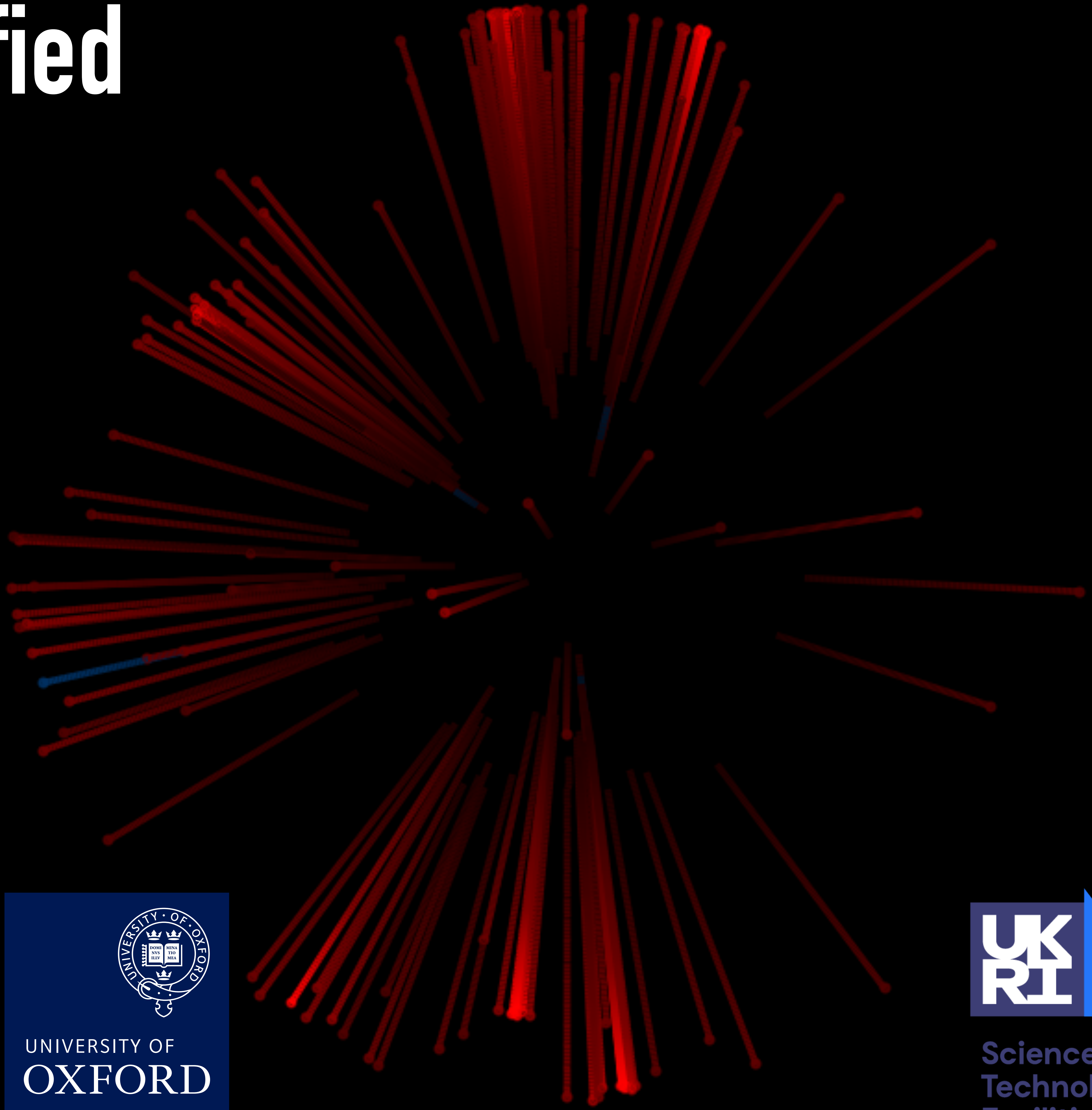
The Strong Force Across Scales
Quantum Simplified

Saturday Mornings of
Theoretical Physics
Oxford
25 October 2025



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

UNIVERSITY OF OXFORD

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Science and Technology Facilities Council

THE ROYAL SOCIETY


LHC
Large Hadron Collider
Grand collisionneur de hadrons


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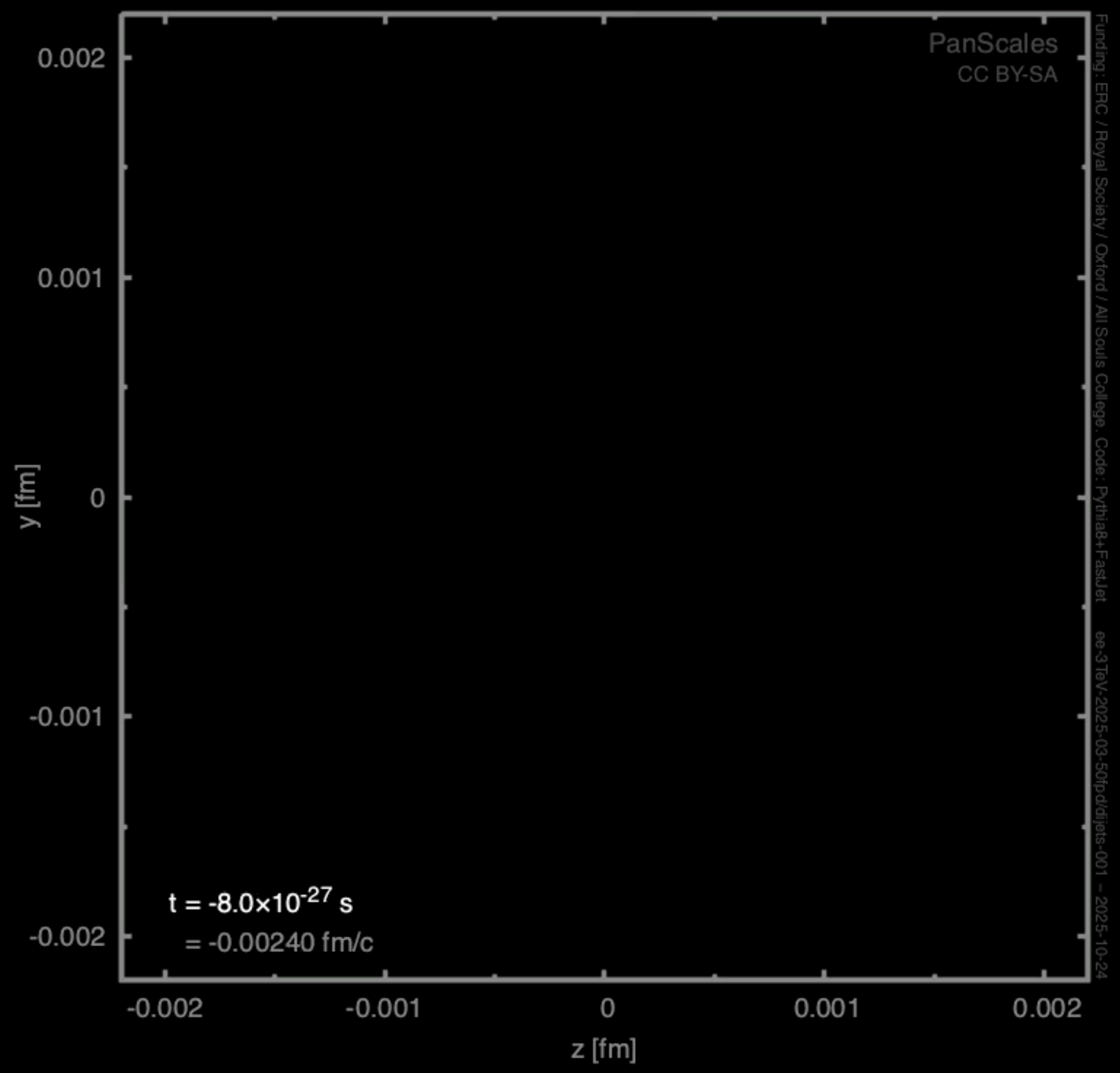
What actually happens in a collision?

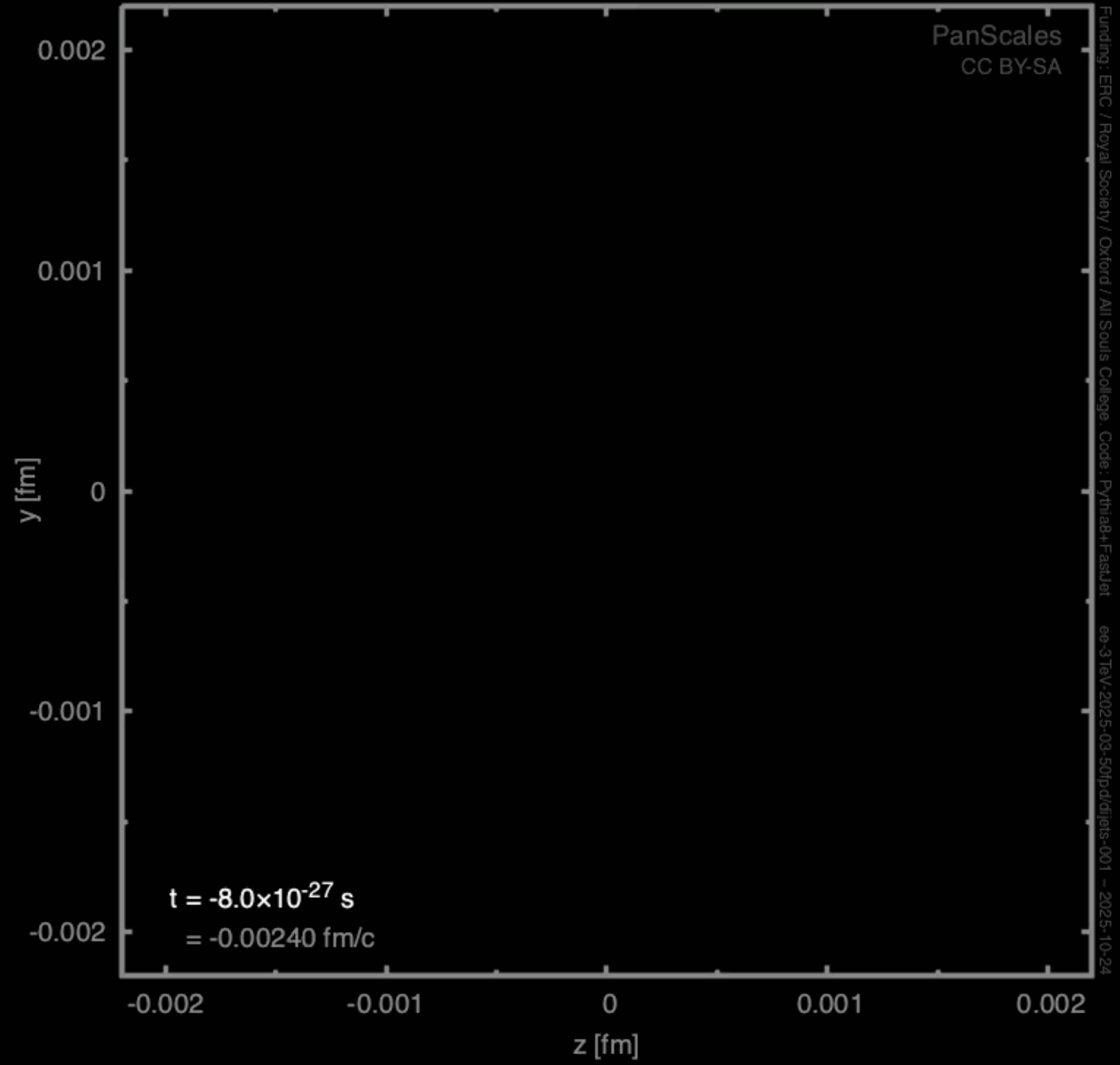


incoming beam particle

intermediate particle (quark or gluon)

final particle (hadron)

Event evolution spans 7 orders of magnitude in space-time



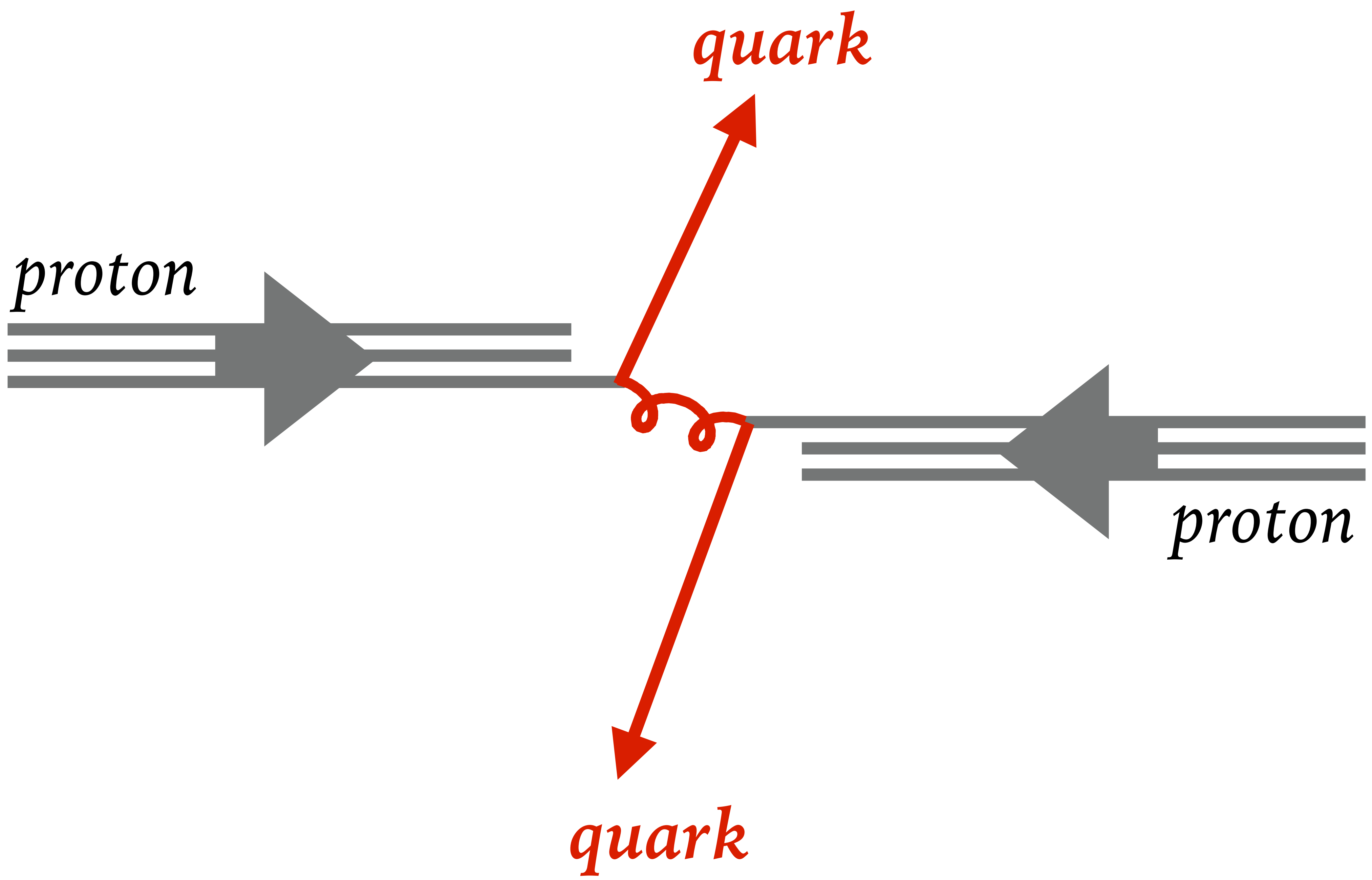
incoming beam particle

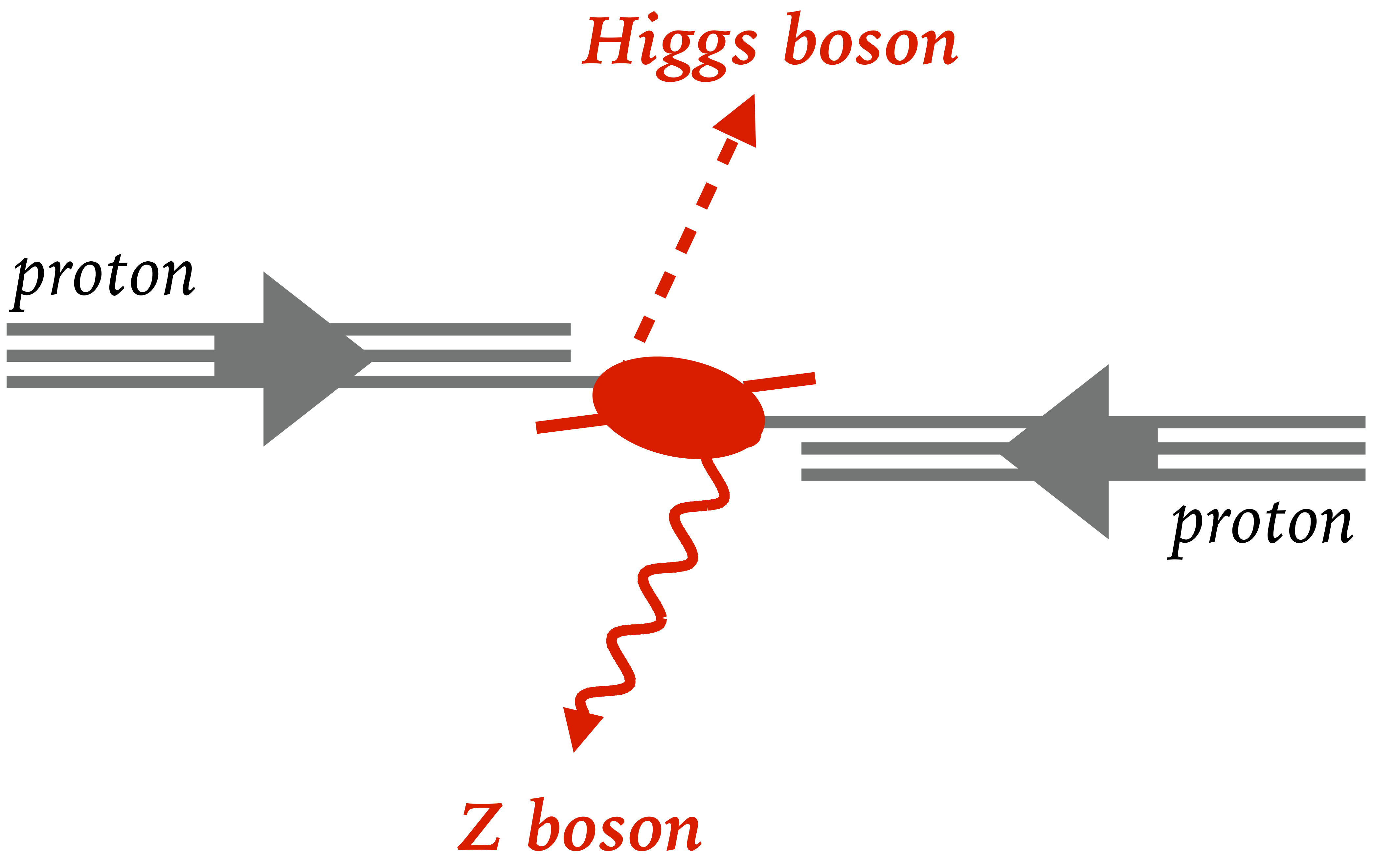
intermediate particle (quark or gluon)

final particle (hadron)

Event evolution spans 7 orders of magnitude in space-time

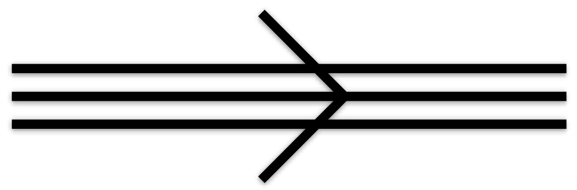
The essence of interpreting collider data (1)



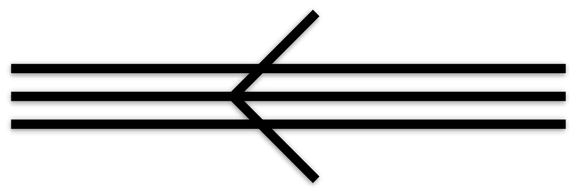


Given hundreds of measured particles from a collision,
which of these two reactions occurred?

A proton-proton collision: INITIAL STATE

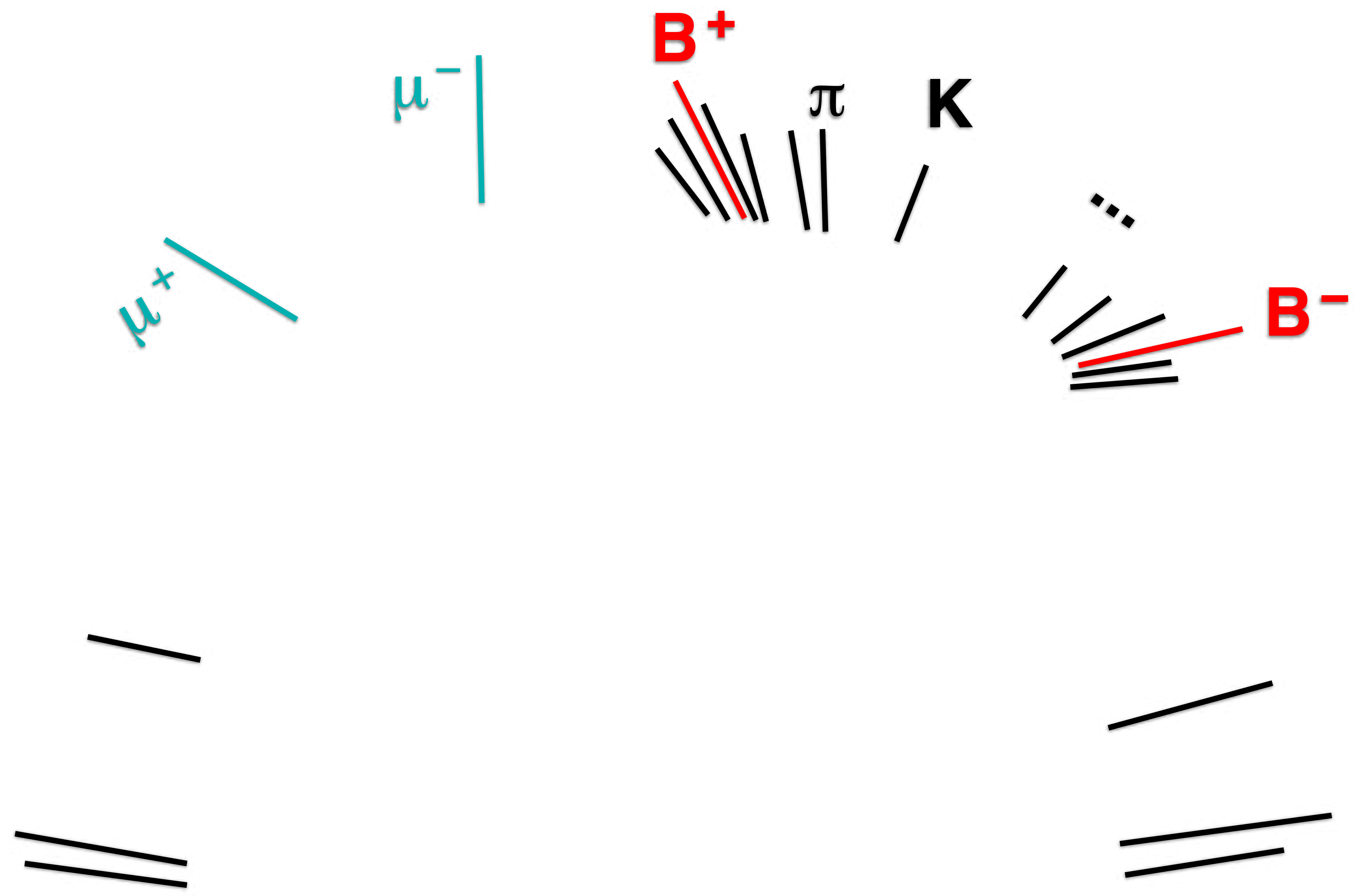


proton

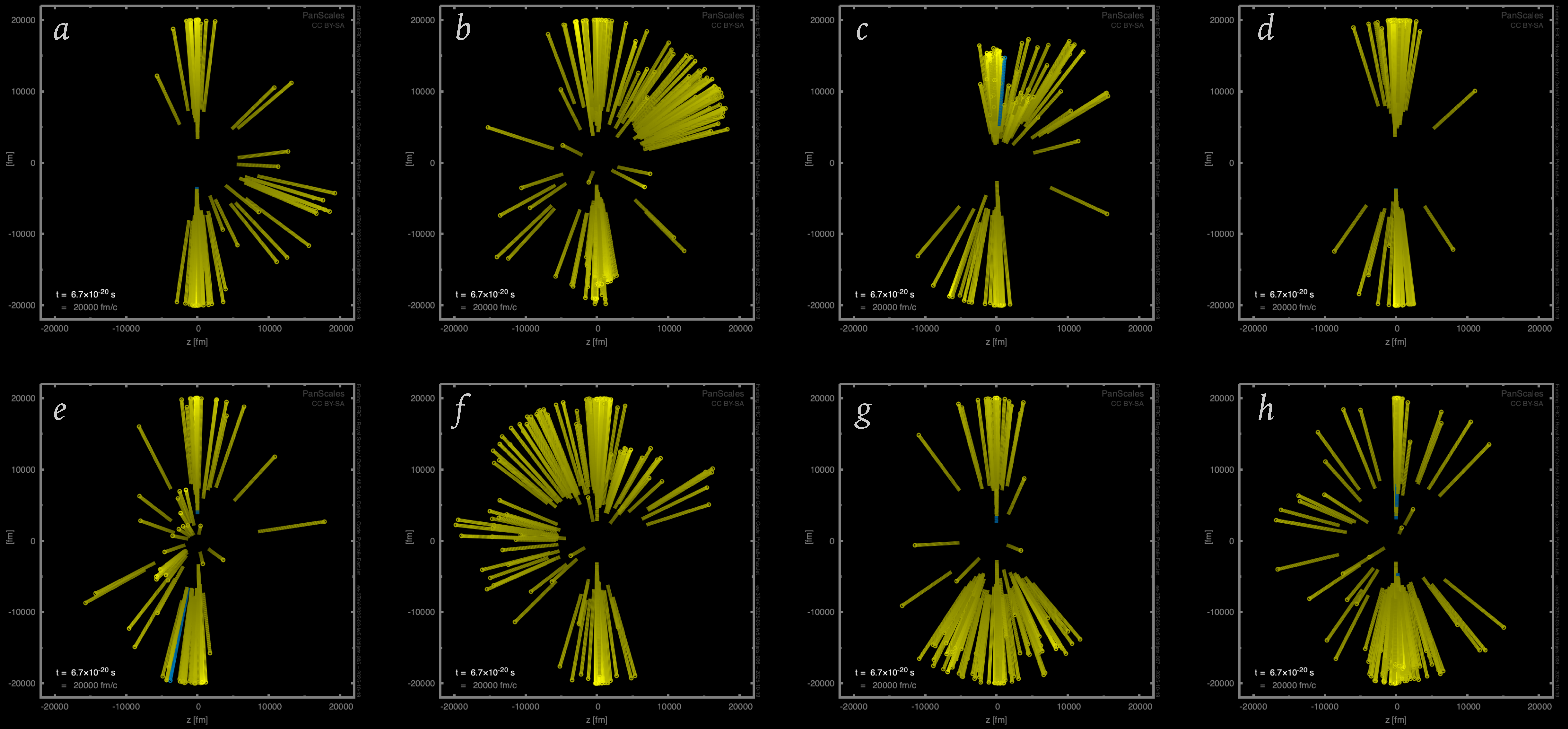


proton

A proton-proton collision: FINAL STATE



(actual final-state multiplicity ~ several hundred hadrons)


a
b
c
d
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h
PanScales
CC BY-SA
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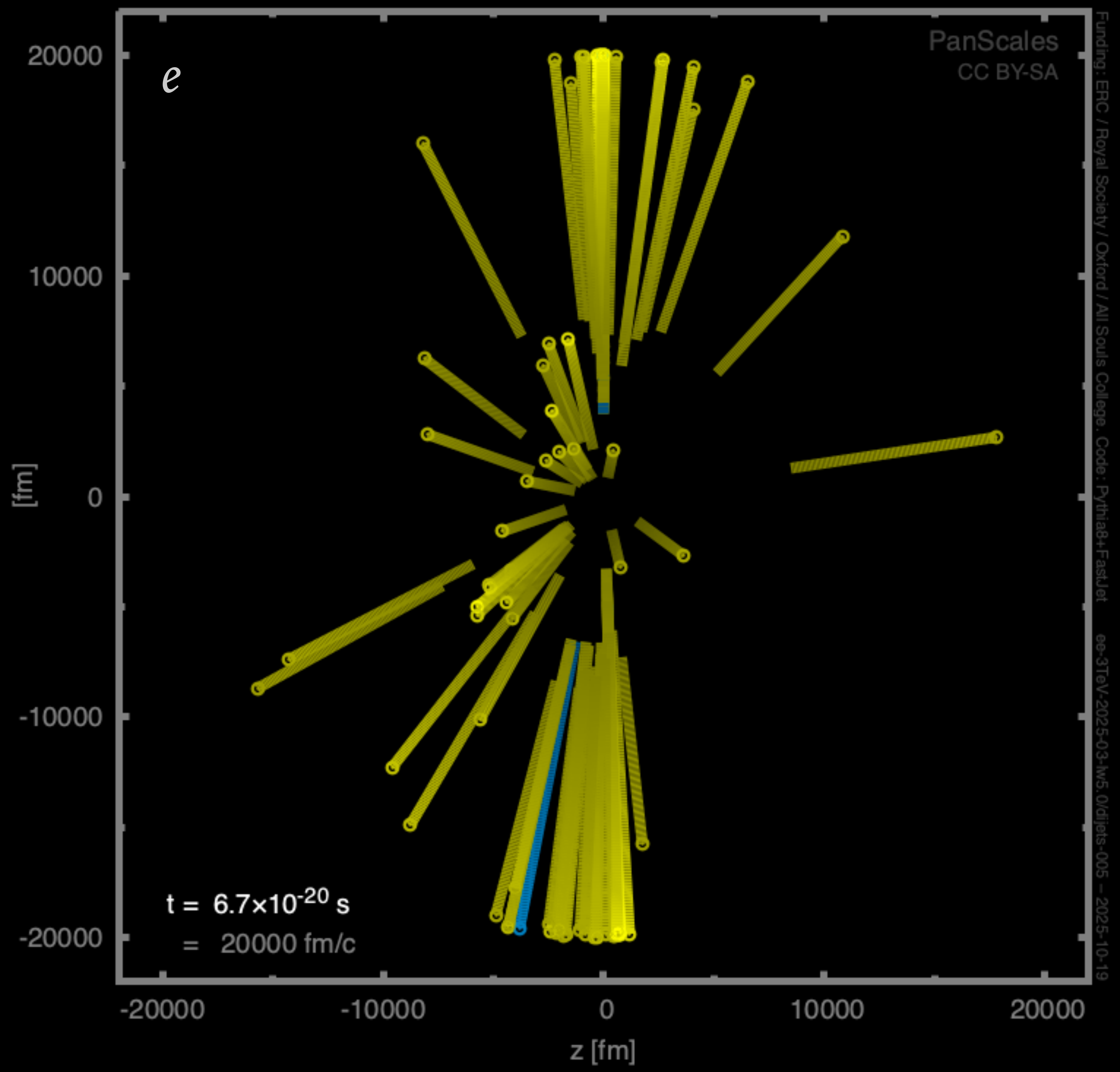
[fm]
20000
10000
0
-10000
-20000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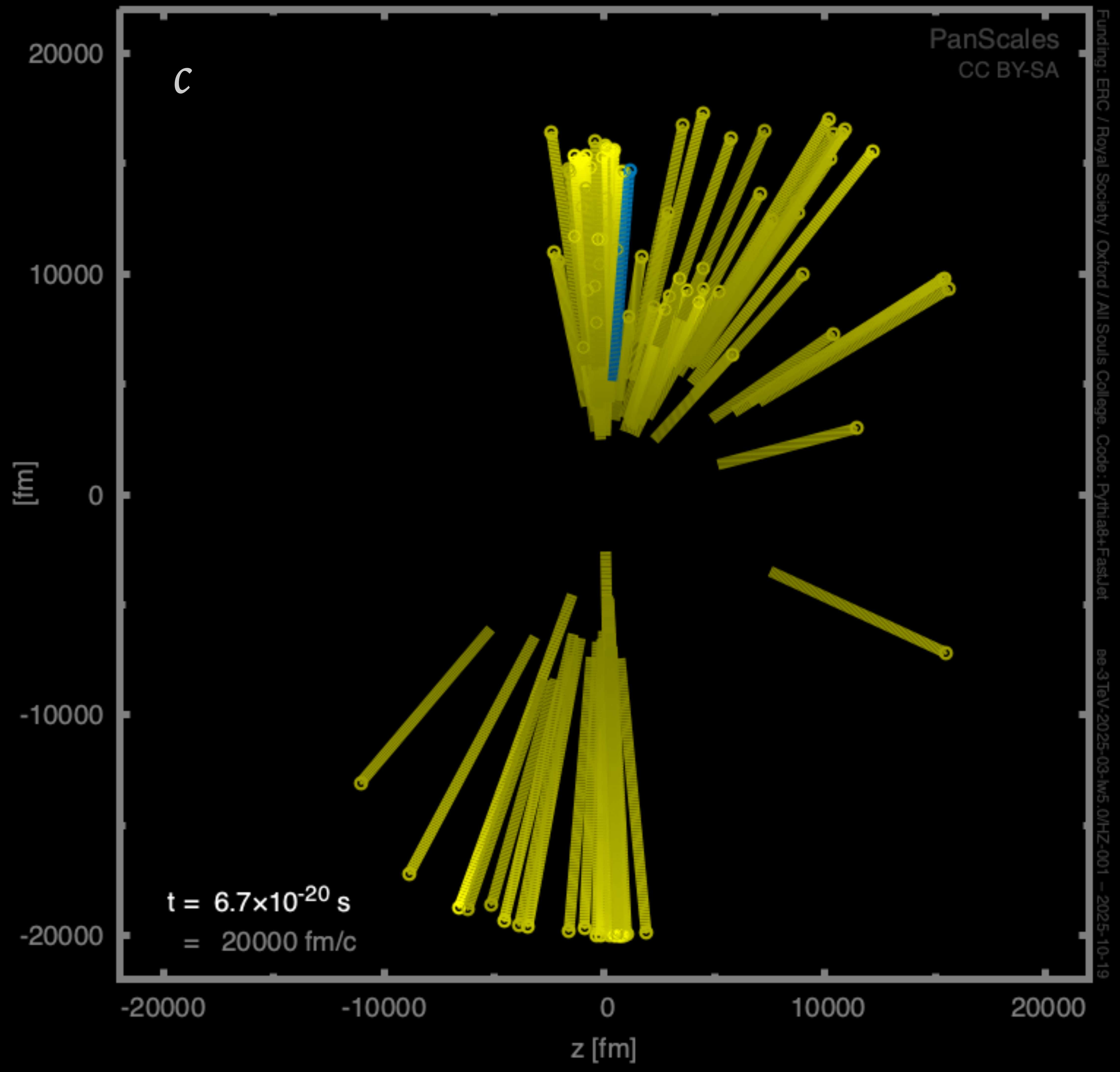
c
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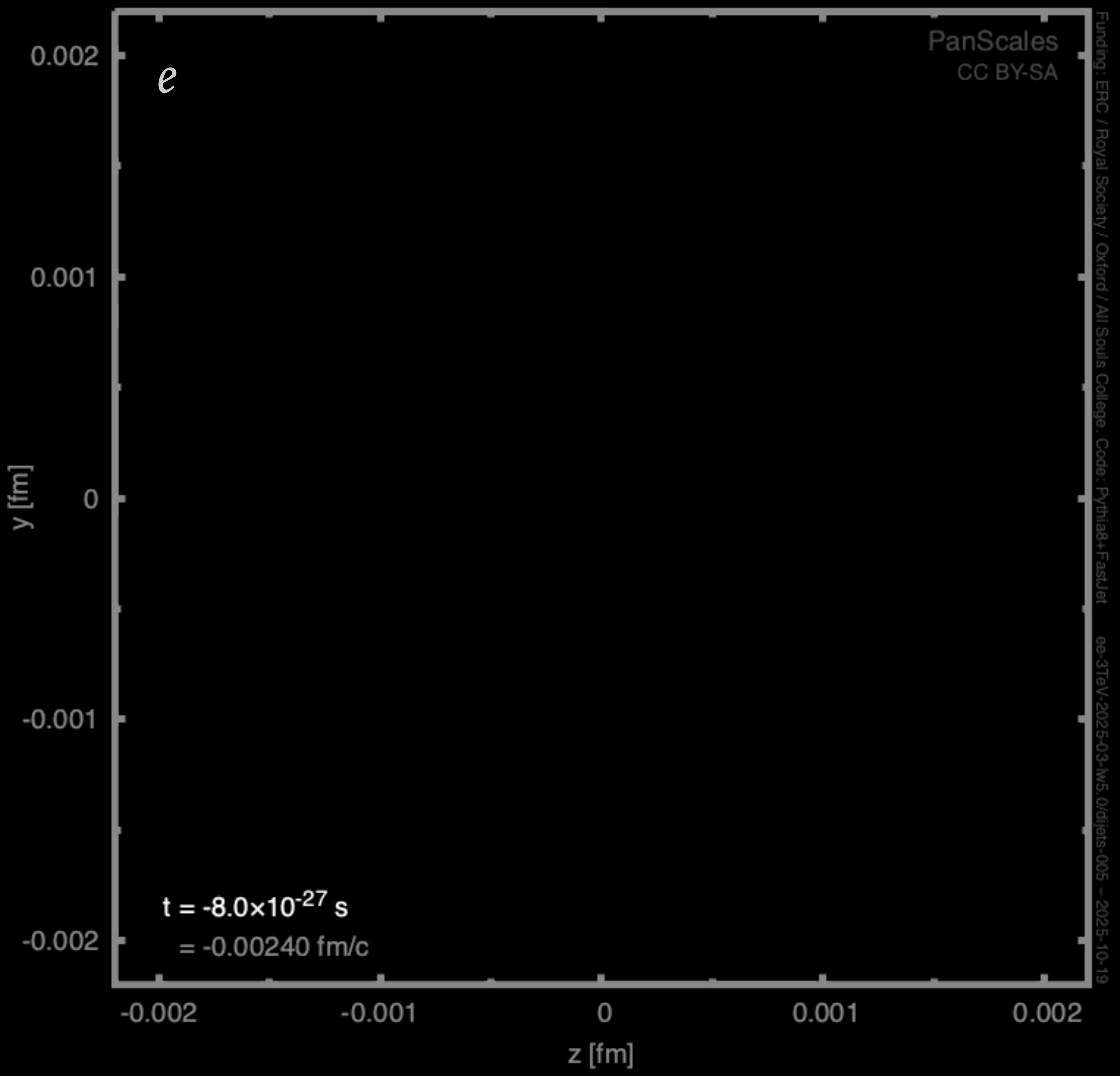

e
PanScales
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Funding: ERC / Royal Society / Oxford / All Souls College. Code: Pythia8+FastJet
ee-3TeV-2025-03-lw5.0/dijets-005 – 2025-10-19
t = -8.0×10^-27 s
= -0.00240 fm/c
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y [fm]
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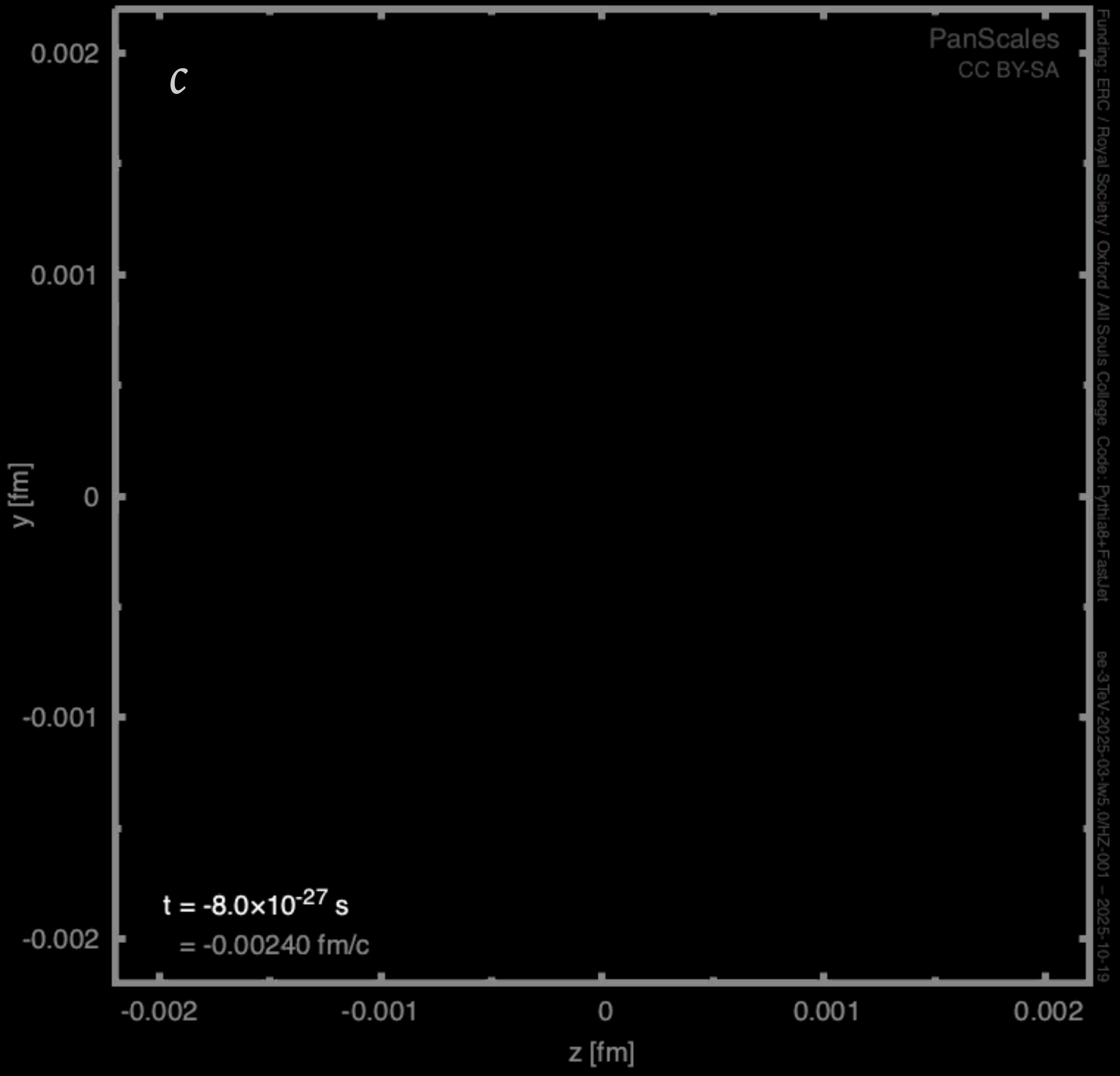
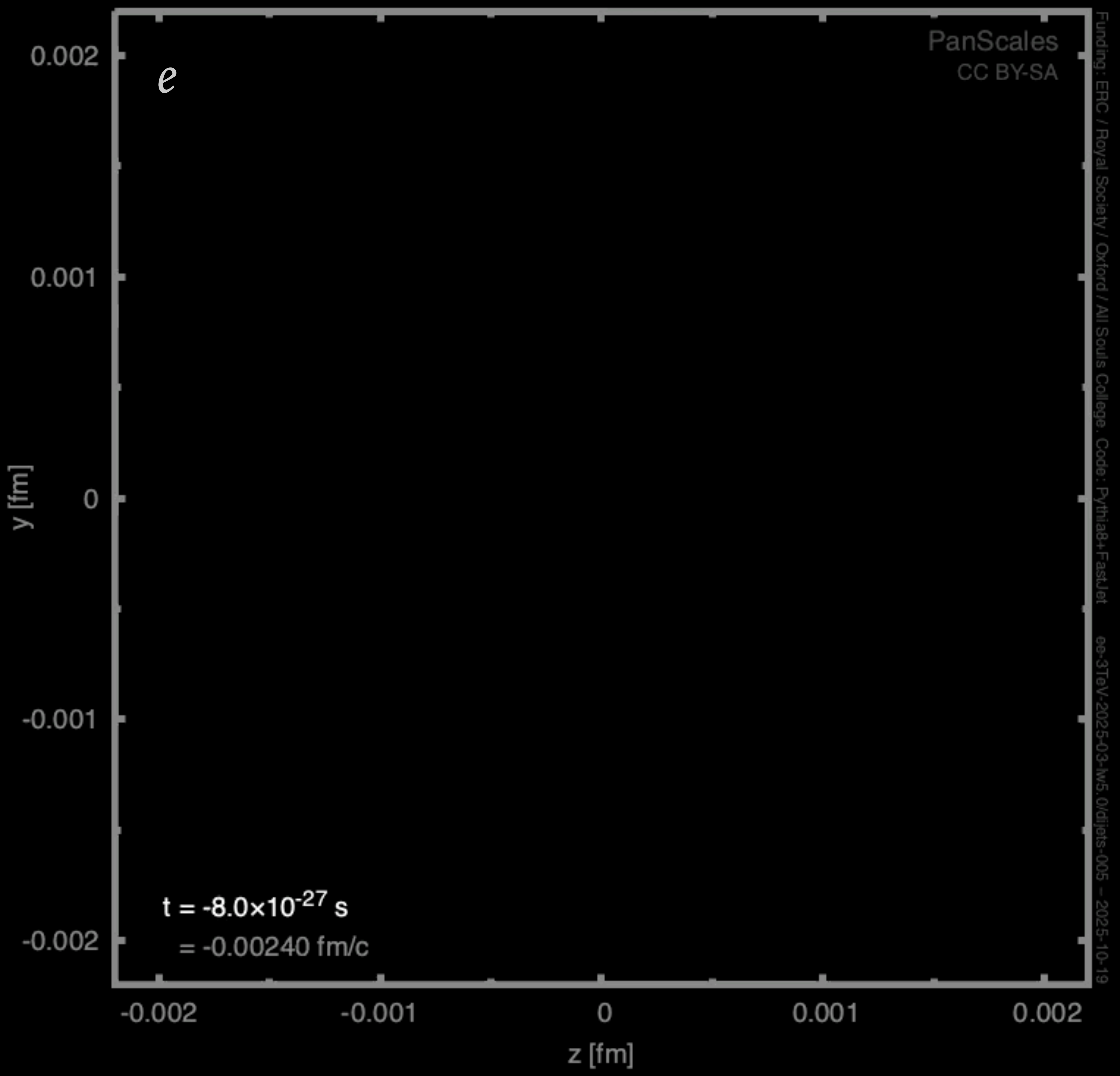
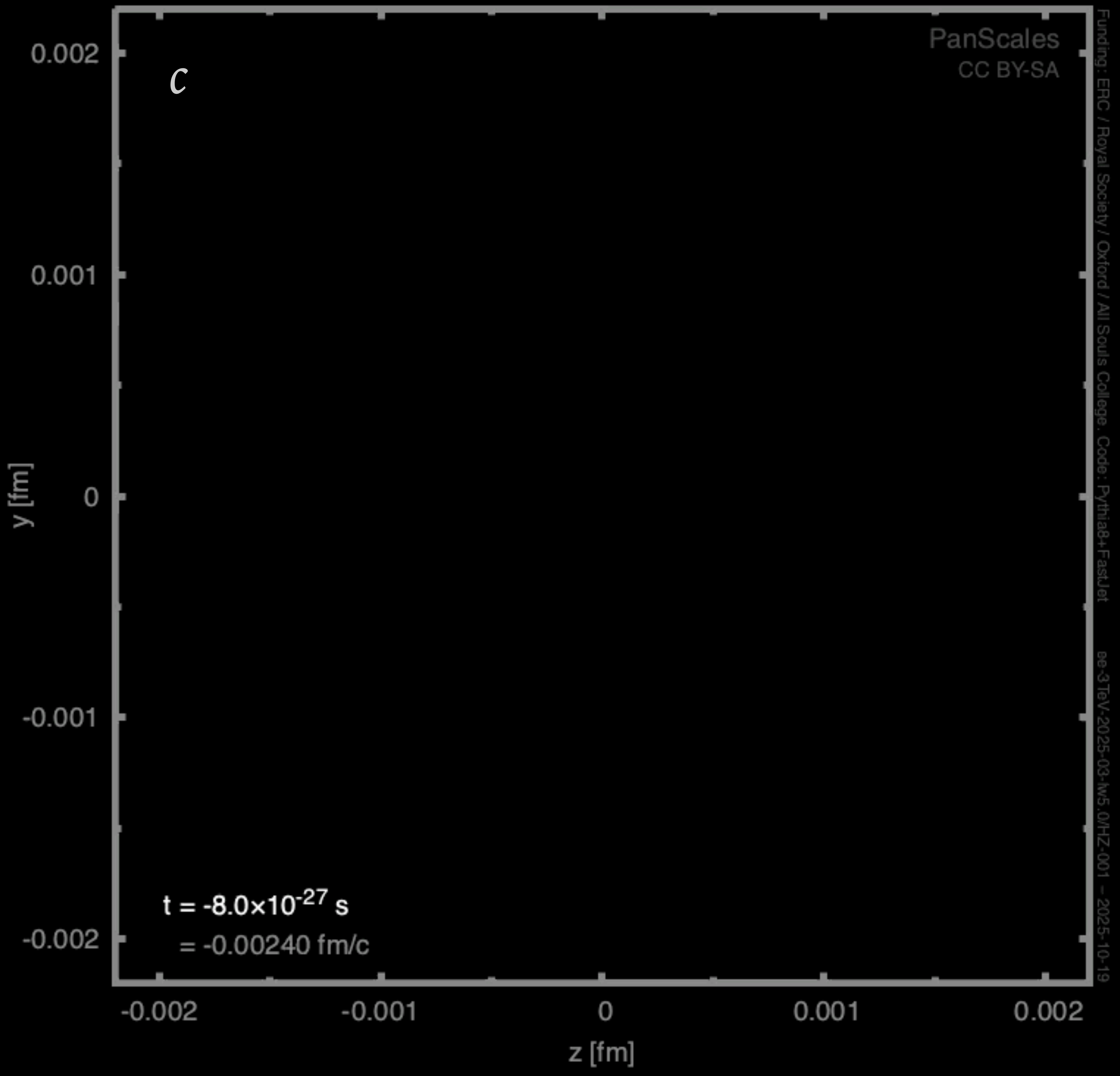


c
PanScales
CC BY-SA
Funding: ERC / Royal Society / Oxford / All Souls College. Code: Pythia8+FastJet
ee-3TeV-2025-03-lw5.0/HZ-001 – 2025-10-19
t = -8.0×10^-27 s
= -0.00240 fm/c
0.002
0.001
0
-0.001
-0.002
y [fm]
-0.002
-0.001
0
0.001
0.002
z [fm]

pure QCD event

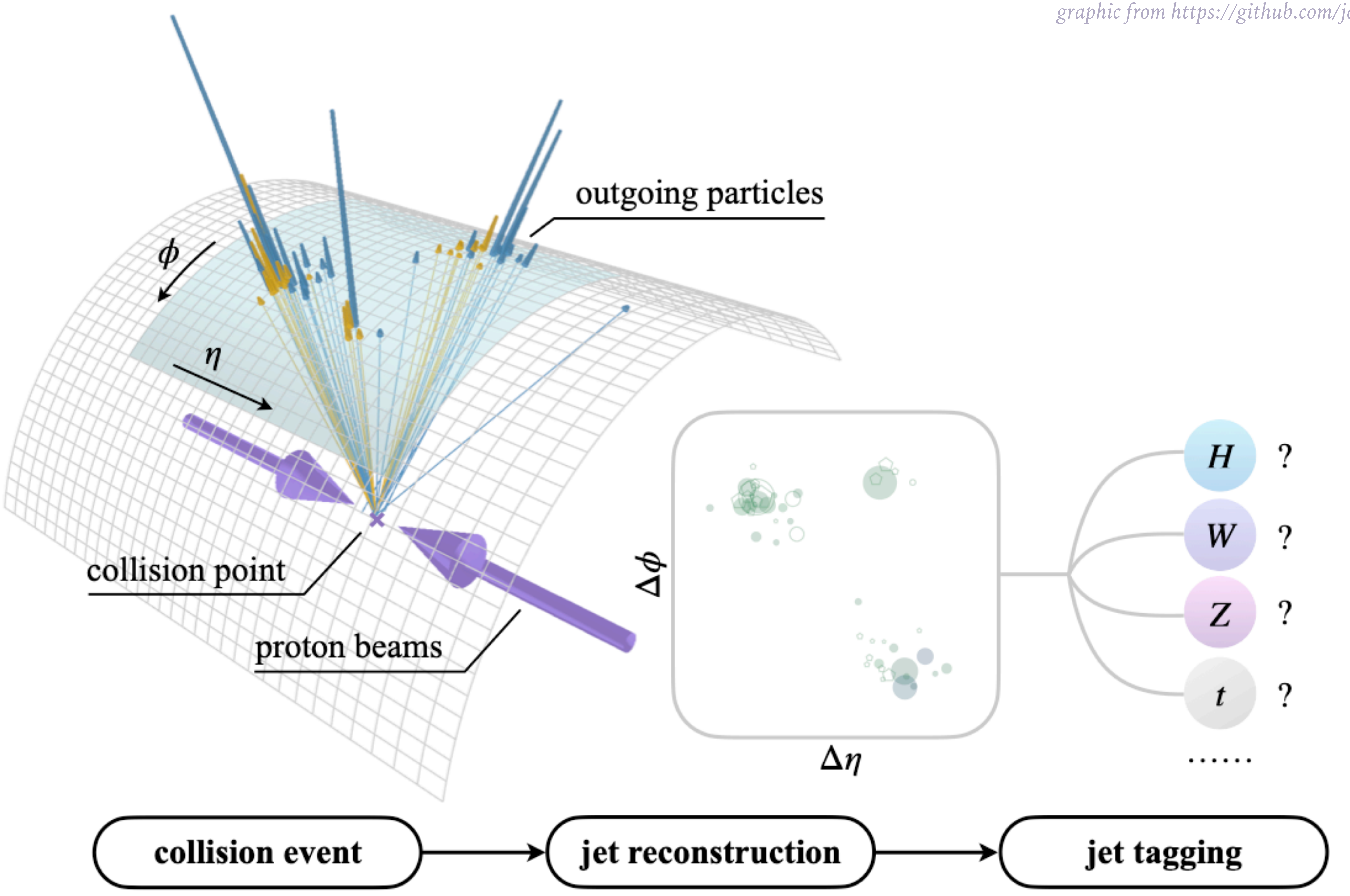


event with Higgs & Z boson decays

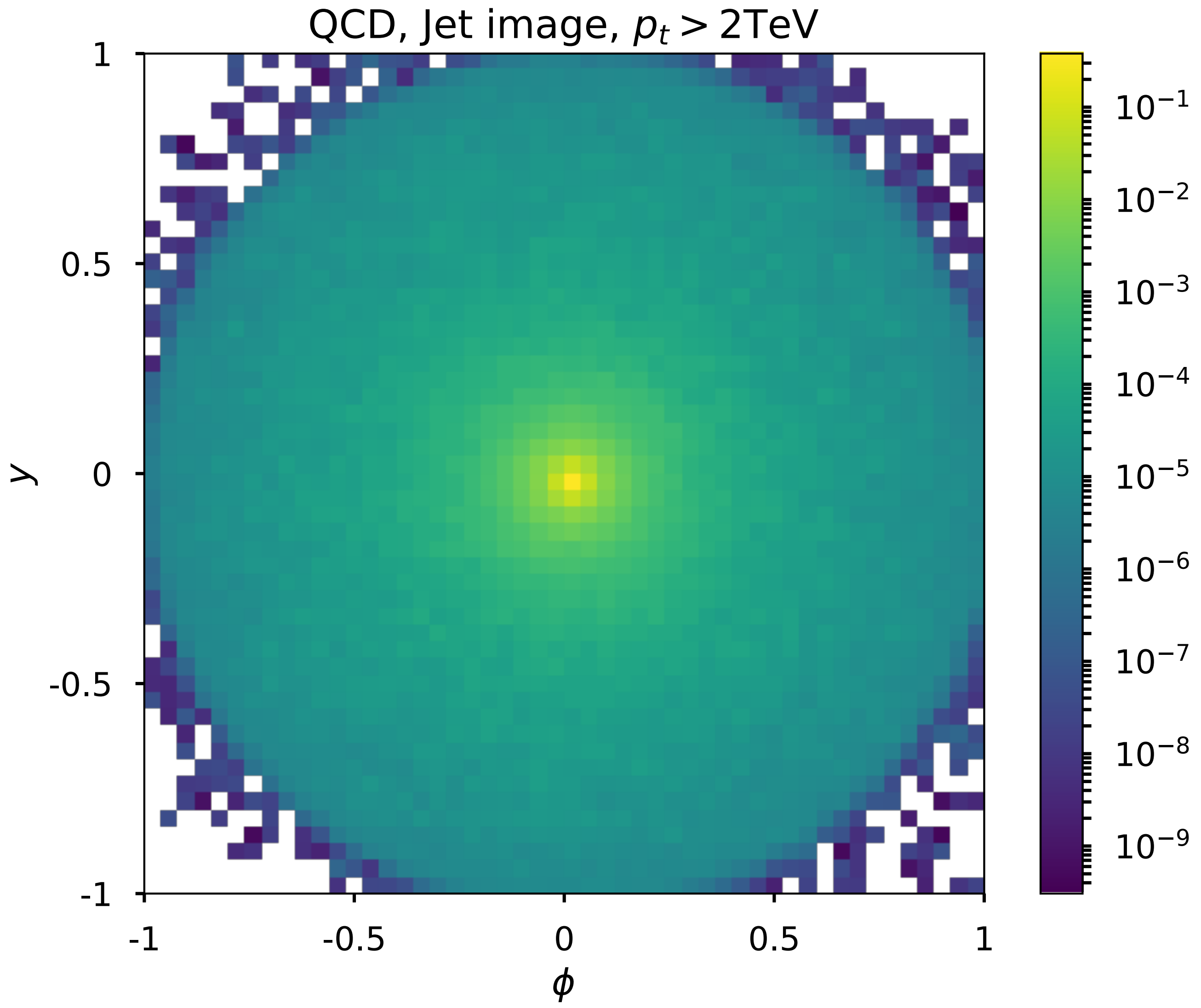


Did the jet of particles come from a quark or a W-boson? → Use machine learning

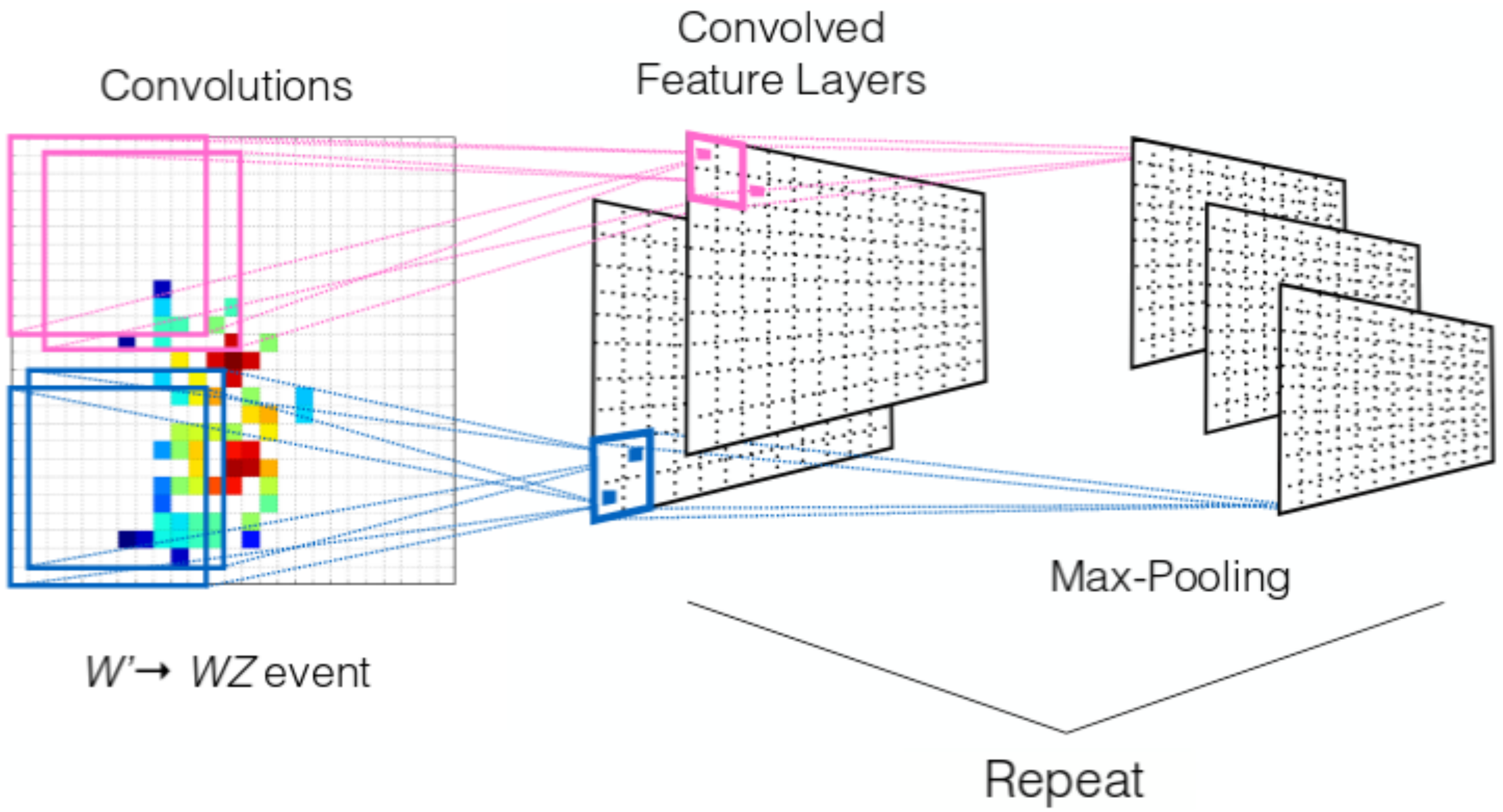
graphic from https://github.com/jet-universe/particle_transformer



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



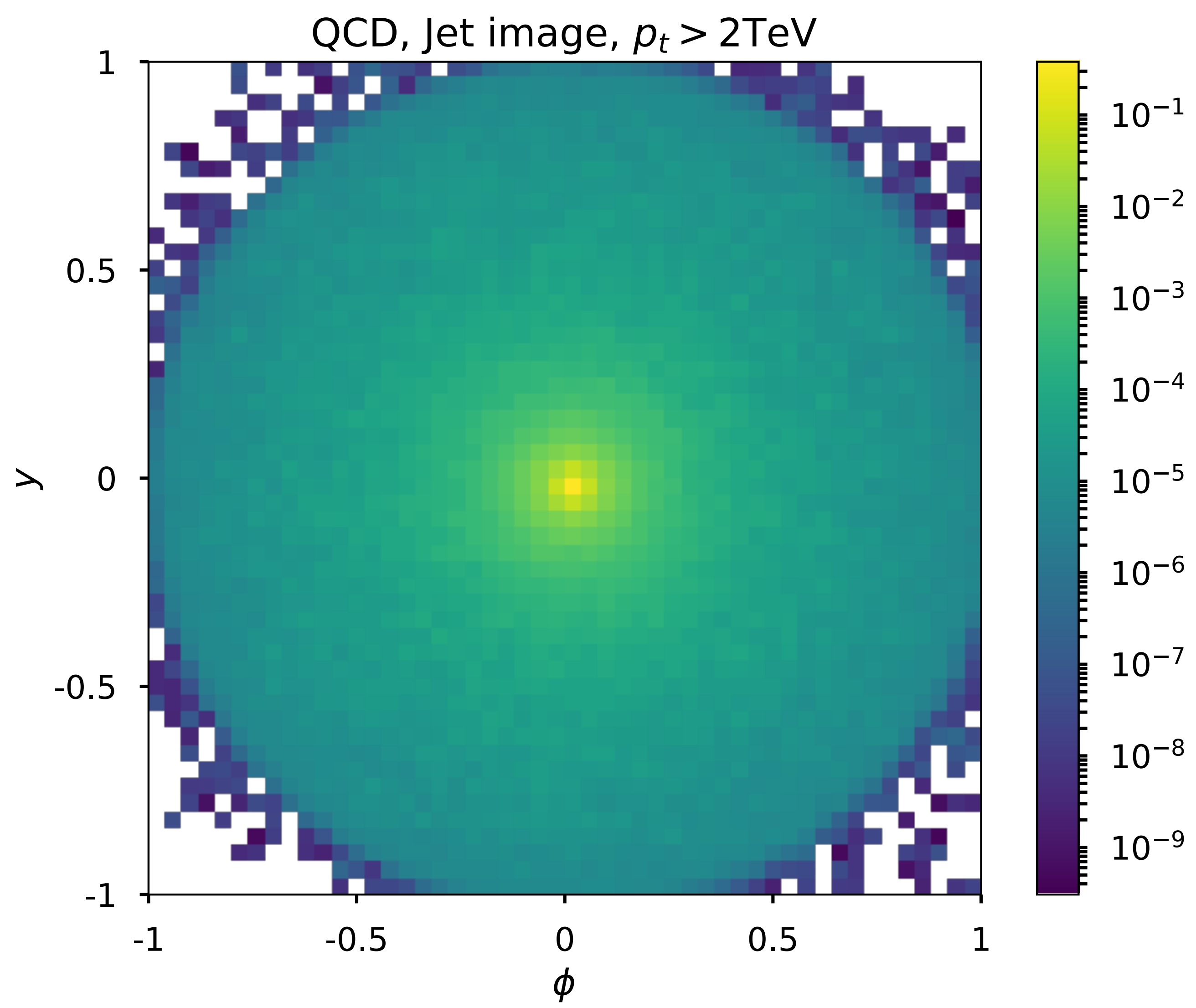
2021 Young Experimental Physicist
EPS HEPP prize



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

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

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



2021 Young Experimental Physicist
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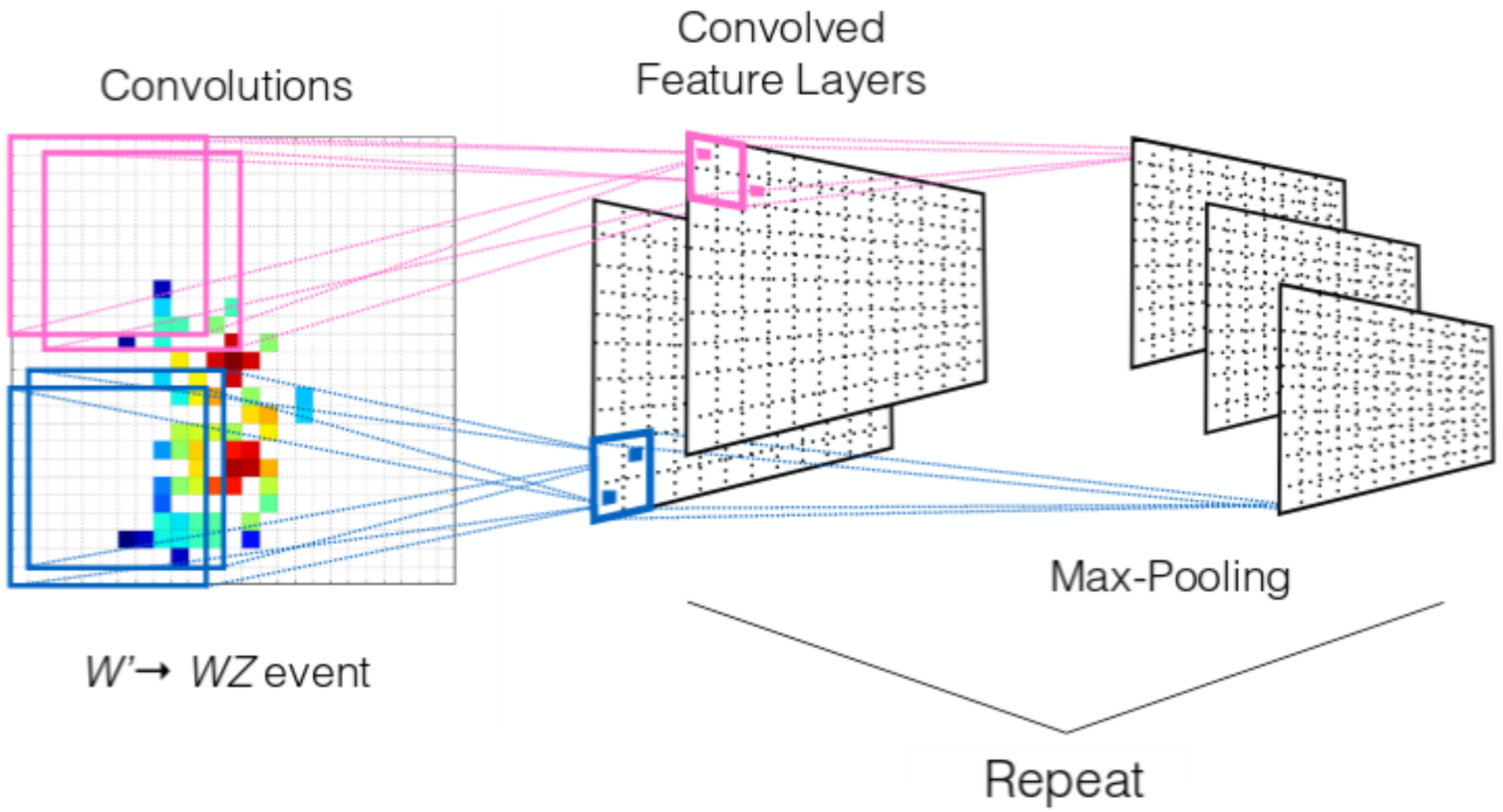

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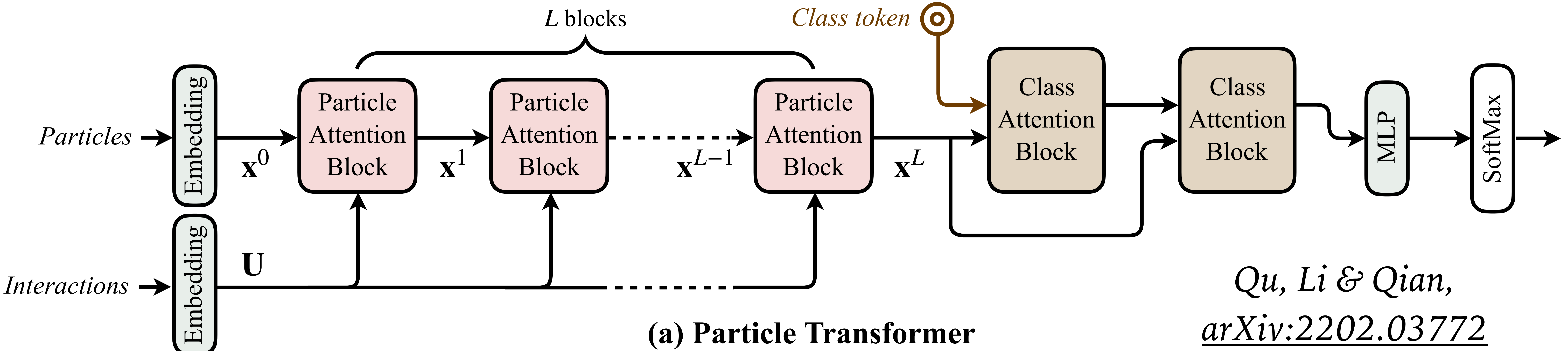


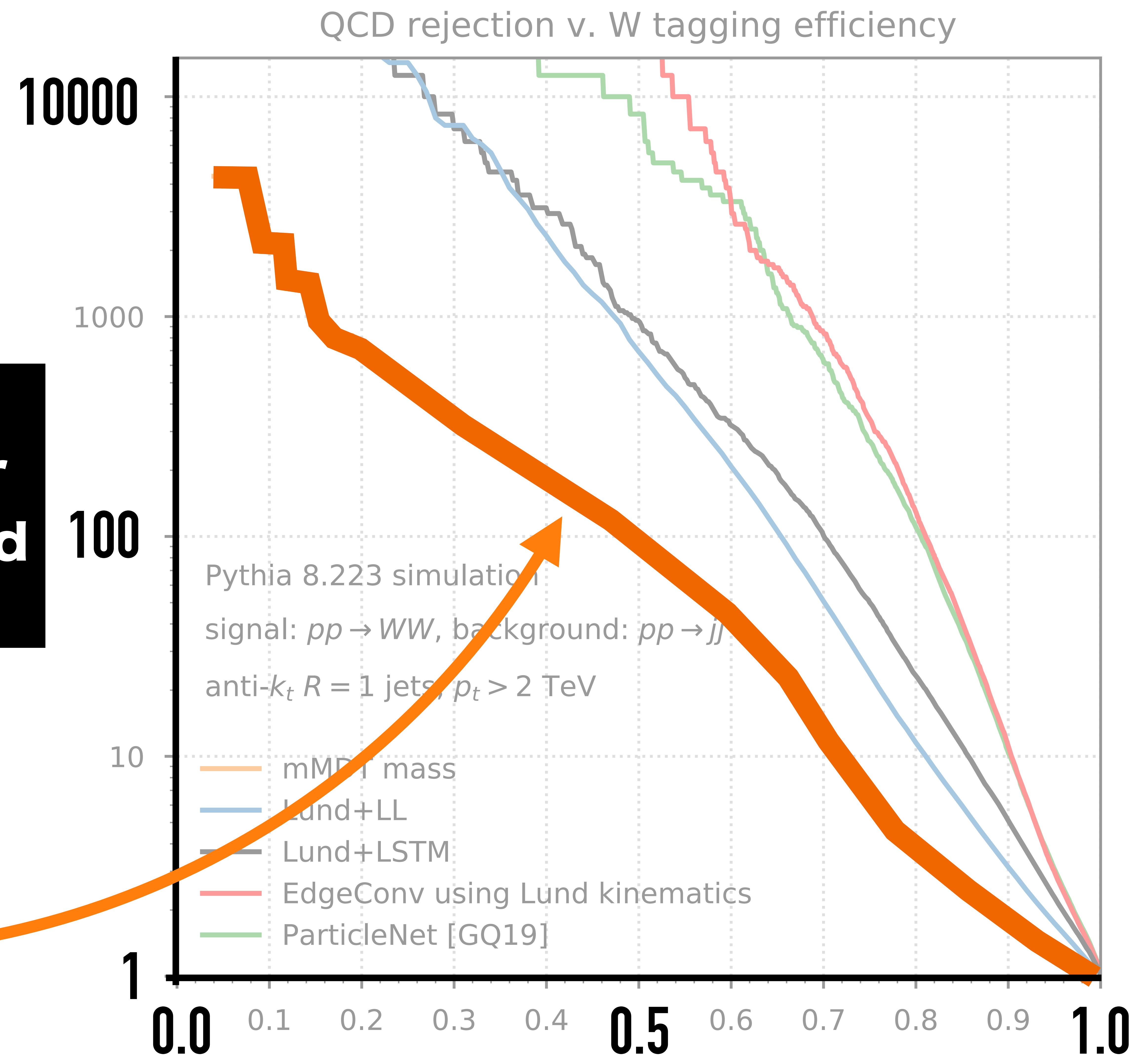
(a) Particle Transformer

Qu, Li & Qian, arXiv:2202.03772

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

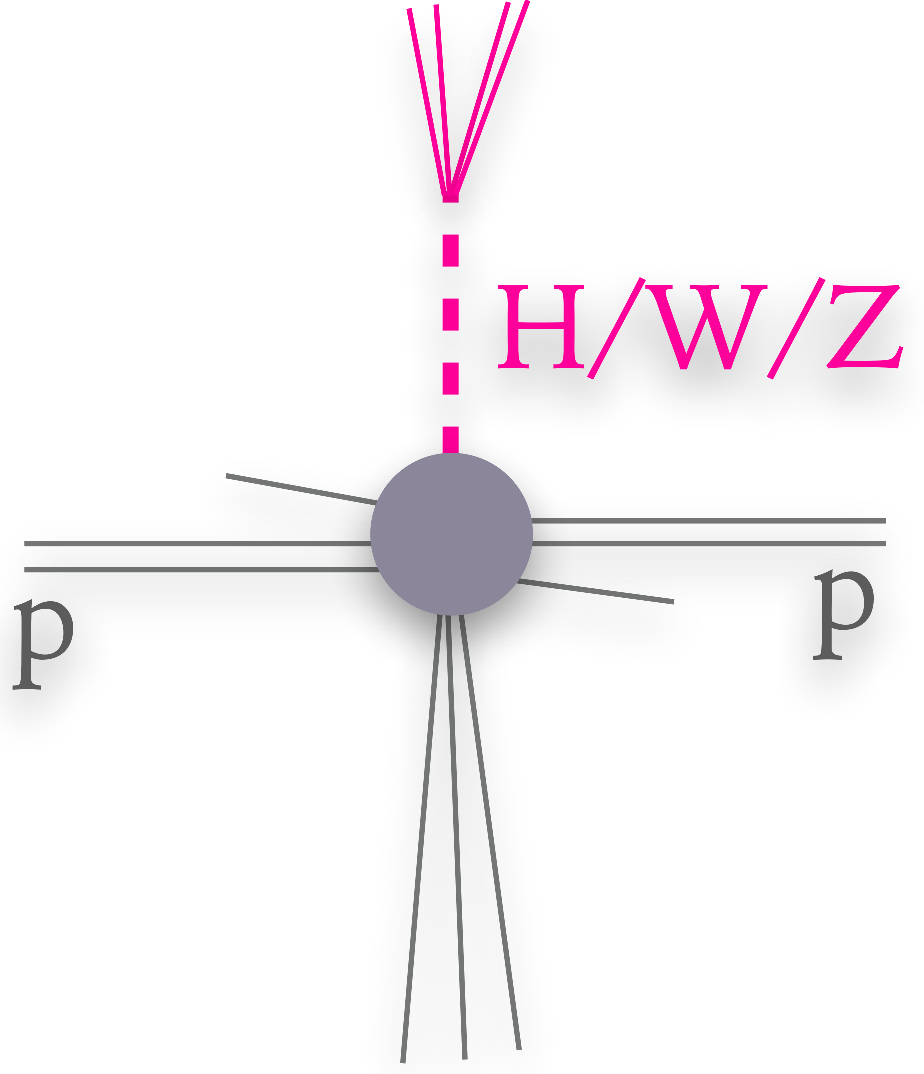
adapted from Dreyer & Qu [2012.08526](2012.08526)

rejection factor for quarks and gluons



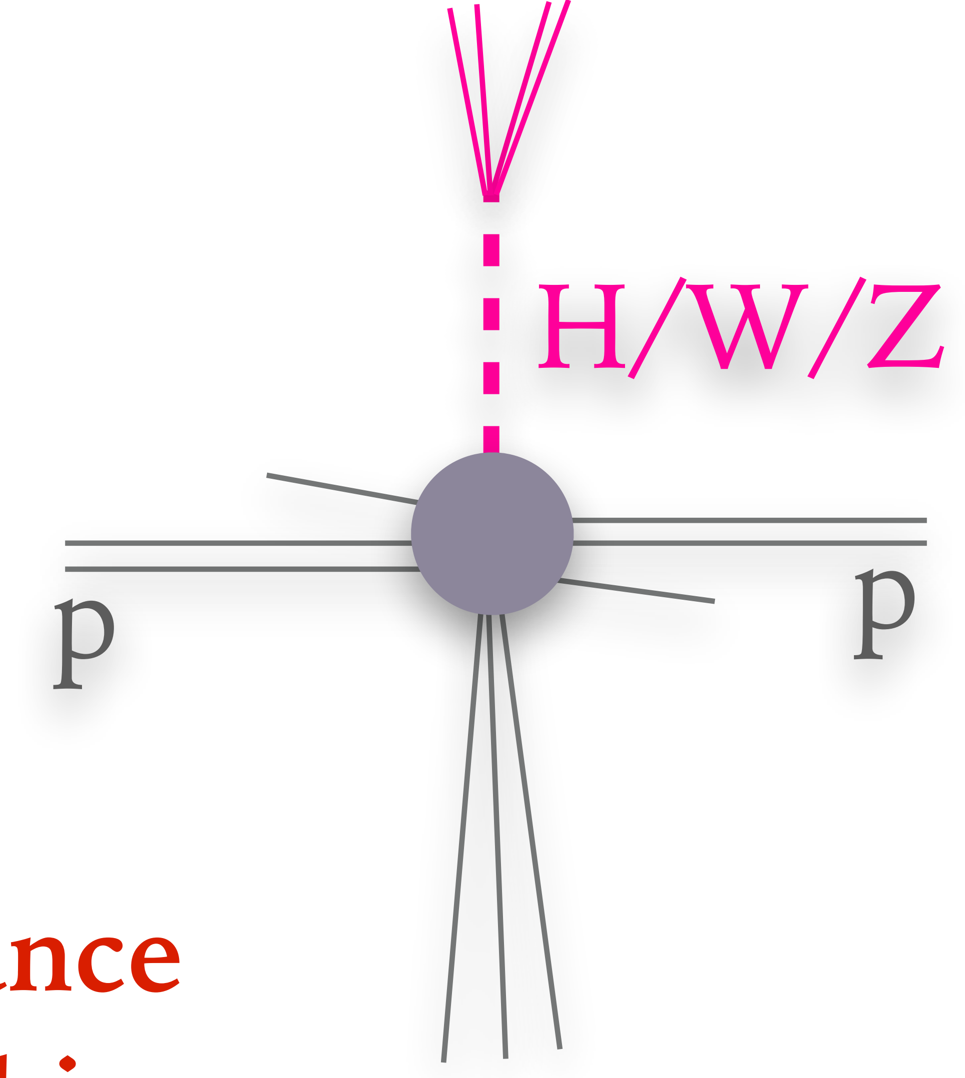
Fraction of W's correctly ID'd

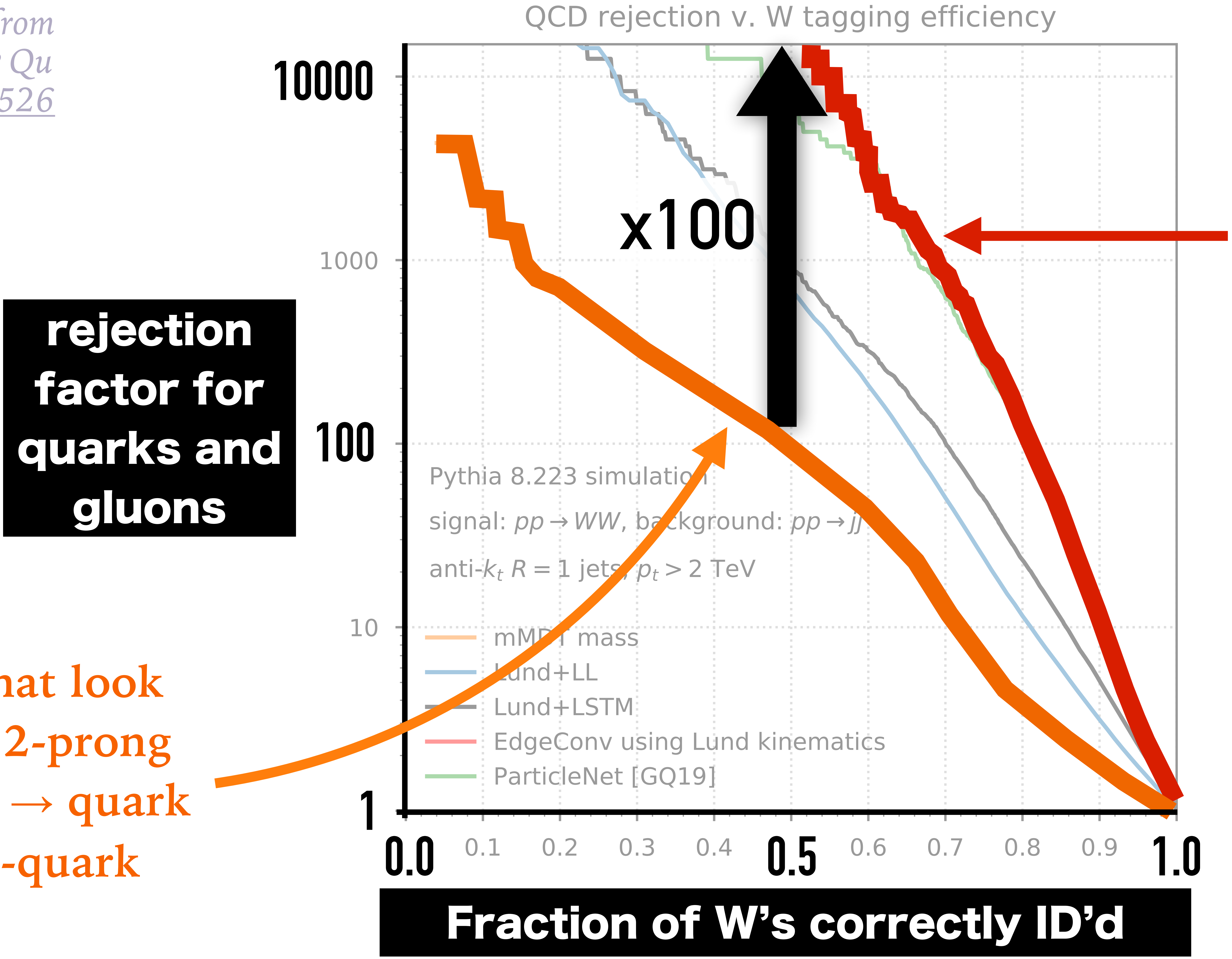
Tools that look just for 2-prong decay W → quark + anti-quark



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

adapted from Dreyer & Qu 2012.08526



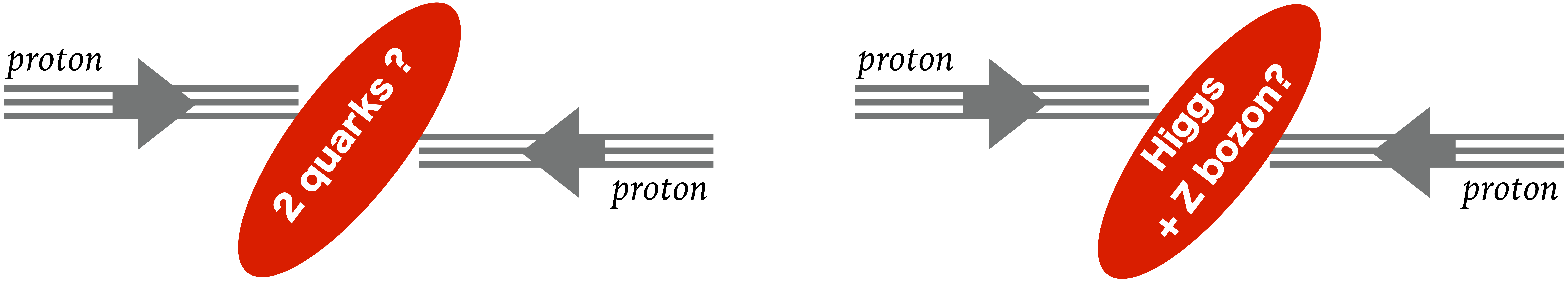


Tools that look just for 2-prong decay W → quark + anti-quark

Performance with machine learning, using all jet particles (2021 tools)

100x better

The essence of interpreting collider data (2)



Collider physics is **quantitative**.

To test a hypothesis (e.g. Standard Model), you ask:

How many Higgs bosons will be produced?

How many of those will be correctly identified?

→ compare that expectation to data

The paradigm: Feynman diagrams and perturbation theory

Nobel Prize in Physics 1965

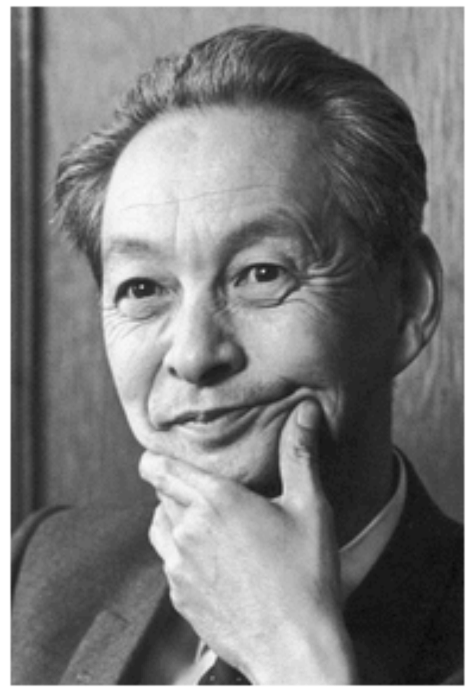


Photo from the Nobel Foundation archive.
Sin-Itiro Tomonaga
Prize share: 1/3

Photo from the Nobel Foundation archive.
Julian Schwinger
Prize share: 1/3

Photo from the Nobel Foundation archive.
Richard P. Feynman
Prize share: 1/3

The Nobel Prize in Physics 1965 was awarded jointly to Sin-Itiro Tomonaga, Julian Schwinger and Richard P. Feynman "for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles"

Nobel Prize in Physics 1999

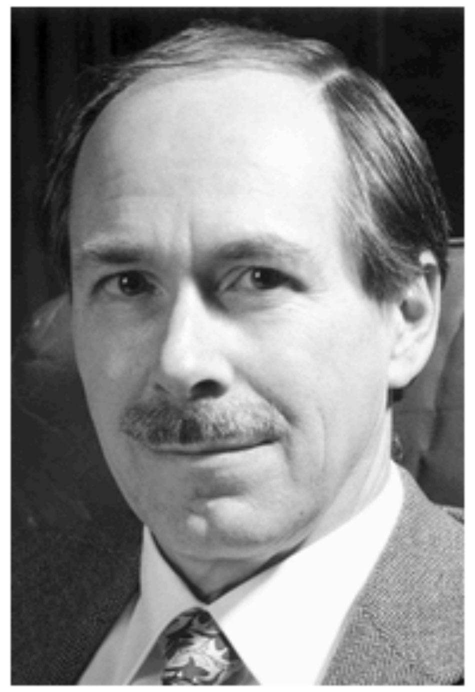


Photo from the Nobel Foundation archive.
Gerardus 't Hooft
Prize share: 1/2

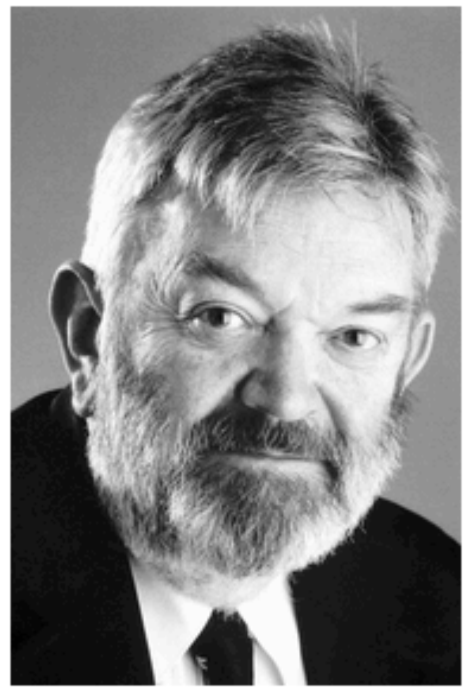


Photo from the Nobel Foundation archive.
Martinus J.G. Veltman
Prize share: 1/2

The Nobel Prize in Physics 1999 was awarded jointly to Gerardus 't Hooft and Martinus J.G. Veltman "for elucidating the quantum structure of electroweak interactions in physics"

Nobel Prize in Physics 2004

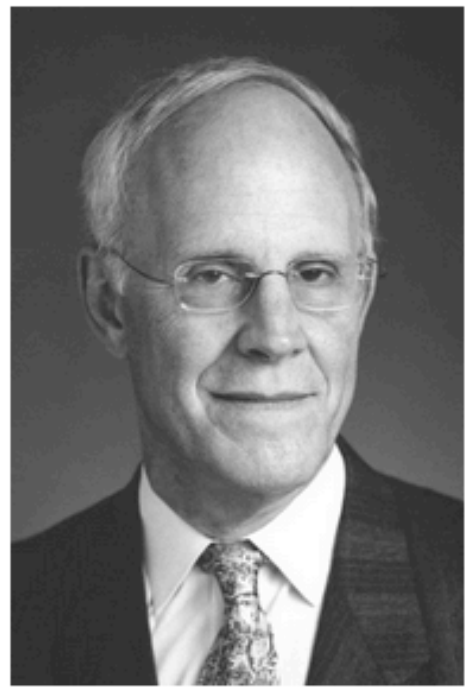


Photo from the Nobel Foundation archive.
David J. Gross
Prize share: 1/3

Photo from the Nobel Foundation archive.
H. David Politzer
Prize share: 1/3

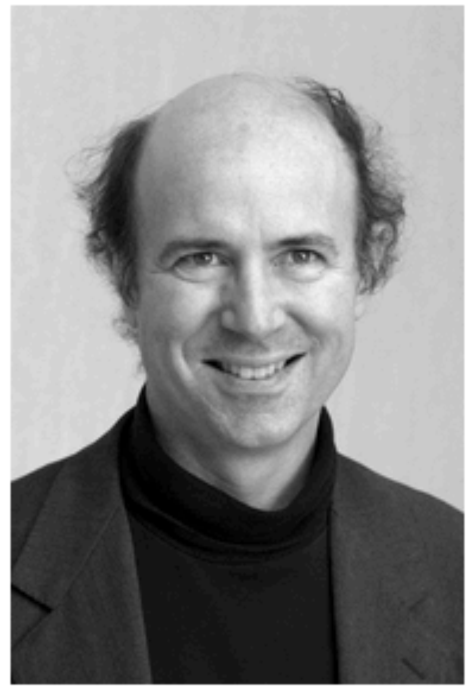
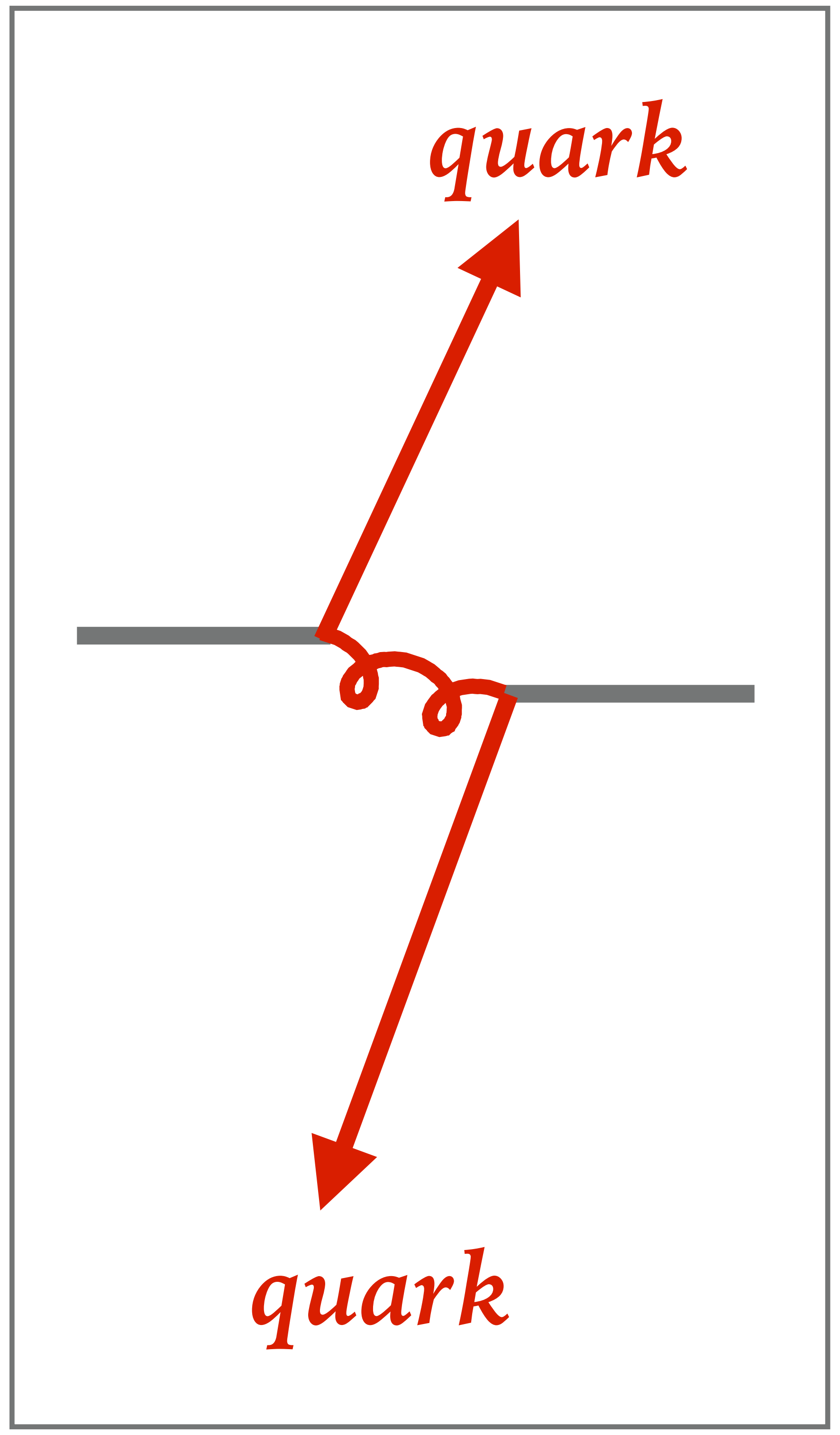


Photo from the Nobel Foundation archive.
Frank Wilczek
Prize share: 1/3

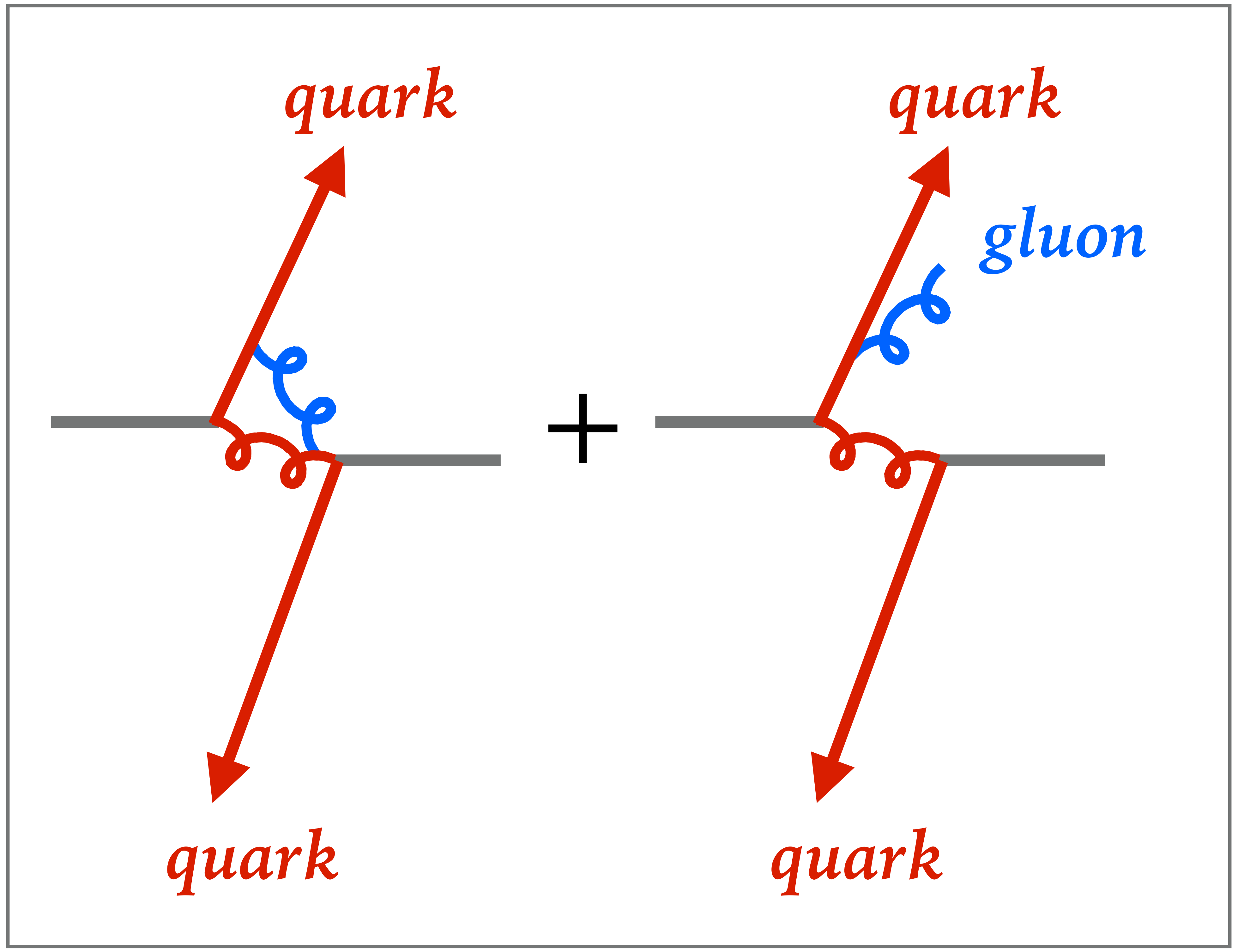
The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek "for the discovery of asymptotic freedom in the theory of the strong interaction"

The standard paradigm: Feynman diagrams and perturbation theory



leading order

+

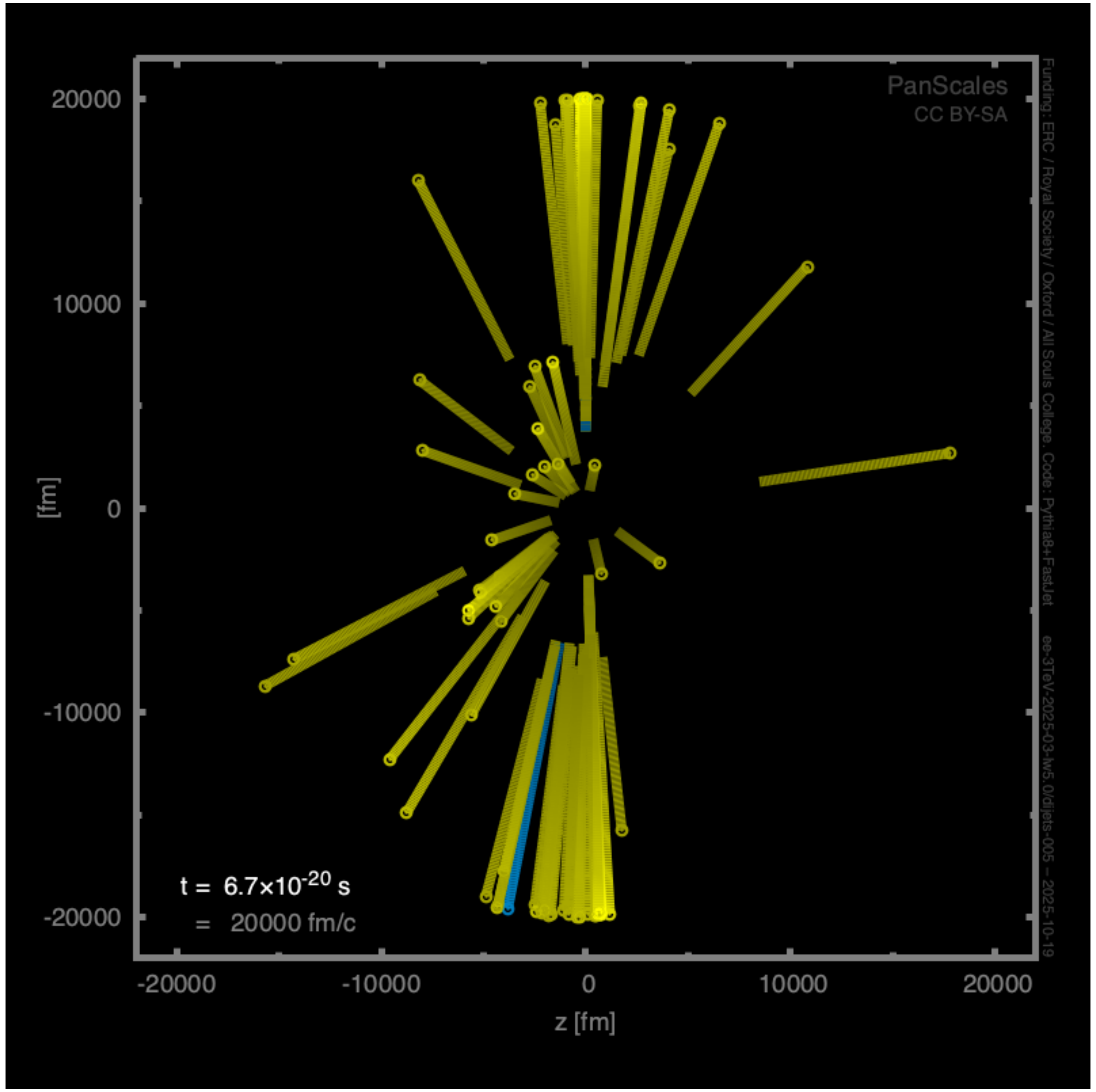


next-to-leading order

+ •••

[the subject of Fabrizio's talk ~ maximum 1 or 2 more orders]

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



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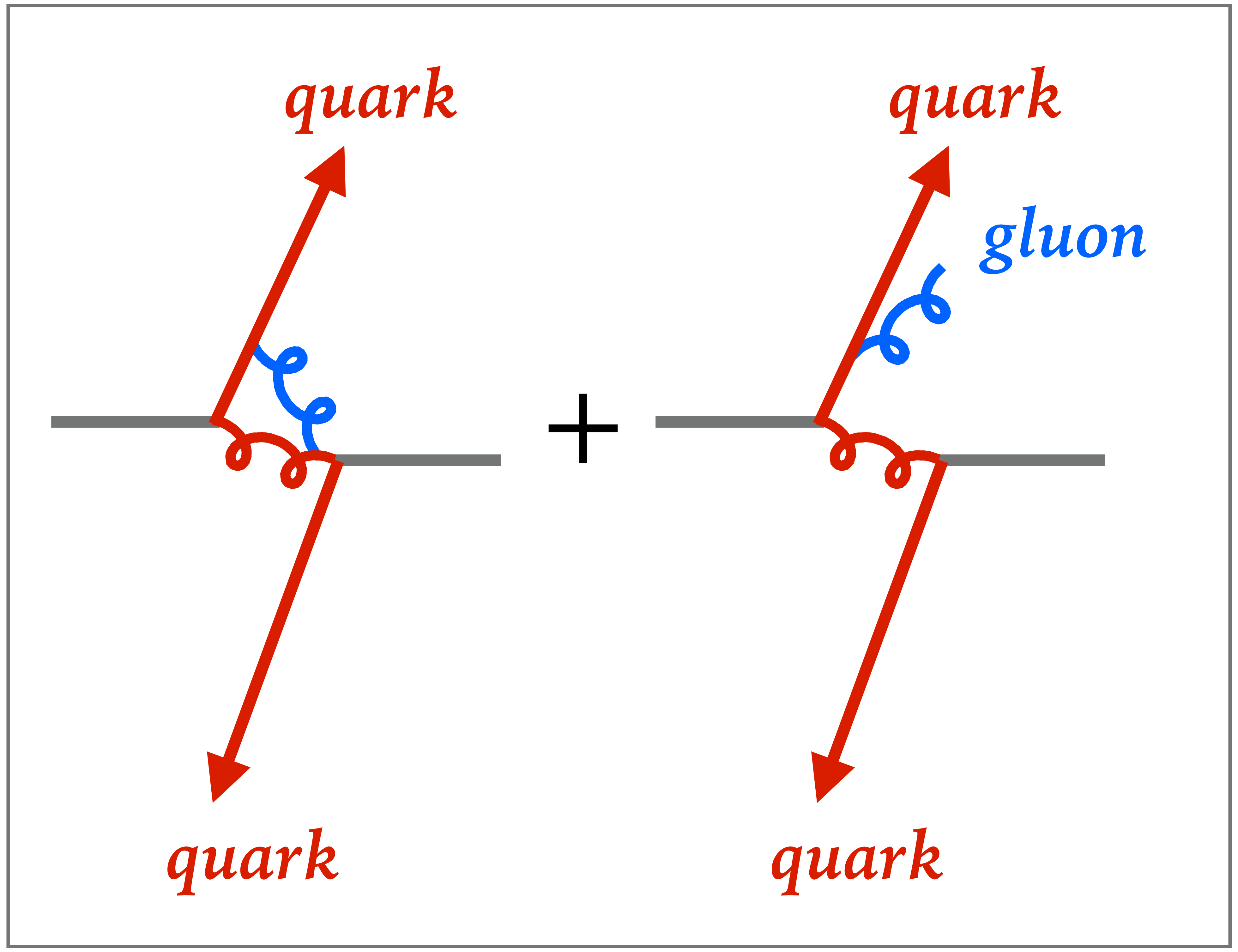


next-to-leading order

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 893.22103**, multiplying (alphas/2pi)
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** **893.22103**, multiplying (alphas/2pi)
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** **-84.49299**, 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

NLO (2-particle) virtual subtraction event
with **weight** **-808.58646**, multiplying (alphas/2pi)
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 2.66667, 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 ($q\bar{q}$)

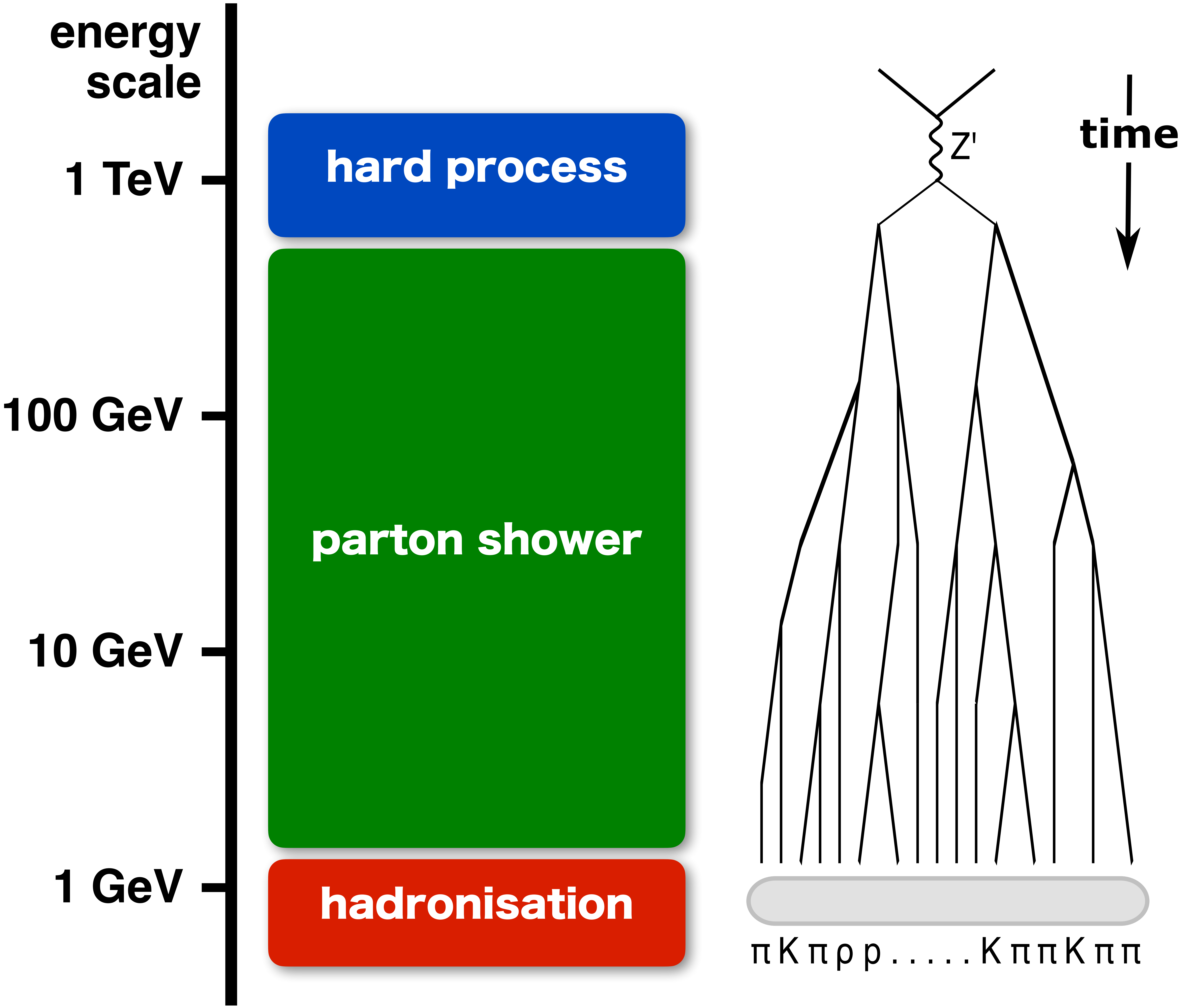
NLO event, with real emission
~ LO event + extra soft gluon
and **large positive weight**

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 evade these problems in perturbation theory if you ask very limited kinds of questions, i.e. nearly always summing real & virtual divergences (infrared safe observable, single momentum scale)*
- but experiments don't limit themselves to those kinds of questions

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

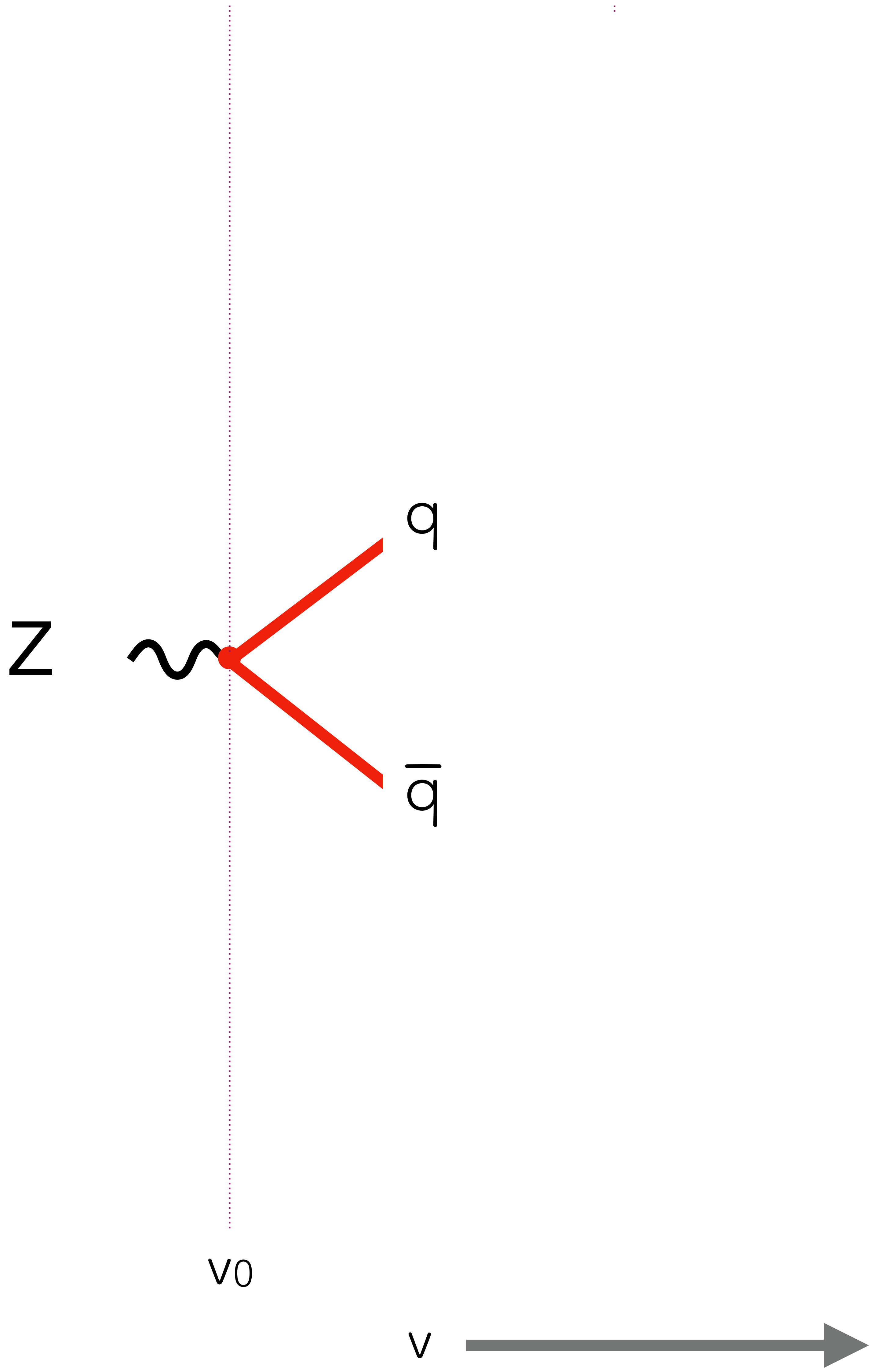


$\alpha_s \sim 0.1$

$\alpha_s \sim 0.1 - 0.25$

$\alpha_s \gtrsim 0.4$
[non-perturbative models]

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

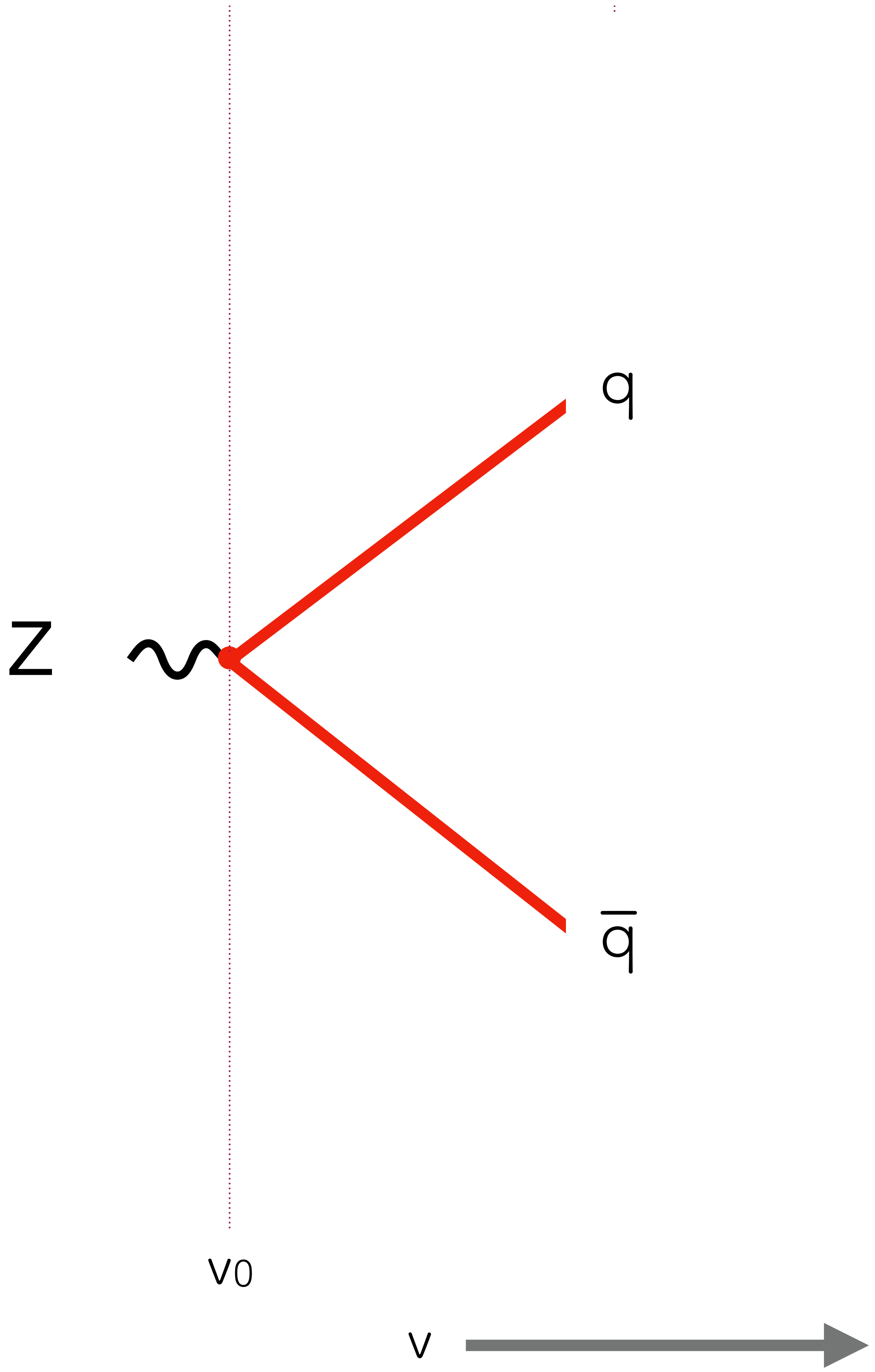


Start with quark (q) antiquark ($\bar{q}$) state.

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

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

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

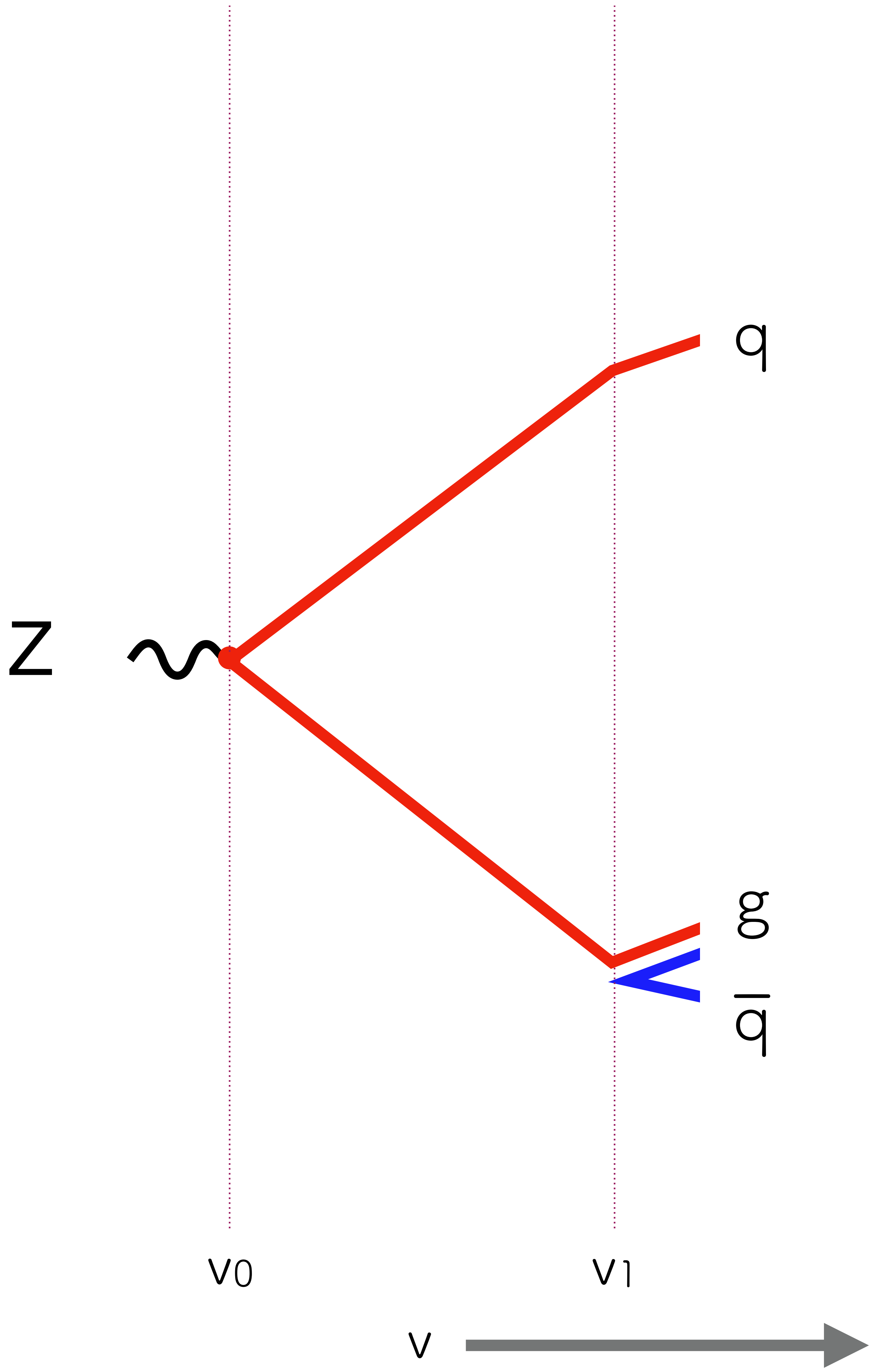


Start with quark (q) antiquark ($\bar{q}$) state.

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.

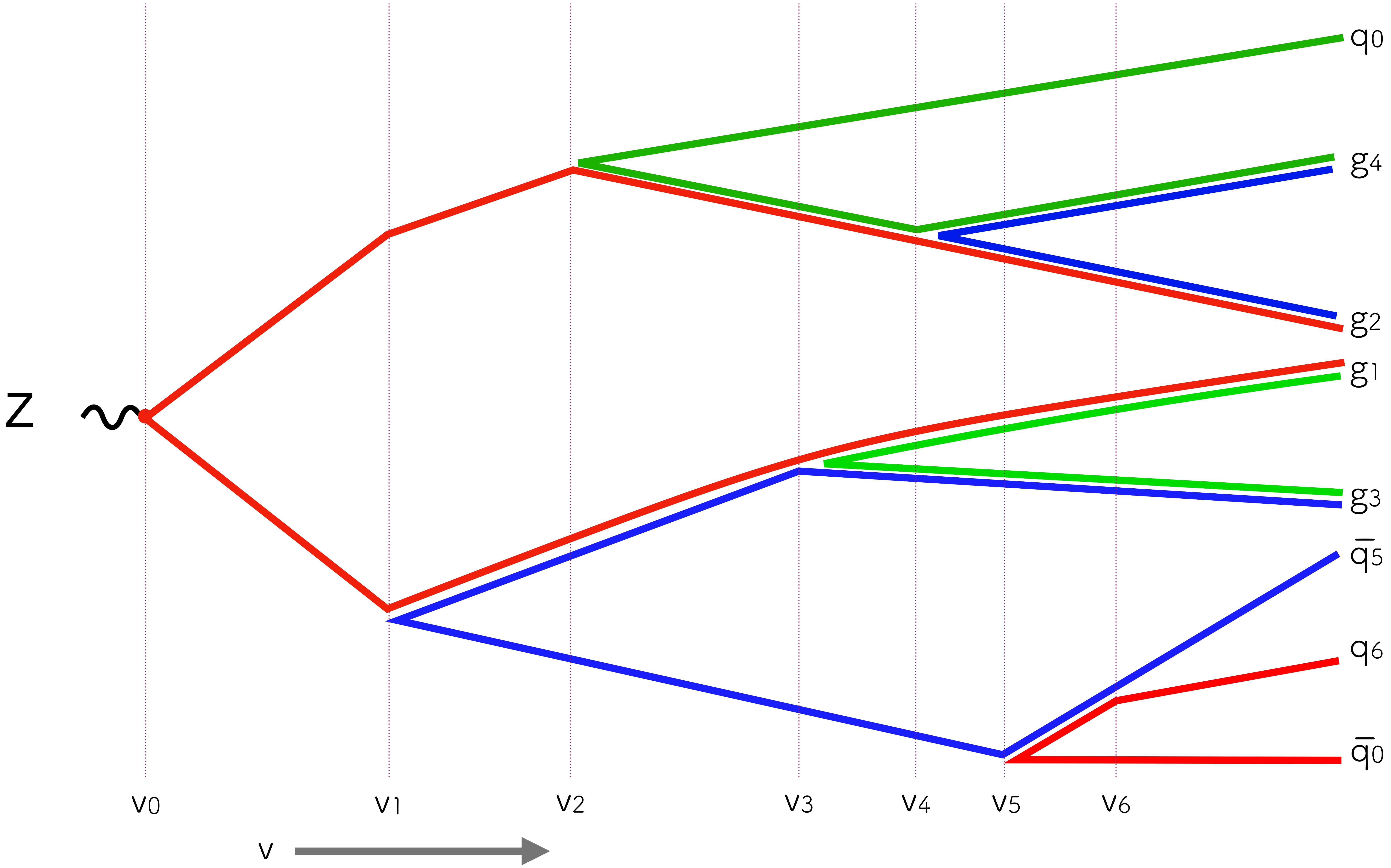
Throw a random number to determine down to what scale state persists unchanged

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 parallel lines

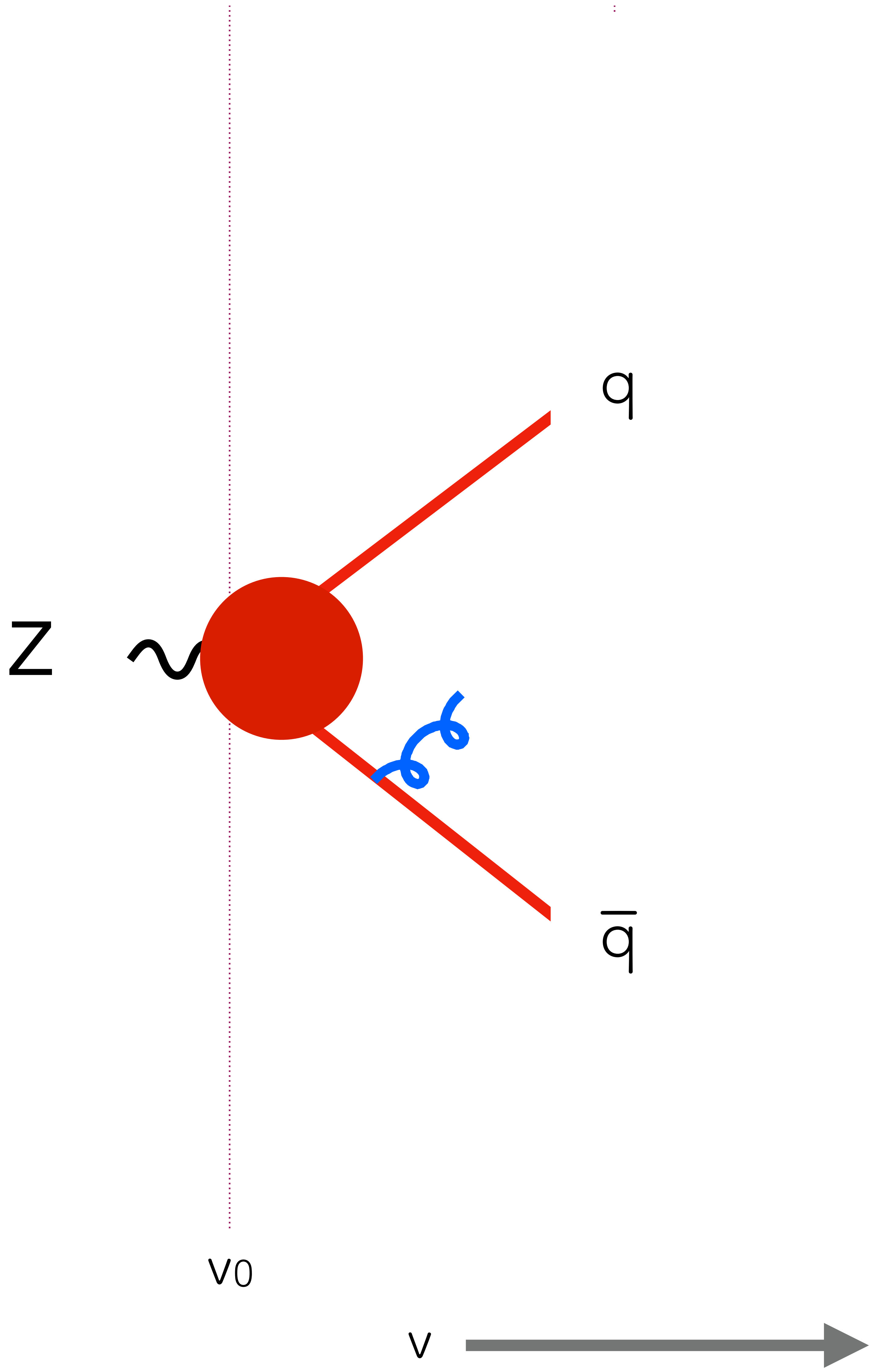
QCD parton shower: an evolution equation (in evolution scale v, e.g. trans.mom.)



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

illustration by K. Hamilton Oxford DPhil '00-'04

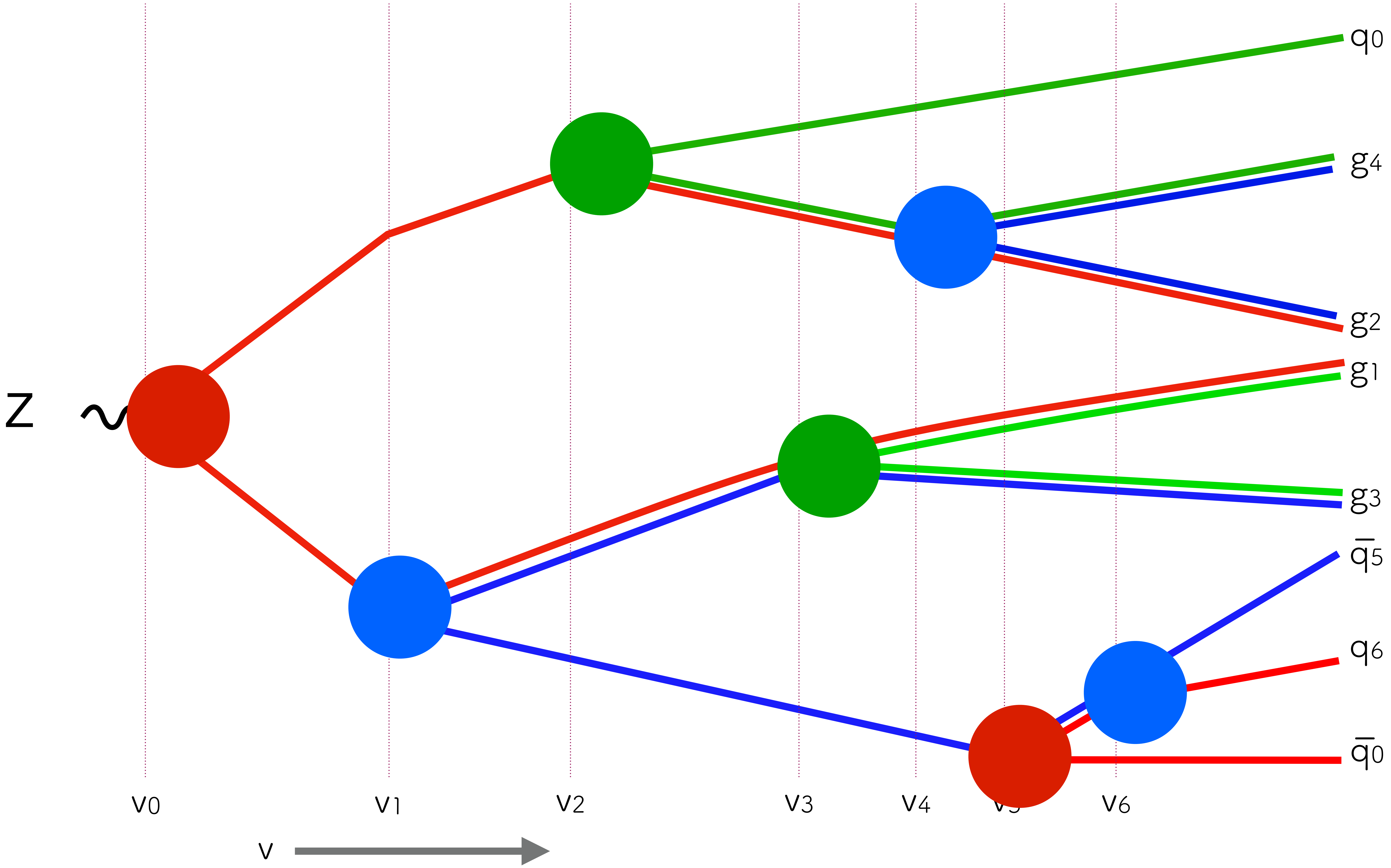
Standard perturbation theory



Improve the red vertex with extra emission(s)

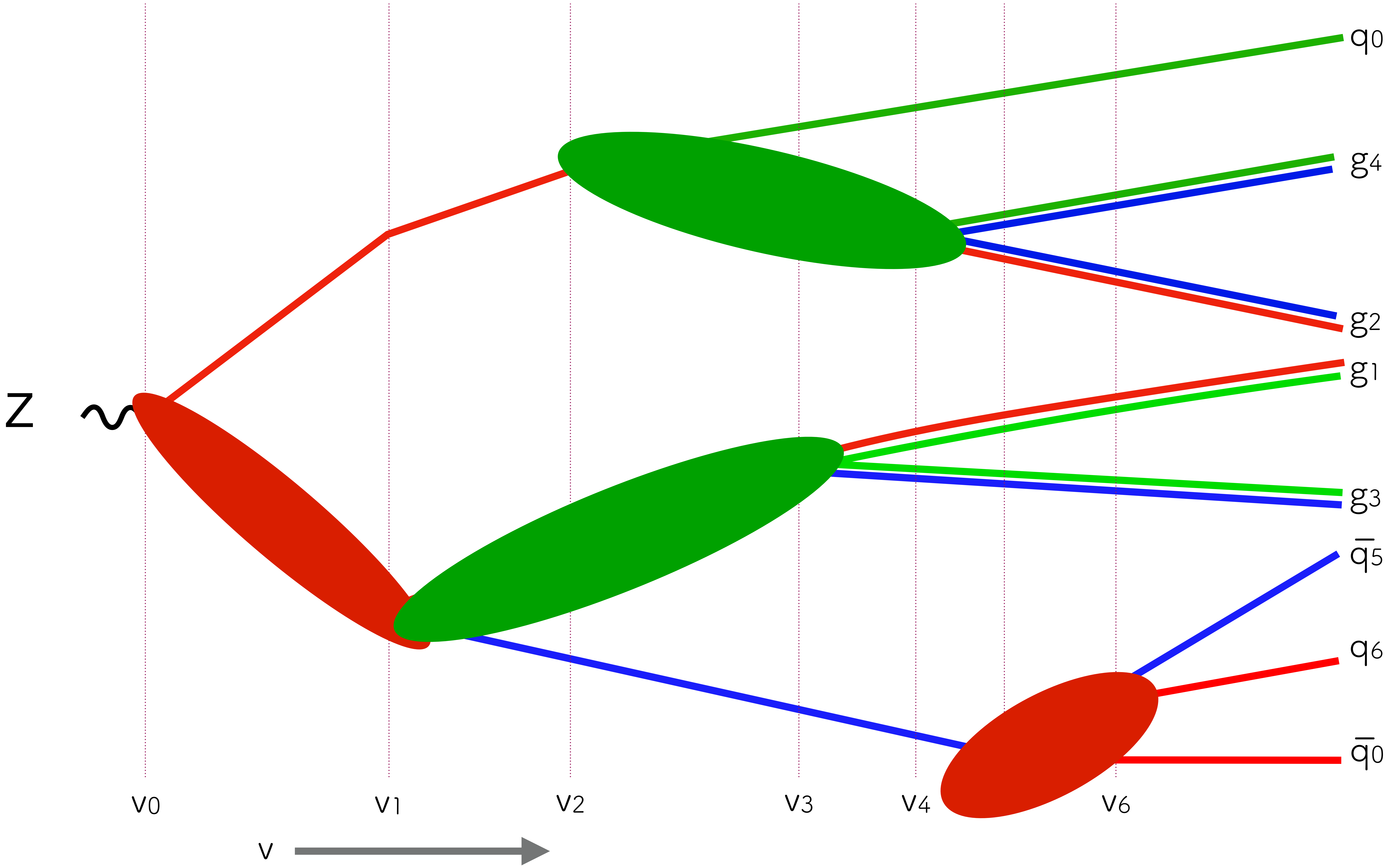
extra virtual (off-shell) particles

A new concept is opening up



improve every vertex

A new concept is opening up

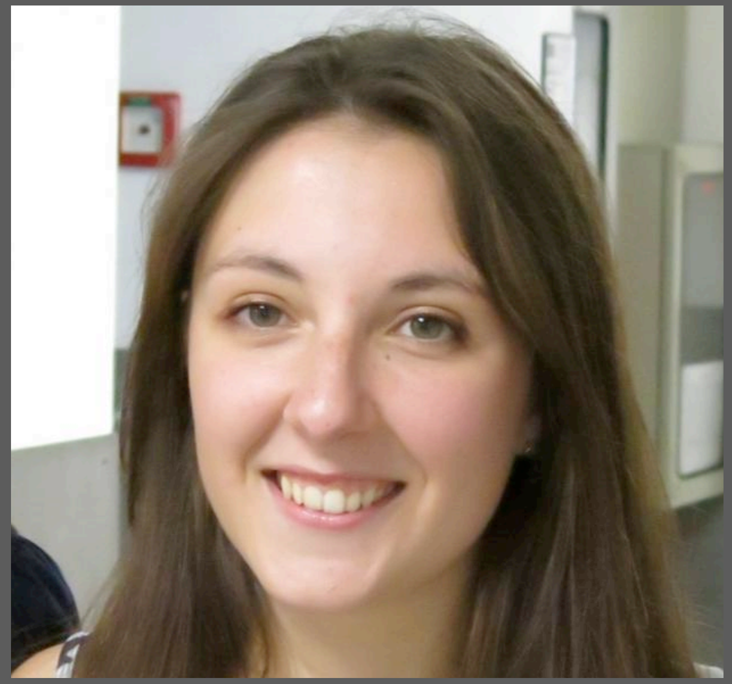


consistently treat every pair of particles, every triplet, etc.


Melissa van Beekveld
NIKEHF


Mrinal Dasgupta
Manchester


Basem El-Menoufi
Turin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Jack Helliwell
Monash


Alexander Karlberg
Oxford


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

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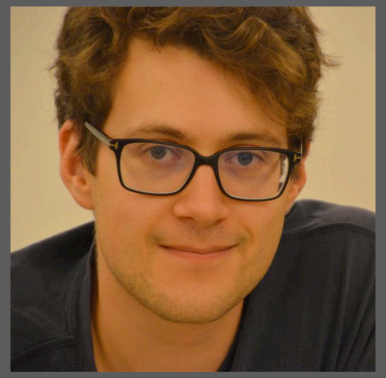
2018–2024

former members

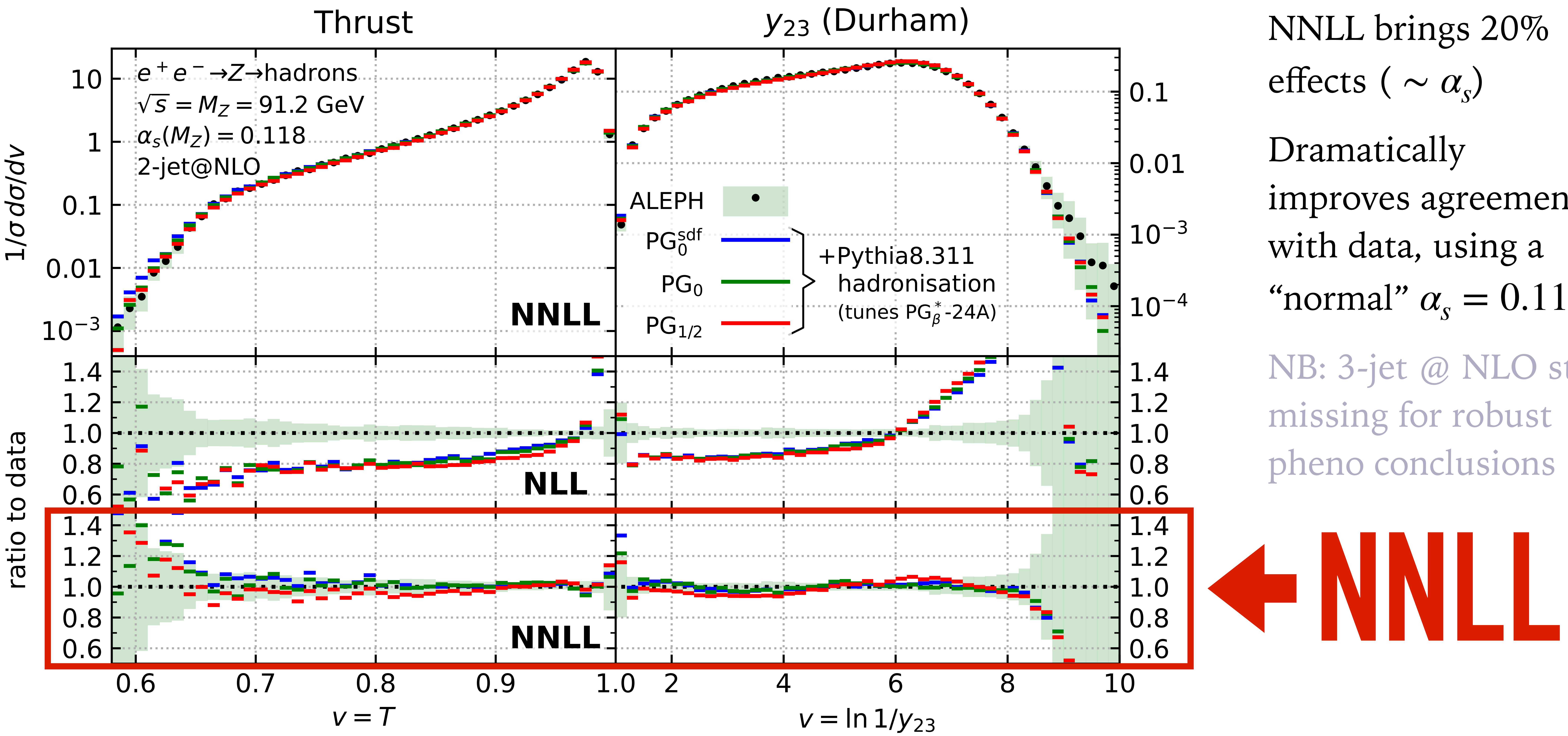

Frédéric Dreyer


Rob Verheyen


Rok Medves


Emma Slade

Comparing to LEP event-shape data



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

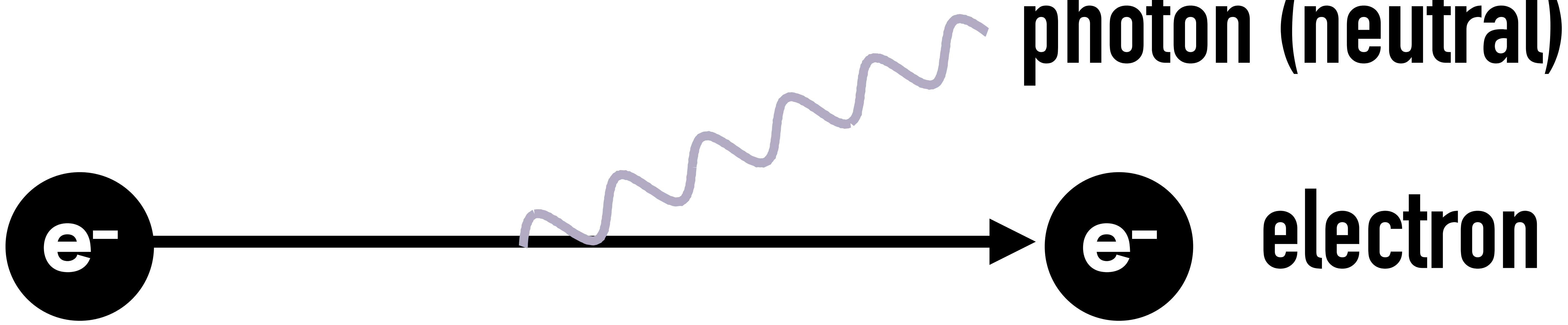
Dramatically improves agreement with data, using a "normal" $\alpha_s = 0.118$

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

one of the quantum aspects:
colour

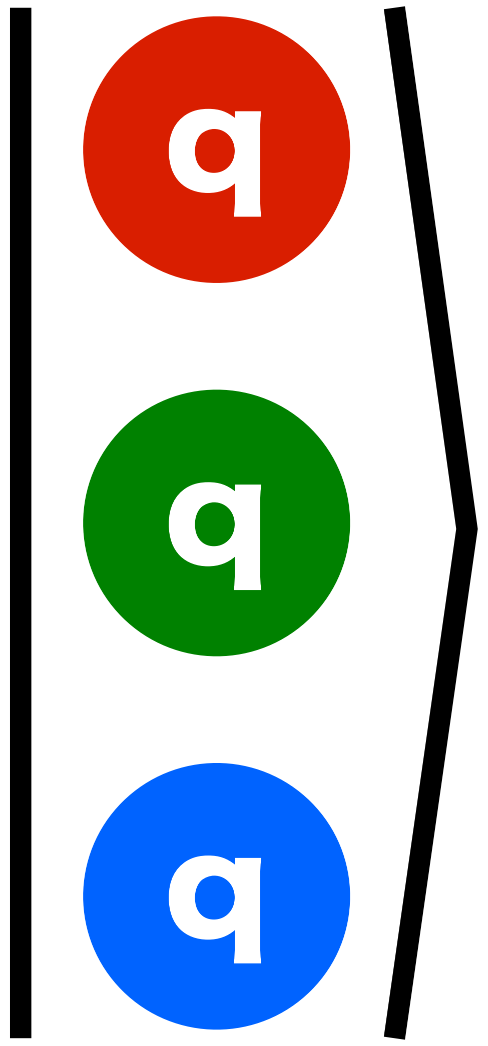
Predictions involve the quantum strong force — a.k.a. Quantum Chromodynamics (QCD)

QED:
electric charge



Predictions involve the quantum strong force – a.k.a. Quantum Chromodynamics (QCD)

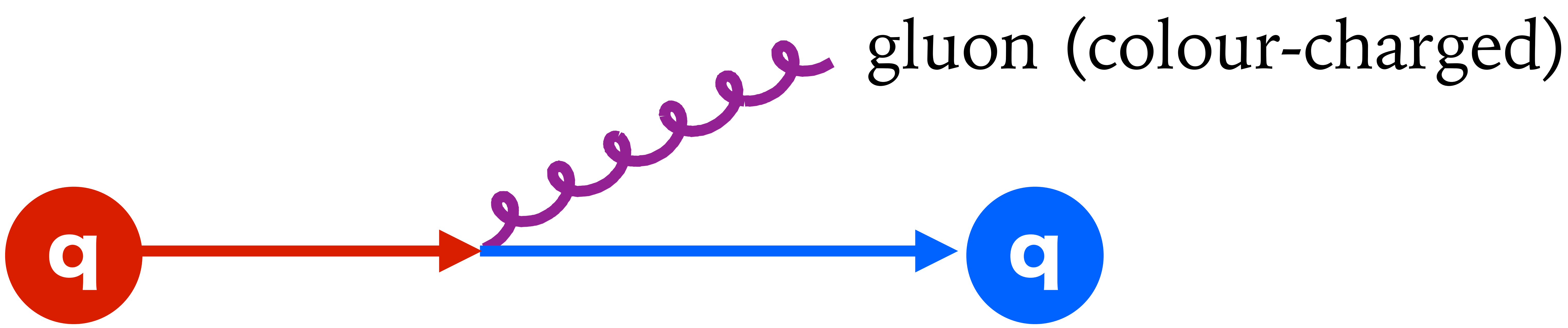
QCD: 3 variants or "colours" of charge, red, green, blue



You always get **quantum superpositions** of different colours

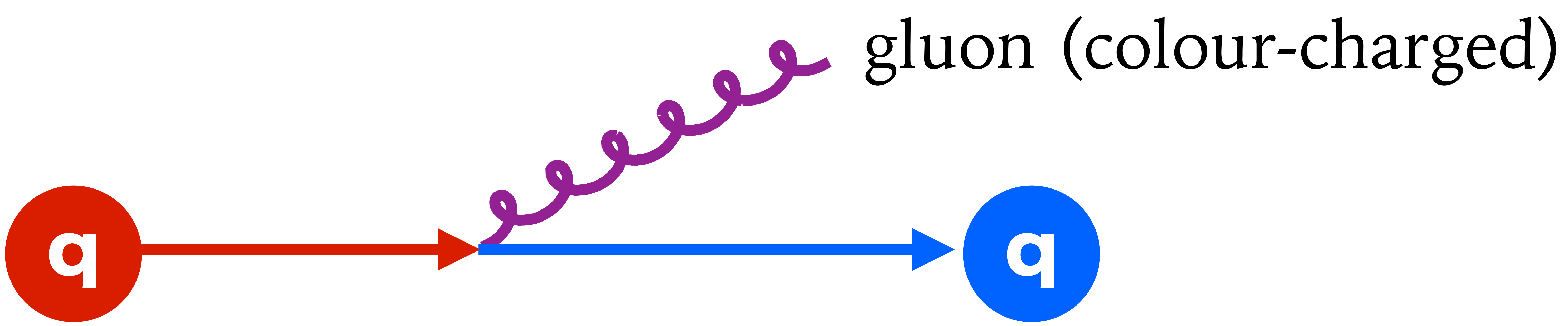
Predictions involve the quantum strong force — a.k.a. Quantum Chromodynamics (QCD)

QCD: emitting a gluon changes the quark's colour

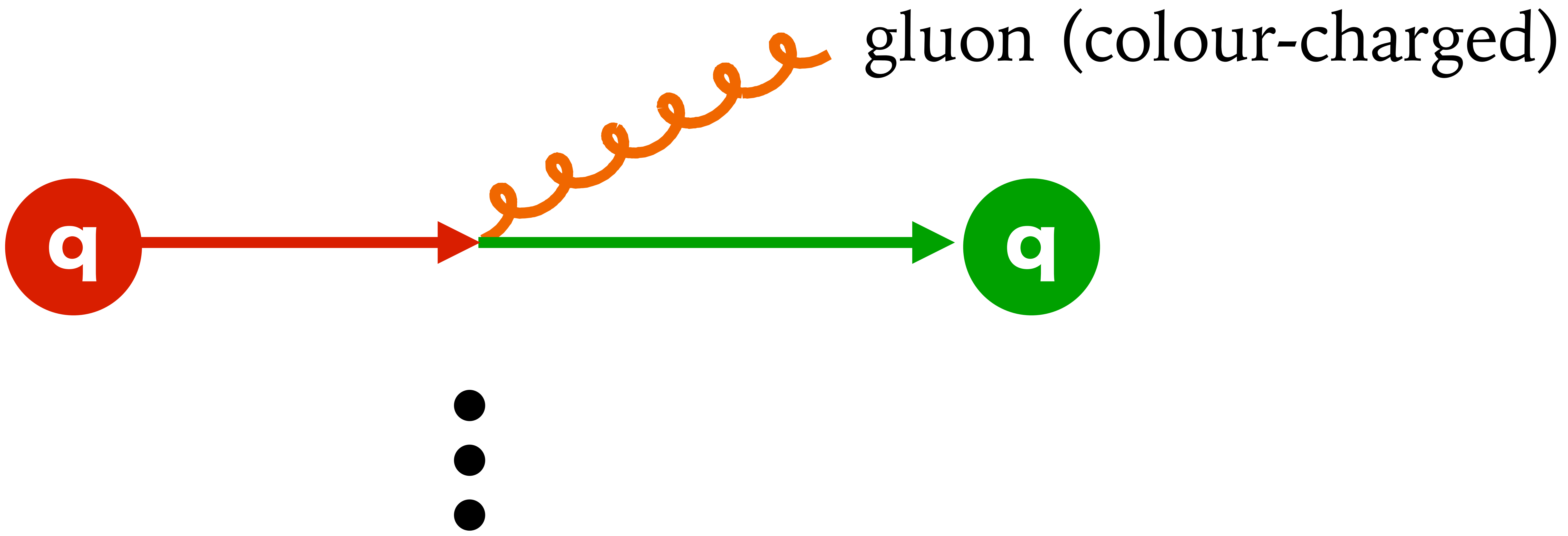


Predictions involve the quantum strong force – a.k.a. Quantum Chromodynamics (QCD)

QCD: emitting a gluon changes the quark's colour



There are 8 gluons
Each acts differently on quark colour



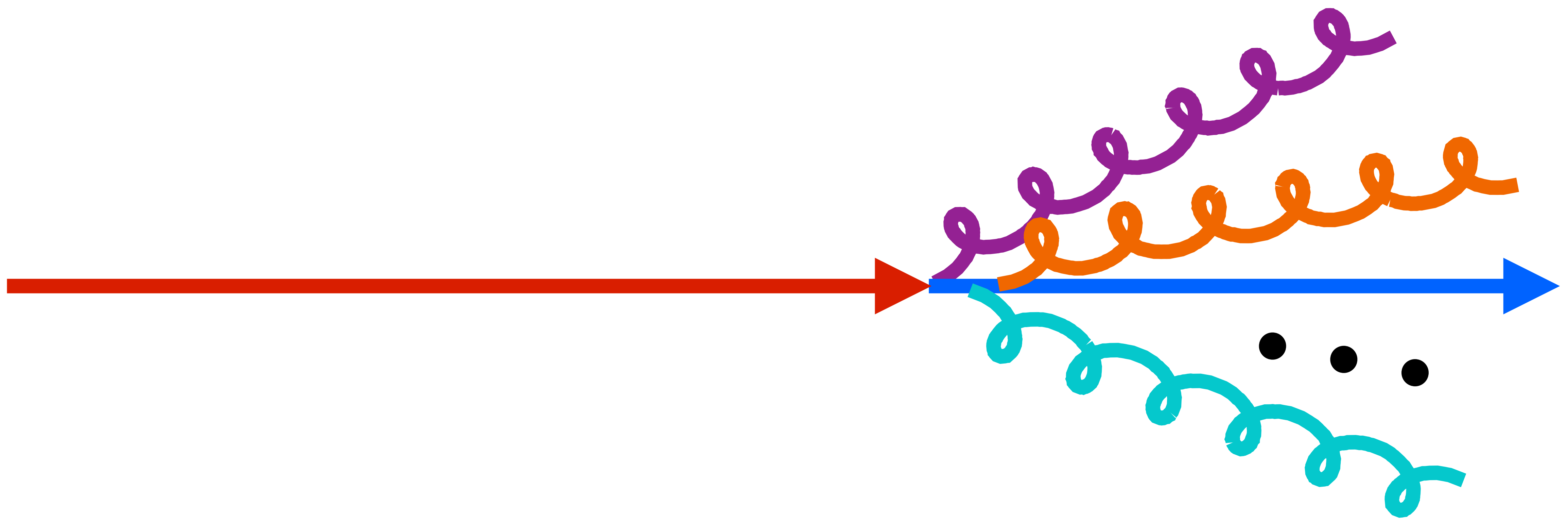
for a quark, anti-quark & N gluons, how many quantum-superposed states?

$q + \bar{q}$	3 states (red+anti-red, green+anti-green, blue+anti-blue)
$q + \bar{q}$ + 1 gluon	17 states
$q + \bar{q}$ + 2 gluons	75 states
⋮	⋮
$q + \bar{q}$ + 20 gluons	1,997,388 states

An event can easily have 30-40 gluons

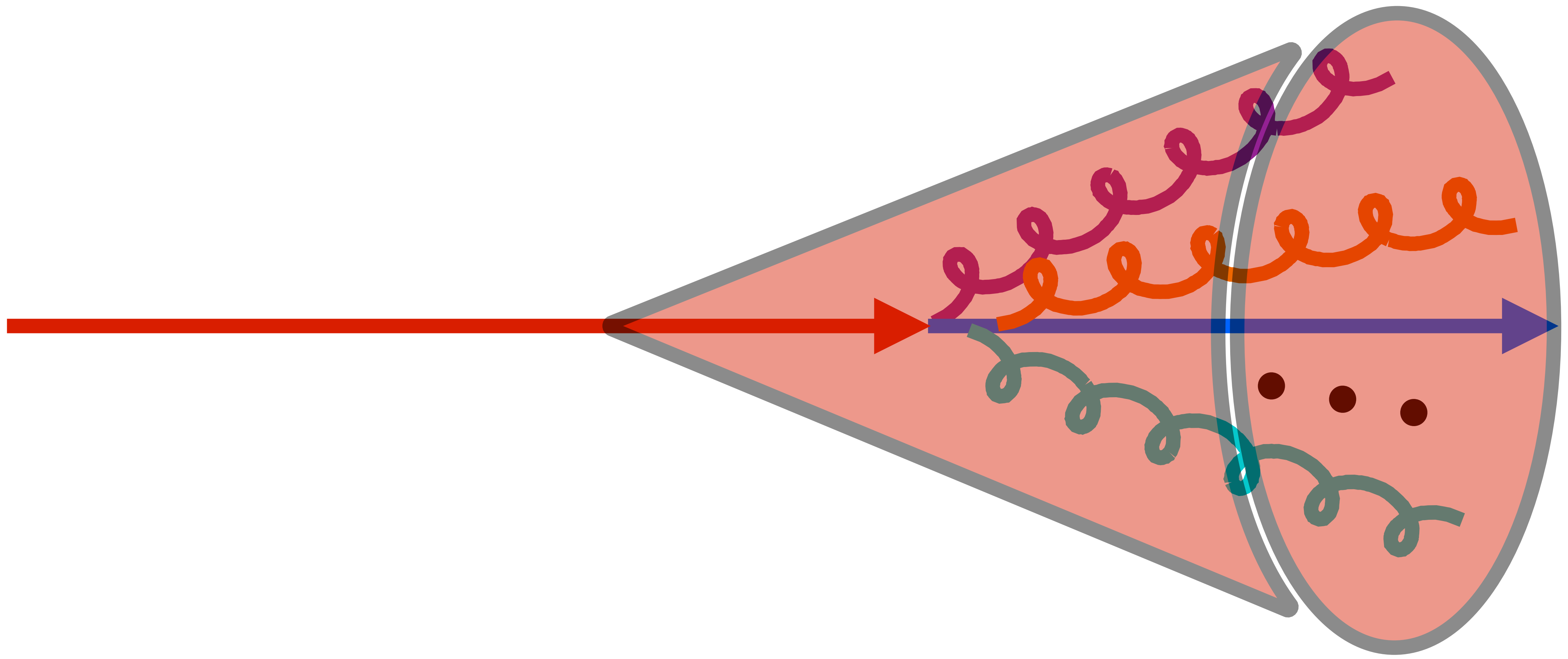
The quantum mechanical density matrix involves the square of the number of states

add one gluon to an ensemble of quarks and gluons



a huge simplification

add one gluon to an ensemble of quarks and gluons



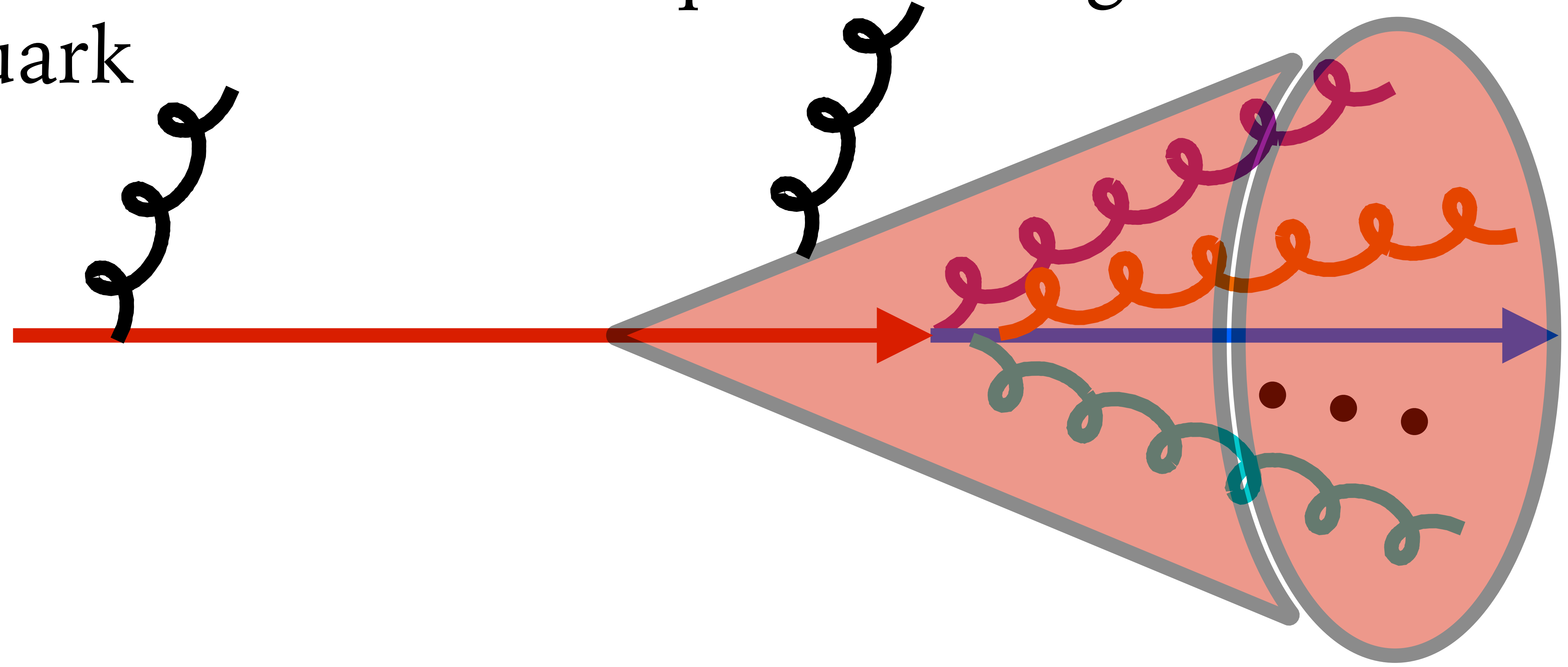
a huge simplification

conservation of colour charge

net colour charge of full ensemble of quark + gluons
= colour charge of incoming quark

add one gluon to an ensemble of quarks and gluons

emission from a single quark $\equiv$ coherent emission from a set of smaller-angle quarks and gluons



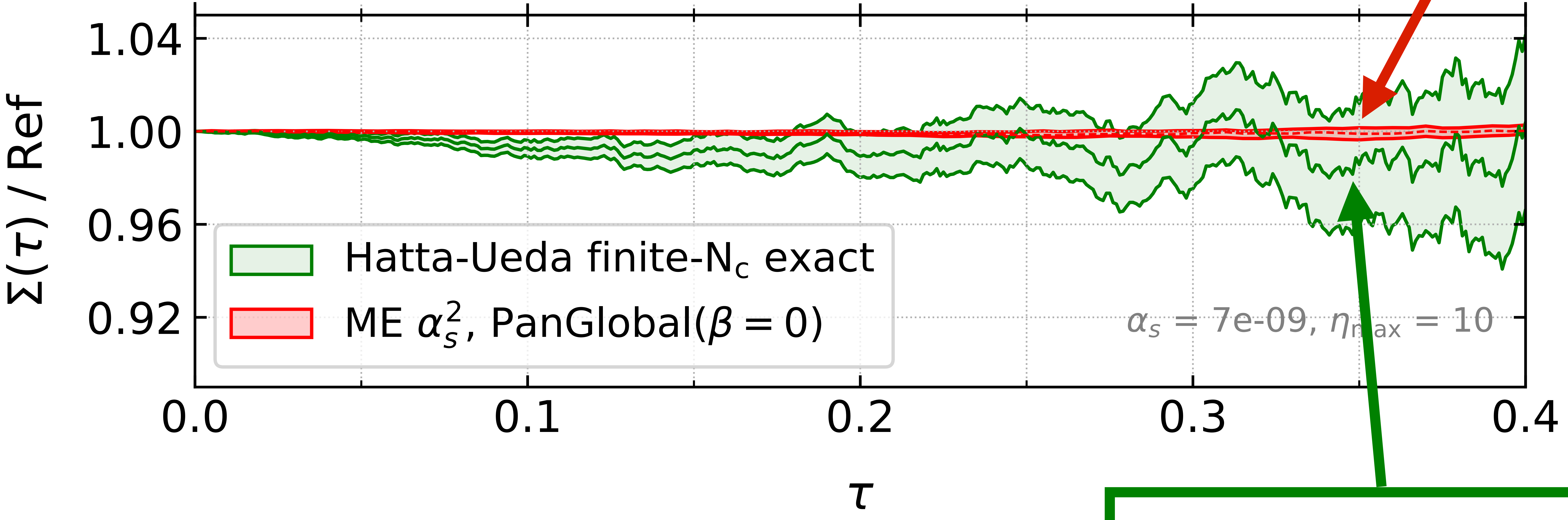
a huge simplification

conservation of colour charge

net colour charge of full ensemble of quark + gluons
= colour charge of incoming quark

Quantum v. "colour coherence" calculations of QCD energy flow

approximate, exploiting colour coherence, $\sim$ 300 CPU core hours



full quantum colour treatment, $\sim$ 40,000 CPU core hours

Hatta & Ueda 2011.04154 (full quantum)
Hamilton, Medves, GPS, Scyboz, Soyez, 2011.10054

Outlook

- we're learning how to reformulate "Feynman rules" or standard perturbative Quantum Field Theory approach
- goal is a systematically improvable framework, that expands around a different starting point: one with an arbitrary number of particles
- important for the ultimate goals of particle physics at colliders (e.g. making full use of machine learning)
- inevitably quantum, but many quantum aspects can be simplified

Backup