Colliders, Higgs and the strong interaction

UCSB Physics Department Colloquium
Santa Barbara, California
April 1, 2025

Gavin Salam

Rudolf Peierls Centre for Theoretical Physics
& All Souls College, Oxford

UNIVERSITY OF OXFORD

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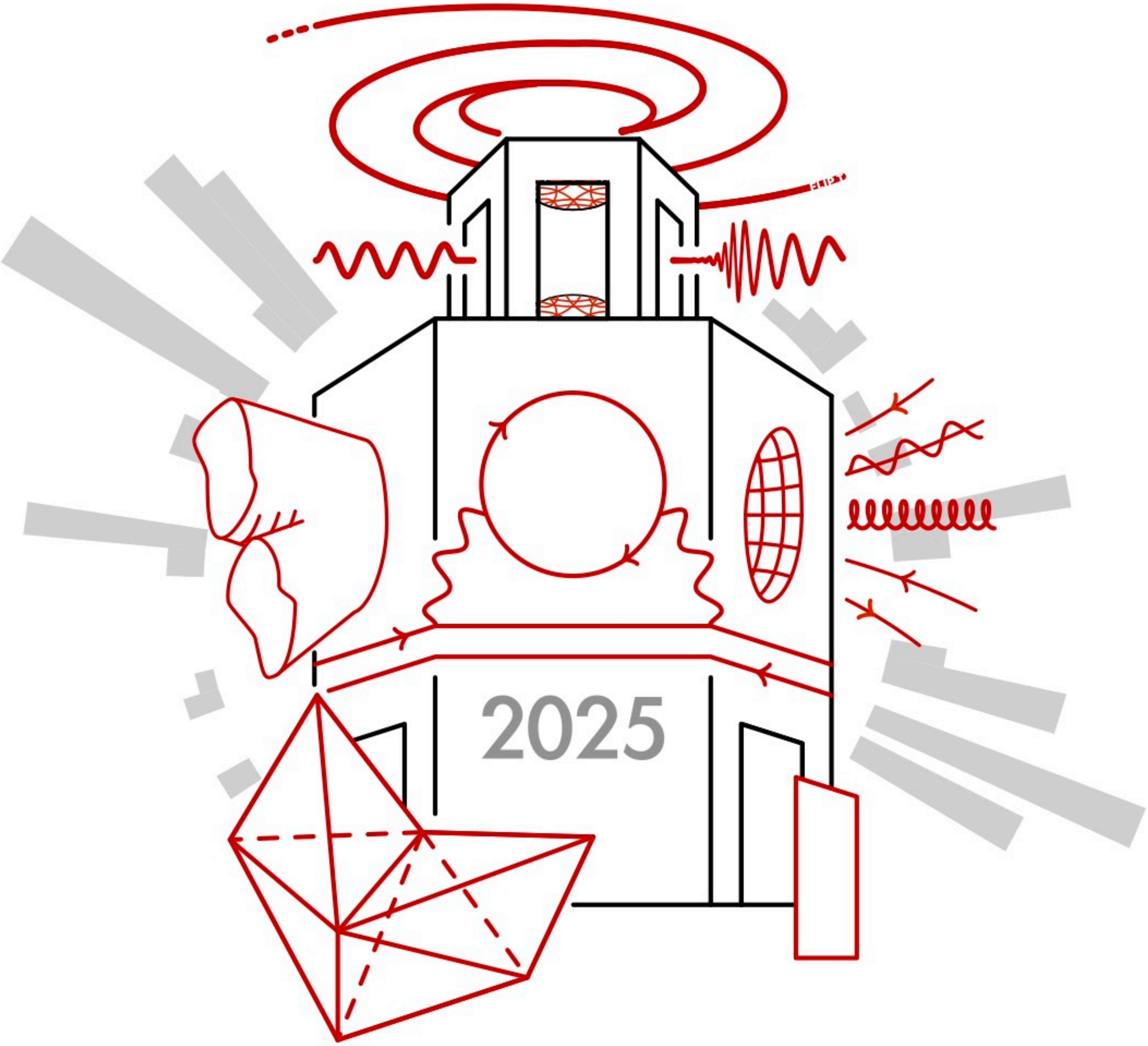
THE ROYAL SOCIETY

What is particle theory?



What is particle ~~theory~~ physics?

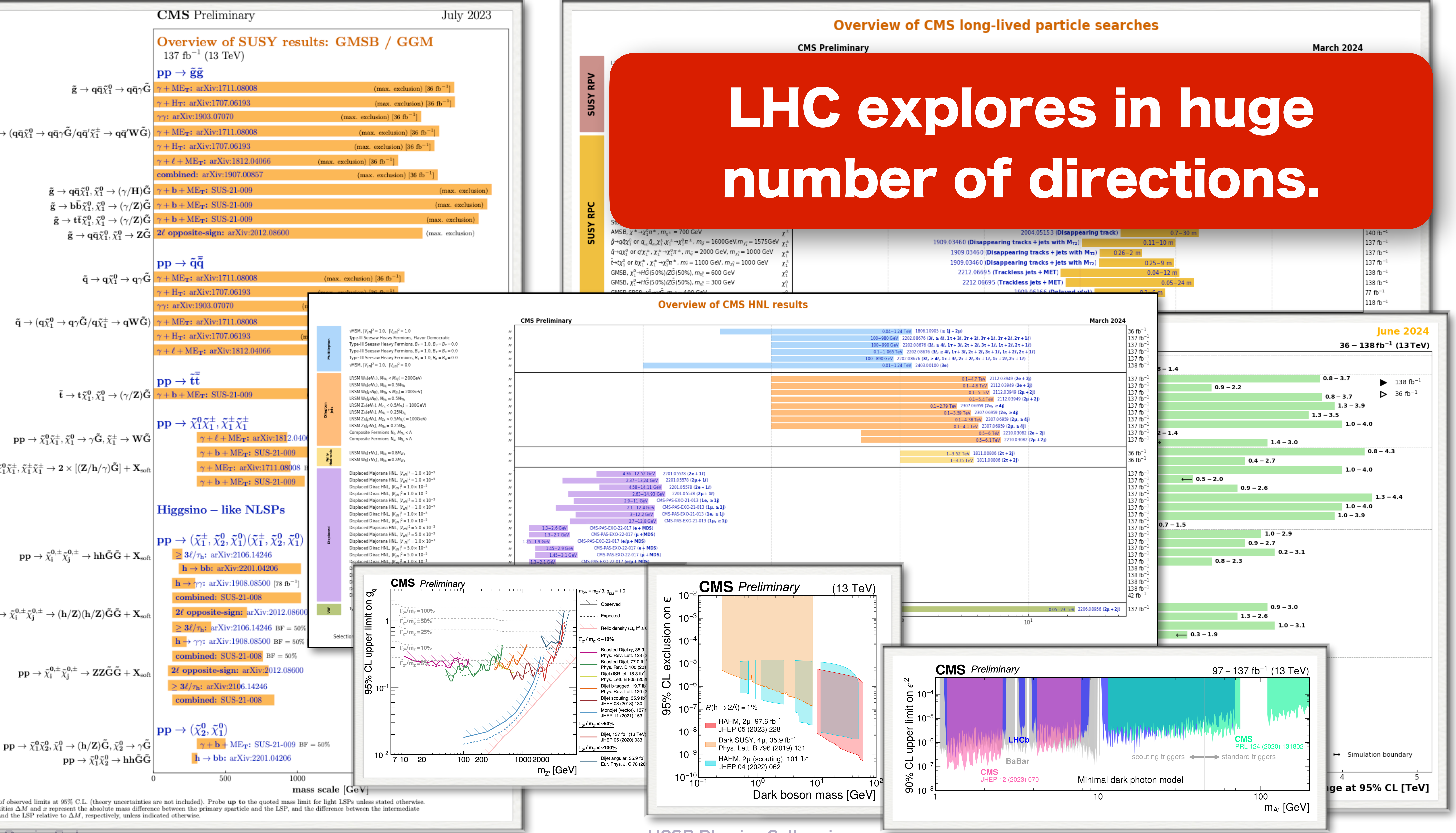
Identifying the fundamental forces and building blocks of the universe

Understanding why they have the properties that we observe

https://cds.cern.ch/images/CERN-PHOTO-202109-138-6/file?size=large

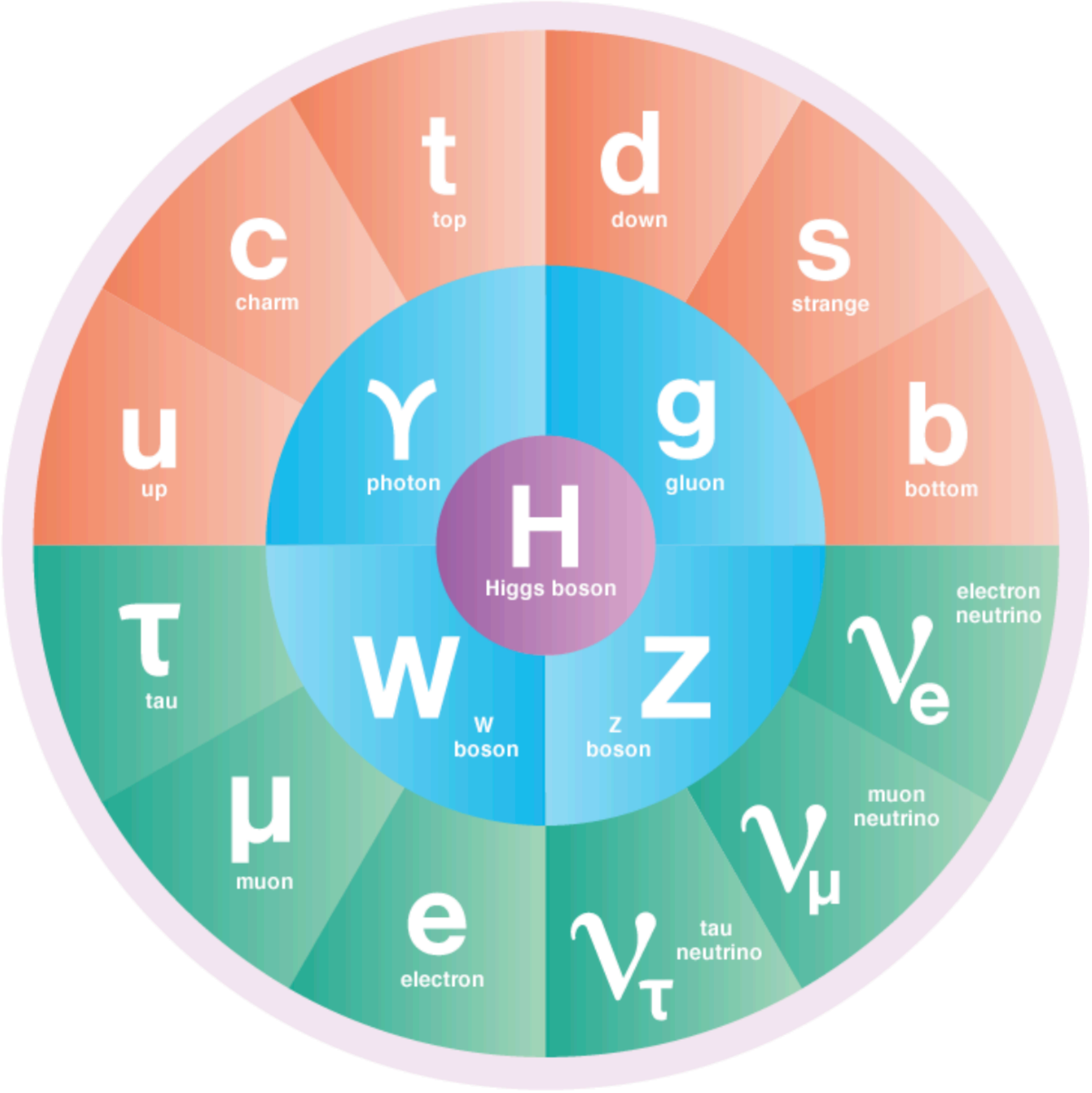
Hertzog, Samuel Joseph: CERN

LHC explores in huge number of directions.



The Standard Model (SM)

https://www.symmetrymagazine.org/standard-model/



particles

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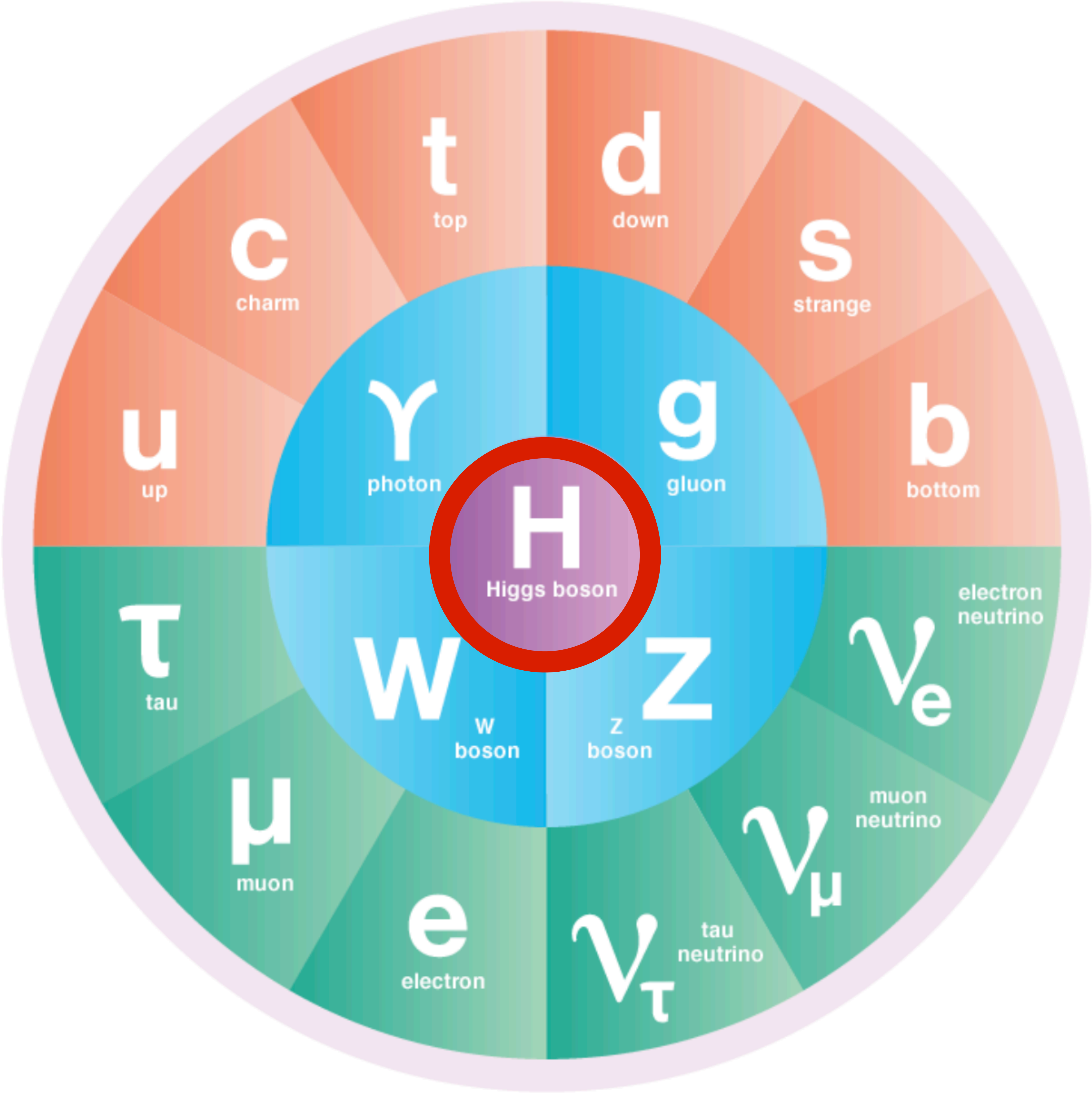

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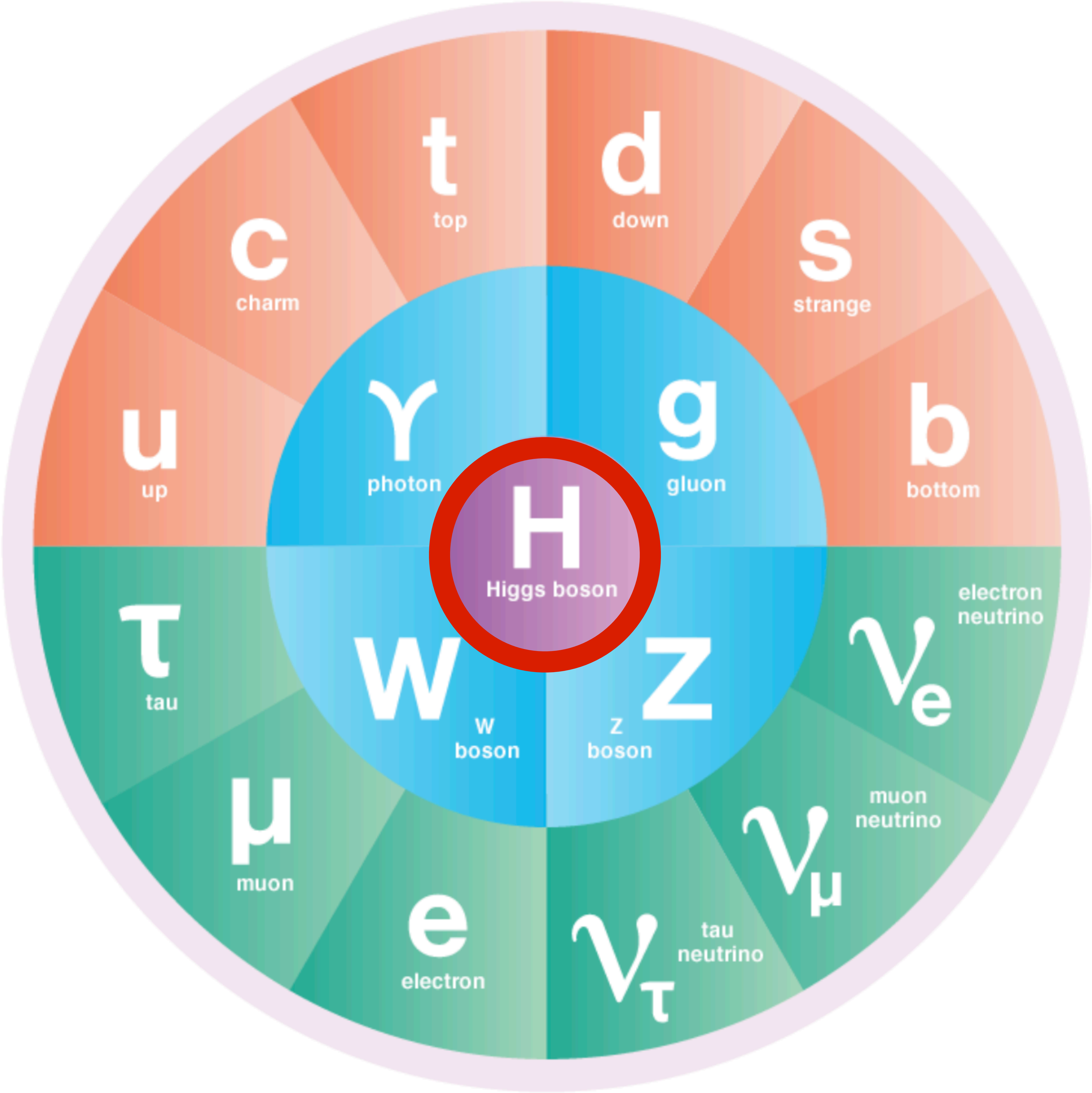
"the standard-model (SM) is complete"

The Standard Model (SM)



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?

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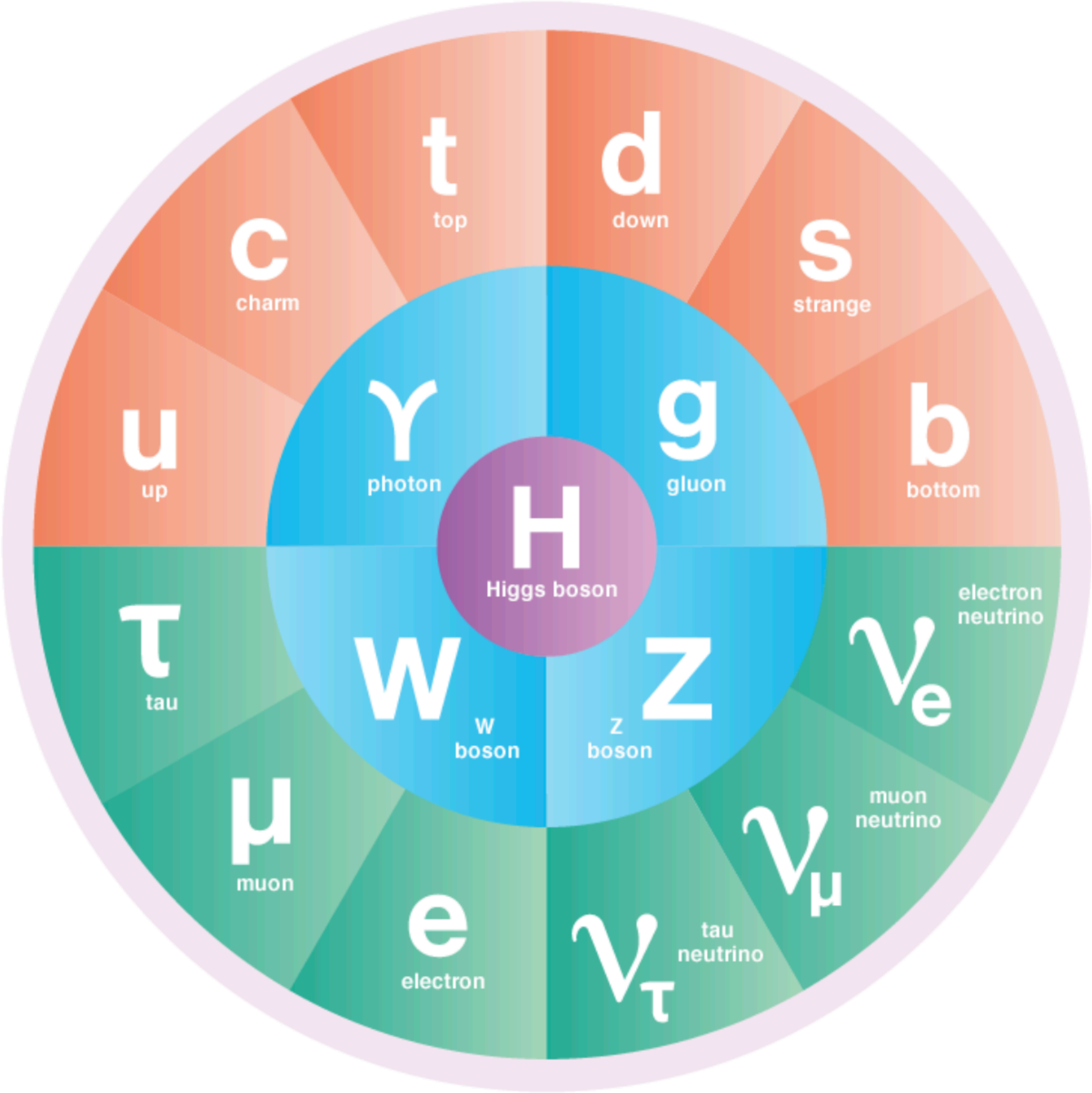

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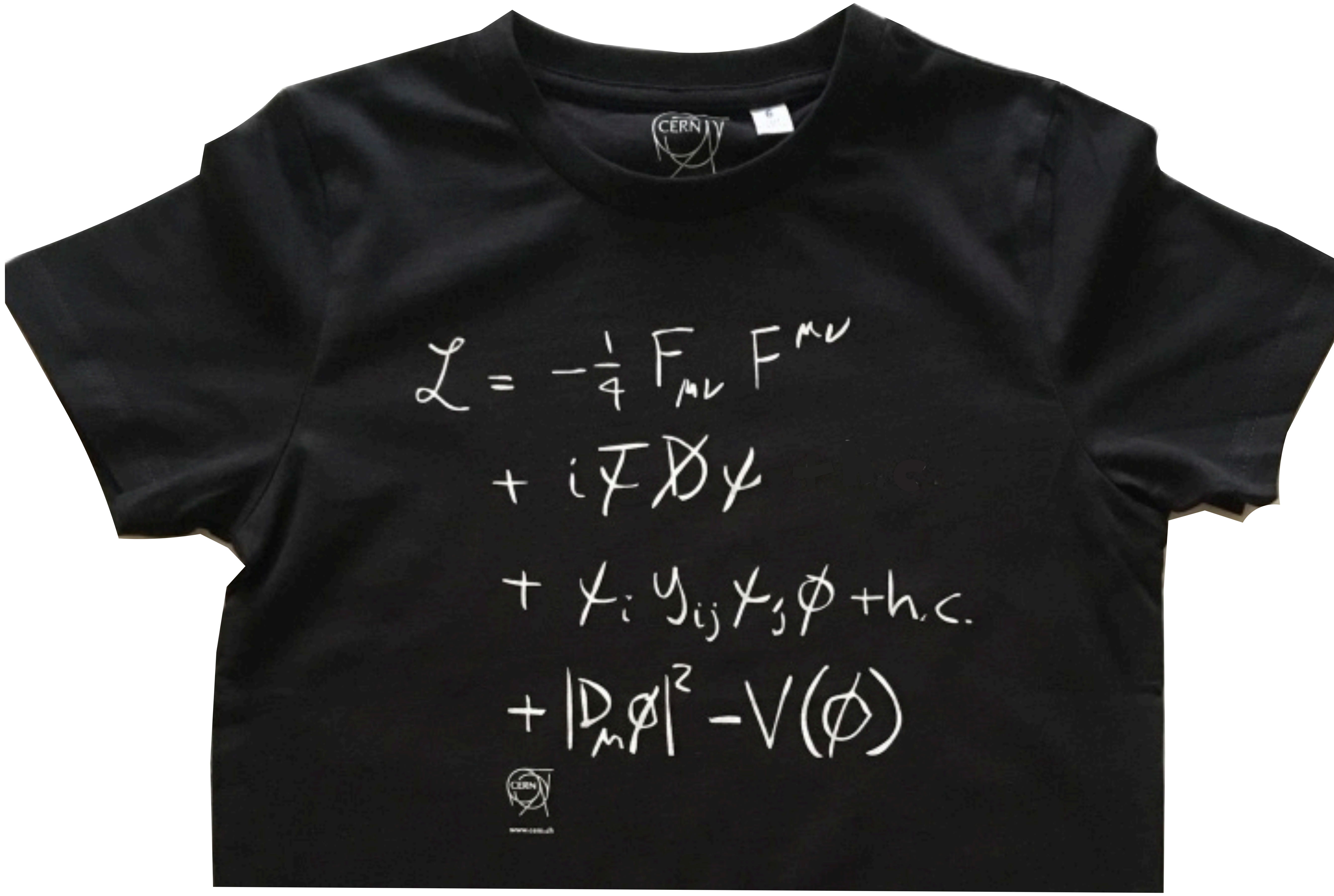

interactions

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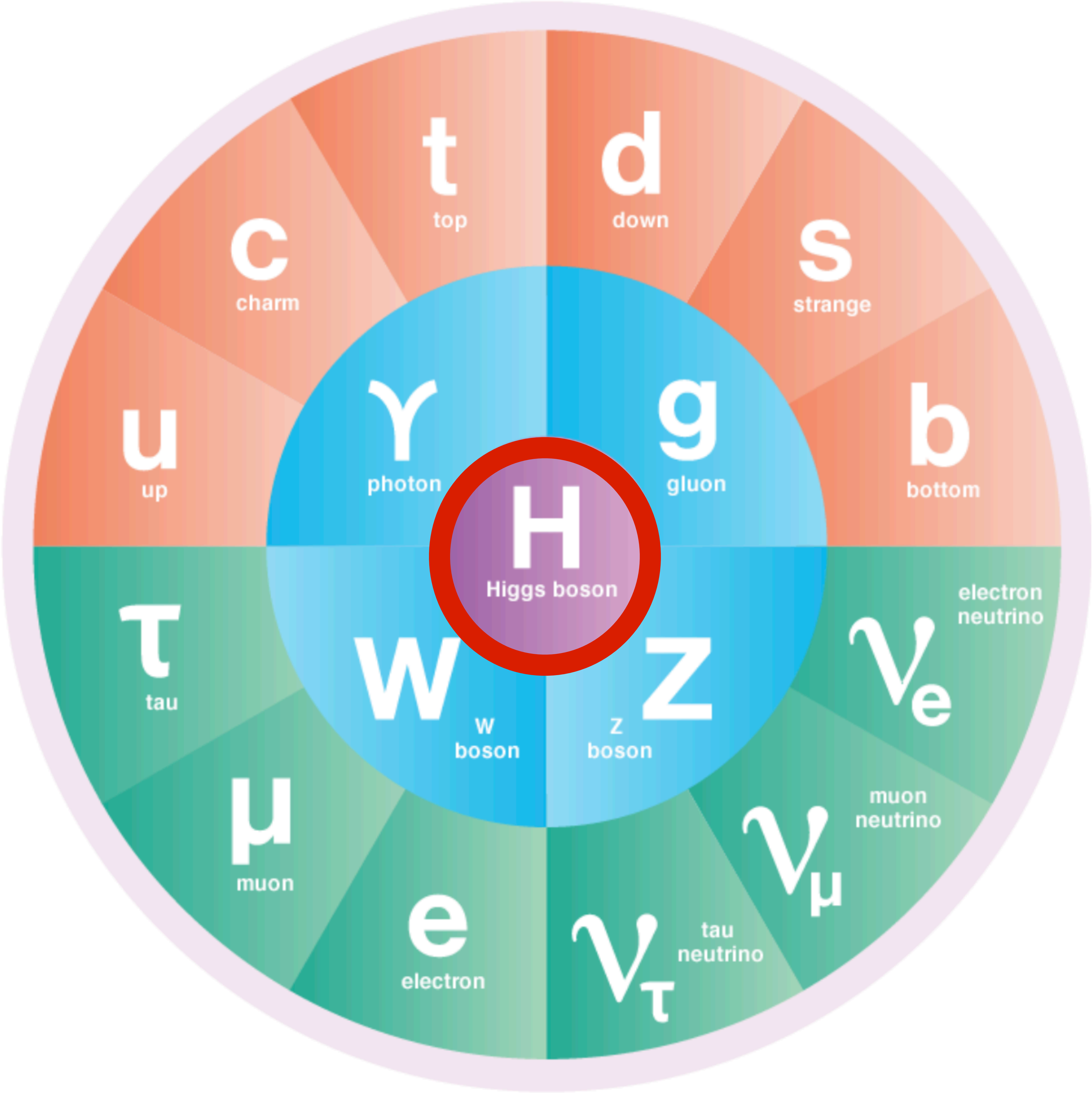

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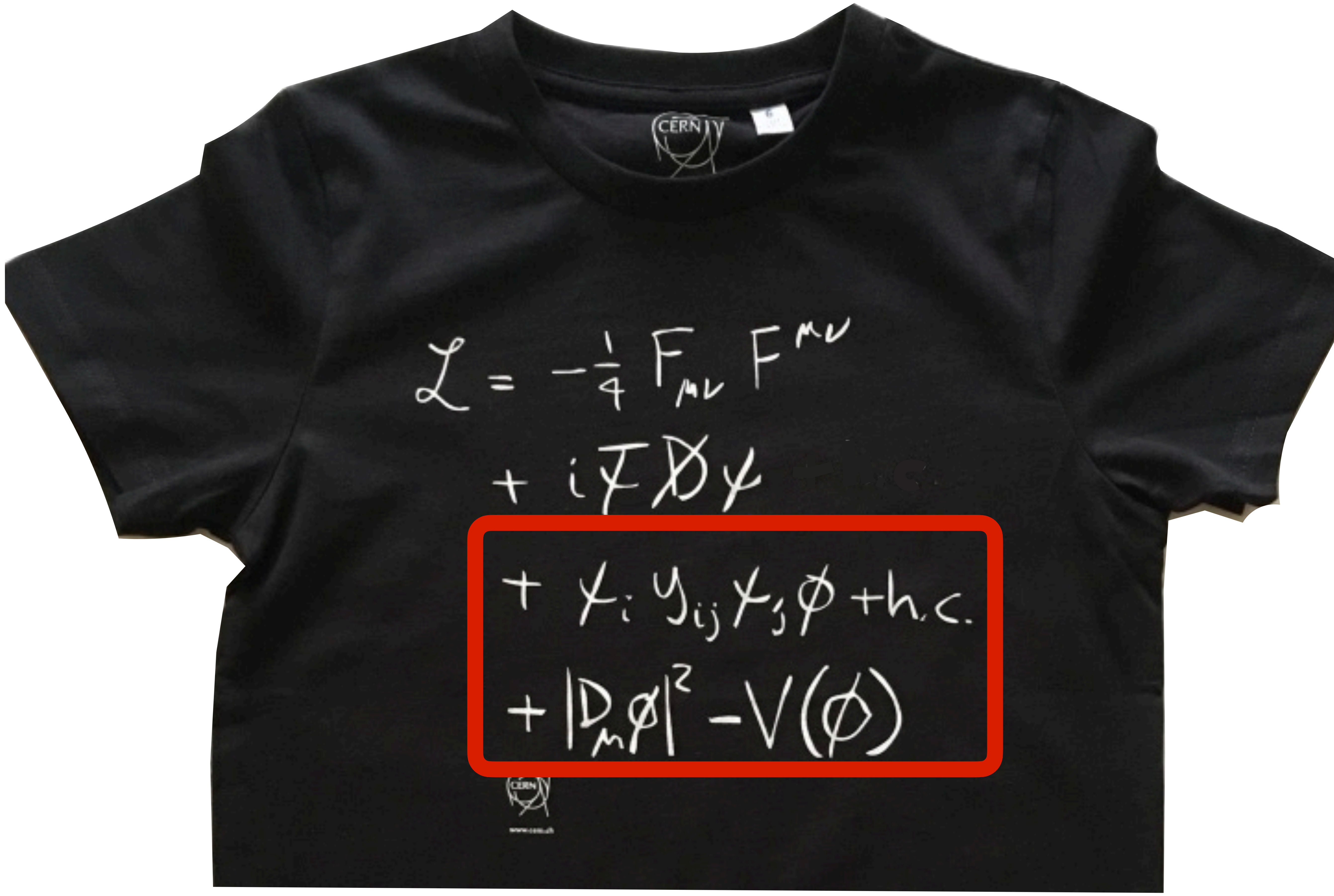


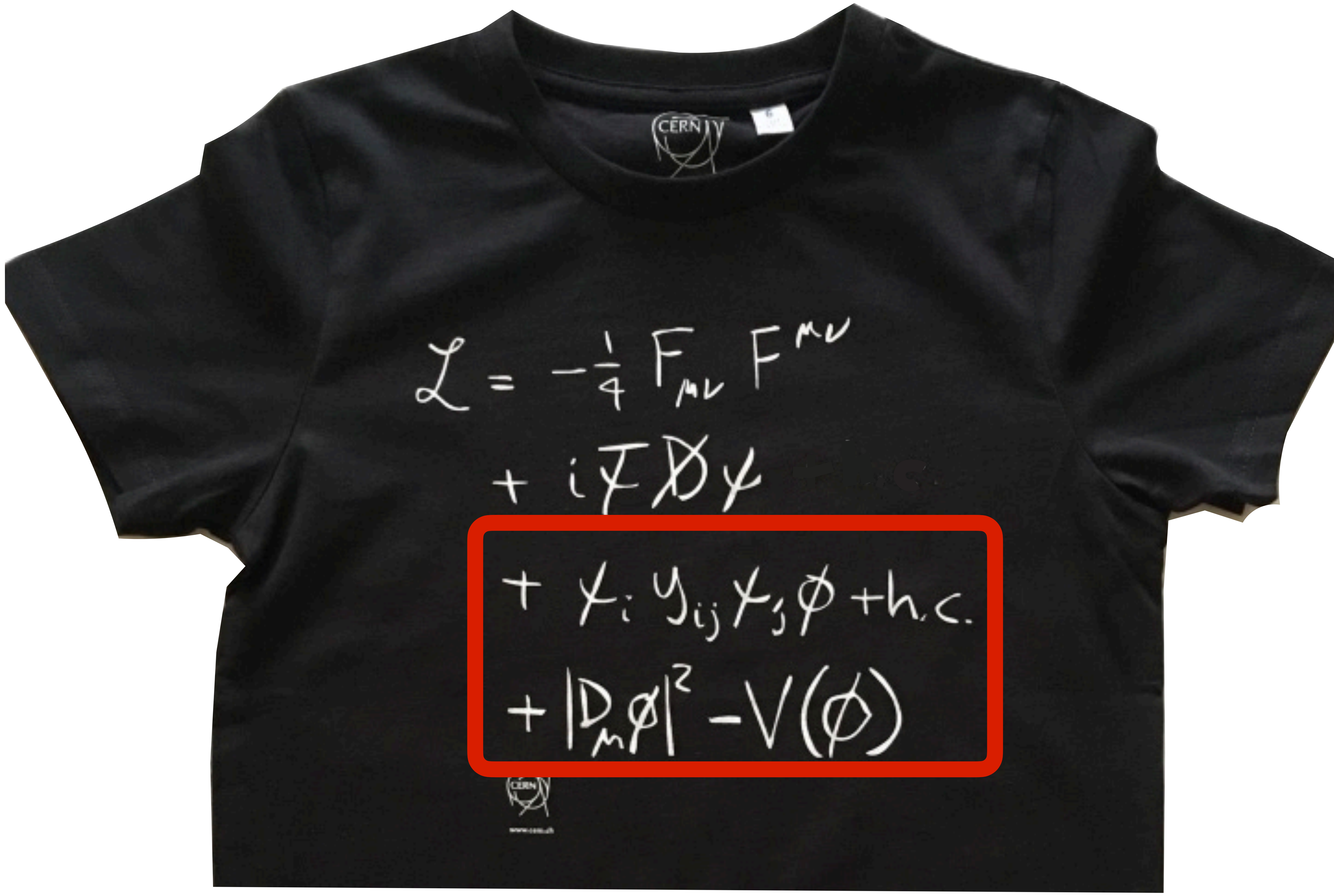
interactions

The Standard Model (SM)

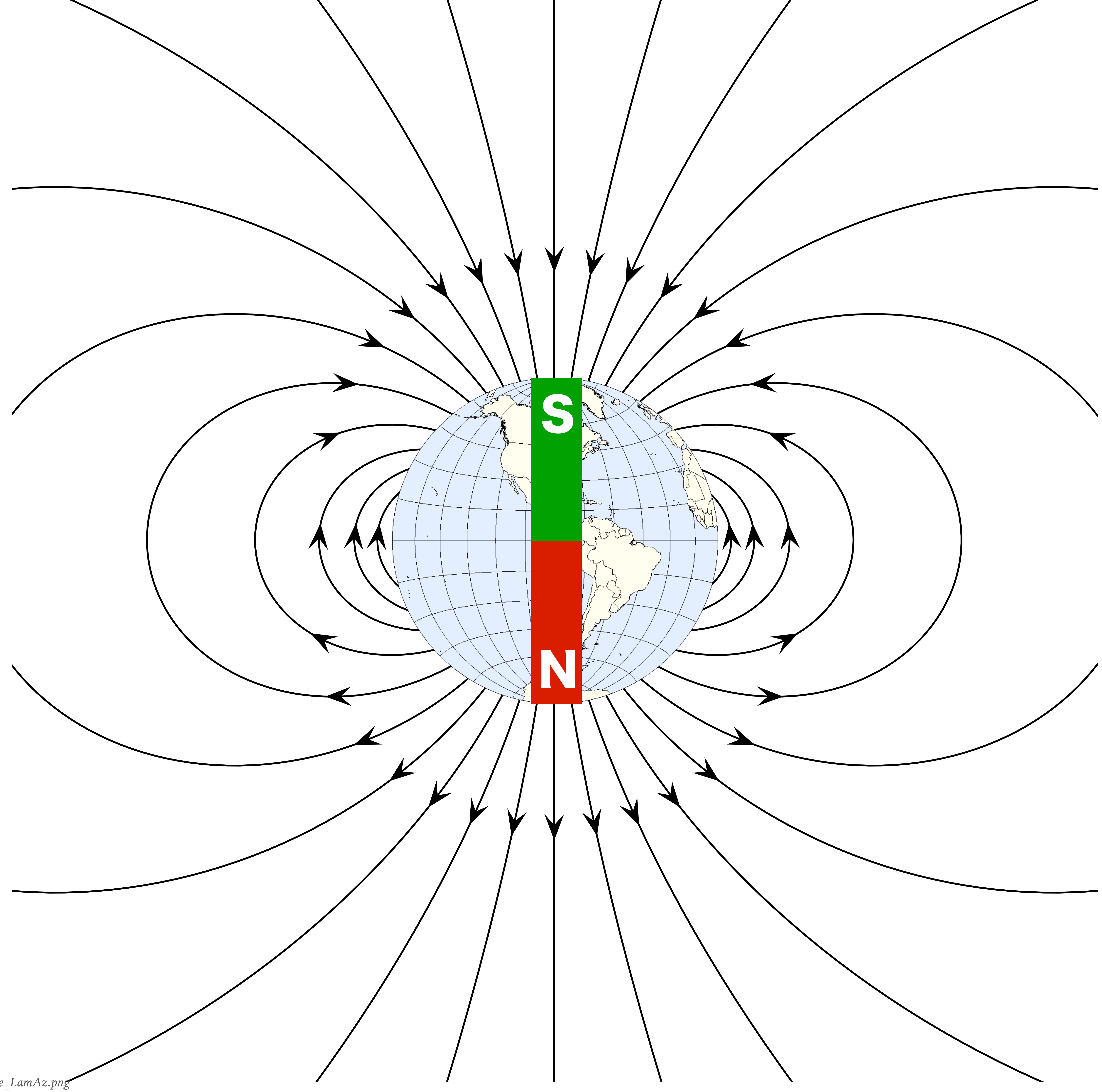
our experimental exploration of the Higgs-related SM interactions is only just starting

parts of this talk adapted from "The Higgs boson turns ten", GPS, Zanderighi and Wang

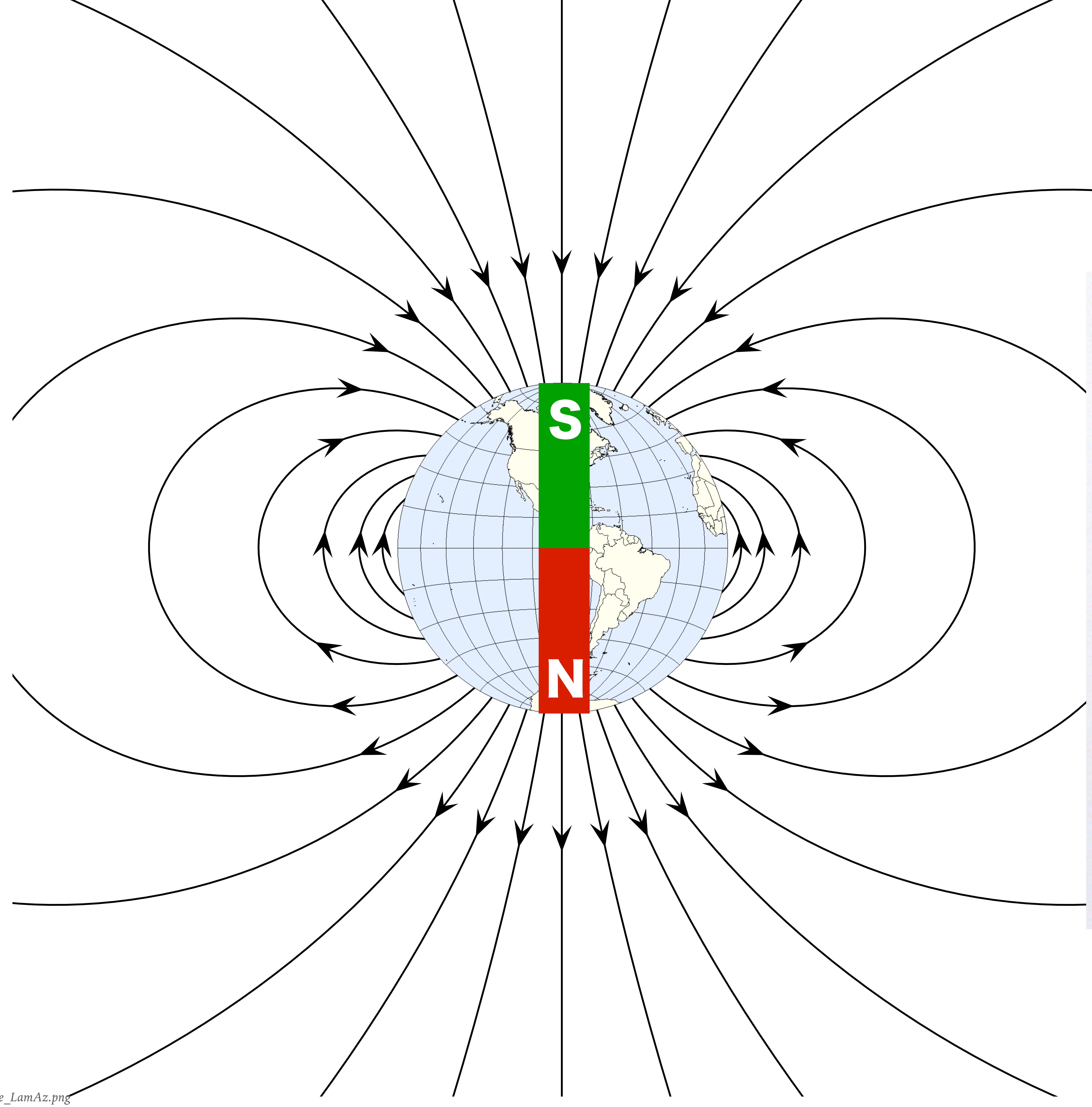
Nature 607 (2022) 7917, 41-47



interactions



https://commons.wikimedia.org/wiki/File:VFPt_Dipole_field.svg
https://en.wikipedia.org/wiki/Western_Hemisphere#/media/File:Western_Hemisphere_LamAz.png



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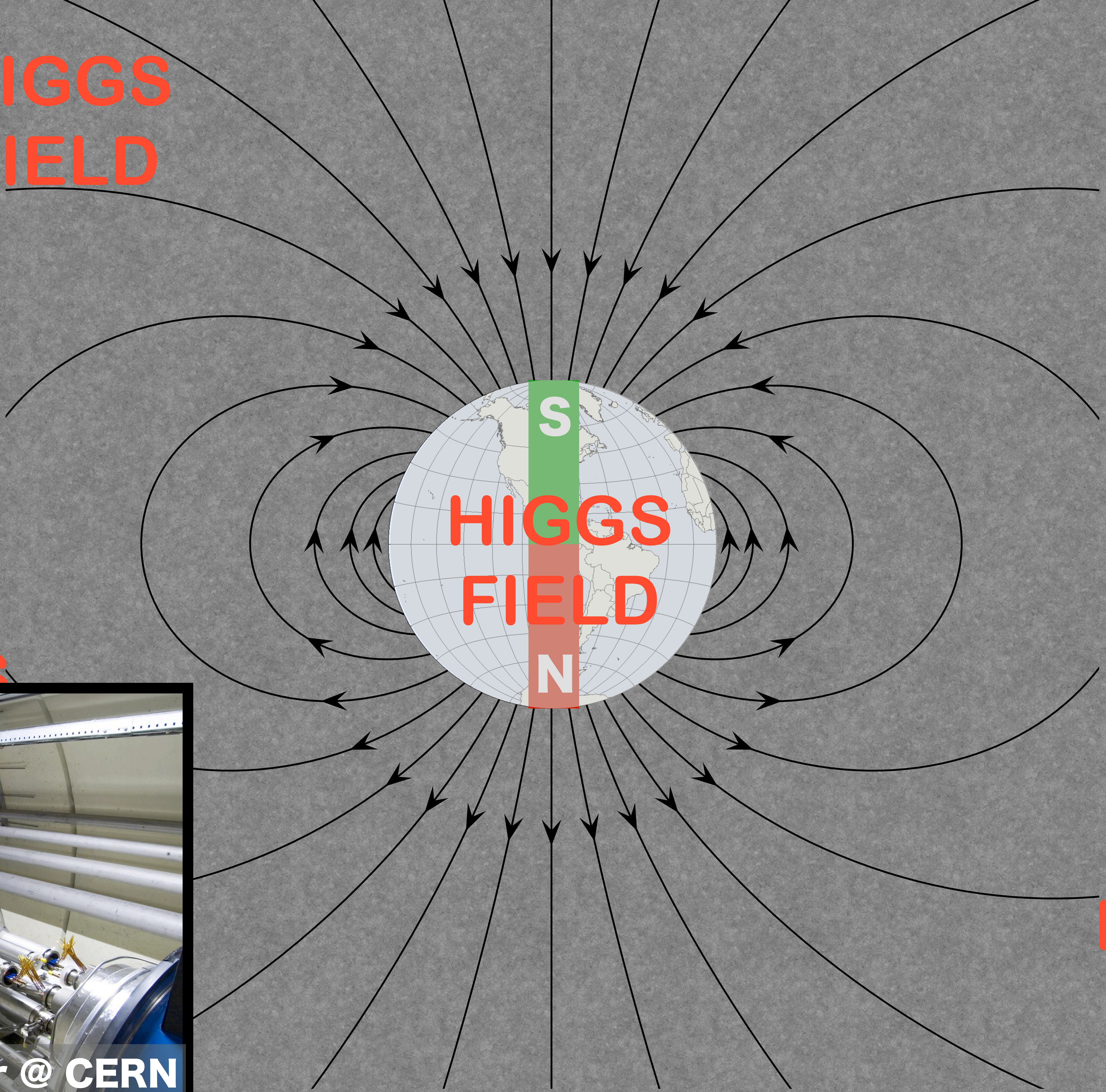
HIGGS
FIELD

HIGGS
FIELD

HIGGS
FIELD



HIGGS
FIELD

HIGGS
FIELD


Large Hadron Collider @ CERN

Higgs field (ϕ) can be different at each point in space

A Higgs boson at a given point in space is a fluctuation of the field

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A Higgs boson at a given point in space is a fluctuation of the field

a core hypothesis of Standard Model

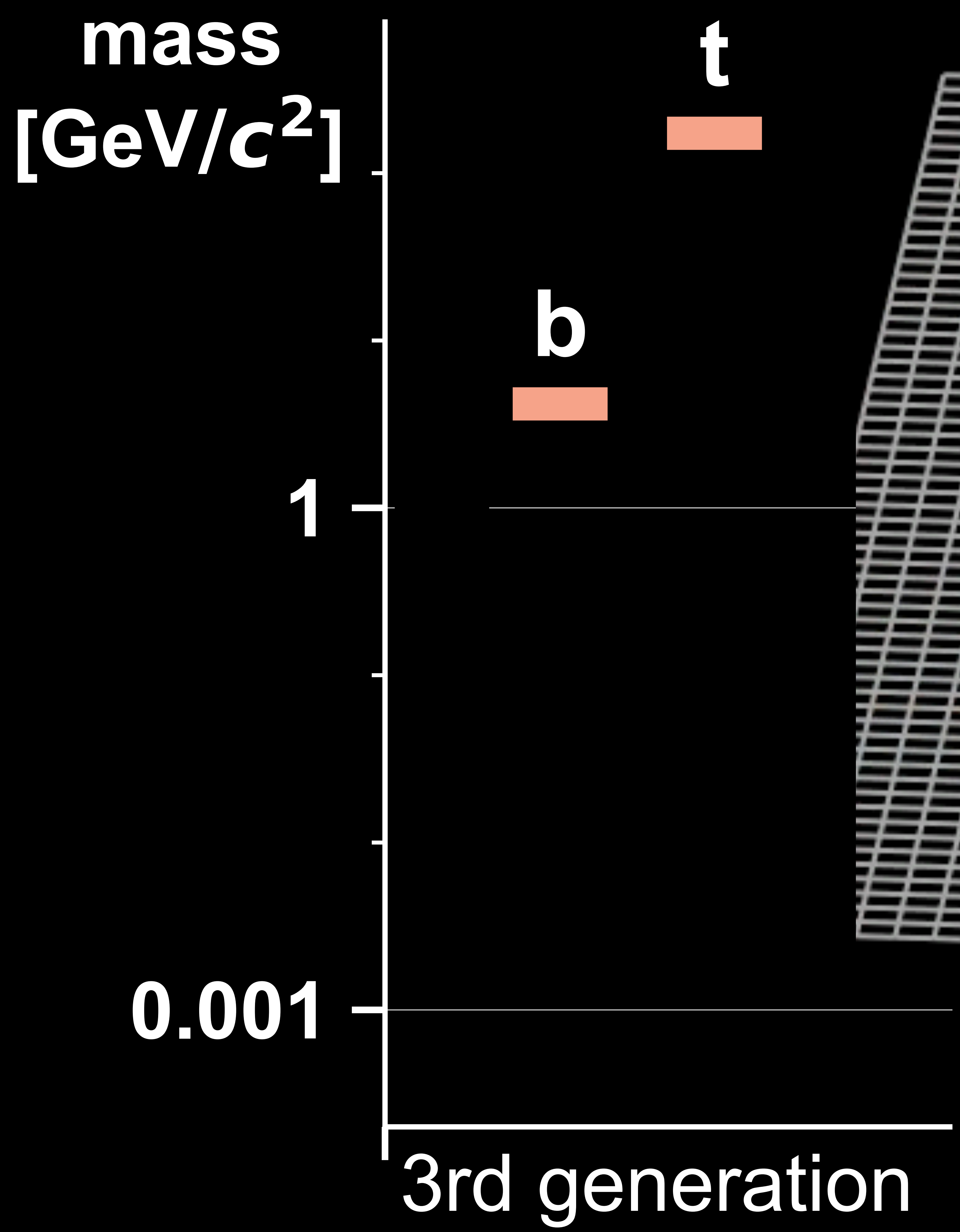
fundamental particles get their mass from interaction with the Higgs field

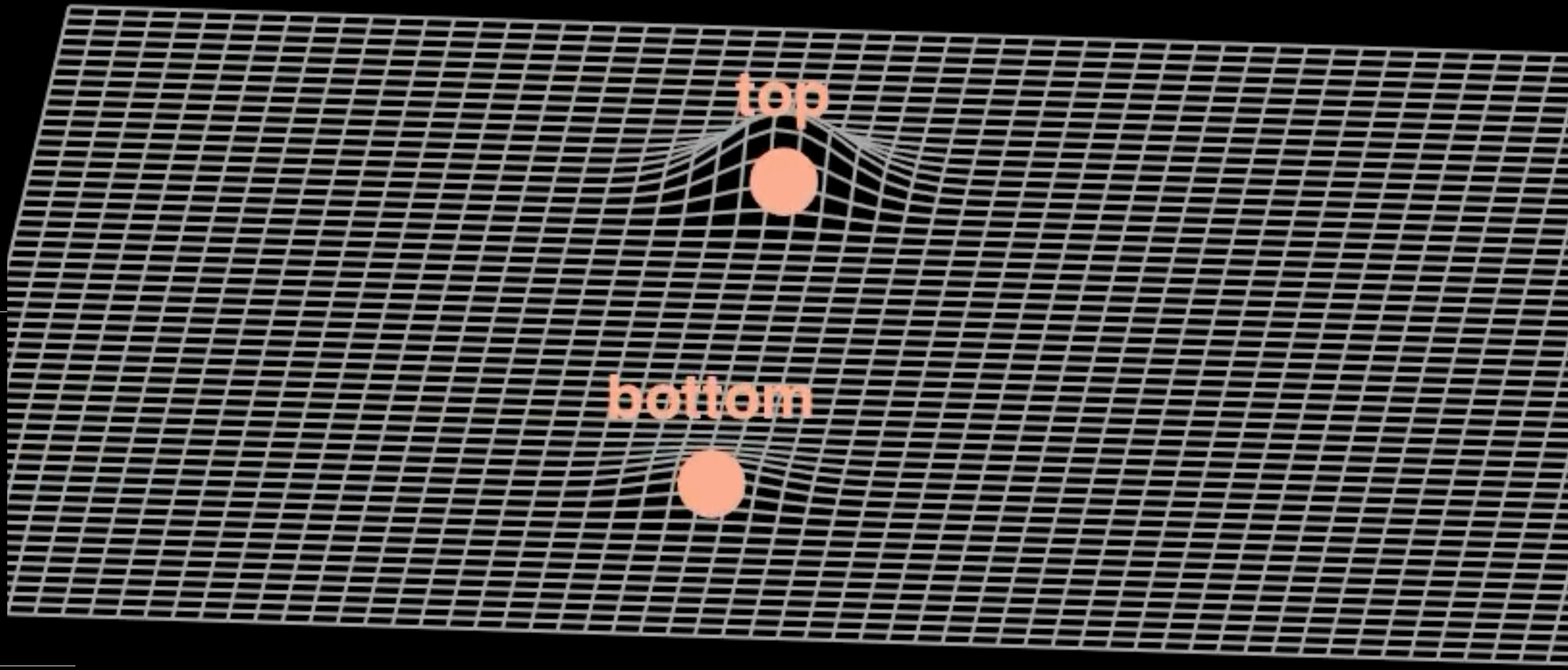
$$+ \chi_i y_{ij} \chi_j \phi + h.c.$$

Standard Model massive particles (except ν)

Standard Model massive particles (except ν)

Higgs field





SM: larger mass of top comes from stronger interaction with Higgs field

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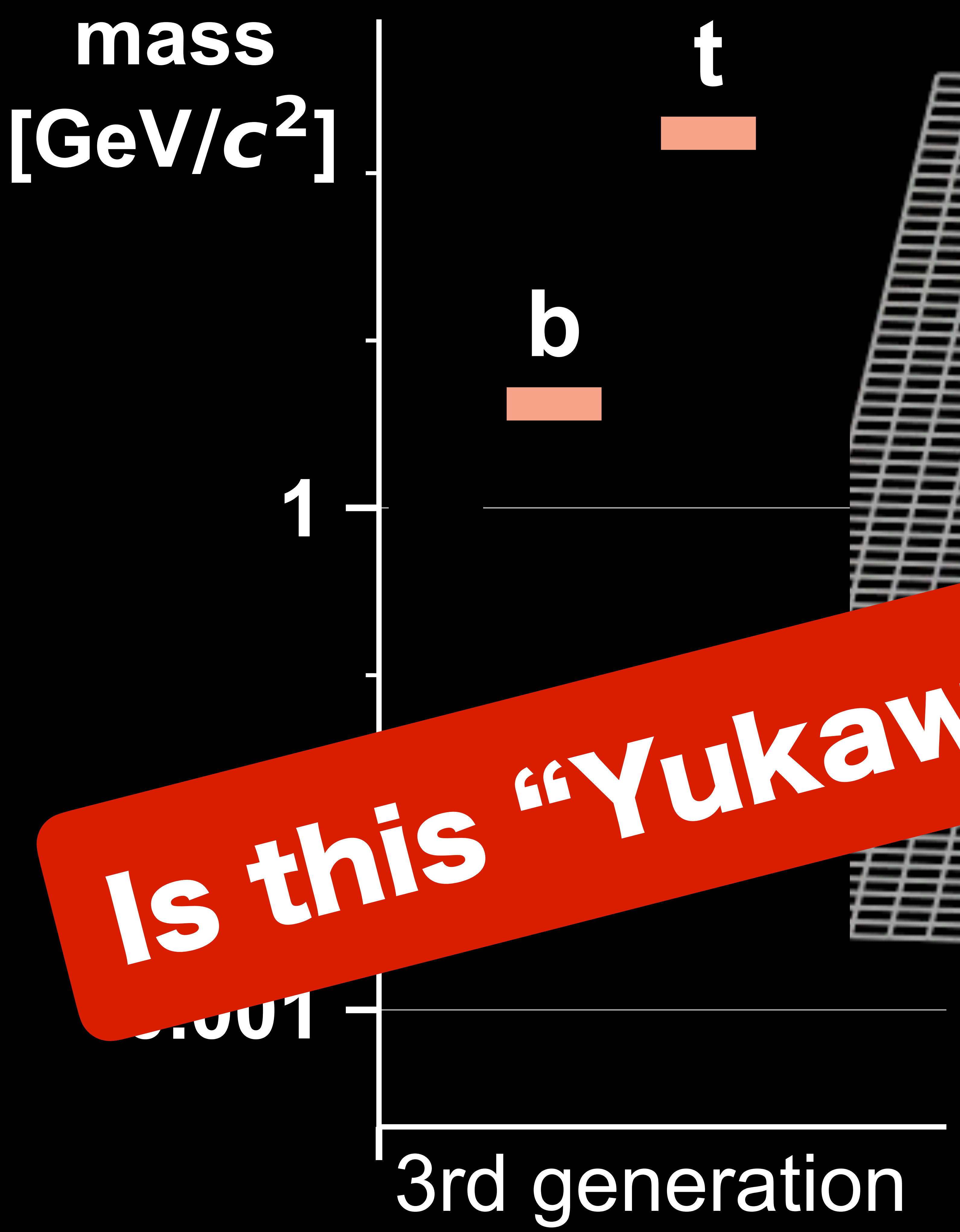
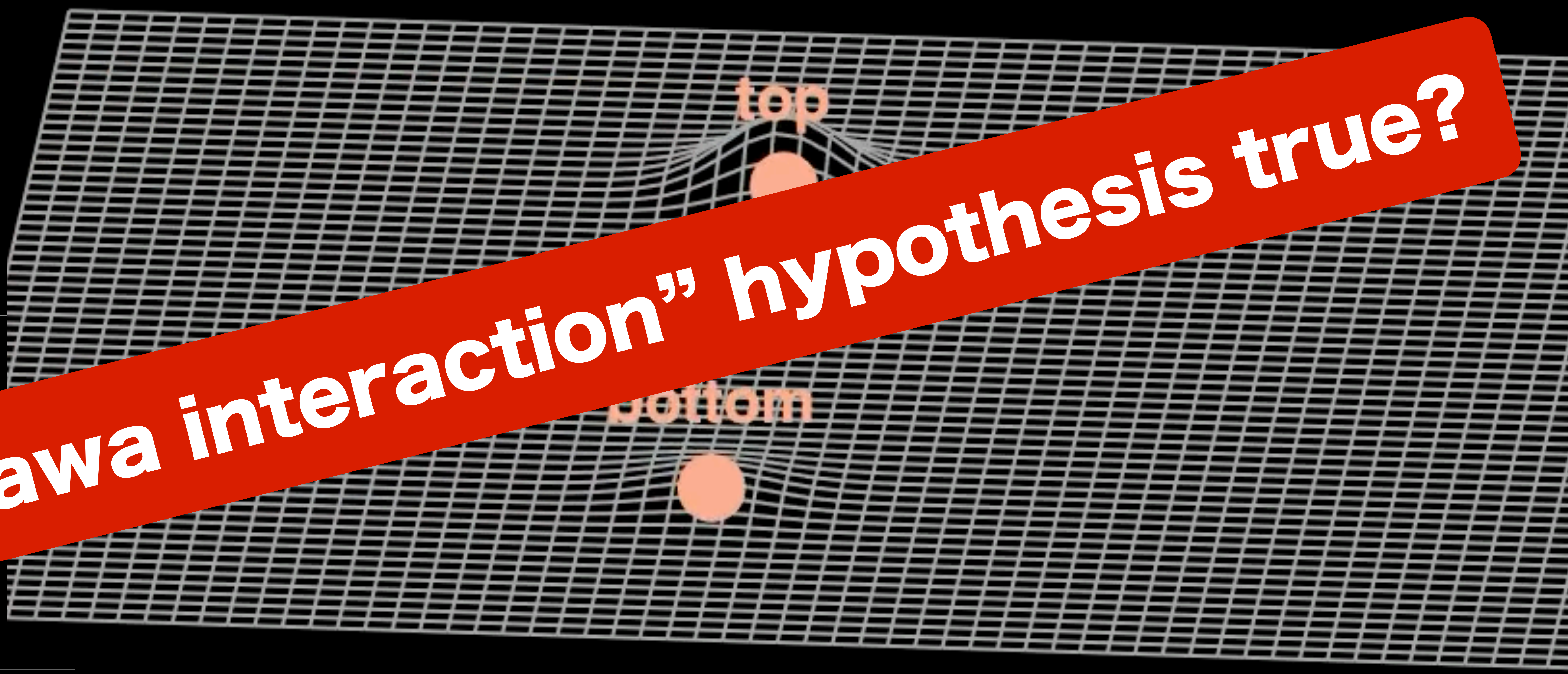
Higgs field

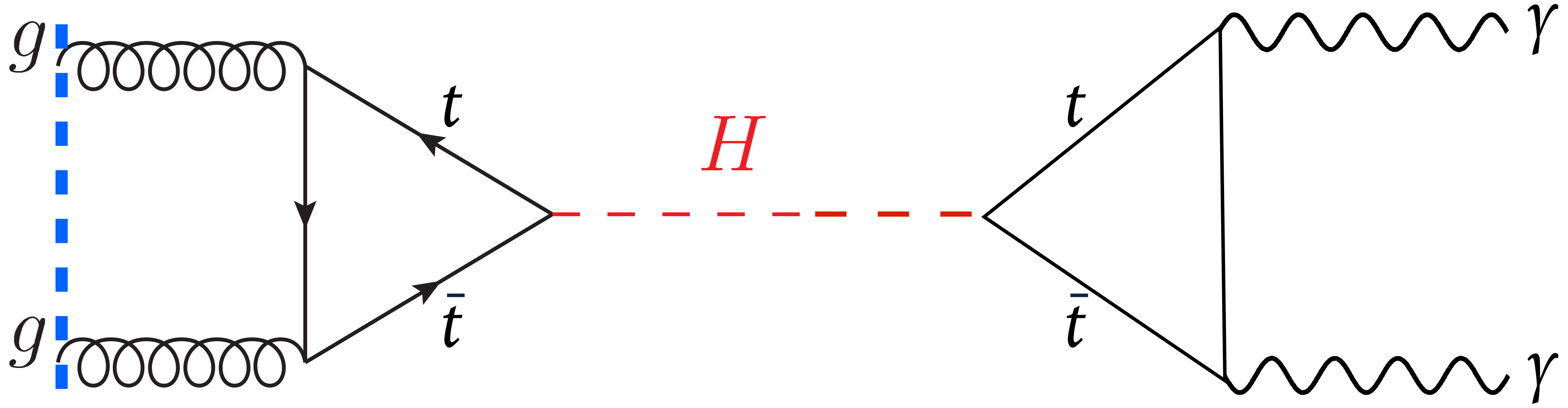




Is this "Yukawa interaction" hypothesis true?

SM: larger mass of top comes from stronger interaction with Higgs field

An LHC collision of the kind that led to the Higgs boson discovery



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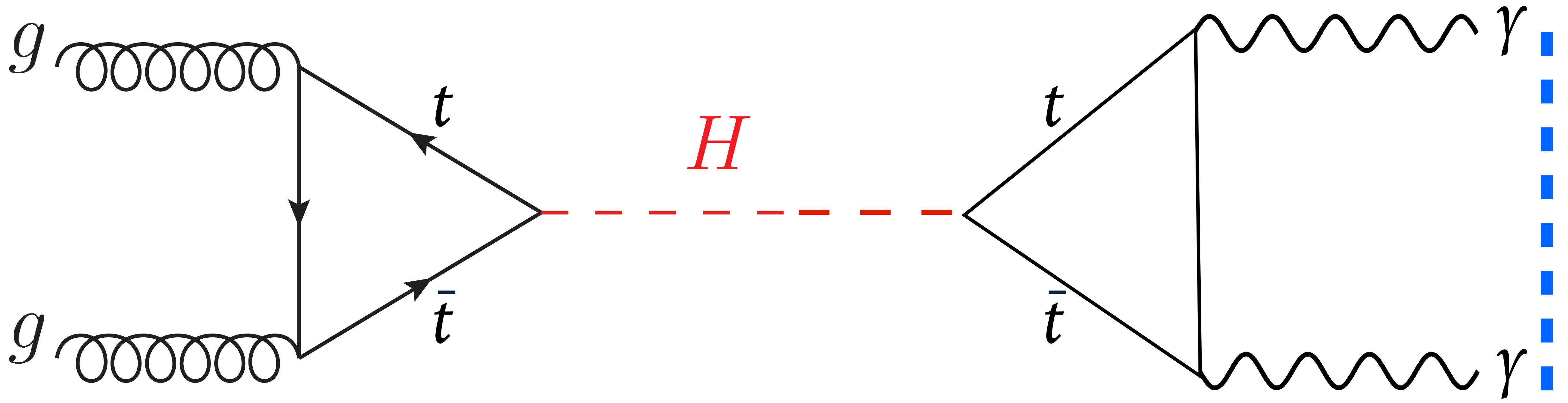
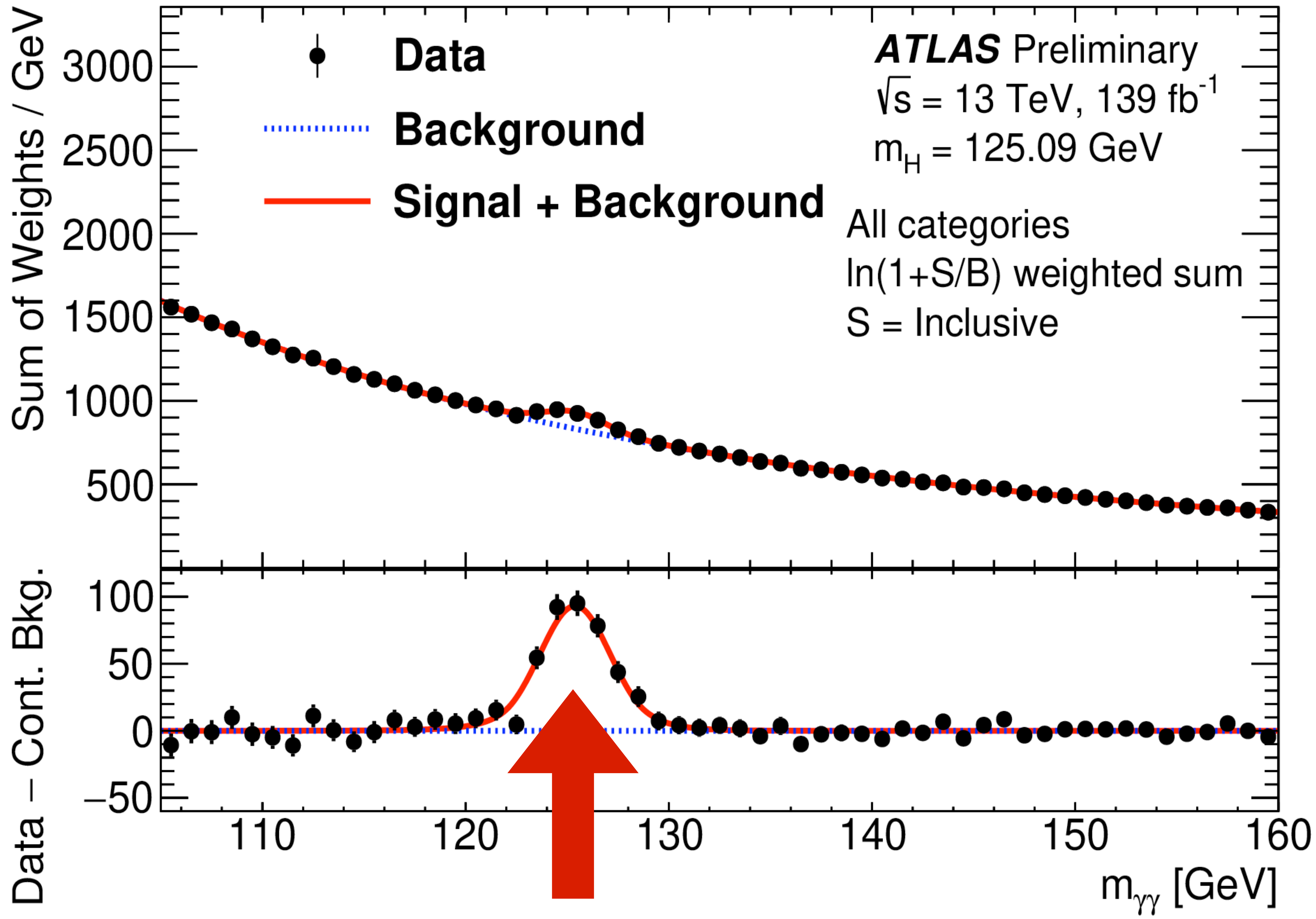


- Record events with two photons;
- classify and count them according to the invariant mass of the two photons (γ)



more events at specific energy
= Higgs bosons

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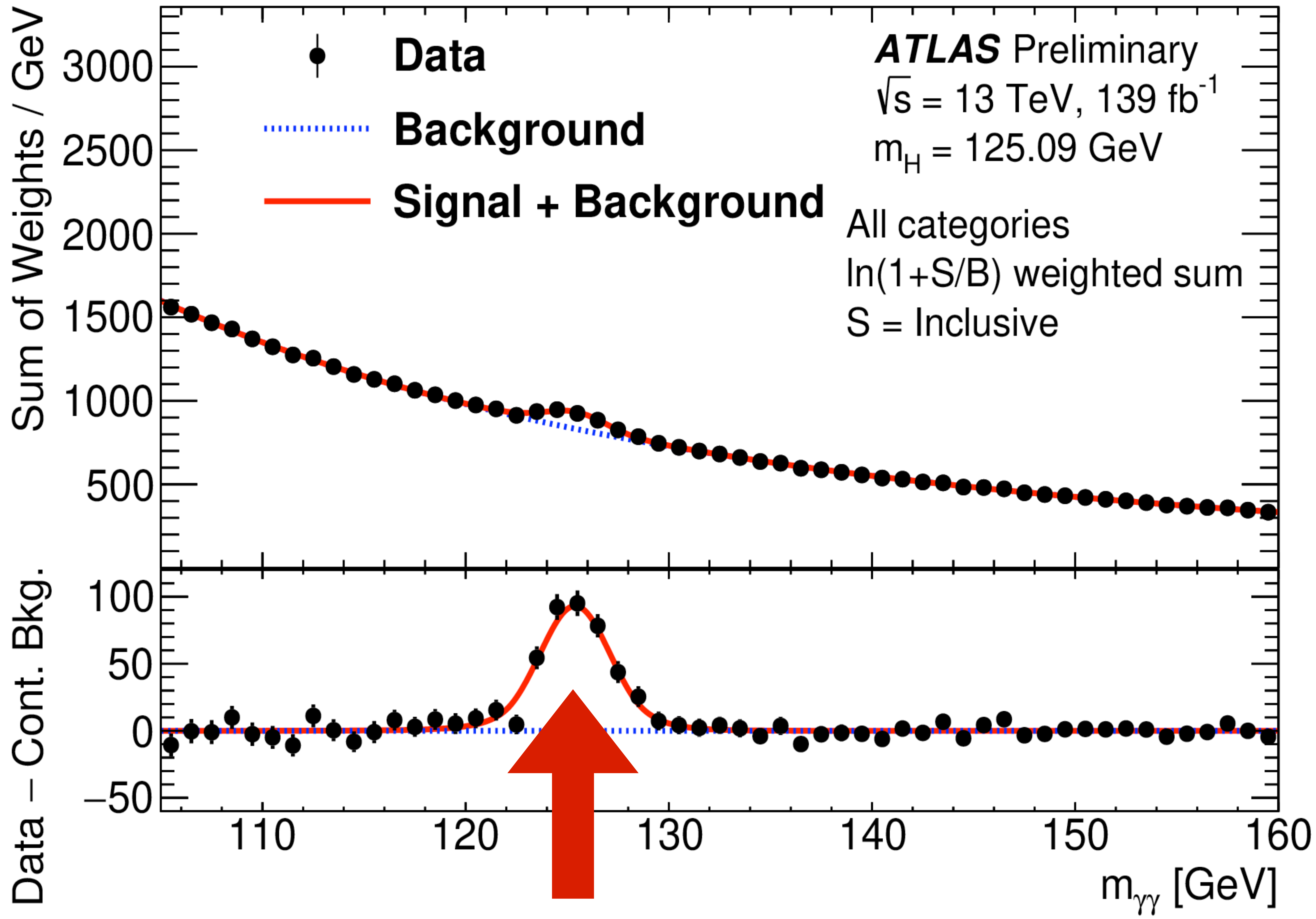

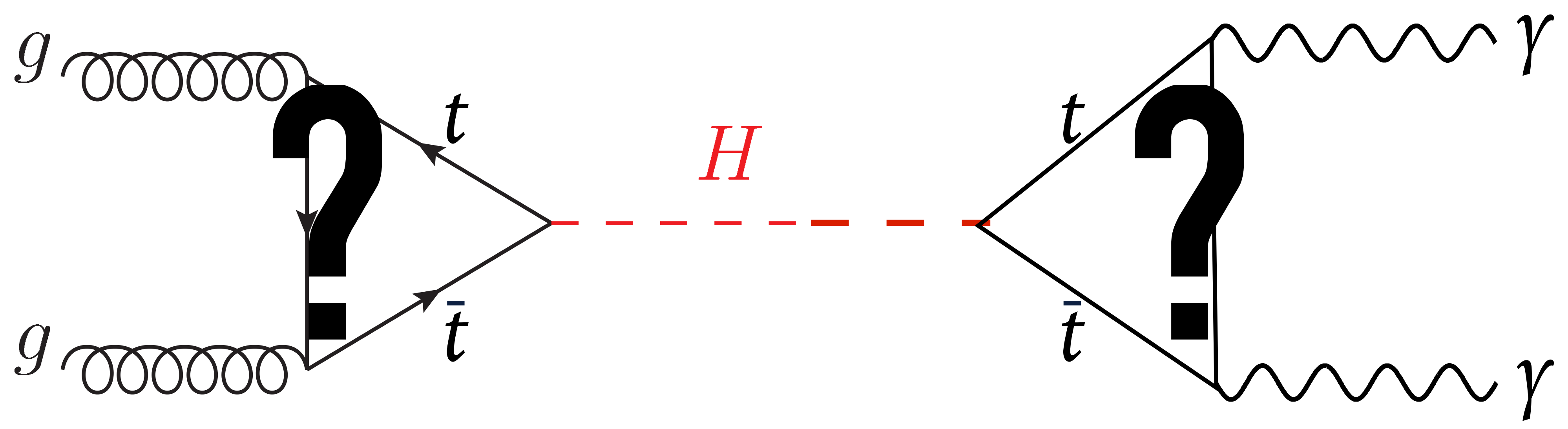

rate of events consistent with SM to ~10%

but how can you be sure it's a top-quark that's in the intermediate stages?

more events at specific energy = Higgs bosons

Press release

KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

13 October 1993

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize Physics for 1993 jointly to **Russell A. Hulse** and **Joseph H. Taylor, Jr**, both of Princeton University, New Jersey, USA **for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation**

Gravity investigated with a binary pulsar

A very important observation was made when the system had been followed for some years […] **reduction of the orbit period by about 75 millionths of a second per year** […] **because the system is emitting energy in the form of gravitational waves** in accordance with what Einstein in 1916 predicted should happen to masses moving relatively to each other. […] the theoretically calculated value from the relativity theory agrees to within about one half of a percent with the observed value. The first report of this effect was made by Taylor and co-workers at the end of 1978, four years after the discovery of the binary pulsar was reported.

Nobel Prize in Physics 1993

Summary

Laureates

Russell A. Hulse

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Press release

Speed read

Award ceremony speech

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indirect observation

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https://www.nobelprize.org/prizes/physics/2017/press-release/

Nobel Prize in Physics 2017

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- Rainer Weiss
- Barry C. Barish
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Prize announcement

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Popular information

Advanced information

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Press release

English
English (pdf)
Swedish
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3 October 2017

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Rainer Weiss
LIGO/VIRGO Collaboration

and the other half jointly to

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and

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"for decisive contributions to the LIGO detector and the observation of gravitational waves"

Gravitational waves finally captured

On 14 September 2015, the universe's gravitational waves were observed for the very first time. The waves, which were predicted by Albert Einstein a hundred years ago, came from a collision between two black holes. It took 1.3 billion years for the waves to arrive at the LIGO detector in the USA.

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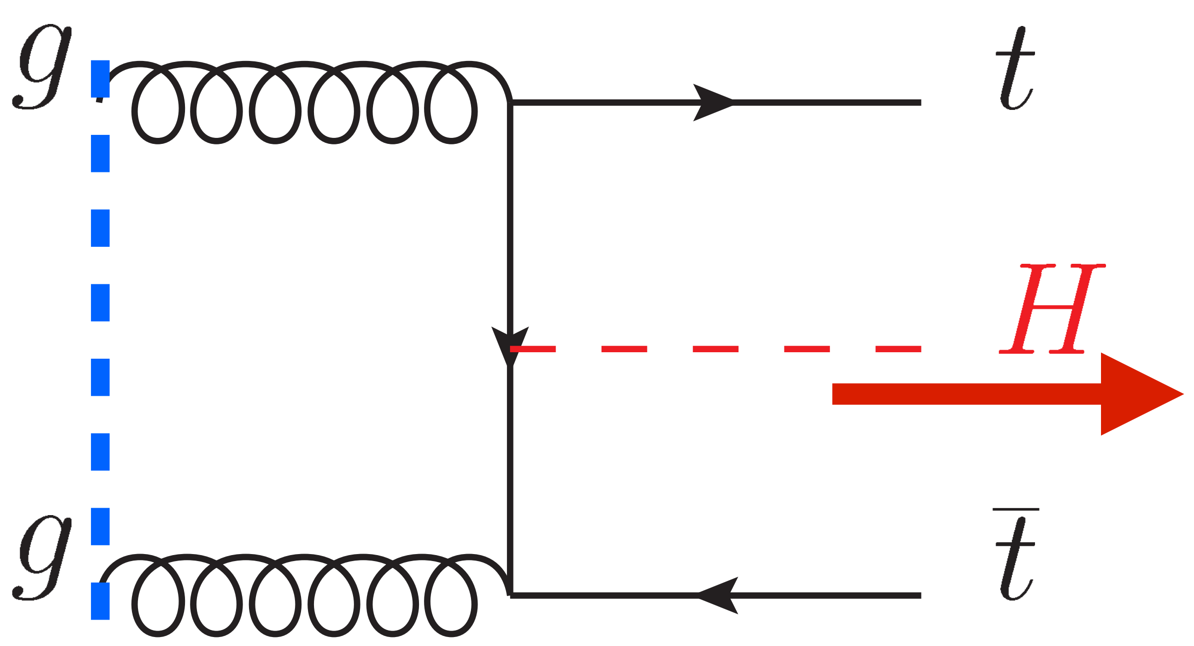
g
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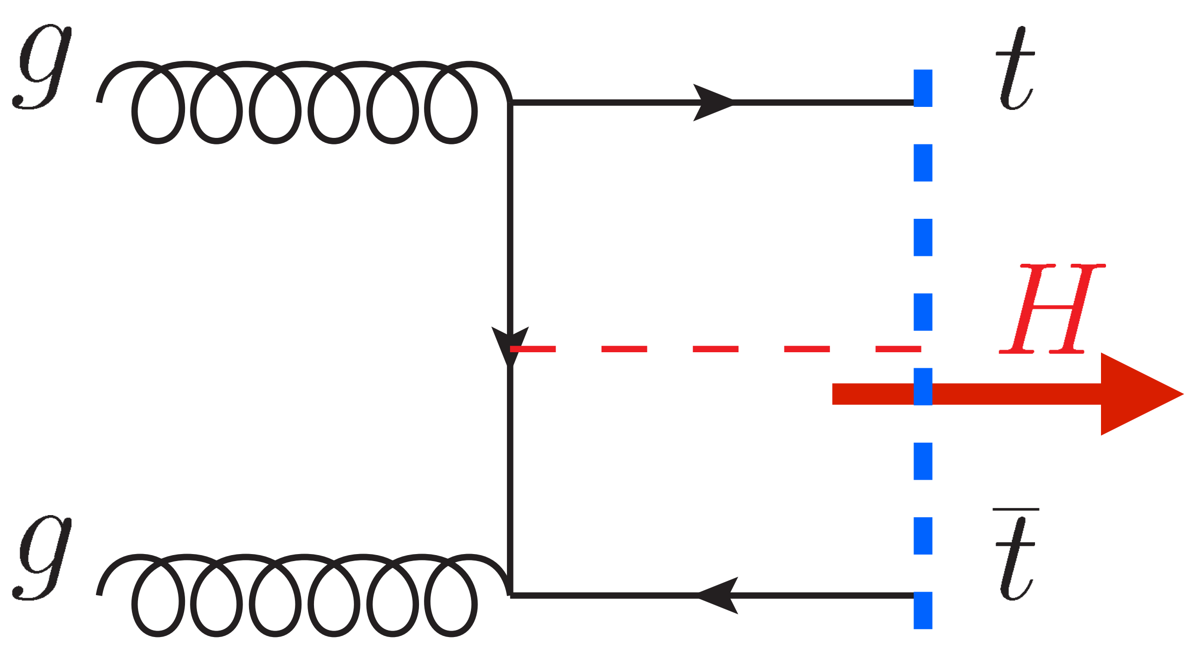
$\bar{t}$


luon
gluo
φ
y
x
Higgs field in space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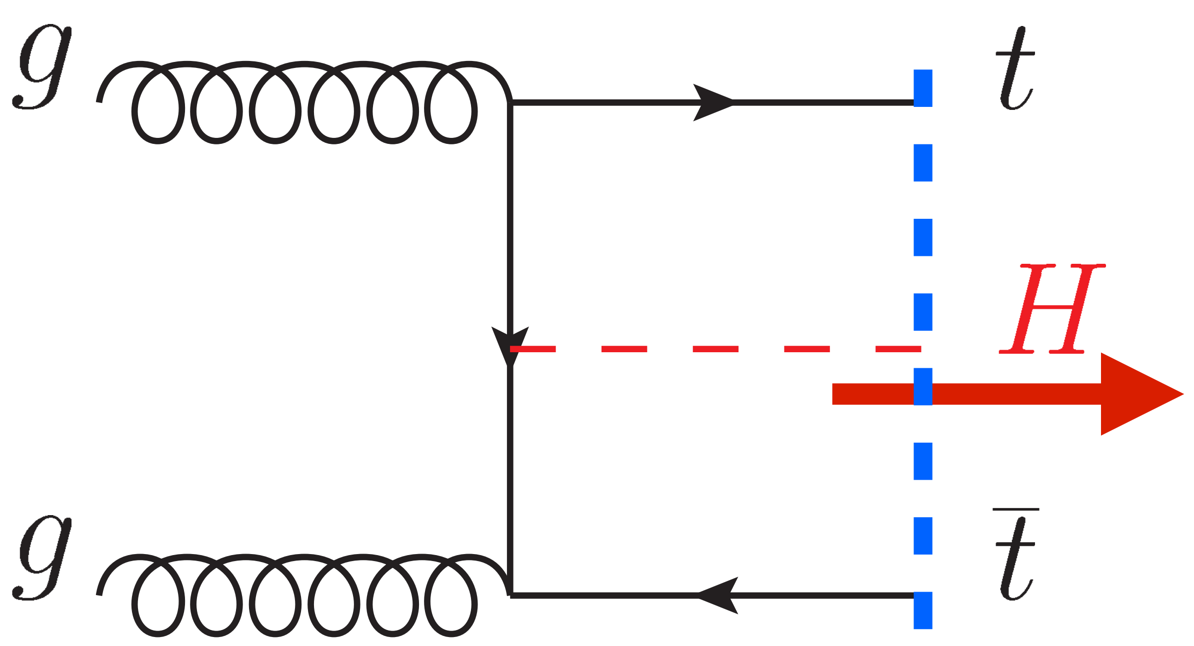
g
g
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luon
gluo
ϕ
y
x
Higgs field in space

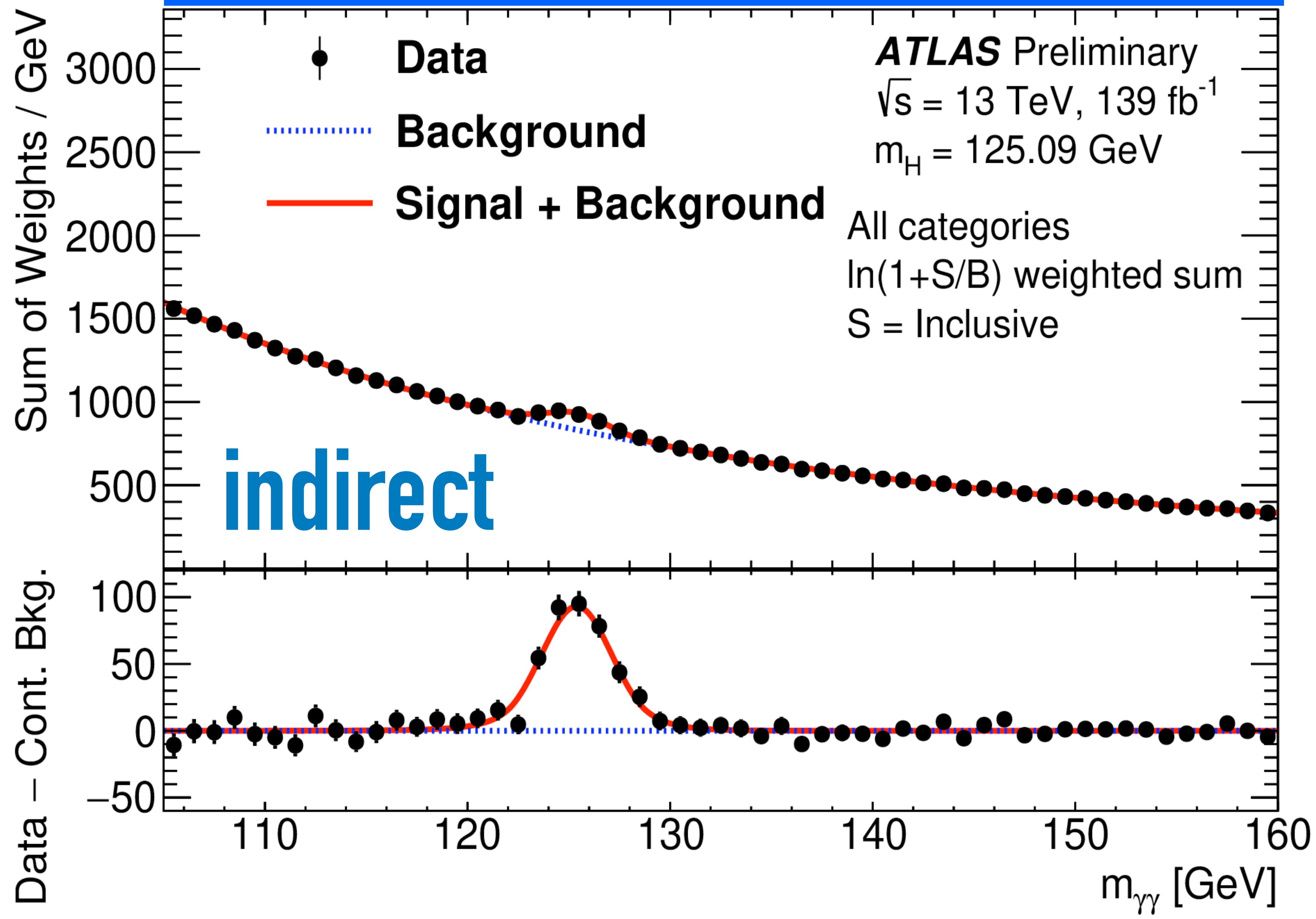
Situation at start of LHC (2009)

"Due to a (too) low signal-to-background ratio S/B ~ 1/9 [ttH] channel might not reach a 5σ significance for any luminosity."

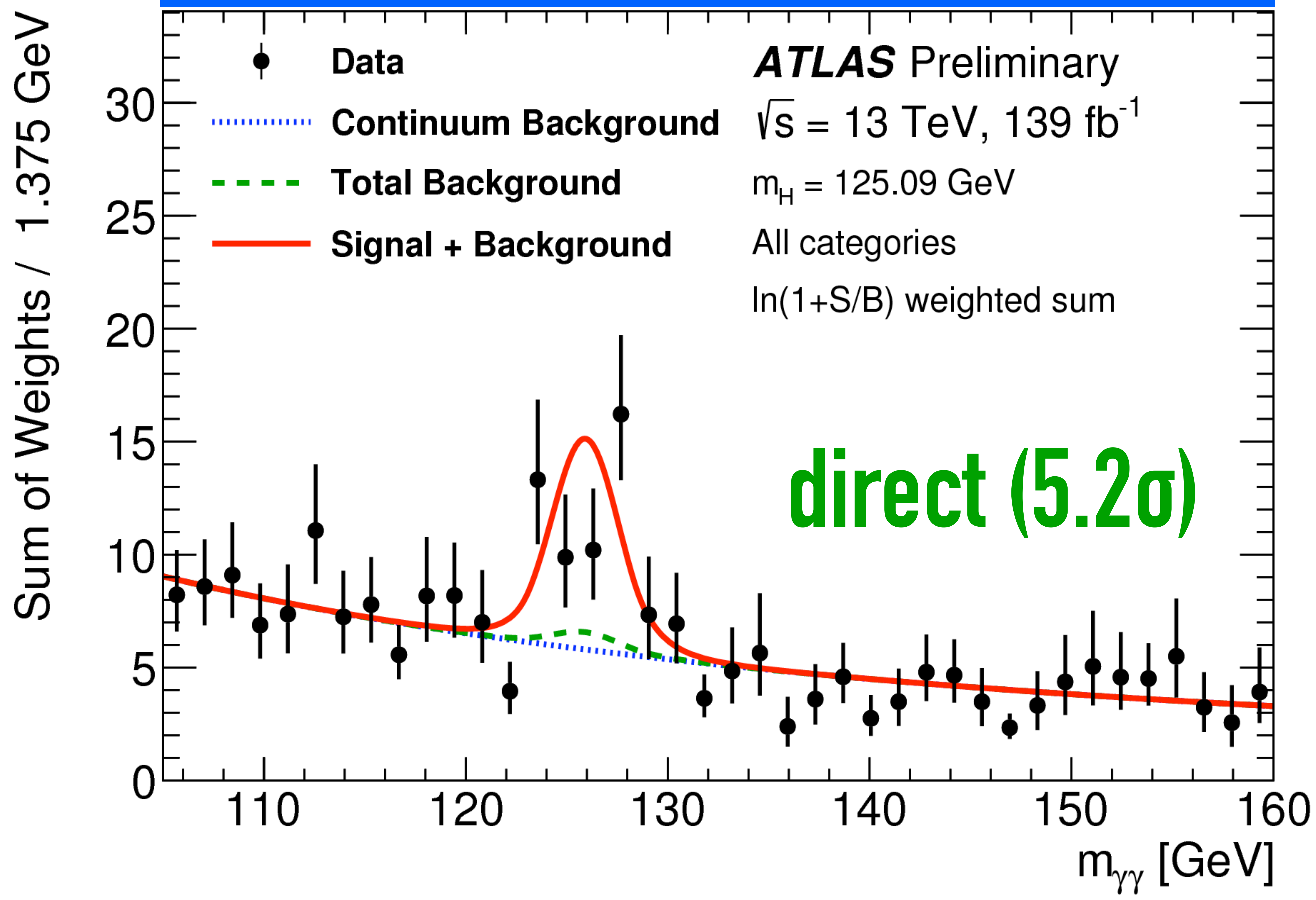
[from introduction to arXiv:0910.5472,
summarising ATLAS and CMS ttH(→bb) studies at that point]

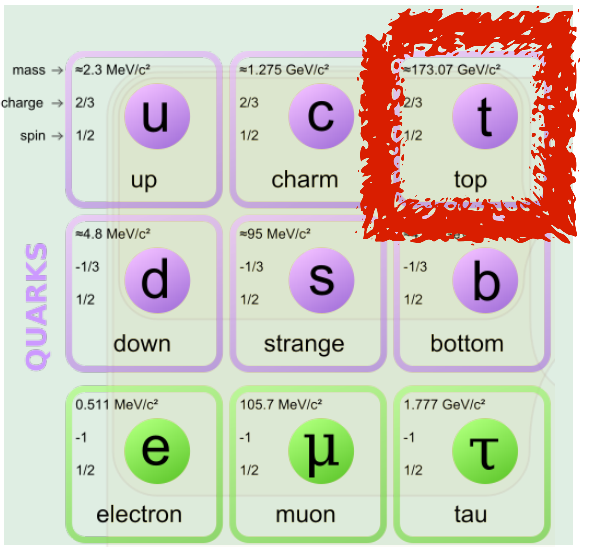
since 2018: ATLAS & CMS see (at >5σ) events with top-quarks & Higgs simultaneously

Higgs = one in 2 billion events



1 in 2,000 events with top quarks



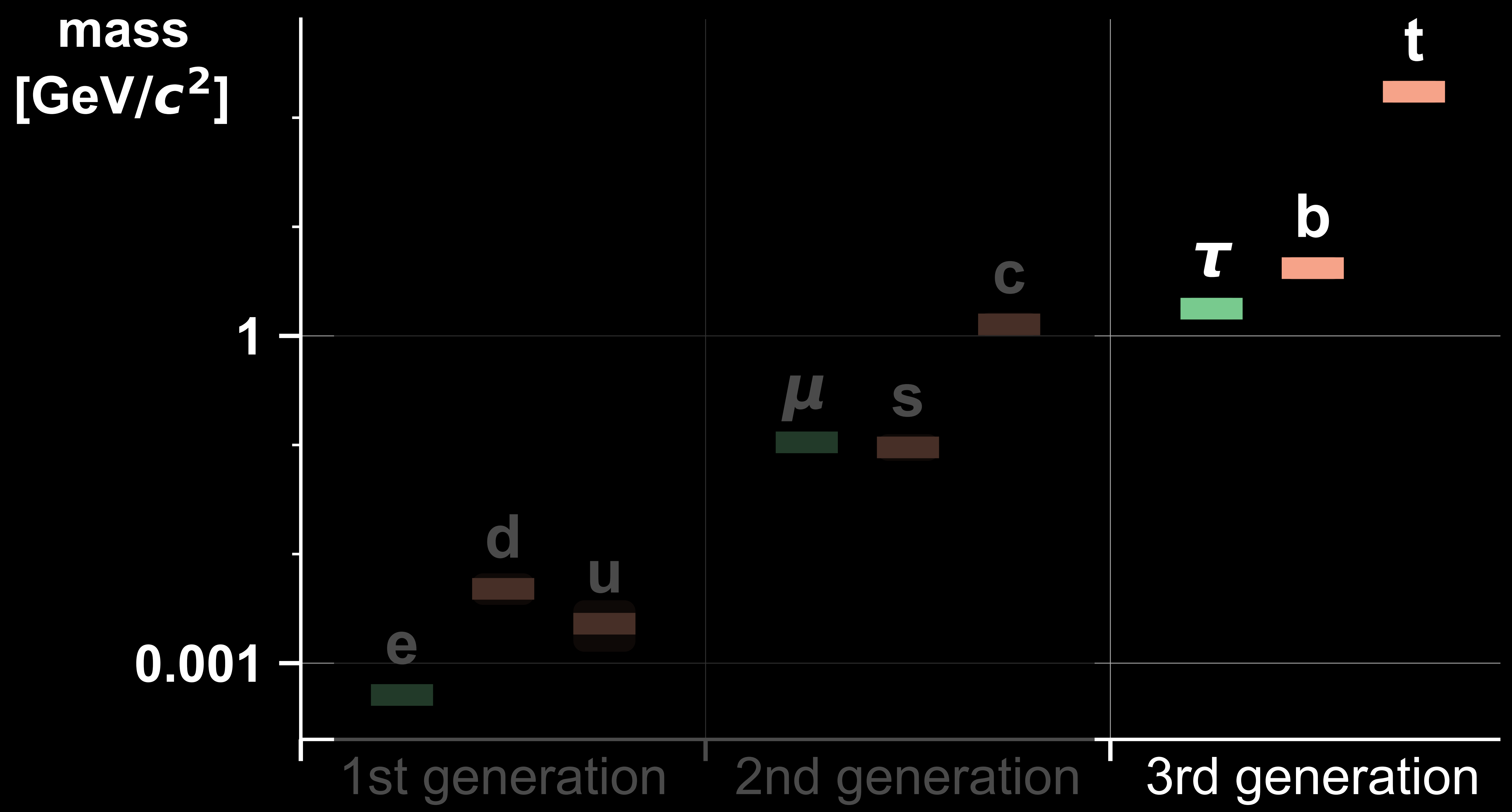


enhanced fraction of Higgs bosons in events with top quarks

→ direct observation of Higgs interaction with tops

(consistent with SM to c. ±25%)

Discovery of 3rd generation—Higgs field interactions by ATLAS & CMS ~ 2018



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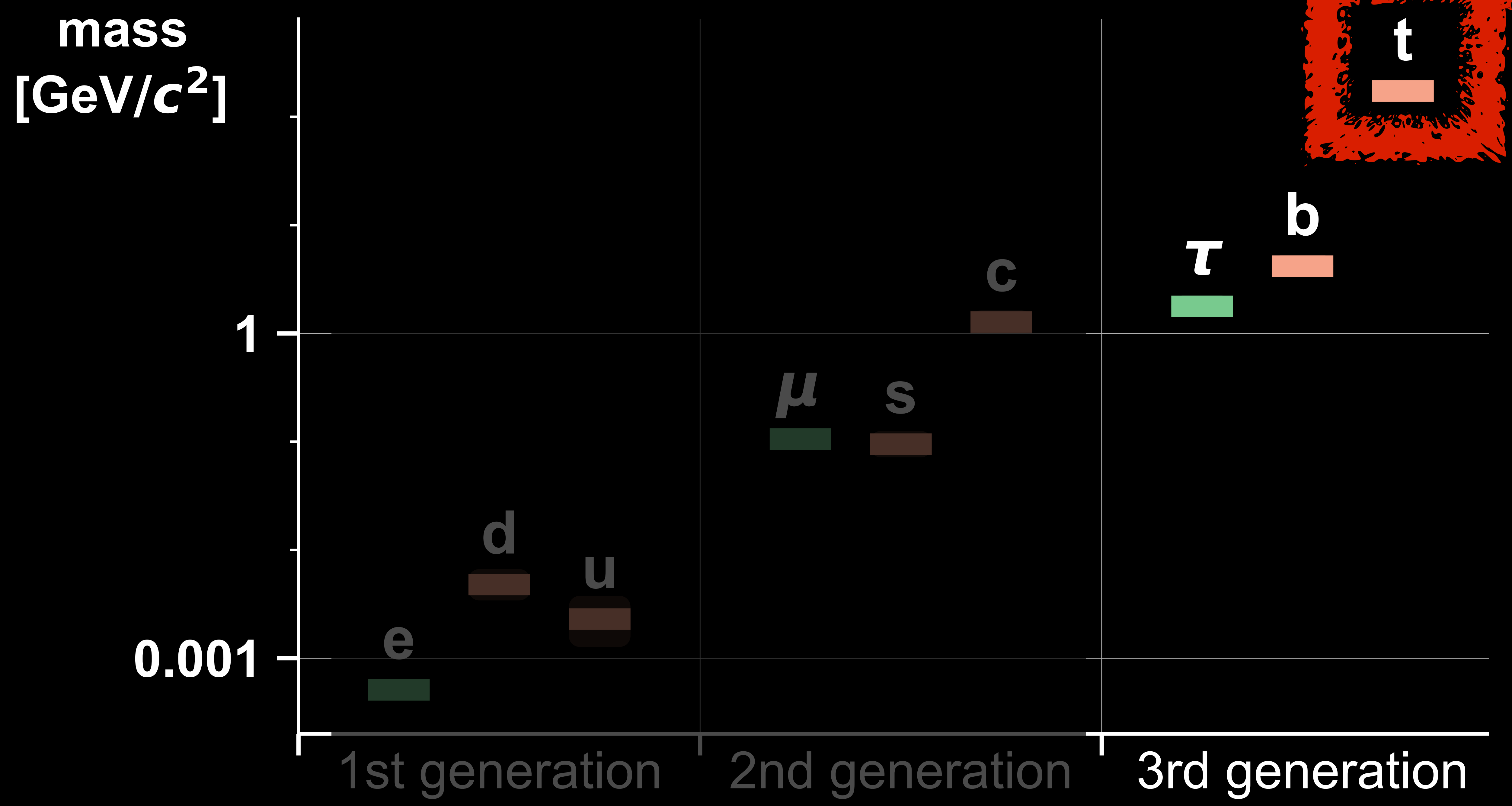
by observing H in association with top quarks



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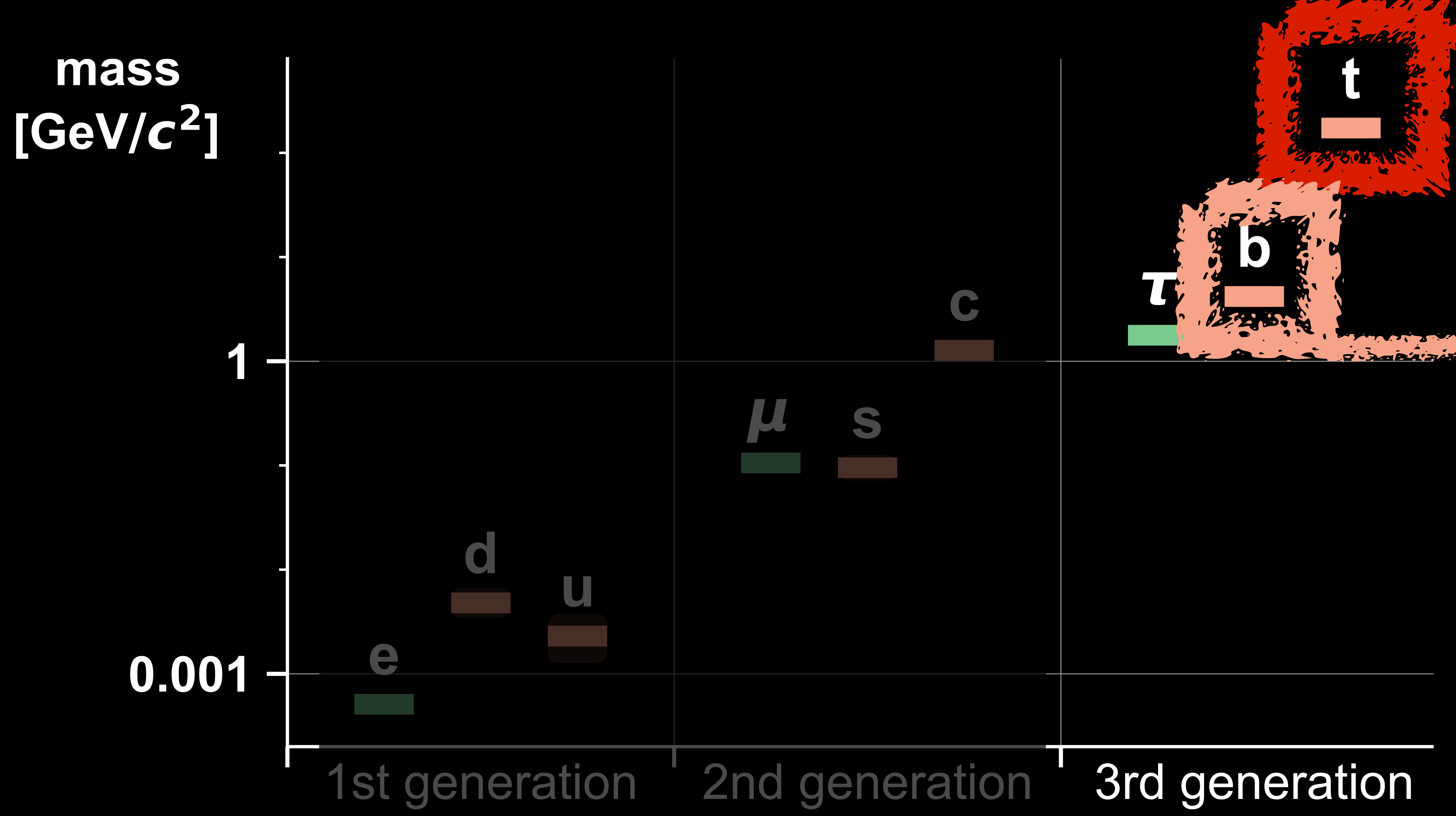
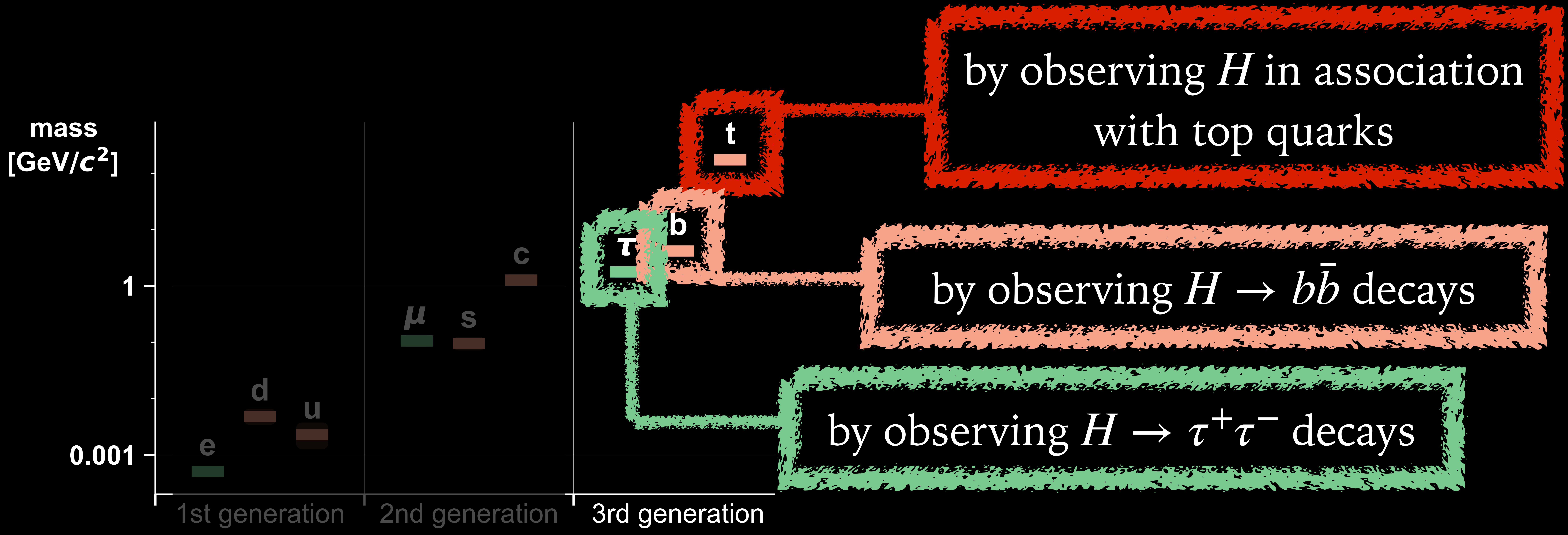


by observing H in association with top quarks

by observing $H \to b\bar{b}$ decays

in part with approach from Butterworth, Davison, Rubin & GPS '08

Discovery of 3rd generation—Higgs field interactions by ATLAS & CMS ~ 2018



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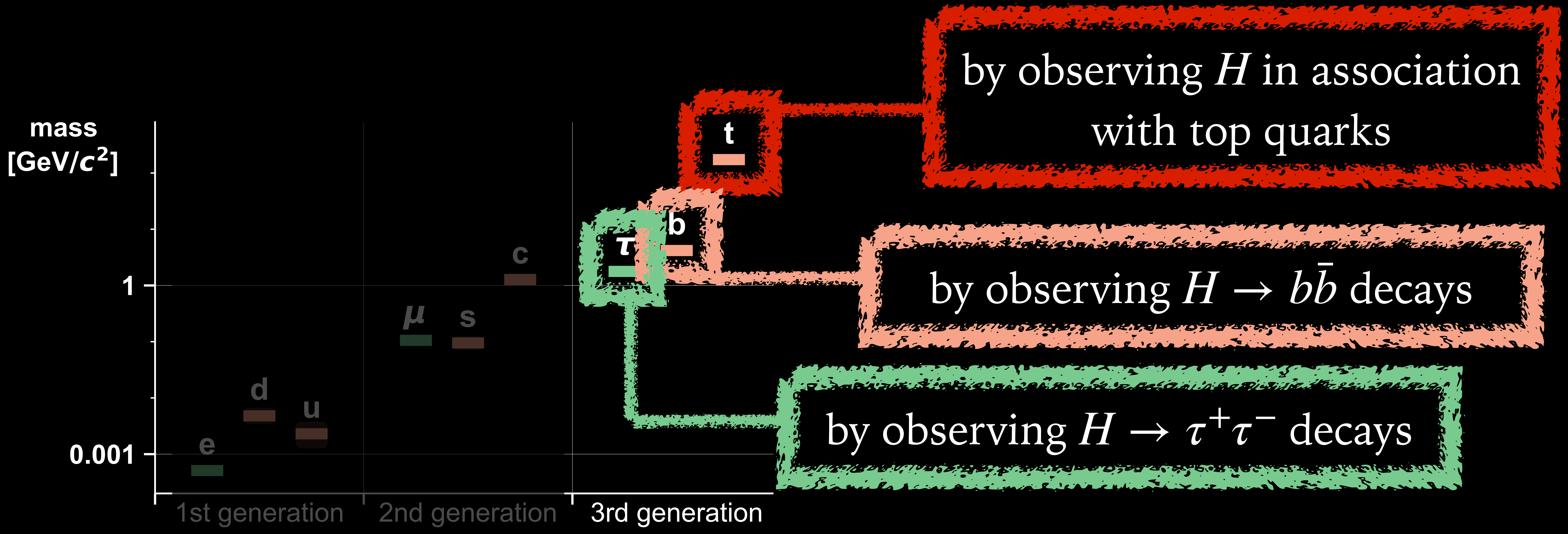
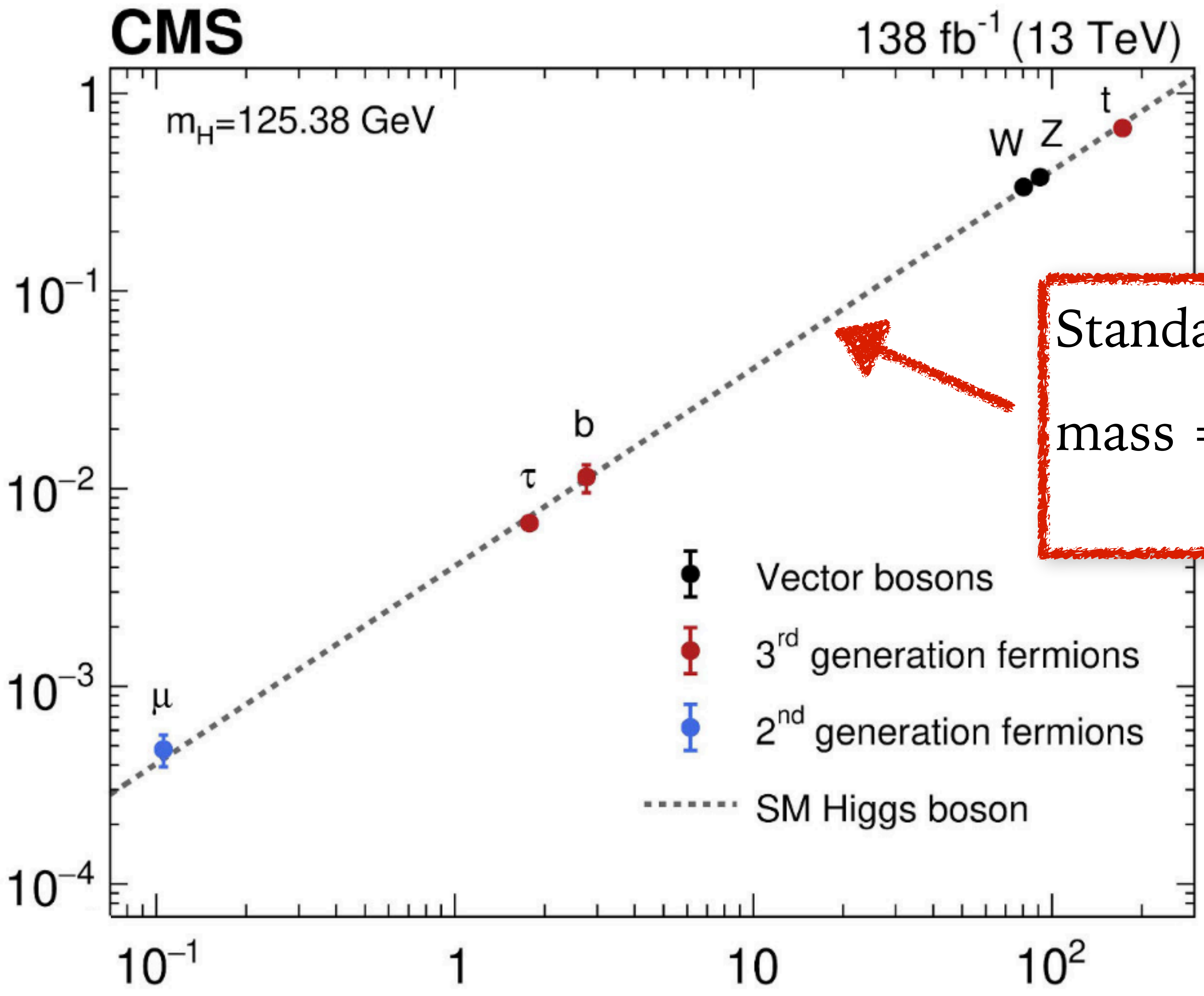


Full 3rd generation Yukawas were not part of the LHC design case. Amazing achievement of LHC experiments to have directly observed them

Particle's strength of interaction with Higgs field



Standard Model prediction:

mass = higgs-field-value × interaction-strength

Particle's mass [GeV]

what could one be saying about it?

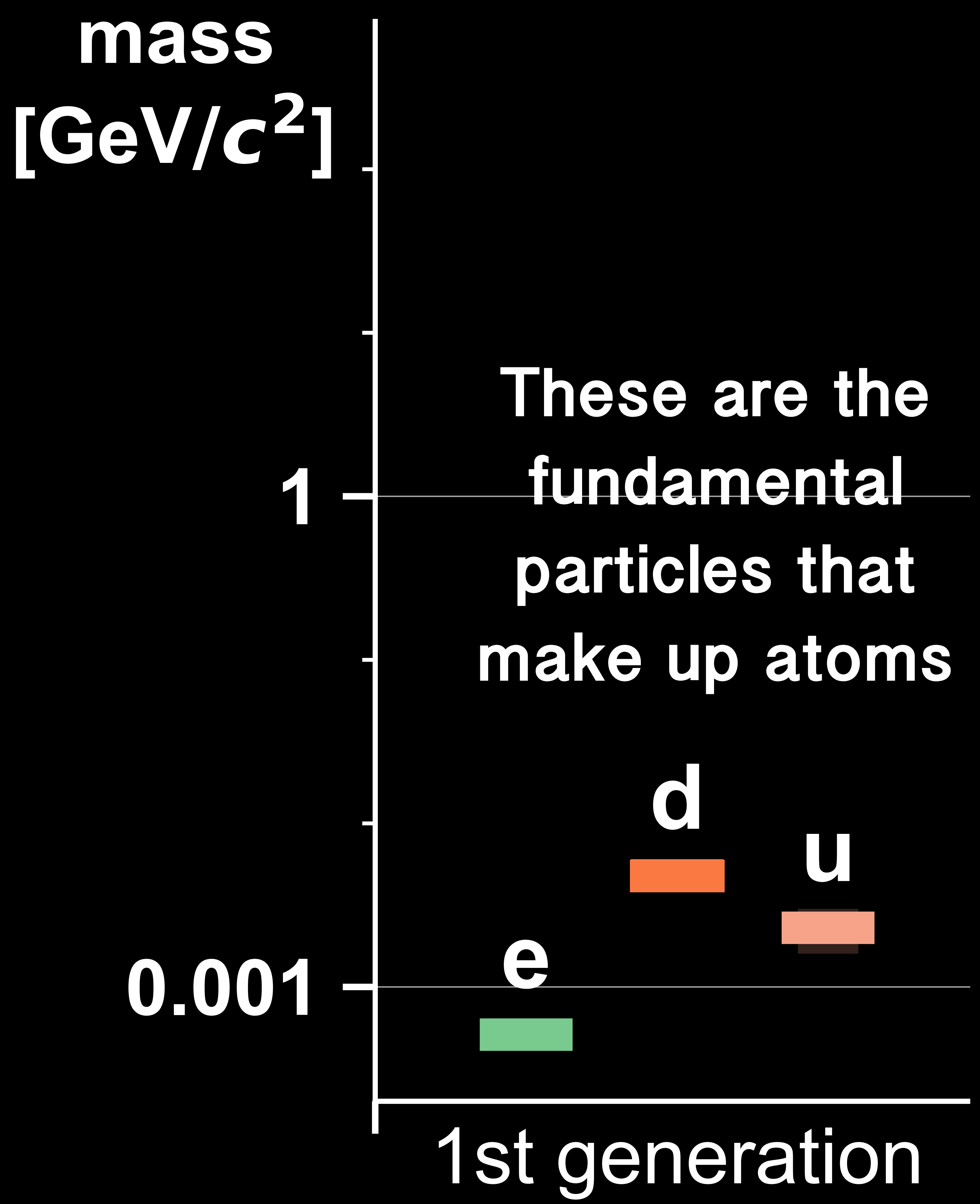
For a full set of particles (3rd generation) that are like the ones we're made of, the LHC has demonstrated that their mass is not an intrinsic property, but is generated by an interaction with a non-zero Higgs field.

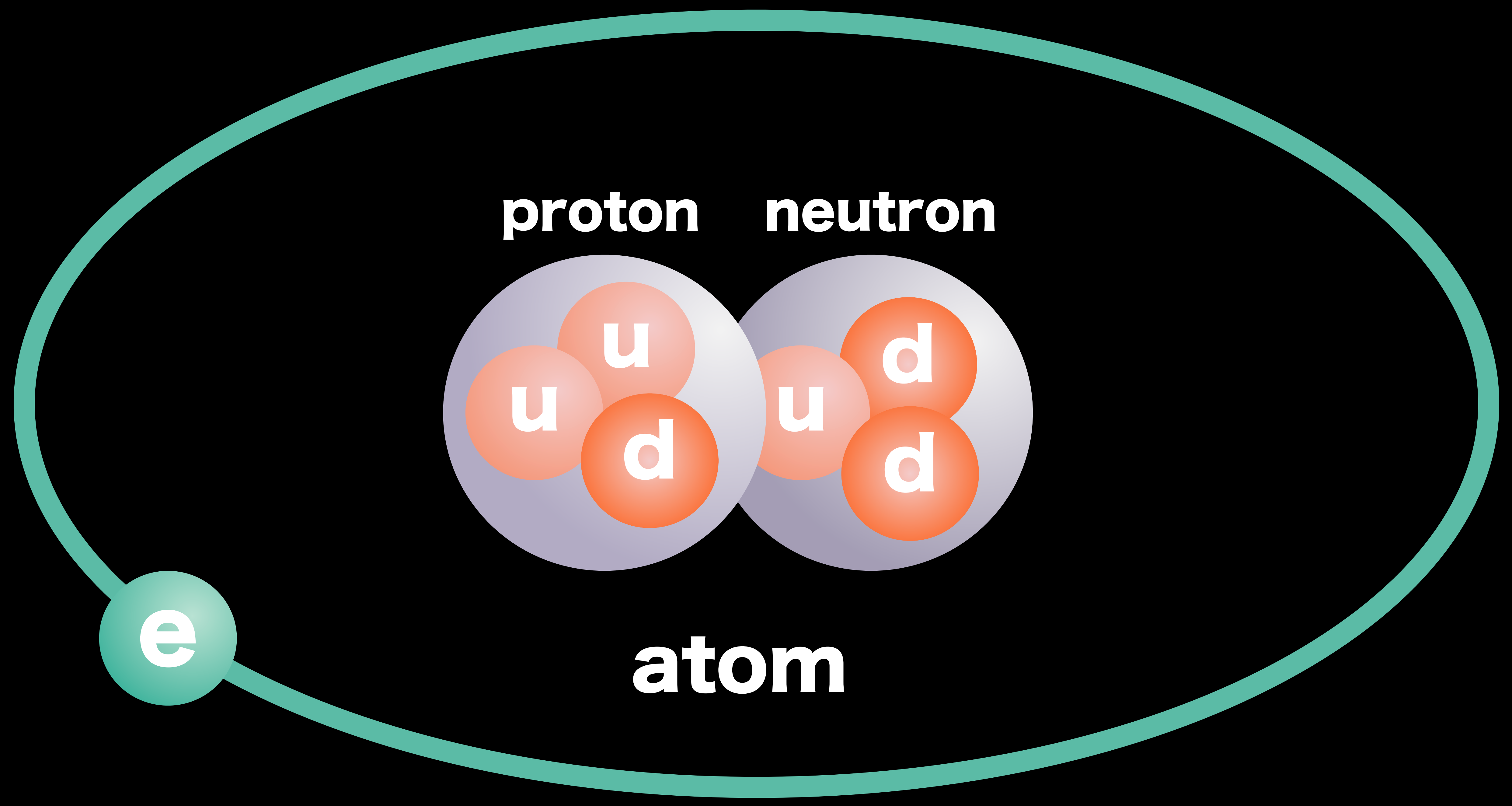
A field is something that can in principle be controlled and modified. Could the masses of elementary particles conceivably also be controlled and modified? Science fiction…

Is this any less important than the discovery of the Higgs boson itself?

My opinion: no

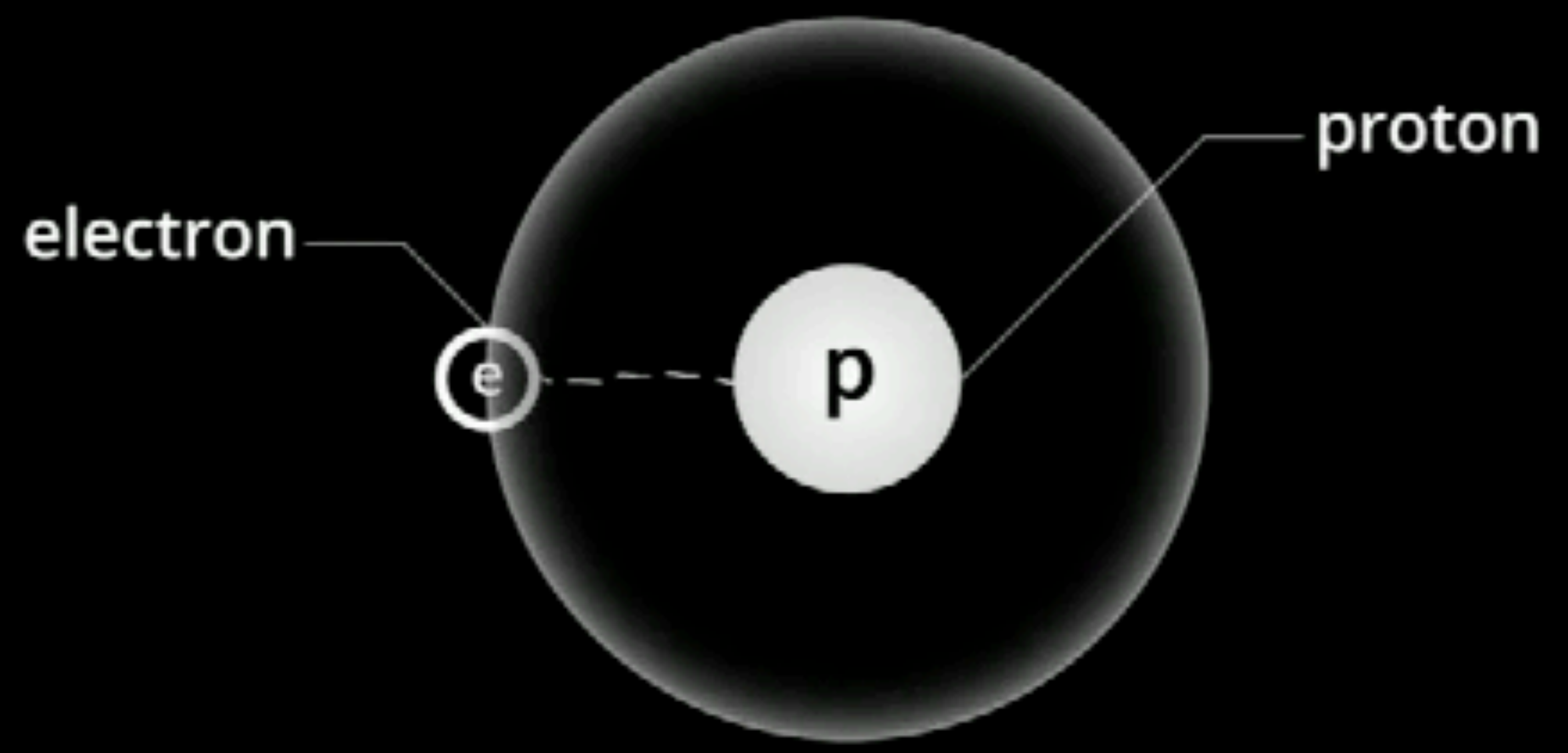
NB: most of mass of proton and neutron comes from other sources

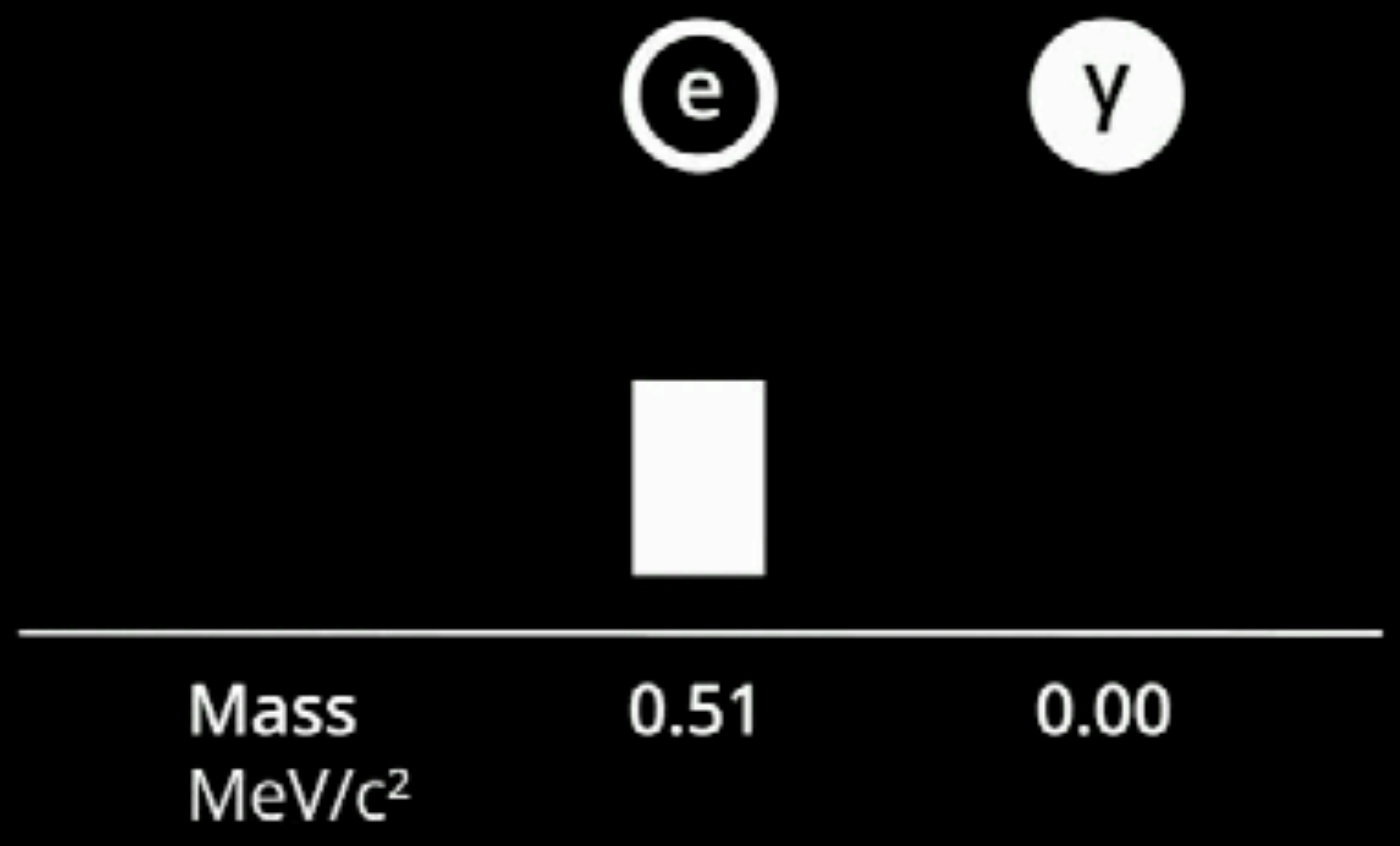


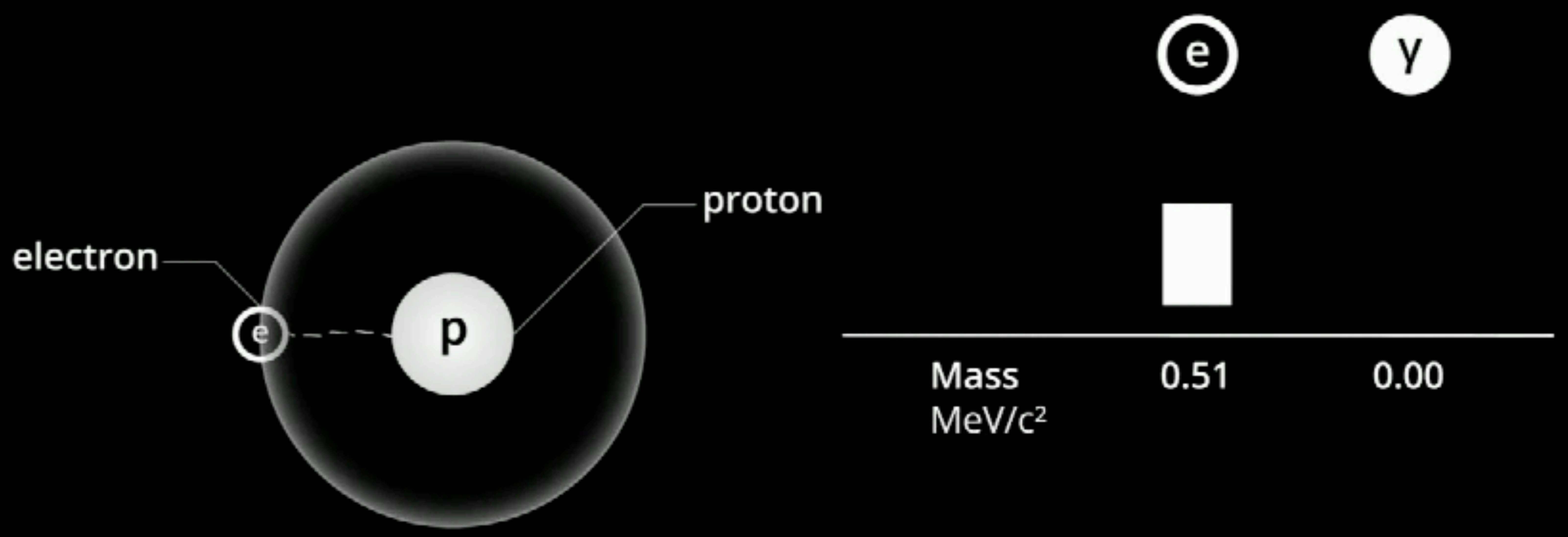


Bohr radius of atom

$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2} = \frac{\hbar}{m_e c \alpha} \propto \frac{1}{y_e}$$






electron
e
p
proton
e
γ
Mass
MeV/c²
0.51
0.00

2.2 MeV **2.2 MeV** 4.7 MeV

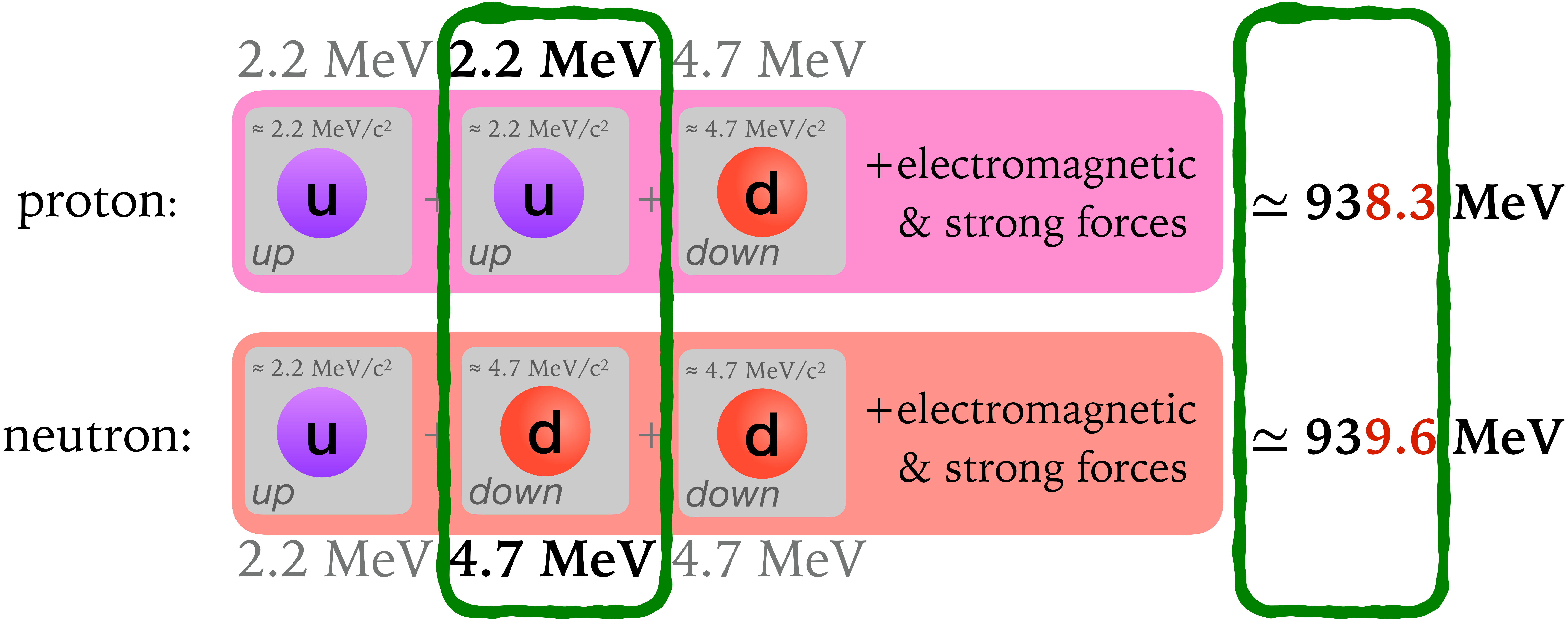
proton: ≈ 2.2 MeV/c^2 **u** *up* + ≈ 2.2 MeV/c^2 **u** *up* + ≈ 4.7 MeV/c^2 **d** *down* +electromagnetic & strong forces $\simeq$ **938.3 MeV**

2.2 MeV **2.2 MeV** 4.7 MeV

proton: ≈ 2.2 MeV/c² u *up* + ≈ 2.2 MeV/c² u *up* + ≈ 4.7 MeV/c² d *down* +electromagnetic & strong forces ≃ **938.3 MeV**

neutron: ≈ 2.2 MeV/c² u *up* + ≈ 4.7 MeV/c² d *down* + ≈ 4.7 MeV/c² d *down* +electromagnetic & strong forces ≃ **939.6 MeV**

2.2 MeV **4.7 MeV** 4.7 MeV


2.2 MeV
2.2 MeV
4.7 MeV
proton:
≈ 2.2 MeV/c²
u
up
≈ 2.2 MeV/c²
u
up
≈ 4.7 MeV/c²
d
down
+electromagnetic
& strong forces
≃ 938.3 MeV
neutron:
≈ 2.2 MeV/c²
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up
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+electromagnetic
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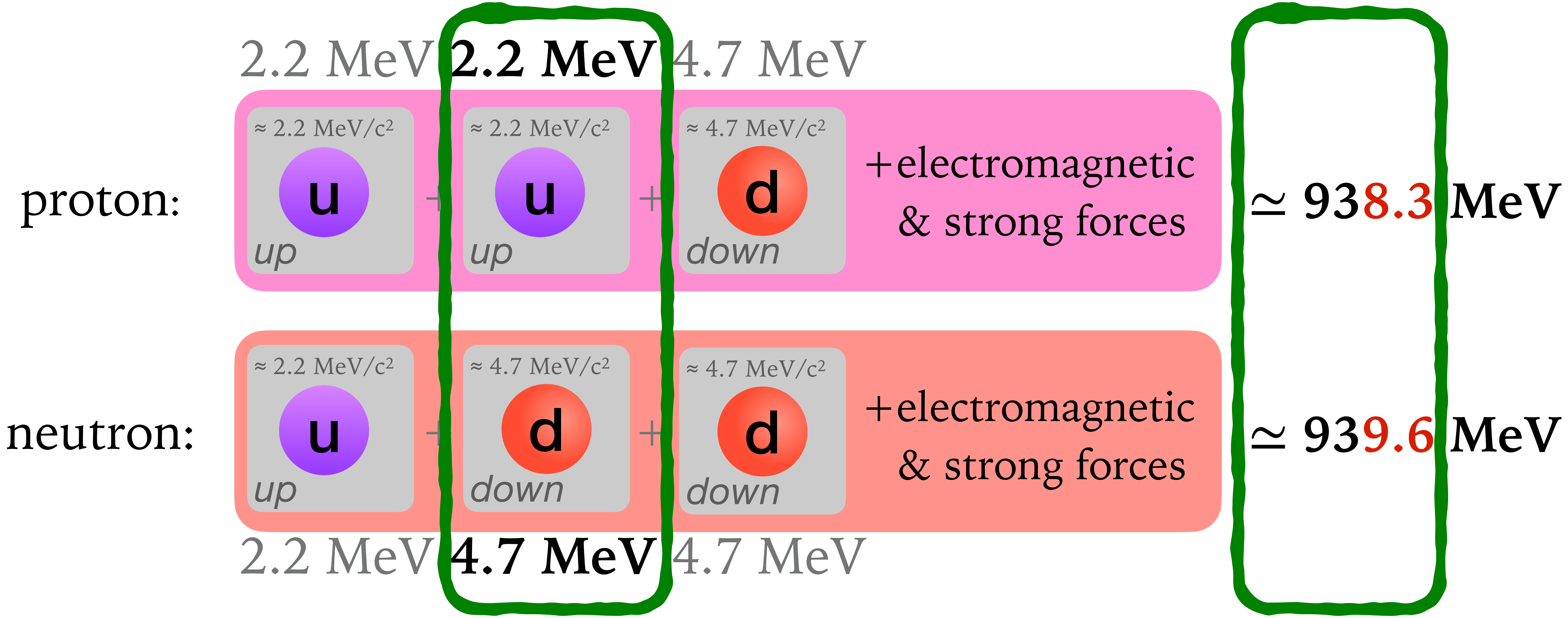
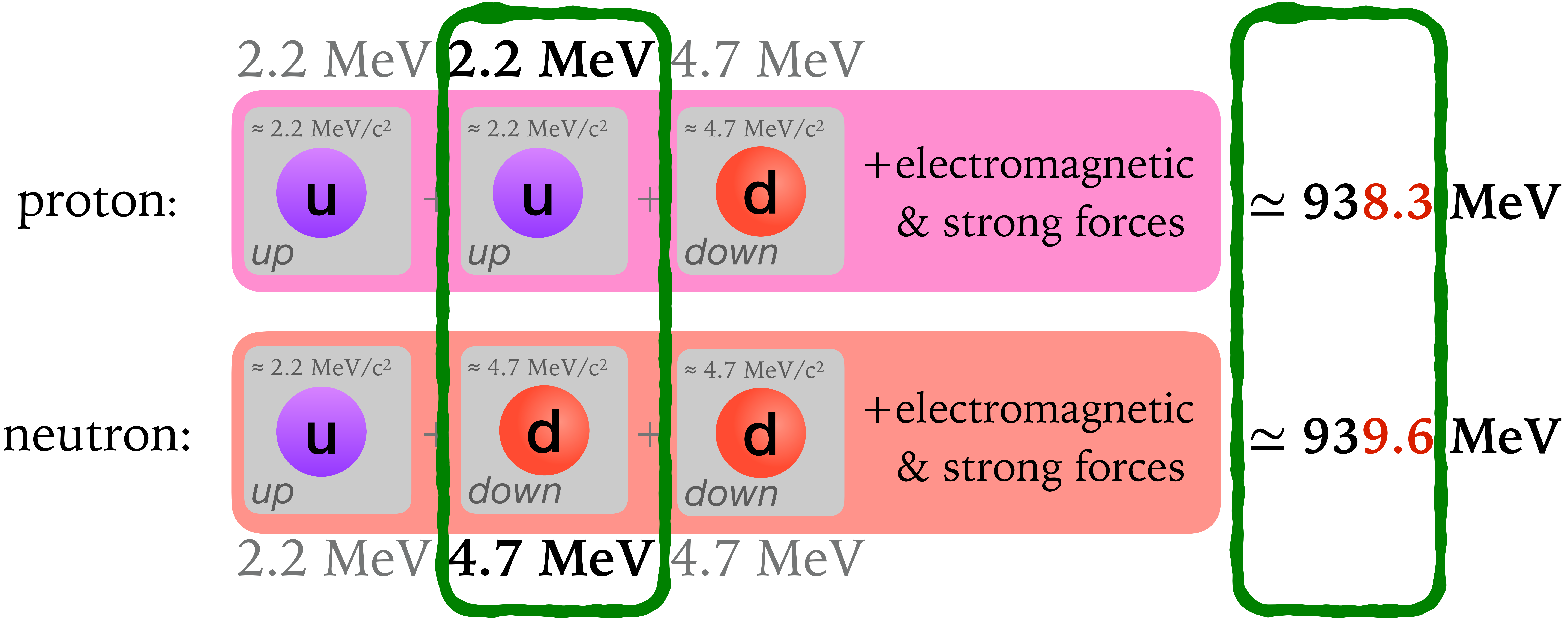


Protons are **lighter** than neutrons→ protons are stable.
Giving us the hydrogen atom, & chemistry and biology as we know it



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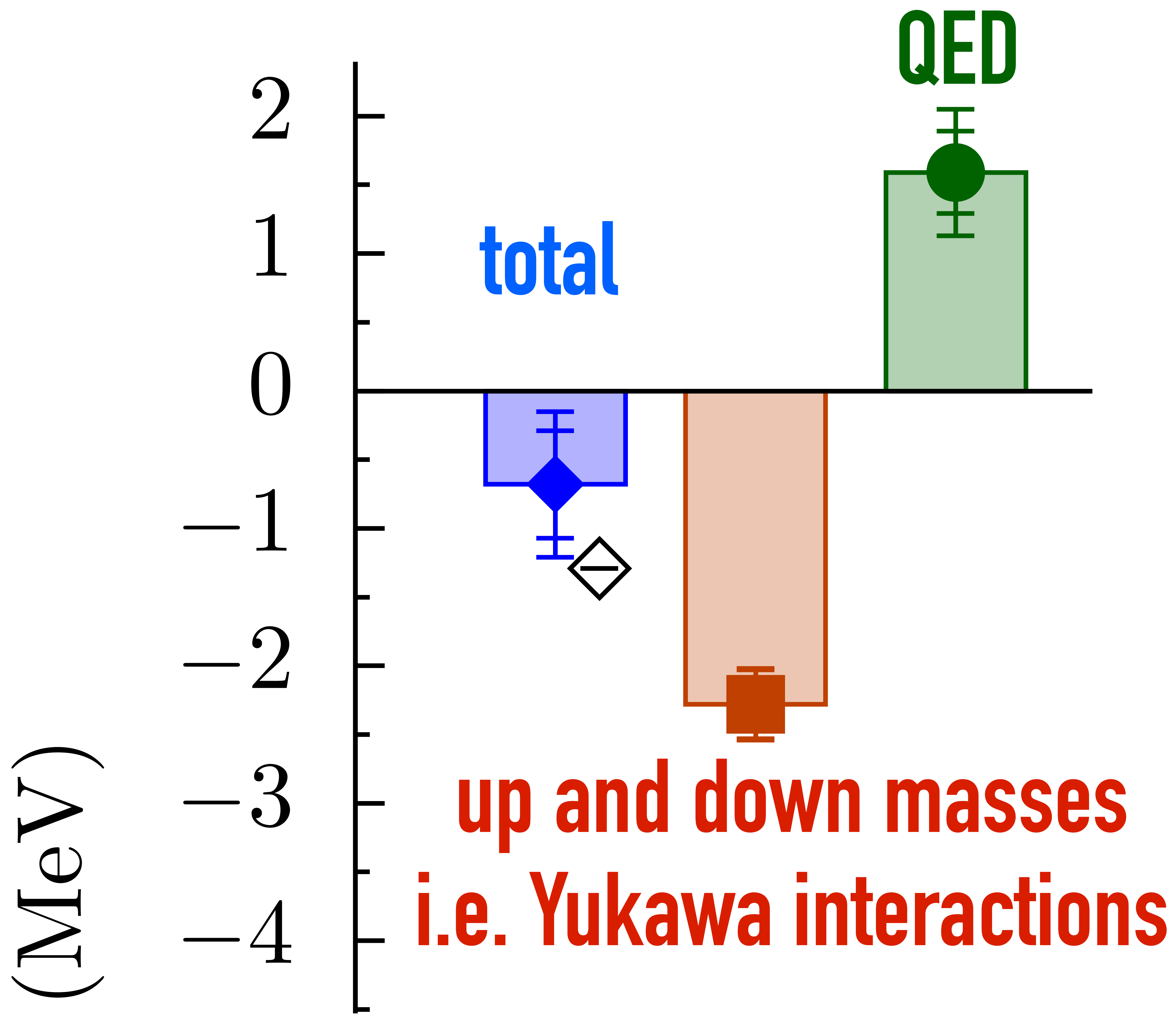
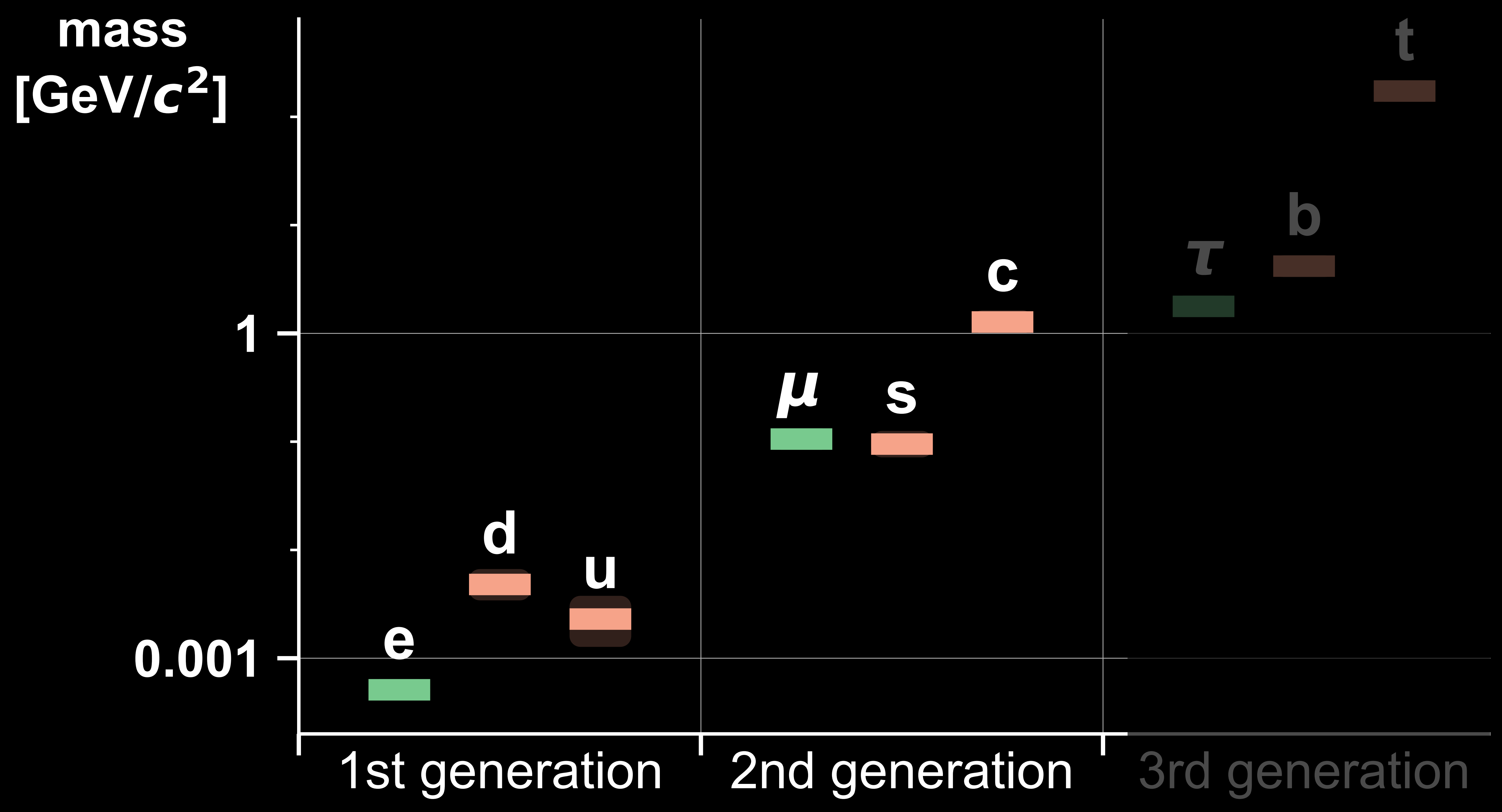
Supposedly because up quarks interact more weakly with the Higgs field than down quarks

proton – neutron mass difference



Lattice calculation
(BMW collab.)
1306.2287
1406.4088

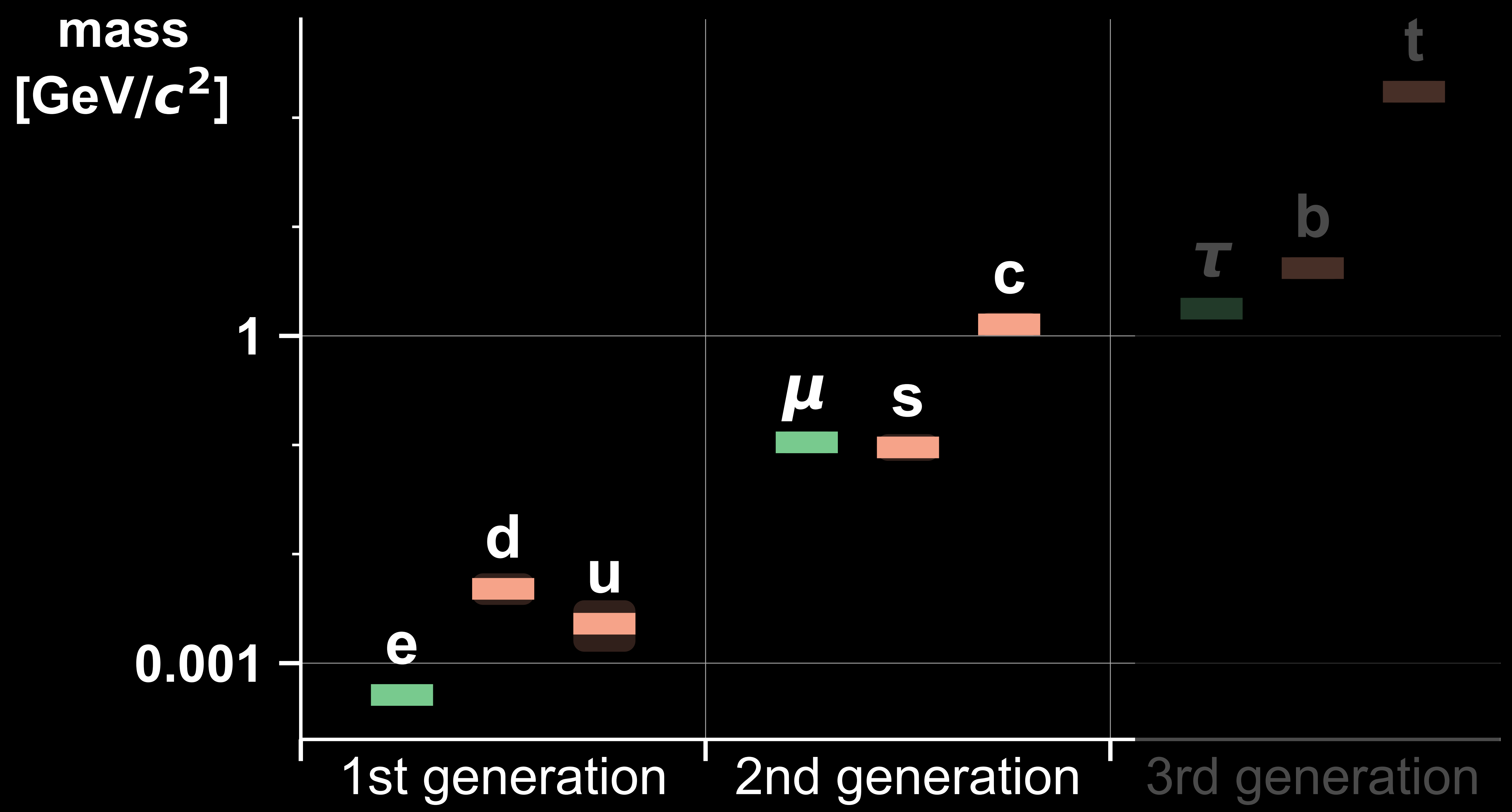
currently we have no evidence that up and down quarks and electron get their masses from Yukawa interactions — it's in textbooks, but is it nature?



a BIG question of particle physics is whether all of these particles acquire their mass in the same way

In SM hypothesis: the lighter the particle, the less it interacts with the Higgs field

→ the more difficult it is establish if it actually gets mass from interactions with the Higgs field



a BIG question of particle physics is whether all of these particles acquire their mass in the same way

[…] cornerstone of Europe's decision-making process for the long-term future of the field

[…] develop a visionary and concrete plan that greatly advances knowledge in fundamental physics through the realisation of the next flagship collider at CERN, and to prioritize alternative options to be pursued if the preferred plan turns out not to be feasible or competitive.

HiLumi
HL-LHC PROJECT

2029–2041

proton–proton
14,000 GeV energy
10× more collisions
than LHC

approved & upgrade under construction

FCC-ee

2045–2060(c.)

electron–positron
91–365 GeV energy
300,000× more
collisions than LEP

[or CEPC@China,
ILC, CLIC, C^3]

FCC-hh

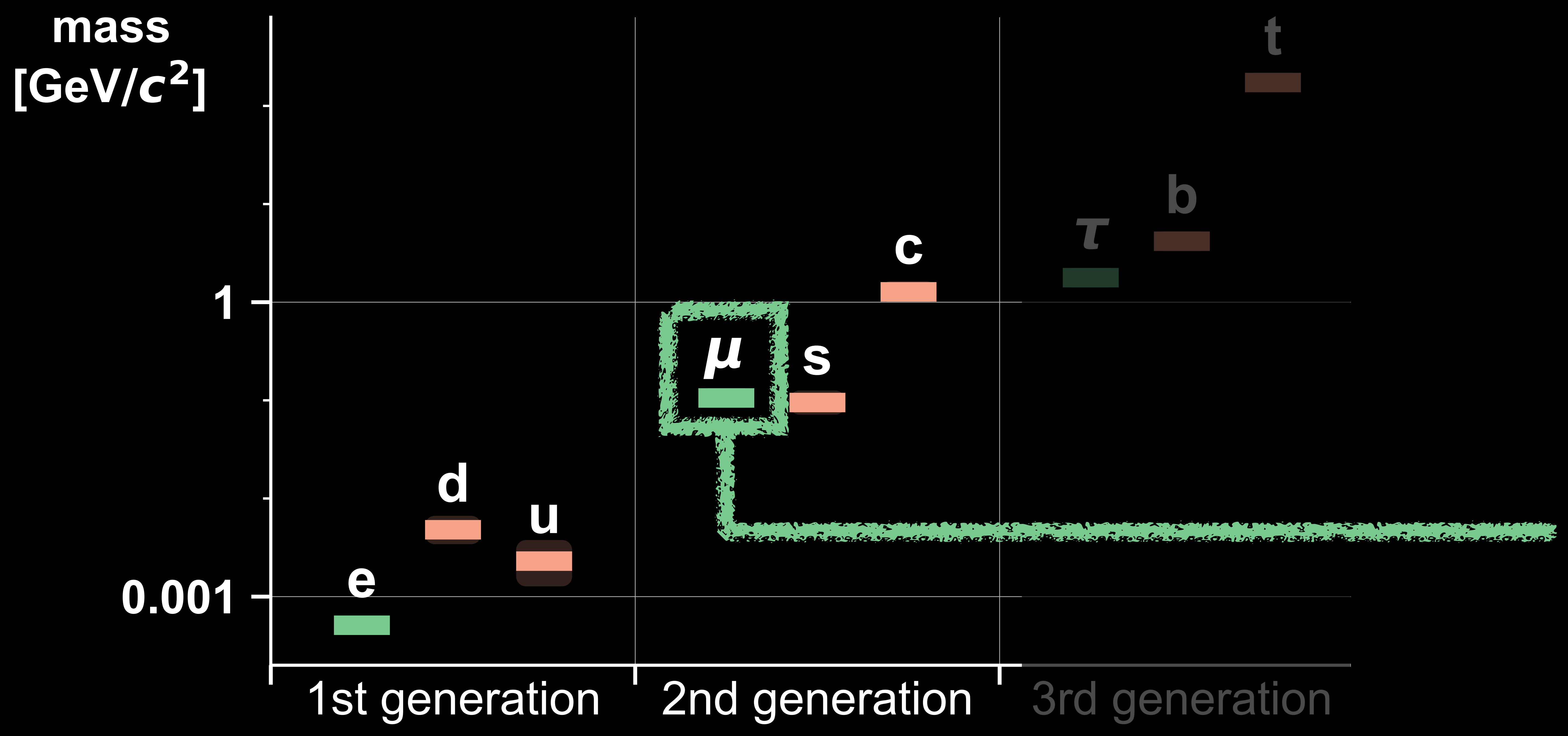
2070–2090(c.)

proton–proton
~100,000 TeV energy
10× more collisions
than HL-LHC

or SppS@China
or muon collider

In SM hypothesis: the lighter the particle, the less it interacts with the Higgs field

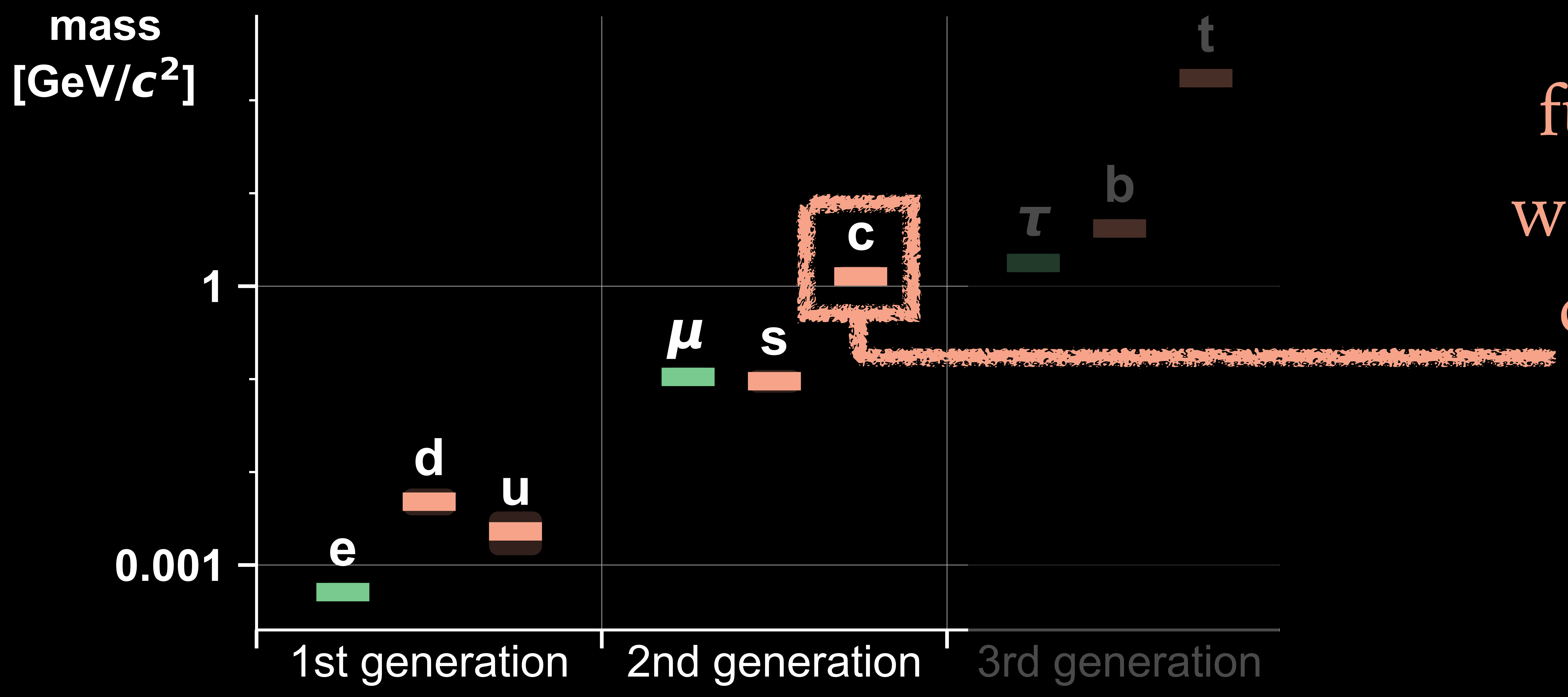
→ the more difficult it is establish if it actually gets mass from interactions with the Higgs field



a major LHC goal of the next years (Run-3 or HL-LHC) will be to establish, for the first time, whether a 2nd generation particle also acquires its mass in the same way

[ATLAS/CMS have first indications, but not yet 5σ]

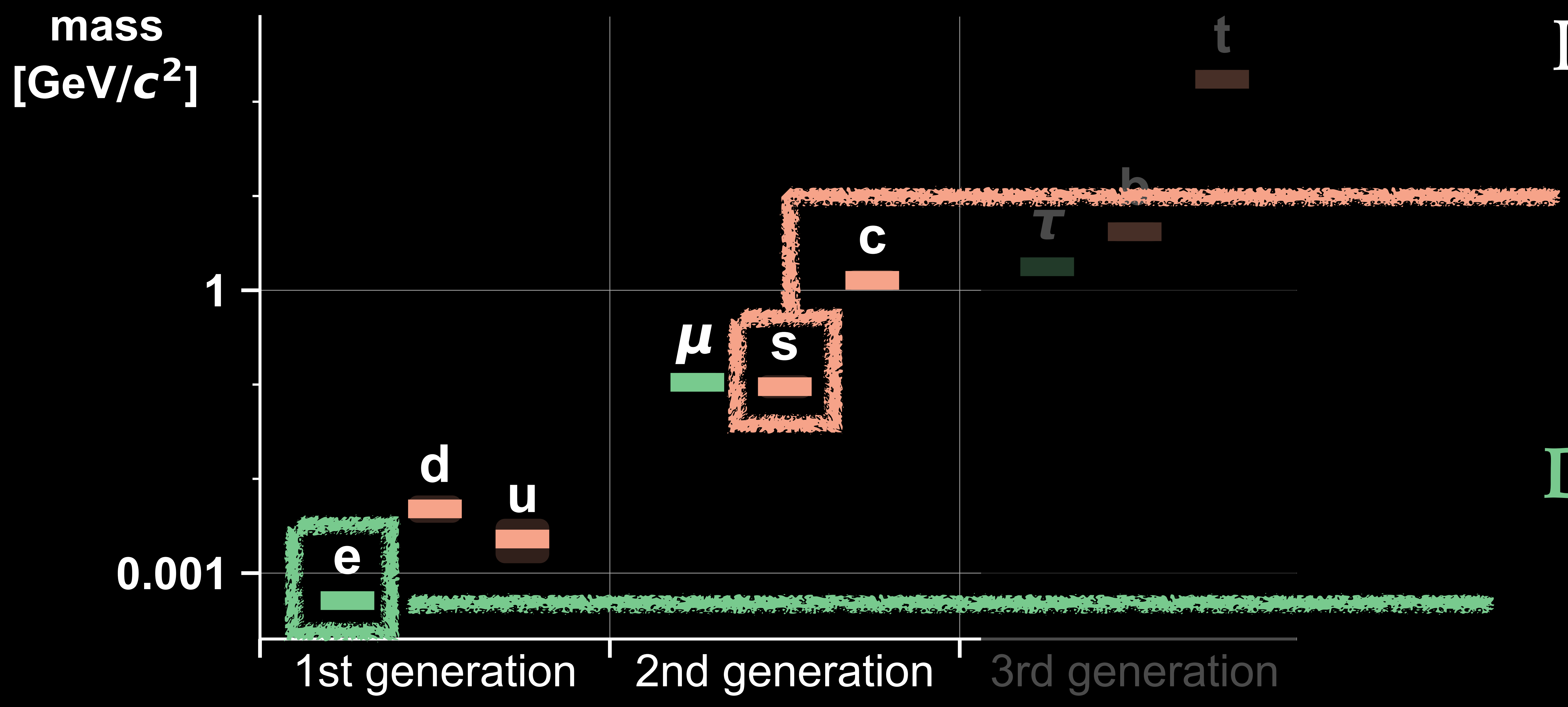
What of future colliders



quarks and yet-lighter particles are much harder

future e^+e^- collider, if built, will clearly establish if charm-quarks get their mass from Higgs-field interactions

What of future colliders



It's becoming clear that strange quark and electron "Yukawas" are just barely at the edge of reach of FCC-ee

Discovering origin of electron mass would be a huge accomplishment

electron Yukawa: see d'Enterria, Poldaru, Wojcik, 2107.02686

desirable features of the next major HEP project(s)?

an important target to be reached ~ guaranteed discovery ?

exploration into the unknown by a significant factor in energy

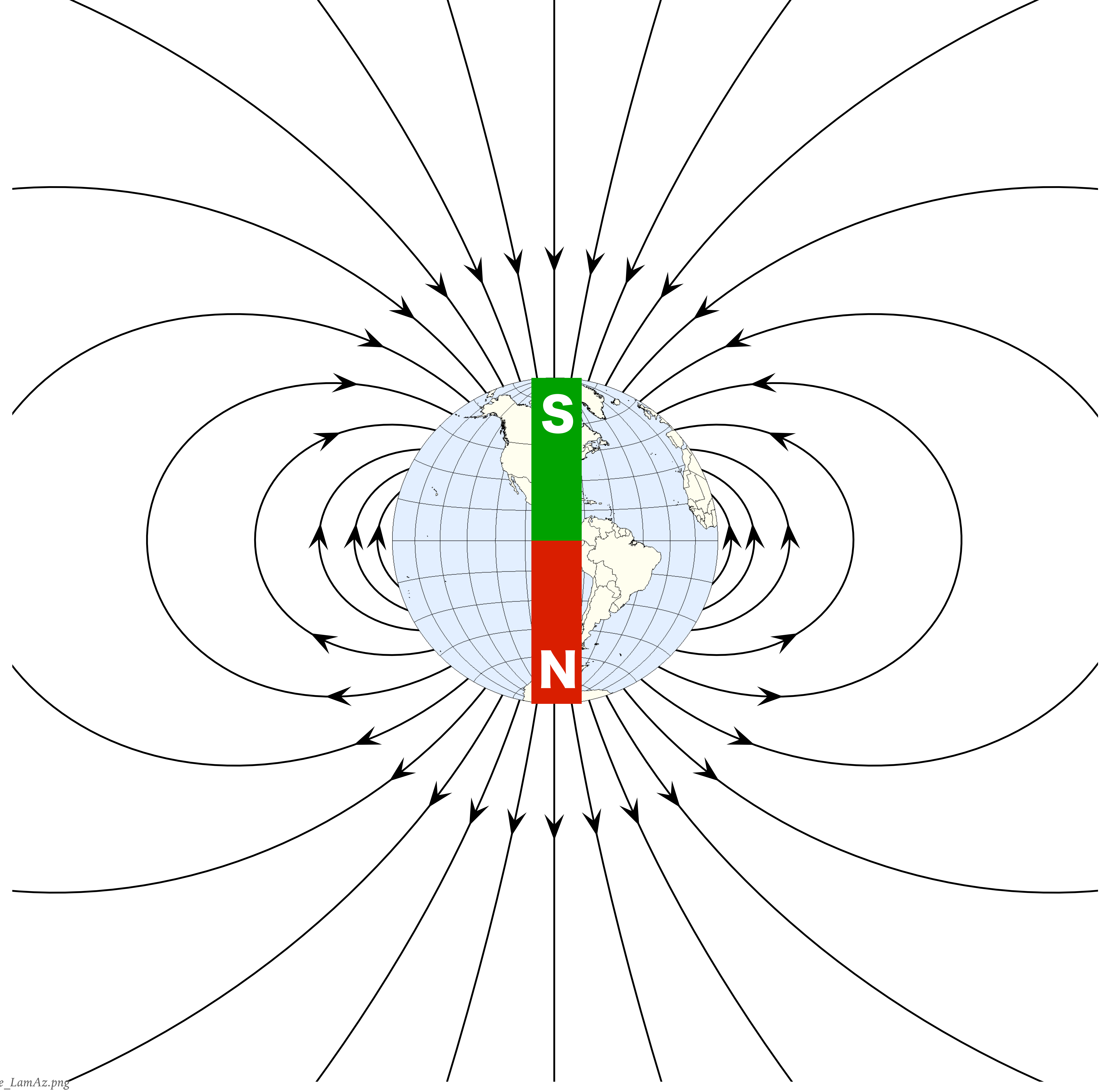
major progress on a broad array of particle physics topics

likelihood of success, robustness (e.g. multiple experiments)

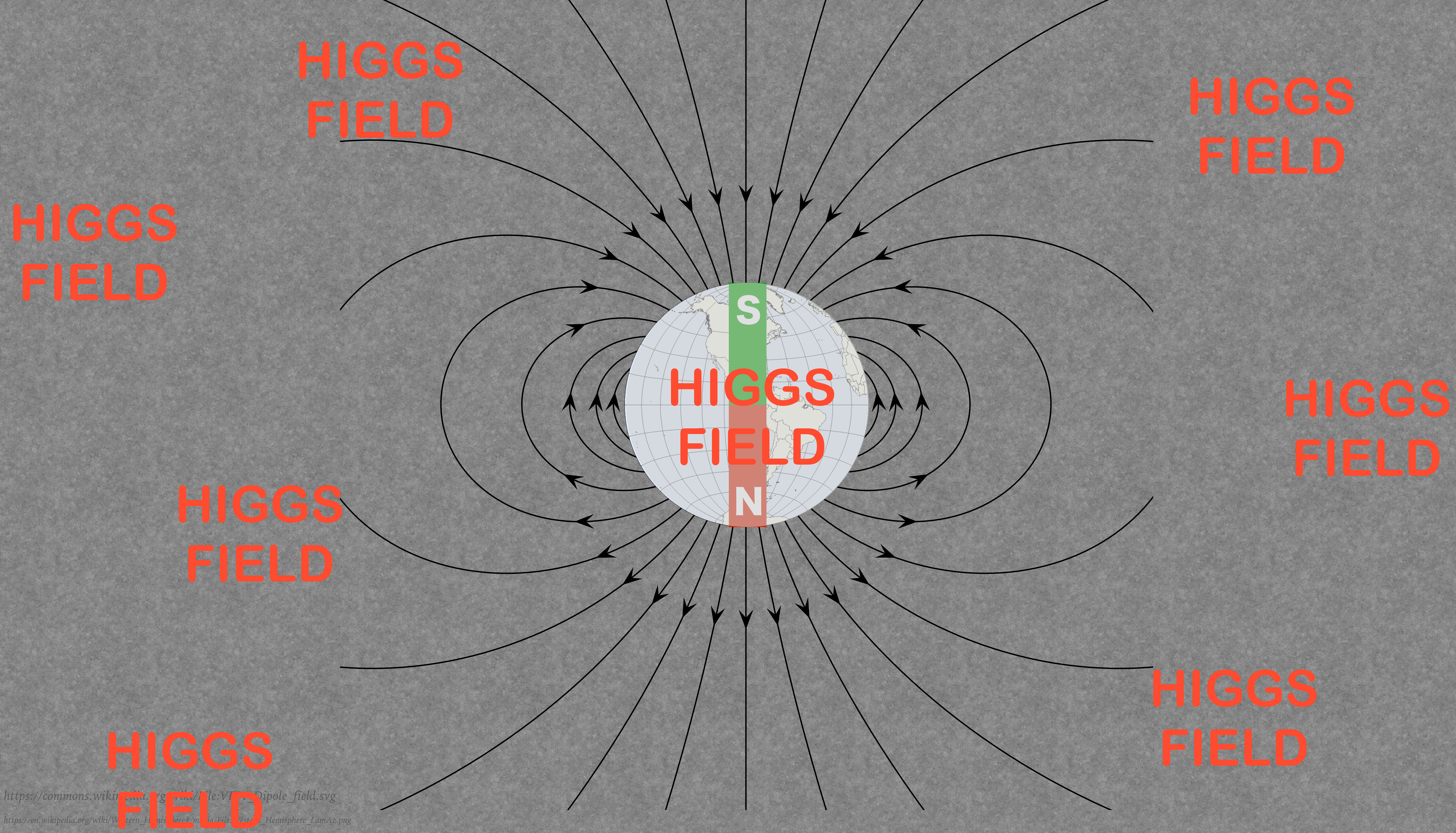
cost-effective construction & operation,
low carbon footprint, novel technologies

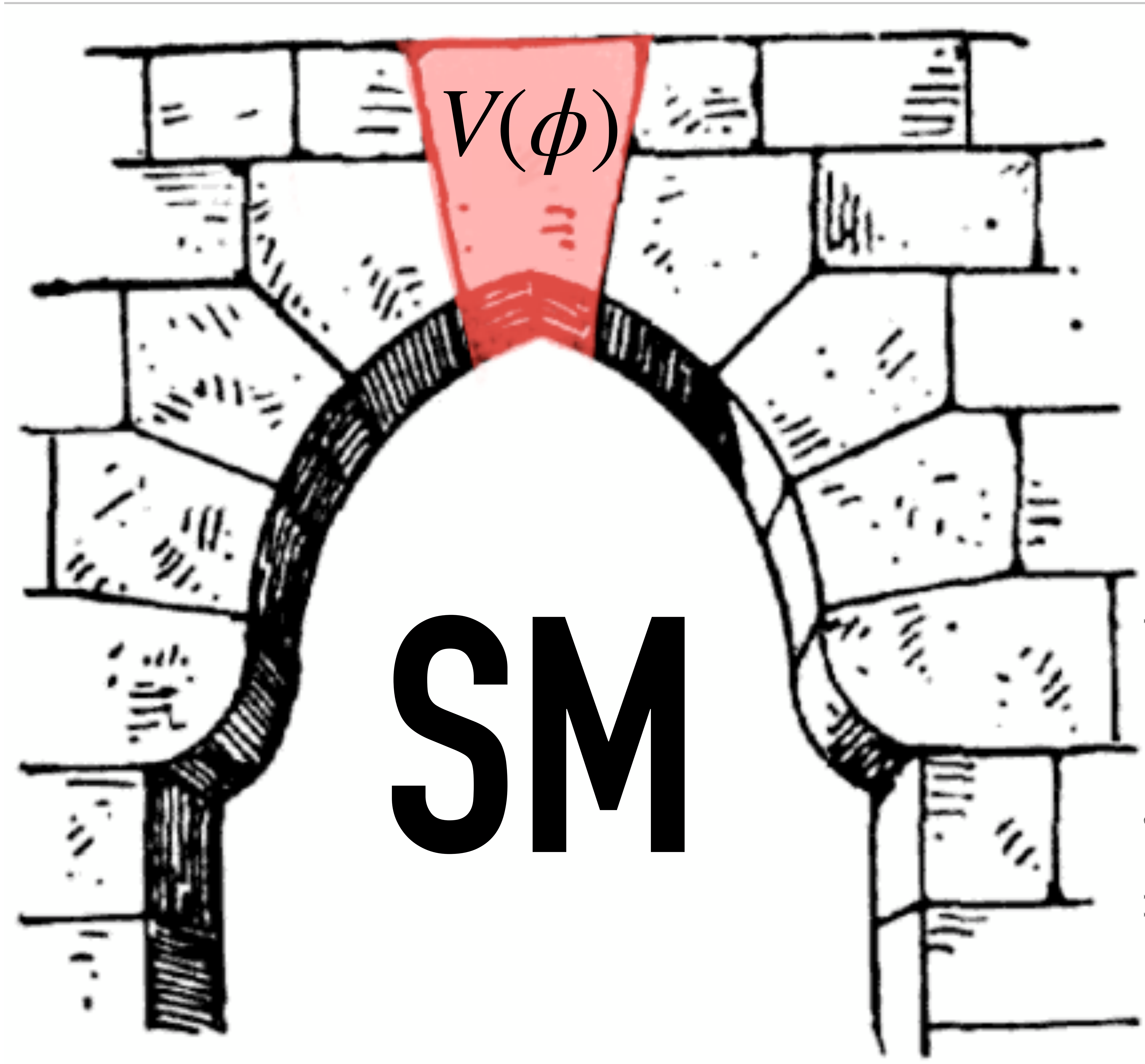
fundamental particles only get mass if the Higgs field is non-zero

Why is the Higgs field non-zero?



https://commons.wikimedia.org/wiki/File:VFPt_Dipole_field.svg
https://en.wikipedia.org/wiki/Western_Hemisphere#/media/File:Western_Hemisphere_LamAz.png


HIGGS FIELD
HIGGS FIELD
HIGGS FIELD
HIGGS FIELD
S
N
HIGGS FIELD
HIGGS FIELD
HIGGS FIELD
HIGGS FIELD



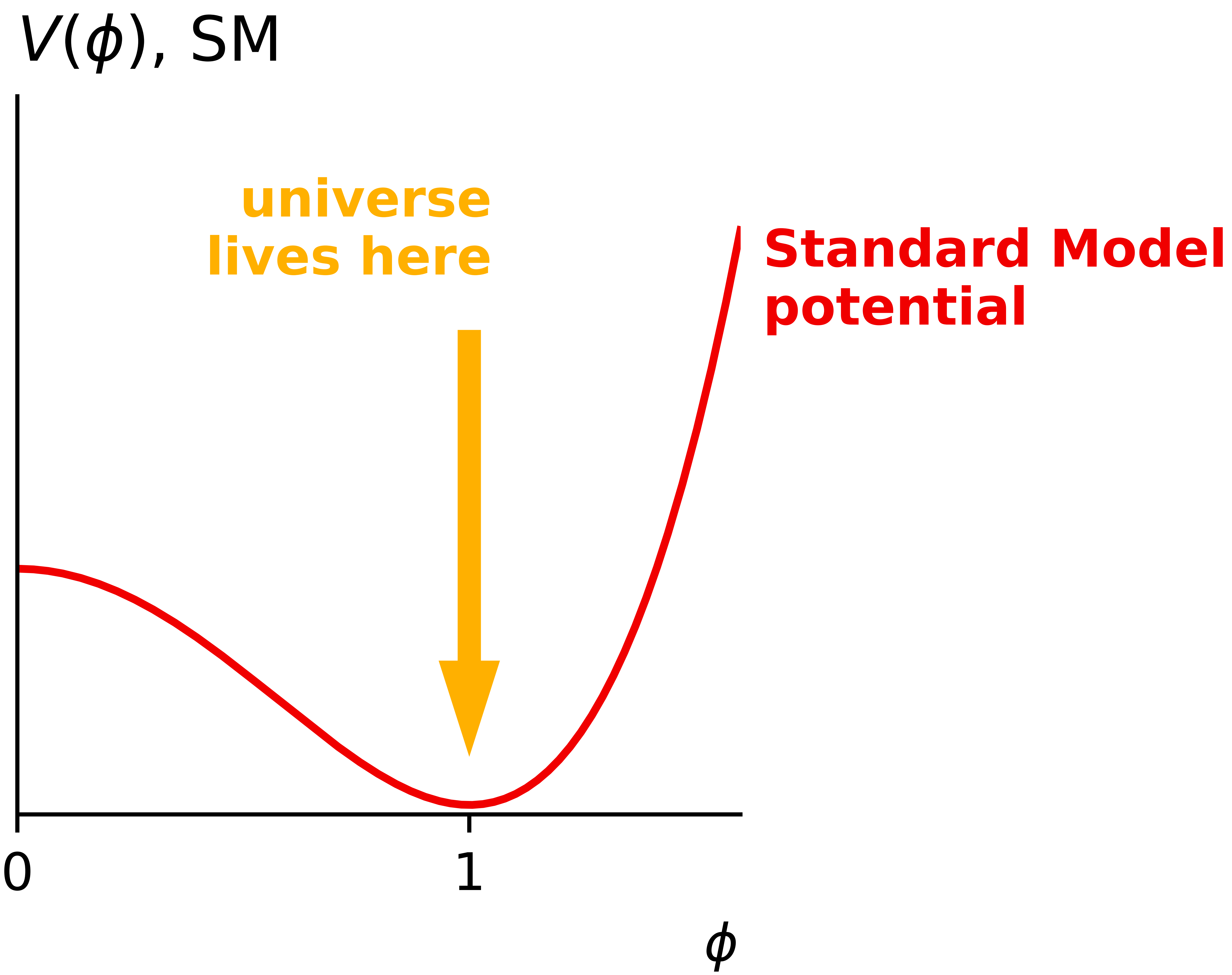
Public Domain, https://commons.wikimedia.org/w/index.php?curid=9502309

unique among all the fields we know, the Higgs field is the only one that is non-zero "classically"

Why?
Higgs potential?

Keystone of SM

Higgs potential

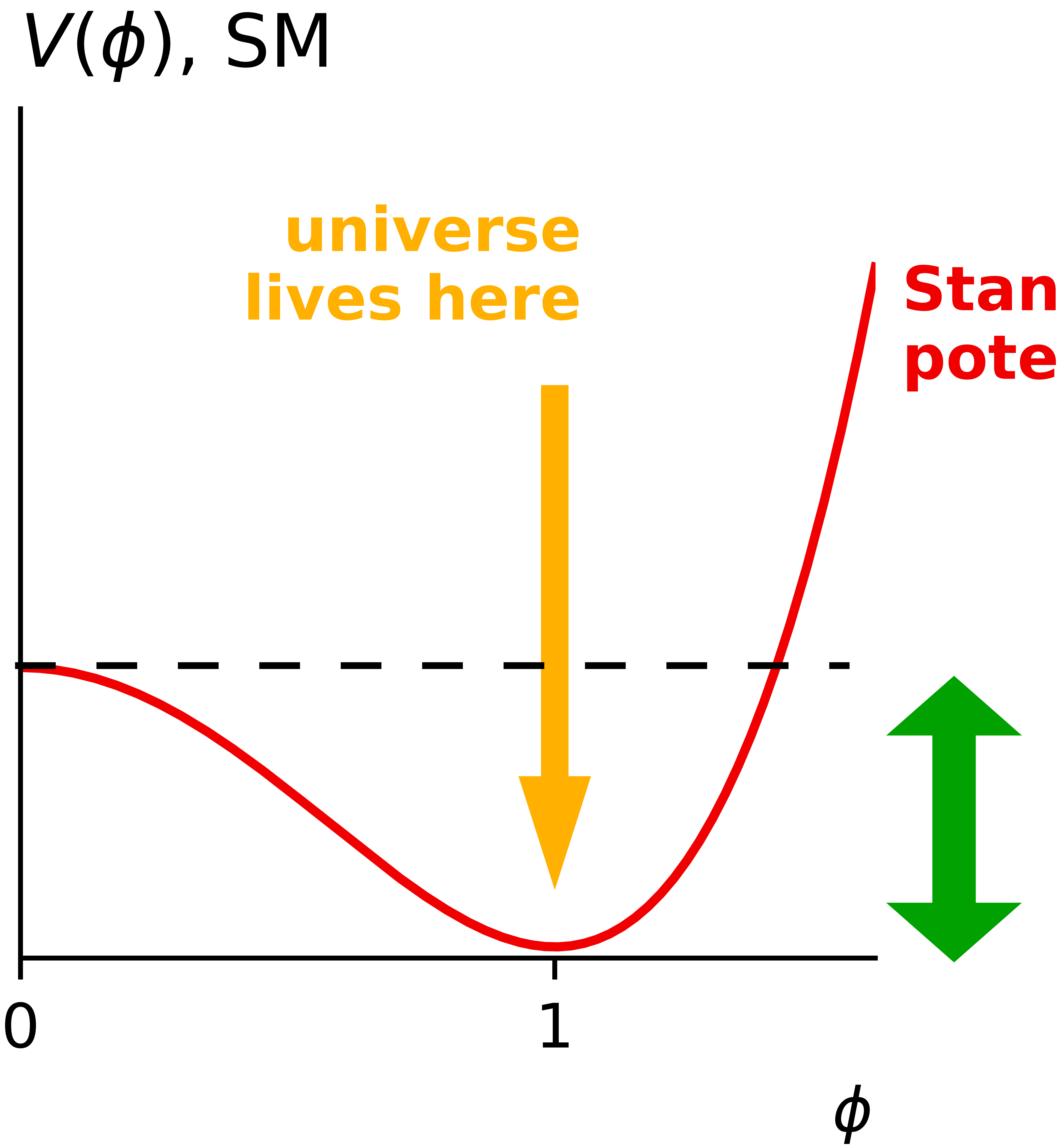


The Higgs field is non-zero because that ensures the lowest potential energy

The SM proposes a very specific form for the potential as a function of the Higgs field

$$V(\phi) \sim -\mu^2\phi^2 + \lambda\phi^4$$

Higgs potential — remember: it's an energy density



Corresponds to an energy density of
1.5×10^{10} GeV/fm^3

$E = mc^2 \rightarrow$ Mass density of 2.6×10^{28} kg/m^3
i.e. >**40 billion times nuclear density**

https://en.wikipedia.org/wiki/Globe#/media/File:World_Globe_Map.jpg
https://en.wikipedia.org/wiki/Old_fashioned_glass#/media/File:Old_Fashioned_Glass.jpg
Harder Stadium, photo from google street view,terms say OK to
“publicly display content with proper attribution online, in video, and in print.”

https://en.wikipedia.org/wiki/Globe#/media/File:World_Globe_Map.jpg
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Harder Stadium, photo from google street view,terms say OK to
“publicly display content with proper attribution online, in video, and in print.”

Earth at neutron star density

https://en.wikipedia.org/wiki/Globe#/media/File:World_Globe_Map.jpg
https://en.wikipedia.org/wiki/Old_fashioned_glass#/media/File:Old_Fashioned_Glass.jpg
Harder Stadium, photo from google street view,terms say OK to
"publicly display content with proper attribution online, in video, and in print."

Earth at neutron star density

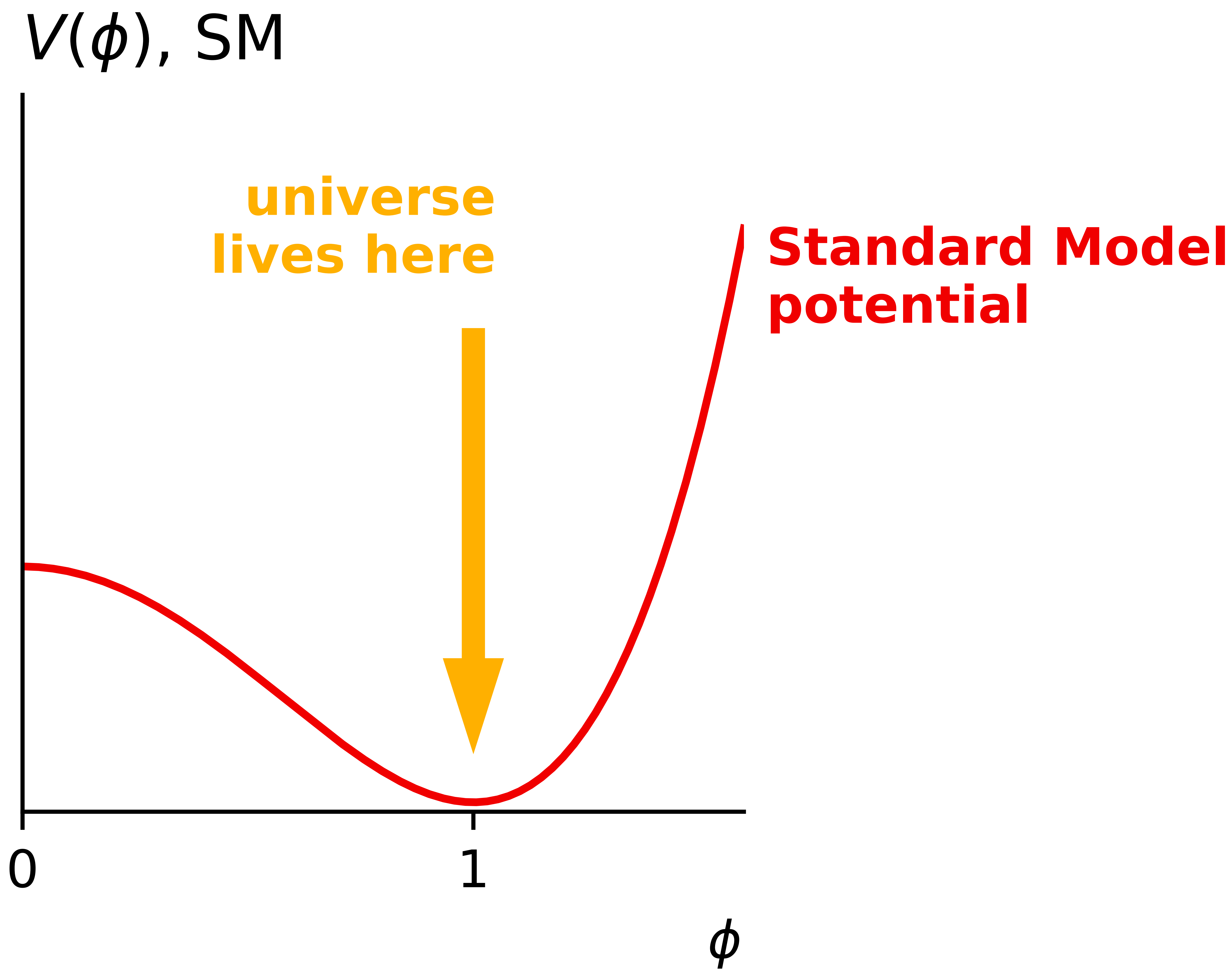
Earth at Higgs potential density


g
g
H
λ3
H
H
luon
gluo
Φ
y
x
Higgs field in space


g
g
H
λ3
H
H
luon
gluo
Φ
y
x
Higgs field in space

g
g
H
λ_3
H
H
luon
gluo
Φ
y
x
Higgs field in space

Higgs potential

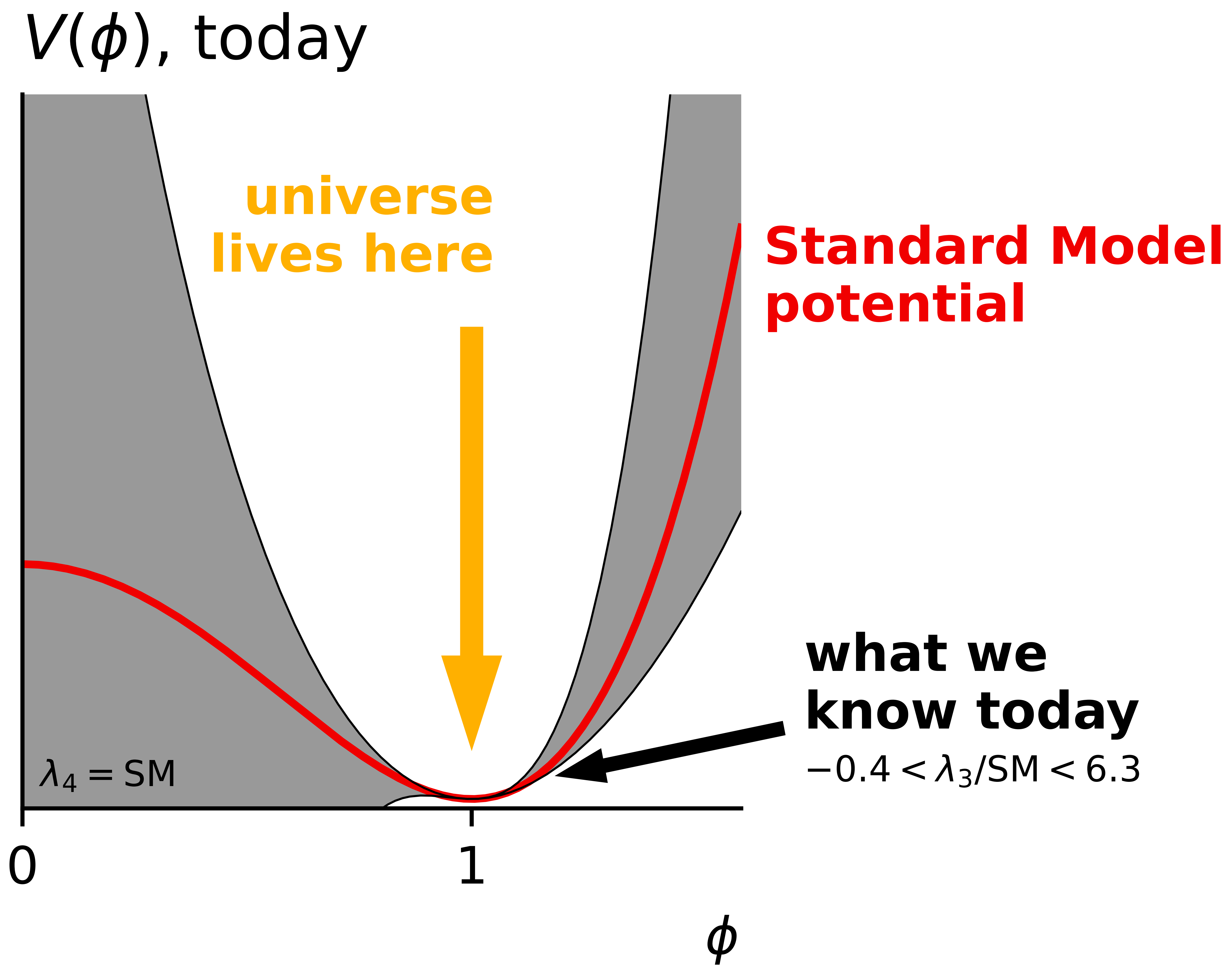


Studying H→HH probes specific mathematical property of the potential's shape:

its third derivative (λ_3), i.e. how asymmetric it is at the minimum

[reconstruction in plot assumes higher derivatives as in SM]

Higgs potential



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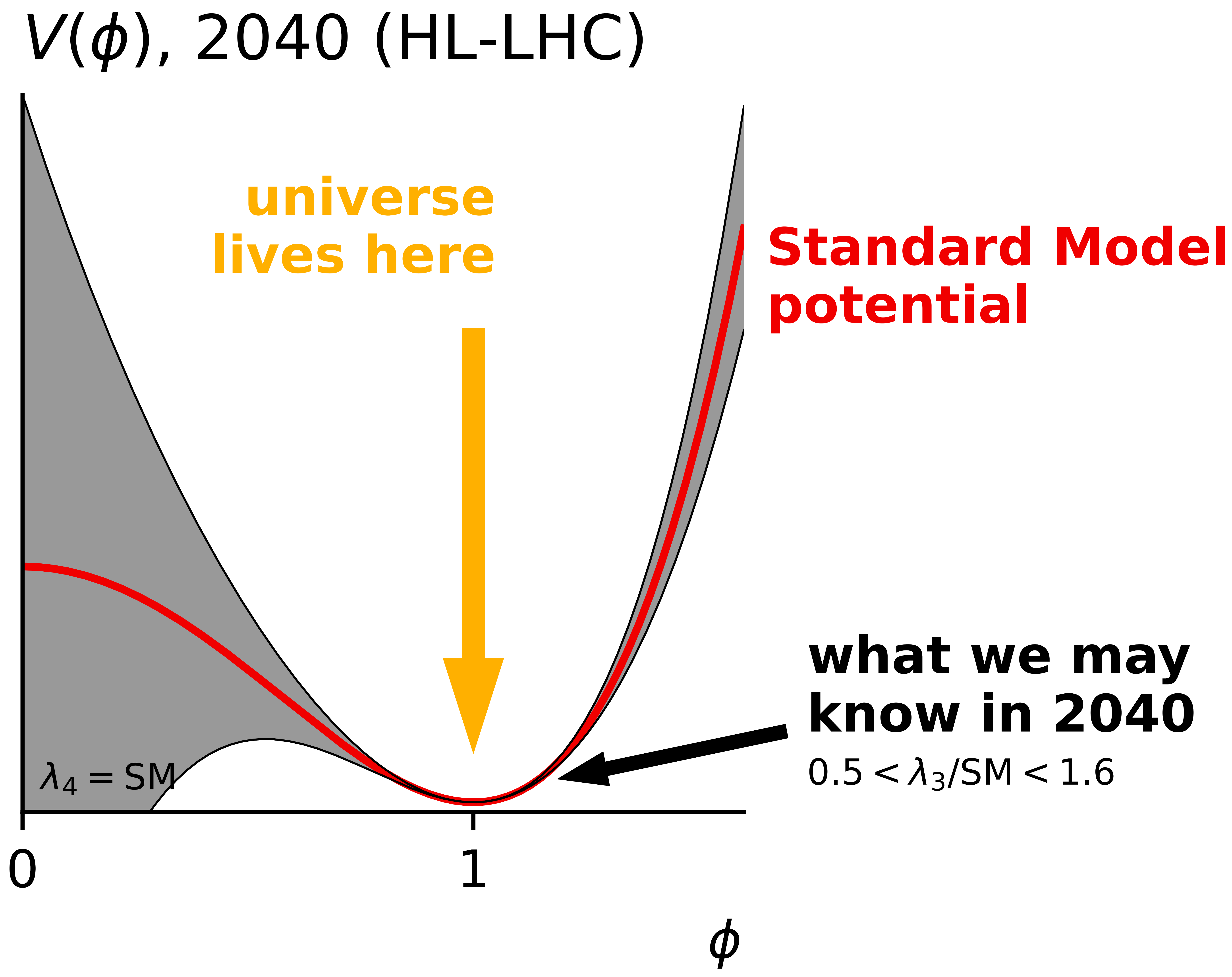
Higgs potential



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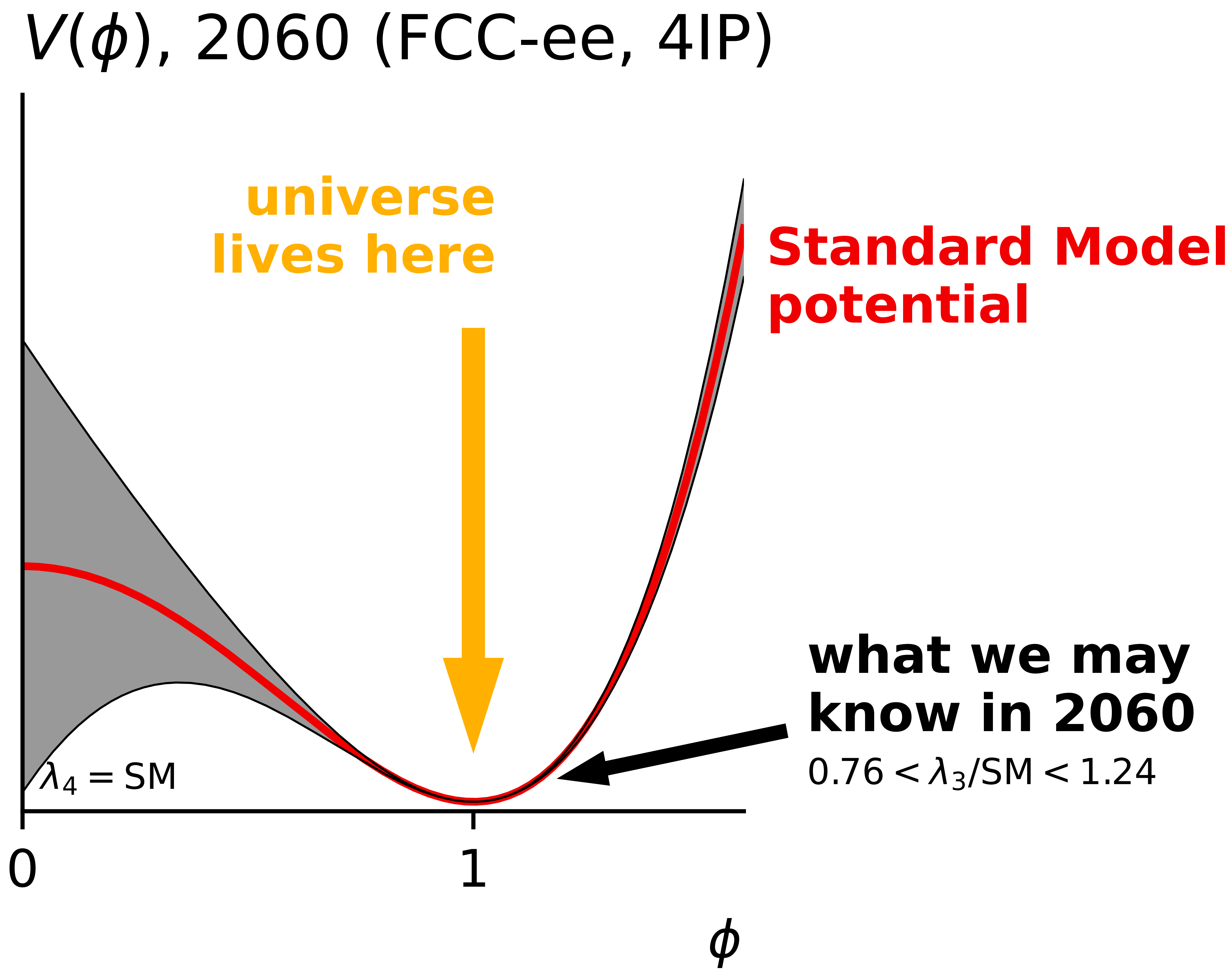


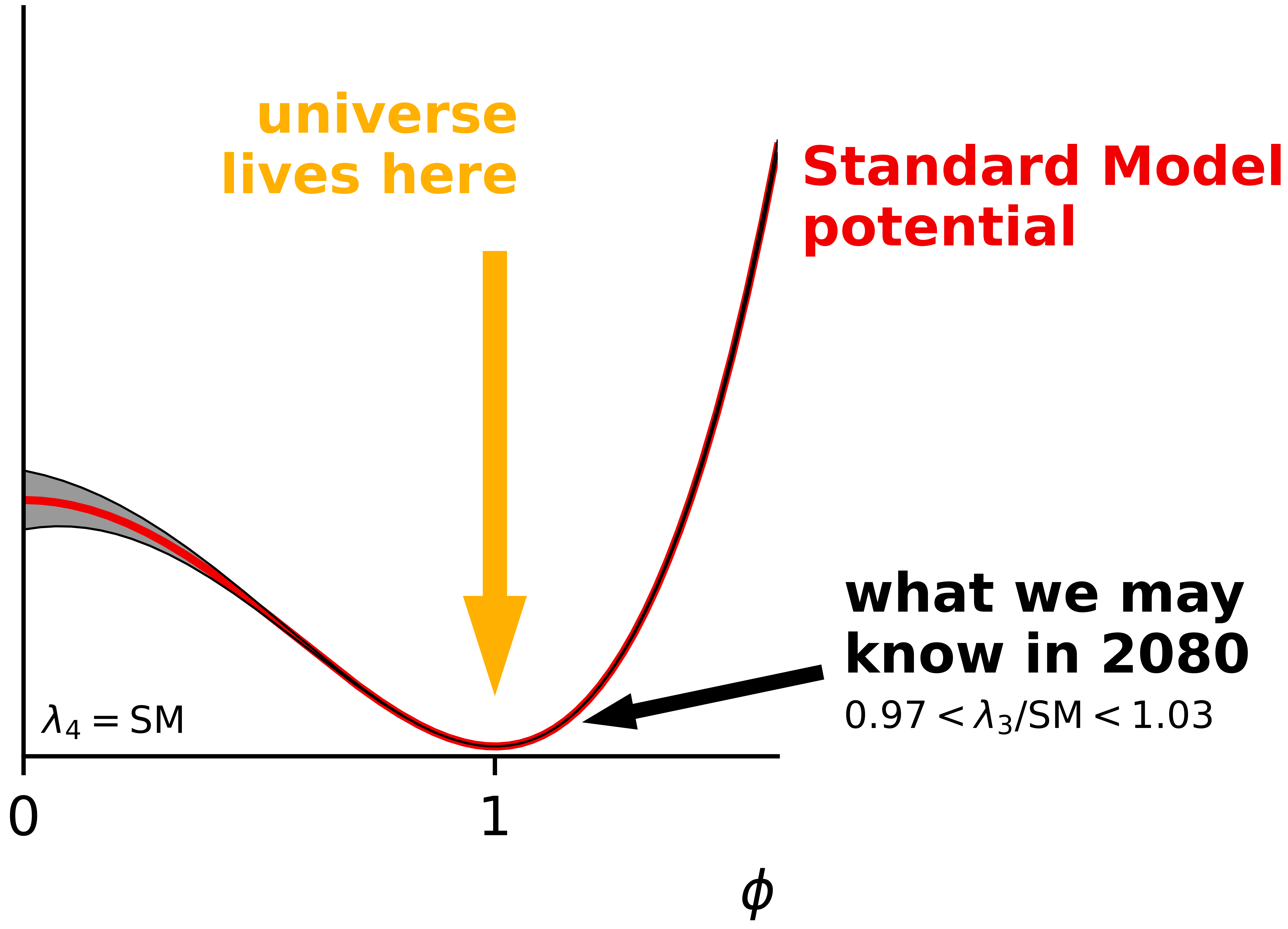
Studying H→HH probes specific mathematical property of the potential's shape:

its third derivative (λ_3), i.e. how asymmetric it is at the minimum

[reconstruction in plot assumes higher derivatives as in SM]

Higgs potential

$V(\phi)$, 2080 (FCC-hh)



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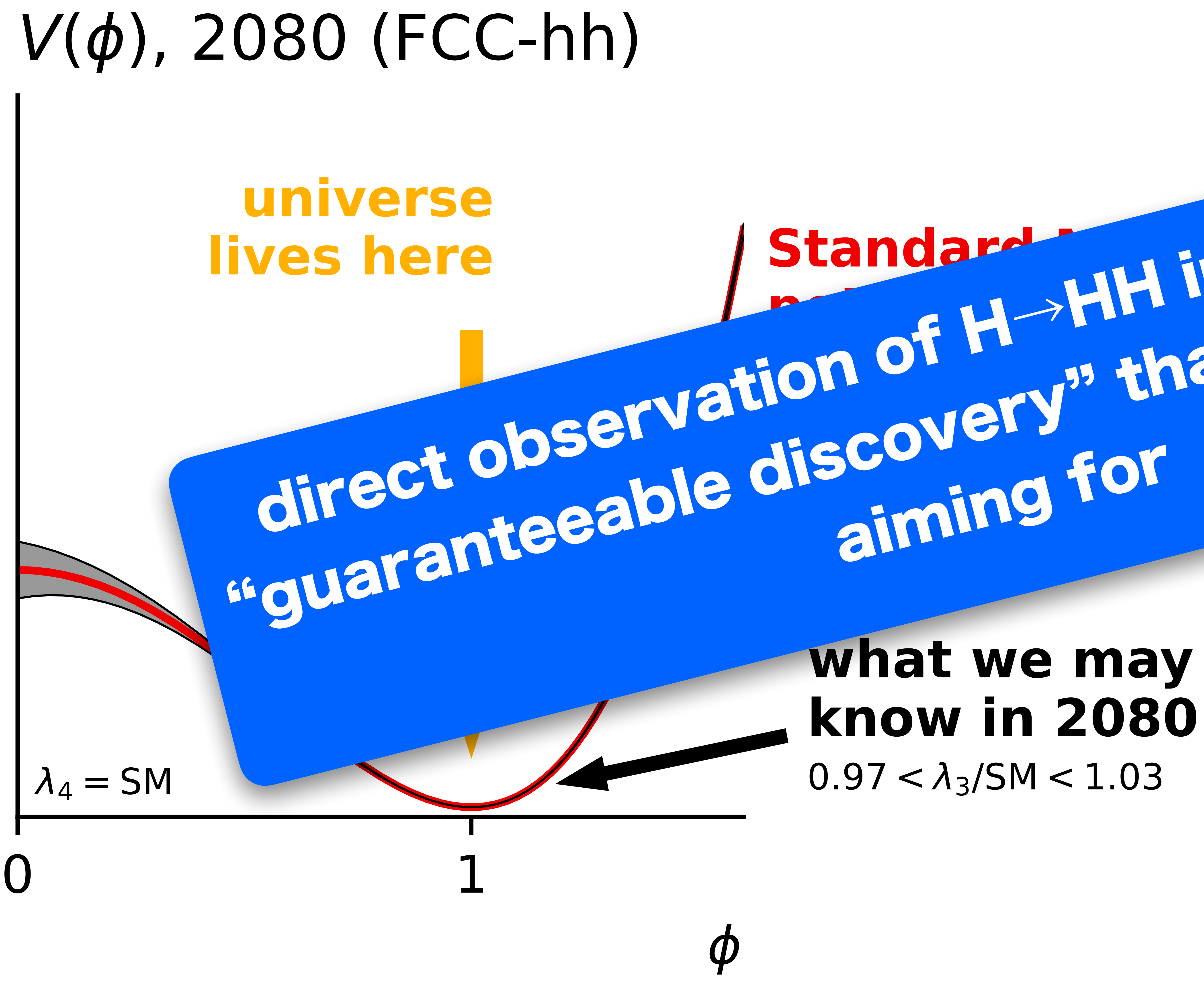
Higgs potential



Studying H→HH probes ... tical property ... l's shape: ... ive (λ_3), ... metric it is at the minimum

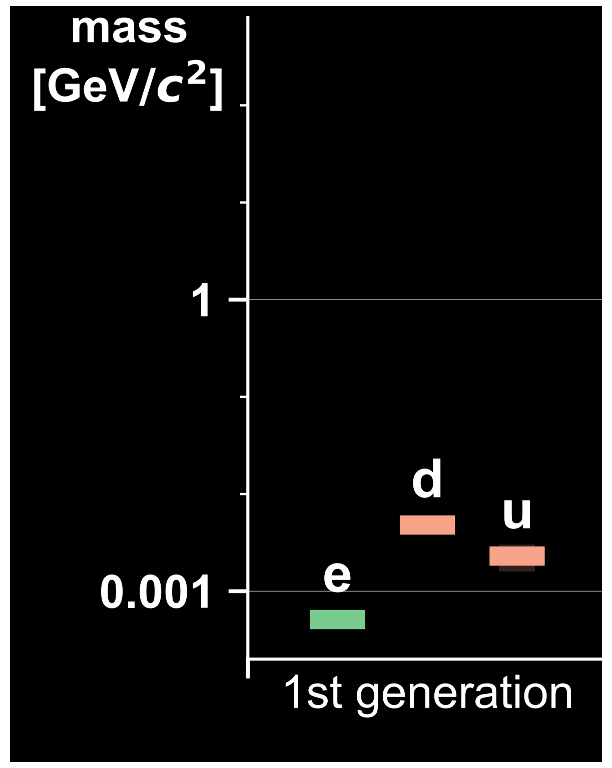
direct observation of H→HH interaction is a "guaranteeable discovery" that HEP should be aiming for

[reconstruction in plot assumes higher derivatives as in SM]

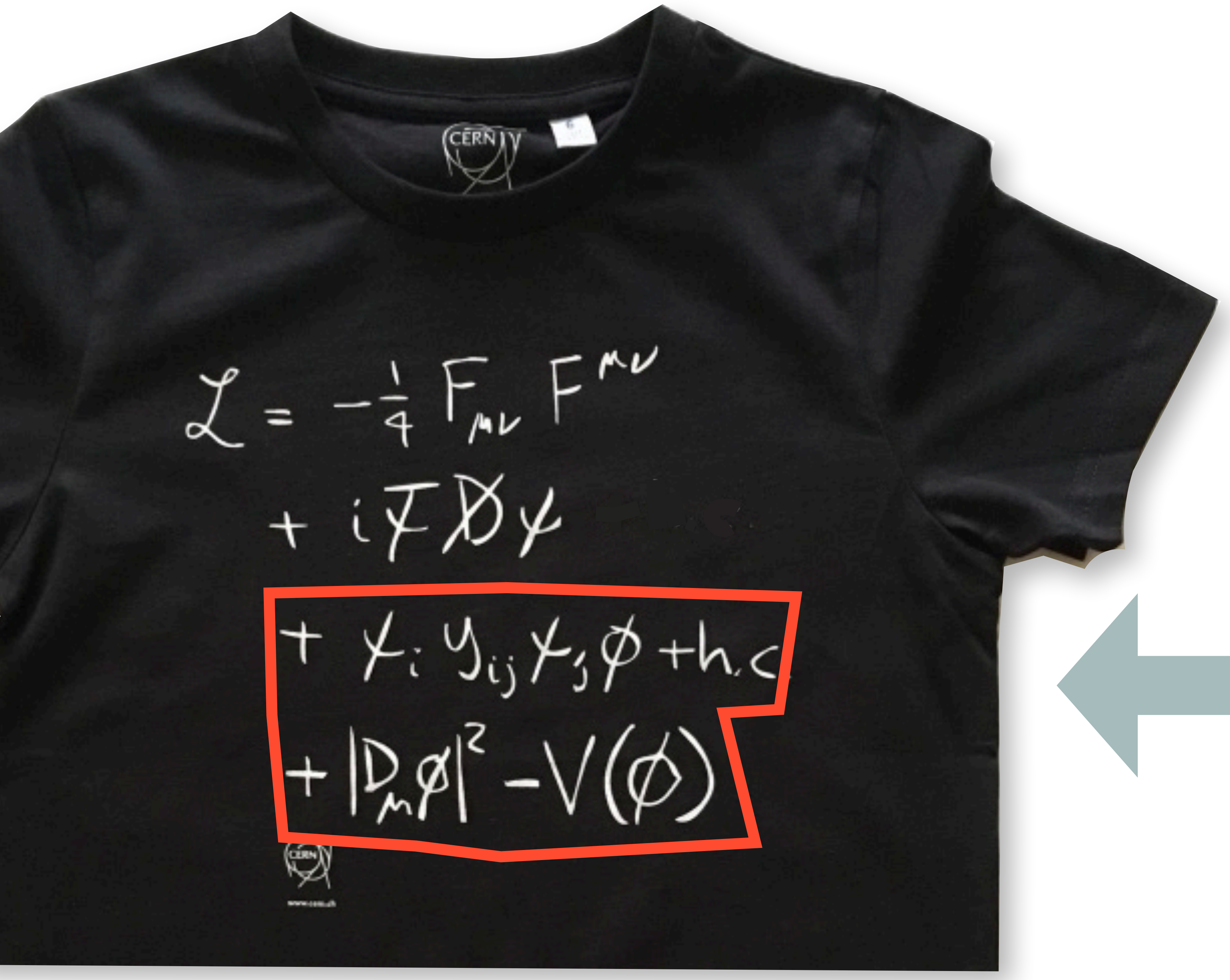
Almost every problem of the Standard Model originates from Higgs interactions

$$\mathscr{L} = y H \psi \bar{\psi} + \mu^2 |H|^2 - \lambda |H|^4 - V_0$$

flavour *naturalness* *stability* *cosmological constant*

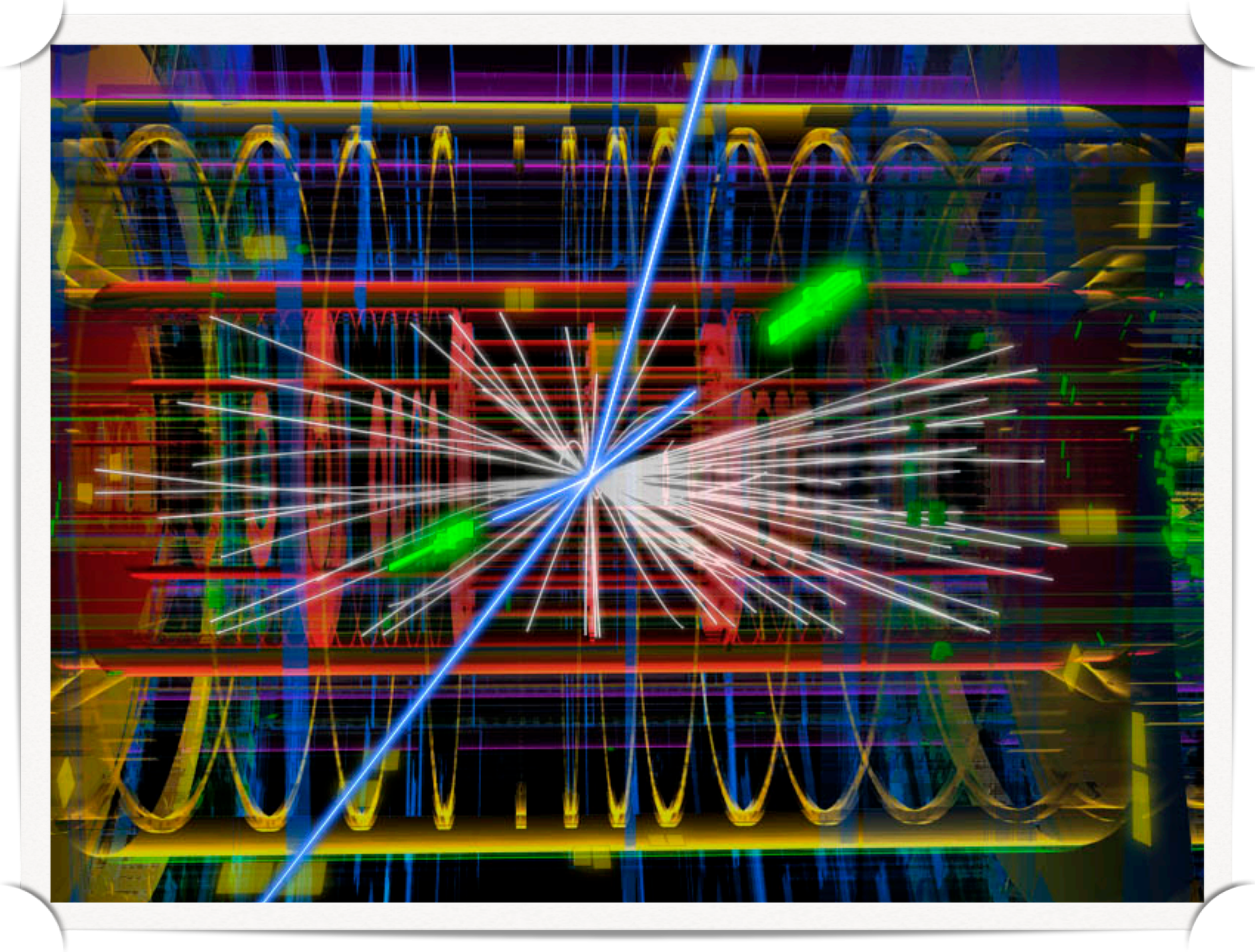


UNDERLYING THEORY



how do you make quantitative connection?

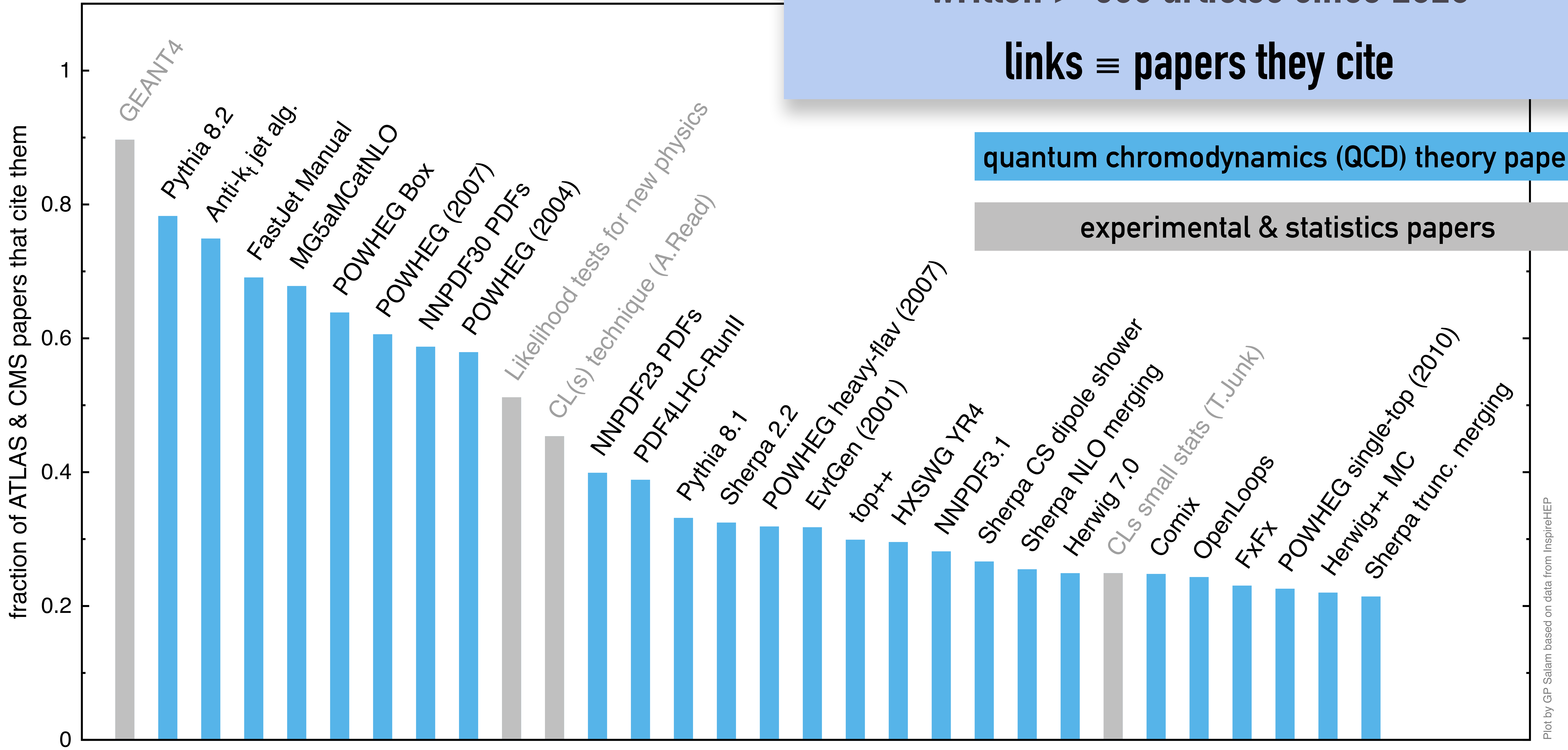
EXPERIMENTAL DATA



Lagrangian ↔ data

ATLAS and CMS (big LHC expts.) have written > 800 articles since 2020

links ≡ papers they cite



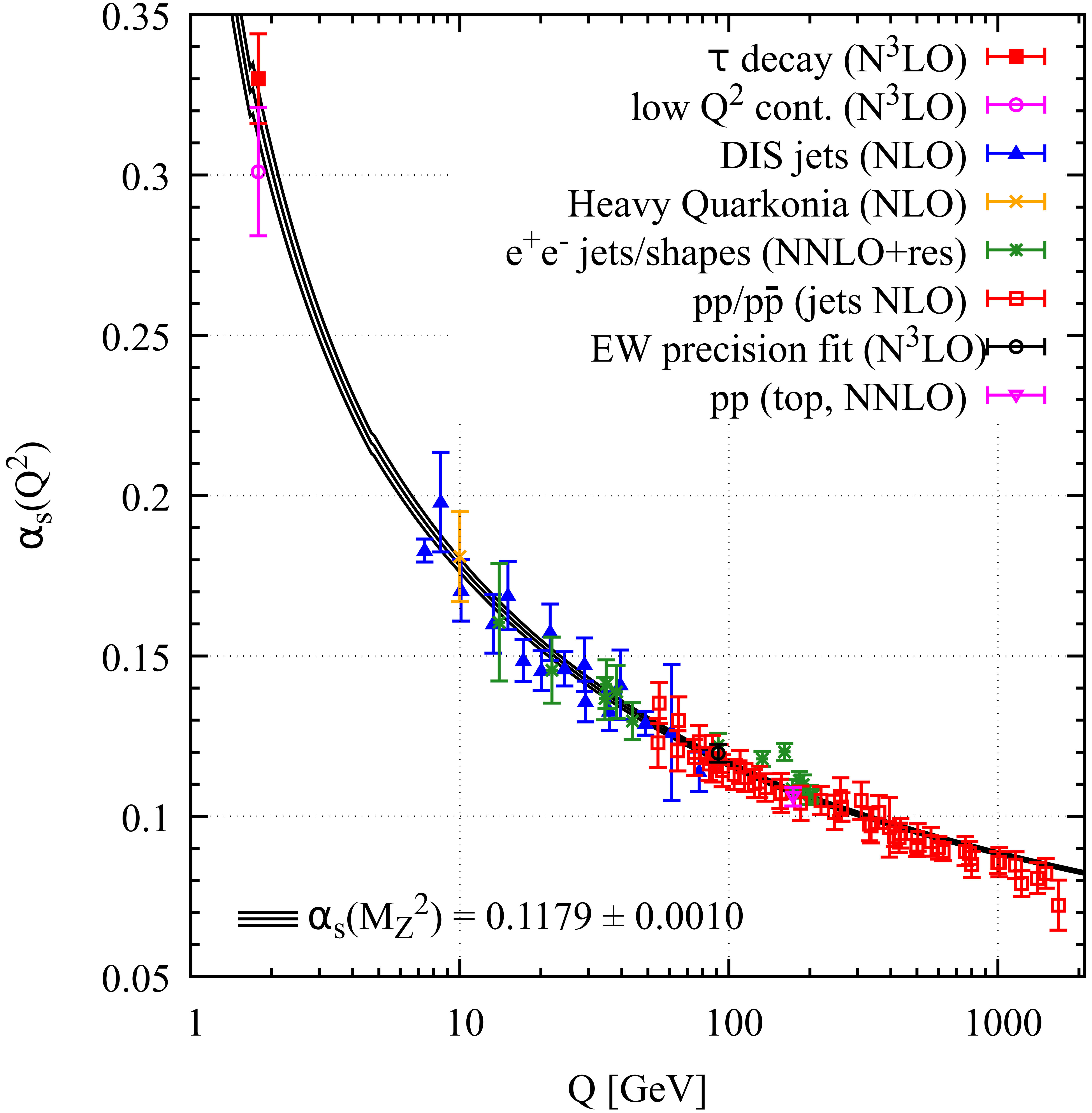
QCD

quantum chromodynamics
the theory of the strong interaction

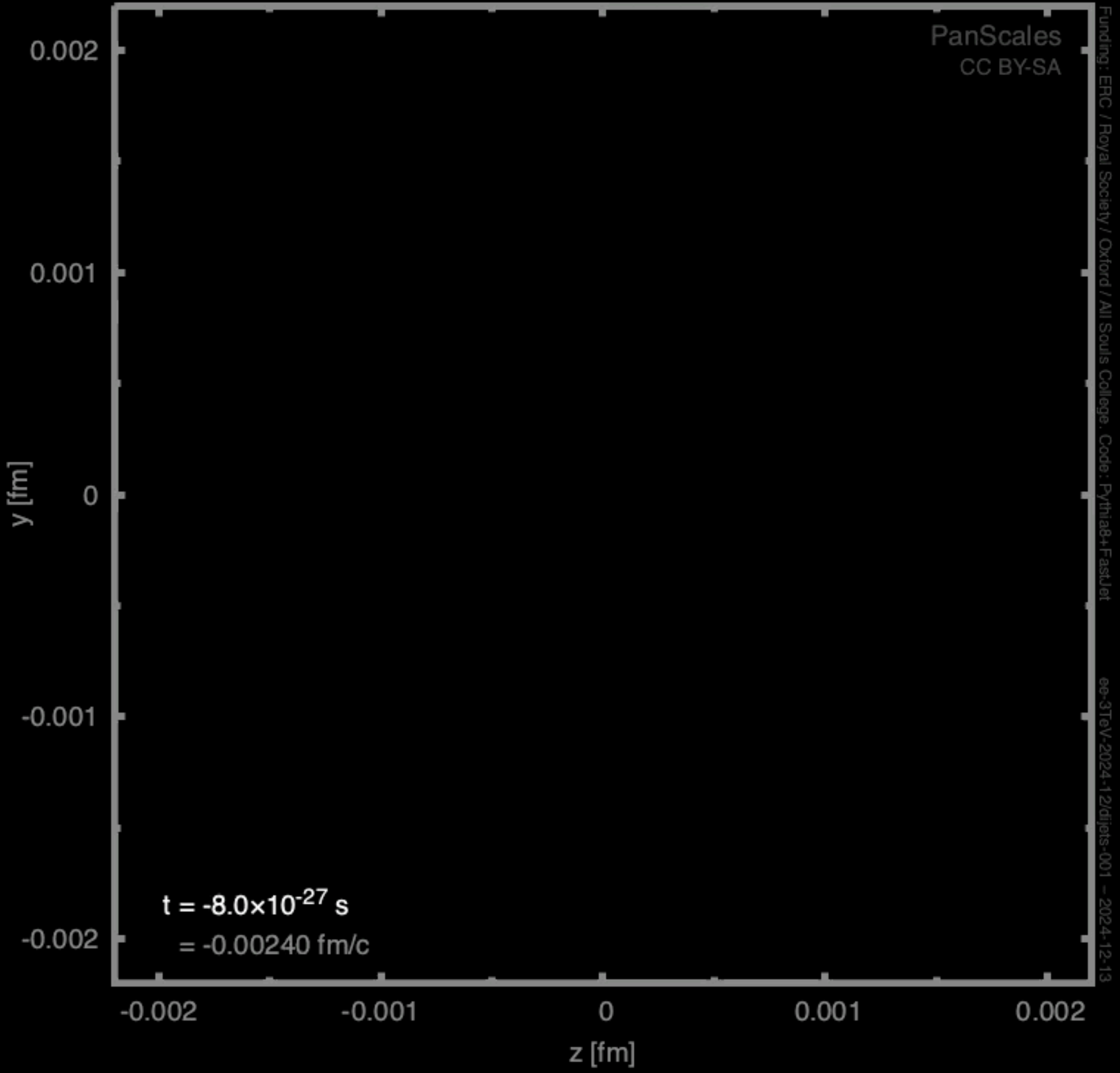
Like QED, with key differences

- Charge comes in three variants (red, green, blue)
- Force carrier (gluon), is charged
- Coupling is larger (and non-perturbative at small momenta)

strong coupling (α_s) v. momentum scale



What actually happens in a collision?

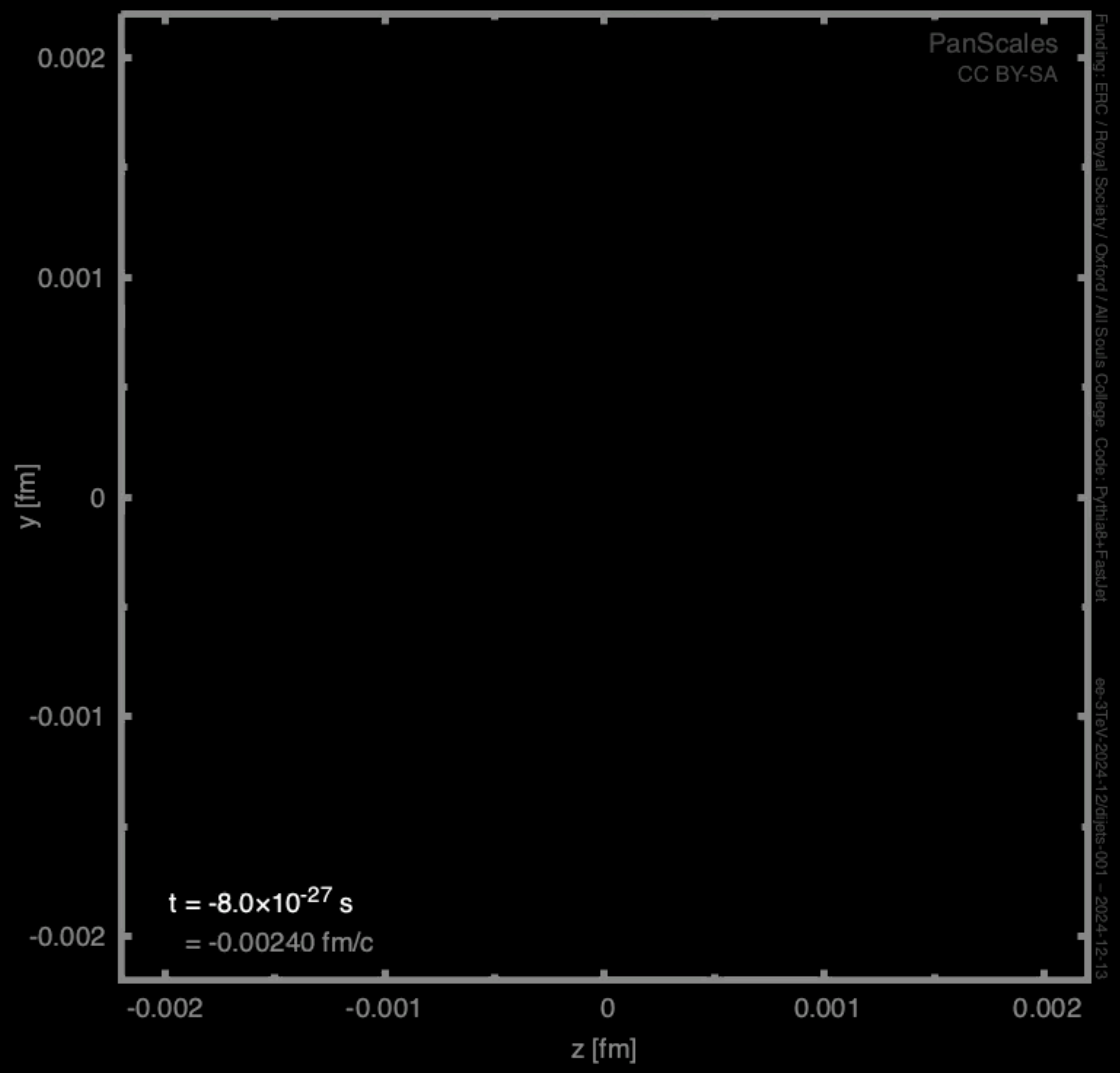


incoming beam particle

intermediate particle (quark or gluon)

final particle (hadron)

Event evolution spans 7 orders of magnitude in space-time



incoming beam particle

intermediate particle (quark or gluon)

final particle (hadron)

Event evolution spans 7 orders of magnitude in space-time

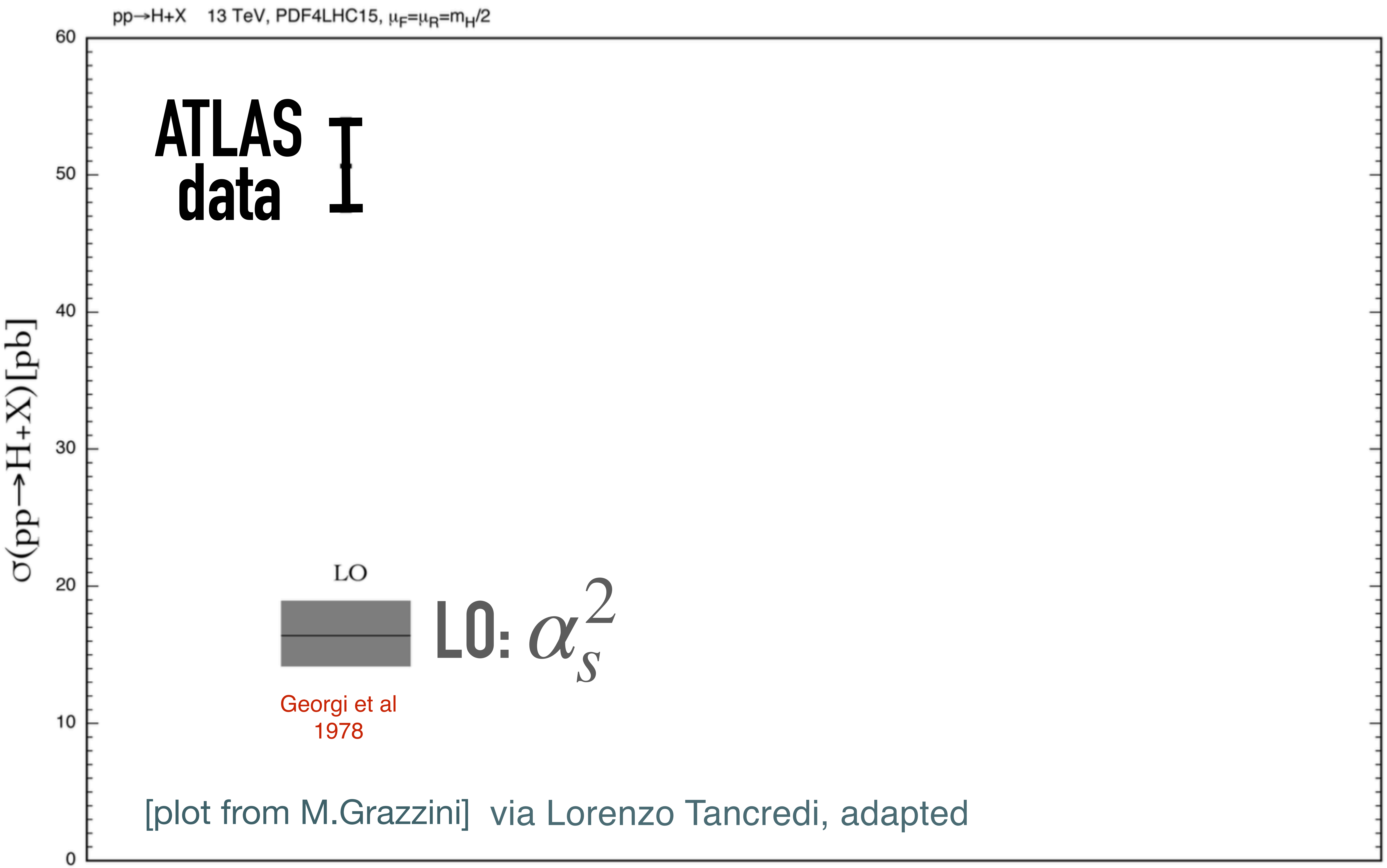

energy scale
1 TeV
100 GeV
10 GeV
1 GeV
hard process
parton shower
hadronisation
Z'
time
π K π ρ p . . . . . K π π K π π
$\alpha_s \sim 0.1$
$\alpha_s \sim 0.1 - 0.25$
$\alpha_s \gtrsim 0.4$
[non-perturbative models]

$\alpha_s \sim 0.1$

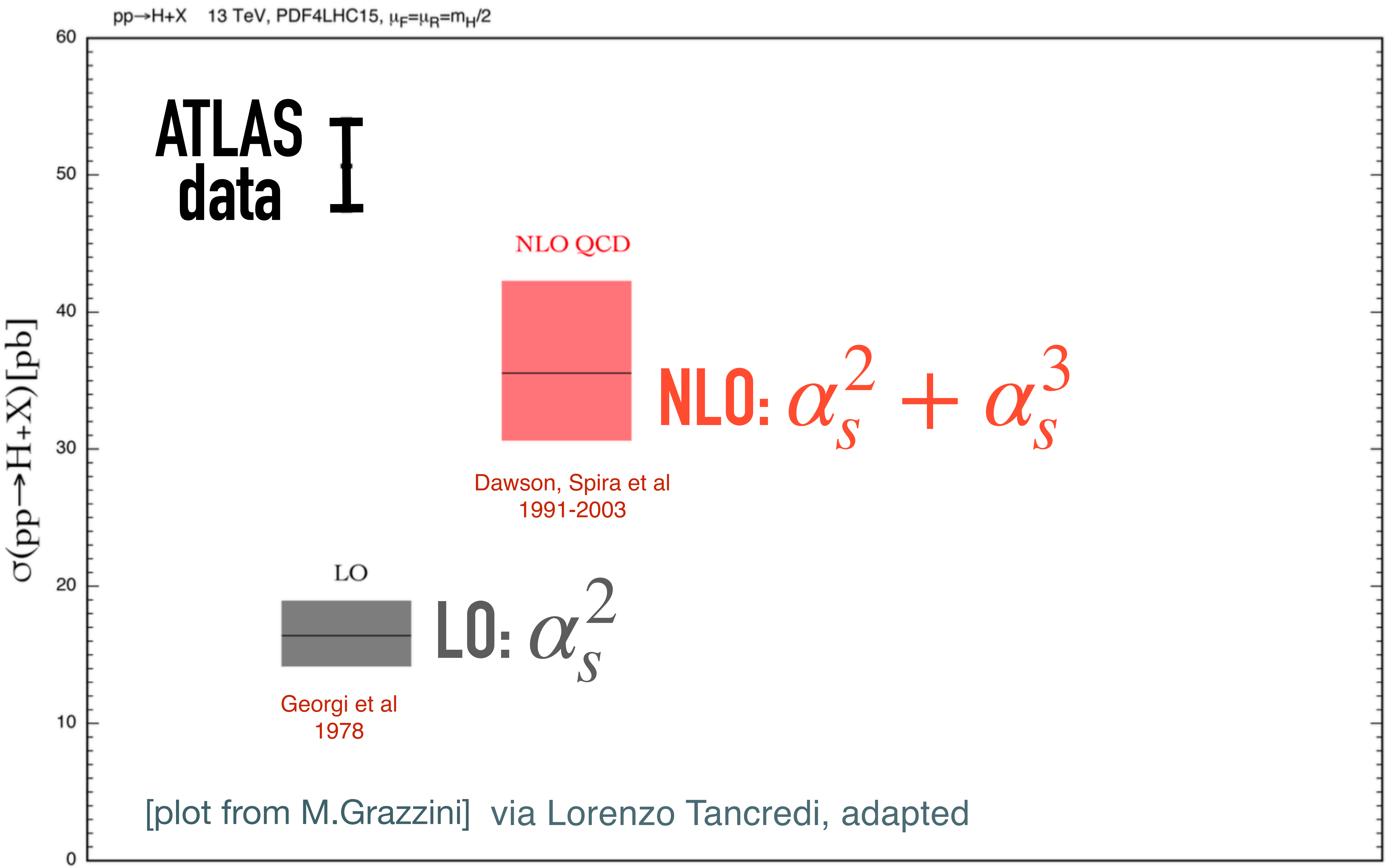
Calculate scattering cross sections as a “perturbative” series expansion in power of the strong coupling α_s

$$\sigma = c_0 + c_1\alpha_s + c_2\alpha_s^2 + \cdots$$

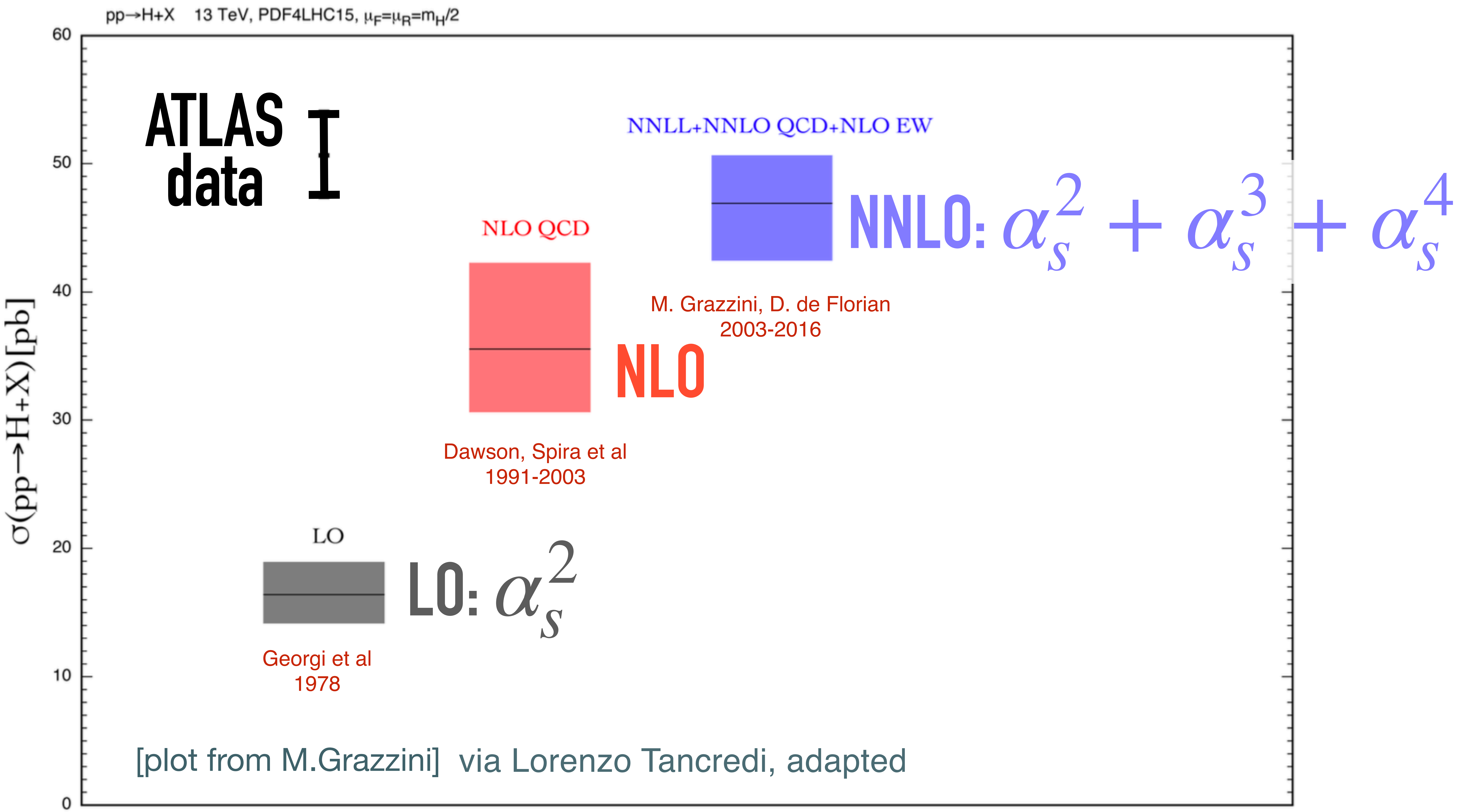
Higgs Boson Cross Section



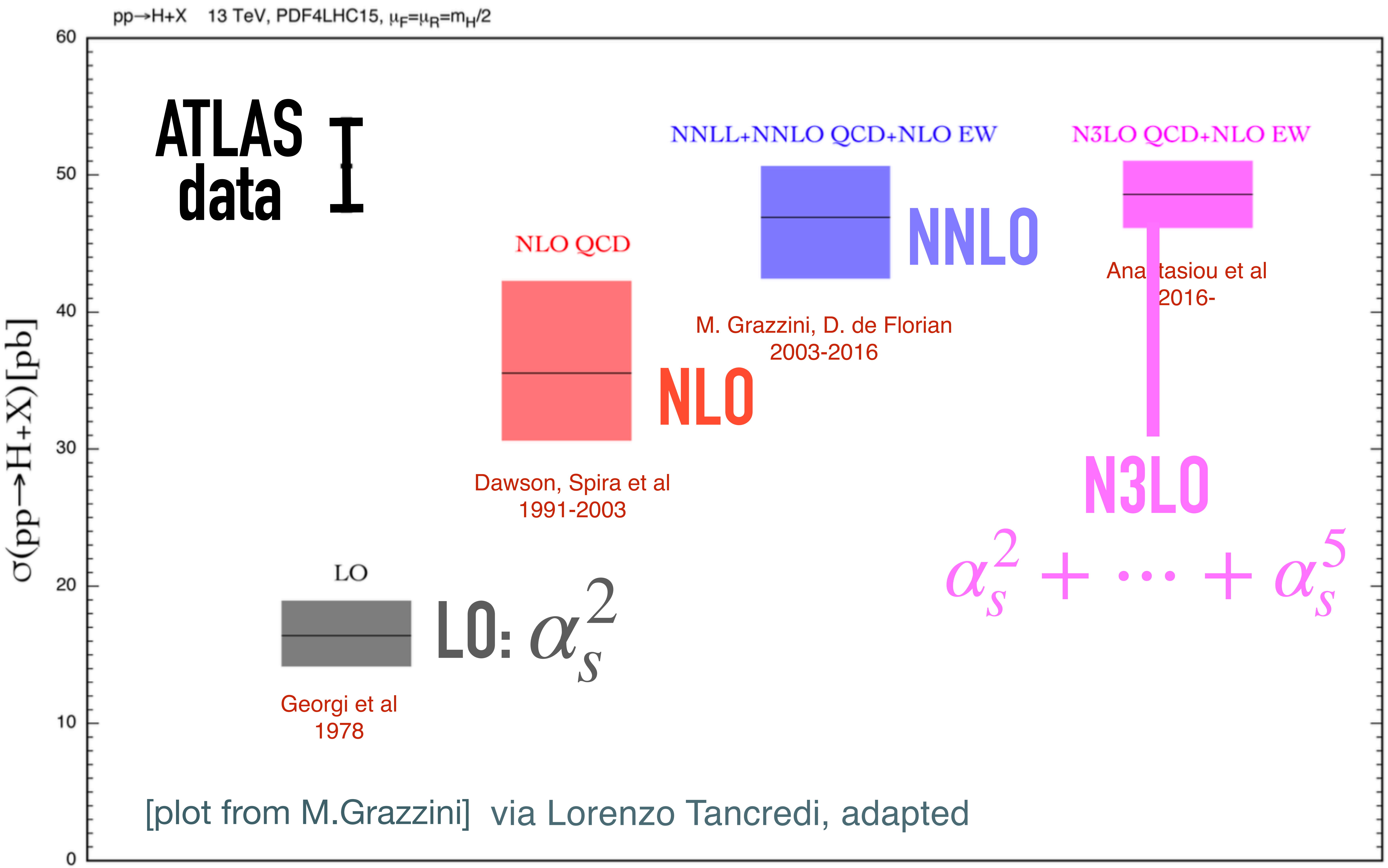
Higgs Boson Cross Section



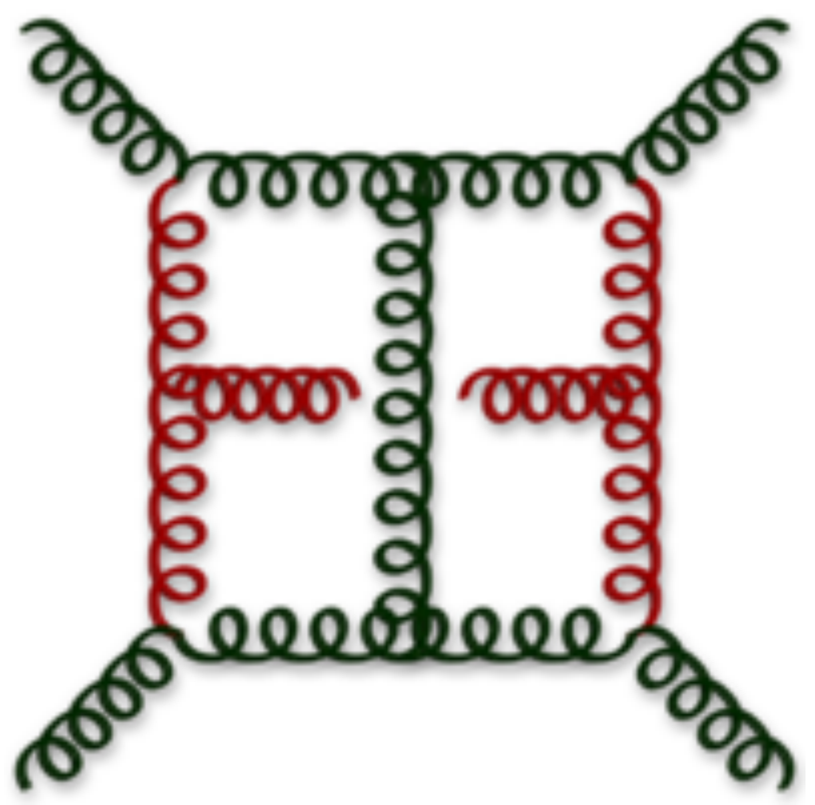
Higgs Boson Cross Section



Higgs Boson Cross Section



FOUR-PARTON SCATTERING TO THREE LOOPS

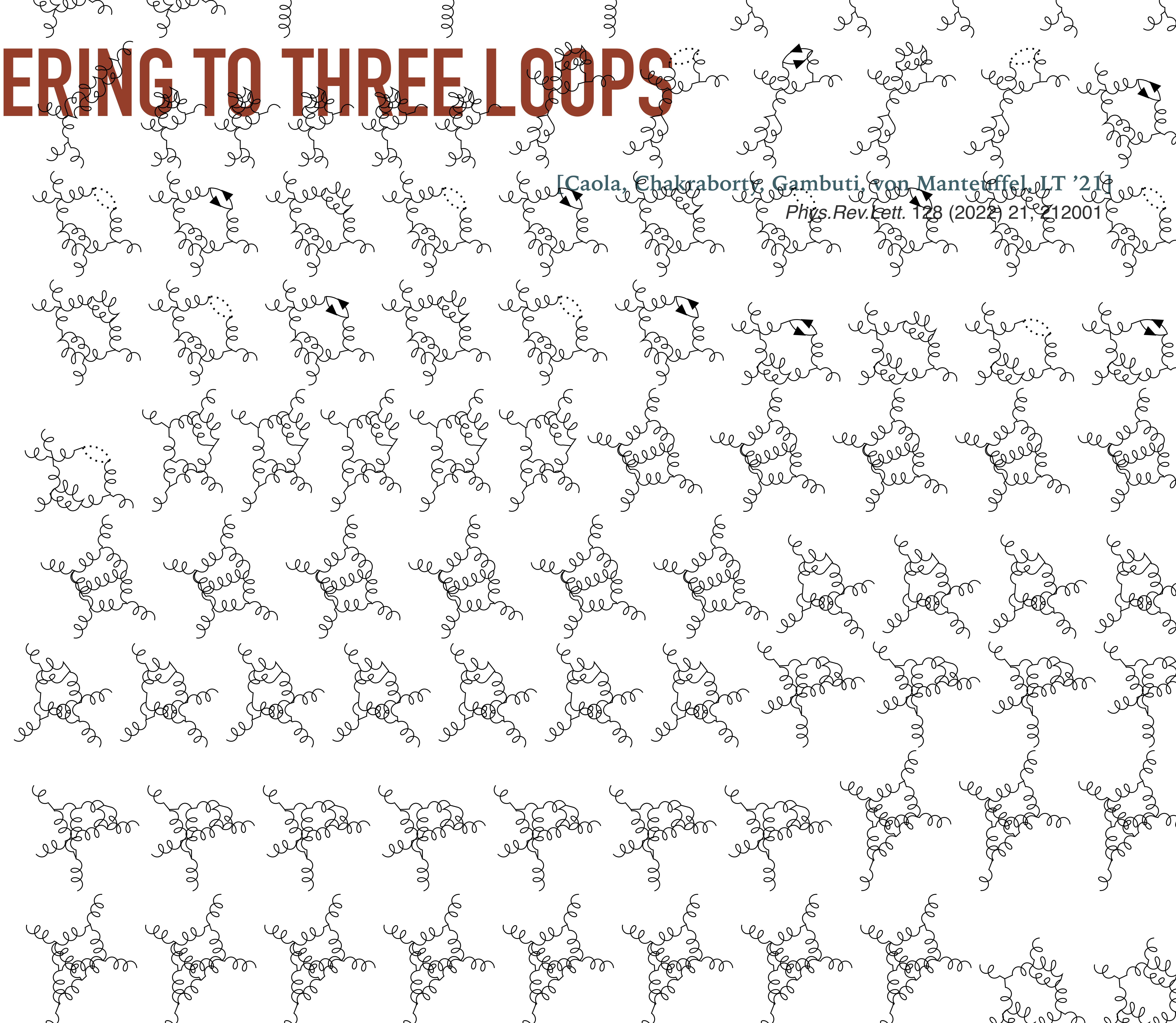


$gg \to gg$ @ 3 loops in QCD

+ 500 more pages

= 50000 Feynman diagrams

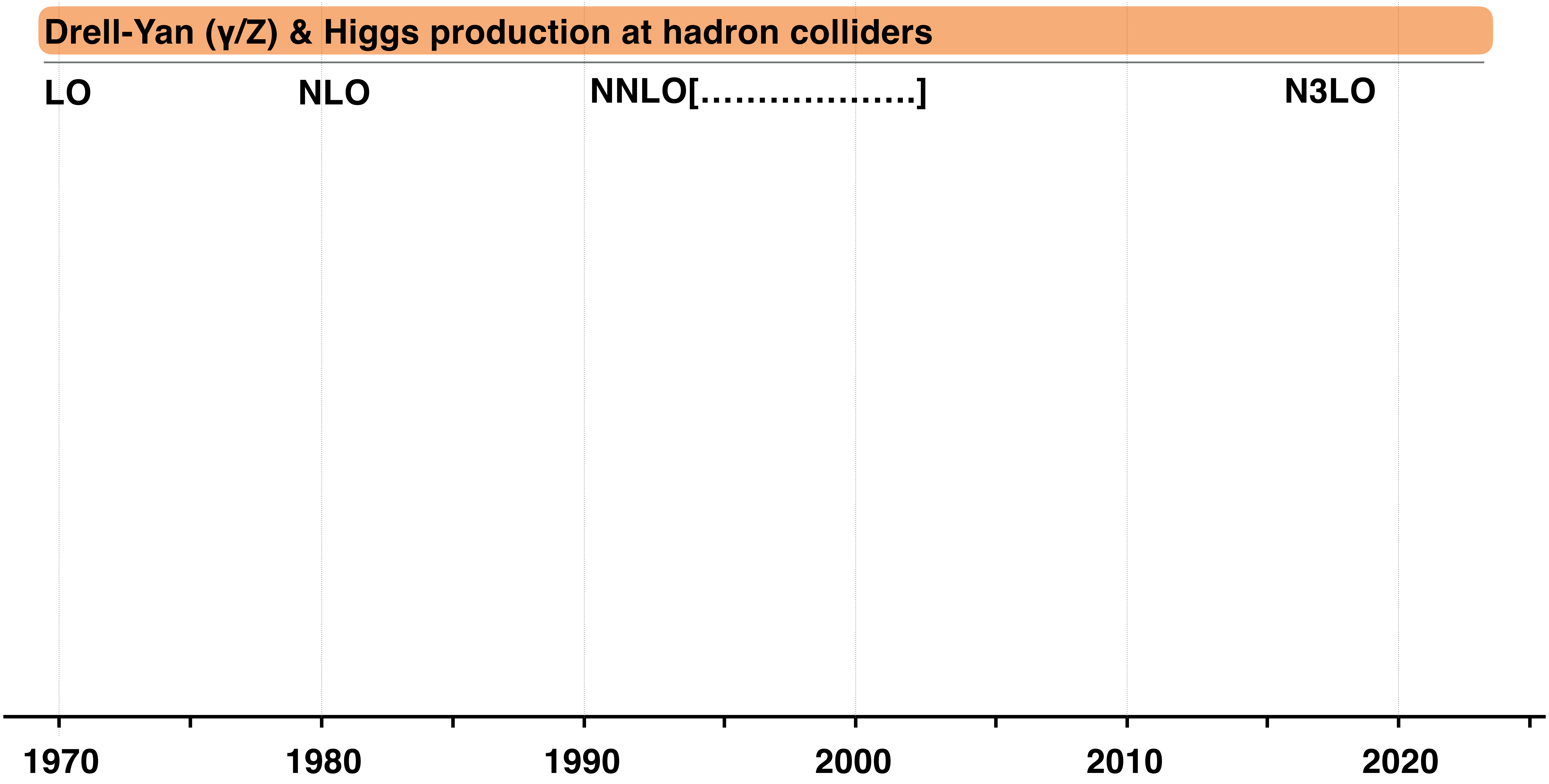
= 10^7 Feynman integrals!



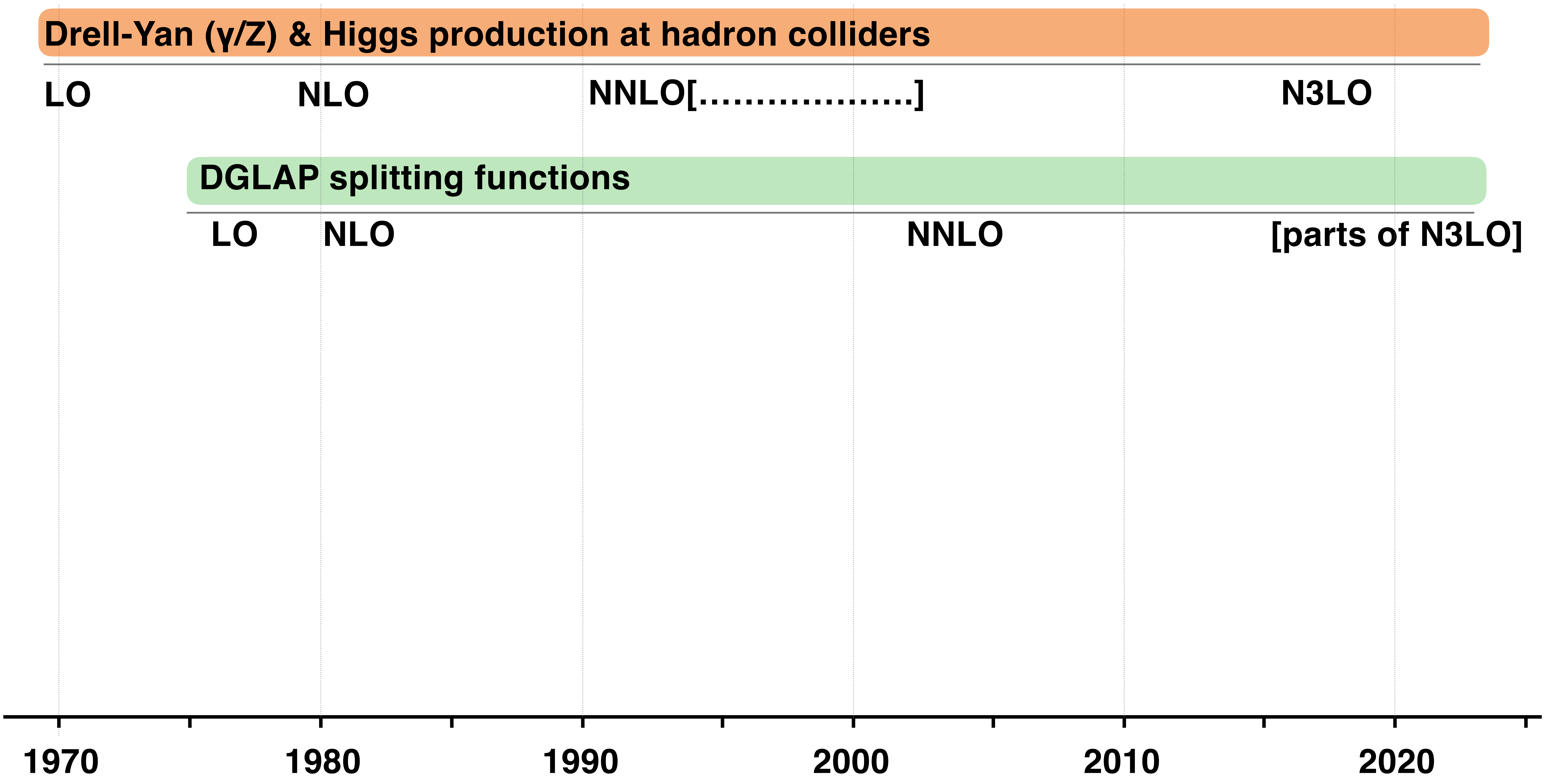
[Caola, Chakraborty, Gambuti, von Manteuffel, LT '21]
Phys.Rev.Lett. 128 (2022) 21, 212001

slide from Lorenzo Tancredi

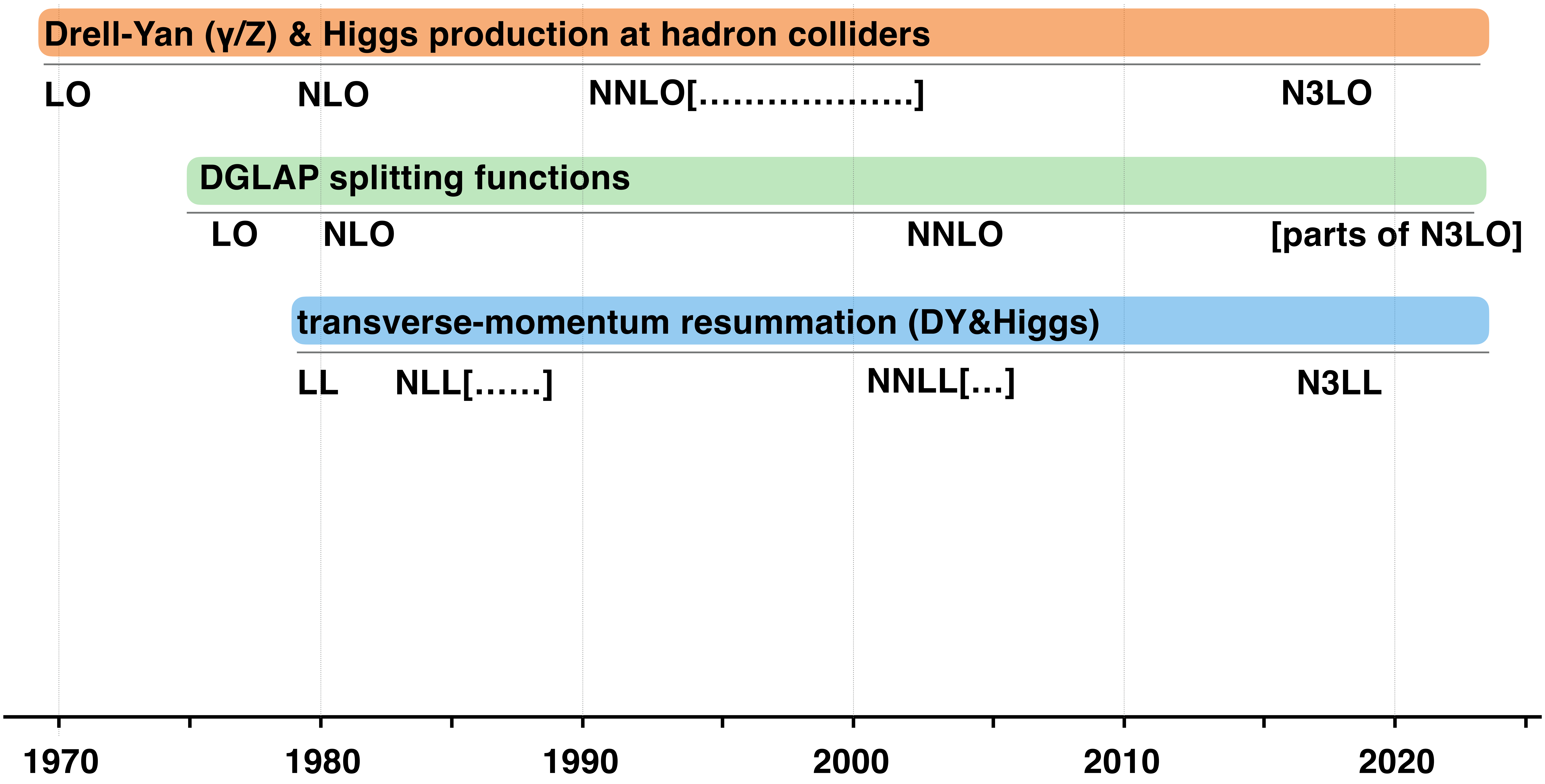
selected collider-QCD accuracy milestones



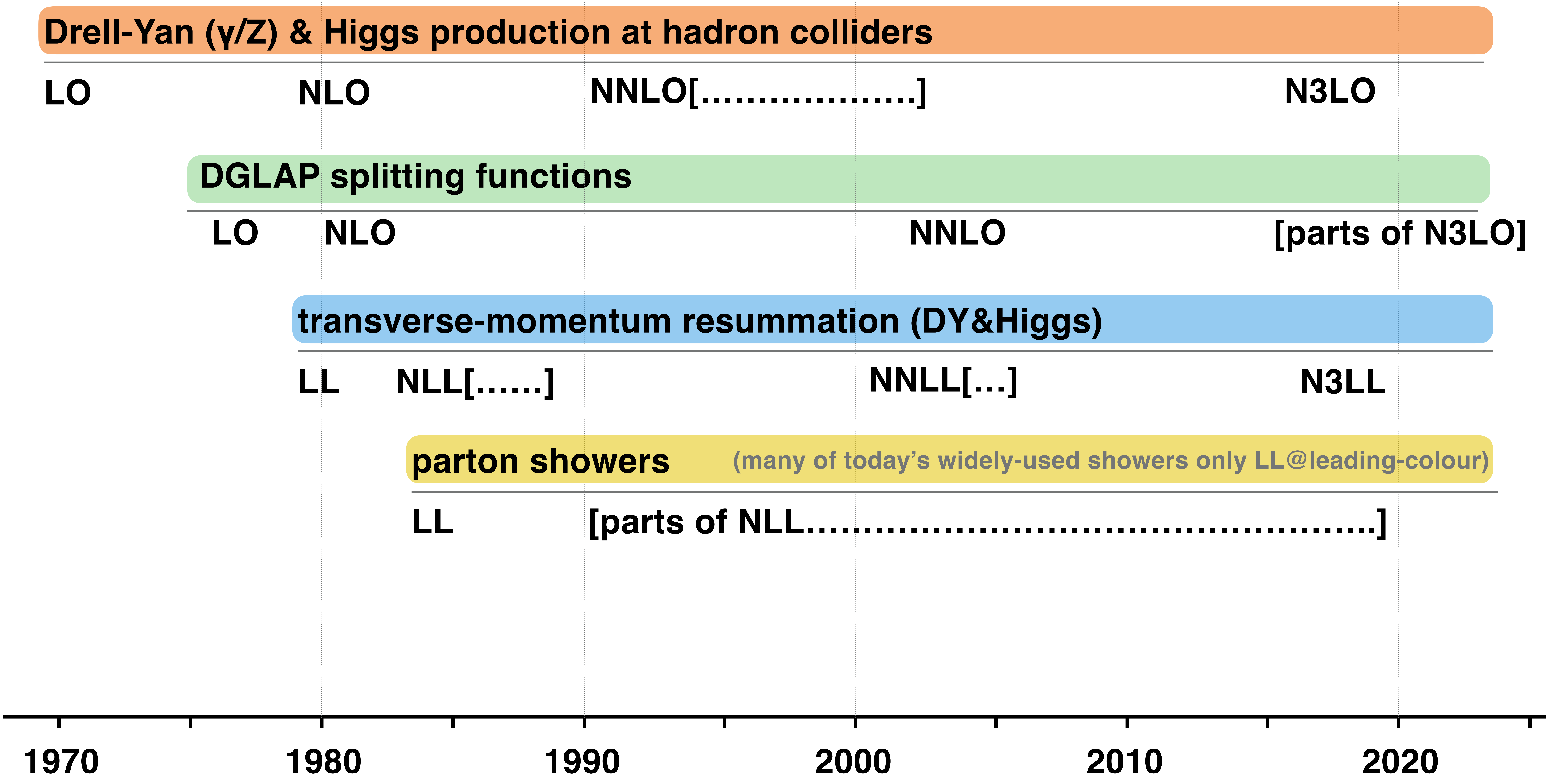
selected collider-QCD accuracy milestones



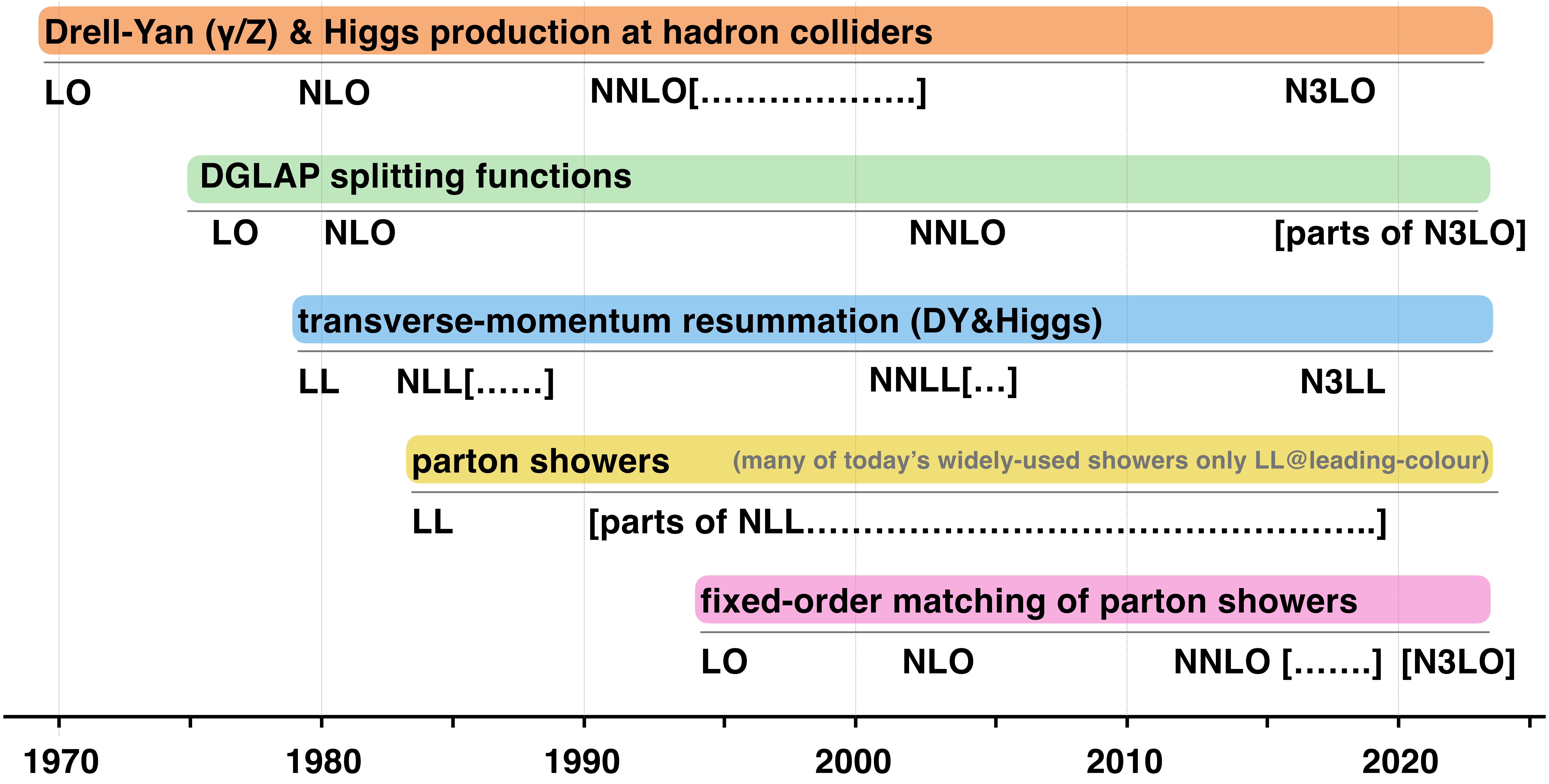
selected collider-QCD accuracy milestones



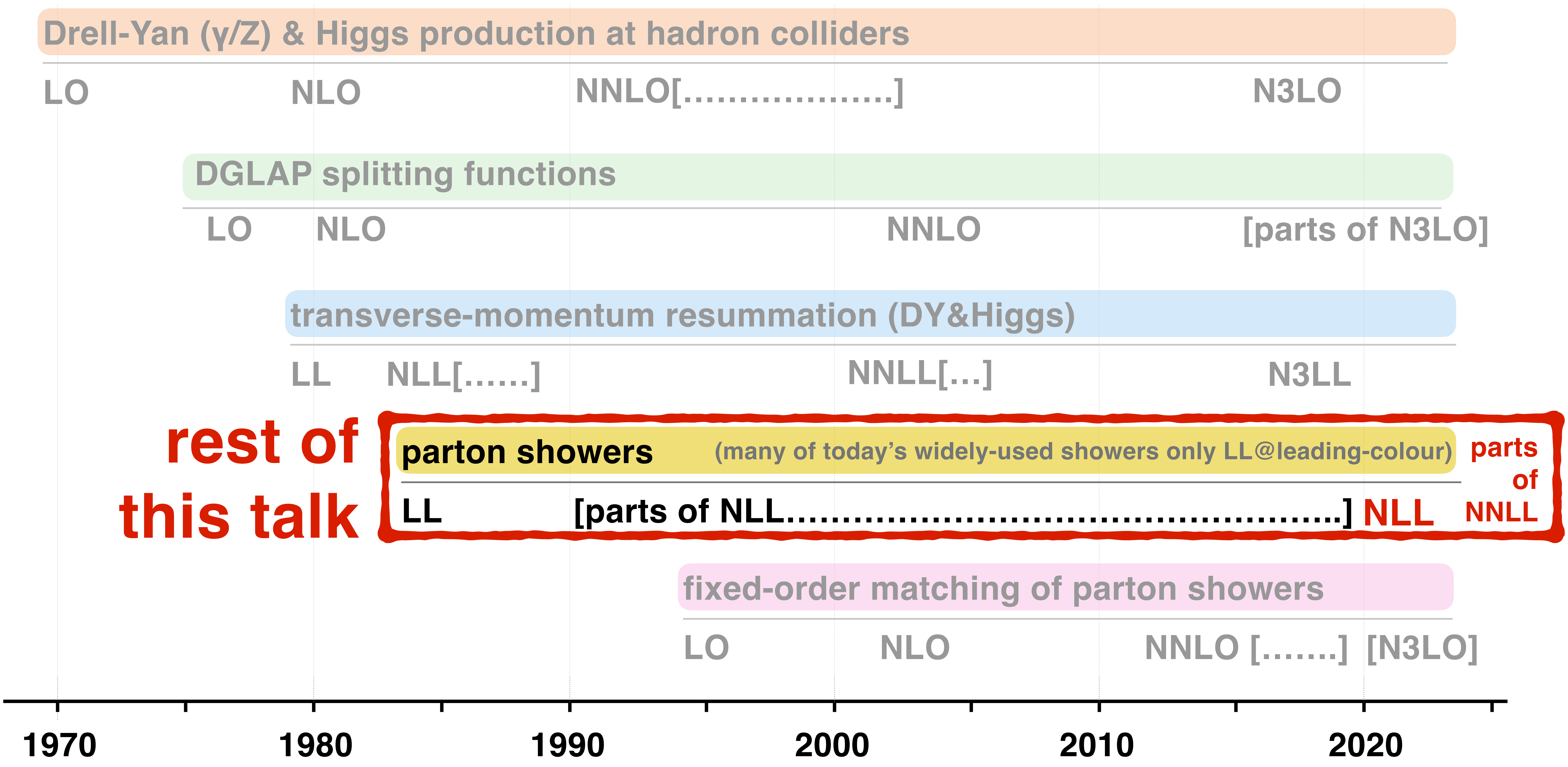
selected collider-QCD accuracy milestones



selected collider-QCD accuracy milestones



selected collider-QCD accuracy milestones

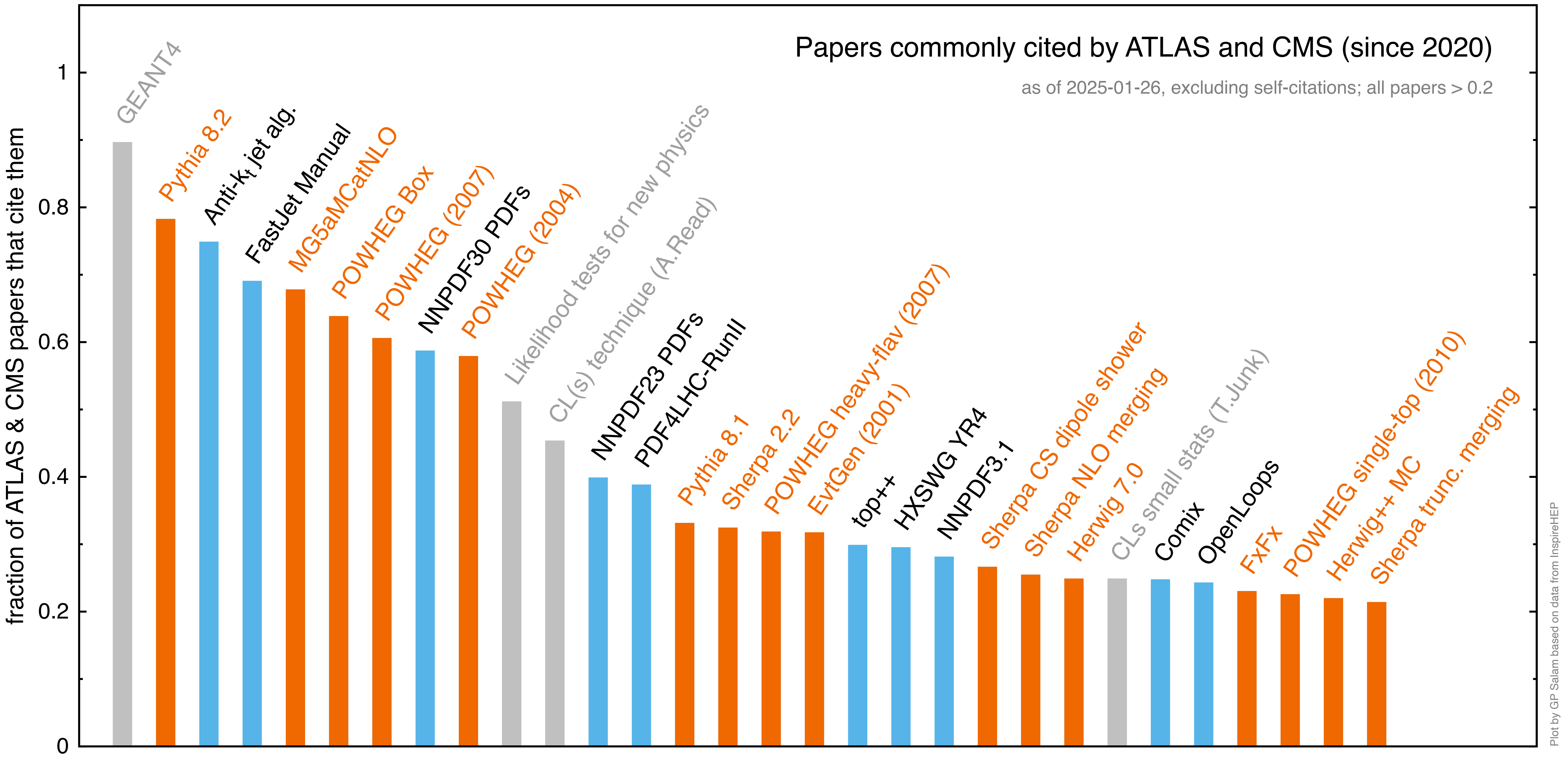


All of this is impossible without simulations

Herwig 7

Pythia 8

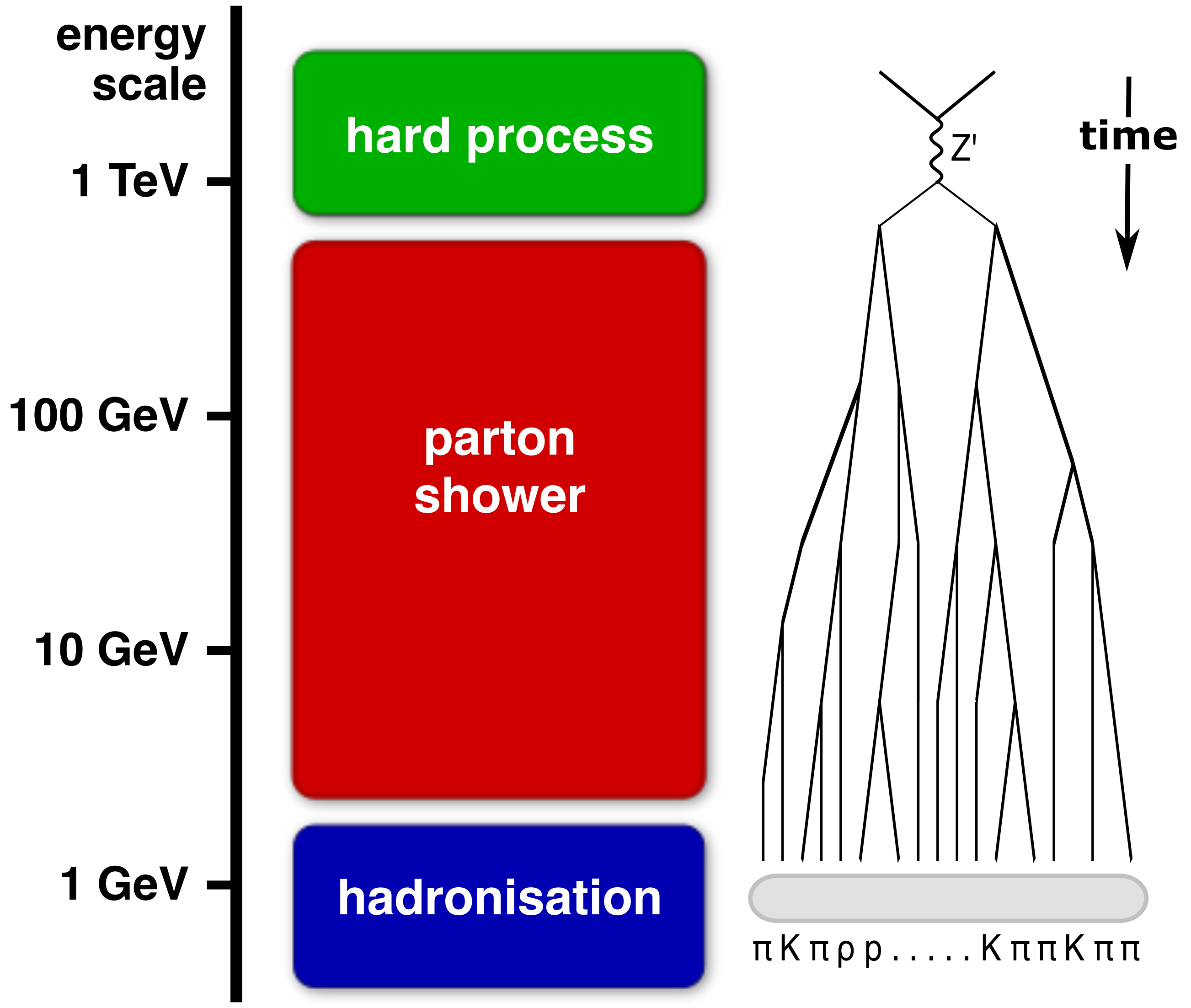
Sherpa 3



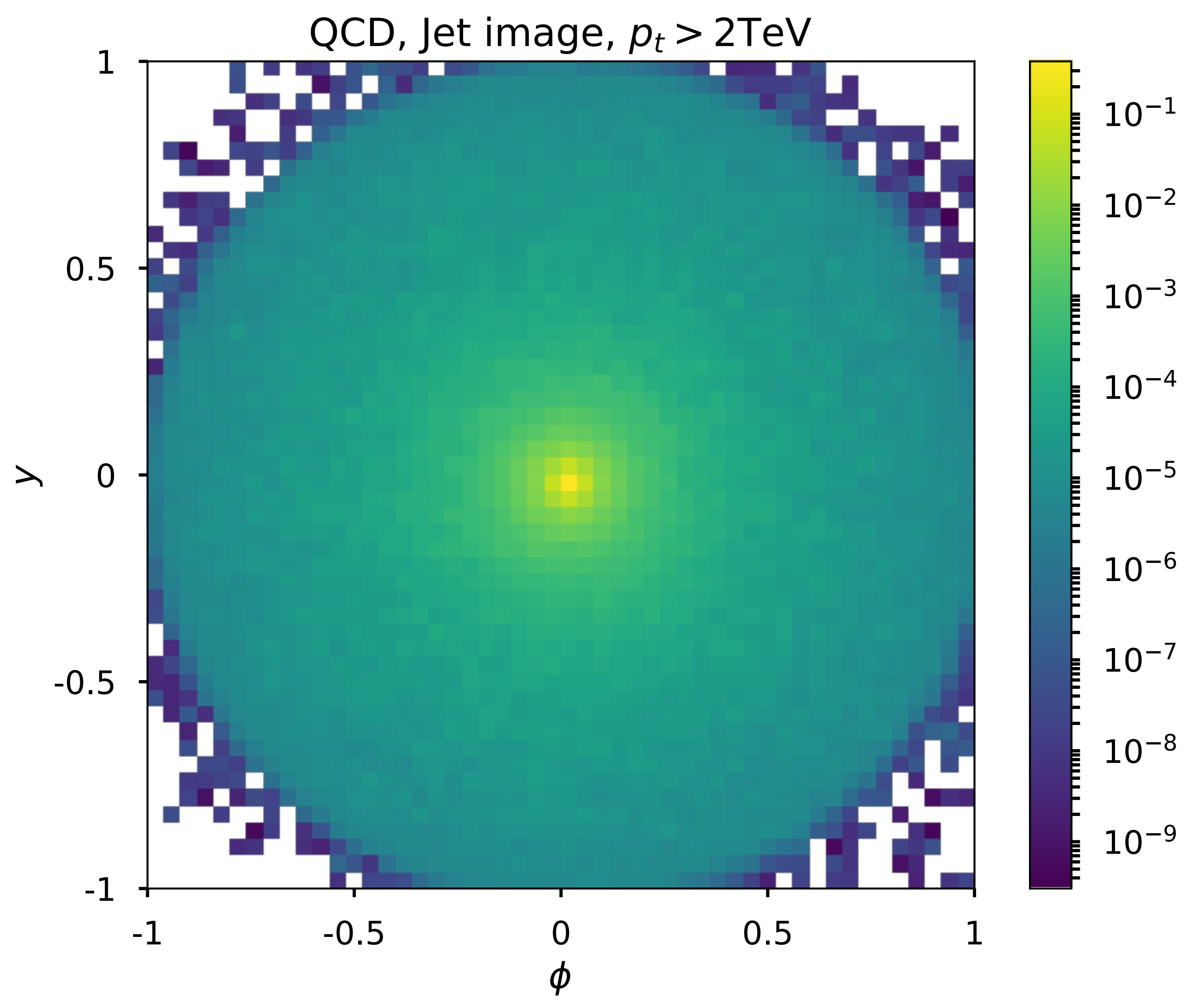
used in ~95% of ATLAS/CMS publications

they do an amazing job of simulating vast swathes of data; collider physics would be unrecognisable without them

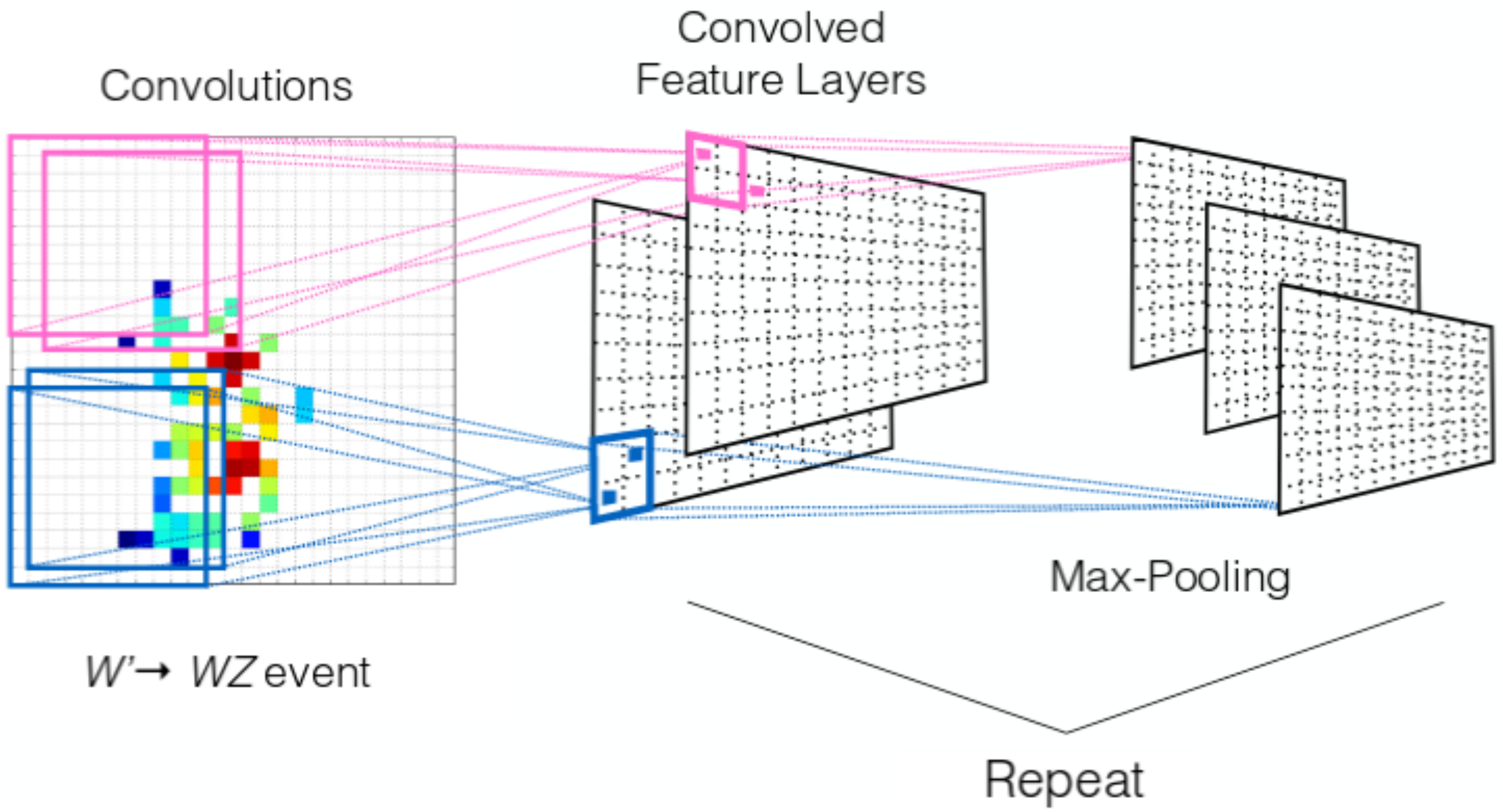
```
 |  *------------------------------------------------------------------------------*  |
 |  |                                                                              |  |
 |  |                                                                              |  |
 |  |   PPP   Y   Y  TTTTT  H   H  III    A      Welcome to the Lund Monte Carlo!  |  |
 |  |   P  P   Y Y     T    H   H   I    A A     This is PYTHIA version 8.303      |  |
 |  |   PPP     Y      T    HHHHH   I   AAAAA    Last date of change:  1 Sep 2020  |  |
 |  |   P       Y      T    H   H   I   A   A                                      |  |
 |  |   P       Y      T    H   H  III  A   A    Now is 19 Jul 2021 at 11:41:40    |  |
 |  |                                                                              |  |
*-------  PYTHIA Process Initialization  --------------------------*
| We collide p+ with p+ at a CM energy of 1.400e+04 GeV            |
|------------------------------------------------------------------|
| Subprocess                                    Code |   Estimated |
|                                                    |    max (mb) |
|------------------------------------------------------------------|
|                                                    |             |
| g g -> H (SM)                                  902 |   3.065e-07 |
--------  PYTHIA Event Listing  (complete event)  ---------------------------------------------------------------------------

    no         id  name            status     mothers   daughters     colours      p_x        p_y        p_z         e          m
     0         90  (system)           -11     0     0     0     0     0     0      0.000      0.000      0.000  14000.000  14000.000
     1       2212  (p+)               -12     0     0   649     0     0     0      0.000      0.000   7000.000   7000.000      0.938
     2       2212  (p+)               -12     0     0   650     0     0     0      0.000      0.000  -7000.000   7000.000      0.938
     3         21  (g)                -21    19     0     5     0   101   102      0.000      0.000     10.638     10.638      0.000
     4         21  (g)                -21    20    20     5     0   102   101      0.000      0.000   -373.110    373.110      0.000
     5         25  (h0)               -22     3     4    21    21     0     0      0.000      0.000   -362.472    383.747    126.000
     6         21  (g)                -31    75    75     8     9   104   105      0.000      0.000    162.462    162.462      0.000
     7         21  (g)                -31    76     0     8     9   106   104      0.000      0.000     -8.450      8.450      0.000
     8         21  (g)                -33     6     7    42    43   106   107      2.904     -9.848     -5.104     11.466      0.000
     9         21  (g)                -33     6     7    44    44   107   105     -2.904      9.848    159.116    159.447      0.000
    10         21  (g)                -31    14     0    12    13   108   109      0.000      0.000     14.037     14.037      0.000
 . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .
  1624        111  pi0                 91  1516     0     0     0     0     0      0.081      0.097     -0.757      0.779      0.135
  1625        111  pi0                 91  1516     0     0     0     0     0     -0.082     -0.156     -0.614      0.653      0.135
  1626        130  K_L0                91  1522  1522     0     0     0     0     -2.188      0.152     13.925     14.106      0.498
                                   Charge sum:  2.000           Momentum sum:     -0.000      0.000     -0.000  14000.000  14000.000
--------  End PYTHIA Event Listing  -----------------------------------------------------------------------------------------
```



Machine learning and jet/event structure

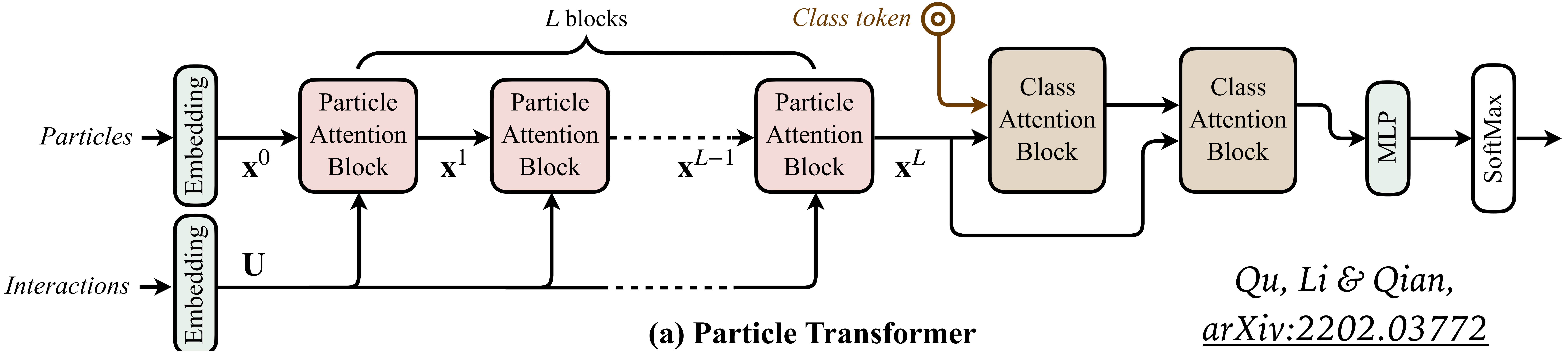


2021 Young Experimental Physicist
EPS HEPP prize



[Cogan, Kagan, Strauss, Schwartzman JHEP 1502 (2015) 118]

[de Oliveira, Kagan, Mackey, Nachman, Schwartzman JHEP 1607 (2016) 069]

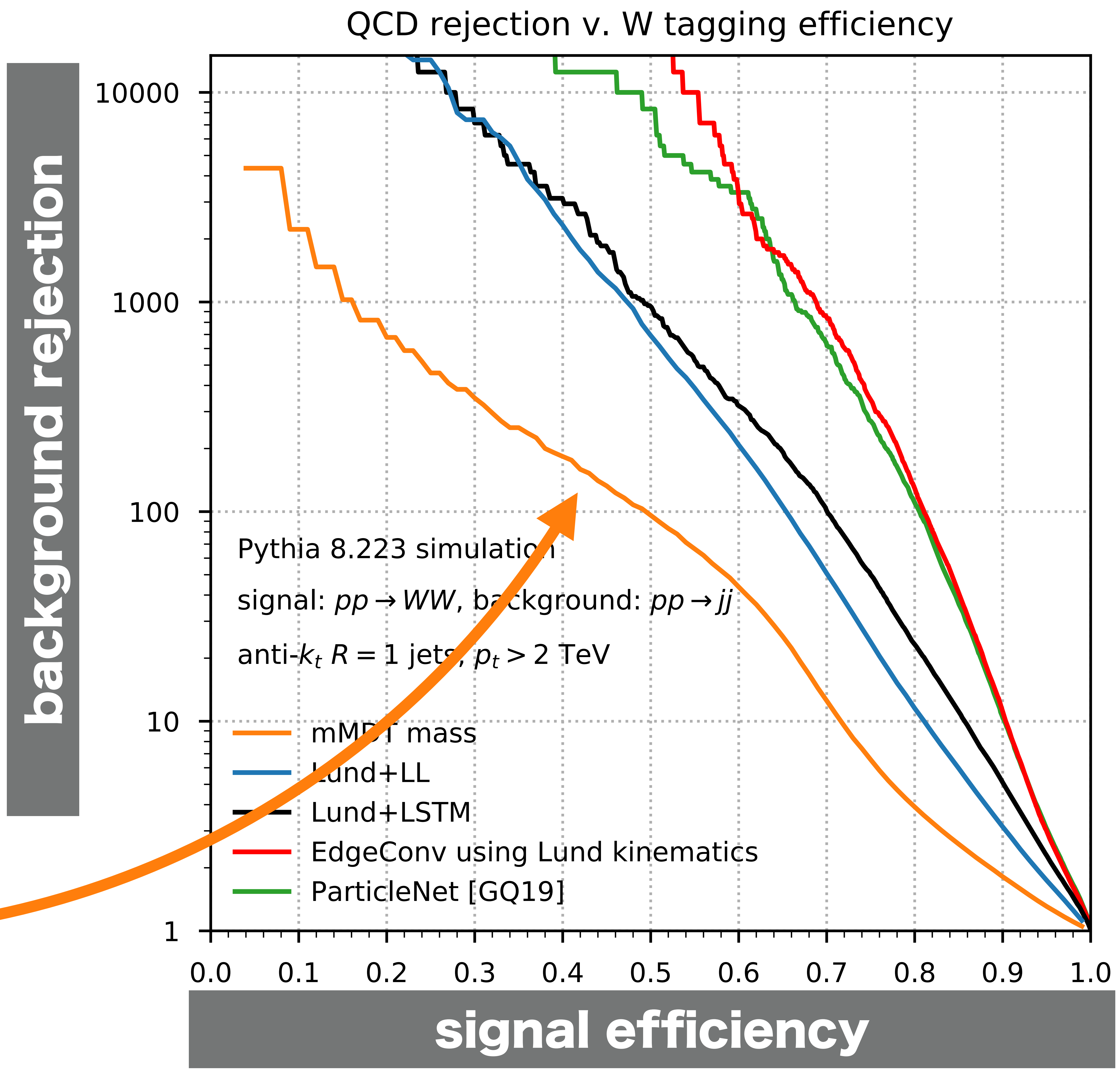


(a) Particle Transformer

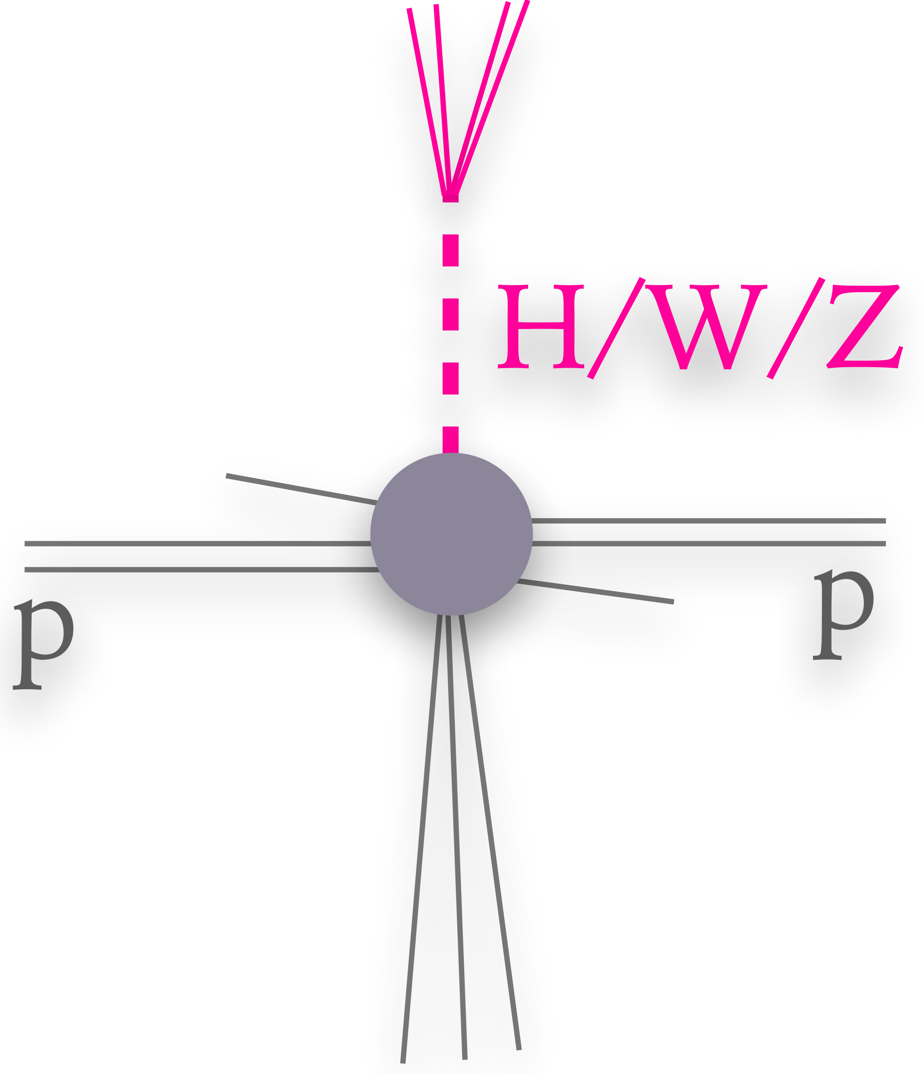
Qu, Li & Qian, arXiv:2202.03772

using full jet/event information for H/W/Z-boson tagging

adapted from Dreyer & Qu [2012.08526](2012.08526)

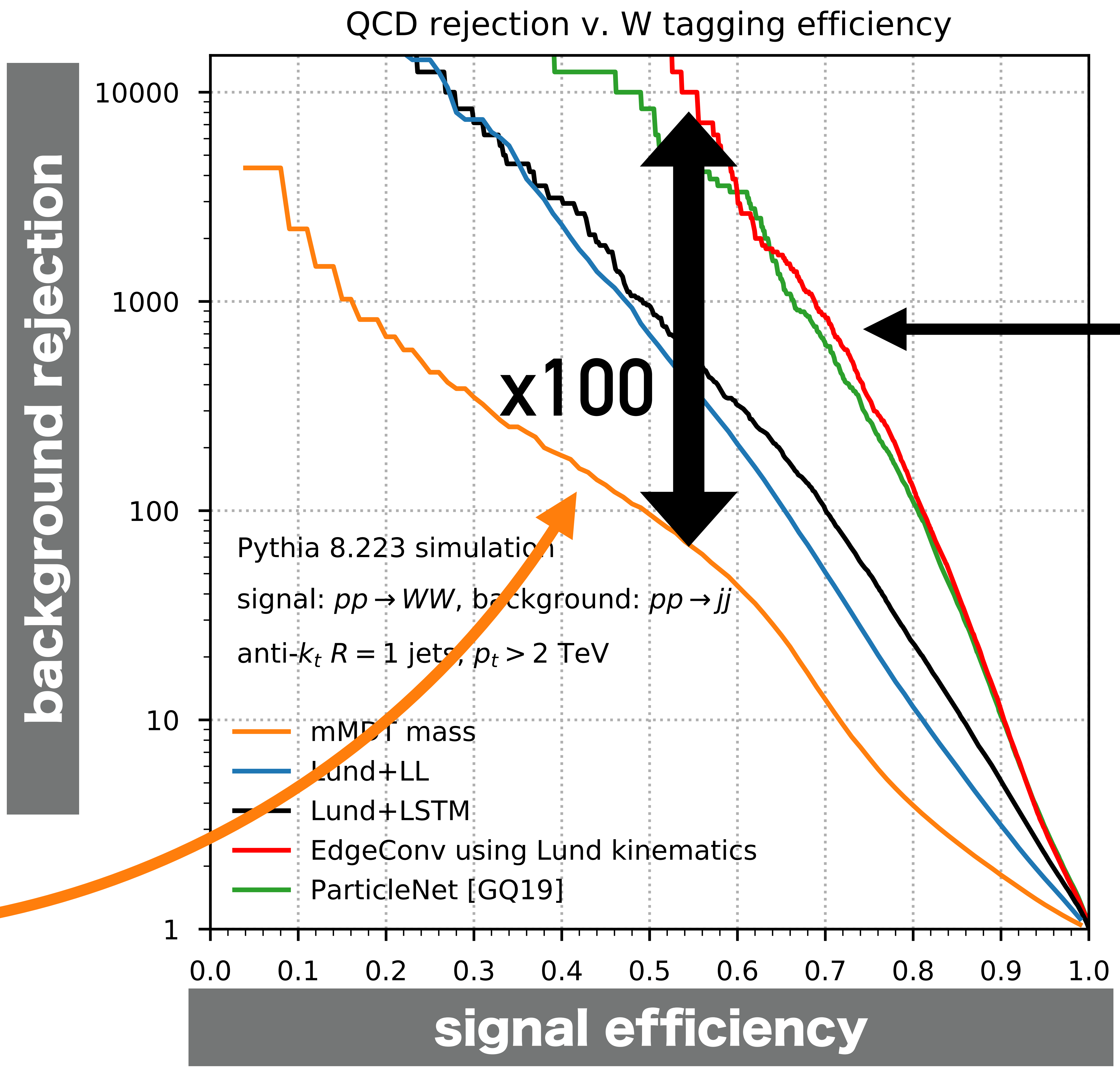


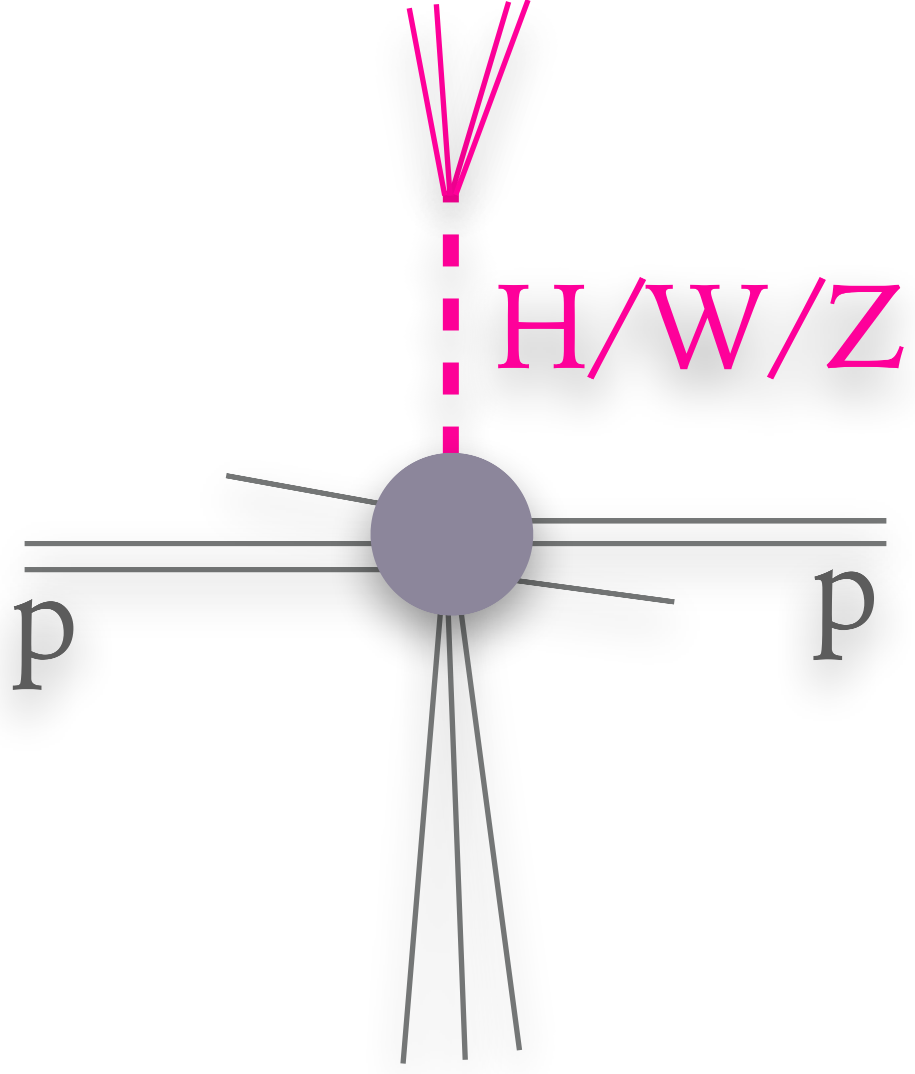
QCD rejection with just jet mass (SD/mMDT) i.e. 2008 tools & their 2013/14 descendants



using full jet/event information for H/W/Z-boson tagging

adapted from Dreyer & Qu *2012.08526*





QCD rejection with use of full jet substructure (2021 tools)

100x better

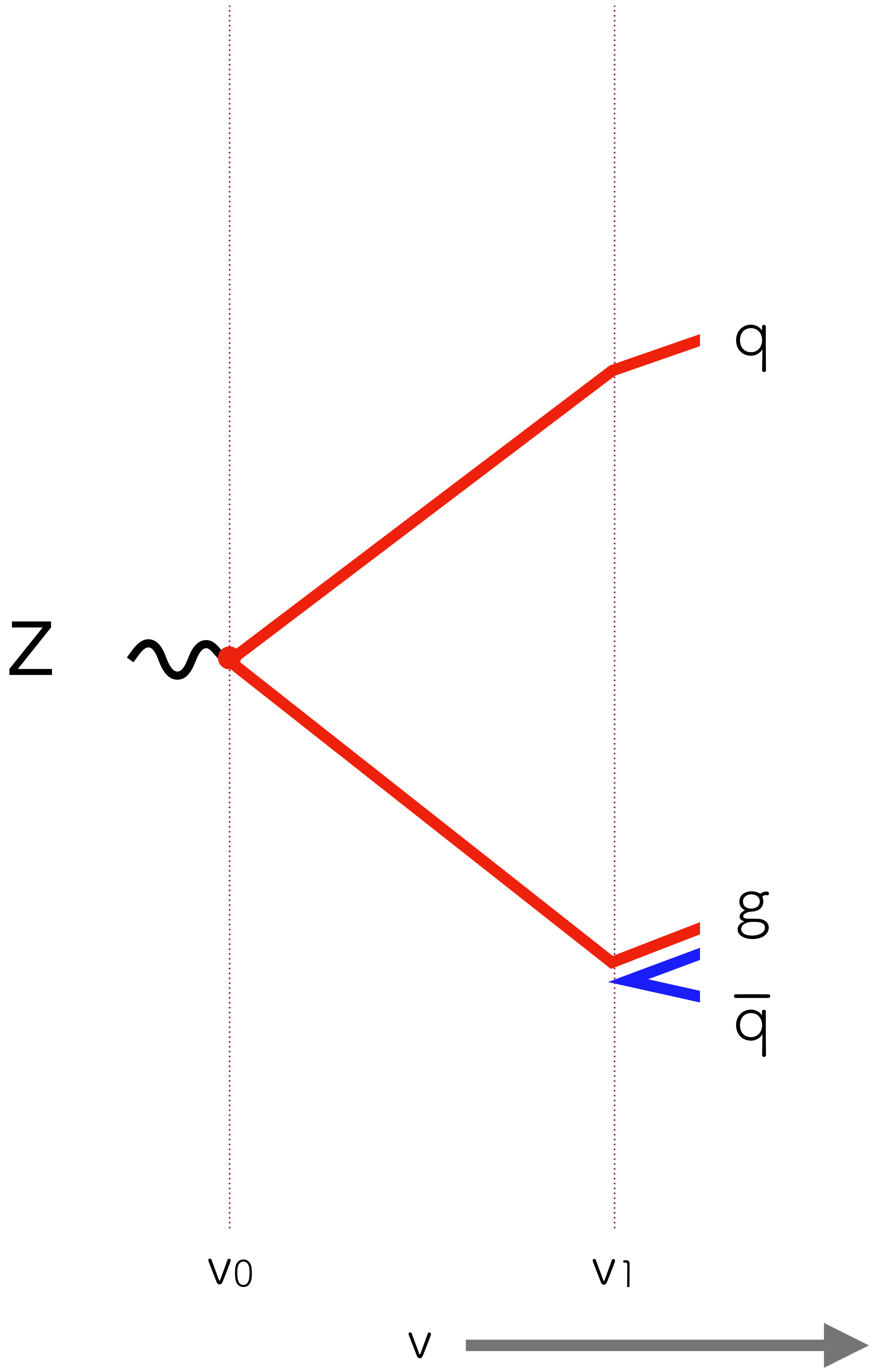
QCD rejection with just jet mass (SD/mMDT) i.e. 2008 tools & their 2013/14 descendants

First started to be exploited by Thaler & Van Tilburg with "N-subjettiness" (2010/11)

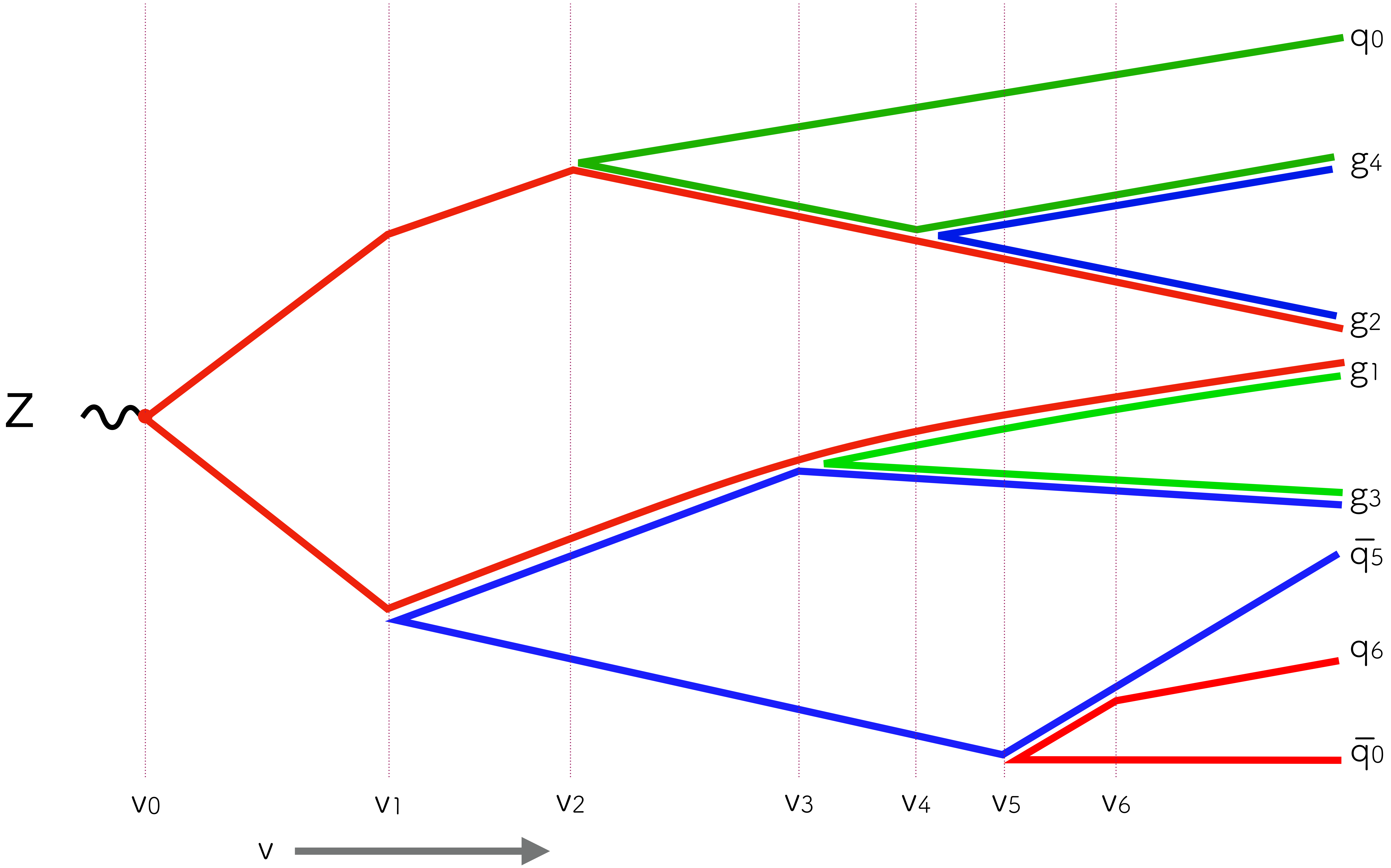
Element #1: what are parton showers trying to achieve?

parton showers span disparate scales
natural language is "logarithmic" accuracy

QCD parton shower: an evolution equation (in evolution scale v, e.g. transverse momentum)



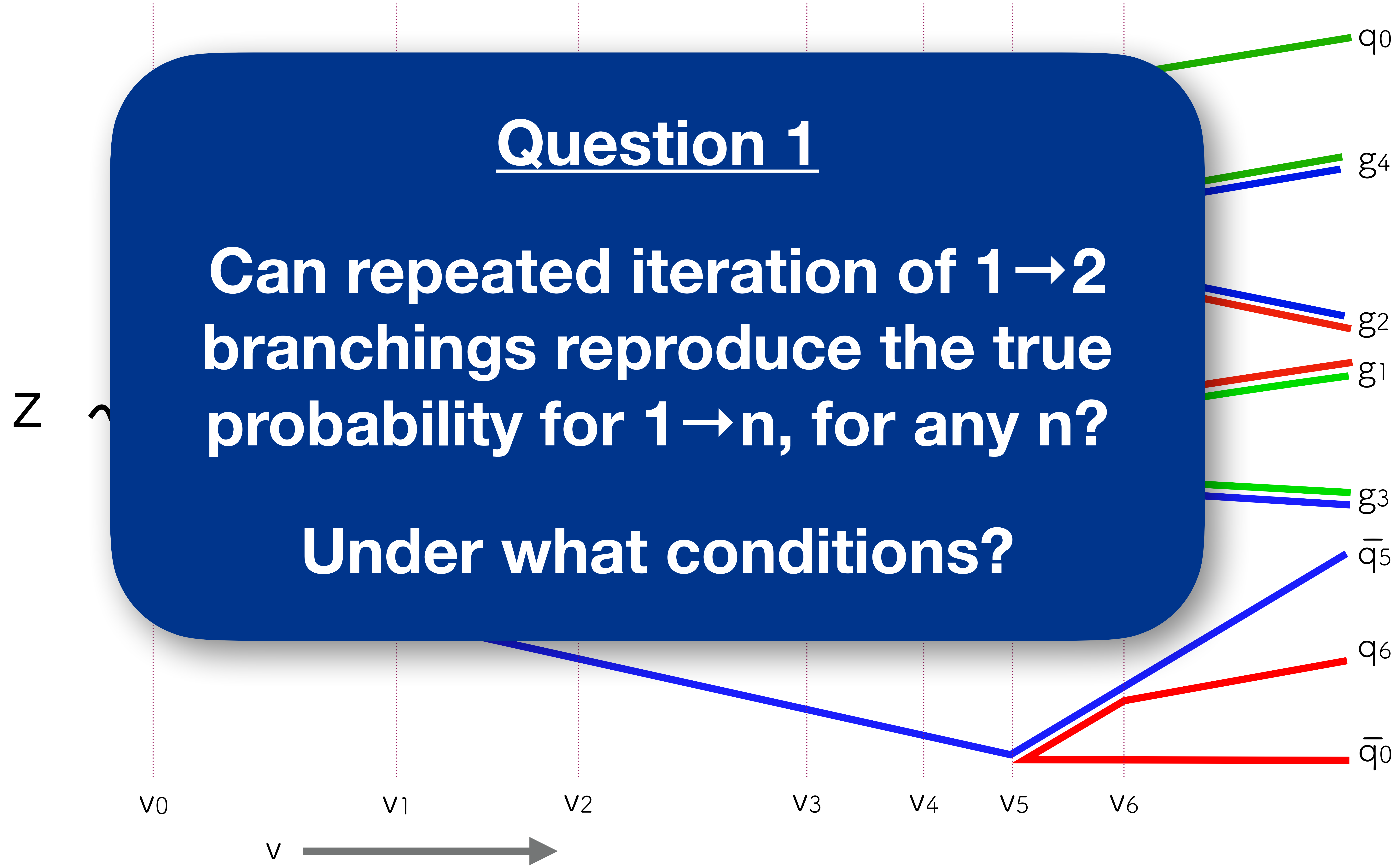
QCD **parton shower**: an evolution equation (in **evolution scale v**, e.g. transverse momentum)



self-similar evolution continues until it reaches a non-perturbative scale

branchings widely separated in space–time treated as ~independent

QCD parton shower: an evolution equation (in evolution scale v, e.g. transverse momentum)



Question 1

Can repeated iteration of 1→2 branchings reproduce the true probability for 1→n, for any n?

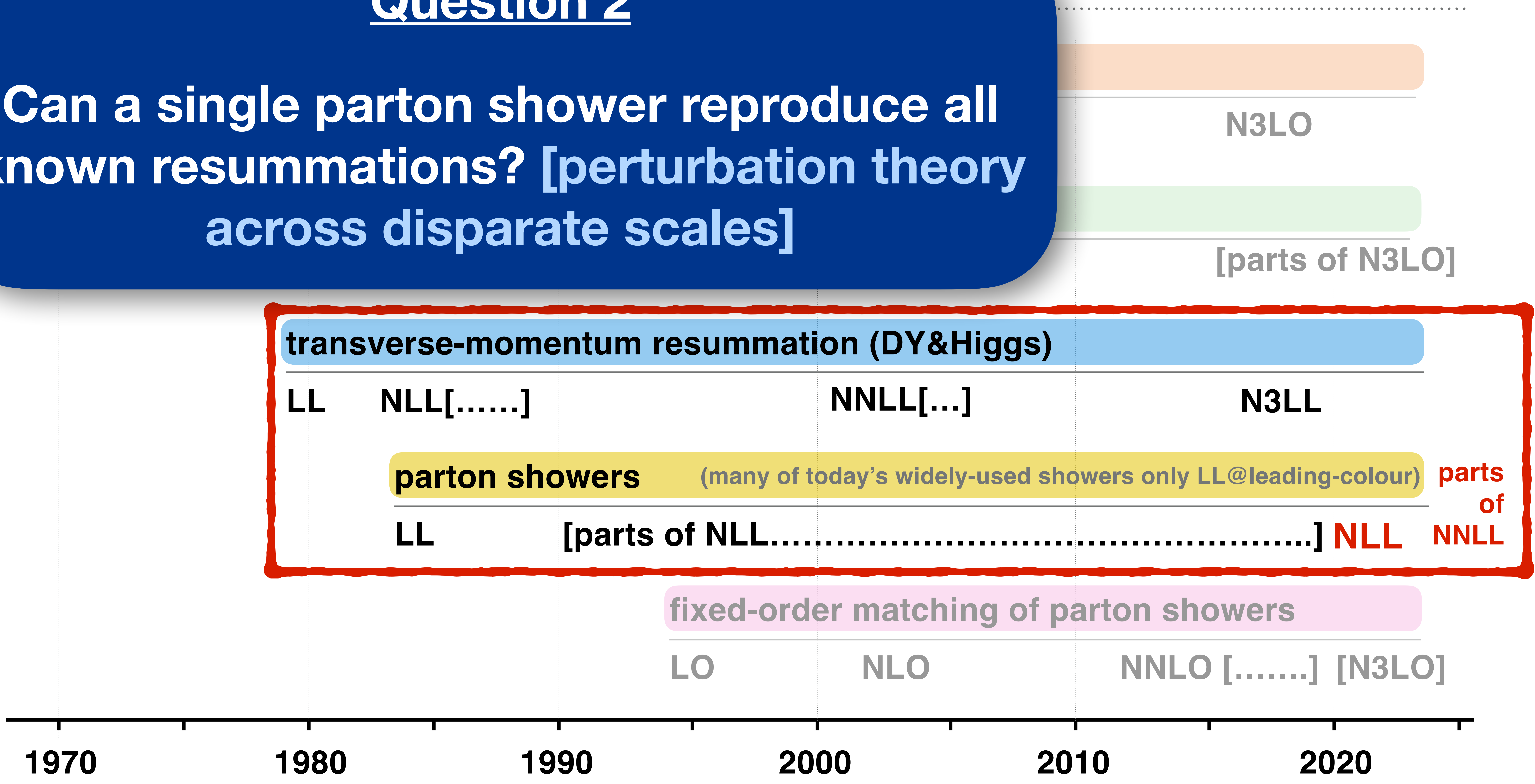
Under what conditions?

self-similar evolution continues until it reaches a non-perturbative scale

branchings widely separated in space–time treated as ~independent

Question 2

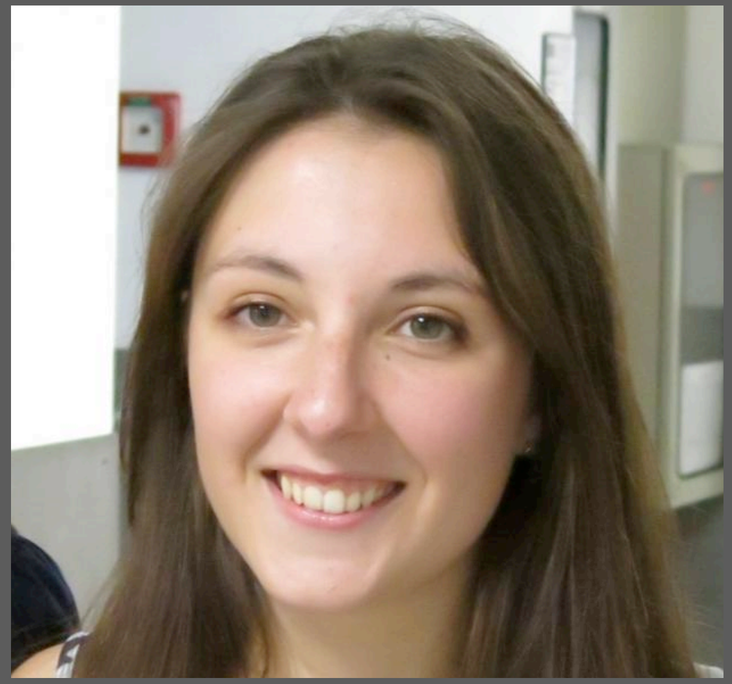
Can a single parton shower reproduce all known resummations? [perturbation theory across disparate scales]




Melissa van Beekveld
NIKEHF


Mrinal Dasgupta
Manchester


Basem El-Menoufi
Monash


Silvia Ferrario Ravasio
CERN


Keith Hamilton
Univ. Coll. London


Jack Helliwell
Monash


Alexander Karlberg
CERN


Pier Monni
CERN


GPS
Oxford


Nicolas Schalch
Oxford


Ludovic Scyboz
Monash


Alba Soto-Ontoso
Granada


Grégory Soyez
IPhT, Saclay


Silvia Zanoli
Oxford

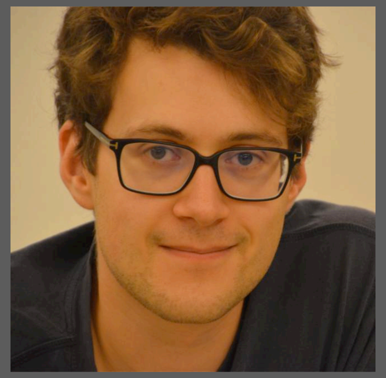
PanScales

A project to bring logarithmic understanding and accuracy to parton showers

European Research Council
Established by the European Commission

ERC funded
2018-2024

former members


Frédéric Dreyer

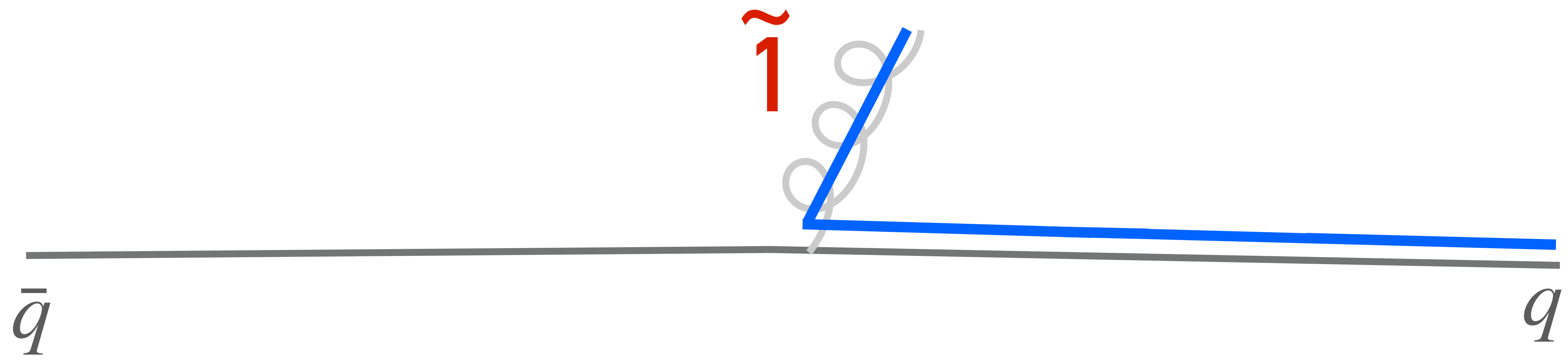

Rob Verheyen


Rok Medves


Emma Slade

1. Momentum conservation: the core of any shower

Dipole showers conserve momentum at each step. Traditional dipole-local recoil:



$$d\mathcal{P}^{\mathrm{FS}}_{\tilde{\imath}\to ik} = \frac{\alpha_s(k_\perp^2)}{2\pi}\frac{dk_\perp^2}{k_\perp^2}\frac{dz}{z}\frac{d\varphi}{2\pi}N_{ik}^{\mathrm{sym}}\left[zP_{\tilde{\imath}\to ik}(z)\right]$$

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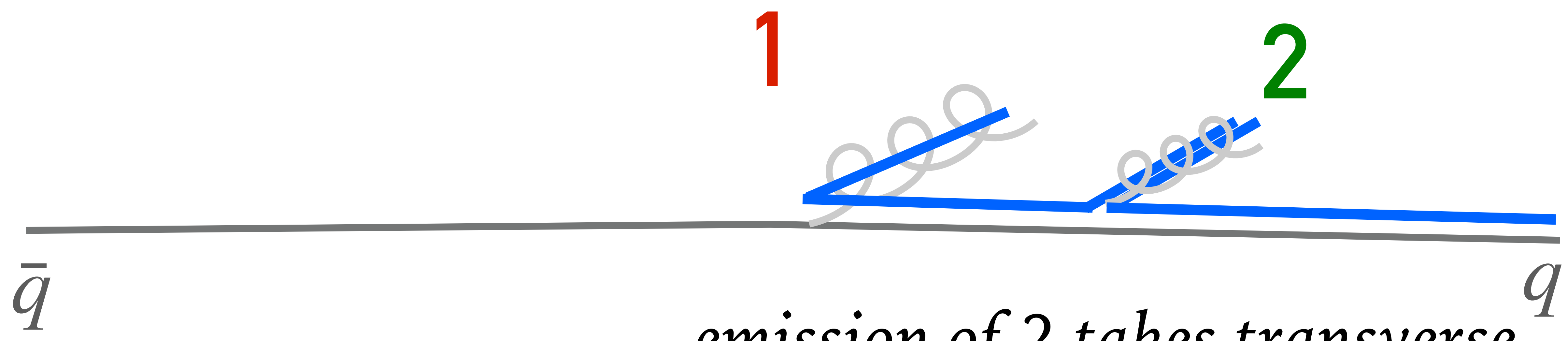

emission of 2 takes transverse recoil from 1

1. Momentum conservation: the core of any shower

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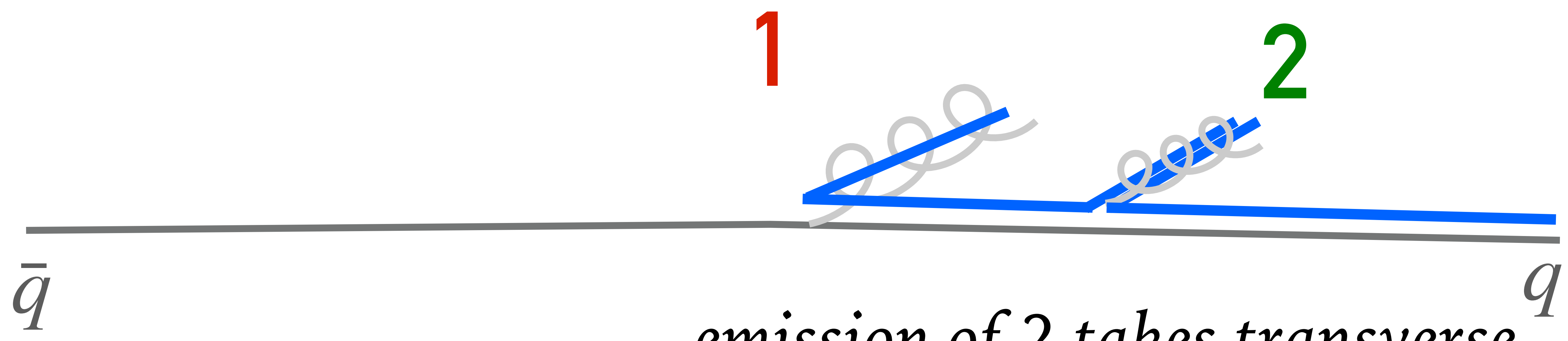

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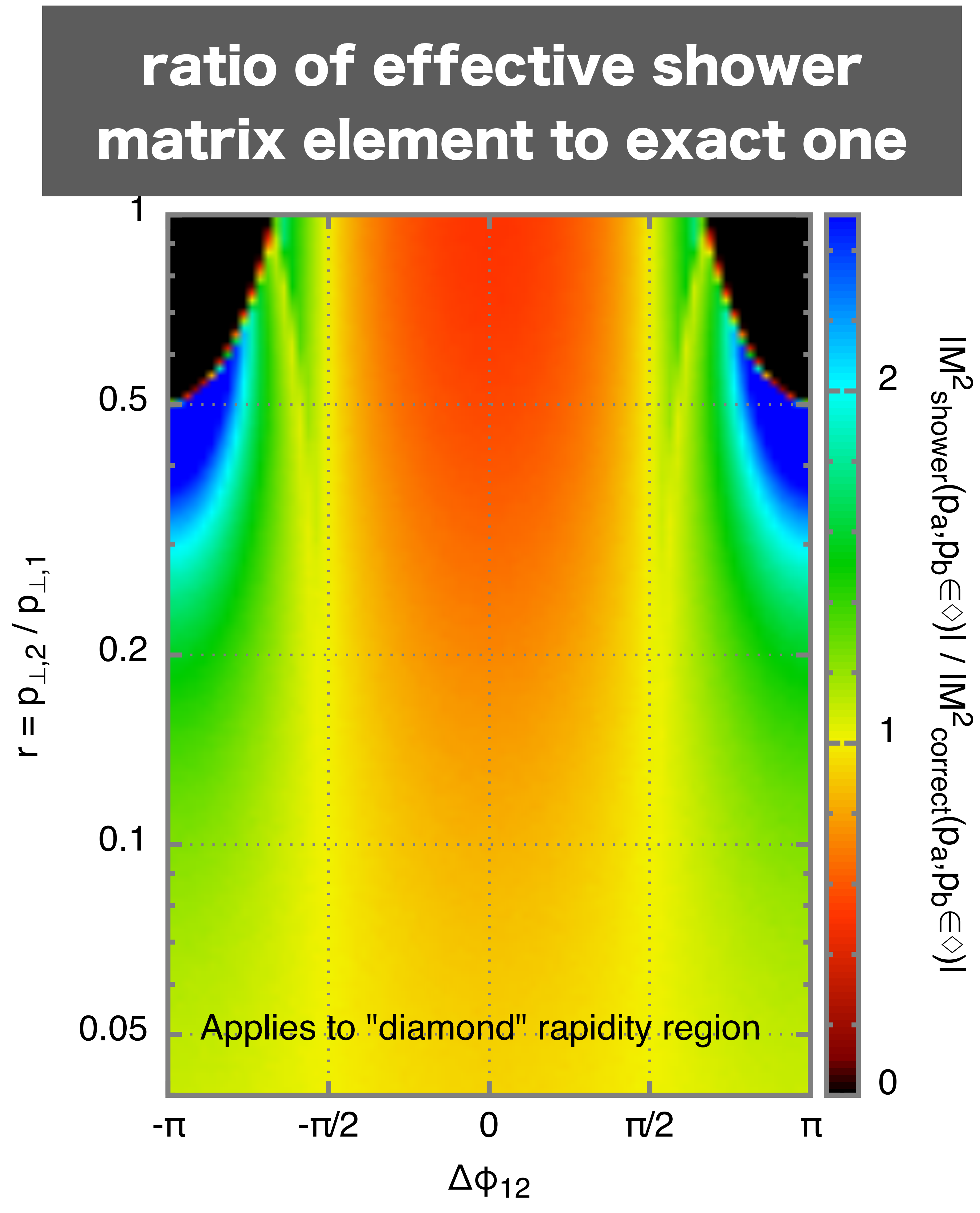


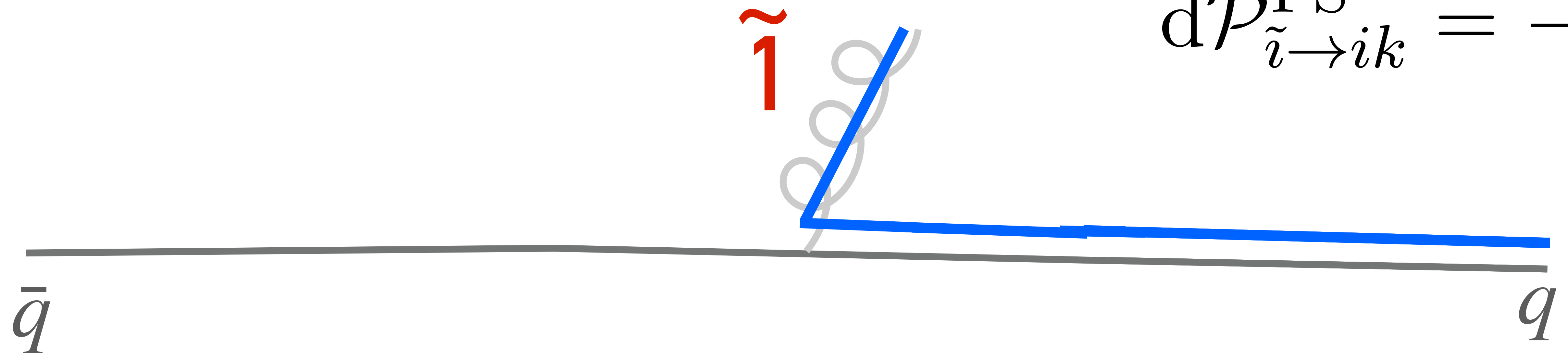
Shower initially generated matrix element for particle $\tilde{1}$, whose momentum differs (by ~ 50%) from final particle 1.

Matrix element is incorrect wrt final momentum 1.

First observed: Andersson, Gustafson, Sjogren '92
Closely related effect present for Z p_t: Nagy & Soper 0912.4534
Impact on log accuracy across many observables: Dasgupta, Dreyer, Hamilton, Monni, GPS, 1805.09327

1. Correct recoil rule: no side effects on other distant emissions

One approach



$$d\mathcal{P}^{\mathrm{FS}}_{\tilde{i}\to ik} = \frac{\alpha_s(k_\perp^2)}{2\pi}\frac{dk_\perp^2}{k_\perp^2}\frac{dz}{z}\frac{d\varphi}{2\pi}N^{\mathrm{sym}}_{ik}\left[zP_{\tilde{i}\to ik}(z)\right]$$

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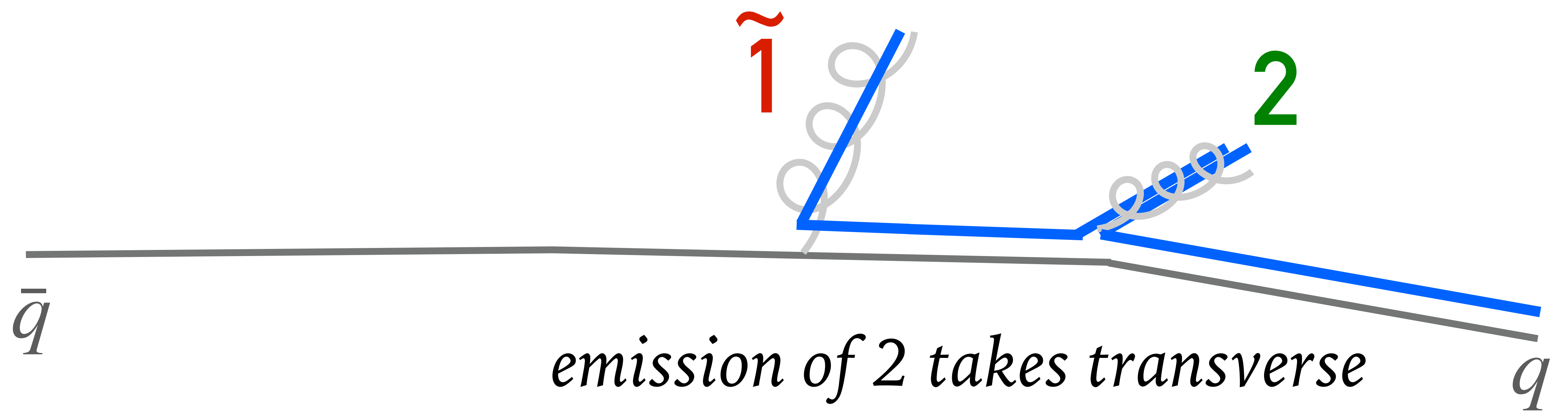
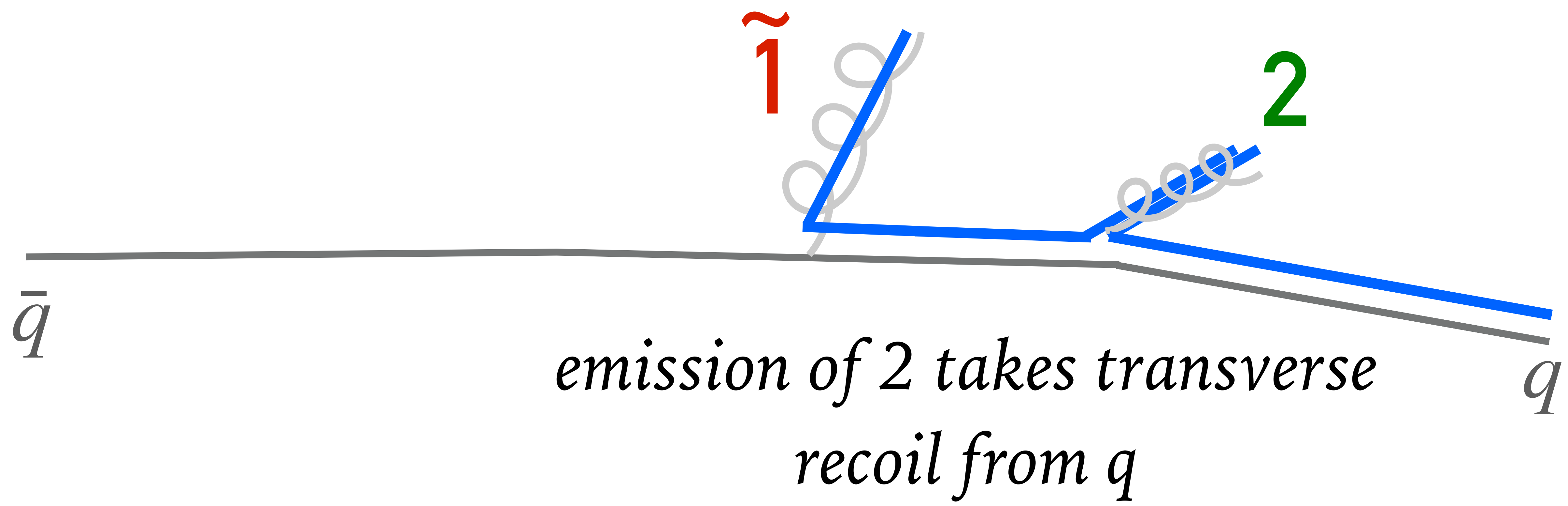


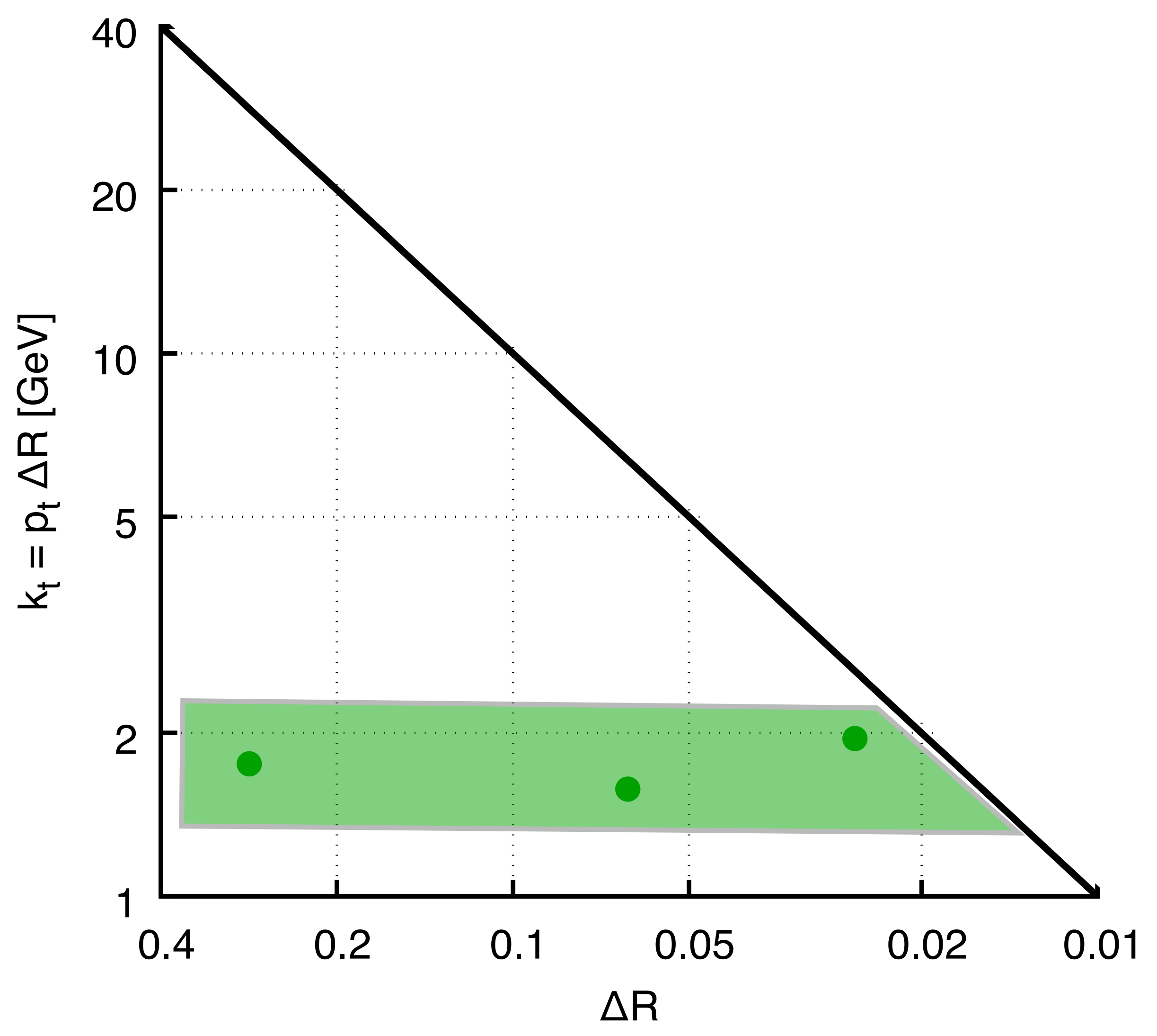
emission of 2 takes transverse recoil from q

θ_{1q} left almost unchanged if ⊥ recoil from emission of 2 taken by (much harder) q

1. Correct recoil rule: no side effects on other distant emissions

One approach





θ_{1q} left almost unchanged if ⊥ recoil from emission of 2 taken by (much harder) q

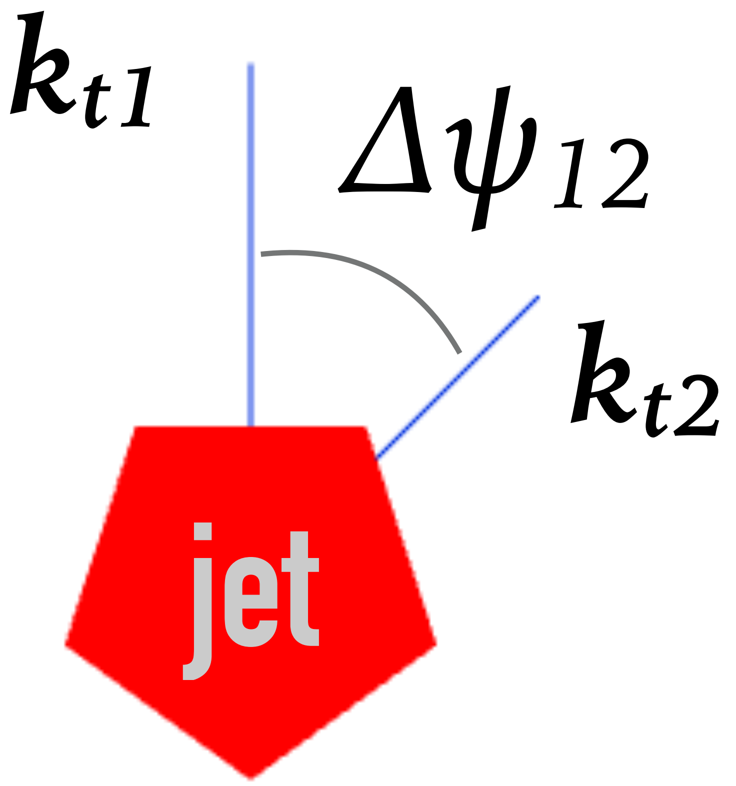
Can be achieved in multiple ways:

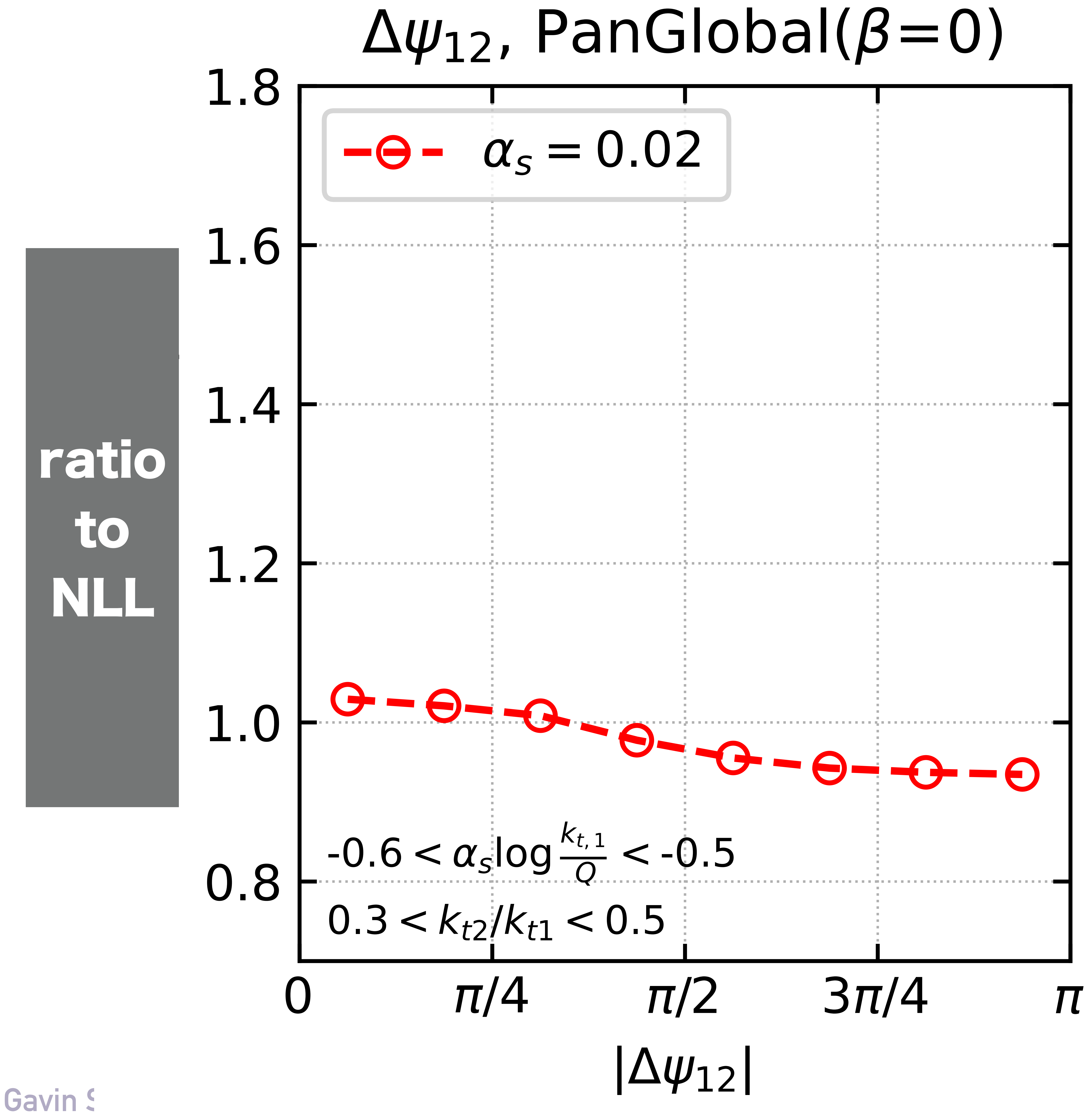
- global transverse recoil
  (Dasgupta et al 2002.11114, "**PanGlobal**"; Holguin Seymour & Forshaw 2003.06400; Alaric 2208.06057 + ⋯, Apollo, 2403.19452)
- local transverse recoil, with non-standard shower ordering & dipole partition
  (2002.11114 "**PanLocal**"; Nagy & Soper 0912.4534 + ⋯, "Deductor")

Element #2: testing correctness

Parton showers operate at all orders and mix many effects. How can you separate out just the orders you aim to control to test they're correct?

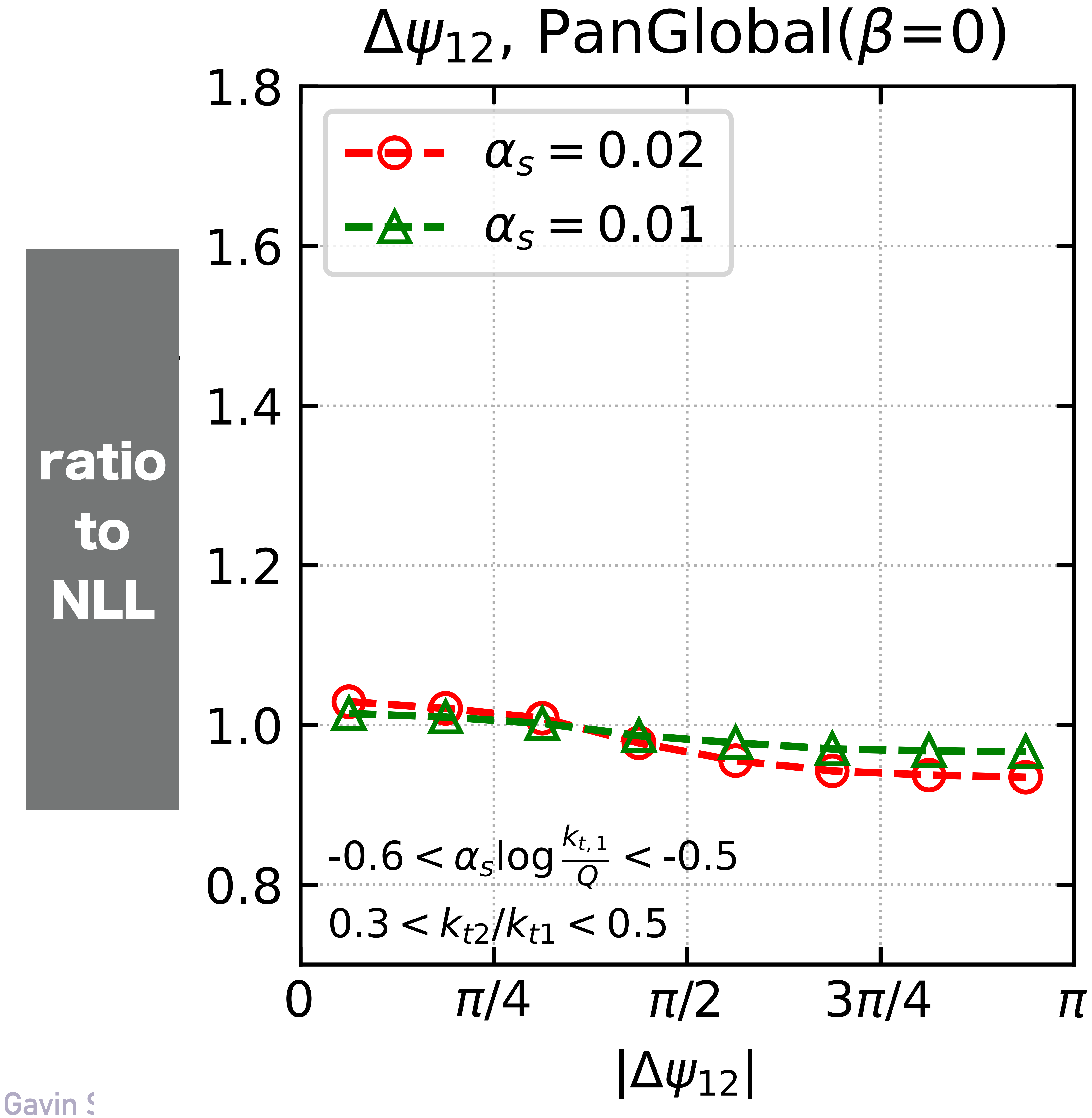
Test class 2: full shower v. all-order NLL

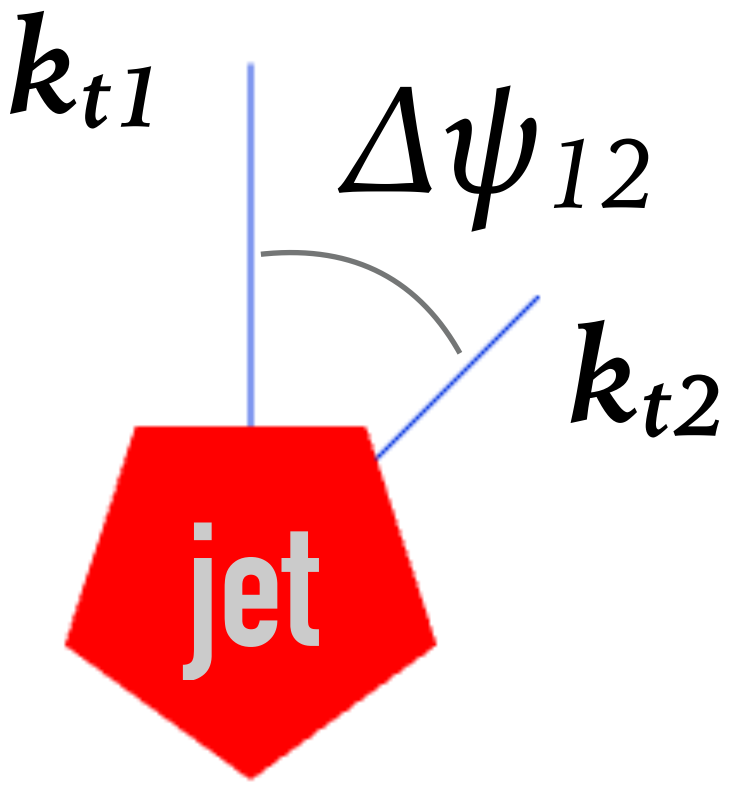




- run full shower & measure specific observable: azimuth between two highest-k_t emissions (soft-collinear)
- Normal QCD: $\alpha_s \simeq 0.1$ and two orders of magnitude in momentum
- Focus on "logarithmic" part by taking smaller **$\alpha_s = 0.02$ and 10 orders of magnitude**
- ratio to NLL should be flat $\equiv 1$
- it isn't: have we got an NLL mistake? Or a residual subleading (NNLL) term?

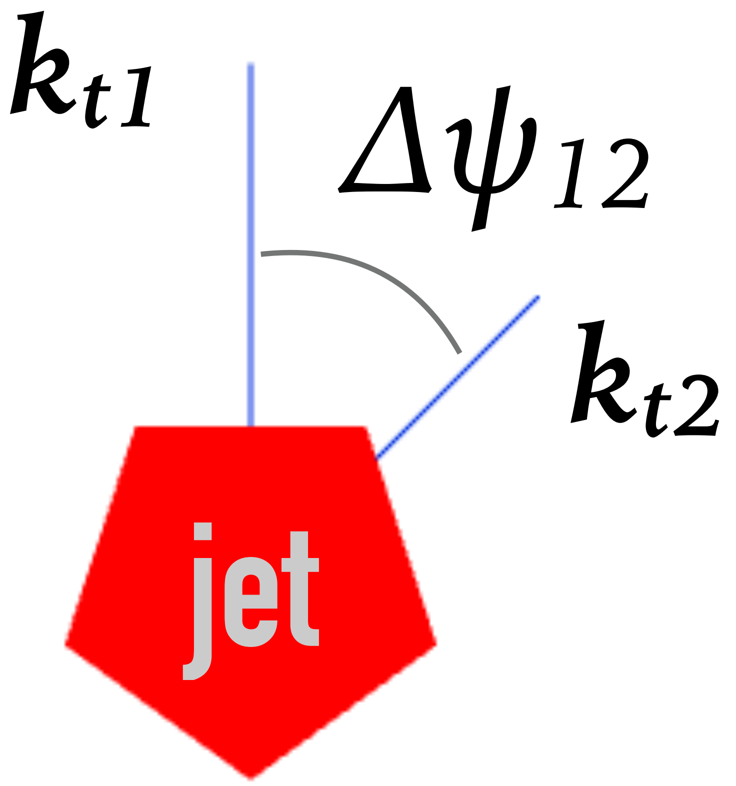
Test class 2: full shower v. all-order NLL

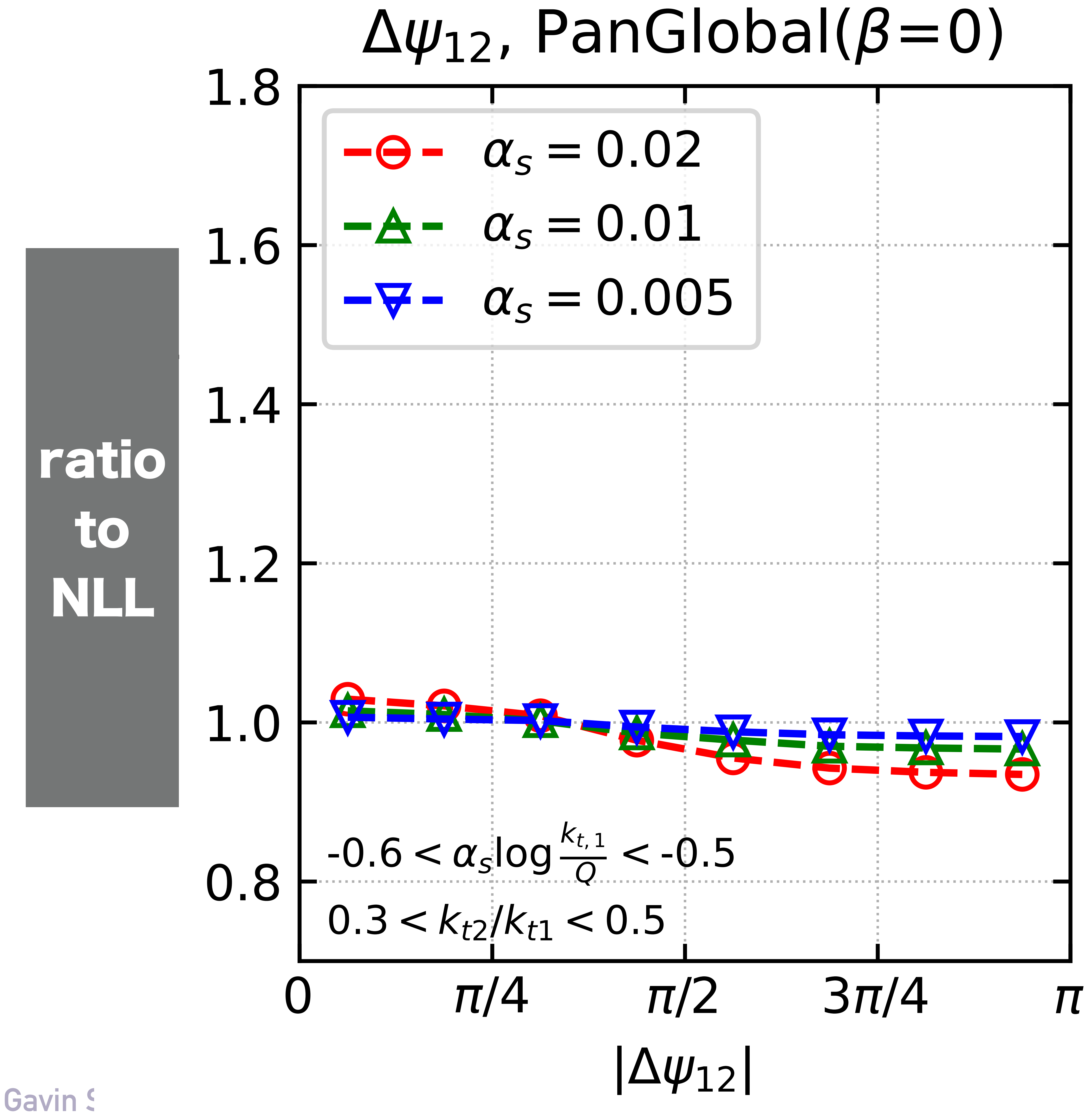




- run full shower & measure specific observable: azimuth between two highest-k_t emissions (soft-collinear)
- Normal QCD: $\alpha_s \simeq 0.1$ and two orders of magnitude in momentum
- Focus on "logarithmic" part by taking smaller $\alpha_s = 0.01$ **and 20 orders of magnitude**
- ratio to NLL should be flat ≡ 1
- it isn't: have we got an NLL mistake? Or a residual subleading (NNLL) term?

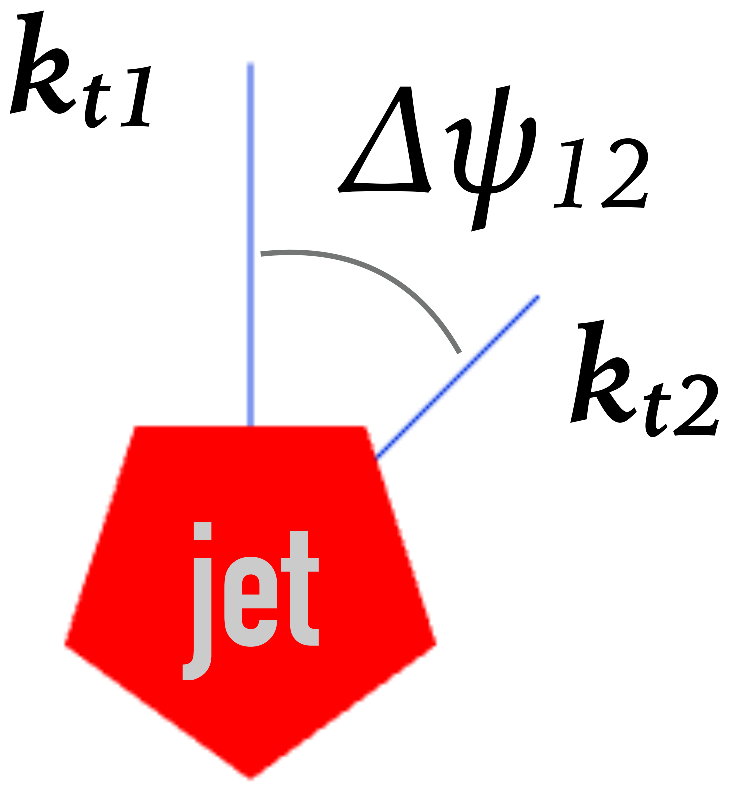
Test class 2: full shower v. all-order NLL

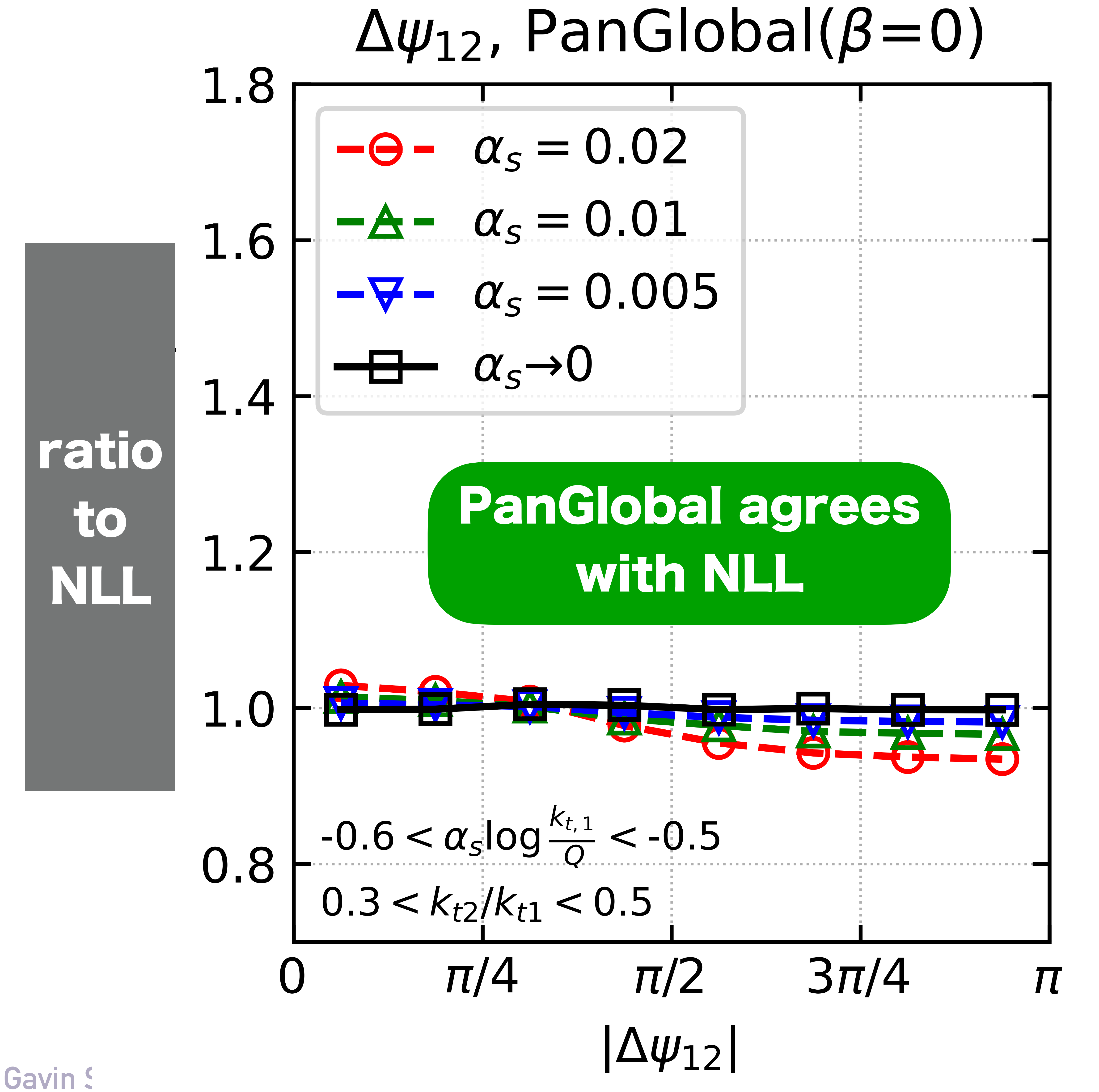




- run full shower & measure specific observable: azimuth between two highest-k_t emissions (soft-collinear)
- Normal QCD: $\alpha_s \simeq 0.1$ and two orders of magnitude in momentum
- Focus on "logarithmic" part by taking smaller **$\alpha_s = 0.005$ and 40 orders of magnitude**
- ratio to NLL should be flat $\equiv 1$
- it isn't: have we got an NLL mistake? Or a residual subleading (NNLL) term?

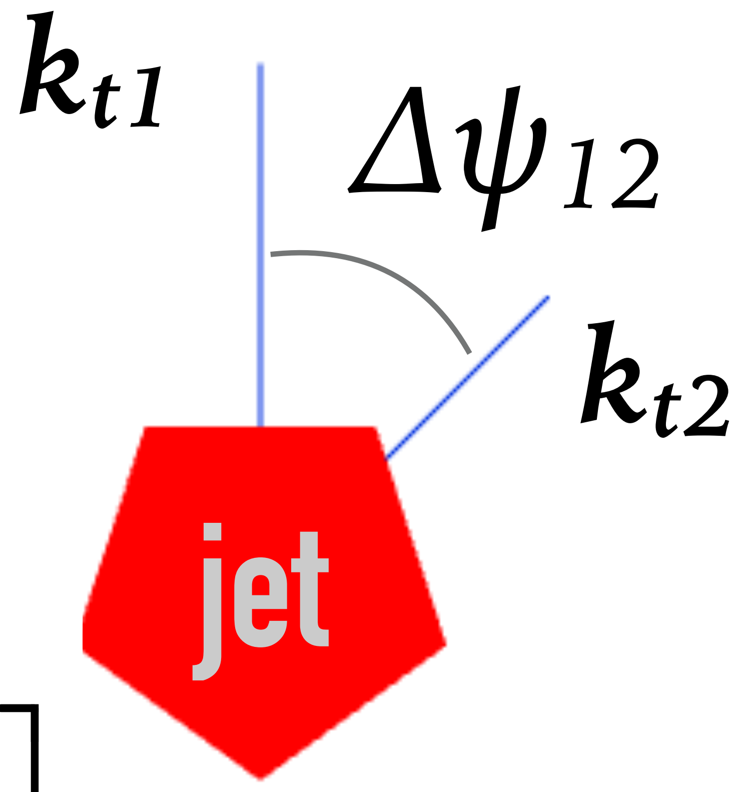
Test class 2: full shower v. all-order NLL



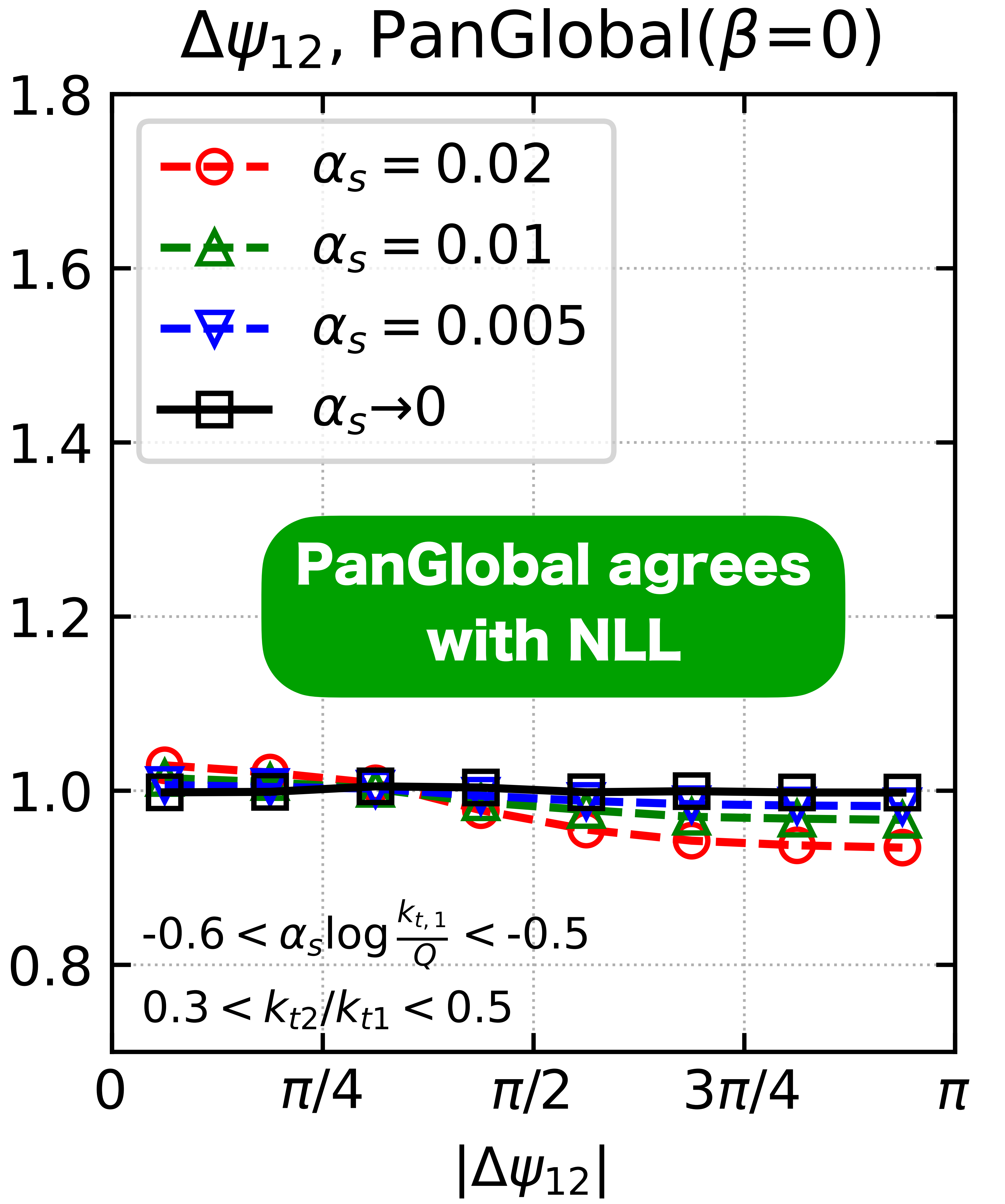


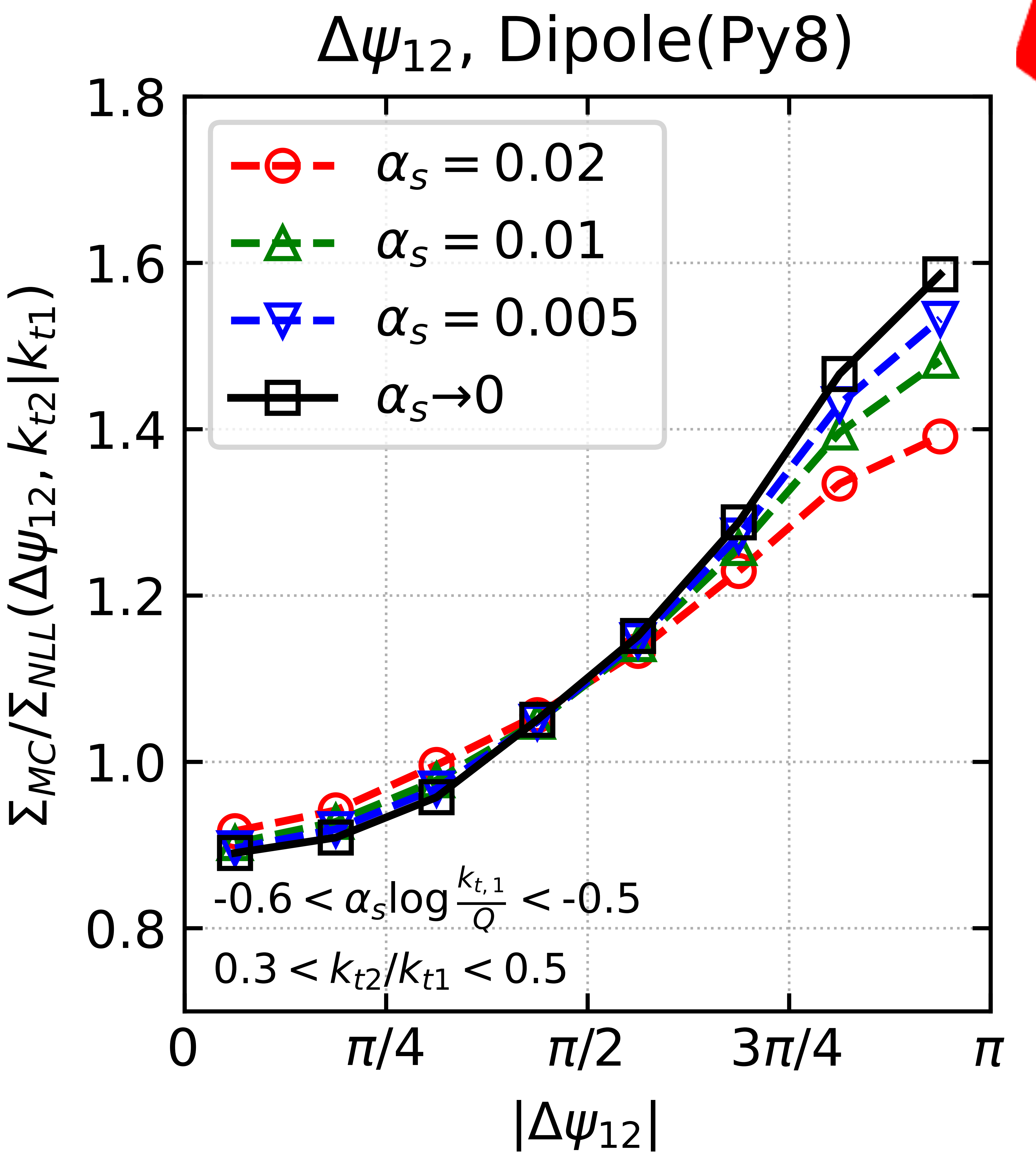
- run full shower & measure specific observable: azimuth between two highest-k_t emissions (soft-collinear)
- Normal QCD: $\alpha_s \simeq 0.1$ and two orders of magnitude in momentum
- Focus on "logarithmic" part by taking smaller $\alpha_s = 0.005$ **and 40 orders of magnitude**
- ratio to NLL should be flat $\equiv 1$
- **extrapolation $\alpha_s \to 0$ agrees with NLL**

Test class 2: full shower v. all-order NLL

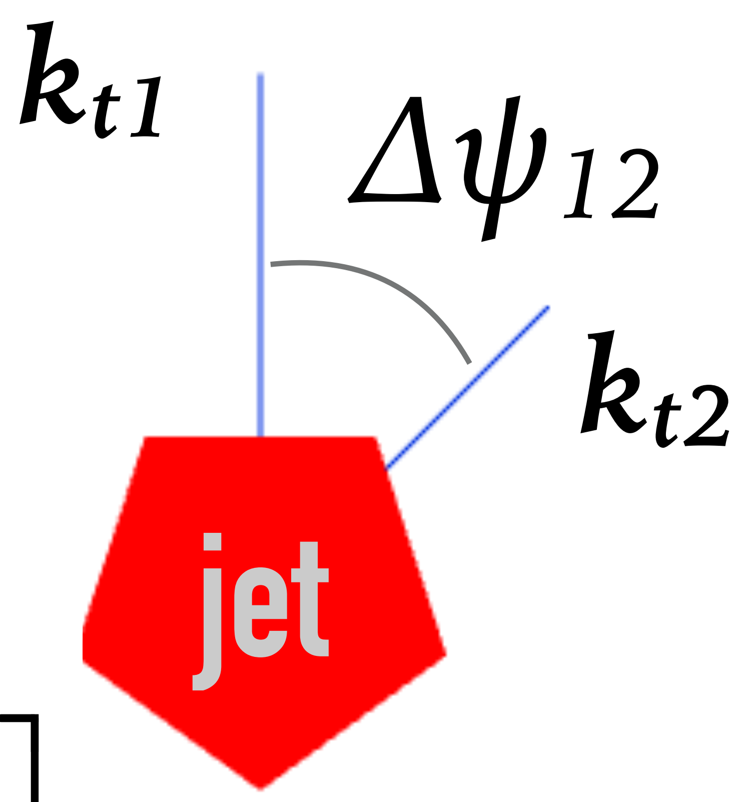


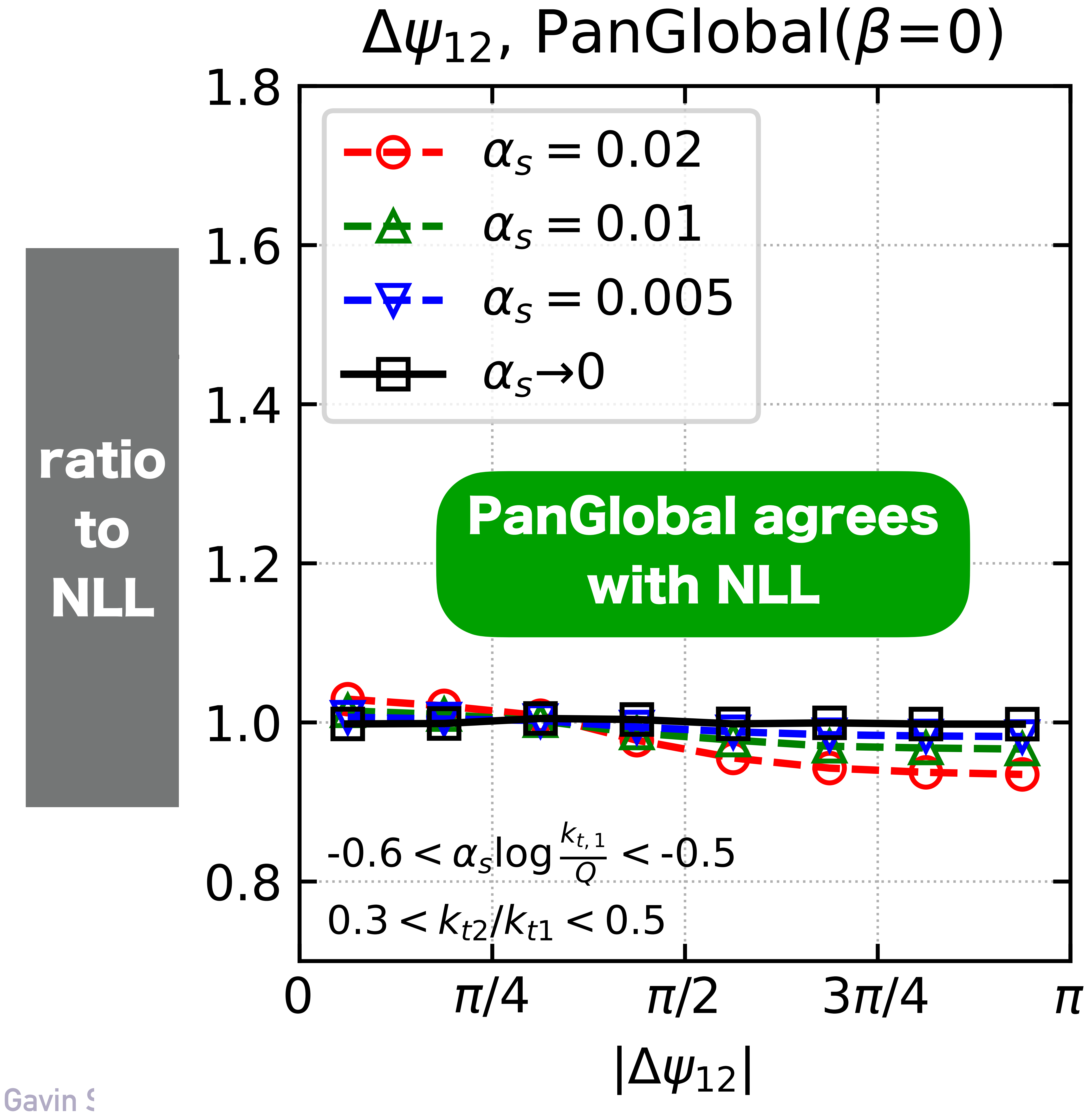
ratio to NLL

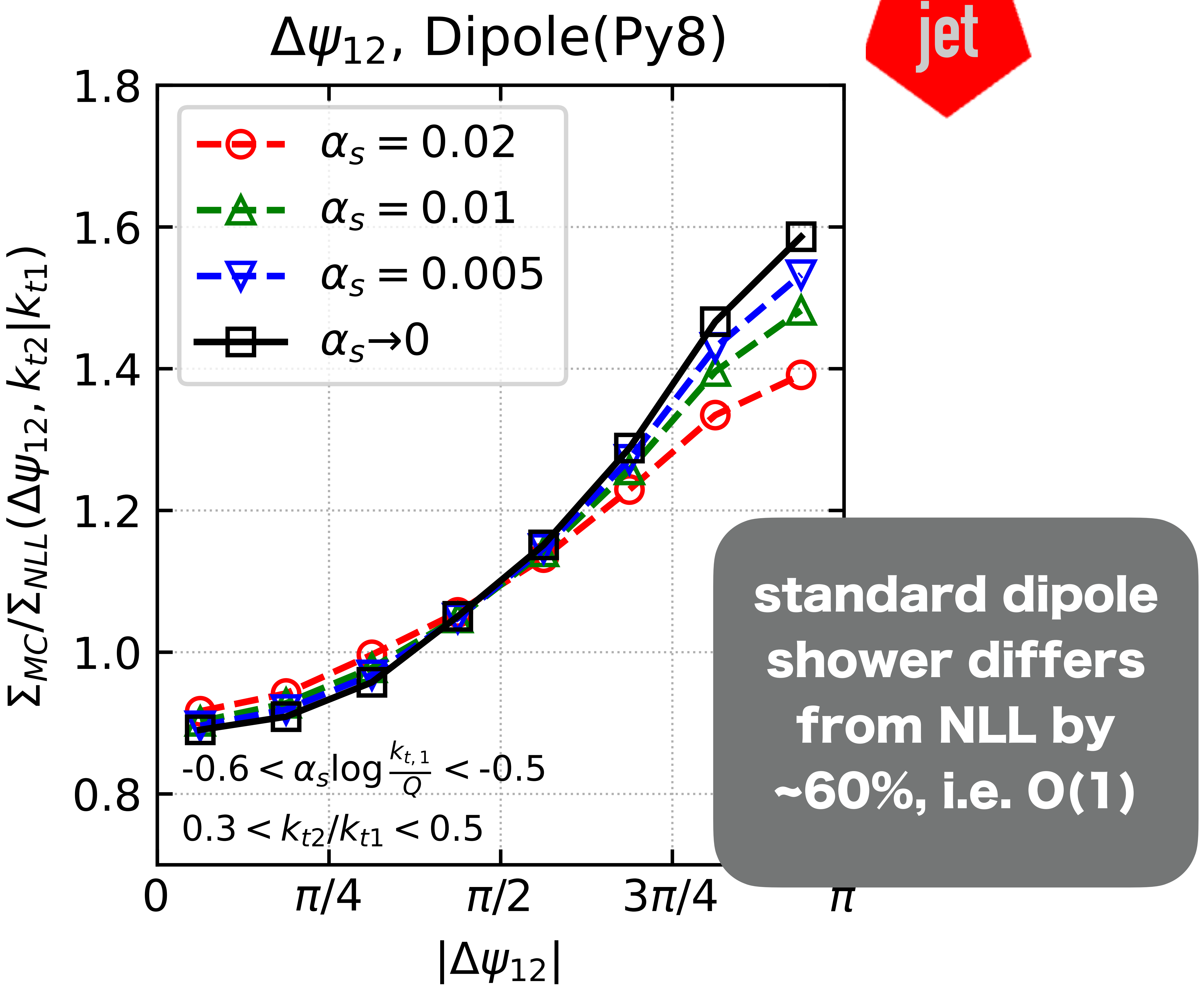




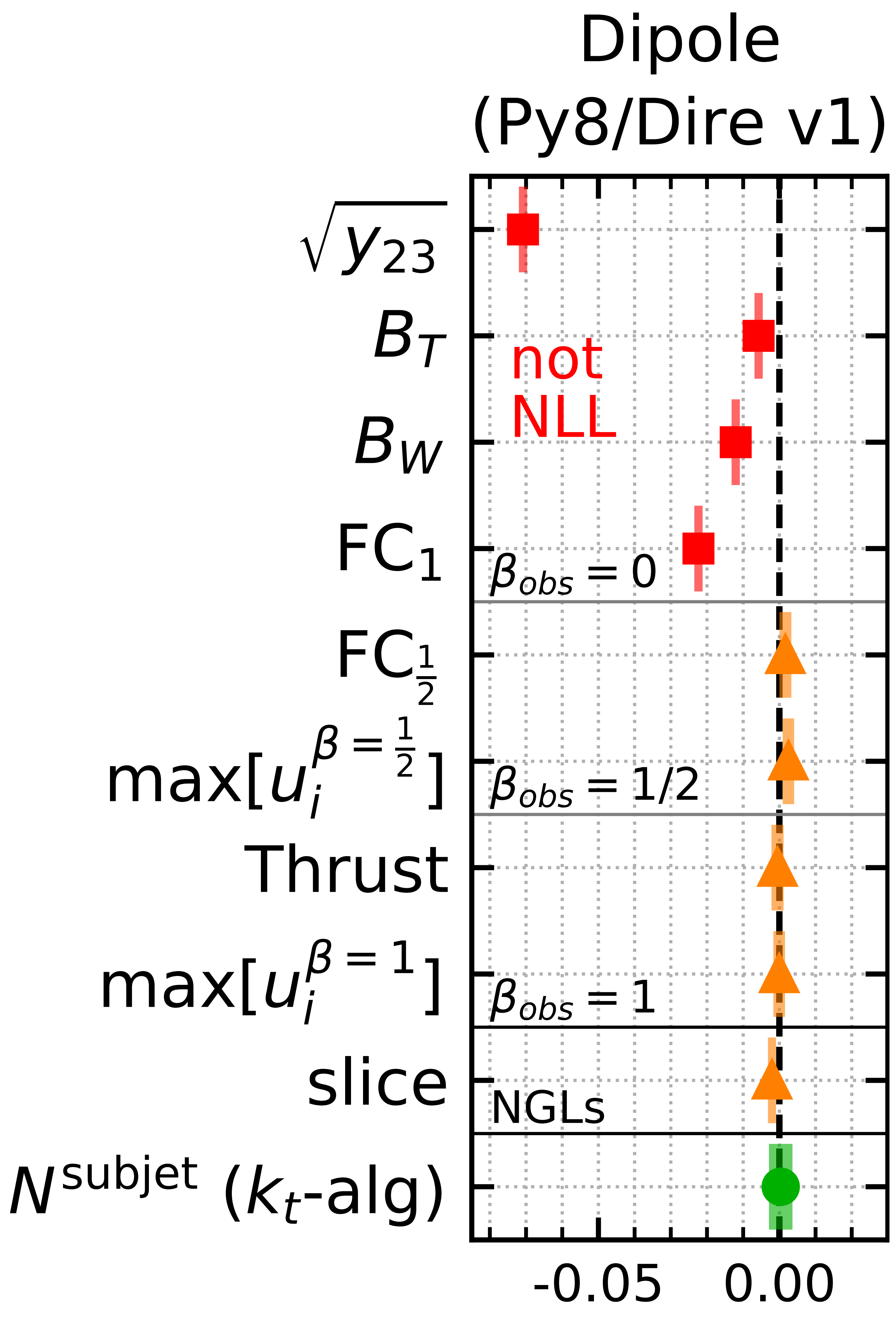
Test class 2: full shower v. all-order NLL





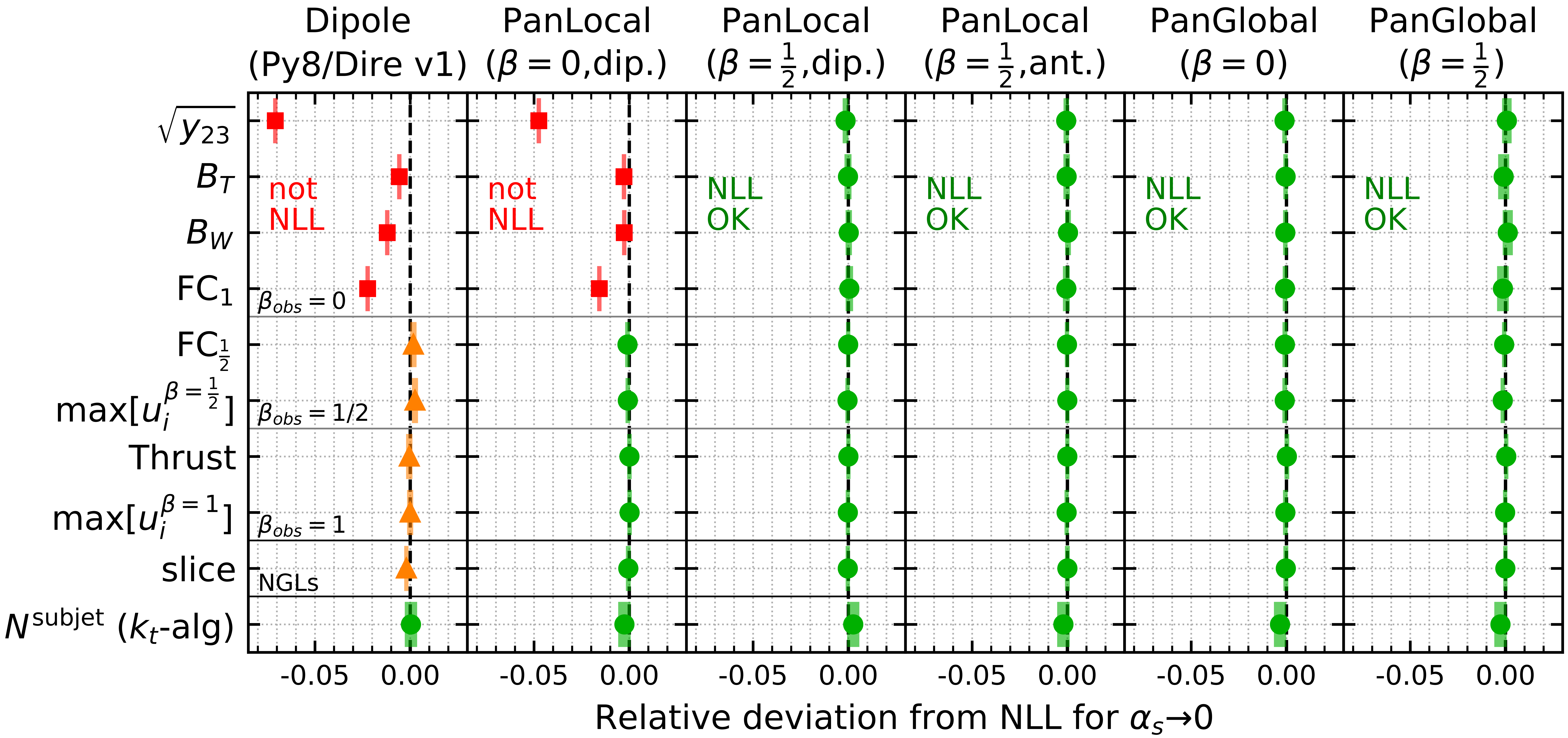


Test class 2: full shower v. all-order NLL — many observables



Relative deviation from NLL for $\alpha_s \to 0$

Test class 2: full shower v. all-order NLL — many observables



NLL accuracy is the becoming the new standard

Logarithmic accuracy of parton showers: a fixed-order study
Dasgupta, Dreyer, Hamilton, Monni, Salam [1805.09327]

Parton showers beyond leading logarithmic accuracy
Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez [2002.11114]

Colour and logarithmic accuracy in final-state parton showers
Hamilton, Medves, Salam, Scyboz, Soyez [2011.10054]

Spin correlations in final-state parton showers and jet observables
Karlberg, Salam, Scyboz, Verheyen [2103.16526]

Soft spin correlations in final-sta parton showers
Hamilton, Karlberg, Salam, Scyboz, Verhe [2111.01161]

PanScales parton showers for hadron collisions: formulation and fixed-order studies
van Beekveld, Ferrario Ravasio, Salam, Soto Ontoso, Soyez, Verheyen [2205.02237]

PanScales

PanScales parton showers for hadron collisions: all-order validation
van Beekveld, Ferrario Ravasio, Hamilton, Salam, Soto Ontoso, Soyez, Verheyen [2207.09467]

Next-to-leading-logarithmic PanScales showers for deep inelastic scattering and vector boson fusion
van Beekveld, Ferrario Ravasio [2305.08645]

Introduction to the PanScales framework, version 0.1
van Beekveld, Dasgupta, El-Menoufi, Ferrario Ravasio, Hamilton, Helliwell, Karlberg, Medves, Monnim Salam, Scyboz, Soto Ontoso, Soyez, Verheyen [2312.13275]

Building a consistent parton shower
Forshaw, Holguin, Plätzer [2003.06400]

Improvements on dipole shower colour
Forshaw, Holguin, Plätzer [2011.15087]

Logarithmic accuracy of angular-ordered parton showers
Bewick, Ferrario Ravasio, Richar Seymour [1904.11866]

Herwig

Initial state radiation in the Herwig 7 angular-ordered parton shower
Bewick, Ferrario Ravasio, Richardson, Seymour [2107.04051]

A new approach to color-coherent parton evolution
Herren, Höche, Krauss, Reichelt, Schönherr [2208.06057]

Alaric

New approach to QCD final-state evolution in processes with massive partons
Assi, Höche [2307.00728]

The Alaric parton shower for hadron colliders
Höche, Krauss, Reichelt [2404.14360]

A partitioned dipole-antenna shower with improved transverse recoil
Preuss [2403.19452]

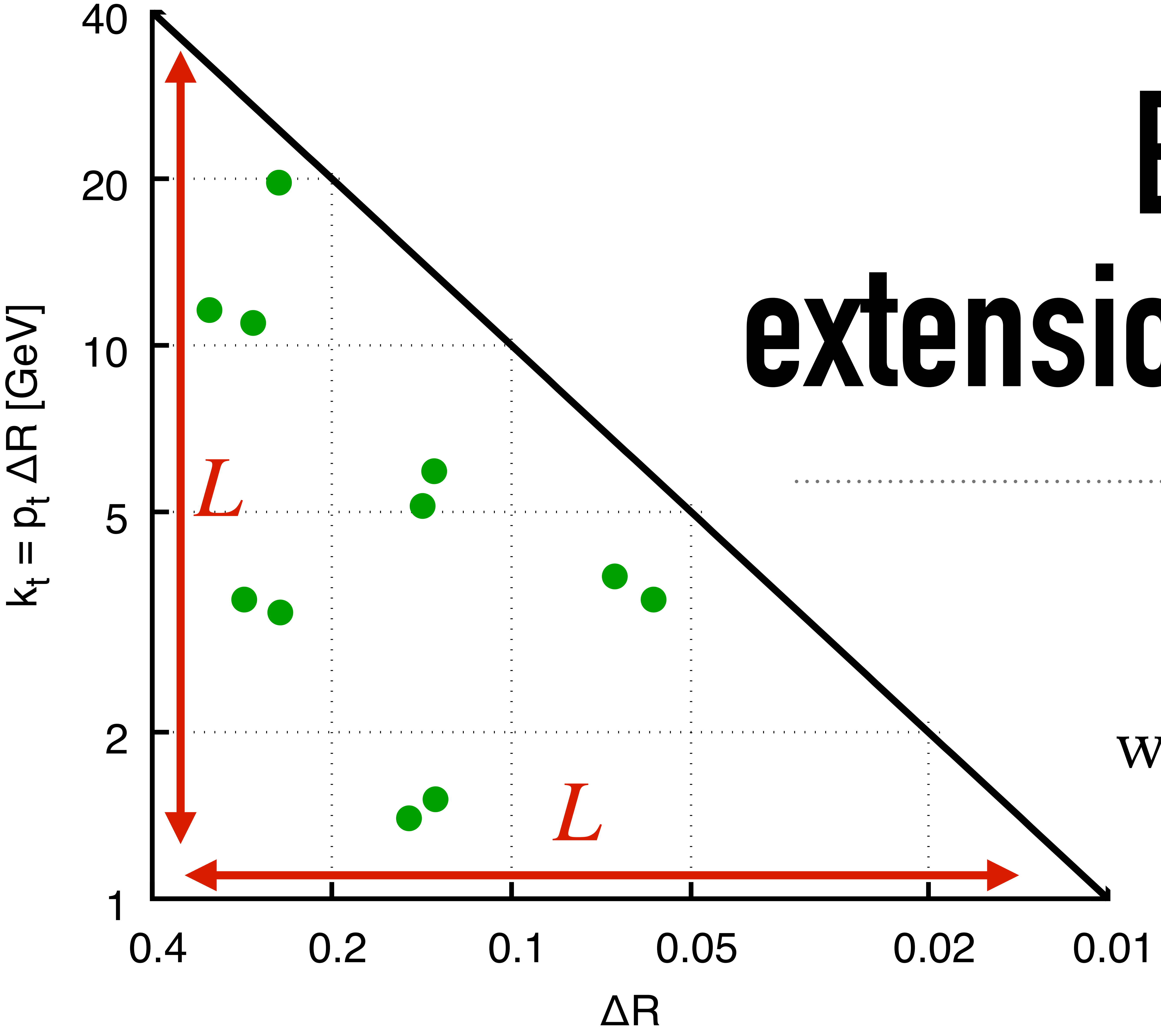
Apollo

Summation of large logarithms by parton showers
Nagy, Soper [2011.04773]

Deductor

Summation by parton showers of large logarithms in electron-positron annihilation
Nagy, Soper [2011.04777]

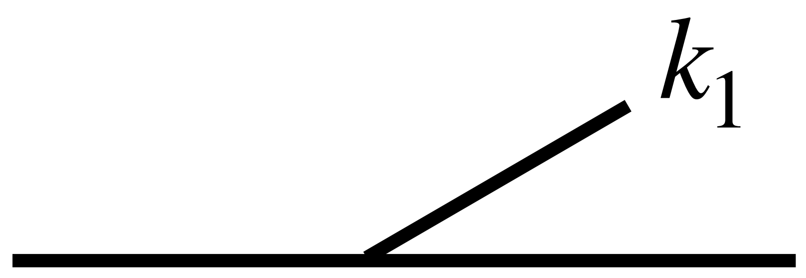
slide from M. van Beekveld



Element #3: extension to higher orders

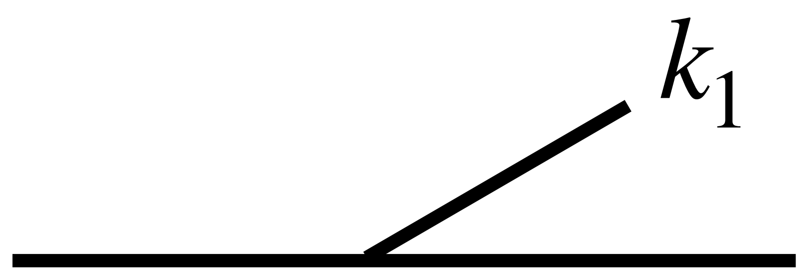
E.g. at NNLL, effective matrix element should be correct even where there are pairs of emissions close by in the Lund plane

Make each new emission's distribution conditional on one previous emission



Distribute k_1 according to $M^2(k_1)$

Make each new emission's distribution conditional on one previous emission



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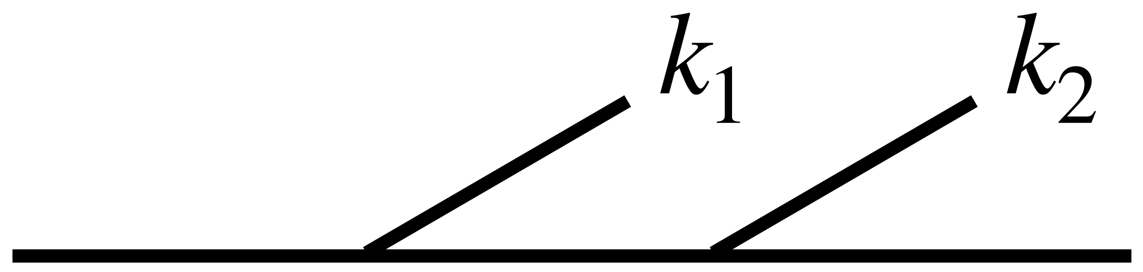
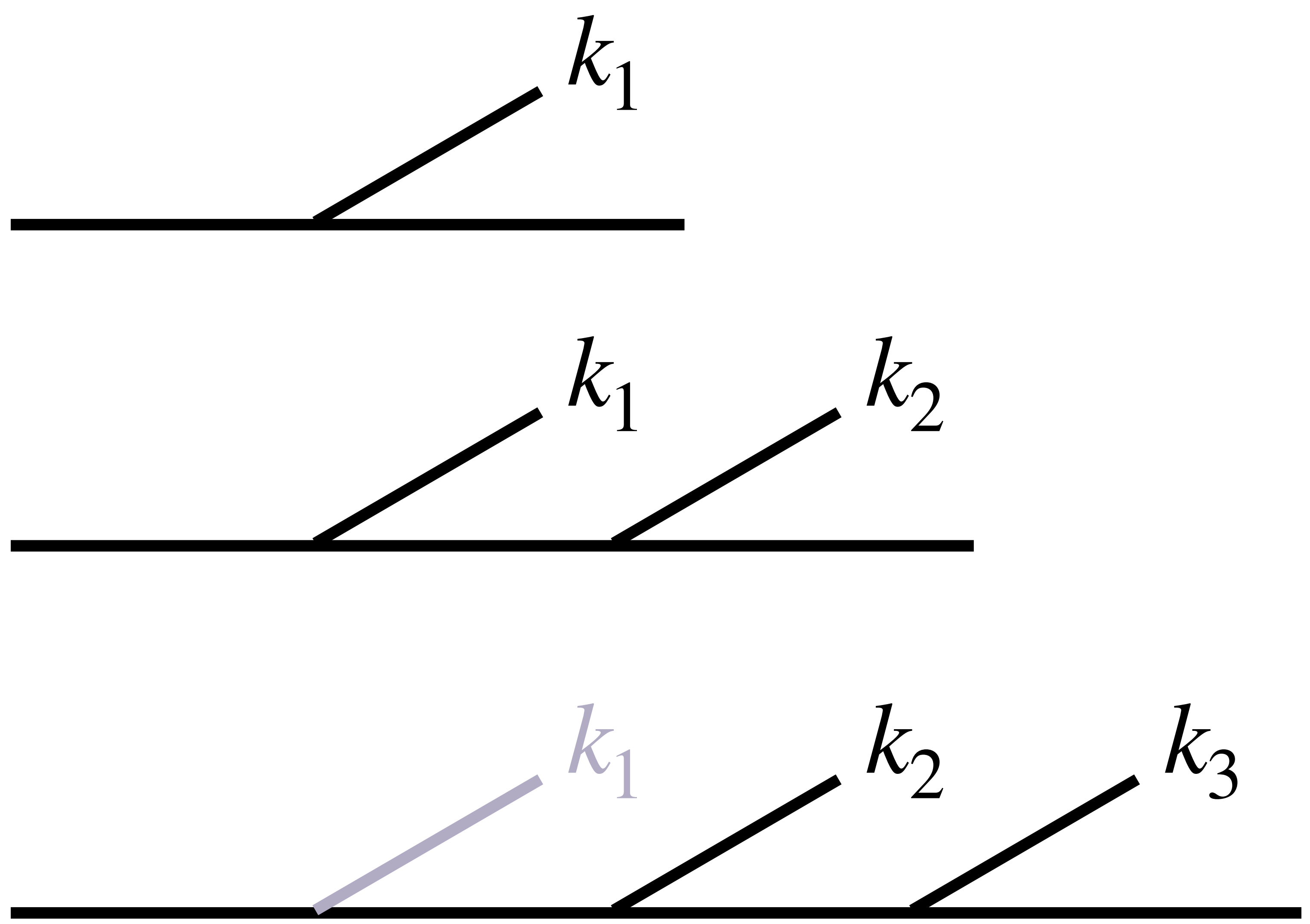


Distribute k_2 according to $M^2(k_1, k_2)/M^2(k_1)$

Make each new emission's distribution conditional on one previous emission

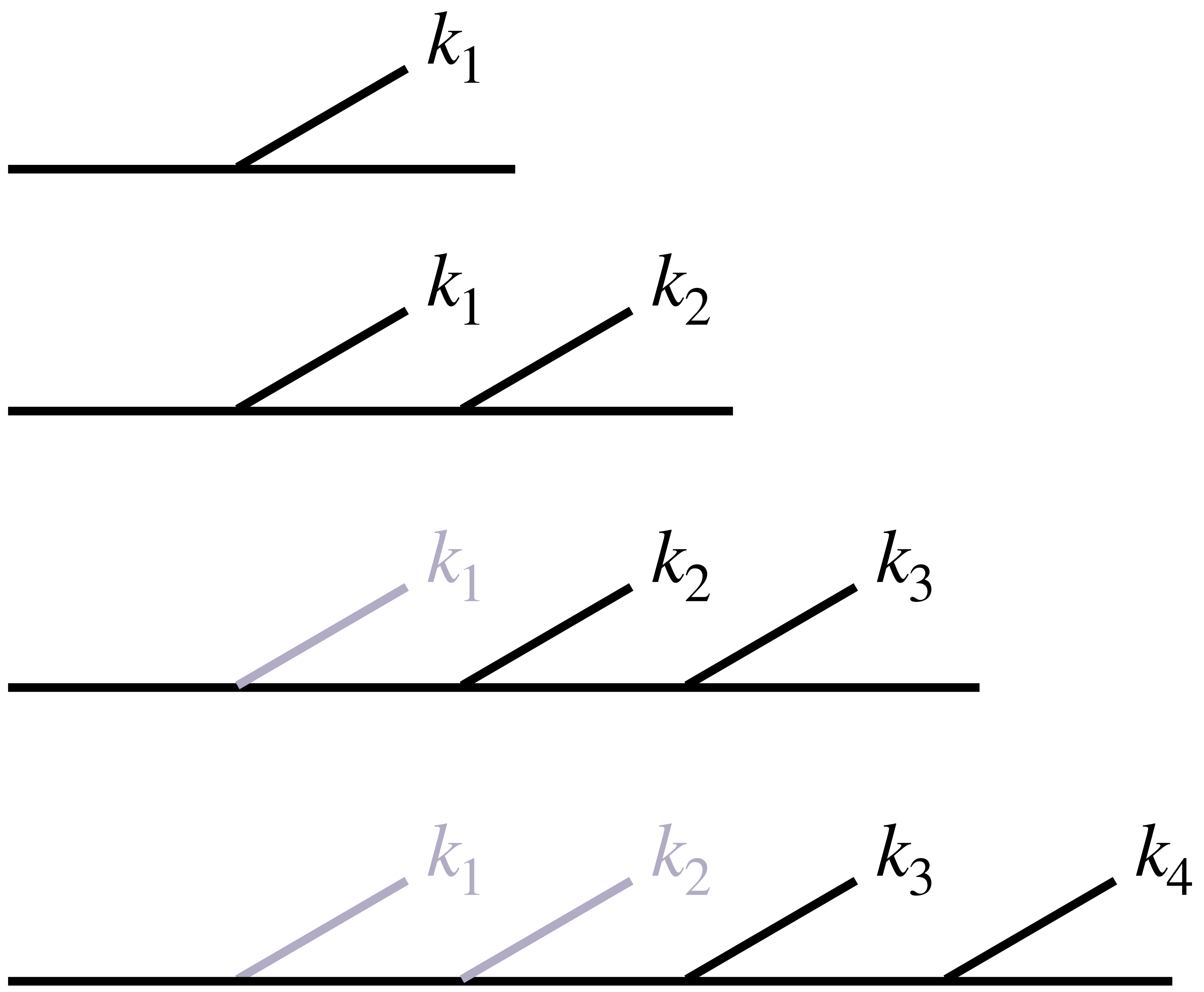


Distribute k_1 according to $M^2(k_1)$

Distribute k_2 according to $M^2(k_1, k_2)/M^2(k_1)$

Distribute k_3 according to $M^2(k_2, k_3)/M^2(k_2)$

Make each new emission's distribution conditional on one previous emission



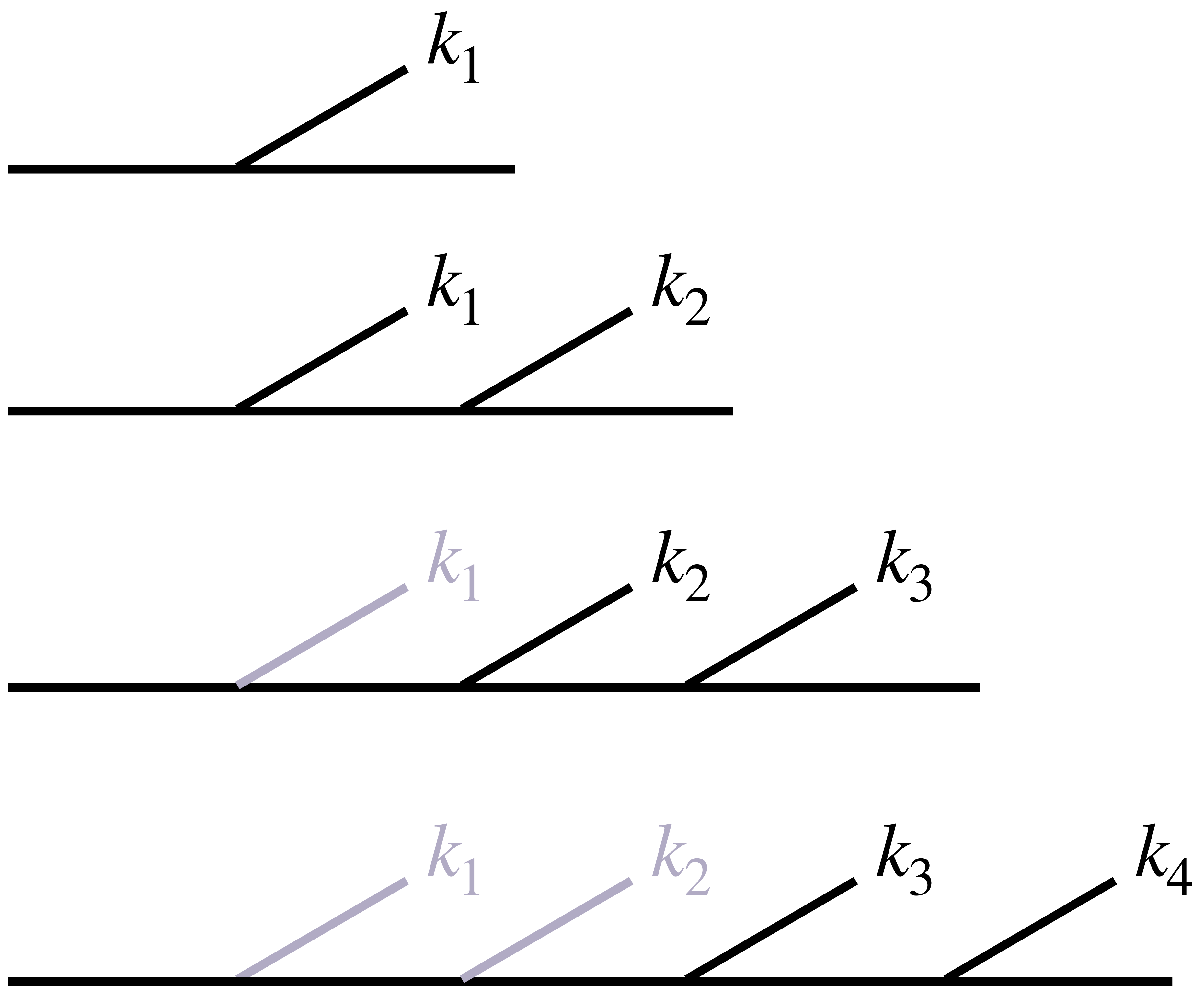
Distribute k_1 according to $M^2(k_1)$

Distribute k_2 according to $M^2(k_1, k_2)/M^2(k_1)$

Distribute k_3 according to $M^2(k_2, k_3)/M^2(k_2)$

Distribute k_4 according to $M^2(k_3, k_4)/M^2(k_3)$

Make each new emission's distribution conditional on one previous emission



Distribute k_1 according to $M^2(k_1)$

Distribute k_2 according to $M^2(k_1, k_2)/M^2(k_1)$

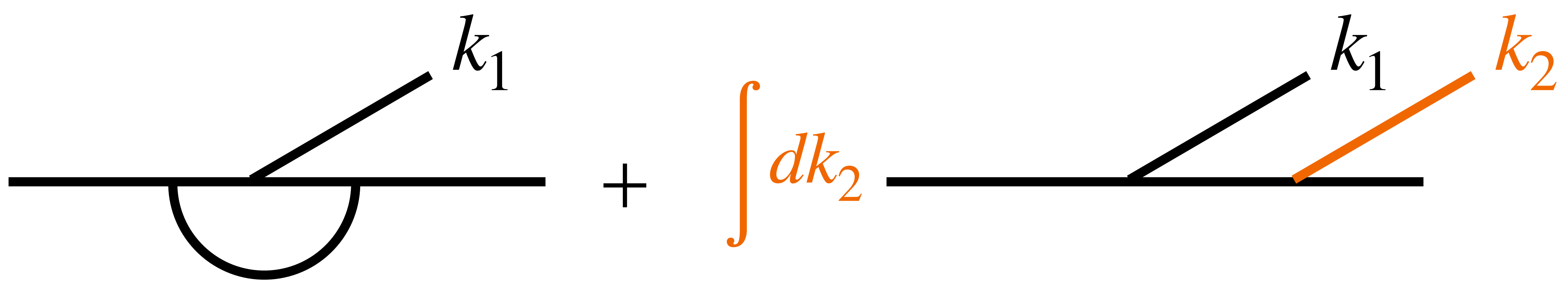
Distribute k_3 according to $M^2(k_2, k_3)/M^2(k_2)$

Distribute k_4 according to $M^2(k_3, k_4)/M^2(k_3)$

Relies on factorisation: e.g. $M^2(k_1, k_2, k_3, k_4)/M^2(k_1, k_2, k_3) \to M^2(k_3, k_4)/M^2(k_3)$
if 3 and 4 well separated in Lund plane from 1 and 2

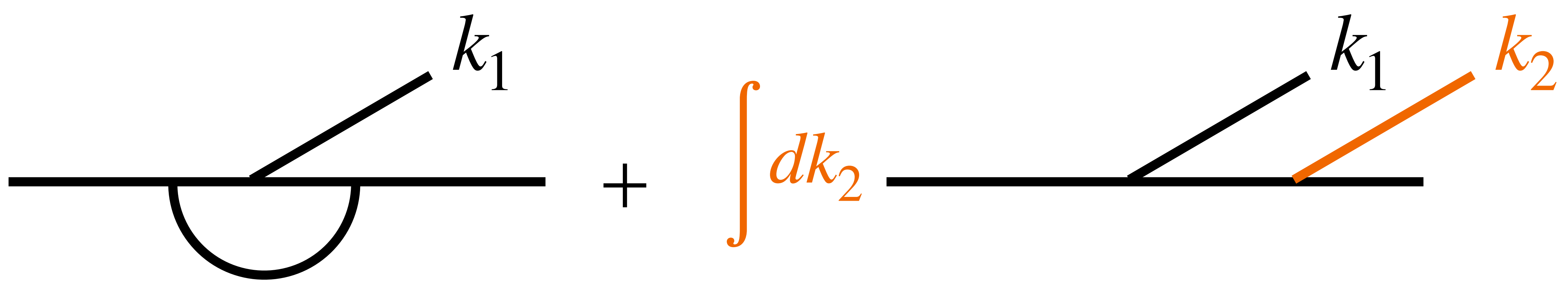
[factorised matrix elements given in Dokshitzer, Marchesini & Oriani '92, Campbell & Glover, hep-ph/9710255, Catani & Grazzini hep-ph/9810389, etc.]

Account for virtual corrections associated with each emission

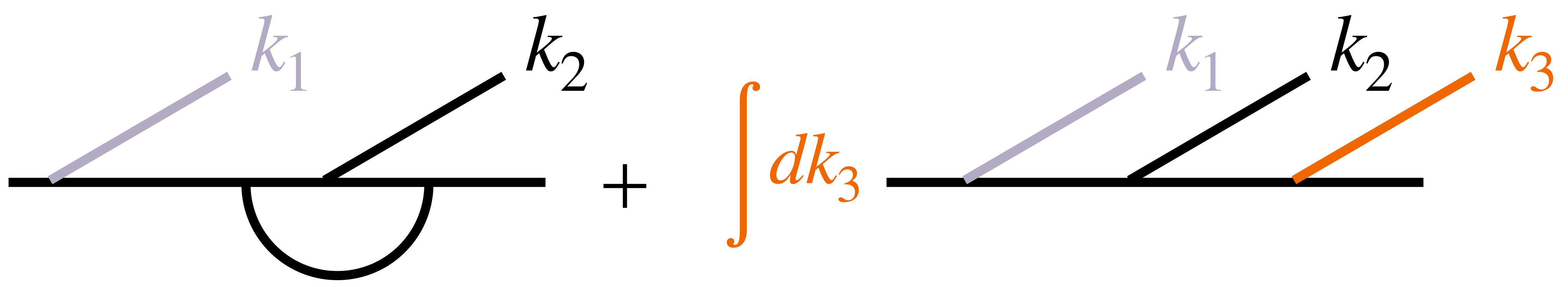


NLO correction to k_1 emission intensity sums loop correction and all possible scenarios for the next emission

Account for virtual corrections associated with each emission



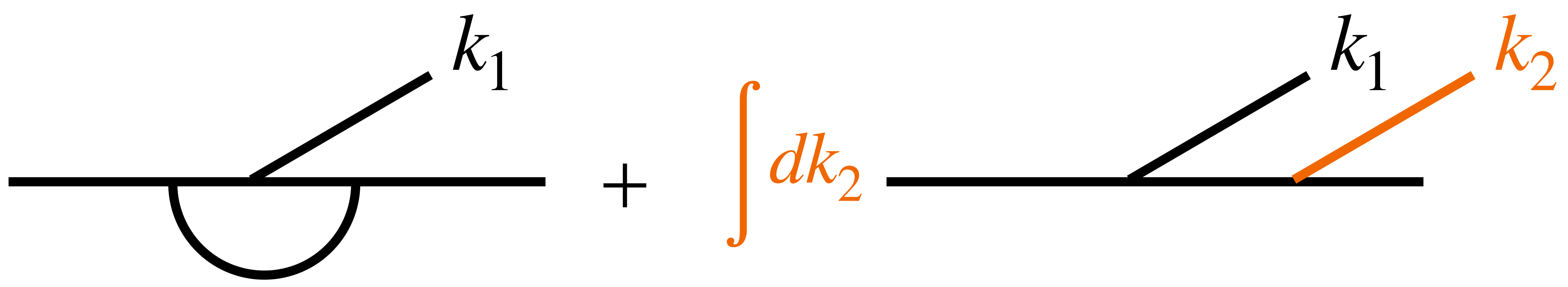
NLO correction to k_1 emission intensity sums loop correction and all possible scenarios for the next emission



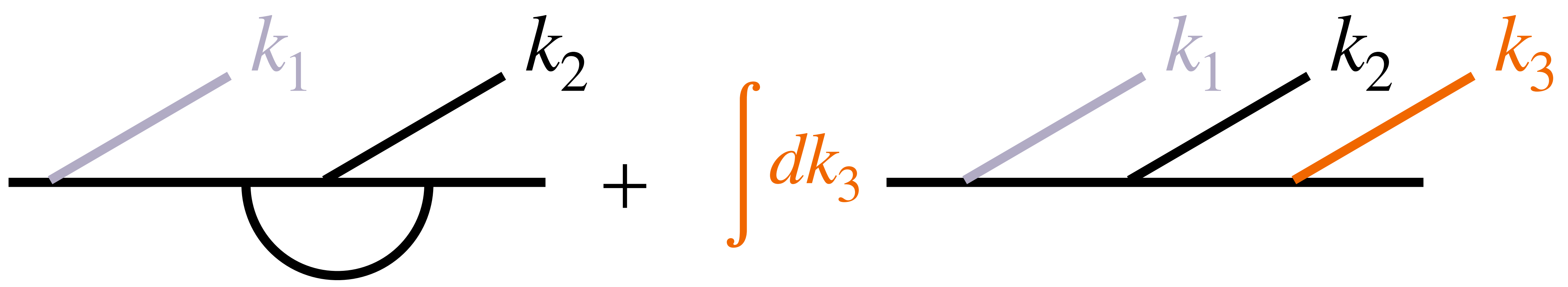
NLO correction to k_2 emission intensity sums loop correction and all possible scenarios for the following emission

etc.

Account for virtual corrections associated with each emission



NLO correction to k_1 emission intensity sums loop correction and all possible scenarios for the next emission

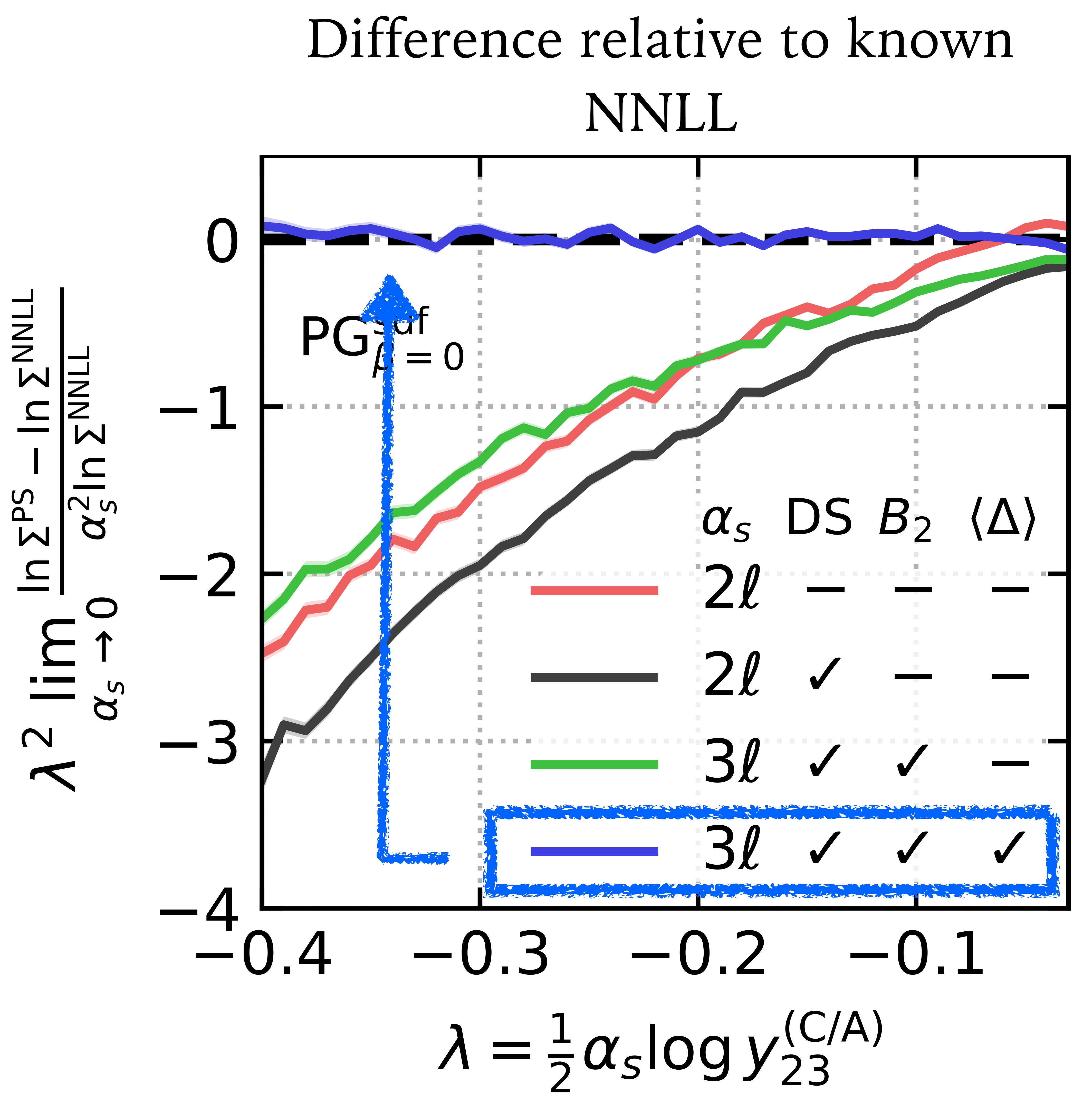


etc.

NLO correction to k_2 emission intensity sums loop correction and all possible scenarios for the following emission

Again relies on factorisation, e.g. when 1 and 2 are well separated in the Lund plane + careful nesting, cf. Ferrario Ravasio et al, 2307.11142; van Beekveld, Dasgupta, El-Menoufi, Helliwell, Monni, GPS 2409.08316
(see also Hartgring, Laenen & Skands, 1303.4974, Campbell et al 2108.07133 at fixed order)

Testing NNLL for event shapes (so far only for e+e− collisions)



need to analyse and account for all possible sources of NNLL contribution

(some, which don't affect event shapes, are still work in progress)

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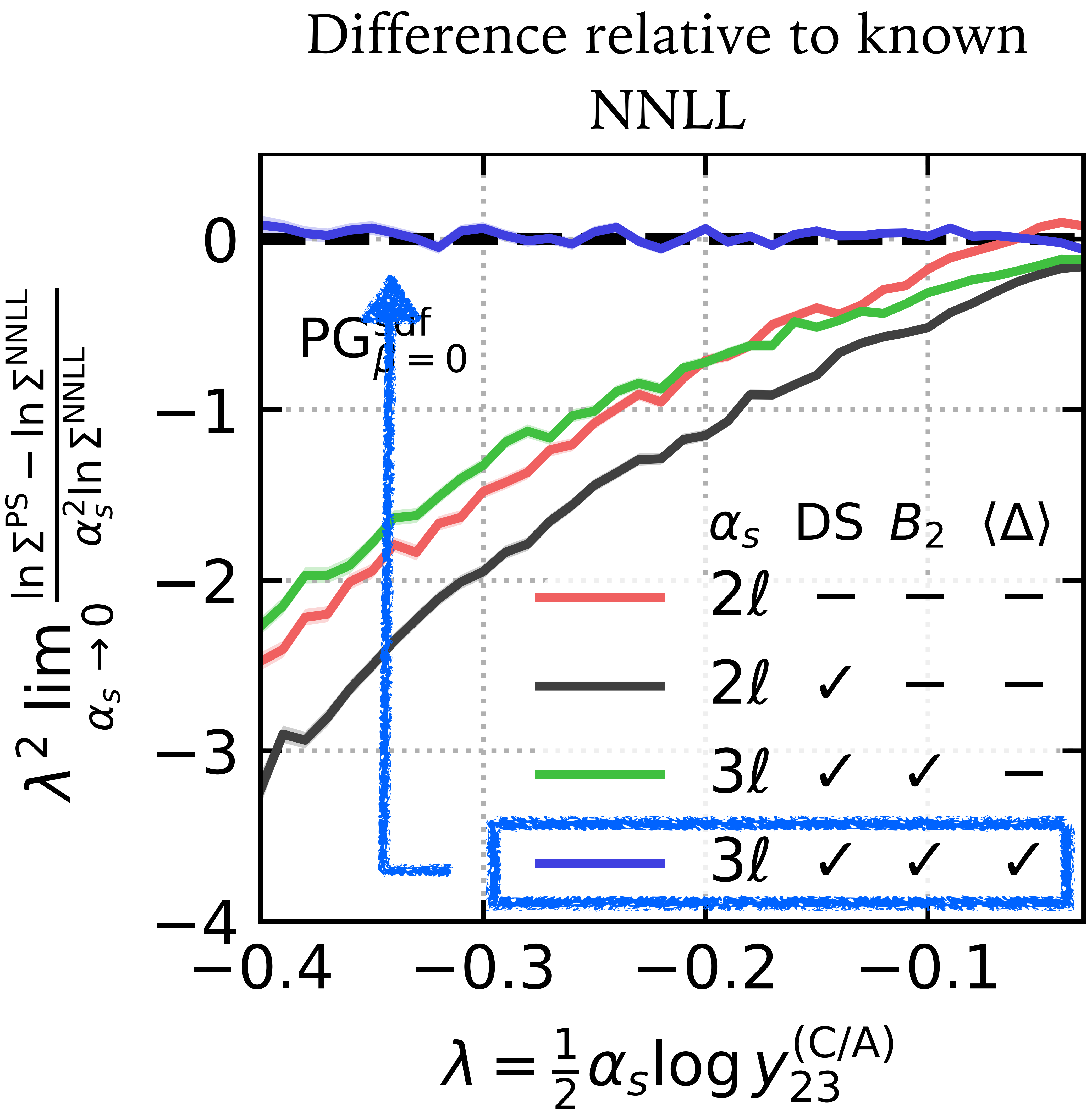

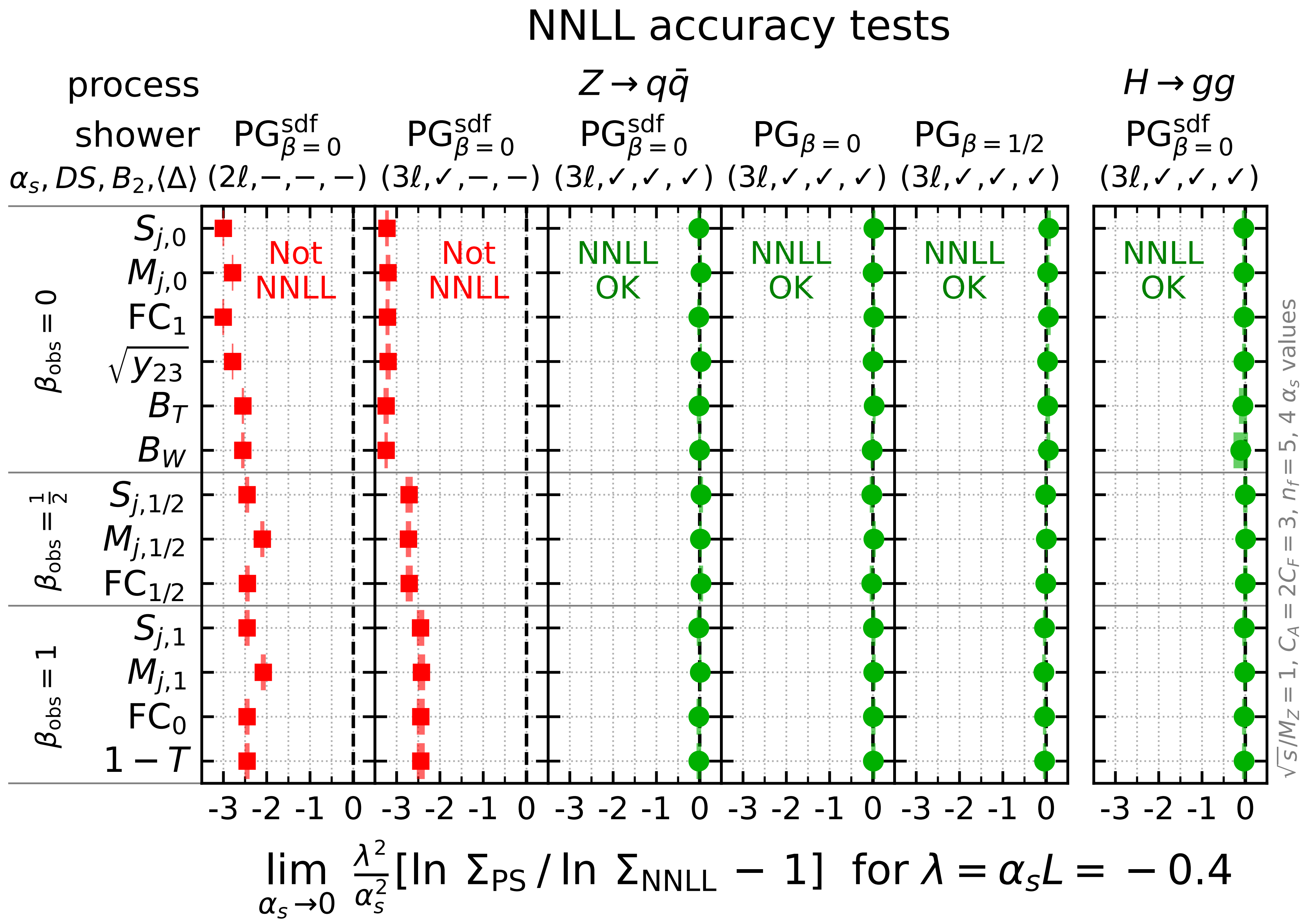

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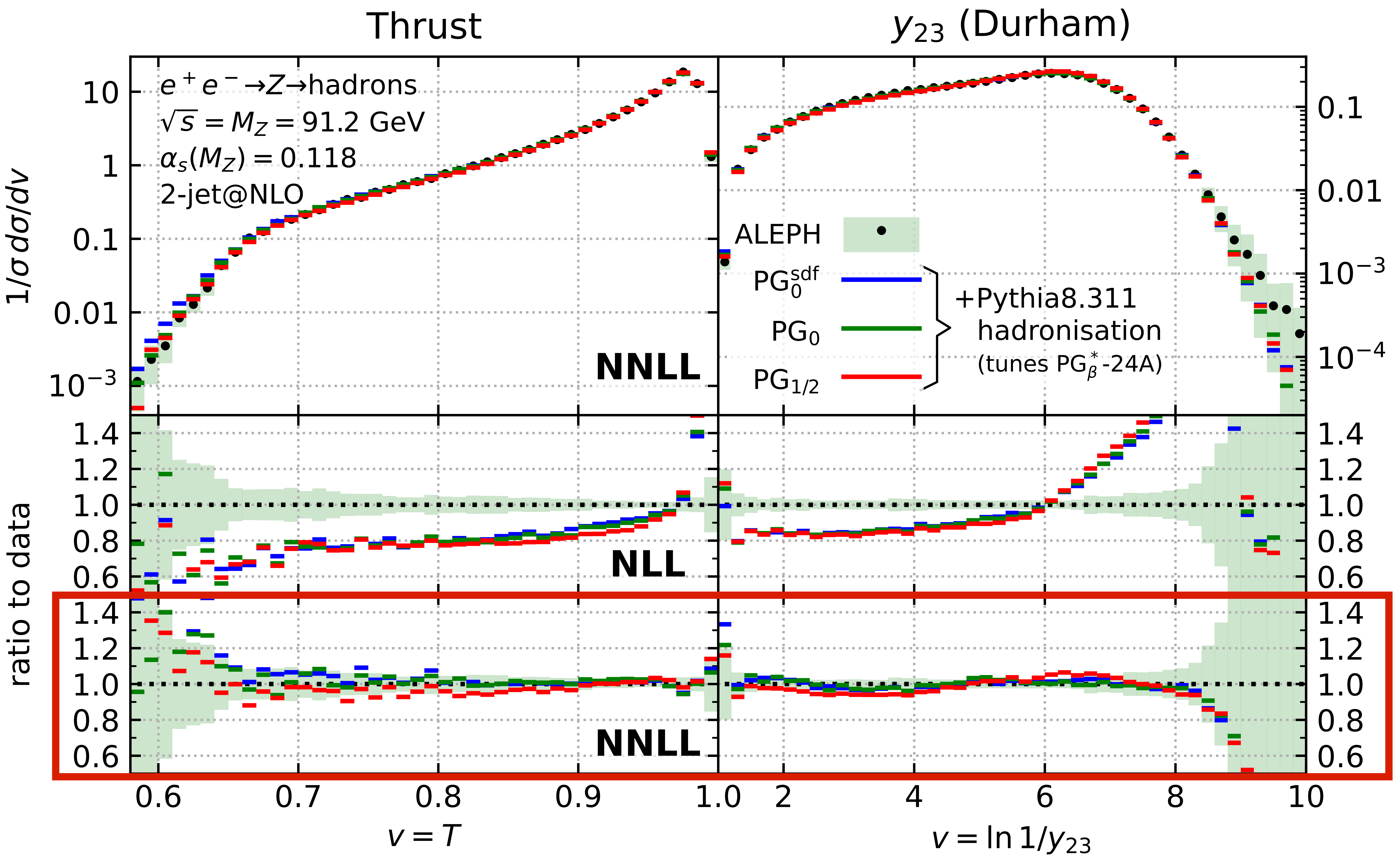
Comparing to LEP event-shape data



NNLL brings 20% effects ($\sim \alpha_s$)

Dramatically improves agreement with data, using a "normal" $\alpha_s = 0.118$

NB: 3-jet @ NLO still missing for robust pheno conclusions

NNLL

Took about 35 years to reach full NLL since the birth of parton showers …

Birth of Herwig (with elements of NLL for global observables)

slide from Pier Monni

SIMULATION OF QCD JETS INCLUDING SOFT GLUON INTERFERENCE

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Istituto di Fisica dell'Università di Parma and INFN, Sezione di Milano, Italy

B.R. WEBBER*
CERN, Geneva, Switzerland

Received 21 March 1983
(Revised 14 December 1983)

We present a new Monte Carlo simulation scheme for jet evolution in perturbative QCD which takes into account the results of recent analyses of soft-gluon interference. Therefore, this scheme accounts correctly not only for the leading collinear singularities, as in previous schemes, but also for leading infrared singularities. In this first paper we study the basic features of gluon jet evolution such as: (i) the interference effects and the corresponding depletion of the parton distributions in the soft region; (ii) the approach to asymptopia; (iii) the efficiency of colour screening (preconfinement), which has been questioned recently by Bjorken.

MONTE CARLO SIMULATION OF GENERAL HARD PROCESSES WITH COHERENT QCD RADIATION*

G MARCHESINI
Dipartimento di Fisica, Università di Parma, INFN, Gruppo Collegato di Parma, Italy

B R WEBBER
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Received 8 February 1988

In this paper we extend our previous work on the simulation of coherent soft-gluon radiation to hard collisions that involve incoming as well as outgoing coloured partons Existing simulations correctly sum the leading collinear singularities for initial- and final-state radiation, and in some cases the leading infrared contributions from outgoing partons, but not those for incoming (or the interference between incoming and outgoing) Asymptotically, however, the leading infrared and collinear contributions are comparable, the bulk of gluon emission occurring in the soft region Furthermore, a correct treatment of leading infrared terms is necessary for the inclusive cancellation of singularities in the Sudakov form factor We show how such a treatment may be formulated in terms of an angular ordering procedure applicable to all hard processes We then describe a new Monte Carlo program which incorporates this procedure, together with other new features such as azimuthal correlations due to gluon polarization and interference The program is designed as a general-purpose event generator, simulating hard lepton–lepton, lepton–hadron and hadron–hadron scattering in a single package Simulation of soft hadronic collisions and underlying events is also included We present the predictions of the program for a wide variety of processes, and compare them with analytical results and experimental data

A MODEL FOR INITIAL STATE PARTON SHOWERS

Torbjörn SJÖSTRAND
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA

Received 25 February 1985

We present a detailed model for exclusive properties of initial state parton showers. A numerically efficient algorithm is obtained by tracing the parton showers backwards, i.e. start with the hard scattering partons and then successively reconstruct preceding branchings in falling sequence of spacelike virtualities Q^2 and rising sequence of parton energies. We show how the Altarelli–Parisi equations can be recast in a form suitable for this, and also discuss the kinematics of the branchings. The complete model is implemented in a Monte Carlo program, and some first results are presented.

Birth of Pythia

Parton showers beyond leading logarithmic accuracy

Mrinal Dasgupta,[1] Frédéric A. Dreyer,[2] Keith Hamilton,[3] Pier Francesco Monni,[4] Gavin P. Salam,[2,*] and Grégory Soyez[5]
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[5] *Institut de Physique Théorique, Université Paris-Saclay, CNRS, CEA, F-91191, Gif-sur-Yvette, France*

Parton showers are among the most widely used tools in collider physics. Despite their key importance, none so far has been able to demonstrate accuracy beyond a basic level known as leading logarithmic (LL) order, with ensuing limitations across a broad spectrum of physics applications. In this letter, we propose criteria for showers to be considered next-to-leading logarithmic (NLL) accurate. We then introduce new classes of shower, for final-state radiation, that satisfy the main elements of these criteria in the widely used large-N_C limit. As a proof of concept, we demonstrate these showers' agreement with all-order analytical NLL calculations for a range of observables, something never so far achieved for any parton shower.

General principles for a NLL parton shower (formulated for e^+e^-, many extensions will follow)

[ca. 800 papers on the subject of event generators …………………………………………………………]

. . . key steps towards NNLL were just O(5) years away

slide from Pier Monni

Birth of Herwig (with elements of NLL for global observables)

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General principles for NNLL parton showers

A new standard for the logarithmic accuracy of parton showers

Melissa van Beekveld,[1] Mrinal Dasgupta,[2] Basem Kamal El-Menoufi,[3] Silvia Ferrario Ravasio,[4] Keith Hamilton,[5] Jack Helliwell,[6] Alexander Karlberg,[4] Pier Francesco Monni,[4] Gavin P. Salam,[6,7] Ludovic Scyboz,[3] Alba Soto-Ontoso,[4] and Gregory Soyez[8]

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[2] *Department of Physics & Astronomy, University of Manchester, Manchester M13 9PL, United Kingdom*
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We report on a major milestone in the construction of logarithmically accurate final-state parton showers, achieving next-to-next-to-leading-logarithmic (NNLL) accuracy for the wide class of observables known as event shapes. The key to this advance lies in the identification of the relation between critical NNLL analytic resummation ingredients and their parton-shower counterparts. Our analytic discussion is supplemented with numerical tests of the logarithmic accuracy of three shower variants for more than a dozen distinct event-shape observables in $Z \to q\bar{q}$ and Higgs $\to gg$ decays. The NNLL terms are phenomenologically sizeable, as illustrated in comparisons to data.

A MODEL FOR INITIAL STATE PARTON SHOWERS

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Parton showering with higher-logarithmic accuracy for soft emissions

Silvia Ferrario Ravasio,[1] Keith Hamilton,[2] Alexander Karlberg,[1] Gavin P. Salam,[3,4] Ludovic Scyboz,[3] and Gregory Soyez[1,5]

[1] *CERN, Theoretical Physics Department, CH-1211 Geneva 23, Switzerland*
[2] *Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK*
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The accuracy of parton-shower simulations is often a limiting factor in the interpretation of data from high-energy colliders. We present the first formulation of parton showers with accuracy one order beyond state-of-the-art next-to-leading logarithms, for classes of observable that are dominantly sensitive to low-energy (soft) emissions, specifically non-global observables and subjet multiplicities. This represents a major step towards general next-to-next-to-leading logarithmic accuracy for parton showers.

General principles for a NLL parton shower
(formulated for e^+e^-, many extensions will follow)

[ca. 800 papers on the subject of event generators ....]

Conclusions

Collider particle physics is a rich and diverse subject

Core exploration of the Higgs sector has only just started

- Many aspects are (hypothesized to be) crucial for the world around us
- Major targets for future colliders: e.g. triple-Higgs interaction $\Longleftrightarrow$ Higgs potential

Central to quantitative collider physics is the strong interaction

- quest for accuracy brings huge challenges & QCD is delivering on multiple fronts
- one of those fronts is the question of how to span disparate momentum scales in simulations: major conceptual steps over past years & soon to be available for practical use.