Why the sky is blue?

A tribute to Cen Zhang's work in theoretical physics

Higgs Hunting, Paris, 2019

Institute of High Energy Physics
Chinese Academy of Sciences

Physics

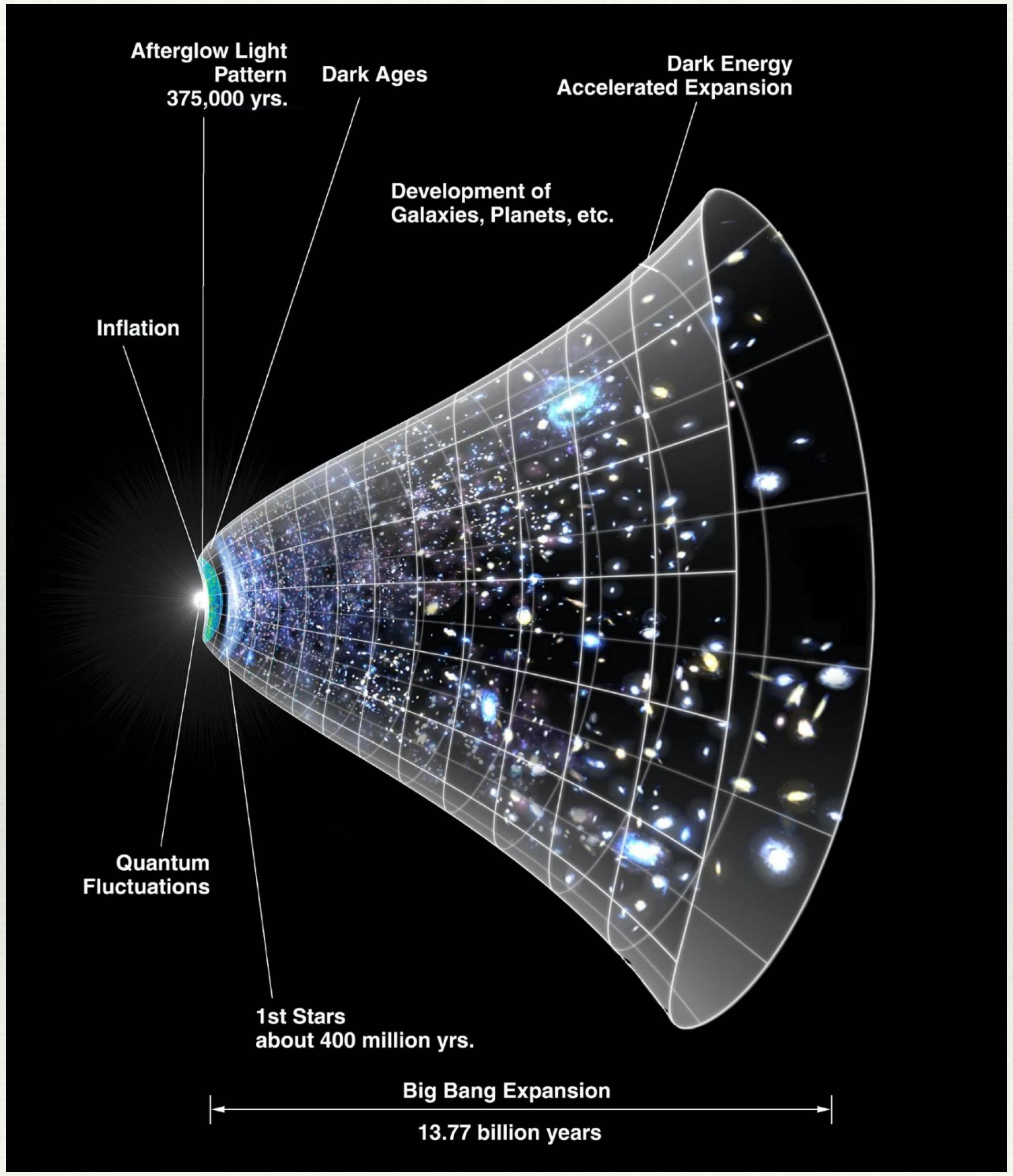
- Physicists admire the beauty of Nature and dare to ask "fundamental questions" to understand its workings:

  - Why bodies fall?
  - Why the Moon is always showing the same face to us?
  - Why the sky is blue?

Physics

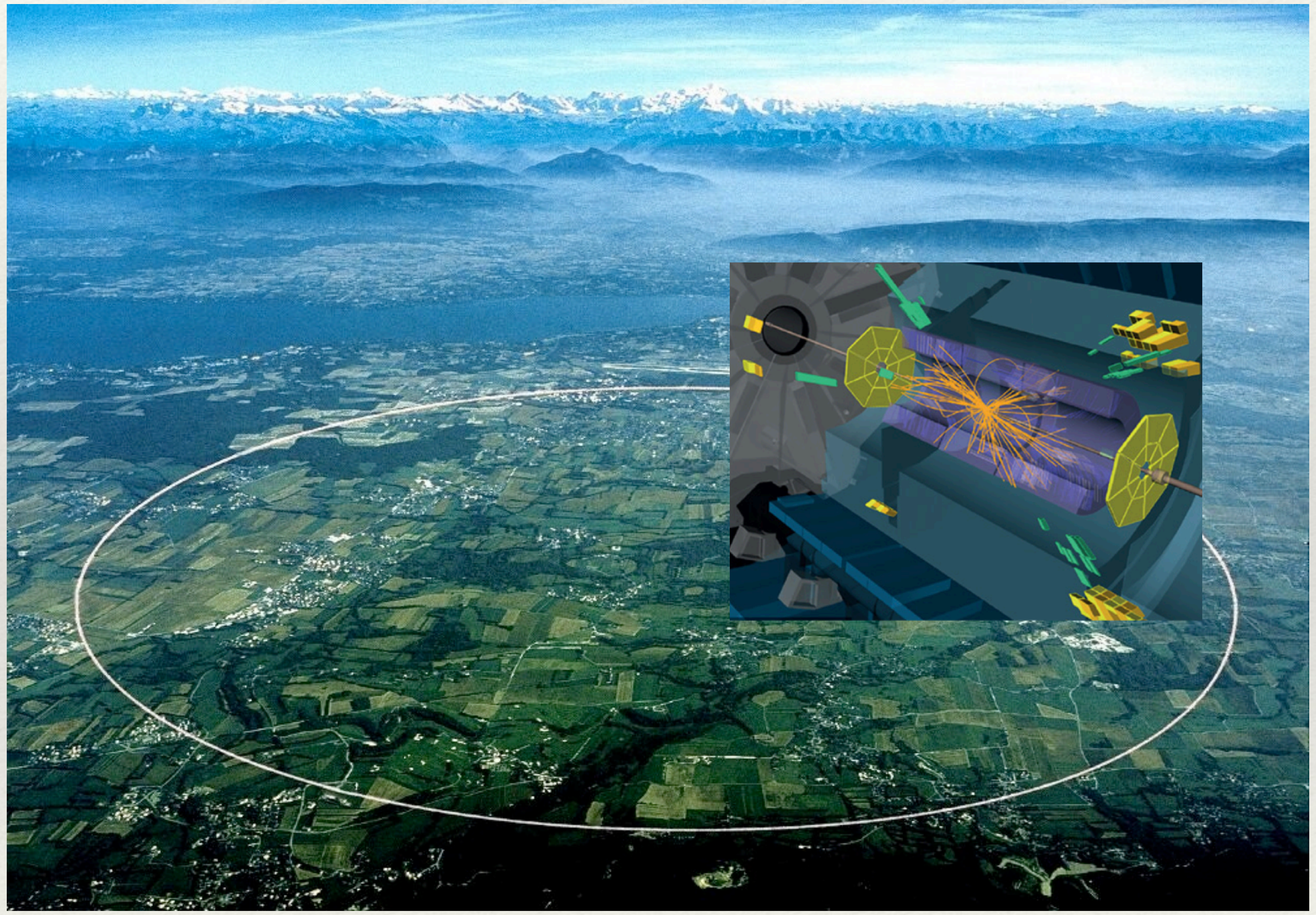
- And once we understand something, we feel confident to ask more difficult ones:

  - What are the fundamental constituents of matter?
  - How do they interact?
  - What is the origin of the Universe? What is the future?
  - Are there good explanations for us to be here, now?



How do we answer to the questions?

- **Experimental physicists** build experiments to measure and/or observe phenomena at very large or very small scales:
  - Radio/telescopes scopes
  - Gravitational waves observatories
  - Satellites
  - Particle accelerators



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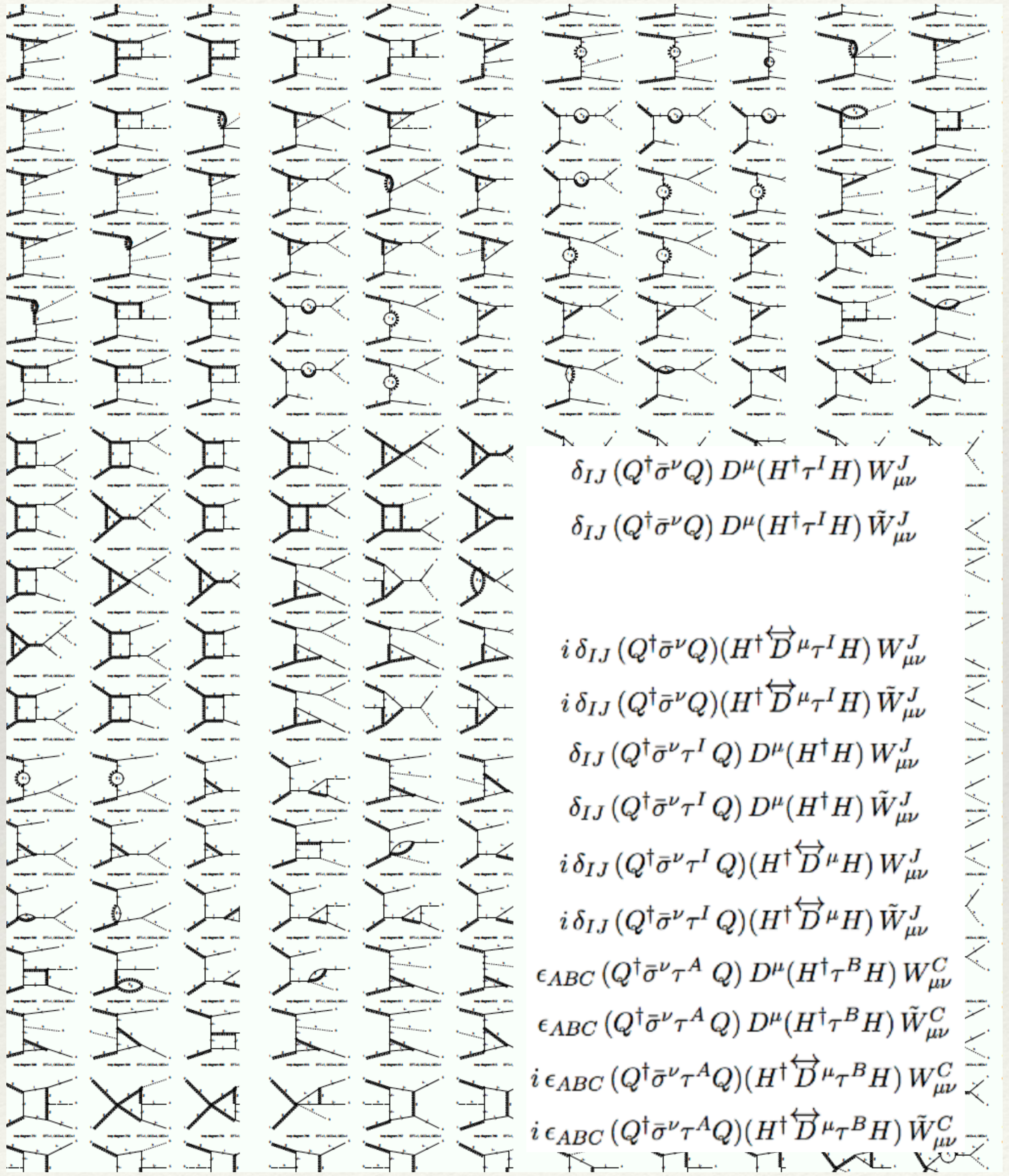
How do we answer to the questions?

- **Theoretical physicists** study the physics models through which we encapsulate our knowledge:
  - They imagine, create and construct models
  - Draw predictions from the model to compare with experimental data



In order to do so they introduce ideas that can be rather abstract, describe phenomena using the language of mathematics making it difficult to explain to a wider audience ⇒ the form a very tight community of experts.

Theoretical physicists

Raffaello Sanzio [1483-1520], *The School of Athens*

Raffaello travelled a lot in the northern Italy, and finally settled in Rome.
He passed away at 37 at the peak of his career. He left works of timeless beauty.

- The early stages of the career of theoretical physicists is quite peculiar.

- At or after the PhD, they move place to place, staying a few years until after a "long" training period, they settle and build their own group.

- This serves three main scopes:
  - Learning new techniques
  - New sources of inspiration
  - Building independence

- This path with the same motivations if often followed by artists (painters, writers,…).


Beijing
2006-2011 PhD
Urbana-Champaign
2012-2014 Post-doc
Louvain
2014-2017 Post-doc
Brookhaven
Sally Dawson
Hooman Davoudiasl
Pier Paolo Giardino
Jiayin Gu
Lian-Tao Wang
Scott Willenbrock
Nicolas Greiner
William J. Marciano
Harrison Mebane
US
Jacob J. Ethier
Giacomo Magni
Luca Mantani
Emanuele R. Nocera
Juan Rojo
Emma Slade
Celine Degrande
Wolfgang Kilian
Olivier Mattelaer
Jian Wang
Diogo Buarque Franzosi
Matthias Neubert
Chien-Yi Chen
Olga Bessidskaia Bylund
Ioannis Tsinikos
Eleni Vryonidou
Benjamin Fuks
Martín Perelló
Marcel Vos
Ken Mimasu
Céline Degrande
Gauthier Durieux
Ilaria Brivio
Sebastian Bruggisser
Rhea Moutafis
Tilman Plehn
Susanne Westhoff
Seth Moortgat
Jorgen D'Hondt
Alberto Mariotti
Europe
Co-authors of publications
(community efforts are excluded)

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(community efforts are excluded)

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Xu Li
Chengjie Yang
Hao Xu
Zi-Yue Wang
Shuang-Yong Zhou
Jiayin Gu
Kimiko Yamashita
Yiming Liu
Yu-Jia Wang
Feng-Kun Guo
Liaoshan Shi
Qi Bi

US

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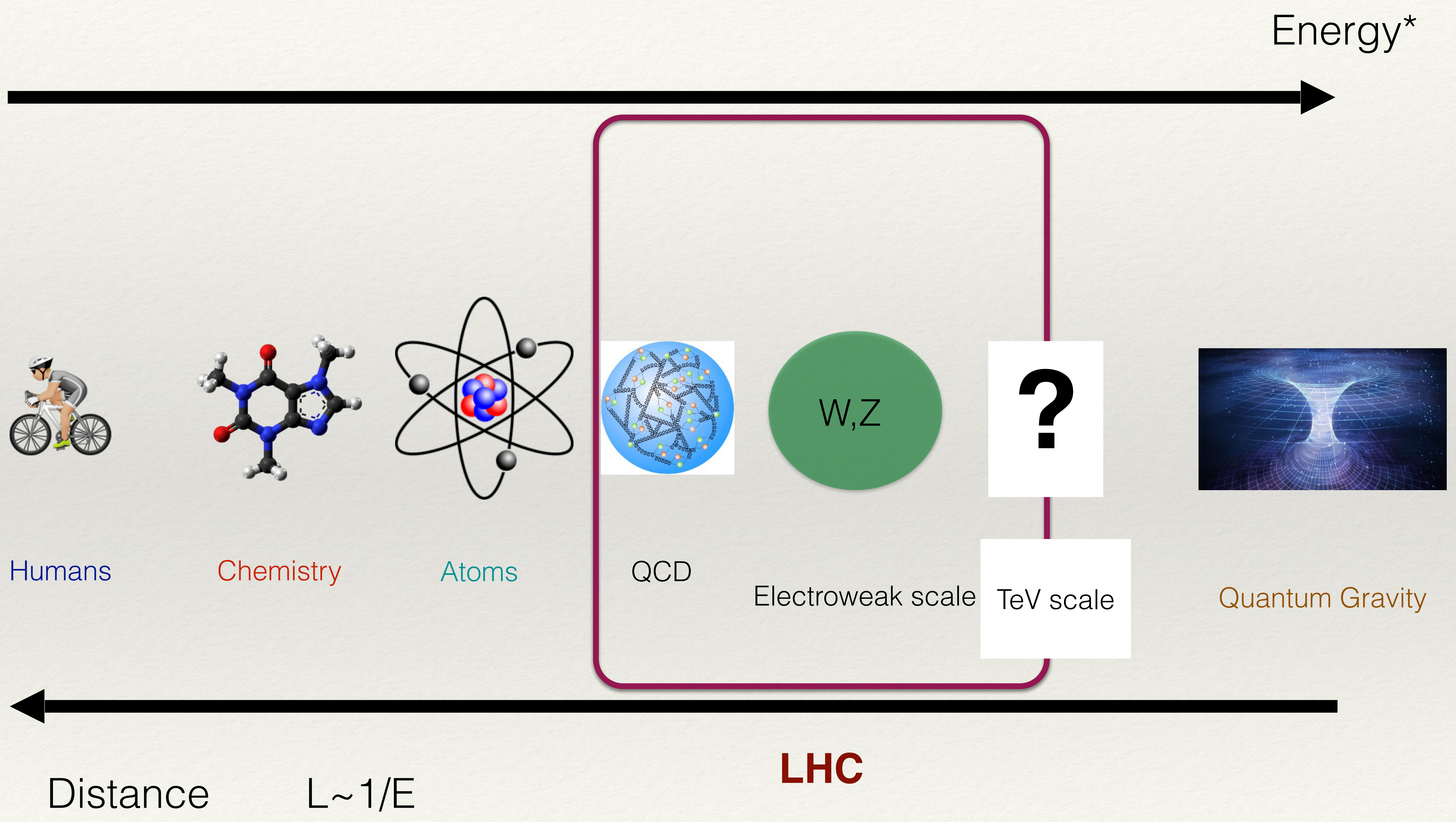
What is an Effective Field Theory?



Why the sky is blue?

$$\mathscr{L} = \psi^\dagger\left(i\partial_t - \frac{\partial^2}{2m}\right)\psi + \mathscr{L}_{\text{int}}$$

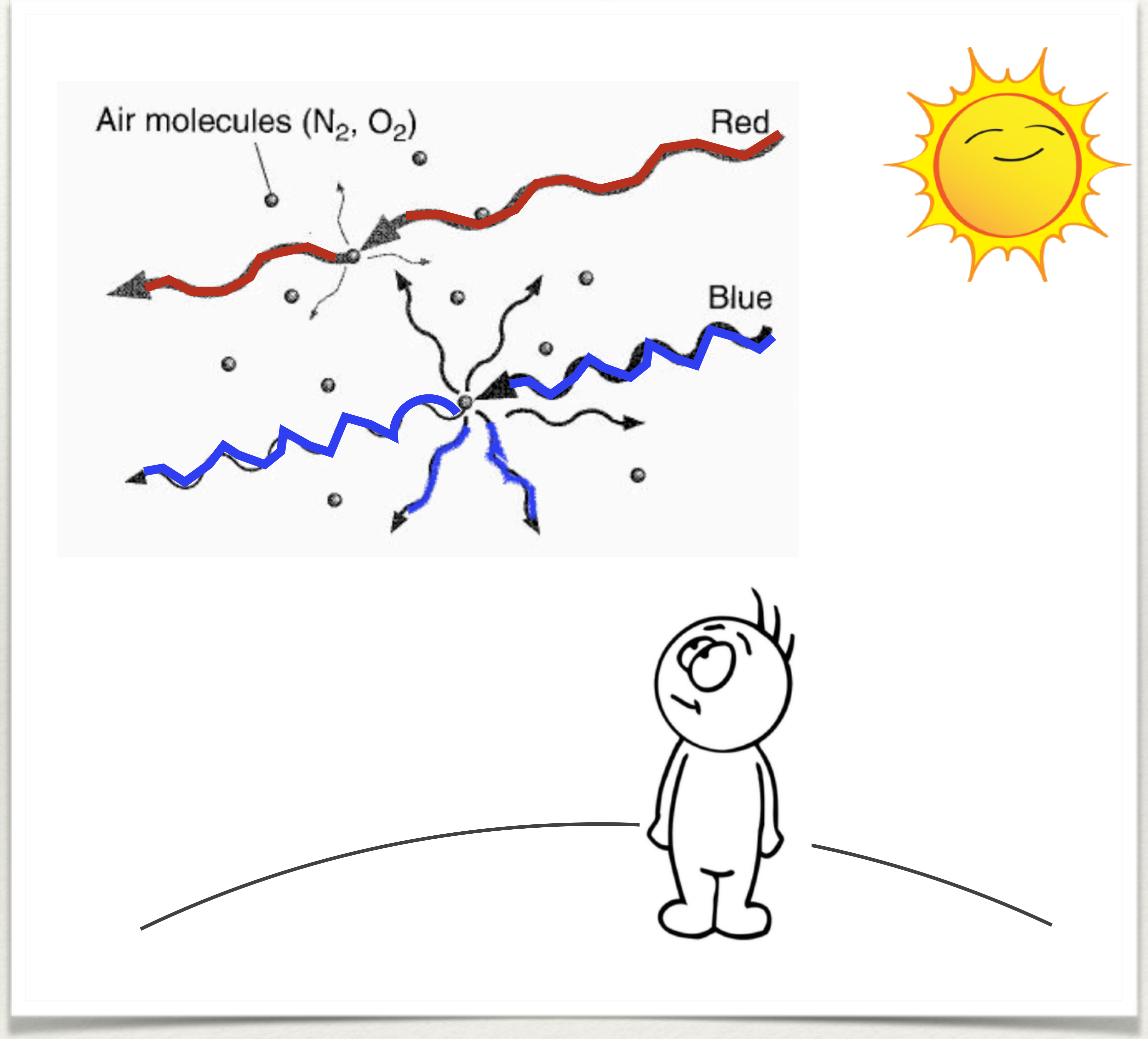
The photon only interacts with the atom when it can resolve its charged constituents, the electron and nucleus, which are separated by a0

$$\mathscr{L}_{\text{int}} = c\frac{\psi^\dagger\psi\left(c_E\mathbf{E}^2 + c_B\mathbf{B}^2\right)}{\Lambda^3}$$

$$[1/\Lambda] = [a_0] = M^{-1} = L$$

This immediately gives:

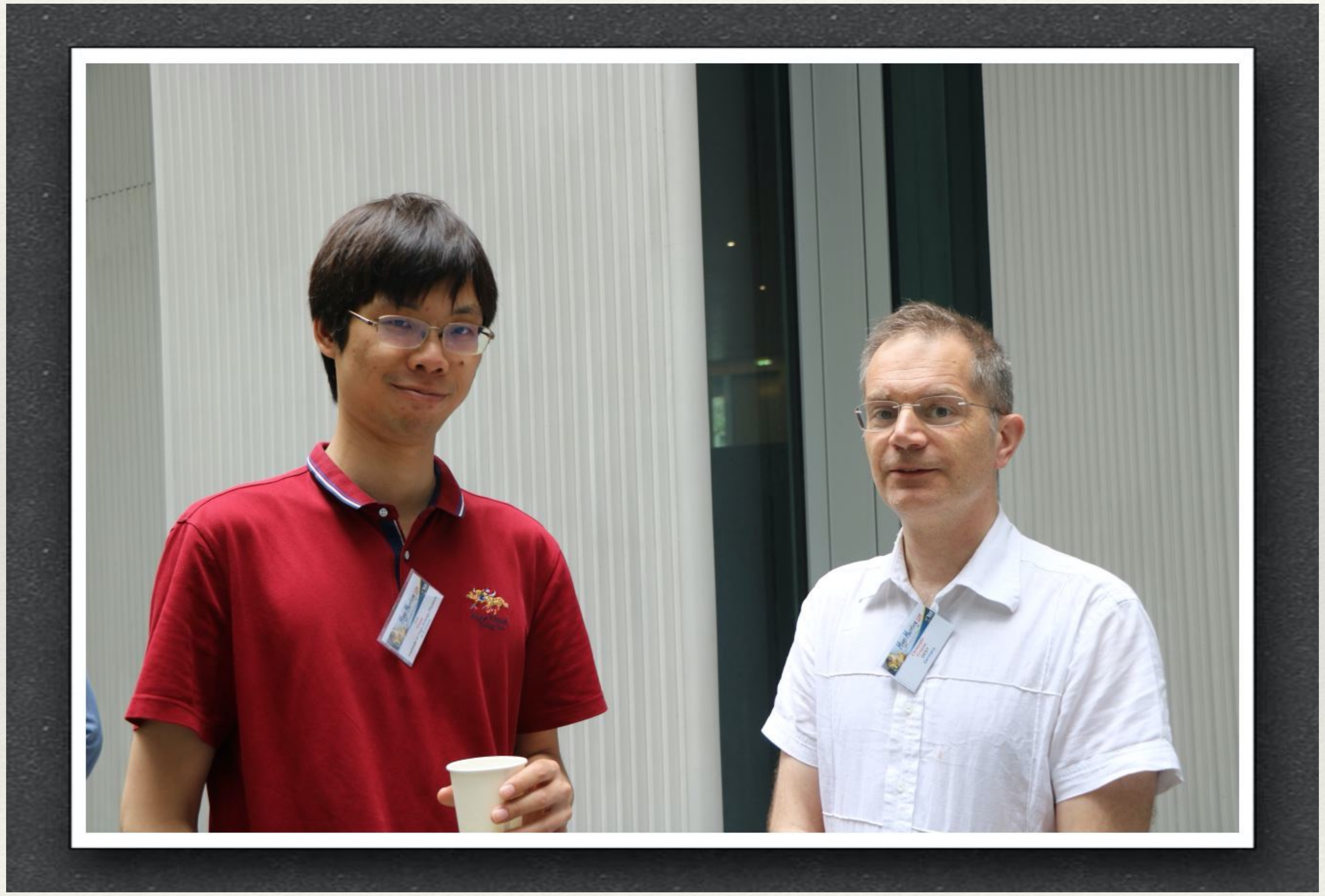
$$\mathscr{A} \sim a_0^3\omega^2 \Rightarrow \sigma \sim a_0^6\omega^4$$



The blue photons can see better the internal constituents of the atom than other colors…

An effective field theory is predictive!

An anedocte



Cen and Christophe at Higgs Hunting 2019

During the Xmas vacation 2013-2014, I was in Barcelona at ICREA. Cen and Scott had just came out with the paper Effective Field Theory Beyond the Standard Model and I remember Alex Pomarol telling me:

"Finally, someone who understands what needs to be done for the EFT!"

Christophe Grojean (DESY)

A young talent

I am so impressed with Cen that I sometimes say that I have not figured out yet what he cannot do. He is an expert in collider physics, precision electroweak physics, and perturbative QCD, both at tree level and one-loop level, and he is very fast to learn and apply new techniques. He is creative and broadly interested in physics. He has continued to branch out into new areas and find important contributions to make. He is so thorough and careful that you can trust his results, and he is honest when he doesn't understand something (which is rare). He thinks deeply about physics, and is not satisfied until he understands things from first principles.

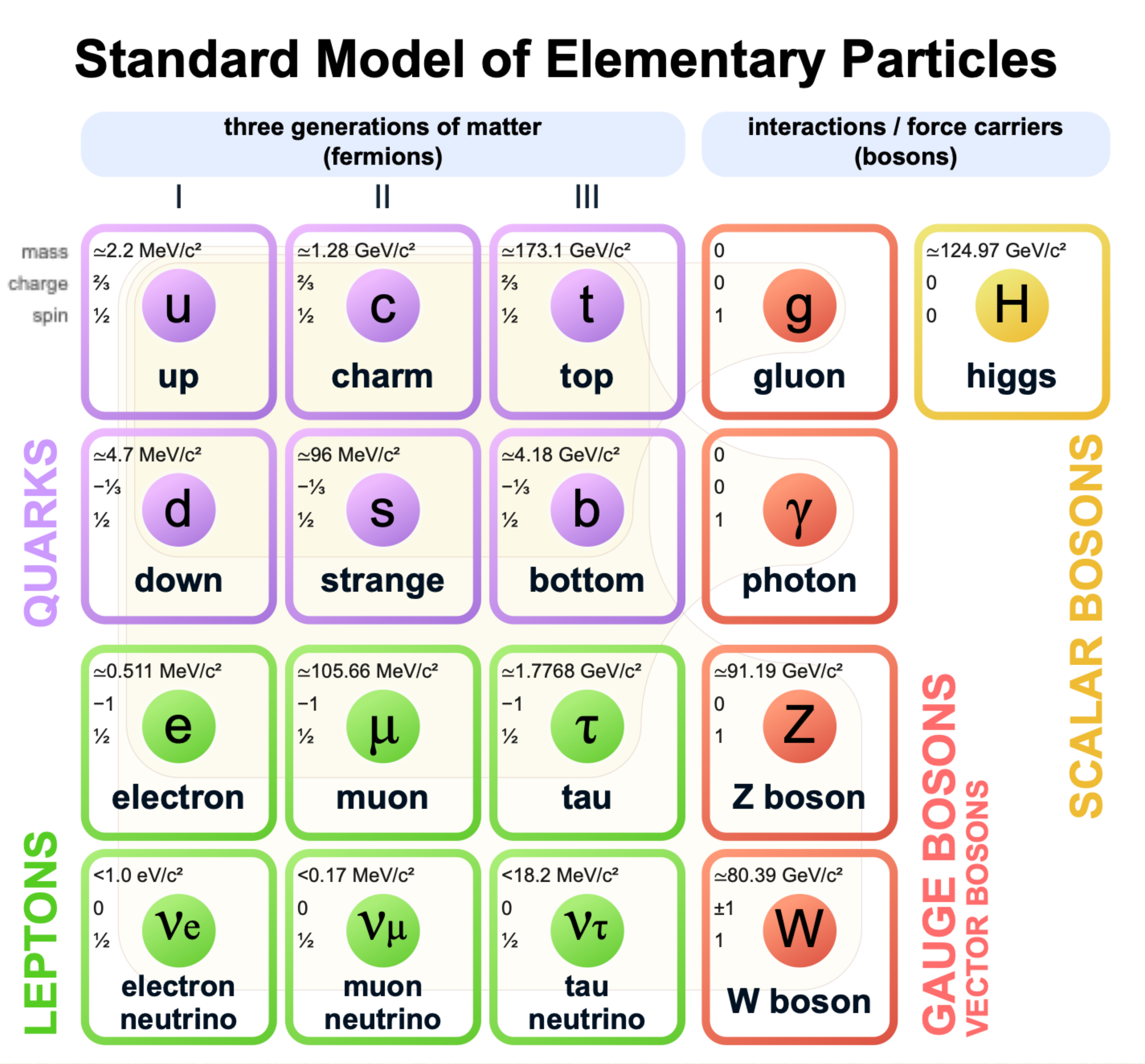
Scott Willenbrock (UIUC)

张岑给我最深的印象就是他几乎是无所不能的。在对撞机物理、电弱物理和微扰QCD理论（包括树图阶和高图理论计算）方面，他都称得上是专家。他接受新知识和新技术非常快，并且能将它们灵活运用。他兴趣广泛，富有创造力，总是不断地涉足新的领域，并且为之做出贡献。他考虑问题全面而细致，总能给出可信赖的结果。当他对某个问题不懂的时候（这样的时候很少），他也能如实告诉您他不懂。他总是深入思考物理问题，直到他能从第一原理出发真正理解了才满意。

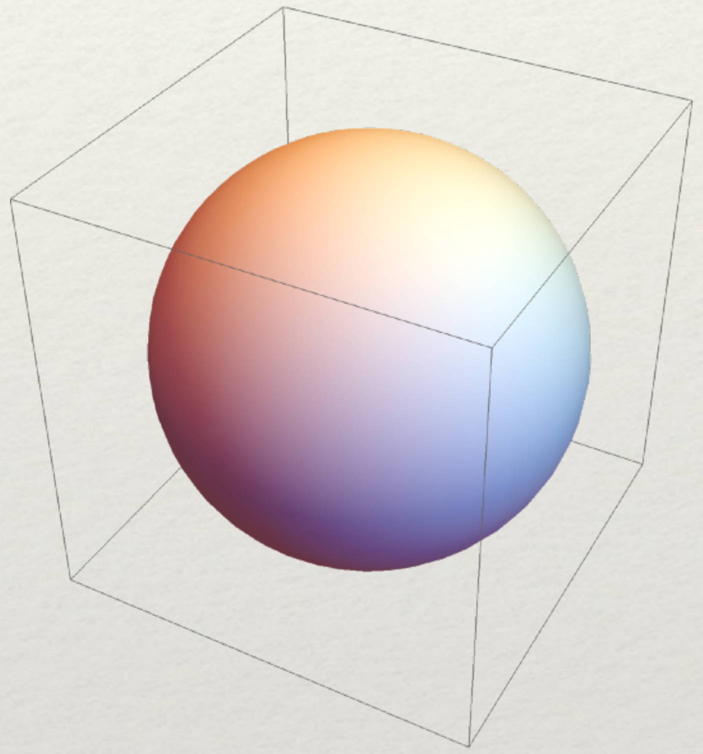
Scott Willenbrock (UIUC)

Cen was awarded of a prestigious grant by **National Young talented program in 2018** at IHEP/UCAS

The Standard Model



$$\mathscr{L}^{(4)}_{SM} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \overline{\psi} i \not{D}\psi$$
$$+ y_{ij}\overline{\psi}^i_L \phi \psi^j_R + \mathrm{h.c.}$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

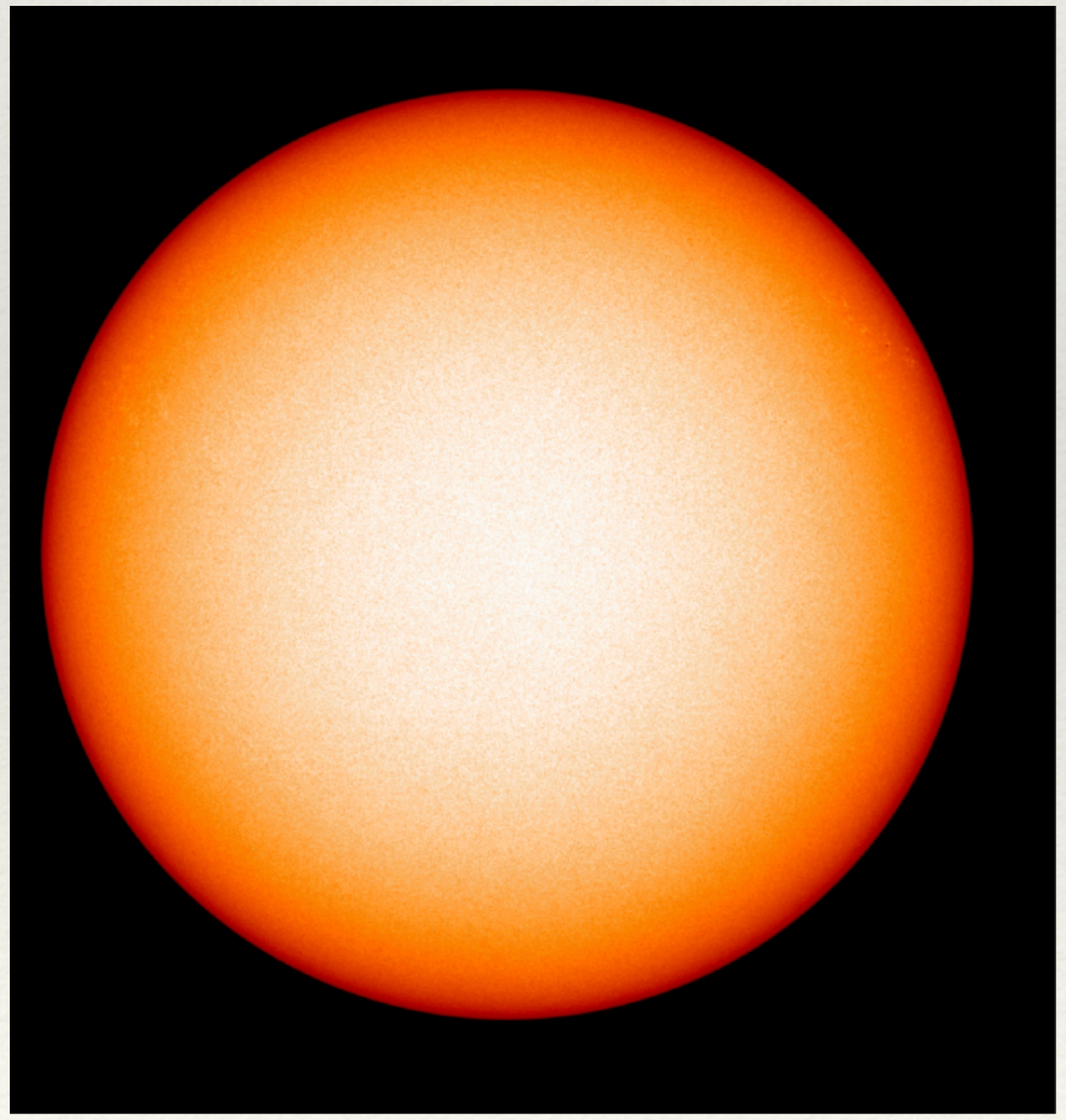


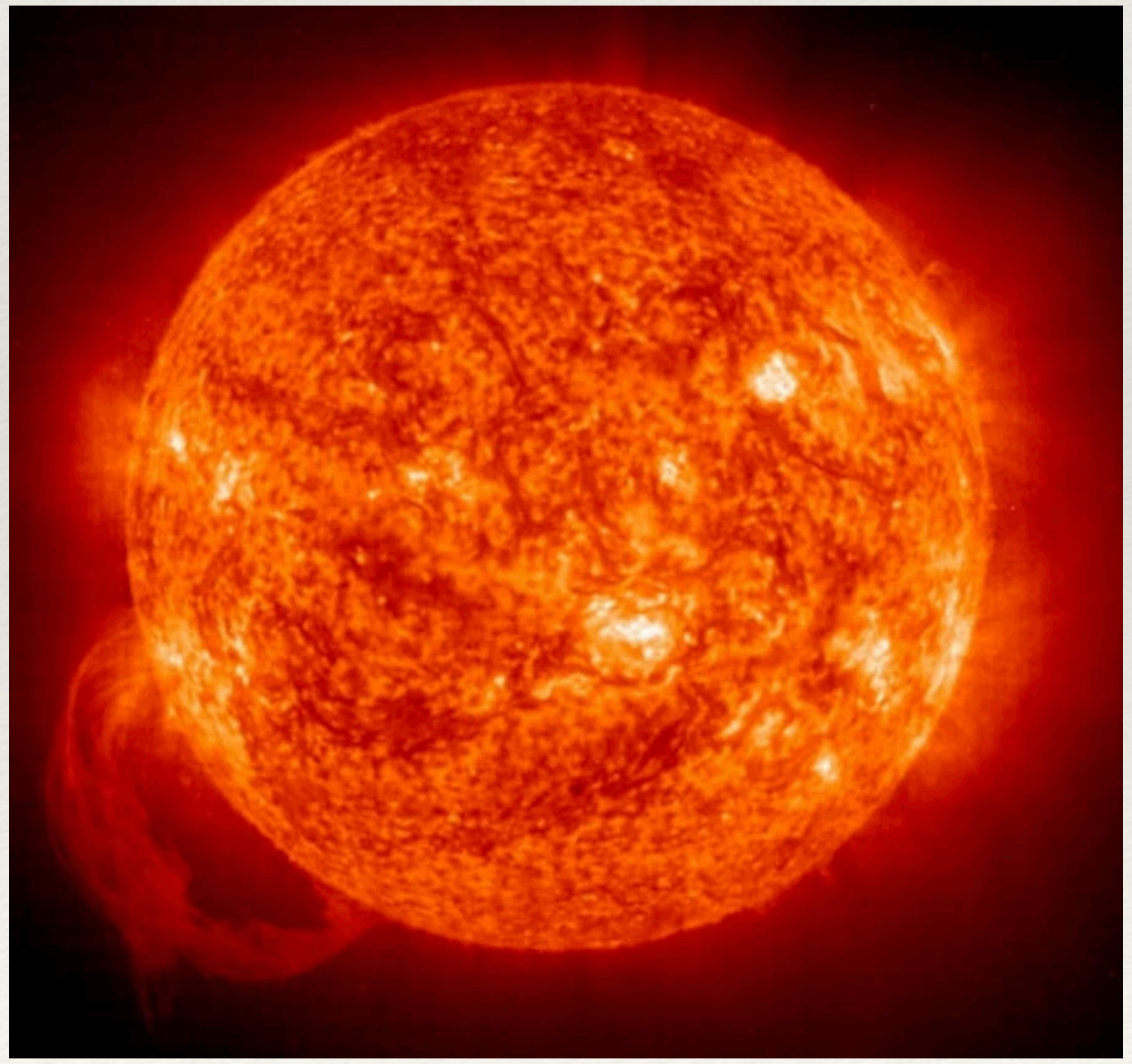
Simple and powerful

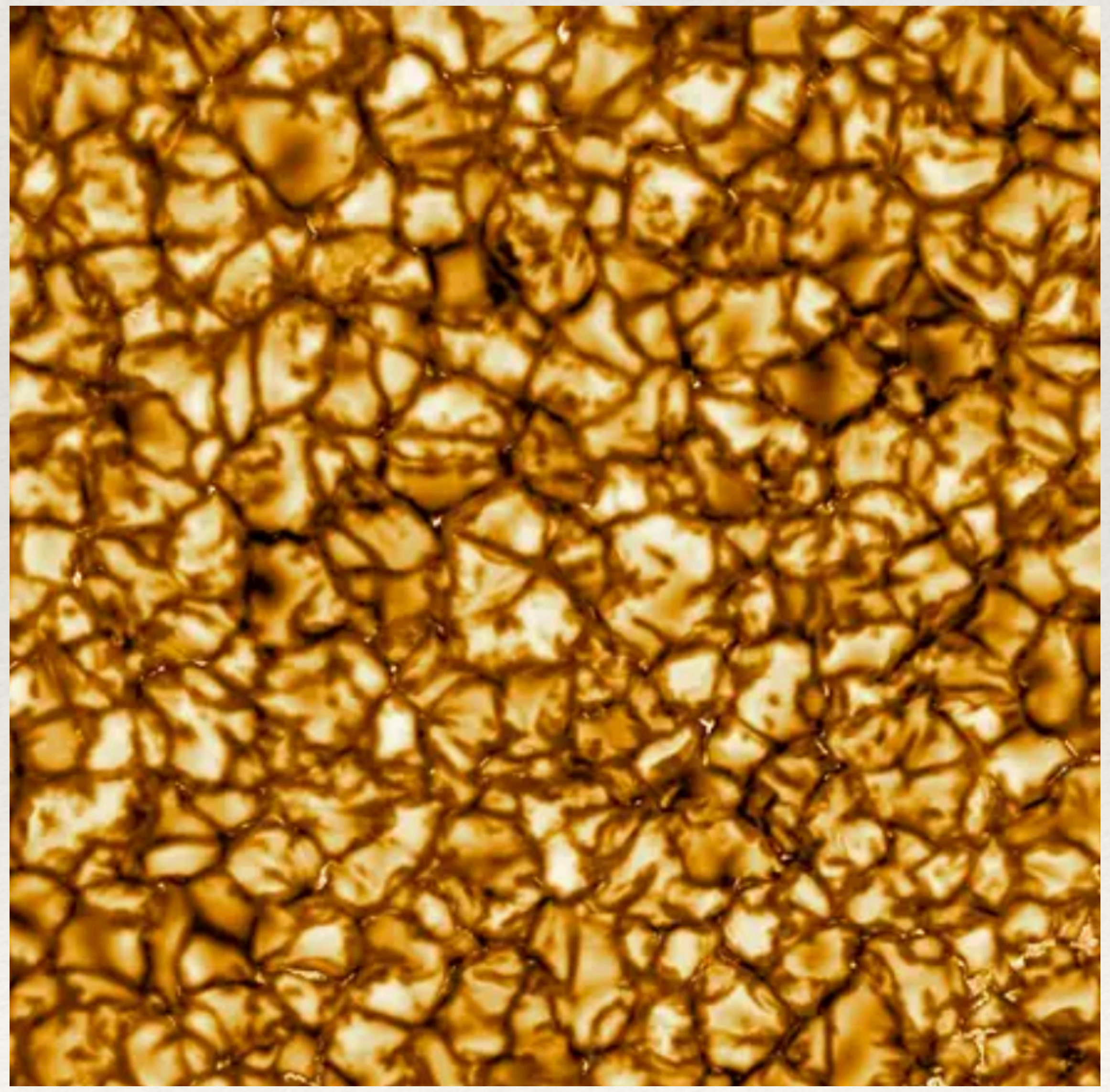
yet unnatural, incomplete…

The Standard Model Effective Field Theory

$$\mathscr{L}_{\text{SM}}^{\text{EFT}} = \mathscr{L}_{SM}^{(4)} + \sum_i \frac{O_i^{(6)}}{\Lambda^2} + \sum_j \frac{O_j^{(8)}}{\Lambda^4}$$







The SMEFT paradigm

* In the last decade, the SMEFT has become a **key part of the LHC physics programme**
* Paradigm shift: we want to measure the parameters of the **Standard Model** ⇒ **Standard Model Effective Field Theory**
* How?

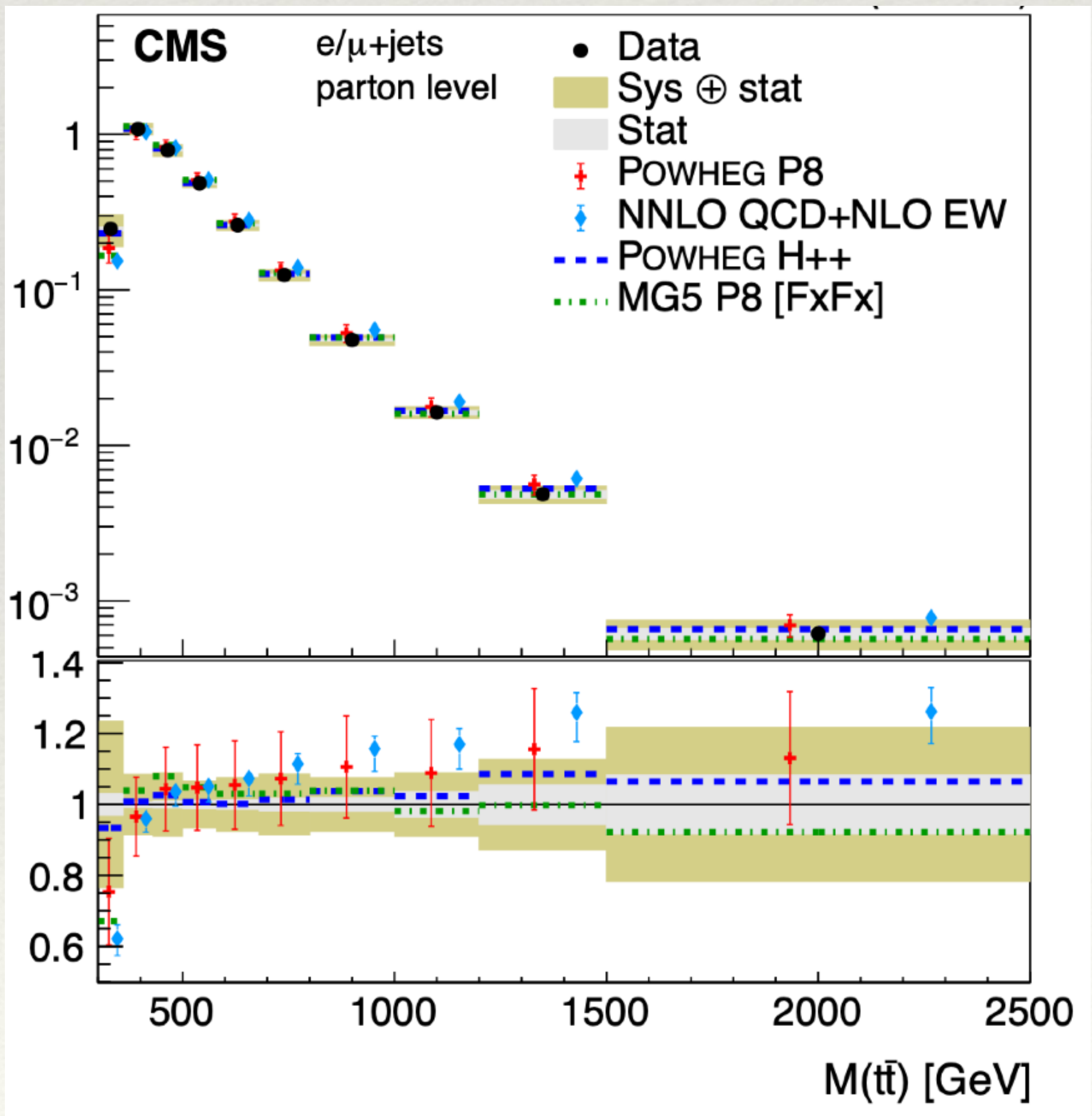
1. Measure observables (O) that depend on them: e.g. particle production at the LHC
2. Compare to theoretical prediction

$$\Delta O_n = O_n^{\text{EXP}} - O_n^{\text{SM}} = \sum_i \frac{a_{n,i}^{(6)} c_i^{(6)}}{\Lambda^2} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

Difference between experiment & SM theory = **New contributions from SMEFT operators**

DataTheory

$\frac{\text{Theory}}{\text{Data}}$



Requires:

a) Good measurements

$\Rightarrow O_n^{\text{EXP}}$

b) Reliable predictions

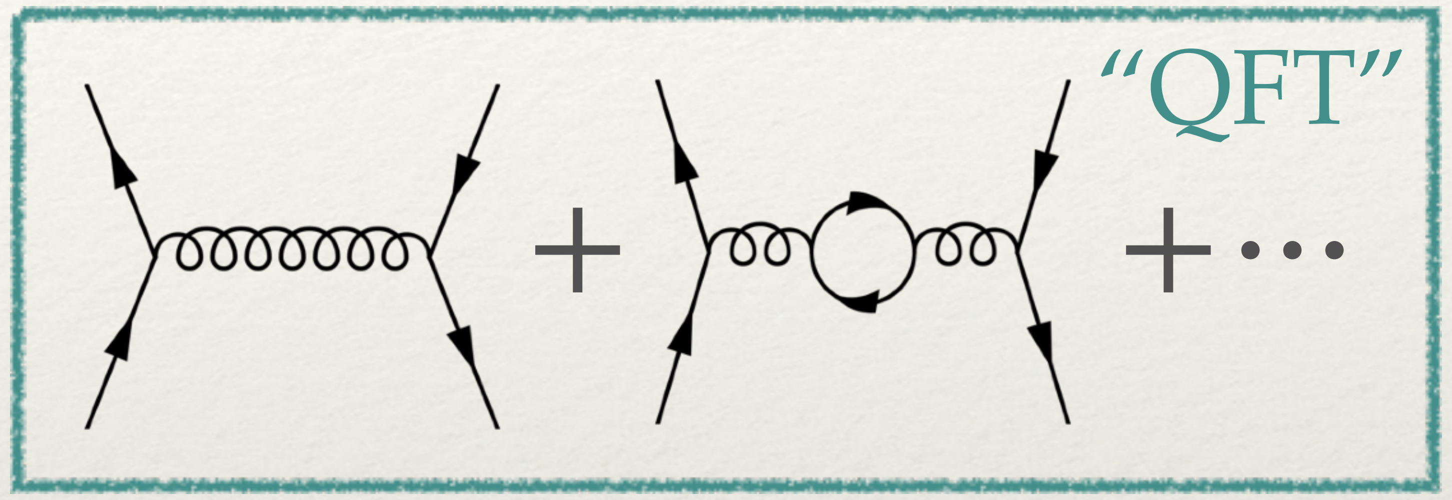
$\Rightarrow O_n^{\text{SM}},\ a_{n,i}^{(6)}$

Cen's expertise

Precise SMEFT

- Quantum Field Theory: make & **systematically improve** predictions for particle production at collider experiments like the LHC (proton-proton scattering)

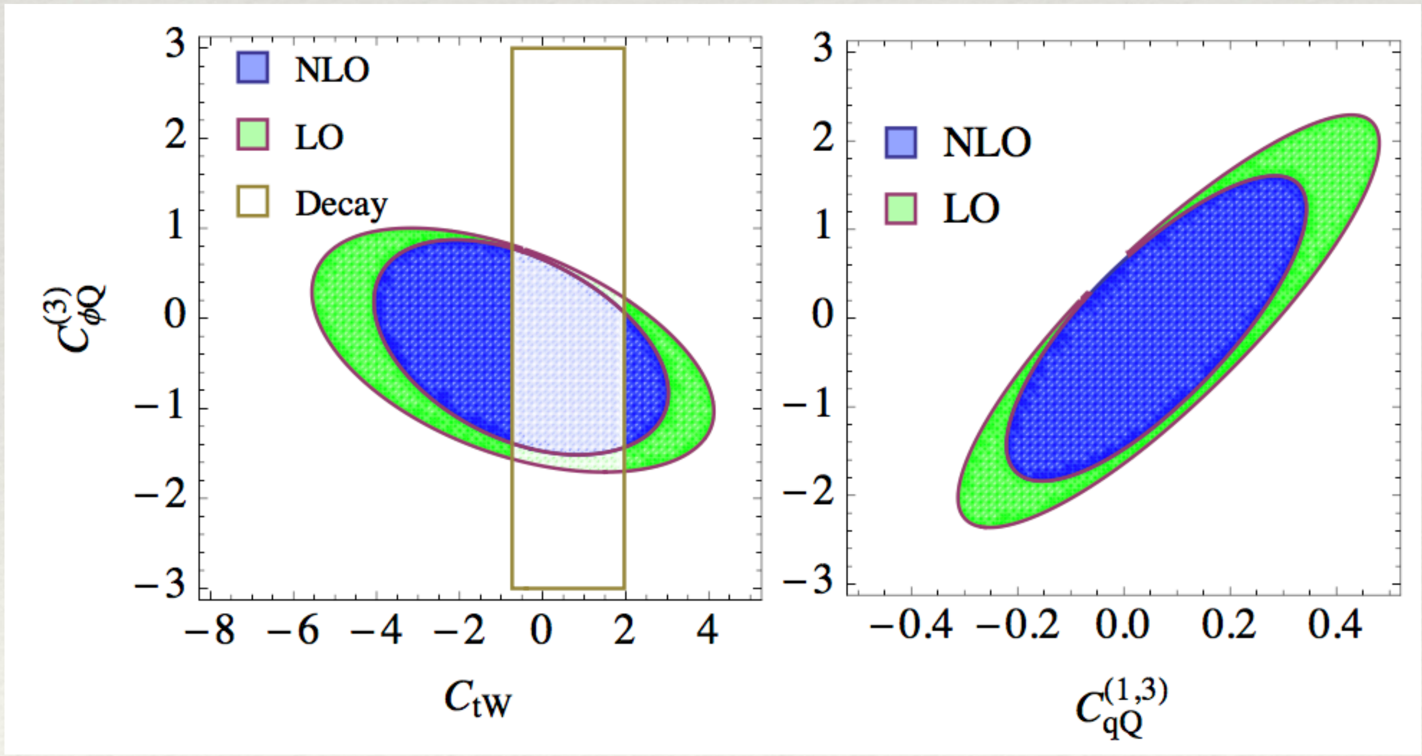
  First approximation: "Leading Order" (LO)
  Improved calculation: "Next-to-Leading Order" (NLO)
  …

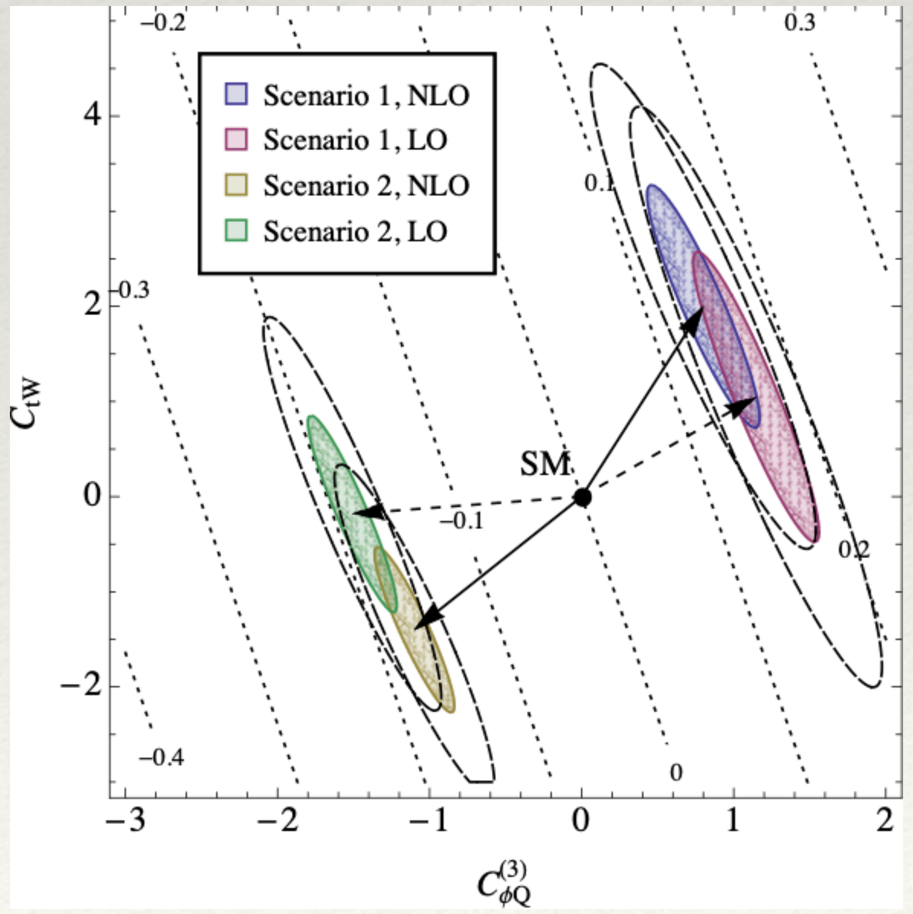


- Cen pioneered the program of **motivating & calculating** precision (NLO) SMEFT predictions for collider processes - top quark, Higgs boson,…

- He showed that NLO affects our accuracy in **determining** the SMEFT couplings & in **pinpointing** the origin of observed deviations from the SM

Single-top production Determination Pinpointing





[CZ; Phys. Rev. Lett. 116 (2016) 16, 162002]

Precise SMEFT

- Cen's work provides invaluable predictions & analysis for many key LHC processes
- Single & pair production of top quarks, and in association with Higgs/Gauge bosons

$t\bar{t}$ [Fransozi & CZ; Phys. Rev. Lett. 116 (2016) 16, 162002]

$t\bar{t} + H$ [Maltoni, Vryonidou & CZ; JHEP 10 (2016) 123]

$t\bar{t} + Z/\gamma$ [Bylund, Maltoni, Tsinikos, Vryonidou & CZ; JHEP 05 (2016) 052]

$t + H/Z$ [Degrande, Maltoni, Mimasu, Vryonidou & CZ; JHEP 10 (2018) 005]

- Crucial in understanding the interactions/dynamics behind the **Electroweak symmetry breaking mechanism**, a major open question of the Standard Model

"How exactly does the Higgs boson give mass to fundamental particles?"

- Major milestone in our programme: development & release of `SMEFT@NLO`

Automated one-loop computations in the standard model effective field theory

Céline Degrande,[1,*] Gauthier Durieux,[2,†] Fabio Maltoni,[1,3,‡] Ken Mimasu,[1,§] Eleni Vryonidou,[4,‖] and Cen Zhang[5,6,¶]

[Phys. Rev. D 103, 096024 (2021)]

- **Generic** NLO SMEFT predictions for collider simulations
- **Industry-standard** tool for experimental & theory communities

Cen and I

- I met Cen around 2014/2015 in the R1 cafeteria at CERN
- I already knew **very well** who he was!
- Even as a junior postdoc, he was recognised as a leading expert

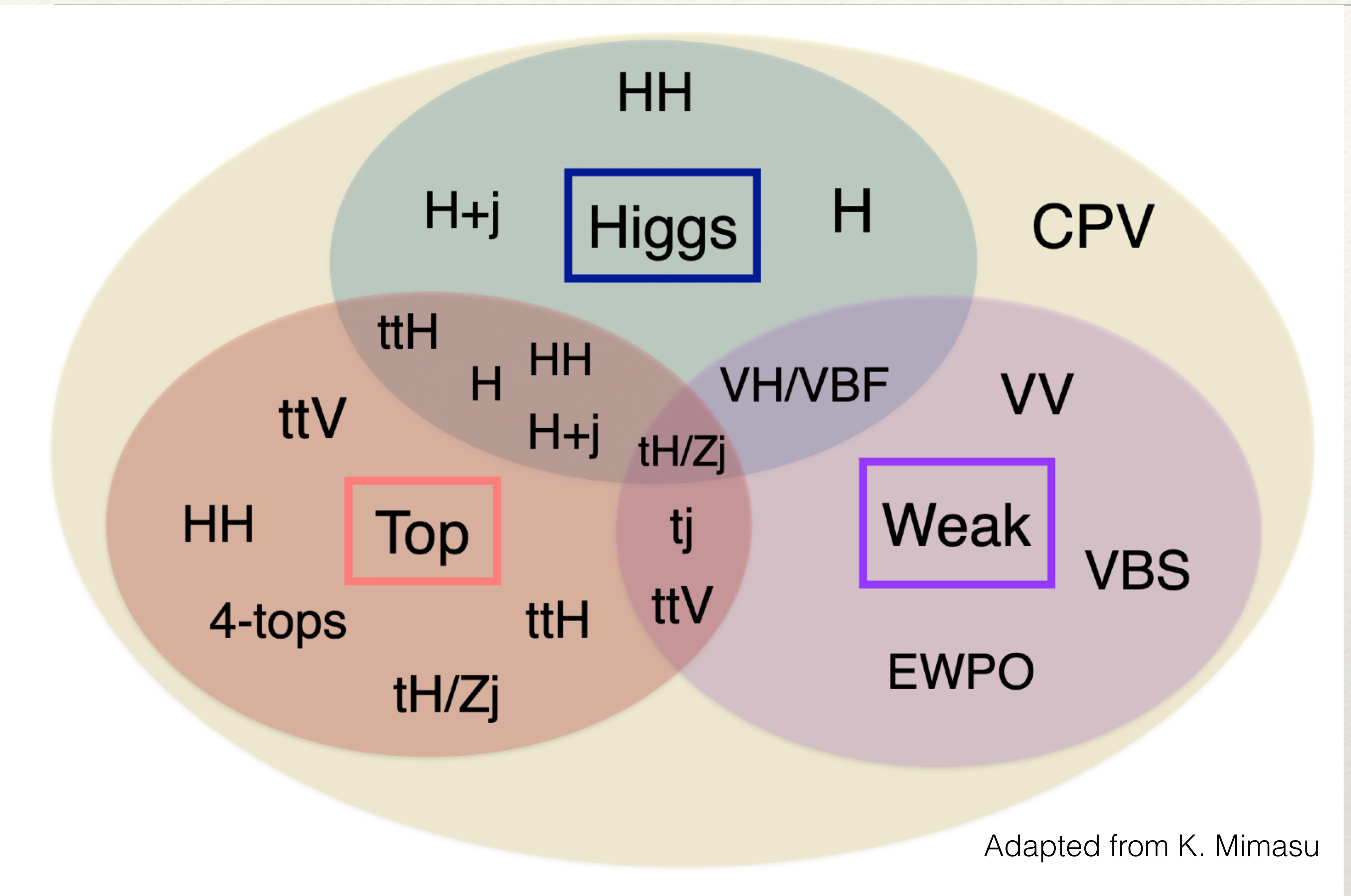
- We started collaborating in 2016
- My **reference point** for all technical & conceptual questions about EFT
- I look up to him as a scientific leader, admire his deep physics intuition and technical calculation skills

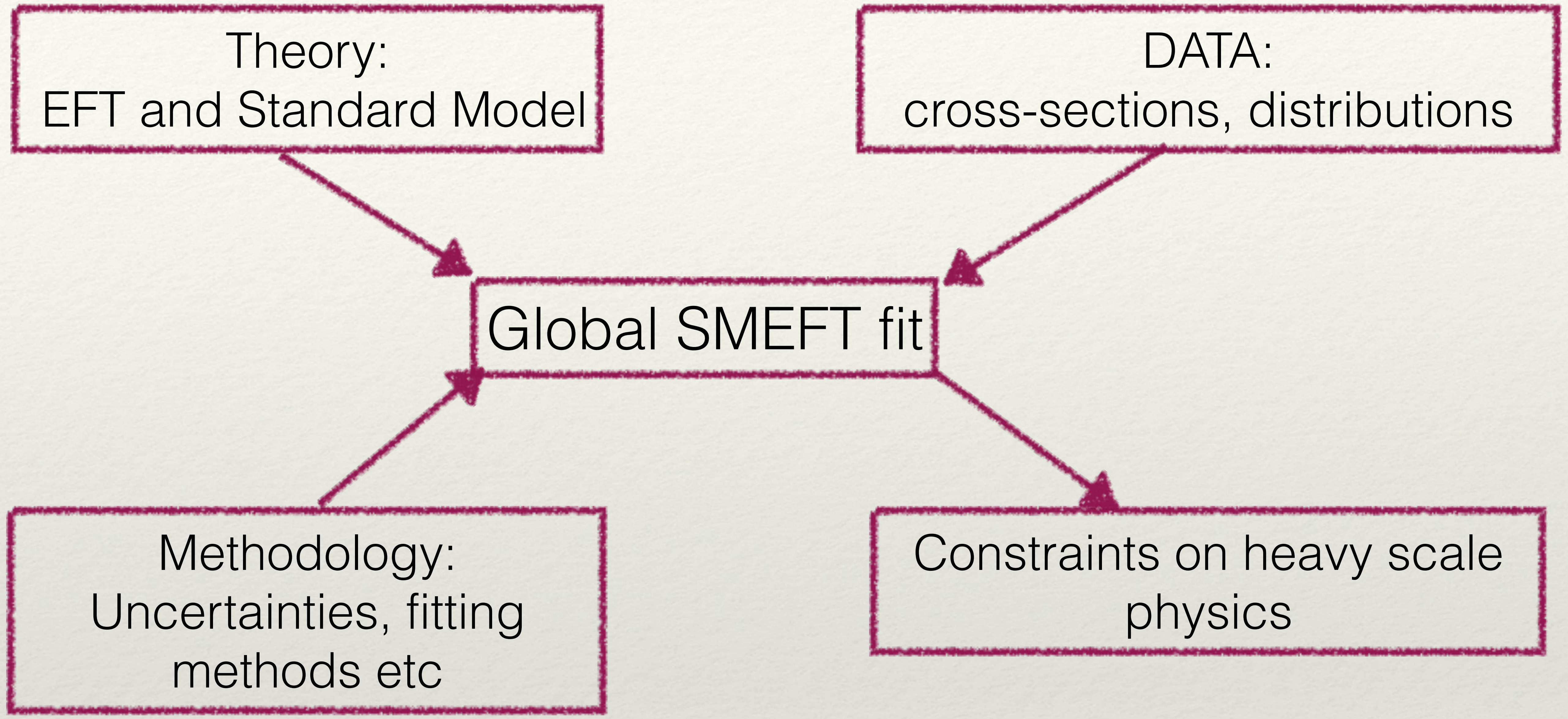
- I am proud to have shared in his research (at least helping by answering his questions about English!)
- Patience, kindness & hospitality during my visits to Beijing
- Fantastic memories of time spent together at intl. conferences

Higgs Couplings 2018 in Tokyo. (photo: G. Durieux)

Top 2019 in Beijing.

Towards global fits for the EFT

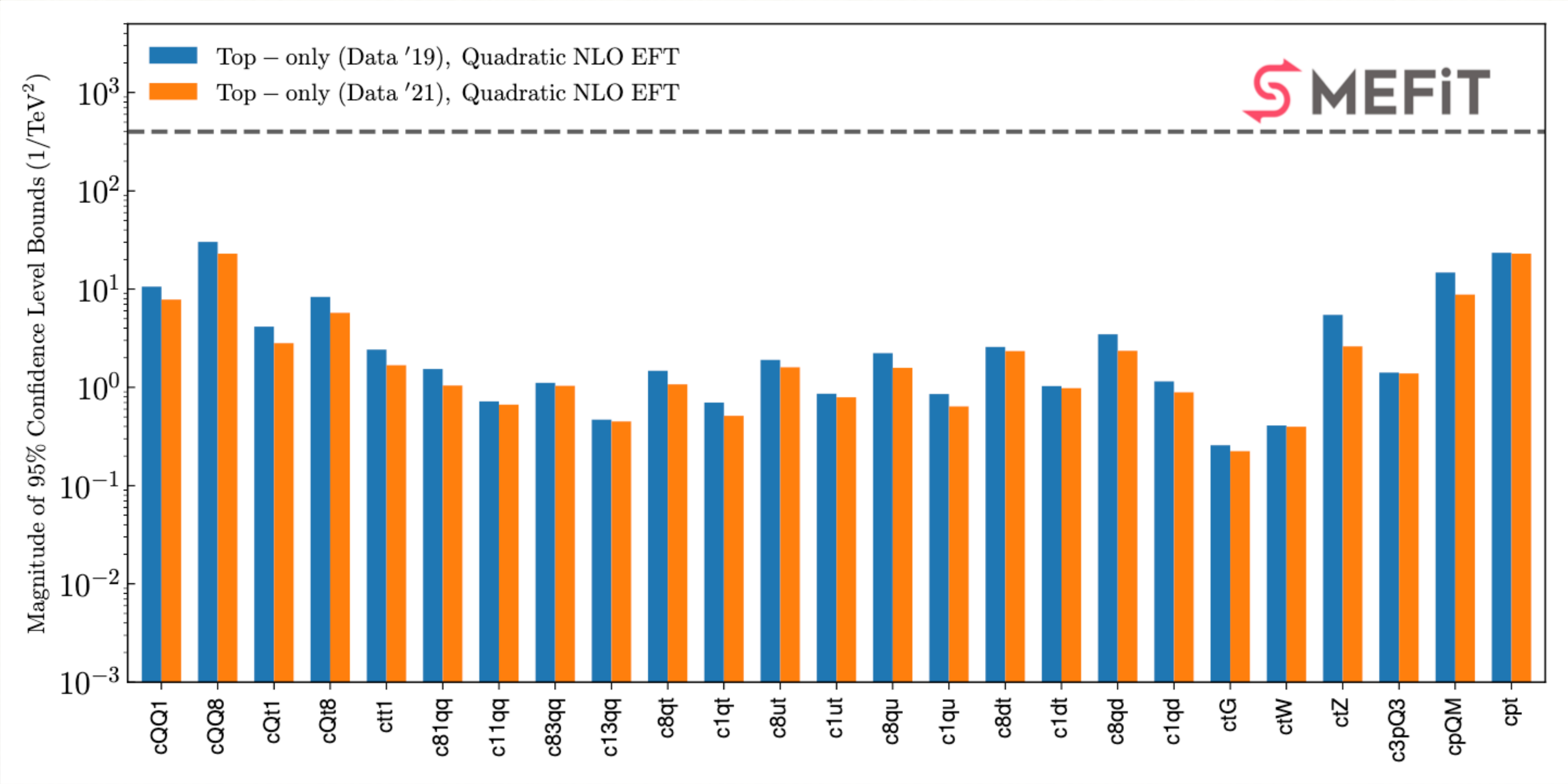




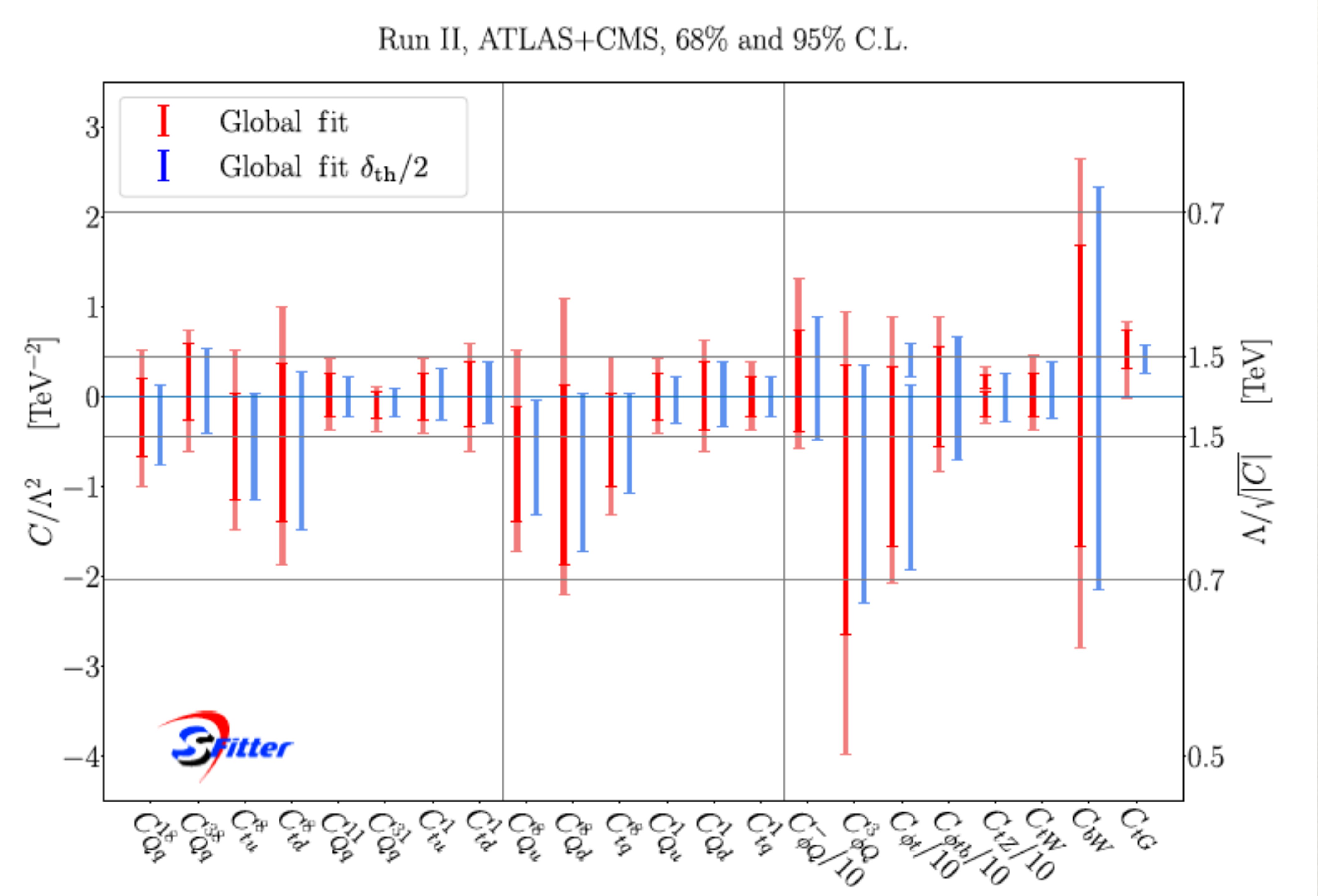
A complicated and difficult procedure but absolutely necessary to identify any deviations from the SM

Cen's physics intuition and computational skills were crucial in this effort

Global EFT fits in the top sector



Ethier, Maltoni, Mantani, Nocera, Rojo, Slade, Vryonidou and Zhang arXiv:2105.00006
Hartland, Maltoni, Nocera, Rojo, Slade, Vryonidou and Zhang, arXiv:1901.05965



$\Lambda/\sqrt{C} = 0.35 - 2\,\text{TeV}$

Brivio, Bruggisser, Maltoni, Moutafis, Plehn, Vryonidou, Westhoff, Zhang arXiv:1910.03606 (SFitter analysis)

Long projects requiring a lot of calculations but also a lot of effort to understand the results

Crucial contributions from Cen

My collaboration with Cen

Cen and I overlapped as postdocs in Belgium, we first met in 2013
Started collaborating around 2015
Worked together continuously since then
Visited Cen in BNL 2015 and Beijing 2018
Cen visited me at CERN in 2019

Wrote 10 papers together, several projects were initiated and driven by Cen
I have learnt a huge amount from Cen, proud to be his most frequent collaborator

Collaborators	
Eleni Vryonidou	14
Fabio Maltoni	12
Gauthier Durieux	9
Shuang-Yong Zhou	8
Ken Mimasu	7

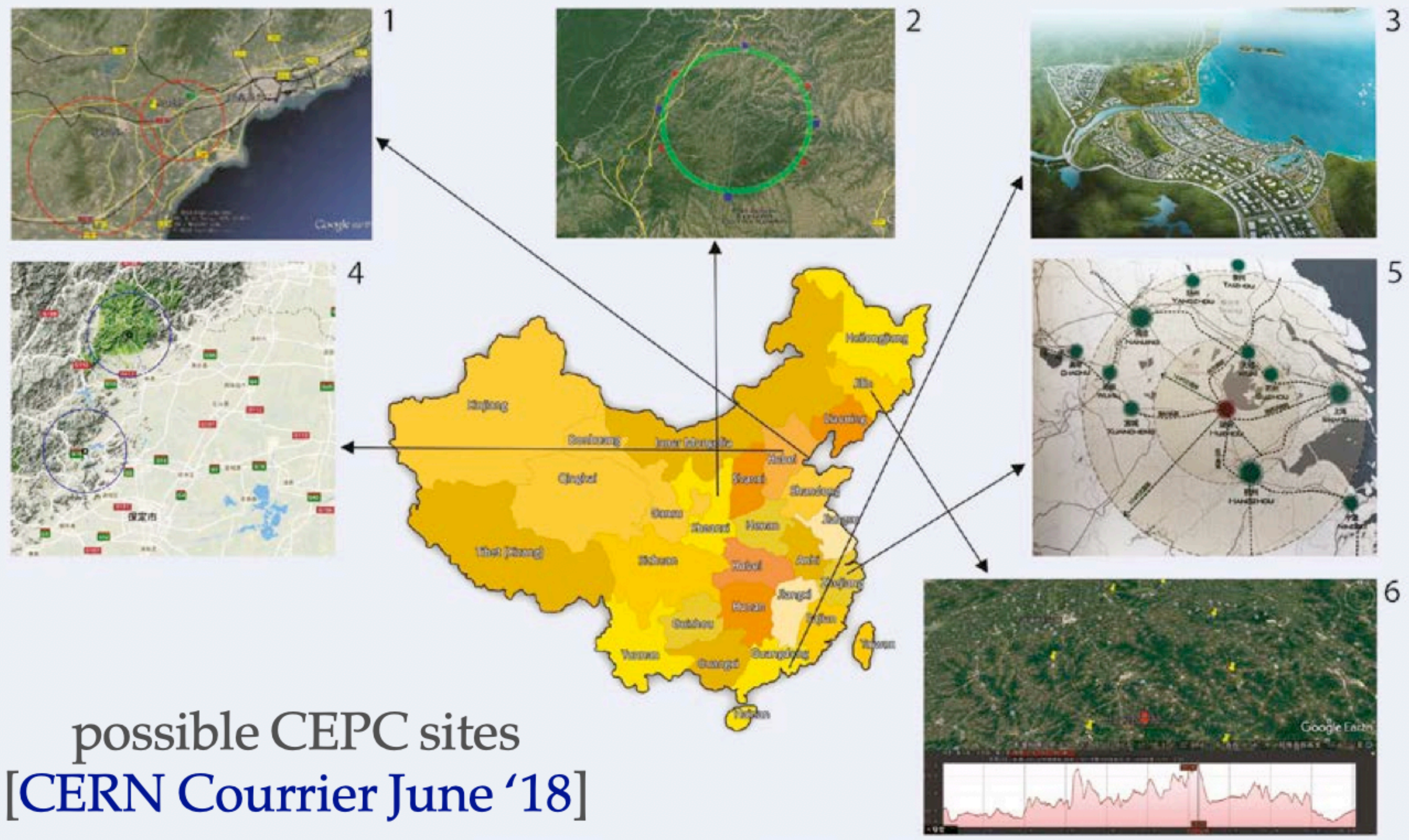
https://inspirehep.net/authors/1333165?ui-citation-summary=true

Cen's hospitality and kindness

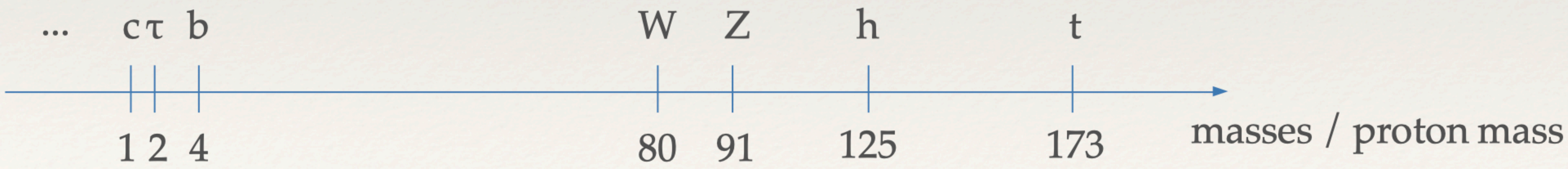
* BNL 2015: Cen had to drive me around for dinner every night because I didn't rent a car
* Beijing and Hefei 2018: Cen had to take me to dinner but also took me to the hospital…

Future e^+e^- collider in China

- 100 km circumference (27 km for LHC)
- Z,W and Higgs boson factory
- What about the top quark?
  1) Push the energy to $e^+e^- \to t\,\bar{t}$
  2) Exploit quantum effects



possible CEPC sites
[CERN Courier June '18]



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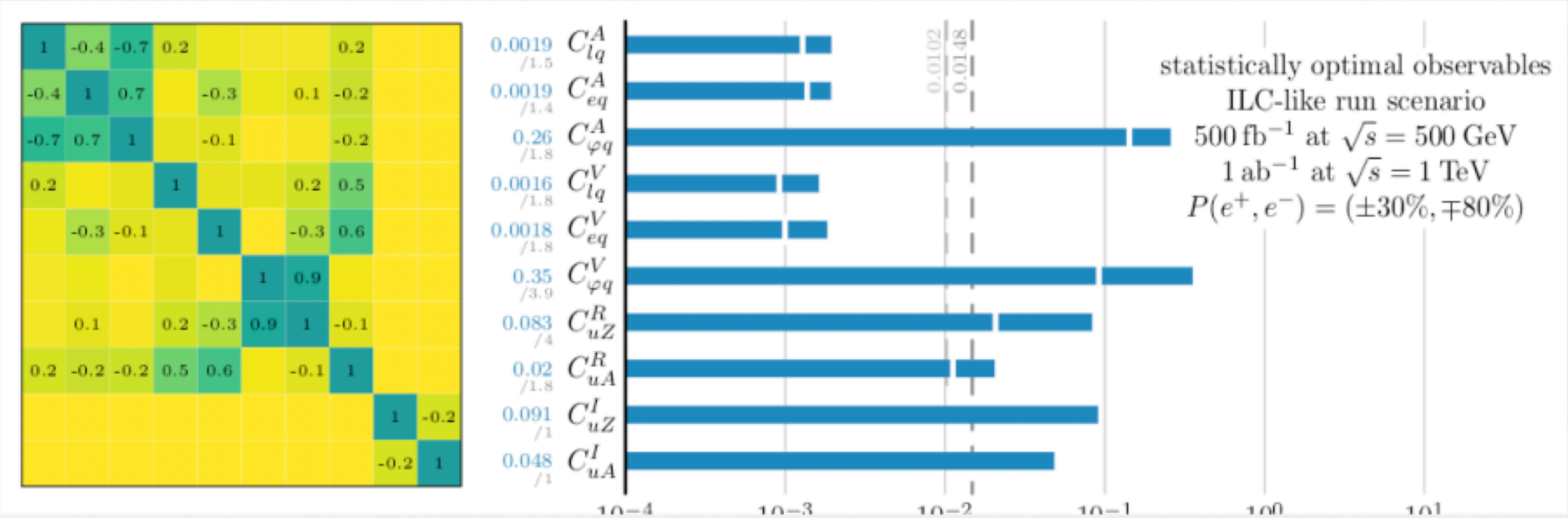
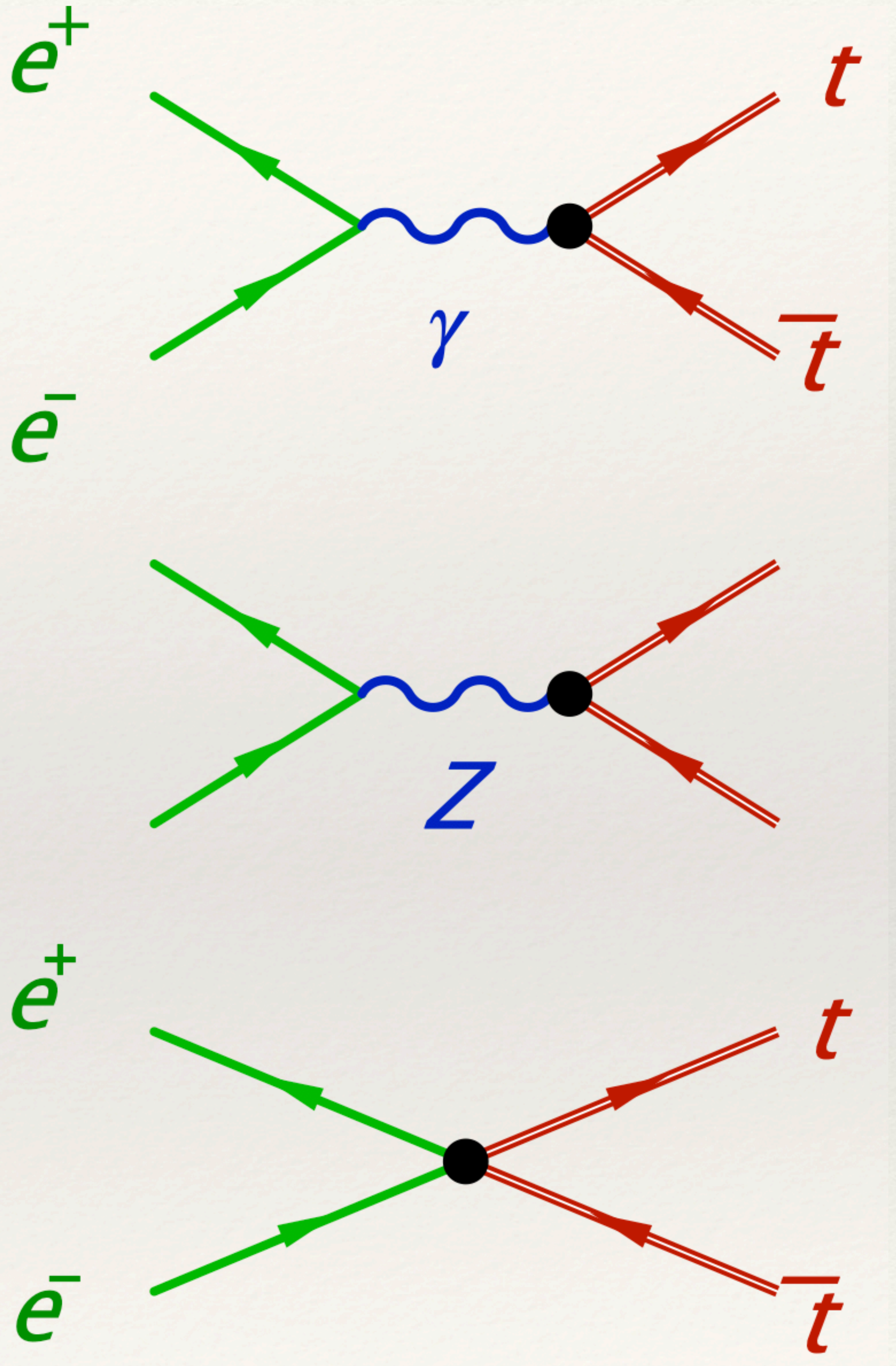
Top EFT in $e^+e^- \to t\bar{t}$

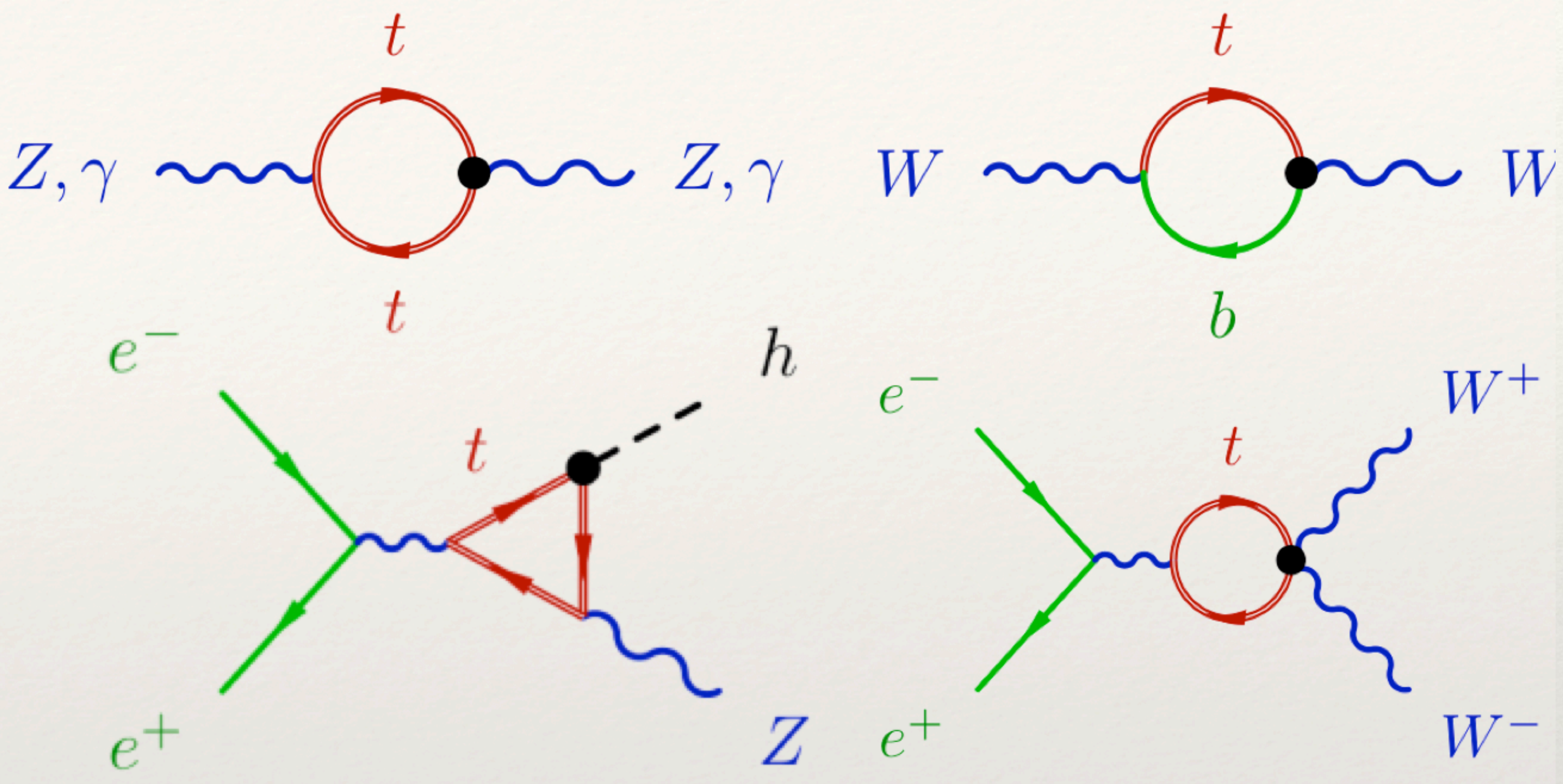
- Probing $t\bar{t}\gamma$, $t\bar{t}Z$, $t\bar{t}e^+e^-$ interactions
- Most comprehensive study to date
  JHEP 10 (2018) 168 (Cen, Martín Perelló, Marcel Vos and myself)





Top EFT via quantum effects

- Pioneered in
  Phys.Rev.D 86 (2012) 014024
  (Cen, Nicolas Greiner, Scott Willenbrock)
- Pursued JHEP 08 (2018) 036
  (Cen, Eleni Vryonidou)
- Applied to e^+e^-
  Chin.Phys.C 42 (2018) 12
  (Cen, Jiayin Gu, Eleni Vryonidou, myself)
  - Demonstrated sensitivity
  - Shown requirement for Higgs precision



My time with Cen

- Cen and I met in Louvain in 2012
- Travelled for two weeks together in Boston and Princeton (2013)
- Visited to Brookhaven (2015)
- MITP Mainz Effective field theories as discovery tools (Aug 2016)
- HEFT 2018 in Mainz and DESY *Theorist of the month* (Apr & May 2018)
- *MadGraph school* in Hefei and *Higgs Coupling* in Tokyo (Nov 2018)
- HEFT 2019 in Louvain (Apr 2019)
- *Top-quark* conference and month-long visit in Beijing (Oct 2019)

Meeting Cen

- met Cen when inviting him to give a talk at USTC in 2018 (2018年因为邀请他来中科大做报告而认识岑)
- he gave a talk on SMEFT (他做了一个关于标准模型有效场论的报告)
- limited office space, he stayed in my office afterwards (办公空间不够，报告后他待在我的办公室)
- I asked: can we use positivity bounds to constrain SMEFT? (我问：能否用正定性约束来限制粒子物理标准模型？)
- Cen took my question seriously…(岑认真地对待了我的问题…)

What are positivity bounds 什么是正定性约束?

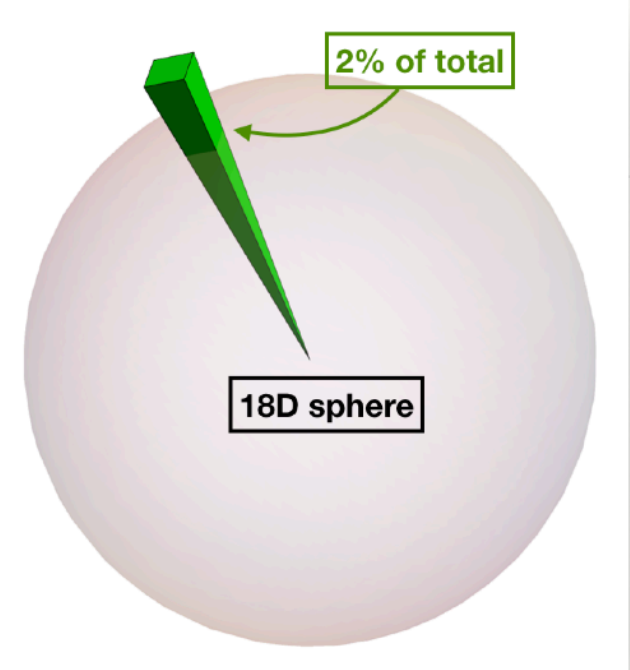
Are all EFTs created equal? No!! 有效场论都是自洽的吗? **不是!**

Axiomatic principles of quantum field theory:
lorentz invariance, unitarity, causality, locality, analyticity
量子场论的基本原理:
洛伦兹不变性, 幺正性, 因果性, 局域性, 解析性

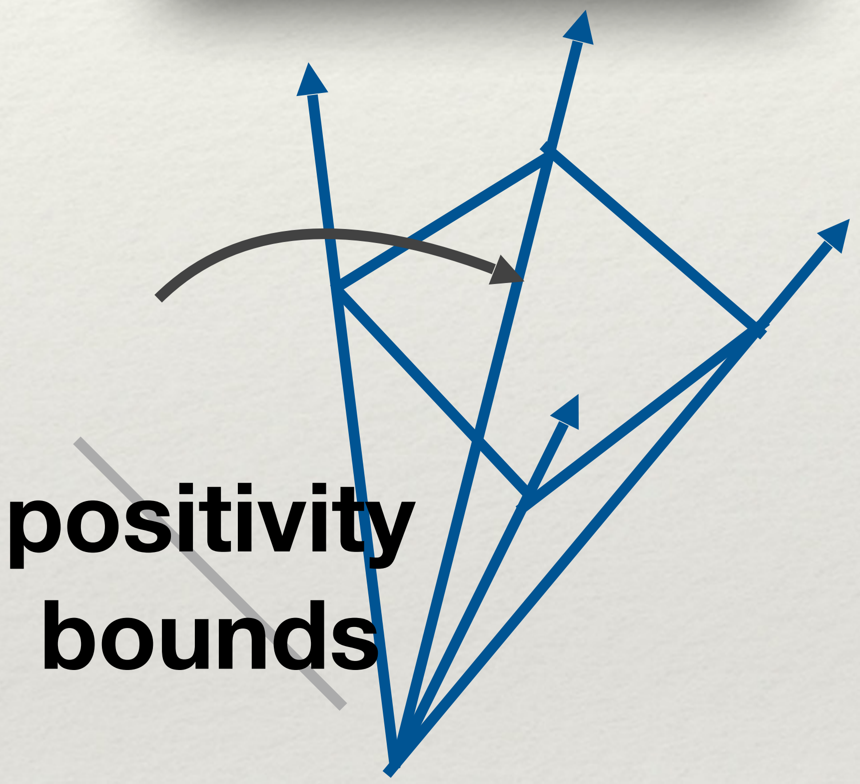
Not every EFT with right symmetries is consistent!
不是所有具有相应对称性的有效场论都是自洽的!

Positivity bounds on Wilson coefficients
威尔逊系数的正定性约束

Positivity bounds

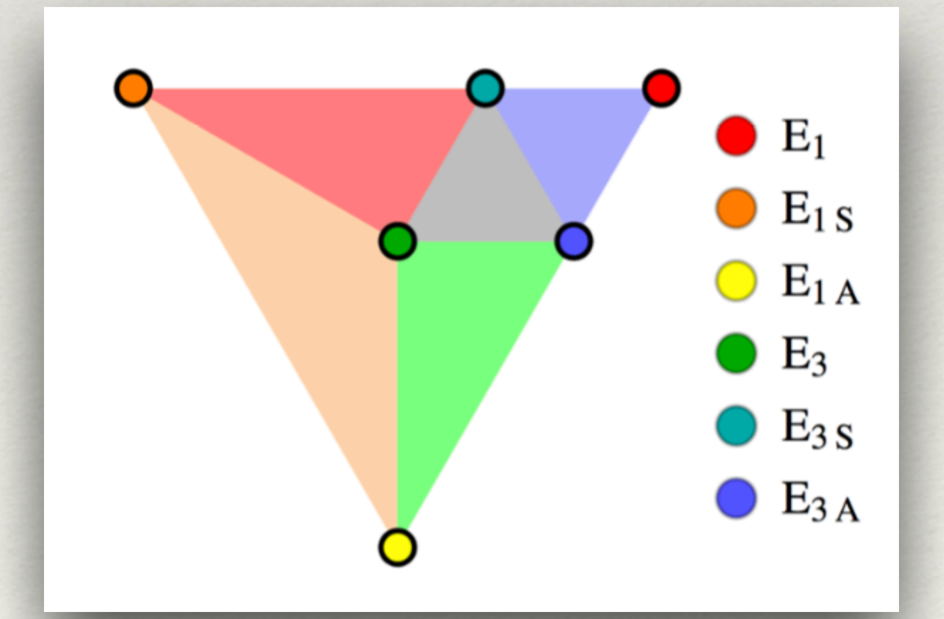


- Parameter space of SMEFT has huge redundancy **CZ** & SYZ, PRD, 1808.00010
  (SMEFT的参数空间有很大的冗余度，大部分参数空间都是理论上不自洽的)



- Get optimal bounds for multiple particles by convex geometry
  (通过凸几何方法获得最佳的多粒子约束，发展了正定性约束理论)

- Find relations between S-matrix cone's extremal rays and UV states
  (找到S矩阵的极射线与紫外态的关系，帮助寻找新物理态) **CZ** & SYZ, PRL, 2005.03047



- Formulate multi-particle bounds as semi-definite program problem
  (将多粒子约束问题转化为半正定规划问题，大大提高计算效率)

  Li, Xu, Yang, **CZ** & SYZ, 2101.01191

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Cen's group at IHEP

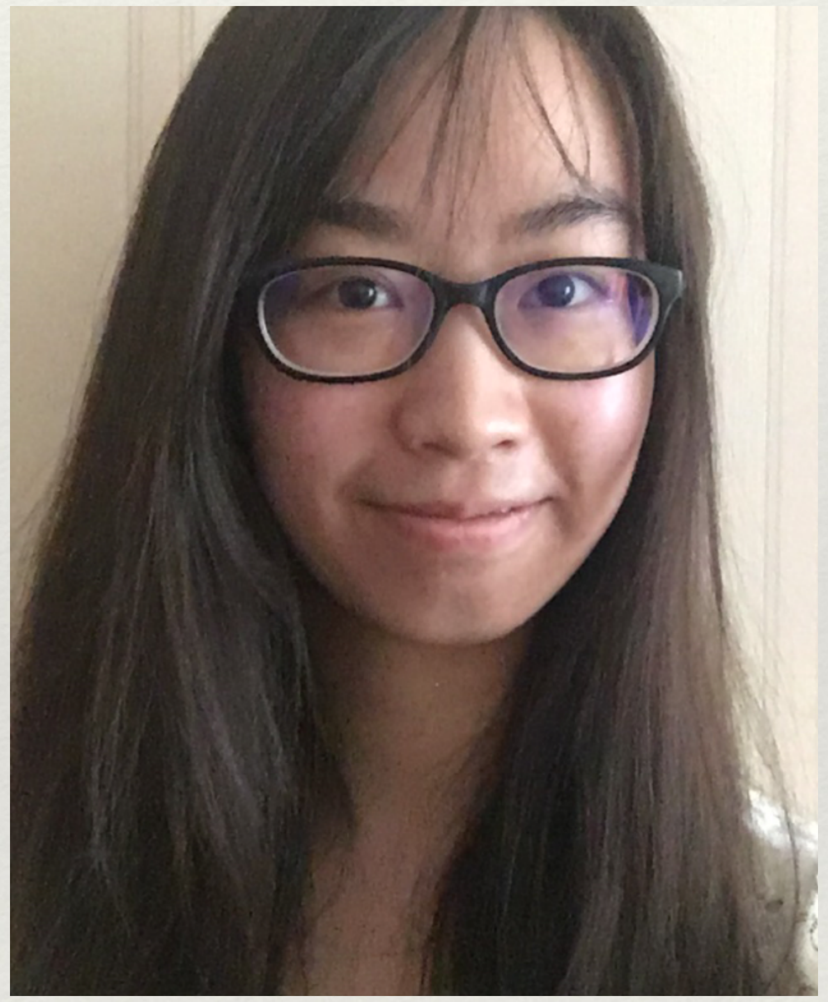
Yi-ming Liu
刘一鸣

Cheng Jie Yang
杨成杰

Cen Zhang
张岑

Xu Li
黎栩

Valerie Wu
Yuchan
吴雨禅

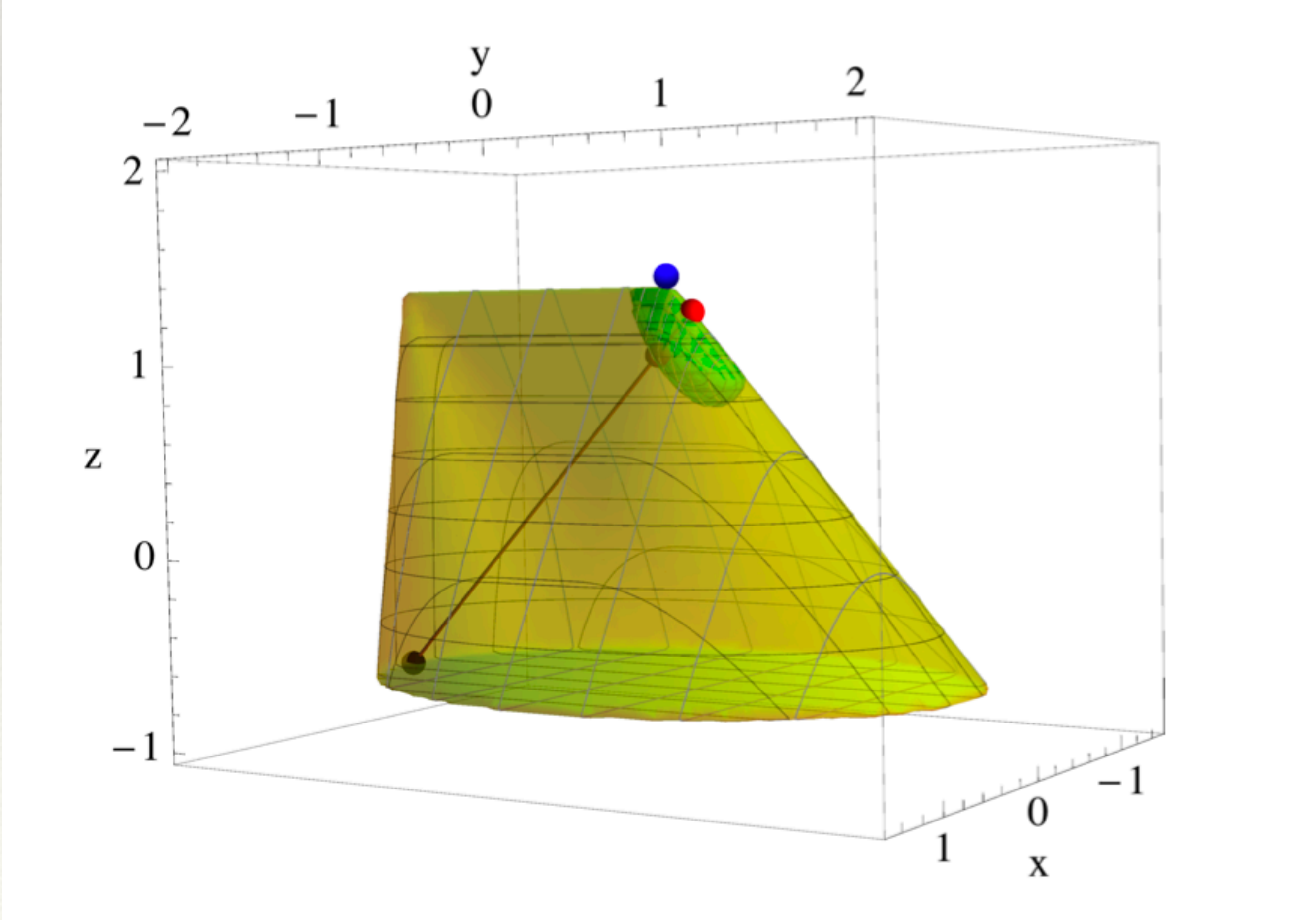


He is trustworthy and warmful. I sometimes felt that he tried to make growing up his students, and also me. I'm very happy that I could be involved in his works partially, and I'm still learning his brilliant works. (Kimiko Yamashita post-doc)

Cen Zhang is a very rigorous, energetic and humorous scientist! As for me, the most impressive instruction from him is that one of the key qualities of being a physicist is prudence. (Yi-ming)

Positivity

- Positivity in e+e- scattering as an example (of Gauthier and Shuang-Yong) before 我将用一个例子(2009.02212)来说明周双勇老师和Gauthier Durieux老师工作。
- We consider positivity bounds on dimension-8 four-electron operators in e+e- scattering at future lepton colliders. 在未来轻子对撞机上，我们通过研究正负电子对撞来约束8维四费米子算符的正定性威尔逊空间 and positivity violation at scales of 1–10 TeV can potentially be probed at future lepton colliders. 在未来轻子对撞机上，我们发现8维算符的威尔逊系数的正定性约束在能标1-10TeV可能被破坏。
- The positive nature of the dimension-8 parameter space often allows us to either directly infer the existence of UV-scale particles, together with their quantum numbers, or to exclude them up to certain scales in a model-independent way. 8维算符的正定性威尔逊的约束空间能够帮我们确定新物理态以及量子数，或者在某个能标下排除新物理态。



Cen's legacy paper

SMEFTs living on the edge: determining the UV theories from positivity and extremality

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ABSTRACT: We study the "inverse problem" in the context of the Standard Model Effective Field Theory (SMEFT): how and to what extend can one reconstruct the UV theory, given the measured values of the operator coefficients in the IR? The main obstacle of this problem is the degeneracies in the space of coefficients: a given SMEFT truncated at a finite mass dimension can be mapped to infinitely many UV theories. We discuss these degeneracies at the dimension-8 level, and show that positivity bounds—a set of bounds derived by assuming a SMEFT can be UV completed—play a crucial role in the inverse problem. In particular, the degeneracy either vanishes or becomes significantly limited, for SMEFTs that live on or close to these bounds. The UV particles of these SMEFTs, and their properties such as spin, charge, other quantum number, and interactions with the SM particles, can often be *uniquely* determined. We first present a systematic approach to construct the set of UV-completable SMEFTs as a positivity cone, by enumerating the generators of the latter. We then show that a geometric notion, extremality, conveniently connects the positivity problem with the inverse problem. We discuss the implications of a SMEFT living on an extremal ray, on a k-face, and on the vertex of the positive cone. We also show that measuring dimension-8 coefficients allows to set exclusion limits on all individual UV states that interact with the SM, independent of specific model assumptions. Our results indicate that SMEFTs at dimension-8 encode much more information than one would naively expect, which can be used to reverse engineer the UV physics from the SMEFT. While these results in general do not apply to dimension-6 coefficients, some possible application is also discussed.

- In the last months Cen had been working on a solo paper which had reached 87 pages already.
- He had sent it to collaborators to read it in late May:

> Hi Fabio,
>
> following this topic, I wrote a paper. It's attached. **I think it's interesting, but in a somewhat strange way...** I would like to hear about your advice or thoughts or any comments.
>
> It's a bit long, 85 pages now, but no hurry, I think it will take another month for me to check the language, calculations, and add refs and so on, and also to implement your comments…
>
> Please let me know and thank you very much!
>
> Cen

- He argued that at dim=8 one could determine the UV theory completely by pairing the information with positivity.

Dear Cen,

Thanks for all you have given us: your generosity, your humbleness, your friendship, your laughs, your love for physics and your amazing insights.

Be sure, we will keeping following your lead.

Your sky is our sky.

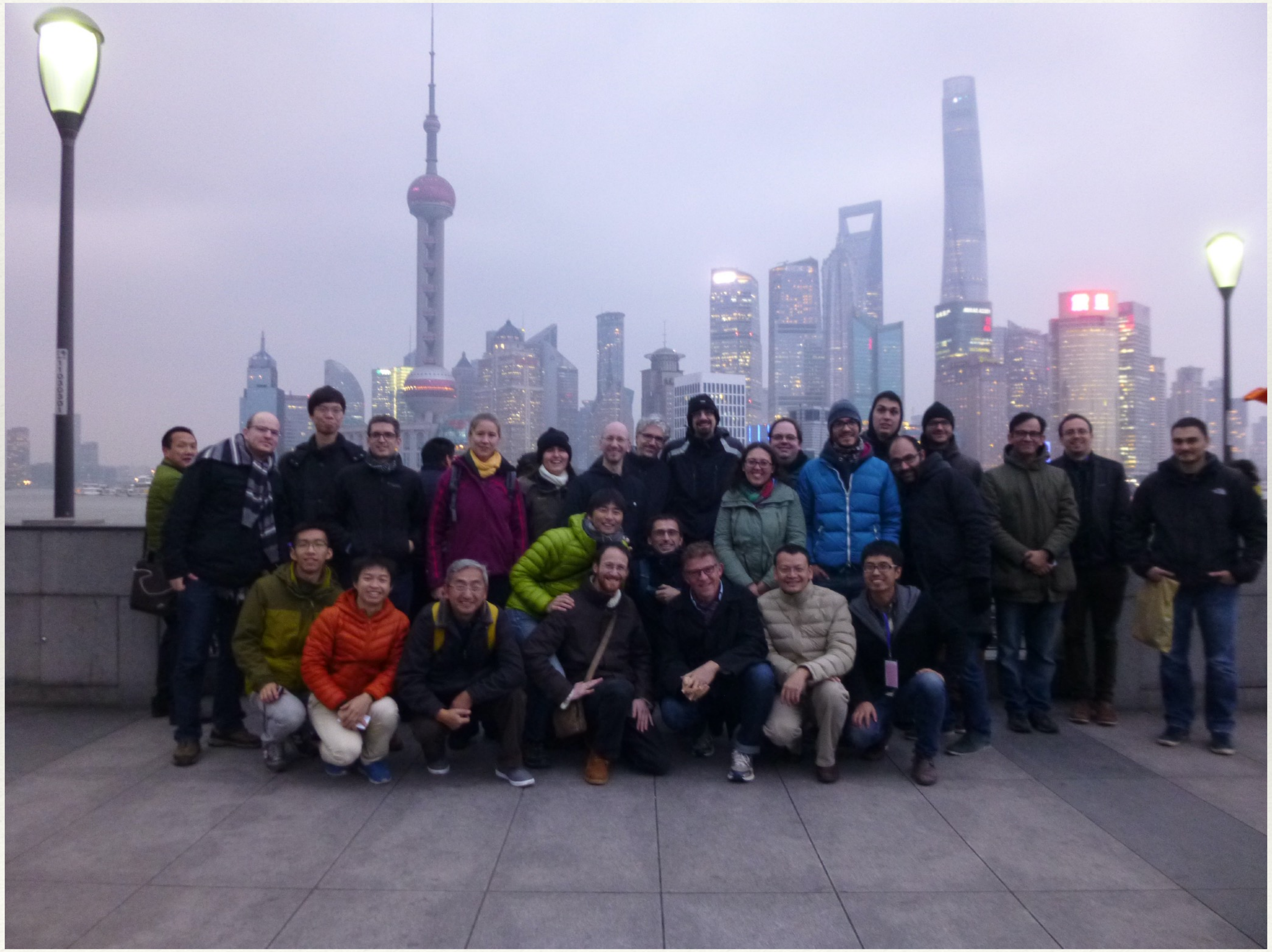
And it is blue.

The Great Wall, Top Quark Workshop, Sept 2019

Recent organizational work

* Co-organiser of Top 2019 at IHEP, Beijing
* Co-organiser of the “All things EFT” seminar series born in 2020 on line widely attended world wide
* Higgs and Effective field theory 2021, Hefei, April 2021 (223 participants)
* MCnet school in June 2021 at UCAS (~50 PhD students)

Memories



Shanghai MadGraph School at SJTU 2015

Cen's lectures

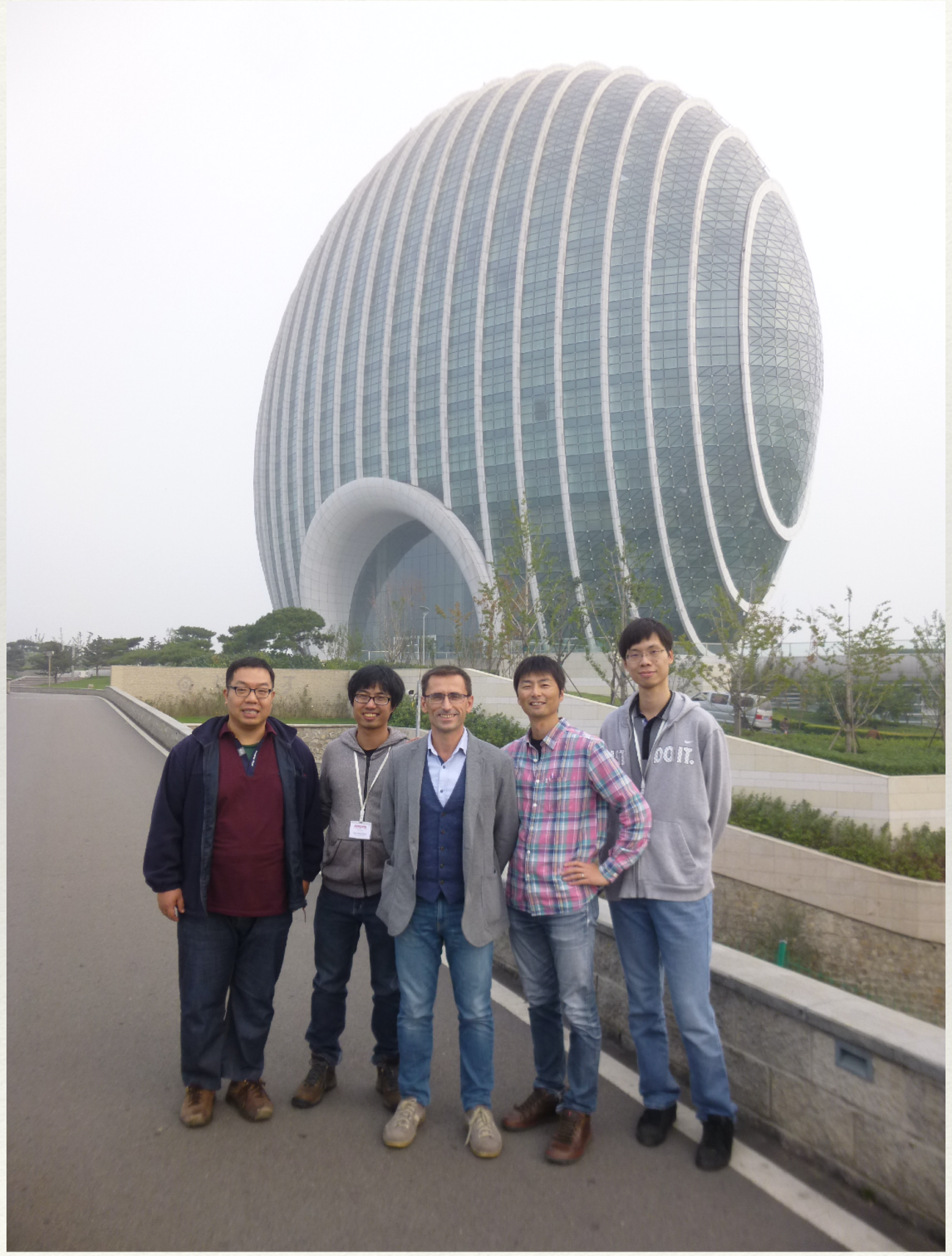
Stefan Prestel and Cen

Memories

Beijing
CERN School
at UCAS 2016

Cen, Fabio, Kentarou (picture taken by Hua-Sheng)

Memories



Qiang Li, Huan-Shao, Fabio, Kentarou, Cen (pic taken by Qi-Shu)

Beijing CERN School at UCAS 2016

Memories

Cen and Ken

Cen, Ramona, Pier Paolo at Tokyo 2017

Memories

HPNP2017, Toyama 2017   Cen's talk

Memories

Memories

Cen and Hua-Sheng at Higgs Hunting 2019

Memories

CERN SCHOOL 2016