Interleaved Resonance Decays

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Resonances appear in a broad variety of settings

SM resonances (W, Z, top, H) (+ in principle same physics among hadrons)

+ additional ones from BSM ?

How (accurately) do we model their production and decay processes?

1) Pole approximation: $\delta(p^2 - m_0^2)$

2) Breit-Wigner approximation ~ F.T. of exponential-decay law

3) **Beyond** the Breit-Wigner Approximation: running widths, non-resonant interferences, **radiative corrections**, …

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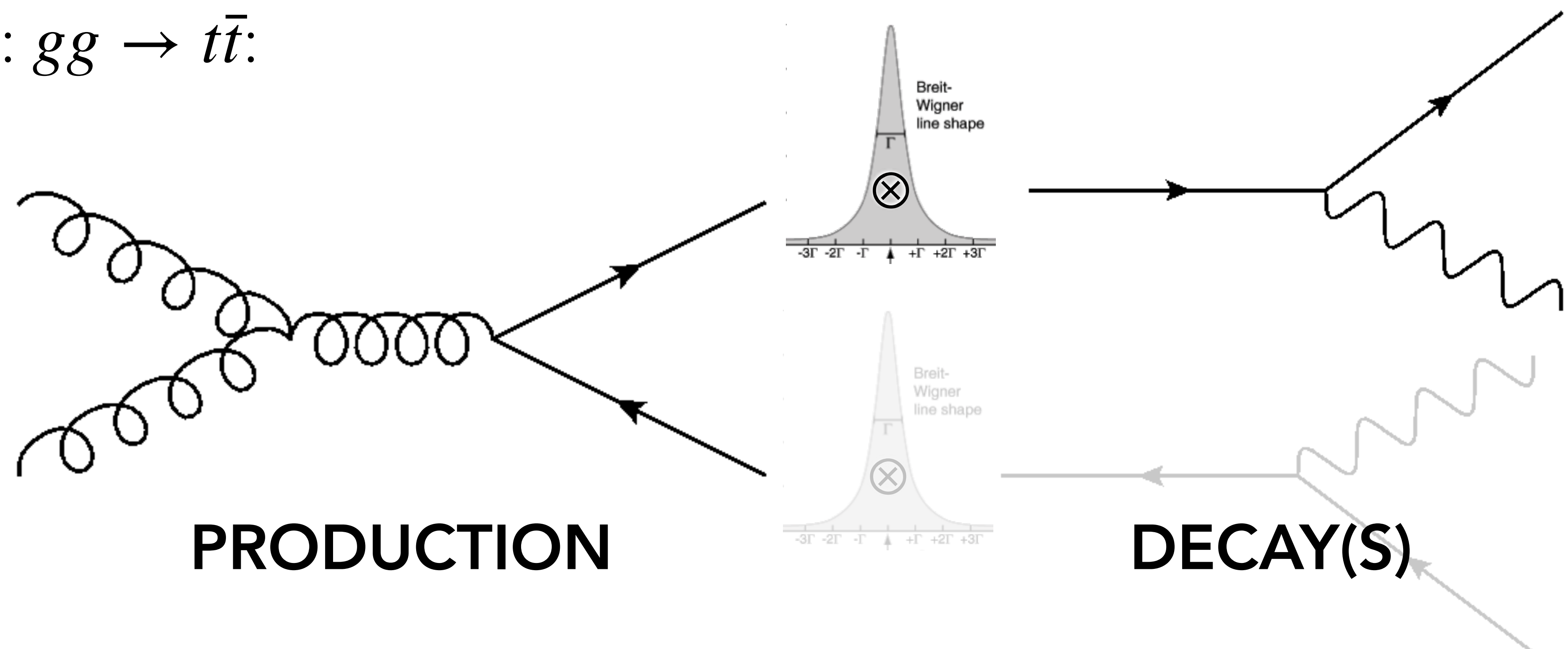
Resonance Production & Decay

In limit Γ ~ 0, factorise **production** and **decay**

First step towards including $\Gamma \neq 0$: Breit-Wigner-improved pole approx:

Replace $\delta(p^2 - m_0^2)$ by $\mathrm{BW}(p^2) = \frac{1}{\pi}\frac{m_0\Gamma_0}{(p^2 - m_0^2)^2 + m_0^2\Gamma_0^2}$

Example: $gg \to t\bar{t}$:



Leading Order
Breit-Wigner-improved Pole Approximation
$\Longrightarrow$ Decay system has BW-distributed mass

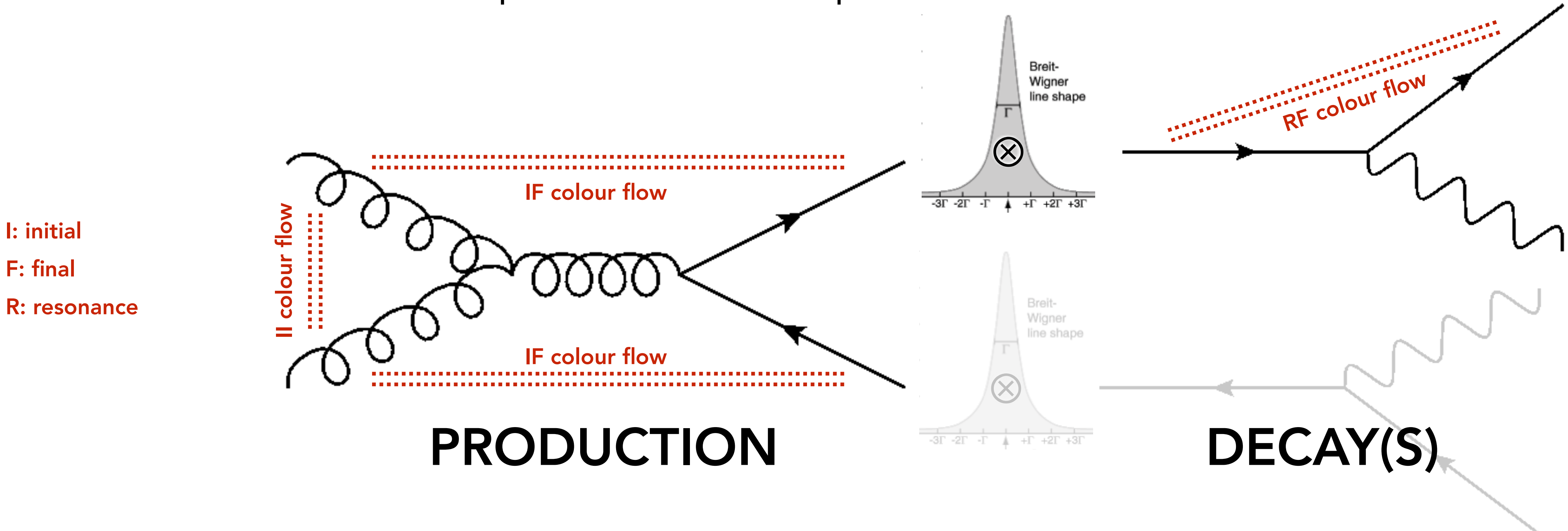
Radiative Corrections

Experiments reconstruct jets, not partons

How does a process with resonances radiate (and hadronise)?

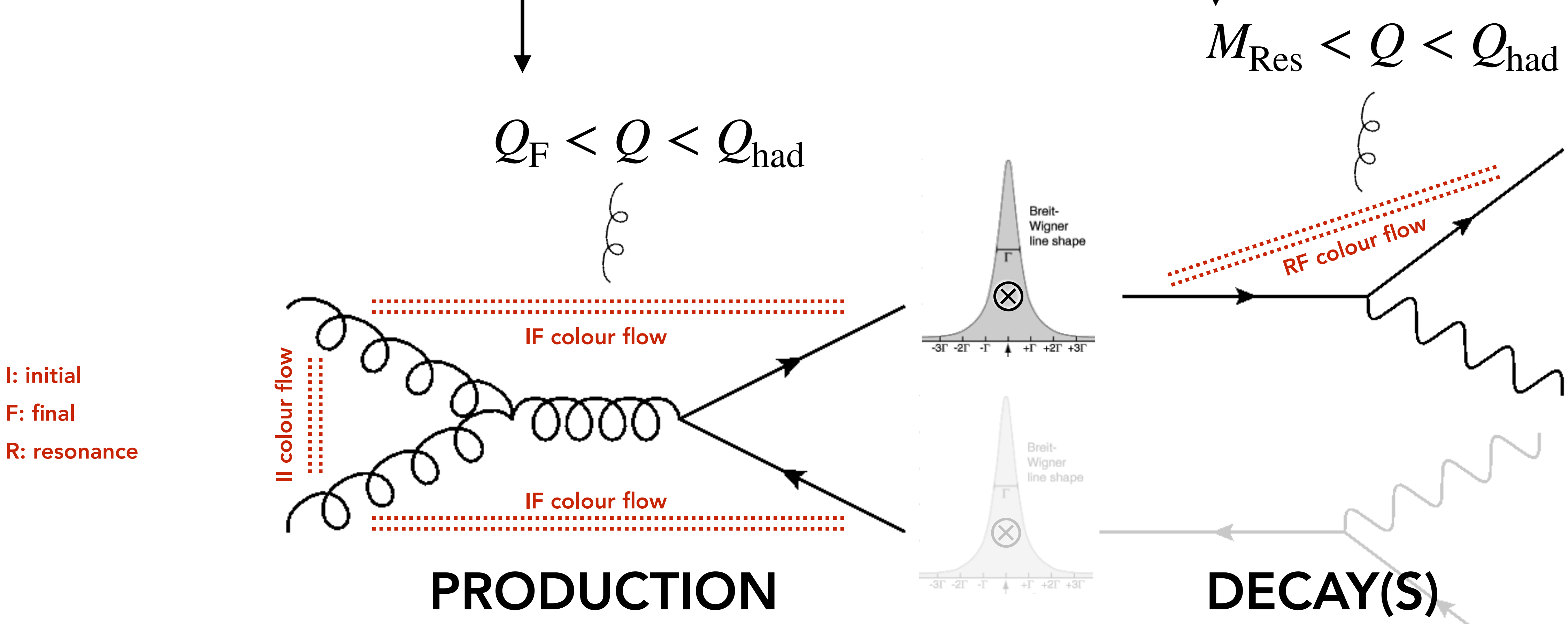
Again, first step = factorise production and decay

Colour flow $\Longrightarrow$ dipole radiation patterns



Production and Decay stages are showered independently

First: treat produced resonance as stable… Then decay it.



Production ISR + FSR shower preserves Breit-Wigner shape

Resonance-Decay FSR showers preserves Breit-Wigner shapes

Resonance Showers

Production and Decay stages are showered independently

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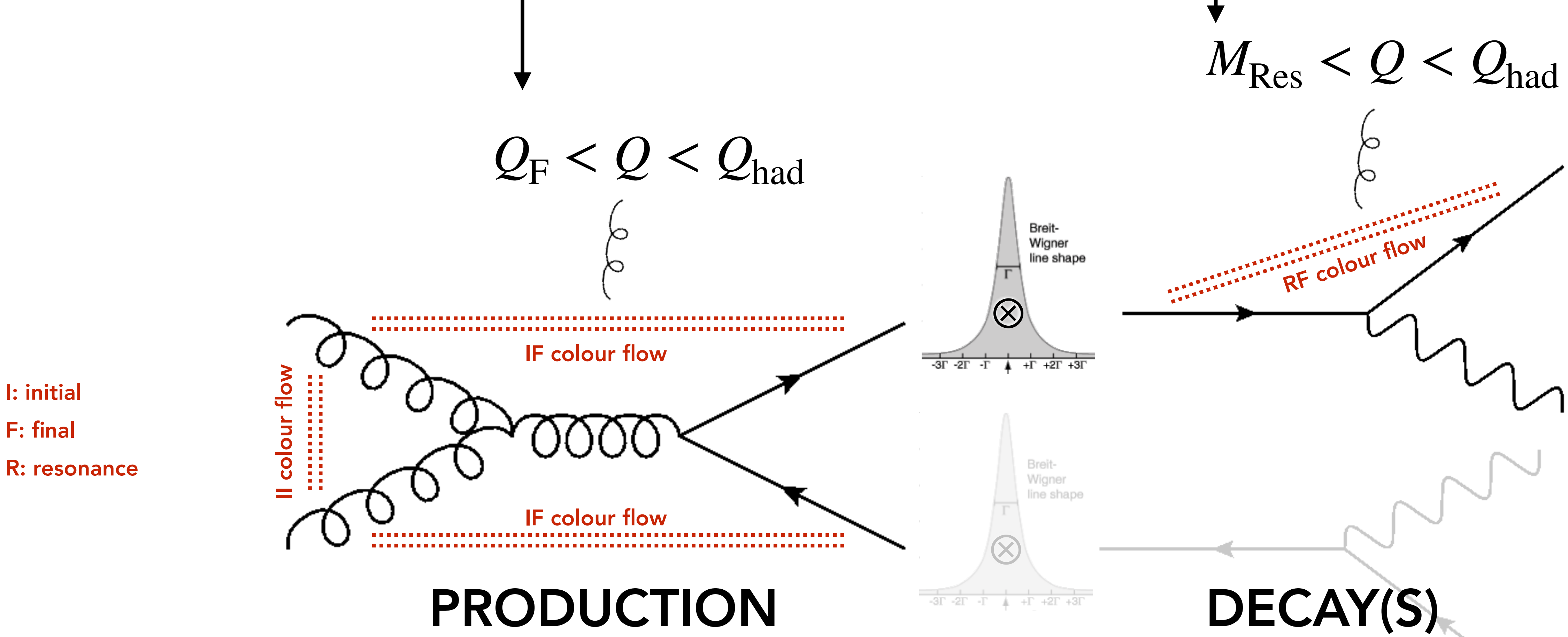


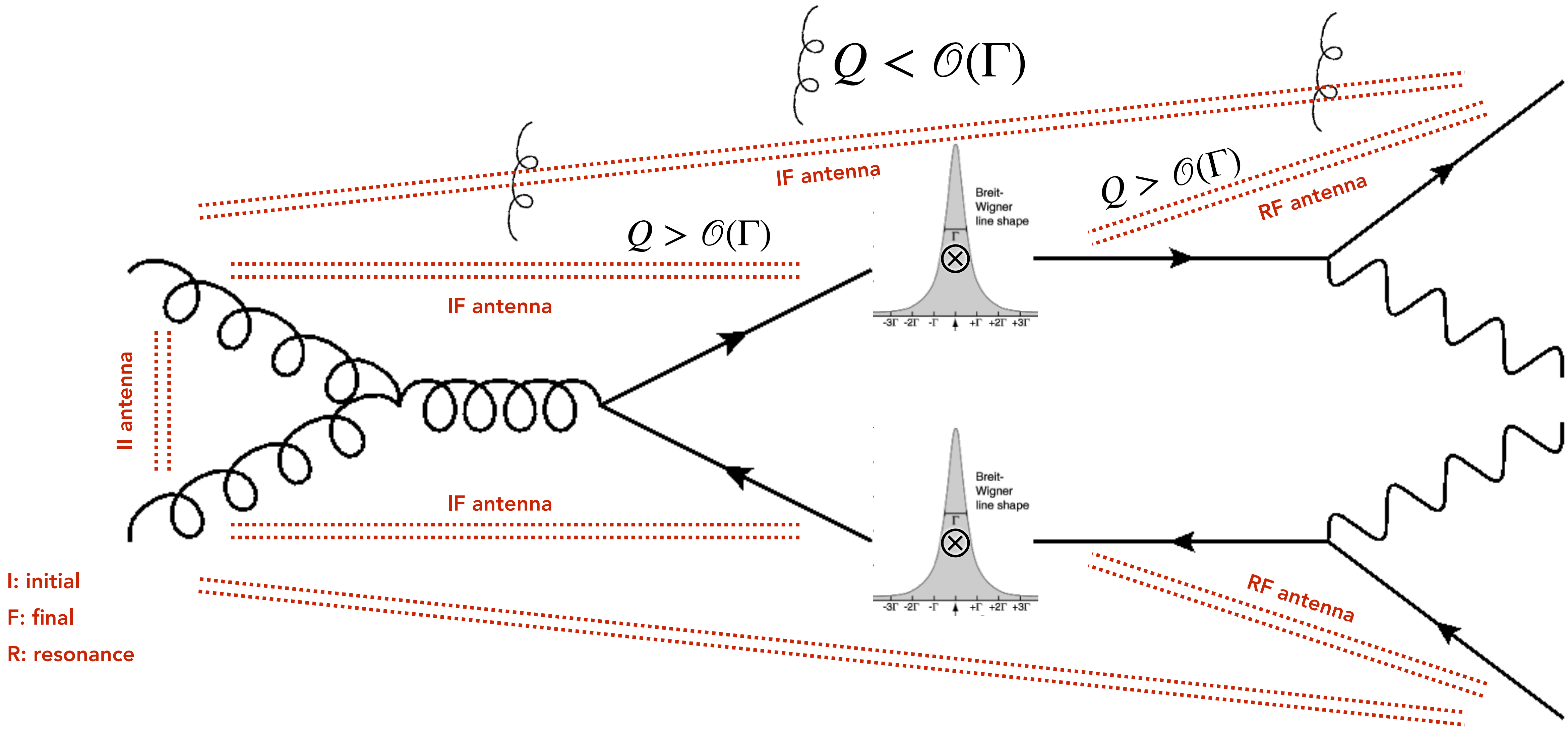
Production ISR + FSR shower preserves Breit-Wigner shape

Resonance-Decay FSR showers preserves Breit-Wigner shapes

Question: what if $\Gamma > Q_{\mathrm{had}} \sim 1\,\mathrm{GeV}$?

What if $\Gamma > Q_{\mathrm{had}}$?

Interference between production and decay stages?



Could distort Breit-Wigner shape ? ↔ Affect experimental mass reconstructions?

(Note: separate from, and in addition to, any non-resonant interferences)

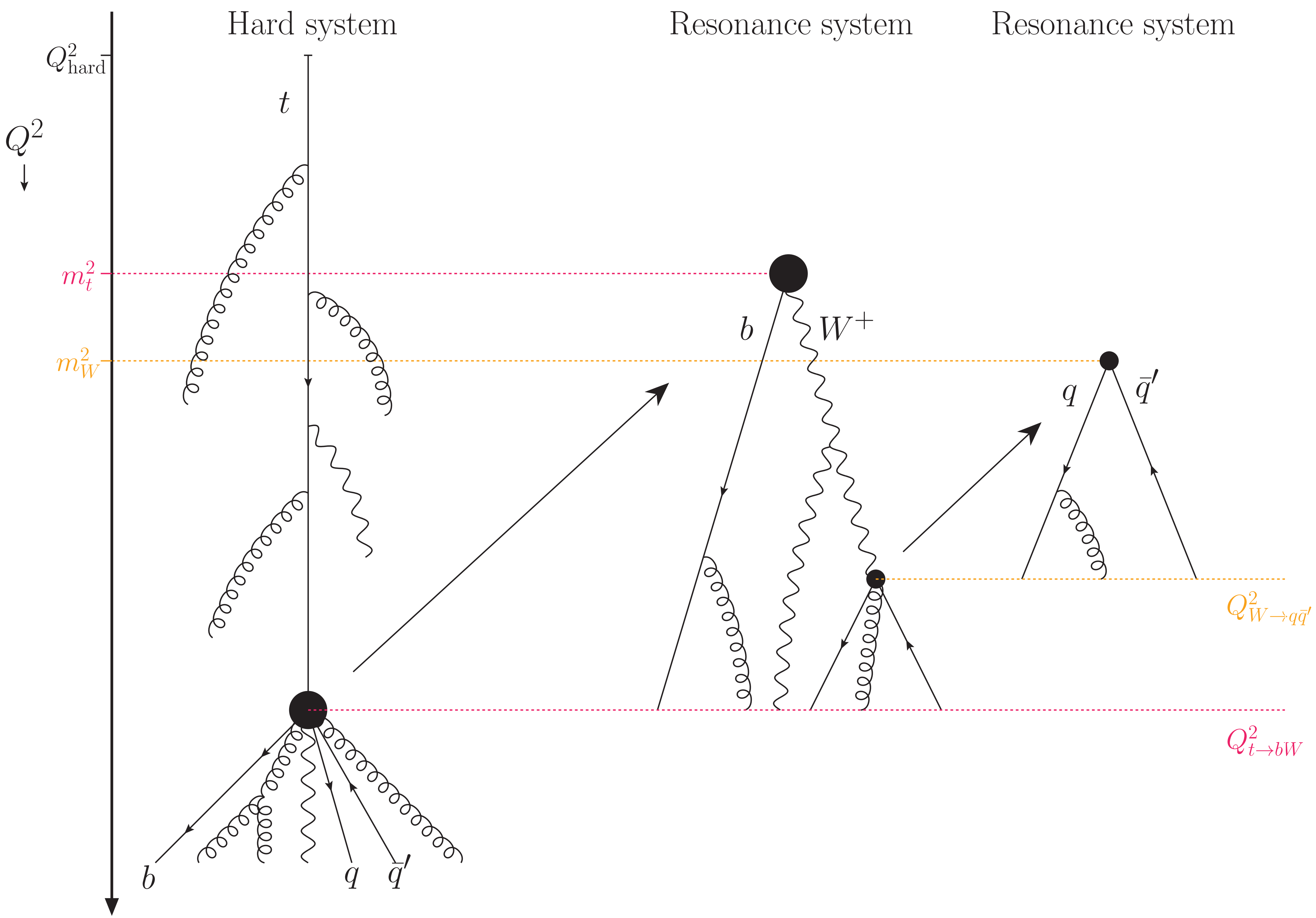
Also relevant for non-SM resonances with $\Gamma \gg \mathcal{O}(1\,\mathrm{GeV})$

Heuristic Arguments

Here, we note that the BWPA is, strictly speaking, not quite consistent with the strong-ordering condition in parton showers. Strong ordering expresses the simple fact that the leading singularity structures of QCD (and QED) amplitudes correspond to Feynman diagrams in which each successive propagator has a much smaller virtuality than the preceding one (or next one, for initial-state legs). Physically, this reflects a formation-time principle; short-lived fluctuations do not have time to emit low-frequency radiation. However, for unstable particles in the BWPA, one can have precisely the situation that a particle which has nominally been assigned an invariant mass quite different from the pole value does emit low-frequency radiation. In the corresponding Feynman amplitudes, there are then two (or more) off-shell propagators, which ought to be suppressed relative to amplitudes in which the low-frequency radiation is emitted after the decay. This leads us to consider an interleaved paradigm for showers off resonance-production + decay processes, in which resonance decays are inserted in the overall event evolution when the perturbative evolution scale reaches a value of order the width of the resonance. [Should

Note: we do not expect **large** finite-width effects for resonances with $\Gamma < \mathcal{O}(1\,\mathrm{GeV})$ (i.e., all SM resonances), cf e.g., Khoze & Sjöstrand Phys.Lett. B328 (1994) 466-476

Interleaved Resonance Decays in Vincia



Resonance Production and Decay in Vincia

For 8.303: **interleaved** resonance decays (Brooks, Skands, Verheyen)

Insert decays in evolution at scale ~ BW off-shellness $Q^2 \equiv (m^2 - m_0^2)^2 / m_0^2$

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}Q^2} = \boxed{\frac{\mathrm{d}\mathcal{P}^{\mathrm{RES}}}{\mathrm{d}Q^2}} + \left(\frac{\mathrm{d}\mathcal{P}^{\mathrm{MPI}}}{\mathrm{d}Q^2} + \frac{\mathrm{d}\mathcal{P}^{\mathrm{ISR+FSR}}}{\mathrm{d}Q^2} \right) \times \exp\left[- \int_{Q^2}^{Q^2_{i-1}} \mathrm{d}Q'^2 \left(\frac{\mathrm{d}\mathcal{P}^{\mathrm{MPI}}}{\mathrm{d}Q'^2} + \frac{\mathrm{d}\mathcal{P}^{\mathrm{ISR+FSR}}}{\mathrm{d}Q'^2} \right) \right]$$

- Unstable resonances "disappear" from evolution at an average scale Q ~ Γ

  Cannot act as emitters or recoilers below that scale; only their decay products can do that.

  The more off-shell a resonance is, the higher the scale at which it disappears.

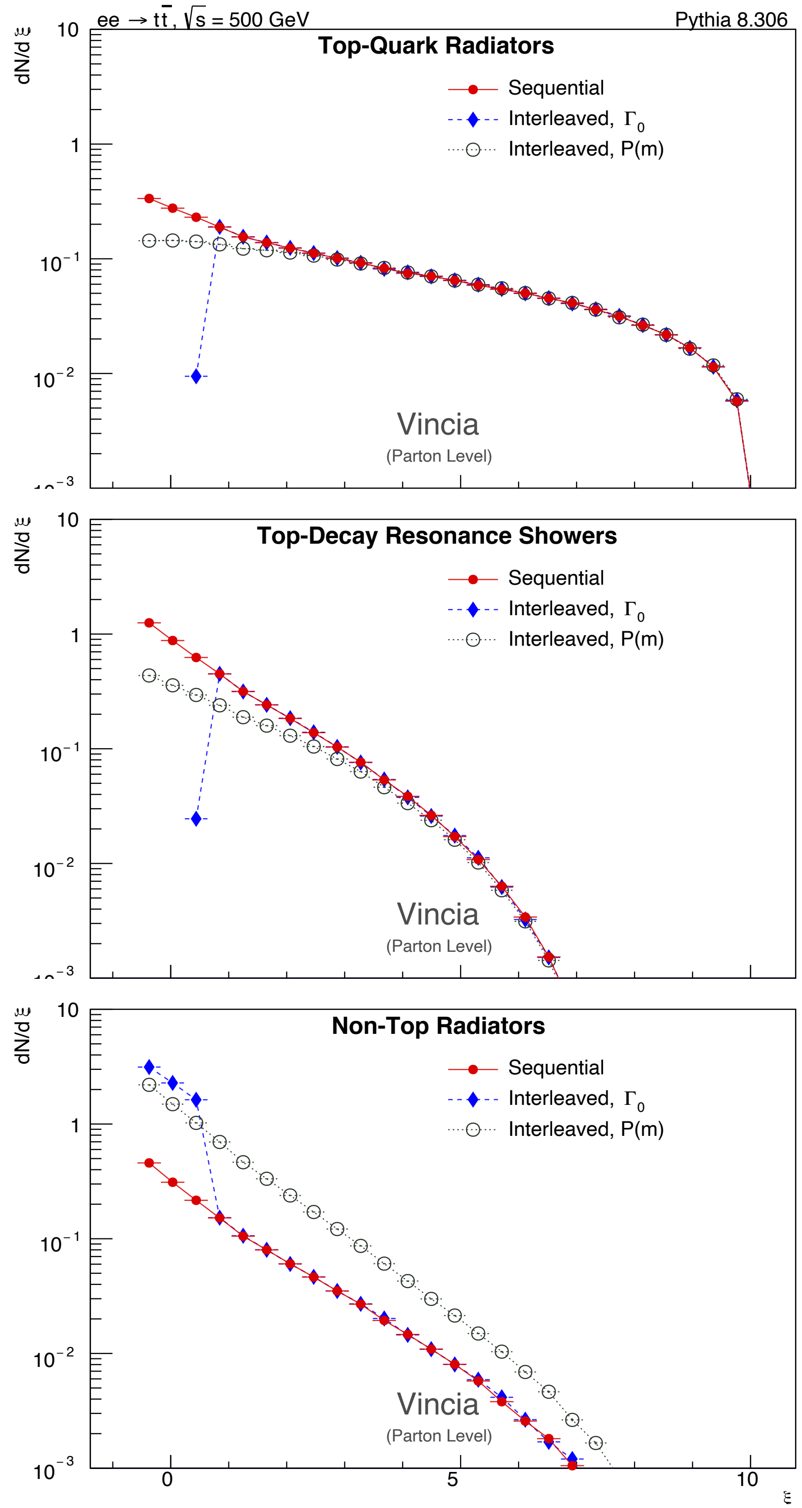
  Roughly corresponds to strong ordering (as measured by propagator virtualities) in rest of shower.

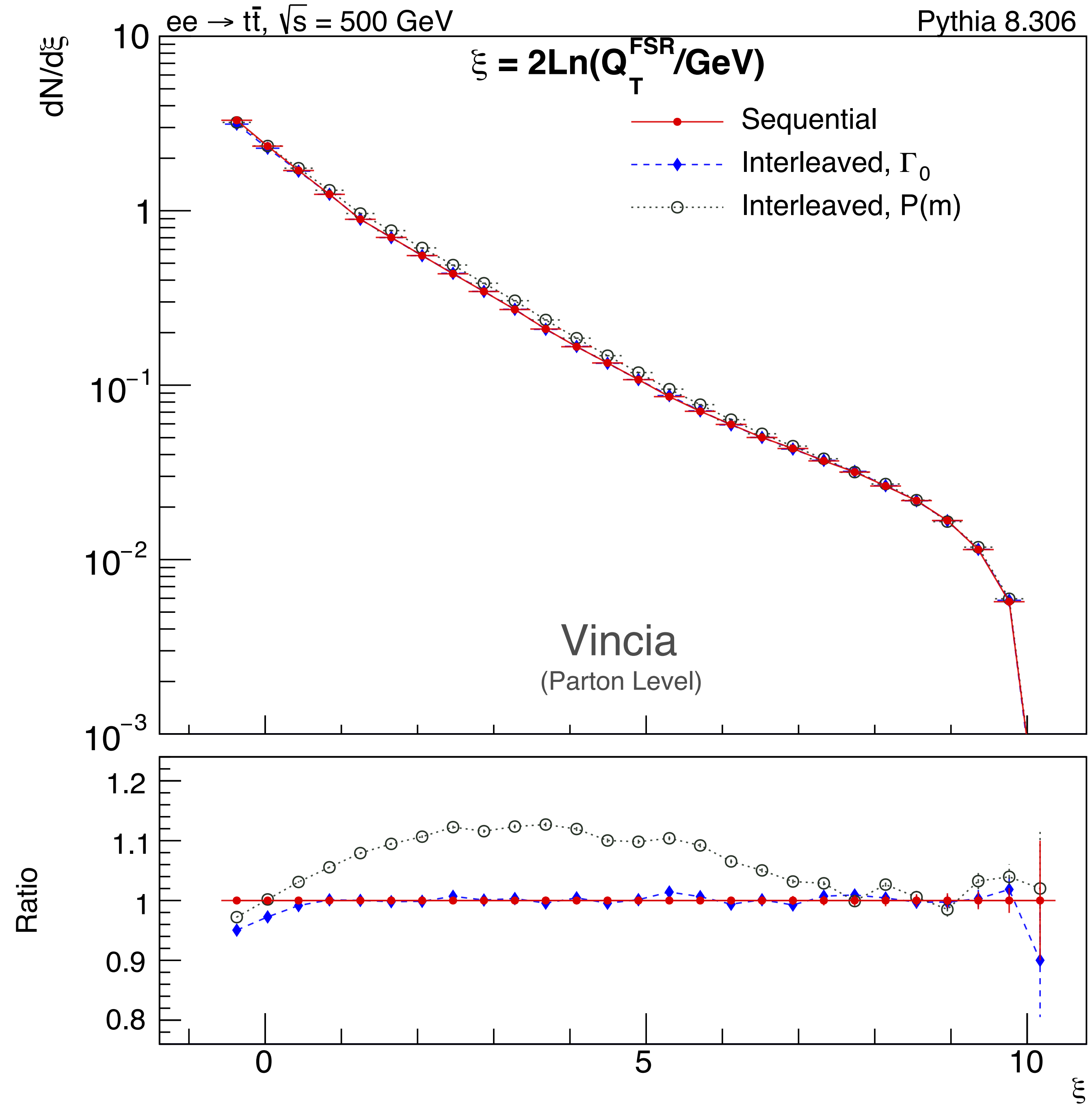
  Allows (suppressed) effects reaching scales > Γ

  (Interesting question: should top quarks close to shell be allowed to hadronize?)

Note: the term $\sum_R \mathrm{BW}_R$ is absent from the Sudakov factor since BW distribution is already unitary (a resonance decay happens once and only once)

Some consequences





Summary

To summarise, the main consequences of the interleaving of resonance decays with the rest of the perturbative evolution are:

- Due to the interleaving, unstable resonances effectively disappear from the evolution at an average scale $Q \sim \Gamma$. They will therefore not be able to act as emitters or recoilers for radiation below that scale; only their decay products can do that.
- After the resonance has disappeared, recoils to partons originating outside of the decay system are in principle allowed, and may distort the Breit-Wigner shape. In practice, such recoil effects are still expected to be relatively small, for several reasons. Firstly, the fact that the interleaving only "kicks in" below the offshellness scale limits any out-of-resonance recoil effects (e.g., in terms of $p_\perp$ kicks) to be smaller than that scale. Secondly, in decays of QCD colour singlets, such as Z and W bosons, there are no leading-colour (LC) dipoles to any partons outside of the decay system and hence no out-of-resonance QCD recoils at all. Even top-quark decays only involve a single such connection, corresponding to the colour flowing through the decay. Analogous arguments also apply to QED radiation, with $\alpha_s \to \alpha_{\mathrm{EM}}$ and the colour of the resonance replaced by its overall electric charge.
- With the dynamical choice of decay scale, highly off-shell particles disappear from the evolution at higher evolution scales than ones nearer the pole mass value, translating to an increasing distortion of the resonance shape further away from the pole. This roughly corresponds to the notion of strong ordering in the rest of the evolution.

Now applying to LHC top mass; paper due out within a week or two