# Physics with ions at the Future Circular Collider

## FCC week 2019

## Brussels, 28th June 2019


**David d'Enterria**

**(for the FCC-ions team)**

**CERN**


**M. Schaumann: Ions at FCC-hh: https://indico.cern.ch/event/727555/contributions/3452761/**

*A. Dainese et al. arXiv:1605.01389; Ch. 16, FCC-CDR EPJC79 (2019) 474; New material*

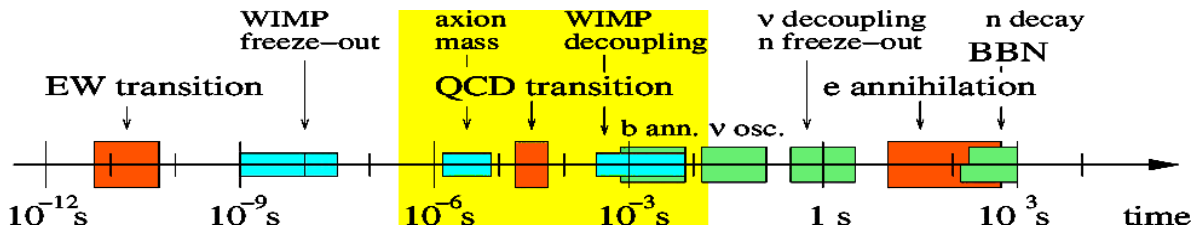
# Unique fundamental physics with heavy-ions

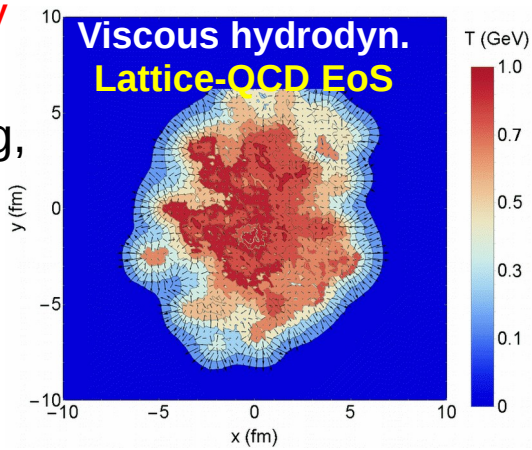
- Central heavy-ion collisions:

1) ONLY way known to experimentally study the thermodynamics & phase transitions of a non-Abelian quantum-field theory. Collective ✔ QCD, ✖ EWK in the lab.

☞ QGP = Least viscous fluid known. Test-bed for string theory applications via AdS/CFT duality.

☞ Understand early Universe "bath" (~1 μs): WIMP decoupling, axion mass, imprints on gravitational wave spectrum? ...

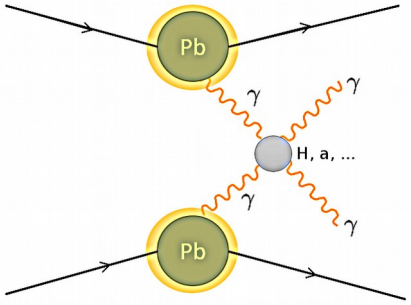



- Ultra-peripheral heavy-ion collisions:

☞ Strongest electromagnetic fields in the Universe (~$10^{15}$ T).

2) Unique SM & BSM studies via photon-photon collisions: light-by-light, axion-like particles, magn. monopoles, Higgs,...




<u>Note</u>: Likely, no other place in Universe produces Pb-Pb collisions at multi-TeV c.m. energies (heaviest cosmic-rays colls.: Fe-Air up to $\sqrt{s_{max}} \approx 400$ TeV).

# Heavy-ion collisions at the FCC-hh

- CM energy $\sqrt{s}$ = 100 TeV for pp means: $\sqrt{s_{NN}} = \sqrt{s}\sqrt{Z_1 Z_2 / A_1 A_2}$ for A-A colls.

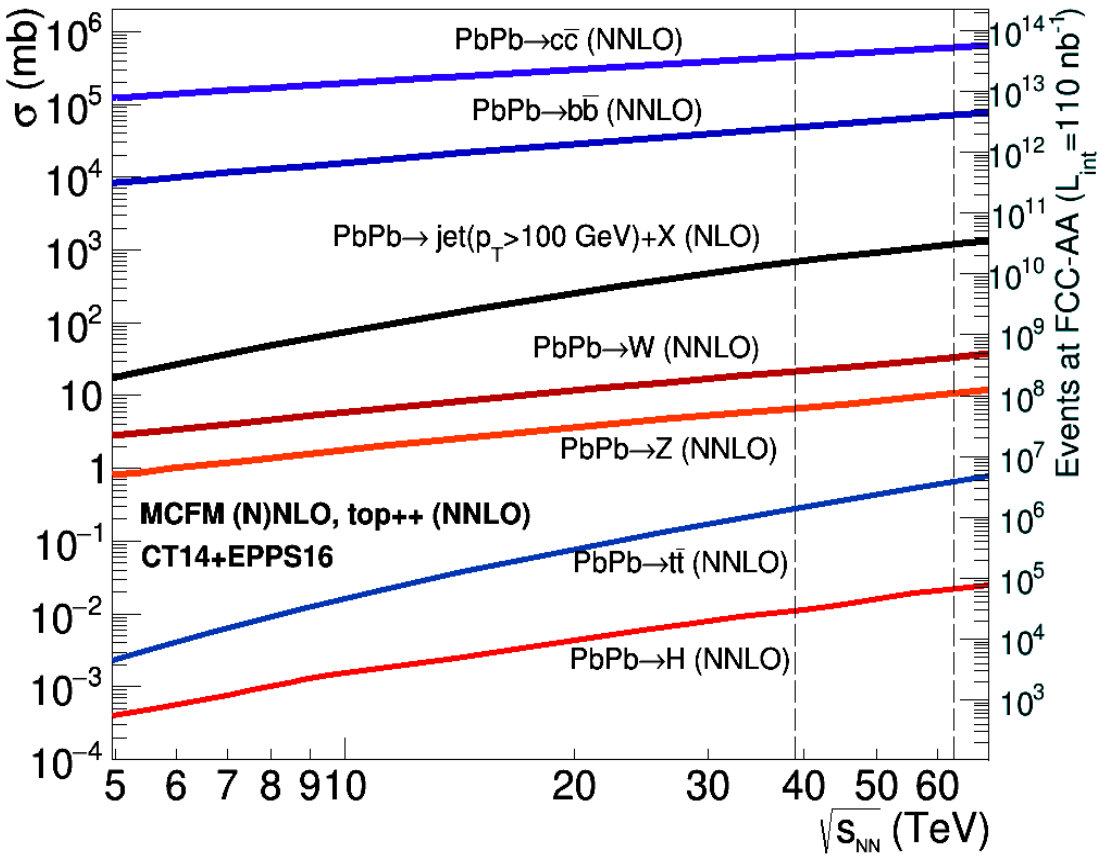
  PbPb: $\sqrt{s_{NN}}$ = 39 TeV, $L_{int}$ = 110 $nb^{-1}$/month

  pPb: $\sqrt{s_{NN}}$ = 63 TeV, $L_{int}$ = 29 $pb^{-1}$/month

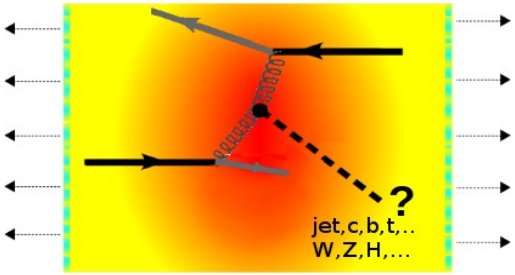
  **$\sqrt{s_{NN}}$: ×7 larger than LHC**

  **$L_{int}$: ×10–30 larger than LHC**

- Huge increase in pQCD cross sections (yields) to probe QGP:




- Charm: ×4 (40) LHC
- Bottom: ×6 (60) LHC
- 100-GeV jets: ×30 (300) LHC
- W: ×7 (70) LHC
- Z : ×7 (70) LHC
- Top: ×80 (800) LHC
- Higgs: ×20 (200) LHC



# PbPb(39 TeV): Bulk QGP properties

| Quantity | Pb–Pb 2.76 TeV | Pb–Pb 5.5 TeV | Pb–Pb 39 TeV |
|---|---|---|---|
| $dN_{ch}/d\eta$ at $\eta = 0$ | 1600 | 2000 | 3600 |
| Total $N_{ch}$ | 17000 | 23000 | 50000 |
| $dE_T/d\eta$ at $\eta = 0$ | 1.8–2.0 TeV | 2.3–2.6 TeV | 5.2–5.8 TeV |
| Homogeneity volume | 5000 fm$^3$ | 6200 fm$^3$ | 11000 fm$^3$ |
| Decoupling time | 10 fm/$c$ | 11 fm/$c$ | 13 fm/$c$ |
| $\epsilon$ at $\tau = 1$ fm/$c$ | 12–13 GeV/fm$^3$ | 16–17 GeV/fm$^3$ | 35–40 GeV/fm$^3$ |

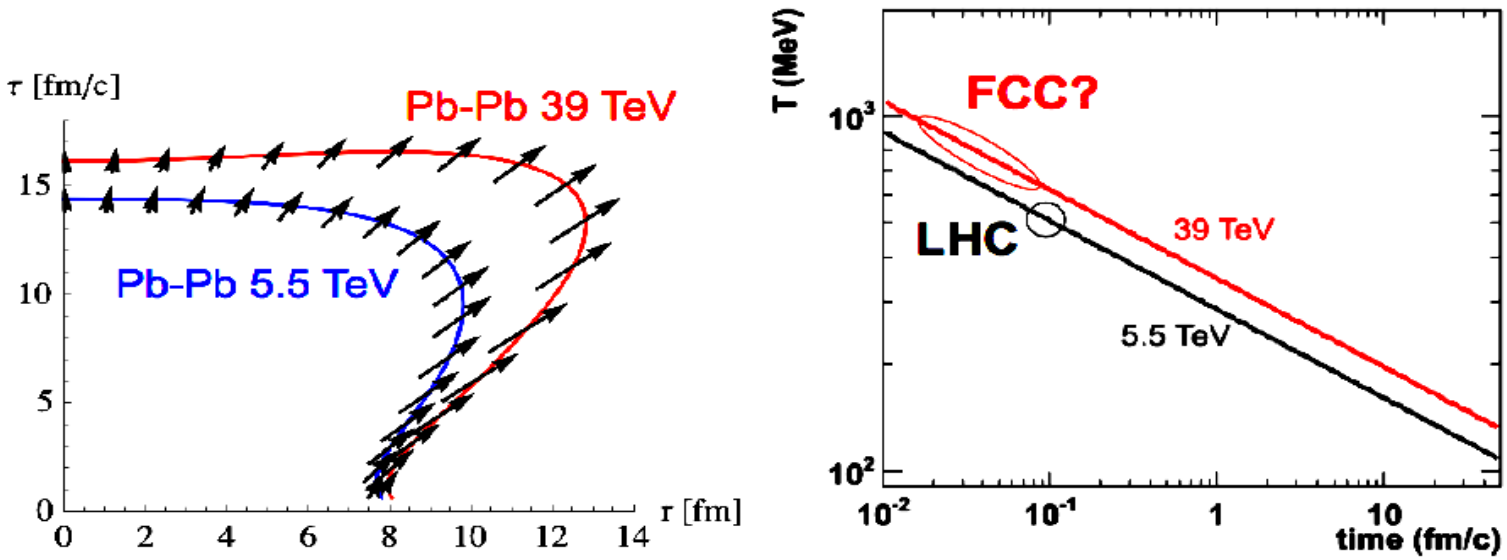
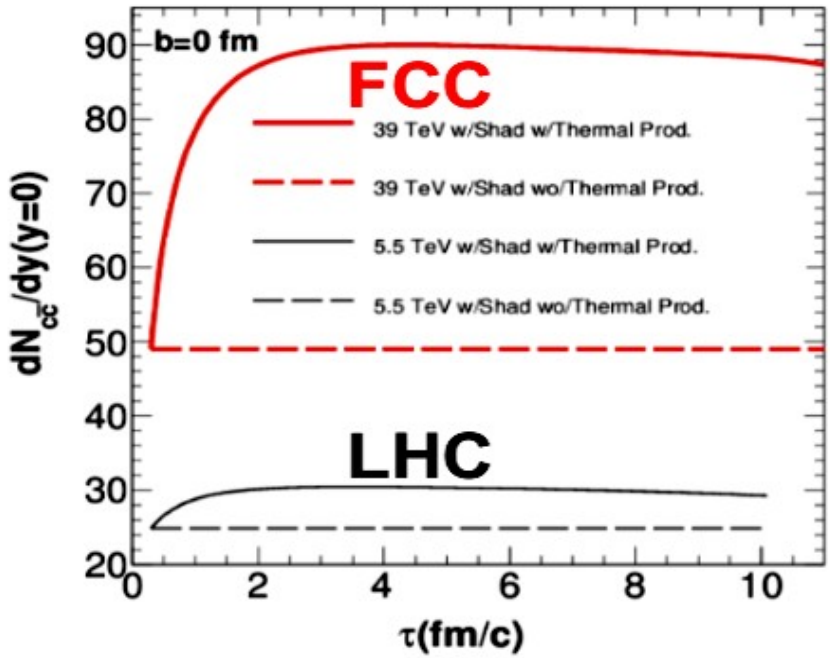



Fig. 2: Left: space-time profile at freeze-out from hydrodynamical calculations for central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV and 39 TeV. Right: time evolution of the QGP temperature as estimated on the basis of the Bjorken relation and the Stefan-Boltzmann equation (see text for details).

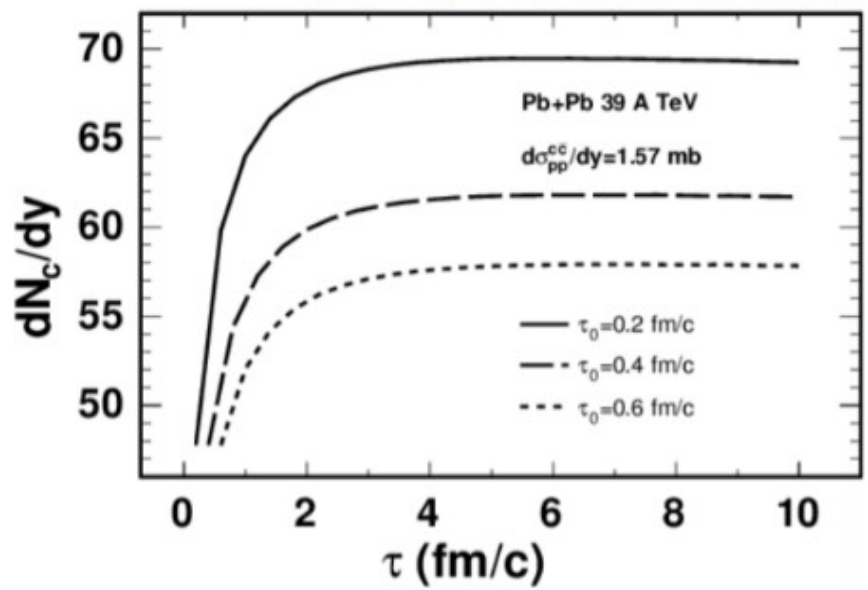
**×2–2.5 larger particle & energy densities (~40 GeV/fm$^3$) than LHC**

# PbPb(39 TeV): Thermalized charm in QGP

- Expect abundant secondary production of $c\bar{c}$ pairs in the medium from $gg \to c\bar{c}$, $q\bar{q} \to c\bar{c}$ + NLO … **(~500 $c\bar{c}$ pairs!)**




K. Zhou et al., arXiv:1602.01667
C.M. Ko, Y. Liu, arXiv:1604.01207

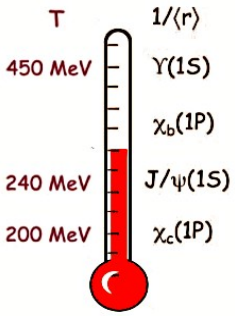


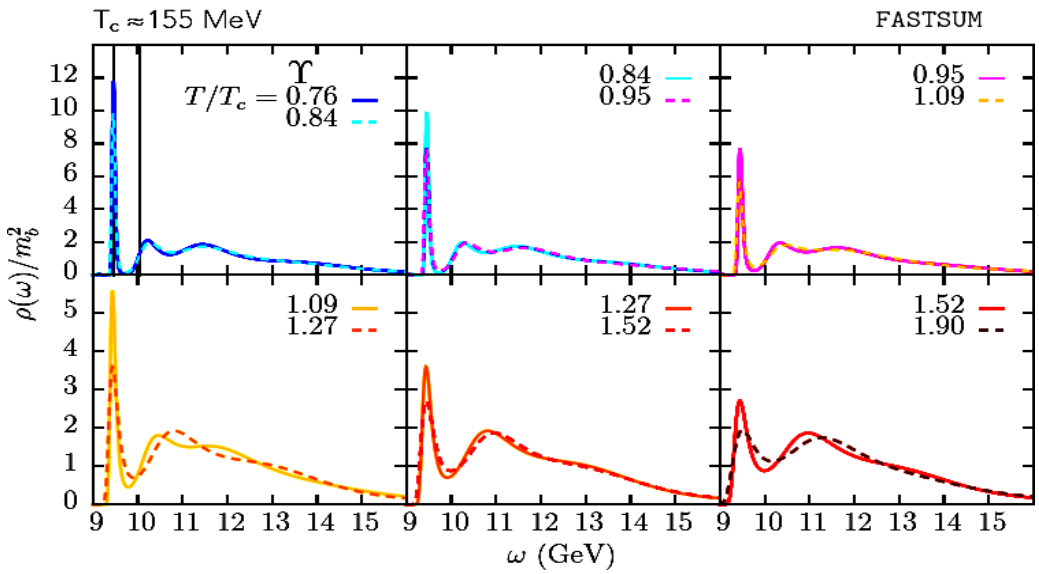

- Up to 50-100% "enhancement" wrt primary charm
- Sensitive to QGP properties: T vs τ, and $\tau_0$ **(active *ndof* in QCD EoS)**

**×3 larger charm-anticharm densities than at the LHC**

# PbPb(39 TeV): $Q\bar{Q}$ melting & recombination in QGP

- FCC ($T_0$~1GeV) can probe QGP temperature through Y(1S) "melting" expected by lattice-QCD at T = 4–5 $T_c$

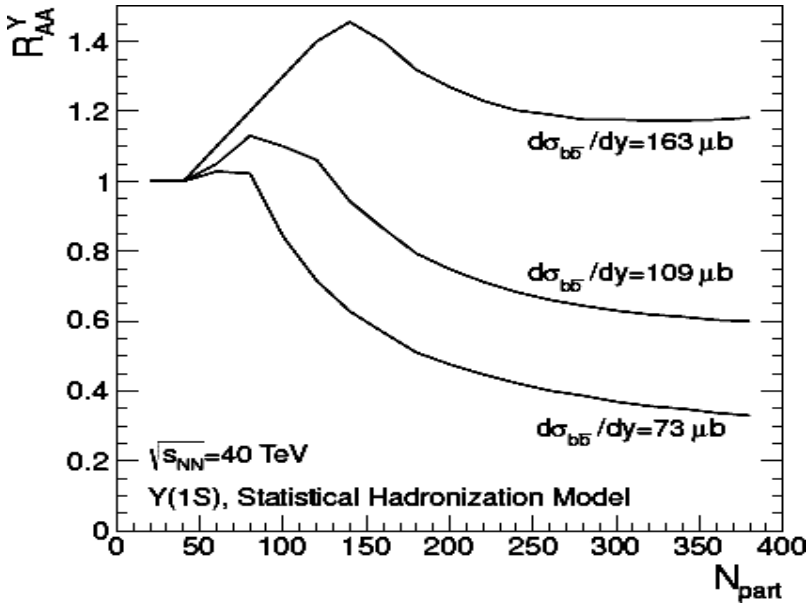



[G. Aarts et al, JHEP 07 (2014) 097]

- Melting compensated by b-$\bar{b}$ recombination? Density of bottom pairs large enough for Y(1S) recombination?

[A.Andronic, et al., JPG38 (2011) 124081]

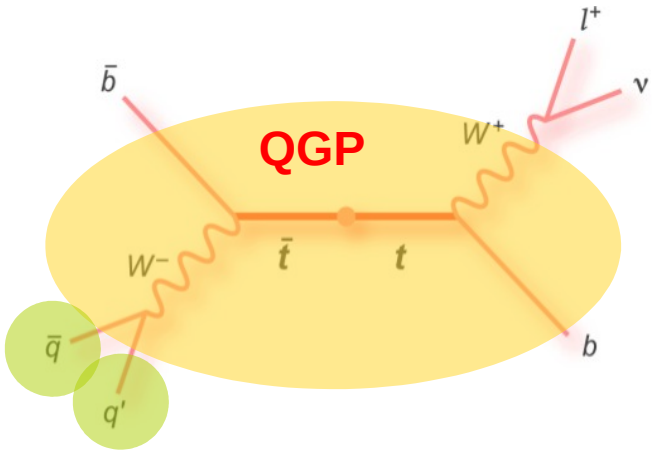


# PbPb(39 TeV): Boosted-top quark in QGP

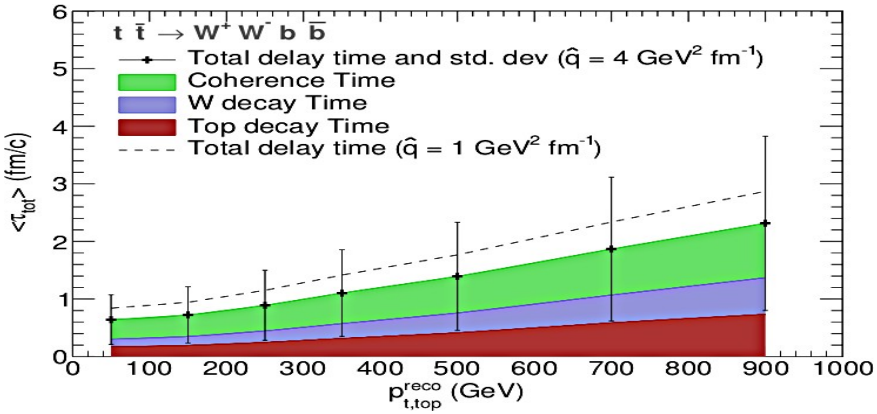
- Top-quark decays (τ~0.1 fm/c) before hadronization into W+b. But, boosted t→W→qq' traverses QGP:

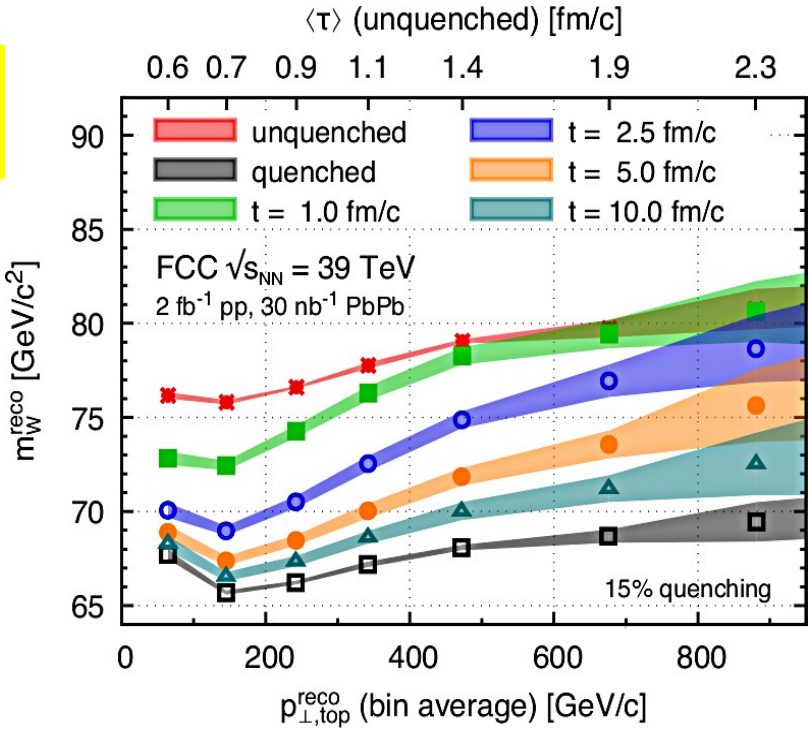
  t → b + 2jets (66%)
  ttbar → bbar + 2jets + 1ℓ + MET(ν) (45%)

→ Colour reconnection of decay b,q,q'?
→ Enhanced gluon radiation in QGP?
→ Boosted t-tbar = Color-singlets probe medium opacity at diff. time scales:



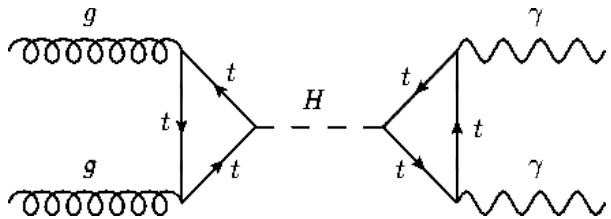

- Reconstructed $m_W(qq)$ vs $p_T(t)$ provides space-time QGP tomography:



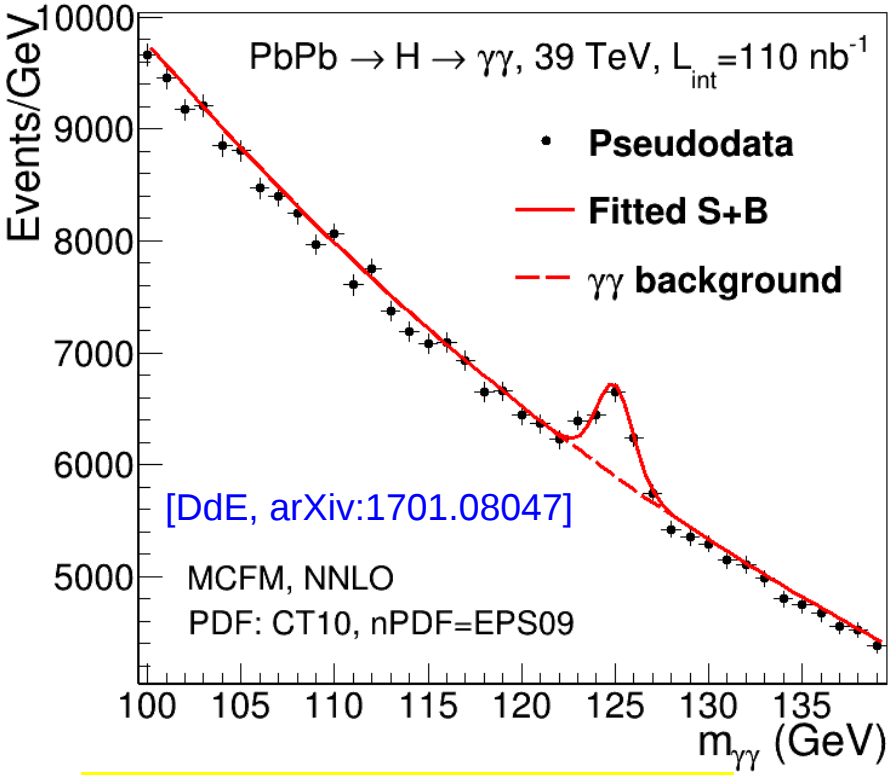

[Apolinaro et al, PRL (2018); 1711.03105]

# PbPb(39 TeV): H→γγ in the QGP

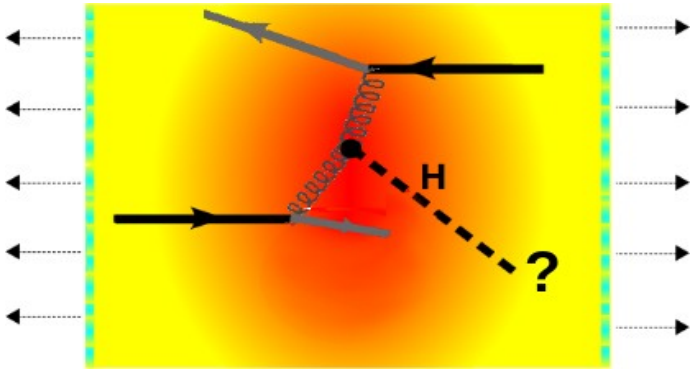


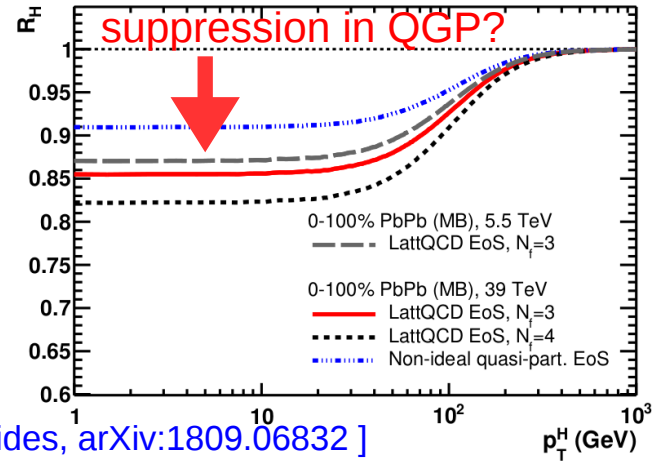

Analysis based on NNLO MCFM cross sections.
Pseudo-data for H(γγ) and γγ backgrounds after typical CMS/ATLAS cuts

- Pb-Pb @ 39 TeV ($L_{int}$= 110 $nb^{-1}$)




- Higgs boson (τ~50 fm) final-state interaction in QGP?




- S/√B~5.7σ observation in just 1st month

[DdE,C.Loizides, arXiv:1809.06832 ]

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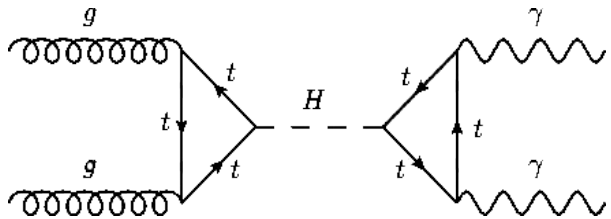


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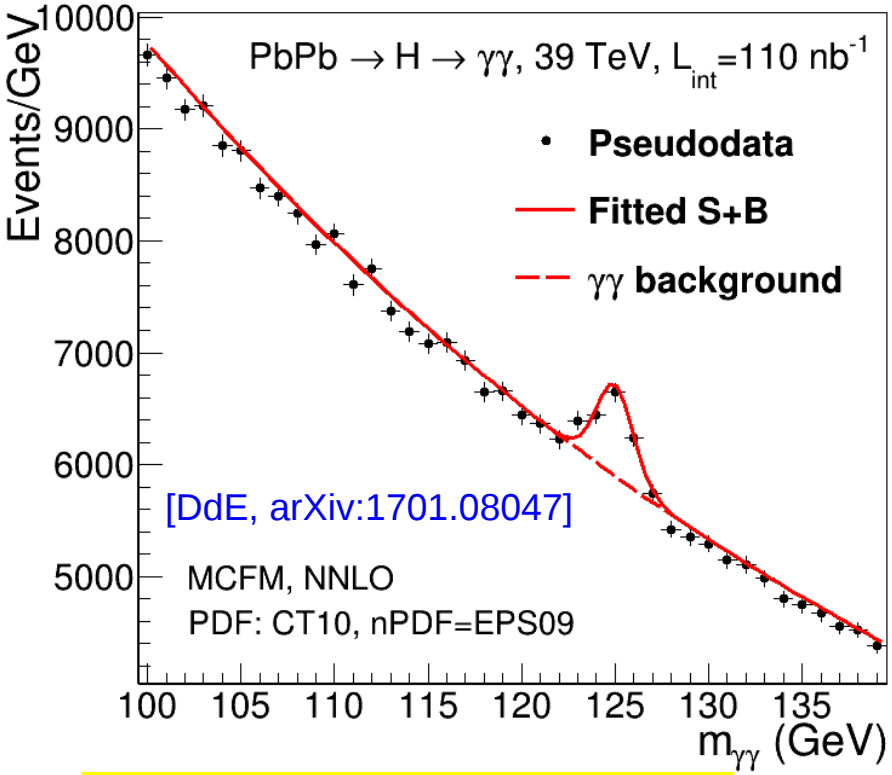


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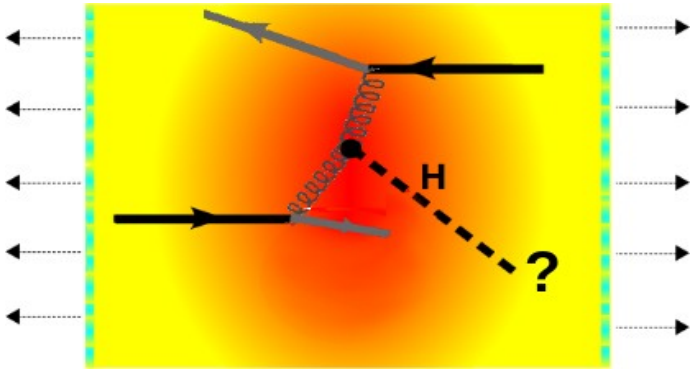



[Ghiglieri & Wiedemann, arXiv:1901.04503]

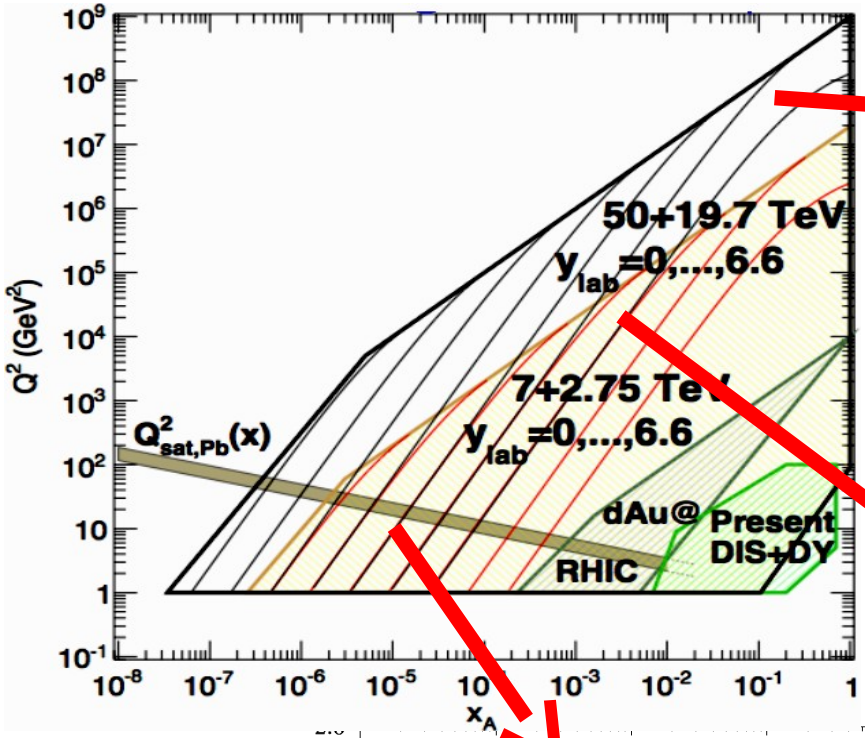
$$\delta\Gamma_{H\to gg} = -\Gamma^{\rm vac}_{H\to gg}\alpha_{\rm s}\frac{T^4}{M_H^4}\frac{112\,\pi^3}{45}\left(8-n_f^T\right)$$

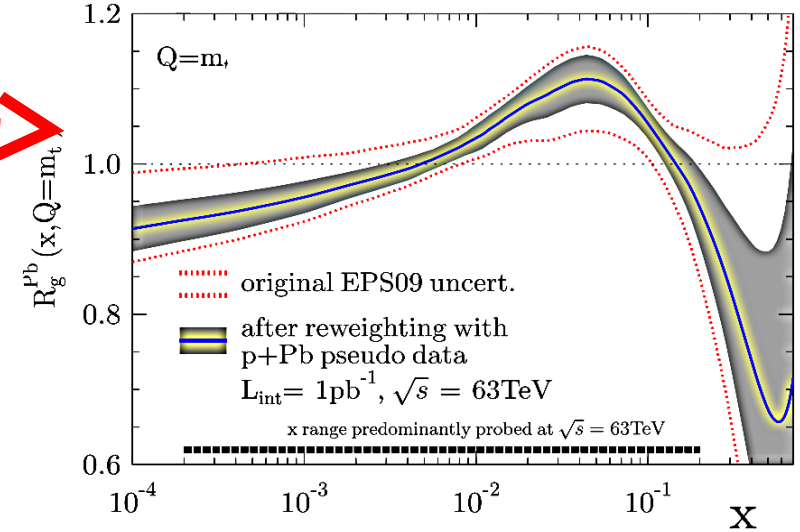
for $H$-decay in the plasma rest frame.

- Negligible modification of Higgs decay width in QGP ~ $(T/m_H)^4$~$10^{-6}$...

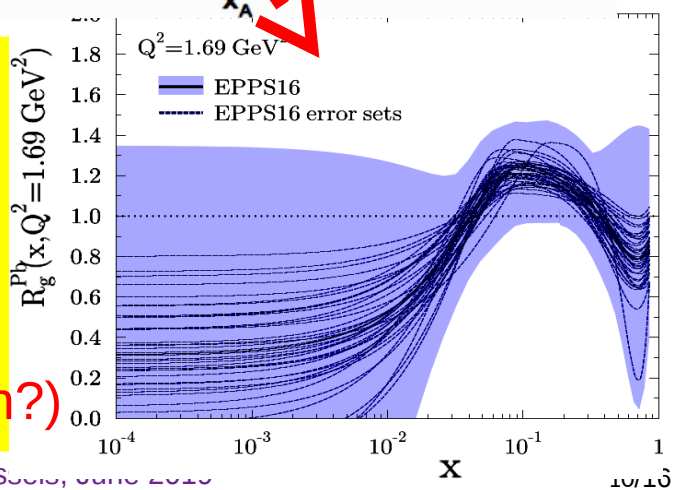
# pPb(63 TeV): Nuclear parton distrib. functions

- Huge nPDF kinematical reach: $Q^2$~2–4·$10^8$ $GeV^2$, x~1–$10^{-7}$

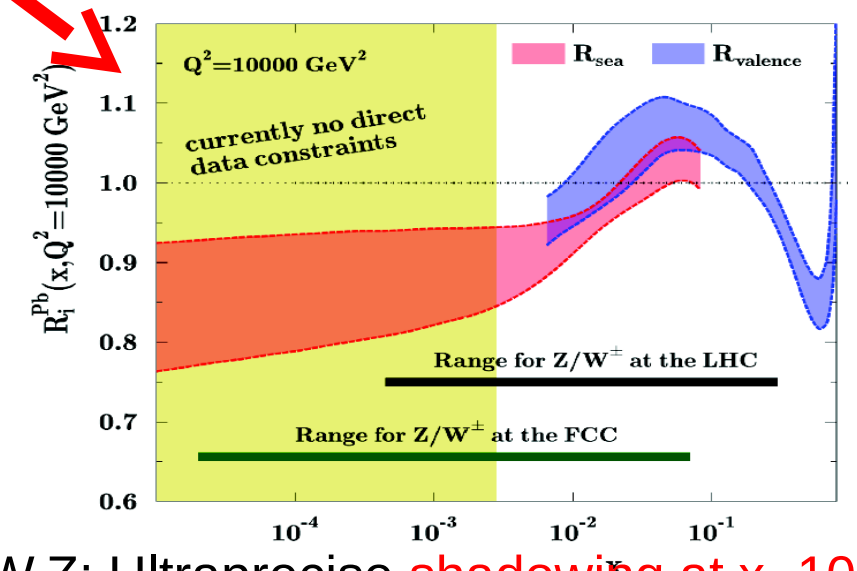



top($l^+l^-$): Antishadow.&EMC at x > 0.1




Unknown nuclear gluon at x<$10^{-4}$ (saturation?)




W,Z: Ultraprecise shadowing at x~$10^{-3}$

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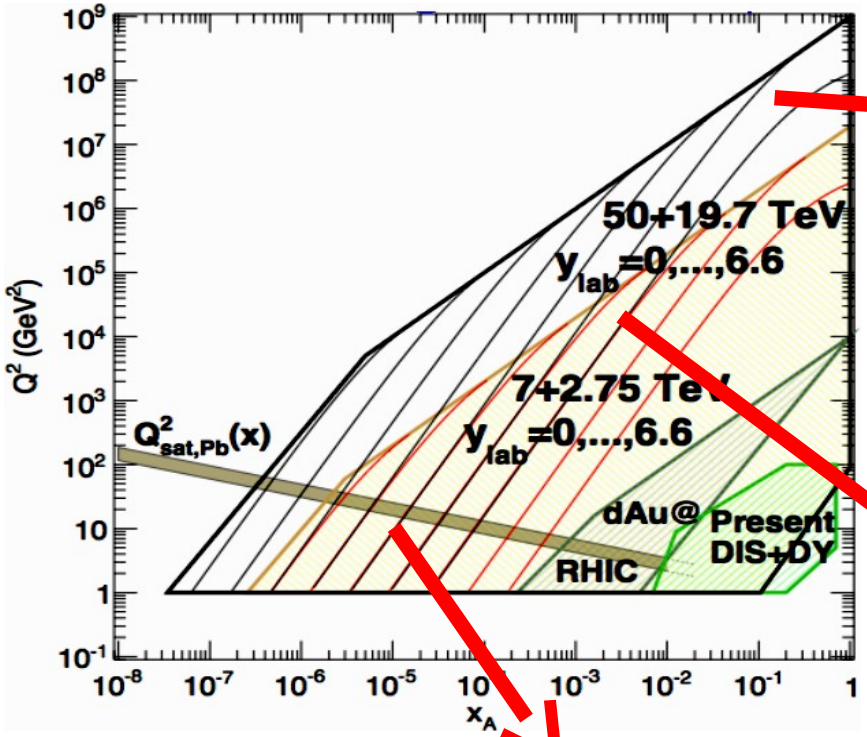
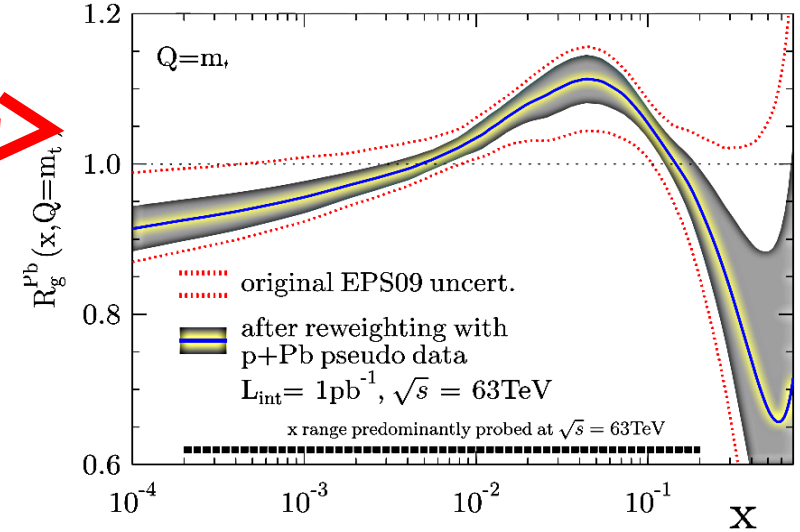
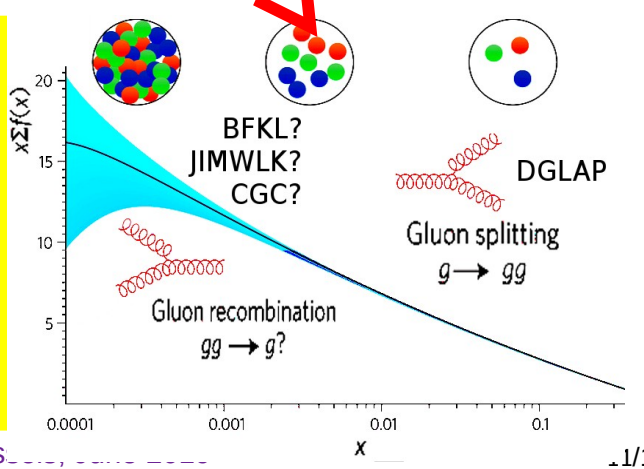
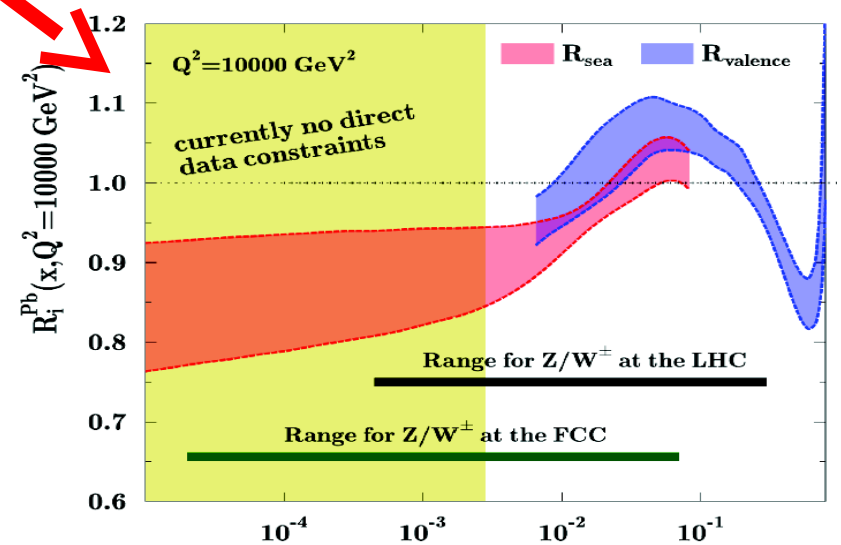



top($l^+l^-$): Antishadow.&EMC at x > 0.1

DGLAP breakdown below $x<10^{-4}$ (CCG?)



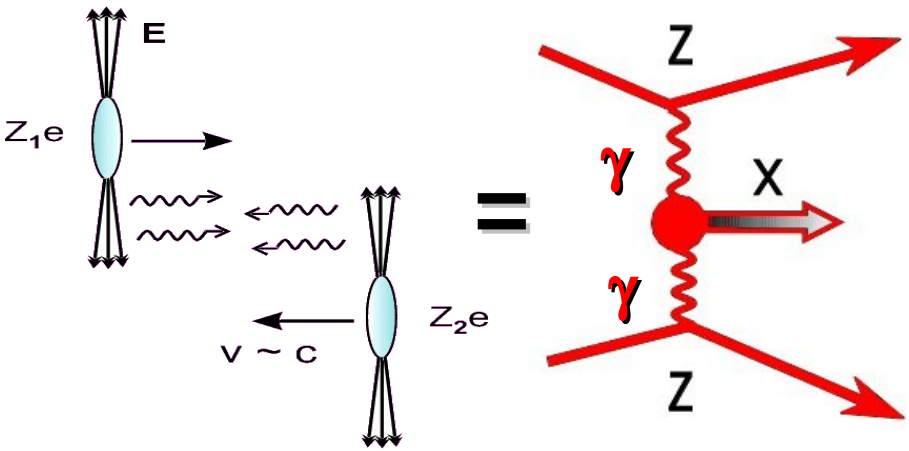




W,Z: Ultraprecise shadowing at x~$10^{-3}$

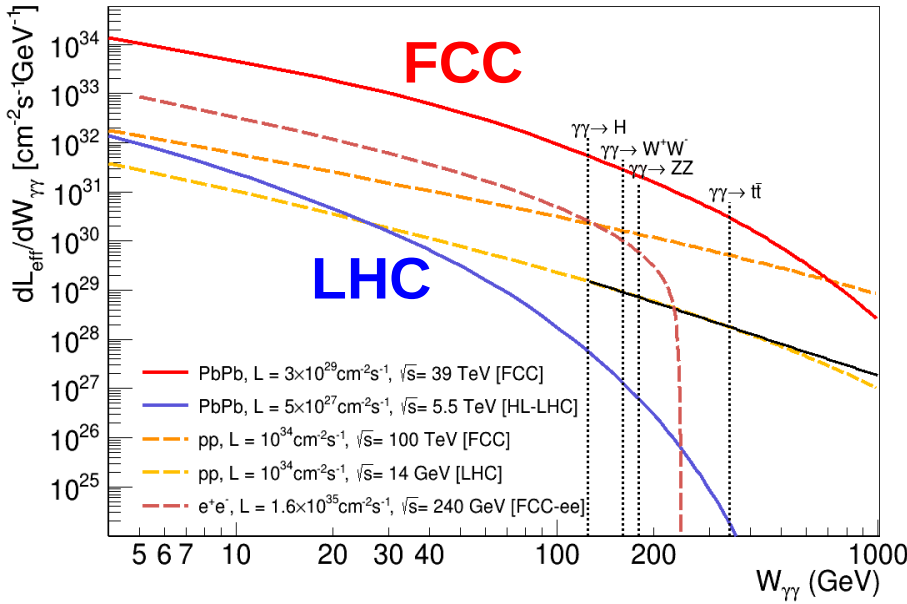
# PbPb(39 TeV): SM & BSM via γγ collisions

- Huge γγ luminosities in AA thanks to collective action of Z=82 charges:

$$\sigma_{PbPb\to\gamma\gamma\to H} \approx Z^4 \times \sigma_{pp\to H} = 5\cdot 10^7 \times \sigma_{pp\to\gamma\gamma\to H}$$

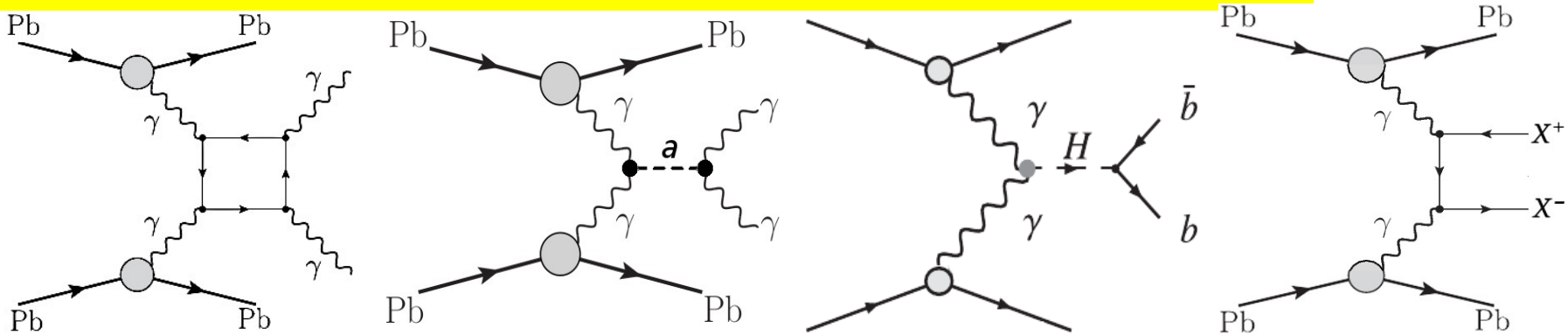



- Large eff. lumi up to $\sqrt{s_{\gamma\gamma}}$~1 TeV




Ultraperipheral interactions: Nuclei survive.

- Unique SM & BSM γ–γ processes acessible without pileup:



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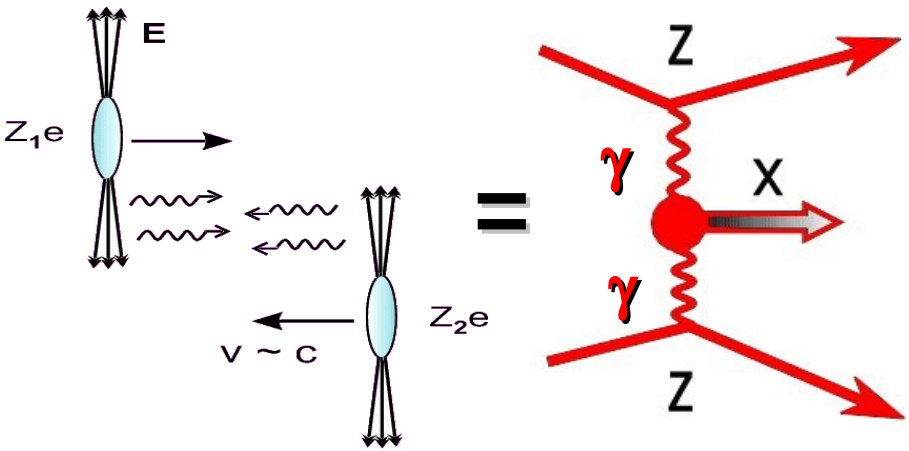


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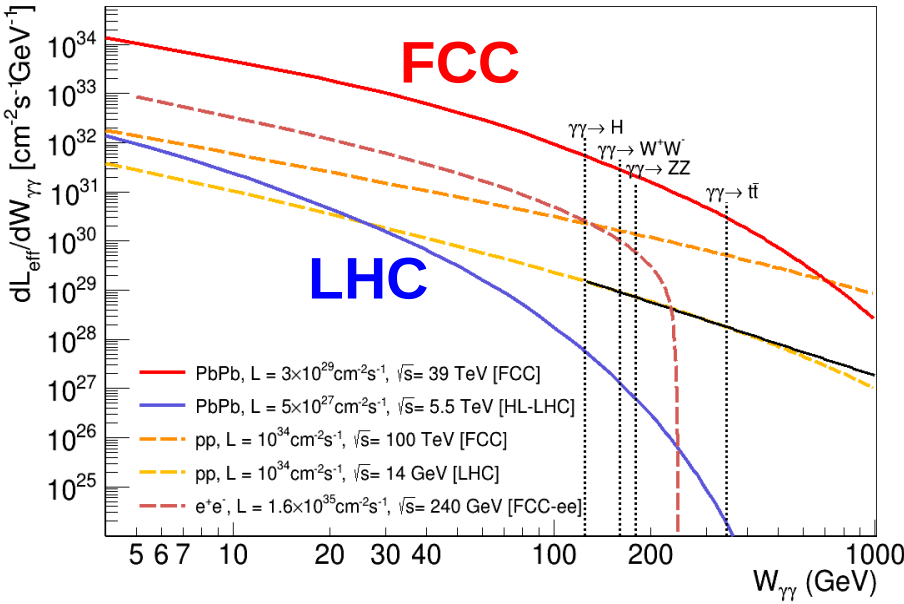
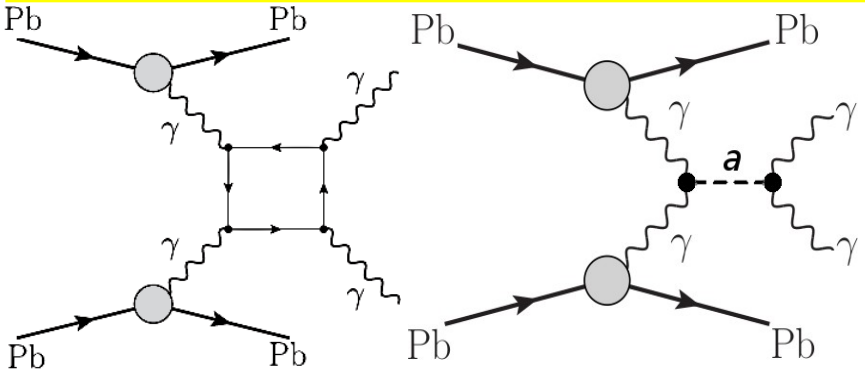
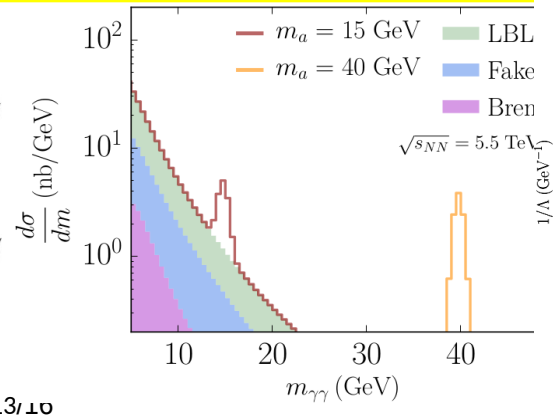
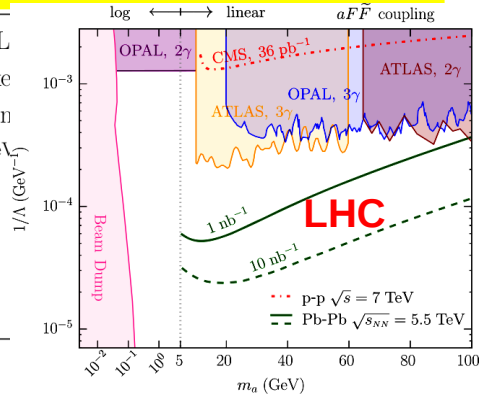



Ultraperipheral interactions: Nuclei survive.

- Unique SM & BSM γ–γ processes acessible without pileup (e.g. ALPs):



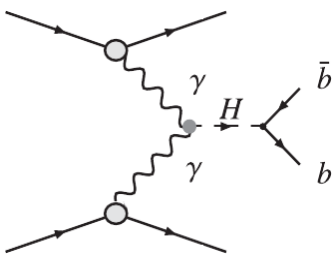



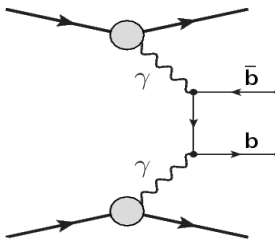
# PbPb(39 TeV): Higgs boson via γ-γ → H → bb

- Expected exclusive Higgs over bb background after cuts:

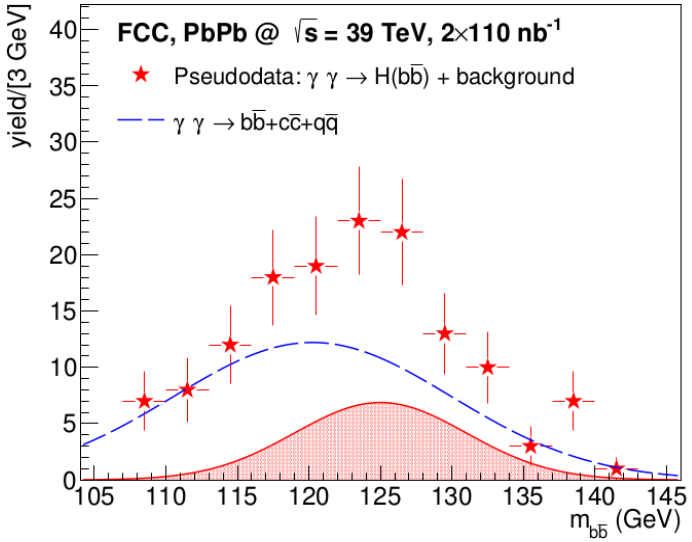
| System | Nominal runs $\mathcal{L}_{AB}$ ($cm^{-2}\,s^{-1}$) | $\Delta t$ (s) | $\langle N_{pileup}\rangle$ | $N_{Higgs}$ total ($H \to b\bar{b}$) | Upgraded $pA$ scenario $\mathcal{L}_{AB}$ ($cm^{-2}\,s^{-1}$) | $\Delta t$ (s) | $\langle N_{pileup}\rangle$ | $N_{Higgs}$ total ($H \to b\bar{b}$) |
|---|---|---|---|---|---|---|---|---|
| $pp$ (14 TeV) | $10^{34}$ | $10^7$ | 25 | 77 (55) | $10^{34}$ | $10^7$ | 25 | 77 (55) |
| $p$Pb (8.8 TeV) | $1.5 \cdot 10^{29}$ | $10^6$ | 0.05 | 0.050 (0.035) | $1 \cdot 10^{31}$ | $10^7$ | 1 | 34 (25) |
| PbPb (5.5 TeV) | $5 \cdot 10^{26}$ | $10^6$ | $5 \cdot 10^{-4}$ | 0.009 (0.007) | $5 \cdot 10^{26}$ | $10^7$ | $5 \cdot 10^{-4}$ | 0.15 (0.1) |

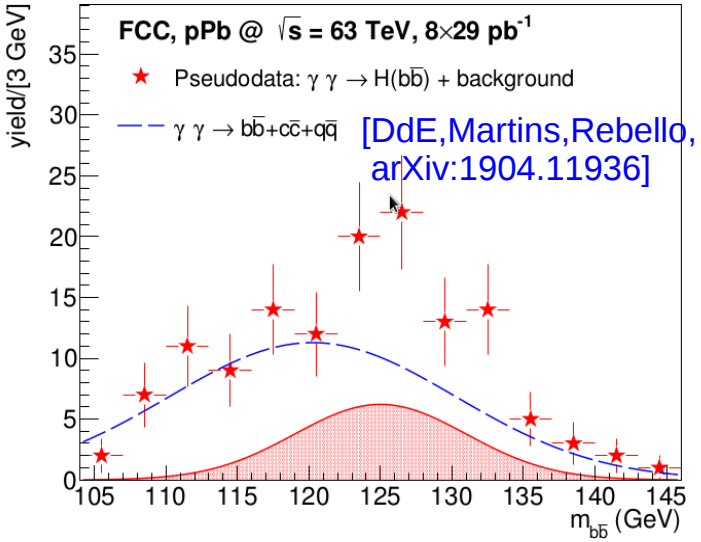



| PbPb at $\sqrt{s_{NN}}$ = 39 TeV | cross section ($b$-jet (mis)tag efficiency) | visible cross section after $p_T^j, \cos\theta_{jj}, m_{jj}$ cuts | $N_{evts}$ ($\mathcal{L}_{int}$ = 110 $nb^{-1}$) |
|---|---|---|---|
| $\gamma\gamma \to H \to b\bar{b}$ | 1.02 nb (0.50 nb) | 0.19 nb | 21.1 |
| $\gamma\gamma \to b\bar{b}$ [$m_{b\bar{b}}$=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 |




- 5σ significance in first PbPb (pPb) month (year):




[DdE,Martins,Rebello, arXiv:1904.11936]

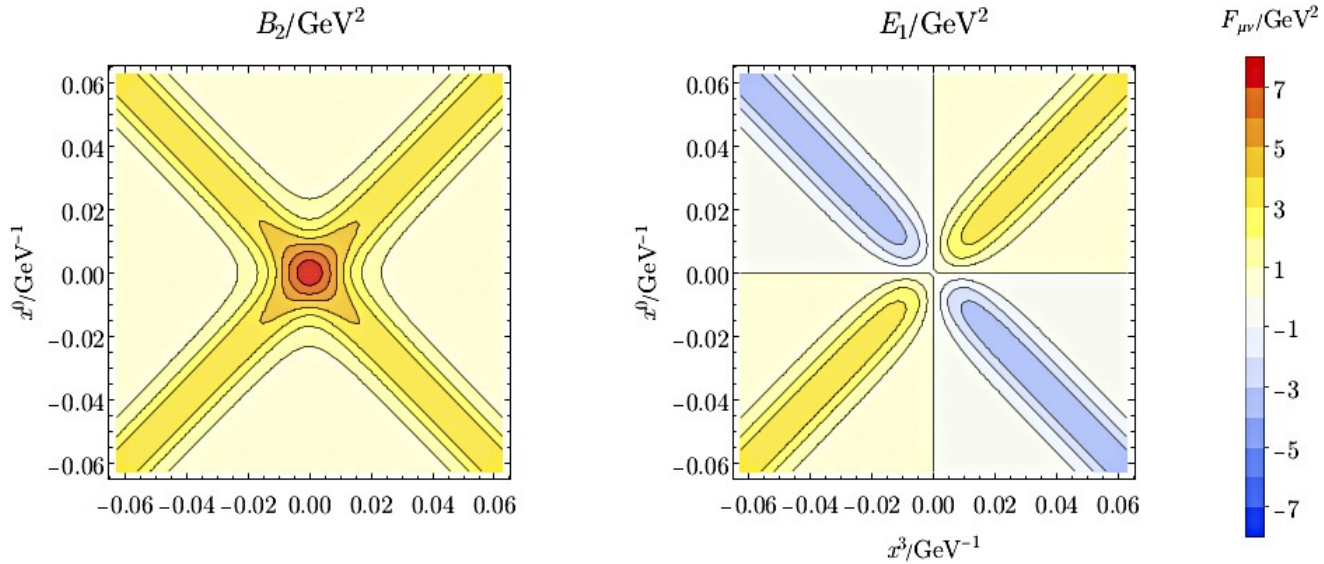
→ Measurement of H-γ coupling not based on decay but s-channel prod.

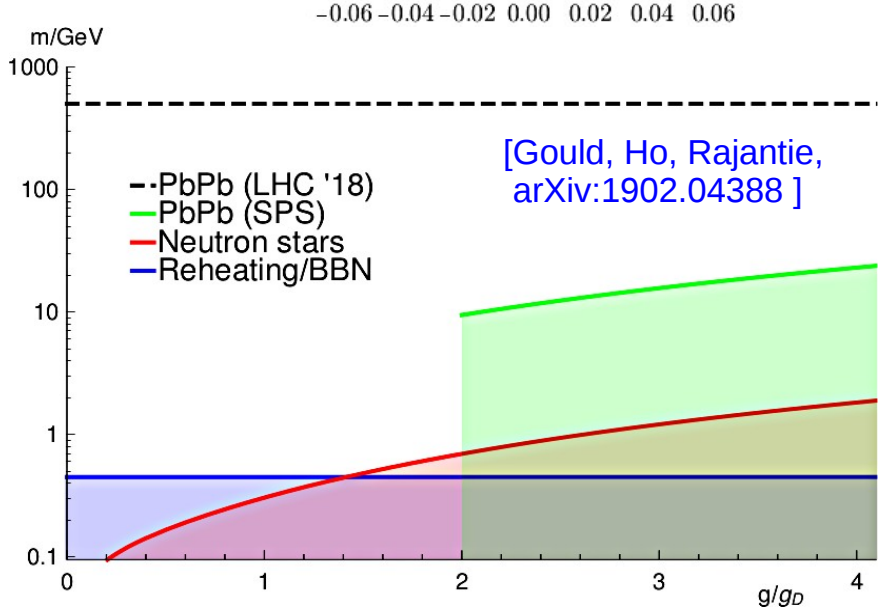
→ Total Higgs width via:

$$\Gamma_H^{tot} = \Gamma(H \to \gamma\gamma)/\mathcal{B}(H \to \gamma\gamma)$$

# PbPb(39 TeV): BSM searches (e.g. magnetic mopoles)

Magnetic fields produced in peripheral heavy-ion collisions are the strongest known in the universe, $\sim 7.5\mathrm{GeV}^2$ at LHC energies.



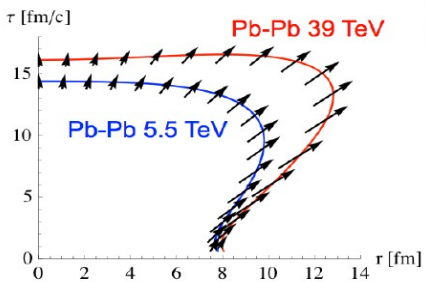

- Magnetic monopoles:
  - Explain charge quantization.
  - Predicted by GUT/string theory.
- 't Hooft-Polyakov magn.monopoles not accesible in p-p,$e^+e^-$ collisions (pair prod. expon. suppressed), but x-section $\sigma \sim \exp(-m^2/(gB))$:

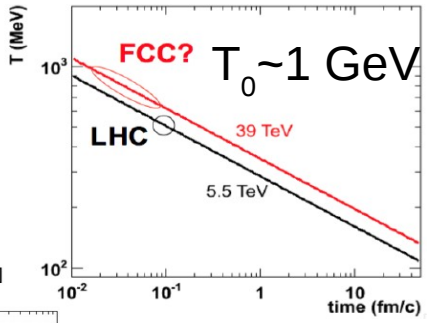
Unique FCC mass bounds m>1 TeV

# Unique heavy-ion physics at FCC

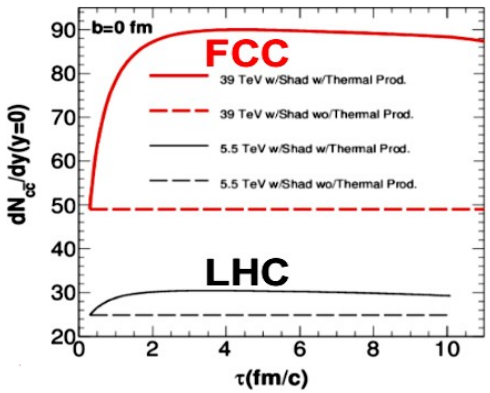
- Unparalleled physics possibilities at ×7 & ×10 larger √s & $L_{int}$ than LHC:

**energy densities: ~40 GeV/fm³**

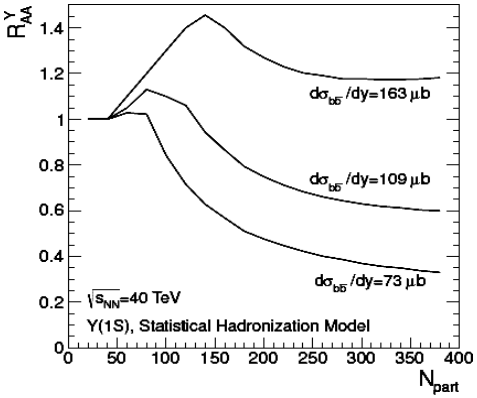


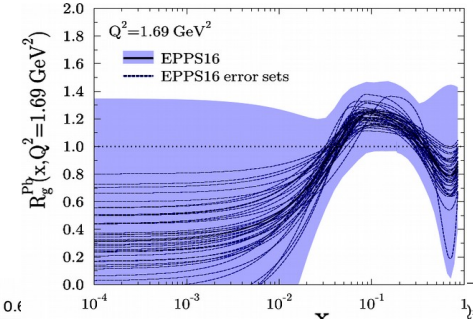




**~500 charm pairs in QGP**

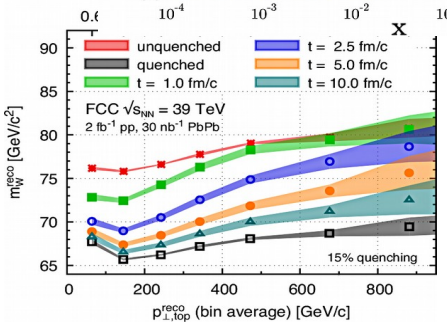


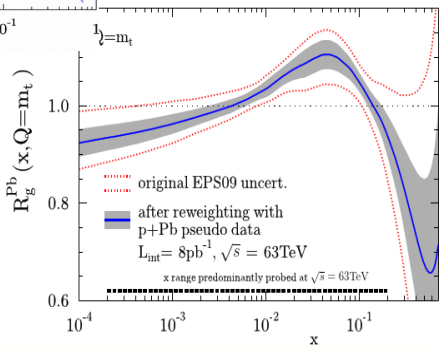

**Y(1S) melt.+recomb.?**



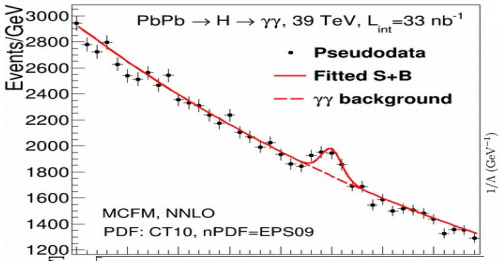

**Gluon saturation down to x~10⁻⁷**

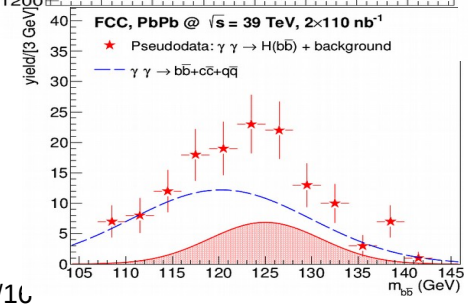


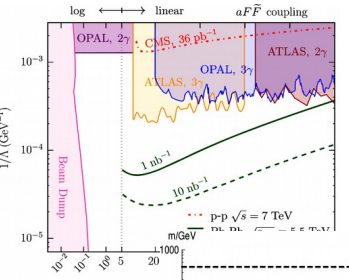

**Top quark = Parton rad. "chrono-fmeter" & high-x gluon nPDF probe**

**Higgs in QGP & γ–γ**

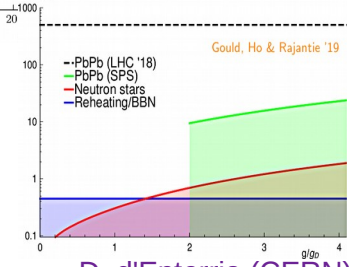



**BSM via γ–γ colls.**

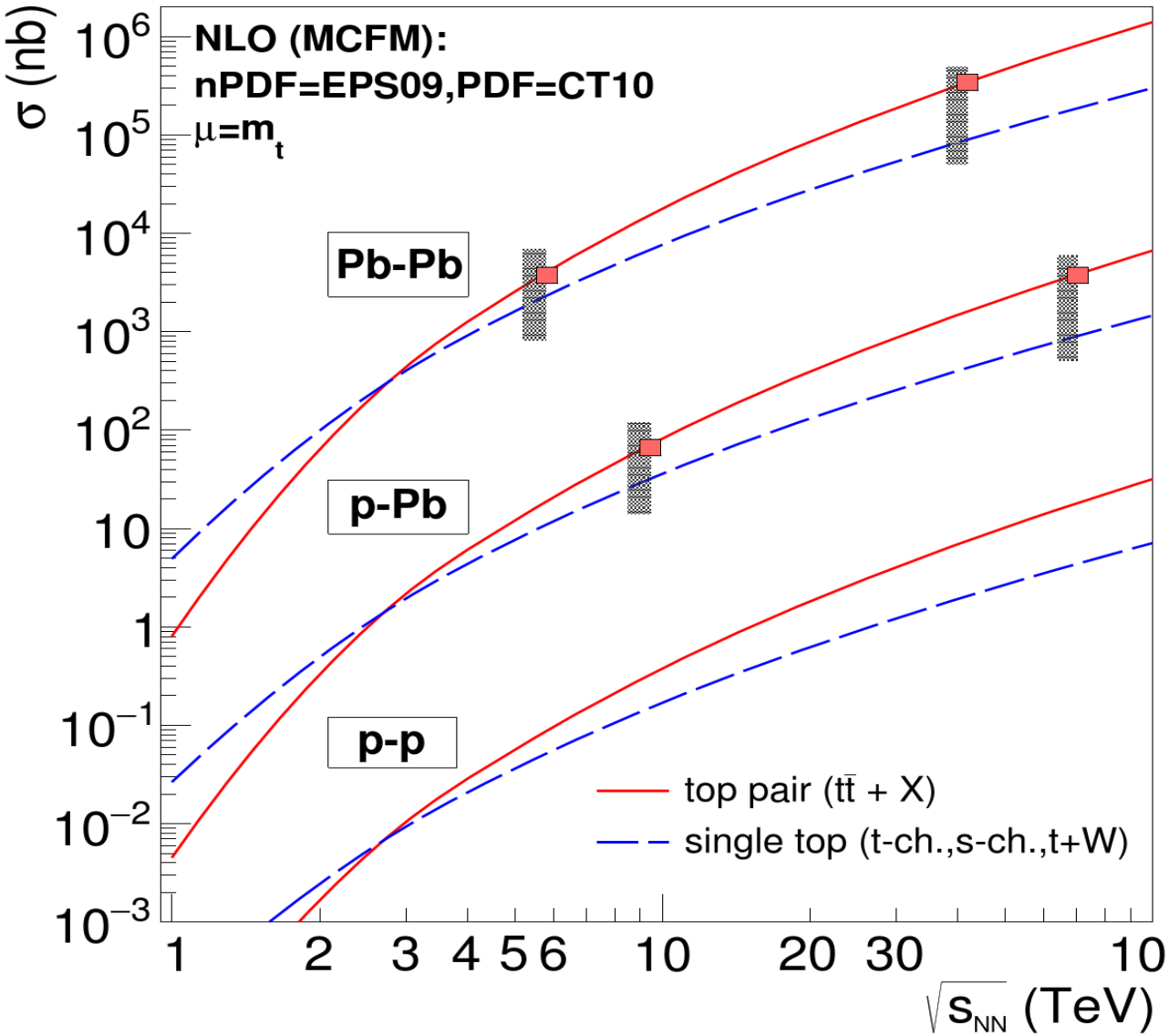



**ALPs, Mono-poles,...**



# Back-up slides

# t-tbar total x-sections in p-p, p-Pb, Pb-Pb




- Pb-Pb:

LHC(5.5 TeV) = 3.4 μb
FCC(39 TeV) = 300 μb

- p-Pb:

LHC(8.8 TeV) = 59 nb
FCC(63 TeV) = 3.2 μb

- p-p (reference):

LHC(5.5 TeV) = 75 pb
LHC(8.8 TeV) = 270 pb
FCC(39 TeV) = 6.5 nb
FCC(63 TeV ) = 15 nb

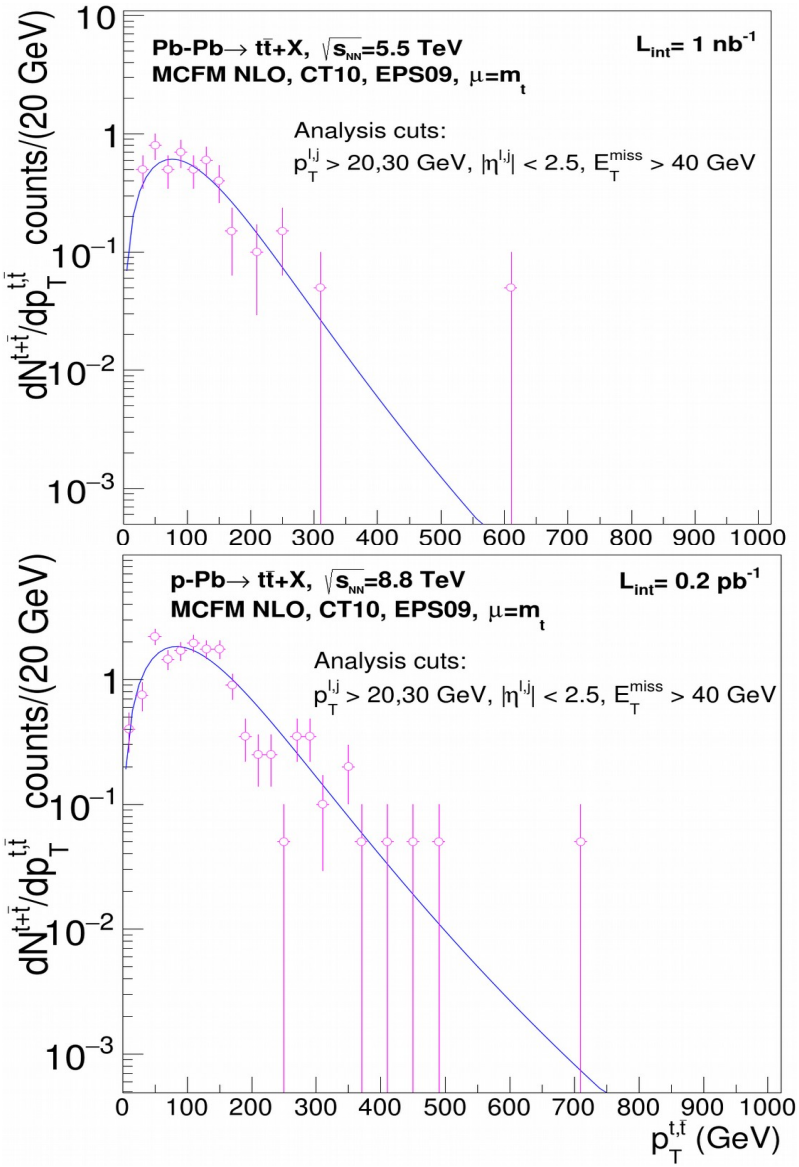
nPDF anti-shadowing increases $\sigma_{tt}$ by +(2-8)%

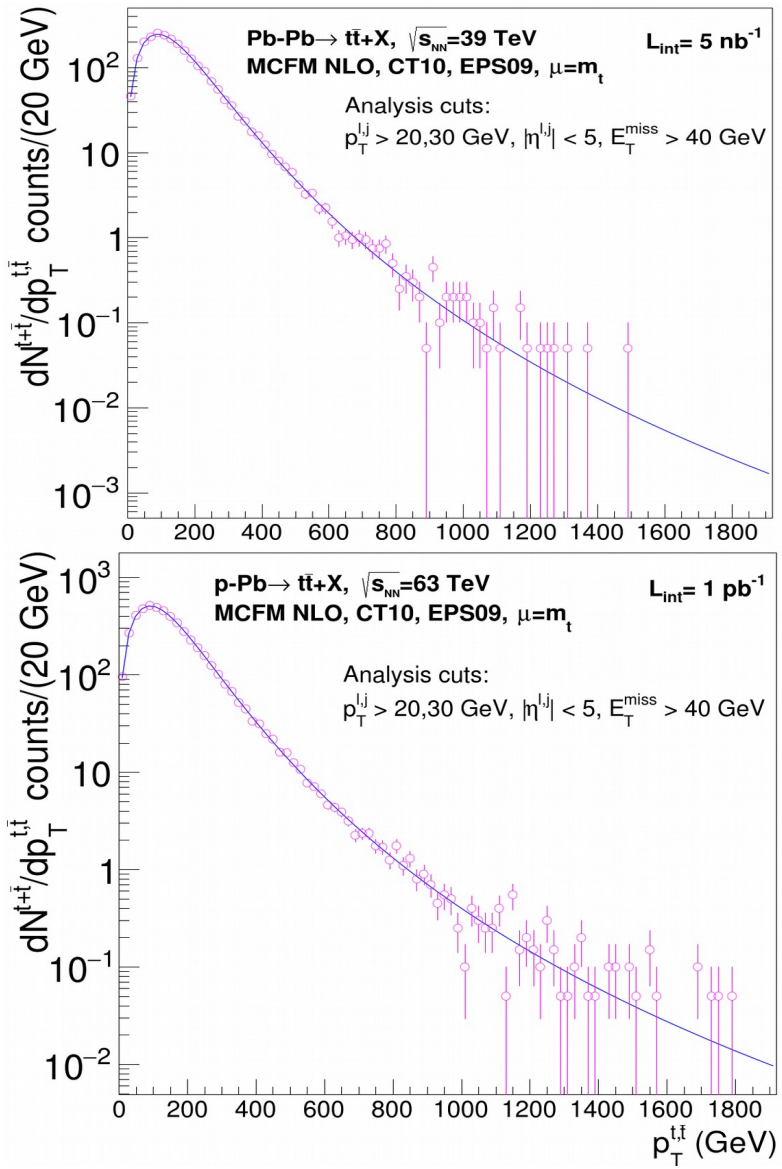
➜ Cross-sections increase by ×55-85 from LHC to FCC

[DdE, K.Krajczaár, H.Paukkunen PLB746 (2015) 64-72]

# Differential top-pair $p_T$ distributions

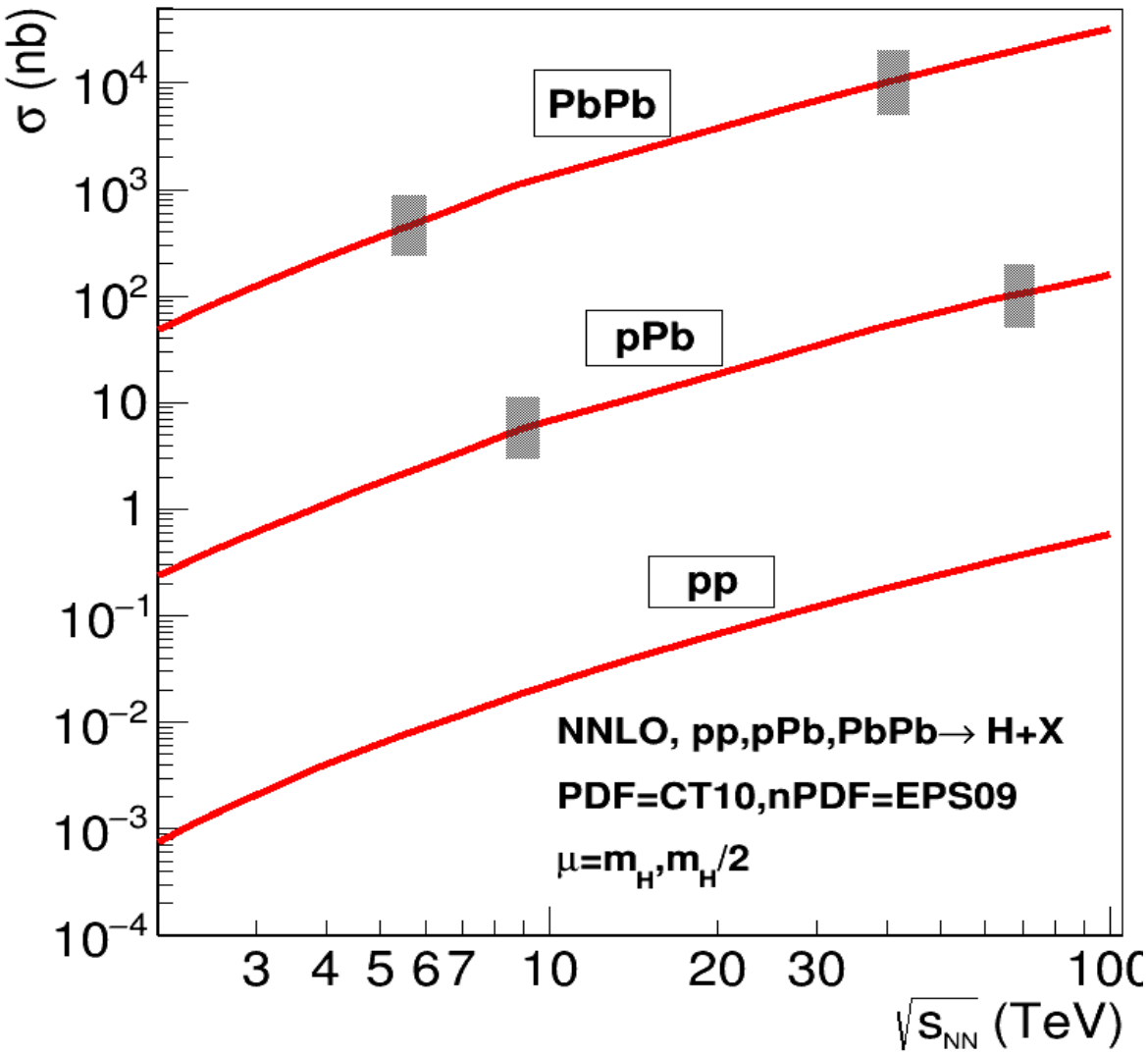
- LHC: $p_T$ reach up to ~500 GeV
- FCC: $p_T$ reach up to ~2 TeV



# 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) = 500 nb
FCC(39 TeV) = 12 μb

- p-Pb:

LHC(8.8 TeV) = 6 nb
FCC(63 TeV) = 120 nb

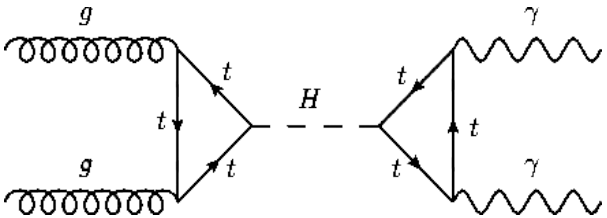
- p-p (reference):

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

[DdE, arXiv:1701.08047]

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

# H→γγ counts after cuts




Analysis based on NNLO MCFM v.8.0

pseudo-data for H(γγ) plus γγ backgrounds

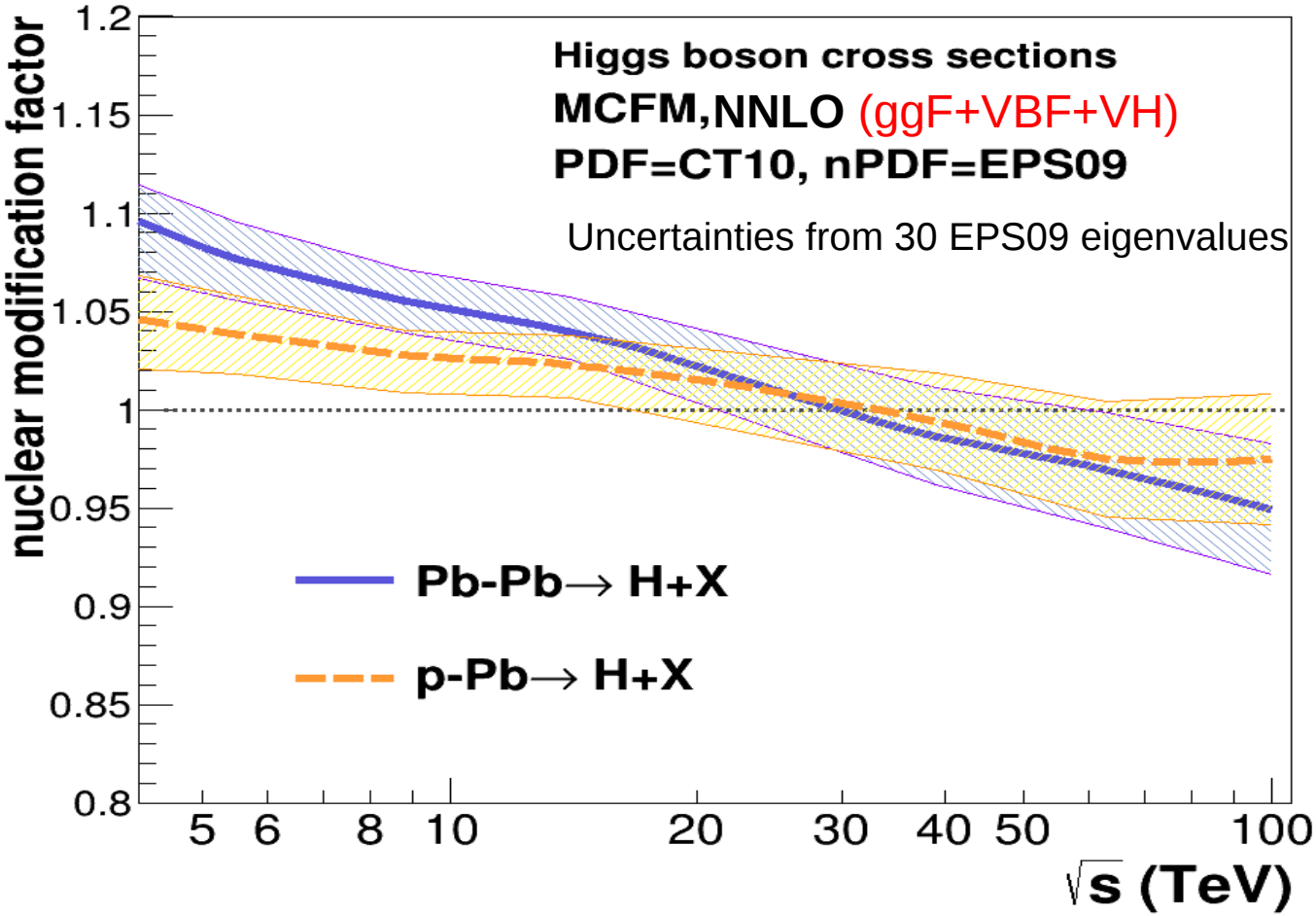
after typical CMS/ATLAS cuts

| System | $\sqrt{s_{NN}}$ (TeV) | $\mathcal{L}_{int}$ | H $\sigma_{tot}$ | $\to \gamma\gamma$ 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 $\mu$b | 450 | 25 |
| pPb | 63 | 8 $pb^{-1}$ | 115 nb | 950 | 50 |

- LHC (nominal $L_{int}$): ~2 Higgs bosons/month in Pb-Pb
- HE-LHC (nominal $L_{int}$): ~10 Higgs bosons/month in Pb-Pb
- FCC (nominal $L_{int}$): ~500 H bosons/month in Pb-Pb

# Higgs nPDF modification factor (p-Pb,Pb-Pb)

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



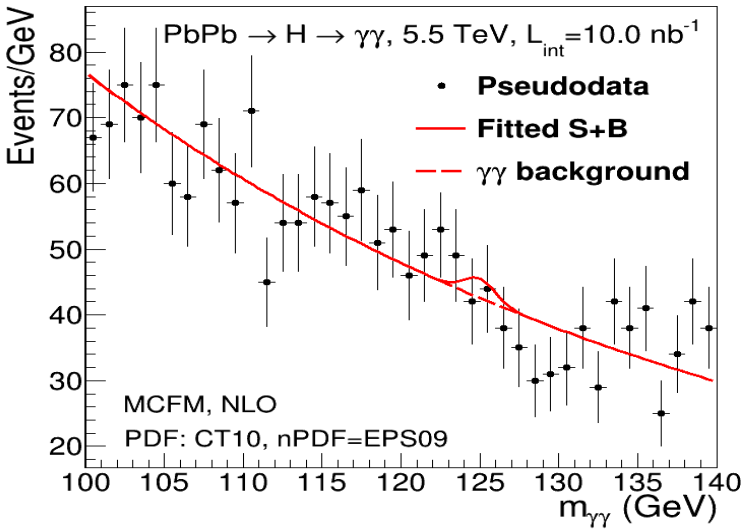

➜ LHC: Small antishadowing: $R_{AA}$~ 1.07, $R_{pA}$~1.03

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

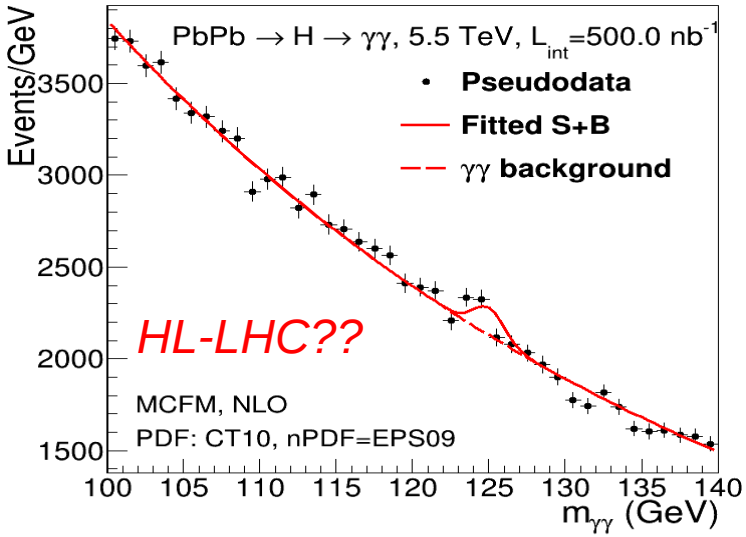
[DdE arXiv:1701.08047]

# H→γγ 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 4$l$)

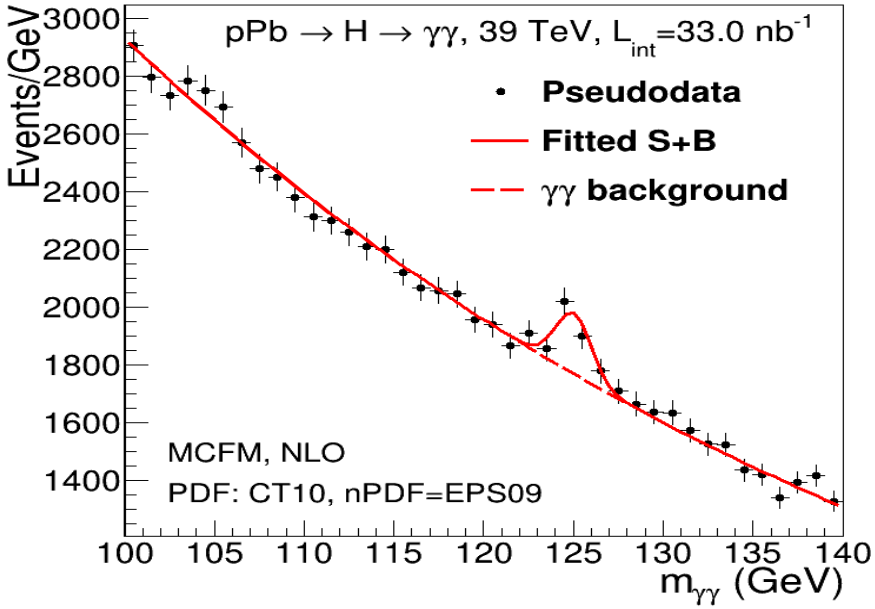
$L_{int}$= 500 nb$^{-1}$: 3σ evidence

4.2σ combined with H(4$l$)

→ FCC (39 TeV, 33 nb$^{-1}$):

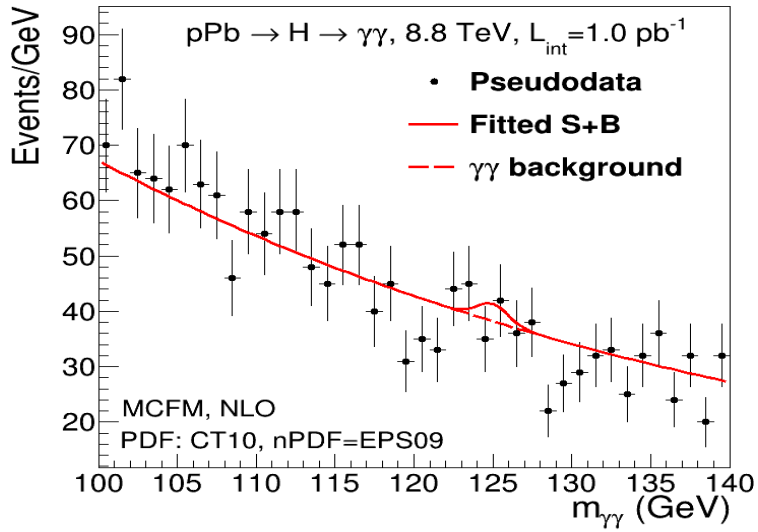
Nominal lumi: S/√B~5.2σ observation

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

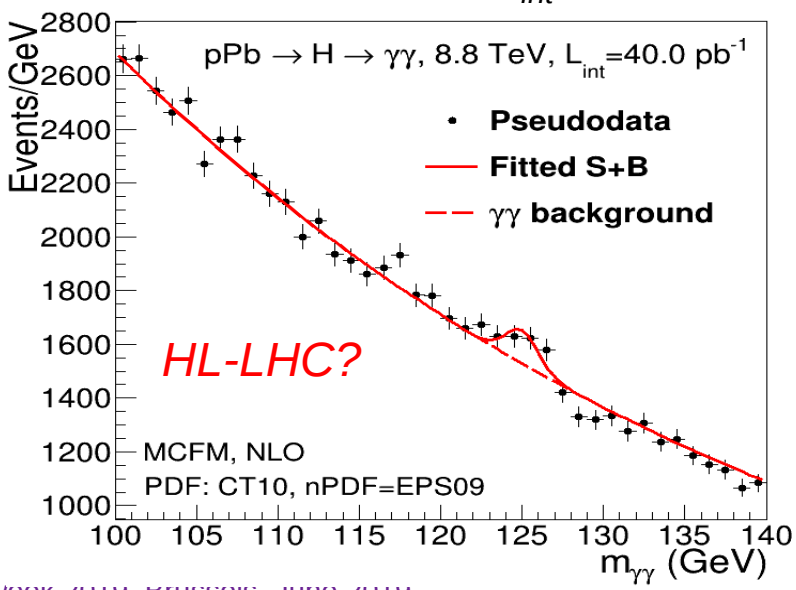


# H→γγ observation in p-Pb (LHC, FCC)

- 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 4*l*)

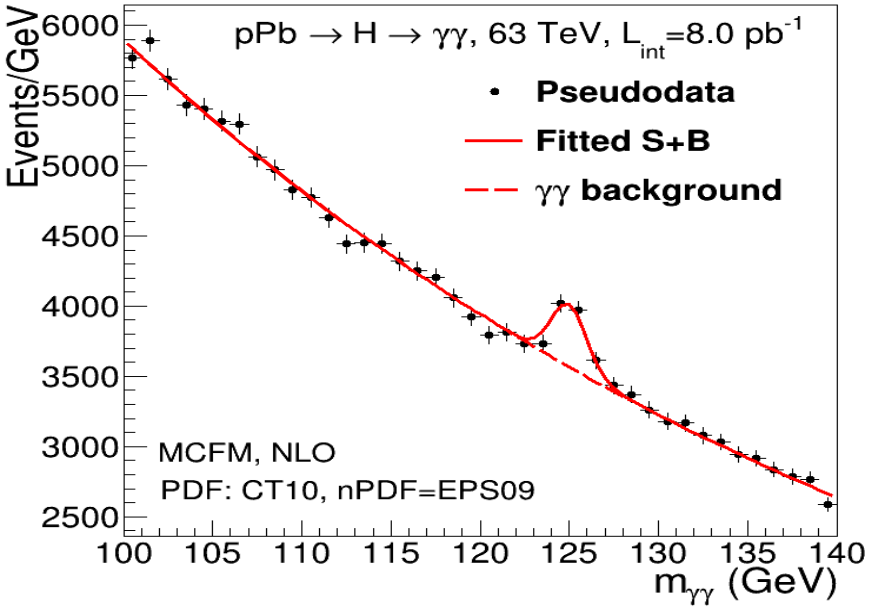
$L_{int}$= 40 $pb^{-1}$: 3σ evidence

4.2σ combined with H(4*l*)

➜ FCC (63 TeV, 8 $pb^{-1}$):

Nominal lumi: S/√B~7.7σ observation

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



# pPb(63 TeV): Triple- hard scatterings

- Kinematical reach at FCC down to $x \sim 10^{-7}$ ($10^{-4}$ with W,Z at y~0)