VINCIA NNLO

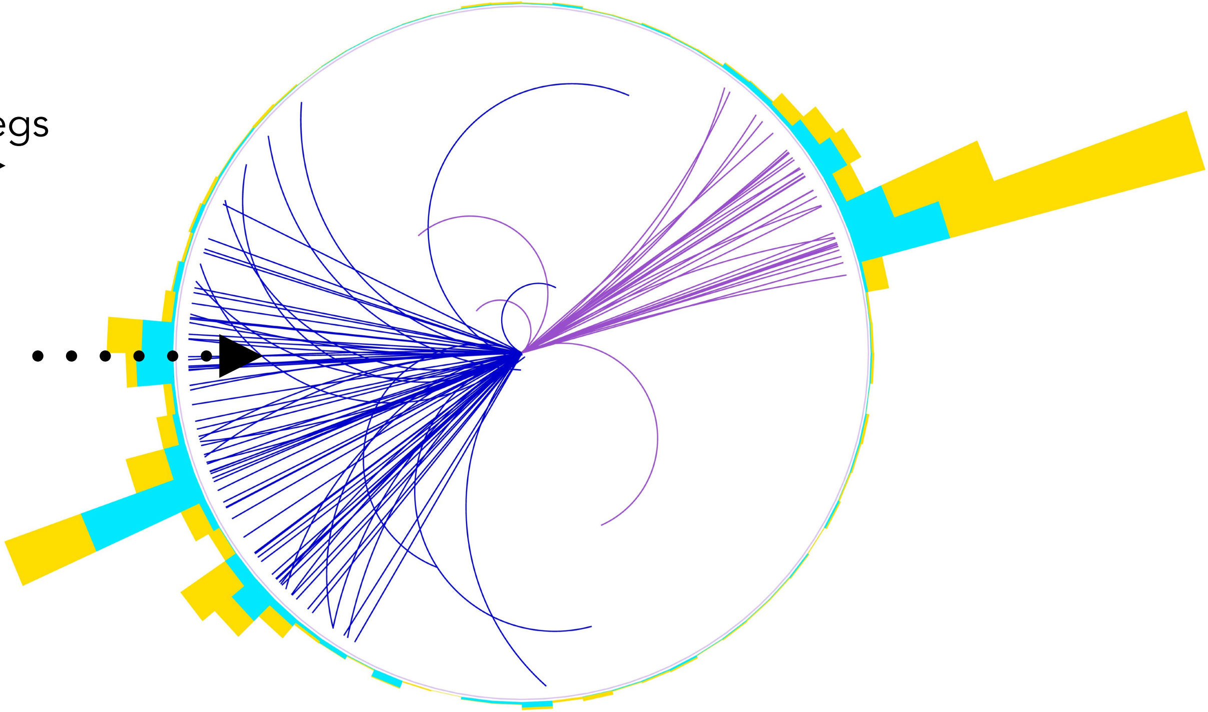
NNLO + Strings

Peter Skands — U of Oxford & Monash U.

	0	1	2
0	B	R	RR
1	V	RV	
2	VV		

Legs

Loops



THE ROYAL SOCIETY

THE UNIVERSITY OF WARWICK

Australian Government
Australian Research Council

MCnet

Introduction & Overview

Current state of the art for perturbation theory: NNLO (→ N3LO)

Matching to showers + hadronization mandatory for explicit collider studies

(+ resummation extends range; hadronization → explicit power corrections; MPI → UE, …)

1. Can use off-the-shelf (LL) showers, e.g. with MiNNLO$_{PS}$

Based on POWHEG-Box ⊕ Analytical Resummation ⊕ NNLO normalisation

Approximate method; depends on several auxiliary scales / choices → can exhibit large variations

2. This talk: VinciaNNLO

Based on nested shower-style phase-space generation with 2nd-order MECs

True NNLO matching → Expect small matching systematics

So far only worked out for colour-singlet decays.

(Also developing extensions towards NLL (→NNLL) showers …)

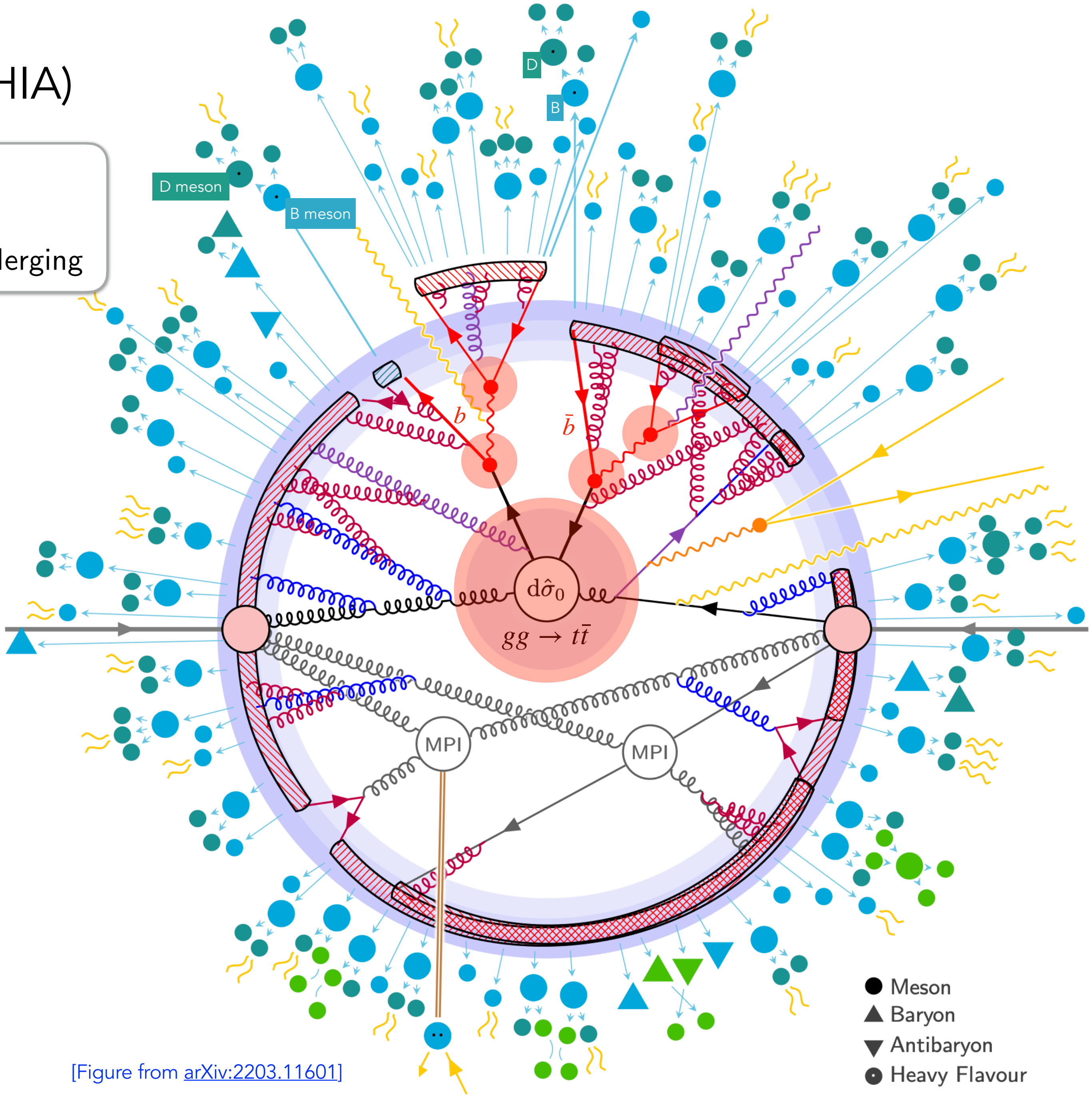
+ Strings

New discoveries at LHC, especially **baryons and strangeness**: possible interpretations

An LHC collision (in PYTHIA)

Hard Process

○ Hard Interaction
● Resonance Decays
■ MECs, Matching & Merging

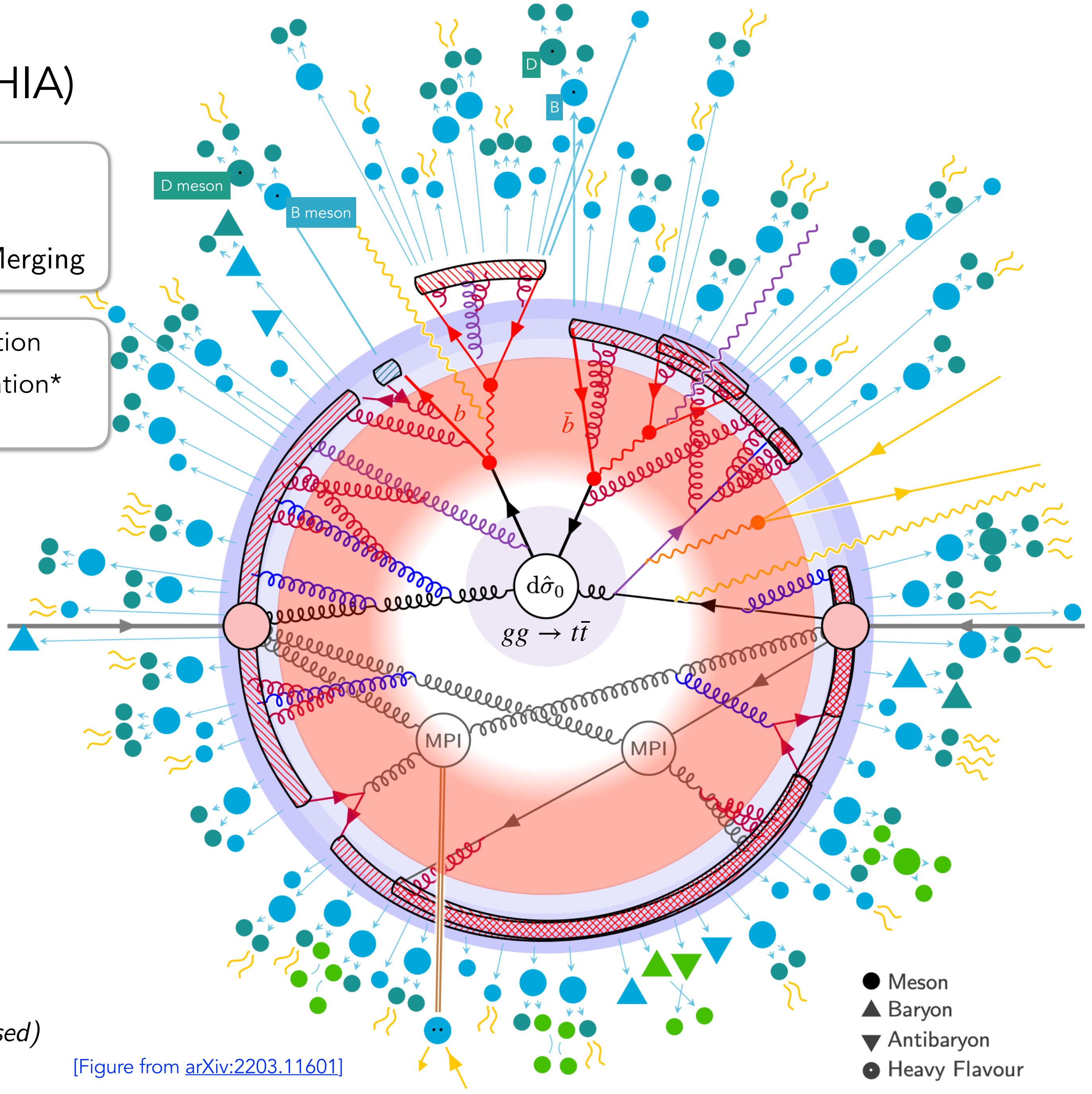


[Figure from arXiv:2203.11601]

An LHC collision (in PYTHIA)

Hard Process
- ○ Hard Interaction
- ● Resonance Decays
- 🟪 MECs, Matching & Merging

Parton Showers
- 🟥 QCD Final-State Radiation
- 🟦 QCD Initial-State Radiation*
- 🟨 Electroweak Radiation



(: incoming lines are crossed)*

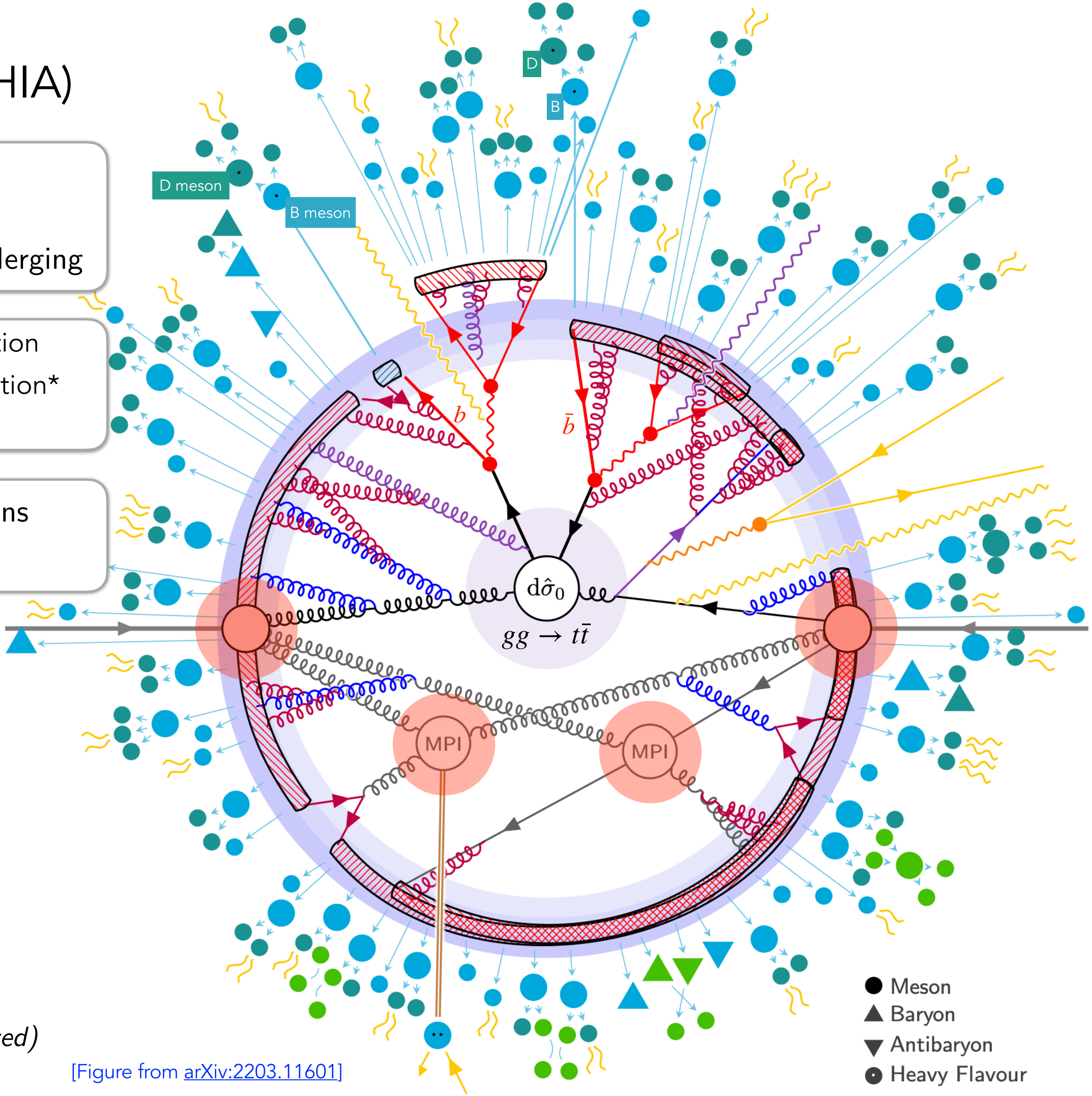
[Figure from arXiv:2203.11601]

An LHC collision (in PYTHIA)

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*



(: incoming lines are crossed)*

[Figure from arXiv:2203.11601]

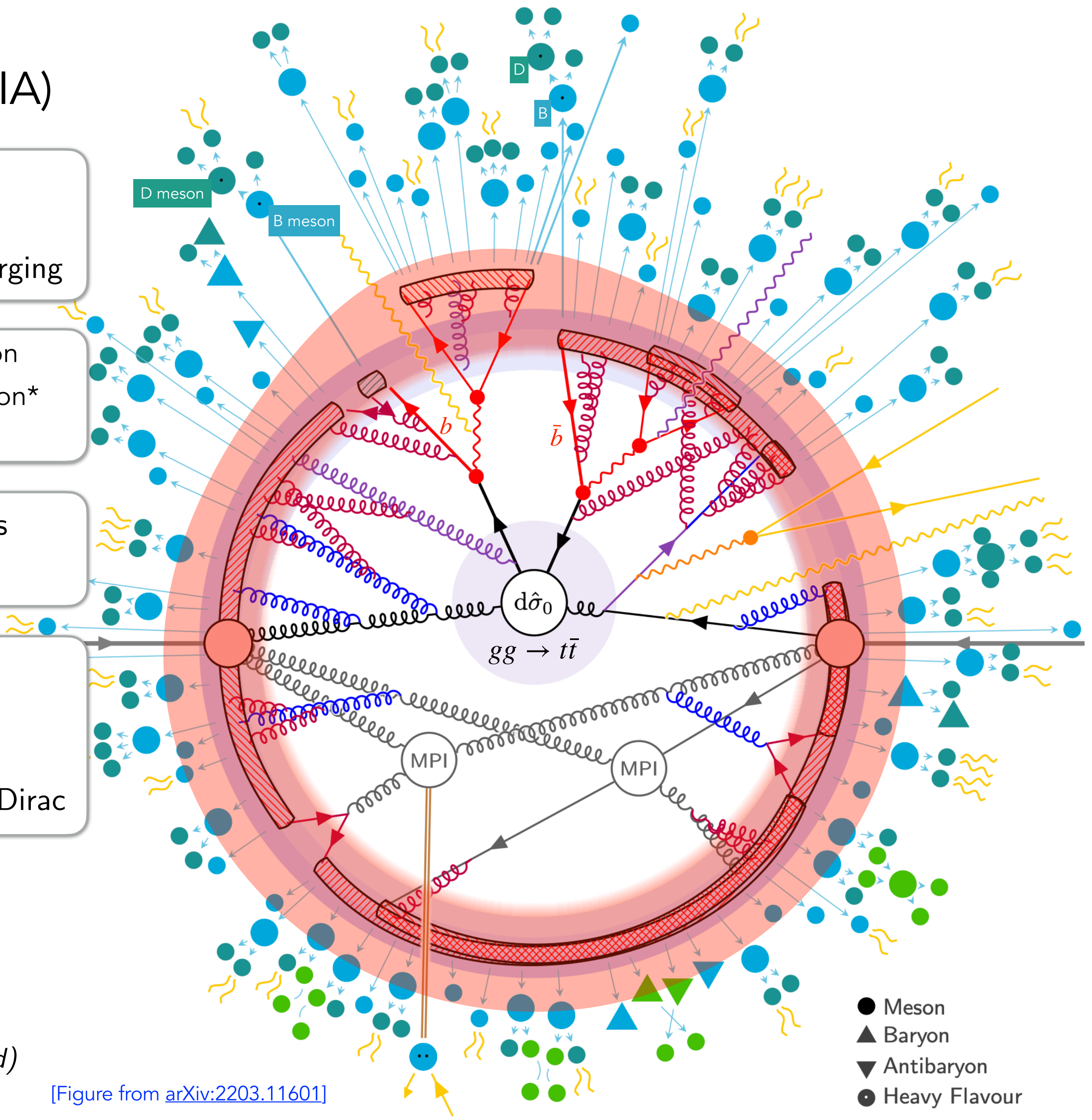
An LHC collision (in PYTHIA)

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



(: incoming lines are crossed)*

[Figure from arXiv:2203.11601]

An LHC collision (in PYTHIA)

Hard Process
- ○ Hard Interaction
- ● Resonance Decays
- ■ MECs, Matching & Merging

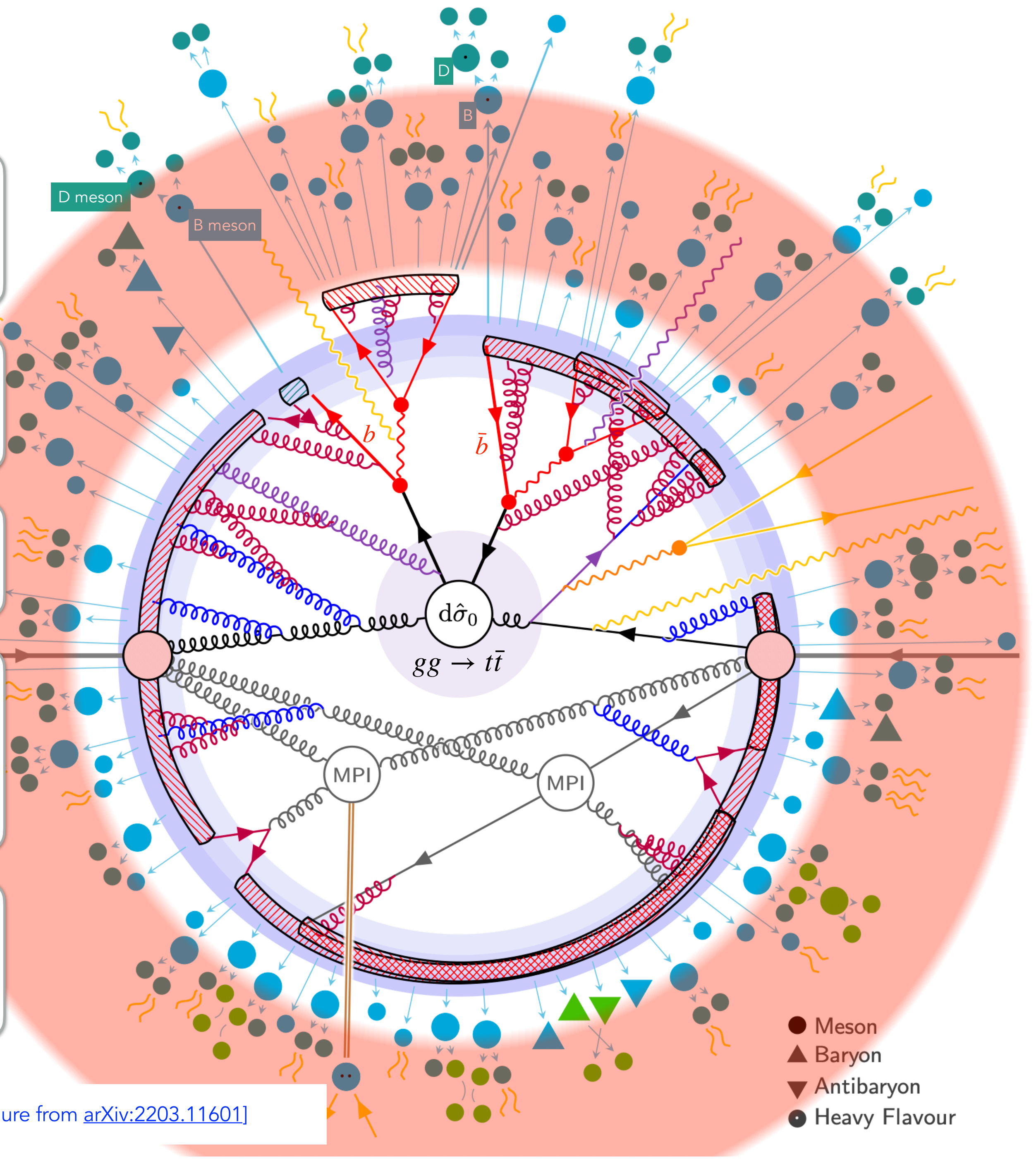
Parton Showers
- ■ QCD Final-State Radiation
- ■ QCD Initial-State Radiation*
- ■ Electroweak Radiation

Underlying Event
- ○ Multiparton Interactions
- ☐ Beam Remnants*

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

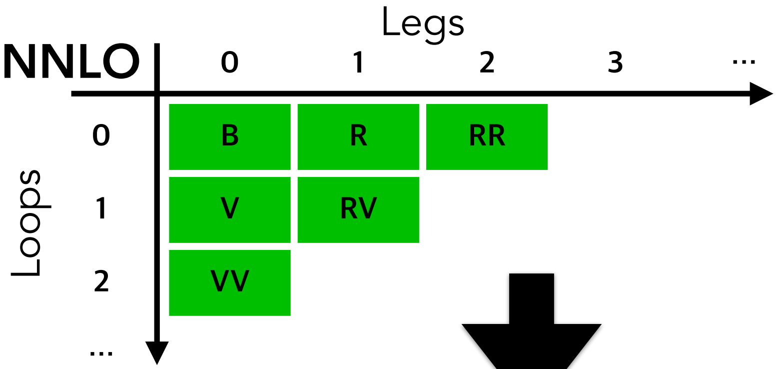
Hadron (& τ) Decays
- ■ Primary Hadrons
- ■ Secondary Hadrons
- ■ Hadronic Reinteractions

(: incoming lines are crossed)*



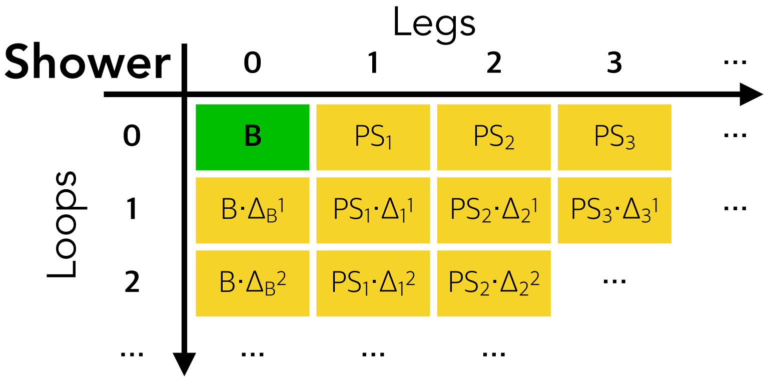
[Figure from arXiv:2203.11601]

The Case for Embedding Fixed-Order Calculations in Showers



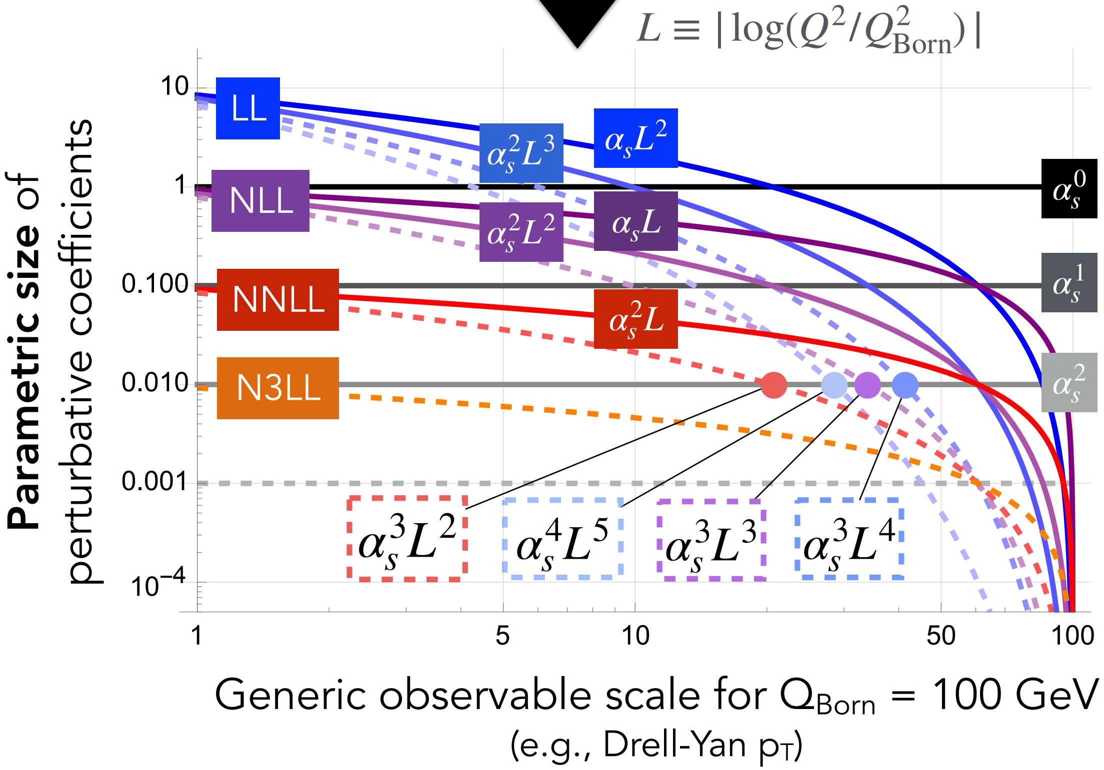
NNLO

Loops \ Legs	0	1	2	3	…
0	B	R	RR		
1	V	RV			
2	VV				
…					



Shower

Loops \ Legs	0	1	2	3	…
0	B	PS_1	PS_2	PS_3	…
1	$B \cdot \Delta_B^1$	$PS_1 \cdot \Delta_1^1$	$PS_2 \cdot \Delta_2^1$	$PS_3 \cdot \Delta_3^1$	…
2	$B \cdot \Delta_B^2$	$PS_1 \cdot \Delta_1^2$	$PS_2 \cdot \Delta_2^2$	…	
…	…	…	…		



$L \equiv |\log(Q^2/Q^2_{\text{Born}})|$

Resummation extends domain of validity of perturbative calculations

Showers ➤ Fully exclusive final states

+ non-perturbative corrections

Target for next generation of MCs:

%-level precision @ LHC

⇒ NNLO + NNLL

Warmup: NLO Matching with POWHEG Box [Alioli et al, 2010]

(Just focusing on the real-radiation part)

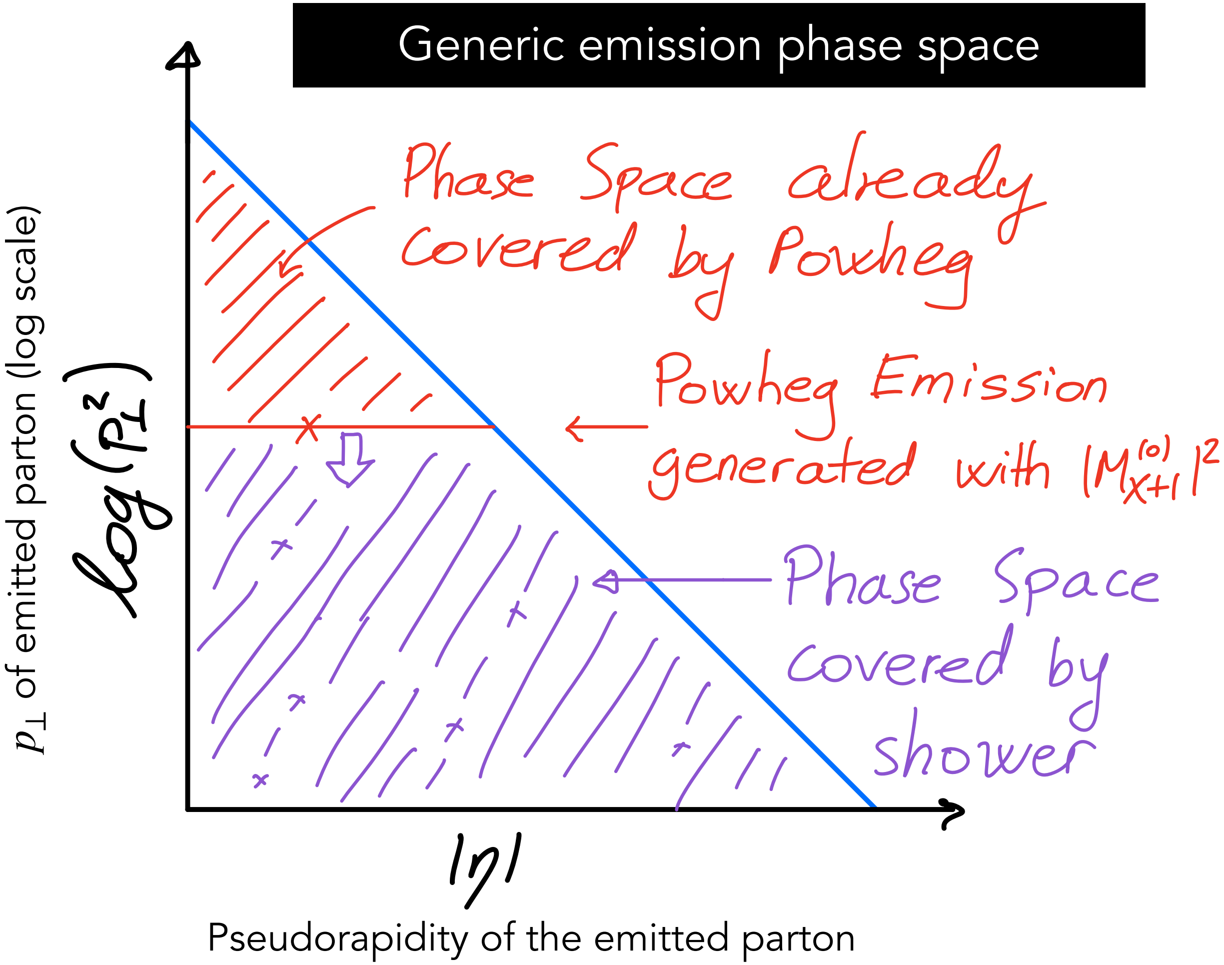
POWHEG generates the 1st (hardest) emission in a shower-like manner (MECs)

Combines Matrix-Element Corrections (MEC) [Bengtsson & Sjöstrand 1987 + …]

with NLO Born-Level Normalization [Nason 2004; Fixione, Nason, Oleari 2007]

Sweeping over the phase space, from high to low p_T

Shower then takes over and generates all softer emissions



Powheg-Box — Important Caveat

PowHeg-Box uses its own definition of "p_T" ≠ shower's p_T

Naive POWHEG Matching

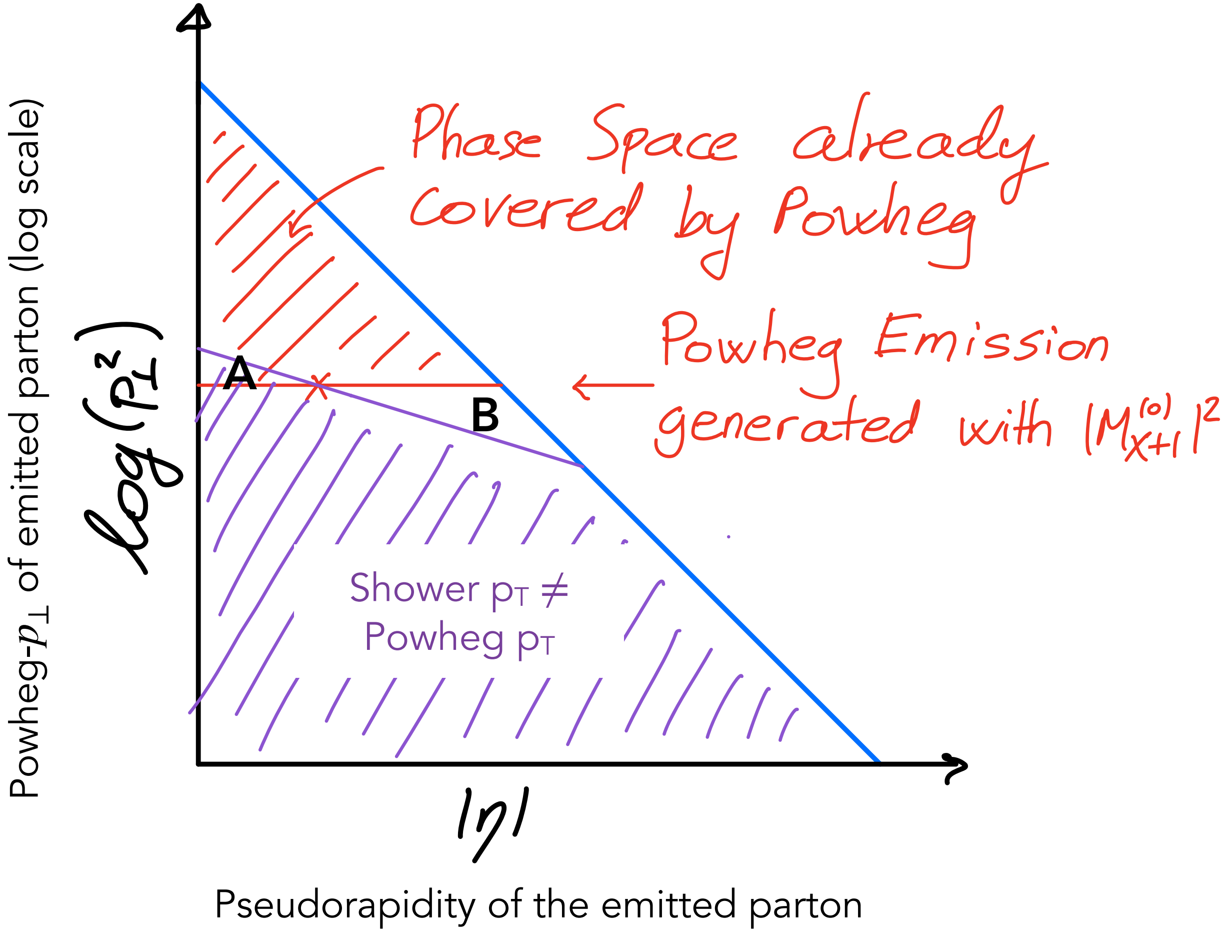
Continue the shower starting from the POWHEG-Box p_T scale

(Saved in LHEF SCALUP value)

FAILS!

Region **A** is double-counted

Region **B** is left empty

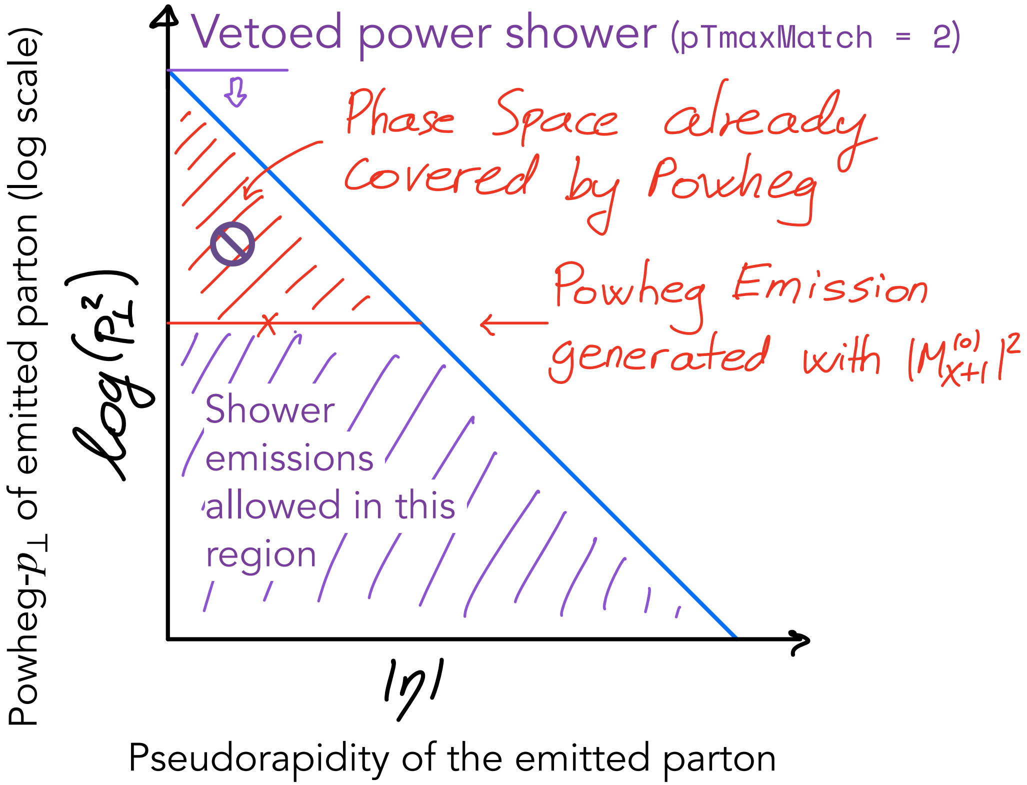


Current best practice

Vetoed "Power Showers" — with PYTHIA's POWHEG hooks (`POWHEG:veto = 1`)

Let shower fill **all** of phase space (⇒ lots of double counting but at least no holes)

Eliminate double counting: for each shower emission, compute the would-be $p_{\perp i}^{\mathrm{Powheg}}$ and veto any that would double-count $p_{\perp 1}^{\mathrm{Powheg}}$



Vetoed Power Showers

Work very well for **simple processes** (like Drell-Yan)

But the ambiguities can be much more severe for more complex processes.

Especially ones involving initial-final colour flows

2. From NLO to NNLO

MiNNLO$_{PS}$ builds on (extends) POWHEG NLO for X + jet

[Hamilton et al. 1212.4504, Monni et al. 1908.06987]

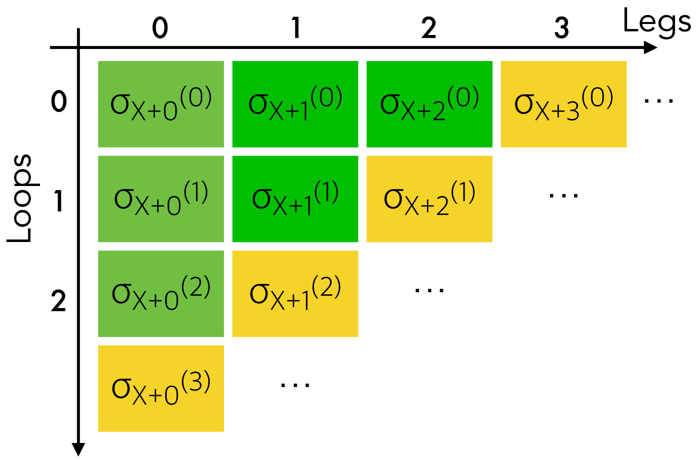
Allow the first jet to approach $p_\perp \to 0$ ~ X + 0

Tame divergence with analytic (NNLL) Sudakov

(introduces additional hardness scale
= resummation scale)

Normalize inclusive $\mathrm{d}\sigma_X$ to NNLO

(ambiguity on how to “spread” the additional
contributions in phase space.)



Loops	0	1	2	3	Legs
0	$\sigma_{X+0}^{(0)}$	$\sigma_{X+1}^{(0)}$	$\sigma_{X+2}^{(0)}$	$\sigma_{X+3}^{(0)}$	…
1	$\sigma_{X+0}^{(1)}$	$\sigma_{X+1}^{(1)}$	$\sigma_{X+2}^{(1)}$	…	
2	$\sigma_{X+0}^{(2)}$	$\sigma_{X+1}^{(2)}$	…		
	$\sigma_{X+0}^{(3)}$	…			

~ Best you can do with current off-the-shelf parton showers

But is approximate; introduces several new (unphysical) ambiguities:

$p_\perp^{\text{Shower}}$ vs $p_\perp^{\text{Powheg}}$ vs $Q_{NNLL}^{\text{resummation}}$ & differential NNLO spreading

MiNNLO$_{PS}$ inherits some issues from POWHEG-Box

Large dependence on pThard scale

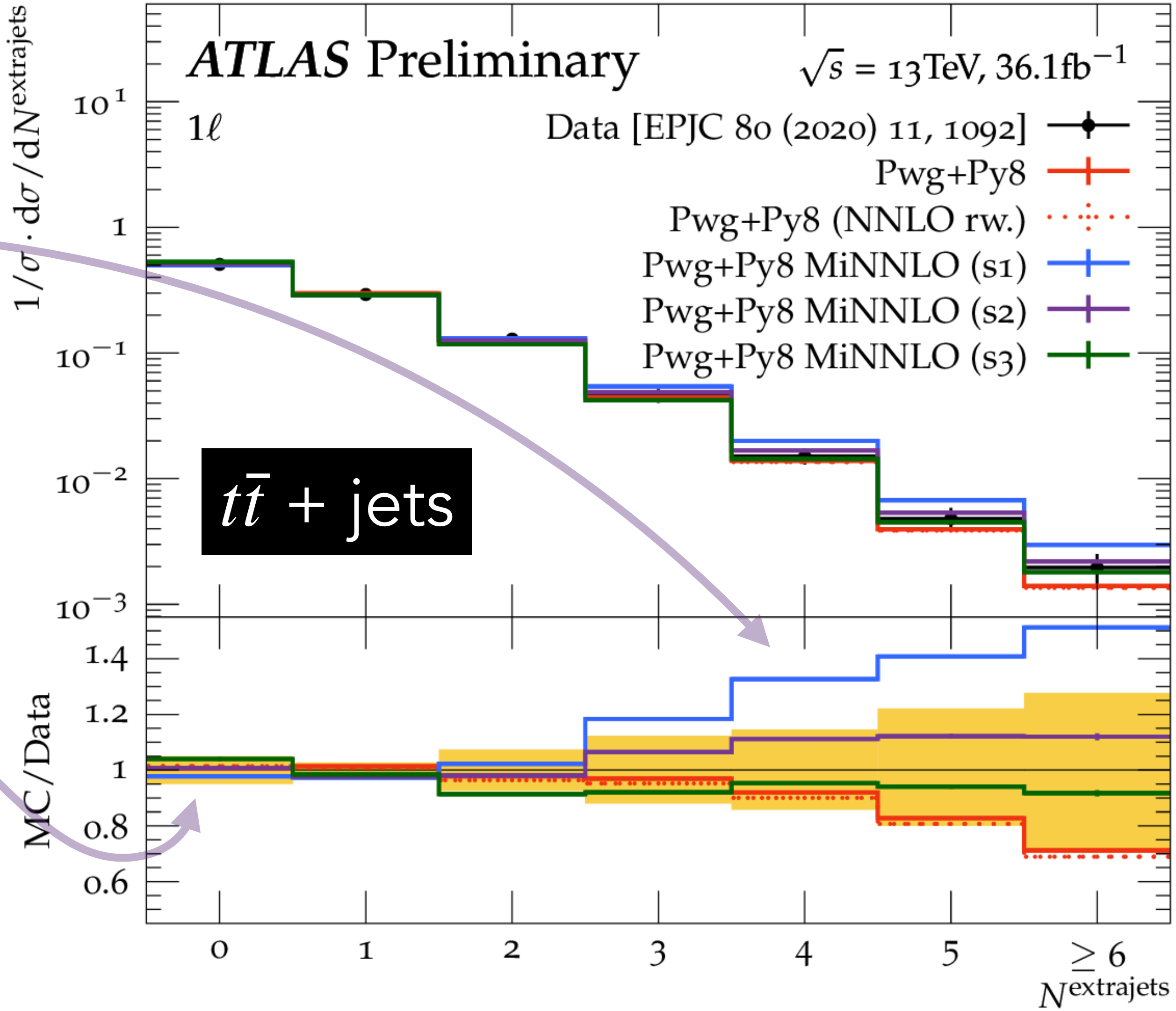
Big variations in predictions for further jets

Calculation "anchored" in NLO for X+jet

$\Longrightarrow$ Also big variations for Born-level (0-jet) observable.

Not the pattern one expects of an NNLO calculation

ATL-PHYS-PUB-2023-029. September 2023.



Recommendations to Users of these Calculations

MiNNLO$_{PS}$ is an *approximate* matching scheme

Does not "match" shower to NNLO point by point in phase space

(Impossible to do with LL showers.)

Does not always do vetoed showers

(This can in principle be done.)

Depends on several auxiliary scales

(Intrinsic to scheme. Physical observables should not depend on them → *vary!*)

Comprehensive variations mandatory to estimate scheme uncertainties

Cannot blindly trust the NNLO label

Nor is the subsequent shower *guaranteed* to preserve accuracy

E.g., Regular POWHEG + proper vetoed showers may do "better" for some observables?

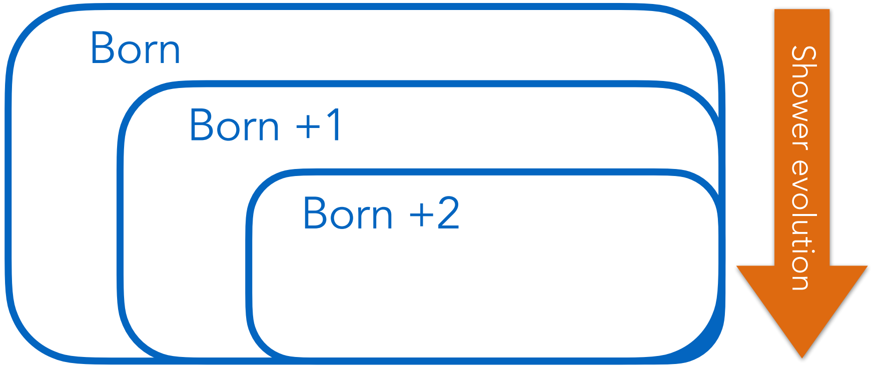
Towards True NNLO Matching

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



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

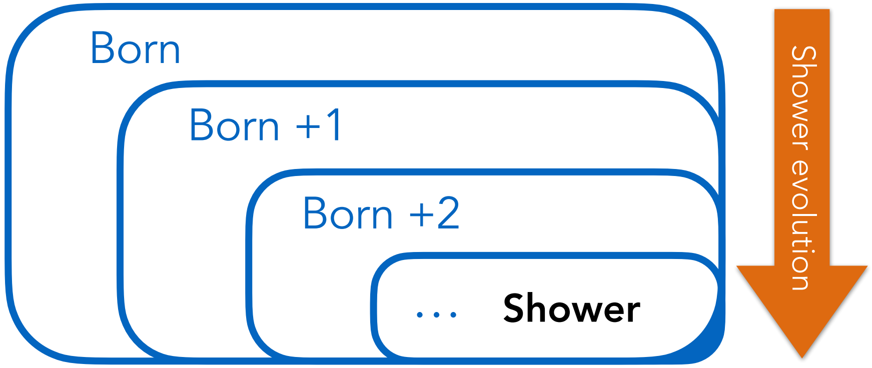
Towards True NNLO Matching

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



Simply continue shower afterwards (à la original MECs and Powheg)

No unphysical scales ⇒ expect small matching systematics

Based on Sector Antenna Showers

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

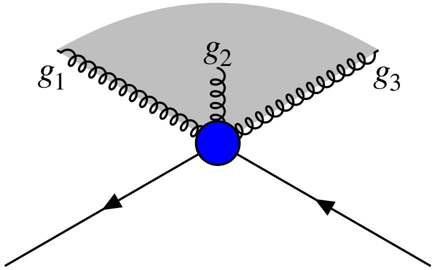
Sector antennae

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 sector definitions based on "ARIADNE p_T":

Gustafson & Pettersson, NPB 306 (1988) 746

$$p^2_{\perp j} = \frac{s_{ij}s_{jk}}{s_{ijk}}$$ with $s_{ij} \equiv 2(p_i \cdot p_j)$ *(+ generalisations for heavy-quark emitters)* Brooks, Preuss & PS 2003.00702

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

Clean scale definitions; shower operator is **bijective** & true **Markov chain**

Proof of Concept in VINCIA

Campbell, Höche, Li, Preuss, **PZS**, 2108.07133

VINCIA NNLO

Focus on hadronic Z decays (for now)

"Two-loop MEC"

$$\langle O\rangle^{\mathrm{V{\scriptsize INCIA}}}_{\mathrm{NNLO+PS}} = \int \mathrm{d}\Phi_2\, \mathrm{B}(\Phi_2)\, \underset{\text{local } K\text{-factor}}{\boxed{k_{\mathrm{NNLO}}(\Phi_2)}}\, \underset{\text{shower operator}}{\boxed{\mathcal{S}_2(t_0, O)}}$$

Need:

❶ Born-Local NNLO ($\mathcal{O}(\alpha_s^2)$) K-factors: $k_{\mathrm{NNLO}}(\Phi_2)$

❷ NLO ($\mathcal{O}(\alpha_s^2)$) MECs in the first $2 \to 3$ shower emission: $k^{2\to3}_{\mathrm{NLO}}(\Phi_3)$

❸ LO ($\mathcal{O}(\alpha_s^2)$) MECs for next (iterated) $2 \to 3$ shower emission: $k^{3\to4}_{\mathrm{LO}}(\Phi_4)$

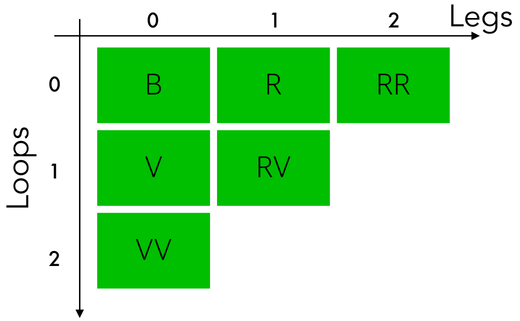
❹ Direct $2 \to 4$ branchings for unordered sector, with LO ($\mathcal{O}(\alpha_s^2)$) MECs: $k^{2\to4}_{\mathrm{LO}}(\Phi_4)$

NEW

❶ Weight each Born-level event by **local** K-factor

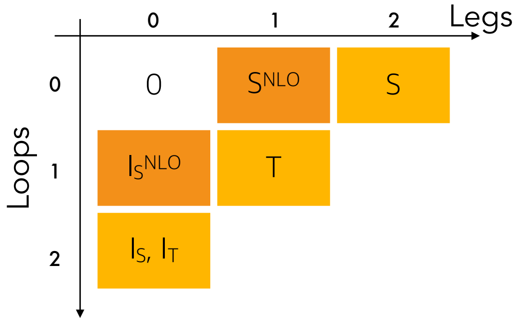
$$k_{\mathrm{NNLO}}(\Phi_2) = 1 + \frac{\mathrm{V}(\Phi_2)}{\mathrm{B}(\Phi_2)} + \frac{\mathrm{I}_{\mathrm{S}}^{\mathrm{NLO}}(\Phi_2)}{\mathrm{B}(\Phi_2)} + \frac{\mathrm{VV}(\Phi_2)}{\mathrm{B}(\Phi_2)} + \frac{\mathrm{I}_{\mathrm{T}}(\Phi_2)}{\mathrm{B}(\Phi_2)} + \frac{\mathrm{I}_{\mathrm{S}}(\Phi_2)}{\mathrm{B}(\Phi_2)}$$
$$+ \int \mathrm{d}\Phi_{+1} \left[\frac{\mathrm{R}(\Phi_2,\Phi_{+1})}{\mathrm{B}(\Phi_2)} - \frac{\mathrm{S}^{\mathrm{NLO}}(\Phi_2,\Phi_{+1})}{\mathrm{B}(\Phi_2)} + \frac{\mathrm{RV}(\Phi_2,\Phi_{+1})}{\mathrm{B}(\Phi_2)} - \frac{\mathrm{T}(\Phi_2,\Phi_{+1})}{\mathrm{B}(\Phi_2)} \right]$$
$$+ \int \mathrm{d}\Phi_{+2} \left[\frac{\mathrm{RR}(\Phi_2,\Phi_{+2})}{\mathrm{B}(\Phi_2)} - \frac{\mathrm{S}(\Phi_2,\Phi_{+2})}{\mathrm{B}(\Phi_2)} \right]$$

Fixed-Order Coefficients:



	0	1	2
0	B	R	RR
1	V	RV	
2	VV		

Subtraction Terms:



	0	1	2
0	0	$\mathrm{S}^{\mathrm{NLO}}$	S
1	$\mathrm{I}_{\mathrm{S}}^{\mathrm{NLO}}$	T	
2	I_{S}, I_{T}		

(not **directly** tied to shower formalism — but must be fully local in Born kinematics Φ_2)

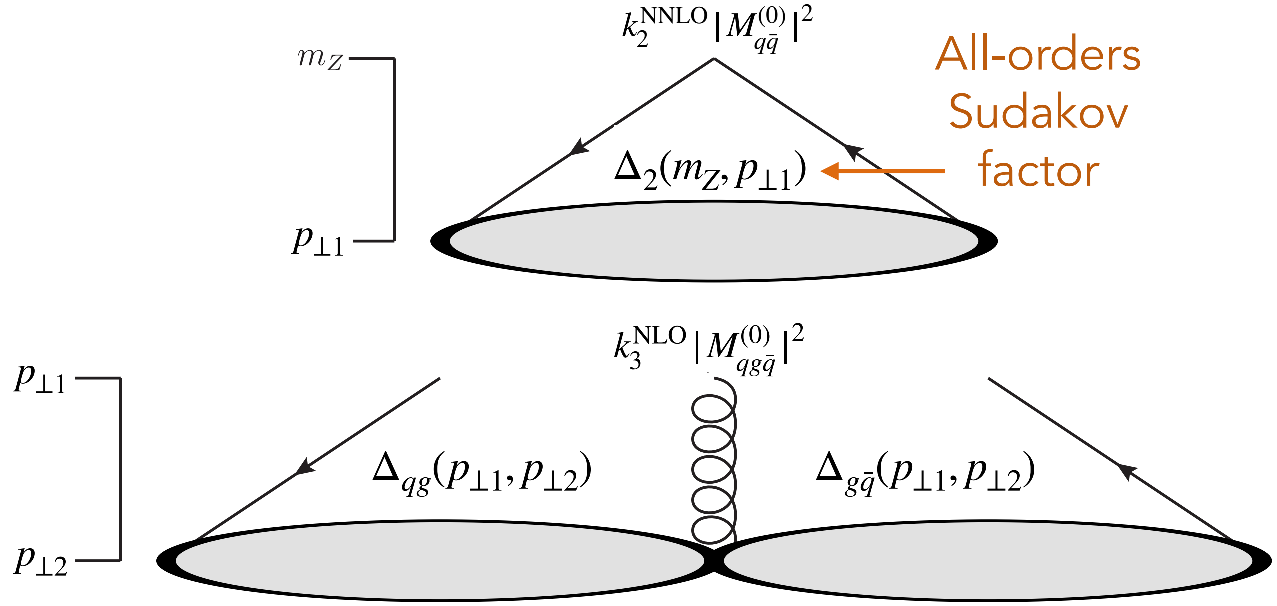
Note: requires "Born-local" NNLO subtraction terms (simple for colour-singlet production).

The Shower Operator (its 2nd-order expansion)

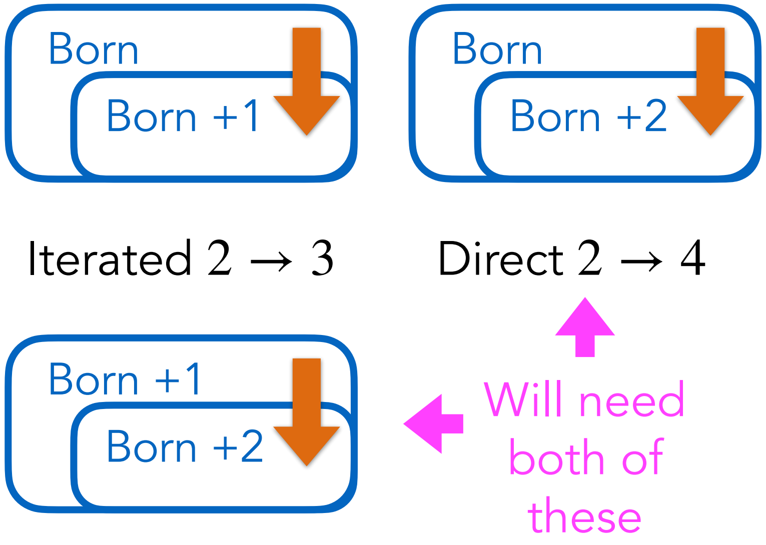
This is the part that differs most from standard fixed-order methods

Recall: the +1 and +2 phase spaces are generated via nested sequences of shower-style branchings. Each of which produces an **all-orders** expansion!

We expand these to second order and correct them to NNLO



All-orders Sudakov factor



Born

Born +1

Born

Born +2

Iterated $2 \to 3$

Direct $2 \to 4$

Born +1

Born +2

Will need both of these

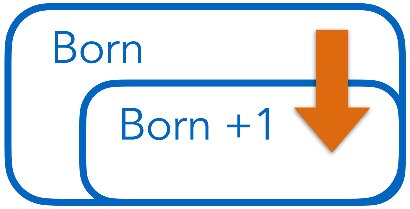
❷ & ❸ Iterated $2 \to 3$ Branchings with NNLO Corrections

Key Aspect:

Up to matched order, include **process-specific $\mathcal{O}(\alpha_s^2)$ corrections** into shower evolution

❷ Correct 1st branching to (fully differential) NLO 3-jet rate [Hartgring, Laenen, PS (2013)]

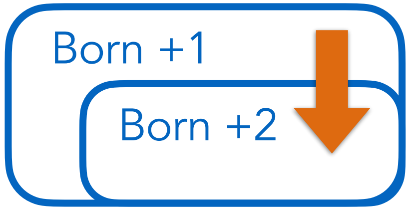
$$\Delta^{\mathrm{NLO}}_{2\to3}\left(\frac{m_Z}{2}, p_{\perp1}\right) = \exp\left\{-\int_{p_{\perp1}}^{\frac{m_Z}{2}} \mathrm{d}\Phi_{[2]+1}\frac{|M^{(0)}_{Z\to3}(\Phi_3)|^2}{|M^{(0)}_{Z\to2}(\Phi_2)|^2}k^{Z\to3}_{\mathrm{NLO}}(\Phi_2, \Phi_{+1})\right\}$$



I will return to the definition of the NLO correction factor $k^{Z\to3}_{\mathrm{NLO}}(\Phi_2, \Phi_{+1})$

❸ Correct 2nd branching to LO ME [Giele, Kosower, PS (2011); Lopez-Villarejo, PS (2011)]

$$\Delta^{\mathrm{LO}}_{3\to4}(p_{\perp1}, p_{\perp2}) = \exp\left\{-\int_{p_{\perp2}}^{p_{\perp1}} \mathrm{d}\Phi_{[3]+1}\frac{|M^{(0)}_{Z\to4}(\Phi_4)|^2}{|M^{(0)}_{Z\to3}(\Phi_3)|^2}\right\}$$



Entirely based on sectorization and (iterated) Matrix-Element Corrections

(Sectorization defines $d\Phi_{[n]+1}$ and allows to use simple ME ratios instead of partial-fractionings)

Slide adapted from C. Preuss

Caveat: Double-Unresolved Phase-Space Points

Iterated shower branchings are strictly ordered in shower p_T

Not all 4-parton phase-space points can be reached this way!

In general, strong ordering cuts out part of the double-real phase space

~ double-unresolved regions; no leading logs here but can contain subleading ones

Vice to Virtue: [Li, PZS (2017)]

Divide double-emission phase space into **strongly-ordered** and **unordered** regions (according to the shower ordering variable)

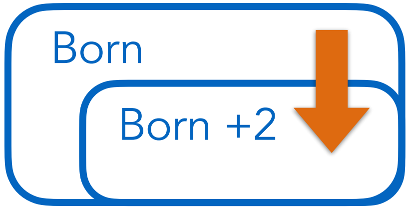
Unordered clusterings ⇔ new direct double branchings

Complementary phase-space regions:

$$\mathrm{d}\Phi_{[2]+2} \;=\; \Theta(\hat{p}_{\perp 1} - p_{\perp 2})\mathrm{d}\Phi_{[2]+1}\mathrm{d}\Phi_{[3]+1} \;+\; \Theta(\hat{p}_{\perp 1} + p_{\perp 2})\mathrm{d}\Phi_{[2]+2}$$

Generated by iterated, ordered branchings

Generated by new direct $2 \to 4$ branchings



④ (New: Direct $2 \to 4$ Double-Branching Generator)

Developed in: Li & PZS, *A Framework for Second-Order Showers*, PLB 771 (2017) 59

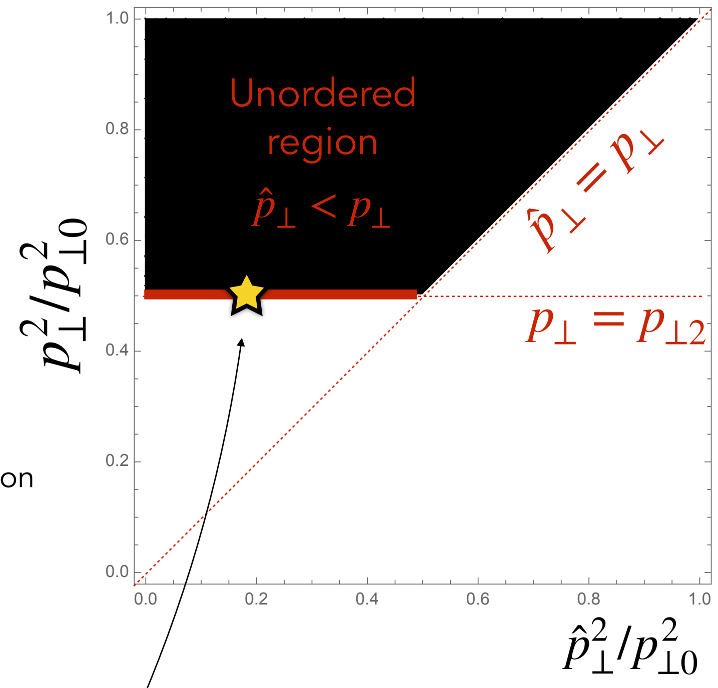
Sudakov trial integral for direct double branchings with $p_\perp \in [p_{\perp 0}, p_{\perp 2}]$:

Scale of intermediate 2→3 stepping stone

Unordered Sector: $\hat{p}_\perp < p_\perp$

$$-\ln \Delta(p_{\perp 0}^2, p_{\perp 2}^2) = \int_0^{p_{\perp 0}^2} \mathrm{d}\hat{p}_\perp^2 \int_{p_{\perp 2}^2}^{p_{\perp 0}^2} \mathrm{d}p_\perp^2 \, \Theta(p_\perp^2 - \hat{p}_\perp^2) \, \frac{N}{p_\perp^4}$$

Generic overestimate of double-branching kernel in unordered region



Trick: **swap integration order**

⇒ outer integral along $p_\perp$ instead of $\hat{p}_\perp$:

$$= \int_{p_{\perp 2}^2}^{p_{\perp 0}^2} \mathrm{d}p_\perp^2 \int_0^{p_\perp^2} \mathrm{d}\hat{p}_\perp^2 \, \frac{N}{p_\perp^4} \equiv \int_{p_{\perp 2}^2}^{p_{\perp 0}^2} \mathrm{d}p_\perp^2 \, F(p_\perp^2)$$

➜ **First** generate physical scale $p_{\perp 2}$, **then** generate $0 < \hat{p}_\perp < p_{\perp 2}$ + two z and φ choices

Summary: Shower Markov chain with NNLO Corrections

❷ Correct 1st (2 → 3) branching to (fully differential) NLO 3-jet rate

[Hartgring, Laenen, **PS** (2013)]

$$\Delta^{\mathrm{NLO}}_{2\to3}\left(\frac{m_Z}{2}, p_{\perp1}\right) = \exp\left\{-\int_{p_{\perp1}}^{\frac{m_Z}{2}} \mathrm{d}\Phi_{[2]+1}\frac{|M^{(0)}_{Z\to3}(\Phi_3)|^2}{|M^{(0)}_{Z\to2}(\Phi_2)|^2}k^{Z\to3}_{\mathrm{NLO}}(\Phi_2, \Phi_{+1})\right\}$$

❸ Correct 2nd (3 → 4) branching to LO ME [Giele, Kosower, **PS** (2011); Lopez-Villarejo, **PS** (2011)]

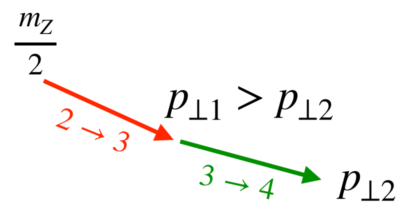
$$\Delta^{\mathrm{LO}}_{3\to4}(p_{\perp1}, p_{\perp2}) = \exp\left\{-\int_{p_{\perp2}}^{p_{\perp1}} \mathrm{d}\Phi^{\mathrm{O}}_{[3]+1}\frac{|M^{(0)}_{Z\to4}(\Phi_4)|^2}{|M^{(0)}_{Z\to3}(\Phi_3)|^2}\right\}$$

❹ Add direct 2 → 4 branching and correct it to LO ME [Li, **PS** (2017)]

$$\Delta^{\mathrm{LO}}_{2\to4}(p_{\perp1}, p_{\perp2}) = \exp\left\{-\int_{p_{\perp2}}^{p_{\perp1}} \mathrm{d}\Phi^{\mathrm{U}}_{[2]+2}\frac{|M^{(0)}_{Z\to4}(\Phi_4)|^2}{|M^{(0)}_{Z\to2}(\Phi_2)|^2}\right\}$$

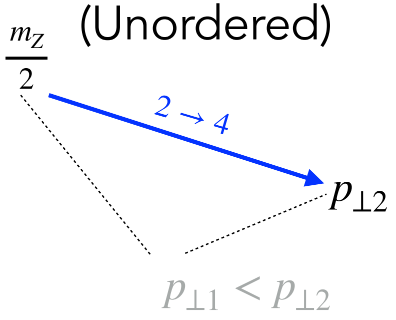
Iterated:

(Ordered)



Direct:

(Unordered)



Entirely based on MECs and Sectorization

By construction, expansion of extended shower **matches** NNLO singularity structure.

But shower kernels **do not** define NNLO subtraction terms* (!)

---

*This would be required for an MC@NNLO scheme (but difficult to realise in antenna showers)

Slide adapted from C. Preuss

Real-Virtual Corrections: NLO MECs

$$k^{\mathrm{NLO}}_{2\to3} = (1 + w^{\mathrm{V}}_{2\to3})$$

Hartgring, Laenen, PS (2013)
Campbell, Höche, Li, Preuss, **PS**, 2108.07133

Local correction given by **three terms**:

$$\begin{aligned}
w^{\mathrm{V}}_{2\mapsto3}(\Phi_2,\Phi_{+1}) = \; & \Bigg(\frac{\mathrm{RV}(\Phi_2,\Phi_{+1})}{\mathrm{R}(\Phi_2,\Phi_{+1})} + \frac{\mathrm{I}^{\mathrm{NLO}}(\Phi_2,\Phi_{+1})}{\mathrm{R}(\Phi_2,\Phi_{+1})} \\
\text{NLO Born+1}j \qquad & + \int_0^t \mathrm{d}\Phi'_{+1} \left[\frac{\mathrm{RR}(\Phi_2,\Phi_{+1},\Phi'_{+1})}{\mathrm{R}(\Phi_2,\Phi_{+1})} - \frac{\mathrm{S}^{\mathrm{NLO}}(\Phi_2,\Phi_{+1},\Phi'_{+1})}{\mathrm{R}(\Phi_2,\Phi_{+1})} \right] \Bigg) \\
\text{NLO Born} \qquad & - \Bigg(\frac{\mathrm{V}(\Phi_2)}{\mathrm{B}(\Phi_2)} + \frac{\mathrm{I}^{\mathrm{NLO}}(\Phi_2)}{\mathrm{B}(\Phi_2)} + \int_0^{t_0} \mathrm{d}\Phi'_{+1} \left[\frac{\mathrm{R}(\Phi_2,\Phi'_{+1})}{\mathrm{B}(\Phi_2)} - \frac{\mathrm{S}^{\mathrm{NLO}}(\Phi_2,\Phi'_{+1})}{\mathrm{B}(\Phi_2)} \right] \Bigg) \\
\text{shower} \qquad & + \Bigg(\frac{\alpha_{\mathrm{S}}}{2\pi} \log\left(\frac{\kappa^2 \mu^2_{\mathrm{PS}}}{\mu^2_{\mathrm{R}}} \right) + \int_t^{t_0} \mathrm{d}\Phi'_{+1}\, \mathrm{A}_{2\mapsto3}(\Phi'_{+1})\, w^{\mathrm{LO}}_{2\mapsto3}(\Phi_2,\Phi'_{+1}) \Bigg)
\end{aligned}$$

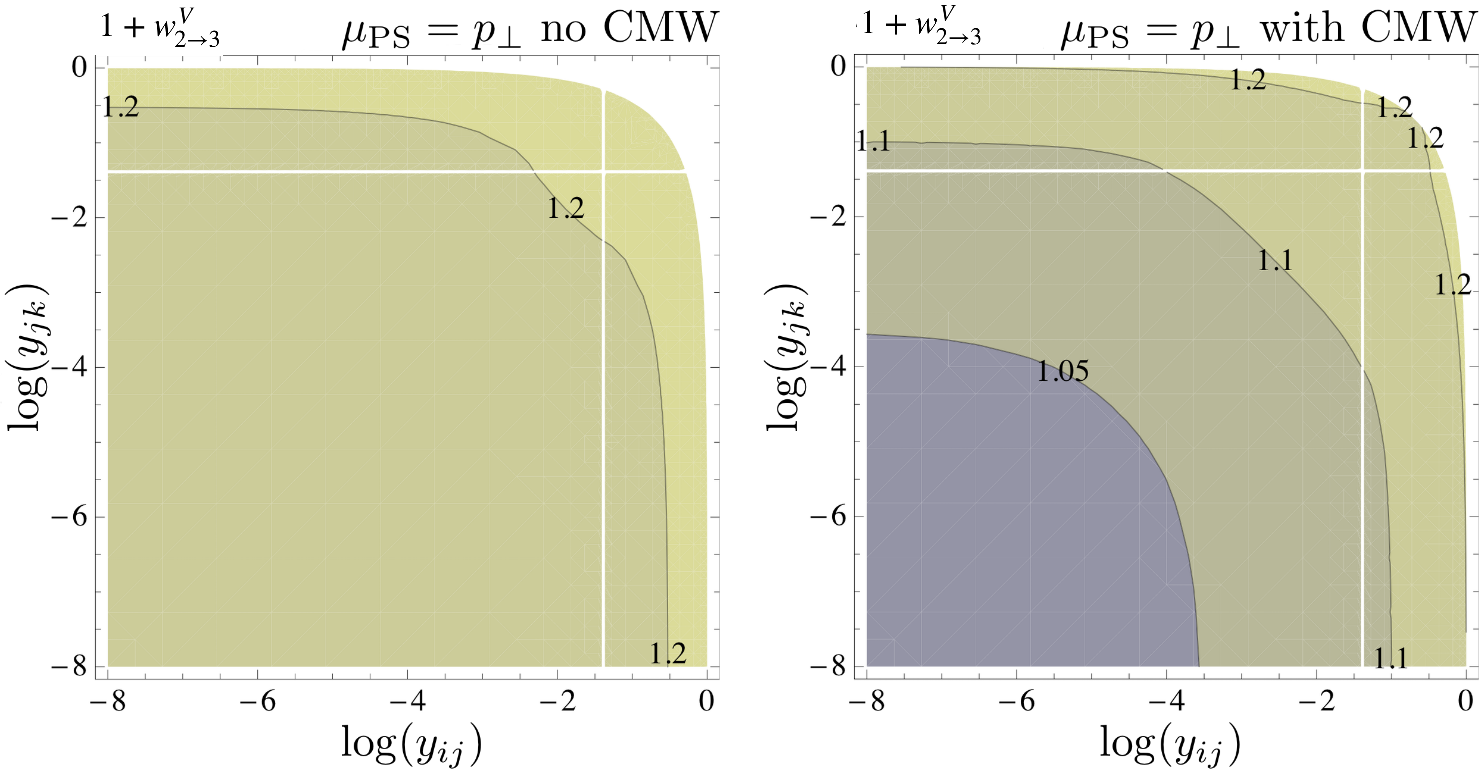
- First and third term from **NLO shower evolution**, second from **NNLO matching**
- Calculation can be **(semi-)automated**, given a suitable NLO subtraction scheme

Slide adapted from C. Preuss

Size of the Real-Virtual Correction Factor (❷)

$$k^{\mathrm{NLO}}_{2\to3} = (1 + w^{\mathrm{V}}_{2\to3})$$

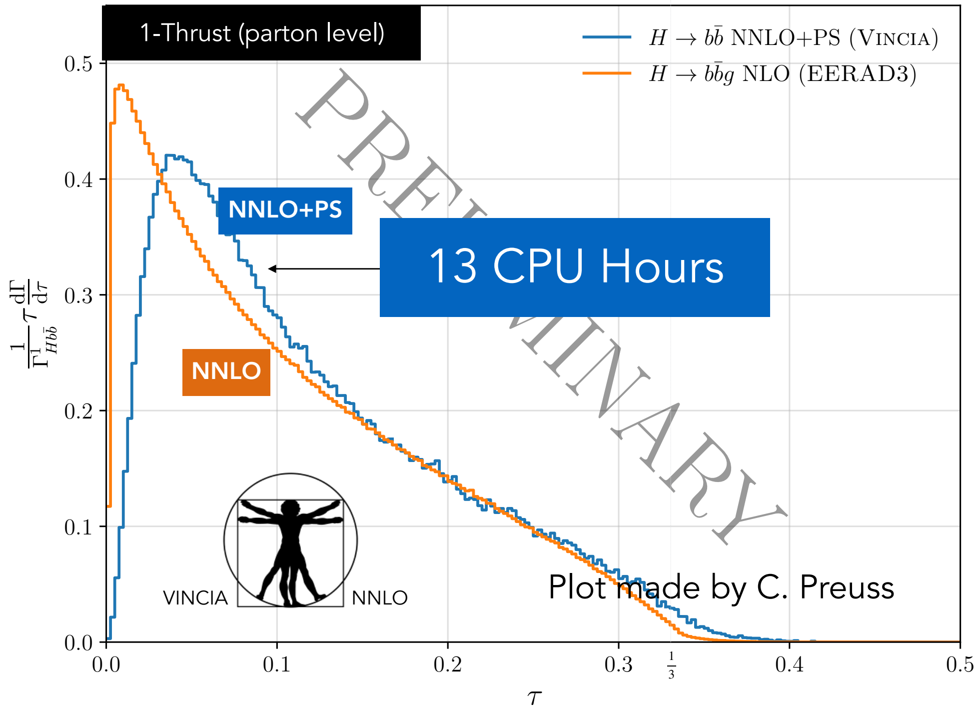
studied **analytically** in detail for $Z \to q\bar{q}$ in Hartgring, Laenen, PS JHEP 10 (2013) 127



⇒ now: **generalisation** & **(semi-)automation** in VINCIA in form of NLO MECs

Slide adapted from C. Preuss

Preview: VINCIA NNLO+PS for $H \to b\bar{b}$

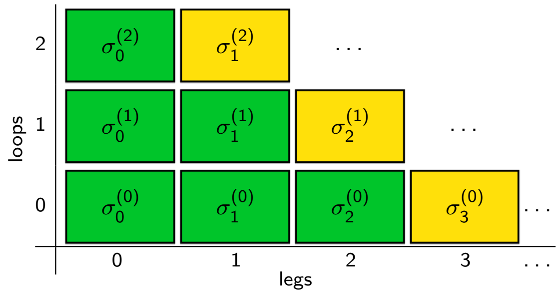


Note:

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

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.**



2	$\sigma_0^{(2)}$	$\sigma_1^{(2)}$	...		
1	$\sigma_0^{(1)}$	$\sigma_1^{(1)}$	$\sigma_2^{(1)}$	...	
0	$\sigma_0^{(0)}$	$\sigma_1^{(0)}$	$\sigma_2^{(0)}$	$\sigma_3^{(0)}$	...
	0	1	2	3	...

So for Thrust,
NNLO $H \to b\bar{b}$ is
effectively

NLO for $\tau < 1/3$

LO for $\tau > 1/3$

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

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

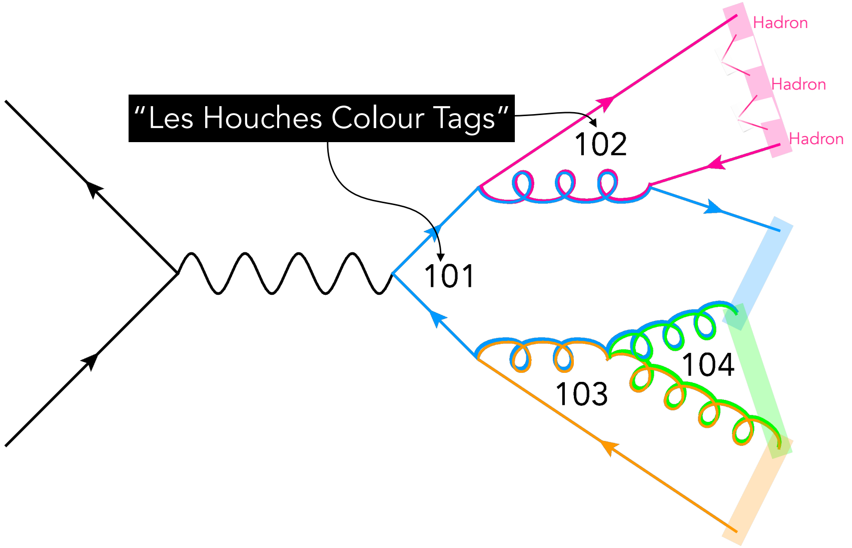
  \+ is **matched to shower** + can be **hadronized**

Proof of concepts now done for $Z/H \to q\bar{q}$; work remains for pp (& for N^{n}LL accuracy)

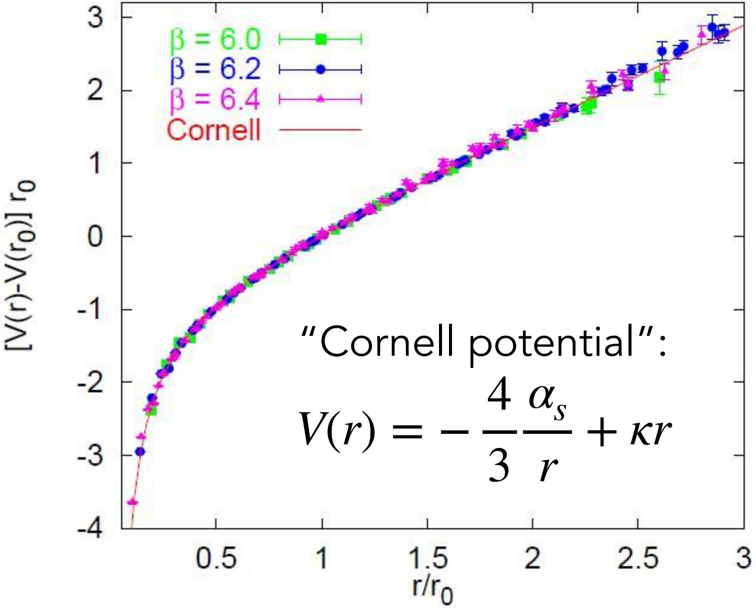
* Already quite optimised: uses analytical MEs, "folds" phase space to cancel azimuthally antipodal points, and uses antenna subtraction (→ smaller # of NLO subtraction terms than Catani-Seymour or FKS).

From Partons to Strings

After the shower: Simplified (leading-N_C) **"colour flow"** ➜ determine between which partons to set up confining potentials



"Linear confinement"
(From Lattice & Hadron Spectroscopy)



"Cornell potential":

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

Map from Partons to Strings:

Quarks ➡ string endpoints; gluons ➡ transverse "kinks"

System then evolves as a string world sheet

+ **String breaks** via spontaneous $q\bar{q}$ pair creation ("Schwinger mechanism") → **hadrons**

Confinement in LHC Collisions

High-energy pp collisions — with ISR, Multi-Parton Interactions, and Beam Remnants

Final states with **very many** coloured partons

With significant overlaps in phase space

Who gets confined with whom?

Each has a colour ambiguity $\sim 1/N_C^2 \sim 10\,\%$

E.g.: **random triplet** charge has 1/9 chance to be in **singlet** state with **random antitriplet**:

$$3 \otimes \bar{3} = 8 \oplus 1$$

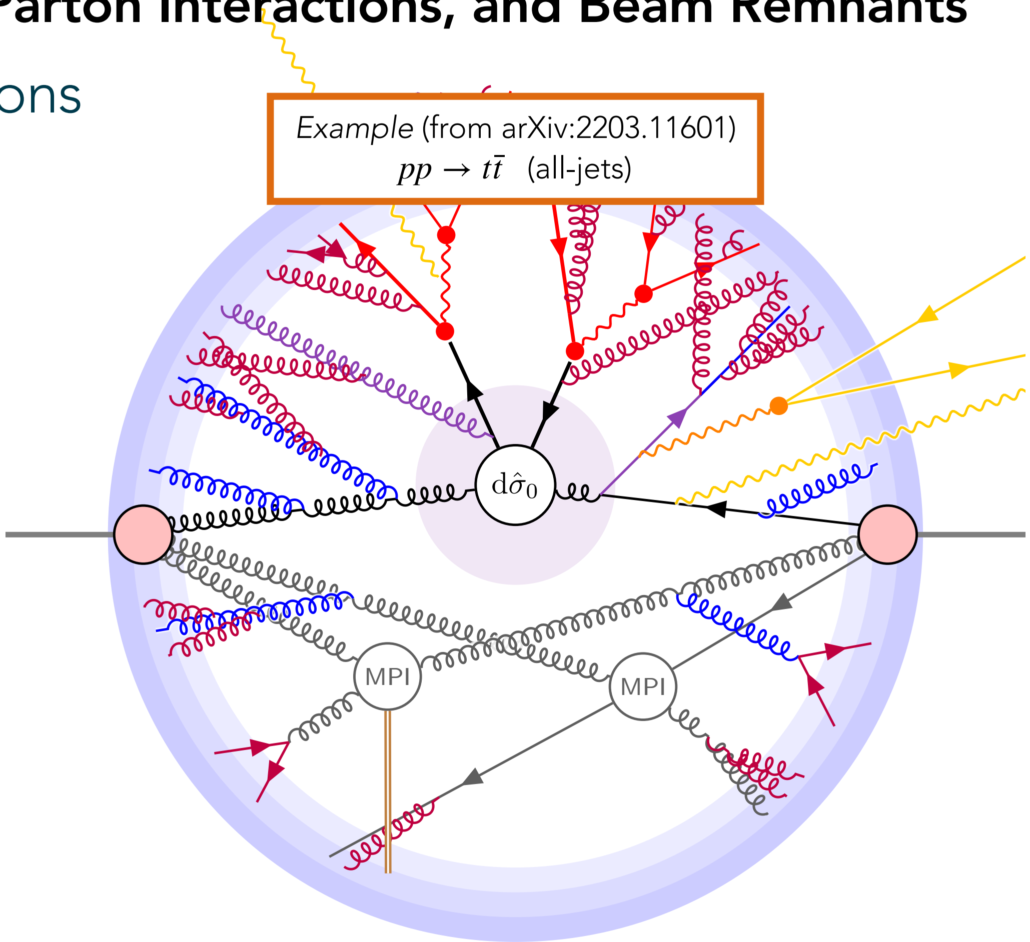
$$3 \otimes 3 = 6 \oplus \bar{3} \quad ; \quad 3 \otimes 8 = 15 \oplus 6 \oplus 3$$

$$8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8_S \oplus 8_A \oplus 1$$

Many charges ➜ Colour Reconnections* (CR)

More likely than not

Example (from arXiv:2203.11601)
$pp \to t\bar{t}$ (all-jets)

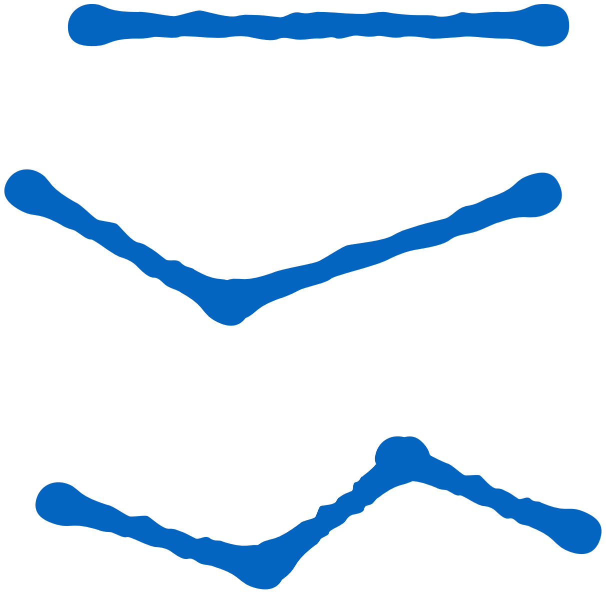


“Parton Level”
(Event structure before confinement)

*): *in this context, QCD CR simply refers to an ambiguity beyond Leading N_C, known to exist.*
Note the term “CR” can also be used more broadly to incorporate further physics concepts.

QCD Colour Reconnections ⟷ String Junctions

Open Strings

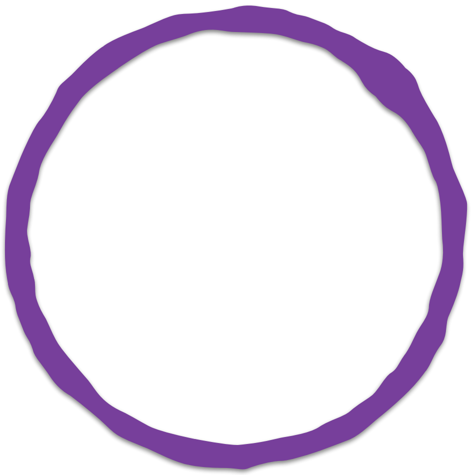


$q\bar{q}$ strings (with gluon kinks)

E.g., $Z \to q\bar{q}$ + shower

$H \to b\bar{b}$ + shower

Closed Strings

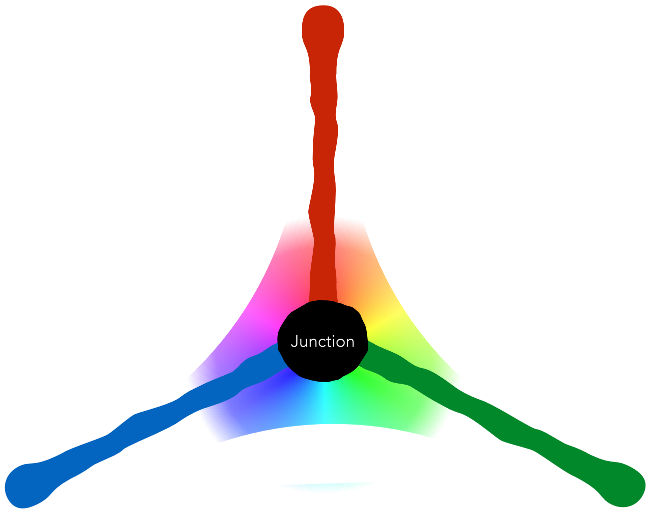


Gluon rings

E.g., $H \to gg$ + shower

$\Upsilon \to ggg$ + shower

SU(3) String Junction

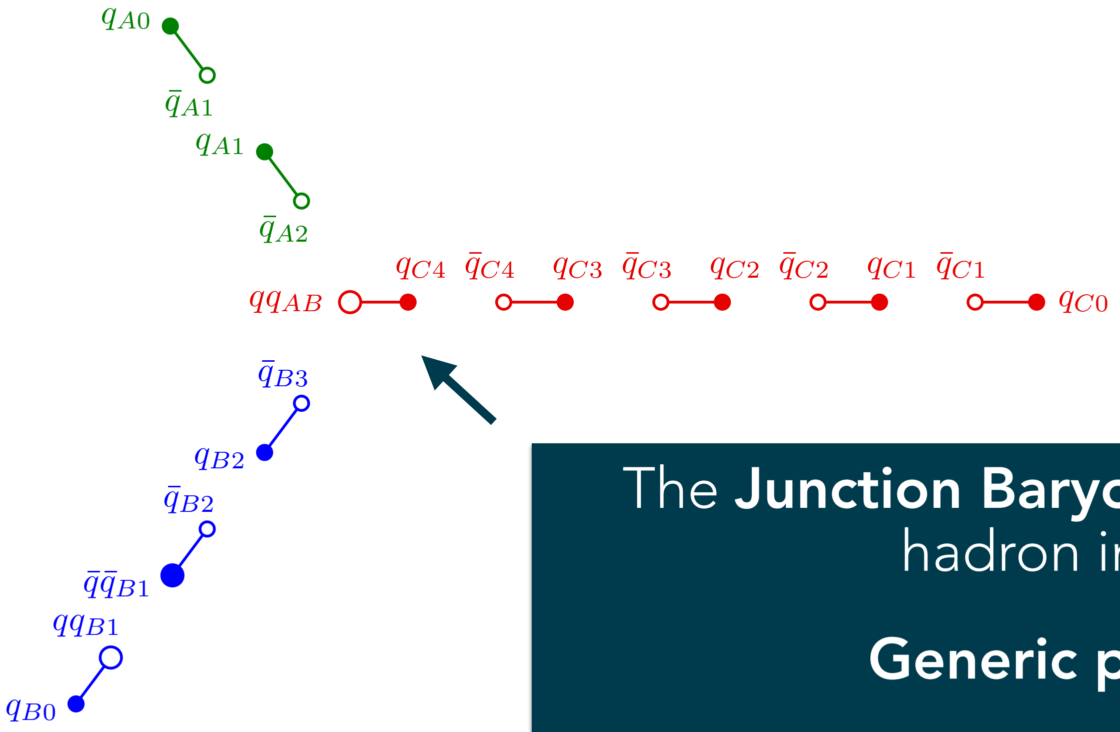


Open strings with $N_C = 3$ endpoints

E.g., Baryon-Number violating neutralino decay $\tilde{\chi}^0 \to qqq$ + shower

Fragmentation of String Junctions

Assume Junction Strings have same properties as ordinary ones
(u:d:s, Schwinger p_T, etc) ➤ **No new string-fragmentation parameters**



[Sjöstrand & **PS**, NPB 659 (2003) 243]
[+ J. Altmann & **PS**, in progress]

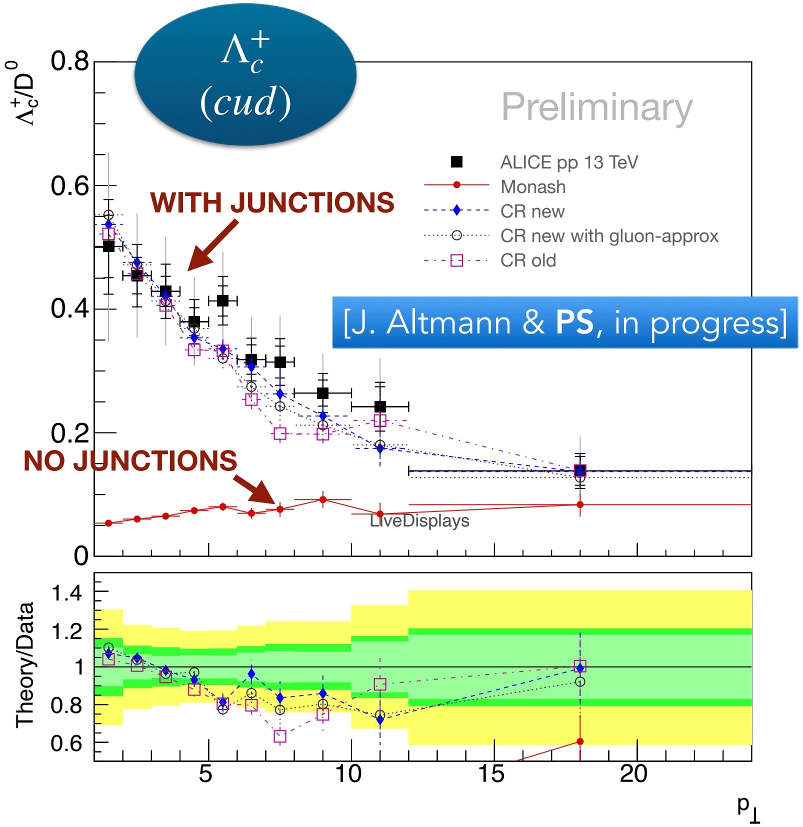
The **Junction Baryon** is the most "subleading" hadron in all three "jets".

Generic prediction: low p_T

A Smoking Gun for String Junctions: Baryon enhancements at low p_T

Confront with Measurements

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



WITH JUNCTIONS

NO JUNCTIONS

[J. Altmann & **PS**, in progress]

+ Lots of interesting new measurements showing changes in **strange** vs nonstrange strange **hadrons**

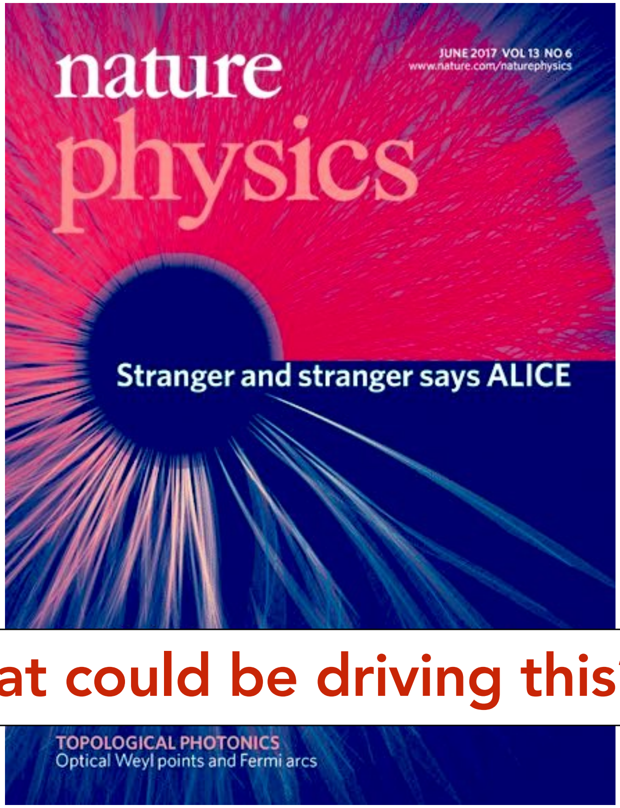
& evidence of **flow-like effects** in pp collisions
→ modifications to p_T spectra

Not reproduced by baseline string/cluster models

Very exciting! Lots of Activity

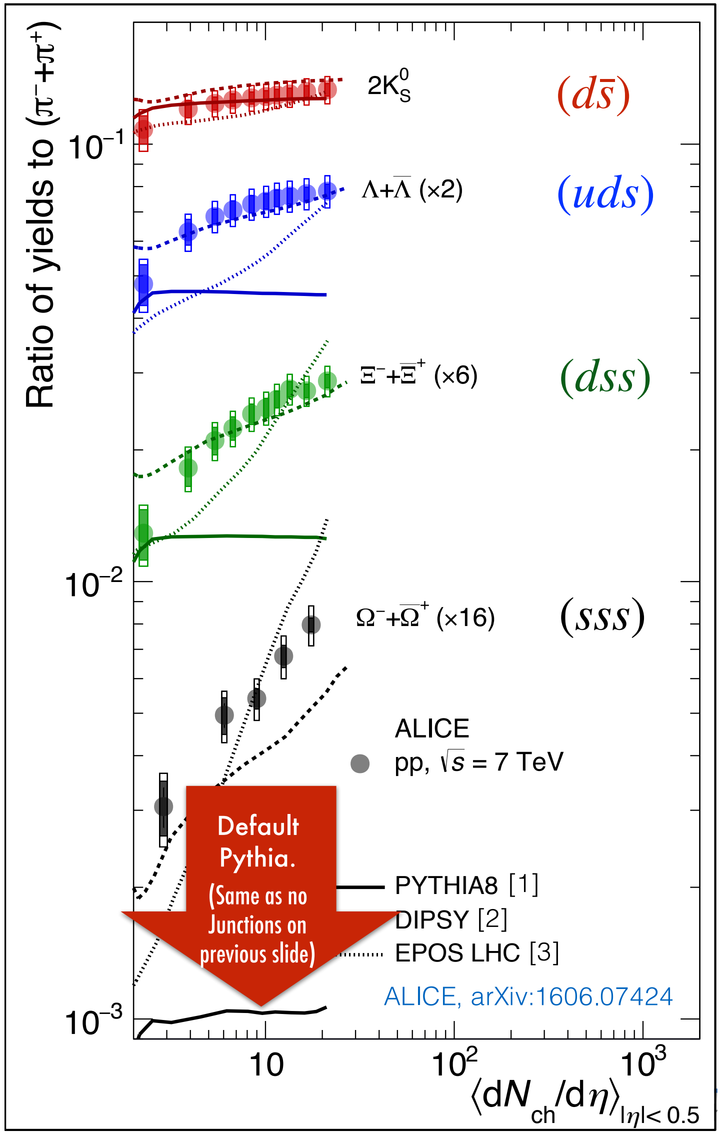
What a **strange** world we live in, said Alice

We also know ratios of strange hadrons to pions strongly increase with event activity



June
2017

What could be driving this?



ALICE, arXiv:1606.07424

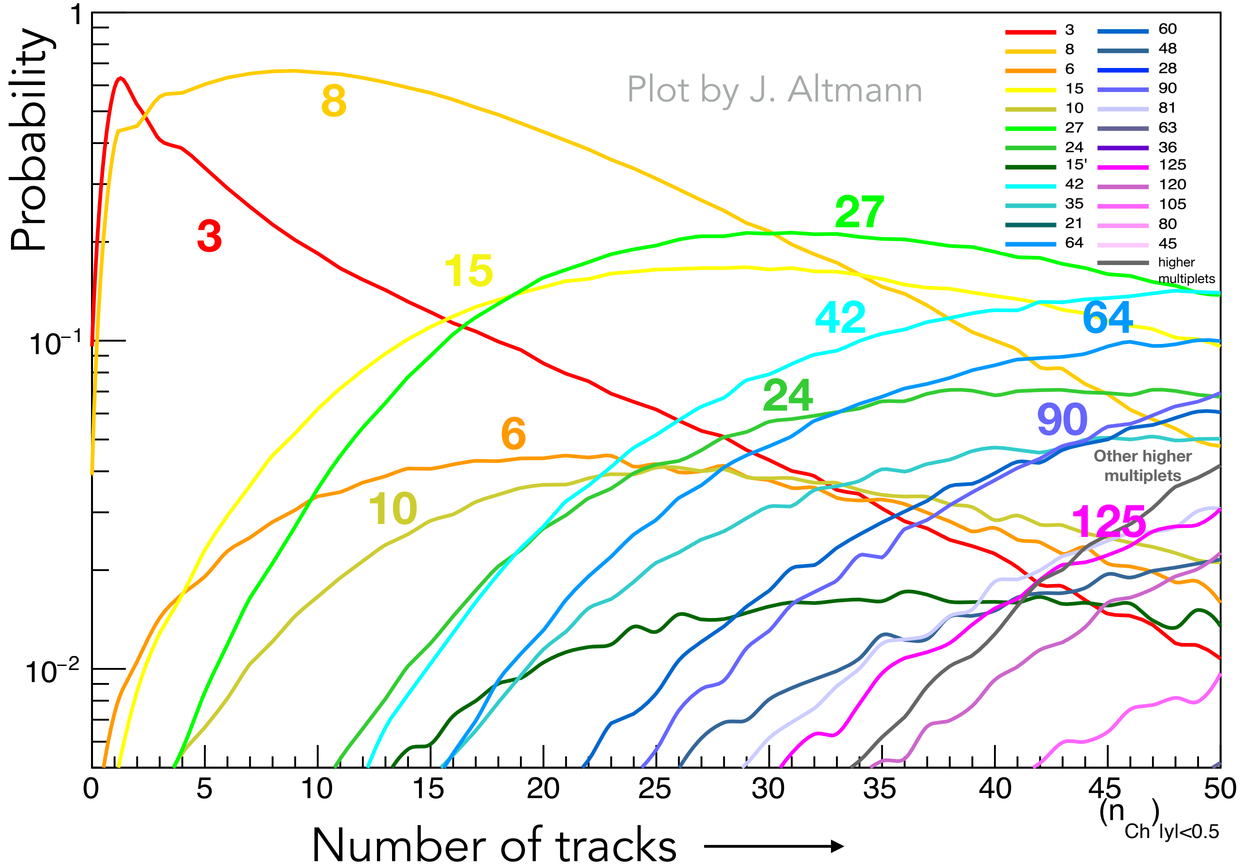
Default Pythia.
(Same as no Junctions on previous slide)

Non-Linear String Dynamics?

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

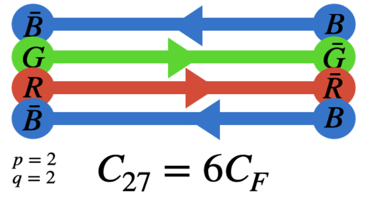
Count **# of (oriented) flux lines** crossing $y = 0$ in pp collisions (according to PYTHIA)

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



Confining fields may be reaching **higher effective representations** than simple quark-antiquark (3) ones.

E.g.: 27



27

$C_{27} = 6C_F$

Two approaches in PYTHIA:

1) Colour Ropes (Lund)

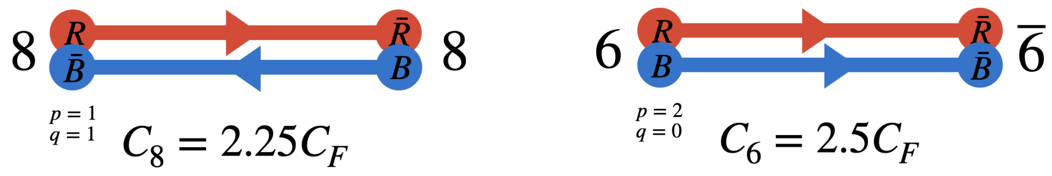
2) Close-Packing (Monash)

NEW

In Progress: Strangeness Enhancement from Close-Packing

Idea: each string exists in an effective background produced by the others

Close-packing



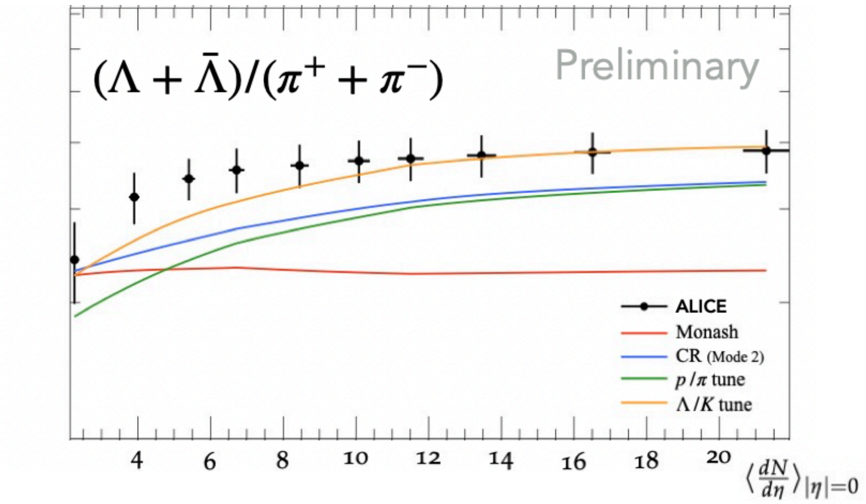
$C_8 = 2.25C_F$

$C_6 = 2.5C_F$

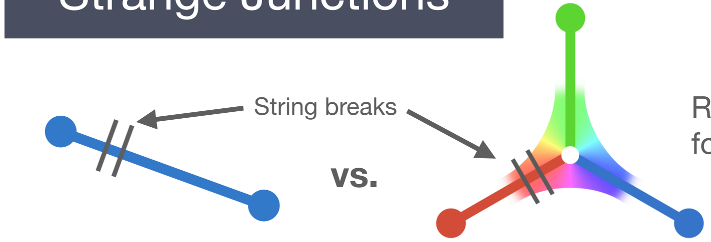
Dense string environments

→ Casimir scaling of **effective string tension**

→ Higher probability of strange quarks

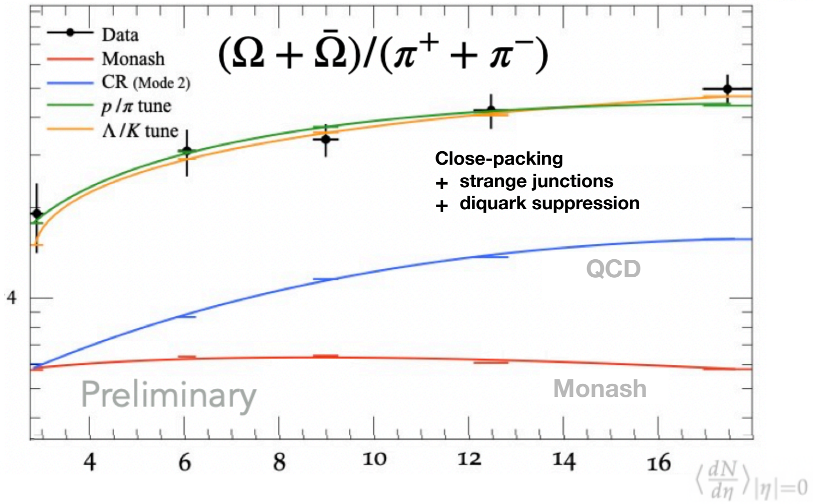


Strange Junctions



Results in strangeness enhancement focused in baryon sector

String tension could be different from the vacuum case compared to near a junction



Slide adapted from J. Altmann

Summary & Outlook

State of the art for perturbation theory: NNLO (→ N3LO)

Matching to showers + hadronization mandatory for collider studies

(+ resummation extends range; hadronization → explicit power corrections; MPI → UE, …)

1. Can use off-the-shelf (LL) showers, e.g. with MiNNLO$_{PS}$

Based on POWHEG-Box ⊕ Analytical Resummation ⊕ NNLO normalisation

Approximate method; depends on several auxiliary scales / choices → can exhibit large variations

2. This talk: ViciaNNLO

Based on nested shower-style phase-space generation with 2nd-order MECs

True NNLO matching → Expect small matching systematics

So far only worked out for colour-singlet decays ➼ **Will soon start on Drell-Yan, VBF, …**

(Also developing extensions towards NLL (→NNLL) showers …)

+ Strings

New discoveries at LHC for baryons and strangeness ➼ **string interactions, string junctions?**

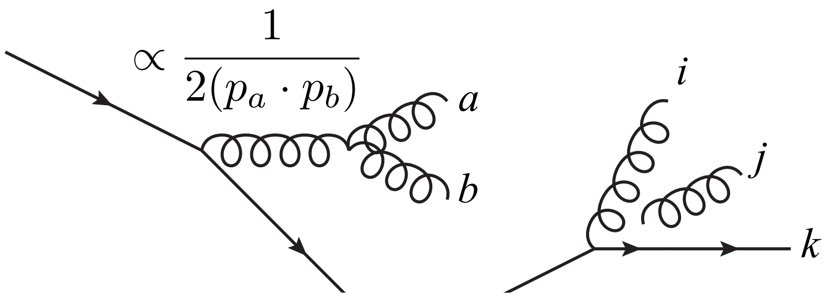
Extra Slides

Parton Showers: Theory

see e.g PS, *Introduction to QCD*, TASI 2012, arXiv:1207.2389

Most bremsstrahlung is driven by divergent propagators → simple structure

Mathematically, **gauge amplitudes factorize** in **singular limits**



Partons ab
→ **collinear**:

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

$P(z)$ = **DGLAP splitting kernels**", with $z = E_a/(E_a+E_b)$

Gluon j
→ **soft**:

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

Coherence → Parton j really emitted by (i,k) "dipole" or **"antenna" (eikonal factors)**

These are the **building blocks of parton showers** (DGLAP, dipole, antenna, …)

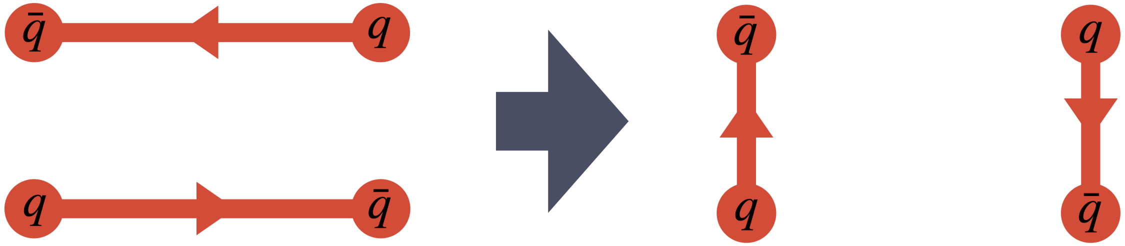
(+ running coupling, unitarity, and explicit energy-momentum conservation.)

QCD Colour Reconnections ⟷ String Junctions

Stochastically restores colour-space ambiguities according to **SU(3) algebra**

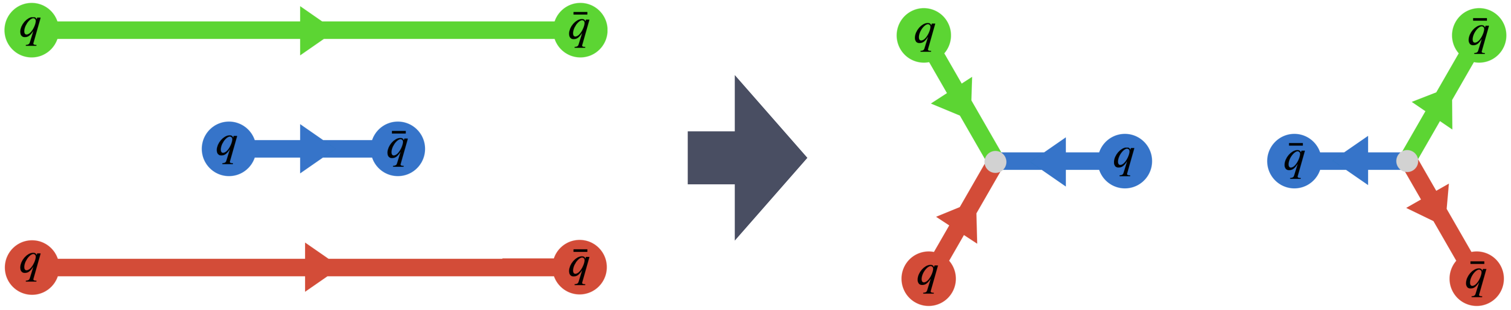
[Christiansen & **PS**
JHEP 08 (2015) 003]

- ➢ Allows for reconnections to minimise string lengths



Dipole-type reconnection

What about the red-green-blue colour singlet state?



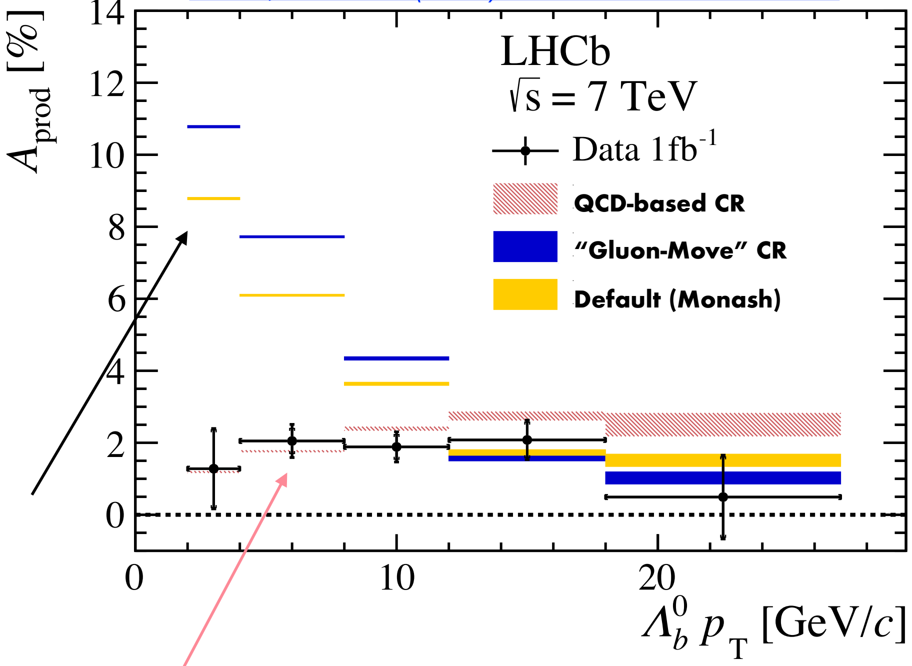
Junctions!

LHCb: also in Bottom

Λ_b asymmetry

$$A = \frac{\sigma(\Lambda_\mathrm{b}^0) - \sigma(\overline{\Lambda}_\mathrm{b}^0)}{\sigma(\Lambda_\mathrm{b}^0) + \sigma(\overline{\Lambda}_\mathrm{b}^0)}$$

LHCb, JHEP 10 (2021) 060 • arXiv: 2107.09593



Without junction CR, an important source of low-pT Λ_b production is when a b quark combines with the proton beam remnant.

Not possible for $\bar{\Lambda}_b$ (no $\bar{p}$ remnant at LHC)

QCD CR adds large amount of low-pT junction Λ_b and $\bar{\Lambda}_b$, in equal amounts. Dilutes asymmetry!