The Challenge of Fragmentation Modelling

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Taggers will be trained on combination of data-driven & MCs

Performance (& Uncertainties!) will depend on **Fidelity of MC modelling**

+ in-situ constraints

Fundamental physics of confinement / hadronization not a solved issue

LHC discoveries: Strangeness and baryon enhancements, collectivity, …

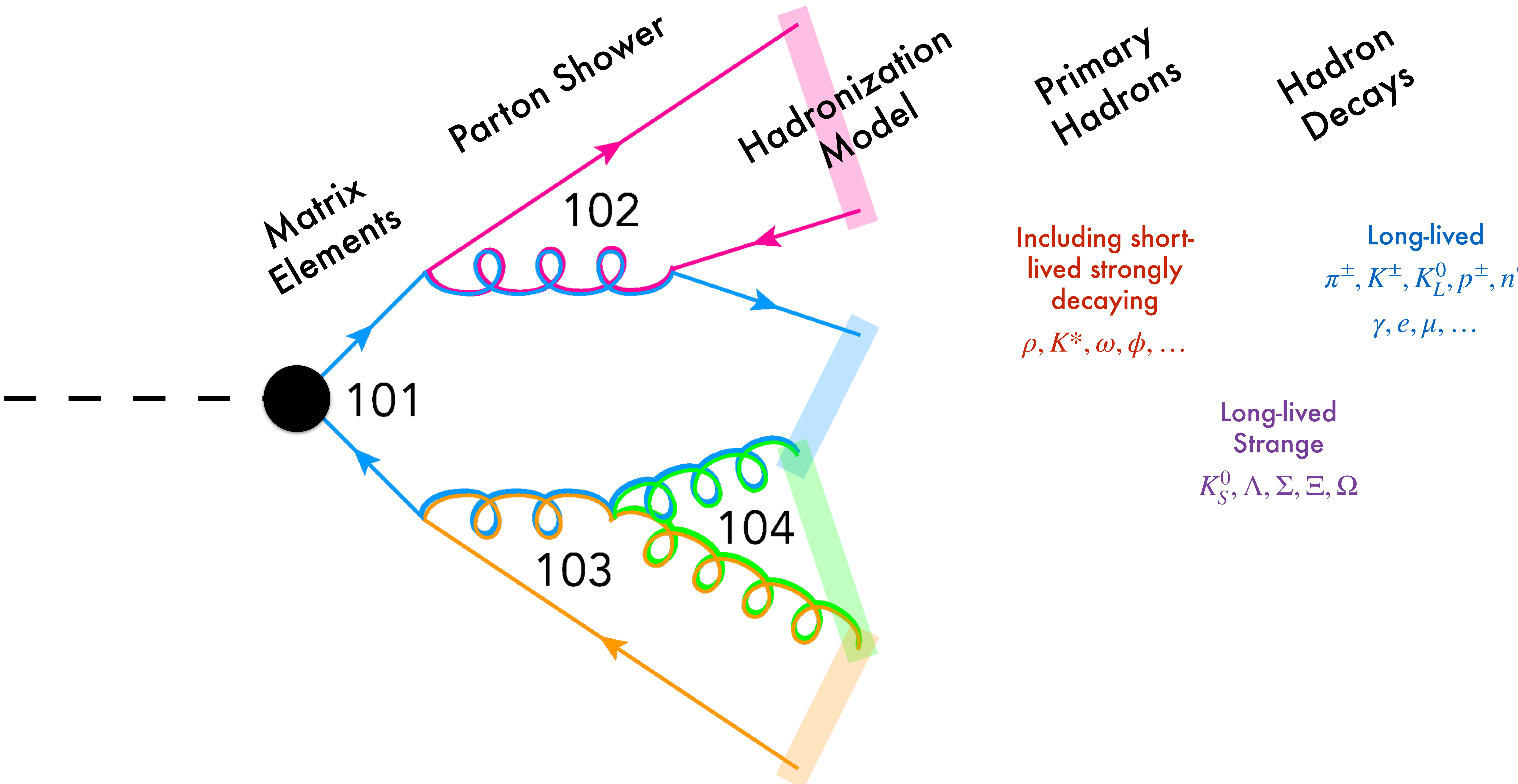
➜ New (more advanced) MC hadronizaton models are being developed

Colour reconnections, octet (gluon) vs triplet (quark) fragmentation, colour ropes, close-packing, string interactions, hot strings, excited strings, baryon colour reconnections, …

Future ee $\Longrightarrow$ Ultimate trial by fire for dynamics of confinement

PID is the sine qua non. Absolutely crucial.

Fragmentation in Colour-Singlet Decays



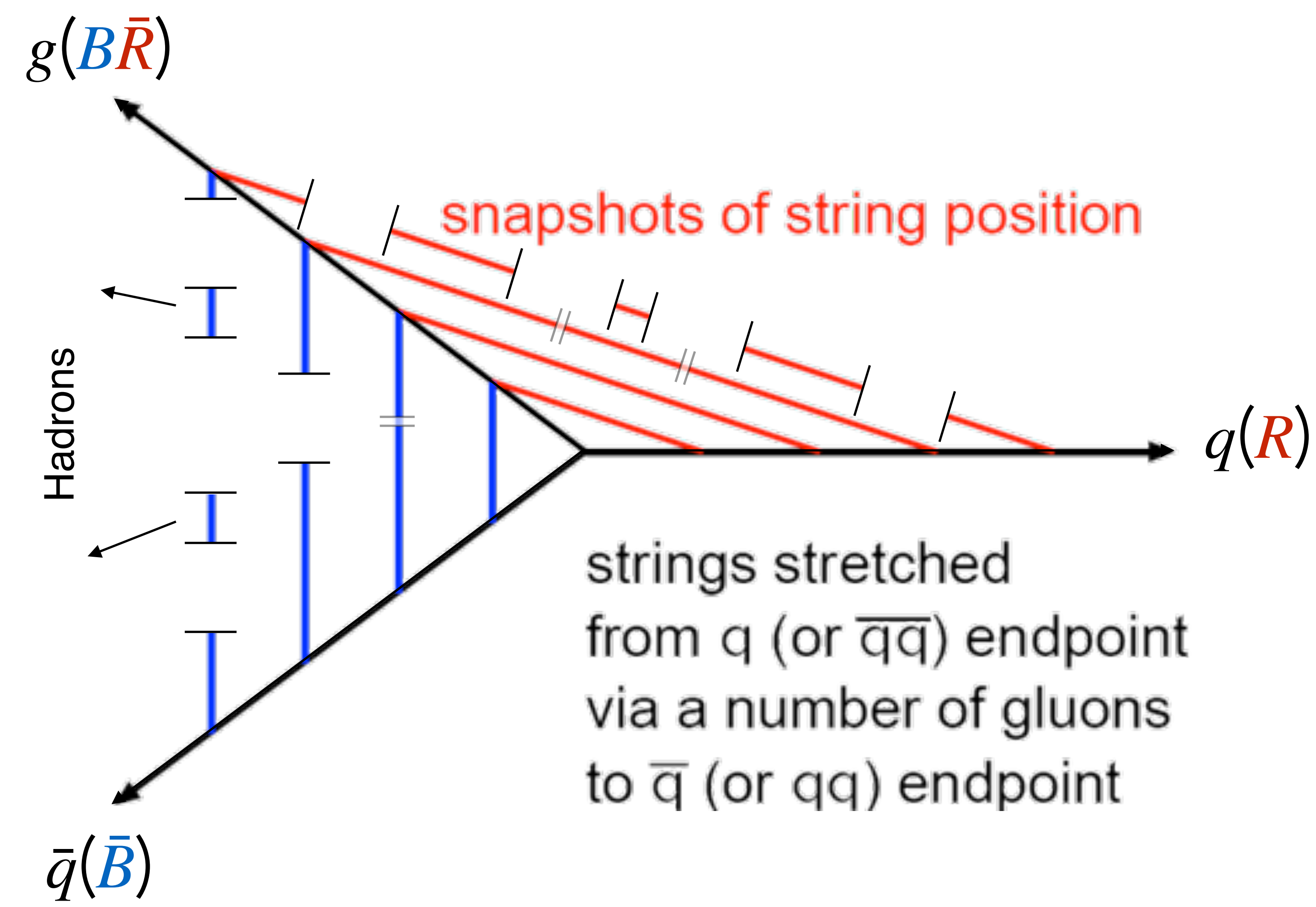
String Fragmentation in One Slide

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!**

The Leading Hadron(s): Rank vs Rapidity

Is the first-rank hadron the hardest one?

Expect ~ 50 GeV for first-rank primary kaons at threshold?

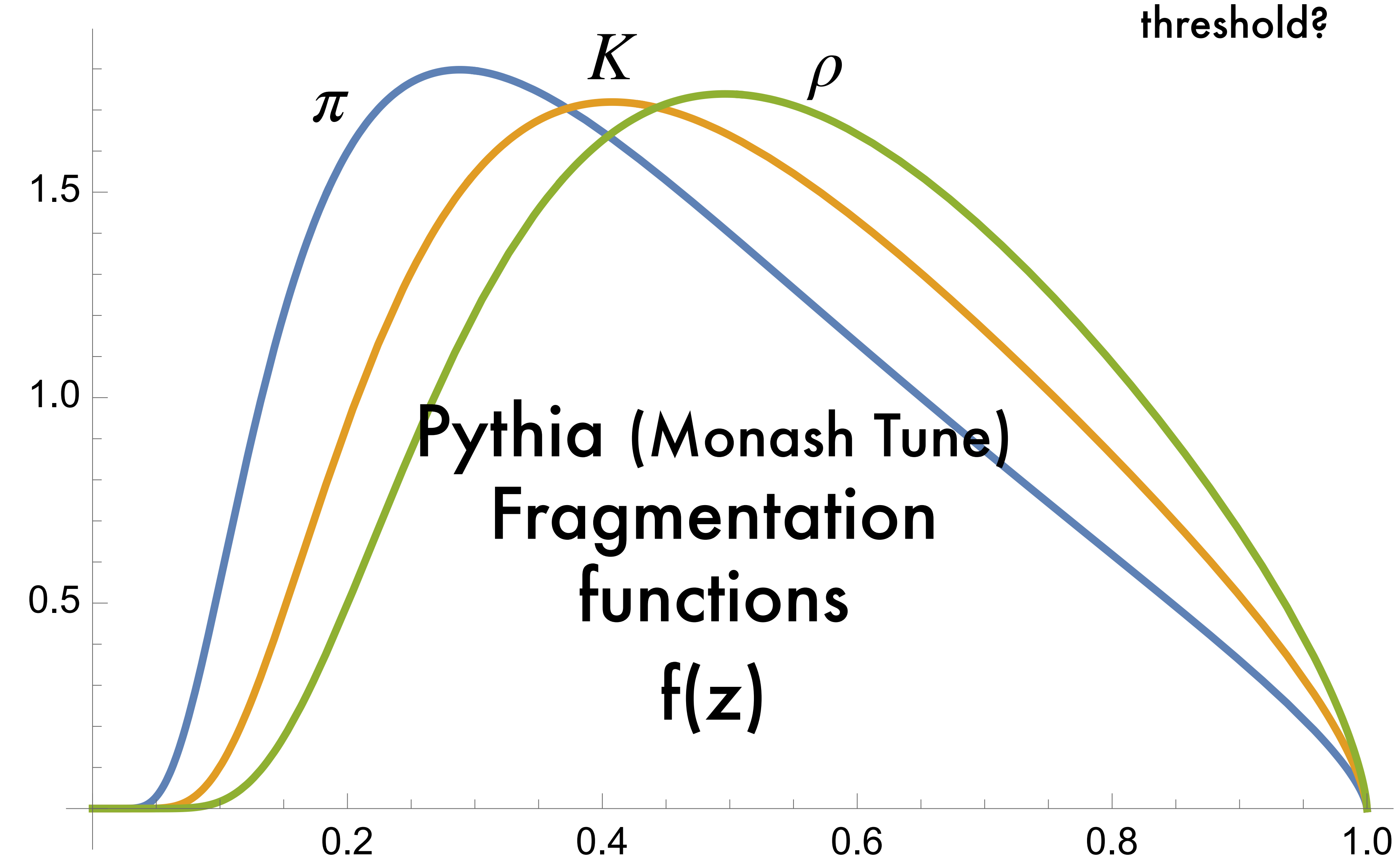
Fluctuations can mix up ranks

Sometimes, the first-rank hadron will take, say 30% of the s quark energy

And the 2nd-rank one may take 70% of the 70% that remains ~ 50% of the s quark energy

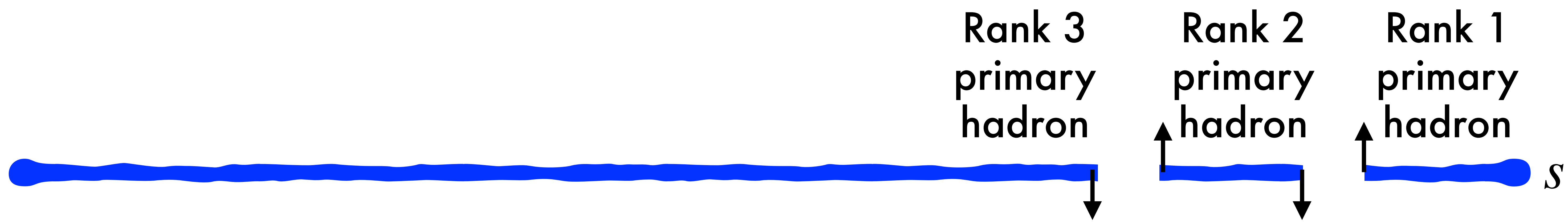
Average of FF is very well constrained

But its width is (currently) quite poorly constrained — should be targeted?



(Heavier particles have harder spectra)

The Leading Hadron(s): pT



The first-rank hadron only receives a single pT kick from a string breakup.

All the other ones receive two

If this is true → exploit that the first-rank one has smaller <pT>?

Can this be tested in Z decays? Has it been?

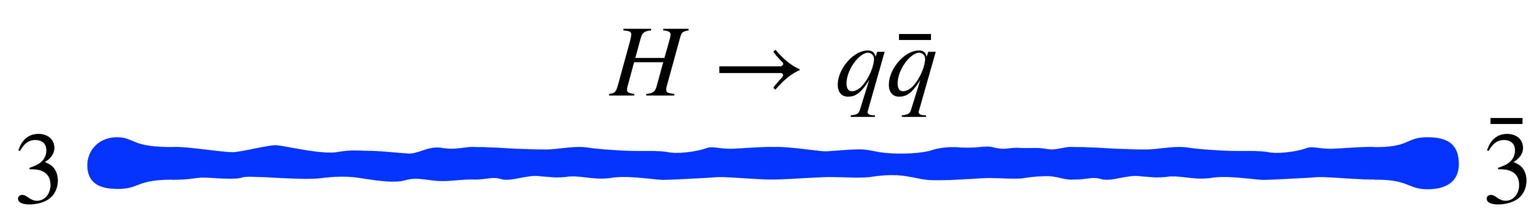
Correlations

How local? Discriminating power will depend on how well we know (and can measure) that

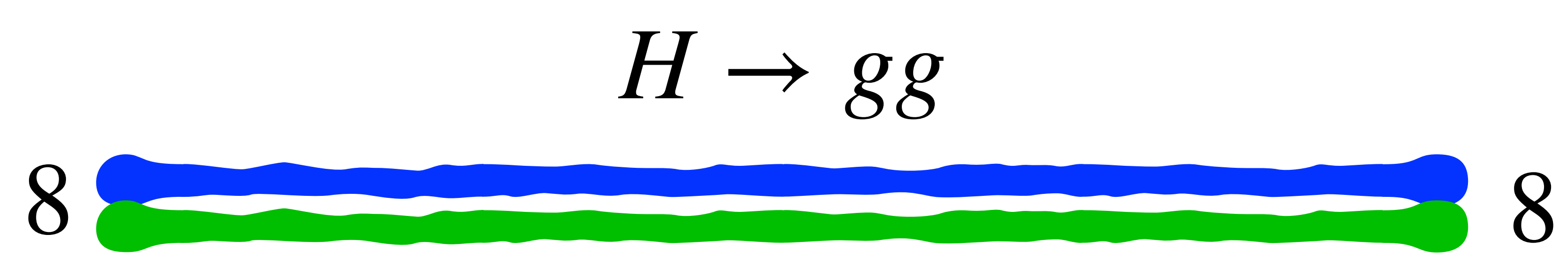
Some studies done at LEP. **Have they been surveyed?** Are they in RIVET? Planning for further studies at future ee (much more precise)?

$s\bar{s}$ versus gg

Want to be able to (reliably/confidently) dinstinguish



(And $Z \to q\bar{q}$, $W \to q\bar{q}'$)



Probably not just 2 x single string?

Quark-Gluon discrimination well studied at LHC

Exploits combination of **IR safe** and **IR sensitive** observables

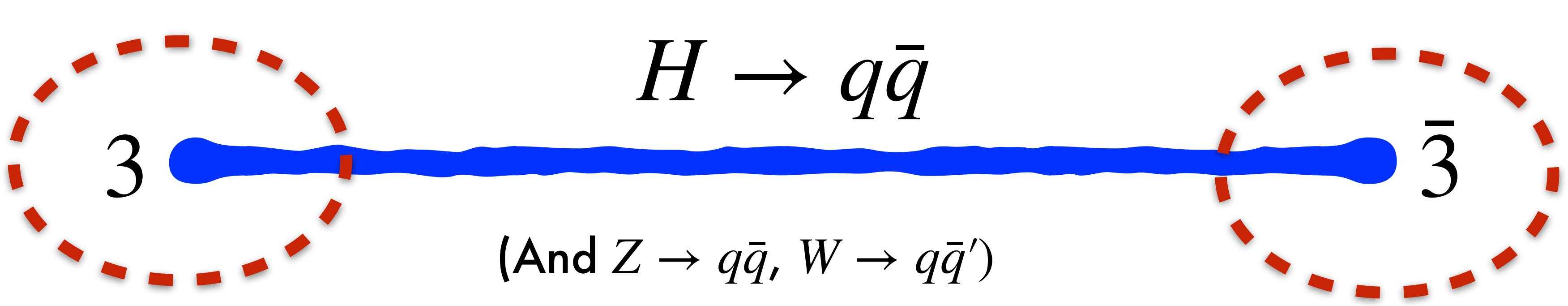
- E.g., number of tracks very powerful discriminator but is IR unsafe
- We do not have the luxury to omit the IR unsafe ones

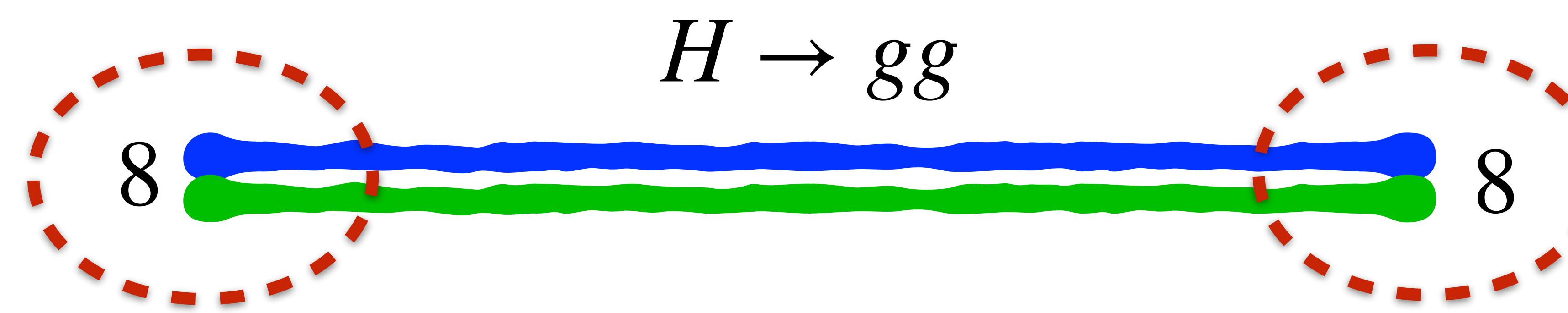
Maximum discrimination requires: Combination of precise perturbation theory AND precise hadronization modelling

Some disagreements among MC models; needs attention?

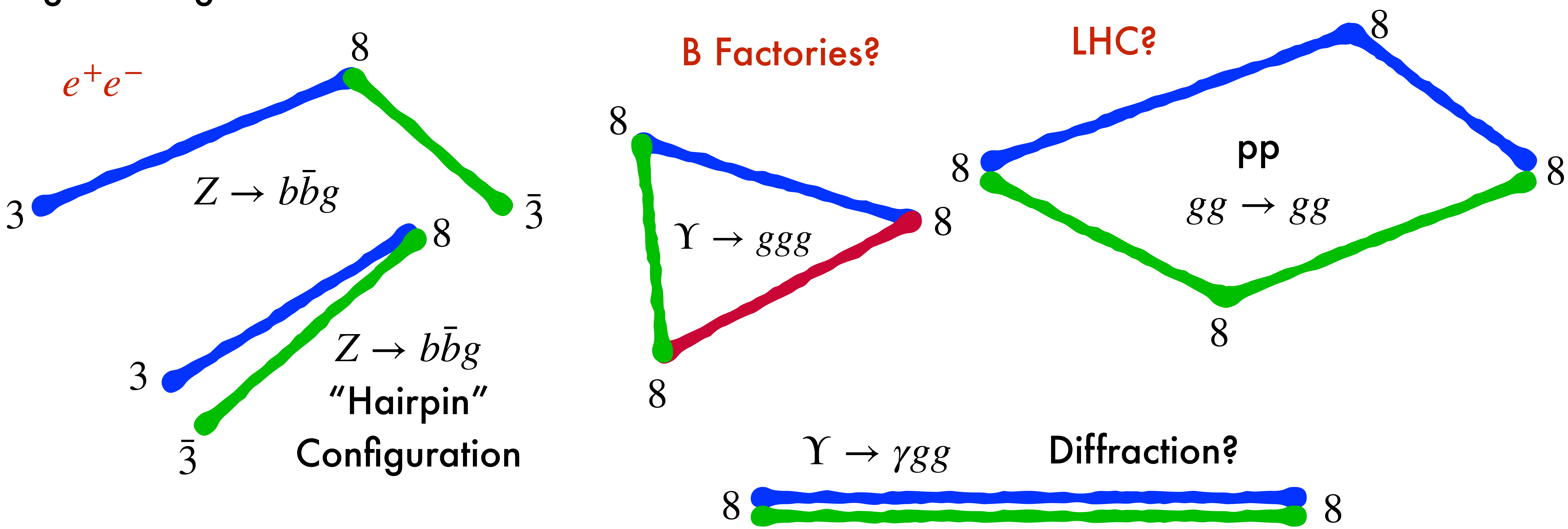
$s\bar{s}$ versus gg

Want to be able to (reliably/confidently) dinstinguish leading fragmentation hadrons





Other gluon fragmentation sources:



Another clean s source? $W \to c\bar{s}$

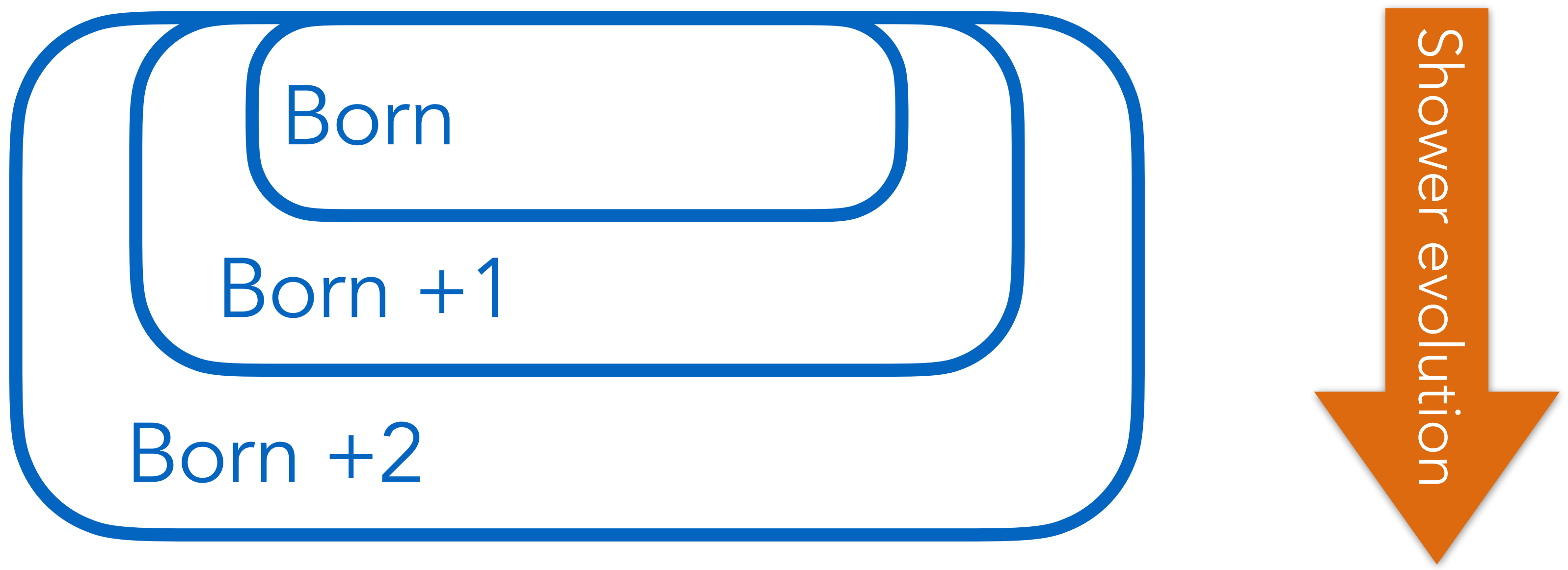
NNLO + Showers for $H \to s\bar{s}$ (preliminary)

VINCIA NNLO

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

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

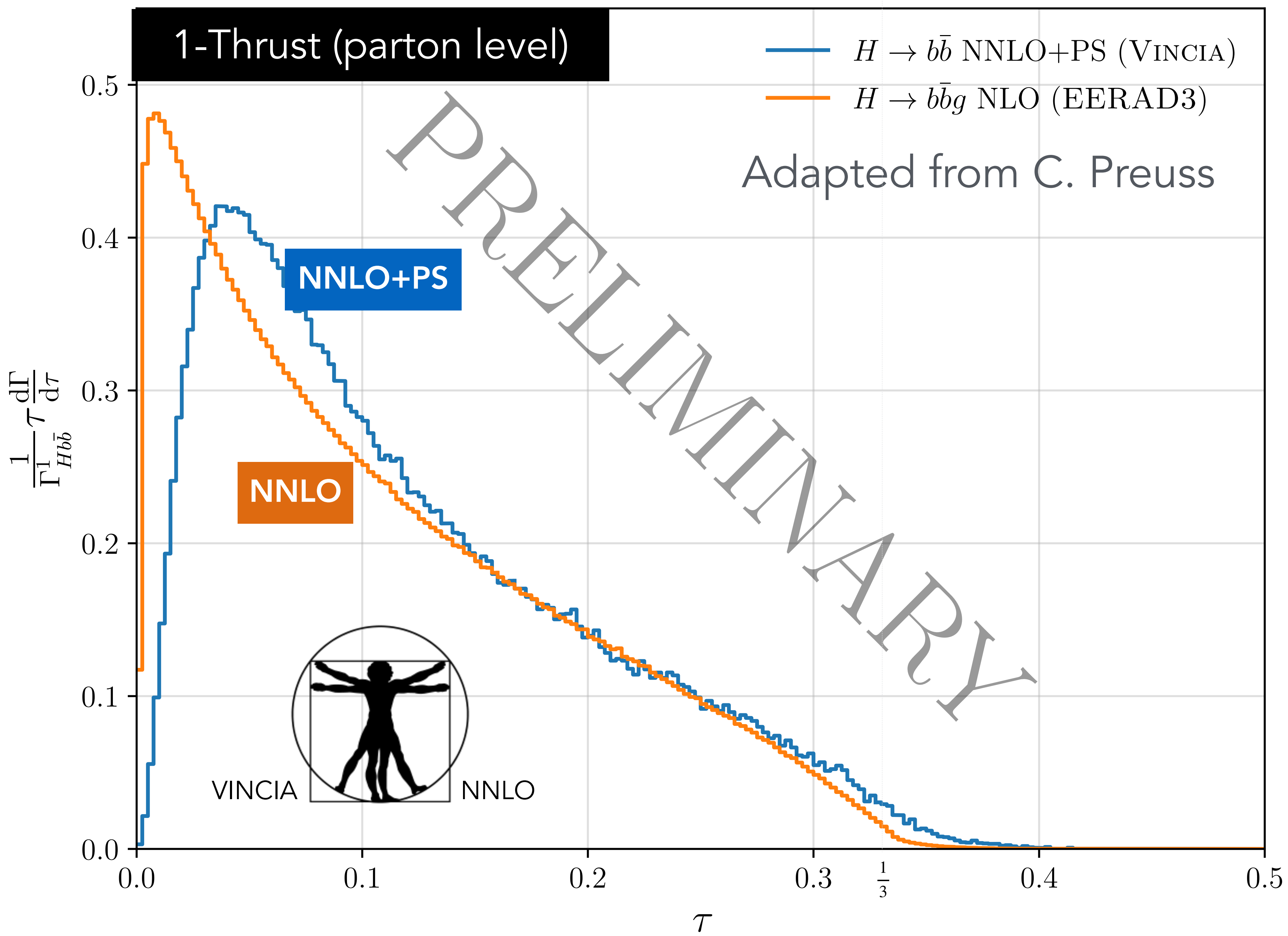
Pre-weighted with the (leading) QCD singular structures = soft/collinear poles



Continue shower afterwards

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

Preview: VinciaNNLO for $H \to q\bar{q}$



For Thrust, NNLO $H \to b\bar{b}$

NLO for $\tau < 1/3$

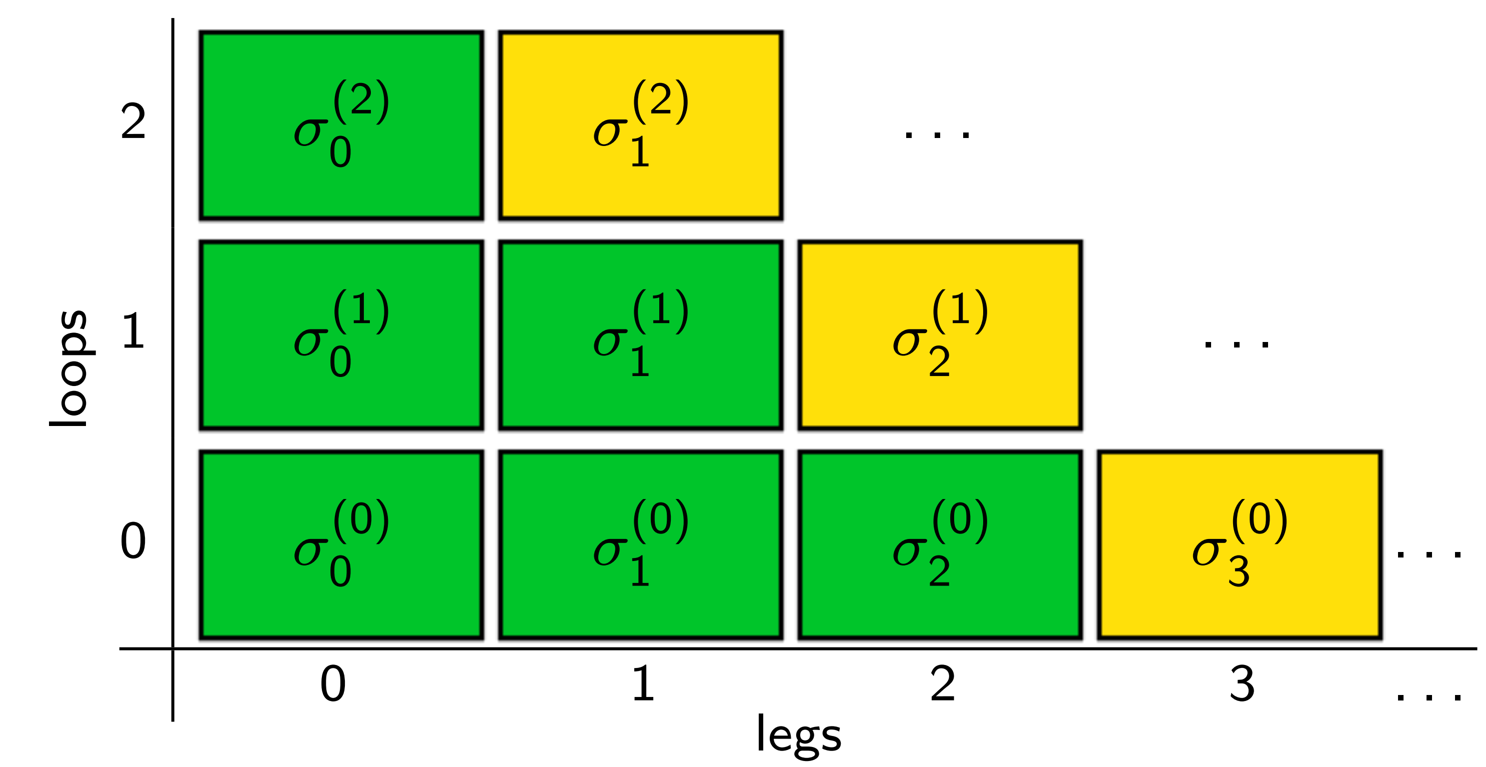
LO for $\tau > 1/3$

Note:

"NNLO Reference" = **EERAD3** NLO $H \to q\bar{q}g$

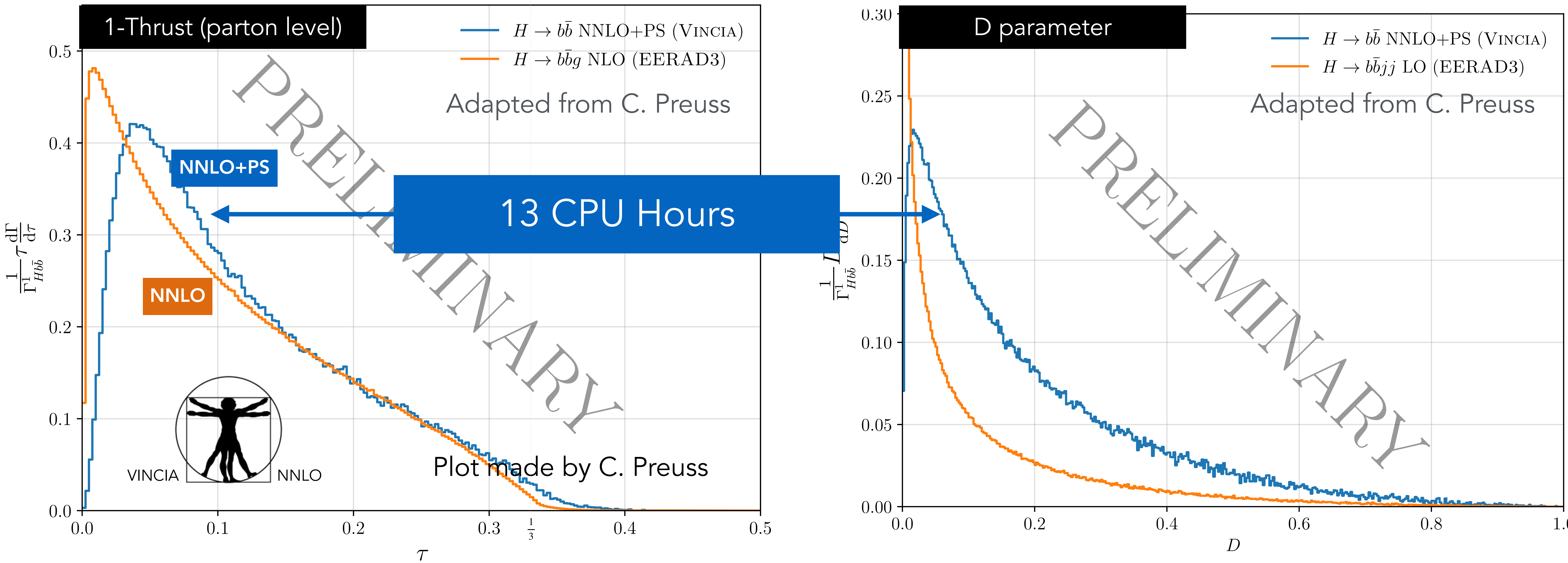
Coloretti, Gehrmann-de Ridder, Preuss, JHEP 06 (2022) 009

NNLO accuracy in $H \to 2j$ implies **NLO correction in first emission** and **LO correction in second emission.**



Preview: VinciaNNLO for $H \to b\bar{b}$

VINCIA NNLO



VINCIA NNLO+PS: shower as phase-space generator: efficient & no negative weights!

➤ Looks ~ 5 x ***faster*** than **EERAD3*** (for equivalent unweighted stats)

+ is **matched to shower** + can be **hadronized**

Proof of concepts now done for $H \to q\bar{q}$ & $Z \to q\bar{q}$; expect public before end of 2024

* Already quite optimised: uses analytical MEs, "folds" phase space to cancel azimuthally antipodal points, and uses antenna subtraction (→ smaller # of NLO subtraction terms than Catani-Seymour or FKS).

Summary

Confinement is **not a solved issue**

LHC has made striking new discoveries

Lessons are making their way into MC hadronization models

Taggers trained on combination of Data-Driven and MC:

Fixed-order Perturbation Theory — NLO (PowHeg, aMC@NLO) → **NNLO**

Parton-Shower Resummations — (N)LL → **NNLL**

Modelling of **Confinement**: Strings vs Clusters

Modelling of Strings/Cluster **Breakups → Hadrons**

Colour Reconnections, Gluon Fragmentation, String Interactions, Baryon Fractions, Strangeness, …

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