Final-state interactions of the Higgs boson in quark-gluon matter

15th LHC Higgs XS WG meeting

CERN, 10th–12th Dec. 2018

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CERN

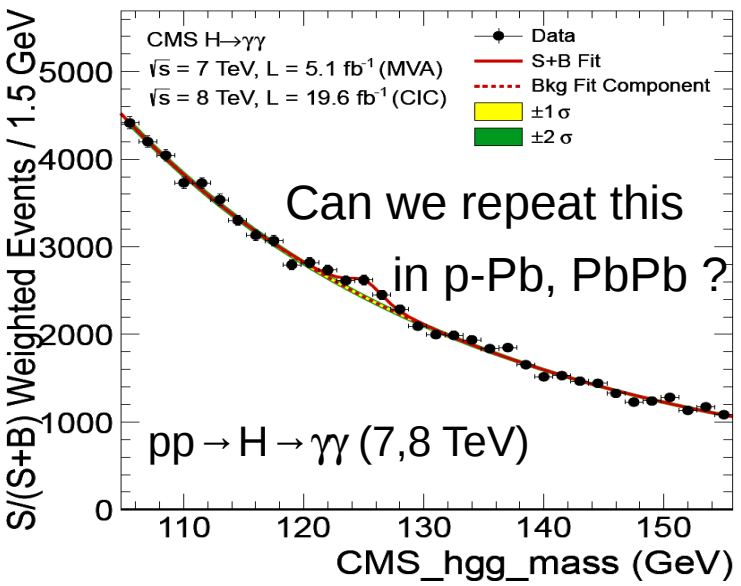
Based on:

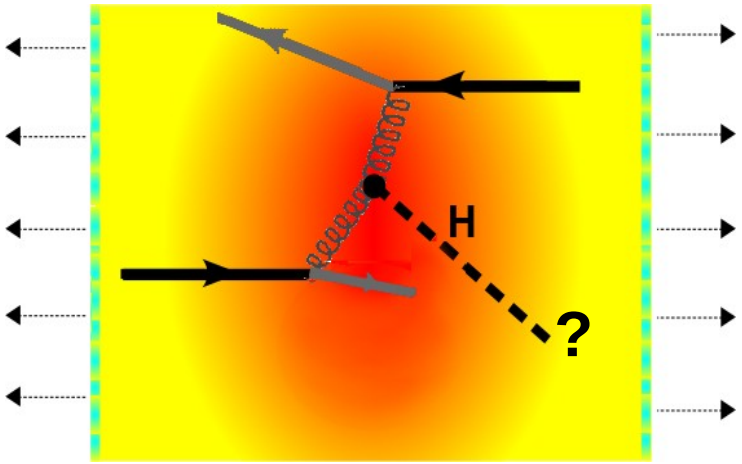
D.d'E Nucl. Part. Phys. Proc. 289-290 (2017) 237, arXiv:1701.08047

D.d'E. & C. Loizides, arXiv:1809.06832

Outline

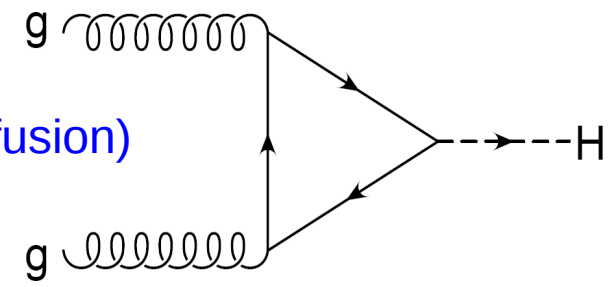
- → Can we measure the Higgs boson in pPb, PbPb colls. at LHC (or FCC) ?
- → What are its production cross sections & visible counts after analysis cuts?
- → What is lumi needed for observation at the FCC? (Any chance at LHC?)
- → What is the fate of the Higgs boson in a QGP?
- → Is the Higgs boson affected in central (high multiplicity) pp collisions?





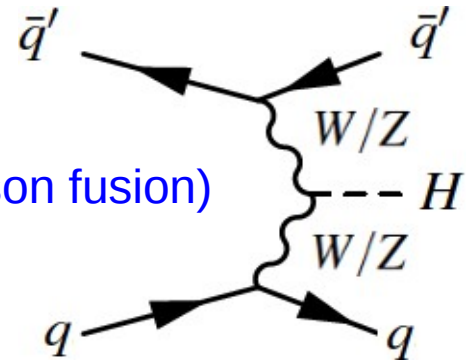
Higgs production in A-A collisions

- Production mechanisms are the same as in p-p.
  Cross sections scaled by A^2: $\sigma_{PbPb\to H} = A^2 \times \sigma_{pp\to H} = 4\cdot 10^4 \times \sigma_{pp\to H}$
  (Modulo small (<5%) mods. of the nuclear g,q, PDFs, see next):



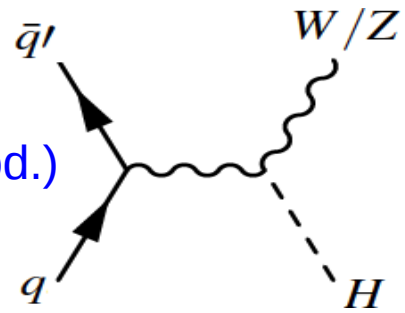
(gluon fusion)

~90% of σ_H



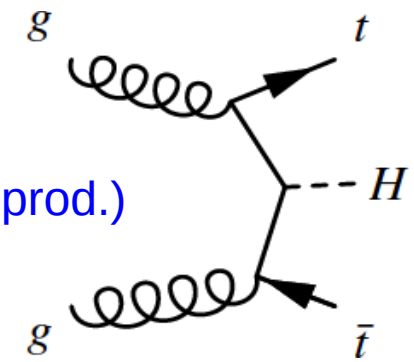
(Vector Boson fusion)

~10% of σ_H



(assoc. W,Z prod.)

~5–3% of σ_H

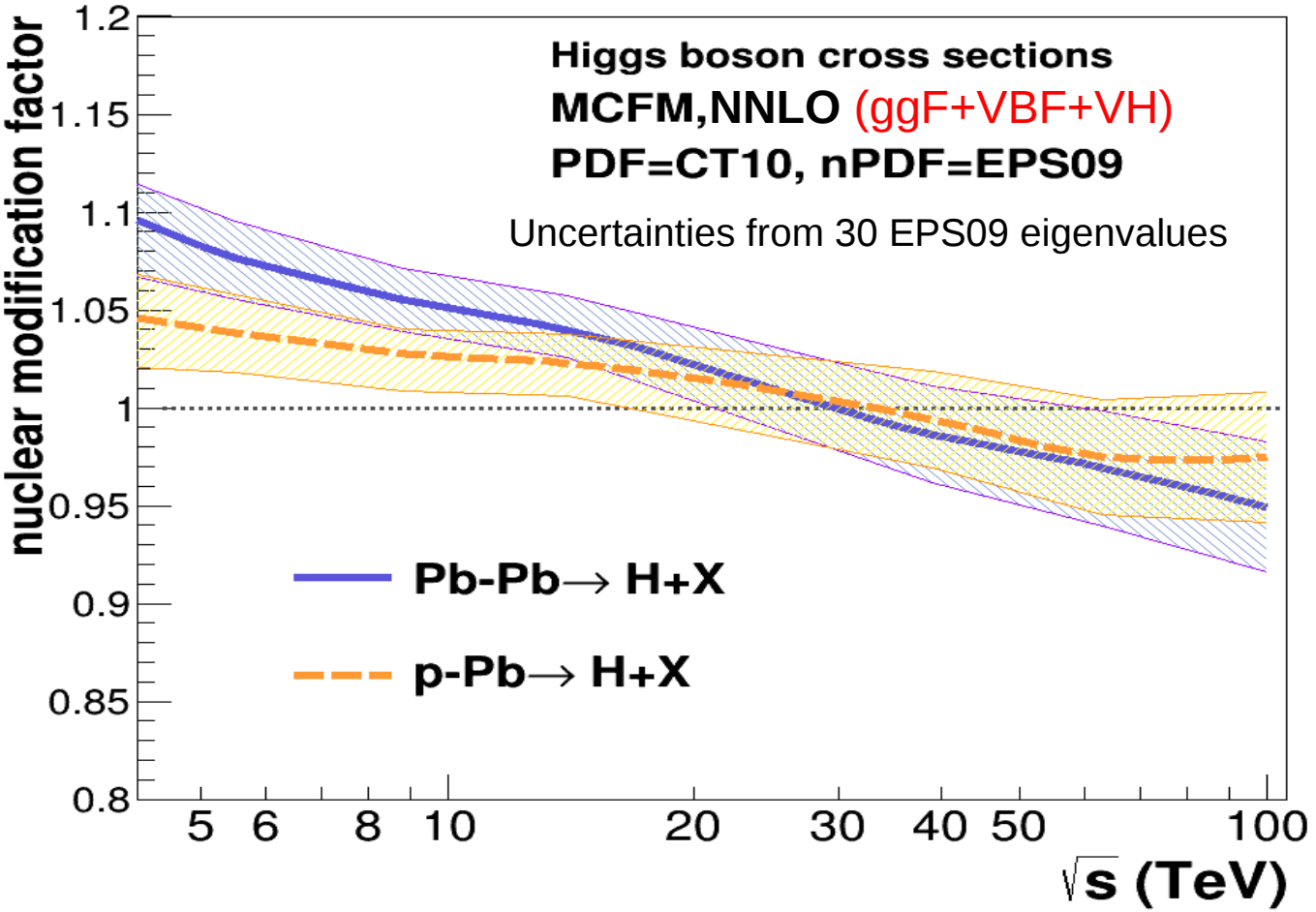


(assoc. ttbar prod.)

~1–4% of σ_H

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

- Nuclear g,q PDFs (EPS09) modify slightly x-sections wrt. pp PDFs:

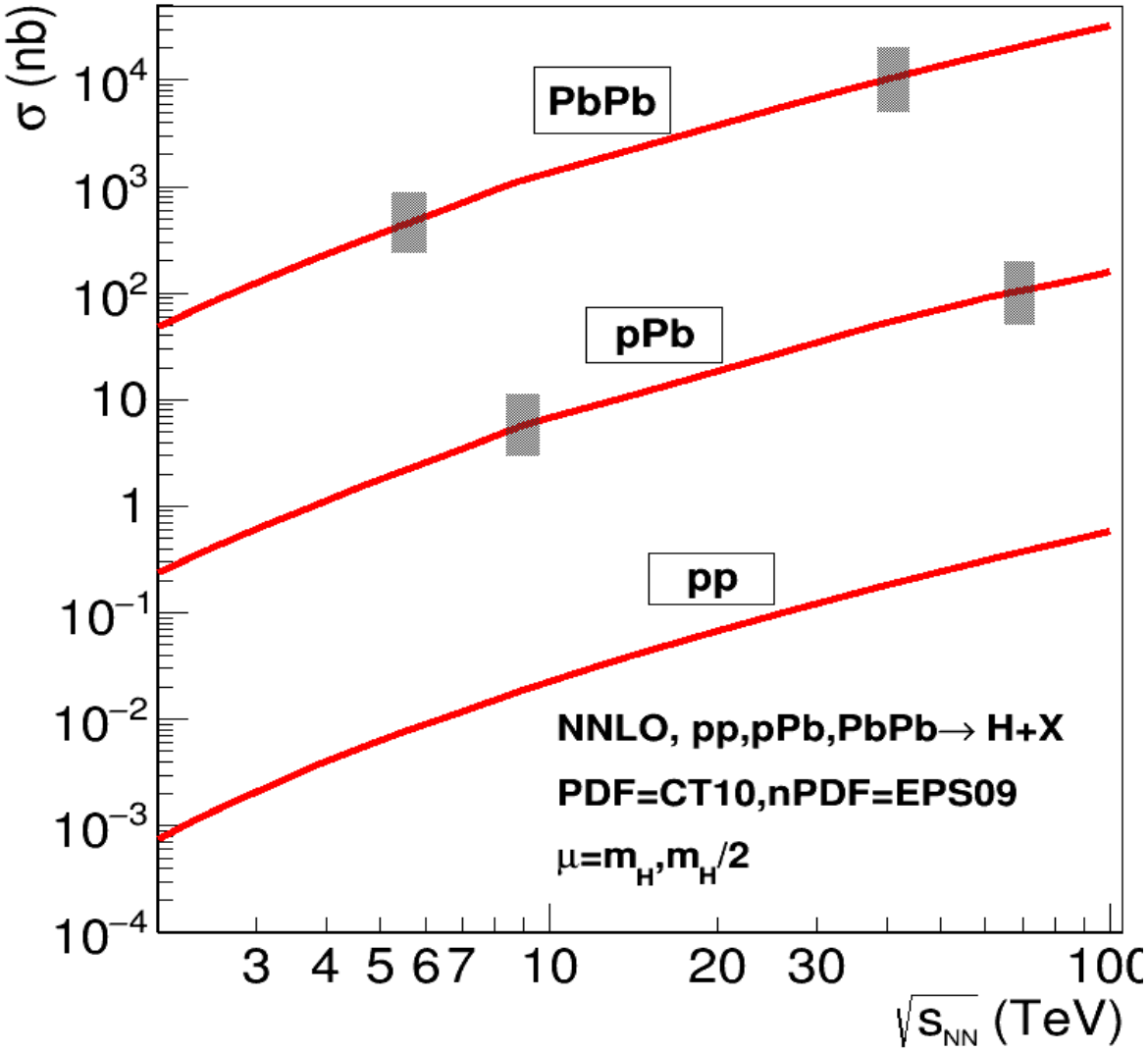


➜ LHC: Small antishadowing: R_{AA}~ 1.07, R_{pA}~1.03

➜ 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

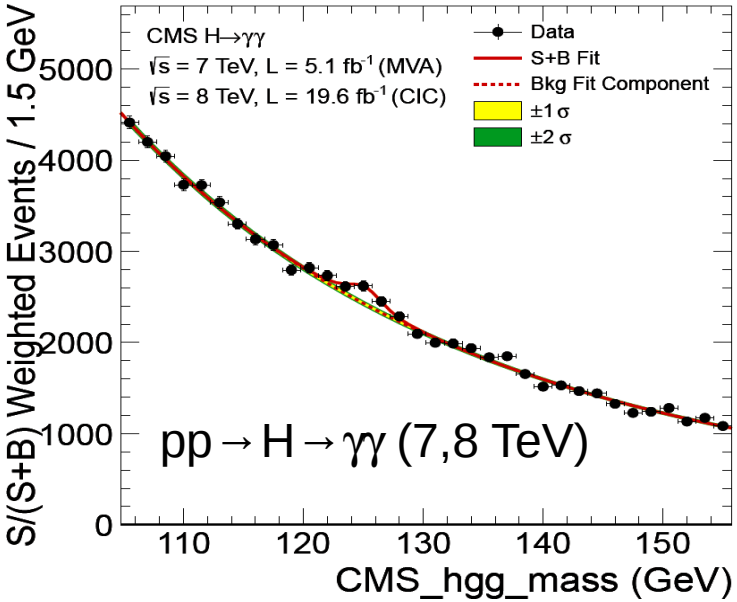
- p-p (reference):

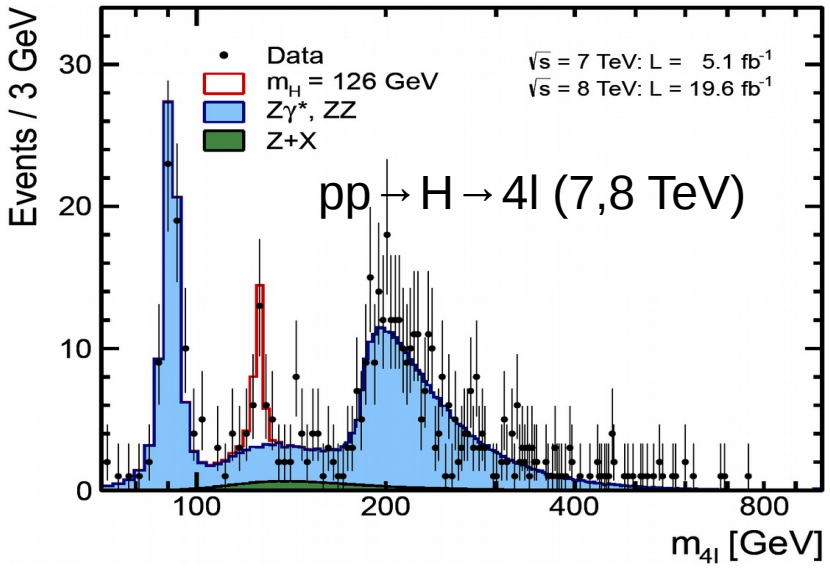
LHC(5.5 TeV) = 12 pb
LHC(8.8 TeV) = 27 pb
FCC(39 TeV) = 270 pb
FCC(63 TeV) = 490 pb

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

H→γγ, 4ℓ (discovery channels) measurement

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





- 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), 0.5 (4ℓ)

N(pPb,8.8 TeV,1 pb^{-1}) = 5.5 nb×BR×L_{int} ≈ 15 (γγ), 0.5 (4ℓ)

FCC: N(PbPb,39 TeV, 110 nb^{-1}) = 10 μb×BR×L_{int} ≈ 3000 (γγ), 130 (4ℓ)

N(pPb,63 TeV, 30 pb^{-1}) = 100 nb×BR×L_{int} ≈ 7500 (γγ), 350 (4ℓ)

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

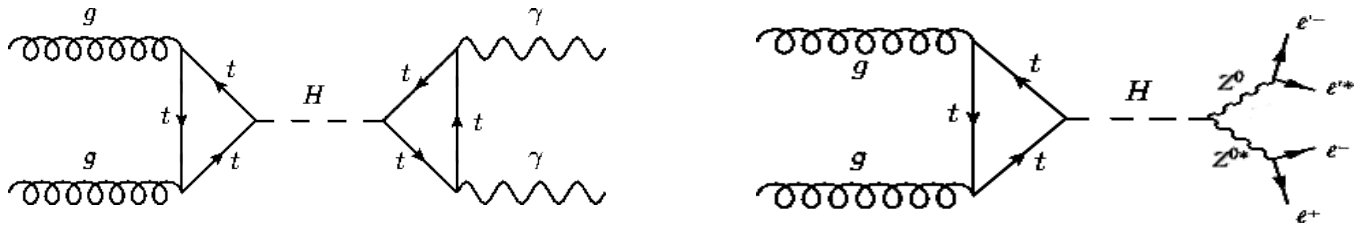
Plus total σ_H for nproc=215 (VBF), 91 (assoc. WH), 101 (assoc. ZH)

- 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 NNLO+NNLL
  (as per LHC-HXSWG, K-factors ~20%)

$H \to \gamma\gamma$, $4l$ (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:

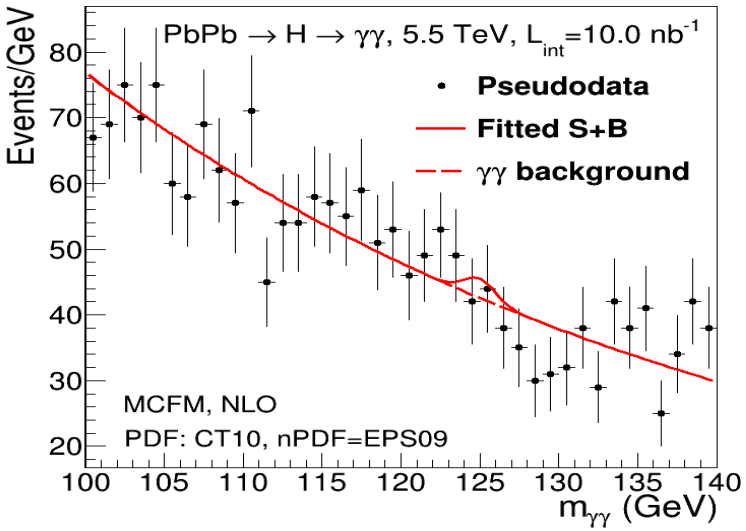
  $\gamma\gamma$: BR = 0.27%, Acc×Eff ~ 45% (LHC), 60% (FCC)
  $ZZ^* \to 4l$: BR = 0.12%, Acc×Eff ~ 60% (LHC), 70% (FCC)

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

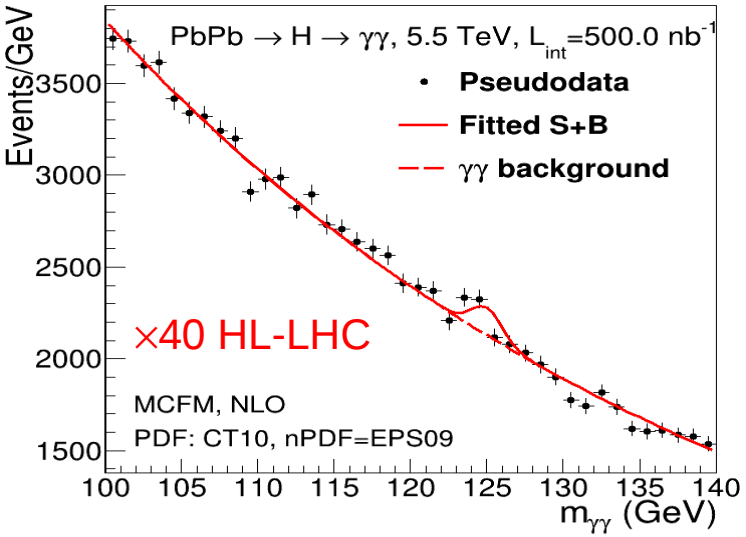
  $\gamma\gamma$: QCD continuum (MCFM $nproc$=285) +30% γ-γ^*_{jet}, γ^*_{jet}-γ^*_{jet}
  $ZZ^* \to 4l$: ZZ* non-resonant (MCFM $nproc$=90)

Pb-Pb: H → γ γ estimates (LHC vs. HE-LHC)

- 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)

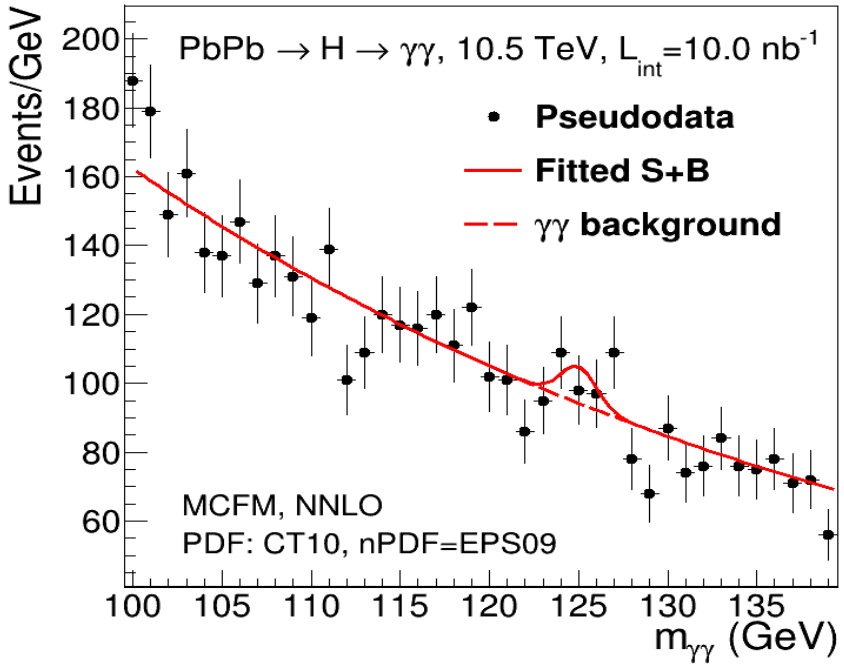
L_{int}= 500 nb^{-1}: 3σ evidence (×40 HL-LHC)

4.2σ combined with H(4l)

➔ HE-LHC (10.6 TeV, 10 nb^{-1}):

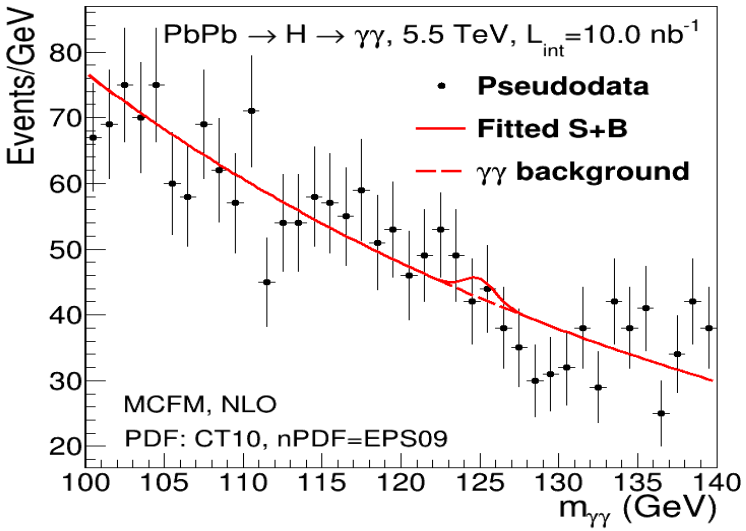
Significance: S/√B~1.3σ

(3σ evidence requires L_{int}= 70 nb^{-1})

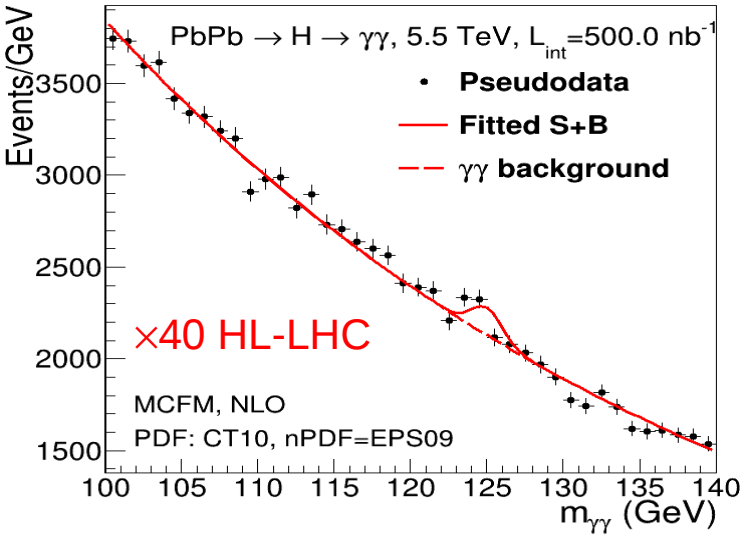


Pb-Pb: H → γ γ estimates (LHC vs. FCC)

- 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}):

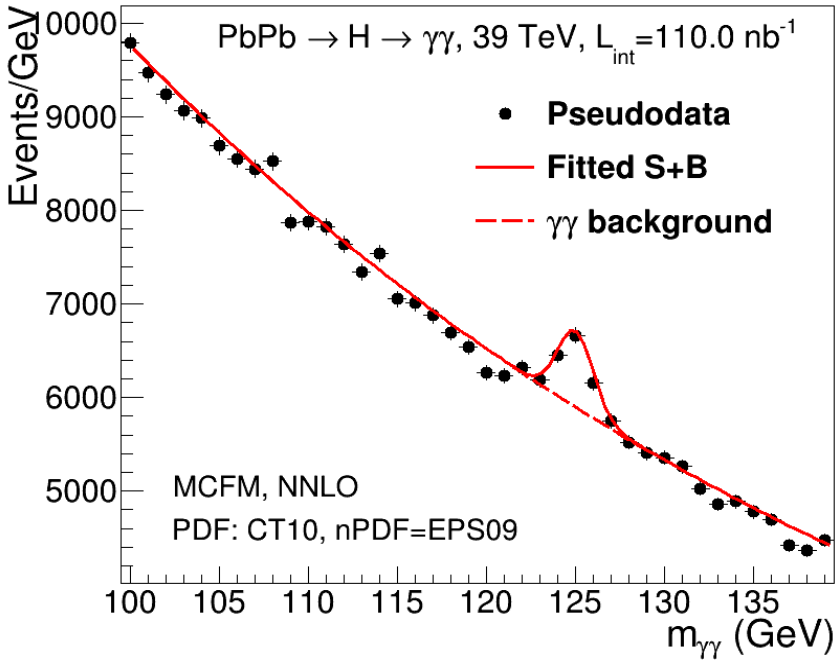
Nomin. lumi: S/√B~0.36 (0.5, adding 4l)

L_{int}= 500 nb^{-1}: 3σ evidence (×40 HL-LHC)

4.2σ combined with H(4l)

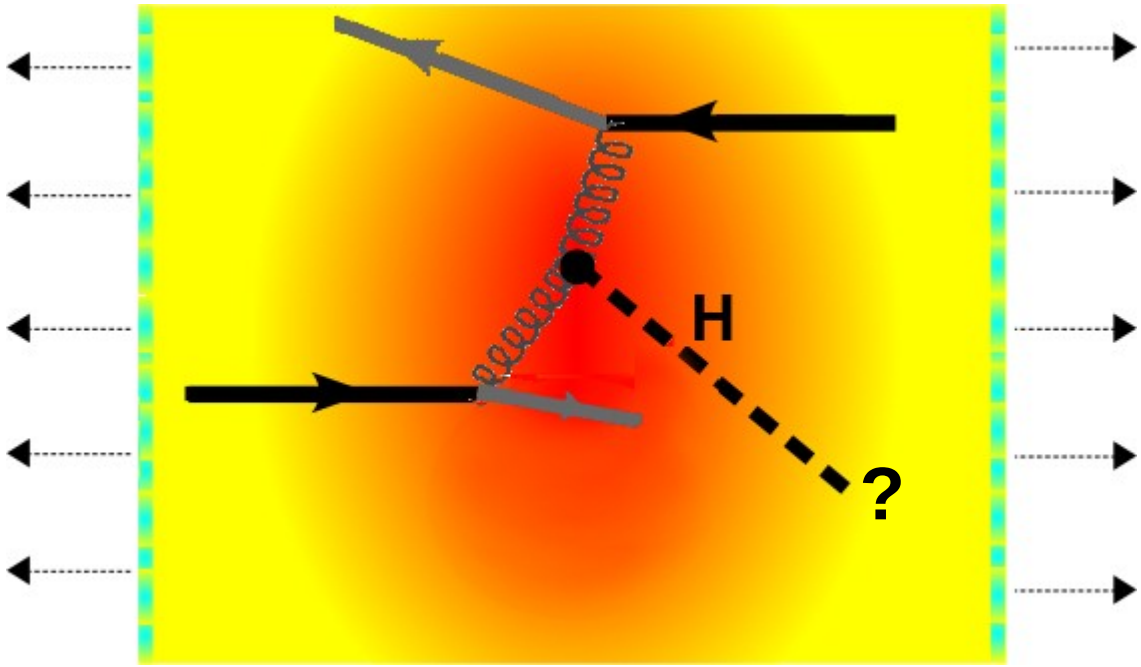
➔ FCC (39 TeV, 110 nb^{-1}):

Nominal lumi: S/√B>>5σ observation



Final-state interactions of the H boson in the QGP

- Central PbPb colls at the LHC produce dense q,q syst. for τ_{QGP}~10 fm
- SM Higgs boson (Γ_H=4 MeV) has a lifetime $\tau = 1/\Gamma_H \sim 50$ fm. Once produced, it will traverse the QGP and decay outside the medium



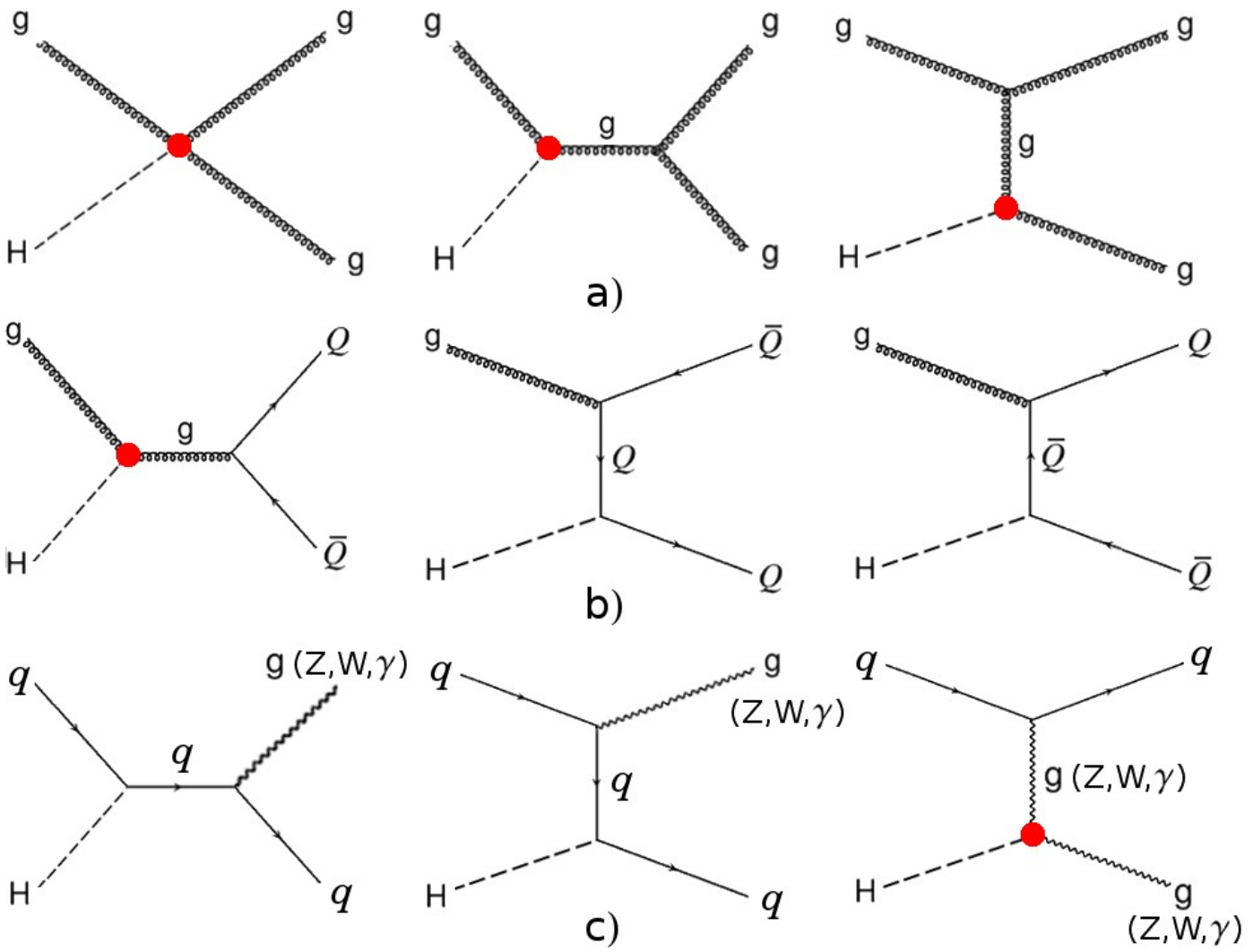
- The SM Higgs couples to QGP gluons (through dominant top loop) and quarks (as per their Yukawas). What's the effect of dense quark-gluon matter on the scalar boson ?

Higgs boson scatterings in a q,g medium

- Gluon-Higgs scatterings:

  $\sigma \sim \mathcal{O}(1\ \mu b)$

Final-states:
Di-gluon, di-quark



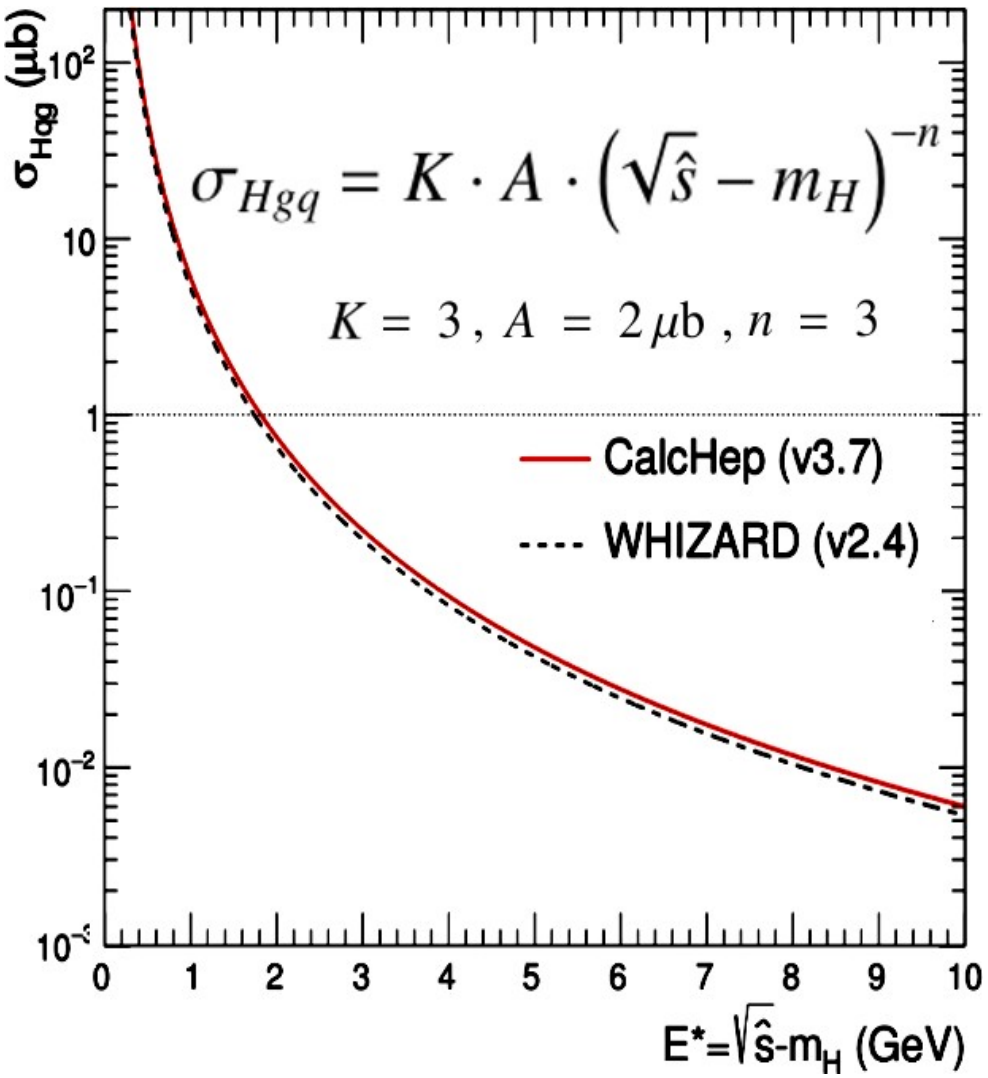
- Quark-Higgs scatterings:

  $\sigma \sim \mathcal{O}(0.1\ nb)$

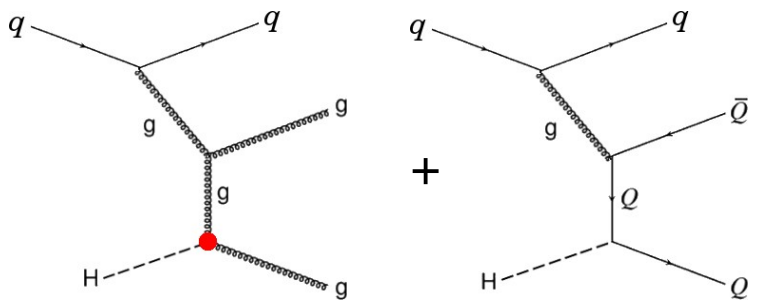
- Note: LO vacuum diagrams. Extra (real,virtual) thermal corrections, not included.

Higgs–parton scattering cross section

- Adding up all diagrams, and parametrizing (power law) scattering x-section vs. Higgs-parton c.m. energy:



- LO x-sections obtained with CalcHEP/WHIZARD, fitted over $E_{g,H}$~1–10 GeV.
- K-factor = 3 from ratio of ($N^3LO+NLL$)/LO ggH x-sections:



+ ... **$\sigma \sim \mathcal{O}(10\ \mu b)$**

- Note: Leading vacuum diagrams. Extra thermal corrections, not included.

Higgs boson survival probability

- The interaction of a Higgs boson with surrounding partons will result in its medium-induced decay into pairs of gluons or (heavy) quarks, and thereby in its effective "disappearance" in the diphoton & 4-lepton discovery channels ➜ " Absorption" cross section.
- Simple estimation of the Higgs "absorption" probability:

$$S \equiv \exp(-L/\lambda) = \exp(-\sigma\,\rho\,L)$$

- Take a Higgs traversing a static quark-gluon medium with L = 10 fm, ρ = 15 fm^{-3}:

$S = 0.99$ for $\sigma = 1\mu b$: 1% reduction of H(γγ,4l) yields
$S = 0.85$ for $\sigma = 10\mu b$: 15% reduction of H(γγ,4l) yields

- In reality: $\sigma = \sigma(\tau), \rho = \rho(\tau, x, y),\ v_{\rm rel},\ \text{path} - \text{dependent},$

General Higgs survival probability formula in expanding q,g-medium:

$$\mathcal{R}_H = \exp\left(-\int_{\tau_0}^{\tau_f} \sigma_{Hgq}\left(\sqrt{\hat{s}}(\tau)\right)\cdot \mathrm{v_{rel}}\left(\sqrt{\hat{s}}(\tau)\right)\cdot \rho(\tau)\,\mathrm{d}\tau\right)$$

(still needs to be integrated over all in-medium Higgs path directions)

Higgs survival probability (MC implementation)

$$R_H = \frac{\int \mathrm{dP}(x_0, y_0)\, \mathrm{d}\phi_0 \, \exp\left(-\int_{\tau_0}^{\tau_f} \overline{\sigma}_{Hqg}(\tau) \cdot \overline{\rho}(\tau) \cdot \mathrm{d}\tau\right)}{\int \mathrm{dP}(x_0, y_0)\, \mathrm{d}\phi_0},$$

where $\overline{\sigma}_{Hqg}(\tau) = \int \sigma_{Hgq} v_{\mathrm{rel}}(\sqrt{\hat{s}})\, f_\tau(E_{g,q})\, d^3\tilde{p}_{g,q}$ is integrated over all parton energies and Higgs–parton relative angles θ, and $\overline{\rho}(\tau) = \rho(x_0 + \beta_H \tau \cos\phi_0, y_0 + \beta_H \tau \sin\phi_0, \tau)$.

- QGP described by 2D+1 (SuperSONIC) hydrodynamics model
  - Initial parton density fixed to reproduce $dN_{ch}/d\eta$ for various systems, $\sqrt{s}$.
  - Snapshots of $T(x,y;\tau)$ thermodynamical profiles
  - Density $\rho(\tau)$ derived from T via Equation-of-State (lattice-QCD, quasiparticle)
- Parton momenta described by B-E (F-D) distributions at T:

  $$f_\tau(E_{g,q}) = (\exp[E_{g,q}/T] \mp 1)^{-1}$$

  Minimum $f(E_{q,g})$ bounded by thermal quark, gluon masses.
- Higgs momenta described by NNLO+NNLL (HqT v2.0) at various $\sqrt{s}$.
- Distribution of initial P(x,y) Higgs boson position and ϕ directions from Glauber MC model.

Higgs survival probability (expanding QGP)

$$R_H = \frac{\int \mathrm{dP}(x_0, y_0)\, \mathrm{d}\phi_0 \, \exp\left(-\int_{\tau_0}^{\tau_f} \overline{\sigma}_{Hqg}(\tau) \cdot \overline{\rho}(\tau) \cdot \mathrm{d}\tau\right)}{\int \mathrm{dP}(x_0, y_0)\, \mathrm{d}\phi_0},$$

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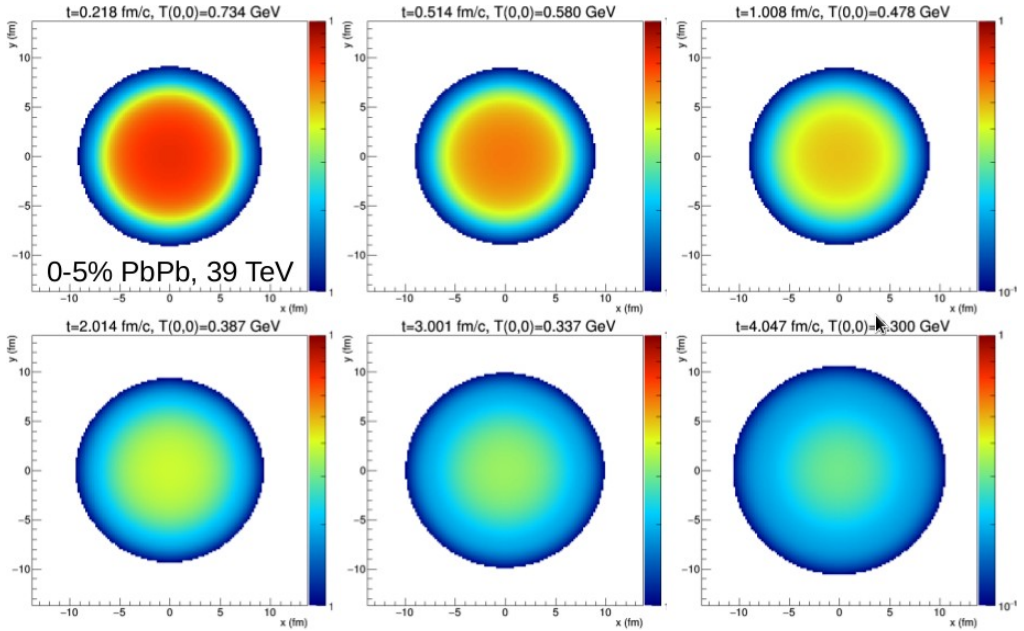

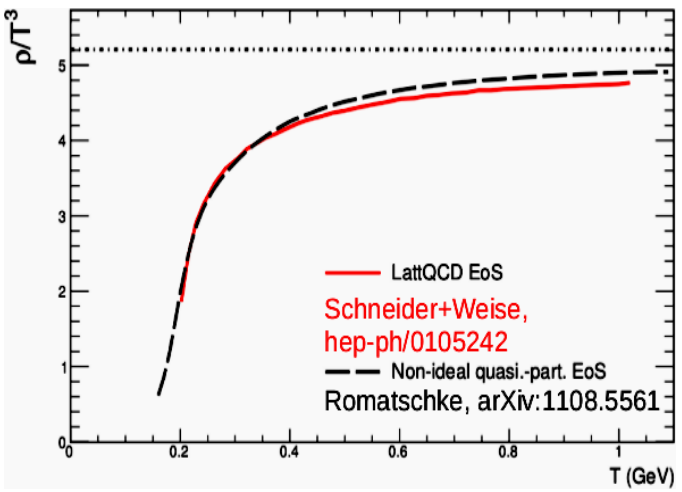

Higgs survival probability (parton momenta)

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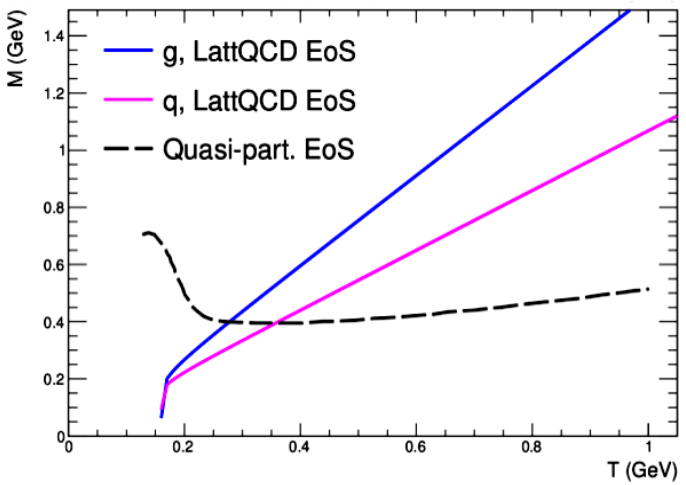
Absorption x-section regularized by thermal quark,gluon masses in $f(E_{q,g})$ from 2 different Equation-of-State (EoS): lattice QCD, quasiparticle plasma.

$m_{q,g}(T)>0.2,0.4$ GeV



Higgs survival probability (Higgs momenta)

$$R_H = \frac{\int \mathrm{dP}(x_0, y_0)\, \mathrm{d}\phi_0 \, \exp\left(-\int_{\tau_0}^{\tau_f} \overline{\sigma}_{Hqg}(\tau) \cdot \overline{\rho}(\tau) \cdot \mathrm{d}\tau\right)}{\int \mathrm{dP}(x_0, y_0)\, \mathrm{d}\phi_0},$$

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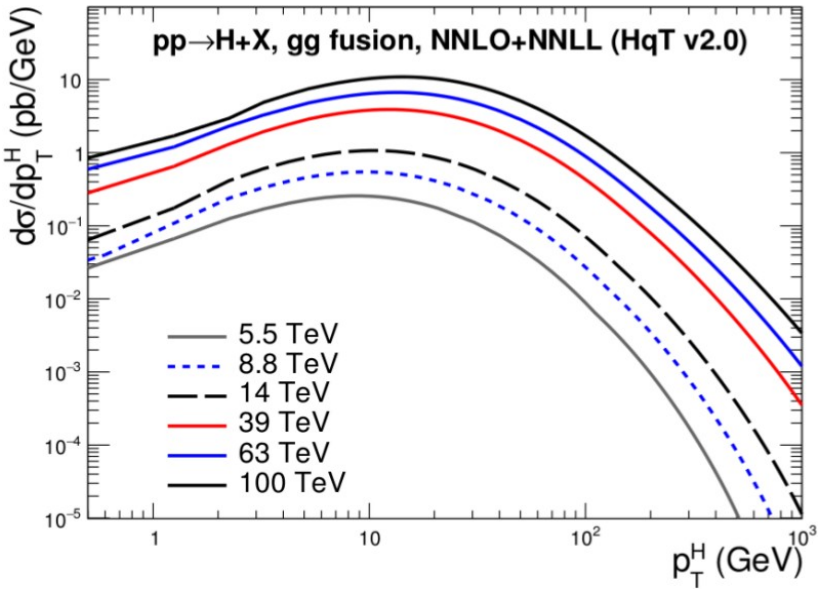
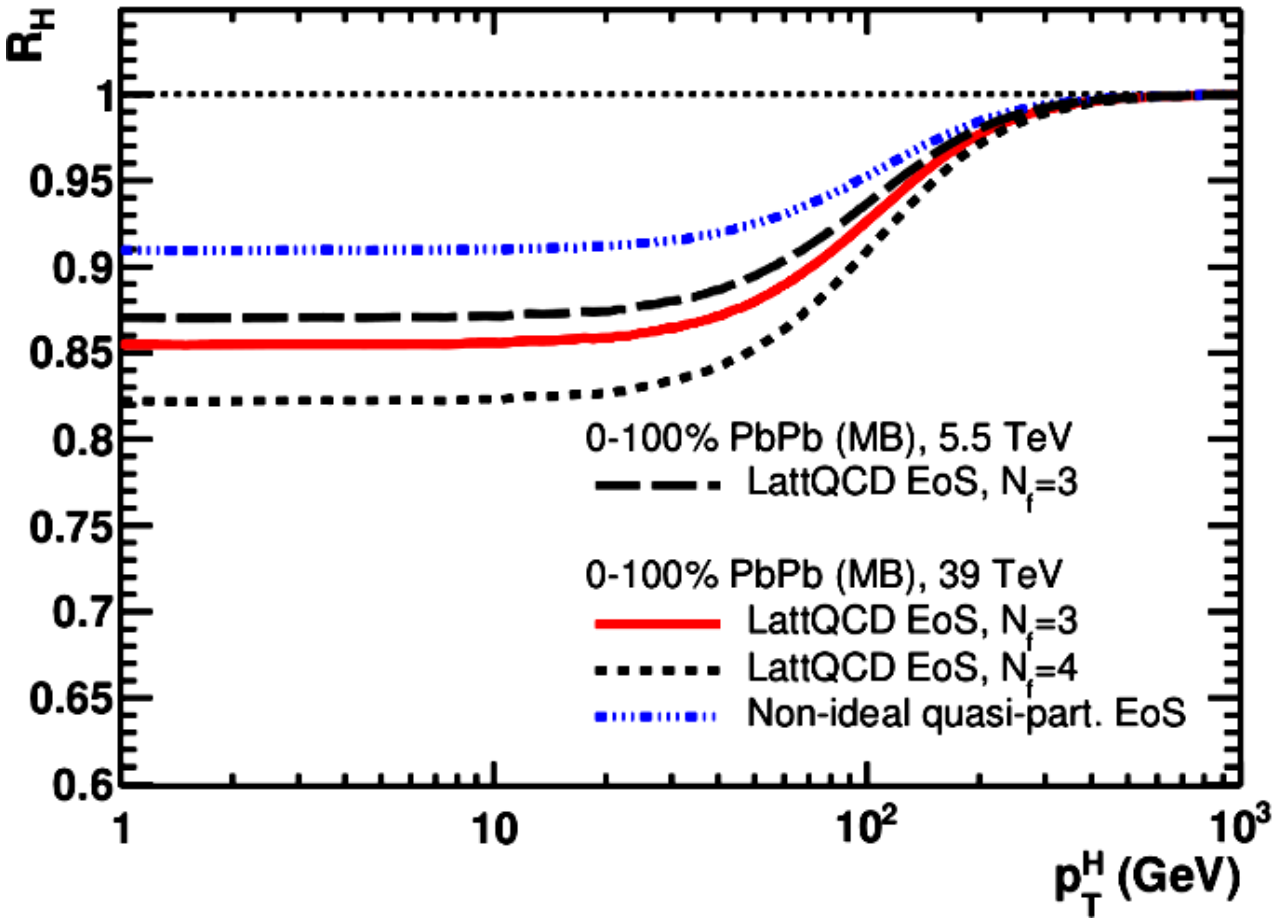
- Higgs momenta described by NNLO+NNLL (HqT v2.0) for various systems at various √s:



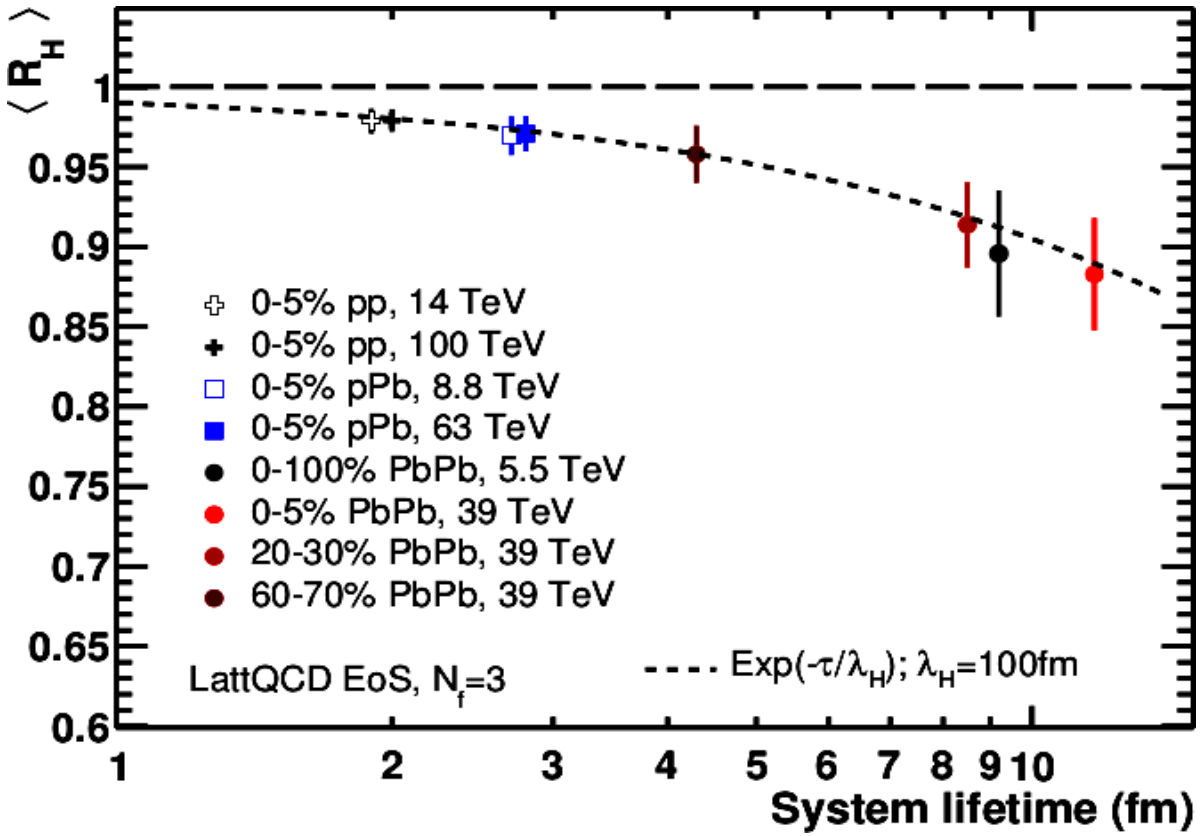
Pb-Pb results: Higgs suppression versus p_T

- Small suppression (10–15% depending on EoS, effective number of flavours in QGP) at low $p_{T,H} < 50$ GeV.
- Suppression gradually disappears as $p_{T,H} \sim m_H$ (no deficit at >300 GeV):



Higgs boson suppression versus system size

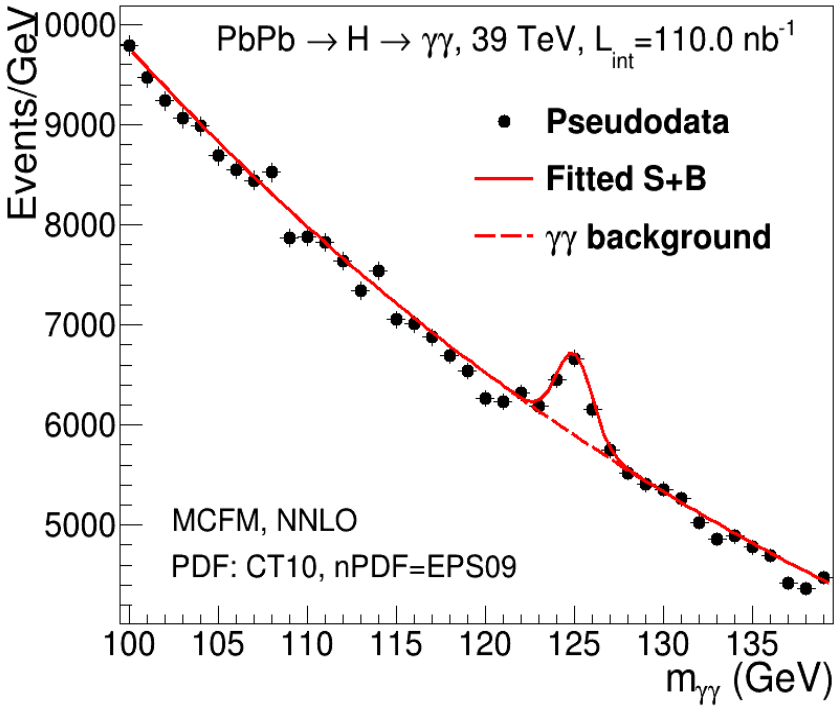
- Hydrodynamic profiles for "small" QGP in central (high-multiplicity) pp, pPb collisions at the LHC.
- Shallow exponential suppression vs. space-time size of the system.
- Few-% suppression in central pp collisions (visible in ratio of very-high- to low-multiplicity Higgs pp events?)

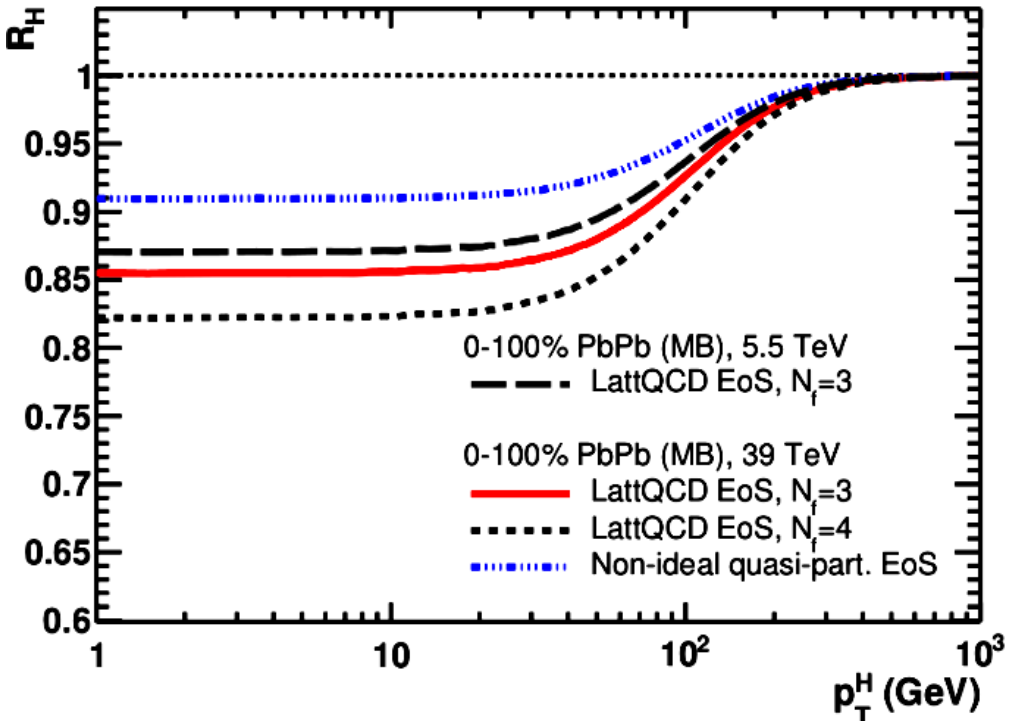


(Error bars from variations between quasiparticle and Nf=4 EoSs)

Conclusions

- 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)
  H→ γγ, 4*l*: ~3σ evidence requires ×40 nominal month-lumis.
- FCC: With default lumis, Higgs boson is clearly observable (>>5σ)
- Small 10–15% suppression expected due to final-state interactions w/ q,g: Important sensitivity to underlying QCD EoS, N_f,...

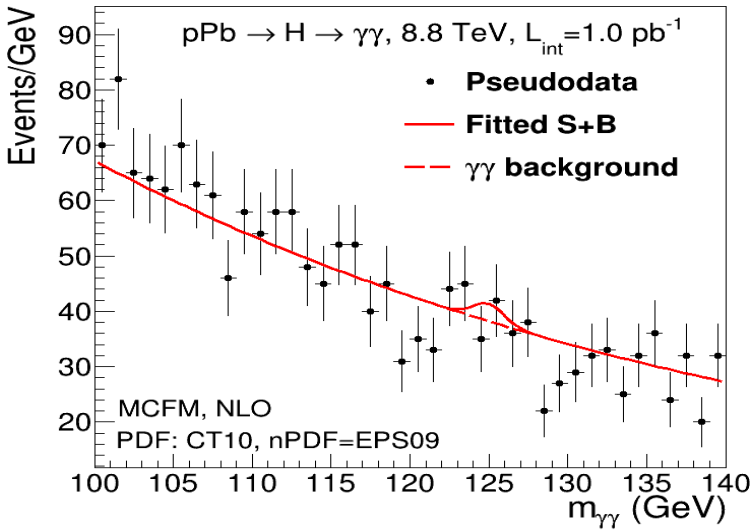




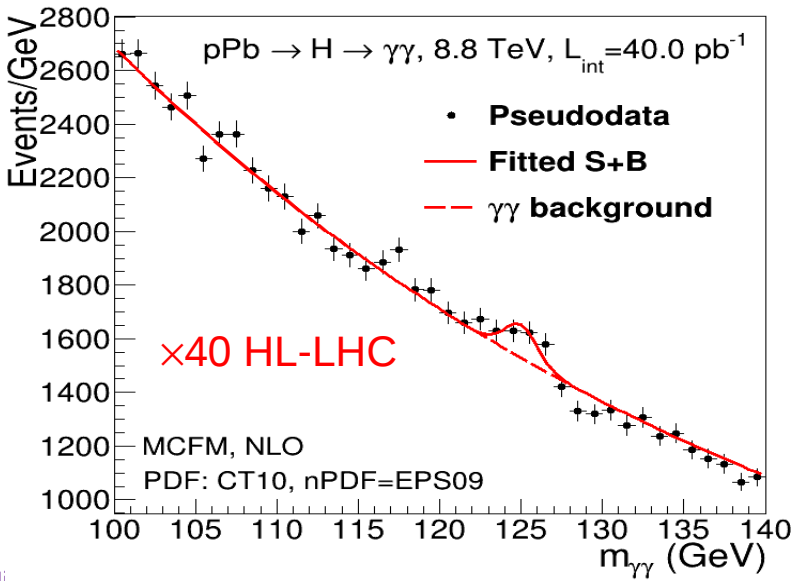
Back-up slides

p-Pb: H → γ γ measurements (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}):

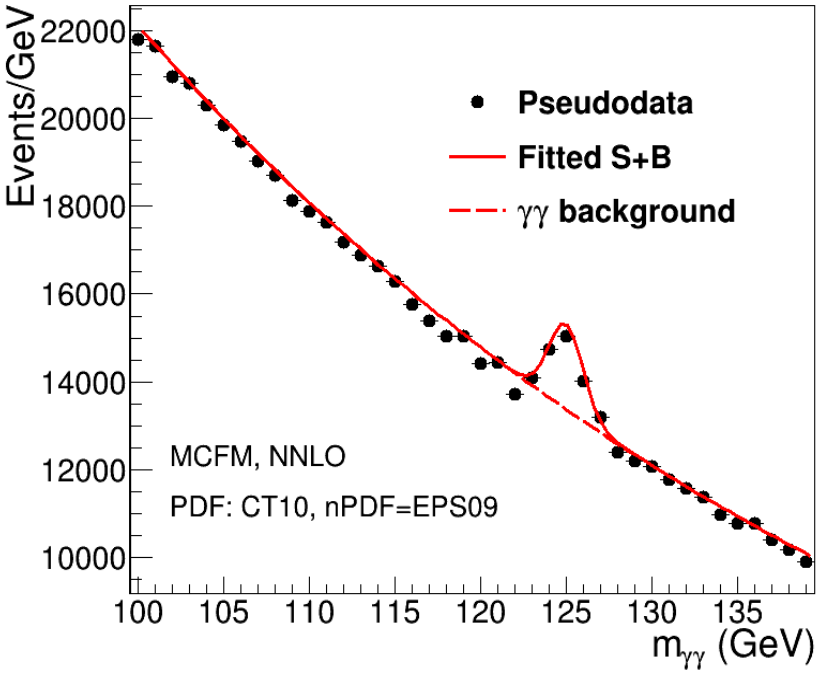
Nominal lumi: S/√B~0.4 (0.6, adding 4l)

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

4.2σ combined with H(4l)

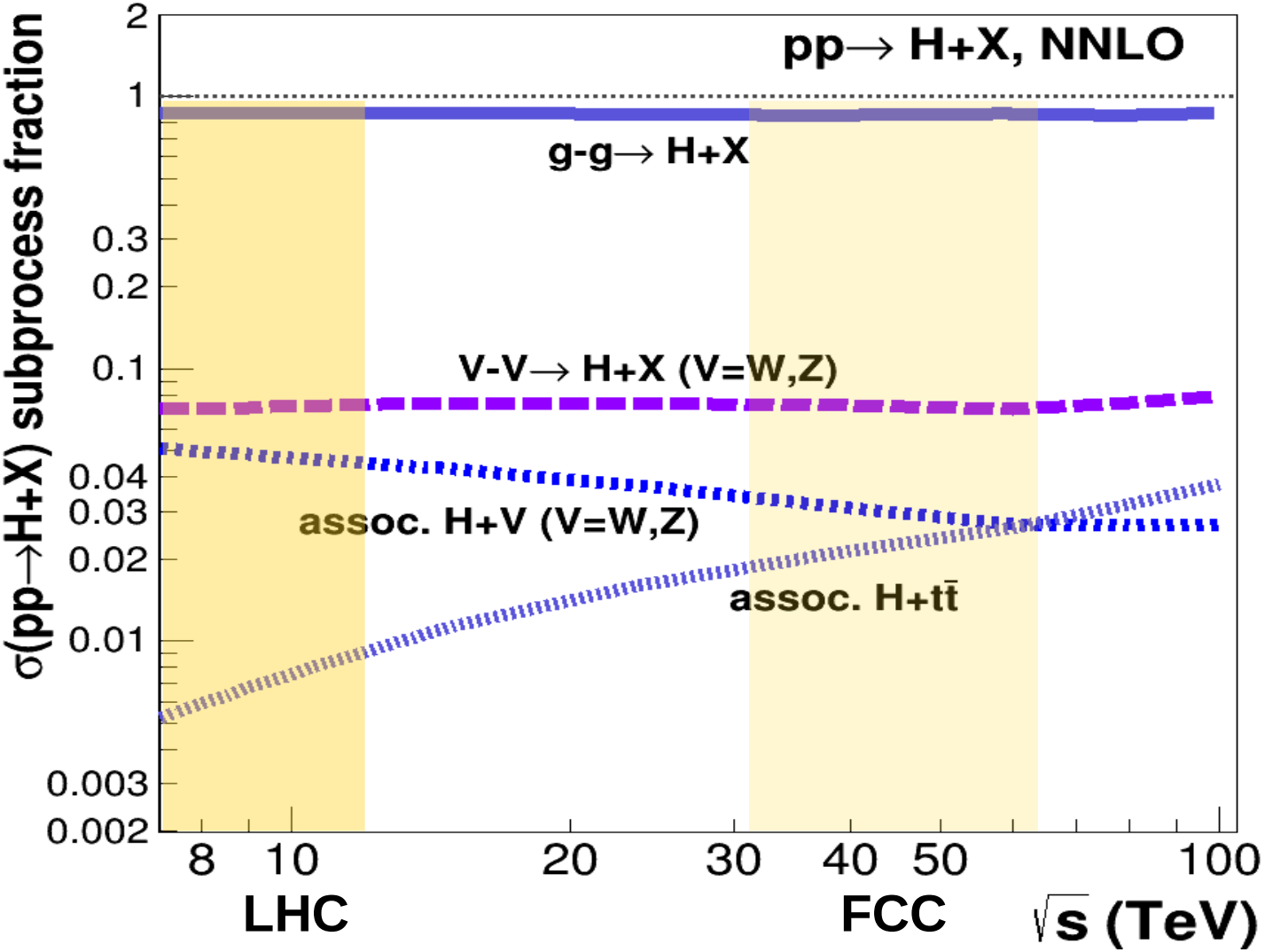
➔ FCC (63 TeV, 30 pb^{-1}):

Nominal lumi: S/√B>>5σ



Higgs subprocess contributions: LHC → FCC

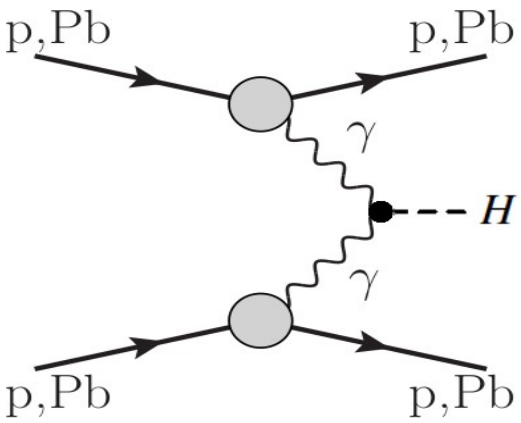
- MCFM σ(ggF+VBF+VH) scaled to NNLO+NNLL pp x-sections
- Production clearly dominated by gg fusion (90%-85%) over 5–63 TeV:

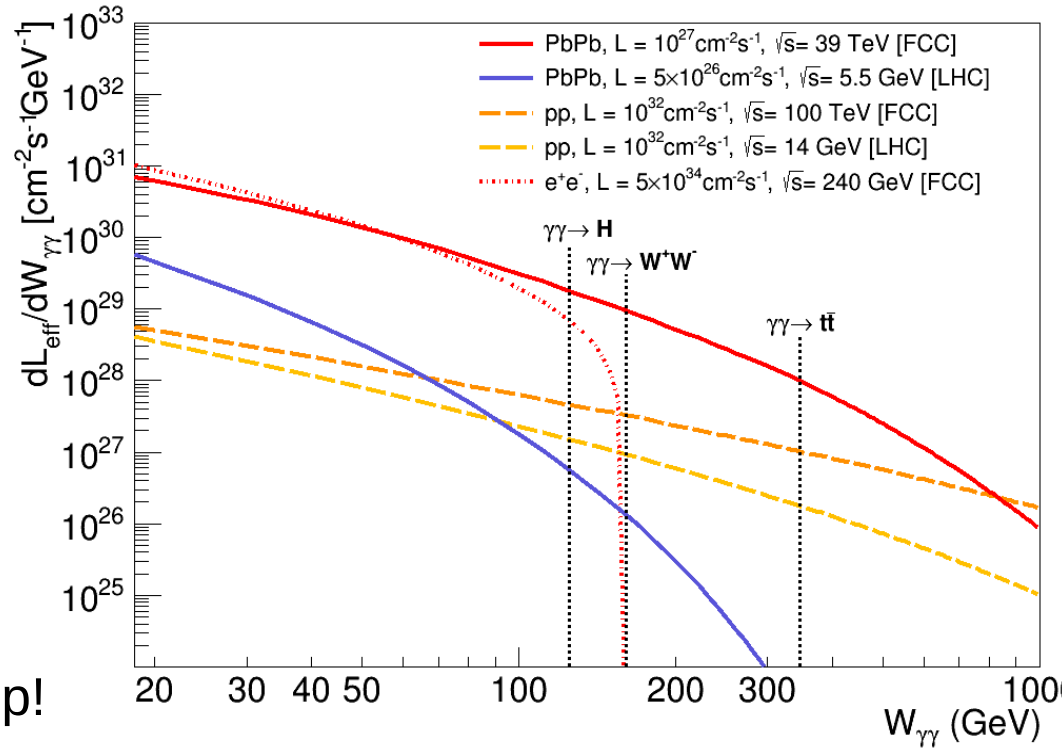


Higgs production in A-A collisions

- 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.

- Plus Z^4-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→$\gamma\gamma$ w/o pileup!