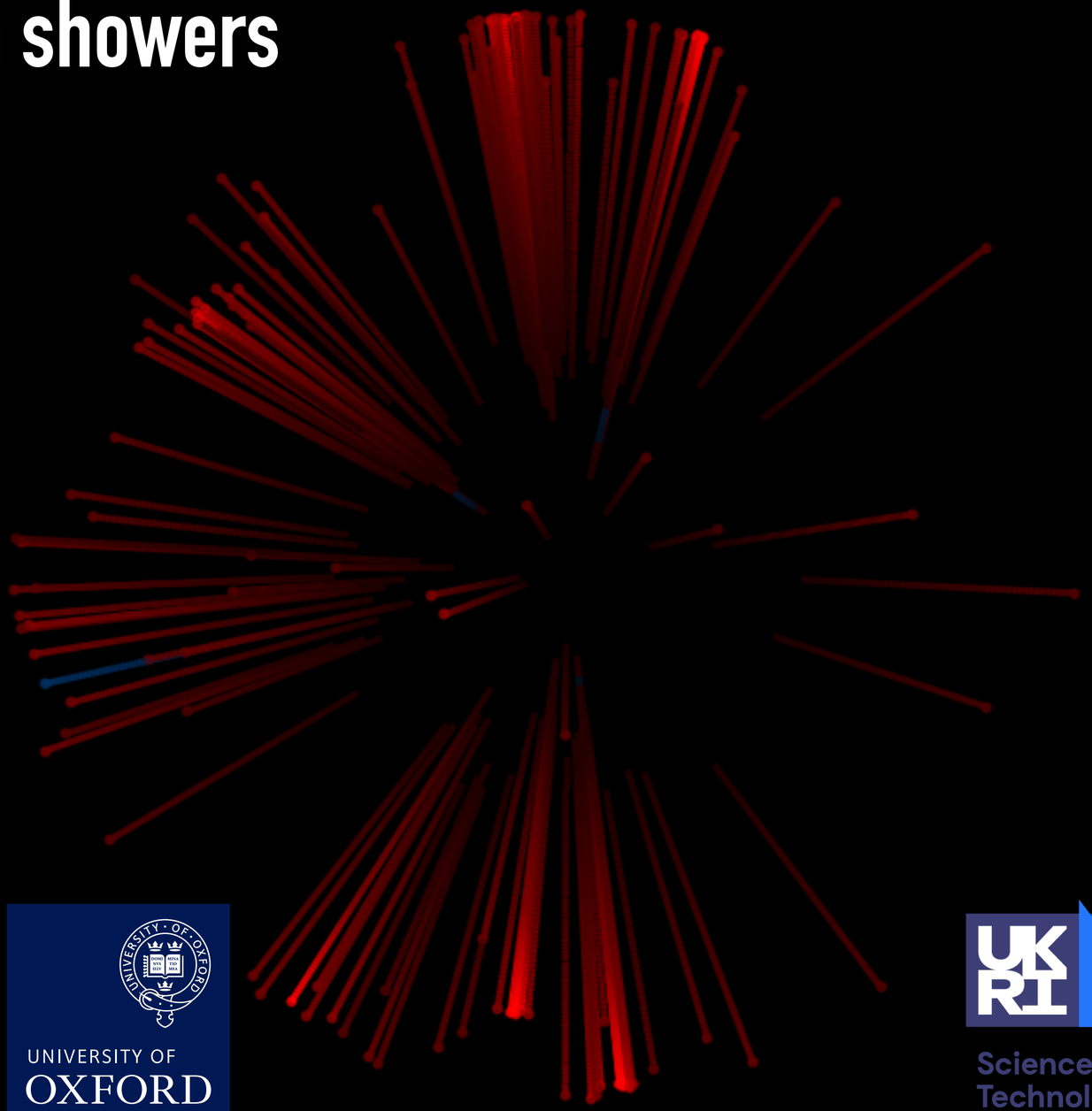
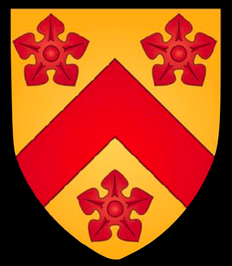
Making perturbative QFT physical, with accurate parton showers

MPP Colloquium
Garching
7 July 2026



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



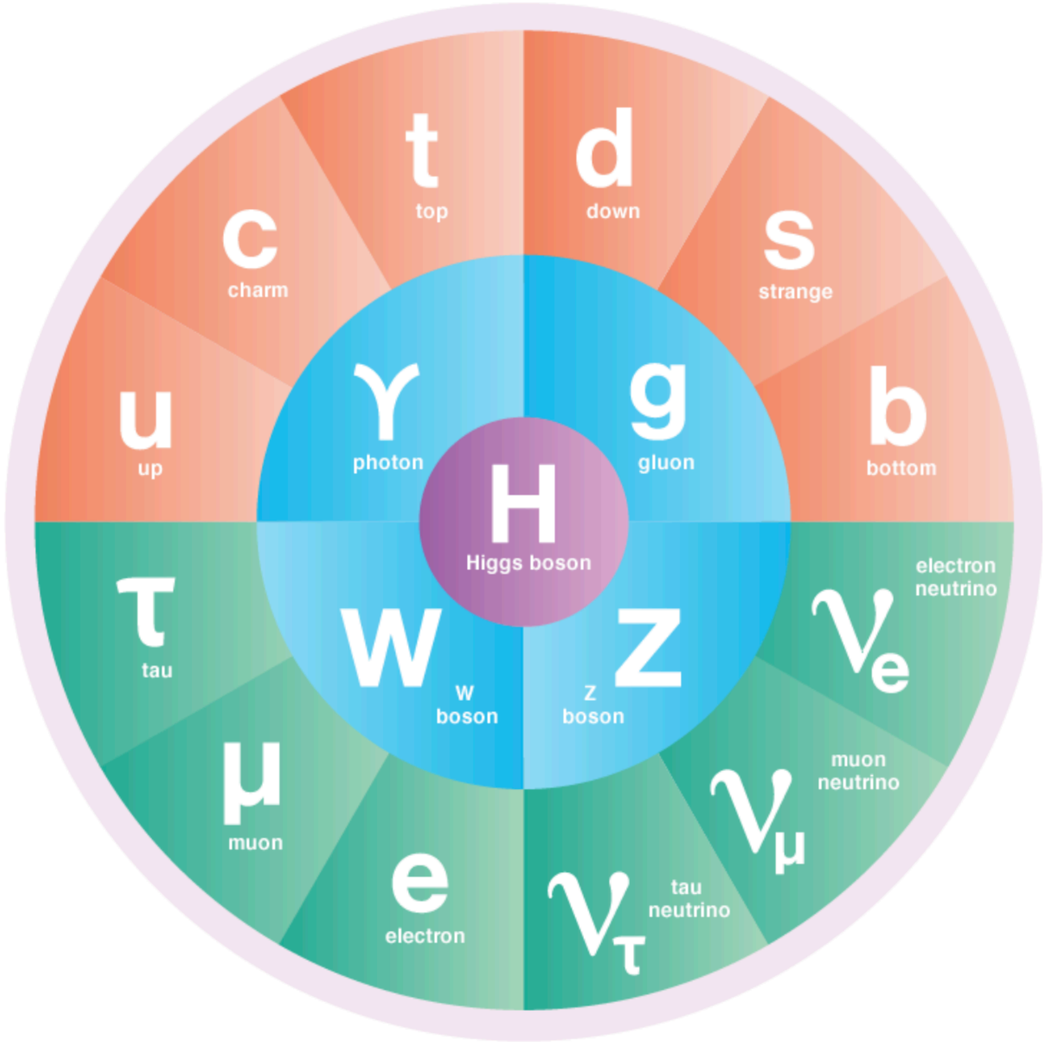




Science and Technology Facilities Council



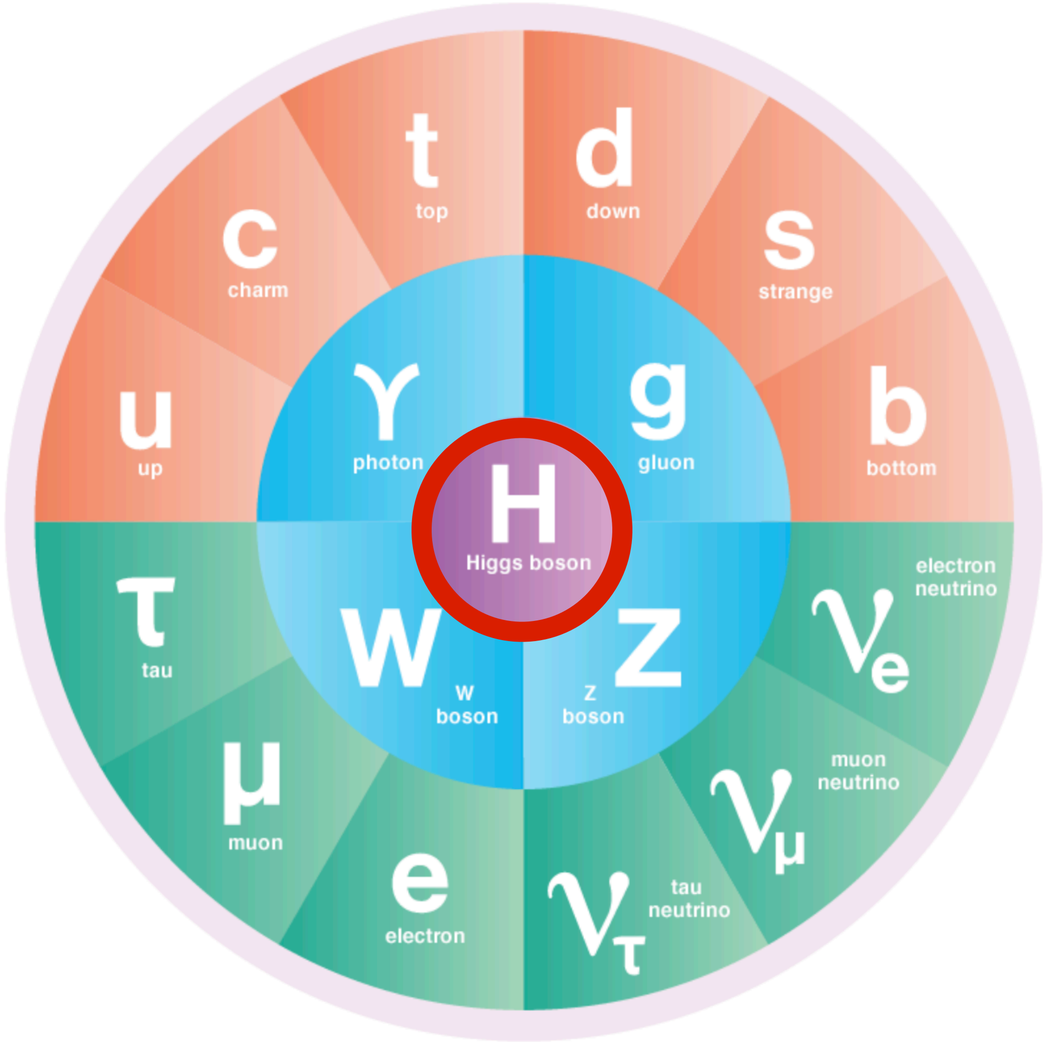
The Standard Model (SM)



particles

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

The Standard Model (SM)

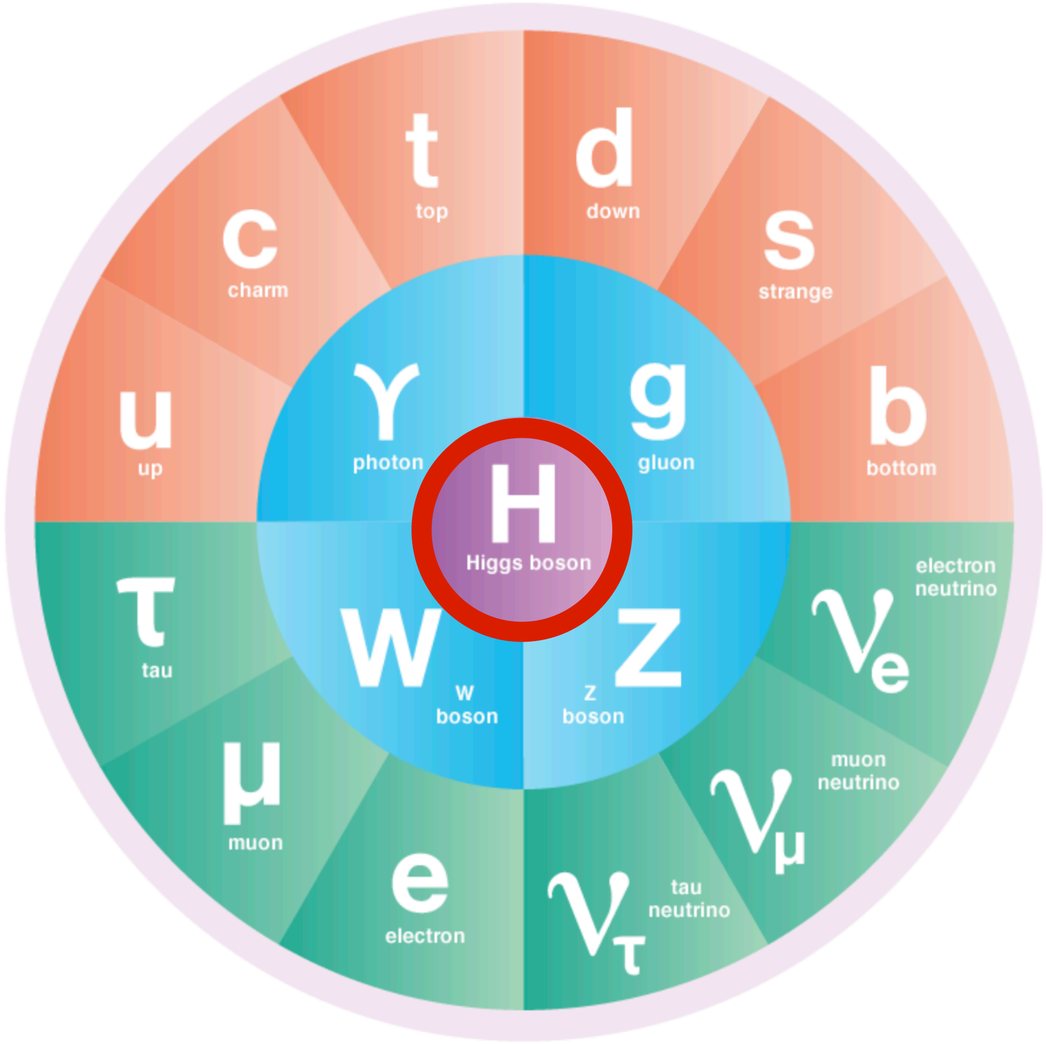


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"the standard-model (SM) is complete"

The Standard Model (SM)



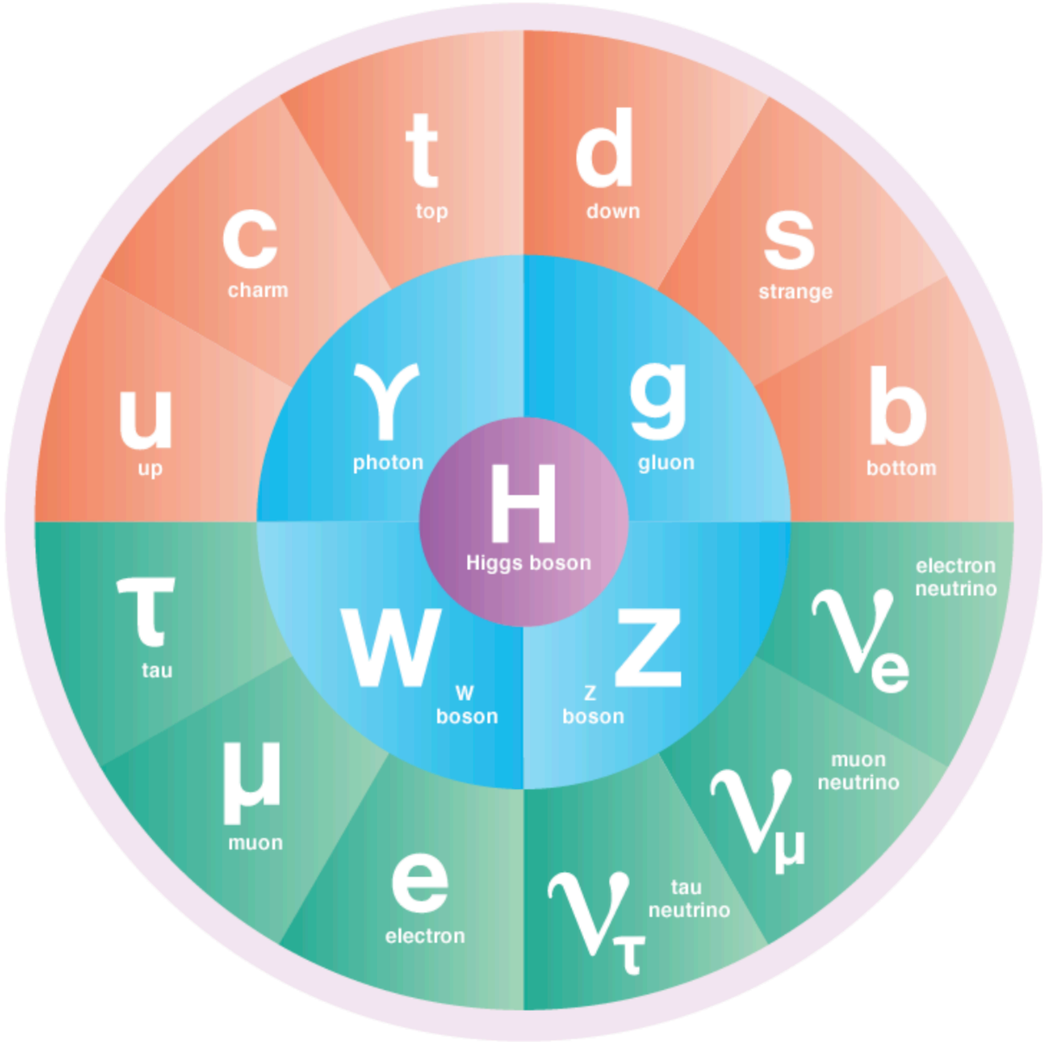
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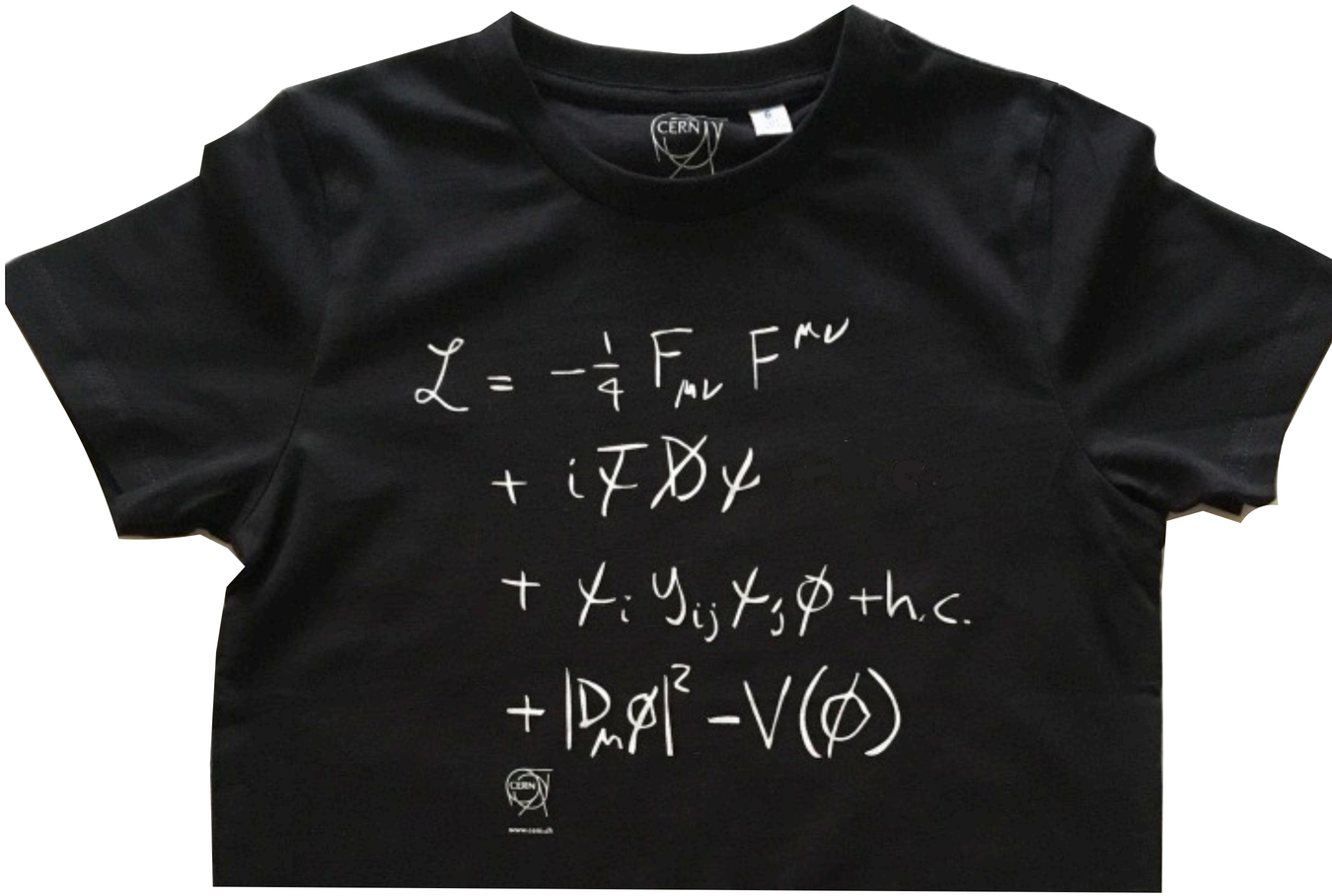
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"the standard-model (SM) is complete"

?

The Standard Model (SM)



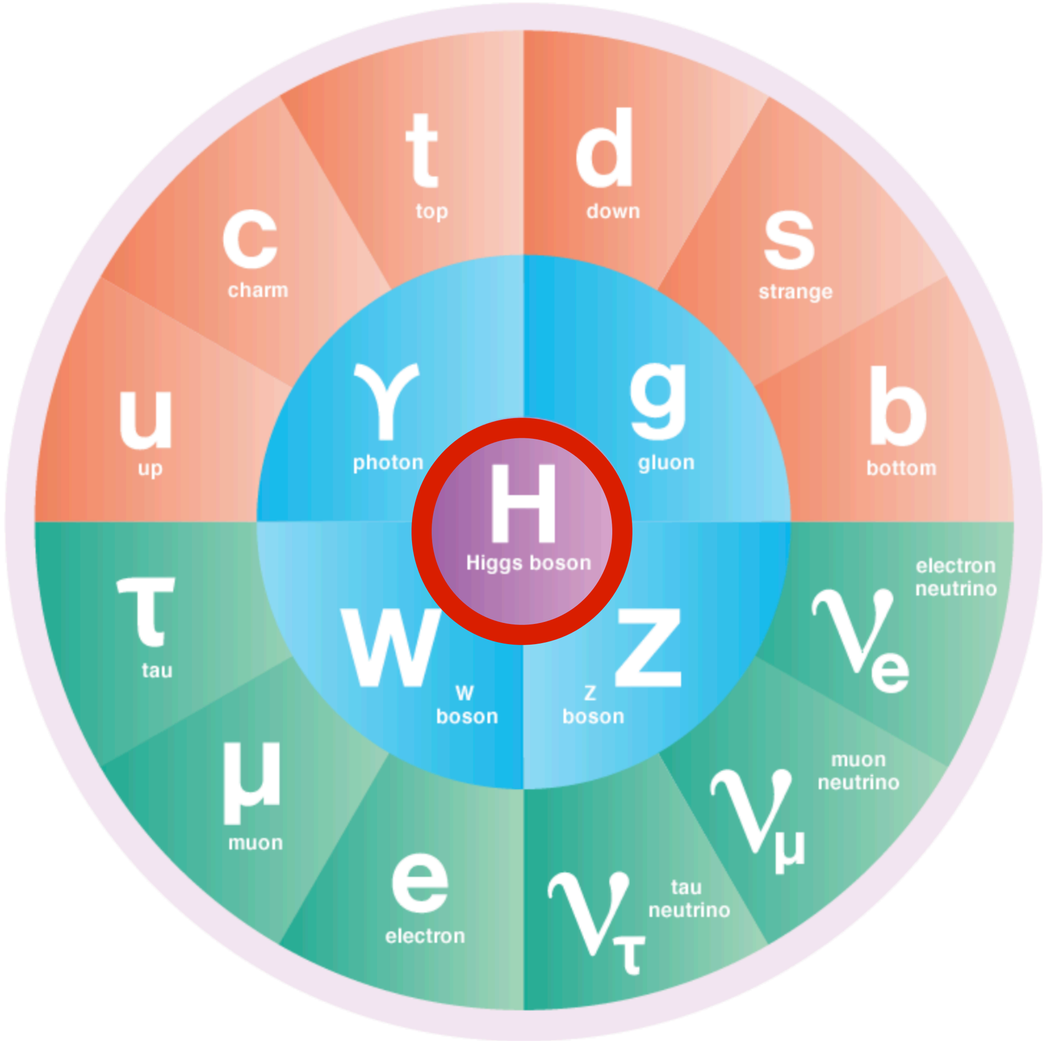


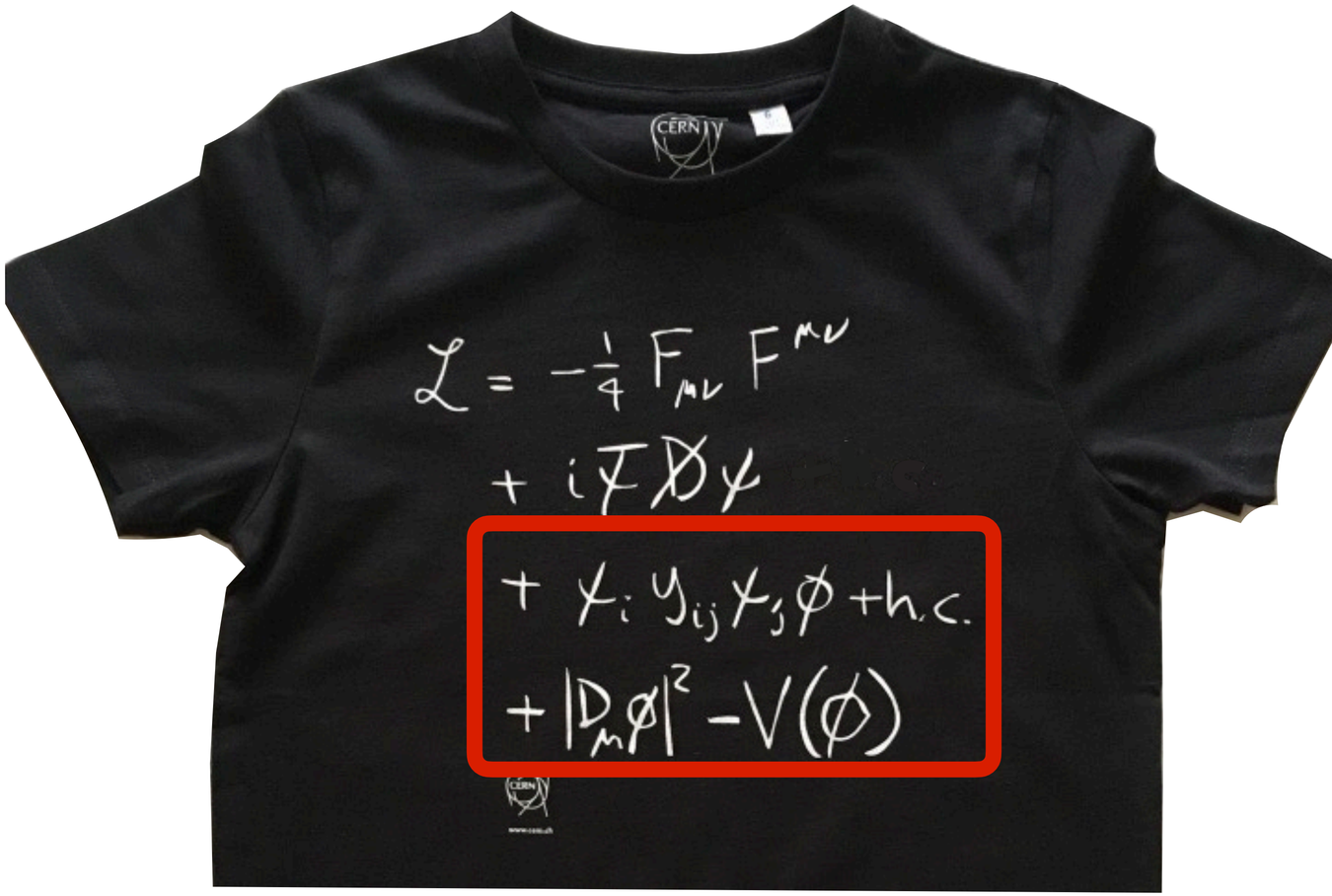
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particles

interactions

The Standard Model (SM)





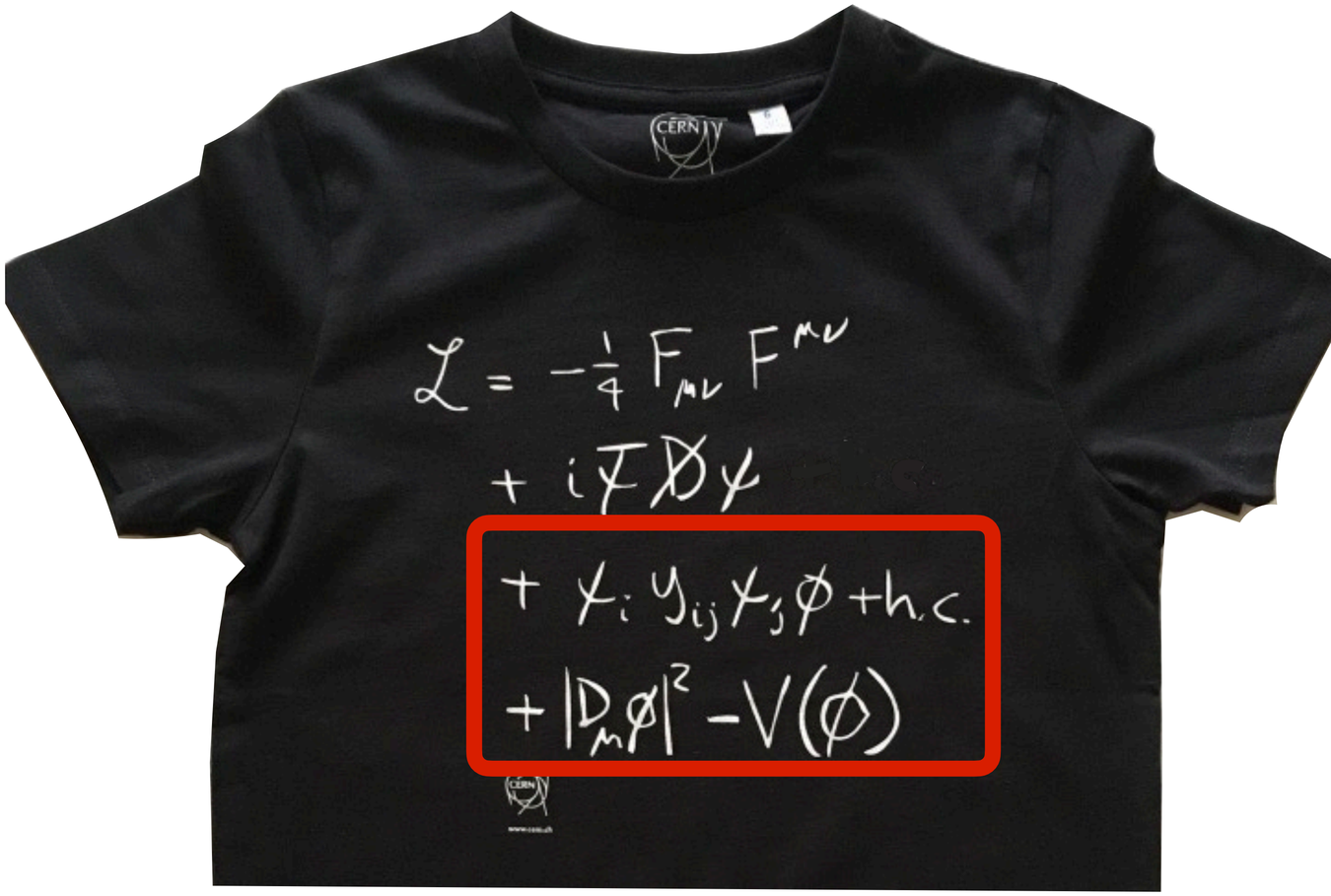
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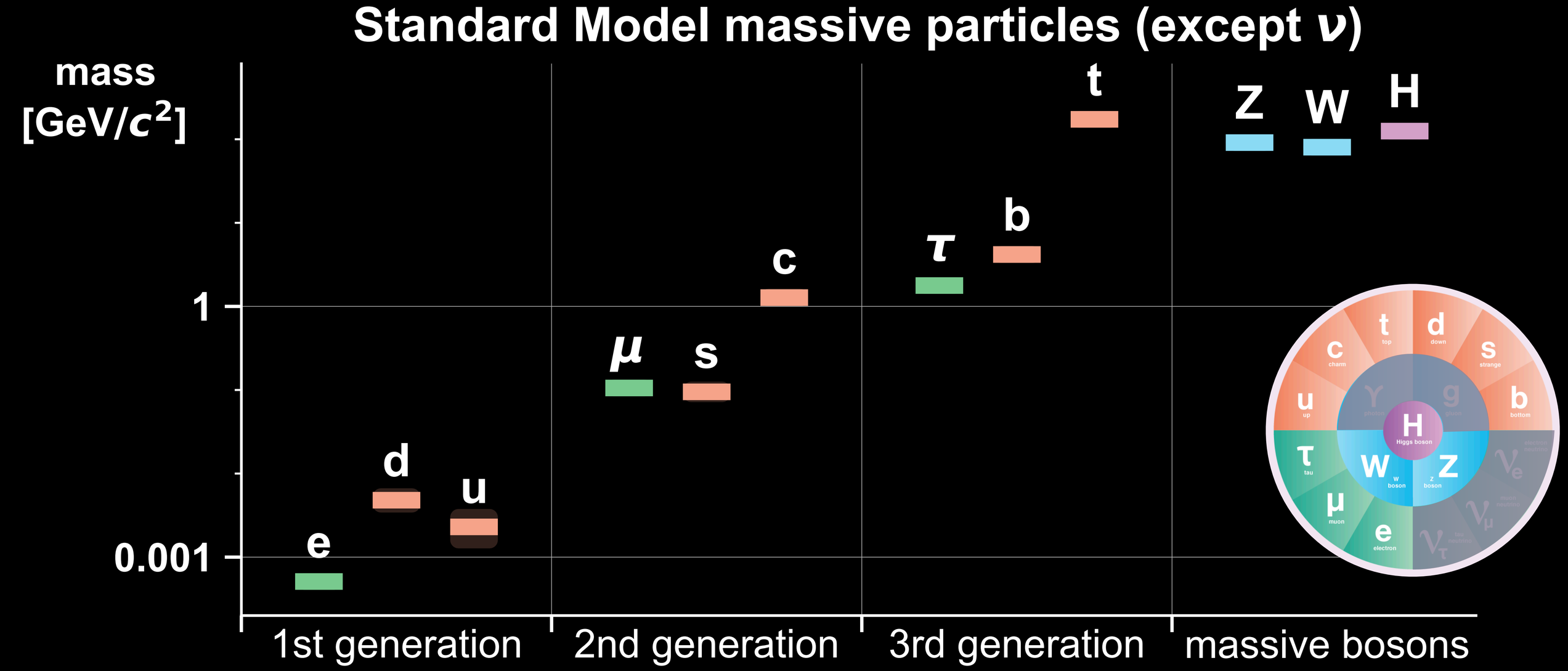
The Standard Model (SM)

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

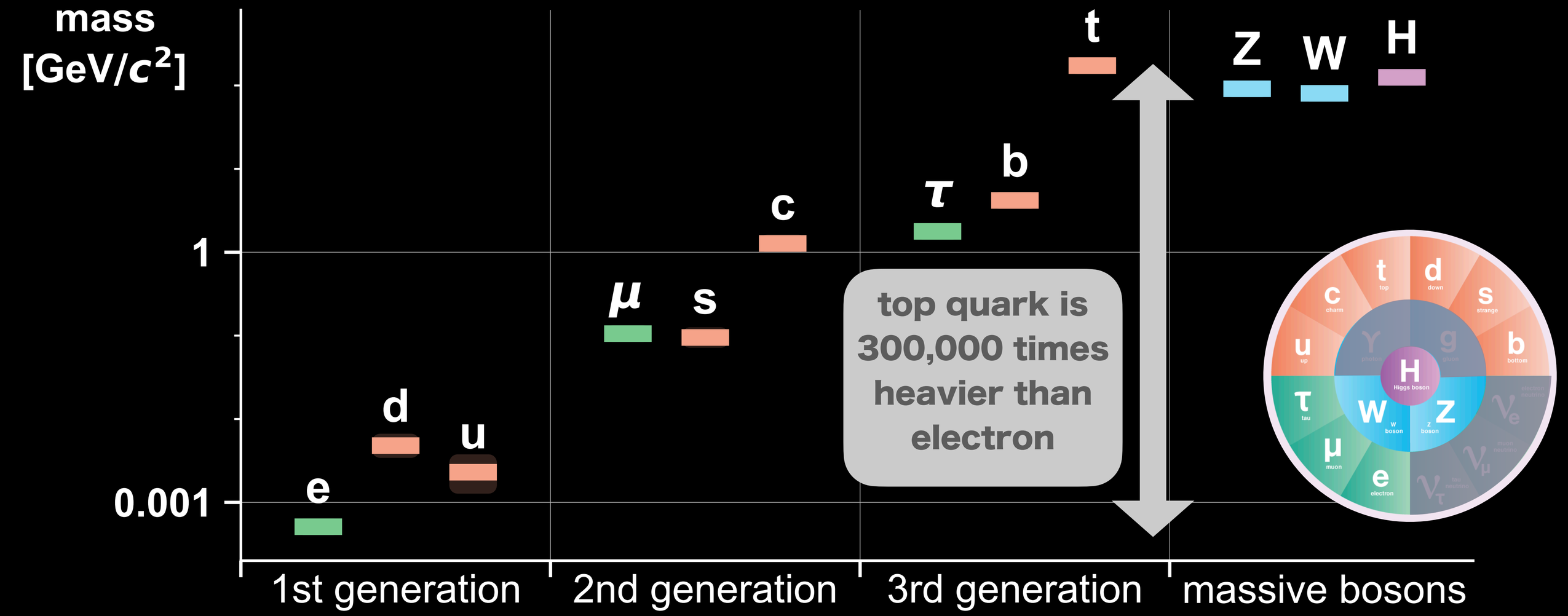


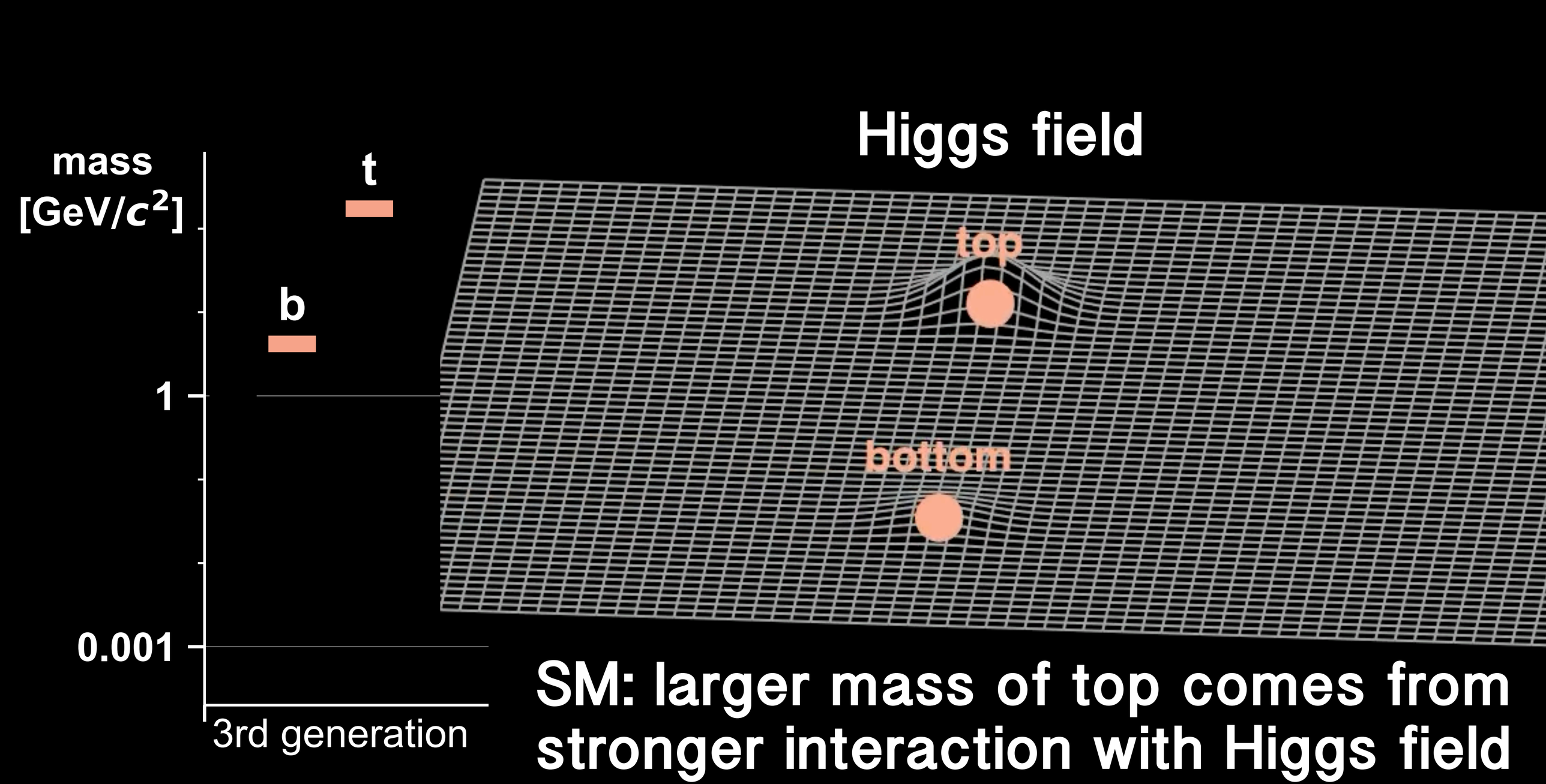
interactions

Standard Model massive particles (except ν)

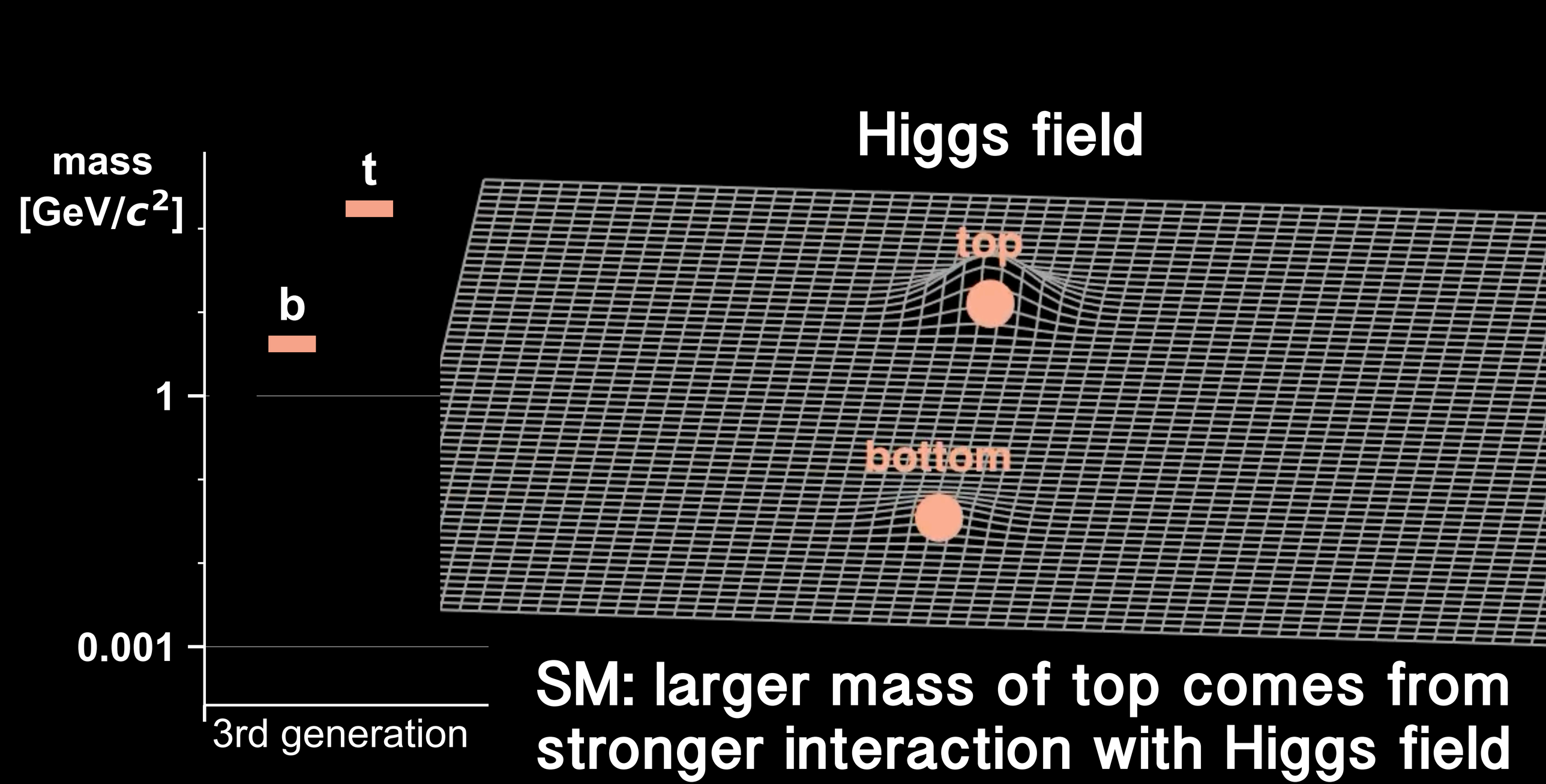


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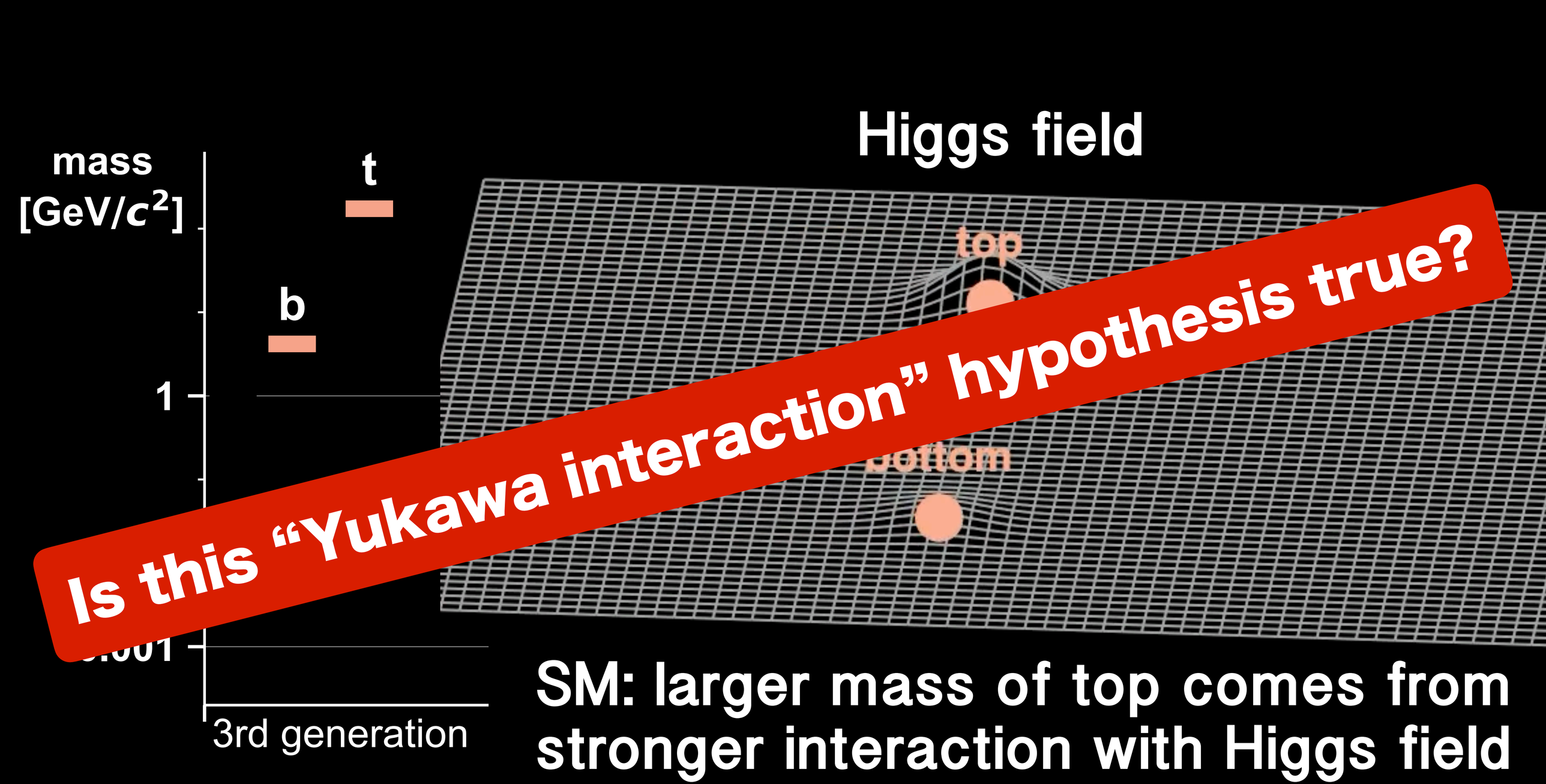




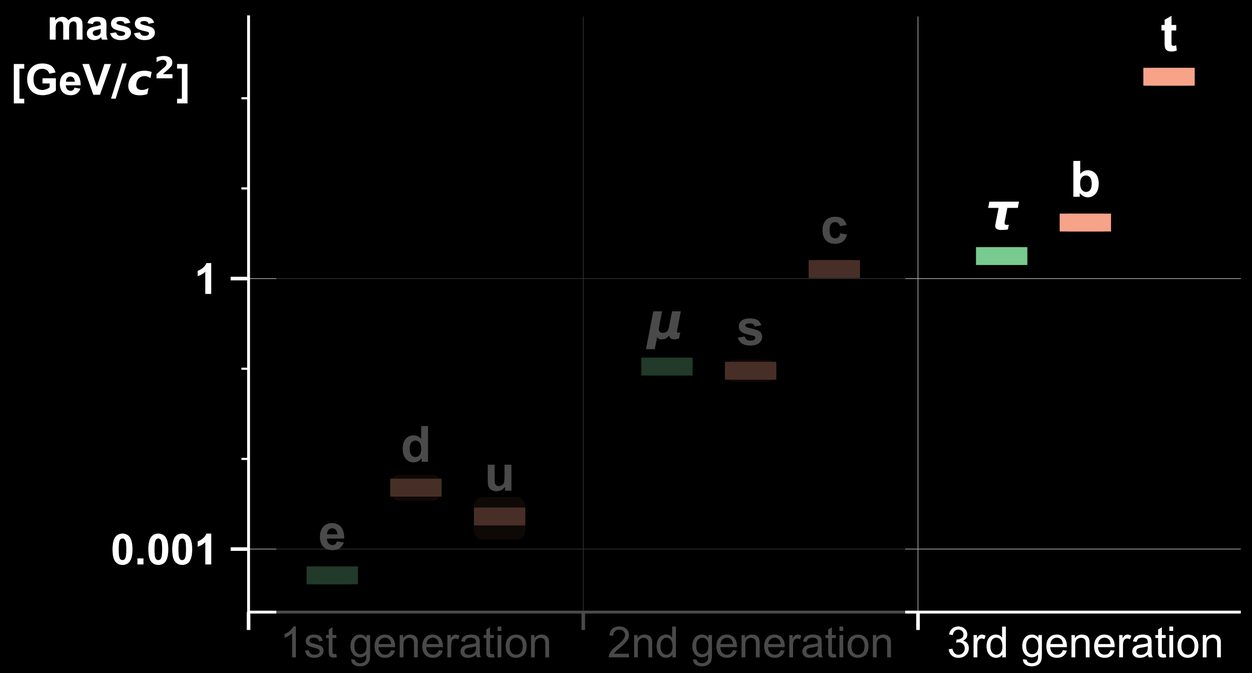
SM: larger mass of top comes from stronger interaction with Higgs field



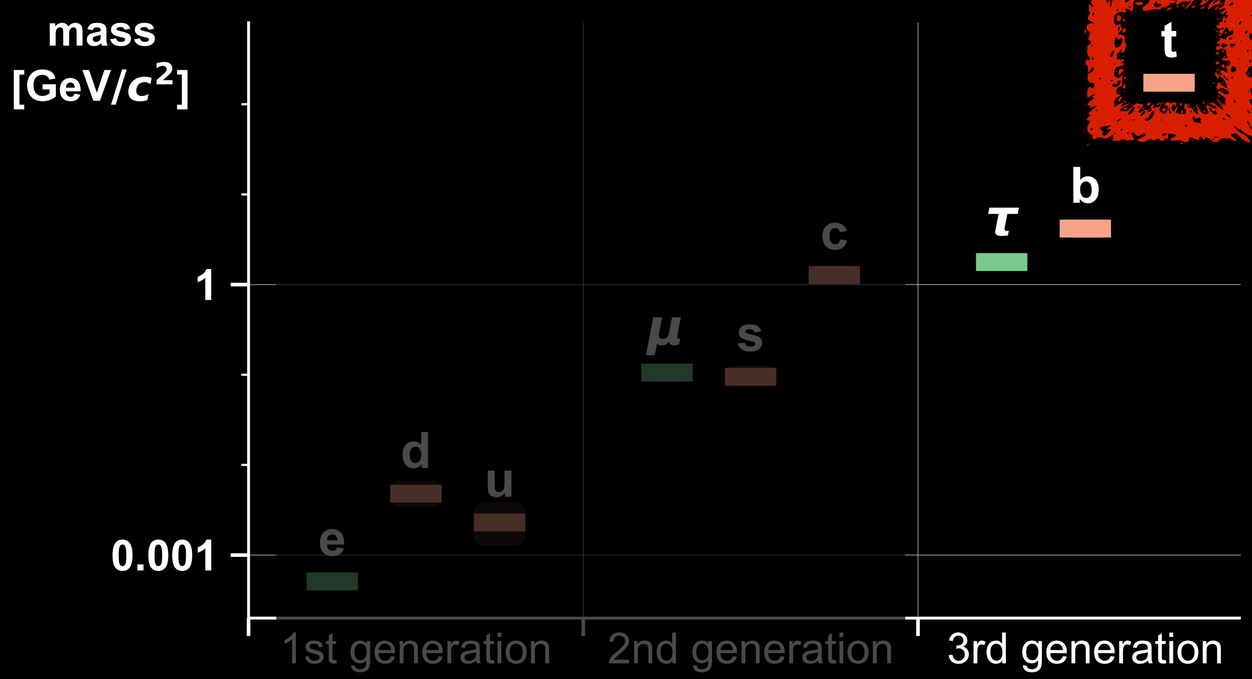
SM: larger mass of top comes from stronger interaction with Higgs field


mass
[GeV/c^2]
t
b
1
3rd generation
Higgs field
top
bottom
Is this “Yukawa interaction” hypothesis true?
SM: larger mass of top comes from stronger interaction with Higgs field

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

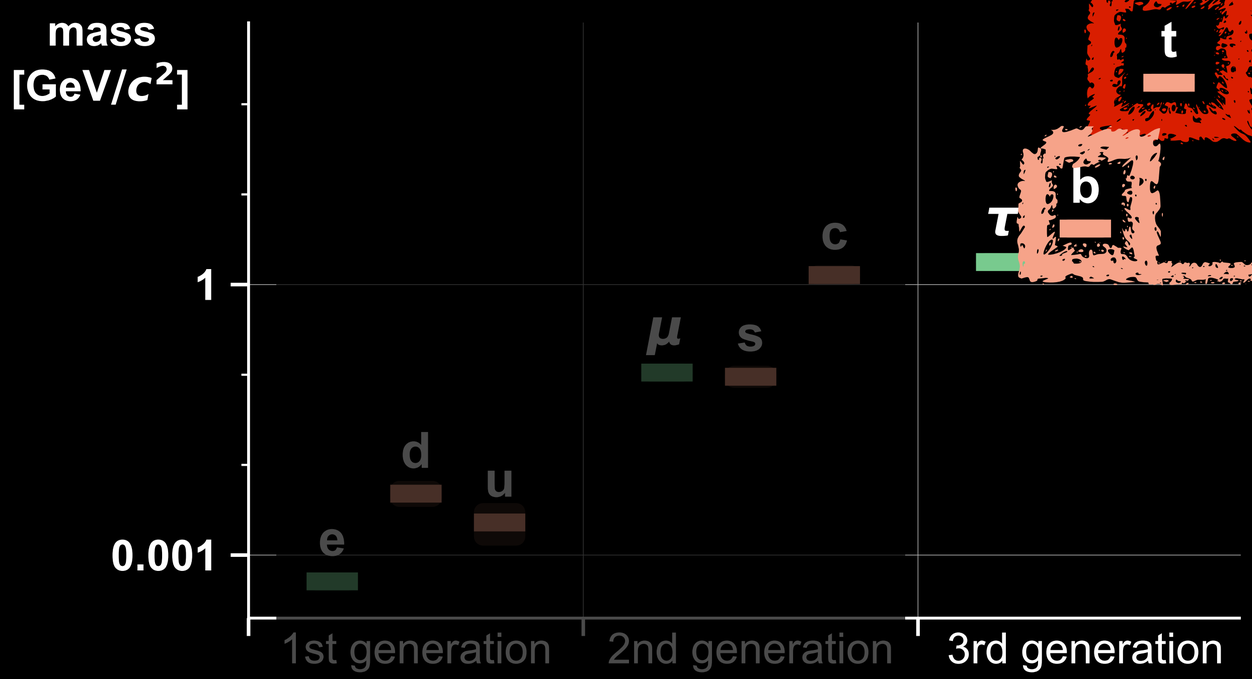


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by observing H in association with top quarks

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

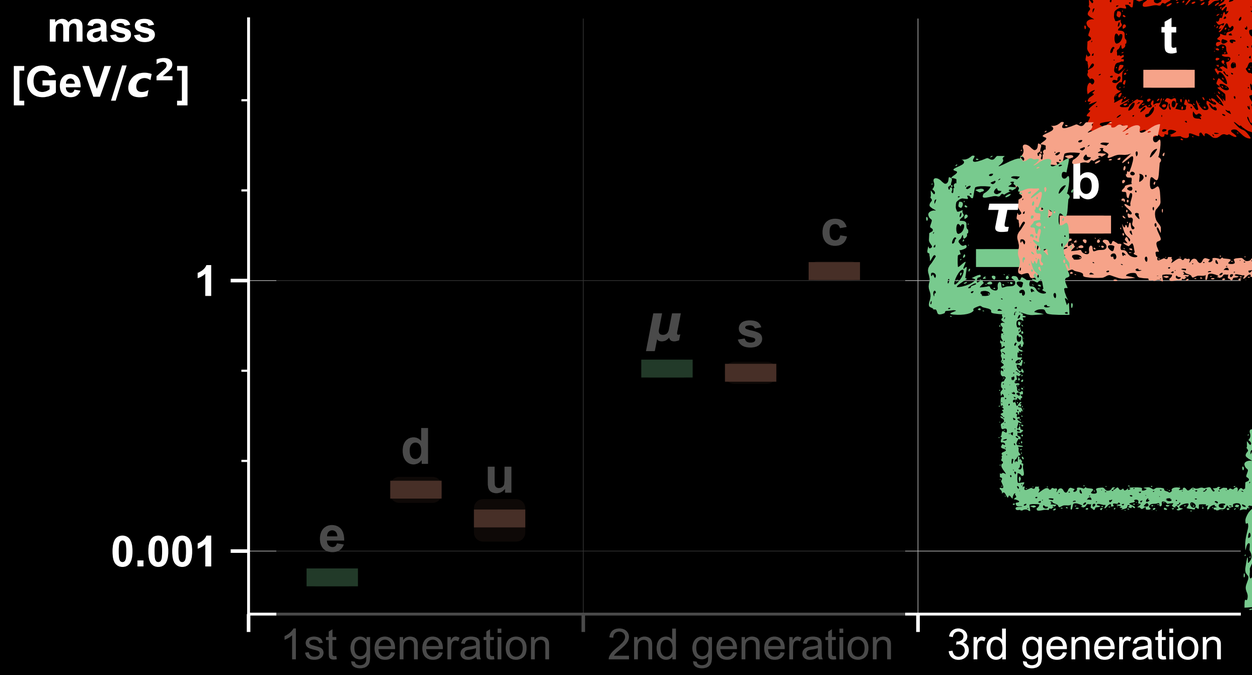


by observing H in association with top quarks

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

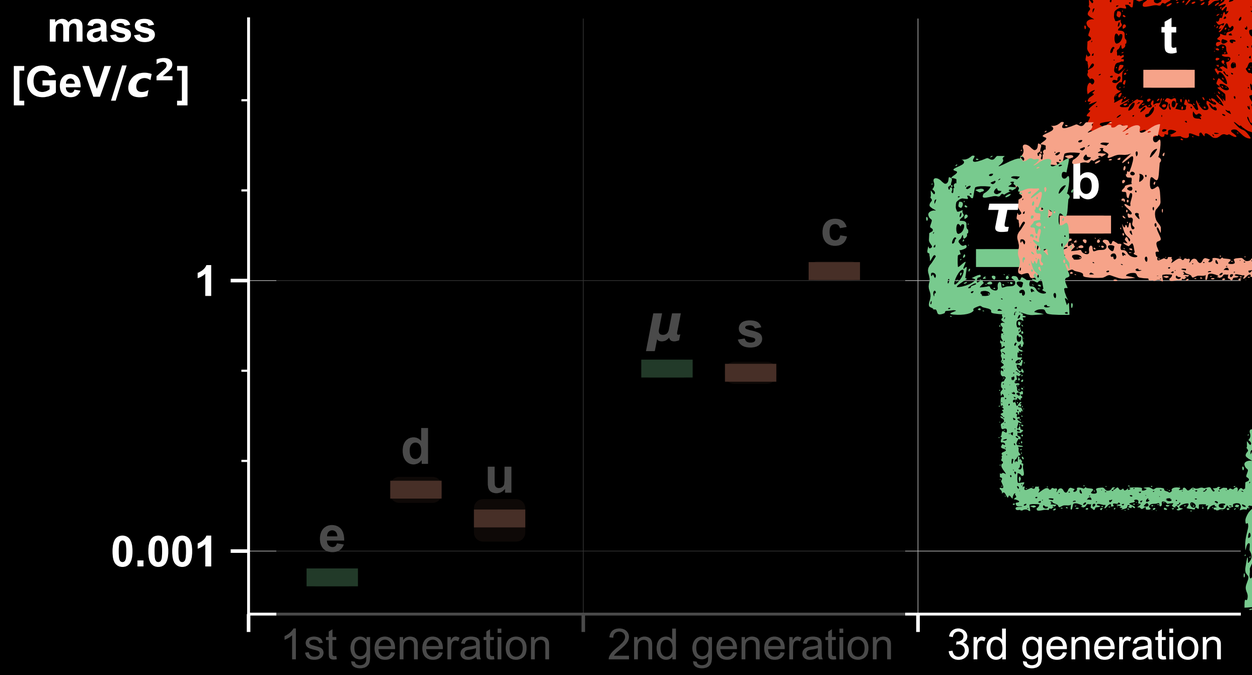


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Discovery of 3rd generation–Higgs field interactions by ATLAS & CMS ~ 2018



by observing H in association with top quarks

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

by observing $H \to \tau^+\tau^-$ decays

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

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.

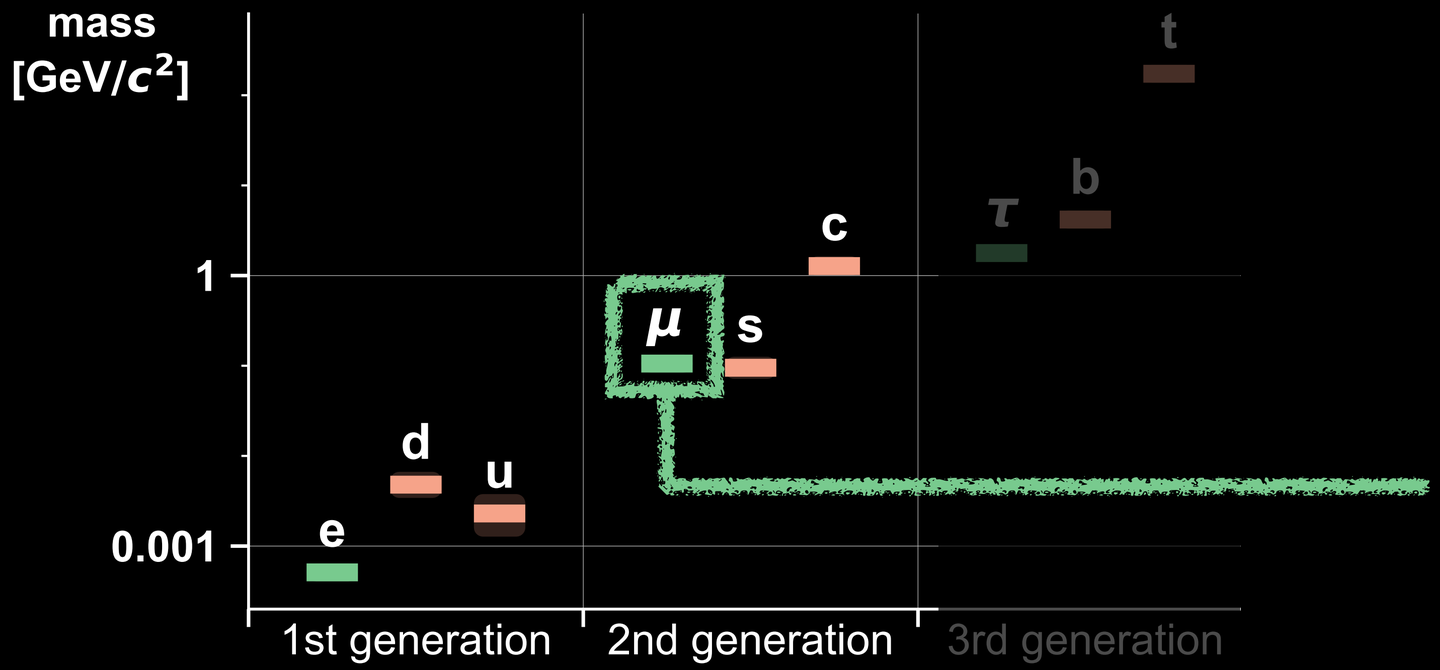
A field is something that can in principle be controlled and modified. Could the masses of elementary particles conceivably also be controlled and modified? Science fiction…

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

My opinion: no

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

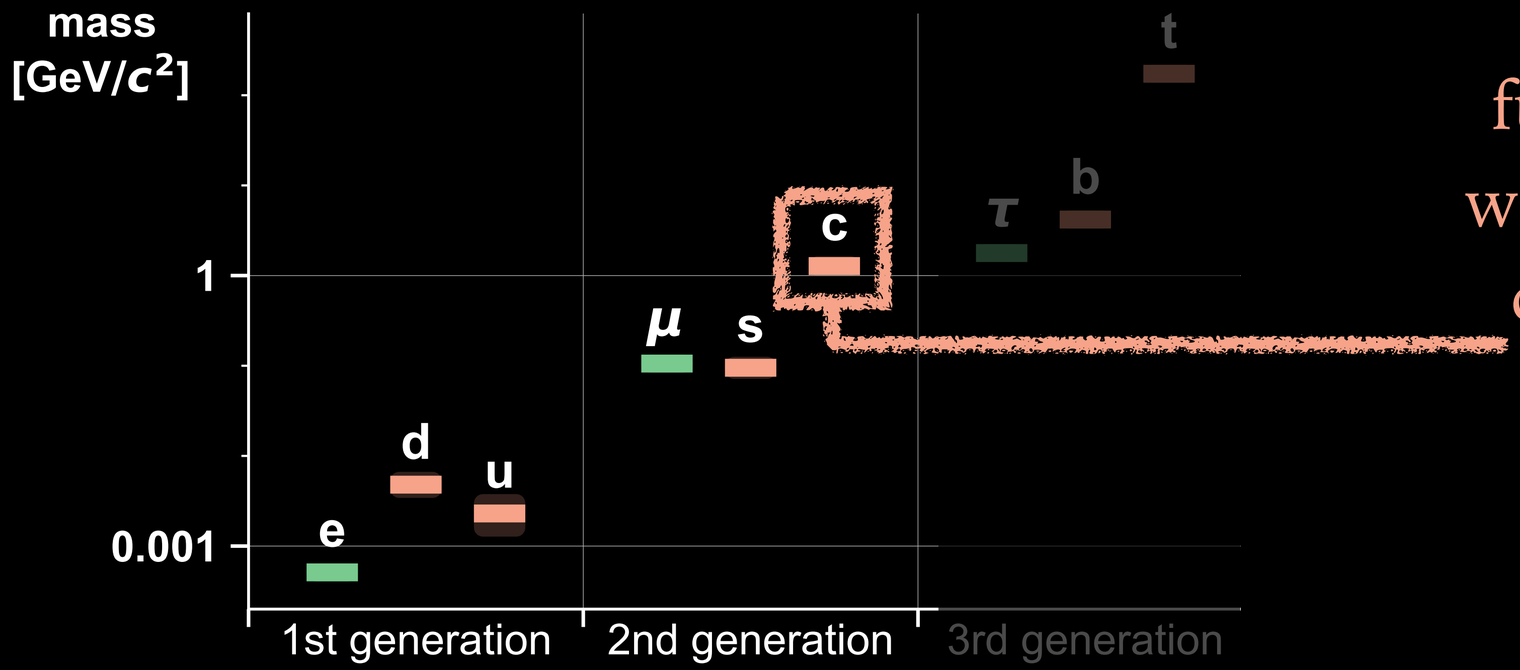
→ the more difficult it is establish if it actually gets mass from interactions with the Higgs field



a major LHC goal of the next years (Run-3 data 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]

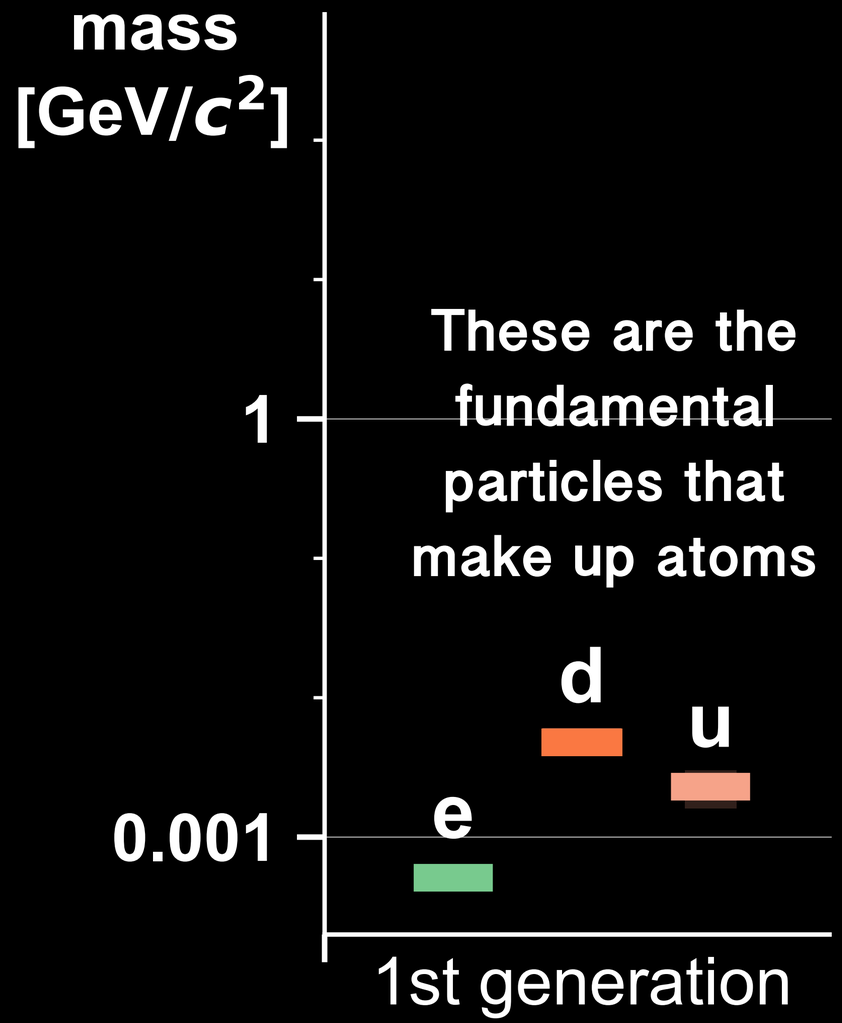
What of future colliders

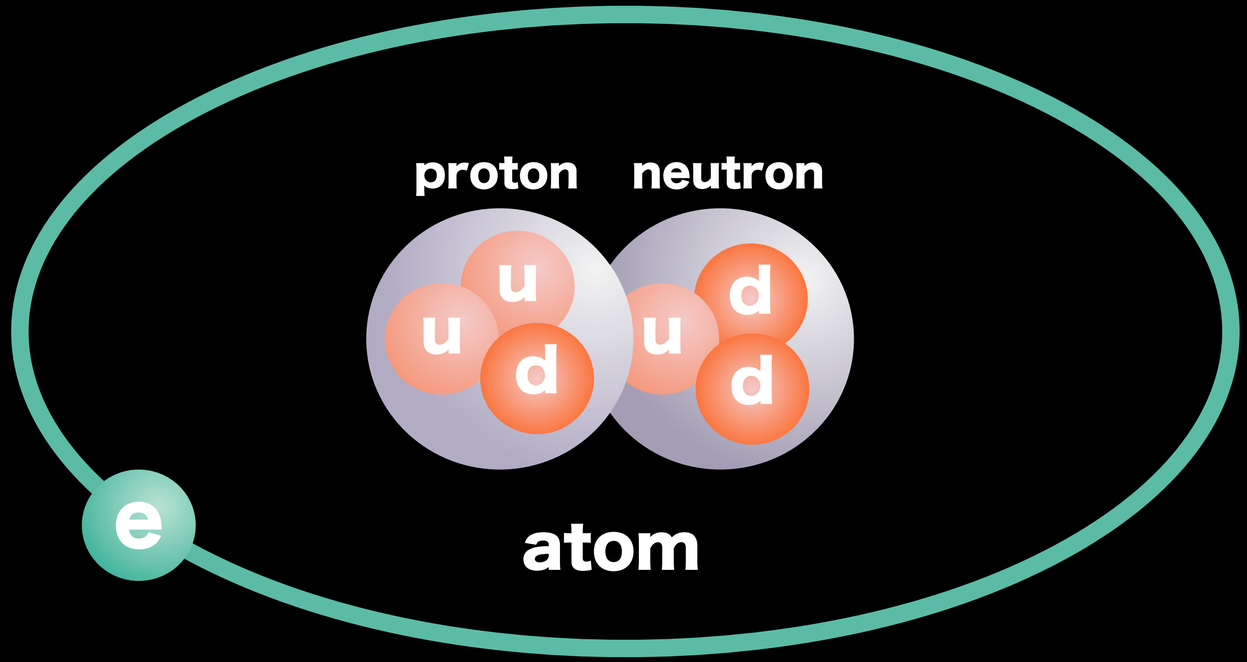


quarks and yet-lighter particles are much harder

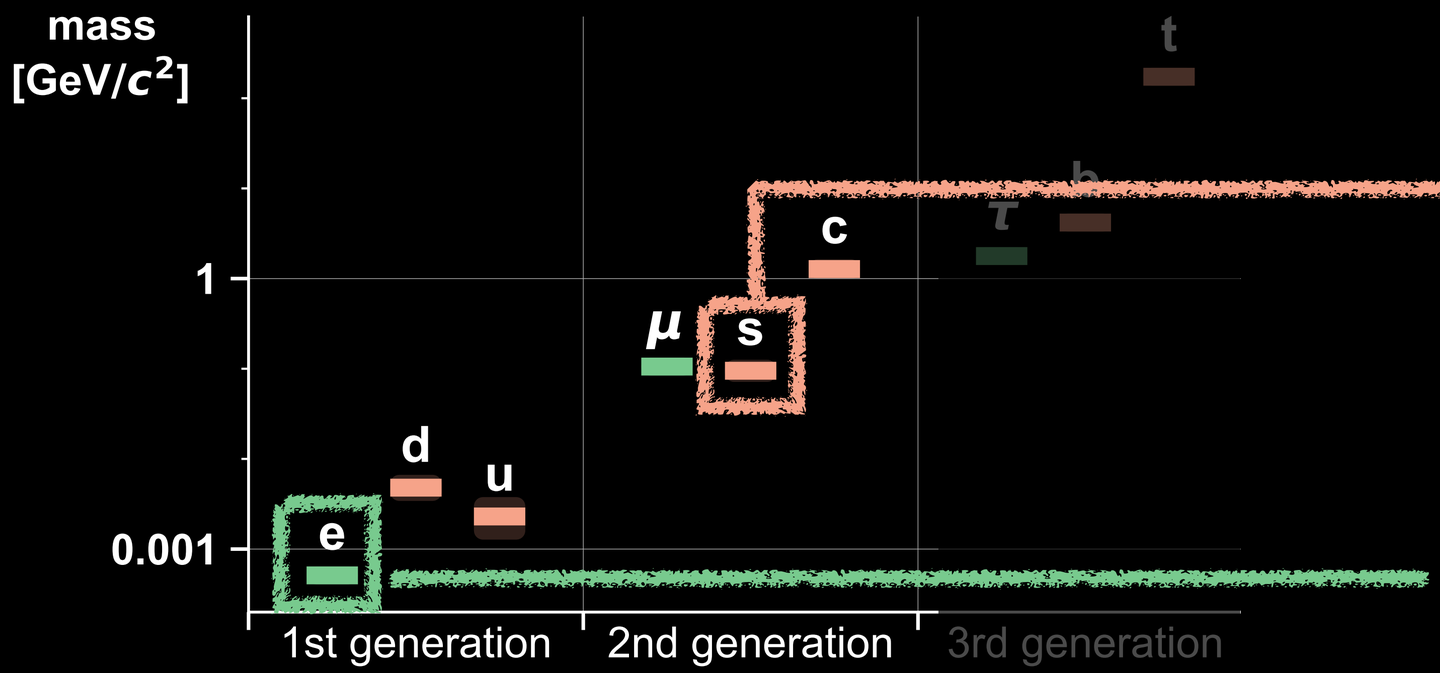
future e^+e^- collider, if built, will clearly establish if charm-quarks get their mass from Higgs-field interactions

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





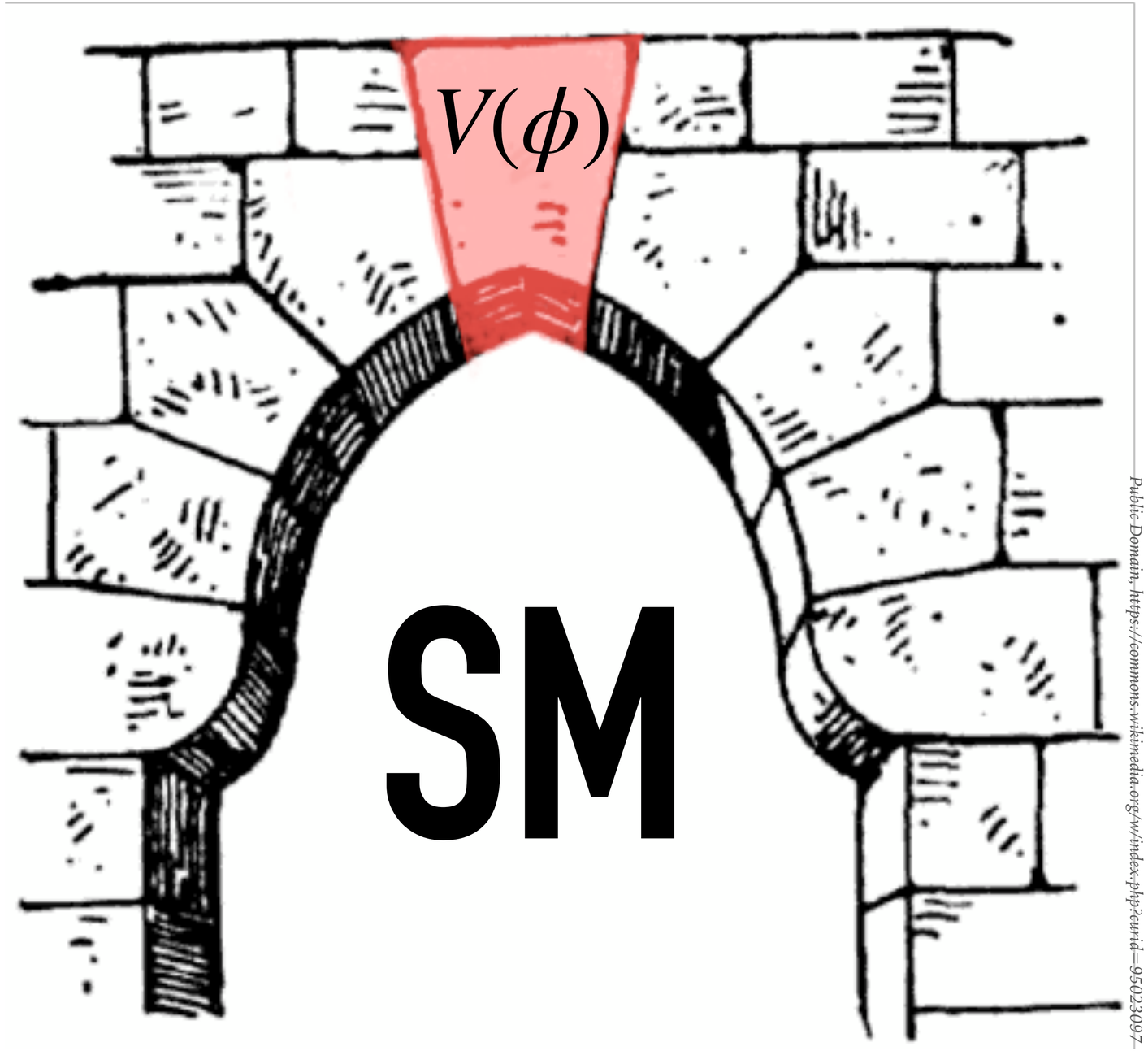
What of future colliders



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



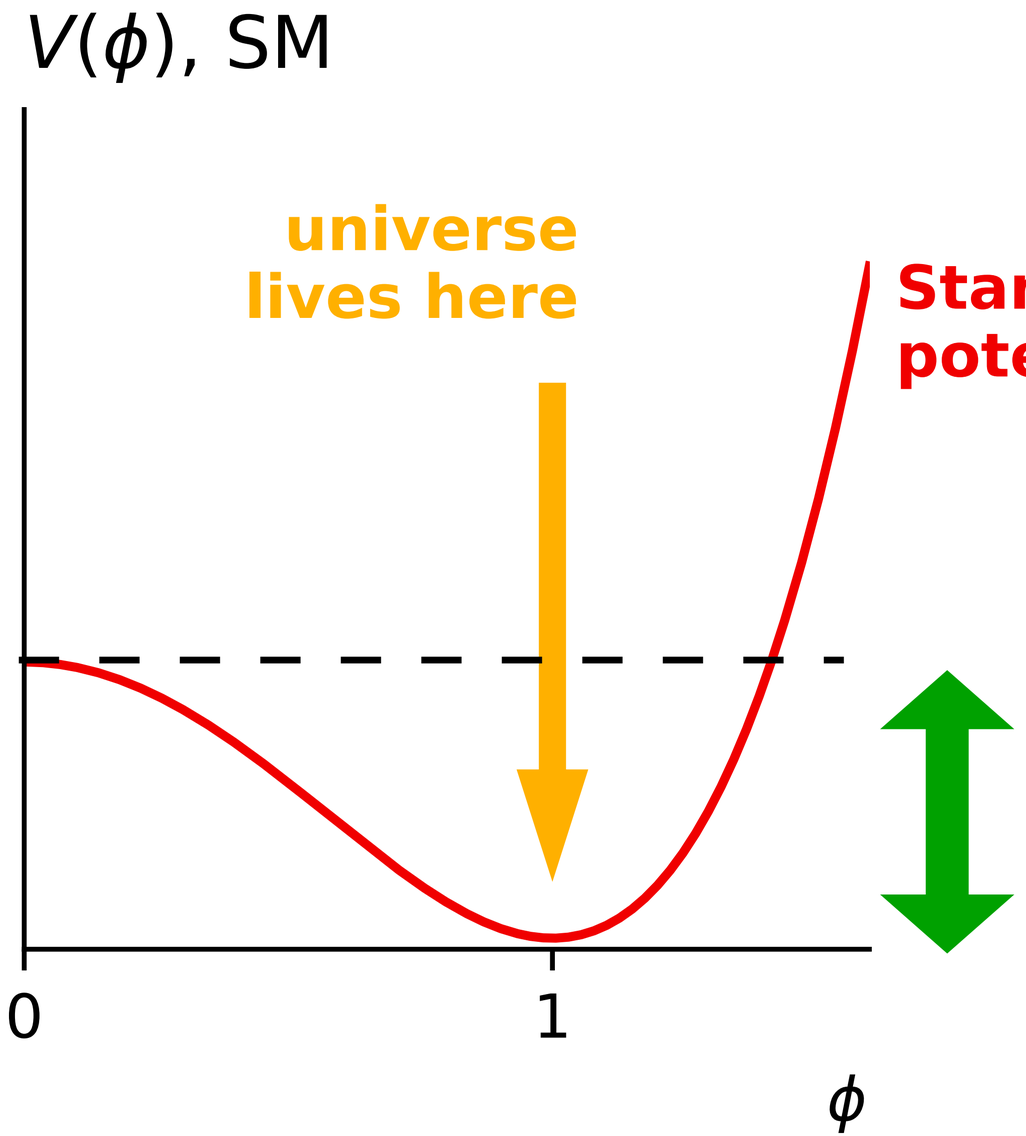
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unique among all the fields we know, the Higgs field is the only one that is non-zero "classically"

Why?
Higgs potential?

Keystone of SM

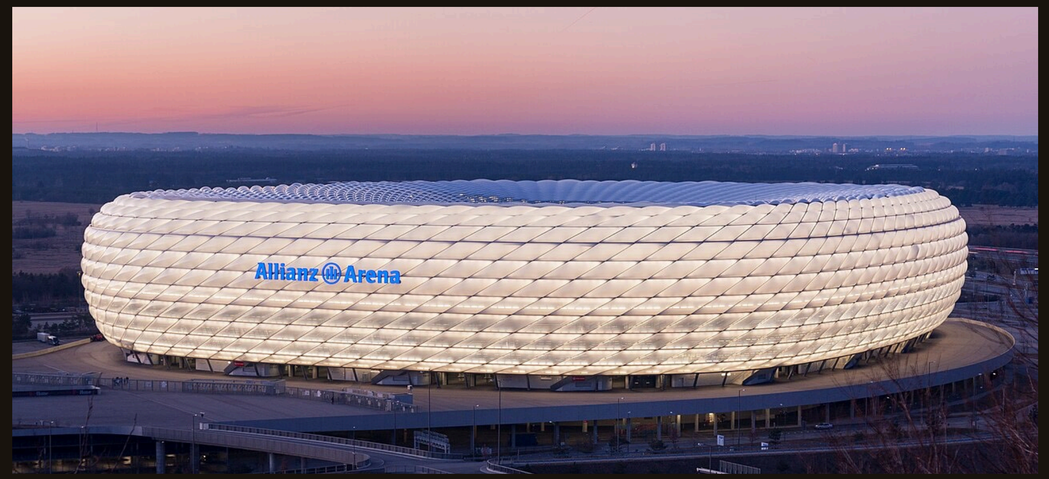
Higgs potential – remember: it's an energy density



Corresponds to an energy density of
$1.5 \times 10^{10}\,\mathrm{GeV/fm^3}$

$E = mc^2 \rightarrow$ Mass density of $2.6 \times 10^{28}\,\mathrm{kg/m^3}$
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
Allianz Arena by 2015 Michael 2015 - Own work, CC BY-SA 4.0,
https://commons.wikimedia.org/w/index.php?curid=121472476





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Earth at neutron star density

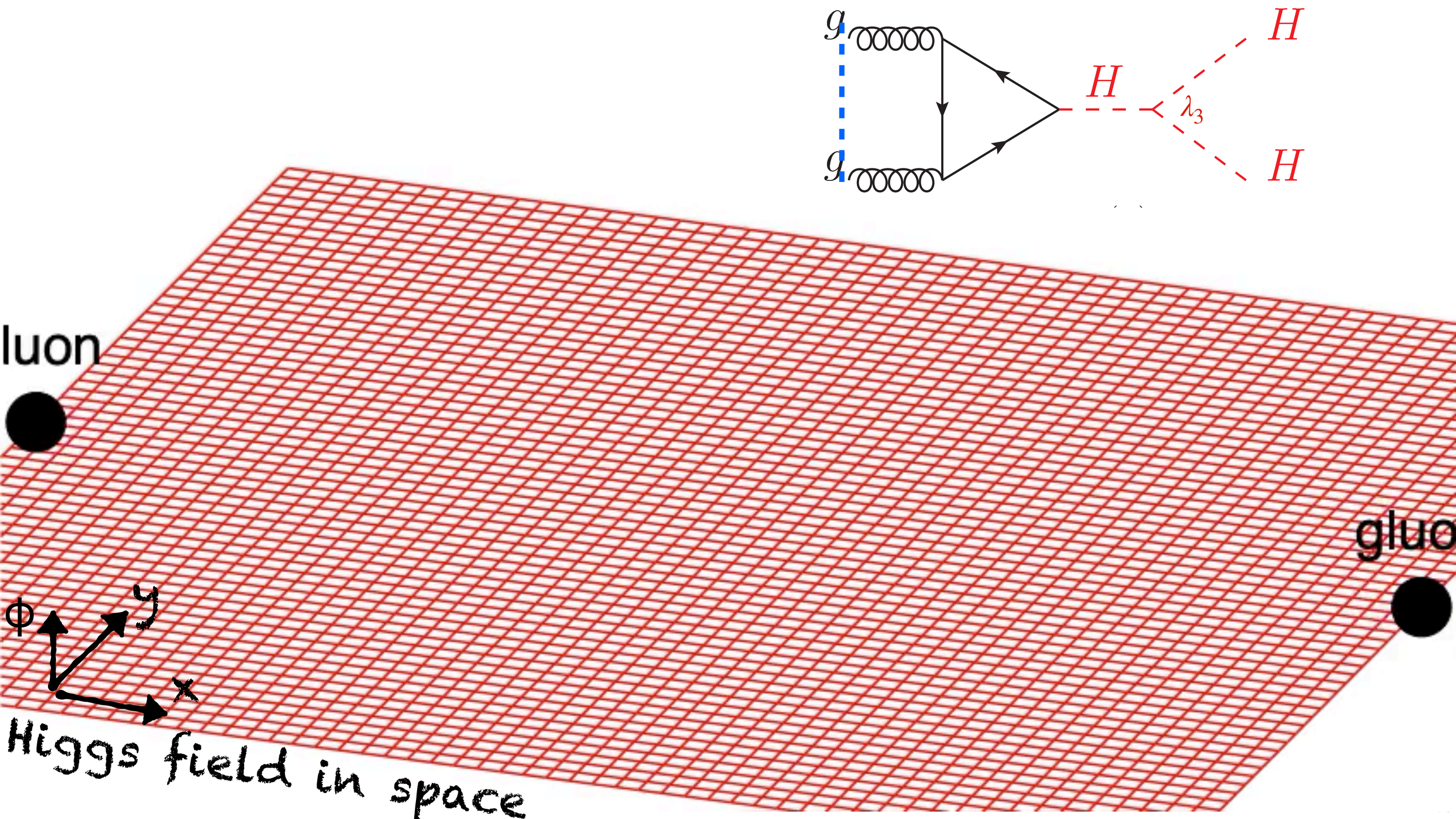
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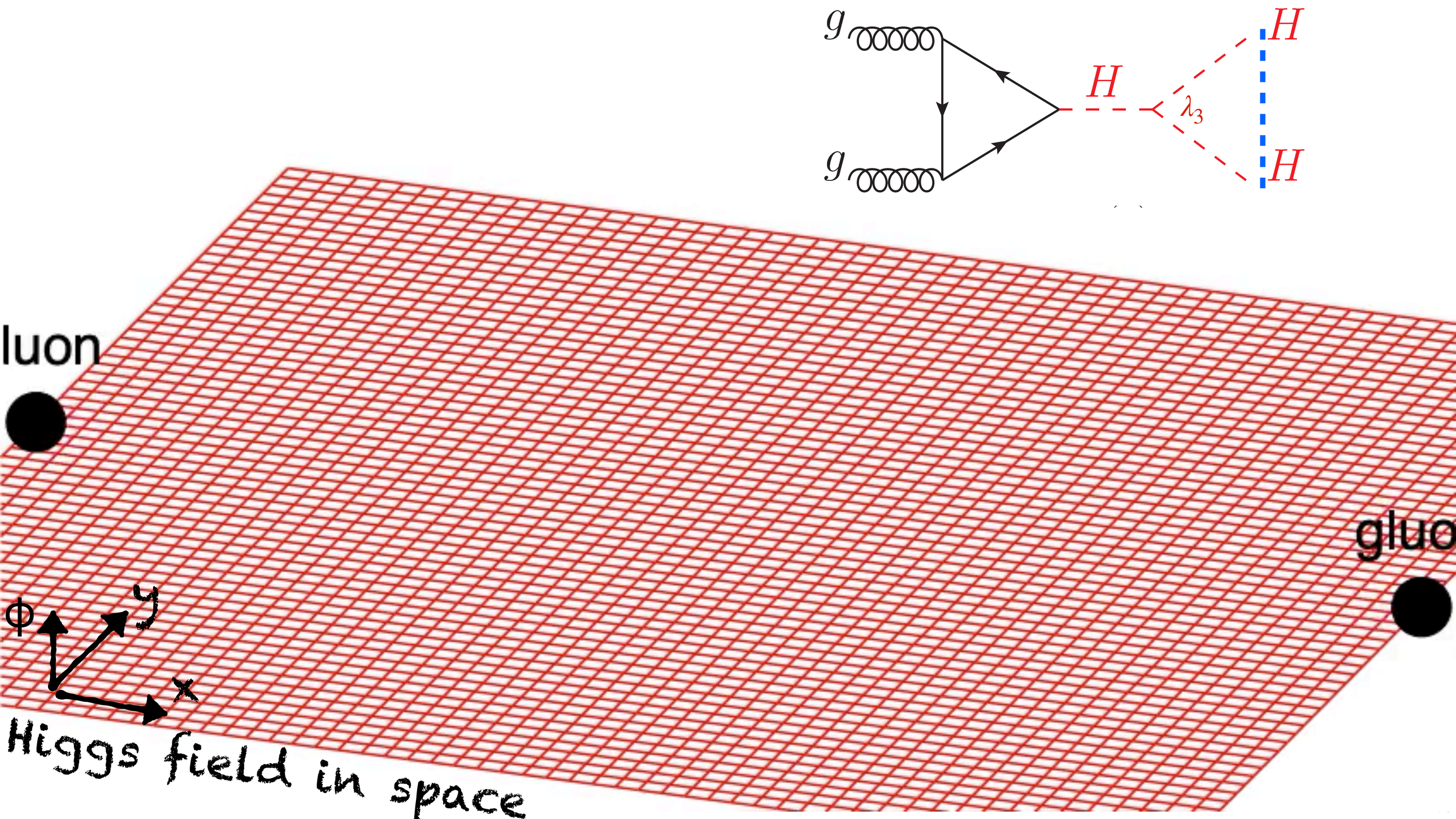


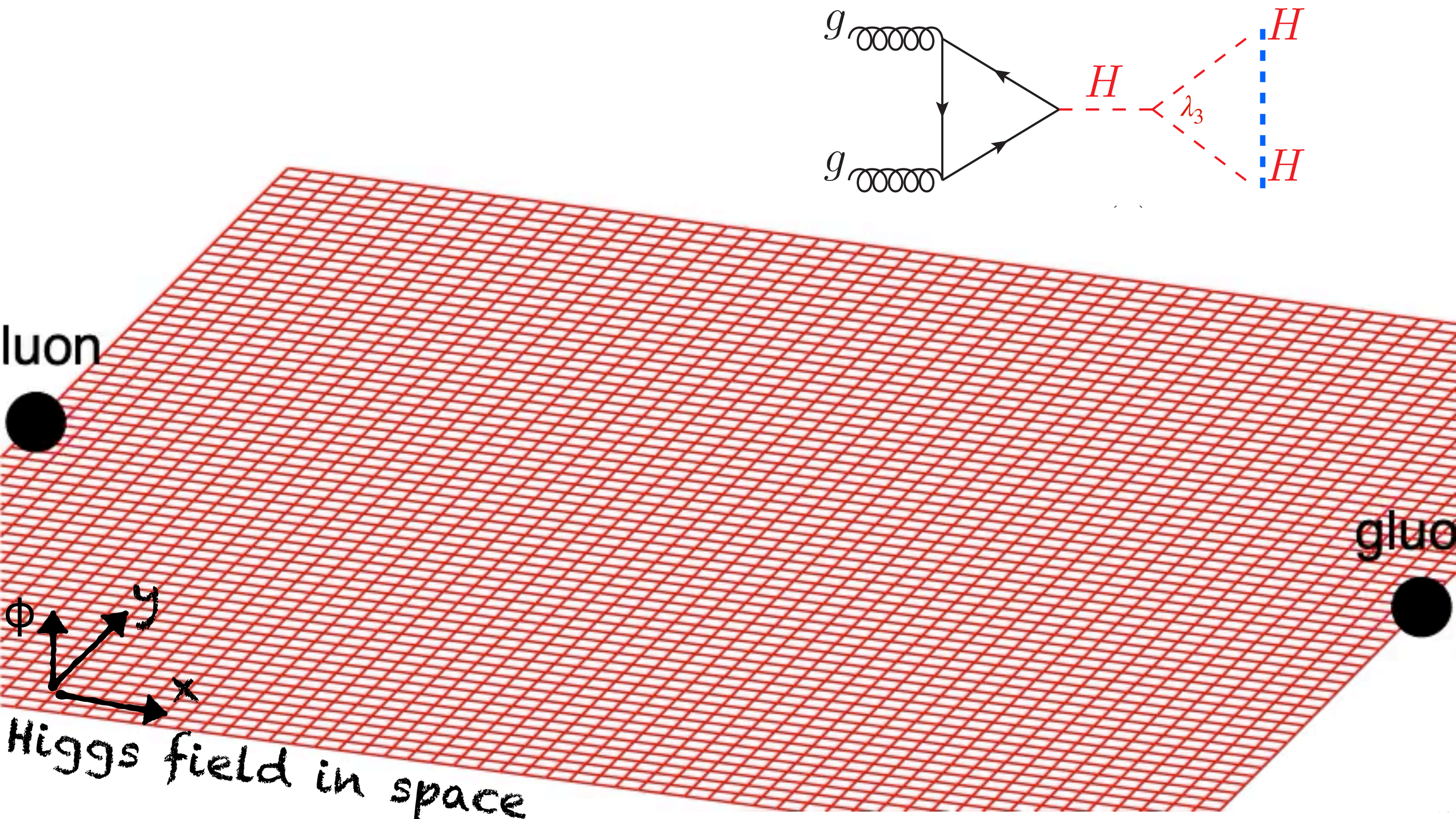
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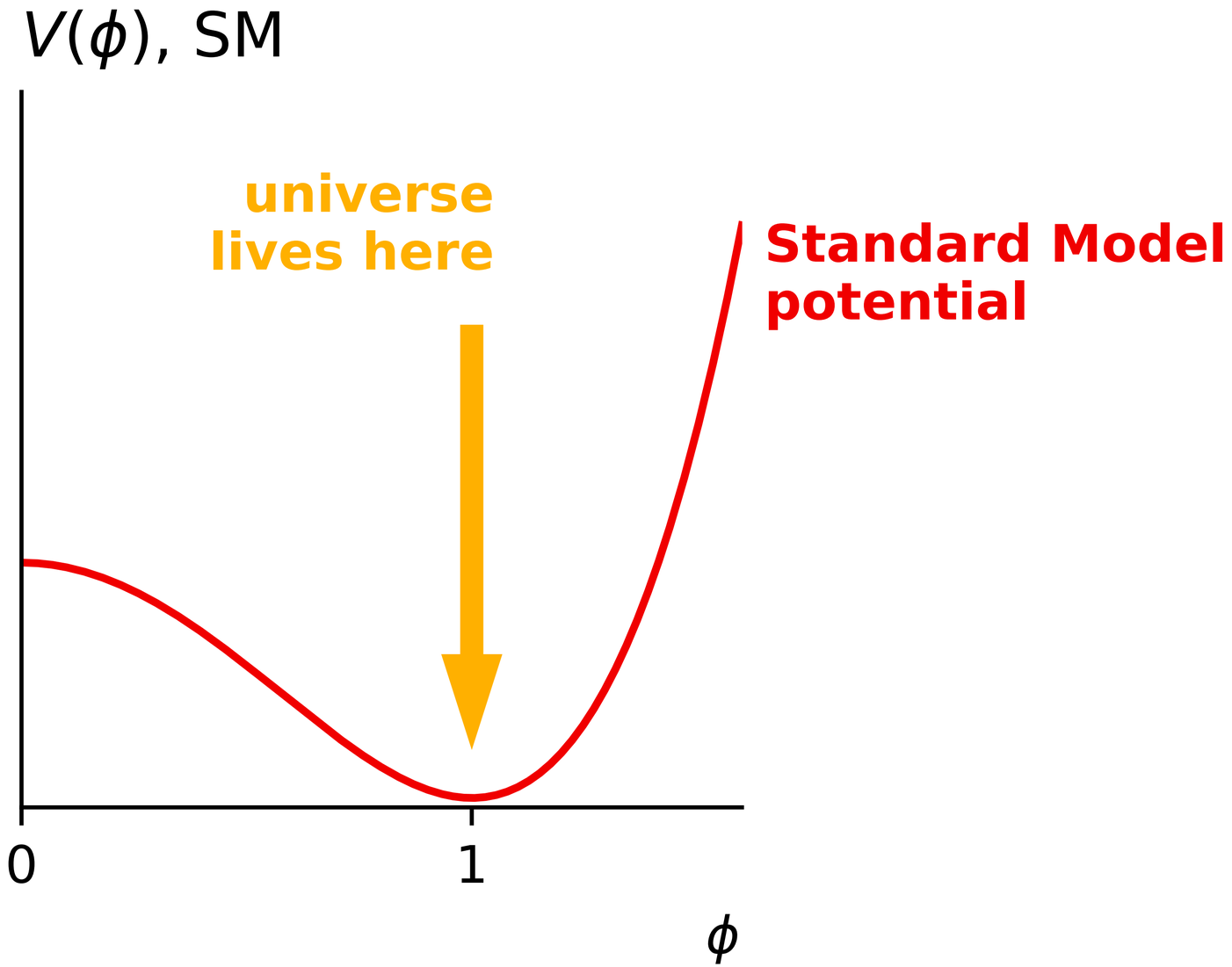
Earth at Higgs potential density


g
g
H
H
H
λ_3
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
λ3
H
H
luon
gluo
Φ
y
x
Higgs field in space

Higgs potential

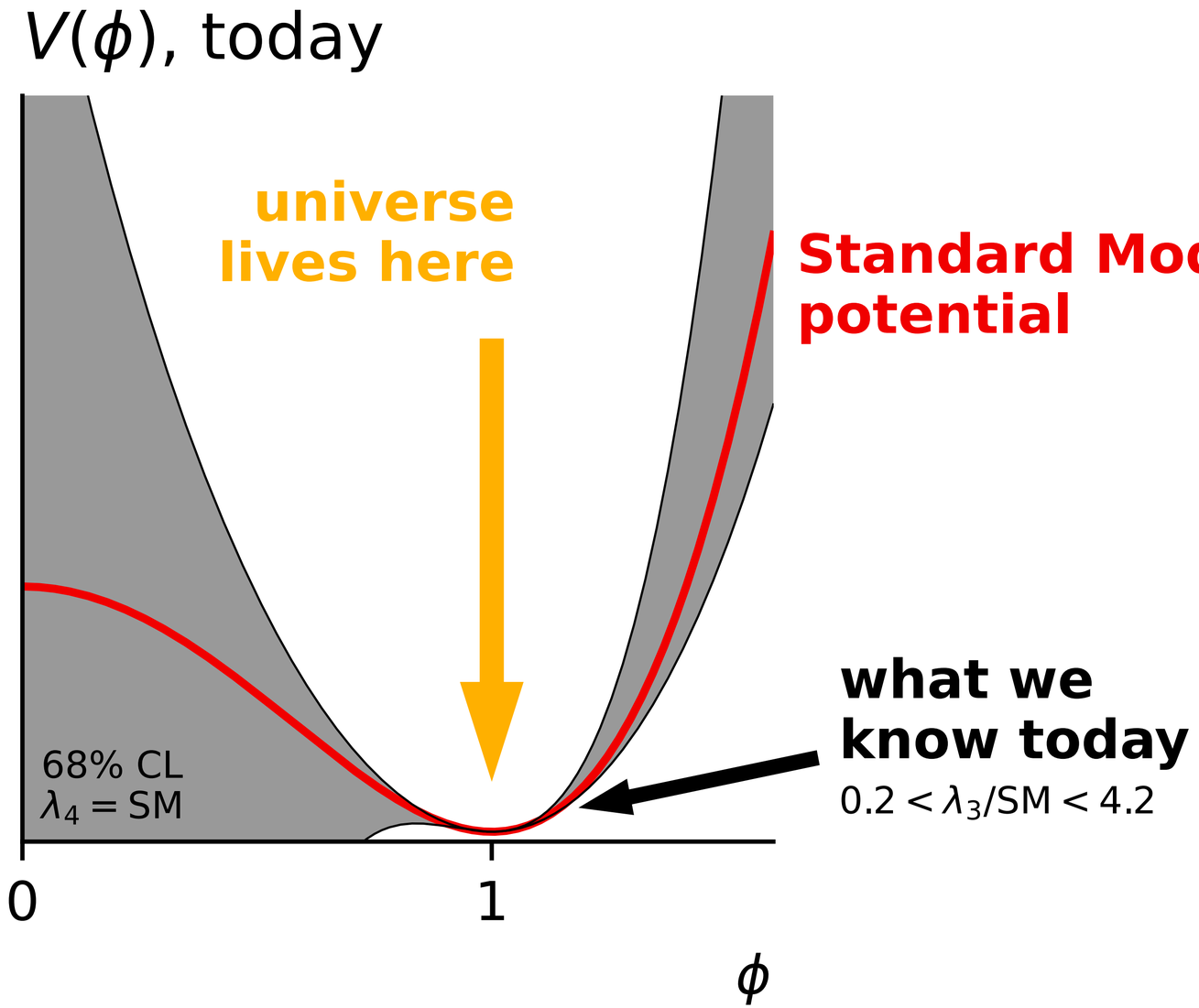


Studying H→HH probes specific mathematical property of the potential's shape:

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

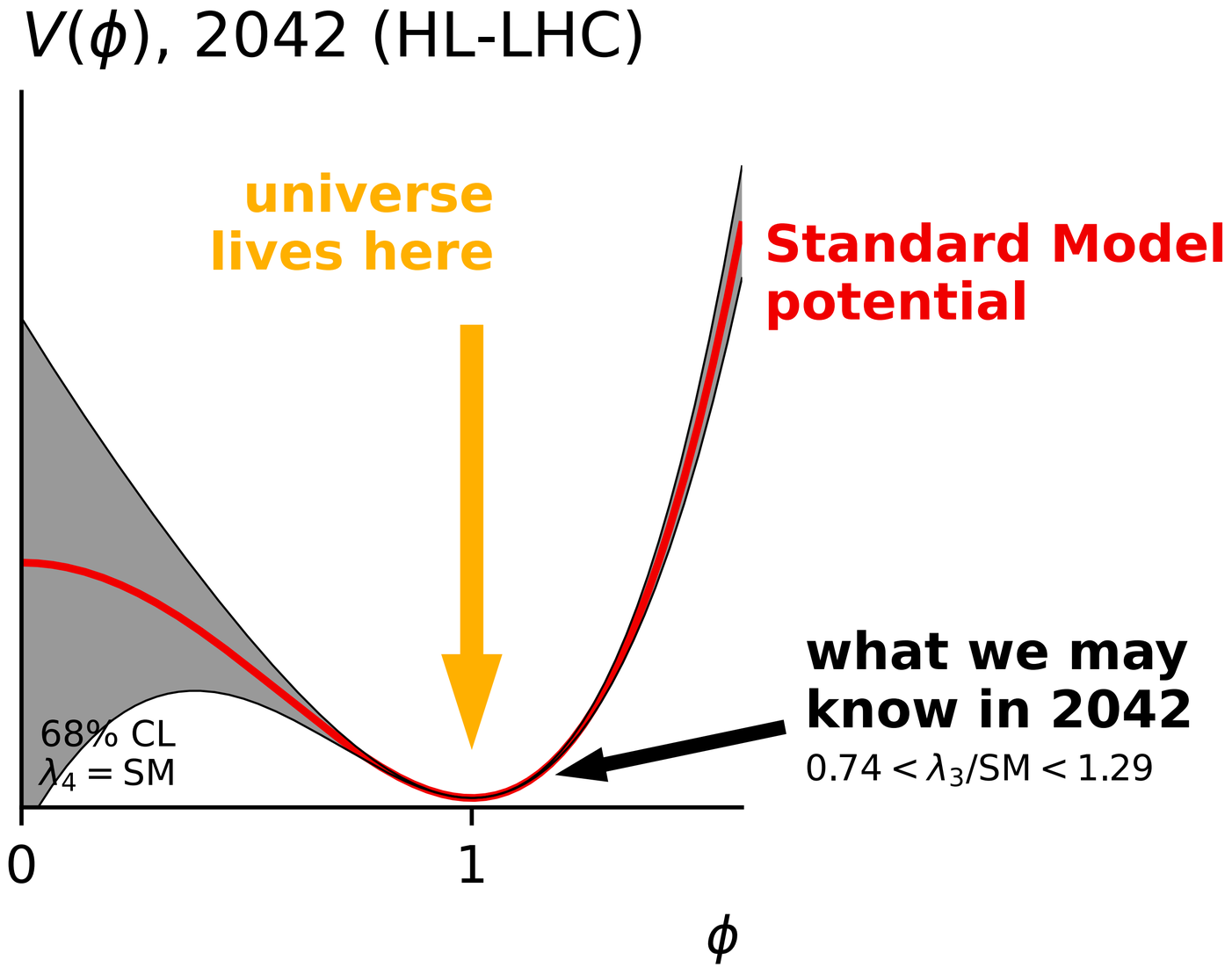


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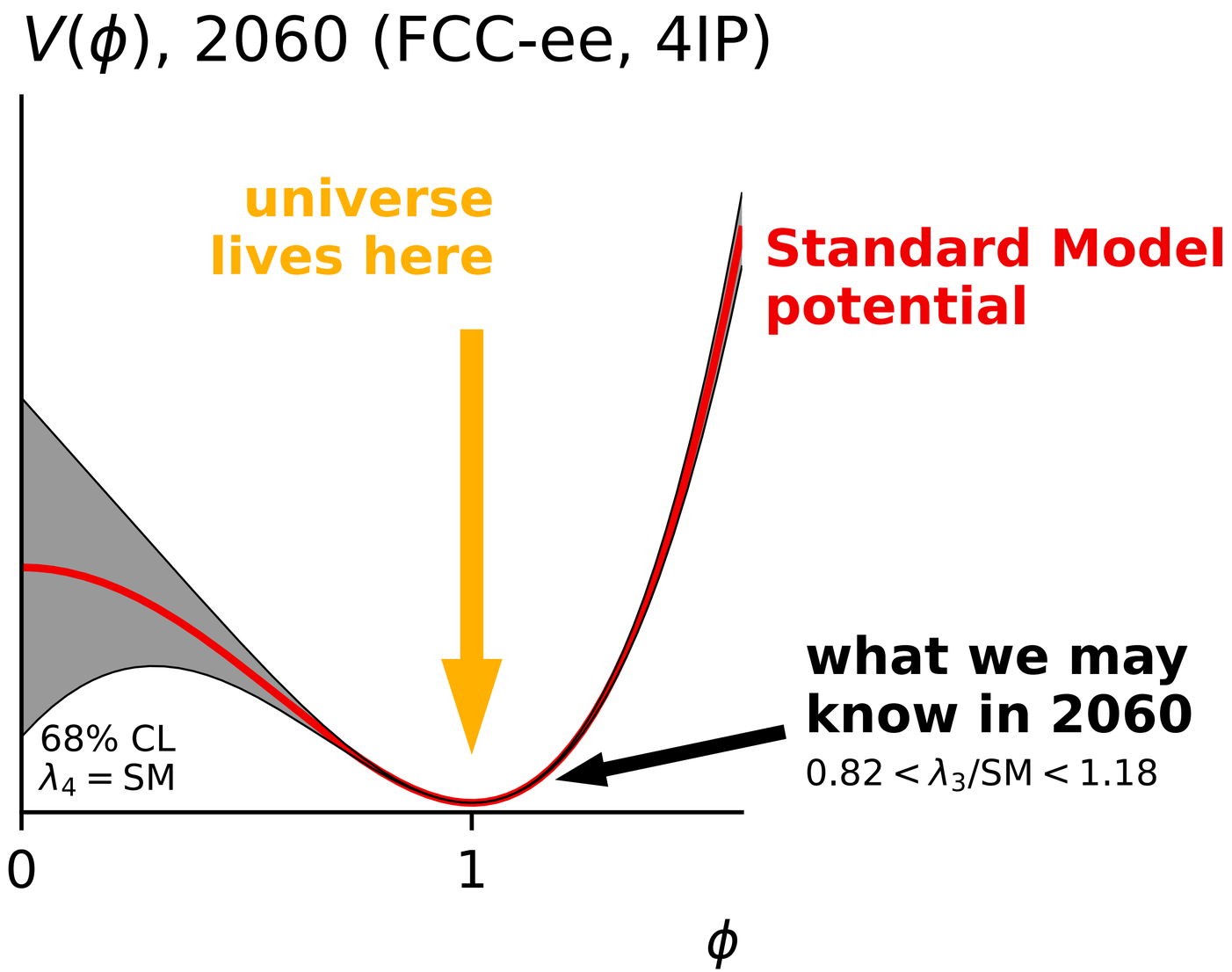


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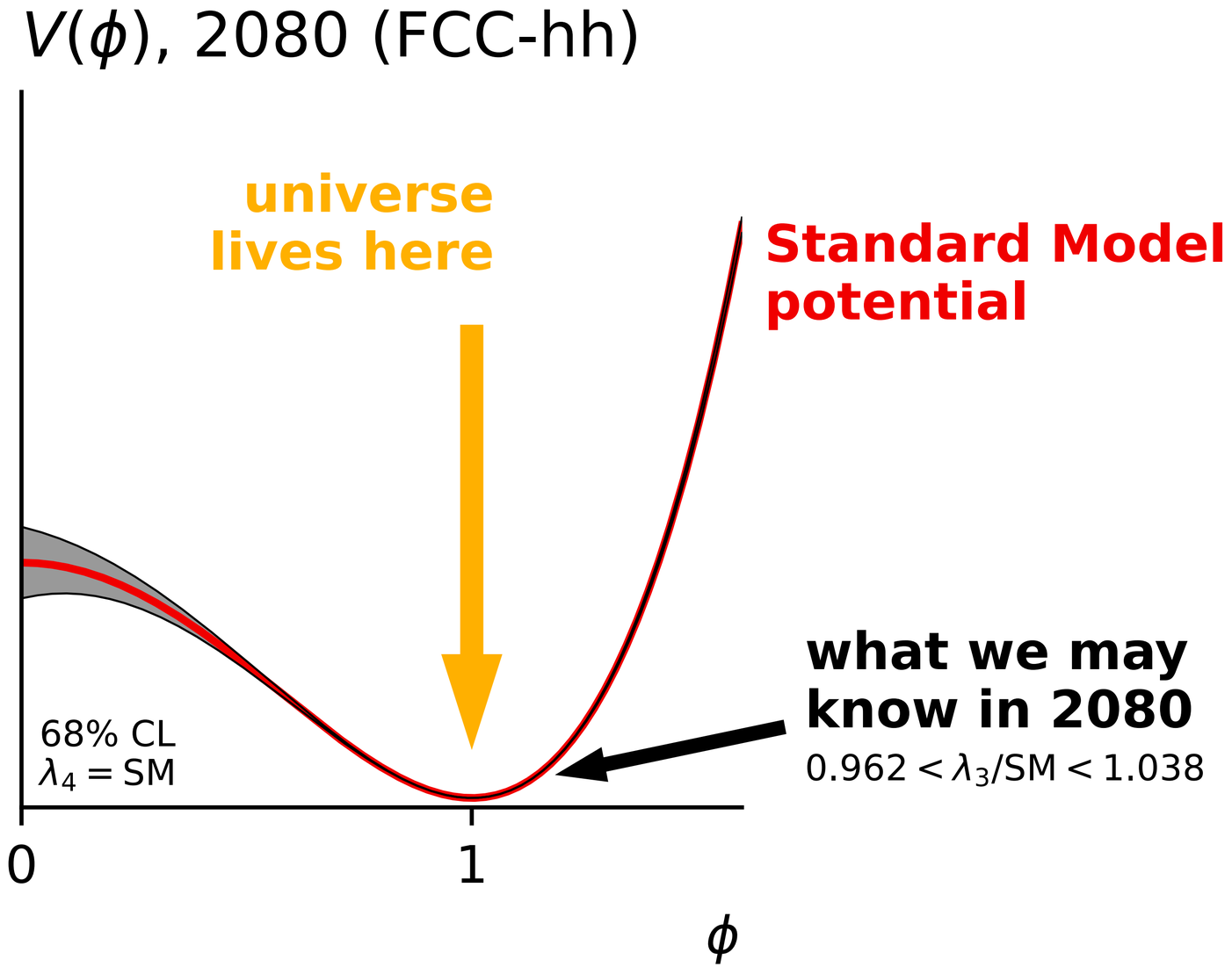


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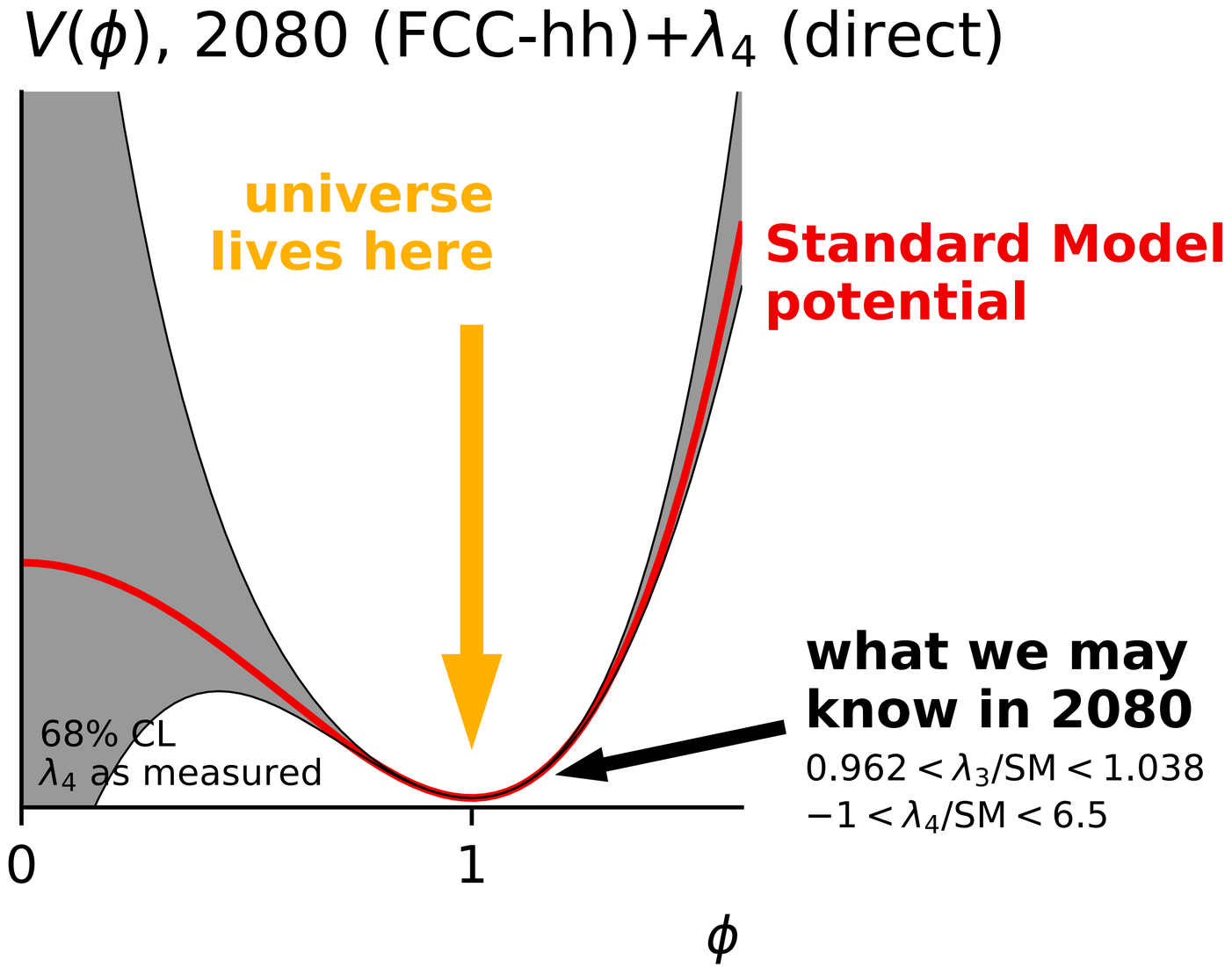


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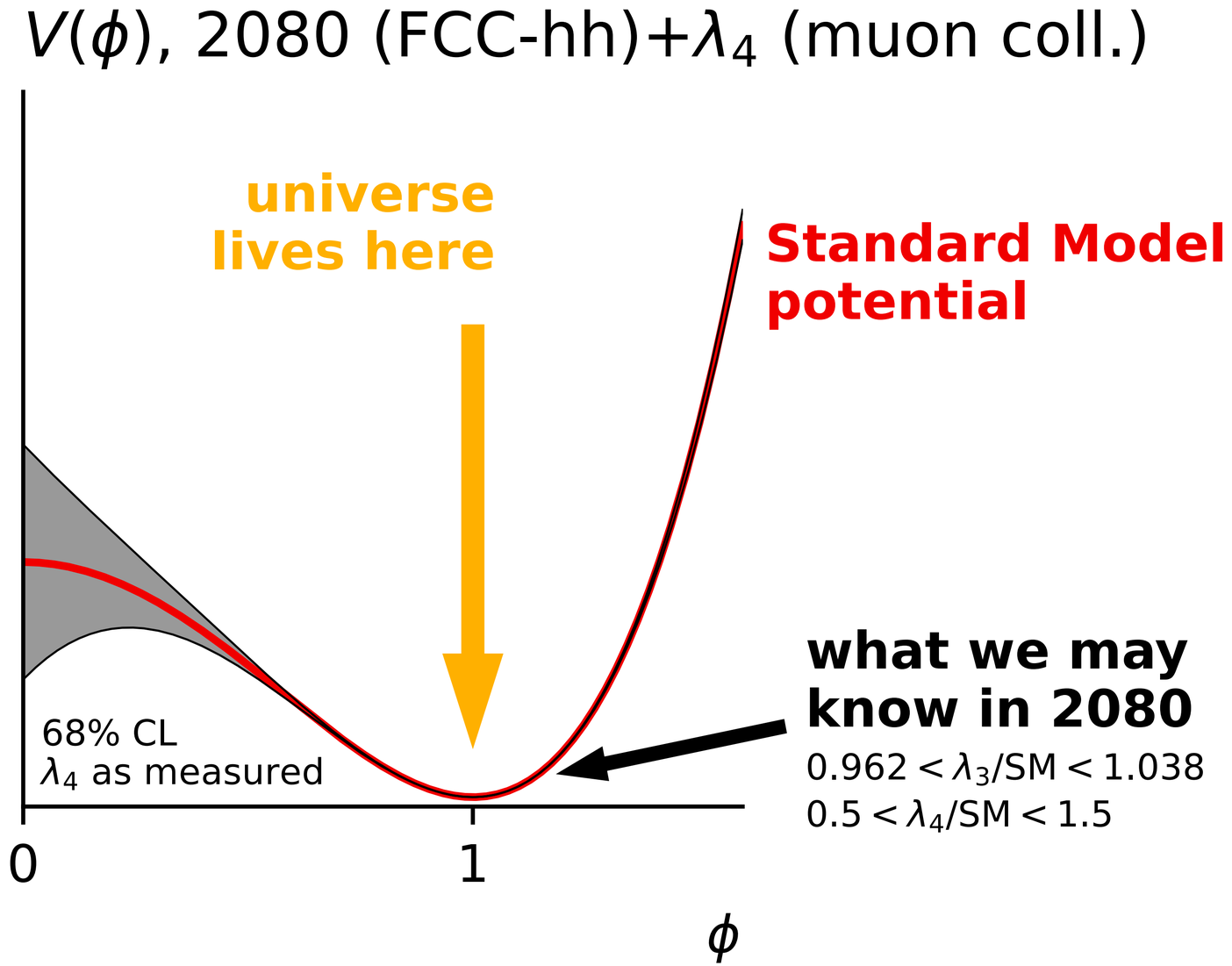


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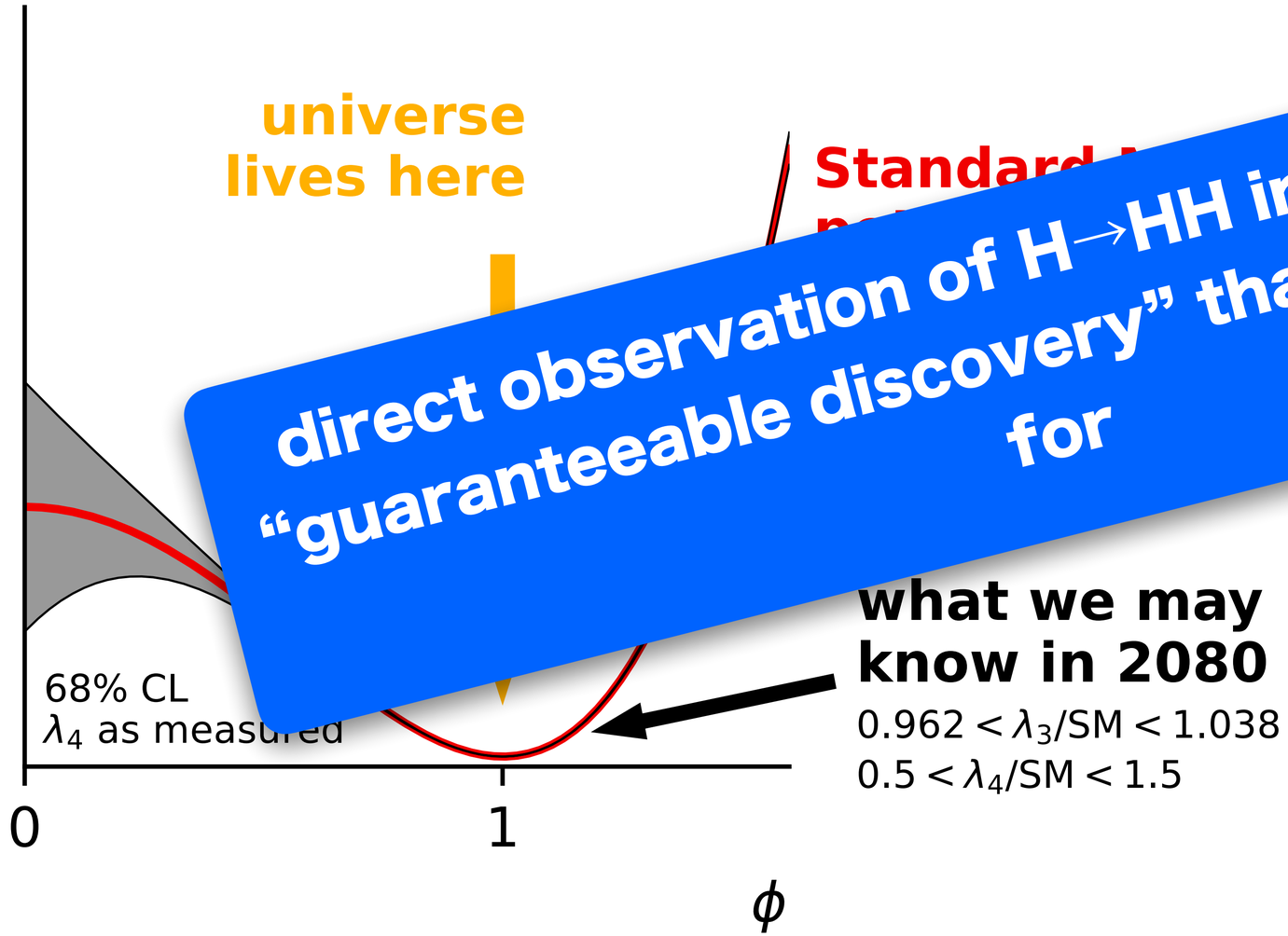
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Higgs potential

$V(\phi)$, 2080 (FCC-hh)+λ_4 (muon coll.)



what we may know in 2080

$0.962 < \lambda_3/\mathrm{SM} < 1.038$

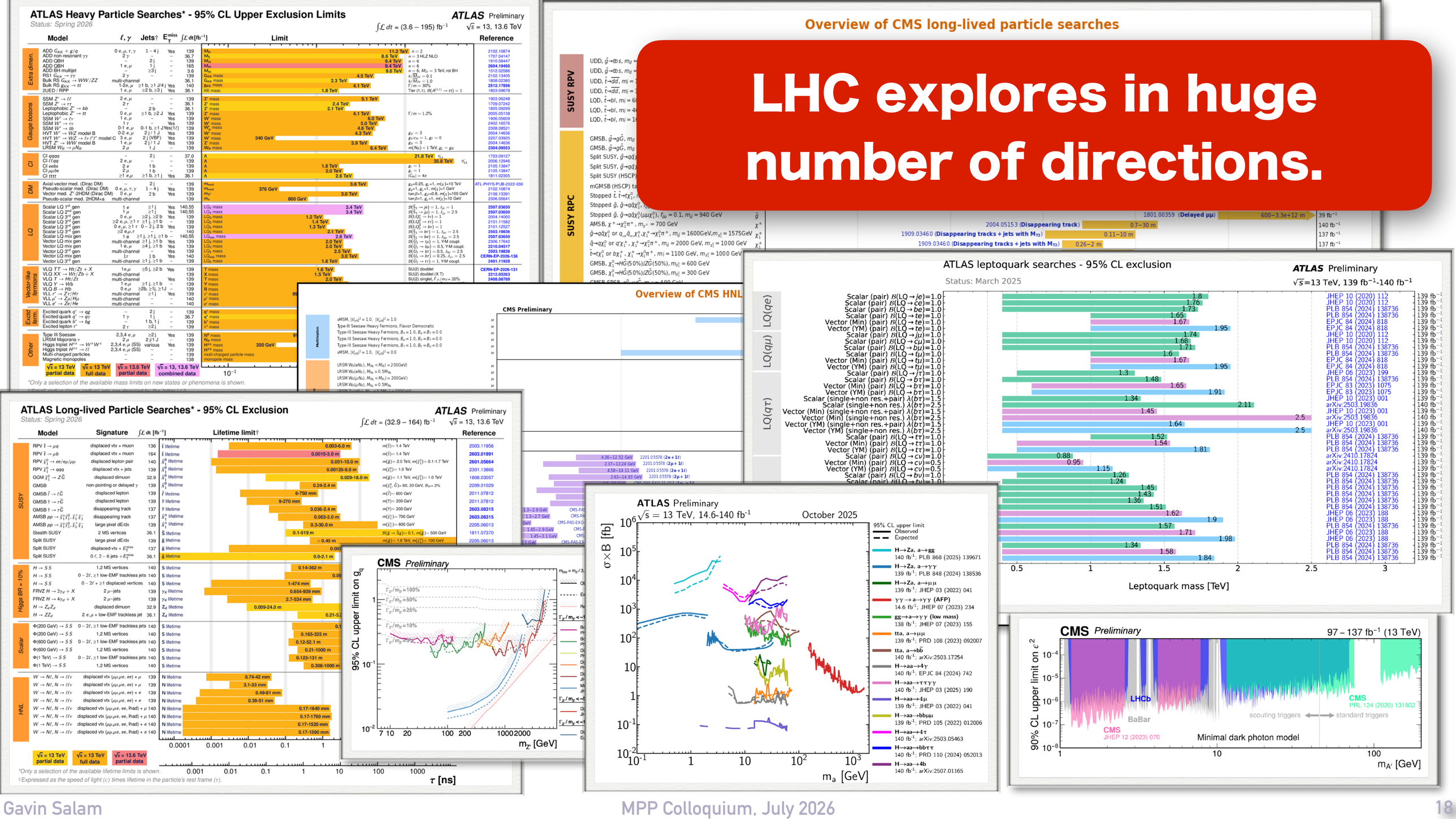
$0.5 < \lambda_4/\mathrm{SM} < 1.5$

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

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

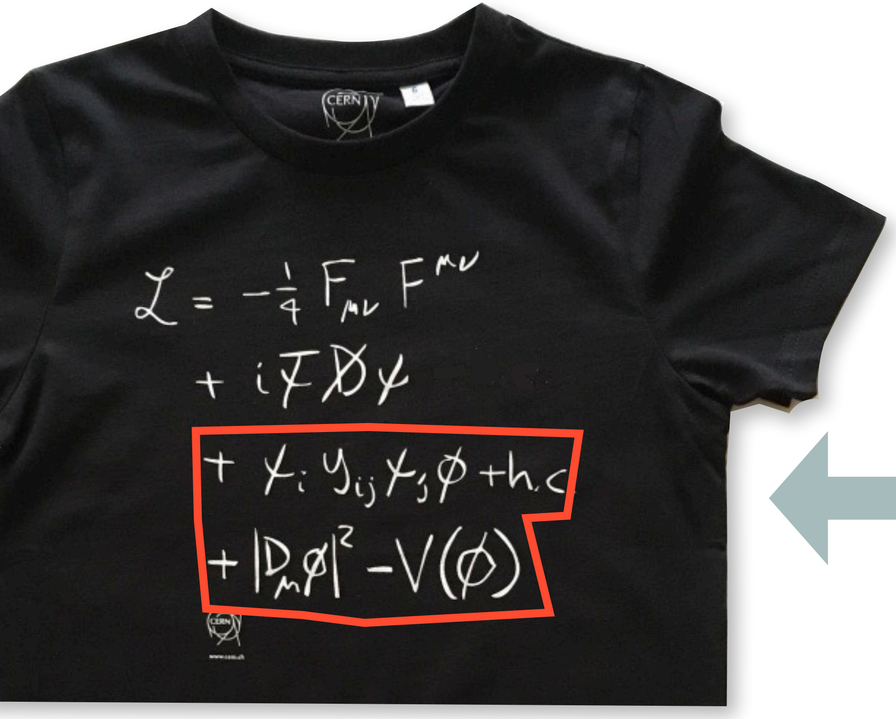
[reconstruction in plot assumes higher derivatives as in SM]

LHC explores in huge number of directions.

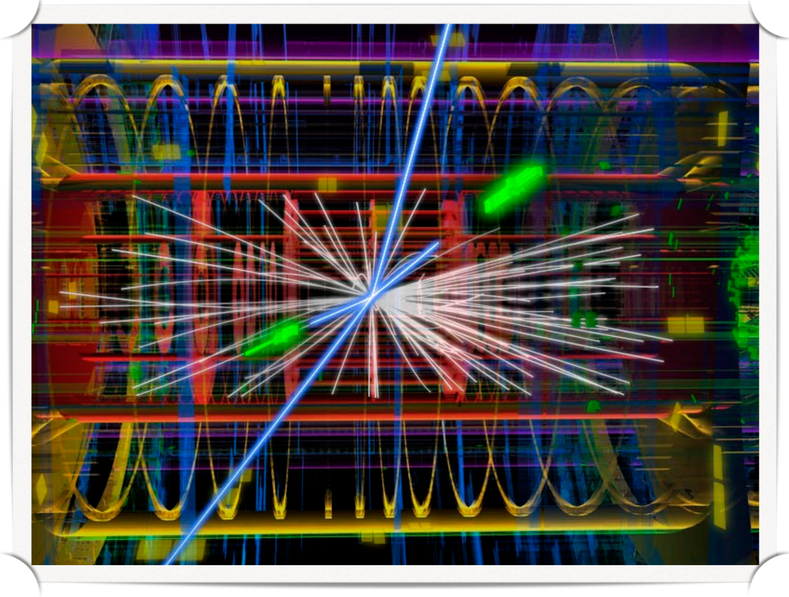


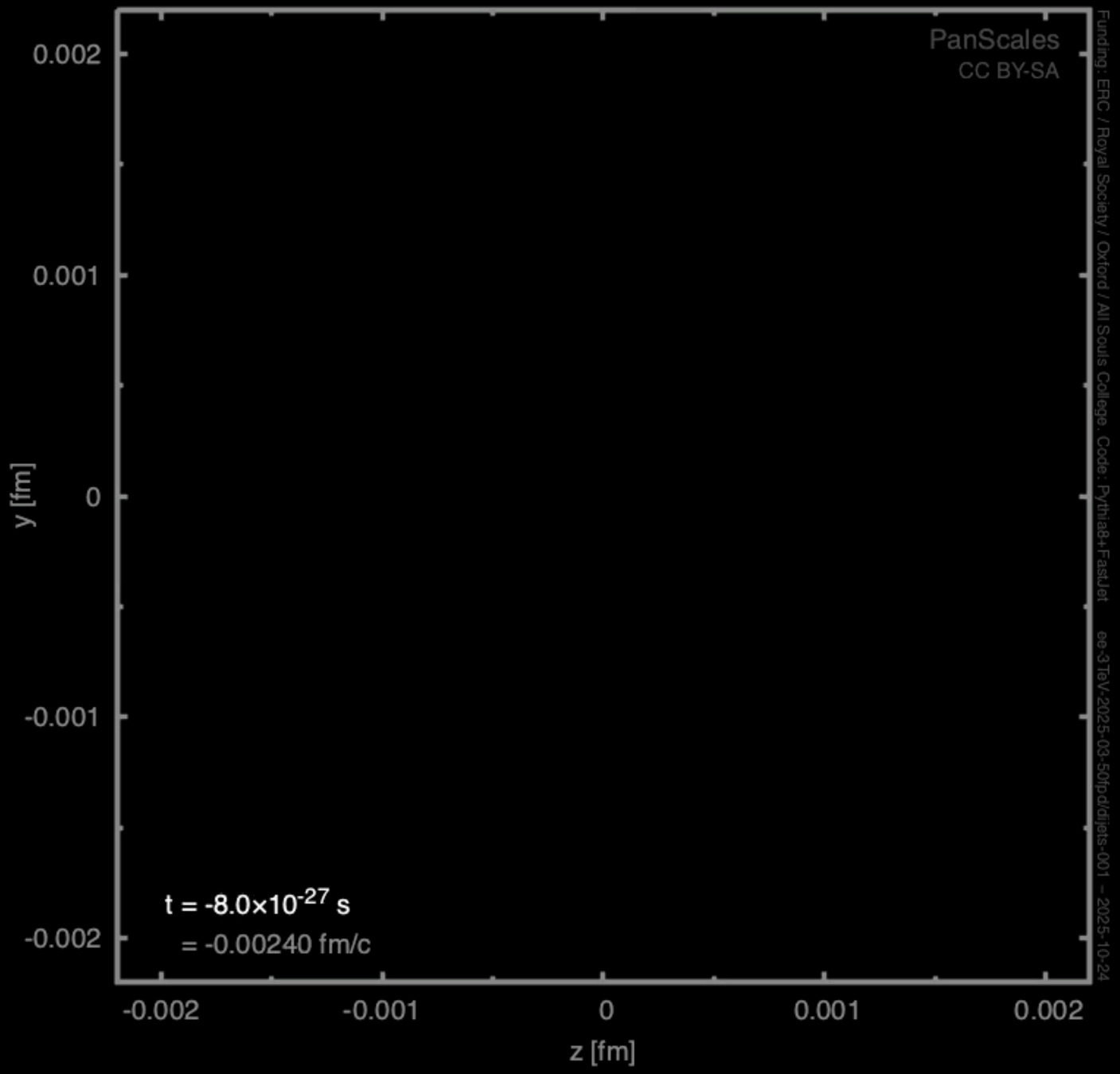
UNDERLYING THEORY

EXPERIMENTAL DATA



how do you make quantitative connection?



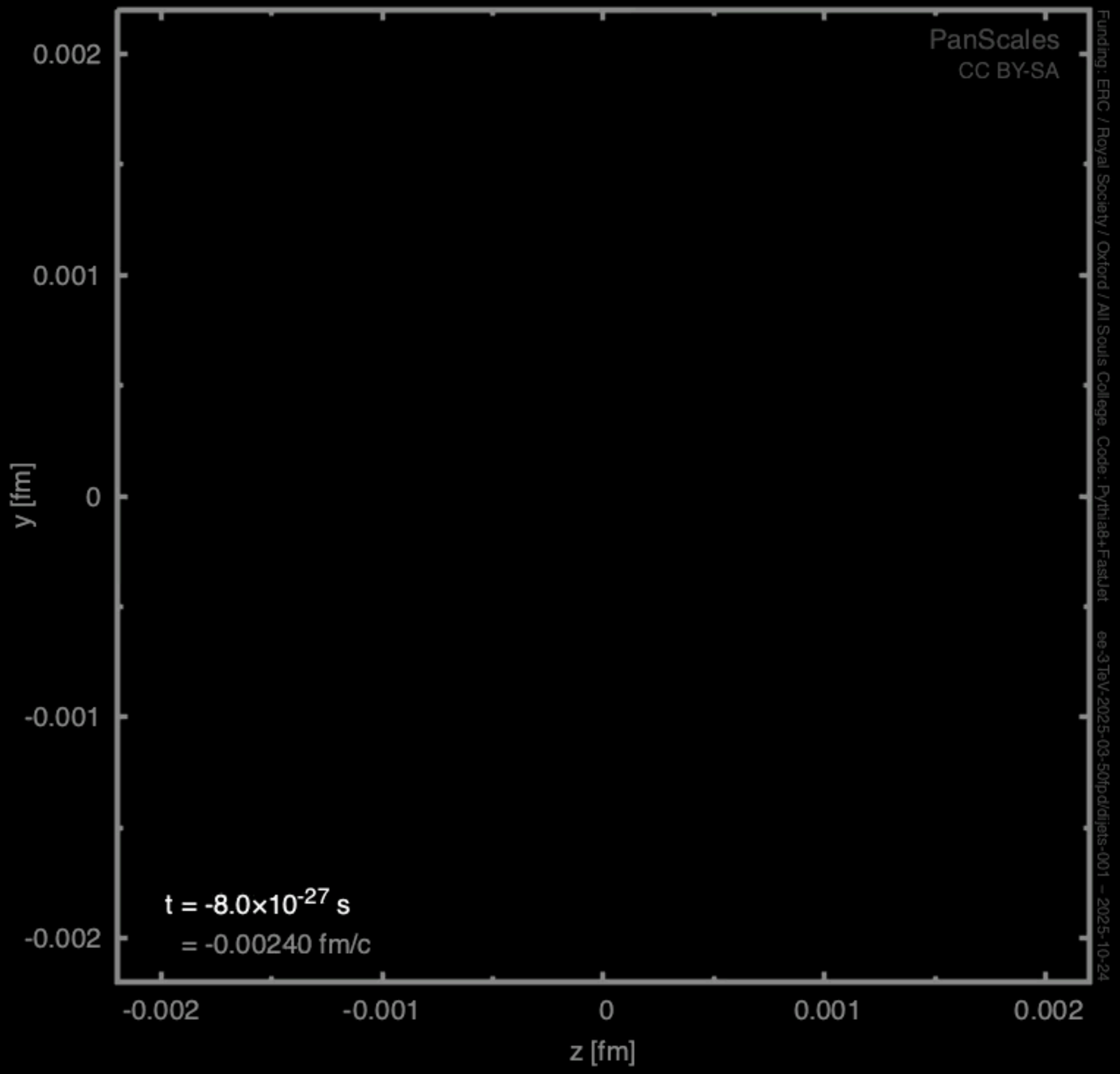


incoming beam particle

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

The promise of perturbative QFT

Follow the rules (Feynman diagrams)

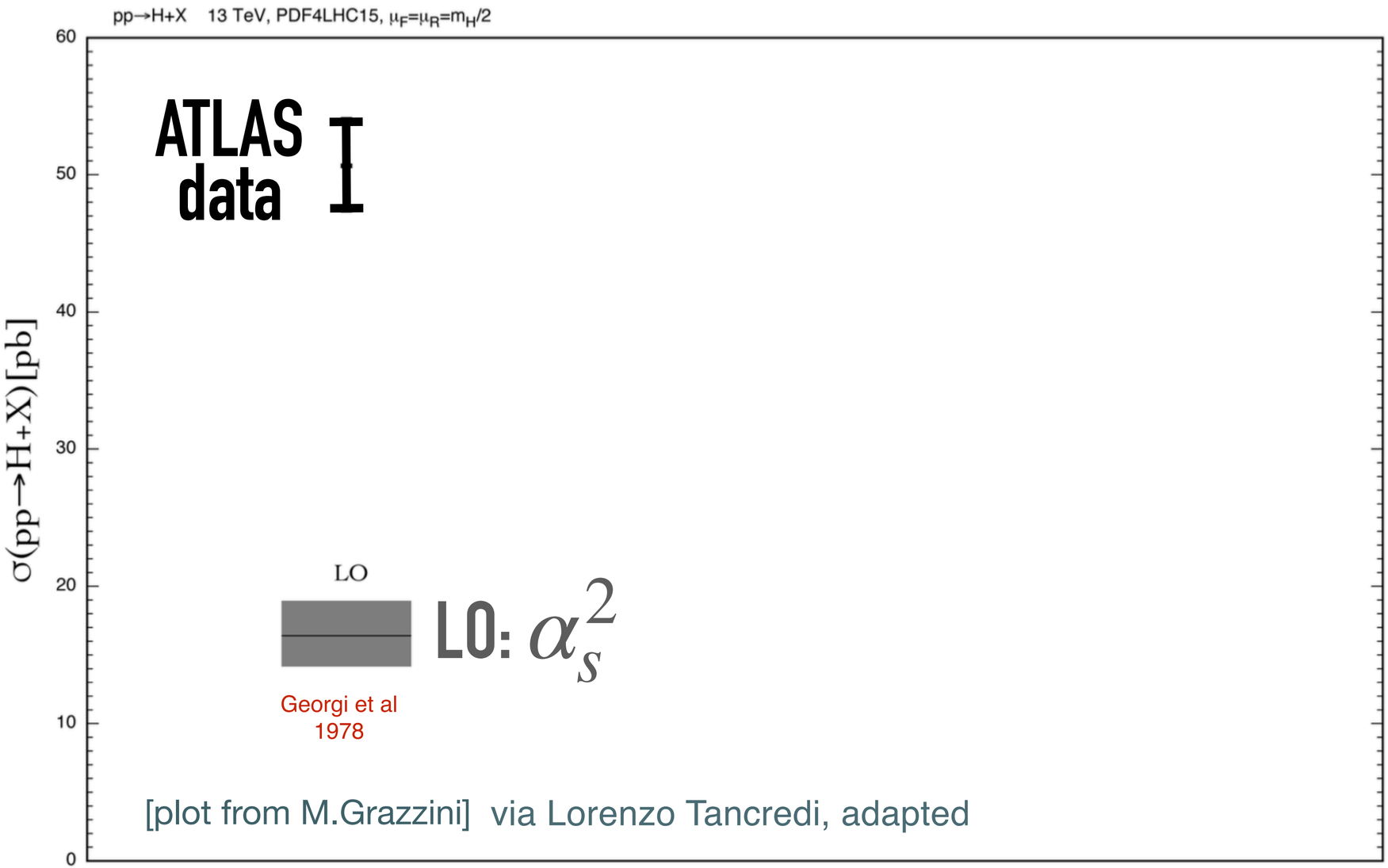
Ask a computer to work through maths

Out comes a prediction

Ask the computer to draw more diagrams, work harder, and you get more accuracy

Does it live up to the promise? [#1]

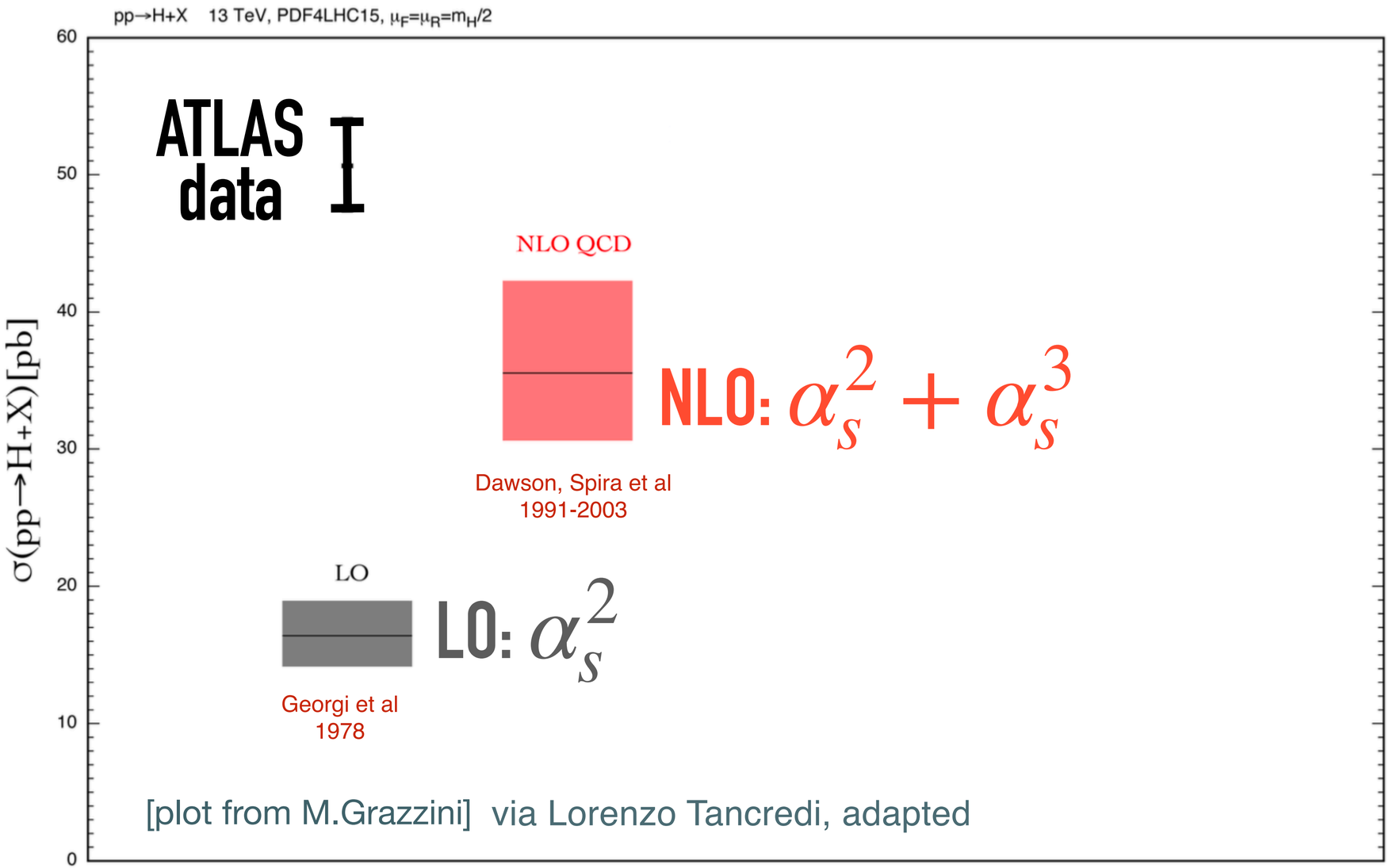
Higgs Boson Cross Section



[plot from M.Grazzini] via Lorenzo Tancredi, adapted

Does it live up to the promise? [#1]

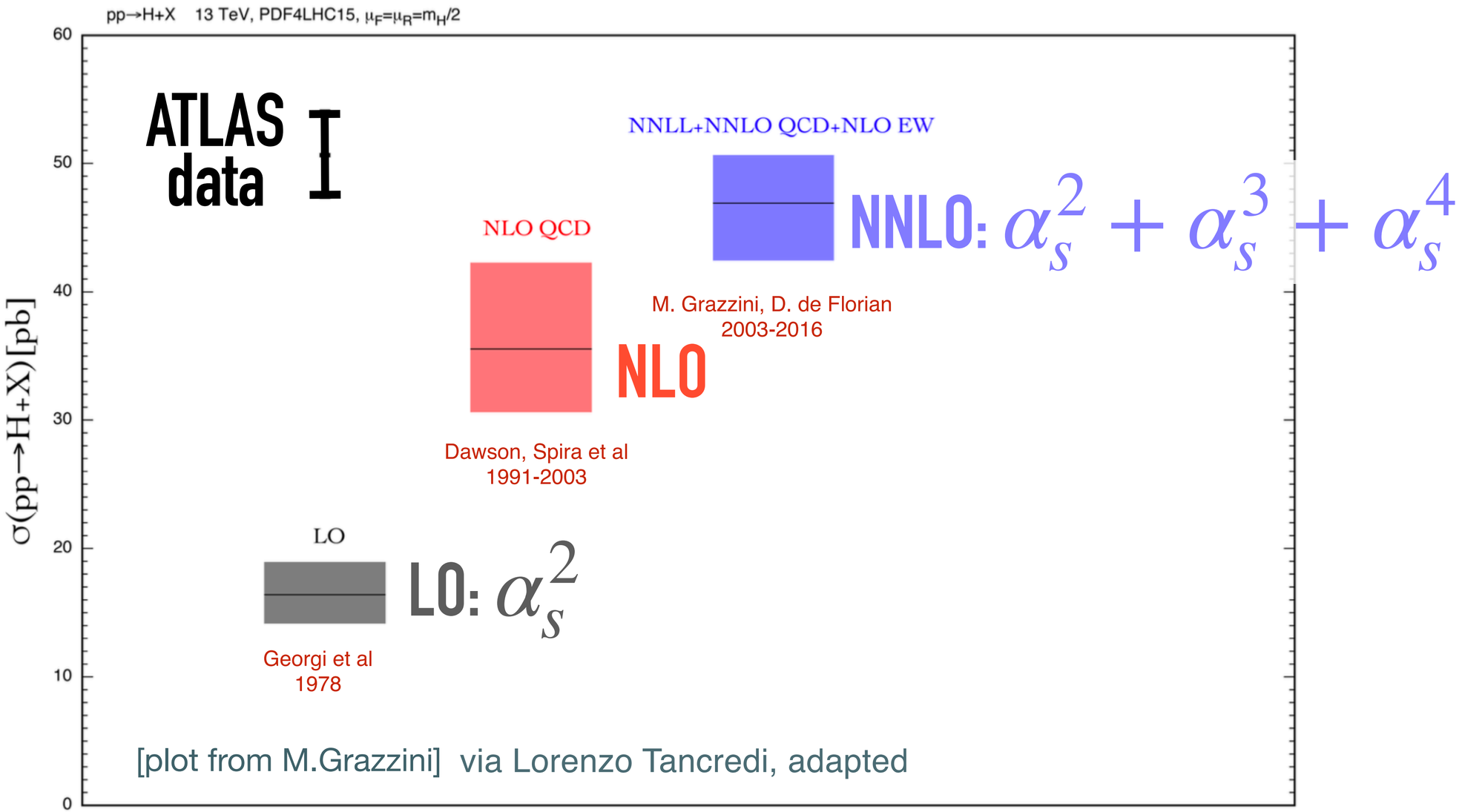
Higgs Boson Cross Section



[plot from M.Grazzini] via Lorenzo Tancredi, adapted

Does it live up to the promise? [#1]

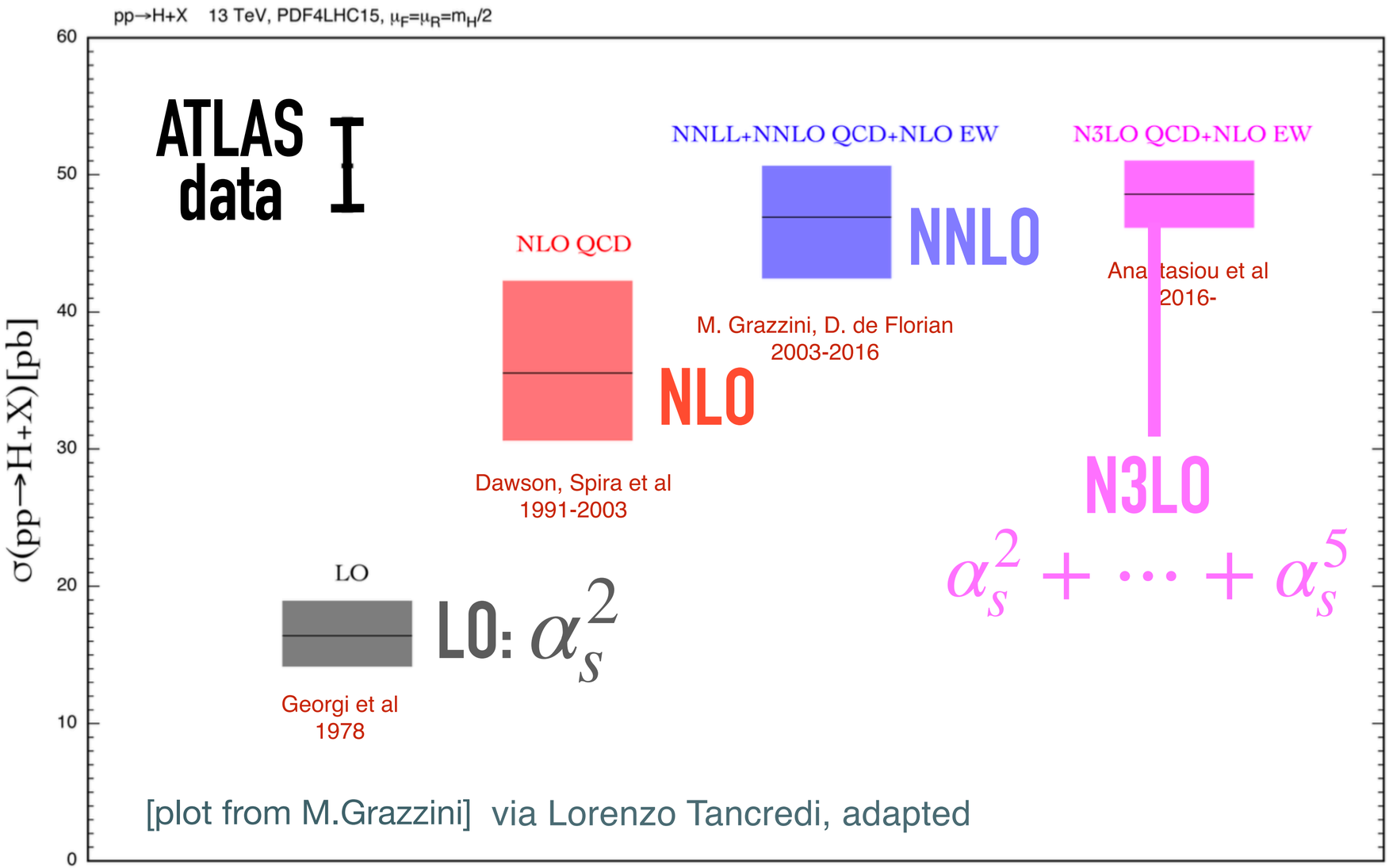
Higgs Boson Cross Section



[plot from M.Grazzini] via Lorenzo Tancredi, adapted

Does it live up to the promise? [#1]

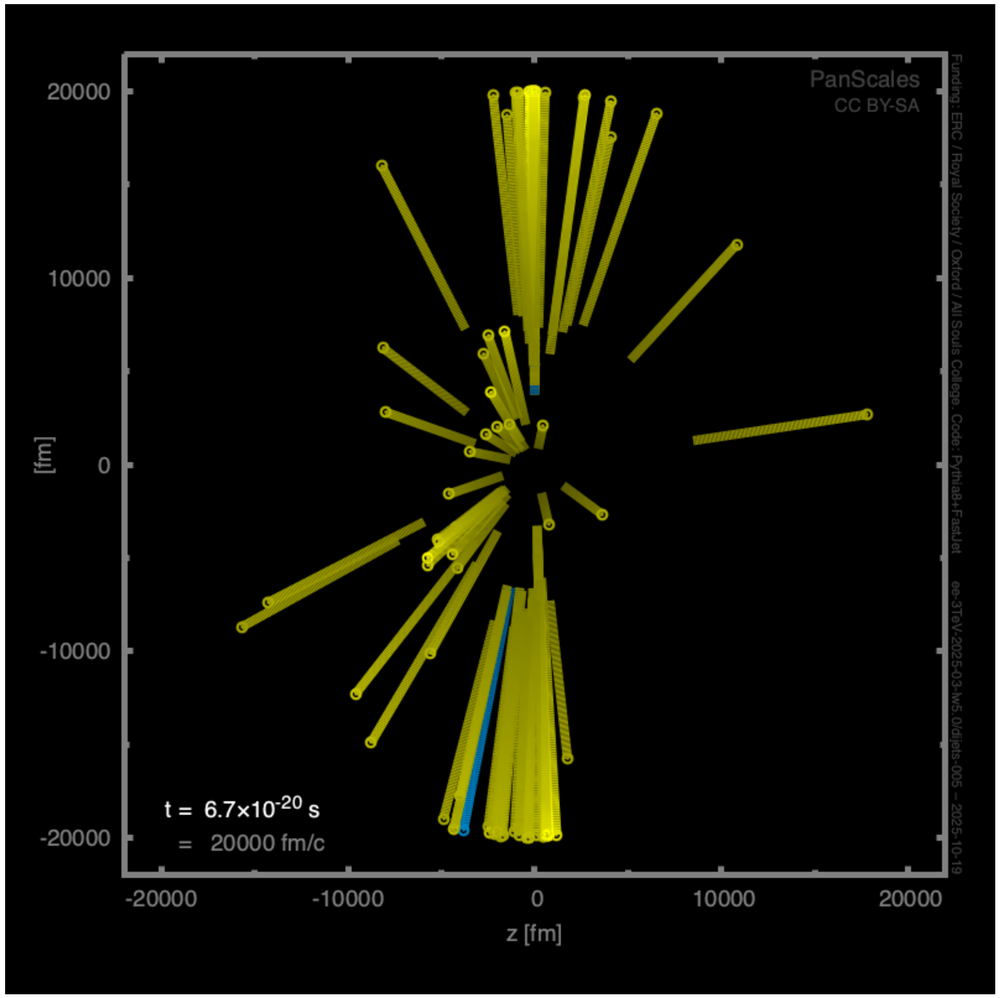
Higgs Boson Cross Section



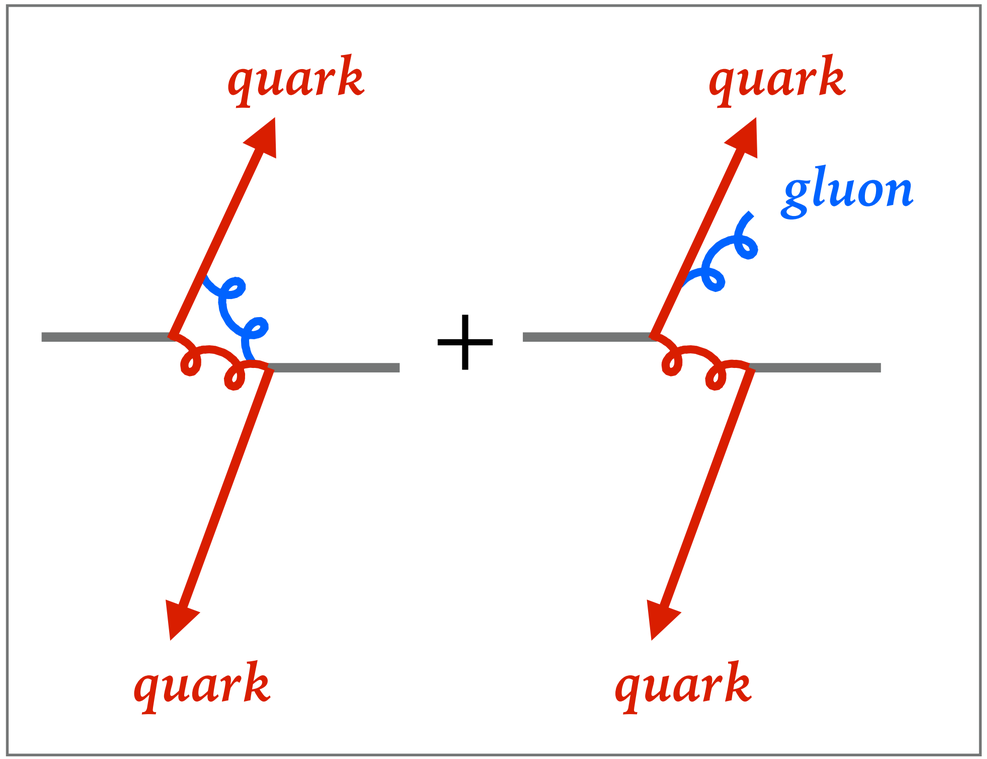
[plot from M.Grazzini] via Lorenzo Tancredi, adapted

Does it live up to the promise? [#2]

A problem: real events and power-house calculational tool look totally different



≠



next-to-leading order

What a NLO calculation gives you (here, Event2, $e^+e^- \to q\bar{q}$)

LO (2-particle) tree-level event
with weight 1.00000
px, py, pz, E = -1.32 -1.38 -49.96 50.00
px, py, pz, E = 1.32 1.38 49.96 50.00

What a NLO calculation gives you (here, Event2, $e^+e^- \to q\bar{q}$)

LO (2-particle) tree-level event
with weight 1.00000
px, py, pz, E = -1.32 -1.38 -49.96 50.00
px, py, pz, E = 1.32 1.38 49.96 50.00

LO event ($q\bar{q}$)

What a NLO calculation gives you (here, Event2, $e^+e^- \to q\bar{q}$)

LO (2-particle) tree-level event
with weight 1.00000
px, py, pz, E = -1.32 -1.38 -49.96 50.00
px, py, pz, E = 1.32 1.38 49.96 50.00

NLO (3-particle) tree-level event
with **weight 16.7749**
px, py, pz, E = -1.60 -1.75 -49.87 49.93
px, py, pz, E = 1.31 1.36 49.25 49.29
px, py, pz, E = 0.30 0.39 0.62 0.79

LO event ($q\bar{q}$)

NLO event, with real emission
~ LO event + extra soft gluon
and **large positive weight**

What a NLO calculation gives you (here, Event2, $e^+e^- \to q\bar{q}$)

LO (2-particle) tree-level event
with weight 1.00000
px, py, pz, E = -1.32 -1.38 -49.96 50.00
px, py, pz, E = 1.32 1.38 49.96 50.00

NLO (3-particle) tree-level event
with **weight 16.7749**
px, py, pz, E = -1.60 -1.75 -49.87 49.93
px, py, pz, E = 1.31 1.36 49.25 49.29
px, py, pz, E = 0.30 0.39 0.62 0.79

NLO (2-particle) virtual subtraction event
with **weight -1.5868**
px, py, pz, E = -1.32 -1.38 -49.96 50.00
px, py, pz, E = 1.32 1.38 49.96 50.00

NLO (2-particle) virtual subtraction event
with **weight -15.1855**
px, py, pz, E = -1.61 -1.75 -49.94 50.00
px, py, pz, E = 1.61 1.75 49.94 50.00

NLO (2-particle) virtual finite event
with weight 0.0501, multiplying (alphas/2pi)
px, py, pz, E = -1.32 -1.38 -49.96 50.00
px, py, pz, E = 1.32 1.38 49.96 50.00

LO event ($q\bar{q}$)

NLO event, with real emission
~ LO event + extra soft gluon
and **large positive weight**

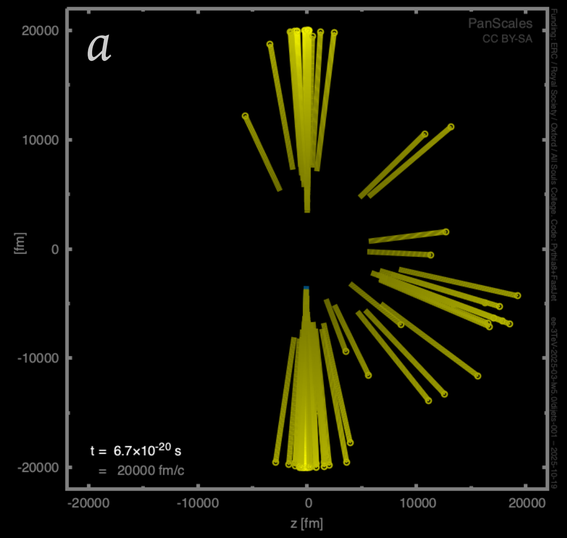
NLO event, “virtual” correction
~ LO event
and **large negative weight**

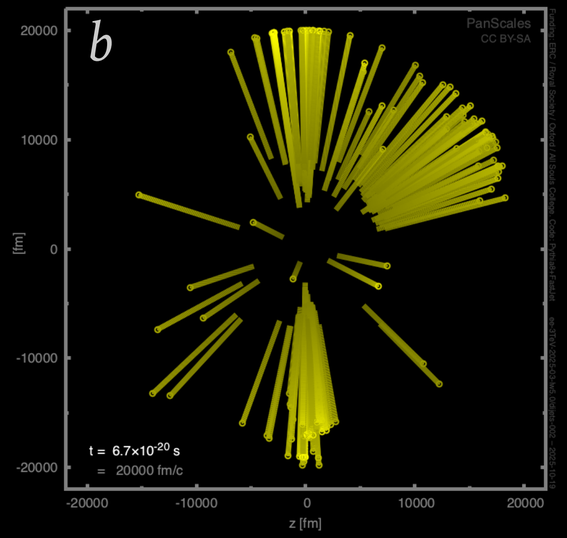
event weights are ~ probabilities

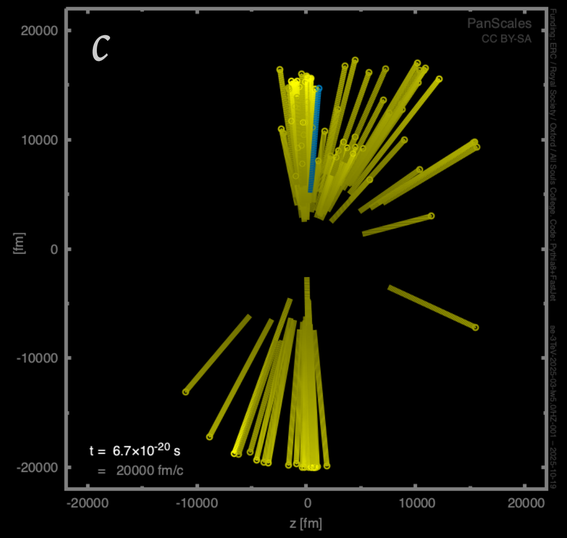
- real life doesn't have negative probabilities
- real life doesn't have (near-)divergent probabilities
- you can avoid these problems in perturbation theory if you ask very limited kinds of questions, i.e. nearly always summing real & virtual divergences (infrared safe, single momentum scale)*
- but experiments don't limit themselves to those kinds of questions

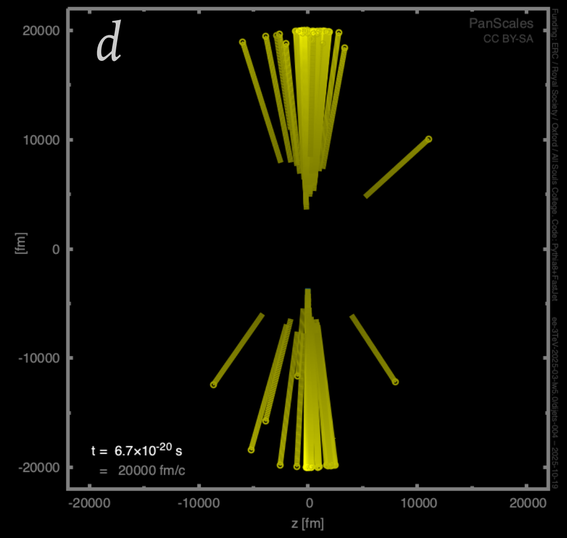
can we be flexible with the questions we ask, yet still get the benefits of perturbation theory?

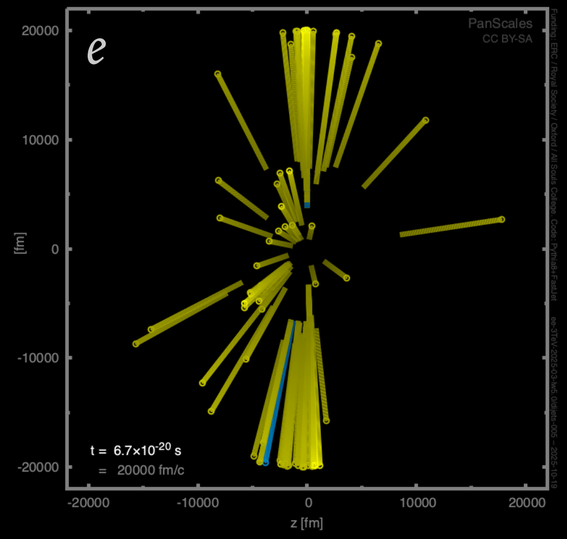
* though there can still be nasty surprises, cf. Chen et al 2102.07607, GPS & Slade 2106.08329

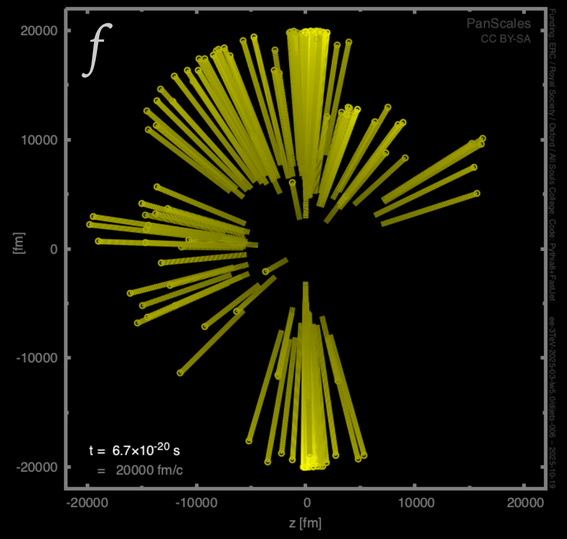

a
PanScales
CC BY-SA
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z [fm]

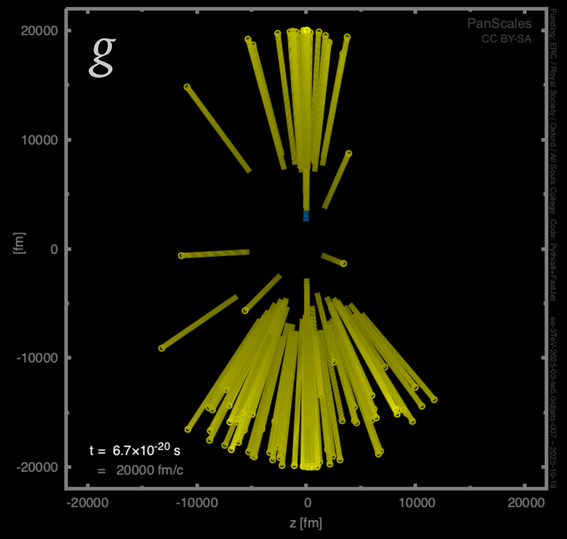

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PanScales
CC BY-SA
t = 6.7×10^-20 s
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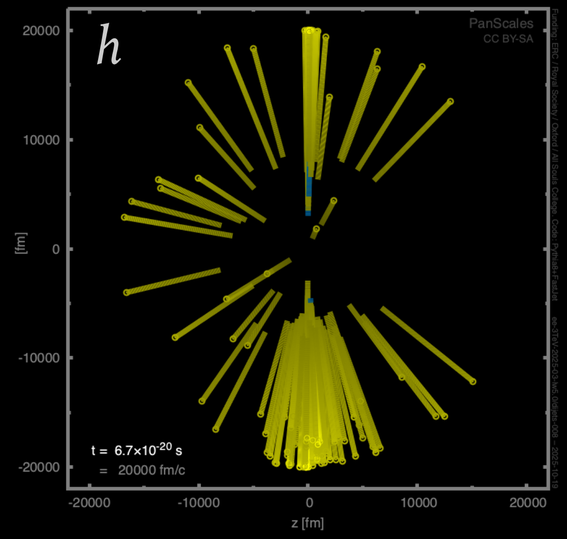

c
PanScales
CC BY-SA
t = 6.7×10^-20 s
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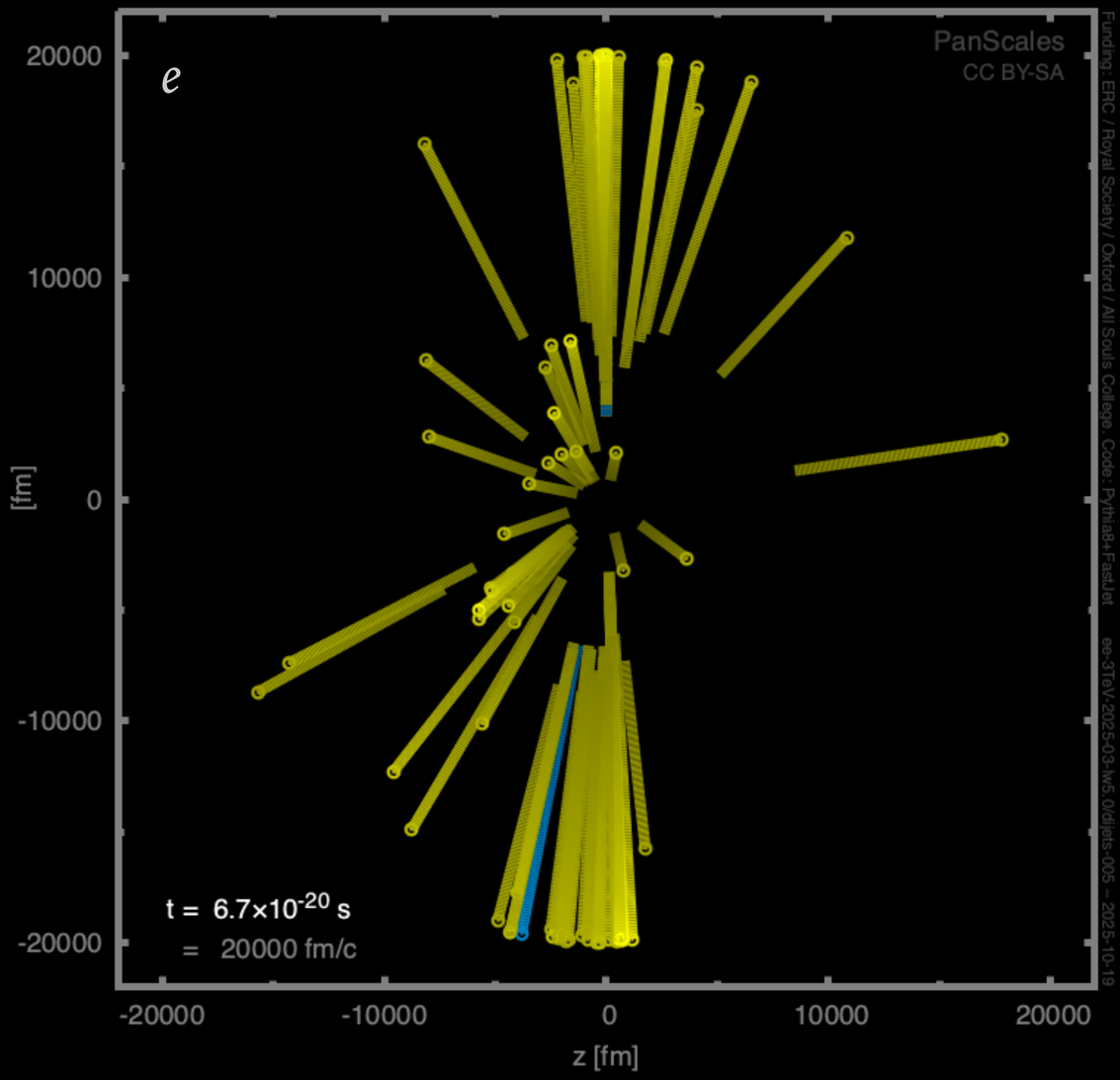

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CC BY-SA
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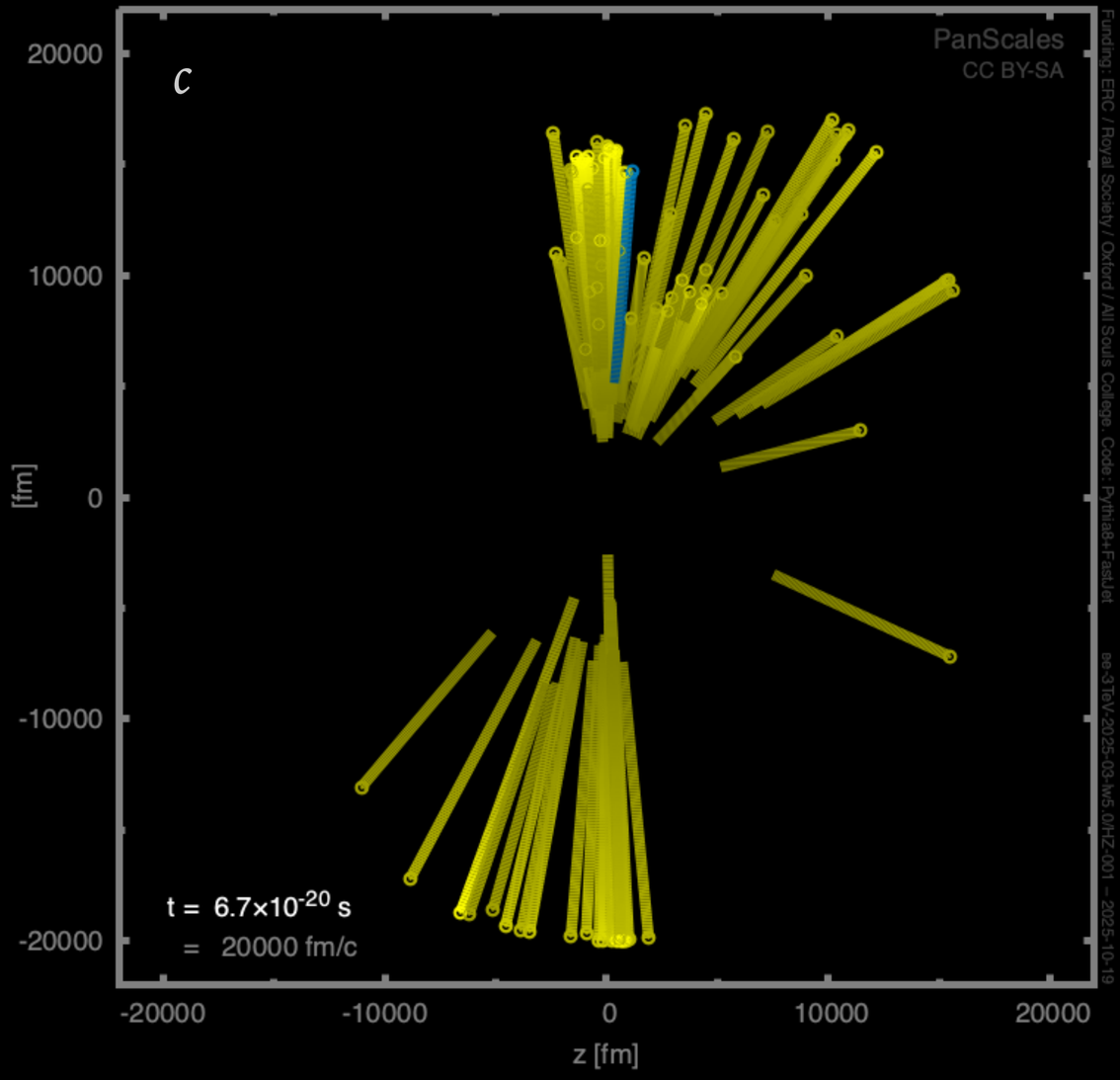

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PanScales
CC BY-SA
t = 6.7×10^-20 s
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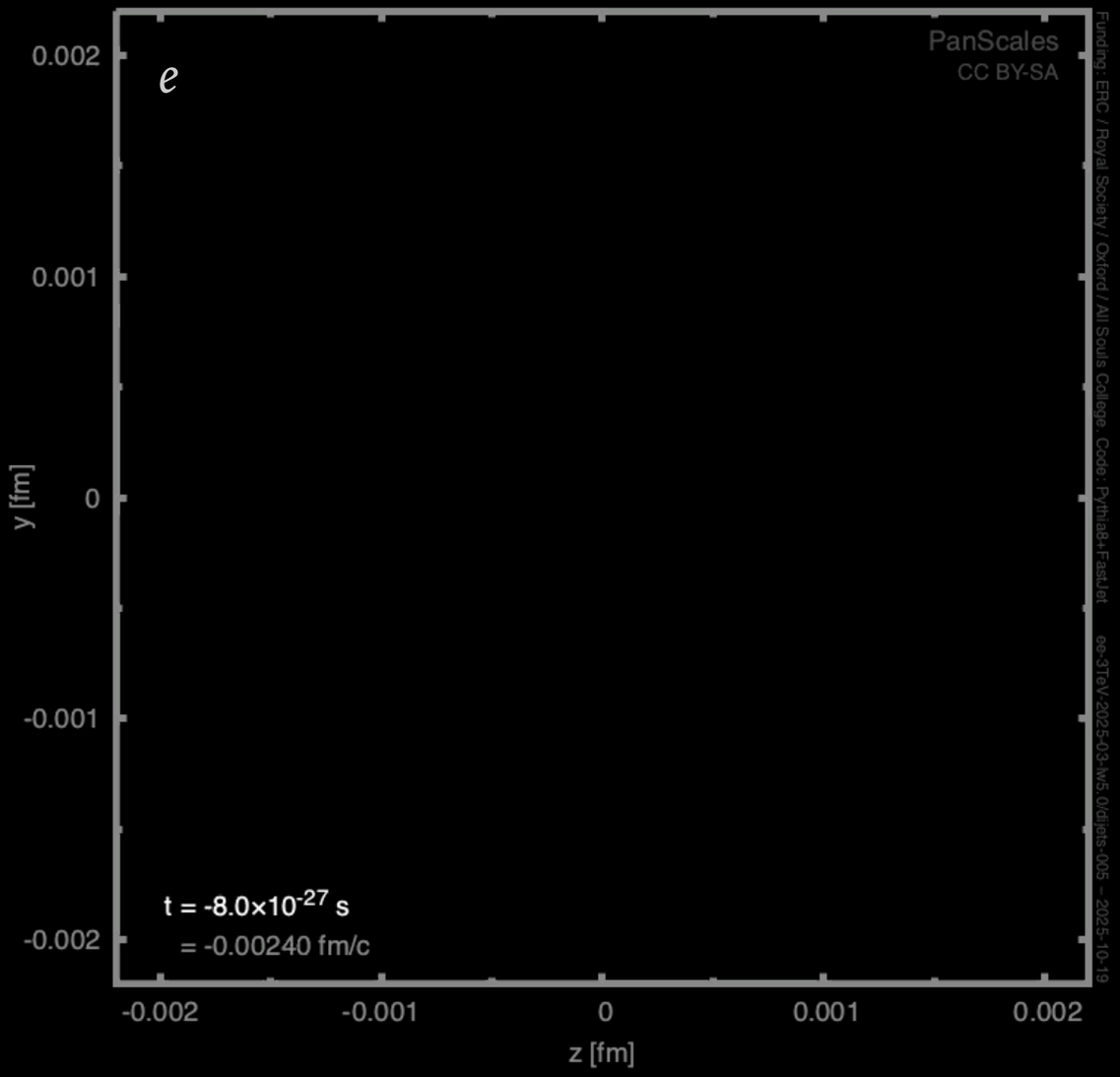

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CC BY-SA
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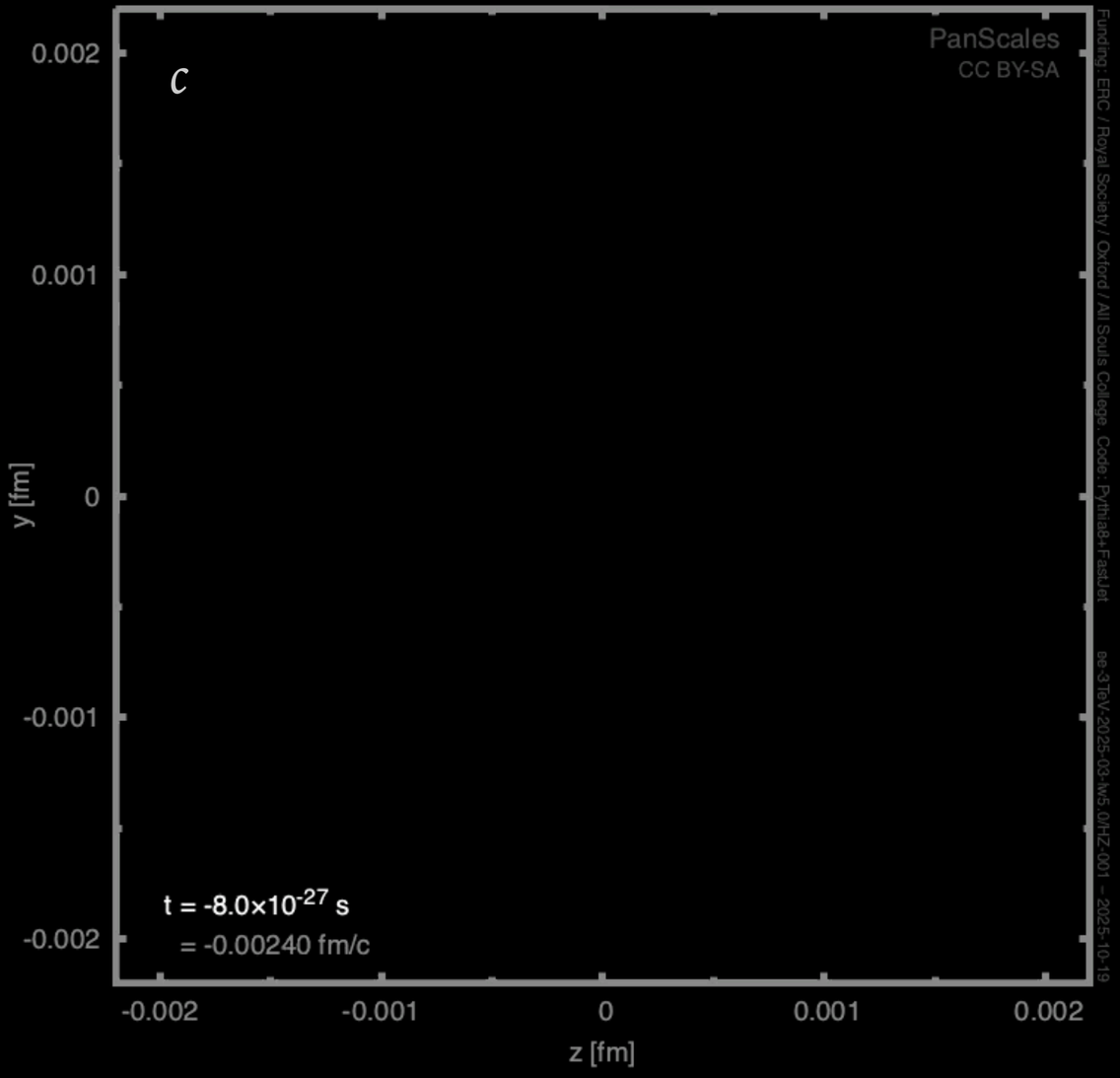

g
PanScales
CC BY-SA
t = 6.7×10^-20 s
= 20000 fm/c
[fm]
z [fm]


h
PanScales
CC BY-SA
t = 6.7×10^-20 s
= 20000 fm/c
[fm]
z [fm]

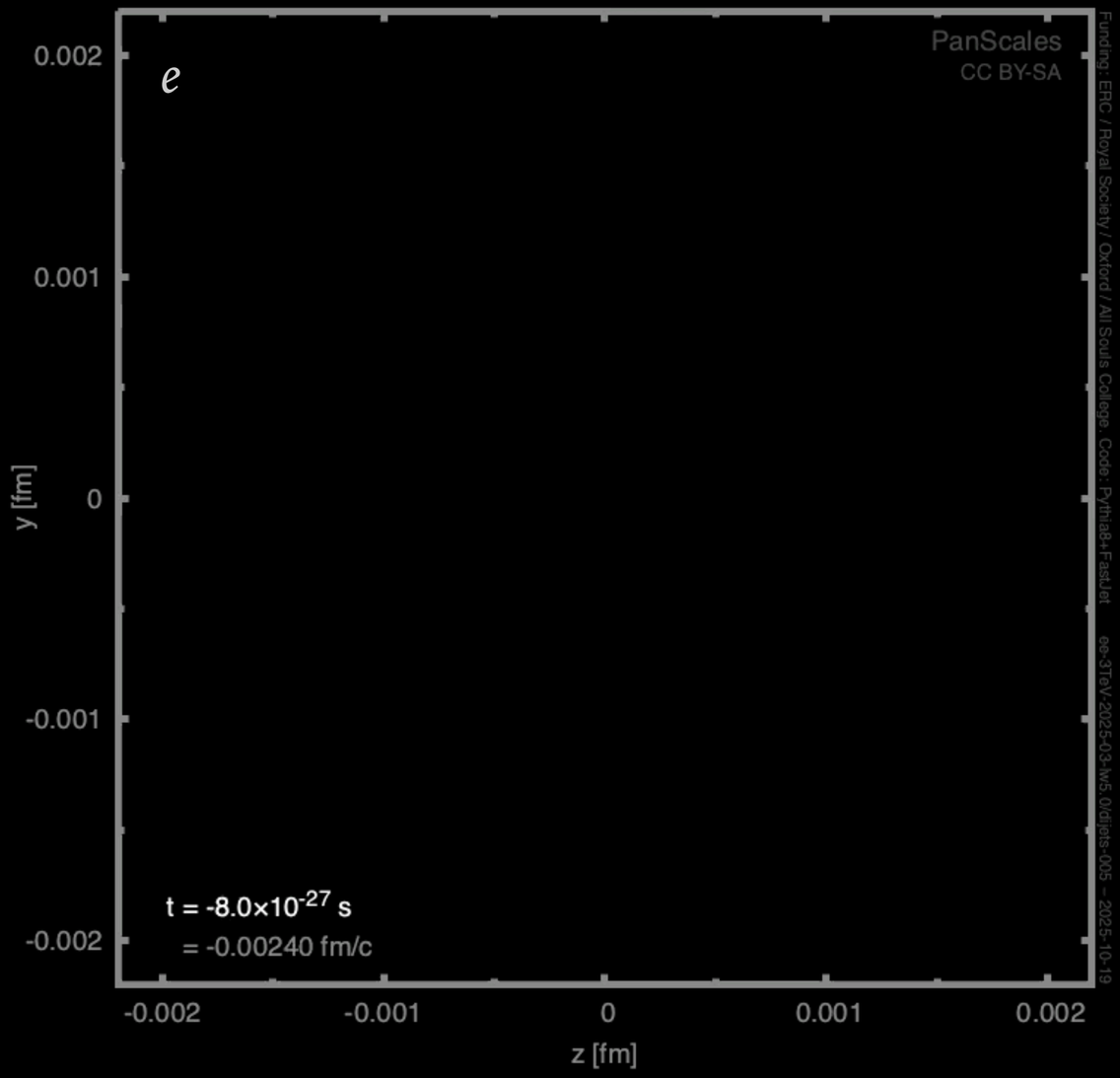

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CC BY-SA
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10000
20000
z [fm]
Funding: ERC / Royal Society / Oxford / All Souls College. Code: Pythia8+FastJet
ee-3TeV-2025-03-lw5.0/djets-005 – 2025-10-19


c
PanScales
CC BY-SA
t = 6.7×10^-20 s
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10000
20000
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Funding: ERC / Royal Society / Oxford / All Souls College. Code: Pythia8+FastJet
ee-3TeV-2025-03-lw5.0/HZ-001 – 2025-10-19

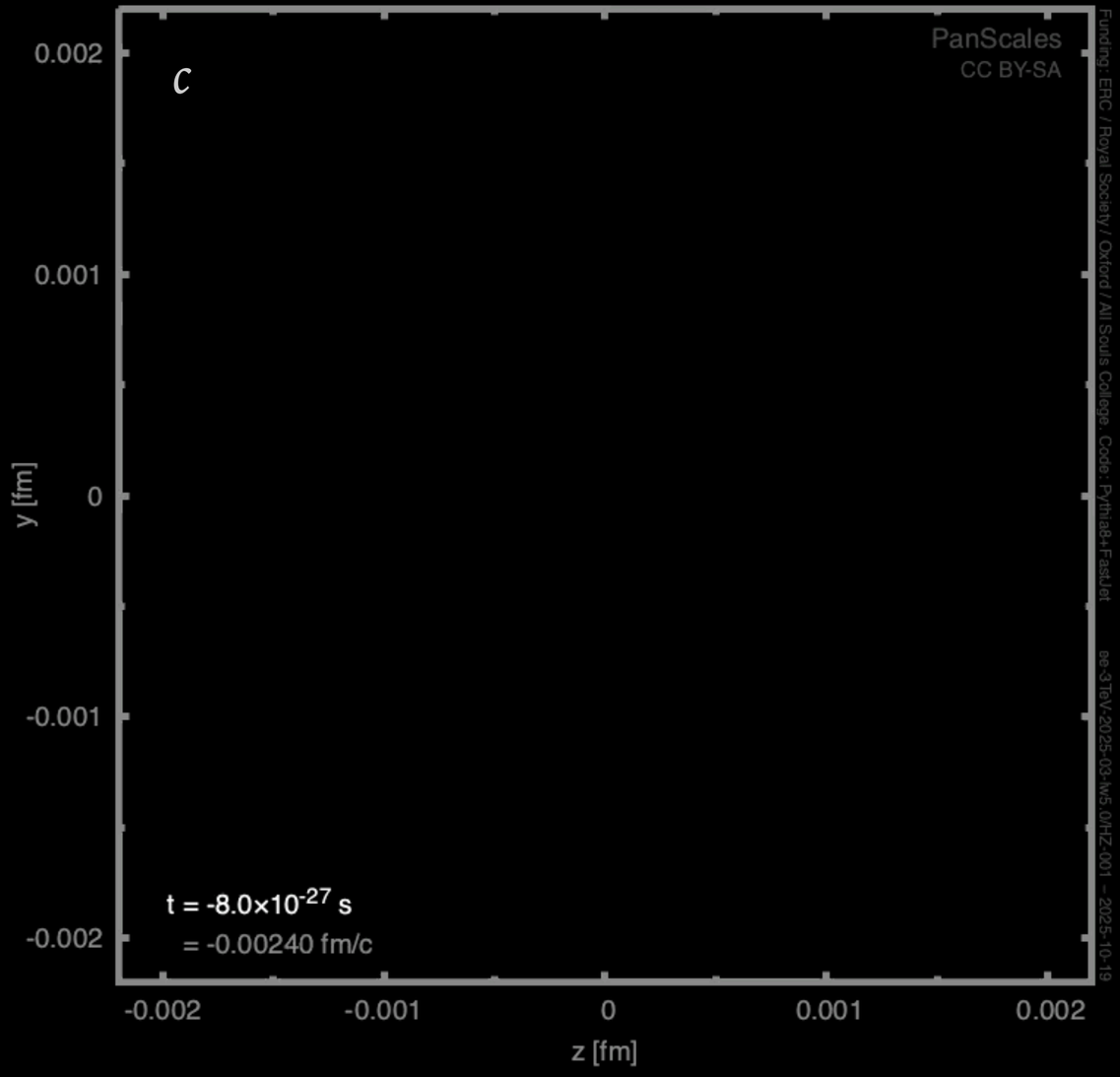

e
PanScales
CC BY-SA
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0.001
0
-0.001
-0.002
-0.002
-0.001
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0.001
0.002
Funding: ERC / Royal Society / Oxford / All Souls College. Code: Pythia8+FastJet
ee-3TeV-2025-03-iw5.0/dijets-005 – 2025-10-19


c
PanScales
CC BY-SA
t = -8.0×10^-27 s
= -0.00240 fm/c
y [fm]
z [fm]
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0
0.001
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Funding: ERC / Royal Society / Oxford / All Souls College. Code: Pythia8+FastJet
ee-3TeV-2025-03-iw5.0/HZ-001 – 2025-10-19

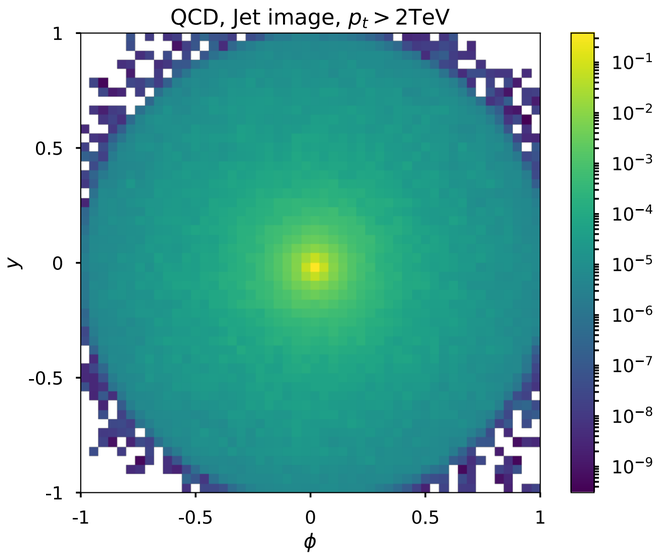
pure QCD event



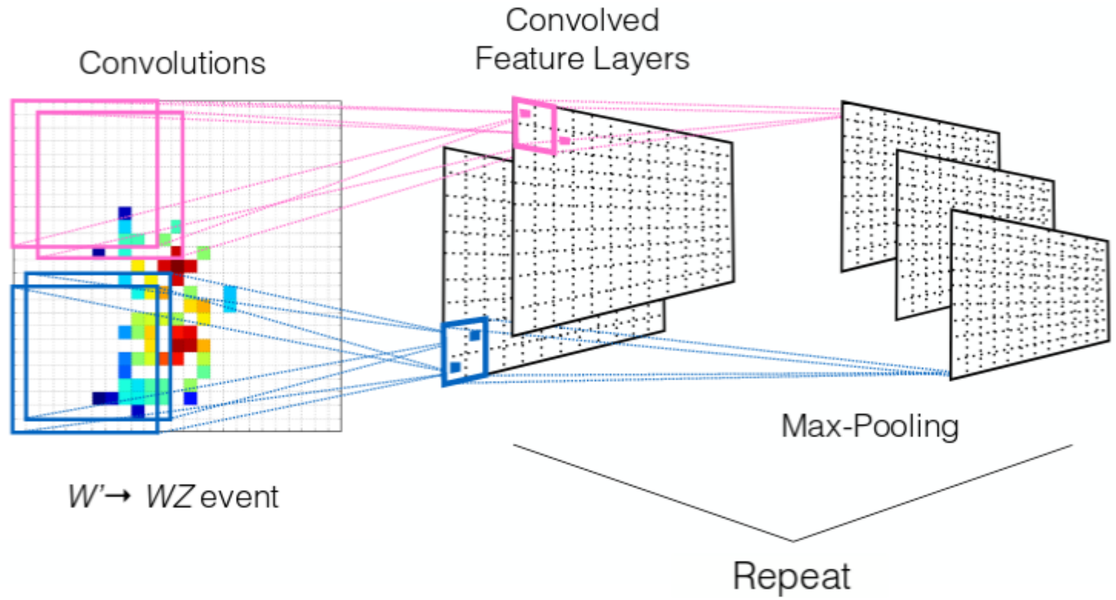
event with Higgs & Z boson decays



Did the jet of particles come from a quark or a W/Z/H-boson? → Use machine learning

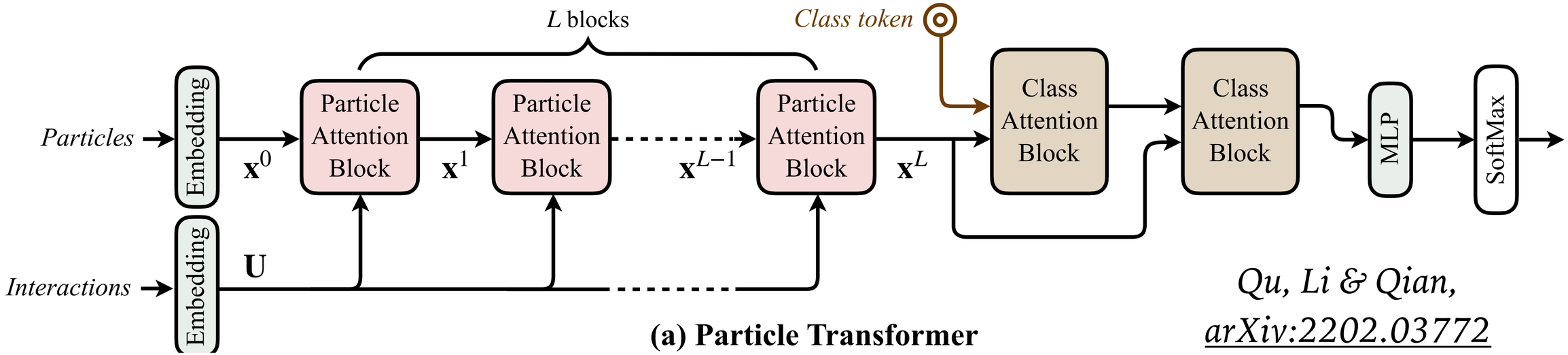


2021 Young Experimental Physicist
EPS HEPP prize



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

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

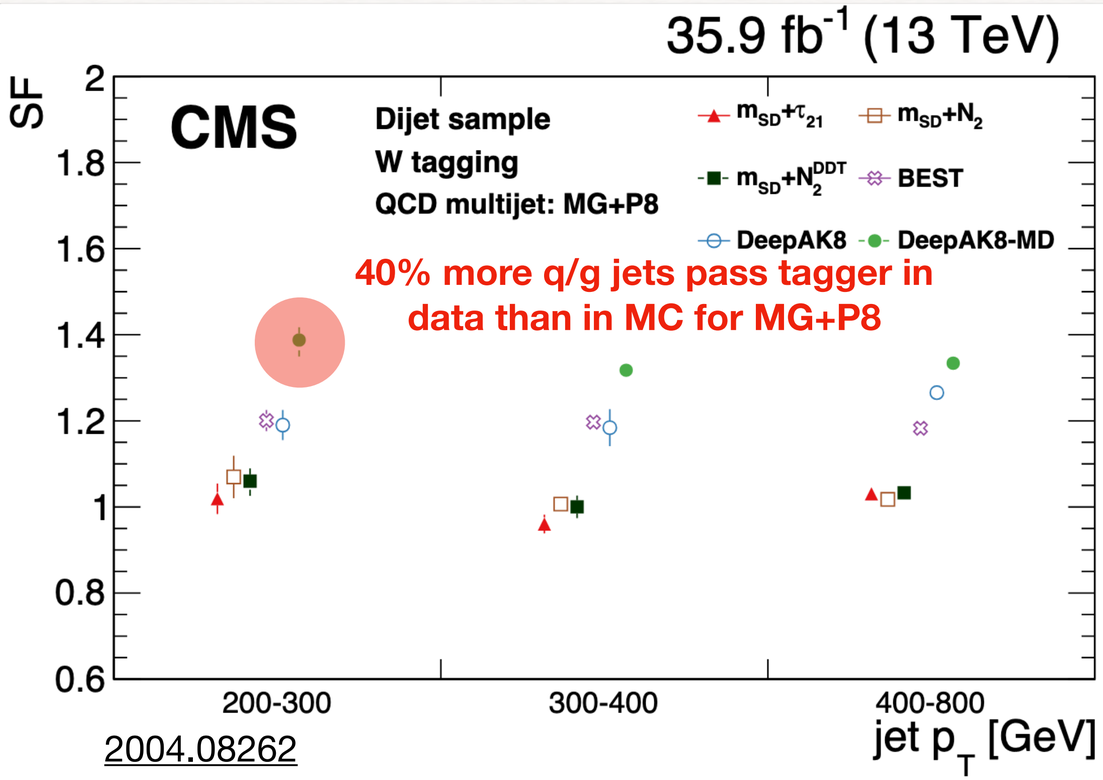


(a) Particle Transformer

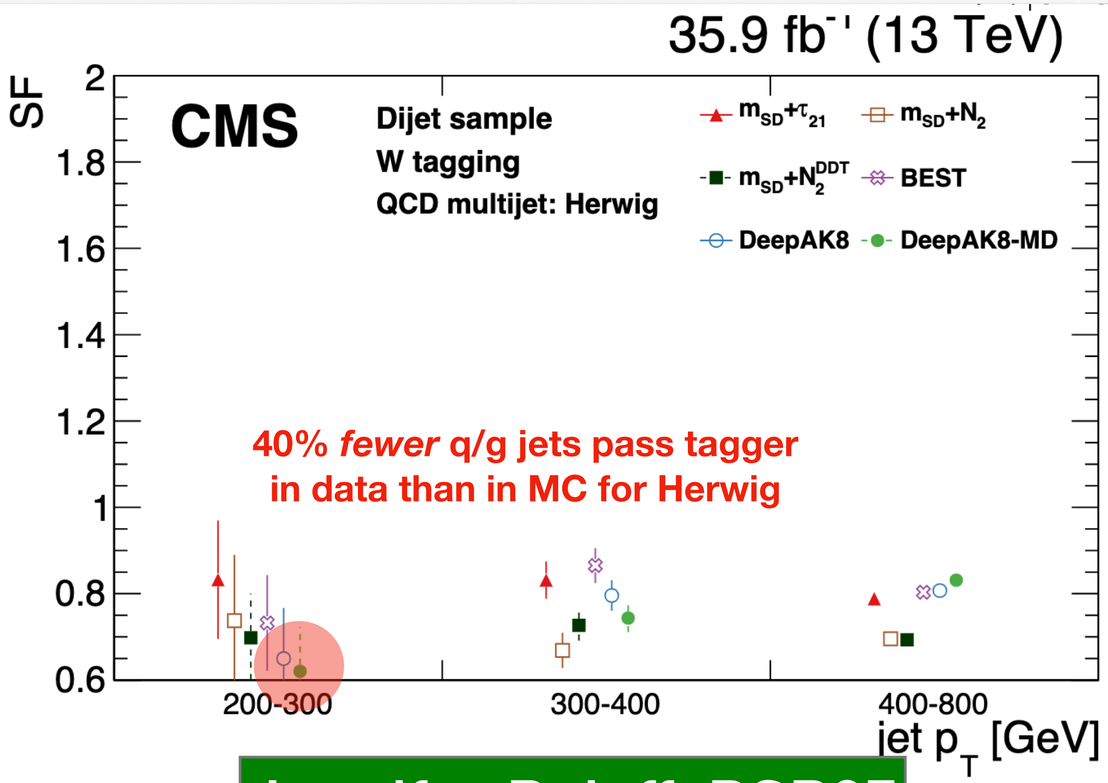
Qu, Li & Qian,
arXiv:2202.03772

We want machine learning to be accurate

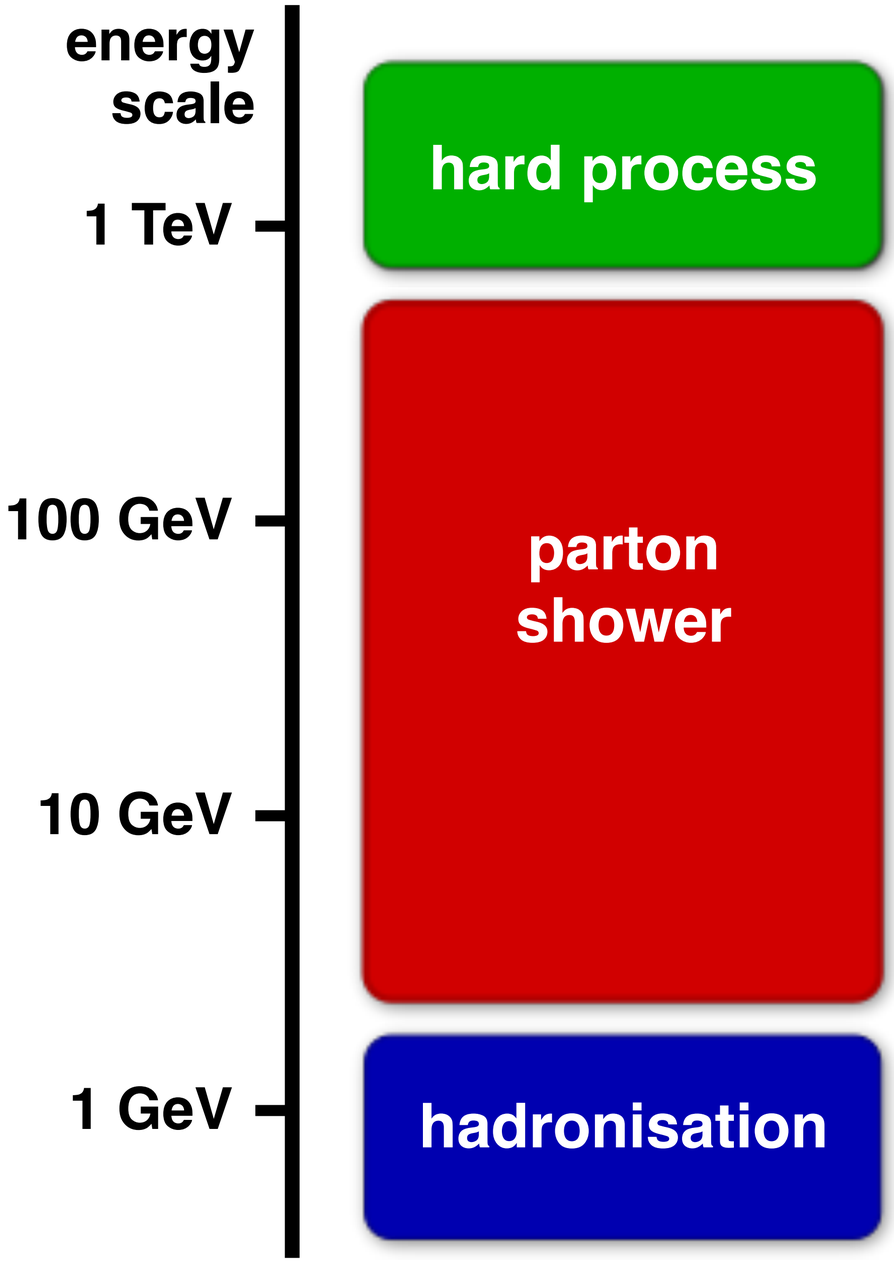
- even simplest ML methods exacerbate sensitivity to imperfections in predictions
- how do we get (perturbative) QFT to be accurate even with ML?

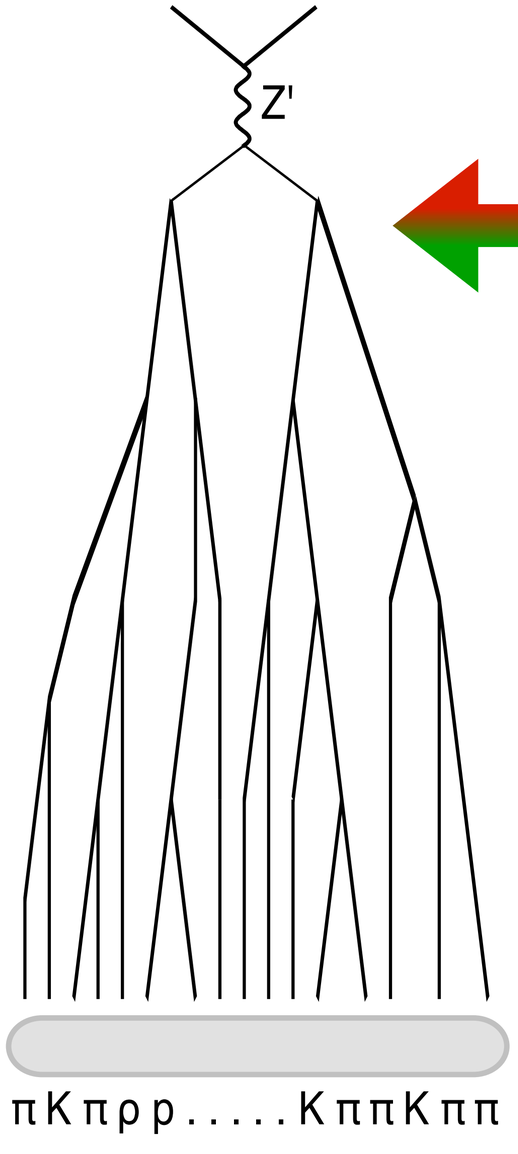


43



Jennifer Roloff, PSR25





Much of past 25 years' work: MLM, CKKW, MC@NLO, POWHEG, MIN(N)LO, FxFx, Geneva, UNNLOPS, Vincia, etc.

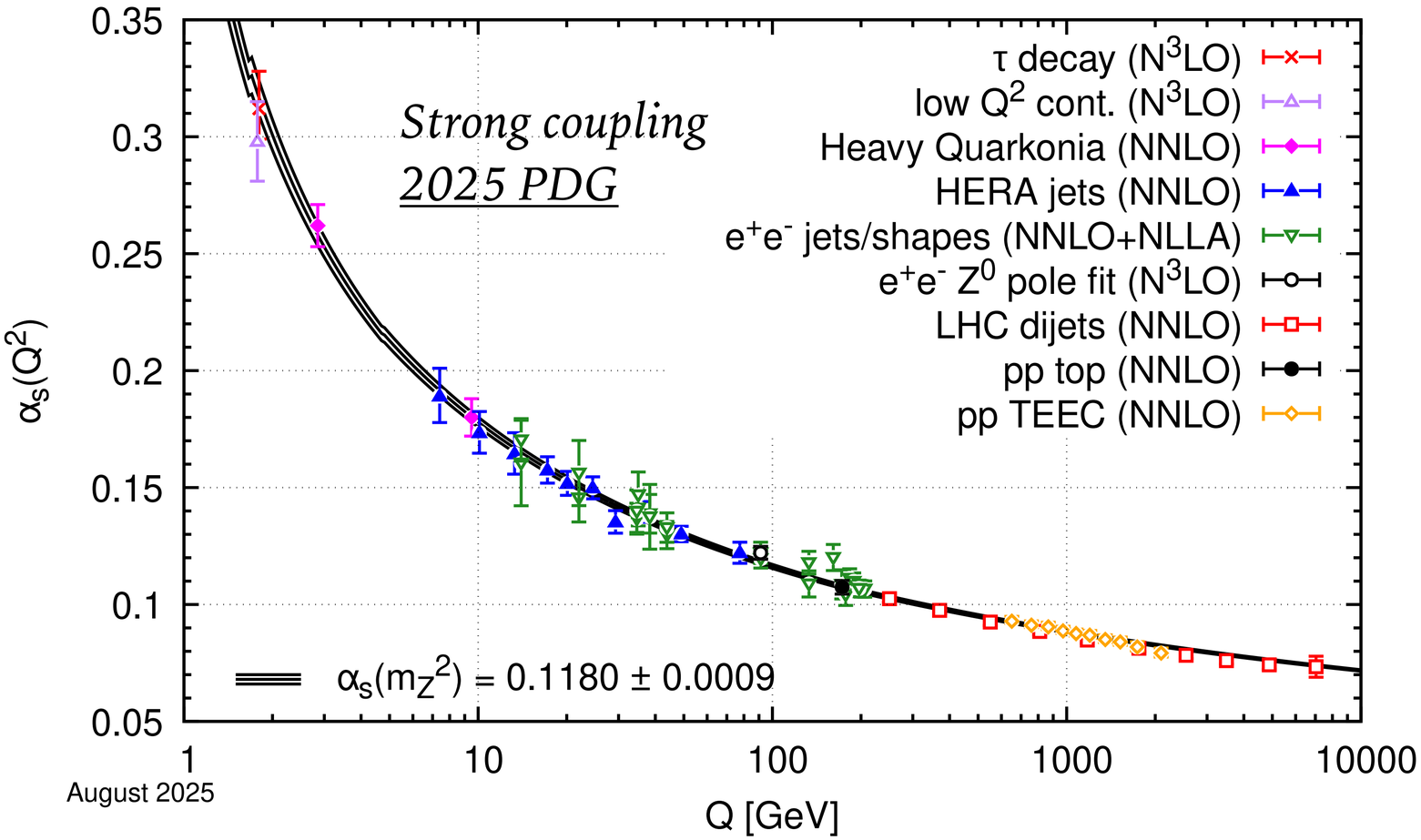
In standard codes, largely based on principles from 20-30 years ago (Herwig, Pythia, Sherpa)

Multi-scale problems in QFT: solve with a differential equation

Simplest example: running coupling.

Precision is achieved by increasing the perturbative accuracy in the kernel of the equation.

Intrinsically stable in perturbative regime,



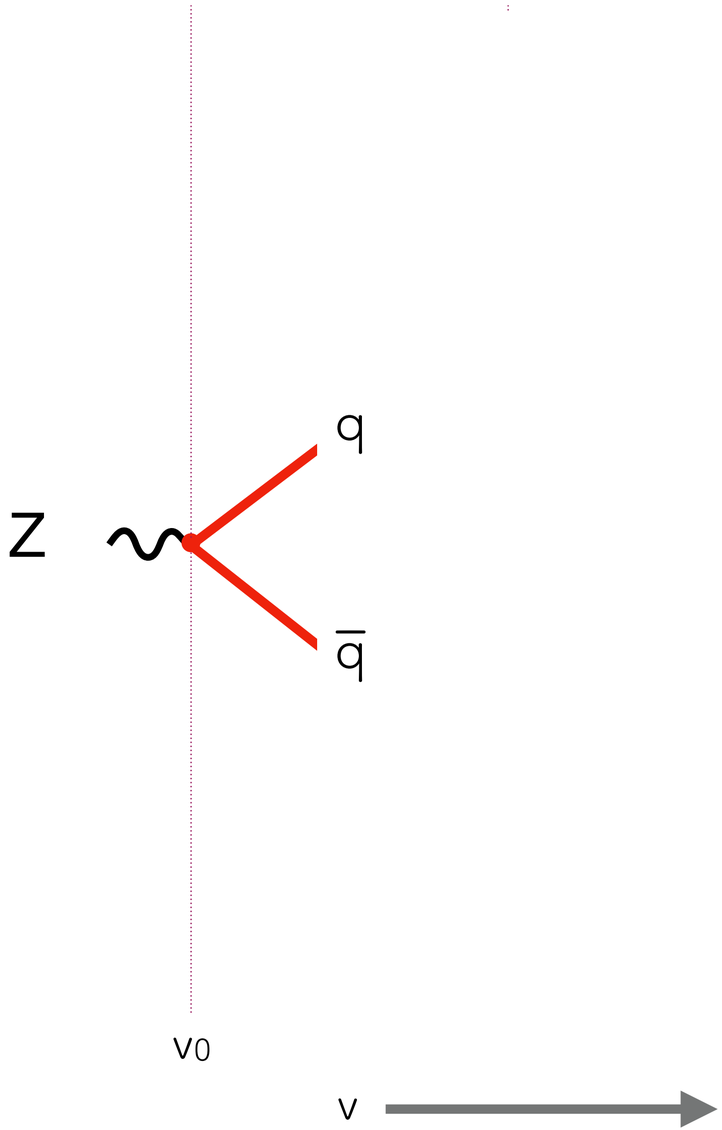
$$Q^2\frac{\partial \alpha_s}{\partial Q^2} = \beta(\alpha_s)\,, \qquad \beta(\alpha_s) = -\alpha_s^2(b_0 + b_1\alpha_s + b_2\alpha_s^2 + \ldots)\,,$$

parton showers: the ultimate differential equation

discussion today is in the large limit of large number of colours

there are also various approaches for subleading-N_C terms

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

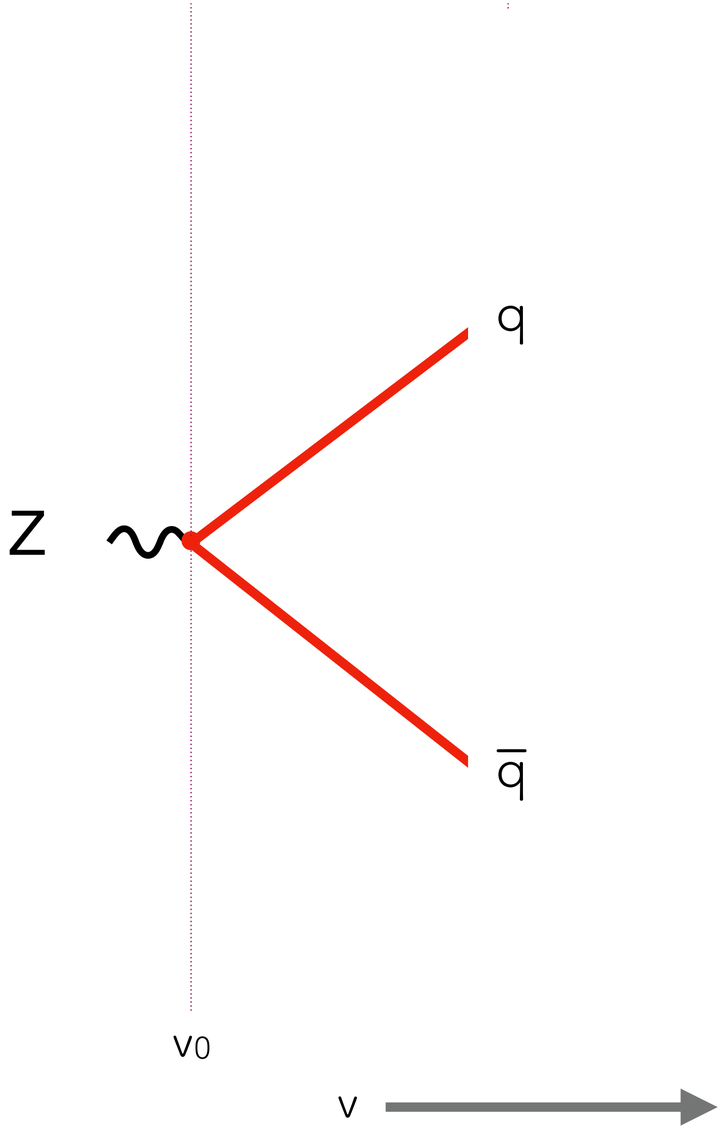


Start with quark (q) antiquark ($\bar{q}$) state.

Throw a random number to determine down to what scale state persists unchanged

$$\frac{dP_2(v)}{dv} = -f^{q\bar{q}}_{2\to 3}(v)\, P_2(v)$$

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

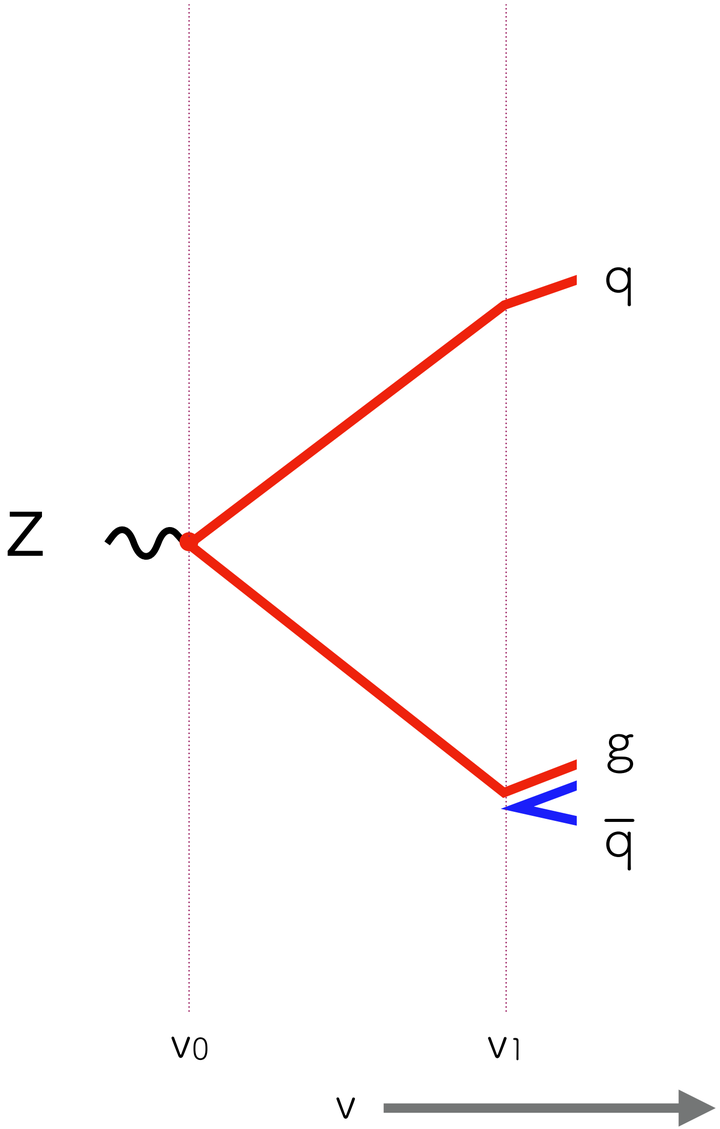


Start with quark (q) antiquark ($\bar{q}$) state.

Throw a random number to determine down to what scale state persists unchanged

$$\frac{dP_2(v)}{dv} = -f^{q\bar{q}}_{2\to 3}(v)\, P_2(v)$$

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



Start with quark (q) antiquark ($\bar{q}$) state.

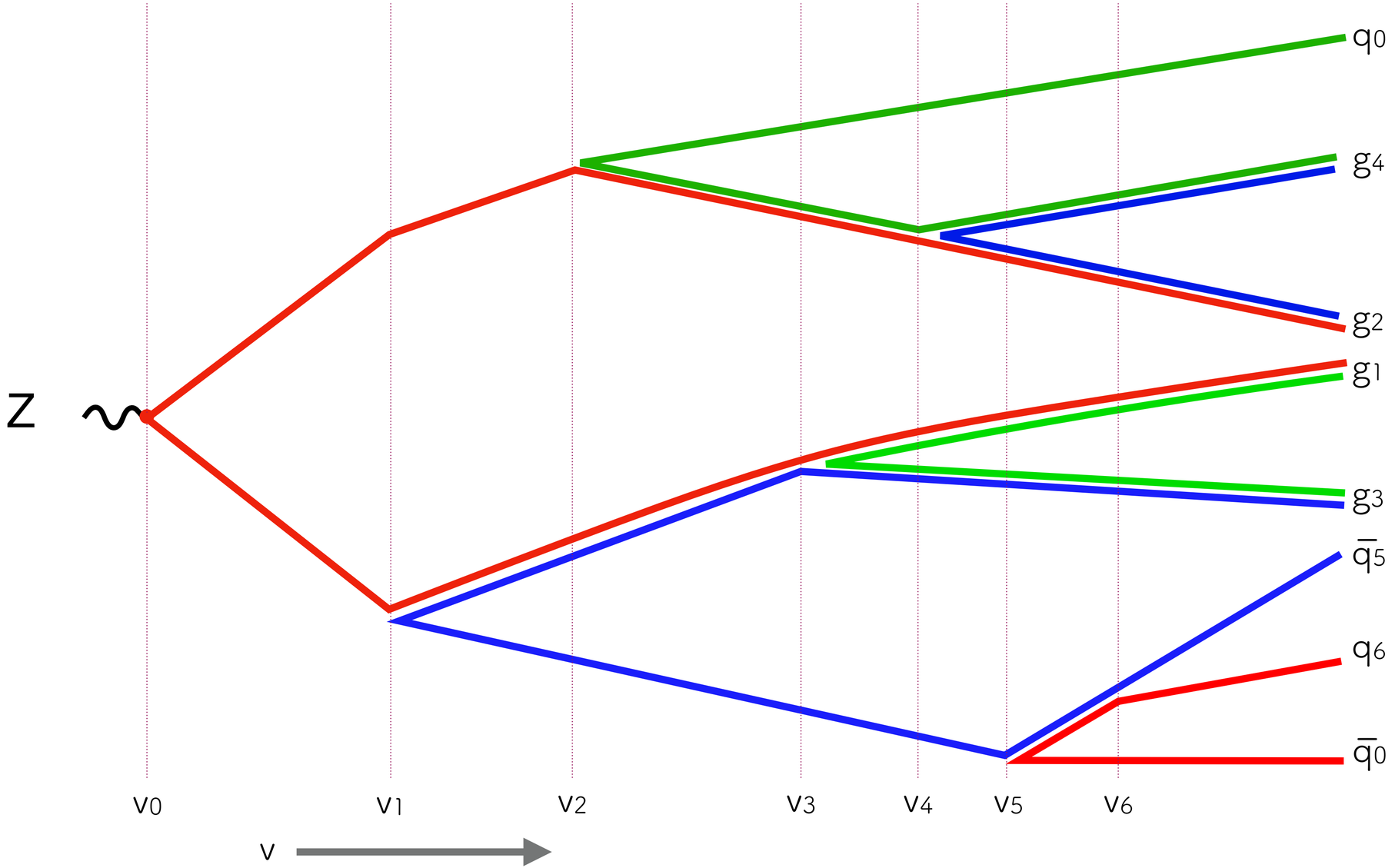
Throw a random number to determine down to what scale state persists unchanged

At some point, **state splits** (2→3, i.e. emits gluon). Evolution equation changes

$$\frac{dP_3(v)}{dv} = -\left[f^{qg}_{2\to3}(v) + f^{g\bar{q}}_{2\to3}(v)\right] P_3(v)$$

gluon (g) here is drawn as two colour lines

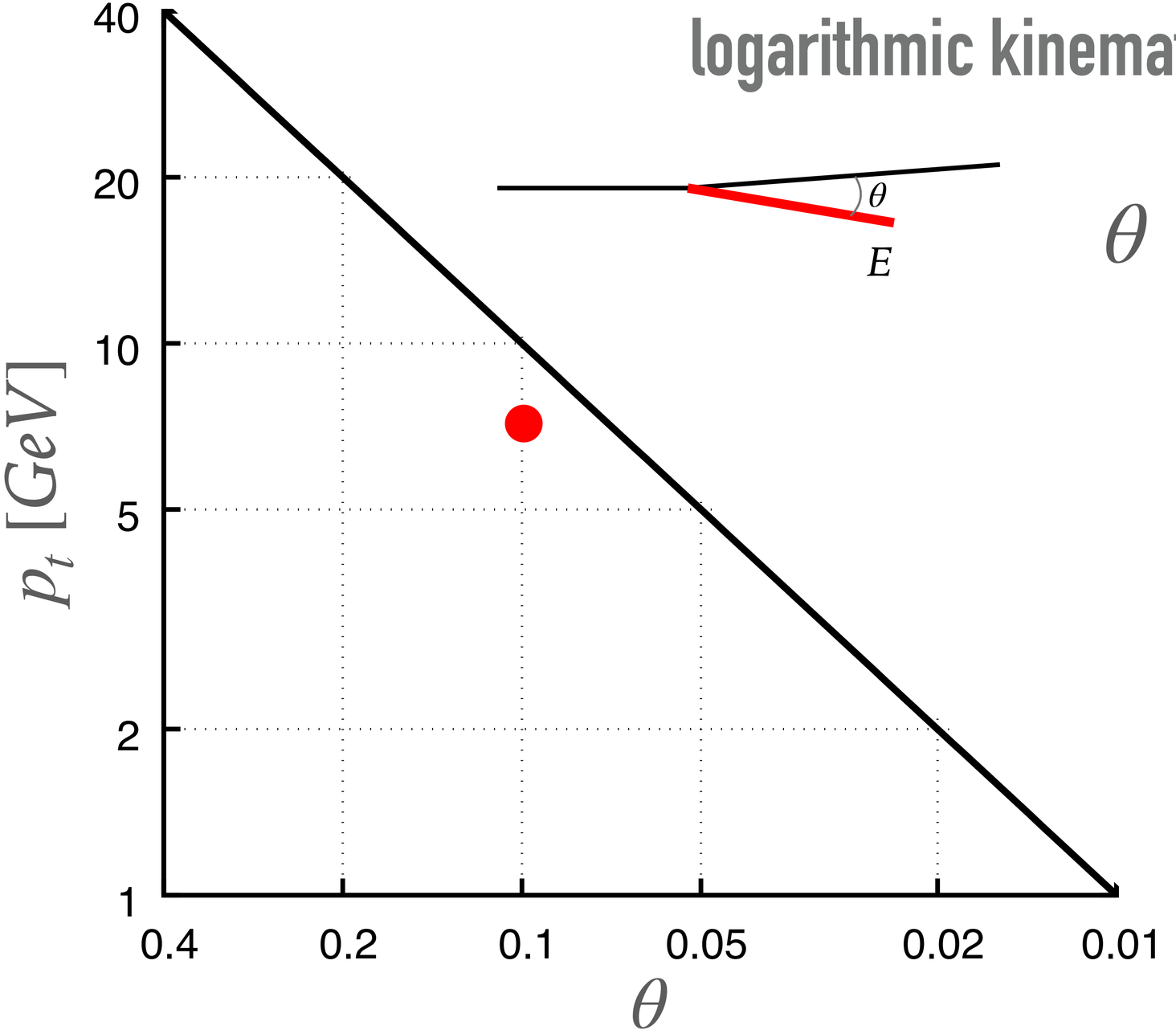
QCD parton shower: an evolution equation (in evolution scale v, e.g. trans.mom.)



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

illustration by K. Hamilton

jet with $R = 0.4$, $p_t = 200\ GeV$



logarithmic kinematic plane whose two variables are

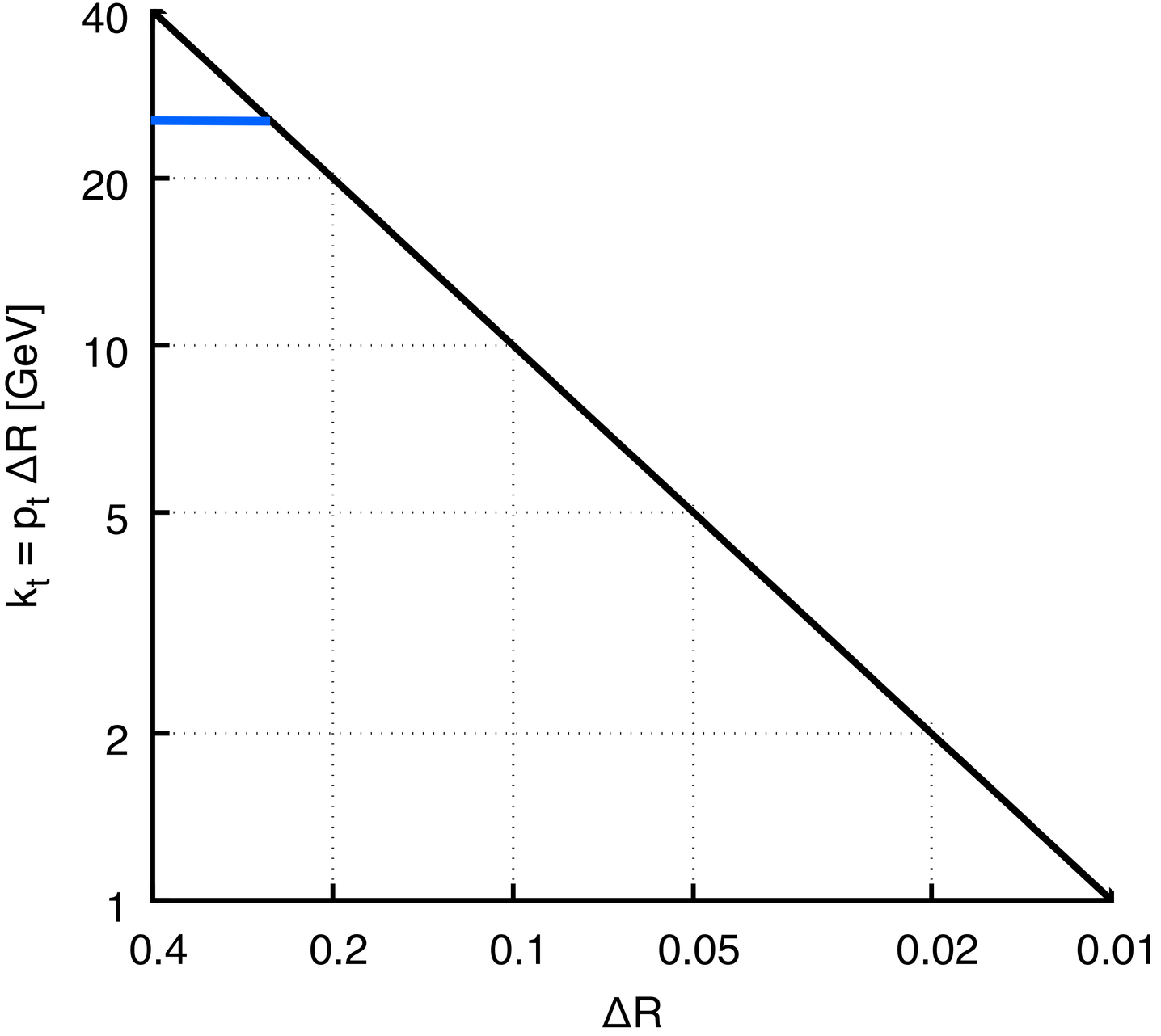
$$\theta \ (or\ \eta = -\ln\tan\frac{\theta}{2})$$

$$p_t = E\theta$$

Introduced for understanding Parton Shower Monte Carlos by Andersson, Gustafson, Lönnblad and Pettersson 1989

The Lund Plane

jet with $R = 0.4$, $p_t = 200$ GeV

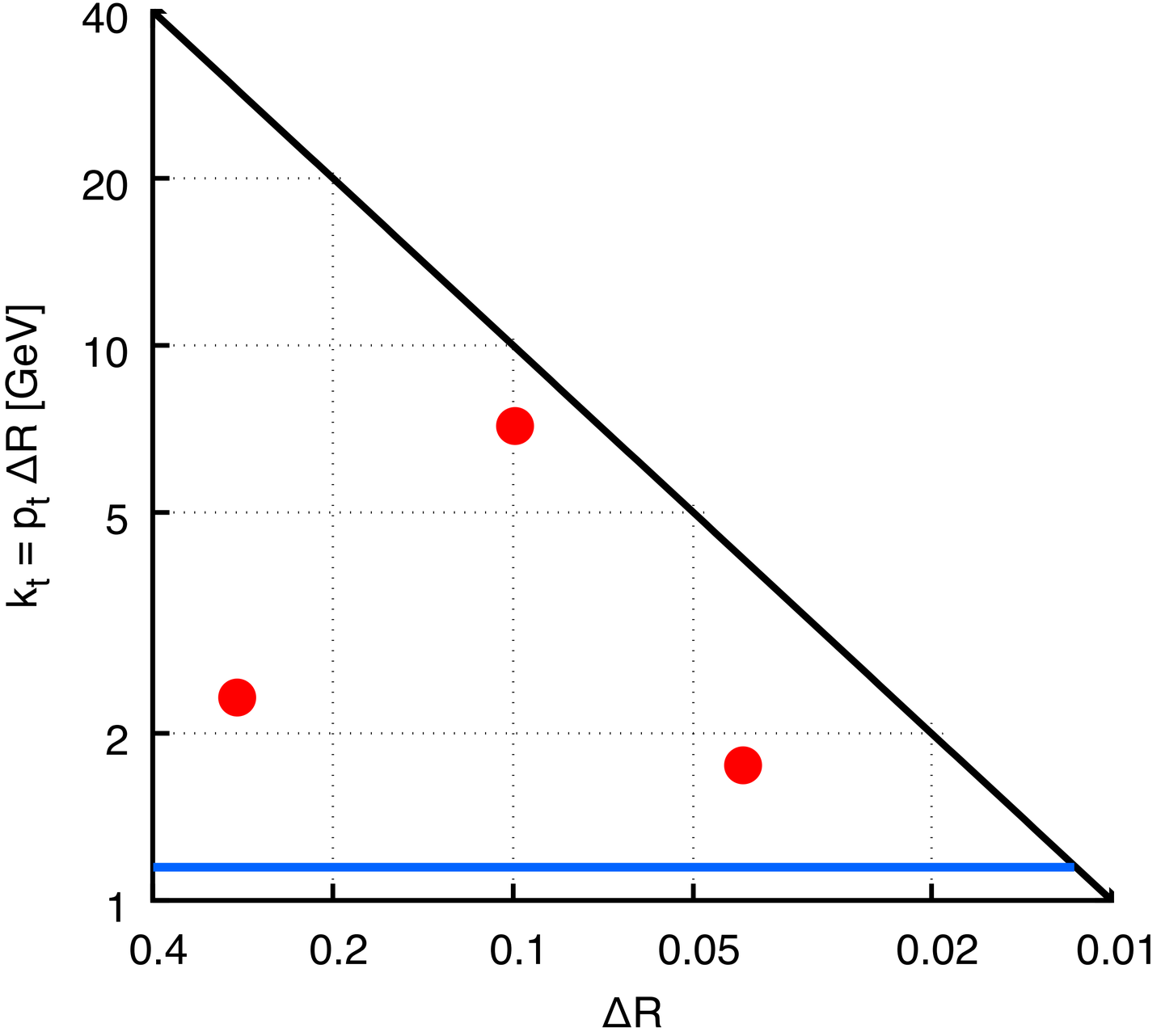


Parton shower is “differential equation” in one variable

You need to **choose** how one variable maps onto the two “logarithmic” dimensions of the Lund plane

A form of scheme choice

jet with $R = 0.4$, $p_t = 200$ GeV

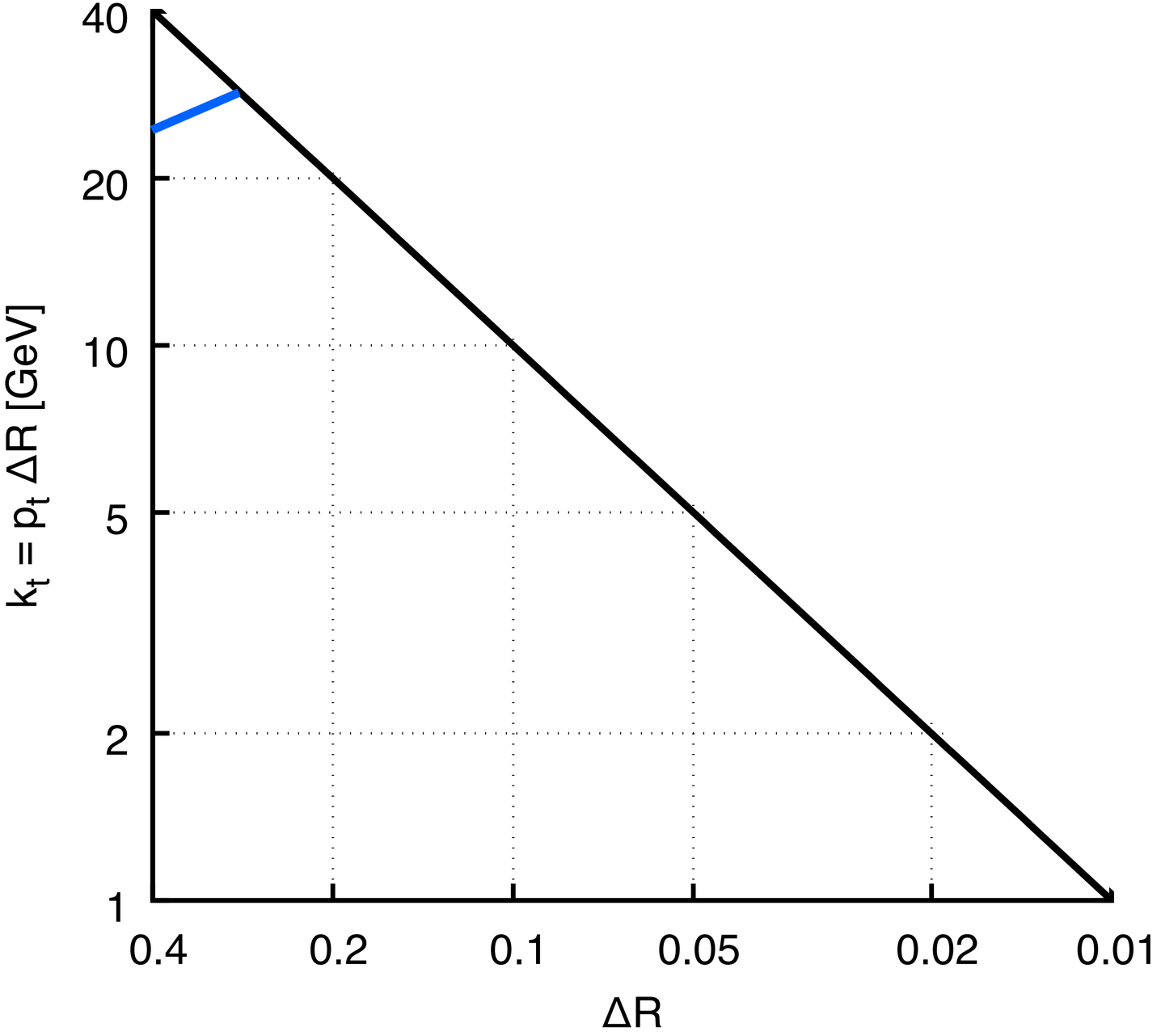


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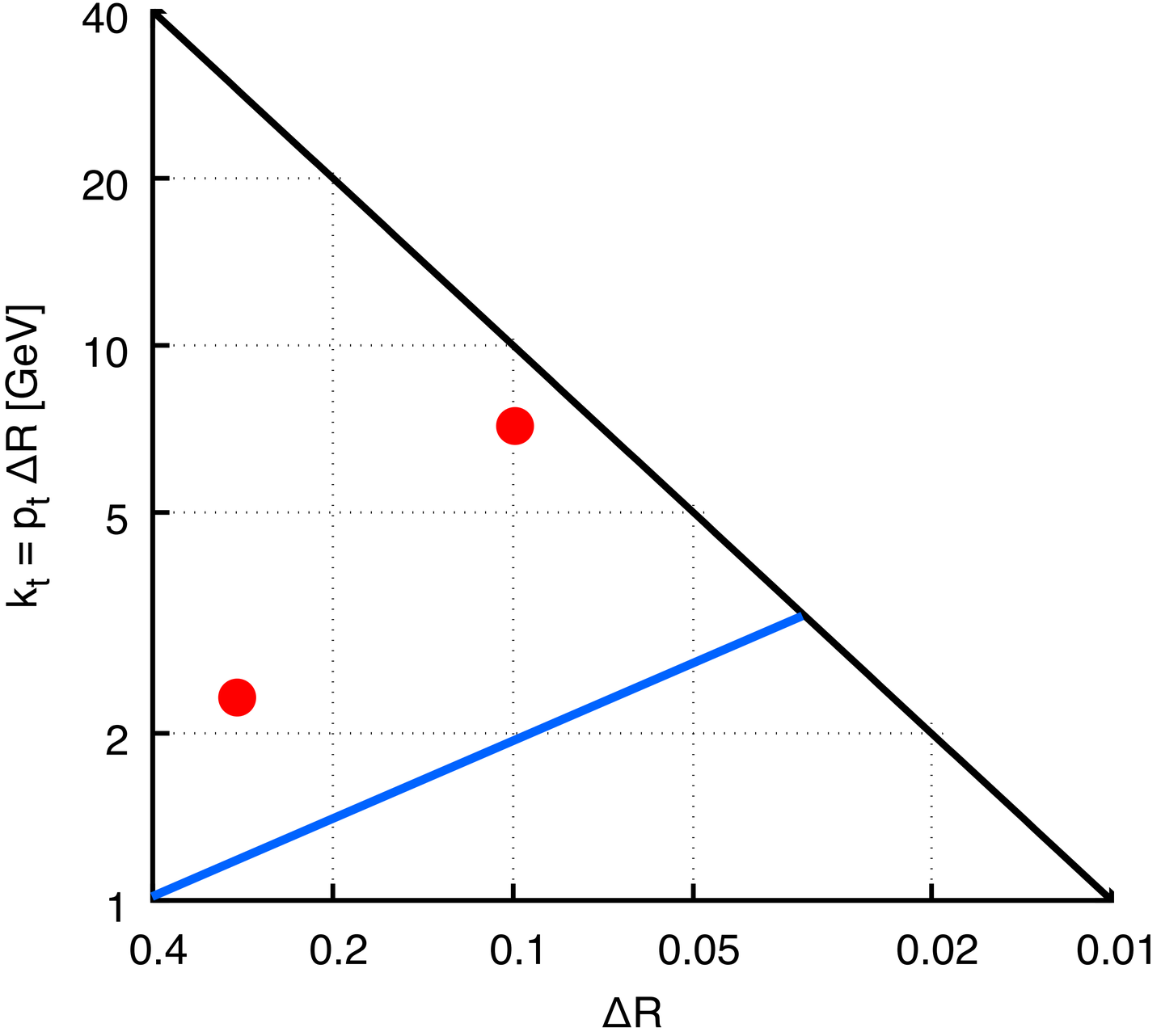


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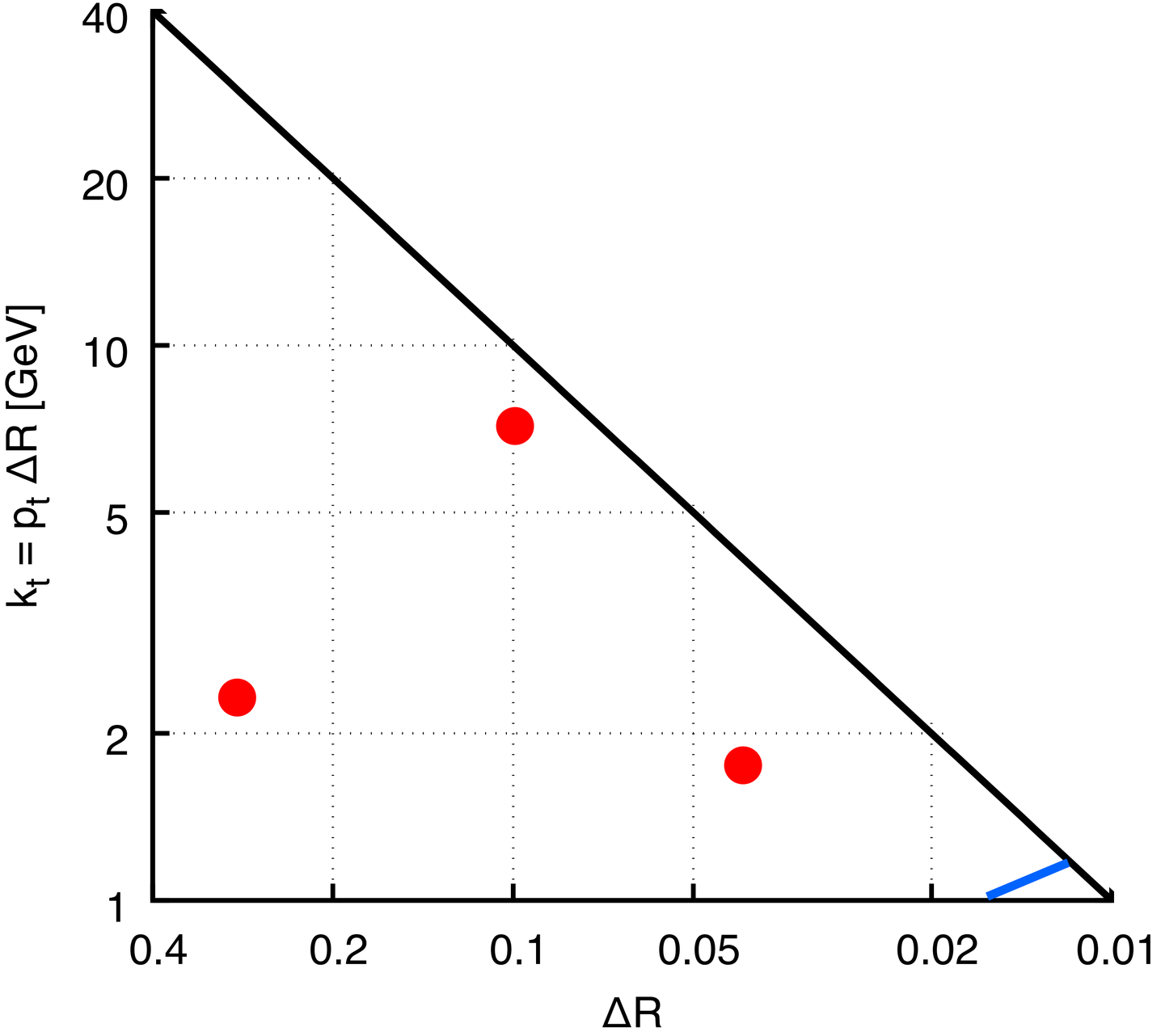


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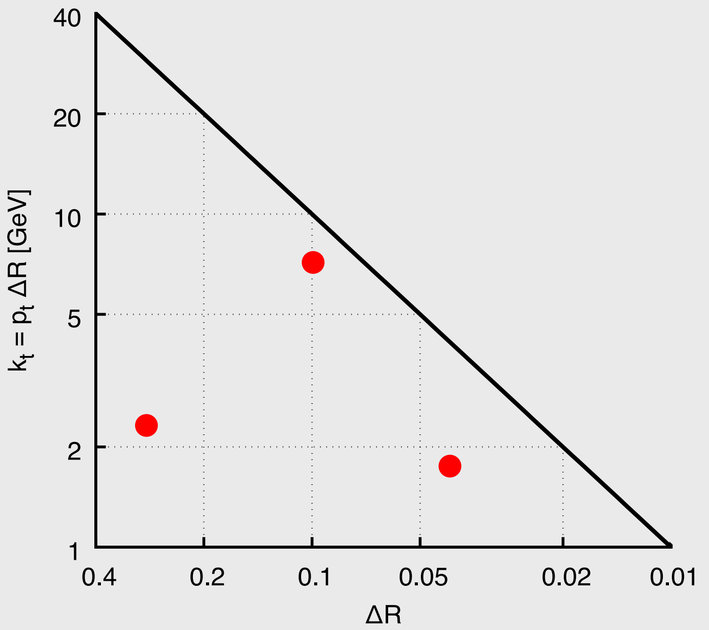
A form of scheme choice — **up to the order you control, results should be independent of the scheme choice.**

NLL: the foundation

Dasgupta, Dreyer, Hamilton, Monni, GPS '18
ibid + Soyez '20

A Matrix Element condition

- correctly reproduce *n*-parton tree-level matrix element for arbitrary configurations, so long as all emissions well separated in the Lund diagram
  (because those configurations are the most likely ones)
- supplement with unitarity, 2-loop running coupling & cusp anomalous dimension



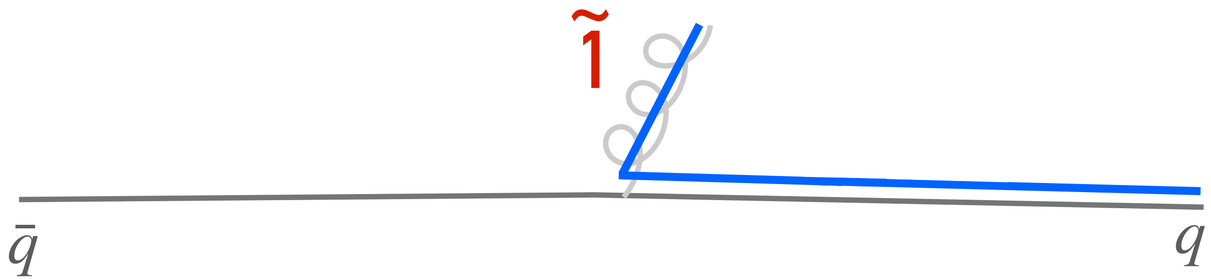
Resummation condition:

reproduce NLL ($\alpha_s^n L^n$) results for all standard resummations

- global event shapes
- non-global observables
- fragmentation functions ($\alpha_s^n L^n$ just leading log)
- multiplicities ($\alpha_s^n L^{2n-1}$)
- …

1. Recoil: the core of any shower

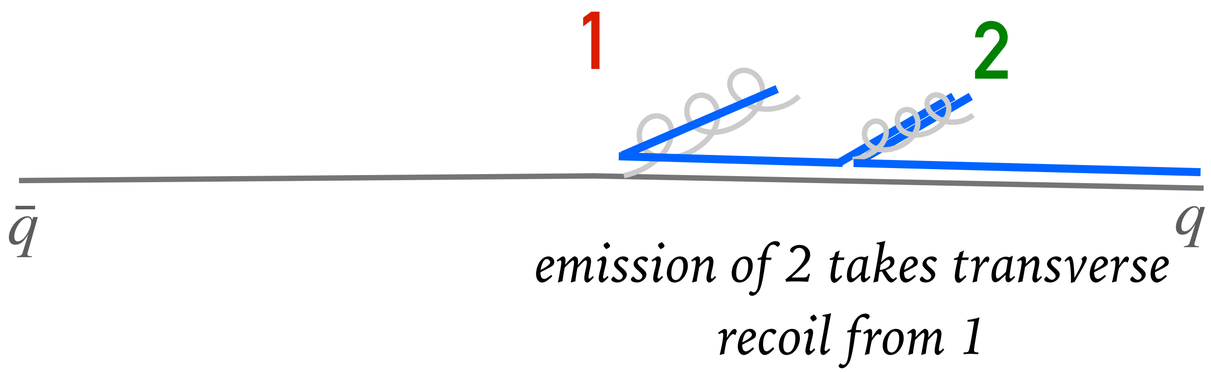
Dipole showers conserve momentum at each step. Traditional dipole-local recoil:



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

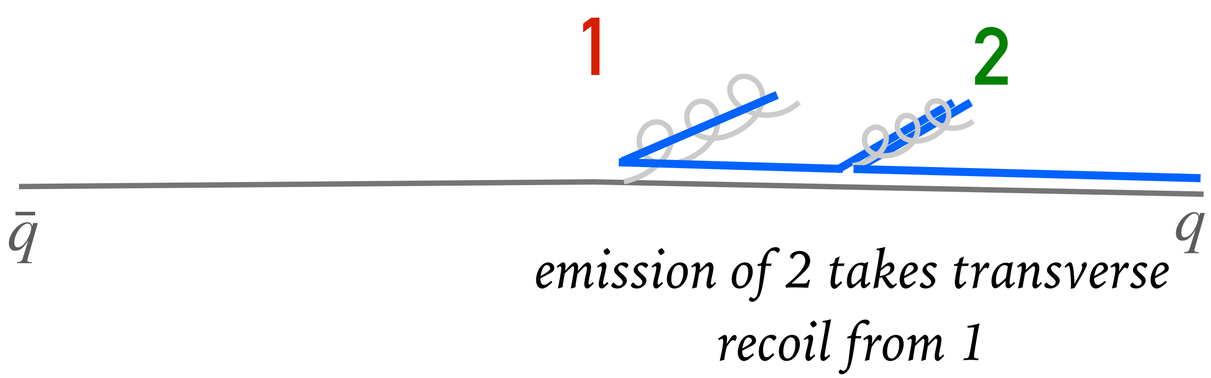
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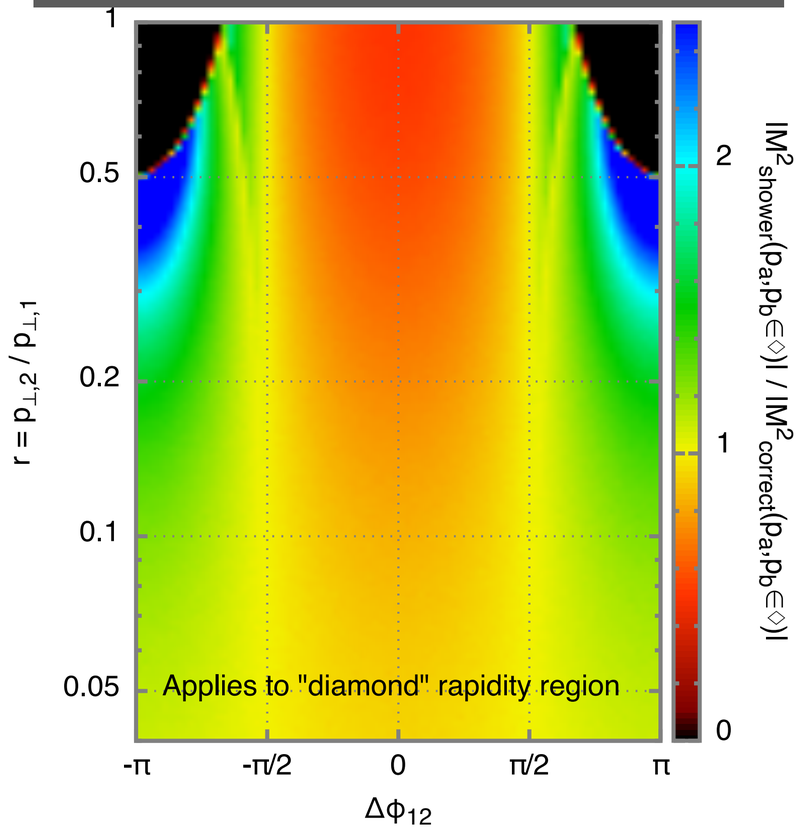


Shower initially generated matrix element for particle $\tilde{1}$, whose momentum differs (by ~ 50%) from final particle 1.

Matrix element is incorrect wrt final momentum 1.

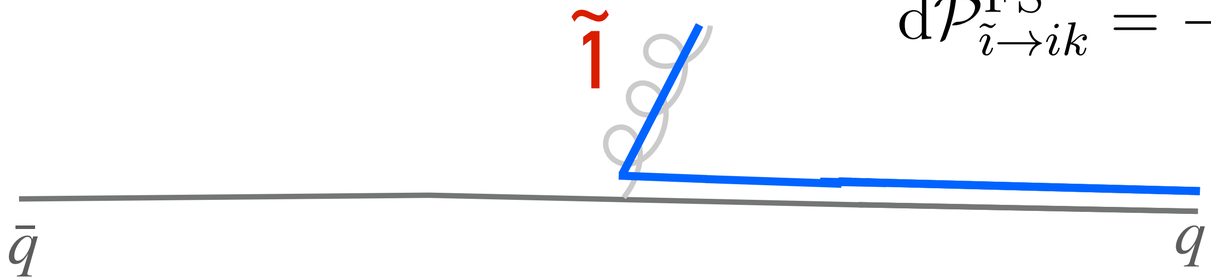
First observed: Andersson, Gustafson, Sjogren '92
Closely related effect present for Z p_t: Nagy & Soper 0912.4534
Impact on log accuracy across many observables: Dasgupta, Dreyer, Hamilton, Monni, GPS, 1805.09327

ratio of effective shower matrix element to exact one



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

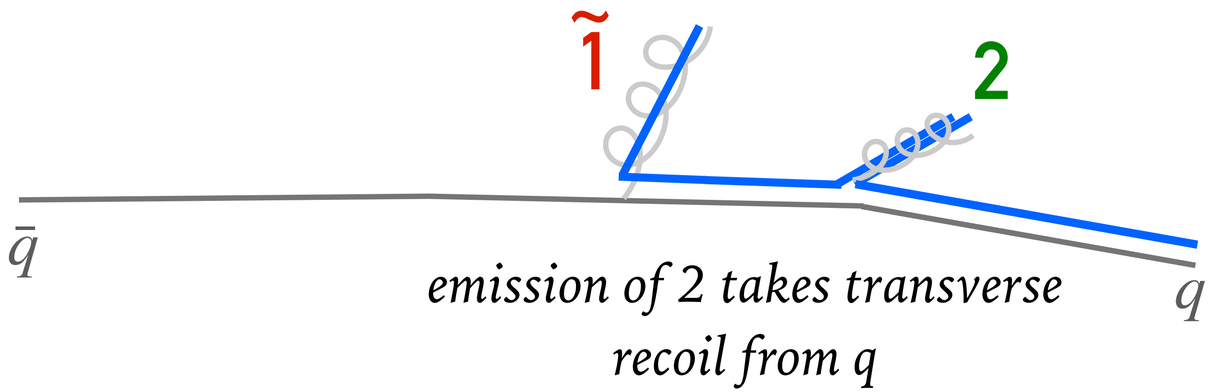
One approach



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

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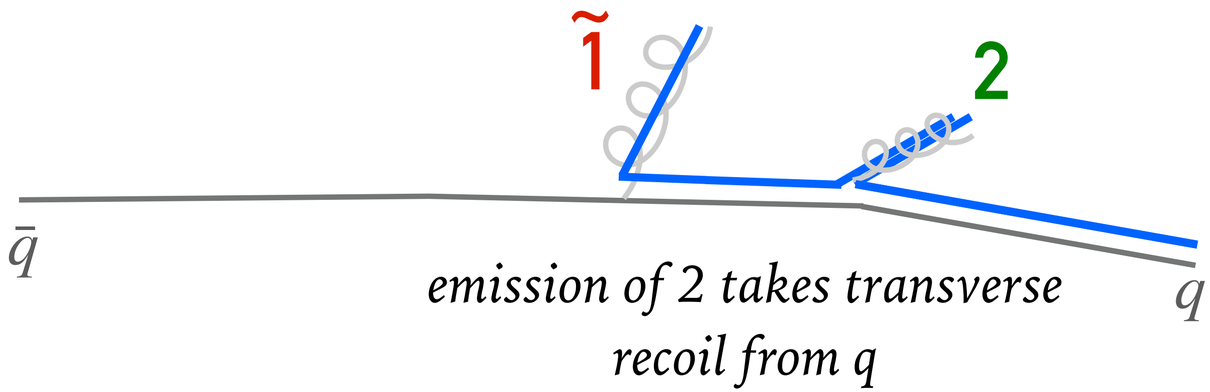
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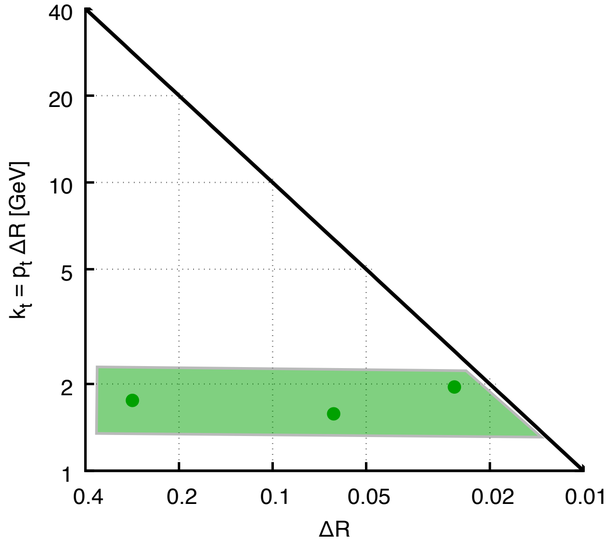


θ_{1q} left almost unchanged if ⊥ recoil from emission of 2 taken by (much harder) q

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")

June 2026 slide from Melissa van Beekveld

	Alaric	Apollo	FHP	Panscales
Available for e+e-?	NLL	NLL	NLL	Partial NNLL
Available for pp?	NLL (no numerical proof beyond colour singlet)	No	No	NLL (no numerical proof beyond colour singlet)
Available for DIS?	No	No	No	NLL
Recoil distribution	Global for soft, local pT for collinear	As Alaric's soft map, different ord. variable	Global	Local (PanLocal) and global (PanGlobal) variants
Splitting functions at LO	Soft with special ref. direction, +coll remainder	Antenna functions	AP with sharp partitioning	AP with smooth partitioning
Spin correlations	Yes in e+e-	No	Yes in e+e-	Yes at NLL
Corrections beyond LC	No	No	No	Yes at NLL (NODS)
NLO matching available?	Yes in e+e-, using S-MC@NLO at exact colour	Yes in e+e- on paper, not yet implemented	Yes in e+e-	Yes for CS (dBNLO, P2B or positive weights ESME)
Multi-jet merging?	In e+e-; 5 jets (NLO), in pp; 3 jets (LO)	No	No	No
Particle masses?	Yes in e+e-	No	No	Yes in e+e-
Resonances?	Yes in e+e-	No	No	No
Publicly available?	Python codes, should become part of Sherpa	No, but should become part of Pythia8	No, but should become part of Herwig	Yes, interfaced to Pythia8



Samuel Bates
Oxford



Melissa van Beekveld
NIKHEF



Mrinal Dasgupta
Manchester



Basem El-Menoufi
Turin



Silvia Ferrario Ravasio
Turin



Keith Hamilton
Univ. Coll. London



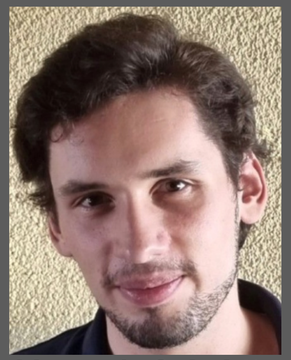
Jack Helliwell
Oxford



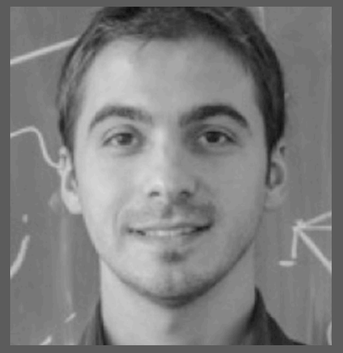
Alexander Karlberg
MPP



Matvei Kuzmin
Oxford



Marco A. C. Leitão
LIP, IPhT



Pier Francesco Monni
CERN



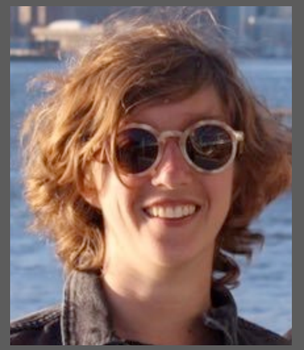
GPS
Oxford



Nicolas Schalch
Oxford



Ludovic Scyboz
Monash



Alba Soto-Ontoso
Granada

PanScales

A project to bring logarithmic understanding and accuracy to parton showers



Grégory Soyez
IPhT, Saclay



Silvia Zanoli
Oxford

Former members



Frédéric
Dreyer



Rok
Medves

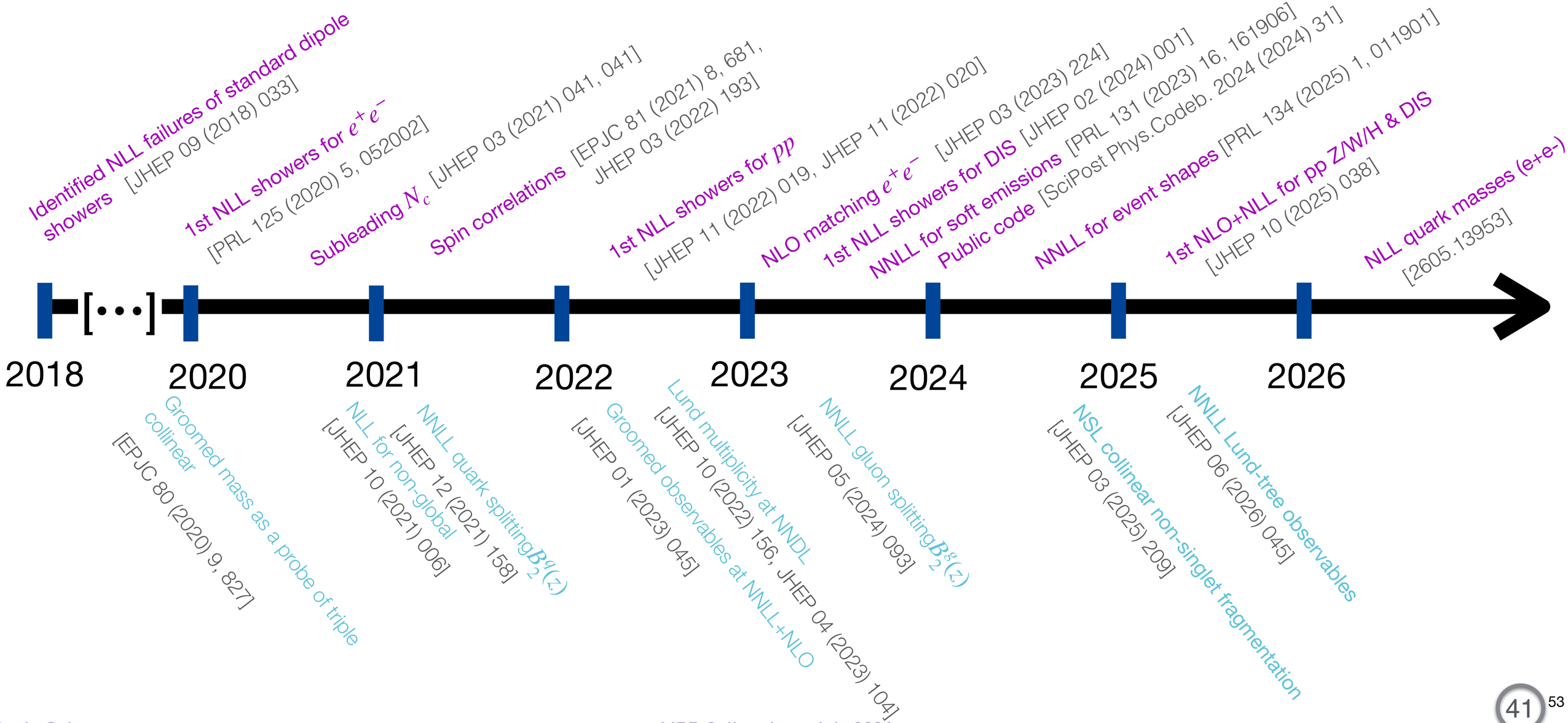


Rob
Verheyen

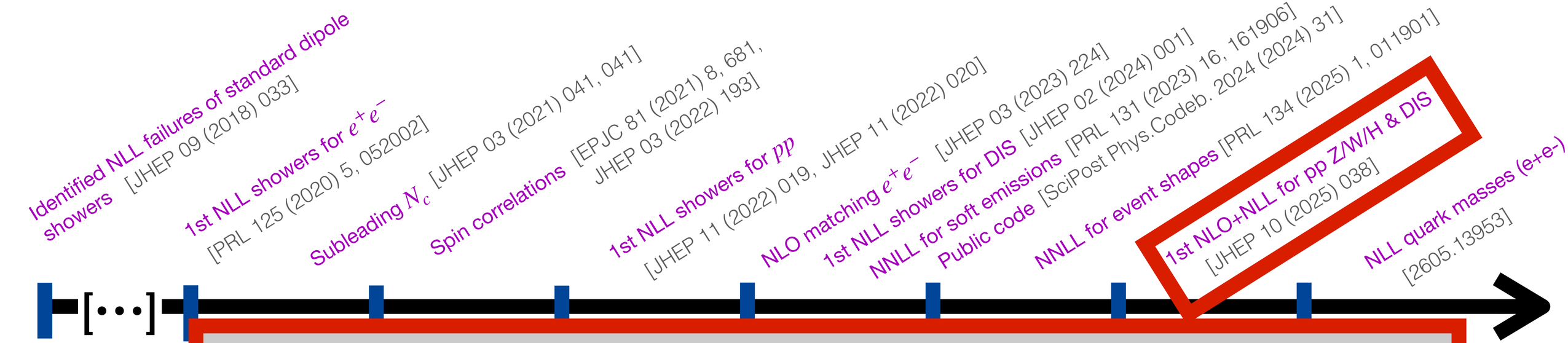


Scarlett
Woolnough

PanScales timeline



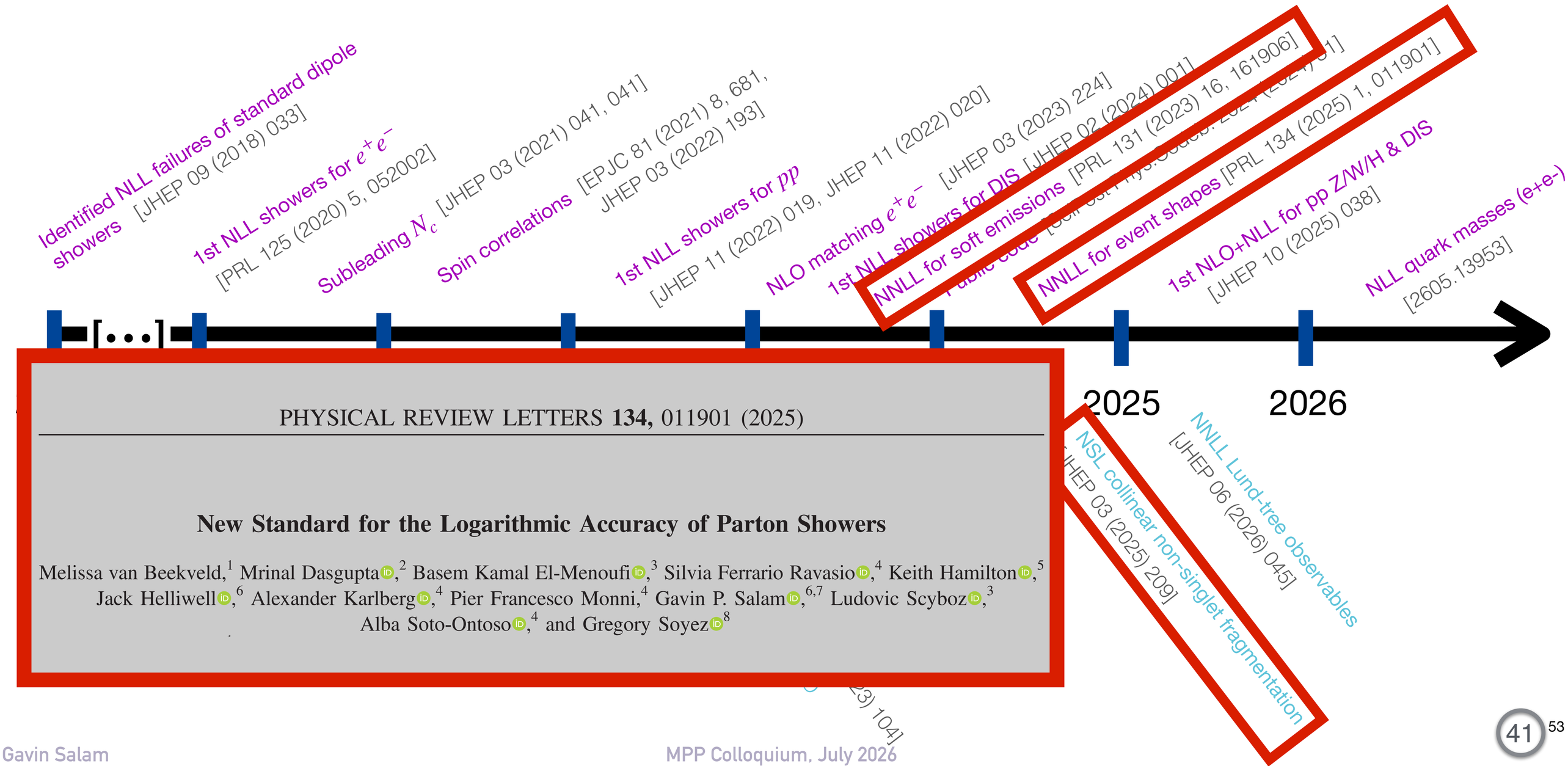
PanScales timeline



Logarithmically-accurate and positive-definite NLO shower matching

Melissa van Beekveld,[a] Silvia Ferrario Ravasio,[b] Jack Helliwell,[c] Alexander Karlberg,[b] Gavin P. Salam,[d,e] Ludovic Scyboz,[c] Alba Soto-Ontoso,[f] Gregory Soyez,[g] Silvia Zanoli[d]

PanScales timeline



N^{p}LL

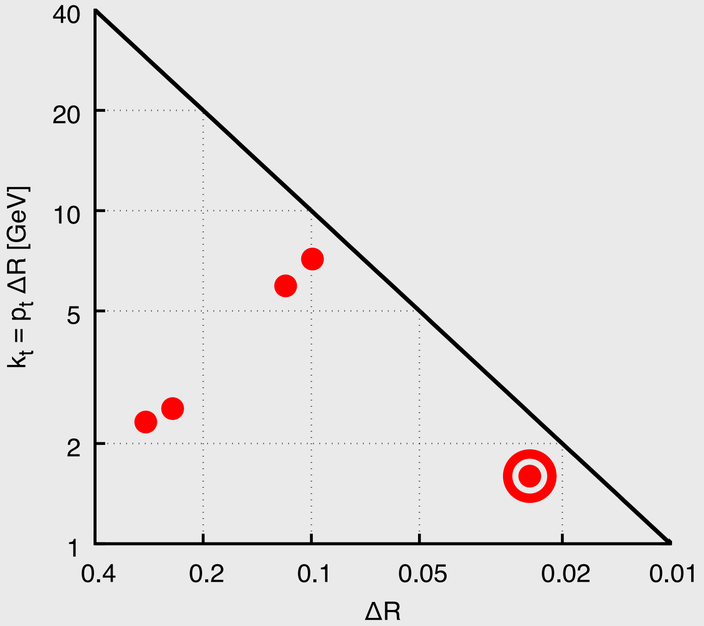
A Matrix Element condition

- correctly reproduce n-parton tree-level matrix element for arbitrary configurations, so long as all groups of up to $\boldsymbol{p}$ emissions are well separated in the Lund diagram
- For groups of $\boldsymbol{k}$ emissions, be accurate up to $\boldsymbol{p-k}$ loops
- supplement with unitarity, $\boldsymbol{p+1}$-loop running coupling & cusp anomalous dimension

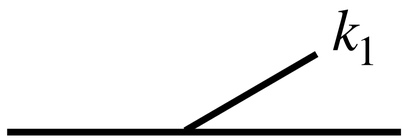
Resummation condition:

reproduce N^{p}LL ($\alpha_s^n L^{n+1-p}$) results for all standard resummations

- global event shapes
- non-global observables
- fragmentation functions ($\alpha_s^n L^{n+1-p} \equiv \mathrm{N}^{p-1}\mathrm{LL}$)
- multiplicities ($\alpha_s^n L^{2n-p}$)
- …

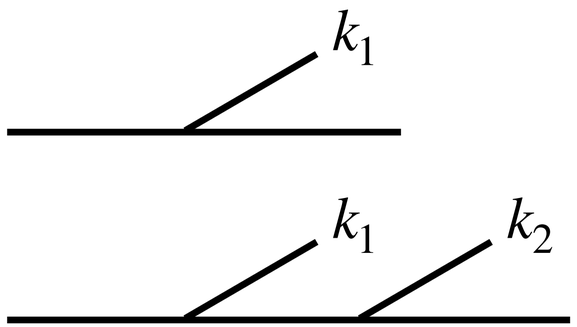


Towards NNLL: each new emission's distribution conditional on previous emission



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

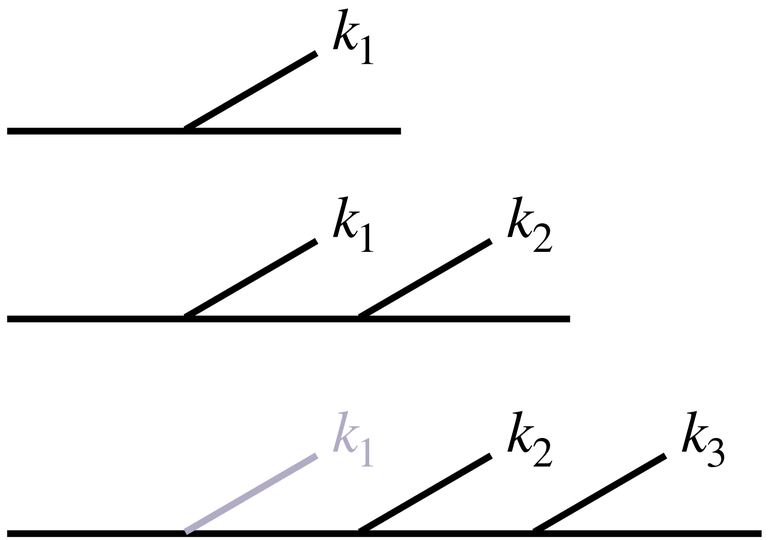
Towards NNLL: each new emission's distribution conditional on previous emission



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

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

Towards NNLL: each new emission's distribution conditional on previous emission

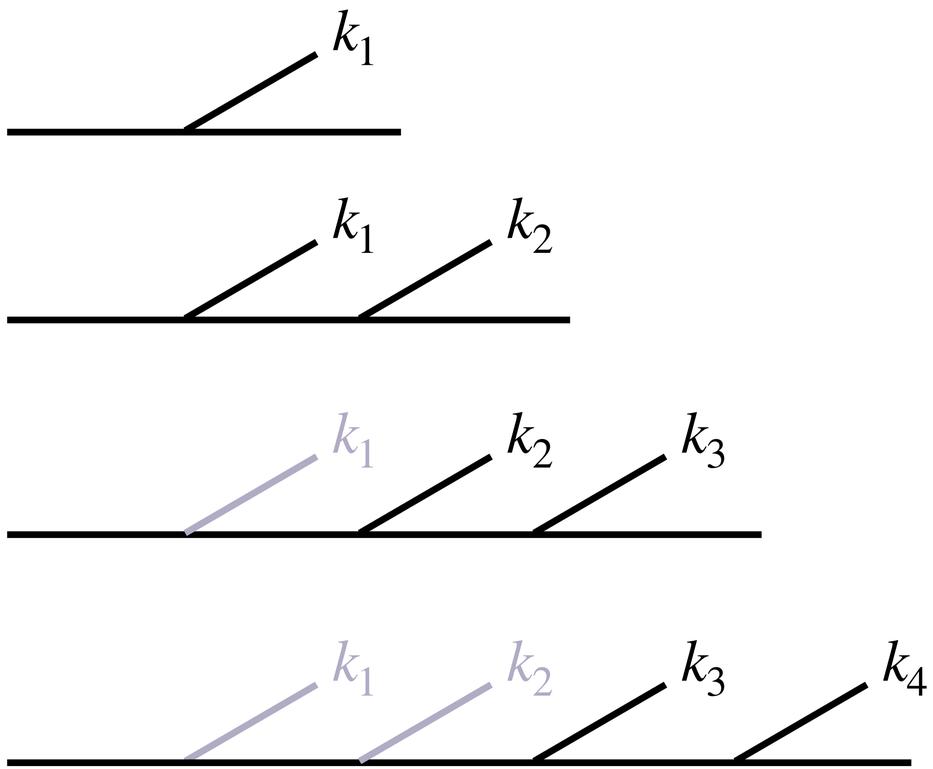


Distribute k_1 according to $M^2(k_1)$

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

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

Towards NNLL: each new emission's distribution conditional on previous emission



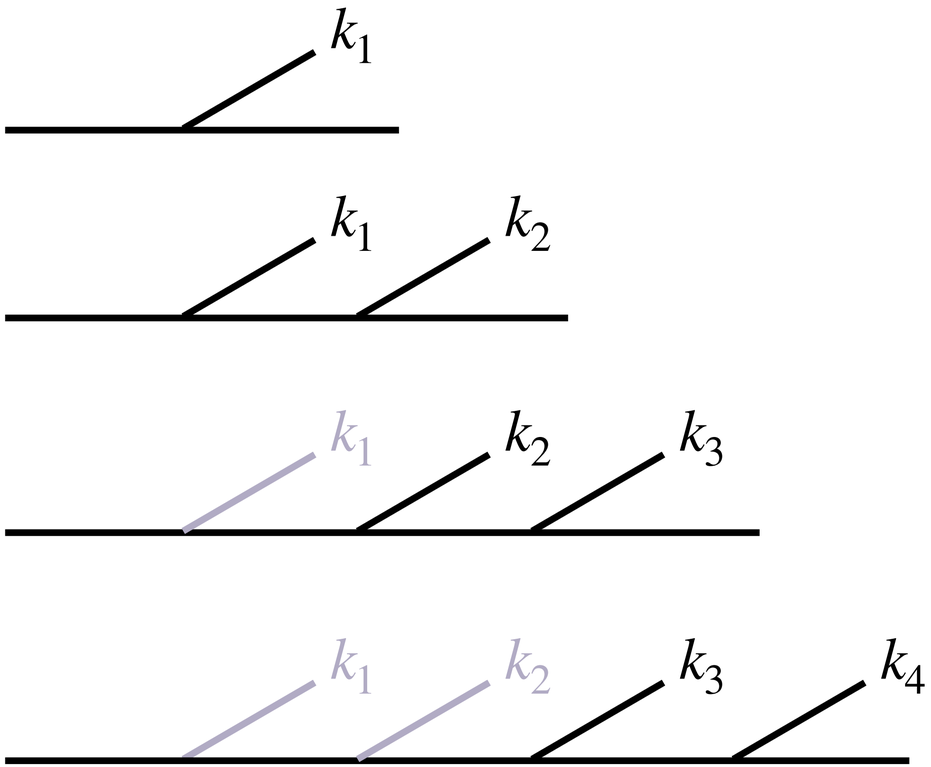
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Distribute k_3 according to $M^2(k_2, k_3)/M^2(k_2)$

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

Towards NNLL: each new emission's distribution conditional on previous emission



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

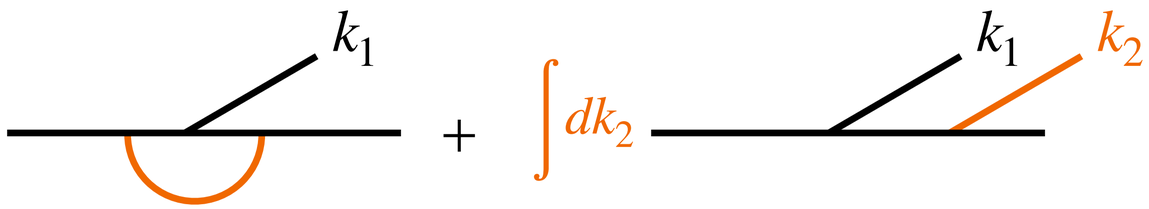
Distribute k_3 according to $M^2(k_2, k_3)/M^2(k_2)$

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

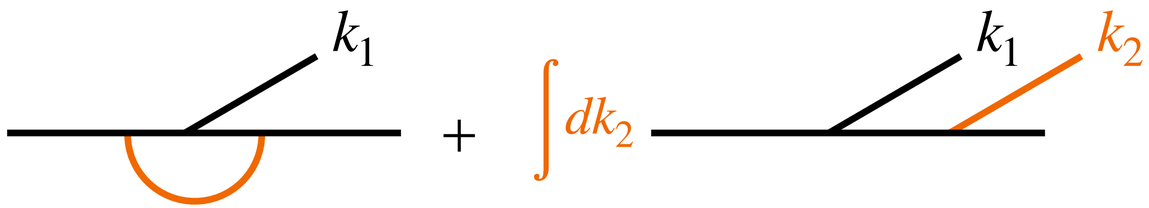
[factorised matrix elements given in Dokshitzer, Marchesini & Oriani '92, Campbell & Glover, hep-ph/9710255, Catani & Grazzini hep-ph/9810389, etc.]

Account for virtual corrections associated with each emission

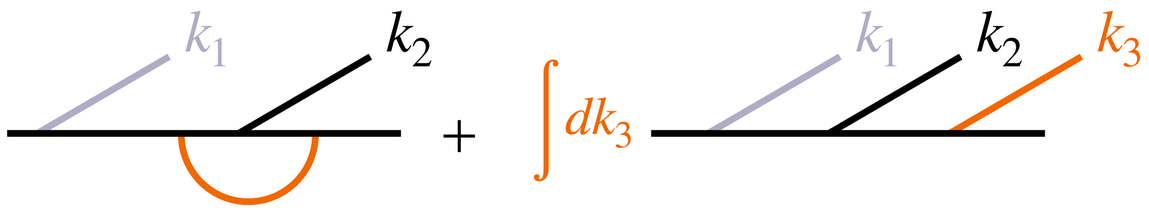


NLO correction to k_1 emission intensity sums loop correction and all possible scenarios for the next emission

Account for virtual corrections associated with each emission



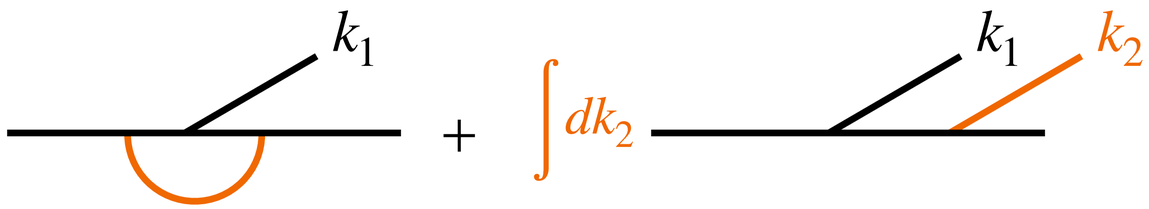
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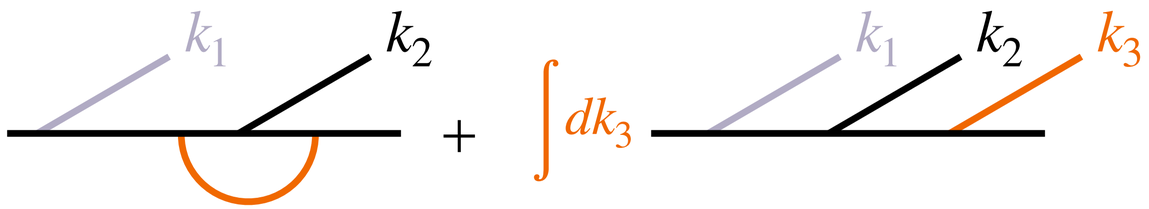
NLO correction to k_2 emission intensity sums loop correction and all possible scenarios for the next emission

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

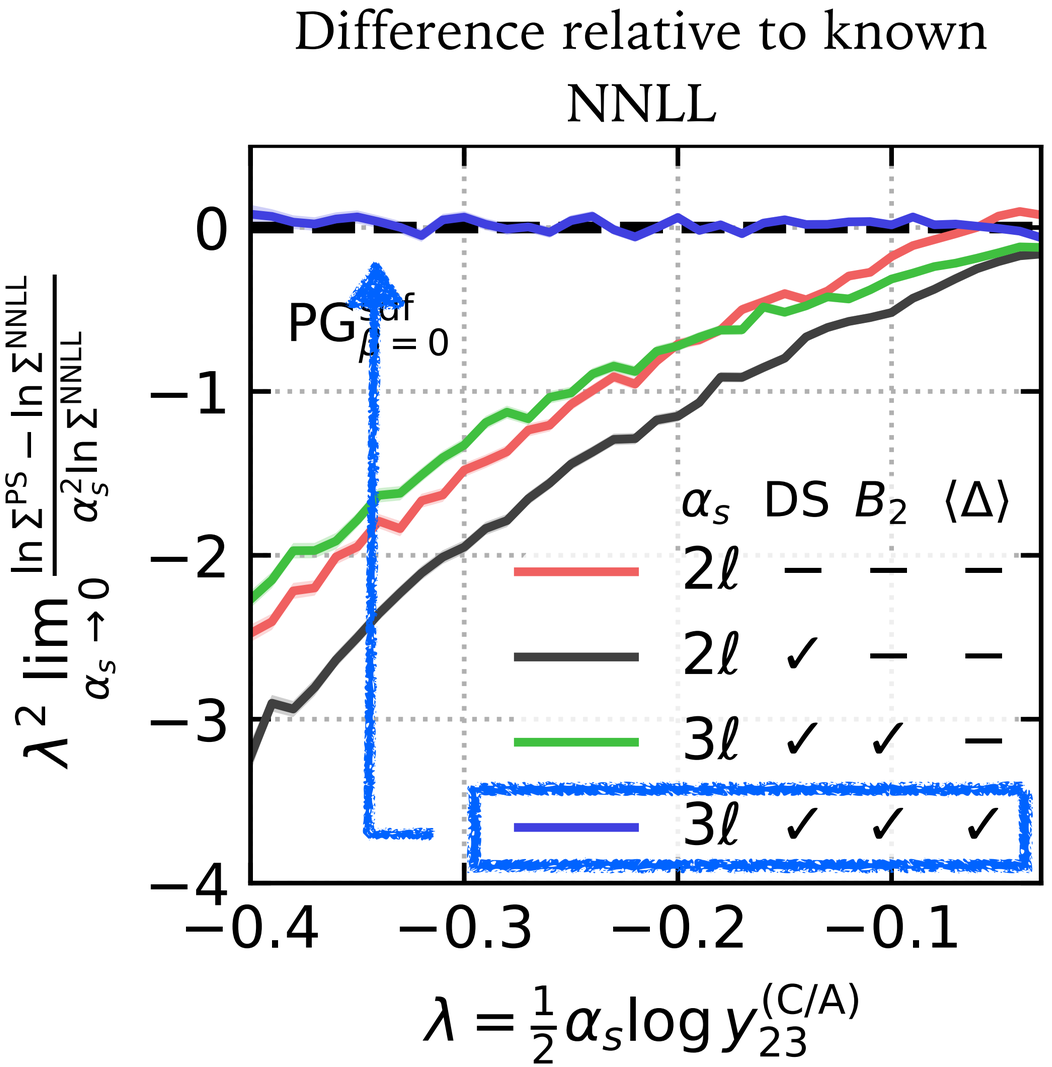


NLO correction to k_2 emission intensity sums loop correction and all possible scenarios for the next emission

etc.

Again relies on factorisation, e.g. when 1 and 2 are well separated in the Lund plane + careful nesting, cf. 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)

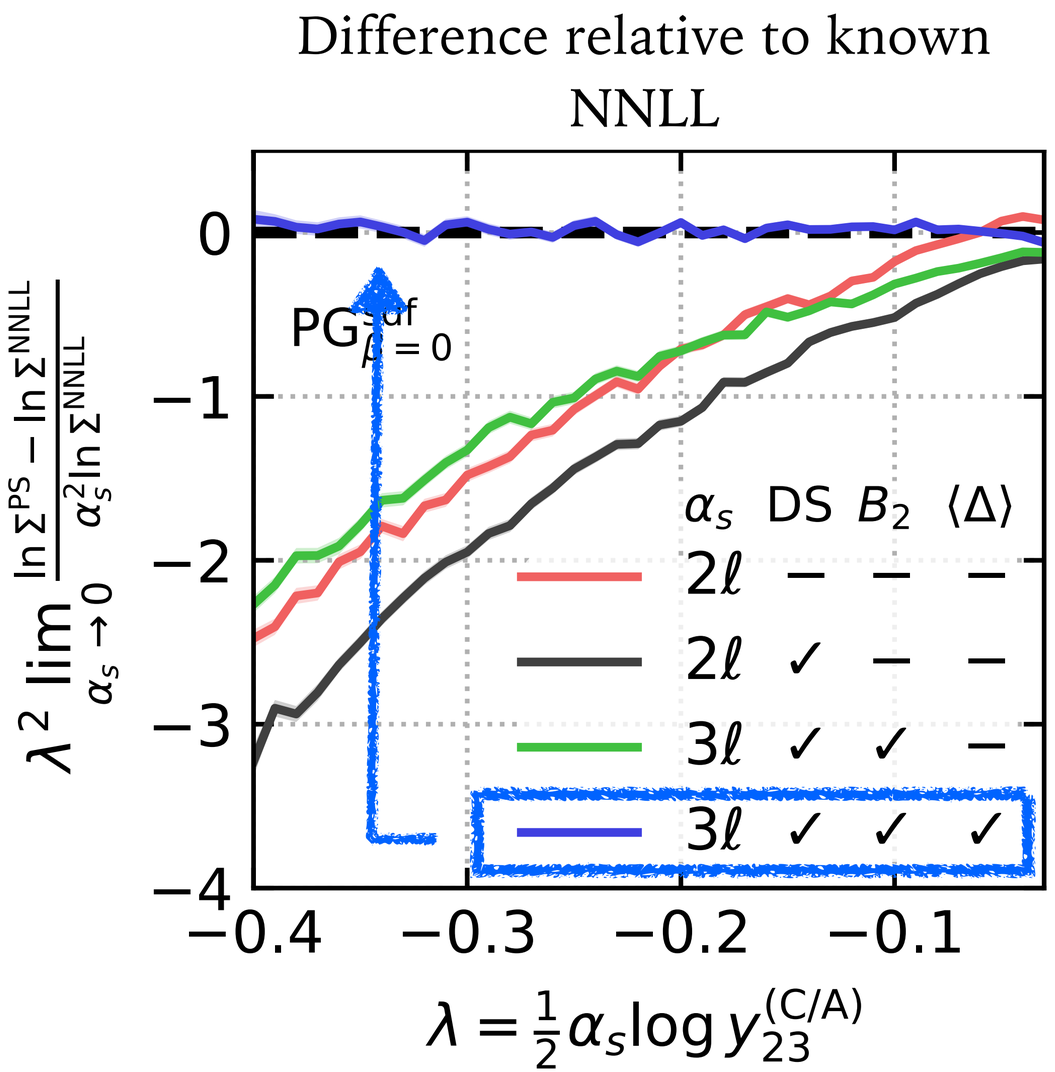
Testing NNLL for event shapes (so far only for e⁺e⁻ collisions)

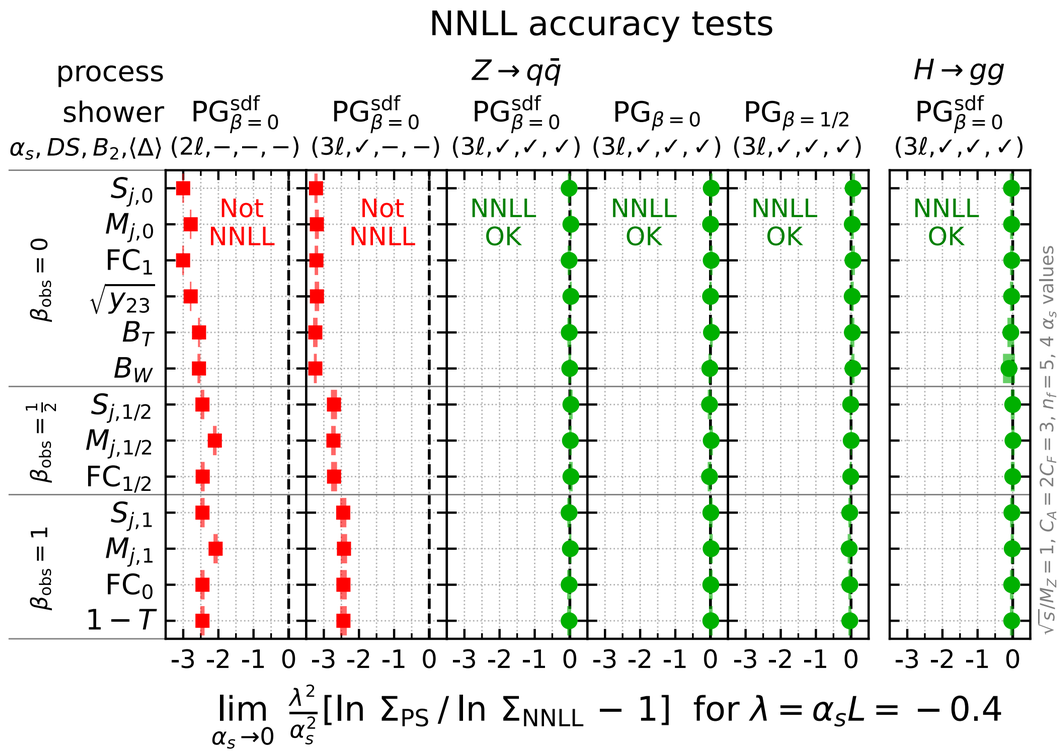


need to analyse and account for all possible sources of NNLL contribution

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

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



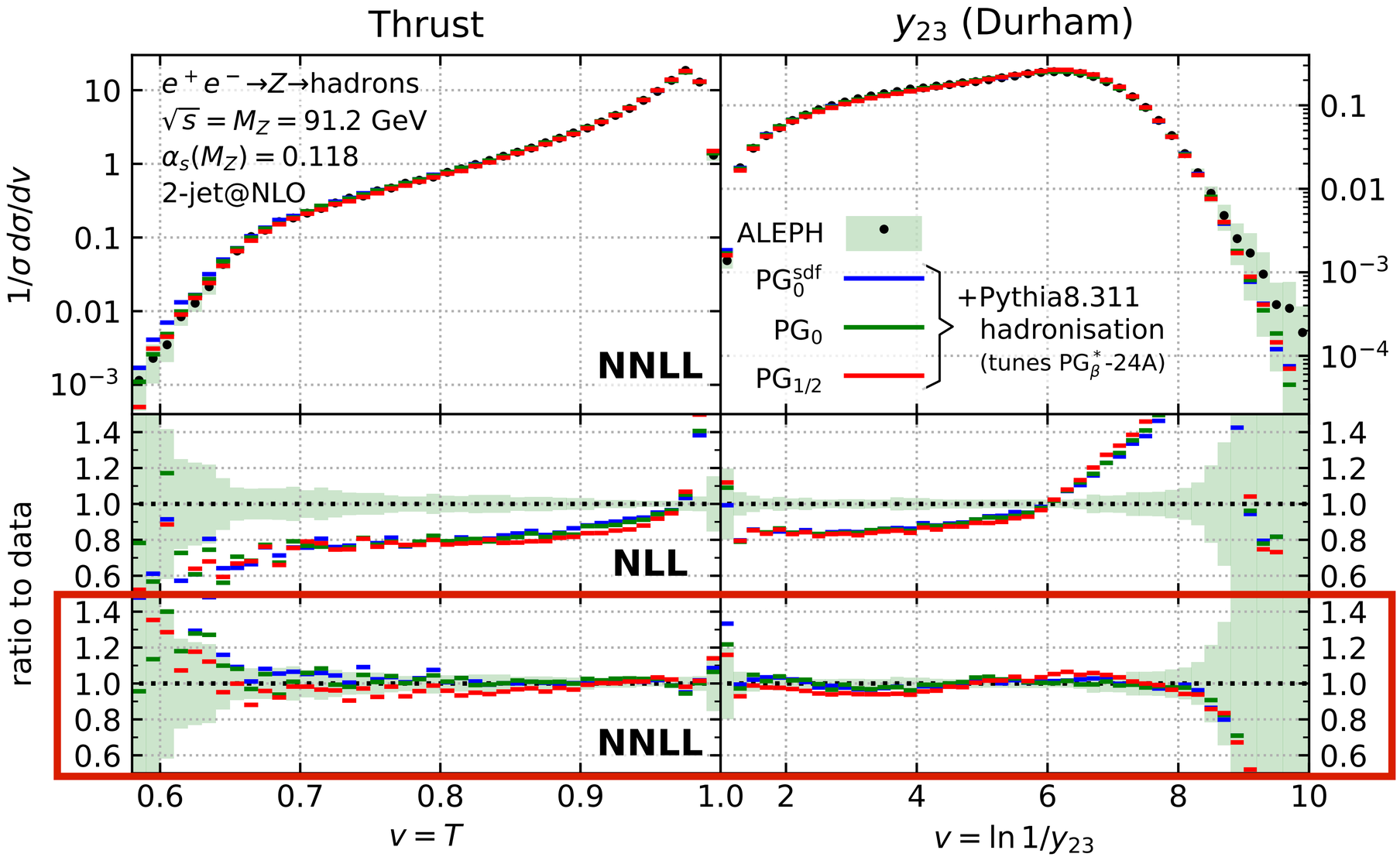


need to analyse and account for all possible sources of NNLL contribution

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

Comparing to LEP event-shape data

Ferrario Ravasio et al, 2307.11142,
van Beekveld et al, 2406.02661



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

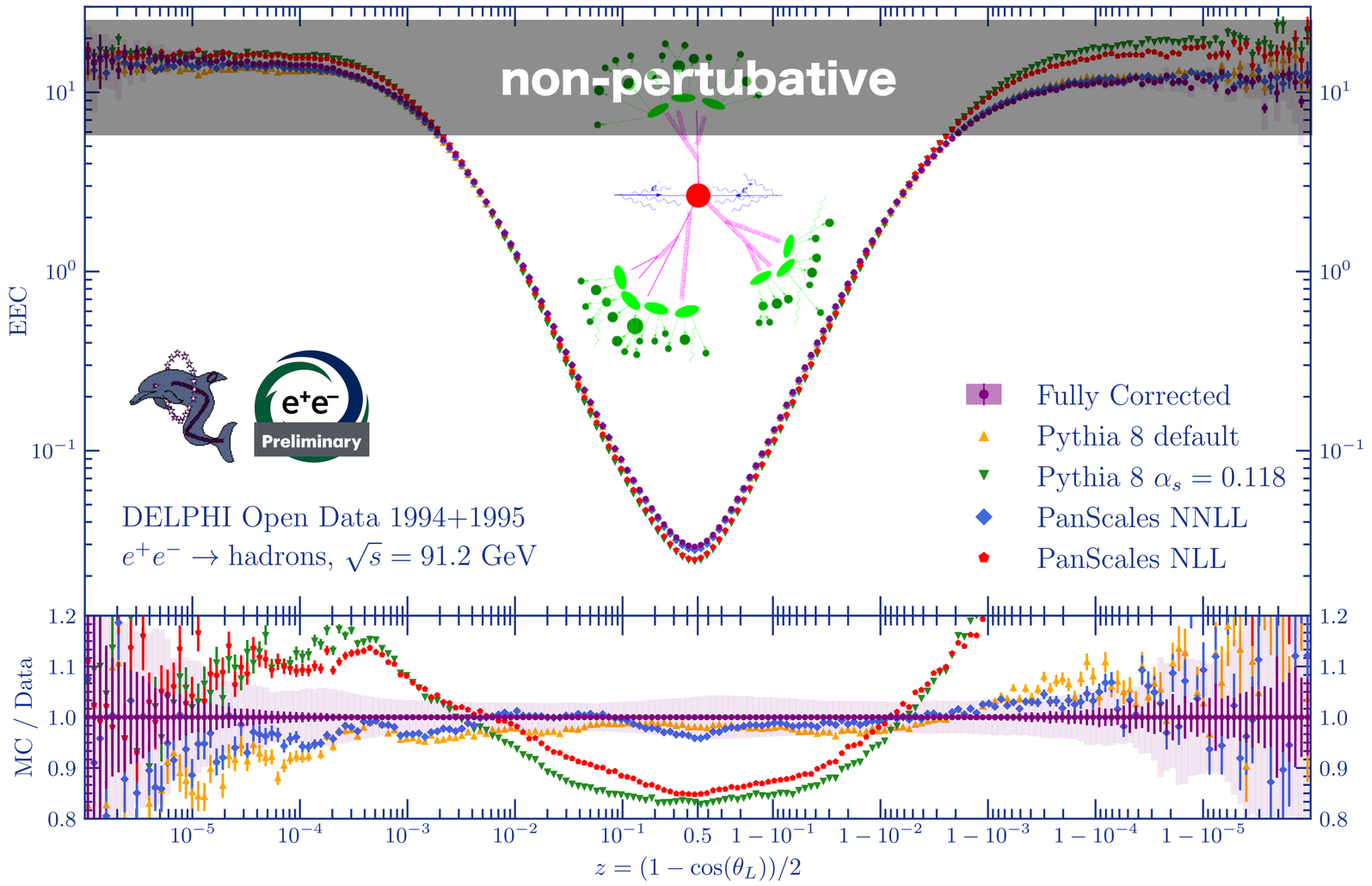
Dramatically improves agreement with data, using a "normal" $\alpha_s = 0.118$

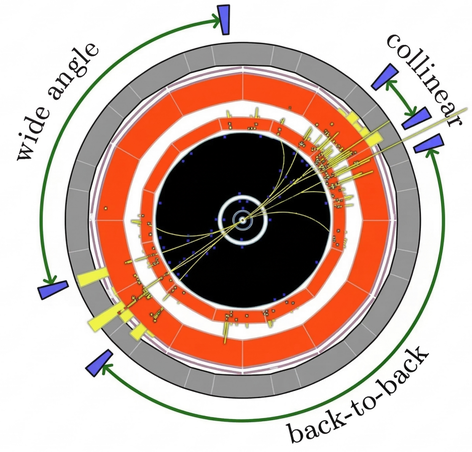
NB: 3-jet @ NLO still missing for robust pheno conclusions

← NNLL

for event shapes; not yet general NNLL

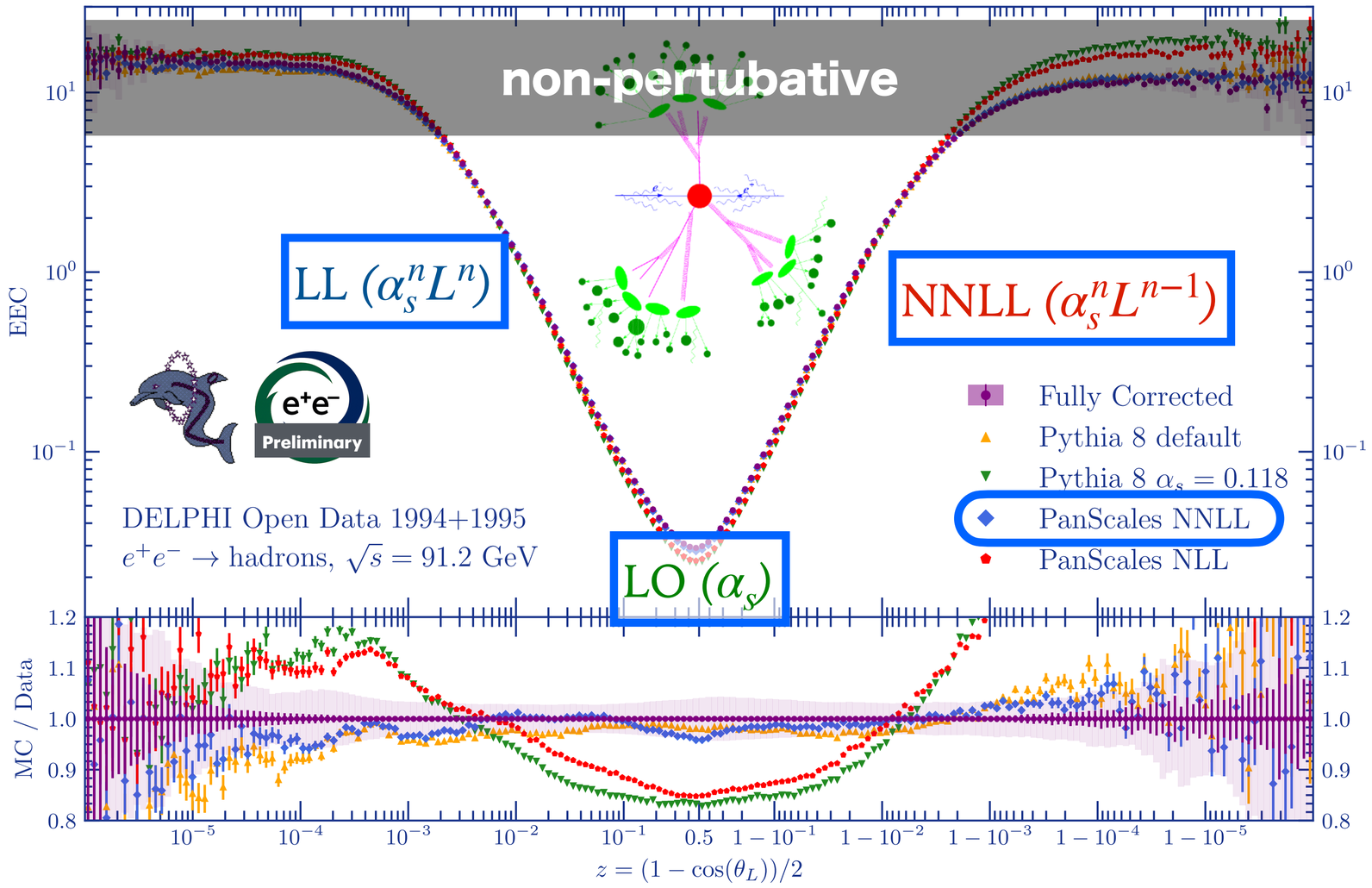
EEC, e⁺e⁻ Alliance measurement on archived data

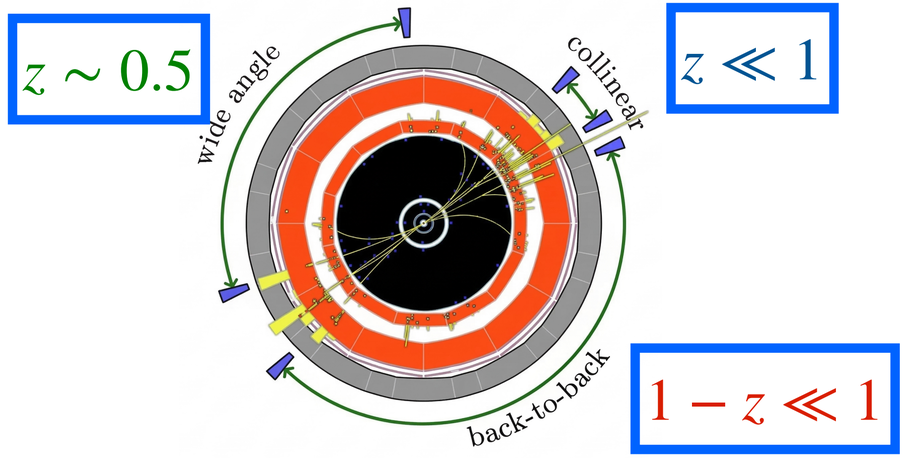




- State-of-the-art PanScales @ NNLL describe the data well without parton shower tuning
  - 3-jets in the ME
- Leading Log Pythia8 generator also describe the data with parton shower tuning

EEC, e⁺e⁻ Alliance measurement on archived data





- State-of-the-art PanScales @ NNLL describe the data well without parton shower tuning
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The promise of perturbative QFT

Follow the rules (Feynman diagrams)

Ask a computer to work through maths

Out comes a prediction

Ask the computer to draw more diagrams, work harder, and you get more accuracy

the hope is that the technology that gets developed for "standard" pQFT calculations can be leveraged to get accuracy not just at fixed order, but across the full range of perturbative scales in simulations