Higgs boson suppression in quark-gluon matter

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Work with David d'Enterria (see arXiv:1809.06832)

Higgs boson suppression in quark-gluon matter

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The final-state interactions of the Higgs boson in a dense quark-gluon medium are studied. Typical Higgs–parton scattering cross sections are found to be $\sigma_{Hqg} \approx$ 1–100 μb in the kinematical range of relevance at current and future hadron colliders. In-medium scatterings effectively lead to an enhancement of the Higgs decays into a pair of jets, mostly via $g\,H \rightarrow\; g\,g, Q\,\bar{Q}$, and thereby to a depletion of its visible yields in the $H \rightarrow \gamma\,\gamma, Z\,Z^{*}(4\ell)$ discovery channels compared to the accurate theoretical predictions for its production and decay in the absence of final-state interactions. By embedding Higgs bosons, with transverse momentum distributions computed at NNLO+NNLL accuracy, in an expanding quark-gluon medium modeled with 2D+1 viscous hydrodynamics with various QCD equations of state, we present realistic estimates of their suppressed yields as functions of transverse momentum p_T^H, and medium space-time size in pp, pPb, and PbPb collisions at LHC and FCC energies. A 10–20% depletion of yields is expected in central PbPb collisions, mostly for $p_T^H \lesssim$ 50 GeV.

Hard Probes 2018

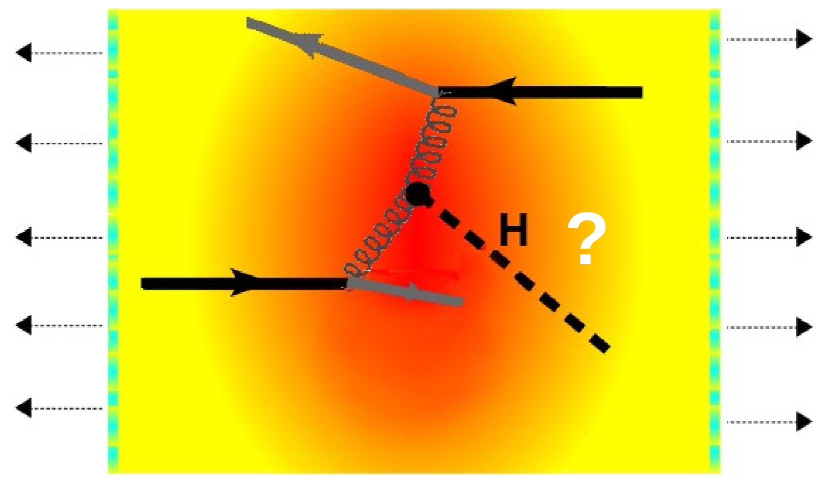
Introduction

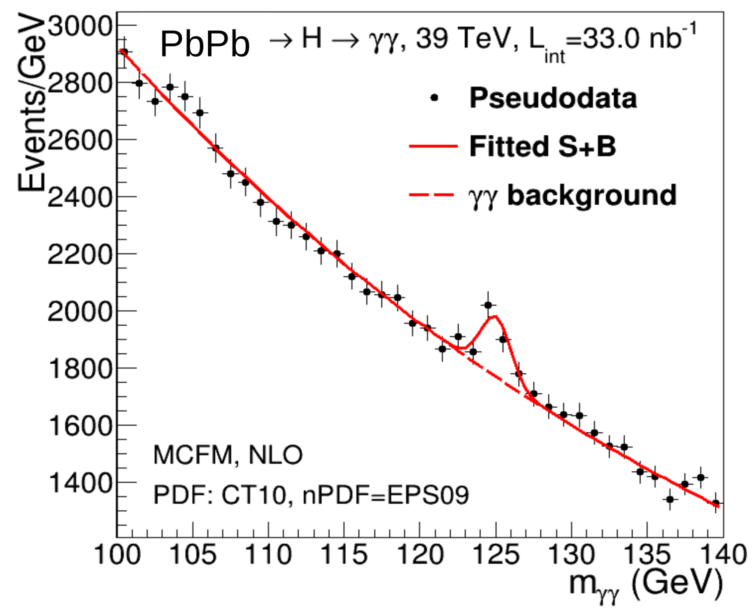
- SM boson (Γ_H=4 MeV) has a lifetime $\tau = 1/\Gamma_H \sim 50$ fm > $\tau_{QGP} \sim 10$ fm. Once produced it will outlive the QGP and decay in vacuum.

- The SM Higgs couples to QGP gluons (through the dominant top loop) and quarks (via Yukawa Coupling)
  → May provoke an earlier decay

- What's the effect of the gluons and quarks in QGP on the scalar boson ?

- Recap: what are the production cross sections & visible counts after analysis cuts in pPb, PbPb colls at LHC and/or FCC?
  (see D.d.E, arXiv:1701.08047)

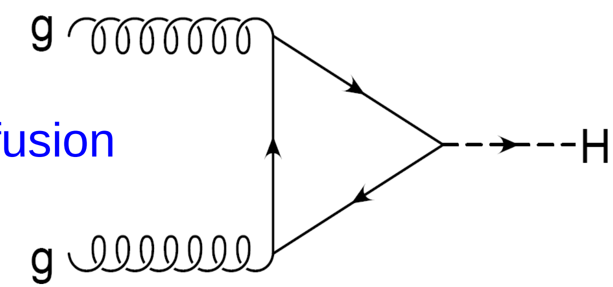




Higgs production cross section in AA

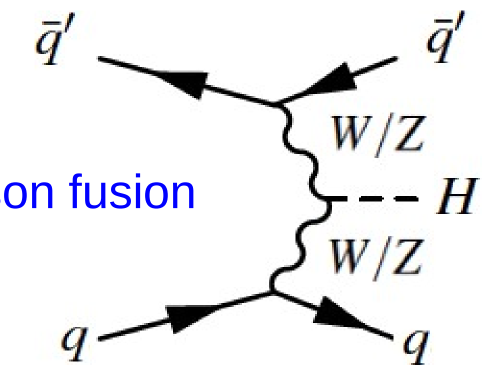
- Production mechanisms are the same as in p-p. Cross sections:
  $\sigma_{pPb\to H} = A\times\sigma_{pp\to H} = 208\times\sigma_{pp\to H}$, $\sigma_{PbPb\to H} = A^2\times\sigma_{pp\to H} = 4\cdot 10^4\times\sigma_{pp\to H}$
  modulo small (<5%) mods. of the nuclear g,q, PDFs

Gluon fusion



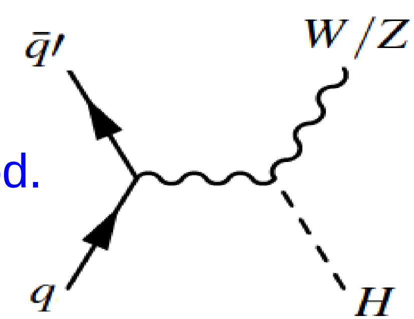
~85% of σ_H

Vector Boson fusion



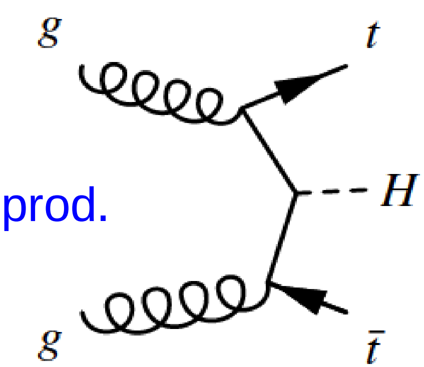
~10% of σ_H

Assoc. W,Z prod.



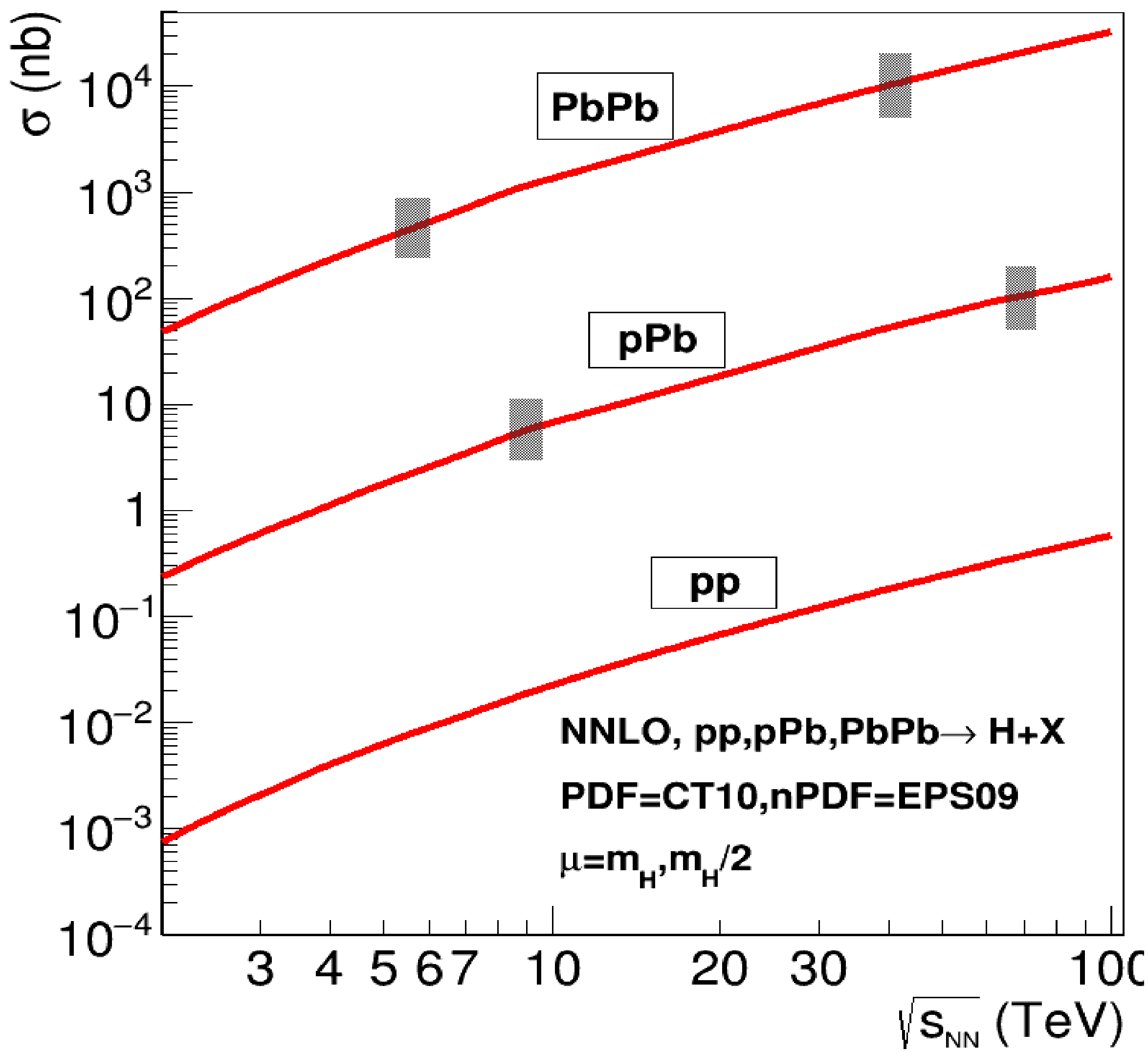
~5(3)% of σ_H

Assoc. ttbar prod.



~1(4)% of σ_H

Higgs production cross section vs $\sqrt{s_{NN}}$



- 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

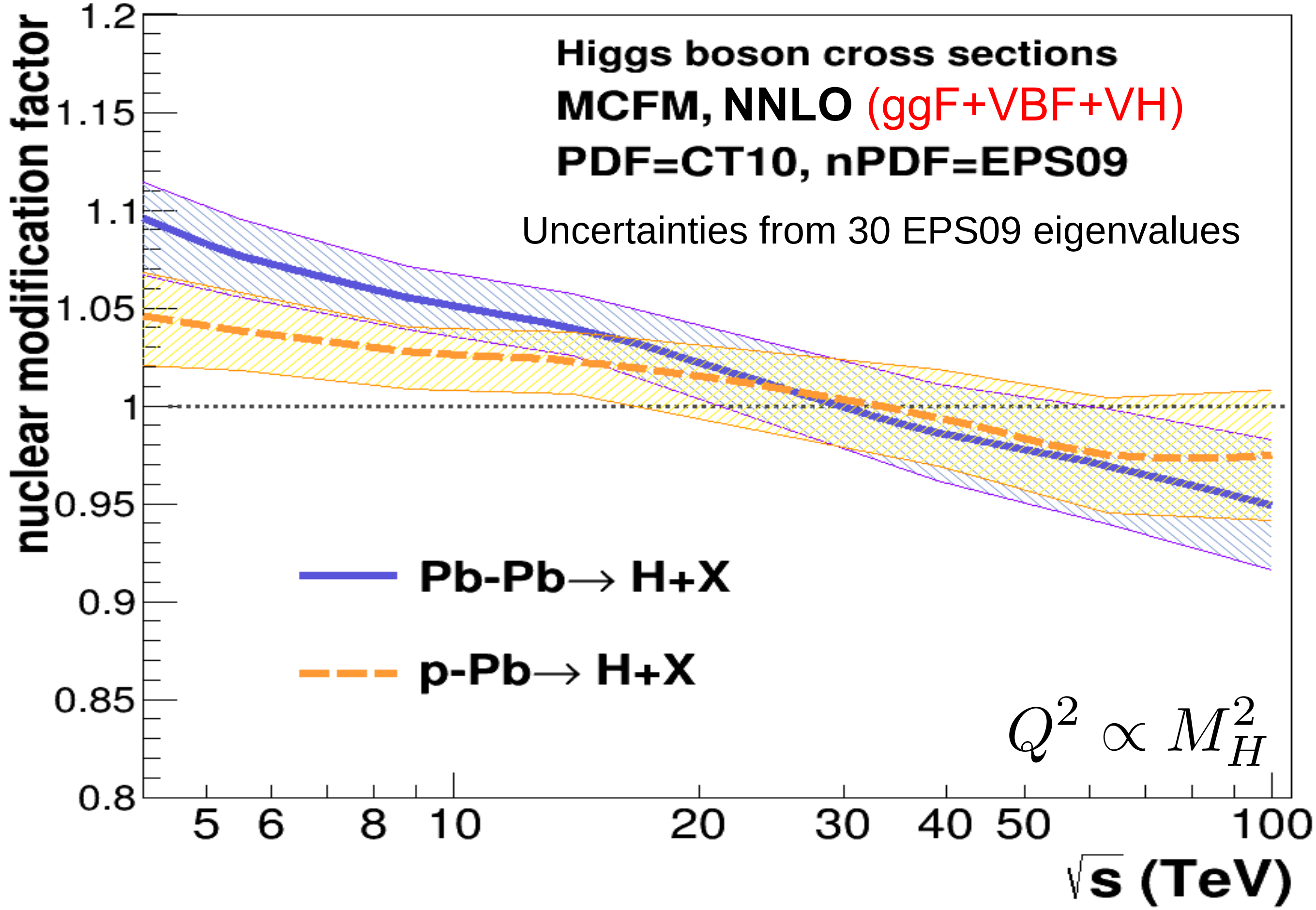
- p-p (reference):

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

D.d.E, arXiv:1701.08047

Nuclear modification



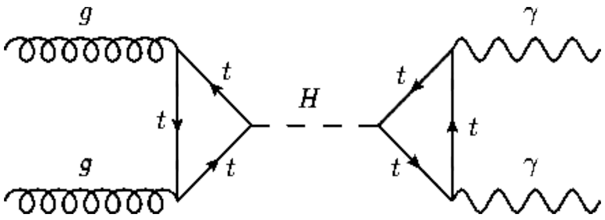
- EPS09 nuclear g,q PDFs modify only slightly x-sections wrt. pp PDFs:

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

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

D.d.E, arXiv:1701.08047

Expected yields after cuts



Analysis based on NNLO MCFM pseudo-data for H(γγ) and γγ backgrounds after typical CMS/ATLAS cuts

System	$\sqrt{s_{NN}}$ (TeV)	$\mathcal{L}_{int}$	H σ_{tot}	$\to \gamma\gamma$ yields	$\to ZZ^*(4\ell)$ yields
PbPb	5.5	10 nb^{-1}	500 nb	6	0.3
pPb	8.8	1 pb^{-1}	6.0 nb	7	0.4
PbPb	39	33 nb^{-1}	11.5 μb	450	25
pPb	63	8 pb^{-1}	115 nb	950	50

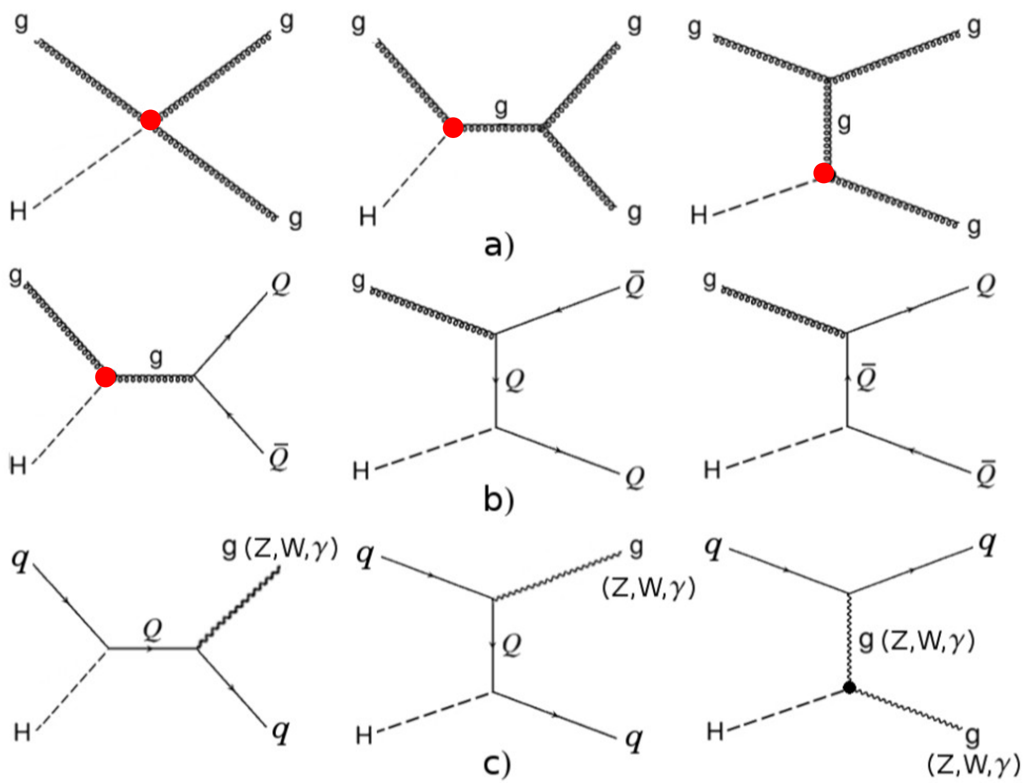
- LHC (nominal L_{int}): ~10 Higgs bosons/month visible in Pb-Pb, p-Pb
- HE-LHC: ~40 Higgs bosons/month in Pb-Pb, p-Pb
- FCC (nominal L_{int}): ~500-1000 H bosons/month in Pb-Pb, p-Pb (*)

(*) latest lumi estimates increased by factor 3

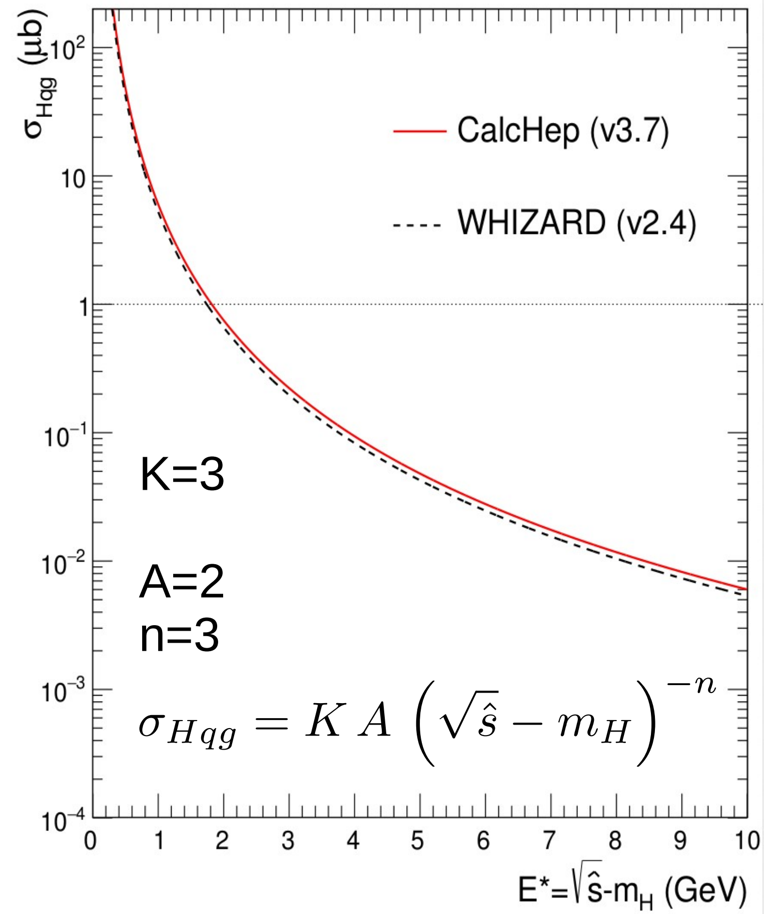
D.d.E, arXiv:1701.08047

Gluon-H + quark-H interaction cross section 7

D.d.E+CL, arXiv:1809.06832



σ~O(1 μb)



- LO x-sections obtained with CalcHEP (and WHIZARD) for $p_H, E_{q,g}$~1-10 GeV
- "Direct" gluon-Higgs scatterings dominate the LO diagrams:
  Quark-Higgs contributions through higher-order corrections via cases where medium quark emits gluon that then scatters with H
- K factor = 3 assumed from ratio of (N3LO+NLL)/LO gluon fusion x-sections
  → Resulting cross section of 0.5-100 μb for low E* between 0.4-2.3 GeV

Absorption cross section

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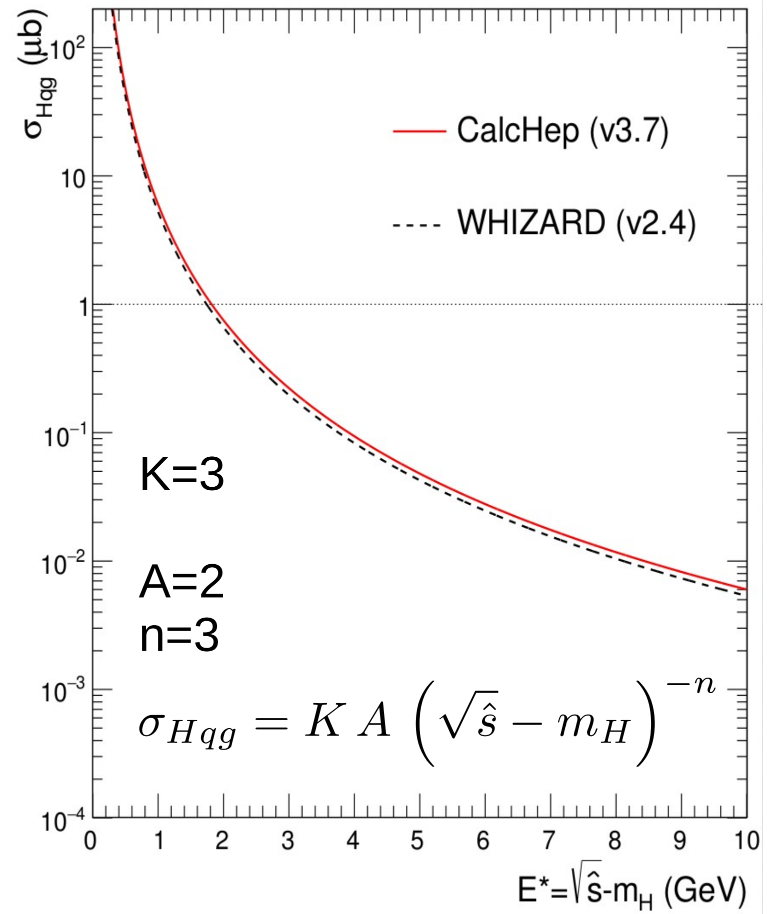

- The interaction of Higgs boson with surrounding partons will result in its medium-induced decay into pairs of gluons or (heavy) quarks, and thereby in its effective “disappearance” in the diphoton and four-lepton discovery channels
  → “Absorption” cross section

- Estimate expected suppression using

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

- Example static case: $\rho = 15\mathrm{fm}^{-3}, L = 10\mathrm{fm},$

$$S = 0.99 \;\; \text{for}\, \sigma = 1\mu b,$$
$$S = 0.85 \;\; \text{for}\, \sigma = 10\mu b,$$
$$S = 0.22 \;\; \text{for}\, \sigma = 100\mu b,$$

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

- Regulation at low E*:

$$\sqrt{\hat{s}} - m_H = [m_H^2 + m_{g,q}^2 + 2E_H E_{g,q}(1 - \beta_H \beta_{g,q}\cos\theta)]^{1/2} - m_H$$

$$= \sqrt{m_{g,q}^2 + p_{g,q}^2} \;\; \text{for} \;\; \beta_H \ll 1$$

Parton in-medium mass important!

Dynamic calculation

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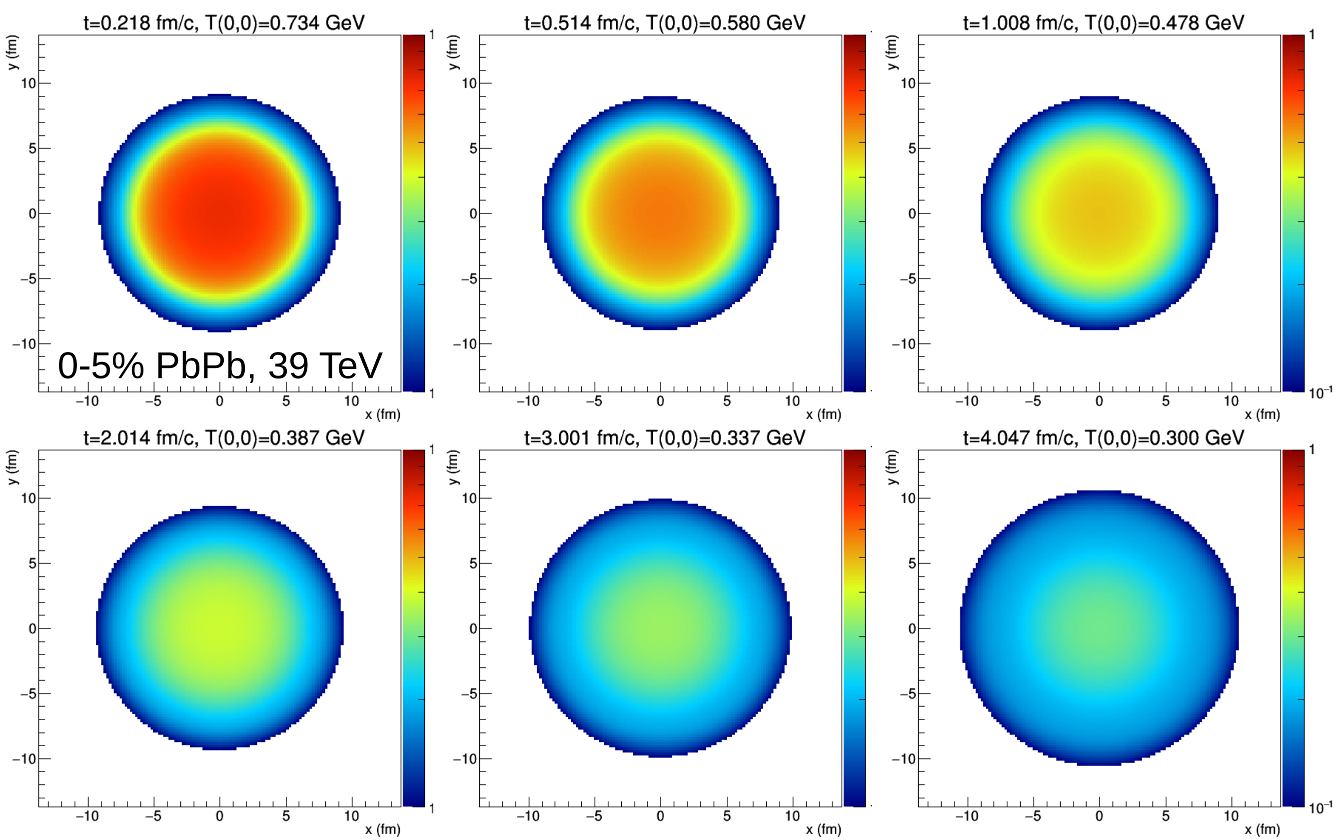
$$R_H(p_T^H) = \frac{\int \mathrm{dP}(x_0, y_0)\,\mathrm{d}\phi_0\;\exp\left(-\int_{\tau_0}^{\tau_f} \overline{\sigma_{Hqg}}(\tau)\cdot\overline{\rho}(\tau)\cdot\overline{v}_{\mathrm{rel}}(\tau)\,\mathrm{d}\tau\right)}{\int \mathrm{dP}(x_0, y_0)\;\mathrm{d}\phi_0}$$

- Medium described by a 2D+1 hydrodynamical model (superSONIC)
  - ➜ Tuned such that expected final state multiplicity is described
  - ➜ Provides T(x,y) in slices of τ



η/s=0.08
ζ/s=0.01

Many thanks to P. Romatschke and R. Weller for providing the calculations

Dynamic calculation

D.d.E+CL, arXiv:1809.06832

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

- Medium described by a 2D+1 hydrodynamical model (superSONIC)
  - ➜ Tuned such that expected final state multiplicity is described
  - ➜ Provides T(x,y) in slices of τ

- Momentum spectrum of medium partons at T(x,y;τ) given by

$$f_\tau(E_{g,q}) = (\exp[E_{g,q}/T] \mp 1)^{-1} \ \text{with}\ E_{g,q} > 0.2\,\mathrm{GeV}$$

- Absorption cross section at T (and Higgs p_T)

$$\overline{\sigma_{Hqg}}(T) = \int \sigma_{Hqg}(\sqrt{\hat{s}}) v_{\mathrm{rel}}\, f_\tau(E_{g,q})\, \mathrm{d}^3\vec{p}_{g,q}$$

- Density ρ(x,y;τ) from EOS

$$\overline{\rho}(\tau) = \rho(x_0 + \beta_H \tau \cos\phi_0, y_0 + \beta_H \tau \sin\phi_0, \tau)$$

- Geometry from Glauber Ncoll distributions

  (or from the earliest hydro profiles in case of the small systems)

EoS + resulting absorption cross sections

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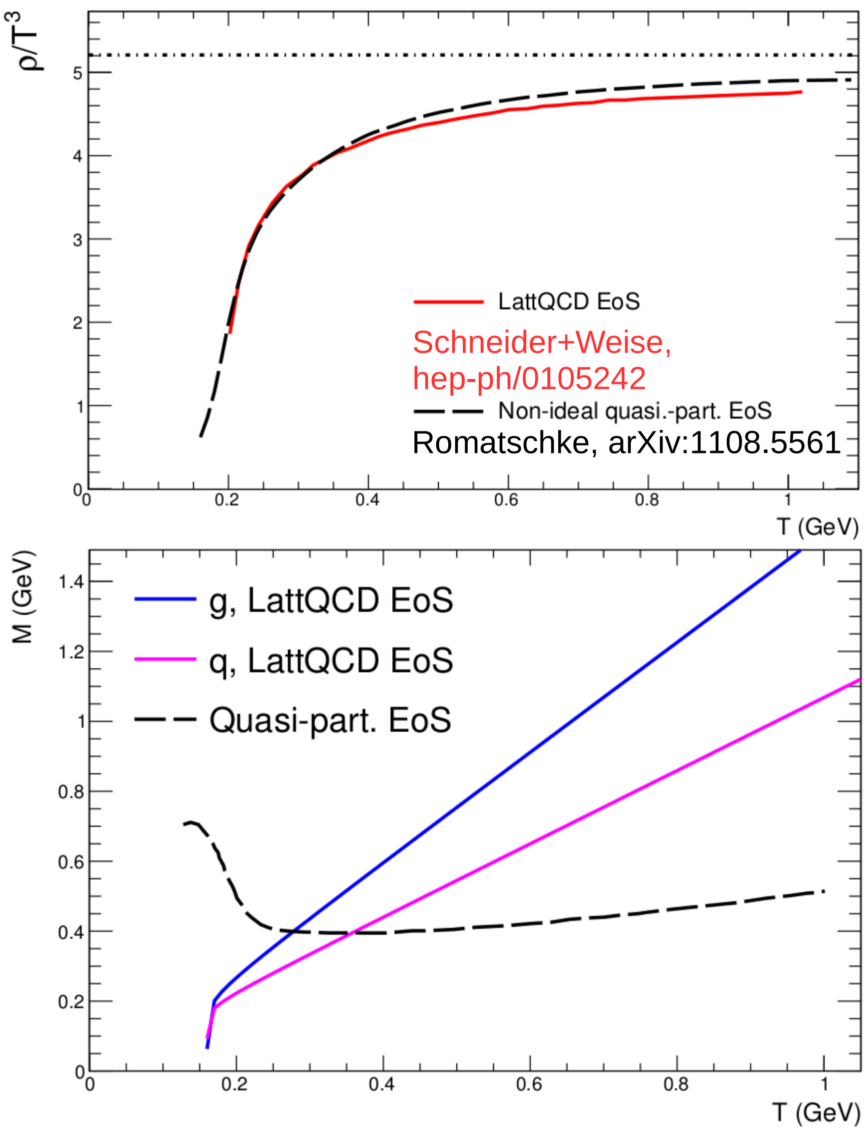

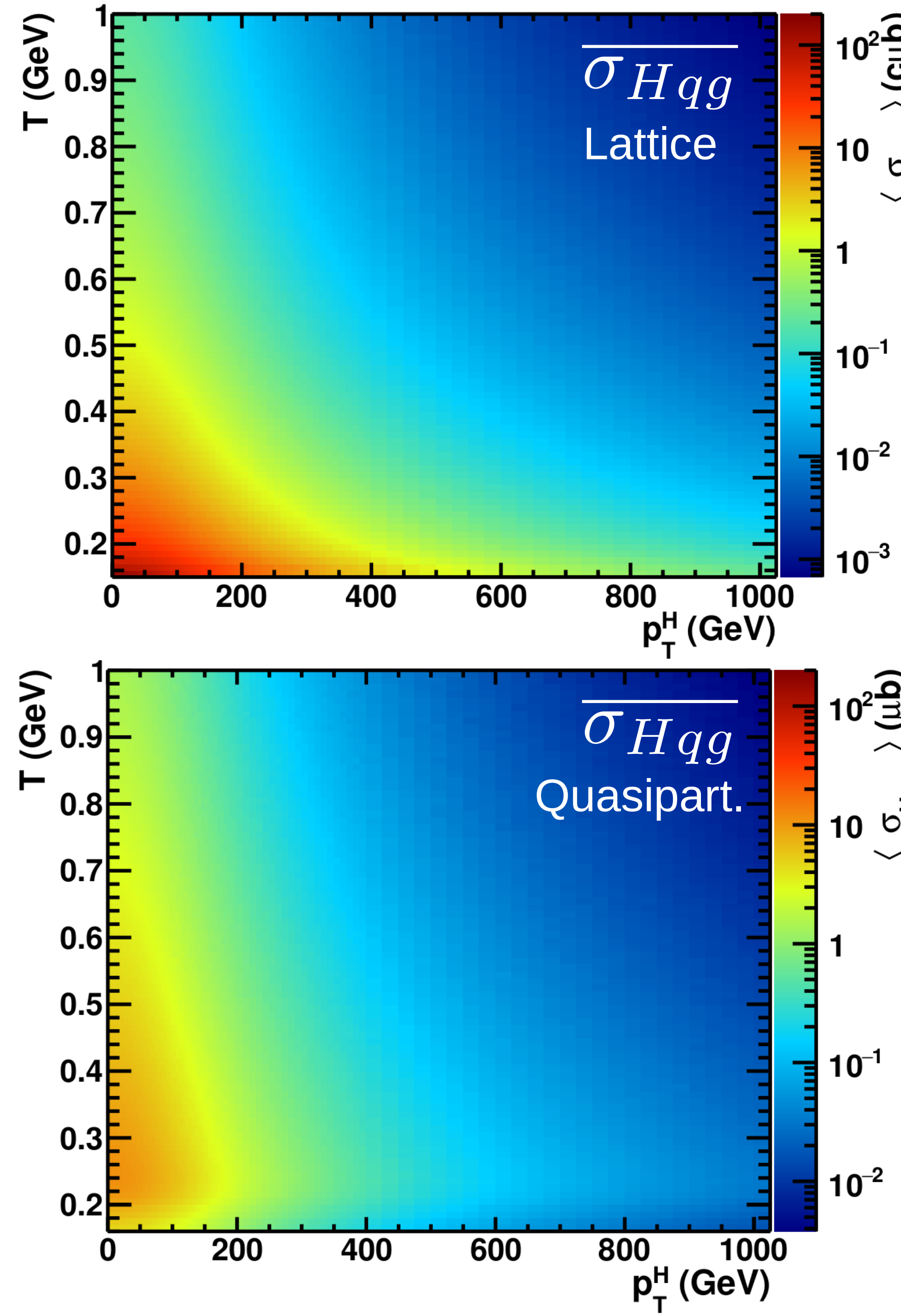

- EoS with quarks/gluons and quasiparticles have vastly different M(T) dependence and lead to significantly different σ(T)

Suppression factor

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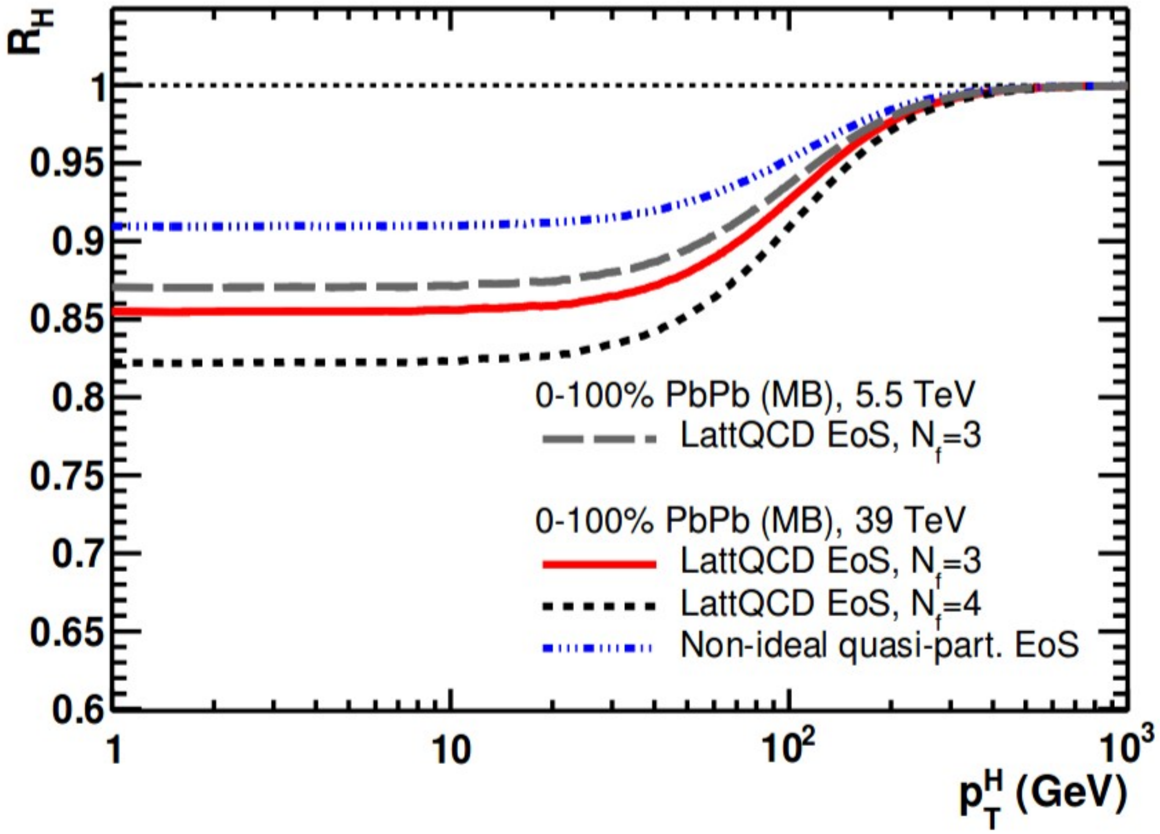
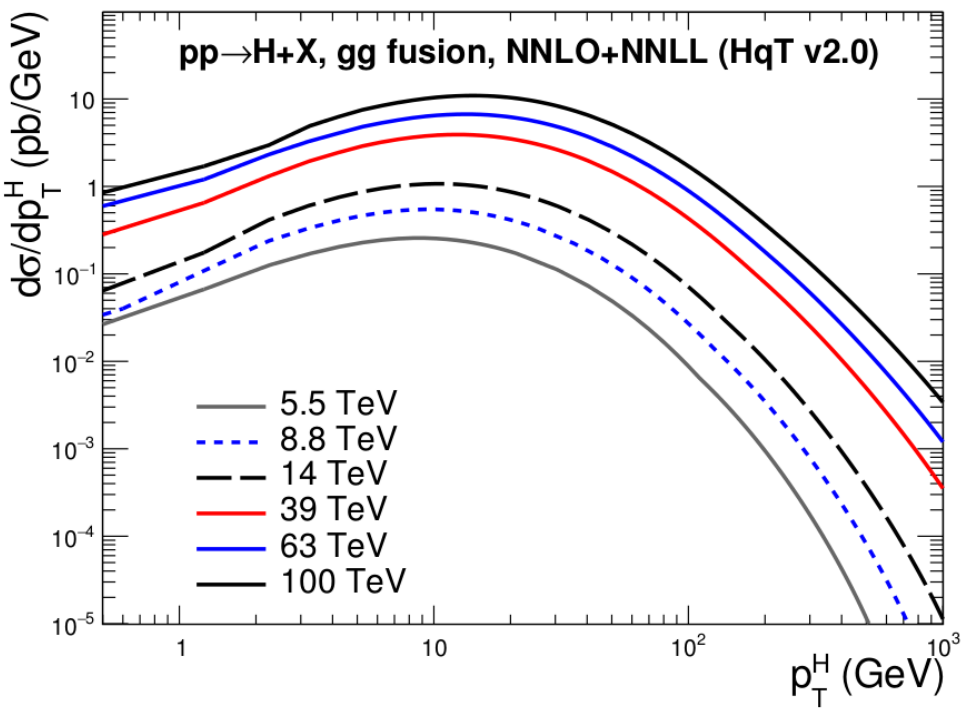


- Significant suppression (R_H≈0.85) in heavy ion collisions
- R_H increase above 50 GeV, and is 1 at 300 GeV.
- Depending on EOS and N_f variations by about ±10%

Comparison with other collision systems

D.d.E+CL, arXiv:1809.06832

System	Centrality	$\sqrt{s_{NN}}$	$dN_{ch}/dy\|_{y=0}$	$\Delta\tau$ (fm)	T_0 (GeV)	$\langle\rho\rangle$ (fm^{-3})	$\langle\sigma_{Hqg}\rangle$ (μb)	$\langle R_H\rangle$
pp	central (0–5%)	14 TeV	21	1.9	0.37	8.6	29.0	0.98 ± 0.01
pp	central (0–5%)	100 TeV	32	2.0	0.43	11.3	27.0	0.98 ± 0.01
pPb	central (0–5%)	8.8 TeV	60	2.7	0.37	7.6	31.2	0.97 ± 0.01
pPb	central (0–5%)	63 TeV	90	2.8	0.43	9.3	29.7	0.97 ± 0.01
PbPb	MB (0–100%)	5.5 TeV	515	9.2	0.51	8.7	40.0	0.88 ± 0.04
PbPb	MB (0–100%)	39 TeV	1028	10.4	0.62	12.8	31.6	0.89 ± 0.03
PbPb	0–5%	39 TeV	3700	11.7	0.90	16.4	36.5	0.88 ± 0.04
PbPb	20–30%	39 TeV	1500	8.5	0.85	15.6	36.5	0.91 ± 0.03
PbPb	60–70%	39 TeV	200	4.3	0.59	7.4	43.2	0.96 ± 0.02



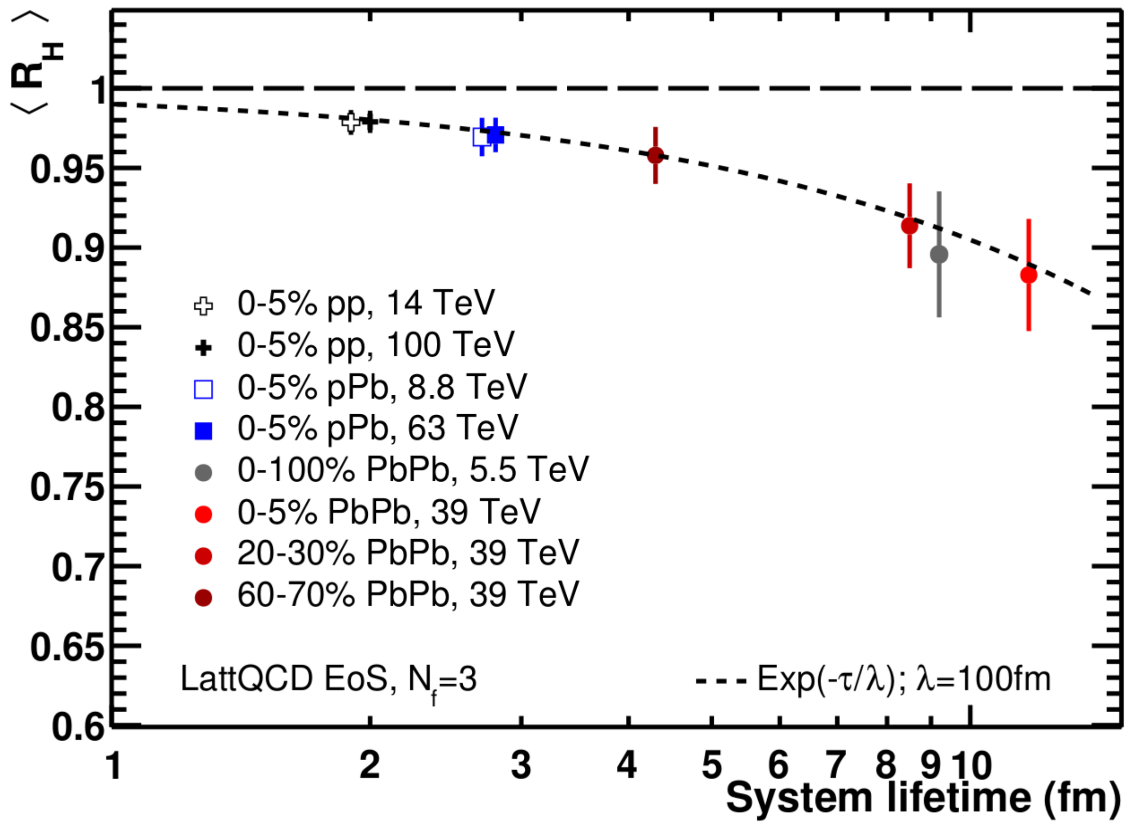
- Average suppression across systems

$$\langle R_H\rangle = \int \frac{d\sigma}{dp_T^H}\, R(p_T^H)\, dp_T^H \Big/ \int \frac{d\sigma}{dp_T^H}\, dp_T^H$$

- Essentially no suppression for small systems, while expected trend with centrality for large (PbPb) systems

Average suppression factor

D.d.E+CL, arXiv:1809.06832



Drawn errors from variations to quasi.particle EOS and Nf=4

- Suppression driven by lifetime (and size) of the system

→ Stimulated decay rate of about 100 fm for all systems

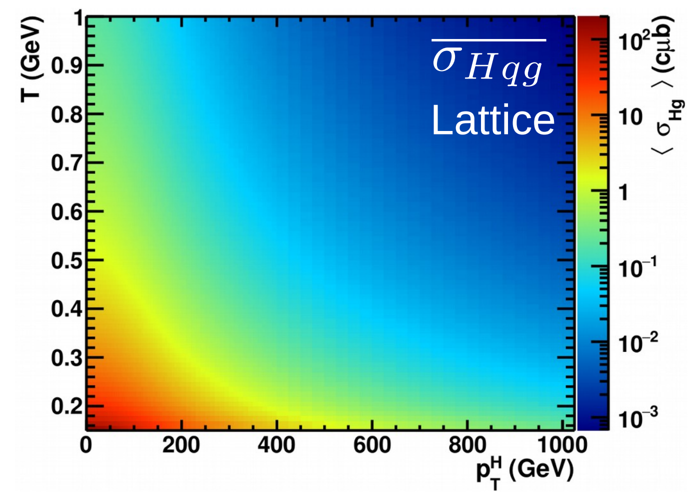
Conclusions

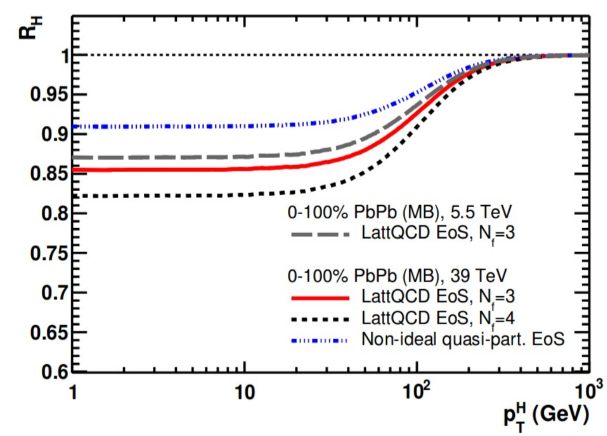
- Higgs parton interactions found to be large; on the level of 1-100μb
  → K=3 assumed from production diagrams

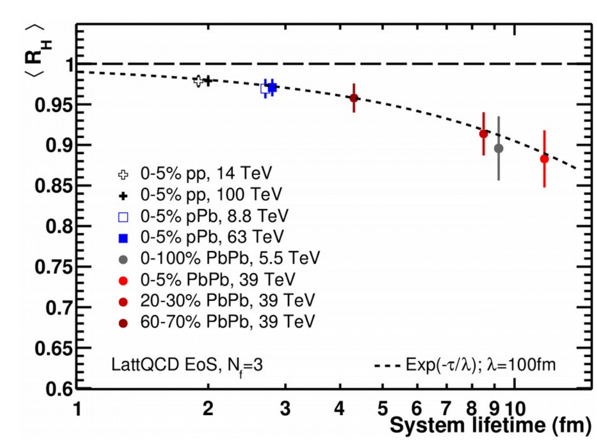
- Our studies lead to a universal stimulated decay rate, resulting larger systems to exhibit a suppression of up to 15%
  → May be accessible at FCC (HE-LHC), where in 1 (10) month ~500 visible Higgs signal counts

- Suppression sensitive to the EOS and mass dependence of the partons leading to about 10% variation

- Our work calls for a theoretical study of the Higgs widths modifications in a QCD medium, compared to the electroweak vacuum.







Extra

NNLO theoretial 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)

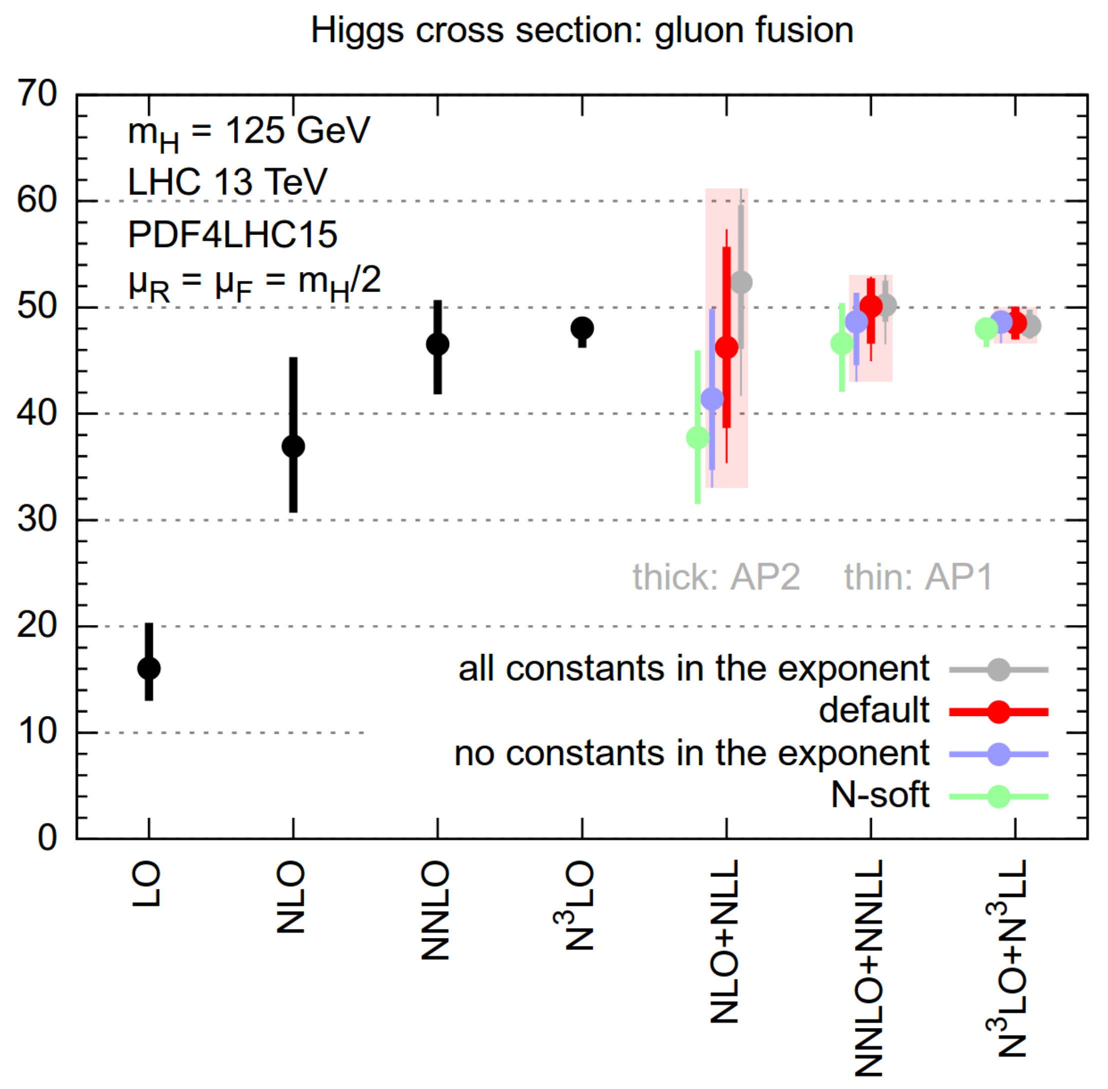
- Higgs $\gamma\gamma$, 4l backgrounds:

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%)

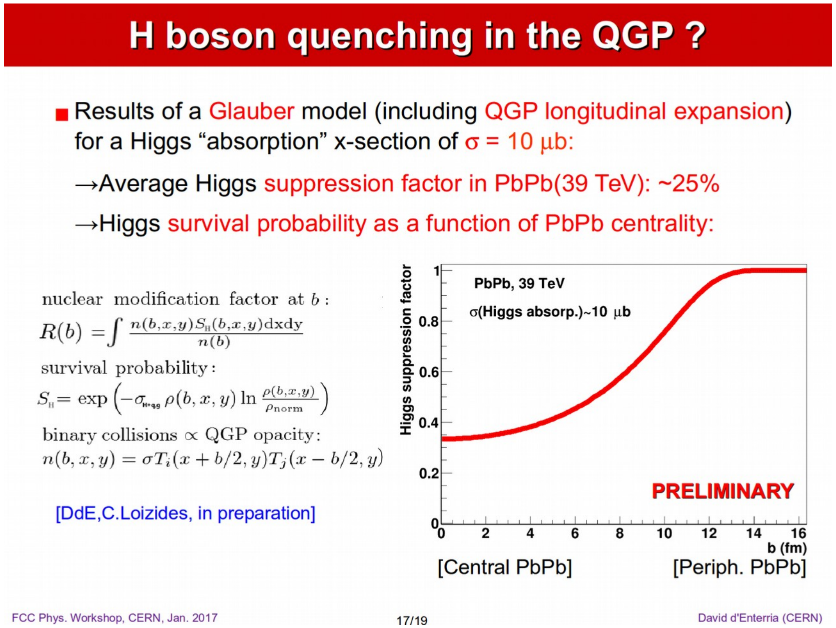
Gluon fusion at various orders

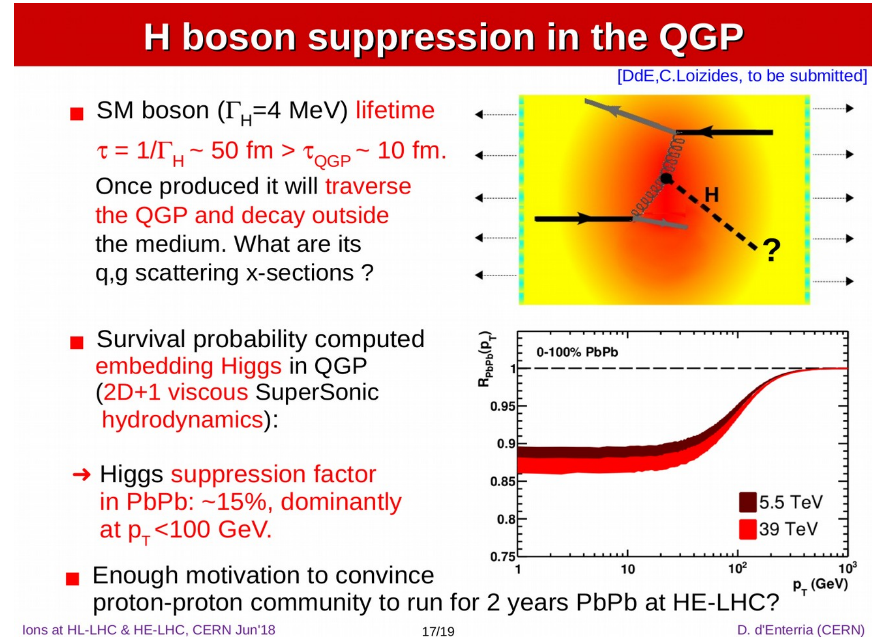
https://www.ge.infn.it/~bonvini/higgs/

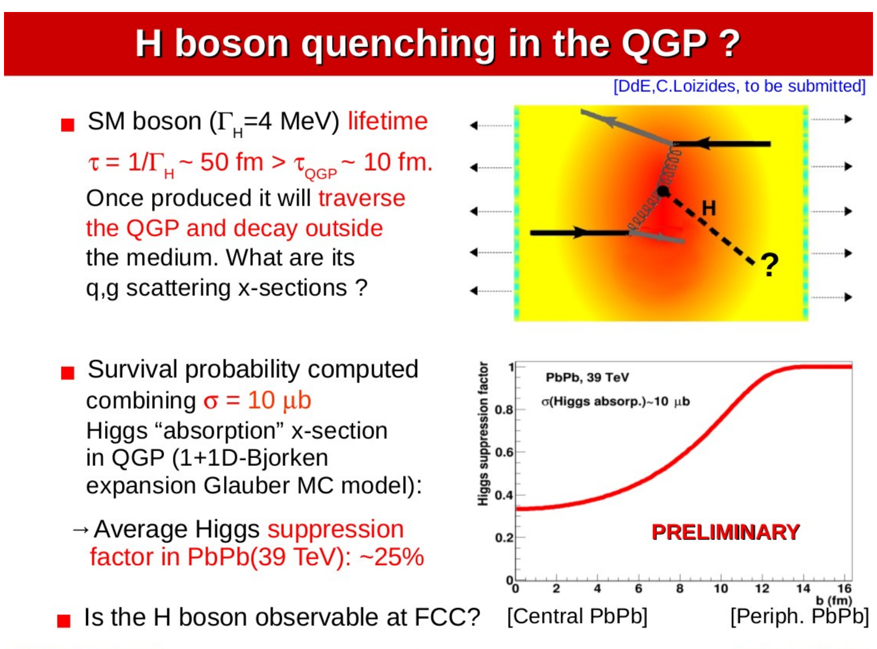


Choice of K-factor = 3 rather conservative for production cross section

History of previously shown results



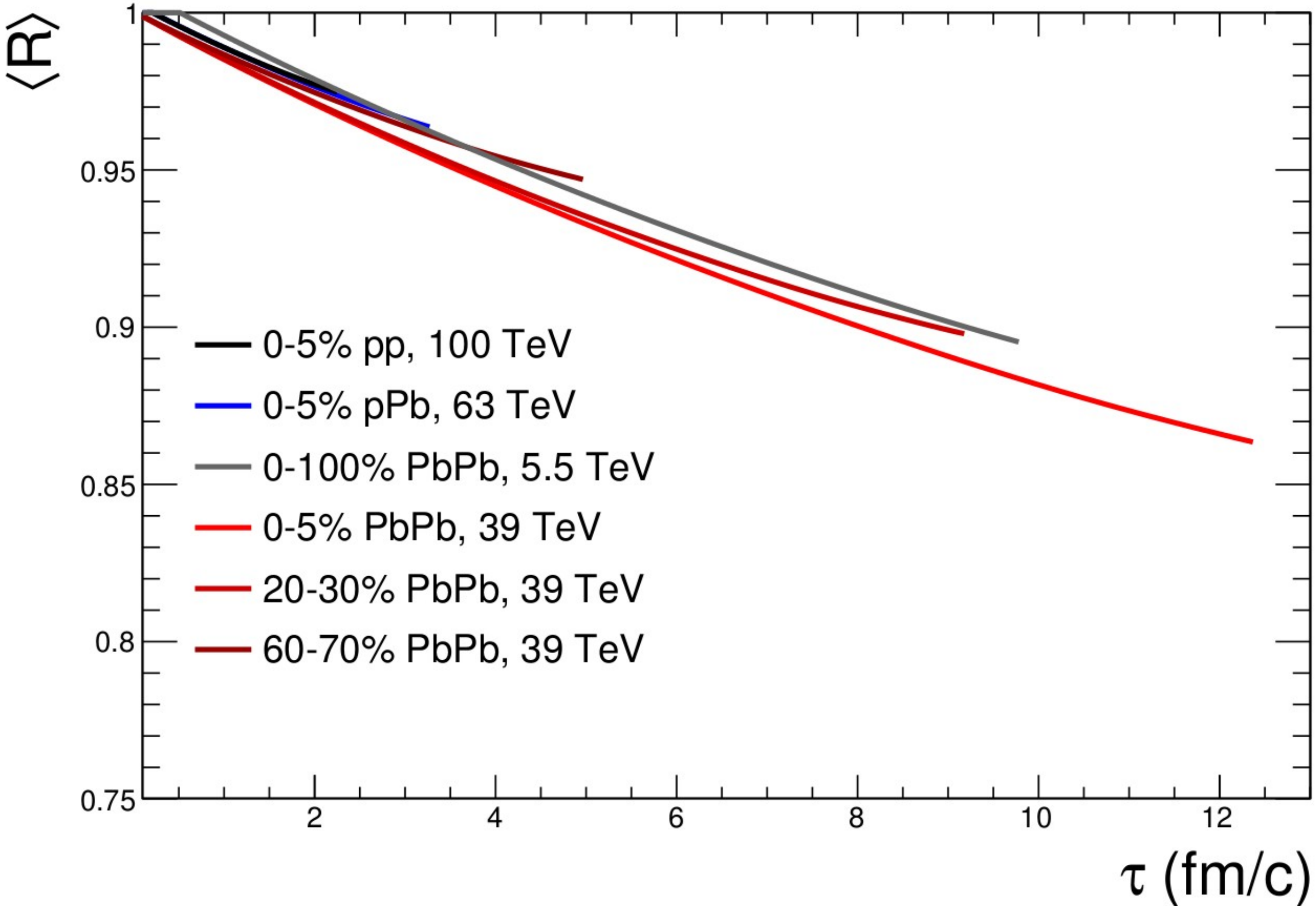




Result shown June 2018 used SU3 EOS, leading to similar suppression.

Results in 2017 (FCC workshop CERN and QM17) used average absorption and only Glauber as model of the medium, and hence overestimated the effect.

Average suppression versus lifetime



- Average suppression versus lifetime of the system