Resonances In Vincia

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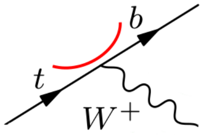
MONASH University

Radboud University

Outline

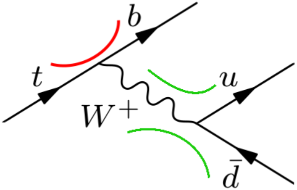
Coherence in Resonance Decays: motivation



Goal: We want to understand what is the effect of coherence in showering off resonances that have decayed.

Why: Better handle on shower uncertainties in e.g. top mass meausurements; assess possible implications for BSM?

Coherence in Resonance Decays: motivation



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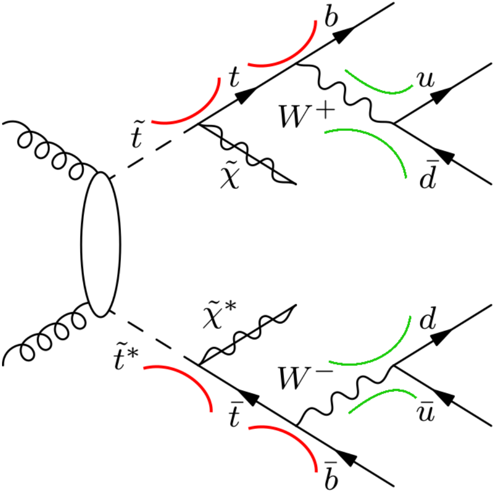
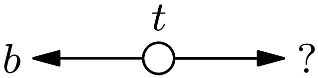
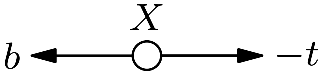


Dipoles vs Antennae in Resonance Showers



- Dipole showers
  - Have a well-defined notion of "radiator".
  - In principle free to choose recoiler, e.g. W in $t \to Wb$
  - Neglect contribution from resonance as radiator (partition can actually become negative).
- Antenna showers
  - Are agnostic as to who is the radiator (coherence built into antenna function): must involve resonance.
  - **Problem:** Mandatory to preserve resonance mass (essential for matching). How should we treat the antenna between the resonance and its decay product(s)?

The Solution: "Resonance-Final" Antennae



- Treat antenna as initial-final: $A \to KX$, $a \to jkX'$, antenna function cast in terms the invariants s_{aj}, s_{jk}, s_{ak}, s_{AK} and masses m_a, m_j, m_k, m_{AK}
- Kinematics map:
  - Preserves invariant mass of resonance: $p_A = p_a$, and
  - Preserves invariant mass of **system of recoilers**: $(p_A - p_K)^2 = (p_a - p_j - p_k)^2$
  - Construct in rest frame of resonance, then boost back to lab frame by p_A
  - For each recoiler i, boost p_i by $p_{X'} - p_X$

Defining the Kinematic Map

- Construct in A rest frame, and rotate such that K is along z.

$$p_k^\mu = \left(E_k, 0, 0, \sqrt{E_k^2 - m_k^2}\right)$$
$$p_j^\mu = \left(E_j, \sqrt{E_j^2 - m_j^2}\sin\theta, \sqrt{E_j^2 - m_j^2}\sin\theta, \sqrt{E_j^2 - m_j^2}\cos\theta\right)$$
$$p_X^\mu = p_a^\mu - p_k^\mu - p_j^\mu$$

where $E_j = s_{aj}/2m_a$, $E_k = s_{ak}/2m_a$,
$\cos\theta = \frac{2E_kE_j - s_{jk}}{2\sqrt{\left(E_k^2 - m_k^2\right)\left(E_j^2 - m_j^2\right)}}$

- Additional ambiguity: rotation about axis perpendicular to branching plane. Specify: in this frame, system X only recoils longitudinally.
- Rotate about z by ϕ (flatly sampled).
- Boost back to lab frame.

Other Ingredients

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

$$Q^2_{\mathrm{evol}} = \frac{s_{aj}s_{jk}}{s_{jk}+s_{AK}} \qquad \zeta = \frac{s_{jk}+s_{AK}}{s_{AK}} \qquad \text{(emissions)}$$

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

- Antenna functions (obtain from massive FF by crossing symmetry):

$$a_{g,qq} = \frac{2s_{ak}}{s_{aj}s_{jk}} - \frac{2m_a^2}{s_{aj}^2} - \frac{2m_k^2}{s_{jk}^2} - \frac{1}{s_{AK}}\left(\frac{s_{jk}}{s_{aj}}+\frac{s_{aj}}{s_{jk}}\right) \qquad \text{(emissions)}$$

$$a_{g,qg} = \frac{2s_{ak}}{s_{aj}s_{jk}} - \frac{2m_a^2}{s_{aj}^2} - \frac{1}{s_{AK}}\left(\frac{s_{jk}}{s_{aj}}+\frac{s_{aj}}{s_{jk}}\frac{s_{AK}-s_{aj}}{s_{AK}}\right) \qquad \text{(emissions)}$$

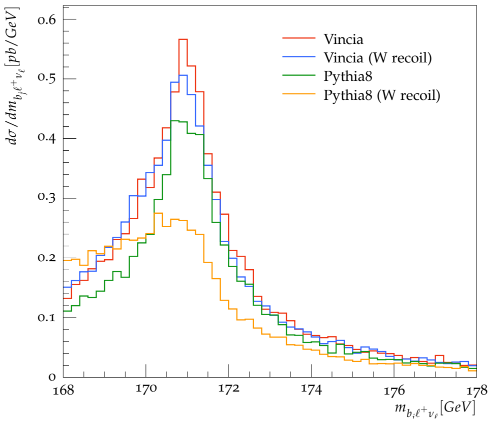
$$a_{q,qg} = \frac{1}{2(s_{jk}+2m_q^2)}\left(\frac{s_{ak}^2+s_{aj}^2}{s_{AK}^2}+\frac{2m_q^2}{s_{jk}+2m_q^2}\right) \qquad \text{(splittings)}$$

Results - Preliminary!

$pp \to t\bar{t} \to b\bar{b}\ell^+\nu_\ell\ell^-\bar{\nu}_\ell$ at $8\,TeV$.

Disclaimer: Not intended as physics result, just a comparison of parton shower.

- LO+PS
- Parton-level, no MPI or hadronisation
- No MECs

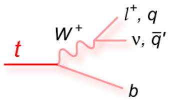


Part I: Mini-Summary

- Introduced "resonance-final" antennae:
  - Antenna function is a massive initial-final
  - Recoil is distributed between all downstream decay products in system.
- This has been implemented in Vincia for both QCD and QED.
- Next steps: systematically assess effects of coherence in e.g. direct top mass measurements.

Electroweak shower

- Spin-dependent couplings
- Particle masses
- Resonance branchings



Contents

1.Branching kernel calculation: Spinor-helicity formalism
2.Details of the shower implementation

Spinor-Helicity formalism

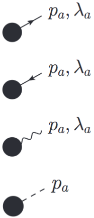
Helicity spinor definitions

$$u_\pm(p) = \frac{1}{\sqrt{2p\cdot k}}(\not{p} + m)u_\mp(k)$$

$$\epsilon^\mu_\pm(p) = \pm\frac{1}{\sqrt{2}}\frac{1}{2p\cdot k}\bar{u}_\mp(k)\not{p}\gamma^\mu u_\pm(k)$$

$$\epsilon^\mu_0(p) = \frac{1}{m}p^\mu - \frac{m}{p\cdot k}k^\mu$$

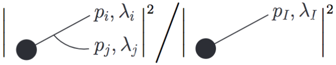
Creation operators



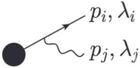
Reference vector

$$k = (1, -\vec{e})$$

$B_{\lambda_I,\lambda_i,\lambda_j}(p_I, p_i, p_j) =$



Splitting functions



$$\sim \frac{1}{Q^2} P(\lambda_I, \lambda_i, \lambda_j, z)$$

$$P(\lambda,\lambda,\lambda,z) = 2(v-\lambda a)^2 \frac{\tilde{Q}^2}{Q^2}\frac{1}{1-z}$$

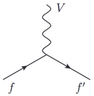
$$P(\lambda,\lambda,-\lambda,z) = 2(v-\lambda a)^2 \frac{\tilde{Q}^2}{Q^2}\frac{z^2}{1-z}$$

$$P(\lambda,-\lambda,\lambda,z) = \frac{2}{Q^2}\left[m_I(v+\lambda a)\sqrt{z} - m_i(v-\lambda a)\frac{1}{\sqrt{z}}\right]^2$$

$$P(\lambda,-\lambda,-\lambda,z) = 0$$

$$P(\lambda,\lambda,0,z) = \frac{1}{Q^2}\left[(v-\lambda a)\left(\frac{Q^2}{m_j} - \frac{m_i^2}{m_j}\frac{1}{\sqrt{z}} + \frac{m_I^2}{m_j}\sqrt{z} - 2m_j\frac{\sqrt{z}}{1-z}\right) + (v+\lambda a)\frac{m_i m_I}{m_j}\frac{1-z}{\sqrt{z}}\right]^2$$

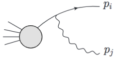
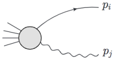
$$P(\lambda,-\lambda,0,z) = \frac{\tilde{Q}^2}{Q^2}\left(\frac{(v+\lambda a)m_I - (v-\lambda a)m_i}{m_j}\right)^2 (1-z)$$



$$= i(v + a\gamma^5)\gamma^\mu$$

$$Q^2 = (p_i + p_j)^2 - m_I^2$$

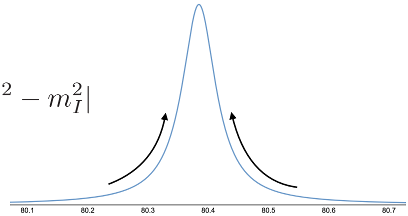
$$\tilde{Q}^2 = Q^2 + m_I^2 - \frac{m_j^2}{1-z} - \frac{m_i^2}{z}$$

Gauge invariance: $P(z) \propto \Bigg($  $+$  $\Bigg)^2$

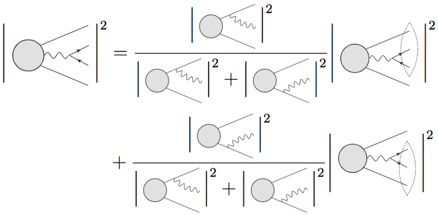
Shower implementation

Ordering scale

$$t = |Q^2| = |(p_i + p_j)^2 - m_I^2|$$



Spectator selection: Use selection probability



Overestimate determination

$$d\Phi_{\text{ant}} = \frac{1}{16\pi} ds_{ij} ds_{jk} \frac{d\varphi}{2\pi}$$

$s_{ij} = 2p_i{\cdot}p_j$

Two problems:

- ~500 different branchings
- Incompatible with the phase space

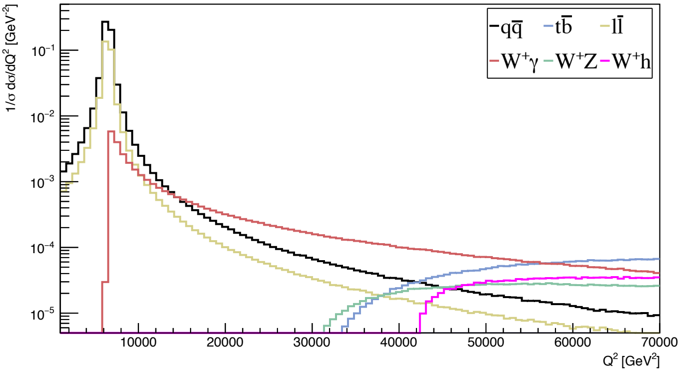
Parameterize overestimate

$$\mathcal{O} = c_1 \frac{1}{Q^2} + c_2 \frac{1}{Q^2} \frac{(p^0_{IK})^2}{s_{ij} + s_{ik} + m_i^2} + c_3 \frac{1}{Q^2} \frac{(p^0_{IK})^2}{s_{ij} + s_{jk} + m_j^2} + c_4 \frac{m_I^2}{Q^4}$$

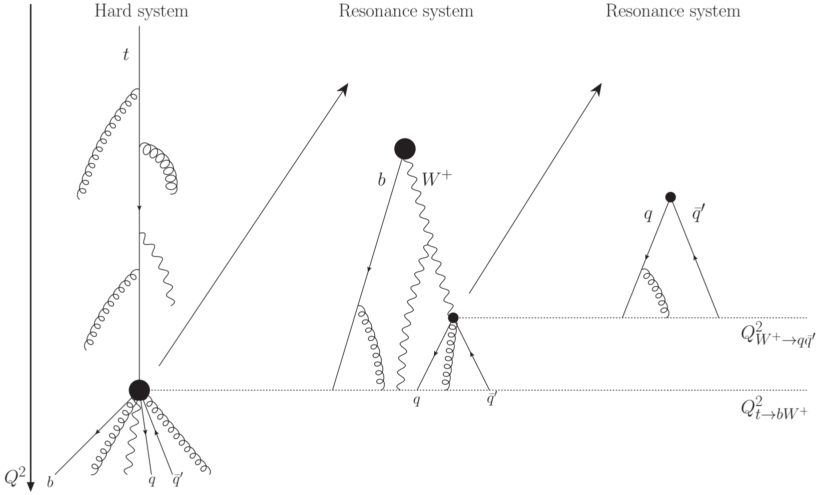
Solve coefficients by linear programming

$$\begin{aligned} \text{Minimize } & \sum_{i=1}^{n} (A\mathbf{c})_i - B_i \\ \text{subject to } & (A\mathbf{c})_i \geq B_i \\ \text{and } & \mathbf{c} \geq 0. \end{aligned}$$

W+ Radiation spectrum



Recursive Resonances: The Concept



Recursive Resonances: In Practice

PartonLevel::next

- VinciaFSR::pTnext
- VinciaFSR::branch: branching accepted at pTWin
  - Generate kinematics, accept/reject step. Update event, partonSystems as normal.
  - if(resonanceDecay): call VinciaFSR::resonanceShower
    - Save current scale pTcutoff = pTWin
    - Create a new system iResSys in partonSystems
    - Call VinciaFSR::prepare for iResSys
      - Set isResonanceSys[iResSys] = true
      - Set up F-F and R-F antennae.
      - Set start scale from available phase space for decay.
    - while(pTnow > pTcutoff)
      - VinciaFSR::pTnext
      - VinciaFSR::branch
    - Merge system iResSys in partonSystems with mother system
    - Reset pTWin = pTcutoff

Summary

- Ready now:
  - ☑ Resonances now implemented in Vincia, with coherent "resonance-final" antennae for both QCD and QED.
- Coming soon:
  - ☐ Electroweak decays generated as part of the shower
  - ☐ Recursive treatment of resonance decays