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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LEVERHULME TRUST

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 decomposition 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.

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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.

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

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

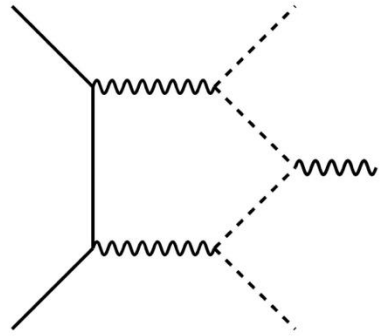
$$P_i \mathcal{A} = F_i$$

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.



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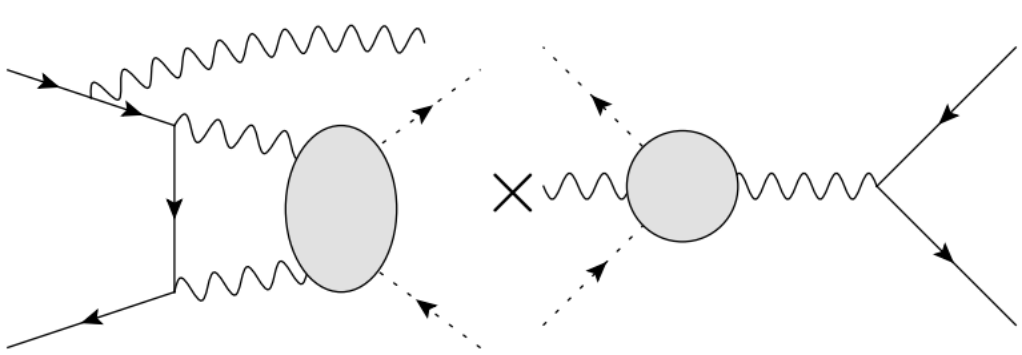
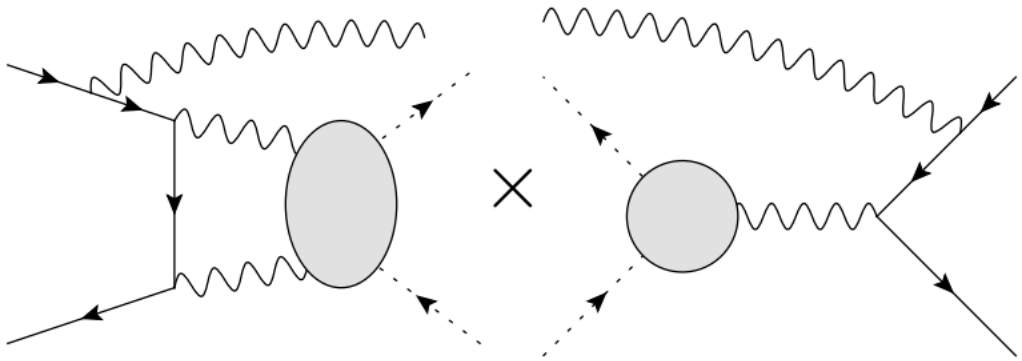
GVMD

- 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.





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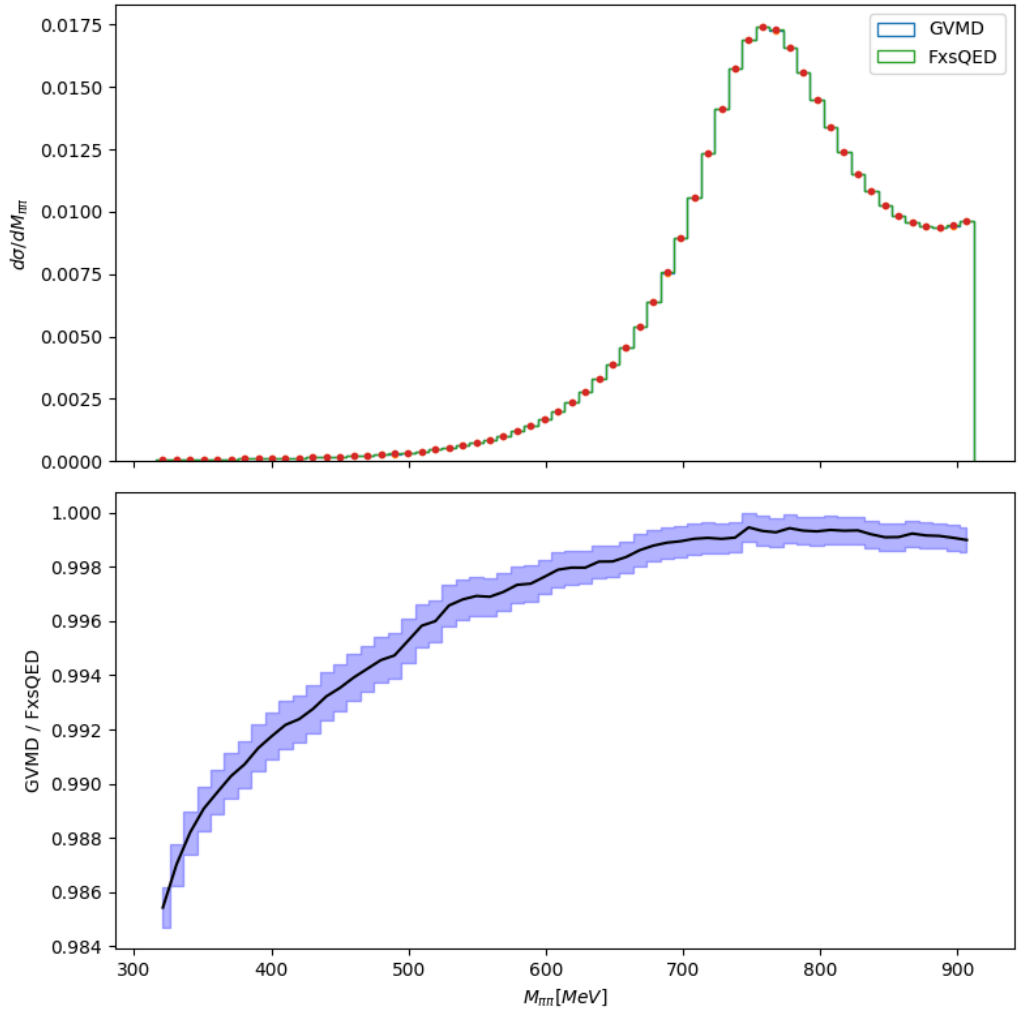
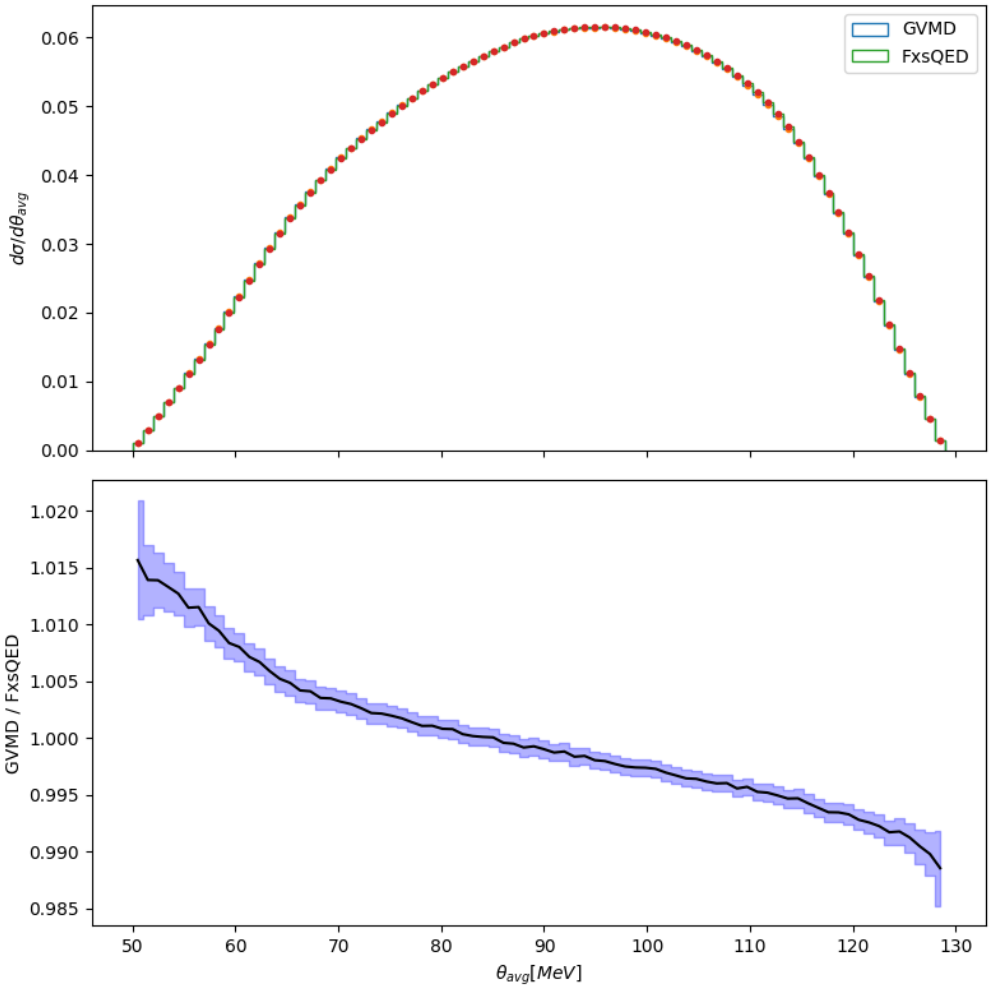
GVMD





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GVMD

- Effects seen are small, but will make a difference if we go beyond 1% level accuracy.
- Useful information can be gathered from the charge asymmetry (forward-backward asymmetry)
- We are missing the one-loop FSR diagrams, however we expect their corrections to have a smaller effect.
- These plots are for the KLOE large angle scenario, we expect the small angle effects to be smaller. But we are working on making the small angle scenario more numerically stable.

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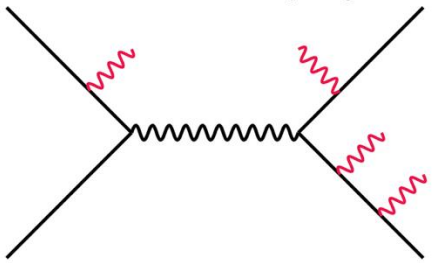
RESUMMATION OF SOFT PHOTON EFFECTS

- 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.
- Taking a different approach to the YFS form factor by computing in a Lorentz-invariant way. This allows us to use the form factor in any reference frame.



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

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RESUMMATION OF SOFT PHOTON EFFECTS

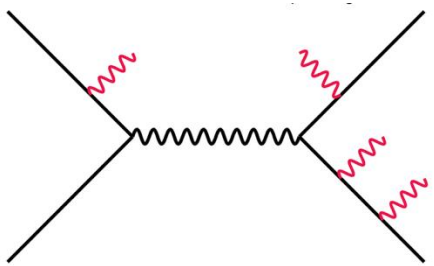
WIP

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



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

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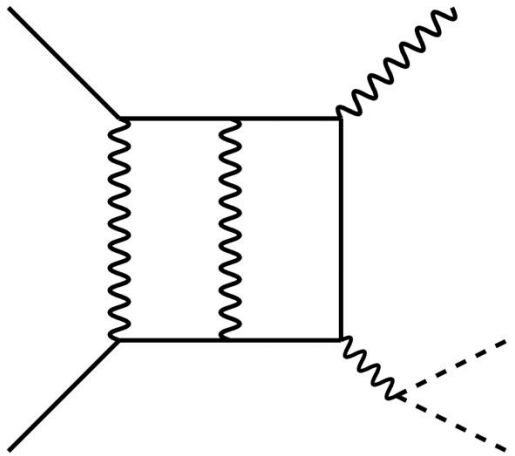
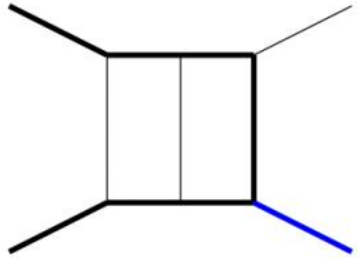
$e^+e^- \to \gamma\gamma^*$ AT NNLO (IN COLLABORATION W/ MATTIA POZZOLI)

- 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 is not possible.
- Focus has been on computing analytic expressions for the two planar families shown by forming differential equations of the form:

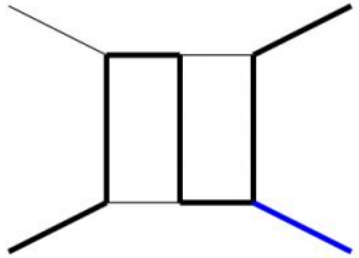
$$\frac{\partial}{\partial x}\vec{I}(x;\epsilon) = \sum_{k=0}^{\max} \epsilon^k A(x)\vec{I}(x;\epsilon)$$

- Work ongoing on further topologies.





(b) Two-loop family PL1.



(c) Two-loop family PL2

CONCLUSION

- In our group we have expertise in the techniques required to compute scattering amplitudes at higher perturbative orders.
- We are using a tensor decomposition approach to obtain polarised amplitudes and interference both analytically and numerically.
- We are making positive strides towards implementing YFS resummation at amplitude level into PHOKHARA.
- We have seen promising results when calculating

  $e^+e^- \to \pi^+\pi^-\gamma$ using the GVMD model.
- We are studying $e^+e^- \to \gamma\gamma^*$ at two-loop order which will be valuable when considering $e^+e^- \to \pi^+\pi^-\gamma$ at NNLO.