QED.jl - A Strong-field particle physics ecosystem

JuliaHEP 2023 Workshop

November 9, 2023 // Uwe Hernandez Acosta

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HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF
TECHNISCHE UNIVERSITÄT DRESDEN
CBG Max Planck Institute of Molecular Cell Biology and Genetics
HELMHOLTZ CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ
Uniwersytet Wrocławski

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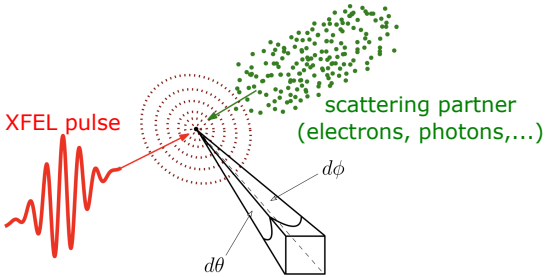
Motivation: our physics use-case



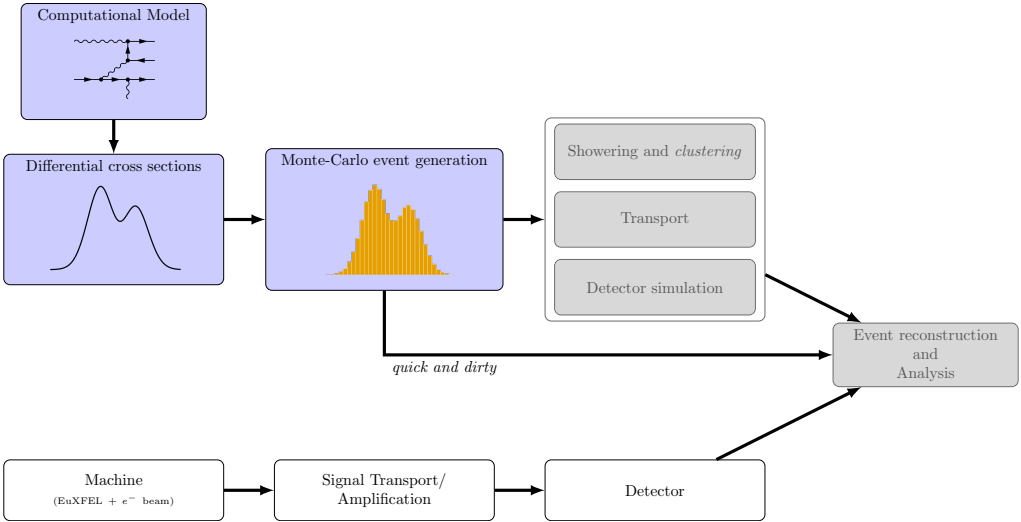
Phenomena

- multi-photon scattering
- non-perturbative effects
- unstable vacuum effects
- electromagnetic cascades

Applications

- Magnetars
- high-luminosity e^-e^+ collider
- Dirac/Weyl semi-metals
- relativistic plasma physics

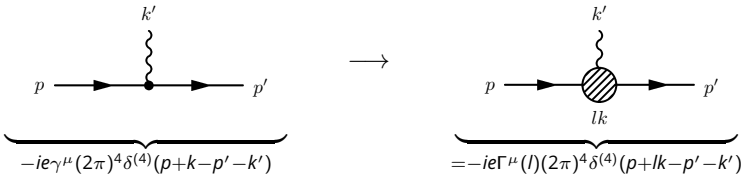
Particle-physics-like simulation workflow



[Stefan Gieseke - MCnet Vietnam summer school (2019)]

Model: strong-field quantum electrodynamics

- Feynman-rule: vertex



- vertex function

$$\Gamma^\mu(l,p,p',k) = \Gamma_0^\mu B_0(l) + \Gamma_1^{\mu\nu} B_{1\nu}(l) + \Gamma_2^\mu B_2(l)$$

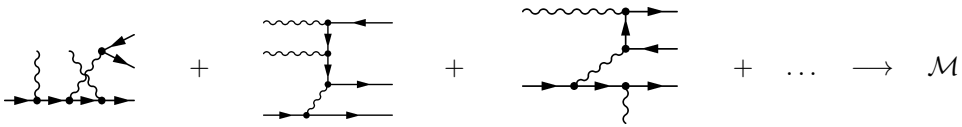
- Phase integrals

$$\left.\begin{matrix} B_0(l) \\ B_1^\mu(l) \\ B_2(l) \end{matrix}\right\} = \int_{-\infty}^{\infty} \mathrm{d}\phi \, \exp(il\phi + iG(\phi)) \left\{\begin{matrix} 1 \\ A^\mu(\phi) \\ A^\mu(\phi)A_\mu(\phi) \end{matrix}\right.$$

[UHA2021 PhD thesis - TU Dresden: ADD PRD]

Differential Cross Sections: $k_1, \ldots, k_M \to p_1, \ldots, p_N$

- Scattering Matrix Element



- Golden Rule

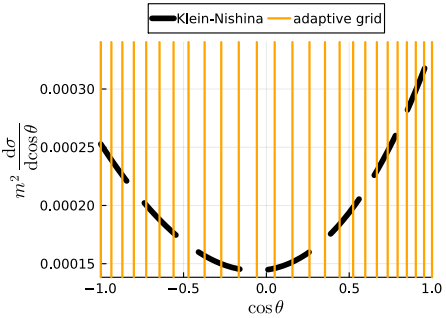
$$\mathrm{d}\sigma = \underbrace{\frac{1}{4\mathcal{I}}}_{\text{incident flux}} \times \underbrace{\sum_{\sigma_1\ldots,\lambda_1\ldots} |\mathcal{M}|^2}_{\text{squared matrix element}} \times \underbrace{\prod_{i=1}^{N} \frac{\mathrm{d}^3 p_i}{(2\pi)^3 2p_i^0} (2\pi)^4 H(k_1, \ldots, k_M, p_1, \ldots, p_N)}_{\text{phase space measure}}$$

$$H(k_1, \ldots, k_M, p_1, \ldots, p_N) = \delta^{(4)}(k_1 + \cdots + k_M - (p_1 + \cdots + p_N)) \times \Theta(\text{cuts})$$

Monte-Carlo Event-Generation: How to generate events

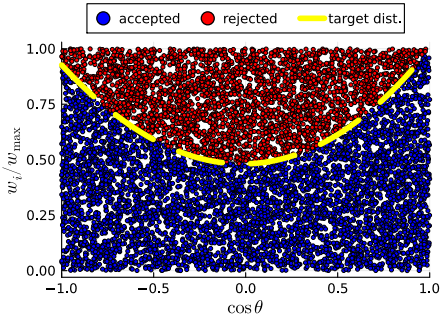
total cross section

$$\sigma \approx \frac{1}{N} \sum_{u \in \mathcal{R}[g]} \underbrace{\frac{\mathrm{d}\sigma/\mathrm{d}u}{g(u)}}_{\sim w_u}$$



sample drawing (unweighting)

$$(u, w_u) \to (\tilde{u}, 1)$$



QED.jl - Strong-field particle physics code

[https://github.com/QEDjl-project]

Requirements

- open source
- user-friendly
- modularised
- extensible
- generic
- performant
- CPU + GPU

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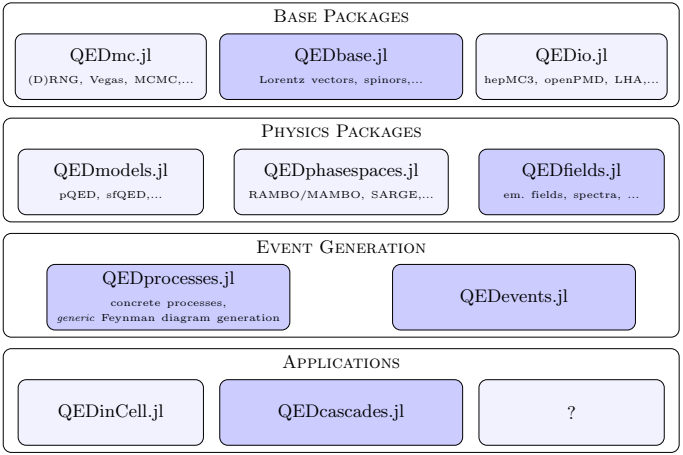

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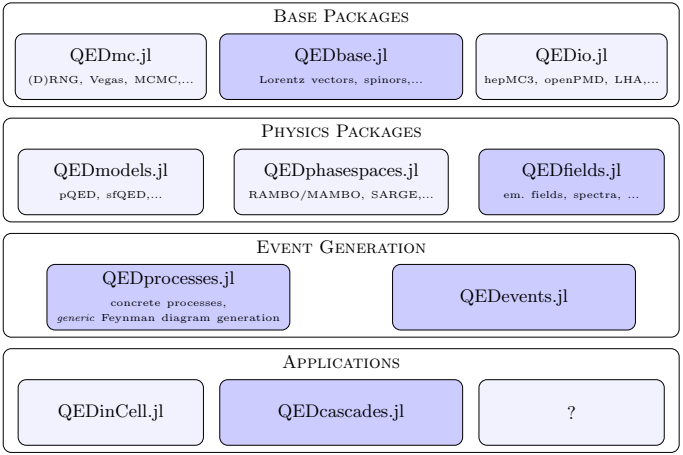


⟶ **not** restricted to quantum electrodynamics

QEDbase.jl

- Lorentz vectors (based on `StaticArrays.jl`)

```
E, m = 2.0, 1.0
p = SFourMomentum(E, 0, 0, sqrt(E^2 - m^2))
@assert isapprox(p*p, m^2)
```

- Spinors and Dirac matrices (based on `StaticArrays.jl`)

```
u = IncomingFermionSpinor(p,m)
u_bar = OutgoingFermionSpinor(p,m)
sp_prod = [u_bar(i)*(slashed(p)*u(j)) for i in 1:2 for j in 1:2]
@assert isapprox(  sum(sp_prod)  , 4*m^2)
```

- Particle types and `Incoming/Outgoing`

```
electron_charge = charge(Electron())
@assert electron_charge = -1
electron_state = base_type(Electron(),Incoming(),p, SpinUp())
@assert isapprox( electron_state, u(1))
```

`QEDfields.jl` – Electromagnetic fields

- Base type: `AbstractField`

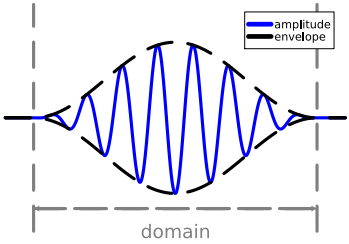
```
domain(::AbstractField)
reference_momentum(::AbstractField)
_amplitude(::AbstractField)
```

- Base type: `AbstractPPWField <: AbstractField`

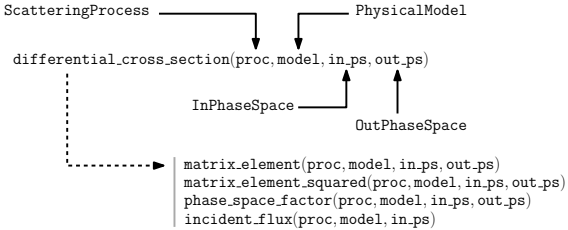
```
phase_duration(::AbstractPPWField)
phase_envelope(::AbstractPPWField)
```

- generic implementations

```
amplitude(::AbstractField, ... )
fourier_transform(::AbstractField, ... )
...
```



QEDprocesses.jl



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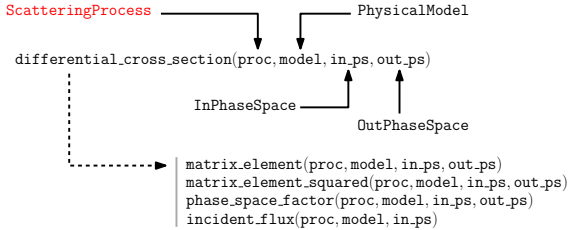
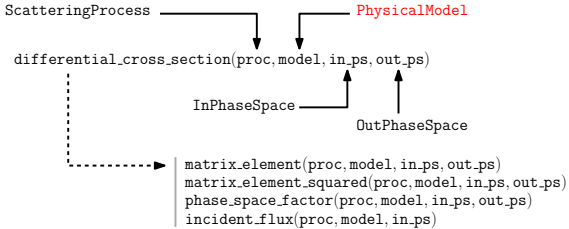


- base type:
  `AbstractScatteringProcess`
- interface function
  `incoming_particles`
  `outgoing_particles`
  `spins`
  `polarizations`

```
julia> Compton(PolX(),SpinUp(),AllPol(),AllSpin())
Compton{PolarizationX, SpinUp, AllPolarization, AllSpin}()
```

QEDprocesses.jl



- base type:
  `AbstractPhysicalModel`
- interface function
  `fundamental_interaction`

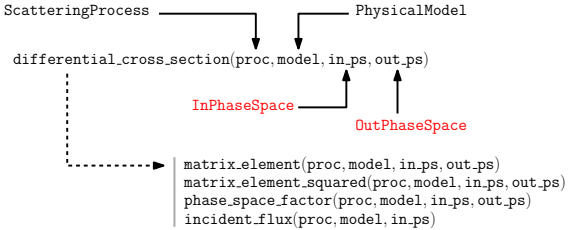
  `in_ps_dim(proc, model)`
  `out_ps_dim(proc, model)`
  `matrix_element`

```
julia> model = PerturbativeQED()
PerturbativeQED()
```

```
julia> field = GaussianField()
GaussianField()

julia> model = StrongFieldQED(field)
StrongFieldQED{GaussianField}()
```

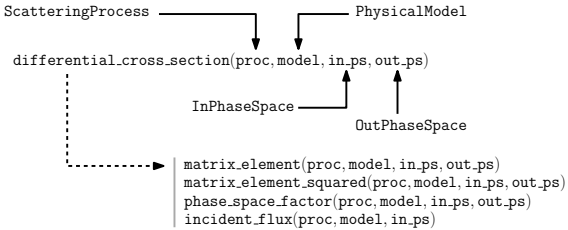
QEDprocesses.jl



- base type

```
AbstractVector{T}
AbstractMatrix{T}
where {T<:AbstractFourMomentum}
```

QEDprocesses.jl




```
julia> proc = Compton(AllPol(),AllSpin(),AllPol(),AllSpin())
Compton{AllPolarization, AllSpin, AllPolarization, AllSpin}()

julia> model = PerturbativeQED()
PerturbativeQED()

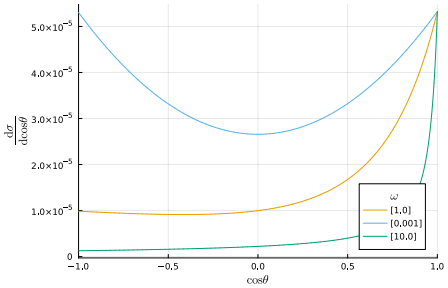
julia> omega = [1.0 1e-3;]
1×2 Matrix{Float64}:
 1.0  0.001

julia> cth_arr = range(-1,1,length=10_000)
-1.0:0.0002000200020002003:1.0

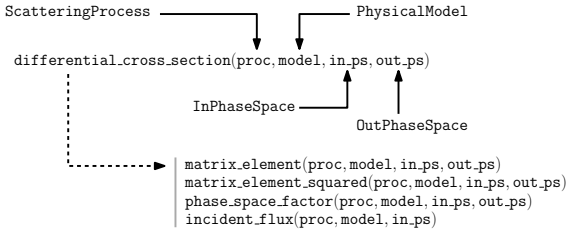
julia> phi_arr = [0.0,]
1-element Vector{Float64}:
 0.0

julia> final_PS = collect_batch(cth_arr,phi_arr);

julia> diffCS = differential_cross_section(proc,model,omega,final_PS);
```



QEDprocesses.jl

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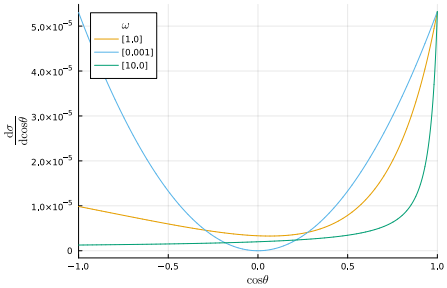


Interlude: the computation setup interface

$$f(\underbrace{u_1, \ldots, u_n}_{\text{input vector}}; \underbrace{\lambda_1, \ldots, \lambda_m}_{\text{parameters}}) = \underbrace{R}_{\text{output}}$$

- base type: `AbstractComputeSetup`
- interface functions

```
_assert_valid_input(stp,input)

_compute(stp, input)

_post_processing(stp, input,
result)
```

- default implementation

```
compute(stp, input)
```

- conceivable input

```
SVector/SMatrix
Vector/Matrix
CuArray
ROCArray
...
```

QEDevents.jl

- General sampler
  base type: `AbstractSampler`

```
Base.eltype(sampler)
setup(sampler)
weight(sampler,x)
Distributions._rand!(rng,sampler, out)
```

- Rejection sampler

```
RejectionSampler<:AbstractSampler

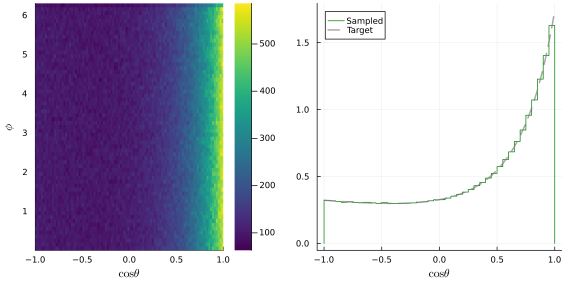
...
proposal(reject_sampler)
```

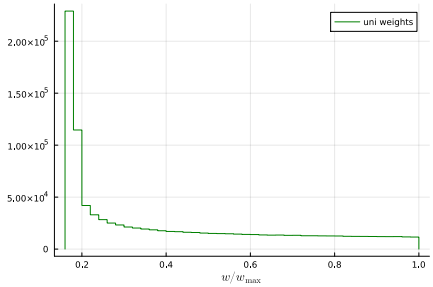
- Proposal sampler
  - Uniform
  - Vegas
  - NIS
  - MCMC
  - ...
- Process sampler
  - Kahn
  - Koblinger
  - Özmutlu
  - KEK_BW
  - FieldSampler
  - ...

Event Generation

```
proc = Compton() # default: all spins/pols summed
model = PerturbativeQED()
in_ps = [1.0; ] # omega = 511 keV
stp = DifferentialCrossSection(proc, model, in_ps)
sampler = RejectionSampler(stp) # default: uniform proposal
samples = rand(sampler,1000_000)

plot_combine(stp,samples)
```





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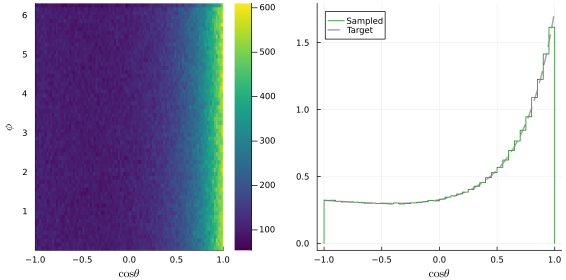
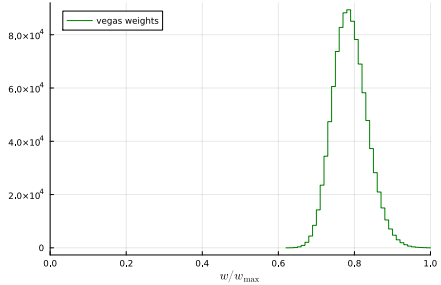
proc = Compton() # default: all spins/pols summed
model = PerturbativeQED()
in_ps = [1.0; ] # omega = 511 keV
stp = DifferentialCrossSection(proc, model, in_ps)
proposal = VegasSampler(stp)
sampler = RejectionSampler(stp, proposal)
samples = rand(sampler,1000_000)

plot_combine(stp,samples)
```





Instead of a summary: lessons learned

- Theory
  - ⇒ there is something besides SM physics
  - ⇒ dynamical Feynman rules are hard to model
- `QED.jl`
  - ⇒ easy interfaces are hard to design
  - ⇒ orthogonal design is mandatory
  - ⇒ Julia is your friend
- Event generation
  - ⇒ good proposals beat bad proposals
  - ⇒ good implementations beat good proposals
  - ⇒ knowing your problem beats everything

- Collaborators

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Klaus Steiniger
Simeon Ehrig
Tom Jungnickel
Anton Reinhard

Prof. Burkhard Kämpfer
René Widera

Prof. Thomas Cowan
Michal Smid
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