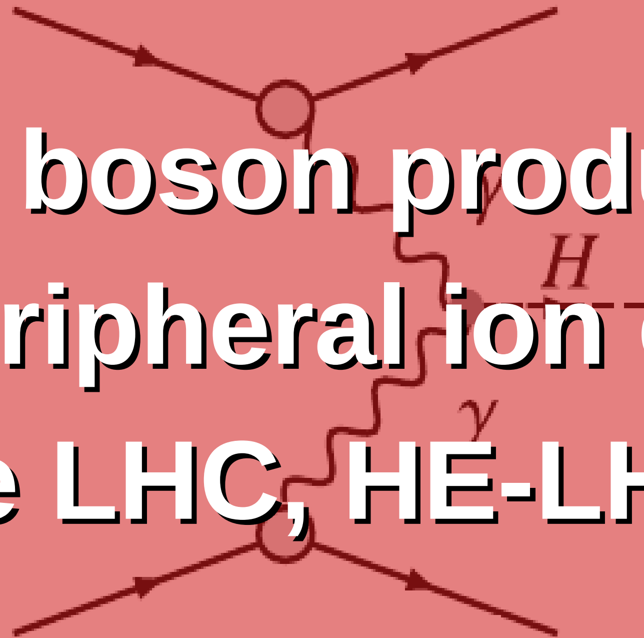
Higgs boson production in ultraperipheral ion collisions at the LHC, HE-LHC, FCC



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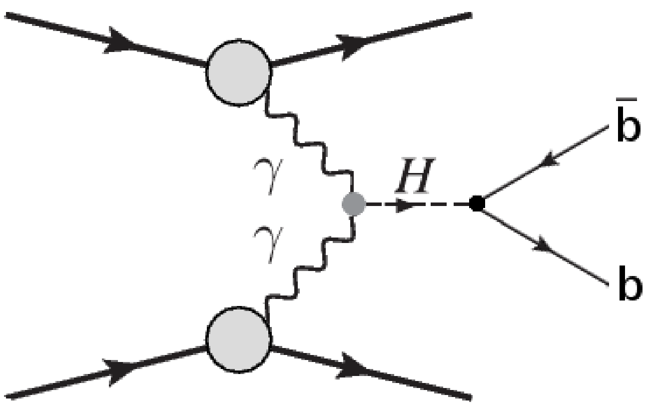
Based on: D.d'E. &J.Ph. Lansberg, PRD 81 (2010) 014004.
D.d'E, D.E. Martins, P. Rebello, CERN Proc. 1 (2018) 33; and arXiv:1904.11936 [hep-ph]

Higgs boson production in $\gamma\gamma$ collisions

- The s-channel production of the Higgs boson in photon-photon collisions has always been one of the key channels of study at a photon collider (Compton-backscattering laser-light off $e^{\pm}$ beams):



→ Independent measurement of the H-γ loop-induced coupling based not on the Higgs decay (LHC) but on its s-channel production mode.

→ Model-independent extraction of total Higgs width combining $\Gamma(H\to\gamma\gamma)$ partial width: $\sigma(\gamma\gamma \to \mathrm{H} \to \mathrm{b\bar{b}}) \propto \Gamma(\mathrm{H} \to \gamma\gamma) \cdot \mathrm{BR}(\mathrm{H} \to \mathrm{b\bar{b}})$ with $BR(H\to\gamma\gamma)$ from LHC:

$$\Gamma_{\mathrm{H}}^{\mathrm{tot}} = \Gamma(\mathrm{H} \to \gamma\gamma)/\mathrm{BR}(\mathrm{H} \to \gamma\gamma)$$

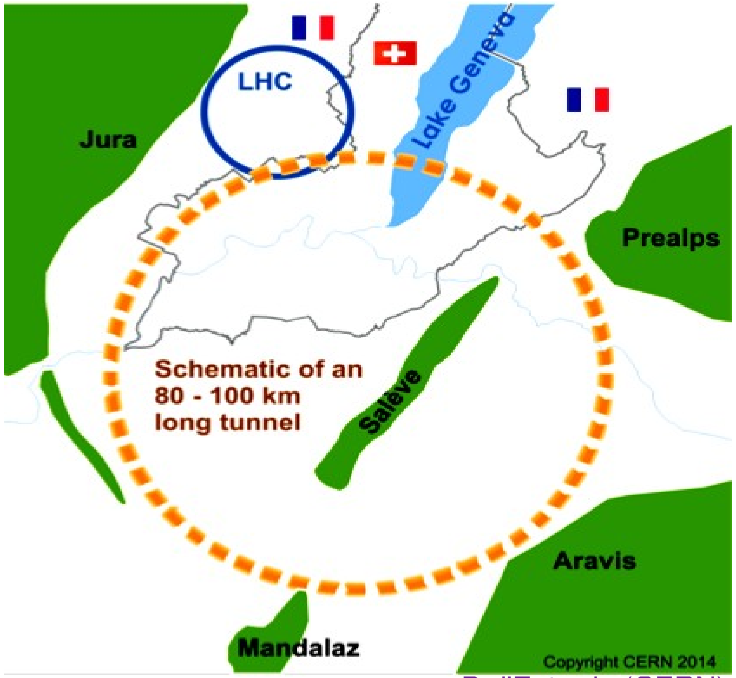
- Before the γ-collider comes to reality, is it possible to observe it using the equiv. γ fluxes of e.m. p,A interactions at LHC or future colliders?

CERN Future Circular Collider (FCC) project

- The next collider project at CERN:

- FCC: 100 km ring, Nb_3Sn 16 T magnets, LHC used as injector:
  - pp at $\sqrt{s}$=100 TeV, L~2x10^{35}, L_{int}= 2 ab^{-1}/yr plus pPb, PbPb at $\sqrt{s_{NN}}$= 39–63 TeV
  - e^+e^- option (before pp) at $\sqrt{s}$=90–350 GeV L≈10^{35}–4·10^{36}, L_{int}=1–40 ab^{-1}/yr for H, Z

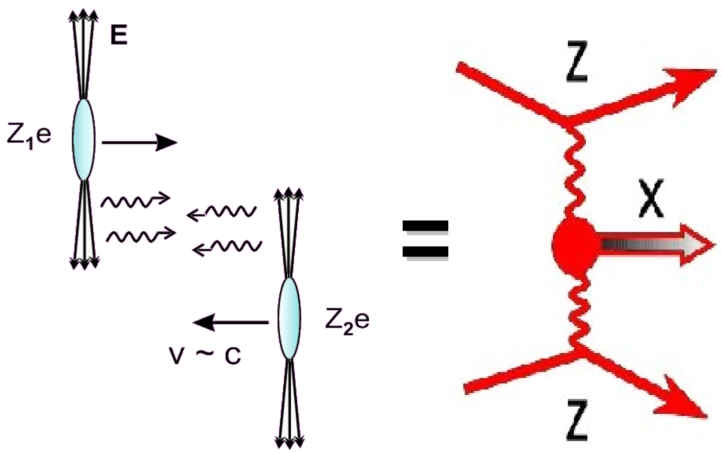
- HE-LHC: LHC + 16 T magnets:
  - pp at $\sqrt{s}$=27 TeV, PbPb at $\sqrt{s_{NN}}$=10.6 TeV

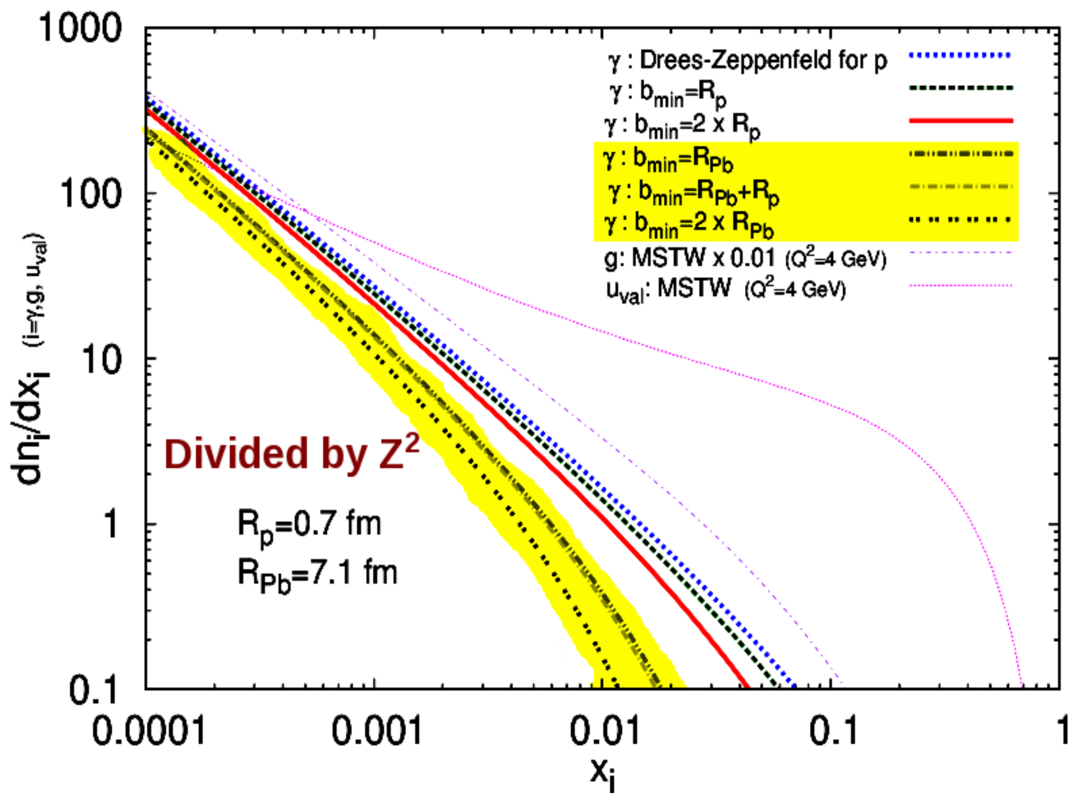


Photon-photon collisions at colliders

- Electromagnetic ultra-peripheral collisions (UPCs): $b_{min} > R_A + R_B$
- HE ions generate huge EM fields (10^{14} T) from coherent action of Z=82 p:

Weizsäcker-Williams (EPA) power-law photon flux:

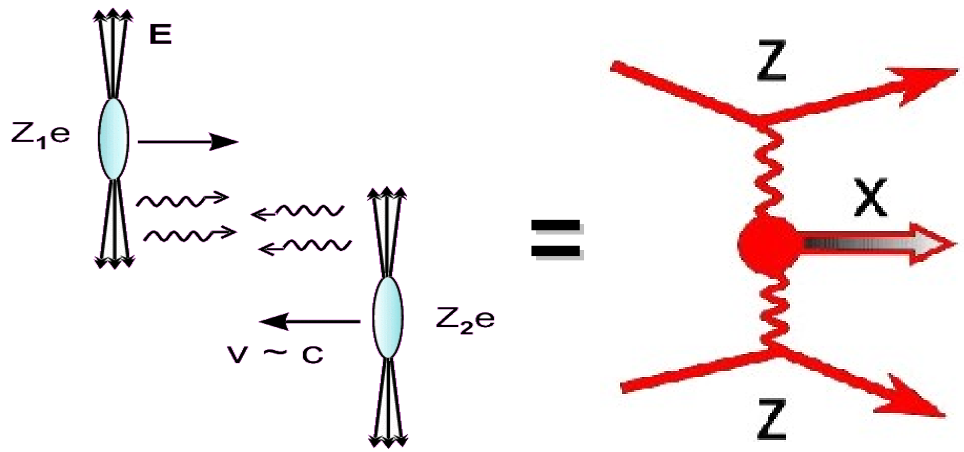




- Quasi-real photons (coherence): $Q \approx 1/R \approx 0.06$ GeV (Pb), 0.28 GeV (p)
- Maximum γ energies (LHC): $\omega < \omega_{max} \approx \frac{\gamma}{R}$ ≈ 80 GeV (Pb), ≈ 2.5 TeV (p)

Photon-photon collisions at the LHC

- Electromagnetic ultra-peripheral collisions (UPCs): $b_{min} > R_A + R_B$
- HE ions generate huge EM fields (10^{14} T) from coherent action of Z=82 p:



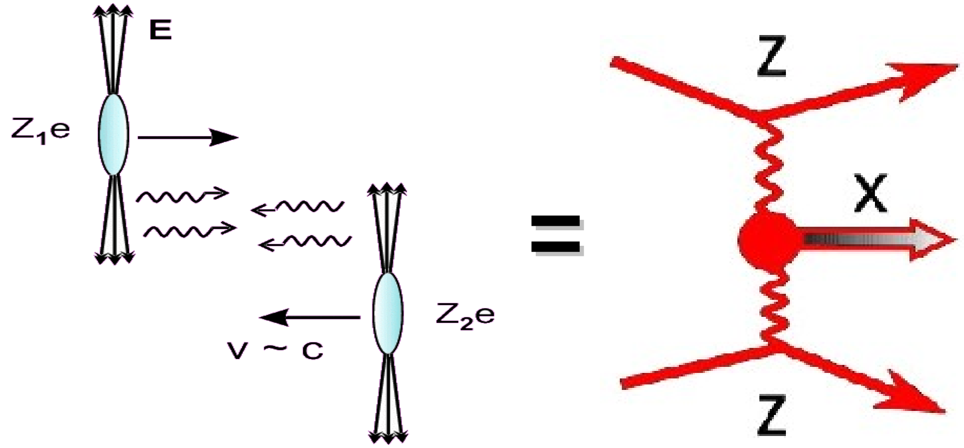
- Huge photon fluxes:
  $\sigma(\gamma\text{-}\gamma) \sim Z^4$ (~$5\cdot10^7$ for PbPb) larger than p,$e^{\pm}$
- Beam-energy dependence:
  Photon luminosities increase as $\propto \log^3(\sqrt{s})$

- Quasi-real photons (coherence): $Q \approx 1/R \approx 0.06$ GeV (Pb), 0.28 GeV (p)
- Maximum γ energies (LHC): $\omega < \omega_{max} \approx \frac{\gamma}{R}$ ≈ 80 GeV (Pb), ≈ 2.5 TeV (p)

System	$\sqrt{s_{NN}}$ (TeV)	γ	R_A (fm)	ω_{max} (GeV)	$\sqrt{s_{\gamma\gamma}^{max}}$ (GeV)
p-p	14	7455	0.7	2450	4500
p-Pb	8.8	4690	7.1	130	260
Pb-Pb	5.5	2930	7.1	80	160

Photon-photon collisions at the FCC

- Electromagnetic ultra-peripheral collisions (UPCs): $b_{min} > R_A + R_B$
- HE ions generate huge EM fields (10^{14} T) from coherent action of Z=82 p:



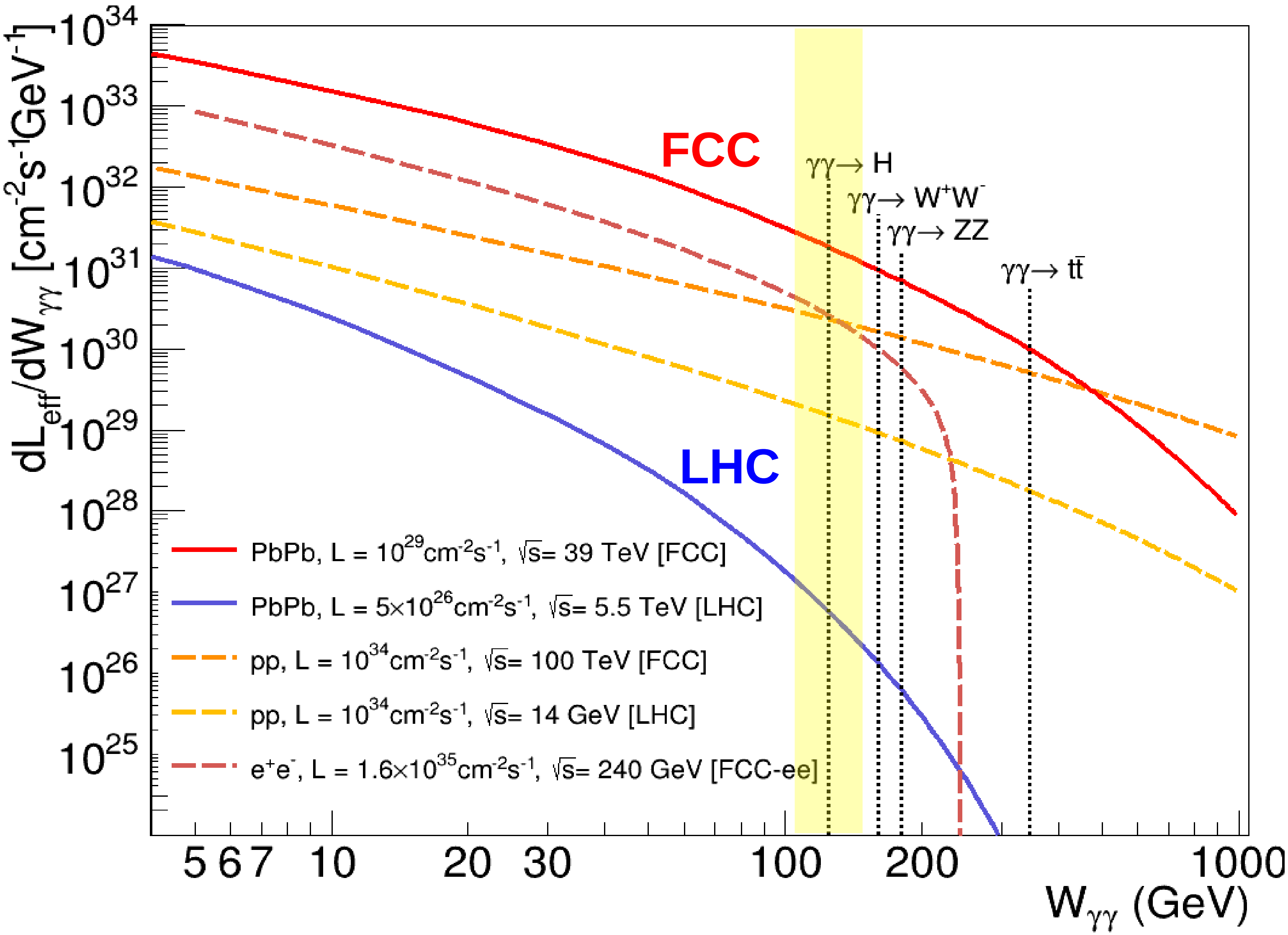
- Huge photon fluxes:
  $\sigma(\gamma\text{-}\gamma) \sim Z^4$ (~$5\cdot10^7$ for PbPb) larger than p,e$^\pm$
- Beam-energy dependence:
  Photon luminosities increase as $\propto \log^3(\sqrt{s})$

- Quasi-real photons (coherence): $Q \approx 1/R \approx$ 0.06 GeV (Pb), 0.28 GeV (p)
- Maximum γ energies (FCC): $\omega < \omega_{max} \approx \frac{\gamma}{R}$ $\approx$ 0.6 TeV (Pb), $\approx$ 18 TeV (p)

System	$\sqrt{s_{NN}}$ (TeV)	$\mathcal{L}_{AB}\cdot\Delta t$ (per year)	γ ($\times10^3$)	ω_{max} (TeV)	$\sqrt{s^{max}_{\gamma\gamma}}$ (TeV)
p-p	100	1 fb^{-1}	53.	17.6	35.2
p-Pb	64	1 pb^{-1}	33.5	0.95	1.9
Pb-Pb	39	5 nb^{-1}	21.	0.60	1.2

Effective $\gamma\gamma$ luminosities in UPCs at LHC/FCC

- Effective $\gamma\gamma$ lumi vs. $\sqrt{s_{\gamma\gamma}}$. Threshold m_{Higgs} surpassed for first time



Theoretical setup

- MadGraph 5.0 (v.2.6.5) MC event generator.
  - → Equivalent photon approximation (EPA):

$$\sigma_{\mathrm{A_1A_2\to H}} = \int dx_1\, dx_2\, f_{\gamma/\mathrm{A_1}}(x_1) f_{\gamma/\mathrm{A_2}}(x_2) \hat{\sigma}_{\gamma\gamma\to\mathrm{H}}$$

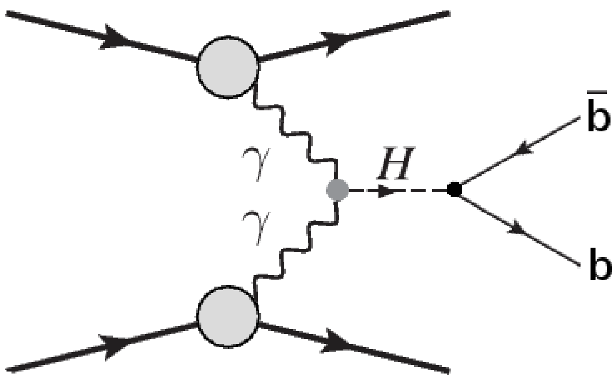
  - → Photon fluxes:

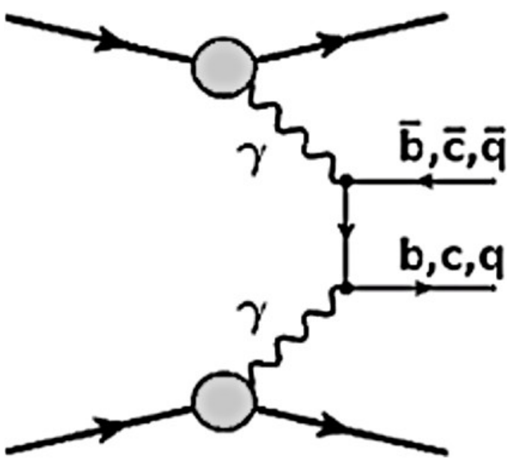
p: (elastic FF) $f_{\gamma/p}(x) = \frac{\alpha}{\pi}\frac{1-x+1/2x^2}{x}\int_{Q^2_{\min}}^{\infty}\frac{Q^2-Q^2_{\min}}{Q^4}|F(Q^2)|^2 dQ^2$

A: $f_{\gamma/A}(x) = \frac{\alpha Z^2}{\pi}\frac{1}{x}\left[2x_i K_0(x_i)K_1(x_i) - x_i^2(K_1^2(x_i) - K_0^2(x_i))\right]$

  - → σ(γ γ →H) cross section in the HEFT-approximation:

$$\mathcal{L}^{\mathrm{eff}}_{\gamma\gamma H} = -\frac{1}{4} g\, F_{\mu\nu} F^{\mu\nu} H$$





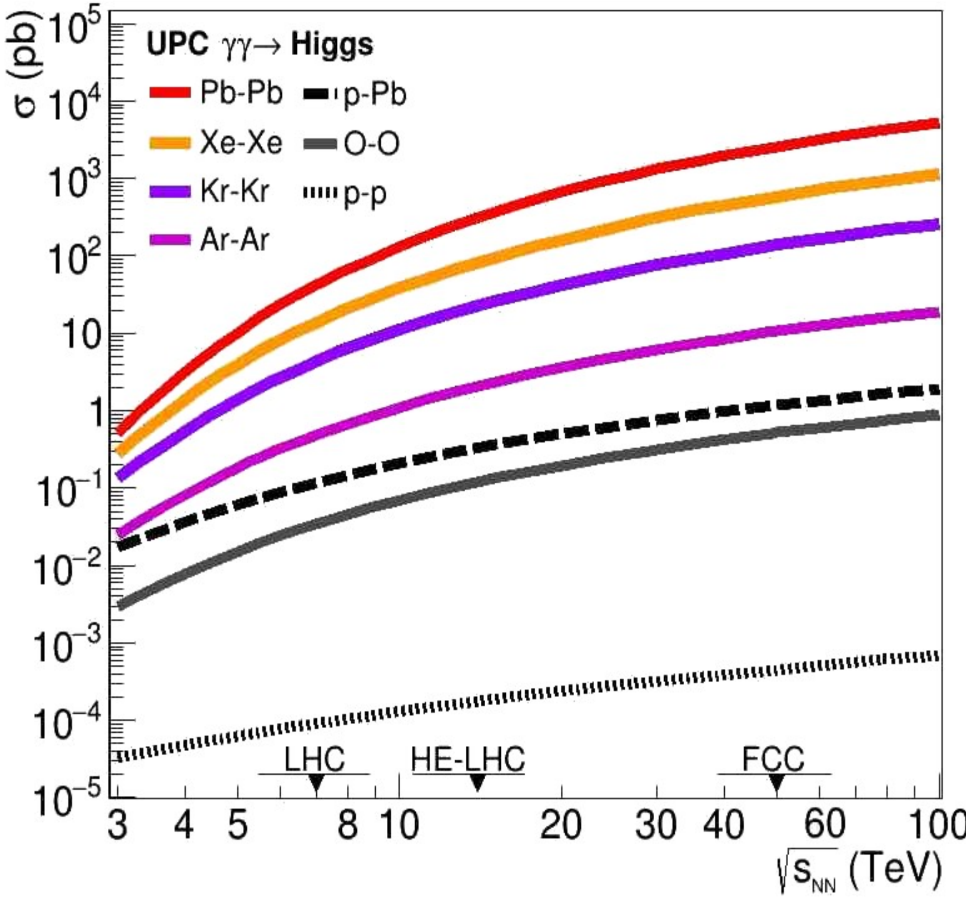
- HDECAY: BR($H\to b\bar{b}$) ≈ 56%
- Backgrounds ($\gamma\gamma\to b\bar{b}$, $c\bar{c}$, $q\bar{q}$) directly computed by MadGraph 5.0.
- PYTHIA-8.2: Shower & hadronization of b (and c, uds) quarks.
- FastJet: Durham jet algo (exclusive n_j=2)

1) TH uncertainties:~20% from form-factors, nuclear overlap,…

2) Semielastic production (×2 yields; p,Pb breakup) not included.

$\gamma\gamma \rightarrow$ Higgs x-sections in A-A, p-A, p-p UPCs

- Total $\sigma(\gamma\gamma \rightarrow H)$ vs. c.m. energy:

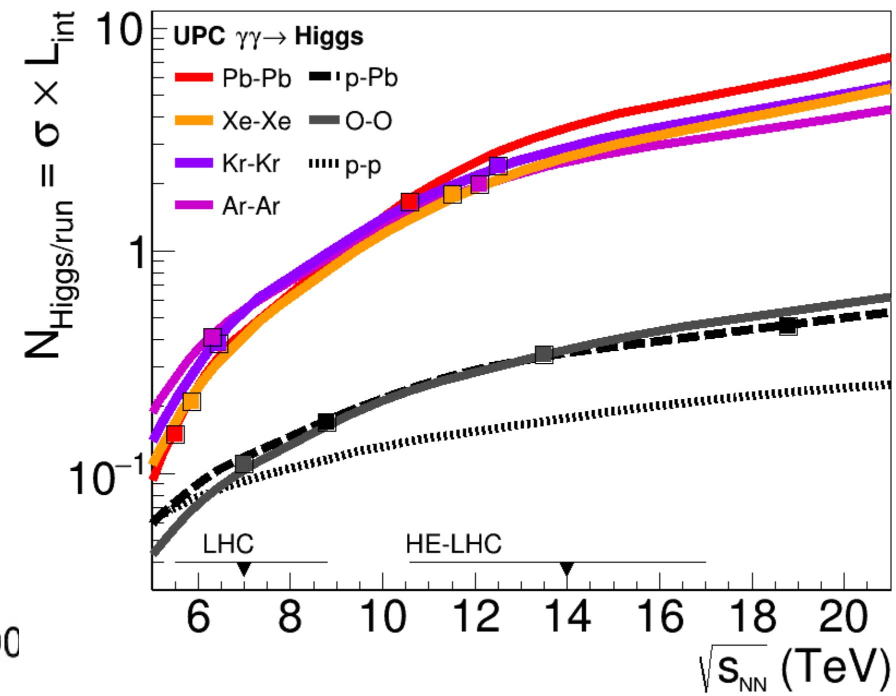


► Z^4 factor enhances significantly the cross-section in Pb-Pb UPCs compared to p-p & lighter ions.

- Total $\gamma\gamma \rightarrow H$ yields vs. c.m. energy per system:

0.1–0.4 Higgs/month at the LHC

1.5–2.5 Higgs/month at HE-LHC



► Larger beam luminosity for lighter ions compensates for smaller x-sections: Larger Higgs yields/mo. for Ar-Ar, Kr-Kr

$\gamma\gamma \to$ Higgs yields in A-A, p-A, p-p UPCs

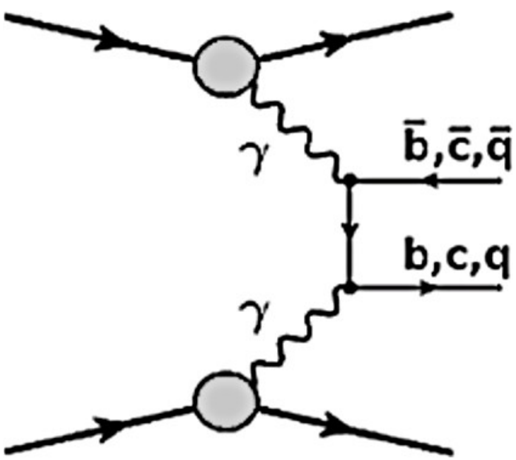
- Total Higgs cross sections & yields per colliding system:

	System	$\sqrt{s_{NN}}$	$\mathcal{L}_{int}$	$E_{beam1} + E_{beam2}$	γ_L	R_A	ω_{max}	$\sqrt{s^{max}_{\gamma\gamma}}$	$\sigma(\gamma\gamma \to H)$	$N(\gamma\gamma \to H)$
LHC	Pb-Pb	5.5 TeV	10 nb^{-1}	2.75 + 2.75 TeV	2950	7.1 fm	80 GeV	160 GeV	15 pb	0.15
	Xe-Xe	5.86 TeV	30 nb^{-1}	2.93 + 2.93 TeV	3150	6.1 fm	100 GeV	200 GeV	7 pb	0.21
	Kr-Kr	6.46 TeV	120 nb^{-1}	3.23 + 3.23 TeV	3470	5.1 fm	136 GeV	272 GeV	3 pb	0.36
	Ar-Ar	6.3 TeV	1.1 pb^{-1}	3.15 + 3.15 TeV	3400	4.1 fm	165 GeV	330 GeV	0.36 pb	0.40
	O-O	7.0 TeV	3.0 pb^{-1}	3.5 + 3.5 TeV	3750	3.1 fm	240 GeV	490 GeV	35 fb	0.11
	p-Pb	8.8 TeV	1 pb^{-1}	7.0 + 2.75 TeV	7450, 2950	0.7, 7.1 fm	2.45 TeV, 130 GeV	2.6 TeV	0.17 pb	0.17
	p-p	14 TeV	1 fb^{-1}	7.0 + 7.0 TeV	7450	0.7 fm	2.45 TeV	4.5 TeV	0.18 fb	0.18
HE-LHC	Pb-Pb	10.6 TeV	10 nb^{-1}	5.3 + 5.3 TeV	5700	7.1 fm	160 GeV	320 GeV	150 pb	1.5
	Xe-Xe	11.5 TeV	30 nb^{-1}	5.75 + 5.75 TeV	6200	6.1 fm	200 GeV	400 GeV	60 pb	1.8
	Kr-Kr	12.5 TeV	120 nb^{-1}	6.25 + 6.25 TeV	6700	5.1 fm	260 GeV	530 GeV	20 pb	2.4
	Ar-Ar	12.1 TeV	1.1 pb^{-1}	6.05 + 6.05 TeV	6500	4.1 fm	320 GeV	640 GeV	1.7 pb	1.9
	O-O	13.5 TeV	3.0 pb^{-1}	6.75 + 6.75 TeV	7300	3.1 fm	470 GeV	940 GeV	0.11 pb	0.33
	p-Pb	18.8 TeV	1 pb^{-1}	13.5 + 5.3 TeV	14 400, 5700	0.7, 7.1 fm	4.1 TeV, 160 GeV	4.2 TeV	0.45 pb	0.45
	p-p	27 TeV	1 fb^{-1}	13.5 + 13.5 TeV	14 400	0.7 fm	4.1 TeV	8.2 TeV	0.30 fb	0.30
FCC	Pb-Pb	39 TeV	110 nb^{-1}	19.5 + 19.5 TeV	21 000	7.1 fm	600 GeV	1.2 TeV	1.8 nb	200
	p-Pb	63 TeV	29 pb^{-1}	50. + 19.5 TeV	53 300, 21 000	0.7,7.1 fm	15.2 TeV, 600 GeV	15.8 TeV	1.5 pb	45
	p-p	100 TeV	1 fb^{-1}	50. + 50. TeV	53 300	0.7 fm	15.2 TeV	30.5 TeV	0.70 fb	0.70

- ► Z^4 factor enhances significantly the $\gamma\gamma$ x-section for Pb-Pb compared to lighter systems: σ(H)=15 pb (LHC) $\xrightarrow[\times 10]{}$ 150 pb (HE-LHC) $\xrightarrow[\times 10]{}$ 1.8 nb (FCC).
- ► Larger beam lumis for lighter systems ($L_{NN}\approx$1 fb^{-1} compared to $\approx$0.1 fb^{-1}) favor Ar-Ar (~0.4 Higgs/mo) at LHC and Xe-Xe(~2 Higgs/mo) at HE-LHC.
- ► FCC: Large x-sections & lumis: ~45–200 Higgs/mo. in pPb, PbPb

$\gamma\gamma \to b\bar{b}, c\bar{c}, q\bar{q}$ irreducible backgrounds

- Heavy-Q pair continuum in photon-photon collisions:



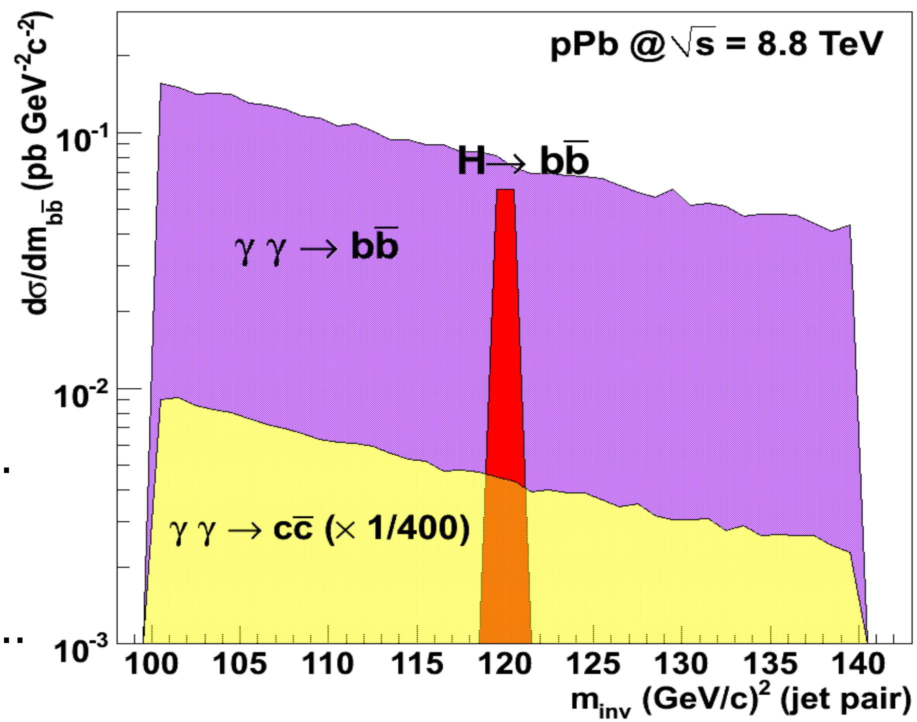
System	$\sqrt{s_{NN}}$ (TeV)	$\sigma(\gamma\gamma\to b\bar{b})$ (pb) [$m_{b\bar{b}}$=100–140 GeV/c^2] elastic	semielastic	$\sigma(\gamma\gamma\to c\bar{c})$ (pb) [$m_{c\bar{c}}$=100–140 GeV/c^2] elastic	$\sigma(\gamma\gamma\to q\bar{q})$ (pb) [$m_{q\bar{q}}$=100–140 GeV/c^2] elastic	$\sigma(\gamma\gamma\to t\bar{t})$ (pb) [all $m_{t\bar{t}}$] elastic
pp	14	$3.4\cdot10^{-3}$	$1.1\cdot10^{-2}$	$7.9\cdot10^{-2}$	0.2	$0.36\cdot10^{-3}$
pO	9.9	$6.8\cdot10^{-2}$	$9.5\cdot10^{-2}$	1.6	3.9	$2.7\cdot10^{-3}$
pAr	9.4	0.27	0.36	6.1	15.8	$8.1\cdot10^{-3}$
pPb	8.8	3.4	4.5	78.	200.	$6.2\cdot10^{-2}$
PbPb	5.5	420	–	$9.4\cdot10^{3}$	$2.5\cdot10^{4}$	$1.8\cdot10^{-2}$

- x-sections (m_{jj}=100–140 GeV/c^2):

1) bbar continuum: ~25×σ(Higgs)

2) ccbar continuum: ~600 times Higgs
   ~1.5×σ(Higgs) after double-mistag prob.

3) qqbar continuum: ~1600 times Higgs
   ~1/3×σ(Higgs) after double-mistag prob..

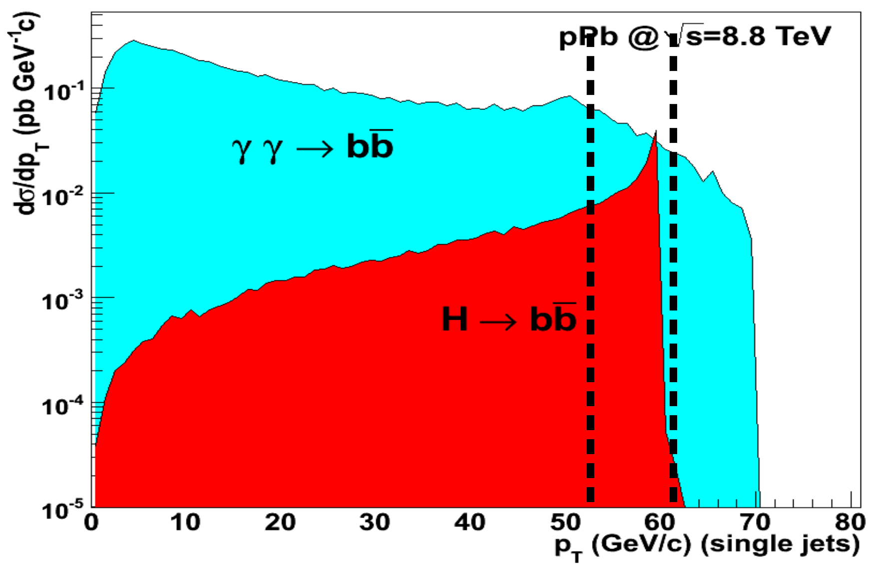


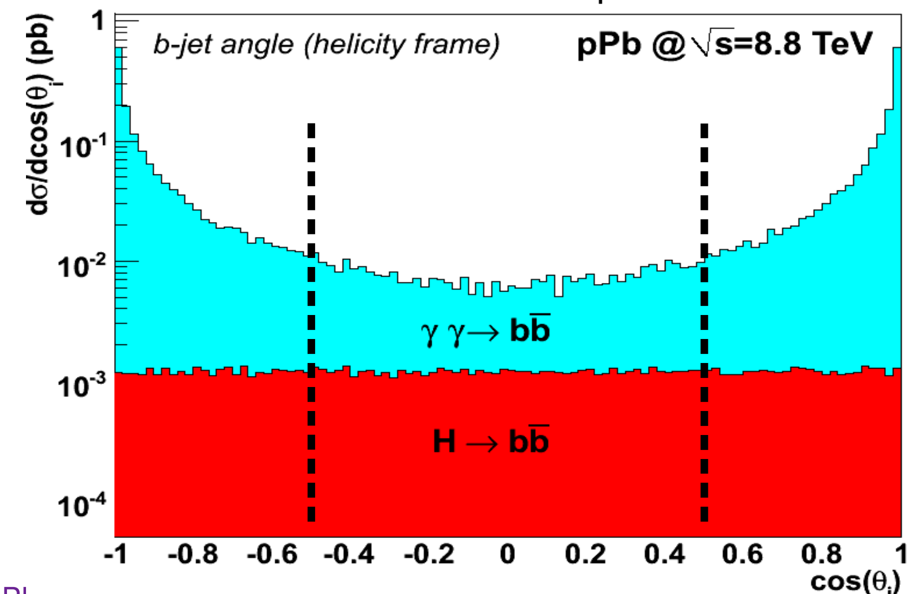
UPC $\gamma\gamma \rightarrow$ Higgs data analysis (I)

- Trigger signal signature: 2 exclusive back-to-back high-p_T (b-)jets
- Experimental reconstruction performance:
  – b-jets reconstructed over $|\eta|<2$ (5) at LHC (FCC).
  – 70% b-jet tagging efficiency, 5% (1.5%) b-jet mistagging probability for charm (light-flavour q) quarks.
  – 7% b-jet energy resolution (mass resolution $\sigma_{jj} \approx 6$ GeV at Higgs peak)
- Acceptance & efficiency losses:
  – Acc $\approx$ 0.8 for signal (central jets), 0.3 for background (fwd-bckwd jets)
  – Eff $\approx$ 0.5 for signal, 1/400 (for bbbar), 1/4500 (for ccbar)
- Luminosities:
  – Nominal p-A, A-A lumis at LHC, HE-LHC/FCC (from CDRs)
  Note: Negligible pileup running in ion-ion mode.
  – p-p: 1 fb^{-1} (1% of L_{int}, at possibly low pileup). Exploiting full pp L_{int} requires proton taggers at 420m in LHC tunnel.
- After all these cuts only $\gamma\gamma\rightarrow$H(bb), $\gamma\gamma\rightarrow$bb continuum remain...

UPC $\gamma\gamma \rightarrow$ Higgs data analysis (II)

- Further kinematical cuts:





- b-jet transverse momentum cut:

At least 1 jet with

$p_T \approx m_H/2 \approx 52 - 67$ GeV/c

Eff $\approx$ 0.5 for signal, 1/20 (for bbbar)

- b-jet acoplanarity cut:

$|\cos(\theta)|<0.5$ in the helicity-frame.

Higgs decays: isotropic
Continuum: u-,t-exchange (fwd/bckw)

Further S/B increase.

UPC $\gamma\gamma \to$ Higgs data analysis (II)

- Event count flow for signal & backgds after each set of cuts:

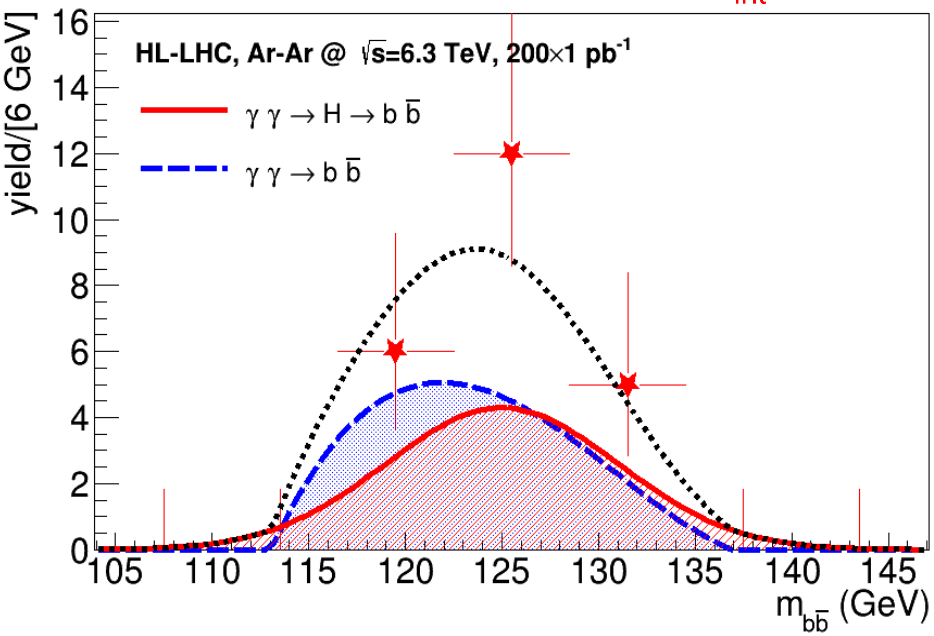
Ar-Ar at $\sqrt{s_{NN}}$ = 6.3 TeV	cross section (b-jet (mis)tag effic.)	visible cross section after η^j, p_T^j, $\lvert\cos\theta_{jj}\rvert$, m_{jj} cuts	N_{evts} ($\mathscr{L}_{int}$ = 1.1 pb^{-1})
$\gamma\gamma \to H \to b\bar{b}$	0.20 pb (0.10 pb)	0.045 pb	0.05
$\gamma\gamma \to b\bar{b}$ [$m_{b\bar{b}}$=100–150 GeV]	8.2 pb (4.0 pb)	0.06 pb	0.06
$\gamma\gamma \to c\bar{c}$ [$m_{c\bar{c}}$=100–150 GeV]	61 pb (0.15 pb)	0.005 pb	0.006
$\gamma\gamma \to q\bar{q}$ [$m_{q\bar{q}}$=100–150 GeV]	70 pb (0.016 pb)	$< 10^{-3}$	$< 10^{-3}$
Kr-Kr at $\sqrt{s_{NN}}$ = 12.5 TeV			N_{evts} ($\mathscr{L}_{int}$ = 0.12 pb^{-1})
$\gamma\gamma \to H \to b\bar{b}$	11 pb (5.5 pb)	2.5 pb	0.30
$\gamma\gamma \to b\bar{b}$ [$m_{b\bar{b}}$=100–150 GeV]	364 pb (178 pb)	2.8 pb	0.34
$\gamma\gamma \to c\bar{c}$ [$m_{c\bar{c}}$=100–150 GeV]	2.7 nb (6.7 pb)	0.24 pb	0.03
$\gamma\gamma \to q\bar{q}$ [$m_{q\bar{q}}$=100–150 GeV]	3.1 nb (0.70 pb)	$< 10^{-3}$	$< 10^{-4}$
Pb-Pb at $\sqrt{s_{NN}}$ = 39 TeV			N_{evts} ($\mathscr{L}_{int}$ = 110 nb^{-1})
$\gamma\gamma \to H \to b\bar{b}$	1.0 nb (0.50 nb)	0.19 nb	21.1
$\gamma\gamma \to b\bar{b}$ [$m_{b\bar{b}}$=100–150 GeV]	24.3 nb (11.9 nb)	0.23 nb	25.7
$\gamma\gamma \to c\bar{c}$ [$m_{c\bar{c}}$=100–150 GeV]	525 nb (1.31 nb)	0.02 nb	2.3
$\gamma\gamma \to q\bar{q}$ [$m_{q\bar{q}}$=100–150 GeV]	590 nb (0.13 nb)	0.002 nb	0.25
p-Pb at $\sqrt{s_{NN}}$ = 63 TeV			N_{evts} ($\mathscr{L}_{int}$ = 29 pb^{-1})
$\gamma\gamma \to H \to b\bar{b}$	0.87 pb (0.42 pb)	0.16 pb	4.8
$\gamma\gamma \to b\bar{b}$ [$m_{b\bar{b}}$=100–150 GeV]	21.8 pb (10.7 pb)	0.22 pb	6.3
$\gamma\gamma \to c\bar{c}$ [$m_{c\bar{c}}$=100–150 GeV]	410 pb (1.03 pb)	0.011 pb	0.3
$\gamma\gamma \to q\bar{q}$ [$m_{q\bar{q}}$=100–150 GeV]	510 pb (0.114 pb)	0.001 pb	0.04

- Final Signal/Backgd ~1, but N_{Higgs}>>1 only at FCC

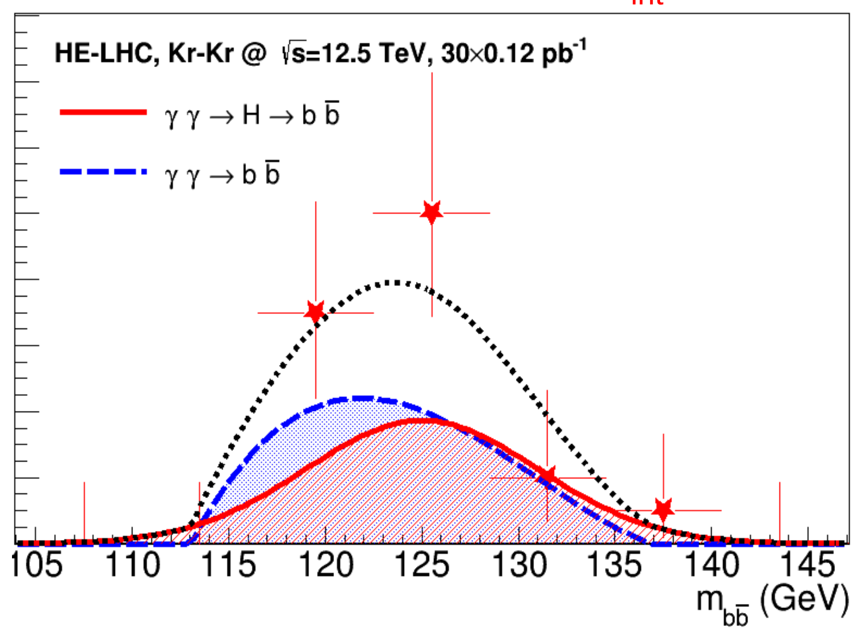
Expected dijet mass spectrum (LHC, HE-LHC)

- What integrated luminosity is needed for evidence (significance $S/\sqrt{B}\sim 3\sigma$) of Higgs signal on top of continuum backgrounds after cuts:

Ar-Ar at 6.3 TeV ($\times 200\ L_{int}$):



Kr-Kr at 6.3 TeV ($\times 30\ L_{int}$):



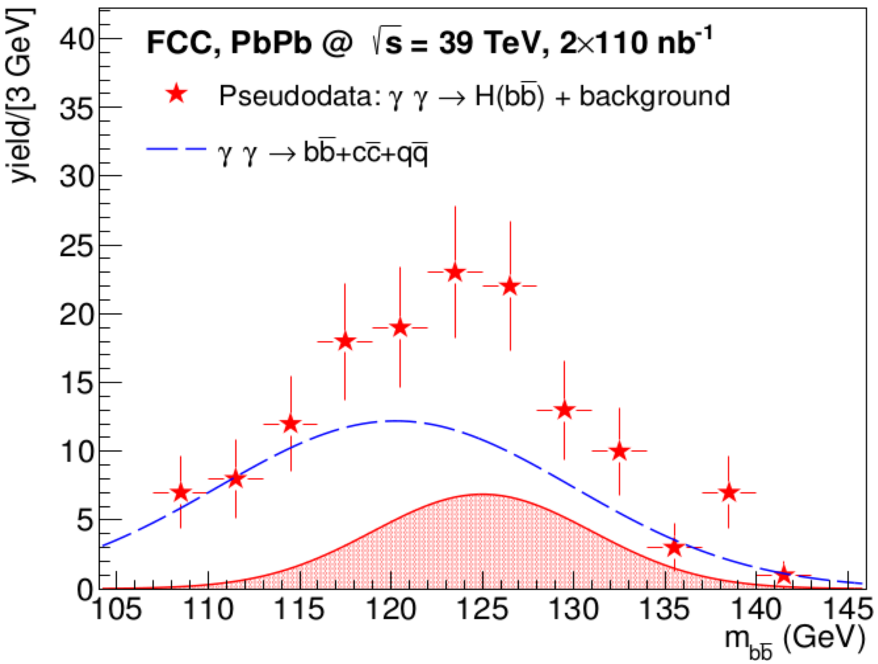
- A factor ×10 more integrated lumi easily reached by running for the duration of a pp (not 1-month heavy-ion) run. But, UPC Higgs observation will very likely remain elusive at the HL-LHC and HE-LHC.

<u>Note</u>: More advanced multivariate studies (and parametric-shape-based significances), rather than simple "cut-based" criteria used here, would enhance $S/\sqrt{B}$ but not by ×10 factor.

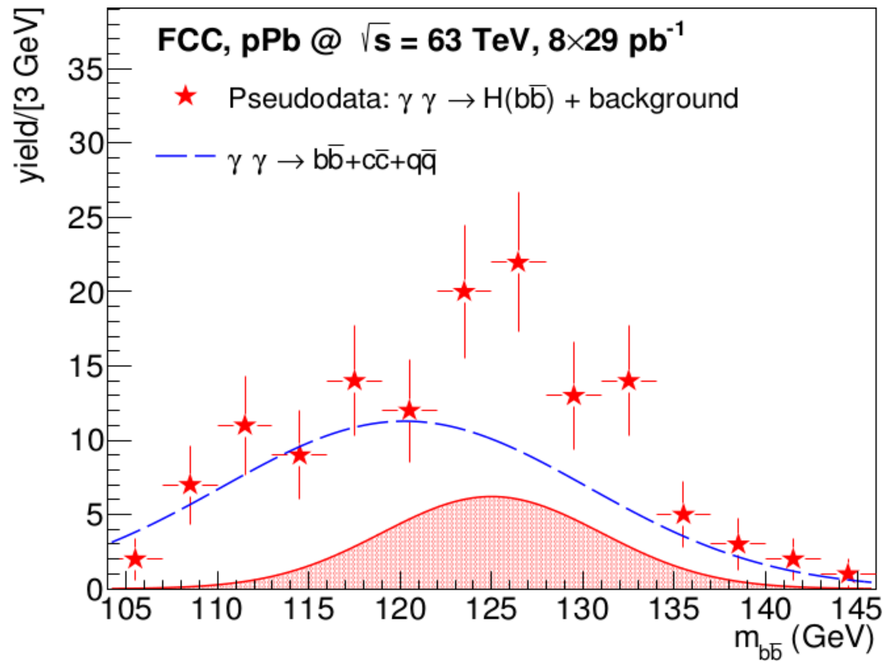
Expected dijet mass spectrum (FCC)

- 5σ Higgs observation on top of continuum backgrounds after cuts:

Pb-Pb at 6.3 TeV (×2 L_{int}):



p-Pb at 6.3 TeV (×8 L_{int}):



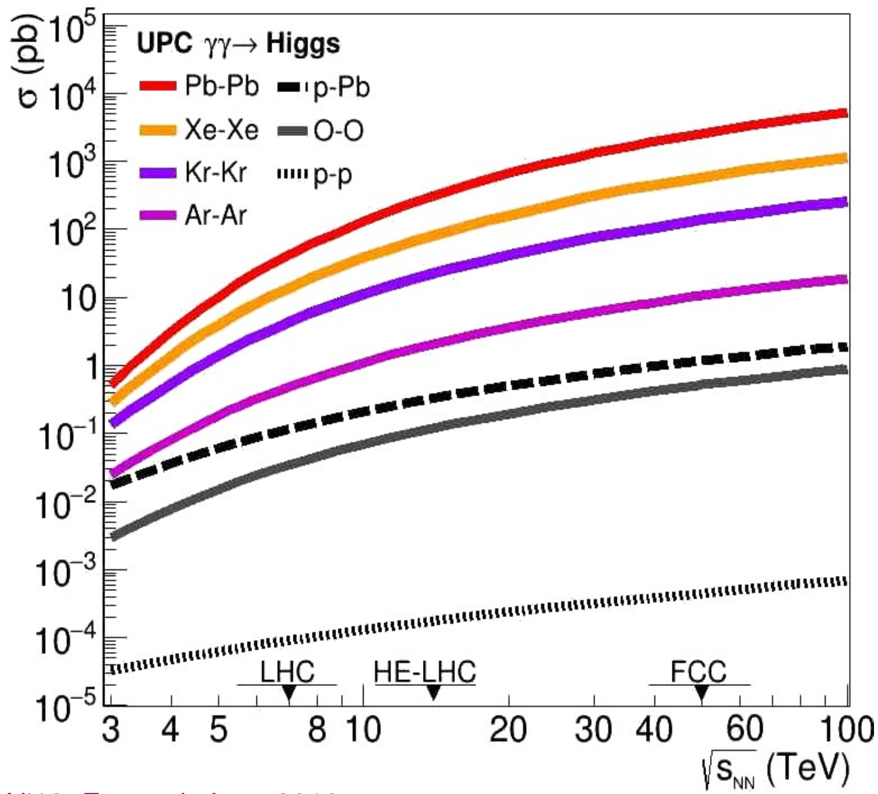
- ~20 (5) signal counts above backgds after cuts in Pb-Pb (p-Pb) collisions

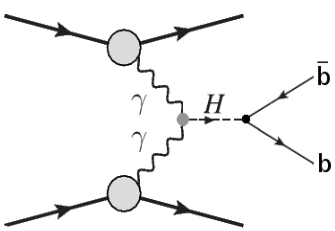
- Observation at 5σ-level achievable in the first FCC run by combining 2 experiments in Pb-Pb (1 month), and by running for about 8 months (or 4 months and combining 2 experiments) in p-Pb.

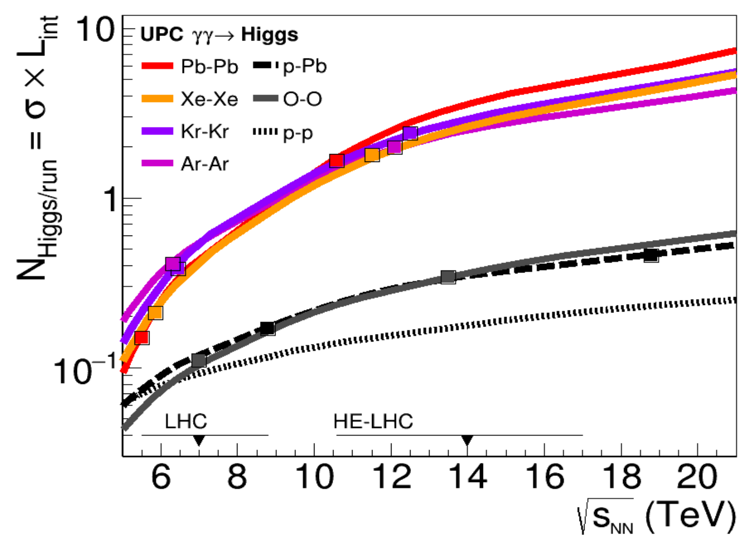
Conclusions (I)

- Is s-channel Higgs boson production observable in UPCs ?
  p-p, p-A, A-A → γγ → H(bb), $\sqrt{s_{NN}}$ = 3–100 TeV (LHC, HE-LHC, FCC)
- Cross sections computed with MadGraph 5.0 (EPA ions + HEFT):

  LHC: Highest x-sections for Pb-Pb (15 pb). Largest rates for Ar-Ar (~0.4 Higgs/mo.)
  HE-LHC: Highest x-sections for Pb-Pb (150 pb). Largest rates for Kr-Kr (~2 Higgs/mo.)
  FCC: Very large x-sections. p-Pb, Pb-Pb rates: 45–200 Higgs/mo.



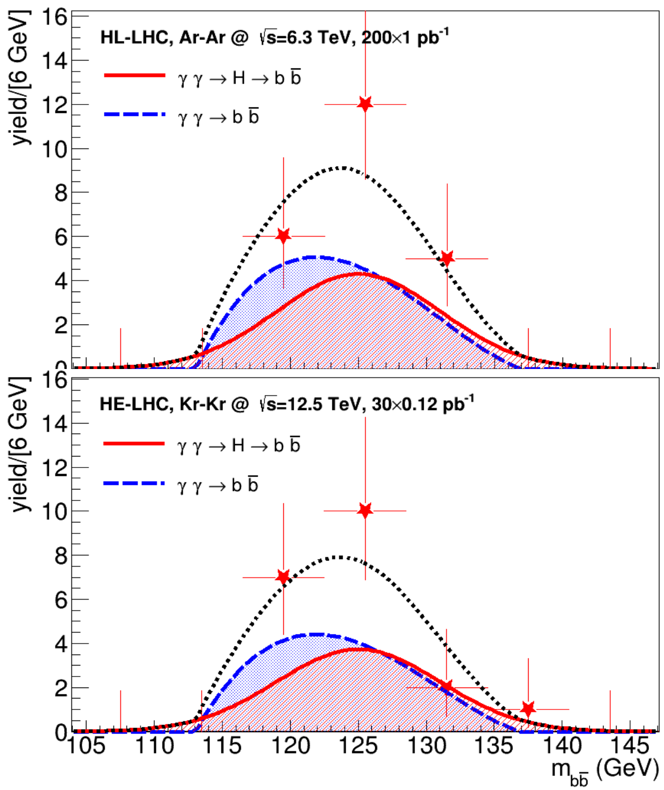


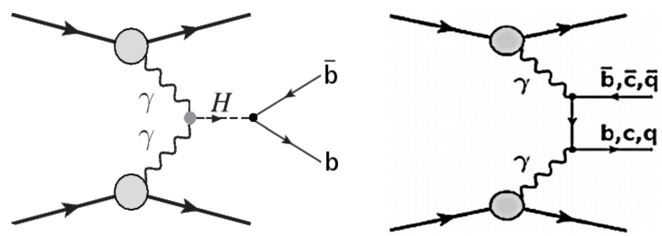


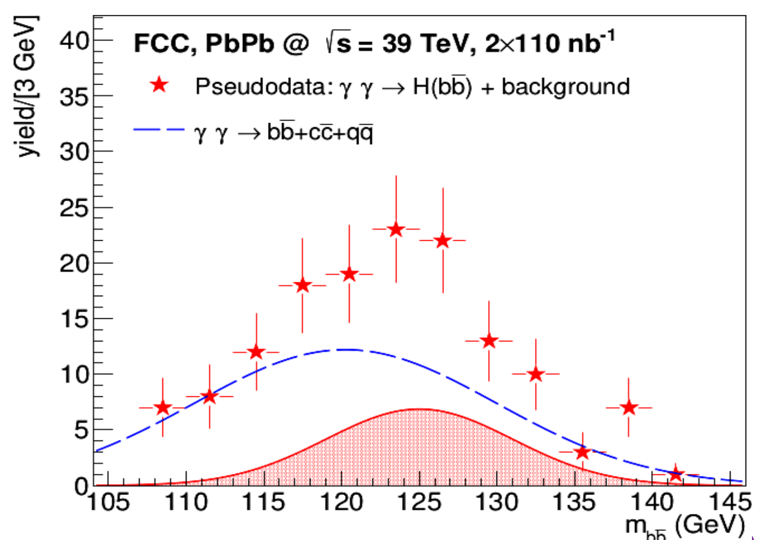
Conclusions (II)

- Is s-channel Higgs boson production observable in UPCs ?
  p-p, p-A, A-A → γ γ → H(bb), $\sqrt{s_{NN}}$ = 3–100 TeV (LHC, HE-LHC, FCC)
- Expected yields for signal & γ γ → bb,cc,qq backgds after analysis cuts:

  LHC: 3σ evidence requires ×200 more integrated luminosities in Ar-Ar
  HE-LHC: 3σ evidence requires ×30 more integrated luminosities in Kr-Kr
  FCC: 20 (5) signal counts after cuts in Pb-Pb (p-Pb) colls. 5σ warranted in 1st year.







Back-up slides