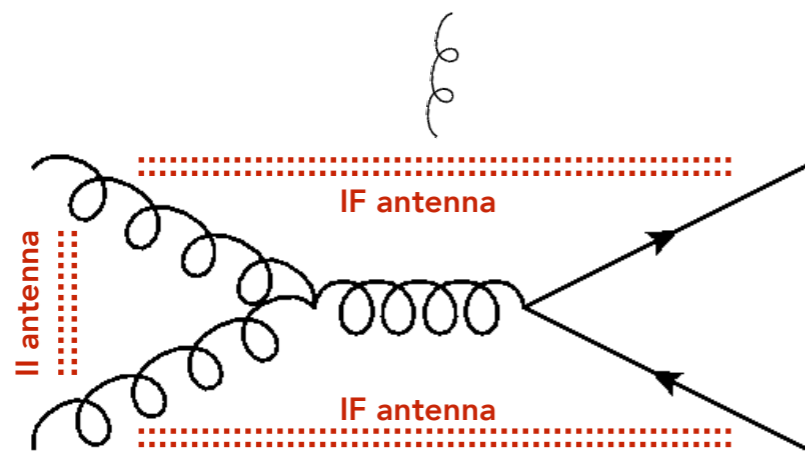


Coherent Showers in Decays of Coloured Resonances

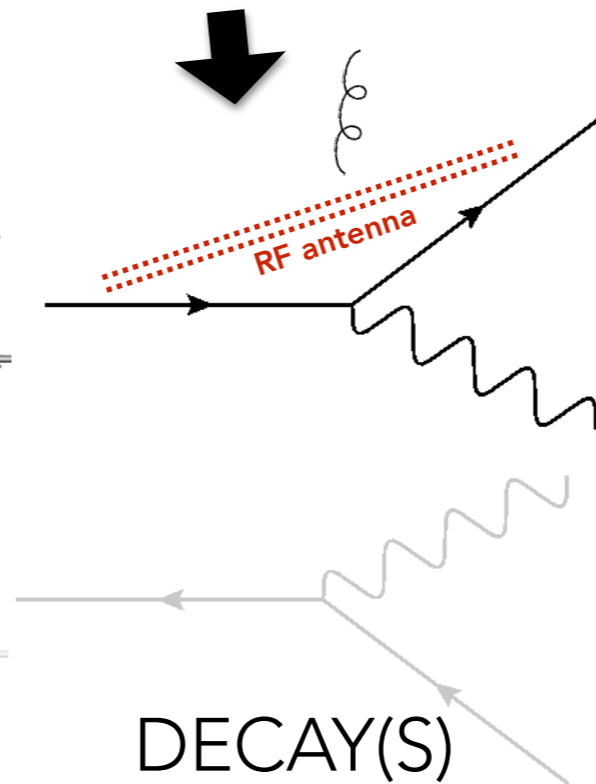
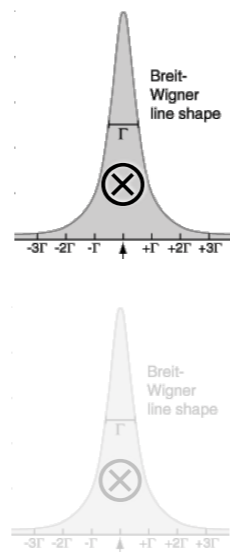
Helen Brooks & Peter Skands (Monash University)



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

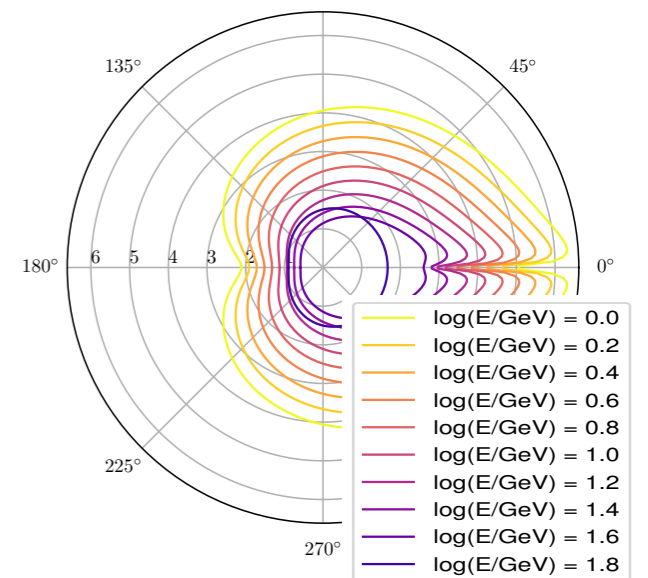


PRODUCTION



DECAY(S)

$\log_{10}(a_{g/q}^{\text{RF}} s_{AK})$ as a function of θ_{jk} in A COM frame



RF ANTENNA PATTERN





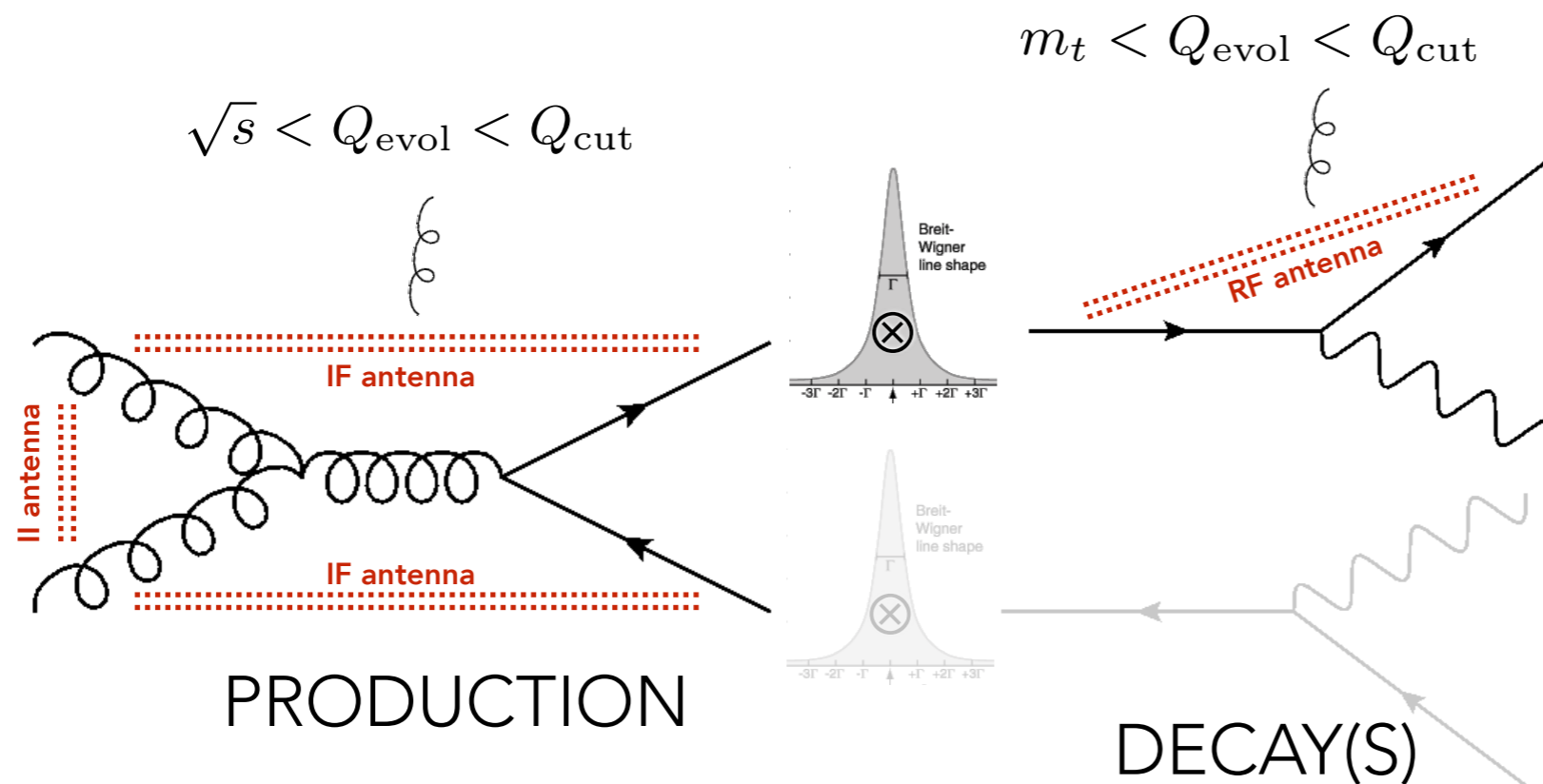
Coherence in Resonance Decays



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.



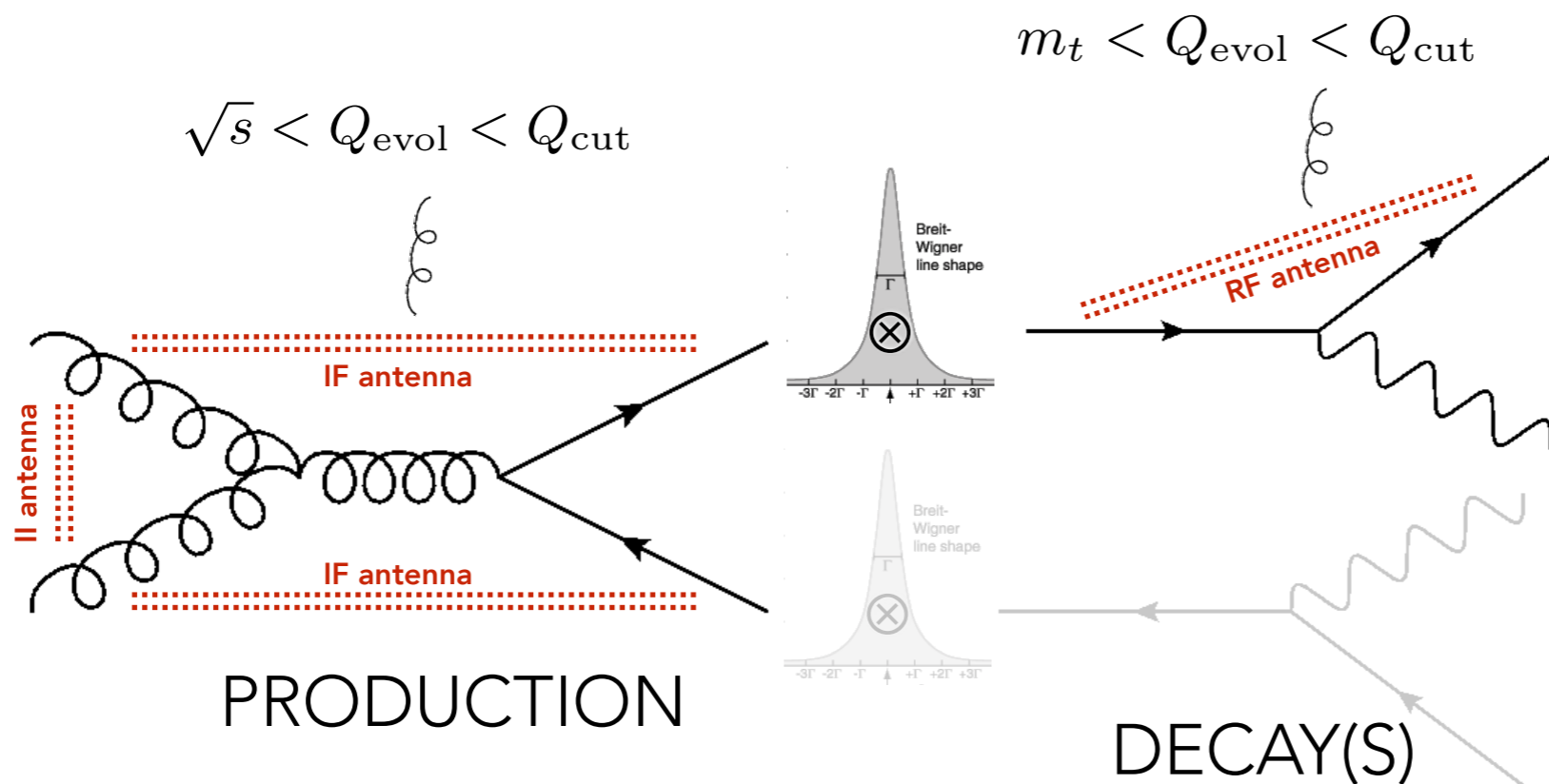
Coherence in Resonance Decays



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 $< \Gamma$; not the topic of this talk



Prime Motivation: Top Quark Mass



arXiv:1801.03944

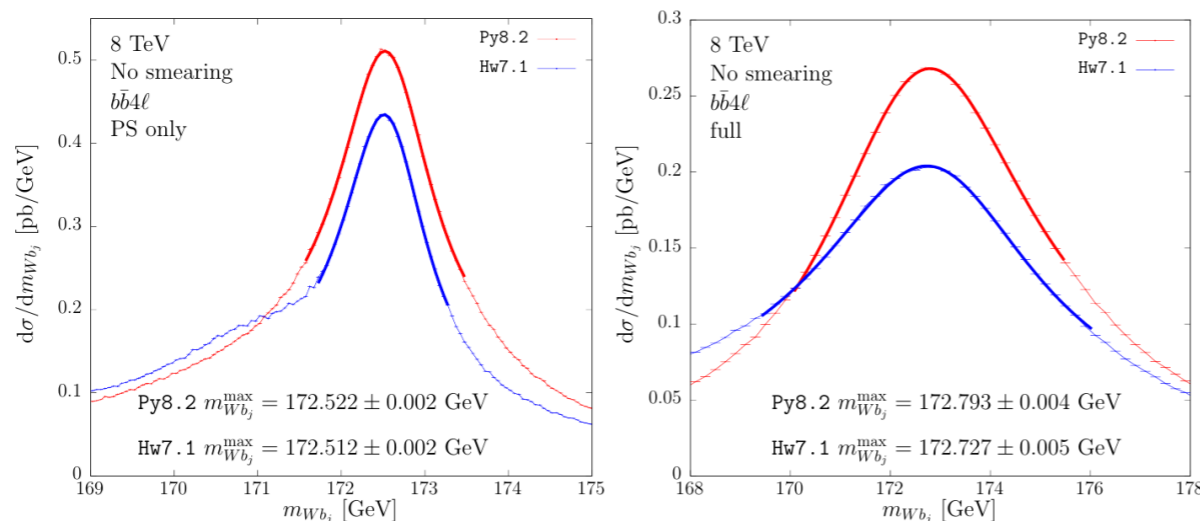
A theoretical study of top-mass measurements at the LHC using NLO+PS generators of increasing accuracy

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

^aUniversità di Milano-Bicocca and INFN, Sezione di Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy

^bPhysics Institute, Universität Zürich, Zürich, Switzerland

^cCERN, 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.”





Dipoles vs Antennae (in resonance decays)

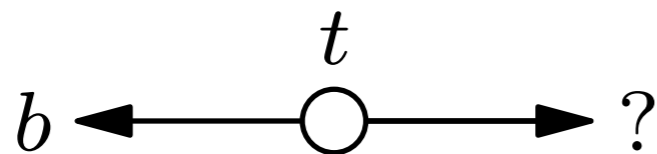


Dipole showers*

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 $t \rightarrow W b$



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

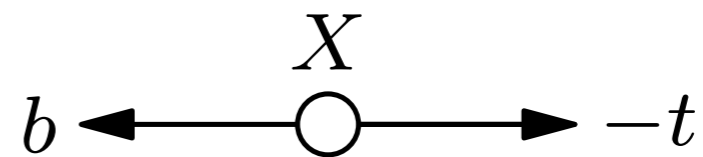
Antenna Showers

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 $X = W \implies W$ 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"



RF Showers 1: Antenna Functions



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!

$$\text{Ant} = \left| \begin{array}{c} \xrightarrow{t} p_a \quad \xrightarrow{t^*} \quad \xrightarrow{b} p_k \\ \text{red wavy } p_j \quad \text{black wavy } p_X \end{array} + \begin{array}{c} \xrightarrow{t} p_a \quad \xrightarrow{b^*} \quad \xrightarrow{b} p_k \\ \text{black wavy } p_X \quad \text{red wavy } p_j \end{array} \right|^2 / \text{Born}$$





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

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





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

→ same forms as FF, IF, II :*

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

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

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

↑
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



RF Showers 2: Evolution Variables



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!

Emissions:

Generalisation
of ARIADNE
 p_T

$$Q_{\text{evol}}^2 = \frac{s_{aj}s_{jk}}{s_{jk} + s_{AK}}$$

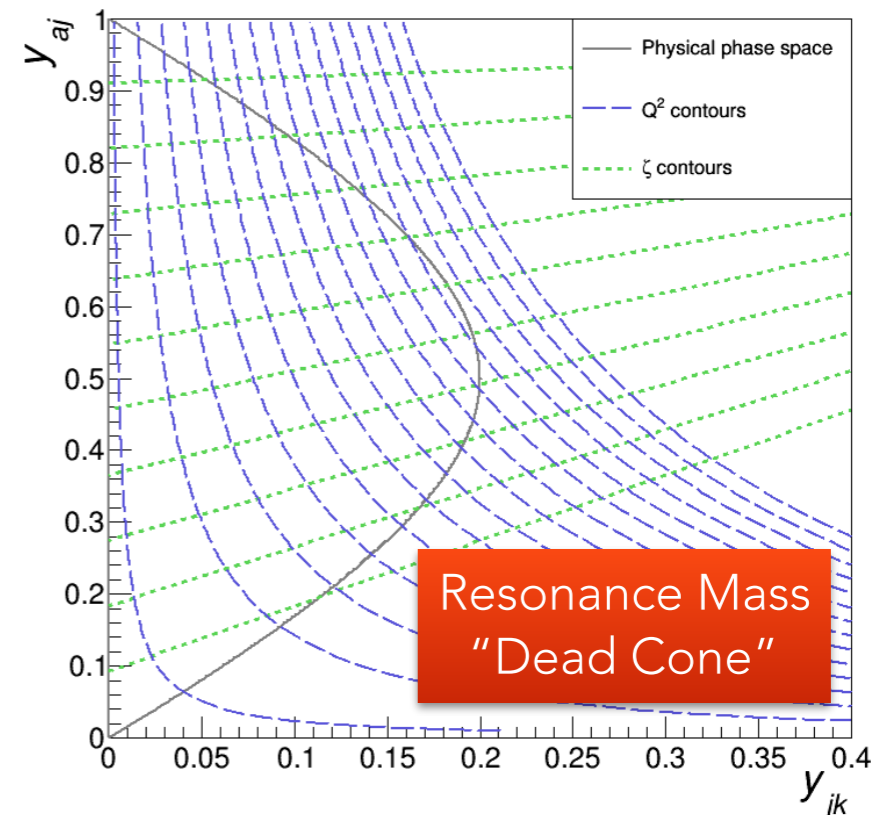
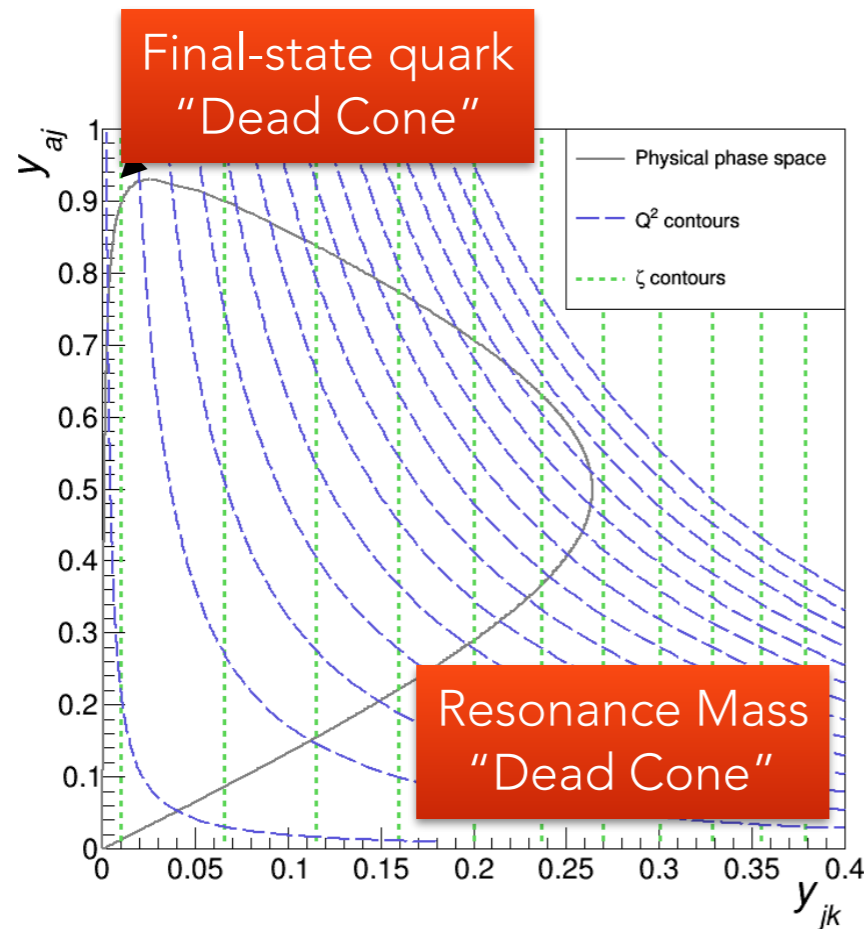
$$\zeta = \frac{s_{jk} + s_{AK}}{s_{AK}}$$

Same since
 $m_j = 0$ for
emission

Splittings:

$$Q_{\text{evol}}^2 = \frac{(s_{jk} + 2m_q^2)(s_{aj} - m_q^2)}{s_{AK} + s_{jk} + 2m_q^2}$$

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





RF Showers 3: Phase-Space Factorisation



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

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

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

- ▶ Factorisation is exact, not just in soft, collinear limits
- ▶ Preserves invariant mass of resonance: $p_A = p_a$
- ▶ Preserves invariant mass of **system of recoilors**:

$$p_A = p_K + p_X \implies m_X^2 = (p_A - p_K)^2 \equiv (p_a - p_j - p_k)^2 = m_X^2,$$

$$\frac{d\Phi_{a \rightarrow jk + \{X\}} = \frac{1}{(4\pi)^5} \frac{ds_{aj} ds_{jk} d\phi}{m_A^2} d\Omega_K}{d\Phi_{A \rightarrow K + \{X\}} = \frac{1}{8(2\pi)^2} \frac{\lambda^{1/2}(m_A^2, m_{AK}^2, m_K^2)}{m_A^2} d\Omega_K} \longrightarrow d\Phi_{\text{ant}} = \frac{1}{16\pi^2} \frac{ds_{aj} ds_{jk}}{\lambda^{1/2}(m_A^2, m_{AK}^2, m_K^2)} \frac{d\phi}{2\pi}$$

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)



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

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** simultaneously 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

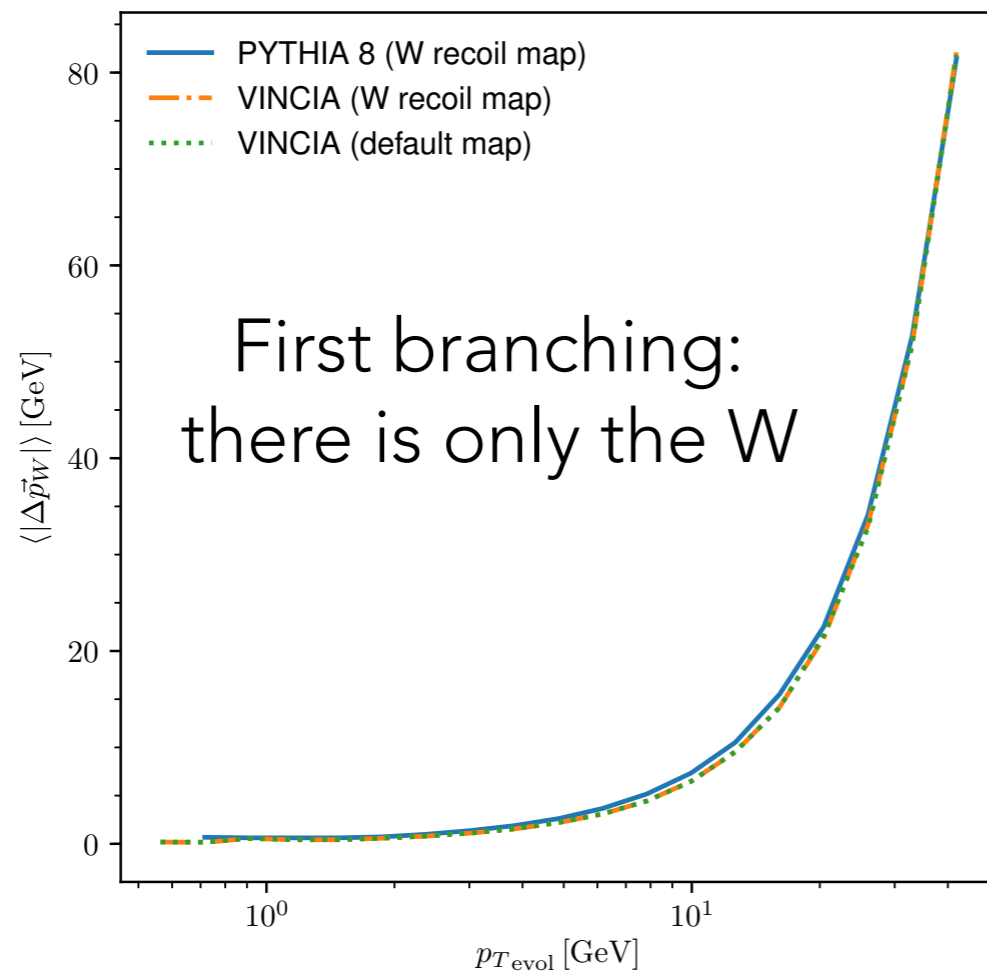


Effect of Kinematics Map

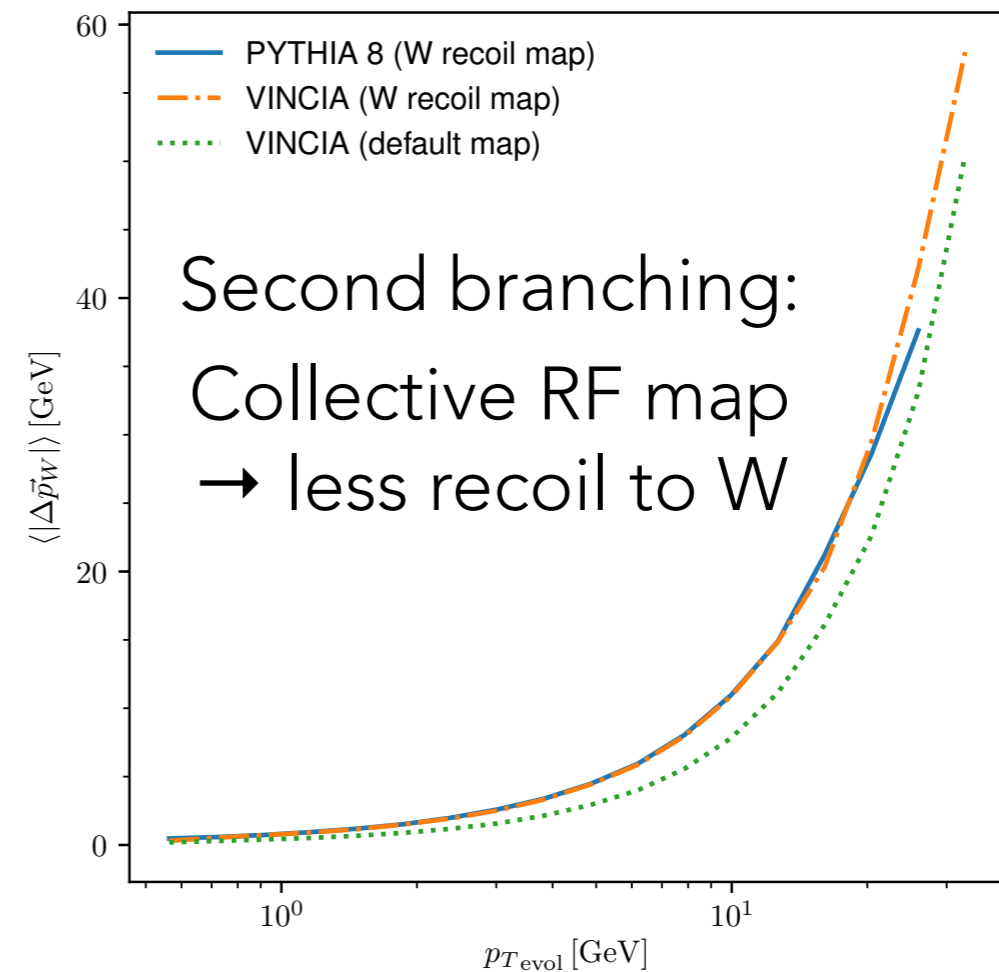


Consider average recoil $|\Delta\vec{p}_W|$, after first and second emission(s).

Recoil after first:



Recoil after second:

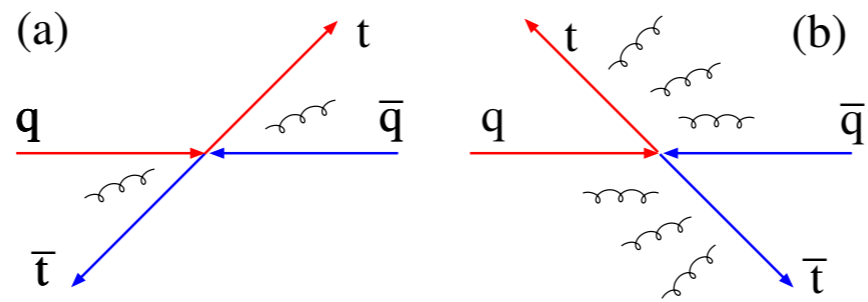




(Coherence In Production)

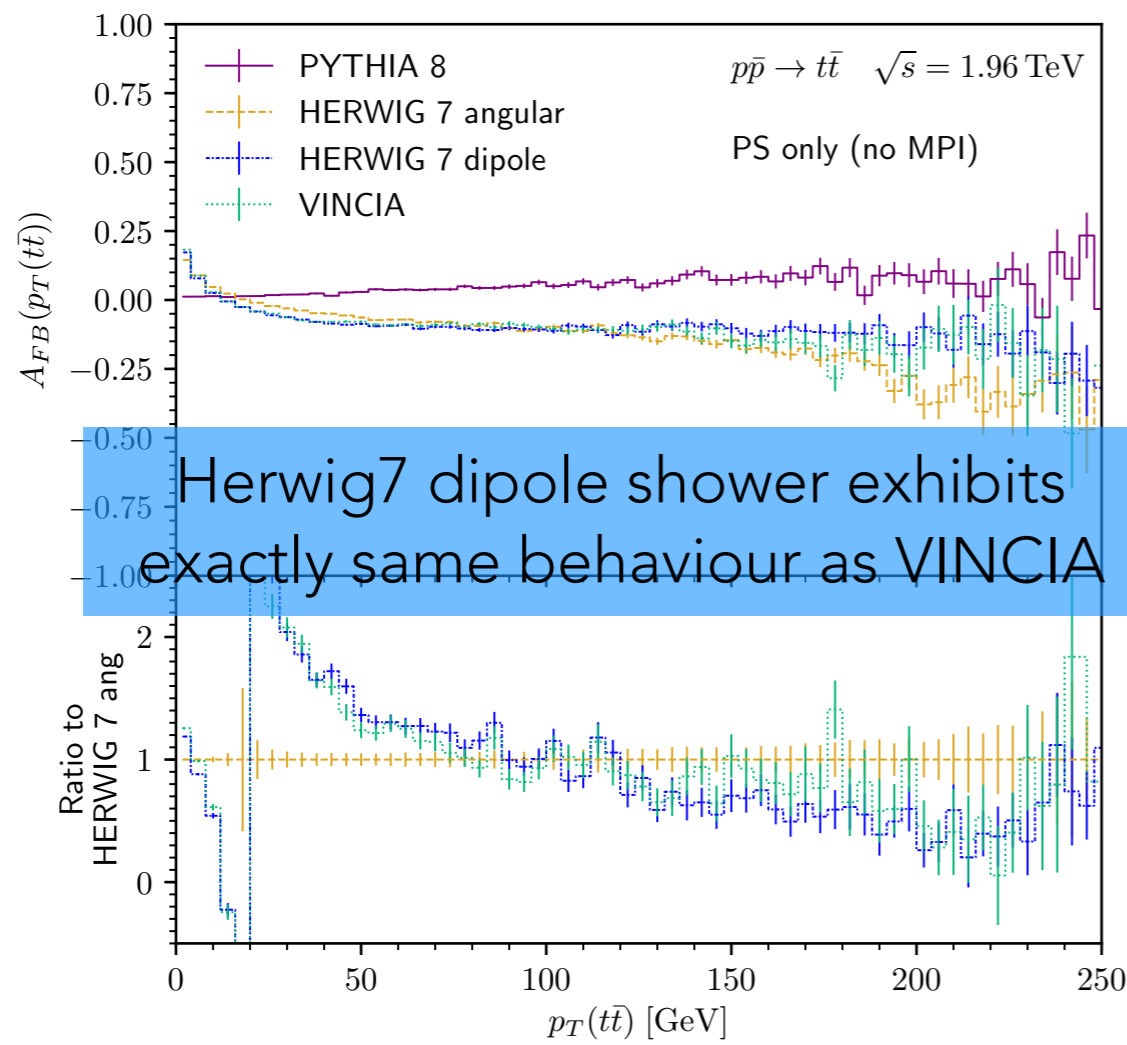


Well-studied effect in p-pbar collisions
Top quark FB asymmetry



Skands, Webber, Winter JHEP 1207 (2012) 151

Coherent showers produce a p_T dependent asymmetry



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 $p_T(tt)$. [1205.1466]

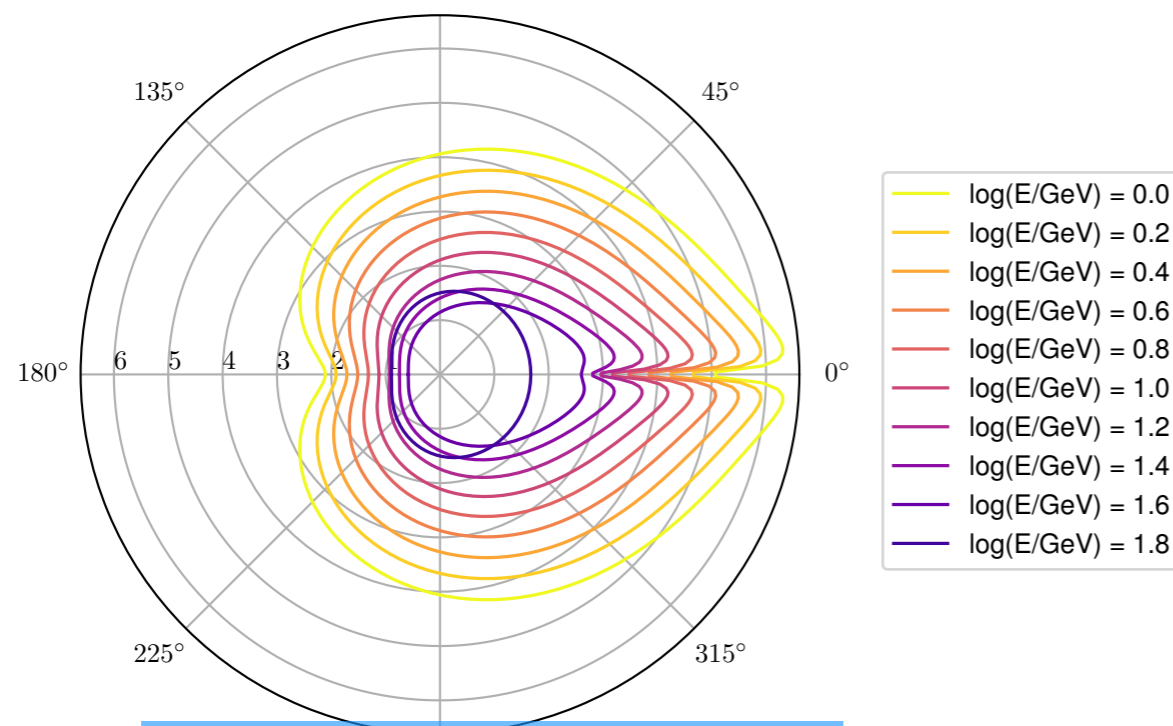




Coherence in Decay

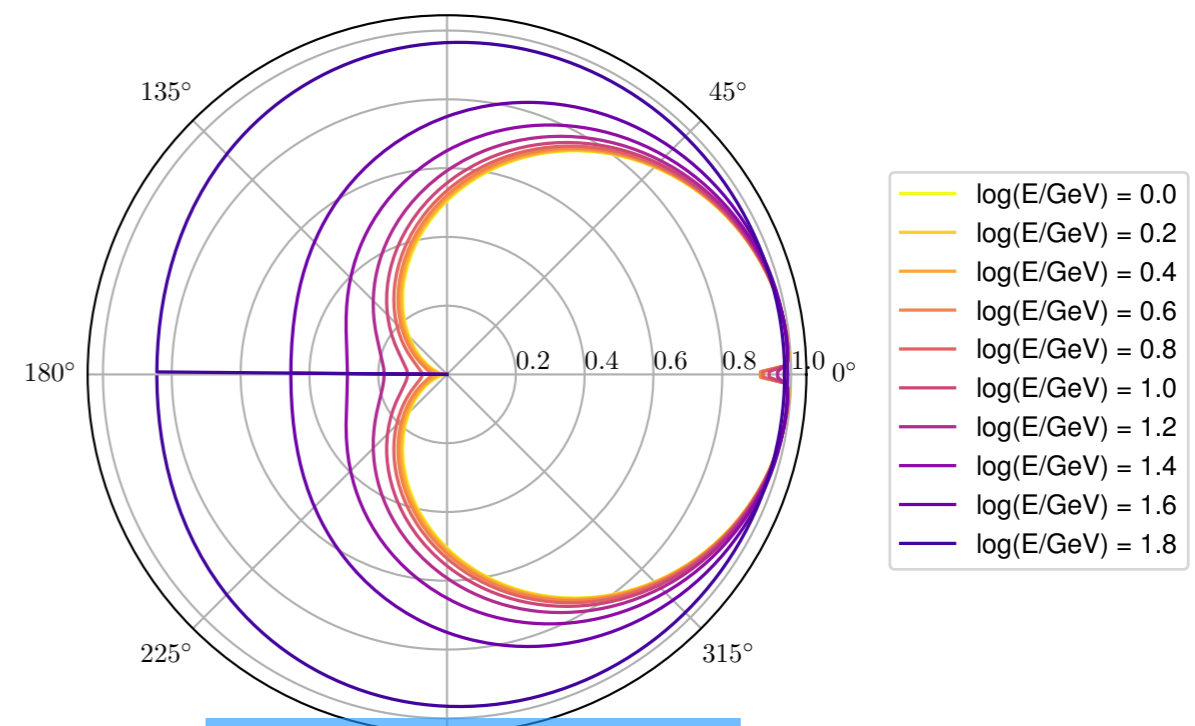
Plot antenna function in top centre of mass frame (b along z):

$\log_{10}(a_{g/qq}^{\text{RF}} s_{AK})$ as a function of θ_{jk} in A COM frame



Log of antenna function

$\frac{a_{g/qq}^{\text{RF}}}{P_{gq}(z)/Q^2}$ as a function of θ_{jk} in A COM frame



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.



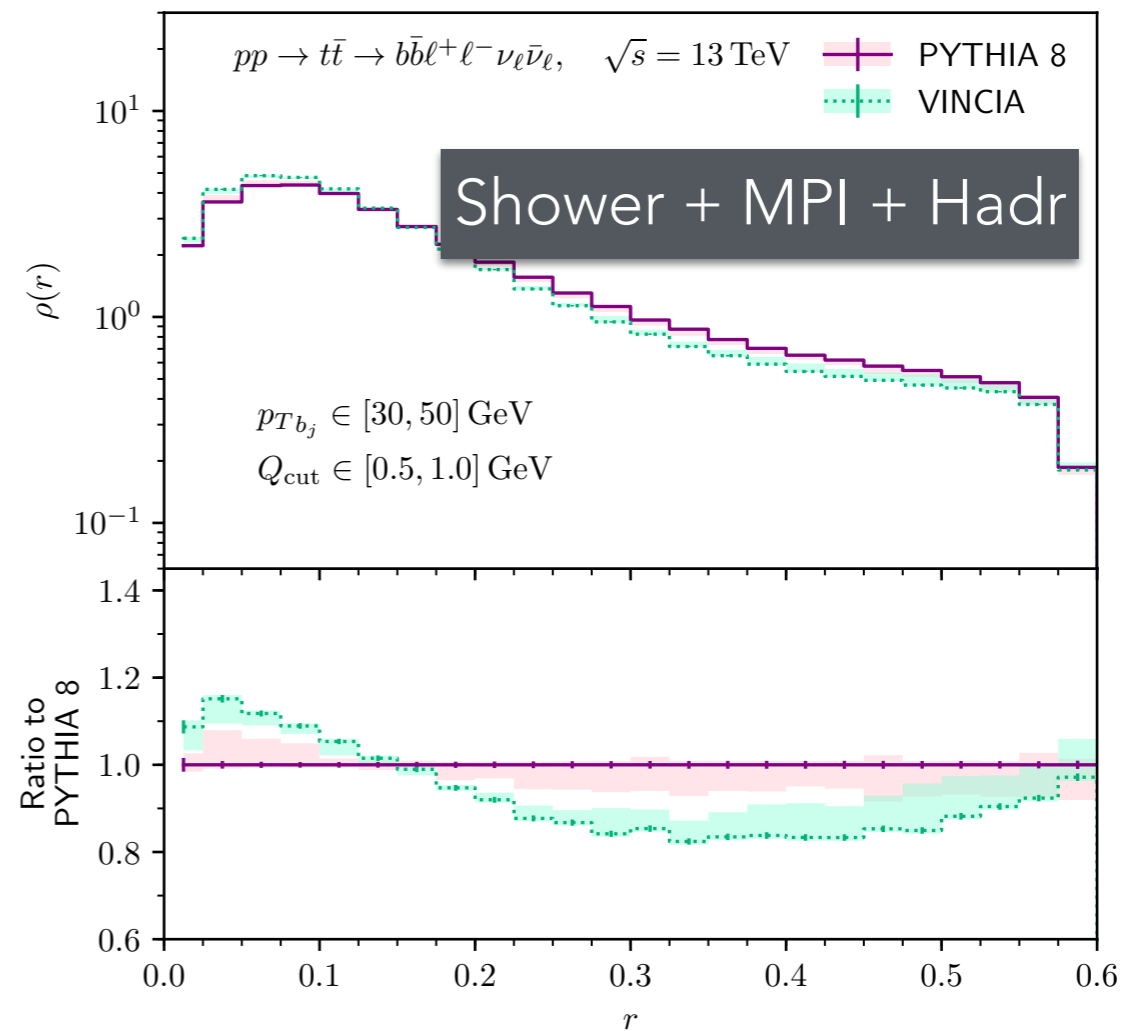
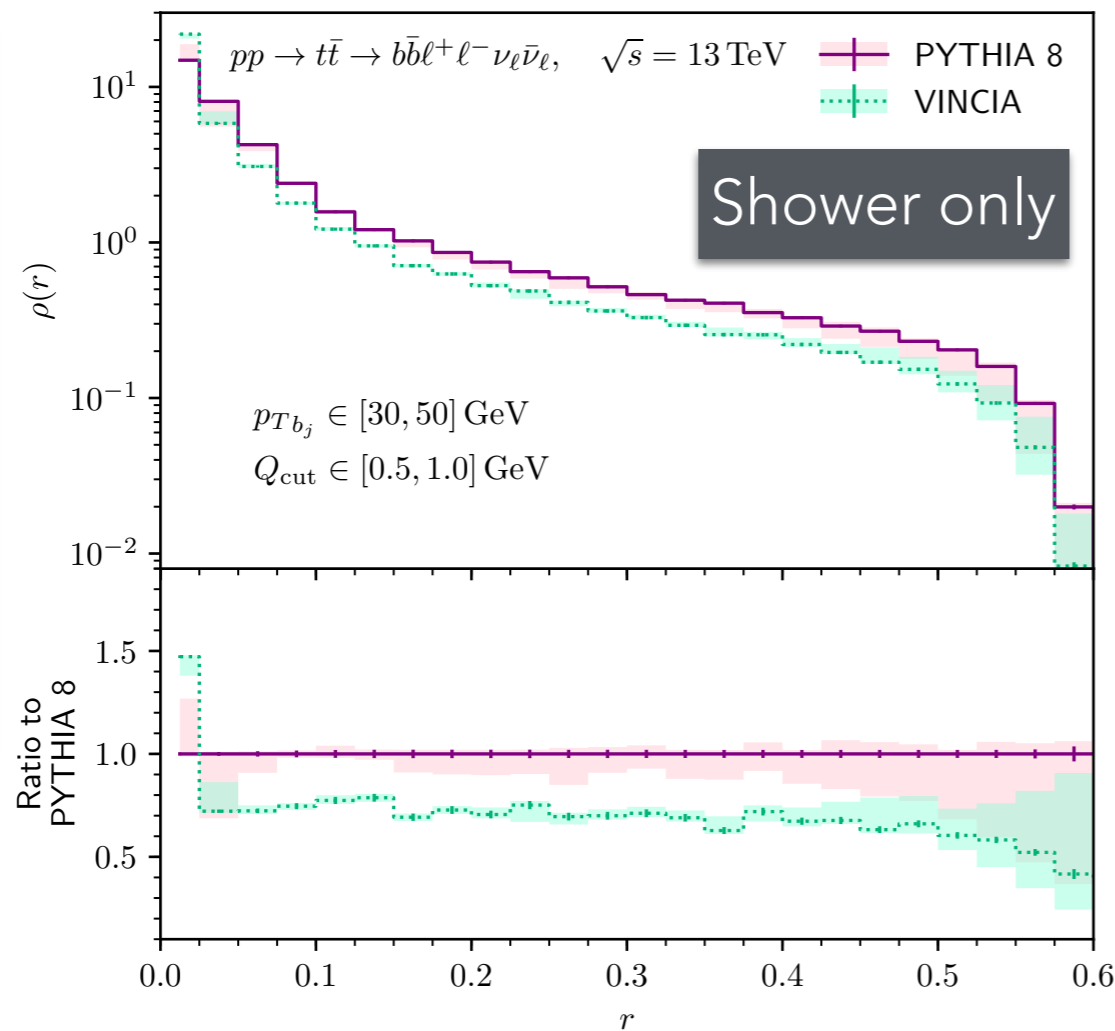
B-Jet Profiles



VINCIA gives narrower b-jets than Pythia 8

Effect survives MPI + hadronisation

Differential jet shape $\rho(r)$



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

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



Matching with POWHEG



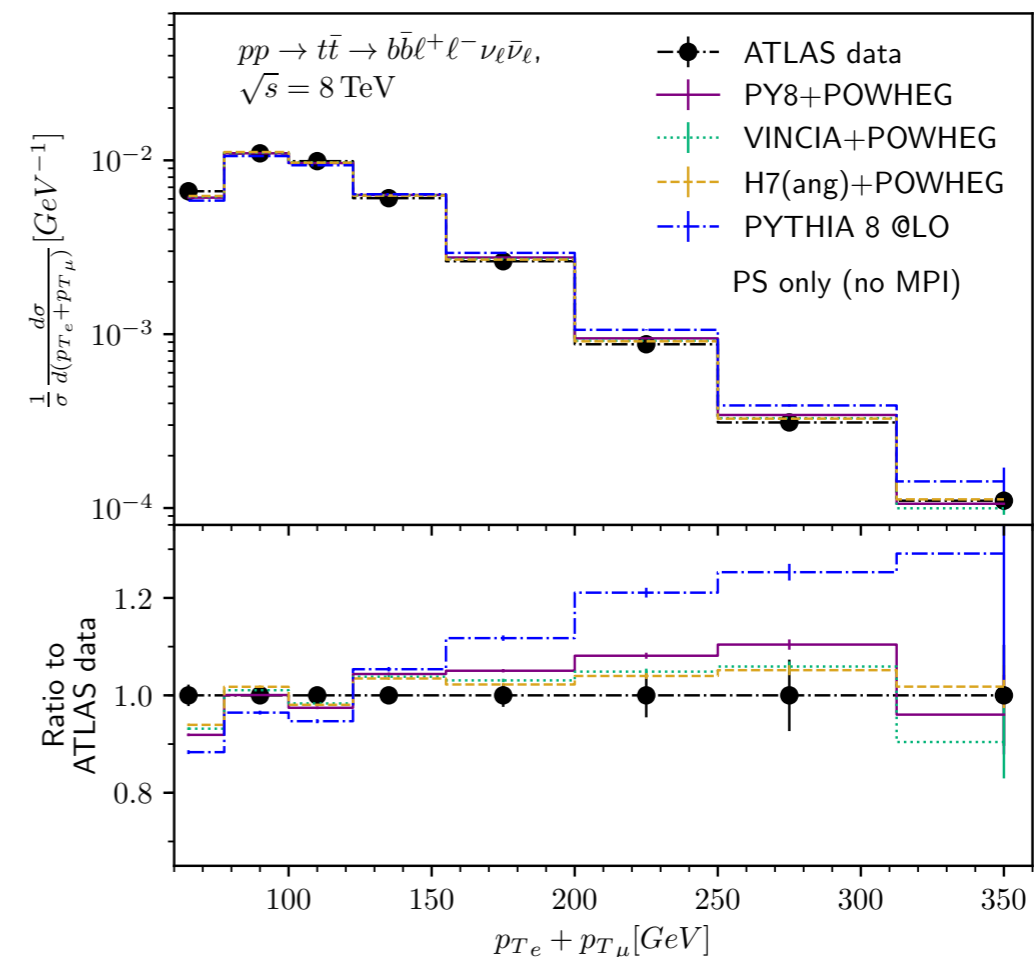
- ▶ Use POWHEG v2 ($t\bar{t}dec$)¹
(no need for exact finite width effects)
- ▶ **Very** similar setup to matching with PYTHIA in ².
- ▶ Veto hardest emission in production with
`Vincia:QmaxMatch = 1`
- ▶ Veto hardest emission in decay with UserHooks interface

¹ [1412.1828], [1509.0907]

² [1801.03944]

³ Thanks to S. Ferrario Ravasio for providing an interface to H7

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





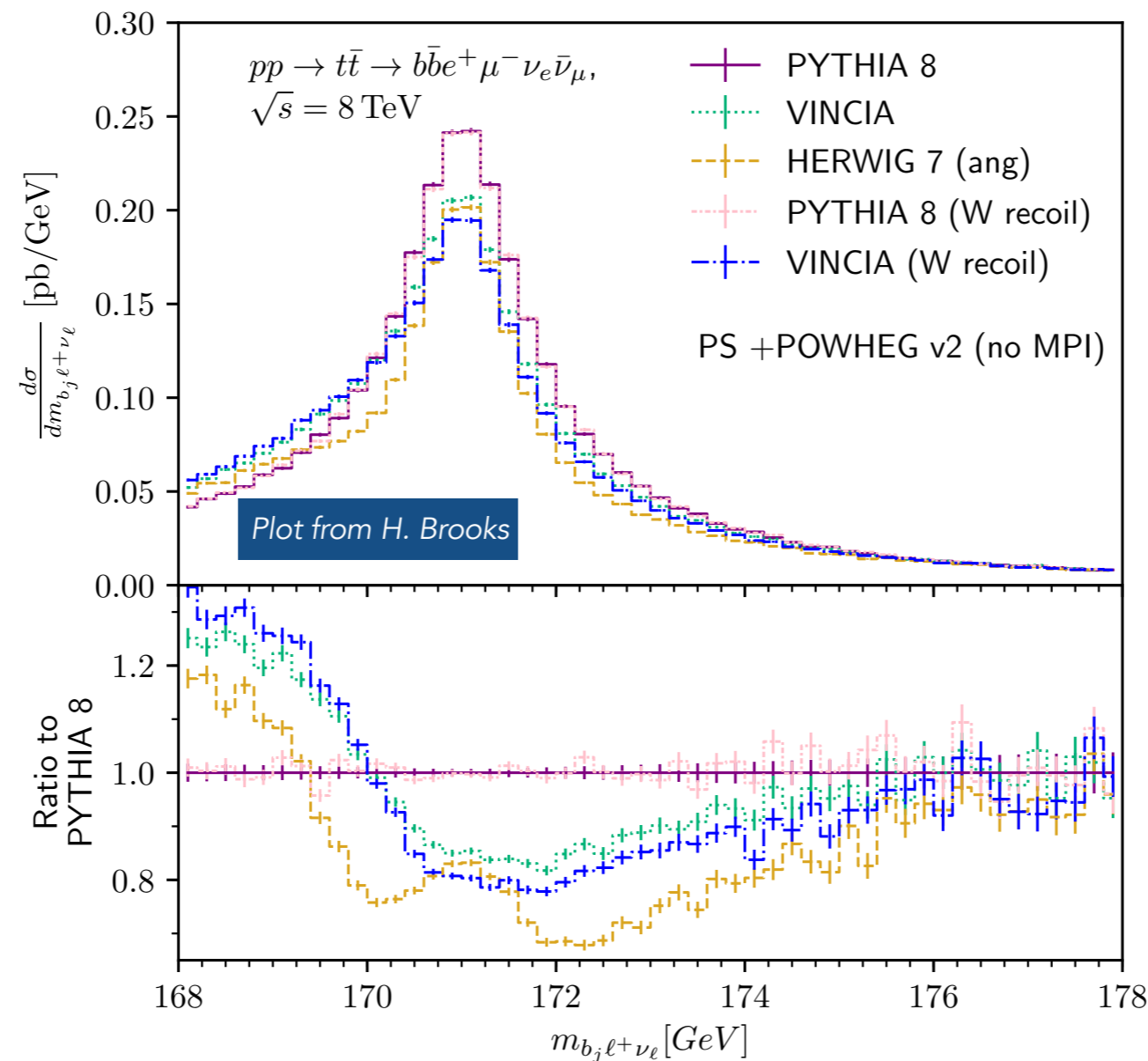
Top Mass Profile @ 8 TeV : Parton Level



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

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

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





Conclusions & Outlook



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 → Watch this space!





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 μ_R , 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 $\approx \Lambda_{\text{QCD}}$,
(colour-reconnections, MPI, beam remnant treatment, hadronisation,
hadron rescattering, hadron and τ decays, ...)



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



Shower Architectures

Table from H. Brooks

Type	Singularities		Coherence?	No dead zones?	Examples
	soft	collinear			
DGLAP	part.	full	X	X	
Angular	full+veto	full+veto	✓	X	H7 \tilde{q}
Dipole	part.	part.	X	✓	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





Current Status of Resonance Decay Showers

Slide from H. Brooks

Shower	Type	Decay shower?	Coherence?
Pythia 8 [hep-ph/0010012] [hep-ph/0408302]	Dipole	✓	✗
Sherpa [1412.6478]	Catani-Seymour	✗ (production only)	(✓)
Herwig 7 (\tilde{q}) [1810.06493]	Angular-ordered	✓	✓
Herwig 7 (dip) [1810.06493]	Catani-Seymour	(✓) (on-shell only)	(✓)
Vincia - NEW!	Antenna	✓	✓



Example: Collinear Limits



Example: qq antenna limits

Can rewrite antenna as:

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

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

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

In collinear limit, $y \rightarrow 0$

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

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

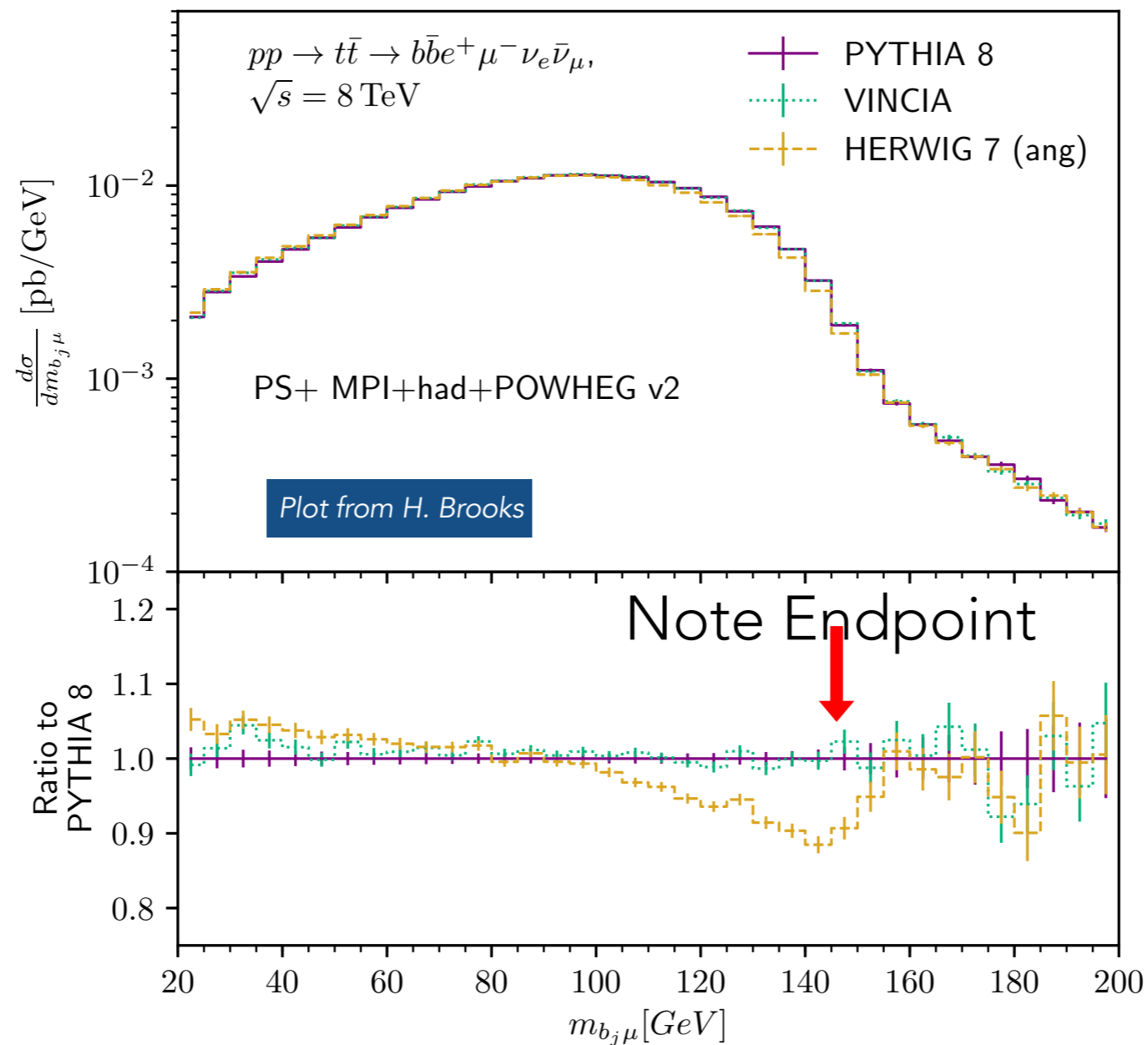


Top Mass Profile @ 8 TeV



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

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

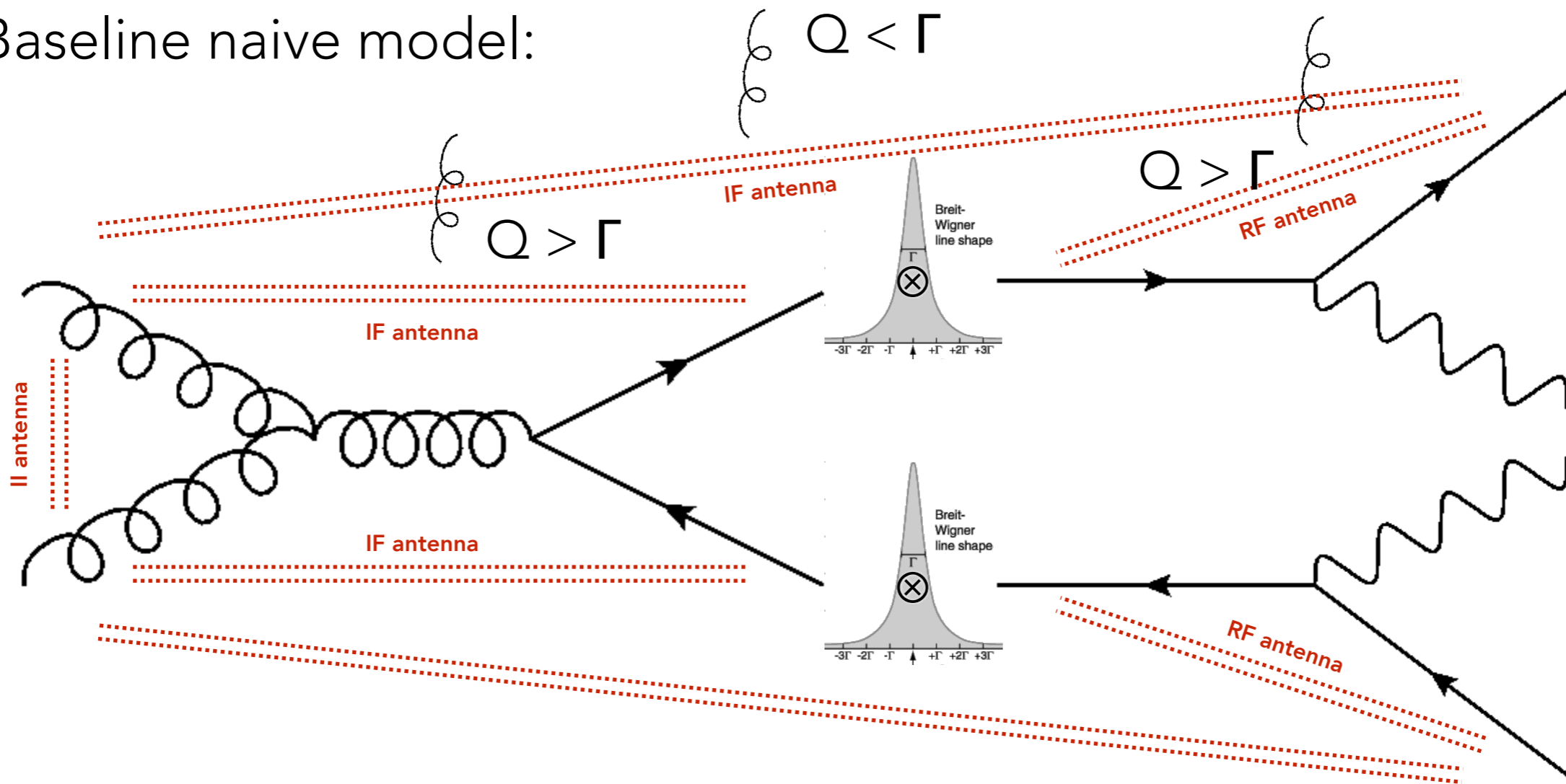




Outlook

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