UNIVERSITY OF LIVERPOOL

LEVERHULME TRUST

Towards a fully NNLO Monte Carlo generator for low energy e+e- data into hadrons and leptons

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University of Liverpool

This work is in collaboration w/ Pau Petit Rosas
F. Ignatov, T. Teubner and G. Venanzoni

ICHEP 2024, Prague
Top Quark and Electroweak Physics
July 19, 2024

This talk: I plan to provide an overview of the status of the Monte Carlo event generator at NNLO, with particular emphasis on the KLOE-2 experiment.

Introduction

RadioMonteCarLow —> Strong 2020 initiative

Eur. Phys. J. C (2010) 66: 585–686
DOI 10.1140/epjc/s10052-010-1251-4

THE EUROPEAN PHYSICAL JOURNAL C

Review

Quest for precision in hadronic cross sections at low energy: Monte Carlo tools vs. experimental data

Working Group on Radiative Corrections and Monte Carlo Generators for Low Energies

STRONG 2020 Virtual Workshop on "Spacelike and Timelike determination of the Hadronic Leading Order contribution to the Muon g-2"

https://agenda.infn.it/event/28089/
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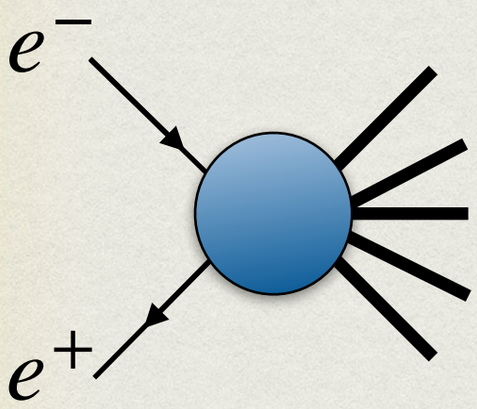

Hadrons

- Compute scattering amplitudes at low energies
- Perform Monte Carlo integration
- Provide theoretical predictions

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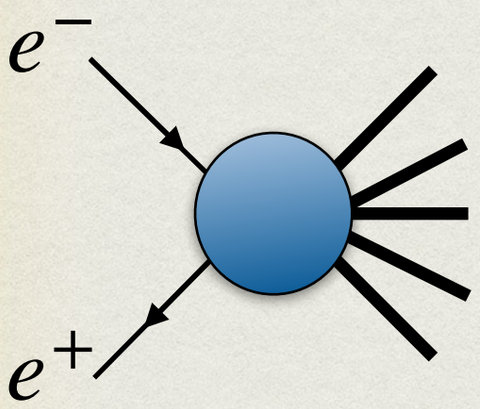
Radiative corrections and Monte Carlo tools for low-energy hadronic cross sections in e^+e^- collisions

Coordinated by A. Kupsc, A. Signer, Y. Ulrich, G. Venanzoni



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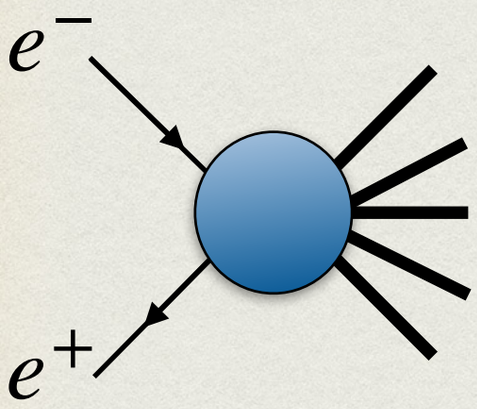

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- Scrutinise in detail form factor insertion in pion processes
- Unravel crucial differences between MC generators
- Fixed order vs resummation

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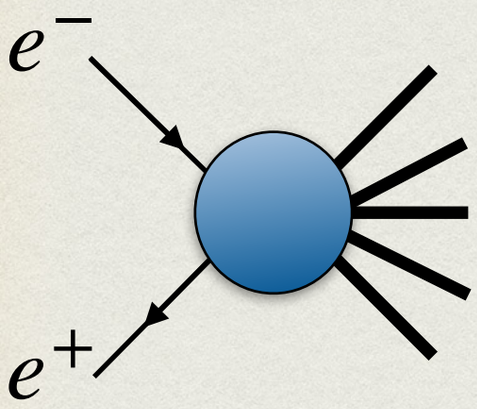

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Today's focus :: `Phokhara` beyond NLO

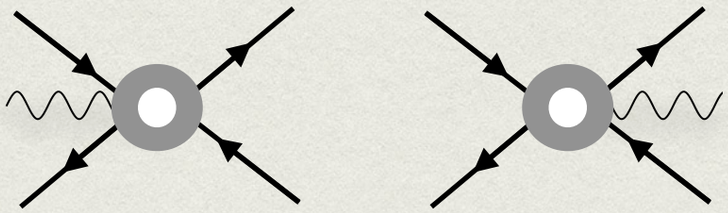
Current Status of `Phokhara 10.0`

(https://looptreeduality.csic.es/phokhara/)

- LO & NLO contribution to radiative return processes

ISR, FSR & Mixed

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



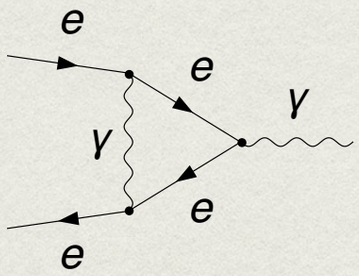
+ real radiations

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

Use of FsQED

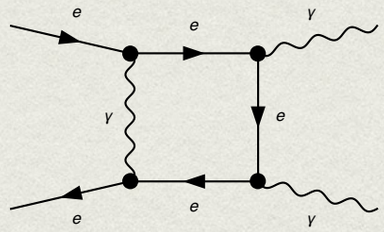
- Three gauge invariant groups

$f^+f^- \to \gamma^* \to F^+F^- + \gamma$



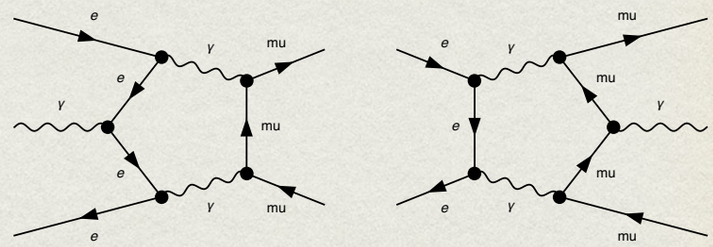
Easy (m_f^2, s)

$f^+f^- \to \gamma\,\gamma^* \to F^+F^-$



Normal (s, t, m_e^2, q^2)

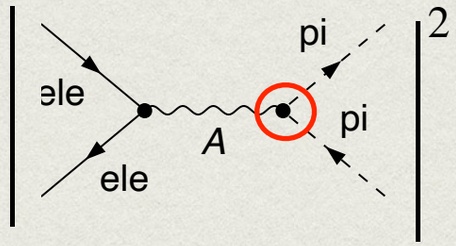
$f^+f^- \to F^+F^-\,\gamma$



Hard $(s_{12}, s_{23}, s_{34}, s_{45}, s_{51}, m_f^2, m_F^2)$

Pion processes

- $e^+e^- \to \pi^+\pi^-$ (ISR)



- Differential cross section in the Center-of-mass frame

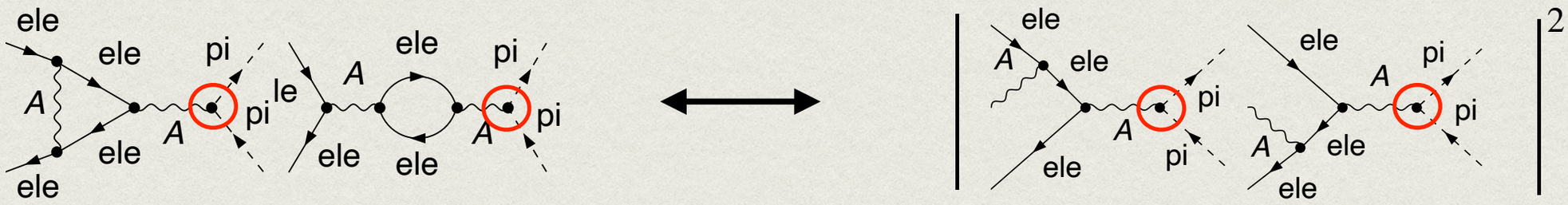
$$\frac{d\sigma_0}{d\cos\theta} = \frac{\pi\alpha^2}{4s}\beta^3\left(1-\cos^2\theta\right)\left|F_\pi(s)\right|^2$$

sQED

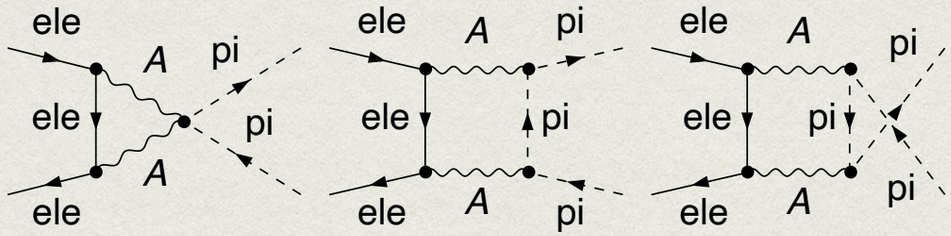
FF

F × sQED

- QED corrections



- FF corrections :: $\mathcal{O}(F(q_i^2)F(q_j^2))$



Include Form factor according to the IR prediction from lower orders

Validation @ NLO

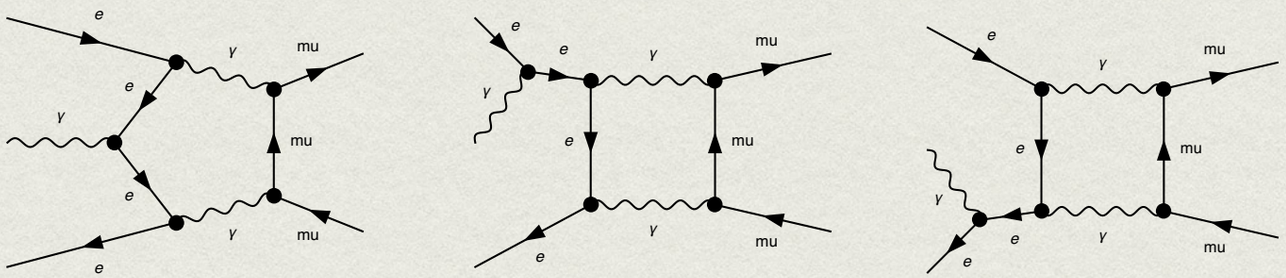
[Petit Rosas, WJT (work in progress)]

- Dimensionally regulated one-loop amplitude ($D = 4 - 2\epsilon$)

$$A^{(1)}\left(f^+f^- \to F^+F^-\gamma\right) = \frac{c_{-1}}{\epsilon} + c_0$$

given by Phokhara

- Organisation of virtual amplitudes

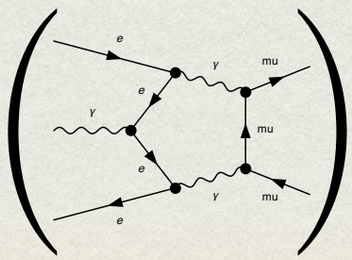
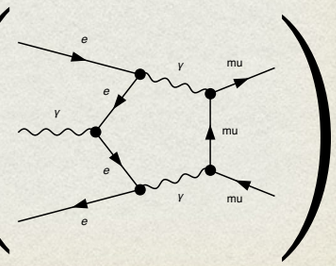


+ crossings & FSR

Automated tools in amplitudes' methodology ::
* `qgraph/FeynArts, Form/FeynCalc` (construction of amplitudes)
* `AMFlow` (numerical evaluation of amplitudes)

- Analytic evaluation of Feynman integrals

$$d\vec{J} = \epsilon\, d\tilde{A}\vec{J}$$

$$\left(\text{  }\right) \times \left(\text{  }\right)^*$$

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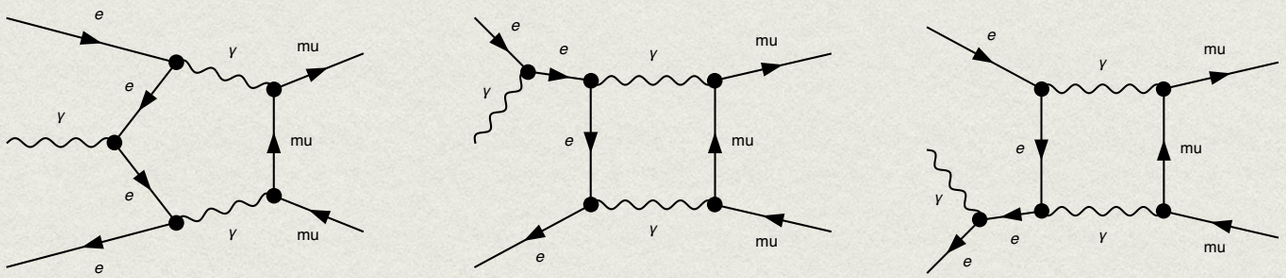
given by Phokhara first results

- Organisation of virtual amplitudes



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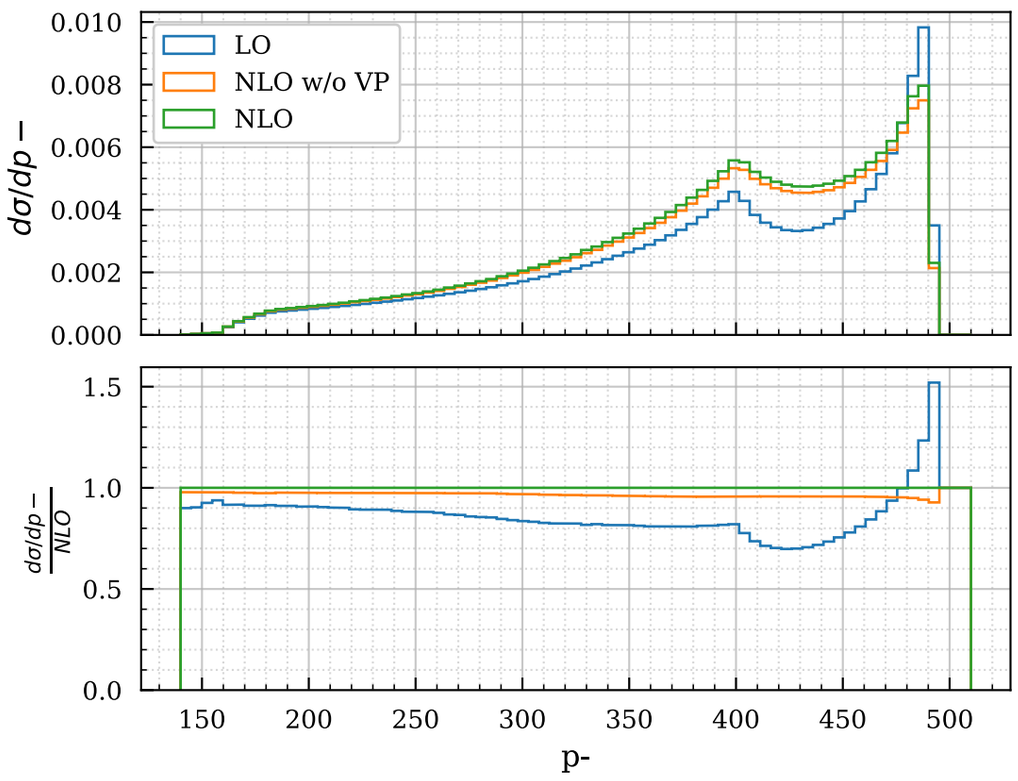
$$\left(\quad\right) \times \left(\quad\right)^*$$

Validation @ NLO

[Courtesy of Petit Rosas]

- Photon emission at large angle



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

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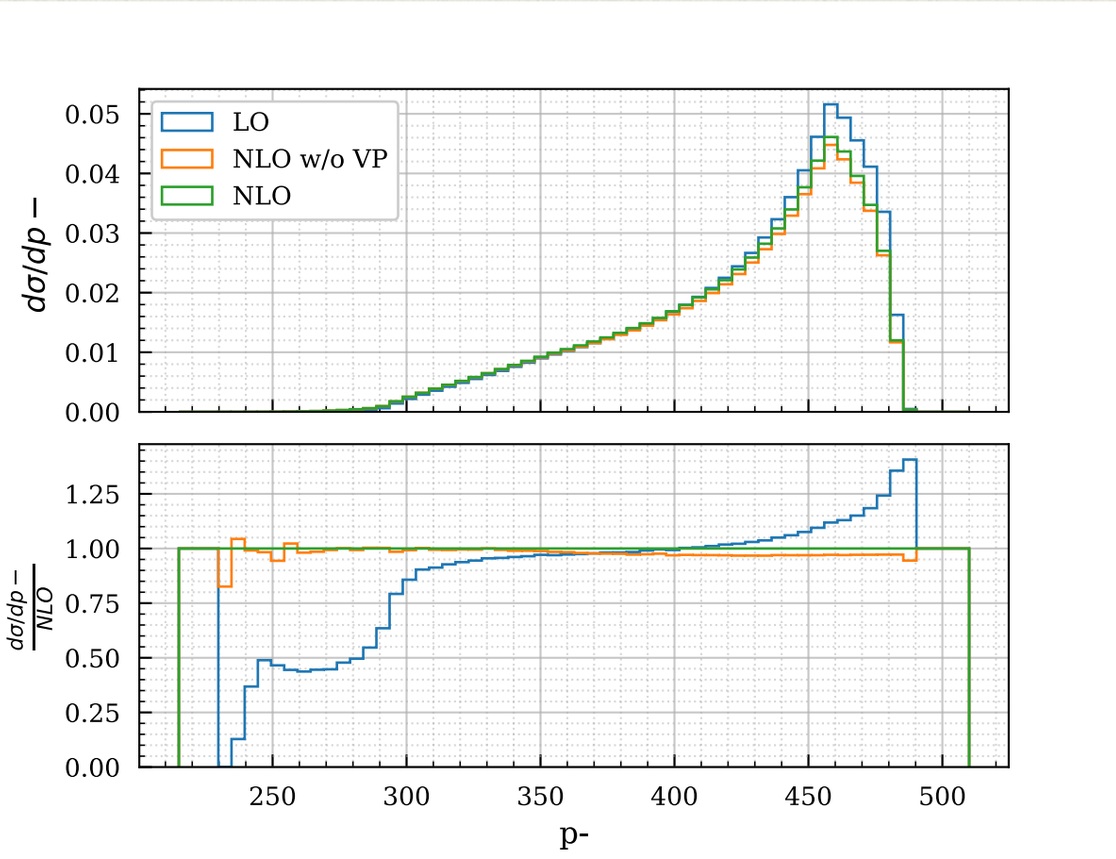

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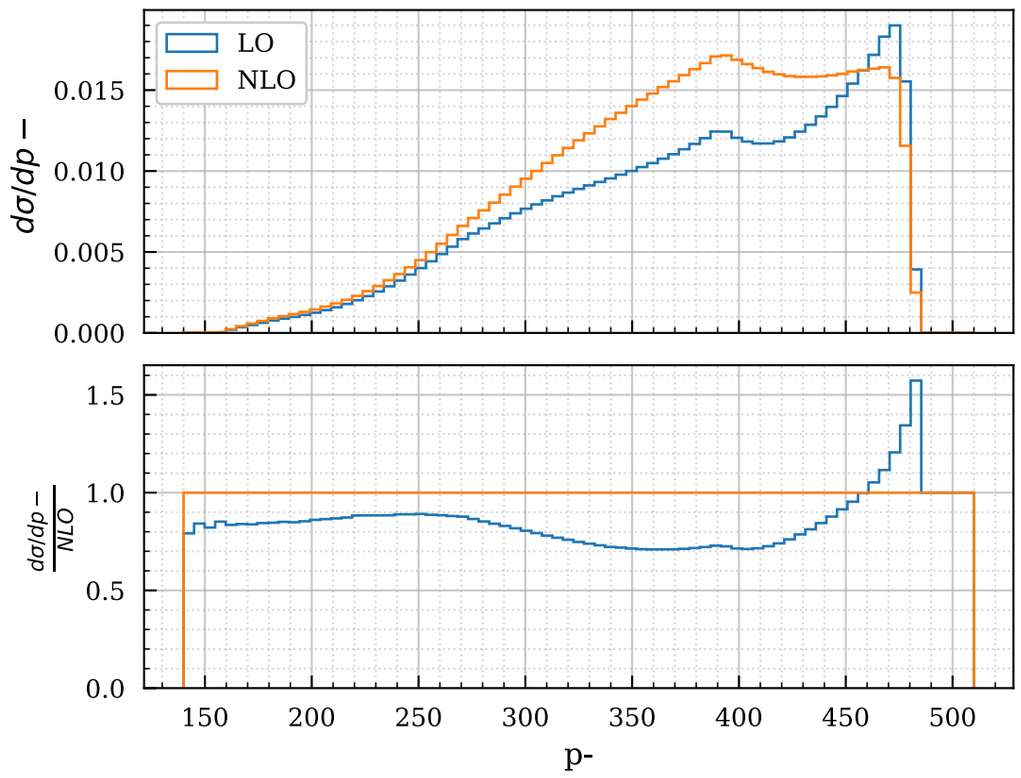

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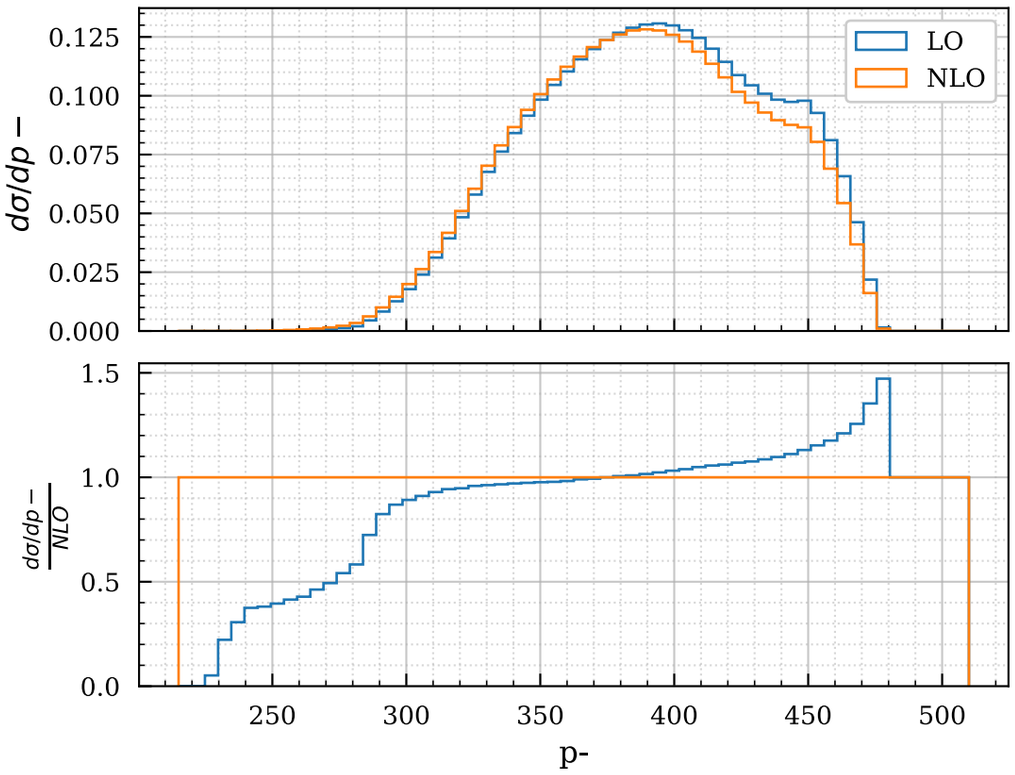


From F × sQED to FsQED

- introduce a parameterisation of the form factor

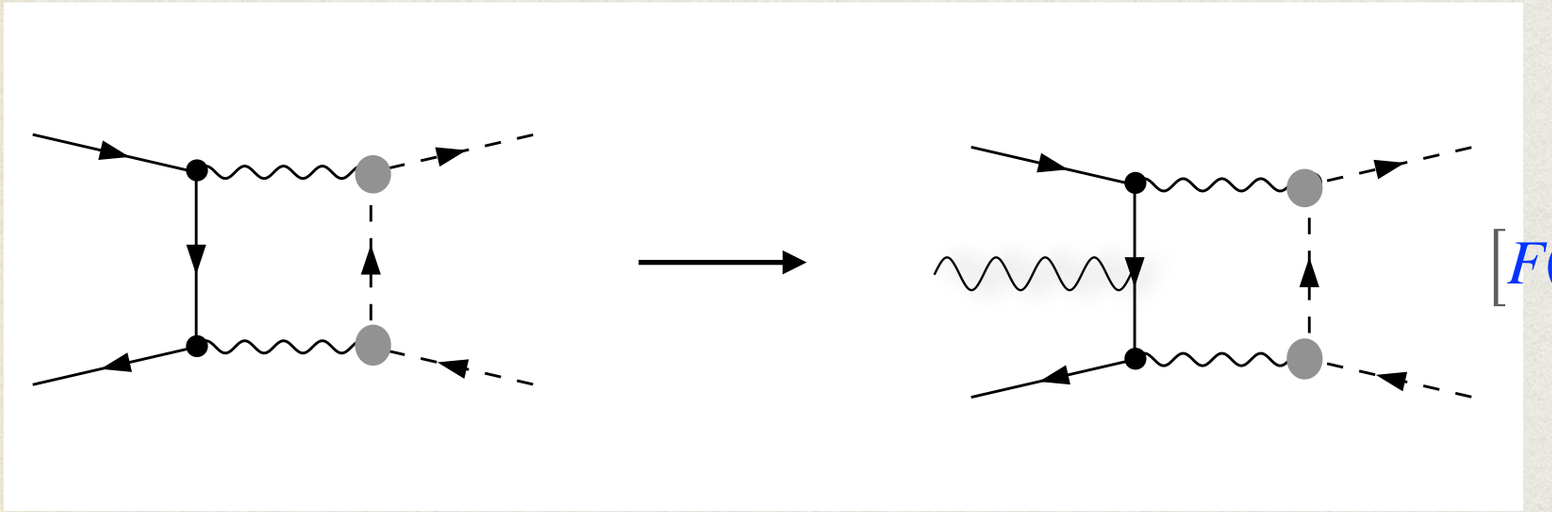
$$F(q^2) = \sum_{v=1}^{n} a_v \frac{\Lambda_n}{\Lambda_n - q^2}\,, \qquad \text{with} \sum_{v=1}^{n} a_v = 1\,.$$

Include Form factor according to the IR prediction from lower orders

- Known results on forward-backward asymmetry of $e^+e^- \to \pi^+\pi^-$

[Lee, Ignatov (2022)]

[Colangelo, Hoferichter, Monnard, Ruiz de Elvira (2022)]



$$\left[F(s) - F(q_1^2)F(q_2^2) + F(s)\right]$$

δ^{V}_{FF} :: UV and IR finite ?

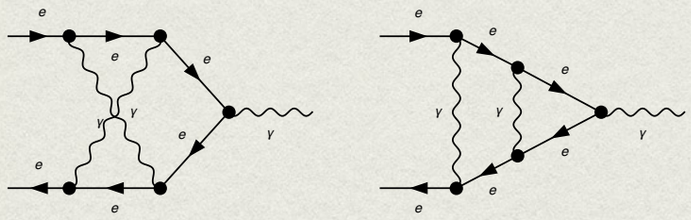
Is IR structure unchanged

Progress on NNLO

[Petit Rosas, WJT (work in progress)]

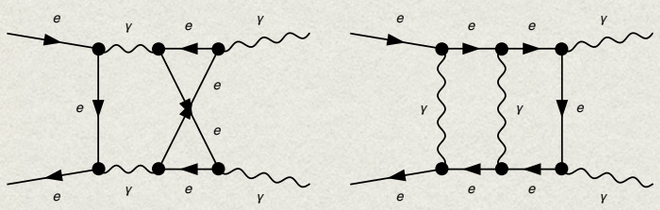
- Two-loop pieces

$$f^+f^- \to \gamma^* \to F^+F^- + \gamma$$



Form factors computed long time ago
Revisited in 2106.13179 [hep-ph]
Can be implemented in `Phokhara` framework
But not of relevant interest

$$f^+f^- \to \gamma\,\gamma^* \to F^+F^-$$



Needs to be carefully analysed
Can we find a "nice" form factor $q_e^a\, q_m^b$?
Use of numerical tools Diffexp/SeaSyde

$$f^+f^- \to F^+F^-\,\gamma$$

Very challenging!!!
Fully numerical framework

Conclusions & Outlook

We have reached:

- ☑ First improvements in the `Phokhara` generator
- ☑ Validation of NLO theoretical predictions for radiative processes
- ☑ Scrutinised in detail form factor insertion within Phokhara
- ☑ Unravel crucial differences between MC generators (Strong2020)

We are working on:

- ☐ Provide efficient approaches to combine numerics & analytics.
- ☐ Use novel mathematic insights in evaluation of Feynman integrals.
- ☐ NNLO theoretical predictions for low energy processes

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