LTP(izza)hD

an experimentalists-friendly overview of the treatment of QED radiative corrections

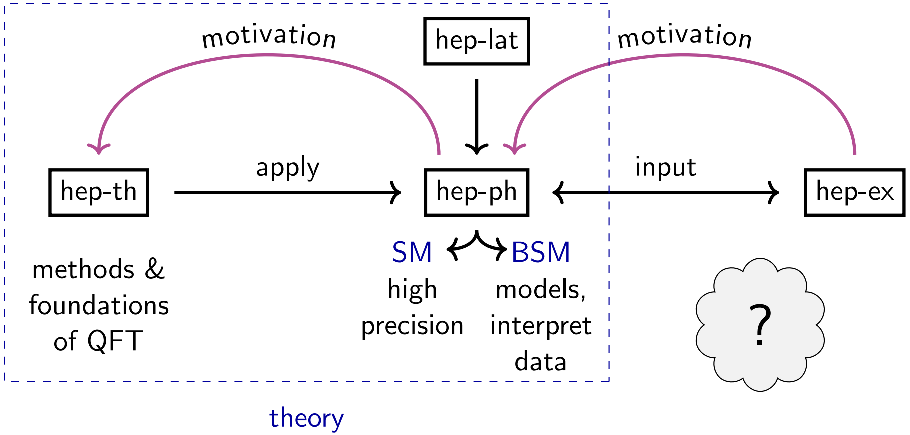
QED corrections for low-energy experiments

Sophie Kollatzsch

LTP theory group

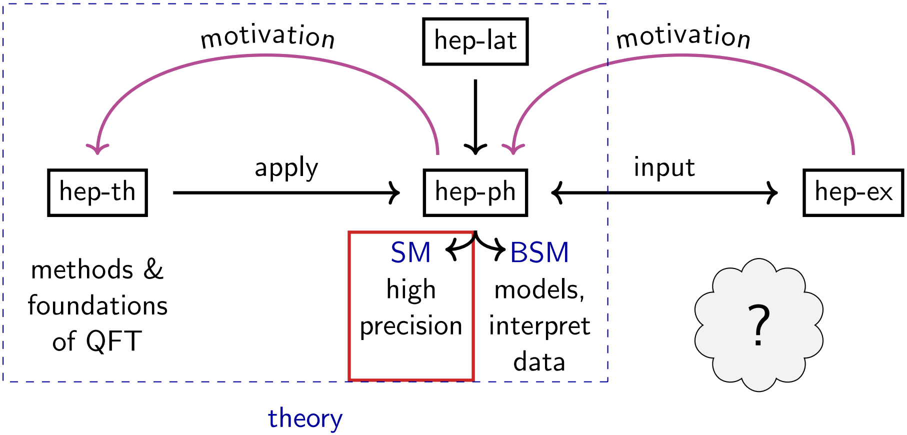
26 September 2023

(my) point of view

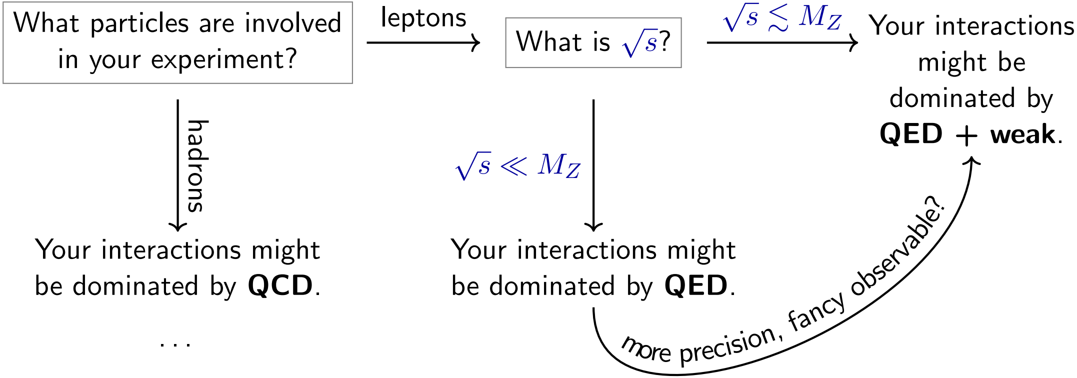


landscape of particle physics

(my) point of view – today's topic



$$\text{SM} = (\text{QED} + \text{weak}) + \text{QCD}$$



testing the SM

$\mathsf{SM} = (\mathsf{QED} + \mathsf{weak}) + \mathsf{QCD}$ today's topic

What particles are involved in your experiment?

→ leptons → What is $\sqrt{s}$?

→ $\sqrt{s} \lesssim M_Z$ → Your interactions might be dominated by **QED + weak**.

→ $\sqrt{s} \ll M_Z$ → Your interactions might be dominated by **QED**.

→ more precision, fancy observable? → Your interactions might be dominated by **QED + weak**.

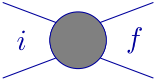
→ hadrons → Your interactions might be dominated by **QCD**.

...

theory prediction

task calculate cross section σ for a given process $i \to f$ as precisely as possible

$$\sigma = \int_{\text{phase space}}$$



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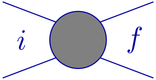

workflow

1. calculate the amplitudes
   1.1 SM theory input
   1.2 regularisation scheme
   1.3 loop integrals
   1.4 tools: OpenLoops

2. do the phase space integration
   2.1 subtraction scheme
   2.2 numerical instabilities
   2.3 adapt to experiment
   2.4 . . .

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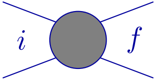

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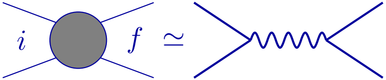
undetected massless particles $\rightsquigarrow$ subtraction scheme

as precise as possible (QED)

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



radiative corrections: add everything that is **indistinguishable experimentally**

as precise as possible (QED)

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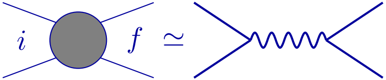
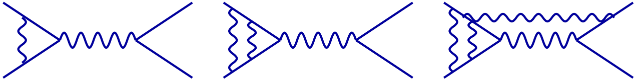


radiative corrections: add everything that is **indistinguishable experimentally**

a) loops



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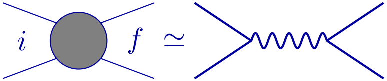

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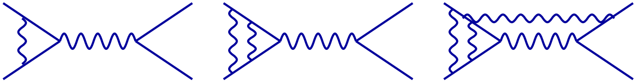
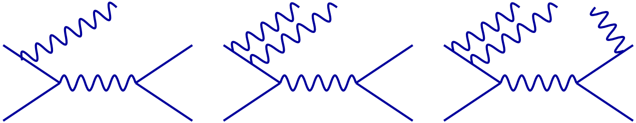
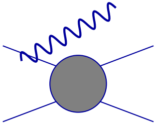


b) (soft) photons – photons with very low energy can escape undetected



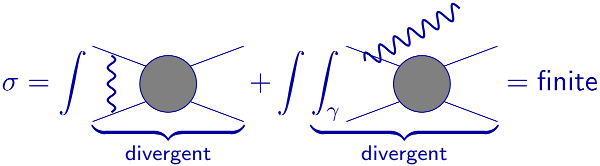
challenge: integration over the photon phase space yields ∞

$\int_{\text{phase space}}$  $\sim \int_0 \frac{1}{E_\gamma^2} \longrightarrow \infty$

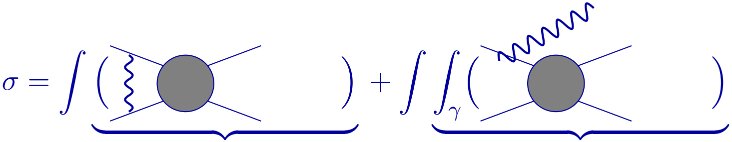
The fact that photons with very low energy can escape undetected becomes visible on the theory side by **divergences**.

physics is finite

Bloch-Nordsieck theorem:
divergences due to photons will cancel against divergences due to loops



$\Longrightarrow$ use subtraction schemes to avoid divergent phase space integrals



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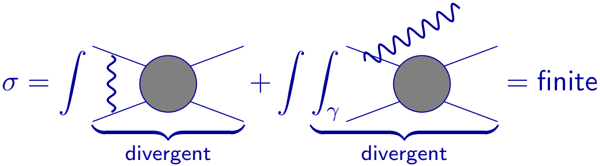

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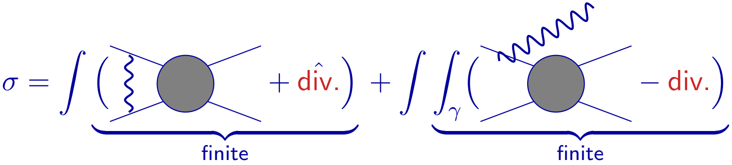


$\Longrightarrow$ allows for numerical evaluation of the integrals

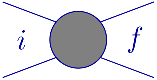
modelling the real world

real world = (detector response) × (actual physics event)

the real world has cuts

- detectors are not perfect
- cuts can disentangle background

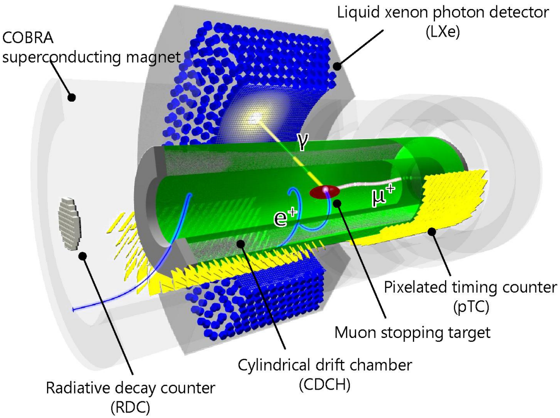
we implement such cuts (i.e. the geometry of the detector) in our calculation

$$\sigma = \int_{\text{phase space}}$$ 

× [measurement function]

$\Longrightarrow$ numerical evaluation of the integrals is indispensable

example 1: MEG geometry



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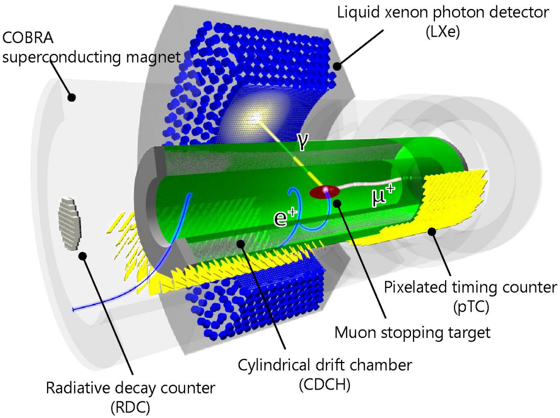
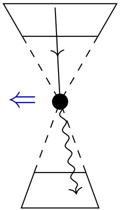
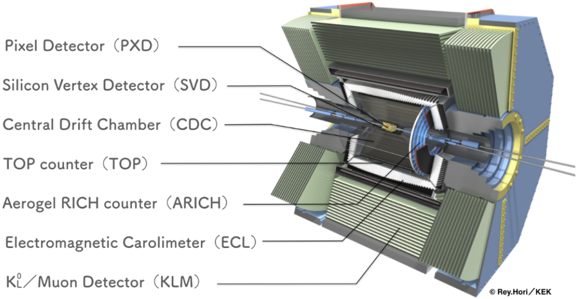




example 2: Belle geometry



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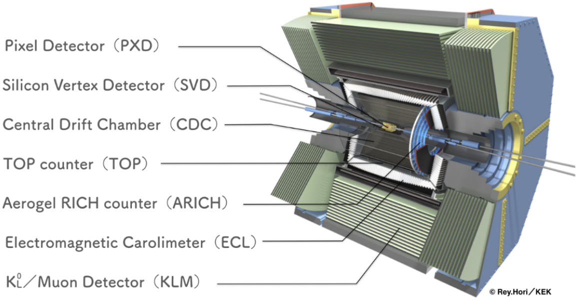
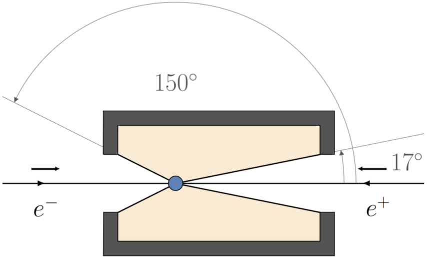




we have a tool!

f.l.t.r.: F.Hagelstein (Mainz), A.Coutinho (IFIC), N.Schalch (Bern), L.Naterop (Zurich & PSI), S.Kollatzsch (Zurich & PSI), A.Signer (Zurich & PSI), M.Rocco (PSI), T.Engel (Freiburg), V.Sharkovska (Zurich & PSI), Y.Ulrich (Durham), A.Gurgone (Pavia)
not pictured: P.Banerjee (IIT Guwahati), D.Moreno (PSI), D.Radic (Tubingen)

input: amplitudes
output: σ and $\frac{\mathrm{d}\sigma}{\mathrm{d\,whatever}}$

McMule

mule-tools.gitlab.io

McMule @ PSI experiments

MEG $\mu \to e\gamma$ and Mu3e $\mu \to eee$

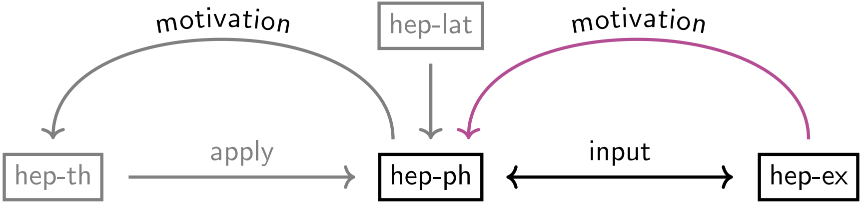
- SM signal zero, goal: BSM
- background $\mu \to e\nu\nu + \gamma$ and $\mu \to e\nu\nu + ee$ for small ν energies
- support for axion-like particle searches in $\mu \to eX$

MUSE $ep \to ep$, $\mu p \to \mu p$

- goal: proton radius + TPE
- LTP seminar in June 2023 by Marco Rocco!

McMule

take-home messages



- Low-energy experiments have motivated PSI theorists to develop McMule, a framework for QED corrections for processes involving leptons.
- McMule provides predictions for MEG, Mu3e, MUSE and many more experiments outside of PSI.
- There are challenges in the calculation of radiative corrections.
  Many of them are under control, many more are waiting to be explored!

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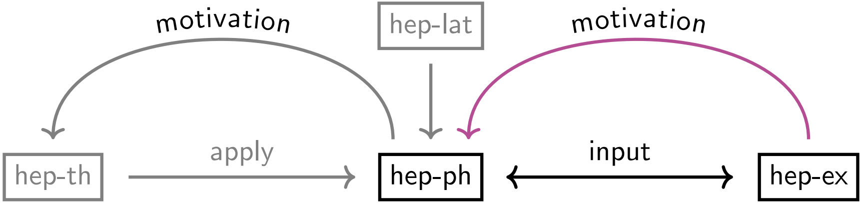

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There are many more things the LTP theory group is working on
$\Rightarrow$ **next theory talks!**

En Guete mitenand!