PHOKHARA AT NNLO

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With the much appreciated support of M. Pozzoli!

Scattering amplitude techniques

GVMD

Resummation of soft photon effects

Progress towards $e^+e^- \to \gamma\gamma^*$ at NNLO

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CALCULATION OF AMPLITUDES

To really progress to NNLO within MC Generators we require the calculation of scattering amplitudes.

Within our group we have expertise in the techniques required to calculate scattering amplitudes at multi-loop level:

- Tensor reduction to gauge invariant form factors
- Integration-by-parts reduction of integrals
- Differential equations

Important as we can directly obtain polarized amplitudes which are becoming the focus of future experiments.

New techniques are required to obtain suitable differential equations for "tricky" integrals.

QUICK DISCUSSION ON TENSOR DECOMPOSITION

Tensor decomposition allows us to express scattering amplitudes in terms of gauge invariant **form factors**.

This gives us analytic expressions that we can perform all intermediate steps as an alternative to considering the interference.

$$M_{ij} = T_i T_j^\dagger$$

$$P_i = \left(M_{ij}\right)^{-1} T_j^\dagger$$

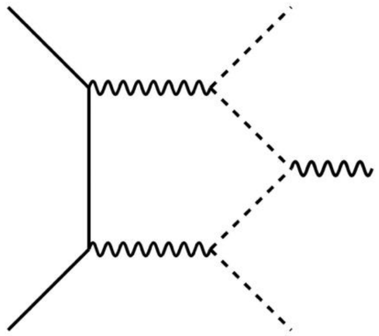
$$P_i \mathcal{A} = F_i$$

Recent Success using Tensor Decomposition

We have been able to re-calculate $e^+e^- \to \pi^+\pi^-\gamma$ at NLO in sQED

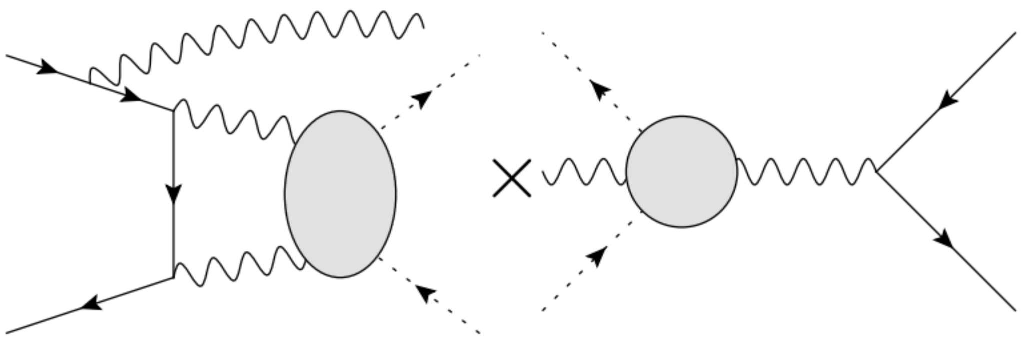
BUT

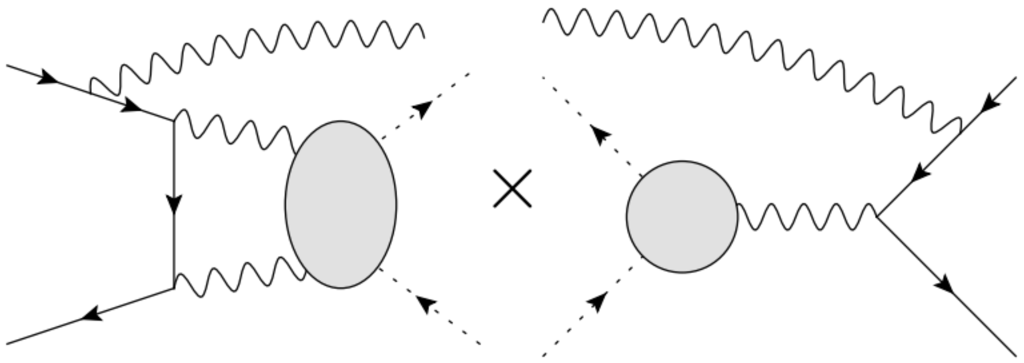
to higher orders in the dimensional regulator, which is crucial to obtain pole free expressions at NNLO.



GVMD

- Alternative to sQED where we represent the pion form factor as $F_\pi(q^2) = \sum_{v=0}^{N} c_N \frac{\Lambda_v^2}{\Lambda_v^2 - q^2}$.
- C-even $Q_e^4 Q_\pi^4$ and C-odd $Q_e^5 Q_\pi^3$ contributions have been calculated under the GVMD model.
- By employing IBPs and a set of finite MIs, the cancellation of poles is purely analytical, and is observed before substituting values for integrals. Furthermore, this leads to a smaller set of integrals to compute.
- The contributions have been implemented in PHOKHARA and are under scrutiny.
- Validation and testing is ongoing along with optimization to speed up evaluation.



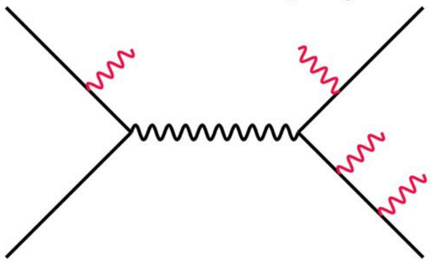


RESUMMATION OF SOFT PHOTON EFFECTS

- Phase-space generation: We have an algorithm to generate explicit events with any number of photons, we are also using VEGAS to boost the phase-space integration.
- We intend to include the CEEX framework used within KKMC in PHOKHARA.
- We have calculated the YFS form factor in dimensional regularization. Both real and virtual contributions have been checked against known results.
- Additionally, we have included an additional term in our YFS form factor to account for soft-collinear resummation.
- Eikonals are calculated using spinor-helicity formalism mimicking KKMC's approach.

WIP

- We can compute IR-Safe β using a tensor decomposition approach.



$$\sum_{n_\gamma=0}^{\infty} \frac{1}{n_\gamma} \int_{\bar{\Omega}} d\mathrm{Lips}_{n_\gamma+2}\ e^{Y_\Omega^{FF}} \left| \left(\prod_{i=1}^{n_\gamma} s_i^{\phi_i} \right) \beta \right|^2$$

RESUMMATION OF SOFT PHOTON EFFECTS

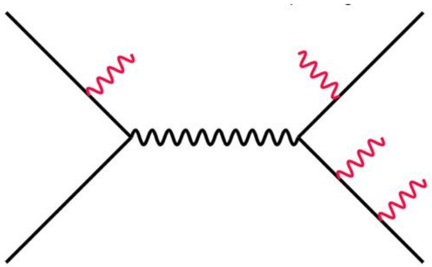
- Currently we have LO + resummation for:

  $e^+e^- \to \mu^+\mu^-$

  $e^+e^- \to \pi^+\pi^-$

  $e^+e^- \to e^+e^-$

- We are now working on NLO + resummation for scan mode and radiative return will come in the future.



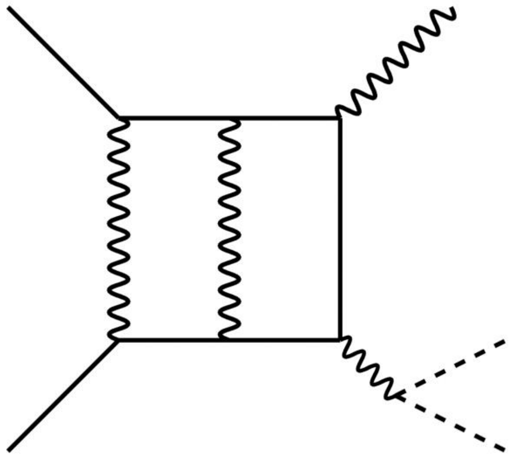
$$\sum_{n_\gamma=0}^{\infty} \frac{1}{n_\gamma} \int_{\bar{\Omega}} d\mathrm{Lips}_{n_\gamma+2}\; e^{Y_\Omega^{FF}} \left| \left(\prod_{i=1}^{n_\gamma} s_i^{\phi_i} \right) \beta \right|^2$$

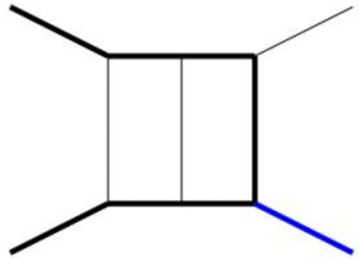
$e^+e^- \to \gamma\gamma^*$ AT NNLO (IN COLLABORATION W/ MATTIA POZZOLI)

- Important when we consider ISR contributions to $e^+e^- \to \pi^+\pi^-\gamma$.
- Integrals that appear are not simple (elliptic integrals), therefore conventional representation in terms of Polylogarithms not possible.
- Focus has been on computing analytic expressions for the two planar families shown by forming differential equations of the form:

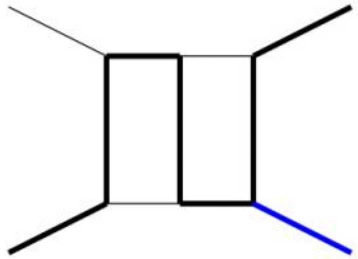
$$\frac{\partial}{\partial x}\vec{I}(x;\epsilon) = \sum_{k=0}^{\max} \epsilon^k A(x)\vec{I}(x;\epsilon)$$

- Work ongoing on further topologies.
- See Mattia's talk for further details.



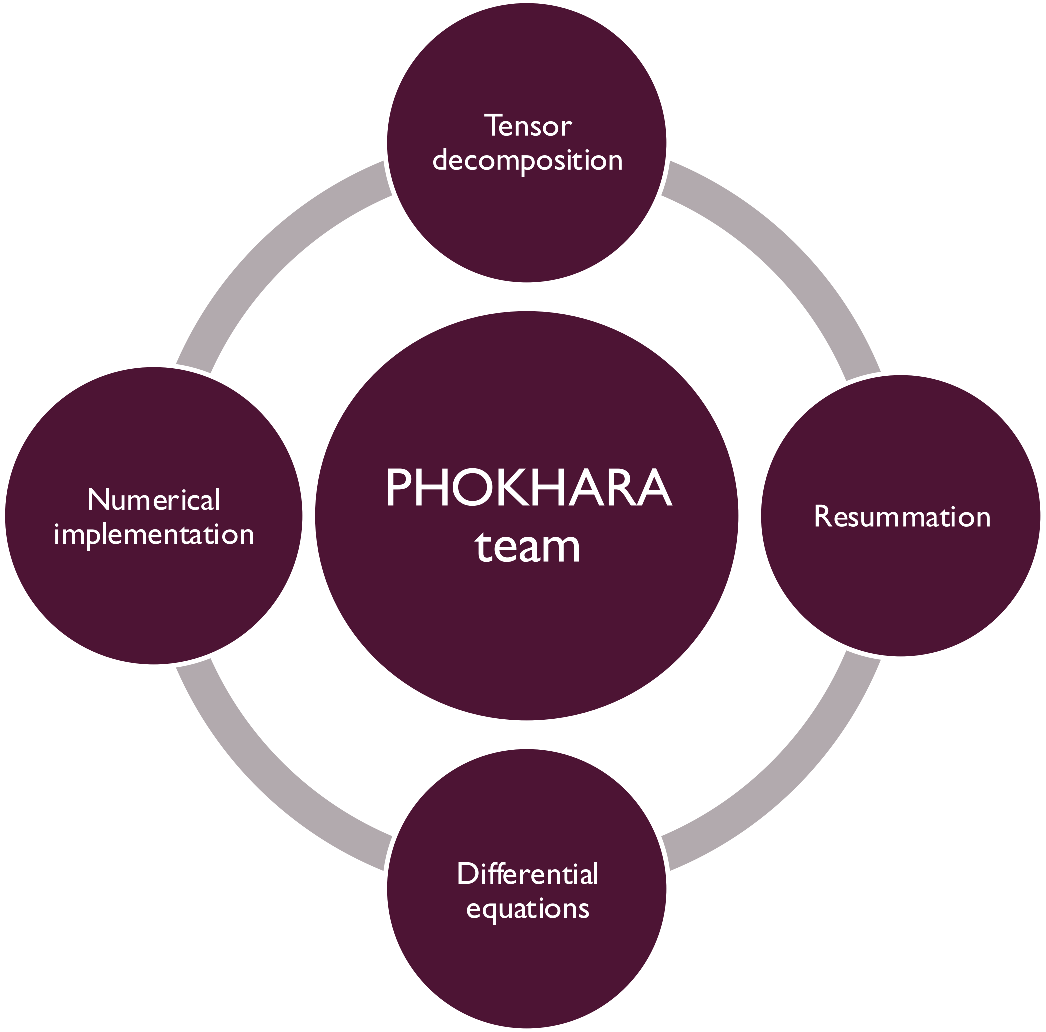


(b) Two-loop family PL1.



(c) Two-loop family PL2

SUMMARY



Tensor decomposition
Numerical implementation
PHOKHARA team
Resummation
Differential equations