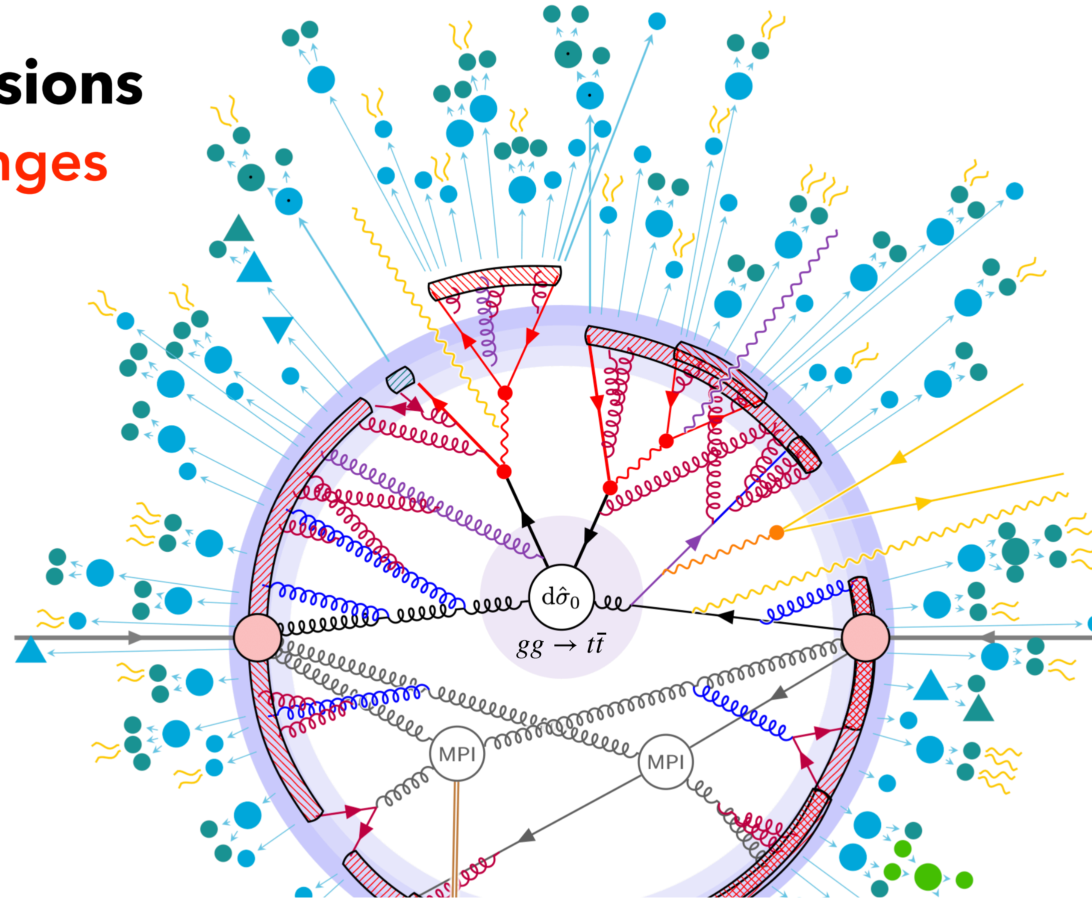
Anatomy of LHC collisions
— and Future Challenges



Peter Z Skands

University of Oxford
& Monash University

IOP Meeting
Liverpool, April 2024

Anatomy of LHC collisions

Physics Separation of scales

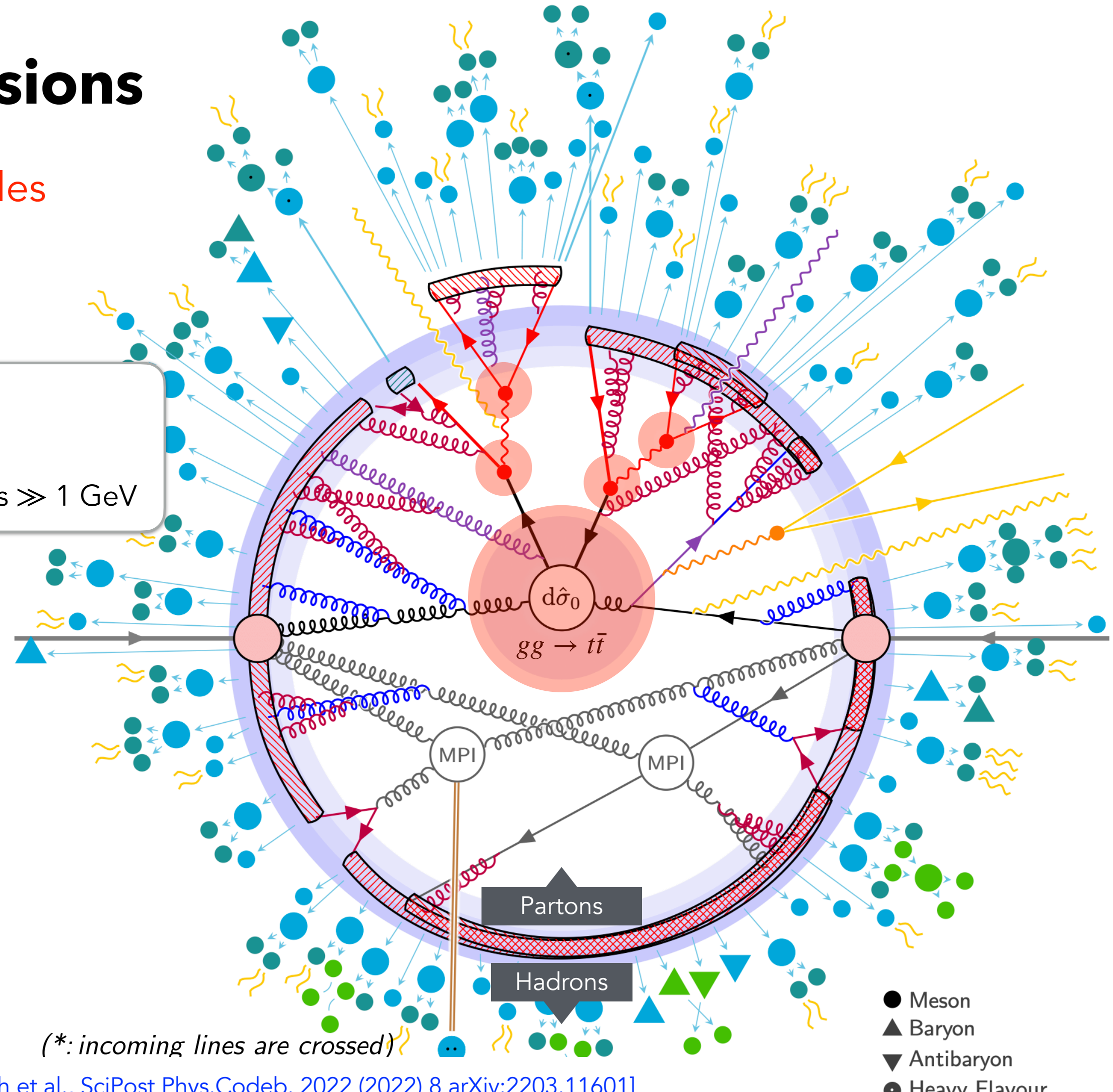
Maths Factorizations

Hard Processes

○ Hard Interaction

● Resonance Decays

"Hard" means large momentum transfers ≫ 1 GeV



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

Anatomy of LHC collisions

Physics Separation of scales

Maths Factorizations

Hard Processes
- ◯ Hard Interaction
- ● Resonance Decays

"Hard" means large momentum transfers ≫ 1 GeV

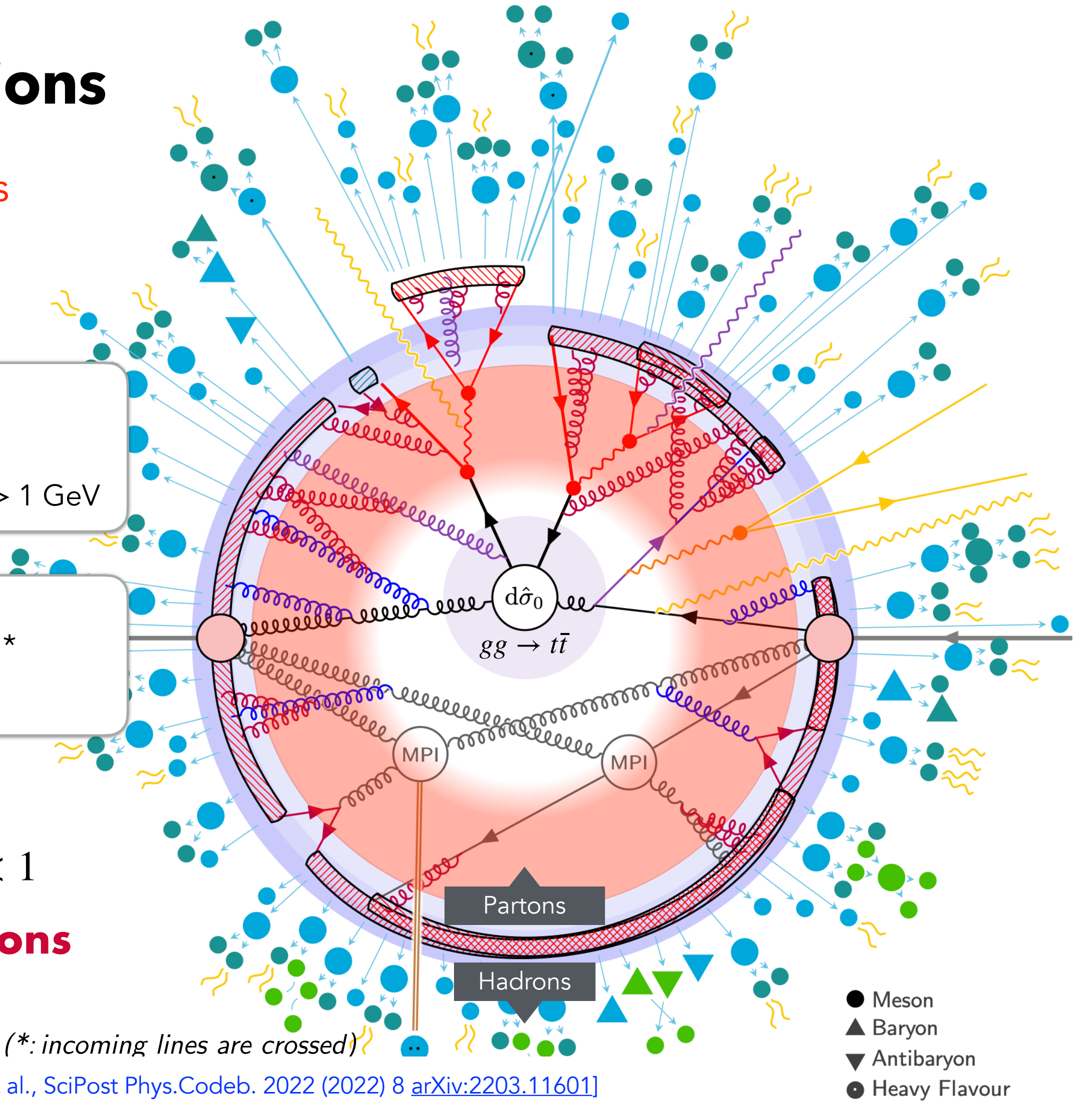
Brems-strahlung
- ■ Final-State Radiation
- ■ Initial-State Radiation*

Down to momentum transfers ~ 1 GeV

For scales $\mu > 1\,\mathrm{GeV}$:

QCD Running Coupling $\alpha_s(\mu) < 1$

➜ Perturbative Approximations



(: incoming lines are crossed)*

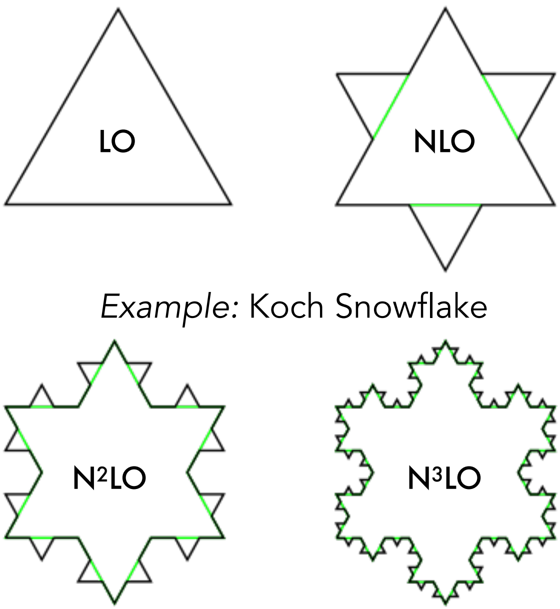
[Figure from Bierlich et al., SciPost Phys.Codeb. 2022 (2022) 8 arXiv:2203.11601]

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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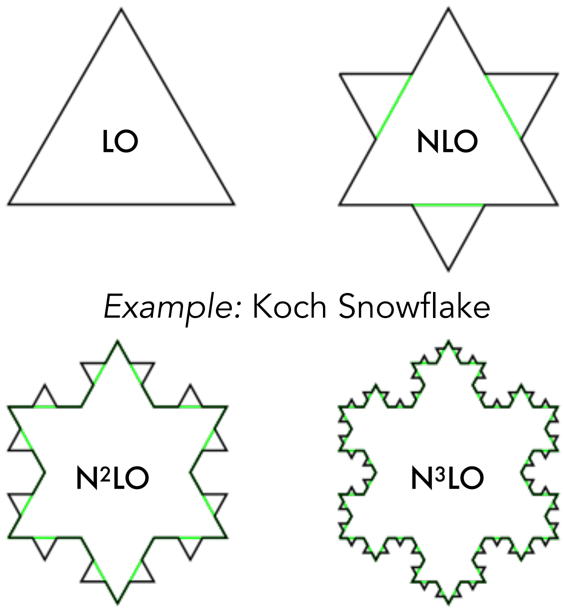
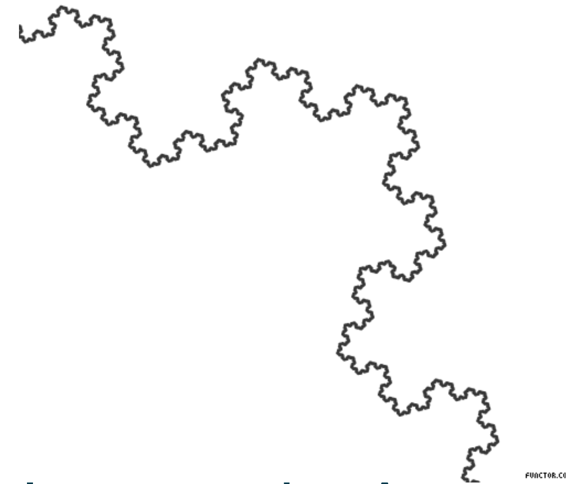


Example: Koch Snowflake

Resummation / Parton Showers



Massless gauge theories

Scale invariance ➜ fractal substructure

(+ not hard to build in running coupling, masses)

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

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

Schematic example:

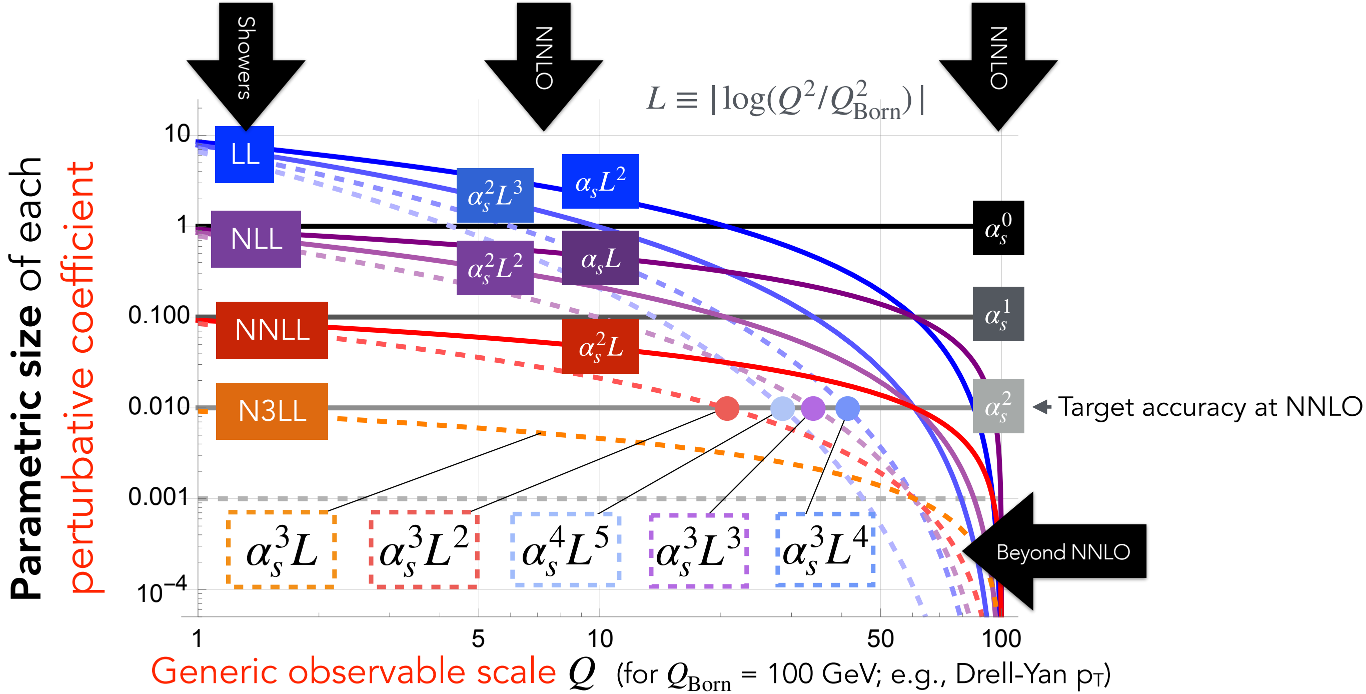
Calculation of the fraction of events passing a **radiation (jet) veto:**

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

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

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

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



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

%-level precision @ LHC ⇒ **NNLO + NNLL** **= Our Target** Not quite there (yet) — but close …

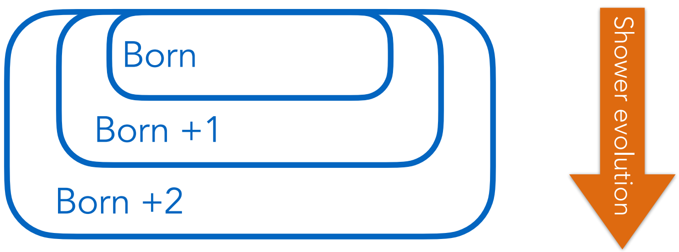
Towards True* NNLO Matching

*In the sense of the fixed-order and shower calculations matching each other point by point in each phase space

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



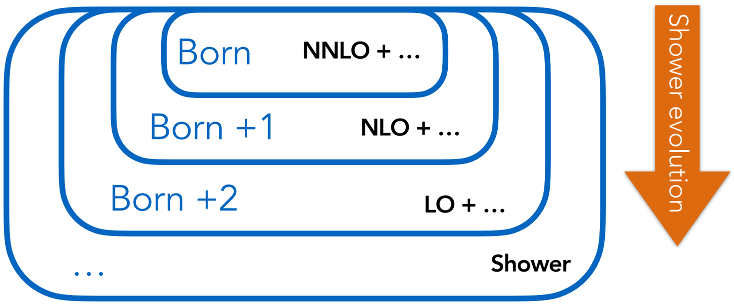
Different from conventional Fixed-Order phase-space generation (eg VEGAS)

Towards True* NNLO Matching

*In the sense of the fixed-order and shower calculations matching each other point by point in each phase space

Continue shower afterwards

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



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

arXiv:2108.07133

arXiv:2310.18671

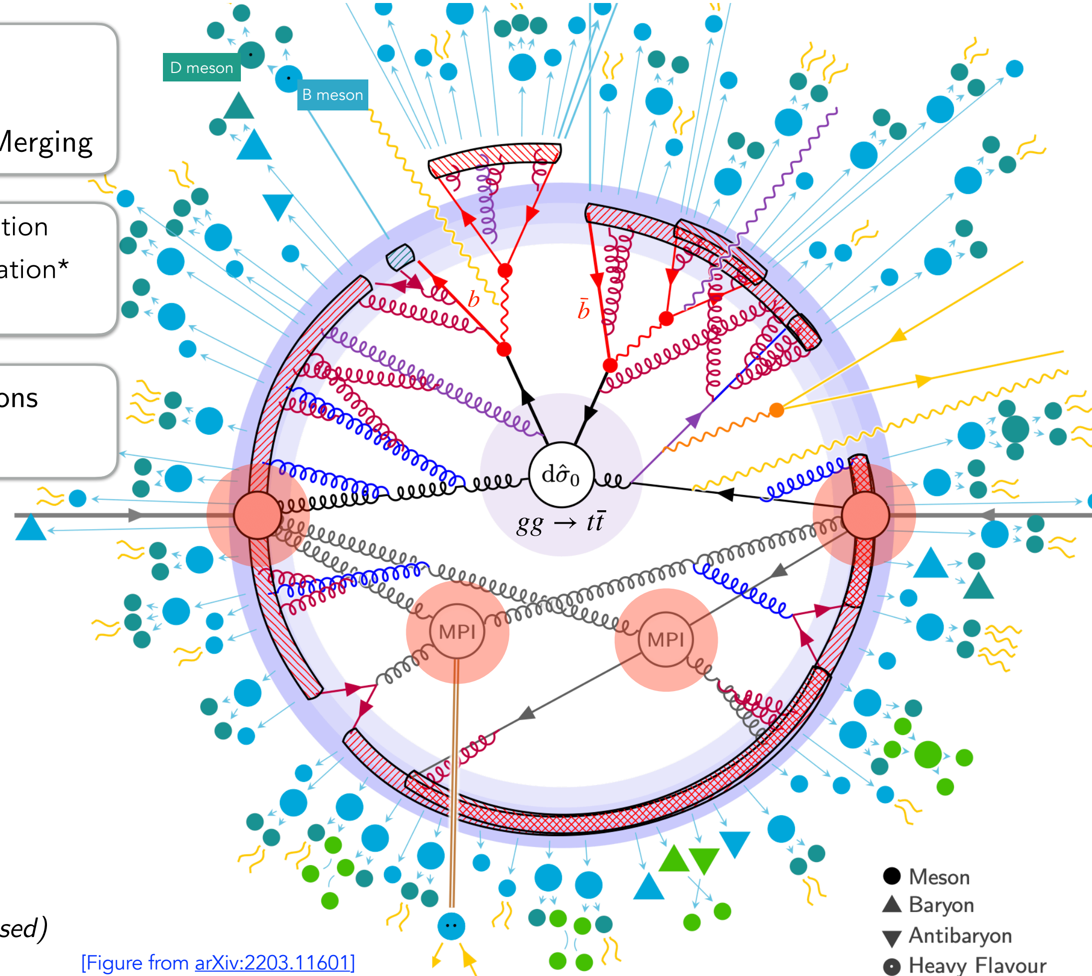
Need:

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: $k_{\mathrm{LO}}^{2\to4}(\Phi_4)$

VINCIA NNLO

Part II – Nonperturbative 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]

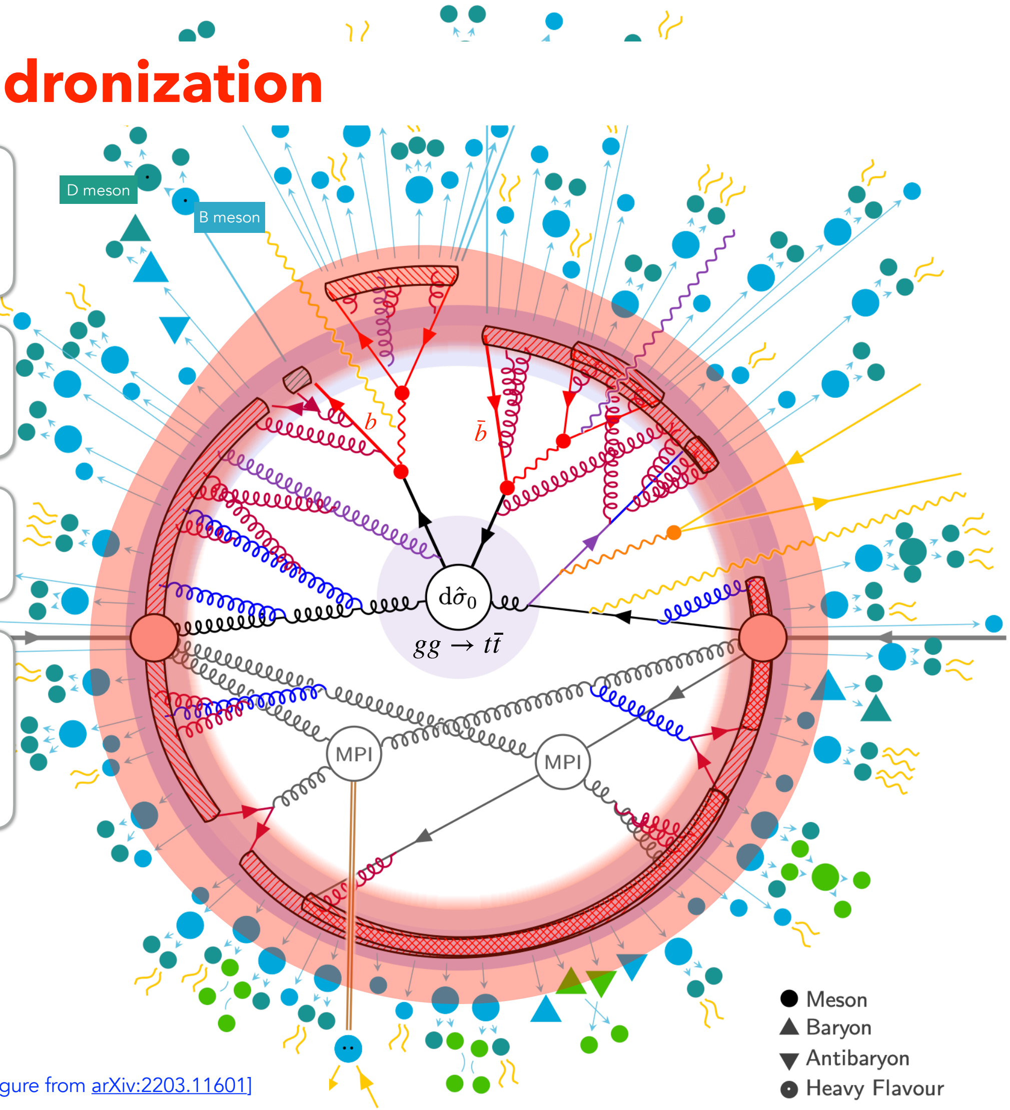
Hadronization

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*

Hadronization
- Strings
- Colour Reconnections
- String Interactions
- Bose-Einstein & Fermi-Dirac



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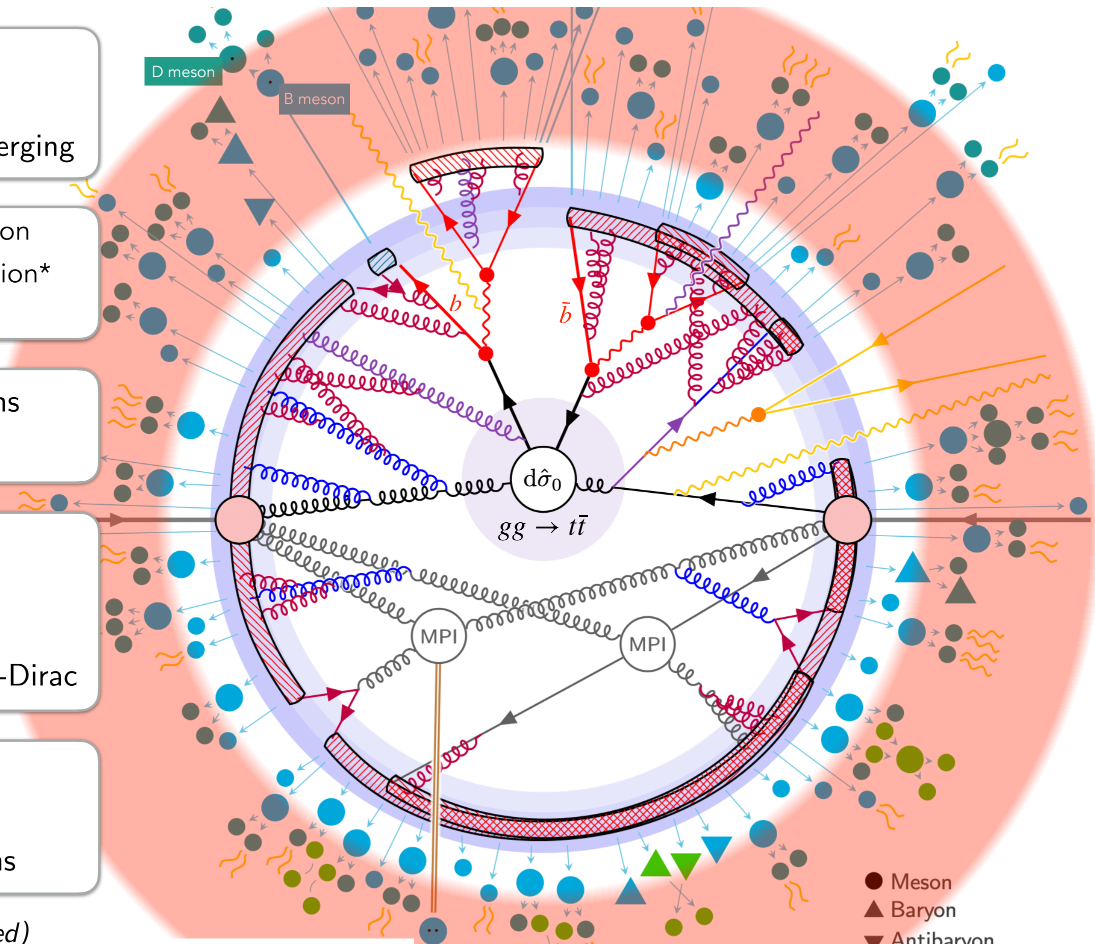
[Figure from arXiv:2203.11601]

Hadron Decays

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

(: incoming lines are crossed)*

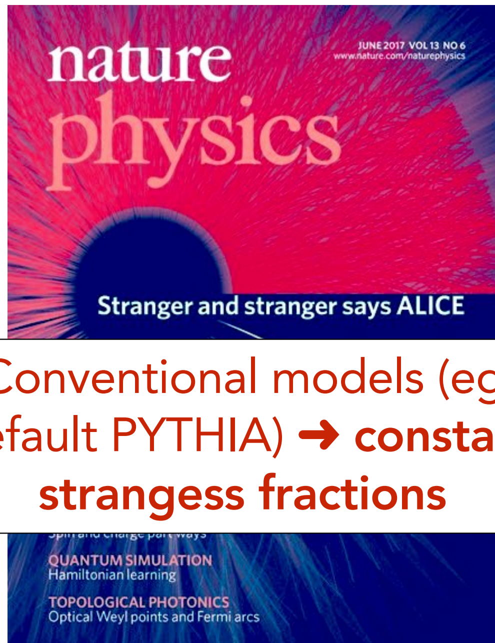


[Figure from arXiv:2203.11601]

New Discoveries in Hadronization

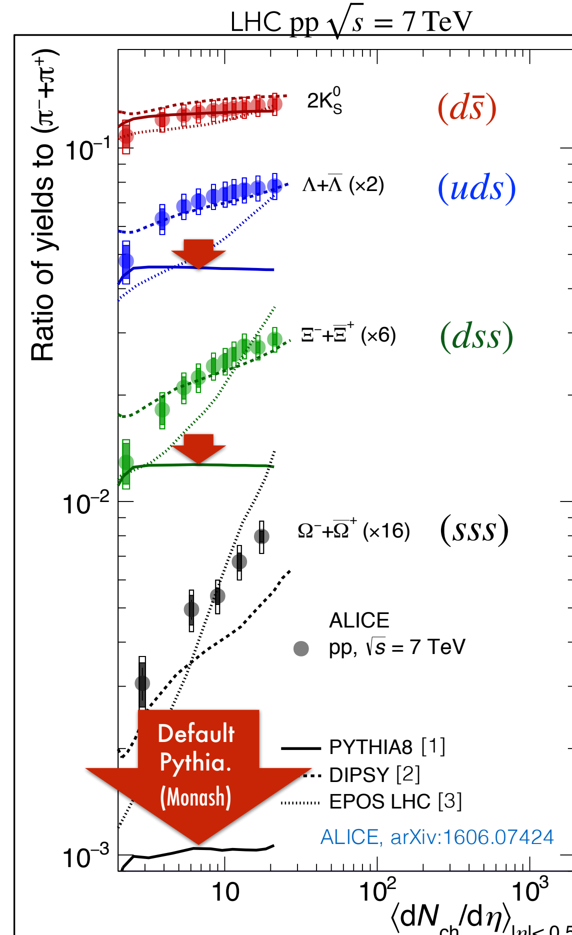
What a strange world we live in, said ALICE

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**

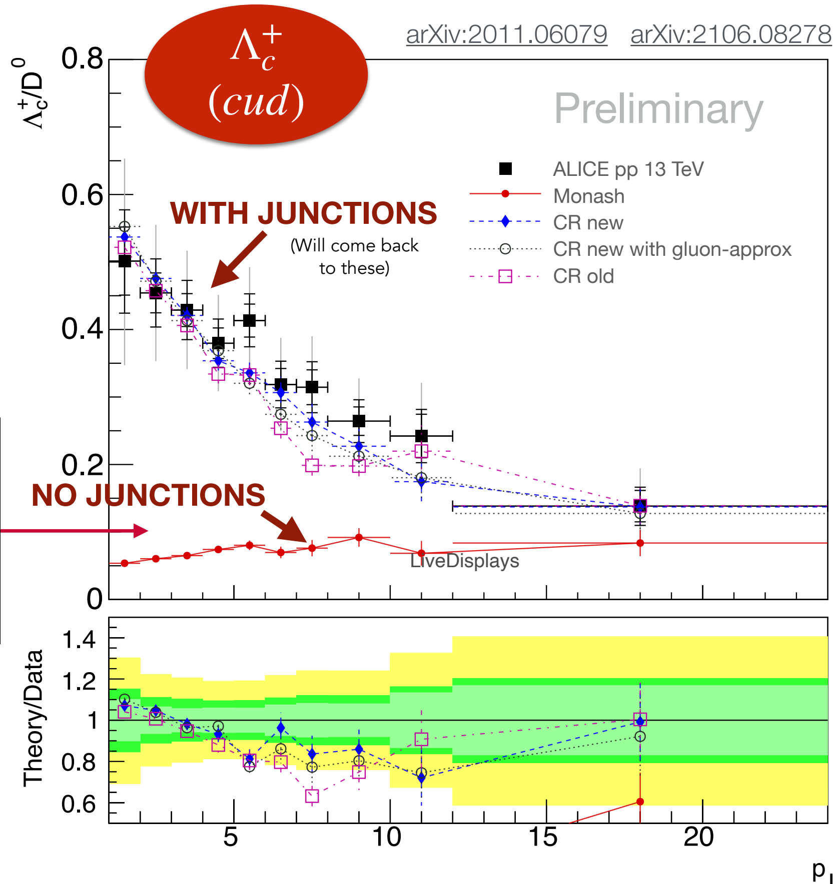
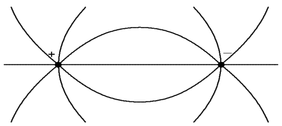


Figure from Altmann & **PZS**, *String Junctions Revisited*, in progress

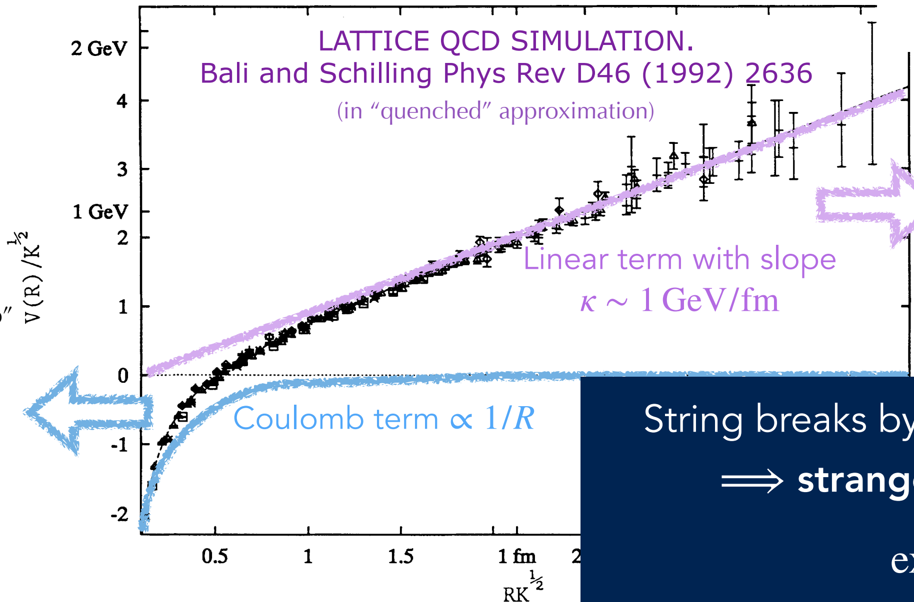
Back to Basics — *Anatomy of (Linear) Confinement*

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

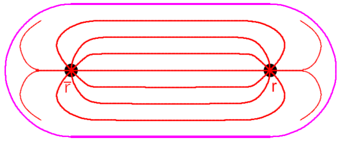
Short Distances ~ "Coulomb"



"Free" Partons



Long Distances ~ Linear Potential



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

String breaks by quark pair production

$\Longrightarrow$ **strangeness suppression**

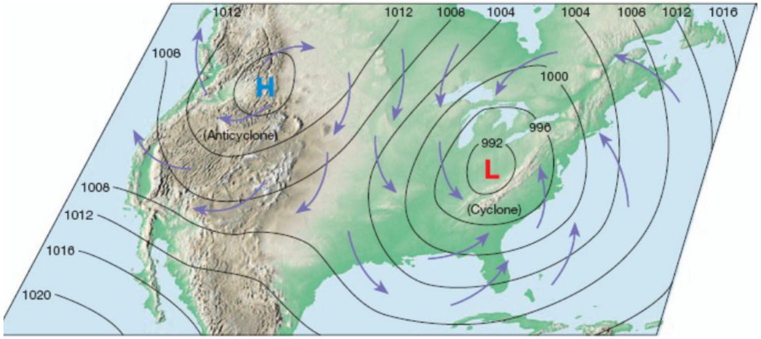
$$\propto \frac{\exp\left(\frac{-\pi m_s^2}{\kappa}\right)}{\exp\left(\frac{-\pi m_{u,d}^2}{\kappa}\right)}$$

➡ **Model as strings (Lund Model)**

Beyond the Static Limit

Regard tension κ as an emergent quantity?
Not fundamental strings

Cyclonic and Anticyclonic Winds



May depend on (invariant) time τ

E.g., hot strings which cool down

Hunt-Smith & **PZS** EPJC 80 **(2020)** 11

May depend on σ (excitations)

Working with E. Carragher & J. March-Russell in Oxford.

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

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

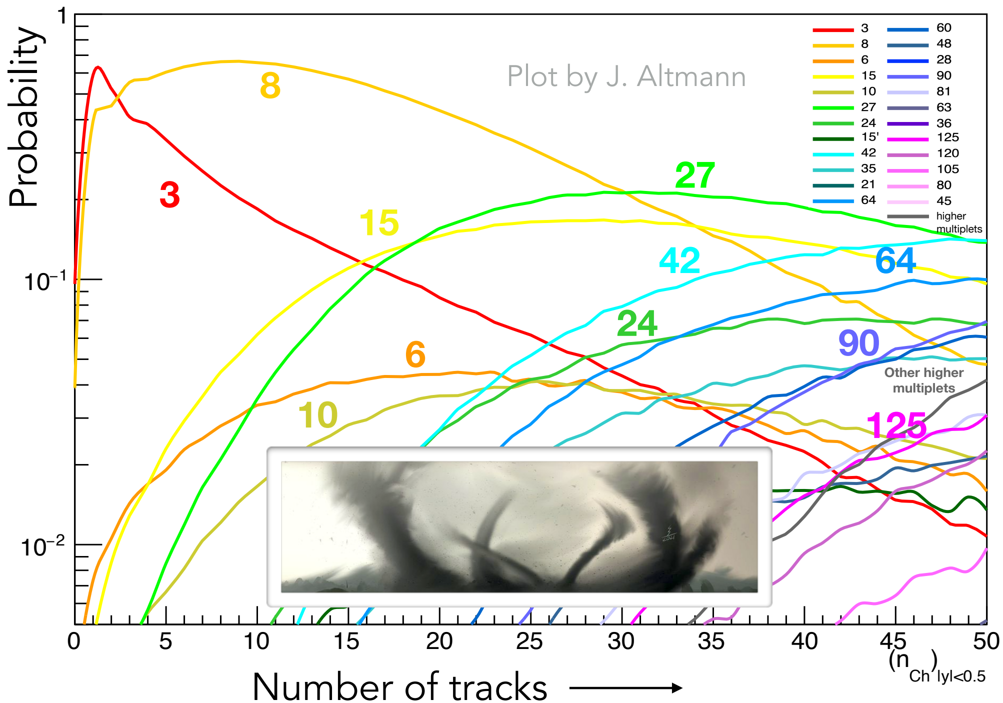
- **Colour Ropes** [Bierlich, Gustafson, Lönnblad, Tarasov JHEP 03 **(2015)** 148; + more recent…]
- **Close-Packing** [Fischer & Sjöstrand JHEP 01 **(2017)** 140; Altmann & **PZS** in progress …]

Non-Linear String Dynamics

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

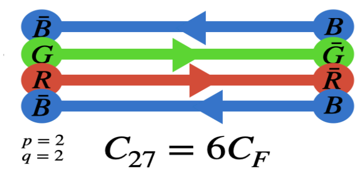
Count **# of (oriented) flux lines** crossing $y = 0$ in pp collisions (according to PYTHIA)

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

$C_{27} = 6C_F$

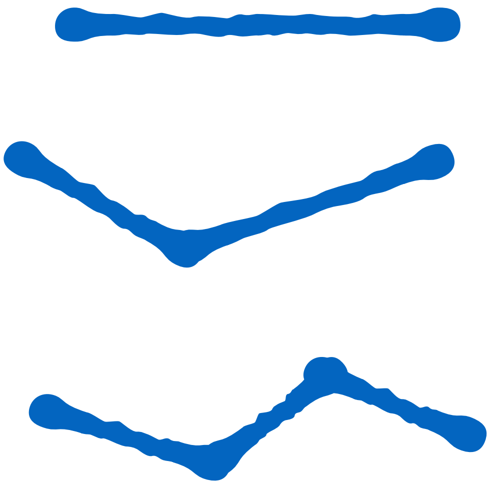
➜ **Is "emergent tension" driving strangeness enhancement in pp?**

Altmann & **PZS** work in progress …

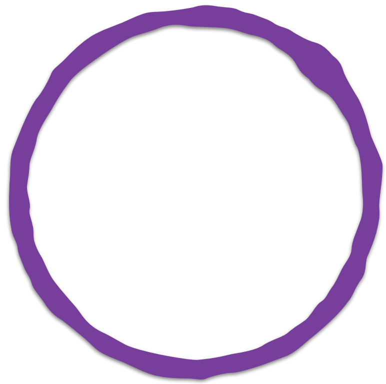
What about Baryon Number?

Types of string topologies:

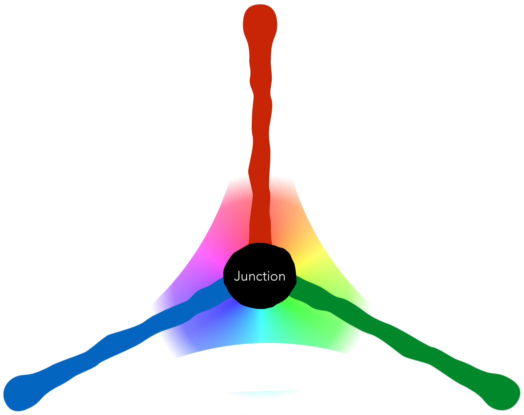
Open Strings



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)

Christiansen & PZS 2015

"QCD Colour Reconnections"

Example of possible colour configuration

Choose this string configuration instead if "string length" ~ total potential energy is lower

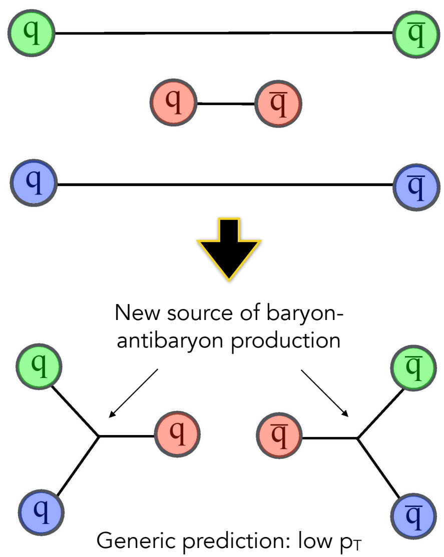
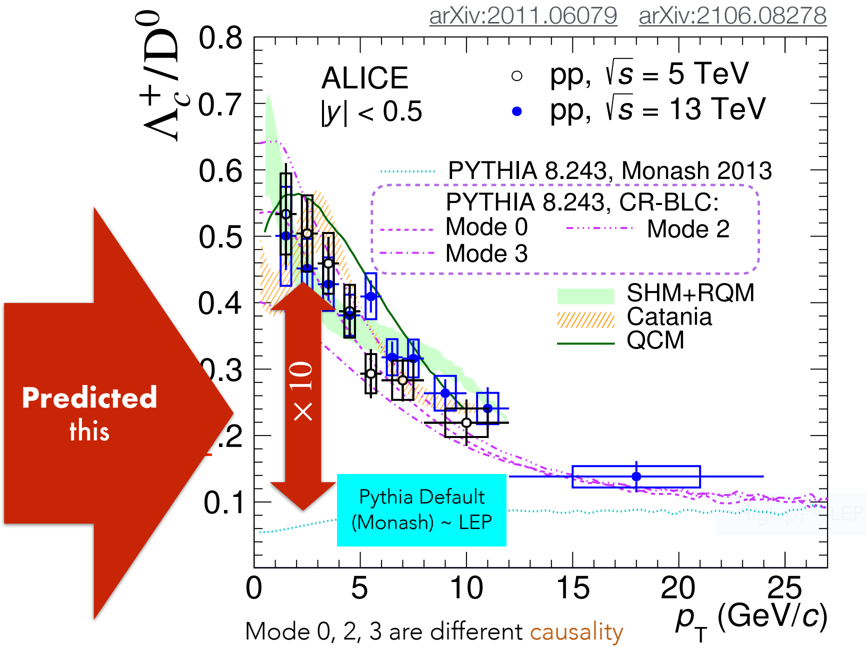


Illustration by J. Altmann

ALICE 2021



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

Summary

The Goal: use LHC measurements to test hypotheses about Nature

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

New insights into perturbation theory — at non-trivial orders

➜ new techniques

(➞ expect %-level accuracies)

Elementary Fields,
Symmetries,
Interactions

"Real Life"

New measurements have challenged conventional paradigms

➜ study confinement beyond static limit

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