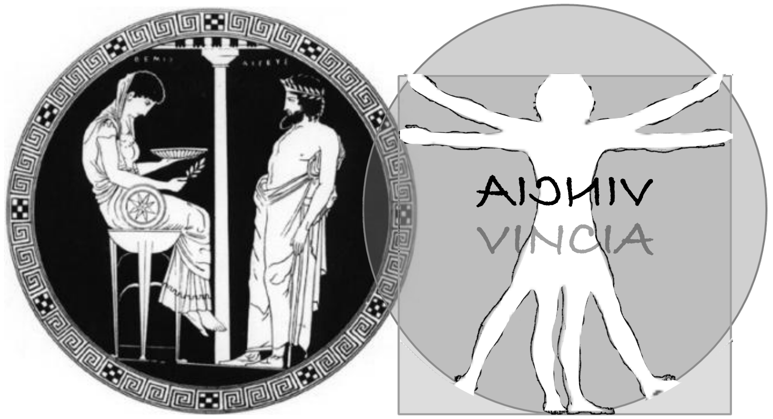
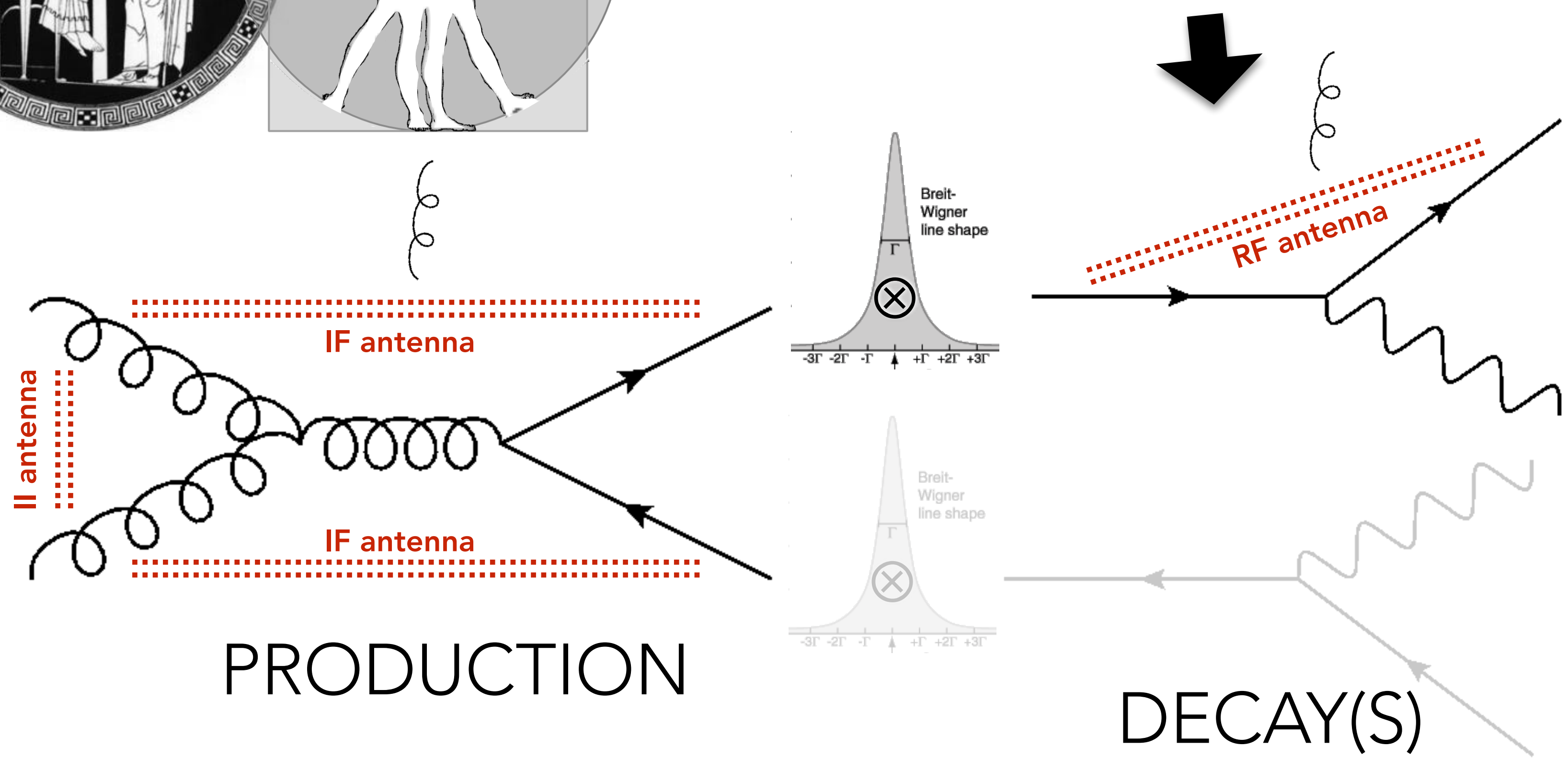
Coherent Showers in Decays of Coloured Resonances

Helen Brooks & ***Peter Skands*** *(Monash University)*

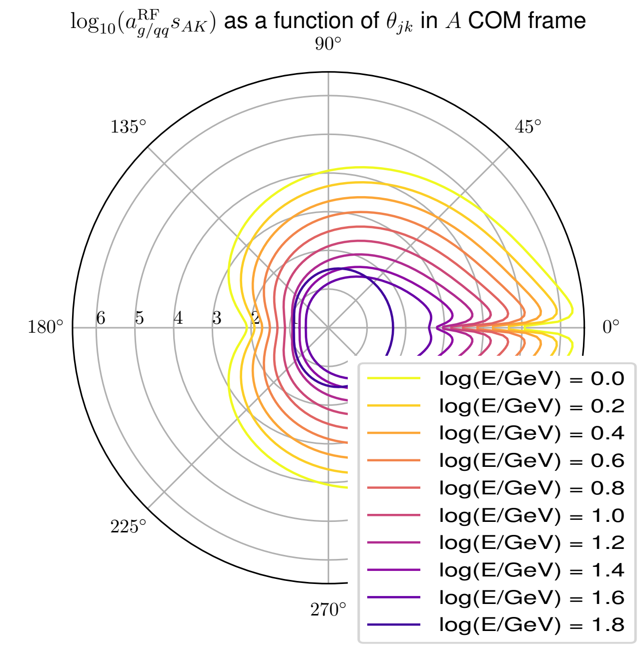


A new shower model based on “Resonance-Final” antennae (with mass- and helicity-dependence)



PRODUCTION

DECAY(S)



RF ANTENNA PATTERN

ANCORA · IMPARO

MCnet

HEP Seminar

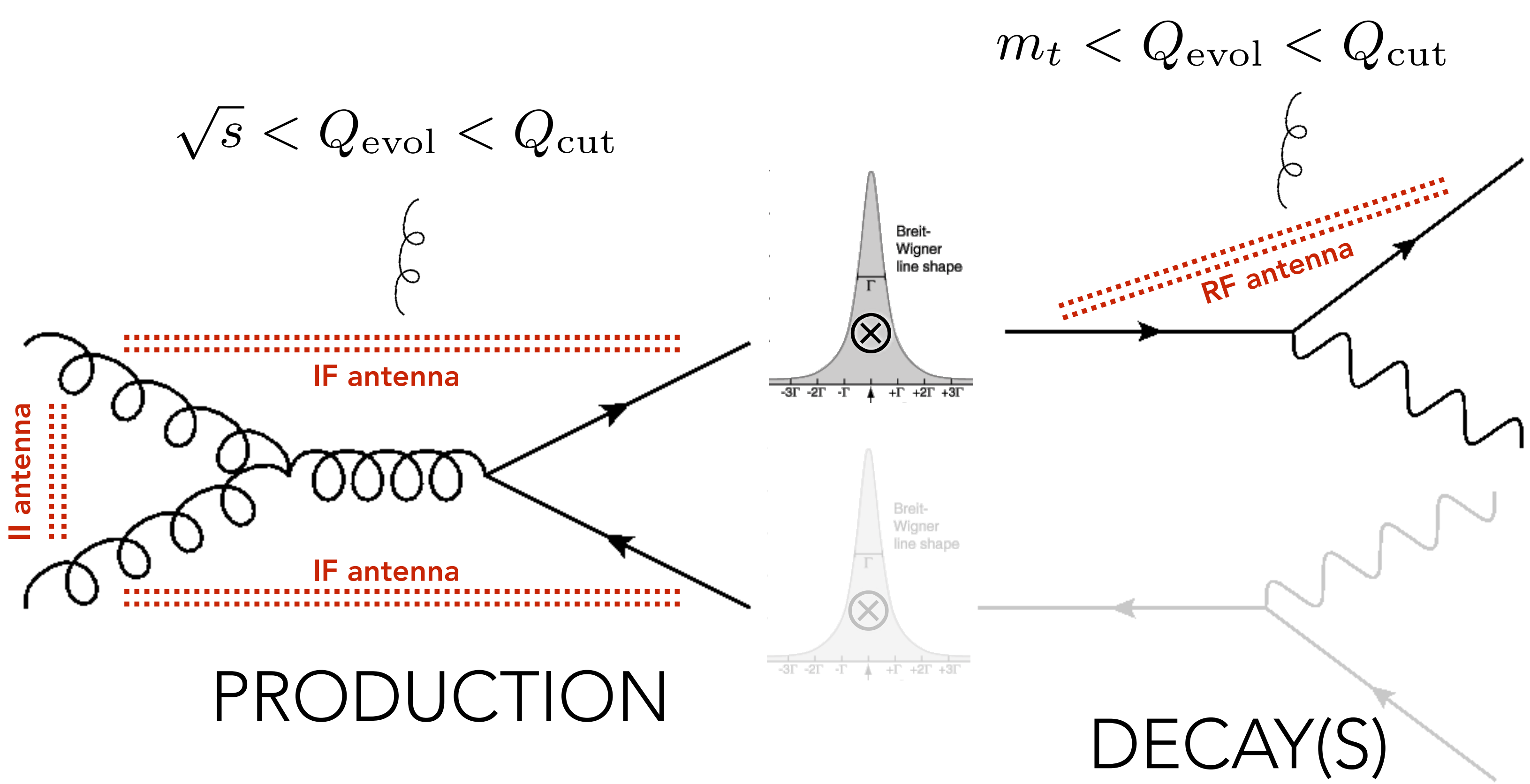
Lund, June 2019

Coherence in Resonance Decays

In narrow width approximation,

Factorise production and decay of resonances;

These stages are showered independently.



Goal is to shower the resonance-final antenna in decay coherently, without modifying the invariant mass of the resonance, needed for resonance-aware matching.

Note: interference between production and decay will occur at scales < Γ; not the topic of this talk

Prime Motivation: Top Quark Mass

arXiv:1801.03944

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

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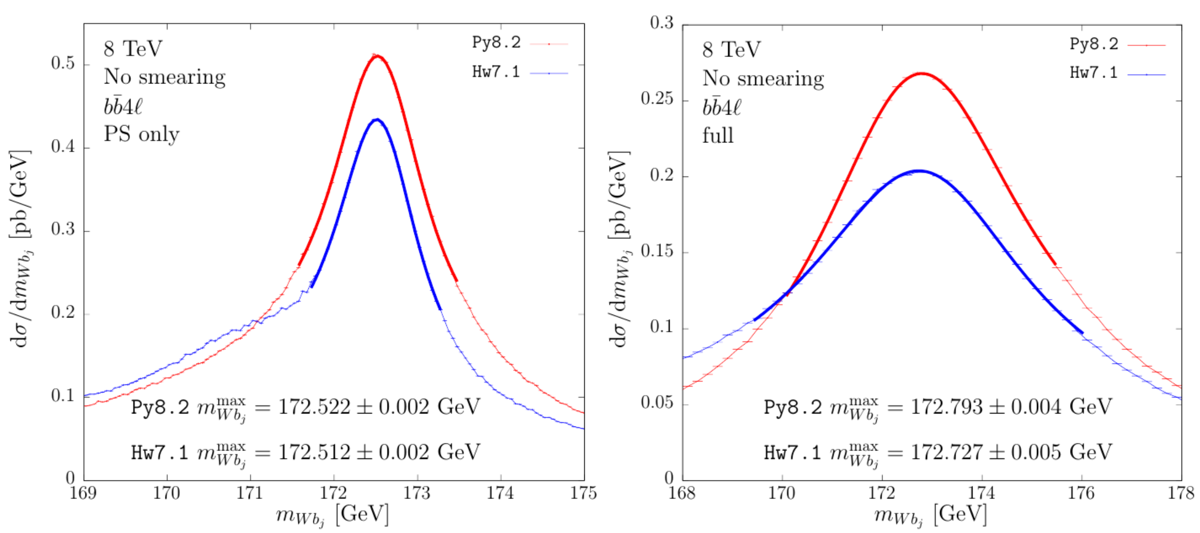


"… the very minimal message that can be drawn from our work is that, in order to assess a meaningful theoretical error in top-mass measurements, the use of different shower models, associated with different NLO+PS generators, is mandatory."

Uncertainties

Fixed-order accuracy (μ_R) + PDFs (μ_F) + matching/merging (*e.g.* h_{damp})

Parton shower ambiguities from logarithmic accuracy

→ Estimate by comparing different shower architectures

+ systematic parametric variations

→ **To reduce**, need systematic improvements:

At LL / LC: coherence & "optimised" choices (for muR, evolution scale, recoil strategies, …)

Beyond LL / LC: genuine subleading colour (beyond optimised LC) and higher-order corrections to shower kernels (beyond optimised LL)

+ Mass Effects, Finite-Width Effects, Polarisation Effects

(+ Non-perturbative: Renormalon pole mass ambiguity $\lesssim \Lambda_{QCD}$, colour-reconnections, MPI, beam remnant treatment, hadronisation, hadron rescattering, hadron and τ decays, …)

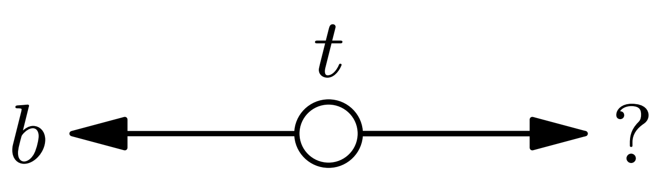
Dipoles vs Antennae (in resonance decays)

Dipole showers*

Each branching has a well-defined "radiator" and a "recoiler", with distinct kinematics maps.

Neglect contribution from resonance as radiator (partition can even become negative).

In principle free to choose recoiler, e.g. W in t → W b



t → b W :

Top sits at rest (does not radiate)

Bottom quark radiates; recoils against the only other final-state parton, W.

More branchings: ambiguous what recoiler to use for parton colour-connected to top

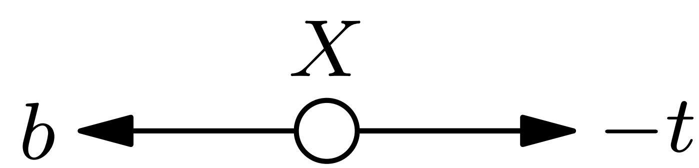
Antenna Showers

Agnostic as to who is the radiator; smooth transition in kinematics

Interpolates between collinear limits

Coherence built in; cannot neglect resonance's contribution

Recoil strategy relates to antenna factorisation



t → b W:

Antenna between bottom and crossed top.

Kinematics map with X = W $\Longrightarrow$ W acquires recoil

More branchings: unambiguous. Parton colour-connected to top participates in the RF antenna; rest = X collectively acquire the recoil.

*Note: the original dipole shower, ARIADNE, is of the type I here call "antenna shower"

Current Status of Resonance Decay Showers

Slide from H. Brooks

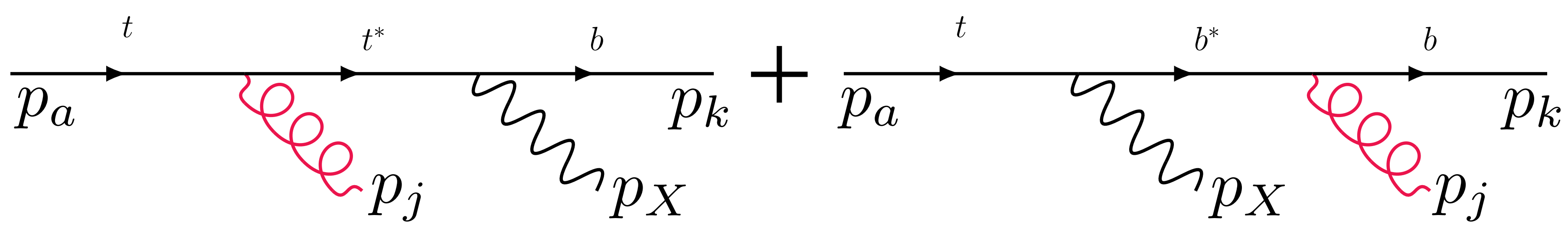
Shower	Type	Decay shower?	Coherence?
Pythia 8 [hep-ph/0010012] [hep-ph/0408302]	Dipole	✓	(✗)* *Via ME corrections
Sherpa [1412.6478]	Catani-Seymour	✗ (production only)	(✓) **(no RF dipole)**
Herwig 7 ($\tilde{q}$) [1810.06493]	Angular-ordered	✓	✓
Herwig 7 (dip) [1810.06493]	Catani-Seymour	(✓) (on-shell only)	(✓) **(no RF dipole)**
Vincia - **NEW!**	Antenna	✓	✓
Dire?*	Dipole	✔?	✔?

*: not completely sure about status

RF Showers 1: Antenna Functions

Labeling: $\underbrace{A_I\, K_F}_{\text{pre-branching}} \to \underbrace{a_I\, j_F\, k_F}_{\text{post-branching}}$

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

Ant = $\Big|$  $\Big|^2$ / Born

Define dimensionless invariants: $y_{aj} \equiv s_{aj}/(s_{AK}+s_{jk}), \quad \mu_a^2 \equiv m_a^2/(s_{AK}+s_{jk}), \quad \ldots$

$$\stackrel{\text{collinear}}{\Longrightarrow} z_k \sim y_{ak} = 1 - y_{aj}\ (+2\mu_j^2)\ , \qquad z_a \sim y_{AK} = 1 - y_{jk}$$

→ same forms as FF, IF, II :*

$$a_{\text{emit}}^{RF} = \frac{1}{s_{AK}} \left[\frac{(1-y_{aj})^{2+\delta_{Kg}} + (1-y_{jk})^2}{y_{aj}y_{jk}} - \frac{2\mu_a^2}{y_{aj}^2} - \frac{2\mu_k^2}{y_{jk}^2} + f(y_{aj}, y_{jk}, \mu_a^2, \mu_k^2) \right]$$

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

↑ Polynomial(s) chosen such that all helicity components remain positive-definite

Note: defined for all helicity configurations & all shower states assigned explicit helicities throughout VINCIA; here just showing summed forms for brevity.

*: difference is $1/(s_{AK} + s_{jk})$ normalisation and phase-space map

Example: Collinear Limits

Labeling: $\underbrace{A_I\,K_F}_{\text{pre-branching}} \to \underbrace{a_I\,j_F\,k_F}_{\text{post-branching}}$

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

$$y_{\alpha\beta} = \frac{s_{\alpha\beta}}{s_{AK} + s_{jk}}$$

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 Structure for Gluon Splittings

Labeling: $\underbrace{A_I\,K_F}_{\text{pre-branching}} \to \underbrace{a_I\,j_F\,k_F}_{\text{post-branching}}$

Example: XGsplitIF

Identical to RF modulo nonsingular terms

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

$$y_{\alpha\beta} = \frac{s_{\alpha\beta}}{s_{AK} + s_{jk}}$$

$$X_A g_K \to X_a \bar{q}_j q_k$$

$$a(X+ \to X-+) = \frac{1}{2m_{jk}^2}\left[y_{ak}^2 - \frac{m_j^2 y_{ak}}{m_{jk}^2(1-y_{ak})}\right],$$

$$a(X+ \to X+-) = \frac{1}{2m_{jk}^2}\left[y_{aj}^2 - \frac{m_j^2 y_{aj}}{m_{jk}^2(1-y_{aj})}\right],$$

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

"Helicity Flip" proportional to mass squared

Helicity conservation; go to zero when "-" daughter gets x→1

HELICITY SUM:

$$a(X_A g_K \to X_a \bar{q}_j q_k) = \frac{1}{2m_{jk}^2}\left[y_{ak}^2 + y_{aj}^2 + \frac{2m_j^2}{m_{jk}^2}\right]$$

Note sum of ++ antennae have same singularities as sum of +- ones => same singular terms obtained when summing over helicity of emitted gluon irrespective of parent helicities

Helicity Structure for Gluon Emissions

Example: QGemitIF

Identical to RF modulo nonsingular terms

Labeling: $\underbrace{A_I\,K_F}_{\text{pre-branching}} \to \underbrace{a_I\,j_F\,k_F}_{\text{post-branching}}$

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

$$y_{\alpha\beta} = \frac{s_{\alpha\beta}}{s_{AK} + s_{jk}}$$

MHV

$$a(++ \to +++) = \frac{1}{s_{AK}}\left[\frac{1}{y_{aj}y_{jk}} + (1-\alpha)\frac{1-2y_{aj}}{y_{jk}} - \frac{\mu_a^2}{y_{aj}^2}\right], \quad \text{(C.28)}$$

ARIADNE VINCIA DEF

"Gluon collinear partitioning" interpolates between GP (α=1) and GGG (α=0)

NMHV

$$a(++ \to +-+) = \frac{1}{s_{AK}}\left[\frac{(1-y_{aj})^3 + (1-y_{jk})^2 - 1}{y_{aj}y_{jk}} - \frac{\mu_a^2(1-y_{jk}-y_{aj})^2(1-y_{aj})}{y_{aj}^2} + 3 - y_{aj}^2\right] \quad \text{(C.29)}$$

Helicity conservation => Suppressed when xk or xa -> 0

$$a(++ \to --+) = \frac{1}{s_{AK}}\left[\frac{\mu_a^2 y_{jk}^2}{y_{aj}^2}\right] \quad \text{(C.30)}$$

"Helicity Flip" proportional to mass squared

$$a(+- \to ++-) = \frac{1}{s_{AK}}\left[\frac{(1-y_{aj})^3}{y_{aj}y_{jk}} - \frac{\mu_a^2(1-y_{aj})^2}{y_{aj}^2}\right], \quad \text{(C.31)}$$

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

$$a(+- \to ---) = \frac{1}{s_{AK}}\left[\frac{\mu_a^2 y_{jk}^2}{y_{aj}^2}\right] \quad \text{(C.32)}$$

"Helicity Flip" proportional to mass squared

Note sum of ++ antennae have same singularities as sum of +- ones => same singular terms obtained when summing over helicity of emitted gluon irrespective of parent helicities

Labeling: $\underbrace{A_I\,K_F}_{\text{pre-branching}} \to \underbrace{a_I\,j_F\,k_F}_{\text{post-branching}}$

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

Emissions:

Generalisation of ARIADNE p_T

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

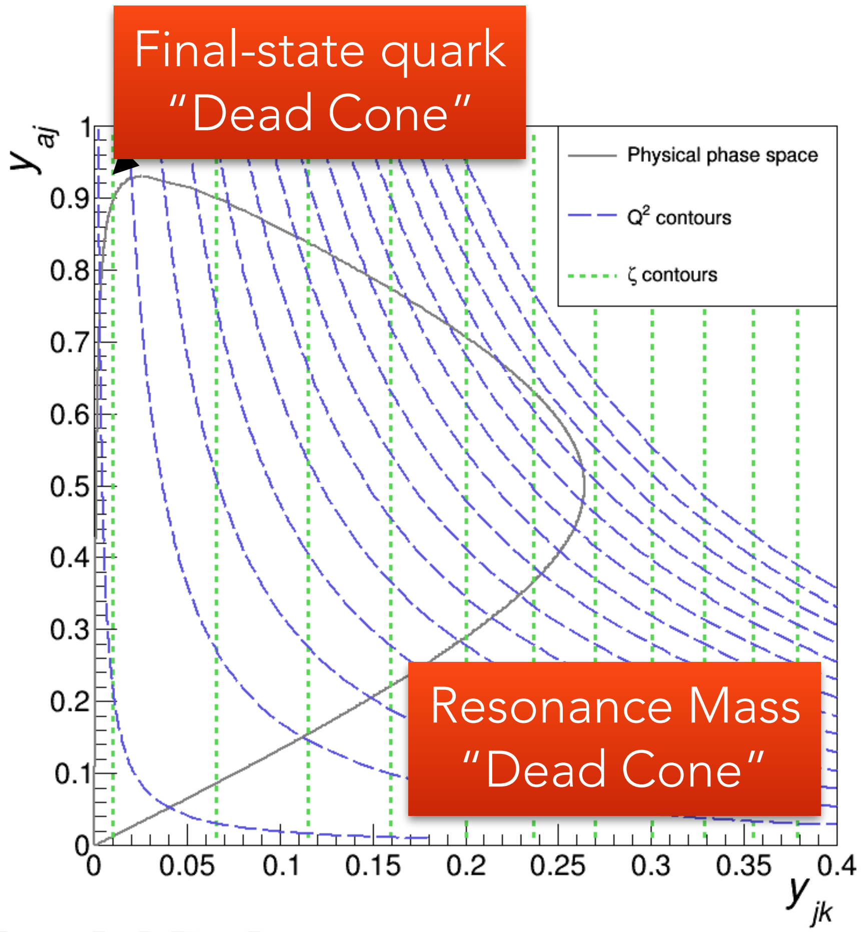
$$\zeta = \frac{s_{jk}+s_{AK}}{s_{AK}}$$

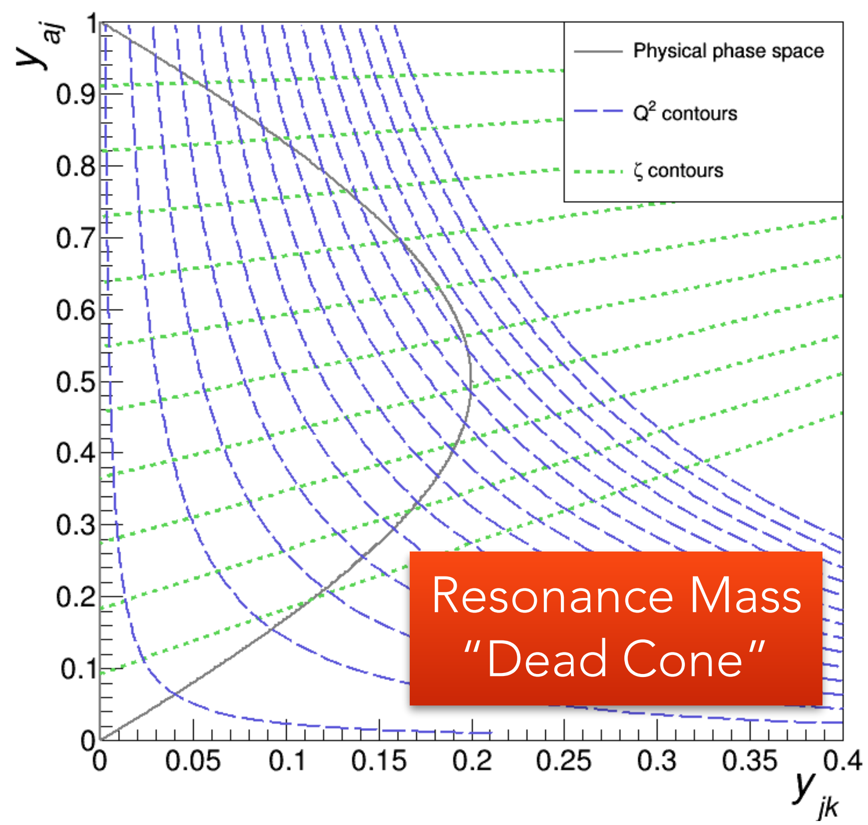
Same since $m_j = 0$ for emission

Splittings:

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

$$\zeta = \frac{s_{ak}}{s_{AK}}$$





RF Showers 3: Phase-Space Factorisation

Labeling: $\underbrace{A_I\,K_F}_{\text{pre-branching}} \to \underbrace{a_I\,j_F\,k_F}_{\text{post-branching}}$

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

2→3 phase-space factorisation: $\mathrm{d}\Phi_{n+1} = \mathrm{d}\Phi_{\mathrm{ant}} \times \mathrm{d}\Phi_n$

- 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**:

$$p_A = p_K + p_X \implies m_X^2 = (p_A - p_K)^2 \equiv (p_a - p_j - p_k)^2 = m_{X'}^2$$

$$\frac{\mathrm{d}\Phi_{a\to jk+\{X\}} = \frac{1}{(4\pi)^5}\frac{\mathrm{d}s_{aj}\mathrm{d}s_{jk}\mathrm{d}\phi}{m_A^2}\mathrm{d}\Omega_K}{\mathrm{d}\Phi_{A\to K+\{X\}} = \frac{1}{8(2\pi)^2}\frac{\lambda^{1/2}(m_A^2, m_{AK}^2, m_K^2)}{m_A^2}\mathrm{d}\Omega_K}$$

➡

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

Same form as the final-final antenna phase space

… with $m_X = m_{AK}$ as one of the Born parameters

RF Showers 4: Kinematics Map (Recoil)

Labeling: $\underbrace{A_I\, K_F}_{\text{pre-branching}} \rightarrow \underbrace{a_I\, j_F\, k_F}_{\text{post-branching}}$

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

- Construct in A rest frame, and rotate such that K is along z.
- Specify system X only recoils longitudinally.
- Rotate about z by ϕ (flatly sampled).
- Boost back to lab frame.
- For each recoiler i, boost p_i by $p_{X'} - p_X$

Note!

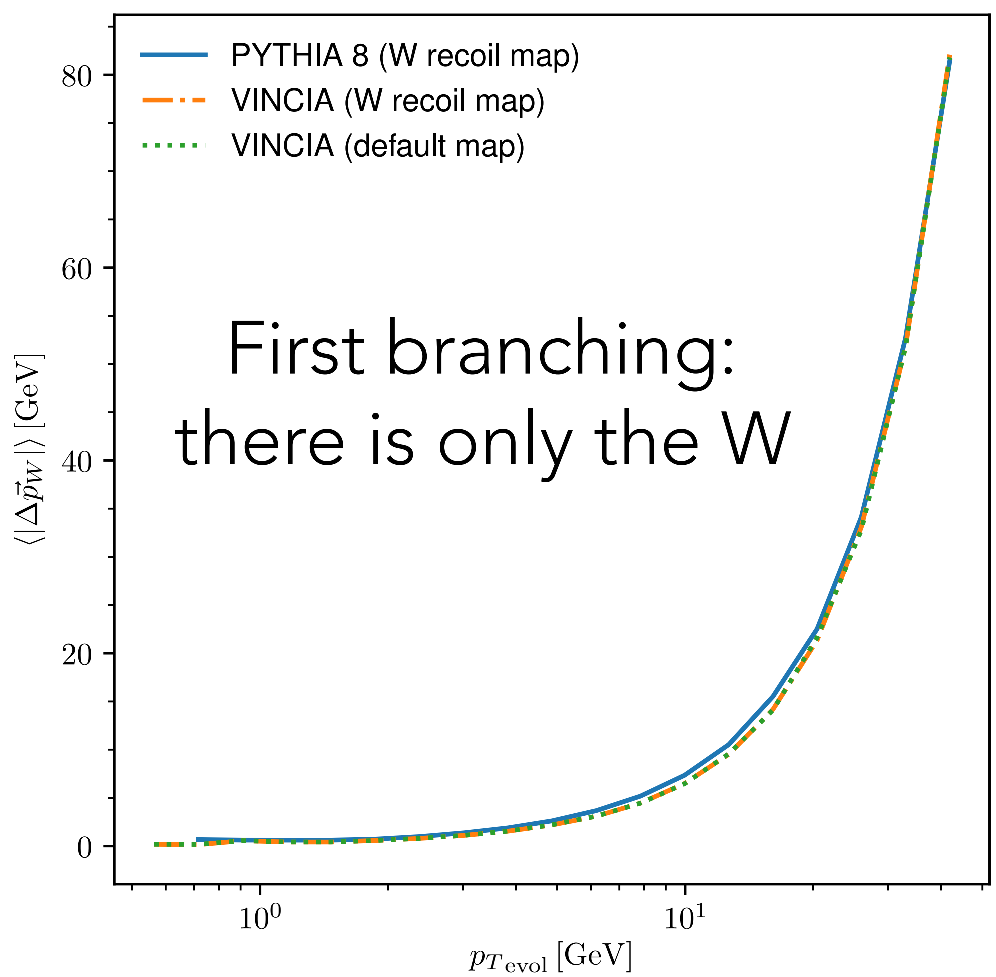
If we fix to just one recoiler i.e. $A \rightarrow RKX$, $a \rightarrow rjkX$ then **CANNOT** simulatenously preserve m_A^2, m_R^2 and m_{AK}^2.
Replace $A \rightarrow A - X$ everywhere.

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

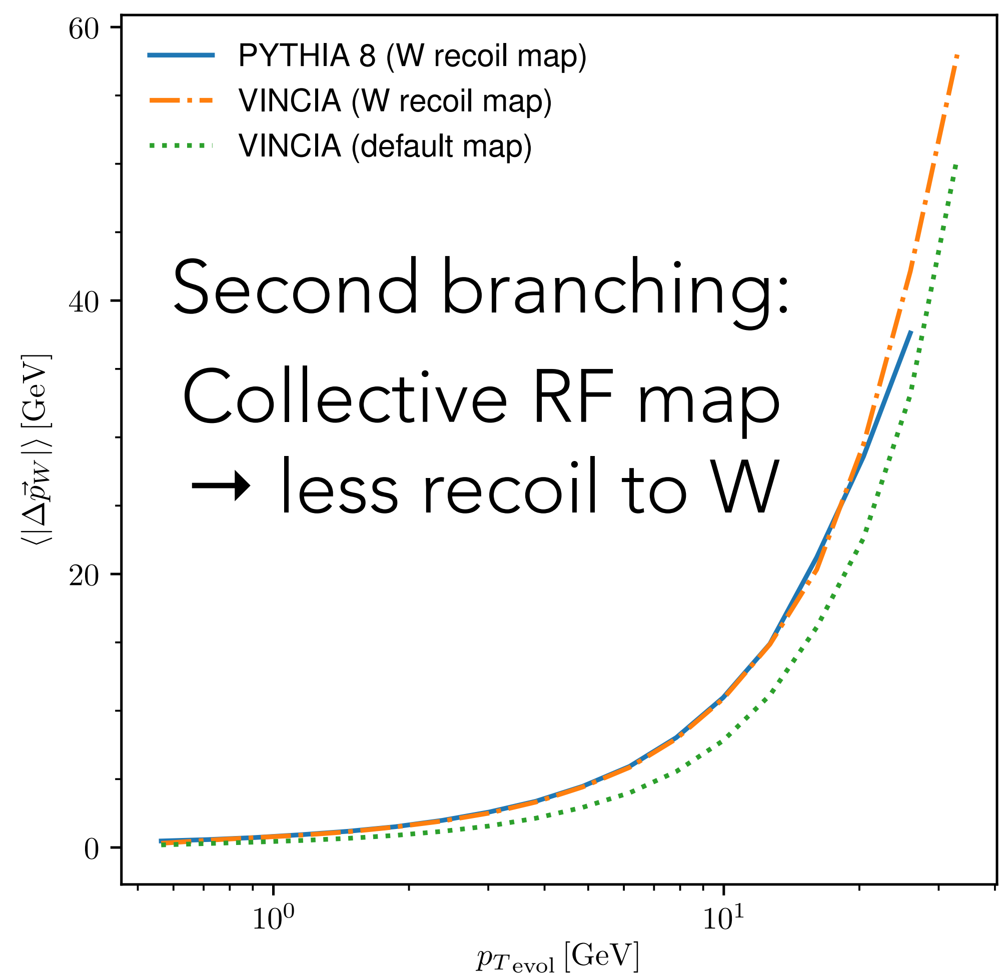
*Note the prescription defined here is similar to one recently implemented in Herwig7 by Cormier et al., arXiv:1810.06493

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

Recoil after first:

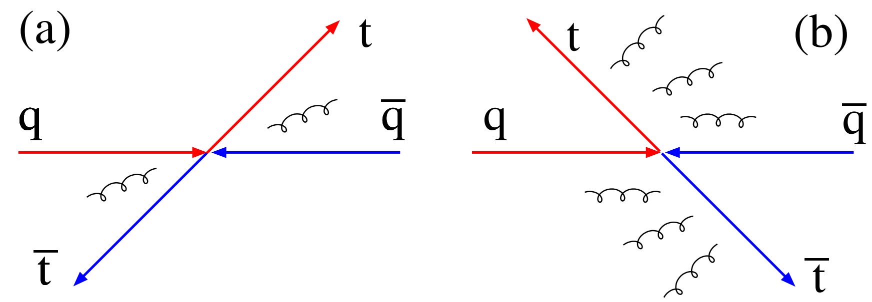


Recoil after second:



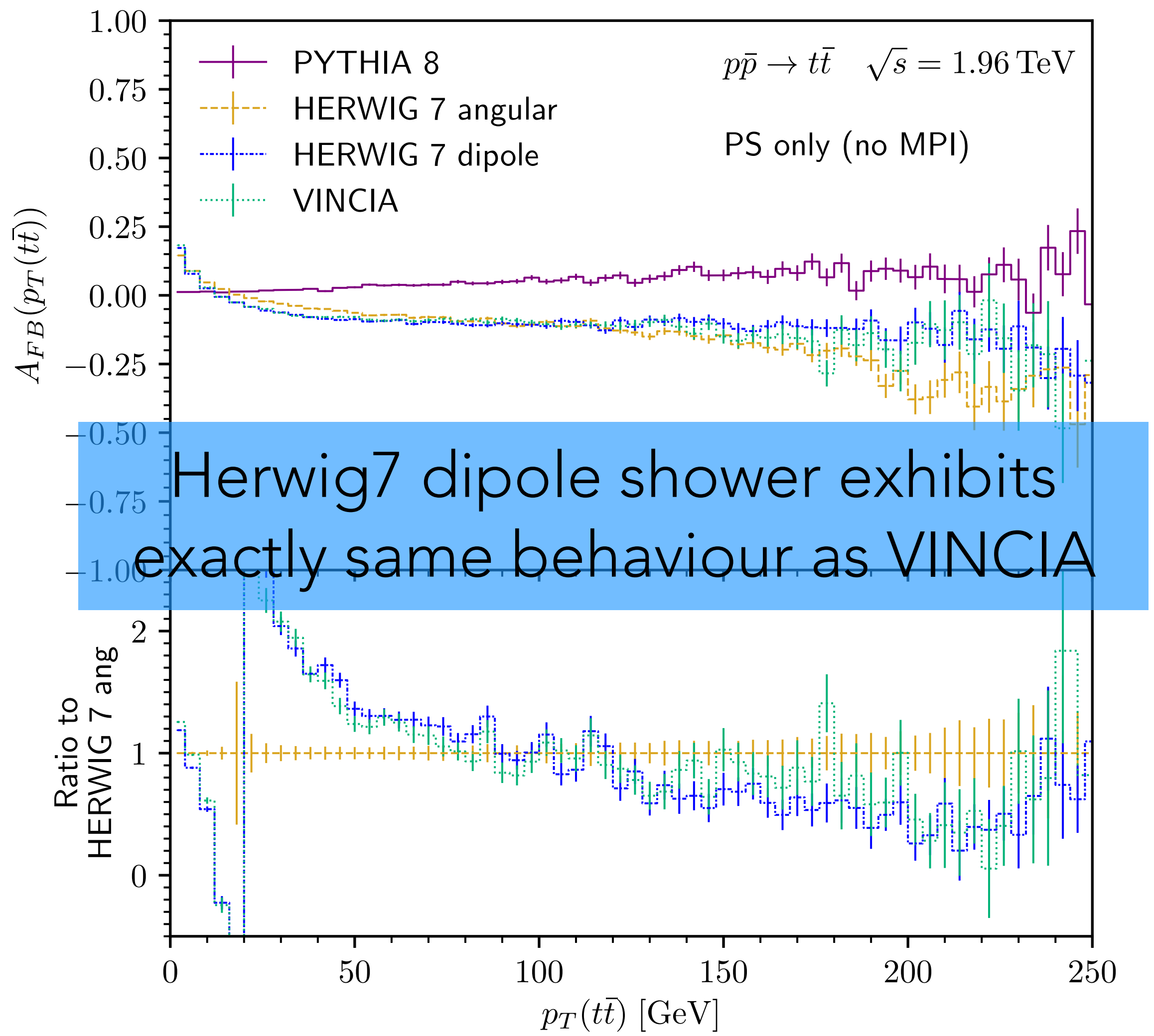
(Coherence In Production)

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

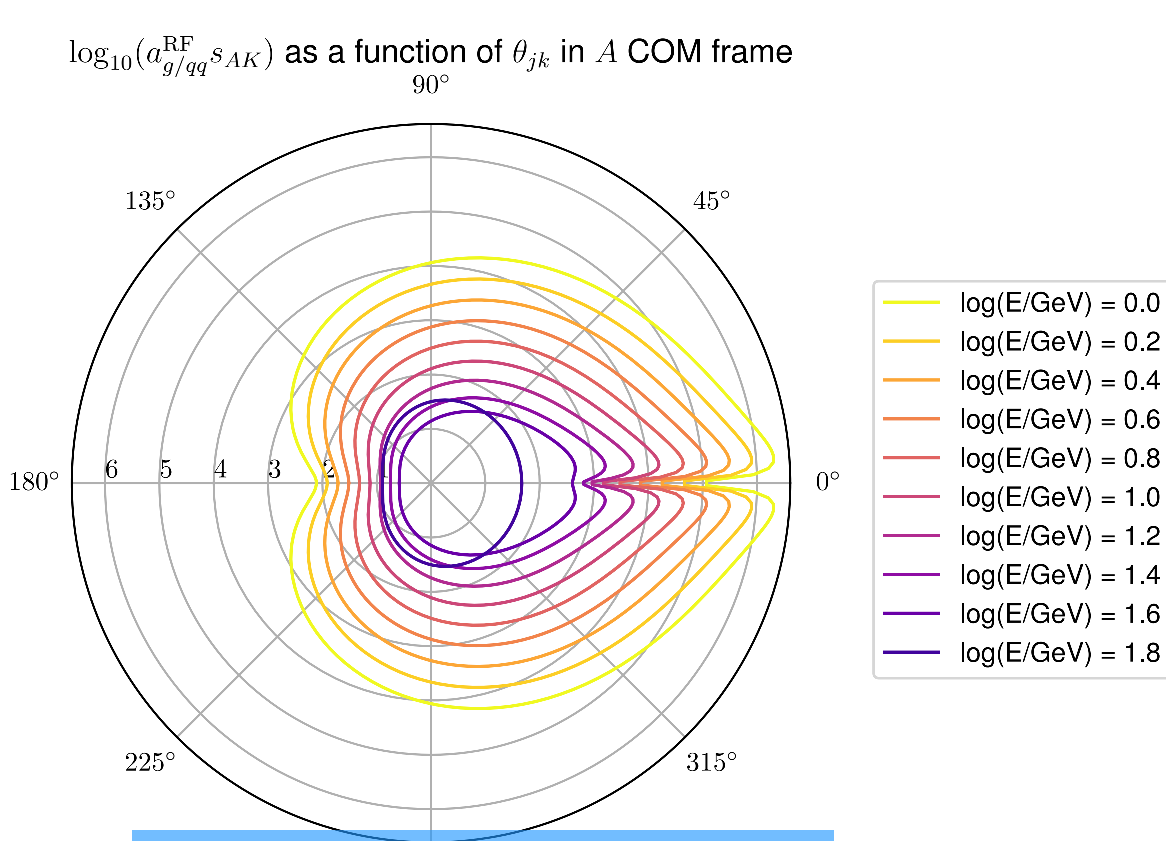
Forward-backwards asymmetry:

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

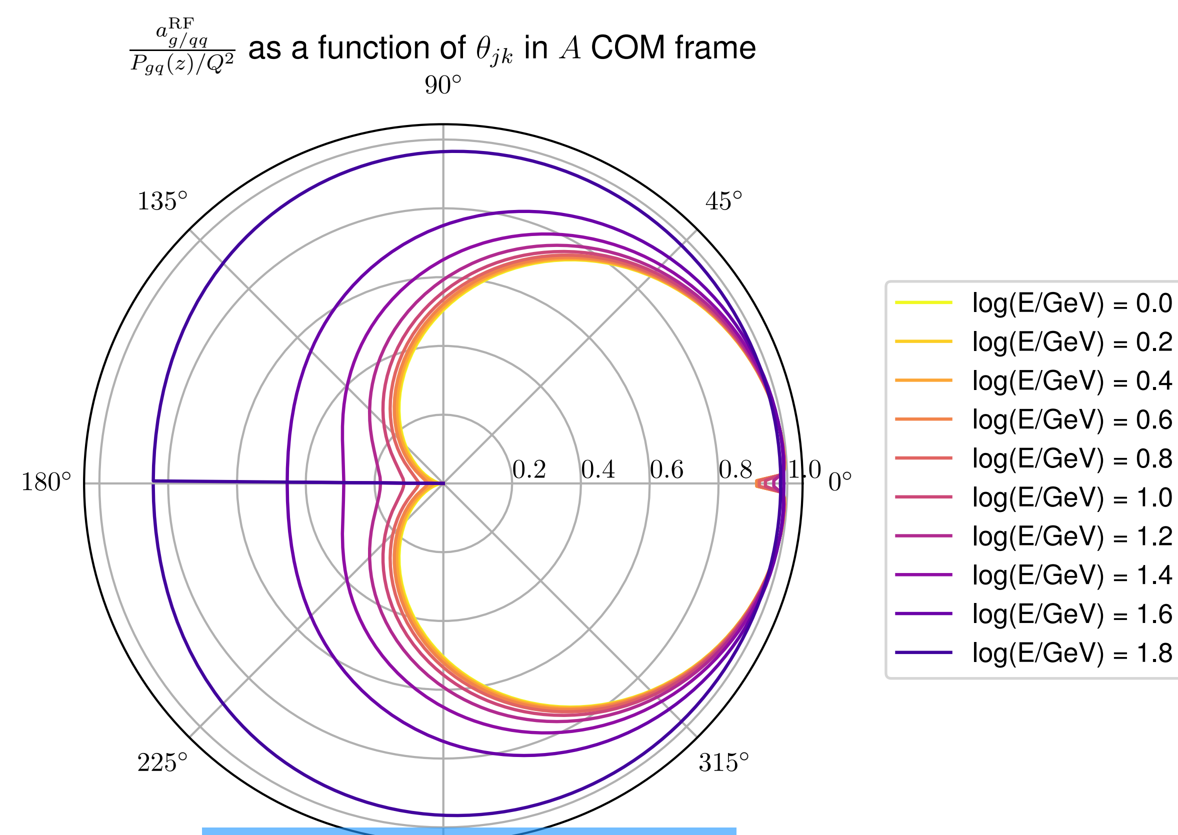
Coherent showers include part of the real emission correction that generates a FB asymmetry that becomes negative for large $p_T(t\bar{t})$. [1205.1466]

Coherence in Decay

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



Log of antenna function



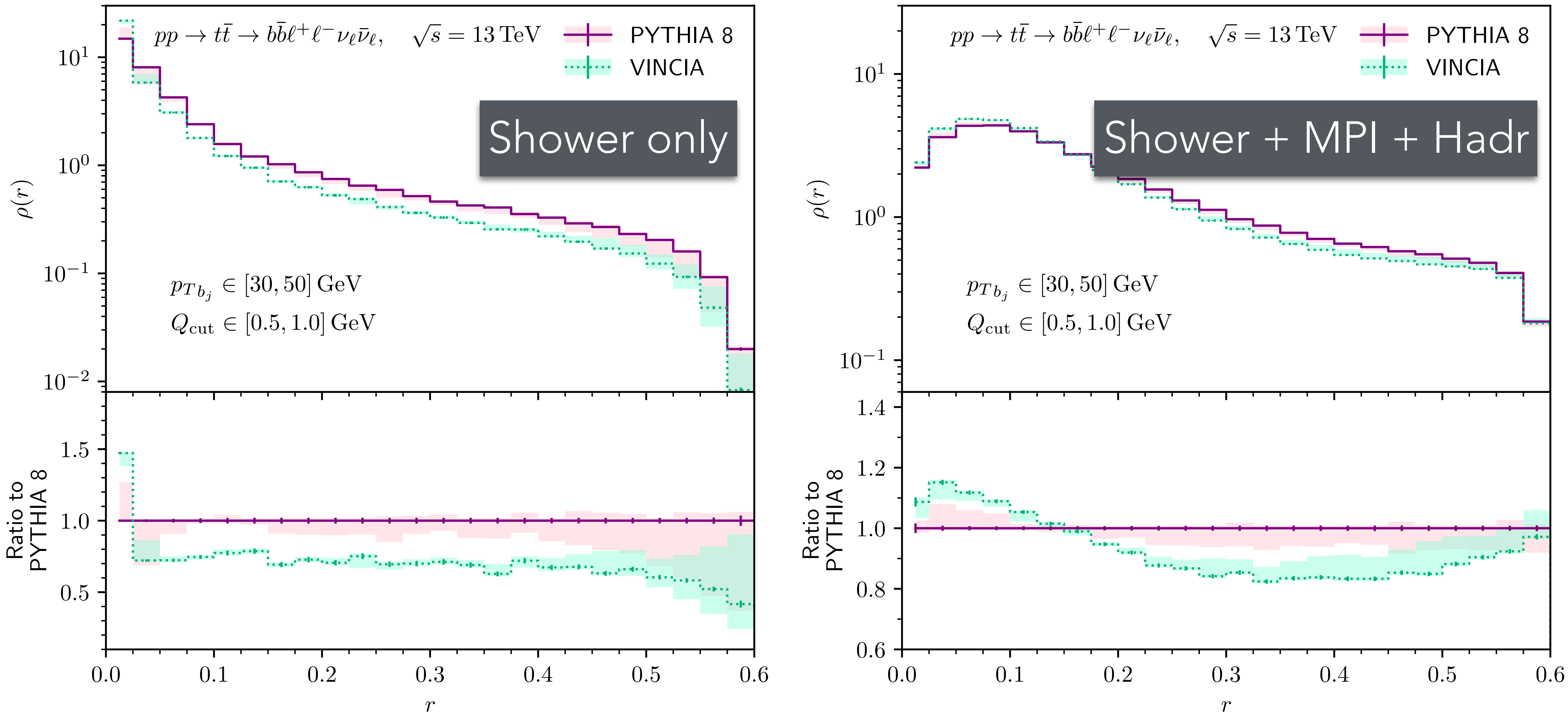
Ratio to AP kernel

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

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

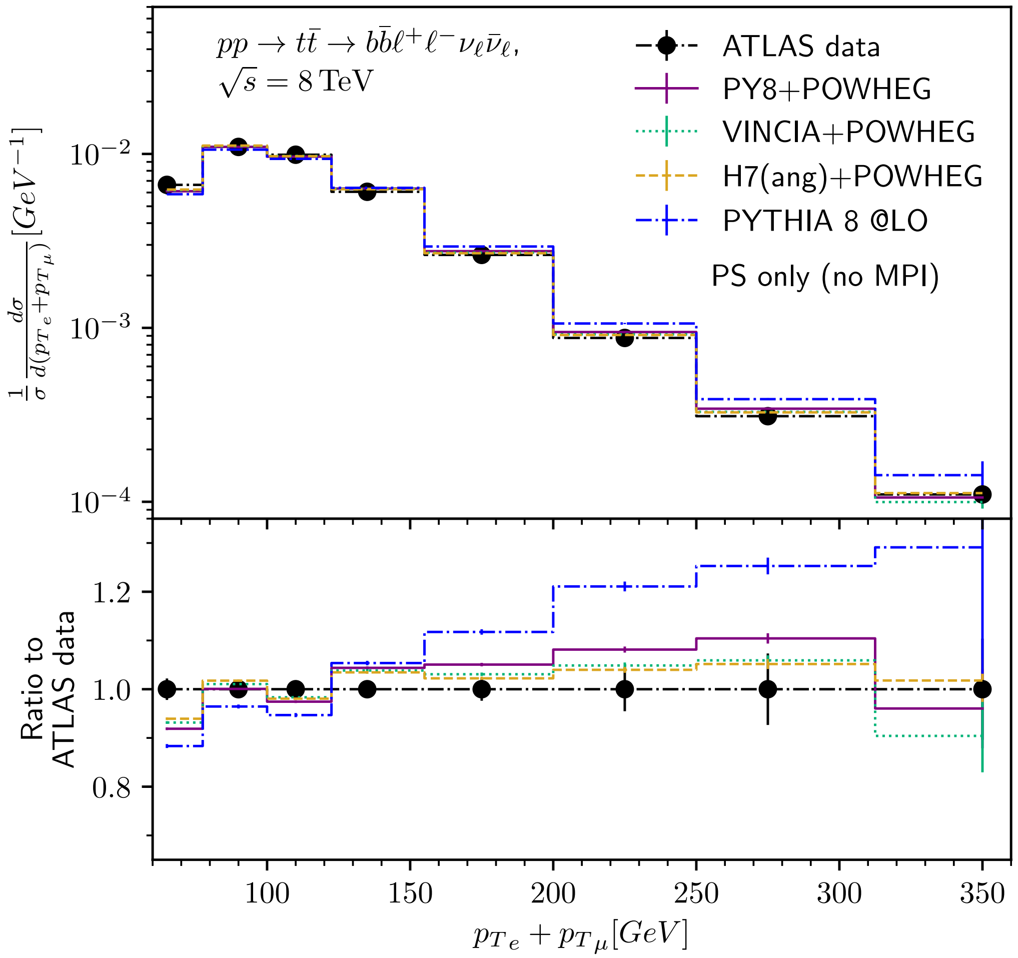
Matching with POWHEG

- 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]

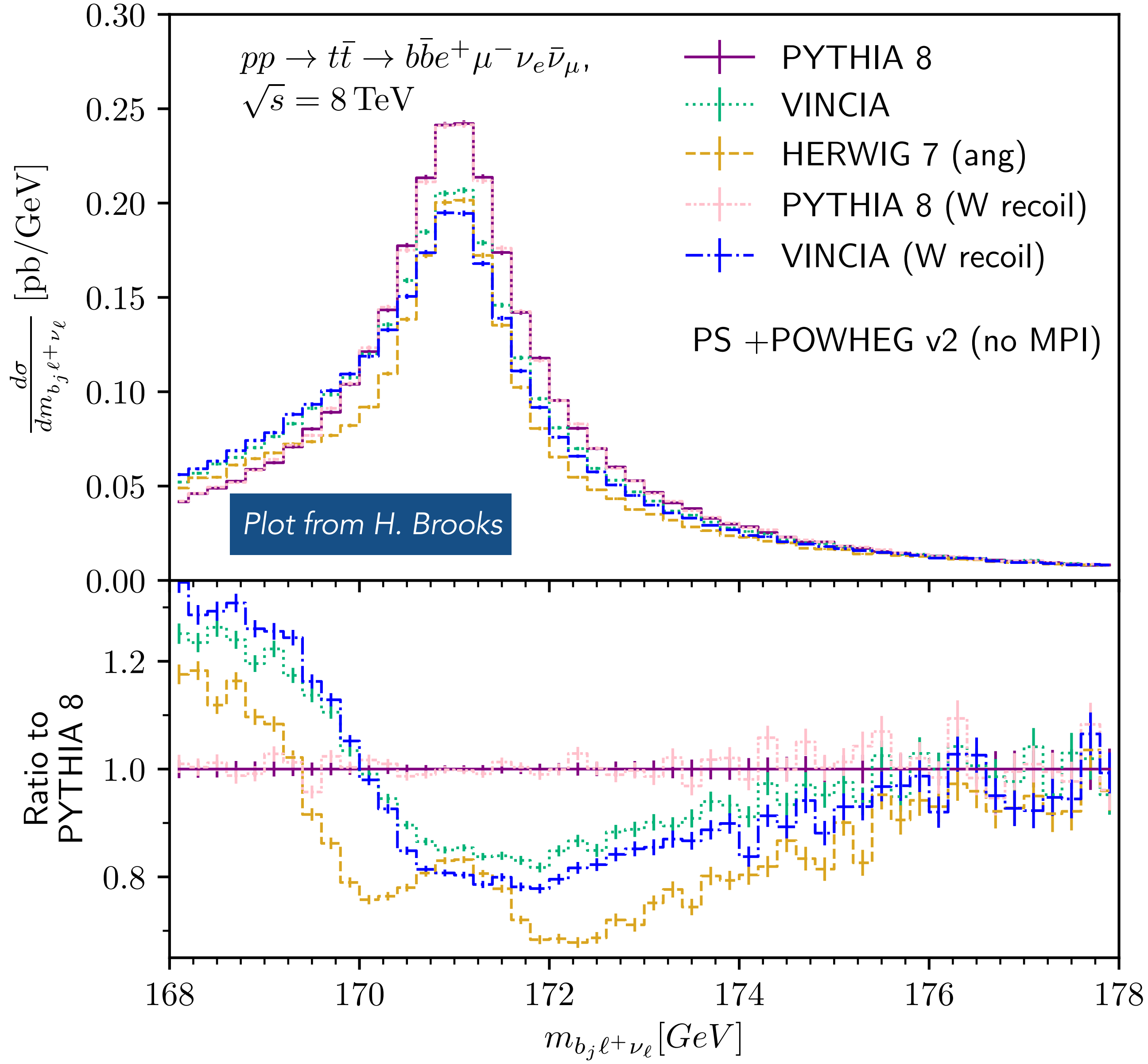


[1] [1412.1828],[1509.0907]
[2] [1801.03944]
[3] Thanks to S. Ferrario Ravasio for providing an interface to H7

$p\bar{p} \to t\bar{t}$ @ 8 TeV: $m_{b_j \ell \nu}$ (looking under the hood / "cheating")

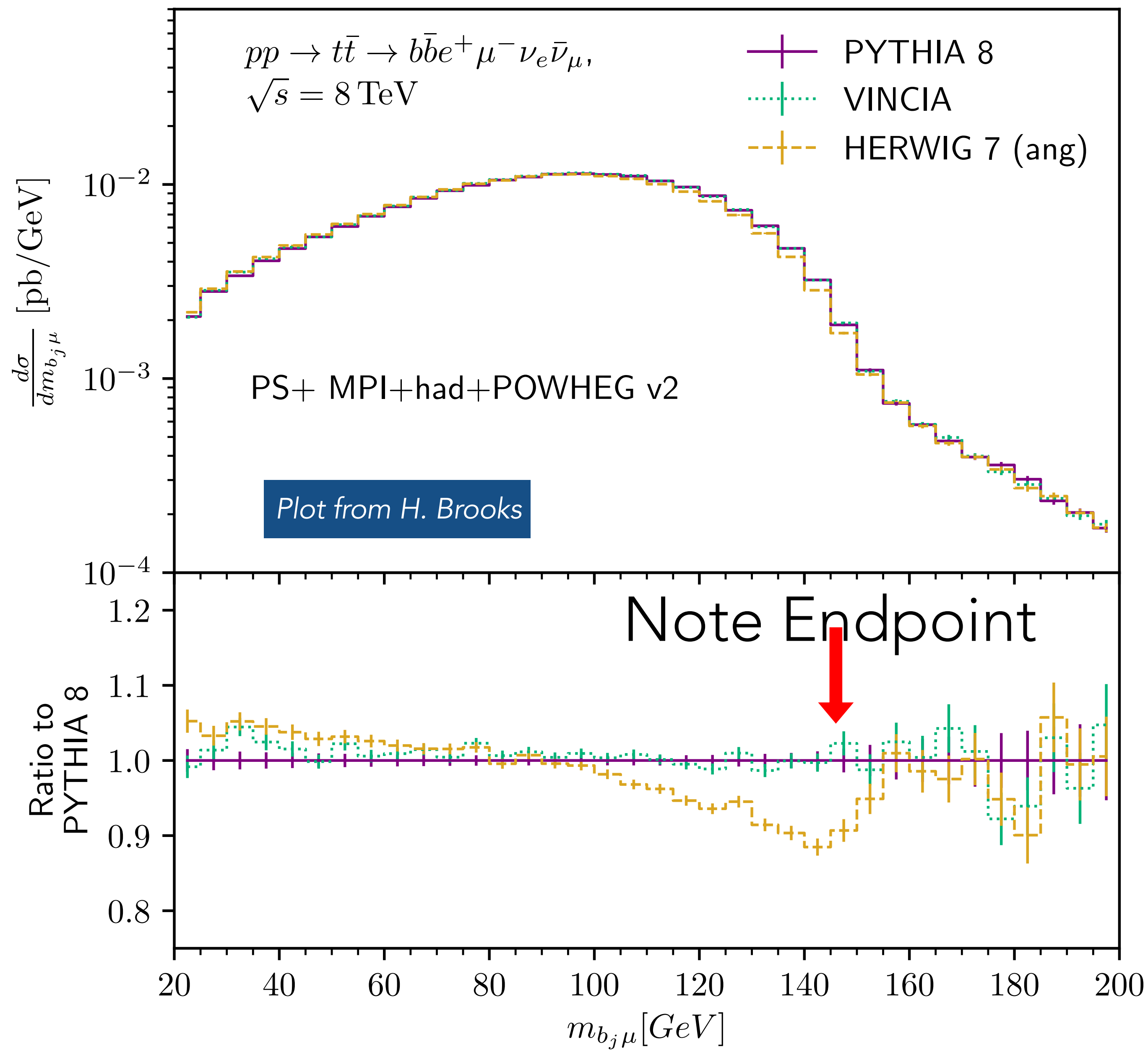
Monte-Carlo "truth" (parton-level) analysis:

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



$p\bar{p} \to t\bar{t}$ @ 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.



VINCIA can now do production and decay of top quarks

- With full mass and helicity dependence

Based on new "**resonance-final**" antennae

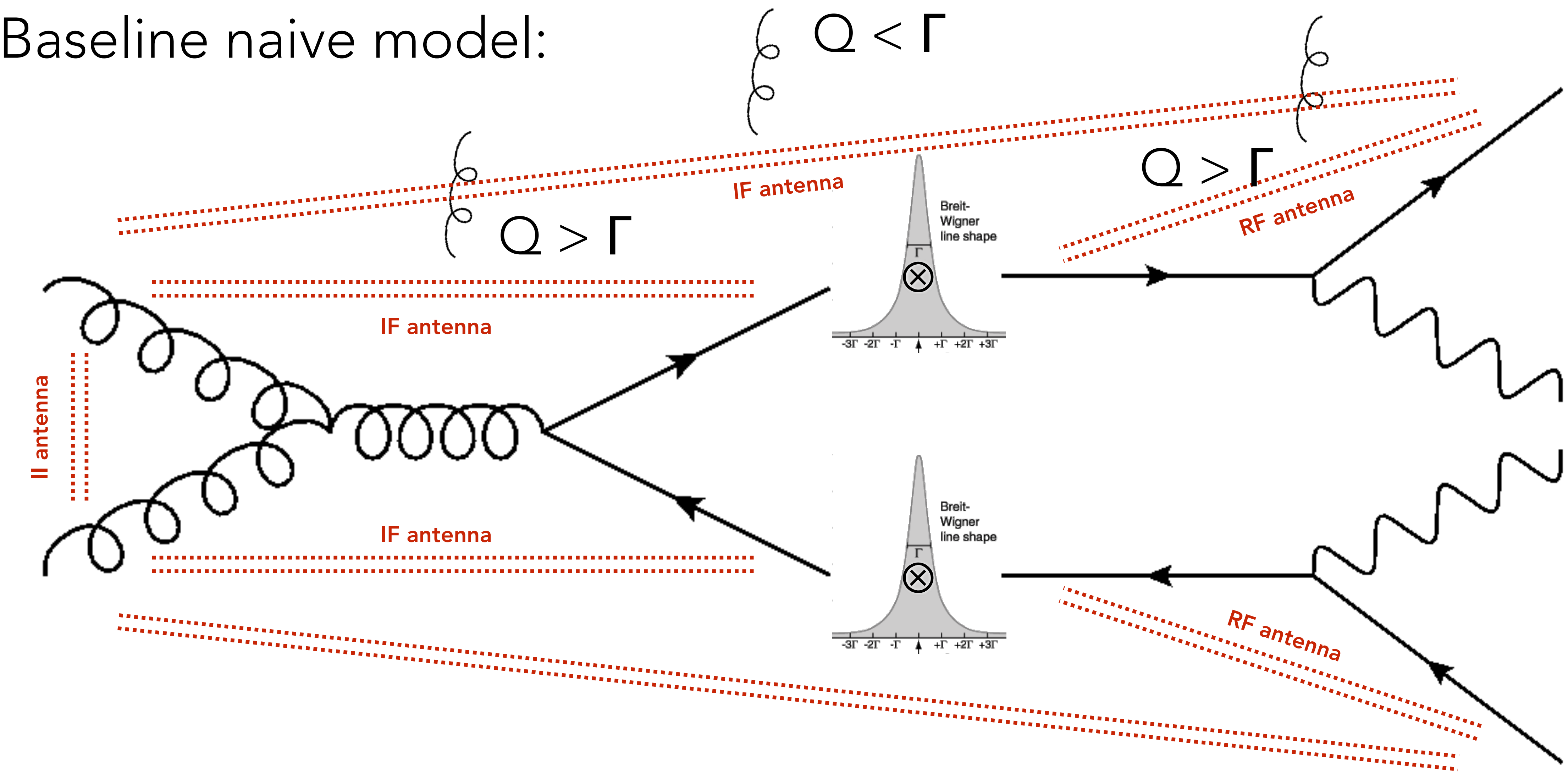
- Coherent top+b (& top+g) radiation patterns
- Collective recoil kinematics

Coming soon...

PYTHIA 8.3 $\rightarrow$ Watch this space!

Finite-width effects

Baseline naive model:



+ some alternatives (with Rob Verheyen)

Note: we do not expect these effects to be large for top decays, cf e.g., Khoze & Sjöstrand Phys.Lett. B328 (1994) 466-476

Shower Architectures

Table from H. Brooks

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

Sum over all dipoles / antennae should reproduce the leading log