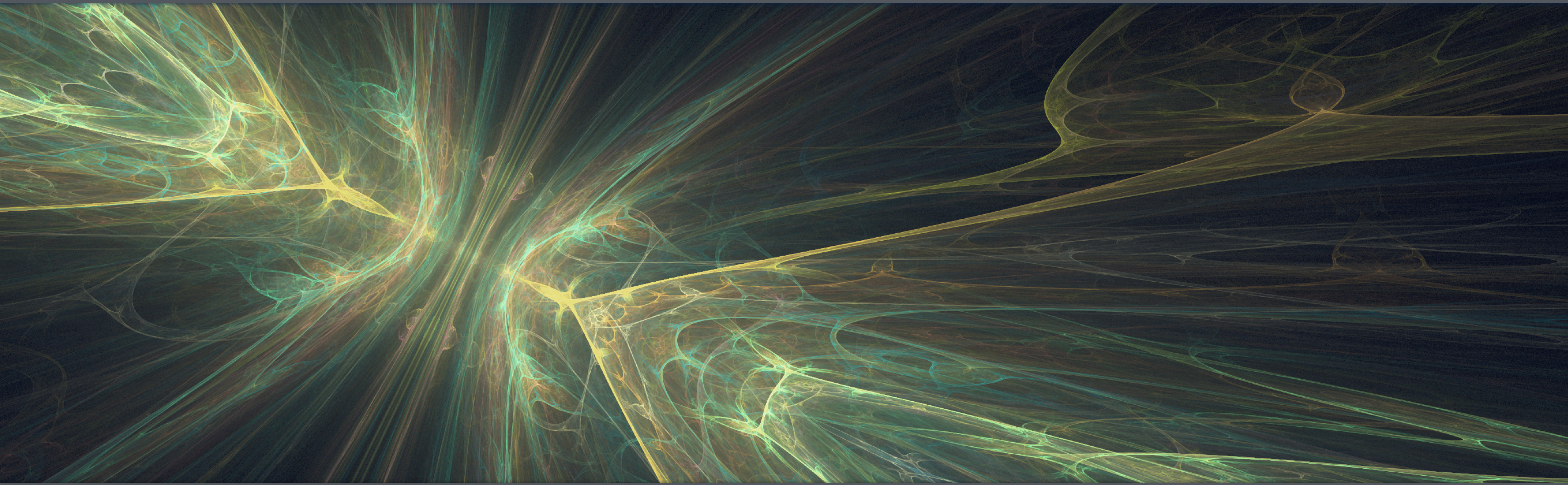
Higgs Colloquium — Edinburgh — October 2023

Emergent Phenomena at High Energies — Their Beauty and Challenges



Peter Skands

RS Wolfson Visiting Fellow, U of Oxford / Merton Coll. & Monash University

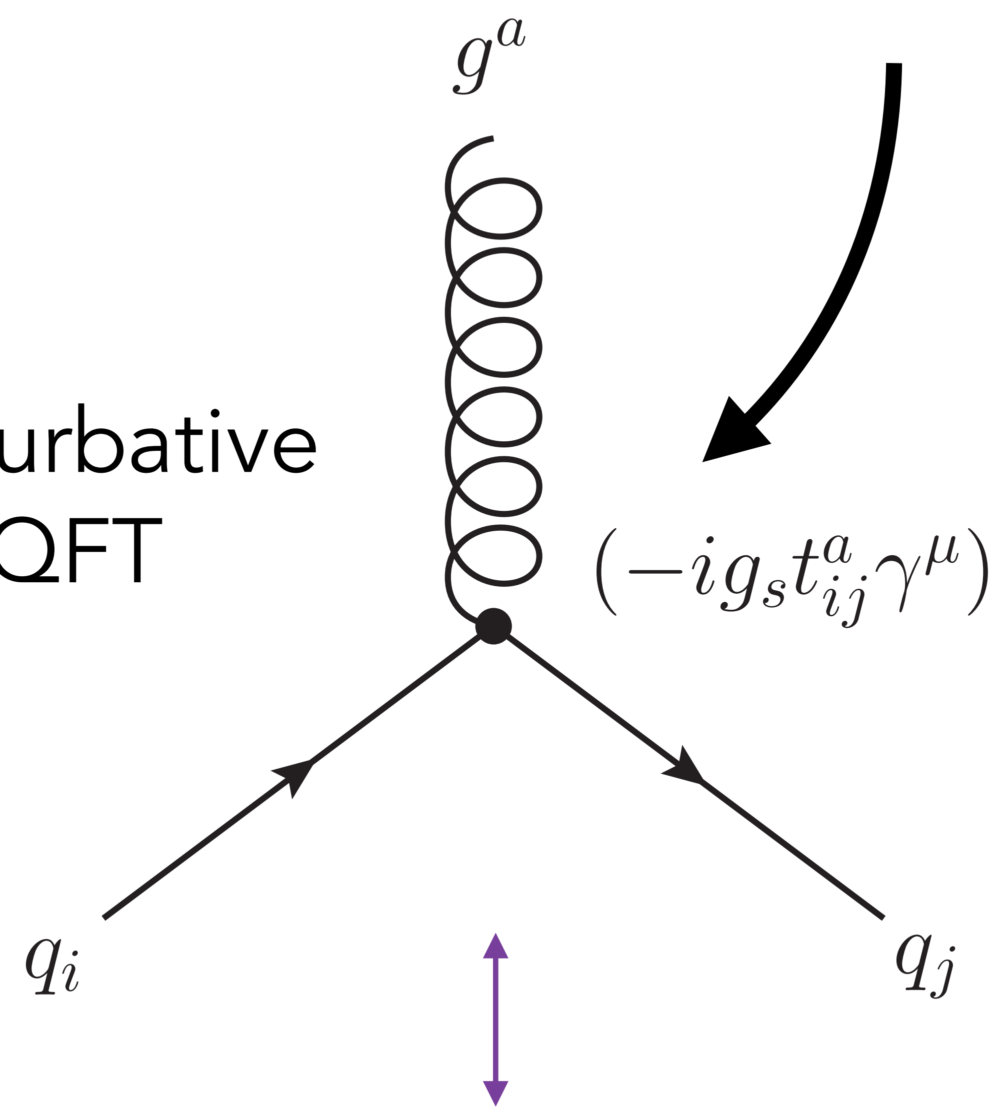
Theory Goal: Use LHC measurements to test hypotheses about Nature

Problem #1: have no exact solutions to QFT for the SM or Beyond

How to make predictions to form (reliable) conclusions?

Elementary Fields,
Symmetries, and Interactions

Perturbative
QFT



"Fundamental" parameters

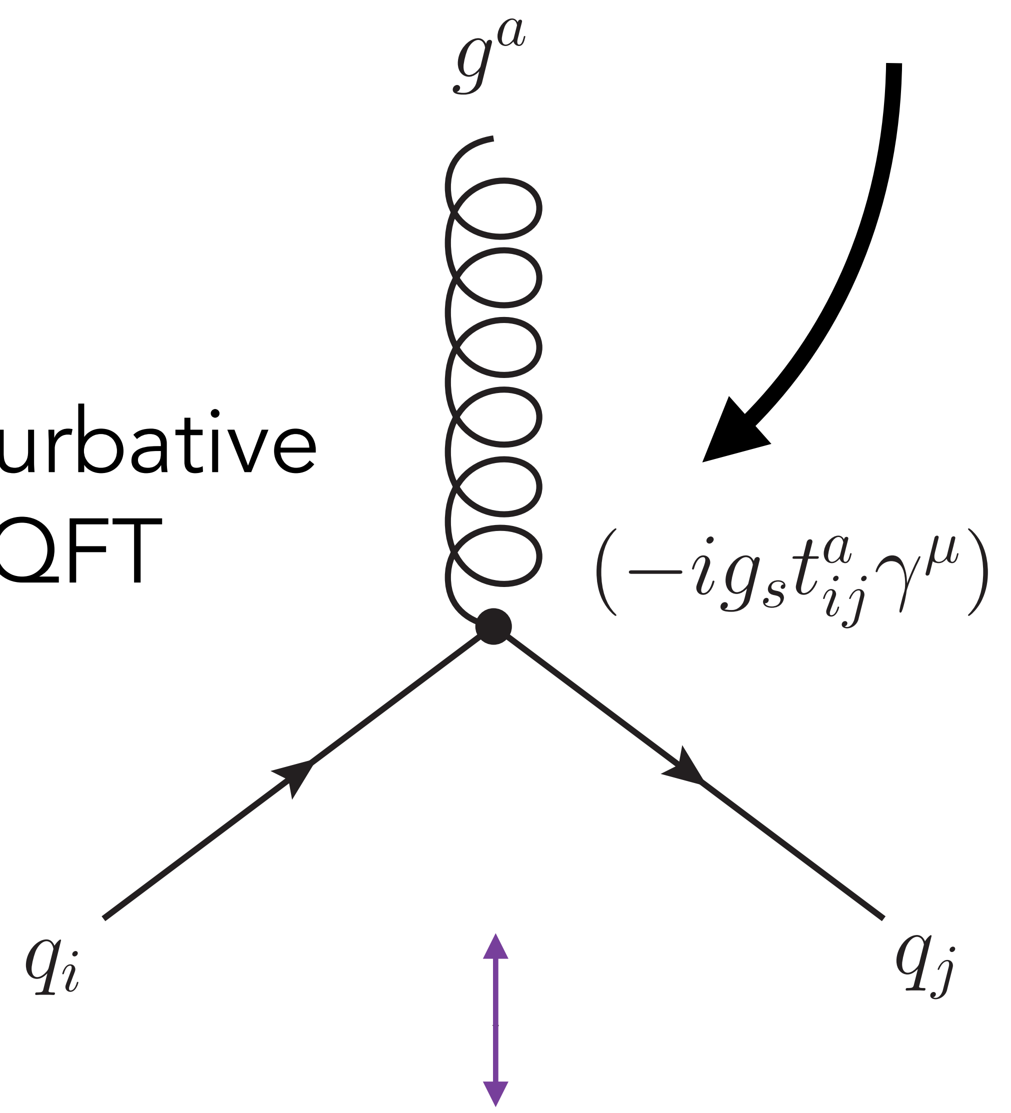
The Problem

Theory Goal: Use LHC measurements to test hypotheses about Nature

Problem #1: have no **exact** solutions to QFT for the SM or Beyond
How to make predictions to form **(reliable)** conclusions?

Elementary Fields,
Symmetries, and Interactions

Perturbative
QFT



"Fundamental" parameters

Problem #2: we are colliding — and observing — hadrons
Strongly bound states of quarks and gluons.

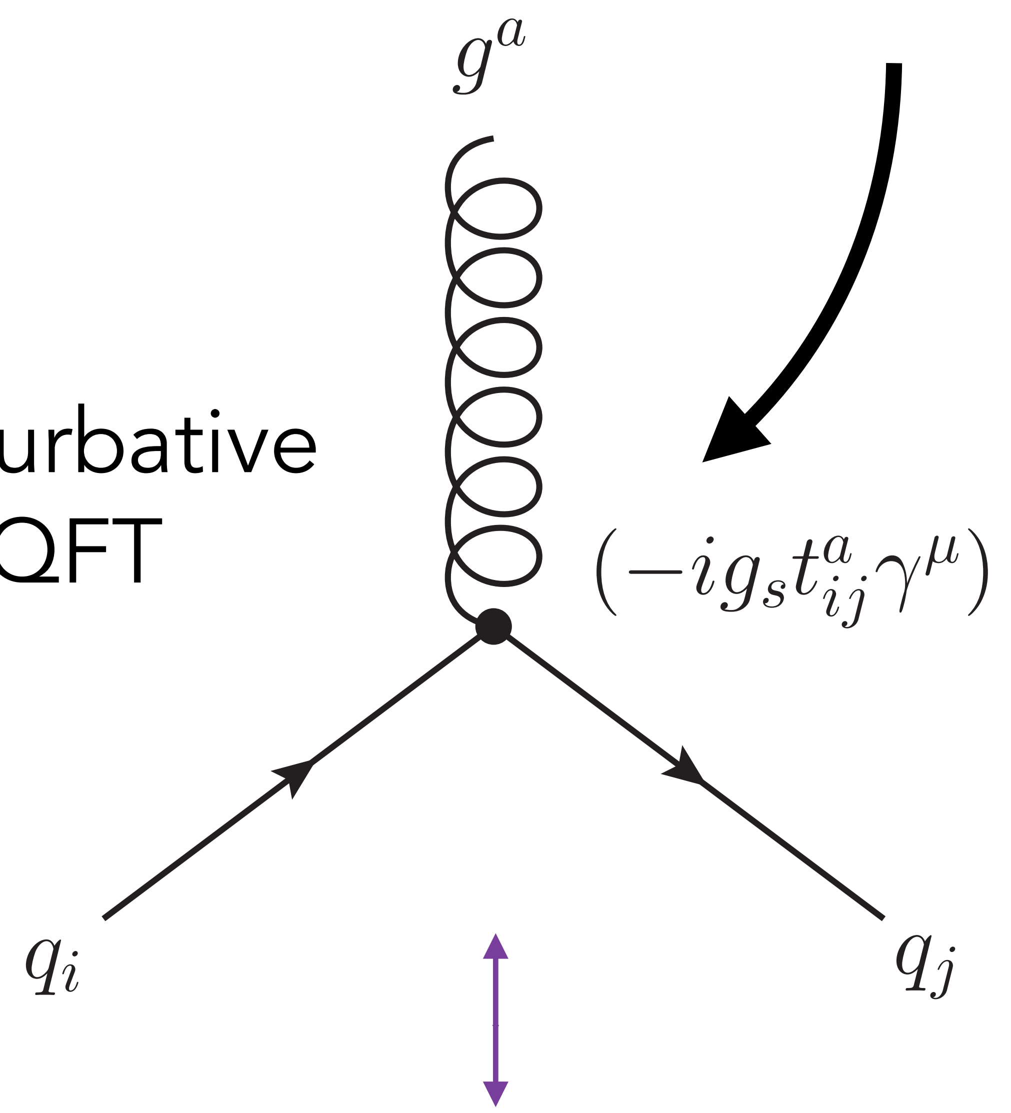
The Problem

How to connect this …

… with this?

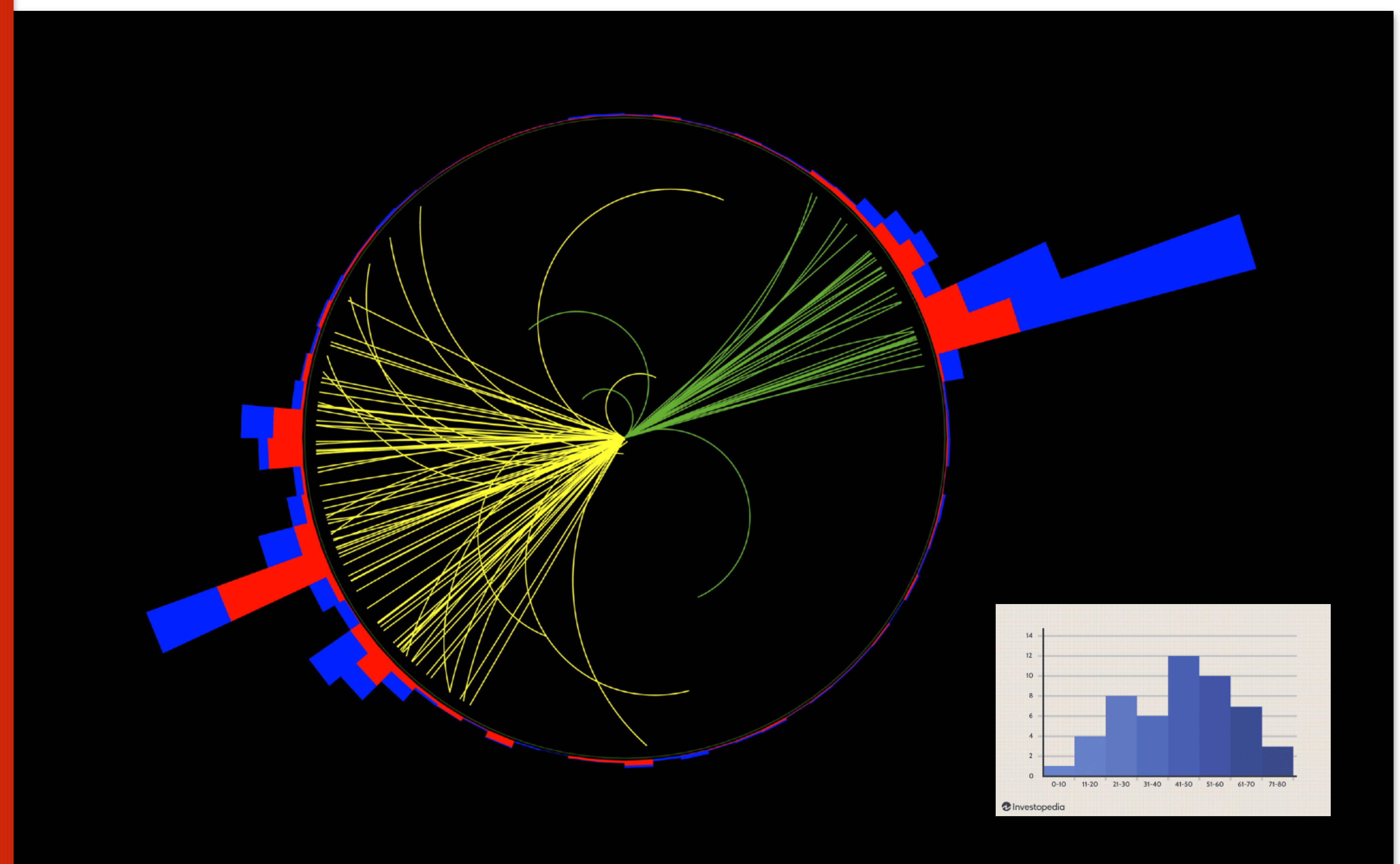
Elementary Fields,
Symmetries, and Interactions

Perturbative QFT



"Fundamental" parameters

CONFINEMENT



"Emergent" degrees of freedom

Jets of **hadrons**

What do I mean by "Emergent" degrees of freedom?

G. H. Lewes (1875): *"the emergent is **unlike its components** insofar as … it **cannot be reduced** to their sum or their difference."*

English Philosopher, coined the term "emergence" in "Problems of Life and Mind"

In Quantum Field Theory:

"Components" = **Elementary interactions** — encoded in the Lagrangian

Perturbative expansions ~ elementary interactions to n^{th} power

What else is there? Structure beyond (fixed-order) perturbative expansions:

Fractal scaling, of jets within jets within jets … JETS

Confinement (in QCD), of coloured partons within hadrons STRINGS

Image Credits: mrwallpaper.com

Image Credits: Yeimaya

(Ulterior Motives for Studying QCD)

The Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

There are more things in
Heaven and Earth, Horatio, than
are dreamt of in your philosophy

Hamlet, Prince of Denmark

+ … ?

LHC: 90% of data still to come

➜ higher sensitivity to smaller signals.

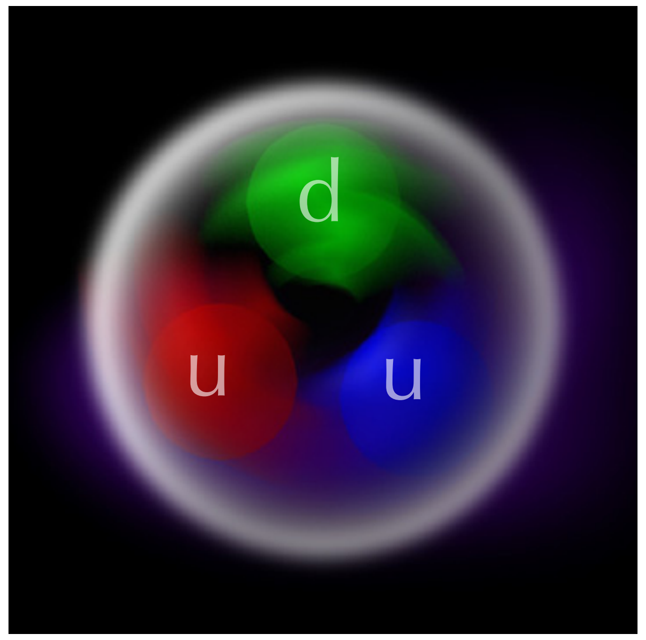
High-statistics data ↔ high-accuracy theory

Consider a hadron; why is it complicated?

Textbook "quark-model" proton:

Popular Science: Three quarks (for muster Mark) [Joyce/Gell-Mann]

Undergraduate ➤ Quark-model flavour ⊗ spin wave functions



Real-life hadrons

Are composite & strongly bound, with time-dependent structure

For wavelengths ~ proton size:

quark & gluon plane waves are not going to be good approximations

$\Longrightarrow$ **forget about the interaction picture and perturbation theory**

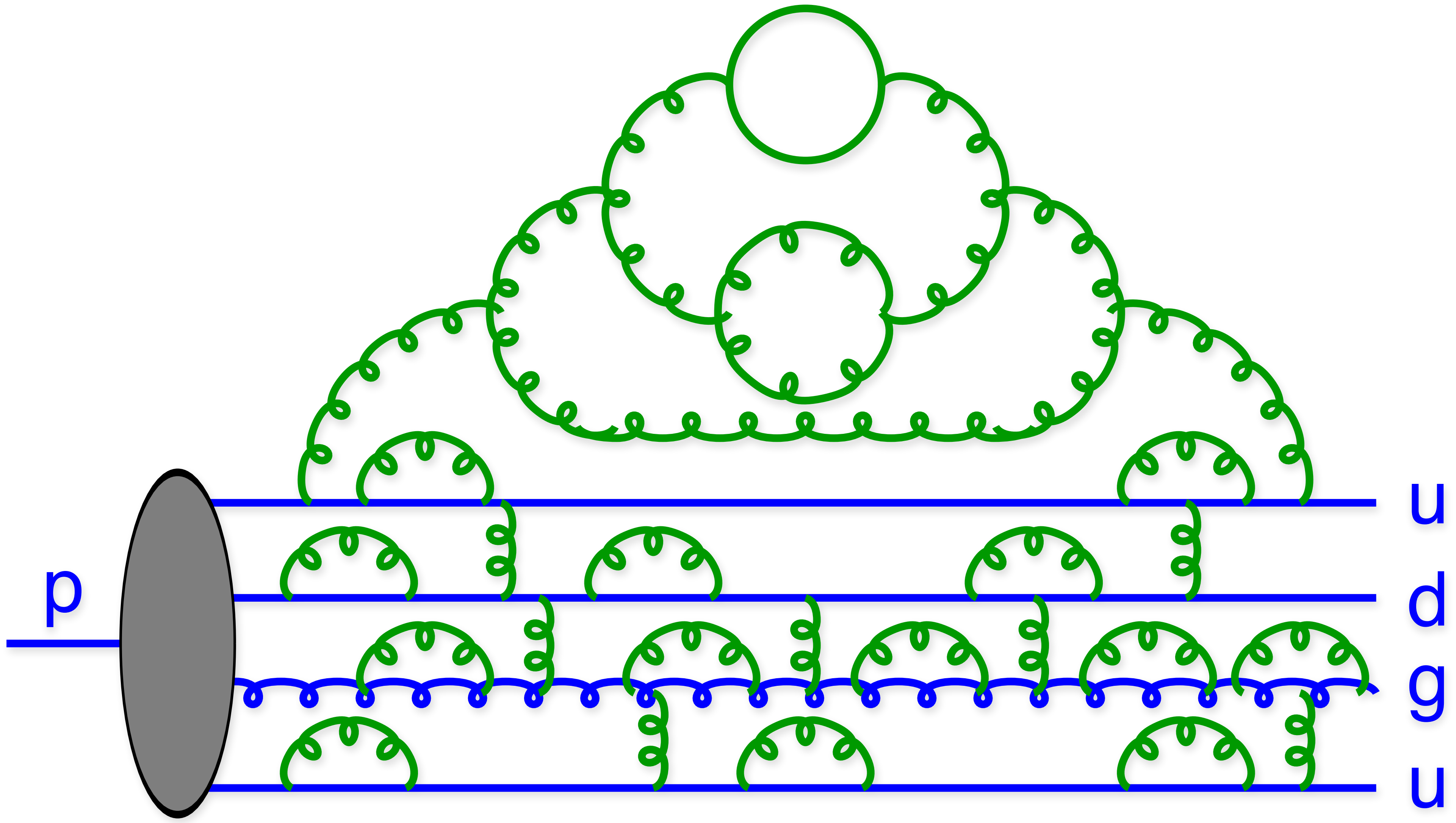
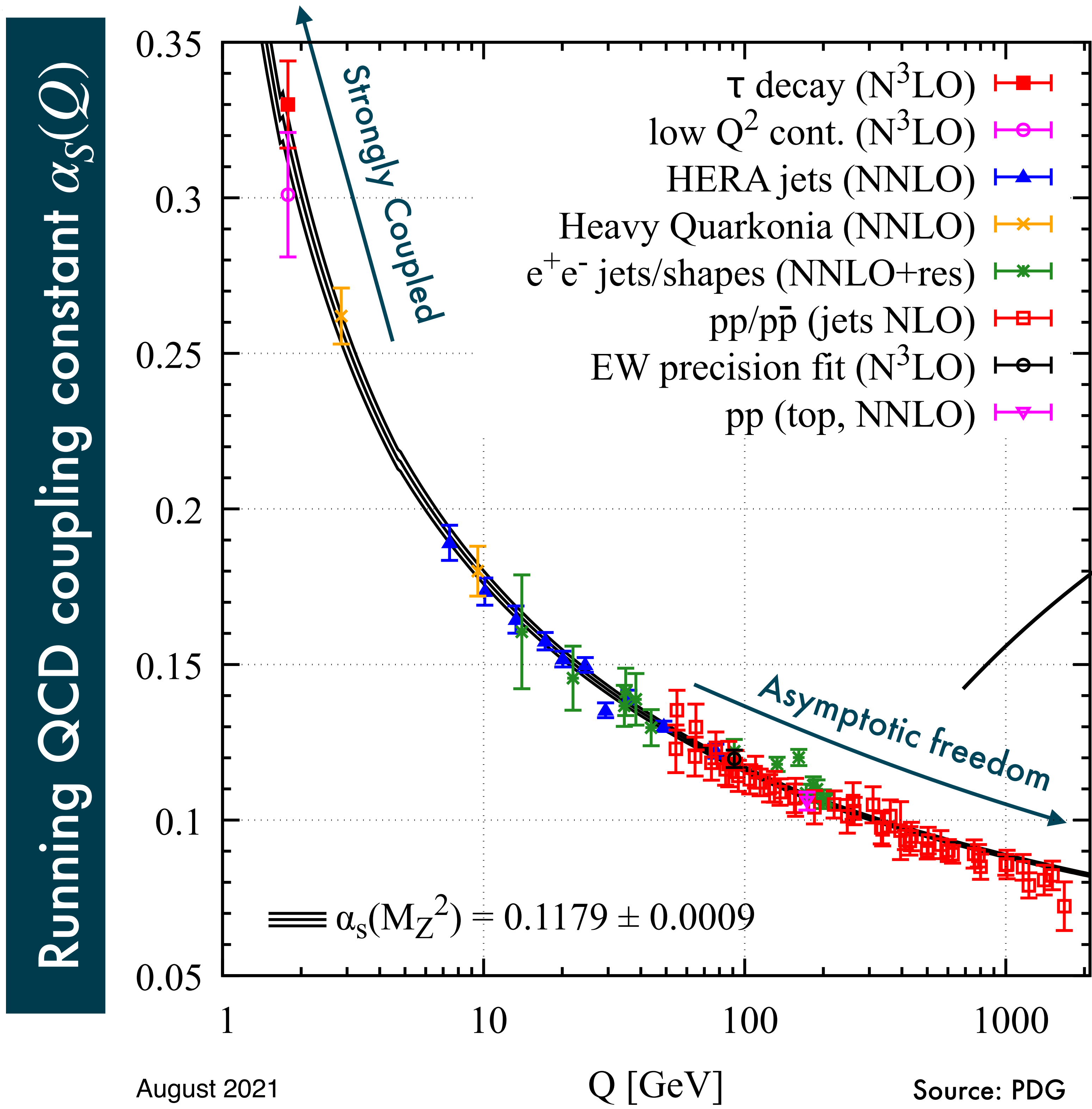


Figure by T. Sjöstrand

Asymptotic Freedom in QCD — Nobel 2004 (Gross, Politzer, Wilczek)

Over **short** distances, quarks and gluons **do** behave like *almost* free particles

Then it's OK to start from free-field solutions (plane waves) and treat interactions as perturbations ⟹ The interaction picture and perturbation theory are saved!



Parametrise "mess" in terms of (measurable) probability densities for each type of plane wave: **Parton Distribution Functions (PDFs)**

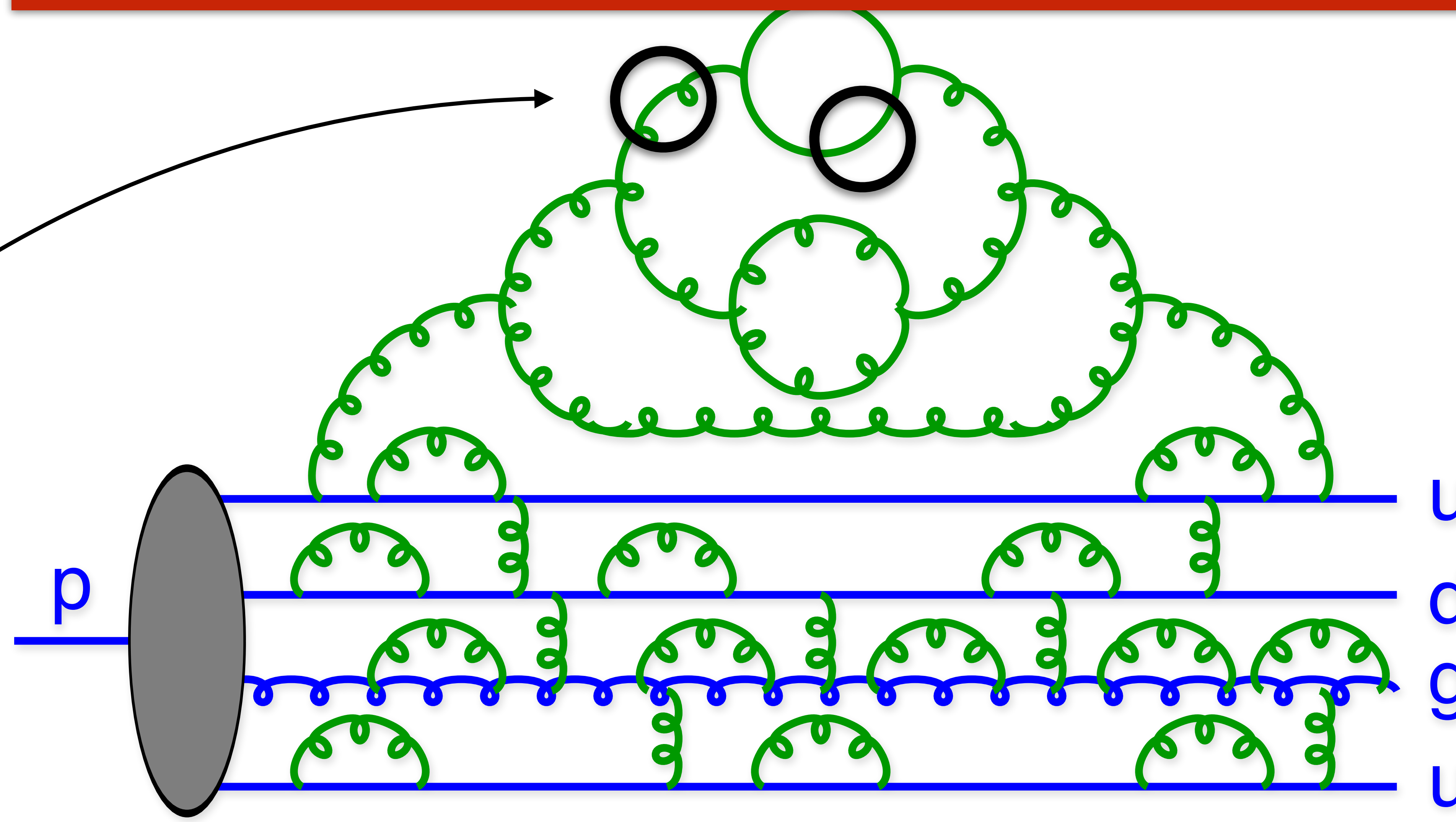
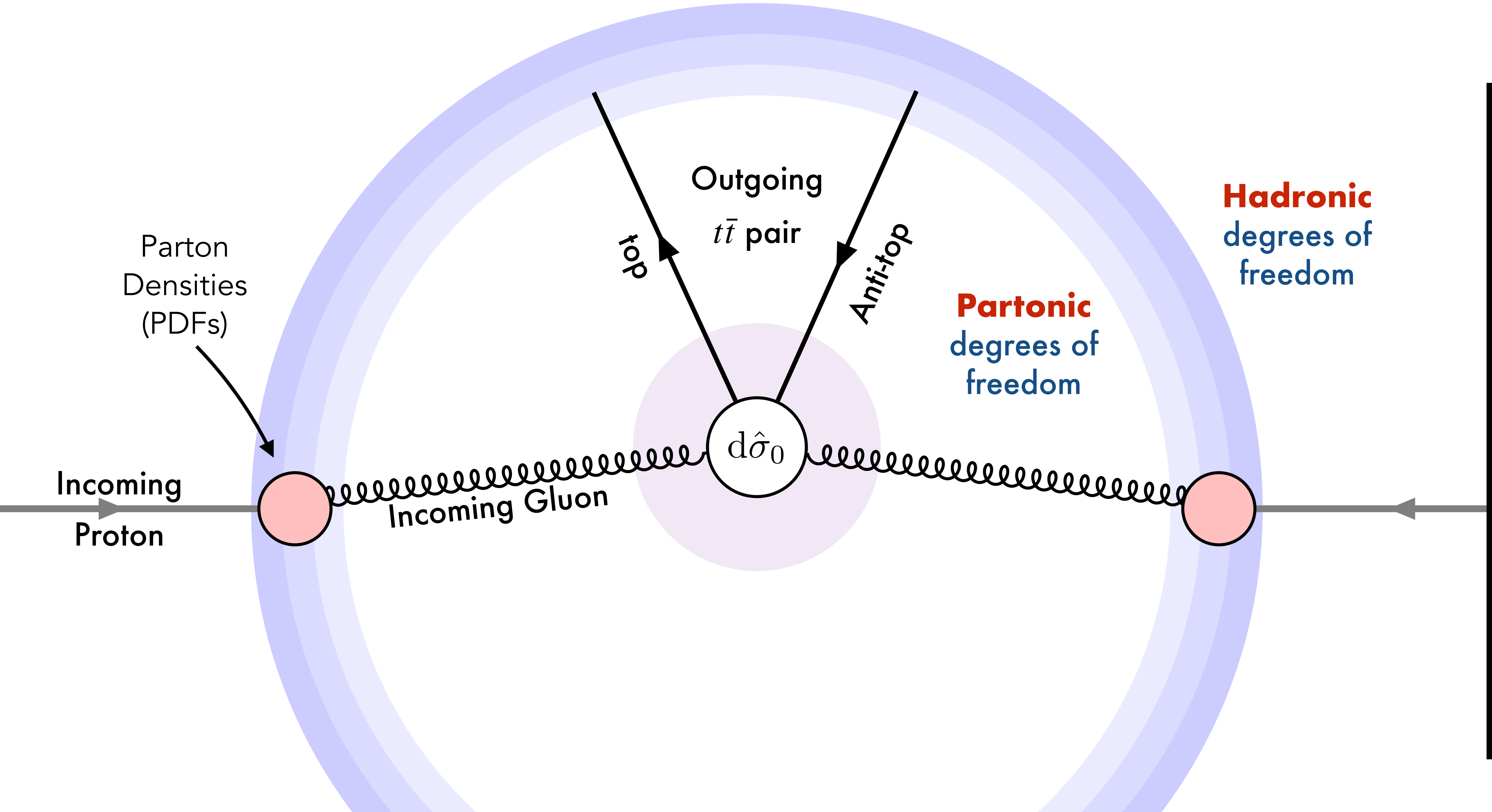


Figure by T. Sjöstrand

Great! Now can we compare to measurements?

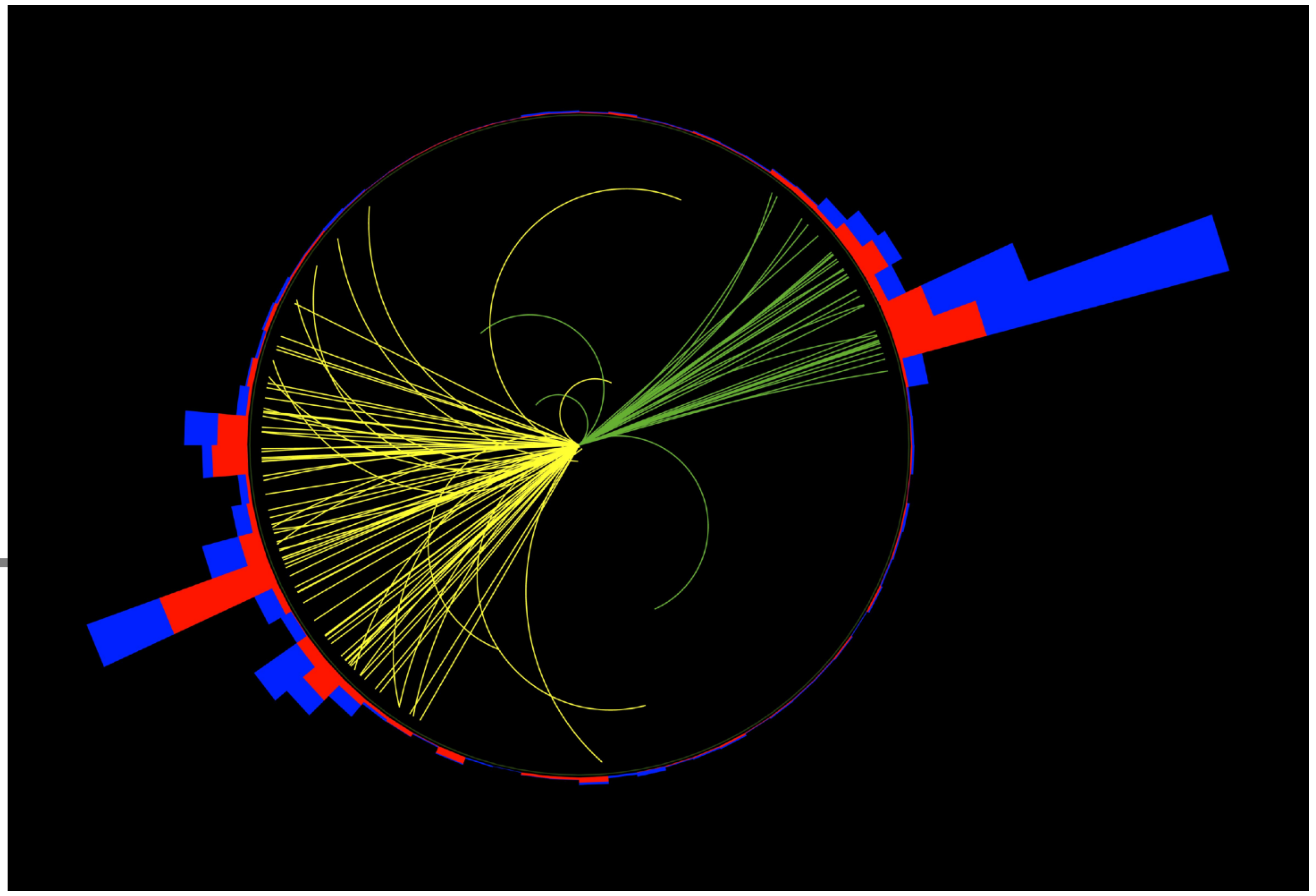
Theorist:

This is a $t\bar{t}$ event



Experimentalist:

Is this a $t\bar{t}$ event?



With factorisation, we recover the use of perturbation theory (for high-scale processes*)

But we also lose a lot of detail (and still cannot address low scales)

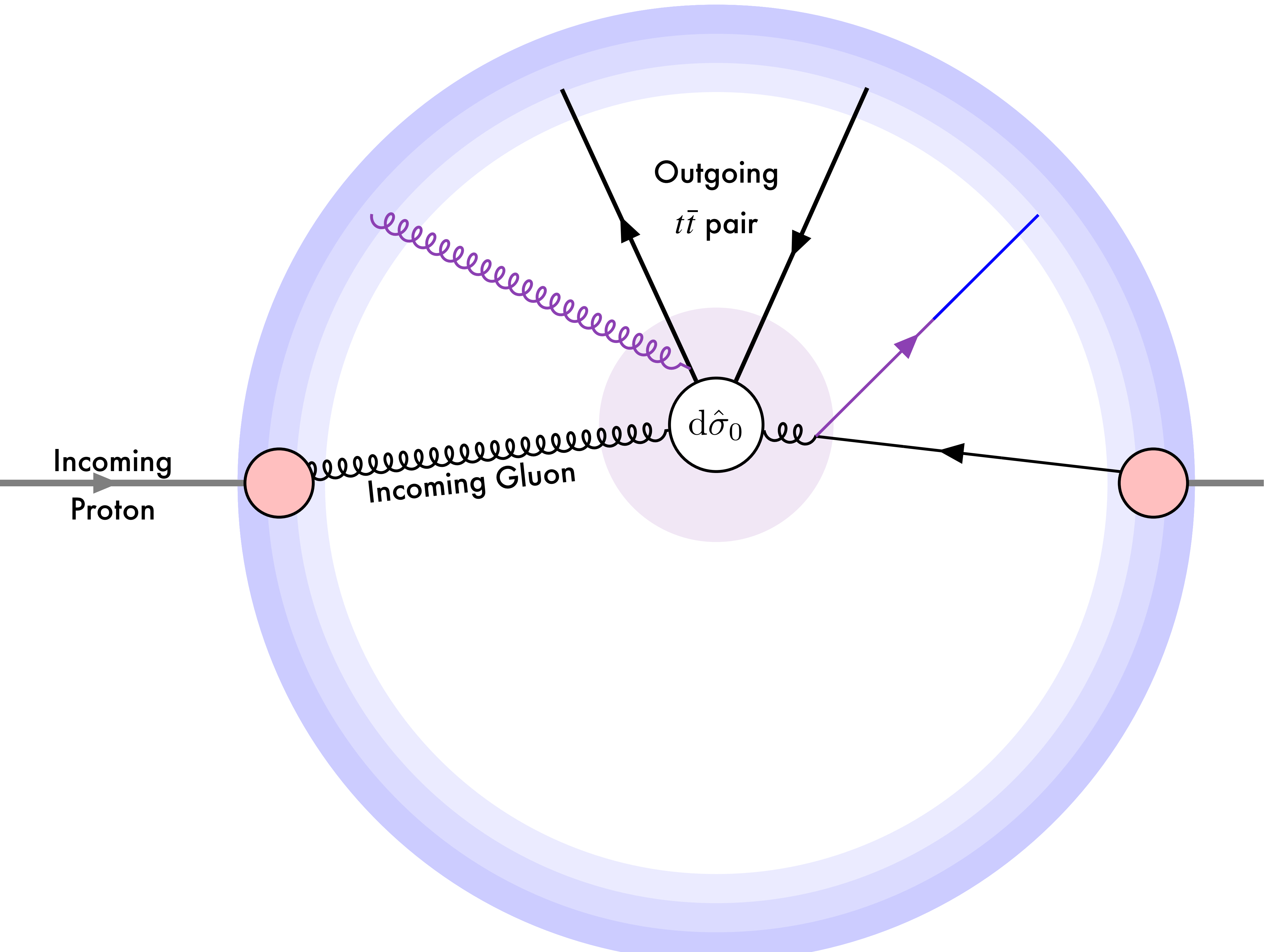
*for so-called Infrared and Collinear Safe Observables

Accuracy & Detail 1: Radiative Corrections

Scattered partons carry QCD ("colour") and/or electric charges

Will give off **bremsstrahlung radiation**, at wavelengths $\lambda > \hbar c/Q$

Probabilities can be computed order by order in perturbation theory



Fixed-order perturbative QCD (pQCD):

- → Leading Order (LO)
- → NLO
- → NNLO
- → N3LO

State of the art for complex processes (NLO, NNLO)

State of the art for simple processes (N3LO)

$\Longrightarrow$ accuracies of order a few % or better

Let's try it: Practical Example

Naively, QCD radiation suppressed by $\alpha_s \sim 0.1$

➞ Truncate at fixed order = Leading Order (LO), NLO, NNLO, …

Example: Pair production of Supersymmetric (SUSY) particles at LHC$_{14}$, with $M_{SUSY} \approx$ 600 GeV + zero, one, or two extra radiations ("jets")

LHC - sps1a - m~600 GeV   Plehn, Rainwater, PS PLB645(2007)217

FIXED ORDER pQCD	σ_{tot}[pb]	$\tilde{g}\tilde{g}$	$\tilde{u}_L\tilde{g}$	$\tilde{u}_L\tilde{u}_L^*$	$\tilde{u}_L\tilde{u}_L$	TT
$p_{T,j} >$ 100 GeV	σ_{0j}	4.83	5.65	0.286	0.502	1.30
inclusive **X + 1 "jet"** →	σ_{1j}	2.89	2.74	0.136	0.145	0.73
inclusive **X + 2 "jets"** →	σ_{2j}	1.09	0.85	0.049	0.039	0.26
$p_{T,j} >$ 50 GeV	σ_{0j}	4.83	5.65	0.286	0.502	1.30
	σ_{1j}	5.90	5.37	0.283	0.285	1.50
	σ_{2j}	4.17	3.18	0.179	0.117	1.21

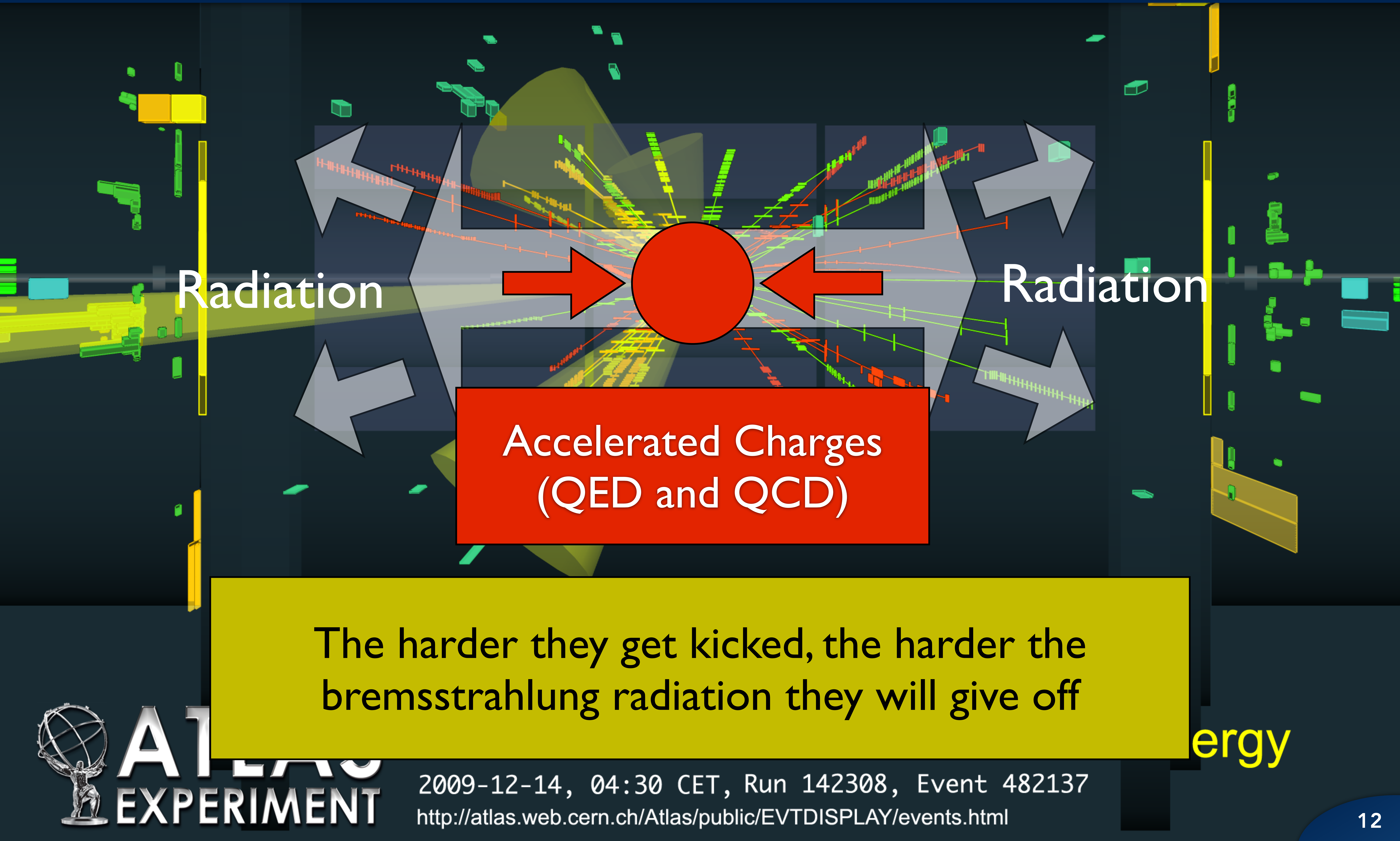
(Computed with SUSY-MadGraph)

σ for X + jets much larger than naive factor-α_s estimate

σ for 50 GeV jets ≈ **larger** than total cross section
→ **what is going on?**

All the scales are **high**, M_i & $p_{\perp,\text{jet}} \gg 1\,\text{GeV}$, so perturbation theory **should** be OK …

This is just the physics of Bremsstrahlung



Accelerated Charges
(QED and QCD)

The harder they get kicked, the harder the bremsstrahlung radiation they will give off

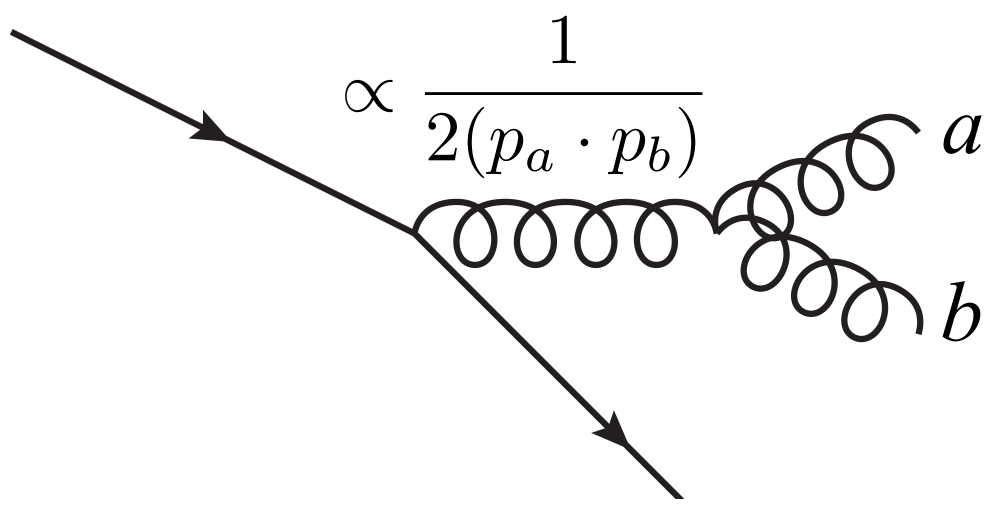
Can we build a simple theoretical model of this?

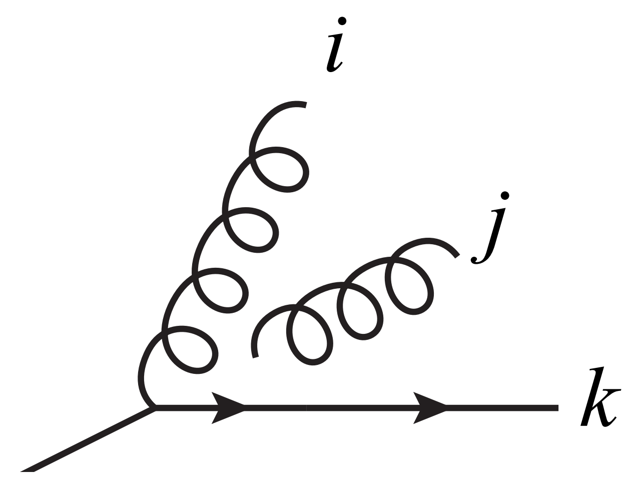
The Lagrangian density of QCD is **scale invariant** (neglecting small quark masses)

+ scaling violation: $g_s^2 \longrightarrow 4\pi\alpha_s(Q^2)$

Most bremsstrahlung is driven by
divergent propagators → simple structure

Gauge amplitudes factorize
in singular limits (→ universal
"conformal" or *"fractal"* structure)





Partons ab
→ collinear:

P(z) = Altarelli-Parisi splitting kernels, with z = $E_a/(E_a+E_b)$

$$|\mathcal{M}_{F+1}(\ldots,a,b,\ldots)|^2 \stackrel{a||b}{\rightarrow} g_s^2 \mathcal{C} \frac{P(z)}{2(p_a \cdot p_b)} |\mathcal{M}_F(\ldots,a+b,\ldots)|^2$$

Gluon j
→ soft:

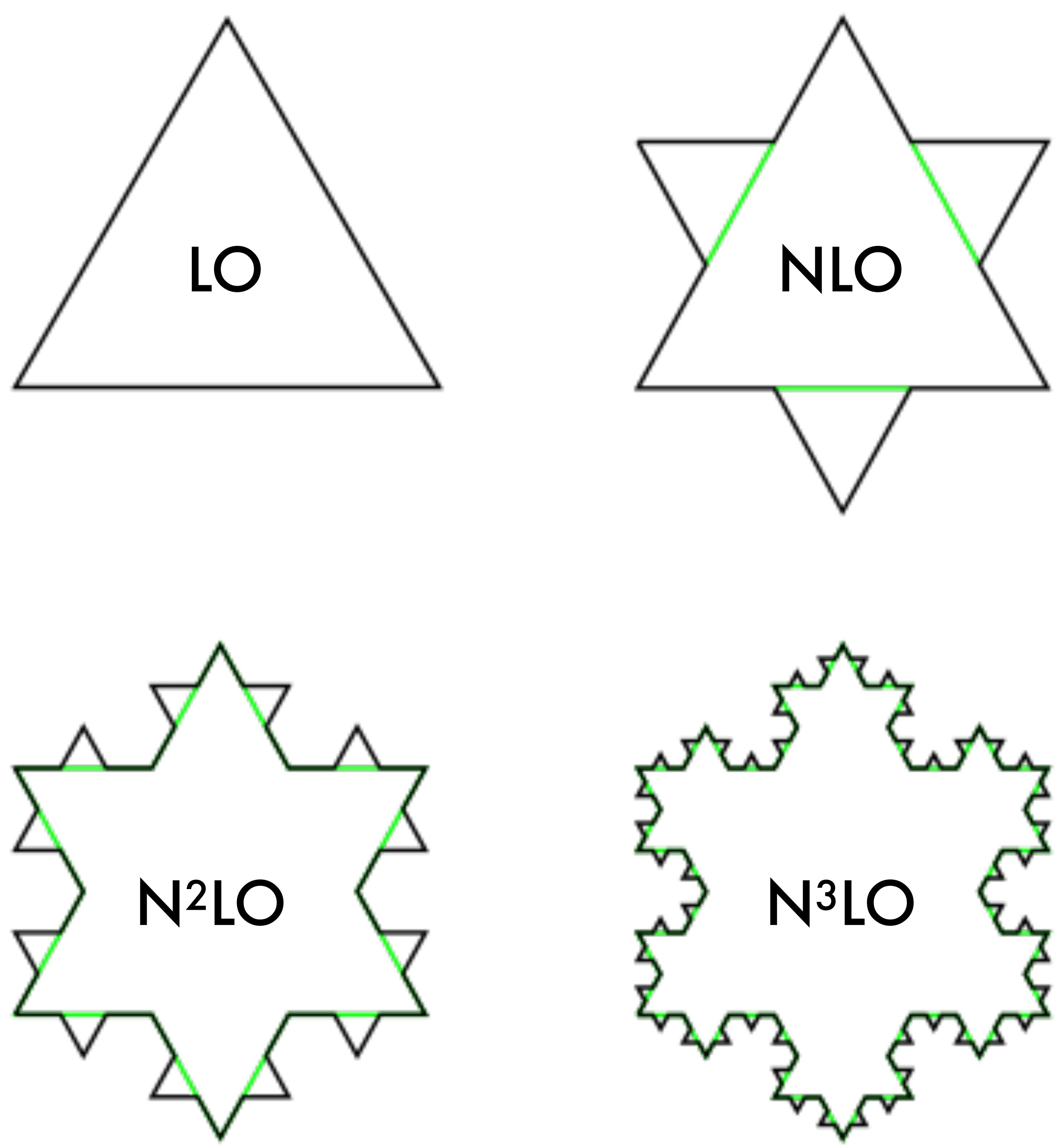
Coherence → Parton j really emitted by (i,k) "antenna"

$$|\mathcal{M}_{F+1}(\ldots,i,j,k\ldots)|^2 \stackrel{j_g\rightarrow 0}{\rightarrow} g_s^2 \mathcal{C} \frac{(p_i \cdot p_k)}{(p_i \cdot p_j)(p_j \cdot p_k)} |\mathcal{M}_F(\ldots,i,k,\ldots)|^2$$

Suggests a formulation as an differential evolution, with scale-invariant kernels

Reformulate Perturbation Theory as a Markov Chain

Simplified Analogy using a **"Koch Snowflake"**
as a stand-in for perturbation theory



Differential cross section for a generic observable "O", expressed as Markov chain:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}O} = \int \mathrm{d}\Phi_0 \; \underbrace{|M_{\mathrm{Born}}|^2 \left(1 + F_{\mathrm{NLO}} + \ldots\right)}_{\text{Fixed–Order Matching Coefficients}} \; \underbrace{\mathcal{S}(\Phi_0, O)}_{\text{Shower}}$$

$$\mathcal{S}_{+1}(\Phi_n, O) = \overbrace{\Delta\left(\Phi_n, Q_{\mathrm{IR}}\right)}^{\text{'Sudakov Factor'}} \; \overbrace{\delta\left(\hat{O}(\Phi_n) - O\right)}^{\text{Evaluate } O \text{ on } \Phi_n}$$

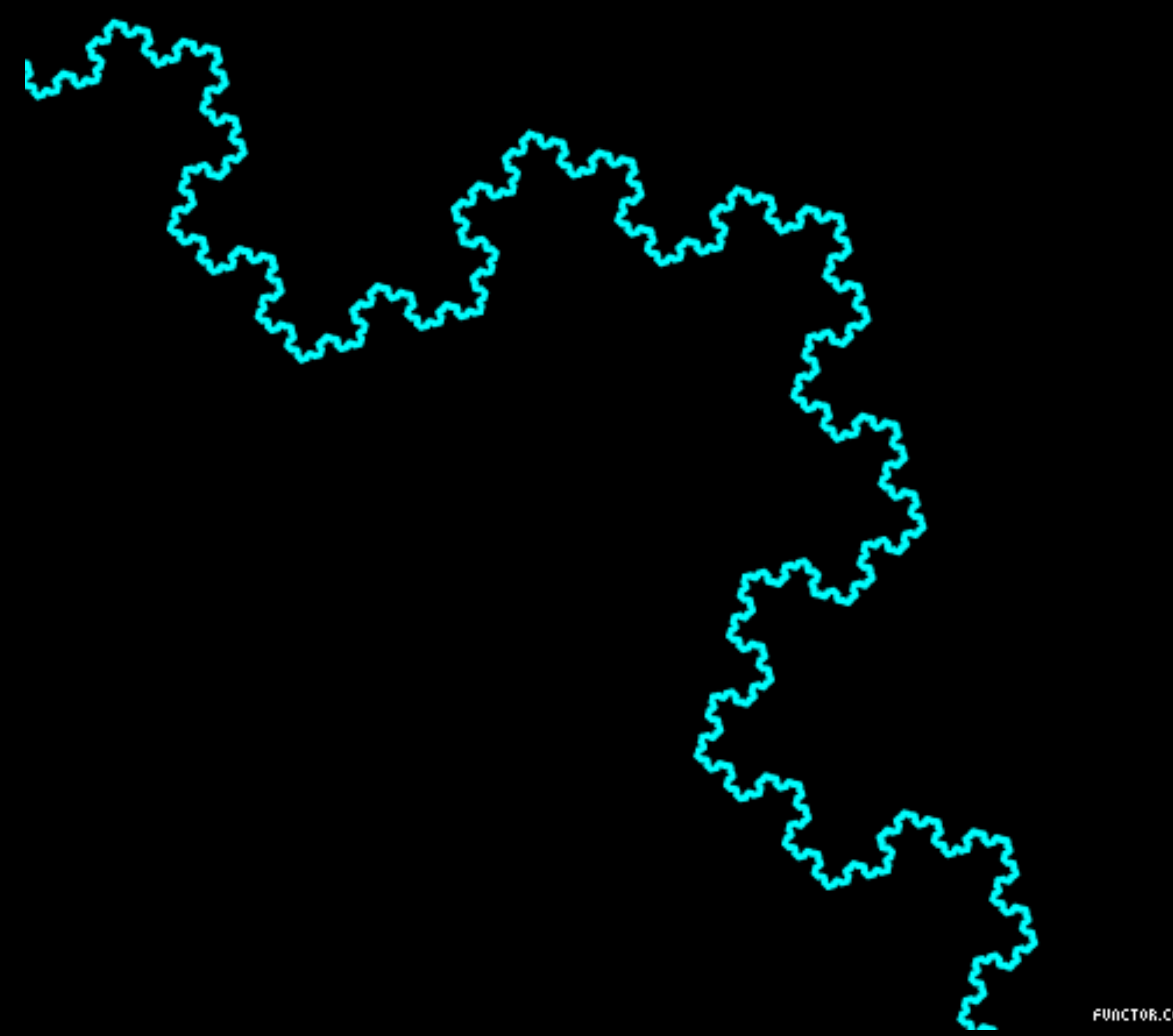
$$+ \int \mathrm{d}\Phi_{+1} \, \Delta\left(\Phi_n, Q_{n+1}\right) \overbrace{\frac{|M_{n+1}|^2}{|M_n|^2}}^{\text{Branching Kernel}} \; \mathcal{S}(\Phi_{n+1}, O)$$

MARKOV CHAIN

UNITARITY

SUDAKOV FACTOR $\Delta(\Phi_n, Q) = \exp\left(- \int_{Q_{\mathrm{IR}}^2}^{Q_n^2} \mathrm{d}\Phi_{+1} \frac{|M_{n+1}|^2}{|M_n|^2} \right)$

Infinite Order



Stochastic differential evolution in “hardness”
(~ measure of frequency, from high to low)

Fractal Schmactal

So we have an explicit representation of the fractal structure - great!

Needed approximations to get there: "Leading Logarithm", "Leading Colour", …

- ➤ **Only good to at best ~ 10%**

I thought LHC physics was supposed to be high-precision stuff?

What good is Peta-Bytes of data if we can only calculate to ~ 10% ?

Precision Frontiers:

Matching & Merging: Combine the best of both worlds

Combine fixed-order and shower expansions, addressing overlaps / double-counting

Shower Accuracy: Several groups working on higher-order formulations of the shower algorithms themselves

PanScales (Oxford) with "NLL-accurate" recoils; that's why I'm on sabbatical there now

Vincia (Monash): 2nd-order shower kernels, with new "direct" $2 \rightarrow 4$ branchings

Precision Frontier 1: Combining Fixed Orders & Showers

Well Established for first few orders ✅

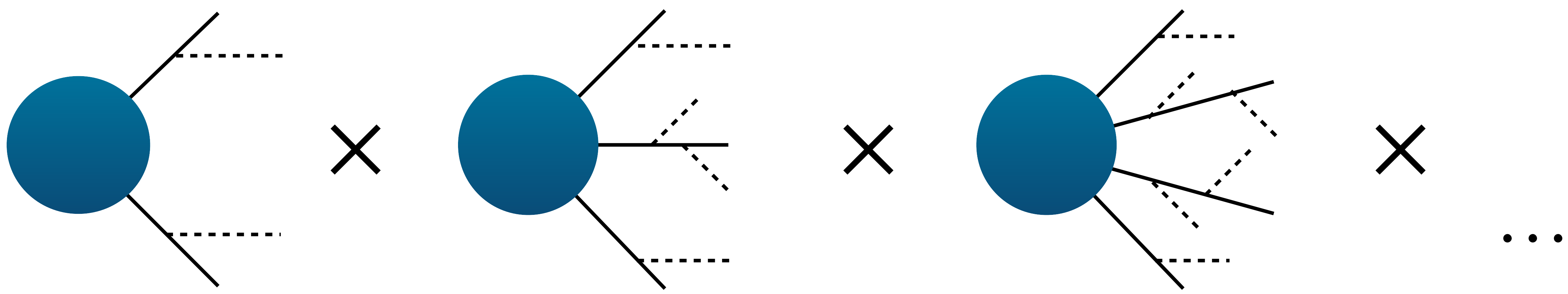
MC@NLO, POWHEG, CKKW-L, UMEPS, UNLOPS, …

(many legs)

Complexity Growth: a **bottleneck** at "high multiplicities"

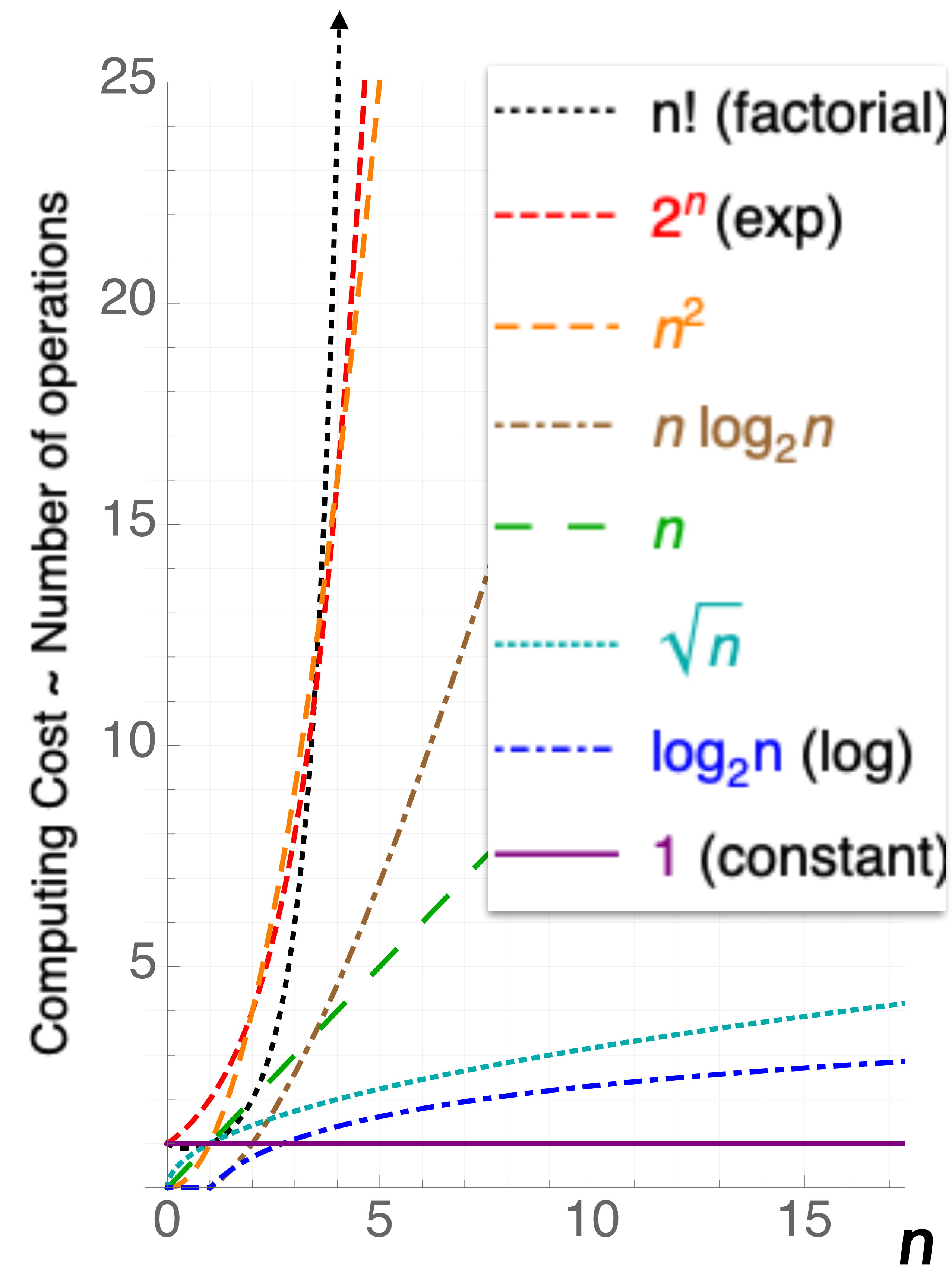
# of possible "shower histories" grows ~ factorially

E.g., for a "dipole shower", for $pp \to W + n$ jets:



Number of Histories for n Branchings						
$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$
2	8	48	384	3840	46080	645120

Relevant for increasingly complex processes *eg* at LHC



Our Approach: Sector Showers

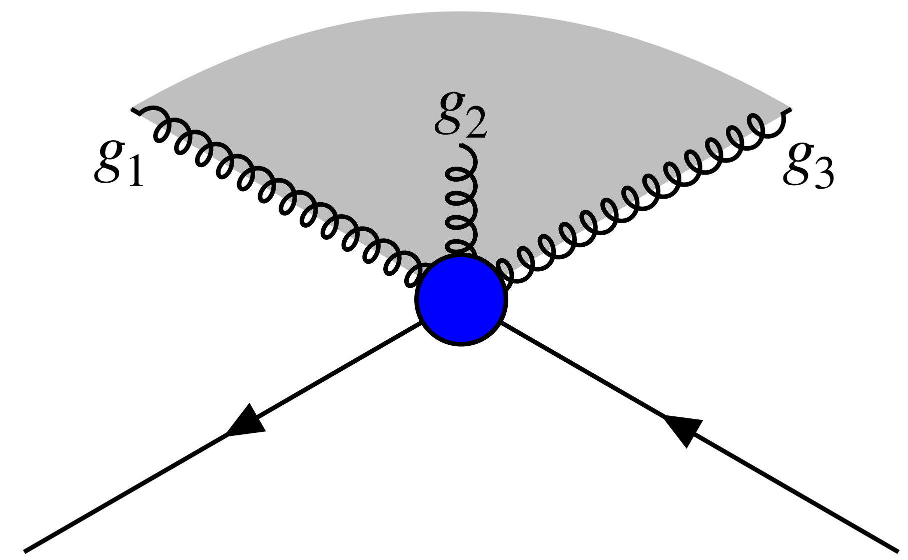
Lopez-Villarejo & **PS** 1109.3608
Brooks, Preuss & **PS** 2003.00702

Sector antennae *Kosower, hep-ph/9710213 hep-ph/0311272 (+ Larkoski & Peskin 0908.2450, 1106.2182)*

Divide the n-**gluon** phase space up into n **non-overlapping sectors** →

Inside each of which **only the most singular** (~"classical") kernel is allowed to contribute.

Example: $Z \to q\bar{q}ggg$



Sectorization:

When 2 is "softest", the **only** contributing history is 2 emitted by 1 and 3

No "sum over histories"

Lorentz-invariant def of "**softest" gluon** based on "ARIADNE p_T": *Gustafson & Pettersson, NPB 306 (1988) 746*

$$p^2_{\perp j} = \frac{s_{ij} s_{jk}}{s_{ijk}} \qquad \text{with } s_{ij} \equiv 2(p_i \cdot p_j)$$

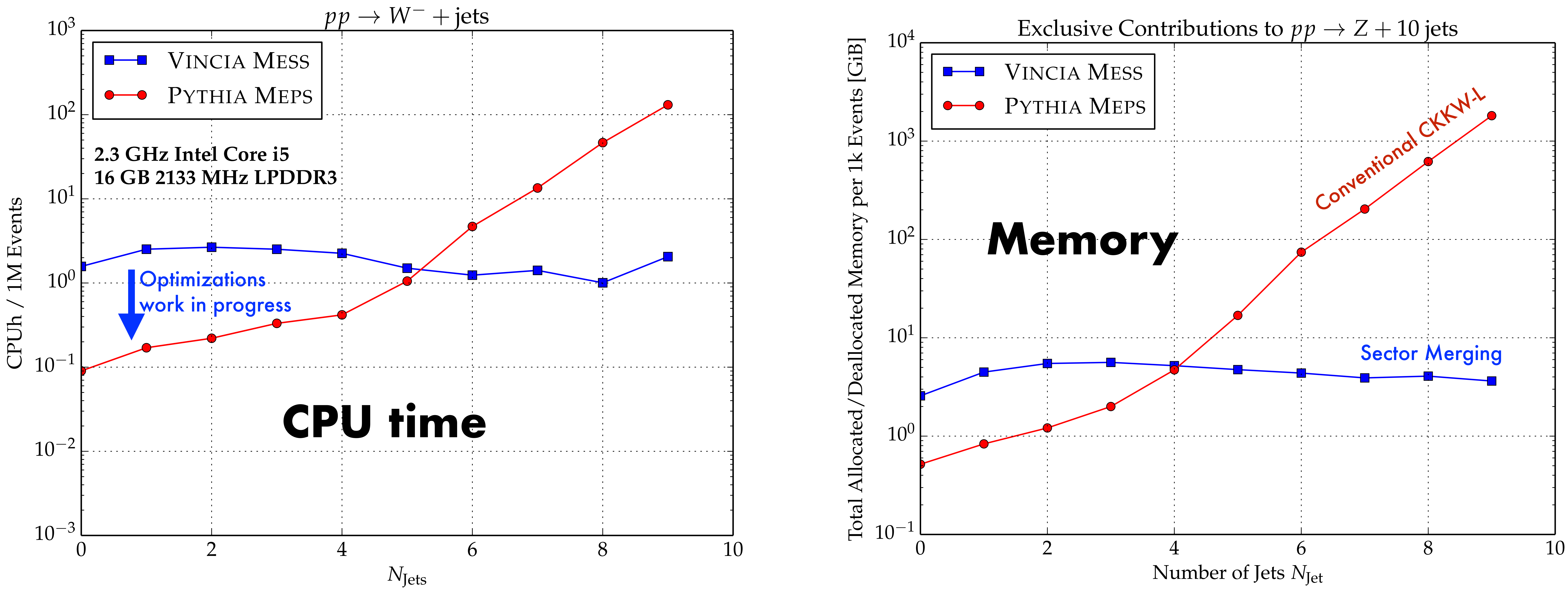
(+ generalisations for heavy-quark emitters)
Brooks, Preuss & PS 2003.00702

Achieves (N)LL **with a single history.**

Factorial → **constant scaling** in number of gluons.

Generalisation to $g \to q\bar{q} \implies$ factorial in # of same-flavour quark pairs.

From Factorial to Constant Scaling



Brooks & Preuss, "Efficient multi-jet merging with the VINCIA sector shower", 2008.09468

Ready for serious applications ("sector merging" publicly available in PYTHIA)

Work ongoing to optimise baseline algorithm.

Discovery Project (22): **NNLO** matching, $2 \to 4$ sector antennae, **NLO** interfaces, …

Precision Frontier 2: Shower Accuracy

Our Approach: 2nd-order (NNLO) Radiative Corrections

Iterating **only** single emissions, one after the other, will fail to properly describe **multi-emission interferences & correlations**

Past: Iterating single **and** double emissions ➜ **problematic overlaps, double counting**

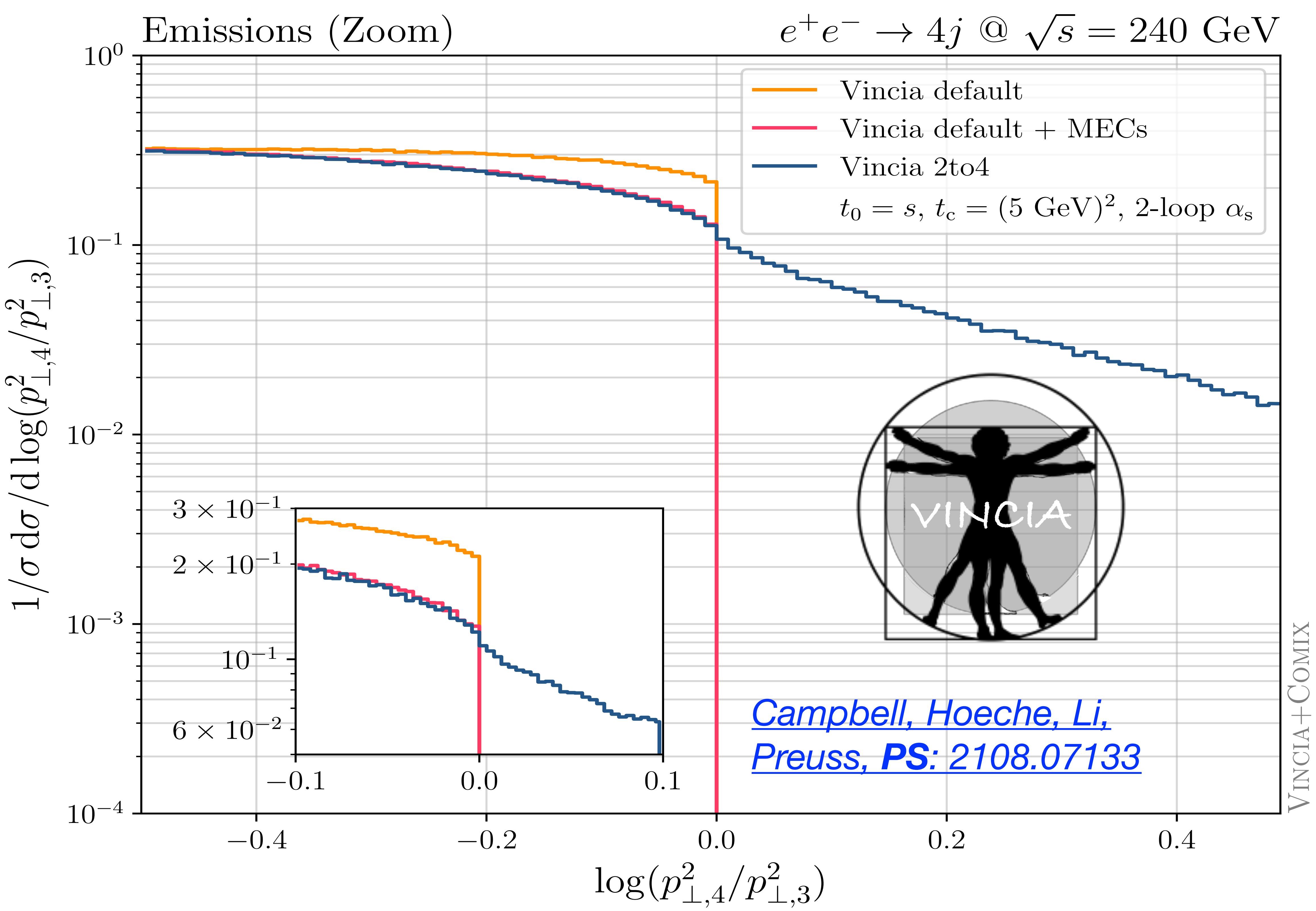
VINCIA sector approach

➜ **Clean separation of phase space** in non-overlapping "iterated" (2→3) and "direct" (2→4) sectors

Proof of concept @ NNLO:

Campbell, Hoche, Li, Preuss, Skands 2108.07133

Goal: iterate full structure ➜ shower



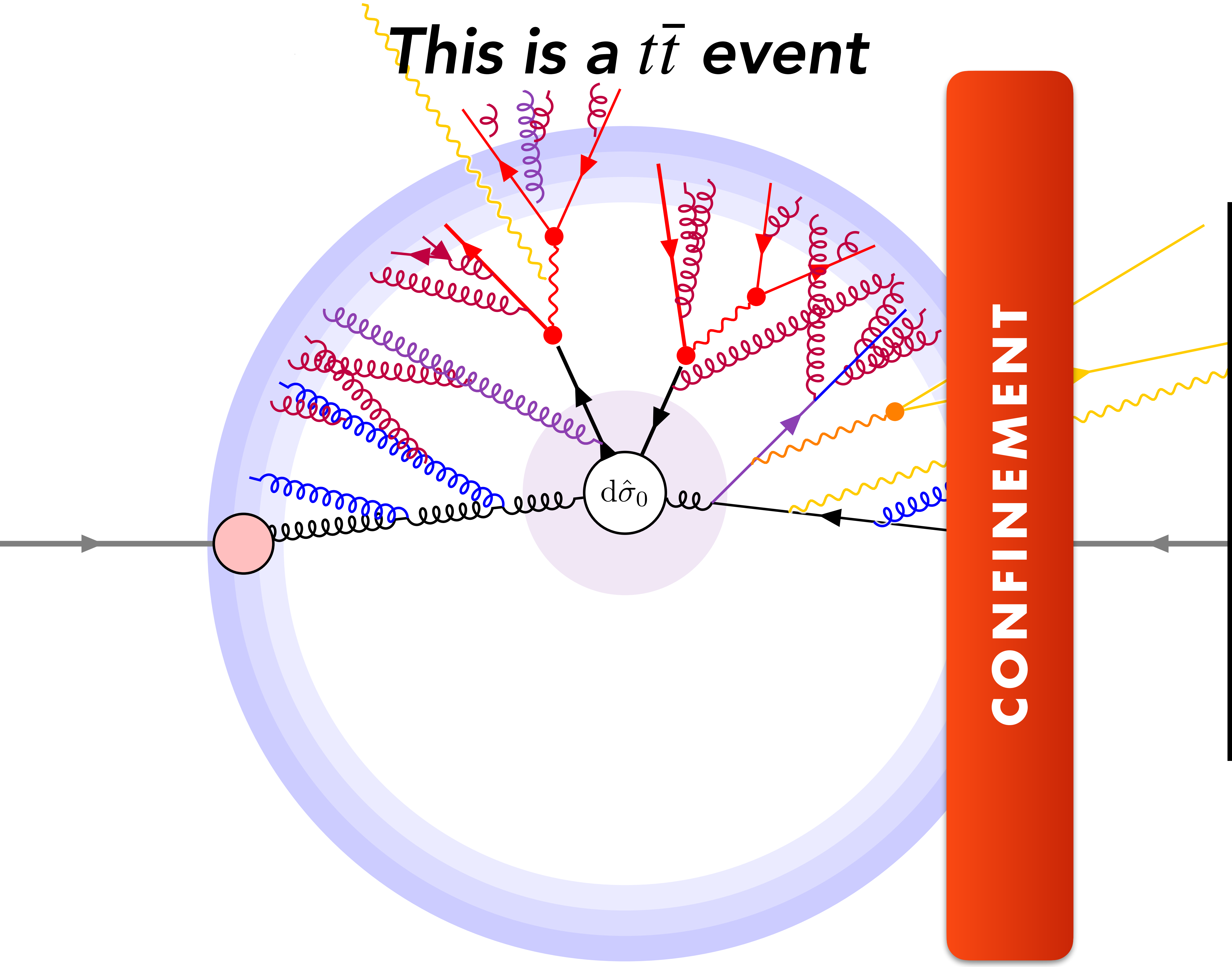
Highly active research field:

Alternative approaches also hotly pursued: E.g.: **PanScales** (Oxford).

Great! *Now* can we compare to measurements?

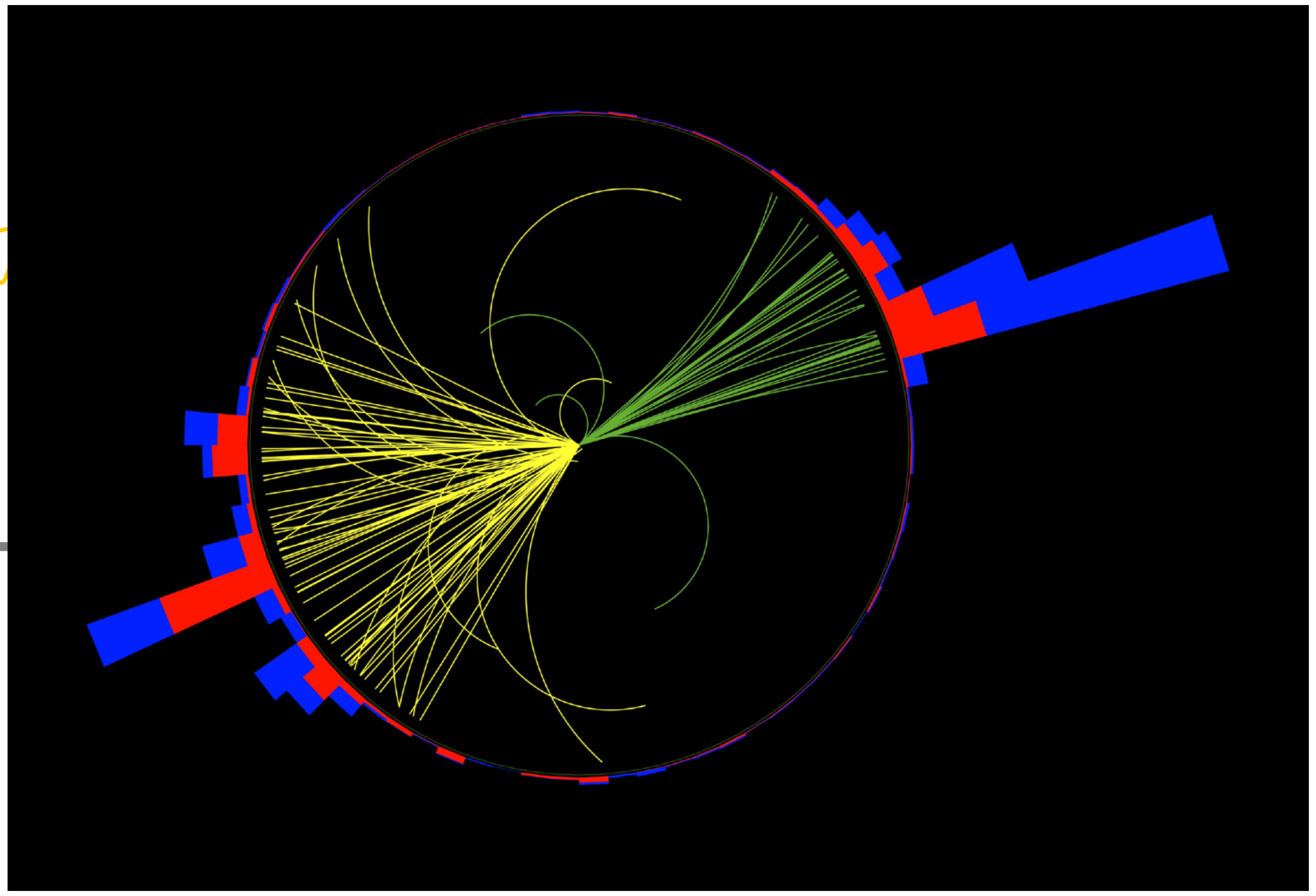
Theorist:

This is a $t\bar{t}$ event



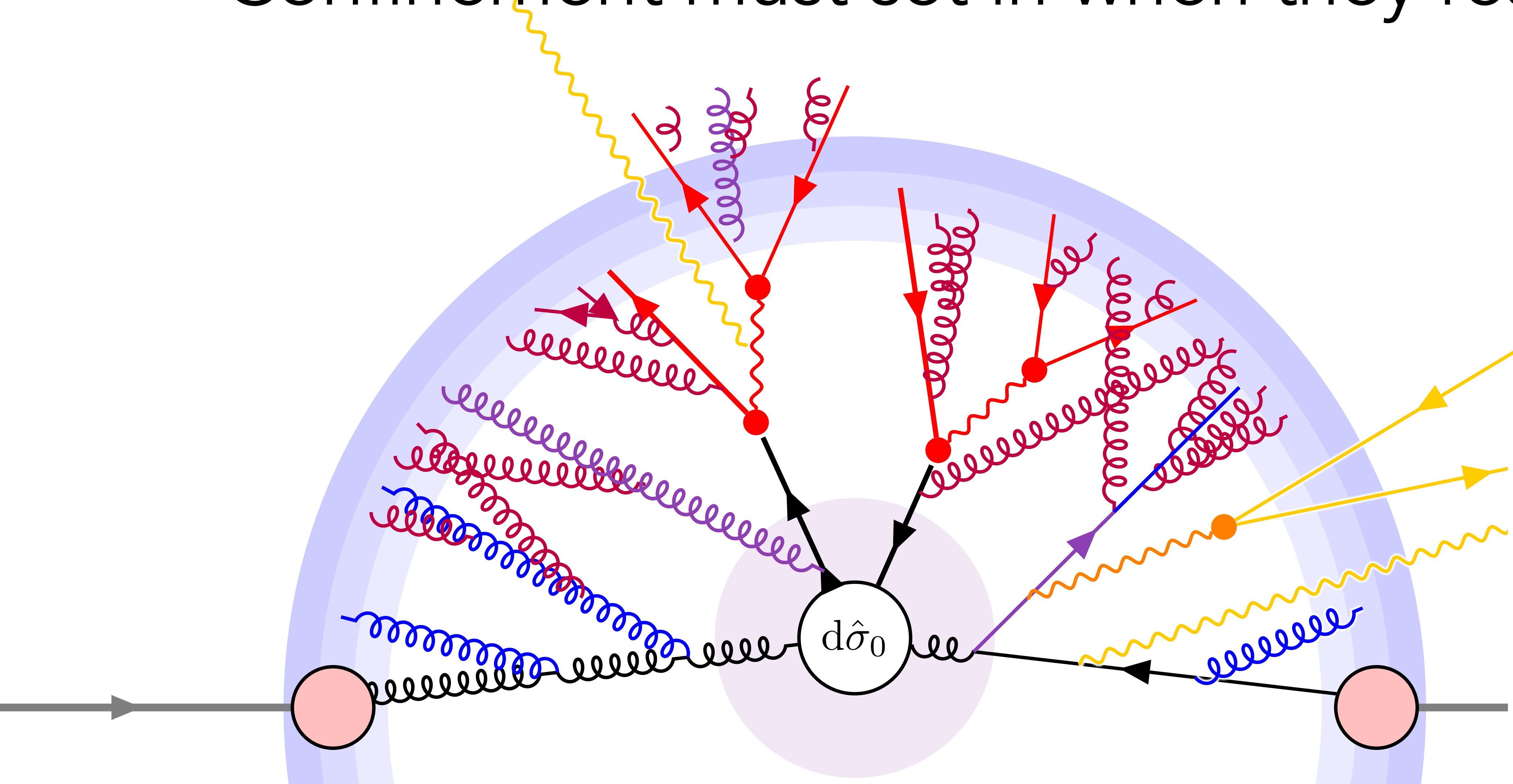
Experimentalist:

Is this a $t\bar{t}$ event?



Event structure still in terms of (colour-charged) quarks & gluons

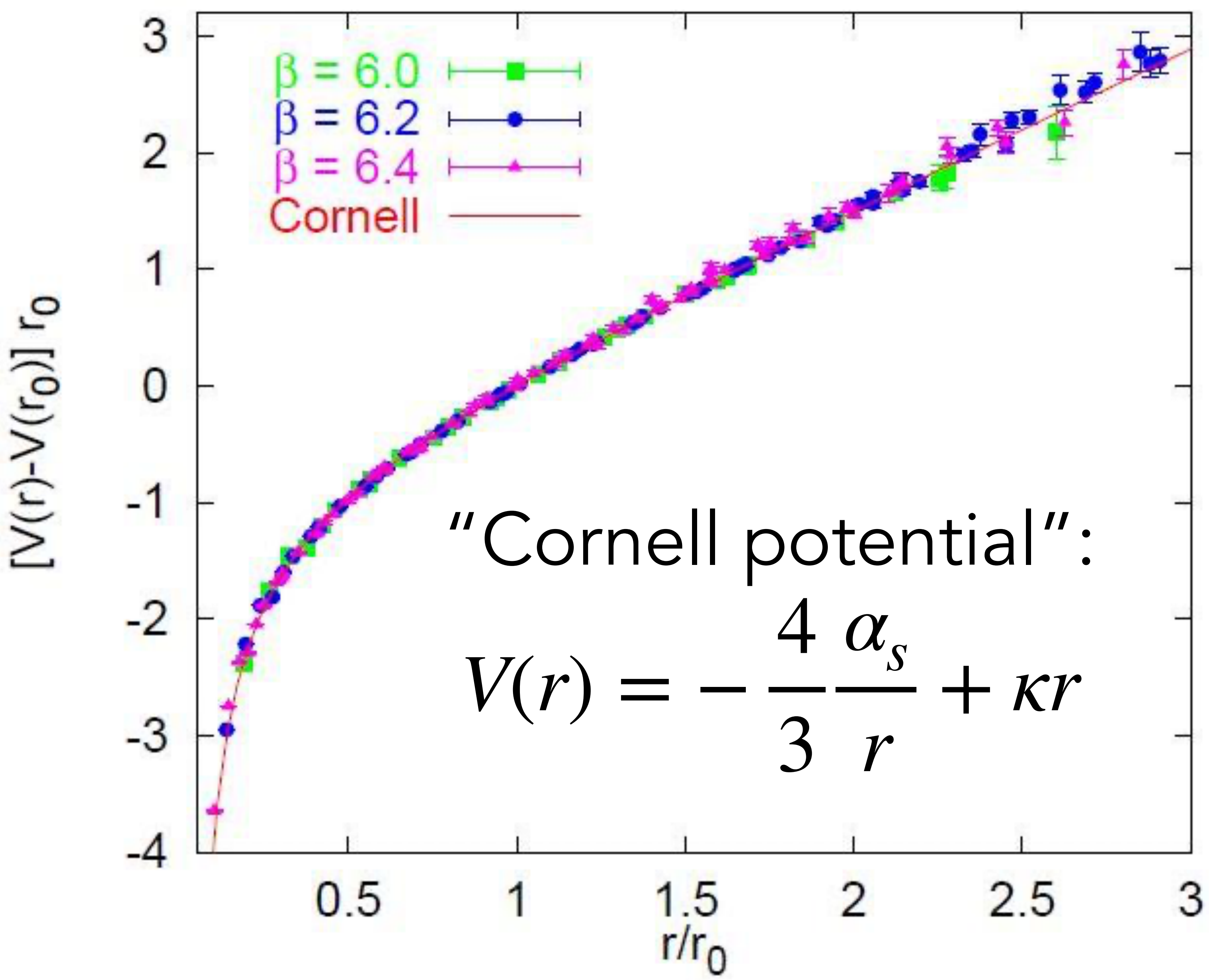
Confinement must set in when they reach O(1fm) relative distances.



Question:

What physical system has a linear potential?

Between a single quark-antiquark pair, we know the long-distance behaviour is a linear potential



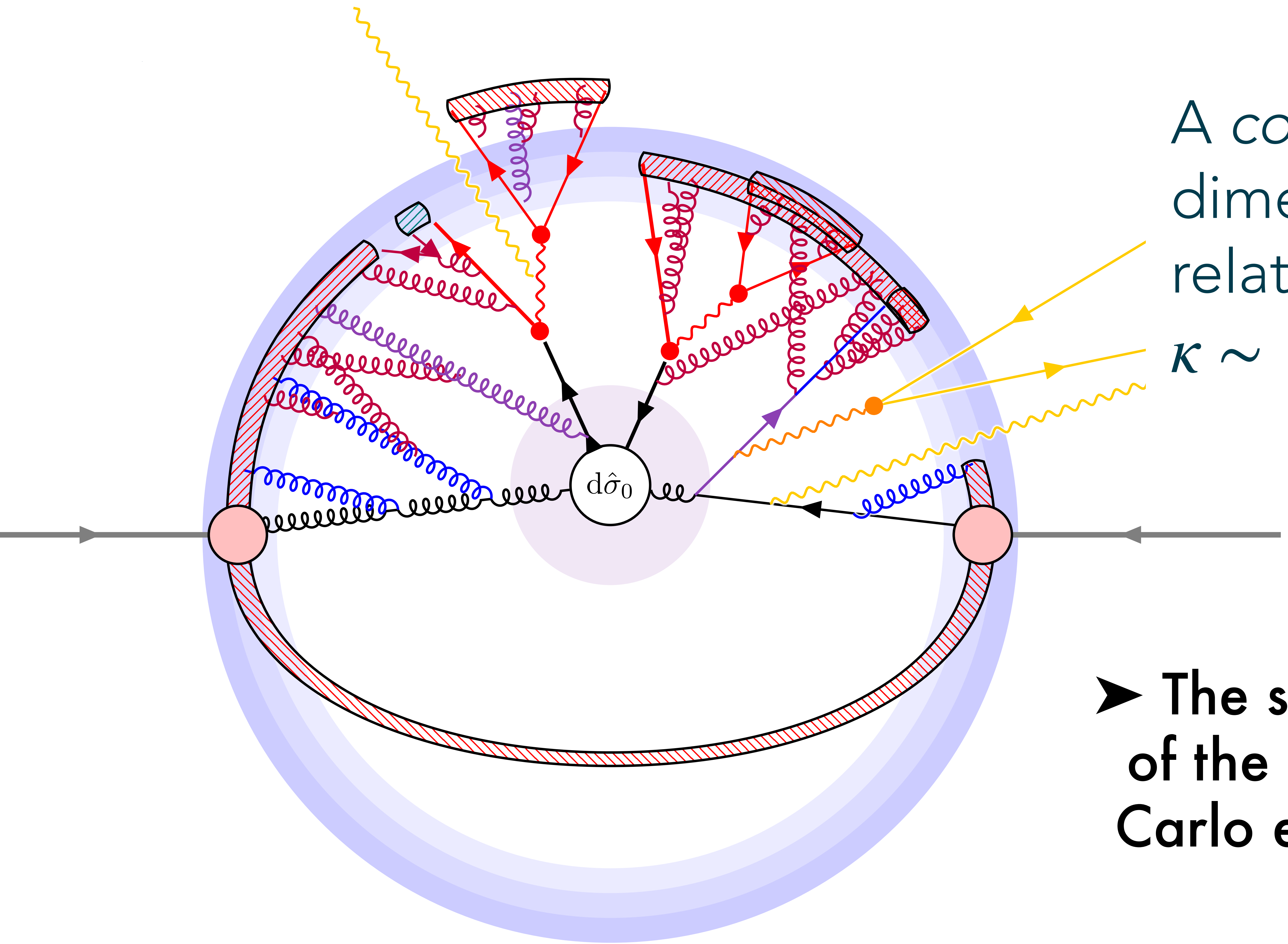
"Cornell potential":

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \kappa r$$

$r_0 = 0.5\mathrm{fm}$ $\kappa \sim 0.9\,\mathrm{GeV/fm}$

This is the basis for the **Lund String Fragmentation Model**

Andersson, Gustafson, Pettersson, Sjöstrand, … ('78 - '83)



A *comparatively* simple 1+1 dimensional model of massless relativistic strings, with tension $\kappa \sim 1\ \mathrm{GeV/fm}$

➤ **The signature feature of the PYTHIA Monte Carlo event generator**

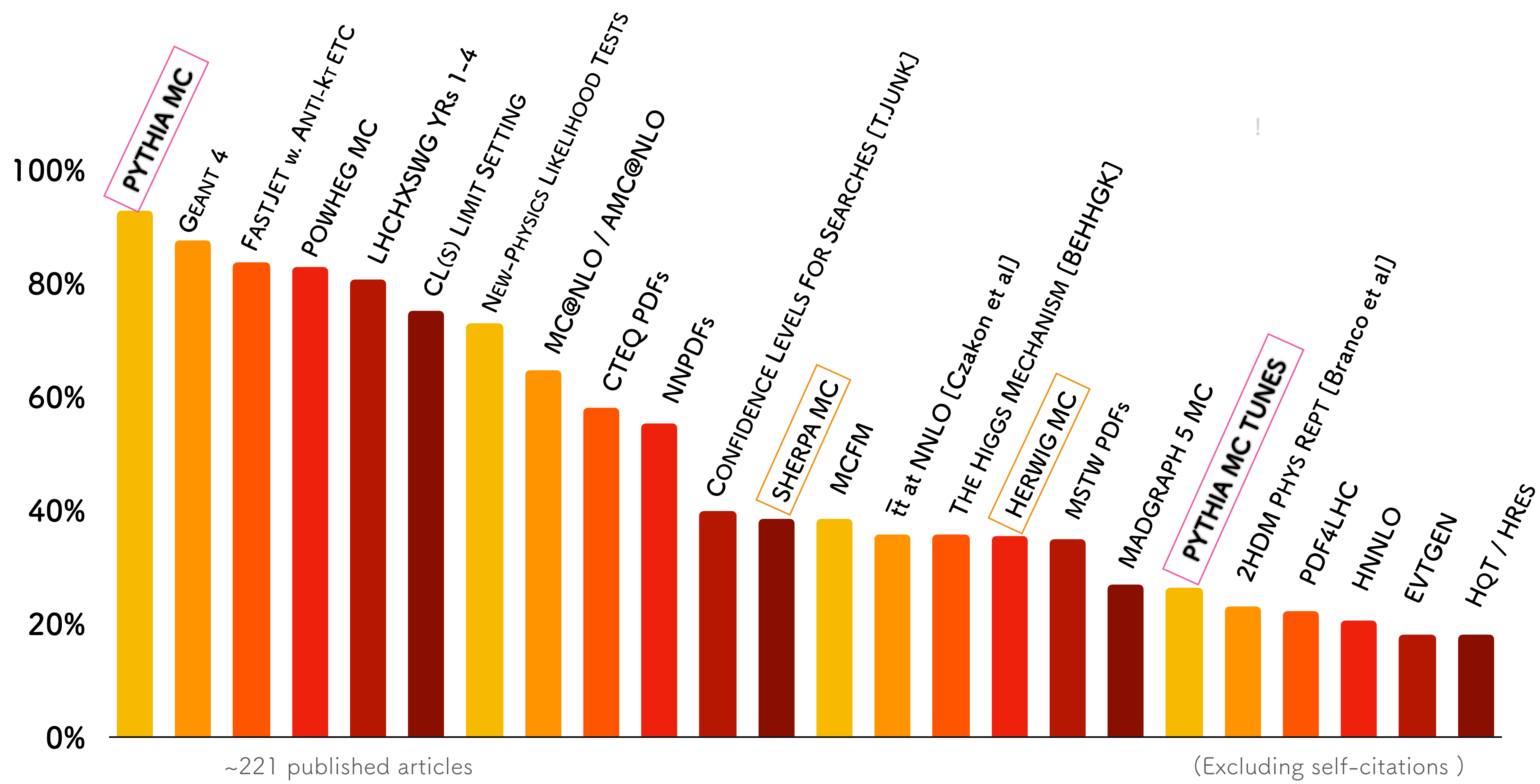
Ability to fully model collider "events" $\Longrightarrow$ versatile vessel for applications

General-purpose event generators (PYTHIA, HERWIG, SHERPA + more specialised) used, in one way or another, by almost every experimental collider-physics study

Theoretical work often closely informed by experimental opportunities & needs

Fairly recent (2019) collation by K. Hamilton (UCL)

% of Higgs papers from LHC experiments citing a given article 2014 — 2019



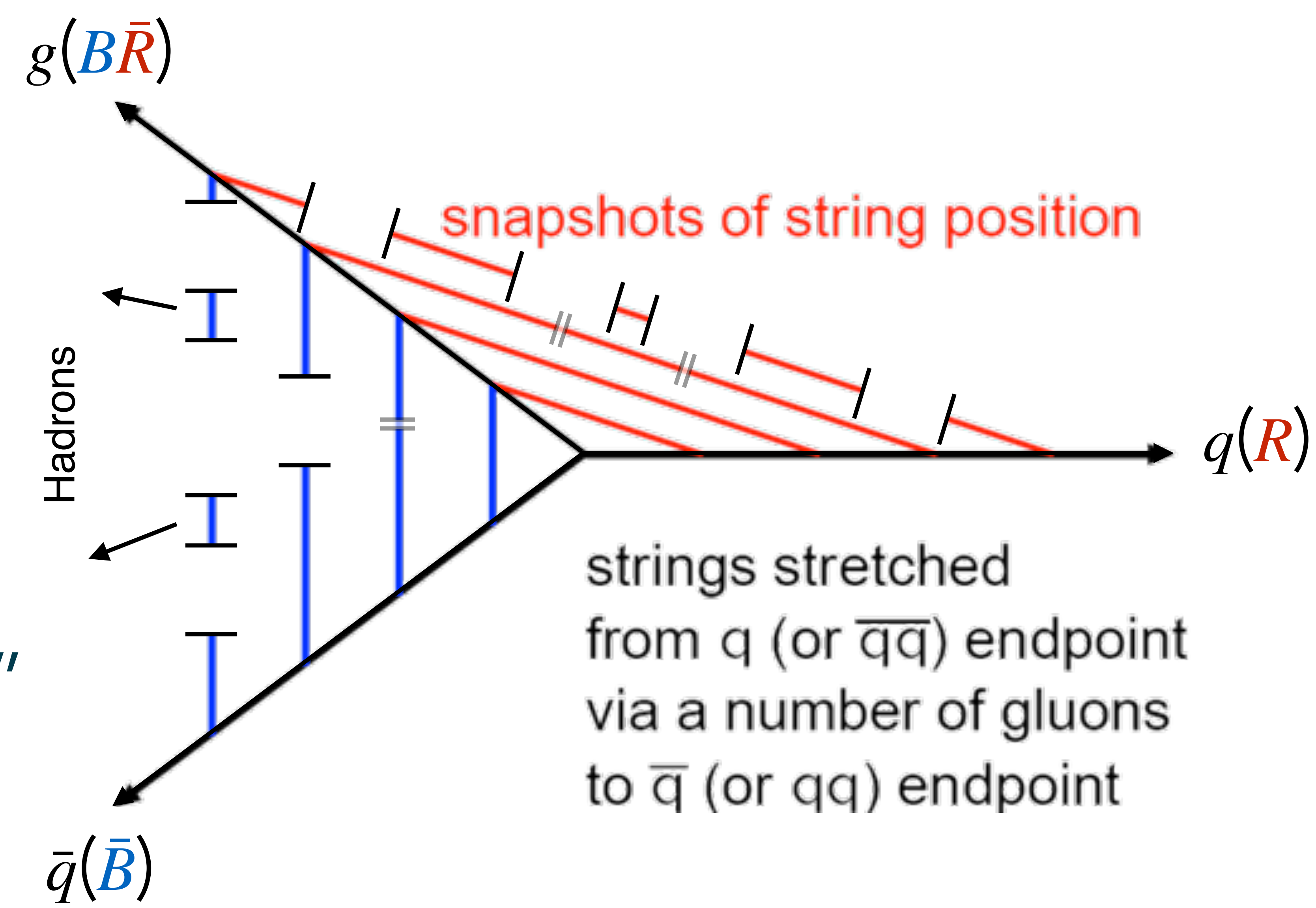
A New Set of Degrees of Freedom

The string model provides a mapping:

Quarks ➤ String endpoints

Gluons ➤ Kinks on strings

Further evolution then governed by string world sheet (area law)



+ string breaks by tunnelling

By analogy with "Schwinger mechanism" in QED (electron-positron pair production in strong electric field)

Predictive for phase-space distribution of hadrons (but not for their spin/flavour composition ➤ **Bierlich, Chakraborty, Gustafson, Lönnblad '22**)

Hyperfine splitting effects in string hadronization

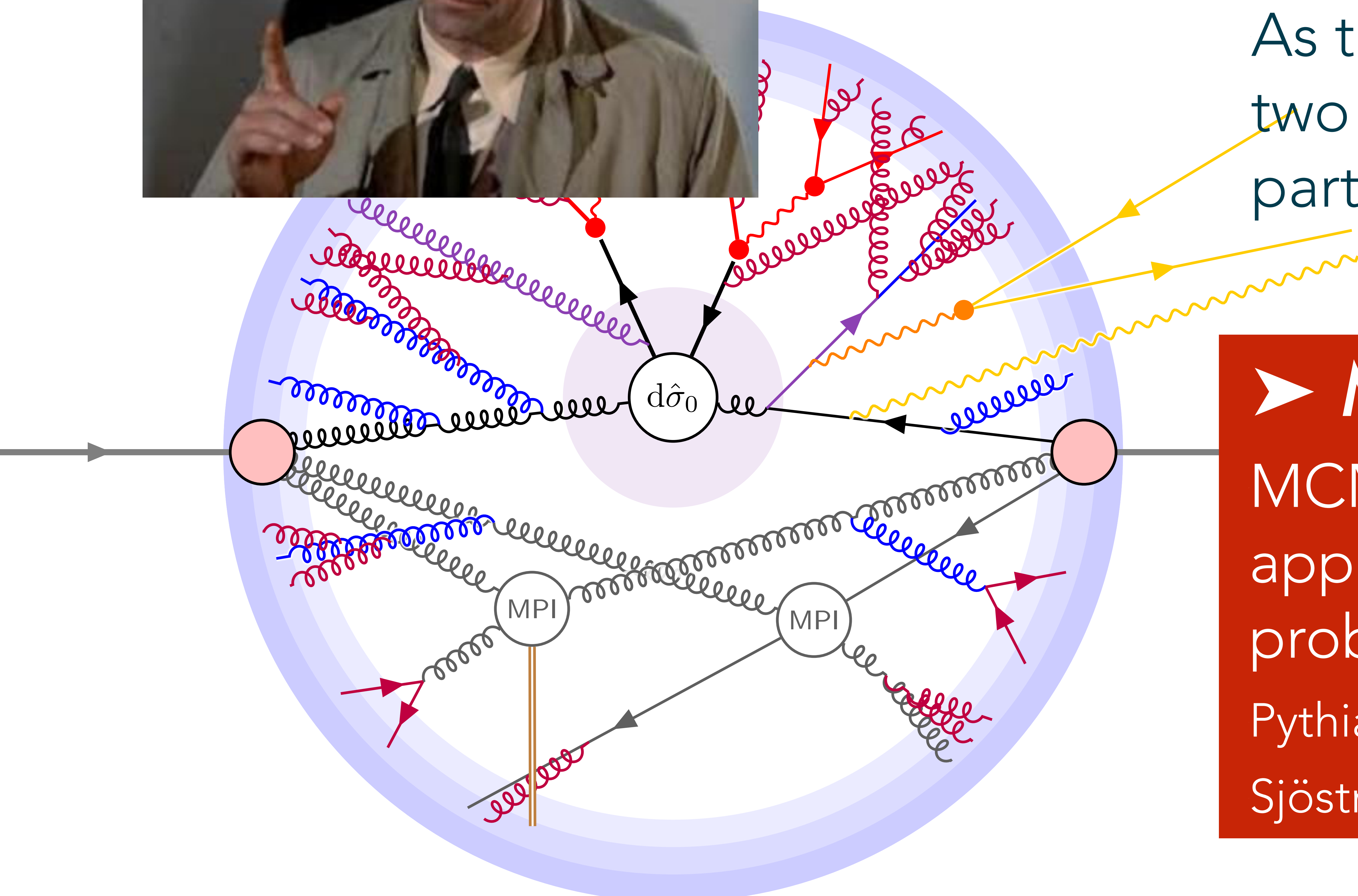
➤ **Jets of Hadrons!**

Such Stuff as Beams are Made Of

Recall that the protons were composite

Who said only a *single* pair of partons collided?

As they pass through each other, the two protons present a **beam** of partons to each other



➤ Multi-Parton Interactions (MPI)

MCMC algorithms with iterated application of factorised scattering probabilities. Around since 80s.

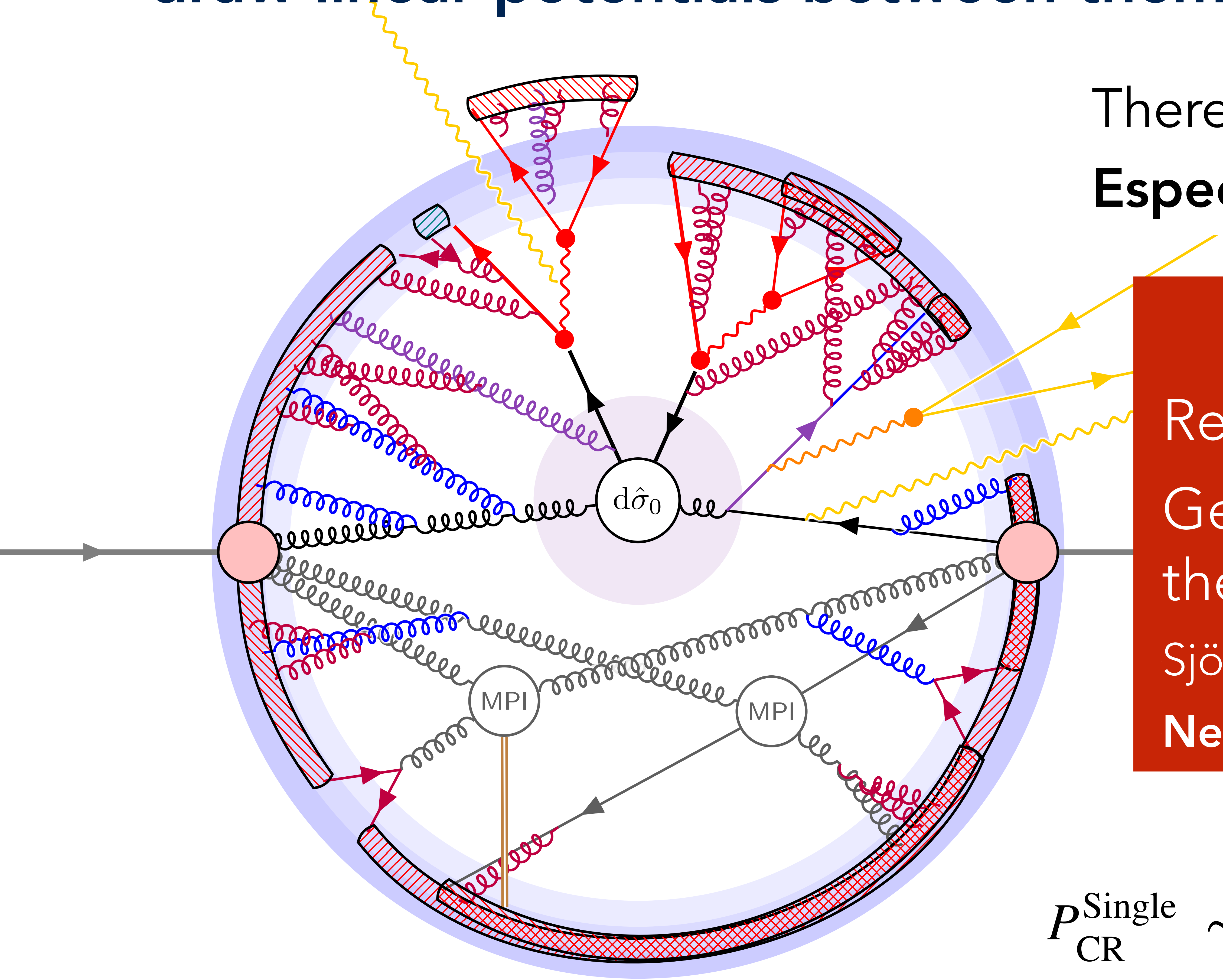
Pythia's "Interleaved" Model:

Sjöstrand + **PS** [EPJC 2005] + a few more recent

Crucial to describe event structure at hadron colliders

Colour Confusion

If **we know which partons are each others' "colour partners", we can draw linear potentials between them:**



There are, however, **ambiguities**

Especially in *complex* events with *many* MPI

➤ Colour Reconnections (CR)

Represented by inner blue shaded band.

Generally thought to act to **minimise** the **total** linear potential.

Sjöstrand & v. Zijl ('85), **PS** & Wicke ('07) , …

New Model based on SU(3)$_C$: Christiansen & **PS** ('15)

$$P_{\mathrm{CR}}^{\mathrm{Single}} \sim \frac{1}{N_C^2} \sim 10\,\% \implies P_{\mathrm{No\ CR}}^{\mathrm{MPI}} \propto \left(1 - \frac{1}{N_C^2}\right)^n \to 0$$

String Junctions — Another Exciting Discovery at LHC ?

Baryon Number Violation & String Topologies: Sjöstrand & PS hep-ph/0212264

String Formation Beyond Leading Colour: Christiansen & PS 1505.01681

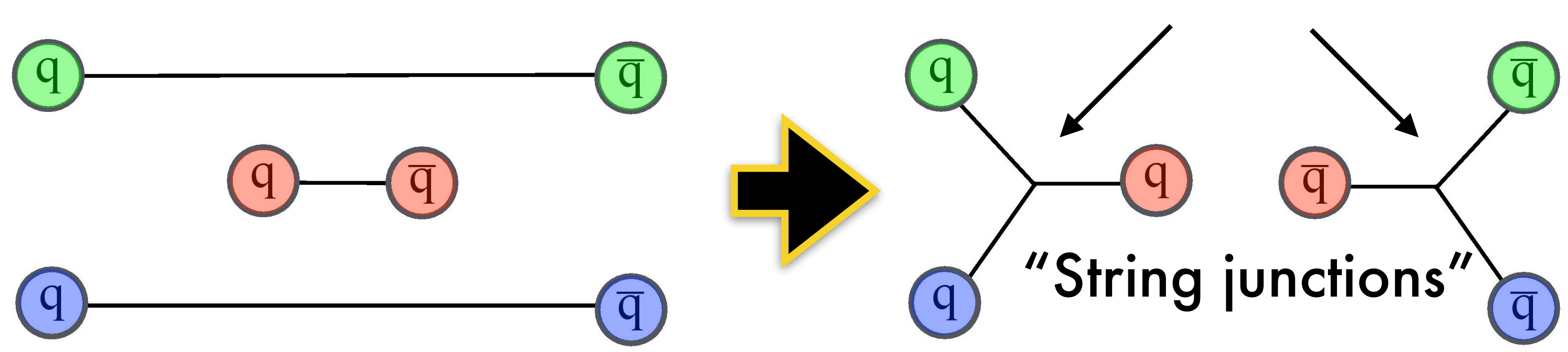
Stochastic sampling of SU(3) group probabilities (e.g., $3 \otimes 8 = 15 \oplus 6 \oplus 3$)

⟹ Random (re)connections in colour space (weighted by group weights)

Christiansen & PS 2015

Illustration by J. Altmann

For example:



New source of low-pT heavy-flavour baryons

Sjöstrand & PS 2002

Limiting case: one leg is a low-p_T heavy quark

➤ **Heavy-flavour** "Diquarks"

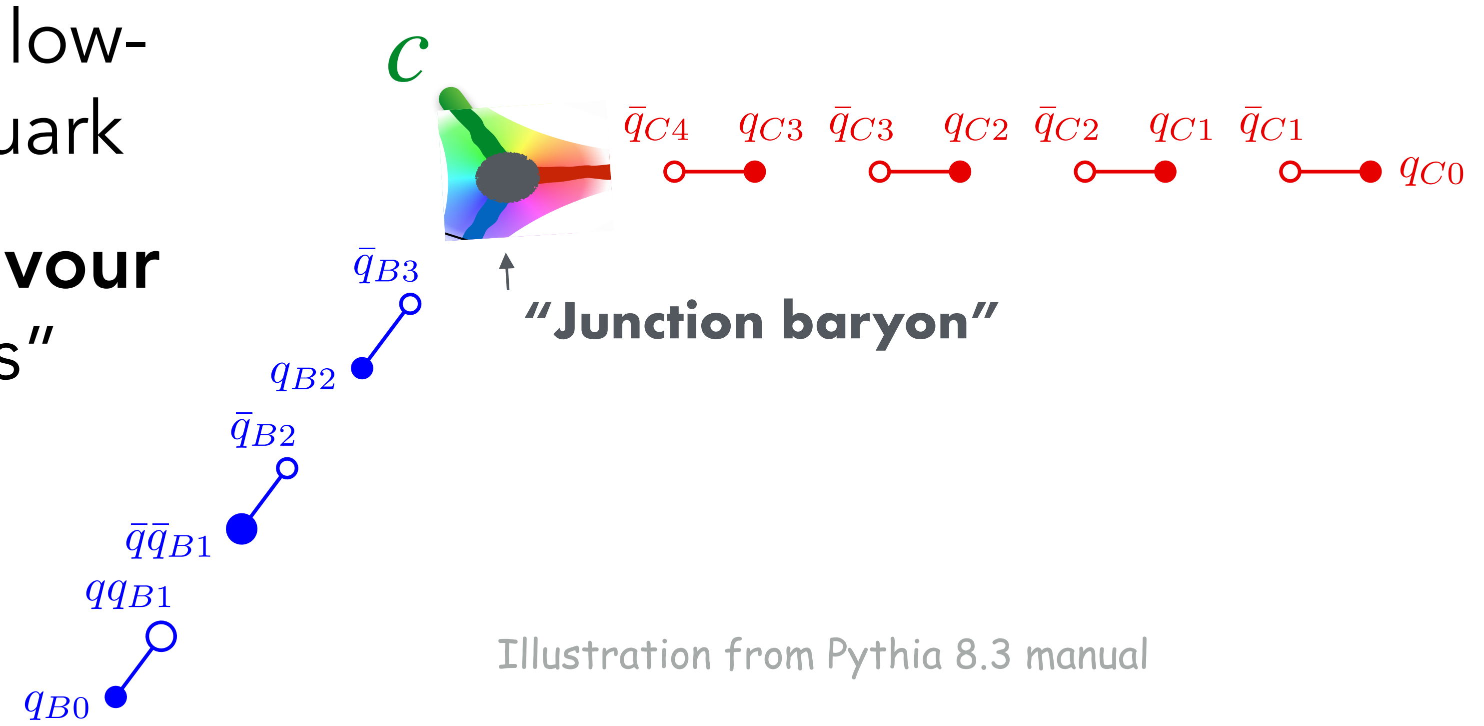
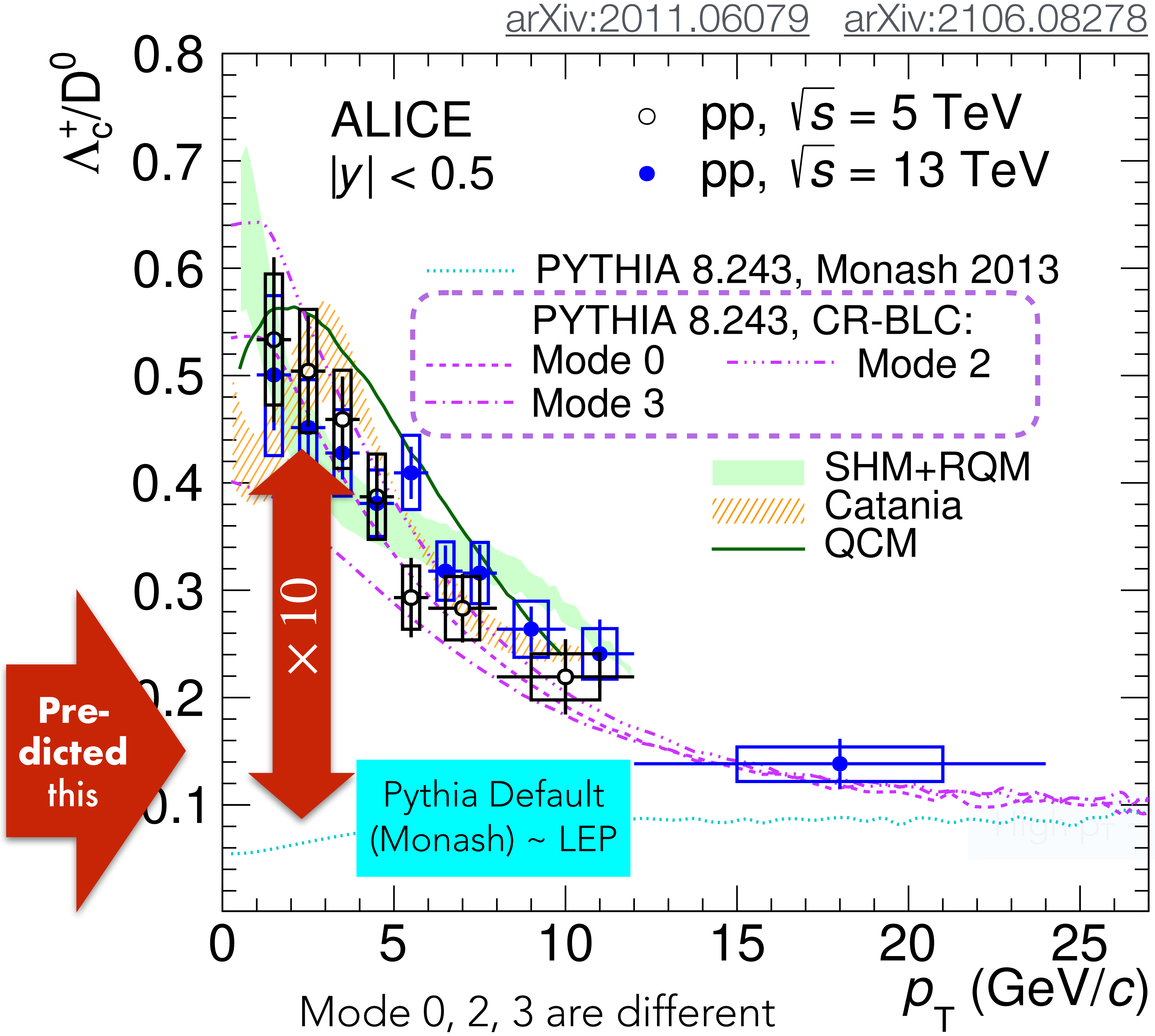


Illustration from Pythia 8.3 manual

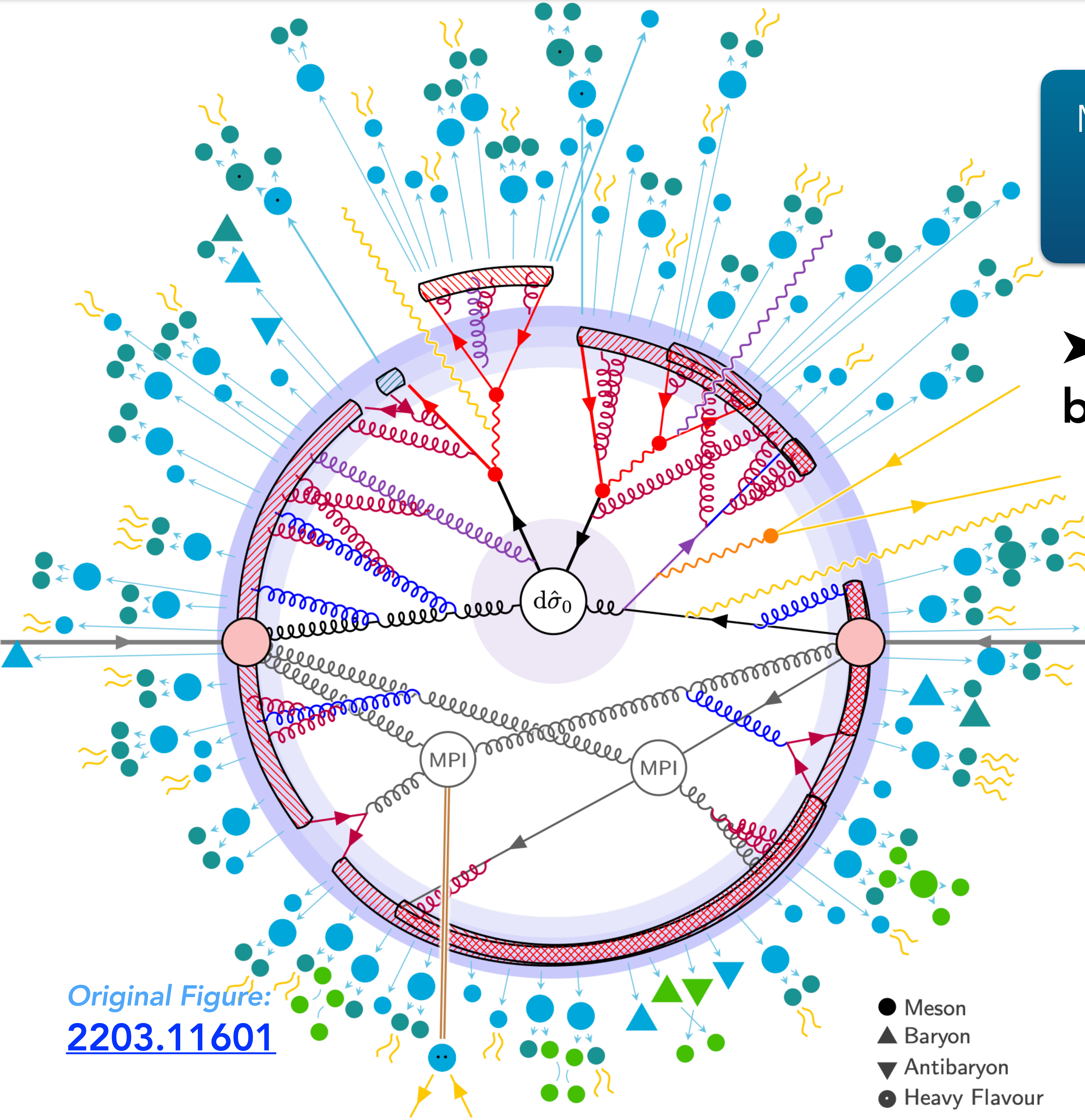
ALICE 2021

arXiv:2011.06079 arXiv:2106.08278



Mode 0, 2, 3 are different causality restrictions (0 = none)

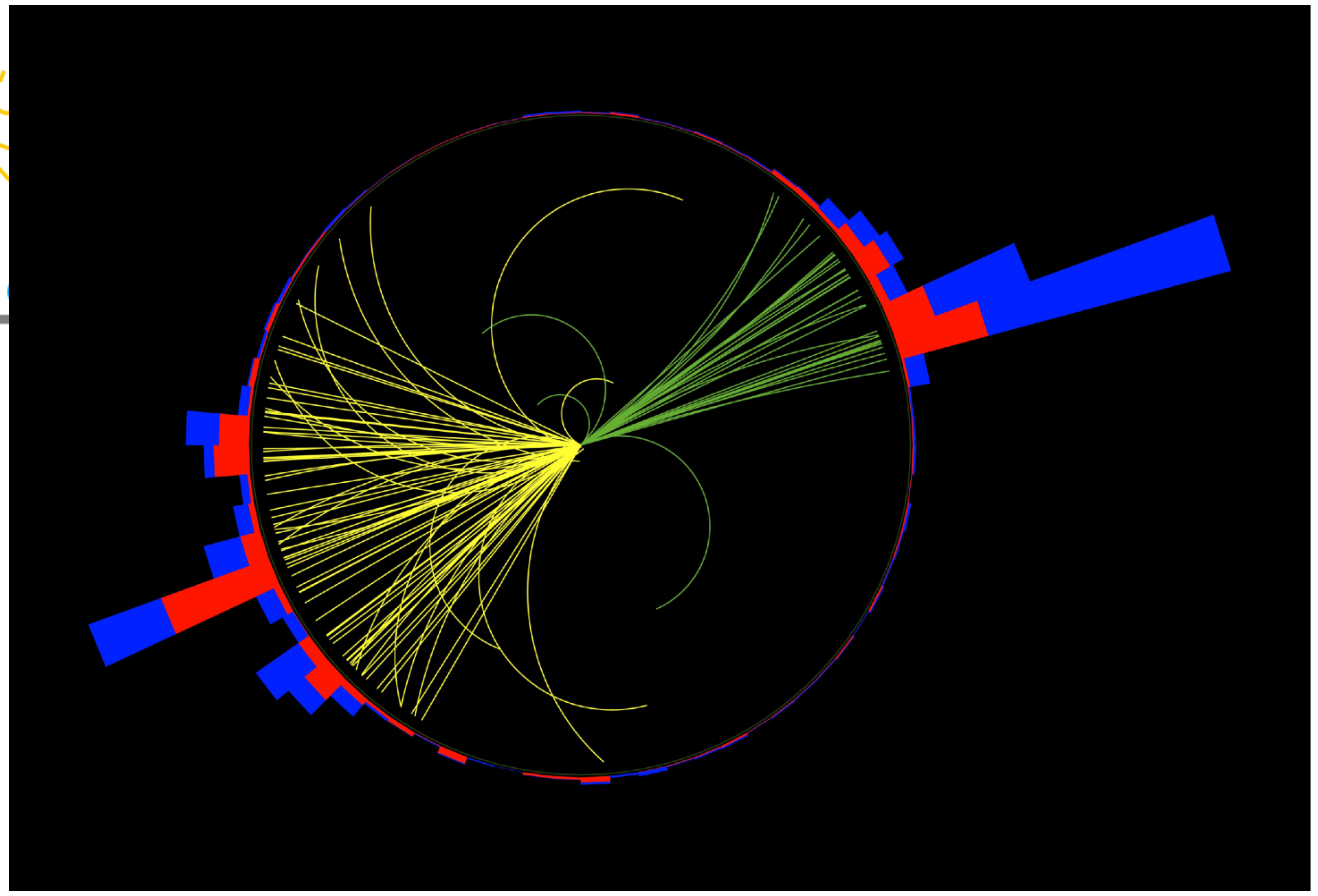
The Anatomy of an LHC Collision



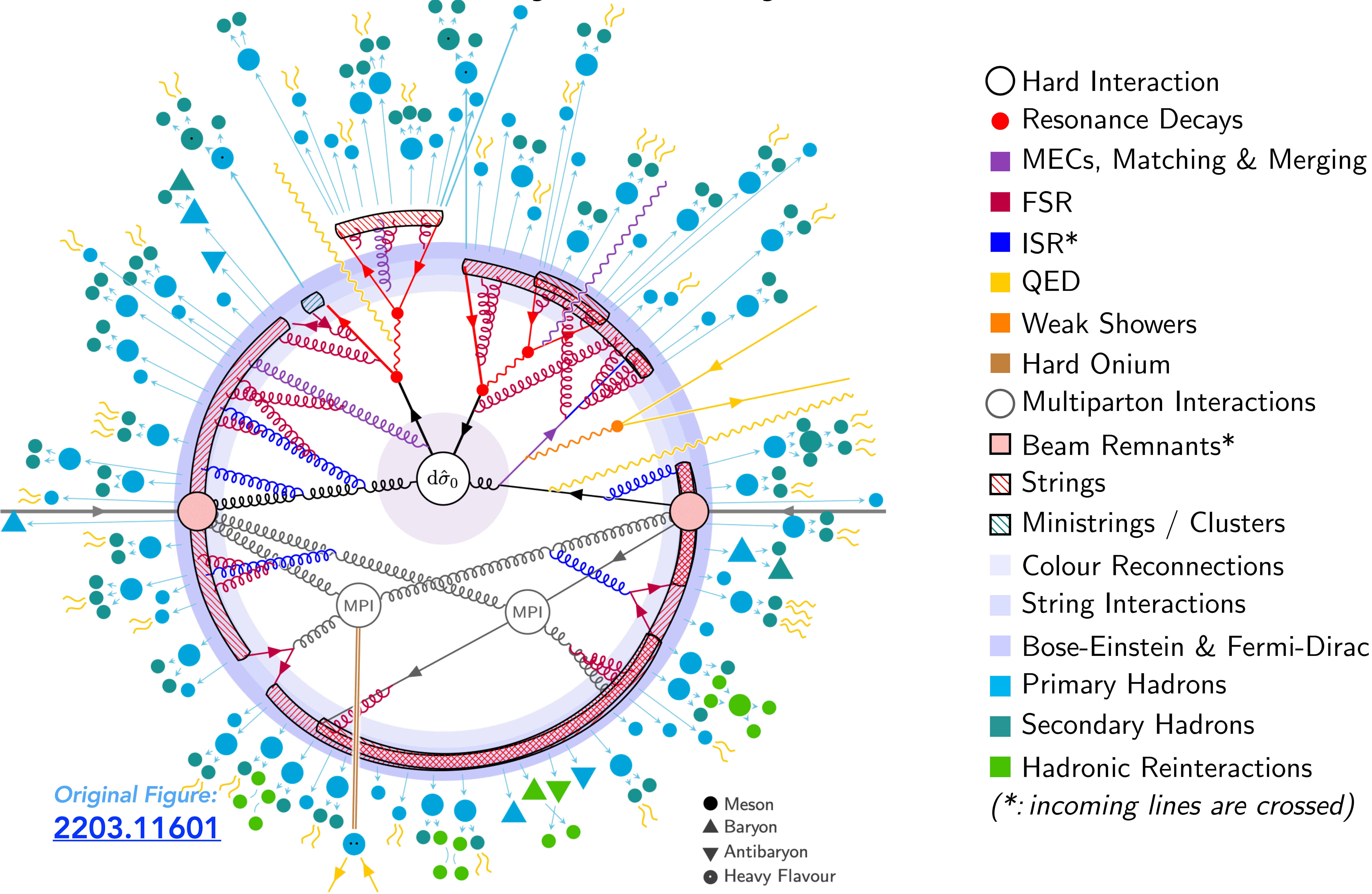
Original Figure:
[2203.11601](https://arxiv.org/abs/2203.11601)

Many more exciting discoveries, studies, mathematics, models, and details, but could not fit in colloquium!

➤ **We finally have a model that can be compared to experiments …**



Thank you for your attention!



Original Figure: 2203.11601