HPNP2023

"Higgs as a Probe of New Physics 2023"

5.-9. June 2023, Osaka University, Japan

Testing Higgs Effective Theories

June 6, 2023

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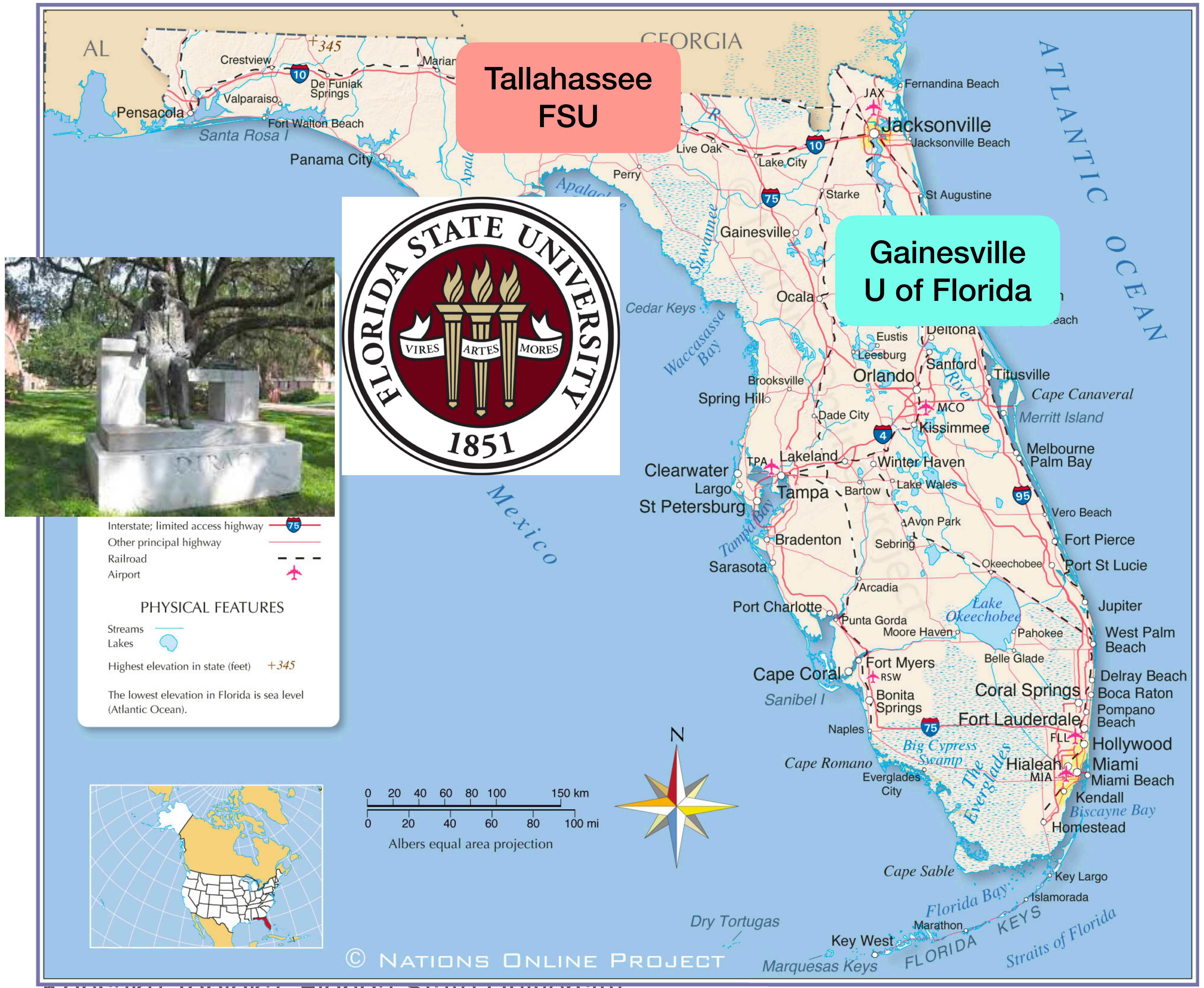
Florida State University, KEK

Work in progress with Shameran Mahmud

Florida State University

- I'm at Florida State U, not Univ of Florida. [I know it's confusing 😜]

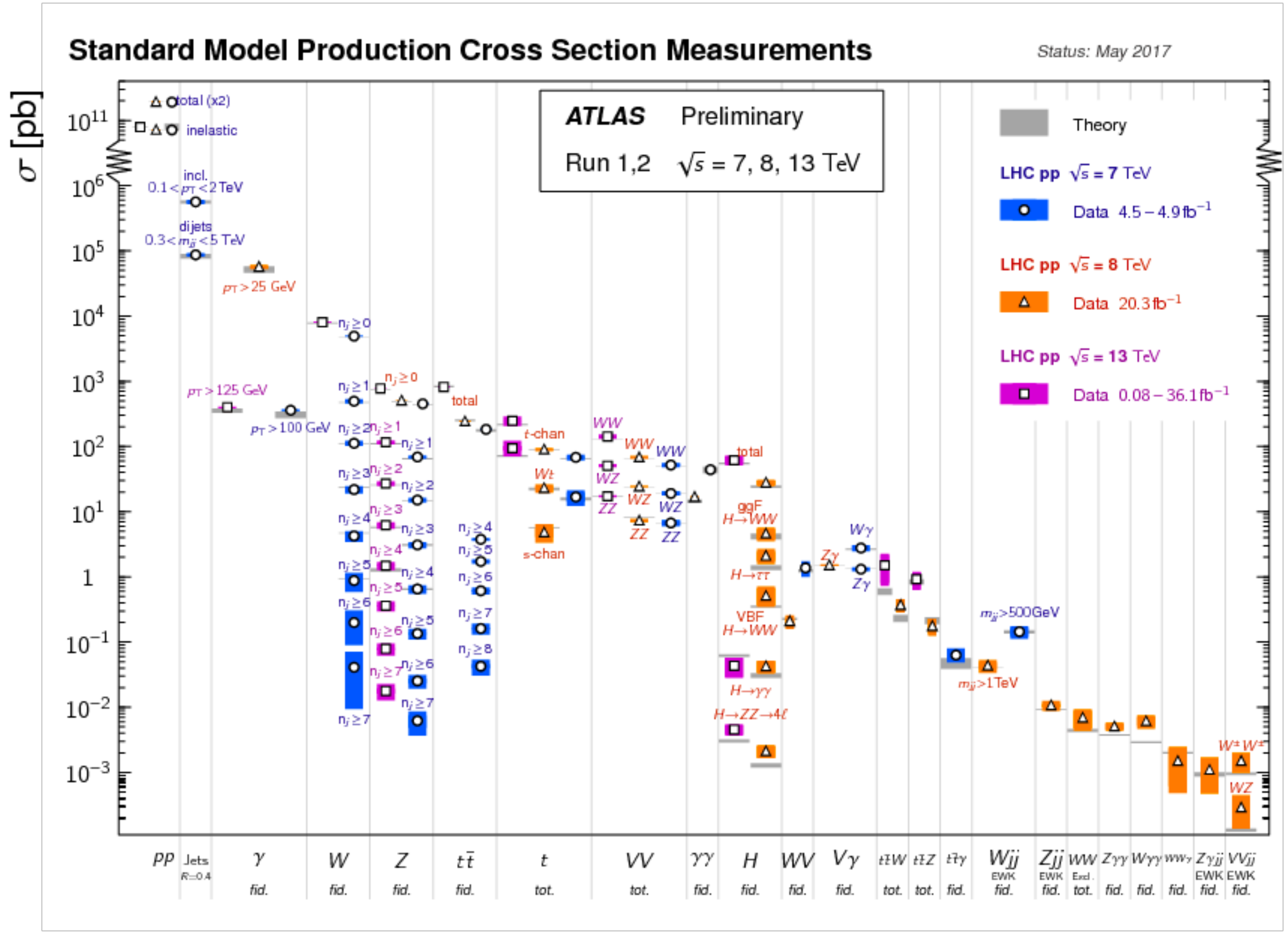


- Willing to host JSPS fellows/visitors! [just write to ktobioka @ fsu.edu]

- BSM theory/ Precision calc., Amplitude together with HEP experiments

Try to get the most out of LHC data

- LHC data is consistent with SM over multiple energy scales, sort of beauty of SM.



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- The SM is not satisfactory at all; Higgs sector/EWSB is very ad hoc.
- "*Higgs as a probe of new physics*" to "*get the most out of the data*"
  - Single Higgs couplings

    E.g. $H \to cc$ coupling, $VH \to cc$ now operated at both CMS/ATLAS, competitive sensitivities!!

    Perez, Soreq, Stamou, KT ['15] *Talks by Ganguly, Sun*

    New idea J/Ψ+cc. *T. Han's talk*
  - Higgs self(cubic)-coupling is the next major challenge.

    Talks by Ganguly, Sun, Braathen, De Curtis, Moretti, Wang, Azevedo, Wong. …

    Also pointing out exotic channels motivated by theory. *Talk by Song …*

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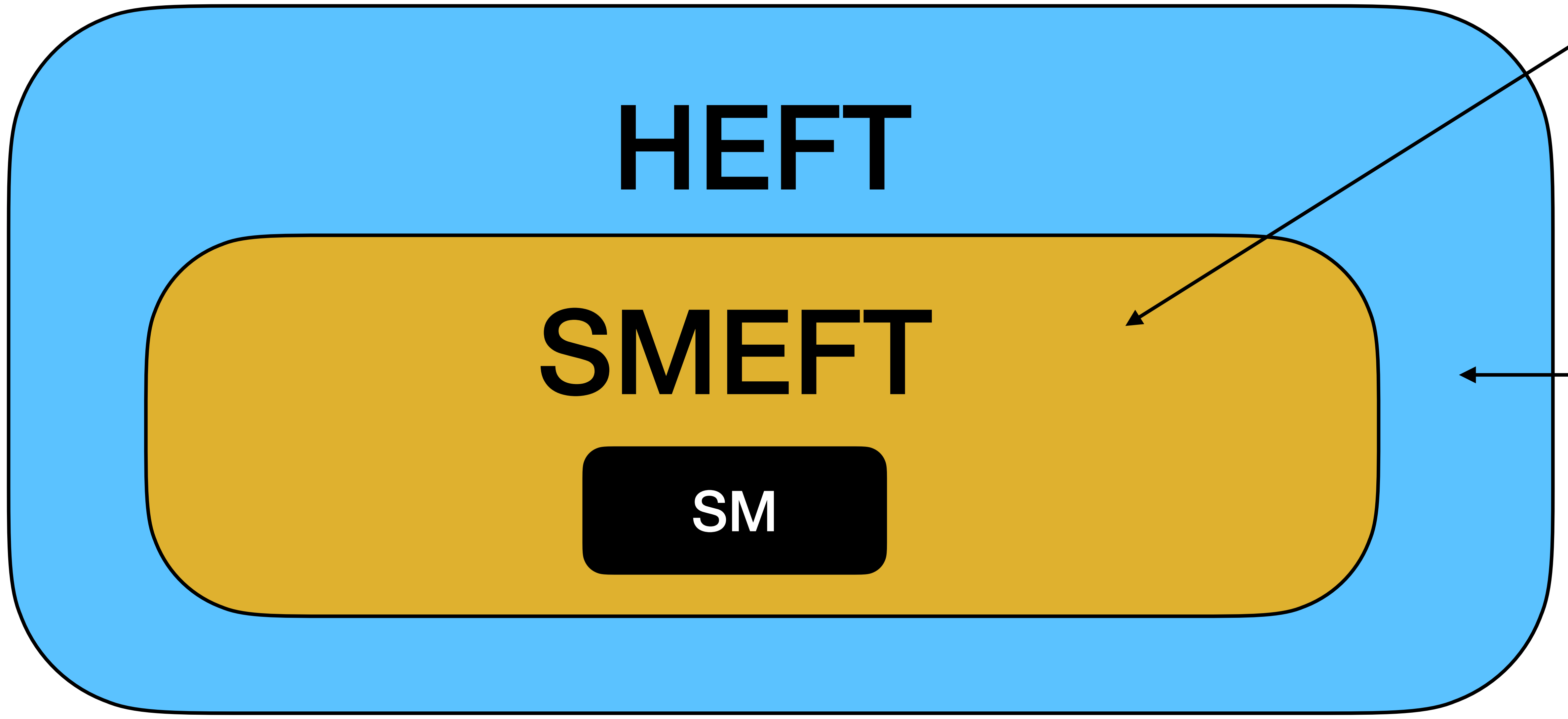
✦What else? I take Higgs Effective Field Theory (HEFT)

What is Higgs EFT? HEFT ⊃SMEFT ⊃SM



- EW linearly realized. H as SU(2) doublet and expand like $|H^\dagger H|^n$…
- EW is non-linearly realized. $SU(3)c \times U(1)_{EM}$ is manifest. h, h^2, h^3…
  - In my talk let me call one excluding SMEFT as HEFT.

- HEFT seems to have more freedom, but actually has constrained structure, e.g. definite cutoff ~**4πv** unlike in SMEFT where NP can decouple.

What models lead to HEFT?

(i) New heavy states acquire the mass dominantly from the Higgs VEV.

(ii) New heavy states participates in the electroweak symmetry breaking.

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Which EFT requires HEFT over SMEFT?

(A) Geometric formulation of EFT and curvature conditions

[arXiv:1511.00724] [arXiv:1605.03602] Alonso, Jenkins & Manohar; [arXiv:2008.08597] Cohen, Craig, Lu, Sutherland

(B) $SU(2)_L$x $U(1)_Y$ invariant form: $\mathscr{L}(h) \to \mathscr{L}(\sqrt{H^\dagger H} - v_{\rm EM})$ where ***H*** is weak doublet.

The EFT would have **non-analyticities at H→0**

Falkowski&Rattazzi [1902.05936]

$$\left(\partial\sqrt{H^\dagger H}\right)^2 \qquad \left(\sqrt{H^\dagger H}\right)^n \qquad (H^\dagger H)^2 \log(H^\dagger H)$$

Tree-level HEFT: singlet example

Cohen, Craig, Lu, Sutherland

- SM gauge singlet S

$$\mathcal{L}_{\rm UV} = |\partial H|^2 + \frac{1}{2}(\partial S)^2 - V$$

Negative

$$V = -\mu_H^2 |H|^2 + \lambda_H |H|^4 + \frac{1}{2}\left(m^2 + \kappa |H|^2\right) S^2 + \frac{1}{4}\lambda_S S^4\,.$$

*For positive S mass leading to Sc=0, non-analyticities appear at loop $(H^\dagger H)^2 \log(H^\dagger H)$

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- If $|\kappa| v_{\mathrm{EM}} > |m|$, EFT should HEFT, otherwise SMEFT expansion .
  EoM yields

$$S_{\mathbf{c}} = \left(\frac{m^2 + \kappa |H|^2}{-\lambda_S}\right)^{1/2} + \mathcal{O}(\partial^2)$$

- Substitute Sc..

$$\frac{1}{2}(\partial S)^2 = \frac{1}{2\lambda_s}\left(\partial \sqrt{-m^2 - \kappa^2 |H|^2}\right)^2$$

Non-analytic if Higgs VEV dominates S mass

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Non-analytic if Higgs VEV dominates S mass

- With m=0, singlet mass=$(-2\kappa)^{1/2}$v
  - $\kappa \sim 4\pi$, $m_S = (8\pi)^{1/2} v$ ⟶ **EFT cutoff ~4πv**
  - $v \sim 0$, $m_S \sim 0$ ⟶ **Non-analytic EFT at H=0**

*For positive S mass leading to Sc=0, non-analyticities appear at loop $(H^\dagger H)^2 \log(H^\dagger H)$

Exploring HEFT

Suppose some non-analyticities in EFT.

	Experimental scope	Generic expectation
‣ Vacuum stability	-	
‣ Single Higgs couplings	✓ on-going, O(10%) precision	Deviation expected in the singlet model. If non-analyticities in potential, no deviation.
‣ Higgs self-coupling	✓ on-going, O(5) precision	Deviation expected
‣ **Perturbative unitarity**	Not established.	Strongly coupled below $4\pi v$ ~3TeV. in Higgs/G scatterings
…		*G: NG bosons, ~Z_L/W_L

Perturbative unitarity of HEFT

- What has been discussed Falkowski&Rattazzi ['19]
  - 2-to-2: GG→hh can be safe [cross section not growing with energy]
    Z. Dong, T. Ma, J. Shu, Z. Zhou; H. Liu, T. Ma, Y. Shadmi, M. Waterbury
  - 2-to-n: **GG→3h** or more, cross section grows with energy.
    Similar observation by Chang, Luty
    See also S. Kanemura, R. Nagai; R. Nagai, M. Tanabashi, K. Tsumura, Y. Uchida

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- Question:
  To observe the energy growing behavior at collider, is **GG→nxh** practical?
  Not easy even at future colliders.

Replacing 2h with 2G

- If 2G→3h scattering is interesting, so is **2G→2G+1h**. Almost same discussion.
- E.g. $\left(\sqrt{H^\dagger H}\right)^n = \left((h+v)^2 + G^2\right)^{n/2}$,

  So far we find
  amplitudes of 2G→2G+1h grow equally or faster than ones of 2G→3h.

  ✳This tendency is more sharp in the singlet model giving $\left(\partial\sqrt{H^\dagger H}\right)^2$
  We find: **A(2G→2G+1h)** ≫ **A(2G→3h).**

WW→WWh more practical at colliders

- WW→3h is hard, because of higgs decay modes. 60% is h→2b-jets. (2%:2γ) Even 2h is very challenging (why h-cubic is poorly constrained).
- W boson has a significant BR to leptons. (WWW was measured at LHC) Also Z boson is better than h.

h+

final state AB (in hAB)	possible measured decays	BR products
hh	$(b\bar{b})(\gamma\gamma)$	1.31×10^{-3}
	$(\gamma\gamma)\ (\gamma\gamma)$	5.20×10^{-6}
ZZ	$(l^+l^-)(l^+l^-)$	1.02×10^{-2}
W^+W^-	$(l^+\nu)(l^-\nu)$	0.106

- We gain signal statistics by ~100 due to practical decay patterns on top of **A(2G→2G+1h) > A(2G→3h)**
- Quantitative sensitivities to be studied.

Thank you!