Bloch-Nordsieck restoration for $l\bar{l} \rightarrow t\bar{t}$

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Abstract: In standard perturbative calculations elementary particles are used to describe scattering experiments. This is in remarkable agreement with experimental data. But it leads to an existential dilemma from the quantum field theoretical point of view, since these states are gauge-dependent. The solution to this dilemma is provided by the Fröhlich-Morchio-Strocchi (FMS) mechanism, where physical states in the electroweak case are composite objects, which effectively reduce to the elementary ones on-shell. This has far-reaching implications off-shell. As an example of the consequences, we demonstrate that this cures the violation of the Bloch-Nordsieck (BN) theorem for the s-channel annihilation in $l\bar{l} \rightarrow t\bar{t}$. This process is of particular interest for future linear colliders, where otherwise Bloch-Nordsieck violations at high energies would be significant according to standard perturbative calculations.

Starting point

- Higher order calculations of scattering processes
- Resummation → divergences
- Solution: cancellations of divergences due to BN theorem

Bloch-Nordsieck theorem and violation [1]

- IR-divergent terms are only sub-results → sum over all Feynman diagrams that contribute to final state
- Bloch-Nordsieck (BN) theorem: sum over indistinguishable final states

$$\sum_f |S_{if}|^2$$

- Sum is finite due to cancellations between members of (gauge) multiplets
- Perturbation theory in electroweak physics: „Spontaneous electroweak symmetry breaking“ allows to prepare individual members of gauge multiplets as initial and final states: Cancellations are no longer possible
- Typical example: $l\bar{l} \rightarrow t\bar{t}$ Both initial and final states are not full multiplets
  - In the SM: Affects only left-handed particles

Resolution: Composite states [2, review in 3]

- Field theory: Elementary states are not suitable asymptotic states
  - Even in presence of a Brout-Englert-Higgs effect
- Asymptotic states need to be composite
- Elementary fields for left-handed fermions $\psi^L = \begin{pmatrix} \nu^L \\ e^L \end{pmatrix}$
- Corresponding composite state

$$\Psi^L = X^\dagger \psi^L$$

where $X = \begin{pmatrix} \phi_2^* & \phi_1 \\ -\phi_1^* & \phi_2 \end{pmatrix}$ is build from the Higgs doublet ϕ_i

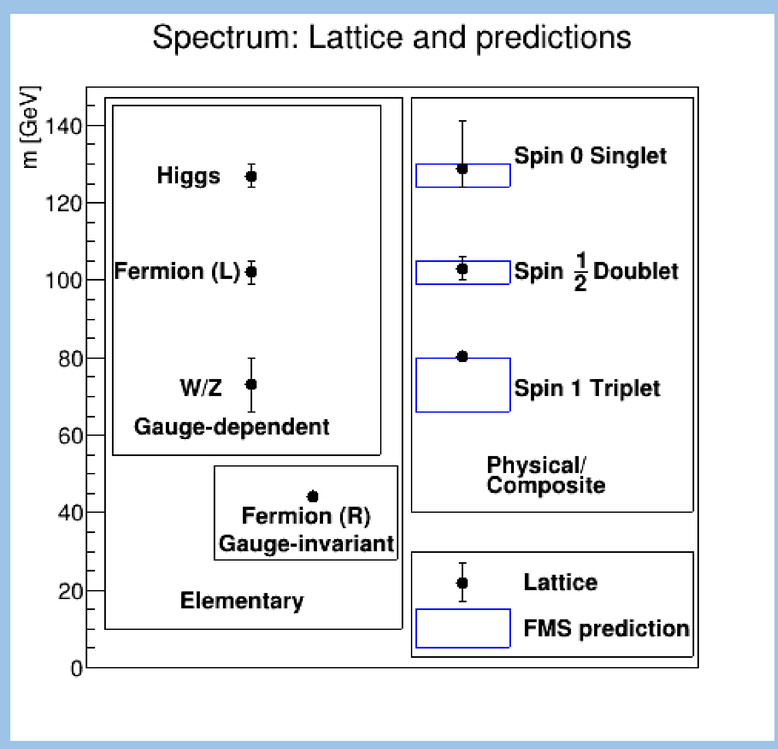
- Such asymptotic states automatically fulfill the Bloch-Nordsieck theorem
- These states have the same on-shell properties as the elementary ones
- Fröhlich-Morchio-Strocchi mechanism: Expand $\phi \rightarrow v + \eta$

$$\langle \bar{\Psi}_L \Psi_L \rangle_{22} = v^2 < \bar{e}_L e_L > + O(v)$$

- Same to leading order in vev – same on-shell behavior
- Can be extended beyond leading order in a systematic way [4]

Verification of the FMS mechanism [3,5]

- Can be systematically tested in lattice calculations
  - Though not (yet) for the full standard model
  - But also for non-standard model theories
  - In all cases the FMS results have been confirmed



$l\bar{l} \rightarrow t\bar{t}$ [3]

- Scattering process described by matrix element $\langle \overline{\Psi_i^L}\, \Psi_j^L\, \overline{T_k}\, T_l \rangle$
- To leading order in the vev just the ordinary matrix element
- When resumming requiring also higher orders in the vev involving the rest of the multiplet
- Summation restores the Bloch-Nordsieck theorem

Estimate of impact

- Bloch Nordsieck violation leads to double-logarithmic grow due to non-cancelled Sudakov logarithms *L(s)* [1]
- Assessment of the impact: $\left(\frac{\Delta\sigma_{e\bar{e}}}{\sigma^H_{e\bar{e}}}\right)^L = \left(\frac{\sigma^H_{\nu\bar{e}} - \sigma^H_{e\bar{e}}}{\sigma^H_{e\bar{e}}}\right)^L \left(\frac{1 - e^{-2L(s)}}{2}\right)$
- For $l\bar{l} \rightarrow t\bar{t}$ at 1 TeV center of mass this leads to a sub-leading correction of order 3.7 α_W/α_S and is thus of the same order as the strong corrections [1]
- Effect is absent in the full FMS calculation
  - May yield additional effects [4]
- Additional standard-model background for new physics searches!

Outlook

- Calculation of full matrix element
- Eventually: Predictions for ILC/CLIC
- LHC could be affected by similar processes [6]

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