A Journey Through the Energy Frontier with Tao

TaoFest - 05.15.2026

Dorival Gonçalves

Beginnings

COLLIDER PHENOMENOLOGY

Basic Knowledge and Techniques*

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Abstract

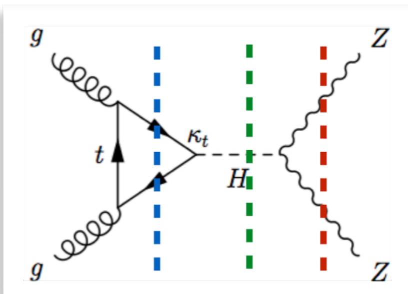
This is the writeup for TASI–04 lectures on Collider Phenomenology. These lectures are meant to provide an introductory presentation on the basic knowledge and techniques for collider physics. Special efforts have been made for those theorists who need to know some experimental issues in collider environments, and for those experimenters who would like to know more about theoretical considerations in searching for new signals at colliders.

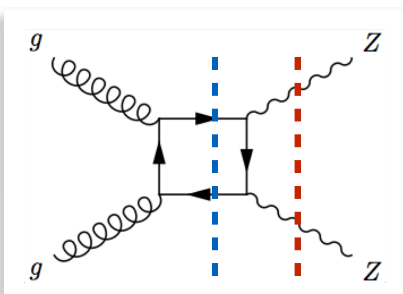
→ São Paulo (Éboli)
→ Heidelberg (PhD with Plehn)
→ IPPP-Durham (PostDoc)
→ Pittsburgh (PostDoc 2016-2019)

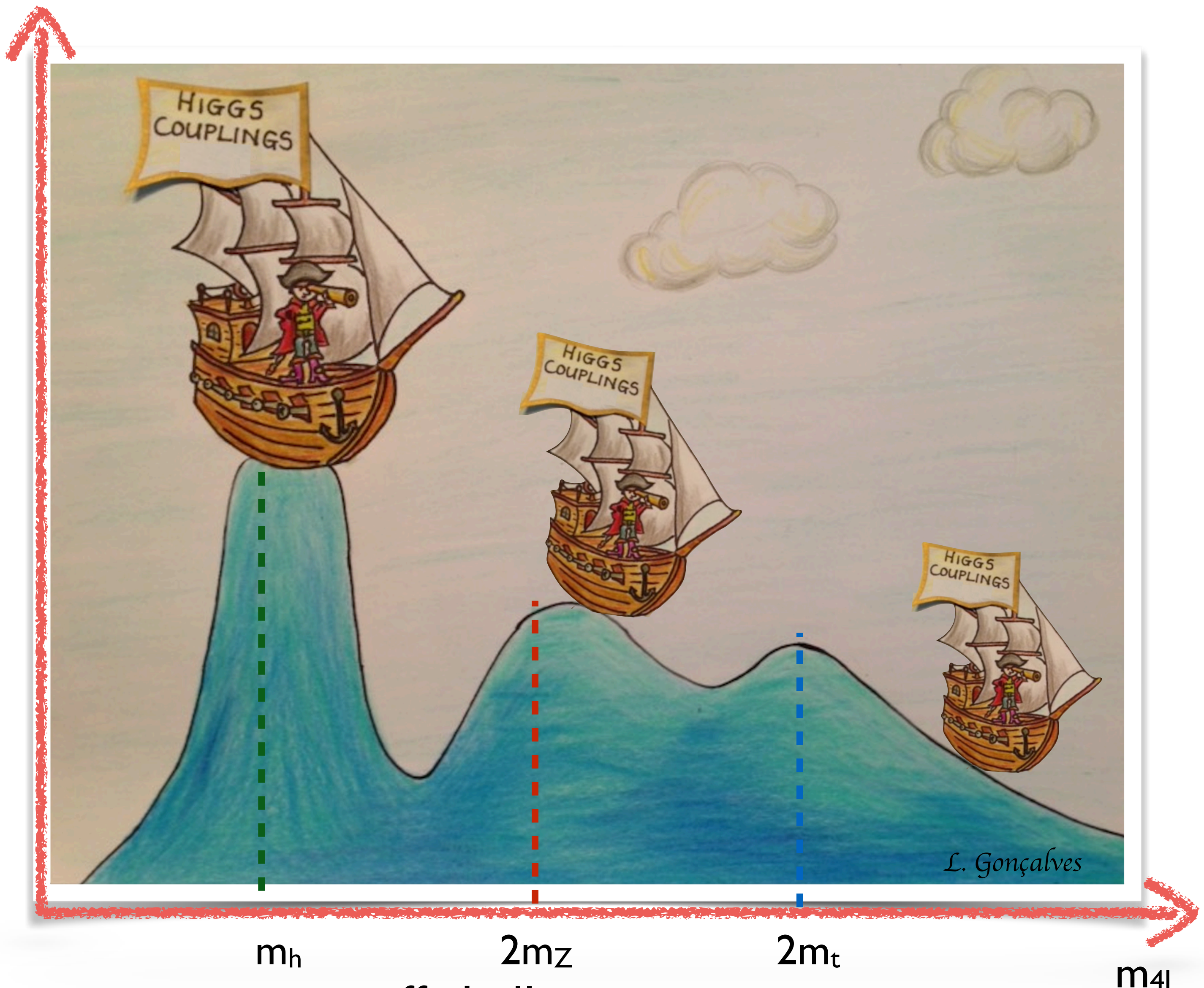
“Tao is great! I’ve had a lot of fun with him!”

Off-Shell Higgs Production

- Since $\Gamma_H/m_H \sim 3\times10^{-5}$ one naively expects very small off-shell rates







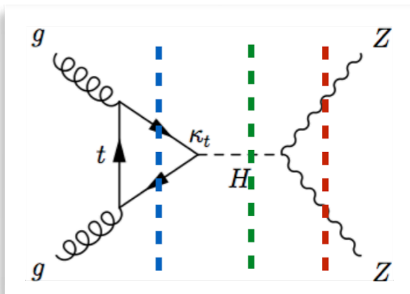
- Spectacular fail of the NWA: $\dfrac{\sigma^{\text{off-shell}}_{h^*\to4\ell}}{\sigma^{\text{on-shell}}_{h\to4\ell}} \sim 10\,\%$ Kauer, Passarino '12

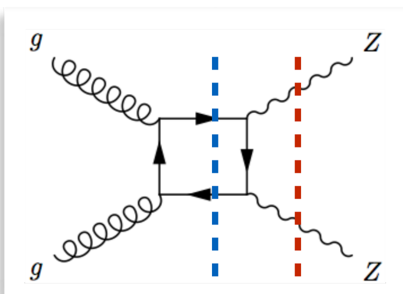
→ $2m_Z$ and $2m_t$ thresholds

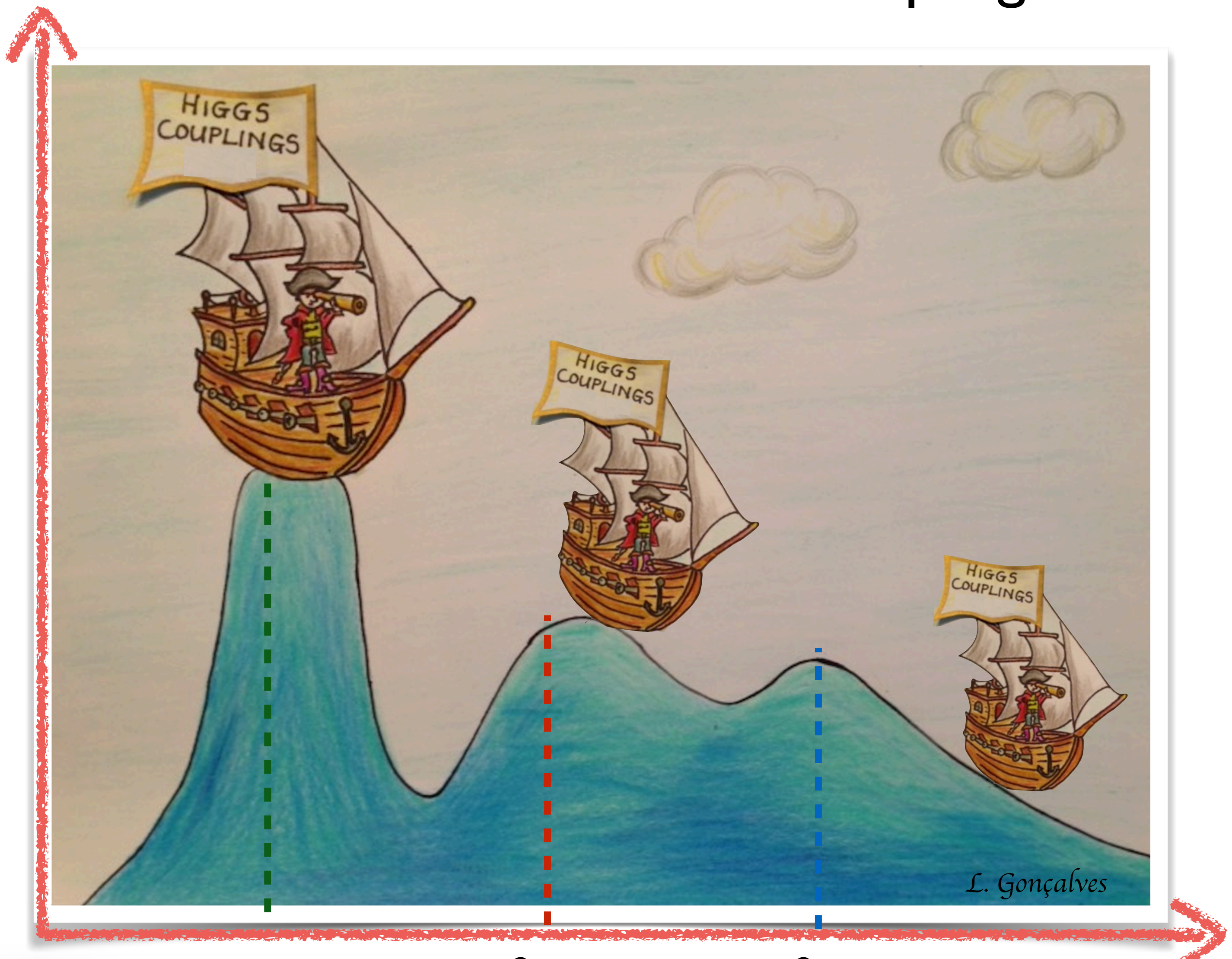
→ Interference $gg\to H^*\to ZZ$ with background $gg\to ZZ$

Off-Shell Higgs Production

- Off-shell Higgs carries information on the H couplings at different energy scales

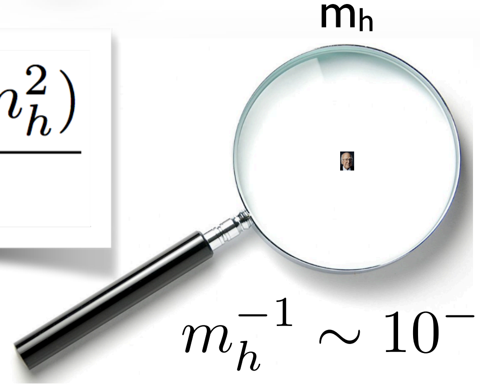




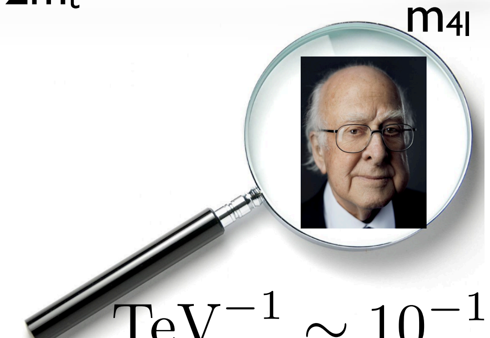


m_h 2m_Z 2m_t m_{4l}

$$\sigma_{\text{on}} \propto \frac{g_i^2(m_h^2)g_f^2(m_h^2)}{m_h\Gamma_h}$$



$$m_h^{-1} \sim 10^{-16}cm$$



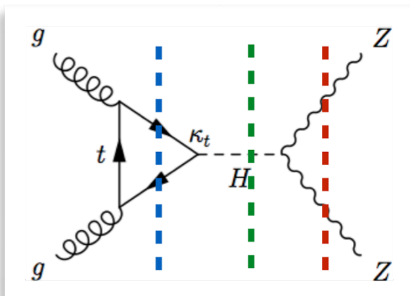
$$\sigma_{\text{off}} \propto \frac{g_i^2(Q^2)g_f^2(Q^2)}{Q^2}$$

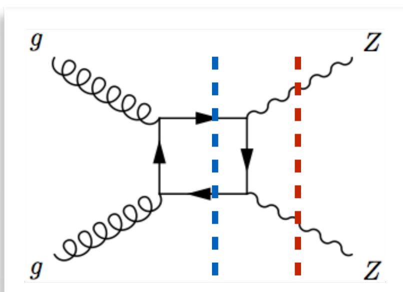
$$\text{TeV}^{-1} \sim 10^{-17}cm$$

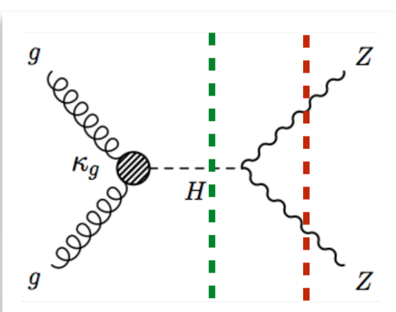
Caola, Melnikov '13

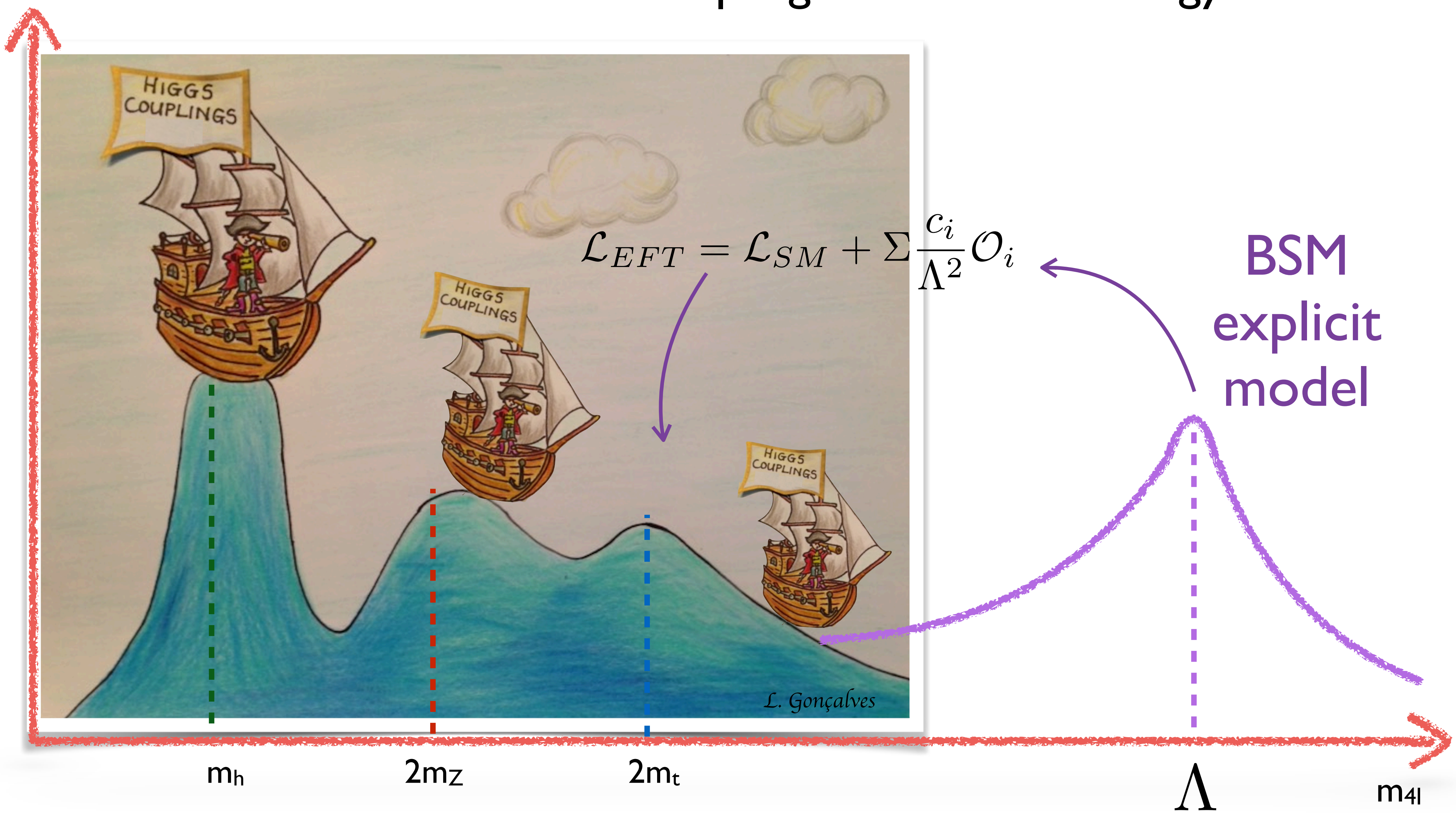
Off-Shell Higgs Production

- Off-shell Higgs carries information on the H couplings at different energy scales







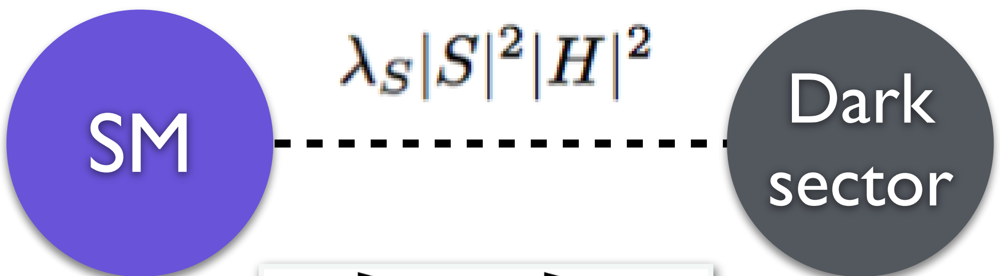


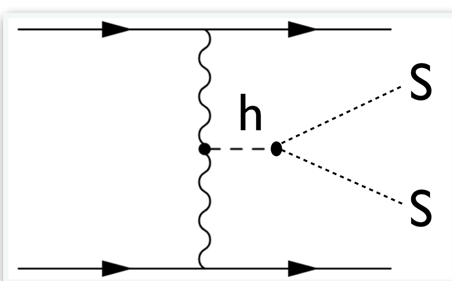
→ What is the new physics scale?

DG, Han, Mukhopadhyay (**PRL** ’17)
DG, Han, Mukhopadhyay (PRD ’18)

Off-Shell Higgs Production

- Hidden states could show up in the scale dependence of Higgs couplings, or more broadly in Higgs production processes through **quantum corrections**

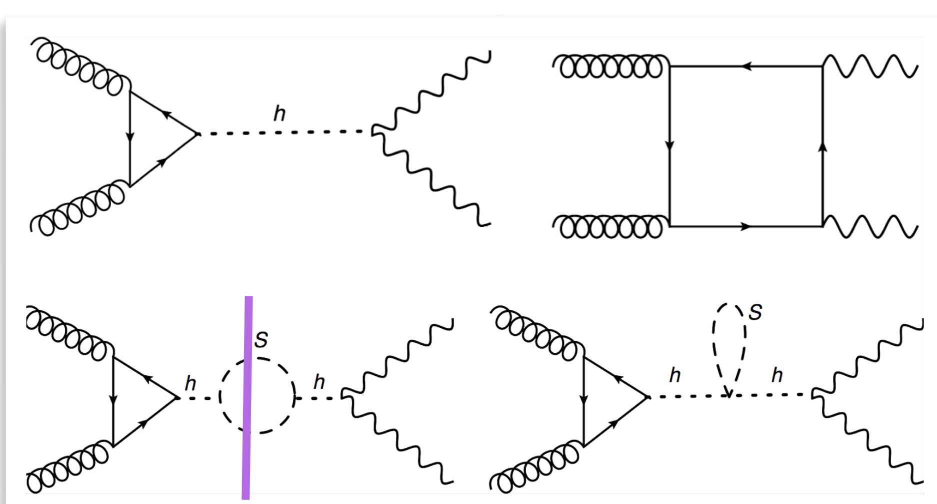


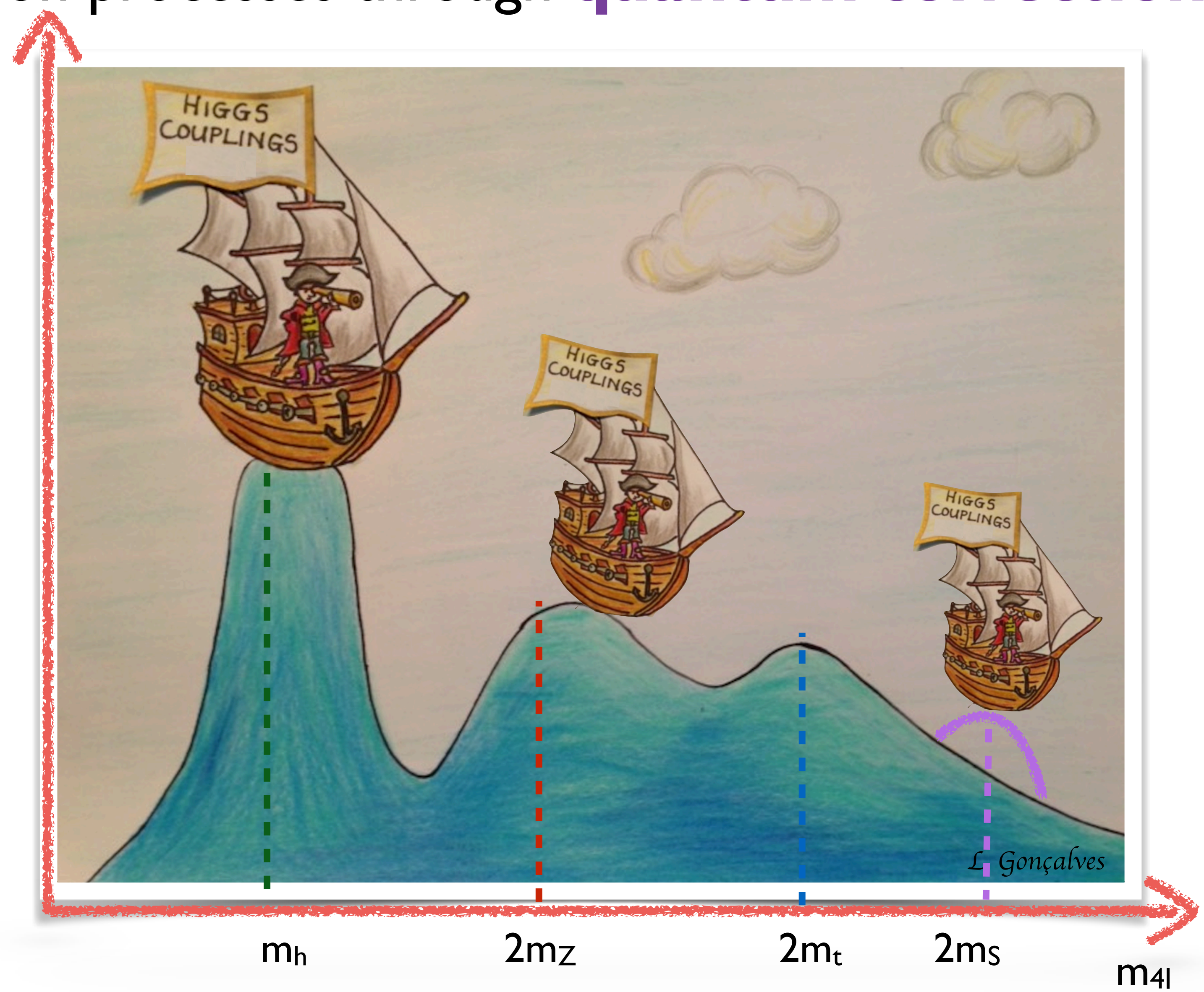


→ $m_h > 2m_S$: strong sensitivity

Eboli, Zeppenfeld 2020

→ $m_h < 2m_S$: sensitivity suppressed





DG, Han, Mukhopadhyay (**PRL** '17)

DG, Han, Mukhopadhyay (PRD '18)

Off-Shell Higgs Production

- The off-shell opens new paths for new physics searches:

→ Higgs width measurement

→ EFT

→ Hidden states through quantum corrections, e.g., Higgs portal

→ Weakly coupled scenario: RG evolution

→ Strong coupled scenario

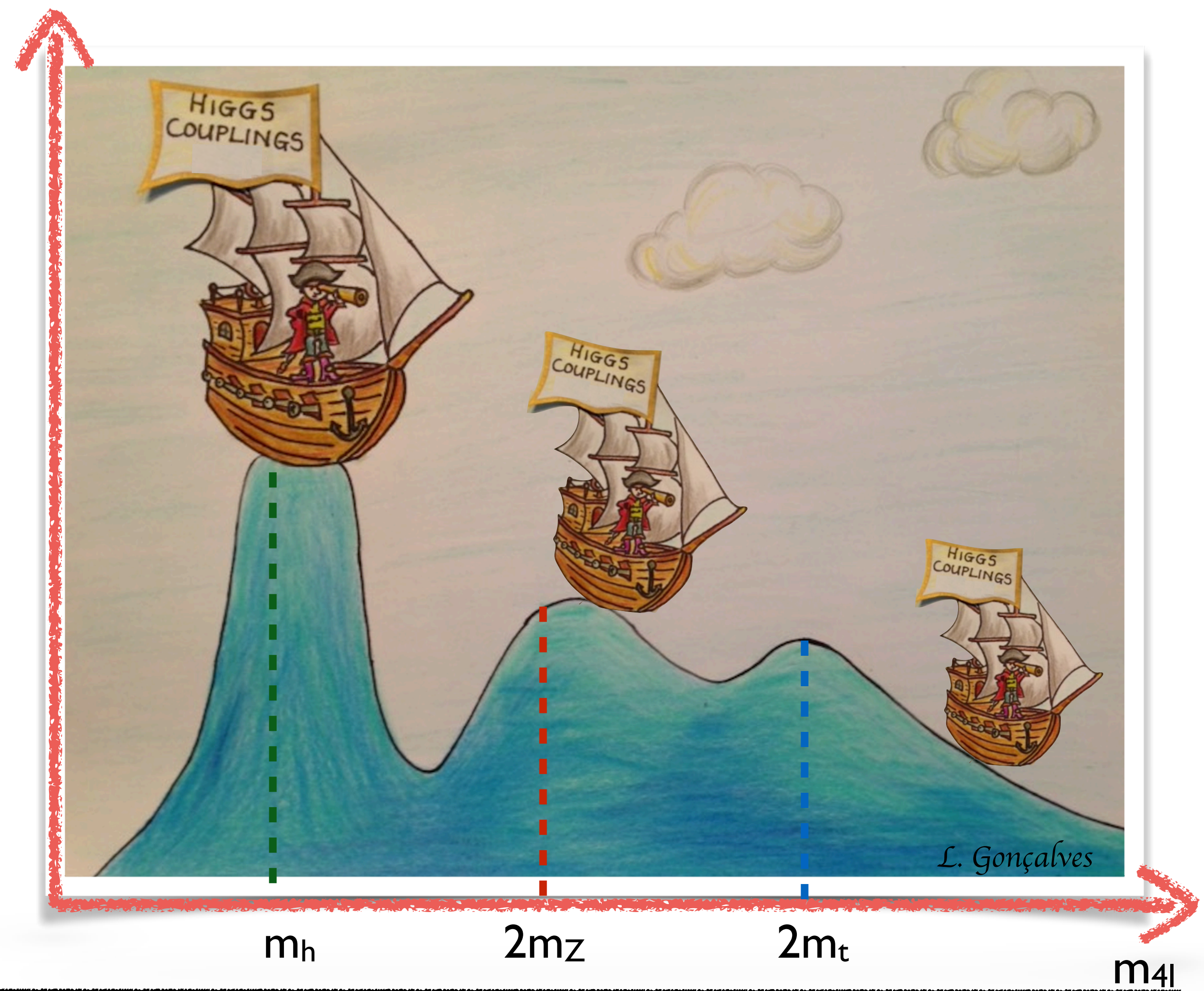
→ New channels: $h^* \to 2\ell 2\nu \ (m_{T,ZZ})$

DG, Han, Mukhopadhyay PRL '17

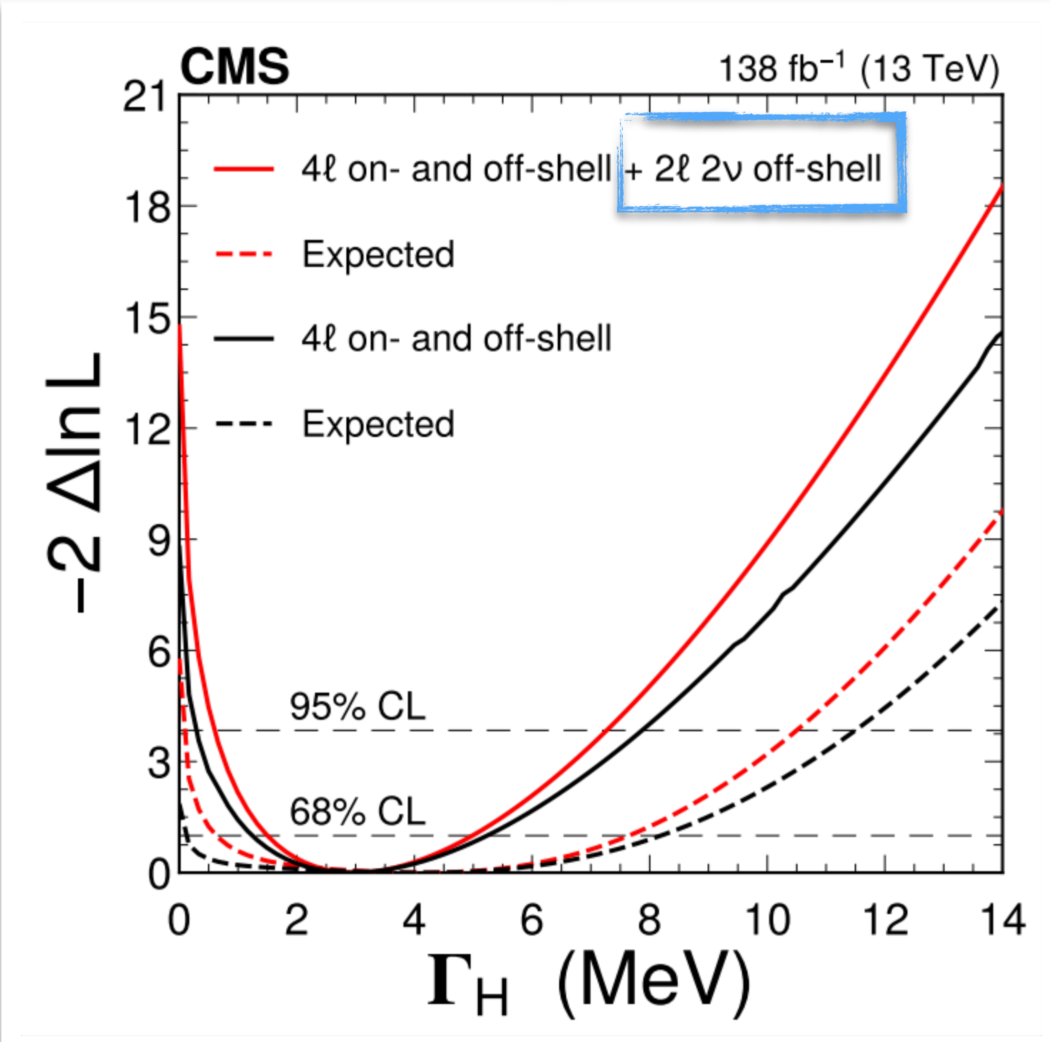
DG, Han, Mukhopadhyay '18

DG, Han, Leung, Qin '20

DG, Han, Leung, Qin '21



Experimental Status



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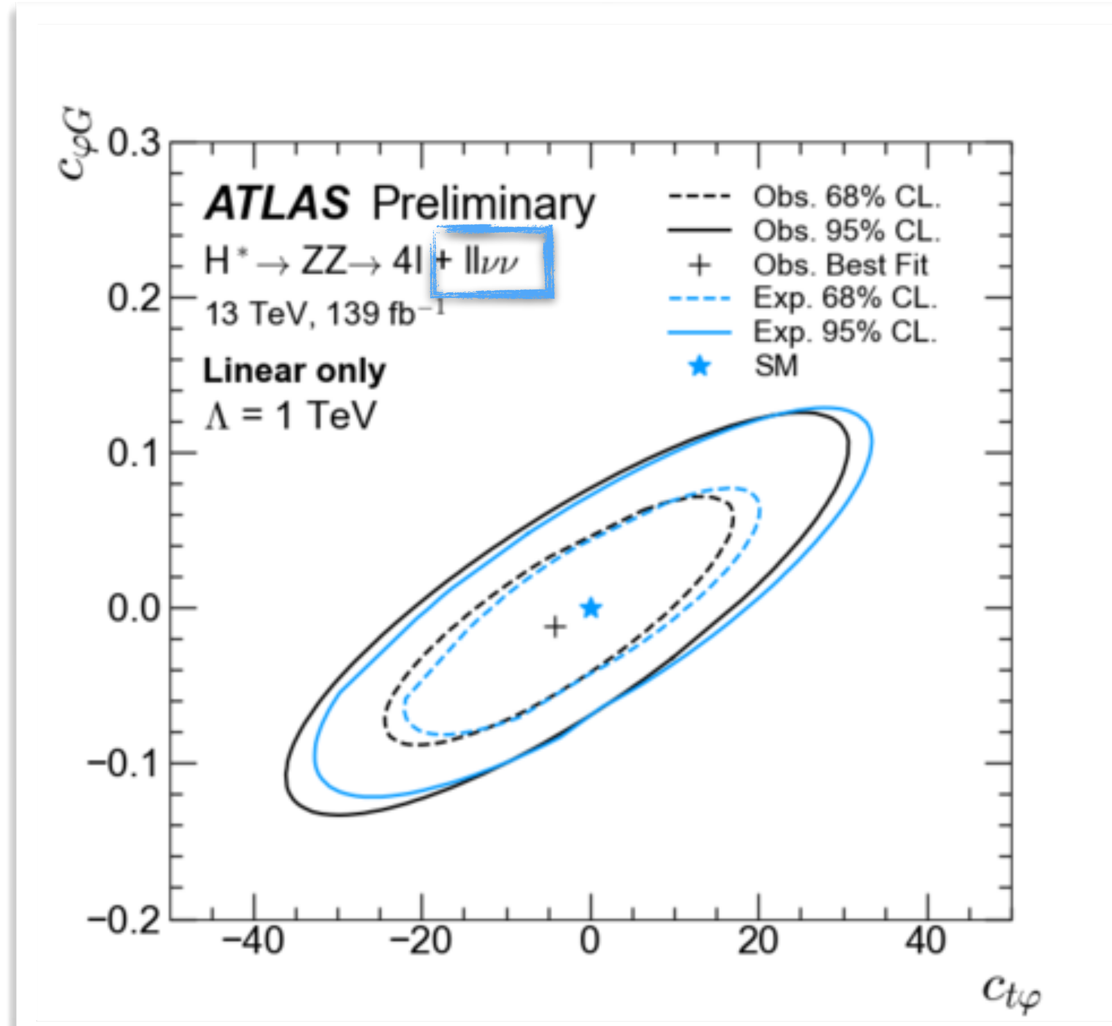
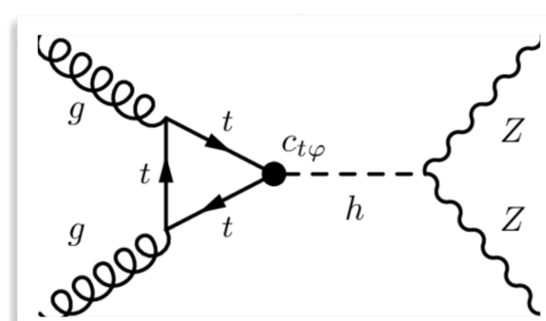
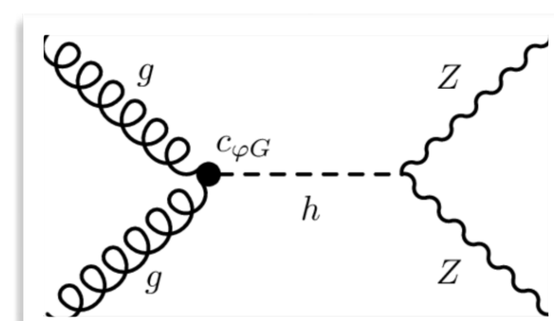


ATL-PHYS-PUB-2023-012

Channel	Observed Γ_H (MeV)	Expected Γ_H (MeV)
4ℓ on- and off-shell	$2.9^{+2.3}_{-1.7}$ [0.3, 7.9]	4.1 ± 4.0 [< 11.5]
4ℓ on- and off-shell + $2\ell 2\nu$ off-shell	$3.0^{+2.0}_{-1.5}$ [0.6, 7.3]	4.1 ± 3.5 [0.1, 10.5]

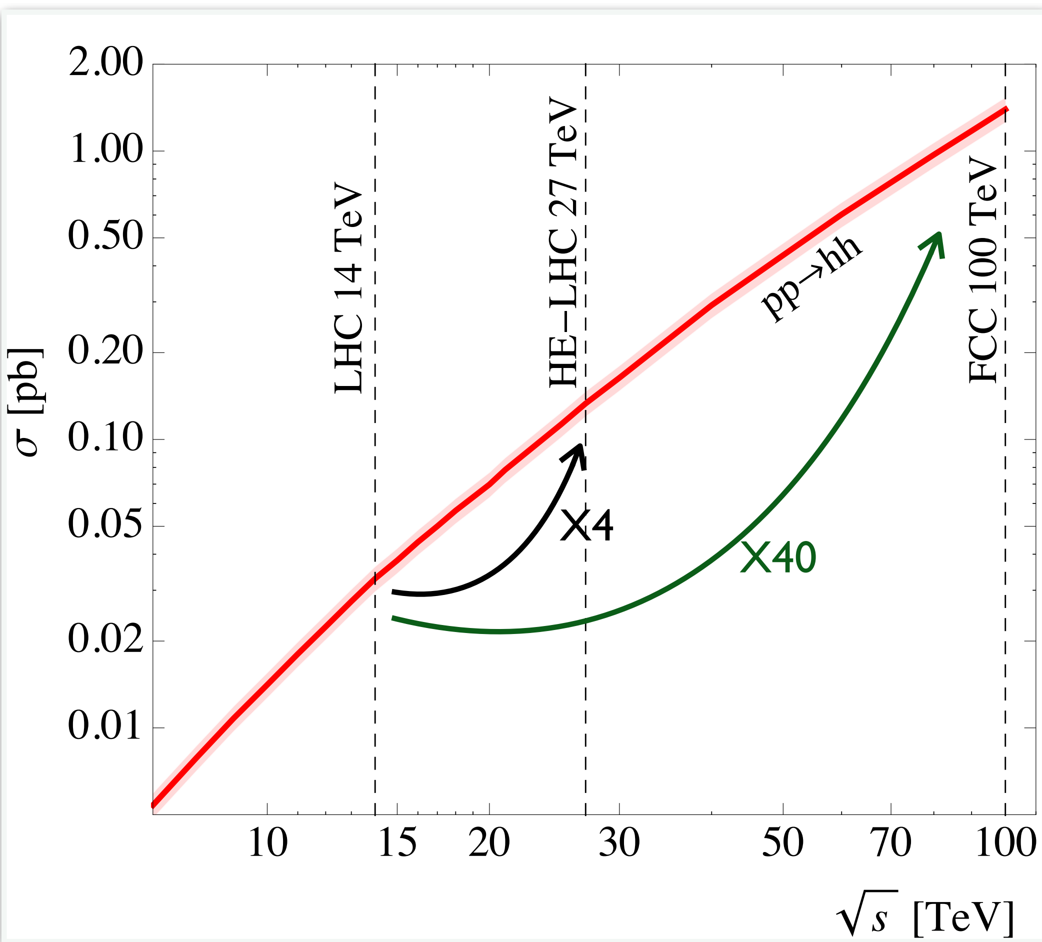
68% CL 95% CL

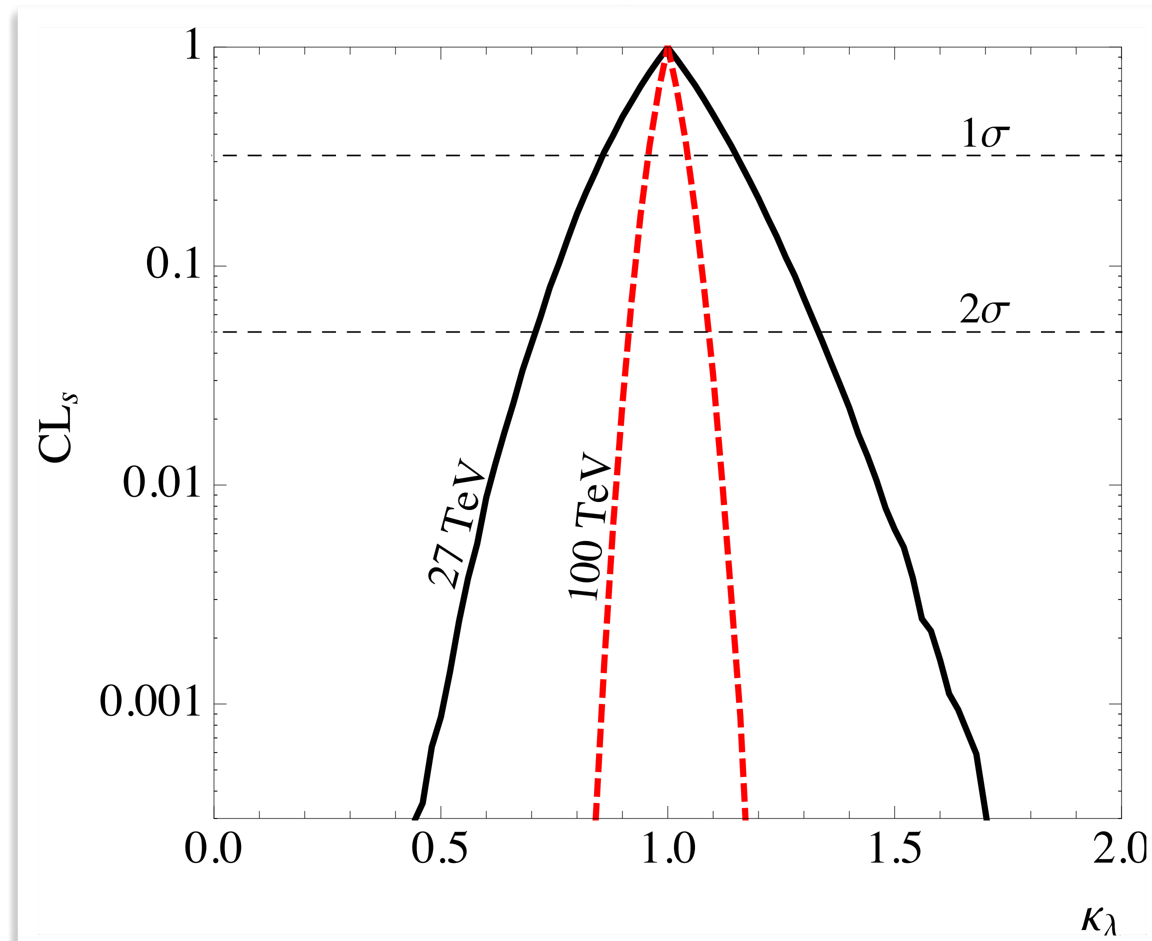




Future Colliders

- Unique opportunity for precision measurement of the Higgs potential





DG, Han, Kling, Plehn, Takeuchi (2018)

4 X 5=20   10 X 2=20

14 TeV → 27 TeV → 100 TeV

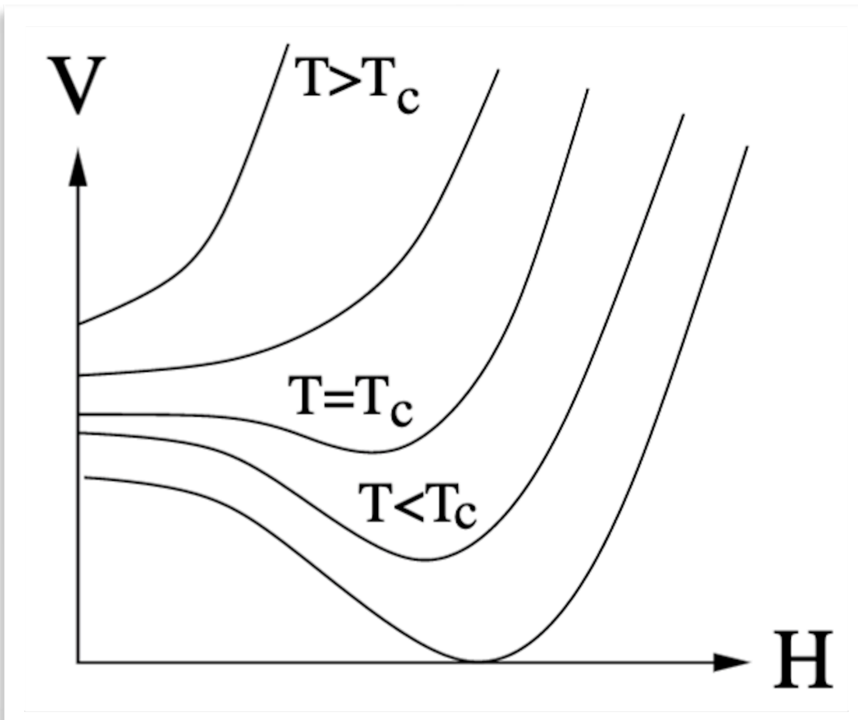
→ m_{hh} shape analysis removes degeneracies from rate-based measurement → symmetric error bars

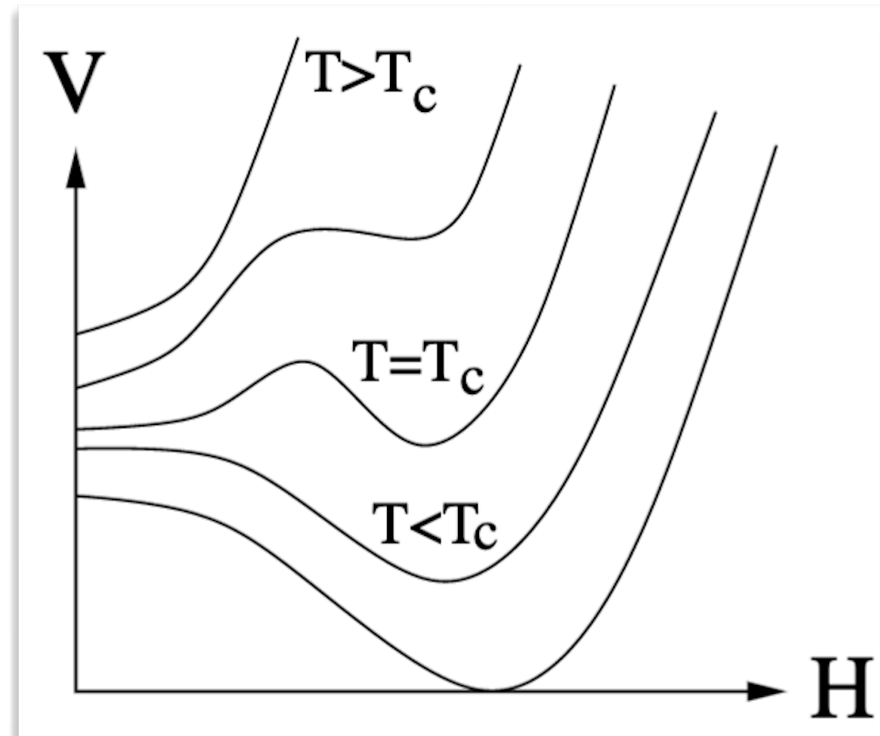
FCC Timeline

For more details, see Marcela's talk at Pheno

Thermal history of our Universe

- What is the order of the Electroweak Phase Transition?



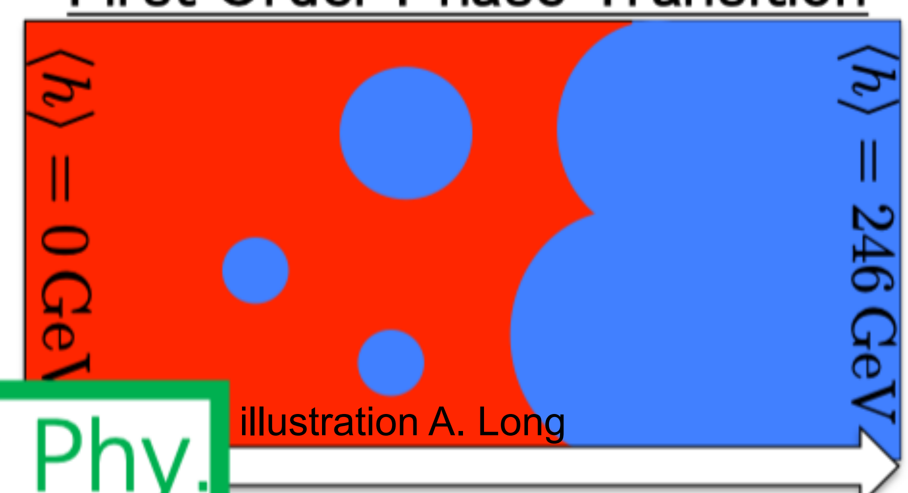


SM

Continuous Crossover

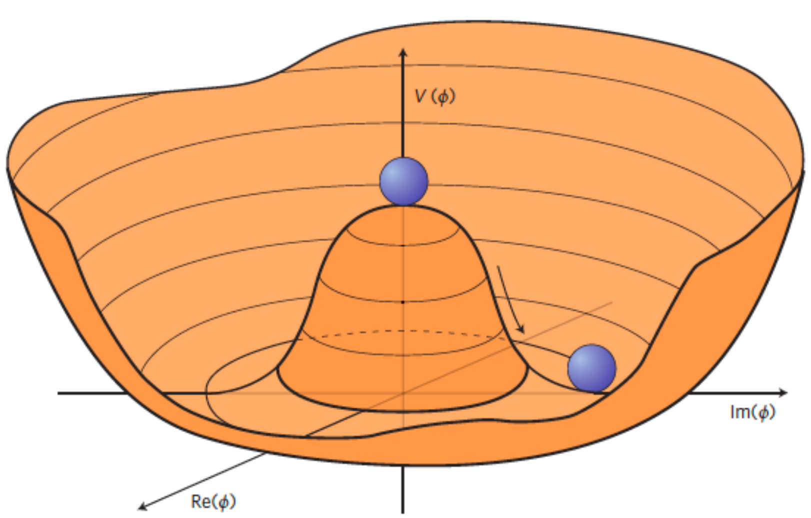
or

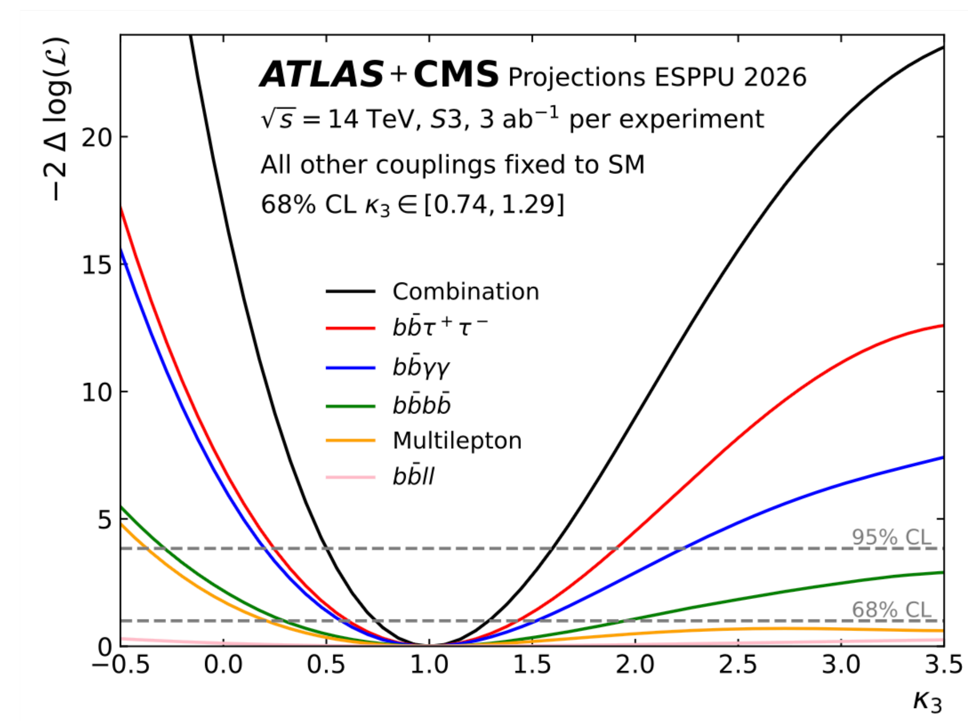
First Order Phase Transition

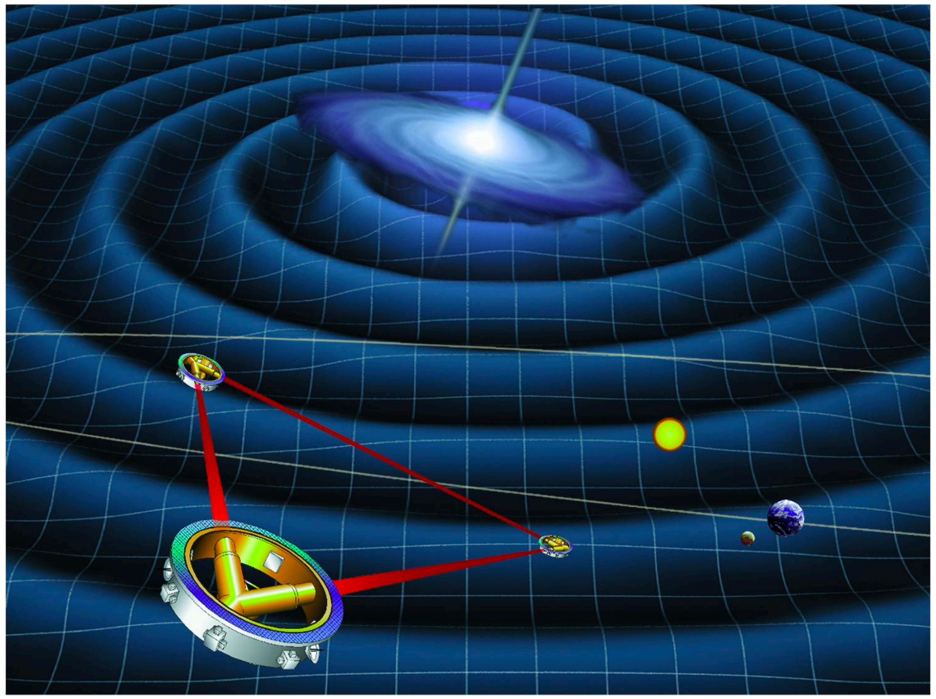


New Phy.

Higgs Potential: Collider & GW Complementarity



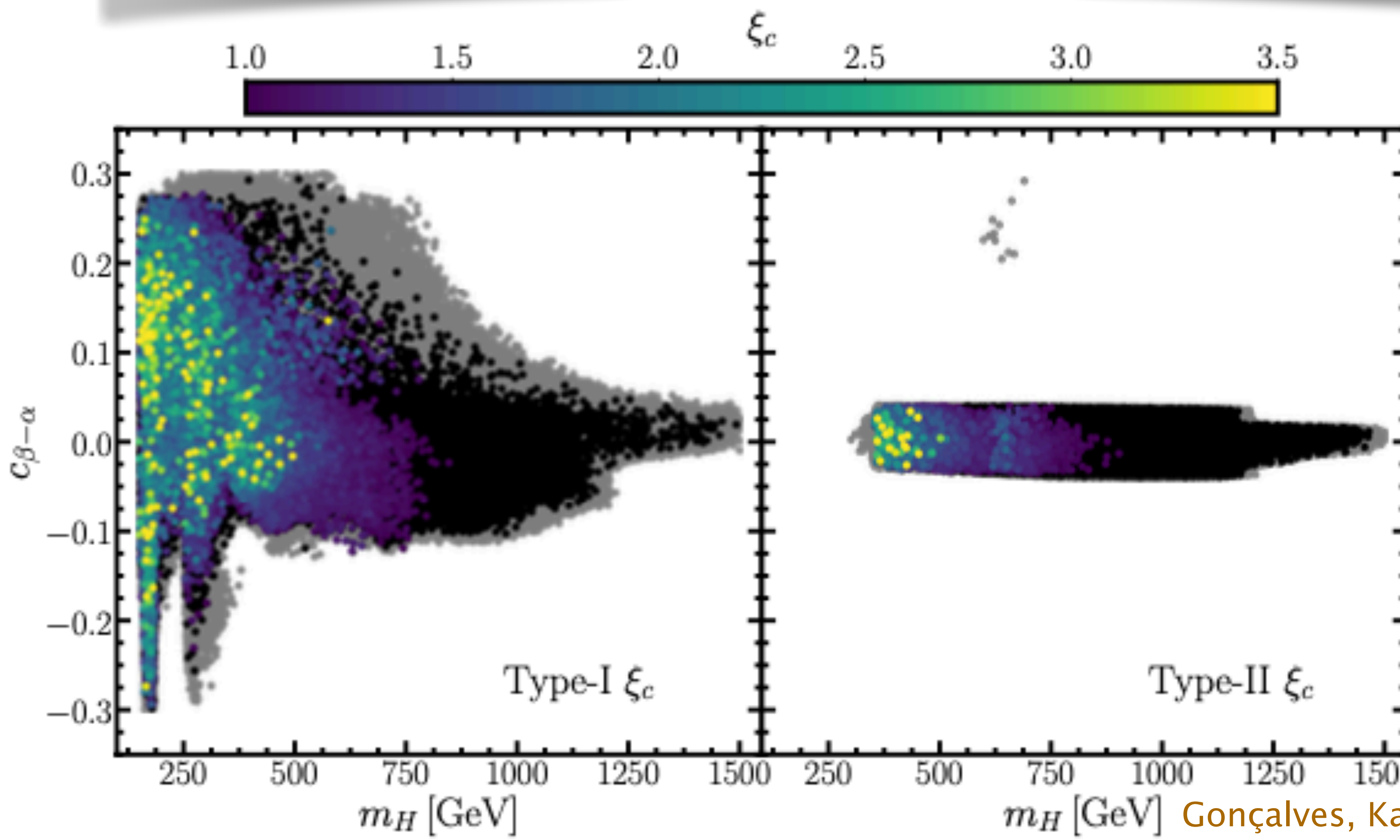




For T_* ~ 100 GeV, GW frequency (redshifted to today) ~ mHz

Signal in sensitivity band of future space-based GW detector **LISA**

Strong first-order phase transition in the 2HDM



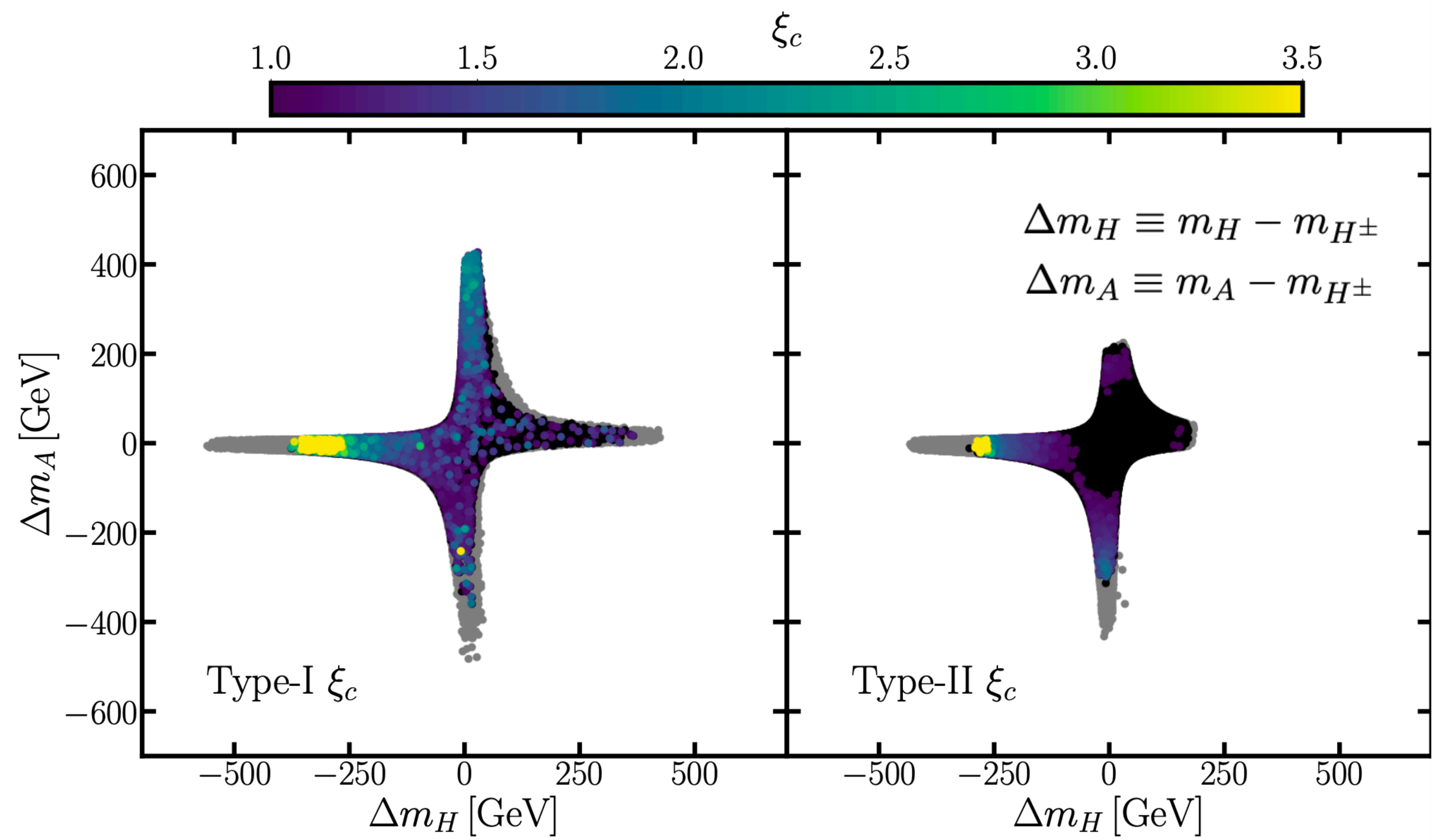
Gonçalves, Kaladharan, Wu ’21

Gonçalves, Kaladharan, Wu '25

- Typically: the higher the order parameter, the lighter the resonance
  $\xi > 1 \;\rightarrow\; m_H \lesssim 750$ GeV
- Strong extra motivation for scalar searches at the LHC

See also Baum, Carena, Shah, Wagner, Wang ’20; Bittar, Roy, Wagner ‘25

Mass Hierarchy for strong first-order phase transition



- Due to the preference for large mass hierarchy among the scalar modes, it is likely that at least one of the scalar states be above the top-quark pair threshold: Favors gg→H/A→tt searches
- $m_H < m_{H^\pm} \approx m_A$: most favorable region for SFOEWPT
  Favors BSM searches via $A \to ZH$ channel

New physics is not simply new particles
New physics is new phenomena

Quantum Entanglement and Bell Inequality Violation in Semi-Leptonic Top Decays

Tao Han, Matthew Low, and Tong Arthur Wu

Maximizing the Azimuthal-Angle Correlation in the Decay of Vector Boson Pairs

Kun Cheng,[1,*] Yi-Jing Fang,[2,3,†] Tao Han,[1,‡] and Matthew Low[1,§]

Optimizing Fictitious States for Bell Inequality Violation in Bipartite Qubit Systems with Applications to the $t\bar{t}$ System

Kun Cheng,[1,2,*] Tao Han,[2,†] and Matthew Low[2,‡]

Entanglement and Bell Nonlocality in $\tau^+\tau^-$ at the LHC using Machine Learning for Neutrino Reconstruction

Yulei Zhang,[4] Bai-Hong Zhou,[1,2,3] Qi-Bin Liu,[1,2,4] Tong Arthur Wu,[5] Shu Li,[1,2,3] Tao Han,[5] Shih-Chieh Hsu,[4] Matthew Low[5]

Optimizing Entanglement and Bell Inequality Violation in Top Anti-Top Events

Kun Cheng,[1,2,*] Tao Han,[1,†] and Matthew Low[1,‡]

Quantum Tomography in Neutral Meson and Antimeson Systems

Kun Cheng,[1,*] Tao Han,[1,†] Matthew Low,[1,‡] and Tong Arthur Wu[1,§]

Quantum Tomography at Colliders: With or Without Decays

Kun Cheng,[1,*] Tao Han,[1,†] and Matthew Low[1,‡]

Quantum Information at the Electron-Ion Collider

Kun Cheng,[1,*] Tao Han,[1,†] and Sokratis Trifinopoulos[2,3,4,‡]

Measuring Quantum Discord at the LHC

Tao Han,[a] Matthew Low,[a] Navin McGinnis,[b] and Shufang Su[b]

Quantum Tomography of Fermion Pairs in e^+e^- Collisions: Longitudinal Beam Polarization Effects

Yu-Chen Guo,[1,2,*] Tao Han,[2,†] Matthew Low,[2,‡] and Youle Su[2,§]

Entanglement and Bell Nonlocality in $\tau^+\tau^-$ at the B

Tao Han,[1,*] Matthew Low,[1,†] and Youle Su[2,‡]

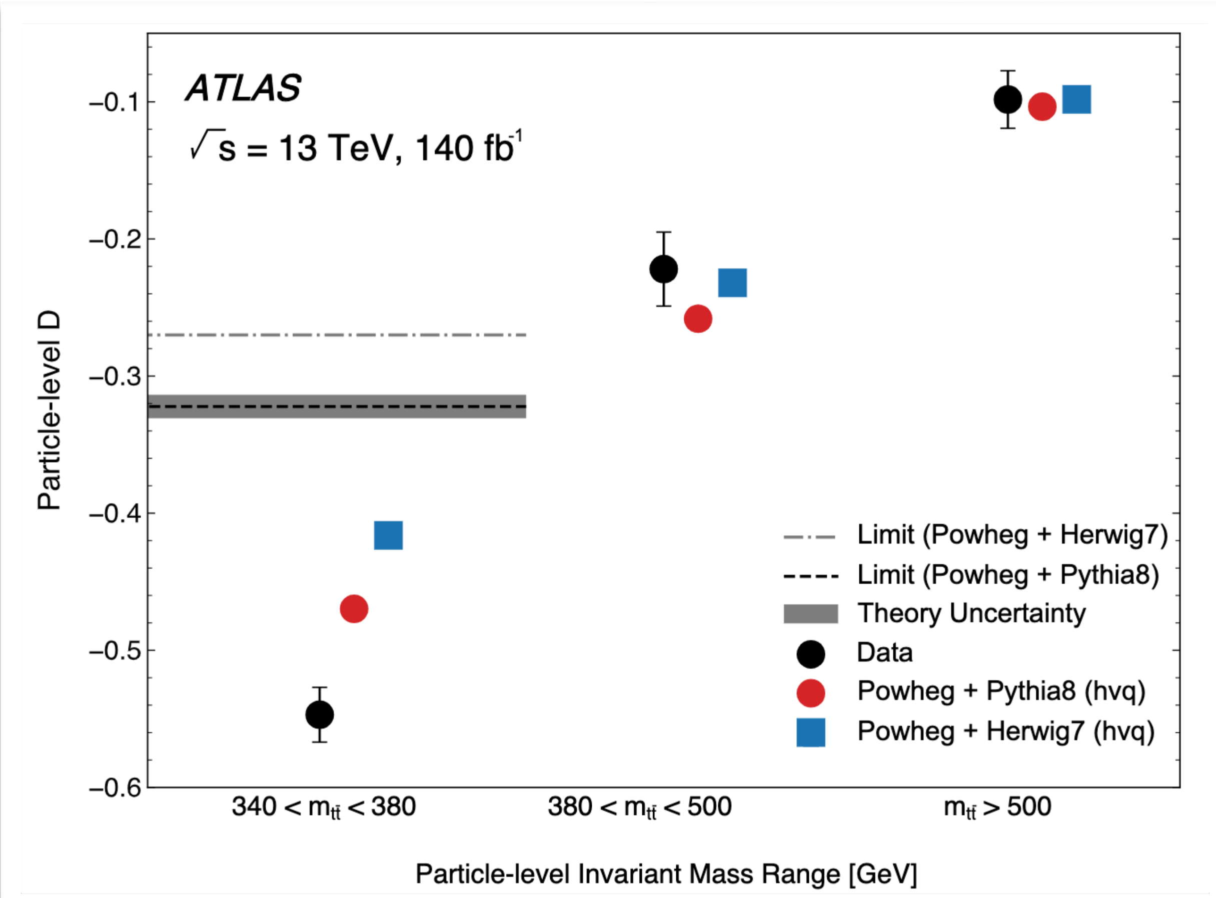
Spin Correlation and Quantum Entanglement of Fermion Pairs in Transversely Polarized e^-e^+ Collisions

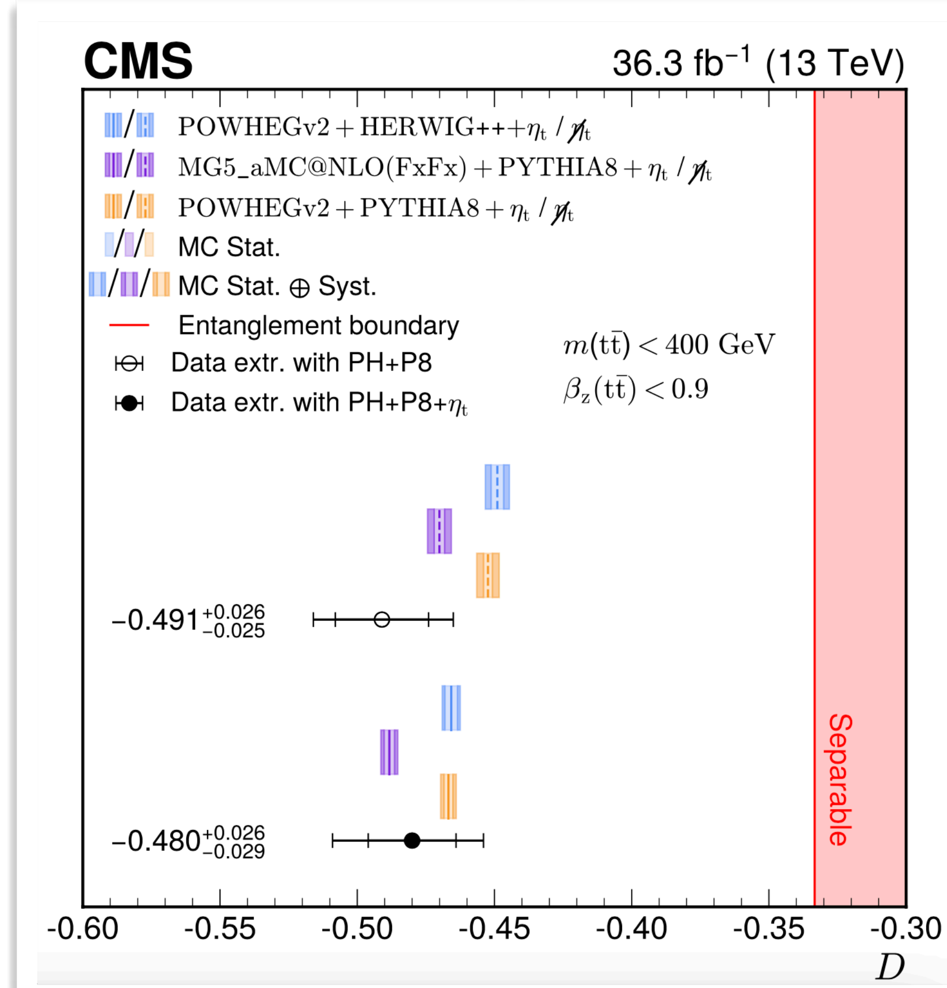
Yi-Jing Fang,[a,b] Amit Bhoonah,[c] Kun Cheng,[c] Tao Han,[c] Yandong Liu,[d,e] and Hao Zhang[a,b,f]

Experimental Observation

Two-qubit entanglement:

First observation of entanglement in a pair of quarks and the highest-energy observation





- Dilepton channel at tt threshold

  Afik, Nova '21, Severi, Boschi, Maltoni, Sioli '21…

  ATLAS Nature vol 633, 542-547 (2024), CMS 2406.03976

See talks by F. Maltoni & R. Demina at Pheno2026

- Lepton+jets channel at boosted regime: CMS 2409.11067

  Entanglement above 5σ level, in agreement with theory expectations: Dong, **DG**, Kong, Navarro '23; **Han**, Low, Wu '23

  Hadronic top quark polarimetry with ML: Dong, **DG**, Kong, Larkoski, Navarro '25

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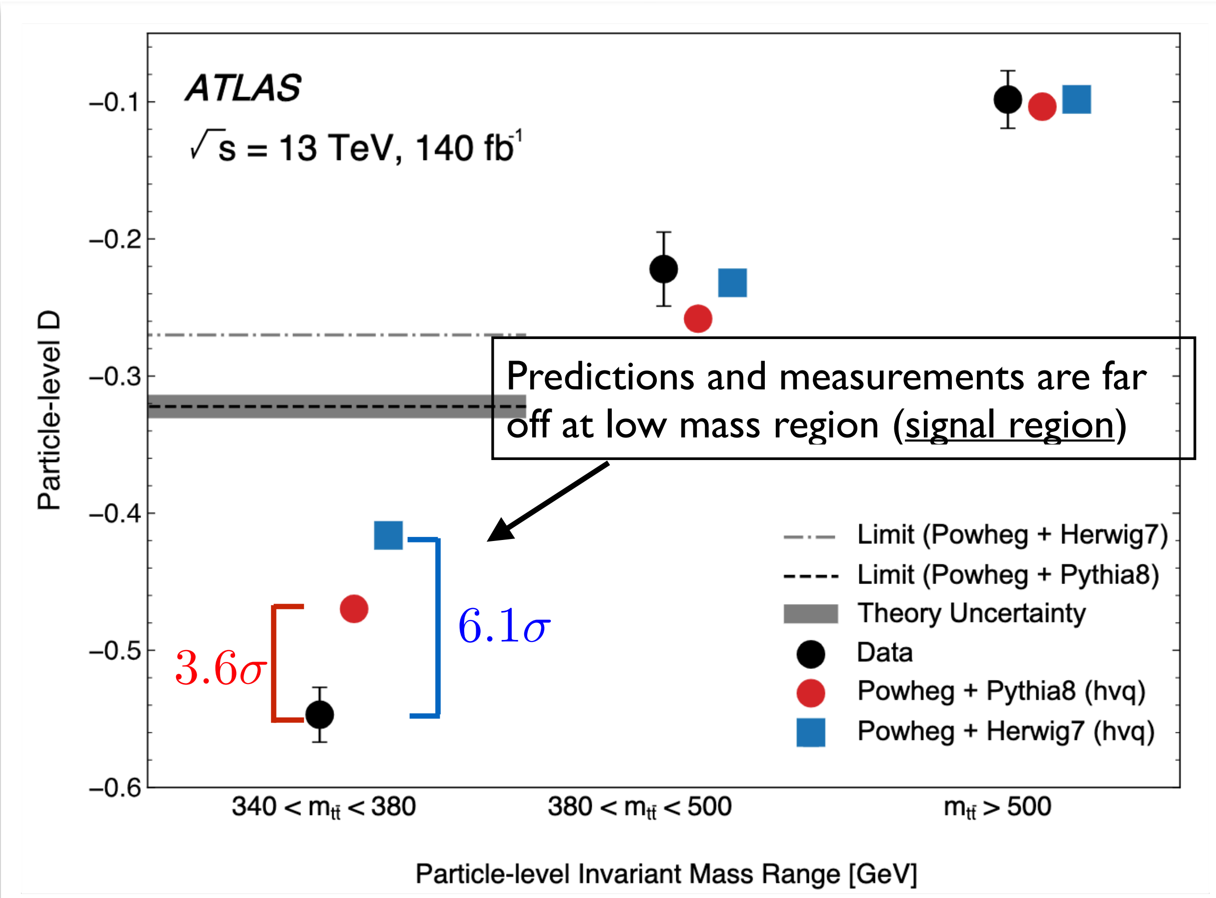

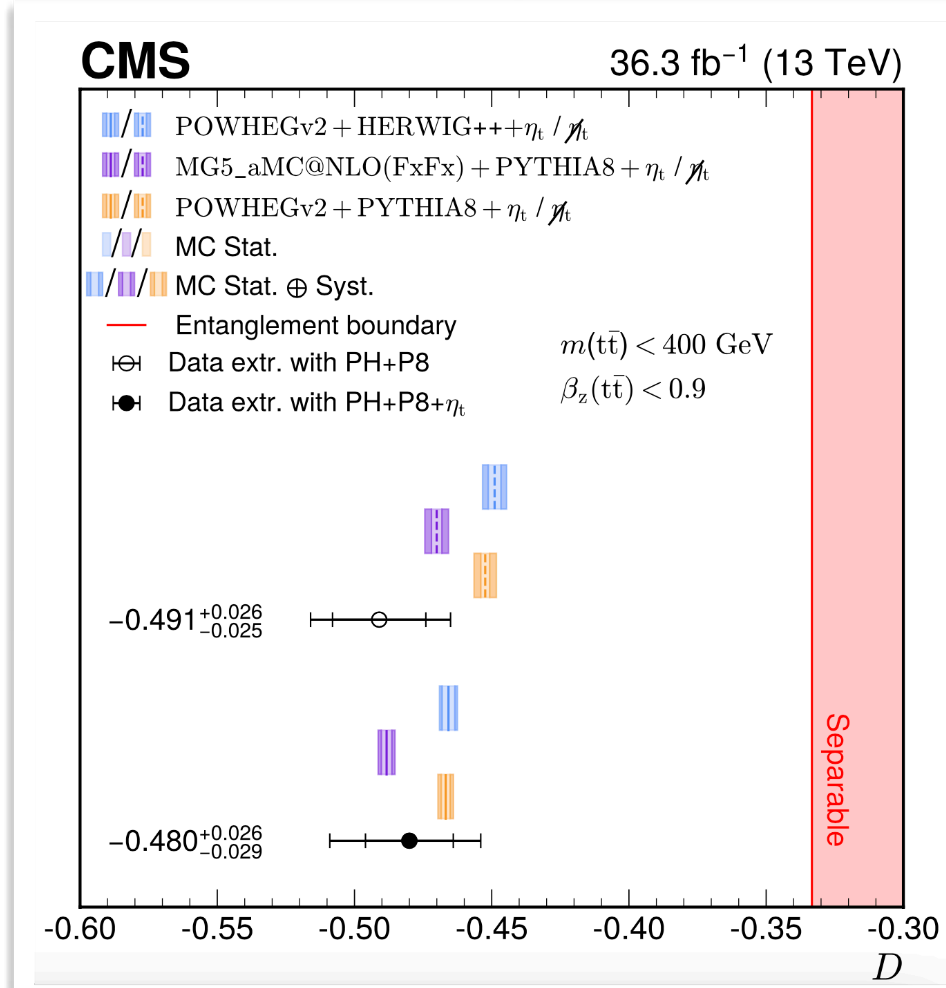

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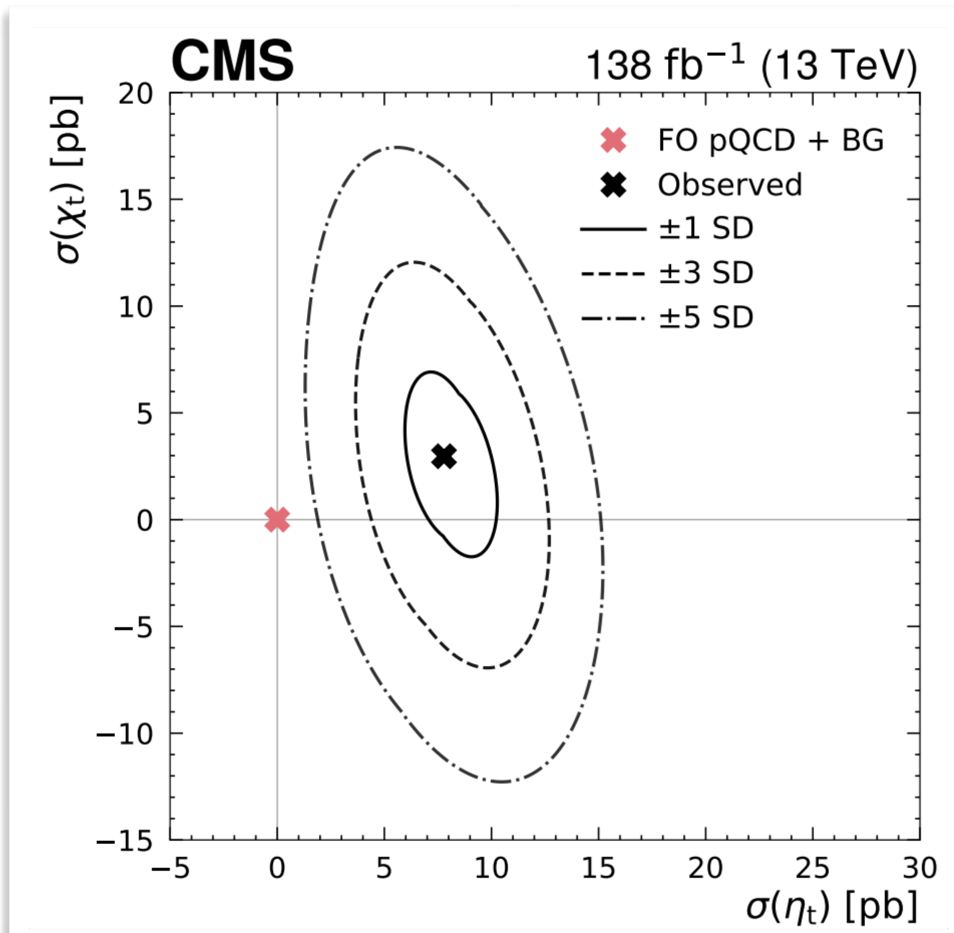
Observation of new (SM) physics

Observation of a pseudoscalar excess at the top quark pair production threshold

The CMS Collaboration*



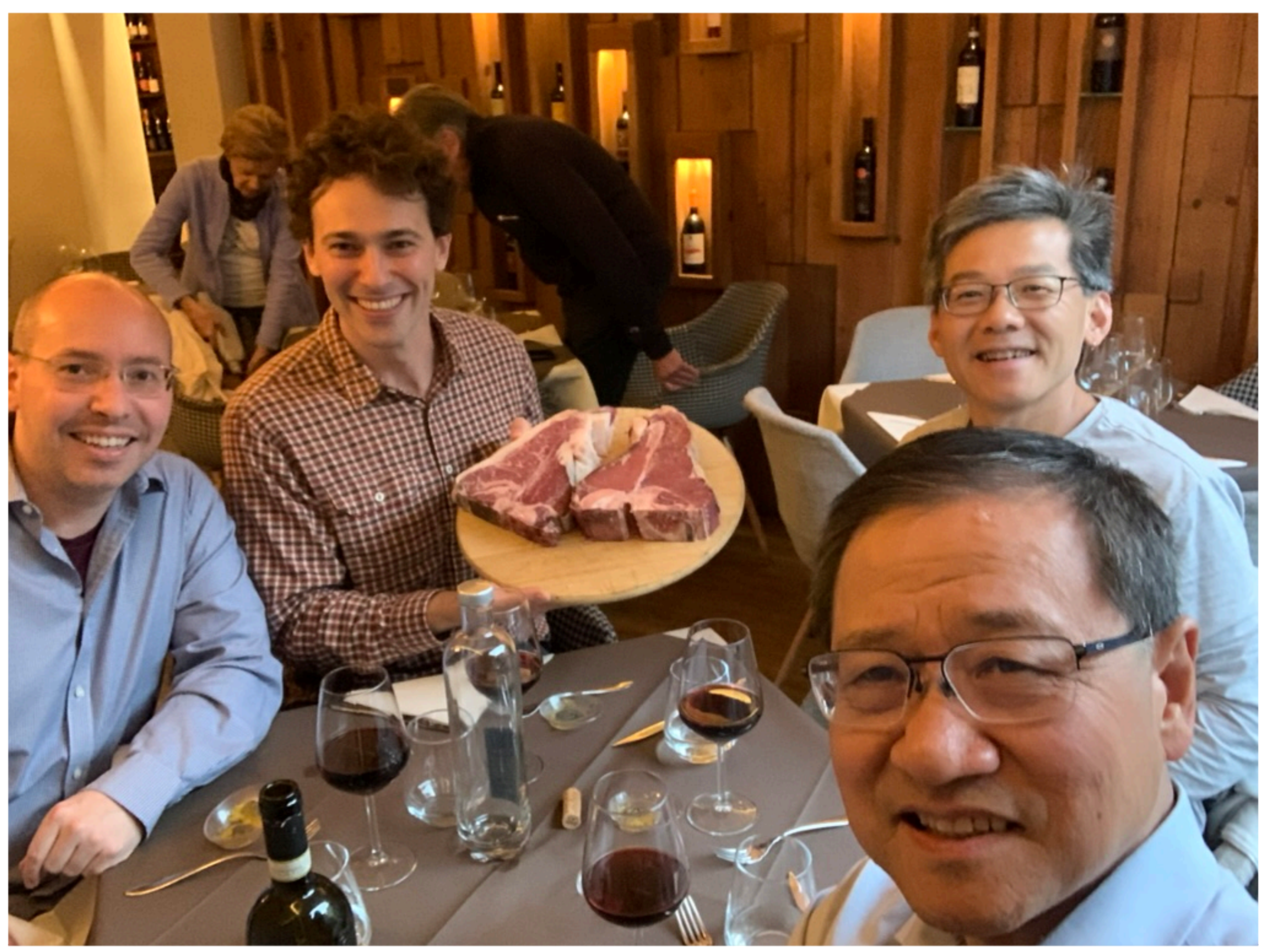
arXiv:2503.22382

- Theory effort to better understand the threshold region and improve MC adding non-relativistic approximation

Fuks,Hagiwara,Ma,Zheng '24
Nason, Re, Rottoli '25...

What I learned from Tao's style of phenomenology

- Get closer to data: new physics is not simply new particles. New physics is new phenomena
- We need to work as a community to succeed
- Keep a broad scientific curiosity (especially when going out for drinks)



Many of us have benefited enormously from Tao's scientific vision, generosity, and ability to build the community. I am certainly one of them

Thank you, Tao!