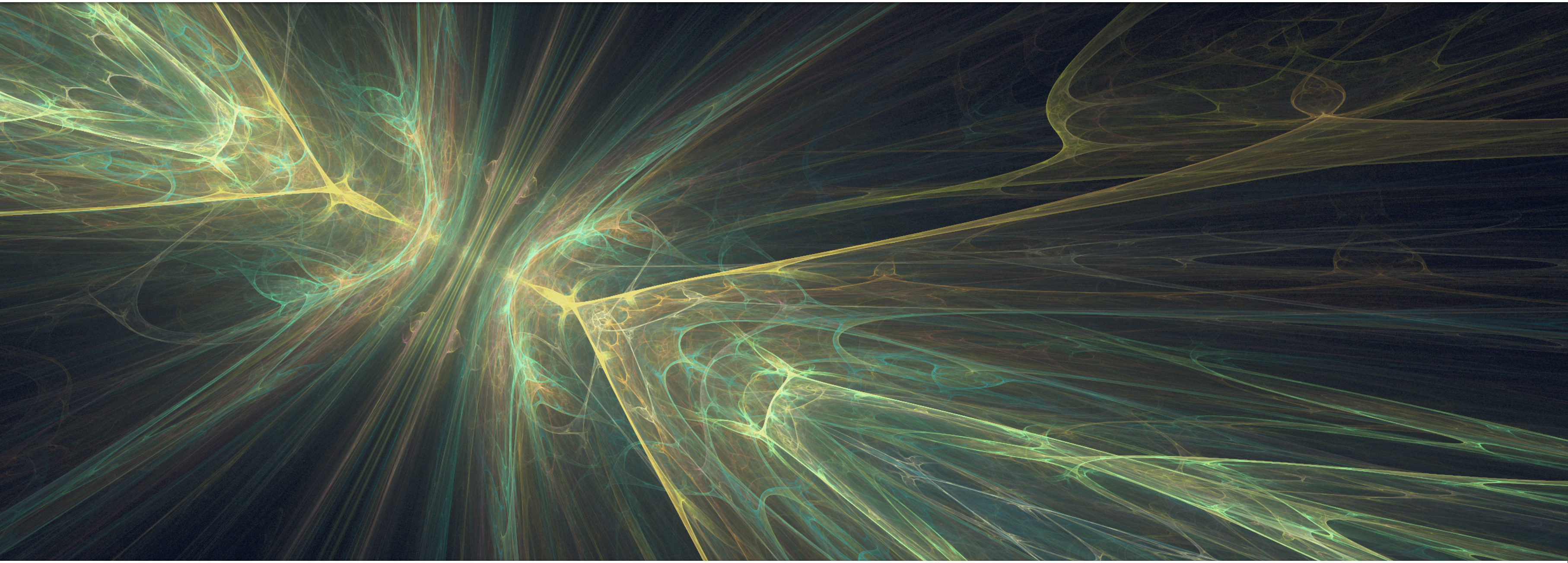
Emergent Phenomena at High Energies

Peter Z Skands — Royal Society Wolfson Visiting Fellow — U of Oxford & Monash U



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The Goal

Use measurements to test hypotheses about Nature

Problem 1: no **exact** solutions to QFT

→ Perturbative **Approximations**

The Goal

Use measurements to test hypotheses about Nature

Problem 1: no **exact** solutions to QFT
➜ Perturbative **Approximations**

New techniques

➜ New insights into perturbation theory at non-trivial orders

➜ new applications

Problem 2: We collide — and observe — **hadrons**

Strongly Bound States

The Goal

Use measurements to test hypotheses about Nature

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➜ Perturbative **Approximations**

New techniques

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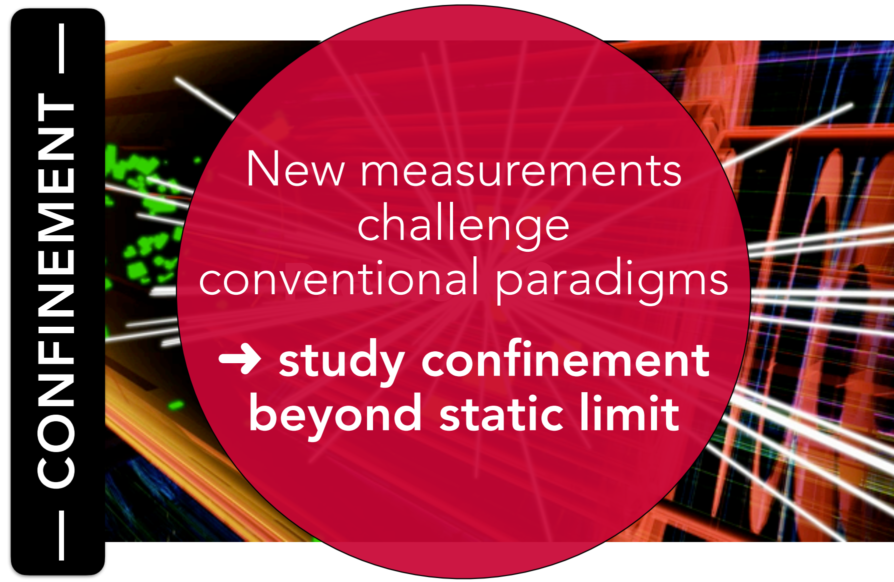


New measurements challenge conventional paradigms

➜ study confinement beyond static limit

Problem 2: We collide — and observe — **hadrons**

Strongly Bound States

Emergent Phenomena at High Energies

G. H. Lewes: *"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", 1875

In Quantum Field Theory:

"Components" ~ **Elementary interactions** — encoded in $\mathscr{L}$

"Sums" ~ Perturbative expansions ~ combinations of elementary interactions

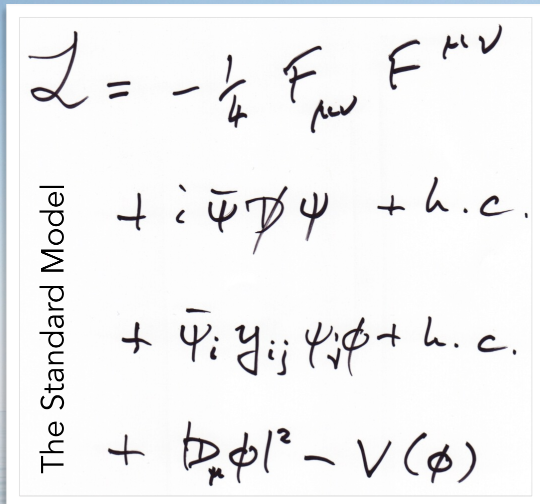
What else is there? Structure beyond (fixed-order) perturbative expansions:

Fractal scaling, of jets within jets within jets …

& loops within loops within loops …

Confinement (in QCD), of coloured partons within hadrons

Ulterior Motives for Studying QCD



+ ?

LHC: 90% of data still to come

➜ higher sensitivity to smaller signals.

High statistics ↔ high accuracy

Consider a hadron; why is it complicated?

Popular science:
Three quarks for
muster mark

Undergraduates:
Quark-Model
wave functions

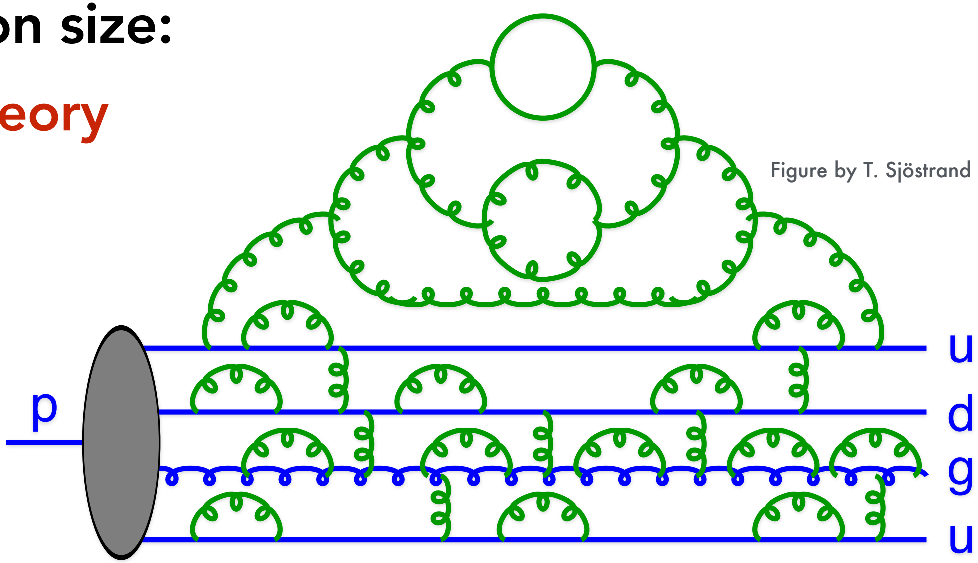
Real-Life Hadrons

Strongly bound states of quarks and gluons

With a complicated time-dependent structure

For wavelengths $\gtrsim$ proton size:

Can't do perturbation theory



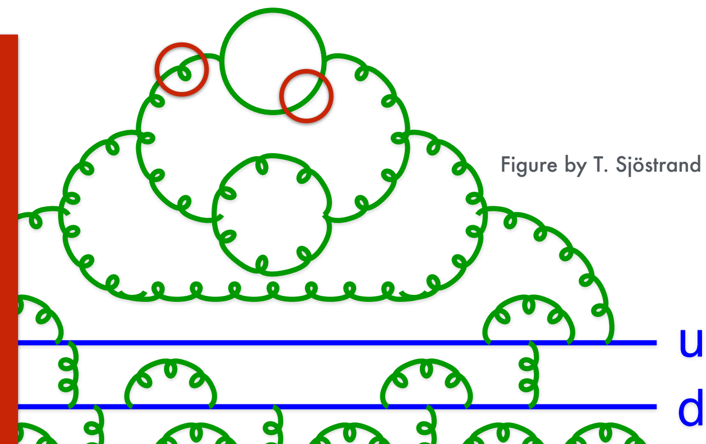
To the Rescue: Asymptotic Freedom

Over short distances ≪ proton radius:

Quarks and gluons do behave like approximately free particles
~ plane waves ➜ can do perturbation theory

Parametrise nonpeturbative "mess" in terms of **probability densities for each type of plane wave** $(g, d, \bar{d}, u, \bar{u}, s, \bar{s}, \ldots)$:

Parton Distribution Functions
(universal and measurable)



Mathematically expressed via a Factorization Theorem

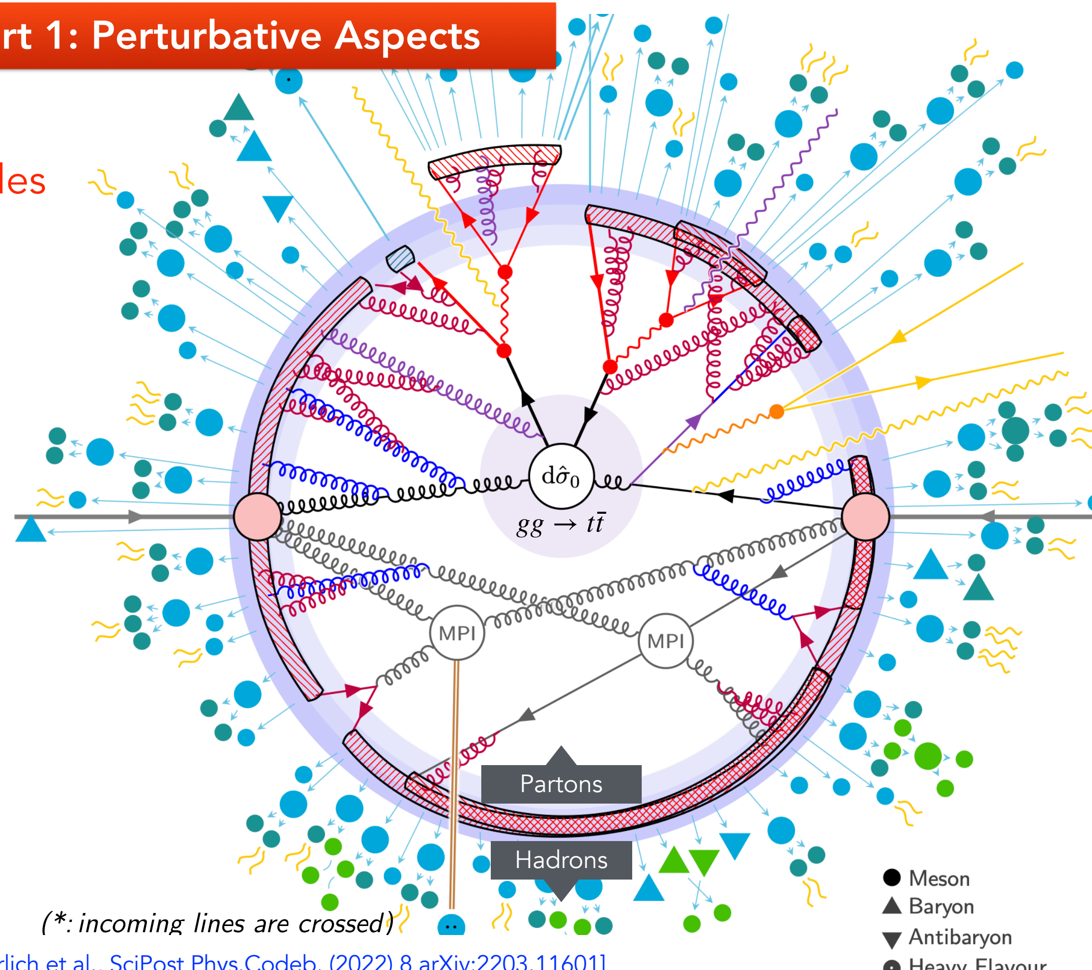
(Example of factorization of short- and long-distance physics)

Organizing High-Energy Scattering Problems

Part 1: Perturbative Aspects

Physics Separation of scales

Maths Factorizations



[Figure from Bierlich et al., SciPost Phys.Codeb. (2022) 8 arXiv:2203.11601]

Organizing High-Energy Scattering Problems

Part 1: Perturbative Aspects

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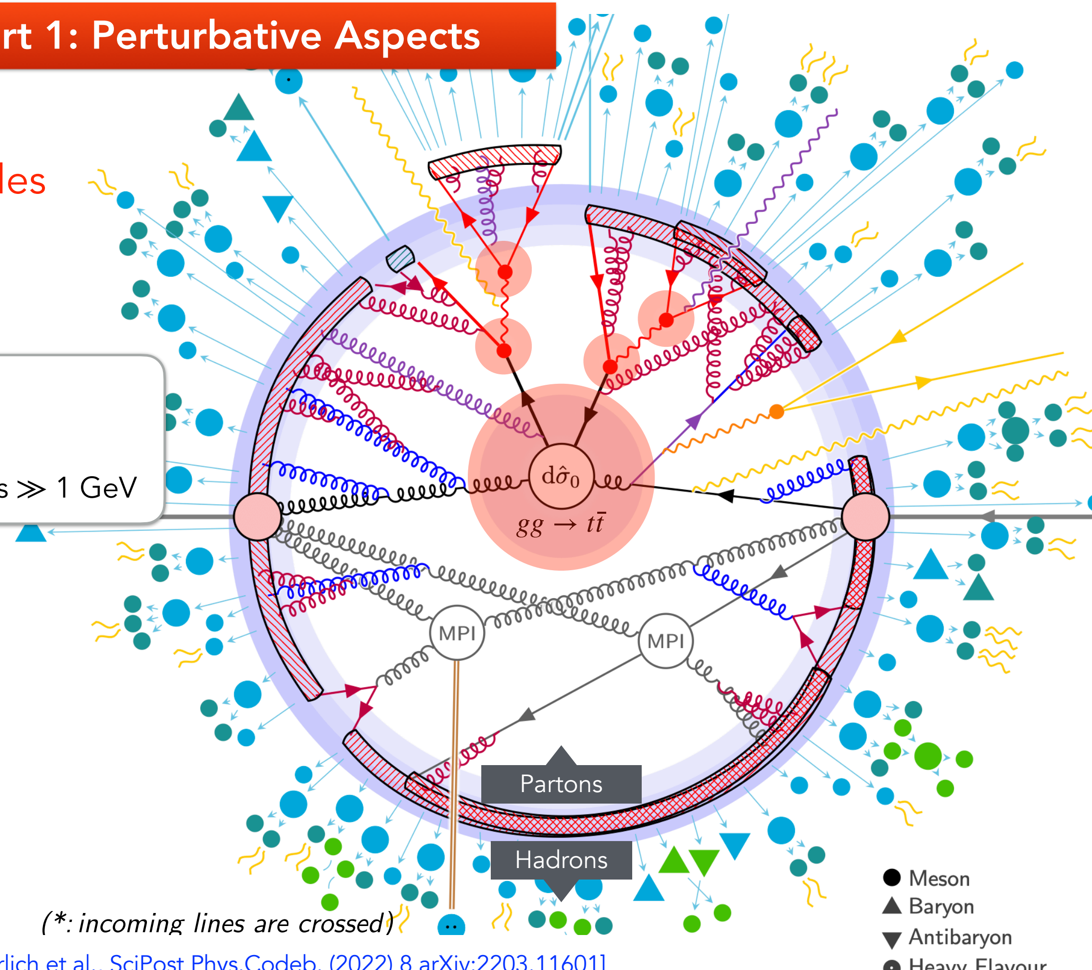
Hard Processes

- ◯ Hard Interaction
- ● Resonance Decays

"Hard" means large momentum transfers $\gg$ 1 GeV



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Organizing High-Energy Scattering Problems

Part 1: Perturbative Aspects

Physics Separation of scales

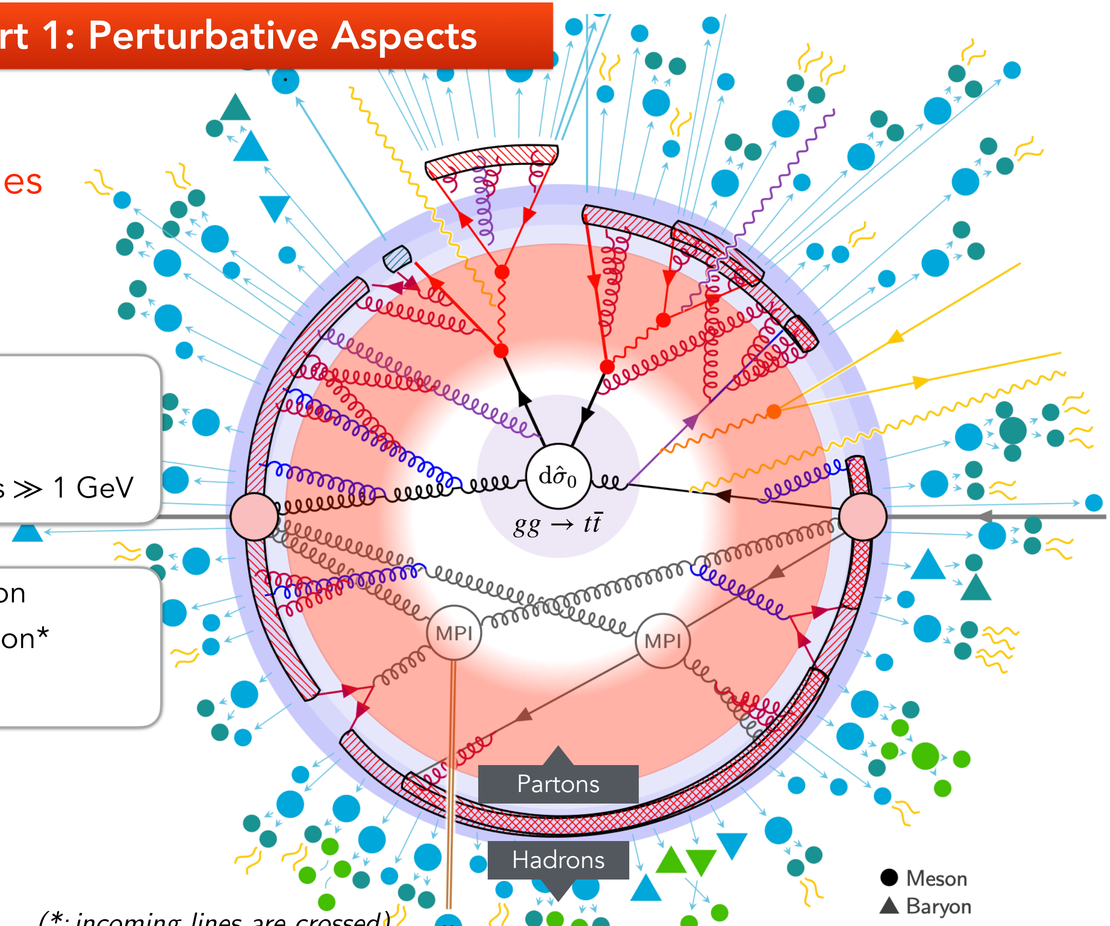
Maths Factorizations

Hard Processes
- ○ Hard Interaction
- ● Resonance Decays

"Hard" means large momentum transfers ≫ 1 GeV

Brems-strahlung
- ■ Final-State Radiation
- ■ Initial-State Radiation*

Down to momentum transfers ~ 1 GeV



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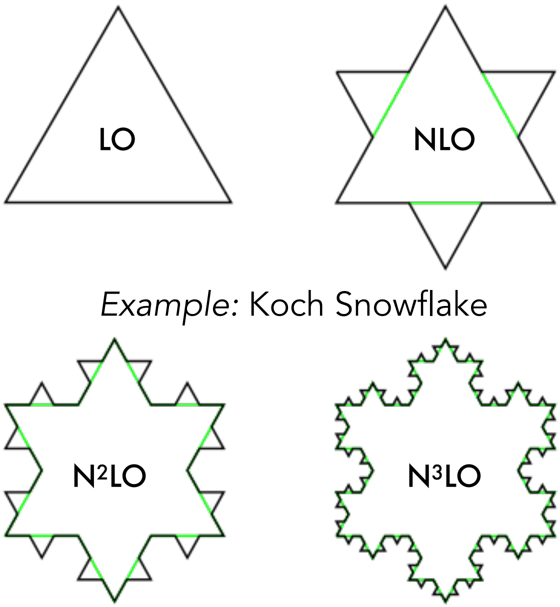
Perturbative Approaches

P.T. ~ Calculate the area of a shape ($d\sigma$) with higher and higher detail

Difference from exact area $\propto \alpha^{n+1}$

Fixed Order



Example: Koch Snowflake

Note: (over)simplified analogy, mainly for IR structure. More at each order than shown here.

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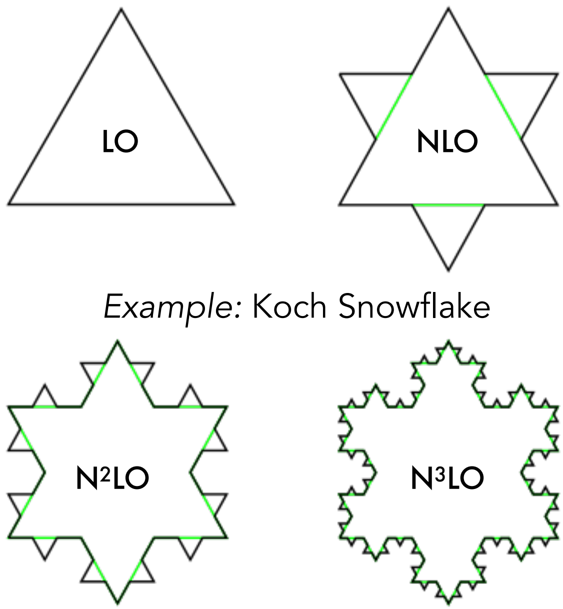
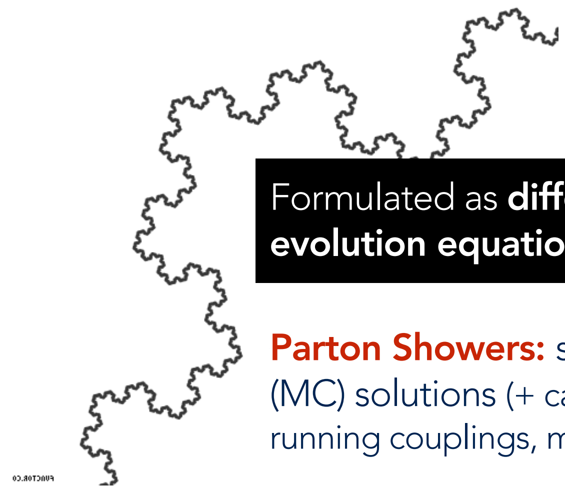


Example: Koch Snowflake

Resummation / Parton Showers

Massless gauge theories

Scale invariance ➜ *fractal* substructure



Formulated as **differential evolution equations**

Parton Showers: stochastic (MC) solutions (+ can build in running couplings, masses)

Note: (over)simplified analogy, mainly for IR structure. More at each order than shown here.

Fractal Schmactal

Parton Showers ➜ Explicit representation of the fractal structure - great!

Needed approximations to get there:

"Leading Logarithm", "Leading Colour", …

➤ **Off-the-shelf parton showers 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

Shower Accuracy

Higher-order corrections within the showers themselves

Oxford: **PanScales** with "NLL-accurate" recoils → NNLL; that's why I'm on sabbatical here

Monash: **Vincia**: 2nd-order shower kernels, new "direct" $2 \to 4$ branchings, iterated MECs

Matching & Merging @ NNLO

Combine fixed orders and showers

Oxford: **MiNNLOPS** (Silvia Z. + collaborators)

Monash: **VinciaNNLO** (PZS + Ludo & Basem + collaborators) → N^3LO?

Fabrizio & collaborators

Why go beyond **Fixed-Order** perturbation theory?

Schematic example:

For an arbitrary "hard process"

("hard" means involving a **large momentum transfer** $Q_{\mathrm{hard}} \gg 1\,\mathrm{GeV}$)

Calculation of the **fraction of events** that pass a **bremsstrahlung veto**

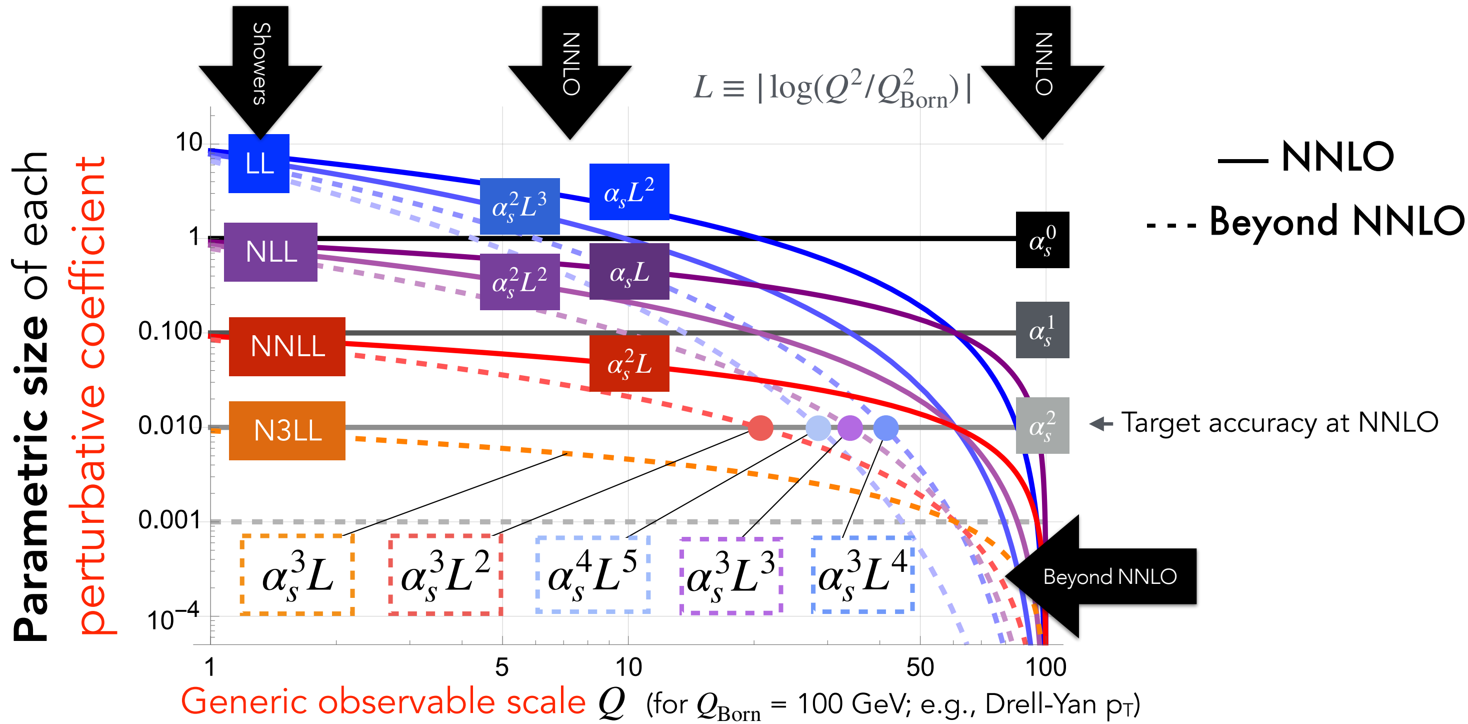
(i.e., **no additional jets** with momentum transfers > Q_{veto}):

$$\overbrace{1}^{\mathrm{LO}} \;-\; \overbrace{\alpha_s(L^2 + L + F_1)}^{\mathrm{NLO}} \;+\; \overbrace{\alpha_s^2(L^4 + L^3 + L^2 + L + F_2)}^{\mathrm{NNLO}} + \;\ldots$$

$$L \propto \ln(Q^2_{\mathrm{veto}} / Q^2_{\mathrm{hard}})$$

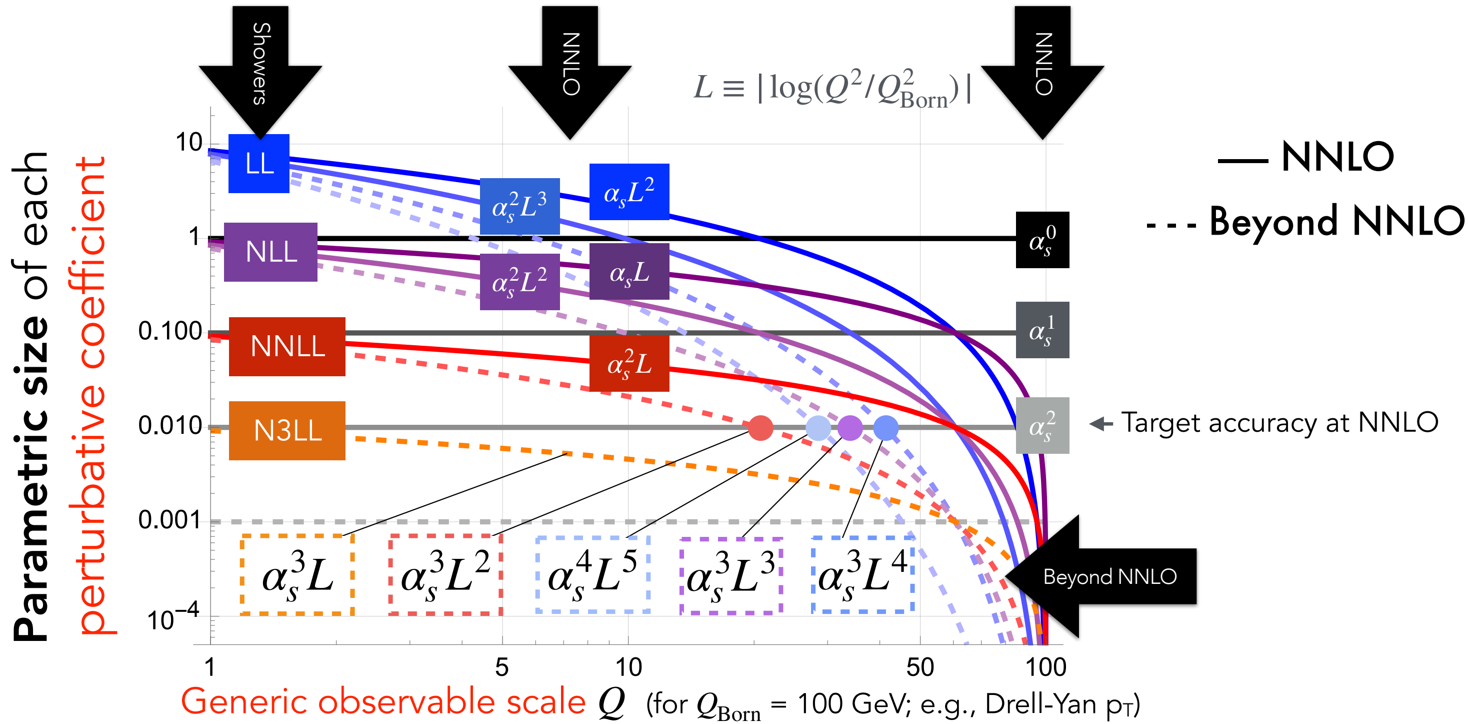
(Logs arise from integrals over propagators $\propto \frac{1}{q^2}$)

The Case for **Embedding** Fixed-Order Calculations **within Showers**



Bremsstrahlung Resummations (Showers) extend domain of validity of perturbative calculations

The Case for **Embedding** Fixed-Order Calculations **within Showers**



%-level precision @ LHC ⇒ **NNLO + NNLL** **Targeted by several groups**

Not quite there (yet) — but close …

Our Approach: Sector Showers

[Lopez-Villarejo & **PZS** 2011](#)
[Brooks, Preuss, **PZS** 2020](#)

Divide the n-gluon phase space up:

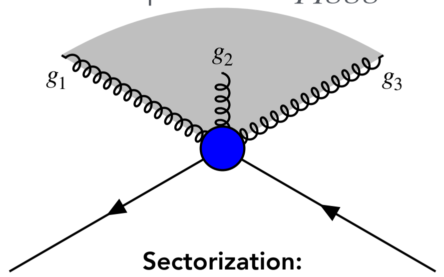
n **non-overlapping sectors**

Inside each: use only **a single evolution kernel**

(the most singular ~"classical" one)

Based on "Ariadne $p_{\perp j}^2$" $= \frac{s_{ij}s_{jk}}{s_{ijk}}$ with $s_{ij} \equiv 2(p_i \cdot p_j)$

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



Sectorization:

g₂ "softest" ⇒ **only** history is g₂ emitted by (g₁ , g₃)

No "sum over histories"

➜ Unique properties (which turn out to be useful for matching):

Unambiguous scale definitions

Shower operator is **bijective** & true **Markov chain**

Achieves LL with a single history (instead of factorial number)

(Generalisations to $g \to q\bar{q}$ and multiple Borns $\Longrightarrow$ sums)

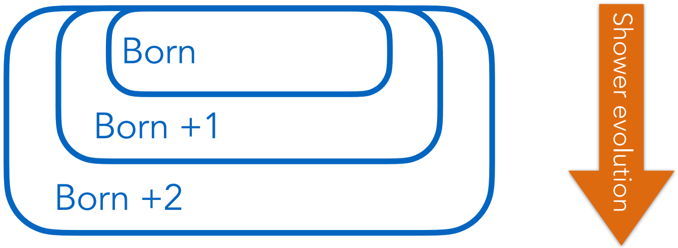
Work in progress on NLL and beyond (with Ludo & Basem)

NNLO Matching with Sector Showers

Idea: Use (nested) Shower Markov Chain as NNLO Phase-Space Generator

Harnesses the power of showers as efficient phase-space generators for QCD

Efficient: Pre-weighted with the (leading) QCD singular structures = soft/collinear poles



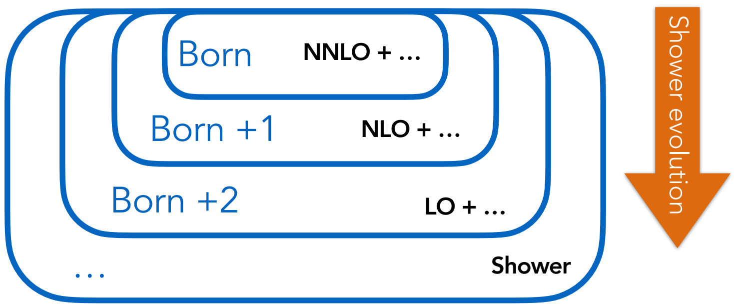
Different from conventional Fixed-Order phase-space generation (eg VEGAS)

NNLO Matching with Sector Showers

Continue parton-shower evolution afterwards

No auxiliary / unphysical scales $\Rightarrow$ expect small matching systematics

(+ generalises to N3LO?)



Proof of concept for $Z \to q\bar{q}$

arXiv:2108.07133

arXiv:2310.18671

VINCIA NNLO

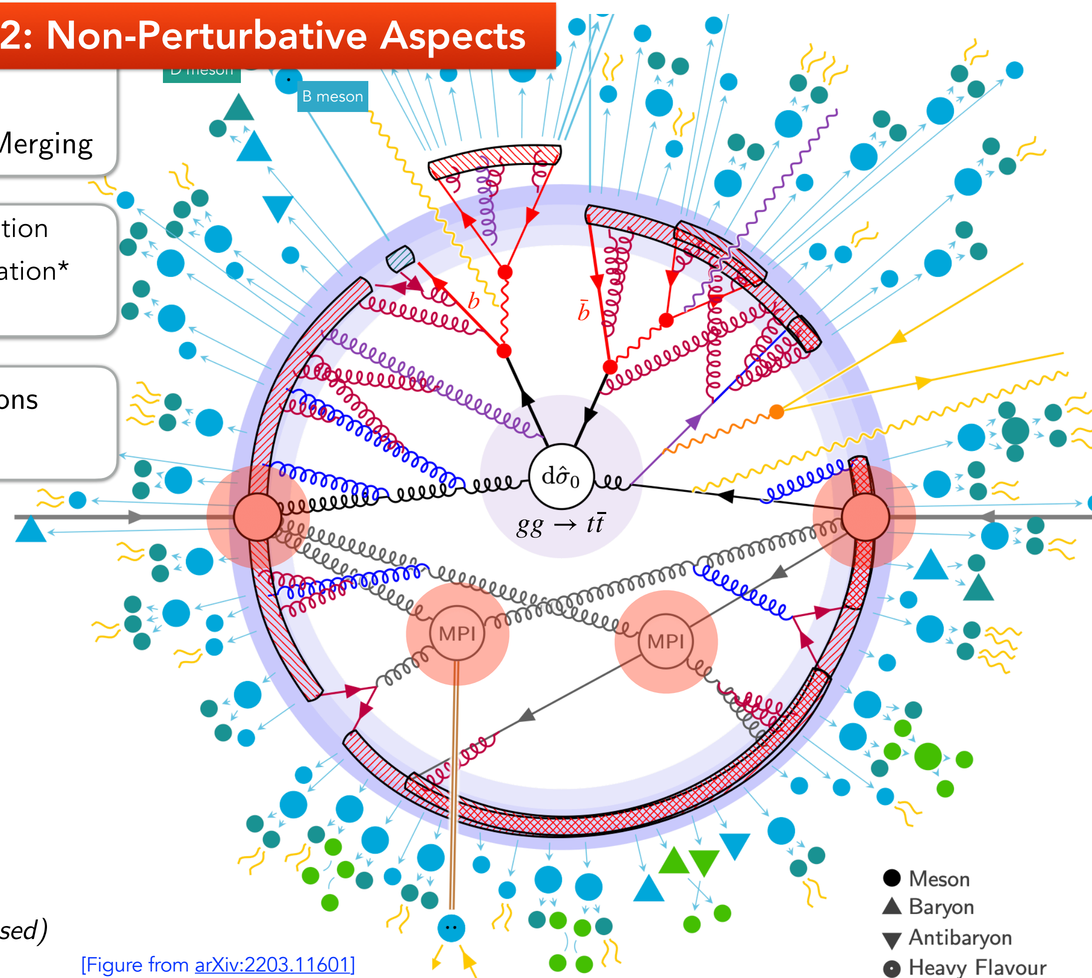
Need:

1. Born-Local NNLO ($\mathcal{O}(\alpha_s^2)$) K-factors: $k_{\mathrm{NNLO}}(\Phi_2)$
2. NLO ($\mathcal{O}(\alpha_s^2)$) MECs in the first $2 \to 3$ shower emission: $k_{\mathrm{NLO}}^{2\to3}(\Phi_3)$
3. LO ($\mathcal{O}(\alpha_s^2)$) MECs for next (iterated) $2 \to 3$ shower emission: $k_{\mathrm{LO}}^{3\to4}(\Phi_4)$
4. Direct $2 \to 4$ branchings for unordered sector, with LO ($\mathcal{O}(\alpha_s^2)$) MECs: $k_{\mathrm{LO}}^{2\to4}(\Phi_4)$

Organizing High-Energy Scattering Problems

Part 2: Non-Perturbative Aspects

Hard Process	◯ Hard Interaction ● Resonance Decays ■ MECs, Matching & Merging
Parton Showers	■ QCD Final-State Radiation ■ QCD Initial-State Radiation* ■ Electroweak Radiation
Underlying Event	◯ Multiparton Interactions □ Beam Remnants*



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[Figure from arXiv:2203.11601]

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Hard Process	Hard Interaction Resonance Decays MECs, Matching & Merging
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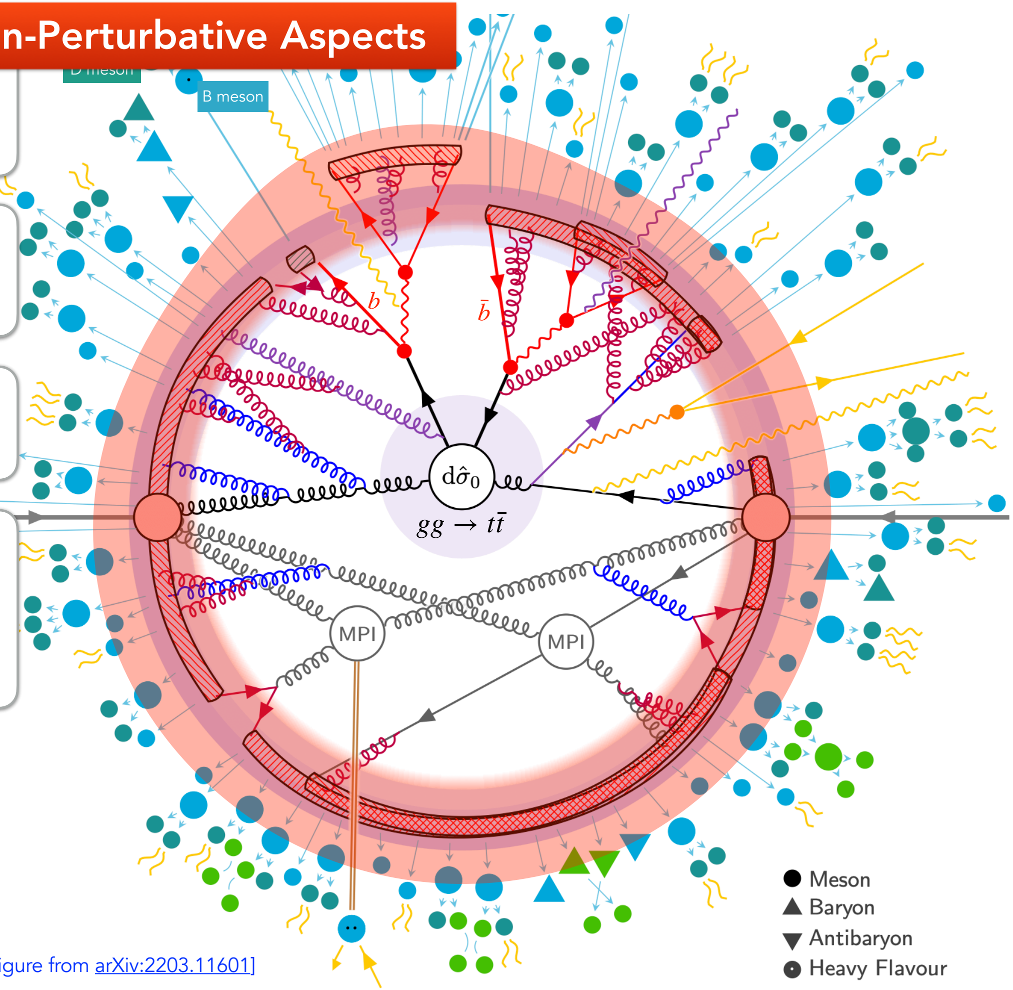
Hadronization	Strings Colour Reconnections String Interactions Bose-Einstein & Fermi-Dirac



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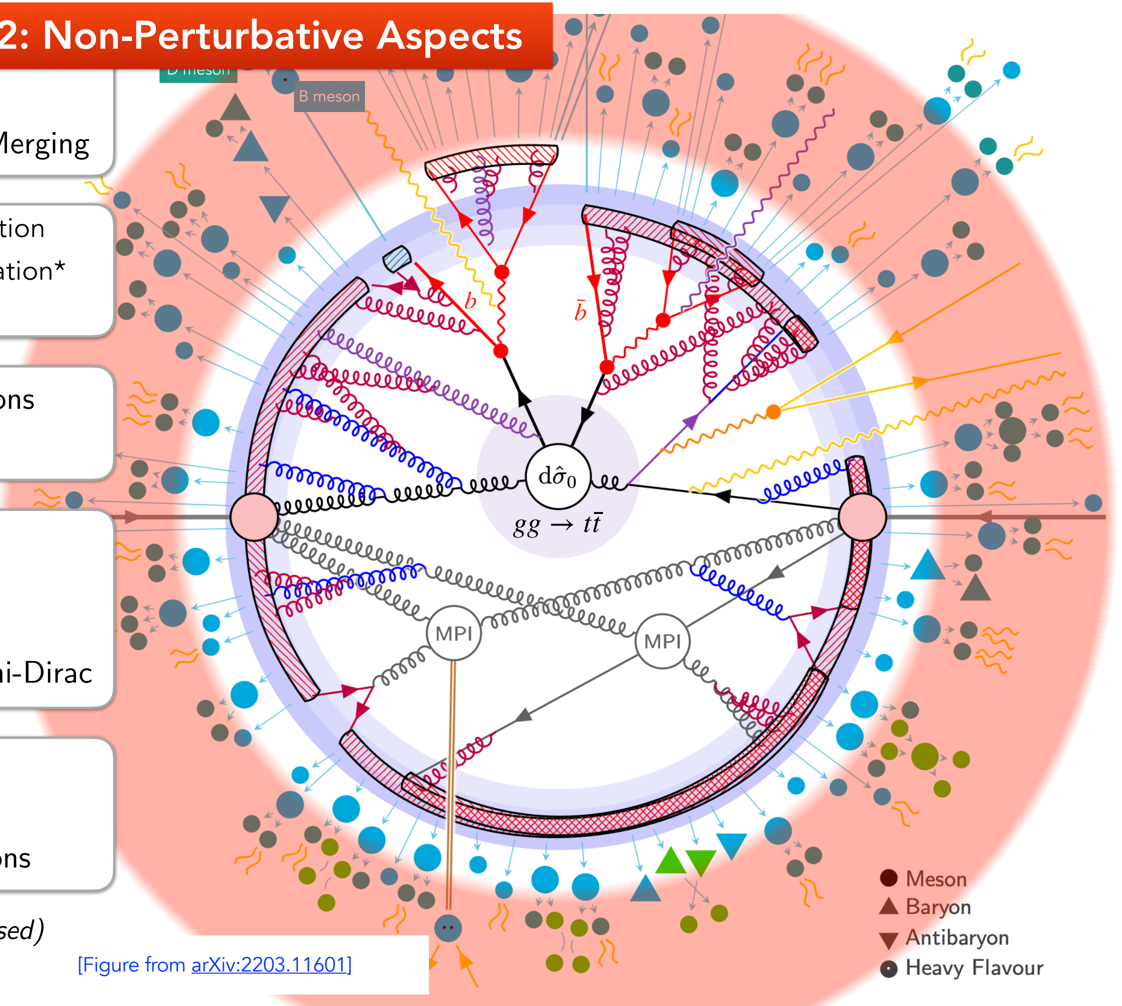
Hadronization	▧ Strings ■ Colour Reconnections ■ String Interactions ■ Bose-Einstein & Fermi-Dirac
Hadron (& τ) Decays	■ Primary Hadrons ■ Secondary Hadrons ■ Hadronic Reinteractions

(: incoming lines are crossed)*

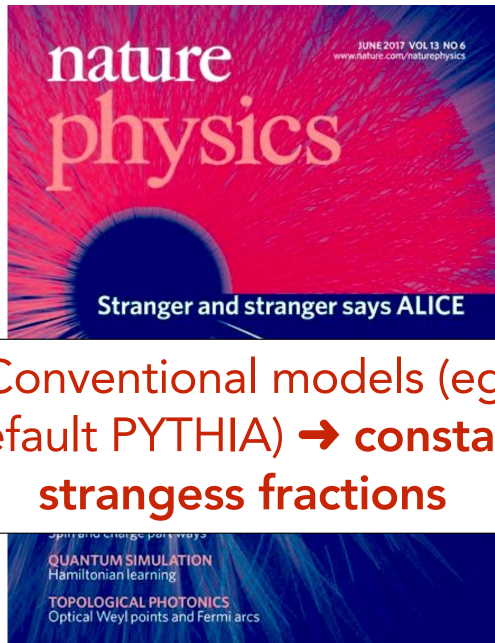


[Figure from arXiv:2203.11601]

New Discoveries in Hadronization

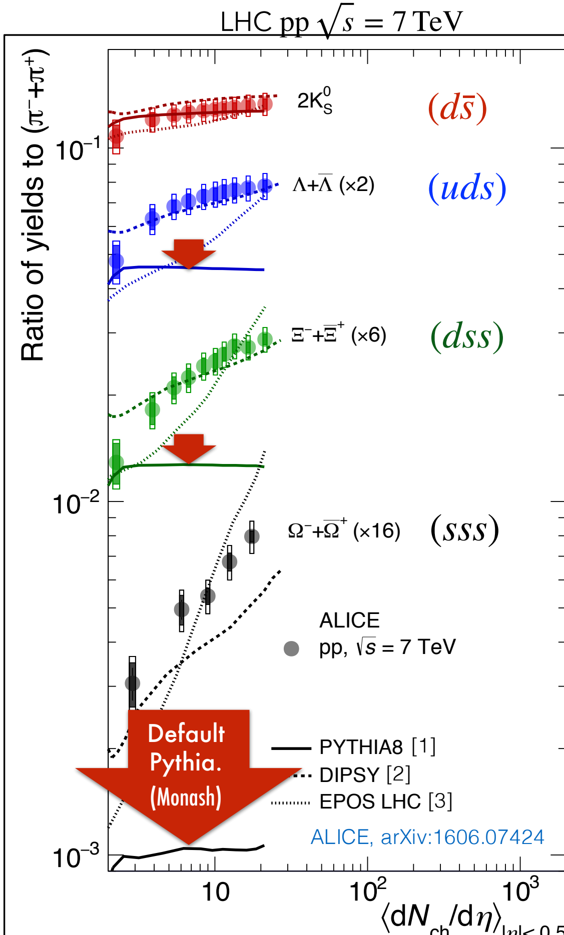
What a strange world we live in, said ALICE

Ratios of **strange** hadrons to pions strongly increase with event activity



June 2017

Conventional models (eg Default PYTHIA) ➜ **constant strangess fractions**



New Discoveries in Hadronization

LHC experiments also report very large **(factor-10)** enhancements in **heavy-flavour** baryon-to-meson ratios **at low p_T!**

Conventional models (eg default PYTHIA) ➜ **constant baryon-to-meson ratio**

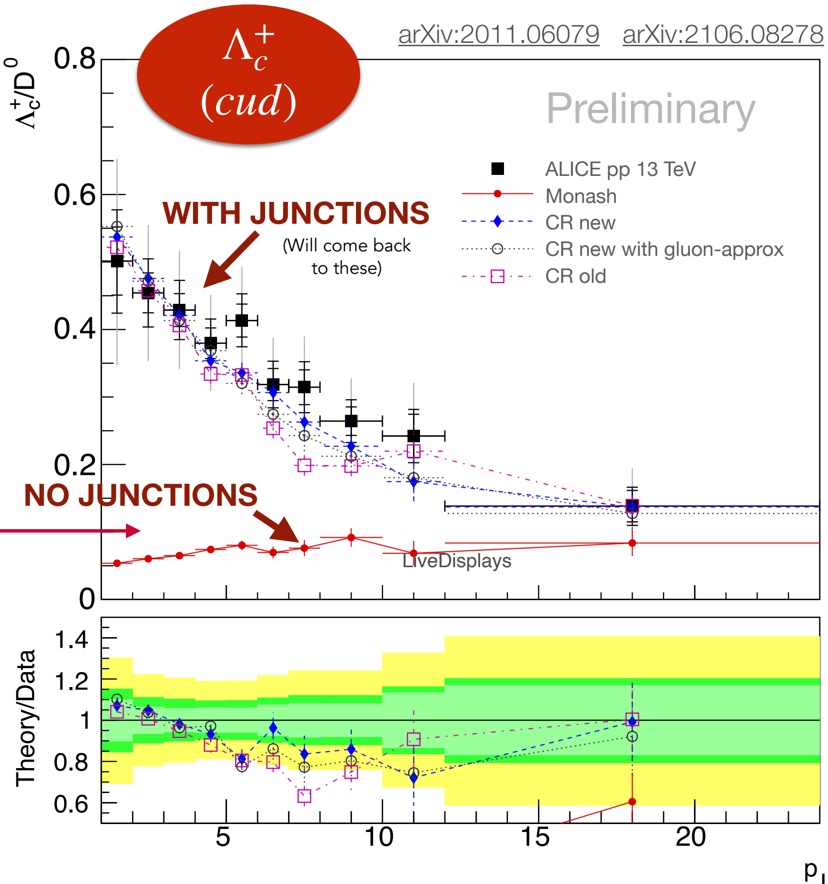
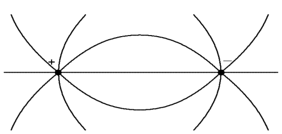


Figure from Altmann & **PZS**, *String Junctions Revisited*, in progress

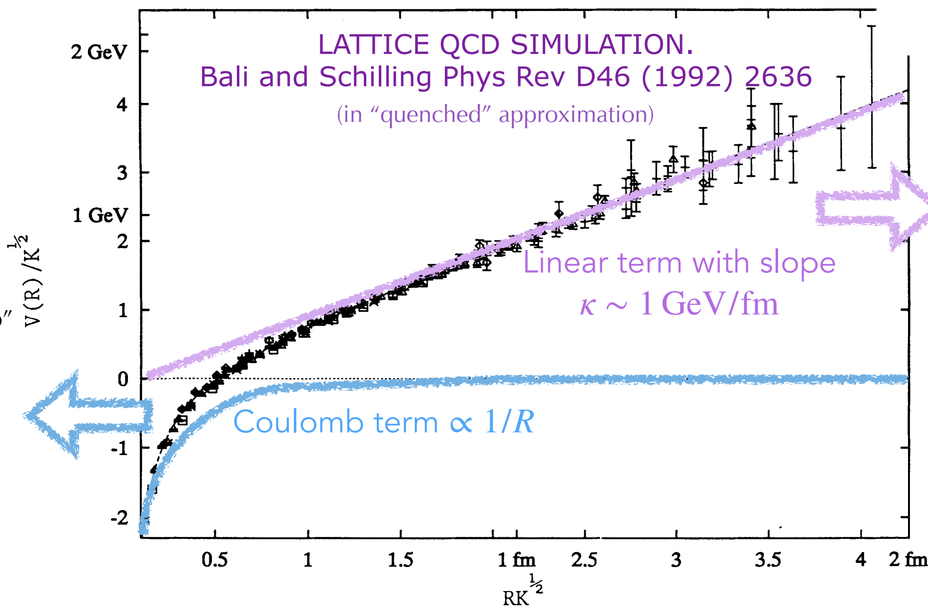
Back to Basics — Anatomy of (Linear) Confinement

On lattice, compute potential energy of a colour-singlet $q\bar{q}$ state, as function of the distance, R, between the q and $\bar{q}$:

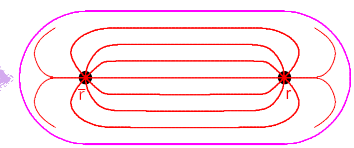
Short Distances ~ "Coulomb"



"Free" Partons



Long Distances ~ Linear Potential



"Confined" Partons
(a.k.a. Hadrons)

Linear Term ➡ Model as strings (Lund Model)

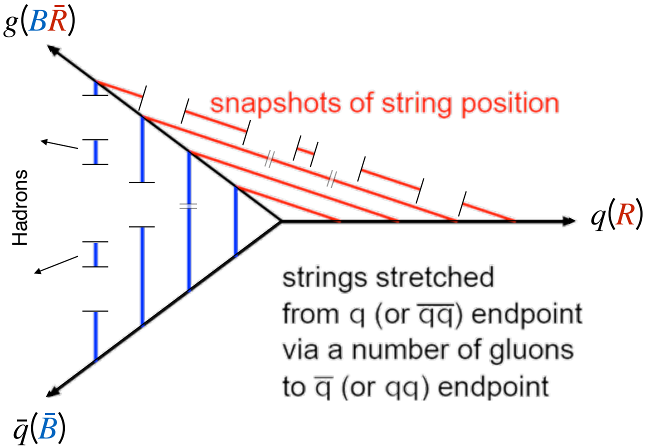
A New Set of Degrees of Freedom

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)

String breaks by quark pair production

$\Longrightarrow$ **strangeness suppression**

$$\propto \frac{\exp\left(\frac{-\pi m_s^2}{\kappa}\right)}{\exp\left(\frac{-\pi m_{u,d}^2}{\kappa}\right)}$$

➤ Jets of Hadrons!

Beyond the Static Limit

Regard tension κ as an emergent quantity?

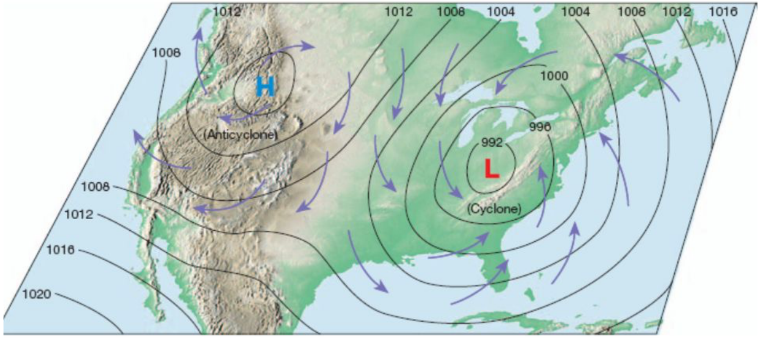
Not fundamental strings

May depend on (invariant) time τ

E.g., hot strings which cool down

Hunt-Smith & **PZS** 2020

Cyclonic and Anticyclonic Winds



May depend on spatial coordinate σ

Working with E. Carragher & J. March-Russell (Oxford).

May depend on environment (e.g., other strings nearby)

Two approaches (so far) within Lund string-model context:

Colour Ropes [Bierlich et al. 2015; + more recent…]

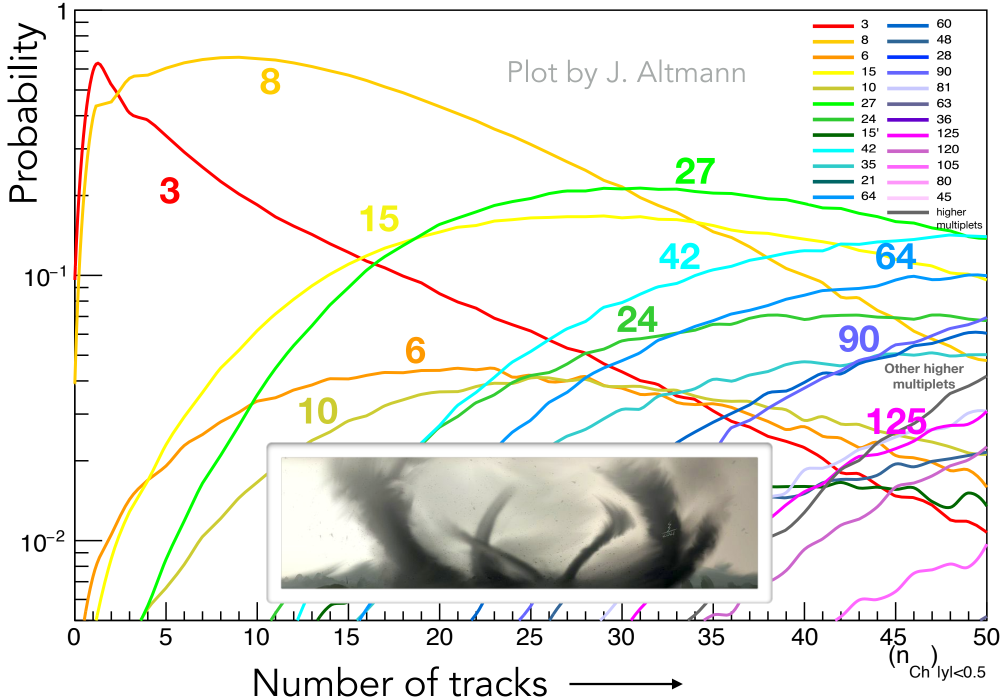
Close-Packing [Fischer & Sjöstrand 2017; Altmann & **PZS** 2024]

Non-Linear String Dynamics?

MPI $\Longrightarrow$ lots of coloured partons scattered into the final states

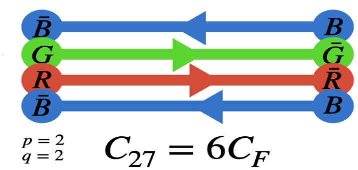
Count **# of (oriented) flux lines** crossing $y = 0$ in pp collisions (according to PYTHIA)

And **classify by SU(3) multiplet:**



Confining fields may be reaching **higher effective representations** than simple $q\bar{q}$ (3) ones.

E.g.: 27



27

$C_{27} = 6C_F$

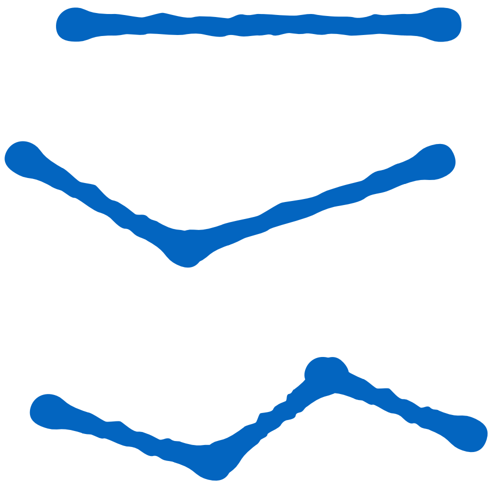
➜ **Is "emergent tension" driving strangeness enhancement in pp?**

Altmann & **PZS** work in progress …

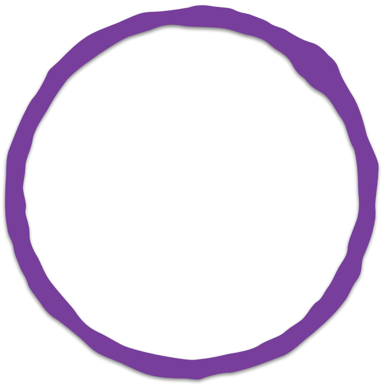
What about Baryon Number?

Types of string topologies:

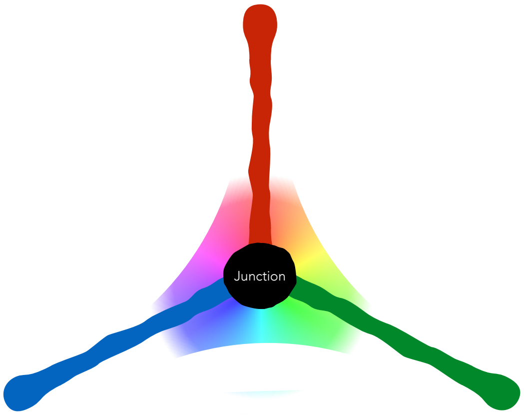
Open Strings



Closed Strings



SU(3) String Junction

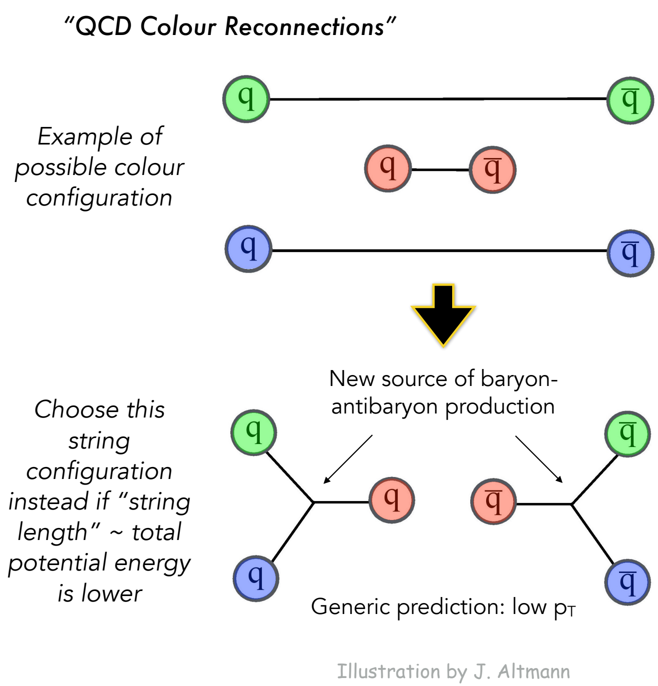


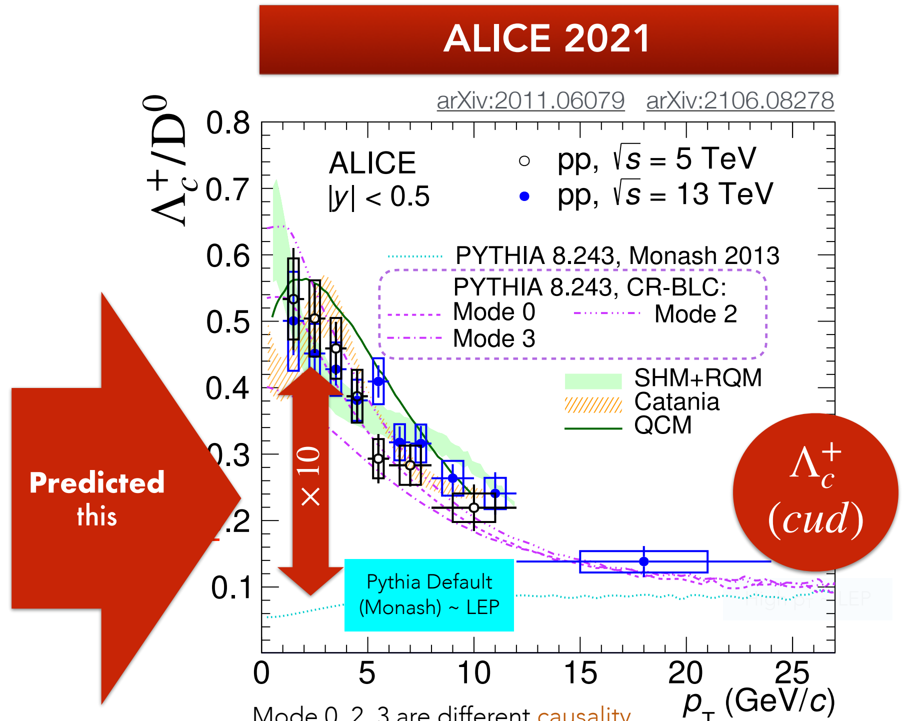
Could we get these at LHC?

String Junctions at LHC ?

Stochastic sampling of SU(3) group probabilities (e.g., $3 \otimes 3 = 6 \oplus \bar{3}$)

$\Longrightarrow$ Random **(re)connections in colour space** (weighted by group weights)





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


Thank you