Recent progress & (some) open issues in top modelling

(mostly $t\bar{t}$)

Peter Skands — June 2025

1. **Matching** in prod. & decays

Systematics & 2nd-order effects

2. **Showers** – coherence & recoils

(effects on b jets & B hadrons)

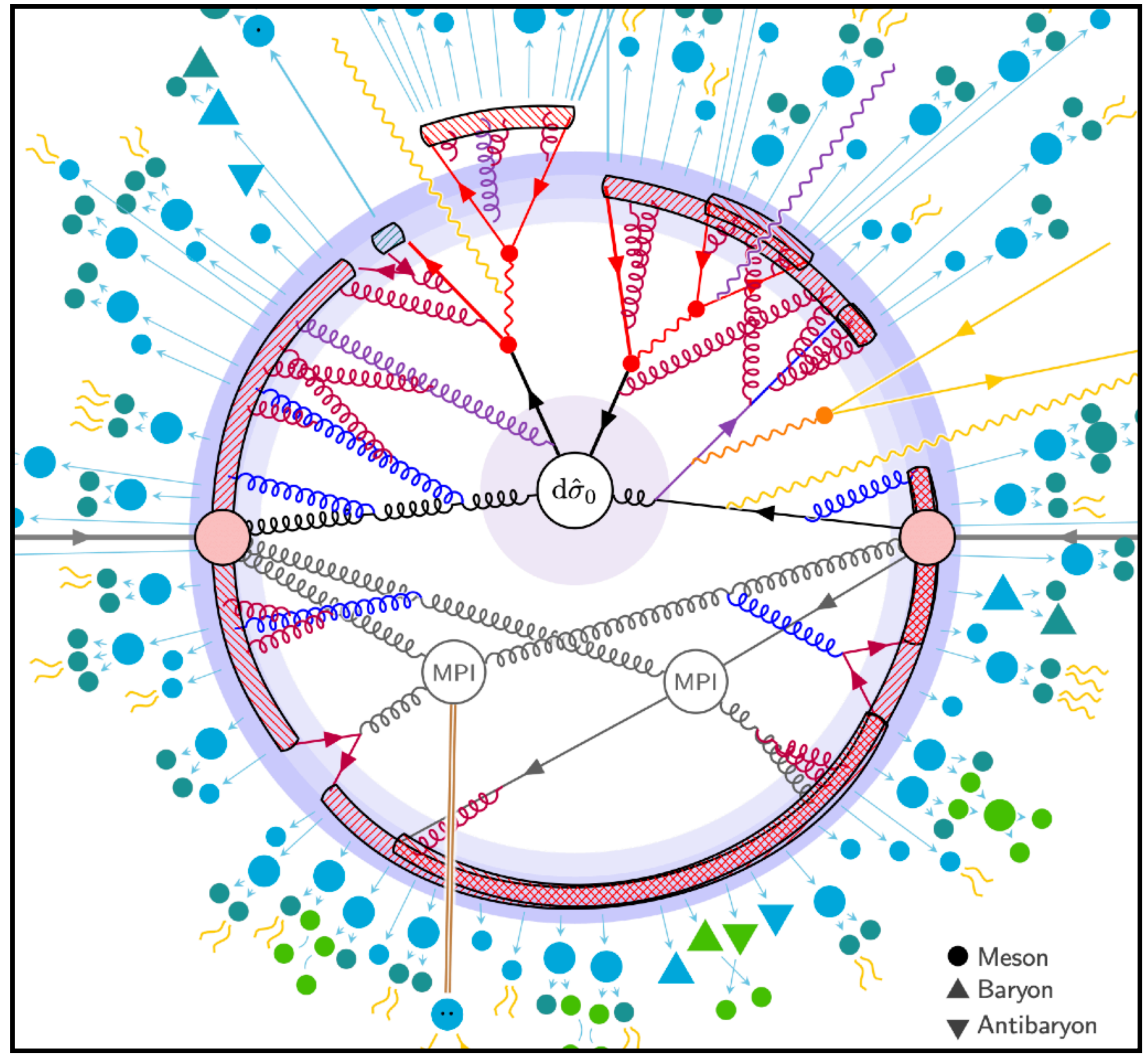
3. **Ongoing work** in PYTHIA

The 2nd emission

Finite Γ_{top}

Colour reconnections

New Pythia tunes



MONASH University
MONASH WARWICK ALLIANCE
Australian Government
Australian Research Council
MCnet

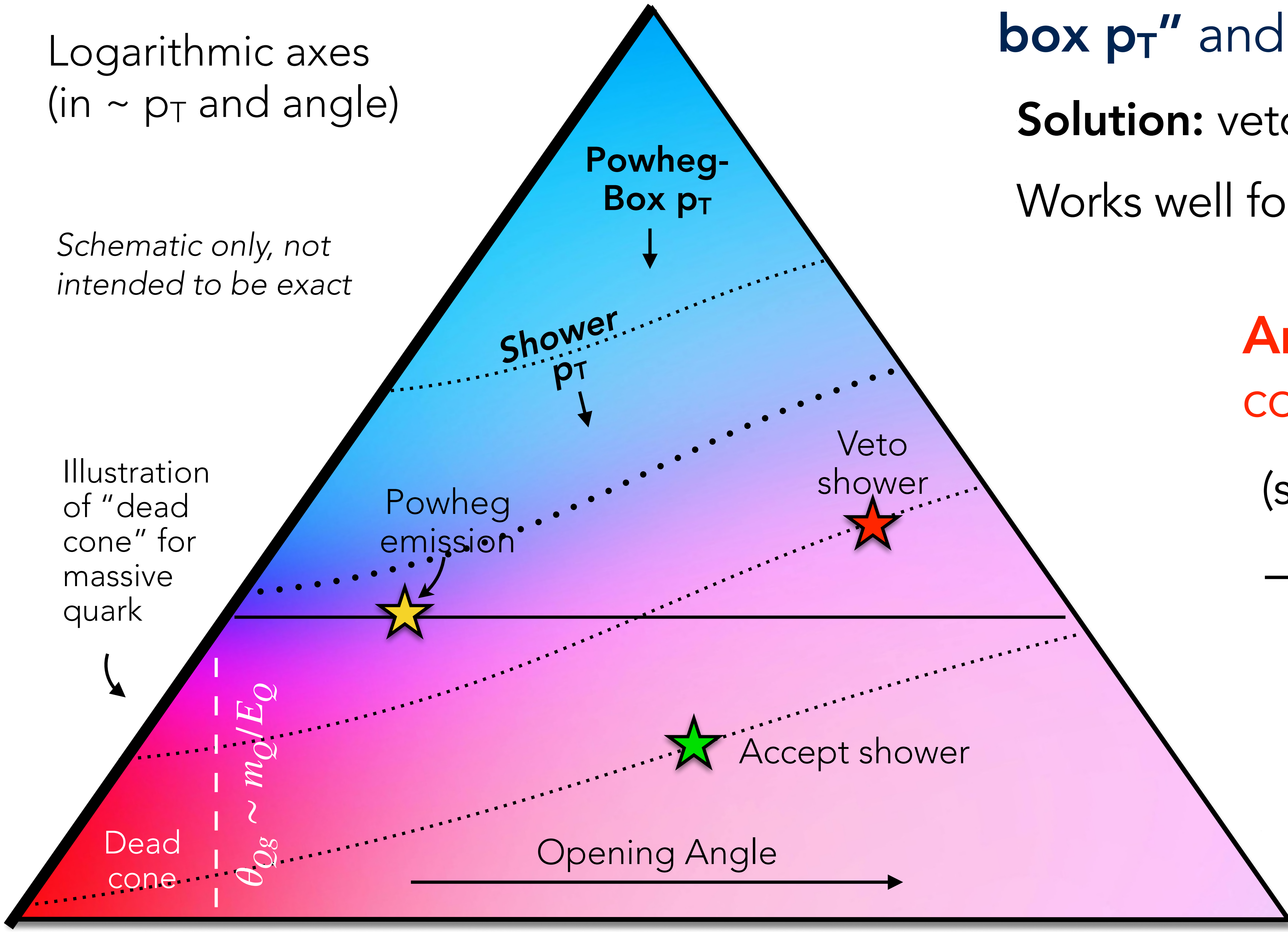
Matching Systematics with Powheg

A radiation phase space

Logarithmic axes
(in ~ p_T and angle)

Schematic only, not intended to be exact

Illustration of "dead cone" for massive quark



Mismatch between **"Powheg-box p_T"** and "**Shower p_T**"

Solution: vetoed showers

Works well for simple cases

Ambiguous for complex processes

(such as $t\bar{t}$, single-t, …)

→ **uncertainty** purely associated with **matching scheme** (not physical)

Leading colour (LC) structure of $gg \to t\bar{t}$ @ LO

Complex process
= multiple emitters
$\rightsquigarrow$ several overlapping phase spaces

***Many* possible p_T definitions:**

$p_\perp$ with respect to the beam

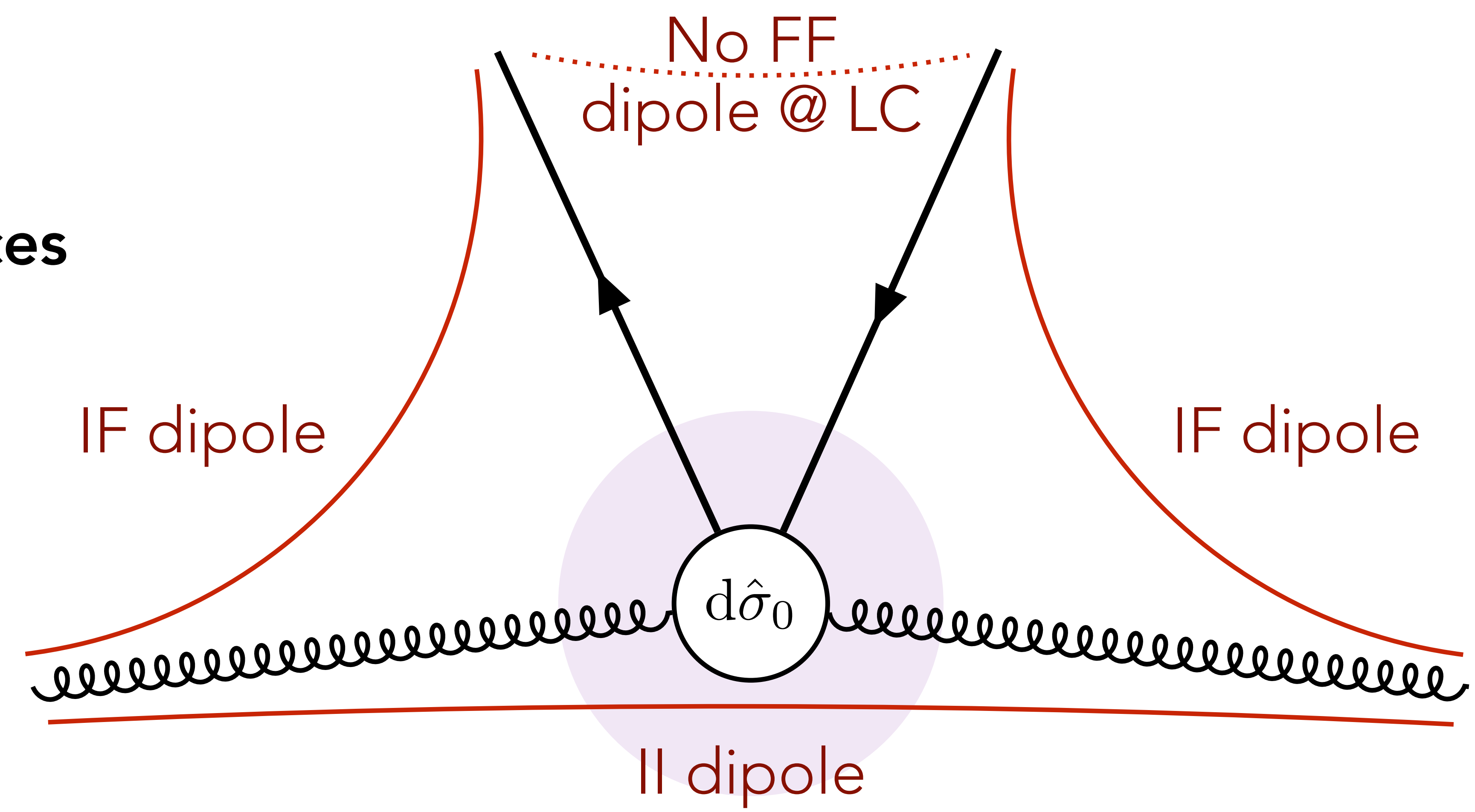
$p_\perp$ with respect to the IF dipoles

$p_\perp$ (or $m_\perp$) with respect to either of the final-state tops

(How) is **mass** treated in the scale definition(s): $p_\perp^2$ vs $m_\perp^2 = m^2 + p_\perp^2$?

(+ PYTHIA defines a problematic FF dipole → coherence issues)

+ Interpolations/combinations of the above …



POWHEG-Box generates **1st emission**
= the one it judges to be the "hardest"
according to its own p_T definition

Leading colour (LC) structure of $gg \to t\bar{t}$ @ LO

Complex process
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⤳ several overlapping phase spaces

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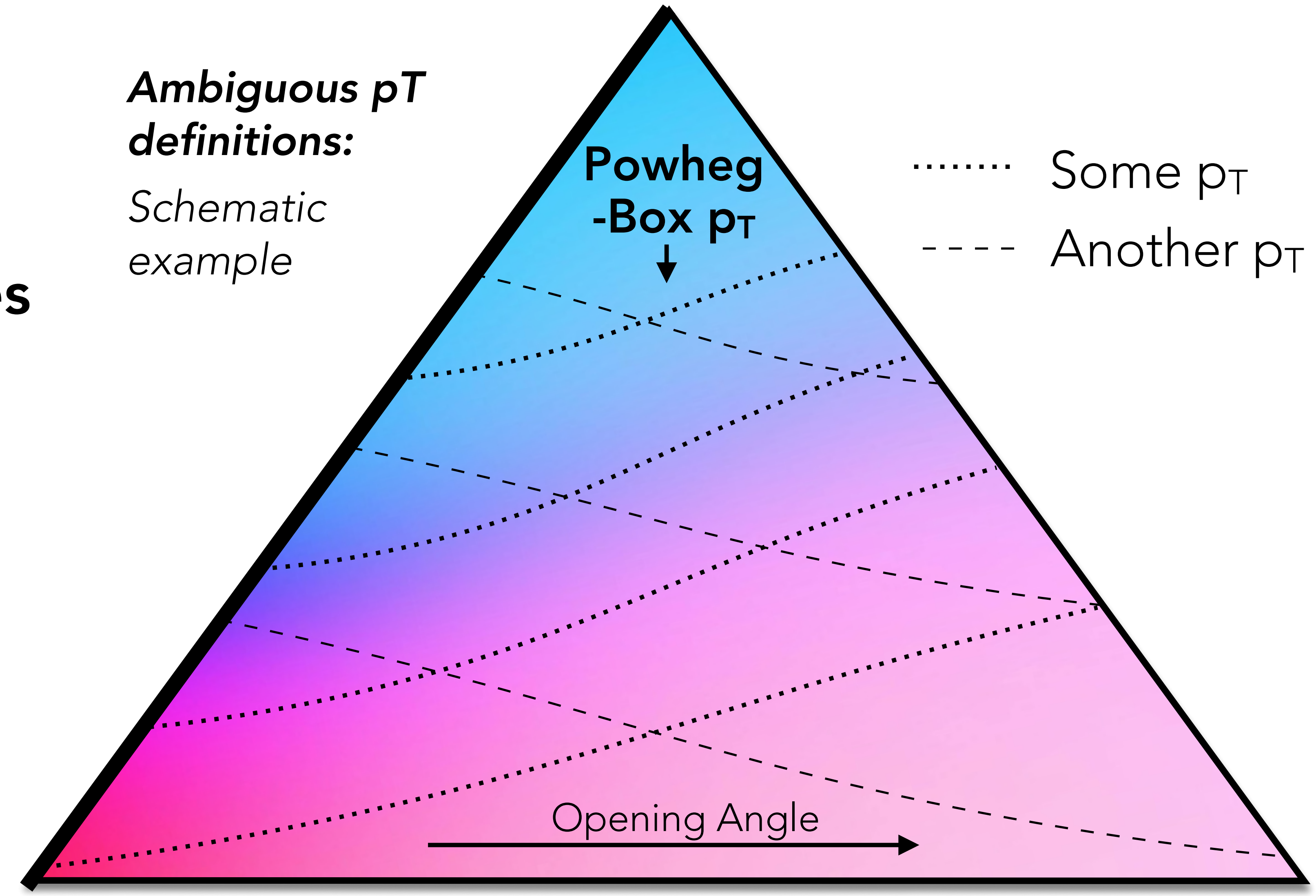

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Extreme Case: VBF Higgs ← (colour structure ~ $t\bar{t}$ without the II dipole and the FF masses)

Varying the POWHEG-Box ↔ PYTHIA hardness-scale ambiguity

"NAIVE", DEF ≤ 8.310

`POWHEG:pThard = 0` # Veto at $p_{\perp j;i}^{\text{POWHEG}}$ = **SCALUP** = scale at which POWHEG says it emitted this parton

DEF ≥ 8.311

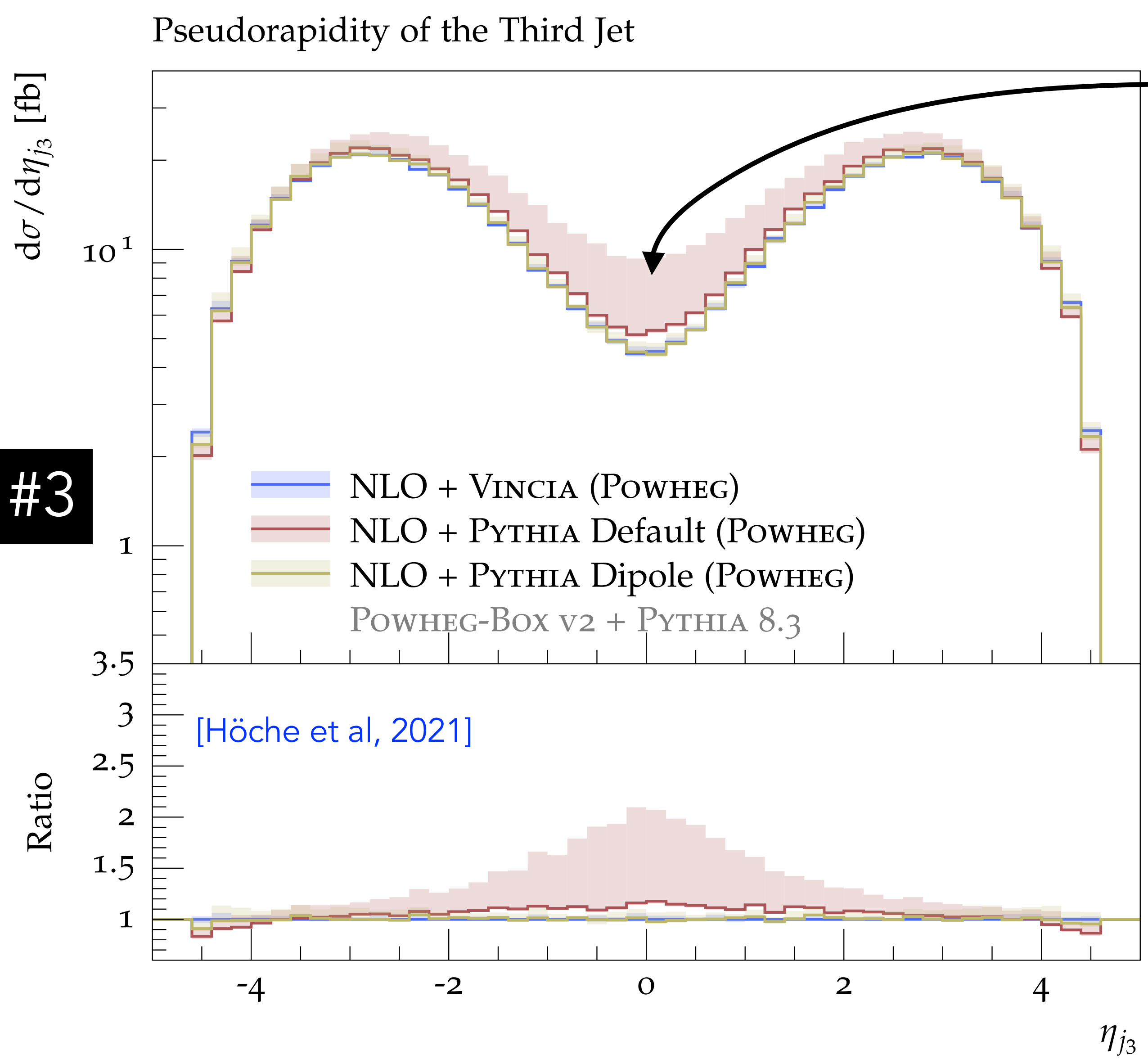
`POWHEG:pThard = 1` # Veto at $\min_i (p_{\perp j;i}^{\text{POWHEG}})$ = smallest scale at which POWHEG **could** have emitted this **parton**

`POWHEG:pThard = 2` # Veto at $\min_{i,j} (p_{\perp j;i}^{\text{POWHEG}})$ = smallest scale at which POWHEG **could** have produced this **event**

Less radiation

[Nason, Oleari 2013]

Jet #3



Powheg + Pythia Default

Big variation with pThard choice ☹️

Tends to fill in the rapidity gap **even for the 3rd jet** (which **should** be under control in POWHEG VBF)

Powheg + Pythia Dipole

Powheg + Vincia

Very little dependence on pThard 😊

Born-Level **NLO accuracy preserved** ✅

A recent study of top processes

ATLAS PUB Note

ATL-PHYS-PUB-2023-029

22nd September 2023

The new approach is based on the PYTHIA 8 parton-shower matching parameter p_T^{hard}. It is designed to surpass the previous method, which involved comparing two generator setups to cover the uncertainty. The old method entangled all differences between the two setups in a single uncertainty while the new prescription implements a focused uncertainty that avoids double-counting with other uncertainties on the modelling of the top processes.

Production: Top quark (and $t\bar{t}$) p_T

Not well modelled by baseline Powheg+PYTHIA

Improved @ NNLO QCD

⇒ take difference between nominal and reweighting to NNLO+NNLL as uncertainty

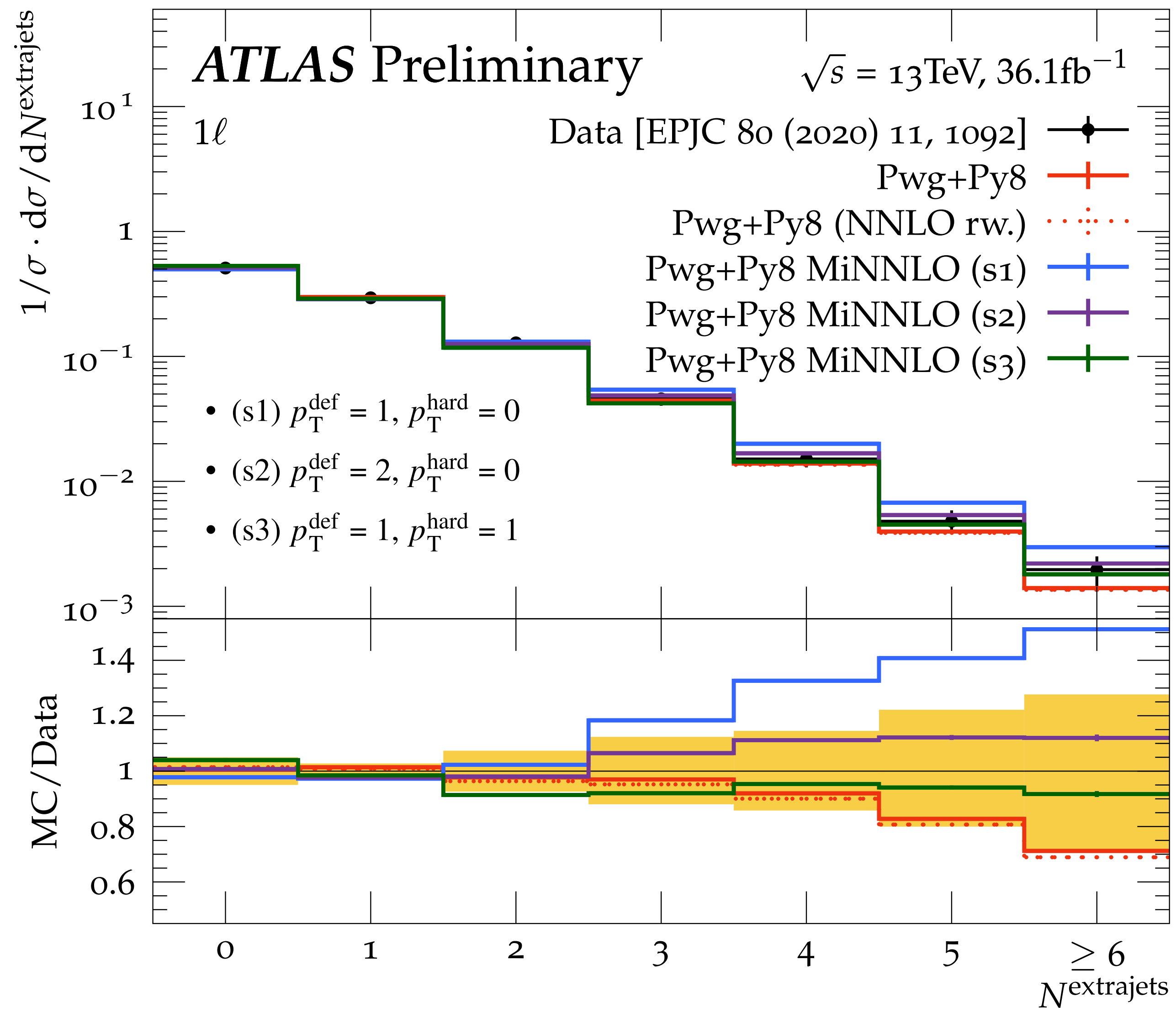
Could be improved upon by MC reaching that accuracy natively

[Mazitelli et al., 2112.12135]

First steps exploring MiNNLO$_{PS}$ for $t\bar{t}$

→ Improvement (but still has pThard ambiguity)

Important target for MC community.

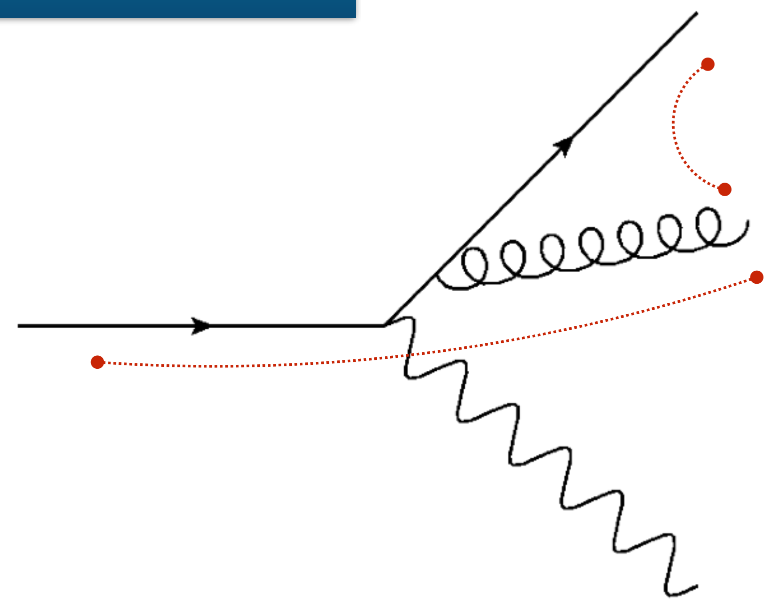


Second emission: big differences

Not controlled by POWHEG, nor by PYTHIA's MECs.

Not as important as 1st. Still highly significant if goal is per-mille precision on m_t

VINCIA RF



tg RF antenna:

Phase space & recoils set by:

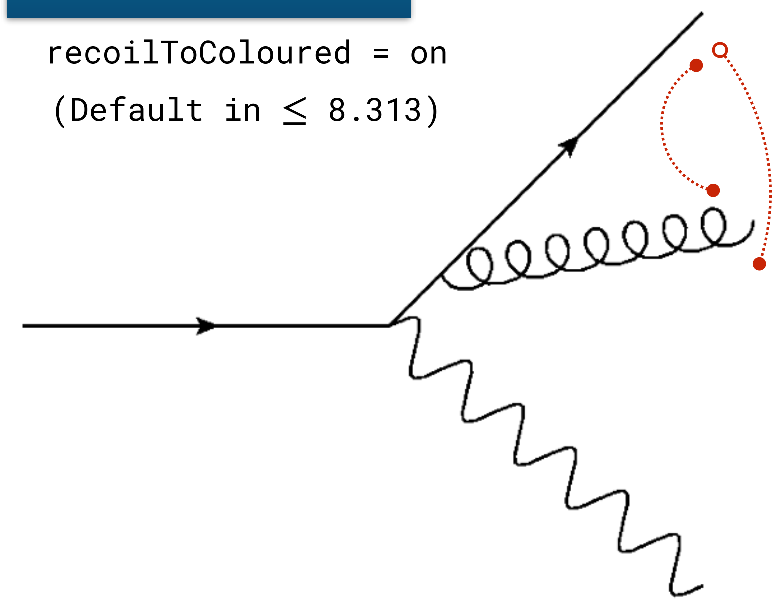
$$t - g = b + W$$

Collective recoil

PYTHIA

`recoilToColoured = on`

`(Default in ≲ 8.313)`



$g - t$ dipole treated as

$g - b$:

Phase space & recoils set by b

Affects b fragmentation

Pythia $\leq$ 8.309

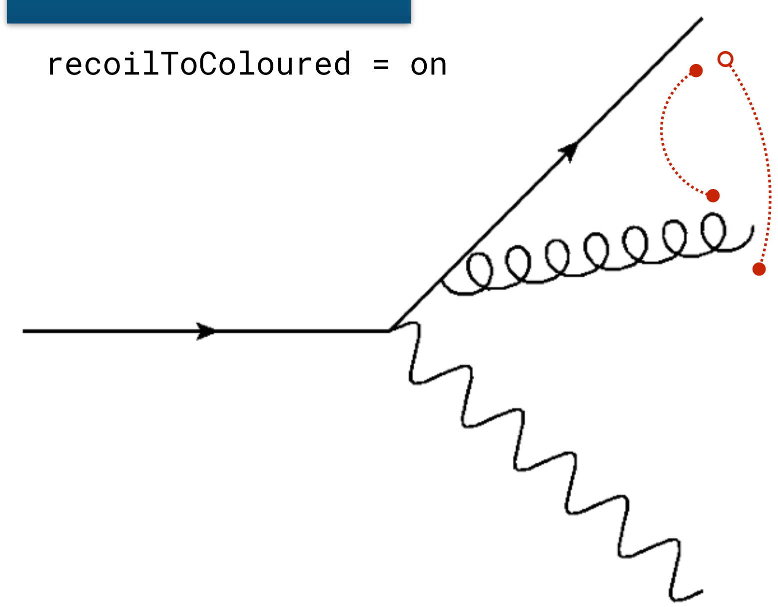
PYTHIA $\leq$ 8.309 allowed two different coherence/recoil options

+ a dedicated UserHook "recoilToTop" for use with recoilToColoured = off

Theoretically the least bad option (in absence of RF)? Needs validations & feedback.

PYTHIA

`recoilToColoured = on`



$g - t$ dipole treated as

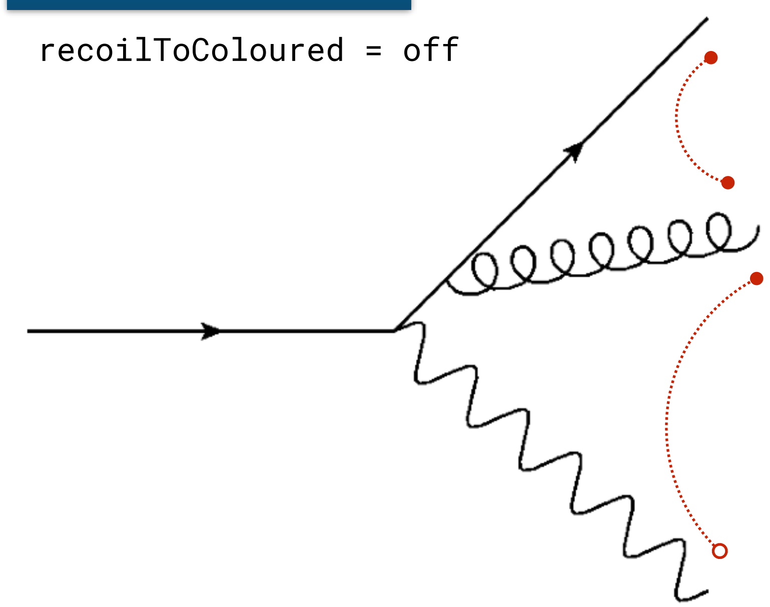
$g - b$:

Phase space & recoils set by b

Affects b fragmentation

PYTHIA

`recoilToColoured = off`



$g - t$ dipole treated as

$g - W$:

Phase space & recoils set by W

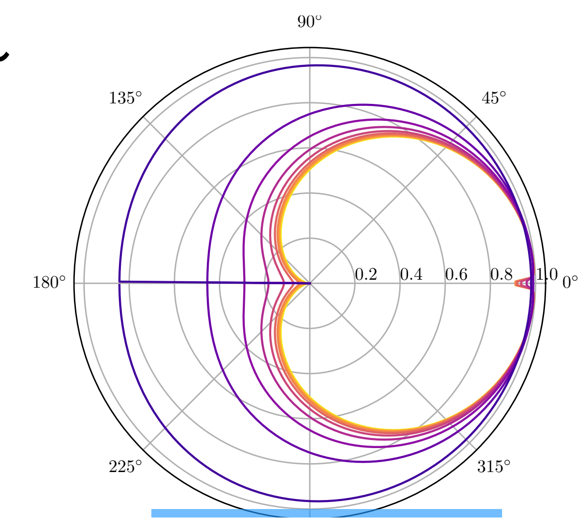
b fragmentation more "normal"?

recoilToTop
UserHook

Suppresses radiation in W hemisphere

$\otimes$ Correction factor

~



PYTHIA $\geq$ 8.314

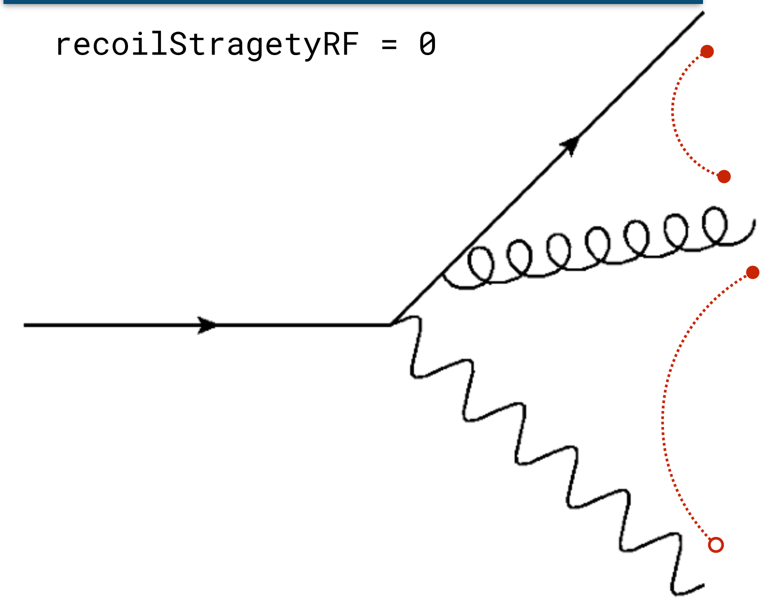
Old recoilToColoured flag replace by new mode **recoilStrategyRF**

New default = apply the RF-eikonal suppression factor (at full strength)

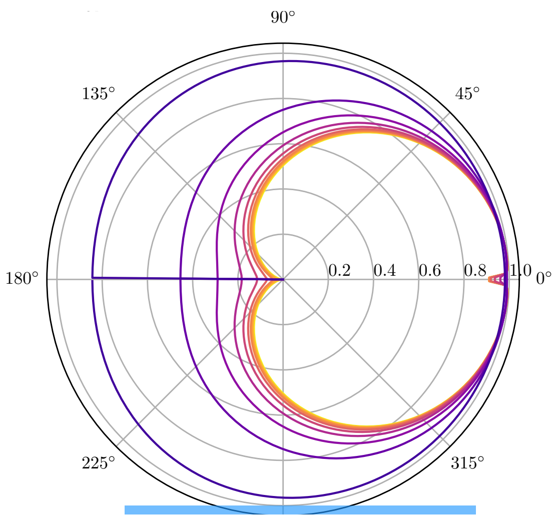
(I.e., new default is what used to be obtained with the recoilToTop userhook)

+ new option to interpolate smoothly between applying and not applying the RF reweighting factor *(thanks to D. Hisrchbuehl and E. Schmidt for this suggestion)*

PYTHIA 8.314 default



$\otimes$ Correction factor $\propto$ **weightRF** $\times$



Suppresses radiation in W hemisphere

Note: important fragmentation bug fix in 8.315 (affects baryon spectra & correlations)
Thus, recommend to move directly to 8.315

3. Ongoing work in PYTHIA

The 2nd emission

VINCIA has improved coherence & recoils through its RF antennae

But previously did not have MECs

Monash student 2025: iterated MECs for $t\bar{t}$ in VINCIA *(supervisor: Ludovic Scyboz)*

⇒ Expect ME-corrected branching rates for (at least) 1st and 2nd branchings

(Also working on approaches to formal NLL accuracy in VINCIA ↔ PANSCALES)

Finite Γ_{top}

See slides from 2022 LHC Top WG meeting

Interleaved resonance decays **(IRD)** = default in VINCIA [Brooks, PS, Verheyen, 2108.10786]

IRD: Unstable particles only radiate at wavelengths shorter than their widths, then disappear from event evolution; replaced by their decay products

Changes soft interference & recoils ⇒ modifications to lineshape beyond Γ_{top}

In principle, can then do MECs also beyond narrow-width limit, e.g., at $gg \to bW^+\bar{b}W^-$ level and/or six-fermion level: have not looked into this yet due to lack of manpower

Colour Reconnections

QCD CR Model [Christiansen & PS, 2005]

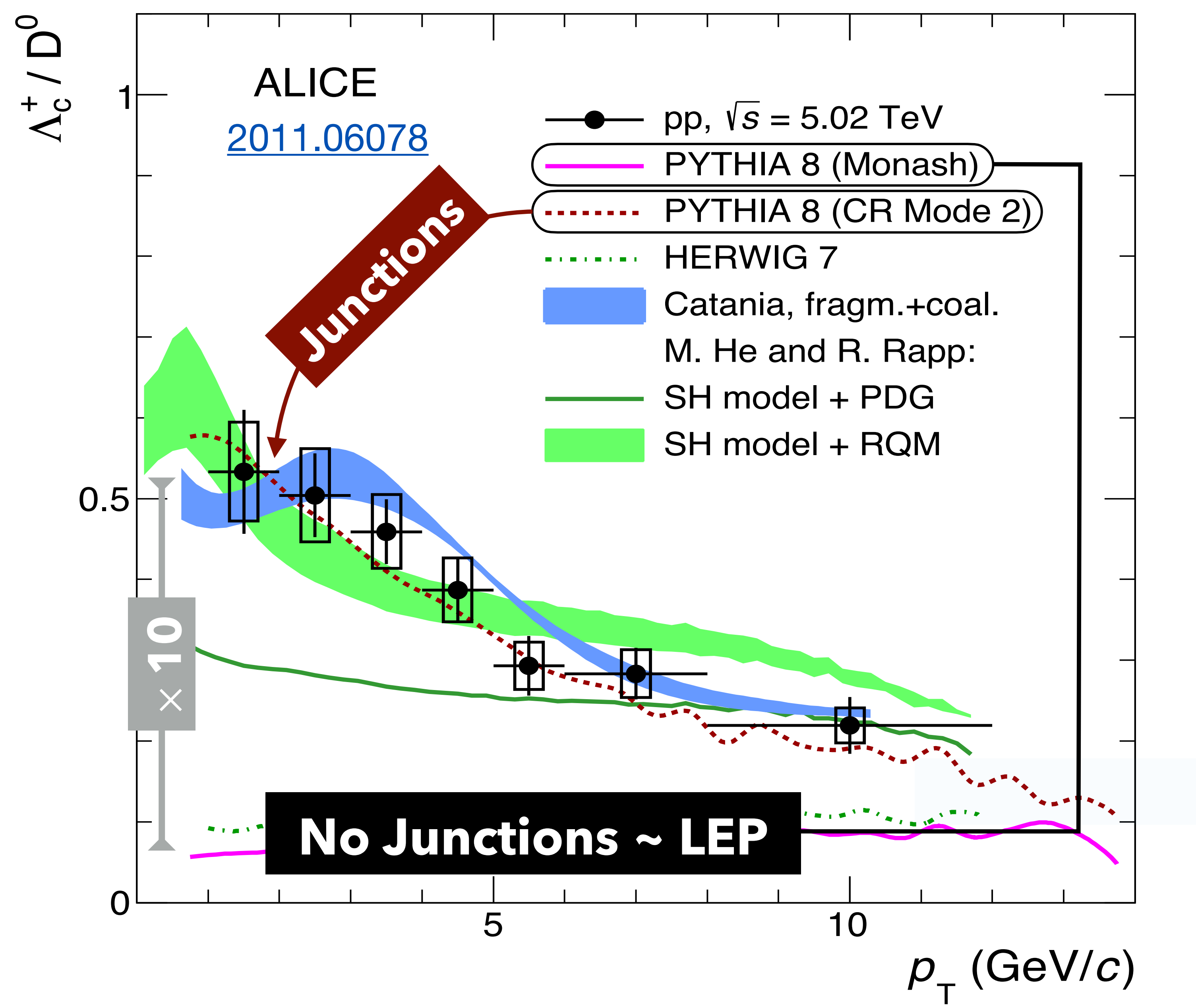
Proposes a physical/mathematical underpinning for CR

Stochastic colour correlations approximating SU(3) products:
$3 \otimes \bar{3} = 8 \oplus 1, 3 \otimes 3 = 6 \oplus \bar{3}, \ldots$

Not the final word but does agree with (& even predicted) a number of min-bias and heavy-flavour observations

Probably worth taking seriously in other hadronization-sensitive contexts

E.g.: **JES** studies & hadronic **top mass**



Note: CR **can** alter baryon fractions but does **not** by itself generate strangeness enhancement or other collective effects.

PYTHIA collaboration actively developing **extensions**: SR-CR, ropes, closepacking, shoving, …

Impact of Particle Composition

ATLAS PUB Note

ATL-PHYS-PUB-2022-021

29th April 2022

Dependence of the Jet Energy Scale on the Particle Content of Hadronic Jets in the ATLAS Detector Simulation

[…] **It is found that the hadronic jet response, i.e. the ratio of the reconstructed jet energy to the true jet energy, varies by ~ 1–2% depending on the hadronisation model used in the simulation. This effect is mainly due to differences in the average energy carried by kaons and baryons in the jet. Model differences observed for jets initiated by *quarks* or *gluons* produced in the hard scattering process are dominated by the differences in these hadron energy fractions indicating that *measurements of the hadron content of jets and improved tuning of hadronization models* can result in an improvement in the precision of the knowledge of the ATLAS jet energy scale.**

Variation largest for **gluon jets**

For E_T = **[30, 100, 200] GeV**

Max JES variation = **[3%, 2%, 1.2%]**

Fraction of E_T carried by baryons (& kaons) varies significantly

Reweighting to force similar baryon and kaon fractions

Max variation ➜ **[1.2%, 0.8%, 0.5%]**

Significant potential for improved Jet Energy Scale uncertainties!

➪ Careful Modelling & Constraints

Interplay with advanced UE models

In-situ constraints from LHC data

Revisit comparisons to LEP data w PID

Fragmentation & Tuning

Serious efforts have started towards a replacement of Monash 2013

Reproducible, with uncertainties, and using more data

Updated fragmentation (LEP) tuning:

Want to get involved?

b fragmentation at LEP/SLD ↔ in top decays (and at LHC more generally)

Fragmentation tunes optimised for 2-loop running & higher-order matching

New options for variations of splitting kernels ↔ beyond scale variations

Updated pp tuning:

New "MC-friendly" PDF sets from all main PDF providers.

Will replace NNPDF 2.3 LO used in Monash

Dedicated efforts optimised for 2-loop running & higher-order matching

Colour reconnections (and other non-perturbative aspects)