Coherent Showers
In Decays of Coloured Resonances

Based on arXiv:1907.08980

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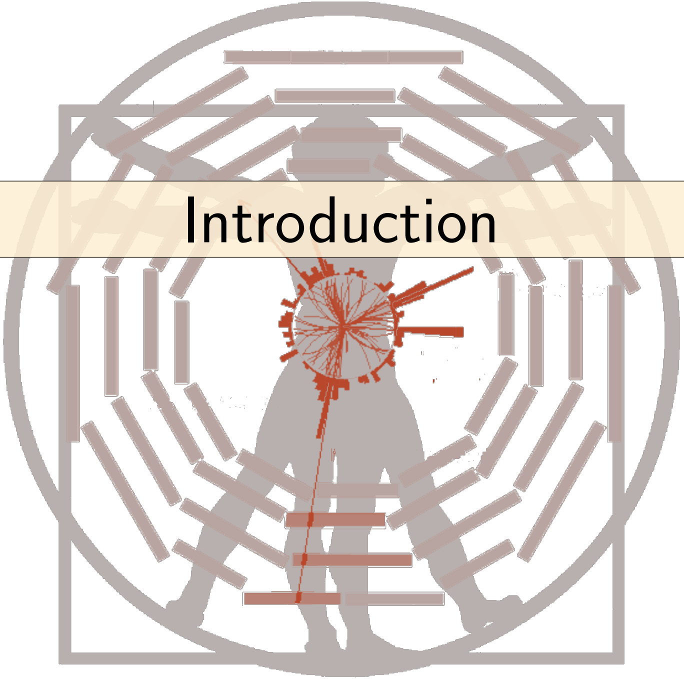
MONASH University

Wed 24th July 2019 - BOOST - MIT, Boston

Introduction



Prologue

...or why you should listen to this talk

- It's no secret that general-purpose event generators are very powerful
  $\rightarrow$ "known-knowns"

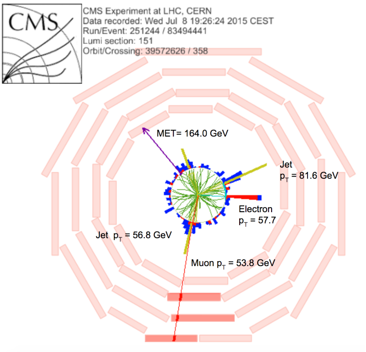
  [e.g. @BOOST - signal and background modelling, training input for taggers and ML algorithms]

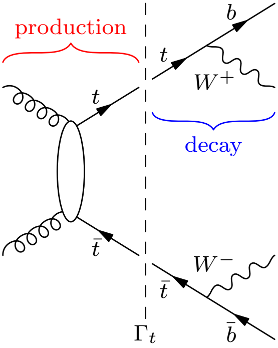
- However, if we do not estimate uncertainties, we cannot assess robustness of theoretical predictions
  $\rightarrow$ "unknown-unknowns"

- Even better: disentangle different sources of uncertainties
  $\rightarrow$ "known-unknowns"

- This way, identify (1) prospects for tuning, and (2) areas where perturbative improvements are needed.
  $\rightarrow$ move towards "knowns"

Coherence Showers in Resonance Decays





Most people here: goal is to find new and improved ways to discriminate boosted objects from background (my naive intepretation)

This talk: goal is to improve modelling of radiation produced in decay of (coloured) resonances by including coherence.

→ Potential implications for e.g. b-taggers

A case study: arXiv:1801.03944

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

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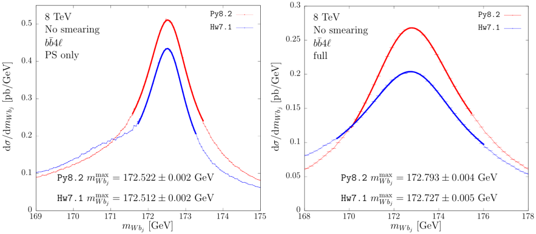


"... the very minimal message that can be drawn from our work is that, in order to assess a meaningful theoretical error in top-mass measurements, the use of different shower models, associated with different NLO+PS generators, is mandatory."

Theoretical uncertainties

...and how to estimate them

Perturbative (missing higher orders)

- Fixed-order accuracy (vary μ_R), PDFs (vary μ_F), Matching ambiguities (vary matching/merging scales e.g. h_{damp})
- Renormalon ambiguity $\rightarrow$ should be small?
- Parton shower ambiguities arising from logarithmic accuracy, e.g. splitting functions, recoil strategy, evolution variables... $\rightarrow$ different choice of shower?

Non-perturbative

- Colour-reconnection
- MPI, and beam remnant treatment
- Hadronisation

$\rightarrow$ estimate NP by using *qualitatively* different models, e.g. string versus cluster hadronisation, in addition to varying internal parameters.

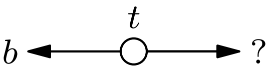
Antennae v. Dipoles for Resonance Decays

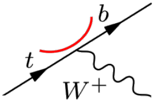
Dipole showers (e.g. PYTHIA)

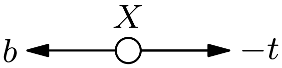
- In each branching, identify "radiator" and "recoiler"
- Neglect contribution from resonance as radiator (partition can actually become negative).
- In principle free to choose recoiler, e.g. W in $t \to Wb$
- Sharp transition in kinematics

Antenna showers (e.g. VINCIA)

- Are agnostic as to who is the radiator: coherence built in
- Cannot neglect resonance's contribution
- Recoil strategy relates to antenna factorisation
- Smooth transition in kinematics (interpolates between collinear limits)







[For current status of alternative showers, see backup.]

Defining the Resonance-Final Antenna Shower

Checklist:

- ☑ Resonance-Final (RF) antenna factorisation
- ☑ Kinematics map
- ☑ RF antenna functions
- ☑ Evolution Variables
- ☑ Trial integral [see backup]

Phase Space Factorisation

- No-emission prob: $\exp\{-\int \mathrm{d}\Phi_{\mathrm{ant}} 4\pi\alpha_s \mathcal{C}\bar{a}\}$ $\bar{a}$: colour coupling stripped antenna function
- Phase space: $\mathrm{d}\Phi_{n+1} = \mathrm{d}\Phi_{\mathrm{ant}}\mathrm{d}\Phi_n$

For the decay $A \to K\{X\}$ (before), $a \to jk\{X'\}$ (after)

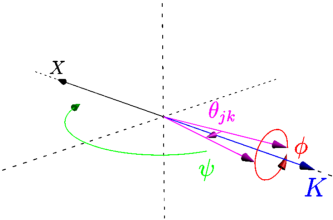
$$\mathrm{d}\Phi_{\mathrm{ant}} = \frac{1}{16\pi^2}\frac{\mathrm{d}s_{aj}\mathrm{d}s_{jk}}{\lambda^{1/2}(m_A^2, m_{AK}^2, m_K^2)}\frac{\mathrm{d}\phi}{2\pi}\ .$$

N.B.: $s_{\alpha\beta} \equiv 2p_\alpha \cdot p_\beta$ throughout!

- Factorisation is exact, not just in soft, collinear limits
- Preserves invariant mass of resonance: $p_A = p_a$
- Preserves invariant mass of **system of recoilers**: $m_{AK}^2 = (p_A - p_K)^2 = (p_a - p_j - p_k)^2$

Kinematic Map (recoil strategy)

- Construct in A rest frame.
- X only recoils longitudinally.
- Rotate about K by ϕ (flatly sampled).
- Boost back to lab frame.
- For each recoiler $i \in X$, boost p_i by $p_{X'} - p_X$



Note!

If we fix to just one recoiler i.e. $A \to RKX$, $a \to rjkX$ then **CANNOT** simulatenously preserve m_A^2, m_R^2 and m_{AK}^2.

- Antenna mass is modified!
- Phase space normalisation is modified!
- Mass used everywhere is $(p_A - p_X)^2$ - not same as propagator!

Antenna Functions: generic form

Define massless invariants:

$$y_{aj} \equiv s_{aj}/(s_{AK}+s_{jk}), \qquad \mu_a^2 \equiv m_a^2/(s_{AK}+s_{jk}), \qquad \text{etc.}$$

$$a^{RF}_{\text{emit}} = \frac{1}{s_{AK}}\left[\frac{(1-y_{aj})^n+(1-y_{jk})^2}{y_{aj}y_{ak}} - \frac{2\mu_a^2}{y_{aj}^2}(1-f_k(y_{aj},y_{jk})) - \frac{2\mu_k^2}{y_{jk}^2}(1-g_k(y_{aj},y_{jk})) + h_k(y_{aj},y_{jk})\right]$$

$$a^{RF}_{\text{split}} = \frac{1}{2m_{jk}^2}\left[y_{ak}^2+y_{aj}^2+\frac{2m_j^2}{m_{jk}^2}\right]$$

where $n=2$ if $k=q$ and $n=3$ if $k=g$.

- f_k, g_k, h_k are polynomials in y_{aj},y_{jk} which vanish in the soft-collinear limits, chosen such that all helicity-dependent antennae are positive-definite over the full phase space. [For full details, see backup.]

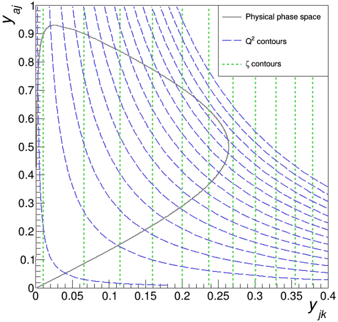
Evolution Variables

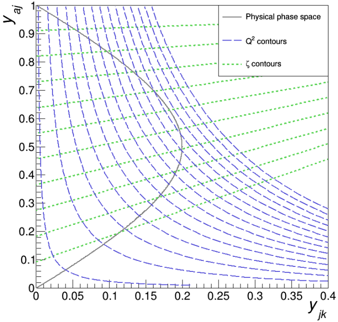
Emissions:

$$Q^2_{\text{evol}} = \frac{s_{aj}s_{jk}}{s_{jk}+s_{AK}}$$
$$\zeta = \frac{s_{jk}+s_{AK}}{s_{AK}}$$

Splittings:

$$Q^2_{\text{evol}} = \frac{(s_{jk}+2m_q^2)(s_{aj}-m_q^2)}{s_{AK}+s_{jk}+2m_q^2}$$
$$\zeta = \frac{s_{ak}}{s_{AK}}$$



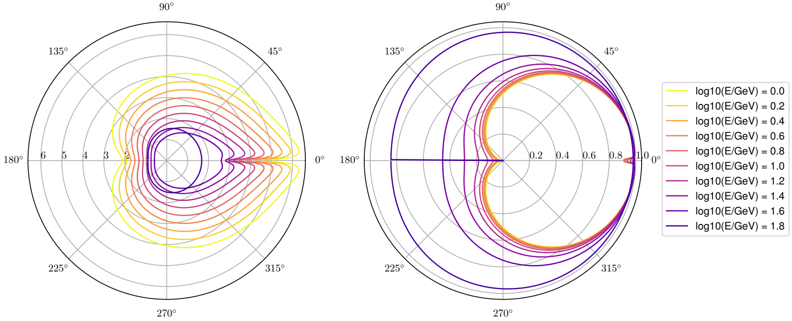


Results

- ☑ Resonances now implemented in VINCIA, with coherent "resonance-final" antennae

Coherence In $t\bar{t}$ Decay

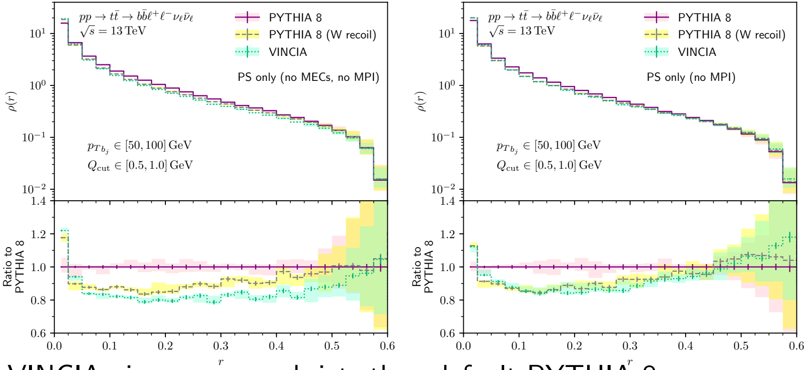
Plot antenna function in top centre of mass frame (b at 0°) as funtion of θ_{gb}: left $r = \log_{10}(a^{RF}_{g/qq} s_{AK})$, right $r = \frac{a^{RF}_{g/qq}}{P_{gq}(z)/Q^2}$.



Antenna function is consistent with Altarelli-Parisi splitting function in (quasi-)collinear direction, coherence results in a suppression in the backwards direction.

b-jet Profiles

$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N_{\text{jets}}}\sum_{\text{jets}}\frac{p_\perp(r-\Delta r/2, r+\Delta r/2)}{p_\perp(0,R)}$$

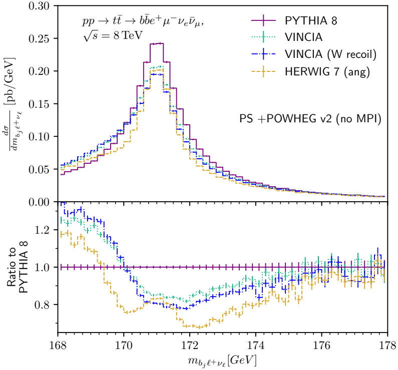


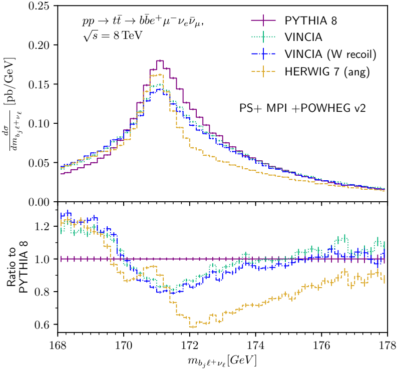
- VINCIA gives narrower b-jets than default PYTHIA 8.
- Coherence / MECs and kinematic map plays a role.
- Effect also survives MPI + hadronisation → tuning prospects?

$pp \to t\bar{t} \to b\bar{b}e^+\bar{\nu}_e\mu^-\nu_\mu, \sqrt{s} = 8$ TeV: $m_{b_j\ell\nu}$

Monte-Carlo "truth" (parton-level) analysis (assumes can reconstruct p_ν, match correct ℓ, b_j pair):

- Low mass region: sensitive to out-of-cone radiation (MECs, coherence, kinematic map).
- High mass region: sensitive to underlying event (MPI)

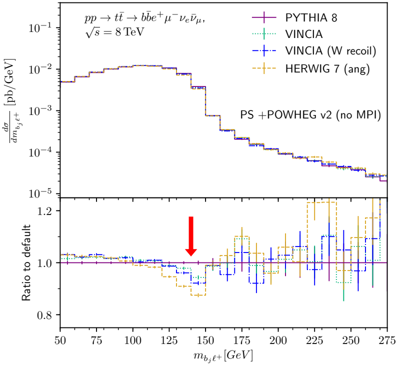


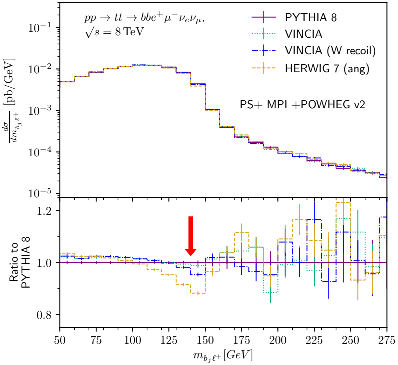


$pp \to t\bar{t} \to b\bar{b}e^+\bar{\nu}_e\mu^-\nu_\mu, \sqrt{s} = 8$ TeV: $m_{b_j\ell}$

Slightly more realistic observable, but still need ℓ, b_j pair.

- Note: endpoint - used when fitting MC to data to extract top quark mass.





Conclusions / Outlook

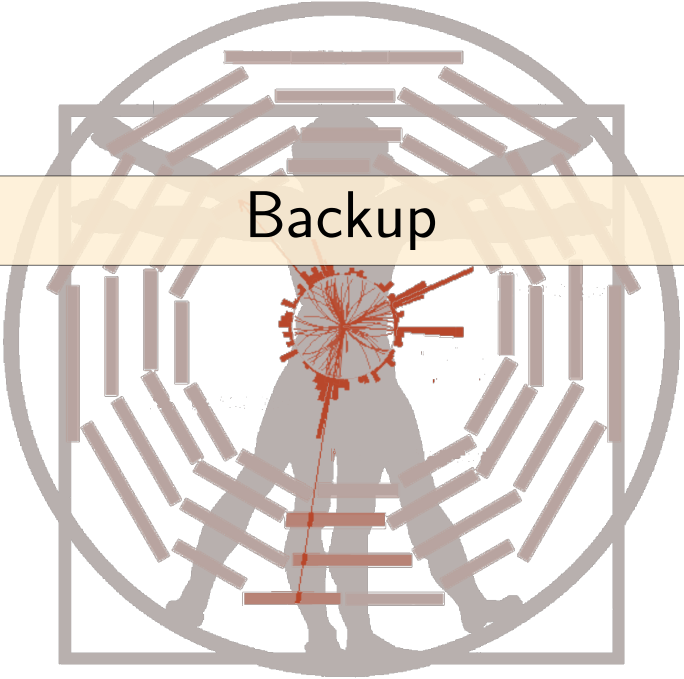
- Antenna-showers for resonance decays have been implemented for VINCIA, a plug-in to PYTHIA.
- Many formally leading-log showers: important to perform shower variations to obtain **realistic estimates of theoretical uncertainties.**
- Clearly strong motivation for **further developments in parton showers.**

Coming soon...

PYTHIA 8.3

→ Watch this space!

Backup



What are all these different showers anyway?

Type	Singularities		Coherence?	No dead zones?	Examples
	soft	collinear			
DGLAP	part.	full	✗	✗	
Angular	full+veto	full+veto	✓	✗	H7 $\tilde{q}$
Dipole	part.	part.	✗	✓	Pythia 8
C-S dip	part.	part.	✓	✓	Sherpa, H7 dip
Antenna (global)	full	part.	✓	✓	Vincia
Antenna (sector)	full	full+veto	✓	✓	Vincia

[**Disclaimer:** Not an exhaustive list.]

Sum over all dipoles should reproduce the correct leading log at LC.

Current Status of Resonance Decays In Showers

Shower	Type	Decay shower?	Coherence?
Pythia 8 [hep-ph/0010012] [hep-ph/0408302]	Dipole	✓	✗ (Improved by MECs)
Sherpa [1412.6478]	C-S dipole	✓ (Res. participates in prod. only)	(✓)
Herwig 7 ($\tilde{q}$) [1810.06493]	Angular-ordered	✓ (Has dead zones)	✓
Herwig 7 (dip) [1810.06493]	C-S dipole	(✓) (Only FI, on-shell res only)	(✓)
Vincia - **NEW!** [1907.08980]	Antenna	✓	✓

Example: qq antenna limits

Can rewrite antenna as:

$$a^{RF}_{g/qq} = \frac{1}{s_{AK}} \left[\underbrace{\frac{2y_{ak}}{y_{aj}y_{jk}} - \frac{2\mu_a^2}{y_{aj}^2} - \frac{2\mu_k^2}{y_{jk}^2}}_{\text{soft}} + \underbrace{\frac{y_{aj}}{y_{jk}} + \frac{y_{jk}}{y_{aj}}}_{\text{collinear}} + \text{n.s.} \right]$$

Define $Q^2 \equiv s_{jk}$; $\quad y \equiv \frac{Q^2}{s_{AK}}$; $\quad z \equiv \frac{s_{ak}}{s_{AK}} \quad \Rightarrow \frac{s_{aj}}{s_{AK}} = 1 + y - z$

$$a^{RF}_{g/qq} = \frac{1}{Q^2} \left[\frac{2z(1+y)}{1+y-z} + (1+y-z) - \frac{2m_k^2}{Q^2} + \mathcal{O}(y) \right] + \text{n.s.}$$

In collinear limit, $y \to 0$

$$\lim_{y \to 0} a^{RF}_{g/qq} = \frac{1}{Q^2} \left[\frac{1+z^2}{1-z} - \frac{2m_k^2}{Q^2} \right] = \frac{1}{Q^2} P_{q \to gq}(z, \tilde{\mu})$$

N.B. Need to sum over neighbouring antennae for gg collinear limit.

Helicity-dependent antennae: $QQ \to QgQ$

$$a(++\to+++) = \frac{1}{s_{AK}}\left[\frac{1}{y_{aj}y_{jk}} - \frac{\mu_a^2}{y_{aj}^2} - \frac{\mu_k^2}{(1-y_{aj})y_{jk}^2}\right],$$

$$a(++\to+-+) = \frac{1}{s_{AK}}\left[\frac{(1-y_{aj})^2+[(1-y_{jk})^2-1](1-y_{aj})^2}{y_{aj}y_{jk}} - \frac{\mu_a^2(1-y_{jk}-y_{aj})^2}{y_{aj}^2} - \frac{\mu_k^2(1-y_{aj})(1-y_{jk})^2}{y_{jk}^2}\right],$$

$$a(++\to--+) = \frac{1}{s_{AK}}\left[\frac{\mu_a^2 y_{jk}^2}{y_{aj}^2}\right],$$

$$a(++\to++-) = \frac{1}{s_{AK}}\left[\frac{\mu_k^2 y_{aj}^2}{(1-y_{aj})y_{jk}^2}\right],$$

$$a(+-\to++-) = \frac{1}{s_{AK}}\left[\frac{(1-y_{aj})^2}{y_{aj}y_{jk}} - \frac{\mu_a^2(1-y_{aj})}{y_{aj}^2} - \frac{\mu_k^2(1-y_{aj})}{y_{jk}^2}\right],$$

$$a(+-\to+--) = \frac{1}{s_{AK}}\left[\frac{(1-y_{jk})^2}{y_{aj}y_{jk}} - \frac{\mu_a^2(1-y_{jk})^2}{y_{aj}^2} - \frac{\mu_k^2(1-y_{jk})^2}{y_{jk}^2(1-y_{aj})}\right],$$

$$a(+-\to---) = \frac{1}{s_{AK}}\left[\frac{\mu_a^2 y_{jk}^2}{y_{aj}^2}\right],$$

$$a(+-\to+-+) = \frac{1}{s_{AK}}\left[\frac{\mu_k^2 y_{aj}^2}{y_{jk}^2(1-y_{aj})}\right].$$

Helicity-dependent antennae: $Qg \to Qgg$

$$
\begin{aligned}
a(++\to+++) &= \frac{1}{s_{AK}}\left[\frac{1}{y_{aj}y_{jk}} + (1-\alpha)\frac{1-2y_{aj}}{y_{jk}} - \frac{\mu_a^2}{y_{aj}^2}\right] , \\
a(++\to+-+) &= \frac{1}{s_{AK}}\left[\frac{(1-y_{aj})^3 + (1-y_{jk})^2 - 1}{y_{aj}y_{jk}}\right. \\
&\quad \left. -\frac{\mu_a^2(1-y_{jk}-y_{aj})^2(1-y_{aj})}{y_{aj}^2} + 3 - y_{aj}^2\right] \\
a(++\to--+) &= \frac{1}{s_{AK}}\left[\frac{\mu_a^2 y_{jk}^2}{y_{aj}^2}\right] \\
a(+-\to++-) &= \frac{1}{s_{AK}}\left[\frac{(1-y_{aj})^3}{y_{aj}y_{jk}} - \frac{\mu_a^2(1-y_{aj})^2}{y_{aj}^2}\right] , \\
a(+-\to+--) &= \frac{1}{s_{AK}}\left[\frac{(1-y_{jk})^2}{y_{aj}y_{jk}} + (1-\alpha)\frac{1-2y_{aj}}{y_{jk}} - \frac{\mu_a^2(1-y_{jk})^2}{y_{aj}^2} + 2y_{aj} - y_{jk}\right] \\
a(+-\to---) &= \frac{1}{s_{AK}}\left[\frac{\mu_a^2 y_{jk}^2}{y_{aj}^2}\right]
\end{aligned}
$$

Helicity-dependent antennae: $Xg \to X\bar{q}q$

$$
\begin{aligned}
a(X+ \to X-+) &= \frac{1}{2m_{jk}^2}\left[y_{ak}^2 - \frac{m_j^2 y_{ak}}{m_{jk}^2(1-y_{ak})}\right] , \\
a(X+ \to X+-) &= \frac{1}{2m_{jk}^2}\left[y_{aj}^2 - \frac{m_j^2 y_{aj}}{m_{jk}^2(1-y_{aj})}\right] , \\
a(X+ \to X++) &= \frac{m_j^2}{2m_{jk}^4}\left[\frac{y_{aj}}{(1-y_{aj})} + \frac{y_{ak}}{(1-y_{ak})} + 2\right] .
\end{aligned}
$$

Trial Integral

Trial antennae (overestimates):

$$a^{RF}_{\text{trial,emit}} = 2\frac{s_{AK} + s_{jk}}{s_{aj}s_{jk}} = \frac{2}{Q^2_{\text{evol}}}$$
$$a^{RF}_{\text{trial,split}} = \frac{x}{2(s_{jk} + 2m_q^2)}$$

where x is a dimensionless factor ≥ 1 and $x \to 1$ in collinear limit

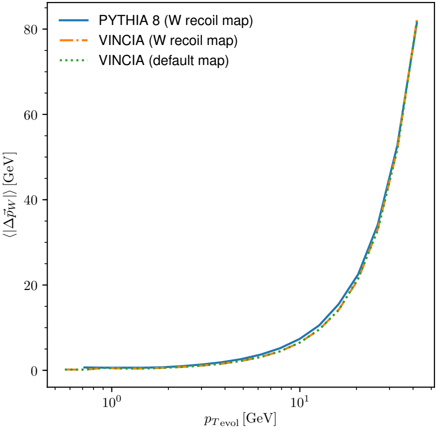
These choices give simple (separable, invertible) trial integrals.

$$\mathcal{A}_{\text{trial,emit}}(Q^2_{\max}, Q^2) = \frac{2\mathcal{C}s_{AK}}{\lambda^{1/2}(m_A^2, m_{AK}^2, m_K^2)} \int \frac{\zeta \mathrm{d}\zeta}{\zeta - 1} \int_{Q^2}^{Q^2_{\max}} \frac{\mathrm{d}\tilde{Q}^2}{\tilde{Q}^2} \frac{\alpha_s(\tilde{Q}^2)}{4\pi}$$
$$\mathcal{A}_{\text{trial,split}}(Q^2_{\max}, Q^2) = \frac{\mathcal{C}s_{AK}(\zeta_{\max} - \zeta_{\min})}{2\lambda^{1/2}(m_A^2, m_{AK}^2, m_K^2)} \int_{Q^2}^{Q^2_{\max}} \frac{\mathrm{d}\tilde{Q}^2}{\tilde{Q}^2} \frac{\alpha_s(\tilde{Q}^2)}{4\pi}$$

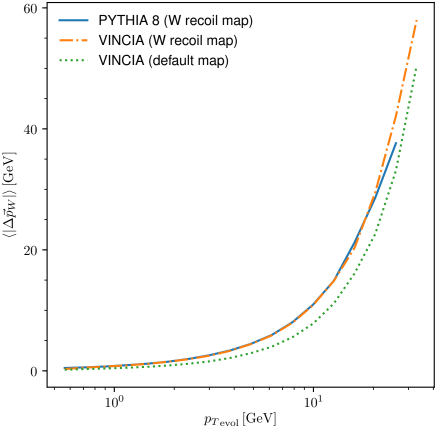
Effect of Kinematic Map

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

Recoil after first:



Recoil after second:



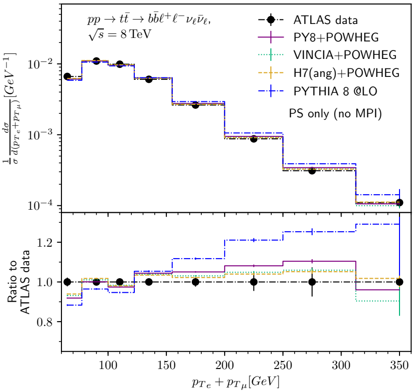
Matching with POWHEG

- 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

ATLAS dileptonic $t\bar{t}$ @ 8 TeV [1709.09407]



[1] [1412.1828],[1509.0907]
[2] [1801.03944]
[3] Thanks to S. Ferrario Ravasio for providing an interface to H7

$pp \to t\bar{t}$ @ 8 TeV: $m_{b_j \mu}$

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