Prospects for Higgs and gauge boson measurements in $\gamma\gamma$ collisions at FCC-ee

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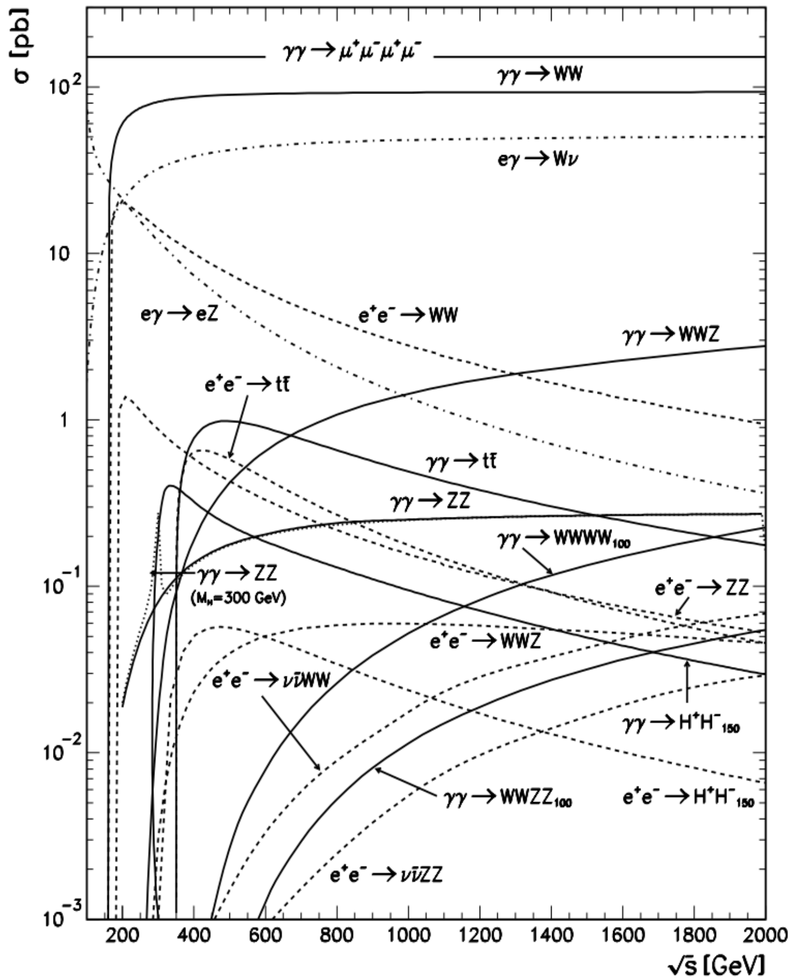
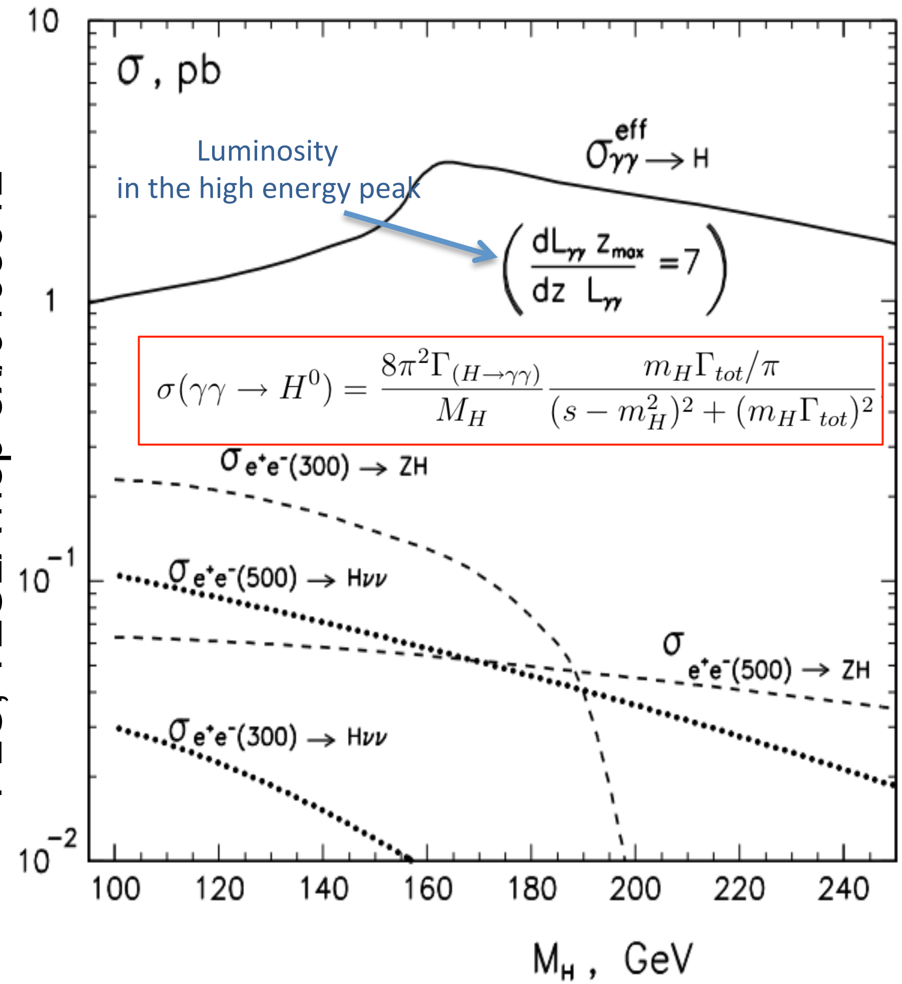
γγ Physics at a Photon Linear Collider*



Typical (unpolarized) XS in γγ, γe and e^+e^- collisions

PLC, TESLA hep-ex/0108012



$$\sigma(\gamma\gamma \to H^0) = \frac{8\pi^2\Gamma_{(H\to\gamma\gamma)}}{M_H} \frac{m_H\Gamma_{tot}/\pi}{(s-m_H^2)^2 + (m_H\Gamma_{tot})^2}$$

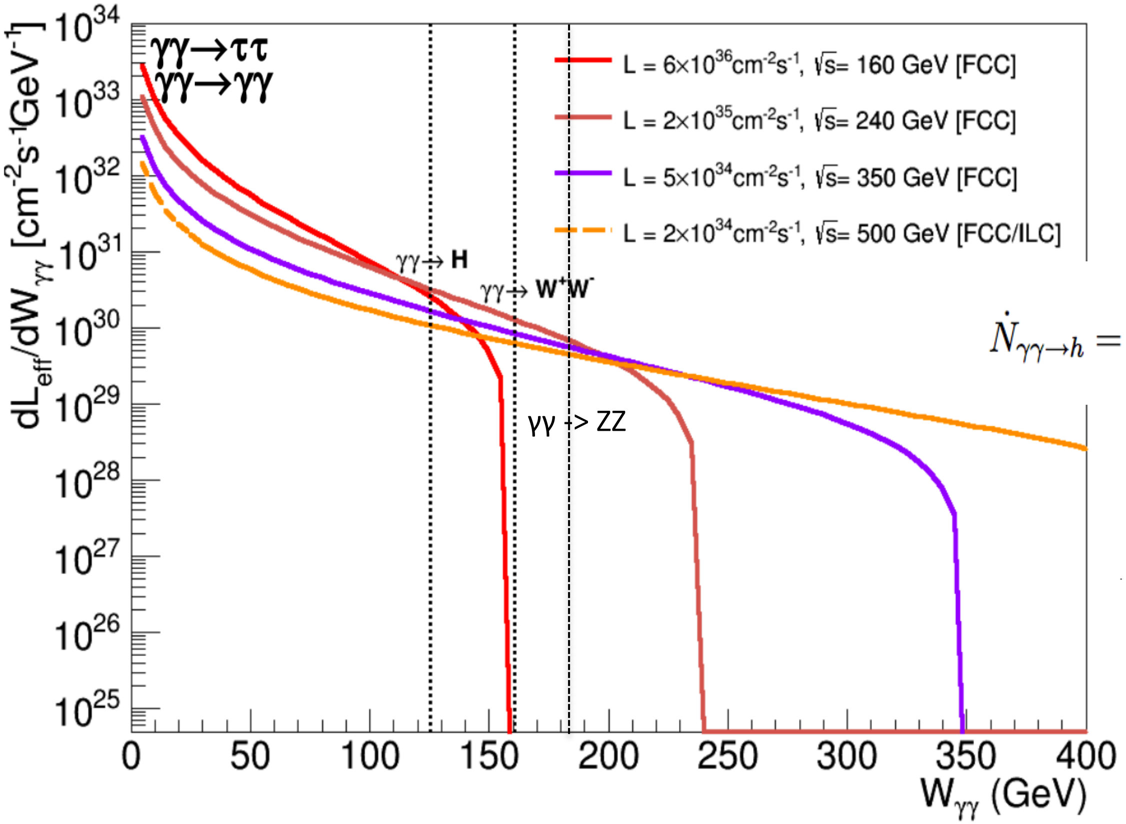
Total cross sections of the Higgs boson production in γγ and e^+e^- collisions.

What fraction of these can be studied @FCC-ee using equivalent photon fluxes surrounding the e^+e^- beams?

(*)Using Compton-backscattered photons from the e^+e^- beams

EWK & Higgs physics with γγ @FCC-ee

Photon-photon effective luminosities using Effective Photon Approximation (EPA) fluxes: $\mathscr{L}_{eff}$(FCC,γγ) ~20 × $\mathscr{L}_{eff}$(pp-LHC,γγ) w/o huge LHC p-p pileup.



$$\dot{N}_{\gamma\gamma\to h} = L_{\gamma\gamma} \times \frac{dL_{\gamma\gamma} M_h}{dW_{\gamma\gamma} L_{\gamma\gamma}} \frac{4\pi^2 \Gamma_{\gamma\gamma}(1+\lambda_1\lambda_2)}{M_h^3} \equiv L_{\gamma\gamma} \times \sigma^{eff}.$$

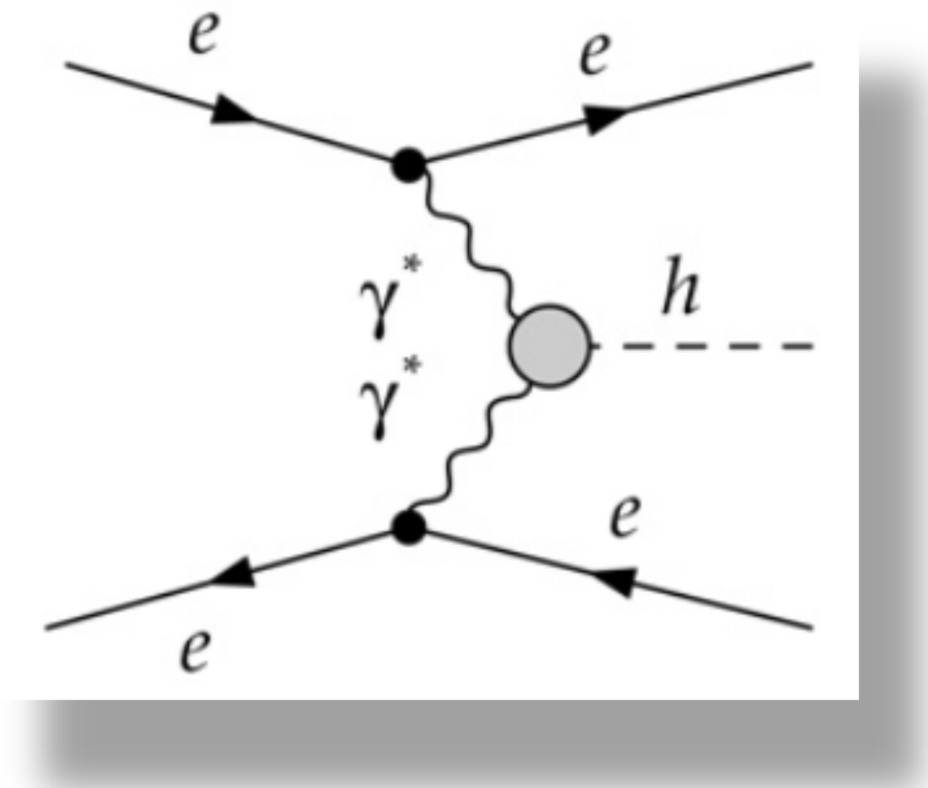
Higgs, WW, ZZ, …
production rates proportional to
γγ luminosity

- Interesting processes, never observed before, become accessible:

  γγ → γγ, γγ → H, ...

- Stringent constraints on anomalous QGC possible: $\gamma\gamma W^+W^-$ and γγZZ

$\gamma\gamma \rightarrow H \rightarrow b\bar{b}$ @ FCC-ee



Theoretical Setup

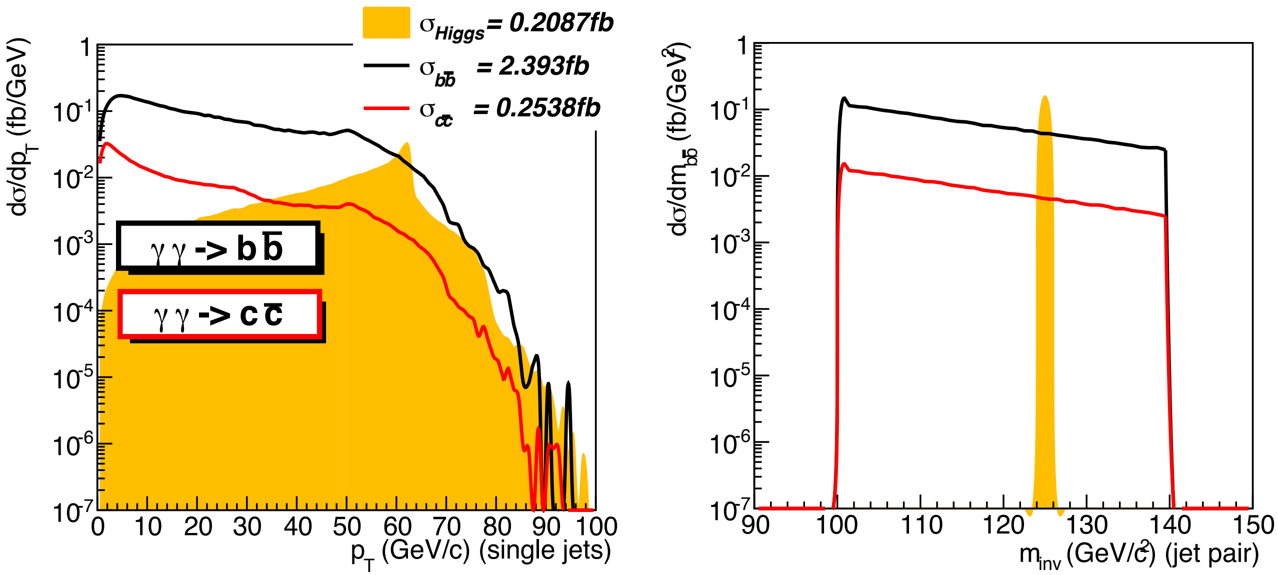
- **WHIZARD** (http://whizard.hepforge.org/) with Weizsäcker-Williams (EPA) fluxes for the $e \to e\gamma$ collinear splitting to allow the simulation of (quasi-) real photon-induced processes (hep-ph/9310350). Processes described by exact matrix-elements & exact kinematics, scattered $e^{\pm}$ info accessible (MC tagging possible). Parameters and flags:

Parameter	Default	Meaning
`epa_alpha`	0/intrinsic	value of α_{QED} for EPA
`epa_x_min`	`0.`	soft photon cutoff in x (mandatory)
`epa_q_min`	`0.`	minimal γ momentum transfer (mandatory)
`epa_mass`	0/intrinsic	mass of the radiating fermion
`epa_e_max`	$0/\sqrt{s}$	upper cutoff for EPA
`?epa_recoil`	`false`	flag to switch on recoil/p_T

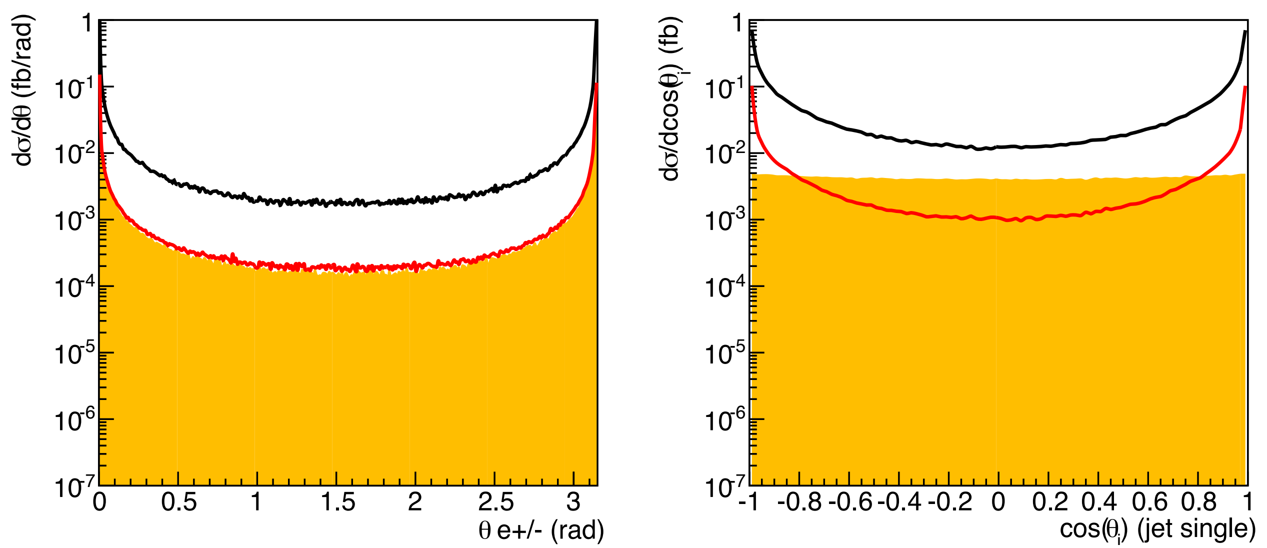
?epa_recoil = true
epa_x_min = 0.00001
epa_mass = me

- $\gamma\gamma \to H \to b\bar{b}$~ (decay with largest BR):
  - "SM_Higgs" for signal, "SM" for backgrounds.
  - 1-loop QCD corrections for $H \to b\bar{b}$~

γγ → H → bb~ @ FCC-ee



Kinematical distributions for √s =240 GeV (before cuts)



- γγ collision offers the unique possibility to produce Higgs boson as s-channel resonance
- Signal:
  √s = 161GeV: 0.053fb
  N(H → bb~)=**53** counts/ab^{-1}

  √s = 240GeV: 0.208fb
  N(H → bb~)=**208** counts/ab^{-1}
- Backgrounds:
  Dominant e^+e^-→Z*,γ*→bb~ (~2 pb without cuts) should be killed with e± tagging.

  Continuum γγ→bb~(cc~,qq~)
  Effic(b-jet reco) = $(70\%)^2$
  Prob(b-mistag.)=$(5\%)^2$ (c)
  Prob(b-mistag.)=$(1.5\%)^2$ (q)

Analysis Cuts $\gamma\gamma \rightarrow H \rightarrow b\tilde{b}$

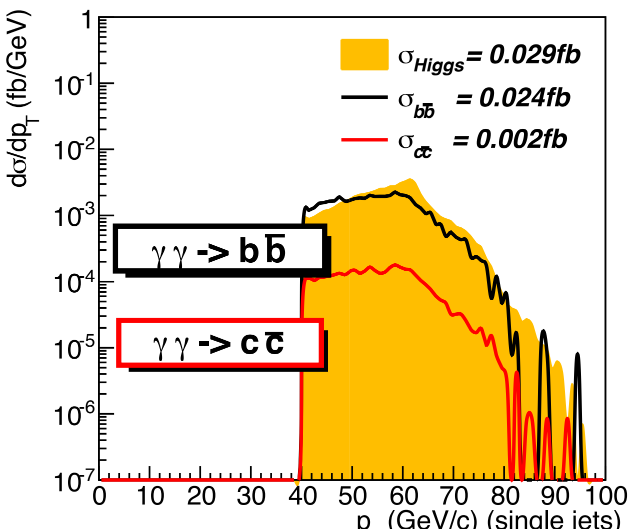
- Tagging $e^{\pm}$ scattered angle is crucial to remove $e^- e^+ \rightarrow$ bb~ background.
  Assumed polar angle acceptance: $1° \leq \theta_{e\pm} \leq 179°$ (LHeC-Note-2012-002).
  This reduces $\gamma\gamma$ processes by ~75% ($\gamma\gamma \rightarrow$ H & continuum backgrounds).

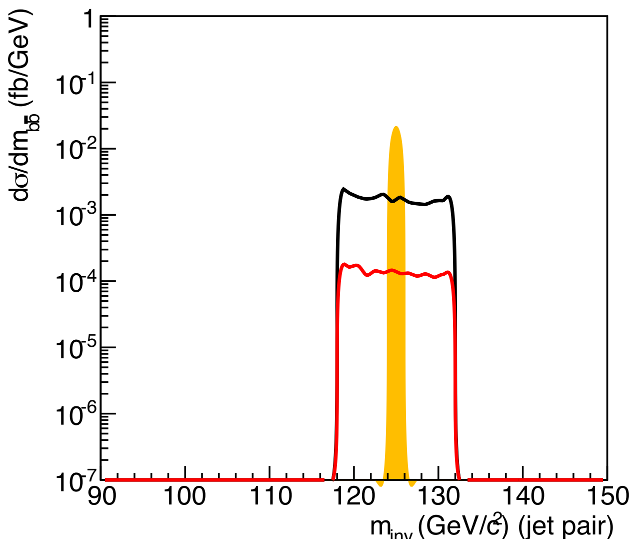
- Removal of irreducible $\gamma\gamma$ backgrounds:

  - Signal b-jets peak at $p_T \approx m_H/2 = 62.5$ GeV/c:
    Selecting events with p_T (jet) > 40 GeV/c removes around 83% (88%) of the bb~ (mistagged cc~, qq~) background while killing ~27% of the signal.

  - Expecting to reconstruct b-jets with p_T = 62. +/- 5. GeV (7% b-jet reco resolution), propagates into m_{bb} resolution of $\sqrt{2} \times 5. \sim 7.$ GeV.
    Applying invariant mass cut within window: 118 GeV < M_{inv} < 132 GeV around m_H returns no signal lost but ~70% removal of backgrounds.

γγ → H → bb~ : results after cuts





Higgs measurement:

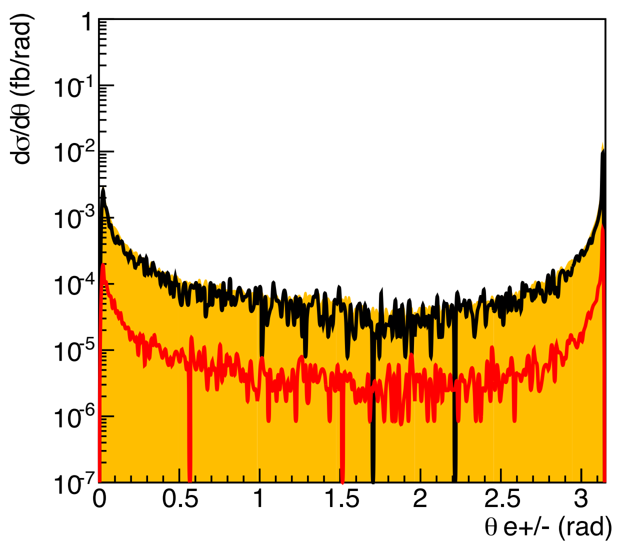
Cuts:

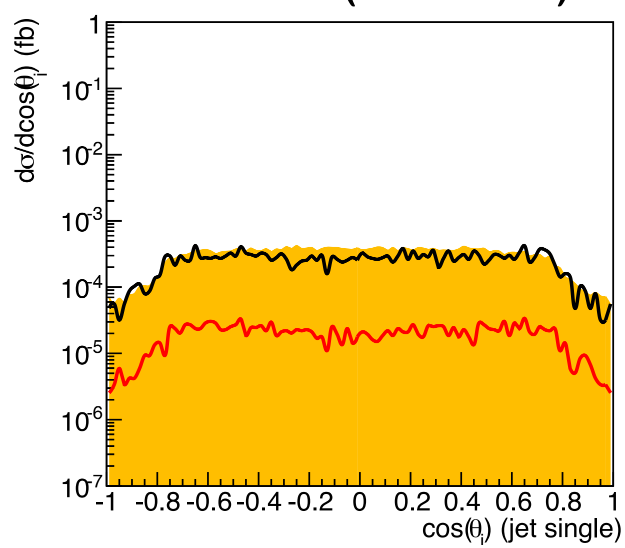
$1° \leq \theta_{e\pm} \leq 179°$

p_{TJets} > 40 GeV

118GeV < M_{bb} < 132GeV

Kinematical distributions for √s =240 GeV (after cuts)





√s = 161 GeV

σ(visible) = 11 ab

S/√B = 3.54 (1 ab-1)

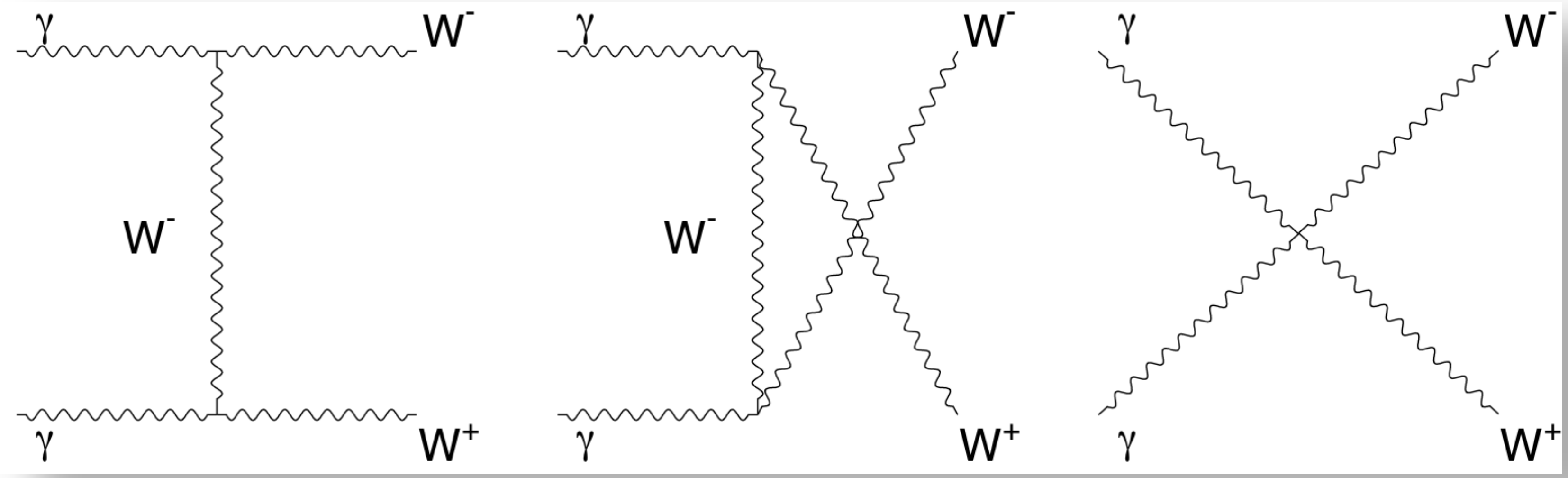
√s = 240 GeV

σ(visible) = 30 ab

S/√B = 5.82 (1 ab-1)

Evidence/Observation γγ→ H → bb~ with 1 ab^{-1} at FCC-ee(160, 240 GeV)

$\gamma\gamma \rightarrow W^+W^- \rightarrow$ 4 jets @ FCC-ee

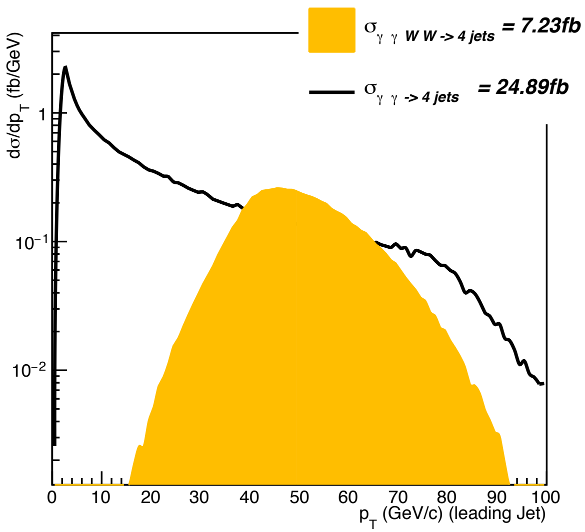


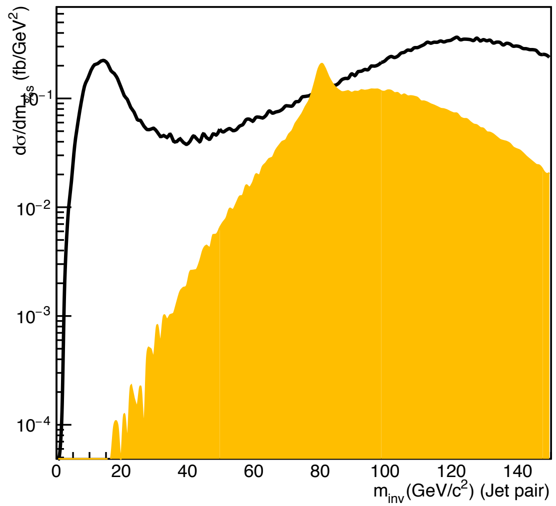
Theoretical Setup*

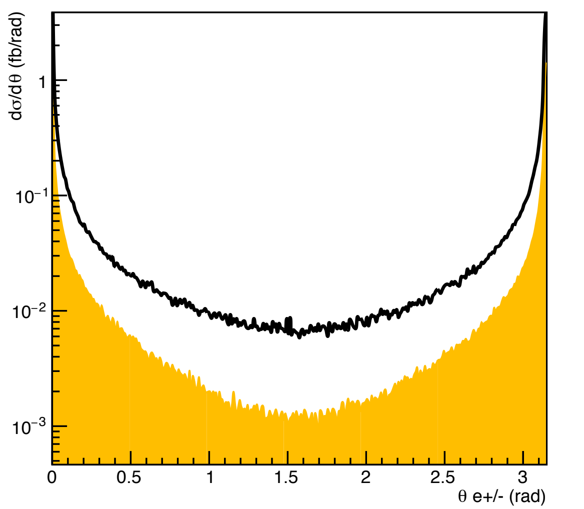
- **Pythia6** (http://pythia6.hepforge.org/) with equivalent photon flux in via "***gamma/e±***" option in PYINIT. e^+e^- event factorized into the flux of virtual γ and their subsequent interactions. Processes described by exact matrix-elements & exact kinematics, scattered $e^\pm$ info accessible (MC tagging possible). Possibility of experimental cuts (relevant for γ-induced processes:
  - ✓ CKIN(61-64) : x_i energy fractions taken from leptons;
  - ✓ CKIN(65-68) : Q_i^2 momentum transfer (photon virtualities);
  - ✓ CKIN(69-72) : θ_i lepton scattering angle;
  - ✓ CKIN(77-78) : W^2 $\gamma\gamma$-invariant mass;
- ISR+FSR+Hadronization
- Jet Reconstruction: e^+e^- kt (Durham)
- $\gamma\gamma$ → **WW** → **4j** (decay with largest BR):
  - ✓ MSUB(68) signal; MSUB(58) back
  - ✓ Hadronic W final-state, BR(W→jj)=2/3, to maximize statistics.
  - ✓ W pair production through $\gamma\gamma$-fusion is very suitable to test EWK theory: probe trilinear WWγ and quartic $\gamma\gamma$WW boson couplings.

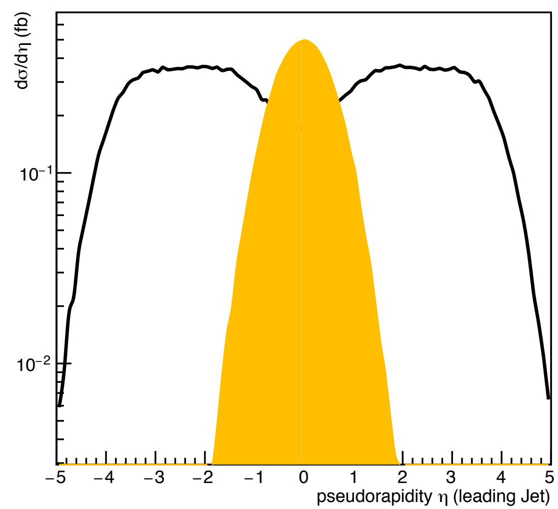
(*) Whizard`s result w/o Jet Reconstruction: https://indico.cern.ch/event/337673/session/3/contribution/19/material/slides/0.pdf

$\gamma\gamma \rightarrow WW \rightarrow 4j$ @ FCC-ee(240GeV) (before cuts)









- Pythia6`s phasespace at WW production + Jet Reconstruction (sorted by Pt):

  CKIN(77) = 160.
  CKIN(78) = -1 (no max limit)

- Signal:

$\sqrt{s}$ = 240GeV: 7.23 fb
N($\gamma\gamma \rightarrow$ WW)=**7e+03** counts/ab^{-1}

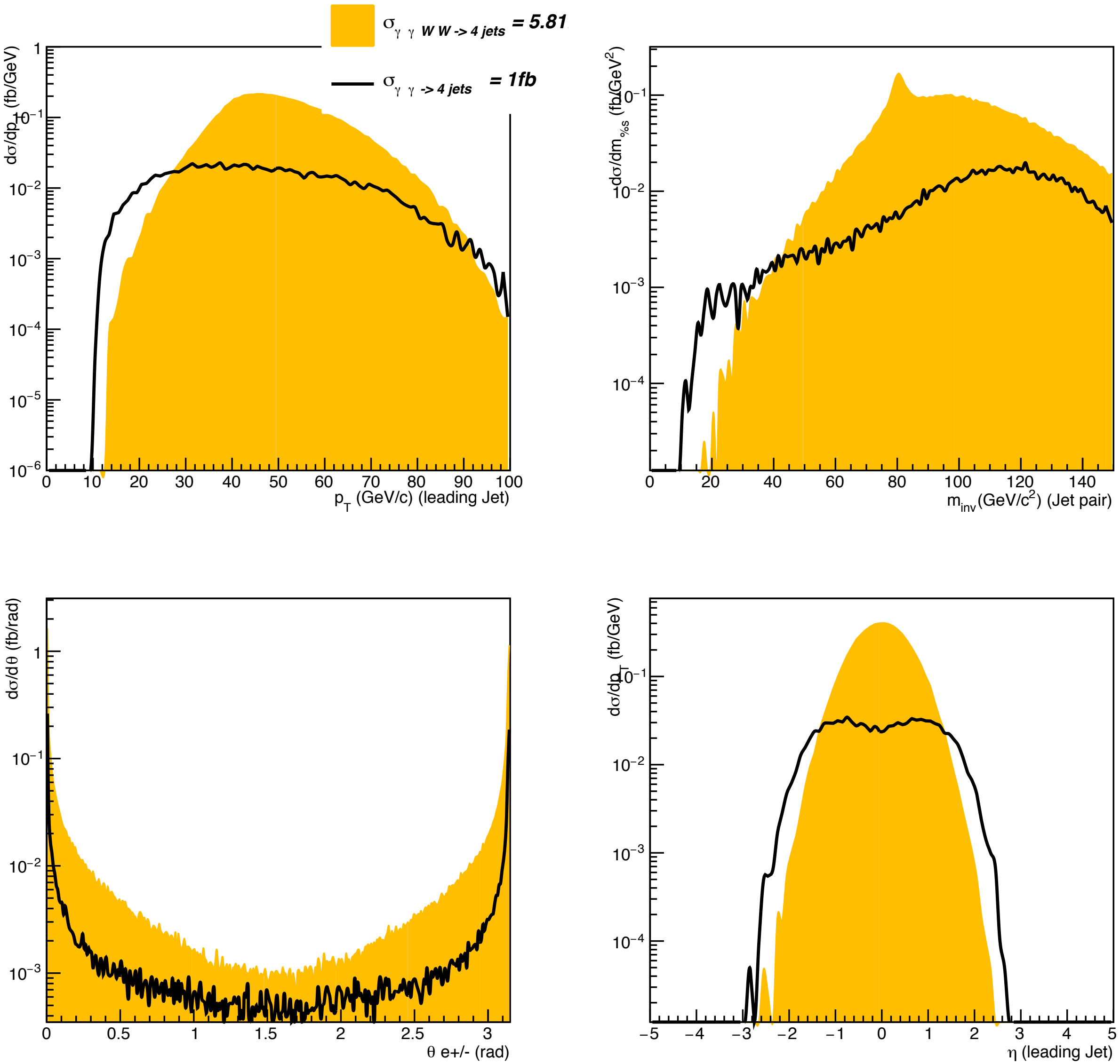
- Backgrounds:

• Dominant $e^+e^- \rightarrow Z^*, g^* \rightarrow 4j$ (~8.8 pb with cuts) should be killed with $e^\pm$ tagging.

• $\gamma\gamma \rightarrow 4$ jets

$\sqrt{s}$ = 240GeV: 24.89 fb
N($\gamma\gamma \rightarrow$ 4Jets)=**25e+03** counts/ab^{-1}

$\gamma\gamma \rightarrow WW \rightarrow 4j$ @ FCC-ee(240GeV) (acceptance cuts)



- Pythia6 (WW production) + Jet Reconstruction (sorted by Pt) + jet acceptance cuts:

  $p_{TJets} > 10GeV$

  $\eta_{Jets} < 5$; $\Delta R_{Jets} > 0.4$

- Signal:

  $\sqrt{s}$ = 240GeV: 5.81 fb

  N($\gamma\gamma \rightarrow$ WW)=**6e+03** counts/ab^{-1}

- Background:

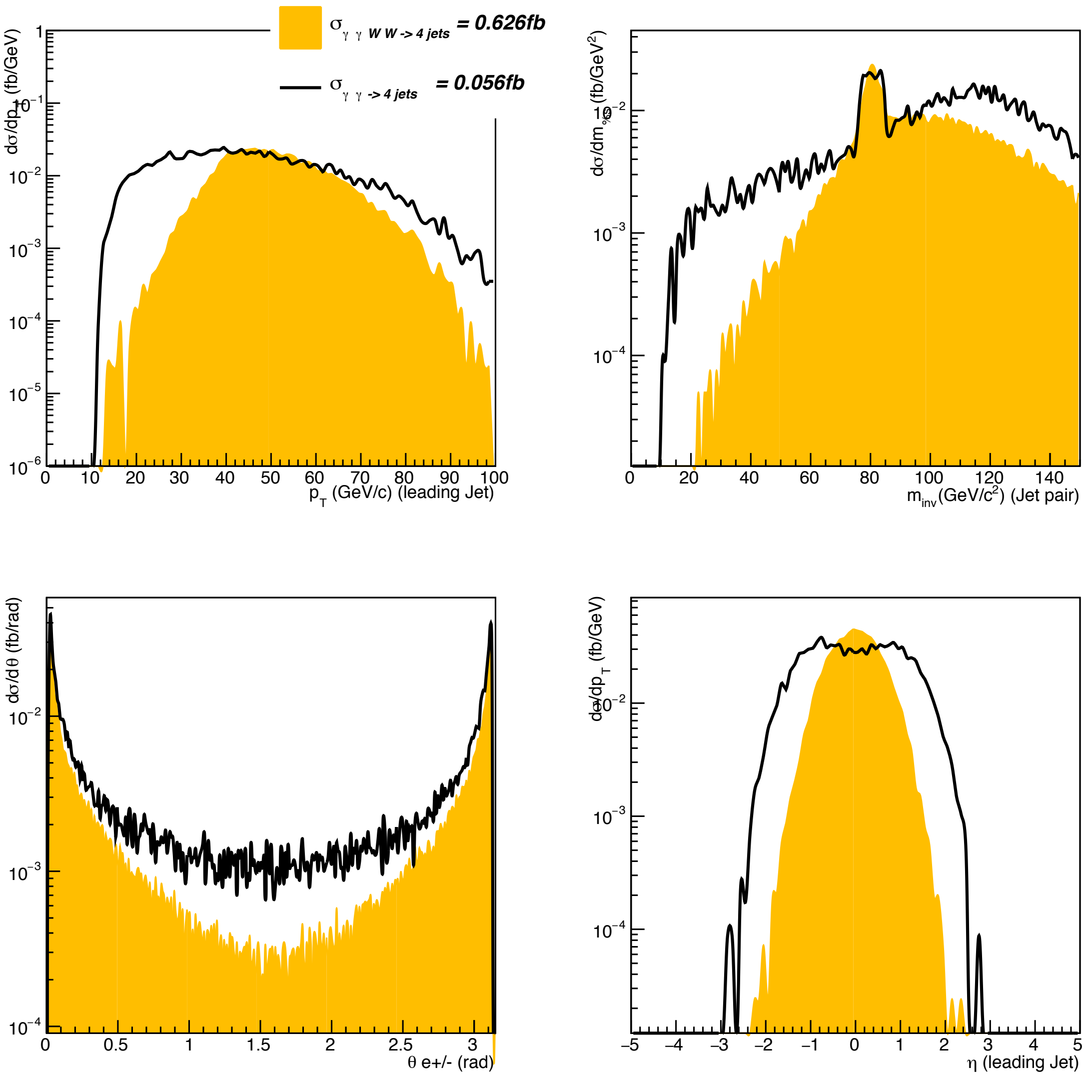
  - $\gamma\gamma \rightarrow$4 jets

  $\sqrt{s}$ = 240GeV: 1 fb

  N($\gamma\gamma \rightarrow$ 4Jets)=**1e+03** counts/ab^{-1}

- ~90% events lost of the back against just 20% of the signal

$\gamma\gamma \rightarrow WW \rightarrow 4j$ @ FCC-ee(240GeV) (final cuts)



- Pythia6 (WW production phasespace) + Jet Reconstruction (sorted by Pt) + jet acceptance + polar angle acceptance + M_W window:

  $p_{TJets} > 10GeV$
  $\eta_{Jets} < 5$; $\Delta R_{Jets} > 0.4$
  $1° \leq \theta_{e\pm} \leq 179°$
  $76.5\ GeV < M_{jj} < 84.5\ GeV$

- Signal:
  $\sqrt{s} = 240GeV$: 0.626 fb
  N($\gamma\gamma \rightarrow WW$) = **6e+02 counts/ab^{-1}**

- Background:
  - $\gamma\gamma \rightarrow 4$ jets

  $\sqrt{s} = 240GeV$: 0.056 fb
  N($\gamma\gamma \rightarrow$ 4Jets) = 60 counts/ab^{-1}

- ~99% events lost of the back against 91% of the signal

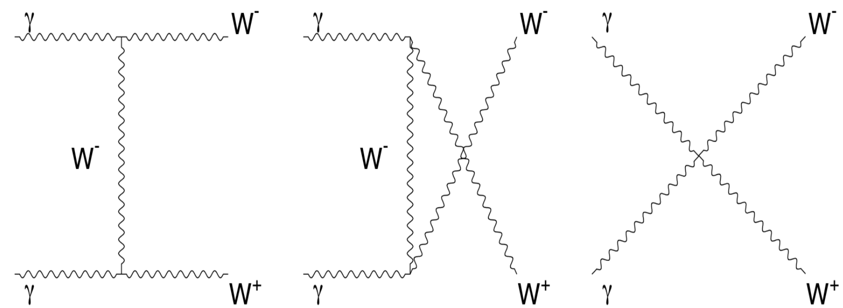
- Significance **S** (*)
  - ✓ **S = 4.8 for L= 0.1 ab^{-1}**
  - ✓ **S = 15.1 for L= 1 ab^{-1}**

Observation of $\gamma\gamma \rightarrow WW \rightarrow 4j$ @ FCC-ee(240GeV)

(*) Eq. 27 from http://www.pp.rhul.ac.uk/~cowan/stat/notes/SigCalcNote.pdf

aQGC via γγ → WW @ FCC-ee

- W pair production through γγ fusion is very suitable to test EWK theory: probe trilinear WWγ and quartic γγWW boson couplings.



  - ✓ Dim6 parameters related with LMs Dim8 ones (hep-ph/9908254 & hep-ph/0606118);

    WWγγ, γγγγ, γγγZ, γγZZ, γZZZ & ZZZZ vertices.

  - ✓ **Pythia8 would be a very powerful tool for this computation: need implementation of few effective vertex.**

Dim 6

$$L_6^0 = \frac{e^2}{8}\frac{a_0^W}{\Lambda^2} F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{e^2}{16\cos^2\Theta_W}\frac{a_0^Z}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha$$

$$L_6^C = \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2} F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W^-_\beta + W^{-\alpha}W^+_\beta) - \frac{e^2}{16\cos^2\Theta_W}\frac{a_C^Z}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta$$

Dim 8

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$

$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$

$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$

$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

$$\mathcal{L}_{M,2} = \left[B_{\mu\nu}B^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{M,3} = \left[B_{\mu\nu}B^{\nu\beta}\right] \times \left[(D_\beta\Phi)^\dagger D^\mu\Phi\right]$$

Results & Perspectives

- Rich physics opportunities in the EWK and Higgs sector of the SM.

- **$\gamma\gamma \rightarrow H \rightarrow b\tilde{b}$** :
  - ✓ $e^+e^- \rightarrow b\tilde{b}$ removed by $e^\pm$ tagging;
  - ✓ Continuum $\gamma\gamma$ backgrounds removed with cuts in suitable kinematical variables ($\theta_{e\pm}$, p_{TJets} and $M_{b\tilde{b}}$);
  - ✓ **Evidence/Observation of $\gamma\gamma \rightarrow H \rightarrow b\tilde{b}$ with 1 ab^{-1} at FCC-ee(160, 240 GeV).**

- **$\gamma\gamma \rightarrow W^+W^- \rightarrow$ 4 jets** :
  - ✓ $e^+e^- \rightarrow Z^*,\gamma^* \rightarrow 4j$ removed by $e^\pm$ tagging.
  - ✓ Backgrounds removed with cuts in suitable kinematical variables (p_{TJets}, η_{Jets}, ΔR_{Jets}, $\theta_{e\pm}$ and M_{jj})
  - ✓ **Observation of $\gamma\gamma \rightarrow W^+W^- \rightarrow$ 4 jets with 0.1 ab^{-1} at FCC-ee(240 GeV).**
  - ✓ Studies with effective operators using EPA: depending on future Monte Carlo implementations.

- EPA implementation in Pythia8 for further studies (in progress by Lund`s group)