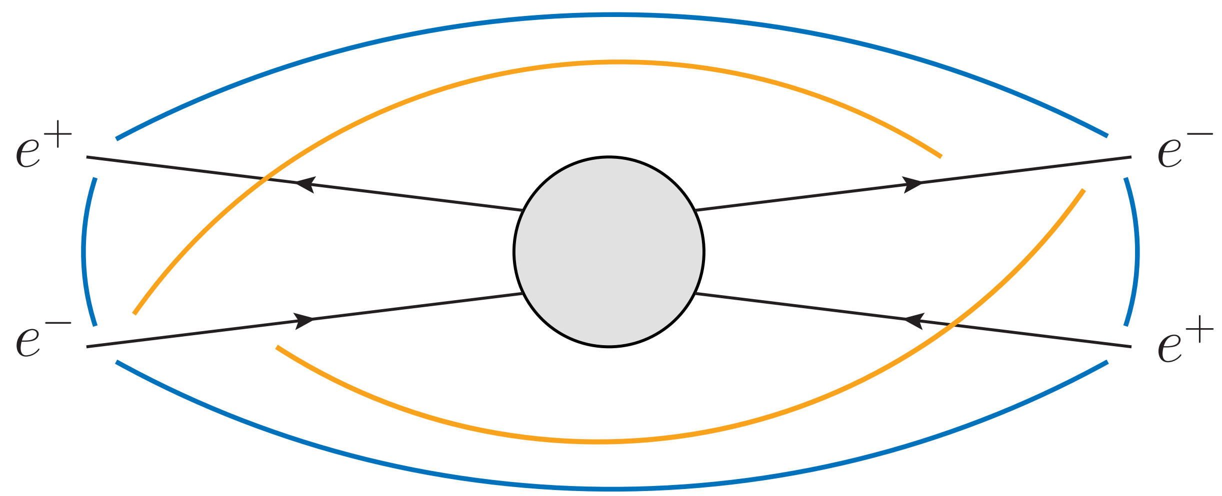
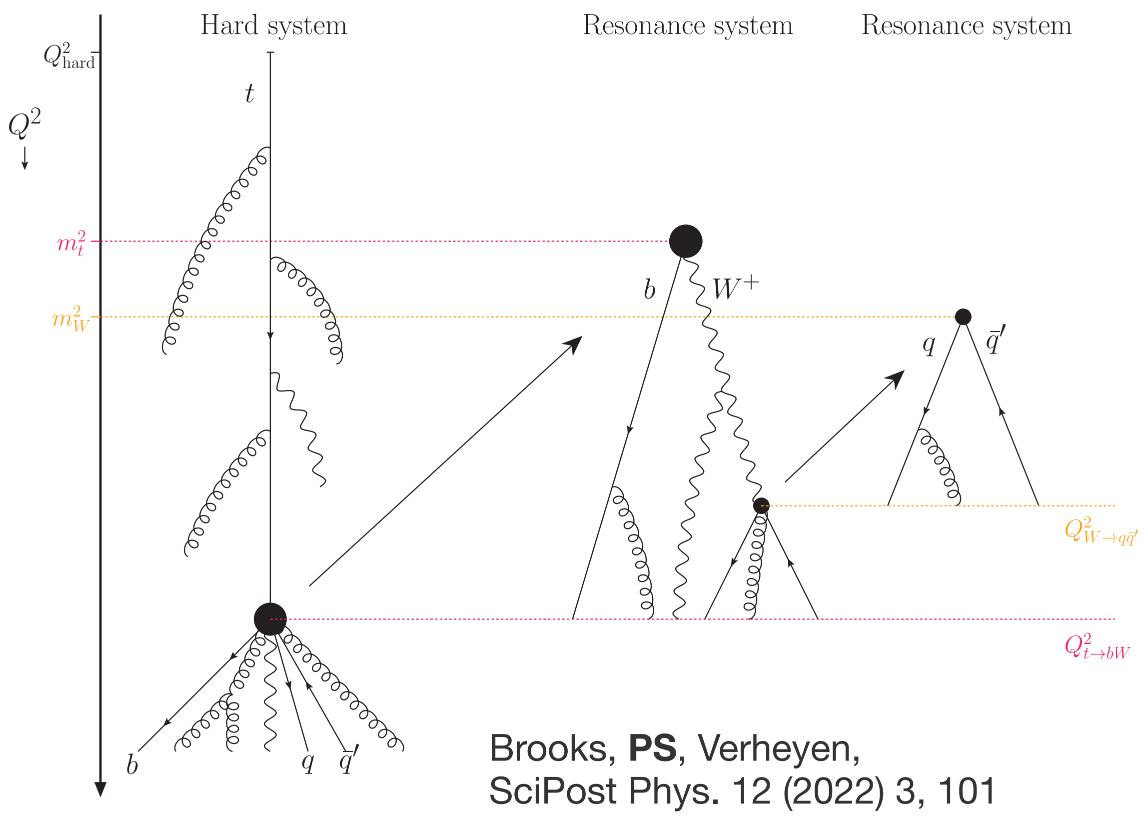
Introductions to:

1. VINCIA's Multipole QED Shower



PS, Verheyen,
Phys.Lett.B 811 (2020) 135878
[arXiv:2002.04939]

2. Interleaved Resonance Decays



Brooks, **PS**, Verheyen,
SciPost Phys. 12 (2022) 3, 101
[arXiv:2108.10786]

Peter Skands (Monash U. & U. of Oxford)

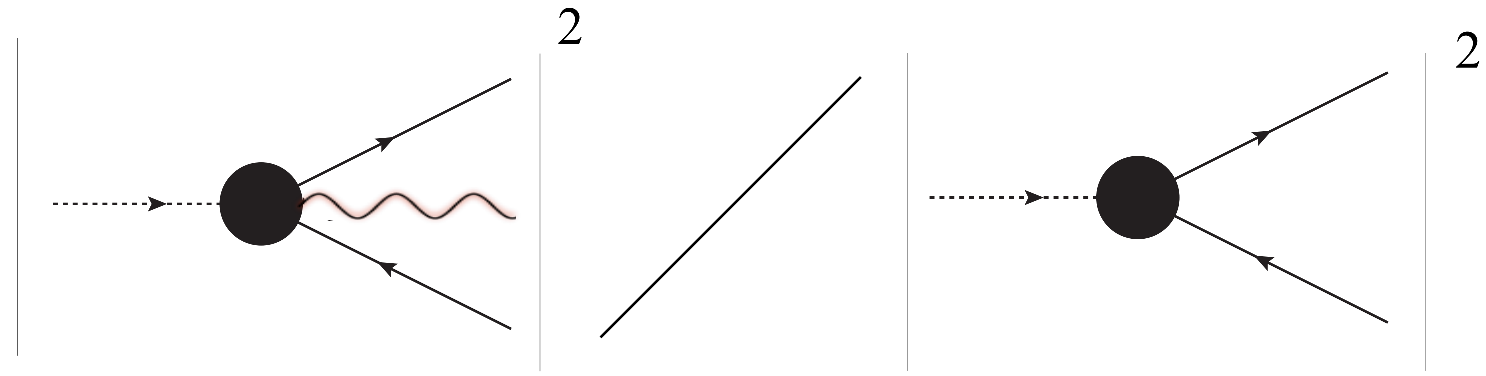
MWAPP Meeting, October 2023

1. Types of (QED) Showers

Simple case:

neutral scalar → 2 charged fermions

= **A single QED dipole**



LO QED $\propto \dfrac{2s_{e^-e^+}}{s_{e^-\gamma}s_{\gamma e^+}} + \dfrac{1}{M_0^2}\left(\dfrac{s_{\gamma e^+}}{s_{e^-\gamma}} + \dfrac{s_{e^-\gamma}}{s_{\gamma e^+}} + 2\right)$

eikonal term   collinear terms

PYTHIA

DGLAP

e^--collinear limit e^+-collinear limit

$$\frac{P_{e^-\to e^-\gamma}(z_1)}{s_{1\gamma}} + \frac{P_{e^+\to e^+\gamma}(z_2)}{s_{2\gamma}}$$

VINCIA

Antenna

All Singular Terms

$$\frac{2s_{e^-e^+}}{s_{e^-\gamma}s_{\gamma e^+}} + \frac{1}{M_0^2}\left(\frac{s_{\gamma e^+}}{s_{e^-\gamma}} + \frac{s_{e^-\gamma}}{s_{\gamma e^+}}\right)$$

Soft limit

HERWIG, SHERPA, PHOTOS

YFS

$$\frac{2s_{e^-e^+}}{s_{e^-\gamma}s_{\gamma e^+}}$$

Note: this is (intentionally) oversimplified. Many subtleties (recoil strategies, gluon parents, initial-state partons, and mass terms) not shown.

Beyond 2-body Systems: QED Multipoles

PYTHIA QED

- Determines a "best" set of dipoles. No genuine multipole effects.
  - I.e., interference beyond dipole level only treated via "principle of maximal screening"
- Works as a parton shower evolution (+ MECs) ➤ interleaved with QCD, MPI, …

YFS QED [Yennie-Frautschi-Suura, 1961 ➤ several modern implementations]

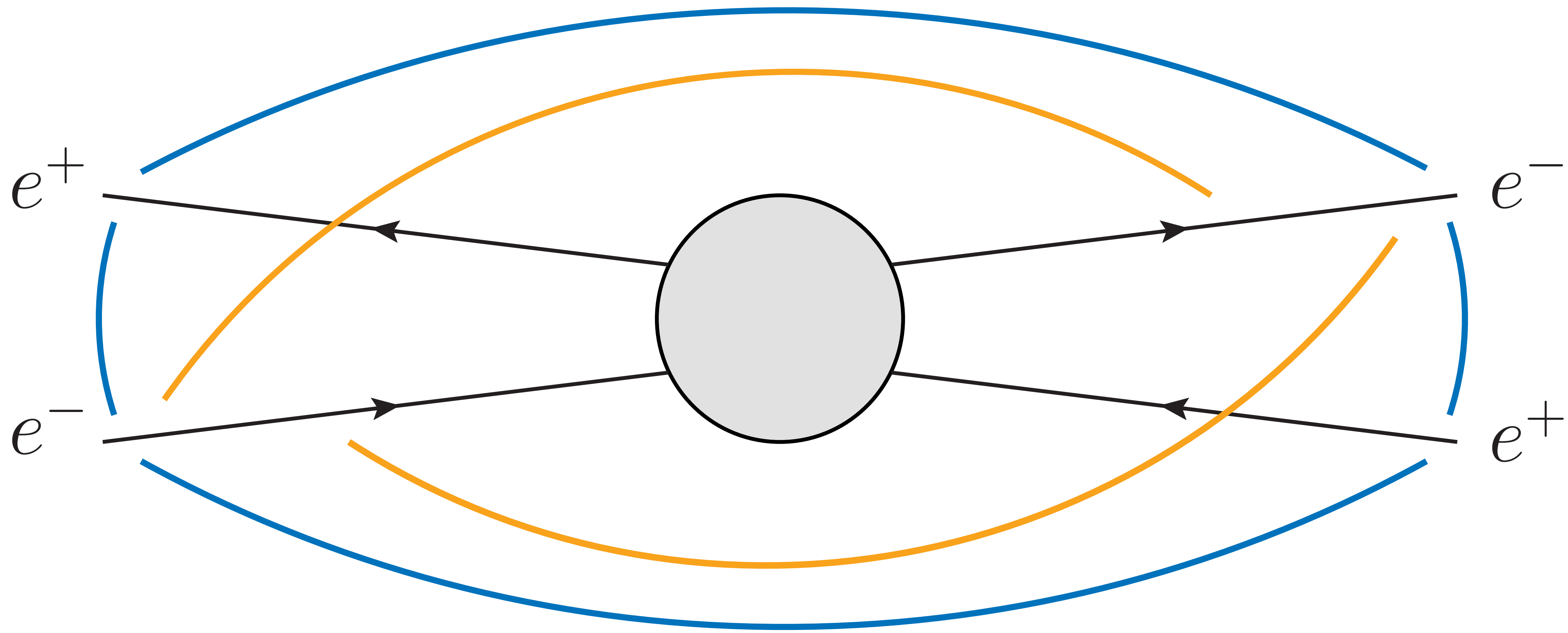
- Allows to take full (multipole) soft interference effects into account
- "Scalar QED"; no spin dependence.
  - I.e., starts from purely soft approximation; collinear terms not automatic
- Is not a shower; works as pure afterburner, adding a number of photons to a final state with predetermined kinematics; no interleaving

VINCIA QED [Kleiss-Verheyen, 2017 ➤ Brooks-Verheyen-PS, 2020]

- Allows to take full (multipole) soft interference effects into account
- Not limited to scalar QED; includes spin dependence
  - I.e., starts from antenna approximation; including collinear terms
- Is a shower; works as a parton shower evolution; can be interleaved (+ MECs).

QED Multipole Radiation Patterns

Example: Quadrupole final state (4-fermion: $e^+e^+e^-e^-$)



Soft Photon Emission: [Dittmaier, 2000]

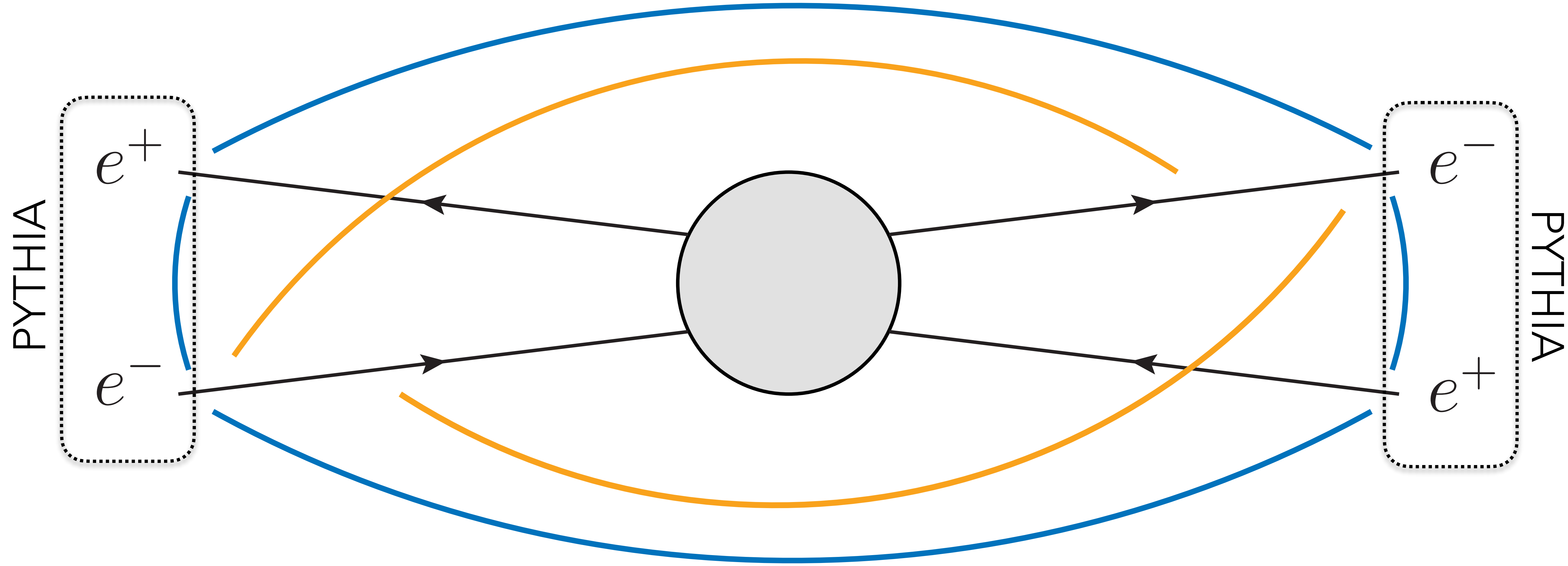
$$|M_{n+1}(\{p\},p_j)|^2 = -8\pi\alpha \sum_{x,y}^{n} \sigma_x Q_x \sigma_y Q_y \frac{s_{xy}}{s_{xj}s_{yj}} |M_n(\{p\})|^2$$

Opposite-charge pairs ➤ positive terms

Same-charge pairs ➤ negative terms

What's the problem?

Example: Quadrupole final state (4-fermion: $e^+e^+e^-e^-$)



Why was this not done as a shower before?

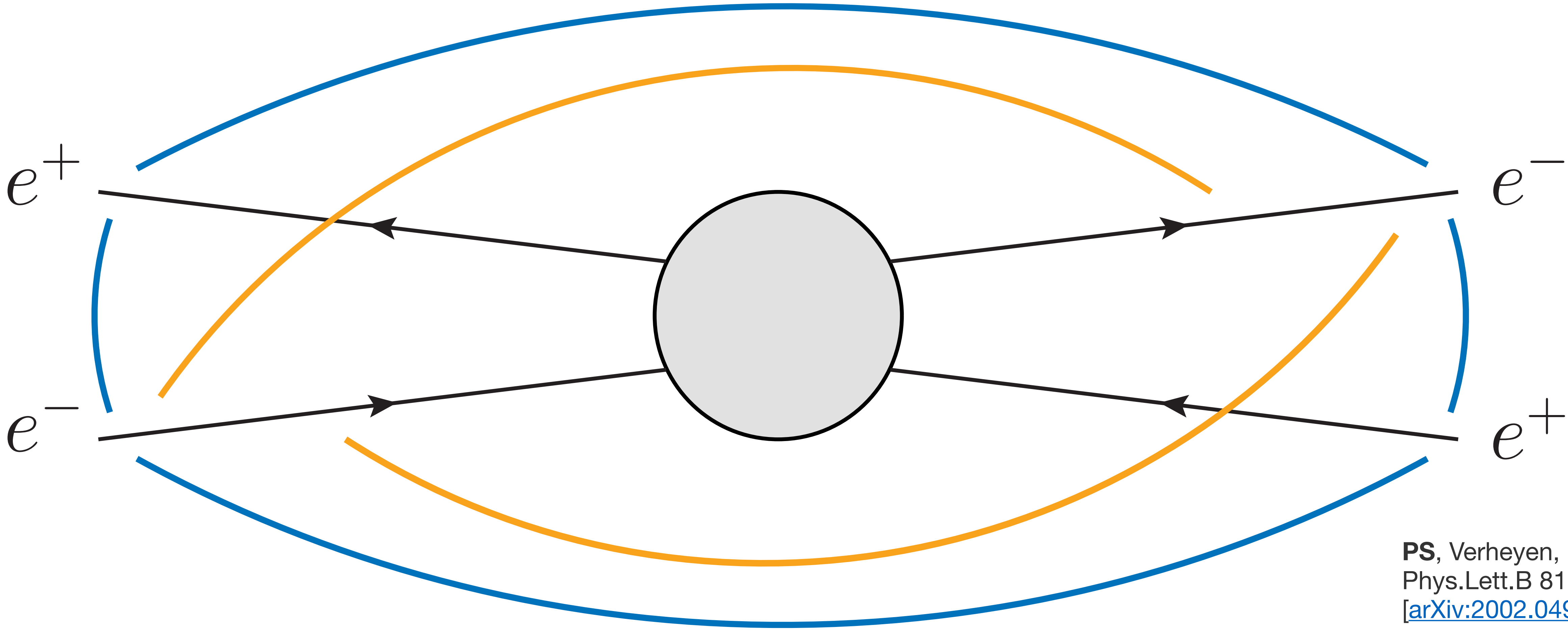
The orange terms are negative ➤ negative weights (+ big cancellations)

YFS is able to get around that by not being formulated as a shower.

Utilises that the sum is always non-negative.

What does VINCIA do differently?

Example: Quadrupole final state (4-fermion: $e^+e^+e^-e^-$)



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Sectorize phase space: for each possible photon emission kinematics p_γ, find the 2 charged particles with respect to which that photon is softest ➤ "Dipole Sector"

Use dipole ***kinematics*** for that sector, but sum **all** the positive and negative *antenna* terms (w spin dependence) to find the **coherent emission** ***probability***.

Further Details

Antenna phase-space factorisation is exact, also for massive particles

+ Universal mass corrections are included in the eikonals

➤ Should have extremely faithful representation of "dead cone" effect (radiation from massive particles strongly damped for $\theta_\gamma \lesssim E/m$) [Gehrmann-de Ridder, Ritzmann, PS, 2012]

Also automatically includes $\gamma \to e^+e^-, \mu^+\mu^-, \dots$ splittings (not in PHOTOS? YFS?)

➤ **First steps towards application of VINCIA QED to Hadron Decays**

Honours project of Giacomo Morgante (Monash, 2023, in collaboration with Warwick)

+ Can incorporate Matrix-Element Corrections [Giele, Kosower, PS, 2011, + more recent]

Not implemented yet. Techniques known; worked out focusing on QCD

Will affect tails of hard radiation (process-dependent non-singular terms), so this is potentially an important still missing feature. Also: Form Factors, VMD contributions, BRs, …

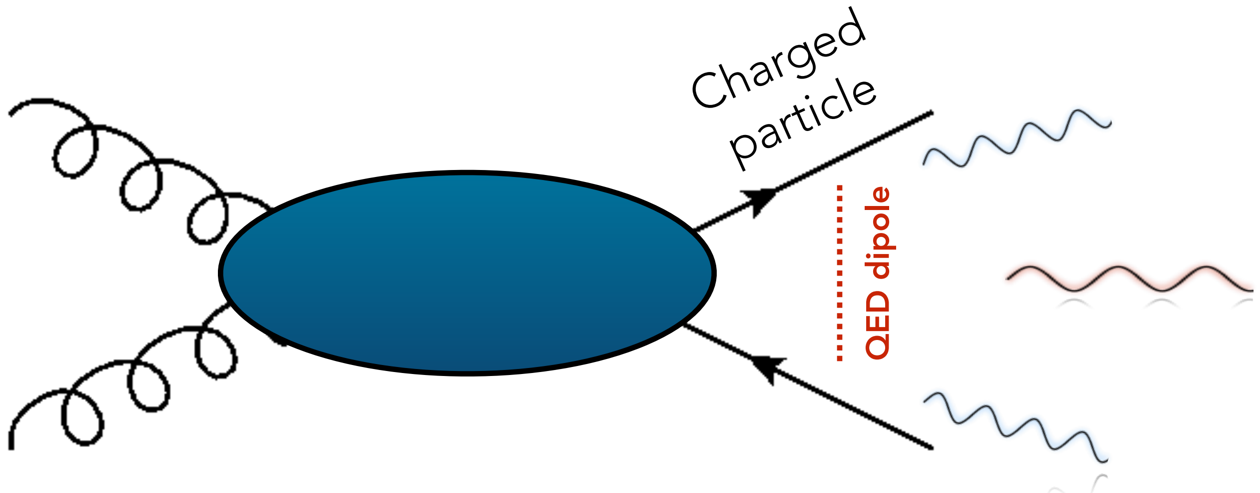
+ Can be interleaved with event evolution, e.g., with **Resonance Decays**

2. How does a process with unstable particles radiate?

First step = factorise production and decay(s)

Treat production as if all produced particles were stable

"Radiation in Production"



Note: for a c or b **hadron**, PYTHIA will do QED radiation off the heavy ***quark***

From the production scale of the quark down to the quark QED cutoff

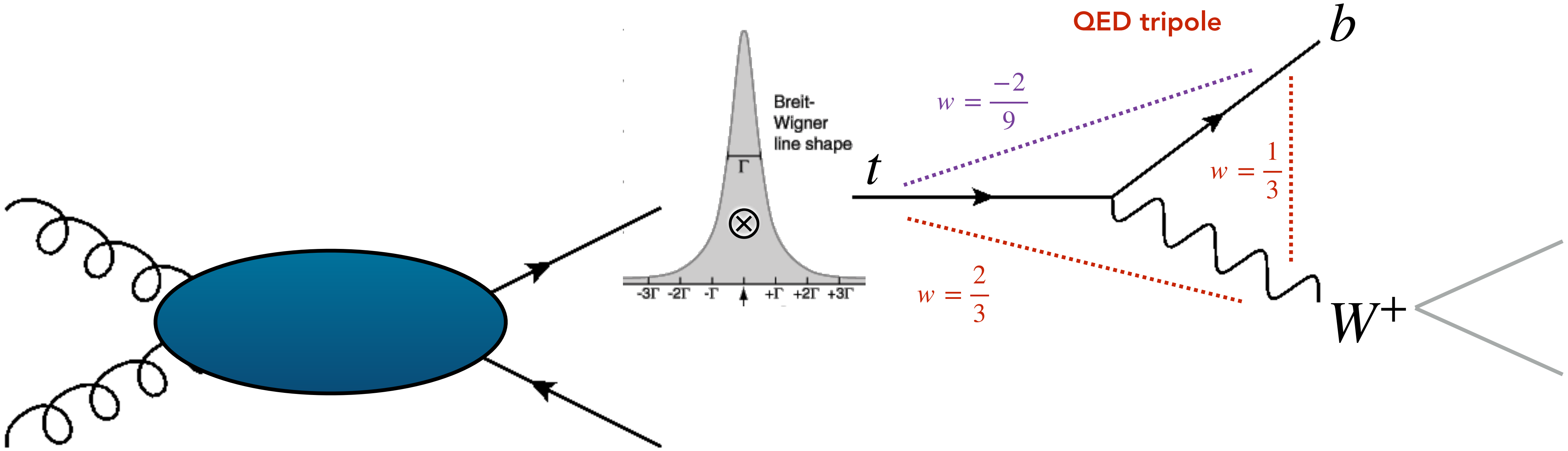
TimeShower:pTminChgQ
(= 0.5 GeV)

Recoil effects do not change the invariant mass of each particle

=> Preserves the Breit-Wigner shape

Conventional "sequential" treatment

Treat each decay (sequentially) as if alone in the universe



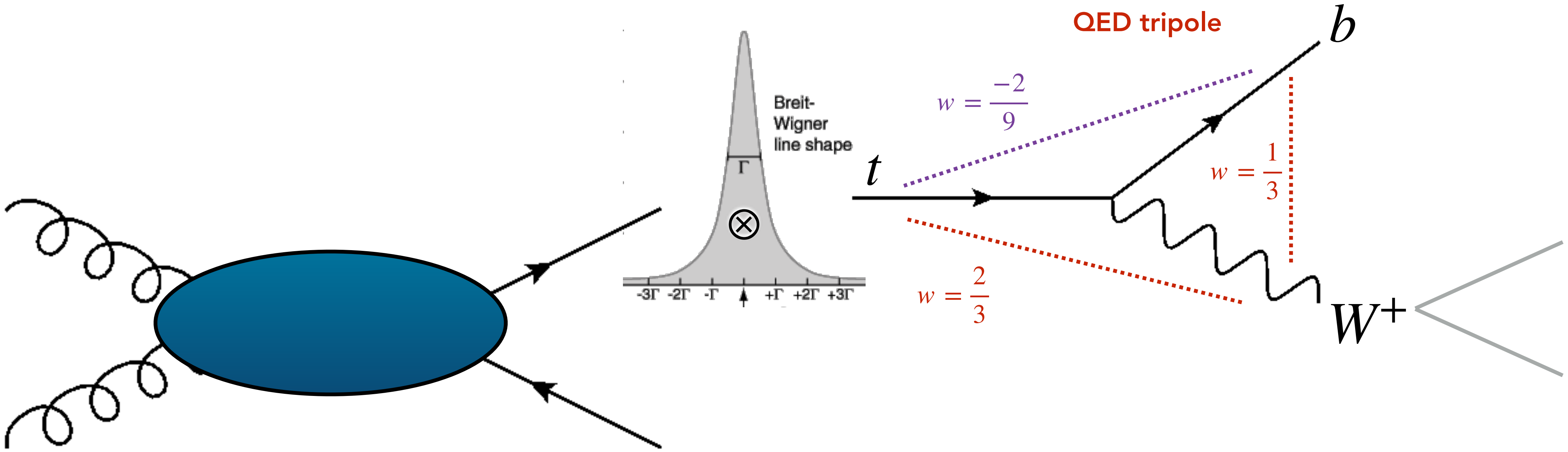
Shower explicitly preserves total invariant mass *inside* each system

=> Preserves the Breit-Wigner shape

Radiation in Decays

Conventional "sequential" treatment

Treat each decay (sequentially) as if alone in the universe

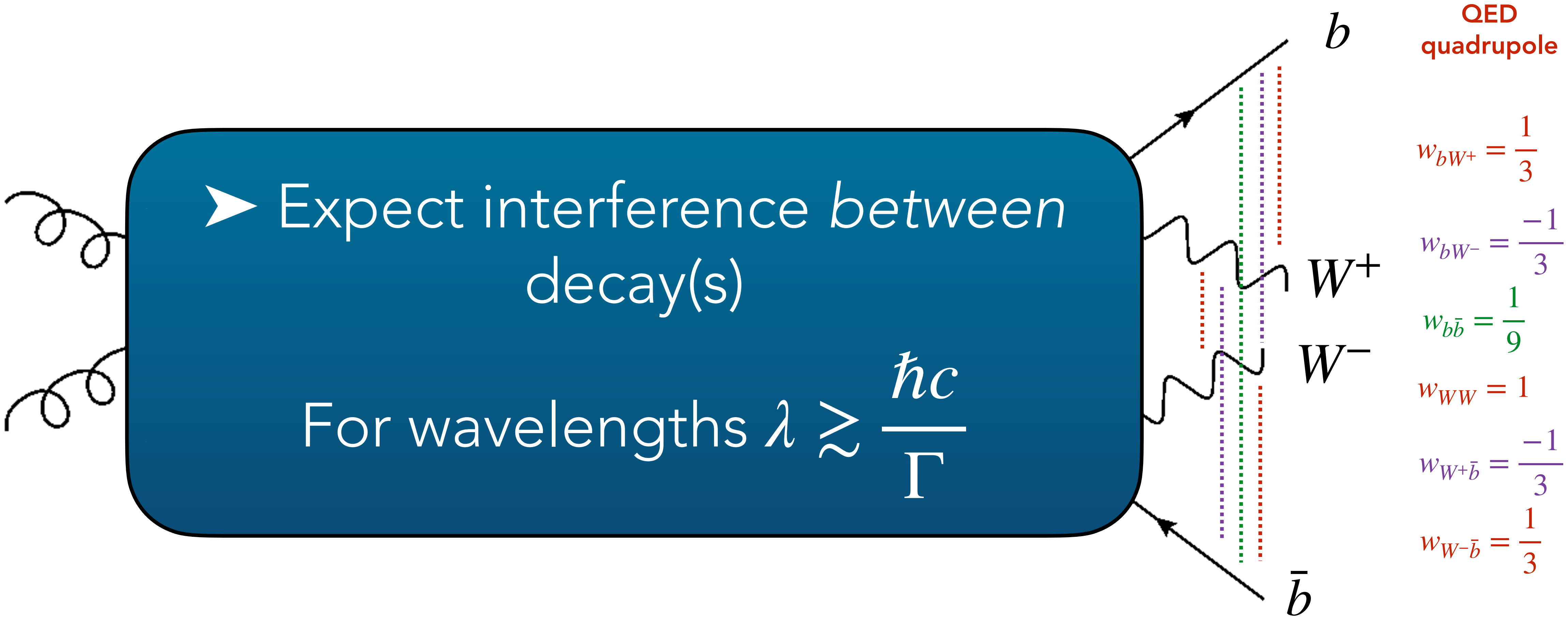


Question:

What about radiation at energies $E_\gamma \lesssim \Gamma_t$ (and $E_\gamma \lesssim \Gamma_W$)?

What does a long-wavelength photon see?

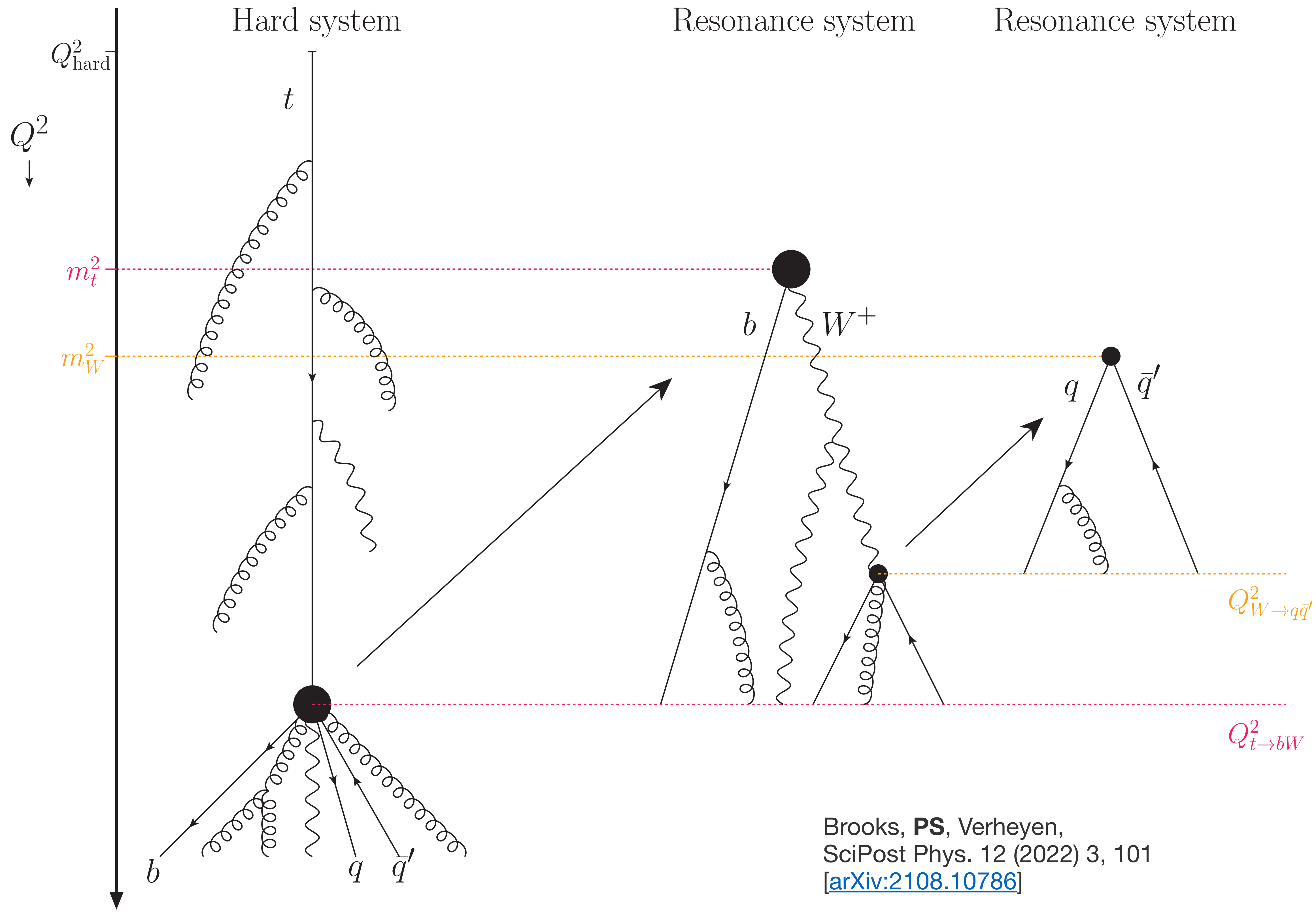
It should not be able to resolve the (short-lived) intermediate state



Should affect radiation spectrum, for energies $E_\gamma \lesssim \Gamma$

+ Interferences and recoils *between* systems => ***non-local BW modifications***

Interleaved Resonance Decays (VINCIA)



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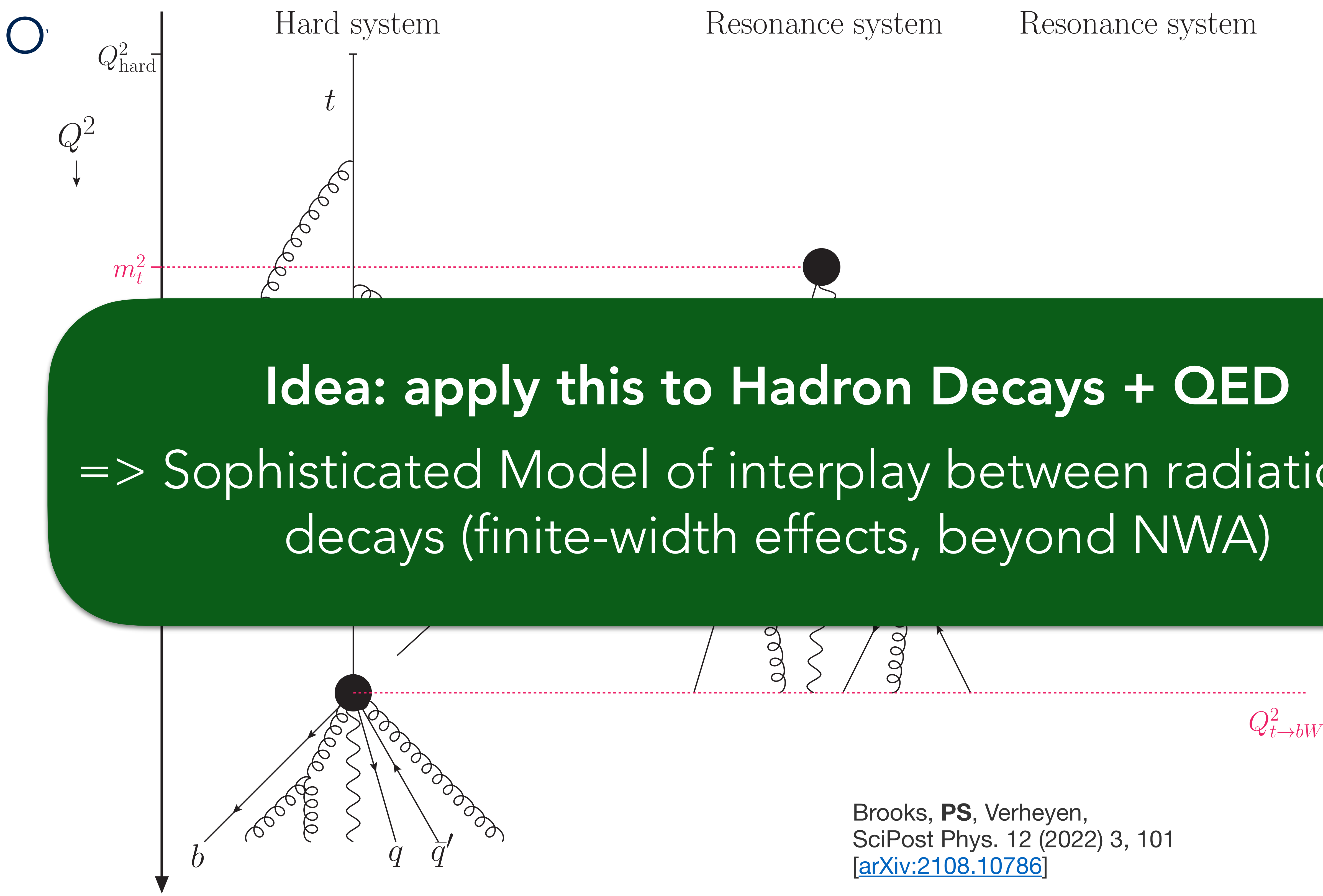
Interleaved Resonance Decays (VINCIA)



Idea: apply this to Hadron Decays + QED

=> Sophisticated Model of interplay between radiation and decays (finite-width effects, beyond NWA)

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Hadronic resonances

Among SM elementary resonances, we always have $\Gamma/M \ll 1$

E.g., Higgs extremely narrow. Even W, Z, top have $\dfrac{\Gamma}{m} \sim \dfrac{\mathcal{O}(100\,\mathrm{GeV})}{\mathcal{O}(1\,\mathrm{GeV})} \sim 1\,\%$

Hadron sector is much richer!

Strong decays => Relatively large widths

E.g. for ρ meson, $\dfrac{\Gamma(\rho)}{m_\rho} \sim \dfrac{150\,\mathrm{MeV}}{770\,\mathrm{MeV}} \sim 20\,\%$

EM decays => Intermediate widths

Weak decays => Small widths

Size of phase spaces also matter (sometimes a lot!)

➤ Plenty of motivation for investigating the effects of applying the idea of interleaved resonance decays to hadron decays

As usual, manpower / time are the main issues

Interleaved Decays: Summary

- 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 [...], 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 $\sim\Gamma$.

- 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.

H. Brooks, P. Skands, R. Verheyen, SciPost Phys. 12 (2022) 3, 101 [arXiv:2108.10786]

Extra Slides

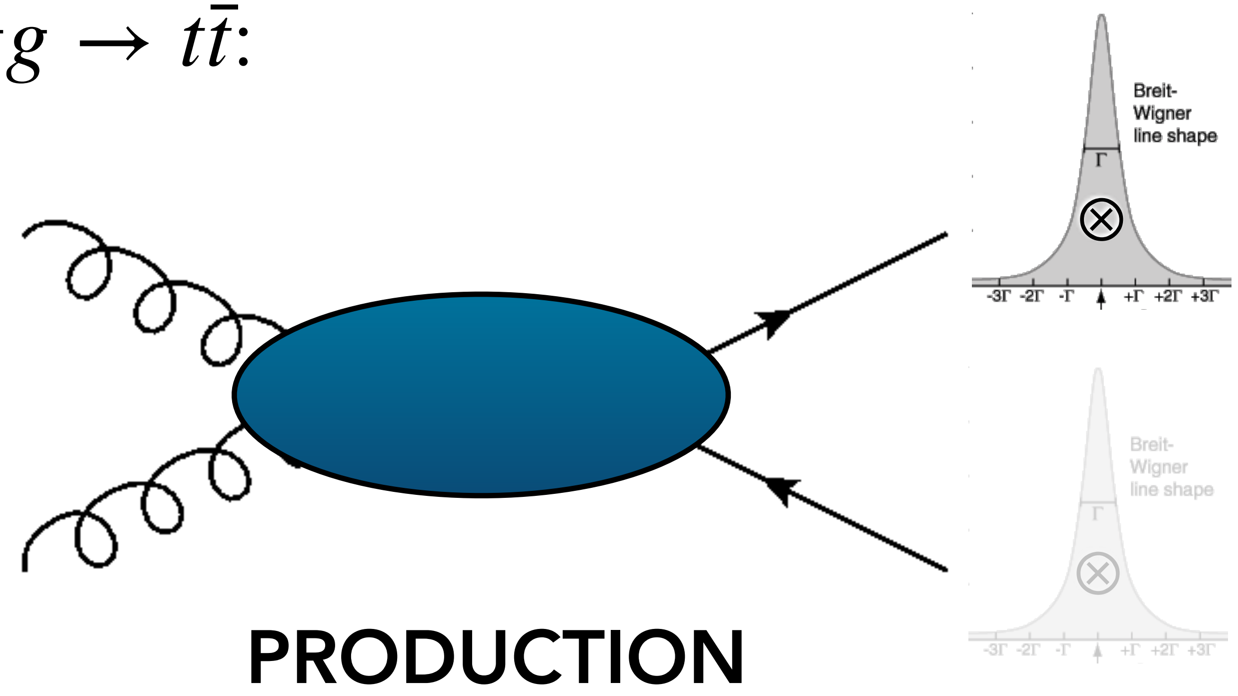
Unstable Particles ("Resonances")

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



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**

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Some consequences