Ions at HE-LHC: Lessons from FCC-AA studies

Workshop on HL-LHC physics & HE-LHC perspectives

CERN, 18th June 2018

David d'Enterria (CERN)

Carlos A. Salgado (USC)

High-Energy-LHC with ions

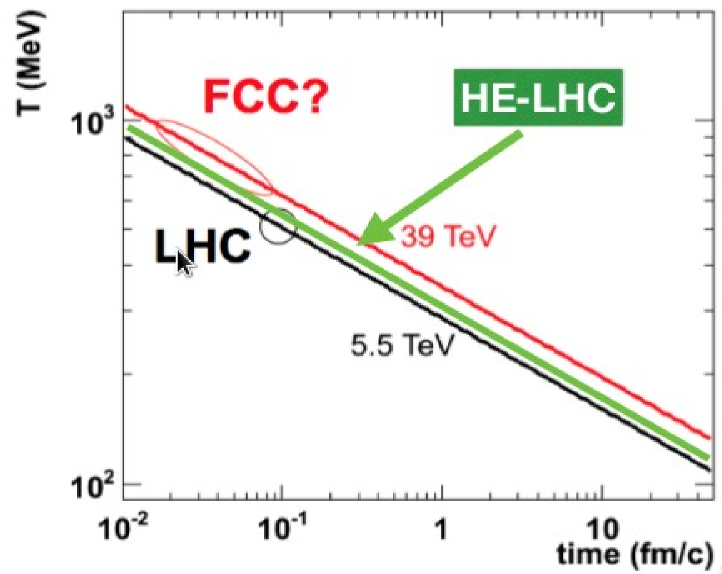
- HE-LHC:
  ☞NN center-of-mass energies ("2×LHC". Note FCC is "7×LHC"):
  $\sqrt{s_{NN}}$ = 27 TeV (pp), 17 TeV (pPb), 10.6 TeV (PbPb), lighter ions?
  ☞Integrated luminosities (~HL-LHC. Note FCC is "30×LHC"!):
  L_{int} ~ 1 pb^{-1}/"year" (pPb), ~3 nb^{-1}/"year" (PbPb), lighter ions?

- Global PbPb event properties: $dN_{ch}/d\eta|_{\eta=0}$~2400 (~20% above LHC)

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
ε at $\tau = 1$ fm/c	12–13 GeV/fm^3	16–17 GeV/fm^3	35–40 GeV/fm^3

$$\left.\frac{dN_{ch}}{d\eta}\right|_{\eta=0} \propto (\sqrt{s_{NN}})^{0.3}.$$

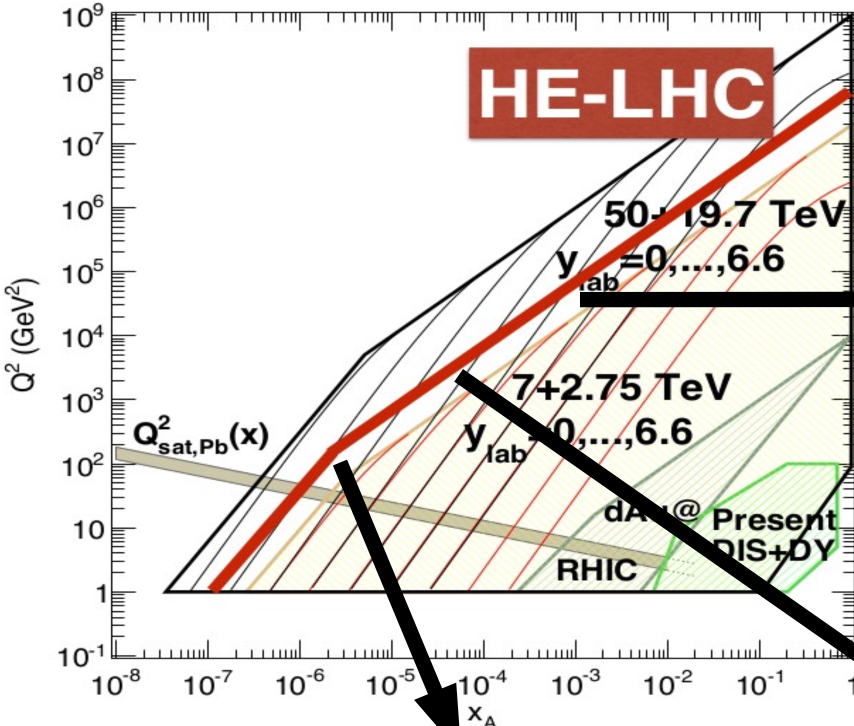
Moderate ~20% increase in multiplicity

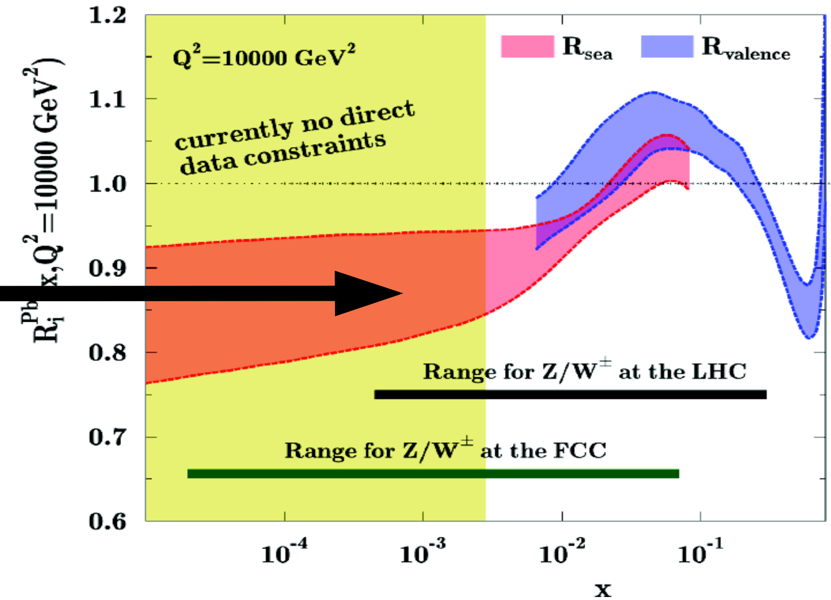


- $^{129}Xe^{129}Xe$(11.3 TeV)? Same dN/dη as PbPb(5.5 TeV), but ×5 lumi

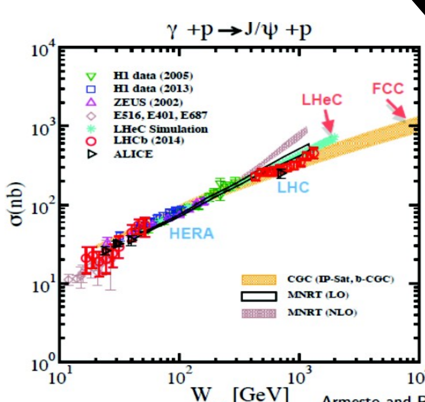
Small-x physics via pPb at HE-LHC

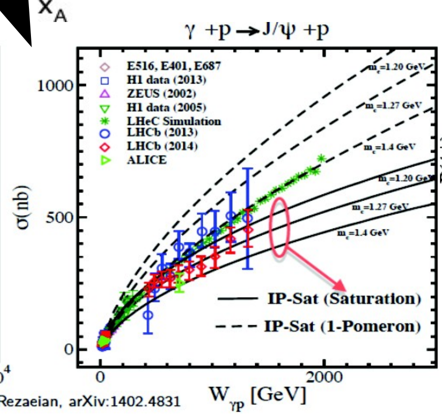
- Kinematical reach: ×2 smaller x than LHC (10^{-3} with W,Z at y~0)





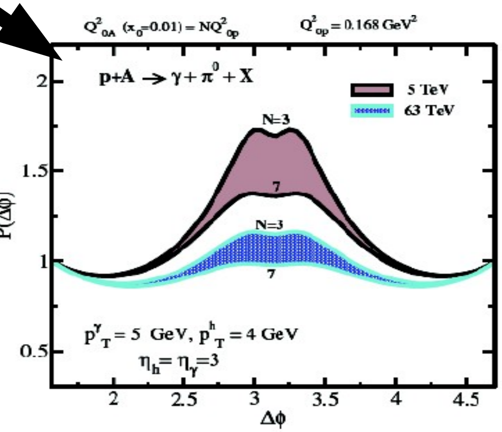
Fwd-Bcwd azimuthal decorrelations:



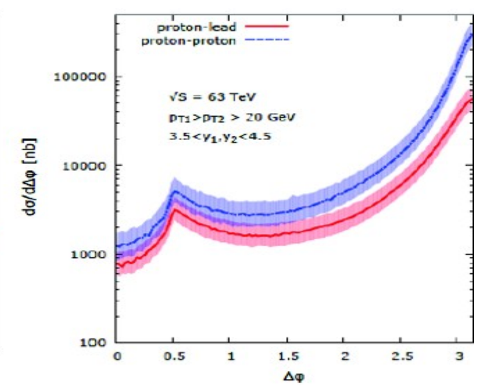


Armesto and Rezaeian, arXiv:1402.4831

Exclusive J/ψ photoproduction



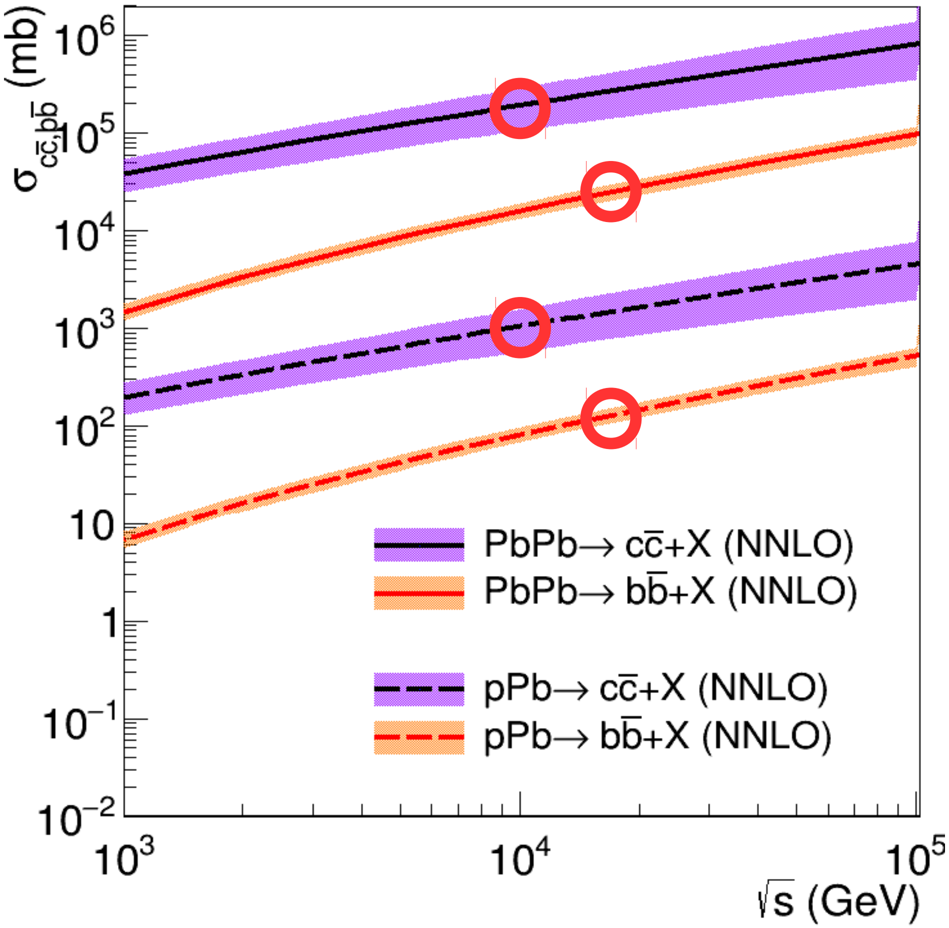
γ-π⁰ in pPb

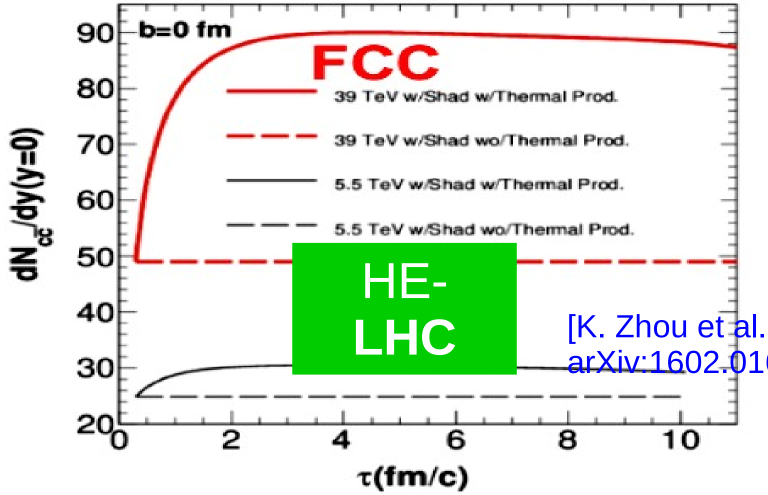


jet-jet in pPb

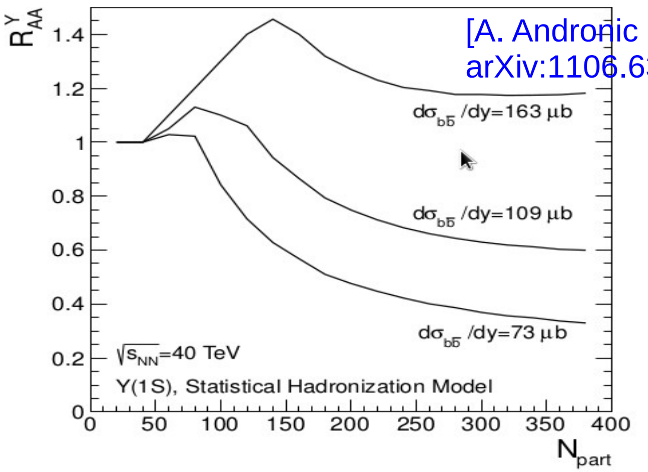
Charm & beauty at HE-LHC

[DdE & Snigirev, arXiv:1612.08112]





[K. Zhou et al., arXiv:1602.01667]

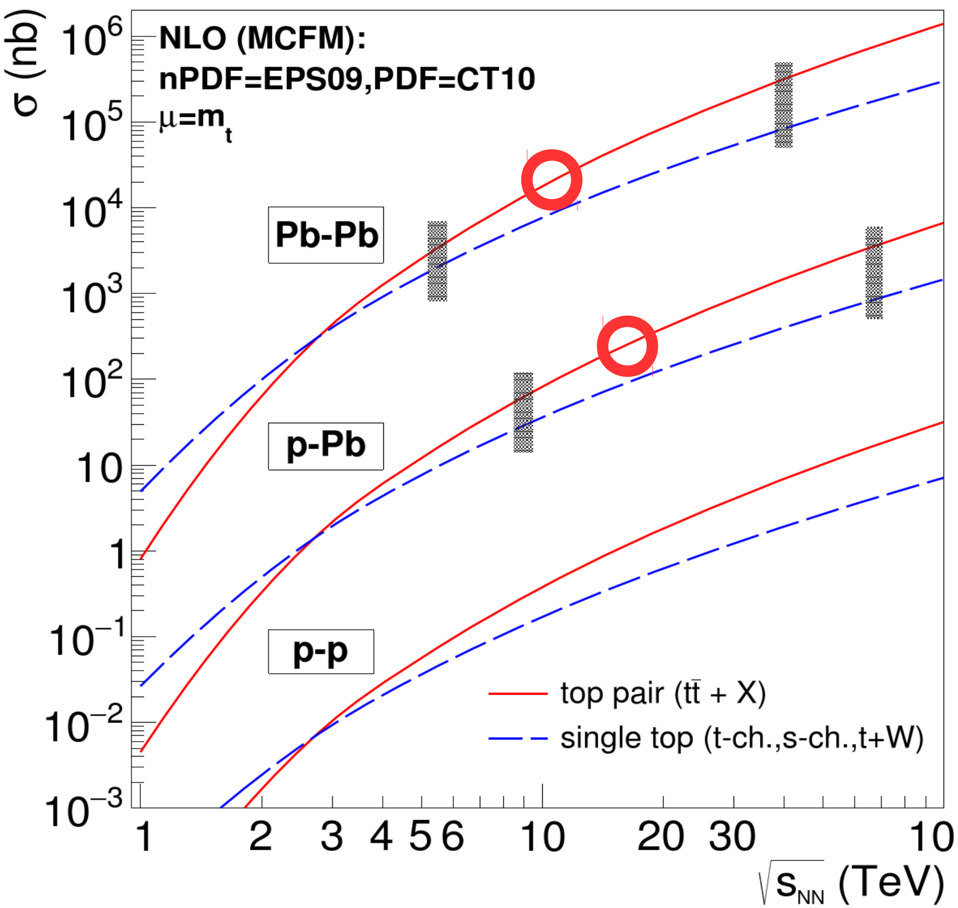


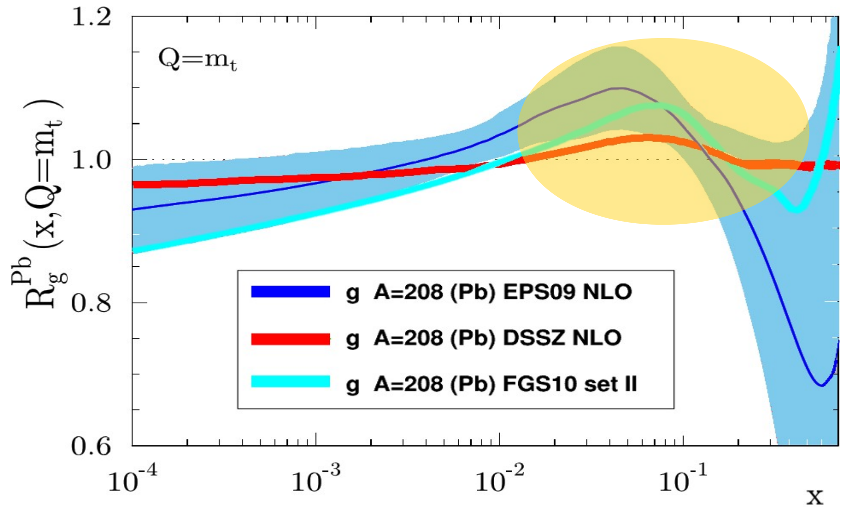
[A. Andronic et al., arXiv:1106.6321]

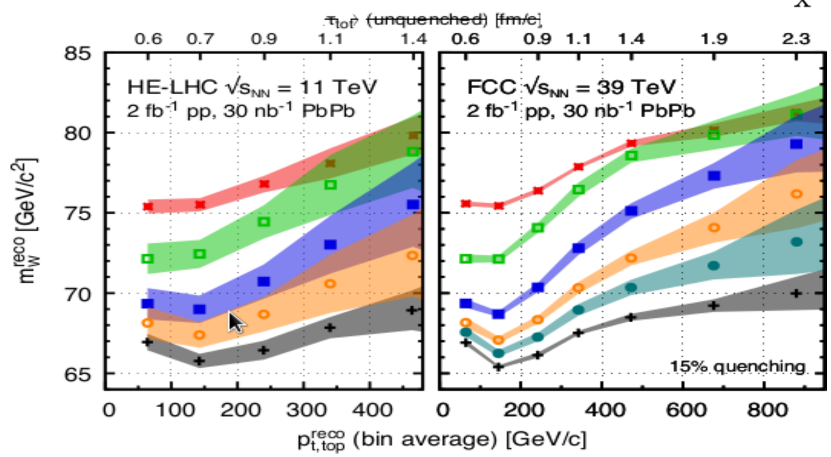
➜ Abundant charm (×1.6 more than LHC) & beauty (×6 more than LHC).
➜ Enough thermal charm to participate in EoS?
➜ Recombination in-between LHC and FCC. Enough for Y(1S) recomb.?
➜ Detailed studies (higher-stats, higher p_T) of HF energy loss possible

Top quarks at HE-LHC

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







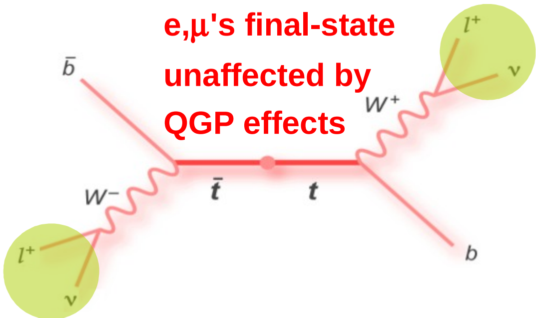
➜ Large t-tbar prod.: ×6 more than LHC (×80 more at FCC). [Apolinaro et al, PRL (2018) 1711.03105]

➜ Studies of high-x gluon PDF in Pb possible.

➜ Jet quenching chronography via boosted-top decay products possible.

Top-quark dileptons measurement

- **Experimental setup**:
  - LHC (ATLAS/CMS): $|\eta_{lepton}|,|\eta_{b\text{-}jet}| < 2.5$
  - FCC ("CMS+LHCb"): $|\eta_{lepton}|,|\eta_{b\text{-}jet}| < 5.0$



- **Analysis cuts** (typical ones in p-p at LHC, l=e,μ):

t-tbar:	$p_T(l)$,p_T(b-jet) > 20,30 GeV; R_{isol}(b-jet,l) = 0.3
	$\|\eta(l)\|$,$\|\eta$(b-jet)$\|$ < 2.5 (LHC), 5.0 (FCC)
	MET > 40 GeV; m_{ll} > 20 GeV; $\|m_{ll}-m_Z\|$ > 15 GeV
Single-t:	Same cuts as for t-tbar
	(only W+t, backgrounds are much worst for s-,t-channel)

- **Branching ratios, acceptance & efficiency losses**:

t-tbar:	BR~5%, Acc×Eff ~ 40% (LHC), 50% (FCC)
Single-top:	BR~22%, Acc×Eff ~ 21% (LHC), 30% (FCC)

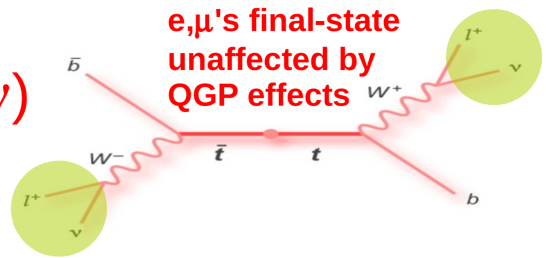
- **Backgrounds** (W,Z+j): Controllable for t-tbar (much worst for single-t)

NOTE: ×4 more stats in ℓ+jets (for pPb)

Top pair & single-top yields: LHC vs. FCC

- Final-state: ttbar → b(bar) + 2ℓ (e,μ) + MET(2ν)
- Final-state: single t → b + 1ℓ (e,μ) + MET(ν)

  Note: ×4 more stats in ℓ+jets (for pPb)



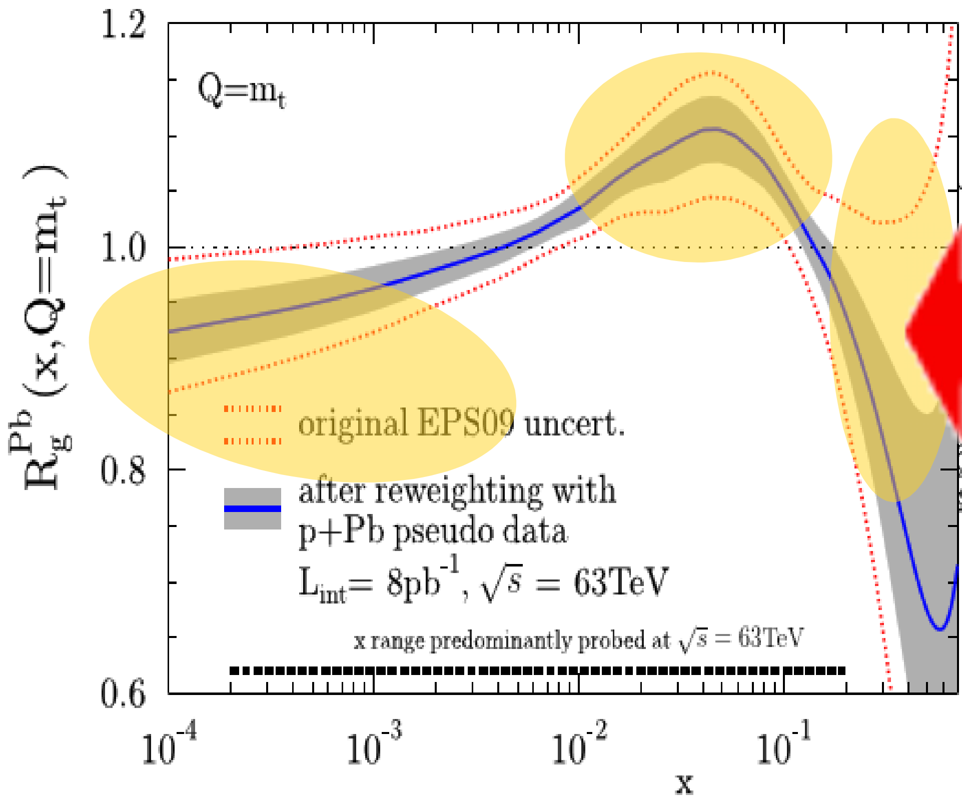
System	$\sqrt{s_{NN}}$ (TeV)	$\mathcal{L}_{int}$	$t\bar{t}$ σ_{tot}	$t\bar{t} \to b\bar{b}\ell\ell\nu\nu$ yields	single-t σ_{tot}	$tW \to b\ell\ell\nu\nu$ yields
PbPb	5.5	10 nb^{-1}	3.4 μb	450	2.0 μb	30
pPb	8.8	1 pb^{-1}	59 nb	750	27 nb	50
PbPb	39	33 nb^{-1}	300 μb	1.5×10^5	80 μb	8000
pPb	63	8 pb^{-1}	3.2 μb	4×10^5	775 nb	2.1×10^4

- LHC (nominal L_{int}): 500–750 t-tbar in Pb-Pb, p-Pb. 5.000 (in ℓ+jets)
- FCC (updated L_{int}): 1–3 million t-tbar pairs in Pb-Pb,p-Pb

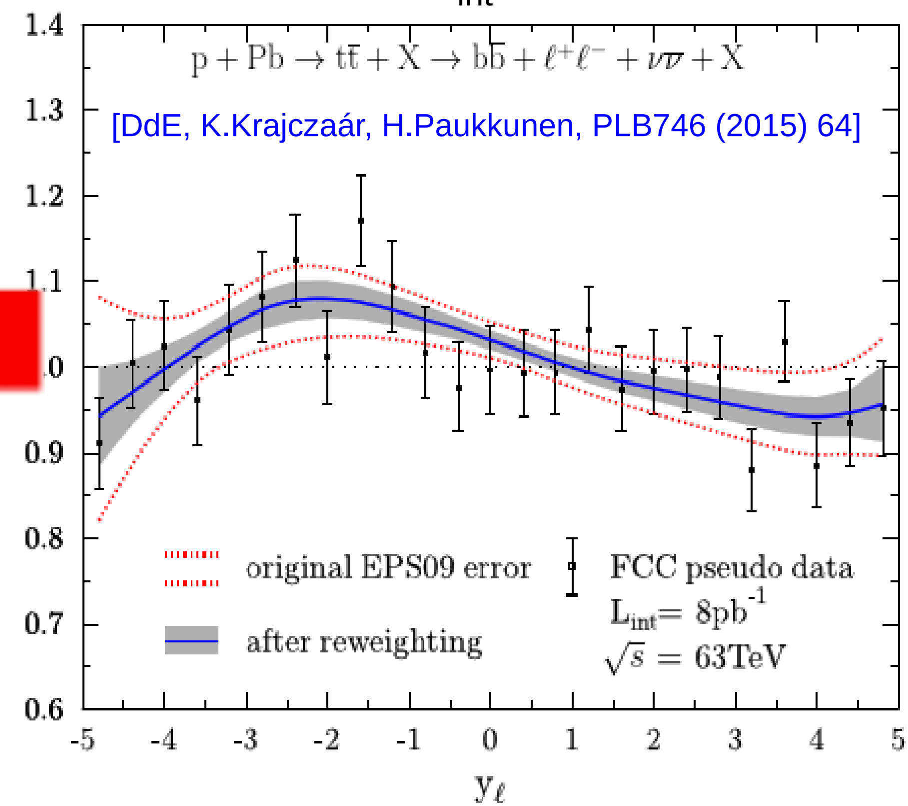
  → HE-LHC: 5.000 (leptonic)–30.000 (ℓ+jets) visible counts

Improved Pb gluon from $\ell^{\pm}$ top at FCC pPb

- Improved gluon density via Hessian PDF reweighting



- Isolated lepton y-distrib. after cuts: (Pseudodata for L_{int}= 8 pb^{-1})



(stat. to dominate over syst. uncertainties)

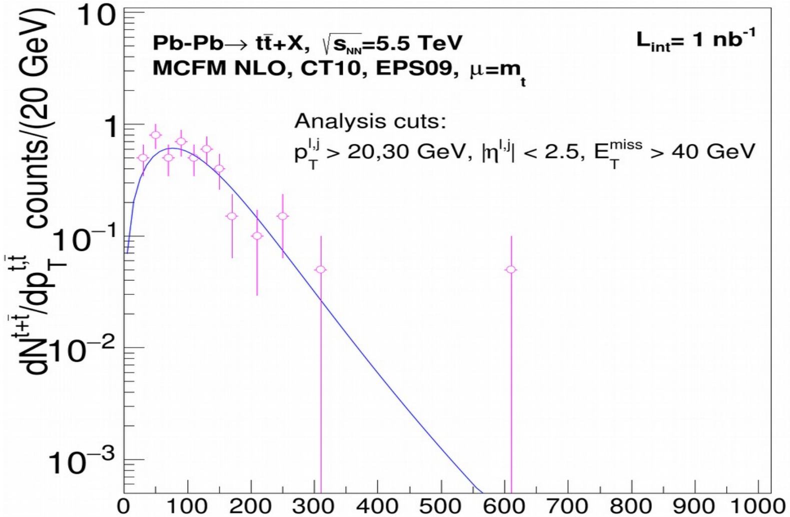
- Significant reduction in uncertainties at low-x ($x<10^{-2}$), antishadowing ($x\sim0.05$) and EMC ($x\sim0.5$) regions

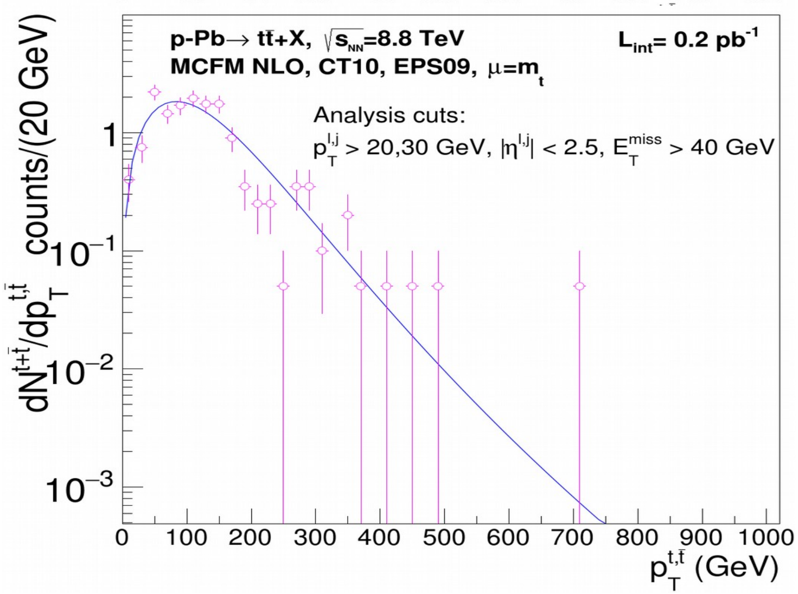
- nPDF effects (lepton): ±10% Strong constraining power

Note: ×3.6 more $\mathscr{L}$, ×4 more stats in l+4j: ×4 better nPDF improvements

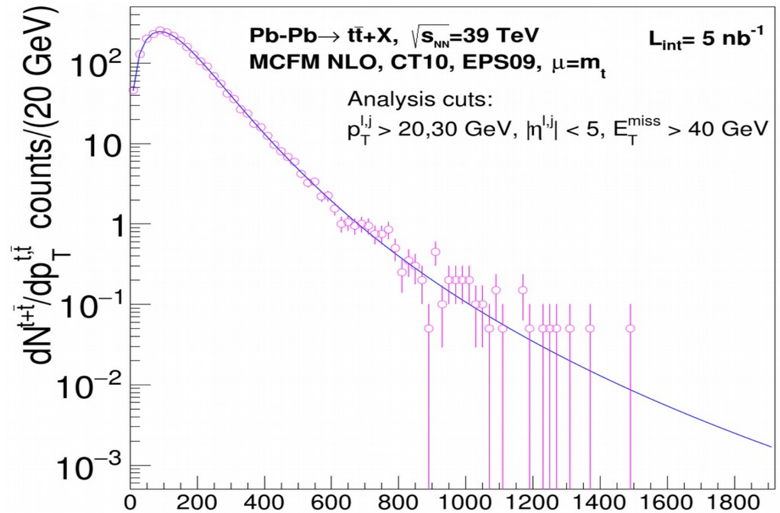
Top-quark p_T reach: LHC vs. FCC

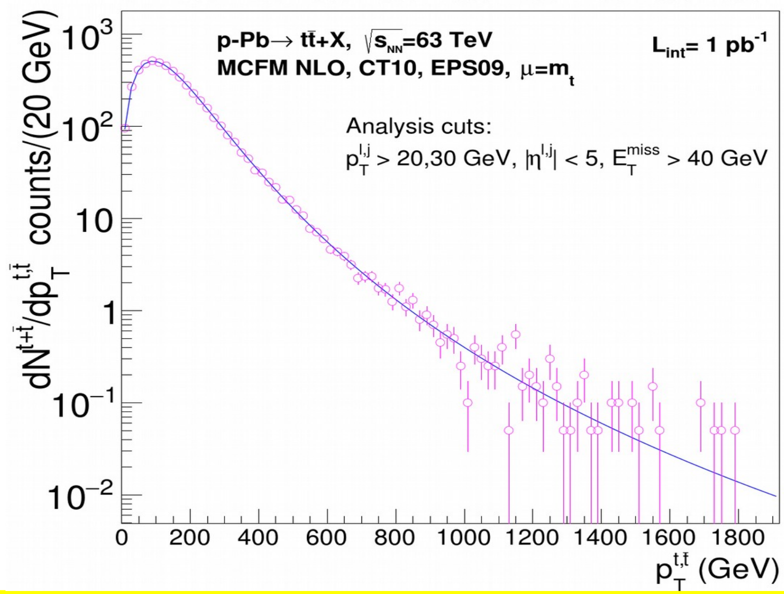
- LHC: p_T reach up to ~500 GeV





- FCC: p_T reach up to ~2 TeV



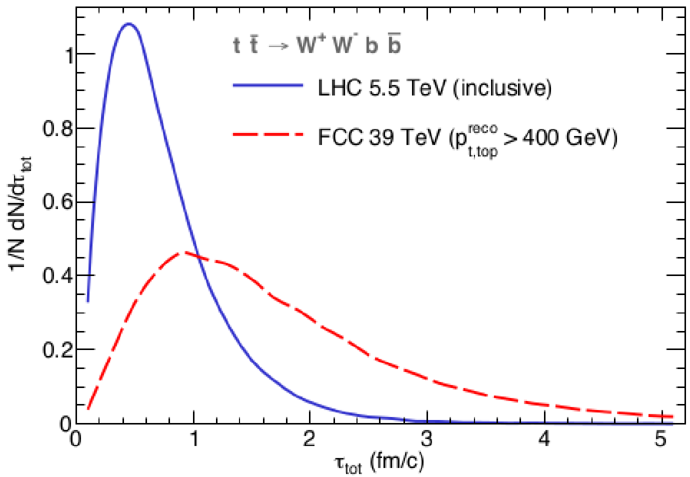


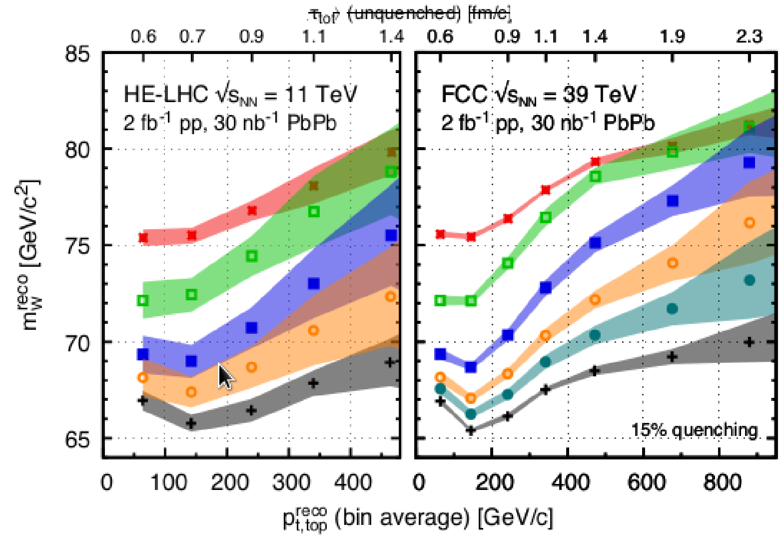
HE-LHC: ×6 larger cross sections: p_T>1 TeV (boosted top studies possible)

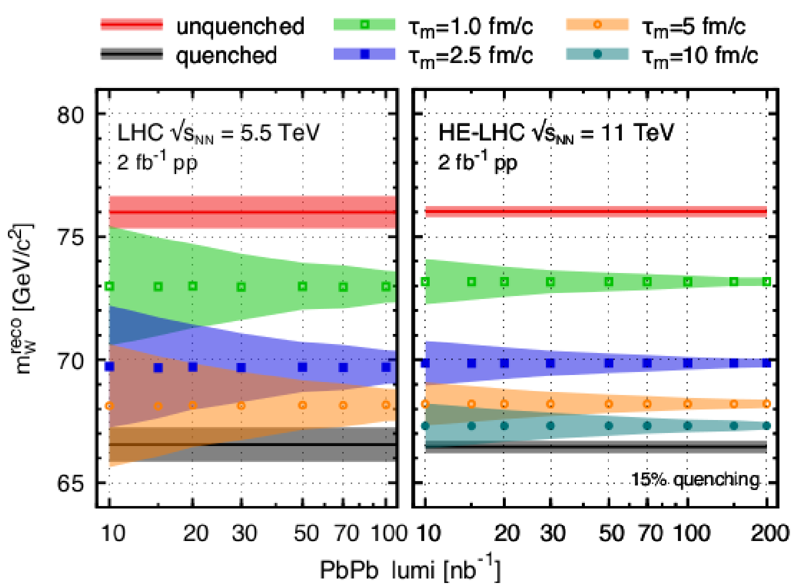
Top-quark jets as a QGP space-time probe

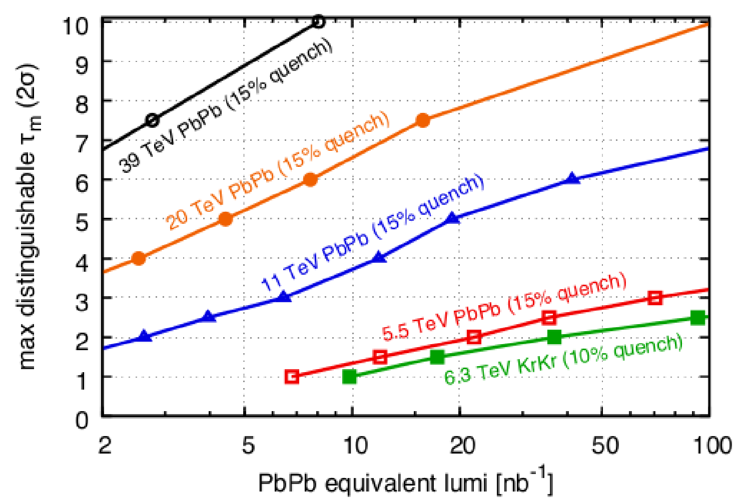
→ Boosted single-top (>1 TeV): τ>1 fm/c (enhanced g radiation in QGP?)

→ Boosted t-tbar = color-singlet W(qq) probes medium opacity at diff. τ





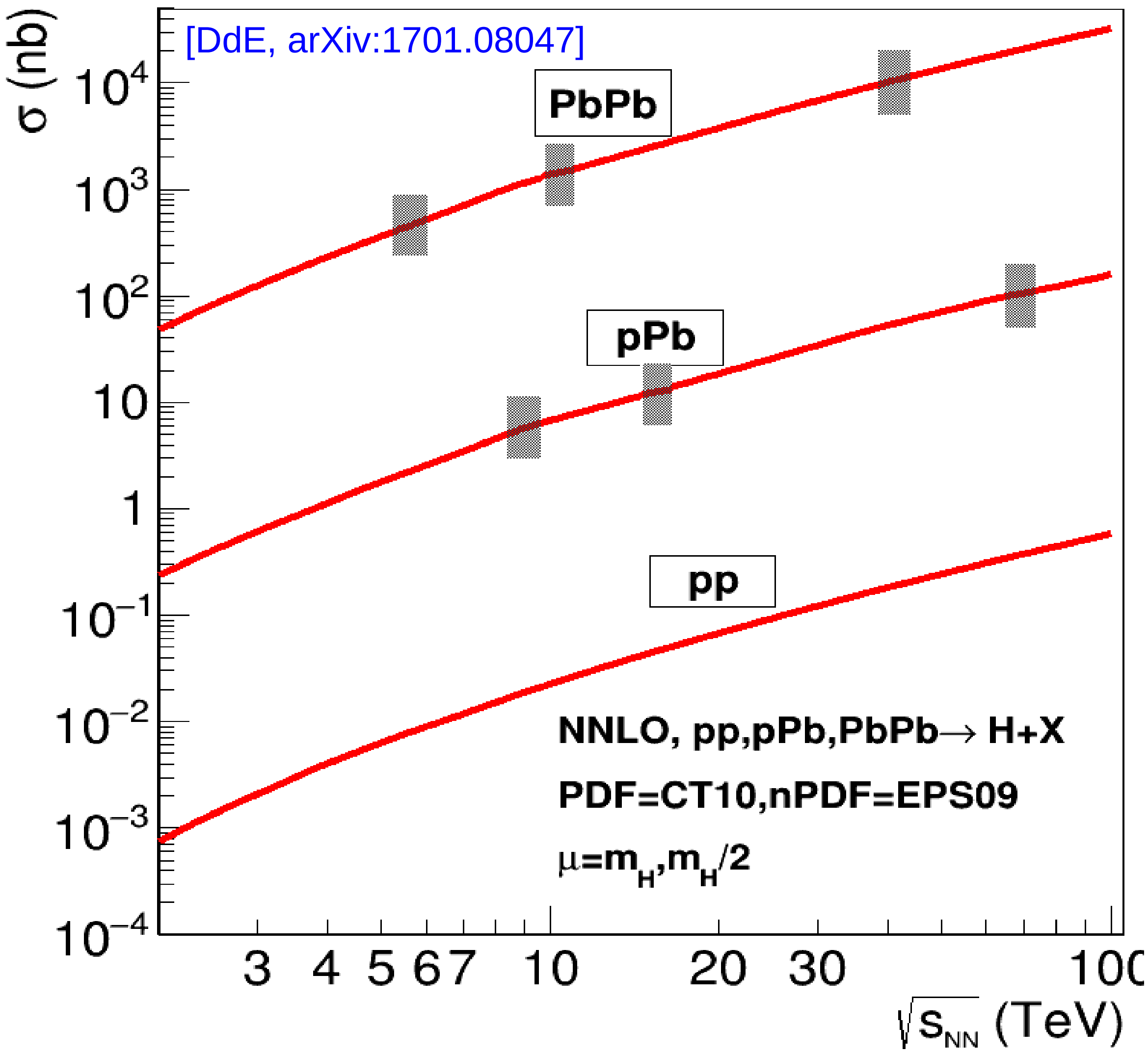




[Apolinaro et al, PRL (2018); 1711.03105]

Higgs total x-sections vs. sqrt(s)

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



- Pb-Pb:

LHC(5.5 TeV) = 500 nb
HE-LHC(10.6 TeV)=1.9 μb
FCC(39 TeV) = 12 μb

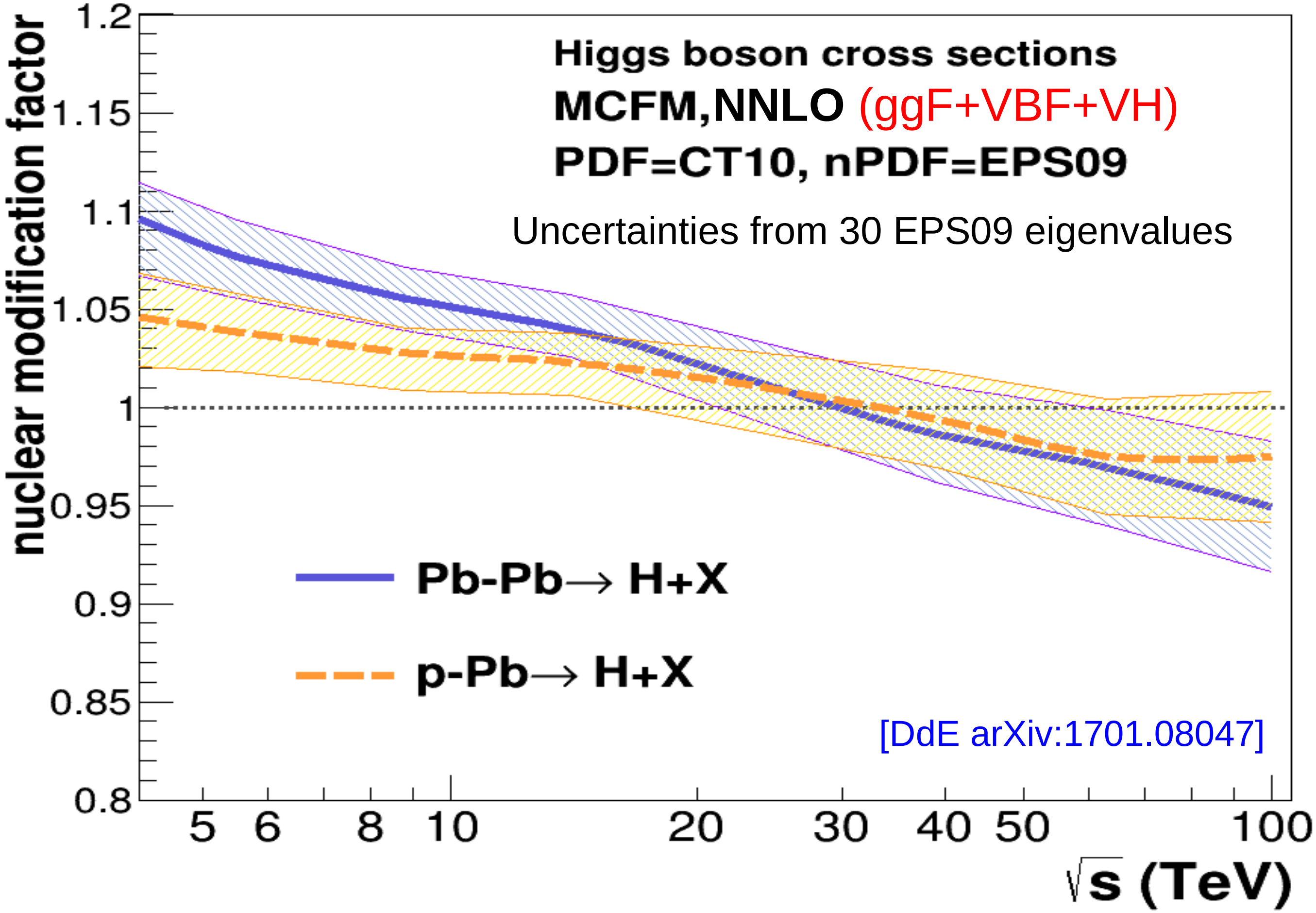
- p-Pb:

LHC(8.8 TeV) = 6 nb
HE-LHC(17 TeV) = 17 nb
FCC(63 TeV) = 120 nb

→ Cross-sections increase by ×4 (×20) from LHC to HE-LHC (FCC)

Higgs nPDF modification factor vs. sqrt(s)

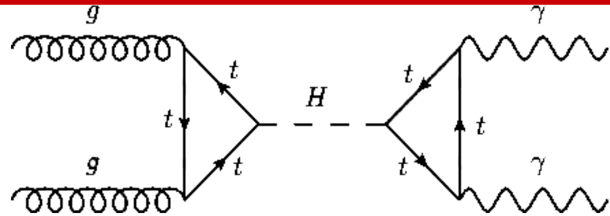
- EPS09 nuclear PDFs modify slightly x-sections wrt. pp PDFs:

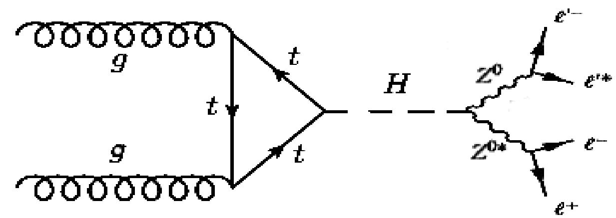


→ HE-LHC: Small antishadowing: R_{AA}~ 1.05, R_{pA}~1.03

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

H→γ γ, 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):

γγ:	$p_T(\gamma_1, \gamma_2) > 40, 30$ 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:

γγ:	BR = 0.27%, Acc×Eff ~ 45% (LHC), 60% (FCC)
ZZ*→4l:	BR = 0.12%, Acc×Eff ~ 60% (LHC), 70% (FCC)

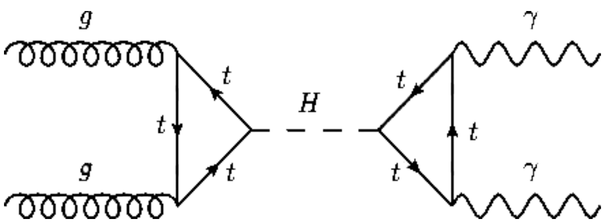
- Backgrounds: As for p-p (under control in pPb,PbPb: high-p_T iso γ,l)

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

[DdE, arXiv:1701.08047]

H→γγ visible counts: LHC vs. FCC

[DdE, arXiv:1701.08047]



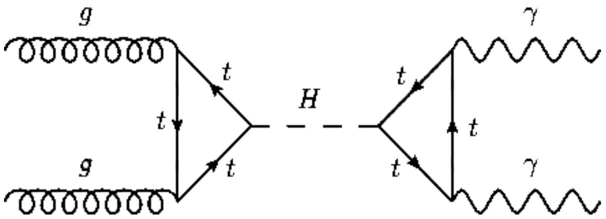
Analysis based on NNLO MCFM pseudo-data for H(γγ) and γγ backgrounds after typical CMS/ATLAS cuts

System	$\sqrt{s_{NN}}$ (TeV)	$\mathcal{L}_{int}$	H σ_{tot}	$\rightarrow \gamma\gamma$ yields	$\rightarrow ZZ^*(4\ell)$ 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 visible in Pb-Pb, p-Pb
- HE-LHC: ~40 Higgs bosons in Pb-Pb, p-Pb
- FCC (nominal L_{int}): 500-1000 H bosons/month in Pb-Pb, p-Pb

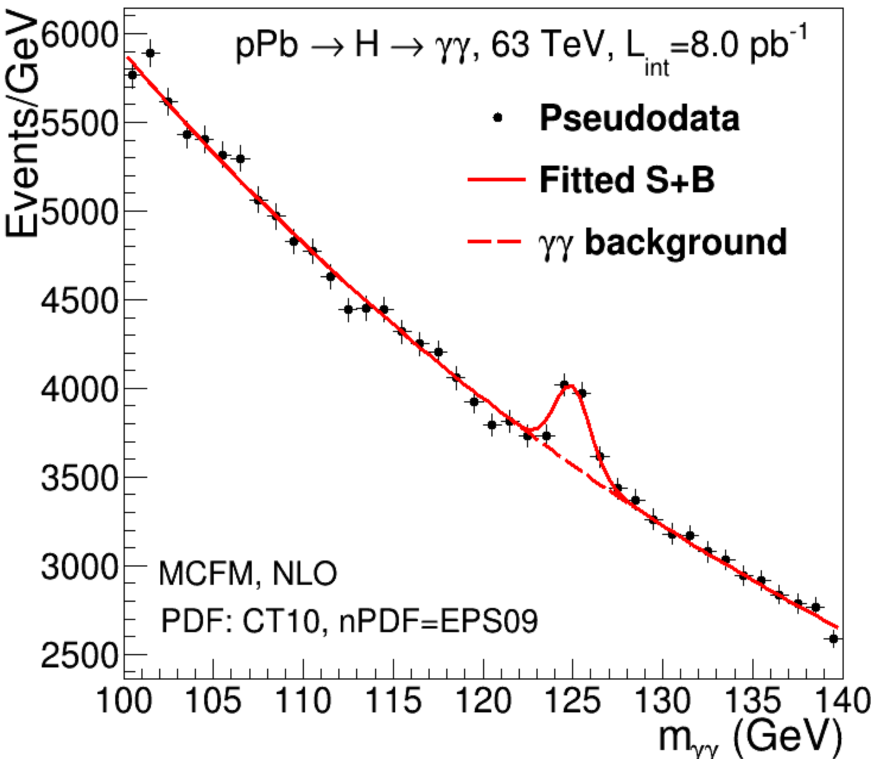
H → γ γ observation at FCC

[DdE, arXiv:1701.08047]



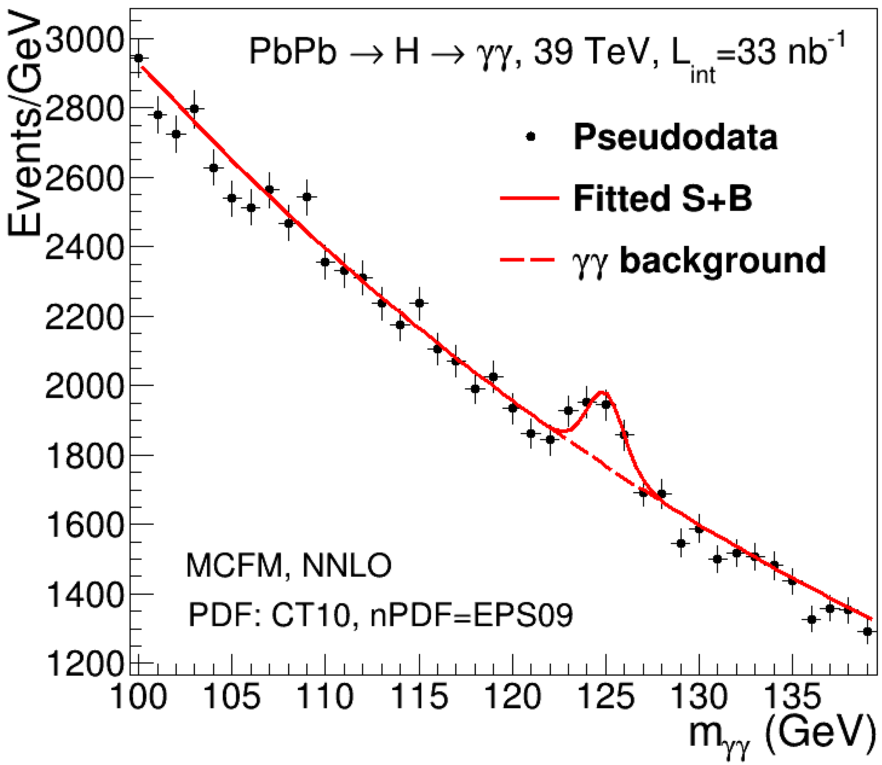
Analysis based on NNLO MCFM pseudo-data for H(γγ) and γγ backgrounds after typical CMS/ATLAS cuts

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



S/√B~7.7σ observation

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



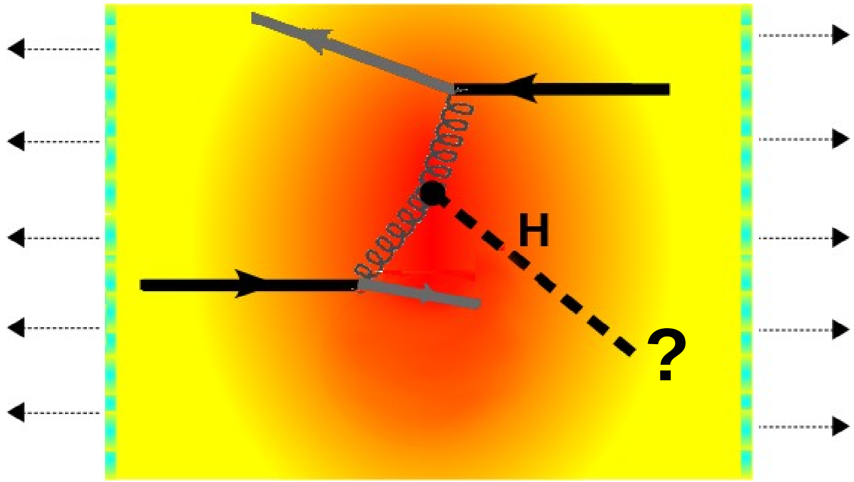
S/√B~5.2σ observation

- HE-LHC: Observation requires ×20 more L_{int} (2-yrs run). Lighter ions?

H boson suppression in the QGP

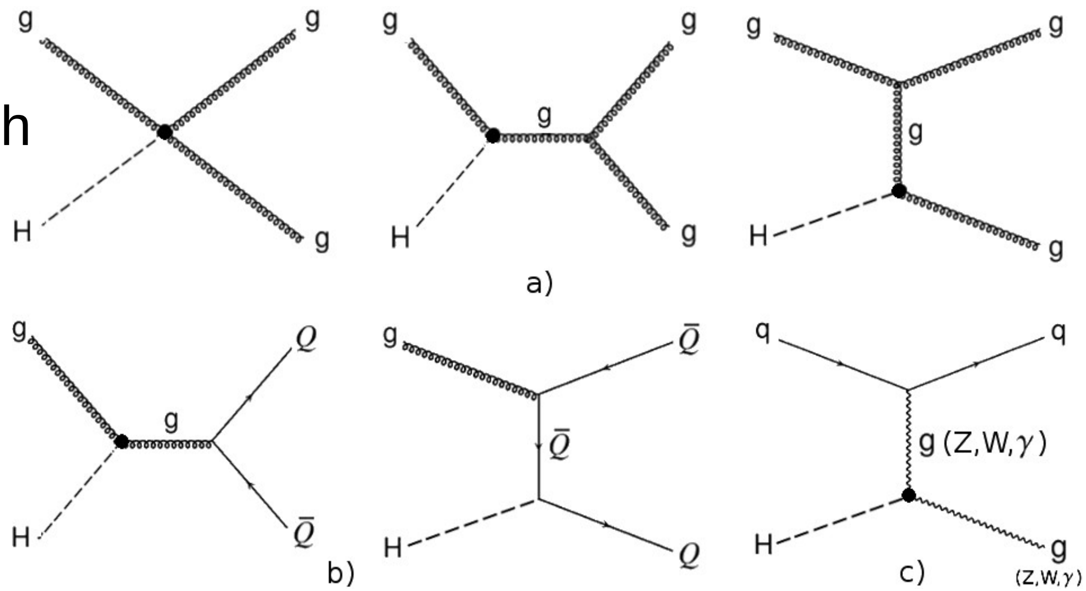
[DdE,C.Loizides, to be submitted]

- SM boson (Γ_H=4 MeV) lifetime $\tau = 1/\Gamma_H \sim 50$ fm > $\tau_{QGP} \sim 10$ fm. Once produced it will traverse the QGP and decay outside the medium. What are its q,g scattering x-sections ?



- The SM Higgs couples to plasma gluons (through dominant top loop) & quarks (as per their Yukawas).

LO x-sections computed (WHIZARD/CalcHEP/MG5) for relevant $E_{g,H}$ ranges

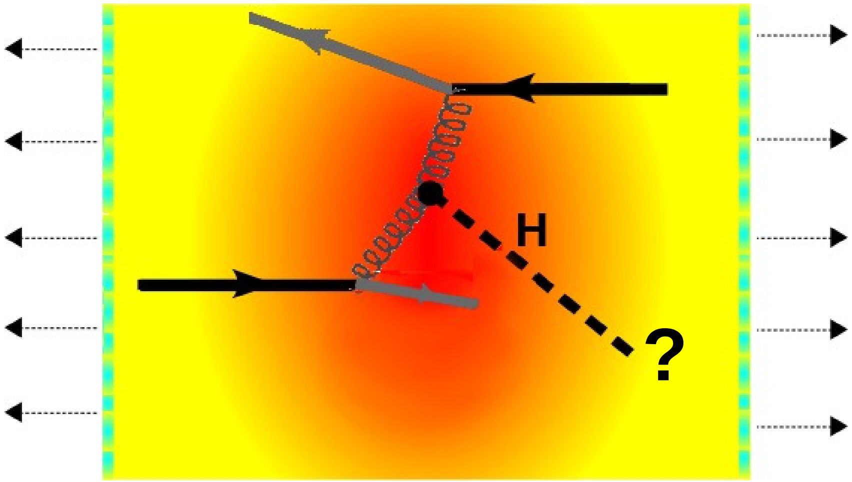


→ Full (including K-factors) Higgs "absorption" x-section: $\sigma \sim \mathcal{O}(1\text{-}10\ \mu b)$

H boson suppression in the QGP

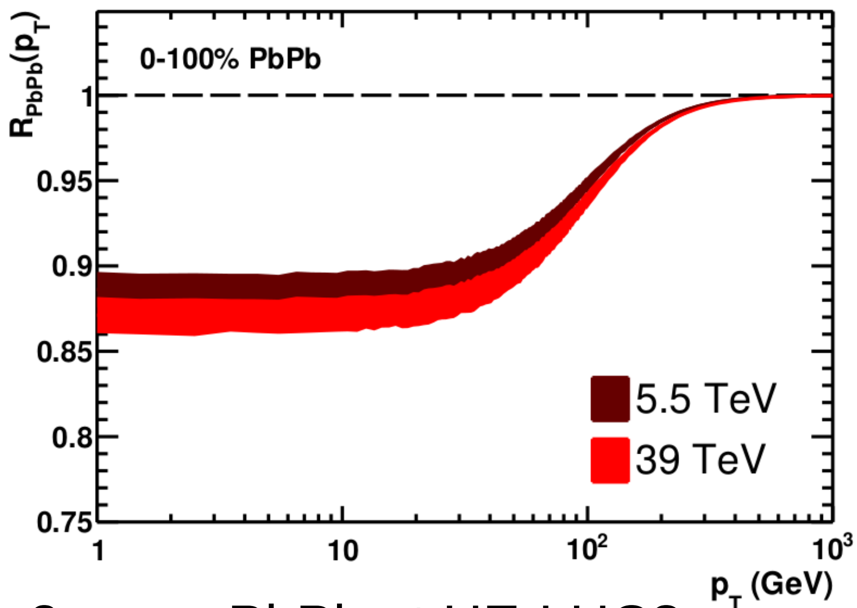
[DdE,C.Loizides, to be submitted]

- SM boson (Γ_H=4 MeV) lifetime $\tau = 1/\Gamma_H \sim 50$ fm $> \tau_{QGP} \sim 10$ fm. Once produced it will traverse the QGP and decay outside the medium. What are its q,g scattering x-sections ?



- Survival probability computed embedding Higgs in QGP (2D+1 viscous SuperSonic hydrodynamics):

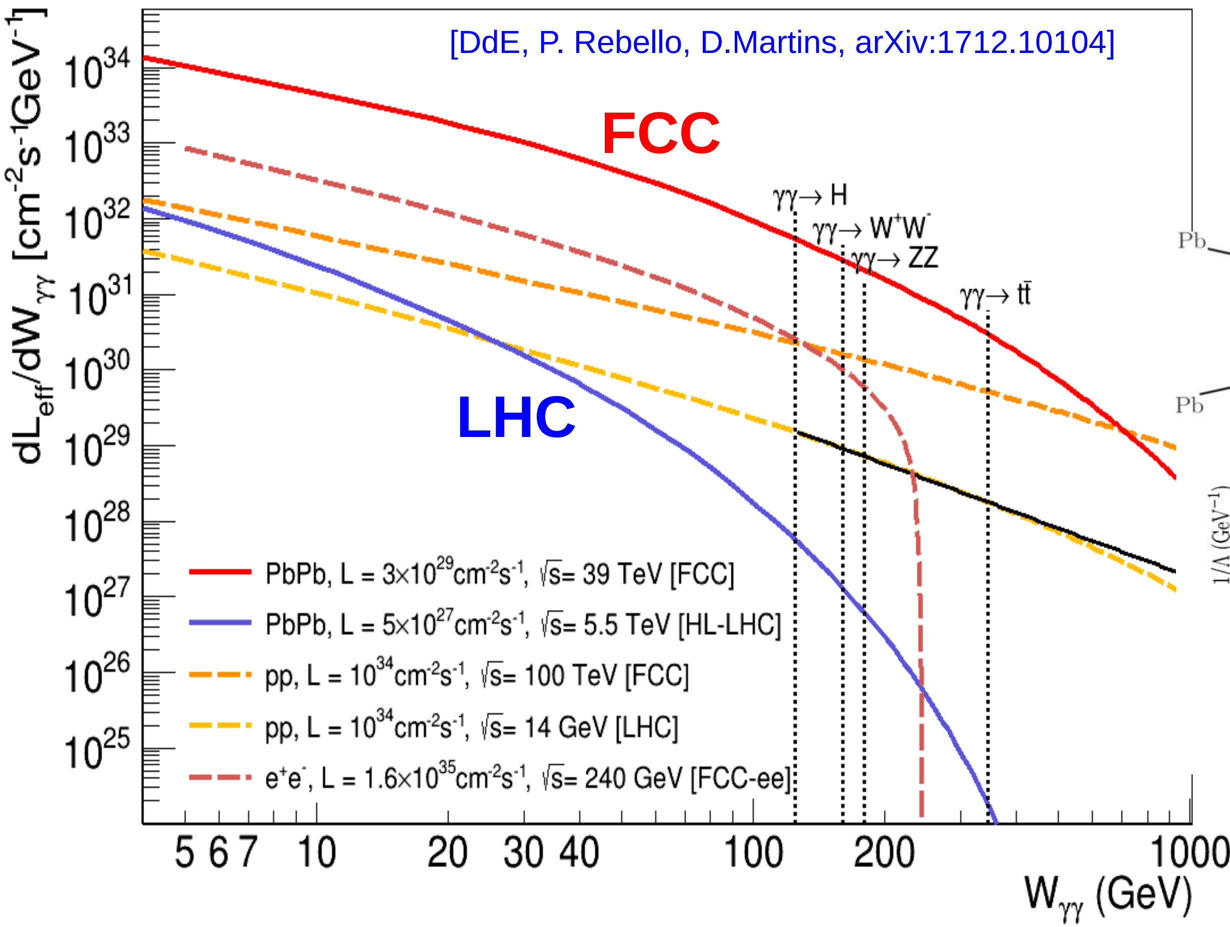
→ Higgs suppression factor in PbPb: ~15%, dominantly at p_T<100 GeV.



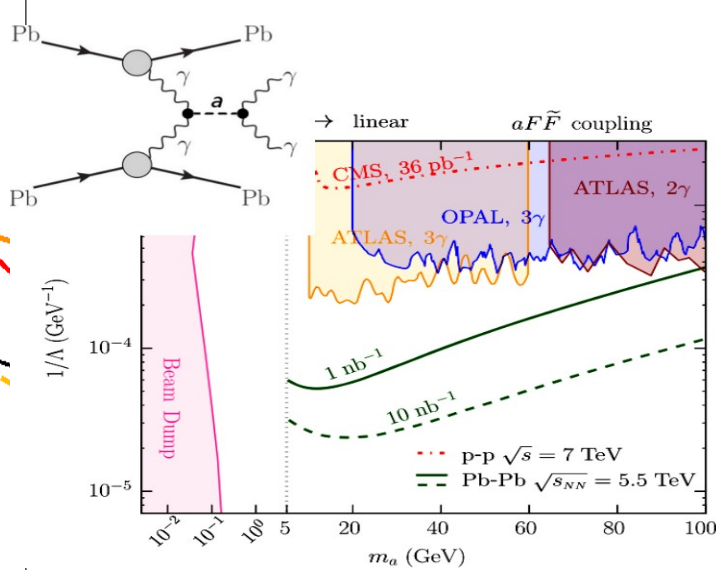
- Enough motivation to convince proton-proton community to run for 2 years PbPb at HE-LHC?

γ-γ luminosity: LHC vs. FCC

- "Low masses": ×2–3 higher effective lumi than at PbPb(5.5 TeV)
  Enough stats for: $\gamma\gamma \to \gamma\gamma$, $\gamma\gamma \to a(\gamma\gamma)$, double VM ($\gamma\gamma \to \rho\rho$, J/ψJ/ψ, ϒϒ)
- Lighter ions (higher lumi, E_γ) would be very beneficial to reach high $m_{\gamma\gamma}$



- Competitive limits in some BSM corners (e.g. axions):



[S.Knapen et al. PRL 118 (2017) 171801]

HE-LHC summary: pPb(17 TeV), PbPb(10.6 TeV)

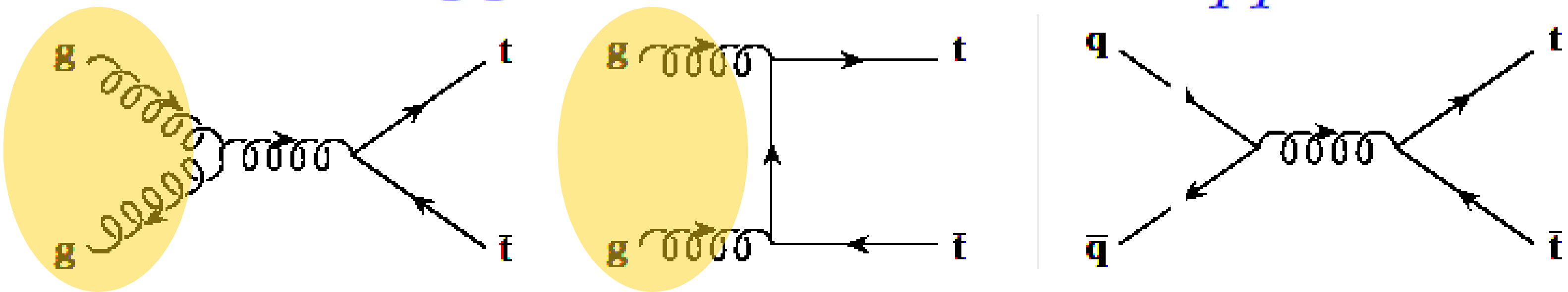
- Accessible HI physics at ×2 larger $\sqrt{s}$ and similar L_{int} than at LHC:
  - ➜ 20% larger particle densities than LHC. Low-x: ×2 smaller than LHC
    $dN_{ch}/d\eta|_{\eta=0}$~2.400
  - ➜ ×1.6 more charm than at LHC:
    Thermal charm participates in QGP EoS?
  - ➜ ×6 more bottom than at LHC:
    Enough to observe Y(1S) recombination?
  - ➜ ×6 more top-quarks than at LHC:
    High-x gluon studies accessible.
    Enough to study QGP space-time via jets from boosted-top decays.
  - ➜ ×4 times more Higgs bosons than at LHC:
    Observation of scalar boson requires ×20 more lumi.
  - ➜ ×2–3 more photon-photon effective luminosity than at LHC:
    Lighter ions more beneficial. Limits on BSM (axions).
- Higher lumis would help a lot: Lighter ions? Quantitative studies needed.

Back-up slides

Top-quark in nuclear collisions

- Top-pair production: QCD interaction dominated by gluon-induced processes (80% → 90% from LHC → FCC energies):

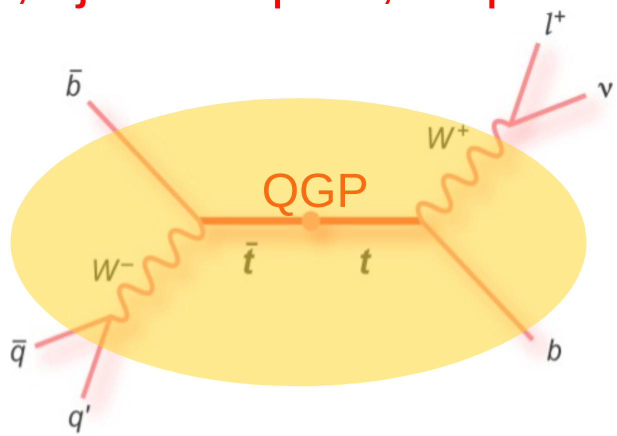
$gg \to t\bar{t}$ $q\bar{q} \to t\bar{t}$



- Top-quark decays (τ~0.1 fm/c) before hadronization into W+b ($BR\sim100\%, V_{tb}\sim1$). 3 final-states: 2bjets+ 4jets, 2jets+1lepton, 2leptons

t → b + 2jets (66%)
t → b + 1ℓ + MET(ν) (33%, w/o τ: 22%)

ttbar → bbar + 4jets (45%)
ttbar → bbar + 2jets + 1ℓ + MET(ν) (45%)
ttbar → bbar + 2ℓ + MET(2ν) (10%, w/o τ: 5%)

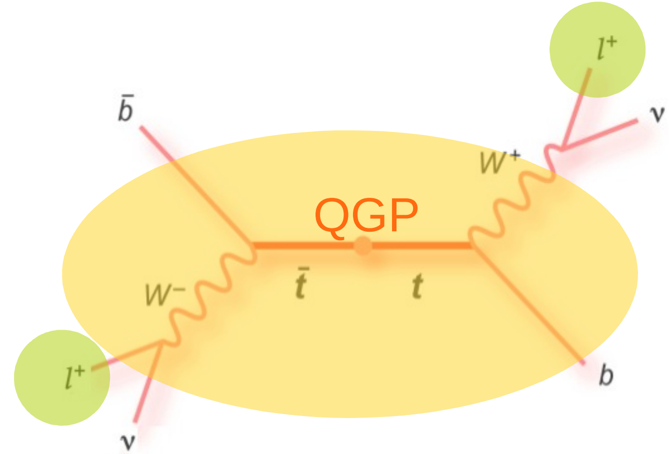


t-tbar (dileptons, AA): high-x gluon nPDFs probe

- Top-quark decays (τ~0.1 fm/c) before hadronization into W+b:

  Final isolated-leptons are unsensitive to final-state QGP interactions:

  t → b + 1ℓ + MET(ν) (33%, w/o τ: 22%)
  ttbar → bbar + 2ℓ + MET(2ν) (10%, w/o τ: 5%)

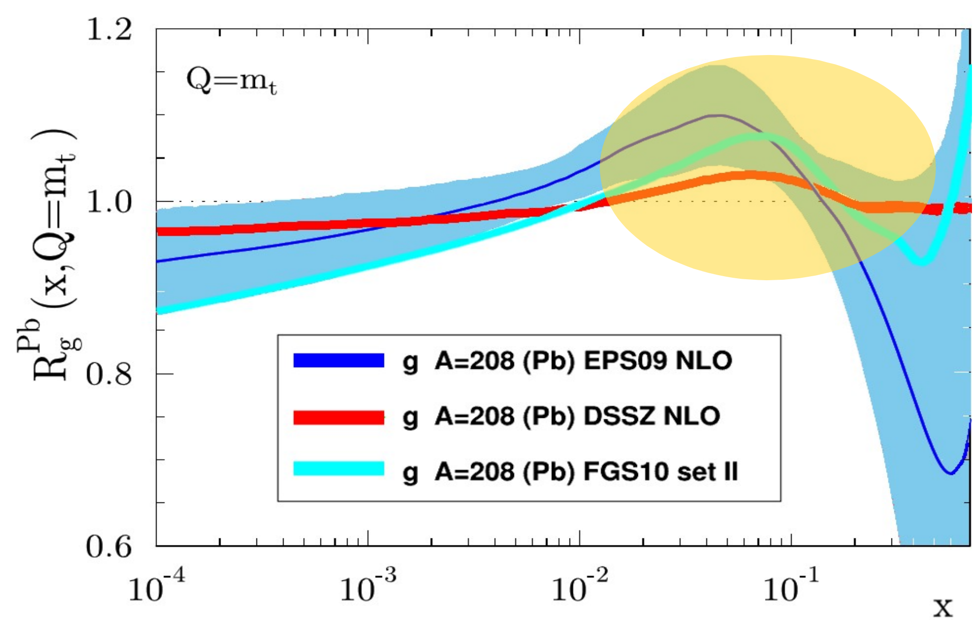


Cleanest decay channels: μ+μ,μ+e,e+e (BR~5%)

- Motivations for leptonic measurement:

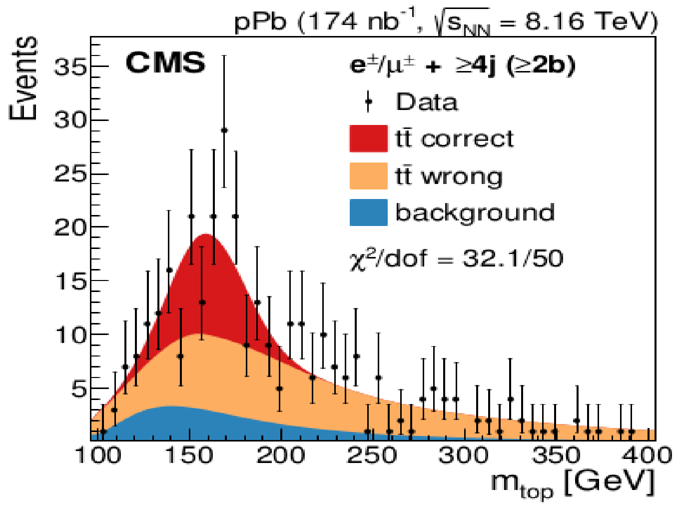
  → Cleanest channel for its first discovery in A-A collisions.

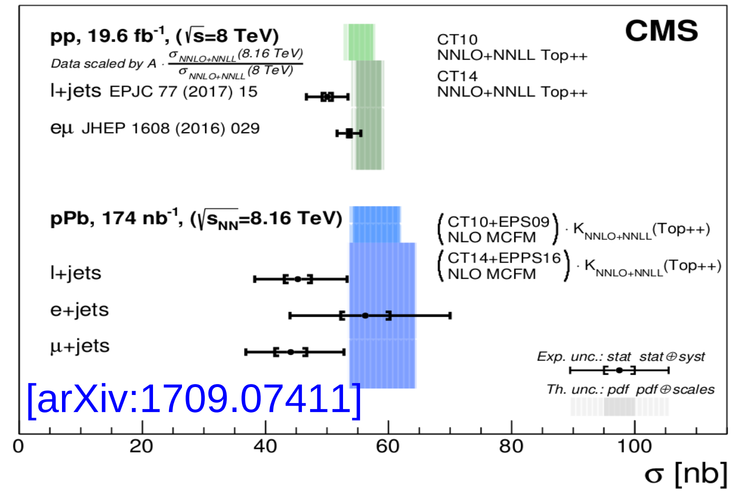
  → Probes gluon nPDF in unexplored high-x range: $x\sim0.3\text{–}10^{-3}$, $Q\sim m_t\sim173$ GeV



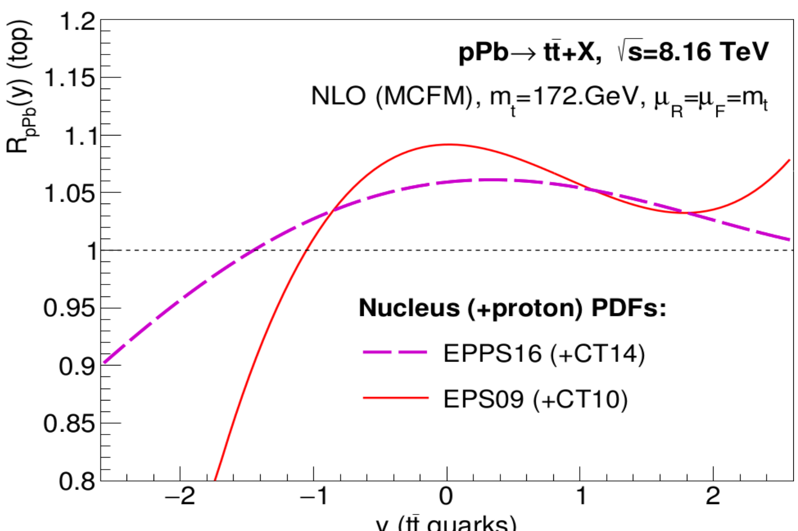
t-tbar (ℓ+jets, pA): high-x gluon nPDFs probe

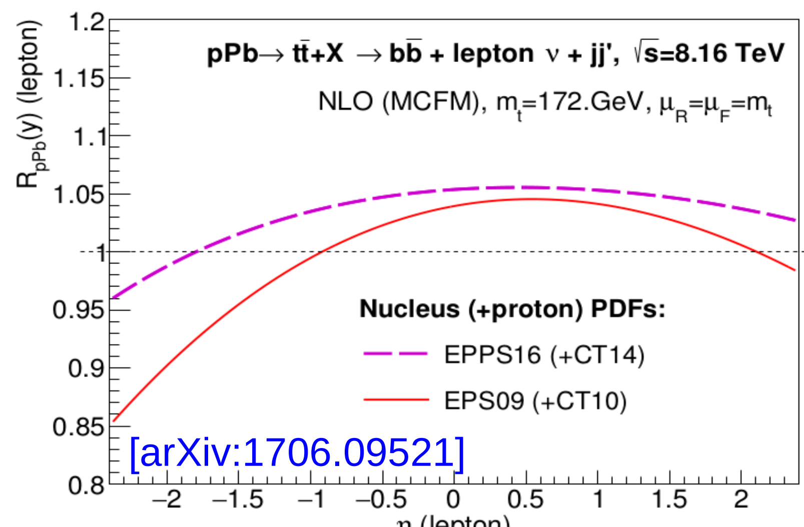
- In p-A collisions one can easily measure ttbar cross sections in the lepton+4jets channel, as demonstrated by CMS in pPb(8.16 TeV):



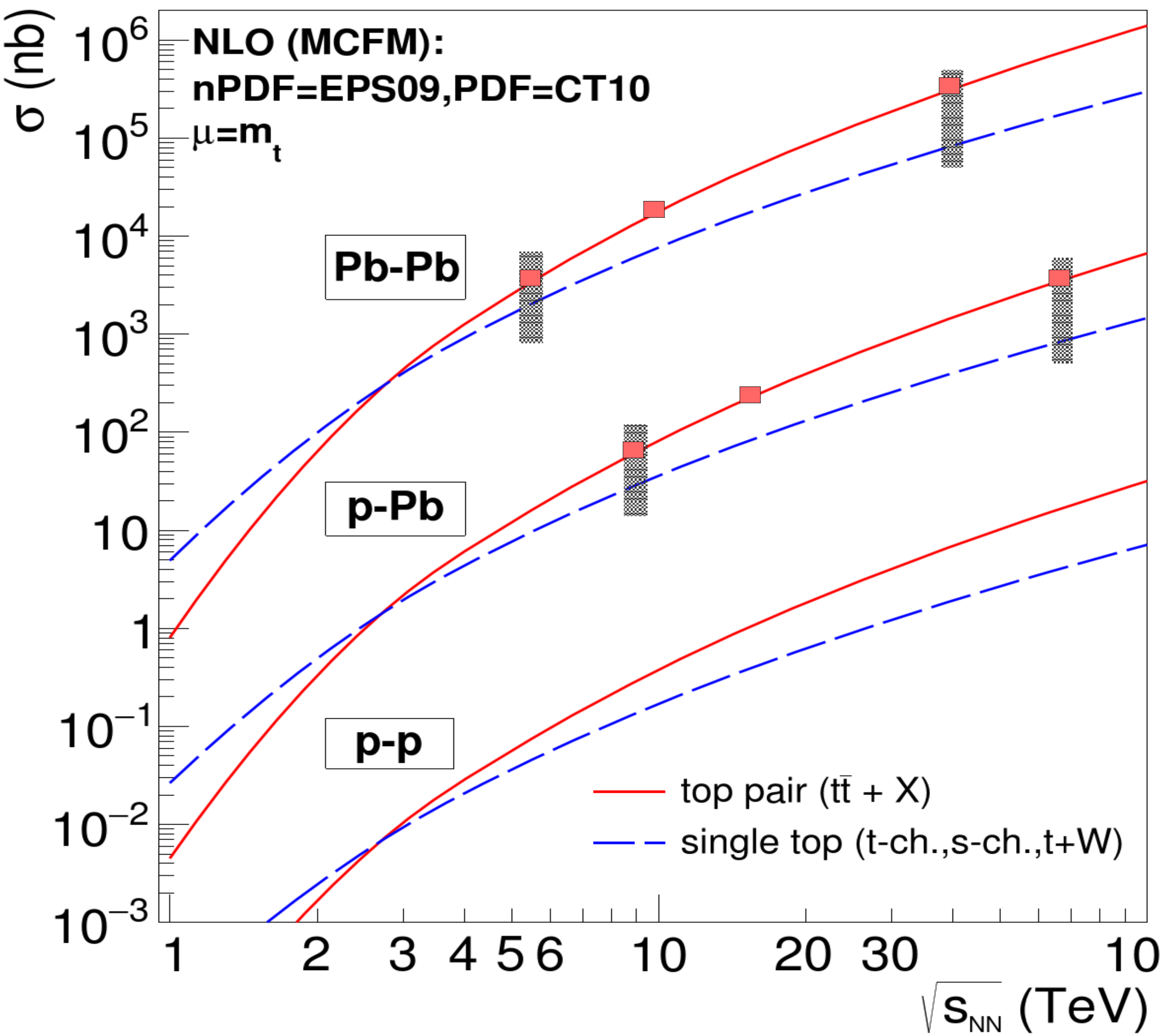


- Differential measurements in pPb at high-lumi will constrain nPDFs:





Top-quark at HE-LHC



- Pb-Pb:

LHC(5.5 TeV) = 3.4 μb
HE-LHC(10 TeV)= 20 μb
FCC(39 TeV) = 300 μb

- p-Pb:

LHC(8.8 TeV) = 60 nb
HE-LHC(16TeV)=250 nb
FCC(63 TeV) = 3.2 μb

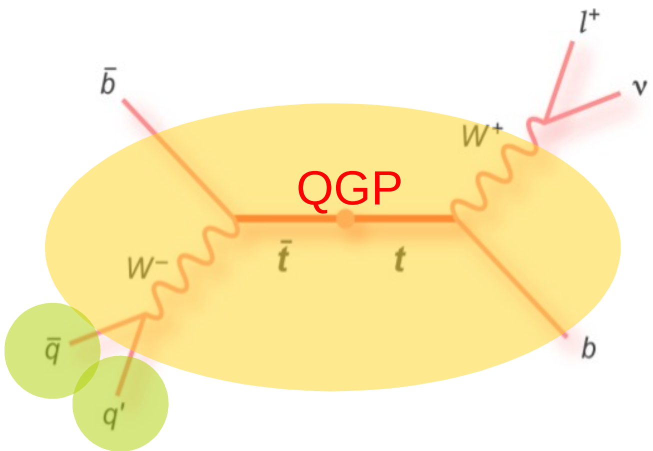
nPDF anti-shadowing increases σ_{tt} by +(2-8)%

→ Cross-sections increase by ×4–6 / 55–85 from LHC to HE-LHC / FCC

t-tbar (ℓ+jets, AA): QGP parton radiation probe

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

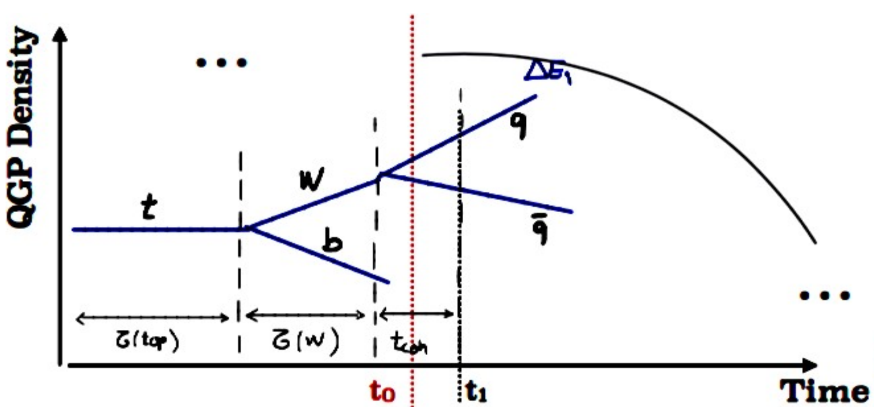
  t → b + 2jets (66%)
  ttbar → bbar + 2jets + 1ℓ + MET(ν) (45%)

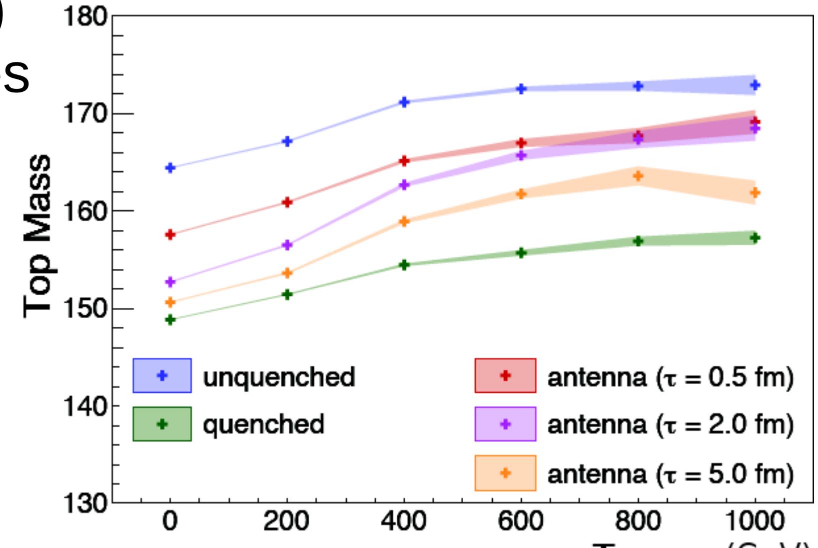


High-stats decay channel: 2jets+2ℓ (BR~45%)

- Motivations for 2j measurement:

→ Colour reconnection of decay b,q,q' ?
→ Boosted single-top (>1 TeV): τ>1 fm/c (enhanced gluon radiation in QGP?)
→ Boosted t-tbar = color-singlet probes medium opacity at diff. τ-scales

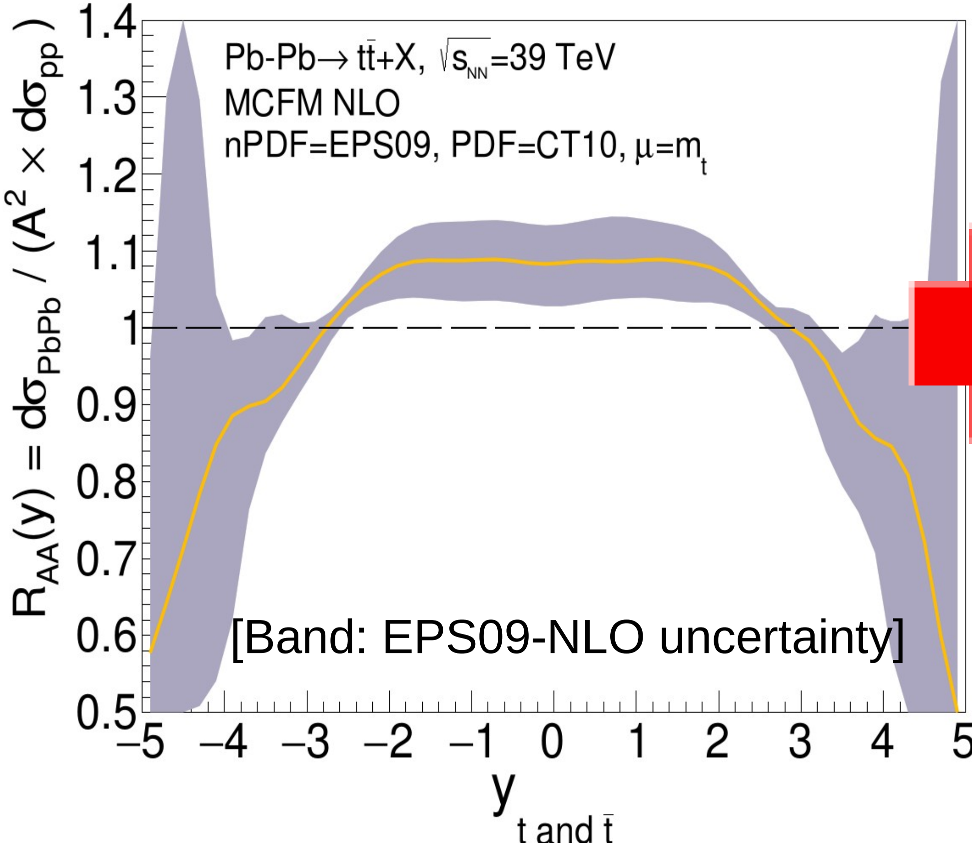




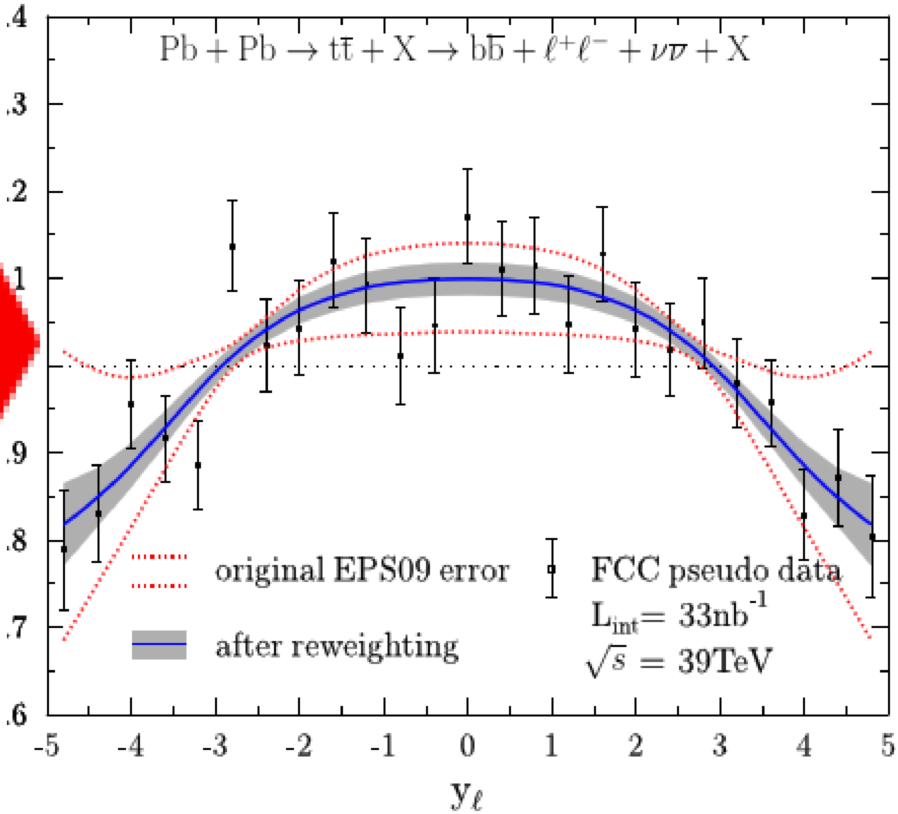
[Apolinário et al., 2017]

Pb-Pb(39 TeV)→ t-tbar: $R_{AA}(y)$ for top & $\ell^{\pm}$

- Top quarks y-distrib. (MC level):



- Isolated lepton y-distrib. after cuts: (Pseudodata for L_{int}= 33 nb^{-1})



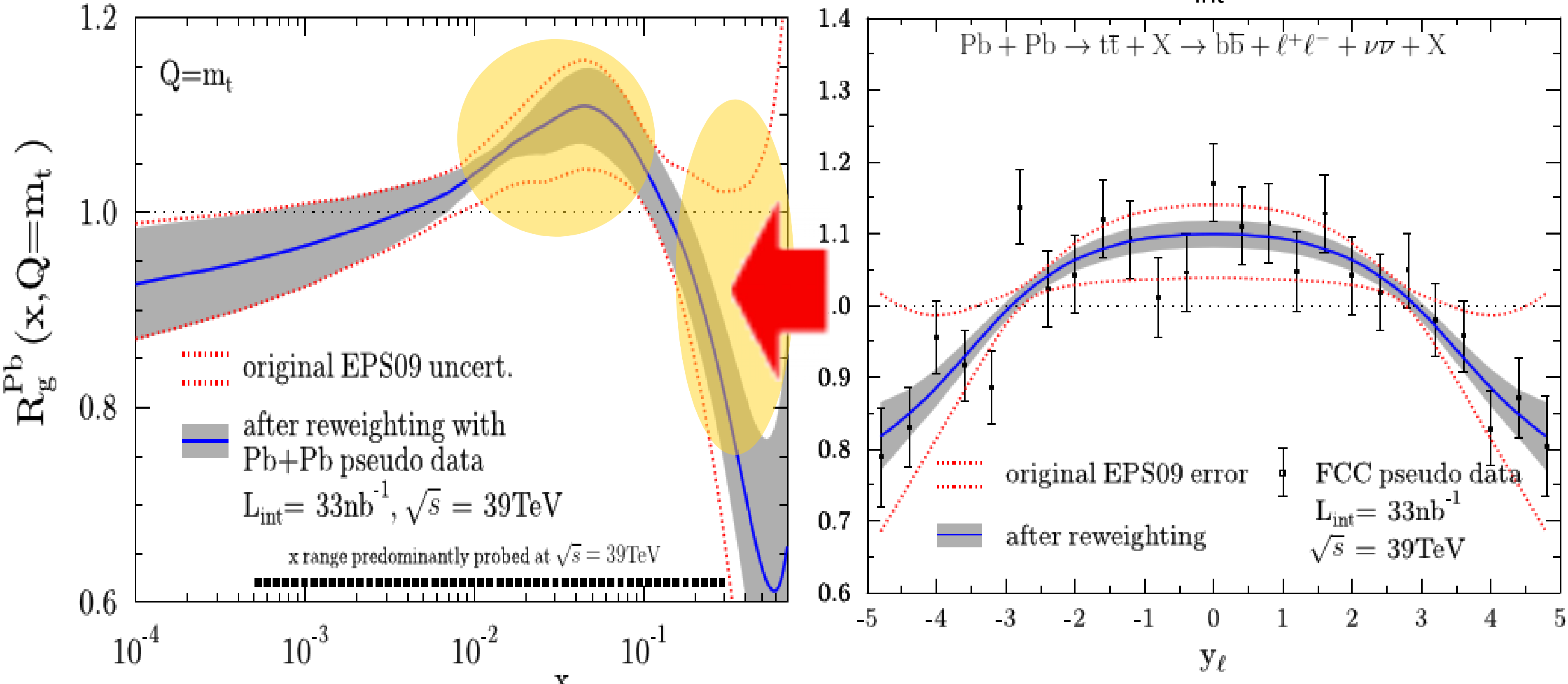
(stat. dominate over syst. uncertainties)

- nPDF effects (top): -20% (fwd/backwd.) +10% (central)
- nPDF effects (lepton): ±(10-20)% Strong constraining power

Pb-Pb(39 TeV)→ t-tbar: $R_{AA}(y)$ for $\ell^{\pm}$ & $R_g^{Pb}(x,Q^2)$

- Improved gluon density via Hessian PDF reweighting

- Isolated lepton y-distrib. after cuts: (Pseudodata for L_{int}= 33 nb^{-1})



(stat. dominate over syst. uncertainties)

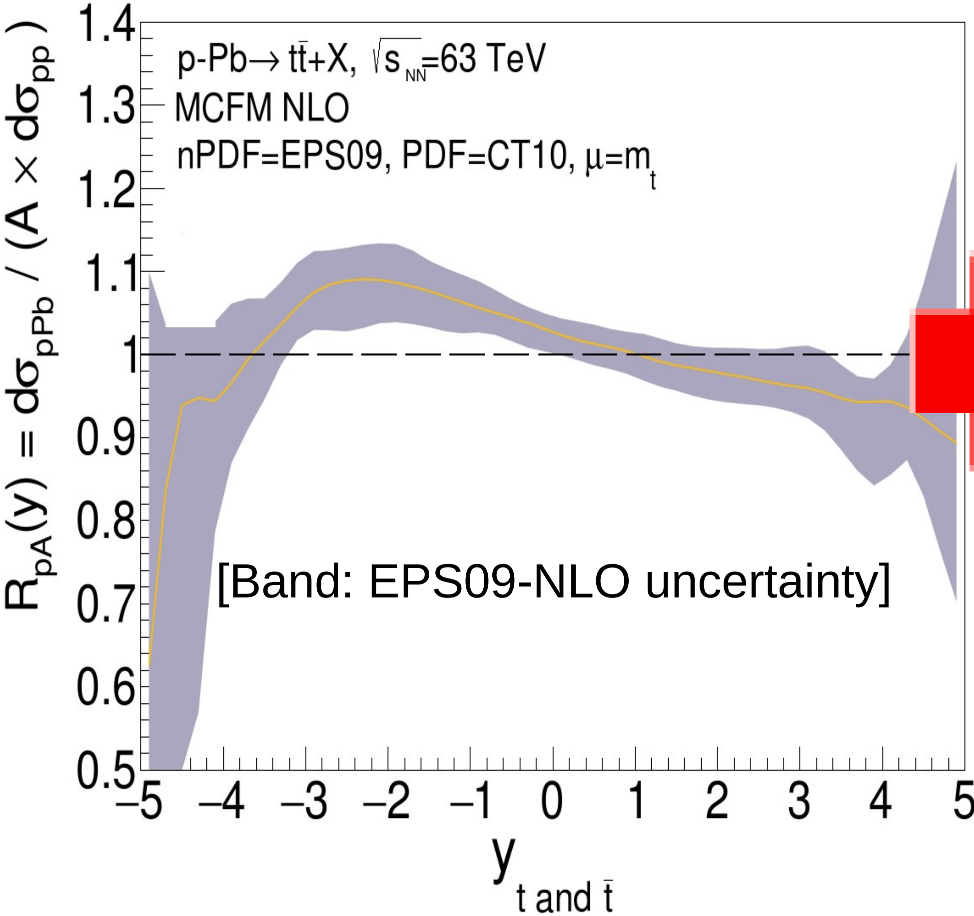
- Significant reduction in uncertainties at antishadowing (x~0.05) and EMC region (x~0.5) regions

- nPDF effects (lepton): ±(10-20)% Strong constraining power

Note: ×3.2 more stats with updated $\mathscr{L}$: ×2 better nPDF improvements

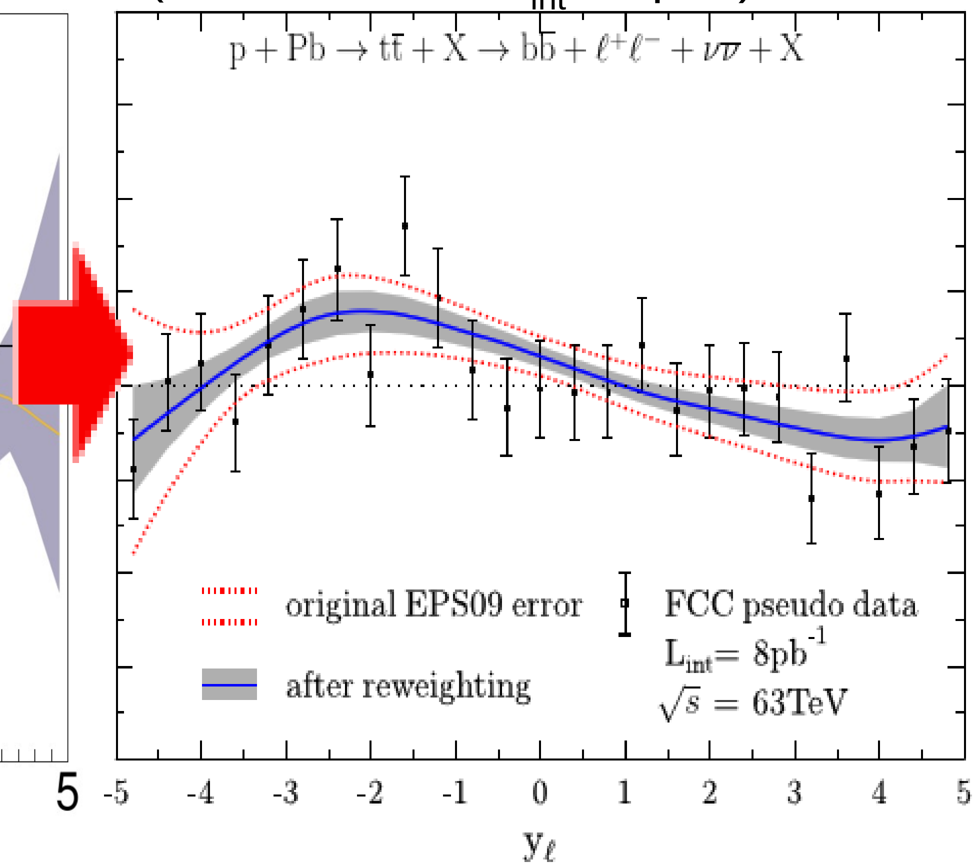
p-Pb(63 TeV)→ t-tbar: $R_{AA}(y)$ for top & $\ell^{\pm}$

- Top quarks y-distrib. (MC level):



- nPDF effects (top): -30% (bckwd)
  ±10% (fwd/cent)

- Isolated lepton y-distrib. after cuts:
  (Pseudodata for L_{int}= 8 pb^{-1})

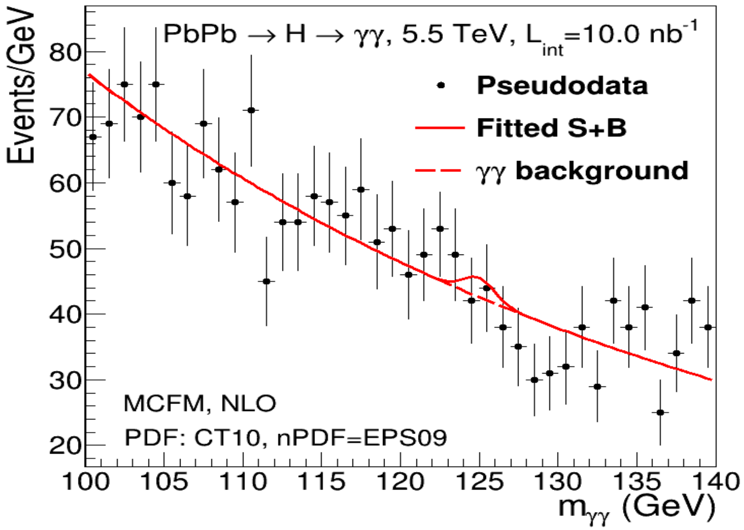


(stat. to dominate over syst. uncertainties)

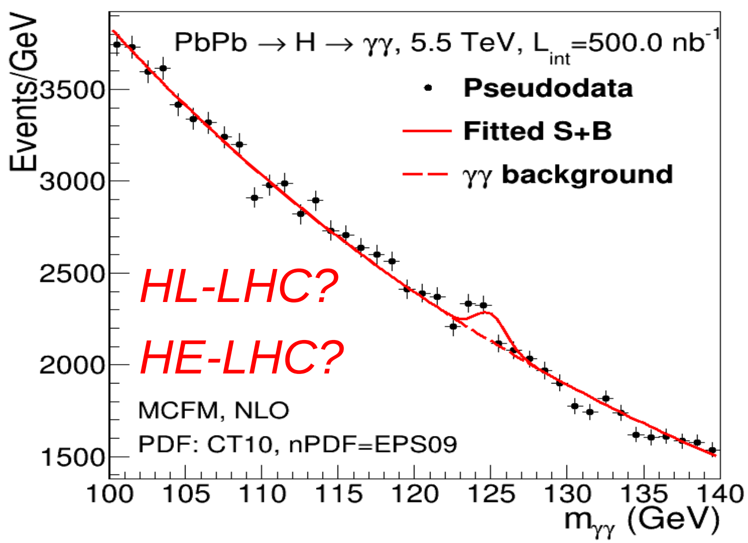
- nPDF effects (lepton): ±10%
  Strong constraining power

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 4*l*)

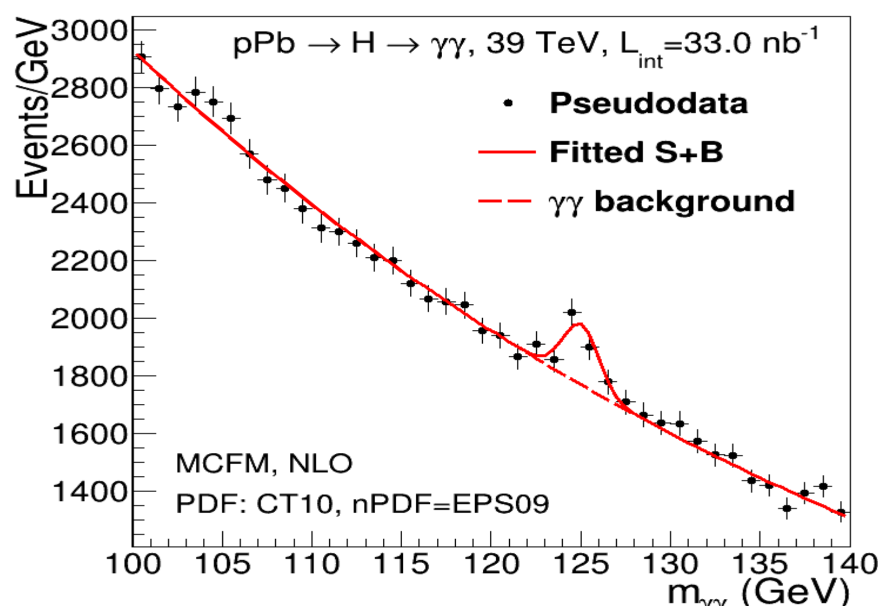
L_{int}= 500 nb^{-1}: 3σ evidence (HL-LHC?)

4.2σ combined with H(4*l*)

➜ FCC (39 TeV, 33 nb^{-1}):

Nominal lumi: S/√B~5.2σ observation

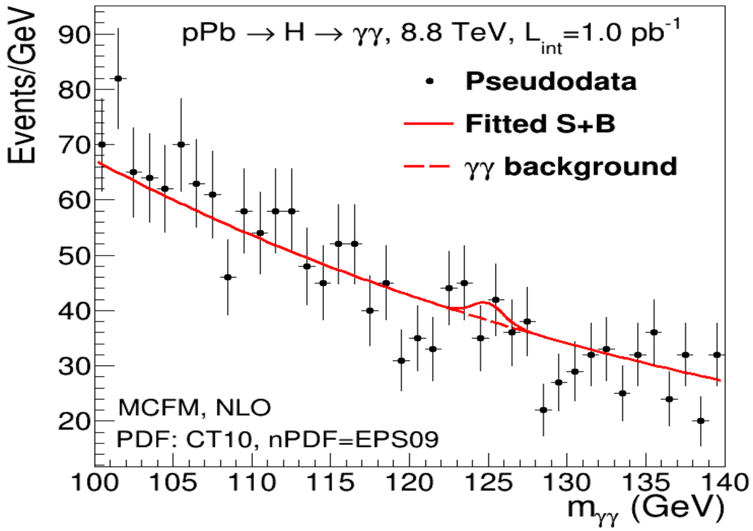
- Pb-Pb @ 39 TeV (L_{int}= 33 nb^{-1})



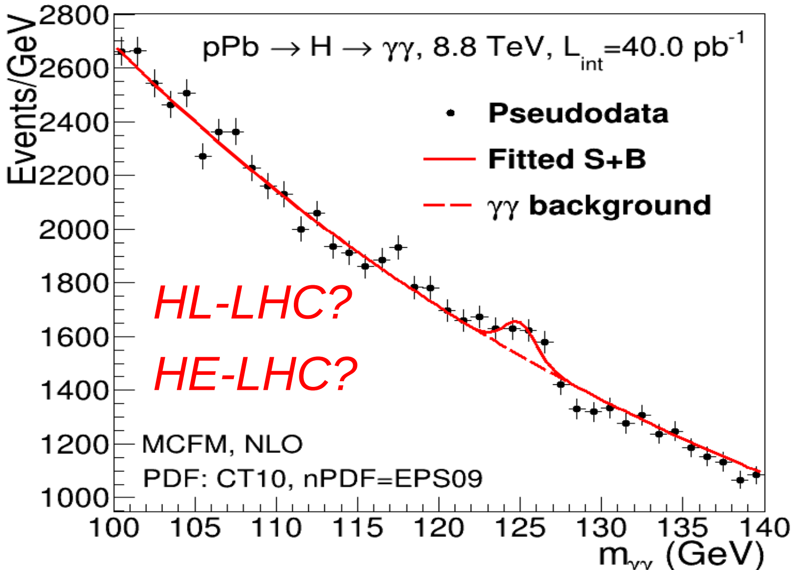
[DdE, arXiv:1701.08047]

$H \rightarrow \gamma\gamma$ 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: $S/\sqrt{B}$~0.4 (0.6, adding 4l)

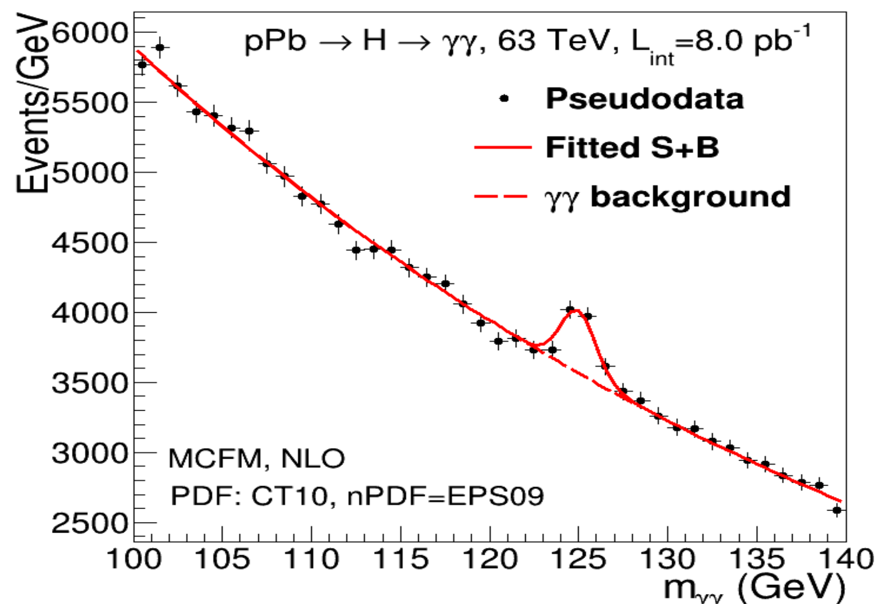
L_{int}= 40 pb^{-1}: 3σ evidence (HL-LHC?)

4.2σ combined with H(4l)

→ FCC (63 TeV, 8 pb^{-1}):

Nominal lumi: $S/\sqrt{B}$~7.7σ observation

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



[DdE, arXiv:1701.08047]