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

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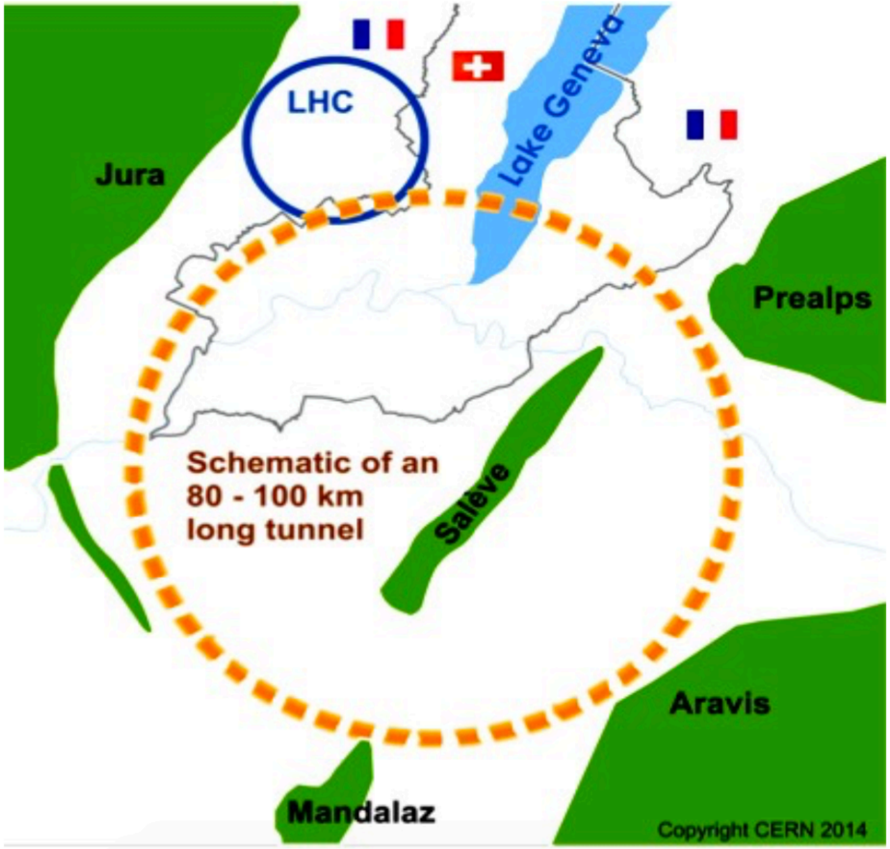
EDS Blois 2017
Prague - Czech Republic
26^{th} – 30^{th} June 2017

CERN Future Circular Collider

- FCC: Post-LHC collider project with R~80 km & B=16–20 T dipoles to achieve p-p collisions at $\sqrt{s}$ = 100 TeV with up to L_{int} ~ 2 ab^{-1}/year. Goals: fully explore SM and search BSM physics with ×10 more $\sqrt{s}$ and L_{int} than LHC.



- Initial phase with e^+e^- collisions at unprecedented energies & lumis:

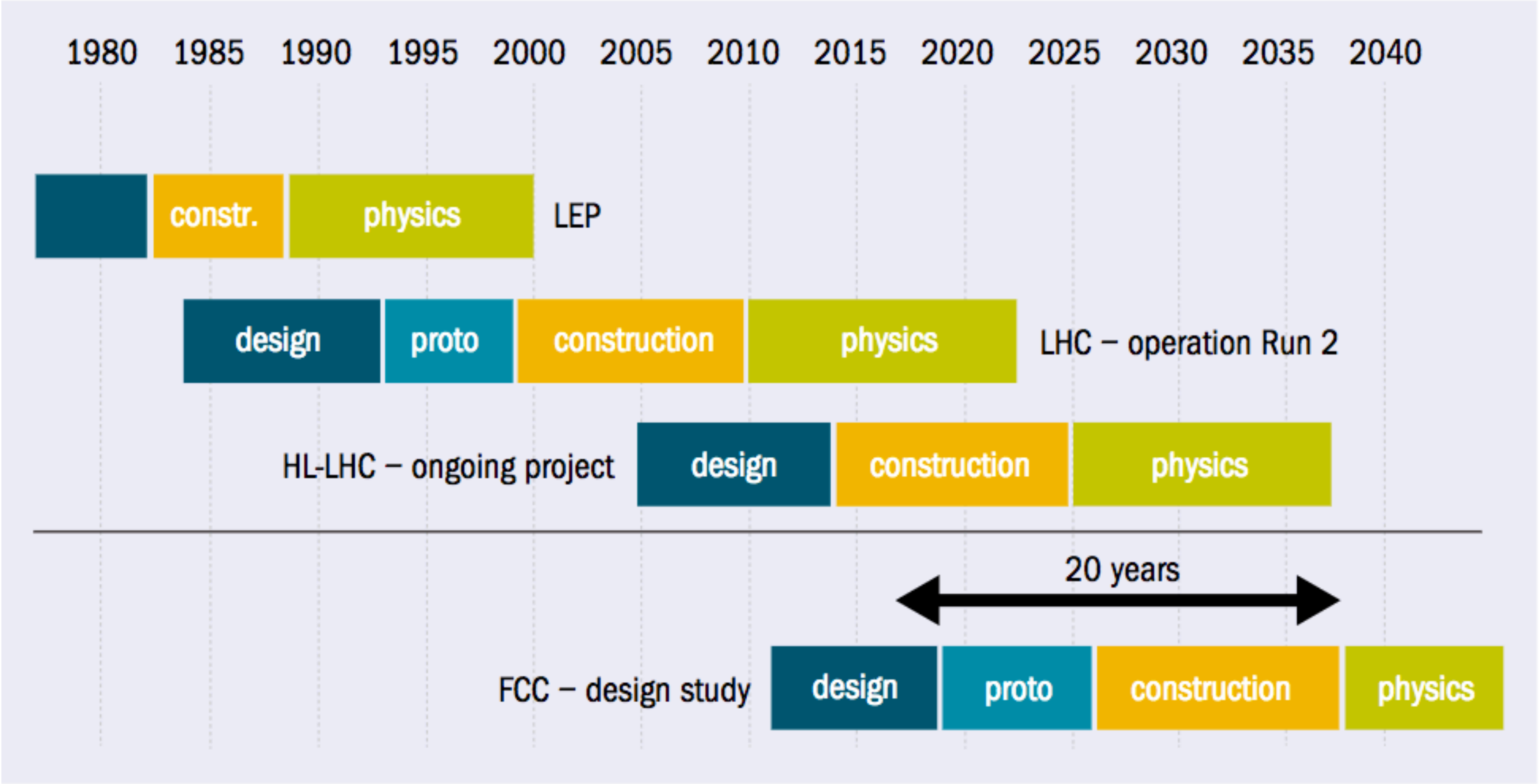
  e^+e^-(91 GeV), L_{int} ~ 80 ab^{-1}/year
  e^+e^-(160 GeV), L_{int} ~ 15 ab^{-1}/year
  e^+e^-(240 GeV), L_{int} ~ 3.5 ab^{-1}/year
  e^+e^-(350 GeV), L_{int} ~ 1 ab^{-1}/year

- Heavy-ions with pPb,PbPb colls. at never-reached energies & lumis:

  pPb(63TeV), L_{int} = 29 pb^{-1}/year
  PbPb(39TeV), L_{int} = 110 nb^{-1}/year

- Plus DIS...

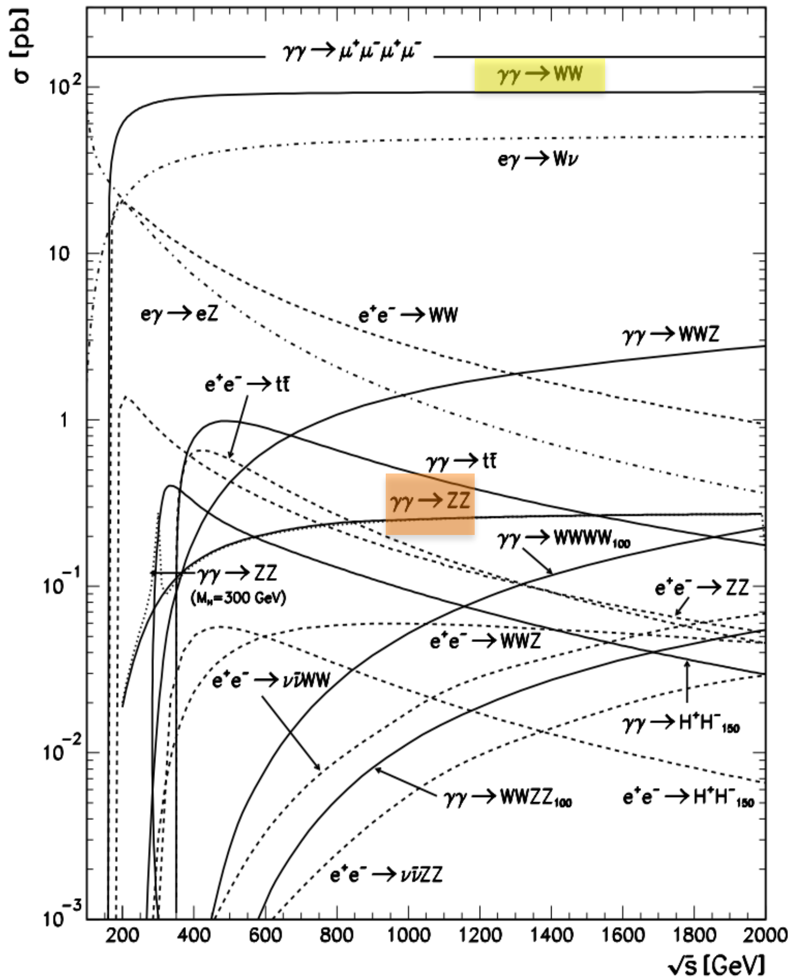
  e-h(3.5 TeV), L_{int} ~ 0.1 ab^{-1}/yr.
  e-Pb(1–3 TeV), L_{int} ~ 1 fb^{-1}/yr.



More information at Physics at its limits
http://cds.cern.ch/record/2262019

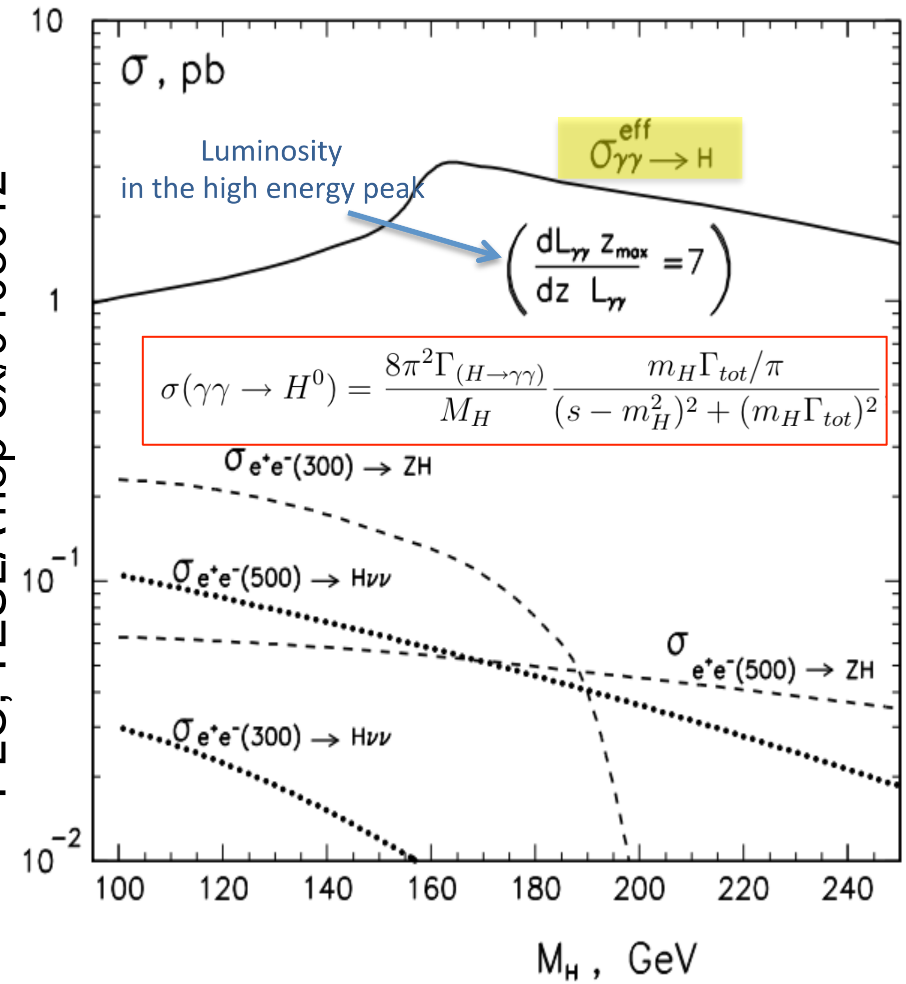
γγ Physics at a Photon Linear Collider*

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



PLC, TESLA hep-ex/0108012

Total XS of the Higgs production in γγ and e^+e^- collisions.



Many interesting Higgs & EWK channels accessible.
What fraction of these can be studied at the FCC using the equivalent photon fluxes surrounding the e+e- and ion-ion beams?

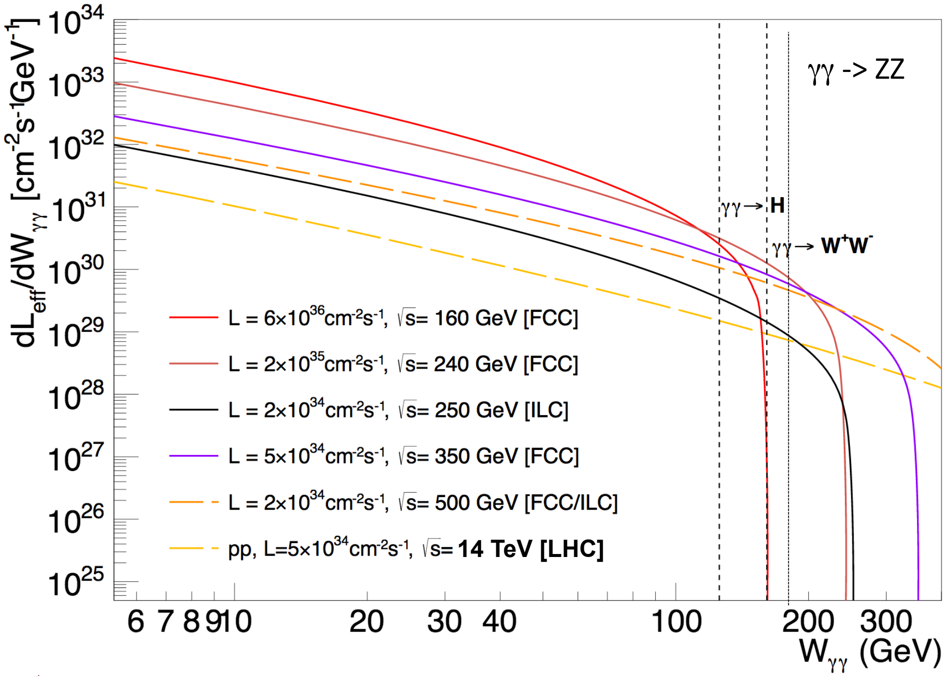
(*)Using Compton-backscattered photons from the e^+e^- beams

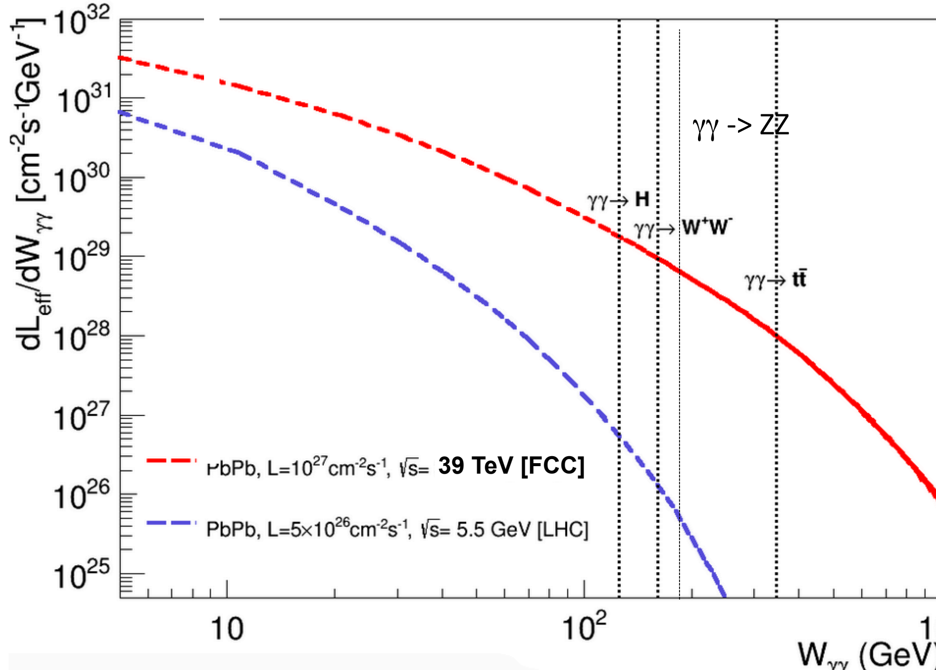
γγ luminosities @FCC(ee, pp, PbPb)

Photon-photon effective luminosities using Effective Photon Approximation (EPA) fluxes: $\mathcal{L}_{eff}(FCC,\gamma\gamma) > \mathcal{L}_{eff}(pp\text{-}LHC,\gamma\gamma)$ 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 **lumi)**

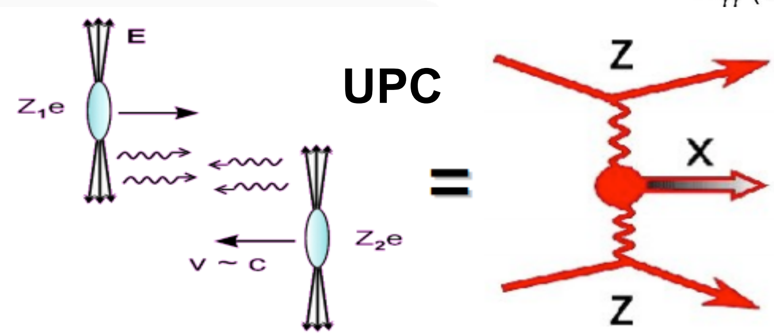




- Interesting processes, never observed before, become accessible:

  γγ → H, γγ → ZZ

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



$\gamma\gamma$ analyses: Theoretical Setup

- **Superchic v2.03/04** (link), a Fortran based Monte Carlo event generator for Central Exclusive Production:
  - many processes with effective photon approximation flux (EPA) from pp and $e^{+/-}$ beams available in the code (more details in the manual);
  - code with dedicated changes to our analysis (thanks to L. Harland-Lang):
    - $\gamma\gamma \to W^+W^-$ (process 61) production (W's decay suppressed);
    - $\gamma\gamma \to W^+W^-$ and $\gamma\gamma \to H \to b\tilde{b}$ channels with photon flux from $e^{+/-}$, pPb and PbPb beams;
    - γ-virtuality constrained to (quasi-)real photon: $0 < Q^2 < 2$ GeV^2

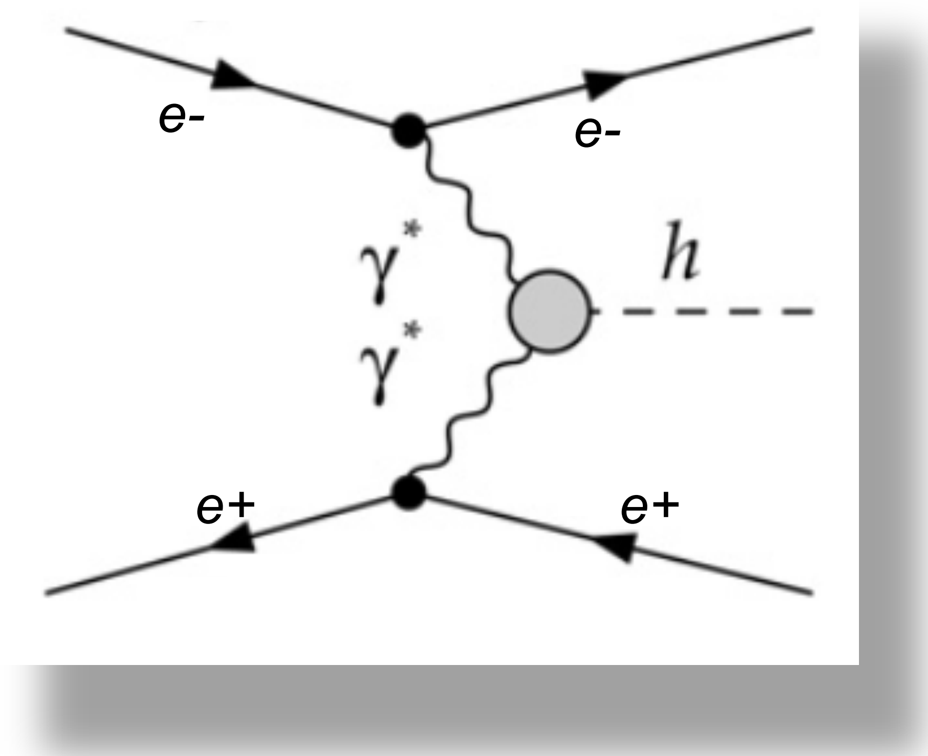
- **Pythia v8.226** (link) new developments in photon processes (thanks to Ilkka Helenius) with photon flux from $e^{+/-}$ beam:
    - signal $\gamma\gamma \to H \to b\tilde{b}$ and continuum backgrounds $\gamma\gamma \to b\tilde{b}$, $c\tilde{c}$ and $q\tilde{q}$
    - only (quasi-)real photons are considered.

- **Madgraph 2.4.5** (link): simulation of EPA processes for pPb and PbPb beams and estimation of aQGC exclusion limits for $e^{+/-}$, pPb and PbPb beam available.

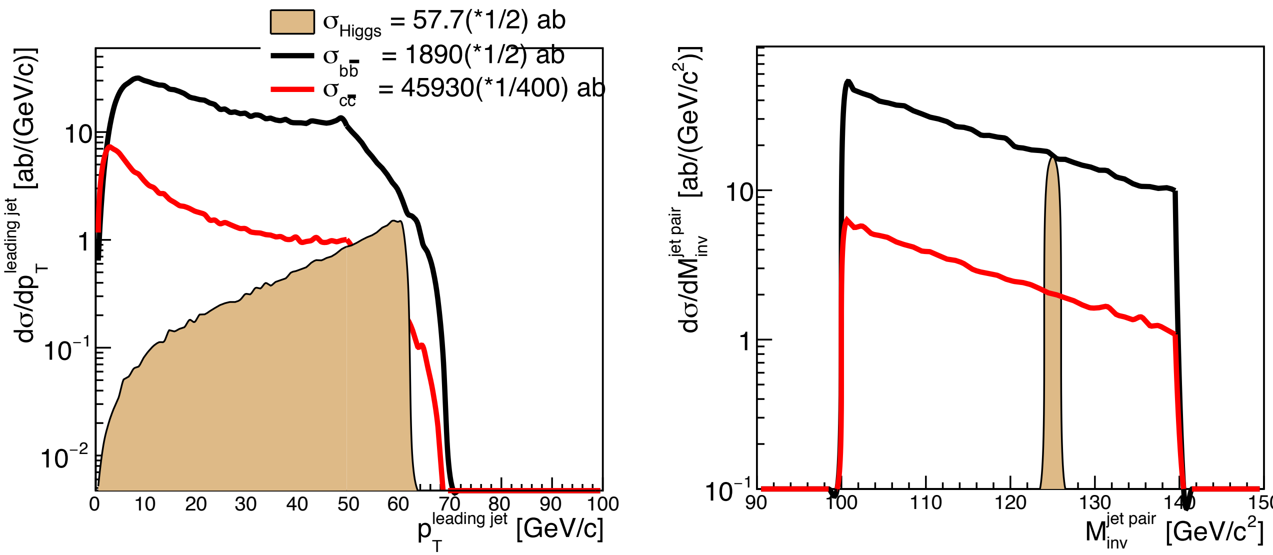
- **Beams tagged** in the FCC-ee detectors scenarios:
  - Central plus Forward tagging: $\theta_{lepton} > 8^o$ plus $3.1^o < \theta_{lepton} < 6.5^o$
    (the region $6.5^o < \theta_{lepton} < 8^o$ is not instrumented)
  - **Beam line tagging: $\theta_{lepton} < 1^o$**

(*) P.R. Teles & D.d'Enterria, Photon'15; arXiv:1510.08141 [hep-ph]

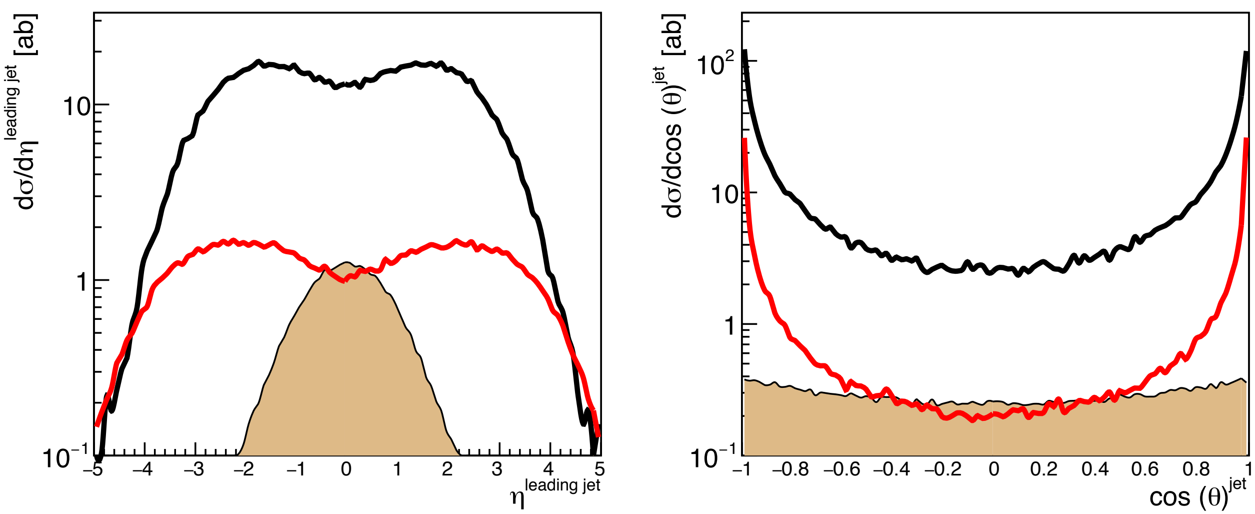
Feasibility measurement study of γγ → H → bb~ @ FCC-ee



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



Kinematical distributions for $\sqrt{s}$ = 240 GeV (b-jet reco & mistag)



- $\gamma\gamma$ collision offers the unique possibility to produce Higgs boson s-channel resonance;
- Superchic and Pythia8 yield similar results;
- Signal:

  $\sqrt{s}$ = 160GeV: 13(*1/2) ab
  L = 15 ab^{-1}/year with 2IP
  N(H → bb~) = 195 counts/year

  $\sqrt{s}$ = 240GeV: 57.7(*1/2) ab
  L = 3.5 ab^{-1}/year with 2IP
  N(H → bb~)= 202 counts/year

  $\sqrt{s}$ = 350GeV: 128.8(*1/2) ab
  L = 1 ab^{-1}/year with 2IP
  N(H → bb~)= 129 counts/year

- Backgrounds:

  Dominant $e^+e^- \rightarrow Z^*,\gamma^* \rightarrow$ bb~ (~2pb over m$\gamma\gamma$ = 40GeV, without cuts) should be killed with e± tag.
  Continuum $\gamma\gamma \rightarrow$ bb~(cc~,qq~)
  Effic(b-jet reco) = $(70\%)^2$
  Prob(b-mistag.)=$(5\%)^2$ (c)
  Prob(b-mistag.)=$(1.5\%)^2$ (q)

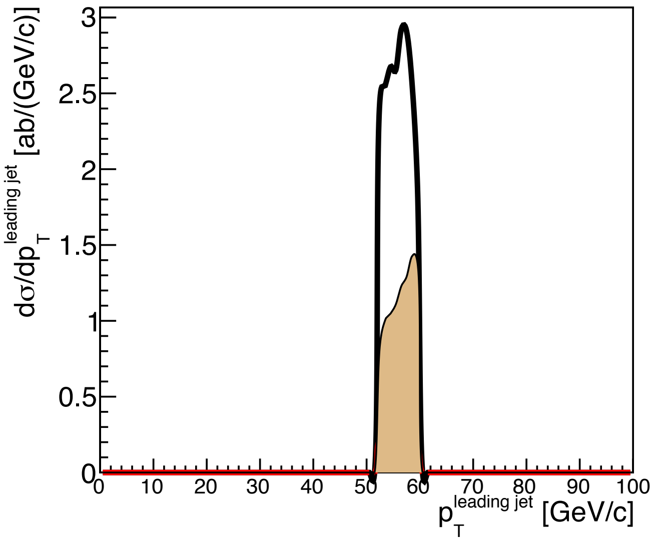
Analysis Cuts

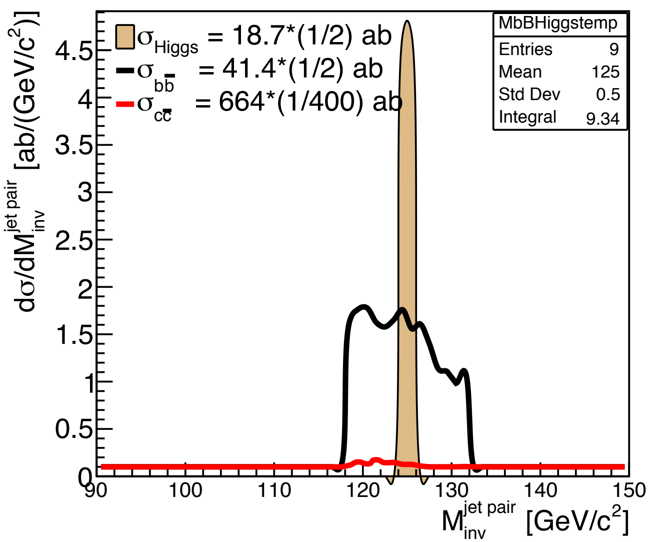
- Tagging $e^{\pm}$ is crucial to remove $e^- e^+ \rightarrow$ bb~ background. Three scenarios considered:
  - Central tagging $\theta_{lepton} > 8^o$: no signal or background events remained;
  - Forward tagging $3.1^o < \theta_{lepton} < 6.5^o$: no signal or background events remained;
  - Beam line tagging $\theta_{lepton} < 1^o$: removes from ~25%(@160GeV) to 6% - 2% (@240GeV - 350GeV) of the signal and 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 52 GeV/c < p_T (jet) < 60 GeV/c removes around 96% (98%) of the bb~ (mistagged cc~, qq~) background while killing ~66% of the signal.

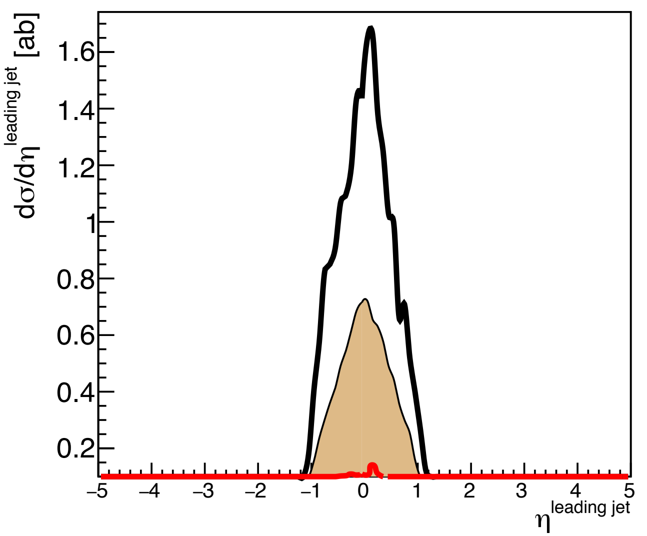
  - Expecting to reconstruct b-jets with p_T = 62. +/- 5. GeV (8% b-jet reco resolution), propagates into m_{bb} resolution of $\sqrt{2}$ X 5. ~ 7. GeV => applying invariant mass cut within window: 118 GeV < M_{inv} < 132 GeV around m_H returns no signal lost but removes ~75% (~80%) of the bb~ (mistagged cc~, qq~) backgrounds.

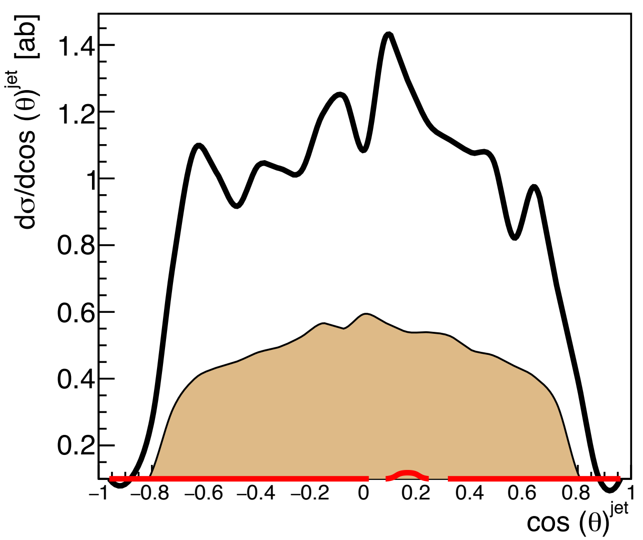
$\gamma\gamma \rightarrow H \rightarrow b\tilde{b}$ @ FCC-ee





Kinematical distributions for $\sqrt{s}$ = 240 GeV (after cuts)





Cuts:

Beam line tagging $\theta_{lepton} < 1^o$

52 GeV/c < $p_{T,jets}$ < 60 GeV/c

118GeV < M_{bb} < 132GeV

$\sqrt{s}$ = 160 GeV

σ(visible) = 3.4 ab

L = 15 ab^{-1}/year with 2IP

N(H → bb~) = 50 counts/yr

Σ(backs) = 121 counts/yr

S/√B = 4.5 (15 ab^{-1}/yr)

$\sqrt{s}$ = 240 GeV

σ(visible) = 18.7 ab

L = 3.5 ab^{-1}/year with 2IP

N(H → bb~) = 65 counts/yr

Σ(backs) = 156 counts/yr

S/√B = 5.2 (3.5 ab^{-1}/yr)

$\sqrt{s}$ = 350 GeV

σ(visible) = 43.4 ab

L = 1.0 ab^{-1}/year with 2IP

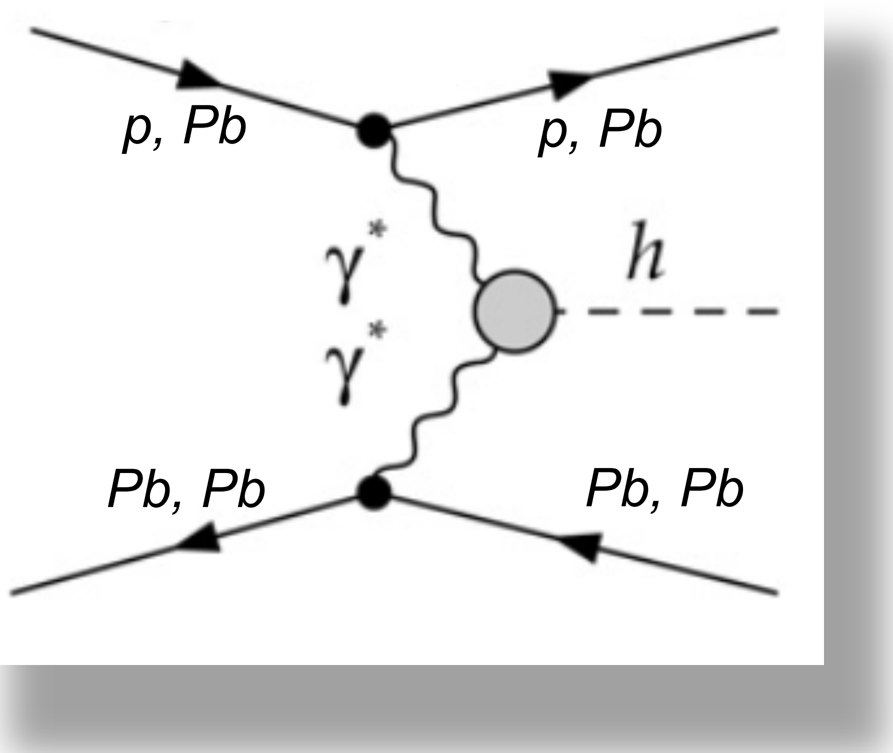
N(H → bb~) = 43 counts/yr

Σ(backs) = 104 counts/yr

S/√B = 4.2 (1 ab^{-1}/yr)

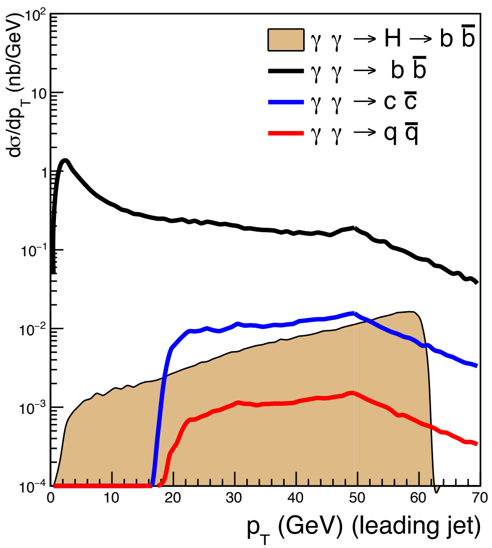
Strong evidence / Observation $\gamma\gamma \rightarrow H \rightarrow b\tilde{b}$ in ~1 year at FCC-ee

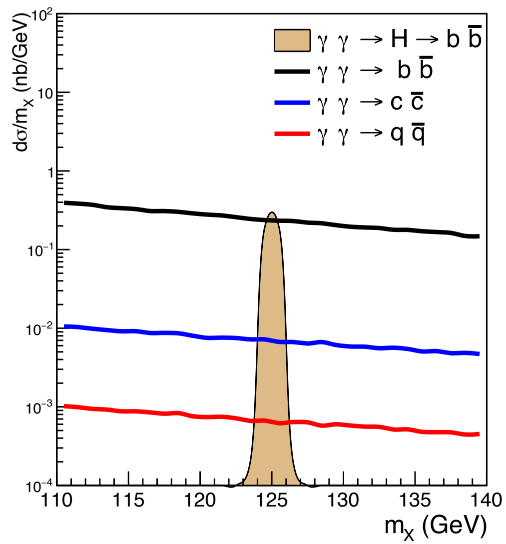
Feasibility measurement study of $\gamma\gamma \rightarrow H \rightarrow b\tilde{b}$ @ FCC-pPb, PbPb



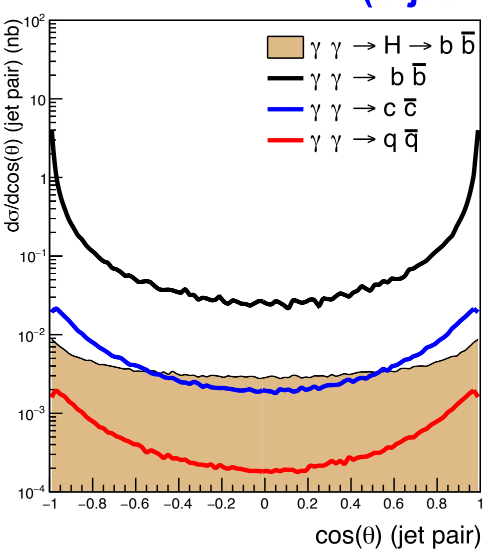
$\gamma\gamma \rightarrow H \rightarrow bb\sim$ @ FCC-PbPb

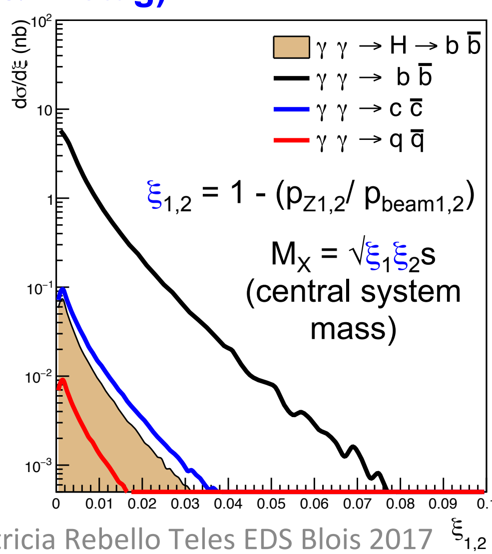
PbPb @ $\sqrt{s}$ = 39 TeV; Lumi$_{int}$ = 110 nb^{-1}/year





Kinematical distributions for PbPb @ $\sqrt{s}$ = 39 TeV (b-jet reco & mistag)





- Superchicv2.03 & Magraph2.5.4, both adapted with photon flux from Pb beam*, and Pythia8.2 (decay+shower.+hadr.)

Restricting phase space:

$100 \leq m_{j1j2} \leq 300$ GeV

$p_{T,jets} \geq 20$ GeV, $-5 \leq \eta_{jets} \leq 5$

Effic(b-jet reco) = $(70\%)^2$

Prob(b-mistag.)=$(5\%)^2$ (c)

Prob(b-mistag.)=$(1.5\%)^2$ (q)

- Signal

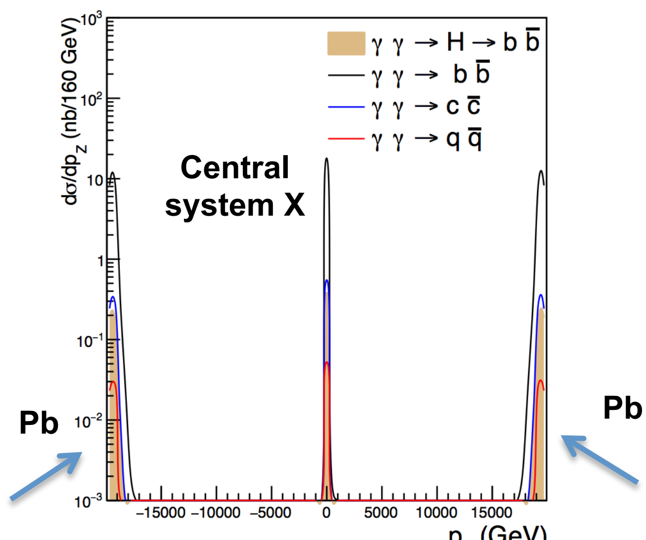
σ (Higgs → bb~) = 0.38 nb ~ 41.8 counts/yr

- Backgrounds

σ(γγ→bb~) = 17.9 nb ~ 1969 counts/yr

σ(γγ→cc~) = 0.552 nb ~ 60.72 counts/yr

σ(γγ→qq~) = 0.053 nb ~ 5.83 counts/yr



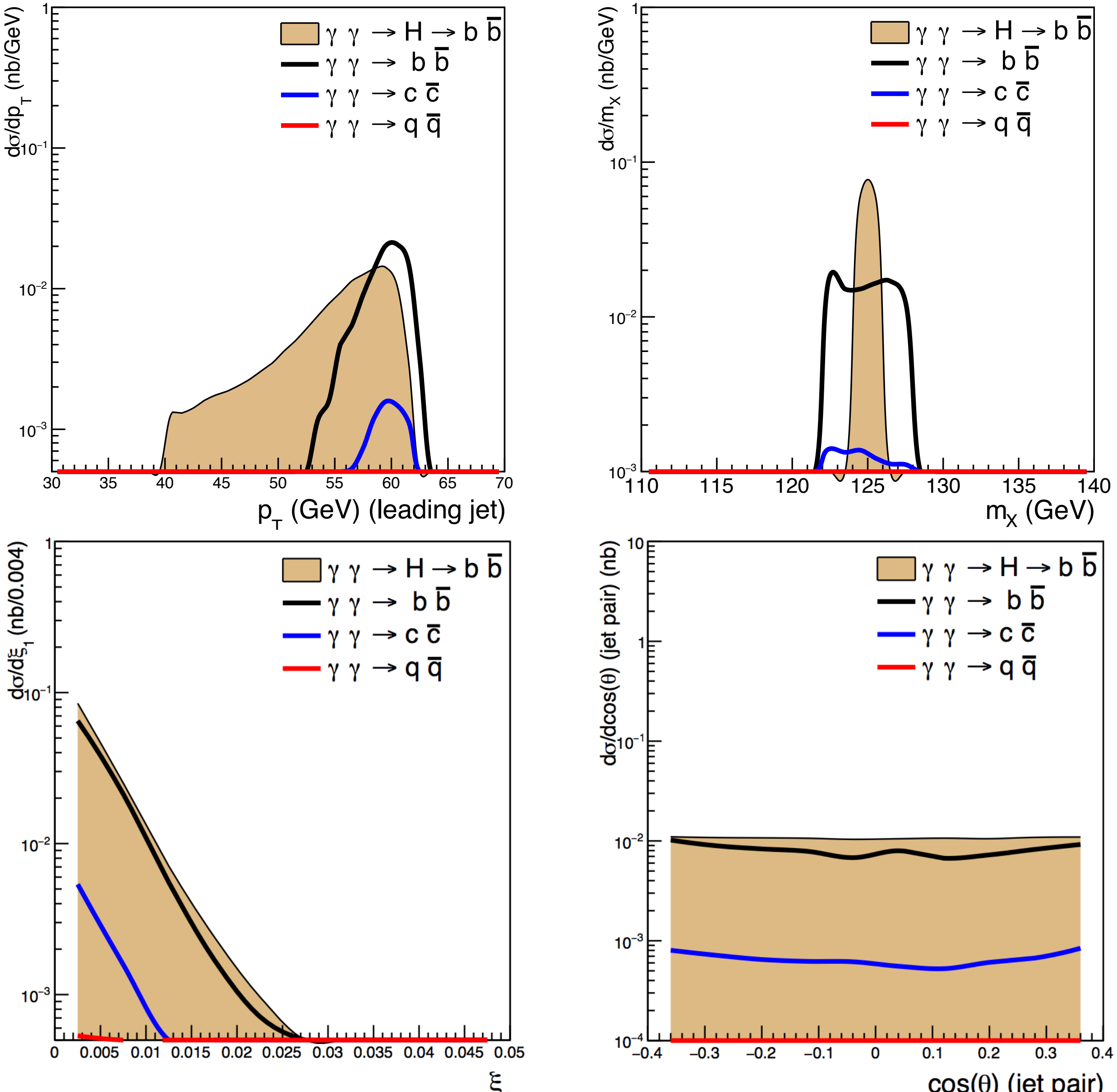
(*) Study of Higgs boson production and its bB decay in γγ processes in proton-nucleus collisions at the LHC. D. d'Enterria et al, Phys. Rev. D 81, 014004 (2010)

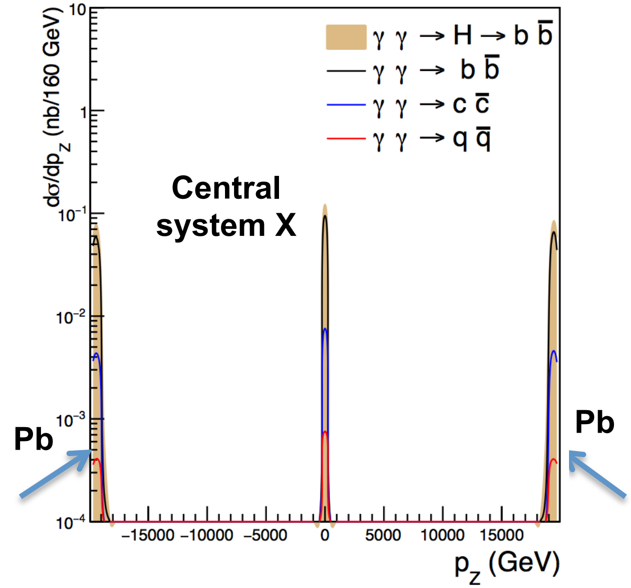
Analysis Cuts & Efficiencies

Following analysis strategy of "Study of Higgs boson production and its bB decay in $\gamma\gamma$ processes in proton-nucleus collisions at the LHC" [D. d'Enterria, Phys. Rev. D 81, 014004 (2010)]

- Removal of irreducible $\gamma\gamma$ backgrounds:
  - Signal b-jets peak at $p_T \approx m_H/2 = 62.5$ GeV/c:
    selecting events with 40 GeV/c < p_T (jet) < 62.5 GeV/c removes around 86% of the bb~, and mistagged cc~, qq~ backgrounds while killing ~35% of the signal.
  - The acoplanarity within $-0.45 < \cos(\theta_{j1j2}) < 0.45$ range, removes 66% of the backgrounds but only 34.1% of the signal: corresponding to $63.3^o \leq \theta_{j1j2} \leq 116.7^o$ (the acoplanarity θ_{j1j2} corresponds to the opening angle between the planes composed of the direction of the jet1 momentum and the beam axis, and the direction of jet2 momentum and the beam axis).
  - Expecting to reconstruct b-jets with p_T = 62. +/- 4.5 GeV (~7% b-jet reco resolution), propagates into m_{bb} resolution of $\sqrt{2}$ X 4.5 ~ 3. GeV. Applying invariant mass within window: 122 GeV < M_{inv} < 128 GeV around m_H returns no signal loss but ~88% removal of backgrounds.

Kinematical distributions for PbPb @ $\sqrt{s}$ = 39 TeV (after cuts)





FCC-PbPb at $\sqrt{s}$ = 39 TeV

σ(visible Higgs) = 0.121 nb

σ(γγ→bb~) = 0.094 nb
σ(γγ→cc~) = 0.0073 nb
σ(γγ→qq~) = 0.00075 nb

L = 110 nb^{-1}/yr

Signal: 13 counts/yr
Σ(Back): 11 counts/yr

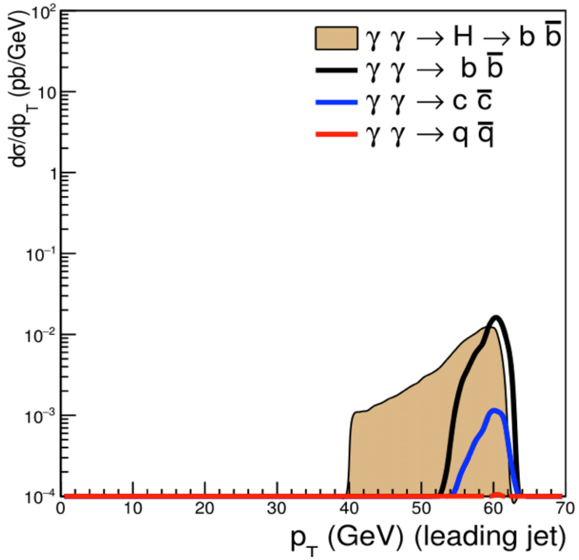
S/$\sqrt{B}$ = 3.97 in one year

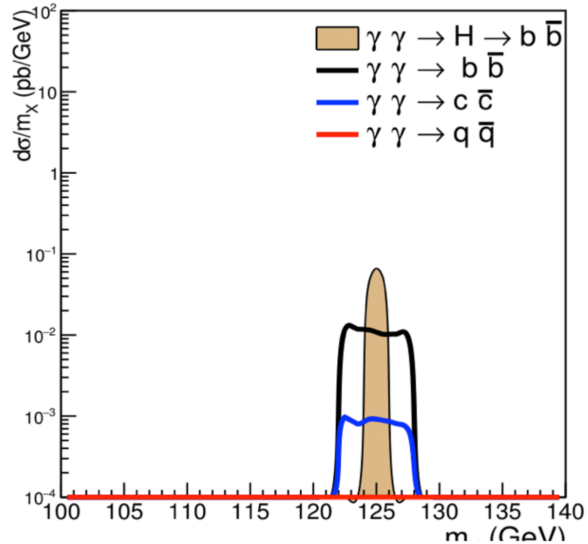
3σ : L = 62.7 nb^{-1} ~7 months
5σ : L = 163nb^{-1} 1.5 years

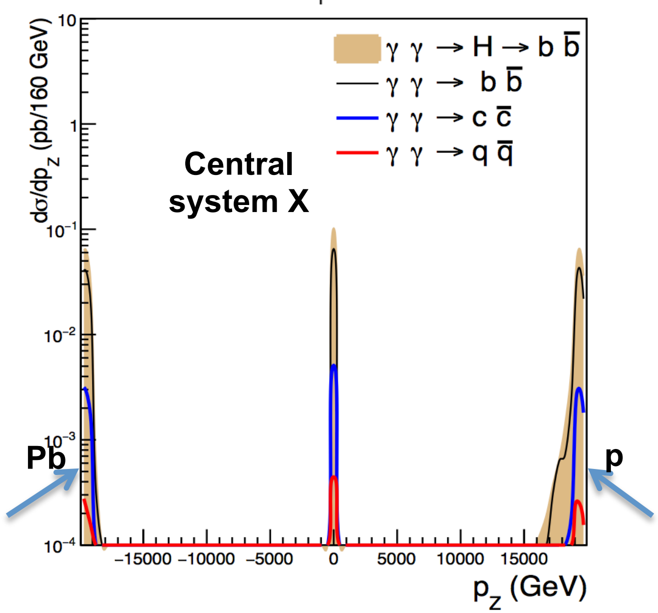
Evidence/Observation of γγ→ H → bb~ @FCC-PbPb

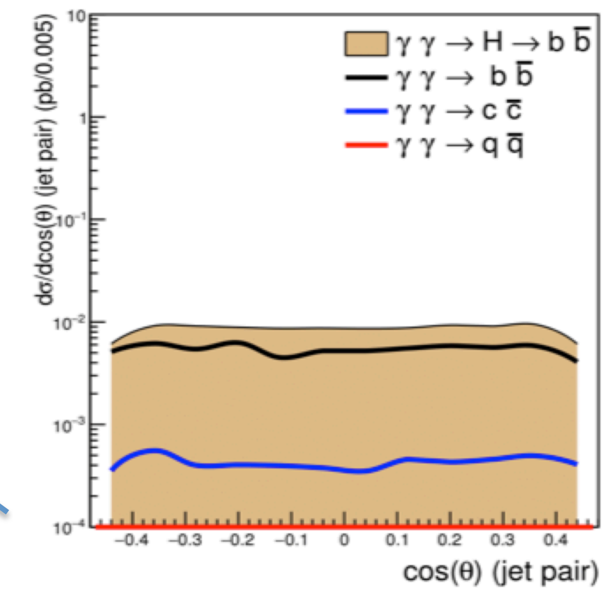
γγ → H → bb~ @ FCC-pPb

Kinematical distributions for pPb √s = 63 TeV (after cuts)









Plots and XS before cuts in backup slide

FCC-pPb at √s = 63 TeV

σ(visible Higgs) = 0.102 pb

σ(γγ→bb~) = 0.065 pb
σ(γγ→cc~) = 0.005 pb
σ(γγ→qq~) = 0.00044 pb

$L = 29\ pb^{-1}$/year

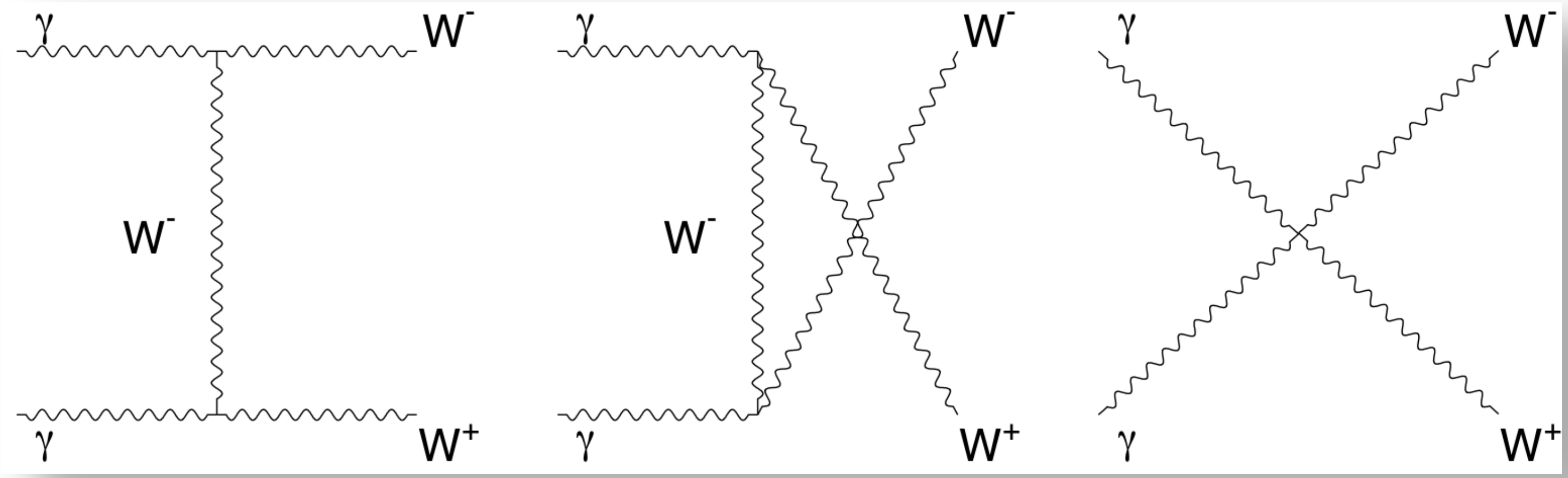
Signal: ~3 counts/year
Σ(Back): ~2 counts/year

S/√B = 2.07 in one year

3σ : $L = 60.93\ pb^{-1}$ ~2 years
5σ : $L = 169.3\ pb^{-1}$ ~ 5.8 years

Evidence of γγ→ H → bb~ @FCC-pPb

Feasibility measurement study of $\gamma\gamma \rightarrow W^+W^- \rightarrow$ 4 jets @ FCC-ee



Theoretical Setup

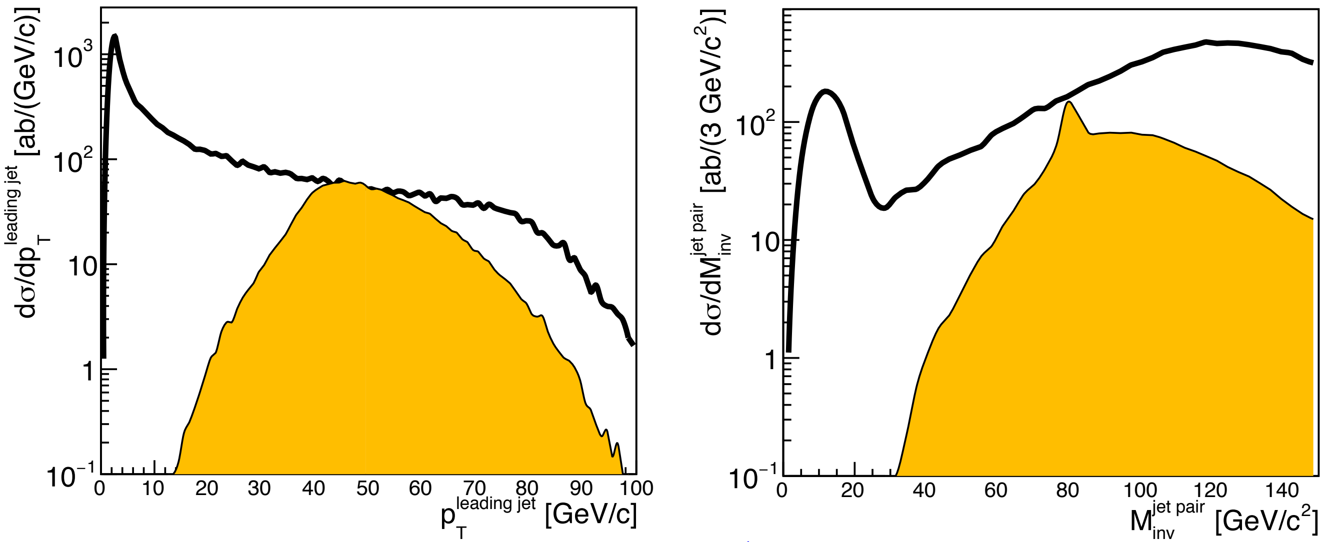
- **For Signal:**
  - **Superchic v.2.04** (for W^+W^- production) + **Pythia8.226** (for decaying, showering and hadronization within WW production phase space region).
    - ✓ Possibility of experimental cuts (relevant for γ-induced processes):
      - "Photon:Q2max = 2."
      - "Photon:Wmin = 161.0"
      - "Photon:Wmax = -1"

- **For Backgrounds:**
  - **Pythia6** (link) with equivalent photon flux in via "***gammale***$^{\pm}$" option in PYINIT. Possibility of experimental cuts (relevant for γ-induced processes):
    - ✓ 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 γγ-invariant mass;
    - ✓ ISR+FSR+Hadronization

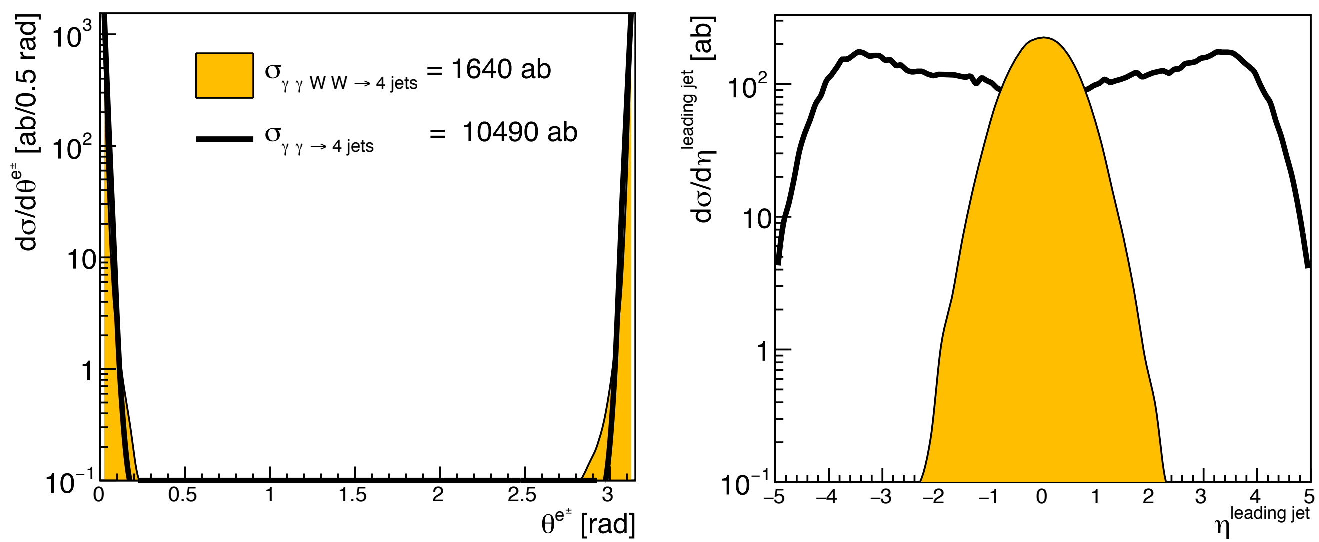
- **Jet Reconstruction**: **FastJet3** (link) with e^+e^- kt (Durham) algorithm.
- γγ → **WW** → **4j** (decay with largest BR):
  - ✓ Process 61 for signal (Superchic properly adapted); MSUB(58) in Pythia6 for backs.
  - ✓ Hadronic W final-state, BR(W→jj)=2/3, to maximize statistics.
  - ✓ W pair production through γγ-fusion is very suitable to test EWK theory: probe trilinear WWγ and quartic γγWW boson couplings.

γγ → WW → 4 jets @ FCC-ee

FCC-ee with 2IP



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



- Signal:

$\sqrt{s}$ = 240 GeV: 1640 ab

L = 3.5 ab^{-1}/yr

N(γγ → WW)=11480 counts/yr

$\sqrt{s}$ = 350 GeV: 10500 ab

L = 1 ab^{-1}/yr

N(γγ → WW)=21100 counts/yr

- Backgrounds:
  - Dominant

e^+e^-→Z*,g*→4j (~8.8 pb with cuts) killed with $e^{\pm}$ tagging.

  - γγ→4 jets

$\sqrt{s}$ = 240 GeV: 10490 ab

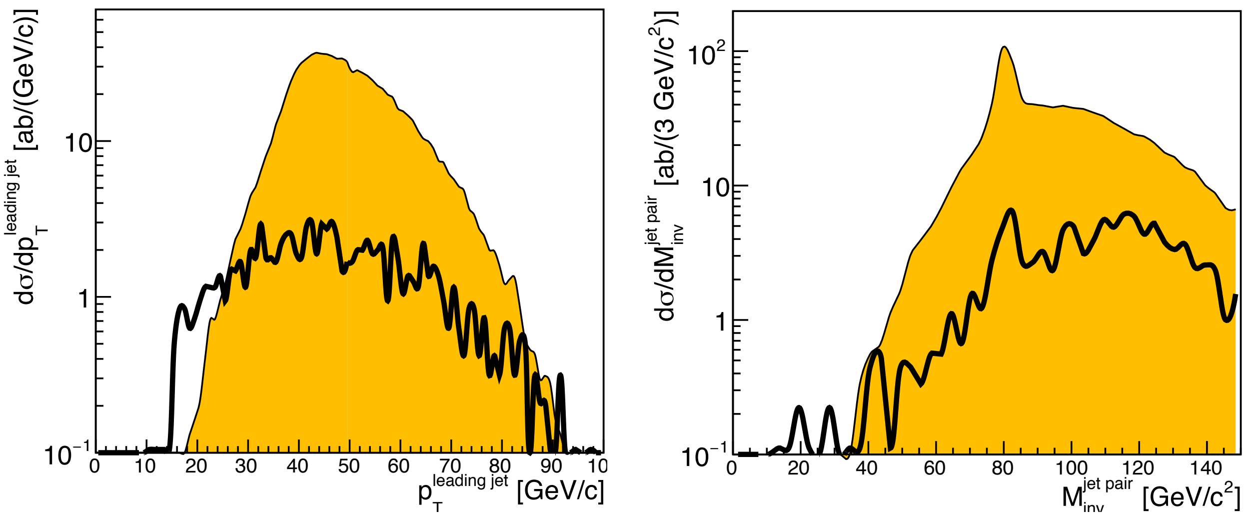
N(γγ → 4Jets) = 74430 counts/yr

$\sqrt{s}$ = 350 GeV: 46844 ab

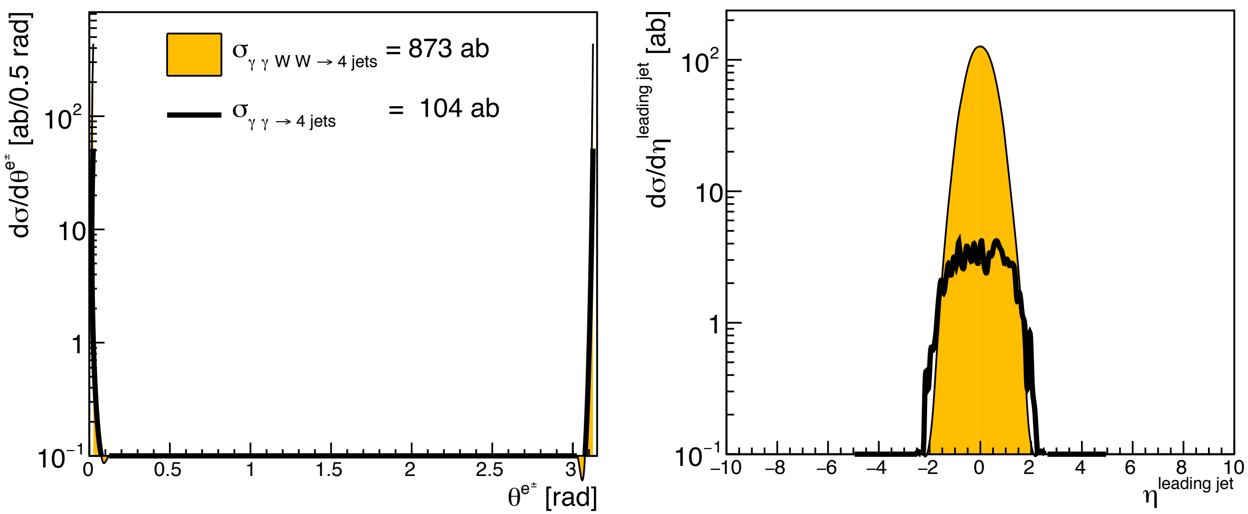
N(γγ → 4Jets) = 93688 counts/yr

$\gamma\gamma \rightarrow$ WW $\rightarrow$ 4 jets @ FCC-ee

Cuts: $p_{TJets} > 10$ GeV; $\eta_{Jets} < 5$; $\Delta R_{Jets} > 0.4$; 76.5 GeV < M_{jj} < 84.5 GeV
Beam line tagging: $q_{lepton} < 1°$



Kinematical distributions for $\sqrt{s}$ =240 GeV (after cuts)



Observation of $\gamma\gamma \rightarrow$ WW $\rightarrow$ 4j @ FCC-ee(240, 350GeV)

Signal:

$\sqrt{s}$ = 240GeV:

σ(visible) = 873 ab

N($\gamma\gamma \rightarrow$ WW) = 6111 counts/yr

$\sqrt{s}$ = 350GeV:

σ(visible) = 6610 ab

N($\gamma\gamma \rightarrow$ WW) = 13220 counts/yr

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

$\sqrt{s}$ = 240GeV: 104 ab

N($\gamma\gamma \rightarrow$ 4Jets) = 728 counts/yr

$\sqrt{s}$ = 350GeV: 520 ab

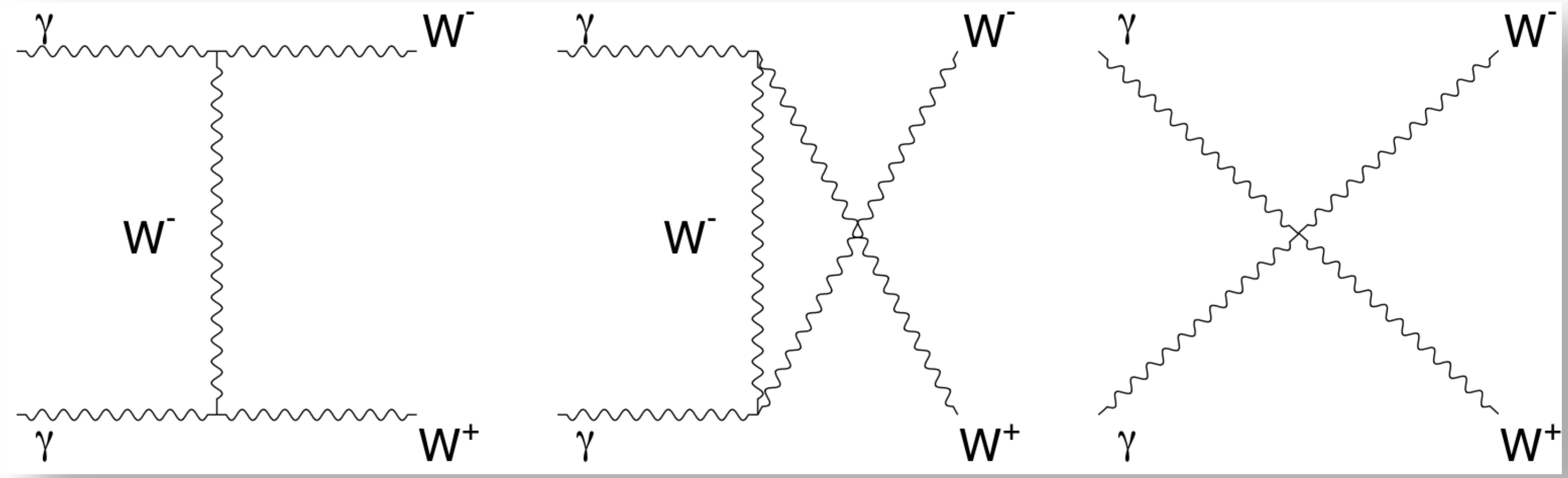
N($\gamma\gamma \rightarrow$ WW) = 1040 counts/yr

- ~ 99% events lost of the back against 53% of the signal
- **Significance: S/$\sqrt{B}$ = 6**

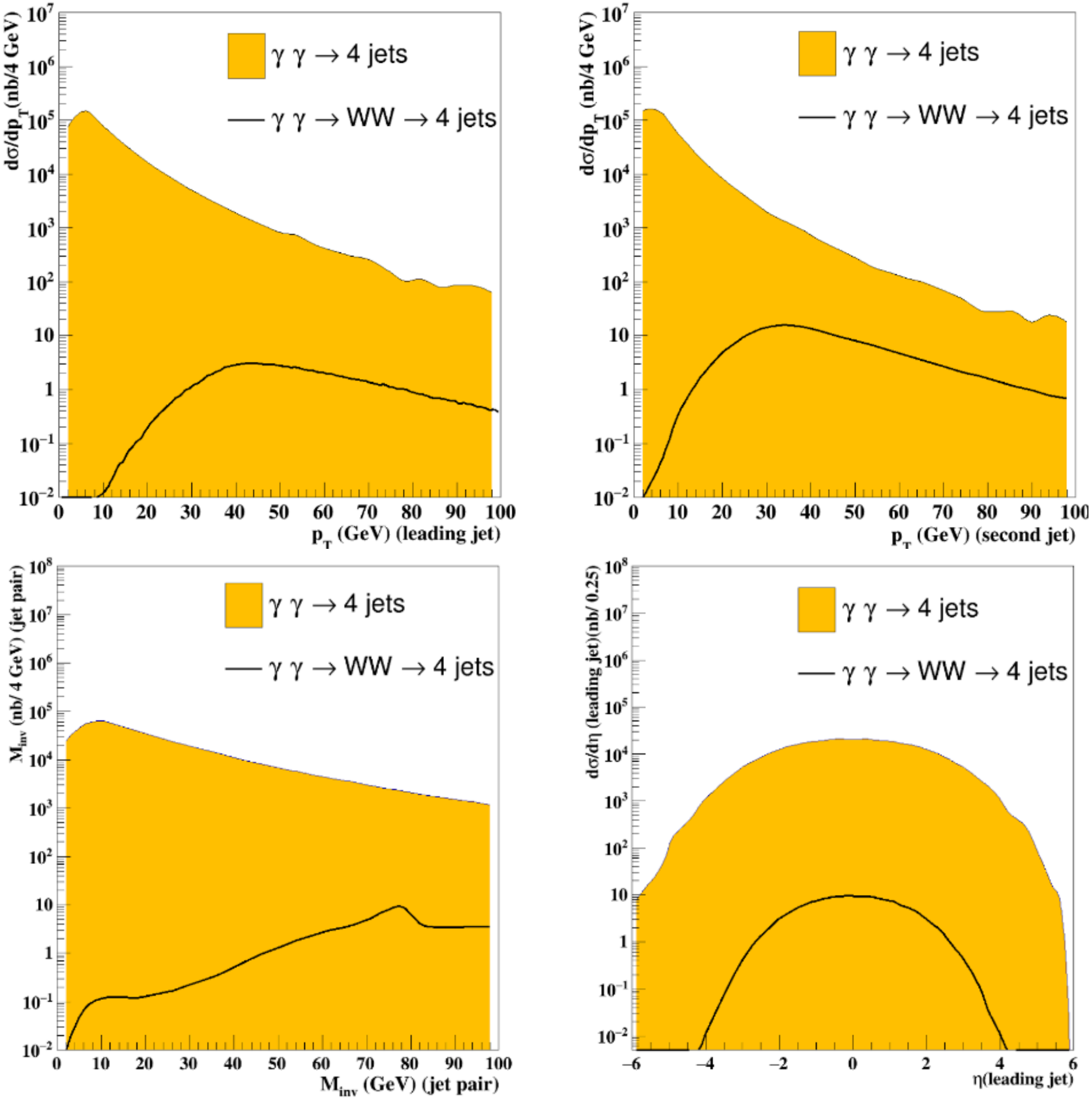
for L = 0.1 ab^{-1} @240GeV

for L = 0.015 ab-1 @350GeV

Feasibility measurement study of $\gamma\gamma \rightarrow W^+W^- \rightarrow$ 4 jets @ FCC-PbPb



γγ → WW → 4 jets @ FCC-PbPb



$\sqrt{s}$ = 39 TeV: (PbPb flux)
Integrated luminosity
L = 110 nb^{-1}/year

Madgraph + Py8 + FastJet3

Exclusive jets are categorized with kt algorithm, **Δ**R > 0.4 and sorted by transverse momentum.

◆ Phase Space:
$10 < m_{jj} < 1000$ GeV
$p_{Tjet} > 1$ GeV
$-8 < \eta_{jet} < 8$
Nucleon mass = 0.9315 GeV

◆ Signal:
σ(γγ → WW → 4jets) = 132.2 nb
N(events) = 14542 counts/yr

◆ Background:
σ (γγ→4jets) = 401305 nb
N(events) = 4.41 x 10^7 counts/yr

$\gamma\gamma \to$ WW $\to$ 4 jets @ FCC-PbPb

- Cuts applied to enhance the signal.

$p_{T(jets)} > 30$ GeV
$-5 < \eta_{(jets)} < 5$
$76.5 < m_{jj} < 84.5$ GeV

- Visible Cross section after cuts:

Signal
σ ($\gamma\gamma \to$ WW $\to$ 4 jets) = 28.42 nb
N(events) Signal = 3126 counts/yr

Background:
σ ($\gamma\gamma \to$bb~) = 32.1 nb
N(events) Background = 3531 counts/yr

Removal of irreducible continum 4-jet background:

- Signal W -jets peak at $p_T \approx m_W/2$ = 40 GeV/c: selecting events with $p_{T(jet)} > 30$ GeV/c removes around 98% of the remaining continuum 4-jet background while keeping ~61.6% of the signal.
- Constraining the pseudorapidity region to $-5 < \eta_{(jets)} < 5$ keeps ~59.8% of the signal
- Expecting to reconstruct W-mass with between the mass window 76.5 GeV - 84.5 GeV retains ~21.5% of the signal and left only ~0.008% of the 4-jet continuum background.

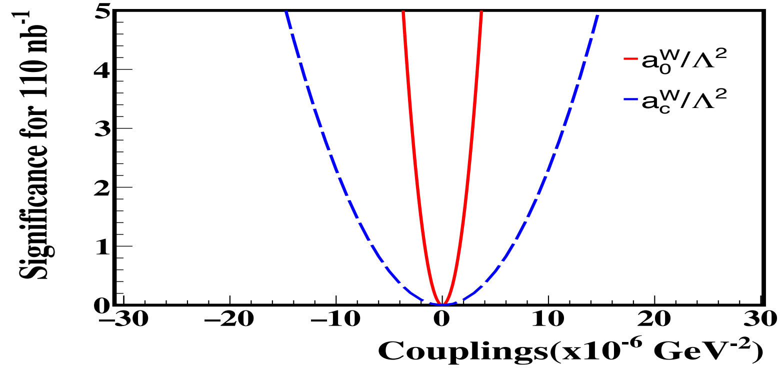
$S/\sqrt{B} = 52.1$ for L = 110 nb^{-1}

- S(3σ) for L = 0.4 nb-1 ~1.2 days
- S(5σ) for L = 1.01 nb^{-1} ~3.3 days

Observation of $\gamma\gamma \to$ WW $\to$ 4j @ FCC-PbPb (39TeV)

aQGC via γγ → WW @ FCC-ee, PbPb

- 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);
  - ✓ **Pythia8.2 and Superchic** (SC) are powerful tools for this computation => **need implementation of effective vertex.**
  - ✓ Events for Dim6 operators, related to γγWW, generated with **Madgraph v2.5.4** => **aQGC XS properly weighted** by the **SM XS factor**, **SC/MG5 = 0.47**, for a reliable approximation in FCC-ee analysis.

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

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

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

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

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

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

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

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

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

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

Observed:
CMS (8TeV): a_0^W = [-4,4] TeV^{-2}
a_C^W = [-15,15] TeV^{-2}

Expected:
FCC-ee (240GeV) : a_0^W = [-2, 2] TeV^{-2}
a_C^W = [-8, 8] TeV^{-2}

FCC-PbPb (39TeV) : a_0w = [-2.9, 2.9] TeV^{-2}
a_C^W = [-11.6, 11.6] TeV^{-2}

✓ Expected better aQGC constraints than recent LHC limits.

Results & Perspectives

- Photon-photon collisions at the FCC-ee,hh provide rich and novel physics opportunities to study EWK and Higgs sector of the SM.
  - Two crucial processes considered: $\gamma\gamma \rightarrow$ **H** (FCC-ee/pPb/PbPb) and $\gamma\gamma \rightarrow$ **W^+W^-** (FCC-ee/PbPb)
  - EPA properly implemented in Superchic v2.04 and Pythia 8.226. Madgraph 2.5.4 suitable for PbPb and pPb fluxes.
  - Superchic used to weight Madgraph's dim6 aQGC events for FCC-ee.

- $\gamma\gamma \rightarrow$ **H $\rightarrow$ bb~** :
  - ✓ **FCC-ee**: cuts based on forward and central regions as well as beam line tagging plus suitable kinematical variables (p_{TJets} and $M_{bb\sim}$). **Evidence/Observation in all center-if-mass energies within one year running.**
  - ✓ **FCC-hh**: Cuts in suitable variables (p_{TJets} and $M_{bb\sim}$). **Evidence/Observation is expected at 39TeV and 63eV from 7 months running.**

- $\gamma\gamma \rightarrow$ **W^+W^- $\rightarrow$ 4 jets @FCC-ee, PbPb**:
  - ✓ cuts based plus on suitable kinematical variables (p_{TJets}, η_{Jets}, ΔR_{Jets}, and M_{jj}). **Observation at FCC-ee(240 GeV, 350GeV) and FCC-PbPb (39TeV) up to 1 month running.**
  - ✓ Preliminary studies of dim6 effective operators using EPA: improvements depending on future Monte Carlo implementations. Pointing to improve the recent CMS exclusion limits.

- **Outlook**:
  - $\gamma\gamma \rightarrow W^+W^-$ & ZZ @FCC-ee, hh with leptonic, semileptonic and hadronic decay channels in progress.

Backup

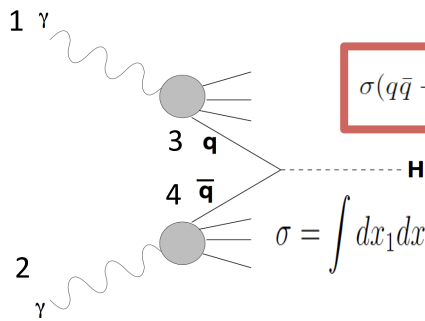
γγ analyses: Theoretical Setup

◆ Resolved Photon Contribution to Higgs production in γγ collisions

- single Higgs boson production in γγ collisions via the hadronic content of the photon at e^+e^- colliders

Pythia8.226 based on (default) Photon PDF by F. Cornet, P. Jankowski, M. Krawczyk and A. Lorca, Phys. Rev. D68 (2003) 014010

- the quark and gluon content of the photon are treated as partons described by partonic distributions, $f_{q/\gamma}(x,Q^2)$ in direct analogy to partons inside hadrons. The associated spectrum of photons (here the Weizsäcker Williams distribution of effective photon approximation - EPA) convolute the cross sections with the photon distributions to obtain cross sections that can be compared to experiment

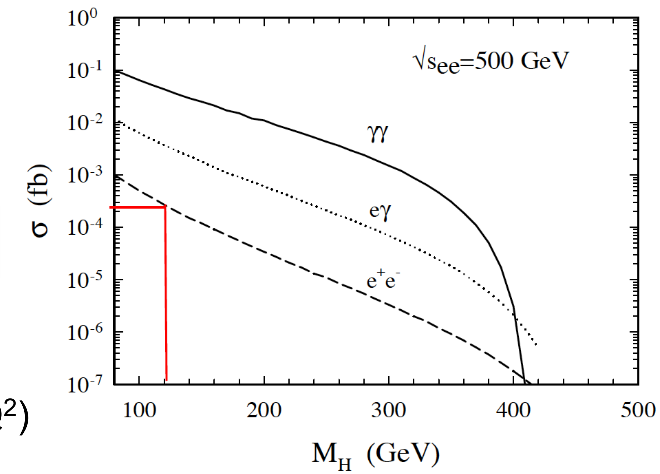


$$\sigma(q\bar{q} \to H) = \frac{G_F \pi}{3\sqrt{2}} m_f^2 \sqrt{(1 - 4m_f^2/M_h^2)}\; \delta(M_H^2 - \hat{s})$$

$$\sigma = \int dx_1 dx_2 dx_3 dx_4 f_{\gamma/e}(x_1, Q^2) f_{\gamma/e}(x_2, Q^2) f_{p_i/\gamma}(x_3, Q^2) f_{p_j/\gamma}(x_4, Q^2)\, \hat{\sigma}(\hat{s})$$

1 and 2 : photon from electron-positron beam => EPA $f_{q/\gamma}(x,Q^2)$

3 and 4: parton in the photon (quark, anti-quark or gluon) => $f_{p/\gamma}(x,Q^2)$

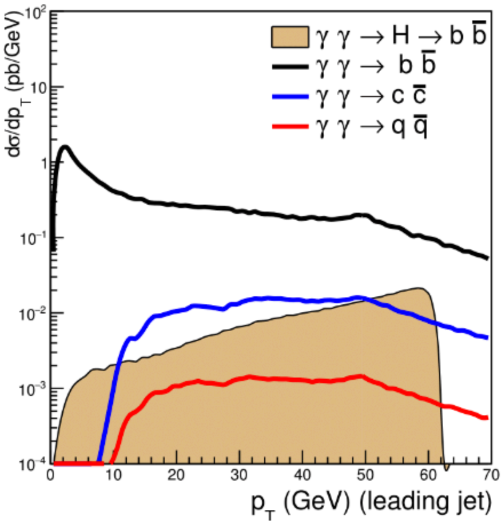


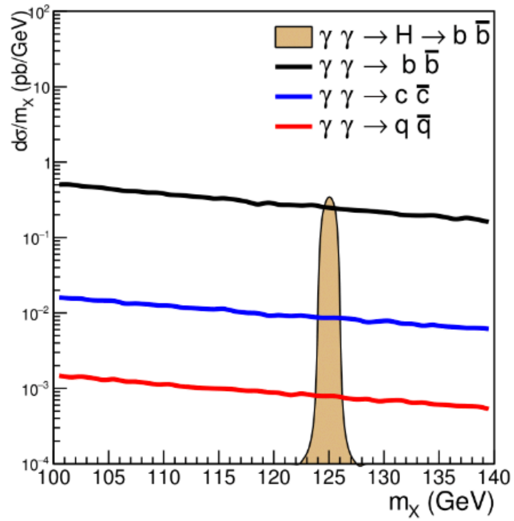
- for FCC-ee @160 – 350 GeV:
  - SM Higgs production cross section via resolved photons varies from 0.13 x 10^{-4} ab to 0.18 x 10^{-3} ab
  - Continuum backgrounds cross sections via resolved photons can reach huge 9.9 x 10^{+8} ab (@350GeV) but events are 100% killed by the $p_T \approx m_H/2$ = 62.5 GeV cut.

(*) M.A.Doncheski & S.Godfrey, Phys.Rev.D67:073021,2003

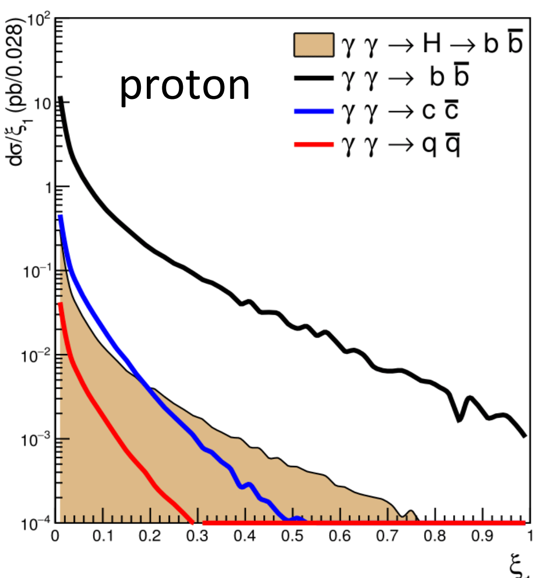
γγ → H → bb~ @ FCC-pPb

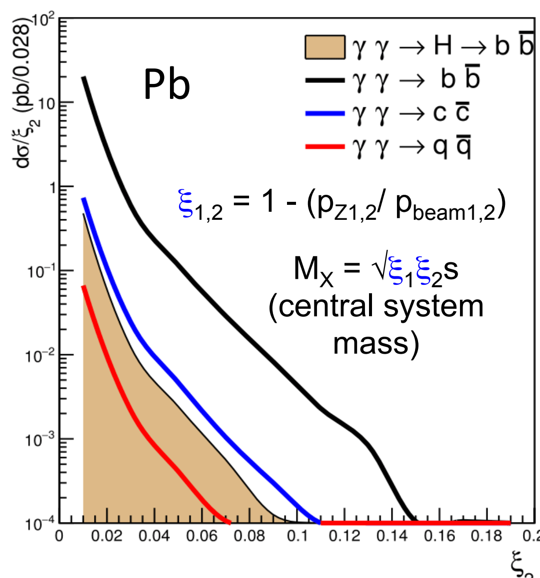
$\sqrt{s}$ = 63 TeV; **Lumi$_{int}$ = 29 pb^{-1}/yr**





Kinematical distributions for $\sqrt{s}$ = 63 TeV (b-jet reco & mistag)





- Superchicv2.03 & Magraph2.5.4, both adapted with photon flux from Pb beam*, and Pythia8.2
- Restricting phase space:

$m_{j1j2} \geq 100$ GeV, $p_{Tjets} \geq 20$ GeV, $-5 \leq \eta \leq 5$

Effic(b-jet reco) = $(70\%)^2$

Prob(b-mistag.)=$(5\%)^2$ (c)

Prob(b-mistag.)=$(1.5\%)^2$ (q)

- Signal:

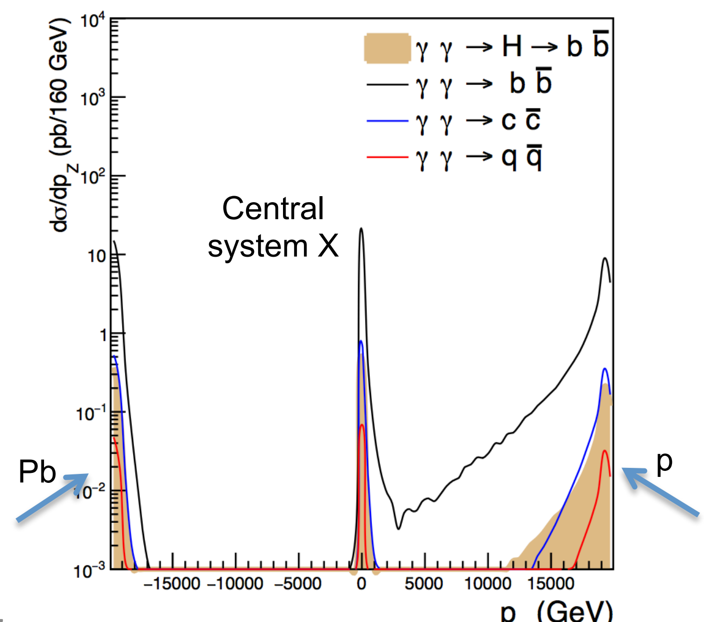
σ (Higgs → bb~) = 0.49 pb ~ 14 counts/yr

- Backgrounds:

σ(γγ→bb~) = 20.93 pb ~ 607 counts/yr

σ(γγ→cc~) = 0.763 pb ~ 22 counts/yr

σ(γγ→qq~) = 0.069 pb ~ 2 counts/yr



(*) Study of Higgs boson production and its bB decay in γγ processes in proton-nucleus collisions at the LHC. D. d'Enterria, Phys. Rev. D 81, 014004 (2010)

Analysis Cuts

- Removal of irreducible $\gamma\gamma$ backgrounds:
  - Signal b-jets peak at $p_T \approx m_H/2 = 62.5$ GeV/c:

    selecting events with 40 GeV/c $< p_T$ (jet) < 62.5 GeV/c removes ~90% of the bb~, and mistagged cc~, qq~ backgrounds while killing ~38% of the signal.

  - The acoplanarity within $-0.45 < \cos(\theta) < 0.45$ range removes 78% of the backgrounds but only 21% of the signal

  - Expecting to reconstruct b-jets with $p_T = 62. \pm 4.5$ GeV (~7% b-jet reco resolution), propagates into m_{bb} resolution of $\sqrt{2} \times 4.5 \sim 3.$ GeV. Applying invariant mass within window: 122 GeV $< M_{inv} < 128$ GeV around m_H returns no signal loss but ~99.7% removal of backgrounds.