Colour & Precision Top Physics

Peter Skands *(Monash University)*

Perturbative aspects of top physics

The top quark mass

Top quark modelling at colliders

A new approach to coherence

Non-perturbative aspects of top physics

Collective effects in pp collisions?

Quo Vadis?

AIP Summer Meeting
RMIT, December, 2019

The Top Quark

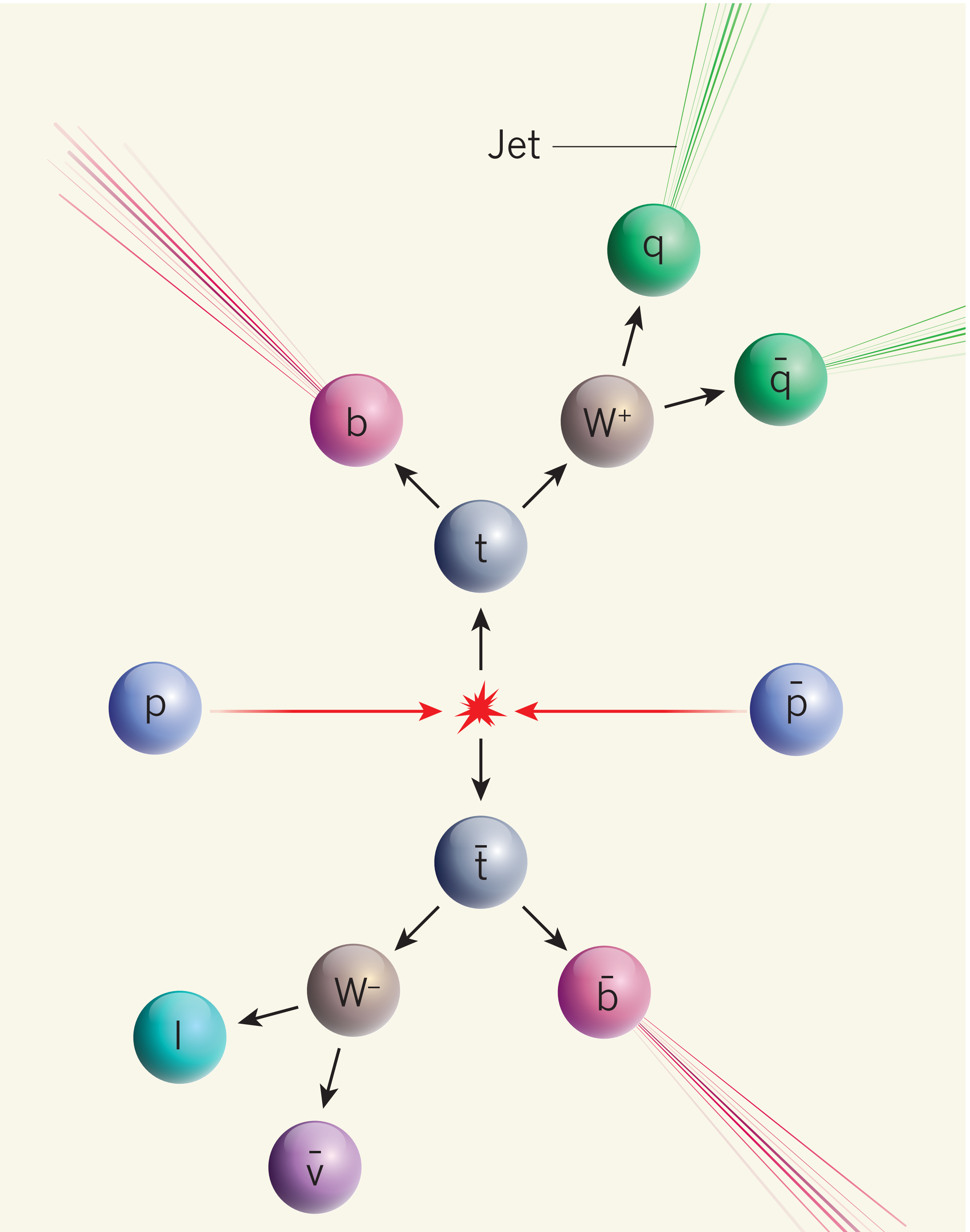


Illustration from: *P Skands, Nature* **514** (2014) 174

Heaviest particle in the SM

m_t ~ 170 GeV/c^2 ~ m_{Au}

Lifetime: 10^{-24} s (Γ_t ~ 1.5 GeV)

Mainly **pair produced** at colliders:

$$gg \to t\bar{t} \qquad q\bar{q} \to t\bar{t}$$

Dominates at LHC — Dominated at Tevatron

Complicated (cascade) decays:

$$t \to bW^+ \qquad \bar{t} \to \bar{b}W^-$$

$$W \to \{q\bar{q}', \ell\nu\}$$

quarks ➝ jets   b-quarks ➝ b-jets

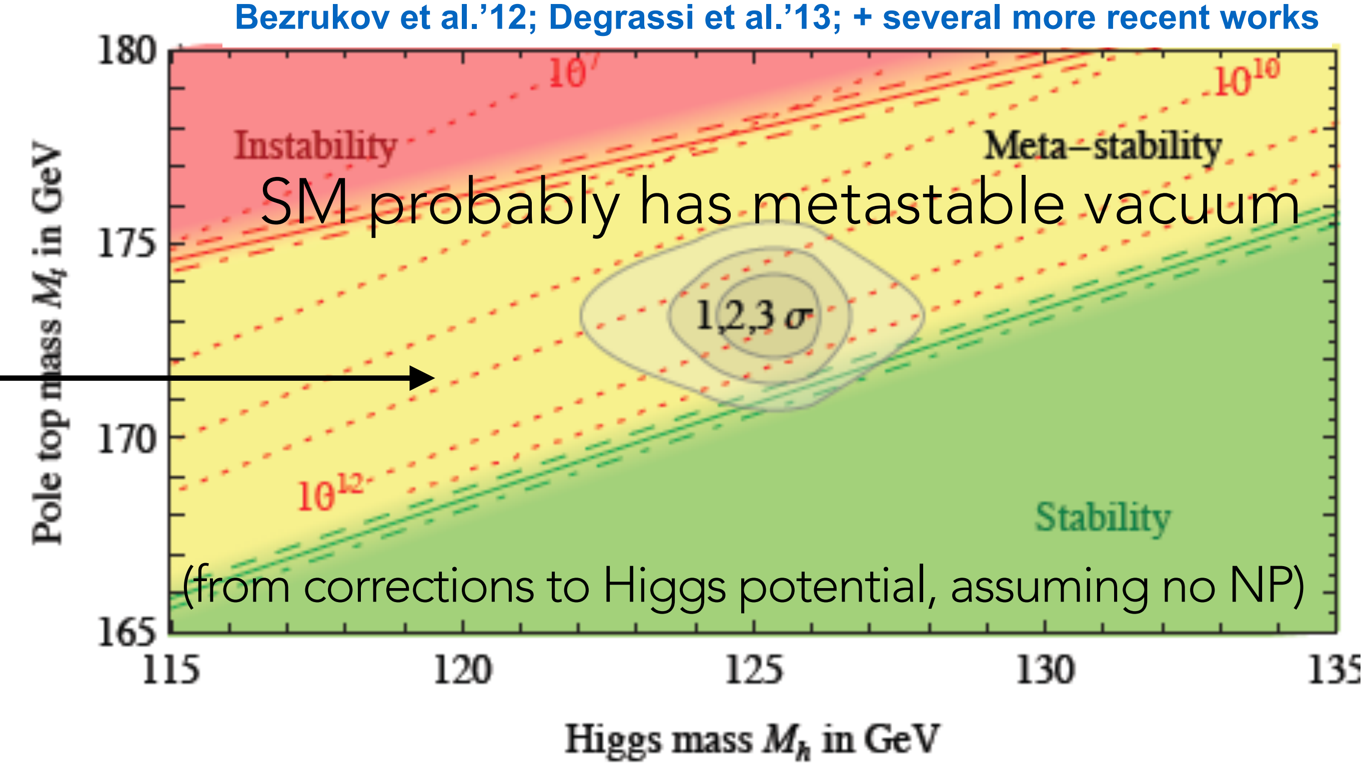
Complex multi-body final states (+ hadronisation) ➜ highly nontrivial to measure mass with high precision (<1%)

The Top Quark Mass

- **Top-Higgs Yukawa coupling**

Gateway to new physics

+ SM vacuum stability



Definition

For this talk, pole mass ~ Breit-Wigner mass ~ MC mass

Important to resolve "renormalon ambiguity" ≲ 100 MeV; not the subject of this talk.

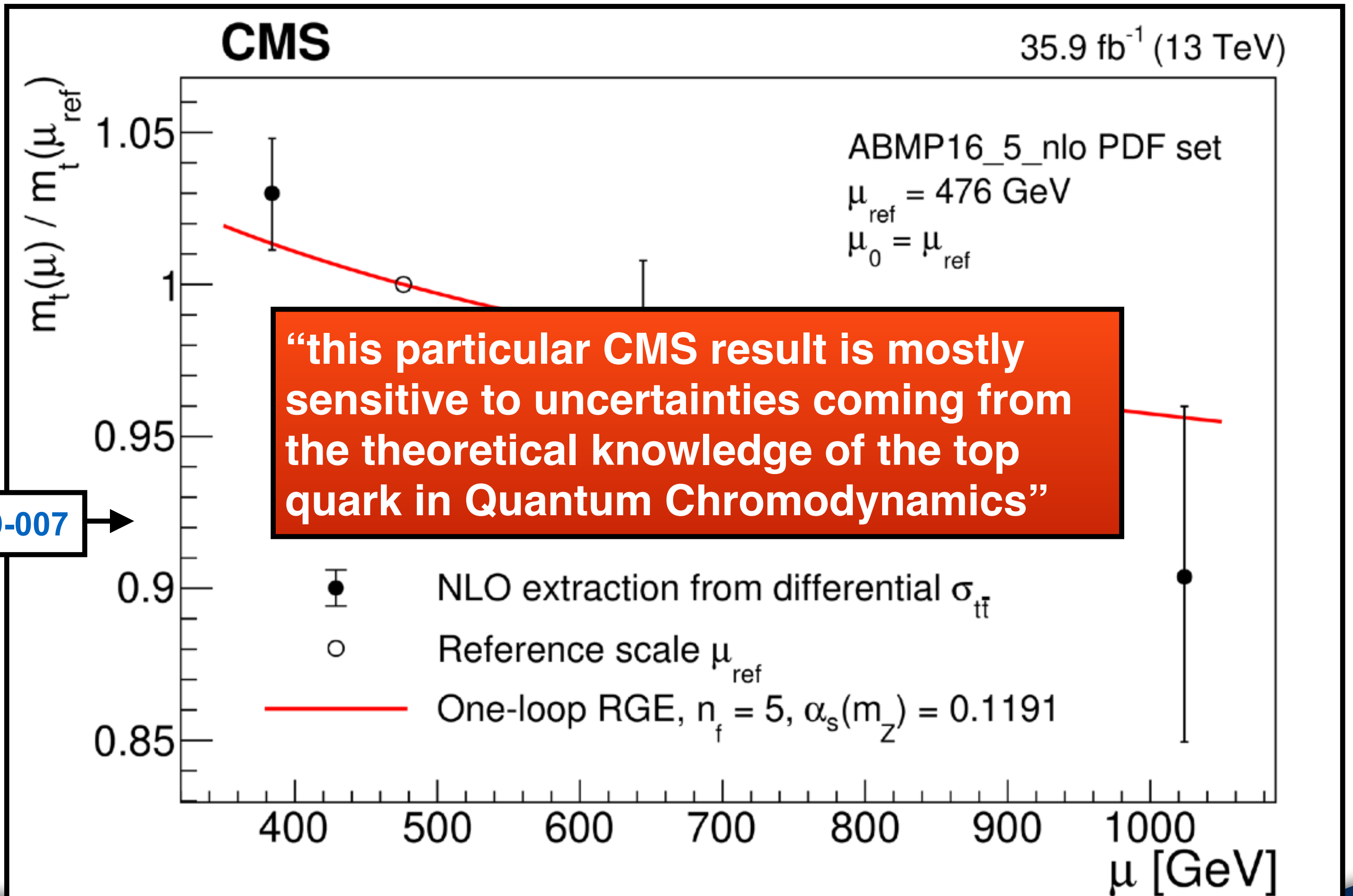
Recent Measurements

Running of top quark mass CMS-TOP-19-007

$\Gamma_t = 1.9 \pm 0.5$ GeV ATLAS-CONF-2019-038

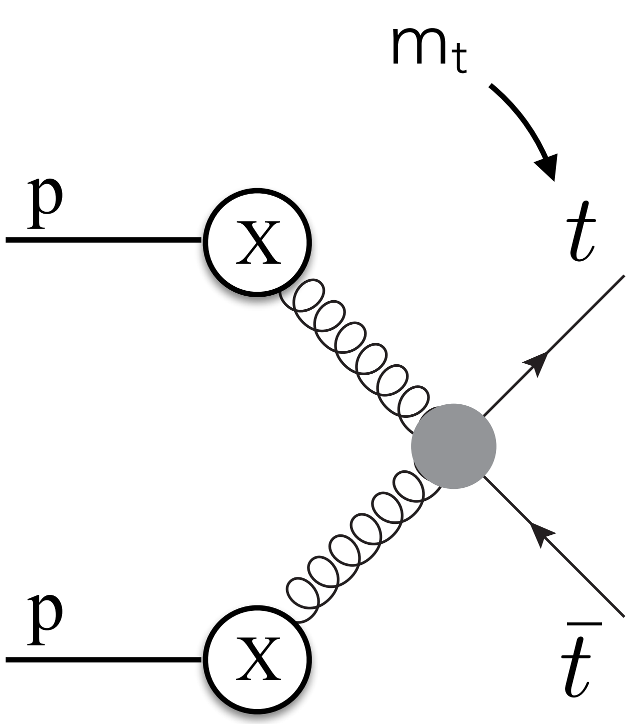
LHC Δm_t ~ 50 MeV ~ 0.3%

See eg LHCTopWG Twiki page

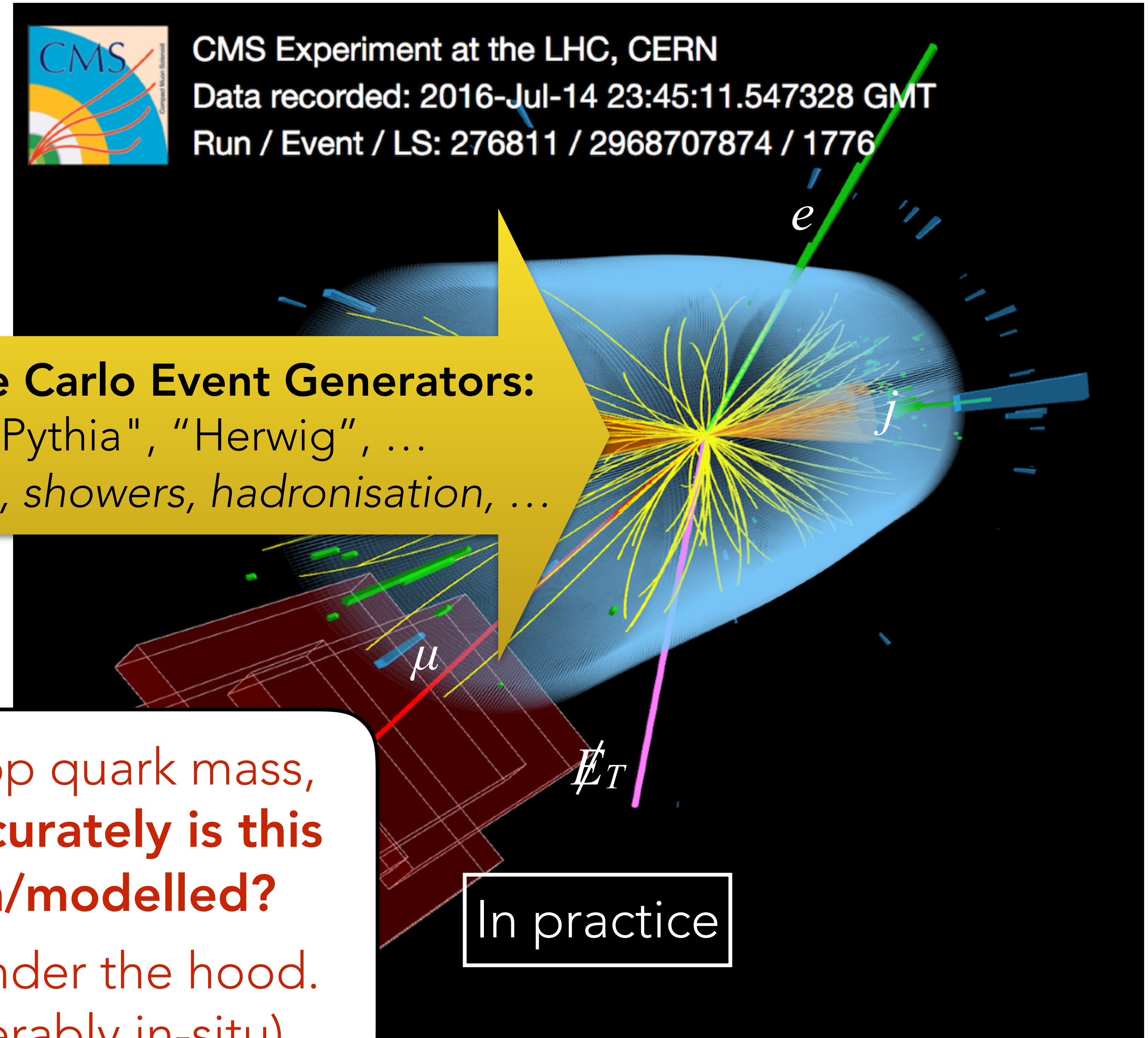


What top quarks look like

In theory



Monte Carlo Event Generators:
"Pythia", "Herwig", …
Decays, showers, hadronisation, …



In practice

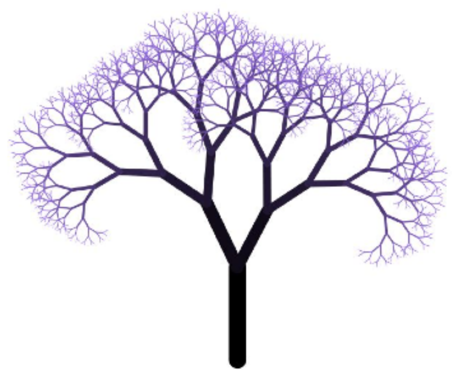
If you are measuring the top quark mass, you want to know: **how accurately is this transfer function known/modelled?**

➜ want **"good physics"** under the hood.
\+ **good validations** (preferably in-situ).

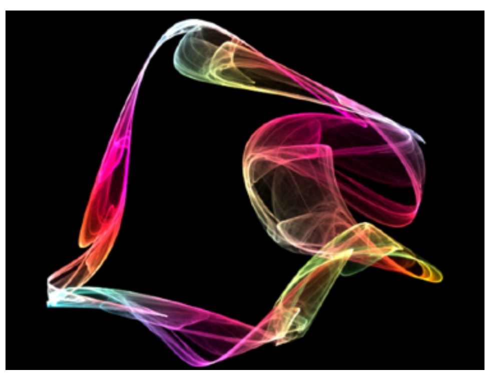
The Physics of Hadronic Jets

More than just a (fixed-order perturbative) expansion in α_s

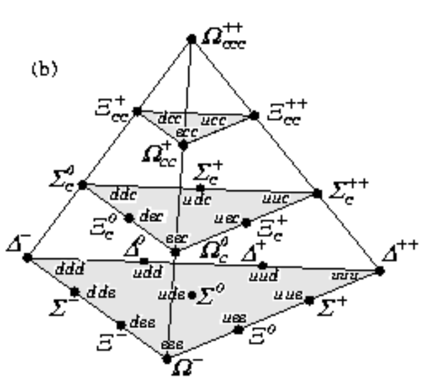
most of my research



Bremsstrahlung: accelerated particles radiate ⟷ Infinite-order perturbative structures of indefinite particle number ⟷ universal amplitude structures in QFT



Confinement (strong gluon fields) ⟷ Hadronization phase transition ⟷ quantum-classical correspondence. Non-perturbative physics. String dynamics. String breaks.



Hadrons ⟷ Spectroscopy (incl excited and exotic states), lattice QCD, (rare) decays, mixing, light nuclei. Hadron beams → multiparton interactions, diffraction, …

Types of Bremsstrahlung Showers

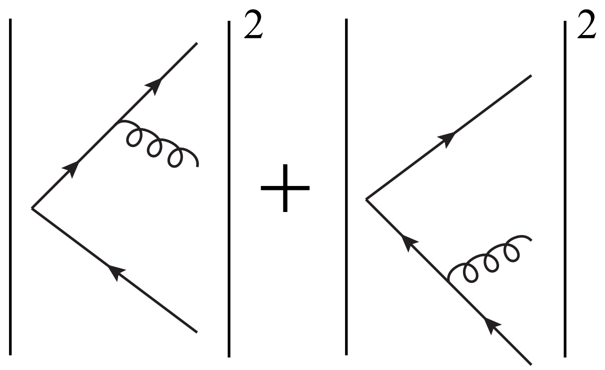
Parton Showers are based on iterated 1→2 splittings

Each **parton** undergoes a sequence of splittings

Exact in limit that **one diagram** dominates: collinear splittings; good starting point for describing jets

Some interference effects can be included via "angular ordering" or "dipole functions" (~partitioned interference terms)

(E,p) conservation achieved via (ambiguous) recoil effects



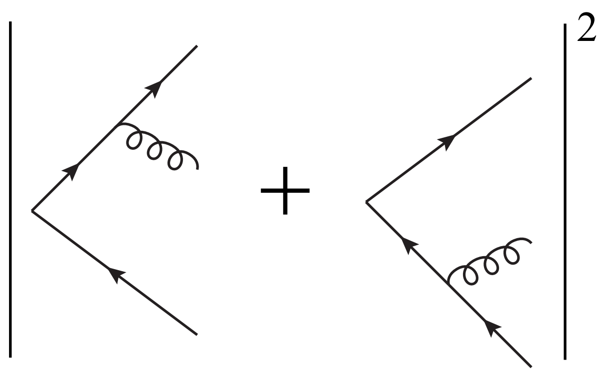
At Monash, we develop an **Antenna Shower**, in which splittings are fundamentally 2→3 (+ working on 2→4…)

Evolution in terms of colour **dipoles/antennae**

+ Intrinsically coherent (to leading power of $1/N_C^2$ ~ 10%)

+ Manifestly Lorentz invariant kinematics with local (E,p) cons.

(+ Markovian/Invertible: important for future applications)



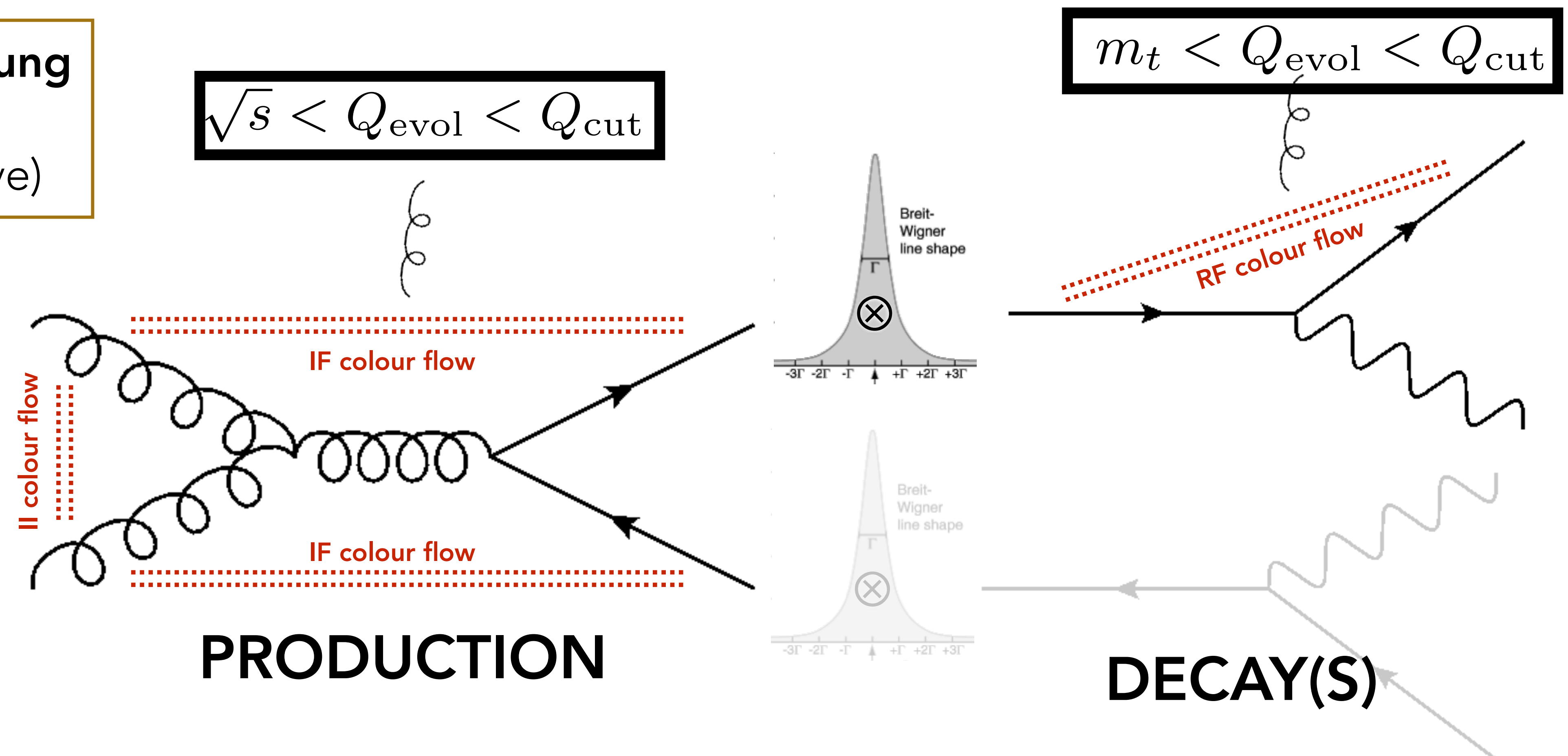
Includes dipole interference

In limit $\Gamma_t \sim 0$, factorise **production** and **decay**

These stages are **showered** independently (regardless of which type of shower)

Bremsstrahlung Showers (perturbative)

I: initial
F: final
R: resonance



Production ISR + FSR shower preserves Breit-Wigner shape

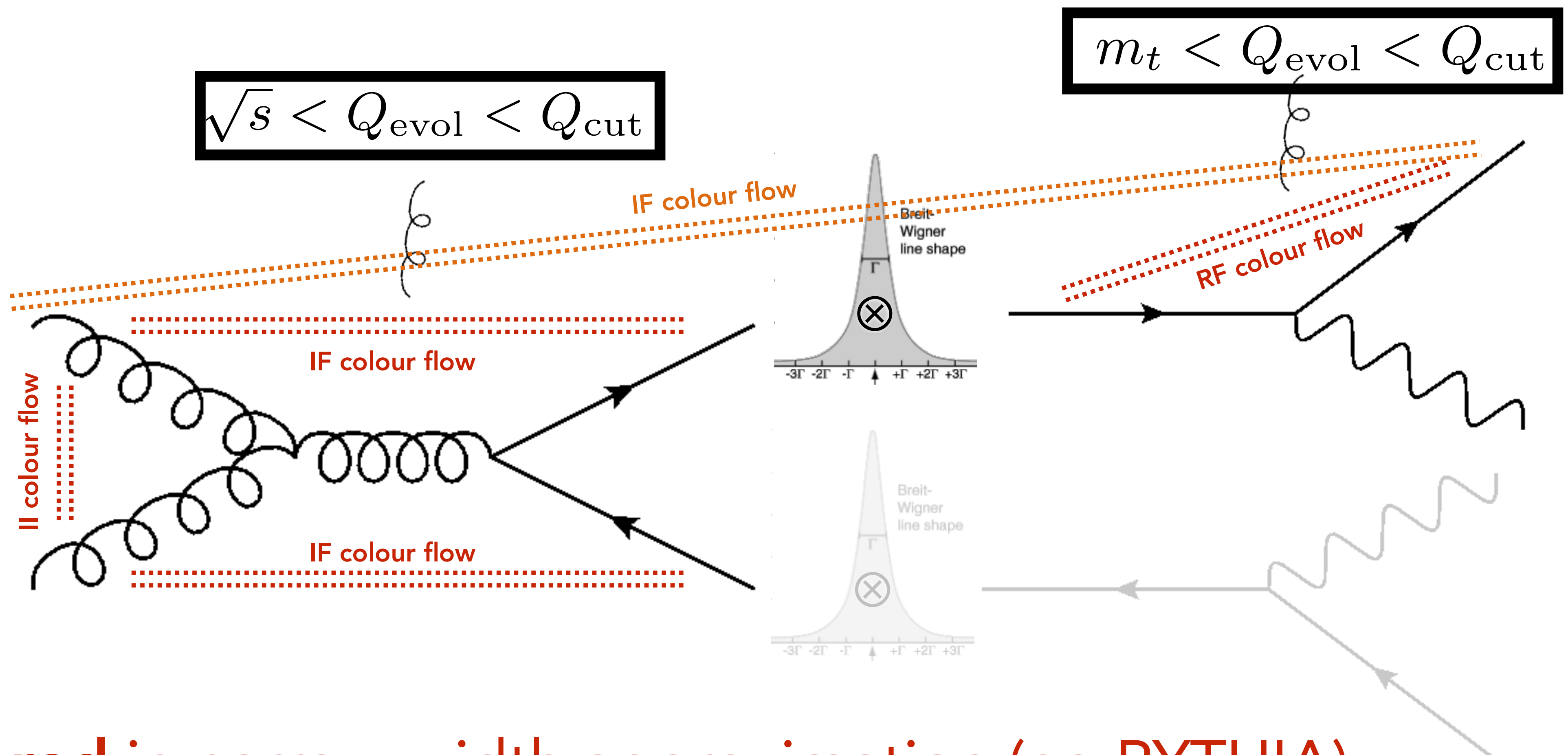
Resonance-Decay FSR shower preserves Breit-Wigner shape

Interference between production and decay?

Would modify BW shape.

But expect small effects. Cutoff of perturbative shower $Q_{cut} \sim 1$ GeV ; $\Gamma_t \sim 1.5$ GeV (in SM); Interference only from scales $1 \text{ GeV} < Q < 1.5 \text{ GeV}$

I: initial
F: final
R: resonance



- **Ignored** in narrow-width approximation (eg PYTHIA).

Production showered to Q_{cut}, decay as well.

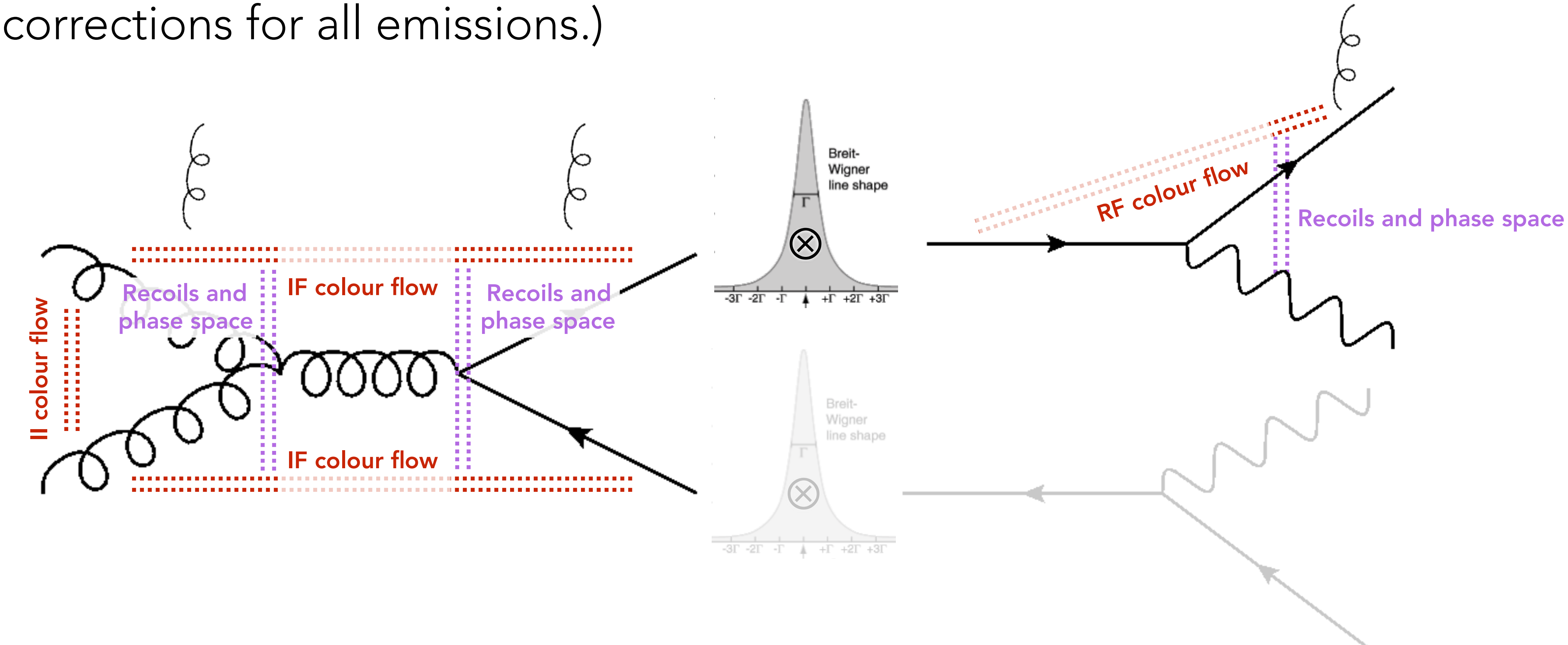
An e^+e^- study found $\Delta m_t < 50$ MeV but not repeated for LHC (to my knowledge)
Khoze, Sjöstrand, Phys.Lett. B328 (1994) 466
though see Ravasio et al, Eur.Phys.J. C78 (2018) no.6, 458

Default "Pythia" showers not fully coherent for "IF" or "RF" flows

All initial-state partons treated as II. (Some coherence by rapidity ~angular vetos)

All final-state partons treated as FF. (MECs ➤ 1st emission in top decay correct; + b mass corrections for all emissions.)

I: initial
F: final
R: resonance



RF not coherent from **2nd emission** onwards. (So eg Powheg does not help.)

Issues for soft wide-angle, recoil effects, and some phase-space effects.

Coherence in VINCIA

Brooks, Skands, Phys.Rev. D100 (2019) no.7, 076006 [ARXIV:1907.08980]

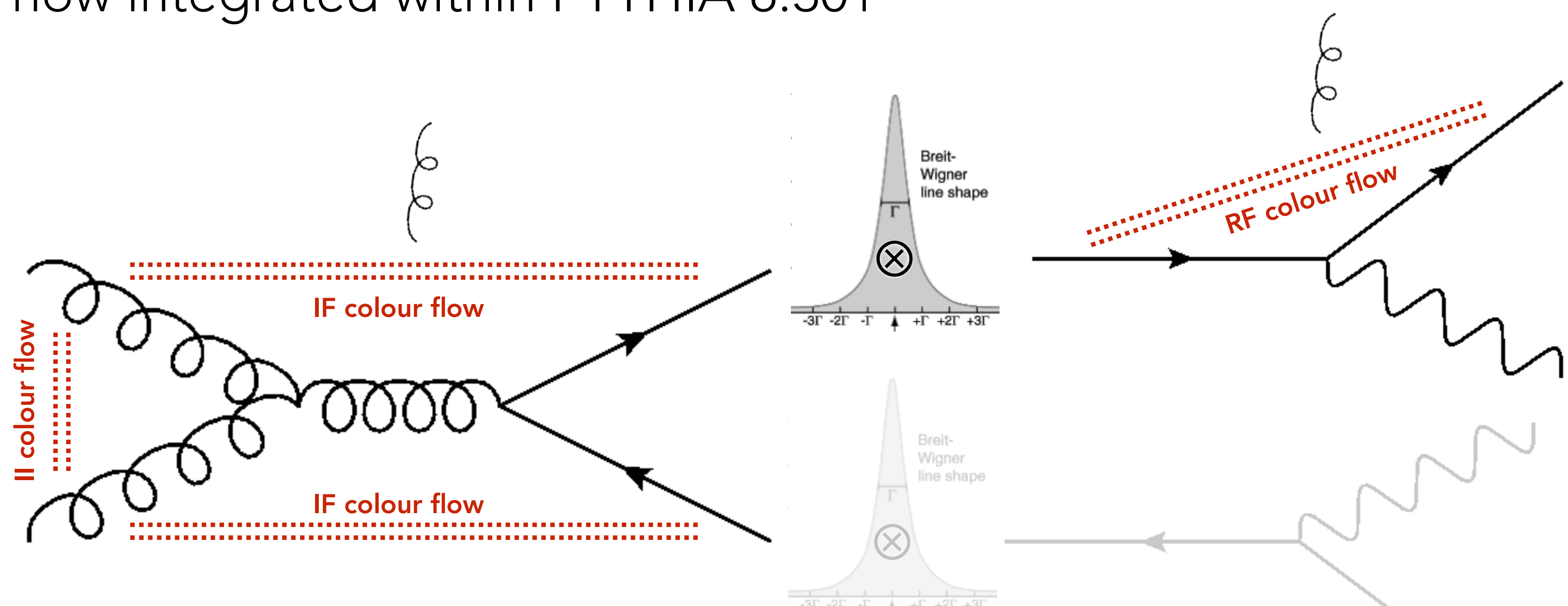
Explicit IF and (recently) RF antennae

Based on **coherent dipole-antenna** patterns, with **full t and b mass** effects.

Collective recoils for RF emissions: coherent radiation recoils against "crossed" top

+ VINCIA now integrated within PYTHIA 8.301

I: initial
F: final
R: resonance



+ Under development (with H. Brooks, R. Verheyen, C. Preuss)

- Interleaved resonance decays ➤ interference between production and decays.
- Matrix-Element Merging & Iterated ME Corrections. (So far it is a pure shower.)
- Automated uncertainty variations (in the same style as internal Pythia 8 ones).
- Electroweak showers, second-order antenna functions, …

Slide from H. Brooks

Ravasio et al, Eur.Phys.J. C78 (2018) no.6, 458

arXiv:1801.03944

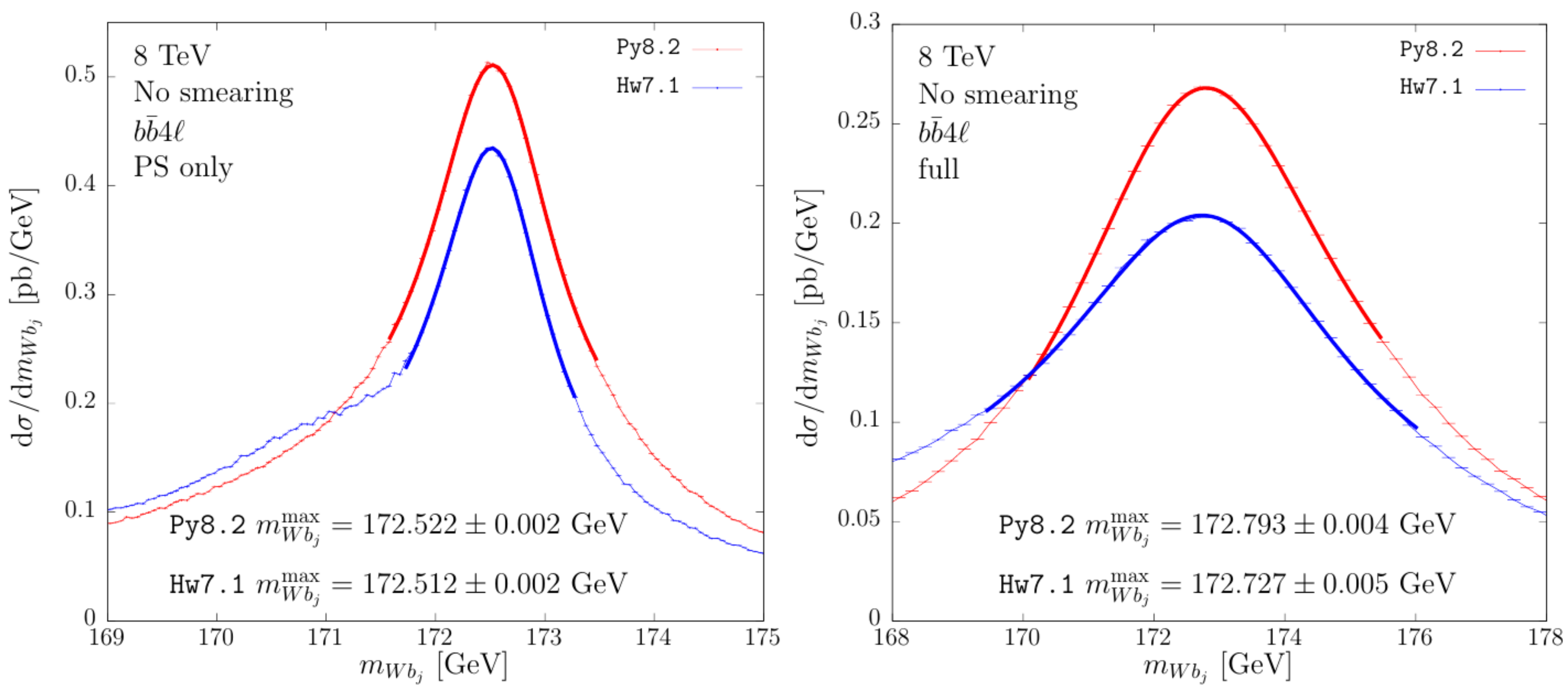
A theoretical study of top-mass measurements at the LHC using NLO+PS generators of increasing accuracy

Silvia Ferrario Ravasio,[a] Tomáš Ježo,[b] Paolo Nason,[c] Carlo Oleari[a]

[a] *Università di Milano-Bicocca and INFN, Sezione di Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy*

[b] *Physics Institute, Universität Zürich, Zürich, Switzerland*

[c] *CERN, CH-1211 Geneve 23, Switzerland, and INFN, Sezione di Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy*

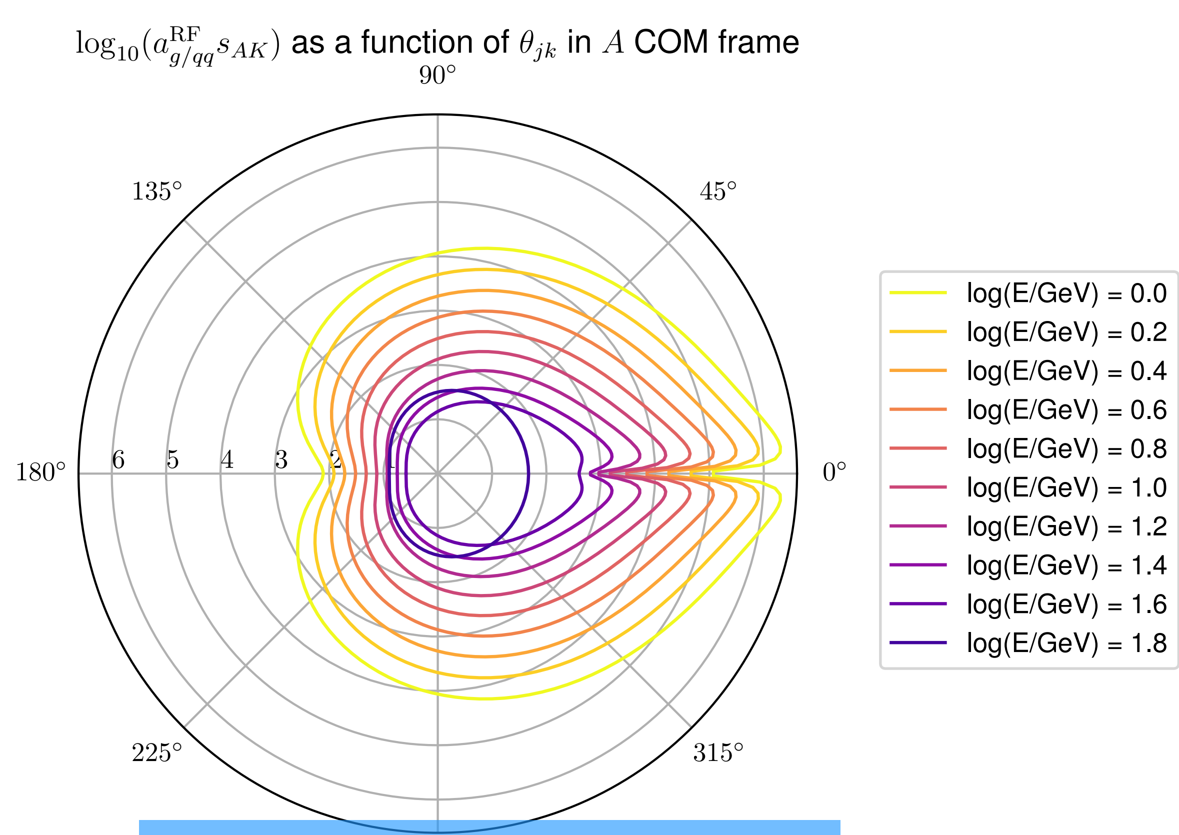


"… the very minimal message that can be drawn from our work is that, in order to assess a meaningful theoretical error in top-mass measurements, the use of different shower models, associated with different NLO+PS generators, is mandatory."

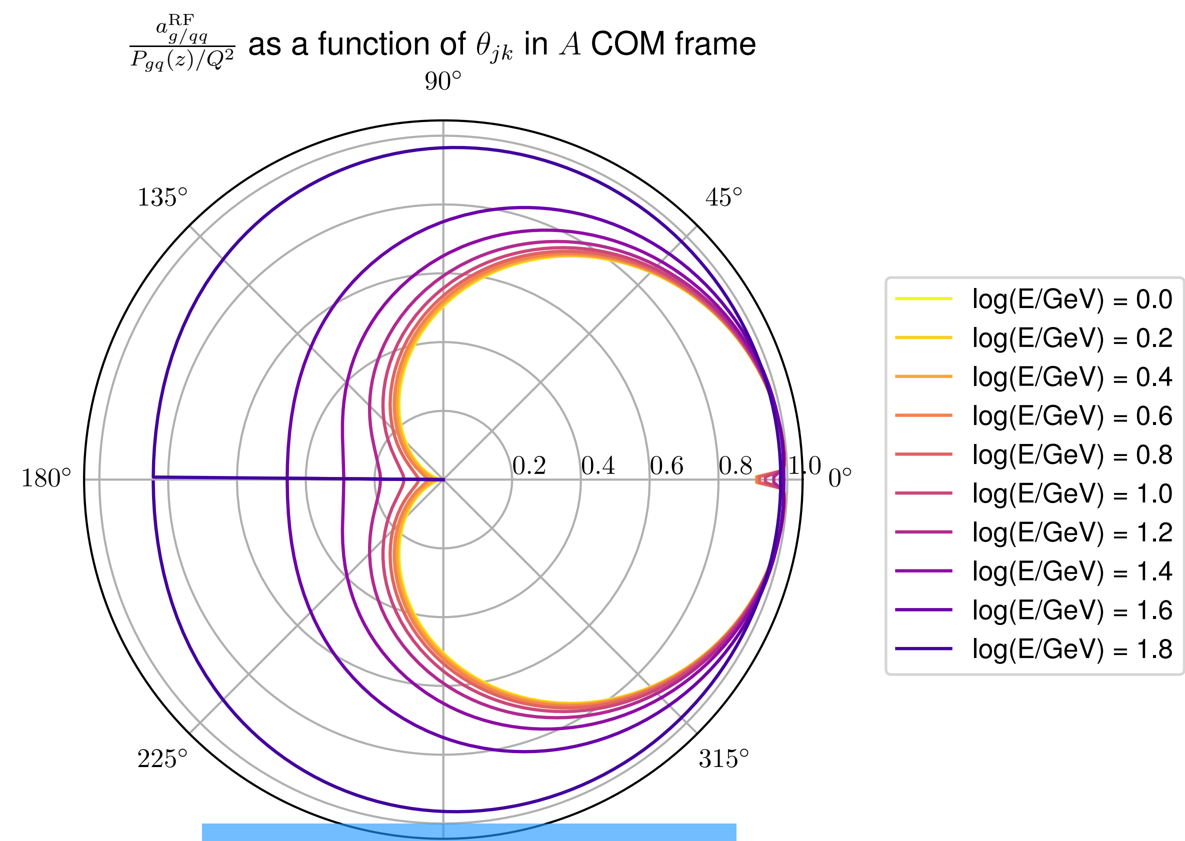
Coherence in Top Decay

Brooks, Skands, Phys.Rev. D100 (2019) no.7, 076006 ARXIV:1907.08980

Plot antenna function in top centre of mass frame (b along z):



Log of antenna function



Ratio to AP kernel

Antenna function ➔ b-quark DGLAP splitting function in forwards (collienar) direction; coherence results in a suppression in the backwards (wide-angle) direction ➤ narrower b-jets

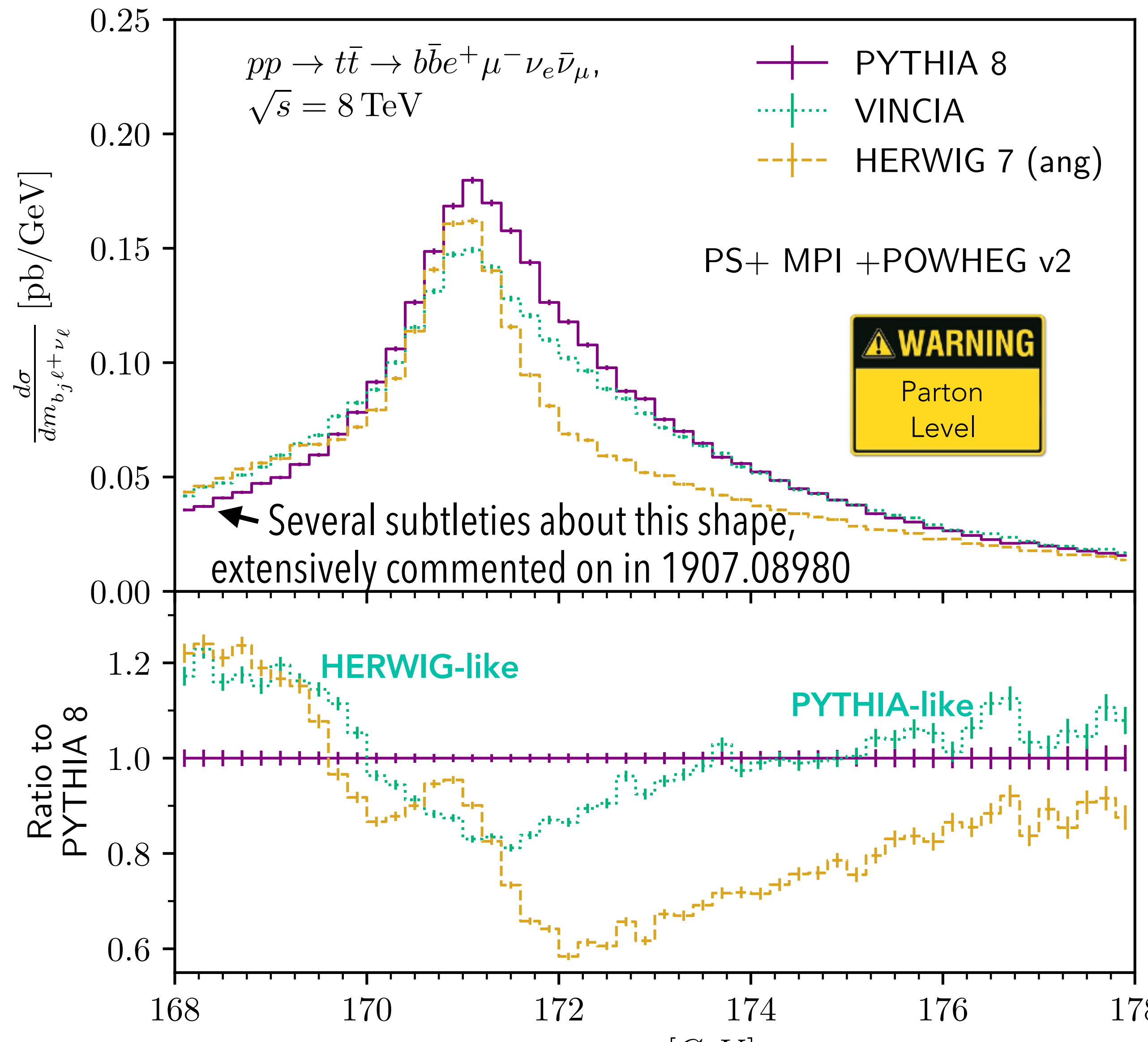
Matching with POWHEG

Brooks, Skands, Phys.Rev. D100 (2019) no.7, 076006 ARXIV:1907.08980

- Use POWHEG v2 ($t\bar{t}dec$)[1] (no need for exact finite width effects)
- **Very** similar setup to matching with PYTHIA in [2].
- Veto hardest emission in production with

```
Vincia:QmaxMatch = 1
```

- Veto hardest emission in decay with `UserHooks` interface



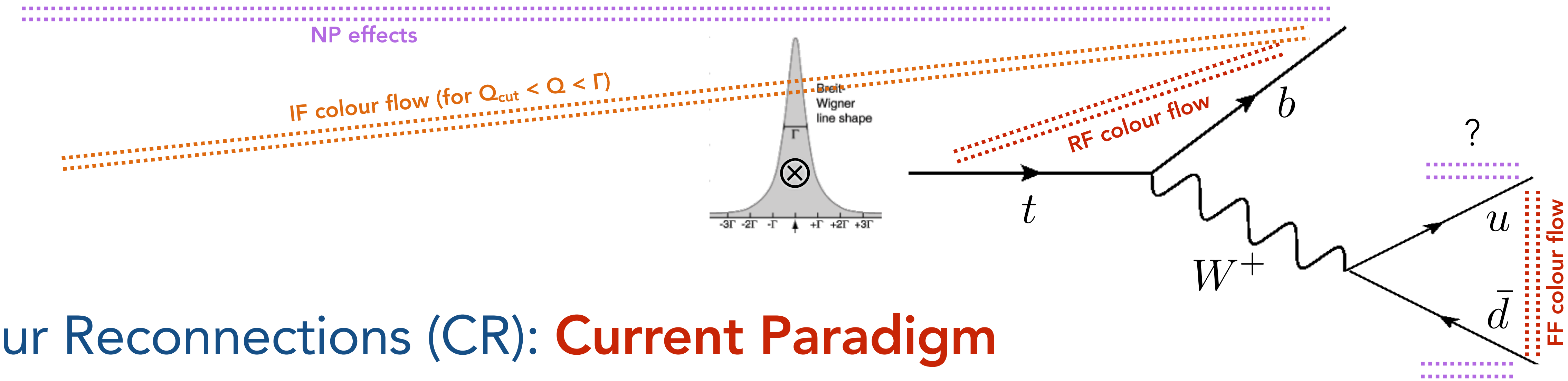
PYTHIA 8.301 released. Includes VINCIA with new resonance-final showers

Still to come in VINCIA: ME merging, multi-leg MECs, automated uncertainty bands, production-decay interference, electroweak showers, NLO antenna functions,…

Will modify BW shape.

Affects hadronisation in b-jet and may (?) affect b→B transition.

May (?) affect hadronic W hadronisation.



Colour Reconnections (CR): Current Paradigm

Partons from different MPI (or ee→WW) can be "close" in phase space.

Nature can make use of **non-LC possibilities** to minimise the confinement potentials ➜ **"QCD-inspired"** model in PYTHIA (String Formation Beyond Leading Colour, Christiansen + PS, JHEP 08 (2015) 003), and in various more or less explicit ways informs most other models of CR.

NB: momentum transfer happens due to **ambiguities** in colour space; indirect

New / Emerging Paradigm

LHC has discovered **new non-perturbative QCD phenomena in pp**, like CMS "ridge" and ALICE strangeness enhancement vs multiplicity

These effects do not seem to be explicable solely in terms of CR.

➤ New paradigm: new non-perturbative **dynamics** (interactions)

New Models:

Lund/NBI: **Collective Strings 1**: (Swing) + Colour Ropes + String Shoving

Monash: **Collective Strings 2**: (QCD CR) + Dynamic String Tensions + Repulsion

Lund: Strings with Spacetime Information + **Hadron Rescattering**

Herwig: Cluster Model with **spacetime CR** + Dynamic strangeness enhancement

Epos: Core/Corona picture with **QGP-like thermal effects** in core component

Expect additional hadron-level effects of order Λ_{QCD}, beyond "conventional" CR.

Good, Bad, or Irrelevant for Top Physics?

Good?

CR is difficult to constrain directly. (Hence we still have a plethora of models.)

But strangeness and baryon enhancements leave **clear smoking-gun traces**.

… which should scale with UE density

Bad?

Expect additional **hadron-level effects of order Λ_{QCD}**, beyond "conventional" CR.

E.g., if strings push on each other, that could exchange momenta of order Λ_{QCD} (per unit rapidity!) between top system and MPI.

And/or if $\mathbf{B_s/B}$ and $\mathbf{\Lambda_b/B}$ rates are affected ➤ modifications to B spectra (+decays)

Irrelevant?

Like CR, effects **may** primarily affect the "soft bulk" of particle production (~ the UE),

(Tips of) **high-pT jets may not be significantly affected**.

Need collaboration with experimentalists to devise dedicated observables (➤tests ➤constraints) on non-perturbative dynamics in top events (*in situ*).

Summary

Top:

The only **coloured resonance** in SM that **decays before it hadronises**

Largest Yukawa coupling in the SM (➜ largest mass)

Important as a **window to new physics** and as **background to new physics**

Outlook:

Aiming for $\Delta m_t/m_t < 1\%$ implies controlling corrections at the 100-MeV level.

➜ **Accurate physics models** (incl. coherence, NLO / ME corrections, etc.)

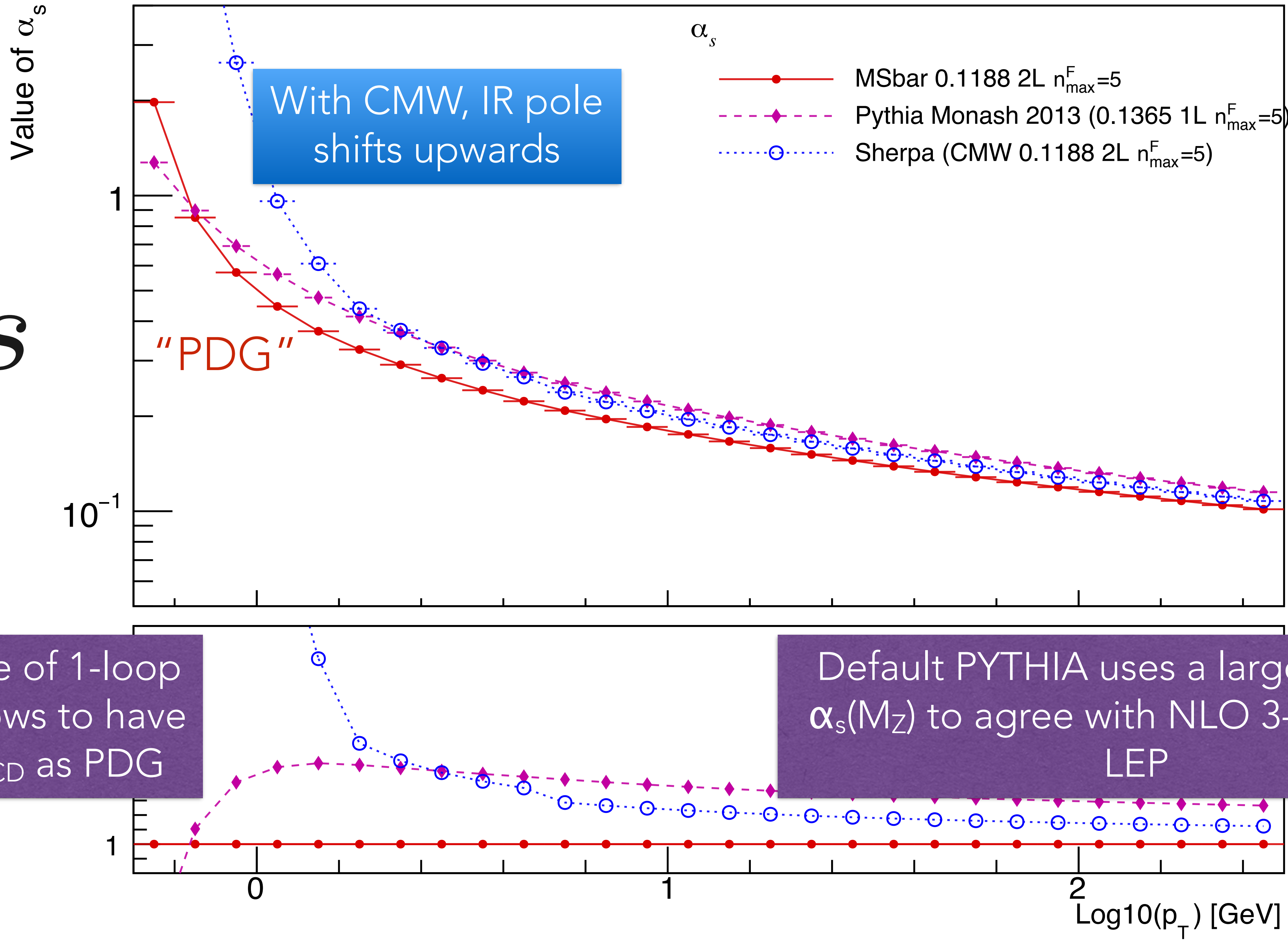
➜ **Non-perturbative QCD.** Toy models of colour reconnections were ~ sufficient in Tevatron era, but cannot be relied upon to deliver the goods (= exhaustive non-perturbative uncertainties) at sub-100-MeV level.

LHC itself is providing hard evidence for new non-perturbative phenomena

Need for collaboration with top physics community on *in-situ* measurements to better constrain non-pert. aspects like **strangeness** in top jets, B_s/B, …

Questions / Discussion ?

α_s



With CMW, IR pole shifts upwards

"PDG"

Slower pace of 1-loop running allows to have similar Λ_{QCD} as PDG

Default PYTHIA uses a large value of $\alpha_s(M_Z)$ to agree with NLO 3-jet rate at LEP

SCALE VARIATIONS: HOW BIG?

Scale variations induce 'artificial' terms beyond truncated order in QFT ~ Allow the calculation to float by (1+O(α_s)).

$$\frac{\alpha_s(k_1^2\mu^2)}{\alpha_s(k_2^2\mu^2)} \sim 1 - b_0 \ln(k_1^2/k_2^2)\alpha_s(\mu^2)$$

Flavour-dependent slope of order 1
$b_0 \sim 0.65 \pm 0.07$

Expansion around μ only sensible if this stays ≲ 1

Proportionality to $\alpha_s(\mu)$ ⟹ can get a (misleadingly?) small band if you choose central μ scale very large.

E.g., some calculations use μ ~ H_T ~ largest scale in event ?!

Worth keeping in mind when considering (uncertainty on) central μ choice

Mainstream view:

Regard scale dependence as unphysical / leftover artefact of our mathematical procedure to perform the calculations.

Dependence on it has to vanish in the 'ultimate solution' to QFT

→ Terms beyond calculated orders must sum up to at least kill μ dependence

Such variations are thus regarded as a useful indication of the size of uncalculated terms. (Strictly speaking, only a lower bound!)

Typical choice (in fixed-order calculations): k ~ [0.5,1,2]

Note: In PYTHIA you specify k^2

TimeShower:renormMultFac

SpaceShower:renormMultFac

Shower Uncertainties: Scale Variations

What do parton showers do?

In principle, LO shower kernels proportional to α_s

Naively: do factor-2 variations of μ_{PS}.

There are at least 3 reasons this could be **too** conservative

1. For soft gluon emissions, we know what the NLO term is

   → even if you do not use explicit NLO kernels, you are effectively NLO (in the soft gluon limit) **if** you are coherent and use $\mu_{PS} = (k_{CMW}\, p_T)$, with 2-loop running and $k_{CMW} \sim 0.65$ (somewhat n_f-dependent). *[Though there are many ways to skin that cat; see next slides.]*

   Ignoring this, a **brute-force** scale variation **destroys** the NLO-level agreement.

2. Although hard to quantify, showers typically achieve better-than-LL accuracy by accounting for **further physical effects** like (E,p) conservation
3. We see empirically that (well-tuned) showers tend to stay far inside the envelope spanned by factor-2 variations in **comparison to data**

See e.g., Perugia radHi and radLo variations on mcplots.cern.ch

Poor man's recipe: Use $\sqrt{2}$?

Sure … but still rather arbitrary

Instead: add compensation term to preserve soft-gluon limit at $O(\alpha_s^2)$

Allowing full factor-2 outside that limit.

Several MCs now implement such compensation terms, at least in context of automated uncertainty bands.

Warning: aggressive definitions can lead to overcompensation / **extremely** optimistic predictions → very small uncertainty bands.

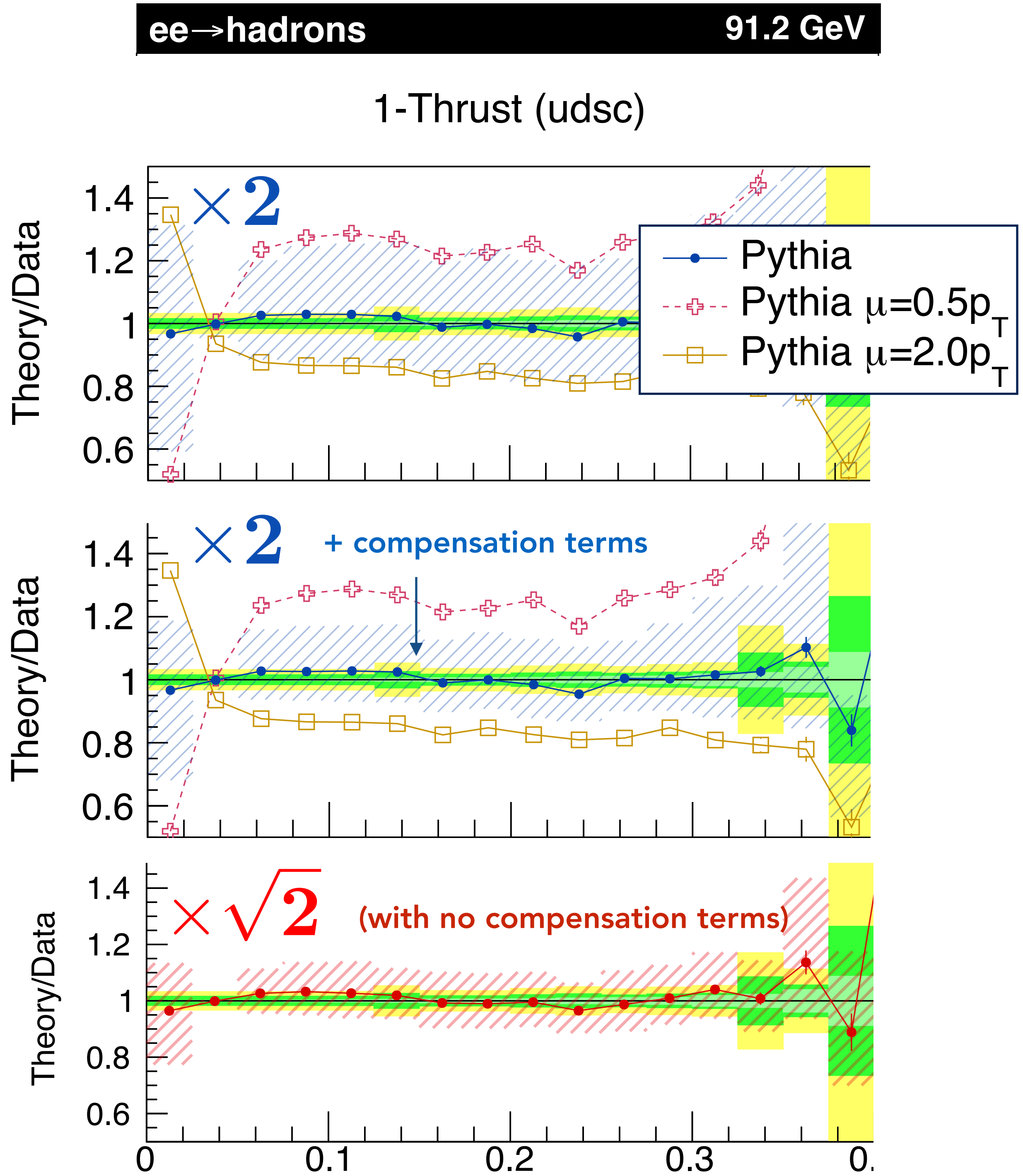
For PYTHIA, we chose a rather conservative definition ➤ larger bands.

$$P'(t,z) = \frac{\alpha_s(kp_\perp)}{2\pi}\left(1+(1-\zeta)\frac{\alpha_s(\mu_{\max})}{2\pi}\beta_0 \ln k\right)\frac{P(z)}{t}$$

Kills the compensation outside the soft limit

Small absolute size of compensation

$$\zeta = \begin{cases} z & \text{for splittings with a } 1/z \text{ singularity} \\ 1-z & \text{for splittings with a } 1/(1-z) \text{ singularity} \\ \min(z,1-z) & \text{for splittings with a } 1/(z(1-z)) \text{ singularity} \end{cases}$$



S. Mrenna & PS: PRD94(2016)074005; arXiv:1605.08352

HOW MANY PARAMETERS TO VARY?

There is of course only a single α_s in nature

But remember we are here just using scale variations as a stand-in for unknown higher-order terms.

ISR and FSR kernels receive different NLO corrections

Physically, ISR also has additional ambiguity tied to the PDF

ISR and FSR have different phase spaces and affect physical observables differently

- FSR: jet shapes, OOC, heavy-flavour parton energy loss, …
- ISR: Recoils to hard system; Soft ISR increases overall H_T. Hard ISR → N_{Jets}.

I therefore conceive of ISR and FSR variations as separate things

(Yes, there are overlapping cases, most obviously when colour flows from initial to final state, as in ttbar: initial-final antennae, and also for subleading colour effects.)

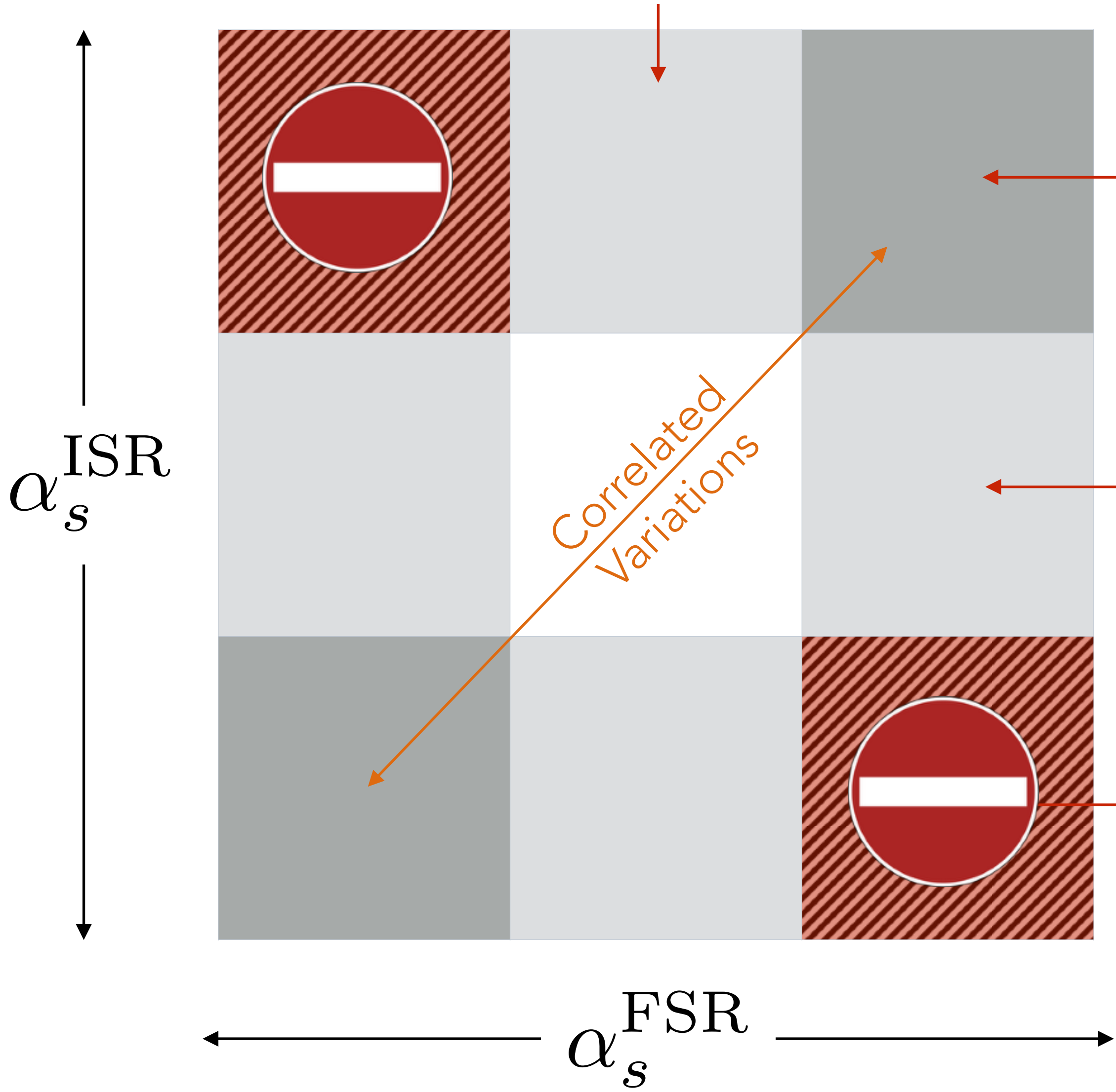
Not to forget (but not main topics of this talk):

PDFs, functional form of central choices of factorisation and renormalisation scales, nonsingular parameters, subleading colour, local vs global recoils …

Correlated or Uncorrelated?

What I would do: **7-point variation** (resources permitting → use the automated bands?)

Increasing only ISR
➠ More H_T and N_{jets}; similar core jet shapes



Increasing both ISR and FSR
➠ More H_T in the events.
➠ More OOC loss (from FSR) but also more H_T and more hard ISR jet seeds → partial cancellation in N_{jets}?

Increasing only FSR
➠ More OOC loss (FSR jet broadening), acting on similar number of seed partons (no increase in ISR).
➠ Similar H_T

Increasing FSR, Decreasing ISR
➠ Double counting? Fewer ISR partons, **and** more smearing of those that remain. *(Easy to rule out?)*
➠ Also from theoretical/mathematical point of view, the artificially induced discrepancy is now proportional to ln(16) = 2.8 instead of ln(4) = 1.4.

Note: I would also do splitting-kernel variations (see extra slides)

AUTOMATED SHOWER UNCERTAINTY BANDS/WEIGHTS

Mrenna, Skands Phys.Rev. D94 (2016) 074005

Idea: perform a shower with nominal settings

Ask: what would the probability of obtaining this event have been with **different choices** of μ_R, radiation kernels, … ?

Easy to calculate **reweighting factors**

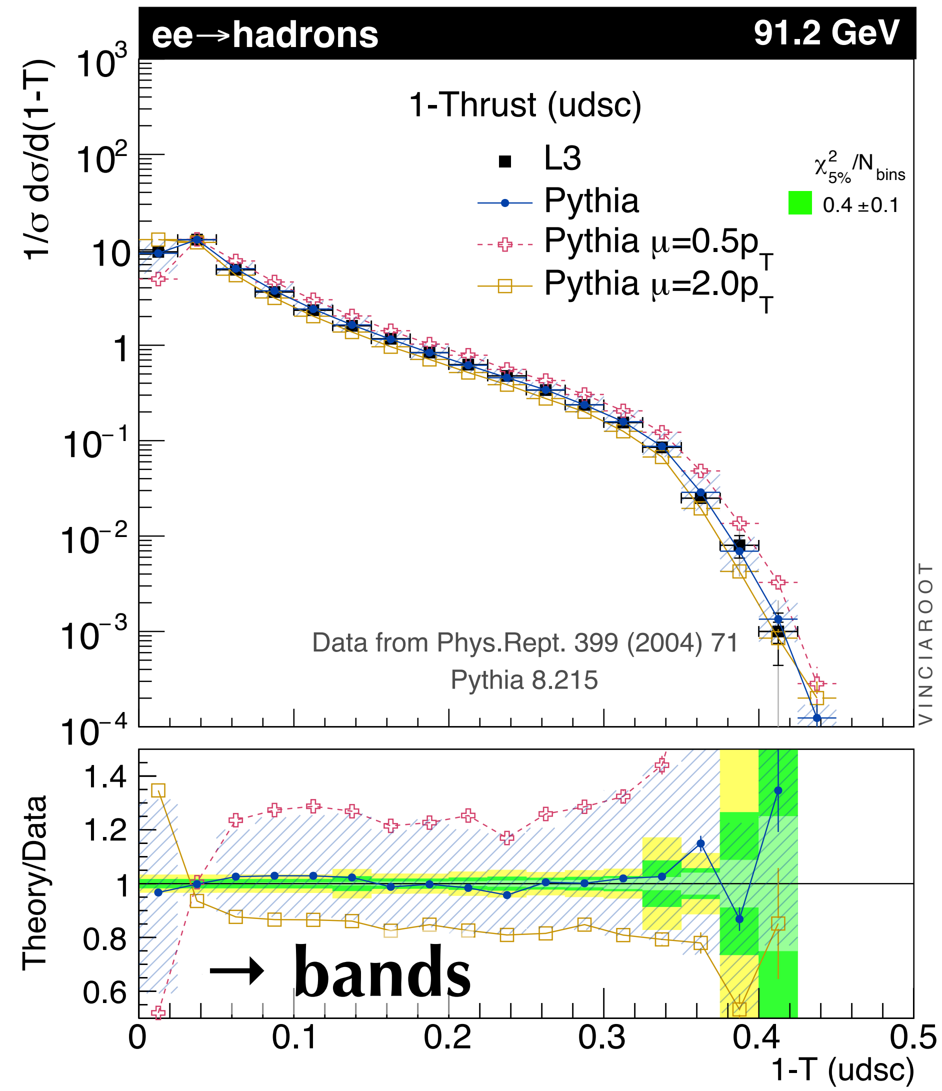
In MC accept/reject algorithm:

for **all** branchings

∀ *Accepted Branchings:* $$R'_{\rm acc}(t) = \frac{P'_{\rm acc}(t)}{P_{\rm acc}(t)}$$

∀ *Rejected Branchings:* $$R'_{\rm rej}(t) = \frac{1 - P'_{\rm acc}(t)}{1 - P_{\rm acc}(t)}$$

Giele, Kosower, Skands PRD84 (2011) 054003



Output: **vector of weights** for each event

One for the nominal settings (unity)

+ Alternative weight for each variation

(Note: similar functionality also in Herwig++ and Sherpa; see 1605.08256 1606.08753)

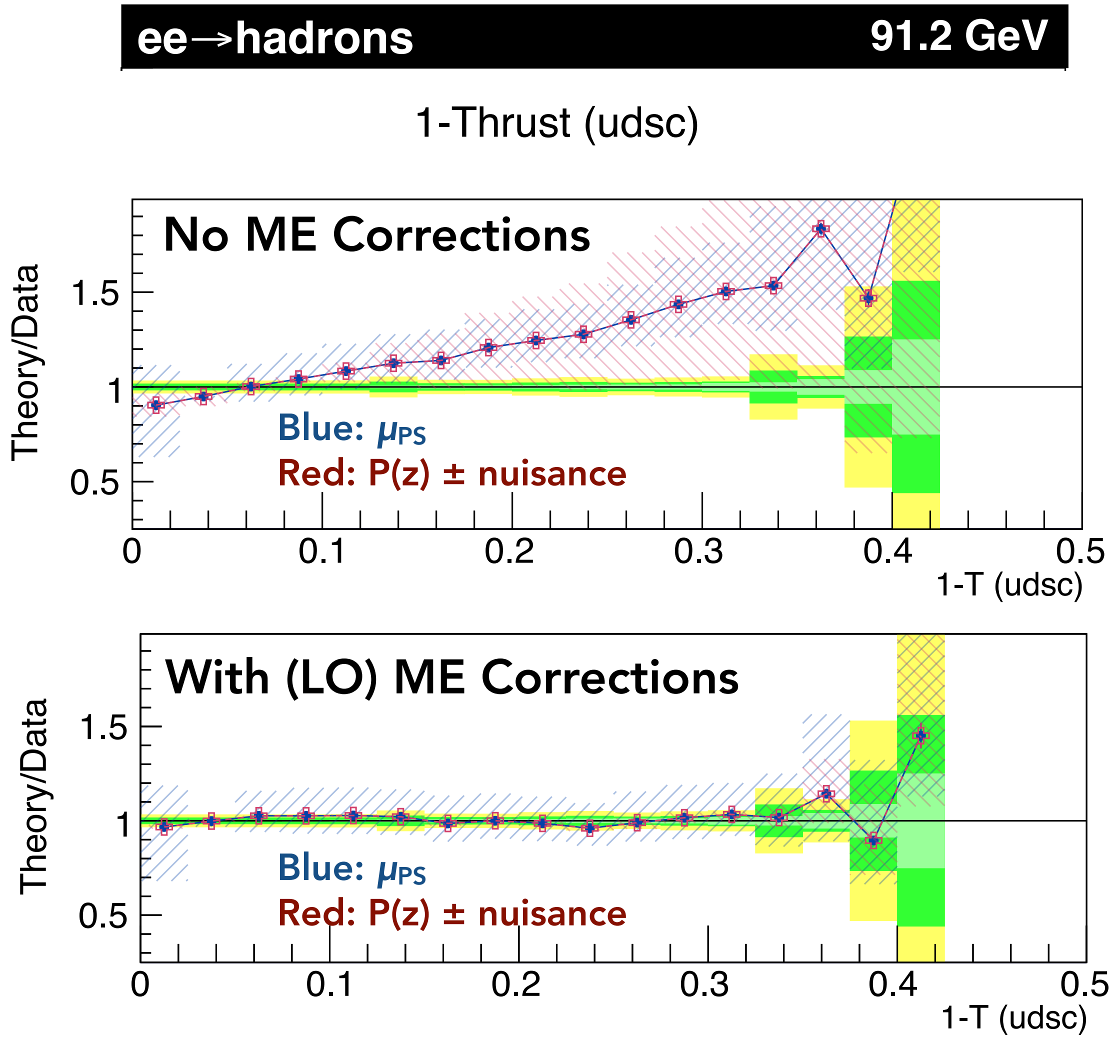
How to test if "More" ME Corrections needed?

The soft and collinear enhanced (singular) terms in the shower kernels are universal, process-independent

Matrix Elements contain the same information, plus process-specific **non-singular** terms.

The shower singularities dominate for soft and collinear radiation

The process-specific non-singular terms dominate for hard radiation



VINCIA: Giele, Kosower & PS: PRD84(2011)054003; arXiv:1102.2126

PYTHIA 8: S. Mrenna & PS: PRD94(2016)074005; arXiv:1605.08352

Suggestion: add nuisance parameter = arbitrary nonsingular term to shower kernels, and **vary** to estimate sensitivity to missing ME terms

Note: by definition, any fit of such a nuisance parameter would be process-specific

AUTOMATED SHOWER UNCERTAINTY BANDS/WEIGHTS

Mrenna, Skands Phys.Rev. D94 (2016) 074005

The benefits: only a single sample needs to be generated, hadronised, passed through detector simulation, etc.

Can add arbitrarily many (combinations of) variations (if supported by code)

The drawback: effective statistical precision of uncertainty bands computed this way (from varying weights) is always less than that of the central sample (which typically has all weights =

(Note: similar functionality also in Herwig++ and Sherpa; see 1605.08256 1606.08753)

7-Point scale variations

Based on factor-2 variations with NLO soft compensation term ON

+ some nonsingular-term variations to estimate sensitivity to process-dependent finite terms (signaling need for further ME correcti

```
UncertaintyBands:doVariations = on
UncertaintyBands:muSoftCorr = on
UncertaintyBands:List = {
  radHi fsr:muRfac=0.5 isr:muRfac=0.5,
  fsrHi fsr:muRfac=0.5,
  isrHi isr:muRfac=0.5,
  radLo fsr:muRfac=2.0 isr:muRfac=2.0,
  fsrLo fsr:muRfac=2.0,
  isrLo isr:muRfac=2.0,
  fsrHardHi fsr:cNS=2.0,
  fsrHardLo fsr:cNS=-2.0,
  isrHardHi isr:cNS=2.0,
  isrHardLo isr:cNS=-2.0
}
```

Note: the soft compensation term may be too conservative especially for ISR
We'd welcome feedback on

CR: Recommendations

Pythia Default CR Model

LC structure of hard process **always preserved** as "backbone" of non-perturbative string topology

With probability defined by strength parameter, partons from MPI are (or are not) allowed to be added as kinks on this structure

Decent starting point, but in context of uncertainties even on/off variation does not span space of physical possibilities, even with ERD on/off.

Recommend to include **at least one of** the alternative models

QCD-inspired: allows stochastic sampling of possibilities beyond LC.

- Qualitatively different from default model
- Generally still predicts reasonably small effects.
- Not designed to be extreme: conservative enough as variation?

Gluon-Move etc: More "brute force" changes to topologies, some of which are intentionally designed to be extreme. Can have very large effects.

Comments on b fragmentation

Skands, Carazza, Rojo, Eur.Phys.J. C74 (2014) no.8, 3024

The Monash tune for heavy flavour [see section 2.3]

Constrained by **LEP event shapes** (incl b tagged), jet rates + particle rates

➤ Relatively large value of TimeShower:alphaSvalue = 0.1365

Regarded at least in part as making up for NLO K-factor for ee→3 jets (Pythia only accurate to LO for 3 jets).

Consistent with 3-flavour Λ_{QCD} ~ 0.35 GeV (since we use 1-loop running)

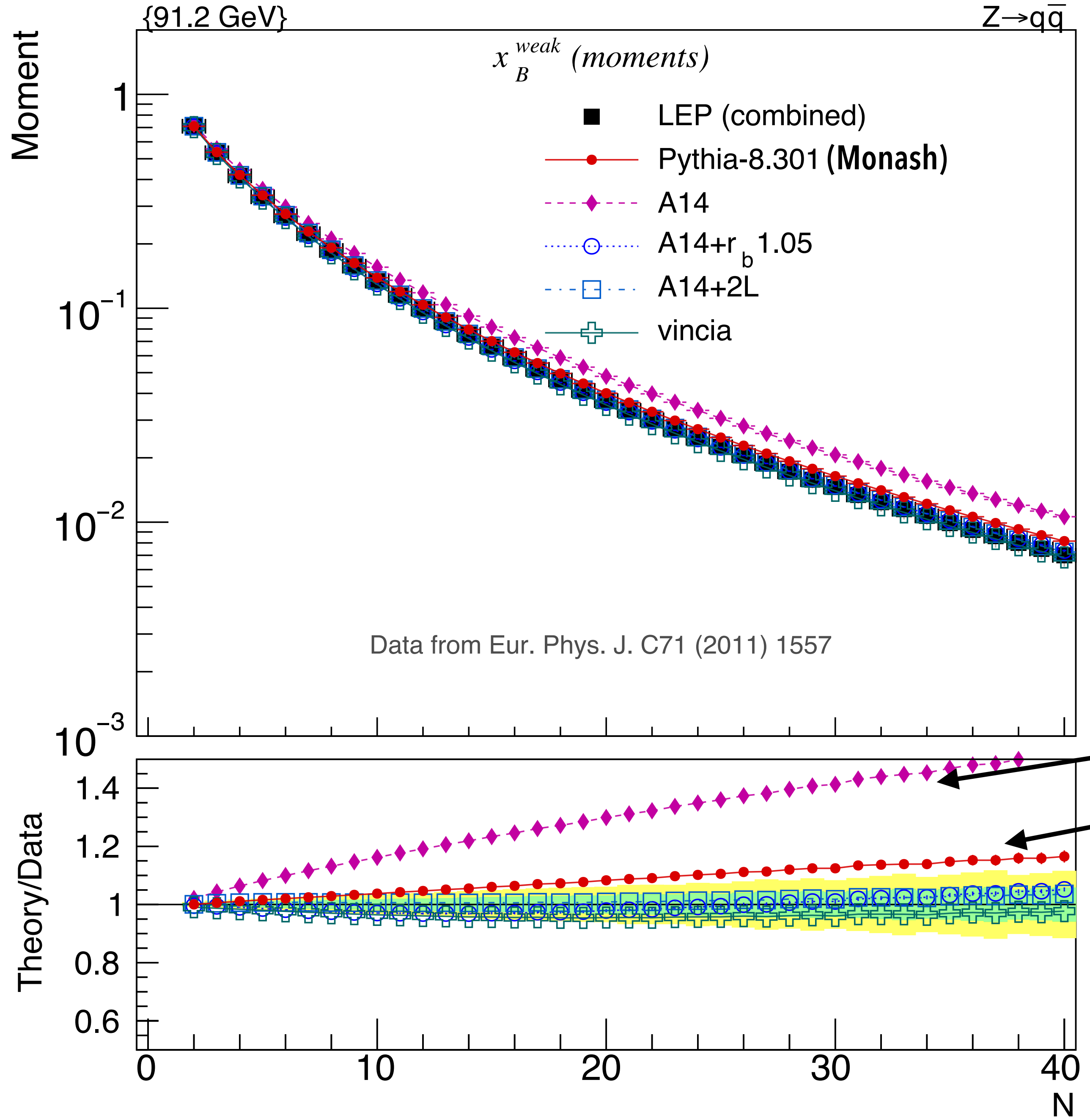
Not guaranteed to be universal. LHC studies tend to prefer lower values

E.g., **A14** uses TimeShower:alphaSvalue = 0.129 (could be reinterpreted via CMW to MSbar alphaS(mZ) ~ 0.12 so consistent with world average.)

(but I would then also change to 2-loop running; would preserve Λ_{QCD} value)

Non-Perturbative b-fragmentation parameter r_b constrained by measured x_B spectra of weakly decaying B hadrons.

➤ StringZ:rFactB = 0.88. Unrealistic to constrain to better than 10% without careful studies of correlations with other NP parameters (eg Lund a, b, sigmaPT, and alphaS values), global observables, LEP ⟷ LHC checks, etc.
(And even then, there is an a priori theory/modelling uncertainty.)



Moments of x_B distribution

(easier / clearer to look at than spectrum itself)

Question: possible to do in-situ constraints or at least cross checks in top / inclusive b / … at LHC?

Lower α_S ➤ B spectrum too hard

(Monash; deliberately slightly hard for global reasons)

Increasing r_b (0.88→1.05) **or** changing to 2-loop running. Both reestablish agreement **but will scale differently**

Also note: lower value of $\alpha_s(M_Z)$ ➤ **lower 3-jet rate**

➤ wrong 2- vs 3-jet mixture (relative to data sample)? **Do reweighting?**

Using a lower value of $\alpha_s(M_Z)$: what happens?

Option 1. Keep 1-loop running ➤ lower value of Λ_{QCD}

Different IR limit of shower ➤ retune (all) non-perturbative parameters.

Problem: lower value of $\alpha_s(M_Z)$ ➤ **lower 3-jet rate**. Cannot tune to data that includes 3-jet events (like inclusive x_B) without separate 3-jet correction; do reweighting for 3-jet rate (or NLO merging).

Or: could use x_B from sample of excl 2-jet events (3-jet veto), but I am not aware that such conditional x_B spectra were measured? Could they be?

Or: if your new $\alpha_s(M_Z)$ value describes LHC jet shapes well, could you constrain r_b *in-situ* from $b \to B$ measurements at LHC?

Option 2. Change to 2-loop running ➤ keep Λ_{QCD} ~ unchanged

➤ Reduced need to retune (though **precision** would still require retuning)

(E.g. VINCIA uses CMW with alphaSvalue = 0.118, 2-loop running, and $\mu_R = 0.8 p_T$)

Recommendations: (t→)b→B fragmentation

Perturbative stage is important in the context of (re)tuning.

Hard process + showers + merging: **b(Q_F) → b(Q_{cut})**

Non-perturbative parameters (HAD+MPI+CR): **b(Q_{cut}) → B**

These two components **scale differently**. Non-universal to force the latter to make up for shortcomings in the former.

At LEP, amount of perturbative radiation emitted from *b* can be validated / controlled by 3-jet rate *(in b-tagged events)*

In top events, presumably *b*-jet substructure and/or rate of additional jets "near" the *b*-jet can be used to check if the b is losing the "right" amount of energy from perturbative radiation?

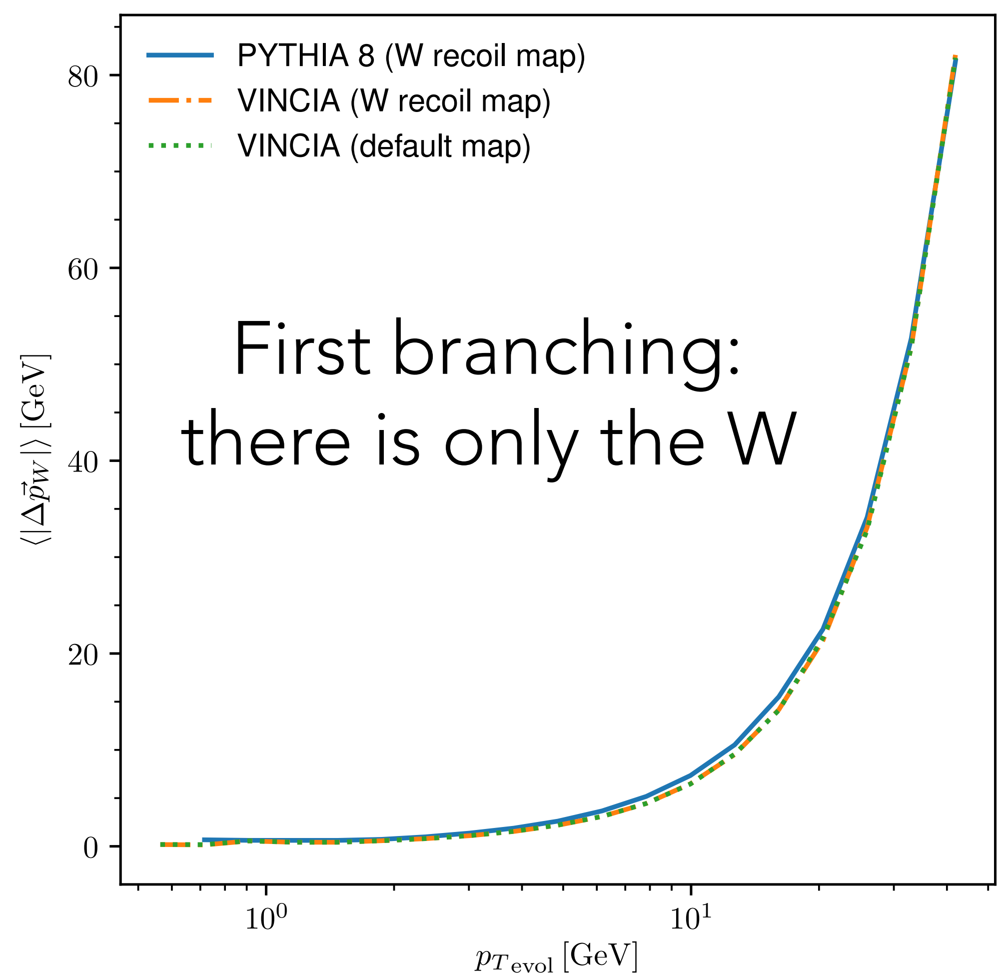
Constrain r_b in-situ? x_B spectra in inclusive *b* jets?

Lesson from LEP: process-dependent factors (eg NLO 3-jet rate) can affect precision tuning ➤ larger uncertainties if not carefully controlled.

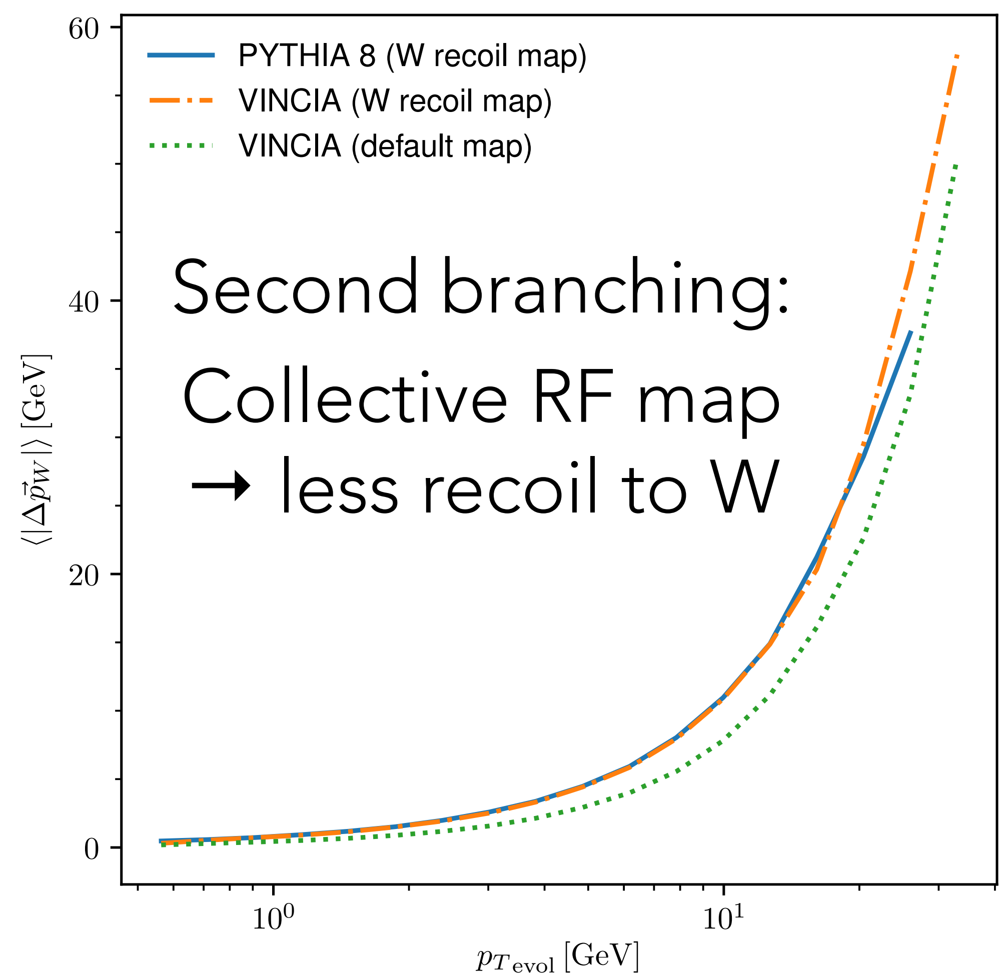
Effect of Kinematics Map

Consider average recoil $|\Delta\vec{p}_W|$, after first and second emission(s).

Recoil after first:

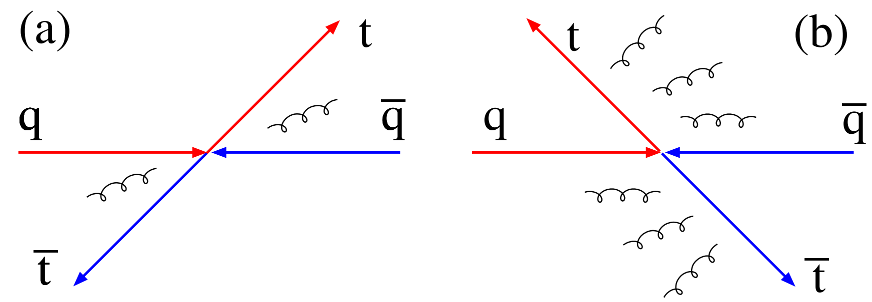


Recoil after second:



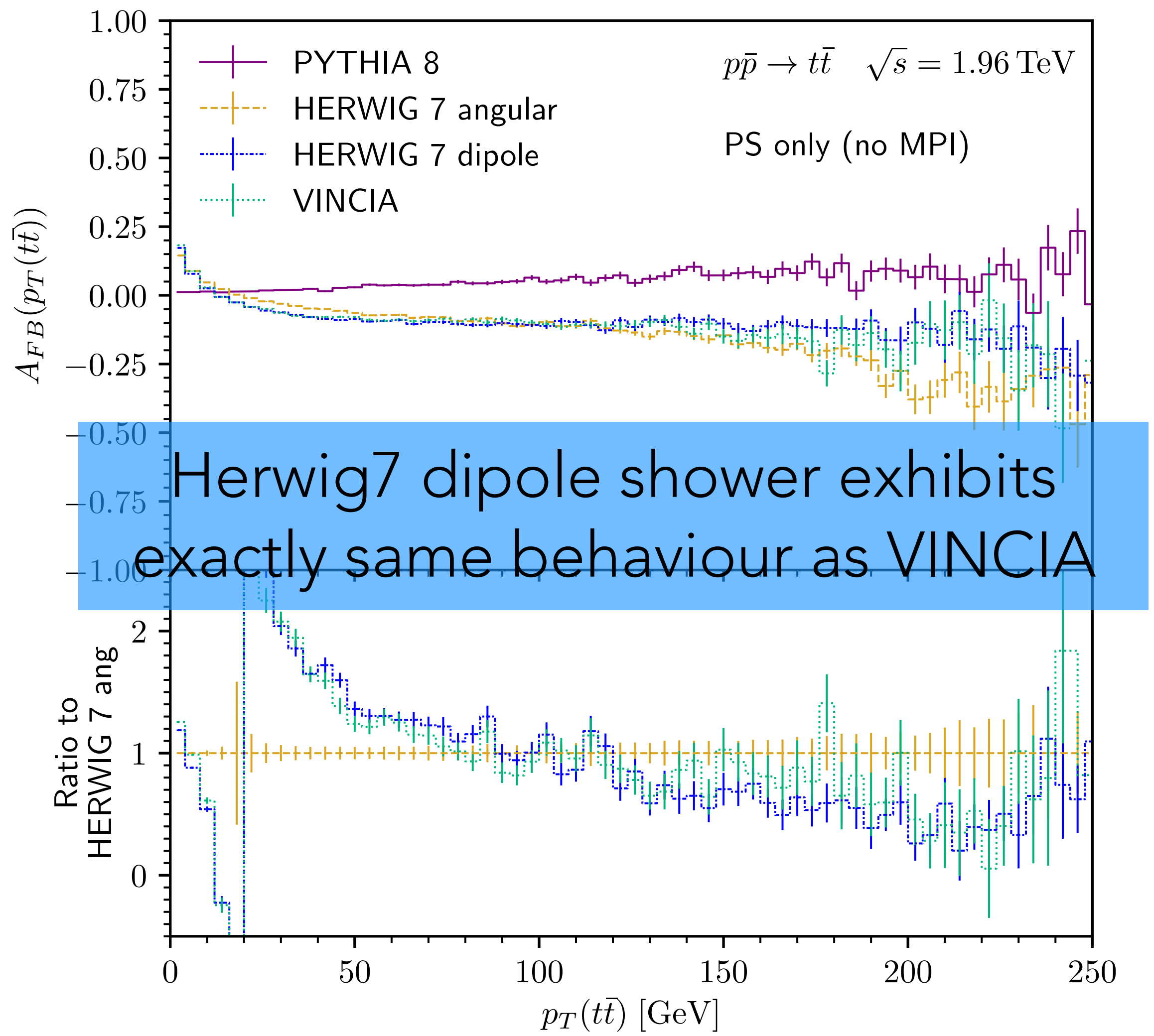
(Coherence In Production)

Well-studied effect in p-pbar collisions
Top quark FB asymmetry



PS, Webber, Winter JHEP 1207 (2012) 151

Coherent showers produce a p_T-dependent asymmetry



Herwig7 dipole shower exhibits exactly same behaviour as VINCIA

Forward-backwards asymmetry:

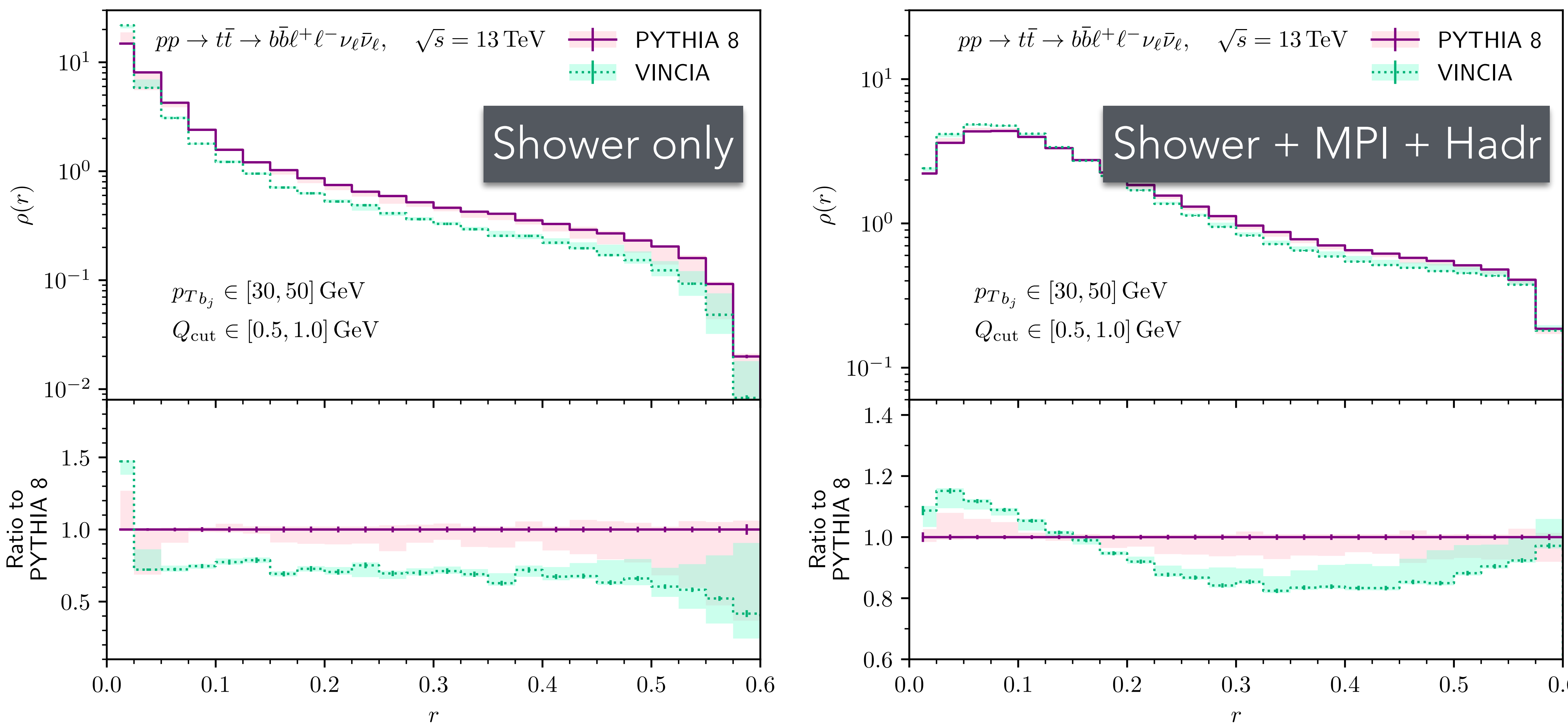
$$A_{FB}(\mathcal{O}) = \frac{\left.\frac{d\sigma}{d\mathcal{O}}\right|_{\Delta y>0} - \left.\frac{d\sigma}{d\mathcal{O}}\right|_{\Delta y<0}}{\left.\frac{d\sigma}{d\mathcal{O}}\right|_{\Delta y>0} + \left.\frac{d\sigma}{d\mathcal{O}}\right|_{\Delta y<0}}$$

Coherent showers include part of the real emission correction that generates a FB asymmetry that becomes negative for large $p_T(t\bar{t})$. [1205.1466]

VINCIA gives narrower b-jets than Pythia 8

Effect survives MPI + hadronisation

Differential jet shape ρ(r)



Tentative conclusion: more coherence ~ more wide-angle suppression?

*Also agrees with intuition from dipole language where "top dipole" can be negative

Top Mass Profile @ 8 TeV : Parton Level

Slide from H. Brooks

Brooks, Skands, Phys.Rev. D100 (2019) no.7, 076006 ARXIV:1907.08980

$p\bar{p} \to t\bar{t}$ @ 8 TeV: $m_{b_j \ell \nu}$

Monte-Carlo "truth" (parton-level) analysis:

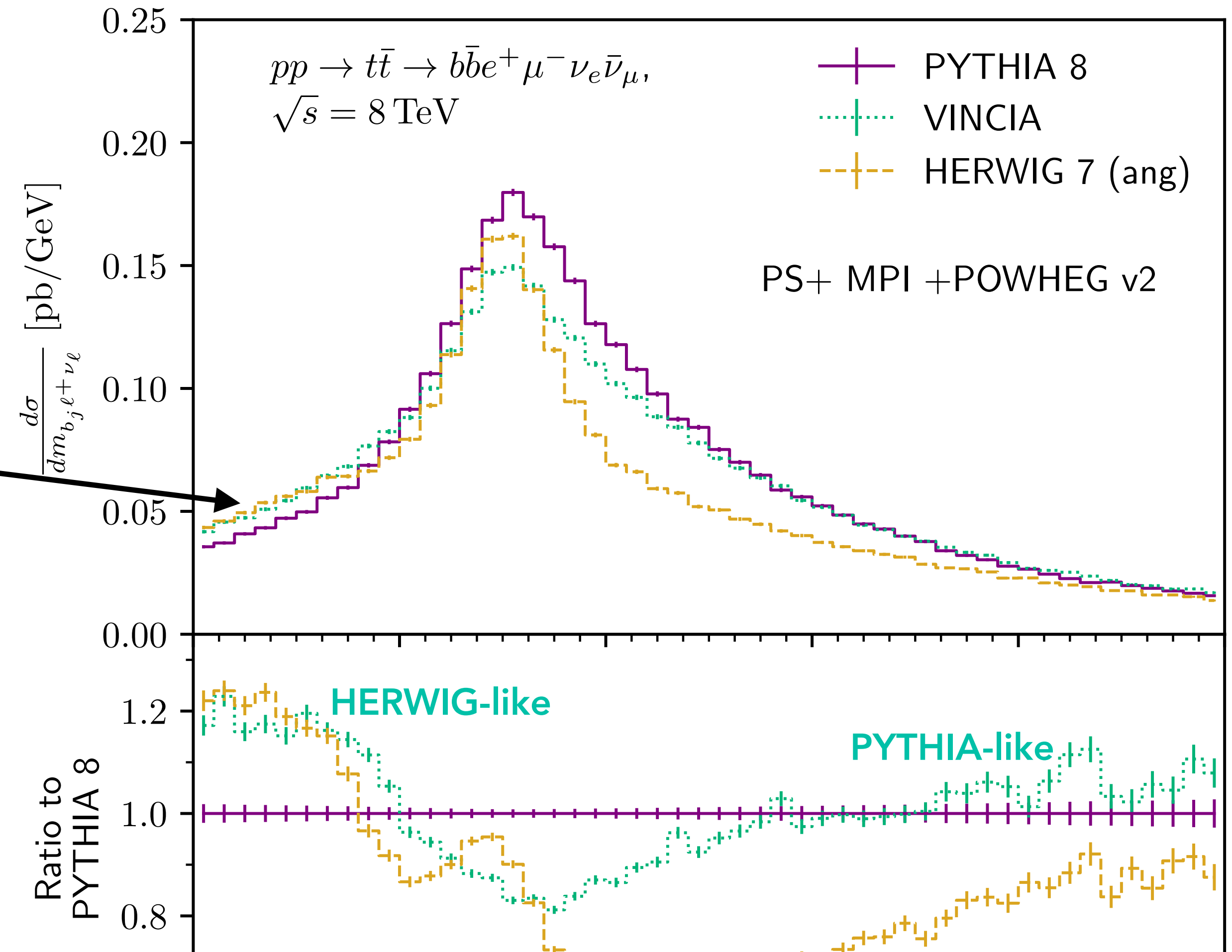
- Assumes we can reconstruct p_ν and match correct ℓ, b_j pair.

Pythia has little population in the low tail. Ascribed to an artificially small phase space (due to a non-coloured dipole) from the 2nd emission onwards.

Many subtleties related to this, especially when combined with POWHEG.

Commented on and illustrated extensively in arXiv:1907.08980

"Cured" in VINCIA.



VINCIA

~ HERWIG-like below m_t

~ PYTHIA-like above m_t

PYTHIA 8.301 released. Includes VINCIA with new resonance-final showers

Not yet recommended for main production runs, but need your feedback.

Still to come in VINCIA: multi-leg MECs, automated uncertainty bands, production-decay interference, electroweak showers, NLO antenna functions,…

Top Mass Profile @ 8 TeV

$p\bar{p} \to t\bar{t}$ @ 8 TeV: $m_{b_j\mu}$ (example of a realistic observable)

Full hadron-level analysis: choose pairing for ℓ, b_j that minimise average mass.