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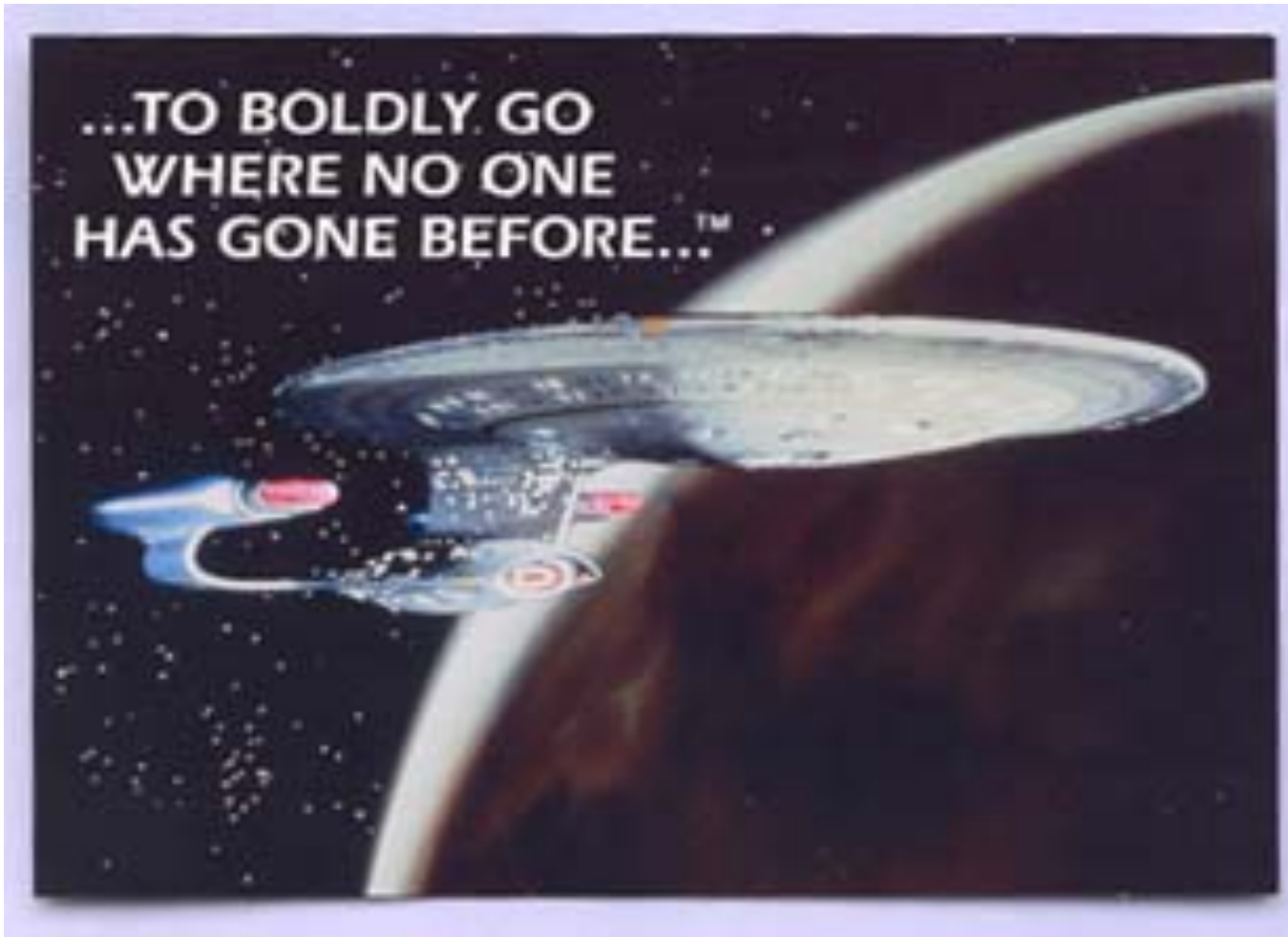
Andreas Crivellin

Universitat Autònoma de Barcelona &
ICREA

Beyond the Standard Model

Special Colloquium for Prof. Ulrich Nierste's 60th birthday
KIT, 03.07.2026

Why Searching for BSM Physics?



Uli in response to my question if a career in particle physics would be the right thing for me:

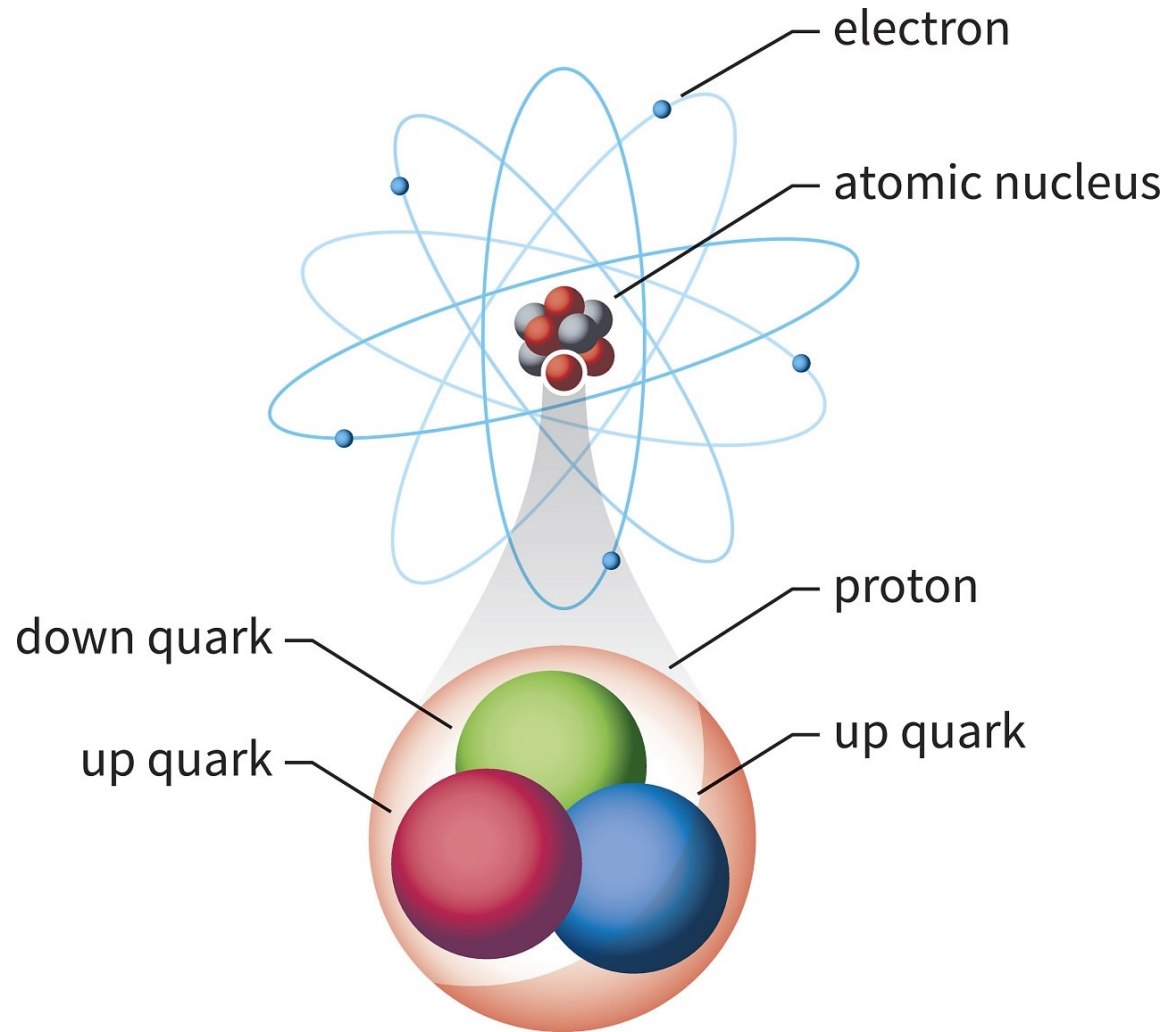
“Zumindest fällt mir nichts anderes in der Welt ein, was du sonst tun könntest.”

“At least I cannot think of anything else in the world that you could to.”

It is human nature to explore the unknown

Fundamental Building Blocks of Matter

- Quarks and leptons are fundamental, i.e. point-like, constituents of matter in the mathematical description of Nature



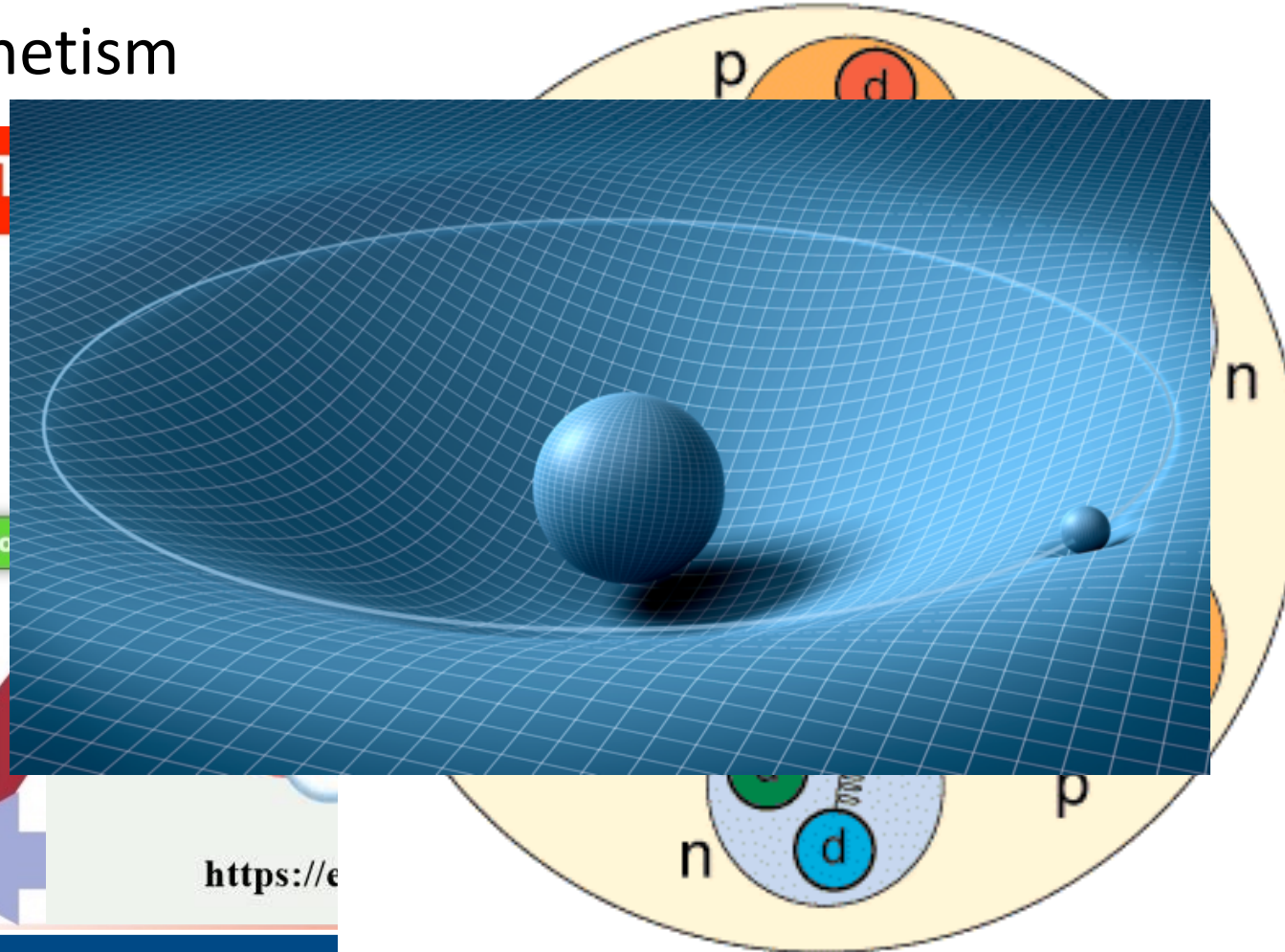
Are quarks and leptons really fundamental?

- Electro-magnetism

- Strong force (QCD)

- Weak force

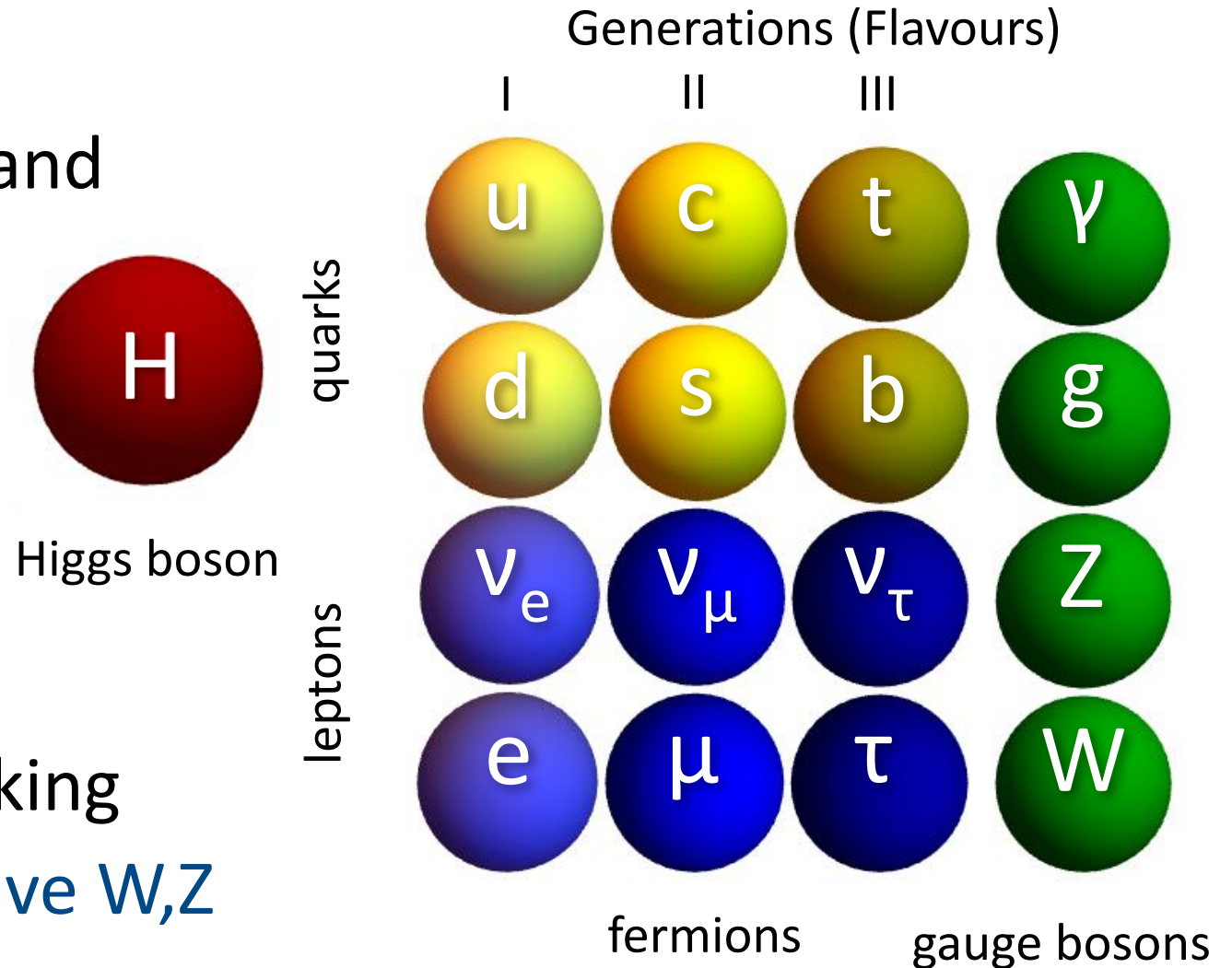
- Gravitation



Are these interactions unified?
Are there more interactions?

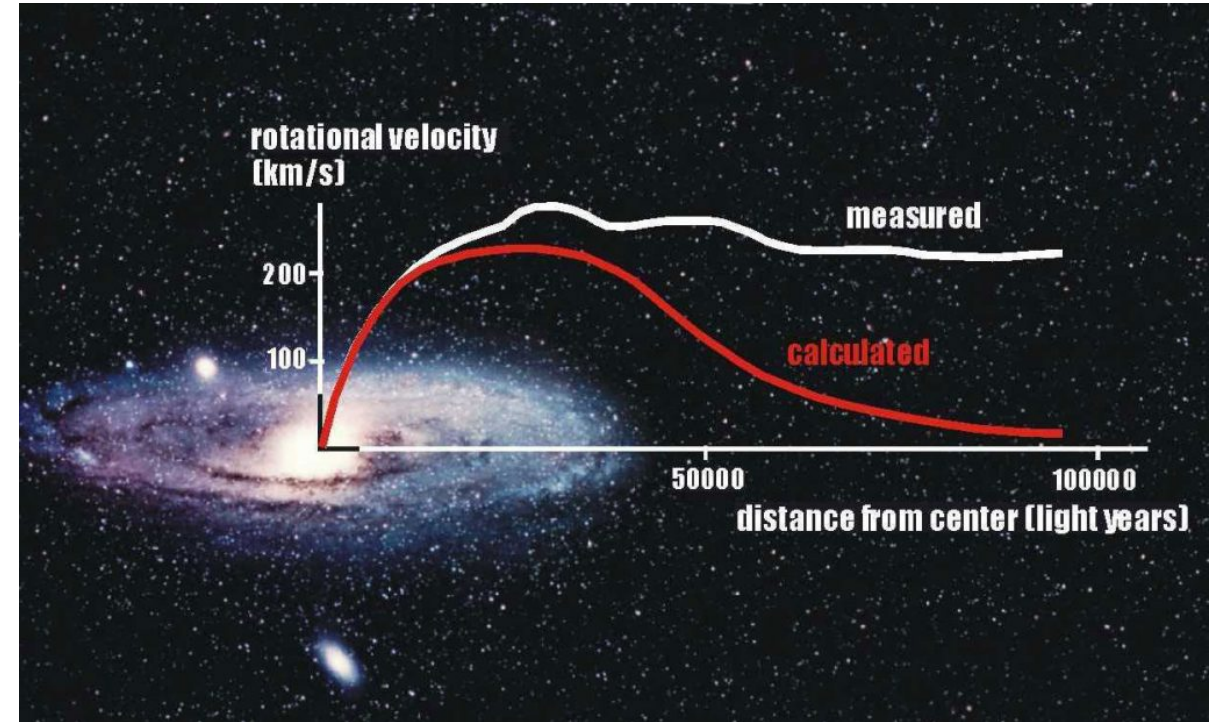
Standard Model of Particle Physics

- Fundamental constituents:
 - Three generations of quarks and leptons (and neutrinos)
- Three forces:
 - Strong force
 - Weak force
 - Hypercharge
- Spontaneous symmetry breaking
 - Massless Photon and massive W,Z



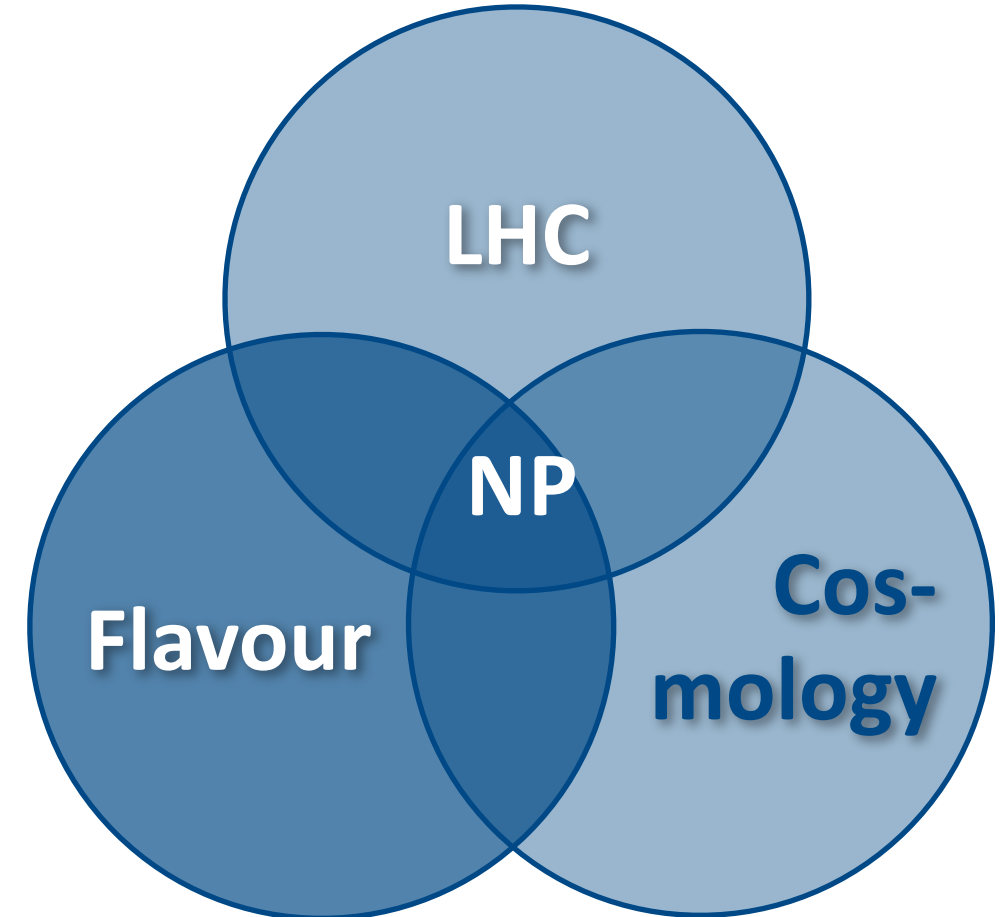
With the Higgs discovery in 2012, the SM is complete

- Dark Matter existence established at cosmological scales
 - New weakly interacting particles
- Neutrinos not exactly massless
 - Right-handed (sterile) neutrinos
- Matter anti-matter asymmetry
 - Additional CP violating interactions



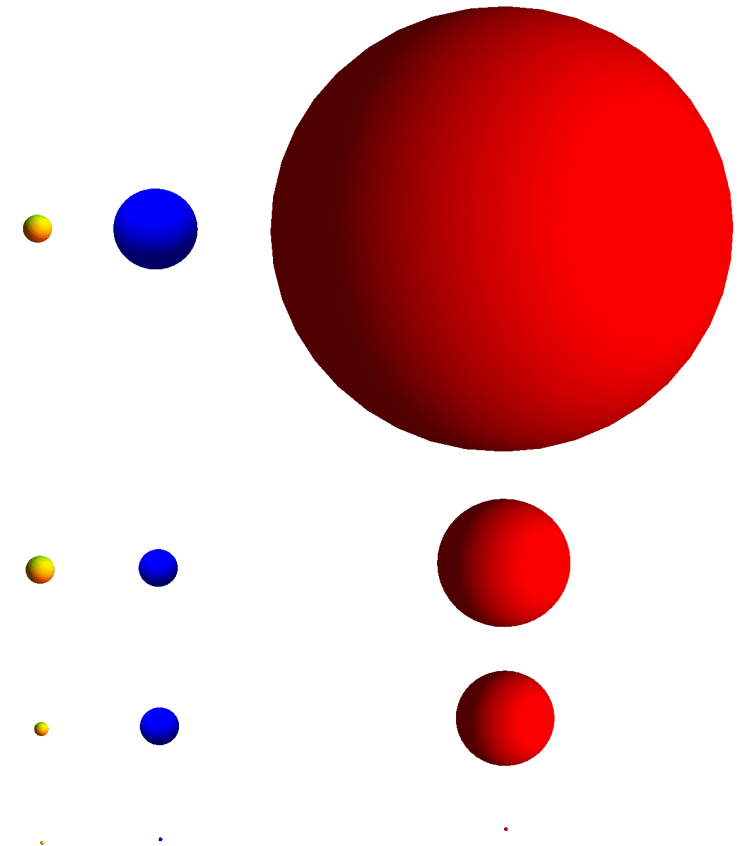
The SM cannot be the ultimate theory of physics

- Direct searches:
 - Dark Matter direct detection
 - Direct LHC searches for new particles
- Indirect searches: High statistics/precision searches for quantum effects of NP
 - Flavour
 - EW precision observables
 - Higgs signal strength
 - Lorentz violation, etc.



In this talk mainly flavour and LHC physics

- Particles of different generations only differ by their mass
- Heavy generations are unstable and decay rapidly to the first generation (which is stable)
- Large mass hierarchy: Order one Yukawa for the top to 10^{-5} for the electron, nearly massless neutrinos



Are the decays of the heavy generations as expected in the SM?

Why not more than 3 Generations?

Impact of a Higgs Boson at a Mass of 126 GeV on the Standard Model with Three and Four Fermion Generations

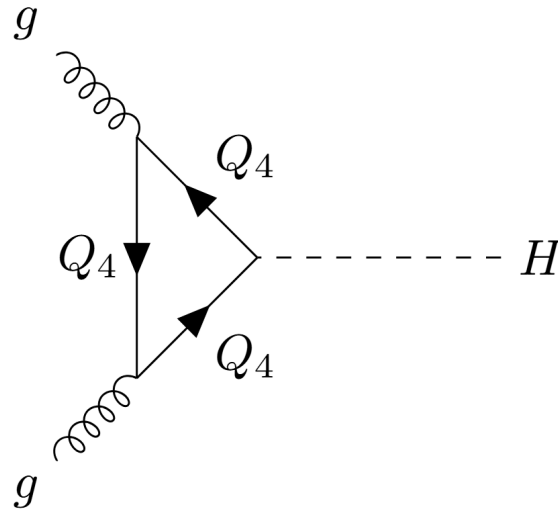
[Otto Eberhardt](#)^{1,*}, [Geoffrey Herbert](#)^{2,†}, [Heiko Lacker](#)^{2,‡}, [Alexander Lenz](#)^{3,§}, [Andreas Menze](#)^{2,||}, [Ulrich Nierste](#)^{1,¶}, and [Martin Wiebusch](#)^{1,**}

Show more

Phys. Rev. Lett. **109**, 241802 – Published 11 December, 2012

DOI: <https://doi.org/10.1103/PhysRevLett.109.241802>

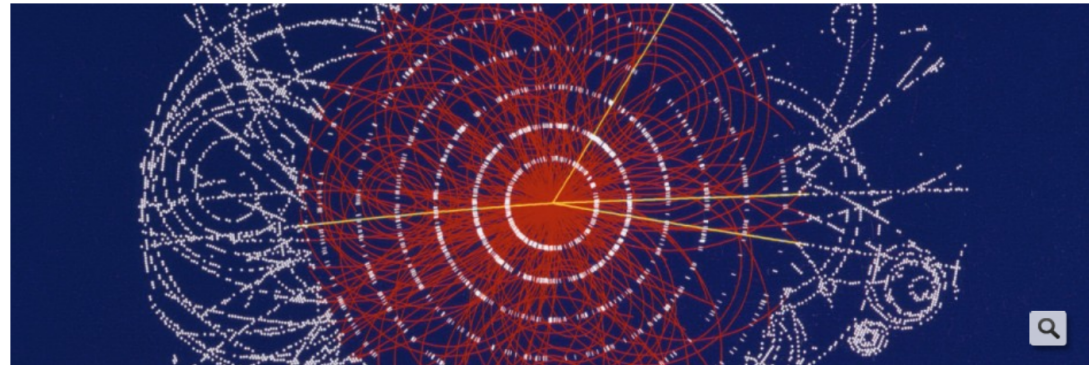
- Excluded by early LHC data



- Factor 9 larger production cross section predicted
- Non-trivial because of possible decays to heavy neutrinos

14. Dezember 2012 16:04 Teilchenphysik

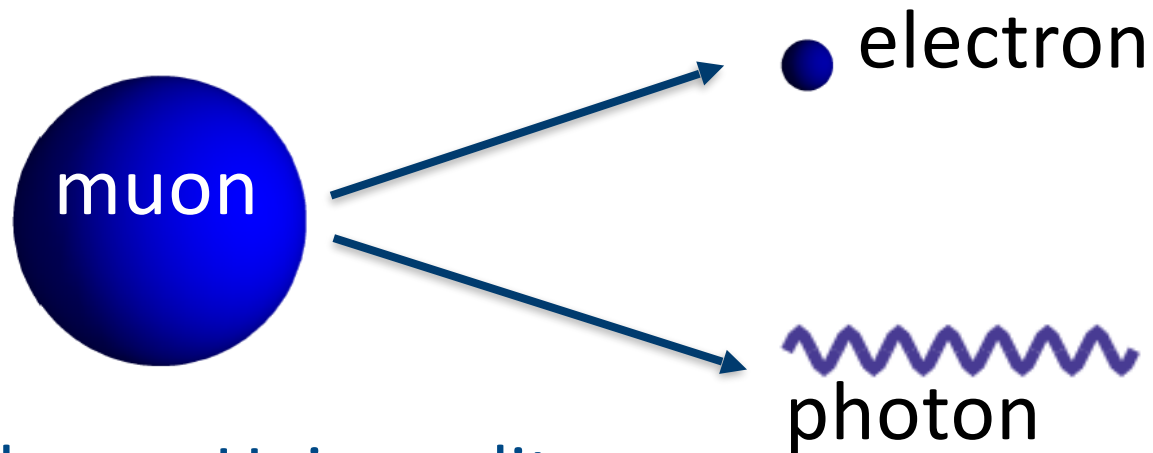
Alle Dinge sind drei



Der Zerfall eines Higgs-Bosons, wie es sich die Wissenschaftler vorstellen. Anhand der Messdaten des Teilchenbeschleunigers am Cern in Genf, die im Sommer das Higgs-Teilchen offenbart haben, kommen Forscher zu dem Schluss, dass die gesamte Materie aus nur wenigen Elementarbausteinen zusammengesetzt ist. (Foto: dpa)

Non-decoupling effects exclude a chiral 4th generation

- **Flavour Physics:** Study decays of heavy fermions into lighter ones
- **Lepton flavour violation** (example)

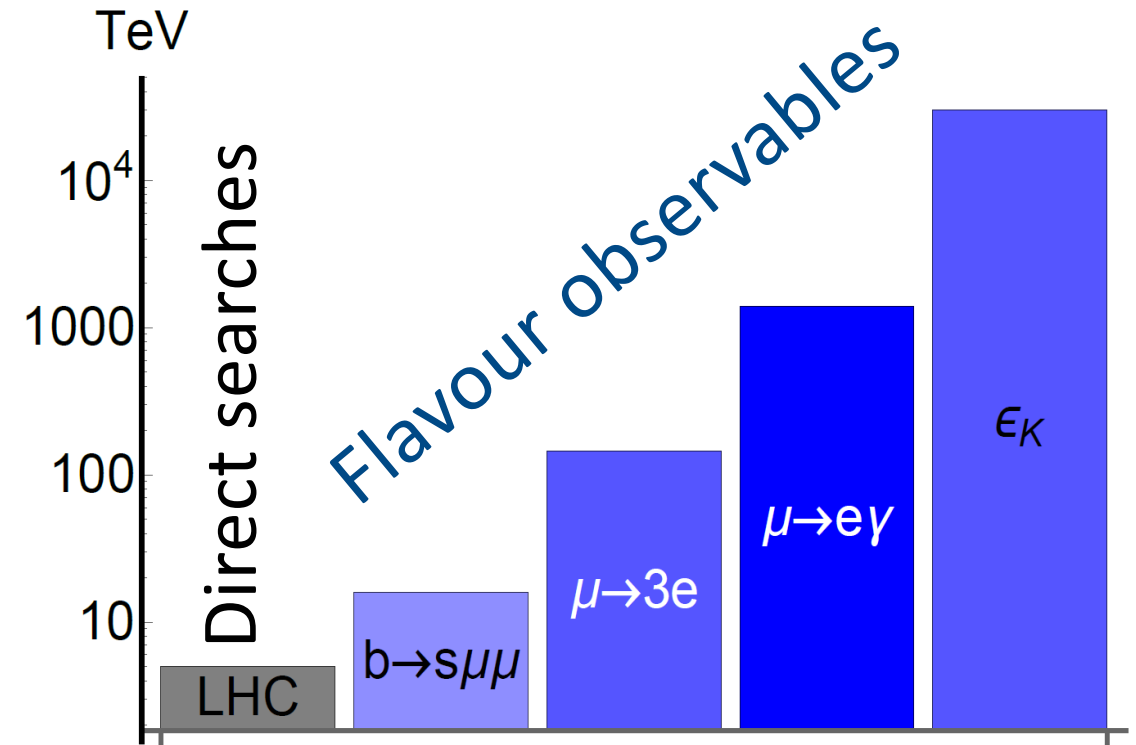
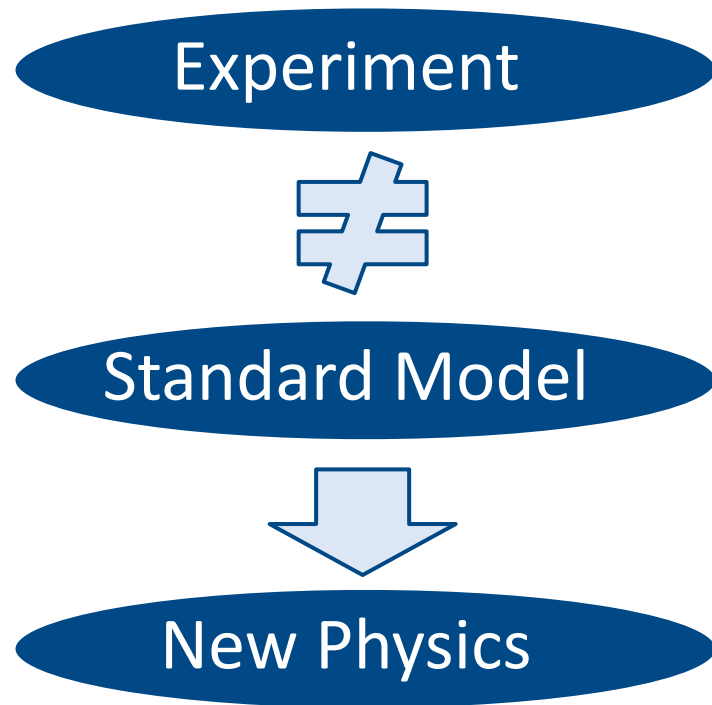


- **Lepton Flavour Universality:**
Leptons (e , μ and τ) interact in the same way

Lepton flavour (universality) conserved in the SM

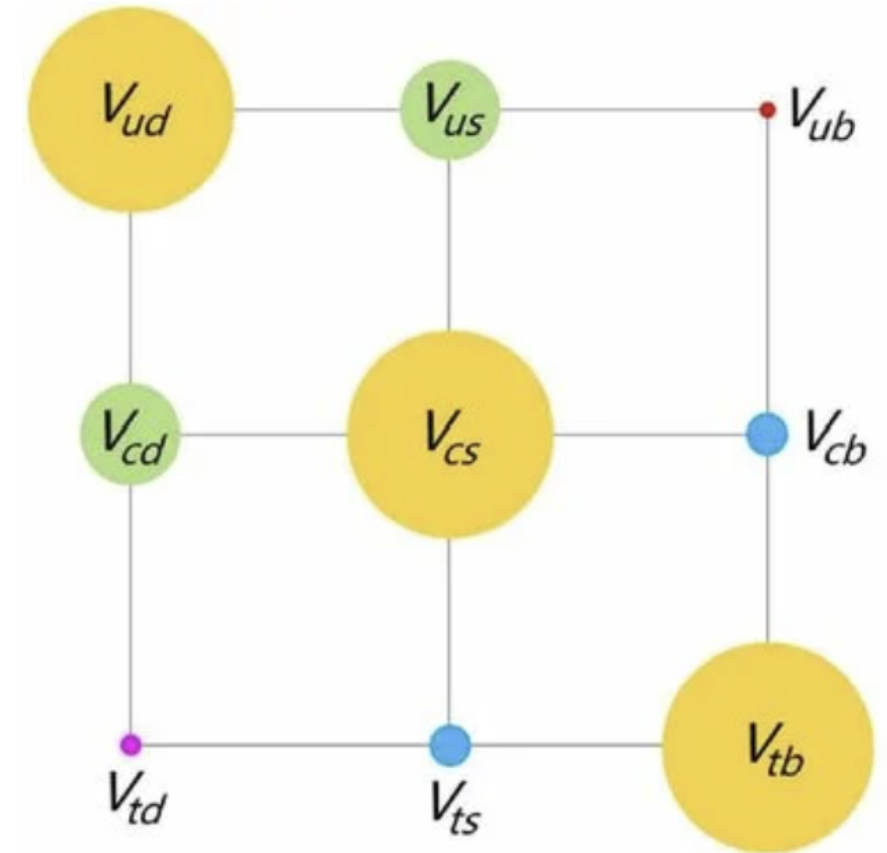
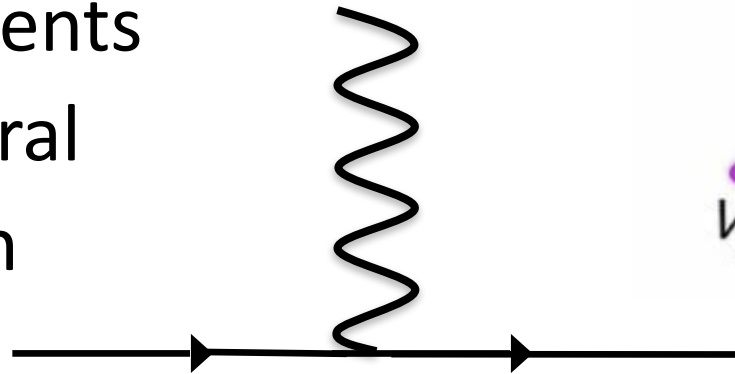
Finding New Physics with Flavour

- At colliders one produces many (up to 10^{14}) heavy quarks or leptons and measures their decays into light flavours



Flavour observables are sensitive to higher energy scales than collider searches

- CKM matrix is the only source of flavour violation in the SM
- Quark flavour violation is suppressed in the SM by the Fermi constant and small off-diagonal CKM elements
- Flavour changing neutral currents are in addition loop-suppressed



Very sensitive to potential new physics effects

- Flavour changing neutral currents loop suppressed

- Loop integrals needed (Diploma)

A. Denner, U. Nierste and R. Scharf,
Nucl. Phys. B **367** (1991), 637-656

The Complete $|\Delta S| = 2$ - Hamiltonian in the next-to-leading order

Stefan Herrlich (DESY, Zeuthen), Ulrich Nierste (Munich, Tech. U.) (Apr, 1996)

Published in: *Nucl.Phys.B* 476 (1996) 27-88 • e-Print: [hep-ph/9604330](https://arxiv.org/abs/hep-ph/9604330) [hep-ph]

- Very sensitive to New Physics

Indirect CP violation in the neutral kaon system beyond leading logarithms

Stefan Herrlich (PSI, Villigen), Ulrich Nierste (Munich, Tech. U.) (Jul, 1995)

Published in: *Phys.Rev.D* 52 (1995) 6505-6518 • e-Print: [hep-ph/9507262](https://arxiv.org/abs/hep-ph/9507262) [hep-ph]

- Calculation of QCD corrections

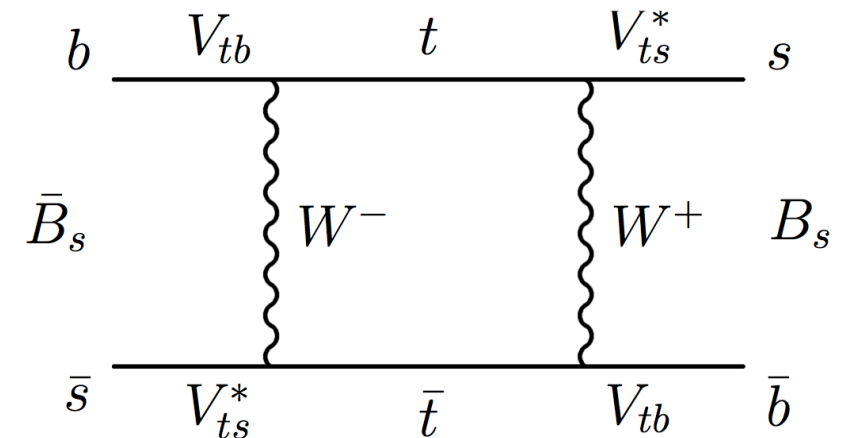
- Proof that perturbative QCD works for Kaon

- Enabled unitary triangle consistency check

Complete next-to-next-to-leading order QCD corrections to the decay matrix in B-meson mixing at leading power

Ulrich Nierste (KIT, Karlsruhe, TTP), Pascal Reek (KIT, Karlsruhe, TTP), Vladyslav Shtabovenko (Siegen U.), Matthias Steinhauser (KIT, Karlsruhe, TTP)

Dec 8, 2025



Andrzej Buras calls Uli the Master of box diagrams

- Are the measurements of the CKM elements consistent?
- Global statistical analysis needed
- Conservative R-fit method

Anatomy of New Physics in $B - \bar{B}$ mixing

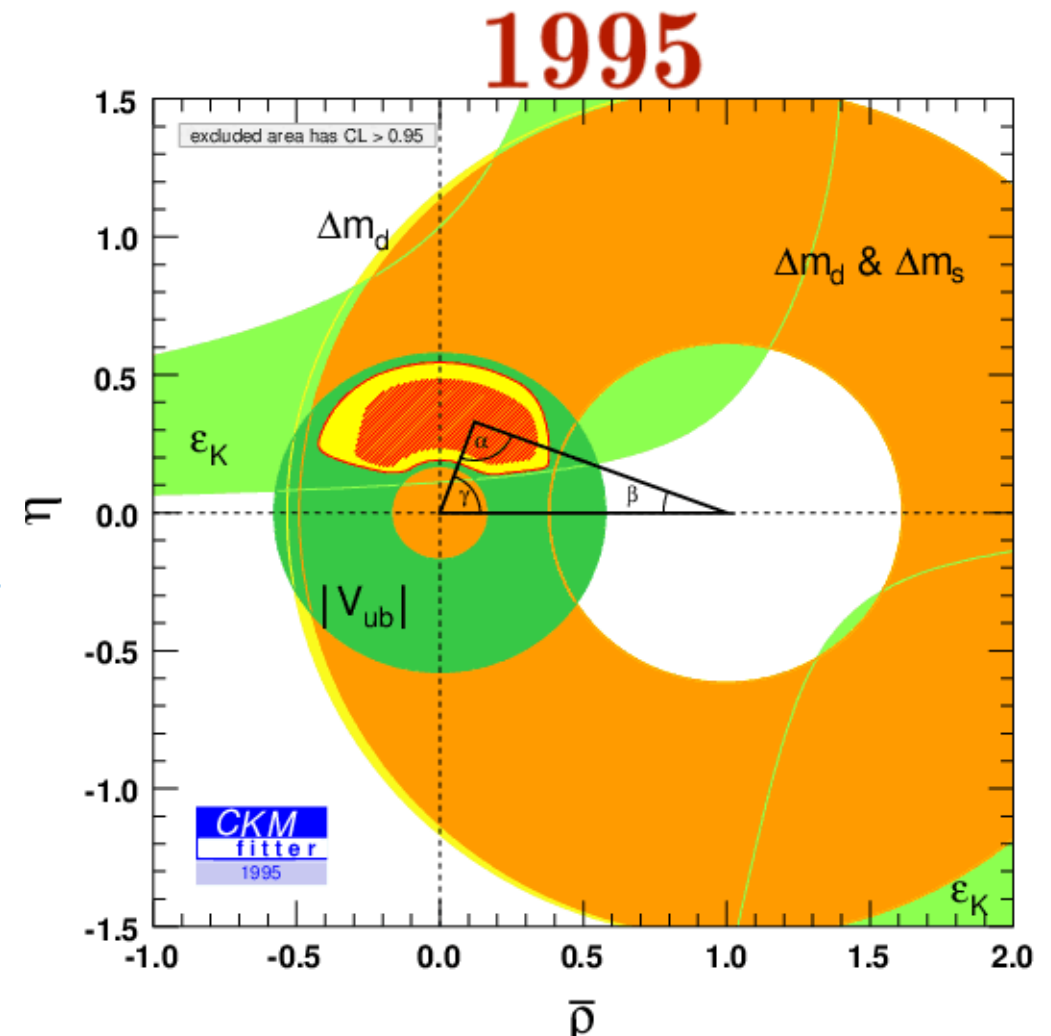
A. Lenz (Dortmund U. and Regensburg U.), U. Nierste (KIT, Karlsruhe, TTP), J. Charles (Marseille, CPT), S. Descotes-Genon (Orsay, LPT), A. Jantsch (Munich, Max Planck Inst.) [Show All\(10\)](#)

Aug, 2010

Constraints on new physics in $B - \bar{B}$ mixing in the light of recent LHCb data

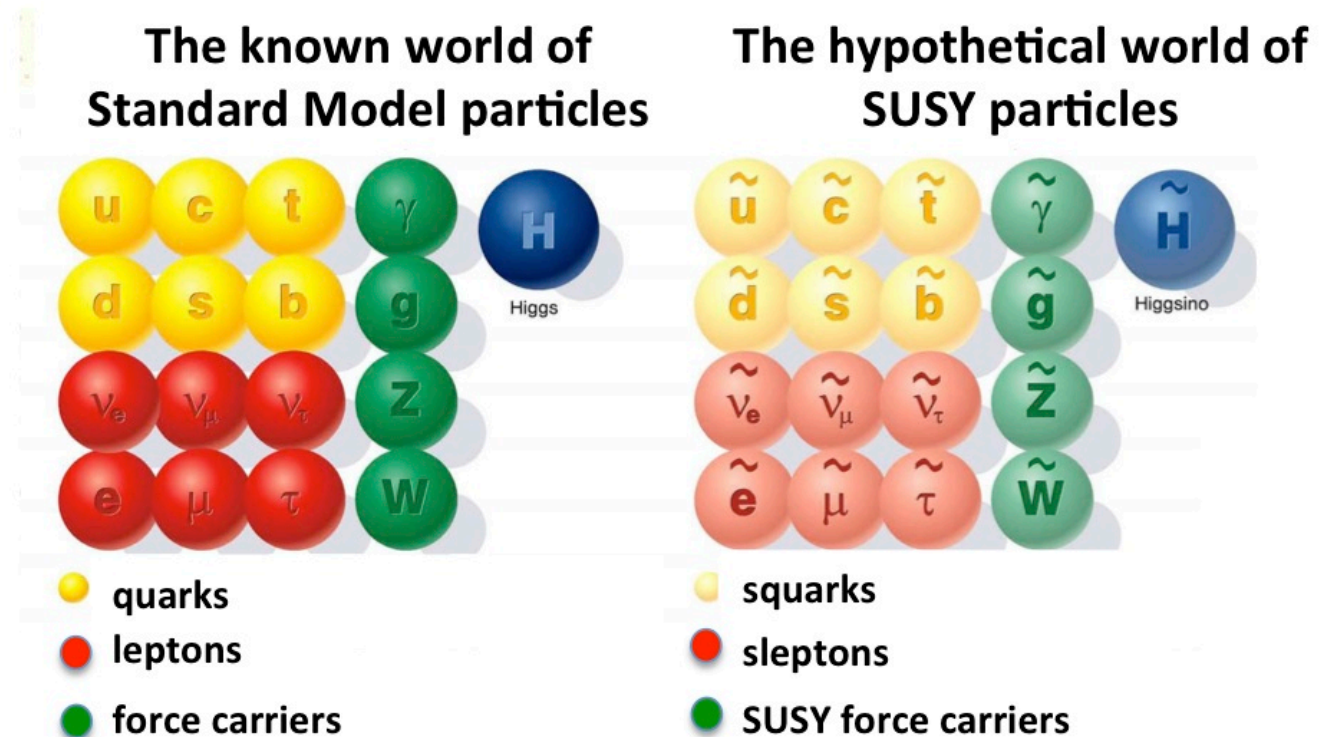
A. Lenz (CERN), U. Nierste (KIT, Karlsruhe, TTP), J. Charles (Marseille, CPT), S. Descotes-Genon (Orsay, LPT), H. Lacker (Humboldt U., Berlin) [Show All\(8\)](#)

Mar, 2012

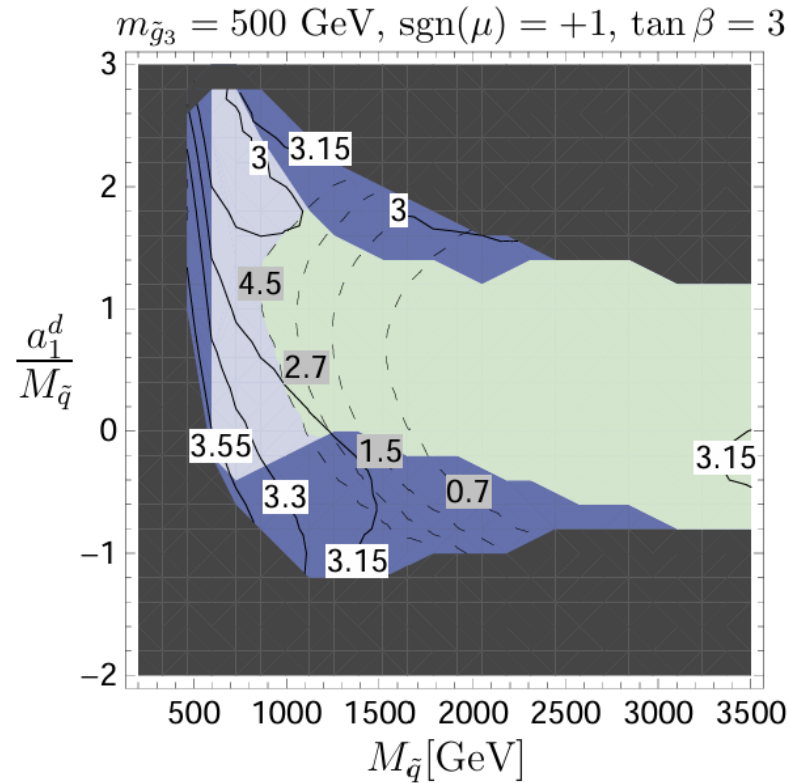


Impressive improvements; agreement with the SM (10% level)

- Start with a symmetry and/or organizing principle at a high-scale
 - Supersymmetry
 - Compositeness
 - Flavour symmetry
- Predict observables which show measurable deviations from the SM predictions
- Hope that future experimental improvements will validate the predictions



Theory guided approach to New Physics



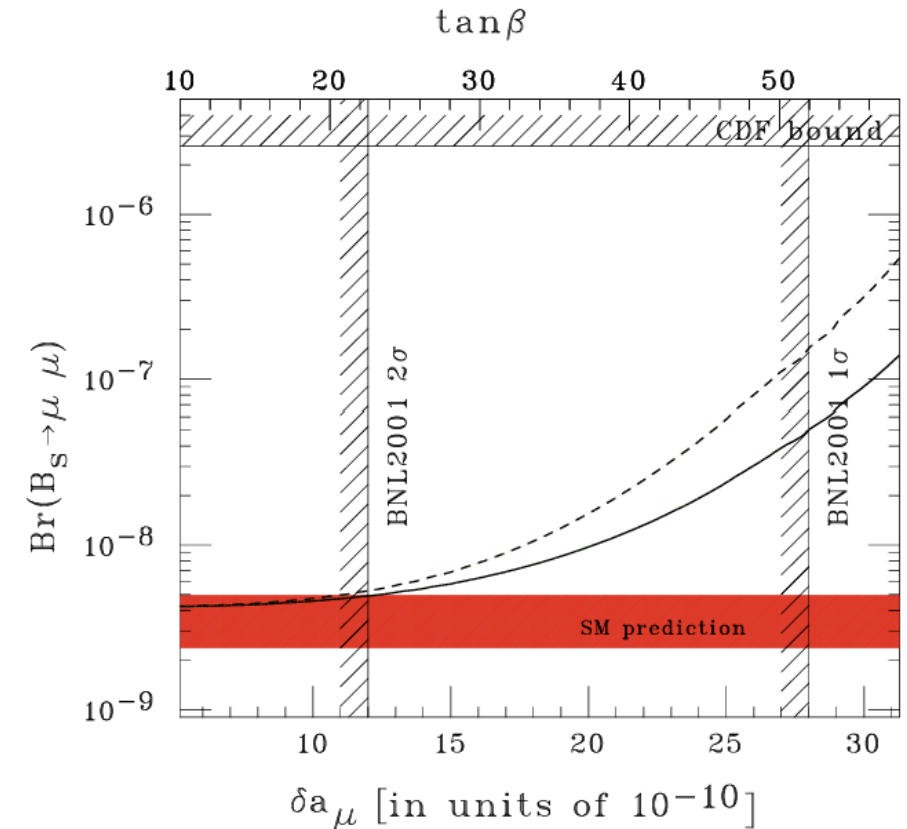
Correlation of $B_s \rightarrow \mu^+ \mu^-$ and $(g-2) (\mu)$ in minimal supergravity

Athanasios Dedes (Bonn U.), Herbert K. Dreiner (Bonn U.), Ulrich Nierste (CERN)

Aug, 2001

4 pages

Published in: *Phys.Rev.Lett.* 87 (2001) 251



Flavor Physics in an SO(10) Grand Unified Model

Jennifer Girrbach (KIT, Karlsruhe, TTP), Sebastian Jager (Sussex U.), Markus Knopf (KIT, Karlsruhe, TTP), Waldemar Martens (KIT, Karlsruhe, TTP), Ulrich Nierste (KIT, Karlsruhe, TTP) [Show All\(7\)](#)

Jan, 2011

Very predictive scenario with clear correlations among observables

- The fermion masses of the first two generations are small since they are generated at the loop-level from soft-SUSY-breaking terms
- SUSY with flavour symmetries
- Testable predictions
- Experimental limit still

outside the plotted range 😊

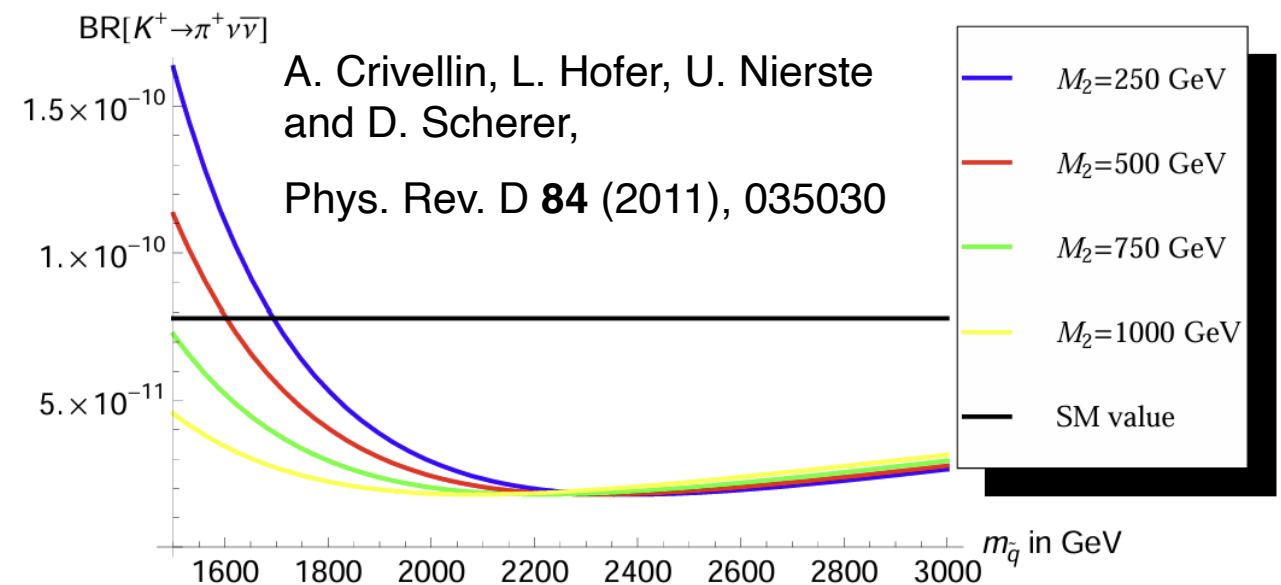
Rare Decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at the Next-to-Next-to-Leading Order in QCD

[Andrzej J. Buras](#)¹, [Martin Gorbahn](#)², [Ulrich Haisch](#)³, and [Ulrich Nierste](#)³

Show more ▾

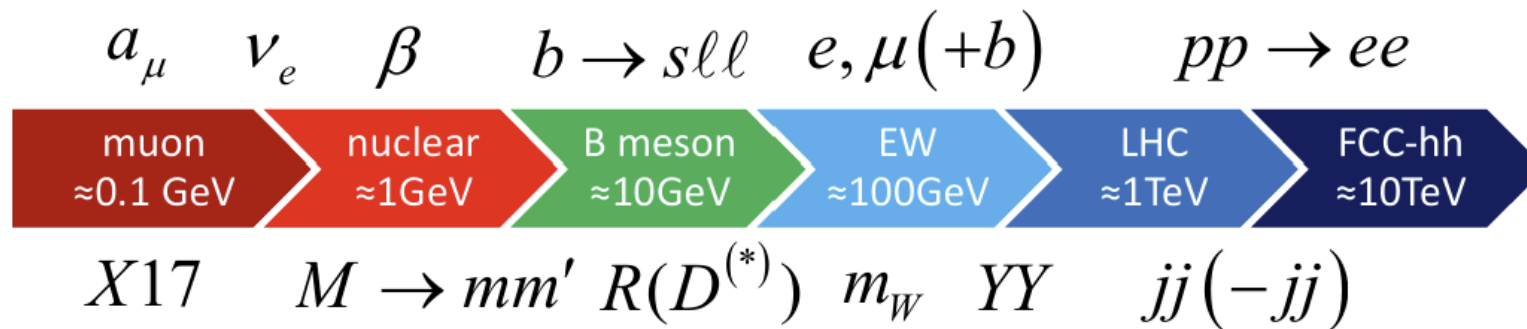
Phys. Rev. Lett. **95**, 261805 – Published 27 December, 2005

DOI: <https://doi.org/10.1103/PhysRevLett.95.261805>



All beautiful ideas, but no discovery so far...

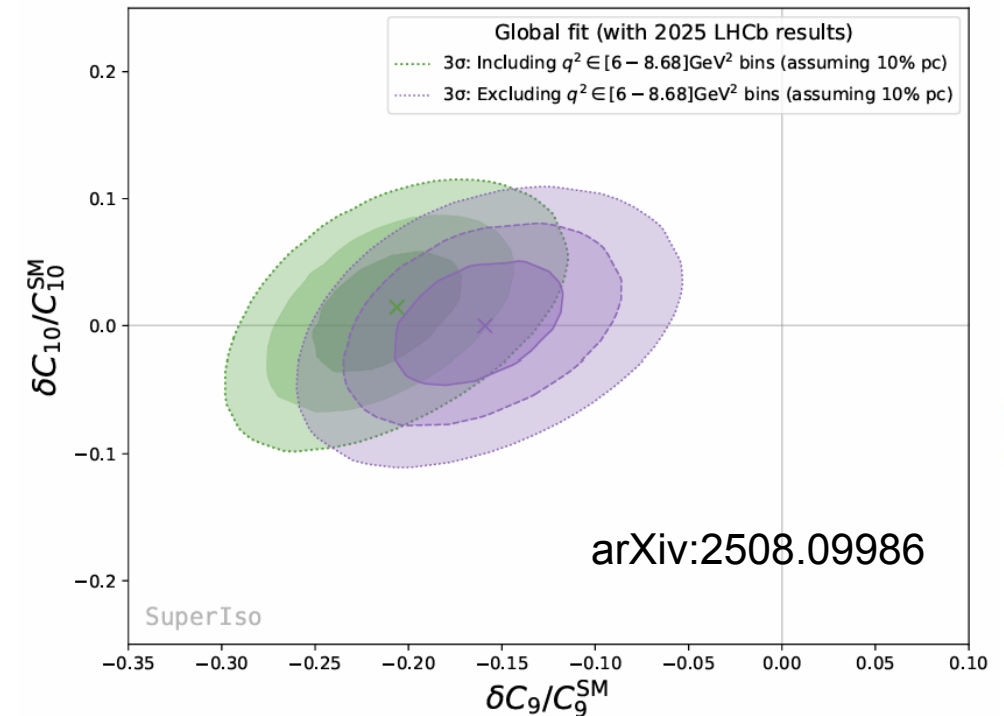
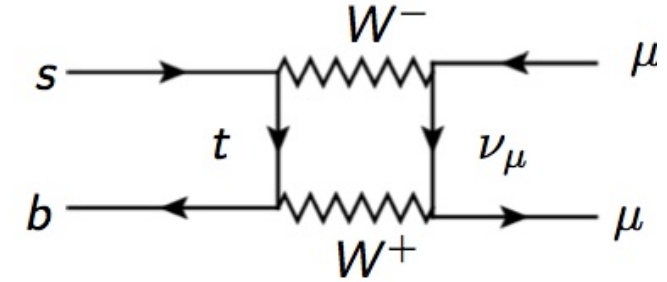
- Look to which extensions of the Standard Model the experimental data points
- Anomalies: Deviations from the Standard Model predictions
- If theory agrees with experiment there is no progress (V. Weisskopf)
- If experiment agrees with theory there is no progress (Andrzej Buras)
- If experiment and theory disagree, there is progress (A.C.)



A.C: Nature Rev. Phys. 6
(2024) no.5, 294-309

We need experimental guidance for the next theory breakthrough

- Flavour Changing Neutral Current (FCNC)
- In the SM it is suppressed by
 - CKM elements, electroweak scale and loop-factor
- Emerging since 2013
- Recent confirmations of
 - $B_s \rightarrow \phi \mu \mu$ (CMS)
 - $B \rightarrow K \mu \mu$ (lattice calculation)
 - $B \rightarrow K^* \mu \mu$ (LHCb and CMS)

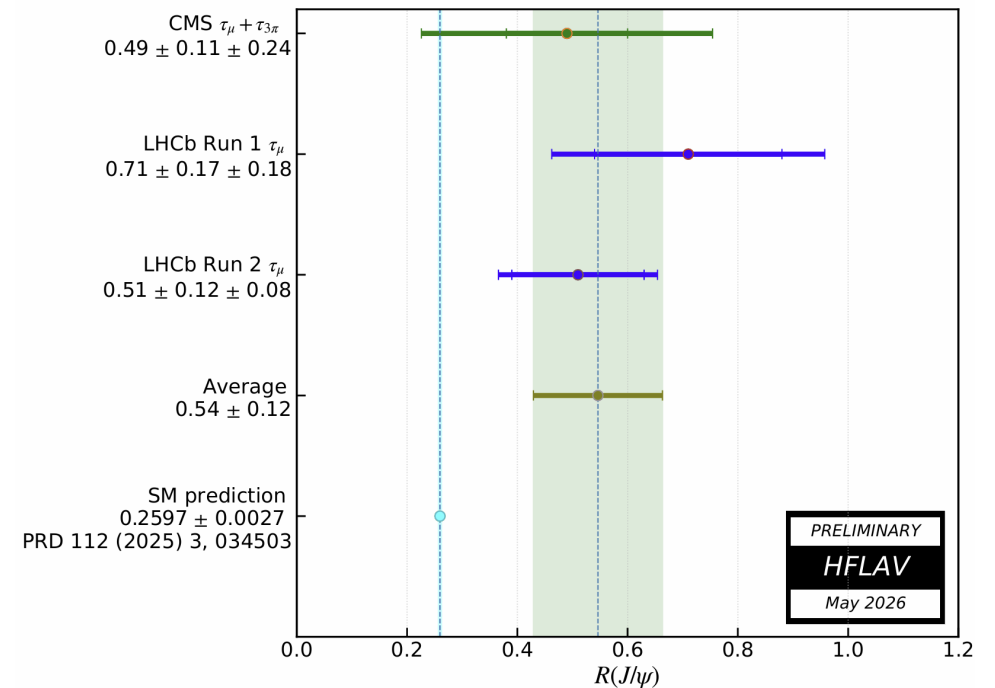
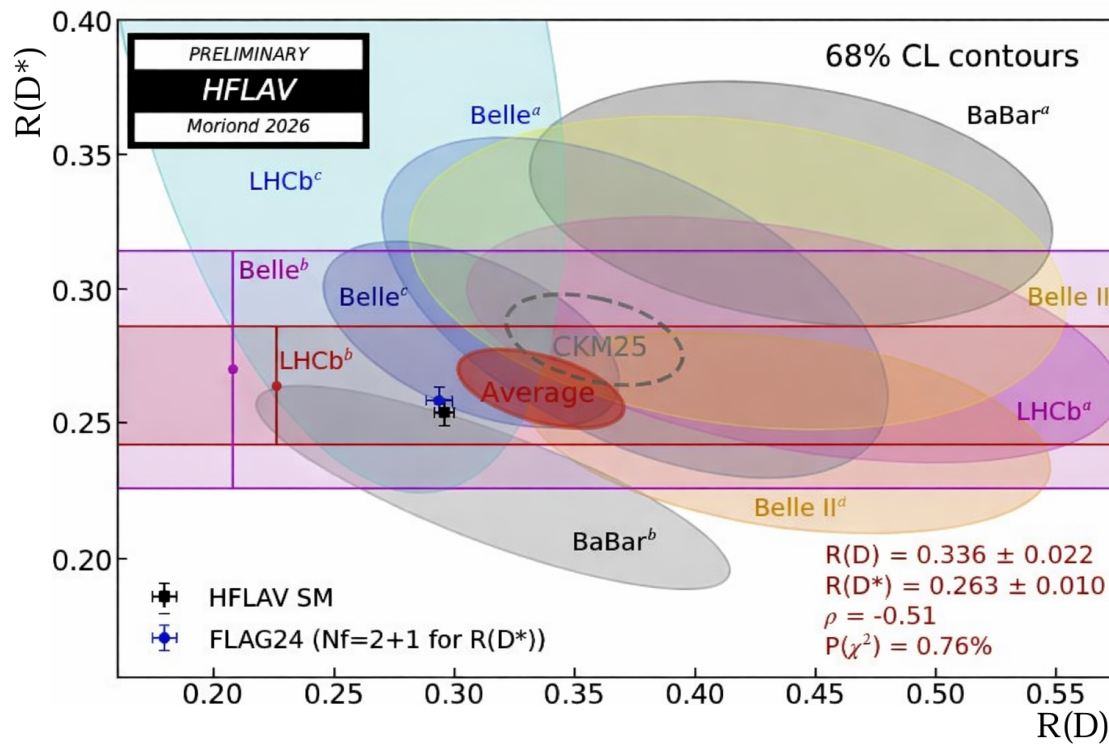


Global significance above 7σ for lepton flavour universal NP

- Related to tau leptons
- Cannot be due to form factors

Discriminating $B \rightarrow D^* \ell \nu$ form factors via polarization observables and asymmetries

Marco Fedele (KIT, Karlsruhe, TTP), Monika Blanke (KIT, Karlsruhe, TTP and KIT, Karlsruhe, IKP), Andreas Crivellin (PSI, Villigen and Zurich U.), Syuhei Iguro (KIT, Karlsruhe, TTP and KIT, Karlsruhe, IKP), Ulrich Nierste (KIT, Karlsruhe, TTP) [Show All\(7\)](#)
May 24, 2023



Indications for 10% new physics in the charged current

- Leptoquarks

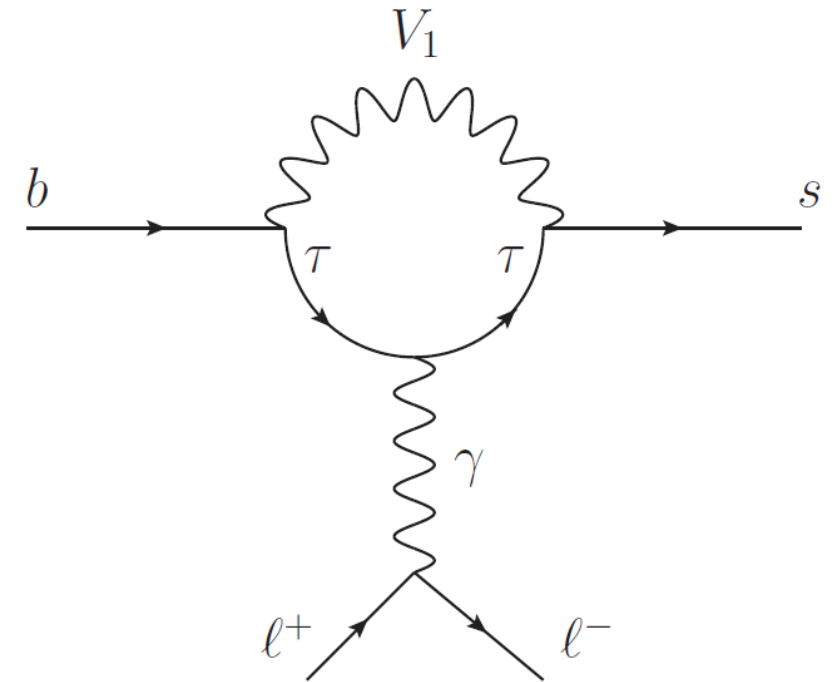
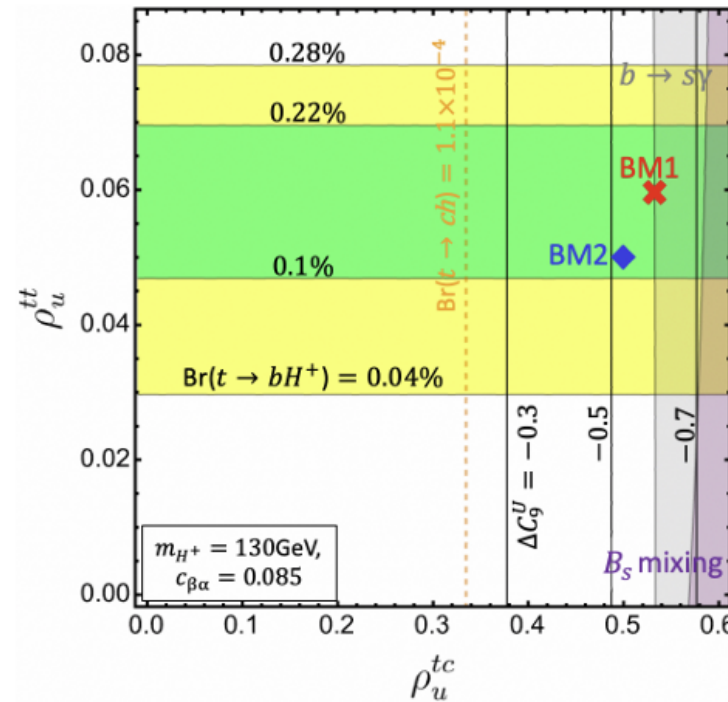
- Tree-level vector-current in $b \rightarrow c \tau \nu$
- Tau-loop induced off-shell photon penguin in $b \rightarrow s \mu \mu$

- Charged Higgs

- Tree-level scalar current in $b \rightarrow c \tau \nu$
- Charm-loop induced off-shell photon penguin in $b \rightarrow s \mu \mu$

Accumulating hints for flavor-violating Higgs bosons at the electroweak scale

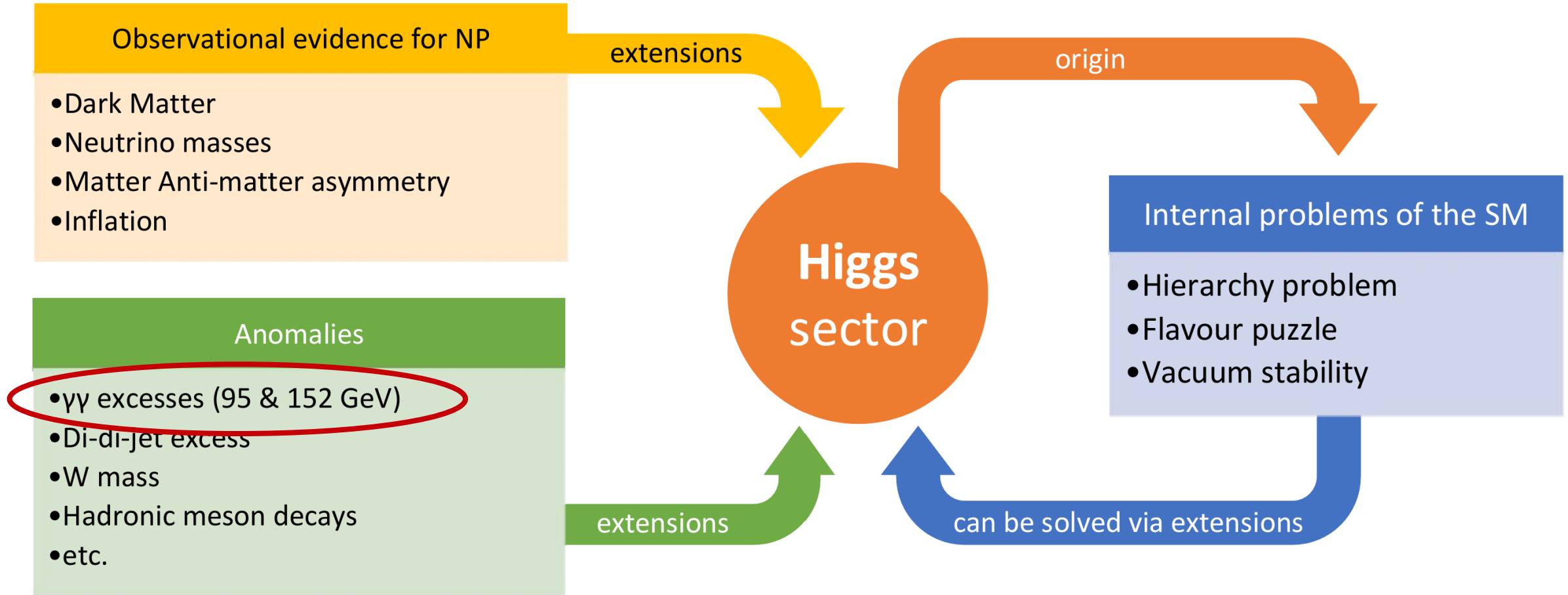
Andreas Crivellin (Zurich U. and PSI, Villigen), Syuhei Iguro (KIT, Karlsruhe, TTP and KIT, Karlsruhe, IAP)



Indications for a 130 GeV charged Higgs at the LHC

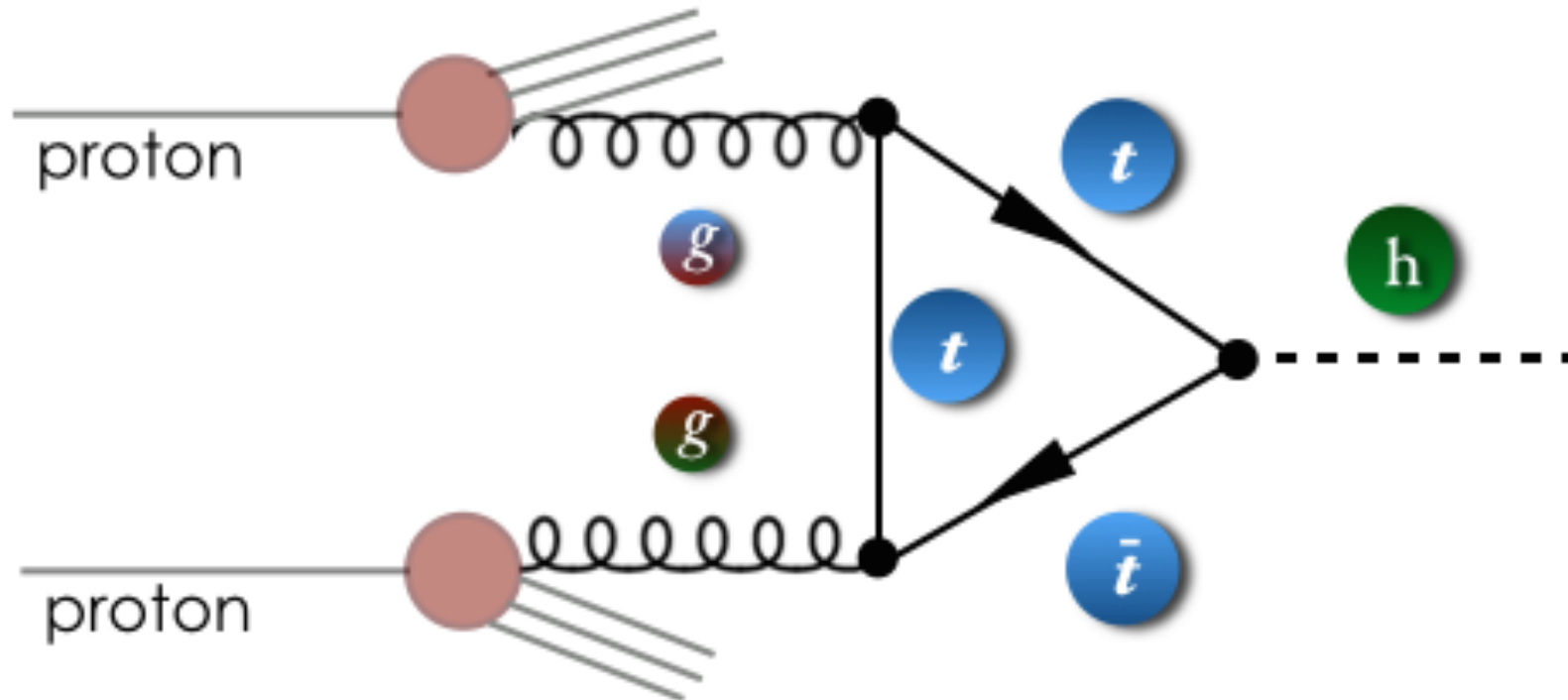
Why new Higgses?

- Minimal realization in the SM not protected by any symmetry principle



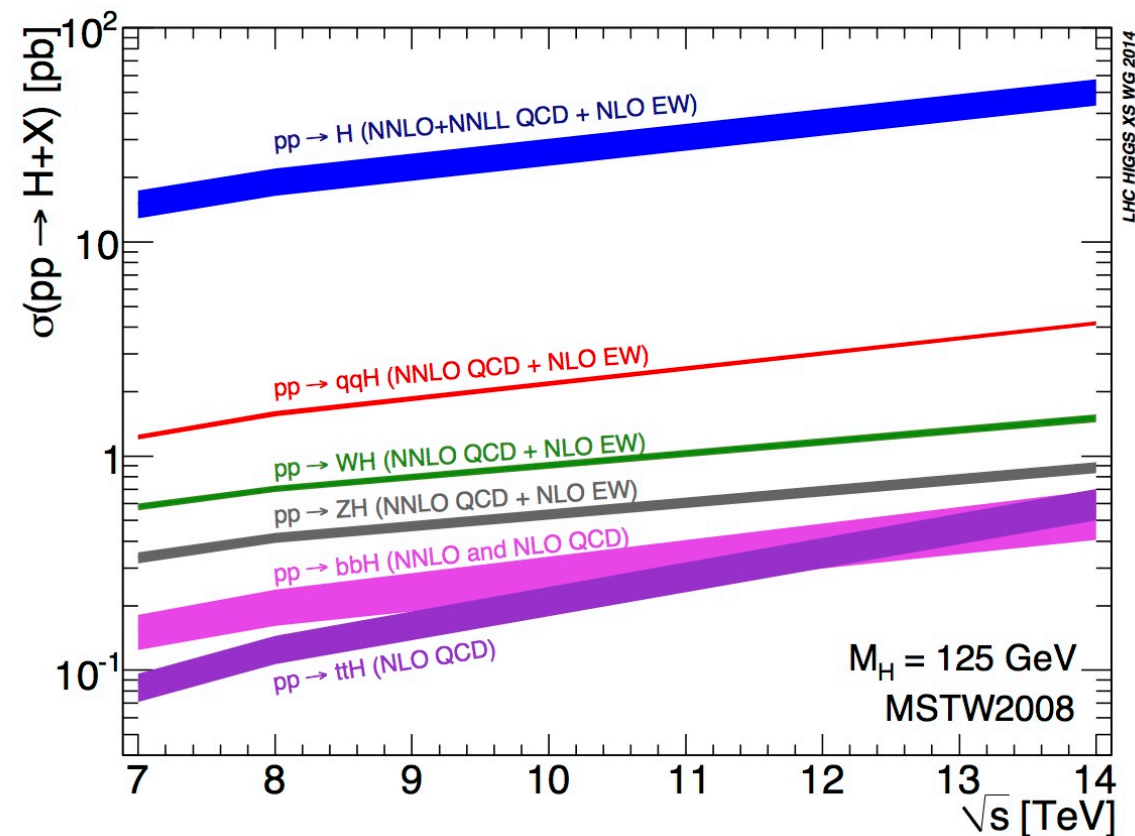
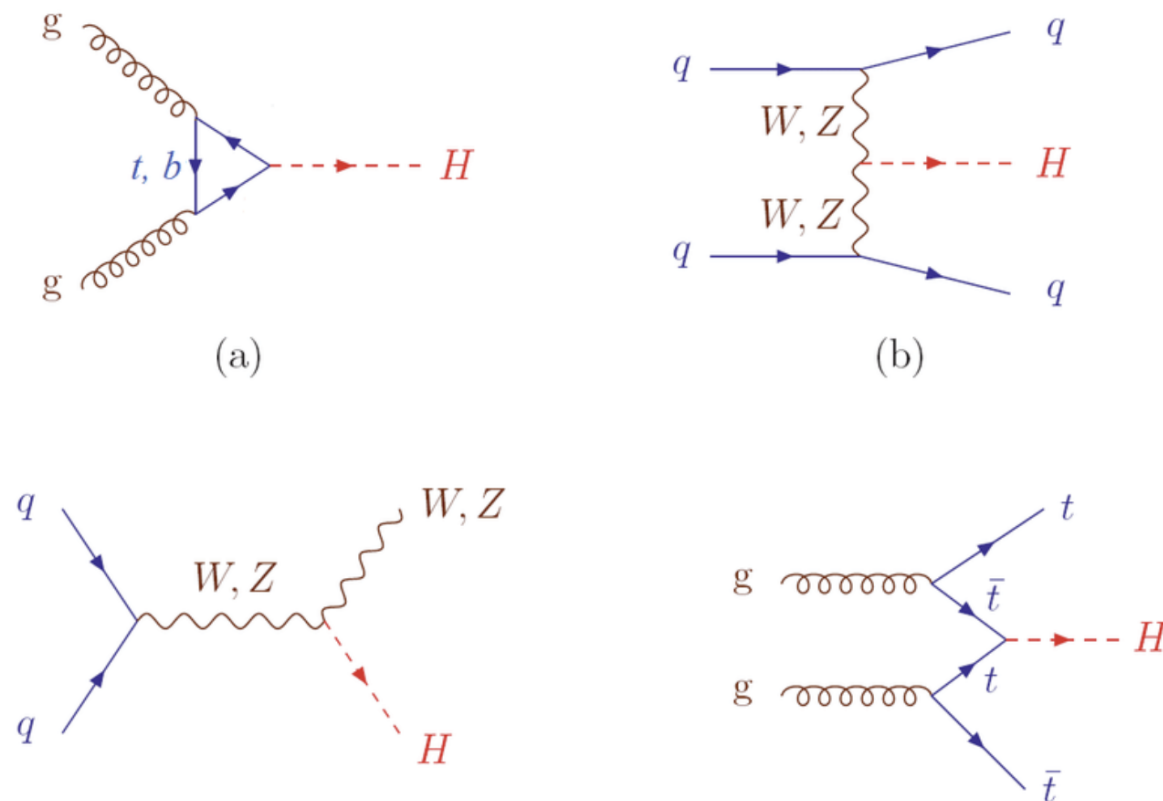
Higgs sector very promising place to expect new physics

- Higgs Production at the “loop-level”, i.e. via quantum fluctuations



Only particle known which was only produced via quantum fluctuations

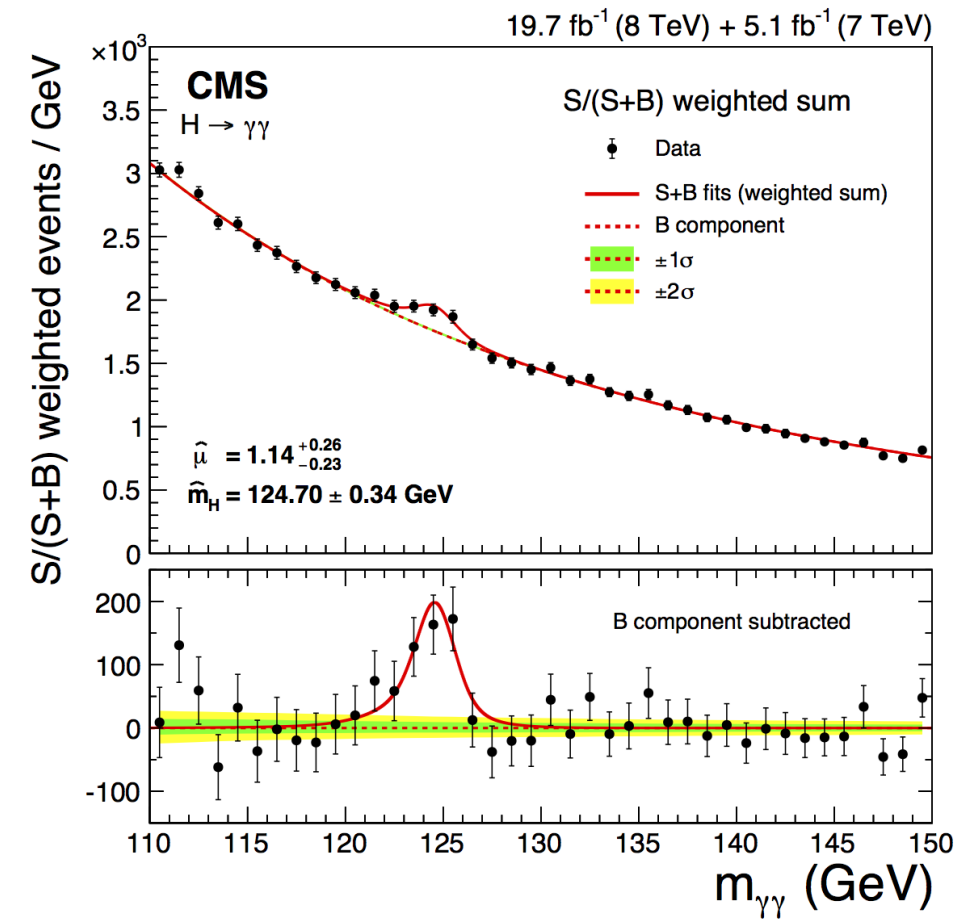
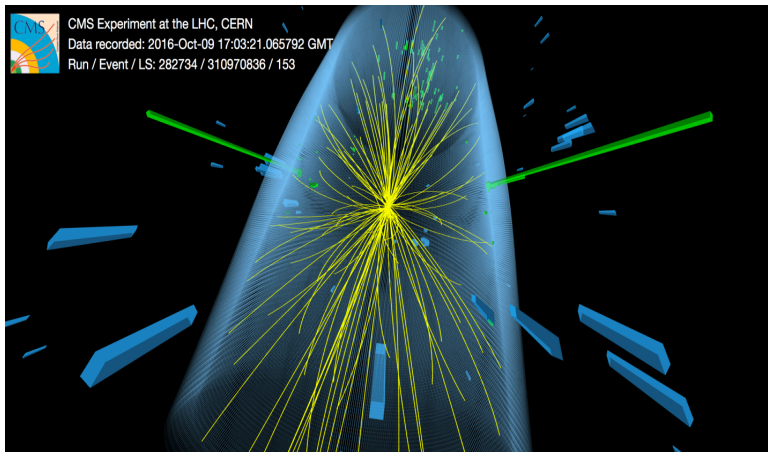
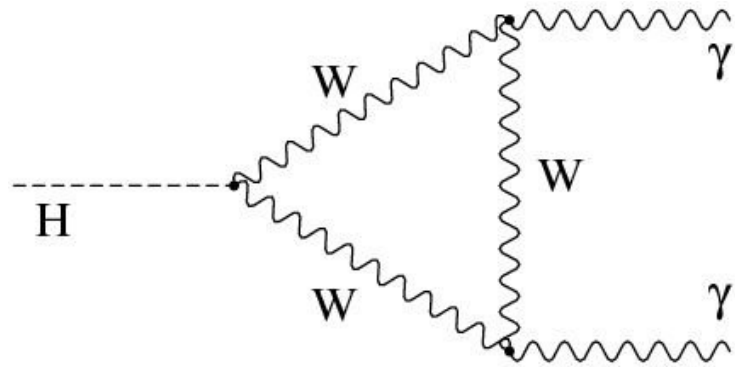
Higgs production



Gluon fusion dominant in the SM $\rightarrow$ inclusive searches most sensitive

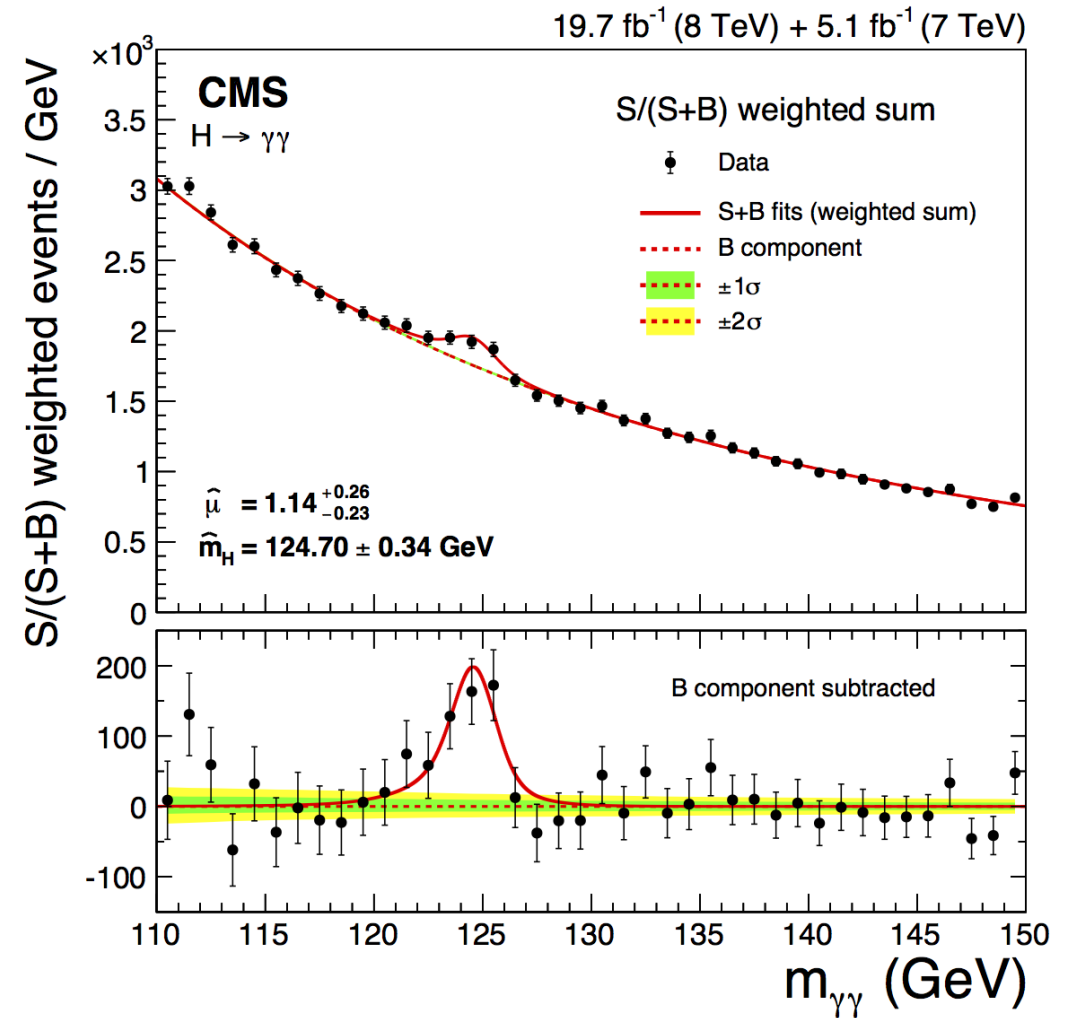
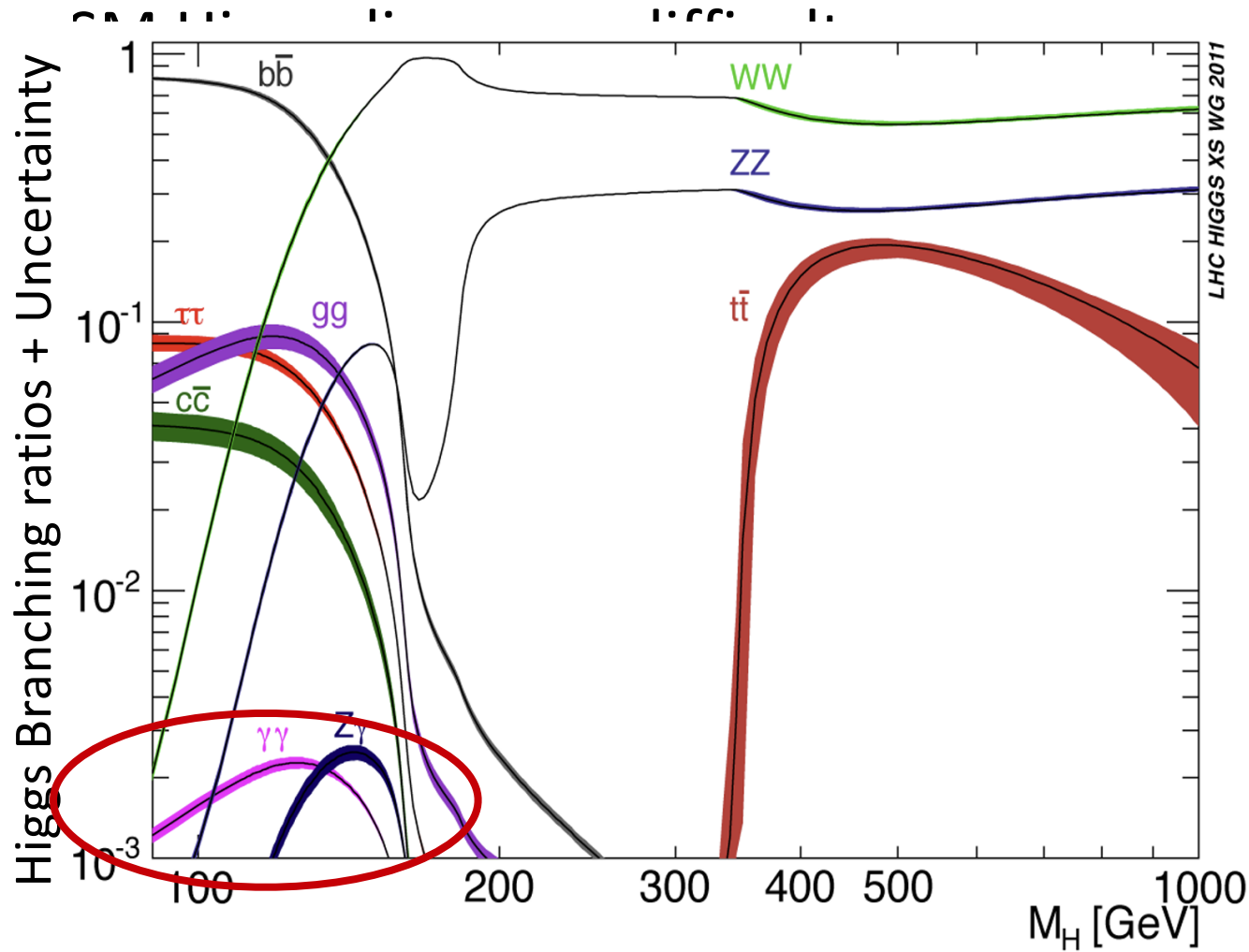
Higgs decays

- Higgs decay to photons a very sensitive channel



Very few events, many collisions needed

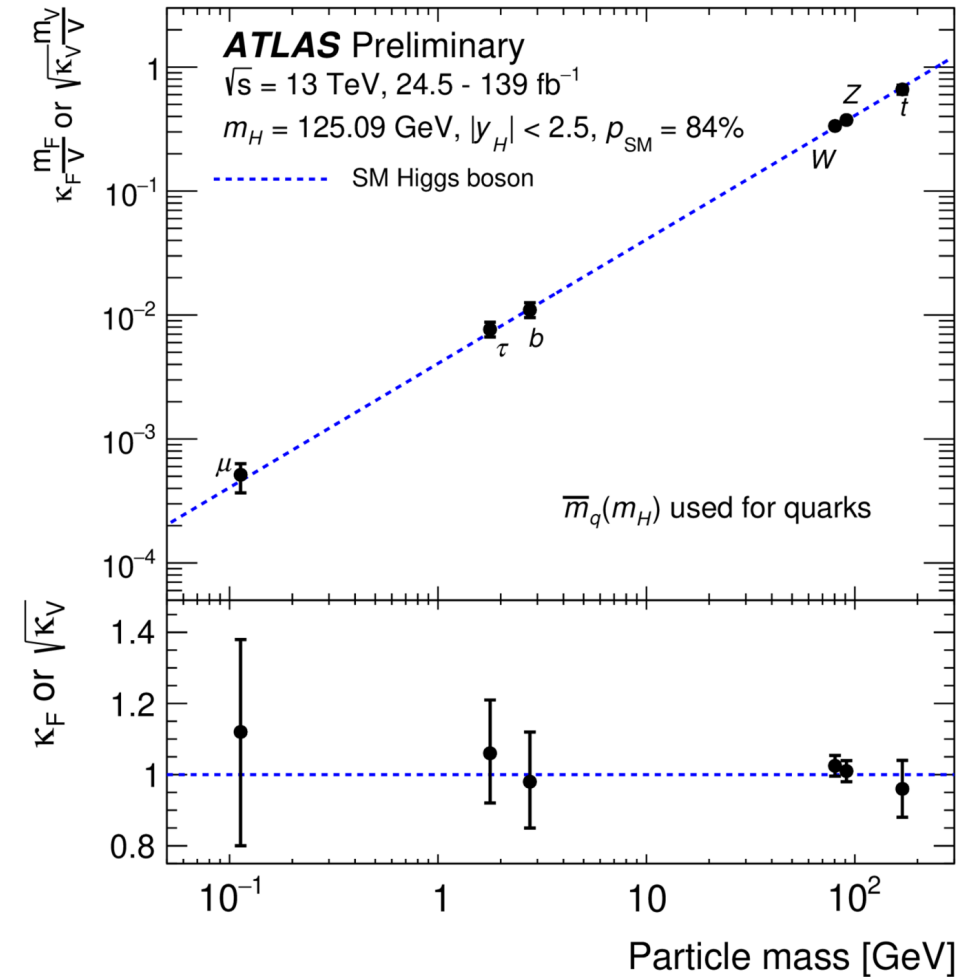
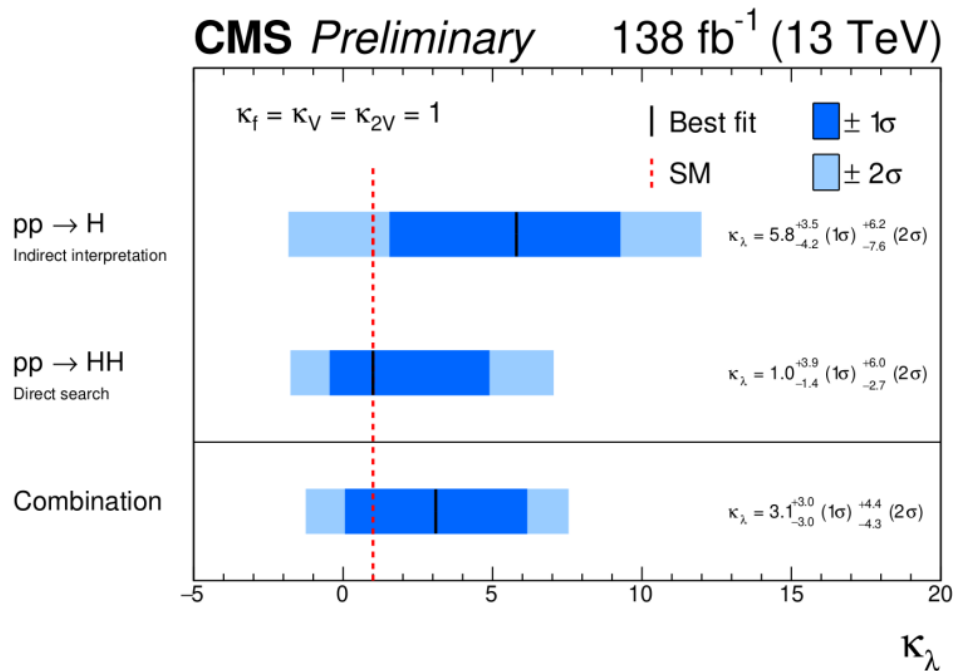
Higgses at the electroweak scale



EW scale Higgses difficult to observe; di-photon natural discovery channel

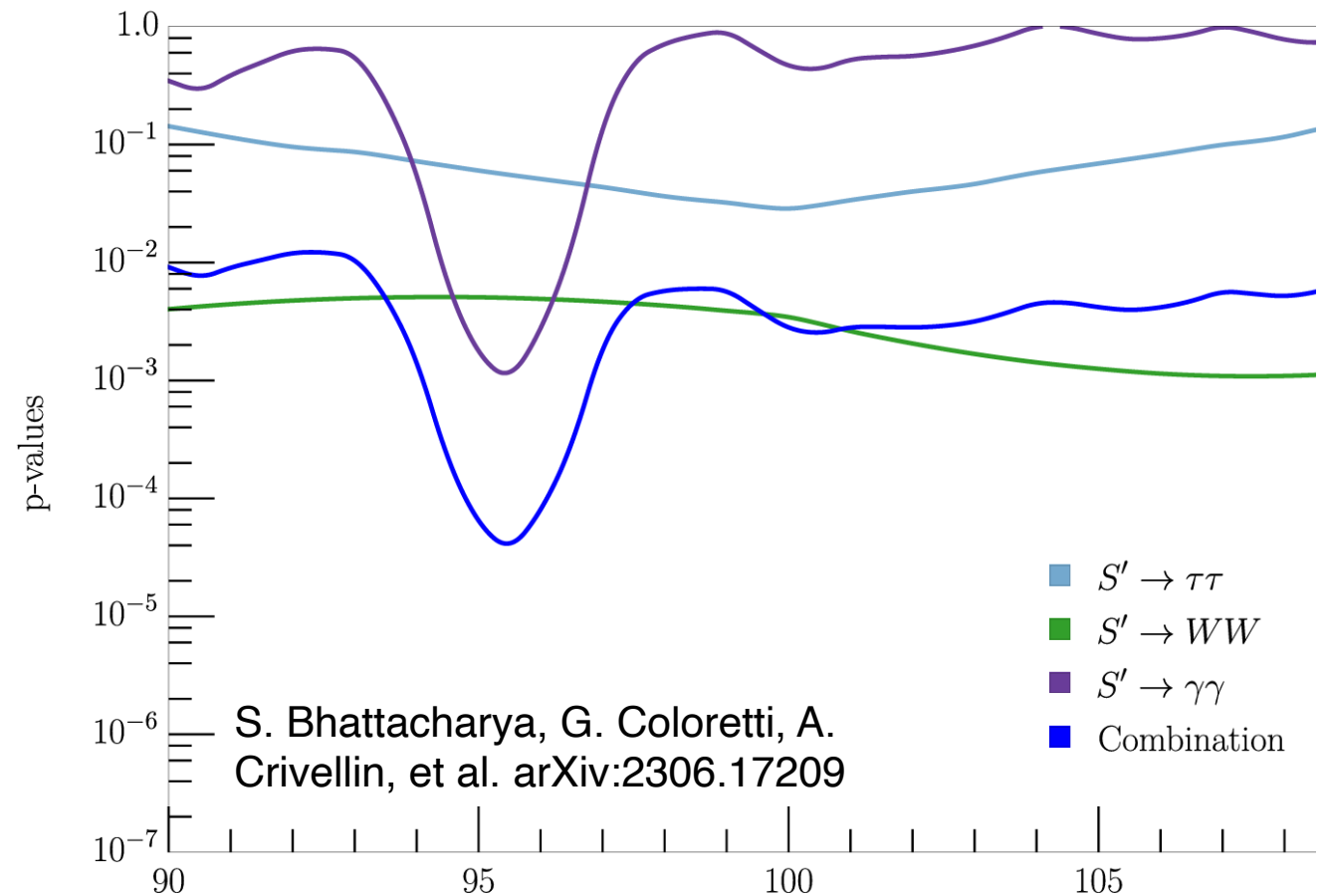
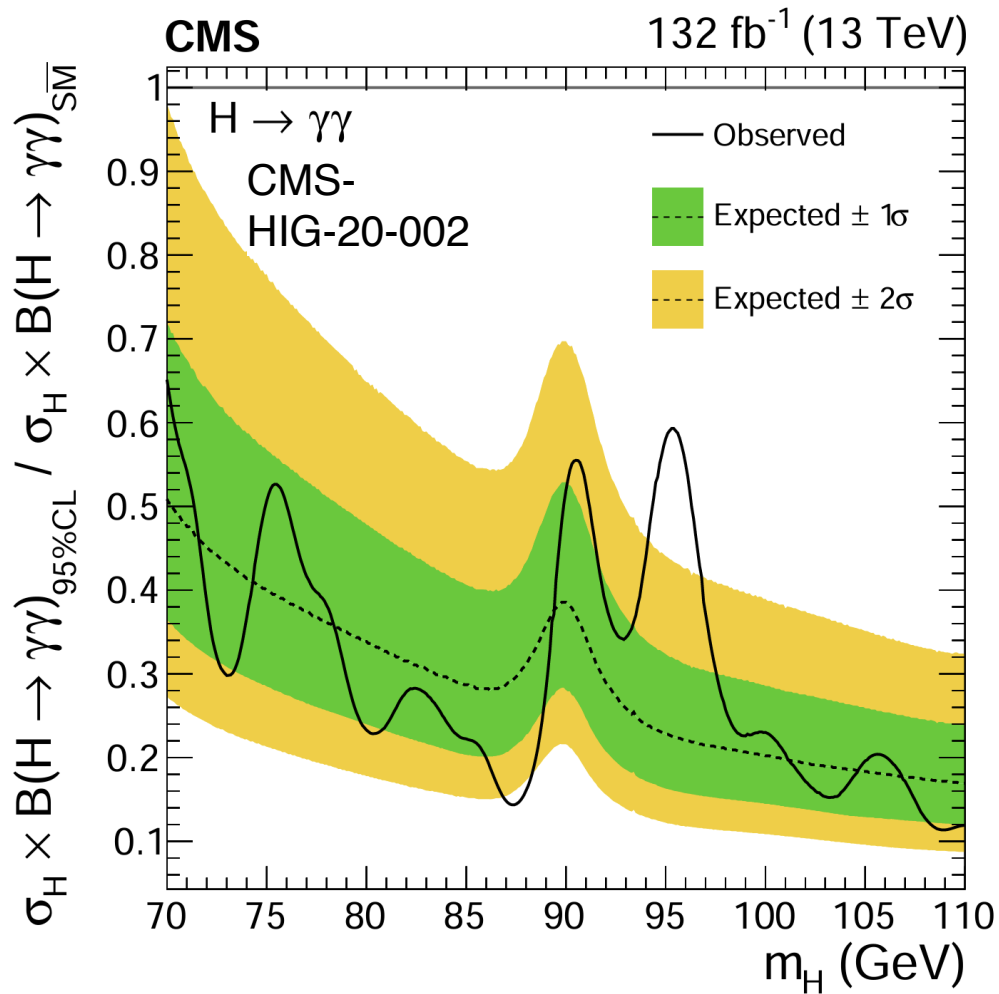
Standard Model Higgs properties

- Higgs decays as expected in the Standard Model (within errors)
- Self-couplings not well known



There can still be new Higgs bosons if they mix weakly with the SM Higgs

Indications for a 95 GeV Higgs

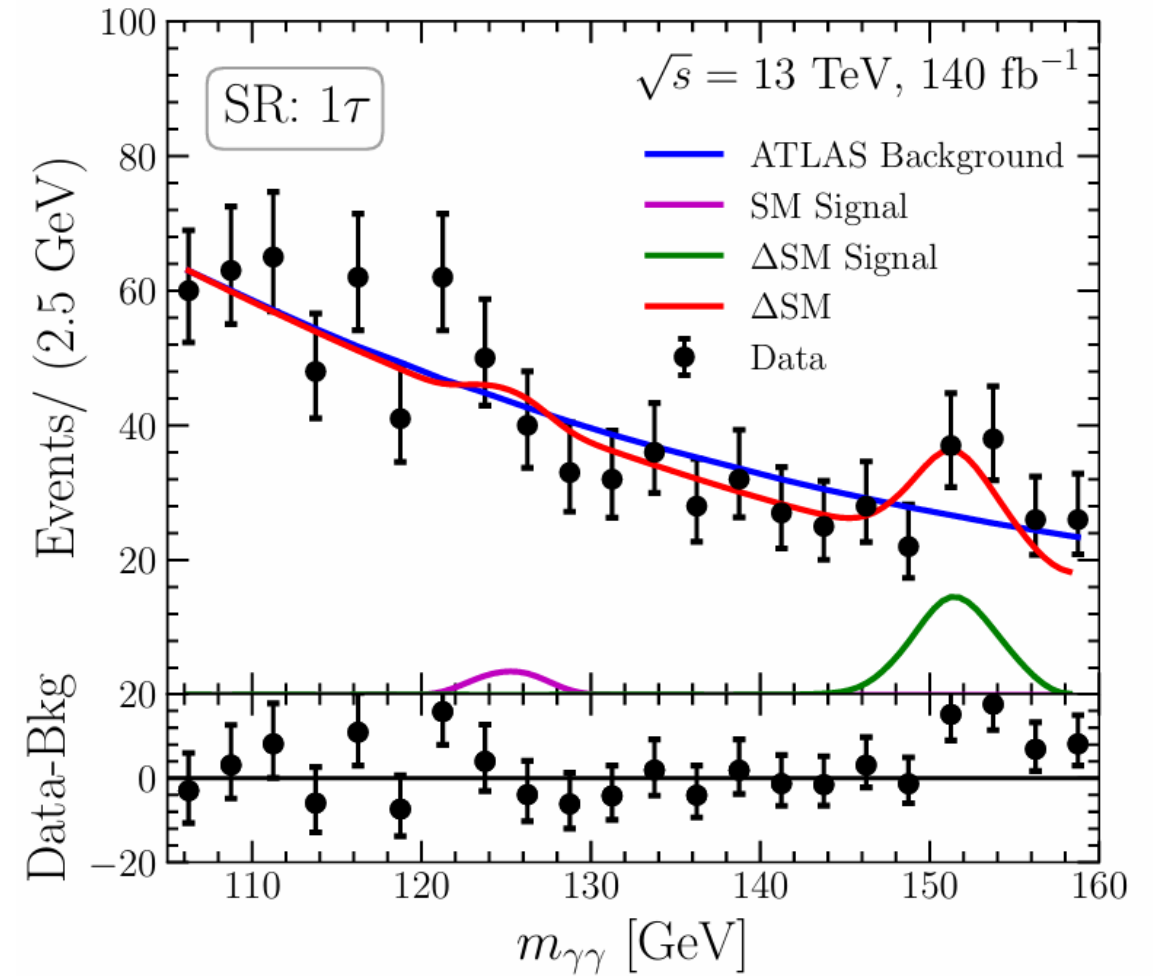
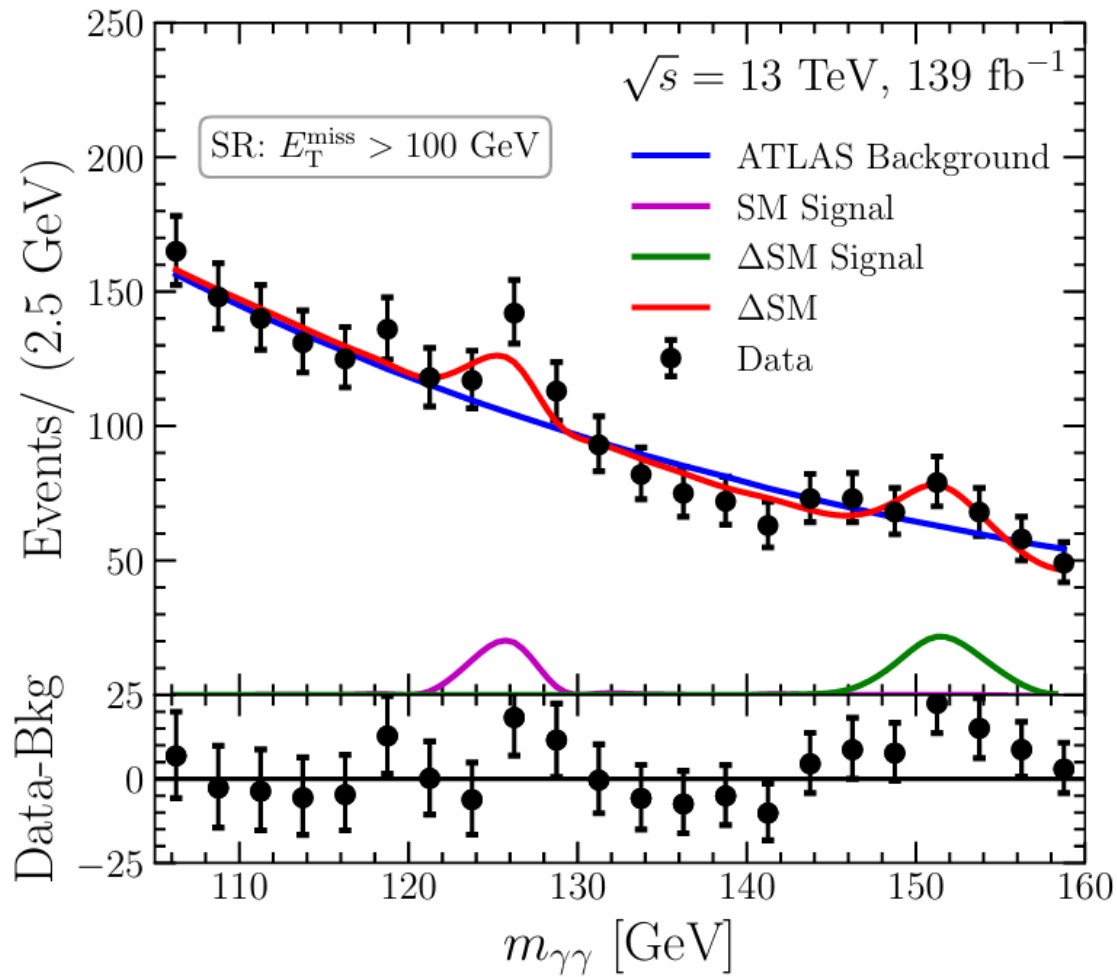


Di-photon channel supported by WW and $\tau\tau$: 3.4 σ global significance

152 GeV Scalar in Associated Production

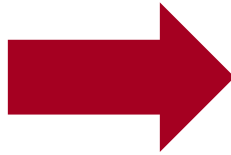
JHEP 07 (2023) 176

ATLAS-CONF-2024-005

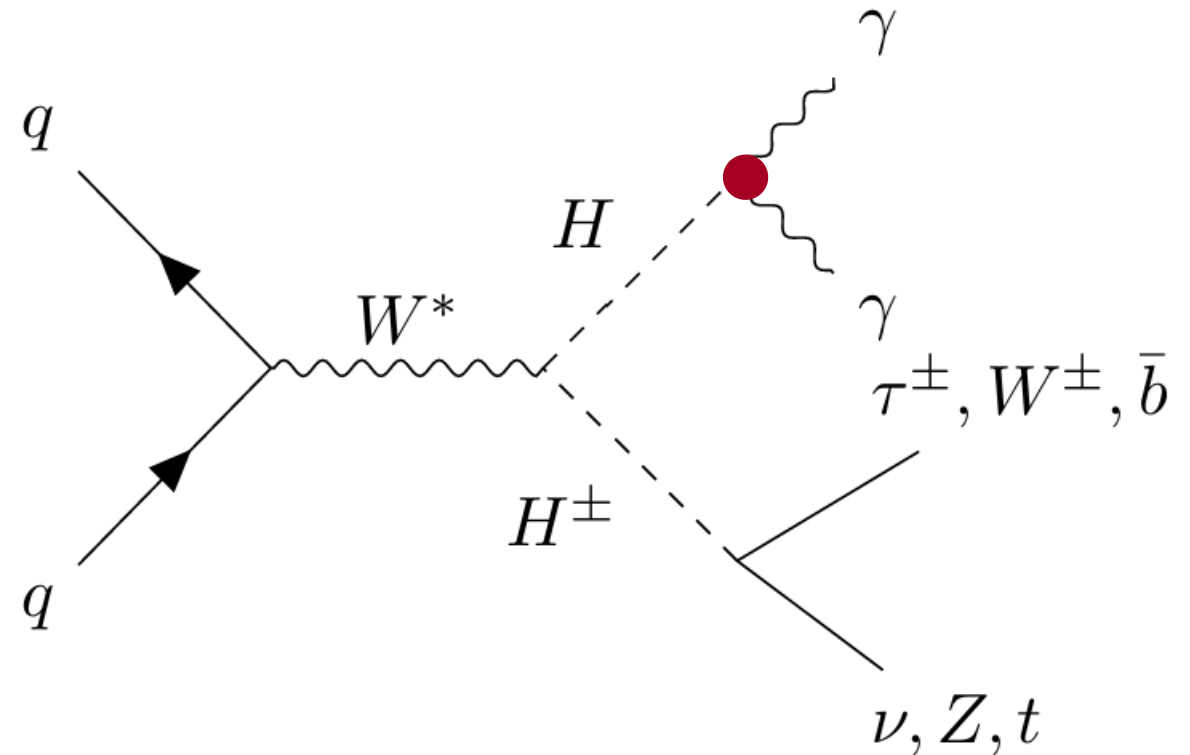


Associated production can enhance signal over background strength

- Looking at all 23 channels, we need:
- Two photons produced in association with
 - One lepton, but not two leptons
 - One tau, but not two taus
 - $1b (\geq 1l + 1b)$, but not $t_{lep} (=1l + 1b)$
 - Moderate missing energy



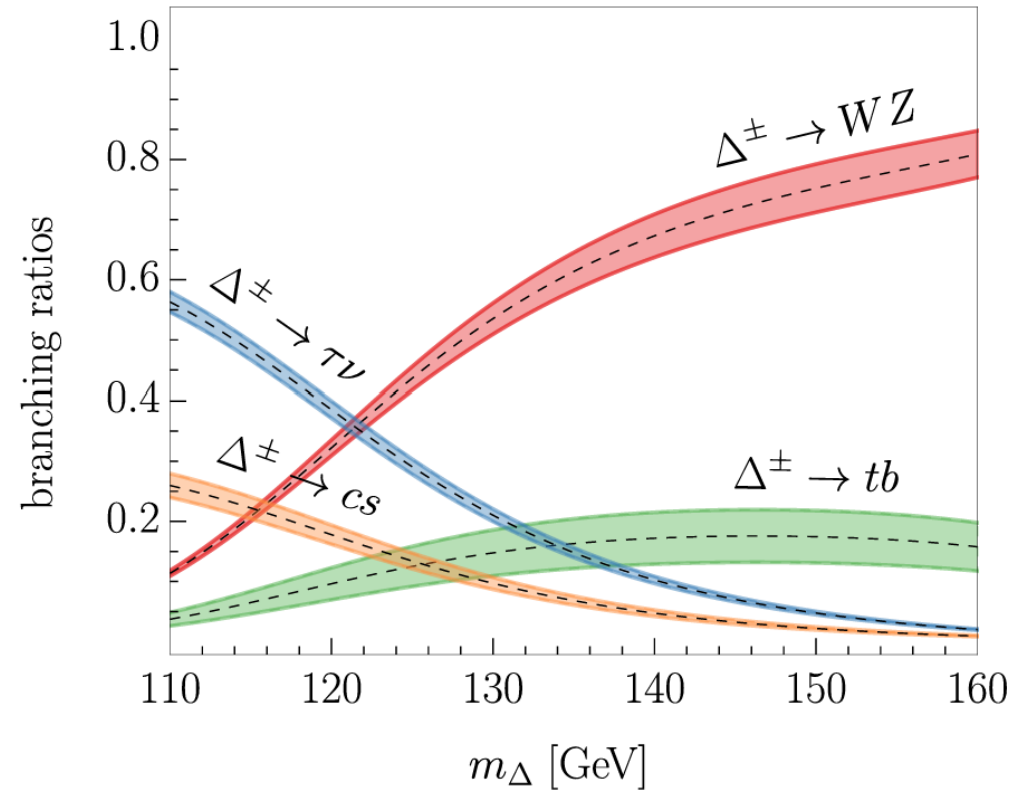
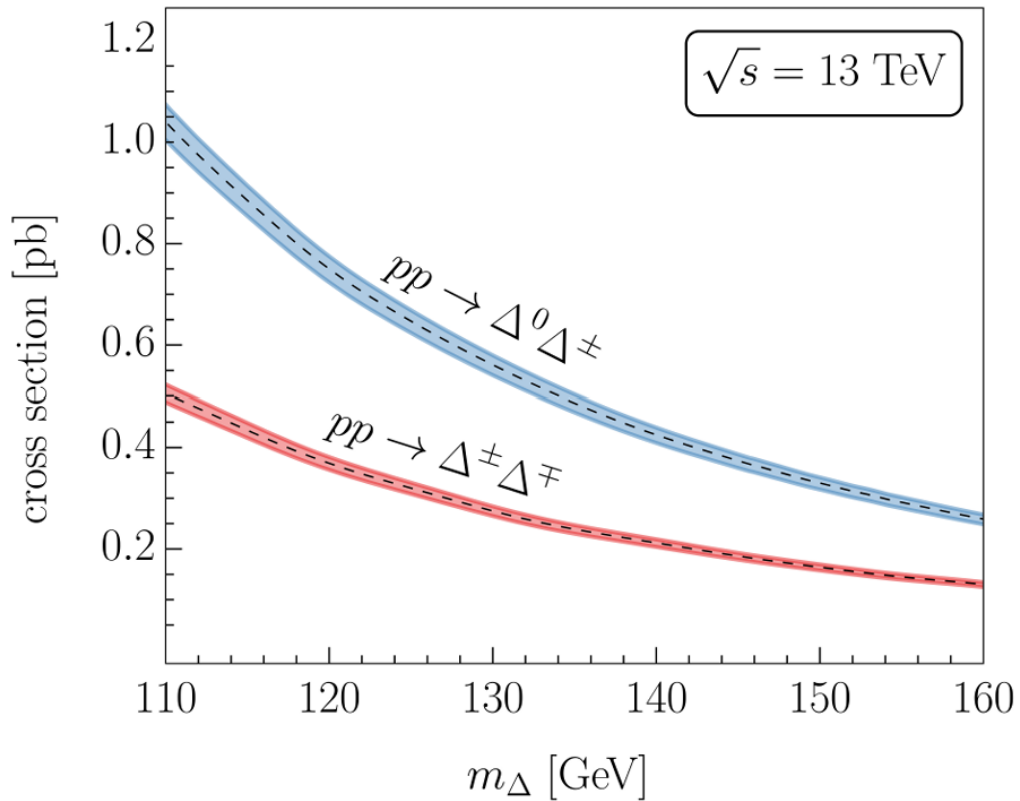
Drell Yan production of a charged and a neutral Higgs



Drell-Yan production leads to the right signature

$SU(2)_L$ Triplet with $Y=0$ (Δ SM)

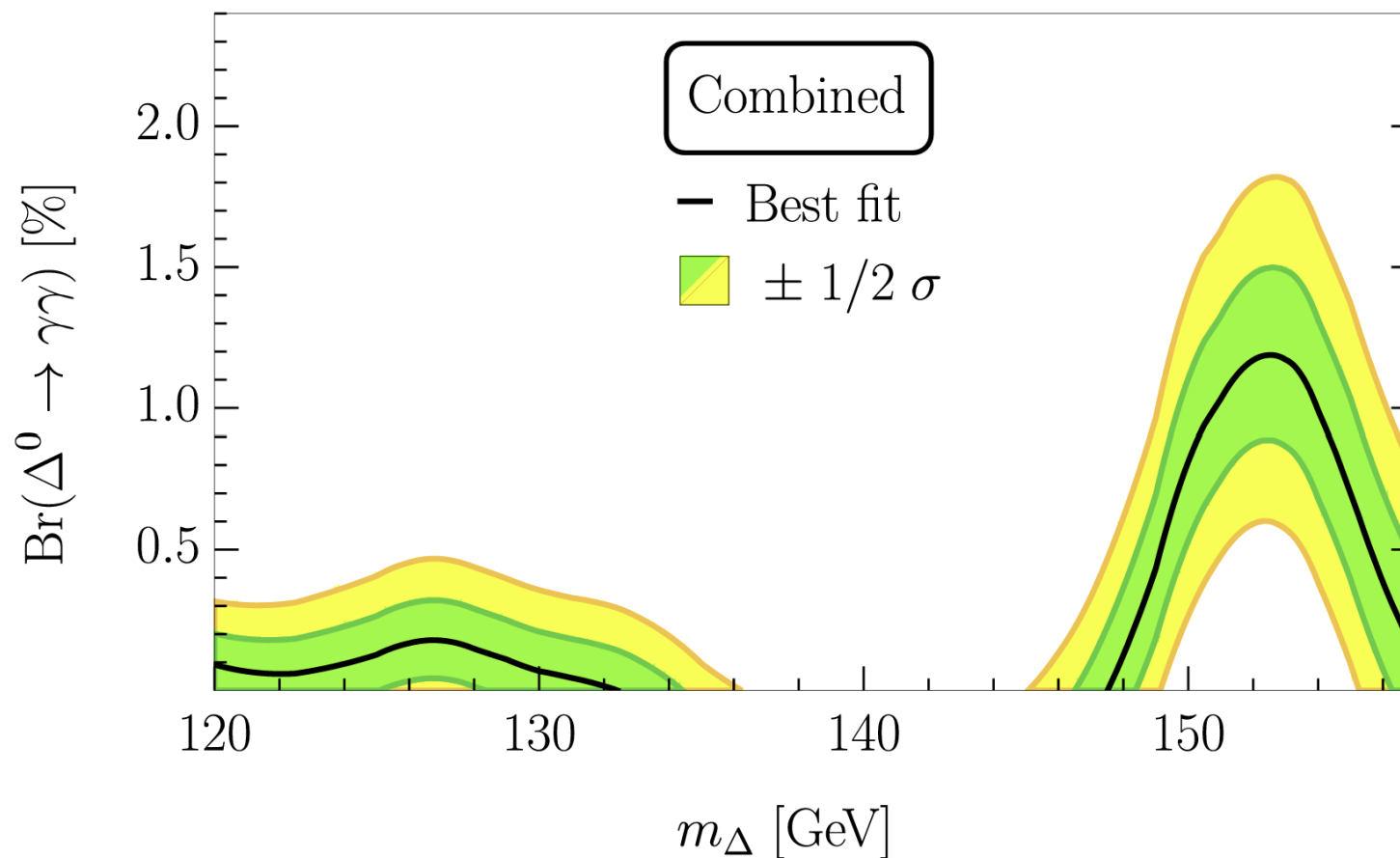
- Contains a charged and a neutral Higgs which are quasi-degenerate
- Production cross section known
- Dependence on the vev cancels



Simple and very predictive model

Saiyad Ashanujjaman (KIT, Karlsruhe, TTP and KIT, Karlsruhe and Beijing, Inst. High Energy

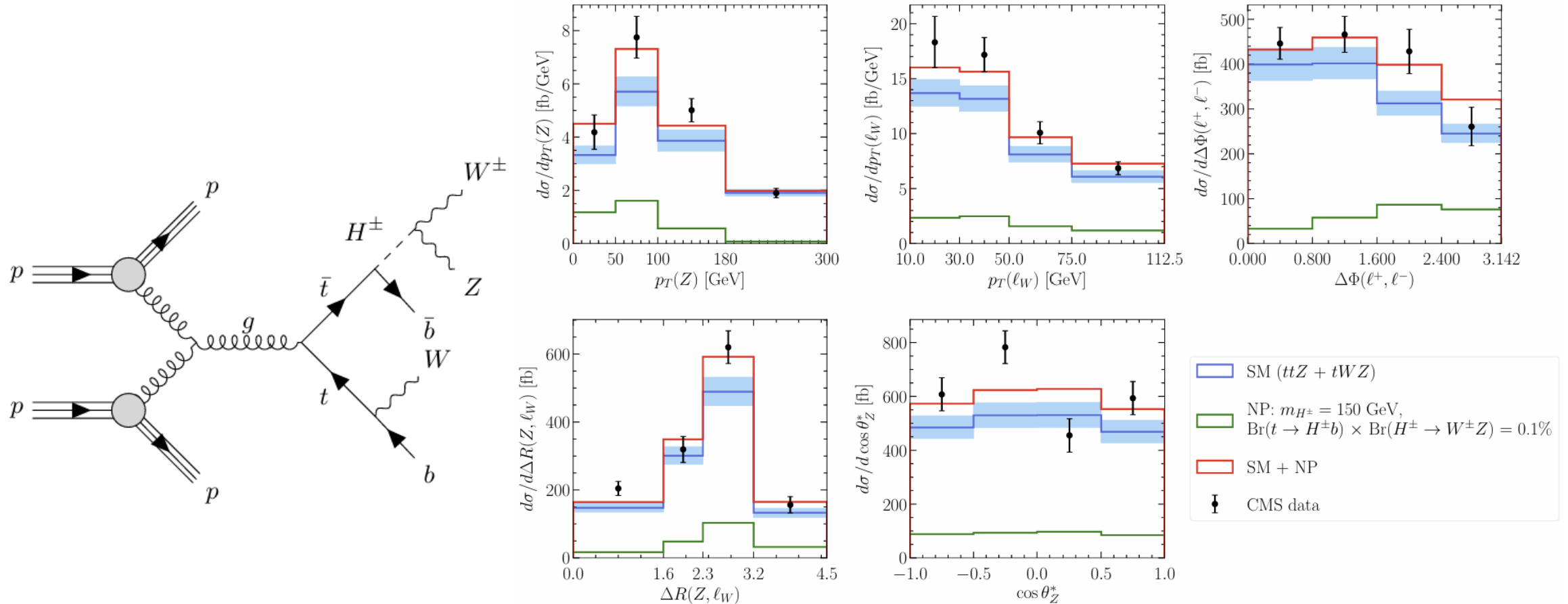
Sumit Banik (PSI, Villigen and Zurich U.), Guglielmo Coloretti (PSI, Villigen and Zurich U.), Andreas Crivellin (PSI, Villigen and Zurich U.), Siddharth P. Maharathy (U. Witwatersrand, Johannesburg, Sch. Phys. and IISER, Pune) [Show All\(6\)](#)



$\approx 4\sigma$ significance at 152 GeV

Triplet Signature in ttZ

S. Ashanujaman, A.C., S. Maharathy,
B. Mellado, 2509.07094

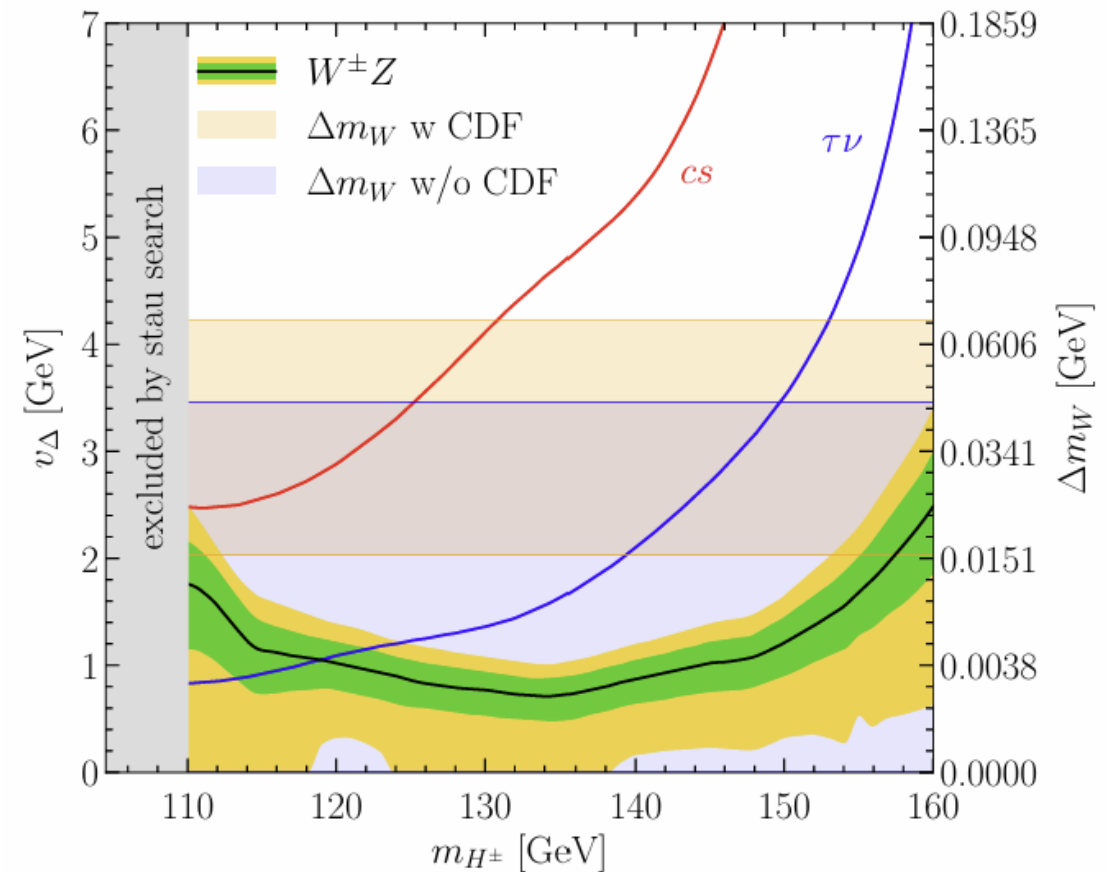
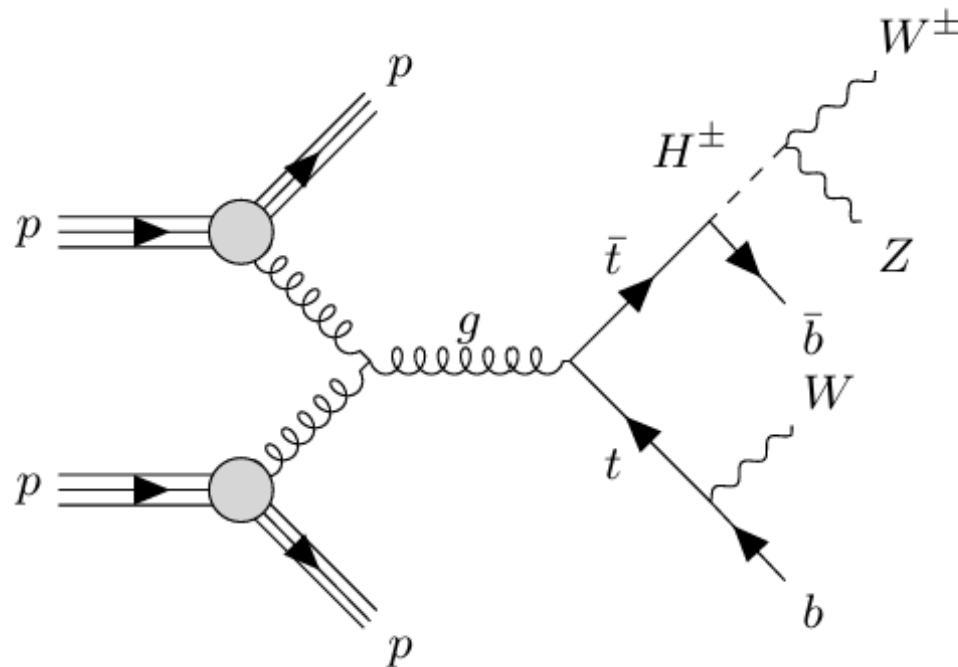


>2 σ significance at ≈ 152 GeV, supporting evidence

Triplet Signature in Top-Quark Decays

S. Ashanujaman, A.C., S. Maharathy,
B. Mellado, 2509.07094

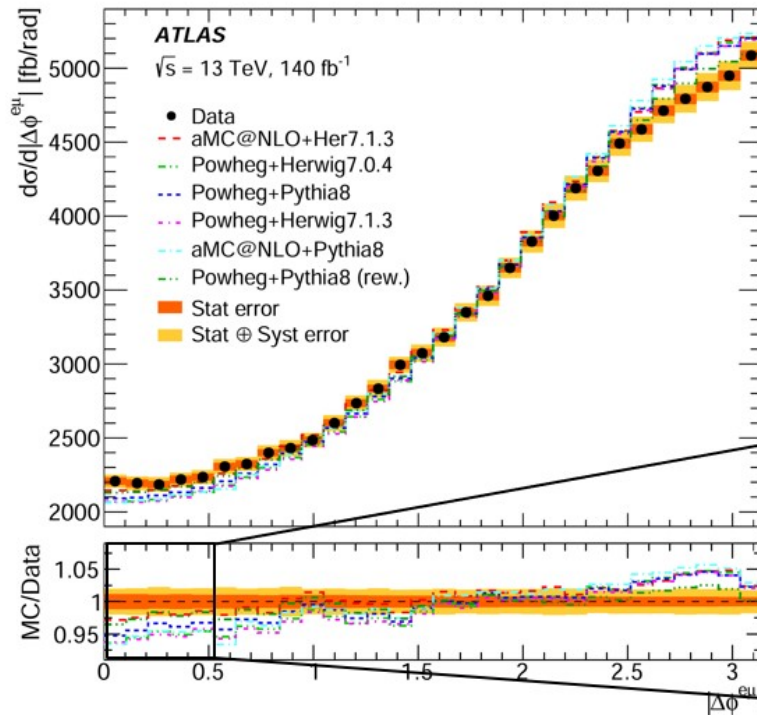
- Triplet with 152 GeV neutral Higgs predicts a charged Higgs production in top decays
- Resembles $t\bar{t}Z$ -like signal in the SM



>2 σ significance at ≈ 152 GeV, supporting evidence

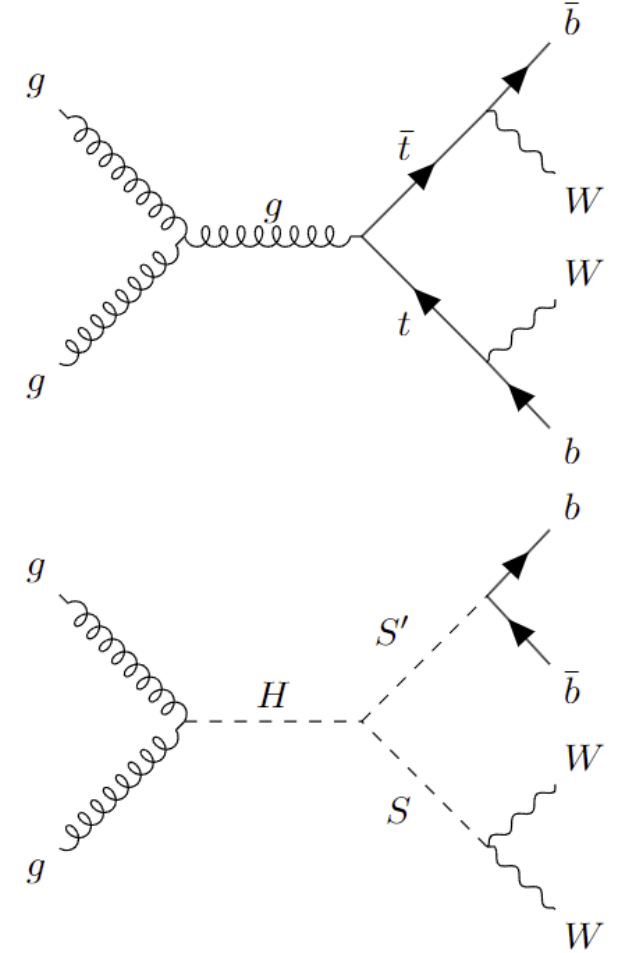
Beyond the Triplet model

- Two Higgses (S and S') produced from the decay of a heavy Higgs (H)
- 95 GeV (S') naturally decays to $b\bar{b}$
- 152 GeV triplet (S) dominantly decays to WW



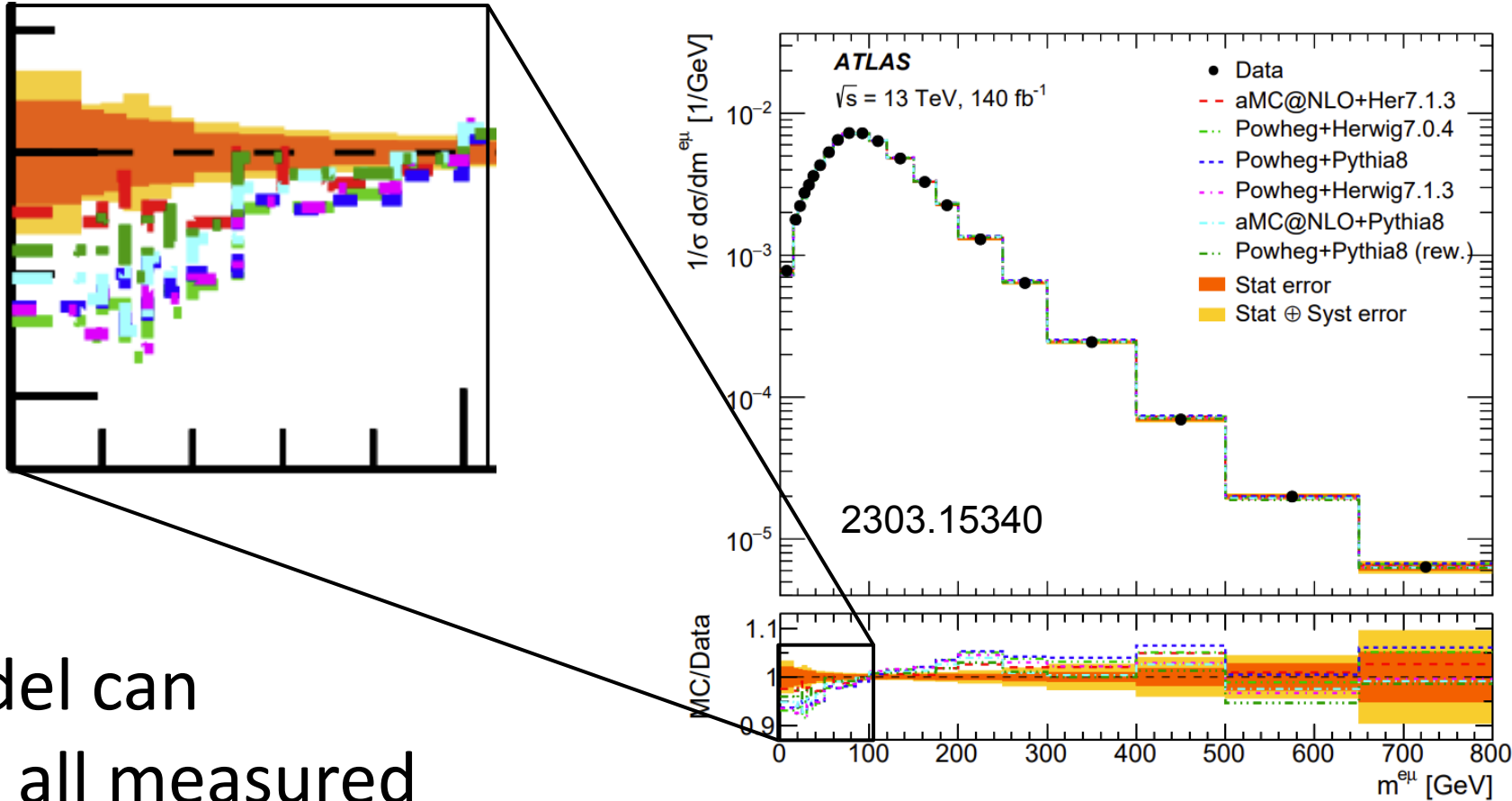
"No model can describe all measured distributions within their uncertainties."
ATLAS 2303.1534

**Mismodelling of SM at the LHC
or new physics effects?**



Can explain tensions in $t\bar{t}$ -differential distributions ($>5\sigma$)

Differential Top-Quark Distributions



- ATLAS:
“No model can describe all measured distributions within their uncertainties.”

New Physics pollution of this SM measurement?

Simplified Model: $H \rightarrow SS' \rightarrow WWbb$

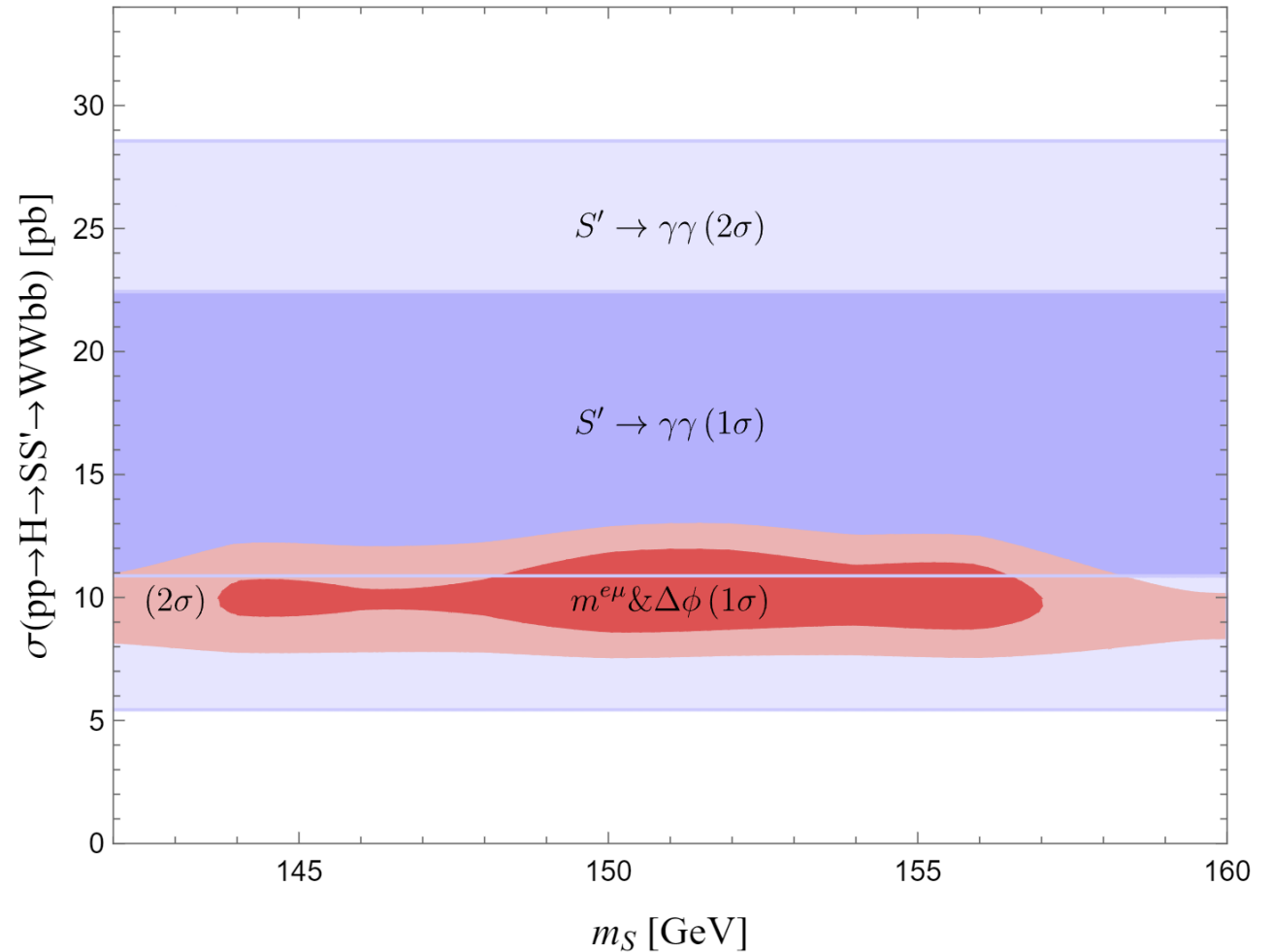
Monte Carlo	χ^2_{SM}	χ^2_{NP}	σ_{NP}	Sig.	$m_S[\text{GeV}]$
Powheg+Pythia8	213	102	9pb	10.5σ	143–156
aMC@NLO+Herwig7.1.3	102	68	5pb	5.8σ	—
aMC@NLO+Pythia8	291	163	10pb	11.3σ	148-157
Powheg+Herwig7.1.3	261	126	10pb	11.6σ	149-156
Powheg+Pythia8 (rew)	69	35	5pb	5.8σ	—
Powheg+Herwig7.0.4	294	126	12pb	13.0σ	149-156
Average	182	88	9pb	9.6σ	143-157

- Improvement of SM prediction imperative!

Agreement with data significantly improved ($>5\sigma$)

Is 95 GeV a singlet? Relation to 152 GeV?

- $S'(95)$: Singlet decays dominantly to $b\bar{b}$
- $S(152)$: Triplet decays dominantly to WW
- Predicts resonant $WW\gamma\gamma(95\text{GeV})$ signal
- CMS analysis B2G-24-010 finishes at 100 GeV



Consistent with 95 GeV $\gamma\gamma$ signal strength

$\Delta 2\text{HDMS}$ and top-quark production

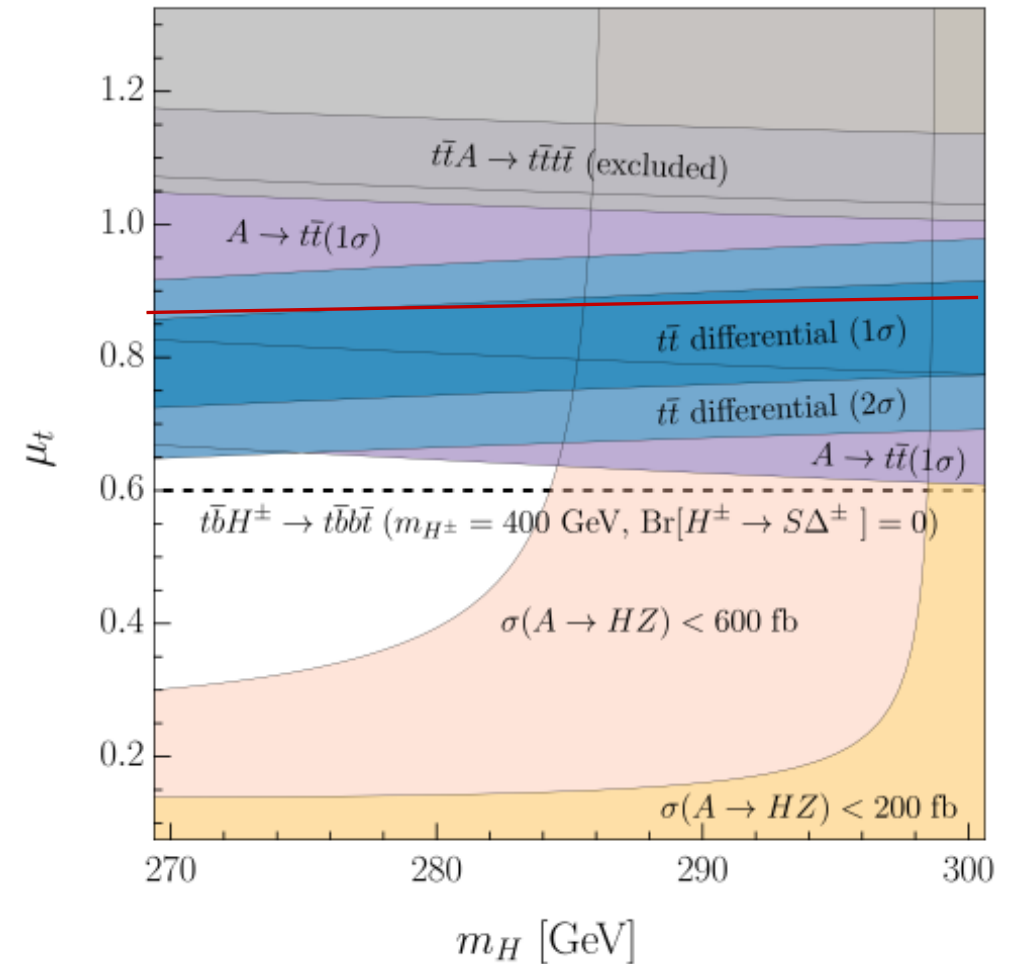
Field	$SU(2)_L$	$U(1)_Y$
ϕ_s	1	0
ϕ_2	2	1/2
ϕ_1	2	1/2
Δ	3	0

Explains:

- Top-quark differential distributions
- Di-photon excesses
- Resonant top-quark production
- Elevated 4-top cross section
- Strong two-step EW phase transition

R. Musolf et al: Phys.Rev.D 93 (2016) 015013

G. Coloretti, A.C. and B. Mellado, 2312.17314



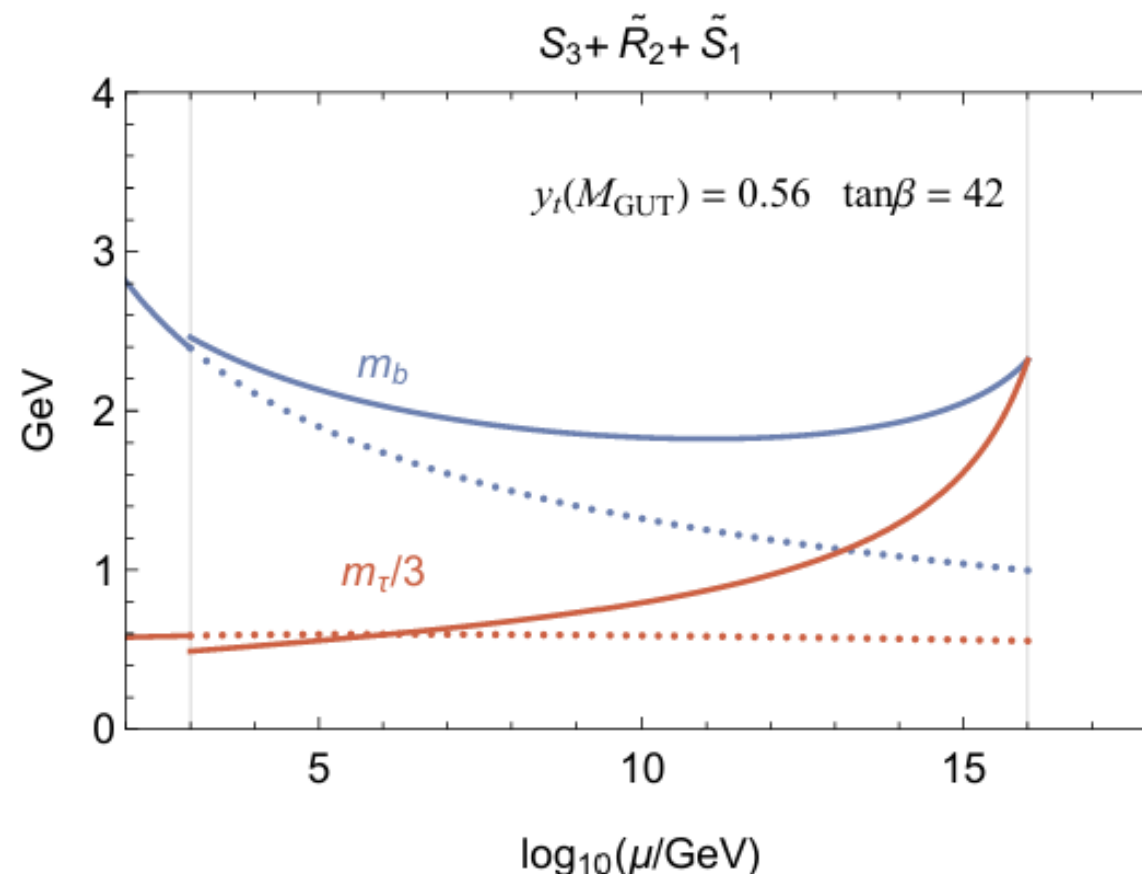
Combined explanation possible

TeV-scale scalar leptoquarks motivated by B anomalies improve Yukawa unification in SO(10) GUT

Xiyuan Gao (KIT, Karlsruhe, TTP), Ulrich Nierste (KIT, Karlsruhe, TTP)

Aug 15, 2025

- Leptoquark explanation of the B anomalies improve bottom-tau Yukawa coupling unification in SO(10) GUT
- Higgs physics implications?

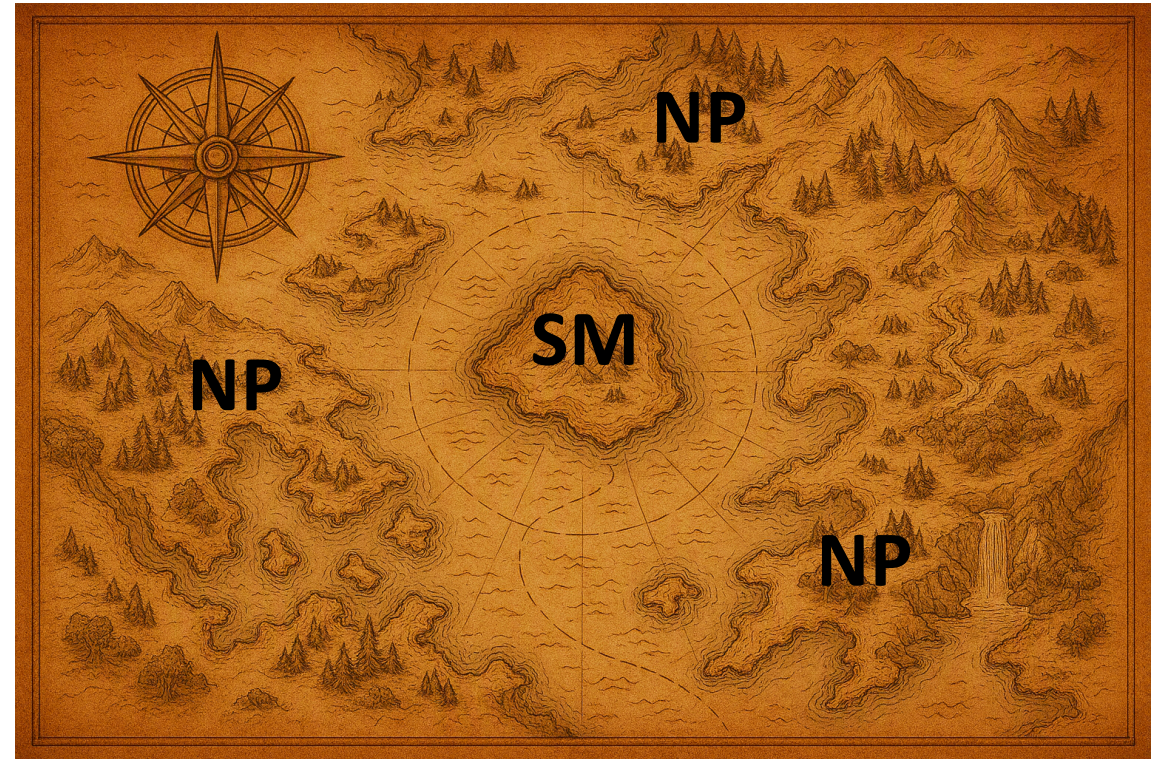


Symmetry-based argument for the B anomalies

The New Physics Landscape



- The boring Universe: New Physics is realized at the Planck scale



- The exciting Universe: New Physics is close by in energy and intricate

We need to explore to know in which world we are living!

Thank you Uli for Everything!



Congratulations and all the best to my “Doktorvater”!!!