Higgs boson in nuclear collisions at the FCC

1st FCC Physics Workshop

CERN, 16th–20th Jan. 2017

David d'Enterria

CERN

Based on: D.d'E., to be submitted. D.d'E. & C.Loizides, in preparation.

Higgs boson (measurement & quenching?) in nuclear collisions at the LHC/FCC

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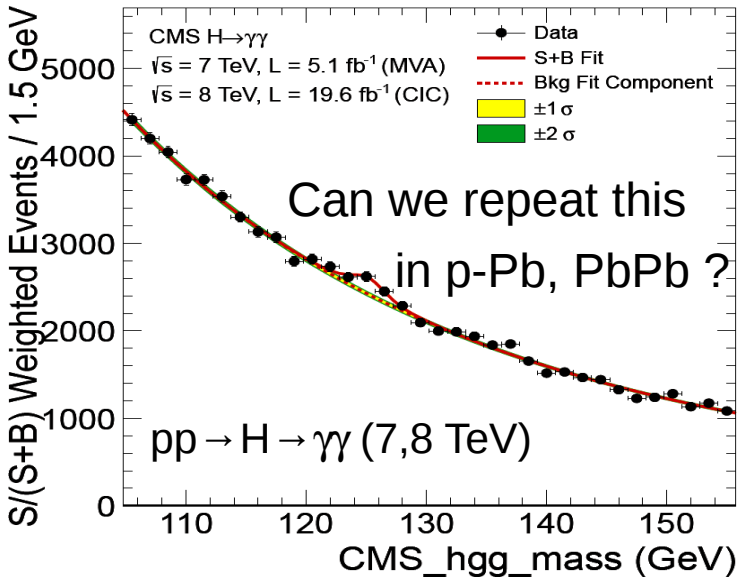
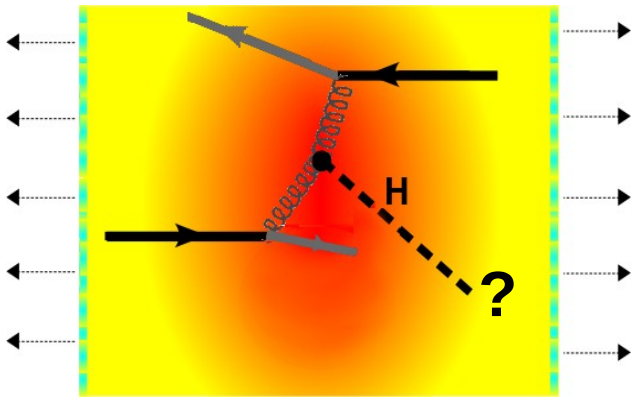
Motivation

(Only 3 SM elem.particles remain unobserved in HI colls: τ, top, **H**)

- ➞ Can we measure the Higgs boson in pPb, PbPb colls. at LHC and/or FCC?
- ➞ What are its production cross sections & visible counts after analysis cuts?
- ➞ What is lumi needed for observation at the FCC? (Any chance at LHC?)
- ➞ What is the fate of the Higgs boson in a QGP?

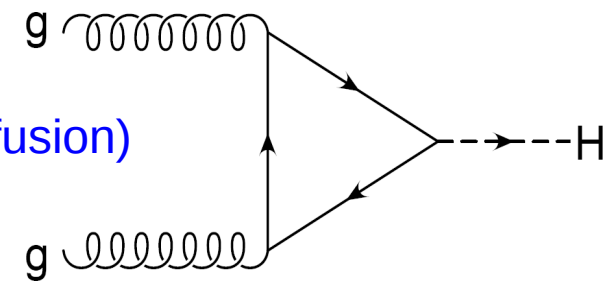




Higgs production in A-A collisions

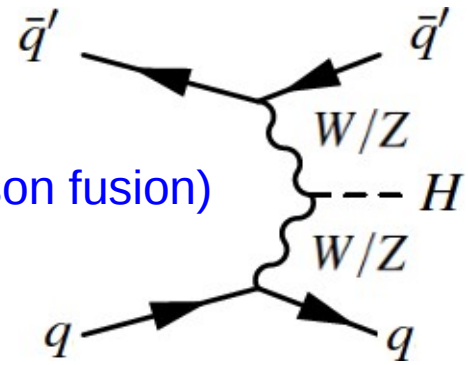
- Production mechanisms are the same as in p-p. Cross sections:
  $\sigma_{pPb\to H} = A\times\sigma_{pp\to H} = 208\times\sigma_{pp\to H}$, $\sigma_{PbPb\to H} = A^2\times\sigma_{pp\to H} = 4\cdot10^4\times\sigma_{pp\to H}$
  modulo small (<5%) mods. of the nuclear g,q, PDFs:

(gluon fusion)



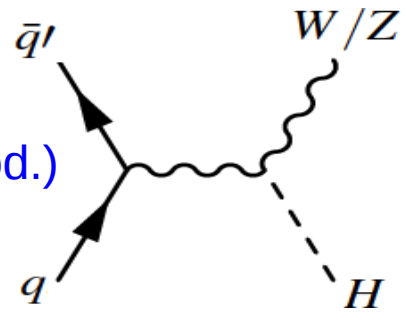
~90% of σ_H

(Vector Boson fusion)



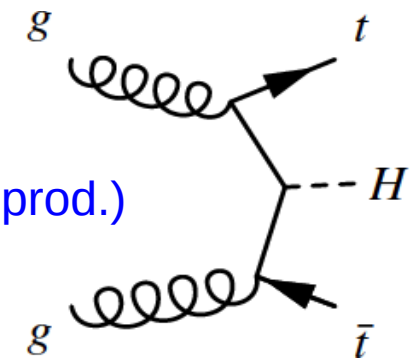
~10% of σ_H

(assoc. W,Z prod.)



~5–3% of σ_H

(assoc. ttbar prod.)



~1–4% of σ_H

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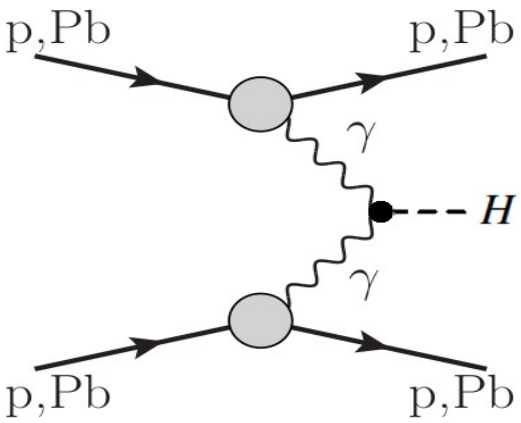
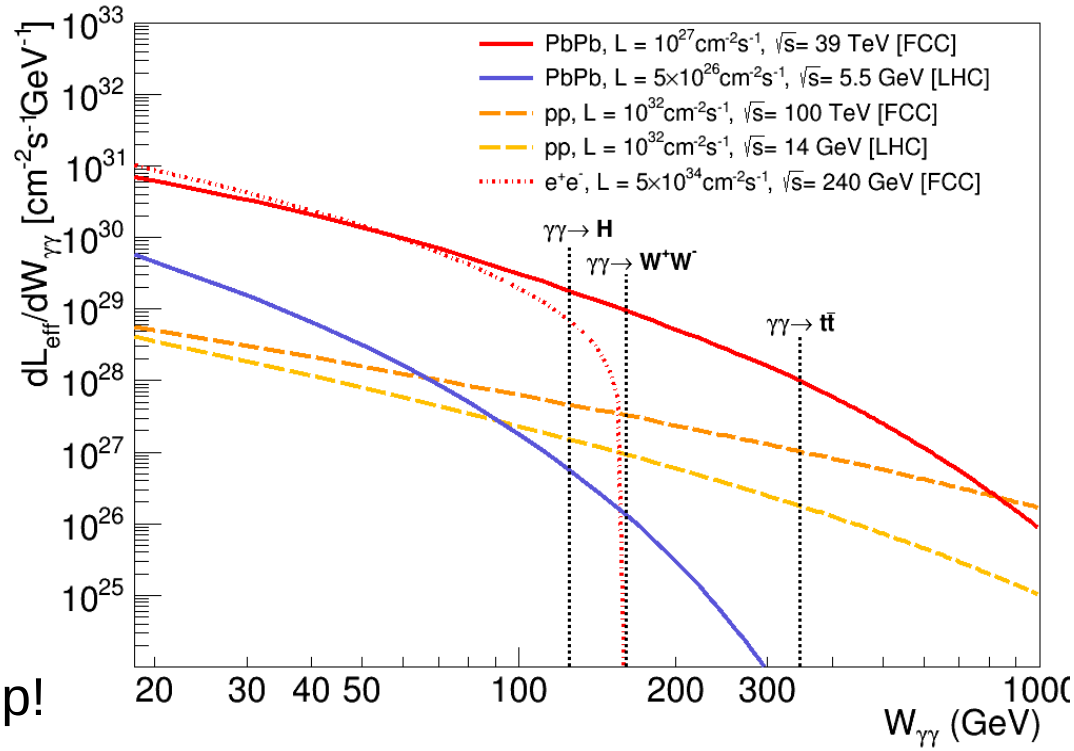
  modulo small (<5%) mods. of the nuclear g,q, PDFs.

- Plus extremely-enhanced $\gamma\gamma$-fusion channel (*not discussed today, see e.g. DdE & Lansberg, PRD81(2010)014004 for LHC*):
  $\sigma_{PbPb\to\gamma\gamma\to H} = Z^4\times\sigma_{pp\to H} = 5\cdot10^7\times\sigma_{pp\to\gamma\gamma\to H}$





$\mathcal{O}(10^3)$ $\gamma\gamma\to$H counts expected in PbPb(39 TeV,30 nb^{-1})

~$\mathcal{O}$(1.5 ab^{-1}) pp$\to\gamma\gamma$ w/o pileup!

NNLO theoretical setup

- MCFM v.8 NNLO event calculator with nuclear PDFs:
  - → Parton densities:
    Proton PDF: CT10 NNLO
    Pb nPDF: EPS09 NLO (central + 30 error sets)
    Isospin (u,d quark) effects included.
  - → Scales choices: $\mu_F = \mu_R = m_{top}$, $\mu_F = \mu_R = m_H/2$
    (scale variations not considered: Cancel in R_{AA}).

- Higgs production (ggF: total & differential discovery $\gamma\gamma$, $4l$ decays):

119	$H(\to \gamma(p_3) + \gamma(p_4))$	NNLO
116	$H(\to Z(\to e^-(p_3) + e^+(p_4)) + Z(\to \mu^-(p_5) + \mu^+(p_6))$	NLO

Plus total σ_H for nproc=215 (VBF), 91 (assoc. WH), 101 (assoc. ZH)

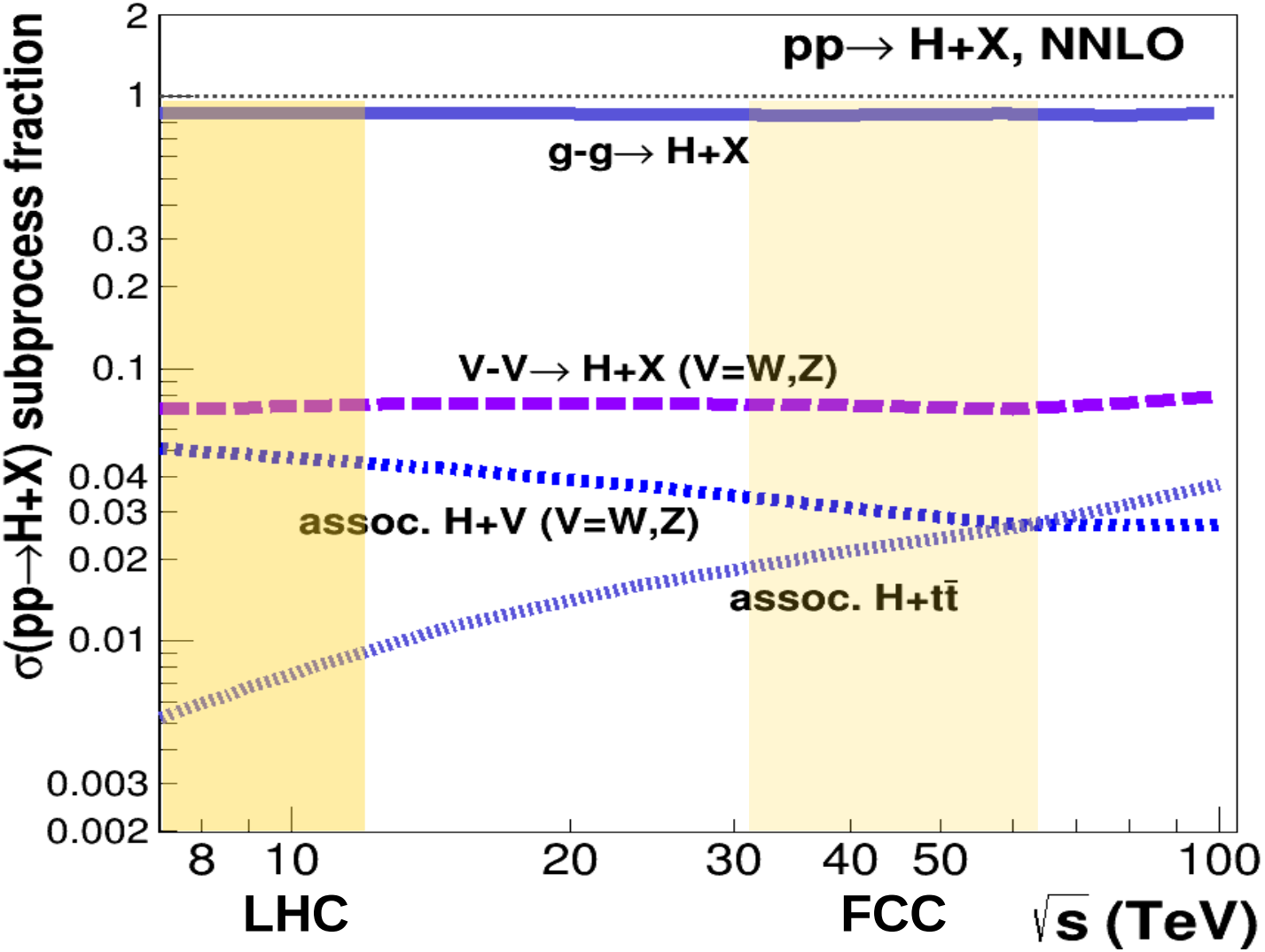
- Higgs $\gamma\gamma$, $4l$ backgrounds:

285	$f(p_1) + f(p_2) \to \gamma(p_3) + \gamma(p_4)$	NLO+F, NNLO
90	$Z(\to e^-(p_3) + e^+(p_4)) + Z(\to e^-(p_5) + e^+(p_6))$	NLO

- All x-sections scaled to state-of-the-art NNLO+NNLL
  (as per LHC-HXSWG, K-factors ~20%)

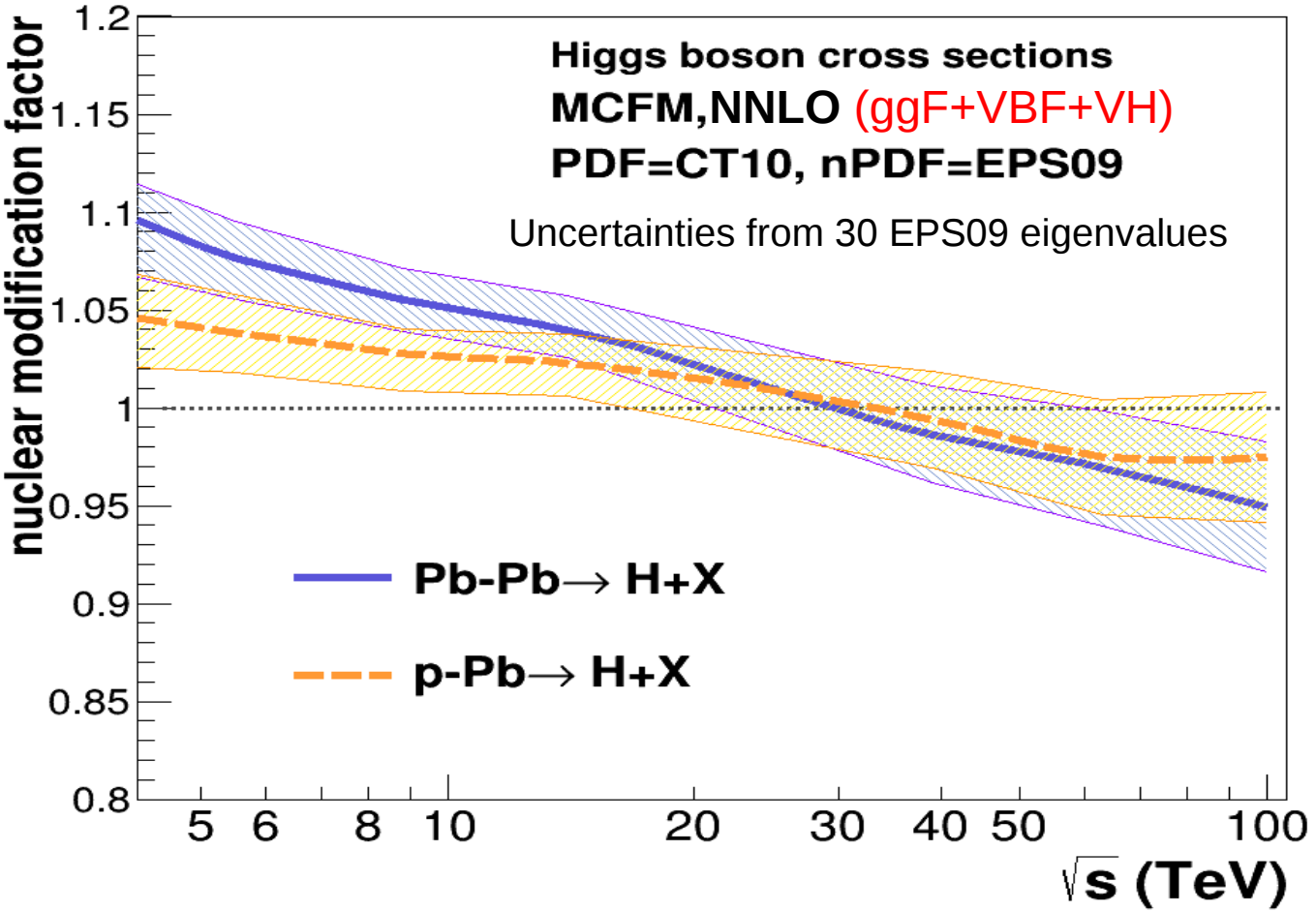
Higgs subprocess contributions: LHC → FCC

- MCFM σ(ggF+VBF+VH) scaled to NNLO+NNLL pp x-sections
- Production clearly dominated by gg fusion (90%-85%) over 5–63 TeV:



Higgs nuclear modification factor (p-Pb,Pb-Pb)

- EPS09 nuclear g,q PDFs modify slightly x-sections wrt. pp PDFs:

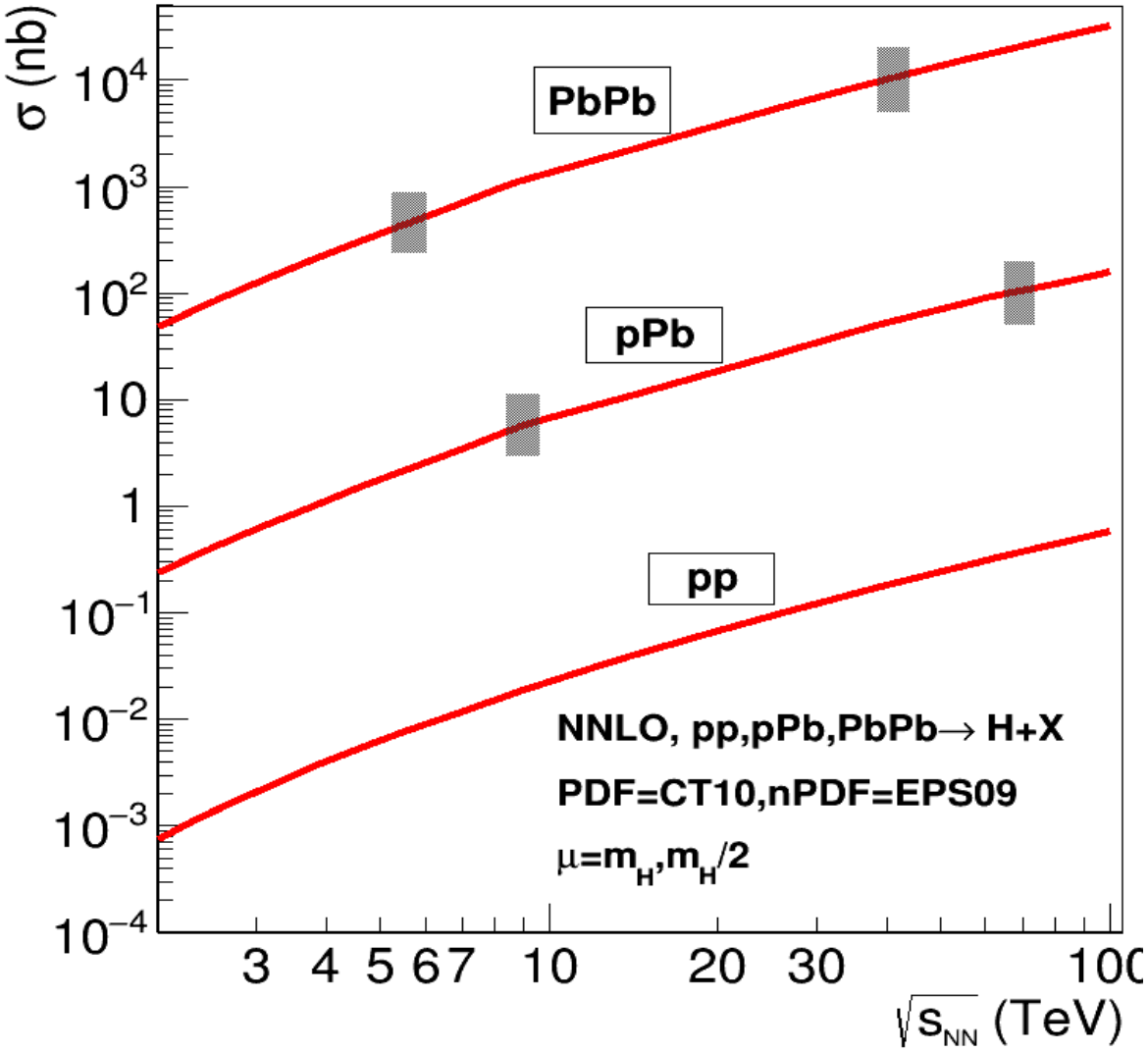


➜ LHC: Small antishadowing: R_{AA}~ 1.07, R_{pA}~1.03

➜ FCC: Mild shadowing: R_{AA}~ R_{pA}~ 0.97

Higgs total x-sections in p-p, p-Pb, Pb-Pb

- MCFM σ(ggF+VBF+VH) scaled to NNLO+NNLL pp x-sections



- Pb-Pb:

LHC(5.5 TeV) = 550 nb
FCC(39 TeV) = 10 μb

- p-Pb:

LHC(8.8 TeV) = 5.5 nb
FCC(63 TeV) = 100 nb

- p-p (reference):

LHC(5.5 TeV) = 12 pb
LHC(8.8 TeV) = 27 pb
FCC(39 TeV) = 270 pb
FCC(63 TeV) = 490 pb

➜ Cross-sections increase by about ×20 from LHC to FCC

H→γγ, 4l (discovery channels) measurement

- Rates pPb,PbPb→H+X at LHC/FCC in discovery H→ γγ, 4l channels:

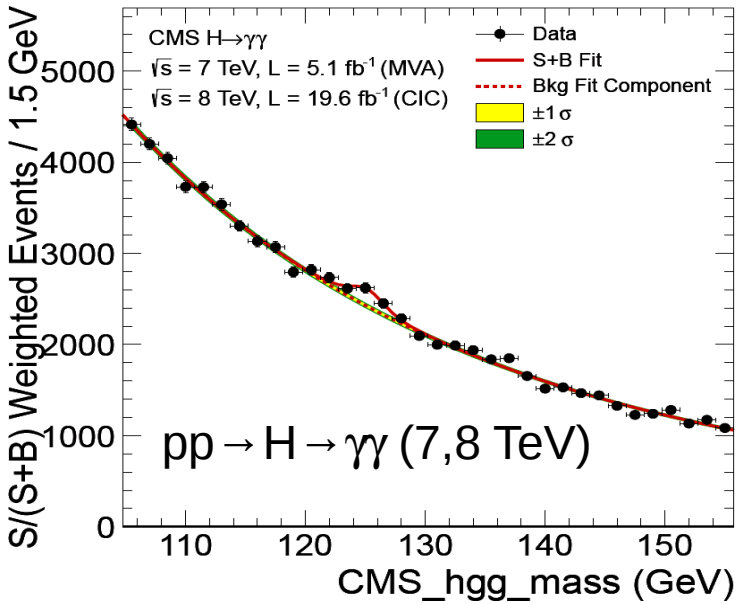
LHC: N(PbPb,5.5 TeV,10 nb^{-1}) = 550 nb×BR×L_{int} ≈ 15 (γγ), 6 (4l)

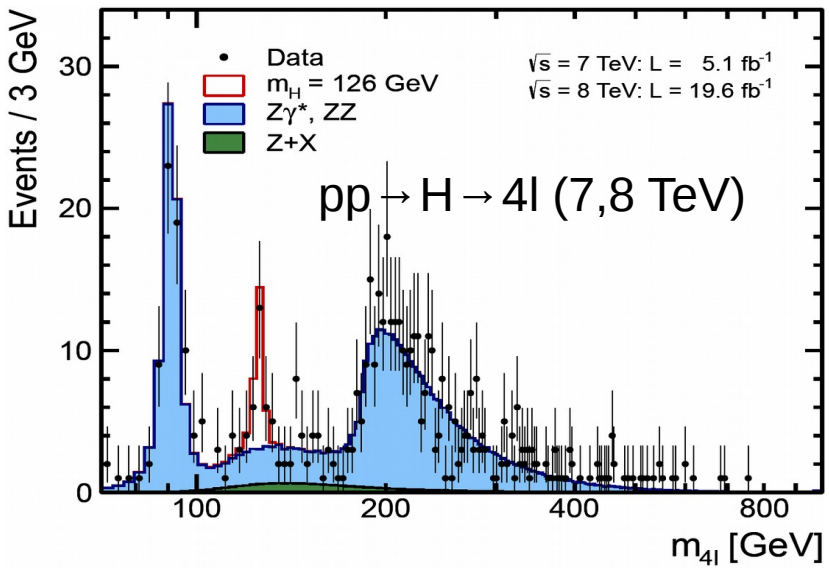
N(pPb,8.8 TeV,1 pb^{-1}) = 5.5 nb×BR×L_{int} ≈ 15 (γγ), 6 (4l)

FCC: N(PbPb,39 TeV,33 nb^{-1}) = 10 μb×BR×L_{int} ≈ 900 (γγ), 400 (4l)

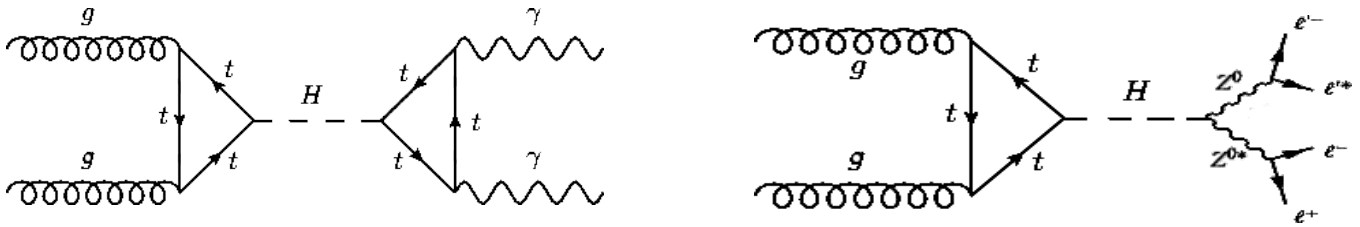
N(pPb,63 TeV, 8 pb^{-1}) = 100 nb×BR×L_{int} ≈ 2000 (γγ), 900 (4l)

- Possible to repeat the pp Higgs observation in pPb,PbPb at LHC/FCC?





$H \to \gamma\gamma$, $4l$ (discovery channels) measurement



- Experimental setup: LHC (FCC): $|\eta_l|,|\eta_\gamma| < 2.5$ (5.0)
- Analysis cuts (typical fiducial cuts in CMS/ATLAS, l=e,μ):

  $\gamma\gamma$: $p_T(\gamma_1, \gamma_2) > 40, 30$ GeV; $R_{isol}(\gamma) = 0.3$
  $|\eta(\gamma)| < 2.5$ (LHC), 5.0 (FCC); $m_{\gamma\gamma} = 100$–140 GeV

  $4l$: $p_T(l_1, l_2, l_3, l_4) > 20,15,10,10$ GeV; $R_{isol}(l) = 0.3$
  $|\eta(l)| < 2.5$ (LHC), 5.0 (FCC); $m_{4l} = 100$–140 GeV

- Branching ratio, acceptance & efficiency losses:

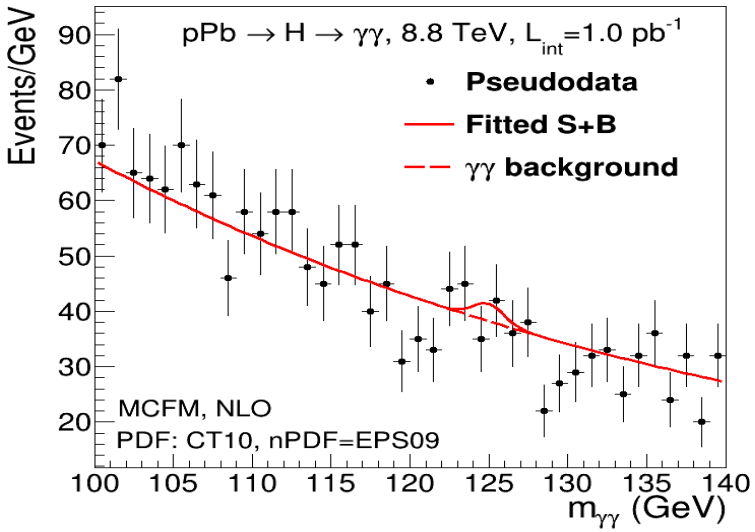
  $\gamma\gamma$: BR = 0.27%, Acc×Eff ~ 45% (LHC), 60% (FCC)
  $ZZ^* \to 4l$: BR = 0.12%, Acc×Eff ~ 60% (LHC), 70% (FCC)

- Backgrounds: As for p-p (under control in pPb,PbPb: high-p_T iso γ,l)

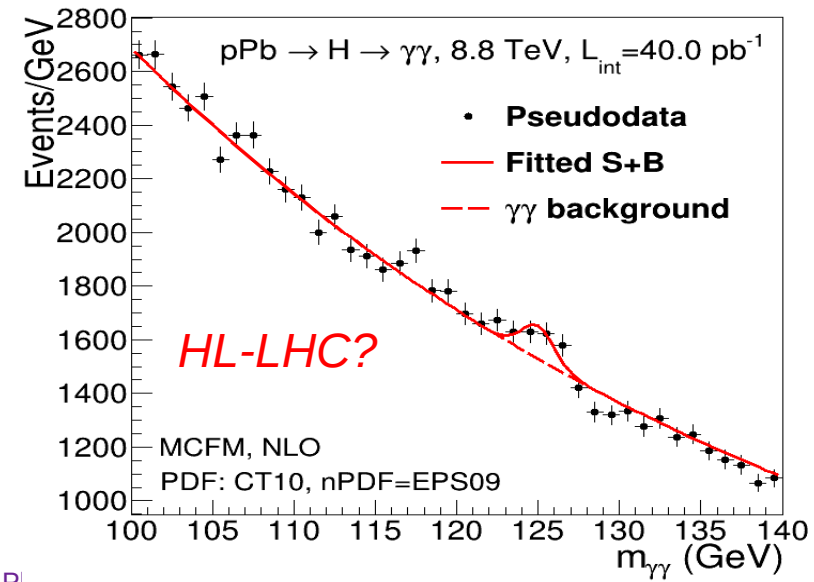
  $\gamma\gamma$: QCD continuum (MCFM $nproc$=285) +30% γ-γ^*_{jet}, γ^*_{jet}-γ^*_{jet}
  $ZZ^* \to 4l$: ZZ* non-resonant (MCFM $nproc$=90)

H → γ γ observation in p-Pb (LHC, FCC)

- p-Pb @ 8.8 TeV (L_{int}= 1 pb^{-1})



- p-Pb @ 8.8 TeV (L_{int}= *40 pb^{-1}*)



➜ LHC (8.8 TeV, 1 pb^{-1}):

Nominal lumi: S/√B~0.4 (0.6, adding 4l)

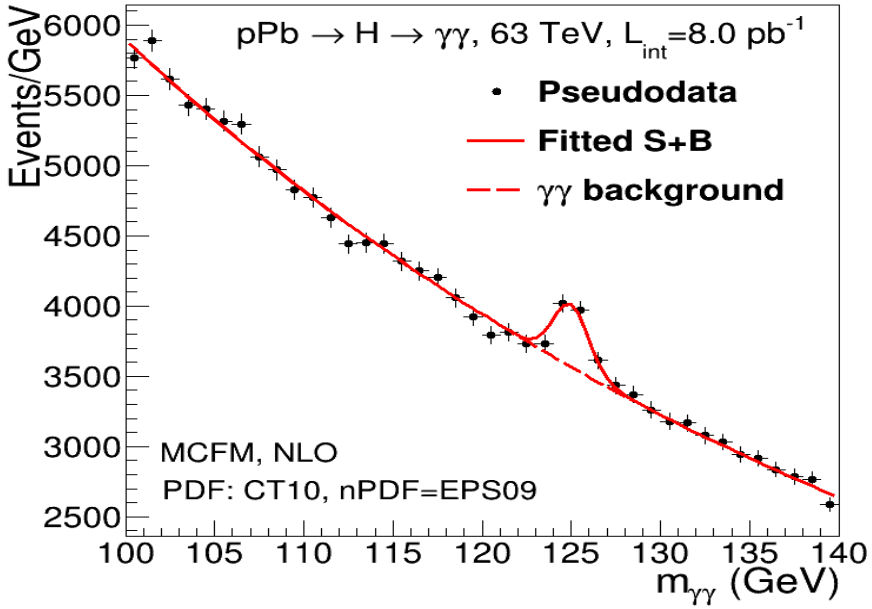
L_{int}= 40 pb^{-1}: 3σ evidence (HL-LHC?)

4.2σ combined with H(4l)

➜ FCC (63 TeV, 8 pb^{-1}):

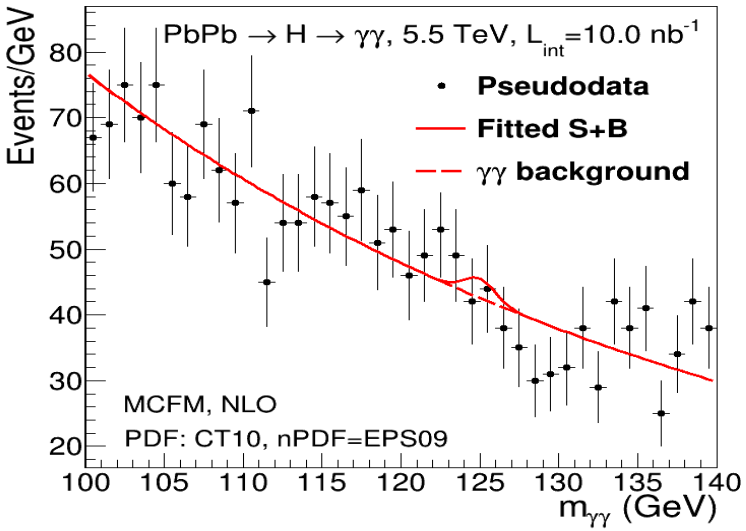
Nominal lumi: S/√B~7.7σ observation

- p-Pb @ 63 TeV (L_{int}= 8 pb^{-1})

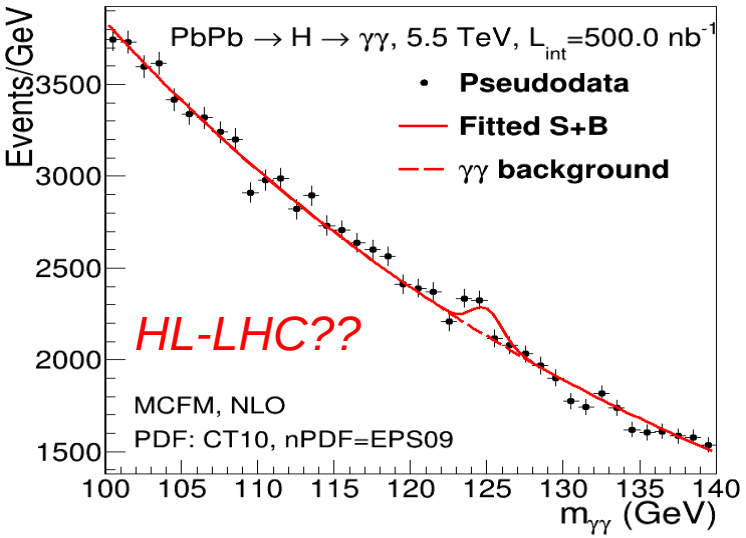


H → γ γ observation in Pb-Pb (LHC, FCC)

- Pb-Pb @ 5.5 TeV (L_{int}= 10 nb^{-1})



- Pb-Pb @ 5.5 TeV (L_{int}=500 nb^{-1})



→ LHC (5.5 TeV, 10 nb^{-1}):

Nomin. lumi: S/√B~0.36 (0.5, adding 4l)

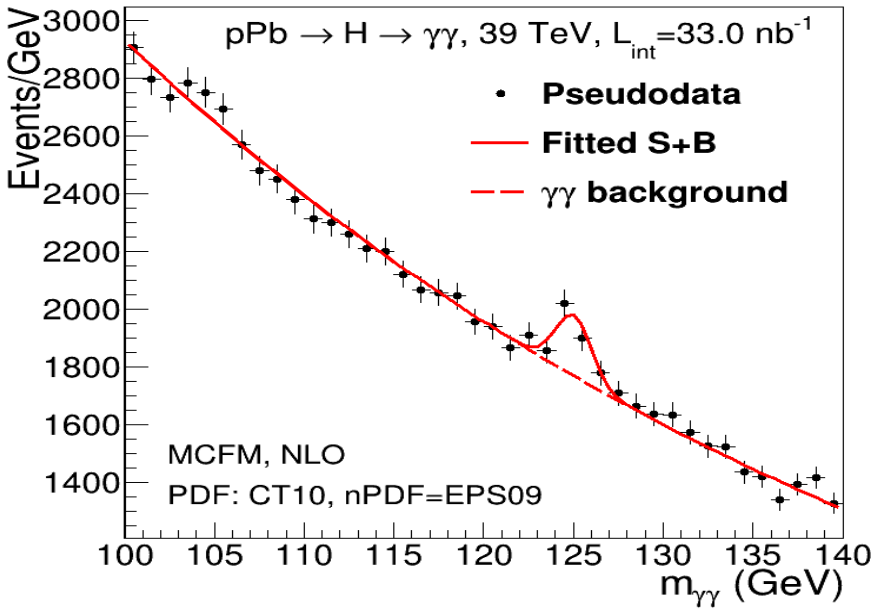
L_{int}= 500 nb^{-1}: 3σ evidence (HL-LHC??)

4.2σ combined with H(4l)

→ FCC (39 TeV, 33 nb^{-1}):

Nominal lumi: S/√B~5.2σ observation

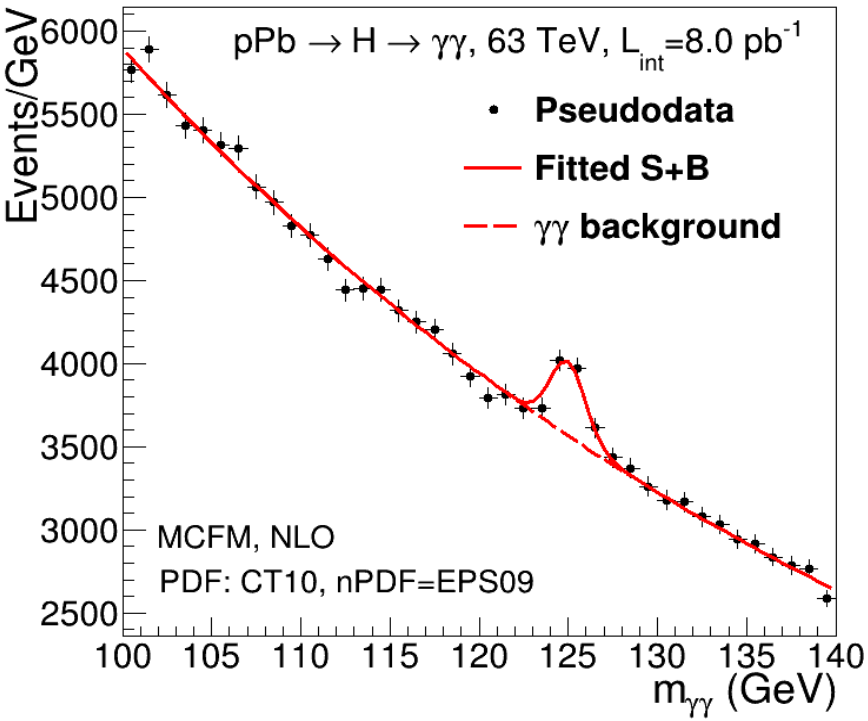
- Pb-Pb @ 39 TeV (L_{int}= 33 nb^{-1})



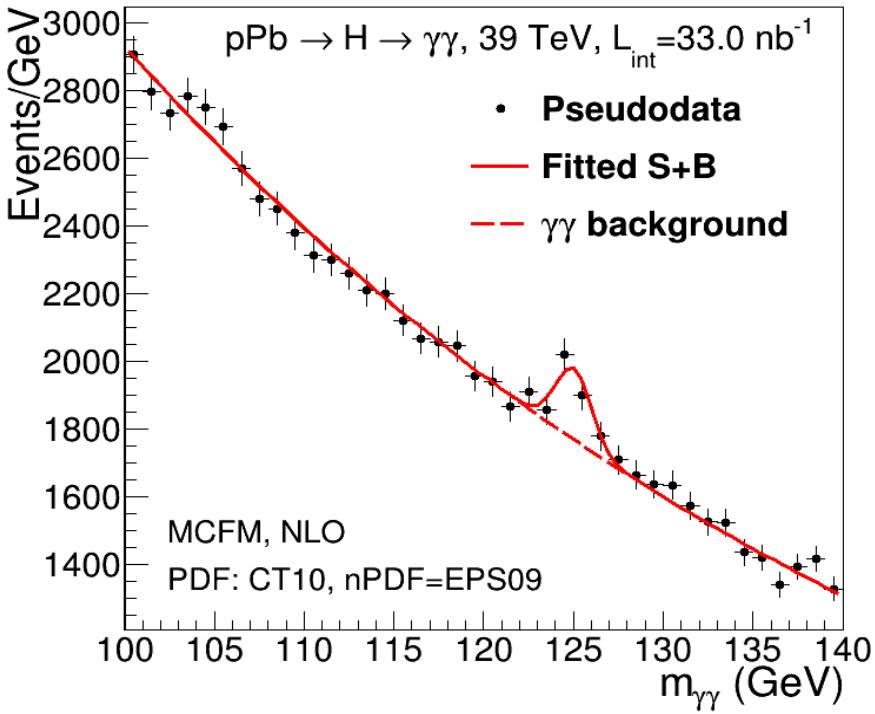
Summary: H → γ γ in pPb,Pb-Pb (LHC,FCC)

- LHC: With default lumis, Higgs boson is unobservable (0.5σ)
  ~3σ evidence requires ×(35–50) nominal lumis.
  (doable for p-Pb, running 10 months with ×5 p intensity?)
- FCC: With default lumis, Higgs boson is clearly observable (6–8σ)

p-Pb @ 63 TeV (L_{int}= 8 pb^{-1})

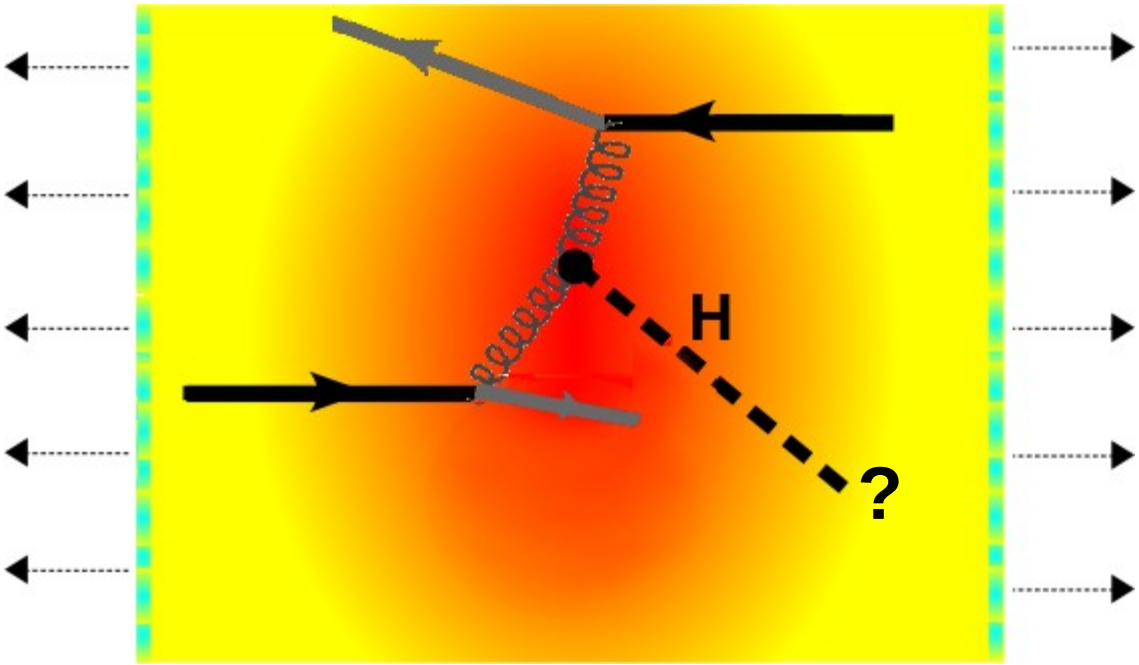


Pb-Pb @ 39 TeV (L_{int}= 33 nb^{-1})



H boson quenching in the QGP ?

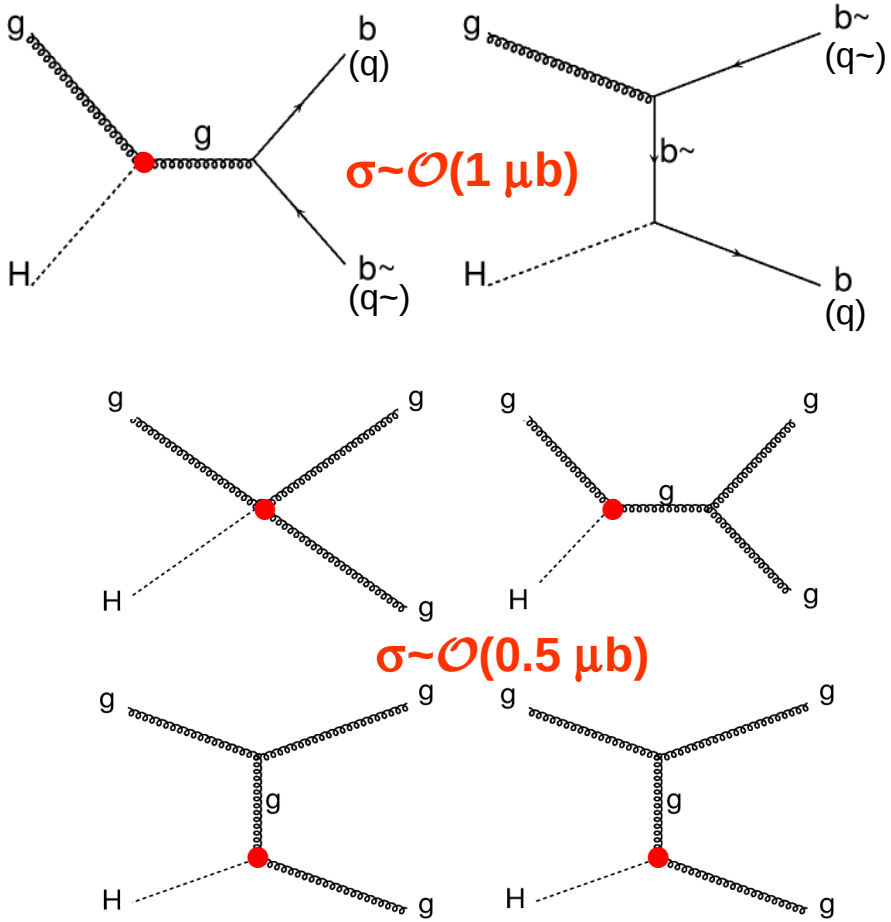
- OK. So we can observe the H boson in PbPb at FCC. So what...?
- SM boson (Γ_H=4 MeV) has a lifetime $\tau = 1/\Gamma_H \sim 50$ fm > $\tau_{QGP} \sim 20$ fm
  Once produced it will traverse the QGP and decay outside the medium



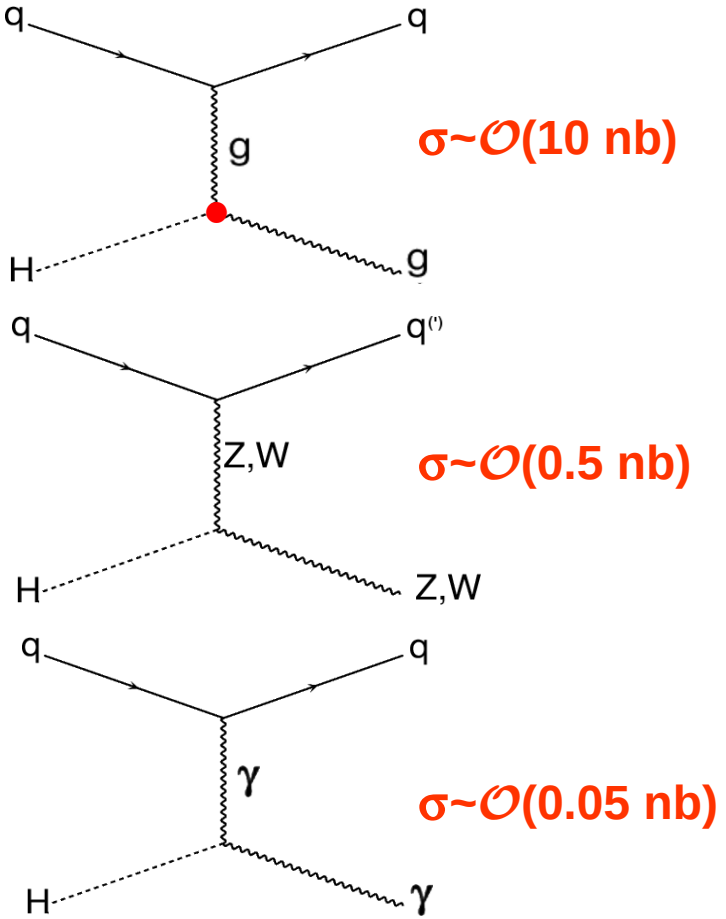
- The SM Higgs couples to QGP gluons (through dominant top loop) and quarks (as per their Yukawas). What's the effect of the QGP on the scalar boson ?

H boson quenching in the QGP ?

- Gluon-Higgs scatterings:



- Quark-Higgs scatterings:



(Other diagrams negligible)

- LO x-sections obtained with WHIZARD/CalcHEP/MG5 for $E_{g,H}$~1–10 GeV
- Full (including K-factors) Higgs "absorption" x-section: **σ~𝒪(10 μb)**

H boson quenching in the QGP ?

- Results of a Glauber model (including QGP longitudinal expansion) for a Higgs "absorption" x-section of σ = 10 μb:
  - → Average Higgs suppression factor in PbPb(39 TeV): ~25%
  - → Higgs survival probability as a function of PbPb centrality:

nuclear modification factor at b :

$$R(b) = \int \frac{n(b,x,y) S_{H}(b,x,y) \mathrm{dxdy}}{n(b)}$$

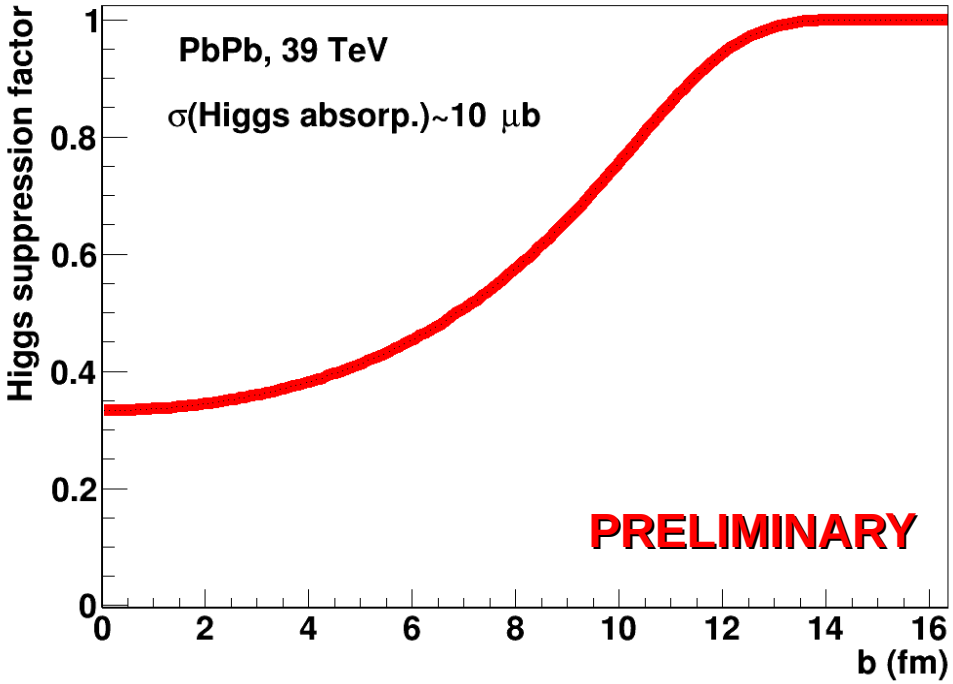
survival probability :

$$S_{H} = \exp\left(-\sigma_{H+q,g}\, \rho(b,x,y) \ln \frac{\rho(b,x,y)}{\rho_{\mathrm{norm}}}\right)$$

binary collisions $\propto$ QGP opacity :

$$n(b,x,y) = \sigma T_i(x+b/2,y) T_j(x-b/2,y)$$

[DdE,C.Loizides, in preparation]



[Central PbPb] [Periph. PbPb]

Conclusion

- Is the H boson observable in HI colls.? What do we learn from it?
- MCFM study: NNLO, CT10 PDF, EPS09 nPDF (30 error sets)
- LHC: With default lumis, Higgs boson is unobservable (~0.5σ)
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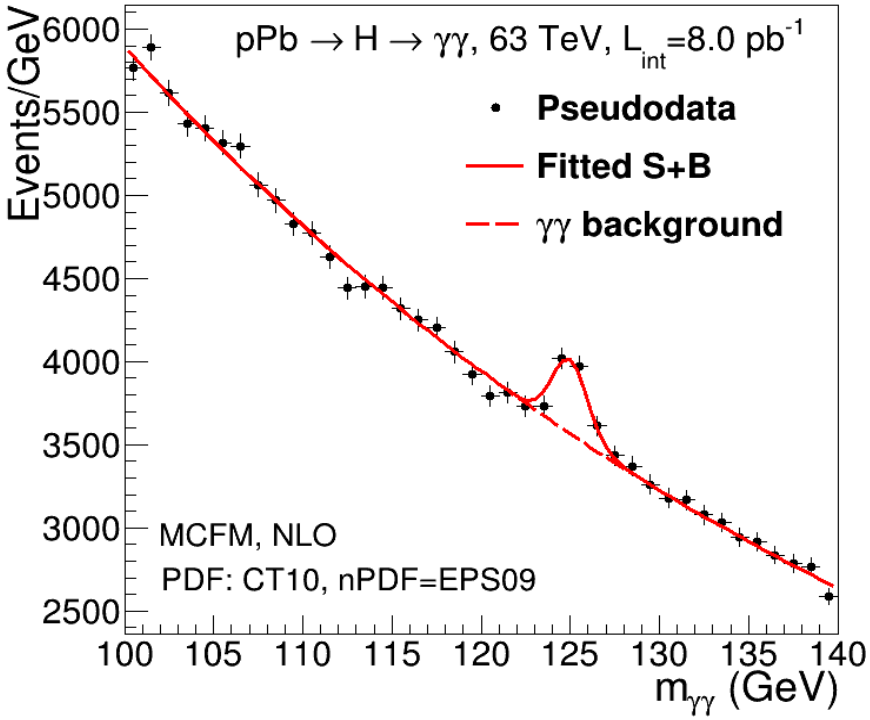
p-Pb @ 63 TeV (L_{int}= 8 pb^{-1})



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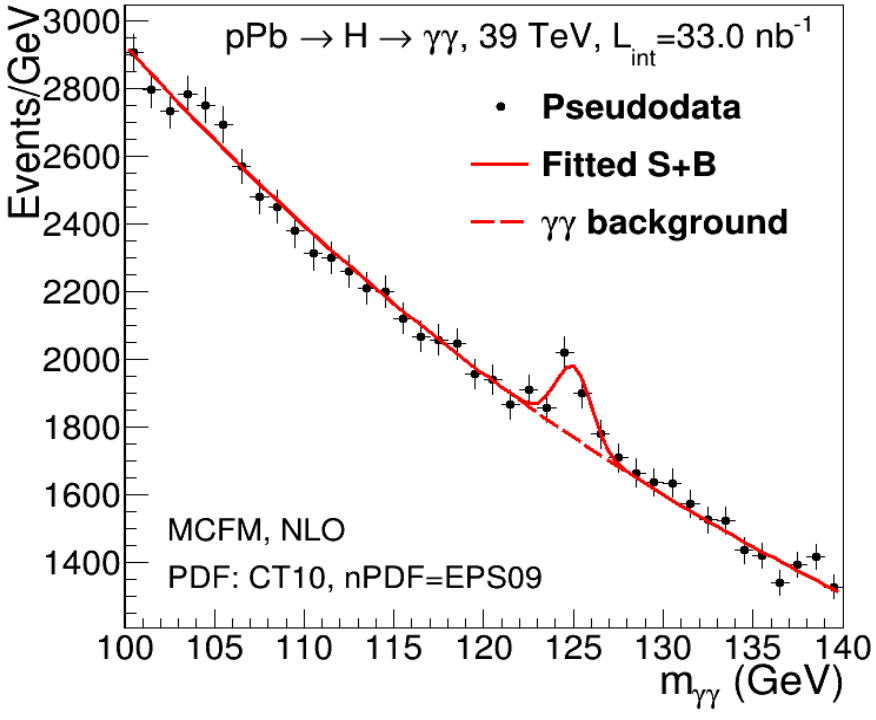

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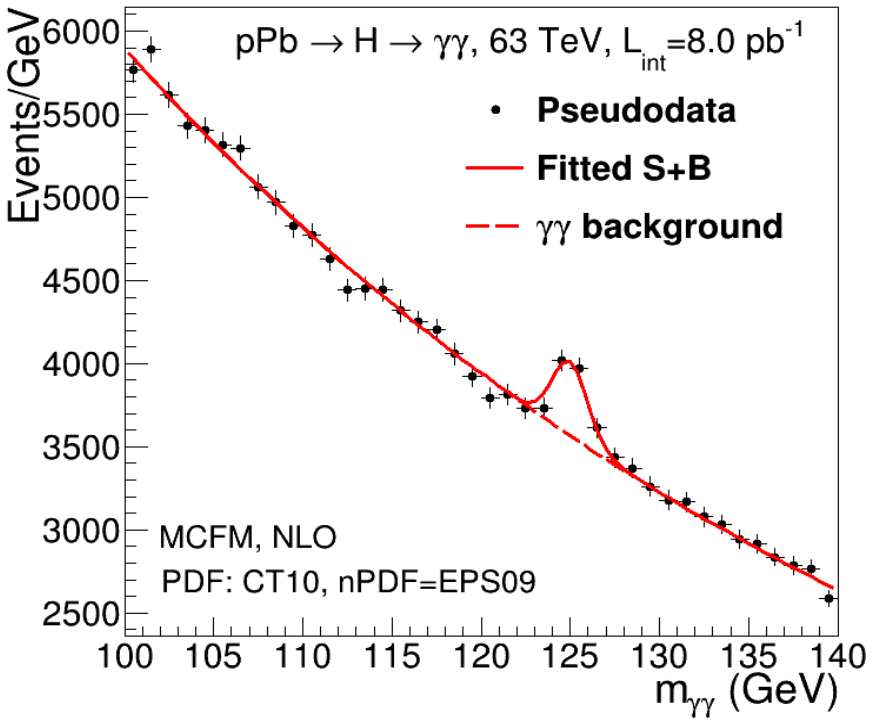
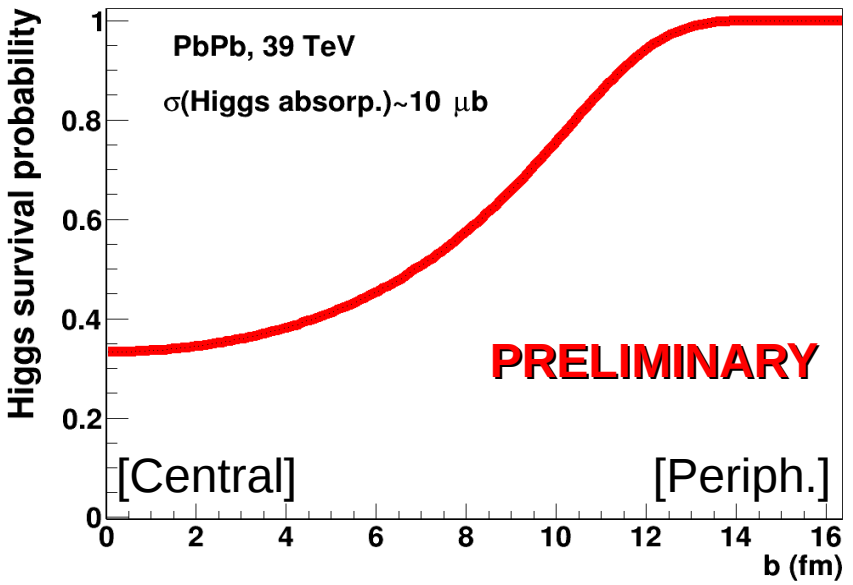


Pb-Pb @ 39 TeV (L_{int}= 33 nb^{-1})

H yields ~25% quenched in QGP?



Back-up slides