New physics prospects with the FPMC generator

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on behalf of the FPMC development team

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FPMC in a nutshell

Monte Carlo events generator for the simulation of diffractive and photon-induced processes

- Herwig used for hadronisation and calculation of the hard matrix element
- Mainly designed for Tevatron/LHC ($p\bar{p}$, pp, pA, AA) usages

Main reference: Boonekamp, M./Dechambre, A./Juranek, V./u. a.[1]

New updated user manual and physics report to be released very soon with a full description of new processes.

Numerous collaborators involved in the development:

- C. Royon, O. Kepka, V. Juranek, M. Boonekamp, M. Rangel, C. Baldenegro, A Vilela, …

[1] FPMC: A Generator for forward physics. (2011).

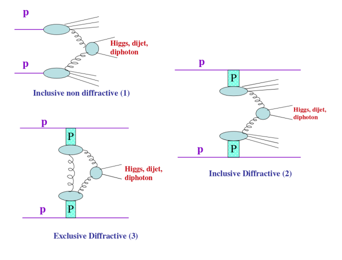
FPMC: list of processes

Inclusive diffraction

- Ingelman-Schlein model for hard single-diffraction and double-pomeron exchange

Exclusive diffraction

- Higgs, dijet production (KMR/Durham model)

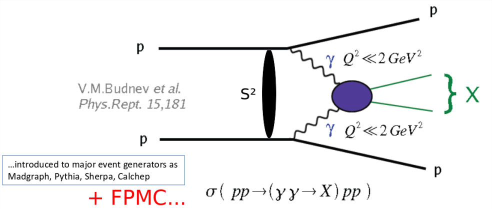


QED processes

- Proton-induced processes (lepton, quarks, gauge bosons pairs)
- Several anomalous models already implemented

Obviously, only covering the photon-induced processes in this talk…

Equivalent photon approximation



All photon-induced processes implementing the equivalent photon/Weizsäcker-Williams approximation (EPA)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \int \mathrm{d}n(\omega_1) \int \mathrm{d}n(\omega_2)\, \delta\left(w_{\gamma\gamma}^2 - 4\omega_1\omega_2\right) \frac{\mathrm{d}}{\mathrm{d}\Omega}\hat{\sigma}_{\gamma\gamma\to X}(w_{\gamma\gamma}; \mathcal{S})$$

with the process-dependent survival probability $\mathcal{S}$

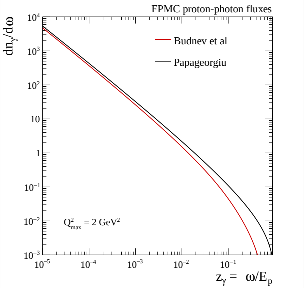
- at this stage, a constant factor $\mathcal{S} = 0.9$ is used for two-photon processes
- full treatment of the impact parameter/Q^2 scale to be added through this framework

Photon fluxes

Following (coherent) photon fluxes are provided for proton and heavy ions:

Photon from proton:

- Papageorgiu[2] (NFLUX=14 ; for $A = Z = 1$)
- Budnev et al[3] (NFLUX=15) default flux for *pp* initial state



Photon from heavy ions:

- Cahn/Jackson[4] ($R \sim 1.2A^{1/3}$) (NFLUX=12)
- Drees et al[5] (NFLUX=13)

Mixed states

- "Cahn" photon/pomeron (and ↔) in *pp* (NFLUX=20/22)
- "Cahn photon/photon in *pA* (and *Ap*) (NFLUX=23/24)
- "Cahn" photon/pomeron in *Ap* (and ↔ for *pA*) (NFLUX=25)

[2] Two photon physics with ultrahigh-energy heavy ion beams. In: Phys. Lett. B250 (1990). S. 155–160.

[3] The Two photon particle production mechanism. Physical problems. Applications. Equivalent photon approximation. In: Phys. Rept. 15 (1975). S. 181–281.

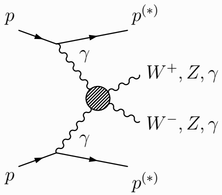
[4] Realistic equivalent photon yields in heavy ion collisions. In: Phys. Rev. D42 (1990). S. 3690–3695.

[5] Can One Detect an Intermediate Mass Higgs Boson in Heavy Ion Collisions? In: Phys. Lett. B223 (1989). S. 454–460.

Light-by-light scattering fully implemented

- Standard model, and anomalous gauge couplings contributions
- Intermediate particles loop (parameterised by m_X/Q_X)

Two-photon production of fermion/gauge boson pairs



- Two-photon production of lepton/quark-antiquark pairs
- Two-photon production of W^+W^-[6] and ZZ bosons
  - Standard model prediction, and anomalous EFT extensions
  - Probing triple- and quartic gauge couplings

New final states recently included

- Intermediate resonances decaying into $\gamma\gamma$[7]
- Intermediate scalar/tensor resonances decaying into γZ, ZZ, W^+W^-, HH, gg
- Anomalous quartic two-photon production of $Z\gamma$ (Baldenegro et al.[8])

[6] Anomalous $WW\gamma$ coupling in photon-induced processes using forward detectors at the LHC. In: Phys. Rev. D78 (2008). S. 073005.

[7] Measuring the Diphoton Coupling of a 750 GeV Resonance. In: Phys. Rev. Lett. 116/23 (2016). S. 231801.

[8] Probing the anomalous $\gamma\gamma\gamma Z$ coupling at the LHC with proton tagging. In: JHEP 06 (2017). S. 142.

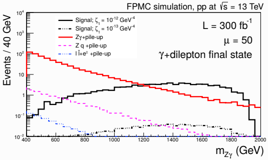
Two-photon production of $Z\gamma$

Dimension-6 EFT extension[9][10] of the SM (e.g. warped extra dimensions, new particles exchanges, composite Higgs production, …):

$$\mathcal{L}_{\gamma\gamma\gamma Z} = \zeta^{Z\gamma} F^{\mu\nu} F_{\mu\nu} F^{\rho\sigma} Z_{\rho\sigma} + \tilde{\zeta}^{Z\gamma} F^{\mu\nu} \tilde{F}_{\mu\nu} F^{\rho\sigma} \tilde{Z}_{\rho\sigma}$$

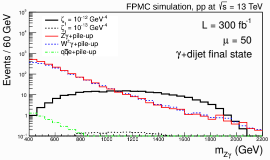
Application to a LHC search with experimental forward proton detection: CMS+CTPPS, or ATLAS+AFP

- signal components generated with FPMC using Budnev photon fluxes



First stage of fiducial cuts:

- proton tags within detectors acceptance: $0.015 < \xi < 0.15$
- 2 final states probed: $(Z \to \mathrm{jj})\gamma$, $(Z \to \ell^+\ell^-)\gamma$
  - dilepton+γ case: $E_\mathrm{T}(\gamma) > 100$ GeV, $p_\mathrm{T}(\ell\ell) > 100$ GeV
  - dijet+γ case: $E_\mathrm{T}(\gamma) > 150$ GeV, $p_\mathrm{T}(\mathrm{jj}) > 100$ GeV



[9] Bosonic quartic couplings at LEP-2. In: Eur. Phys. J. C13 (2000). S. 283–293.

[10] $pp \to \mathrm{jj}e^{\pm}mu^{\pm}\nu\nu$ and $\mathrm{jj}e^{\pm}mu^{\mp}\nu\nu$ at $\mathcal{O}(\alpha_{em}^6)$ and $\mathcal{O}(\alpha_{em}^4\alpha_S^2)$ for the study of the quartic electroweak gauge boson vertex at CERN LHC. In: Phys. Rev. D74 (2006). S. 073005.

Two-photon production of $Z\gamma$ (cont.)

Major sources of background: inclusive $V+\gamma$ and $V+\mathrm{j}$ productions

Good discrimination power through 2-dimensional matching between $m(Z\gamma)/m_{pp} = \sqrt{s\xi_1\xi_2}$ and $y(Z\gamma)/y_{pp} = \frac{1}{2}\log\frac{\xi_1}{\xi_2}$

Cuts flow for 300 fb^{-1} at $\langle\mu\rangle = 50$:

Cut/Process	Signal ζ ($\tilde{\zeta}=0$)	Signal $\zeta=\tilde{\zeta}$	γZ +pile-up	$W^{\pm}\gamma$ +pile-up	$jje^{\pm}$ +pile-up
$0.015<\xi_{1,2}<0.15$, $p_{T\gamma}>150$ GeV $p_{Tjj}>100$ GeV]	38.6	51.4	1951.8	1631	8.47
$m_{\gamma Z}>700$ GeV	37	49.5	349.8	358.9	1.3
$p_{Tjj}/p_{T\gamma}>0.90$, $\lvert\Delta\phi-\pi\rvert<0.02$	33.8	45.1	144.7	145.4	0.54
$\sqrt{\xi_1\xi_2 s}=m_{\gamma Z}\pm 10\%$	28.2	35.7	19.7	19.3	0.1
$\lvert y_{pp}-y_{\gamma Z}\rvert<0.05$	25.5	32.7	1.5	1.6	0

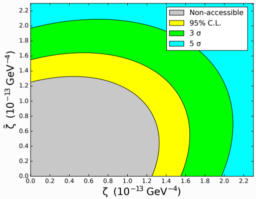
Table 1: Number of signal and background events in the $jj\gamma$ channel after the selection cuts for an integrated luminosity of 300 fb^{-1} and $\mu=50$ at $\sqrt{s}=13$ TeV, and for $\zeta=4\cdot10^{-13}$ GeV^{-4}. Non-exclusive events were simulated on PYTHIA8 at leading-order and signal events in the FPMC. Jets are reconstructed with the anti-k_t clustering-algorithm using $R=0.5$ and $p_{T\,\mathrm{min}}=10$ GeV.

Cut/Process	Signal ζ ($\tilde{\zeta}=0$)	Signal $\zeta=\tilde{\zeta}$	γZ +pile-up	$\ell\bar{\ell}j$ +pile-up	$\ell\bar{\ell}e^{\pm}$ +pile-up
[$0.015<\xi_{1,2}<0.15$, $p_{T\gamma}>100$ GeV $p_{T\ell\bar{\ell}}>100$ GeV]	13.2	17.4	2239.2	64.5	1.2
$m_{\gamma Z}>600$ GeV	12.9	17.1	227	3.8	0.2
$p_{T\gamma}/p_{T\ell\bar{\ell}}>0.95$, $\lvert\Delta\phi-\pi\rvert<0.02$	12.6	16.7	175	0	0
$\sqrt{\xi_1\xi_2 s}=m_{\gamma Z}\pm 5\%$	12.2	16.4	12.7	0	0
$\lvert y_{pp}-y_{\gamma Z}\rvert<0.03$	10	13.7	0.6	0	0

Table 2: Same as Tab. 1 for the $\ell\bar{\ell}\gamma$ channel. The selection yields a signal efficiency of about 75% with an essentially background-free measurement in this channel.

~ 3(no) background events remaining for dijet (dilepton) final state
66%(75%) signal efficiency

Combined dijet+dilepton sensitivity 3 orders of magnitude tighter than previous attempts!



Summary and outlook

FPMC is a useful tool for the study of the vast two-photon induced phenomenology in *pp*, *pA*, *AA*, … colliders

Easy integration of new two-photon processes in the full simulation chain. Very active community involved in these new modellings.

To quote a few in the last few months:

- SM, and anomalous (EFT, resonances) $\gamma\gamma \to \gamma\gamma$
- anomalous $\gamma\gamma \to \gamma Z$ production

Continuous development ongoing (code being migrated to: github.com/fpmc-hep/fpmc)

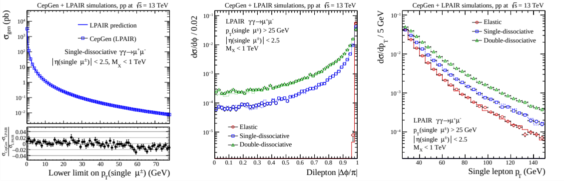
A (late) birthday present to Antoni: the *CepGen* events generator

Generic central exclusive processes events generator to ease the phenomenological study of $\gamma\gamma$ processes for a broad Q^2 spectrum (with or without proton(s) dissociation)

- fast, C++ implementation, $\mathcal{O}(10^3)$ (unweighted) events/s

Modular in the processes definition ; two implementations of the $\gamma\gamma \to \ell^+\ell^-$ process handled in the current release:

- original LPAIR (elastic dipole form factors + various proton structure functions already embedded),



- new k_T factorisation algorithm (see Wolfgang's lecture on Tuesday)

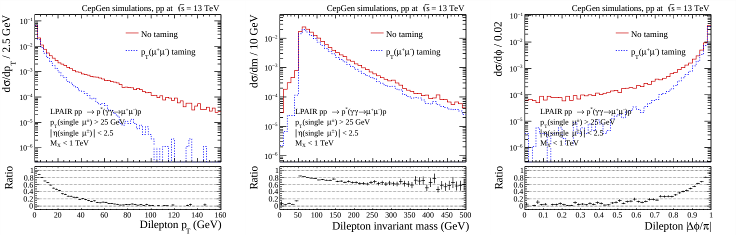
More $\gamma\gamma$ processes to be included soon. E.g. W^+W^- (see Marta's talk)...

A (late) birthday present to Antoni: the *CepGen* events generator

Survival factor corrections

User control over initial and final states in usual cuts-based Ω definition and weighting functions

- implementation of rescattering corrections through taming of incoming photon fluxes (before full treatment), or taming of final state kinematics (e.g. $t \sim -p_\mathrm{T}^2(\ell\ell)$)
- any user-defined functional available, parsed "on-the-fly" from input steering card
- e.g. 1-dimensional taming of the dilepton p_T in the single-dissociative "LPAIR" $\gamma\gamma \to \mu^+\mu^-$ process at $\sqrt{s} = 13$ TeV ($\mathrm{d}\sigma \mapsto \mathrm{d}\sigma \otimes e^{-\frac{1}{25}p_\mathrm{T}(\mu\mu)}$, corresponding to an integrated $\mathcal{S} = 0.76$)



Code available on CERN's GitLab (access on request), to be publicly released soon (fortunately before Antoni's 70th birthday...)