



The CepGen event generator

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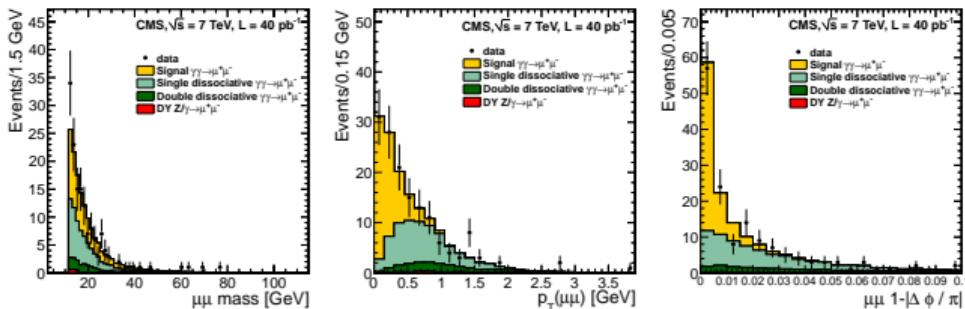
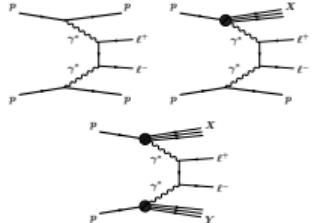
A bit of context – LHC-CMS run 1 exclusive searches

Given low levels of event pileup in LHC startup (2008-2009), first experimental attempts¹ to tag central exclusive, $\gamma\gamma$ events

- “standard candle”: $\gamma\gamma \rightarrow l^+l^-$, envisioned as a tool for luminometry at LHC
- experimentally striking (a pair of central, coplanar leptons, with low underlying activity in tracker/forward calorimeters)

Issue: central detector-only information, no scattered proton tagging to ensure exclusivity
(CMS-PPS/ATLAS-AFP appeared in LHC run 2)

- need for a theoretical description of elastic, but also single- and double-dissociative spectra
- back then, a few generators “on the market” for photon-induced productions, very few allowing an equivalent treatment of all three cases ; $\gamma\gamma \rightarrow l^+l^-$ process: LPAIR²



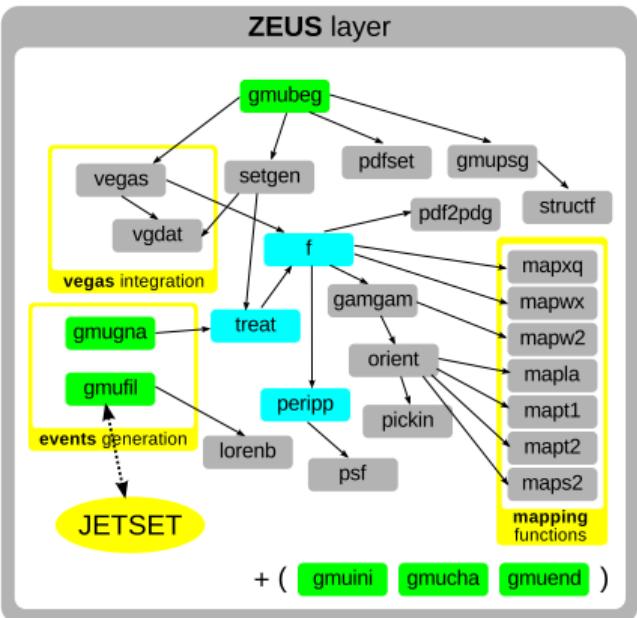
¹ CHATRCHYAN *et al* 2012

² BARANOV *et al* 1991

HERA heritage, implementation into an event generator of a framework³ to model the $ep \rightarrow e(\gamma\gamma \rightarrow l^+l^-)p$ process

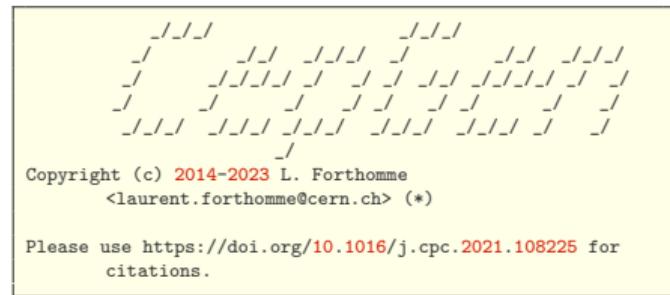
Later used at LEP (OPAL/L3), and more recently at LHC (CMS/ATLAS)

- **major pros:**
 - natively handles (electron/proton) elastic and proton-dissociative cases as two separate sub-processes for photon-from-beam particle emission
 - very flexible modelling of proton structure functions (Suri-Yennie continuum, Fiore-Brasse resonances, PDFlib parton-level parameterisations)
 - with help of Jetset, handles dissociation of diffractive state for inelastic photon emissions
- **major cons:**
 - FORTRAN 77-based, with ~35 common blocks sharing memory segments (not convenient for experimentalists in a “multithreaded world”),
 - lots of CERNLIB dependences (latest versions from ZEUS Collaboration), increasingly challenging to maintain (even on CERN-LXPLUS),
 - only one supported process, $\gamma\gamma \rightarrow l^+l^-$



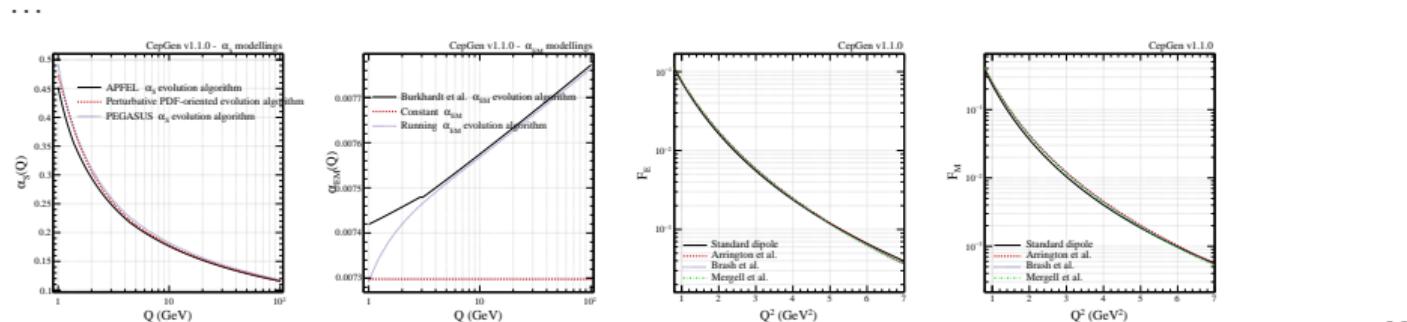
³VERMASEREN 1983

Very generic integration/event generation framework⁴, easily extendable through various user-steerable modules:



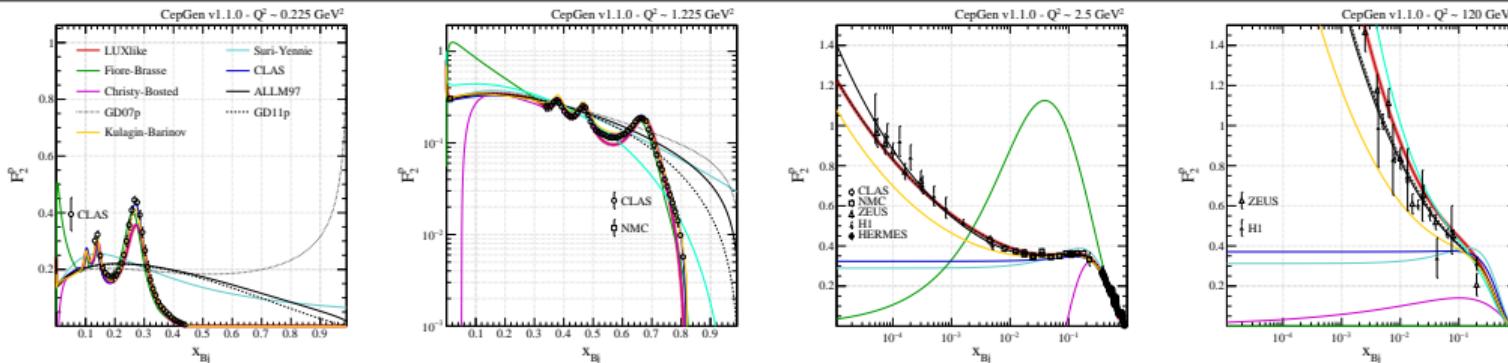
- 6 Monte-Carlo integration algorithms (Vegas, MISER, Foam, ...)
- wrapped from “standard” libraries (GSL, ROOT, Boost...)
- 6 steering cards + command line handlers
 - legacy LPAIR steering cards handled
 - Python 3-based interpreter usage is preferred
- more than 10 output formats and interfaces to external event processing libraries
 - stack compatible with LHC/future prospect studies frameworks

Easily extendable, plugin-like interfacing to modern toolsets: Pythia, LHAPDF, APFEL, TAUOLA, HepMC, ROOT, Rivet, Delphes,



⁴FORTHOMME 2022

Nucleon diffractive structure functions modellings



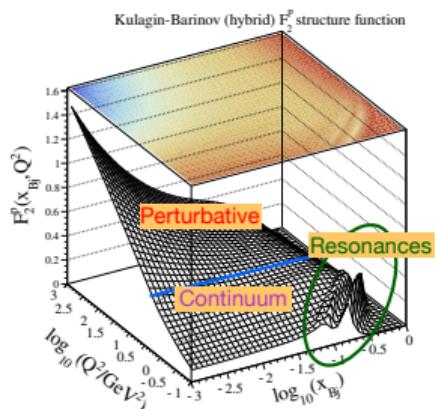
- Broad range of x_{Bj}, Q^2 covered, from low- x_{Bj} , low- Q^2 , low-mass **resonances regime**,
- to high- Q^2 **perturbative** modellings, $F_2 = \sum_q e_q^2 (q + \bar{q})$ (PDF inputs from LHAPDF, APFEL)
- through intermediate scale, **continuum** models

But also including a couple of “modern” parameterisations, combining all regimes into one continuous set of structure functions, e.g.:

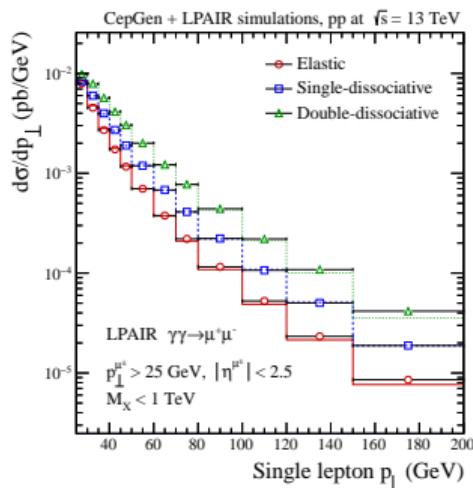
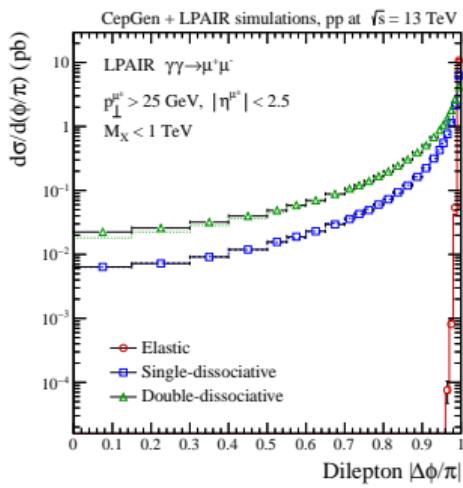
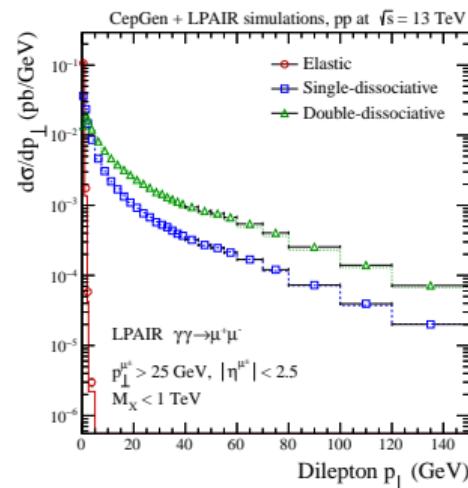
- a “LUXqed-like” approach, reproducing the division of the Q^2/w^2 phase space into three regions of interest^a
- another recent parameterisation following the same paradigm^b

^aMANOHAL *et al* 2017

^bKULAGIN and BARINOV 2022



1-to-1 validated with LPAIR in systematic scans of broad spectrum of event kinematics/incoming beams/... properties



Solid line: LPAIR prediction ; open markers: CepGen validation

Exercise: reproduce these validation plots, adapt them to a set of run 3 ATLAS/CMS conditions, and include acceptance cuts for proton taggers

A minimal LPAIR example

Most flexible configuration can be steered through a Python 3 snippet, readable by CepGen main executable.

```
import Config.Core as cepgen
from Config.PDG_cfi import PDG
from Config.generator_cff import generator as _gen_template # event generation parameters
from Config.OutputModule.ROOTTree_cfi import rootTree

process = cepgen.Module('lpair', # physics process name
    processParameters = cepgen.Parameters( # process-specific parameters
        mode = cepgen.ProcessMode.InelasticElastic, # or ElasticElastic/ElasticInelastic/InelasticInelastic
        pair = PDG.muon,
    ),
    inKinematics = cepgen.Parameters( # definition of the incoming beam properties
        pz = (6500., 6500.),
        structureFunctions = cepgen.StructureFunctions.SuriYennie,
    ),
    outKinematics = cepgen.Parameters( # definition of the produced system's phase space
        pt = (25.,), # single lepton pt > 25 GeV/c
        eta = (-2.5, 2.5), # single lepton pseudo-rapidity
        invmass = (20.,), # two-lepton invariant mass > 20 GeV
        mx = (1.07, 1000.), # outgoing scattered dissociated beam mass range (GeV/c^2)
    ),
)
generator = _gen_template.clone(
    numEvents = 100000, # maximum number of events to generate
    printEvery = 10000, # frequency of event printout during generation
)
output = cepgen.Sequence(
    rootTree, # dump the whole generation content into `events` + `run` metadata ROOT trees
)
```

More steering card examples for various processes/conditions in cepgen/Cards

Other processes in CepGen – k_T factorisation

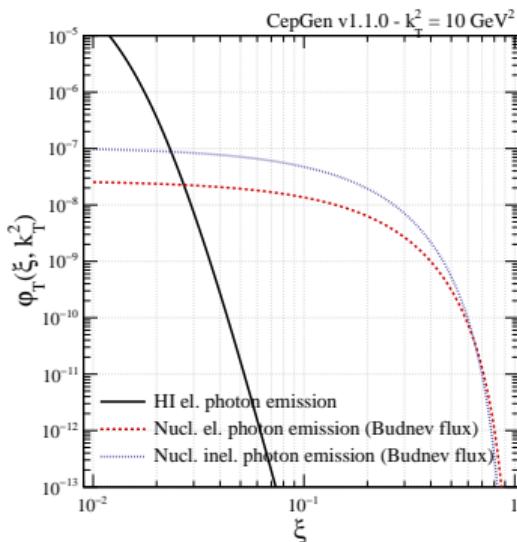
- Transposition to the photon-induced case⁵ of a well-established factorisation technique
- Both elastic, and dissociative photon-from-beam emission modes handled, unintegrated $\gamma(x) \mapsto \Phi_T^{\text{el,inel}}(\xi, k_T^2)$

Both gluon (KMR), and photon-from-nucleon supported in CepGen

- for example, γ -from-proton elastic and dissociative/inelastic emissions:

$$\Phi_T^{\text{el}}(\xi, k_T^2; m_p) = \frac{\alpha}{\pi} \left[(1 - \xi) \left(\frac{k_T^2}{k_T^2 + \xi^2 m_p^2} \right)^2 F_E(Q^2) + \frac{\xi^2}{4} \left(\frac{k_T^2}{k_T^2 + \xi^2 m_p^2} \right) F_M(Q^2) \right]$$

$$\begin{aligned} \Phi_T^{\text{inel}}(\xi, k_T^2; m_p, M_X^2) = & \frac{\alpha}{\pi} \left[(1 - \xi) \left(\frac{k_T^2}{k_T^2 + \xi(M_X^2 - m_p^2) + \xi^2 m_p^2} \right)^2 \frac{F_2(x_{\text{Bj}}, Q^2)}{Q^2 + M_X^2 - m_p^2} + \right. \\ & \left. + \frac{\xi^2}{4} \frac{1}{x_{\text{Bj}}^2} \left(\frac{k_T^2}{k_T^2 + \xi(M_X^2 - m_p^2) + \xi^2 m_p^2} \right) \frac{2x_{\text{Bj}} F_1(x_{\text{Bj}}, Q^2)}{Q^2 + M_X^2 - m_p^2} \right] \end{aligned}$$

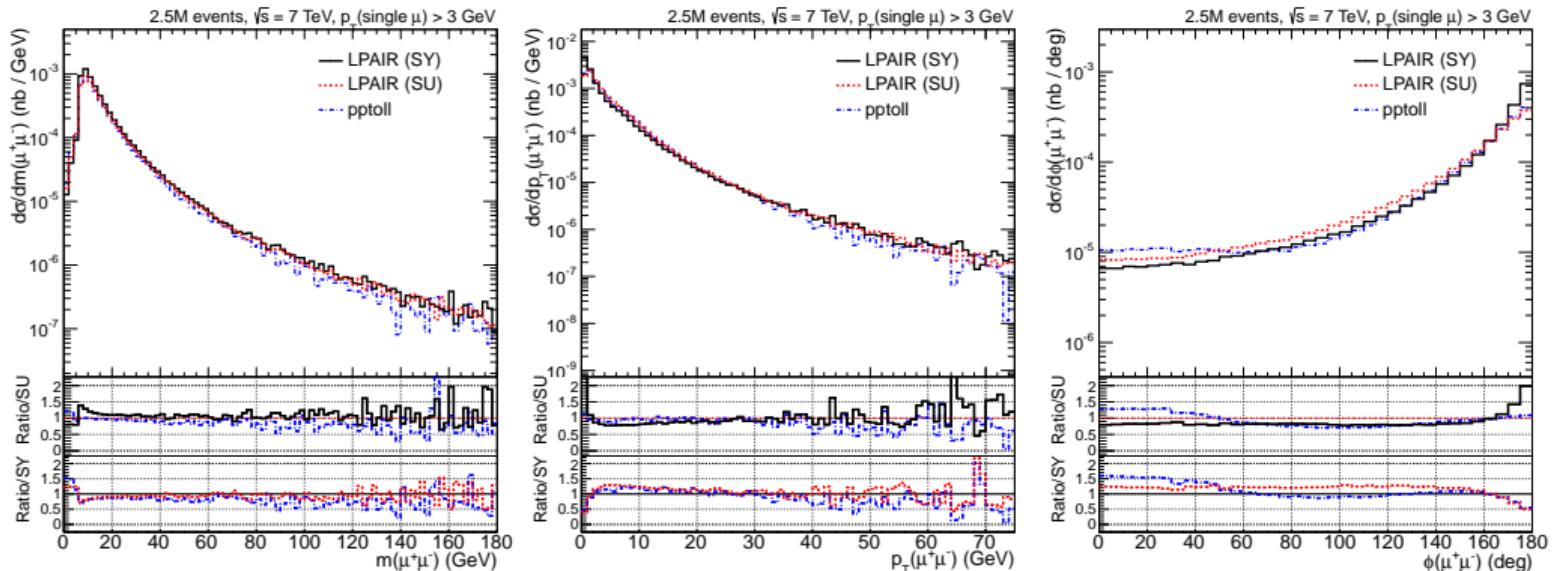


⁵SILVEIRA *et al* 2015

$\gamma\gamma \rightarrow I^+I^-$ in LPAIR vs. k_T factorisation

One-to-one comparison⁶ in various kinematic schemes showed the equivalence of LPAIR/ k_T -factorised formalisms

- e.g. single-dissociative $\gamma\gamma \rightarrow I^+I^-$, with two modellings of proton structure functions F_2/F_L (Suri-Yennie: legacy LPAIR, Szczurek-Uleshchenko: partonic)



- slight distortion observed in large acoplanarity regions, still within experimental uncertainties

⁶SILVEIRA et al 2015

SM & BSM $\gamma\gamma \rightarrow W^+W^-$

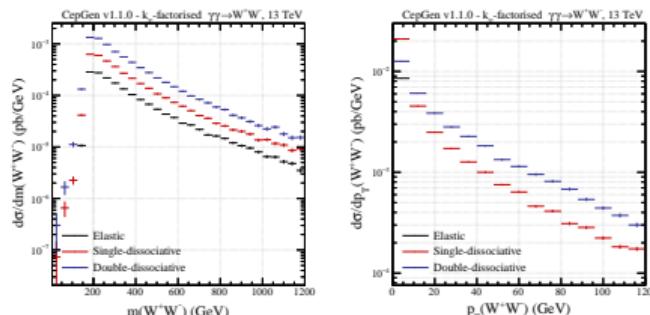
Unconstrained angular distributions for non-collinear parton emission allows the modelling of increasingly challenging MEs, such as the $\gamma\gamma \rightarrow W^+W^-$ one^a

- e.g. helicity-dependent $\mathcal{M}(\lambda_{\gamma_1}\lambda_{\gamma_2} \rightarrow \lambda_{W^+}\lambda_{W^-})$ formalism introduced by Nachtmann *et al*^b accounts either for SM, or dimension-6 EFT extension
- development ongoing to implement dimension-8 EFT^c more conventionally used at LHC

^aŁUSZCZAK, SCHÄFER and SZCZUREK 2018

^bNACHTMANN *et al* 2006

^cBELANGER *et al* 2000 ; EBOLI, GONZALEZ-GARCIA and MIZUKOSHI 2006



Diffractive $gg \rightarrow q\bar{q}, g\gamma \rightarrow q\bar{q}$

- noticeably similar matrix element to the $\gamma\gamma \rightarrow l^+l^-$ ($\gamma\gamma \rightarrow f\bar{f}$) case
- for the proton/gluon side KMR⁷ unintegrated parameterisation of diffractive PDFs, $\Phi_g(\xi, k_T^2)$
- $g\gamma$ also handled for asymmetric pA

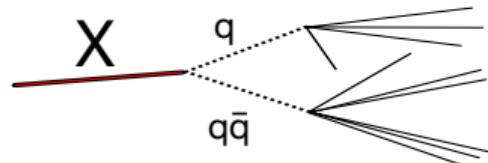
⁷KIMBER, MARTIN and RYSKIN 2000, 2001

Plugin-based implementation of event-basis filters and event output modules

Beam remnants treatment

Several schemes already implemented:

- Jetset/Pythia 6 (“LPAIR way”): kinematic splitting of diffractive proton into a quark/diquark system + string fragmentation
 - mixing of string-tied (d , $(uu)_1$), $(u, (ud)_0)$, and $(u, (ud)_1)$
- Pythia 8: full event treatment through Pythia’s BeamRemnants framework (\rightarrow ISR/FSR/MPI + fragmentation)
 - time-consuming, relies on boosts into/from system where both partons are collinear to beam
 - used, e.g. in experimental modelling of “survival probability”
- Interfacing module for Herwig 7 cluster fragmentation still in preparation



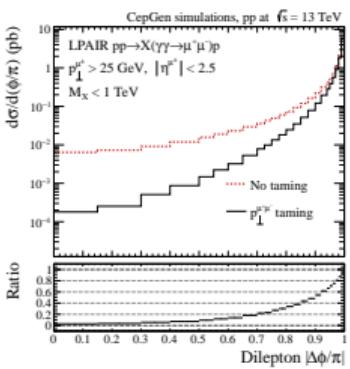
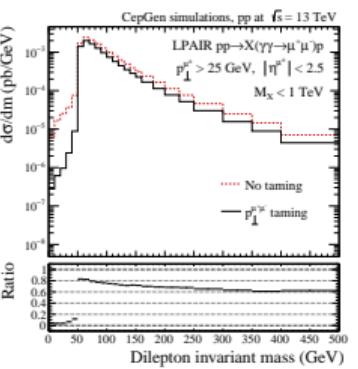
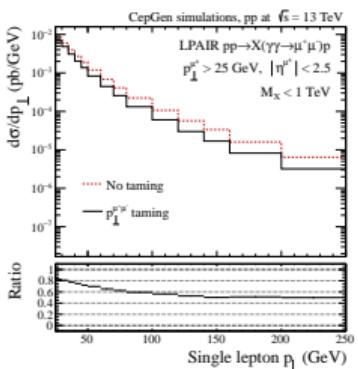
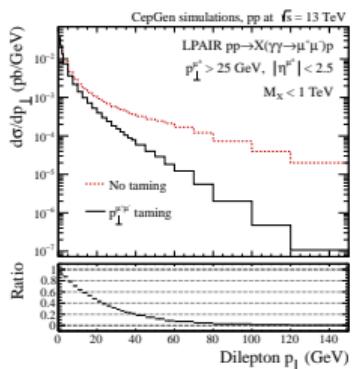
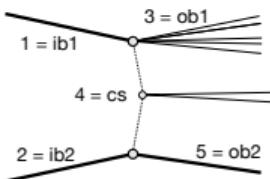
Decay algorithms & output modules

- Decay of “unstable particles”: interfacing to Pythia 6/8, and Tauola(/Photos), with more to come
- Support for export in major data formats (LHEF, HepMC2/3, ProMC, custom ROOT TTrees) and common analysis tools (Delphes, Rivet)

Advanced features: functional reweighting

- single, and multi-variable based event-by-event reweighting through analytic forms
- allows rescattering corrections, paves the ground for the rough *tuning* of various distributions to observed spectra
- e.g. overall survival factor $S \sim 0.76$ computed (SuperCHIC) for CMS-TOTEM observation of $\gamma\gamma \rightarrow l^+l^-$ with proton tags⁸ for single-dissociative $\gamma\gamma \rightarrow l^+l^-$ process, corresponding to a $d\sigma \mapsto d\sigma \otimes e^{-p_T(l^+l^-)/25}$ taming

```
process = cepgen.Module('process_name', # [... process kinematics definition + other blocks ...]
    tamingFunctions = [
        cepgen.Parameters( # single taming function definition
            variables = ["pt(4)"], # central system's transverse momentum reweighting (e.g. pt(l+l-) in LPAIR)
            expression = "(pt(4)>0.) ? exp(-pt(4)/25) : 1.0"
        )
    ],
)
```



⁸SIRUNYAN et al 2018

Advanced features: new processes definition

Only a few minimal requirements for the definition of a physics process

- k_T factorisation framework even simpler: only central ME definition required. E.g. 2-to-4 ($pp \rightarrow p^{(*)}(\gamma\gamma \rightarrow X_1X_2)p^{(*)}$):

```
#include "CepGen/Modules/ProcessFactory.h" // process registration utilities
#include "CepGen/Process/Process2to4.h" // base object definition

struct MyProcess : public cepgen::proc::Process2to4 {
    explicit MyProcess(const cepgen::ParametersList& params) // allows user-steering of parameters
        : cepgen::proc::Process2to4(
            params,
            {cepgen::PDG::photon, cepgen::PDG::photon}, // incoming partons
            steer<cepgen::ParticleProperties>("pair").pdgid // outgoing pair of particles
    ) {
        const auto my_parameter = steer<double>("myParameter");
    }
    // specify a few cuts on the phase space/prepare some internal members values not to be recomputed for each event
    void prepareProcessKinematics() override {
        if (!kinematics().cuts().central.pt_diff.valid())
            kinematics().cuts().central.pt_diff = {0., 50.}; // usage of the kinematics() block: constrain 0 < D(pt) < 50 GeV
    }
    // central ME weight, to be carefully optimised (to say the least) by the user
    double computeCentralMatrixElement() const override {
        if (shat() == 0. || that() == 0. || uhat() == 0.) // we already have access to all event-level variables/(q1()/q2()/pc(i)/pA()/pX()...)
            return 0.;
        return 1.;
    }
};
REGISTER_PROCESS("my_process", MyProcess); // register process into CepGen runtime database
```

Exercise: implement the matrix element for the two-photon production of a pair of charged scalars (e.g. charged Higgs), as a particularisation of a k_T -factorised 2-to-4 process

Developed for backward compatibility of user code.

- allows to directly plug the matrix element into the CepGen runtime environment
 - interfacing through shared memory (Fortran common blocks/C structures) and cross-languages utilities (e.g. user-steered parameters into Fortran code, evaluation of coupling constants/fluxes/...)
- no need to “reinvent the wheel” for each new process, can directly rely on CepGen’s incoming parton fluxes (k_T -factorised, or integrated), EM/strong coupling evolution, event treatment and output, ...

```
function dummy_process()
implicit none
double precision dummy_process
!-----
!  
! CepGen overhead
!
!
include 'CepGen/Process/Fortran/KTBlocks.inc' ! mandatory, include the kinematics common blocks
call CepGen_print    ! optional, display some run parameters information
!
!
! end of overhead, beginning of process definition
!
!
dummy_process = 1.0D0 ! placeholder, your actual definition is to be
                      ! implemented here
!
!
! end of process definition
!
!
return
end
```

More information/usage at: github.com/cepgen/CepGenFortranProcess

- CepGen: project started as a short-term replacement of a niche MC implementation, before it gained a broader theoretical/experimental interest
- Currently stabilised, and implementing a few major two-photon and diffractive $\gamma g/gg$ processes, either for $pp/pA/AA/ee$ colliders
 - tools exist to ease implementation of new processes, either in C++/Fortran
 - more links to be forged (e.g. integration with MadGraph/CalcHEP/...-generated on-shell ME)
- Future prospects
 - handling of additional matrix elements, lasting collaboration built around CepGen (exp./pheno.)
 - very limited personpower, would profit from the input of any (experimentalist/theoretician) collaborator...
 - lots of little tasks (incl. some highly “educational”) still uncovered, e.g. in systematic checks of various processes/phase space definitions, new interfacing code developments, ...

Thanks for your attention!

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