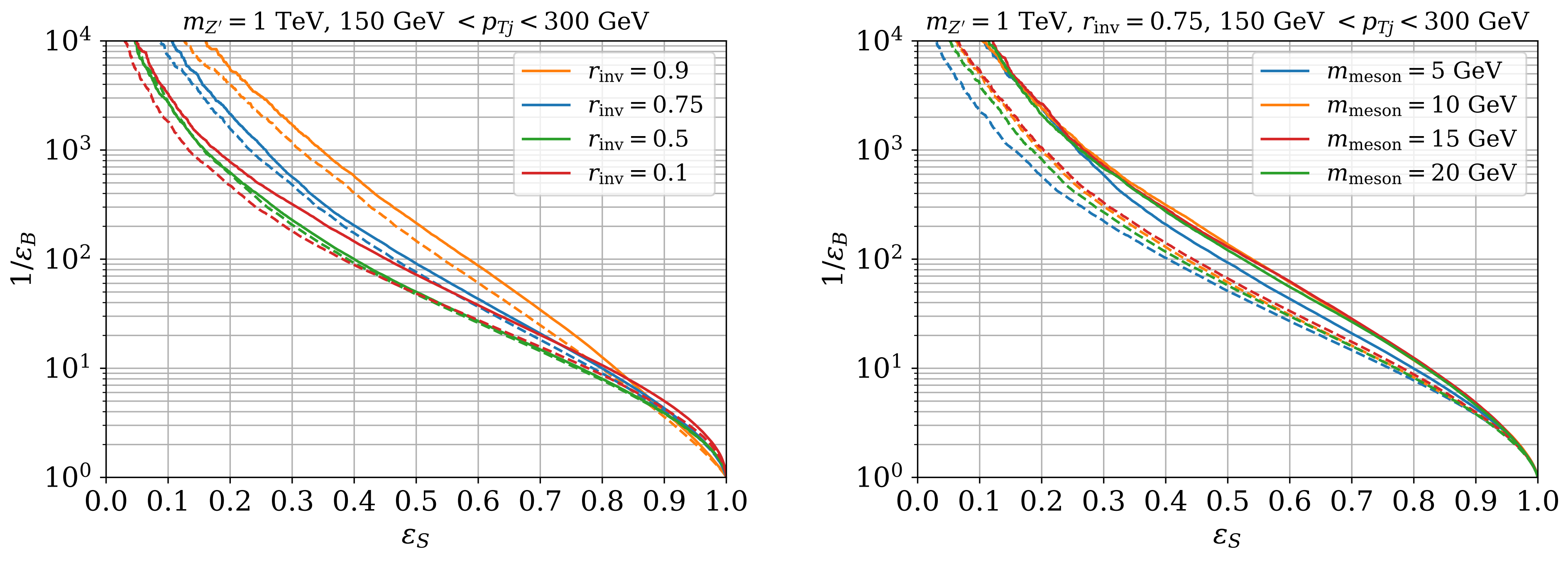
Brivio, Bruggisser, Maltoni, Moutafis, Plehn, Vryonidou, Westhoff

Project B3a: Dark sectors at the LHC (and in flavour experiments)

Principal investigator: F. Kahlhoefer, Krämer, Plehn*

If the dark sector is strongly-interacting and confining, its phenomenology at colliders may mimic that of QCD with many "dark hadrons" being produced and forming jet-like structures. Can one distinguish such jets from light QCD-jets?

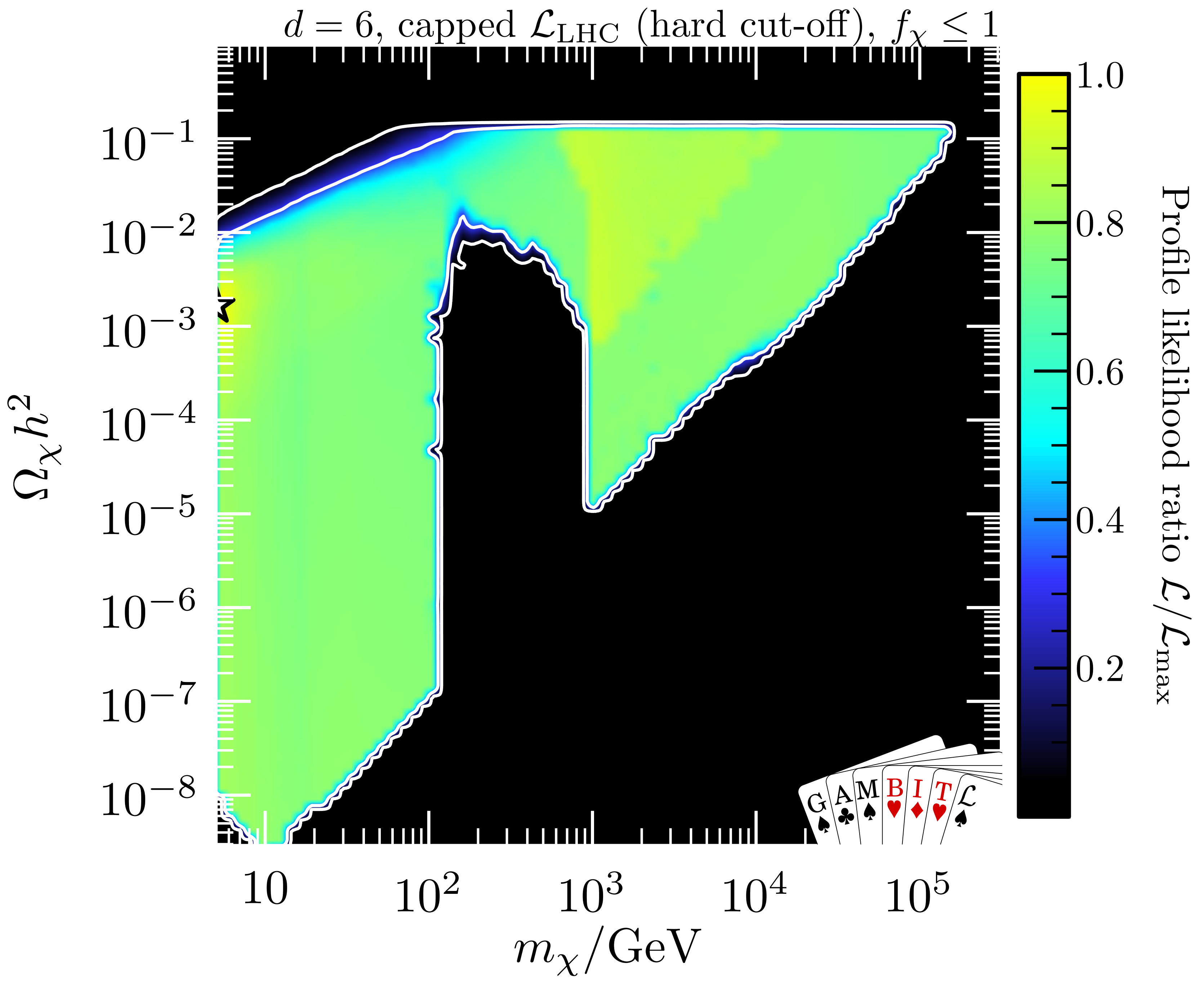




Bernreuther, Finke, Kahlhoefer, Krämer, Mück

Can the DM particle be a Dirac fermion? A difficult question that requires global analysis in an EFT framework (GAMBIT).

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm int} + \overline{\chi}\,(i\partial\!\!\!/ - m_\chi)\,\chi$$



$$\mathcal{Q}^{(6)}_{1,q} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu q)\,,$$
$$\mathcal{Q}^{(6)}_{2,q} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu q)\,,$$
$$\mathcal{Q}^{(6)}_{3,q} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu\gamma_5 q)\,,$$
$$\mathcal{Q}^{(6)}_{4,q} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu\gamma_5 q)$$

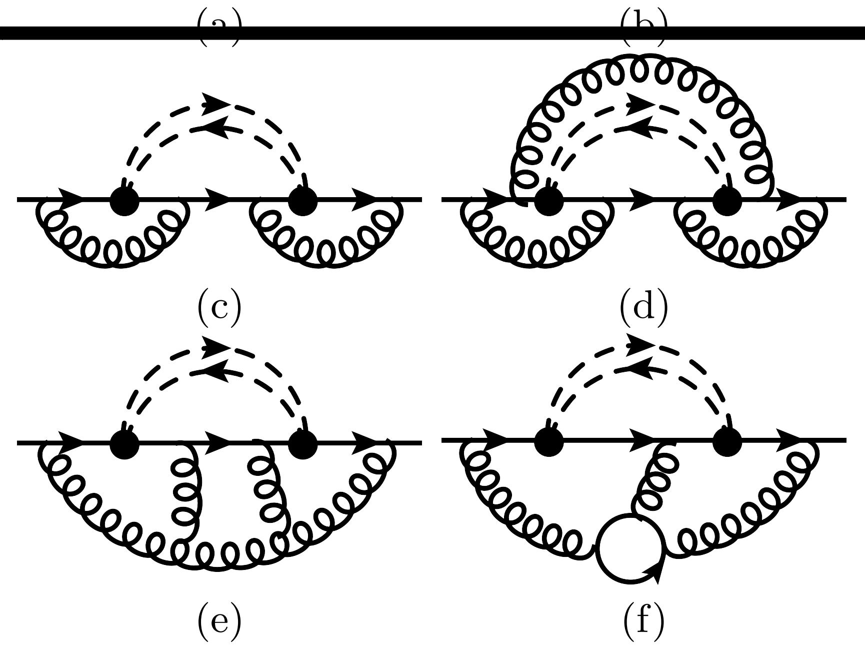
Kahlhoefer et al. (Gambit collaboration)

Project C1a: Inclusive semileptonic, rare and radiative decays of B-mesons

Principal investigator: Huber, Mannel, Steinhauser

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

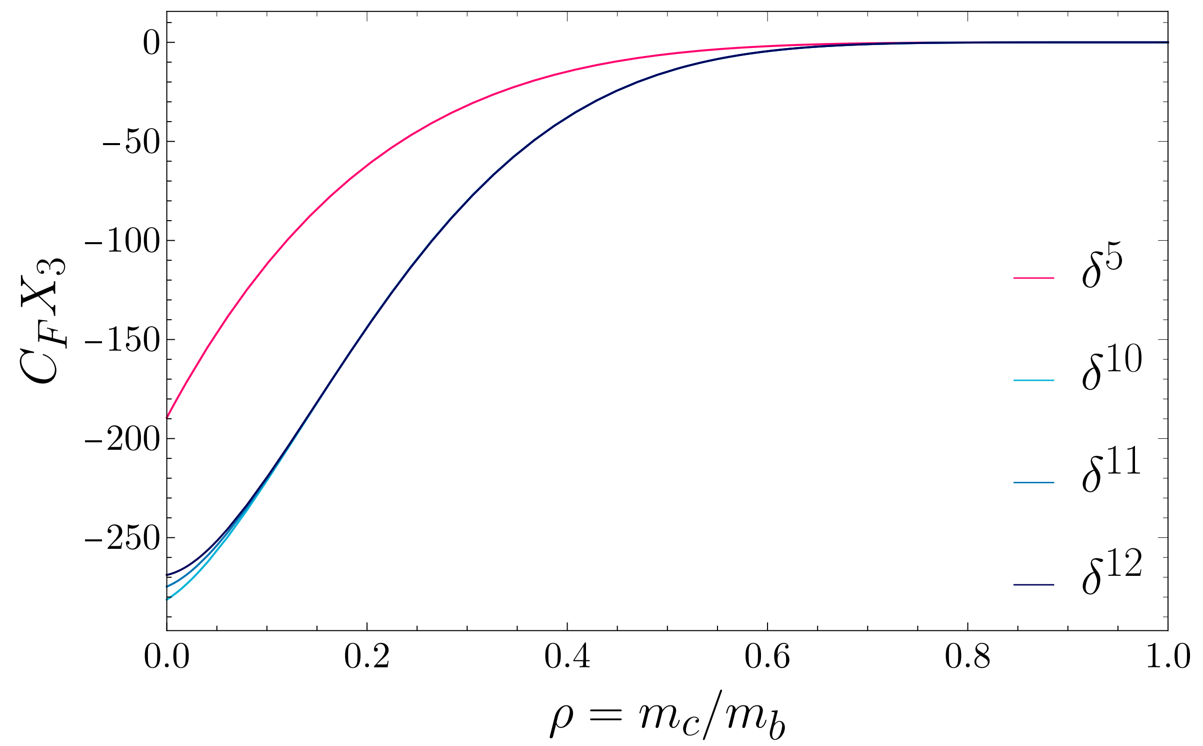
$$\Gamma(B \to X_c \ell \bar{\nu}_\ell) = \Gamma^0 |V_{cb}|^2 \left[C_0 - C_{\mu_\pi} \frac{\mu_\pi^2}{2m_b^2} + C_{\mu_G} \frac{\mu_G^2}{2m_b^2} - C_{\rho_D} \frac{\rho_D^3}{2m_b^3} - C_{\rho_{LS}} \frac{\rho_{LS}^3}{2m_b^3} \right],$$



$$\int \frac{\mathrm{d}^d l}{(2\pi)^d} \frac{1}{(2lp+\delta)^{n_1} (l^2)^{n_2}}$$

$$\delta = m_b^2 - m_c^2$$

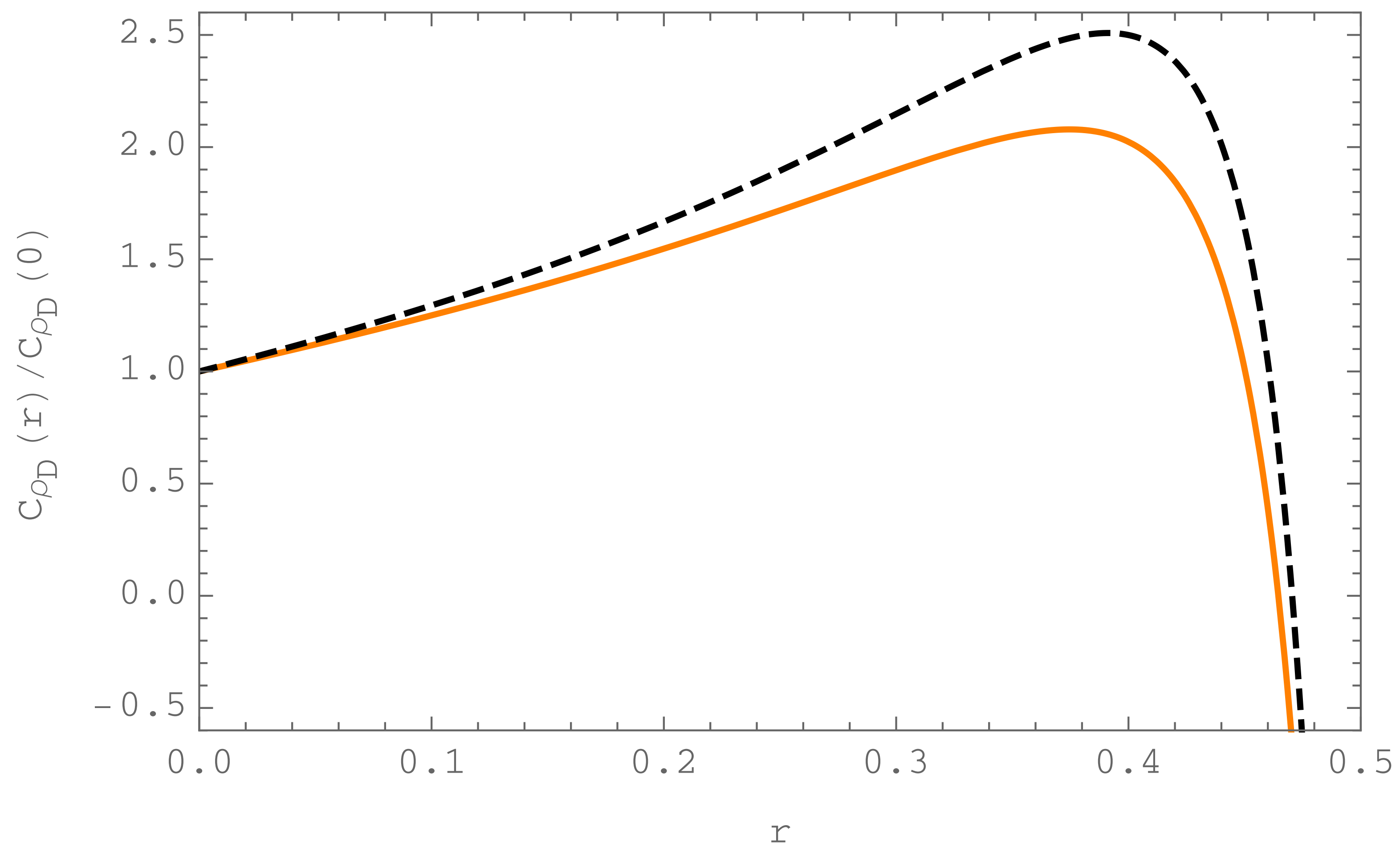
Expansion around the equal-mass limit; radiation is always soft.



$$\frac{\Gamma(b \to X_c l \bar{\nu})}{\Gamma_0} = 0.648\,(1 - 0.087 - 0.018 - 0.0003) \approx 0.580.$$

Fael, Schönwald, Steinhauser

$$\begin{aligned}
\mathcal{O}_0 &= \bar{h}_v h_v && \text{(mass dimension three)},\\
\mathcal{O}_v &= \bar{h}_v v\cdot\pi h_v && \text{(mass dimension four)},\\
\mathcal{O}_\pi &= \bar{h}_v \pi_\perp^2 h_v && \text{(mass dimension five)},\\
\mathcal{O}_G &= \frac{1}{2}\bar{h}_v[\gamma^\mu,\gamma^\nu]\pi_{\perp\mu}\pi_{\perp\nu} h_v && \text{(mass dimension five)},\\
\mathcal{O}_D &= \bar{h}_v[\pi_{\perp\mu},[\pi_\perp^\mu, v\cdot\pi]] h_v && \text{(mass dimension six)},\\
\mathcal{O}_{LS} &= \frac{1}{2}\bar{h}_v[\gamma^\mu,\gamma^\nu]\{\pi_{\perp\mu},[\pi_{\perp\nu}, v\cdot\pi]\} h_v && \text{(mass dimension six)},
\end{aligned}$$

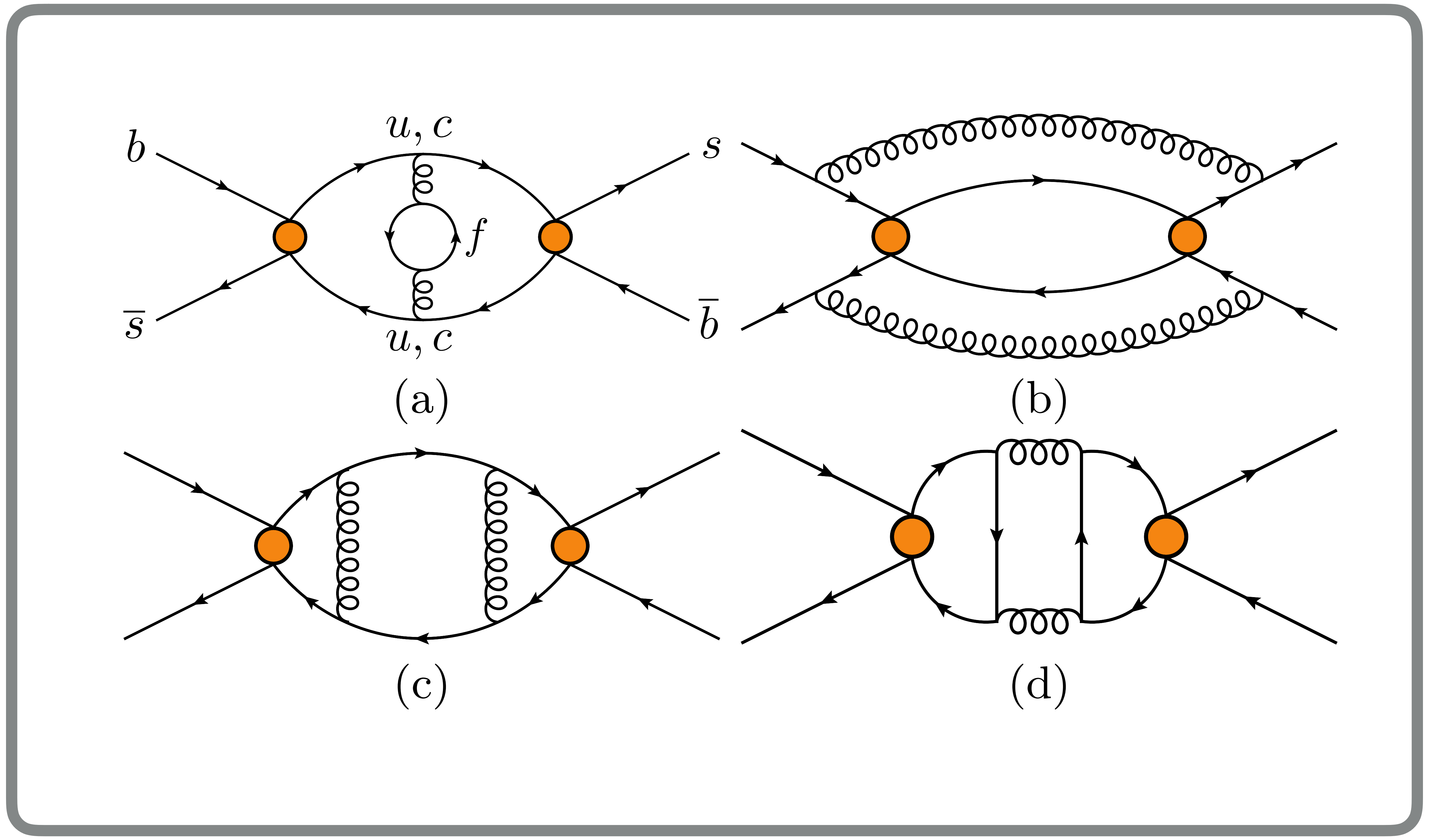


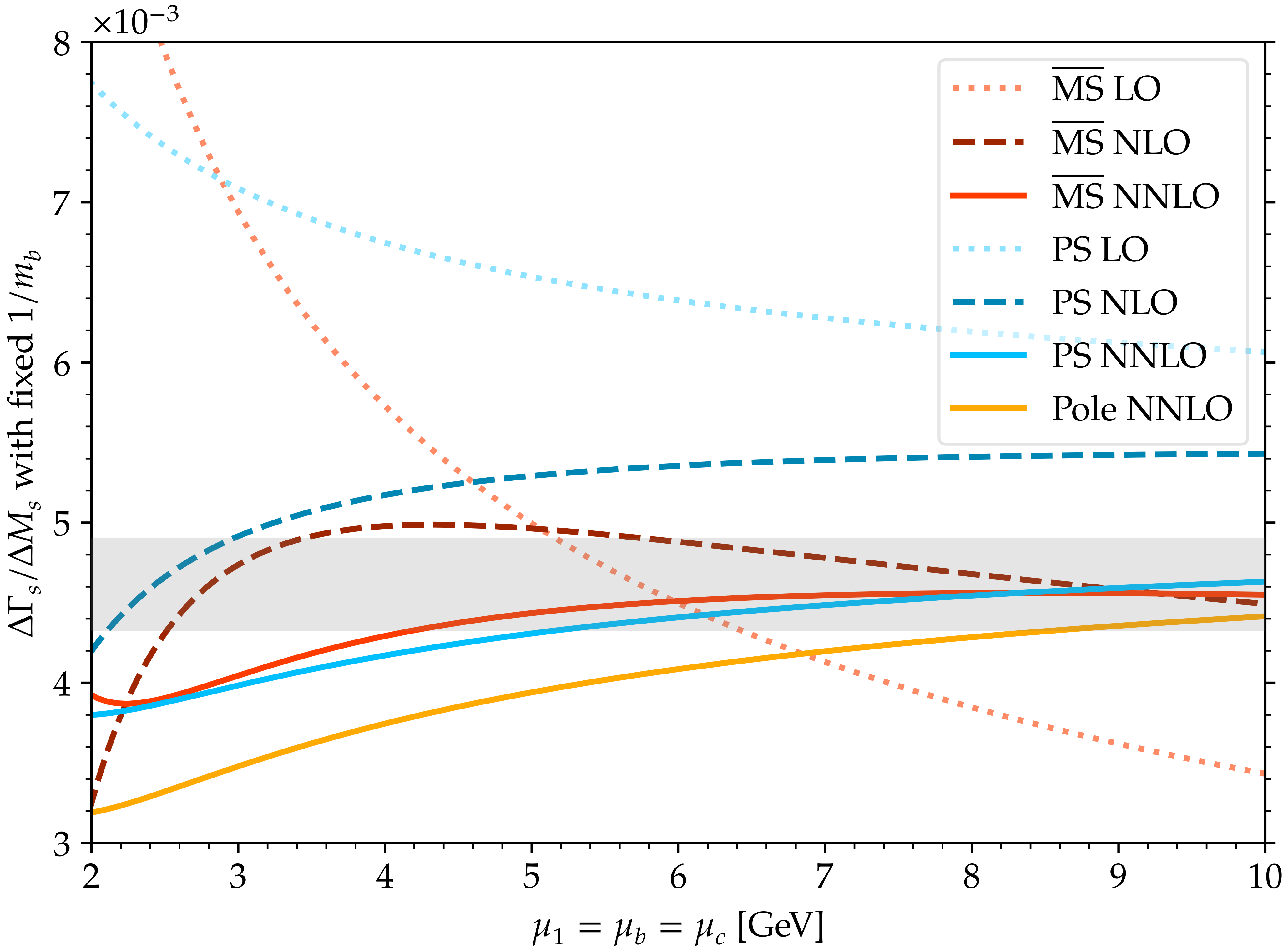
(c) Darwin operator coefficient.

Mannel, Moreno, Pivovarov

Project C1b: B-$\overline{\text{B}}$ mixing, CP-violations and lifetimes

Principal investigator: Lenz, Nierste, Steinhauser**





$$\Delta\Gamma_s = \Gamma_L - \Gamma_H$$

$$\Delta\Gamma_s^{\rm exp} = (0.082 \pm 0.005)\ {\rm ps}^{-1}[8]\,,$$

$$\Delta\Gamma_s = (0.076 \pm 0.017)\ {\rm ps}^{-1}\,.$$

Uncertainty of the theoretical result is still a factor 3 larger than the result of the experimental measurement.

Gerlach, Nierste, Shtabovenko, Steinhauser

Project C2a: Hadronic matrix elements and exclusive semileptonic decays

Principal investigator: Feldmann, Mannel

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

$$\tilde{\phi}_+(\tau;\mu) = \frac{\langle 0|\bar{q}(\tau n)\,[\tau n,0]\,\not{n}\gamma_5\, h_v(0)|B(v)\rangle}{\langle 0|\bar{q}(0)\,\not{n}\gamma_5\, h_v(0)|B(v)\rangle}$$

P1: $\tilde{\phi}_+(\tau)$ is analytic in the lower complex half plane $\mathrm{Im}\,\tau < 0$.

P2: $\tilde{\phi}_+(\tau)$ is analytic on the real τ axis, except for a single point $\tau = 0$ where it has a logarithmic singularity of measure zero, with a branch cut extending along the positive imaginary axis. Hence $\tilde{\phi}_+(\tau)$ is Lebesque-integrable with

P4: The position space LCDA must asymptotically fall off at least as fast as $1/\tau^2$:

$$0 \le \lim_{\tau\to\infty} \left|\tau^2\,\tilde{\phi}(\tau)\right| < \infty\,.$$

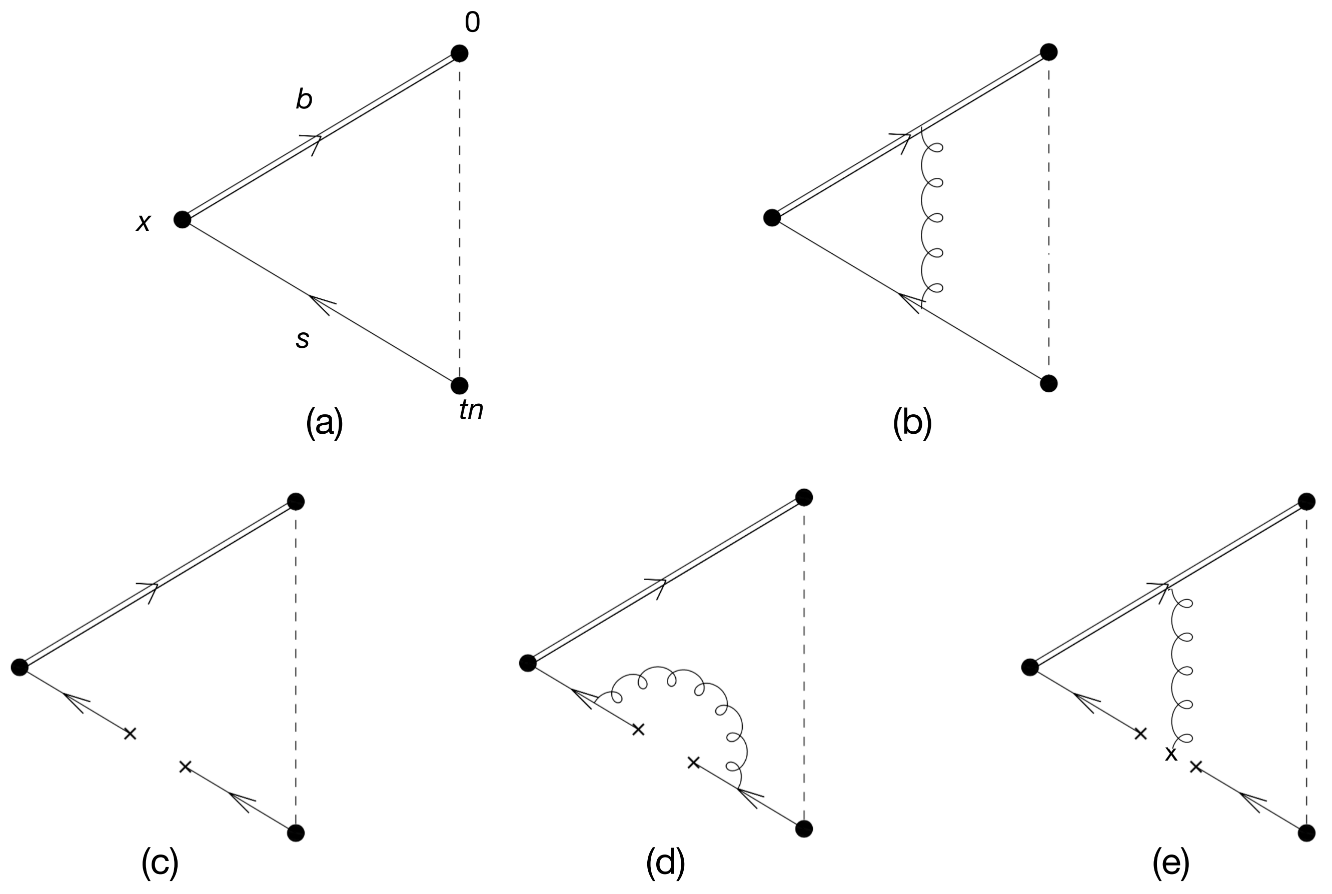
inverse moment	$\lambda_B^{-1}(\mu_0) = \frac{1}{\omega_0}\sum_{k=0}^{K} a_k(\mu_0)\,\frac{1+(-1)^k}{2\,(1+k)}$ (only even k)
logarithmic moment	$\sigma_B(\mu_0) = -\ln\xi - \frac{1}{\xi}\sum_{k=0}^{K} a_k(\mu_0)\left[\frac{\mathrm{d}}{\mathrm{d}t}\,{}_2F_1(-k,1+t;2;2)\right]_{t=0}$
derivative at $\omega = 0$	$\phi_+'(0,\mu_0) = \frac{1}{\omega_0^2}\sum_{k=0}^{K} a_k(\mu_0)$

$$\tilde{\phi}_+(\tau;\mu_0) = \frac{1}{(1+i\omega_0\tau)^2}\sum_{k=0}^{K} a_k(\mu_0)\left(\frac{i\omega_0\tau-1}{i\omega_0\tau+1}\right)^k$$

Feldmannn, Lüghausen, Dyk

$$\lambda^{-1}_{B_{(s)}}(\mu) = \int_0^\infty \frac{dk}{k}\,\phi_+^{B_{(s)}}(k,\mu)$$

$$\mathcal{P}_s(\omega,t) = i\int d^4x e^{-i\omega\, v\cdot x}\langle 0|T\left\{\bar{s}(tn)i\gamma_5\,\not{n}[tn,0]h_v(0)\bar{h}_v(x)i\gamma_5 s(x)\right\}|0\rangle$$



$$\frac{\lambda_{B_s}}{\lambda_B} = 1.19 \pm 0.14\,,$$

Khodjamirian, Mandal, Mannel

Project C2b: Exclusive non-leptonic and rare b-decays

Principal investigator: Bell*, Feldmann, Huber

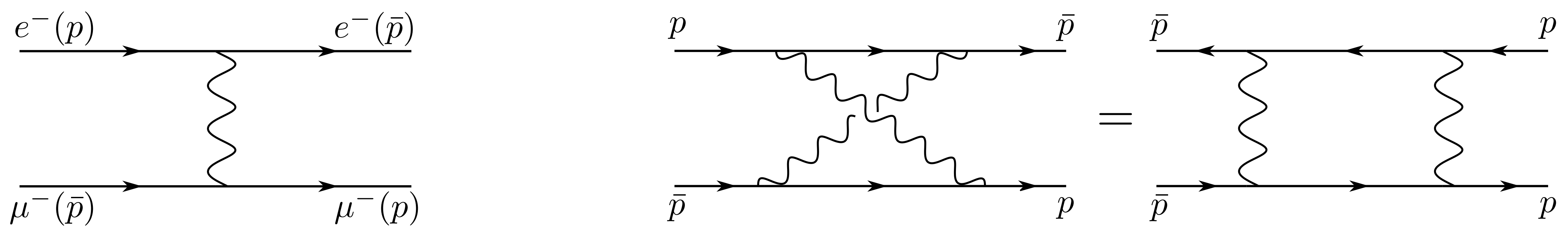
TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

Channel	CP asymmetries in percent		Channel	CP asymmetries in percent	
	Experimental	Theoretical		Experimental	Theoretical
$B^- \to \pi^0\pi^-$	3 ± 4	$5.45^{+22.02}_{-20.60}$	$B^- \to \eta\pi^-$	-14 ± 7	$-11.37^{+14.49}_{-26.90}$
$B^- \to K^0 K^-$	4 ± 14	$18.82^{+36.93}_{-30.83}$	$B^- \to \eta'\pi^-$	6 ± 16	$4.71^{+59.79}_{-57.97}$
$\bar{B}^0 \to \pi^+\pi^-$	32 ± 4	$35.01^{+3.19}_{-22.29}$	$\bar{B}_s \to \eta K^0$	< 0.1	$0.10^{+0.00}_{-100.07}$
$\bar{B}^0 \to \pi^0\pi^0$	33 ± 22	$-10.58^{+40.69}_{-89.40}$	$\bar{B}_s \to \eta' K^0$	Not available	$-0.58^{+100.57}_{-79.58}$
$\bar{B}^0 \to K^0\bar{K}^0$	-60 ± 70	$-6.88^{+85.39}_{-81.37}$	$B^- \to \eta K^-$	-37 ± 8	$-42.23^{+42.23}_{-16.00}$
$\bar{B}_s \to \pi^- K^+$	22.1 ± 1.5	$20.84^{+2.39}_{-2.57}$	$B^- \to \eta' K^-$	0.4 ± 1.1	$0.63^{+3.98}_{-4.30}$
$B^- \to \pi^0 K^-$	3.7 ± 2.1	$3.72^{+7.19}_{-4.35}$	$\bar{B}^0 \to \eta K^0$	Not available	$-0.01^{+40.07}_{-0.02}$
$B^- \to \pi^- K^0$	-1.7 ± 1.6	$-1.08^{+1.76}_{-2.32}$	$\bar{B}^0 \to \eta' K^0$	-6 ± 4	$0.03^{+4.82}_{-11.69}$
$\bar{B}^0 \to \pi^+ K^-$	-8.3 ± 0.4	$-8.38^{+8.38}_{-1.01}$	$\bar{B}^0 \to \eta\pi^0$	Not available	$-27.39^{+127.11}_{-72.58}$
$\bar{B}^0 \to \pi^0 \bar{K}^0$	0 ± 13	$-0.97^{+19.35}_{-3.20}$	$\bar{B}^0 \to \eta'\pi^0$	Not available	$-43.67^{+143.63}_{-56.33}$
$\bar{B}_s \to K^+K^-$	-14 ± 11	$-10.58^{+10.58}_{-3.60}$	$\bar{B}_s \to \eta\pi^0$	Not available	$0.88^{+94.98}_{-98.70}$
$\bar{B}_s \to \pi^+\pi^-$	Not available	$17.56^{+11.84}_{-38.25}$	$\bar{B}_s \to \eta'\pi^0$	Not available	$1.57^{+77.56}_{-95.66}$
$\bar{B}_s \to \pi^0\pi^0$	Not available	$17.56^{+11.84}_{-38.25}$	$\bar{B}^0 \to \eta\eta$	Not available	$3.46^{+96.50}_{-103.45}$
$\bar{B}_s \to K^0\bar{K}^0$	Not available	$0.31^{+5.07}_{-4.59}$	$\bar{B}_s \to \eta\eta$	Not available	$14.29^{+76.81}_{-113.09}$
$\bar{B}^0 \to K^+K^-$	Not available	$-78.45^{+161.99}_{-20.78}$	$\bar{B}^0 \to \eta'\eta'$	Not available	$42.41^{+57.55}_{-142.41}$
$\bar{B}_s \to \pi^0 K^0$	Not available	$13.74^{+29.49}_{-113.73}$	$\bar{B}_s \to \eta'\eta'$	Not available	$-2.05^{+15.29}_{-13.44}$
			$\bar{B}^0 \to \eta'\eta$	Not available	$-12.32^{+112.32}_{-87.67}$
			$\bar{B}_s \to \eta'\eta$	Not available	$3.43^{+96.36}_{-103.22}$

Results of the fit to decay amplitudes under the assumption of $SU(3)_F$ symmetry.

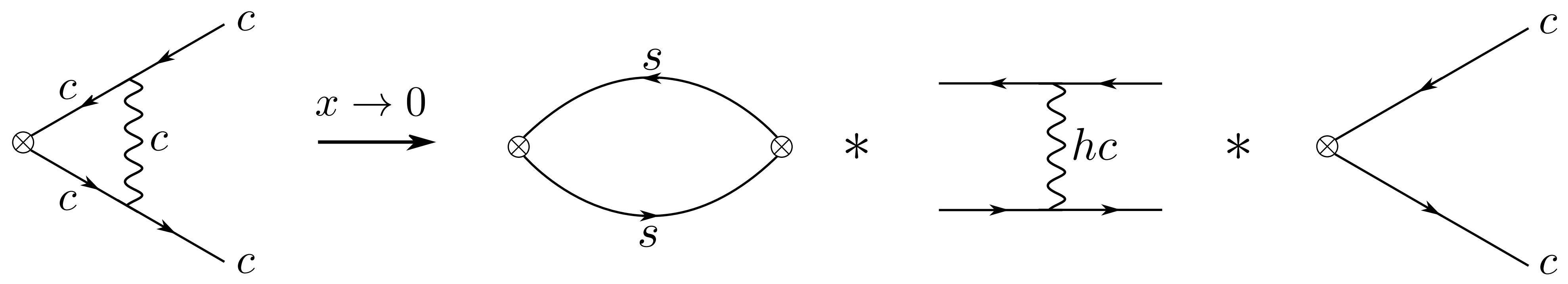
Huber, Tetlalmatzi-Xolocotzi

$$\int_0^1 \frac{dx}{x}\phi(x)\,T(x) = ? \quad T(0) \neq 0, \quad \phi(0) \neq 0.$$



$$F_1(\lambda) = \sum_{n=0}^{\infty}\left(\frac{\alpha_{em}}{2\pi}\right)^n F_1^{(n)}(\lambda) \simeq \sum_{n=0}^{\infty}\frac{\left(\frac{\alpha_{em}}{2\pi}\ln^2\lambda^2\right)^n}{n!(n+1)!} = \frac{I_1\left(2\sqrt{\frac{\alpha_{em}}{2\pi}\ln^2\lambda^2}\right)}{\sqrt{\frac{\alpha_{em}}{2\pi}\ln^2\lambda^2}}$$

$$\lambda^2 = \frac{s}{m_\mu^2}$$



Bell, Böer, Feldmann

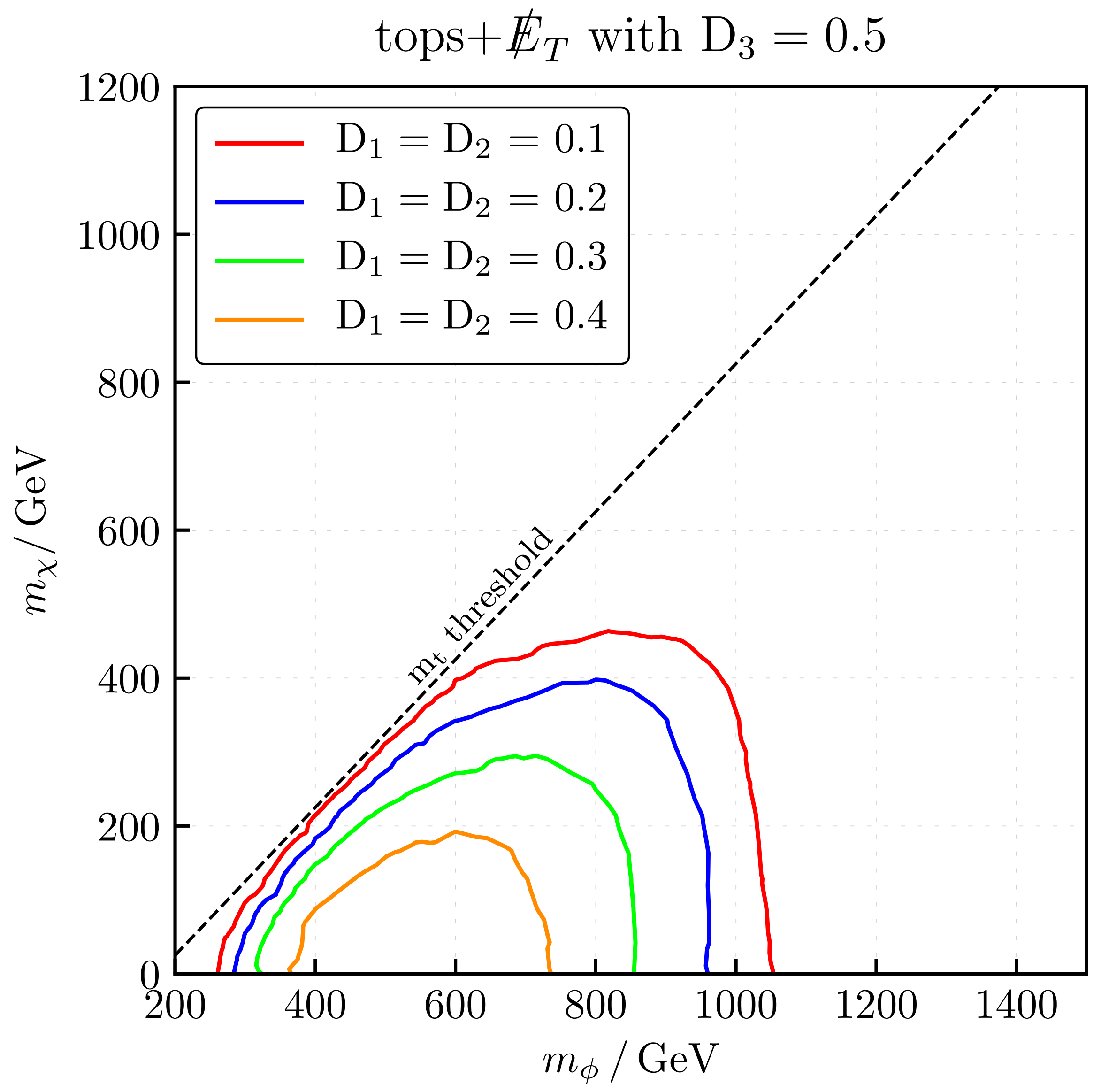
Project C3a: New sources of flavour violation at high transverse momentum

Principal investigator: Blanke, Krämer, Mühlleitner*

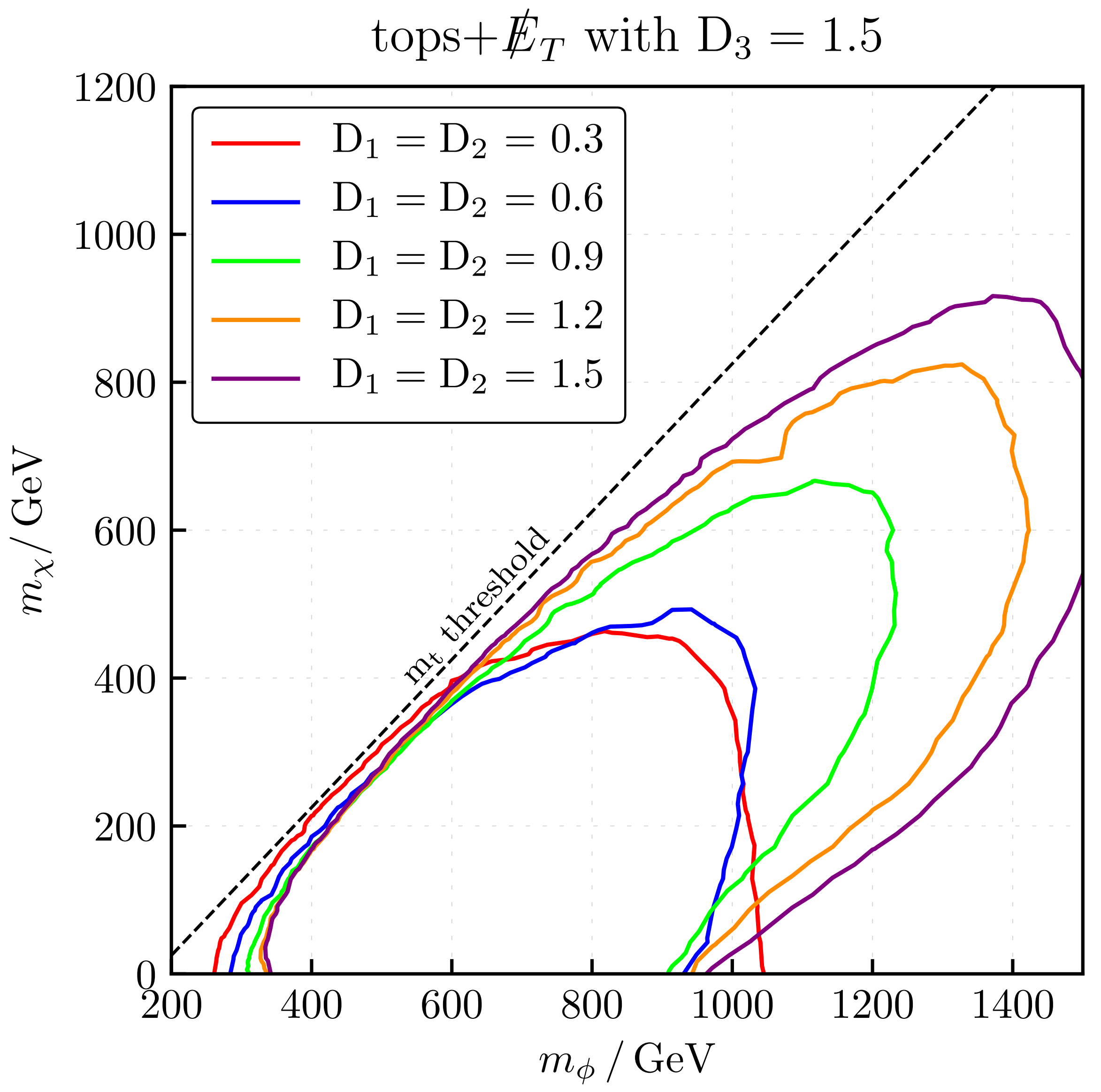
TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

$$L = L_{\rm SM} + \frac{1}{2}\left(i\bar{\chi}\hat{\partial} - M_\chi\bar{\chi}\chi\right) - (\lambda_{ij}\bar{u}_{Ri}\chi_j\phi + h.c.) + (D_\mu\phi)^+(D^\mu\phi) - m_\phi^2\phi^+\phi + \lambda_{H\phi}\phi^+\phi H^+ H + \lambda_{\phi\phi}\left(\phi^+\phi\right)^2 .$$

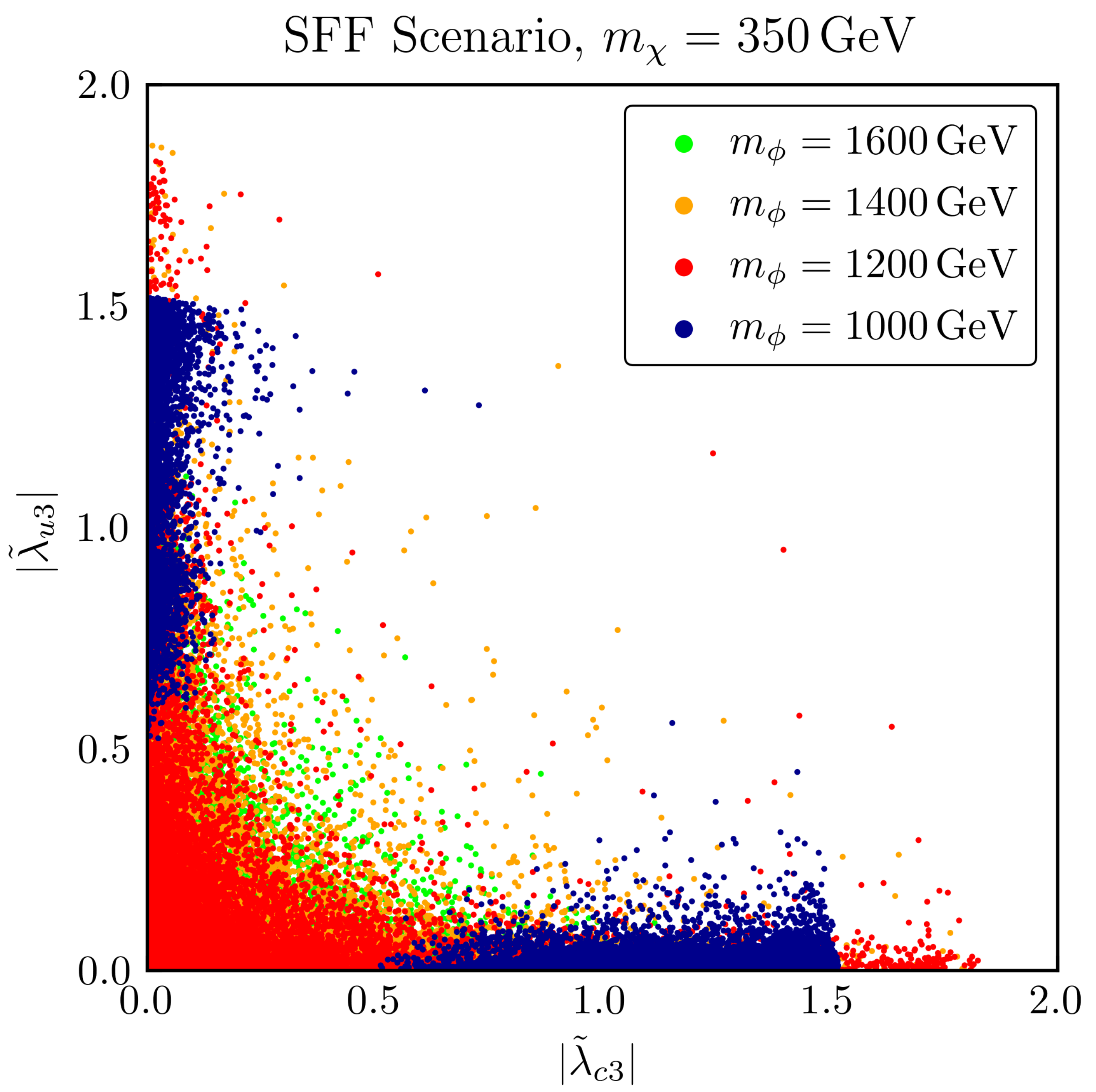
$pp \to \phi\phi \to \chi_i\chi_j q_k q_l$



$pp \to \phi^+\phi \to \chi_i\chi_j q_k \bar{q}_l$



Direct LHC constraints

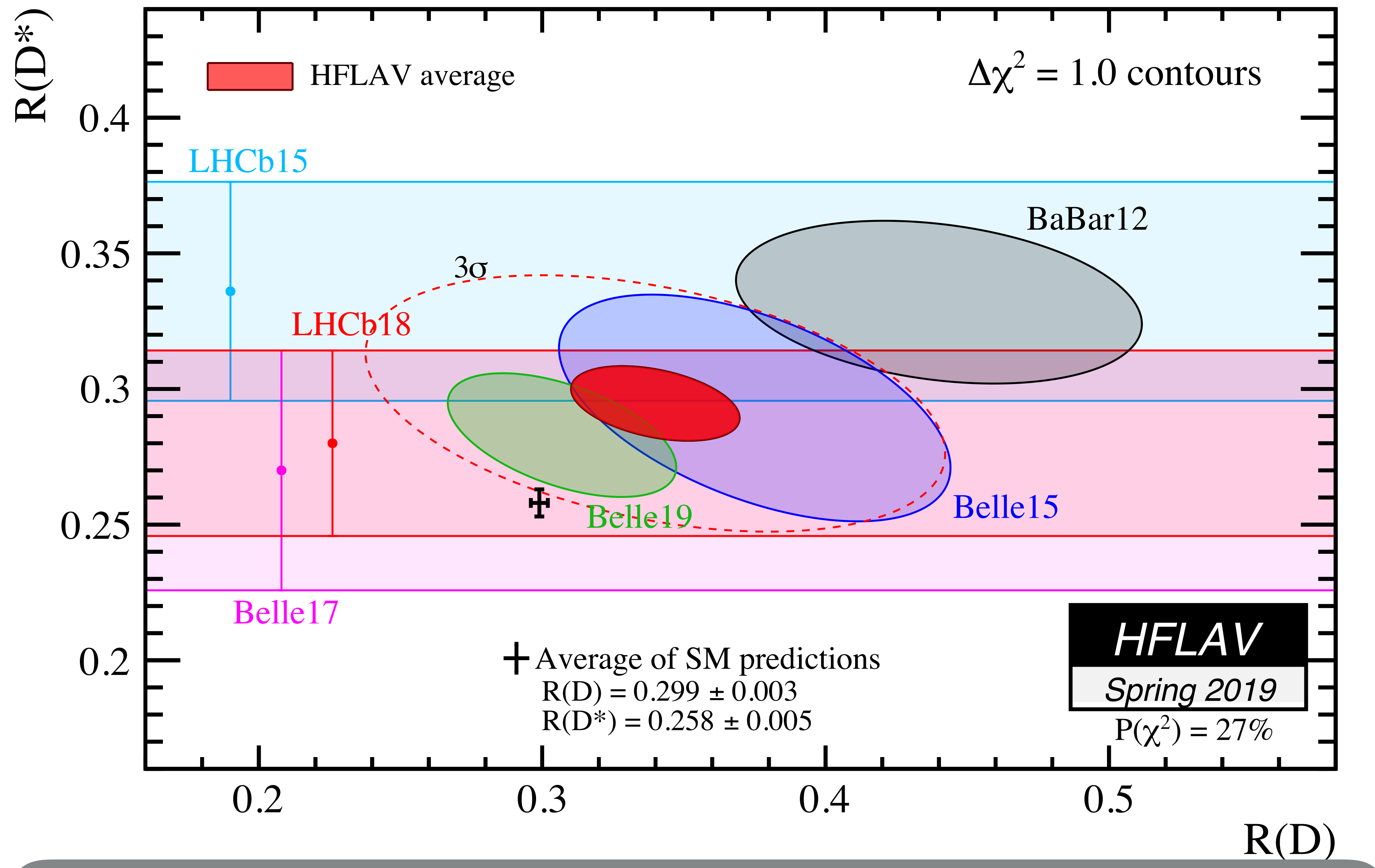


LHC, cosmological, flavour constraints lead to significantly reduce the parameter space of possible couplings' values.

Acaroglu, Blanke

Project C3b: New physics models for flavour observables

Principal investigator: Nierste

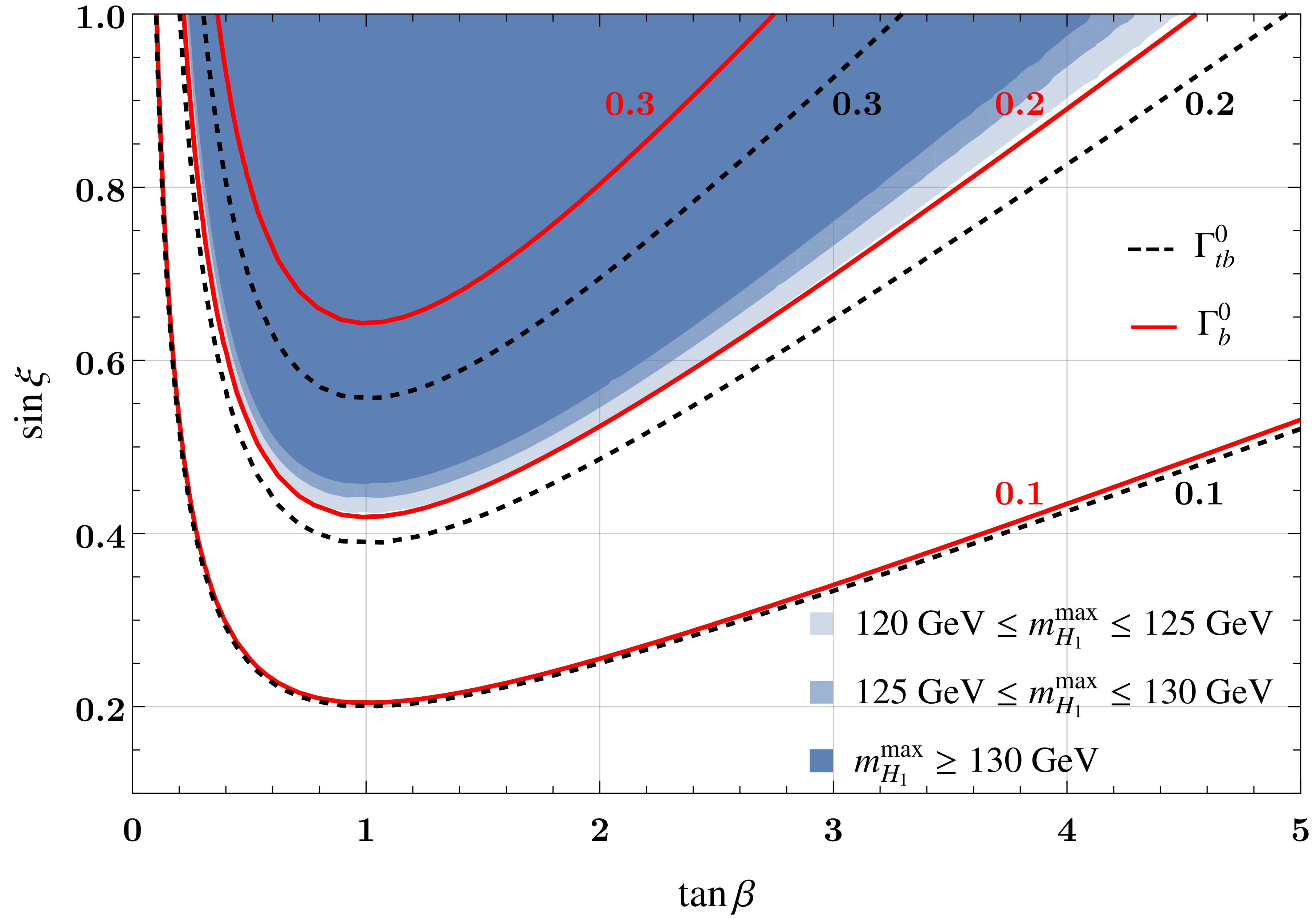


$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}_{\rm SM}(\Lambda_c)} \simeq 0.262\frac{\mathcal{R}(D)}{\mathcal{R}_{\rm SM}(D)} + 0.738\frac{\mathcal{R}(D^*)}{\mathcal{R}_{\rm SM}(D^*)} .$$

$$\mathcal{R}(\Lambda_c) = \mathcal{R}_{\rm SM}(\Lambda_c)\,(1.15 \pm 0.04)$$
$$= 0.38 \pm 0.01 \pm 0.01 ,$$

$$\mathcal{R}(\Lambda_c)_{\rm exp} = 0.24 \pm 0.08$$

Blanke, Crivellin, Kitahara, Moscati, Nierste, Nisandzic



2HDM with spontaneous CP-violation generically predicts large couplings of a charged Higgs and quarks. Possible to test this mechanism of CP-violation by studying associated production of the charged Higgs bosons at the LHC:

$$pp \to tbH^+ \qquad\qquad pp \to cbH^+$$

Nierste, Tabet, Ziegler

Conclusions

TRR 257 - Particle Physics Phenomenology after the Higgs Discovery

- Scientifically, the first funding period of the CRC was a sounding success. We produced many interesting, diverse results that had and continue to have an impact on particle physics phenomenology.
- Pandemic was a serious obstacle but, by and large, we managed to minimize its impact.
- The focus of the CRC research program will remain the same. However new elements will be added to the research program — machine learning, non-perturbative physics, lattice.
- We hope that these changes will make the research program of the CRC even more diverse and interesting in the long run.